

중력파 데이터 분석

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2026 수치상대론 및 중력파 여름학교

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- CBC Parameter Estimation
 - 모수추정(parameter estimation)
 - LALInference
 - Bilby
 - PESummary
- 맺음 말(Closing)

큰 그림

중력파 실험이란?

(what is gravitational wave experiment)

중력파가 있나?

검출이 되나?

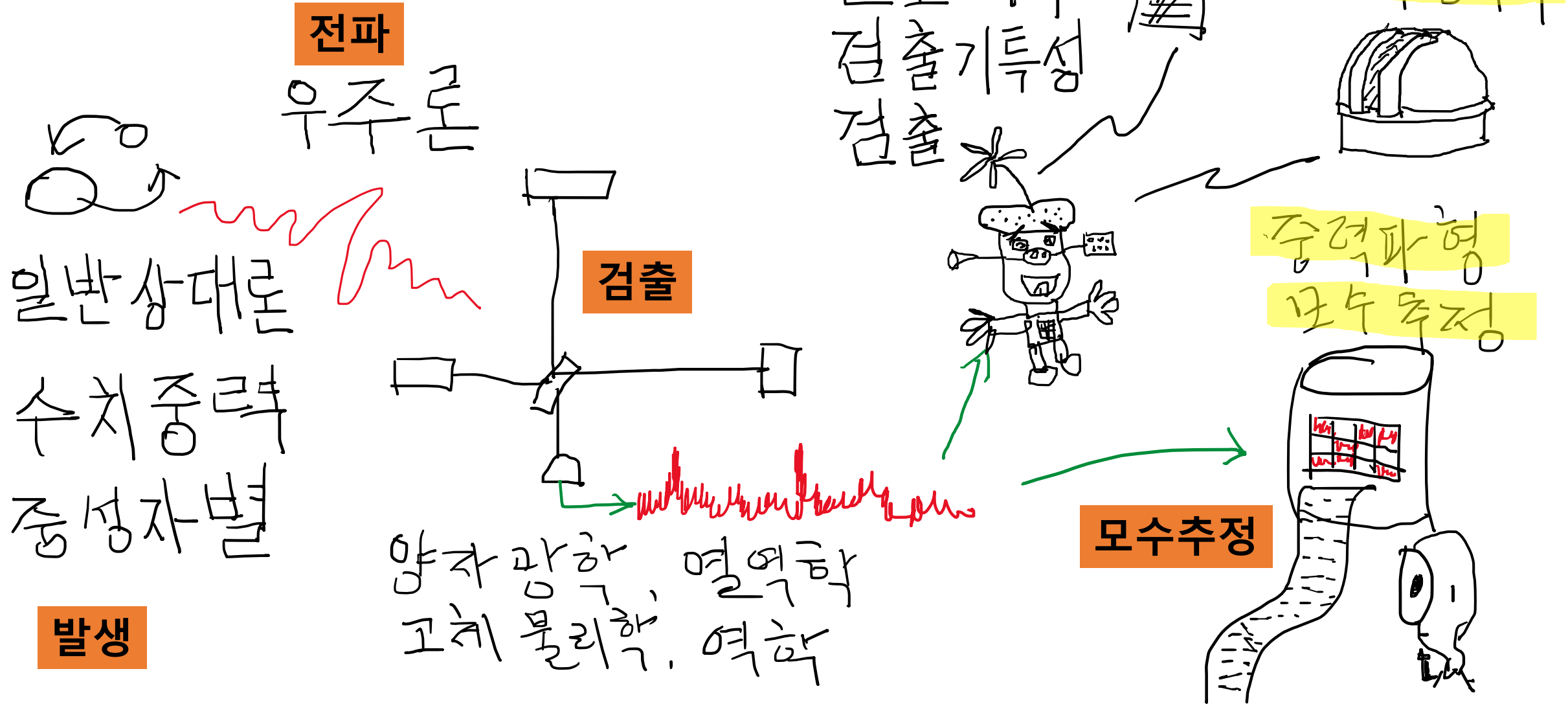
파원은 뭐지?

발생(generation)

검출(detection)

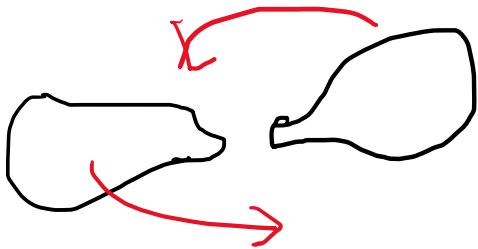
모수추정(parameter estimation)

큰 그림(중력과 실험)



중력과 발생

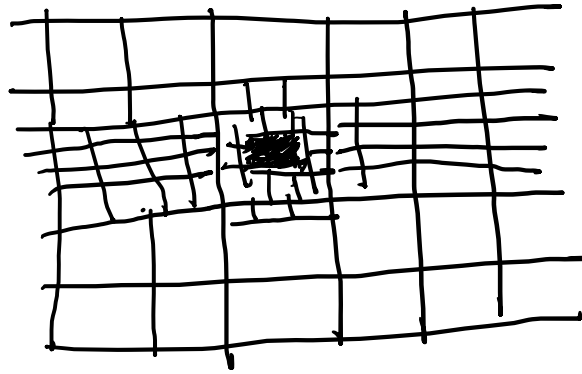
- 아인슈타인 방정식
- 선형근사
- 포스트뉴턴안 근사
- 수치중력
- 중성자별 상태 방정식



$$1916$$
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$\frac{GM}{Rc^2} \sim \frac{v^2}{c^2} \ll 1$$



우주론

아인슈타인방정식과 블랙홀

- 공변거리(comoving distance)
- 고유거리(proper distance)
- 광도거리(luminosity distance)

FRW 계량

$$c^2 d\tau^2 = c^2 dt^2 - a^2(t) \left(\frac{dr^2}{1-kr^2} + r^2 d\Omega^2 \right)$$

$$\chi = \int_{t_{src}}^{t_{obs}} \frac{cdt'}{a(t')} = c \int_0^z \frac{dz'}{H(z')}$$

$$D = a(t_{obs}) \chi$$

$$\tilde{h}(f_{obs}) = (1+z) \tilde{h}(f_{src})$$

$$\approx \frac{1}{d_L} \left(\underbrace{(1+z)M}_{M_{def}} \right)^{5/6} f^{-7/6} e^{i4\pi f D}$$

$f \rightarrow f_{obs}$

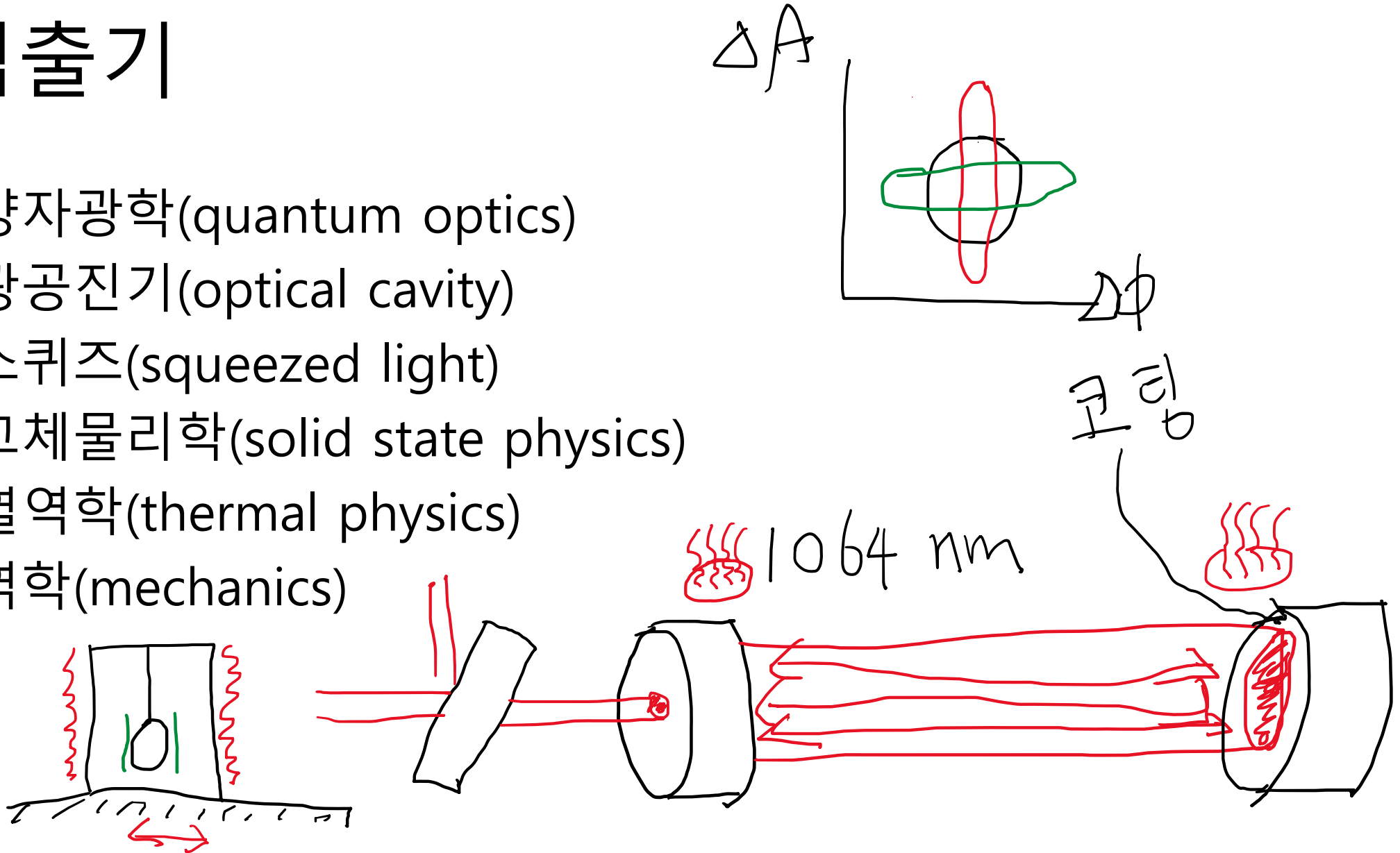
$$d_L = (1+z) D$$

$$H^2 = \frac{8\pi G}{3} \rho$$

$$f_{src} = (1+z) f_{obs}$$

검출기

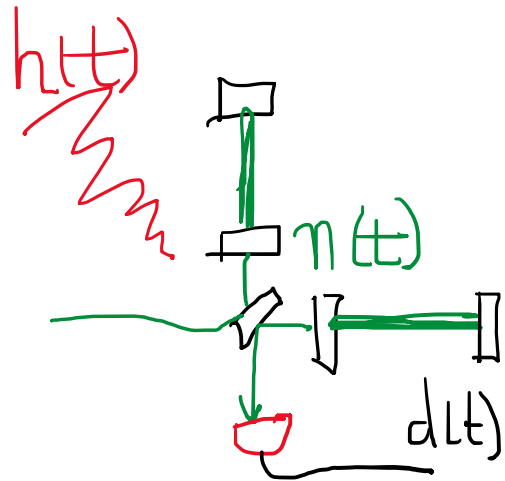
- 양자광학(quantum optics)
- 광공진기(optical cavity)
- 스퀴즈(squeezed light)
- 고체물리학(solid state physics)
- 열역학(thermal physics)
- 역학(mechanics)



신호처리

중력파 신호탐색

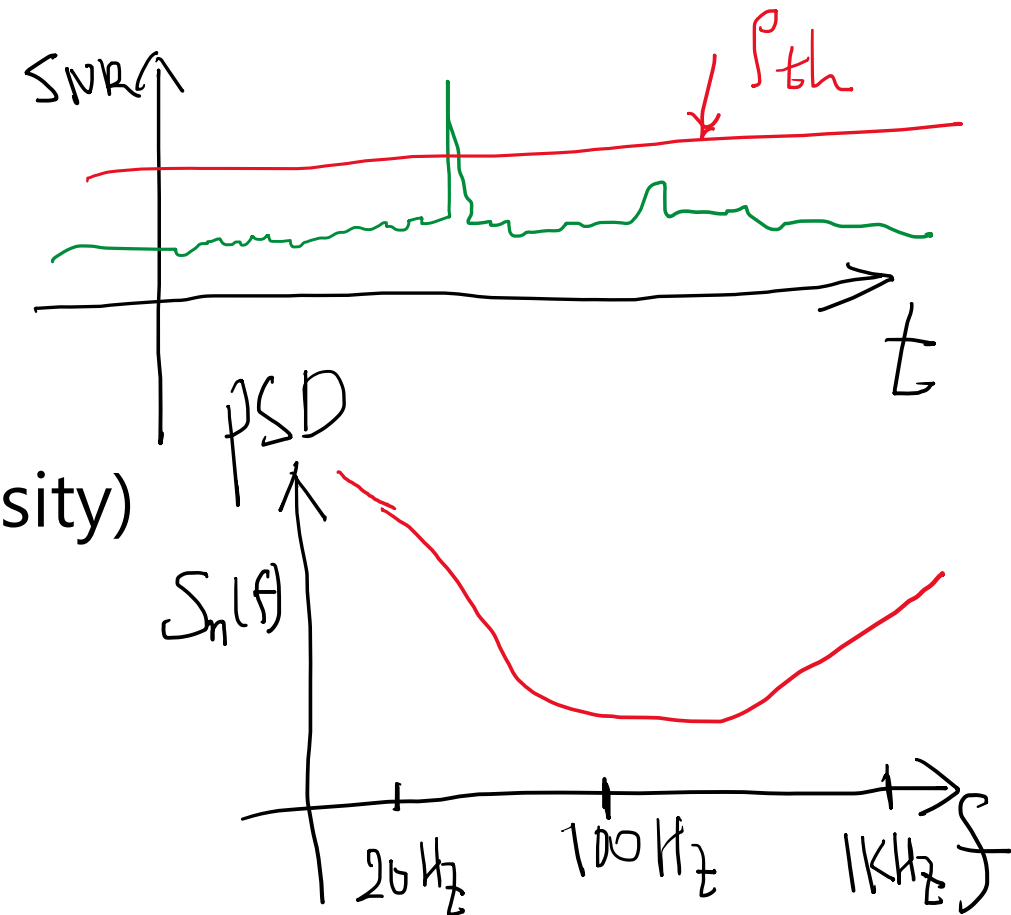
- 정합필터(Matched Filter)
- 전력스펙트럼밀도(Power Spectral Density)
- 검출(Search)
- 신호대잡음비(Signal to Noise Ratio)



$$\Lambda(h, |s) = e^{(s, h) - \frac{1}{2} (h, h)}$$

$$(s, h) = 4 \operatorname{Re} \int_0^{\infty} \frac{\tilde{z}(f) \tilde{h}^*(f)}{S_n(f)} df$$

$$\sigma^2 = (g, g)$$



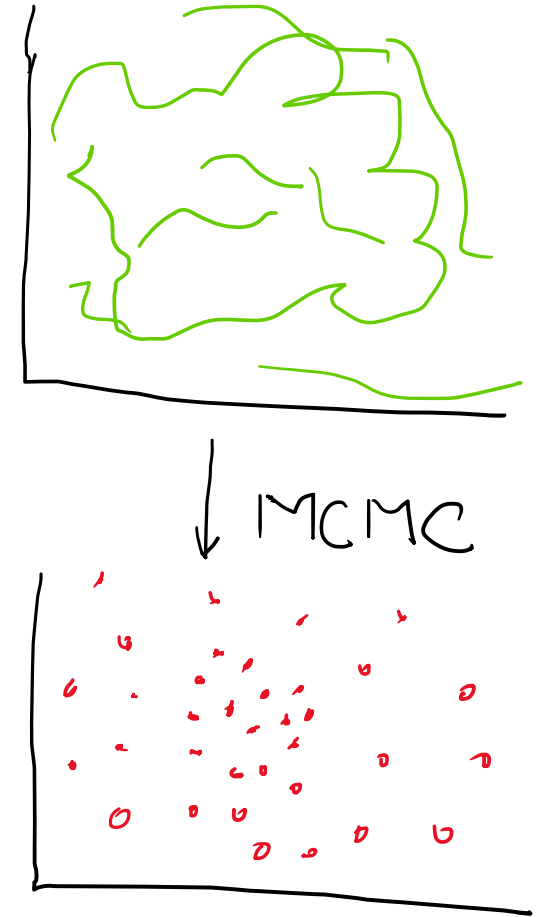
$$\rho^2 = (h, h), \quad \rho = \frac{\mathcal{Z}}{\sigma} \quad \text{template}$$

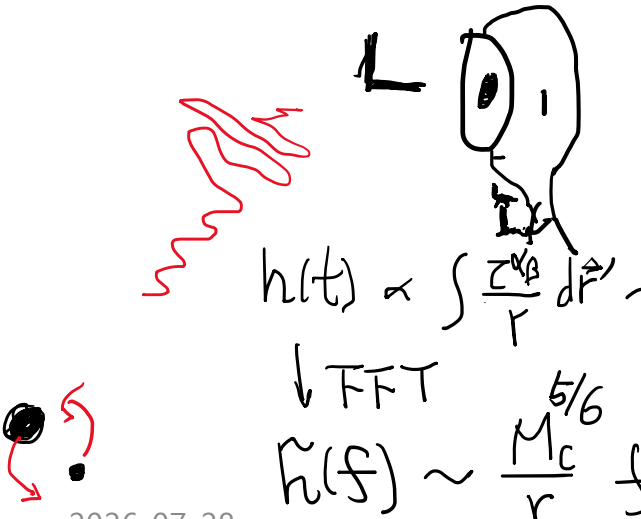
$$h(t) = A g(t), \quad x = (s, g)$$

모수추정(Parameter Estimation)

중력파 데이터 분석

- 중력파형(Waveforms)
- 통계처리(Statistical Analysis)
- 베이지언 추정(Bayesian Inference)
- 몬테카를로(Markov Chain Monte Carlo)
- 네스티드(Nested)





$$h(t) \propto \int \frac{z^{k_B}}{r} d\vec{r}' \sim \frac{\ddot{I}}{r}$$

$$\downarrow \text{FFT}$$

$$\tilde{h}(f) \sim \frac{M_c^{5/6}}{r} f^{-7/6} e^{i\varphi(f)}$$

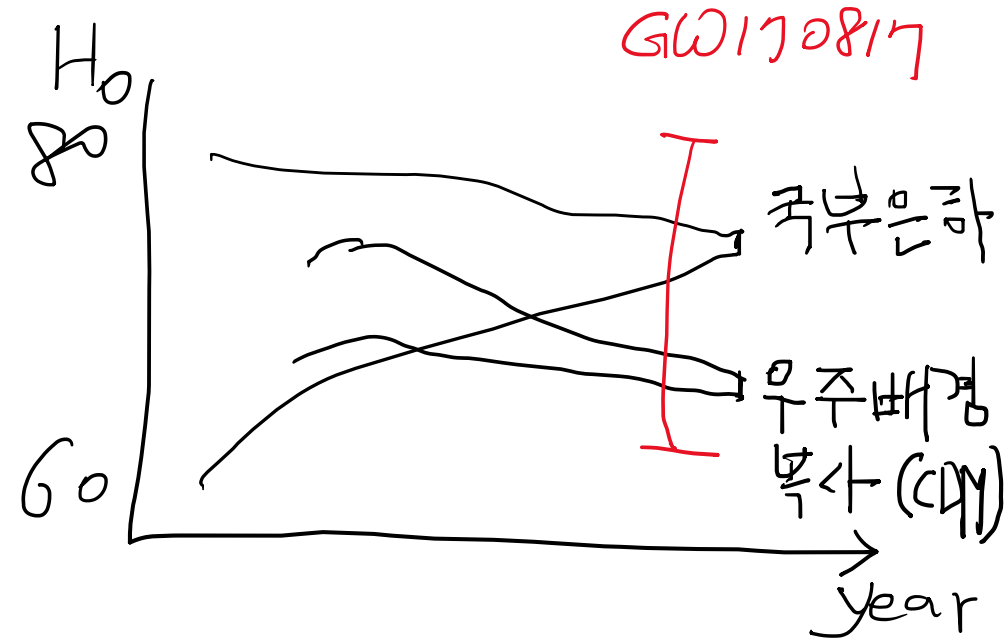
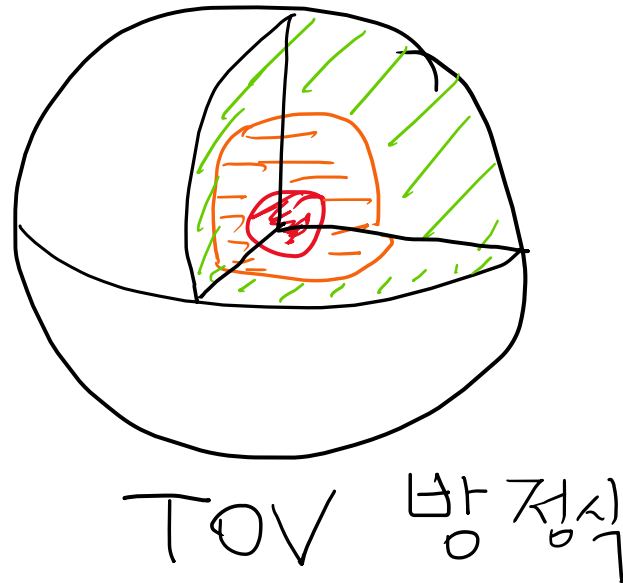
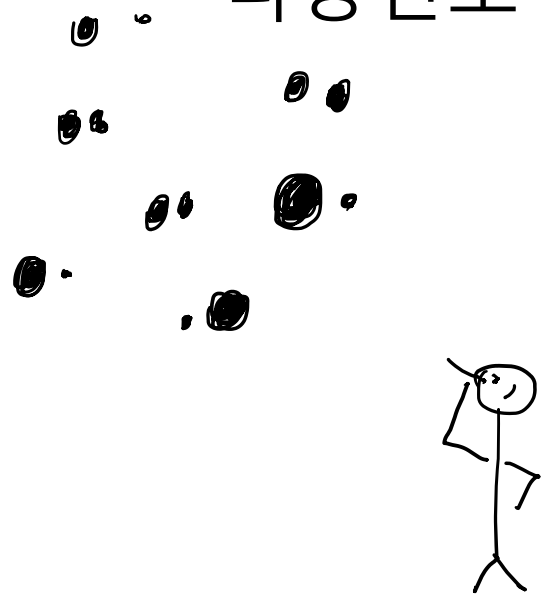
$$d(t) = n(t) + h(t)$$

$$\mathcal{L} \sim e^{-\frac{1}{2}(d-h, d-h)}$$

$$p(\vec{\theta} | \vec{d}) \sim \mathcal{L}(\vec{d} | \vec{\theta}) p(\vec{\theta})$$

천체물리학(Astrophysics)

- 블랙홀 병합율(Blackhole Merger rate)
- 중성자별 상태 방정식(Equation of State of NS)
- 허블 상수(Hubble Constant)
- 다중신호 천문학



Gravitational Wave

$$g_{\mu\nu} \cong \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1+h_{11} & h_{12} & 0 \\ 0 & h_{12} & 1-h_{11} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G}{c^4}T_{\mu\nu}$$

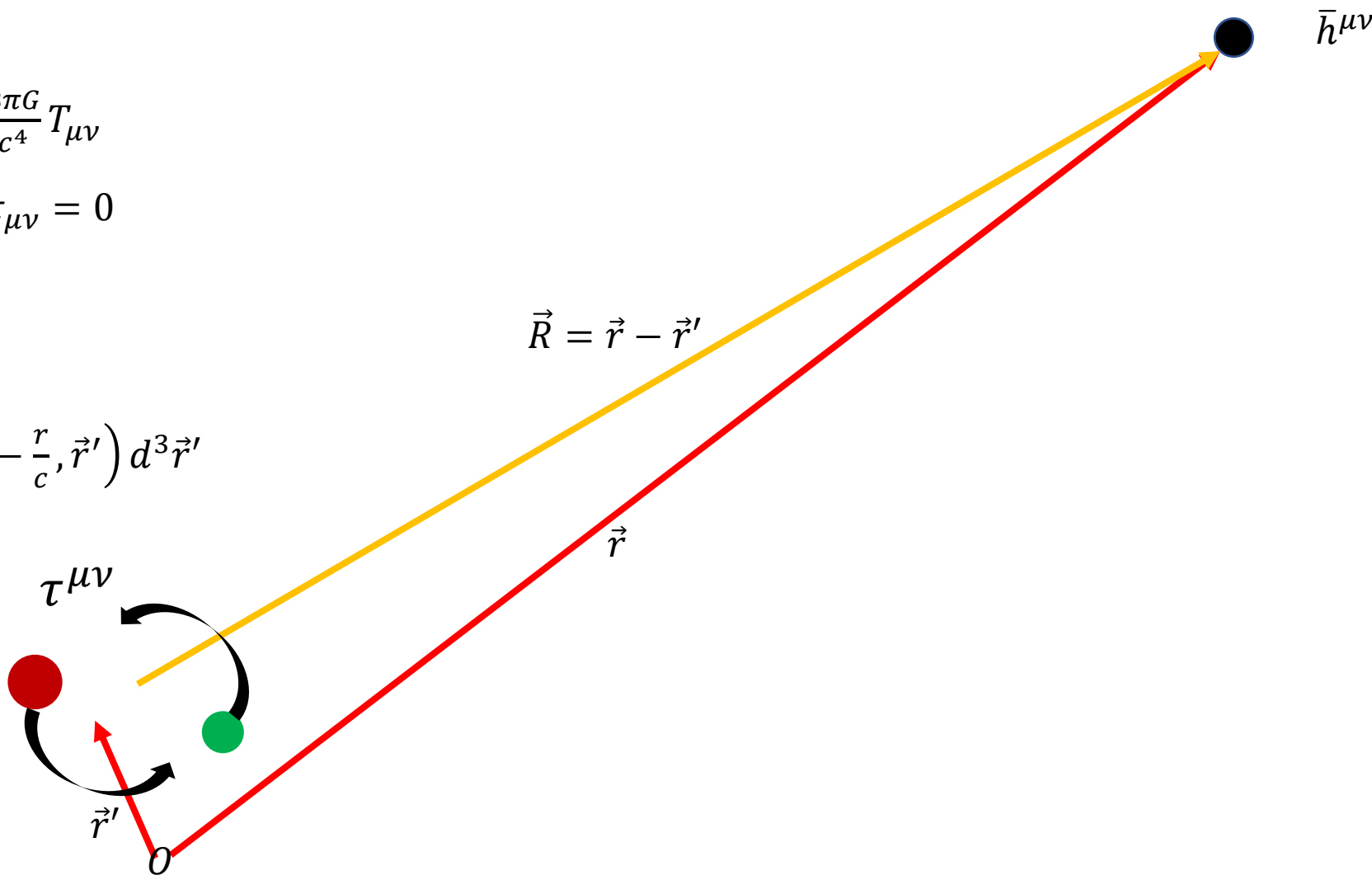
$$\square \bar{h}_{\mu\nu} = -\frac{16\pi G}{c^4}\tau_{\mu\nu}, \quad \partial^\mu \tau_{\mu\nu} = 0$$

$$\|\vec{r} - \vec{r}'\| \cong r, \quad r \ll r'$$

$$t - \frac{\|\vec{r} - \vec{r}'\|}{c} \cong t - \frac{r}{c}$$

$$\bar{h}^{\mu\nu}(t, \vec{r}) \cong \frac{4G}{c^4 r} \int \tau^{\mu\nu} \left(t - \frac{r}{c}, \vec{r}' \right) d^3\vec{r}'$$

$$h_{ij}^{TT} \cong \frac{2G}{c^4 r} \ddot{I}_{ij}^{TT} \left(t - \frac{r}{c} \right)$$



Solution in vacuum

- $\square \bar{h}_{\mu\nu} = 0, \partial^\mu \bar{h}_{\mu\nu} = 0$
- $\bar{h}_{\mu\nu} = A_{\mu\nu} \cos(k_\alpha x^\alpha - \phi_{(\mu)(\nu)}), \eta^{\alpha\beta} k_\alpha k_\beta = 0$
- $x^\alpha = \{ct, x, y, z\}, k^\alpha = \left\{\frac{\omega}{c}, k^x, k^y, k^z\right\}$
- $k_\alpha x^\alpha = -\omega t + \vec{k} \cdot \vec{x}, \omega = 2\pi f = c |\vec{k}|$
- $\bar{h}_{\mu\nu} = A_{\mu\nu} \cos(\omega t - \vec{k} \cdot \vec{x} + \phi_{(\mu)(\nu)}), \bar{h}_{\mu\nu} k^\nu = 0$
- $\xi^\alpha(t, \vec{x}) = B^\alpha \cos(\omega t - \vec{k} \cdot \vec{x} + \phi_{(\alpha)})$
- $x'^\mu = x^\mu + \xi^\mu$

This equations reduce 10 to 6

Transverse Traceless coordinate

- $\bar{h}'_{\mu\nu} U'^{\nu} = 0, \eta^{\mu\nu} \bar{h}'_{\mu\nu} = 0, \bar{h}'_{\mu\nu} k'^{\nu} = 0, \bar{h}'_{\mu\nu} = h'_{\mu\nu}$ TT gauge

Trace reversed and original is same in TT gauge

Global Lorentz transformation $x'^{\alpha} = \Lambda^{\alpha}_{\beta} x^{\beta}$ preserve all these properties.

Choose coordinate to be $U^{\mu} = \frac{dx^{\mu}}{dt} = (1, 0, 0, 0)$

Rotate coordinate to be $k^{\mu} = \left(\frac{\omega}{c}, 0, 0, \frac{\omega}{c}\right)$

$h_{\mu\nu} =$

$$\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_{11} & h_{12} & 0 \\ 0 & h_{12} & -h_{11} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$h_{\mu 0} = 0$$

$$h_{\mu 3} = 0$$

$$h_{11} + h_{22} = 0$$

Transverse Traceless coordinate

- $h_+ \equiv h_{11} = -h_{22}, h_{\times} \equiv h_{12} = h_{21}$

- $$h_{\mu\nu}^{TT}(t, \vec{x}) = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+(t, \vec{x}) & h_{\times}(t, \vec{x}) & 0 \\ 0 & h_{\times}(t, \vec{x}) & -h_+(t, \vec{x}) & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+\left(t - \frac{z}{c}\right) & h_{\times}\left(t - \frac{z}{c}\right) & 0 \\ 0 & h_{\times}\left(t - \frac{z}{c}\right) & -h_+\left(t - \frac{z}{c}\right) & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

- $h_+(t, \vec{x}) = A_+ \cos\left[\omega\left(t - \frac{z}{c}\right) + \phi_+\right]$

- $h_{\times}(t, \vec{x}) = A_{\times} \cos\left[\omega\left(t - \frac{z}{c}\right) + \phi_{\times}\right]$

- $h_{\mu\nu}^{TT}(t, \vec{x}) = h_+(t, \vec{x})e_{\mu\nu}^+ + h_{\times}(t, \vec{x})e_{\mu\nu}^{\times}$

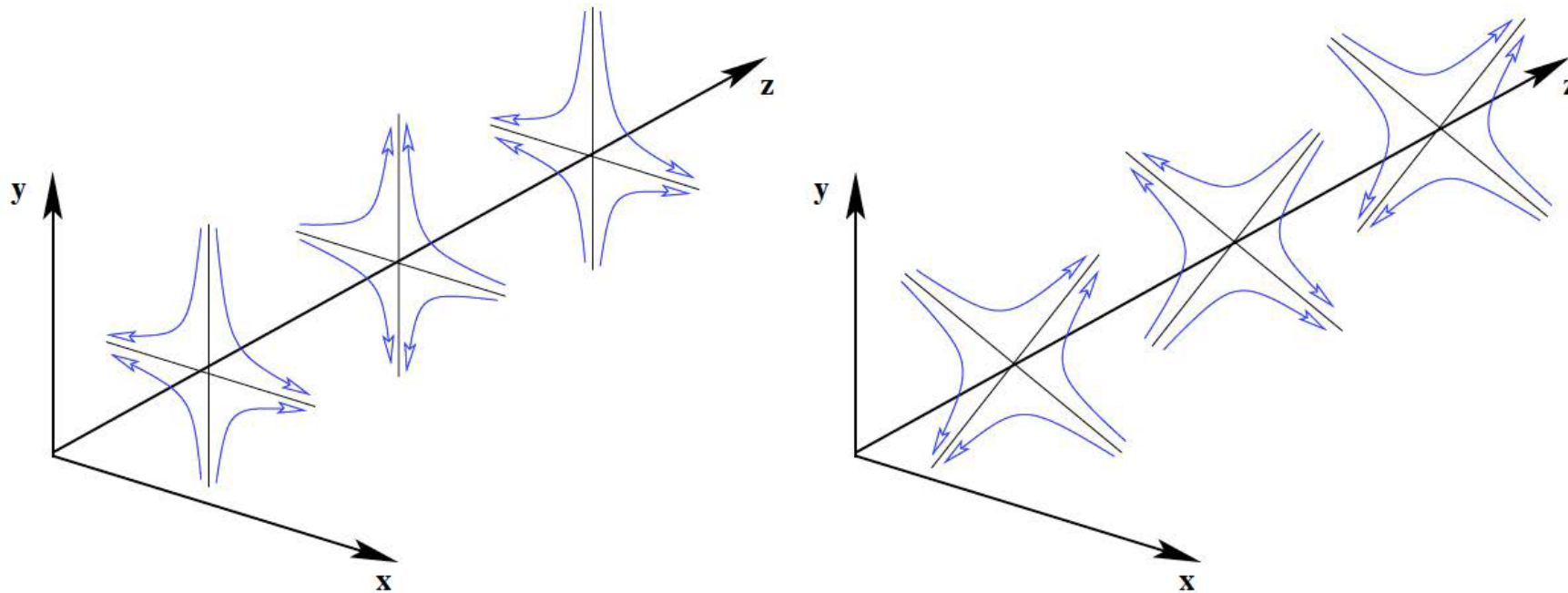
$$e_{\mu\nu}^+ = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}, e_{\mu\nu}^{\times} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

- $R_{x0x0}^{TT} = -R_{y0y0}^{TT} = -R_{x0xz}^{TT} = R_{y0yz}^{TT} = R_{xzxz}^{TT} = -R_{yzyz}^{TT} = -\frac{1}{2}\partial_0^2 h_+$

- $R_{x0y0}^{TT} = -R_{x0yz}^{TT} = -R_{y0xz}^{TT} = R_{xzyz}^{TT} = -\frac{1}{2}\partial_0^2 h_{\times}$

GWs and lines of force

Lines of force for h_+^{TT} and $h_\times^{\text{TT}}$



GW Sources

Modelled

Unmodelled

Transient

Compact Binary Coalescence



Burst



CBC, Supernovae, GRB, Pulsar glitch

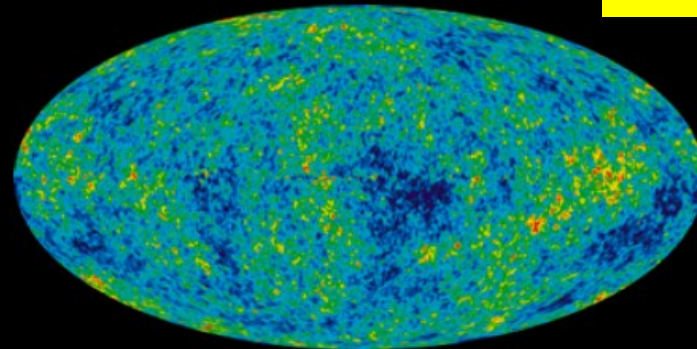
Continuous

Continuous waves



Pulsar rotation, Binary

Stochastic



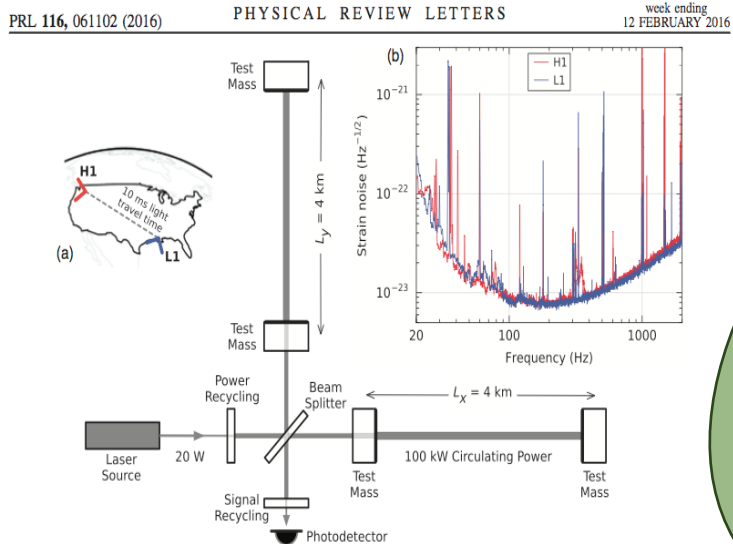
Early Universe, Astronomical origin

CBC Search

Signal Detection

- Matched filter to detect the signal from noises(well known technique)
- Difficulties for gravitational wave
 - Waveform is not known perfectly
 - Detector noise is not stationary Gaussian
- Extended techniques
 - Quadrature sum of complex matched filter output for unknown phase
 - FFT for various arrival times
 - Template bank to cover parameter space
 - Frequency-band limited matched filter to veto glitches(non Gaussian)

Question

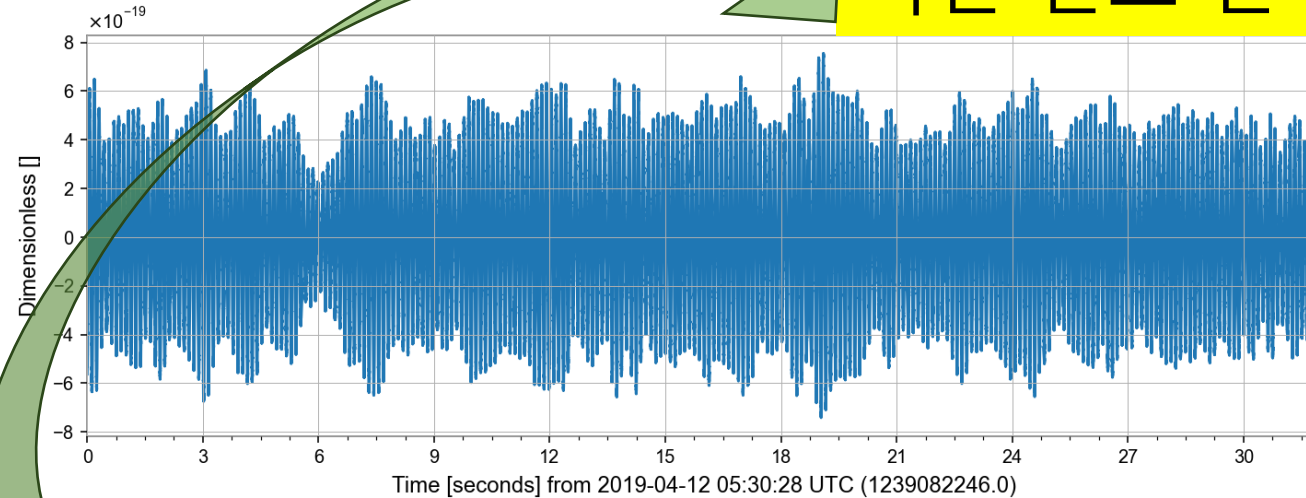


이런 관측기에서 나온

From this kind Detector

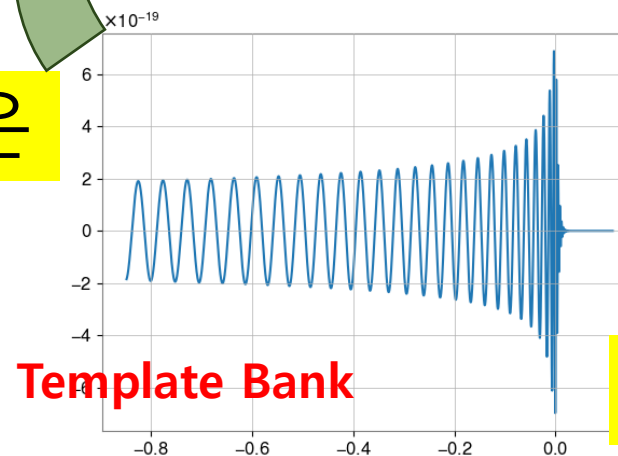
Get this kind of Signal

이런 신호 안에



Check for this kind of Template Waveform

이런 중력파신호가



존재하는 시간과 확률은 얼마인가?

When and How probable?

Basic Workflow

- Calculate matched-filter output for each template waveform
- Compute chi-square discriminant to veto glitches
- Select candidate events or triggers
- Additional works
 - Data selection and conditioning
 - Template bank generation
 - Vetoes based environmental data and coincidence
 - Computation false alarm rate(FAR)

Fourier Transform

- Continuous signal
- $\tilde{x}(f) = \int_{-\infty}^{+\infty} x(t)e^{-2\pi ift} dt$
- $x(t) = \int_{-\infty}^{+\infty} \tilde{x}(f)e^{2\pi ift} df$

Note that

$$\delta(f) = \int_{-\infty}^{+\infty} e^{-2\pi ift} dt$$
$$\delta(t) = \int_{-\infty}^{+\infty} e^{2\pi ift} df$$

- Discrete approximation

- $\tilde{x}[k] = \Delta t \sum_{j=0}^{N-1} x[j]e^{-2\pi ijk/N}$, $x[j] = x(j\Delta t)$, $f_s = \frac{1}{\Delta t}$
- $x[j] = \Delta f \sum_{k=0}^{N-1} \tilde{x}[k]e^{2\pi ijk/N}$, $\tilde{x}[k] = \tilde{x}(k\Delta f)$, $\Delta f = \frac{1}{N\Delta t}$

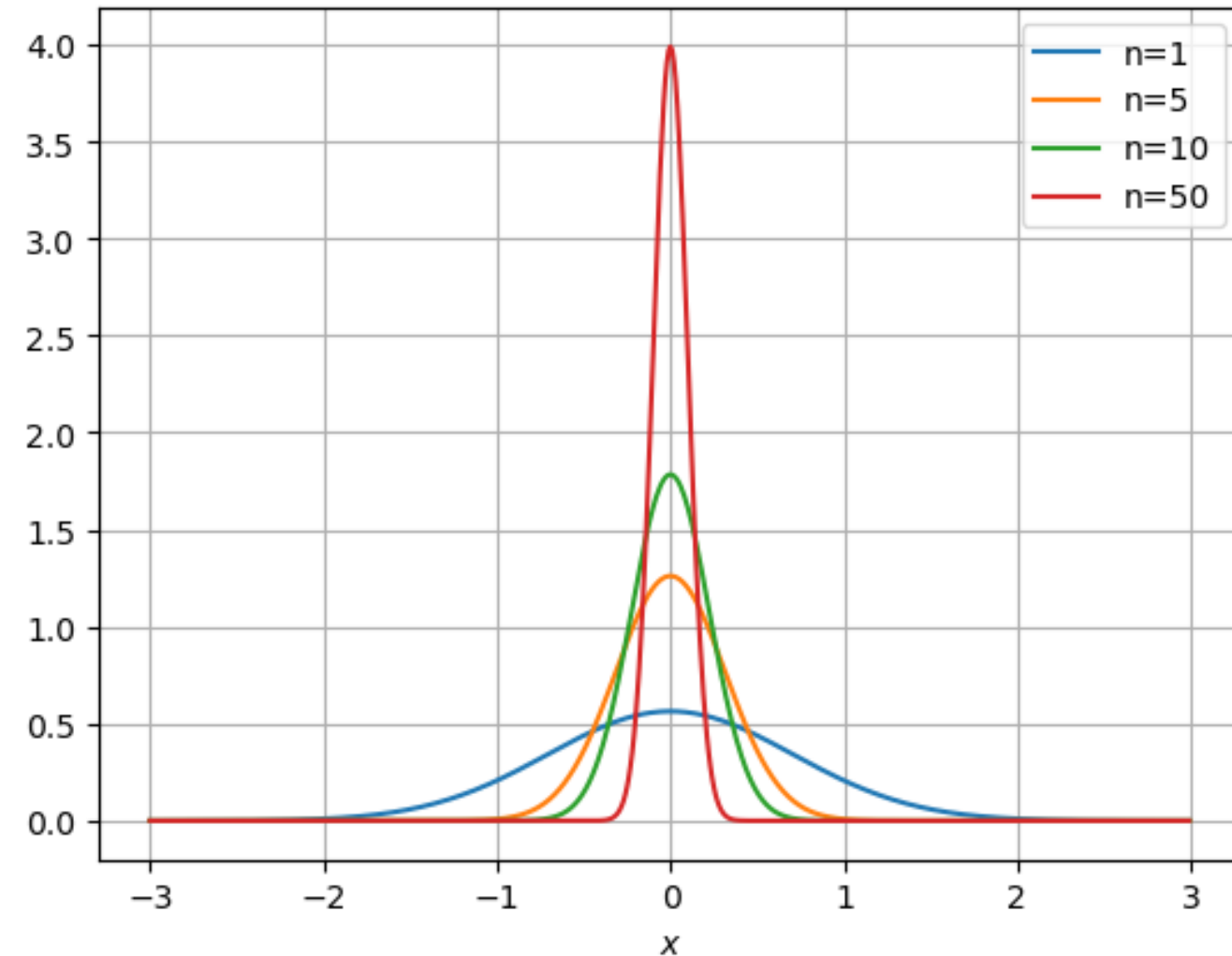
FFT package calculate

$$y[k] = \sum_{j=0}^{N-1} x[j]e^{\mp 2\pi ijk/N}$$

Dirac delta function

- $\delta(x) = 0, \text{ if } x \neq 0$
- $\int_{-\infty}^{+\infty} \delta(x - a) f(x) dx = f(a)$
- $\lim_{n \rightarrow \infty} \int_{-\infty}^{+\infty} \delta_n(x - a) f(x) dx = \int_{-\infty}^{+\infty} \delta(x - a) f(x) dx$
- $\delta_n(x - a) = \sqrt{\frac{n}{\pi}} e^{-n(x-a)^2}, \quad \lim_{n \rightarrow \infty} \delta_n(x - a) = \delta(x - a)$
- $\int_{-\infty}^{+\infty} e^{-(2\pi t)^2/(4n)} e^{2\pi i(x-a)t} dt = \sqrt{\frac{n}{\pi}} e^{-n(x-a)^2}$
- $\lim_{n \rightarrow \infty} \int_{-\infty}^{+\infty} e^{-(2\pi t)^2/(4n)} e^{2\pi i(x-a)t} dt = \int_{-\infty}^{+\infty} e^{2\pi i(x-a)t} dt = \delta(x - a)$

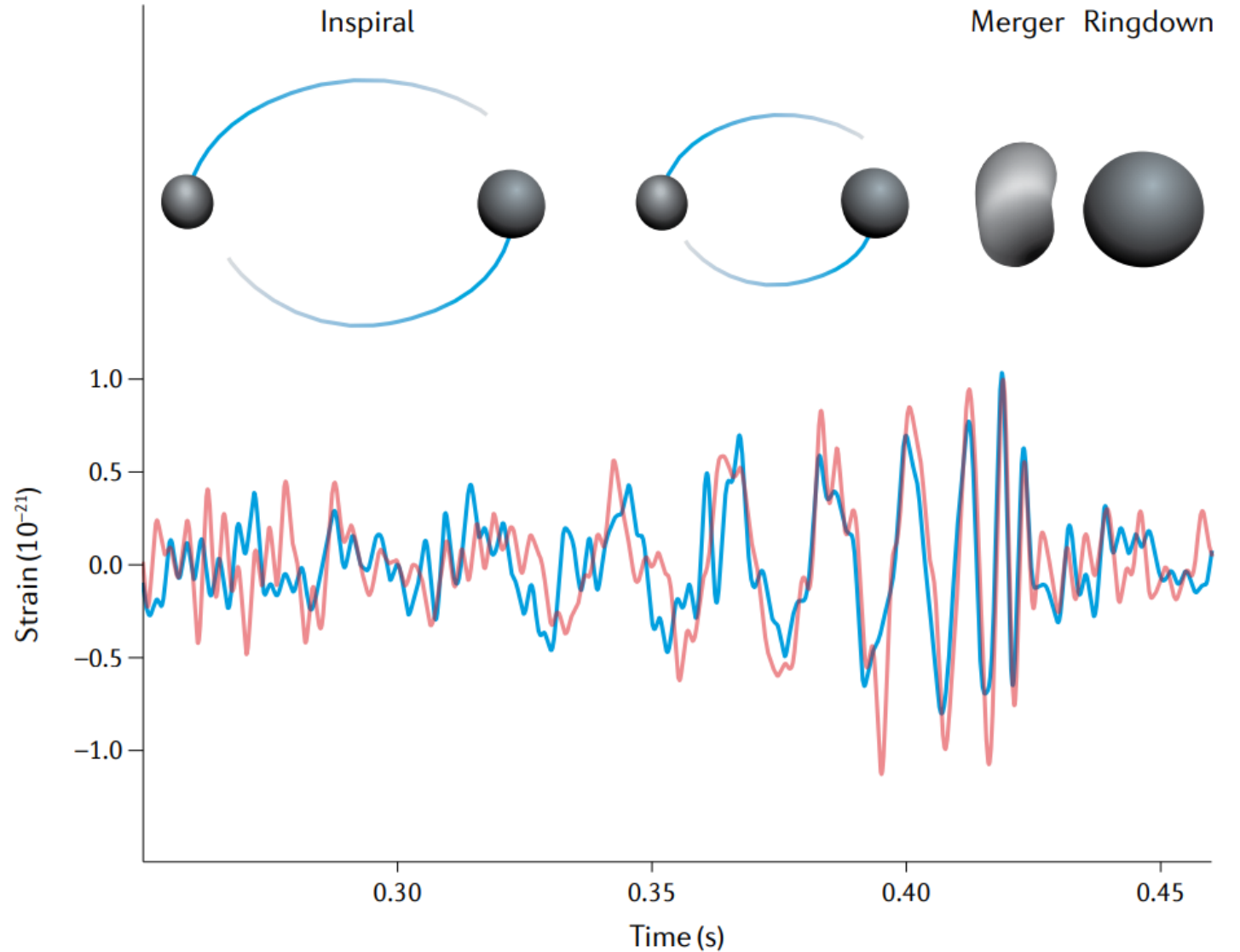
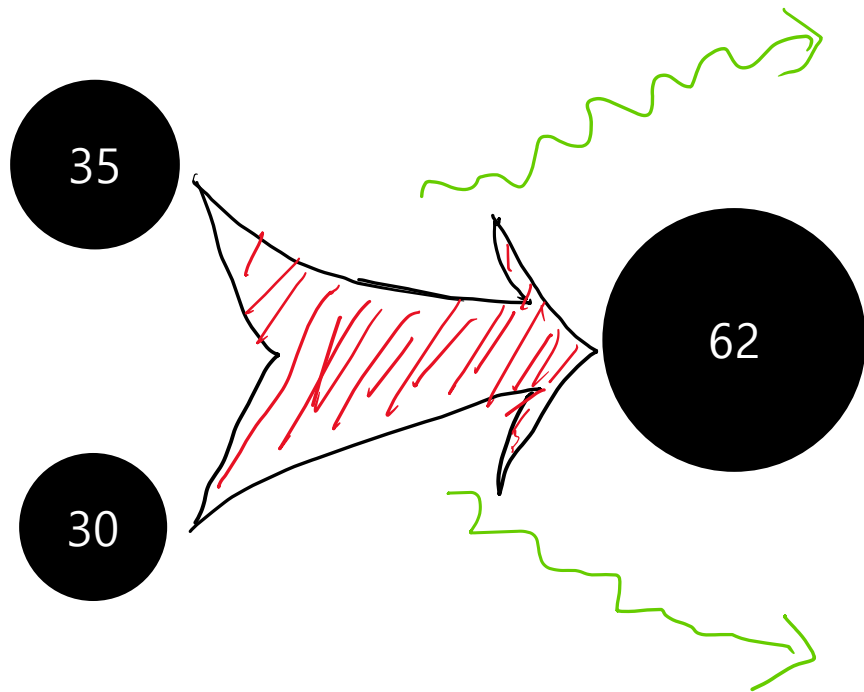
Dirac delta function



$$\delta_n(x - a) = \sqrt{\frac{n}{\pi}} e^{-n(x-a)^2}$$

중력파

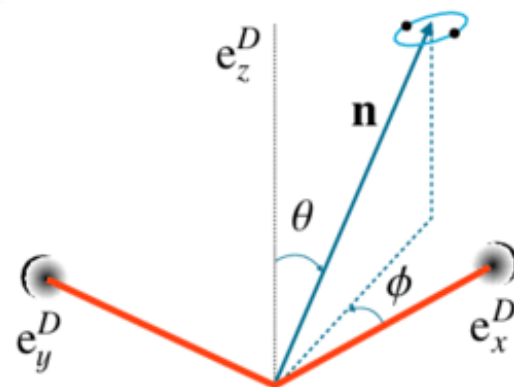
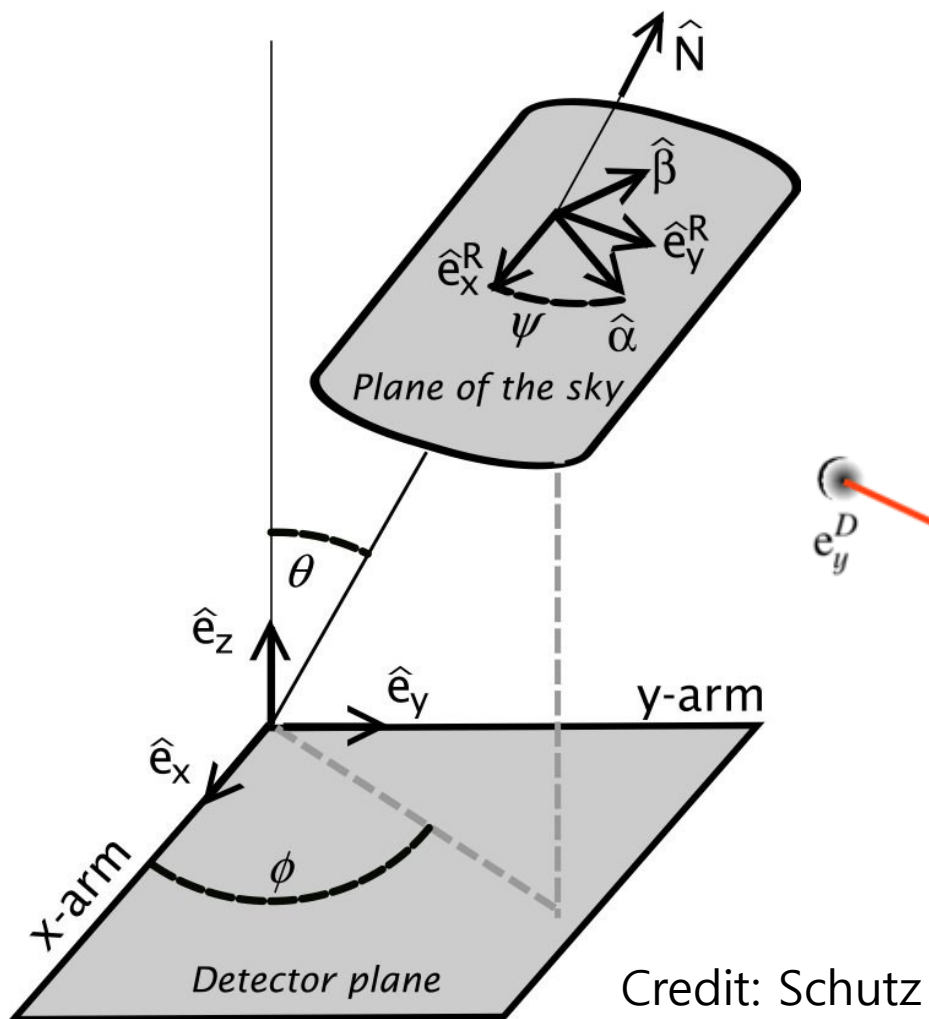
GW150914



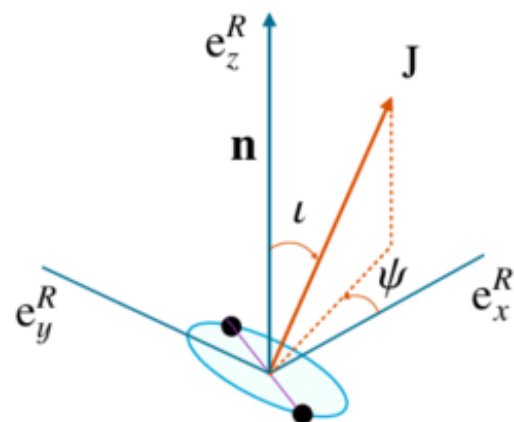
Waveform

- $h_+(t) = -\frac{1+\cos^2\iota}{2} \left(\frac{G\mathcal{M}}{c^2 D}\right) \left(\frac{t_0-t}{5G\mathcal{M}/c^3}\right)^{-1/4} \cos[2\phi_c + 2\phi(t - t_c; M, \mu)]$
- $h_\times(t) = -\cos\iota \left(\frac{G\mathcal{M}}{c^2 D}\right) \left(\frac{t_0-t}{5G\mathcal{M}/c^3}\right)^{-1/4} \sin[2\phi_c + 2\phi(t - t_c; M, \mu)]$
- $\mathcal{M} = \mu^{3/5} M^{2/5} = \eta^{3/5} M, M = m_1 + m_2, \mu = \frac{m_1 m_2}{M}, \eta = \frac{m_1 m_2}{M^2}$
- $h(t) = F_+(\alpha, \delta, \psi, t) h_+(t + t_c - t_0) + F_\times(\alpha, \delta, \psi, t) h_\times(t + t_c - t_0)$
 - t_0 : coalescence time at detector
 - t_c : coalescence time at source
 - $t_0 - t_c$: propagation time

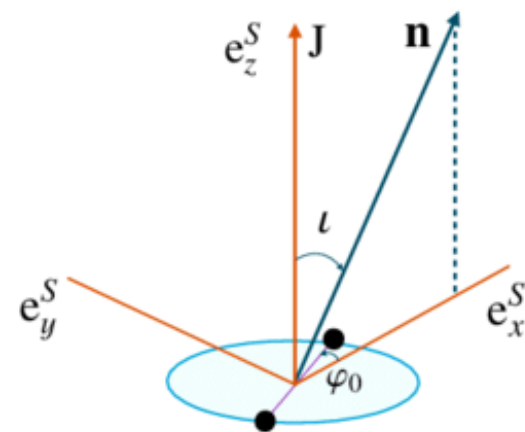
Geometry



Detector frame



Radiation frame



Source frame

Credit: Purrer

Waveform PhysRevD.85.122006

- $$h(t) = - \left(\frac{G\mathcal{M}}{c^2 D_{eff}} \right) \left(\frac{t_0 - t}{5G\mathcal{M}/c^3} \right)^{-1/4} \cos[2\phi_0 + 2\phi(t - t_0; M, \mu)]$$

- $$D_{eff} = D \left[F_+^2 \left(\frac{1 + \cos^2 \iota}{2} \right)^2 + F_\times^2 \sin^2 \iota \right]^{-1/2}$$

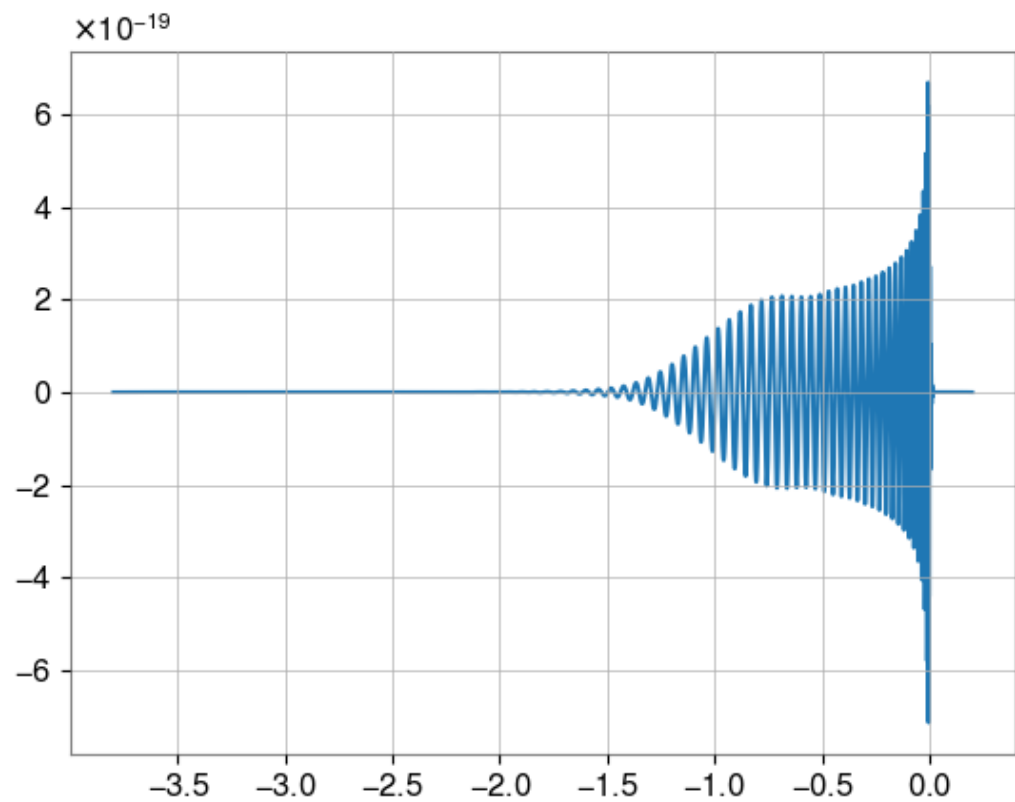
- $$2\phi_0 = 2\phi_c - \text{Tan}^{-1} \left(\frac{F_\times}{F_+} \frac{2 \cos \iota}{1 + \cos^2 \iota} \right)$$

- $$\begin{aligned} \tilde{h}(f) &= - \left(\frac{5\pi}{24} \right)^{\frac{1}{2}} \left(\frac{G\mathcal{M}}{c^3} \right) \left(\frac{G\mathcal{M}}{c^2 D_{eff}} \right) \left(\frac{G\mathcal{M}}{c^3} \pi f \right)^{-\frac{7}{6}} e^{-i\Psi(f; M, \mu)} \\ &= \left(\frac{1 \text{ Mpc}}{D_{eff}} \right) A_{1 \text{ Mpc}}(M, \mu) f^{-7/6} e^{-i\Psi(f; M, \mu)} \end{aligned}$$

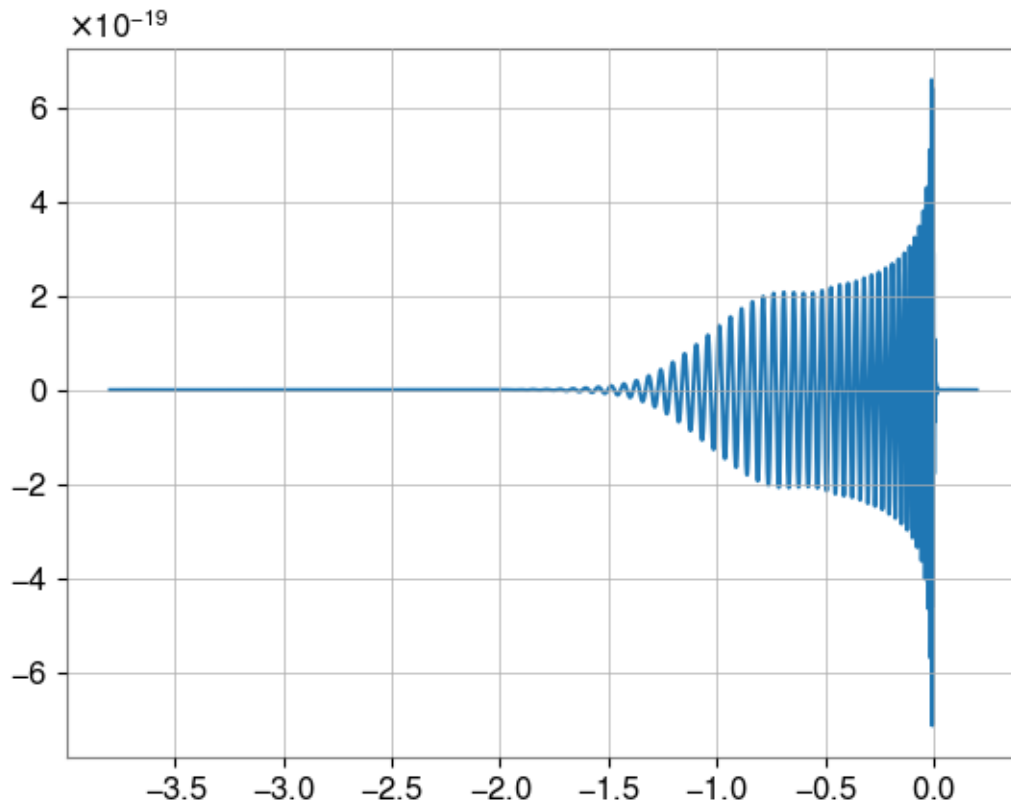
$$\begin{aligned} \mathcal{A}_{1 \text{ Mpc}}(M, \mu) &= - \left(\frac{5}{24\pi} \right)^{1/2} \left(\frac{GM_\odot/c^2}{1 \text{ Mpc}} \right) \left(\frac{\pi GM_\odot}{c^3} \right)^{-1/6} \left(\frac{\mathcal{M}}{M_\odot} \right)^{5/6}, \\ \Psi(f; M, \mu) &= 2\pi f t_0 - 2\phi_0 - \pi/4 + \frac{3}{128\eta} \left[v^{-5} + \left(\frac{3715}{756} + \frac{55}{9} \eta \right) v^{-3} \right. \\ &\quad \left. - 16\pi v^{-2} + \left(\frac{15\,293\,365}{508\,032} + \frac{27\,145}{504} \eta + \frac{3085}{72} \eta^2 \right) v^{-1} \right], \\ v &= \left(\frac{GM}{c^3} \pi f \right)^{1/3} \end{aligned}$$

파형 예

IMRPhenomD(30,30)

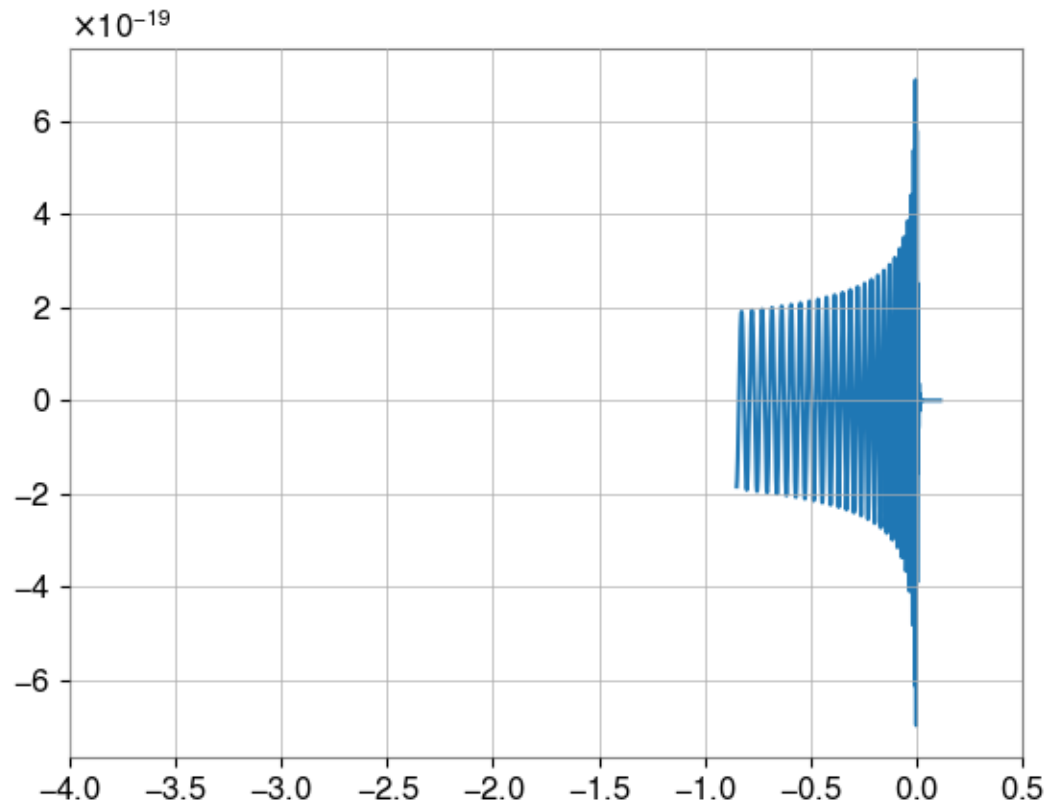
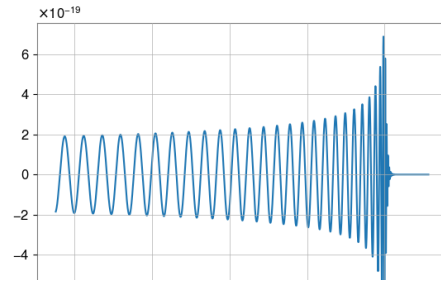


IMRPhenomPv2(30,30)

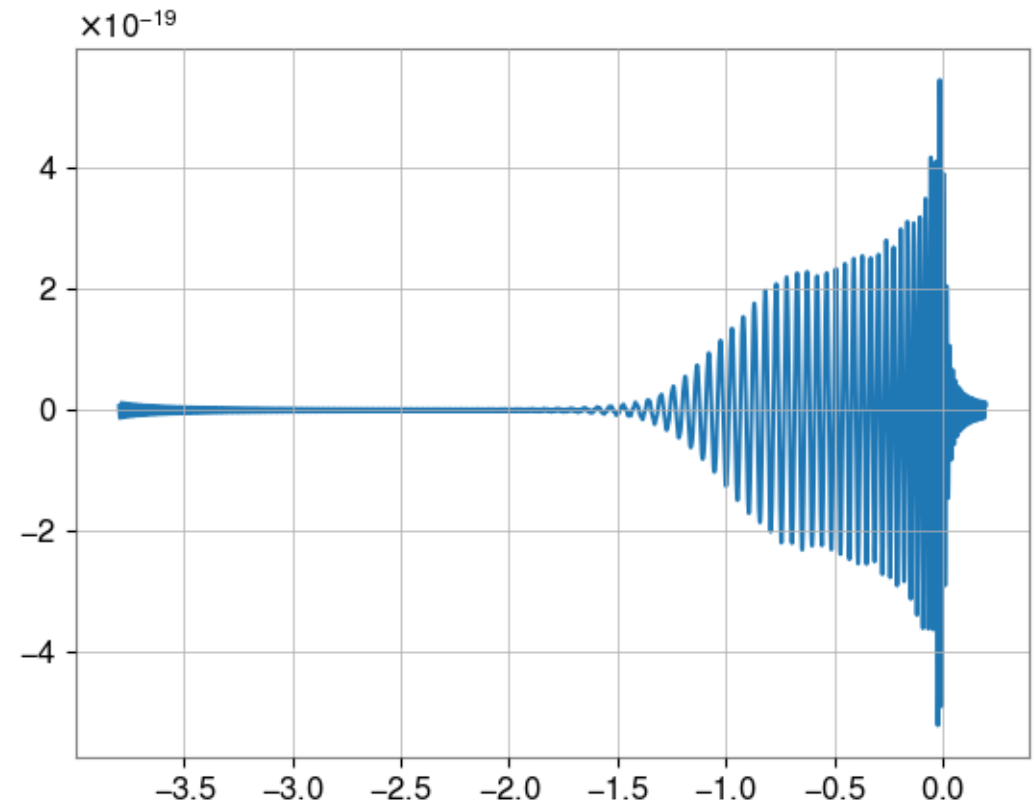


파형 예

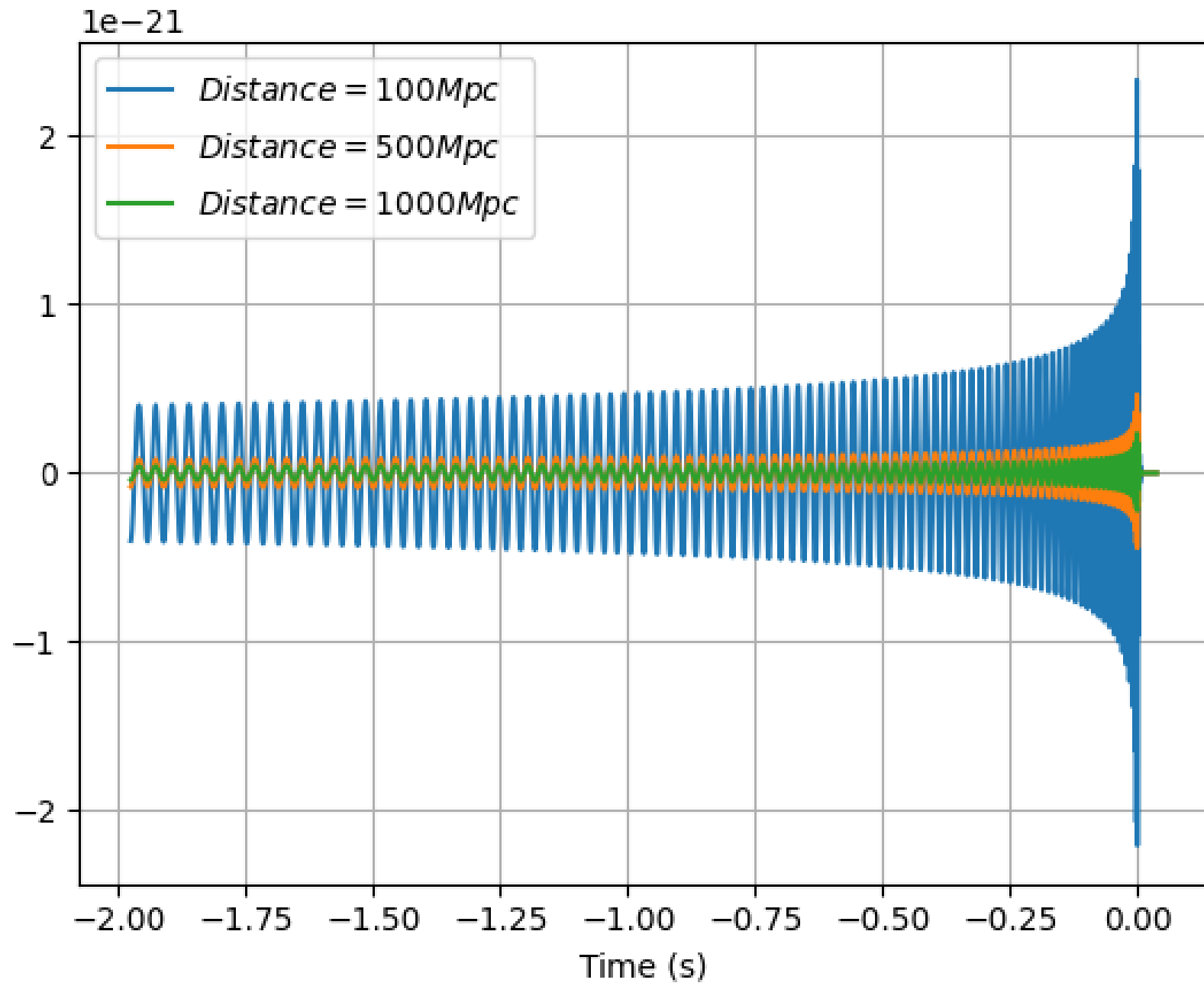
SEOBNRv4(30,30)



TaylorF2(30,30)



SEOBNRv4_opt



Chirp length

- $T_{chirp} = \frac{5}{256\eta} \frac{GM}{c^3} \frac{1}{v_{low}^8} \left[1 + a_2 v_{low}^2 + a_3 v_{low}^3 + a_4 v_{low}^4 \right]$ 2PN

- $a_2 = \frac{743}{252} + \frac{11}{3}\eta$

- $a_3 = -\frac{32\pi}{5}$

- $a_4 = \frac{3\,058\,673}{508\,032} + \frac{5429}{504}\eta + \frac{617}{72}\eta^2$

- $v_{low} = \left(\frac{GM}{c^3} \pi f_{low} \right)^{1/3}$

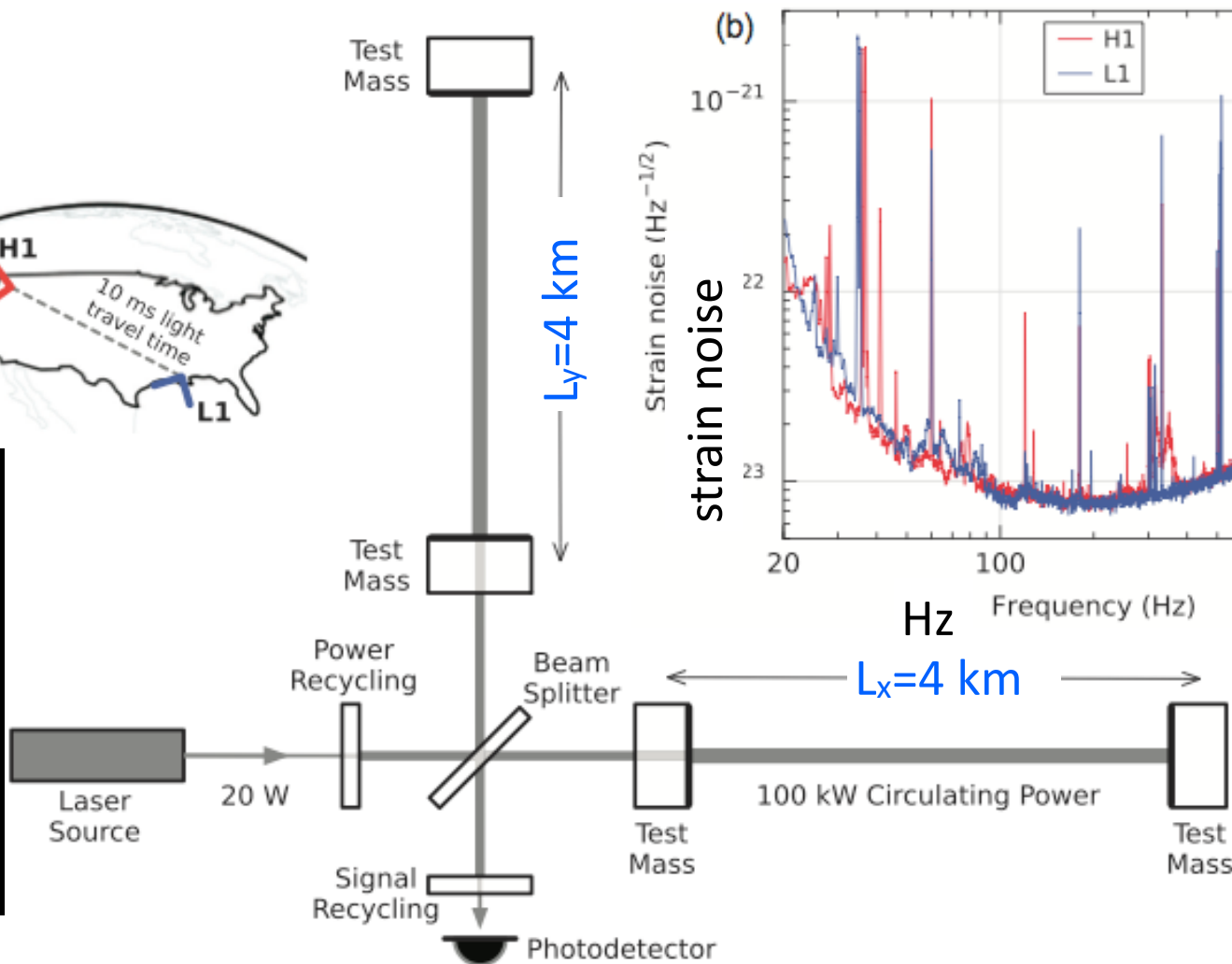
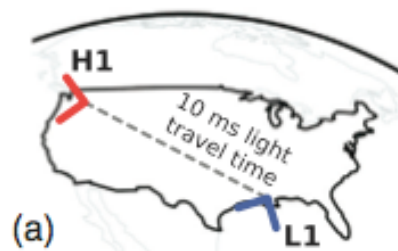
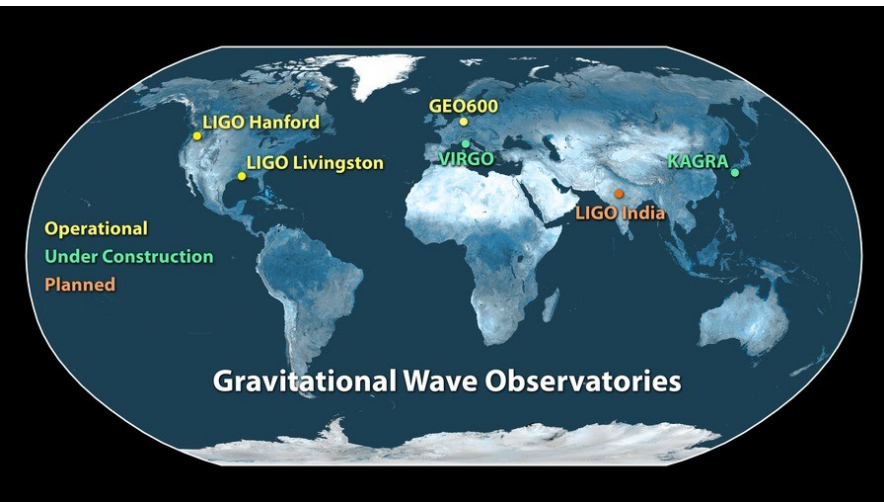
$$f_{isco} = \frac{c^3}{6\sqrt{6}\pi GM}$$

Chirp length

- $$T_{chirp} = \frac{5}{256\eta} \frac{GM}{c^3} \frac{1}{v_{low}^8} \left[1 + a_2 v_{low}^2 + a_3 v_{low}^3 + a_4 v_{low}^4 + a_5 v_{low}^5 + a_6 v_{low}^6 + a_7 v_{low}^7 \right]$$

3.5PN
- $$a_5 = \frac{13}{3}\eta - \frac{7729}{252}$$
- $$a_6 = \frac{6848\gamma_E}{105} - \frac{10\,052\,469\,856\,691}{23\,471\,078\,400} + \frac{128\pi^2}{3} + \left(\frac{3\,147\,553\,127}{3\,048\,192} - \frac{451\pi^2}{12} \right) \eta - \frac{15\,211}{1\,728} \eta^2 + \frac{25\,565}{1\,259} \eta^3 + \frac{6848}{105} \ln(4v_{low})$$
- $$a_7 = \left(\frac{14\,809}{378} \eta^2 - \frac{75\,703}{756} \eta - \frac{15\,419\,335}{127\,008} \right) \pi$$
- $$\gamma_E = 0.57721\,56649\,01532\,86060\,65120\,90082\,402 \dots$$

중력파 검출



$$\Delta L(t) = \delta L_x - \delta L_y = h(t)L \sim 10^{-21} \times 4000 \text{ m} \sim 10^{-15} \text{ m}$$

Generation of $h(t)$

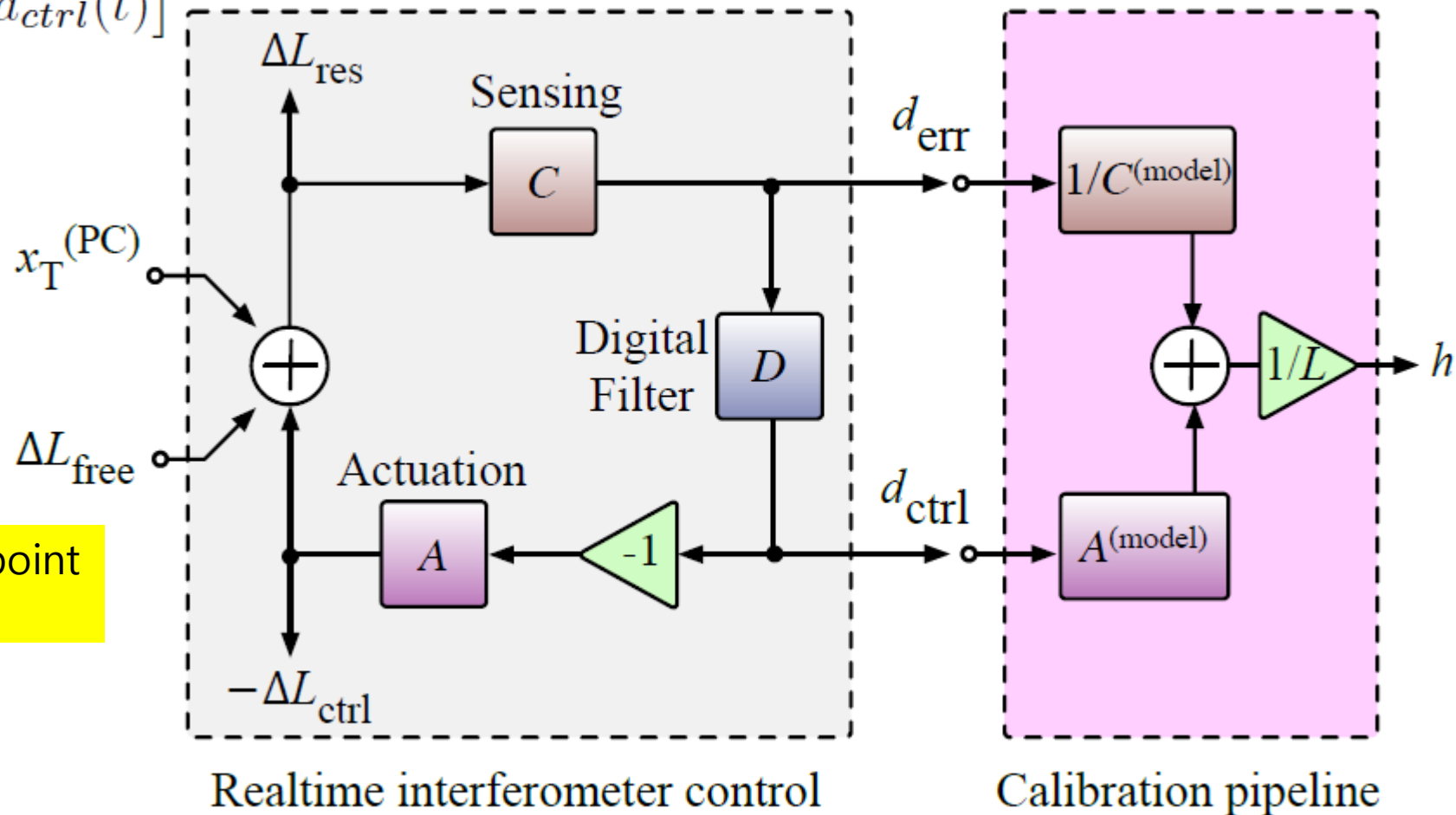
$$d_{err} = \mathcal{C}(\Delta L_{free} + x_T - \mathcal{A}d_{ctrl})$$

$$\Delta L_{free} = \mathcal{C}^{-1}d_{err} + \mathcal{A}d_{ctrl} - x_T$$

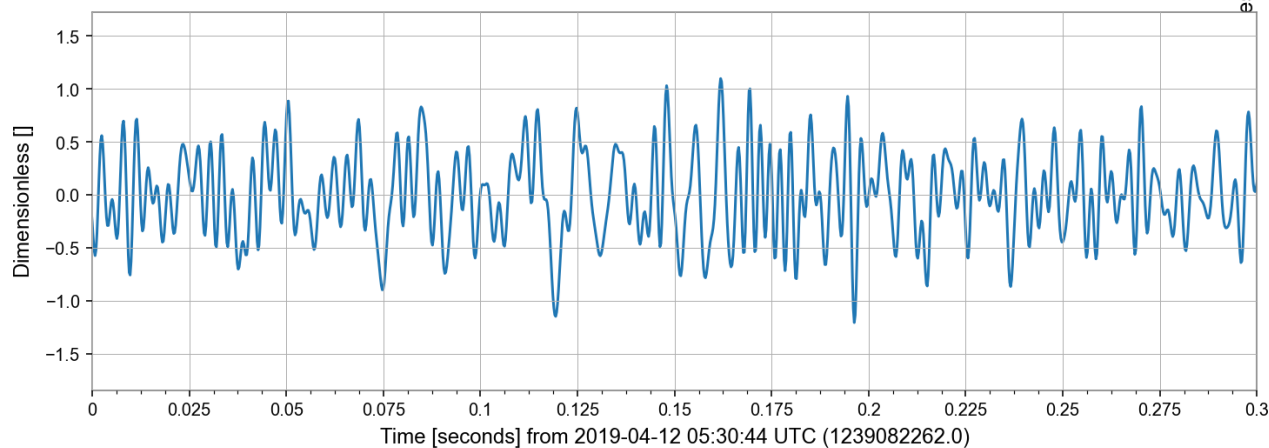
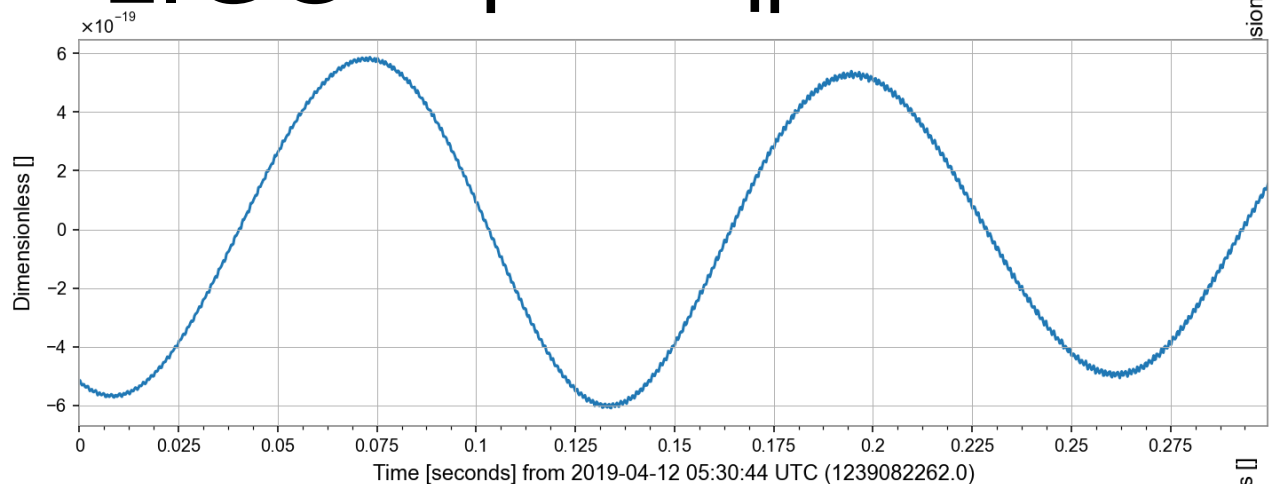
$$h(t) = \frac{1}{L} [\mathcal{C}^{-1} * d_{err}(t) + \mathcal{A} * d_{ctrl}(t)]$$

$$h(t) = \frac{\Delta L_{free}}{L}$$

Keep interferometer at "operation" point
No difference appear dark point



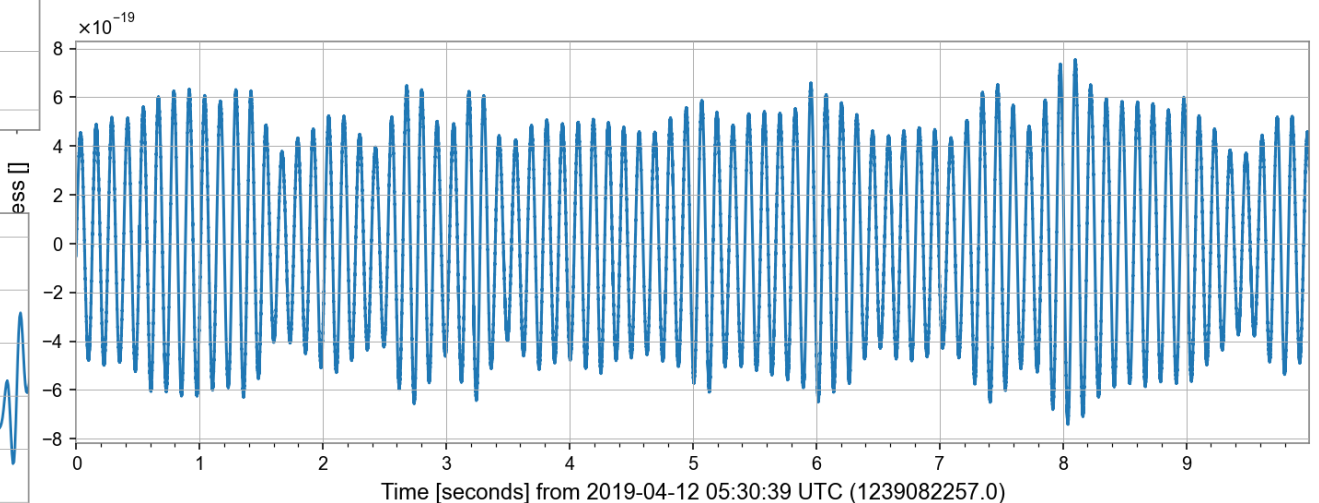
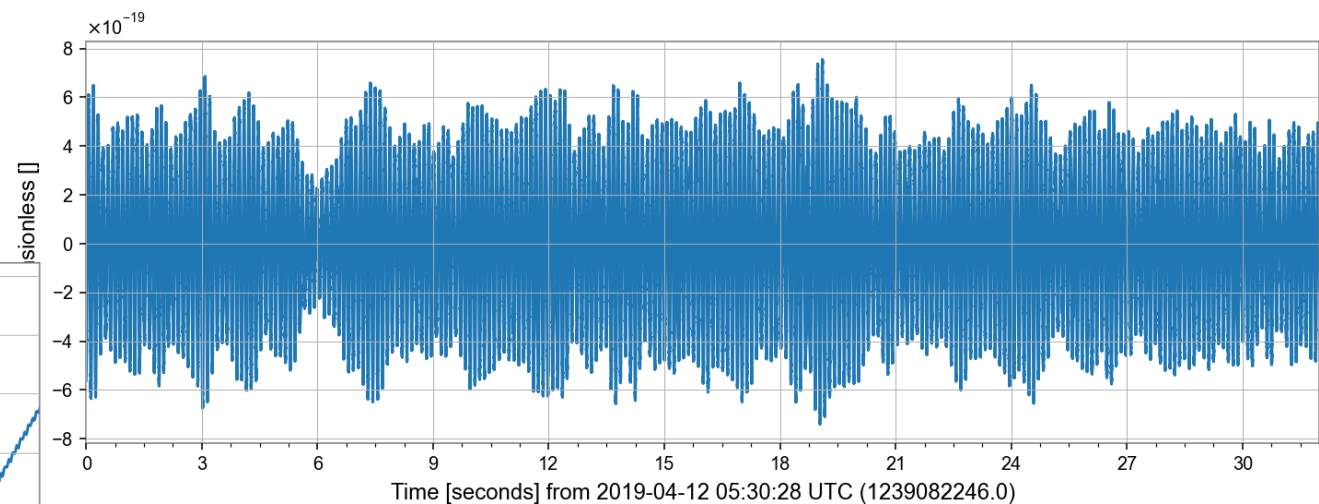
LIGO 자료 예

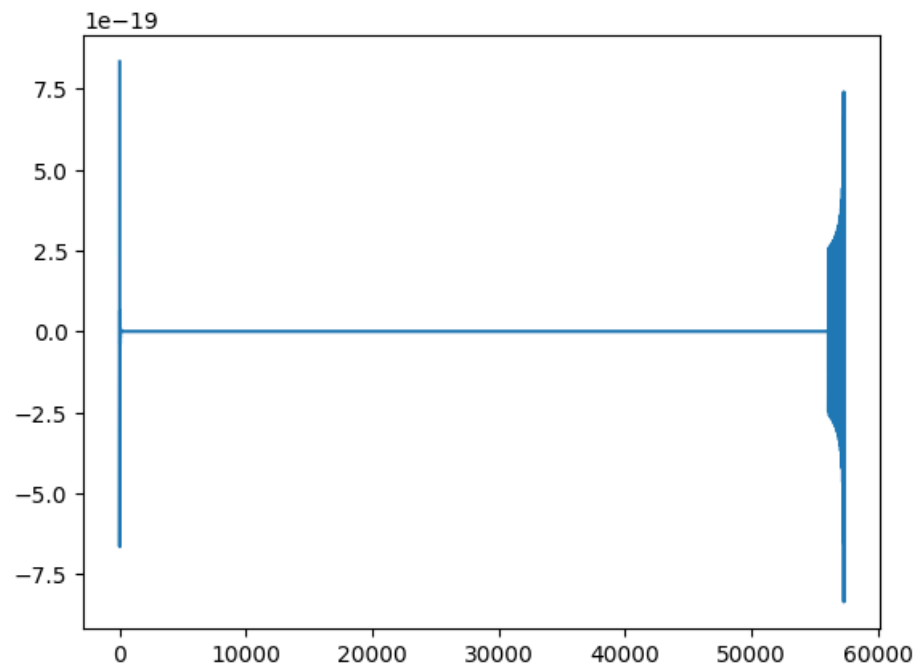
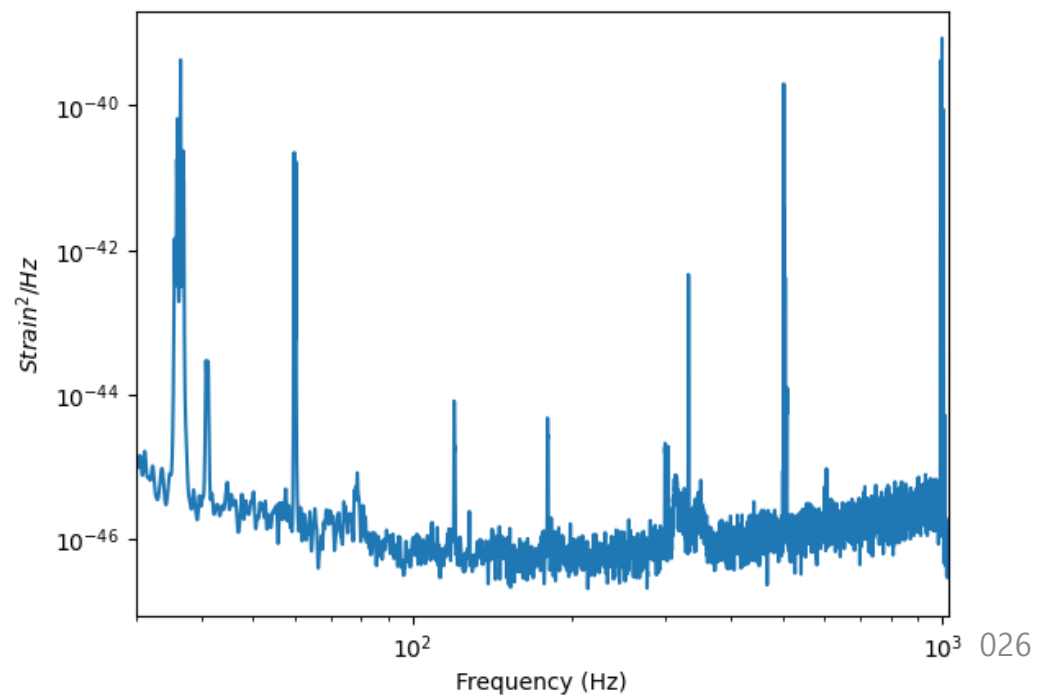
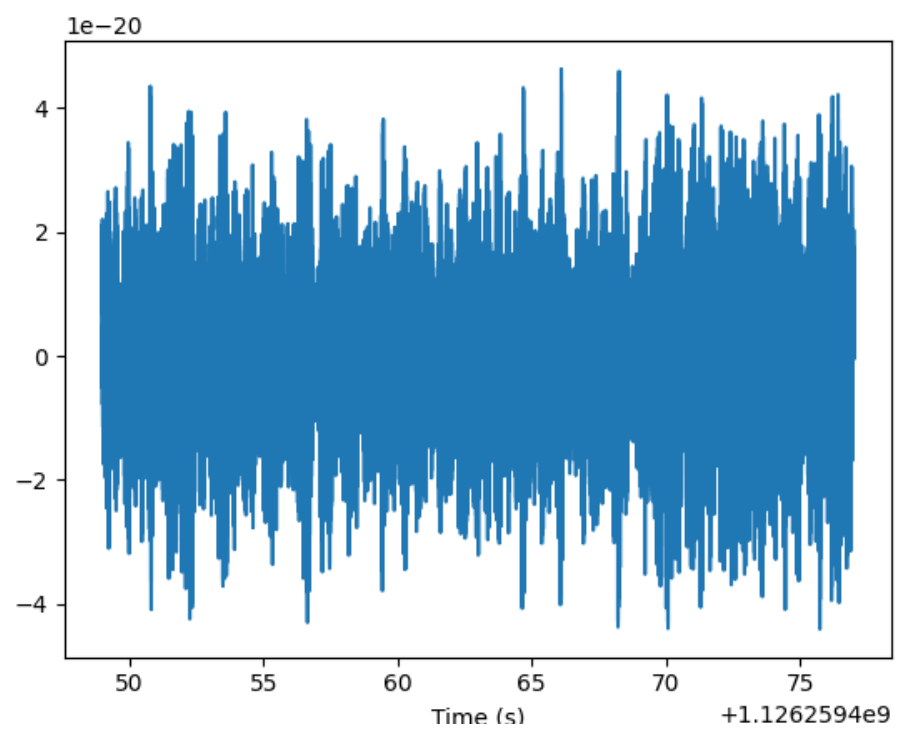
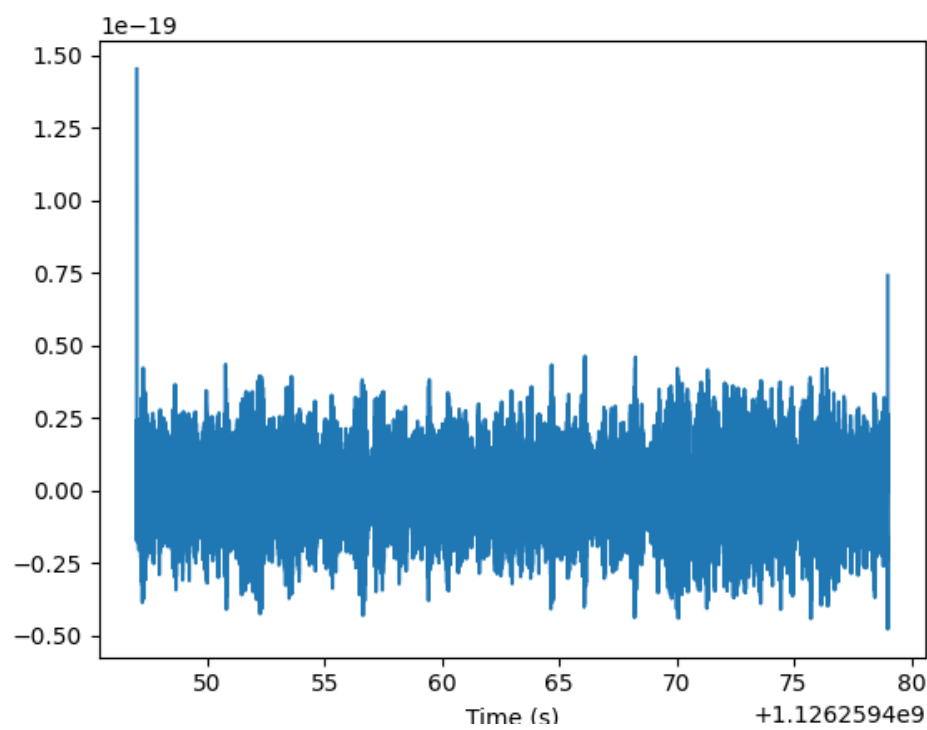


$t_0 = 1239082262.2$

Odw4, GW190412

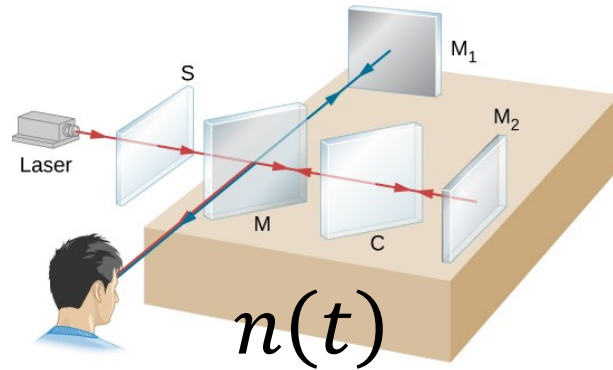
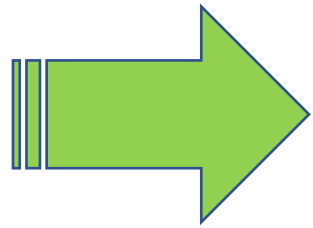
[GWOSC \(gw-openscience.org\)](https://www.gwosc.org/)



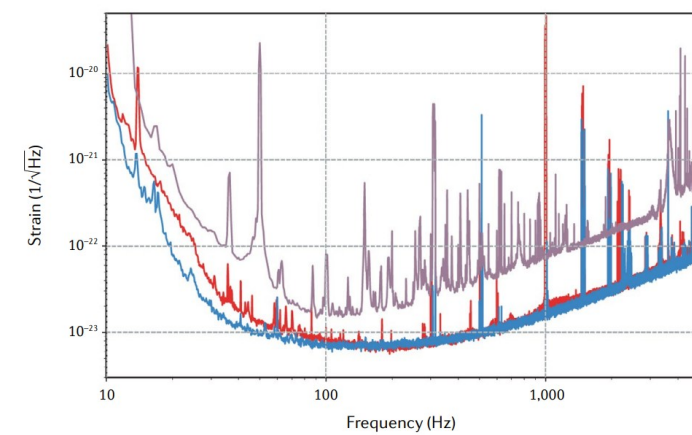
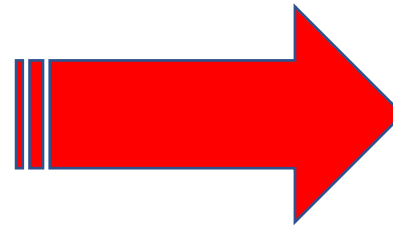


Linear Optimal Filter

$h(t)$



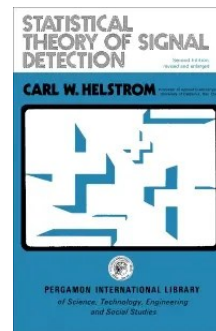
$$d(t) = h(t) + n(t)$$



$$\text{minimize } \overline{\varepsilon^2} \quad K(f) \propto \frac{h(f)}{S_n(f)}$$

$$\varepsilon(t) = \mathcal{H}(d(t)) - h(t)$$

Statistical Theory of Signal Detection
by C.W. Helstrom



$$\langle \tilde{n}(f) | \tilde{n}^*(f') \rangle = \frac{1}{2} \delta(f - f') S_n(f)$$

정합 필터(Matched Filter) PhysRevD.85.122006

$$\bullet x(t_0) = 2 \int_{-\infty}^{+\infty} \frac{\tilde{s}(f) \tilde{h}_T^*(f)}{S_n(f)} df = 4\Re \int_0^{+\infty} \frac{\tilde{s}(f) [\tilde{h}_T^*(f)]_{t_0=0}}{S_n(f)} e^{2\pi i f t_0} df$$

- 1. Template amplitude
- 2. Coalescence phase
- 3. Masses

We do not know

$t_0 = 0, \phi_0 = 0$

$$\bullet z(t_0) = x_{\text{re}}(t_0) + i x_{\text{im}}(t_0) = 4 \int_0^{+\infty} \frac{\tilde{s}(f) [\tilde{h}_T^*(f)]_0}{S_n(f)} e^{2\pi i f t_0} df$$

The best matched value for unknown phase is the modulus of $z(t_0)$

정합 필터(Matched Filter) PhysRevD.85.122006

- We need template banks to find matched masses

$$\sigma_m^2 = 4 \int_0^\infty \frac{|\tilde{h}_{1 \text{ Mpc}, m}(f)|^2}{S_n(f)} df, \quad \text{SNR at 1 Mpc template arrived}$$

- If signal comes from D_{eff} of template waveform m , then

$$s(t) = n(t) + \frac{1 \text{ Mpc}}{D_{eff}} h_{1 \text{ Mpc}, m}(t) \quad \langle z_m(t_0) \rangle = 1 \text{ Mpc } \sigma_m^2 / D_{eff}$$

$$\rho_m(t) = \frac{|z_m(t)|}{\sigma_m} \quad \text{Amplitude of SNR} \quad \hat{D}_{eff} = \frac{\sigma_m}{\rho_m} \text{ Mpc}$$

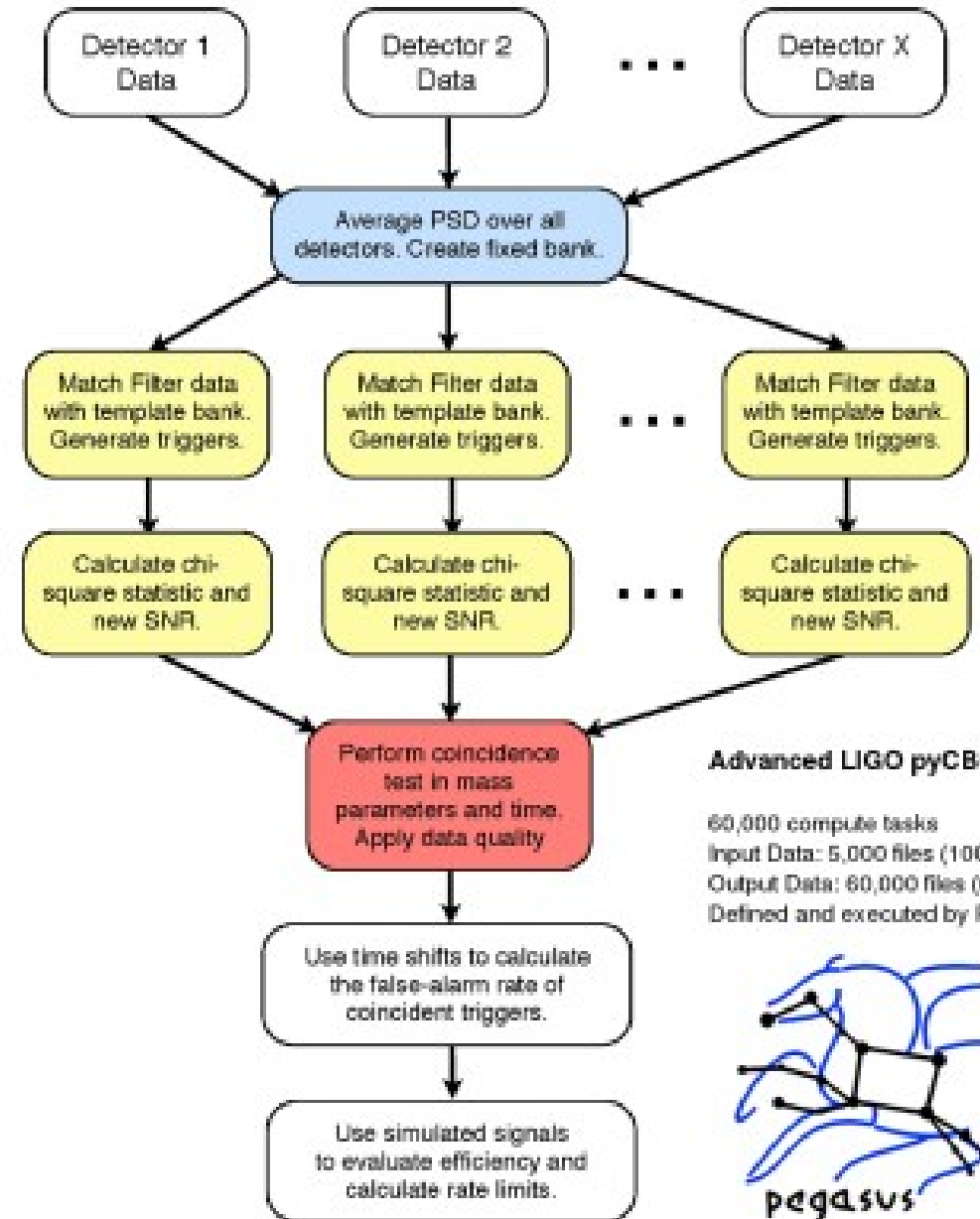
Purpose of FINDCHIRP

The goal of the FINDCHIRP algorithm is largely to construct the quantity $\rho_m(t)$ and to identify the values of the parameters t_0 , ϕ_0 , and m that maximize it.

It is highly unlikely to be $\rho_m \gg 1$, for stationary Gaussian noise.

PyCBC Workflow

1. Get Data
2. Place template bank
3. Matched filter
4. Coincidence
5. Calculate significance
6. Evaluate efficiency

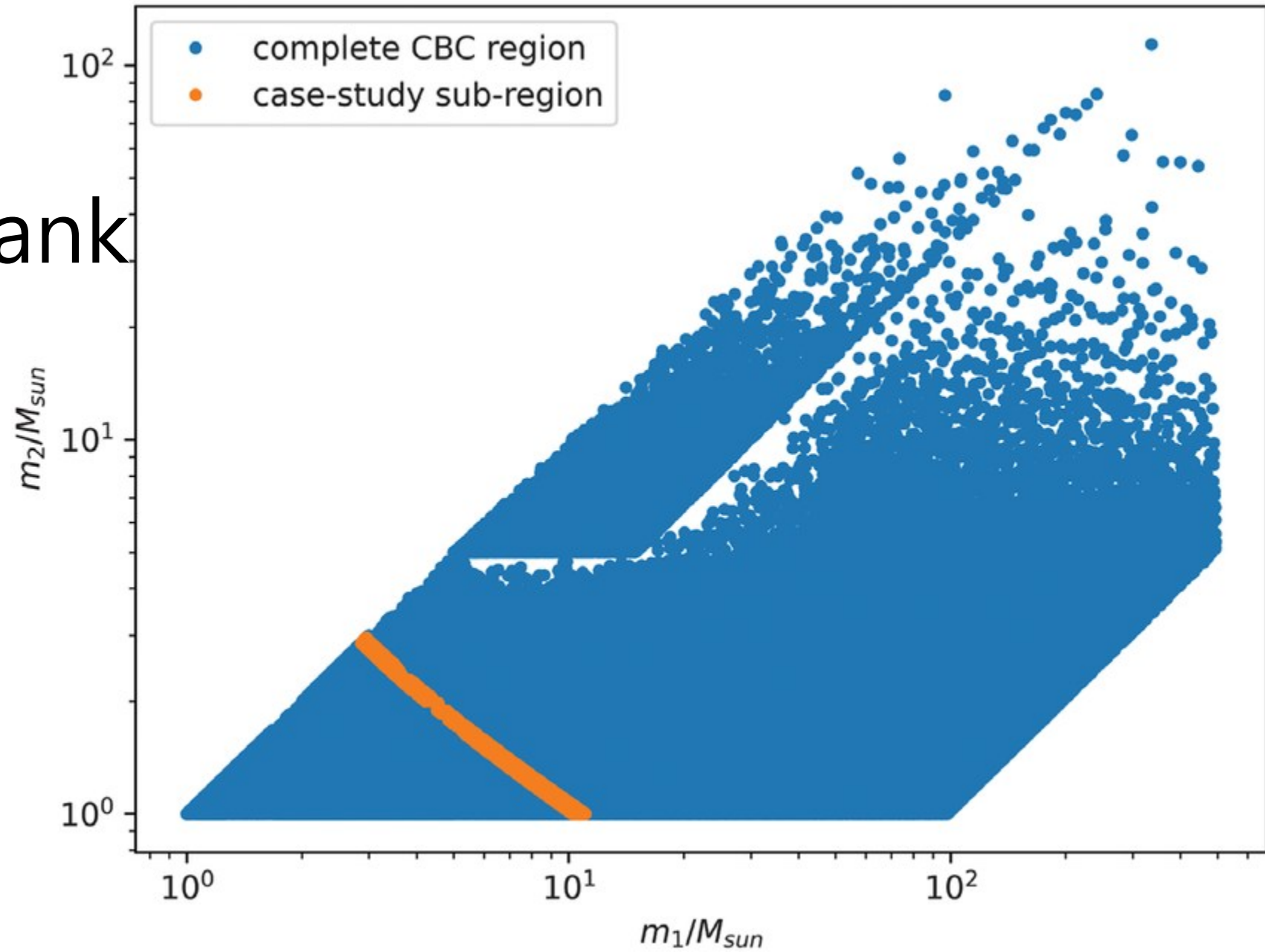


Advanced LIGO pyCBC Workflow

60,000 compute tasks
Input Data: 5,000 files (10GB total)
Output Data: 60,000 files (60GB total)
Defined and executed by Pegasus WMS



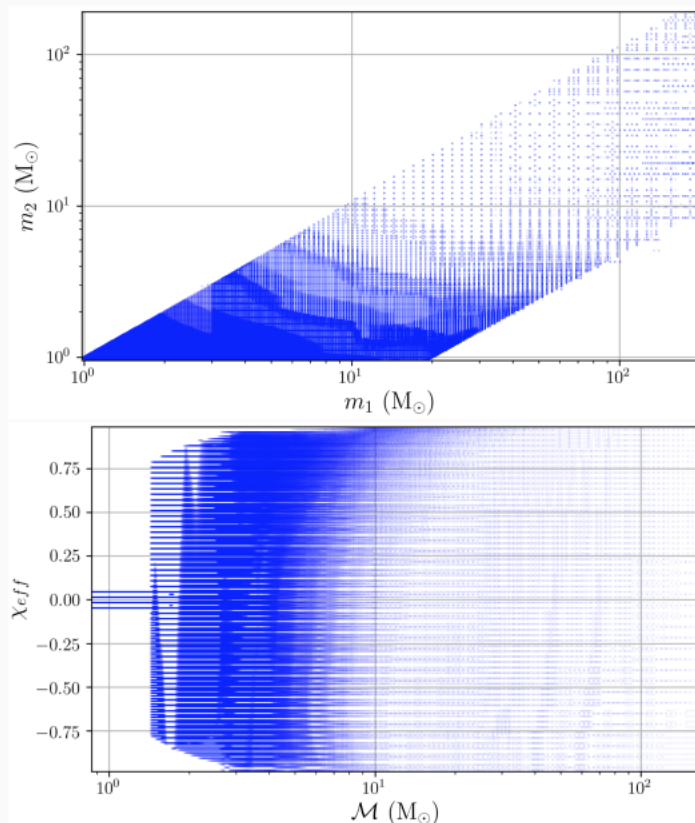
O2 Template Bank



O4 Template Bank

<https://dcc.ligo.org/LIGO-G2300231>, Shio Sakon

5. Template Bank Design



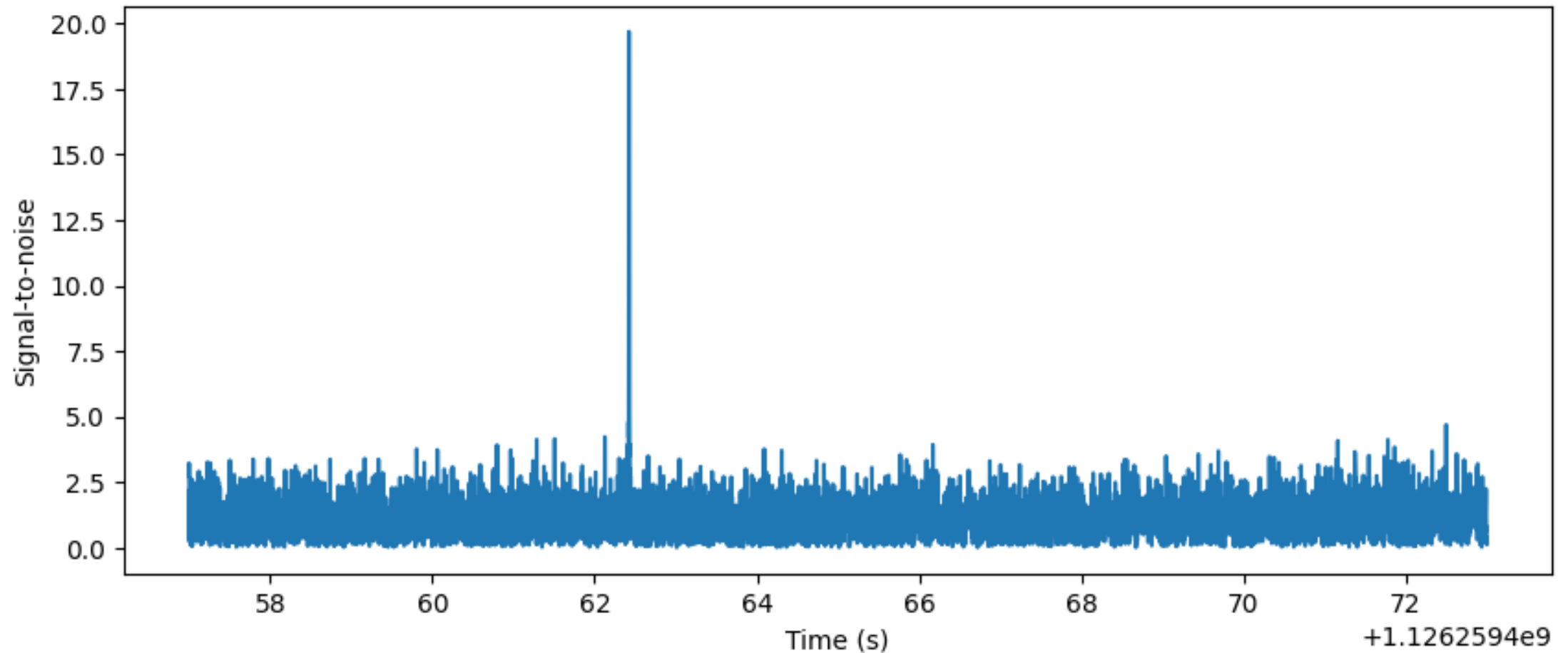
The following are the properties of the O4 template bank:

- Template bank covers CBCs (BNSs, NSBHs, BBHs) with component masses of $1\text{-}200 M_\odot$.
- The total mass is $2M_\odot \leq \text{total mass} \leq 400M_\odot$.
- The mass ratio ($q \equiv m_1/m_2$) is $1 \leq q \leq 20$.
- Dimensionless spin range for masses $1\text{-}3 M_\odot$ is ± 0.05 and for masses $3\text{-}200 M_\odot$ it is ± 0.99 .
- The minimal match of the templates is $\sim 97\%$. The BBH parameter space has a minimal match of $\sim 99.5\%$ due to the coordinate volume condition (the second condition in "Method" 3.).
- The O4 template bank consists of $\sim 1.8 \times 10^6$ templates. (Similar size as the O3 template bank generated with sbank.)
- There are no holes in the template placements.
- The SSM and IMBH template banks' generations and searches are conducted separately.

Here,

- Chirp mass: $\mathcal{M} = (m_1 m_2)^{3/5} / (m_1 + m_2)^{1/5}$
- Effective spin: $\chi_{eff} = (m_1 \times s_{1,z} + m_2 \times s_{2,z}) / (m_1 + m_2)$

SNR Time series



Data Analysis

Detector Characterization

- Noise identification
- Detector performance

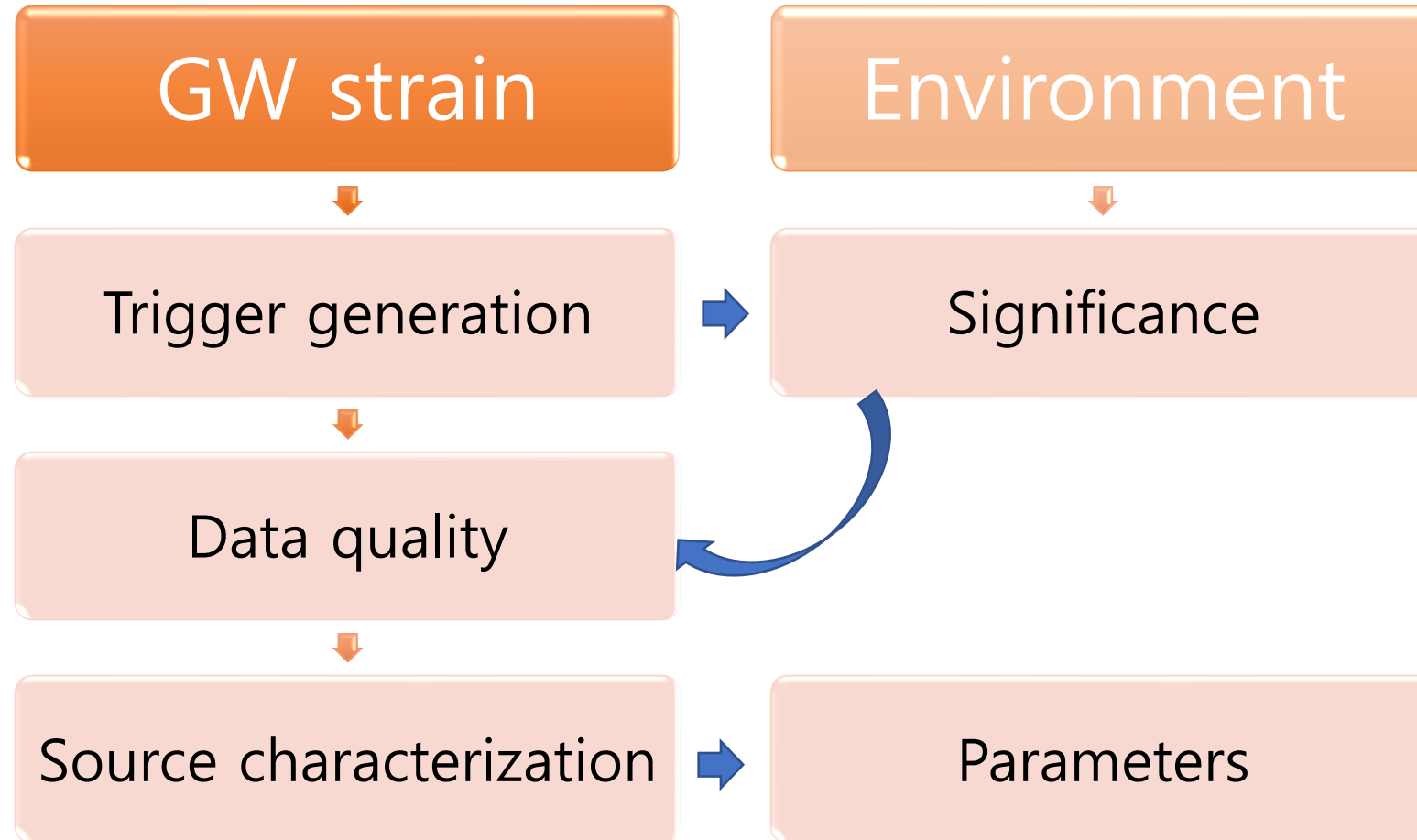
Search

- Matched filter
- Masses, Distance, Sky location

Parameter Estimation

- Better accuracy
- Distribution

Data Analysis Pipeline



Credit V. Raymond

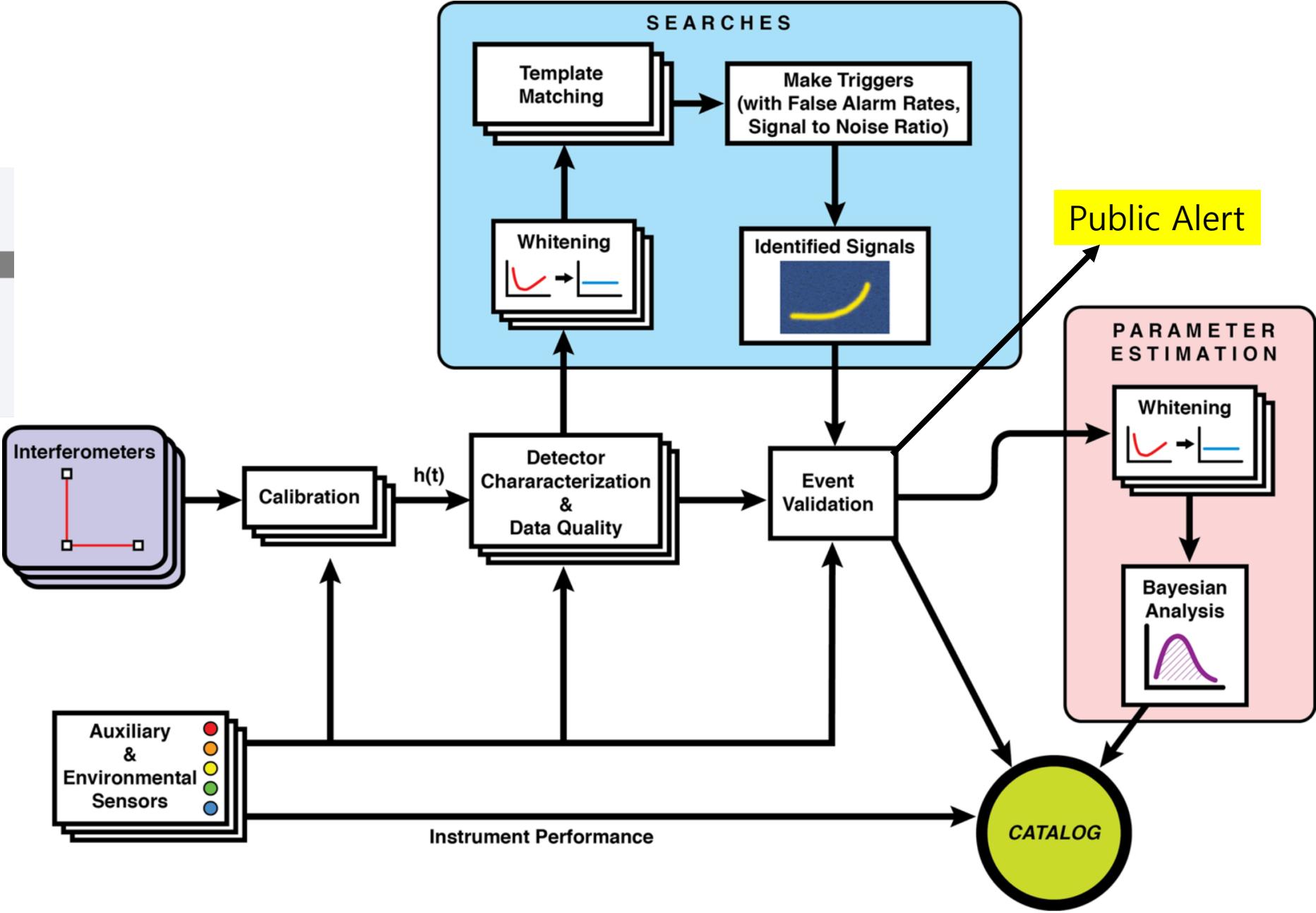
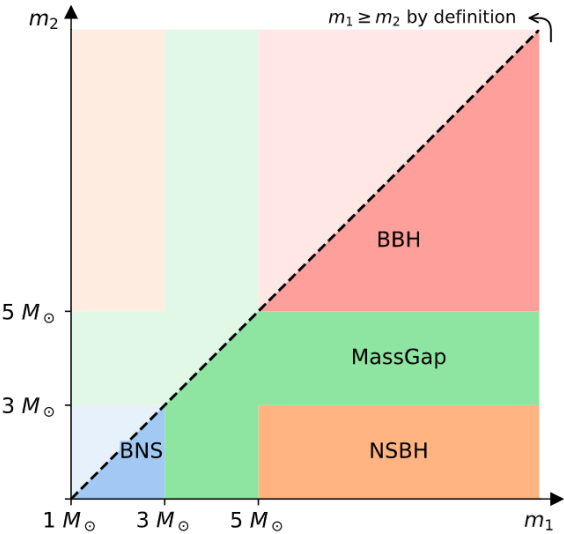
Data flow

LIGO/Virgo O3 Public Alerts

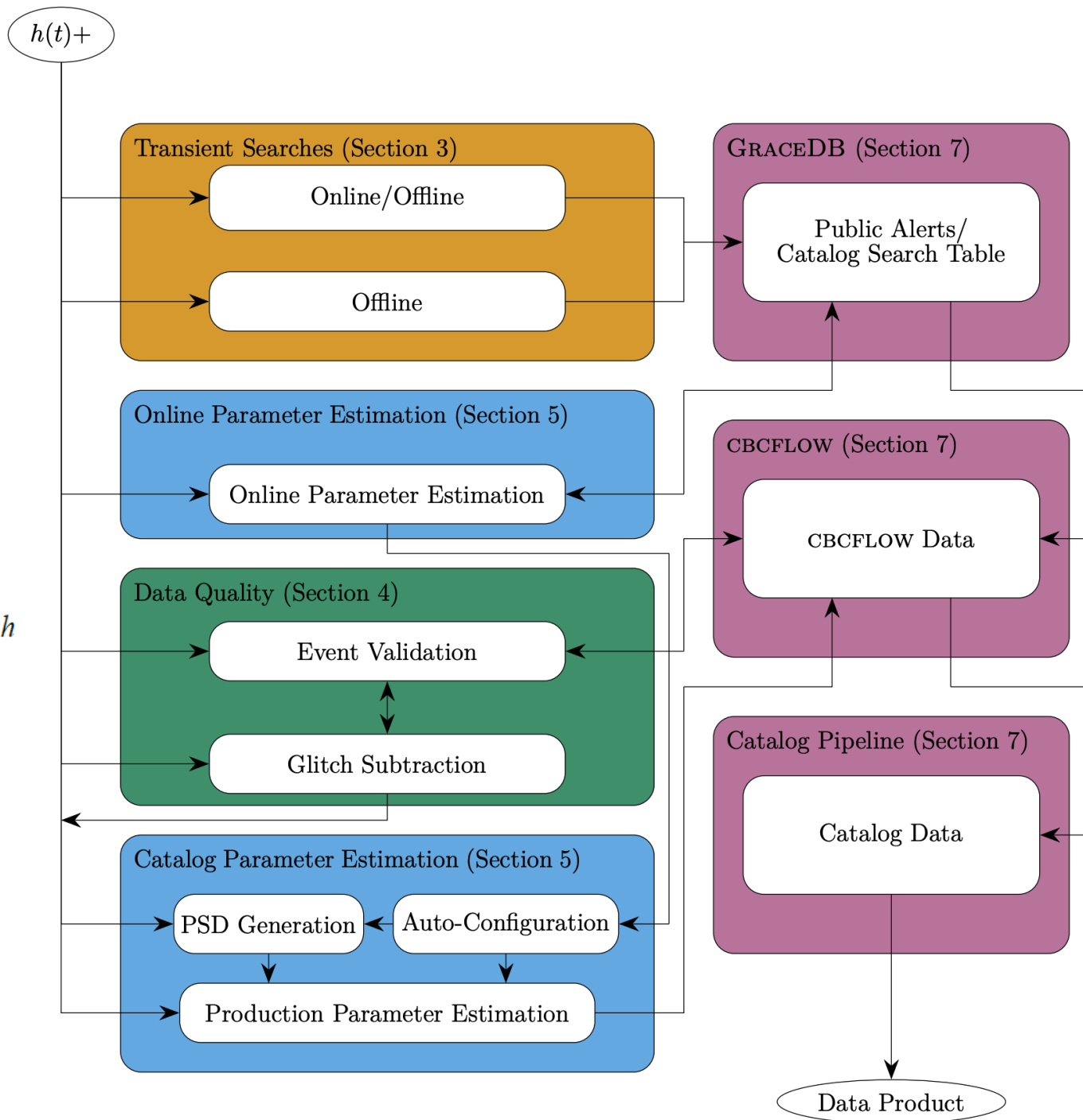
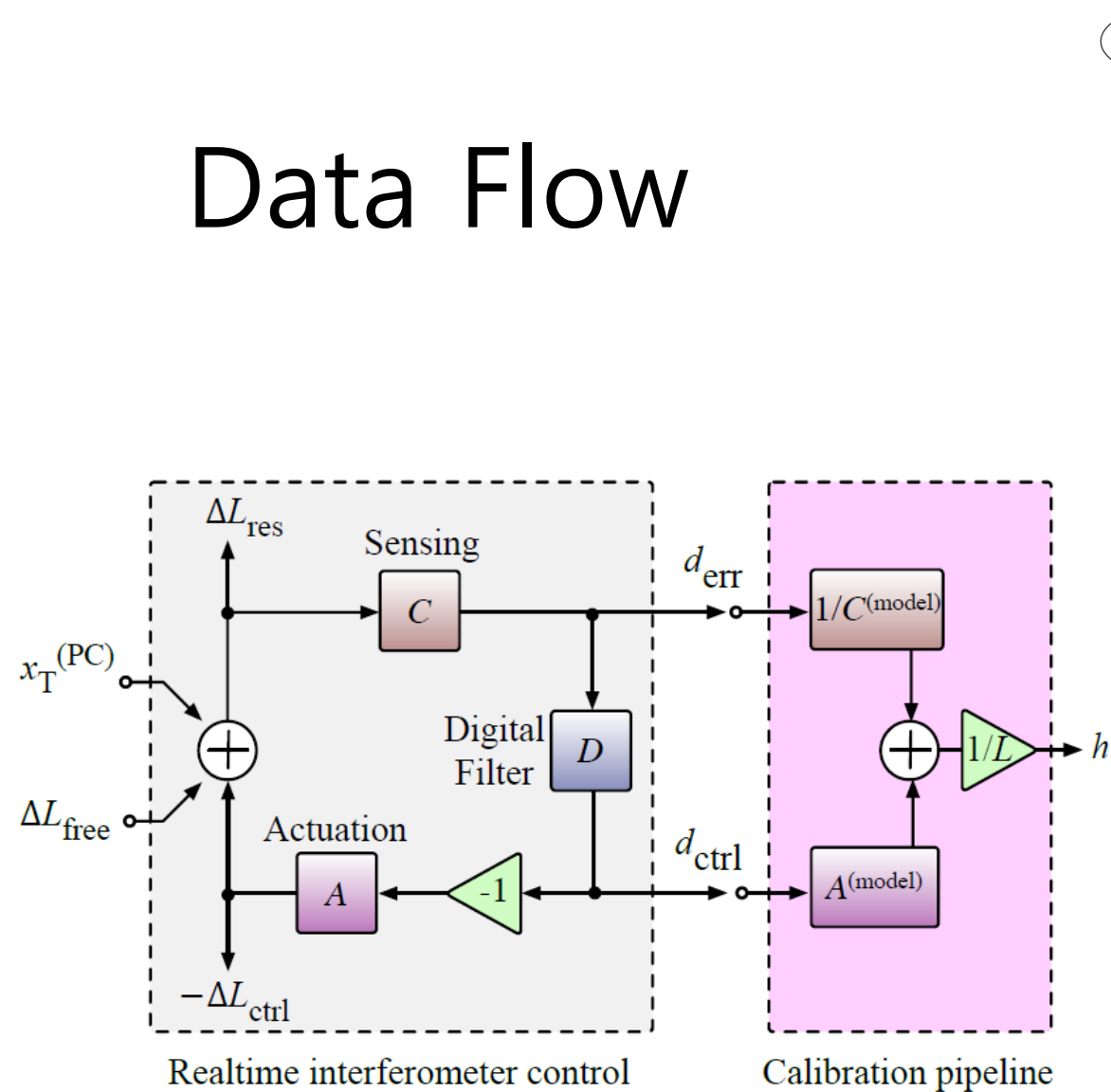
Detection candidates: 56

SORT: EVENT ID (A-Z)

Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Comments
S200316bj	MassGap (>99%)	March 16, 2020 21:57:56 UTC	GCN Circulars Notices VOE		1 per 446.44 years	
S200311bg	BBH (>99%)	March 11, 2020 11:58:53 UTC	GCN Circulars Notices VOE		1 per 3.5448e+17 years	



Data Flow



검색엔진

- 파형의존

- GstLAL: Gstreamer from LALSuite
- MBTA: Multi-Band Template Analysis
- PyCBC Broad
- PyCBC BBH
- SPIIR

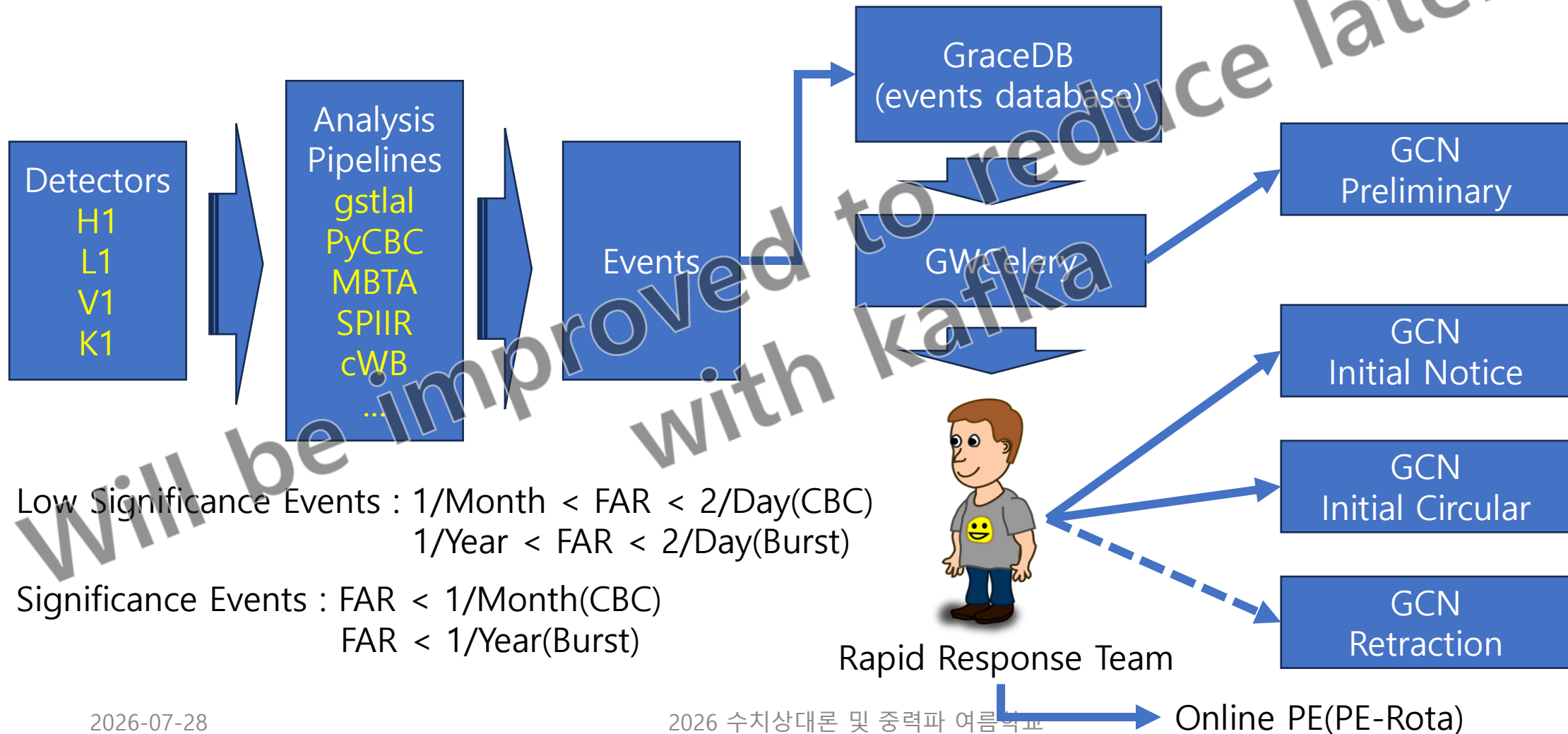
- 파형독립

- cWB: Coherent Wave-Burst

알려진 CBC중력파형 사용
정합필터와 파형집합 사용
검출기 사이의 동시성 확인
GstLAL은 한 검출기 검색 가능

CBC이외의 중력파 검출 가능
정합필터 사용하지 않음
검출기 사이의 동시성 확인
초과 에너지 계산

Public Alert System



공공 알림(Public Alerts)

GCN: The Gamma-ray Coordinates Network (TAN: Transient Astronomy Network)

https://gcn.nasa.gov

An official website of the United States government [Here's how you know](#)

NASA General Coordinates Network

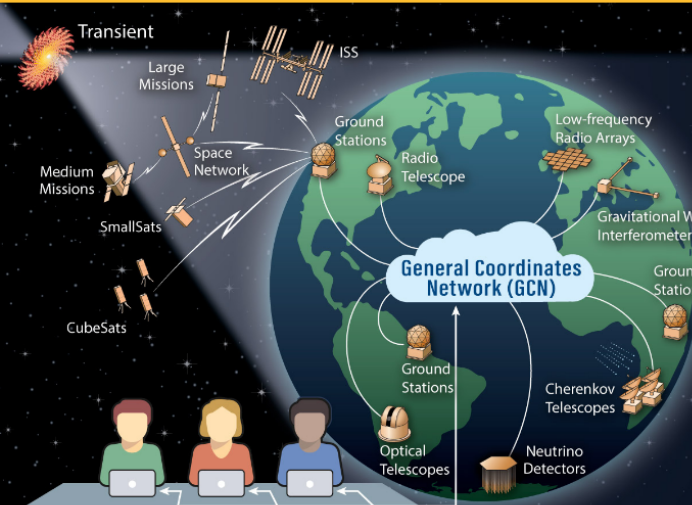
Missions Notices Circulars Documentation Sign in / Sign up

GCN Circulars are now part of the new GCN! See [news and announcements](#)

GCN: NASA's Time-Domain and Multimessenger Alert System

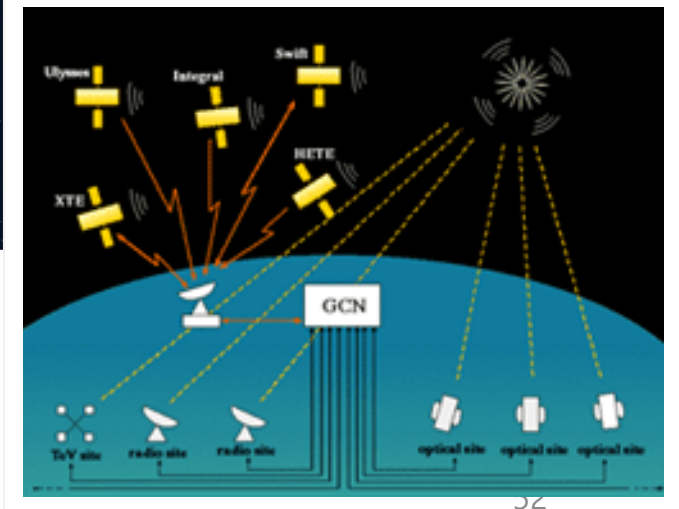
GCN distributes alerts between space- and ground-based observatories, physics experiments, and thousands of astronomers around the world.

[Start streaming GCN Notices](#) [Post a GCN Circular](#)



The General Coordinates Network (GCN) is a public collaboration platform run by NASA for the astronomy research community to share alerts and rapid communications about high-energy, multimessenger, and transient phenomena. For more information, see [What is GCN?](#) or check out our [slide deck](#).

There are three ways to stream GCN Notices in real time:



GCN Circulars

GCN Circulars are rapid astronomical bulletins submitted by and distributed to community members worldwide. They are used to share discoveries, observations, quantitative near-term predictions, requests for follow-up observations, or future observing plans related to high-energy, multi-messenger, and variable or transient astrophysical events. See the [documentation](#) for help with subscribing to or submitting Circulars.

   New

Search for Circulars by submitter, subject, or body text (e.g. 'Fermi GRB').

To navigate to a specific circular, enter the associated Circular ID (e.g. 'gcn123', 'Circular 123', or '123').

- 34231. [Swift GRB230720.30: Global MASTER-Net observations report](#)
- 34230. [IPN triangulation of GRB 230715D](#)
- 34229. [Swift Trigger 1180063 is not a GRB](#)
- 34228. [Swift Trigger 1180060 is not a GRB](#)
- 34227. [Swift Trigger 1180055 is not a GRB](#)
- 34226. [GRB 230718A: Final Localization Correction](#)
- 34225. [GRB 230718A: Fermi GBM Final Real-time Localization](#)
- 34224. [Fermi Gamma-ray Burst Monitor trigger 711329677/230717982 is not a GRB](#)
- 34223. [IPN triangulation of GRB 230712C \(short\)](#)
- 34222. [IPN triangulation of GRB 230712A \(short\)](#)
- 34221. [LIGO/Virgo/KAGRA S230708z: Updated Sky localization](#)
- 34220. [GRB 230717A: Fermi GBM Final Real-time Localization](#)
- 34219. [LIGO/Virgo/KAGRA S230715bw: Retraction of GW compact binary merger candidate](#)
- 34218. [Fermi trigger No 711088412: Global MASTER-Net observations report](#)
- 34217. [GRB 230715A: Fermi GBM Final Real-time Localization](#)
- 34216. [Fermi GRB 230713A: Global MASTER-Net observations report](#)

LVC Event Information

([LVC Event Information \(nasa.gov\)](https://gcn.gsfc.nasa.gov/lvc_events.html), https://gcn.gsfc.nasa.gov/lvc_events.html)

← ↻ 🔒 https://gcn.gsfc.nasa.gov/lvc_events.html

LVC Event Information

O1 and O2 era:

This page contains the Notices ONLY for the "G" and "GW" events that LVC has released to the public.

These G/GW events occurred during the O1 and O2 science operations intervals which was a private-phase mode of operation (i.e. Notices were sent to only those sites that had an MOU with the LVC).

As the LVC publishes on each GW event, the Notices for that event are moved from the private portion of the GCN to the public portion.

(Please note that for the next science operation (O3, starting in early 2019), the Notices (& Circulars) are immediately public and distributed without the need of an MOU.)

Post O2 Further Release to Public:

Two of the four GW events mentioned in the Dec 01, 2018 press release have been moved to this public page: G296853(=GW170809) and G298936(=GW170823).

O3 era:

During ER14 and O3, the events released to the public will be prefixed with and "S" (for "Super events").

This page changes after each Notice, so hit your <reload> button NOW.

This table contains information about LVC Triggers and the potential Counterparts found in follow-up observations.
The most recent Notice is listed first (reverse time order).



Primer on public alerts for astronomers from the LIGO, Virgo, and KAGRA gravitational-wave observatories.

IGWN | Public Alerts User Guide

Getting Started Checklist

Observing Capabilities

Data Analysis

Alert Contents

Sample Code

Additional Resources

🌟 Early-Warning Alerts

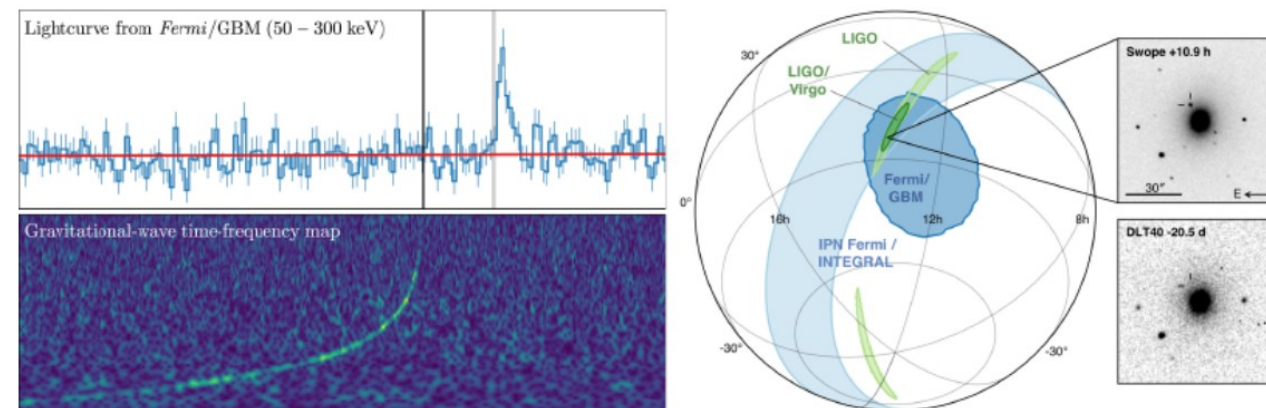
Change Log

Glossary

Question? Issues? Feedback?

Email emfollow-userguide@support.ligo.org

LIGO/Virgo/KAGRA Public Alerts User Guide



Welcome to the LIGO/Virgo/KAGRA Public Alerts User Guide! This document is intended for both professional astronomers and science enthusiasts who are interested in receiving alerts and real-time data products related to gravitational-wave (GW) events.

Four sites ([LHO](#), [LLO](#), [Virgo](#), [KAGRA](#)) together form a global network of ground-based GW detectors. The [LIGO Scientific Collaboration](#), the [Virgo Collaboration](#), and the [KAGRA Collaboration](#) jointly analyze the data in real time to detect and localize transients from compact binary mergers and other sources. When a signal candidate is found, an alert is sent to astronomers in order to search for counterparts (electromagnetic waves or neutrinos).

GraceDB Overview

The **Gravitational-Wave Candidate Event Database (GraceDB)** is a service operated by the [LIGO Scientific Collaboration](#). It provides a centralized location for aggregating and retrieving information about candidate gravitational-wave events. GraceDB provides an [API](#) for programmatic access, and a [client package](#) is available for interacting with the API.

Useful information

- Information about GW alerts and real-time data products is available in the [LIGO/Virgo Public Alert Guide](#).
- [Real-time status of the LIGO Data Grid](#) (LVK Credentials Required).
- Need help? Send an email to computing-help@ligo.org, or LIGO/Virgo users can report issues on the GraceDB [Gitlab page](#).

GraceDB Notifications

GraceDB notifies registered users of Gravitational-Wave candidate detections in real-time during LIGO/Virgo/KAGRA observation periods. Current notifications mechanisms are:

- Phone alerts (calls/SMS) are enabled
- Email alerts are enabled
- `igwn-alert` messages to `kafka://kafka.scimma.org/` are enabled
 - Messages are sent to group: `gracedb`

Server code version: [2.28.0-1](#)

Latest as of 28 July 2024 22:03:34 UTC

Test and MDC events and superevents are not included in the search results by default; see the [query help](#) for information on how to search for events and superevents in those categories.

Query:

Search for:

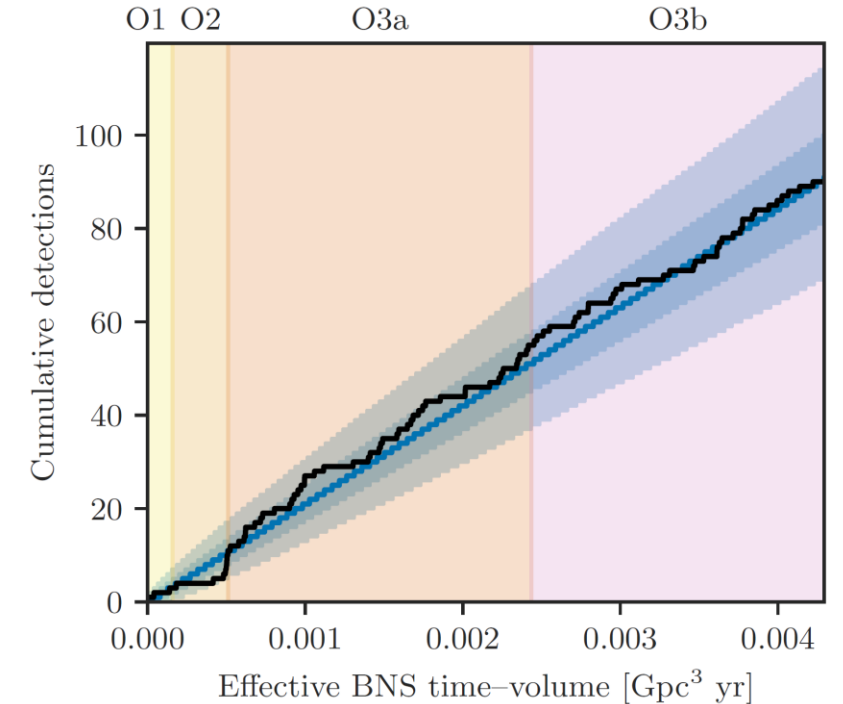
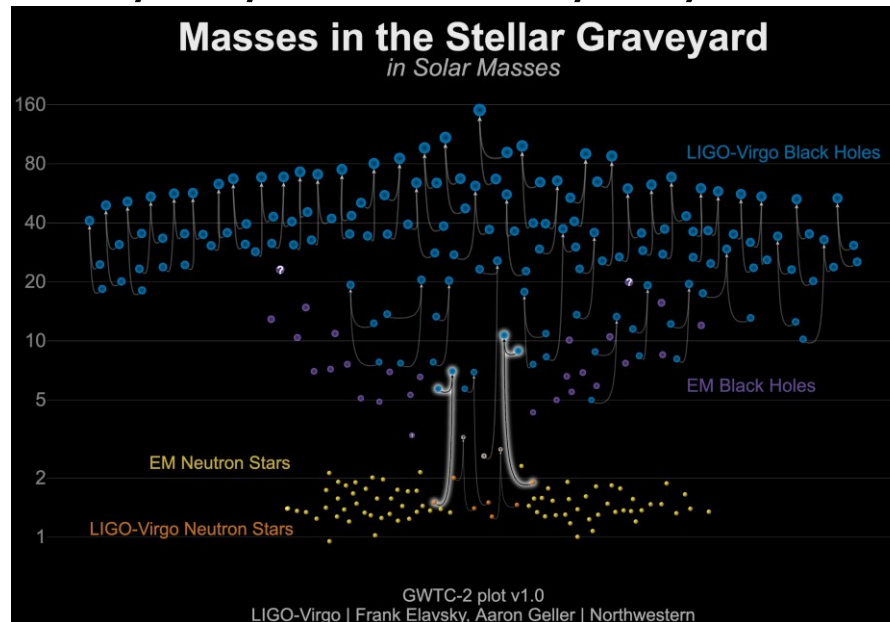
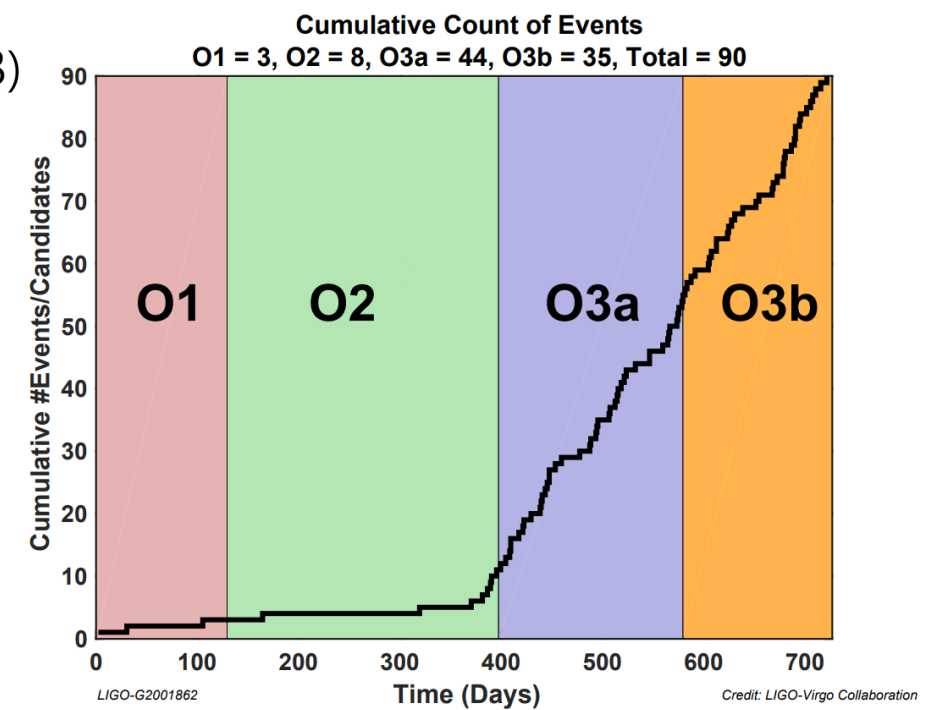
Search

Tap on entry for detailed information

UID	Labels	FAR (Hz)	Created ▾
S240725a	DQOK LOW_SIGNIF_LOCKED EM_READY PASTRO_READY SKYMAP_READY EMBRIGHT_READY LOW_SIGNIF_PRELIM_SENT EM_COINC	1.989e-05	2024-07-25 06:43:43 UTC
S240723b	EM_READY EMBRIGHT_READY SKYMAP_READY LOW_SIGNIF_PRELIM_SENT DQOK LOW_SIGNIF_LOCKED PASTRO_READY	1.376e-05	2024-07-23 03:32:42 UTC
S240722i	PASTRO_READY EMBRIGHT_READY LOW_SIGNIF_PRELIM_SENT DQOK LOW_SIGNIF_LOCKED EM_READY SKYMAP_READY	2.713e-06	2024-07-22 12:29:49 UTC
S240722f	DQOK EMBRIGHT_READY LOW_SIGNIF_LOCKED SKYMAP_READY EM_READY LOW_SIGNIF_PRELIM_SENT PASTRO_READY EM_COINC	1.986e-05	2024-07-22 09:50:31 UTC

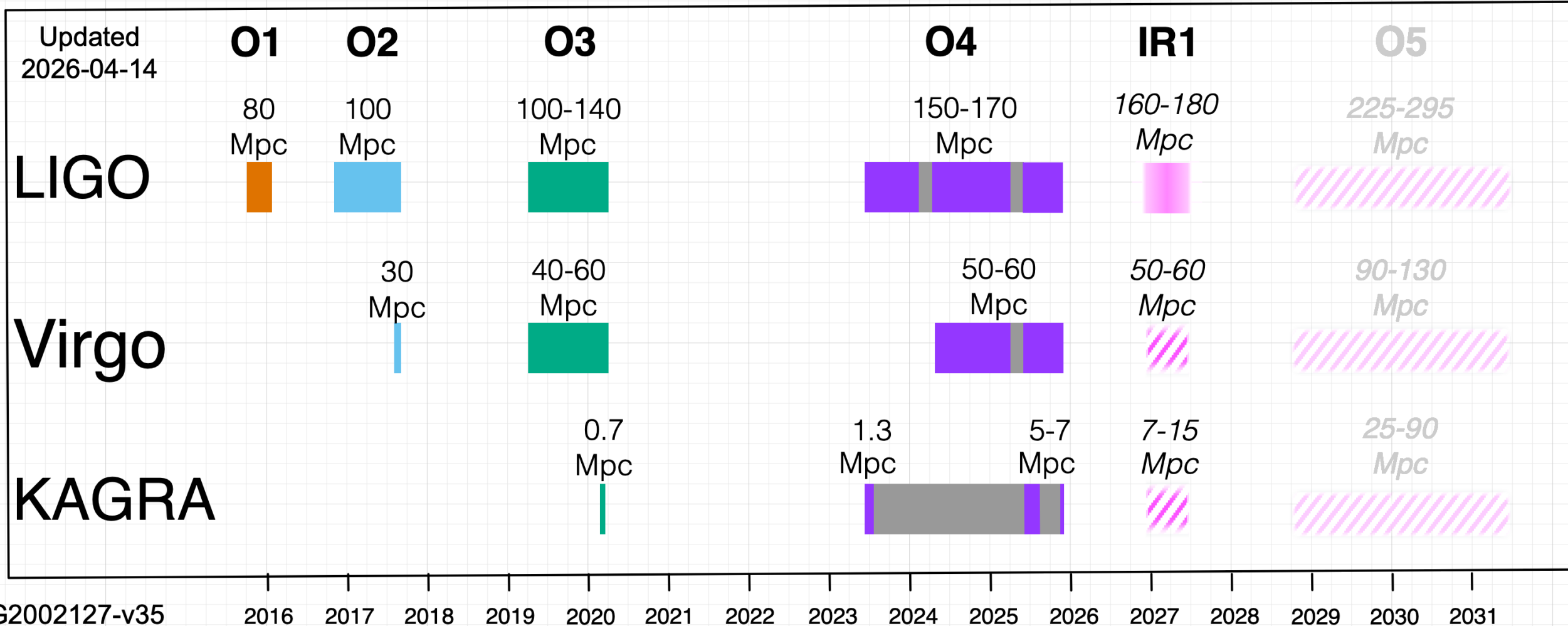
관측결과(Observations)

- O1: 2015/09/12~2016/01/19
- O2: 2016/11/30~2017/08/25
- O3a : 2019/04/01~2019/09/30
- O3b : 2019/11/01~2020/03/27

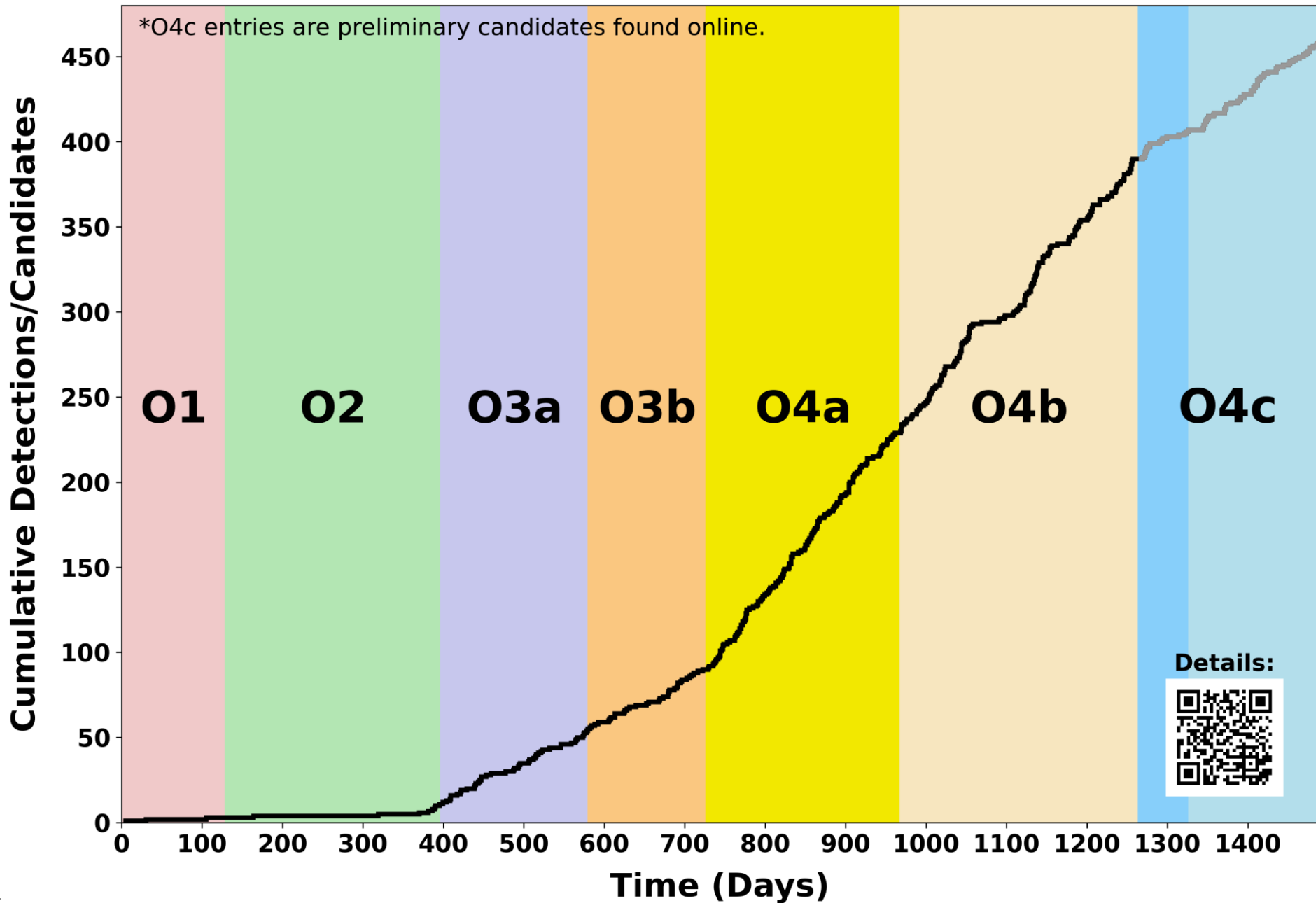


Observing schedule

([IGWN](#) | [Observing Plans](#))



O1 (3) + O2 (8) + O3a (44) + O3b (35) + O4a (139) + O4b (161) = 390, O4c* = 68, Total = 458



The gravitational-wave story

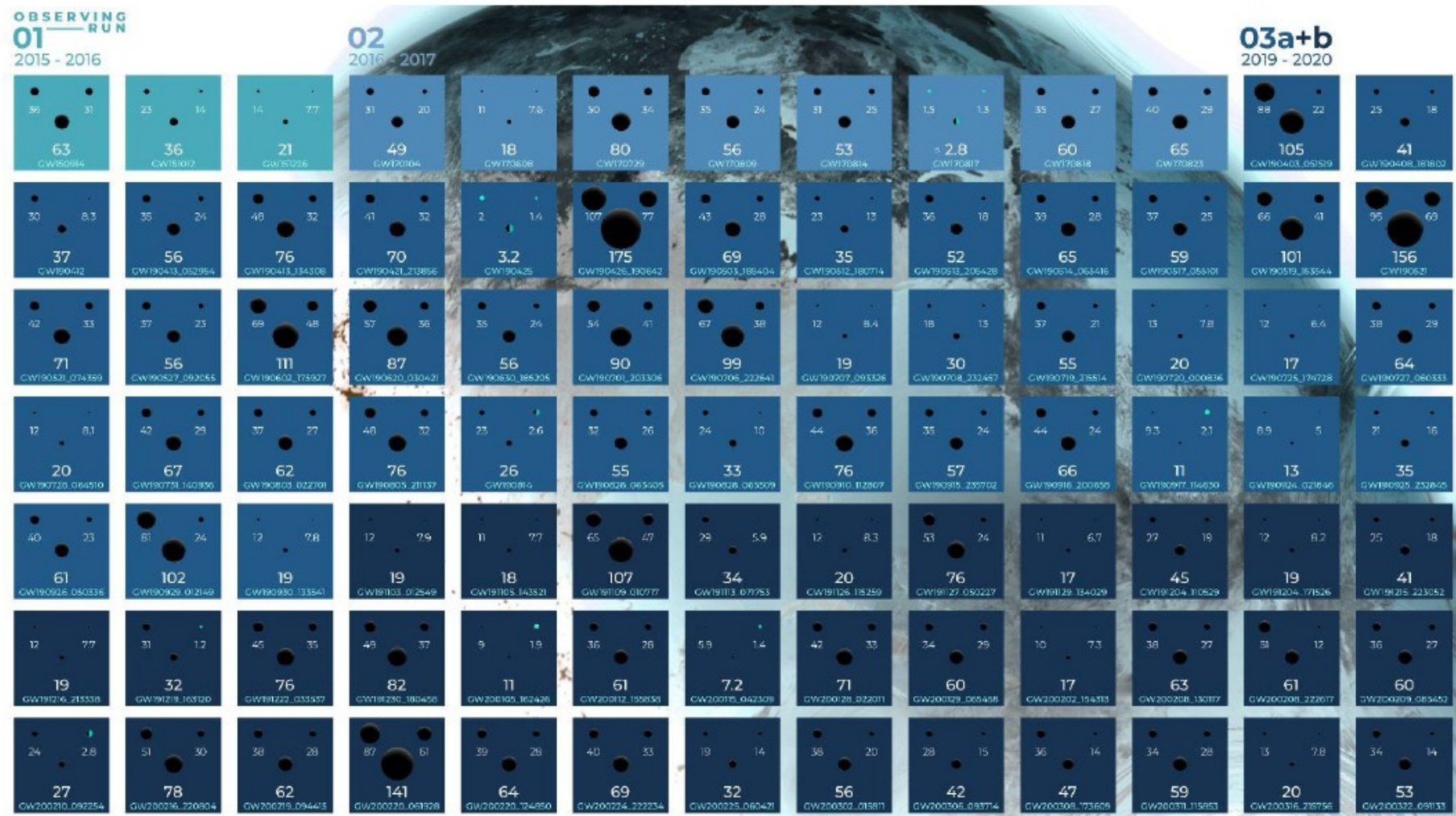
1916 Einstein predicts gravitational waves in general relativity

1974 First indirect evidence of gravitational waves from binary pulsars

2015 First observation of gravitational waves at the start of O1

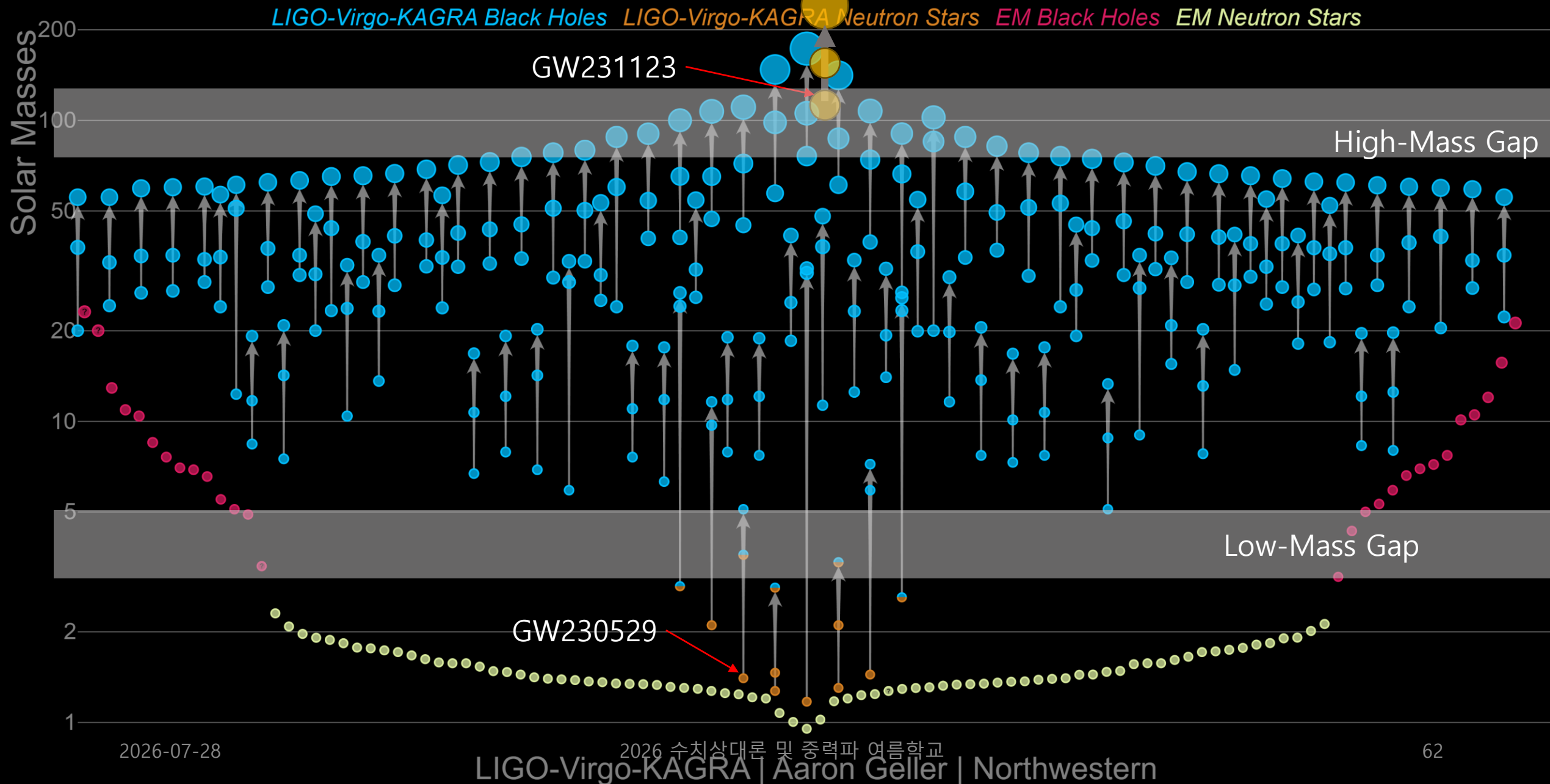
Observing runs
 O1: 2015-2016
 O2: 2016-2017
 O3: 2019-2020
 O4: ~2022-2023

2026-07-28

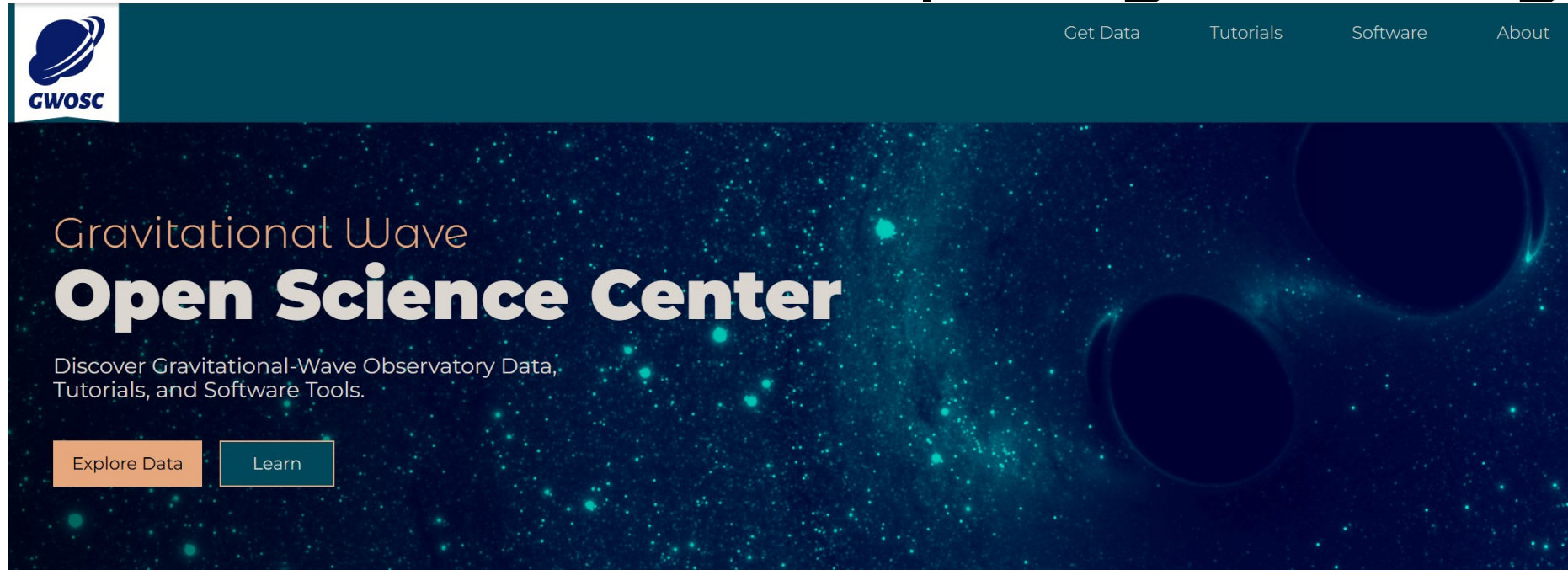


~~2026 수치상대론 및 중력파 여름학교~~

Masses in the Stellar Graveyard



Observed Events(<https://gwosc.org>)



Event Catalog

The Gravitational-wave Transient Catalog (GWTC) is a cumulative set of events detected by LIGO, Virgo, and KAGRA.



Open Data Workshop

Participants will receive a crash-course in gravitational-wave data analysis that includes lectures, software tutorials, and a data challenge.

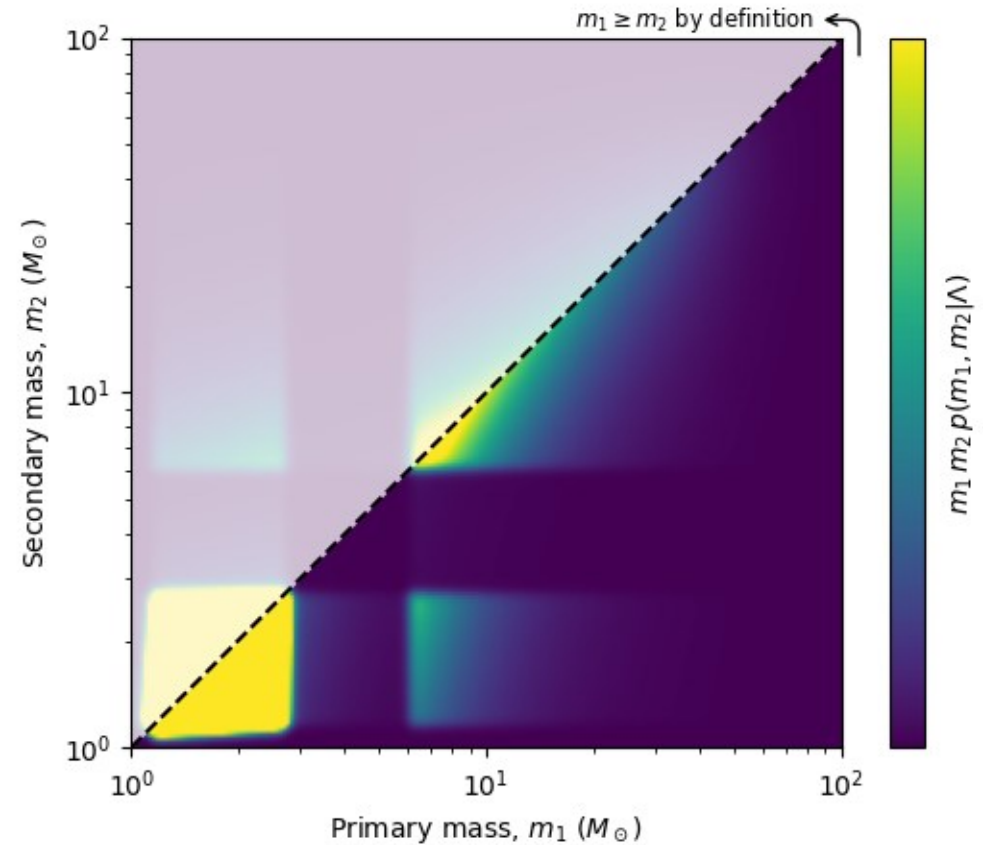
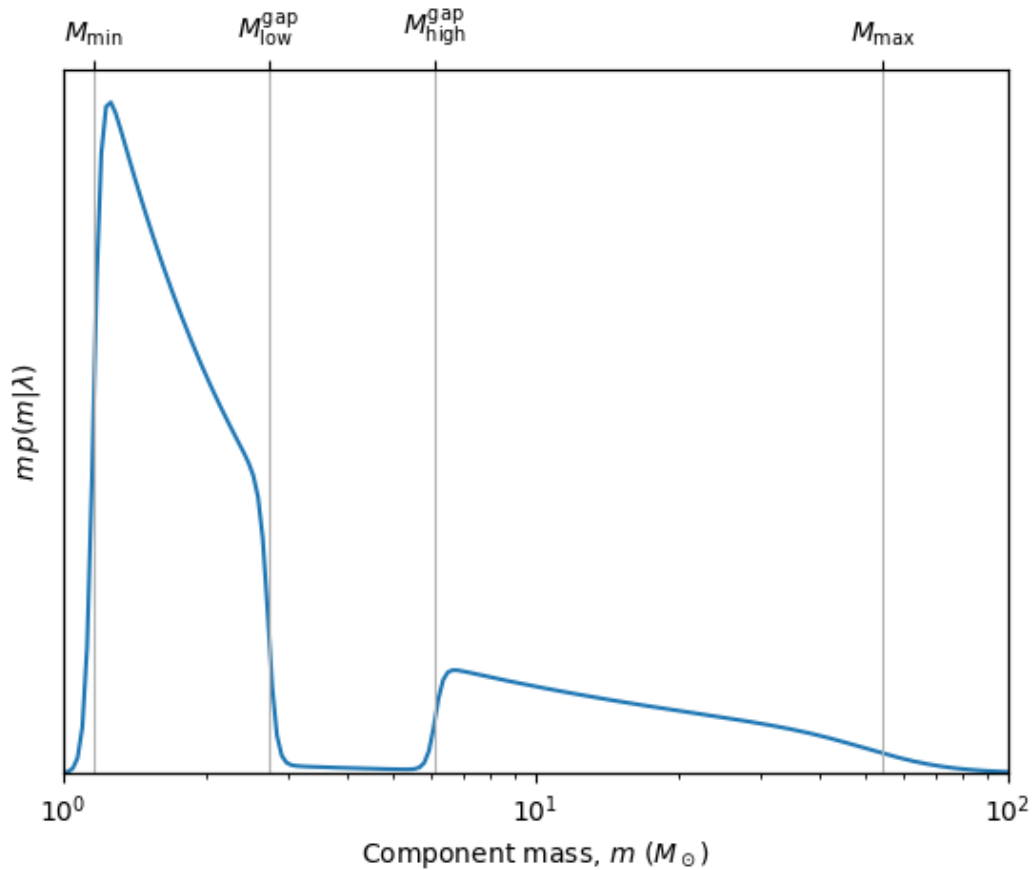


Tutorials

Learn with tutorials that will lead you step-by-step through some common data analysis tasks.

질량분포

LIGO Scientific Collaboration & Virgo Collaboration 2021, *The population of merging compact binaries inferred using gravitational waves through GWTC-3*. [arXiv:2111.03634](https://arxiv.org/abs/2111.03634)



Farah, A., Fishbach, M., et al. 2022, *Bridging the Gap: Categorizing Gravitational-wave Events at the Transition between Neutron Stars and Black Holes*. *Astrophys. J.*, 931, 108. [doi:10.3847/1538-4357/ac5f03](https://doi.org/10.3847/1538-4357/ac5f03)

IGWN Observing Plans

24 May 2023 for 18Months

([IGWN | Observing Plans \(ligo.org\)](https://observing.docs.ligo.org/plan), <https://observing.docs.ligo.org/plan>)

Updated
2023-01-23

O1 O2 O3 O4 O5

80
Mpc

100
Mpc

100-140
Mpc

160-190
Mpc

240-325
Mpc

LIGO



30
Mpc

40-50
Mpc

80-115
Mpc

150-260
Mpc

Virgo



0.7
Mpc

1-3 Mpc ≈ 10 Mpc ≥ 10 Mpc

25-128
Mpc

KAGRA

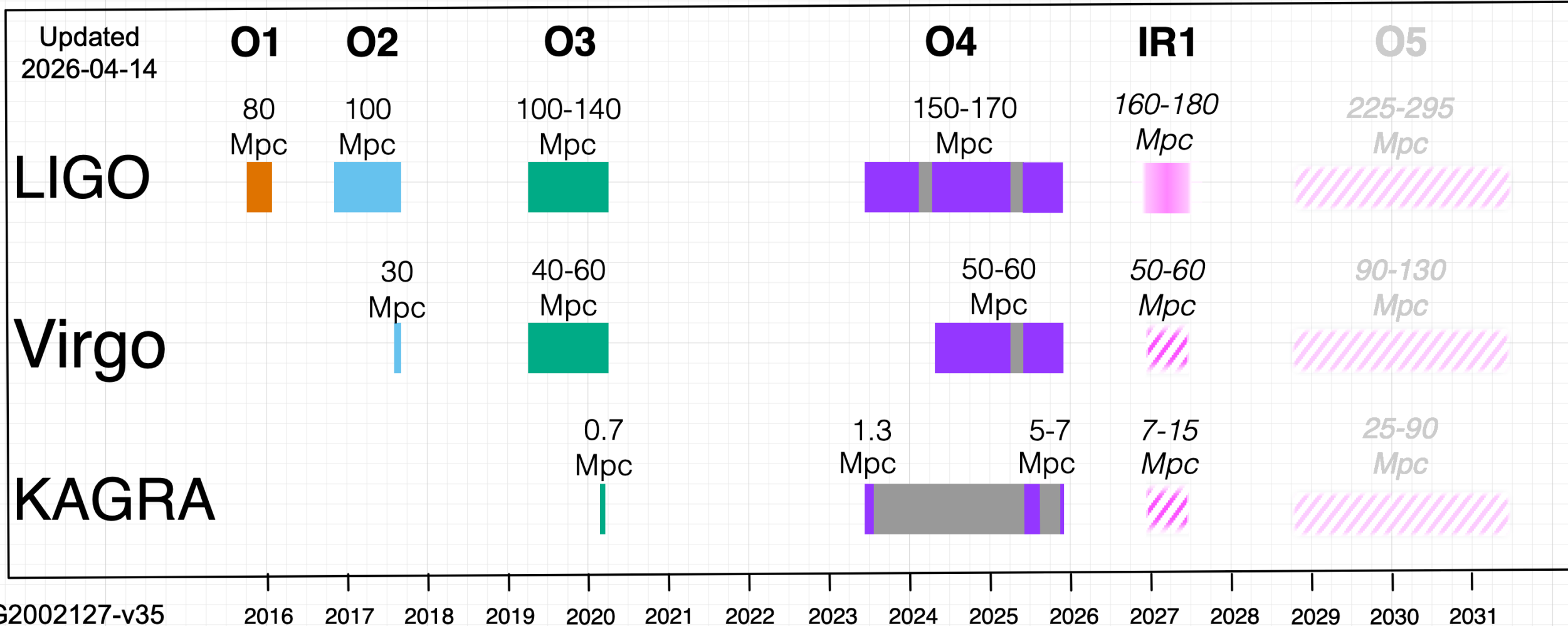


G2002127-v18

2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029

Observing schedule

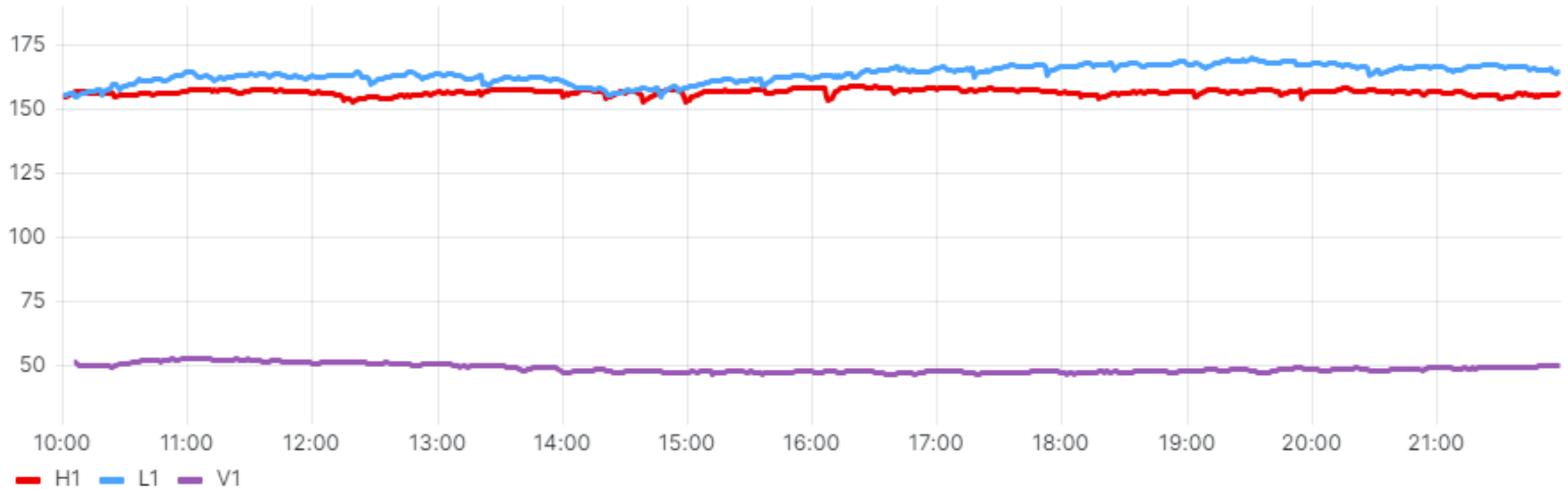
([IGWN](#) | [Observing Plans](#))



Observations in year 2024

20240401 10:00:00 – 21:59:59 UTC

GstLAL Inspiral Detector Range History (Mpc)



중력과 천체물리학

[Nat. Rev. Physics, May 2021](#)

2026-07-28

Box 1 | Fundamental questions addressed through gravitational-wave observations

- What is the physics of stellar core collapse? How often do core-collapse supernovae occur^{257,258}?
- What is the equation of state, and what are the radii, of neutron stars^{120,121}?
- What are the multi-messenger emission mechanisms of high-energy transients (gamma-ray bursts and kilonovae)²⁵⁹?
- How do binary black holes of tens of solar masses form and evolve^{260,261}?
- How did super-massive black holes at the cores of galactic nuclei form and evolve, and what were their seeds and demographics²⁶²?
- Are black hole spacetimes as predicted by general relativity¹³⁶?
- Are there any signatures of horizon structure or other manifestations of quantum gravity accessible to gravitational-wave observations²⁶³?
- Is dark matter composed, in part, of primordial black holes, or must it be composed solely from exotic matter such as axions or dark fermions²⁶³?
- What is the expansion rate of the Universe²⁶⁴?
- What is the nature of dark energy²⁶⁴?
- Is there a measurable gravitational-wave stochastic background due to phase transitions in the early Universe? If so, what were its properties^{265–267}?
- How does gravity behave in the strong/highly dynamical regime^{99–102}?
- Do we live in a Universe with large extra dimensions¹¹⁶?
- Are black holes, neutron stars and white dwarfs the only compact objects in our Universe, or are there even more exotic objects¹³³?

CBC Parameter Estimation

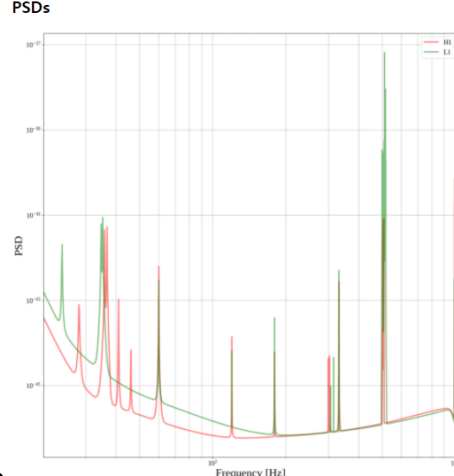
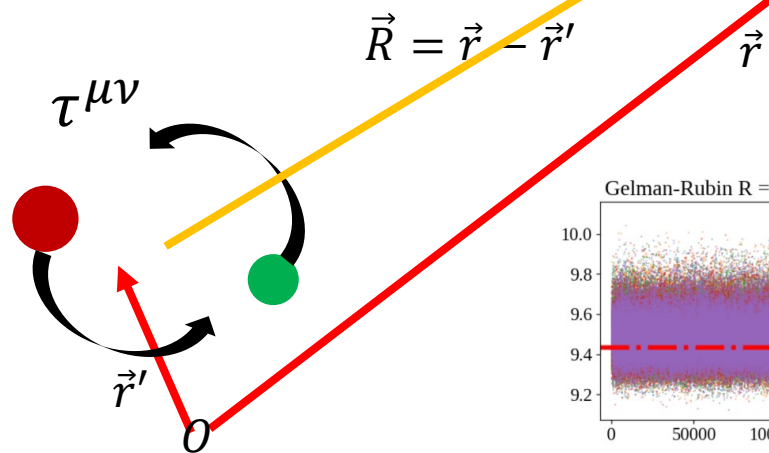
데이터분석

- 고유특성

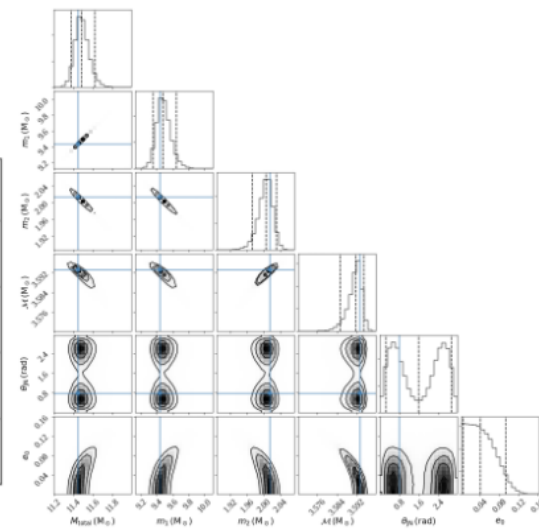
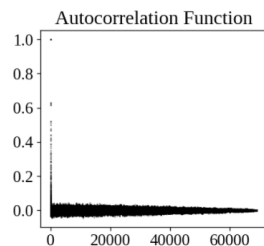
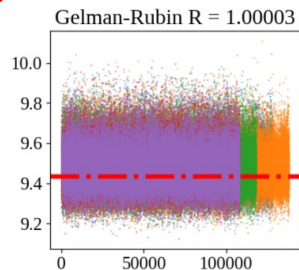
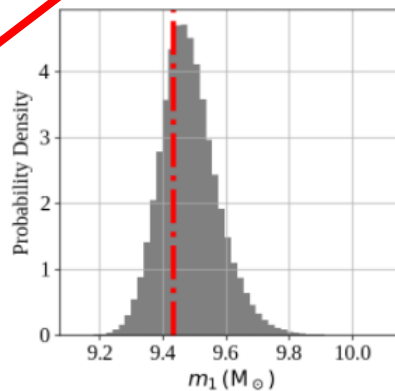
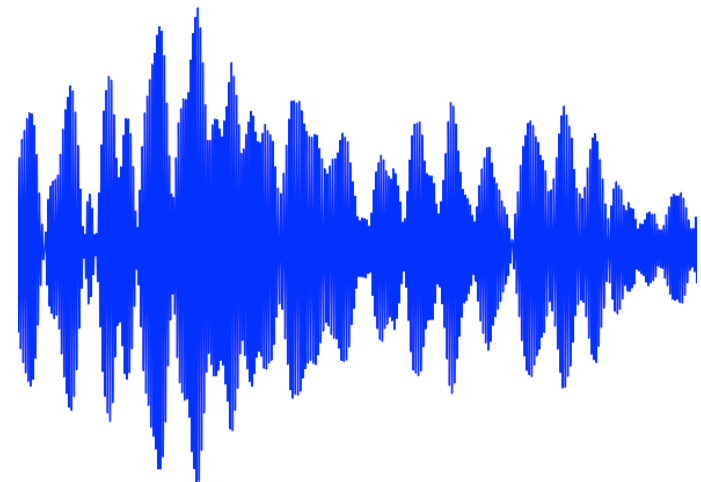
- $m_1, m_2, \vec{S}_1, \vec{S}_2, \Lambda_1, \Lambda_2, e_0$

- 외부특성

- $t_c, \varphi_c, \alpha, \delta, D, \theta_{JN}, \psi$



$$\bar{h}^{\mu\nu}$$



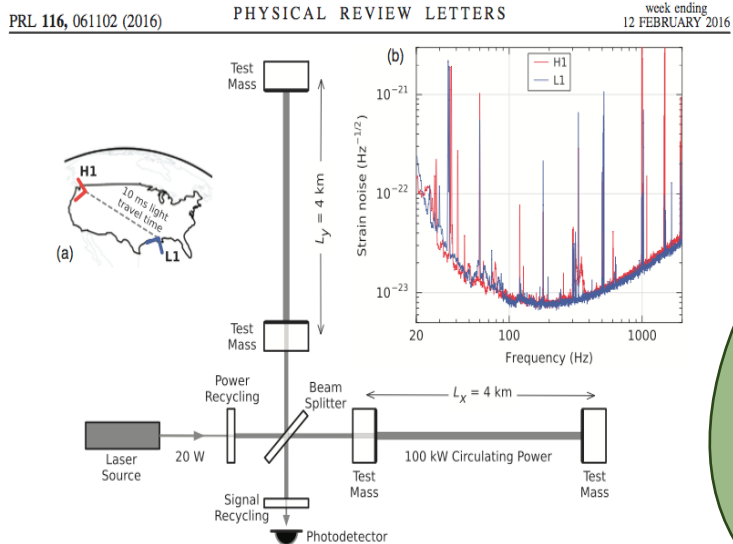
얼마나 비슷한가?
Likelihood

베이지언 추론
Posterior

적분
매개변수 분포

샘플생성
MCMC, Nested, RIFT

Question

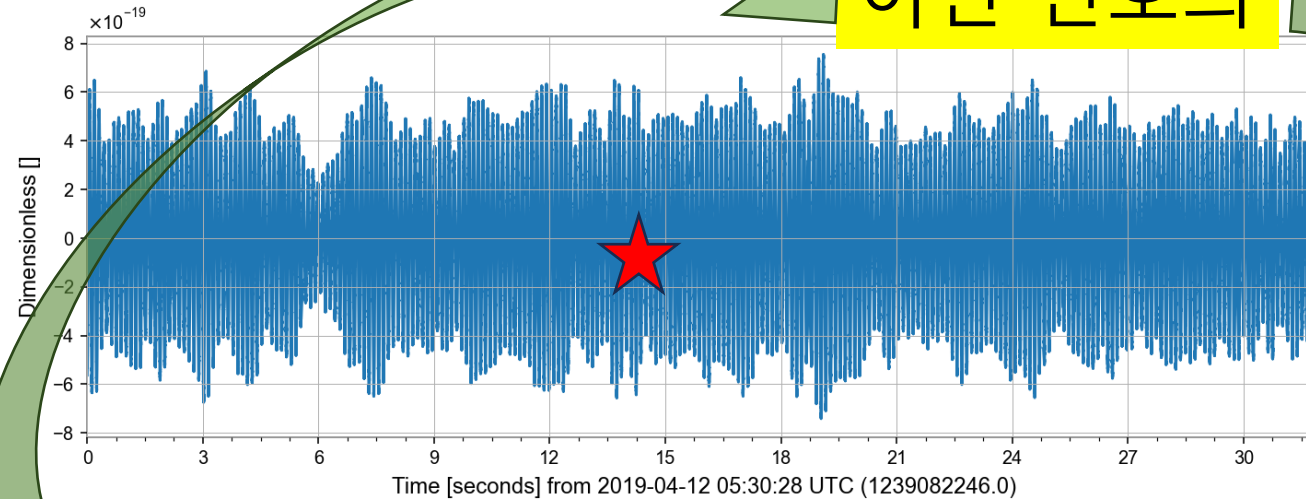


이런 관측기에서 나온

From this kind Detector

In this Signal

이런 신호의



Gravitational wave exist here

이 곳에 중력파신호가 있는데

파원이 어떤 물리적 특성을 갖는가?

pycbc Implementations

```
from pycbc.waveform import td_approximants, fd_approximants
# List of td approximants that are available
(td_approximants())
# List of fd approximants that are currently available
(fd_approximants())
```

- TD waveforms

- ['TaylorT1', 'TaylorT2', 'TaylorT3', 'SpinTaylorT1', 'SpinTaylorT4', 'SpinTaylorT5', 'PhenSpinTaylor', 'PhenSpinTaylorRD', 'EOBNRv2', 'EOBNRv2HM', 'TEOBResum_ROM', 'SEOBNRv1', 'SEOBNRv2', 'SEOBNRv2_opt', 'SEOBNRv3', 'SEOBNRv3_pert', 'SEOBNRv3_opt', 'SEOBNRv3_opt_rk4', 'SEOBNRv4', 'SEOBNRv4_opt', 'SEOBNRv4P', 'SEOBNRv4PHM', 'SEOBNRv2T', 'SEOBNRv4T', 'SEOBNRv4_ROM_NRTidalv2', 'SEOBNRv4_ROM_NRTidalv2_NSBH', 'HGimri', 'IMRPhenomA', 'IMRPhenomB', 'IMRPhenomC', 'IMRPhenomD', 'IMRPhenomD_NRTidalv2', 'IMRPhenomNSBH', 'IMRPhenomHM', 'IMRPhenomPv2', 'IMRPhenomPv2_NRTidal', 'IMRPhenomPv2_NRTidalv2', 'TaylorEt', 'TaylorT4', 'EccentricTD', 'SpinDominatedWf', 'NR_hdf5', 'NRSur7dq2', 'NRSur7dq4', 'SEOBNRv4HM', 'NRHybSur3dq8', 'IMRPhenomXAS', 'IMRPhenomXHM', 'IMRPhenomPv3', 'IMRPhenomPv3HM', 'IMRPhenomXP', 'IMRPhenomXPHM', 'TEOBResumS', 'IMRPhenomT', 'IMRPhenomTHM', 'IMRPhenomTP', 'IMRPhenomTPHM', 'TaylorF2', 'SEOBNRv1_ROM_EffectiveSpin', 'SEOBNRv1_ROM_DoubleSpin', 'SEOBNRv2_ROM_EffectiveSpin', 'SEOBNRv2_ROM_DoubleSpin', 'EOBNRv2_ROM', 'EOBNRv2HM_ROM', 'SEOBNRv2_ROM_DoubleSpin_HI', 'SEOBNRv4_ROM', 'IMRPhenomD_NRTidal', 'SpinTaylorF2', 'TaylorF2NL', 'SpinTaylorF2_SWAPPER']

- FD waveforms

- ['EccentricFD', 'TaylorF2', 'TaylorF2Ecc', 'TaylorF2NLTides', 'TaylorF2RedSpin', 'TaylorF2RedSpinTidal', 'SpinTaylorF2', 'EOBNRv2_ROM', 'EOBNRv2HM_ROM', 'SEOBNRv1_ROM_EffectiveSpin', 'SEOBNRv1_ROM_DoubleSpin', 'SEOBNRv2_ROM_EffectiveSpin', 'SEOBNRv2_ROM_DoubleSpin', 'SEOBNRv2_ROM_DoubleSpin_HI', 'Lackey Tidal 2013', 'SEOBNRv2_ROM', 'SEOBNRv4_ROM', 'SEOBNRv4HM_ROM', 'SEOBNRv4_ROM_NRTidal', 'SEOBNRv4_ROM_NRTidalv2', 'SEOBNRv4_ROM_NRTidalv2_NSBH', 'SEOBNRv4T_surrogate', 'IMRPhenomA', 'IMRPhenomB', 'IMRPhenomC', 'IMRPhenomD', 'IMRPhenomD_NRTidal', 'IMRPhenomD_NRTidalv2', 'IMRPhenomNSBH', 'IMRPhenomHM', 'IMRPhenomP', 'IMRPhenomPv2', 'IMRPhenomPv2_NRTidal', 'IMRPhenomPv2_NRTidalv2', 'SpinTaylorT4Fourier', 'SpinTaylorT5Fourier', 'NRSur4d2s', 'IMRPhenomXAS', 'IMRPhenomXHM', 'IMRPhenomPv3', 'IMRPhenomPv3HM', 'IMRPhenomXP', 'IMRPhenomXPHM', 'SpinTaylorF2_SWAPPER', 'TaylorF2NL', 'TaylorF2_INTERP', 'SEOBNRv1_ROM_EffectiveSpin_INTERP', 'SEOBNRv1_ROM_DoubleSpin_INTERP', 'SEOBNRv2_ROM_EffectiveSpin_INTERP', 'SEOBNRv2_ROM_DoubleSpin_INTERP', 'EOBNRv2_ROM_INTERP', 'EOBNRv2HM_ROM_INTERP', 'SEOBNRv2_ROM_DoubleSpin_HI_INTERP', 'SEOBNRv4_ROM_INTERP', 'SEOBNRv4', 'IMRPhenomC_INTERP', 'IMRPhenomD_INTERP', 'IMRPhenomPv2_INTERP', 'IMRPhenomD_NRTidal_INTERP', 'IMRPhenomPv2_NRTidal_INTERP', 'SpinTaylorF2_INTERP', 'TaylorF2NL_INTERP', 'SpinTaylorF2_SWAPPER_INTERP']

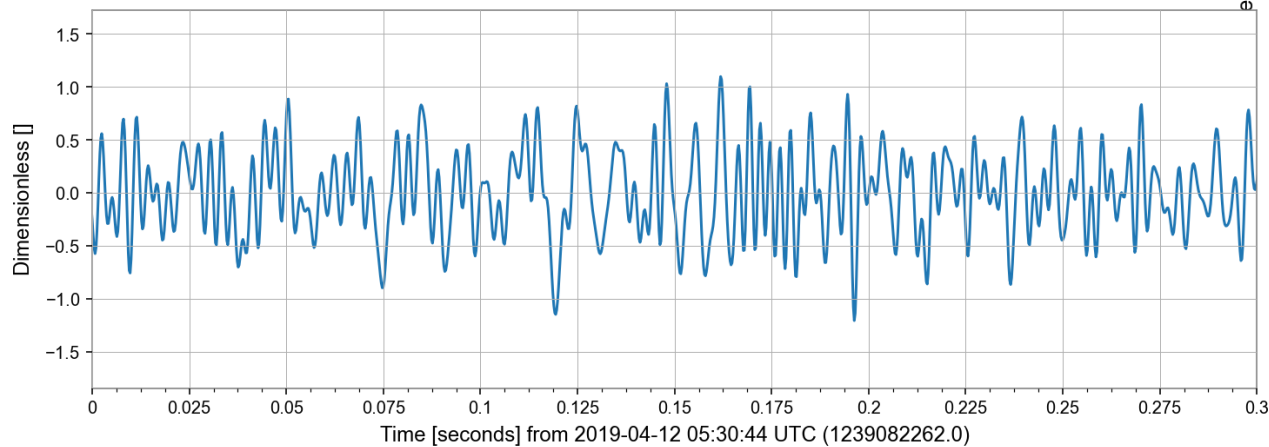
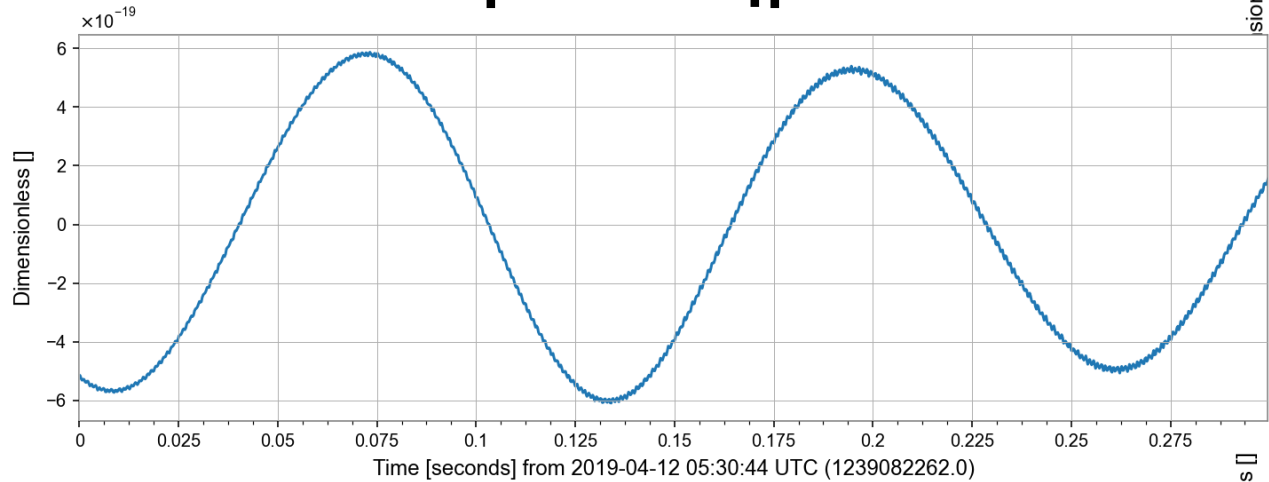
중력파형

- 107 Waveforms
- Post-Newtonian
- Time-domain
- Frequency-domain
- Tidal effects
- Spin effects
- NR approximation
- Effective One Body

```
enum Approximant {  
    TaylorT1, TaylorT2, TaylorT3, TaylorF1,  
    EccentricFD, TaylorF2, TaylorF2Ecc, TaylorF2NLTides,  
    TaylorR2F4, TaylorF2RedSpin, TaylorF2RedSpinTidal, PadeT1,  
    PadeF1, EOB, BCV, BCVSpin,  
    SpinTaylorT1, SpinTaylorT2, SpinTaylorT3, SpinTaylorT4,  
    SpinTaylorT5, SpinTaylorF2, SpinTaylorFrameless, SpinTaylor,  
    PhenSpinTaylor, PhenSpinTaylorRD, SpinQuadTaylor, FindChirpSP,  
    FindChirpPTF, GeneratePPN, BCVC, FrameFile,  
    AmpCorPPN, NumRel, NumRelNinja2, Eccentricity,  
    EOBNR, EOBNRv2, EOBNRv2HM, EOBNRv2_ROM,  
    EOBNRv2HM_ROM, TEOBResum_ROM, SEOBNRv1, SEOBNRv2,  
    SEOBNRv2_opt, SEOBNRv3, SEOBNRv3_pert, SEOBNRv3_opt,  
    SEOBNRv3_opt_rk4, SEOBNRv4, SEOBNRv4_opt, SEOBNRv4P,  
    SEOBNRv4PHM, SEOBNRv2T, SEOBNRv4T, SEOBNRv1_ROM_EffectiveSpin,  
    SEOBNRv1_ROM_DoubleSpin, SEOBNRv2_ROM_EffectiveSpin, SEOBNRv2_ROM_DoubleSpin_HI,  
    Lackey_Tidal_2013_SEOBNRv2_ROM, SEOBNRv4_ROM, SEOBNRv4HM_ROM, SEOBNRv4_ROM_NRTidal,  
    SEOBNRv4_ROM_NRTidalv2, SEOBNRv4_ROM_NRTidalv2_NSBH, SEOBNRv4T_surrogate, HGimri,  
    IMRPhenomA, IMRPhenomB, IMRPhenomFA, IMRPhenomFB,  
    IMRPhenomC, IMRPhenomD, IMRPhenomD_NRTidal, IMRPhenomD_NRTidalv2,  
    IMRPhenomNSBH, IMRPhenomHM, IMRPhenomP, IMRPhenomPv2,  
    IMRPhenomPv2_NRTidal, IMRPhenomPv2_NRTidalv2, IMRPhenomFC, TaylorEt,  
    TaylorT4, EccentricTD, TaylorN, SpinTaylorT4Fourier,  
    SpinTaylorT5Fourier, SpinDominatedWf, NR_hdf5, NRSur4d2s,  
    NRSur7dq2, NRSur7dq4, SEOBNRv4HM, NRHybSur3dq8,  
    IMRPhenomXAS, IMRPhenomXHM, IMRPhenomPv3, IMRPhenomPv3HM,  
    IMRPhenomXP, IMRPhenomXPHM, TEOBResumS, IMRPhenomT,  
    IMRPhenomTHM, IMRPhenomTP, IMRPhenomTPHM, NumApproximants  
}
```

LALSimInspiral.h

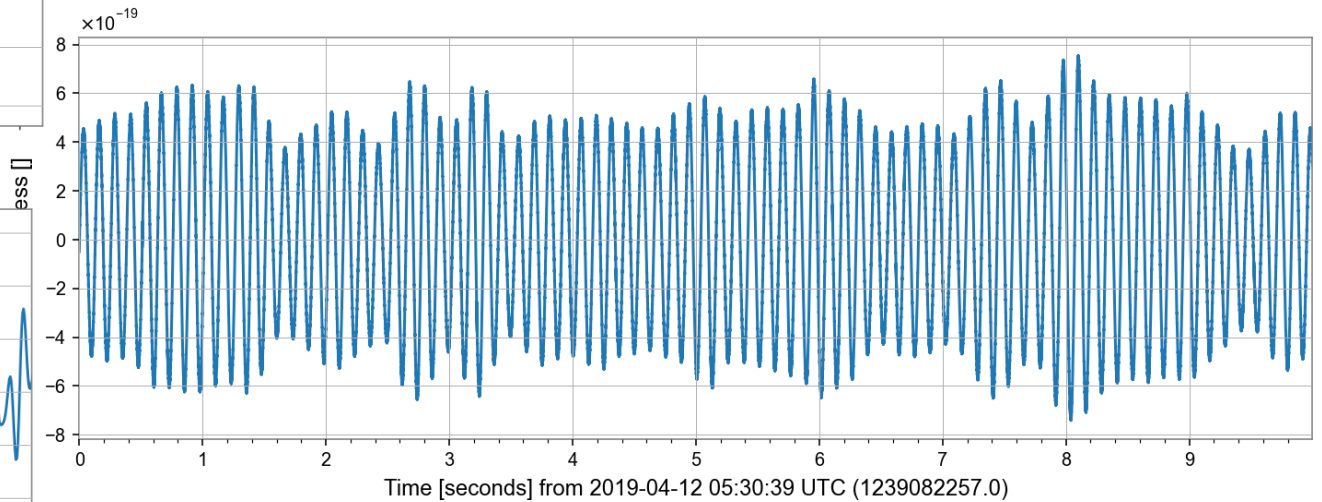
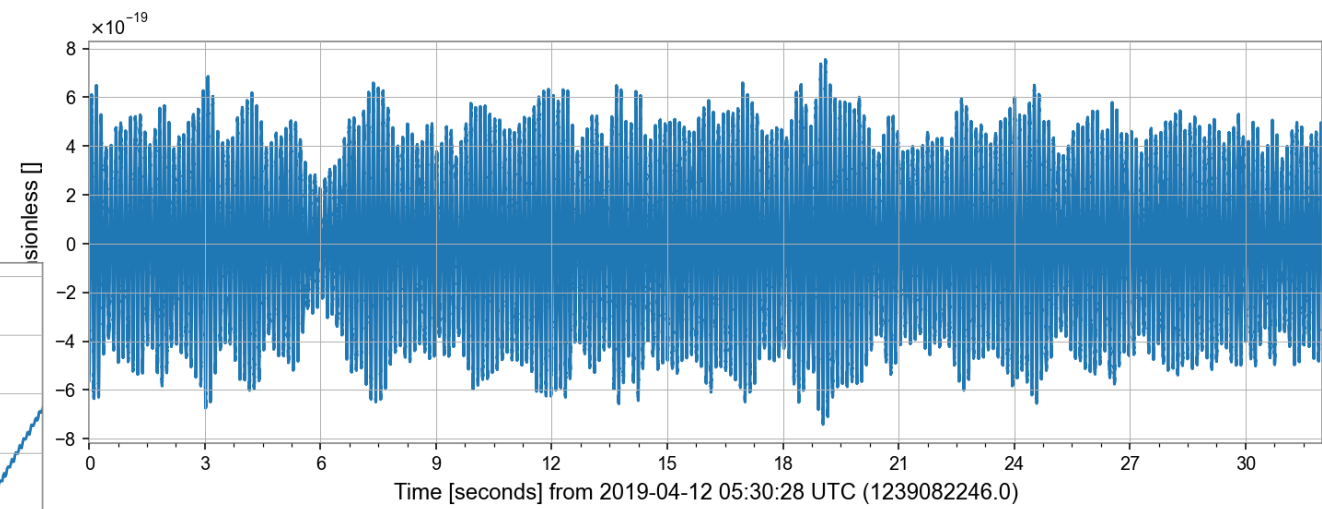
LIGO 자료 예



$t_0 = 1239082262.2$

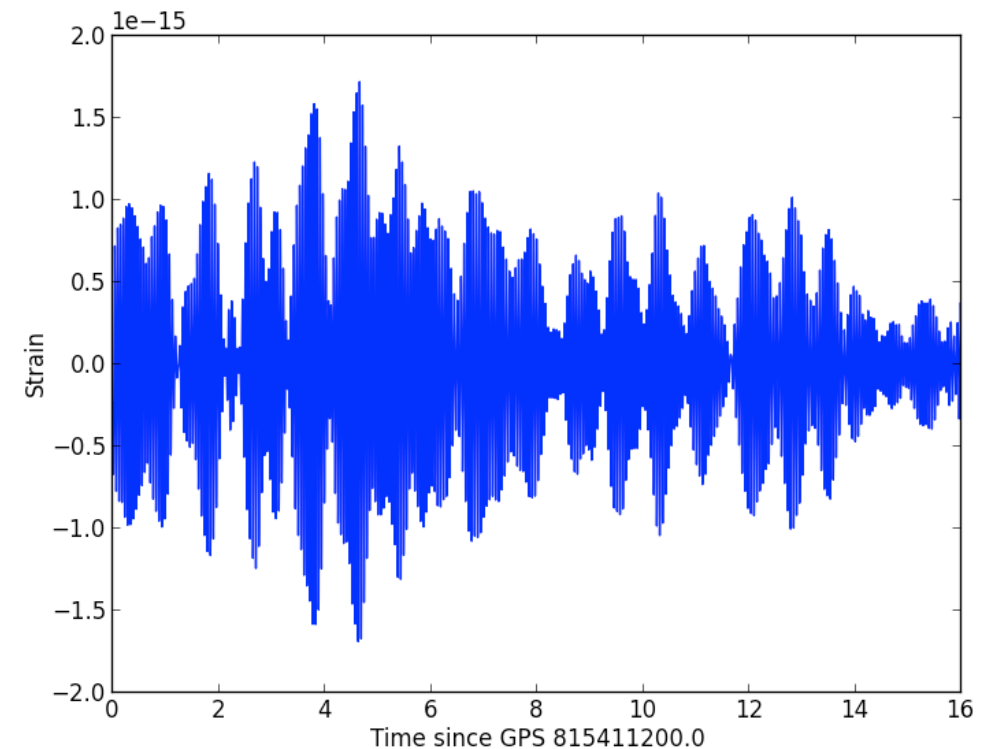
Odw4, GW190412

[GWOSC \(gw-openscience.org\)](https://www.gwosc.org)



LIGO 자료

- Discretely sampled time-series data
- Sampling rate (fs)
- $h(t)$ – calibrated strain
 - ALSO: hundreds of “auxiliary” channels
- Recorded at 16384 Hz sample rate
- ~300 MB per hour
- Stored in .gwf “frame” files
 - Also HDF5(Hierarchical Data Format version 5)



어디서 자료를 가져올 수 있나?

(<https://www.gw-openscience.org/>)



Gravitational Wave Open Science Center

[Data](#) [Software](#) [Online Tools](#) [Learning Resources](#) [About GWOSC](#)

[New Search](#) [Help](#)

Event List

- Toggle columns on/off with widget at right.
- Click an event name for all versions and more information.
- Values in the table below are from the **Default SEARCH** and **Default PE** cases found in the individual event's page.
- See [Event Portal Usage Notes](#) for more details.

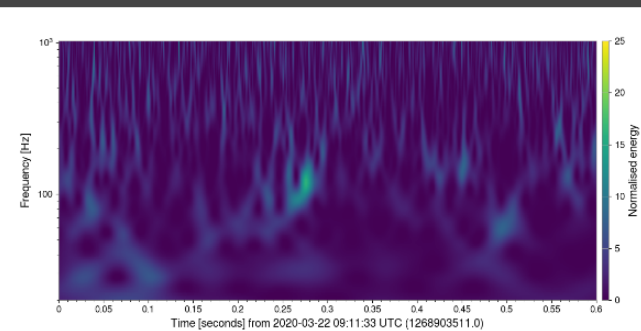
List contains 181 events. ✕

SORT: GPS ↓

Name	Version	Release	GPS ↓	Mass 1 ($M_{\odot}$)	Mass 2 ($M_{\odot}$)	Network SNR	Distance (Mpc)	χ_{eff}	Total Mass ($M_{\odot}$)
GW200322_091133	v1	GWTC-3-confident	1268903511.3	⁺⁴⁸ ₃₄ ⁻¹⁸	^{+16.8} _{14.0} ^{-8.7}	^{+1.7} _{6.0} ^{-1.2}	⁺⁷⁰⁰⁰ ₃₆₀₀ ⁻²⁰⁰⁰	^{+0.45} _{0.24} ^{-0.51}	⁺³⁷ ₅₅ ⁻²⁷
GW200316_215756	v1	GWTC-3-confident	1268431094.1	^{+10.2} _{13.1} ^{-2.9}	^{+1.9} _{7.8} ^{-2.9}	^{+0.4} _{10.3} ^{-0.7}	⁺⁴⁷⁰ ₁₁₂₀ ⁻⁴⁴⁰	^{+0.27} _{0.13} ^{-0.10}	^{+7.2} _{21.2} ^{-2.0}
GW200311_115853	v1	GWTC-3-confident	1267963151.3	^{+6.4} _{34.2} ^{-3.8}	^{+4.1} _{27.7} ^{-5.9}	^{+0.2} _{17.8} ^{-0.2}	⁺²⁸⁰ ₁₁₇₀ ⁻⁴⁰⁰	^{+0.16} _{-0.02} ^{-0.20}	^{+5.3} _{61.9} ^{-4.2}
GW200311_103121	v1	GWTC-3-marginal	1267957899.7	--	--	9.2	--	--	--
GW200308_173609	v1	GWTC-3-confident	1267724187.7	^{+11.2} _{36.4} ^{-9.6}	^{+7.2} _{13.8} ^{-3.3}	^{+0.5} _{7.1} ^{-0.5}	⁺²⁷⁰⁰ ₅₄₀₀ ⁻²⁶⁰⁰	^{+0.17} _{0.65} ^{-0.21}	^{+10.9} _{50.6} ^{-8.5}
GW200306_093714	v1	GWTC-3-confident	1267522652.1	^{+17.1} _{28.3} ^{-7.7}	^{+6.5} _{14.8} ^{-6.4}	^{+0.4} _{7.8} ^{-0.6}	⁺¹⁷⁰⁰ ₂₁₀₀ ⁻¹¹⁰⁰	^{+0.28} _{0.32} ^{-0.46}	^{+11.8} _{43.9} ^{-7.5}
GW200302_015811	v1	GWTC-3-confident	1267149509.5	^{+8.7} _{37.8} ^{-8.5}	^{+8.1} _{20.0} ^{-5.7}	^{+0.3} _{10.8} ^{-0.4}	⁺¹⁰²⁰ ₁₄₈₀ ⁻⁷⁰⁰	^{+0.25} _{0.01} ^{-0.26}	^{+9.6} _{57.8} ^{-6.9}
GW200225_060421	v1	GWTC-3-confident	1266645879.3	^{+5.0} _{19.3} ^{-3.0}	^{+2.8} _{14.0} ^{-3.5}	^{+0.3} _{12.5} ^{-0.4}	⁺⁵¹⁰ ₁₁₅₀ ⁻⁵³⁰	^{+0.17} _{-0.12} ^{-0.28}	^{+3.6} _{33.5} ^{-3.0}

Name	Version	Release	Run	GPS	Mass 1 (M _⊙)	Mass 2 (M _⊙)	Network SNR	Distance (Mpc)	χ _{eff}	Total Mass (M _⊙)
GW250120_042414	v1	GWTC-5.0	O4b	1421382272.1	--	--	8.7	--	--	--
GW250119_190238	v1	GWTC-5.0	O4b	1421348576.3	^{+1.95} 11.54 _{-0.81}	^{+0.77} 9.95 _{-1.56}	21.3	⁺²⁸⁹ 311 ₋₆₈	^{+0.05} 0.09 _{-0.03}	^{+0.55} 21.64 _{-1.03}
GW250119_025138	v1	GWTC-5.0	O4b	1421290316.8	^{+6.3} 33.8 _{-4.8}	^{+5.6} 26.7 _{-6.3}	14.5	⁺¹¹⁰⁰ 3100 ₋₁₃₀₀	^{+0.18} 0.06 _{-0.18}	^{+8.8} 59.9 _{-5.4}
GW250118_170523	v1	GWTC-5.0	O4b	1421255141.2	^{+8.1} 38.1 _{-5.6}	^{+5.4} 29.6 _{-6.3}	13.9	⁺⁸⁰⁰ 1910 ₋₇₄₀	^{+0.18} 0.12 _{-0.19}	^{+7.9} 67.8 _{-6.7}
GW250118_055802	v1	GWTC-5.0	O4b	1421215100.5	^{+7.5} 10.3 _{-1.8}	^{+1.5} 6.9 _{-2.6}	10.5	⁺⁶³⁰ 940 ₋₃₈₀	^{+0.24} 0.11 _{-0.09}	^{+4.7} 17.5 _{-1.6}
GW250118_023225	v1	GWTC-5.0	O4b	1421202763.9	⁺¹⁵ 44 ₋₁₀	⁺¹¹ 31 ₋₁₁	9.0	⁺³⁸⁰⁰ 5800 ₋₂₉₀₀	^{+0.28} 0.04 _{-0.31}	⁺²⁰ 74 ₋₁₃
GW250116_051426	v1	GWTC-5.0	O4b	1421039685.0	--	--	7.9	--	--	--
GW250116_015318	v1	GWTC-5.0	O4b	1421027616.4	^{+14.5} 34.2 _{-9.3}	^{+8.8} 21.3 _{-8.3}	8.0	⁺³⁹⁰⁰ 5200 ₋₂₅₀₀	^{+0.31} 0.15 _{-0.33}	⁺¹⁶ 56 ₋₁₁
GW250114_082203	v2	GWTC-5.0	O4b	1420878141.2	^{+1.28} 33.76 _{-0.90}	^{+0.95} 32.26 _{-1.47}	78.6	⁺⁸⁴ 405 ₋₇₃	^{+0.04} -0.03 _{-0.05}	^{+1.1} 66.0 _{-1.2}
GW250109_083206	v1	GWTC-5.0	O4b	1420446744.3	--	--	10.5	--	--	--
GW250109_074552	v1	GWTC-5.0	O4b	1420443970.4	^{+8.3} 39.0 _{-6.3}	^{+6.8} 30.2 _{-7.2}	10.7	⁺¹⁴⁰⁰ 2300 ₋₁₁₀₀	^{+0.20} 0.07 _{-0.20}	^{+10.5} 69.2 _{-8.6}
GW250109_010541	v1	GWTC-5.0	O4b	1420419959.5	^{+14.7} 37.5 _{-7.1}	^{+8.0} 27.4 _{-8.9}	13.1	⁺¹⁷⁰⁰ 3400 ₋₁₇₀₀	^{+0.27} -0.11 _{-0.29}	^{+14.7} 64.9 _{-8.6}
GW250108_152221	v1	GWTC-5.0	O4b	1420384959.7	⁺¹⁵ 54 ₋₁₂	⁺¹⁰ 36 ₋₁₀	11.8	⁺²⁴⁰⁰ 3800 ₋₁₉₀₀	^{+0.28} 0.05 _{-0.28}	⁺¹⁷ 90 ₋₁₃
GW250105_134047	v1	GWTC-5.0	O4b	1420119665.7	--	--	8.7	--	--	--
GW250104_015122	v1	GWTC-5.0	O4b	1419990700.3	^{+11.0} 45.8 _{-8.8}	^{+10.7} 34.5 _{-9.9}	12.1	⁺²⁵⁰⁰ 4800 ₋₂₃₀₀	^{+0.22} 0.11 _{-0.23}	⁺¹⁸ 80 ₋₁₁

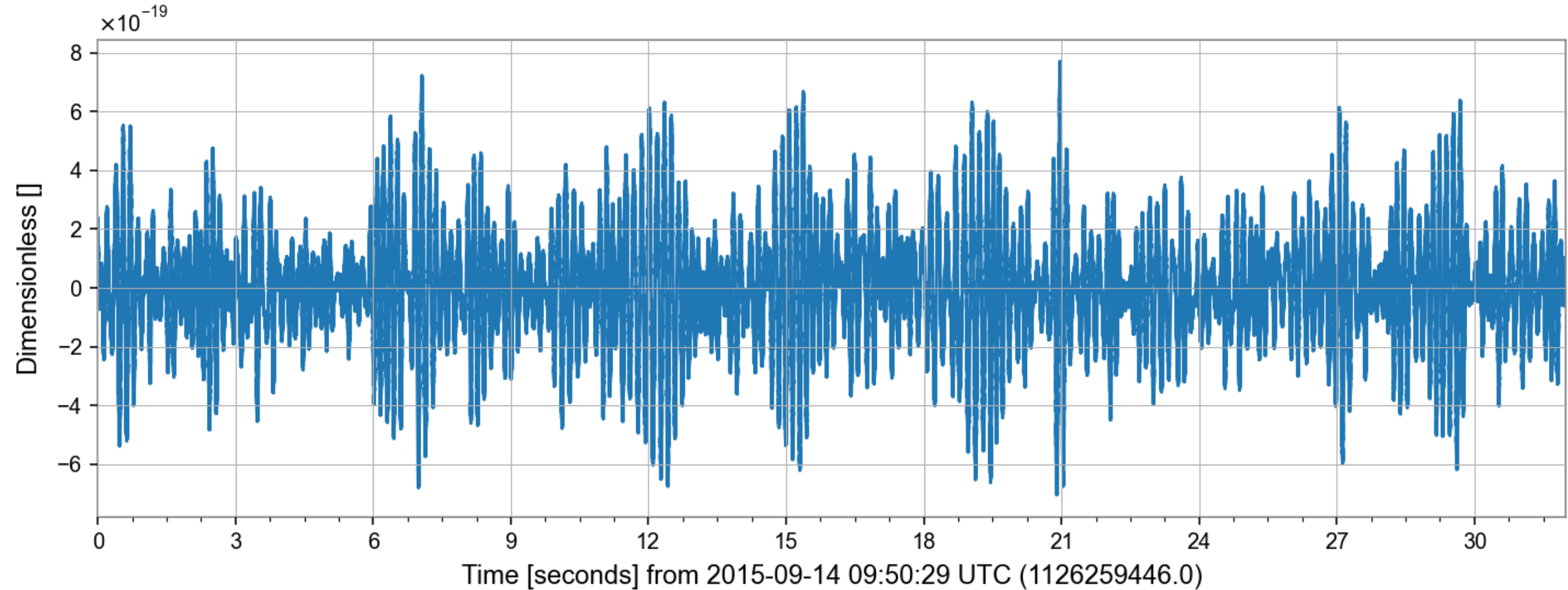
H1 strain



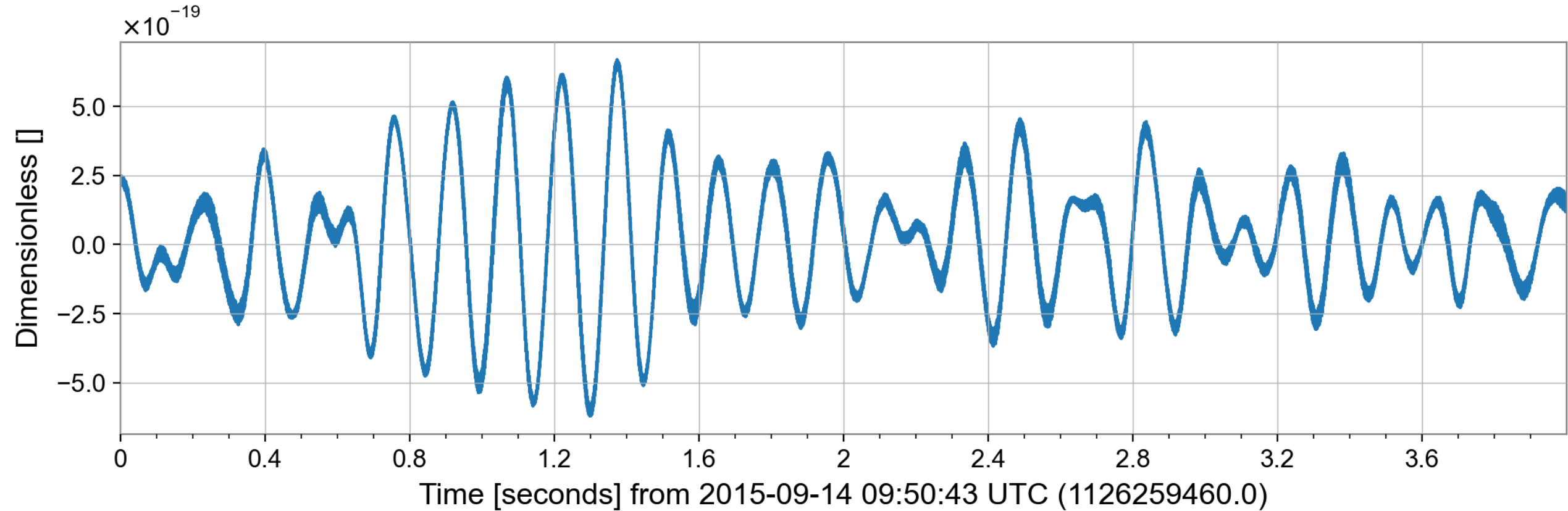
4096sec · 4KHz: GWF HDF TXT

FrameChannels: [H1:DCS-CALIB_STRAIN_CLEAN_SUB60HZ_C01, L1:DCS-CALIB_STRAIN_CLEAN_SUB60HZ_C01, V1:Hrec_hoft_16384Hz]

중력파 자료(32.0초) GW150914

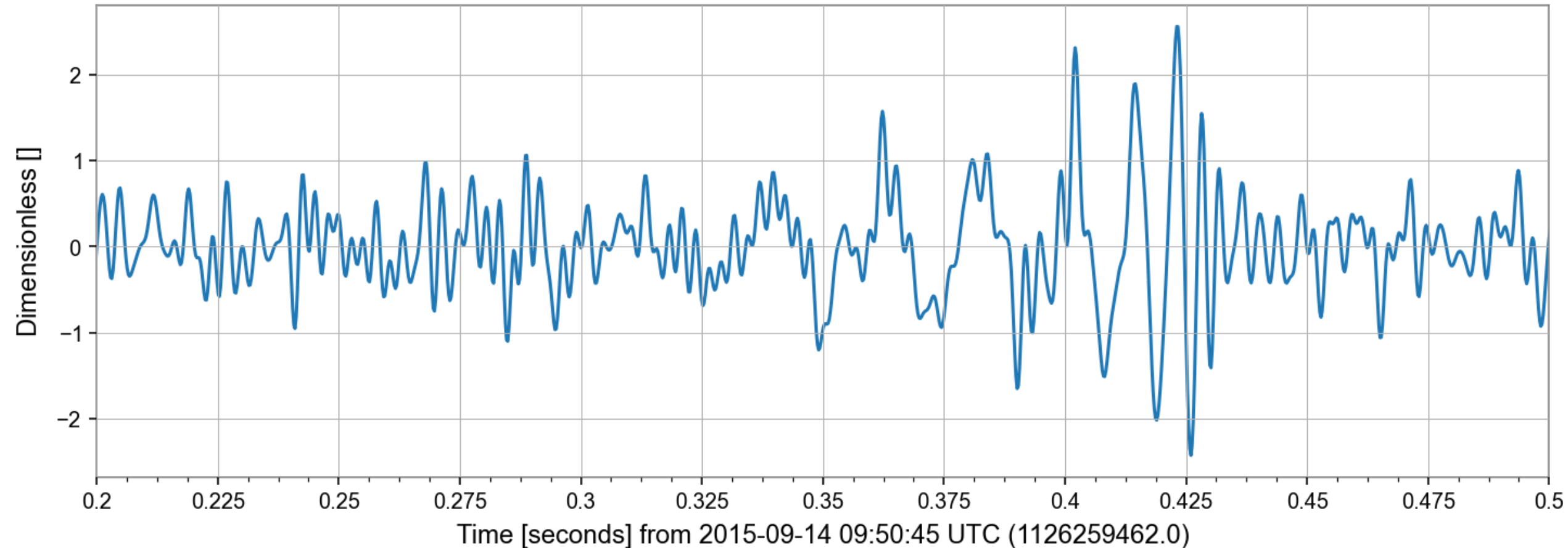


중력파 자료(4.0초) GW150914

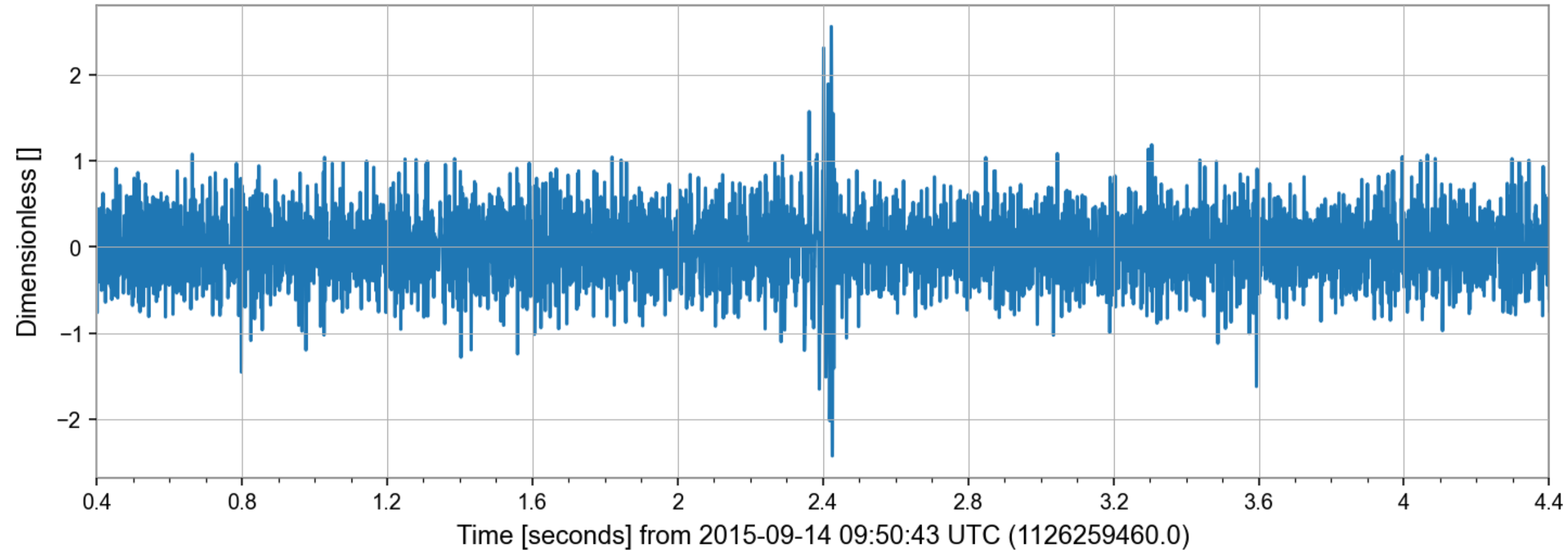


중력파 자료(0.3초) GW150914

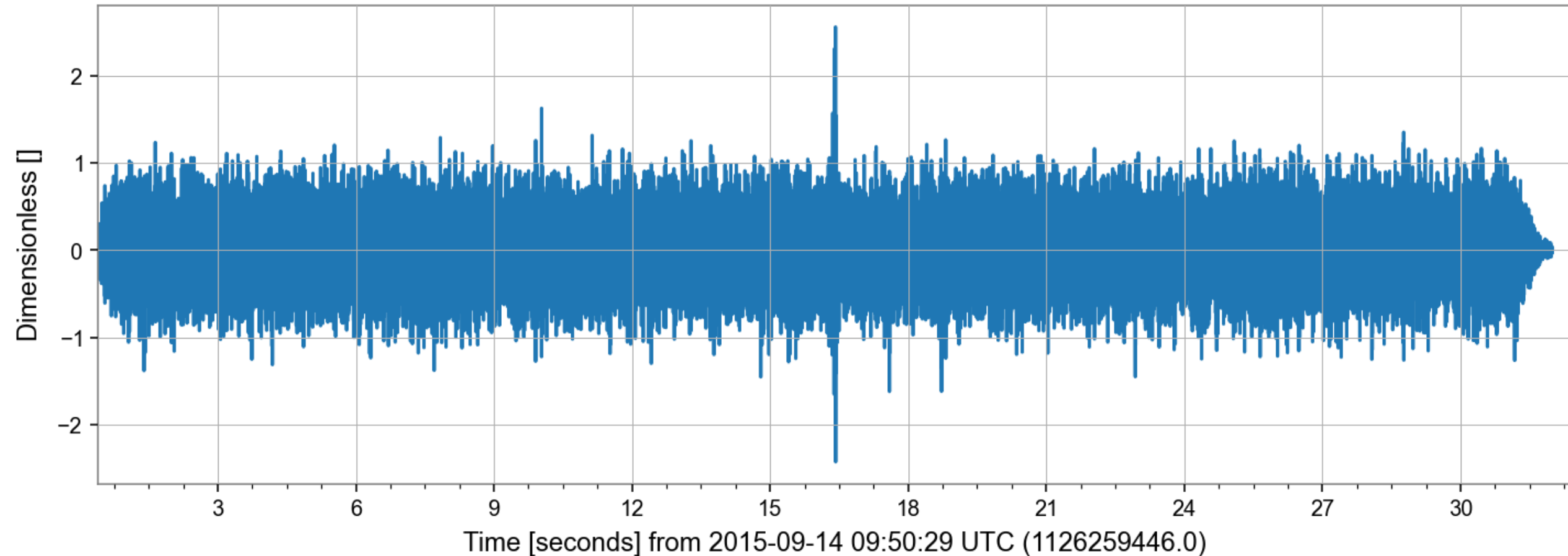
(whitening, band pass)

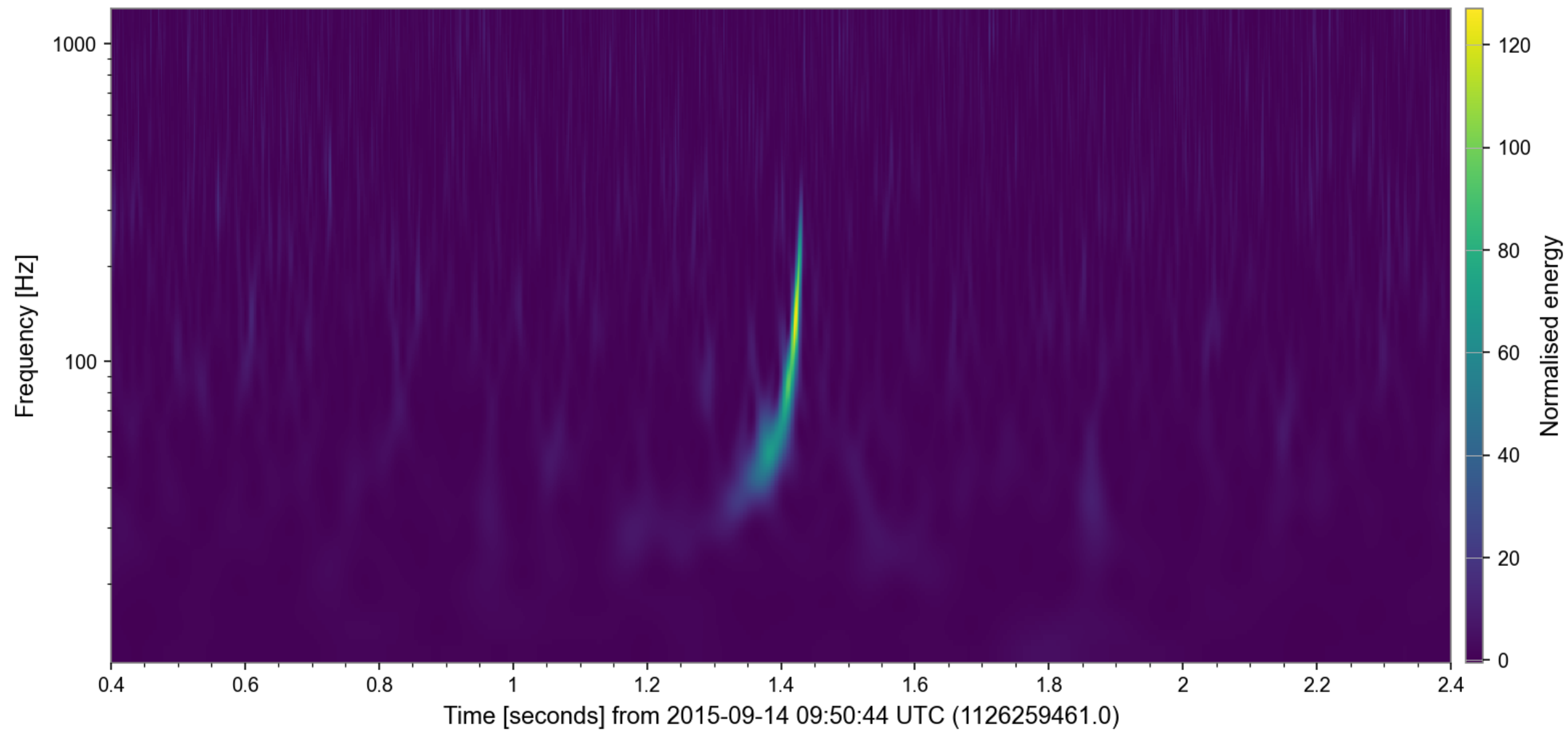


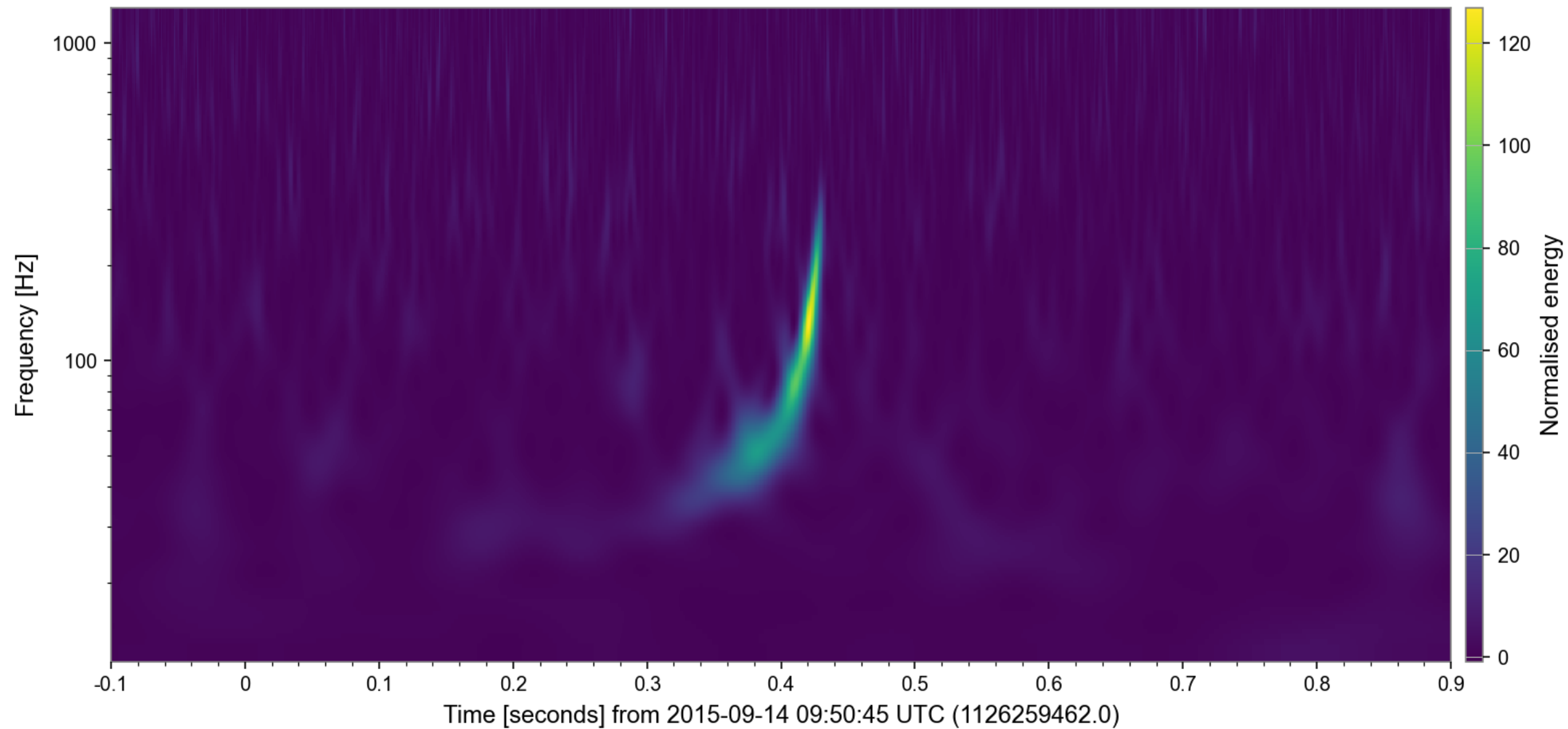
중력파 자료(4.0초) GW150914 (whitening, band pass)



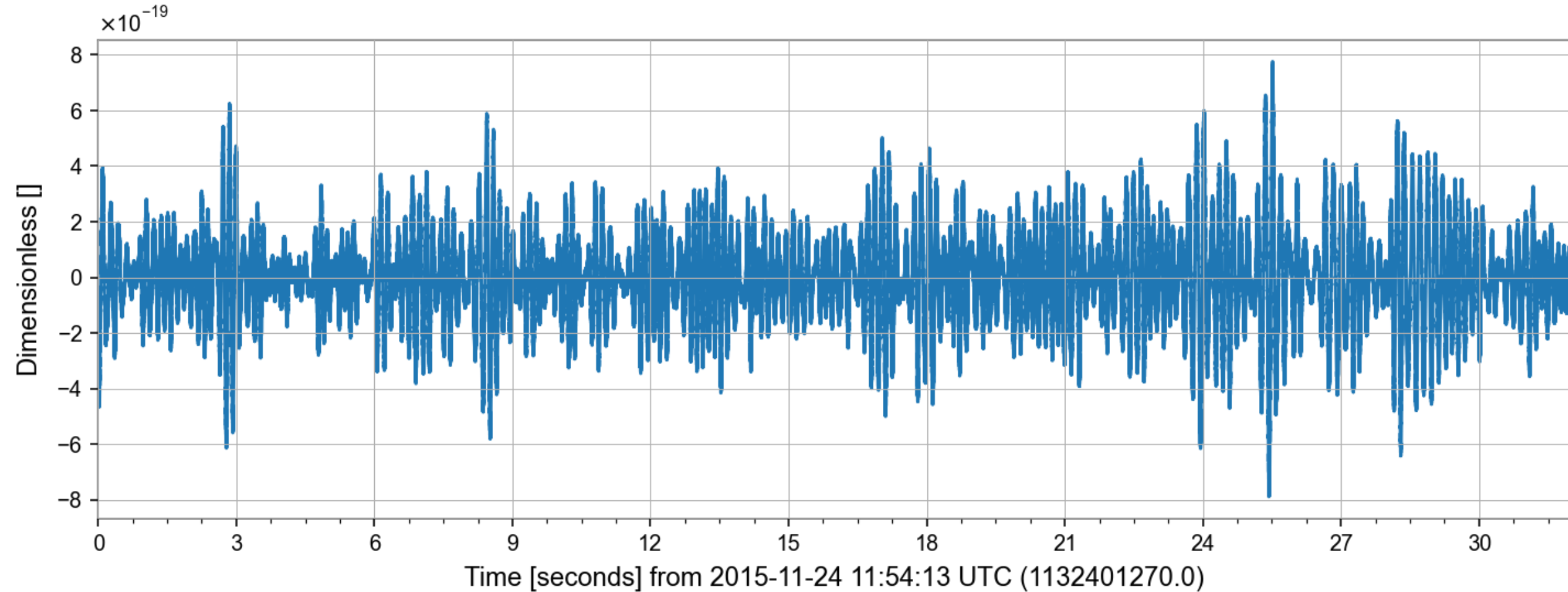
중력파 자료(32.0초) GW150914 (whitening, band pass)



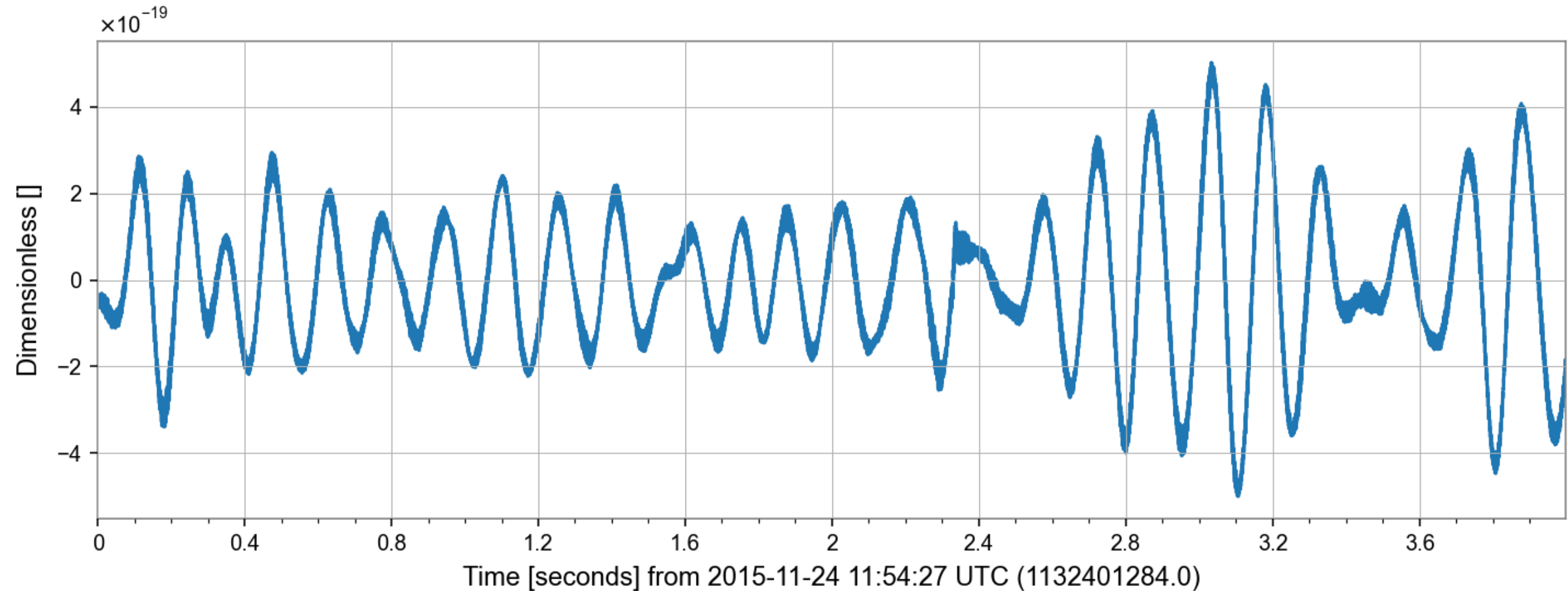




중력파 자료(32.0초) Glitch



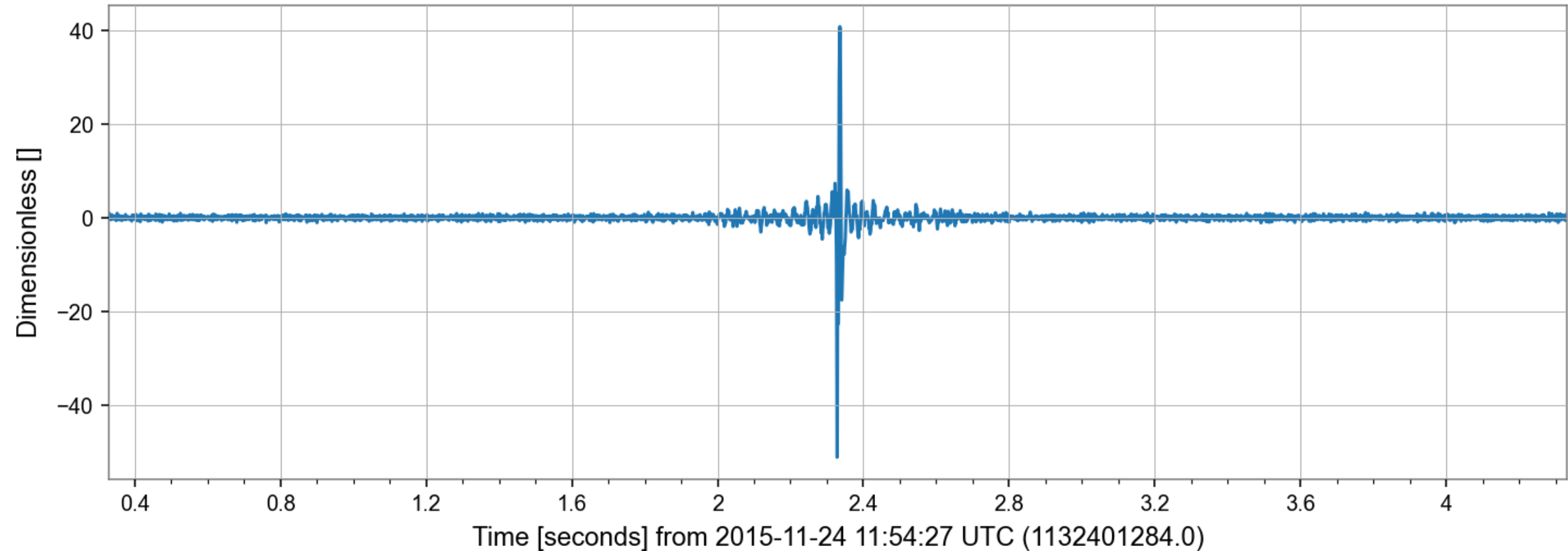
중력파 자료(4.0초) Glitch



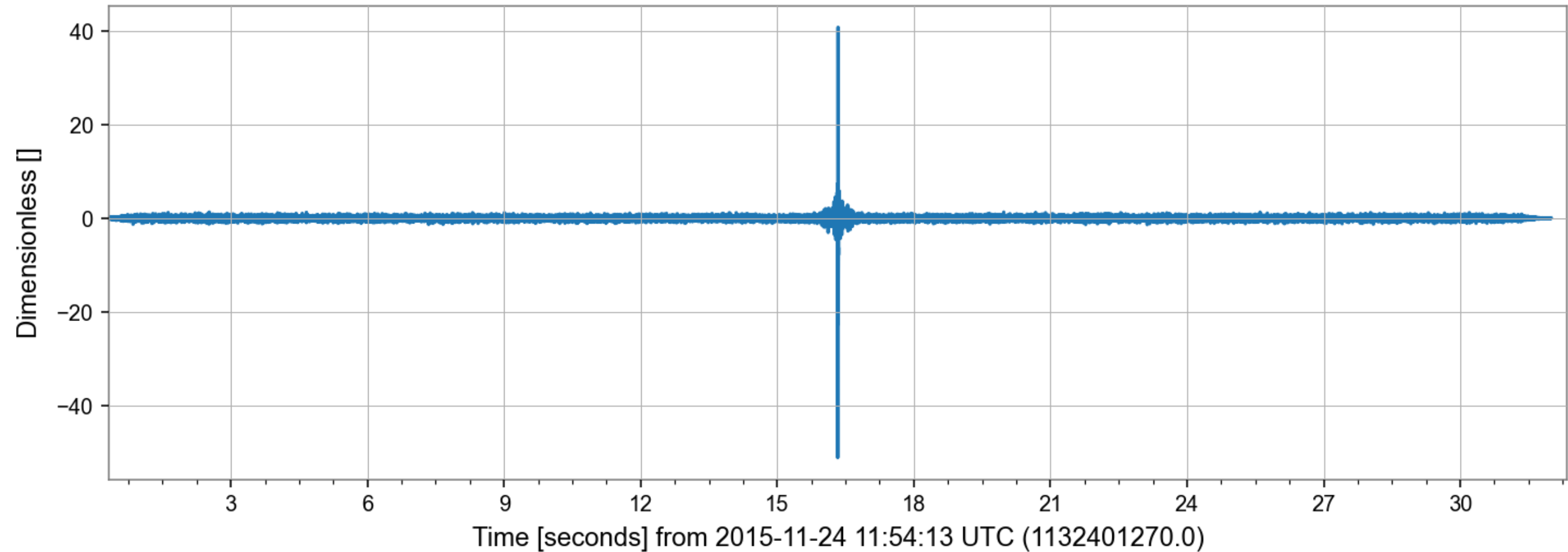
중력파 자료(0.3초) Glitch (whitening, band pass)

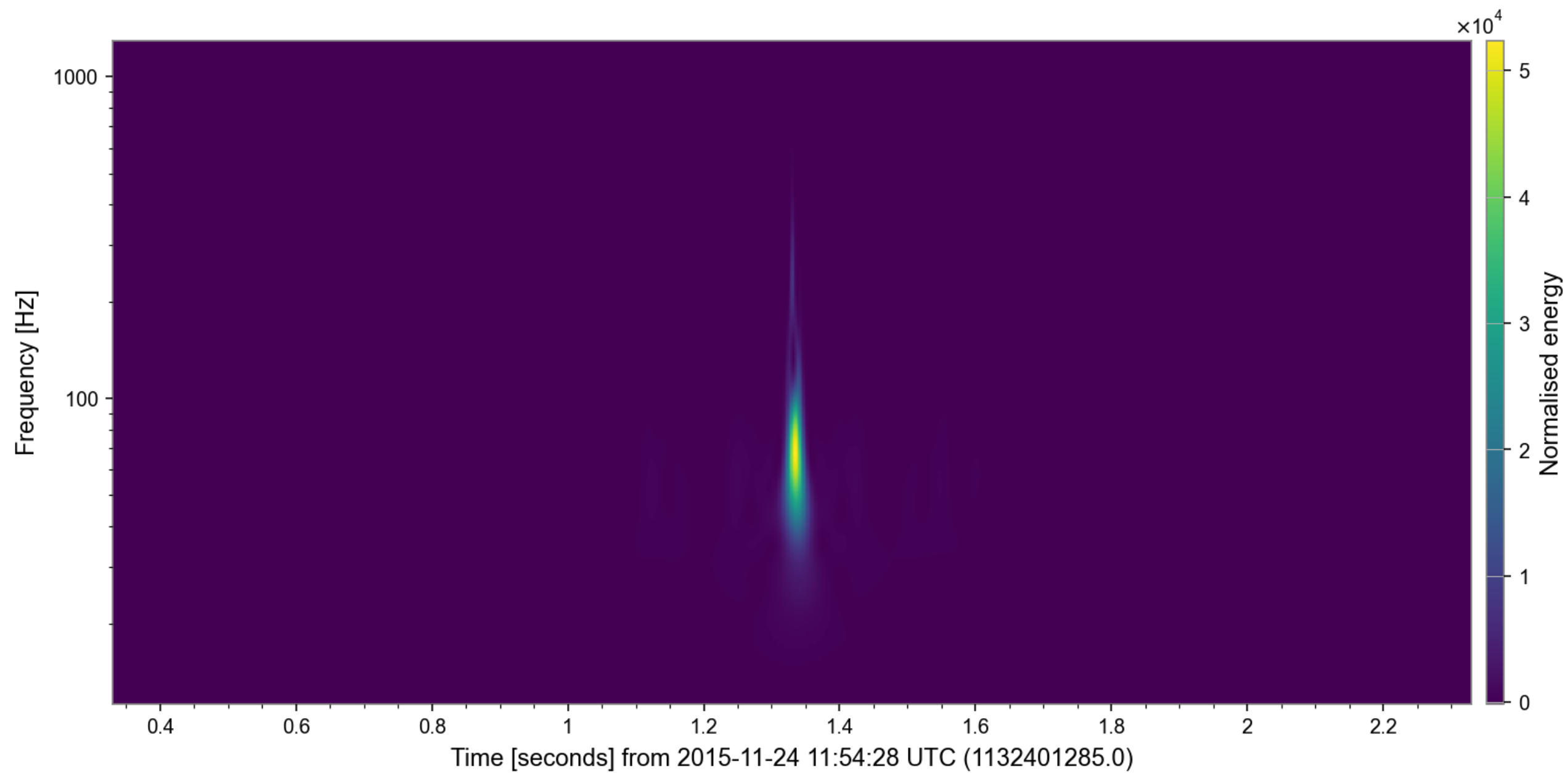


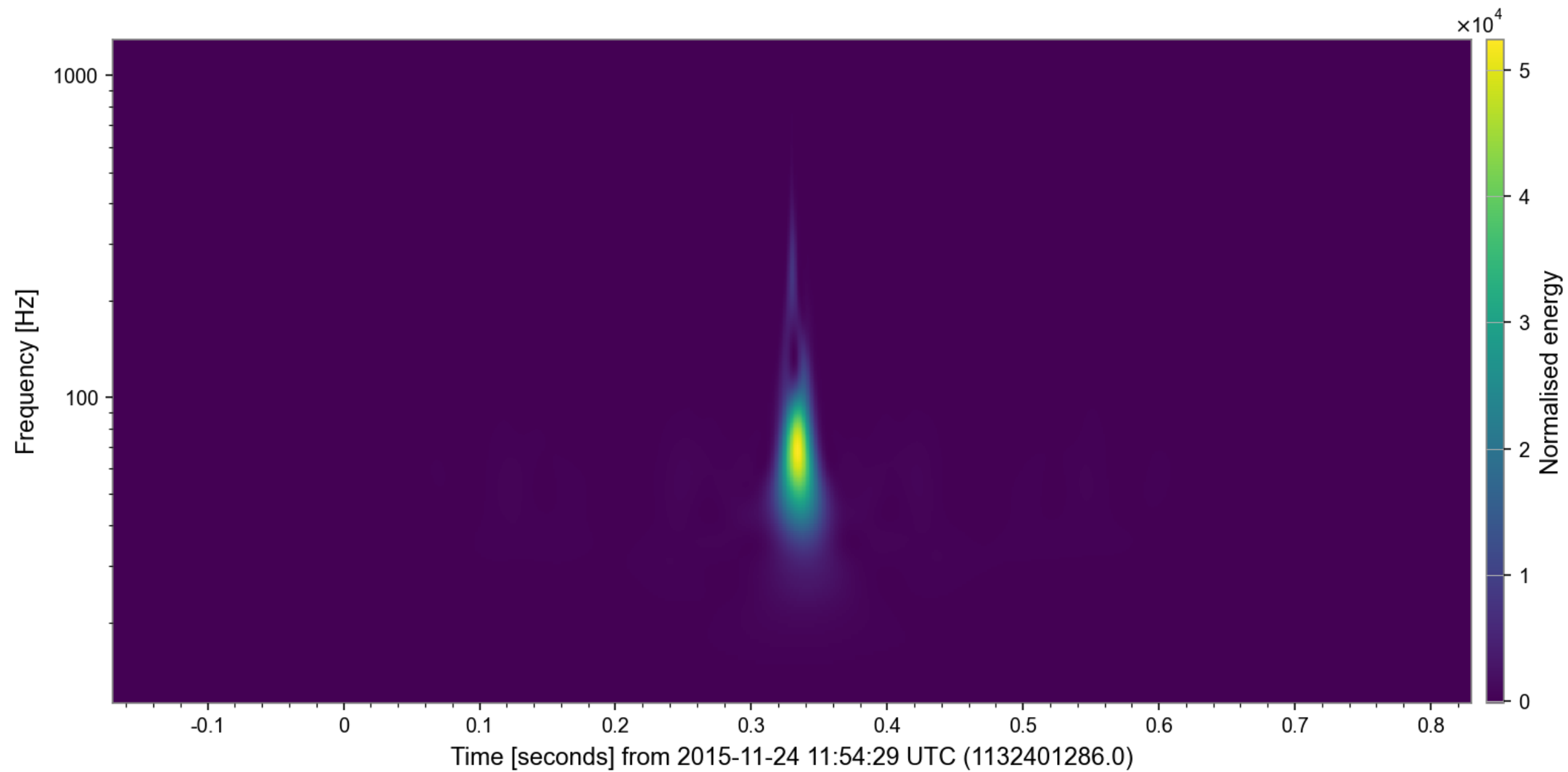
중력파 자료(4.0초) Glitch (whitening, band pass)



중력파 자료(32.0초) Glitch (whitening, band pass)







Search vs PE

- SNR vs Likelihood
- Threshold vs posterior
- Template Bank vs no-template bank

통계적처리 방법

	Frequentist	Bayesian
Probability is:	Limiting relative frequency	Degree of belief
Parameter θ is a:	Fixed constant	Random variable
Probability statements are about:	procedures	parameters
Frequency guarantees?	yes	no

가능도 함수(Likelihood Function)

- 관측된 자료의 가능도 함수는 실험장치에 대한 정량적 지표이다.



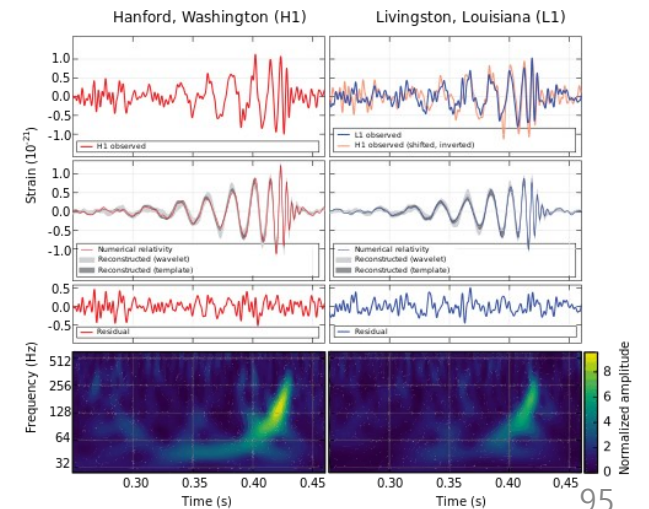
2026-07-28

Understand
Device



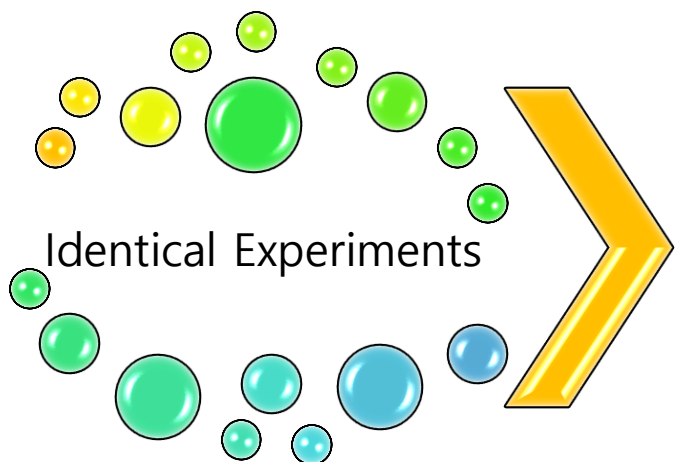
Calculate
Probability

Likelihood

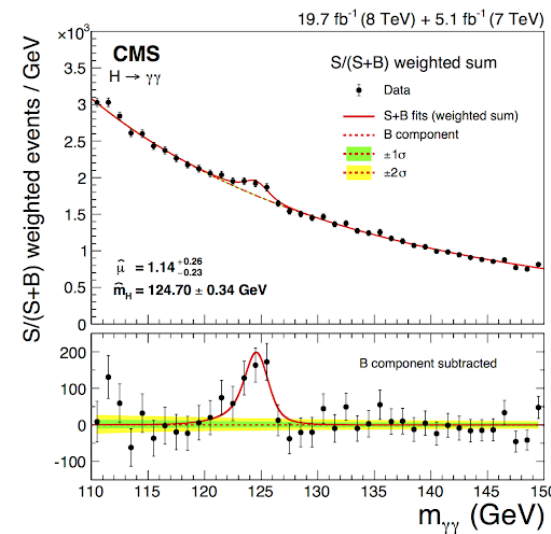
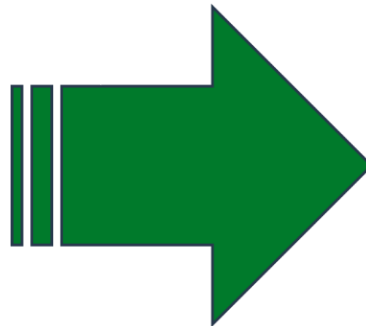
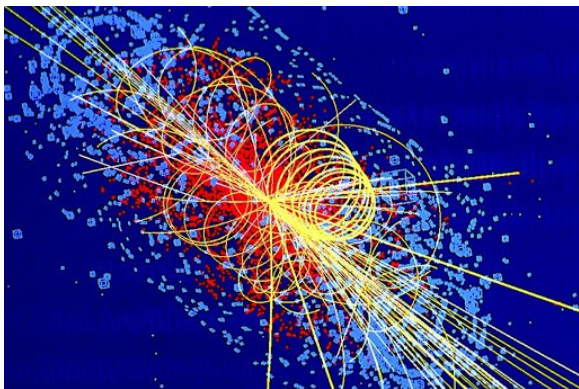
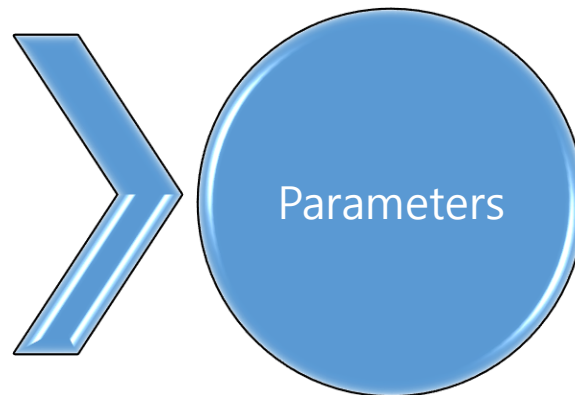


실험실 자료 처리

- 질문 : “동일한 조건의 많은 실험을 통하여 획득한 물리적인 매개변수의 분포는 어떻게 되는가?”



Data Process



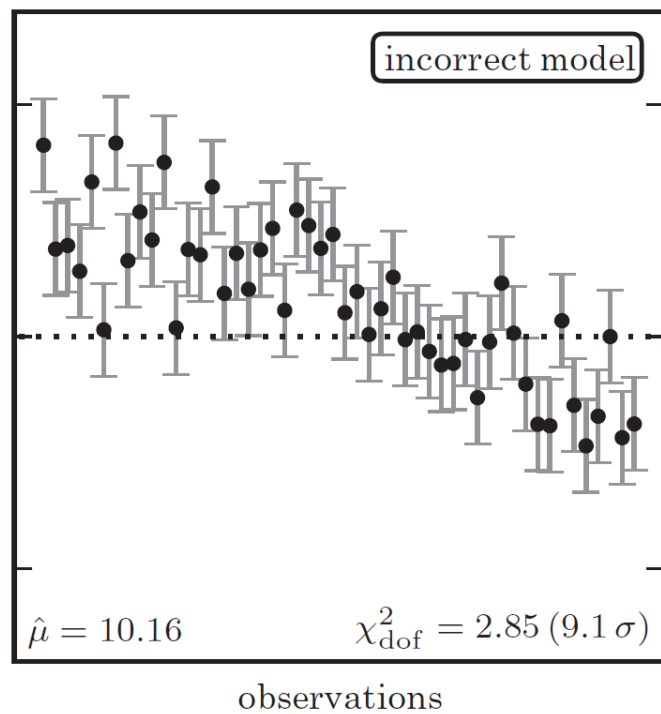
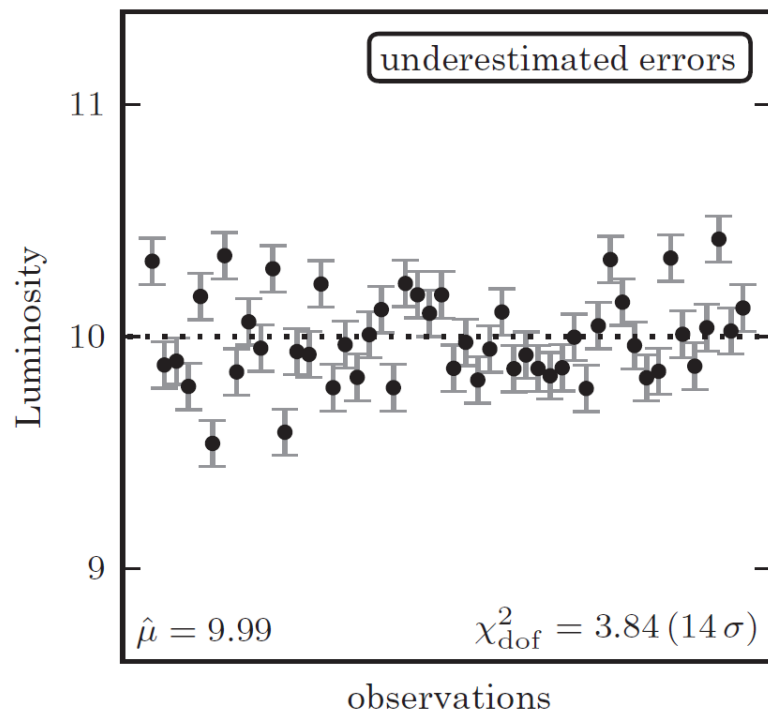
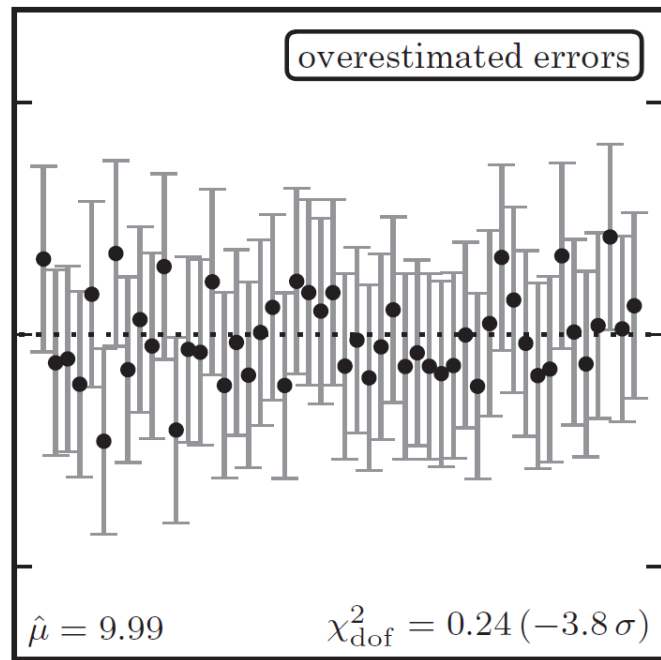
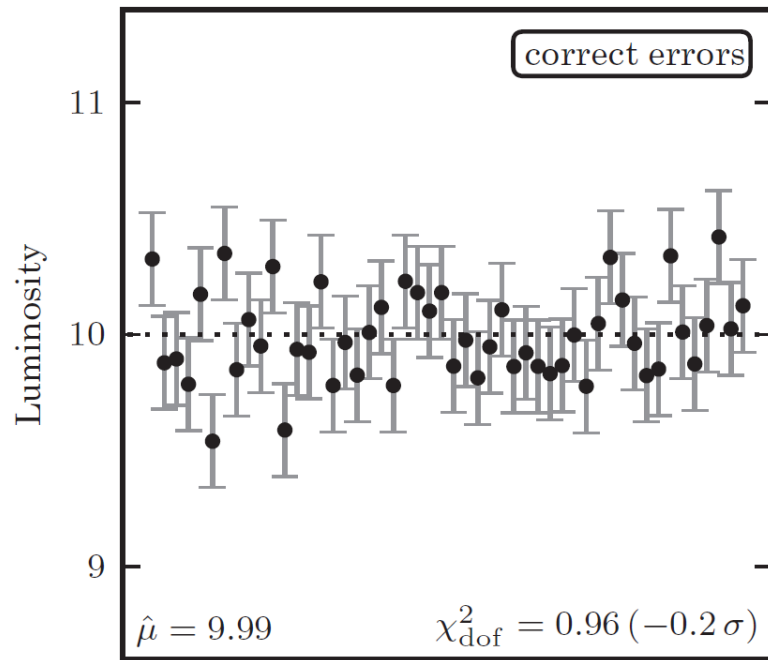
Maximum Likelihood Approach

1. Formulate Likelihood function for some model, $p(D|M)$
2. Find the best parameter θ^0 maximizing $p(D|M)$
3. Determine confidence level of θ^0 using bootstrap, jackknife, cross-validation
4. Perform hypothesis test

The Goodness of fit for a model

$$\ln L = \text{constant} - \frac{1}{2} \sum_{i=1}^N z_i^2 = \text{constant} - \frac{1}{2} \chi^2 \quad z_i = (x_i - \mu)/\sigma$$

$$\chi_{\text{dof}}^2 = \frac{1}{N - k} \sum_{i=1}^N z_i^2 \approx 1$$

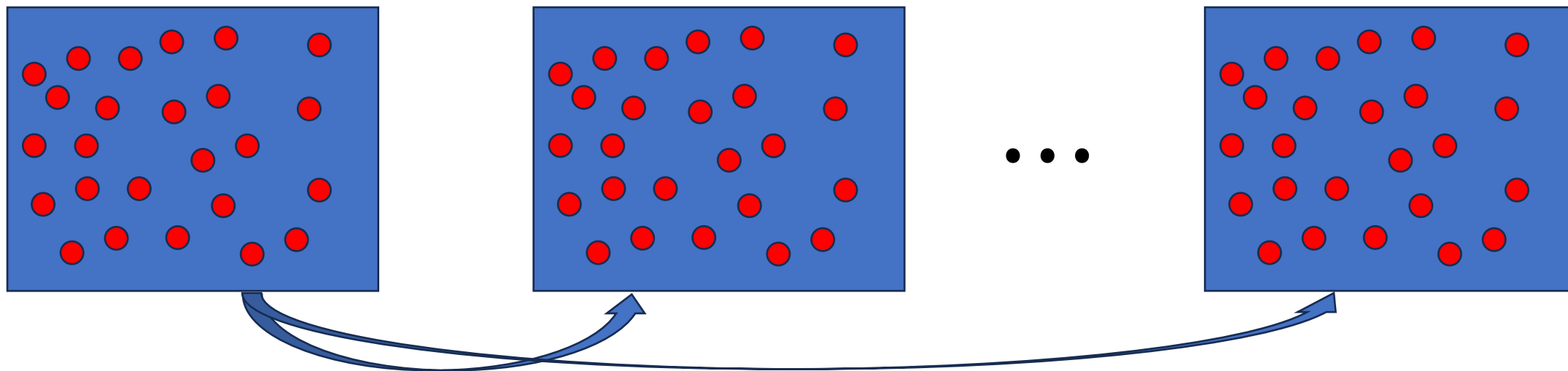


Observing fixed luminosity star

What about confidence

- How to find confidence level of MLE values.
- Bootstrapping
- Jackknife

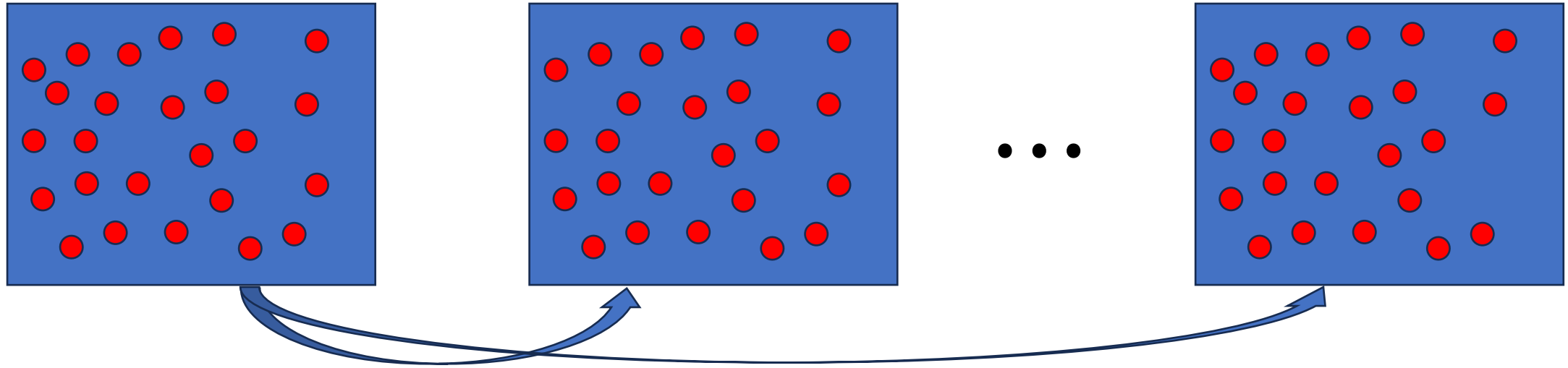
Bootstrapping



Random selections of the same sample size

Estimate the confidence level for measures values

Jackknife



Random elimination of one sample

Estimate the confidence level for measures values

가능도 함수

The probability of the data given the model

$\mathcal{N}(\mu, \sigma)$

$$L \equiv p(\{x_i\} | M(\theta)) = \prod_{i=1}^n p(x_i | M(\theta))$$

$$x_i: \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x_i - \mu)^2}{2\sigma^2}}$$
$$\prod_{i=1}^N \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(x_i - \mu)^2}{2\sigma^2}\right)$$

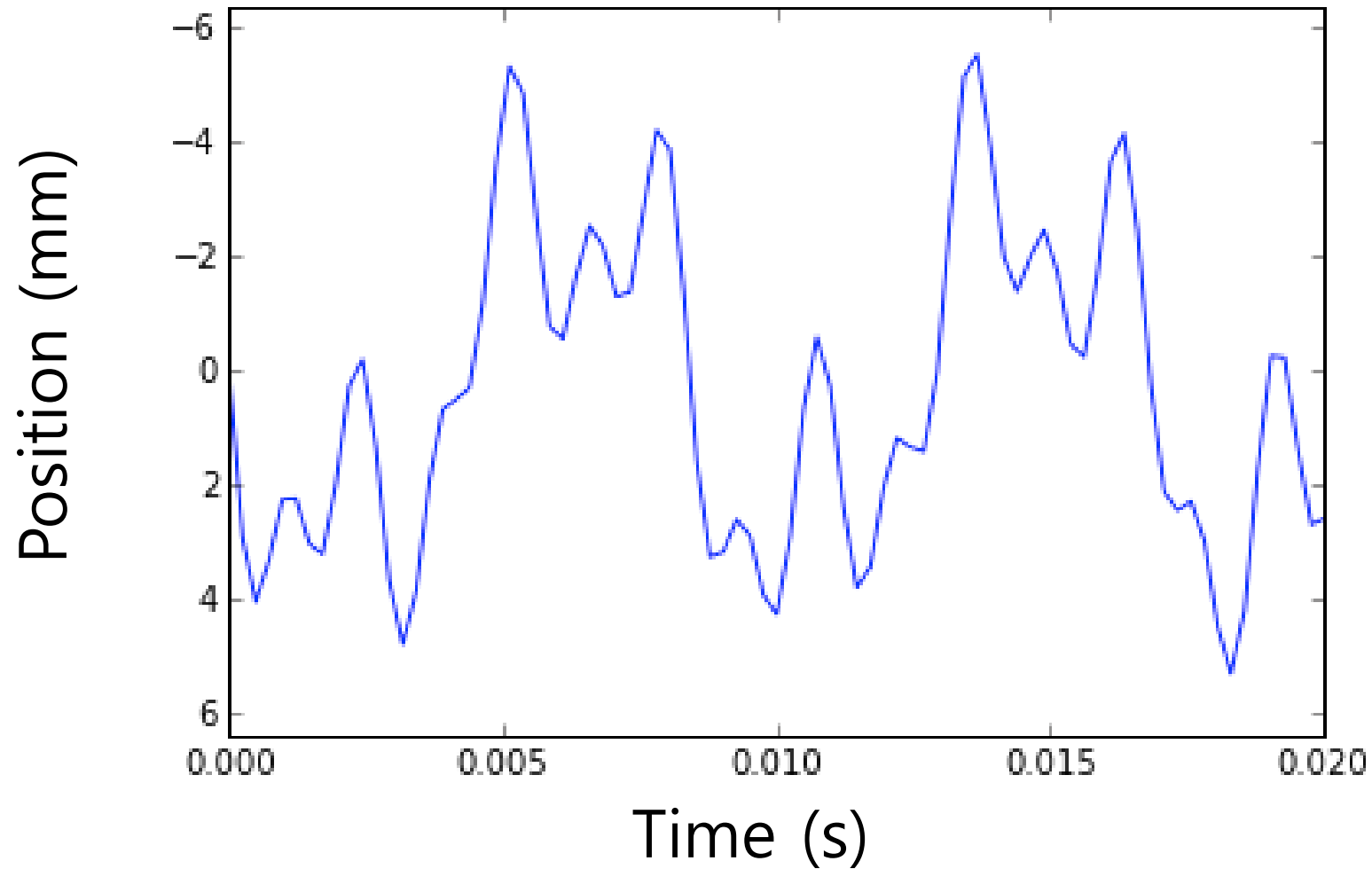
Observe

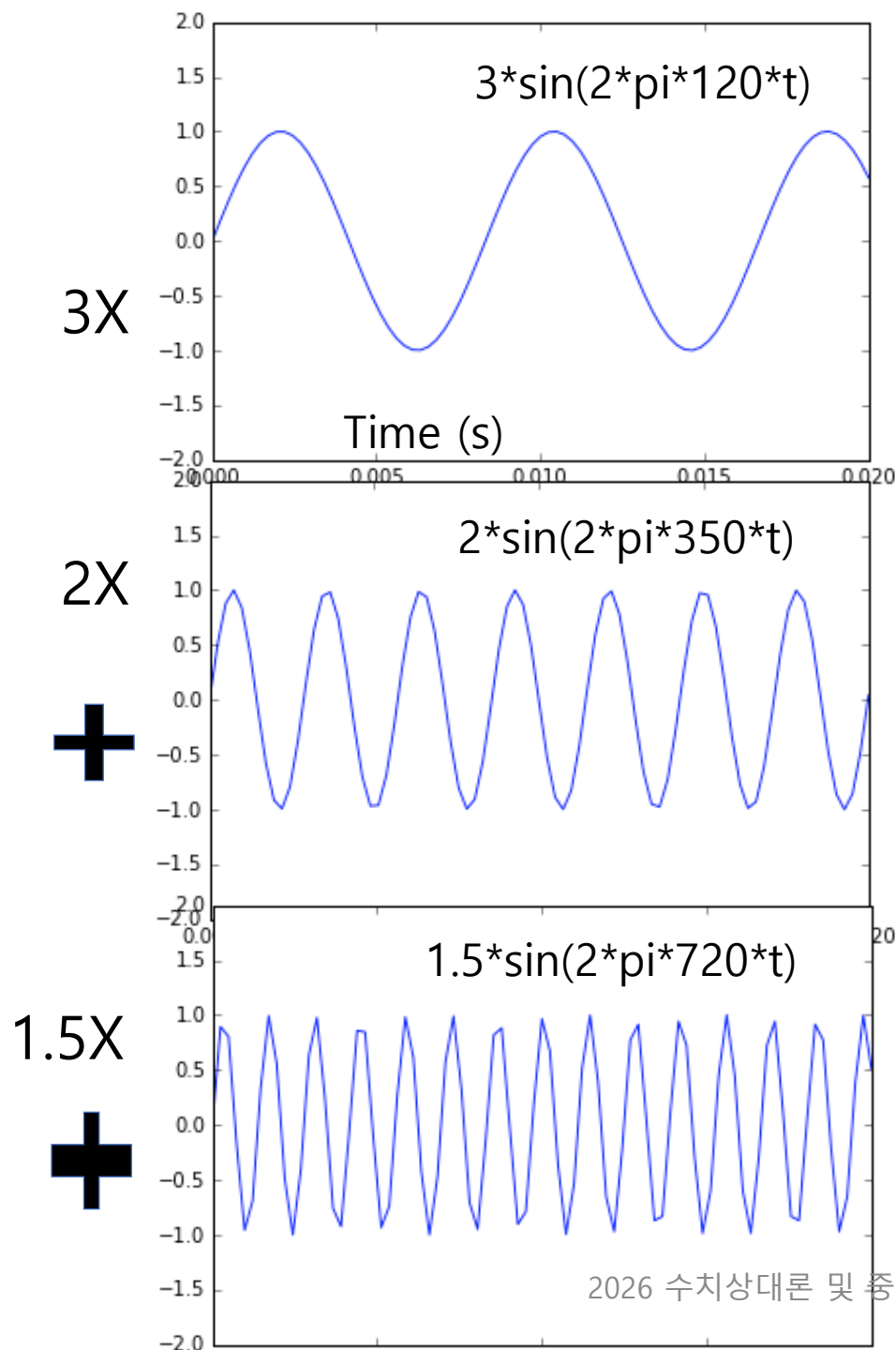
Likelihood is a function of x for given model

Likelihood is a function of model parameters for given data

Work in Frequency Domain

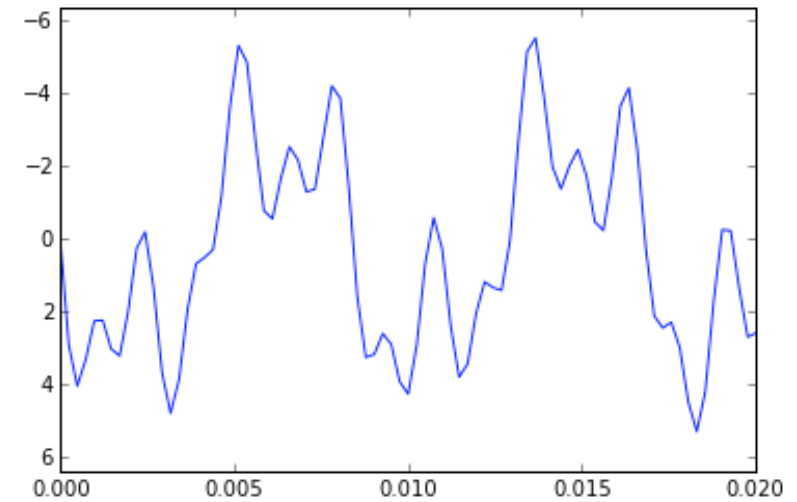
How would you describe this function?





Noise in the time domain

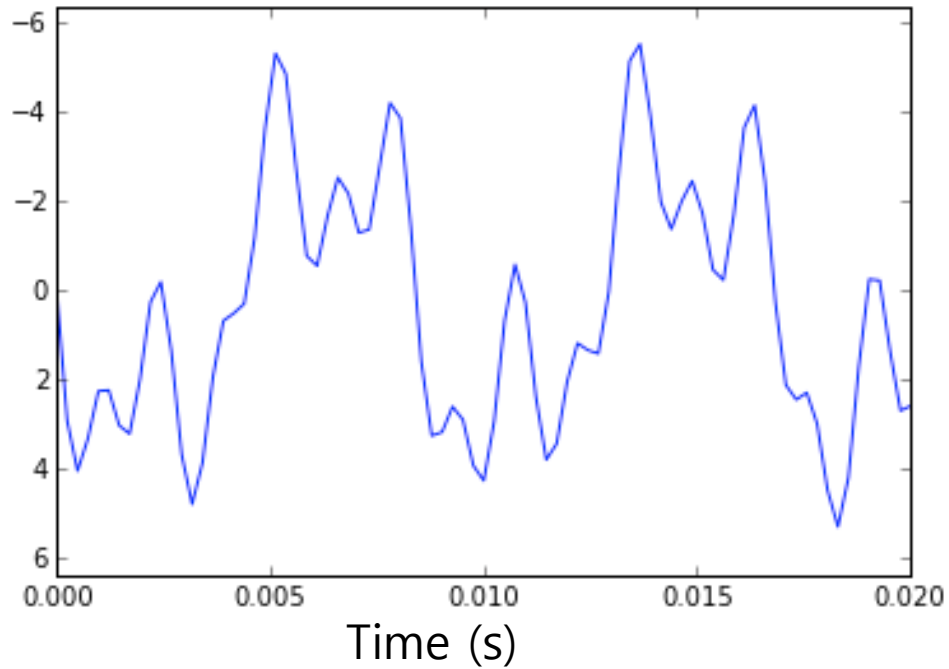
=



Amplitude -> Loudness -> "Power"

Frequency -> Pitch

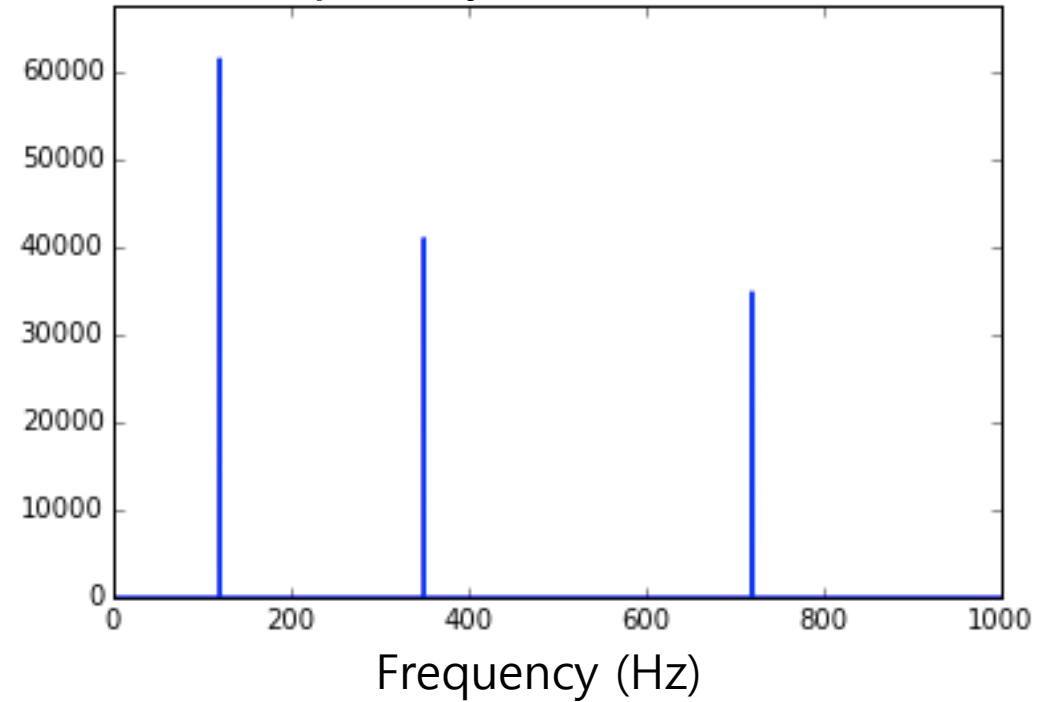
Time Domain



$h(t)$ – Position as a function of time

$$h(t) = 3 * \sin(2\pi * 120 * t) + 2 * \sin(2\pi * 350 * t) + 1.5 * \sin(2\pi * 720 * t)$$

Frequency Domain



$H(f)$ – Amplitude and phase as a function of frequency

$$\begin{aligned} |H(120 \text{ Hz})| &= 3 \\ |H(350 \text{ Hz})| &= 2 \\ |H(720 \text{ Hz})| &= 1.5 \\ H(f) &= 0 \quad \text{otherwise} \end{aligned}$$

← Fourier Transform →

Key Concept

Any function can be represented as a sum of sine waves.

$$h(t) = A_1 \sin(\omega_1 t + \varphi_1) + A_2 \sin(\omega_2 t + \varphi_2) \dots$$

In the “frequency domain”, we are plotting the amplitudes (or phases) of each of these sine waves.

$$|H(\omega_n)| = A_n$$

Fourier Transform is used to represent data in the frequency domain

Fourier transform

$$\tilde{x}(f) = \int_{-\infty}^{\infty} dt \, x(t) e^{-i2\pi ft}$$

$$\Rightarrow x(t) = \int_{-\infty}^{\infty} df \, \tilde{x}(f) e^{i2\pi ft}$$

$|\tilde{x}(f)|^2$ can be interpreted as energy spectral density

Efficient way to calculate complete discrete Fourier Transform:
Fast Fourier Transform (FFT)

Power Spectral Density

Parseval's theorem:

$$\int_{-\infty}^{\infty} dt |x(t)|^2 = \int_{-\infty}^{\infty} df |\tilde{x}(f)|^2$$

⇒ Total energy in the data can be calculated in either time domain or frequency domain

$|\tilde{x}(f)|^2$ can be interpreted as energy spectral density

When noise (or signal) has infinite extent in time domain, can still define the **power spectral density (PSD)**

$$\lim_{T \rightarrow \infty} \frac{1}{T} \left| \tilde{x}_T(f) \right|^2 \quad \langle n(f)n^*(f') \rangle = \delta(f - f') S_n(f)$$

Watch out for one-sided vs. two-sided PSDs

Slide from P. Shawhan

Estimating the PSD

Simplest approach: FFT the data, calculate square of magnitude of each frequency component – this is a **periodogram**

For stationary noise, one can show that the frequency components are statistically independent

This estimate is unbiased (has the correct mean), but has a large variance – so average several periodograms

Alternately, smooth periodogram; give up frequency resolution either way

Generally apply a “window” to the data to avoid **spectral leakage**

Leakage arises from the assumption that the data is periodic!

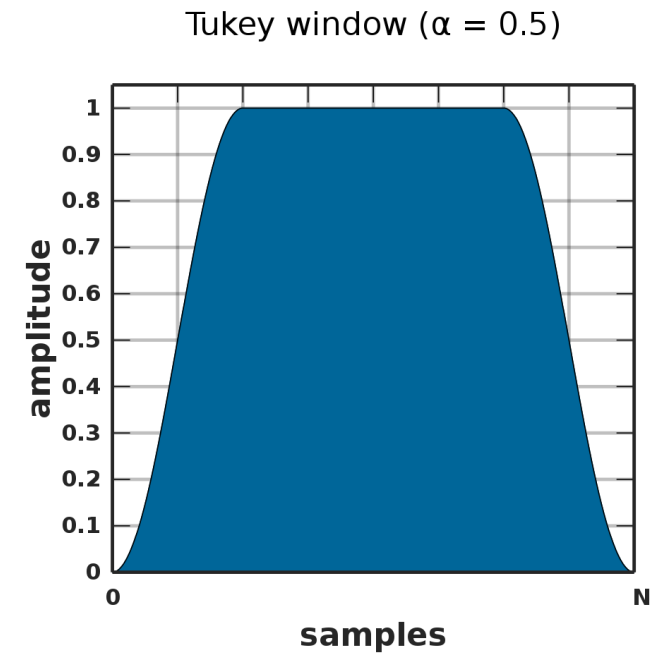
Tapered window forces data to go to zero at ends of time interval

****Welch's method** of estimating a PSD averages periodograms calculated from windowed data**

Slide from P. Shawhan

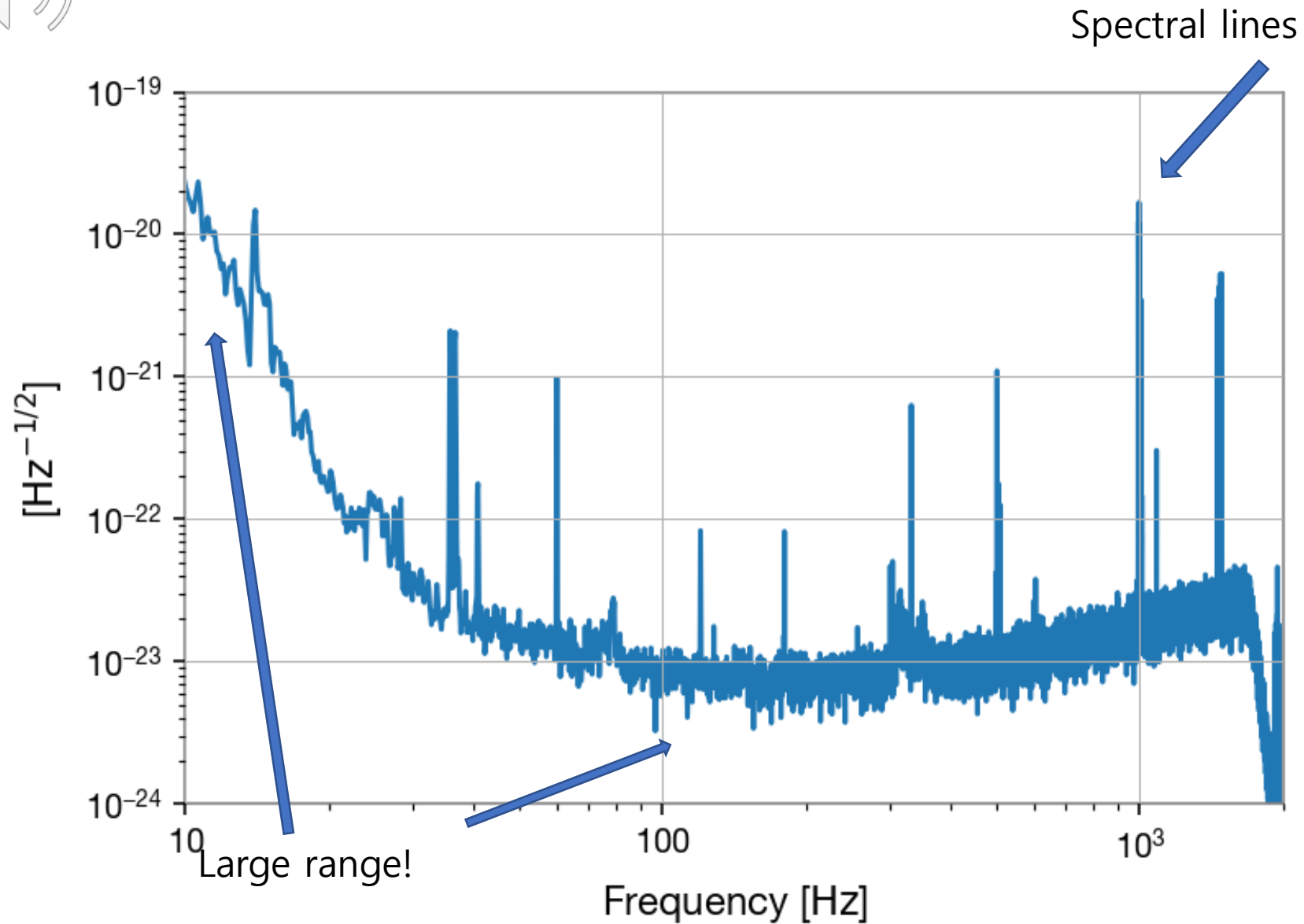
PSD Estimation

- Welch average: `XLALREAL8AverageSpectrumWelch()`
- Median selection: `XLALREAL8AverageSpectrumMedian()`



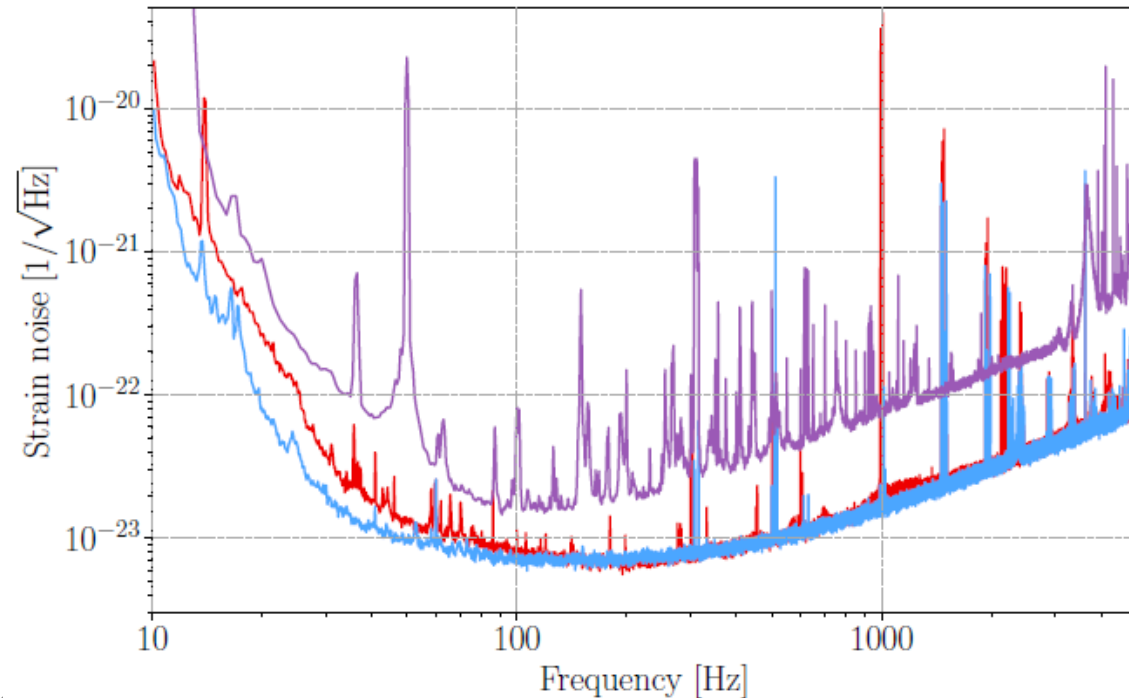
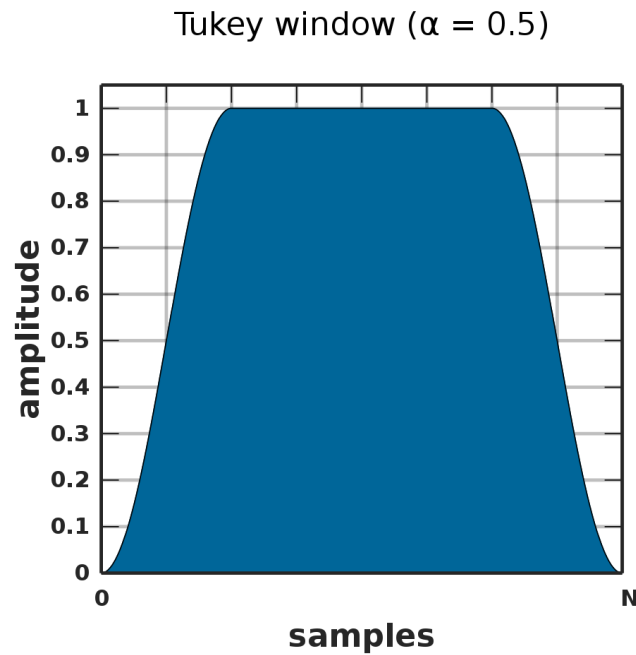


ASD of some LIGO noise



Data Analysis

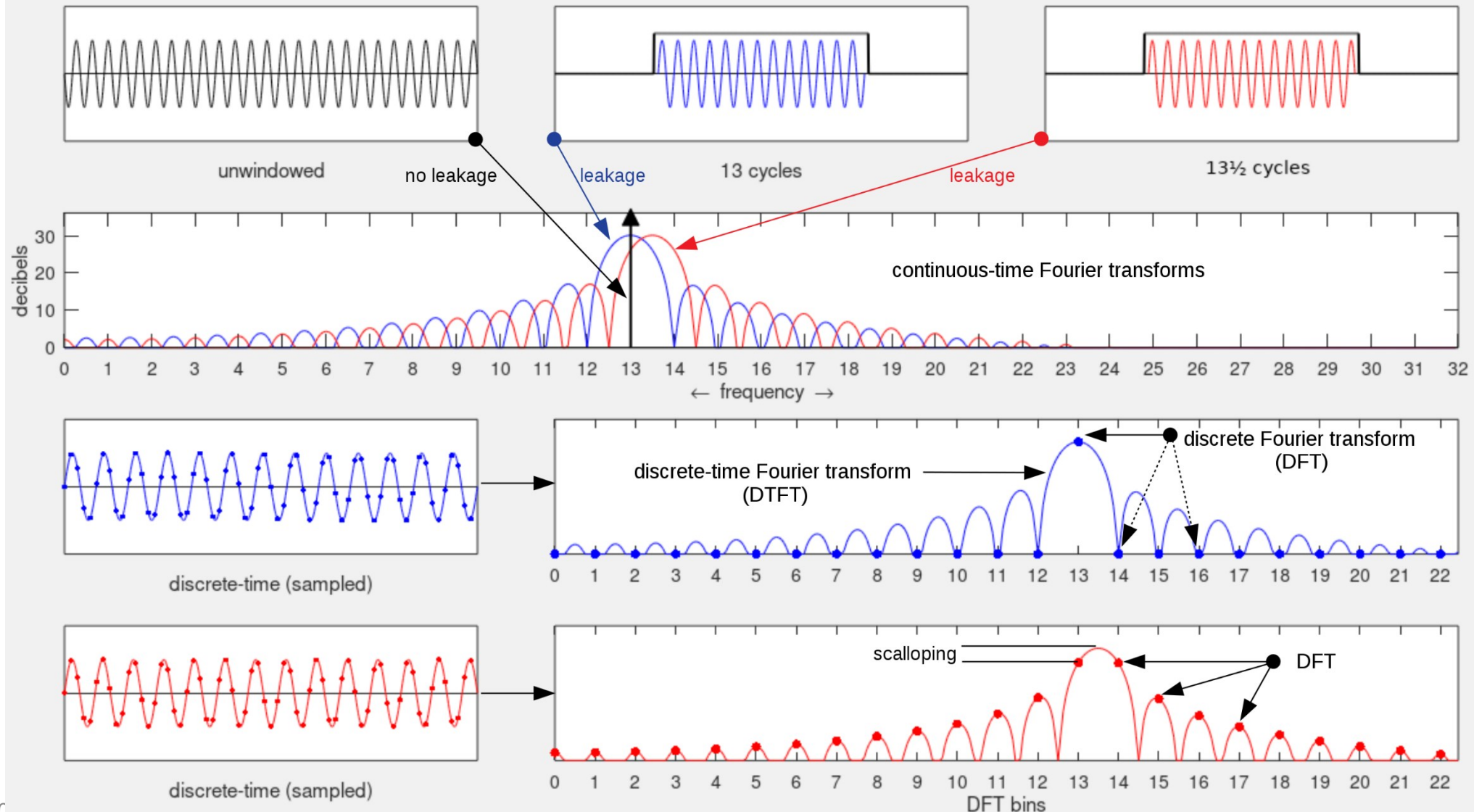
$$d(t) \xrightarrow{\text{FFT}} \tilde{d}(f) \xrightarrow{\text{Whiten}} \tilde{d}_w(f) = \frac{\tilde{d}(f)}{S_n^{1/2}(f)} \xrightarrow{\text{iFFT}} d_w(t)$$



Window and power leakage

[Window function - Wikipedia](#)

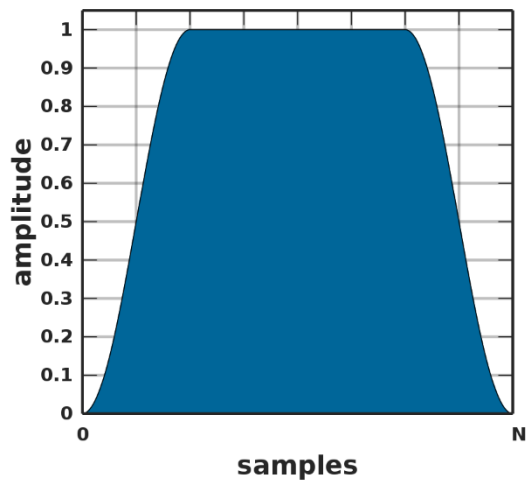
Spectral leakage caused by “windowing”



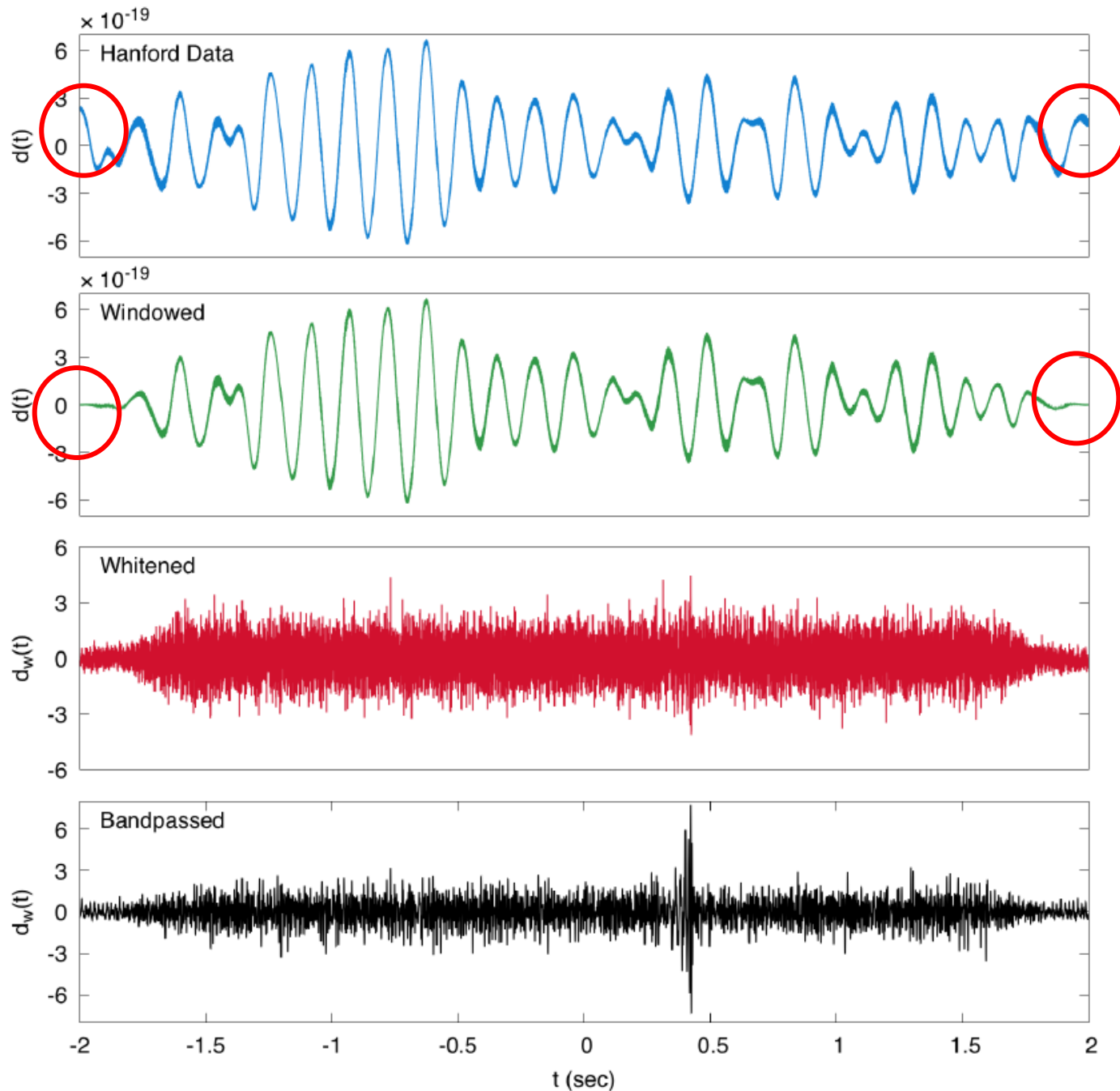
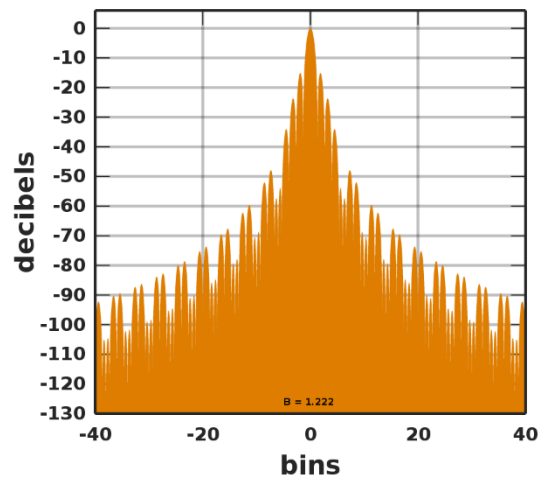
- GW150914

$$\left. \begin{aligned} w[n] &= \frac{1}{2} \left[1 - \cos\left(\frac{2\pi n}{\alpha L}\right) \right], & 0 \leq n < \frac{\alpha L}{2} \\ w[n] &= 1, & \frac{\alpha L}{2} \leq n \leq \frac{N}{2} \\ w[N - n] &= w[n], & 0 \leq n \leq \frac{N}{2} \end{aligned} \right\}$$

Tukey window ($\alpha = 0.5$)



Fourier transform



내적 (Inner Product)

$$K(f) \propto \frac{h(f)}{S_n(f)}$$

- $\langle a|b \rangle \equiv 4\Re \int_0^\infty \frac{\tilde{a}(f)\tilde{b}^*(f)}{S(f)} df$
- $\langle a|b \rangle = 2\Re \int_{-\infty}^\infty \frac{\tilde{a}(f)\tilde{b}^*(f)}{S(|f|)} df = \int_{-\infty}^\infty \frac{\tilde{a}(f)\tilde{b}^*(f) + \tilde{a}^*(f)\tilde{b}(f)}{S(|f|)} df$
- $p_x[x(t)] \propto e^{-\langle x|x \rangle/2}$

- We can consider each frequency bin distributed as

$$p_x[\tilde{x}(f)] = \frac{1}{\sqrt{2\pi}} \sqrt{\frac{4\Delta f}{S_x(f)}} e^{-\frac{1|\tilde{x}(f)|^2\Delta f}{2 S_x(f)/4}}$$

$$\Delta f = \frac{1}{T}$$

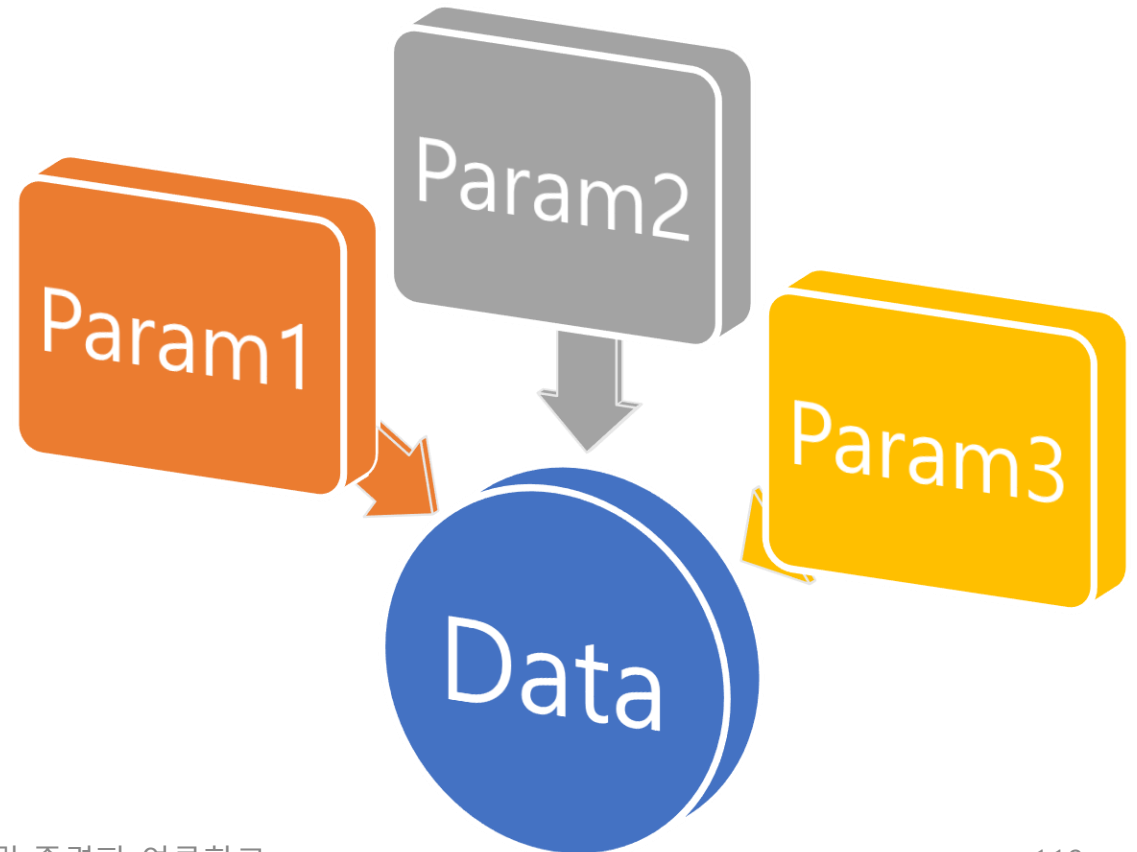
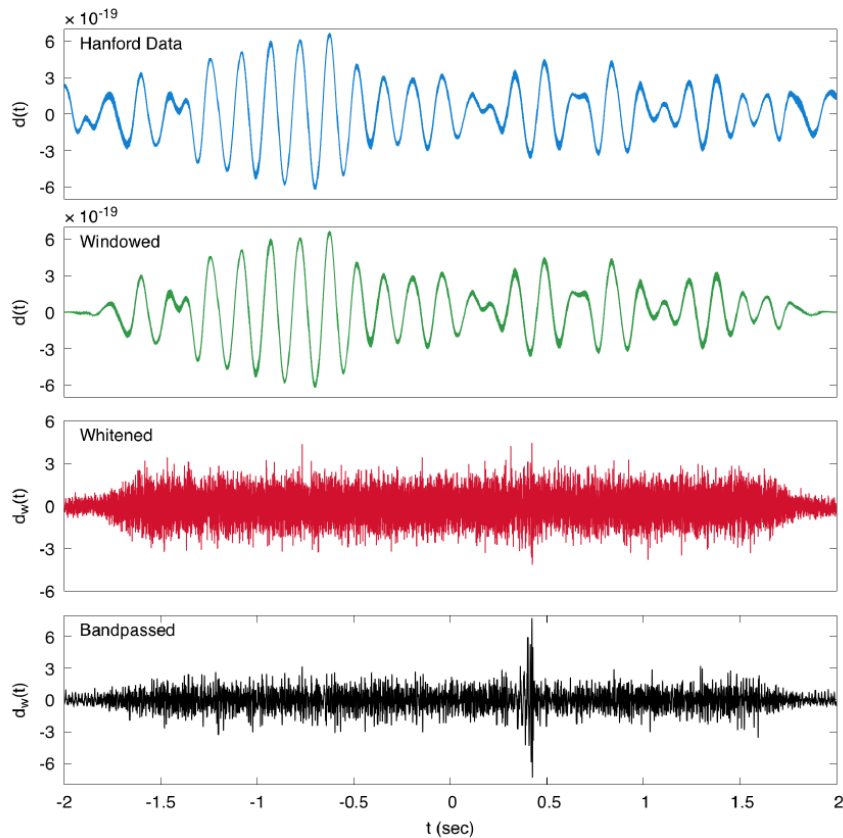
$$p_x[x(t)] \propto \exp \left\{ -\frac{1}{2} 4 \int_0^\infty \frac{|\tilde{x}(f)|^2}{S_x} df \right\}$$

가능도 함수(Likelihood)

- $p(d|\theta)$: 모델 매개변수 θ 가 만든 중력파가 신호 d 를 생성할 확률
- 신호 d 가 파형 $h(\theta)$ 를 포함할 확률
 - 만약 d 가 파형 $h(\theta)$ 를 포함한다면, $d - h$ 는 순 잡음이다.
- $p(d - h|\theta) = p(n|\theta)$
- $p_d[\tilde{d}(f_j) - \tilde{h}(f_j)] = \frac{1}{\sqrt{2\pi}} \sqrt{\frac{4\Delta f}{S_n(f_j)}} e^{-\frac{1}{2} \frac{|\tilde{d}(f_j) - \tilde{h}(f_j)|^2 \Delta f}{S_n(f_j)/4}}$
- $p(d|\theta) = \prod_{j=0}^{N-1} \frac{1}{\sqrt{2\pi}} \sqrt{\frac{4\Delta f}{S_n(f_j)}} e^{-\frac{1}{2} \frac{|\tilde{d}(f_j) - \tilde{h}(f_j)|^2 \Delta f}{S_n(f_j)/4}} \propto e^{-\langle d - h | d - h \rangle / 2}$

베이지언 추론

- 질문: “관측된 자료를 가장 잘 설명하는 중력파원의 물리적 매개변수의 분포는 어떻게 되는가?”



베이지언 추론 기본

- Bayes' rule(theorem)

가능도 함수

사전확률

결합확률

사후확률

$$p(M|D) = \frac{p(D|M) p(M)}{p(D)}$$

$$p(M, D) = p(M|D)p(D) = p(D|M)p(M)$$

- 모델에 대한 개선된 믿음의 정도는 기존 믿음의 정도와 모델이 관측된 자료를 생성할 확률의 곱이다.

$$p(M, \theta|D, I) = \frac{p(D|M, \theta, I) p(M, \theta|I)}{p(D|I)}$$

$$p(M, \theta|I) = p(\theta|M, I) p(M|I)$$

베이지언 추론 과정

1. 가능도 함수 $p(D|\vec{\theta}, M)$ 결정
2. 매개변수에 대한 사전확률 함수 $p(\vec{\theta}|M)$ 결정
3. 사후 확률함수밀도 $p(\vec{\theta}|D, M)$ 계산

4. 최대 사후확률 값(MAP)
최대 가능도 함수 값(ML)
사후확률평균 $\bar{\theta} = \int \theta p(\theta|D, M) d\theta$

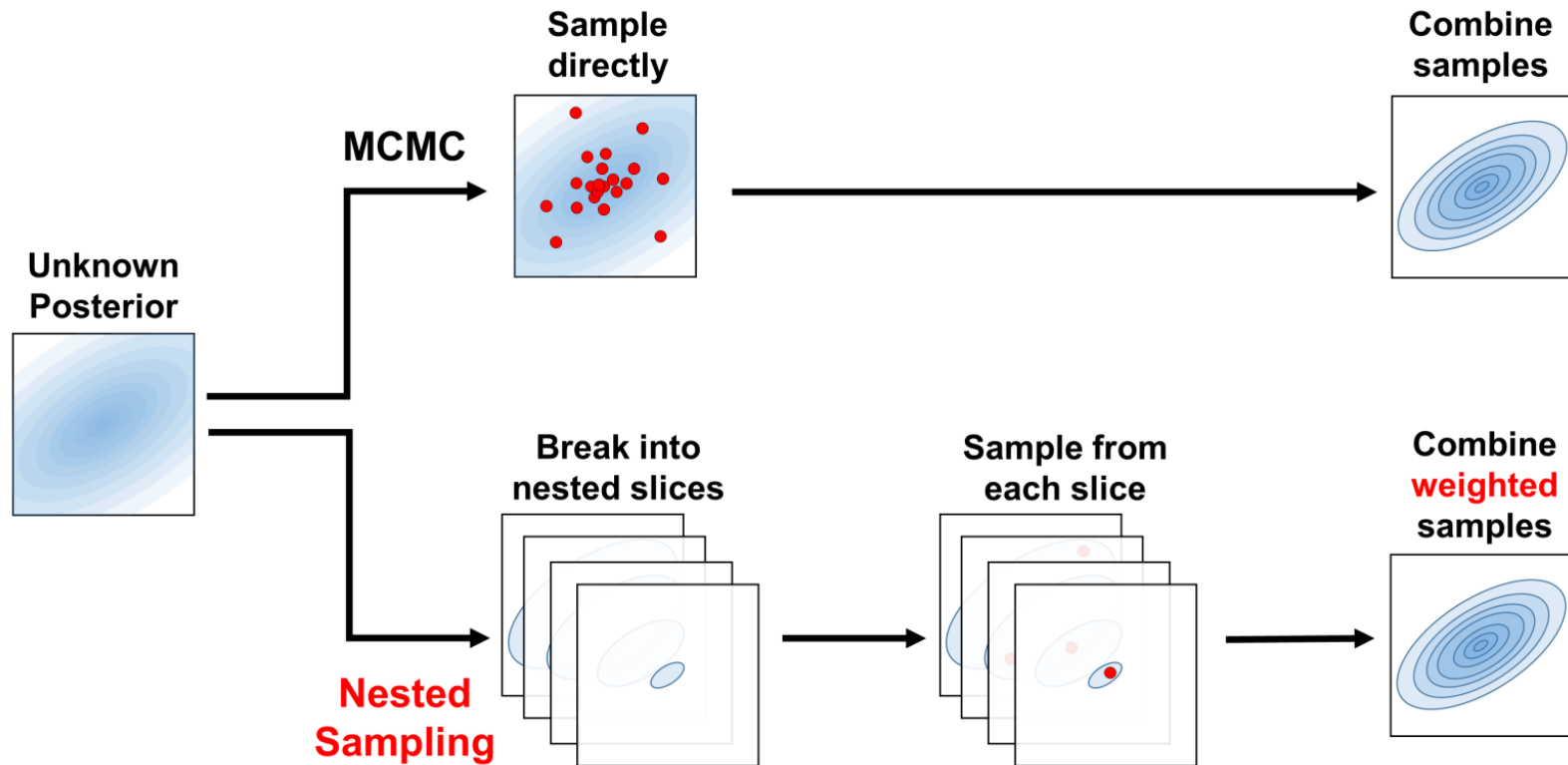
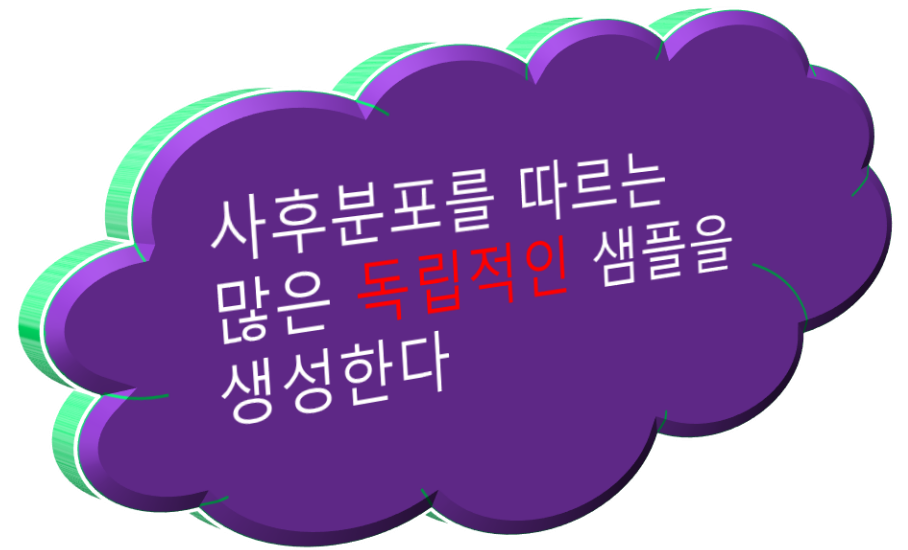
marginalization

$$p(\theta|D, M) = \int p(\vec{\theta}|D, M) d\vec{\theta}', \text{ 다른 매개변수에 대한 적분}$$

5. 매개변수에 대한 분산
6. 모델과 매개변수에 대한 가설검증

샘플 생성 방법

- Markov Chain Monte Carlo(MCMC)
- Nested Sampling



$$Z = \int p(\vec{\theta}|D) d\vec{\theta}$$

$$p(\vec{\theta}|D) = \frac{p(D|\vec{\theta})p(\vec{\theta})}{p(D)}$$

[MNRAS 493, 3132\(2020\)](#)

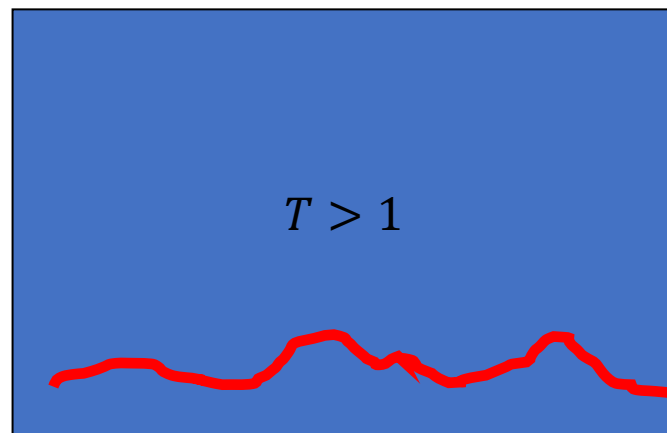
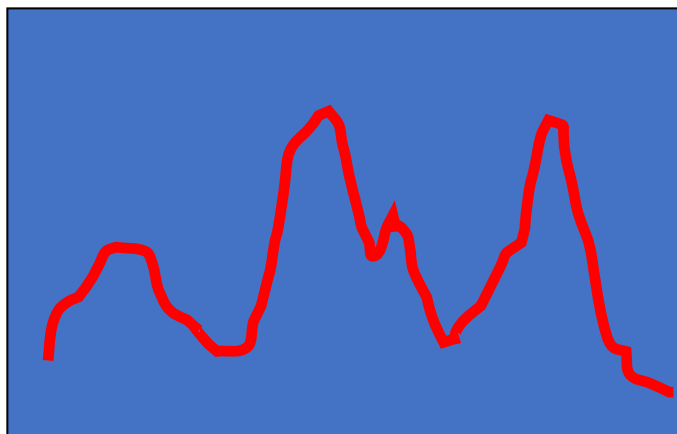
MCMC 알고리즘

- Metropolis algorithm
 - Metropolis-Hasting algorithm
 - Gibbs sampling algorithm
 - Hamiltonian Monte Carlo
 - ...
-
- 초기수렴(Burn In)
 - 수렴(Convergence)
 - 혼합(Mixing)

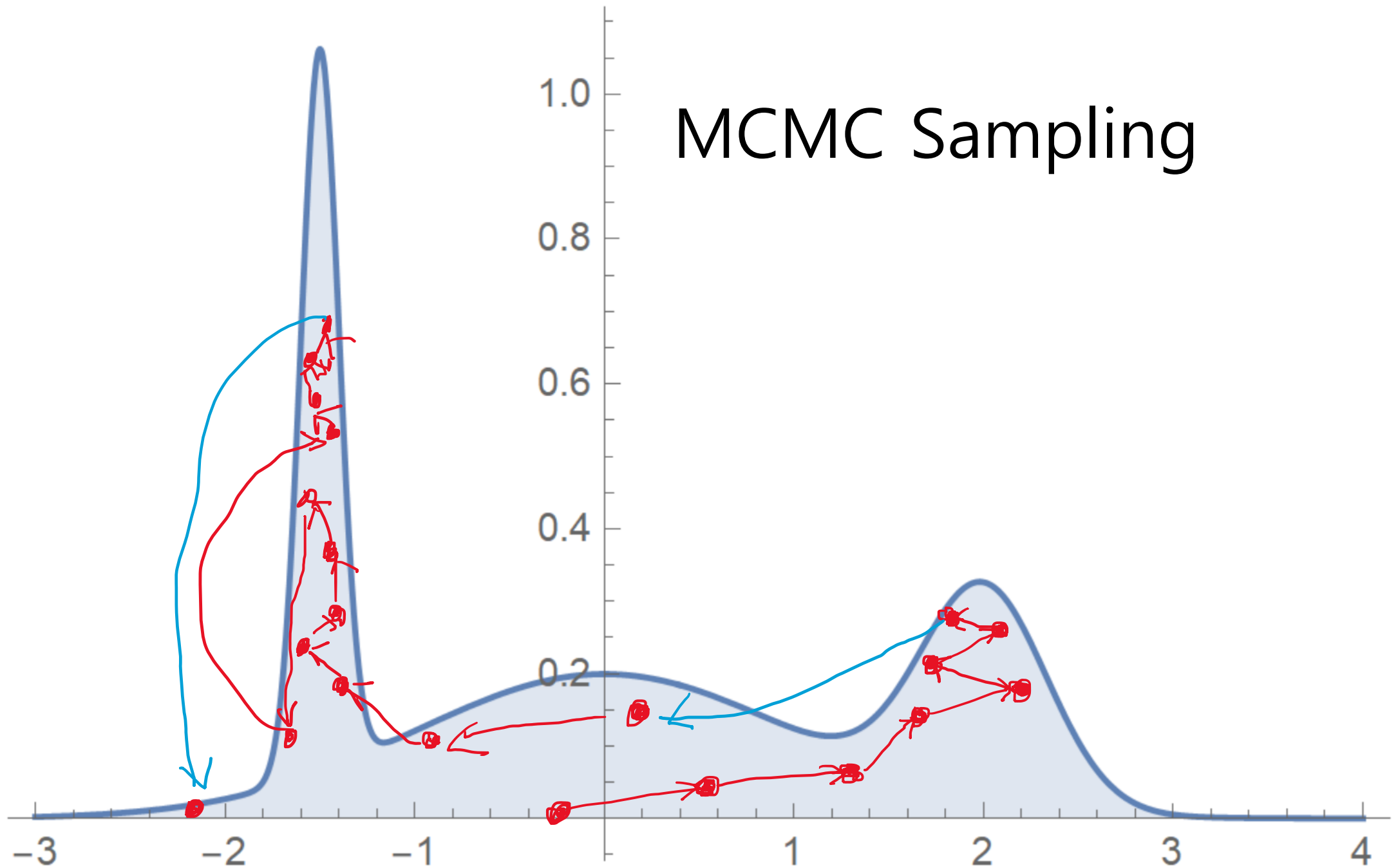


온도 병렬계산(parallel tempering)

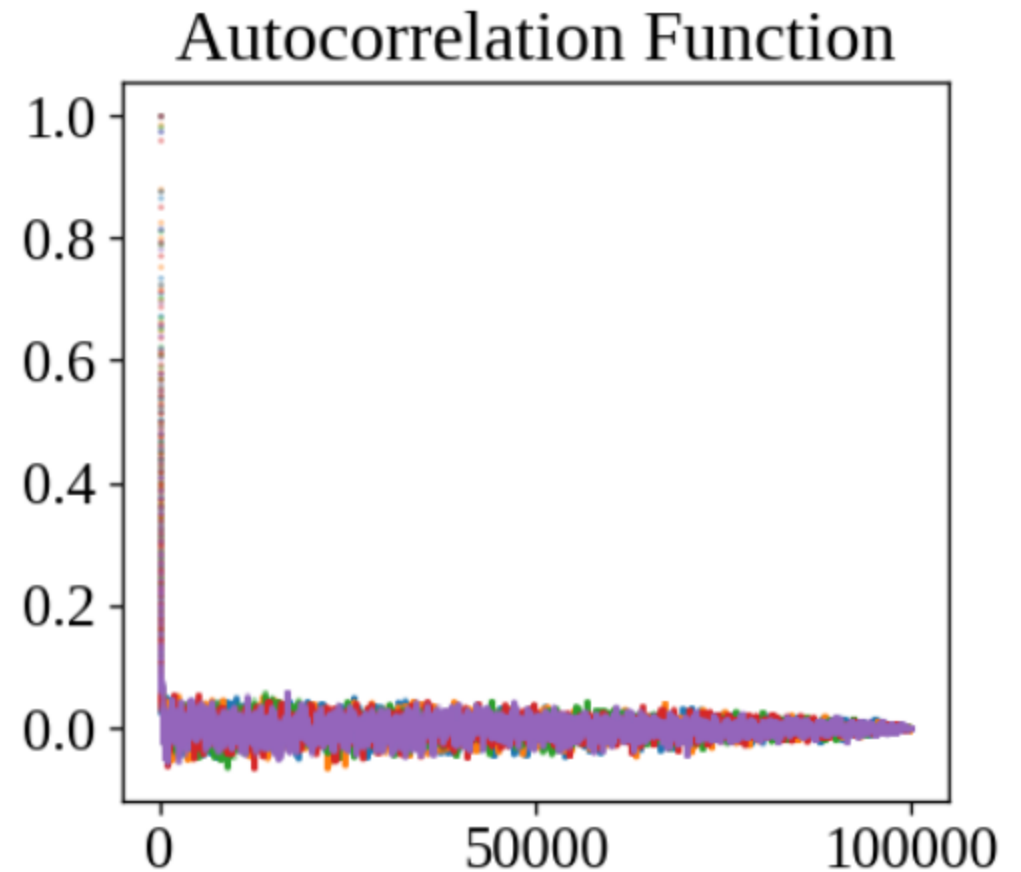
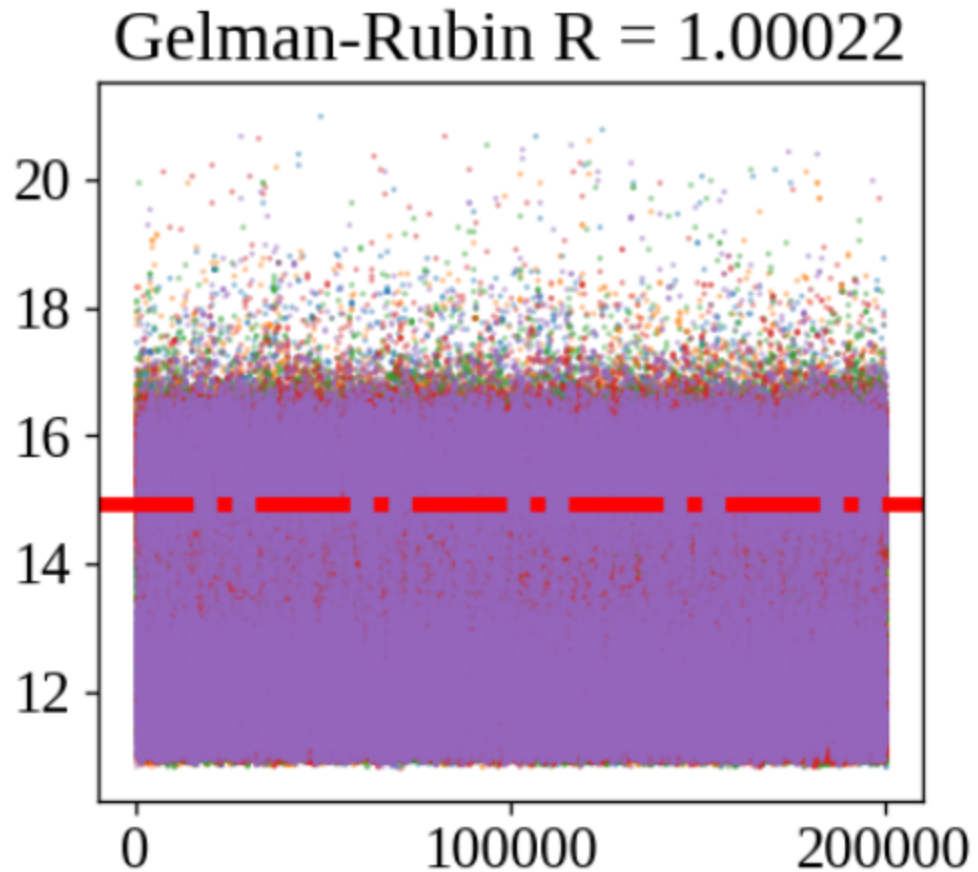
- 몇 개의 다른 가상의 온도를 사용한다
- 가능도 함수를 온도로 조정한다 $p(D|\theta)^{\frac{1}{T}}$, $T > 1$
- $T_{max} = \frac{(Network\ SNR)^2}{n_{par}}$
- 수렴과 혼합을 개선한다



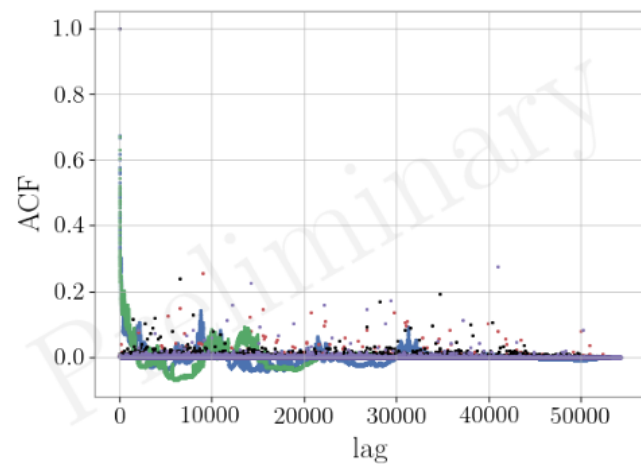
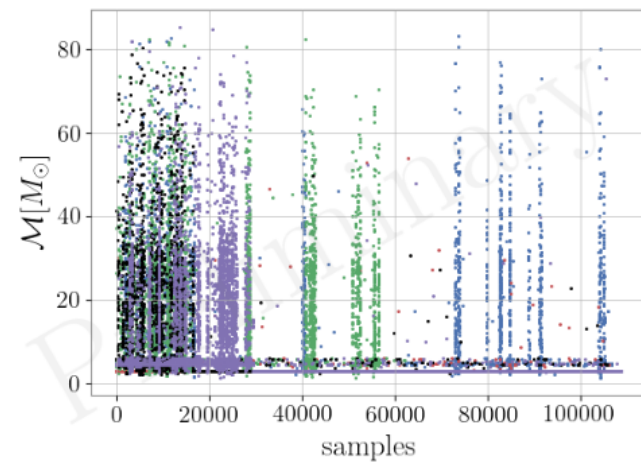
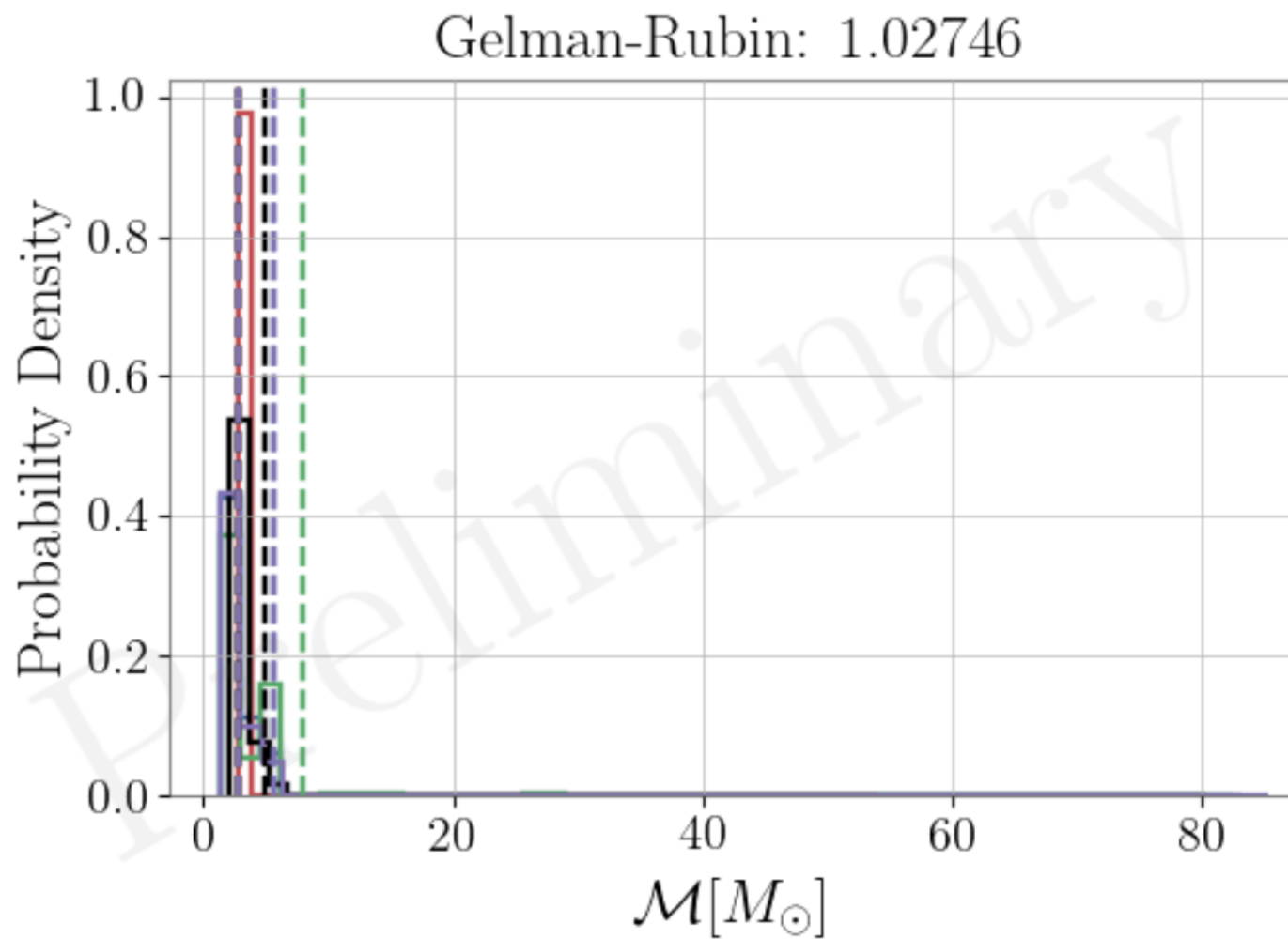
MCMC Sampling



계산이 잘 되었나?



계산이 잘 되었나?



ACL Definition

- Smallest s such that $1 + 2 \sum_{k=1}^{M \cdot s} R(k) < s$
- LALInferenceMCMCSampler.c computeMaxAutoCorrLen()

```
/* Define ACL as the smallest s such that
 *
 * 1 + 2*ACF(1) + 2*ACF(2) + ... + 2*ACF(M*s) < s,
 *
 * the short length so that the sum of the ACF function
 * is smaller than that length over a window of M times
 * that length.
 *
 * The maximum window length is restricted to be N/K as
 * a safety precaution against relying on data near the
 * extreme of the lags in the ACF, where there is a lot
 * of noise.
 */
```

Integrated ACT

- $C(\tau) = \langle (X_t - \mu)(X_{t+\tau} - \mu) \rangle$
- $\sigma^2 = C(0) = \langle (X_t - \mu)(X_t - \mu) \rangle$
- $R(\tau) = \frac{C(\tau)}{C(0)} = \frac{\langle (X_t - \mu)(X_{t+\tau} - \mu) \rangle}{\sigma^2}$
- $\mu = \frac{1}{N} \sum_{t=1}^N X_t$
- $\sigma^2(\mu) = \langle (\mu_k - \mu)(\mu_k - \mu) \rangle = \frac{\sigma^2}{N}$ (independent samples)

Integrated ACT

- $\sigma^2(\mu) = \langle (\mu_k - \mu)(\mu_k - \mu) \rangle = \frac{\sigma^2}{N} \left[1 + 2 \sum_{\tau=1}^{N-1} \left(1 - \frac{\tau}{N} \right) R(\tau) \right] = \frac{\sigma^2}{N} \tau_{\text{int}}$
- $\tau_{\text{int}} = 1 + 2 \sum_{\tau=1}^{N-1} \left(1 - \frac{\tau}{N} \right) R(\tau)$
- $\tau_{\text{int}} = 1 + 2 \sum_{\tau=1}^{\infty} R(\tau)$ (Integrated Autocorrelation Time)
- $1 + 2 \sum_{t=1}^{M\tau} R(t) < \tau$

Gelman-Rubin diagnostic

- M independent chains of size N
 - $W = \frac{1}{M} \sum_{j=1}^M \sigma_j^2$, $\sigma_j^2 = \frac{1}{N-1} \sum_{i=1}^N (\theta_j^i - \mu_j)^2$
Average of the variances of each chain, underestimate true variance since not reached to stationary distribution.
 - $B = \frac{N}{M-1} \sum_{j=1}^M (\mu_j - \mu)^2$, $\mu = \frac{1}{M} \sum_{j=1}^M \mu_j$
Variance of the chain means multiplied by N .

Gelman-Rubin diagnostic

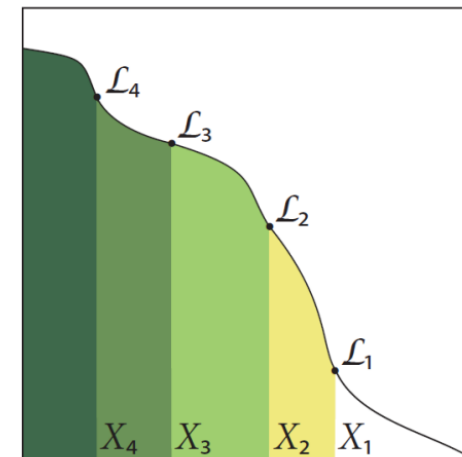
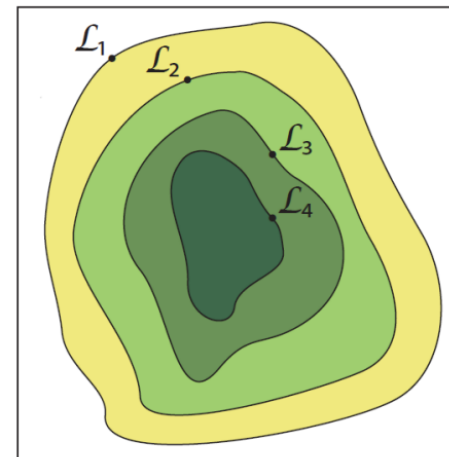
- Estimated Variance
 - $Var(\theta) = \left(1 - \frac{1}{N}\right)W + \frac{1}{N}B$
overestimate true variance for overdispersed starting values.
- Potential scale reduction factor
 - $R = \sqrt{\frac{Var(\theta)}{W}} = \sqrt{1 - \frac{1}{N} + \frac{1}{N} \frac{B}{W}}$

Nested Algorithm

- 믿음(evidence) 계산

$$Z = \int_{\Omega_{\vec{\theta}}} p(D|\vec{\theta}, M) p(\vec{\theta}|M) d\vec{\theta} = \int_0^1 p(D, M, X) dX$$

$$X(\lambda) = \int_{\Omega_{\vec{\theta}}: p(D|\vec{\theta}, M) \geq \lambda} p(D|\vec{\theta}, M) p(\vec{\theta}|M) d\vec{\theta},$$
$$X(\lambda = 0) = 1, X(\lambda = \infty) = 0$$



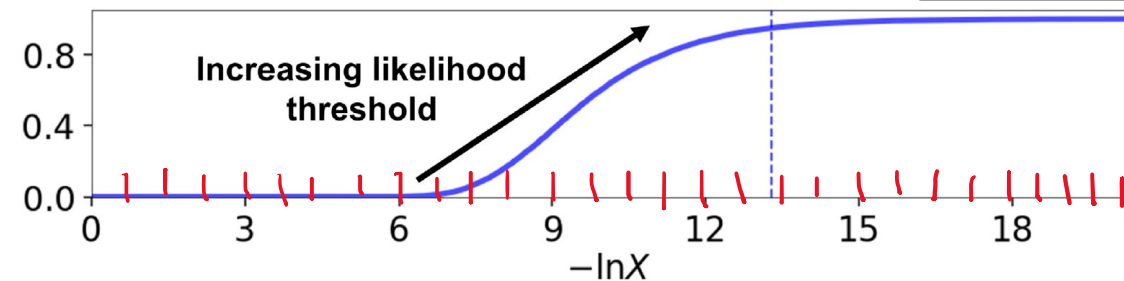
Feroz et al. (2013)

높은 차원의 적분을 효과적으로 1차원 적분으로 계산

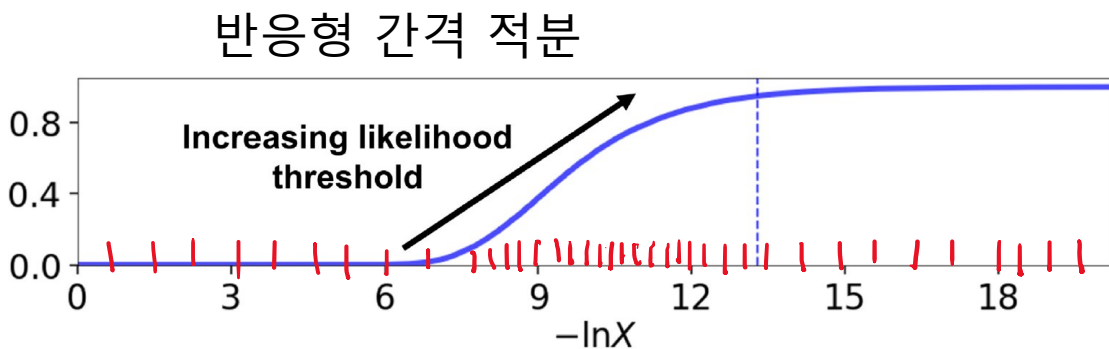
Algorithm 1: Static Nested Sampling

```
// Initialize live points.  
Draw  $K$  “live” points  $\{\Theta_1, \dots, \Theta_K\}$  from the prior  $\pi(\Theta)$ .  
// Main sampling loop.  
while stopping criterion not met do  
    Compute the minimum likelihood  $\mathcal{L}^{\min}$  among the current set of live points.  
    Add the  $k$ th live point  $\Theta_k$  associated with  $\mathcal{L}^{\min}$  to a list of “dead” points.  
    Sample a new point  $\Theta'$  from the prior subject to the constraint  $\mathcal{L}(\Theta') \geq \mathcal{L}^{\min}$ .  
    Replace  $\Theta_k$  with  $\Theta'$ .  
    // Check whether to stop.  
    Evaluate stopping criterion.  
end  
// Add final live points.  
while  $K > 0$  do  
    Compute the minimum likelihood  $\mathcal{L}^{\min}$  among the current set of live points.  
    Add the  $k$ th live point  $\Theta_k$  associated with  $\mathcal{L}^{\min}$  to a list of “dead” points.  
    Remove  $\Theta_k$  from the set of live points.  
    Set  $K = K - 1$ .  
end
```

등간격 적분



[MNRAS 493, 3132\(2020\)](#)

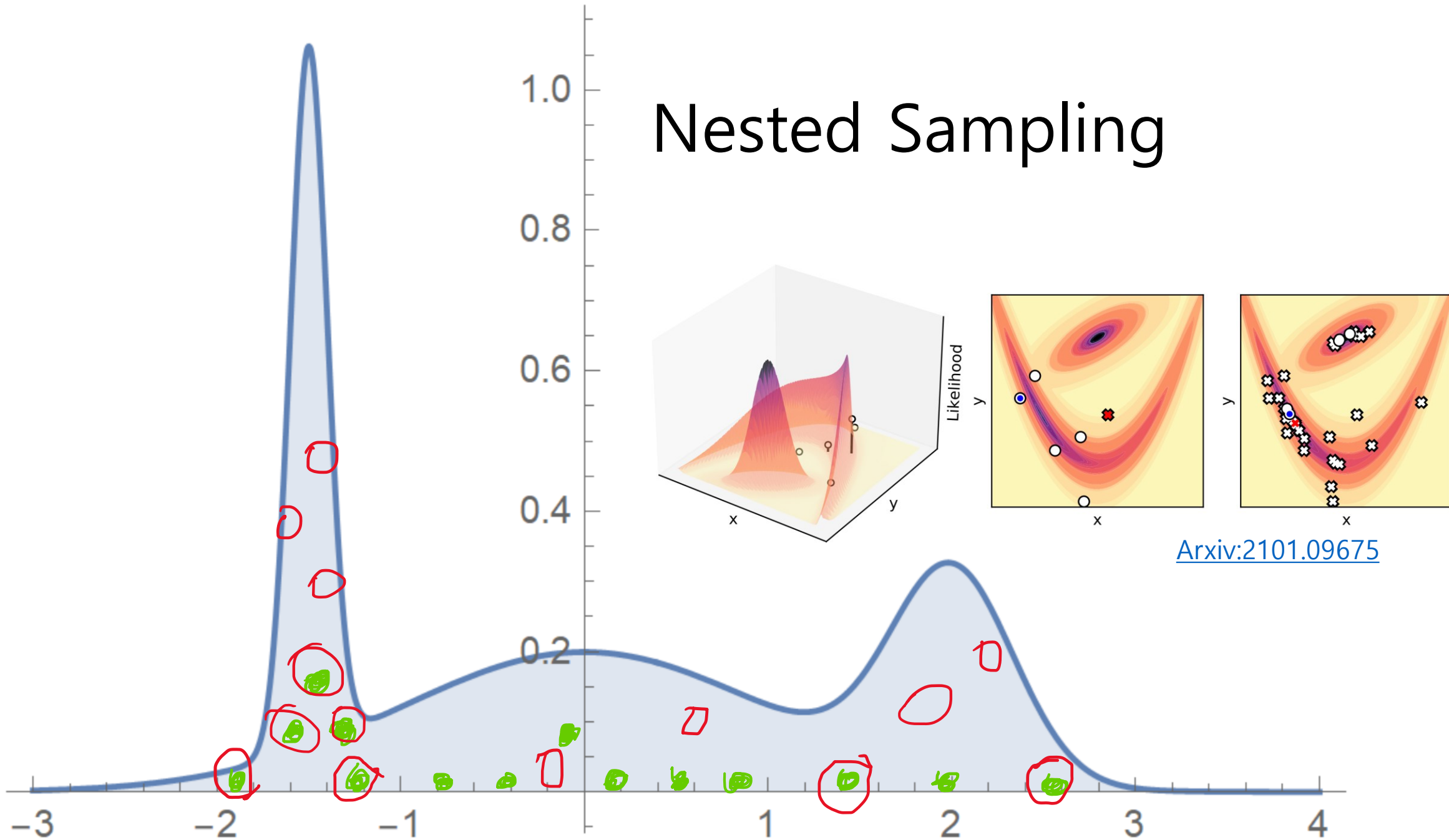


Algorithm 2: Dynamic Nested Sampling

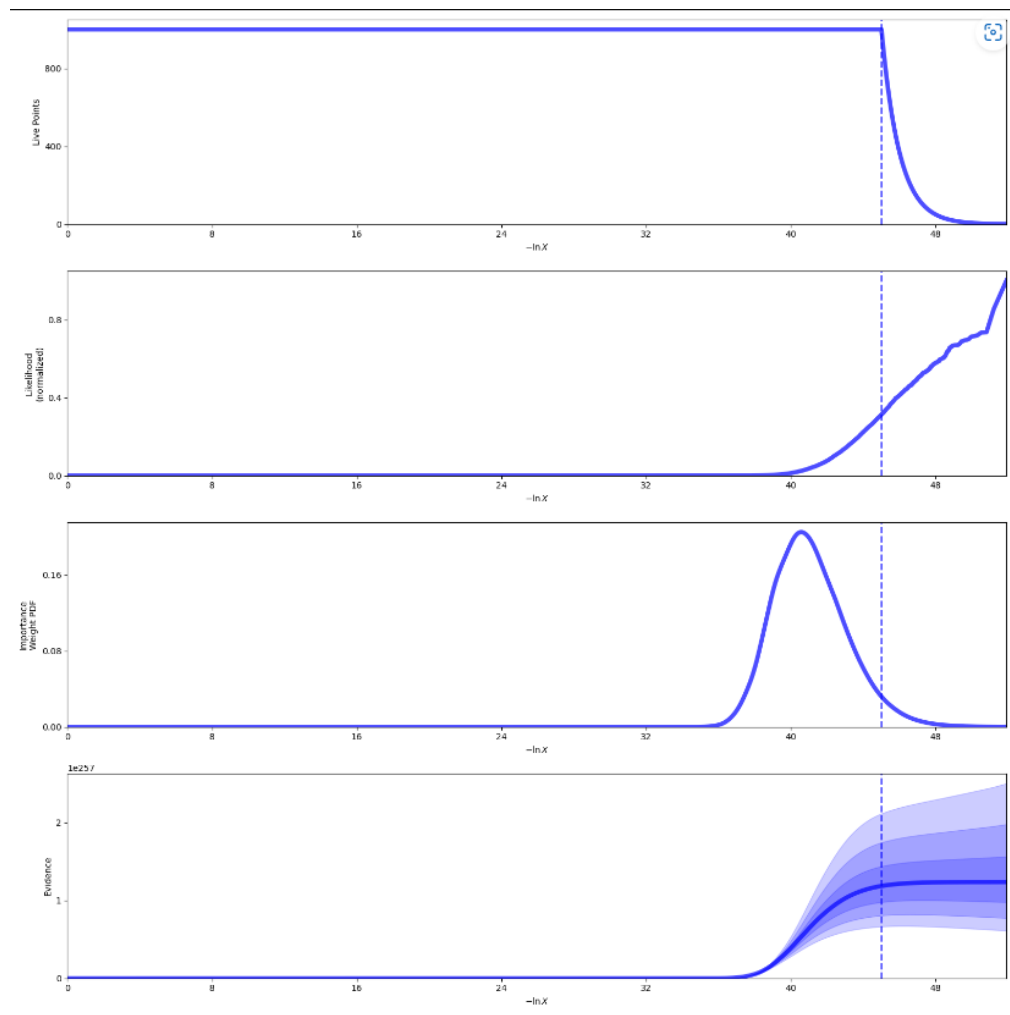
```
// Initialize first set of live points.
Draw  $K$  “live” points  $\{\Theta_1, \dots, \Theta_K\}$  from the prior  $\pi(\Theta)$ .
// Main sampling loop.
Set  $\mathcal{L}^{\min} = 0$  and  $K_0 = K$ .
while stopping criterion not met do
    // Get current number of live points.
    Compute the previous number of live points  $K$  and the current number of live points  $K'$ .
    if  $K' \geq K$  then
        // Add in new live points.
        while  $K' > K$  do
            Sample a new point  $\Theta'$  from the prior subject to the constraint  $\mathcal{L}(\Theta') \geq \mathcal{L}^{\min}$ .
            Add  $\Theta'$  to the set of live points.
            Set  $K = K + 1$ .
        end
        // Replace worst live point.
        Compute the minimum likelihood  $\mathcal{L}^{\min}$  among the current set of  $K$  live points.
        Add the  $k$ th live point  $\Theta_k$  associated with  $\mathcal{L}^{\min}$  to a list of “dead” points.
        Replace  $\Theta_k$  with  $\Theta'$ .
    else
        // Iteratively remove live points.
        while  $K' < K$  do
            Compute the minimum likelihood  $\mathcal{L}^{\min}$  among the current set of  $K = K'$  live points.
            Add the  $k$ th live point  $\Theta_k$  associated with  $\mathcal{L}^{\min}$  to a list of “dead” points.
            Remove  $\Theta_k$  from the set of live points.
            Set  $K = K - 1$ .
        end
    end
    // Check whether to stop.
    Evaluate stopping criterion.
end
// Add final live points.
while there are live points remaining do
    Compute the minimum likelihood  $\mathcal{L}^{\min}$  among the current set of live points.
    Add the  $k$ th live point  $\Theta_k$  associated with  $\mathcal{L}^{\min}$  to a list of “dead” points.
    Remove  $\Theta_k$  from the set of live points.
end
```

[MNRAS 493, 3132\(2020\)](#)

Nested Sampling

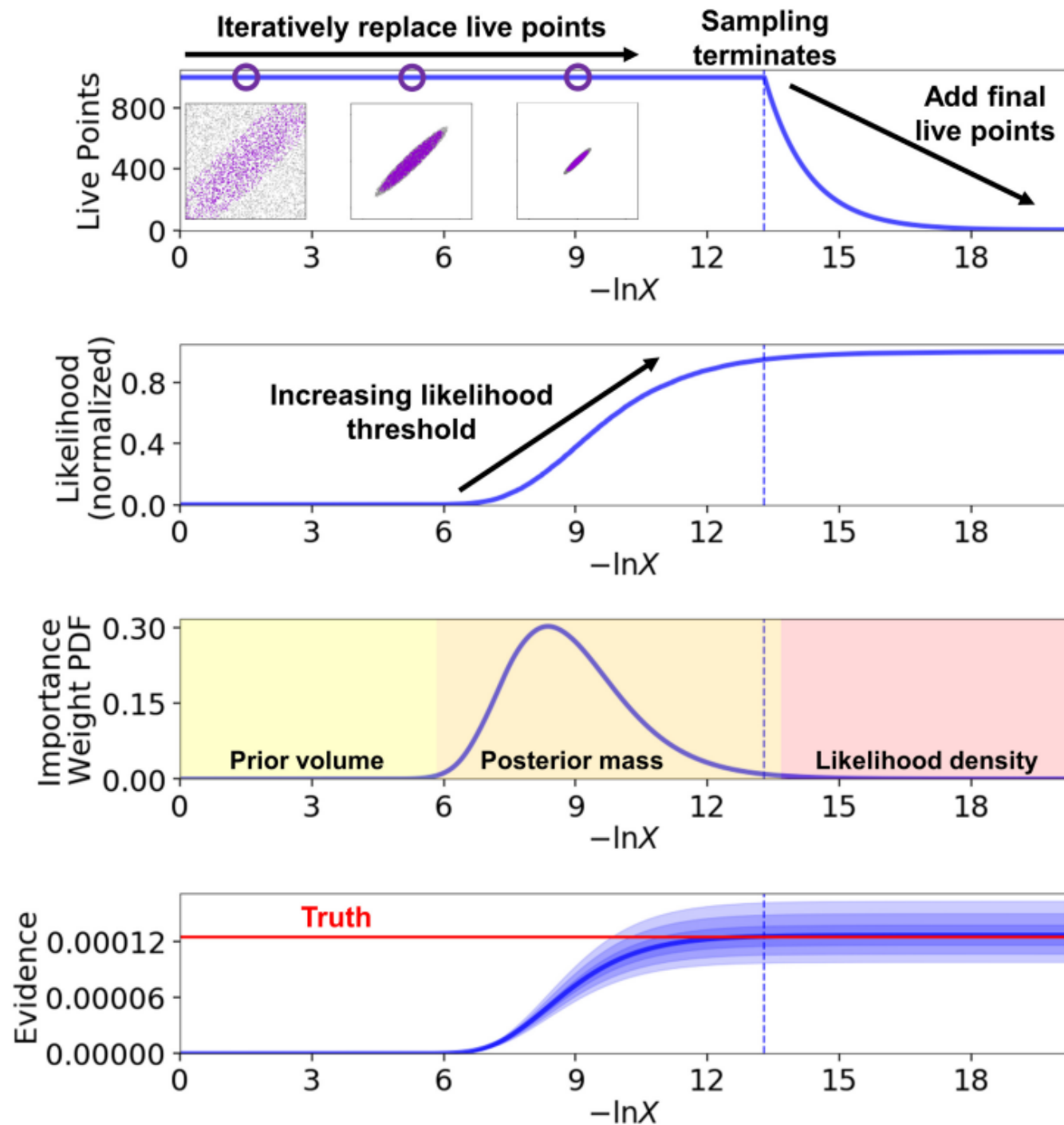


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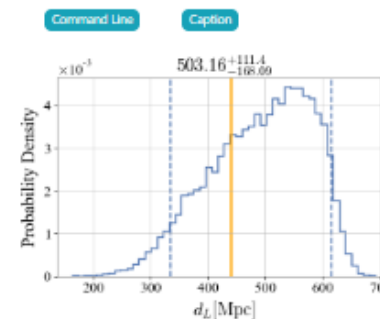
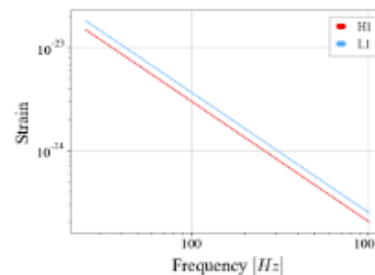
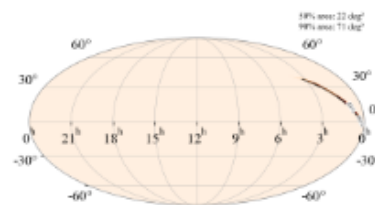
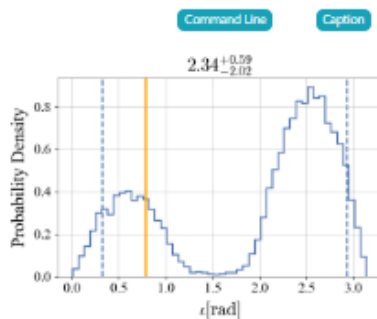
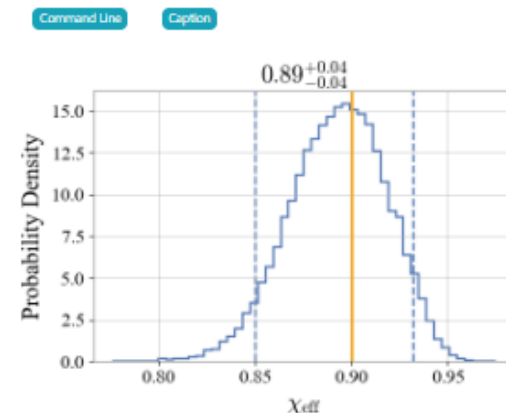
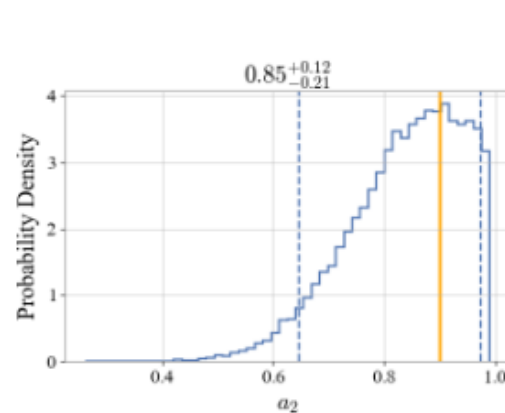
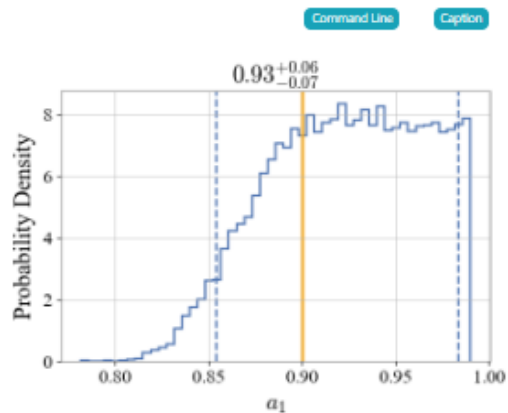
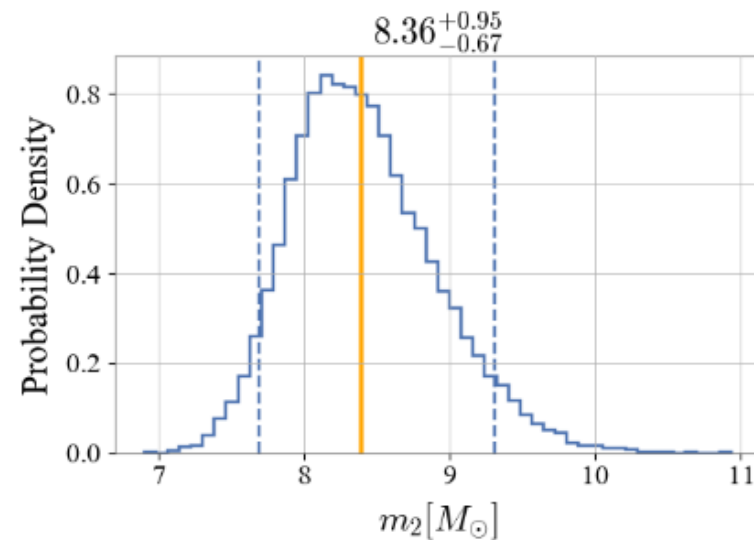
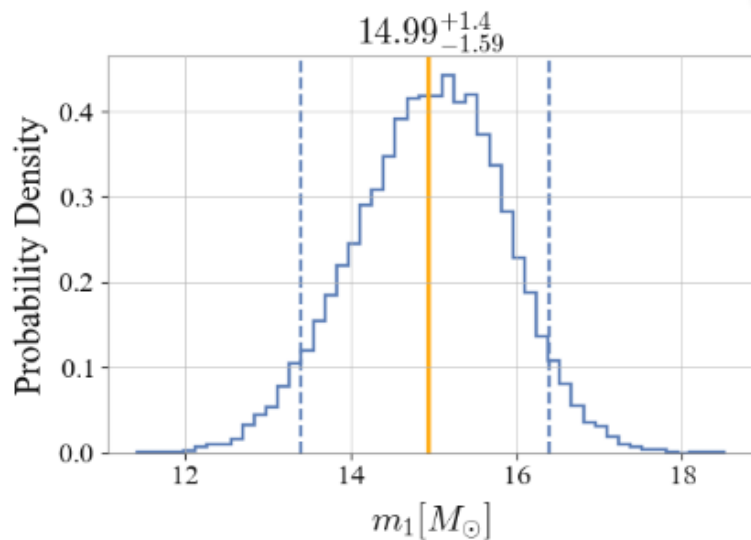


2026-07-28

2026 수치



계산이 잘 되었나?



분석 도구

LALSuite([LALSuite: Main Page \(ligo.org\)](http://ligo.org))

- C based LSC Algorithm Library Suite
- LALInferenceMCMC.c : MCMC Sampler
- LALInferenceNest.c : Nested Sampler
- [RIFT\(Rapid Iterative Fitting\)](#)

LALSuite from source

Building LALSuite from source

Dependencies

Build tools

The following build tools will be needed to build LALSuite components from source

- a C compiler with support for the C99 standard
- autoconf (building from git only)
- automake (building from git only)
- make
- pkg-config

Library dependencies

For LAL the library dependencies are:

- [GSL](#) - The GNU Scientific Library.
- [FFTW](#) - The Fastest Fourier Transform in the West.
- [HDF5](#) - The HDF5 library
- [zLib](#) - A Massively Spiffy Yet Delicately Unobtrusive Compression Library

Other subpackages need at least (but not limited to):

- [lframe](#) - LIGO/Virgo Frame library (needed for LALFrame)
- [lmetaio](#) - LIGO_LW XML library ([LALMetaIO](#))
- [cfitsio](#) - A FITS File Subroutine Library (needed for LALPulsar)

All Dependencies can be installed using an appropriate Package manager, **you should not need to compile any of these yourself.**

The Python layers for each subpackage will have extra requirements that are not specified here.

LALSuite from source

Building from the git repository

The repository is hosted on the LIGO [GitLab](#) instance, please see the following [computing guide](#) page for details on accessing repositories hosted here. The LALSuite repository also utilizes `git-lfs` for the management of large file so please ensure that you have [configured](#) `git-lfs` on your system.

You can then clone the repository using:

```
git clone git@git.ligo.org:lscsoft/lalsuite.git
```

You can also clone using the https interface but the above SSH URL is recommended as this is more robust:

```
git clone https://git.ligo.org/lscsoft/lalsuite.git
```

If you are cloning anonymously then you *must* use the https URL.

You can then install LAL as follows:

```
LAL_INSTALL_PREFIX="${HOME}/opt/lalsuite" # change as appropriate
pushd lal
./00boot
./configure --prefix=${LAL_INSTALL_PREFIX}
make
make install
```

LALSuite install in conda

Cloning the Repository

We now utilize [Git LFS](#) for the management of large files and as such `git-lfs` needs to be installed and configured to correctly clone this repository. After installing `git-lfs` it can be configured using:

```
$ git lfs install
```

This only needs to be done once for each machine you access the repository. It can then be cloned using:

```
$ git clone git@git.ligo.org:lscsoft/lalsuite.git
```

Building from Source

The recommended way to build LALSuite from source is in a `conda` environment. [A recipe file](#) is available with all main dependencies. This can serve as the base for custom recipes, or be used directly via:

```
$ conda env create -f conda/environment.yml
```

Pulling in dependencies may take a while depending on your internet connection. After the environment setup succeeded, you can activate it with:

```
$ conda activate lalsuite-dev
```

You can then build the suite by executing, in order:

1. `./00boot` (once at first time)
2. `./configure` with appropriate options (see `./configure --help`)
3. `make`

After pulling updates or making your own changes, you will usually only need to call `make` again, as reconfiguration and re-running `00boot` should be handled automatically if needed.

LALInference

([LALInference: Main Page \(ligo.org\)](https://lalinference.ligo.org/))

lalinference_mcmc
lalinference_nest

Documentation

Here is a list of all modules:

▼ General Packages	
Header LALInference.h	Main header file for LALInference common routines and structures
Header LALInferenceLikelihood.h	Header file for likelihood functions used by LALInference codes
Header LALInferenceNestedSampler.h	Nested sampler written for LALInference
Header LALInferencePrior.h	Collection of commonly used Prior functions and utilities
Header LALInferenceProposal.h	Jump proposals for exploring the GW signal parameter space
Header LALInferenceReadData.h	Utility functions for handling IFO data
Header LALInferenceRemoveLines.h	Utility functions for identifying lines in IFO data to be removed in LALInference
Header LALInferenceTemplate.h	Main header file for LALInference signal template generating functions
Header LALInferenceVCSInfo.h	VCS and build information for LALInference
▼ SWIG Interfaces	This package provides Octave and Python wrappings of LALInference functions and data structures generated using SWIG
Interface SWIGLALInferenceAlpha.i	SWIG code which must appear <i>before</i> the LALInference headers
Interface SWIGLALInferenceOmega.i	SWIG code which must appear <i>after</i> the LALInference headers
Python Packages	

SWIG(Simplified Wrapper and Interface Generator)

- SWIG is a software development tool that connects programs written in C and C++ with a variety of high-level programming languages. SWIG is used with different types of target languages including common scripting languages such as Javascript, Perl, PHP, Python, Tcl and Ruby. The list of [supported languages](#) also includes non-scripting languages such as C#, D, Go language, Java including Android, Lua, OCaml, Octave, Scilab and R. Also several interpreted and compiled Scheme implementations (Guile, MzScheme/Racket) are supported. SWIG is most commonly used to create high-level interpreted or compiled programming environments, user interfaces, and as a tool for testing and prototyping C/C++ software. SWIG is typically used to parse C/C++ interfaces and generate the 'glue code' required for the above target languages to call into the C/C++ code. SWIG can also export its parse tree in the form of XML. SWIG is free software and the code that SWIG generates is compatible with both commercial and non-commercial projects.



The diagram illustrates the HPC system architecture. A User (represented by a person icon) connects to the Internet (represented by a cloud). The Internet connects to the Login Node (represented by a server icon). The Login Node connects to the HCondor batch manager (represented by a server icon). The HCondor batch manager connects to the NAS Storage (represented by a server rack icon) and the Work Nodes (represented by a server rack icon). The NAS Storage is labeled with 550 TB. The Work Nodes are labeled with 996 Cores and 6 GPU. The Grid Storage (represented by a cloud icon) is also connected to the Internet.

Grid Storage

Internet

User

Login Node

HCondor batch manager

NAS Storage 550 TB

996 Cores
6 GPU

Work Nodes

2026-07-28

2026 수치상대로 및 중력파 여류학교

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작업 수행

```
[screen 0: bash] hwlee@ldg-ui01:/data/ligo/scratch/hwlee/eccwork/gw151226/ecc-ecc-0.04
#!/bin/sh

module load openmpi-x86_64
#source /opt/intel/parallel_studio_xe_2018.1.038/bin/psxevars.sh
#export masterdir=/data/ligo/scratch/pe/LAL/lalinference_o2_eccTides/
export masterdir=/data/ligo/scratch/pe/LAL/eccentricity_160810
source $masterdir/etc/lscsoftrc
export PYTHON=/usr/lib64/python2.7/site-packages

date

cd /data/ligo/scratch/hwlee/eccwork/gw151226/ecc-ecc-0.04
condor_submit 0noiseecc0.sub
condor_submit 0noiseecc0.sub
condor_submit 0noiseecc0.sub
condor_submit 0noiseecc0.sub
condor_submit 0noiseecc0.sub

exit
```

```
[screen 0: bash] hwlee@ldg-ui01:/data/ligo/scratch/hwlee/eccwork/gw151226/ecc-ecc-0.04
universe = vanilla
getenv = true
executable = /usr/lib64/openmpi/bin/mpirun
arguments = -np 11 /data/ligo/scratch/pe/LAL/eccentricity_160810/bin/lalinference_mcmc --outfile PTMCMC.output.%(Cluster)-%(Process)
.h5 --ifo H1 --H1-cache LALSimAdLIGO --H1-flow 25 --trigtime 894383679.0 --psdstart 894383379.0 --psdlength 1024.0 --seglen 16 --sra
te 2048 --inj ./taylorF2EccH1onlyBBHGW151226.xml --event 4 --inj-fref 100 --inj-spinOrder 0 --inj-tidalOrder -1 --approx TaylorF2Ec
cthreePointFivePN --fref 100 --nsteps 20000000 --skip 100 --neff 10000 --amporder Newtonian --spinOrder 0 --tidalOrder -1 --radi
ation-frame --margtime --tempLadderBottomUp --differential-buffer-limit 100000 --dataseed 12345 --0noise --noSpin --tidalT --quadpar
am

output = %(Cluster)-%(Process).f2ecc-ecc.gw151226.0noise.out
error = %(Cluster)-%(Process).f2ecc-ecc.gw151226.0noise.err
log = %(Cluster)-%(Process).f2ecc-ecc.gw151226.0noise.log
request_cpus = 11
request_memory = 11*6*1024

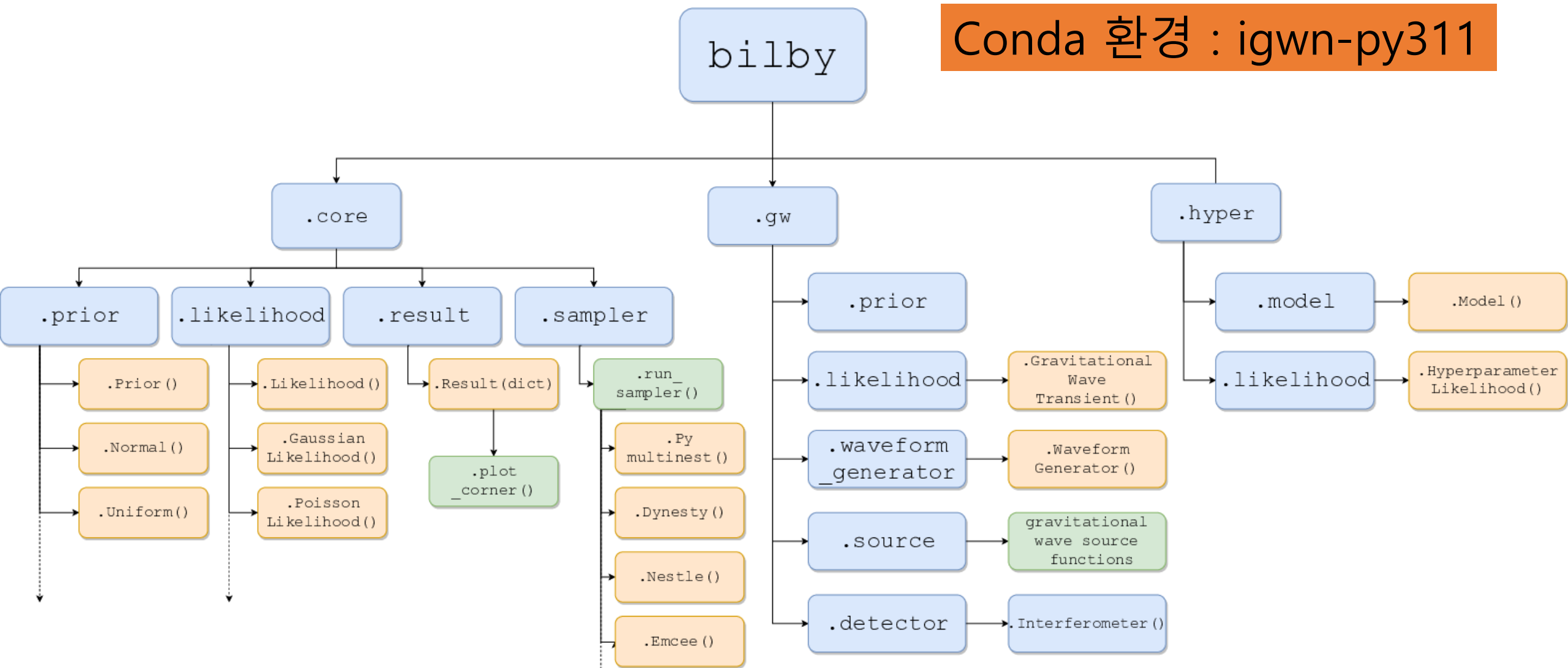
queue 1
```



Bilby

[Welcome to bilby's documentation! — bilby 2.8 documentation](#)

Conda 환경 : igwn-py311



Installation

Conda

Pip

```
$ conda install -c conda-forge bilby
```

Supported python versions: 3.10-3.12.

This will install all requirements for running `bilby` for general inference problems, including our default sampler `dynesty`. Other samplers will need to be installed via pip or the appropriate means.

To install the requirements for running `bilby.gw` for gravitational wave inference, please additionally run the following commands.

Conda

Pip

```
$ conda install -c conda-forge gwpy python-lalsimulation
```

Conda

Pip

```
$ pip install bilby
```

Conda

Pip

```
$ pip install gwpy lalsuite
```

Install bilby from source

`bilby` is developed and tested with Python 3.11+. In the following, we assume you have a working python installation, [python pip](#), and [git](#). See [Installing python](#) for our advise on installing anaconda python.

Clone the repository, install the requirements, and then install the software:

```
$ git clone git@github.com:bilby-dev/bilby.git
$ cd bilby/
$ pip install -r requirements.txt
$ pip install .
```

Dynesty Guide

The Dynesty sampler is just one of the samplers available in bilby, but it is well-used and found to be fast and accurate. Here, we provide a short guide to its implementation. This will not be a complete guide, additional help can be found in the [Dynesty documentation](#).

All of the options discussed herein can be set in the `bilby.run_sampler()` call. For example, to set the number of live points to 1000

```
>>> bilby.run_sampler(likelihood, priors, sampler="dynesty", nlive=1000)
```

Bilby MCMC Guide

Bilby MCMC is a native sampler built directly in `bilby` and described in [Ashton & Talbot \(2021\)](#). Here, we describe how to use it. For detailed API information see the API section.

Quickstart and output

To use the `bilby_mcmc` sampler, we call

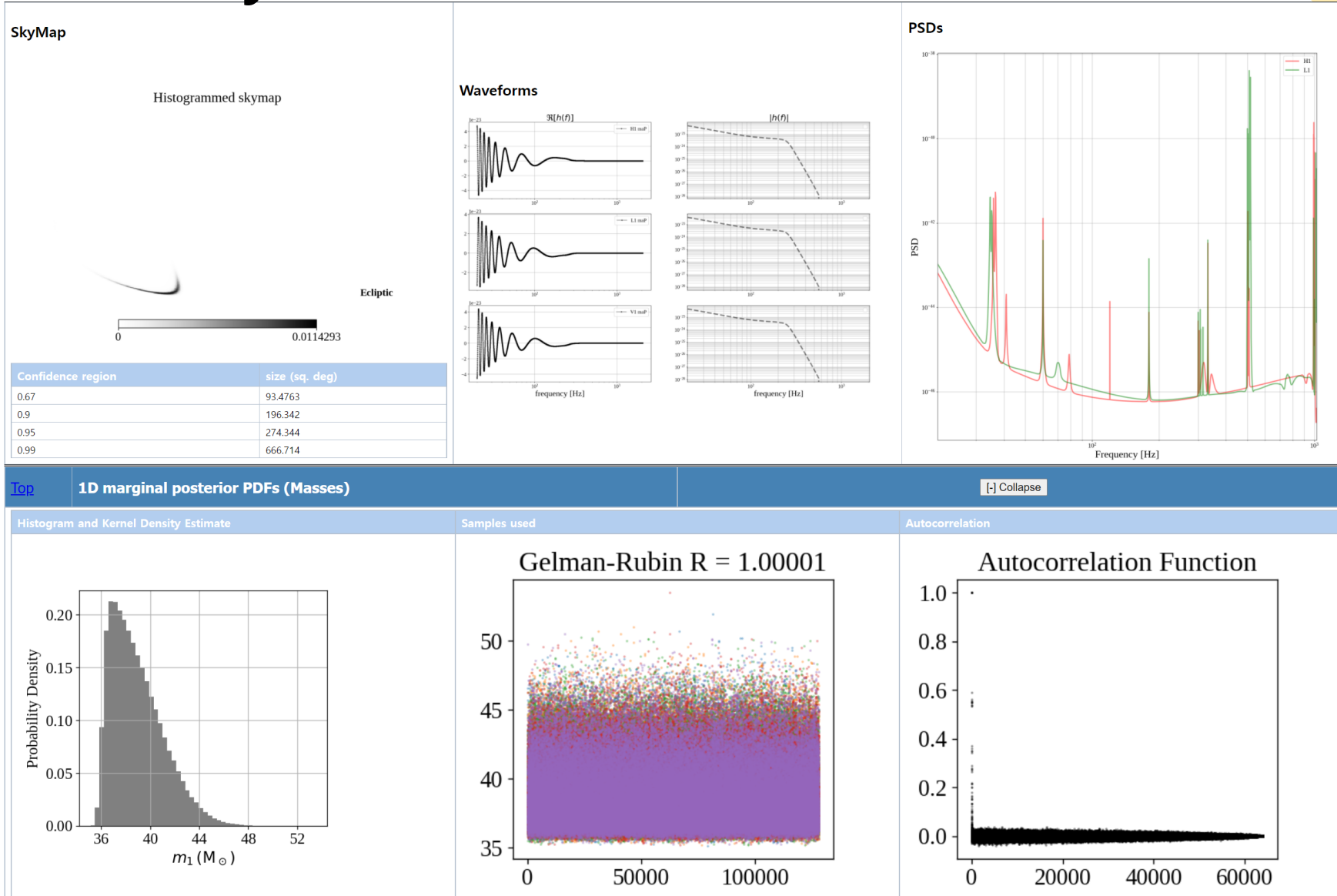
```
>>> bilby.run_sampler(likelihood, priors, sampler="bilby_mcmc", nsamples=1000)
```

This will run the MCMC sampler until 1000 independent samples are drawn from the posterior. As the sampler is running, it will print output like this

```
2.18e+04 | 10:13:34 | 9.96e+02 (AD) | t=56 | n=1874 | a=0.15 | e=1.1e-02% | 16.68ms/ev | maxl=71.70 | ETF=0:38:52  
2.18e+04 | 10:14:34 | 9.96e+02 (AD) | t=56 | n=1877 | a=0.15 | e=1.1e-02% | 16.73ms/ev | maxl=71.70 | ETF=0:38:03  
2.19e+04 | 10:15:35 | 9.96e+02 (AD) | t=56 | n=1880 | a=0.15 | e=1.1e-02% | 17.94ms/ev | maxl=71.70 | ETF=0:39:50
```

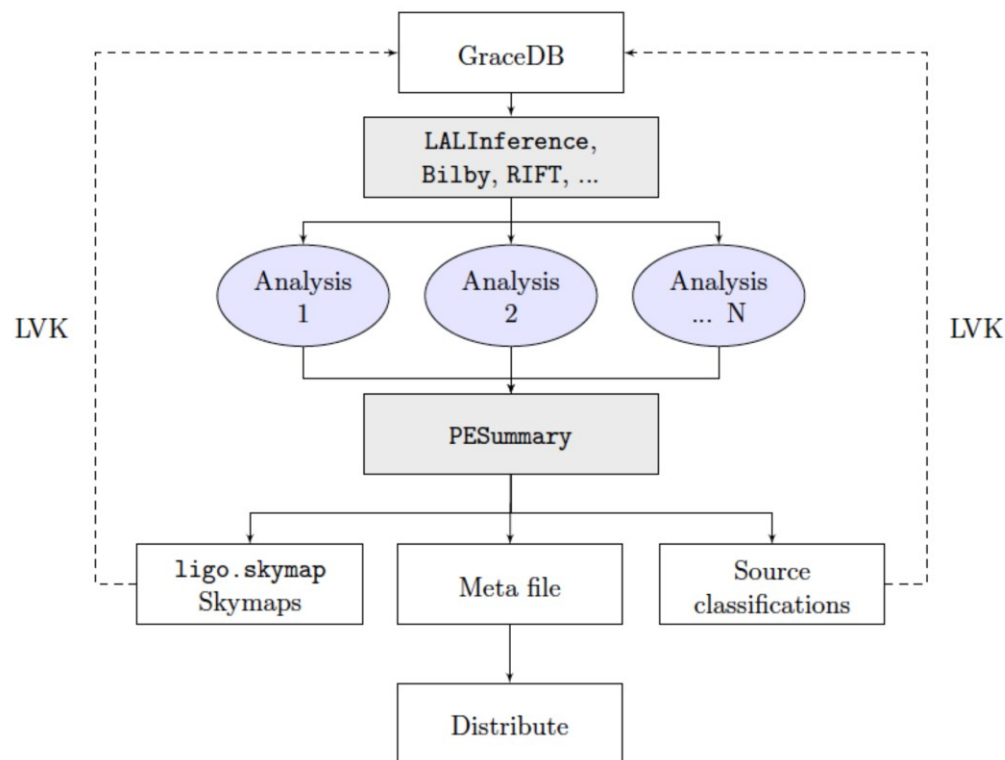
후처리 도구

CBCBayesPostProc



PESummary [PESummary \(ligo.org\)](https://pysummary.ligo.org)

- 모수추정 후처리 결과 생성 라이브러리



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Install PESummary

`PESummary` is developed and tested for python 3.5+. We recommend that this code is installed inside a virtual environment using `virtualenv`. This environment can be installed with python 3.5+ using `pyenv`.

For detailed instructions on how to set up your virtual environment, please refer to [setting up a virtual environment](#).

Installing PESummary using pip

If you choose to install `PESummary` using `pip`, then simply run:

```
$ source ~/virtualenvs/pesummary_py3.6/bin/activate
$ pip install pesummary
```

Installing PESummary using conda

If you choose to install `PESummary` using `conda`, then simply run:

```
$ source ~/virtualenvs/pesummary_pyenv3.6/bin/activate
$ conda install -c conda-forge pesummary
```

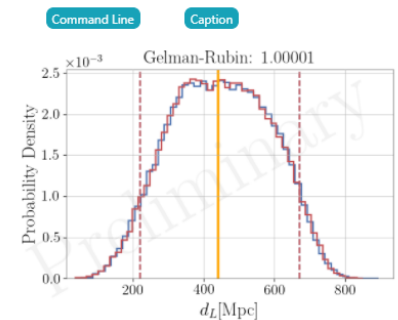
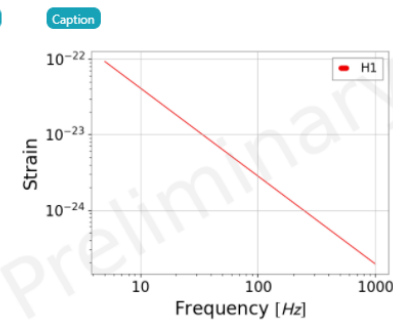
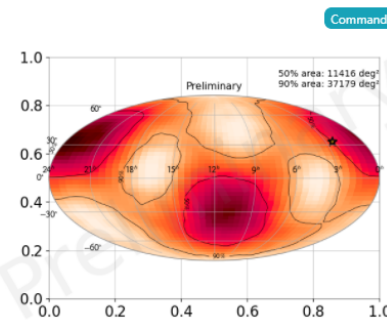
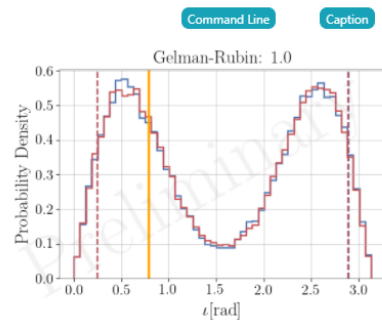
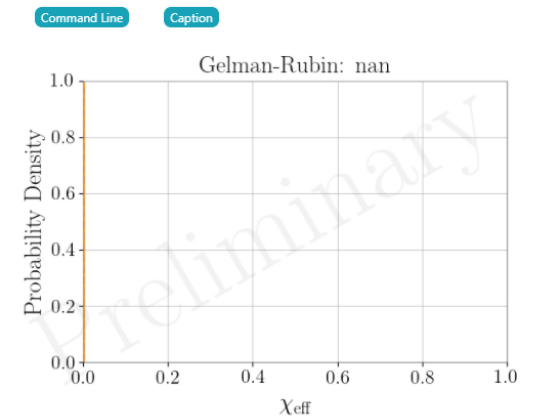
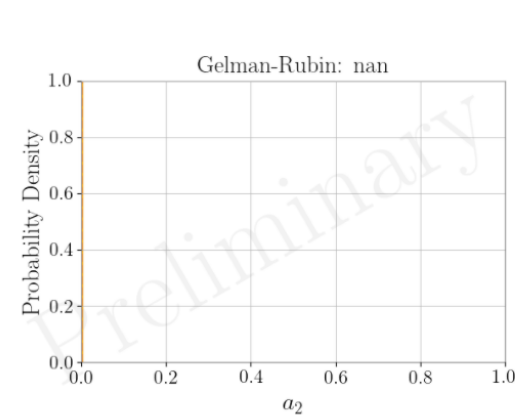
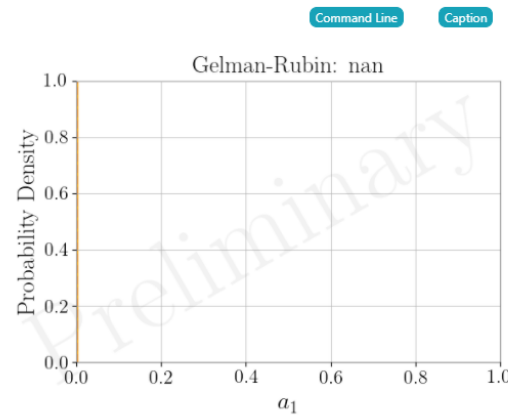
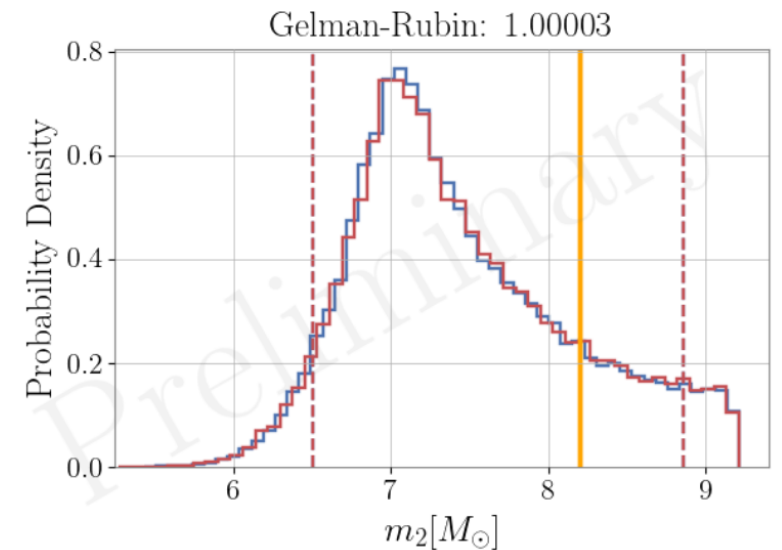
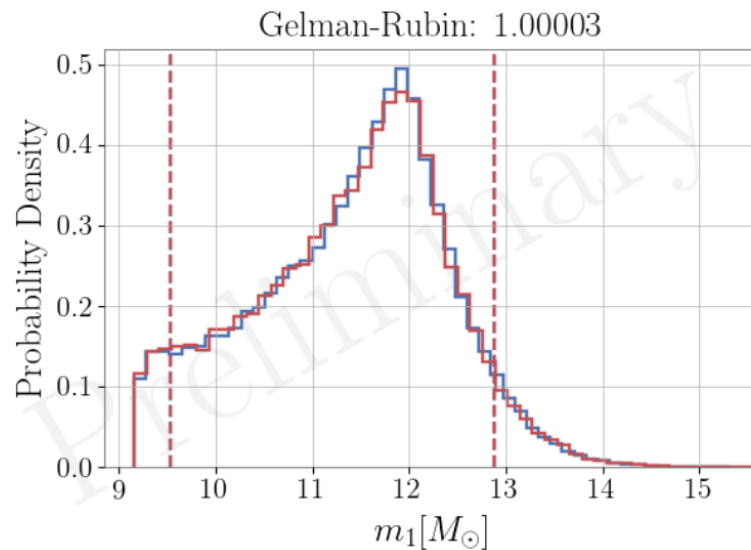
Pulling the PESummary docker image

If you would like, you are able to pull the `PESummary` docker image. To do this, simply run:

```
$ docker pull 08hojc/pesummary
```

PESummary 출력

- Bootstrap css
- Interactive



`bilby_pipe`

[lscsoft / bilby_pipe · GitLab \(ligo.org\)](https://lscsoft.github.io/bilby_pipe/)

```
conda activate igwn
```



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[bilby-pipe · PyPI](#)

bilby-pipe 1.4.0



[Latest version](#)

`pip install bilby-pipe`



Released: Jun 29, 2024

Automating the running of bilby for gravitational wave signals

Navigation

[Project description](#)

[Release history](#)

[Download files](#)

Verified details

These details have been verified by PyPI

Maintainers



[bilbydev](#)

Project description

pipeline

passed

coverage

unknown

pypi package

1.4.0

conda-forge

v1.4.0

python

3.9 | 3.10

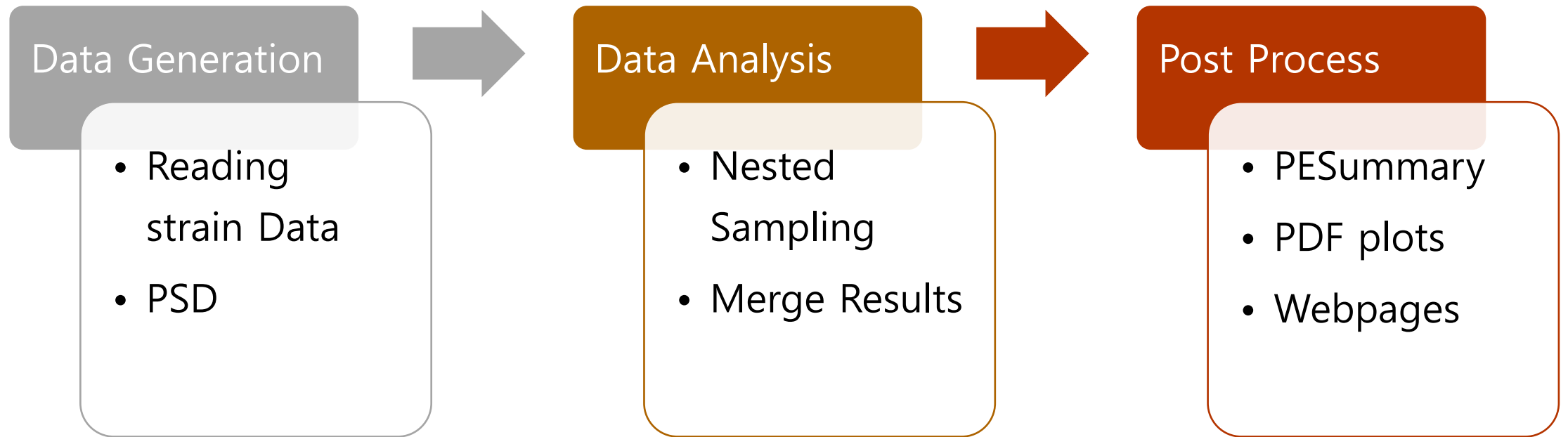
bilby_pipe

A package for automating transient gravitational wave parameter estimation

- [Installation instructions](#)
- [Documentation](#)
- [Issue tracker](#)
- See the [bilby.page](#) for help channels.

2026-07-28

How bilby_pipe works?



How to Run

```
$ bilby_pipe my-run.ini
```

```
my-run.ini
outdir/
-> data/
-> log_data_analysis/
-> log_data_generation/
-> log_results_page/
-> result/
-> results_page/
-> submit/
```

Directory Structure

```
./TaylorF2/
├── GW151226_injection.ini
├── GW151226_injection_test_TF2_dlogz0p1_asdDic_new
│   ├── data
│   ├── final_result
│   ├── GW151226_injection_test_config_complete.ini
│   ├── log_data_analysis
│   ├── log_data_generation
│   ├── log_results_page
│   ├── result
│   │   ├── GW151226_injection_test_data0_894383679-0_analysis_H1L1_dynesty.pickle
│   │   ├── GW151226_injection_test_data0_894383679-0_analysis_H1L1_result.hdf5
│   │   └── GW151226_injection_test_data0_894383679-0_analysis_H1L1_resume.pickle
│   ├── results_page
│   │   └── overview.html
│   └── submit
│       ├── bash_GW151226_injection_test.sh
│       ├── dag_GW151226_injection_test.submit
│       ├── GW151226_injection_test_data0_894383679-0_analysis_H1L1_final_result.submit
│       ├── GW151226_injection_test_data0_894383679-0_analysis_H1L1.submit
│       ├── GW151226_injection_test_data0_894383679-0_generation.submit
│       └── GW151226_injection_test_pesummary.submit
├── GW151226.prior
├── LIGO-PSD.txt
└── LIGO-T1800044-v5-aLIGO_DESIGN.txt
```

GW151226_injection.ini

```
accounting = ligo.dev.o4.cbc.pe.bilby
accounting-user = hyungwon.lee
label = GW151226_injection_test
outdir = GW151226_injection_test_TF2_dlogz0p1_asdDic_new
```

```
detectors = [H1, L1]
duration = 4
```

```
sampler = dynesty
sampler-kwarg = {'nlive': 1000, 'dlogz': 0.1}
waveform-approximant = 'TaylorF2'
```

```
prior-file = GW151226.prior
```

```
injection = True
zero-noise = True
gaussian-noise = False
injection-waveform-approximant = 'TaylorF2'
injection-dict = {mass_1:14.933, mass_2:8.393, a_1:0.9, a_2:0.9, tilt_1:0.0, tilt_2:0.0, phi_12:0.0, phi_jl:0.0, dec:
0.5747465, ra:0.648522, psi:2.605872, phase:3.309695, geocent_time:894383679, luminosity_distance:440, theta_jn=0.785
}
```

```
n-simulation = 1
request-cpus = 4
osg = False
```

```
sampling_frequency = 2048.0
minimum-frequency=25
```

```
psd-dict = {'H1': 'LIGO-PSD.txt', 'L1': 'LIGO-PSD.txt'}
```

```
create-summary = True
save-psd-plain = True
trigger-time = 894383679
```

```
JOB GW151226_injection_test_data0_894383679-0_generation_arg_0 GW151226_injection_test_TF2_dlogz0p1_asdDic_new/submit/GW151226_injection_test_data0_894383679-0_generation.submit
VARS GW151226_injection_test_data0_894383679-0_generation_arg_0 ARGS="GW151226_injection_test_TF2_dlogz0p1_asdDic_new/GW151226_injection_test_config_complete.ini --save-psd-plain=True --label GW151226_injection_test_data0_894383679-0_generation --idx 0 --trigger-time 894383679.0"
Retrv GW151226_injection_test_data0_894383679-0_generation_arg_0 3

JOB GW151226_injection_test_data0_894383679-0_analysis_H1L1_arg_0 GW151226_injection_test_TF2_dlogz0p1_asdDic_new/submit/GW151226_injection_test_data0_894383679-0_analysis_H1L1.submit
VARS GW151226_injection_test_data0_894383679-0_analysis_H1L1_arg_0 ARGS="GW151226_injection_test_TF2_dlogz0p1_asdDic_new/GW151226_injection_test_config_complete.ini --save-psd-plain=True --outdir GW151226_injection_test_TF2_dlogz0p1_asdDic_new --detectors H1 --detectors L1 --label GW151226_injection_test_data0_894383679-0_analysis_H1L1 --data-dump-file GW151226_injection_test_TF2_dlogz0p1_asdDic_new/data/GW151226_injection_test_data0_894383679-0_generation_data_dump.pickle --sampler dynesty"
Retrv GW151226_injection_test_data0_894383679-0_analysis_H1L1_arg_0 3

JOB GW151226_injection_test_data0_894383679-0_analysis_H1L1_final_result_arg_0 GW151226_injection_test_TF2_dlogz0p1_asdDic_new/submit/GW151226_injection_test_data0_894383679-0_analysis_H1L1_final_result.submit
VARS GW151226_injection_test_data0_894383679-0_analysis_H1L1_final_result_arg_0 ARGS="GW151226_injection_test_TF2_dlogz0p1_asdDic_new/result/GW151226_injection_test_data0_894383679-0_analysis_H1L1_result.hdf5 --outdir GW151226_injection_test_TF2_dlogz0p1_asdDic_new/final_result --extension hdf5 --max-samples 20000 --lightweight --save"
JOB GW151226_injection_test_pesummary_arg_0 GW151226_injection_test_TF2_dlogz0p1_asdDic_new/submit/GW151226_injection_test_pesummary.submit
VARS GW151226_injection_test_pesummary_arg_0 ARGS="--webdir GW151226_injection_test_TF2_dlogz0p1_asdDic_new/results_page --config GW151226_injection_test_TF2_dlogz0p1_asdDic_new/GW151226_injection_test_config_complete.ini --samples GW151226_injection_test_TF2_dlogz0p1_asdDic_new/result/GW151226_injection_test_data0_894383679-0_analysis_H1L1_result.hdf5 -a TaylorF2 --gwdata GW151226_injection_test_TF2_dlogz0p1_asdDic_new/data/GW151226_injection_test_data0_894383679-0_generation_data_dump.pickle --psd LIGO-PSD.txt LIGO-PSD.txt"

#Inter-job dependencies
Parent GW151226_injection_test_data0_894383679-0_generation_arg_0 Child GW151226_injection_test_data0_894383679-0_analysis_H1L1_arg_0
Parent GW151226_injection_test_data0_894383679-0_analysis_H1L1_arg_0 Child GW151226_injection_test_data0_894383679-0_analysis_H1L1_final_result_arg_0
Parent GW151226_injection_test_data0_894383679-0_analysis_H1L1_arg_0 Child GW151226_injection_test_pesummary_arg_0
```

Data Generation

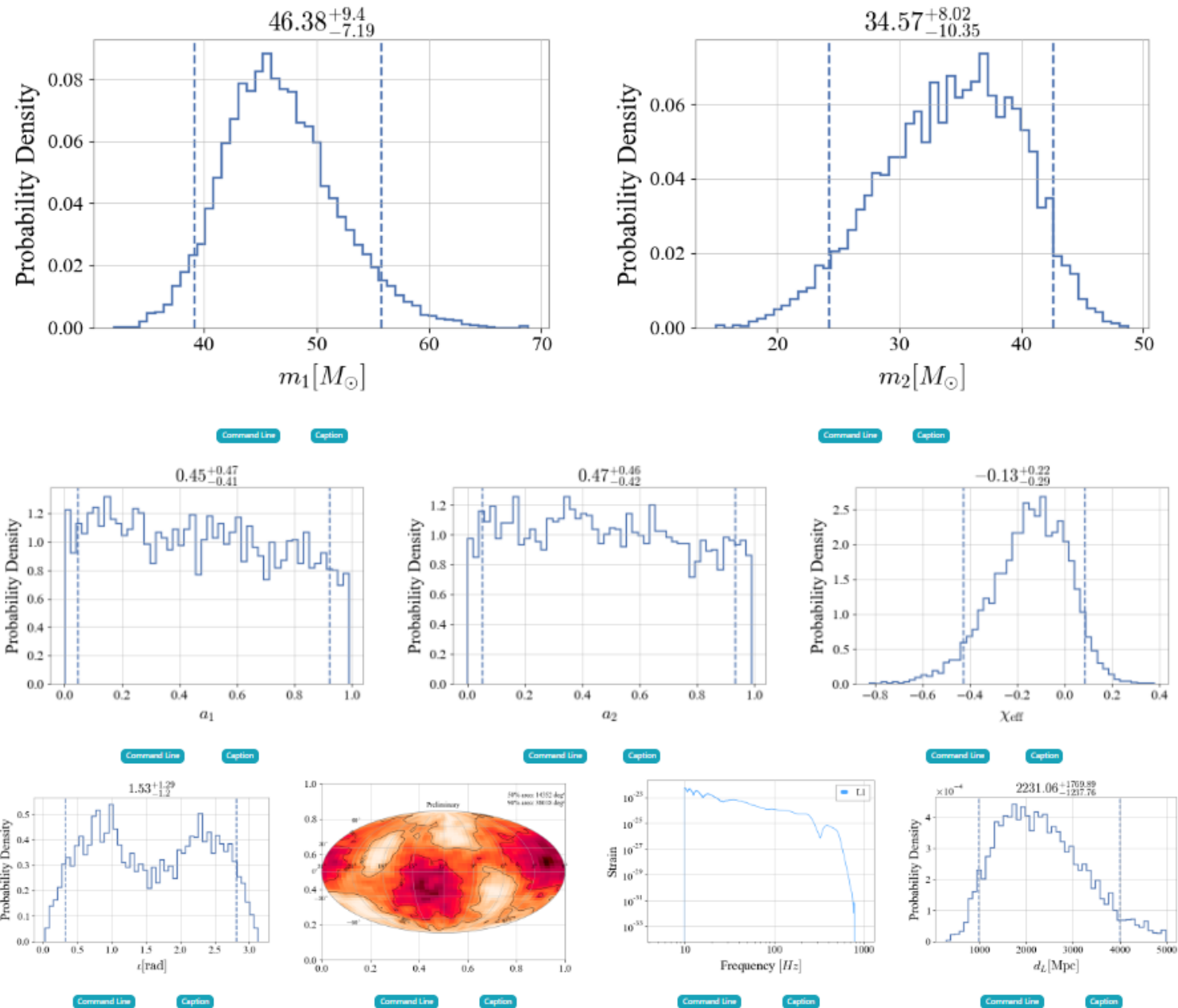
Data Analysis

Merge Results

Post Process

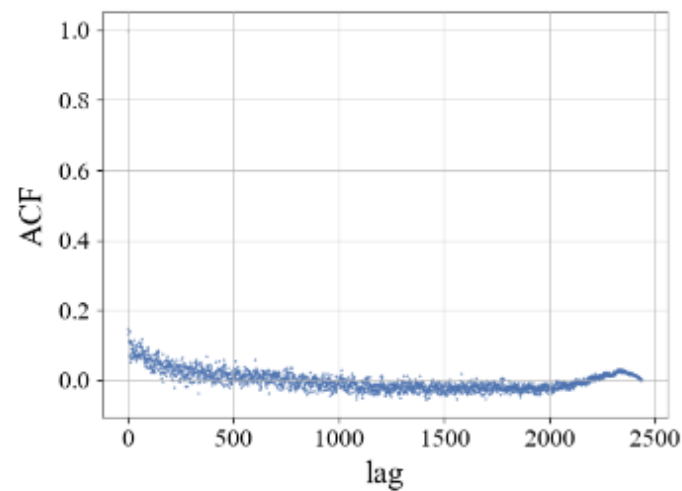
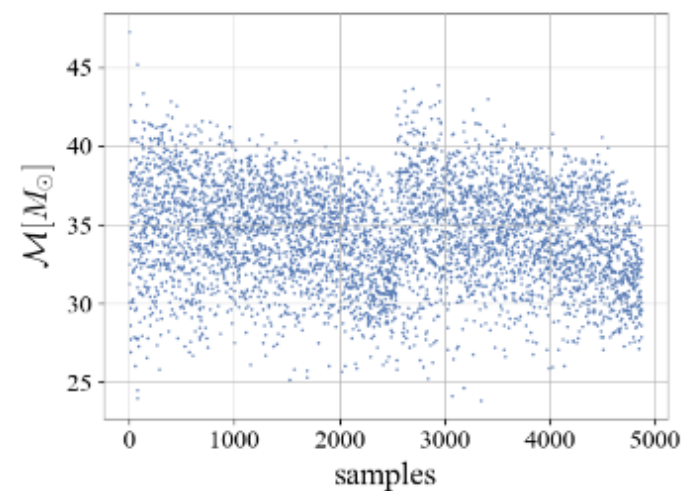
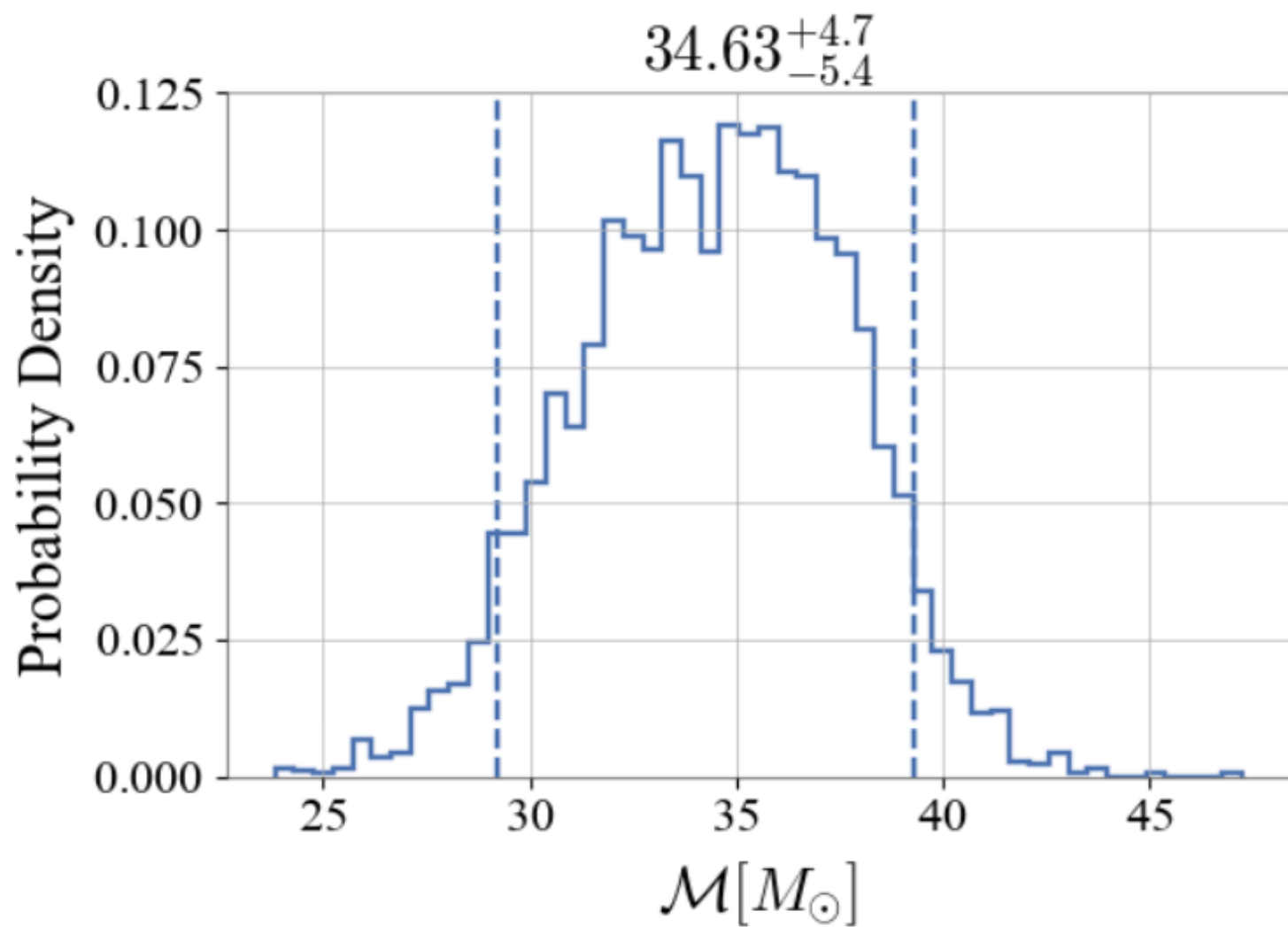
The figures below show the plots for G407786_Online_Ecc





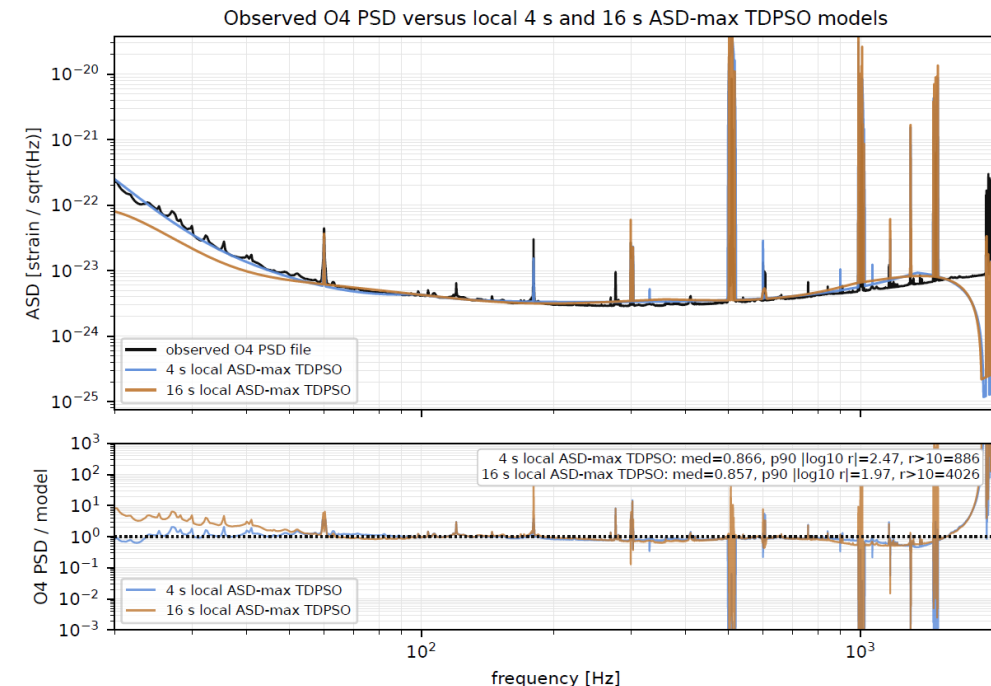
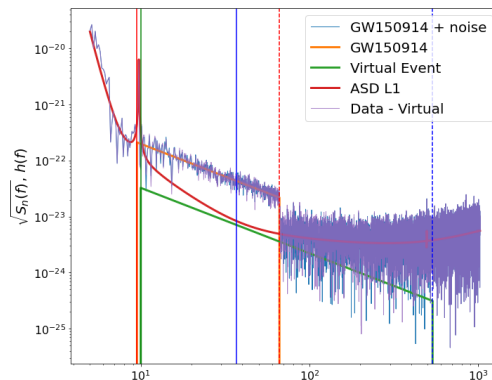
chirp_mass

The figures below show the summary plots for the run



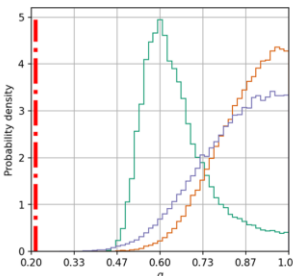
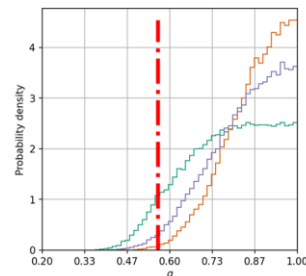
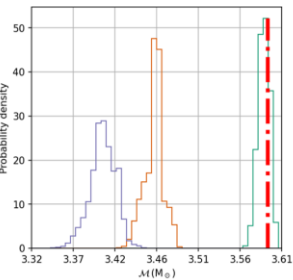
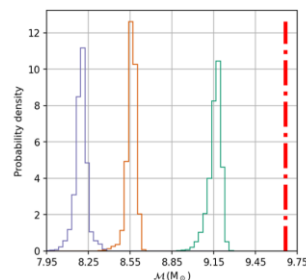
Current interests

- Eccentricity measurement
- Finite Size effect for Data analysis
- Overlap of Gravitational Waves
- Mitigation of detector noise

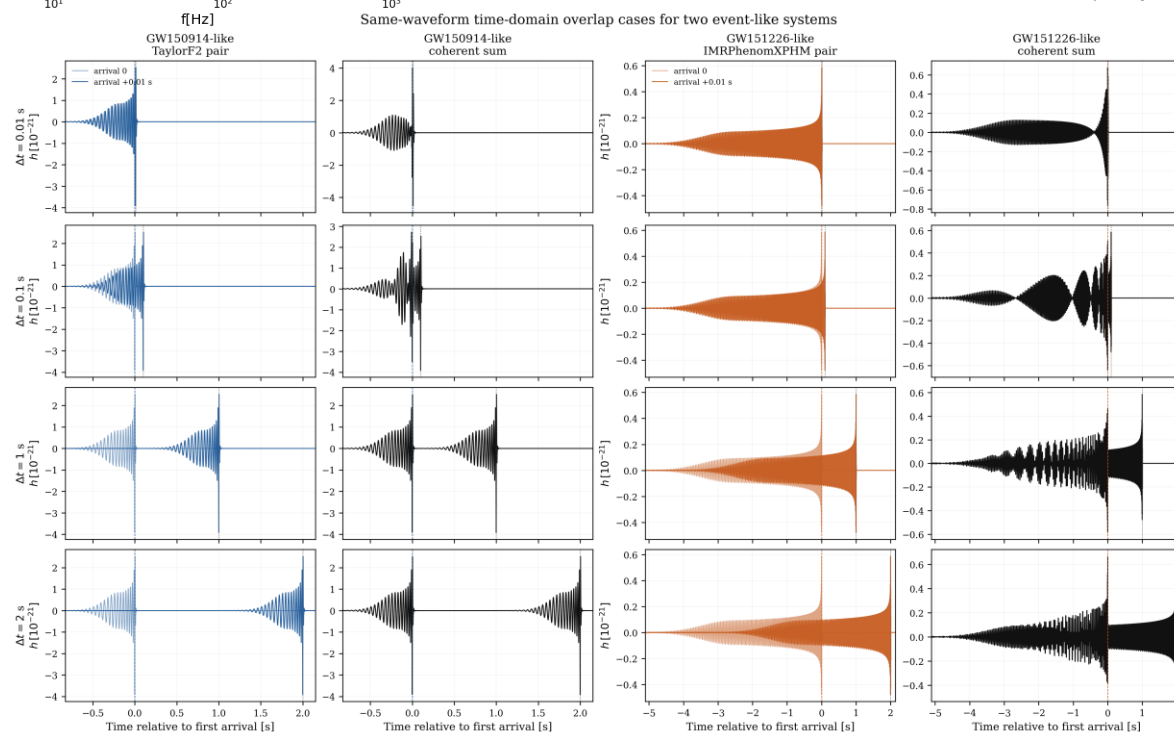


GW151226 (BBH, total mass=23.32 M_{sun})

GW200105 (NSBH, total mass=11.45 M_{sun})



2026-07-28



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맺음말

중력과 관측은 매우
어려운 일이다

중력과 관측을 통하여
다양한 물리를 할 수
있다

중력파

중력과 관측을 위해서는
종합적인 물리,
공학기술이 필요하다

중력과 물리학의 미래를
위해서 여러분이
필요하다

질문

감사합니다