중력파 CBC Search/PE

인제대학교 이형원

2024 수치상대론 및 중력파 여름학교

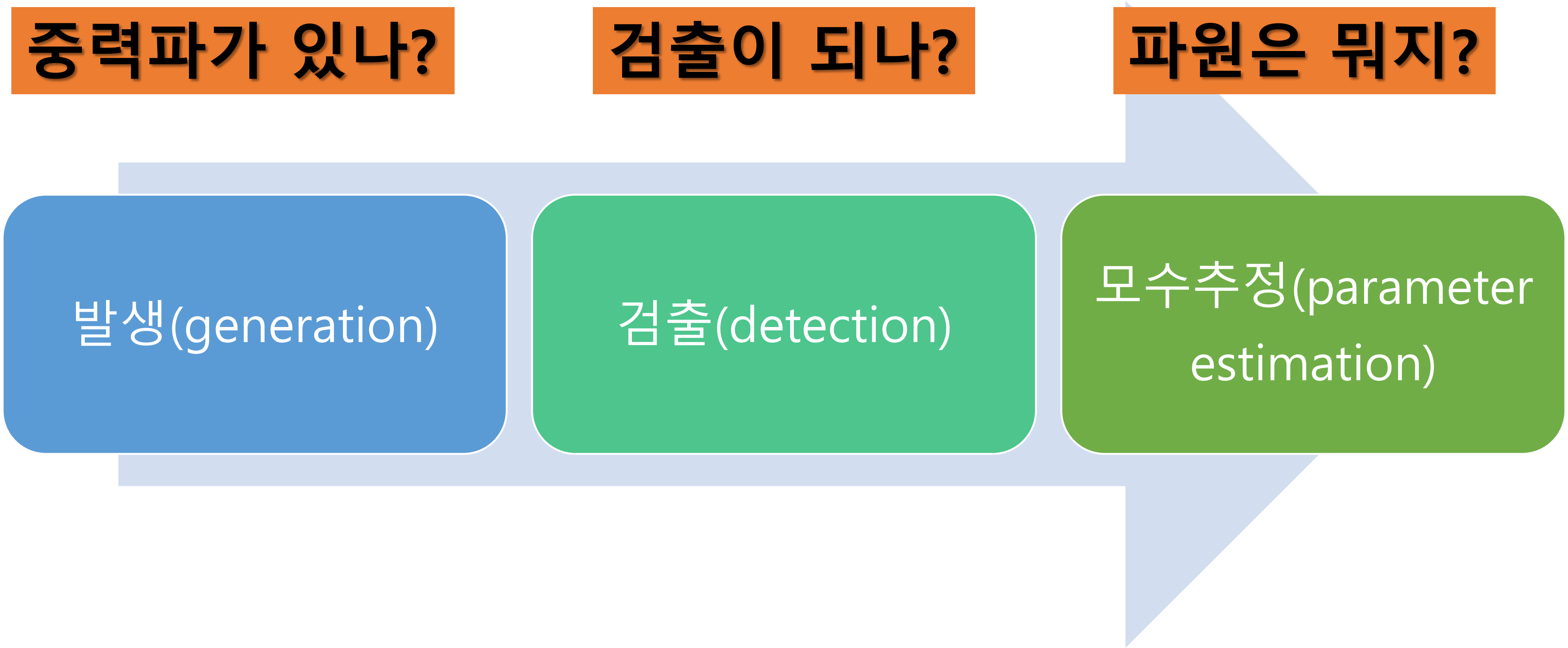
2024년 7월 31일

목차

- CBC Search
  - 중력파
  - 중력파 검출
  - 중력파 자료 생성 과정
  - 검출 Pipeline
- CBC Parameter Estimation
  - 모수추정
  - LALInference
  - Bilby
  - PESummary
- 맺음 말

큰 그림

중력파 실험이란?
(what is gravitational wave experiment)



강의진행

7월 29일 (월)

12:30 ~ 13:20	등록		
13:20 ~ 13:30	환영사		
13:30 ~ 14:20	일반상대론 기초 1	발생	강궁원
14:30 ~ 15:20	일반상대론 기초 2		강궁원
15:20 ~ 16:00	Coffee Break & 휴식		
16:00 ~ 16:50	중력파 기초 1	발생	오정근
17:00 ~ 17:50	중력파 기초 2		오정근

강의진행

7월 30일 (화)

9:30 ~ 10:20	일반상대론 기초 3	발생	강궁원
10:30 ~ 11:20	일반상대론 기초 4		강궁원
11:30 ~ 13:30	점심식사		
13:30 ~ 14:20	3+1 형식화 1	발생	현영환
14:30 ~ 15:20	3+1 형식화 2		현영환
15:20 ~ 16:00	Coffee Break & 휴식		
16:00 ~ 16:50	중력파 데이터 분석을 위한 수리통계학	검출	김영민
17:00 ~ 17:50	DQ impact on GW search		김영민

강의진행

7월 31일 (수)

9:30 ~ 10:20	수치해석기초 1	발생	임록택
10:30 ~ 11:20	수치해석기초 2		임록택
11:30 ~ 13:30	점심식사		
13:30 ~ 14:20	중력파 - CBC 1: Search	검출/모수추정	이형원
14:30 ~ 15:20	중력파 - CBC 1: PE		이형원
15:20 ~ 16:00	Coffee Break & 휴식		
16:00 ~ 16:50	중력파 검출기 1	검출	박준규
17:00 ~ 17:50	중력파 검출기 2		박준규

강의진행

8월 1일 (목)

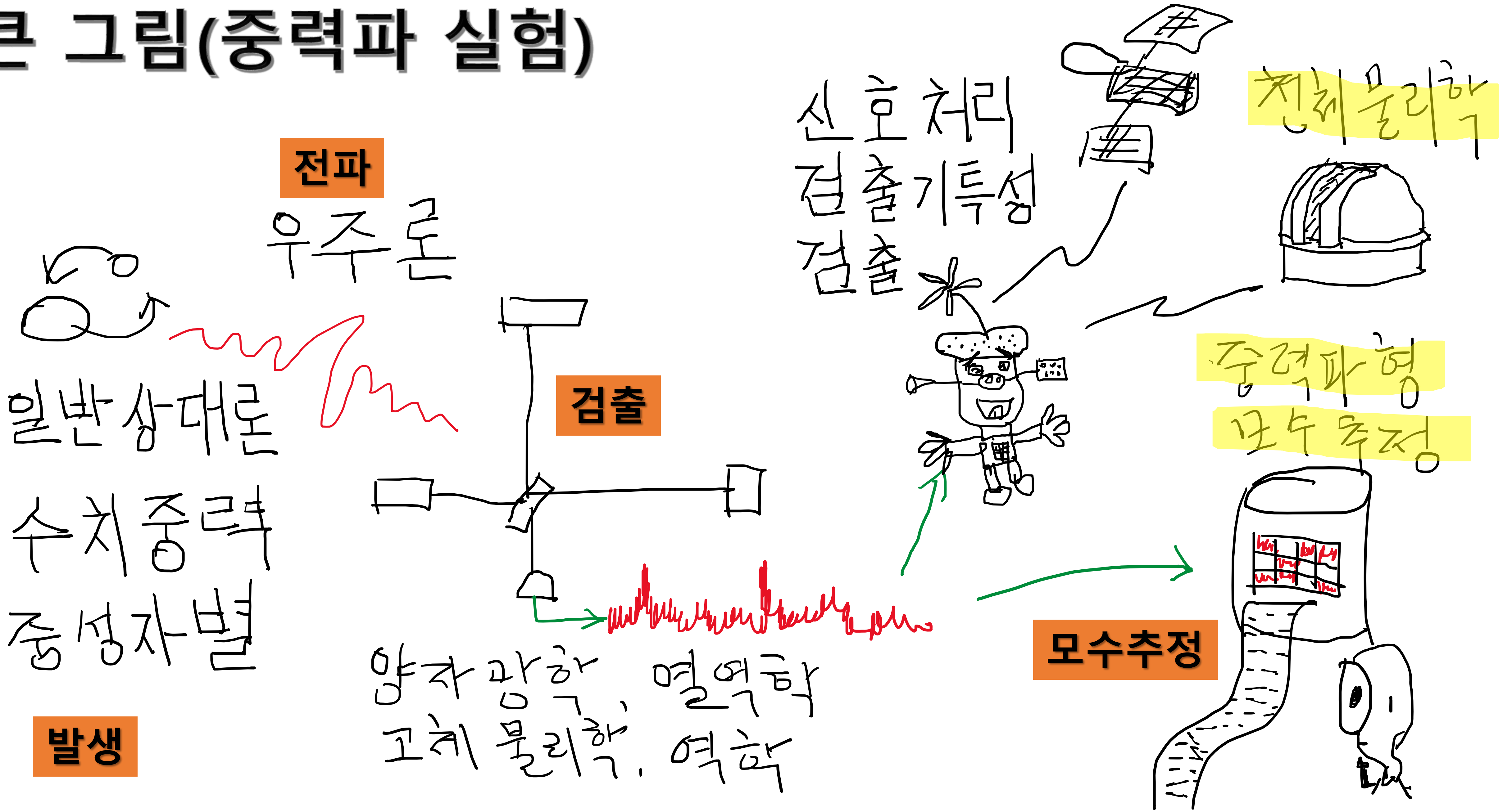
9:30 ~ 10:20	중력파 렌징	중력렌즈 효과	김경민
10:30 ~ 11:20	블랙홀 쌍성의 형성과 진화	중력파원/천문학	배영복
11:30 ~ 13:30	점심식사		
13:30 ~ 14:20	다중신호천문학 1	천문학	김정리
14:30 ~ 15:20	다중신호천문학 2		김정리
15:20 ~ 16:00	Coffee Break & 휴식		
16:00 ~ 16:50	중성자별과 상대론적 유체역학	중성자별	김진호
17:00 ~ 17:50	ODW session		

강의진행

8월 2일 (금)

9:30 ~ 10:20	중력파 Stochastic Background	검출/자료처리	정동희
10:30 ~ 11:20	중력파 우주론	우주론	이형목
11:50 ~ 12:00	폐회사		

큰 그림(중력파 실험)


전파
우주론
일반상대론
수치중력
중성자별
발생
검출
양자광학, 열역학
고체물리학, 역학
신호처리
검출기특성
검출
천체물리학
중력파형
모수추정
모수추정

중력파 발생

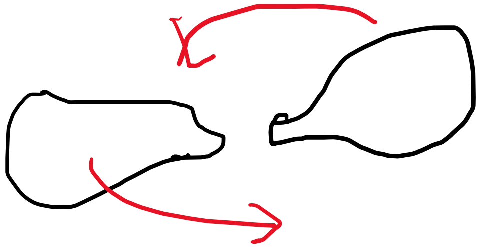
- 아인스타인 방정식
- 선형근사
- 포스트뉴터니안 근사
- 수치중력
- 중성자별 상태 방정식

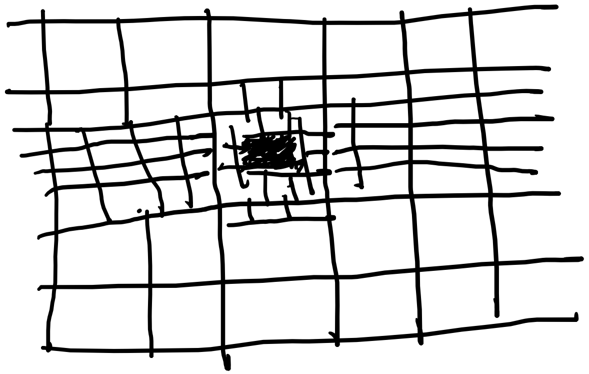
1916

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

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

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





우주론

아인슈타인방정식과 블랙홀

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

FRW 계량

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

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

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

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

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

$$\approx \frac{1}{d_L}\left((1+z)M\right)^{5/6} f^{-\frac{7}{6}} e^{i\Psi(f)}$$

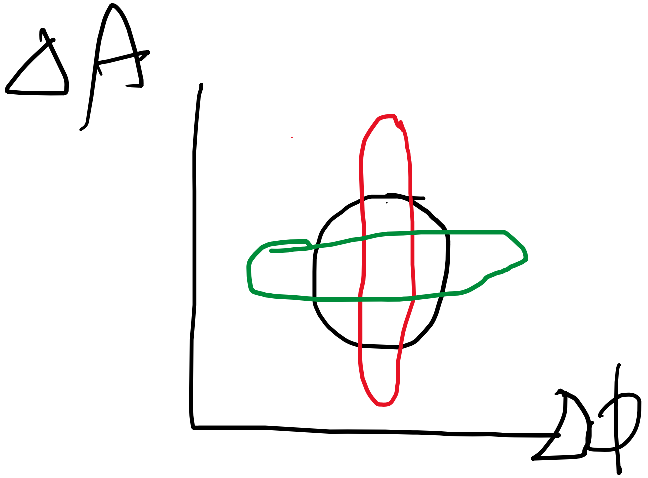
$(1+z)M \to M_{det}$, $f \to f_{obs}$

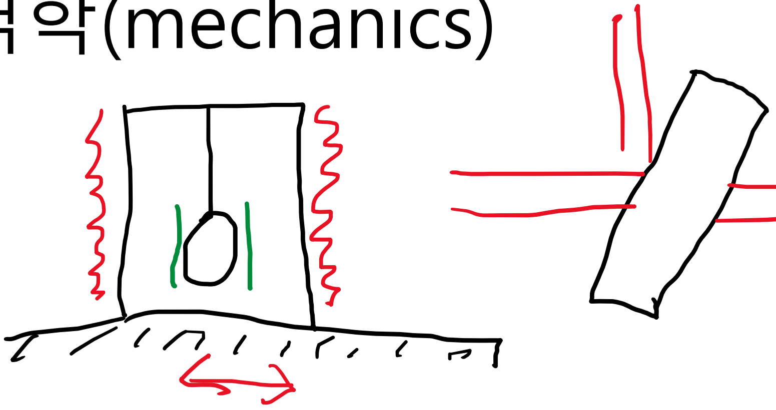
$$H^2 = \frac{8\pi G}{3}\rho$$

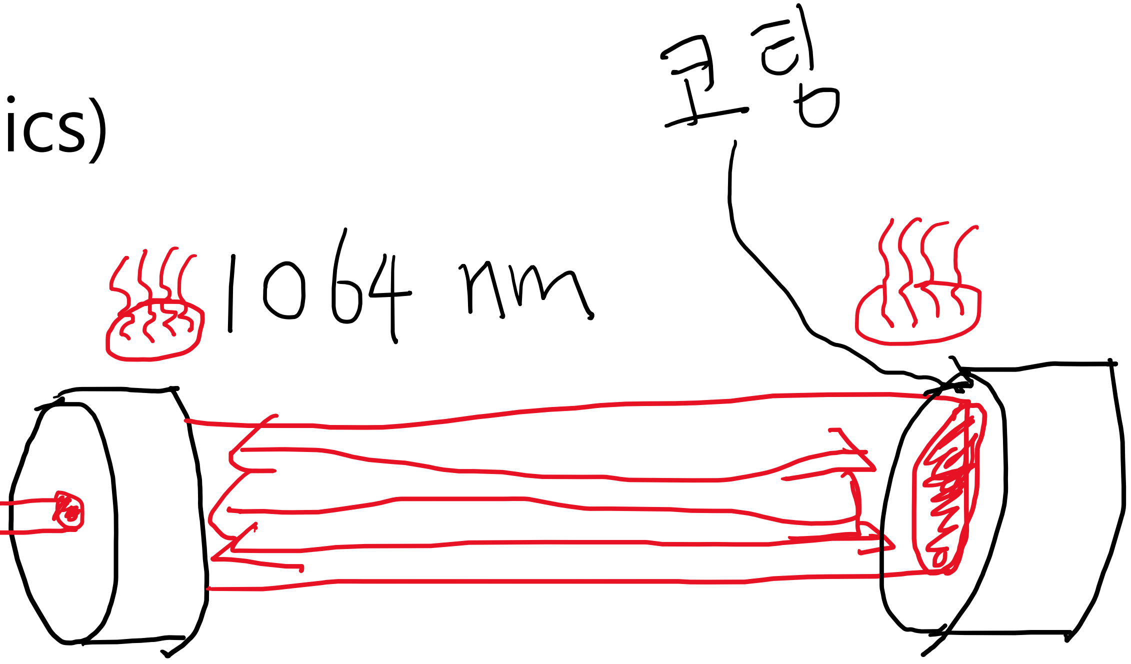
$$f_{src} = (1+z) f_{obs}$$

검출기

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



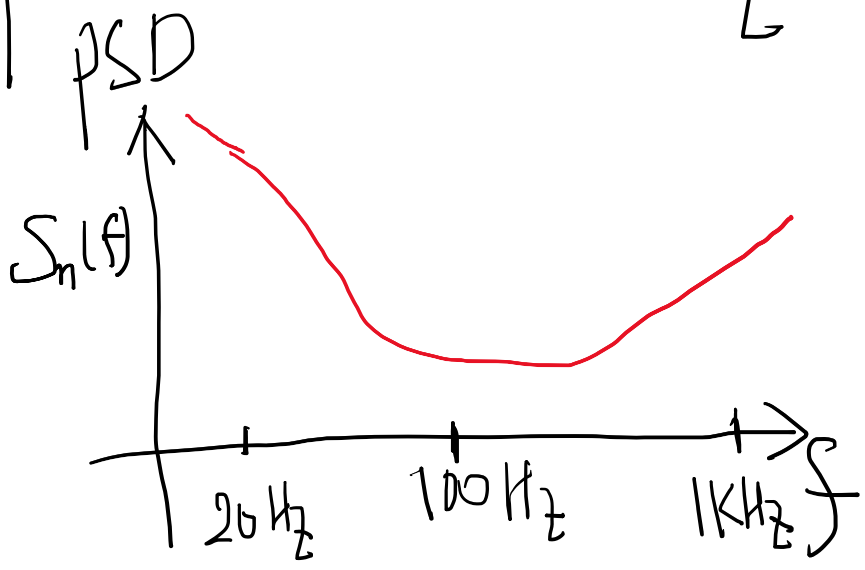


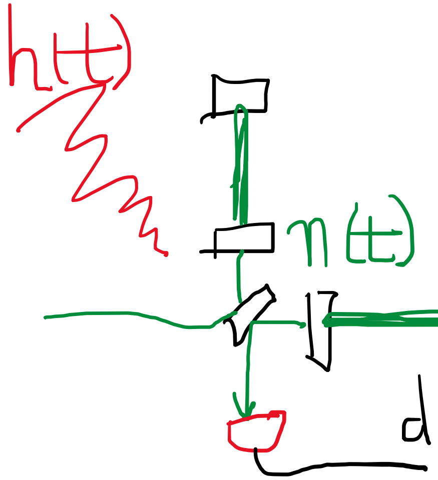


신호처리

중력파 신호탐색

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





$$\Lambda(H_1|s) = e^{(s,h)-\frac{1}{2}(h,h)}$$

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

$$d(t) = n(t) + h(t) \qquad \sigma^2 = (g,g)$$

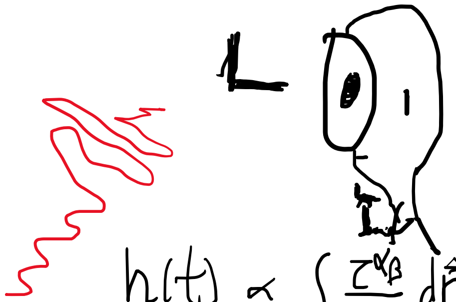
$$\rho^2 = (h,h), \quad \rho = \frac{x}{\sigma}$$ template

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

모수추정(Parameter Estimation)

중력파 데이터 분석

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



$$h(t) \propto \int \frac{\tau^{\alpha\beta}}{r} d\hat{r} \sim \frac{\ddot{I}}{r}$$

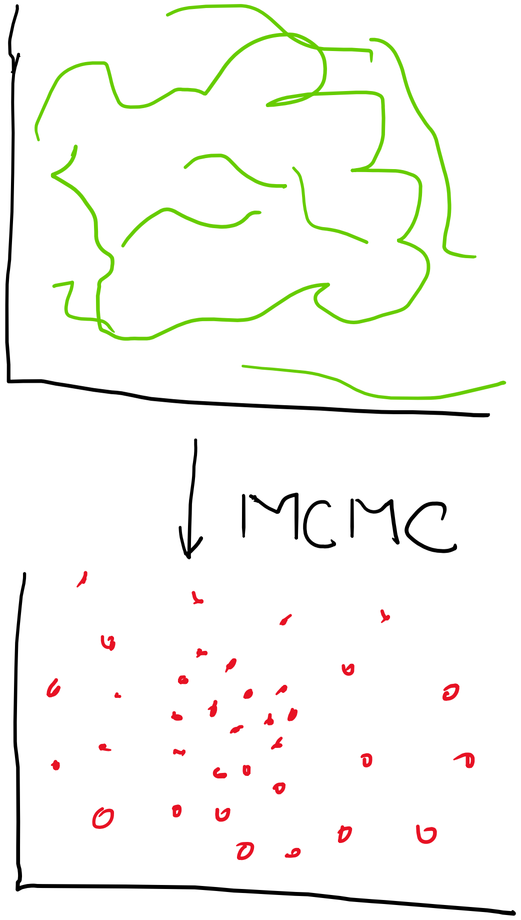
↓FFT

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

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

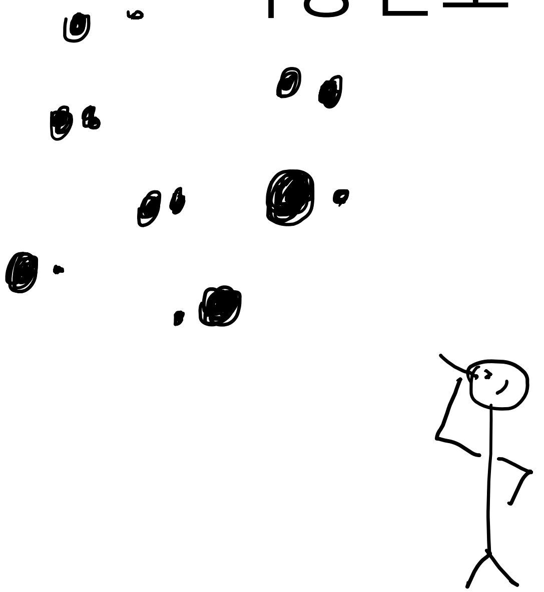
$$\mathcal{L} \sim e^{-\frac{1}{2}(d-h,\, d-h)}$$

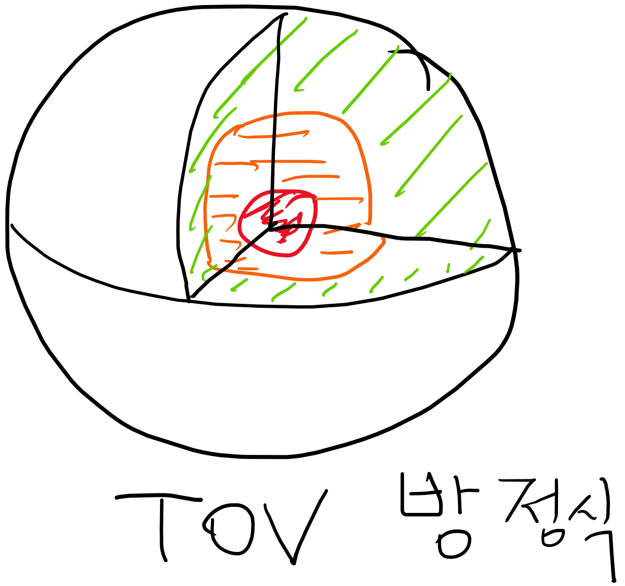
$$p(\vec{\theta}\,|\,\vec{d}) \sim \mathcal{L}(\vec{d}\,|\,\vec{\theta})\, p(\vec{\theta})$$

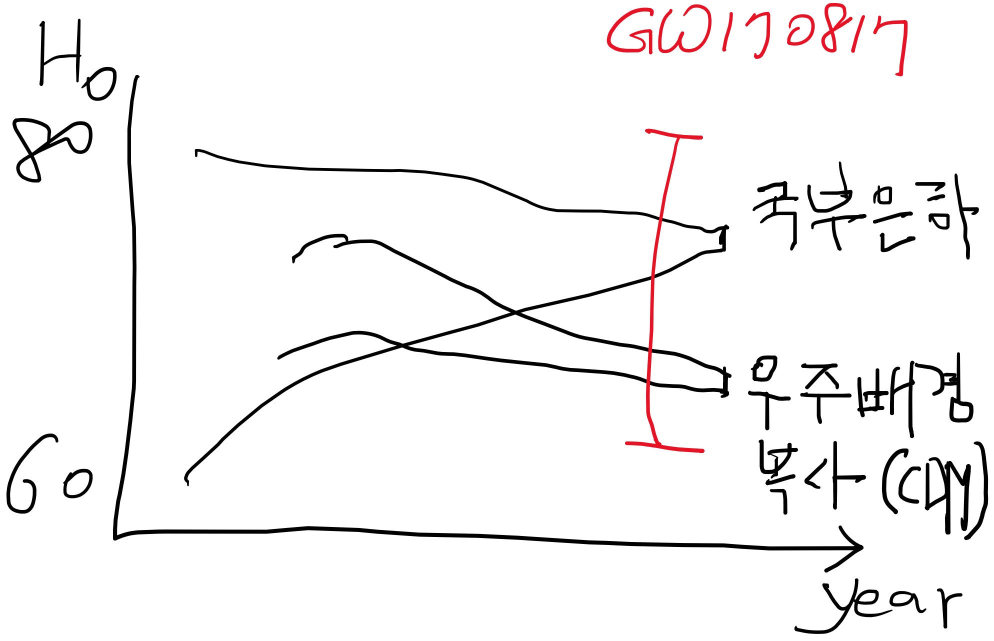


천체물리학(Astrophysics)

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



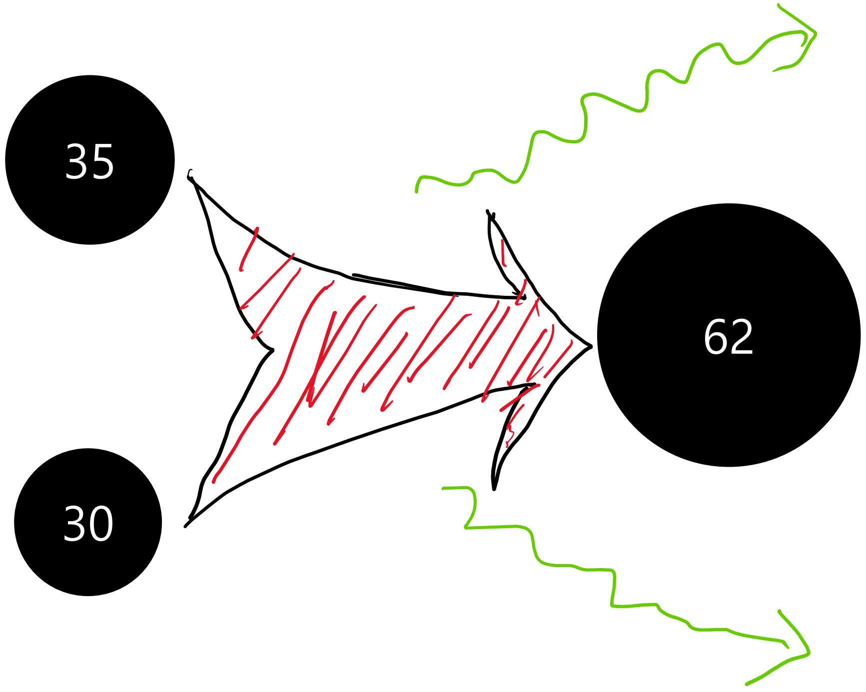


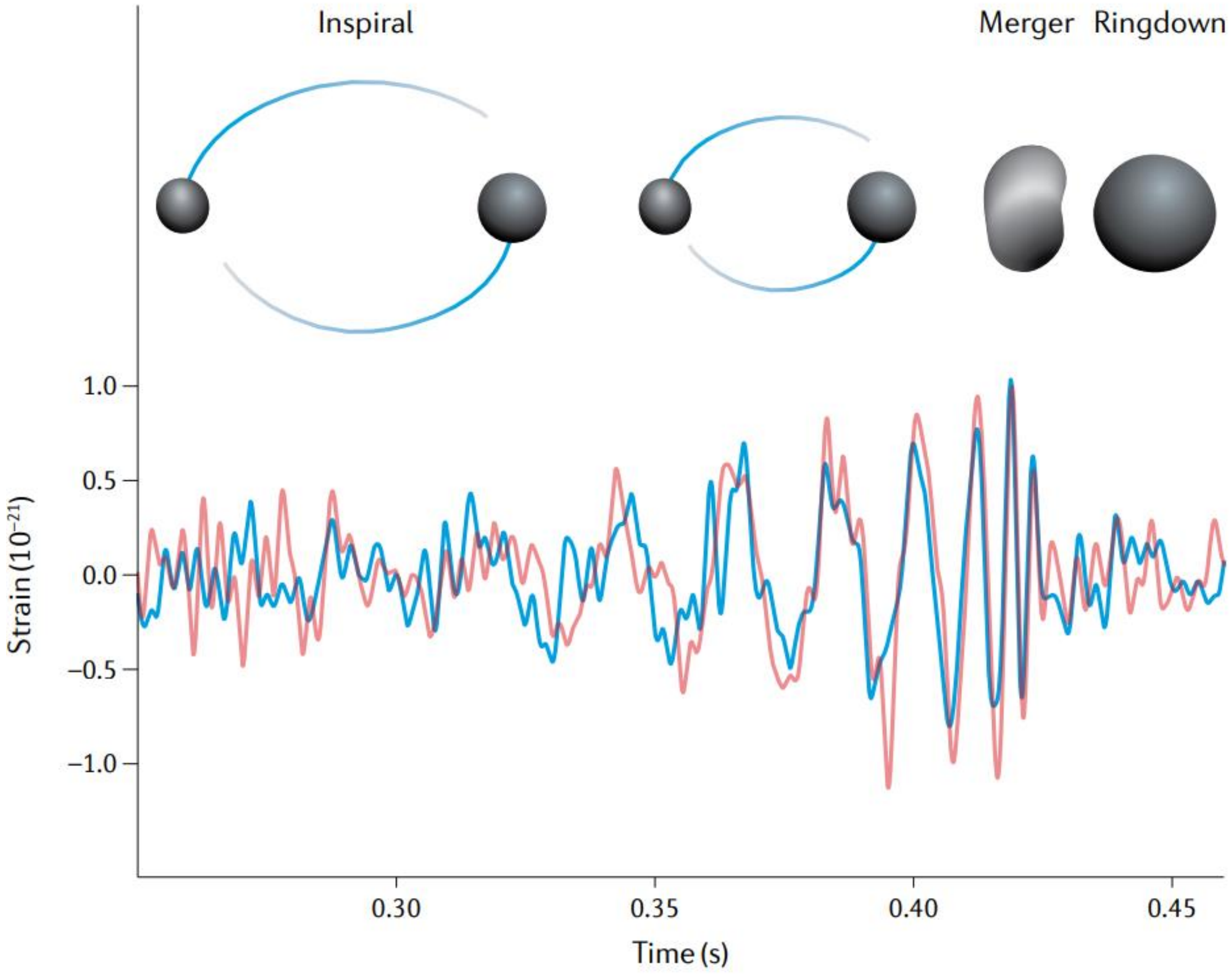


CBC Search

중력파

GW150914





Waveform PhysRevD.85.122006

- $h(t) = -\left(\frac{G\mathcal{M}}{c^2 D_{eff}}\right)\left(\frac{t_0-t}{5G\mathcal{M}/c^3}\right)^{-1/4} \cos[2\phi_0 + 2\phi(t-t_0; M,\mu)]$
- $D_{eff} = D\left[F_+^2\left(\frac{1+\cos^2\iota}{2}\right)^2 + F_\times^2 \sin^2\iota\right]^{-1/2}$
- $2\phi_0 = 2\phi_c - \mathrm{Tan}^{-1}\left(\frac{F_\times}{F_+}\frac{2\cos\iota}{1+\cos^2\iota}\right)$
- $\tilde{h}(f) = -\left(\frac{5\pi}{24}\right)^{\frac{1}{2}}\left(\frac{G\mathcal{M}}{c^3}\right)\left(\frac{G\mathcal{M}}{c^2 D_{eff}}\right)\left(\frac{G\mathcal{M}}{c^3}\pi f\right)^{-\frac{7}{6}} e^{-i\Psi(f;M,\mu)}$

$$= \left(\frac{1\mathrm{Mpc}}{D_{eff}}\right) A_{1\mathrm{Mpc}}(M,\mu) f^{-7/6} e^{-i\Psi(f;M,\mu)}$$

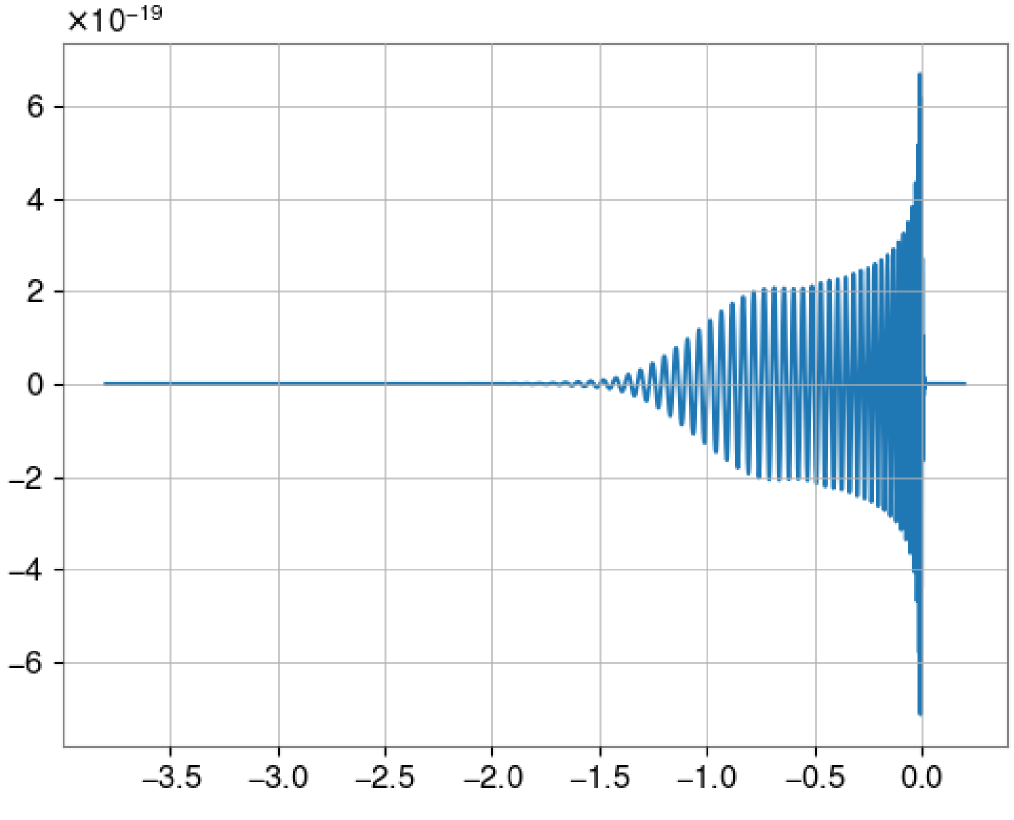
$$\mathcal{A}_{1\ \mathrm{Mpc}}(M,\mu) = -\left(\frac{5}{24\pi}\right)^{1/2}\left(\frac{GM_\odot/c^2}{1\ \mathrm{Mpc}}\right)\left(\frac{\pi G M_\odot}{c^3}\right)^{-1/6}\left(\frac{\mathcal{M}}{M_\odot}\right)^{5/6},$$

$$\Psi(f;M,\mu) = 2\pi f t_0 - 2\phi_0 - \pi/4 + \frac{3}{128\eta}\left[v^{-5} + \left(\frac{3715}{756} + \frac{55}{9}\eta\right)v^{-3} - 16\pi v^{-2} + \left(\frac{15\,293\,365}{508\,032} + \frac{27\,145}{504}\eta + \frac{3085}{72}\eta^2\right)v^{-1}\right],$$

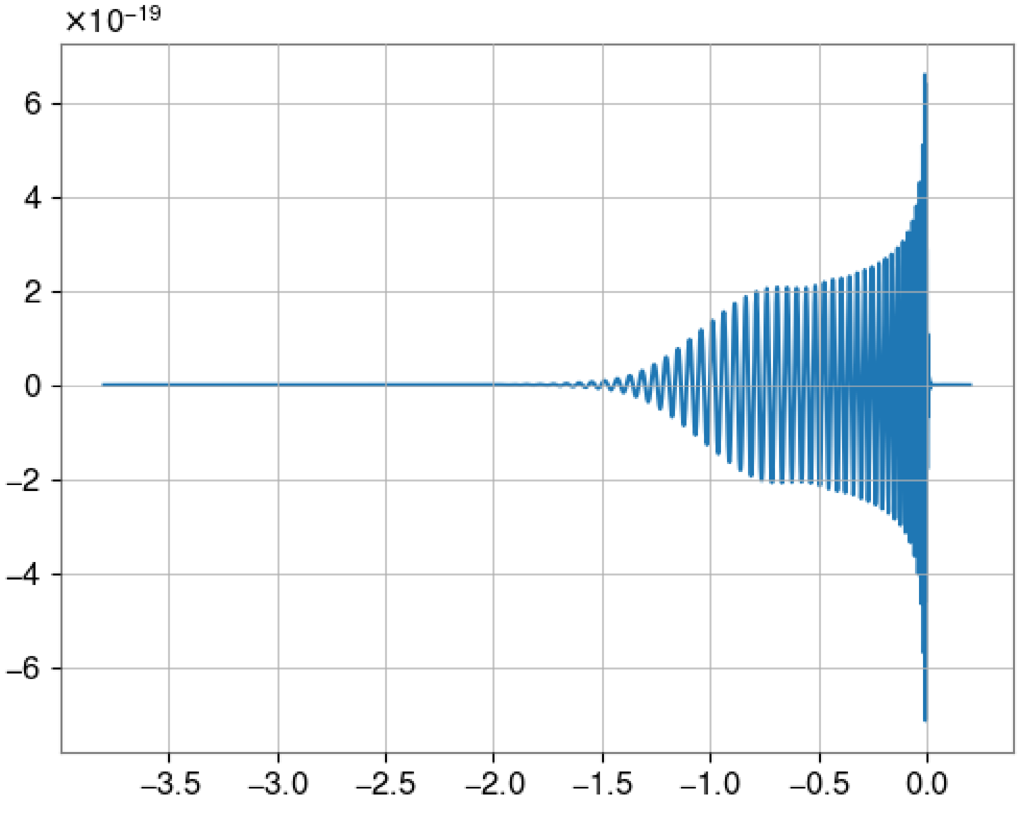
$$v = \left(\frac{GM}{c^3}\pi f\right)^{1/3}$$

파형 예

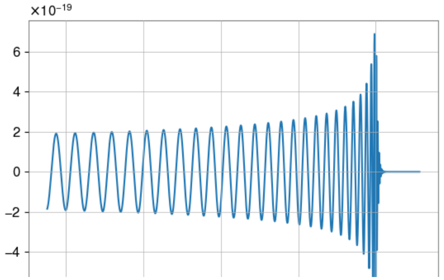
IMRPhenomD(30,30)



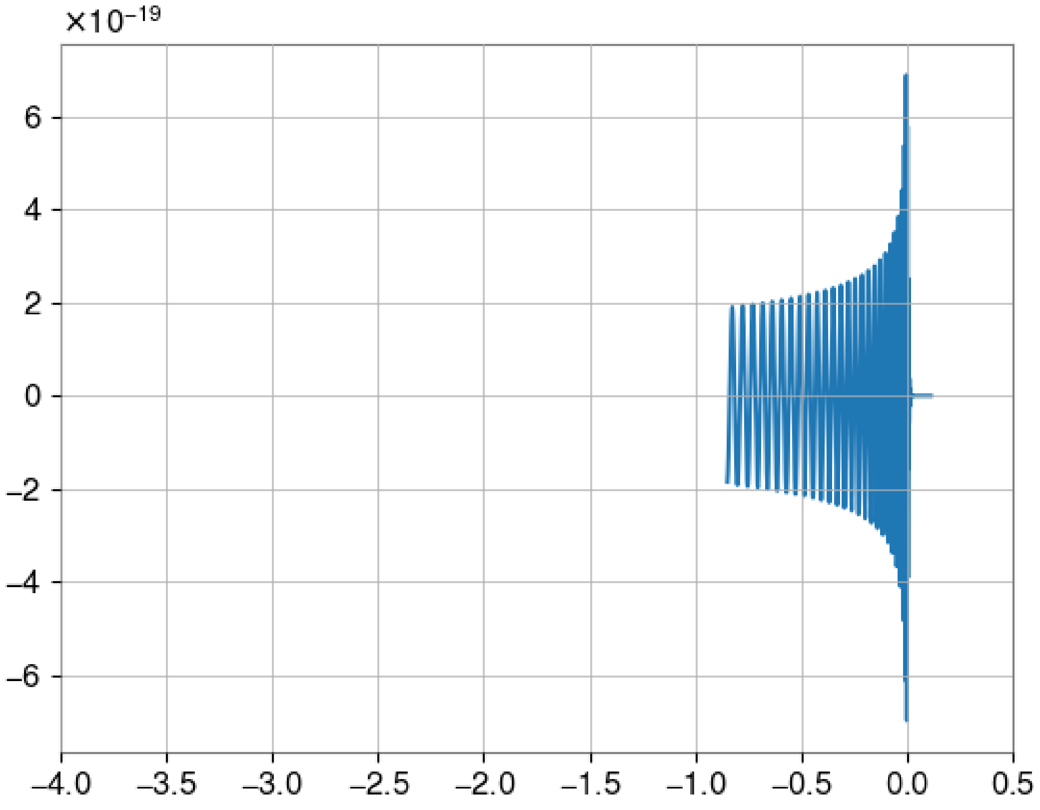
IMRPhenomPv2(30,30)



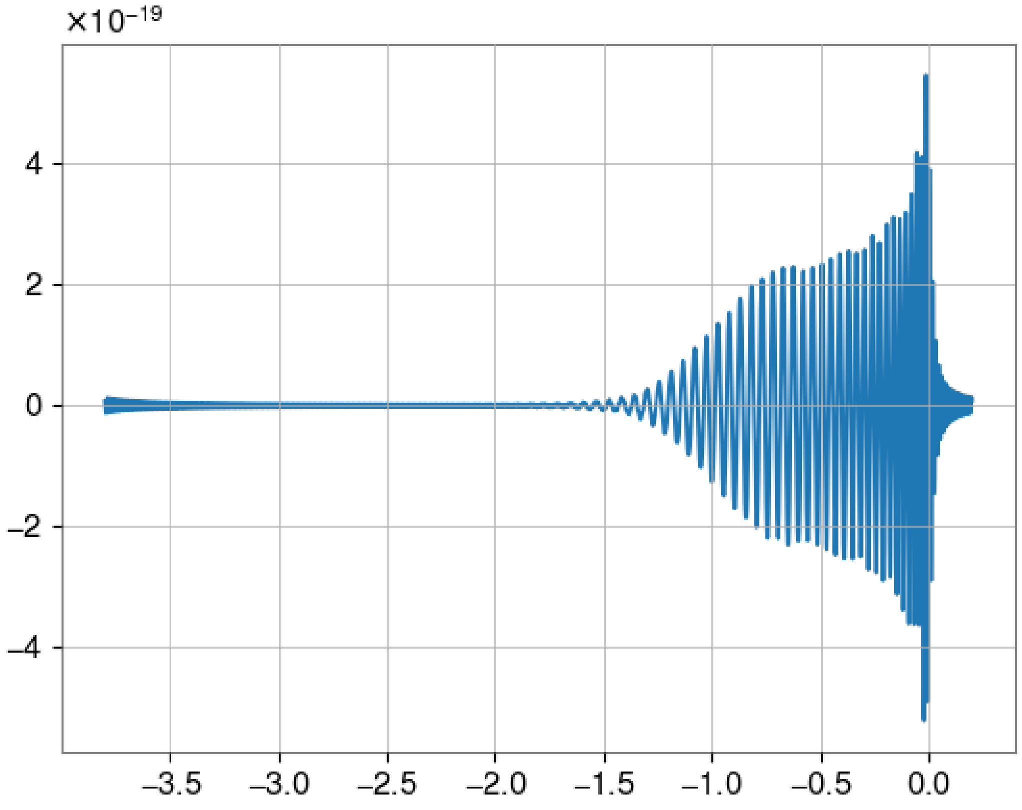
파형 예



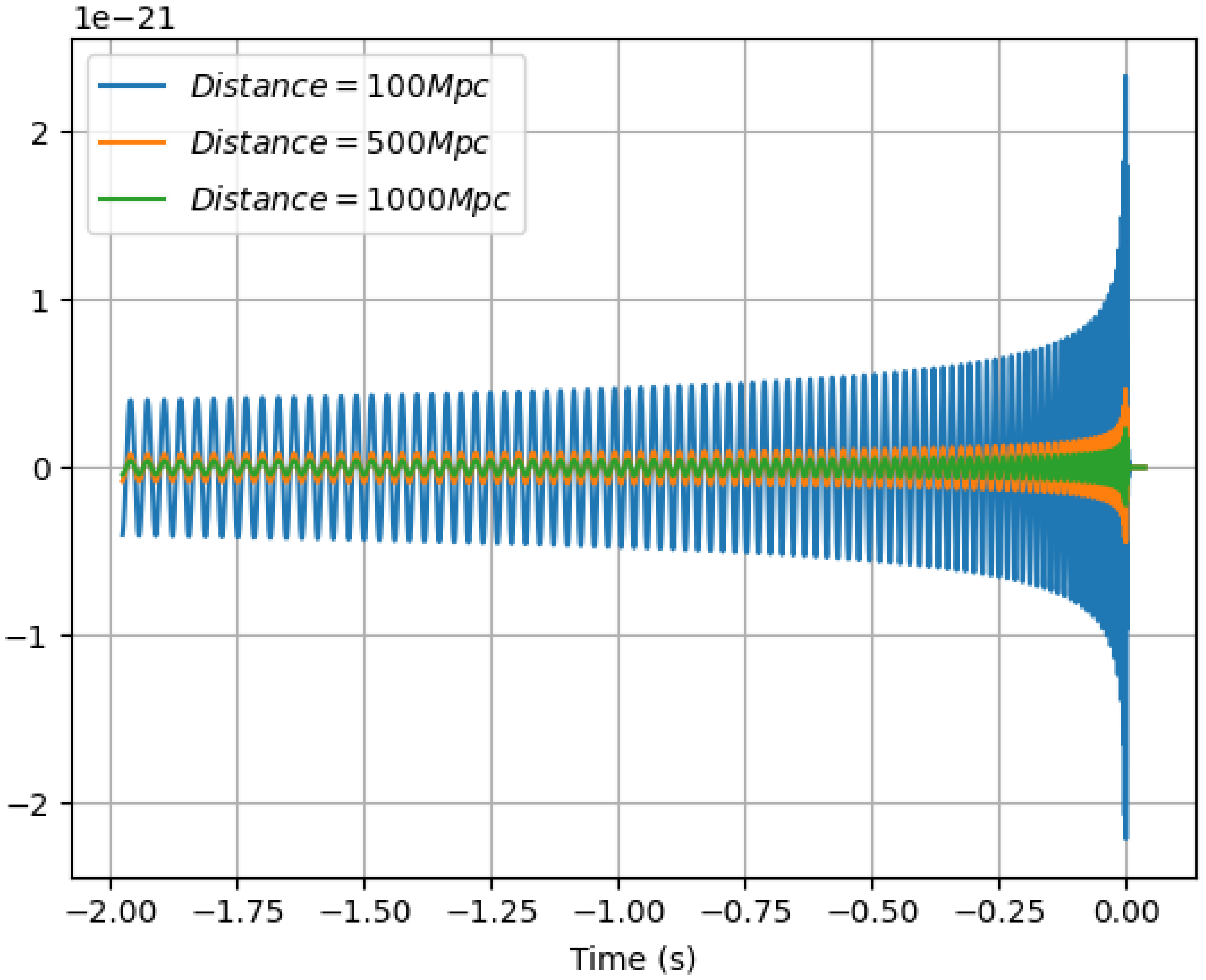
SEOBNRv4(30,30)



TaylorF2(30,30)

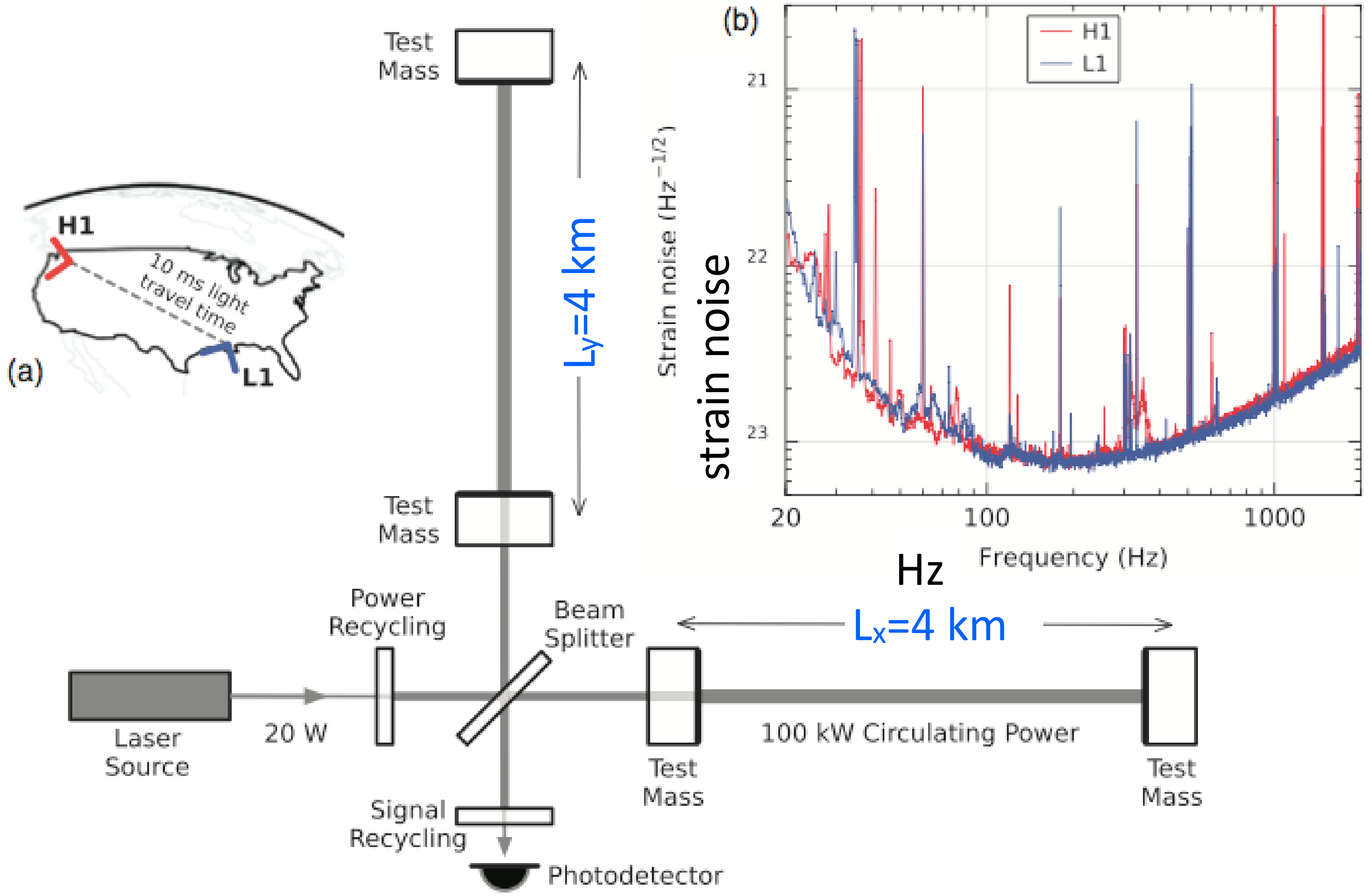


SEOBNRv4_opt



PRL 116, 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

중력파 검출



$$\Delta L(t) = \delta L_x - \delta L_y = h(t)L$$

~ 10^{-21} x 4000 m

~ 10^{-15} m

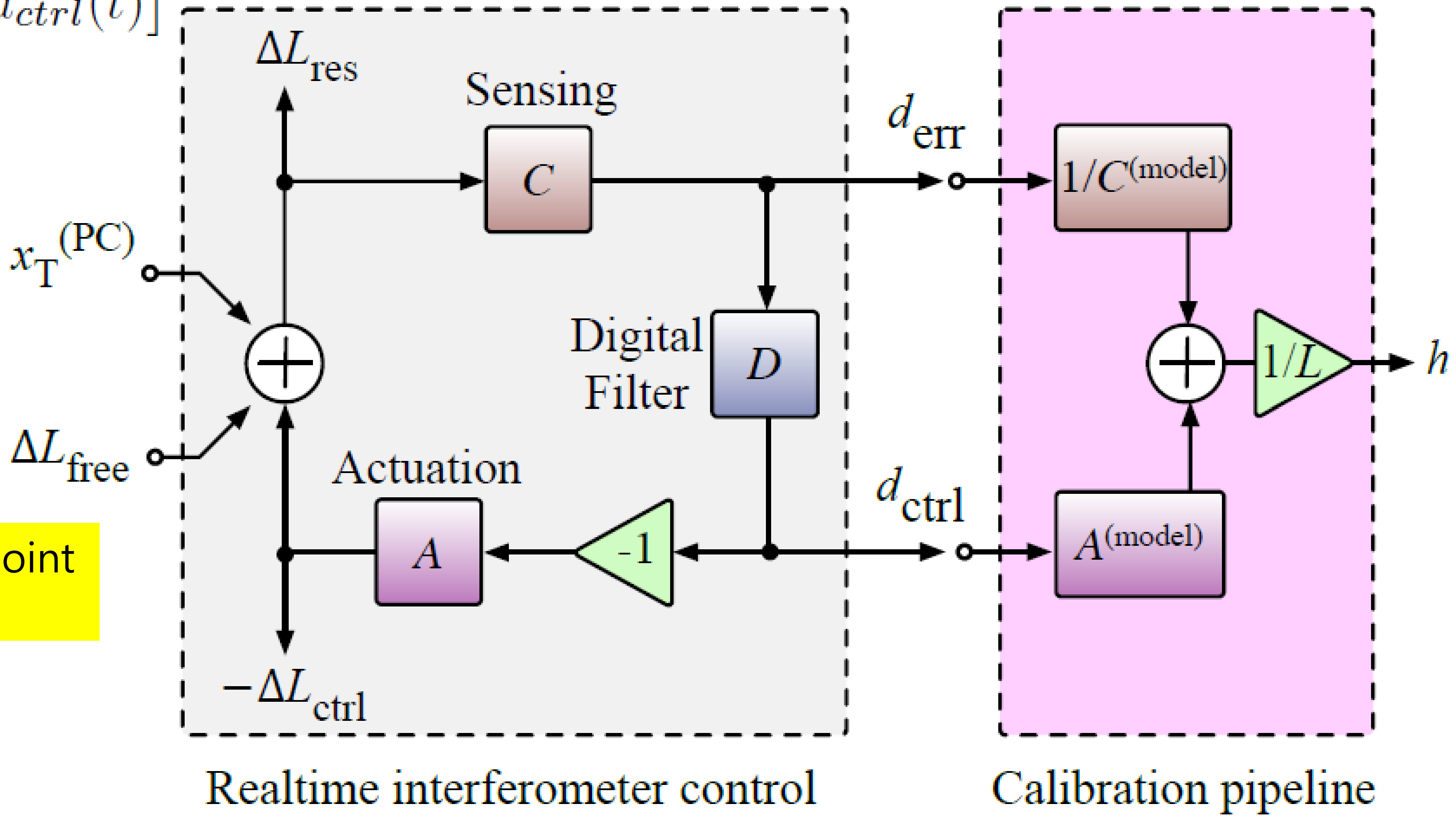
Generation of h(t)

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

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

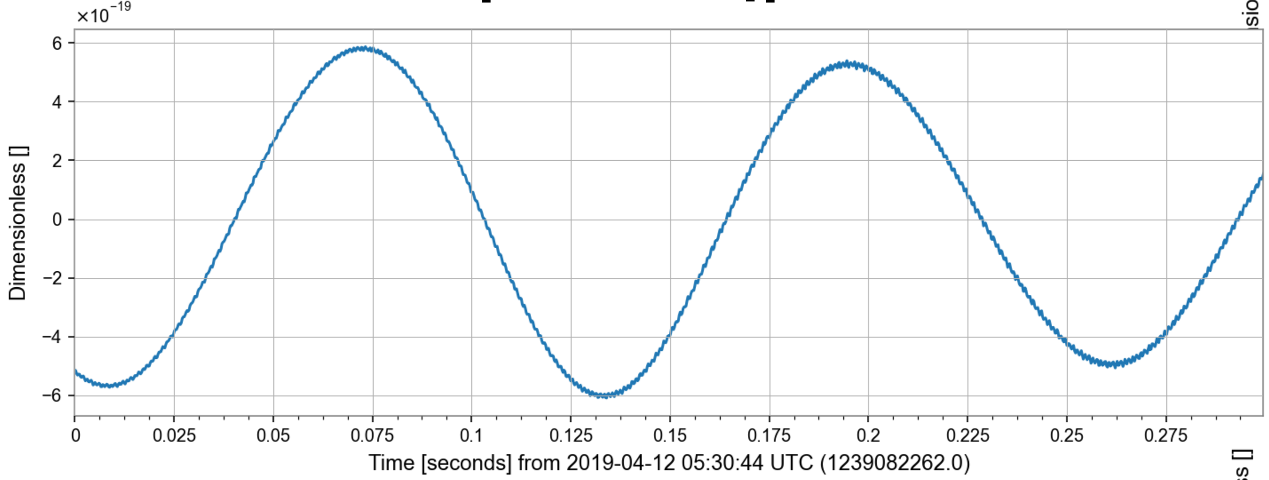
$$d_{err} = \mathcal{C}(\Delta L_{free} + x_T - \mathcal{A} d_{ctrl})$$

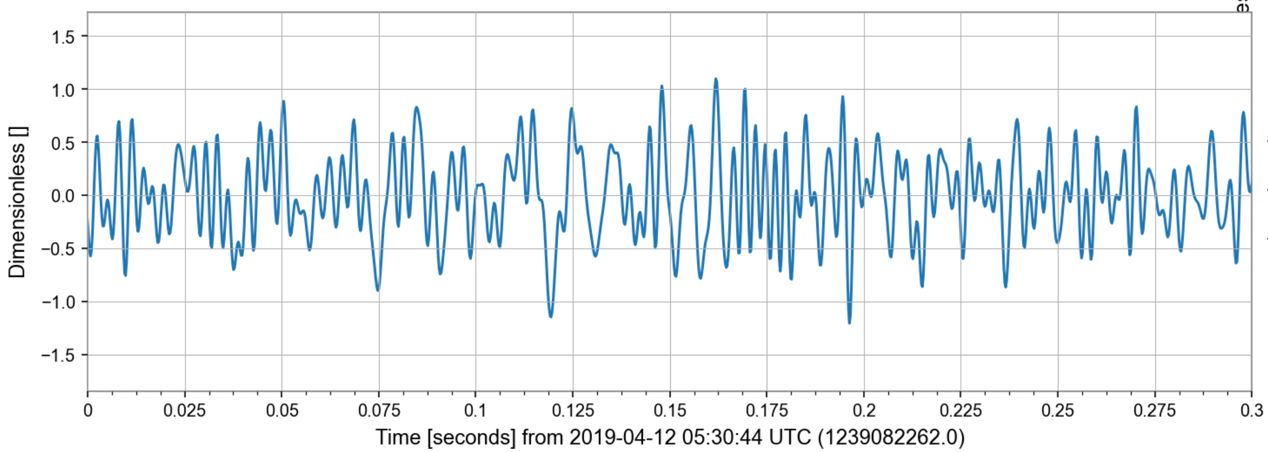
$$\Delta L_{free} = \mathcal{C}^{-1} d_{err} + \mathcal{A} d_{ctrl} - x_T$$

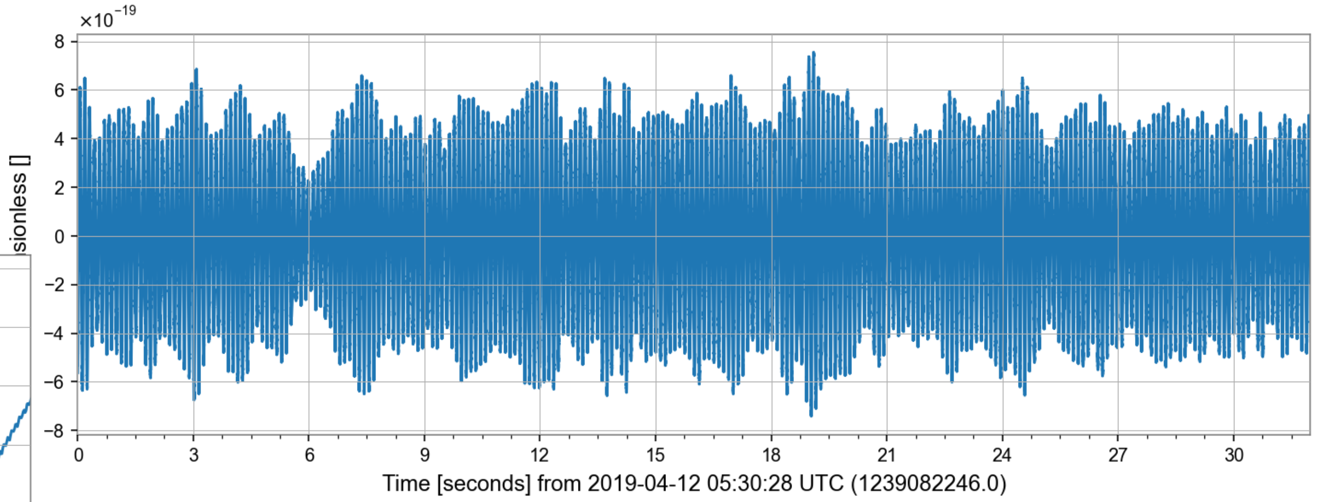


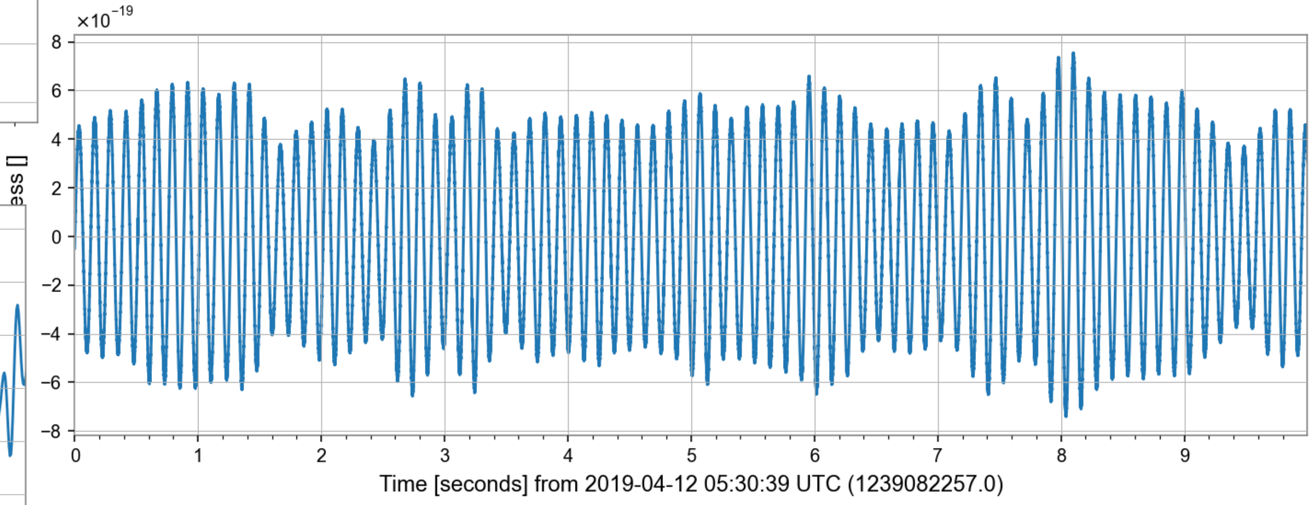
Keep interferometer at "operation" point
No difference appear dark point

LIGO 자료 예



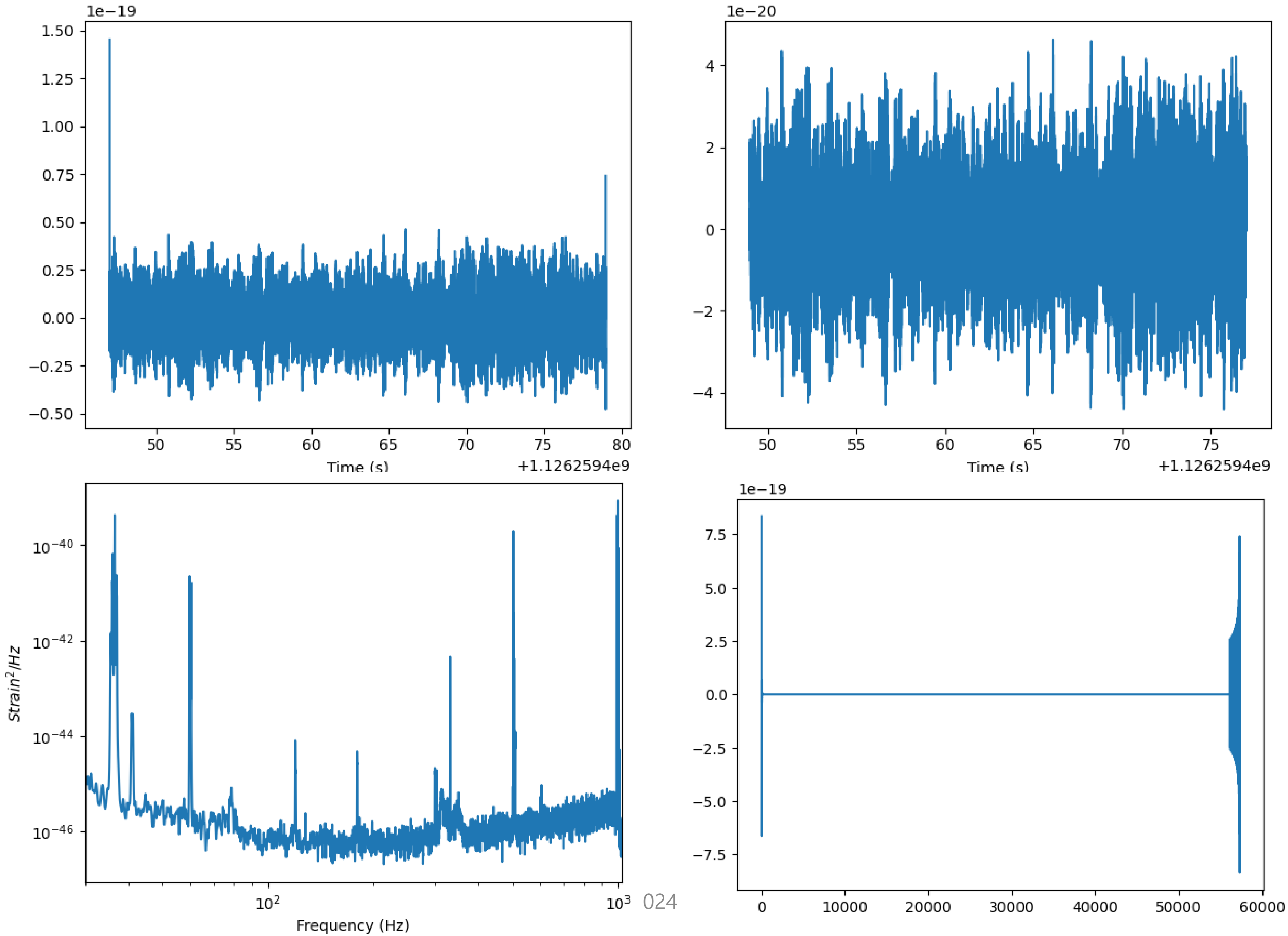






t0 = 1239082262.2

Odw4, GW190412 GWOSC (gw-openscience.org)

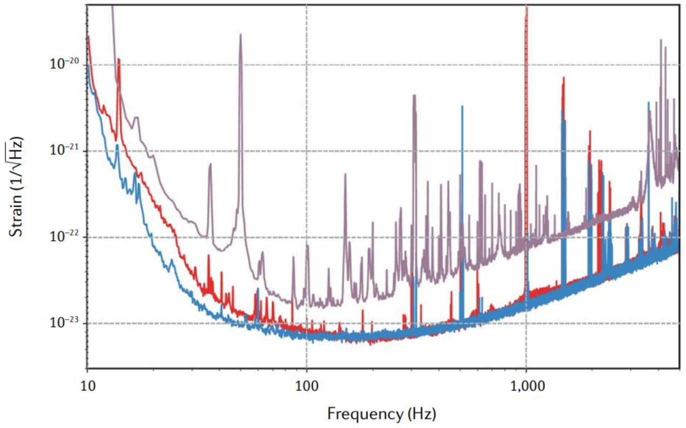

1e−19
1.50
1.25
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
50 55 60 65 70 75 80
Time (s)
+1.1262594e9
1e−20
4
2
0
−2
−4
50 55 60 65 70 75
Time (s)
+1.1262594e9
$Strain^2/Hz$
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^2
10^3
Frequency (Hz)
1e−19
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5
0 10000 20000 30000 40000 50000 60000

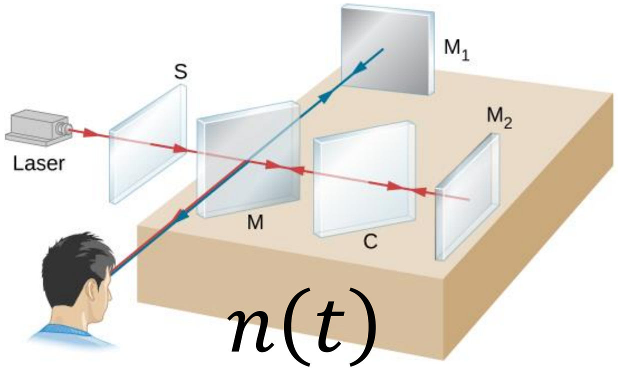
024

Linear Optimal Filter

$h(t)$

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





$n(t)$

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

minimize $\overline{\varepsilon^2}$

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

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

정합필터(Matched Filter) PhysRevD.85.122006

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

1. Template amplitude
2. Coalescence phase
3. Masses

We do not know

$t_0 = 0, \phi_0 = 0$

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

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

정합필터(Matched Filter) PhysRevD.85.122006

- We need template banks to find matched masses

$$\sigma_m^2 = 4 \int_0^\infty \frac{|\tilde{h}_{1\ \mathrm{Mpc},m}(f)|^2}{S_n(f)} df.$$

SNR at 1 Mpc template

- If signal comes from D_{eff} of template waveform m, then
- $s(t) = n(t) + \frac{1\ \mathrm{Mpc}}{D_{eff}} h_{1\mathrm{Mpc},m}(t)$ $\quad \langle z_m(t_0) \rangle = 1\mathrm{Mpc}\, \sigma_m^2 / D_{\mathrm{eff}}$

$$\rho_m(t) = \frac{|z_m(t)|}{\sigma_m}$$

Amplitude of SNR

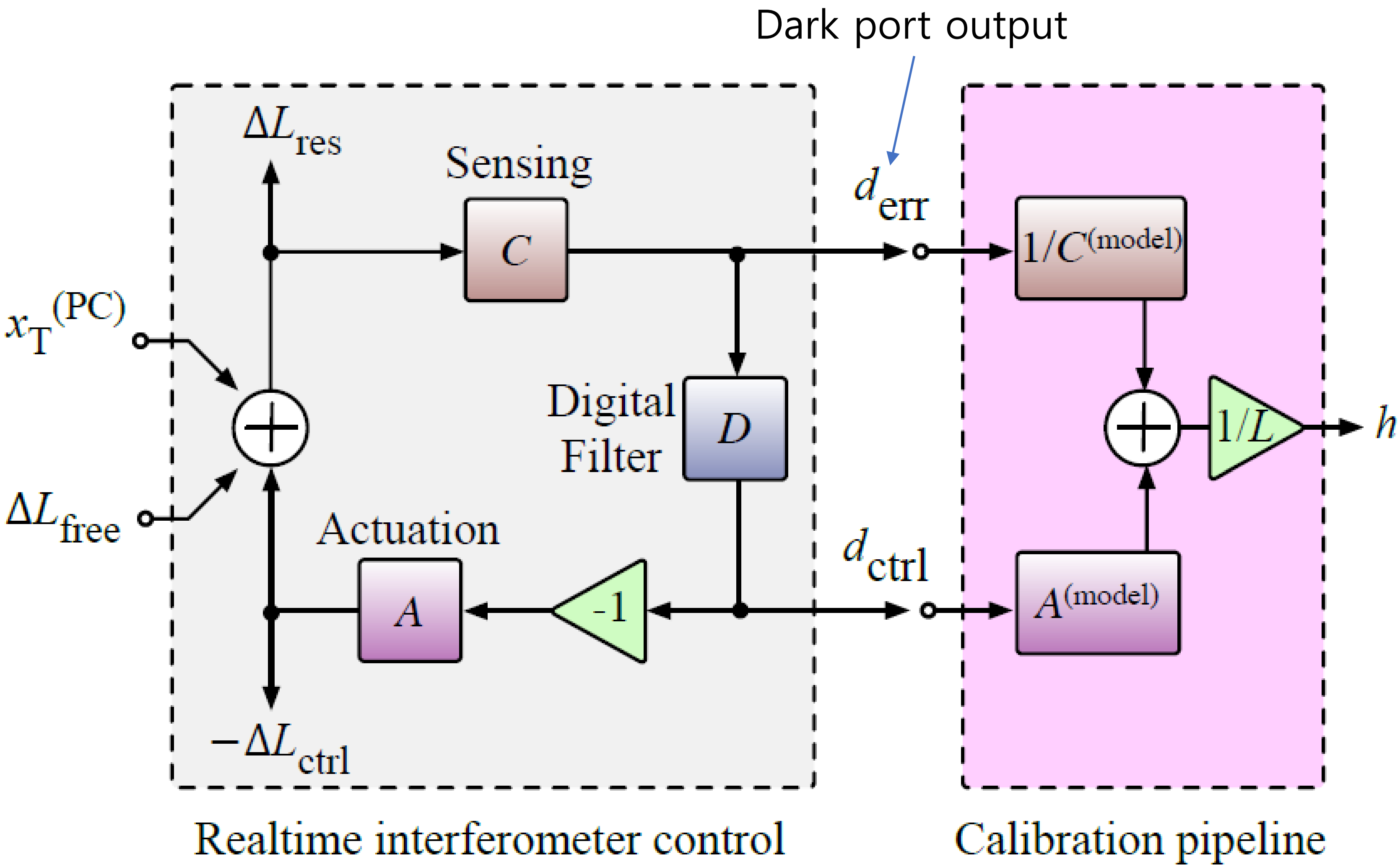
$$\widehat{D}_{eff} = \frac{\sigma_m}{\rho_m} \mathrm{Mpc}$$

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.

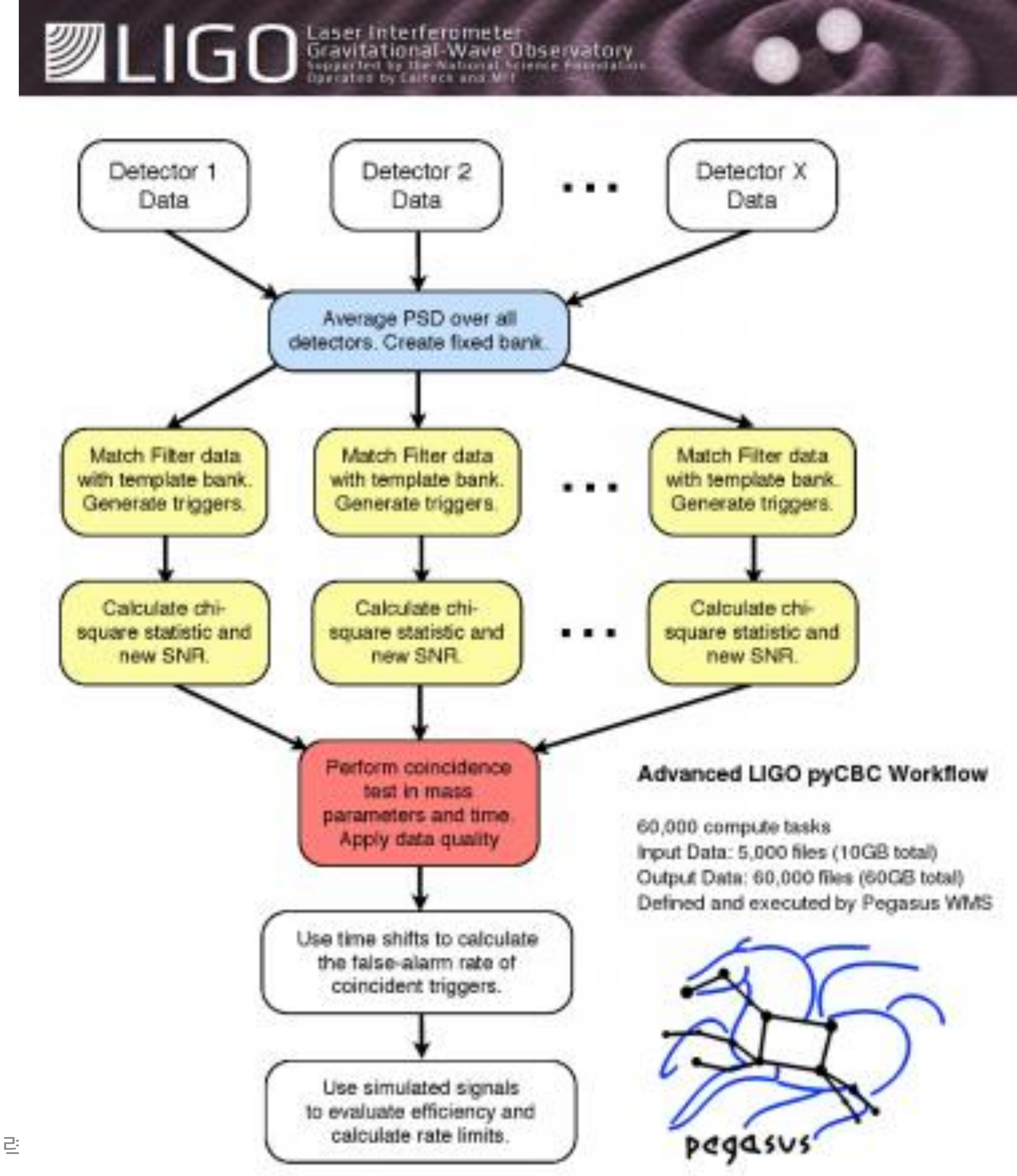
It is highly unlikely to be $\rho_m \gg 1$, for stationary Gaussian noise.

Calibration(CQG20, S903, CQG21, S1723)

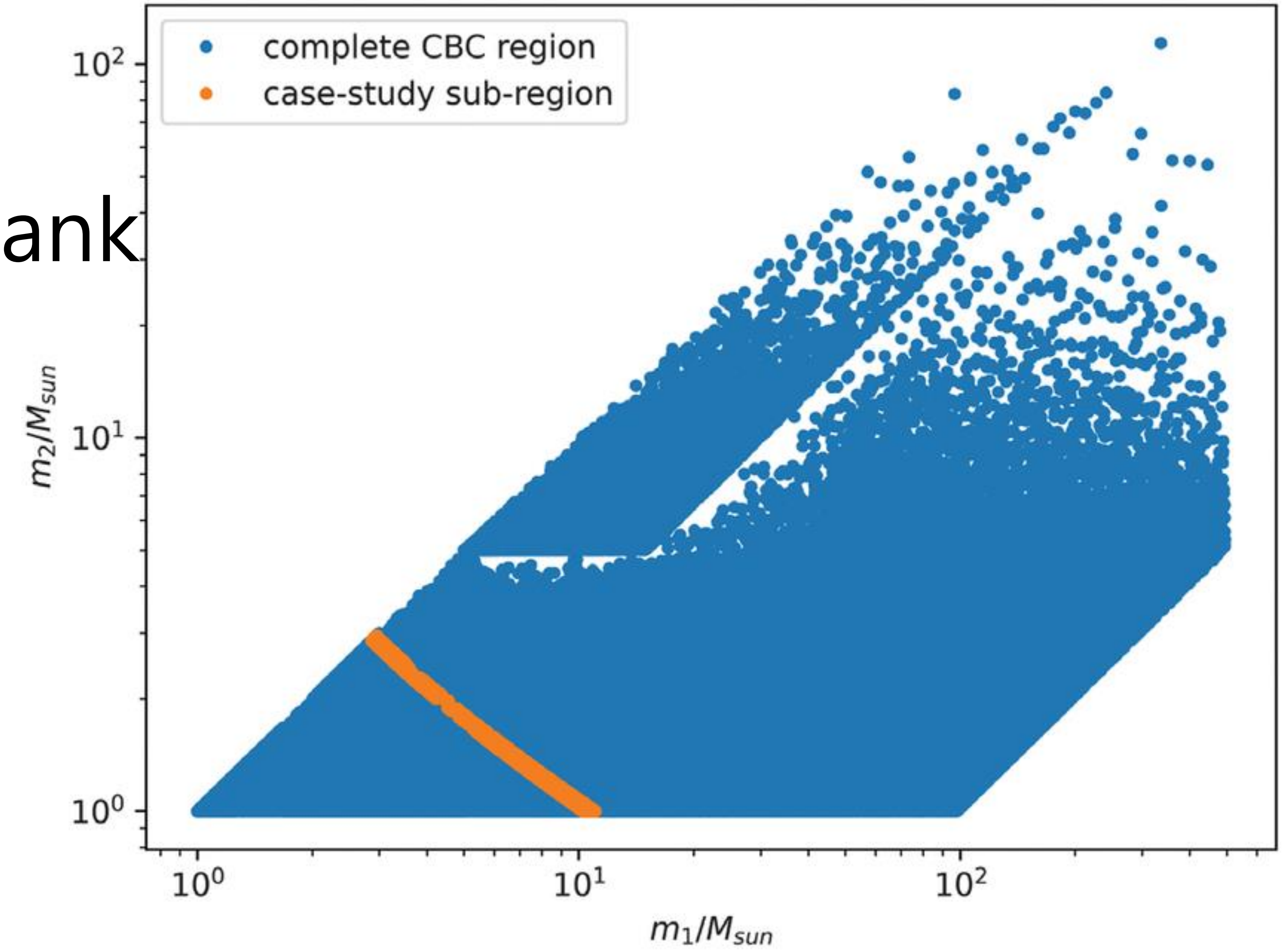


PyCBC Workflow

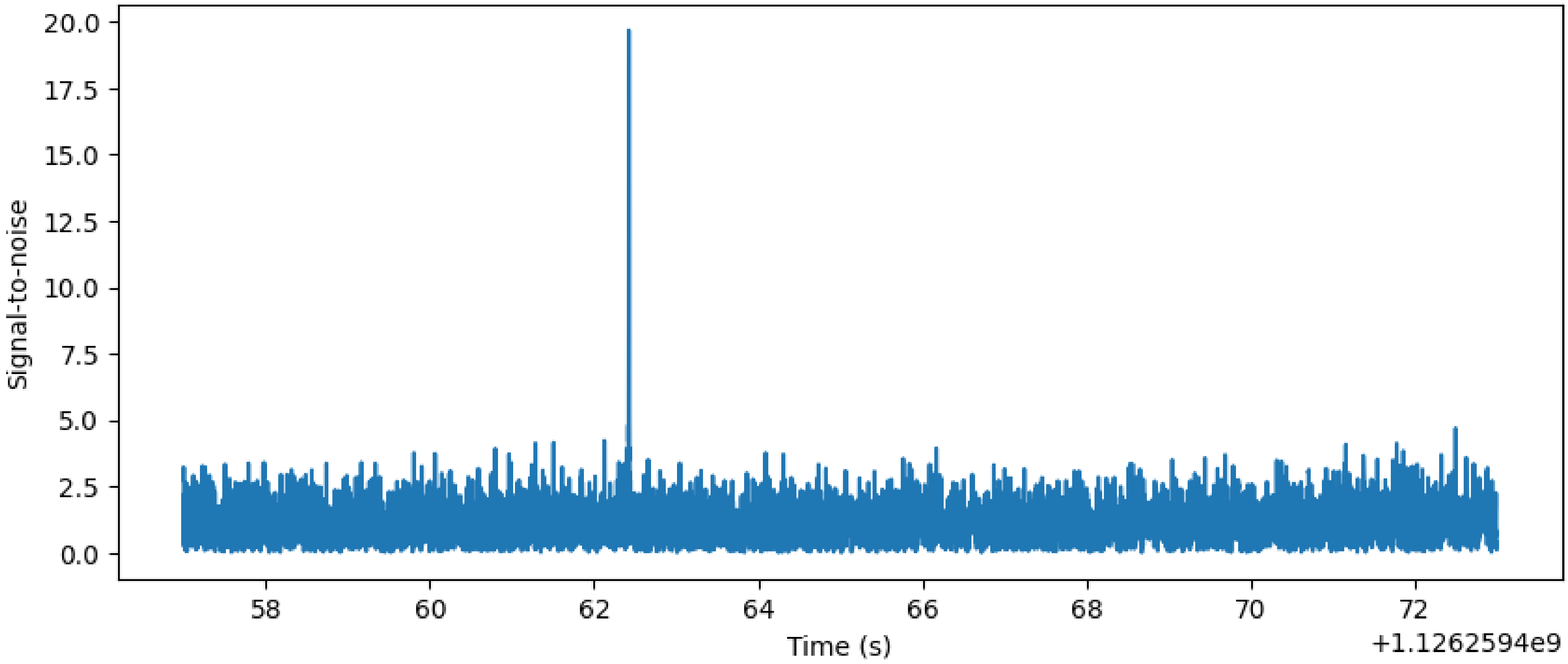
1. Get Data
2. Place template bank
3. Matched filter
4. Coincidence
5. Calculate significance
6. Evaluate efficiency



O2 Template Bank



SNR Time series



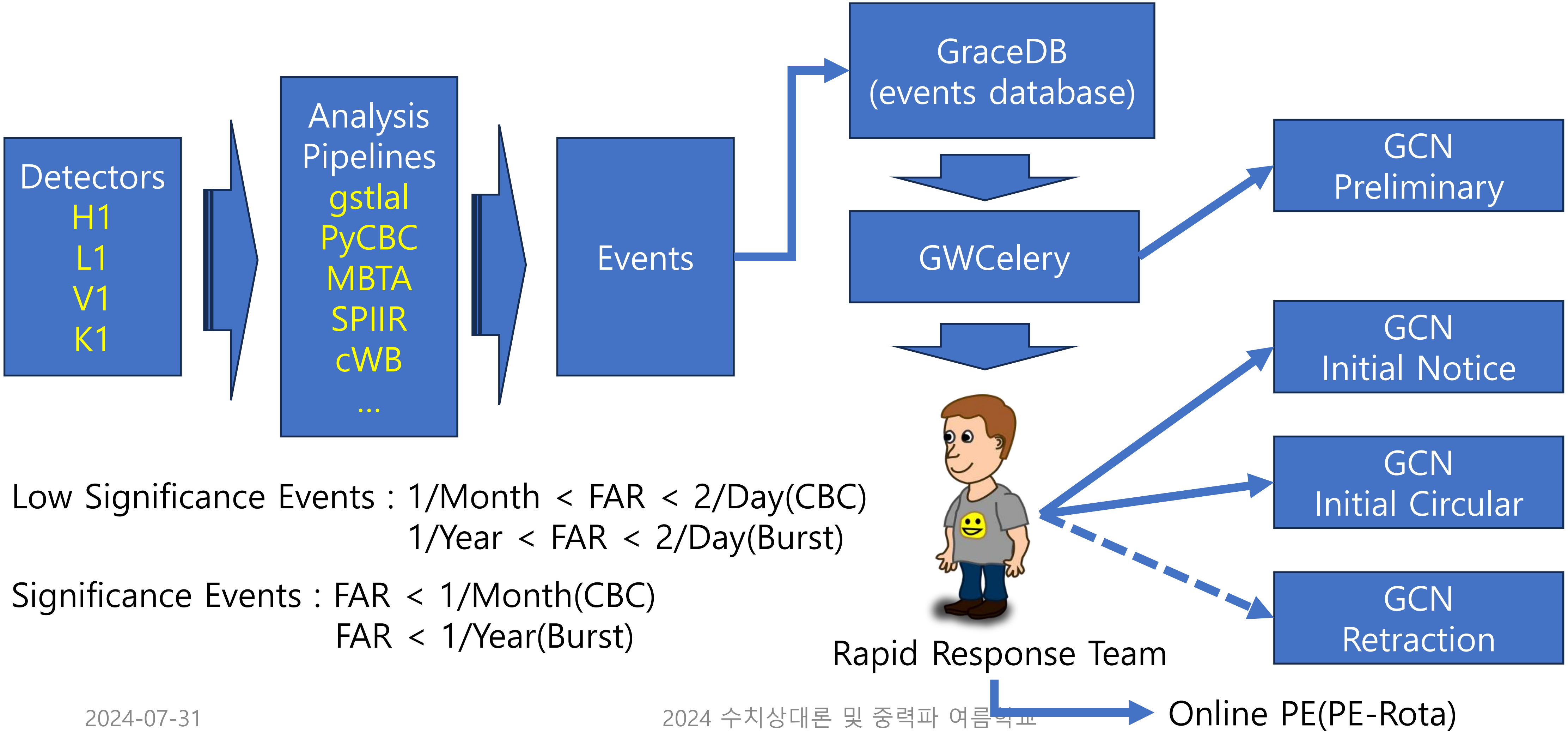
검색엔진

- 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

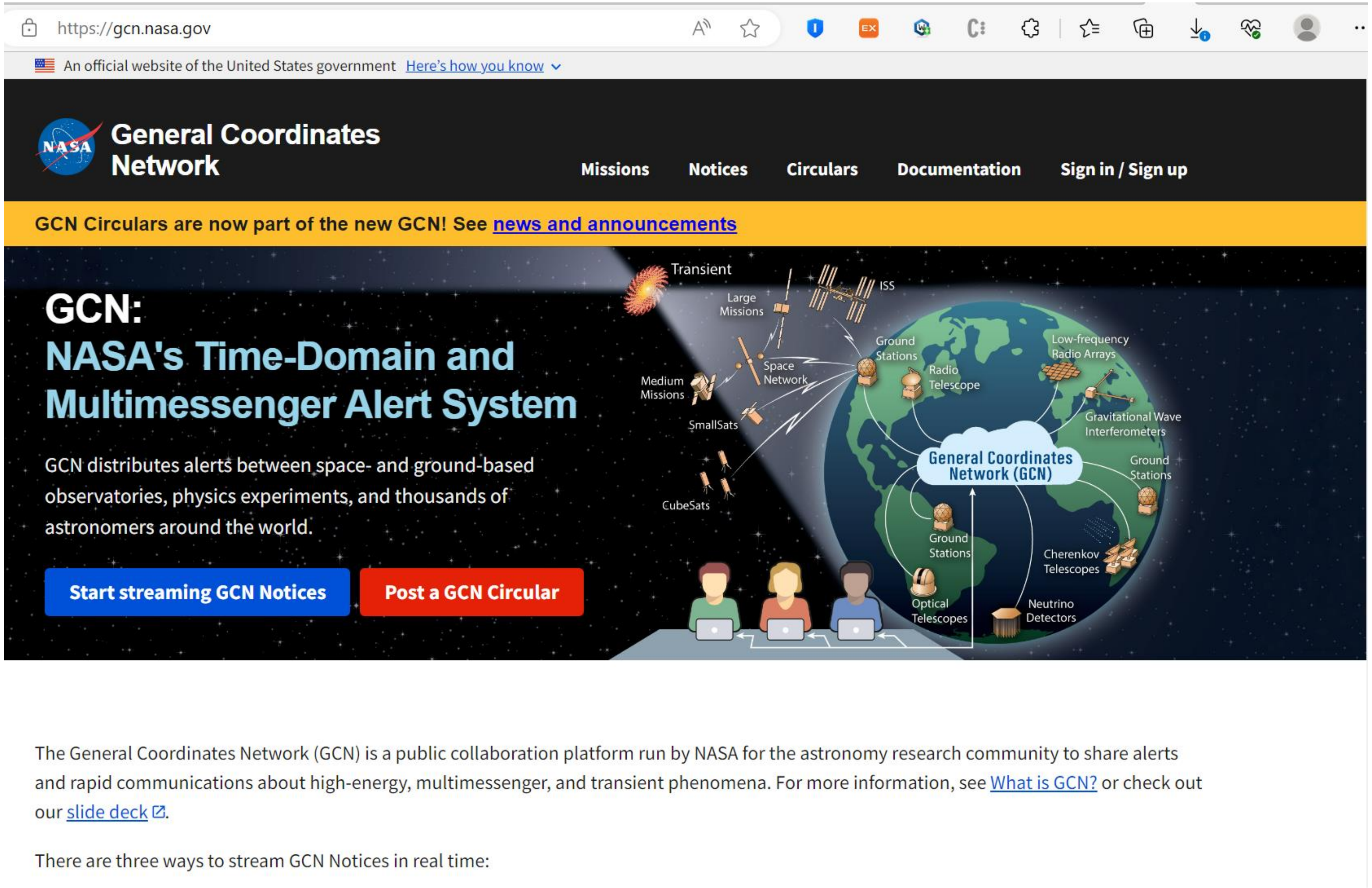


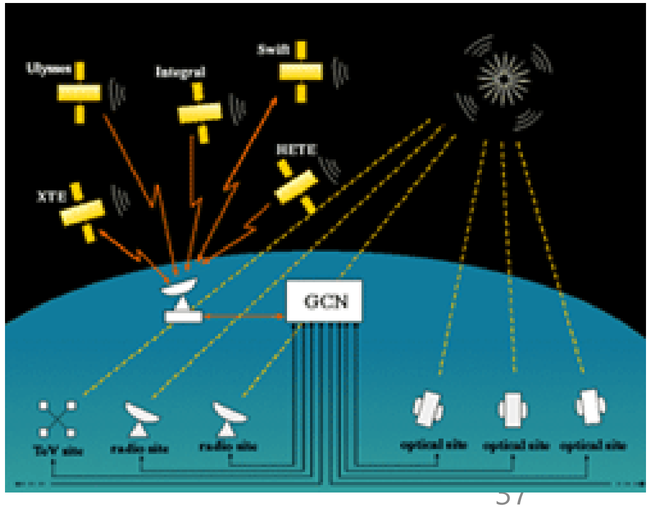
Low Significance Events : 1/Month < FAR < 2/Day(CBC)
1/Year < FAR < 2/Day(Burst)

Significance Events : FAR < 1/Month(CBC)
FAR < 1/Year(Burst)

공공 알림(Public Alerts)

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





https://gcn.nasa.gov/circulars

An official website of the United States government Here's how you know

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 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.

Search | 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

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).

https://emfollow.docs.ligo.org/userguide/

IGWN | Public Alerts User Guide

Search

userguide

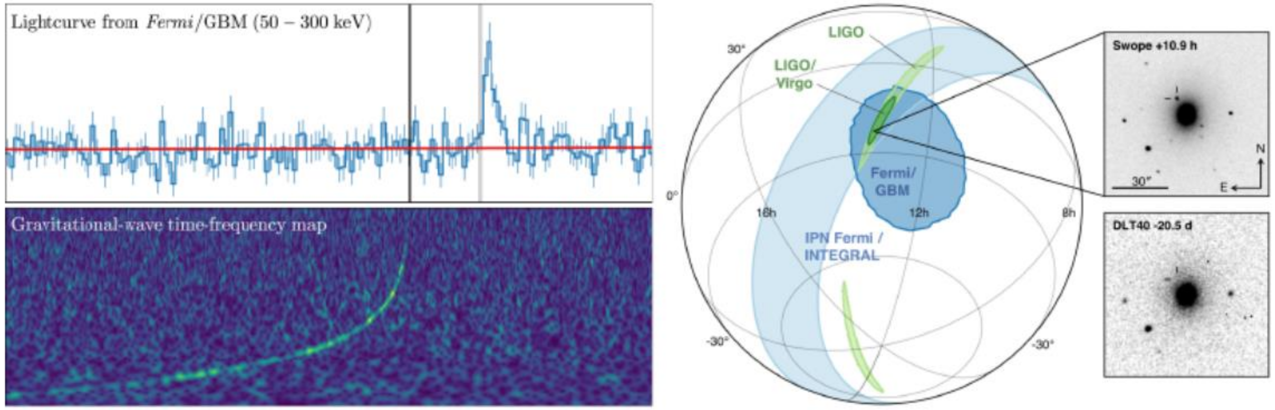
Primer on public alerts for astronomers from the LIGO, Virgo, and KAGRA gravitational-wave observatories.

- 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.ligo.org

LSC - LIGO Scientifi... WebHome < CBC... KAGRA Gmail YouTube 지도 LIGO 연구비 모든 북마크

GraceDB Public Alerts Latest Search Documentation Login

Please log in to view full database contents.

GraceDB Overview

The **Gra**vitational-Wave **C**andidate **E**vent **D**ata**b**ase (**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`

NSF LIGO LSC VIRGO KAGRA

2 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: Superevent

Search

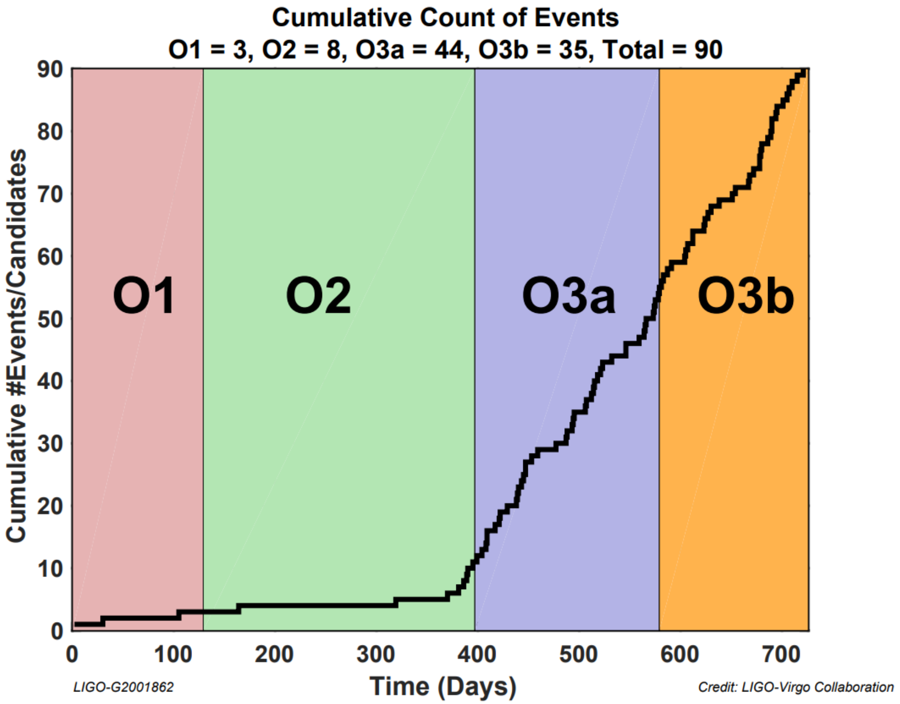
Tap on entry for detailed information

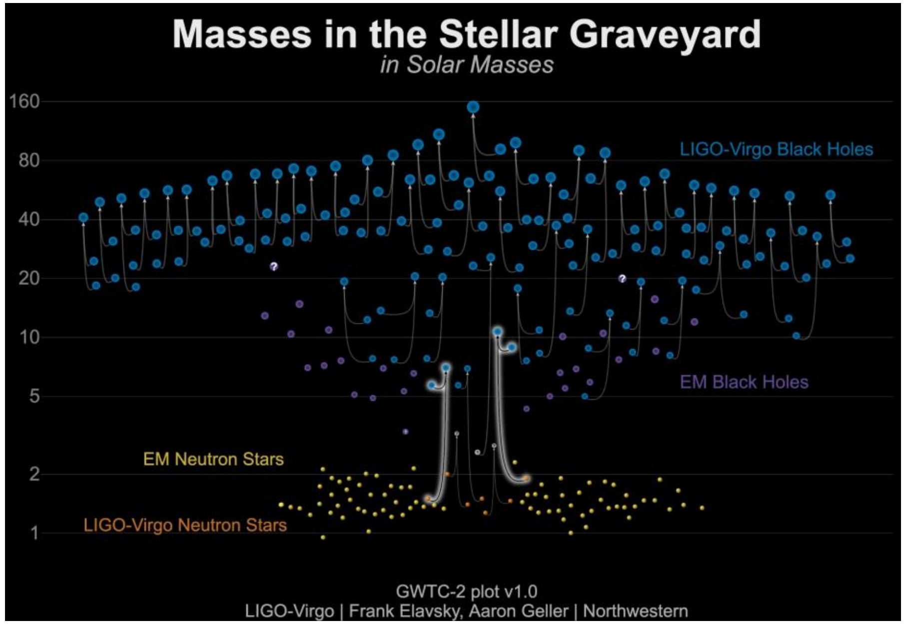
UID	Labels	FAR (Hz)	Created
S240725a	DQOK LOW_SIGNIF_LOCKED EM_READY PASTRO_READY SKYMAP_READY EMBRIGHT_READY LOW_SIGNIF_PRELIM_SENT EM_COINC	1.989e-05	2024-07-25 06:43:43 UTC
S240723b	EM_READY EMBRIGHT_READY SKYMAP_READY LOW_SIGNIF_PRELIM_SENT DQOK LOW_SIGNIF_LOCKED PASTRO_READY	1.376e-05	2024-07-23 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

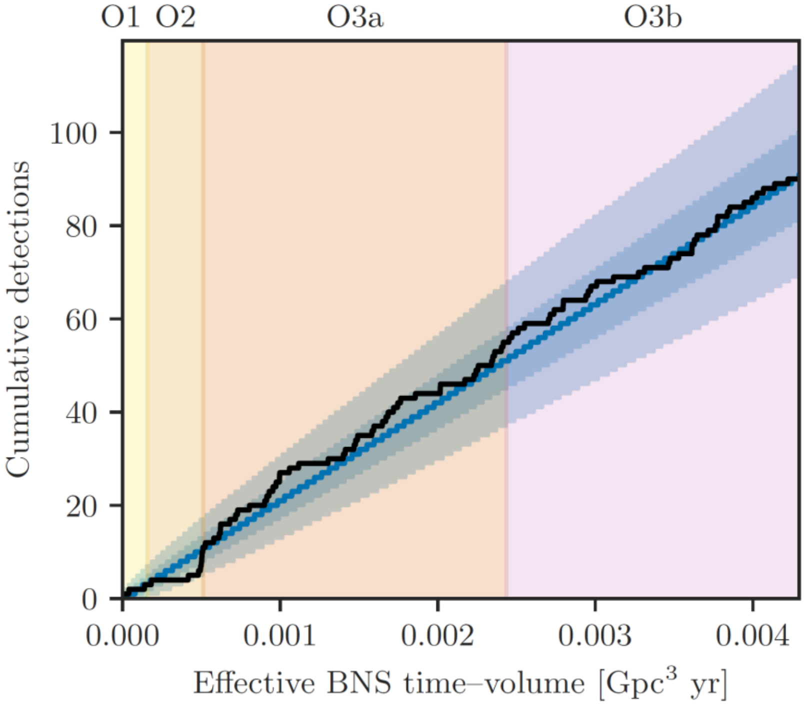
PRX13, 041039(2023)

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

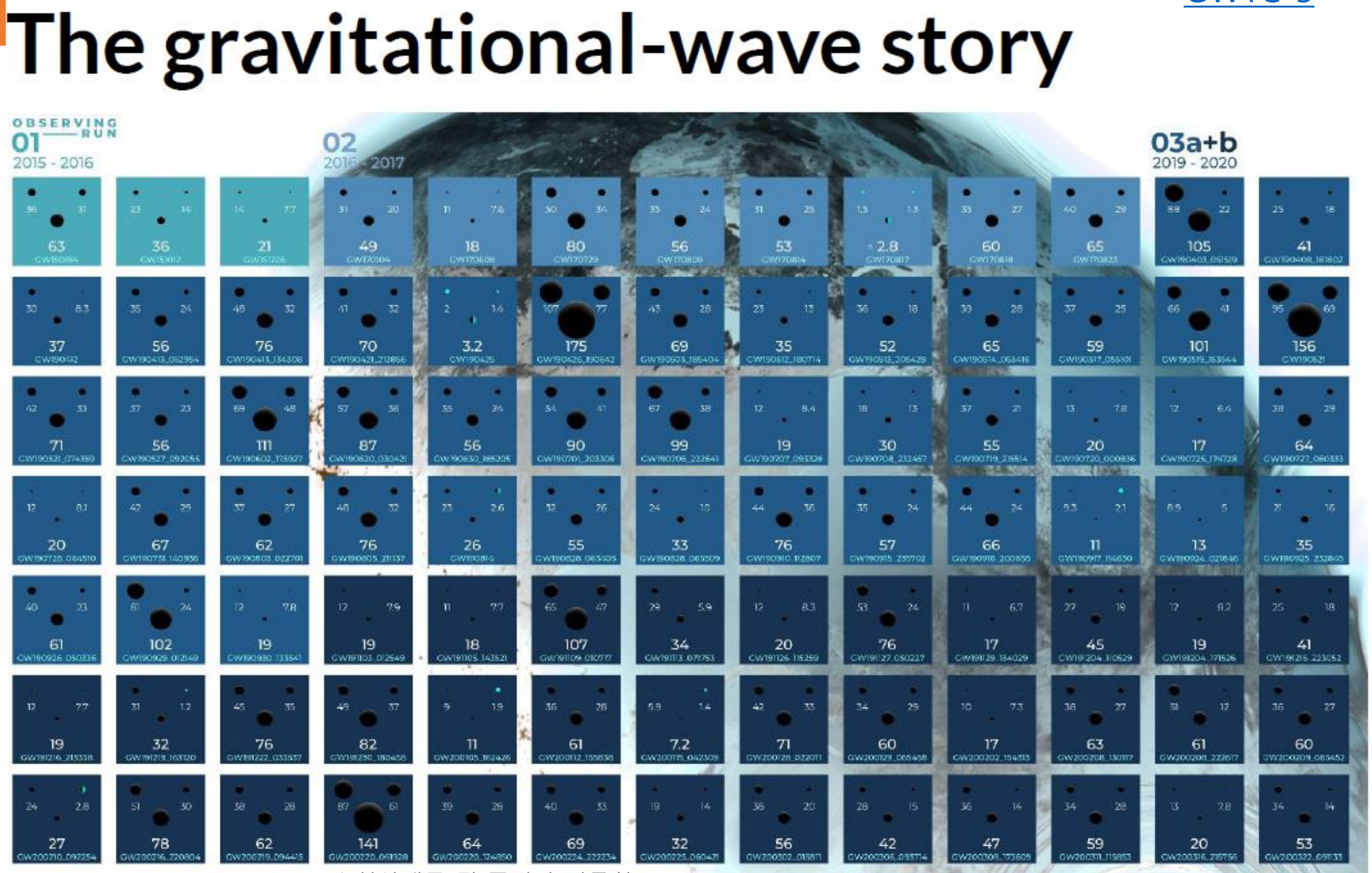






관측결과(90)

GWTC-3



1916 Einstein predicts gravitational waves in general relativity

1974 First indirect evidence of gravitational waves from binary pulsars

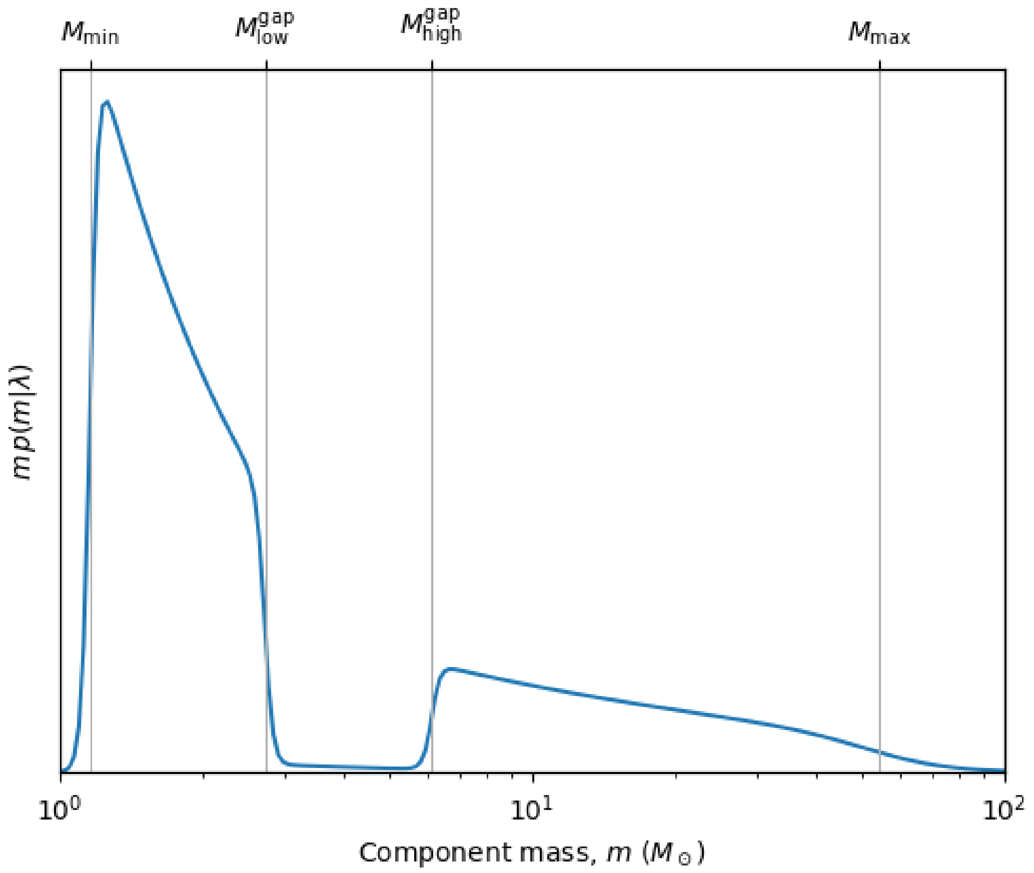
2015 First observation of gravitational waves at the start of O1

Observing runs

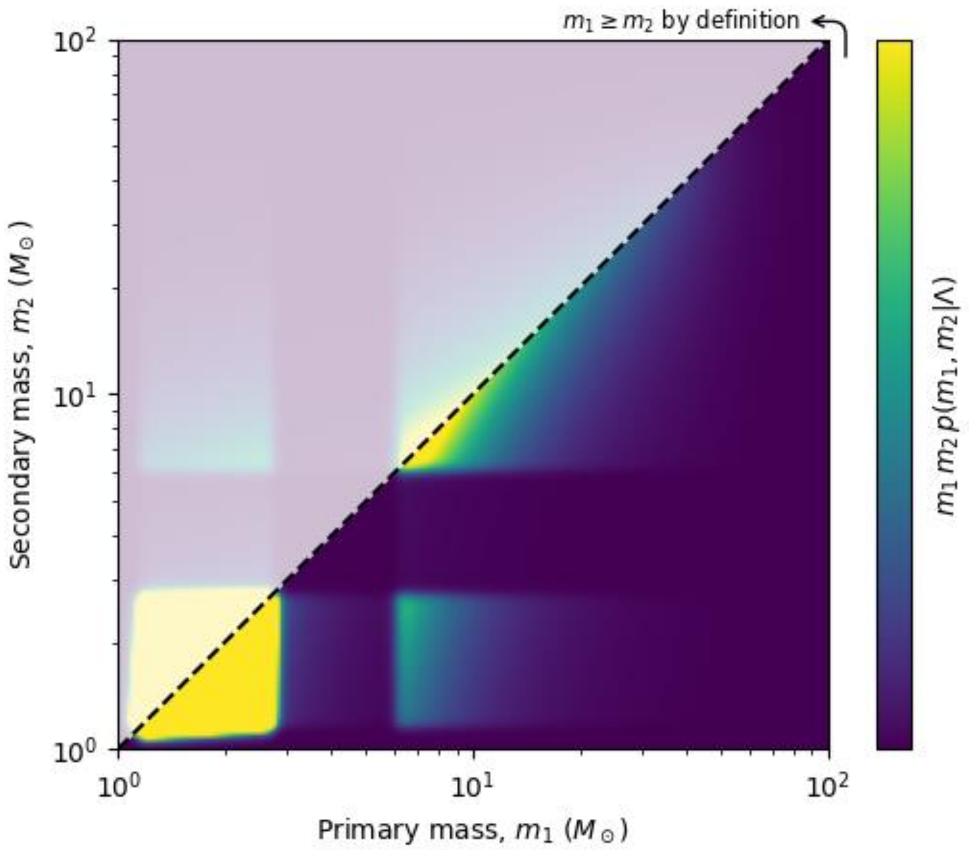
O1: 2015–2016
O2: 2016–2017
O3: 2019–2020
O4: ~2022–2023

질량분포

LIGO Scientific Collaboration & Virgo Collaboration 2021, *The population of merging compact binaries inferred using gravitational waves through GWTC-3*. arXiv:2111.03634



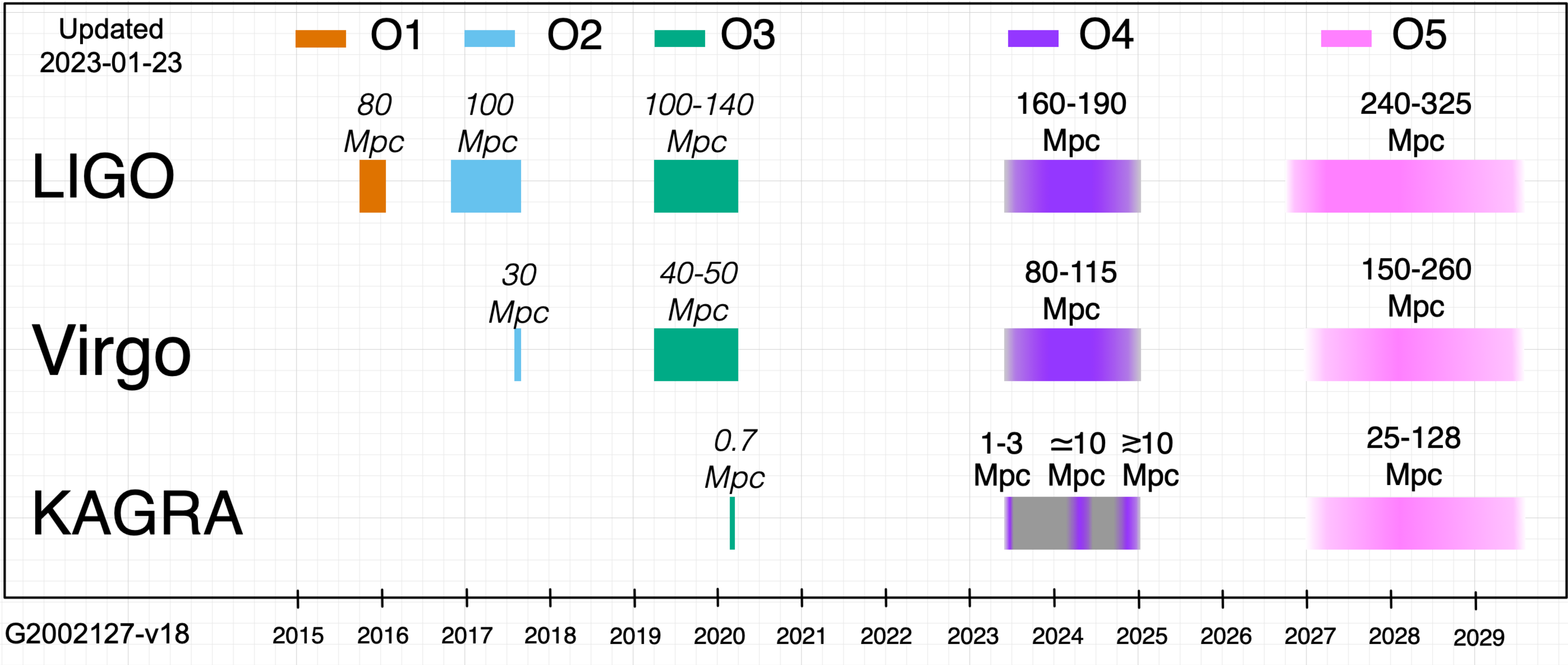
Farah, A., Fishbach, M., et al. 2022, *Bridging the Gap: Categorizing Gravitational-wave Events at the Transition between Neutron Stars and Black Holes*. *Astrophys. J.*, 931, 108. doi:10.3847/1538-4357/ac5f03



IGWN Observing Plans

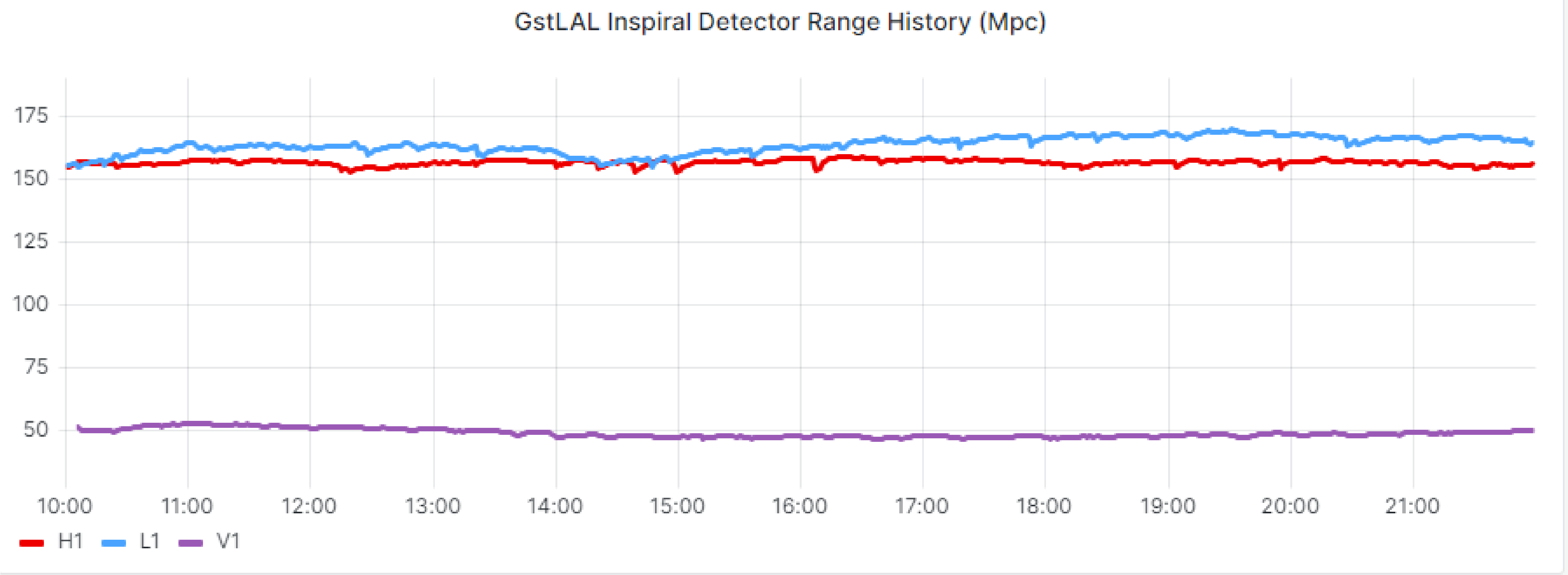
24 May 2023 for 18Months

(IGWN | Observing Plans (ligo.org), https://observing.docs.ligo.org/plan)



Current Observations

20240401 10:00:00 – 21:59:59 UTC



중력파 천체물리학

Nat. Rev. Physics, May 2021

2024-07-31

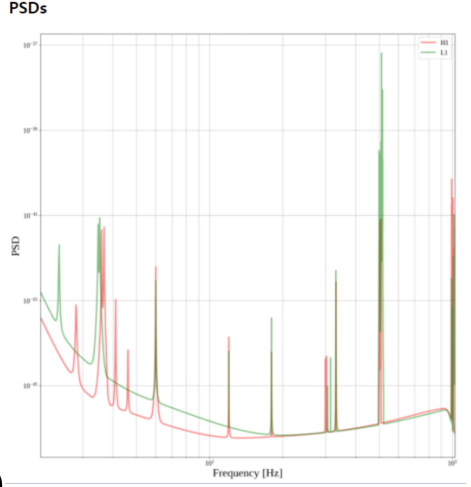
Box 1 | Fundamental questions addressed through gravitational-wave observations

- 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 demographics[262]?
- Are black hole spacetimes as predicted by general relativity[136]?
- Are there any signatures of horizon structure or other manifestations of quantum gravity accessible to gravitational-wave observations[263]?
- Is dark matter composed, in part, of primordial black holes, or must it be composed solely from exotic matter such as axions or dark fermions[263]?
- What is the expansion rate of the Universe[264]?
- What is the nature of dark energy[264]?
- 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 dimensions[116]?
- Are black holes, neutron stars and white dwarfs the only compact objects in our Universe, or are there even more exotic objects[133]?

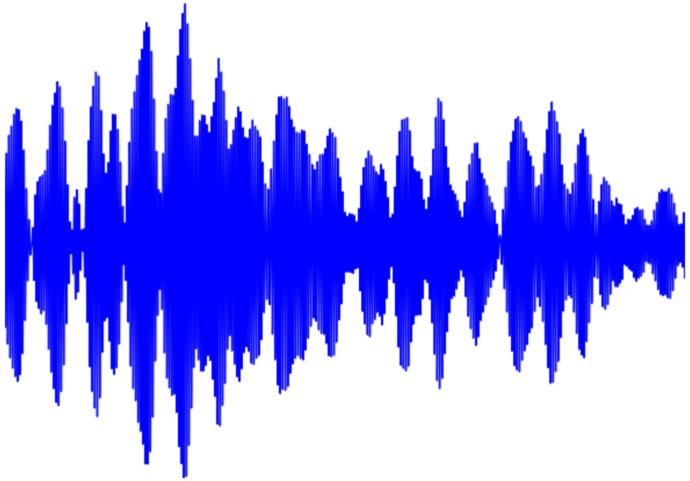
CBC Parameter Estimation

데이터분석

- 고유특성
  - $m_1, m_2, \vec{S}_1, \vec{S}_2, \Lambda_1, \Lambda_2, e_0$
- 외부특성
  - $t_c, \varphi_c, \alpha, \delta, D, \theta_{JN}, \psi$

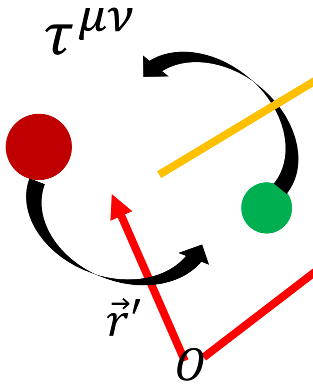


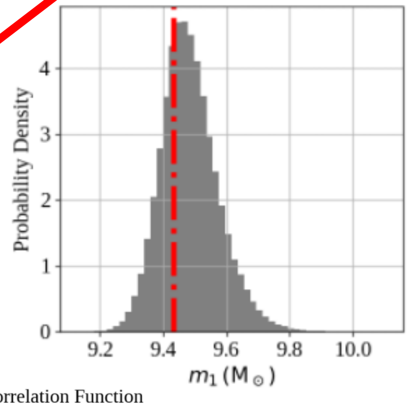
$\bar{h}^{\mu\nu}$

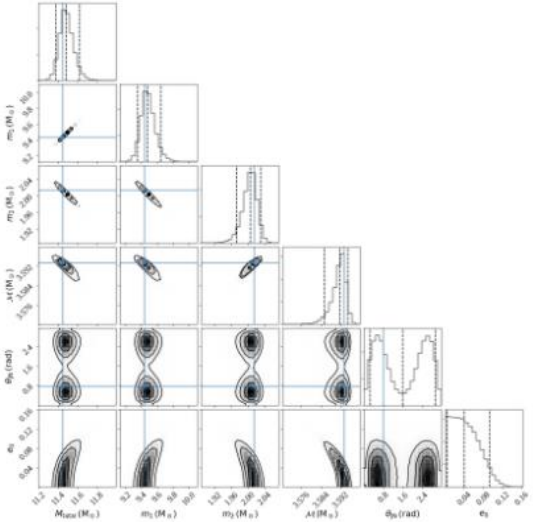


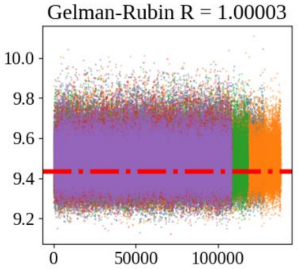
$\vec{R} = \vec{r} - \vec{r}'$

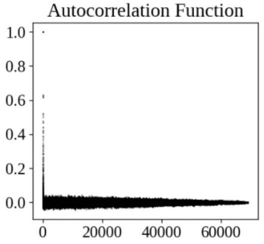
$\vec{r}$

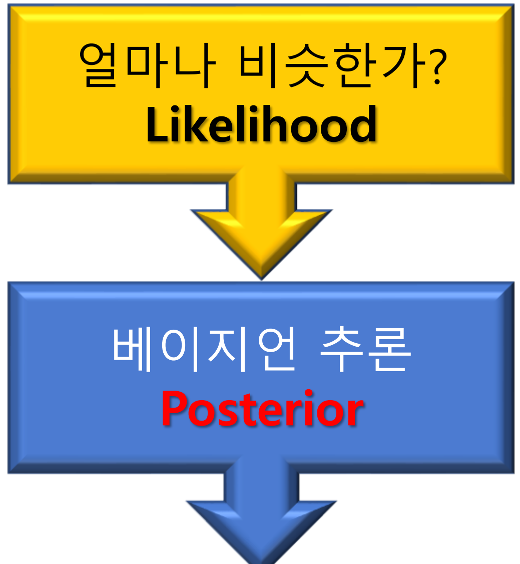


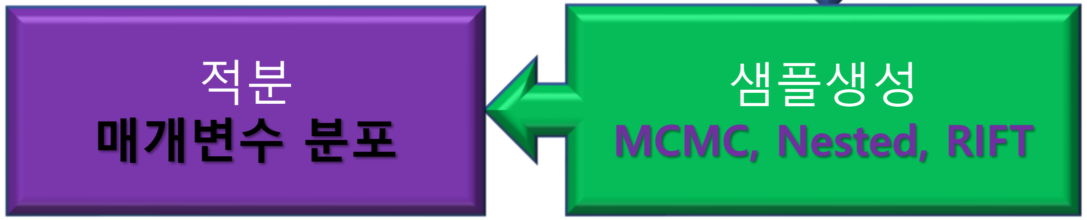












pycbc Implementations

```python
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']

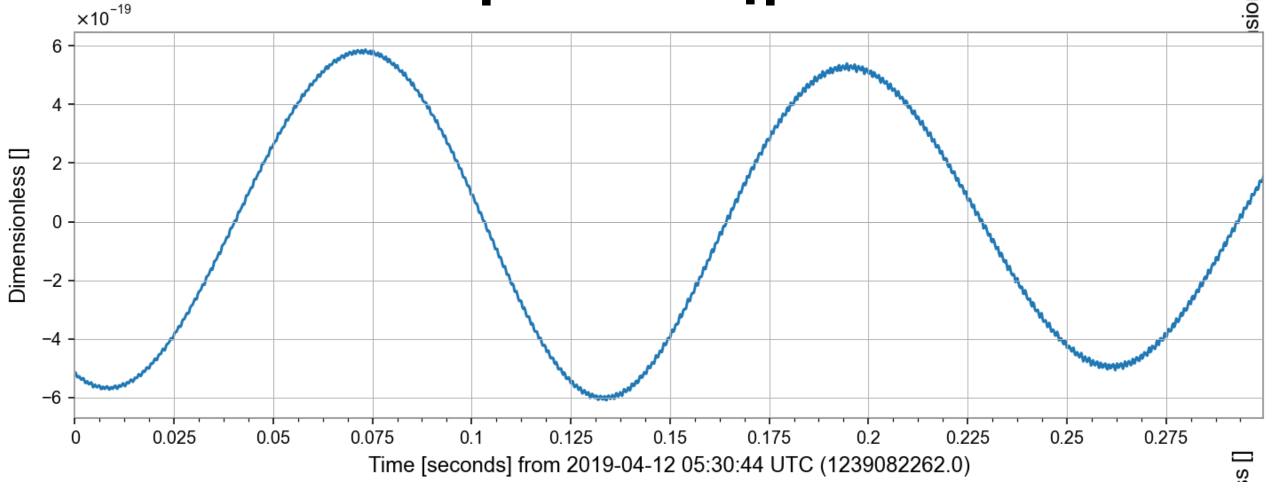
중력파형

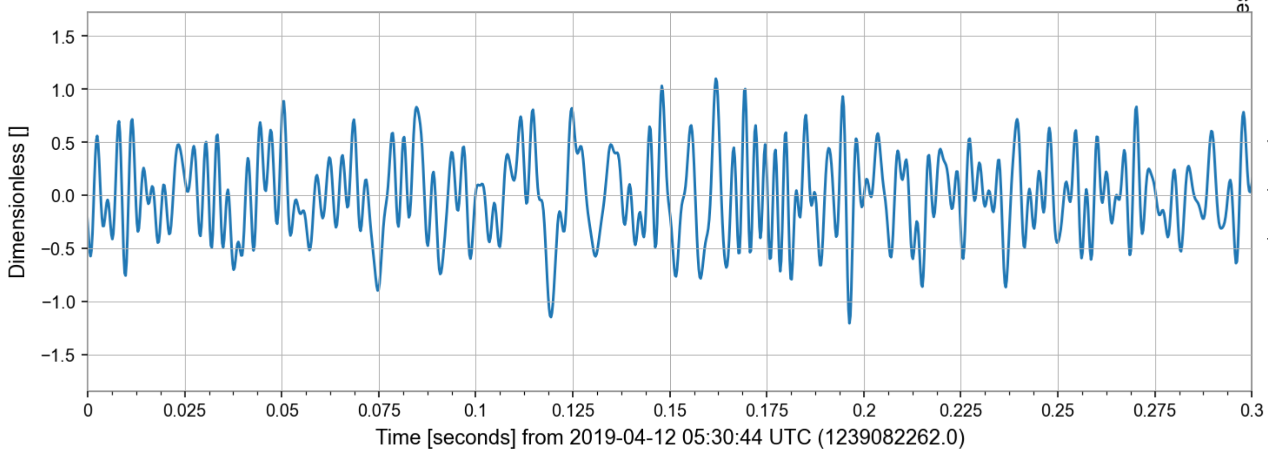
- 107 Waveforms
- Post-Newtonian
- Time-domain
- Frequency-domain
- Tidal effects
- Spin effects
- NR approximation
- Effective One Body

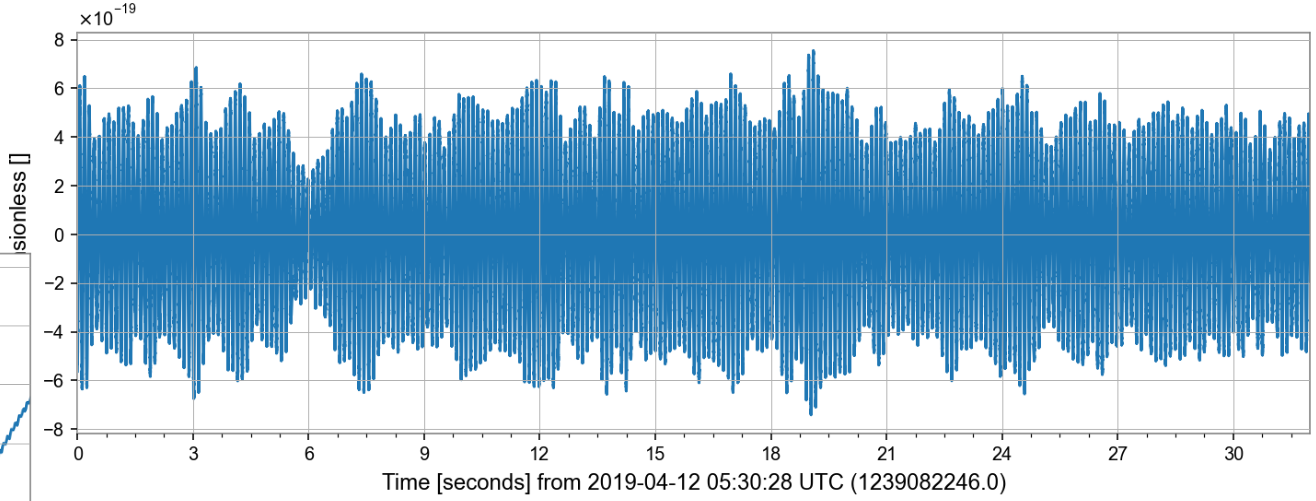
LALSimInspiral.h

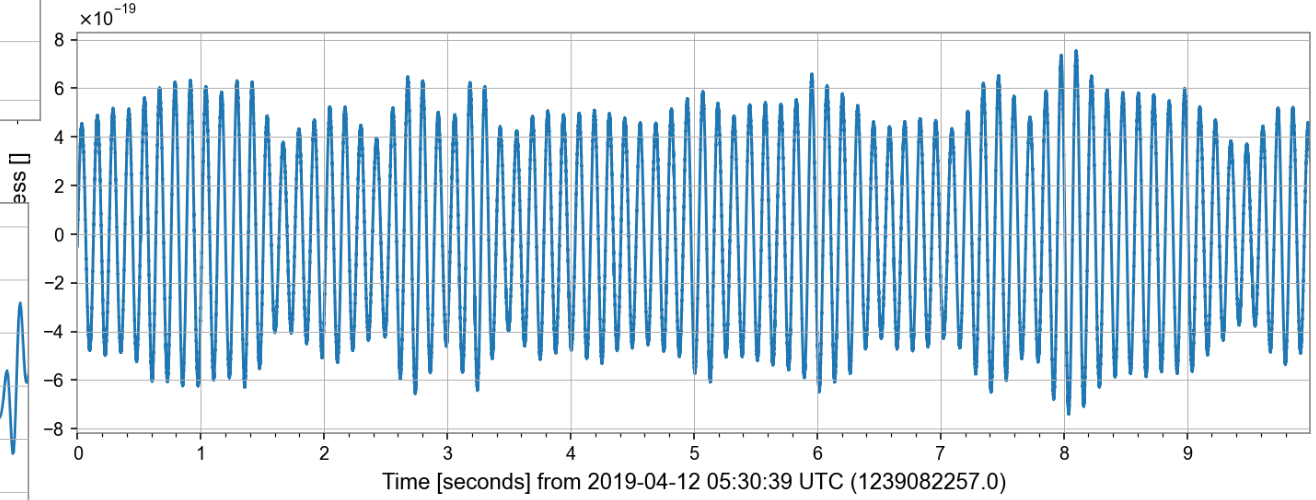
```
enum   Approximant {
    TaylorT1, TaylorT2, TaylorT3, TaylorF1,
    EccentricFD, TaylorF2, TaylorF2Ecc, TaylorF2NLTides,
    TaylorR2F4, TaylorF2RedSpin, TaylorF2RedSpinTidal, PadeT1,
    PadeF1, EOB, BCV, BCVSpin,
    SpinTaylorT1, SpinTaylorT2, SpinTaylorT3, SpinTaylorT4,
    SpinTaylorT5, SpinTaylorF2, 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, 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
  }
```

LIGO 자료 예







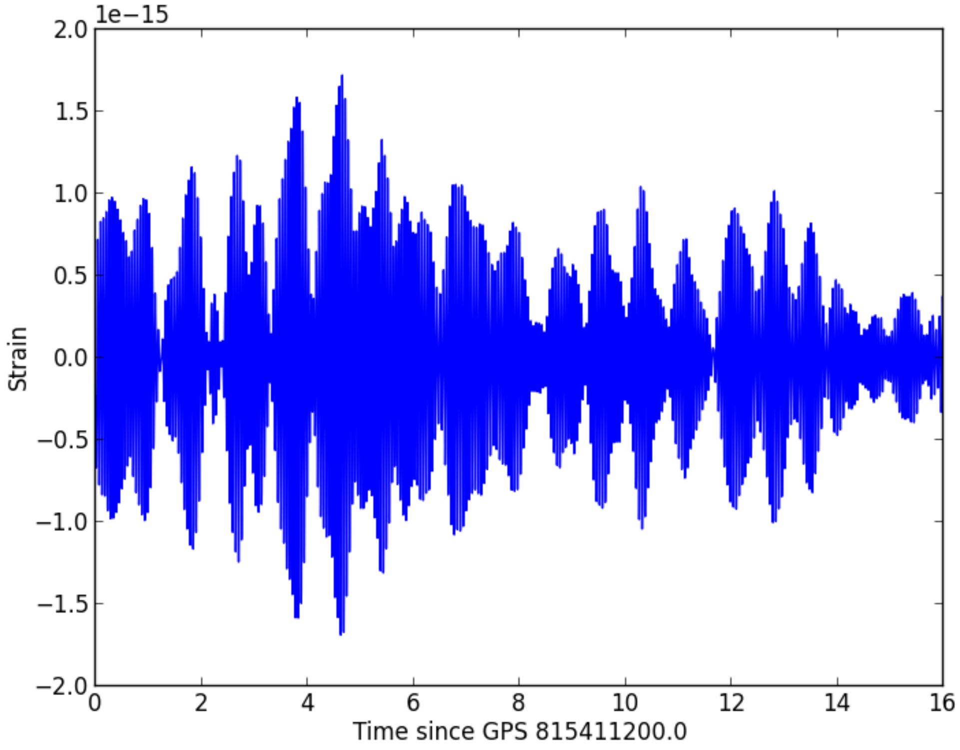


t0 = 1239082262.2

Odw4, GW190412 [GWOSC (gw-openscience.org)](https://gw-openscience.org)

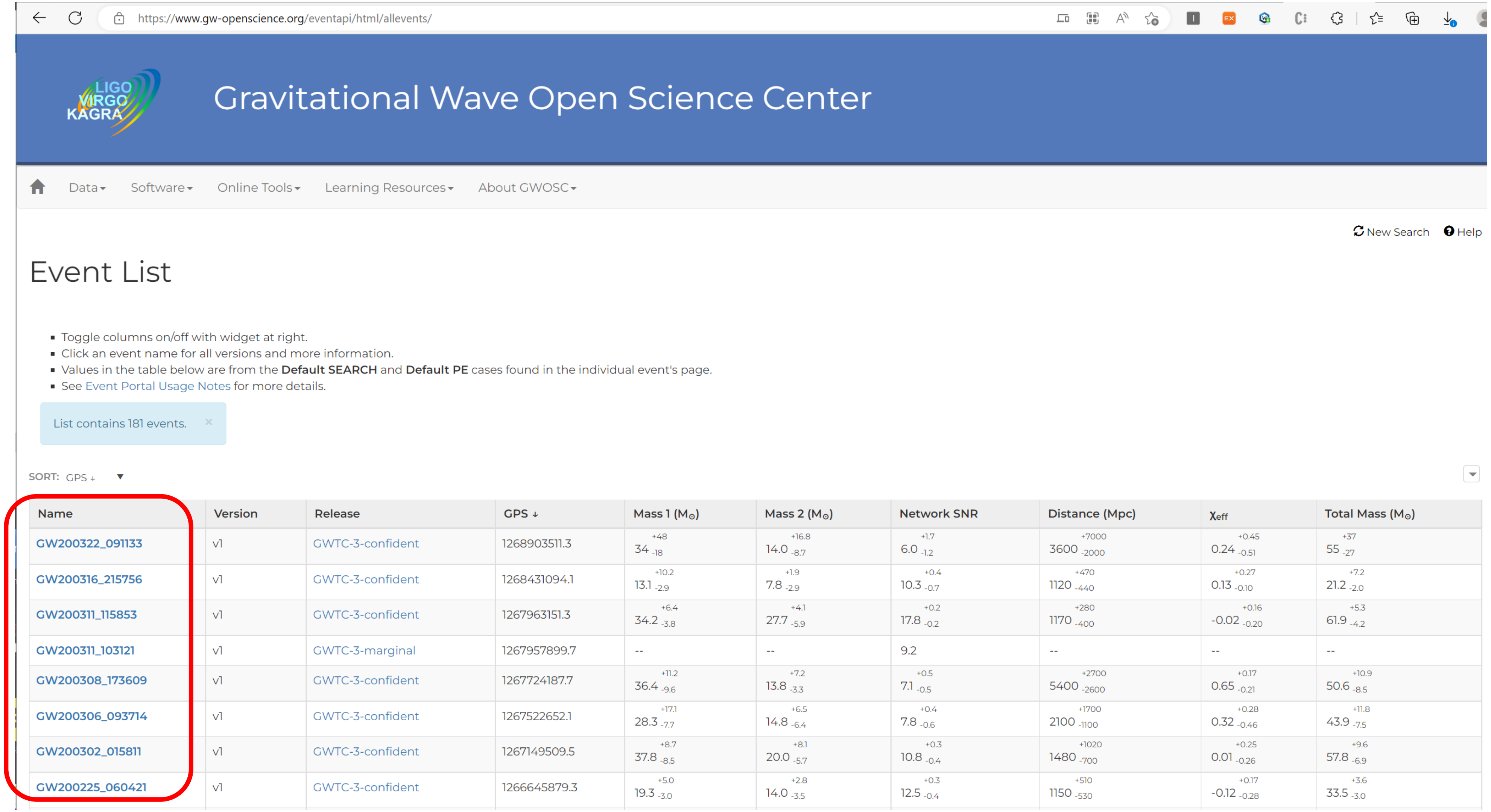
LIGO 자료

- 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/)


https://www.gw-openscience.org/eventapi/html/allevents/

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

https://www.gw-openscience.org/eventapi/html/GWTC-3-confident/GW200322_091133/v1

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New Search Help

GW200322_091133

Documentation

Release: GWTC-3-confident

Event UID: GW200322_091133-v1

Names: GW200322_091133

GPS: 1268903511.3

UTC Time: 2020-03-22 09:11

GraceDB: S200322ab

GCN: Notices · Circulars

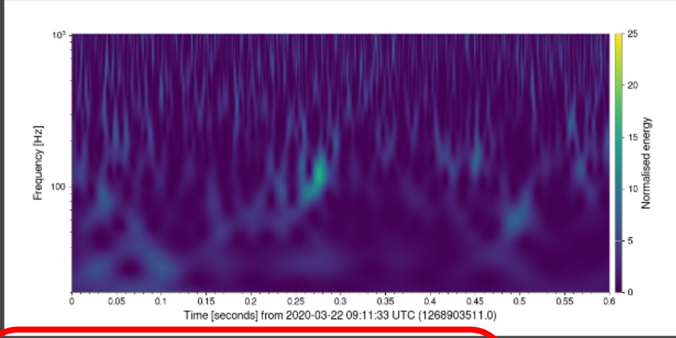
Timeline: Query for segments

DOI: https://doi.org/10.7935/b024-1886

Data sourced from frame channels.

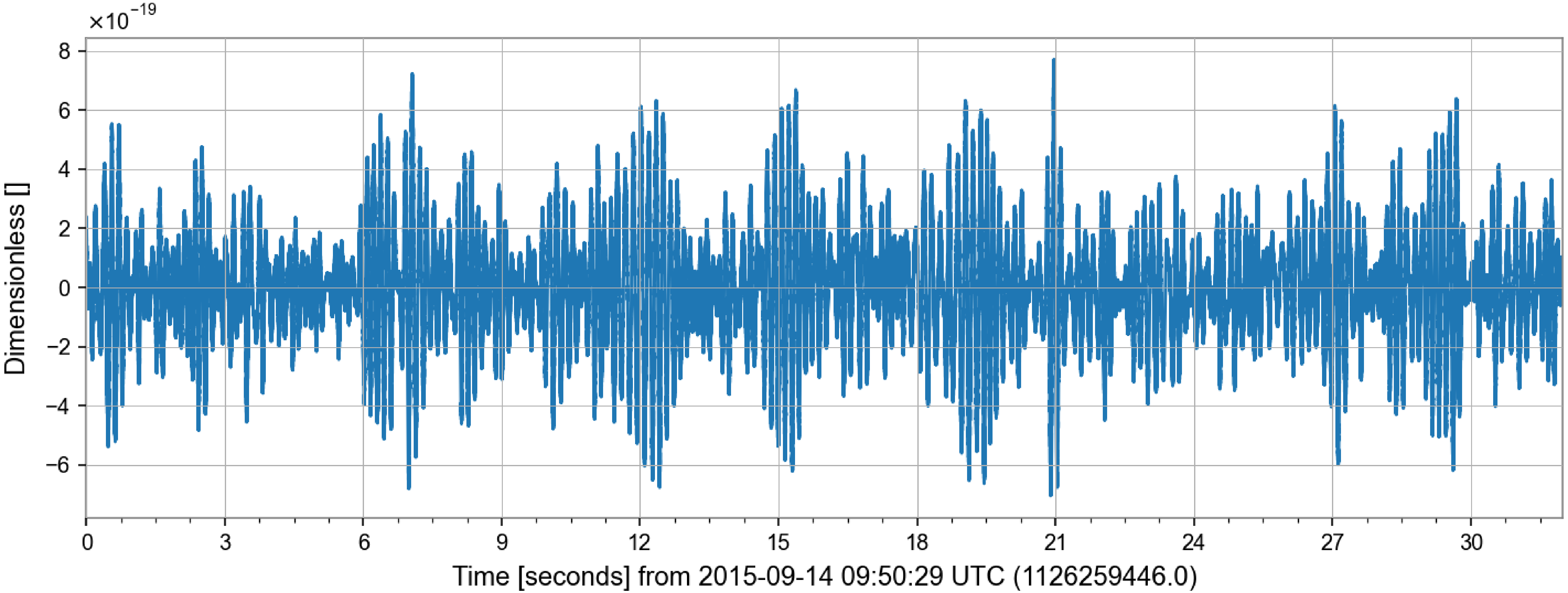
FrameChannels: [H1:DCS-CALIB_STRAIN_CLEAN_SUB60HZ_C01, L1:DCS-CALIB_STRAIN_CLEAN_SUB60HZ_C01, V1:Hrec_hoft_16384Hz]

H1 strain

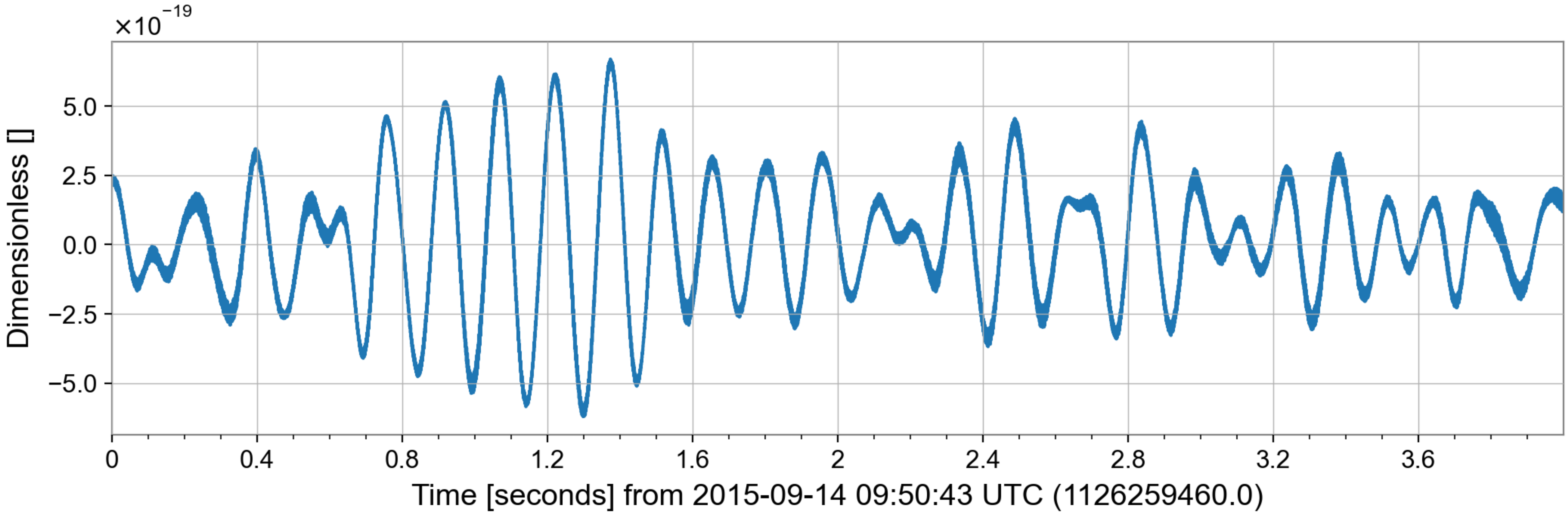


32sec · 16KHz:	GWF	HDF	TXT
32sec · 4KHz:	GWF	HDF	TXT
4096sec · 16KHz:	GWF	HDF	TXT
4096sec · 4KHz:	GWF	HDF	TXT

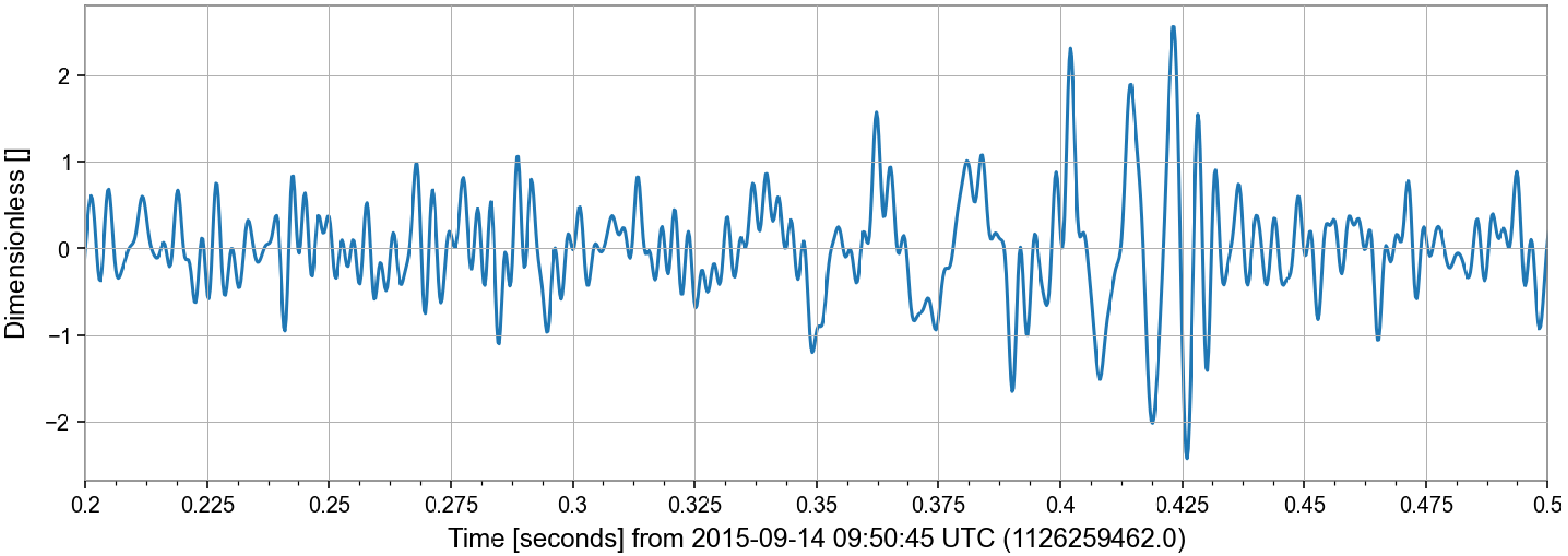
중력파 자료(32.0초) GW150914



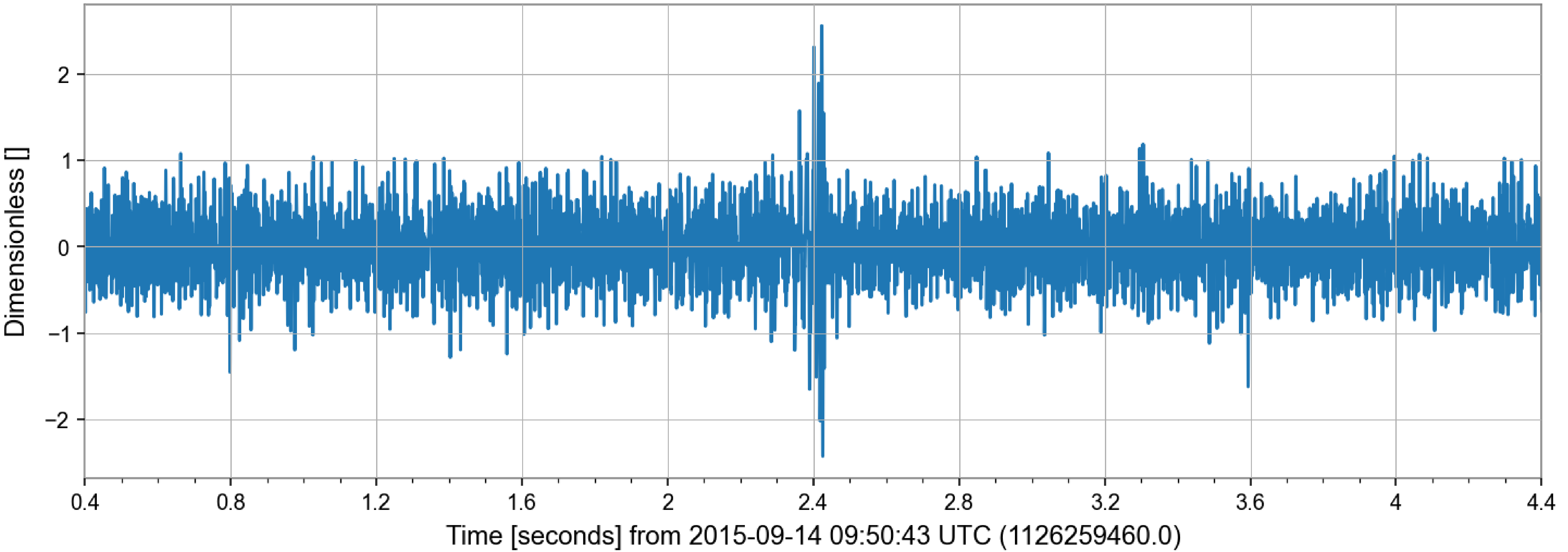
중력파 자료(4.0초) GW150914



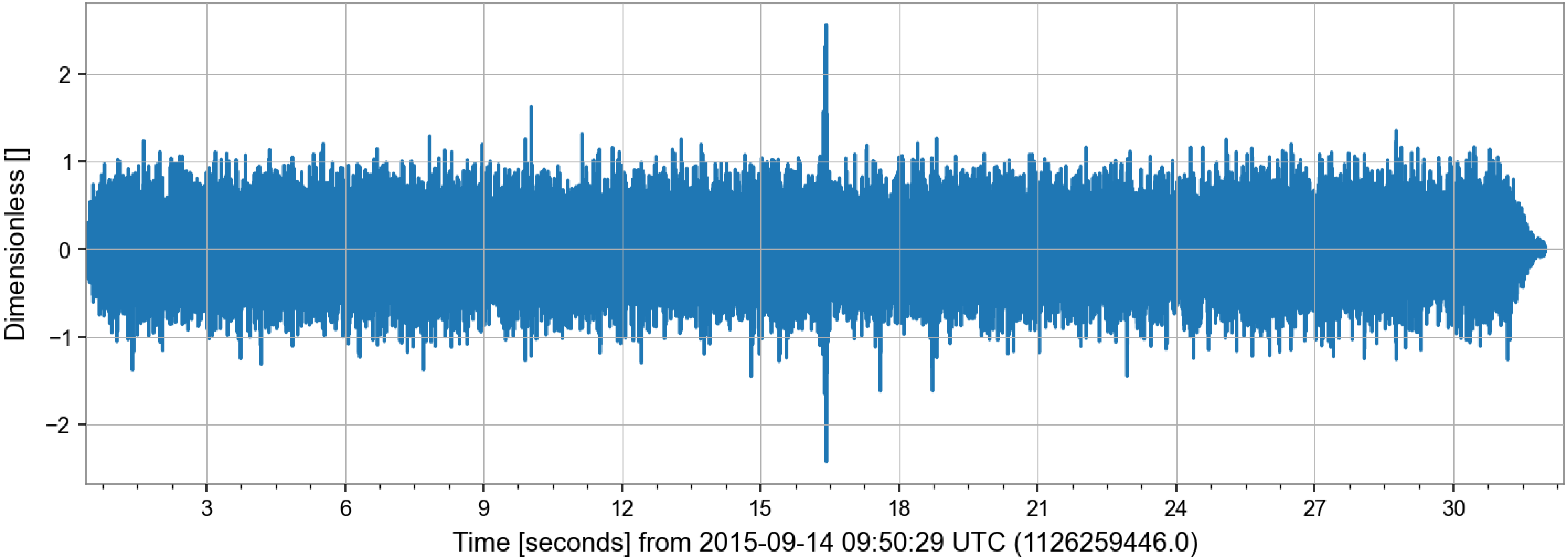
중력파 자료(0.3초) GW150914
(whitening, band pass)

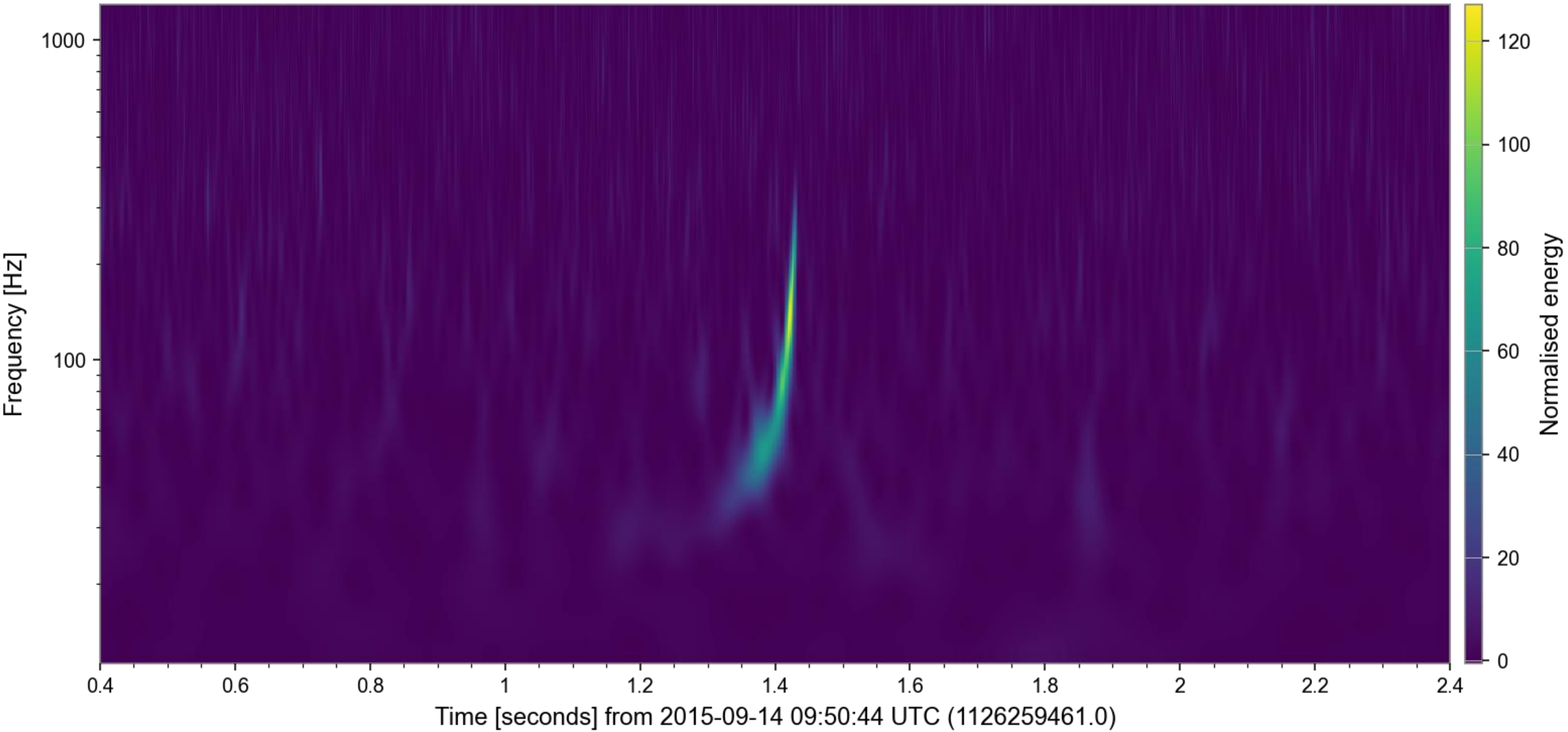


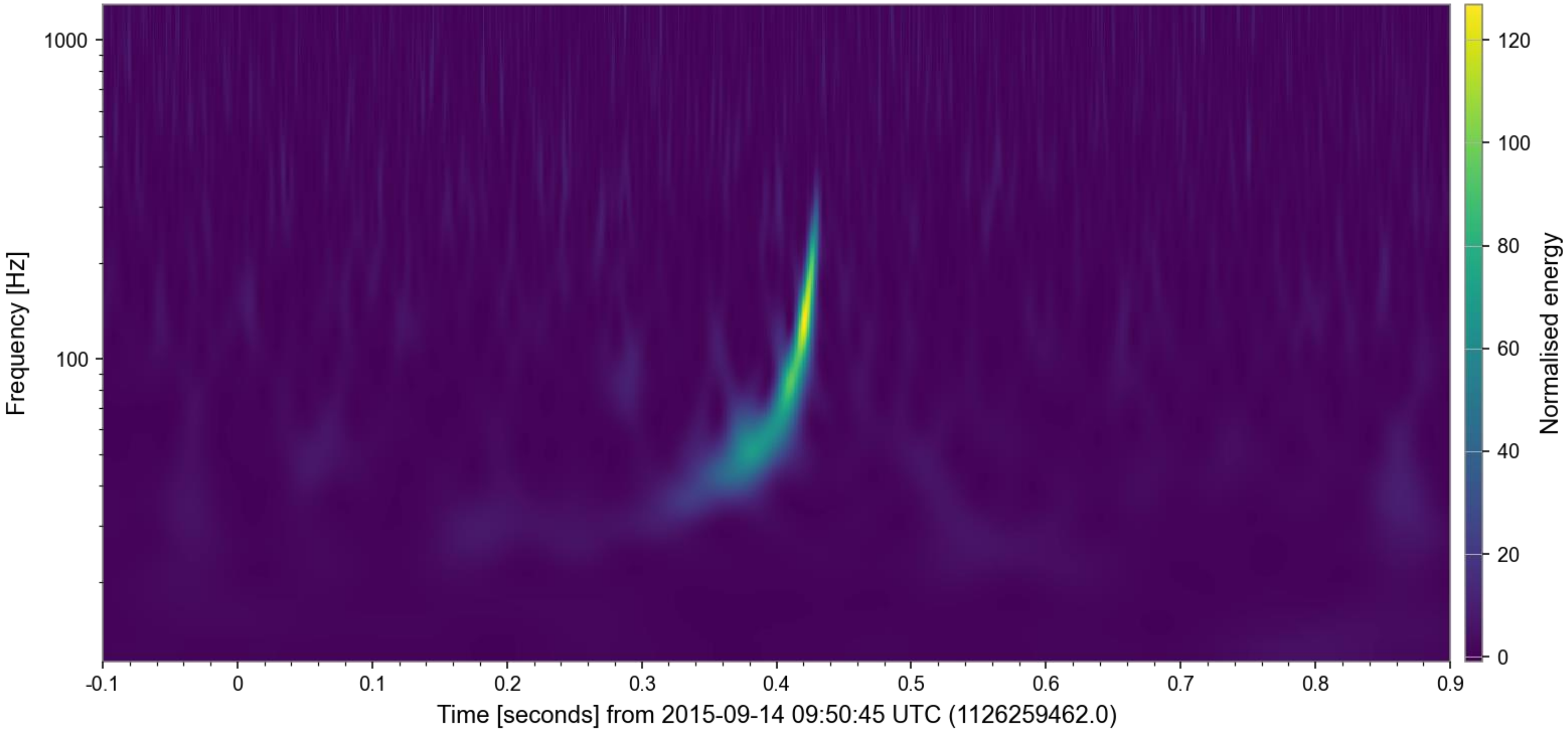
중력파 자료(4.0초) GW150914 (whitening, band pass)



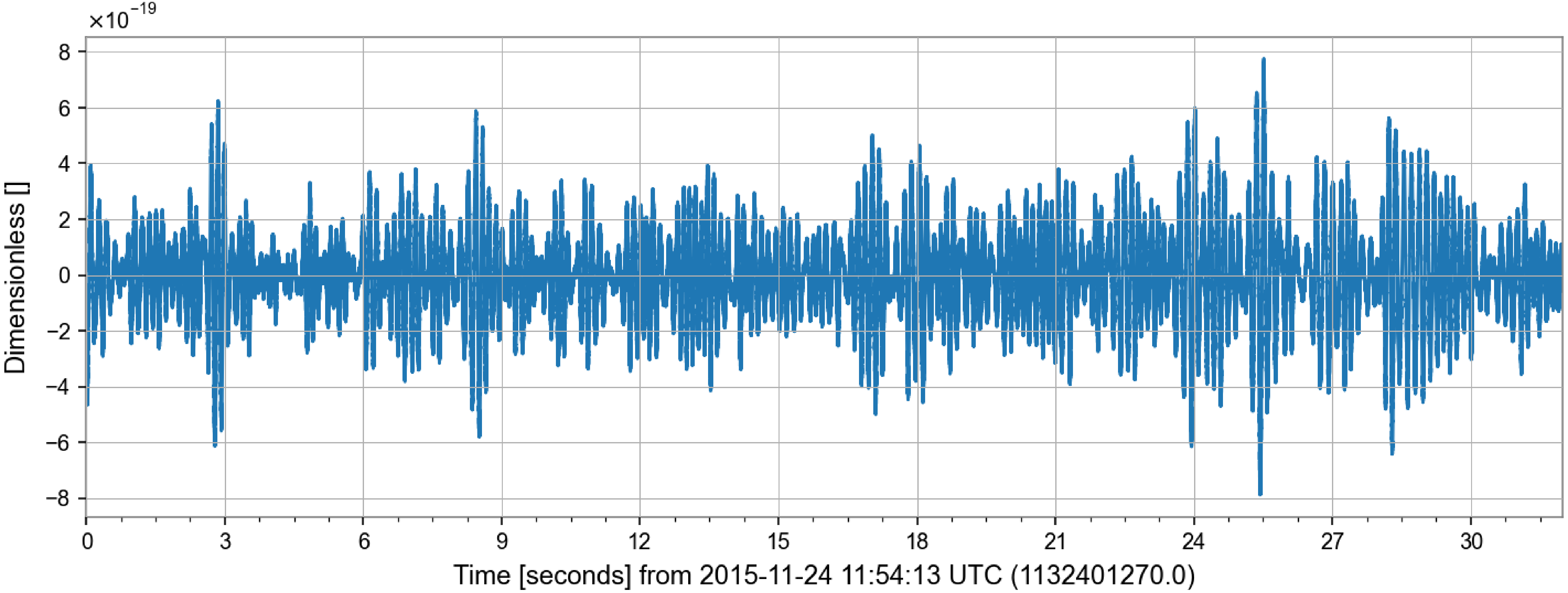
중력파 자료(32.0초) GW150914 (whitening, band pass)



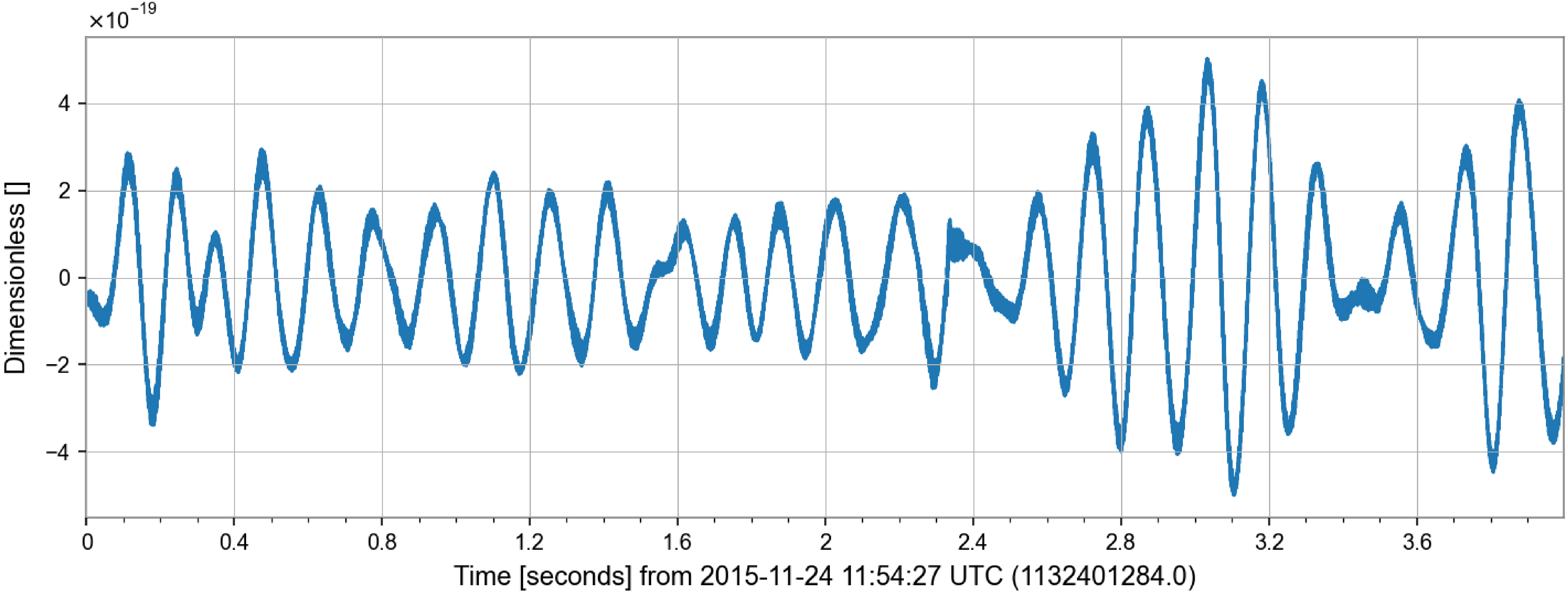

1000
100
Frequency [Hz]
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
Time [seconds] from 2015-09-14 09:50:44 UTC (1126259461.0)
120
100
80
60
40
20
0
Normalised energy


1000
100
Frequency [Hz]
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Time [seconds] from 2015-09-14 09:50:45 UTC (1126259462.0)
0
20
40
60
80
100
120
Normalised energy

중력파 자료(32.0초) Glitch

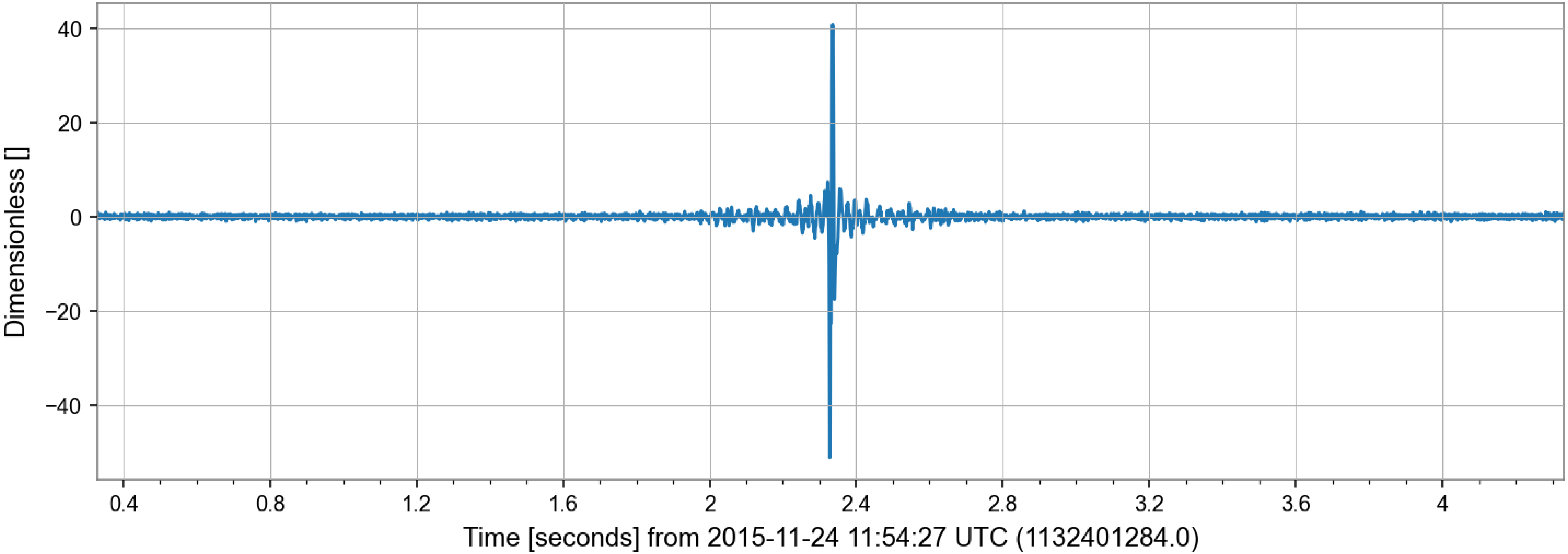


중력파 자료(4.0초) Glitch

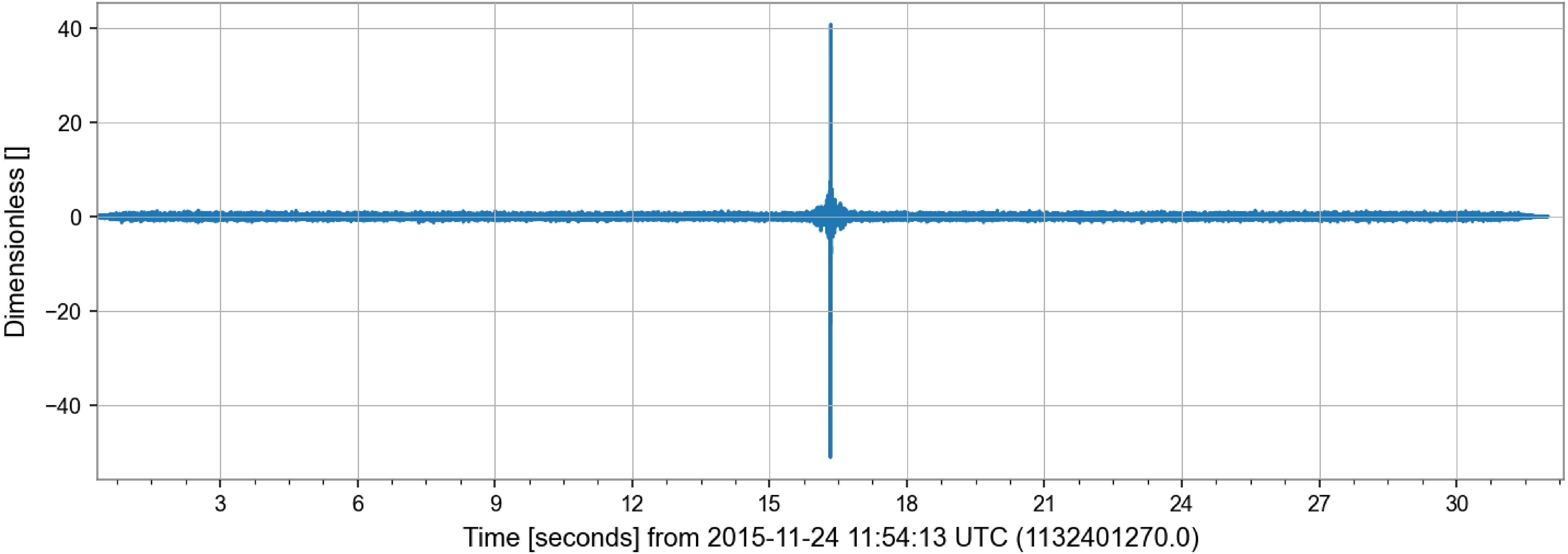


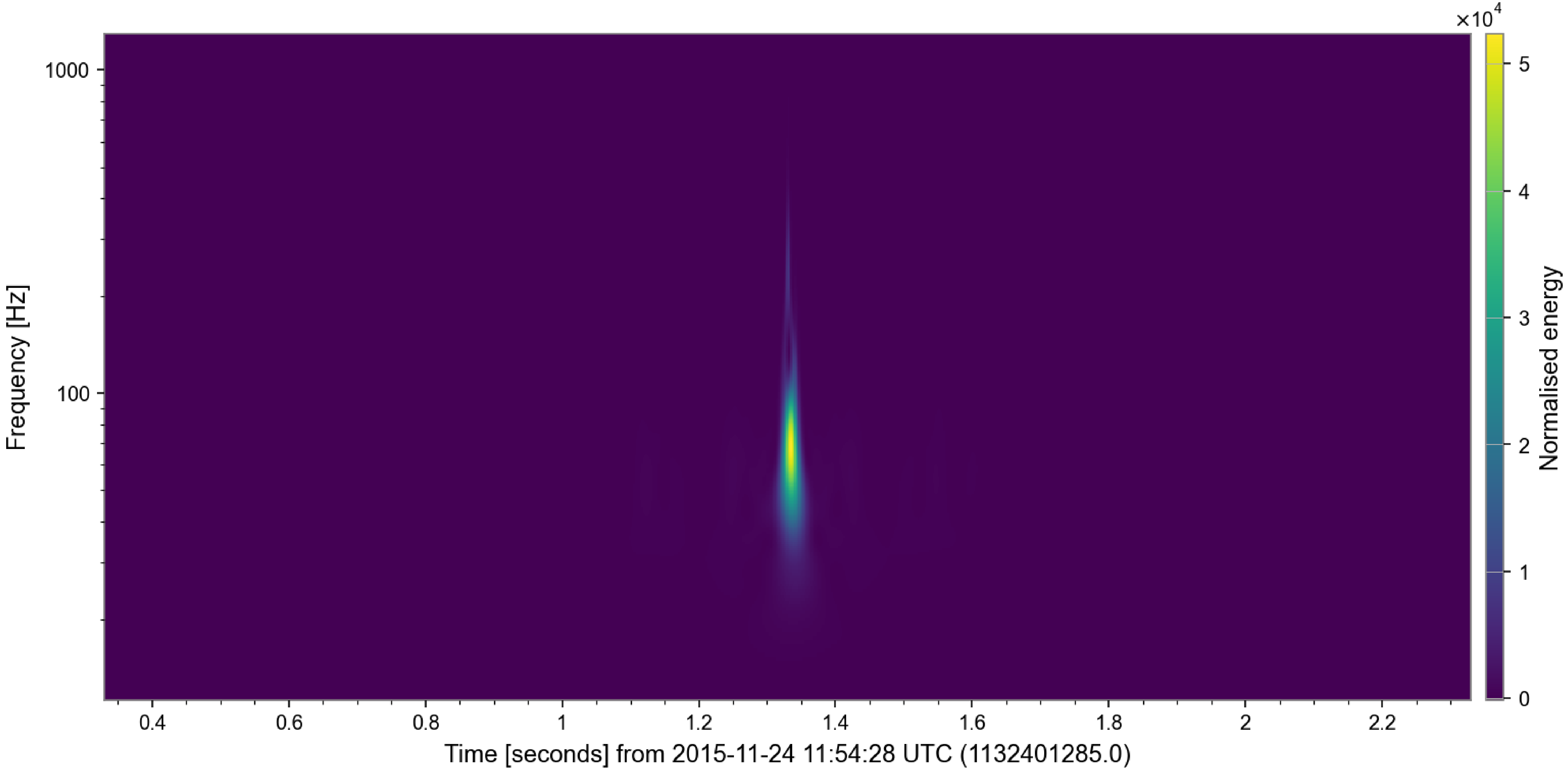
중력파 자료(0.3초) Glitch (whitening, band pass)

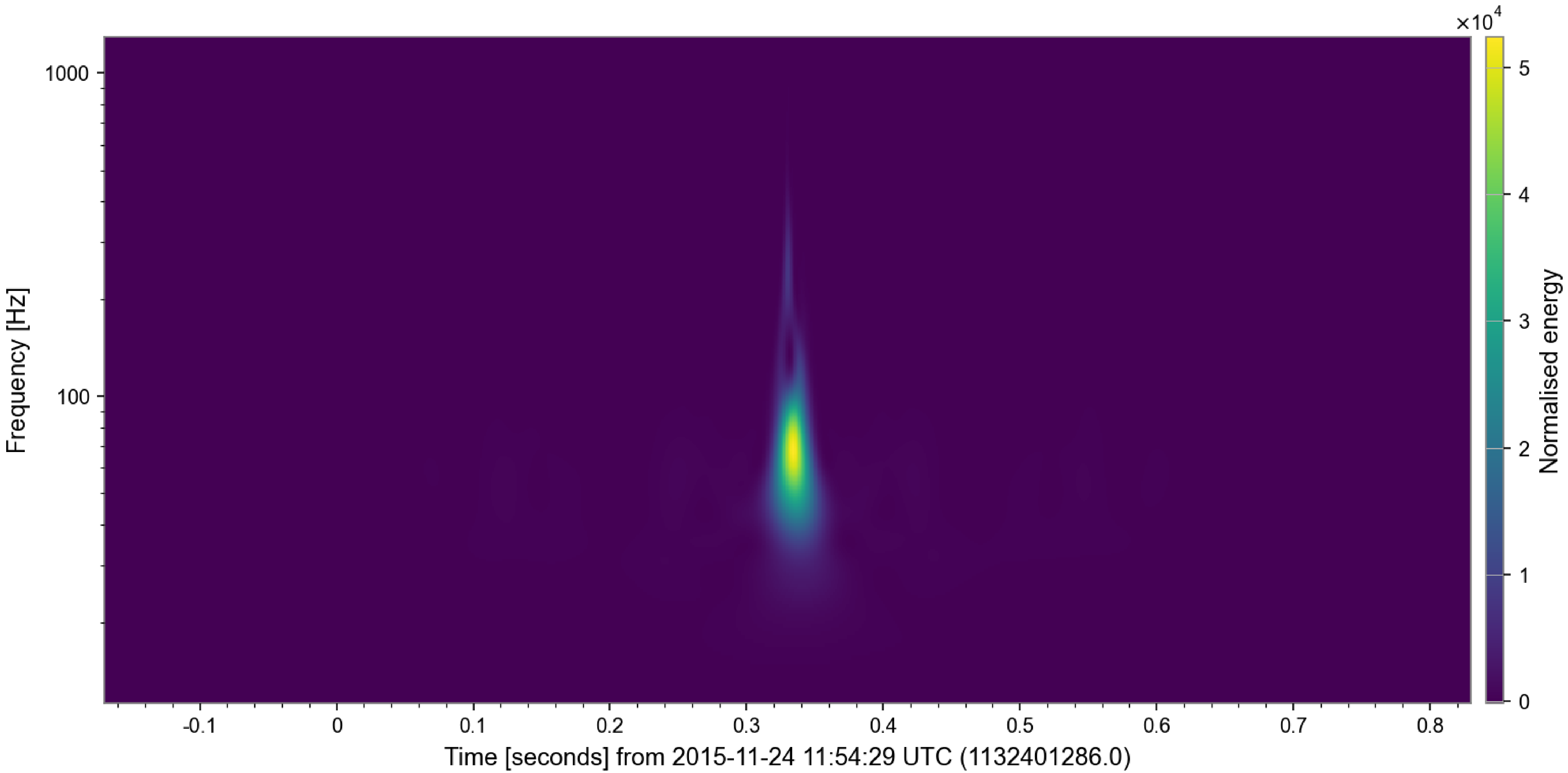
중력파 자료(4.0초) Glitch (whitening, band pass)



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




×10^4
1000
100
Frequency [Hz]
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
Time [seconds] from 2015-11-24 11:54:28 UTC (1132401285.0)
5
4
3
2
1
0
Normalised energy


×10^4
1000
100
Frequency [Hz]
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Time [seconds] from 2015-11-24 11:54:29 UTC (1132401286.0)
5
4
3
2
1
0
Normalised energy

Search vs PE

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

통계적처리 방법

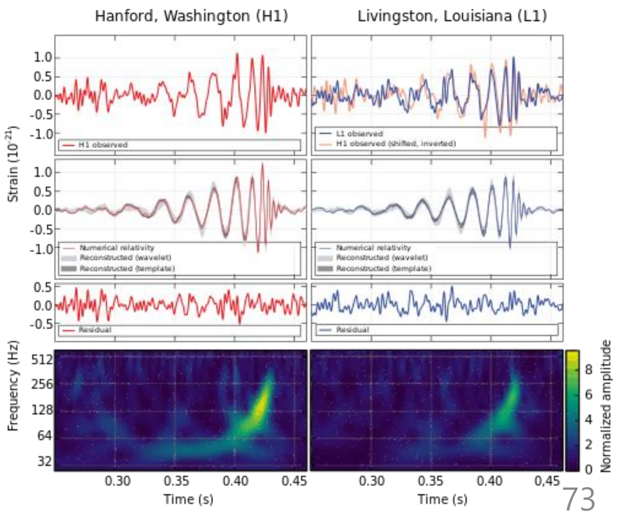
	Frequentist	Bayesian
Probability is:	Limiting relative frequency	Degree of belief
Parameter θ is a:	Fixed constant	Random variable
Probability statements are about:	procedures	parameters
Frequency guarantees?	yes	no

가능도 함수(Likelihood Function)

- 관측된 자료의 가능도 함수는 실험장치에 대한 정량적 지표이다.

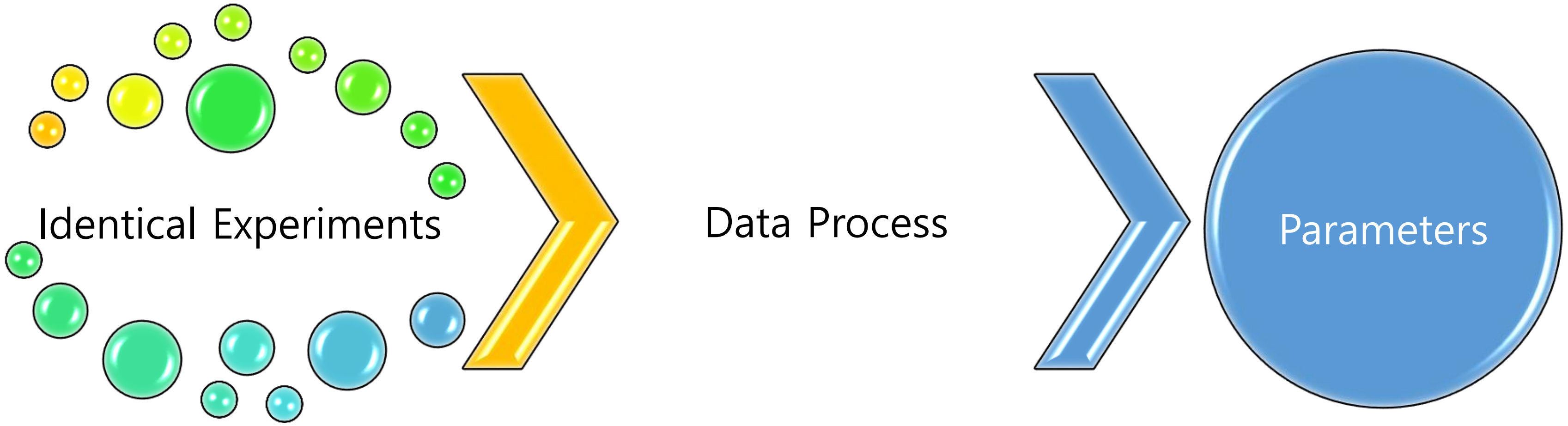
Understand Device → Calculate Probability

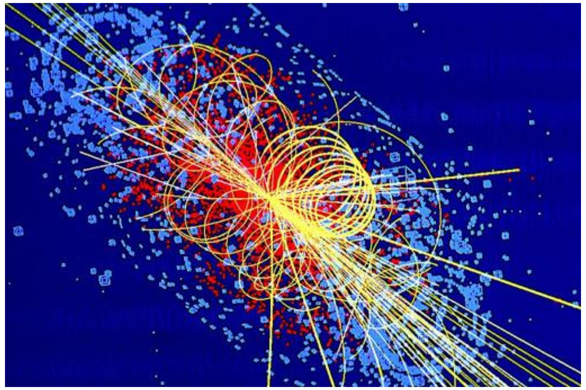
Likelihood

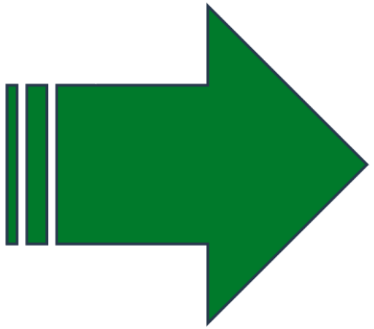


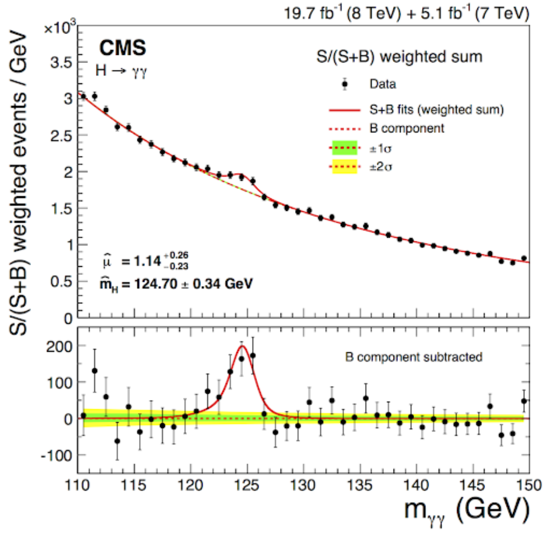
실험실 자료 처리

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









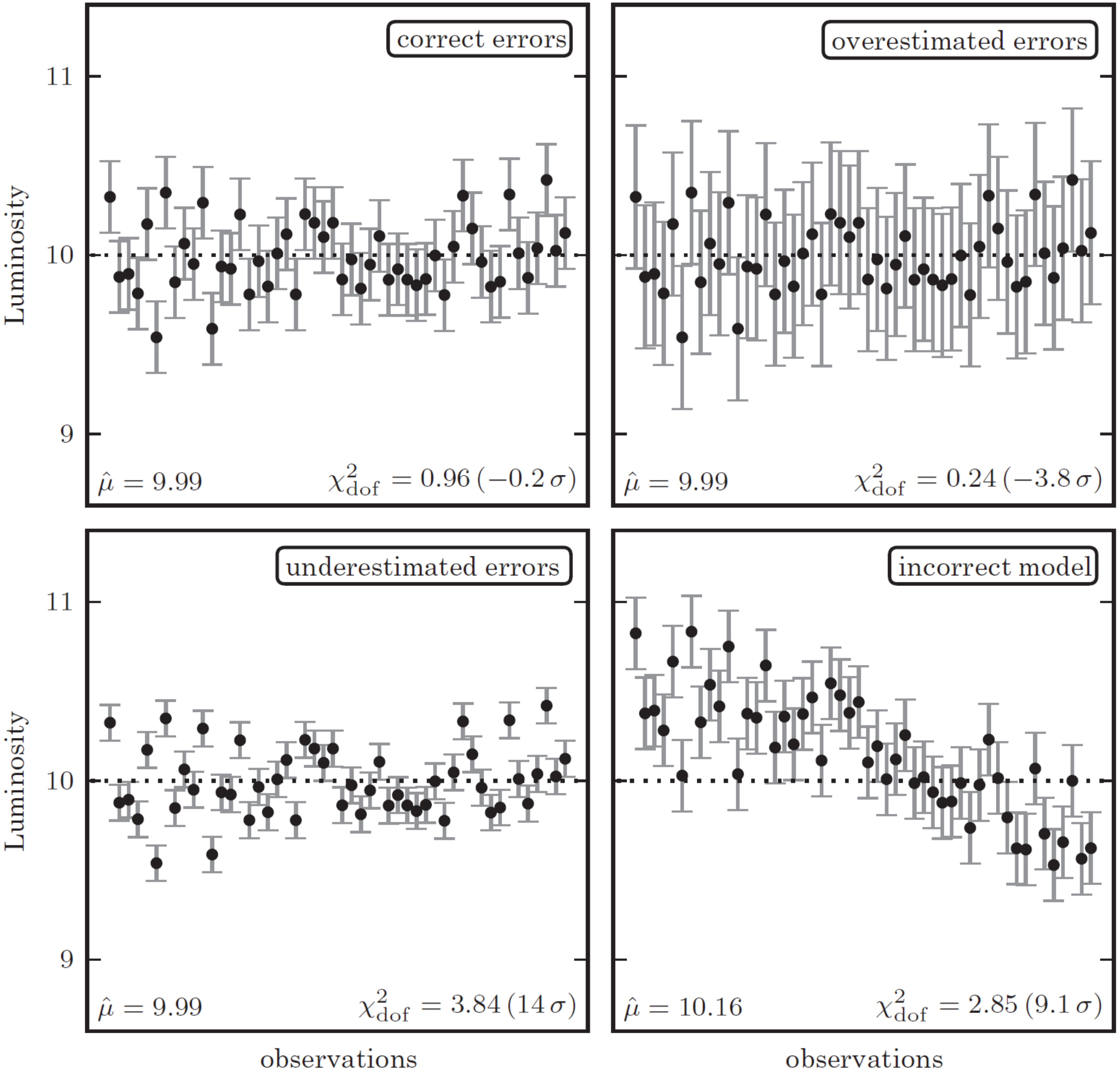
Maximum Likelihood Approach

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

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

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

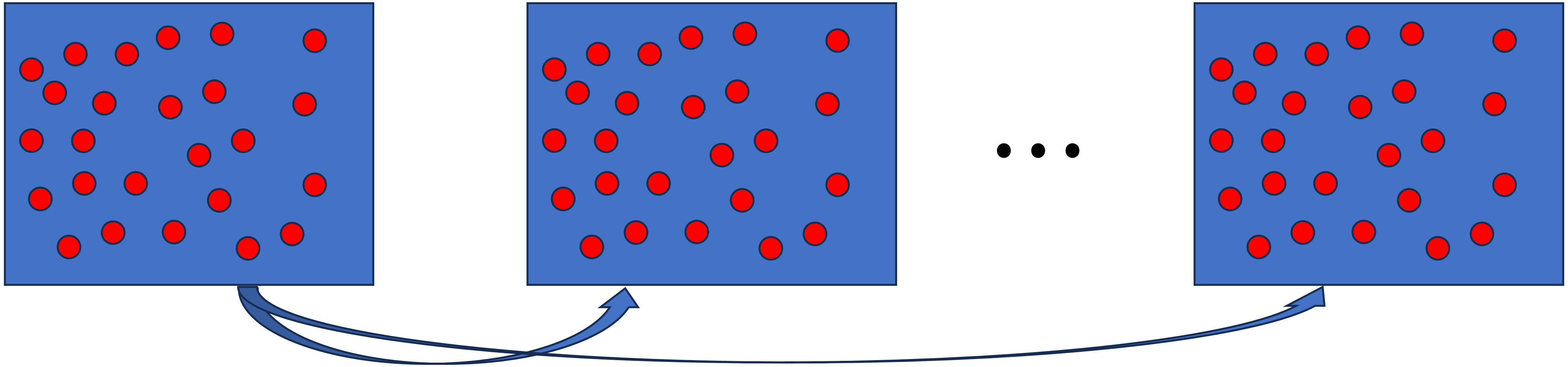


Observing fixed luminosity star

What about confidence

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

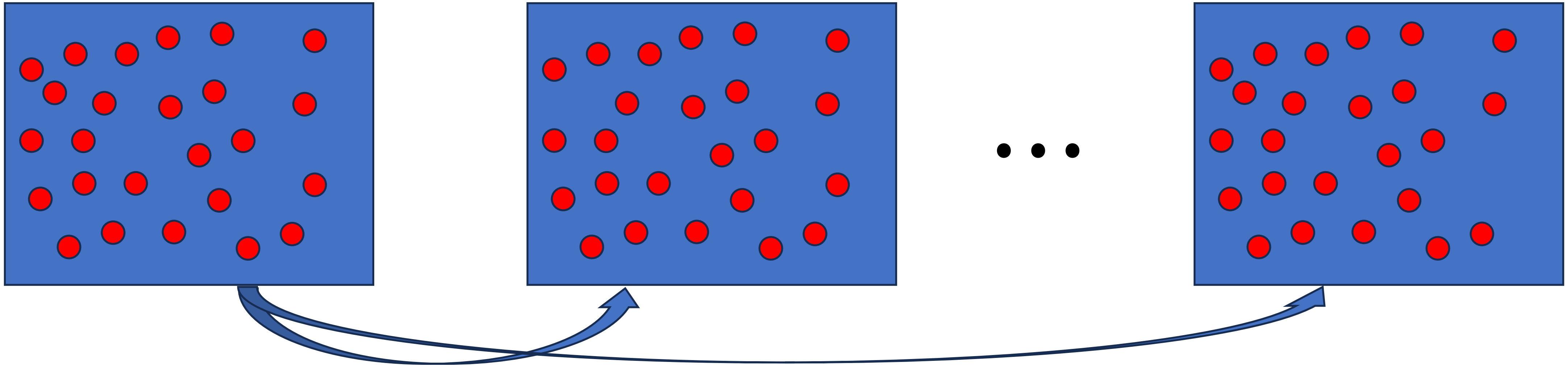
Bootstrapping



Random selections of the same sample size

Estimate the confidence level for measures values

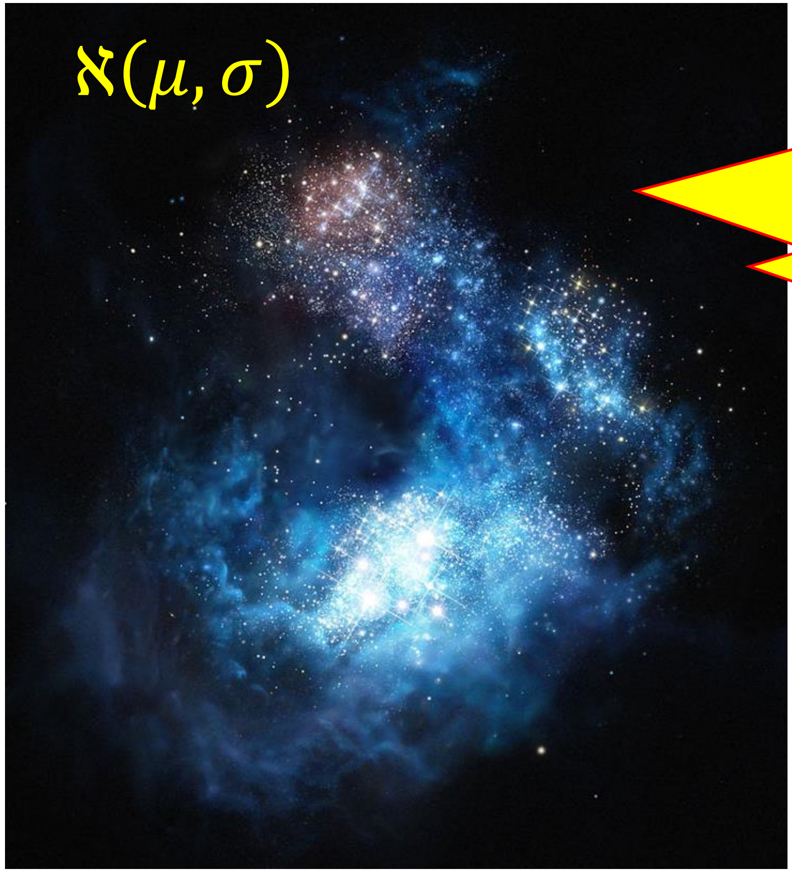
Jackknife



Random elimination of one sample

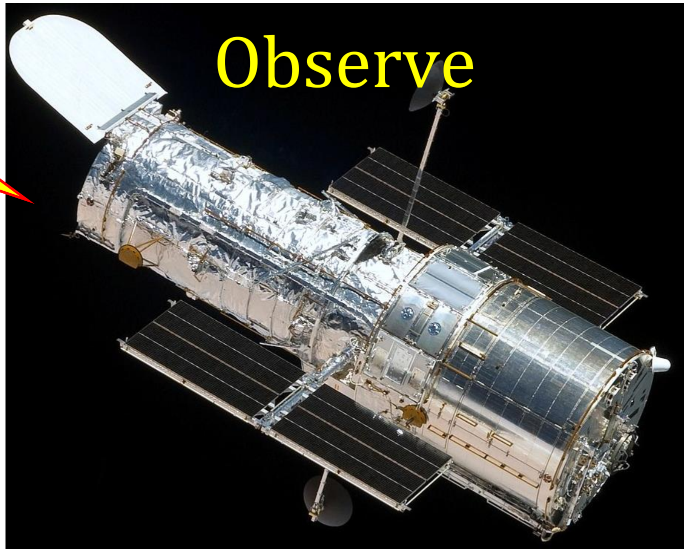
Estimate the confidence level for measures values

가능도 함수



The probability of the data given the model

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



$$x_i: \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x_i-\mu)^2}{2\sigma^2}}$$

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

Likelihood is a function of x for given model

Likelihood is a function of model parameters for given data

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

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

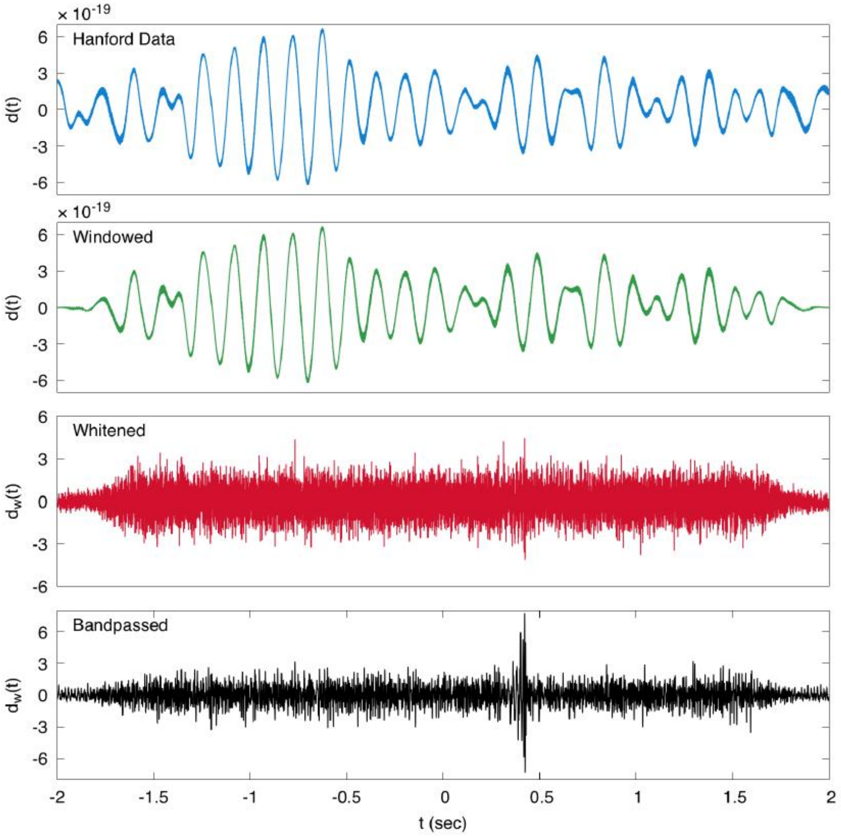
$$\Delta f = \frac{1}{T}$$

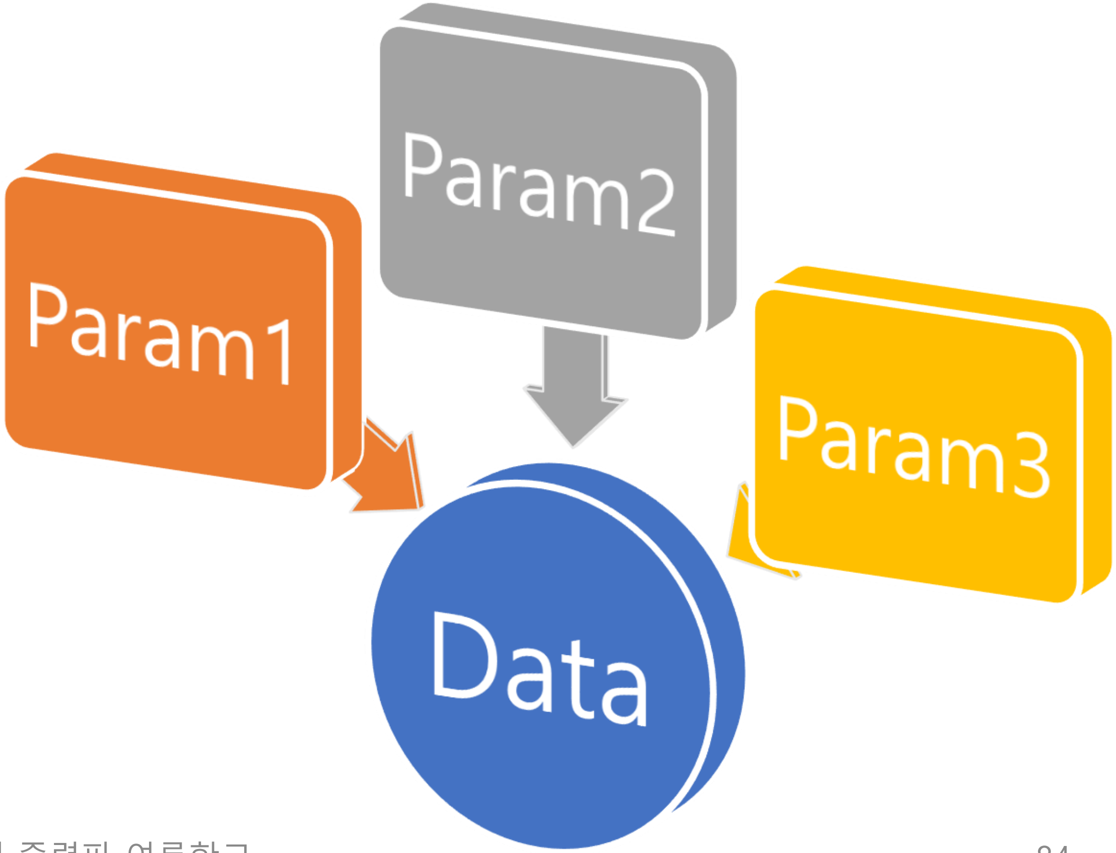
가능도 함수(Likelihood)

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

베이지언 추론

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





베이지언 추론 기본

- Bayes' rule(theorem)

사후확률 · 가능도 함수 · 사전확률 · 결합확률

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

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

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

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

베이지언 추론 과정

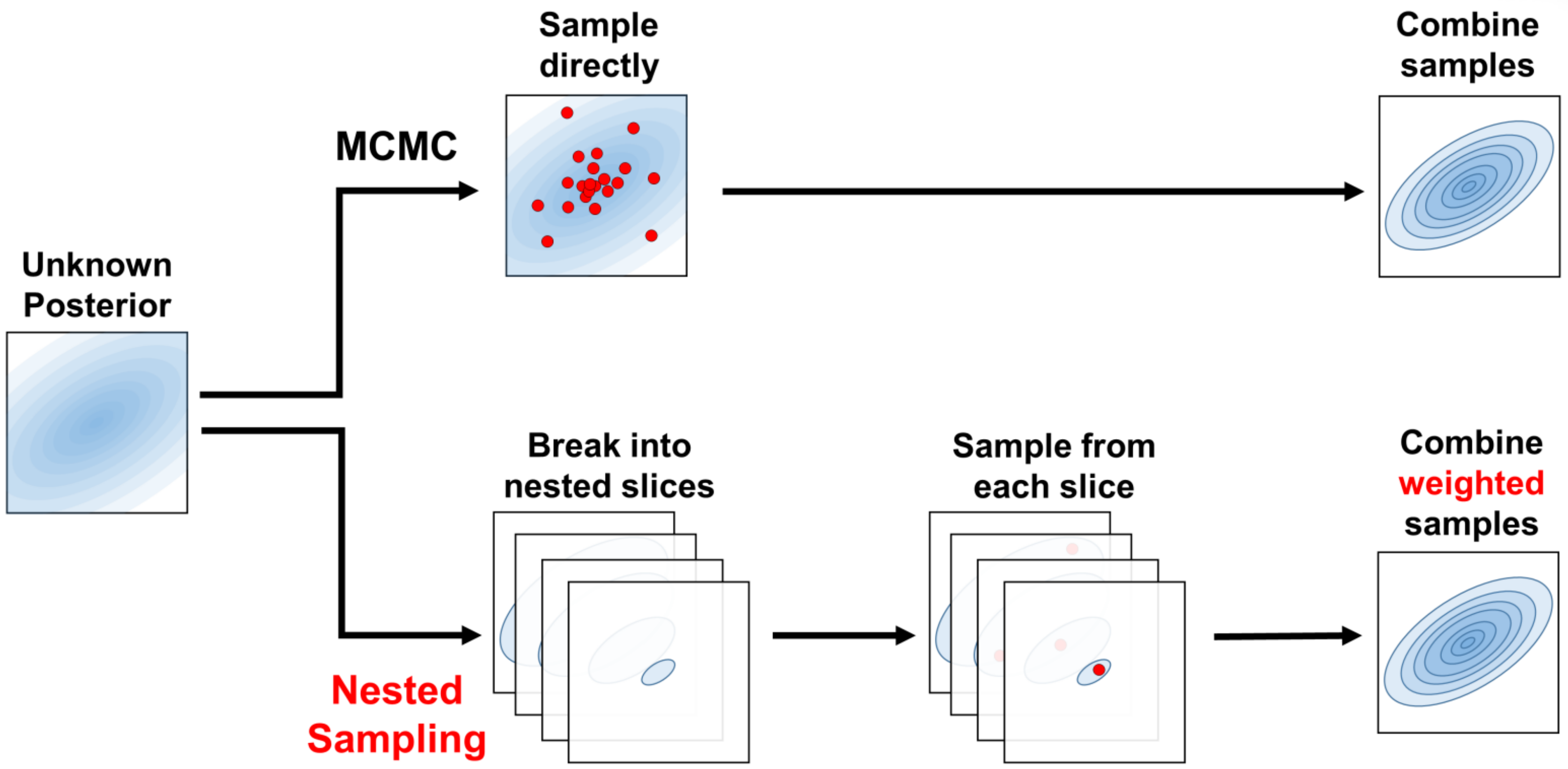
1. 가능도 함수 $p(D|\vec{\theta}, M)$ 결정
2. 매개변수에 대한 사전확률 함수 $p(\vec{\theta}|M)$ 결정
3. 사후 확률함수밀도 $p(\vec{\theta}|D, M)$ 계산
4. 최대 사후확률 값(MAP)
   최대 가능도 함수 값(ML)
   사후확률평균 $\bar{\theta} = \int \theta p(\theta|D, M) d\theta$
   $p(\theta|D, M) = \int p\left(\vec{\theta}\middle|D, M\right) d\overrightarrow{\theta'}$, 다른 매개변수에 대한 적분
5. 매개변수에 대한 분산
6. 모델과 매개변수에 대한 가설검증

marginalization

샘플 생성 방법

- Markov Chain Monte Carlo(MCMC)
- Nested Sampling

사후분포를 따르는 많은 독립적인 샘플을 생성한다



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

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

MNRAS 493, 3132(2020)

MCMC 알고리즘

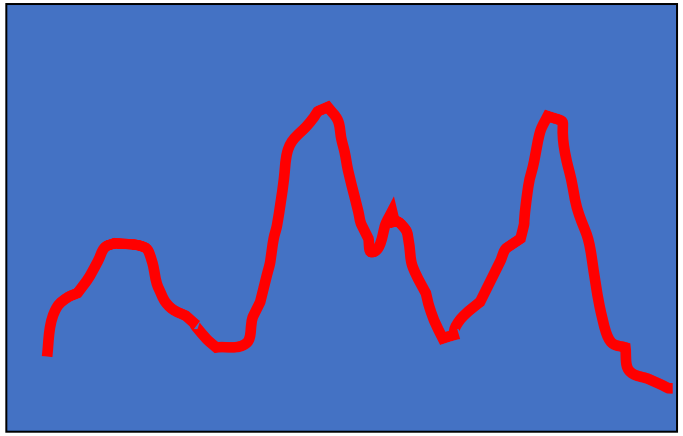
- Metropolis algorithm
- Metropolis-Hasting algorithm
- Gibbs sampling algorithm
- Hamiltonian Monte Carlo
- …

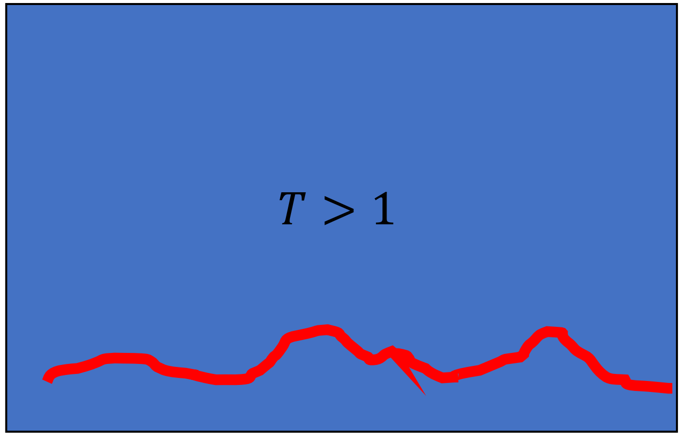
- 초기수렴(Burn In)
- 수렴(Convergence)
- 혼합(Mixing)

샘플 생성함수에 따라 수렴정도가 달라진다

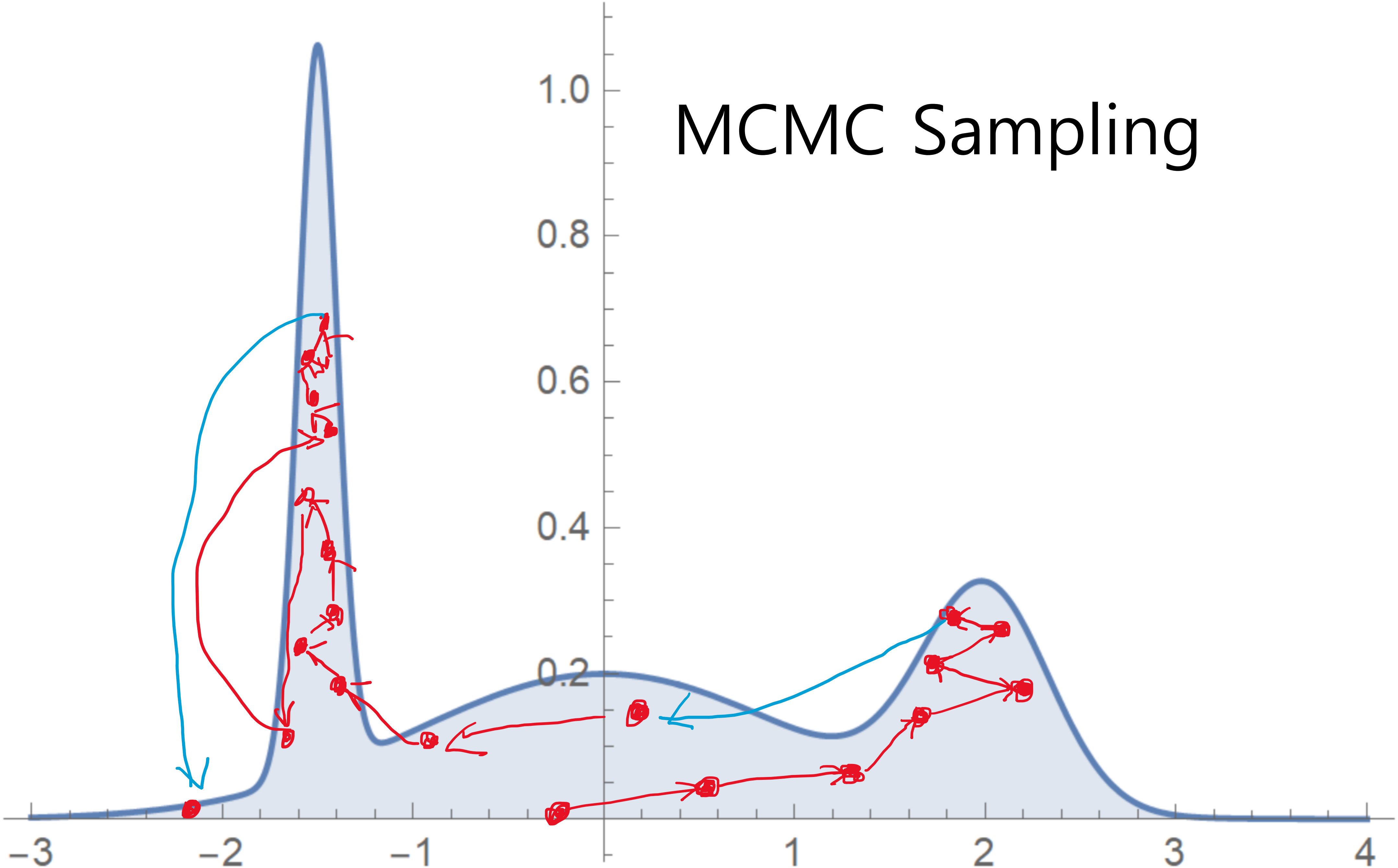
온도 병렬계산(parallel tempering)

- 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

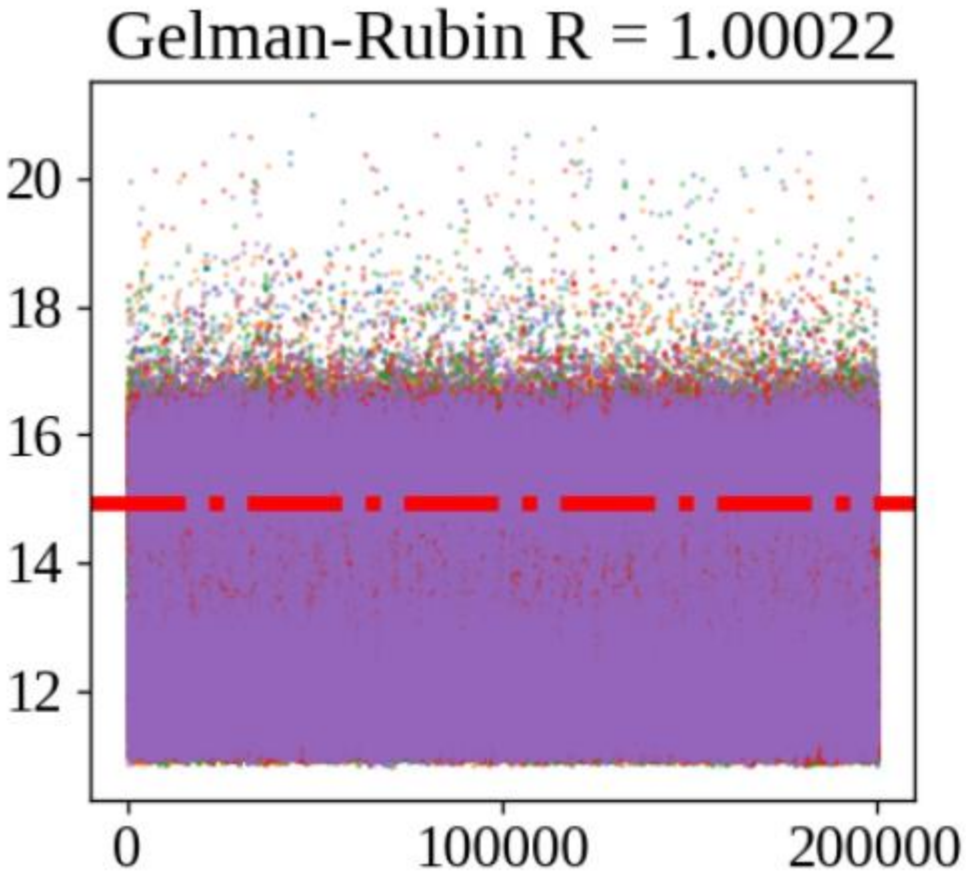


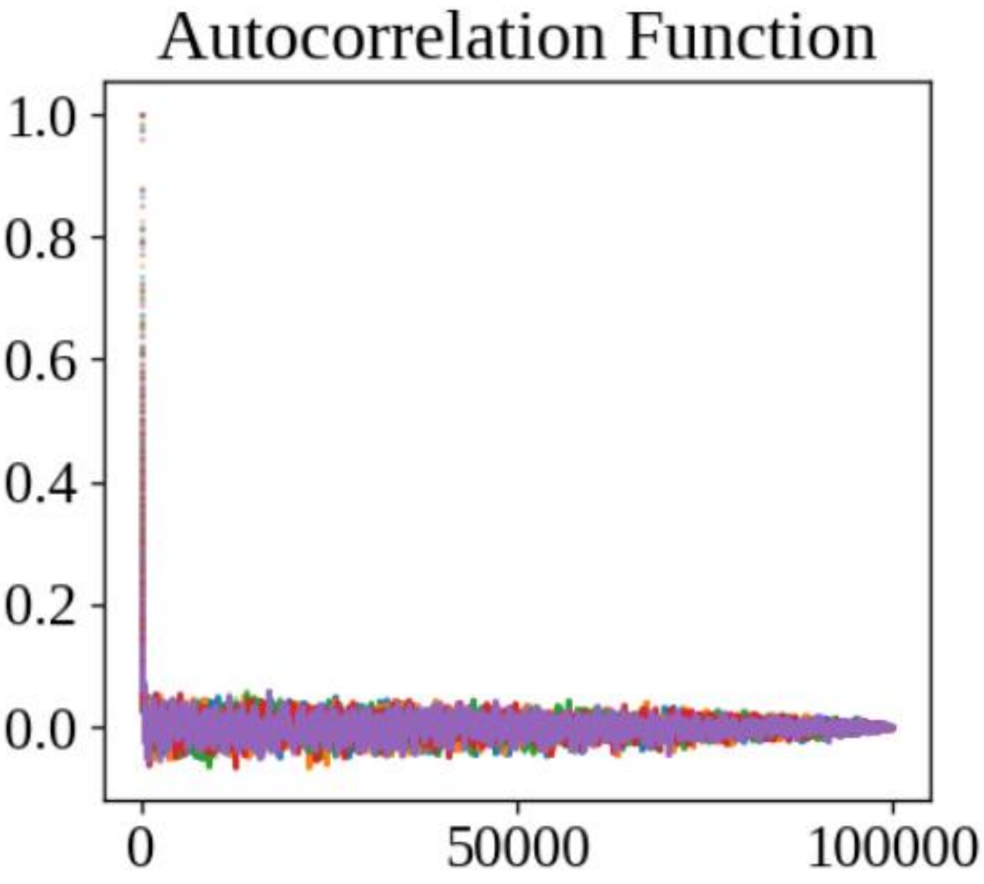


MCMC Sampling

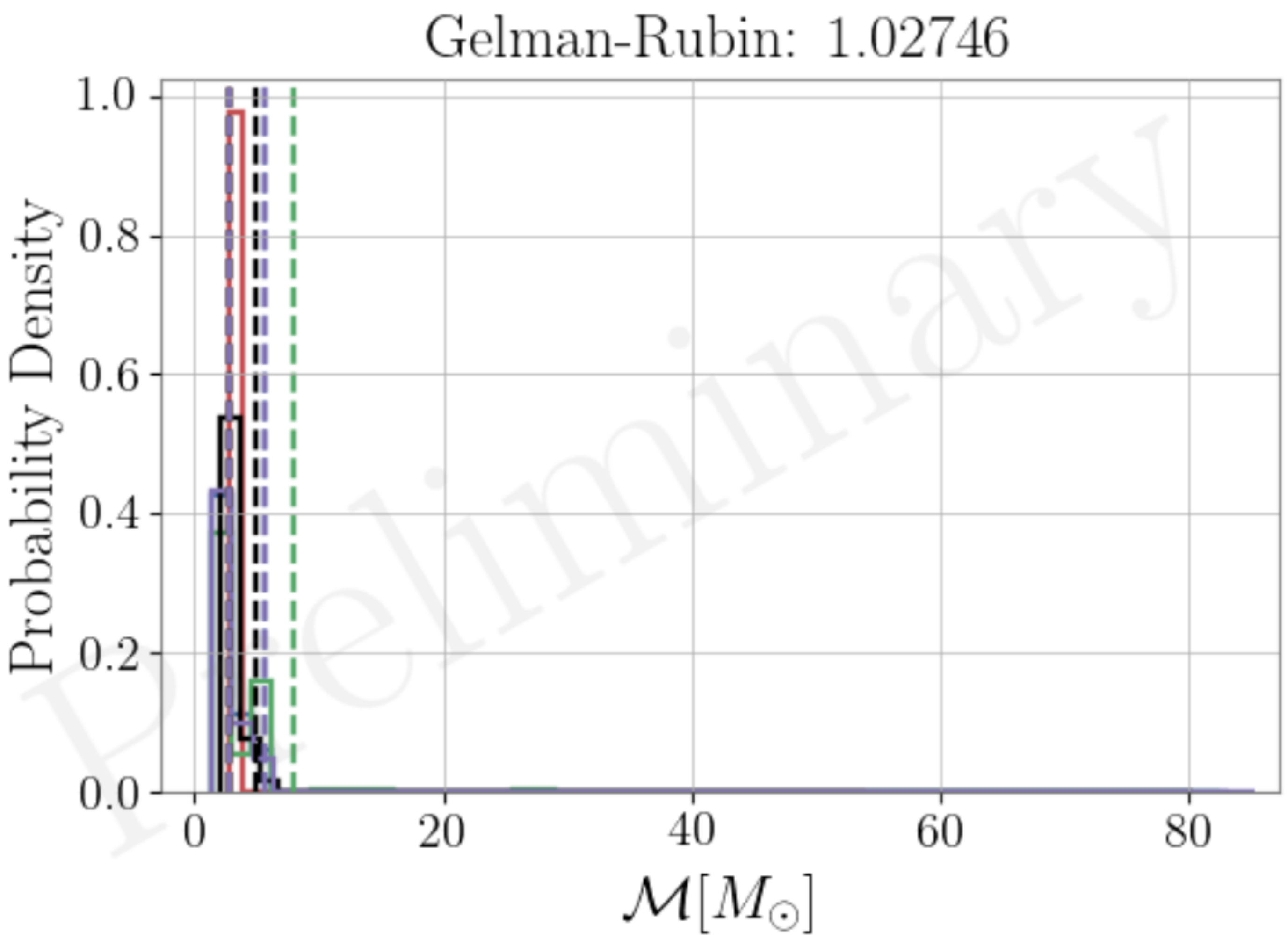


계산이 잘 되었나?

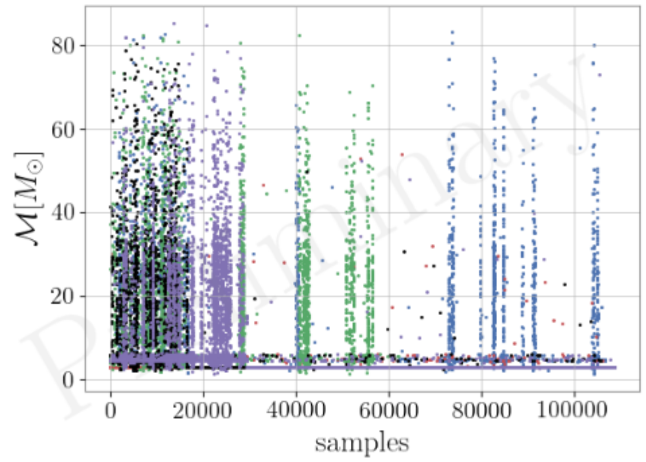

Gelman-Rubin R = 1.00022
20
18
16
14
12
0
100000
200000


Autocorrelation Function
1.0
0.8
0.6
0.4
0.2
0.0
0
50000
100000

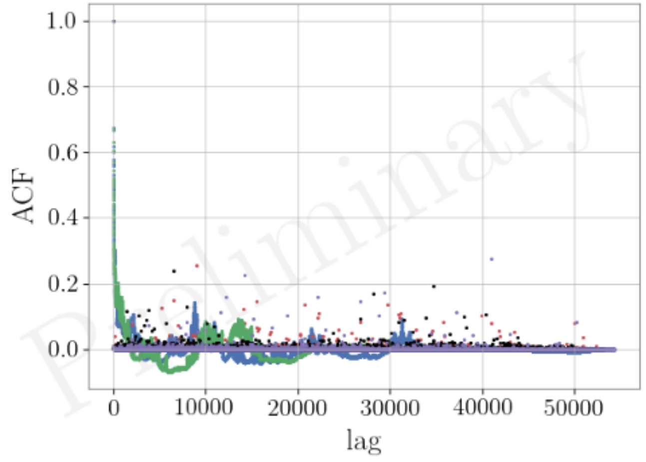
계산이 잘 되었나?



Gelman-Rubin: 1.02746
Probability Density
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
$\mathcal{M}[M_\odot]$
Preliminary



$\mathcal{M}[M_\odot]$
80
60
40
20
0
0
20000
40000
60000
80000
100000
samples
Preliminary



ACF
1.0
0.8
0.6
0.4
0.2
0.0
0
10000
20000
30000
40000
50000
lag
Preliminary

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

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

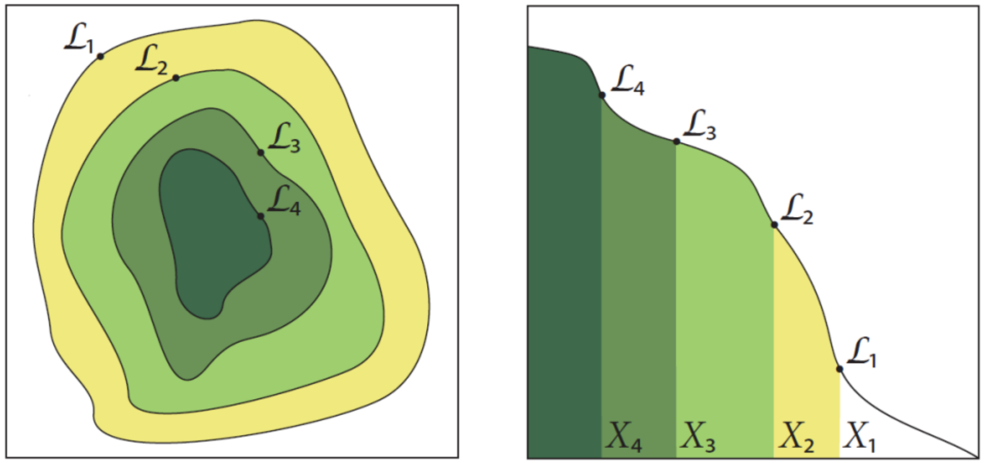
Gelman-Rubin diagnostic

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



Feroz et al. (2013)

- 믿음(evidence) 계산
- $Z = \int_{\Omega_{\vec{\theta}}} p(D|\vec{\theta}, M)p(\vec{\theta}|M)d\vec{\theta} = \int_0^1 p(D, M, X)dX$
- $X(\lambda) = \int_{\Omega_{\vec{\theta}}:p(D|\vec{\theta},M)\geq\lambda} p(D|\vec{\theta}, M)p(\vec{\theta}|M)d\vec{\theta}$,
  $X(\lambda = 0) = 1, X(\lambda = \infty) = 0$

높은 차원의 적분을 효과적으로 1차원 적분으로 계산

Algorithm 1: Static Nested Sampling

```
// Initialize live points.
```
Draw K "live" points$\{\boldsymbol{\Theta}_1, \ldots, \boldsymbol{\Theta}_K\}$ from the prior $\pi(\boldsymbol{\Theta})$.
```
// Main sampling loop.
```
while stopping criterion not met **do**

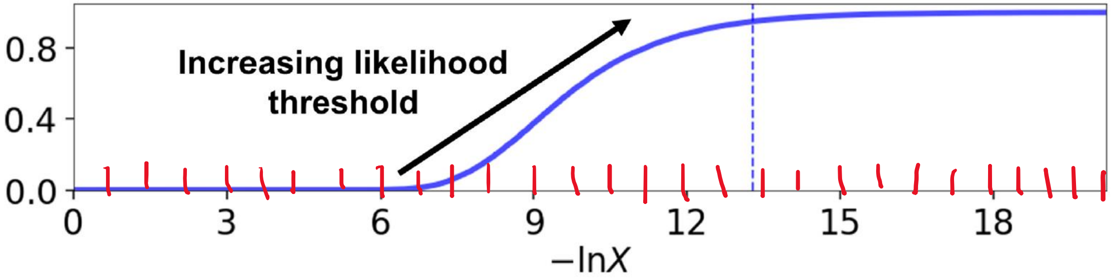
- Compute the minimum likelihood $\mathcal{L}^{\min}$ among thecurrent set of live points.
- Add the kth live point $\boldsymbol{\Theta}_k$ associated with $\mathcal{L}^{\min}$to a list of "dead" points.
- Sample a new point $\boldsymbol{\Theta}'$ from the prior subject to the constraint$\mathcal{L}(\boldsymbol{\Theta}') \geq \mathcal{L}^{\min}$.
- Replace $\boldsymbol{\Theta}_k$ with $\boldsymbol{\Theta}'$.
- `// Check whether to stop.`
- Evaluate stopping criterion.

end
```
// Add final live points.
```
while $K > 0$ **do**

- Compute the minimum likelihood $\mathcal{L}^{\min}$ among thecurrent set of live points.
- Add the kth live point $\boldsymbol{\Theta}_k$ associated with $\mathcal{L}^{\min}$to a list of "dead" points.
- Remove $\boldsymbol{\Theta}_k$ from the set of live points.
- Set $K = K - 1$.

end

등간격 적분



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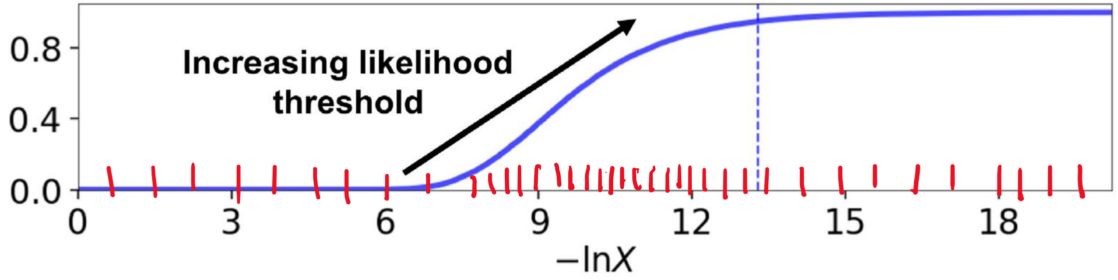
반응형 간격 적분

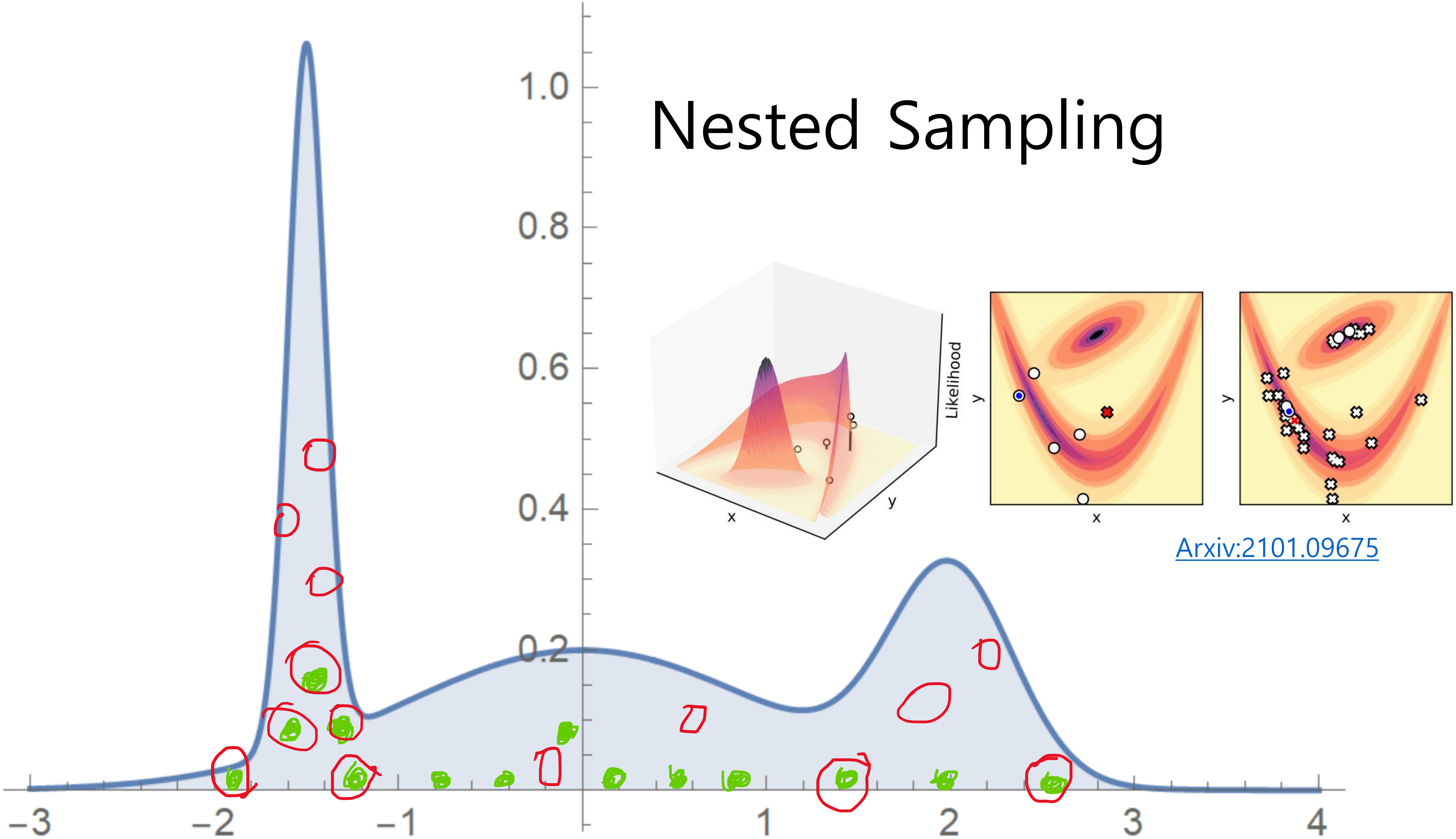


Algorithm 2: Dynamic Nested Sampling

// Initialize first set of live points.
Draw K "live" points$\{\boldsymbol{\Theta}_1, \ldots, \boldsymbol{\Theta}_K\}$ from the prior $\pi(\boldsymbol{\Theta})$.
// 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 thecurrent number of live points K'.
  if $K' \geq K$ **then**
    // Add in new live points.
    while $K' > K$ **do**
      Sample a new point $\boldsymbol{\Theta}'$ from the prior subject to the constraint$\mathcal{L}(\boldsymbol{\Theta}') \geq \mathcal{L}^{\min}$.
      Add $\boldsymbol{\Theta}'$ to the set of live points.
      Set $K = K + 1$.
    end
    // Replace worst live point.
    Compute the minimum likelihood $\mathcal{L}^{\min}$ among thecurrent set of K live points.
    Add the kth live point $\boldsymbol{\Theta}_k$associated with $\mathcal{L}^{\min}$to a list of "dead" points.
    Replace $\boldsymbol{\Theta}_k$ with $\boldsymbol{\Theta}'$.
  else
    // Iteratively remove live points.
    while $K' < K$ **do**
      Compute the minimum likelihood $\mathcal{L}^{\min}$ among thecurrent set of $K = K'$ live points.
      Add the kth live point $\boldsymbol{\Theta}_k$ associated with $\mathcal{L}^{\min}$to a list of "dead" points.
      Remove $\boldsymbol{\Theta}_k$ 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 thecurrent set of live points.
  Add the kth live point $\boldsymbol{\Theta}_k$ associated with $\mathcal{L}^{\min}$to a list of "dead" points.
  Remove $\boldsymbol{\Theta}_k$ from the set of live points.
end

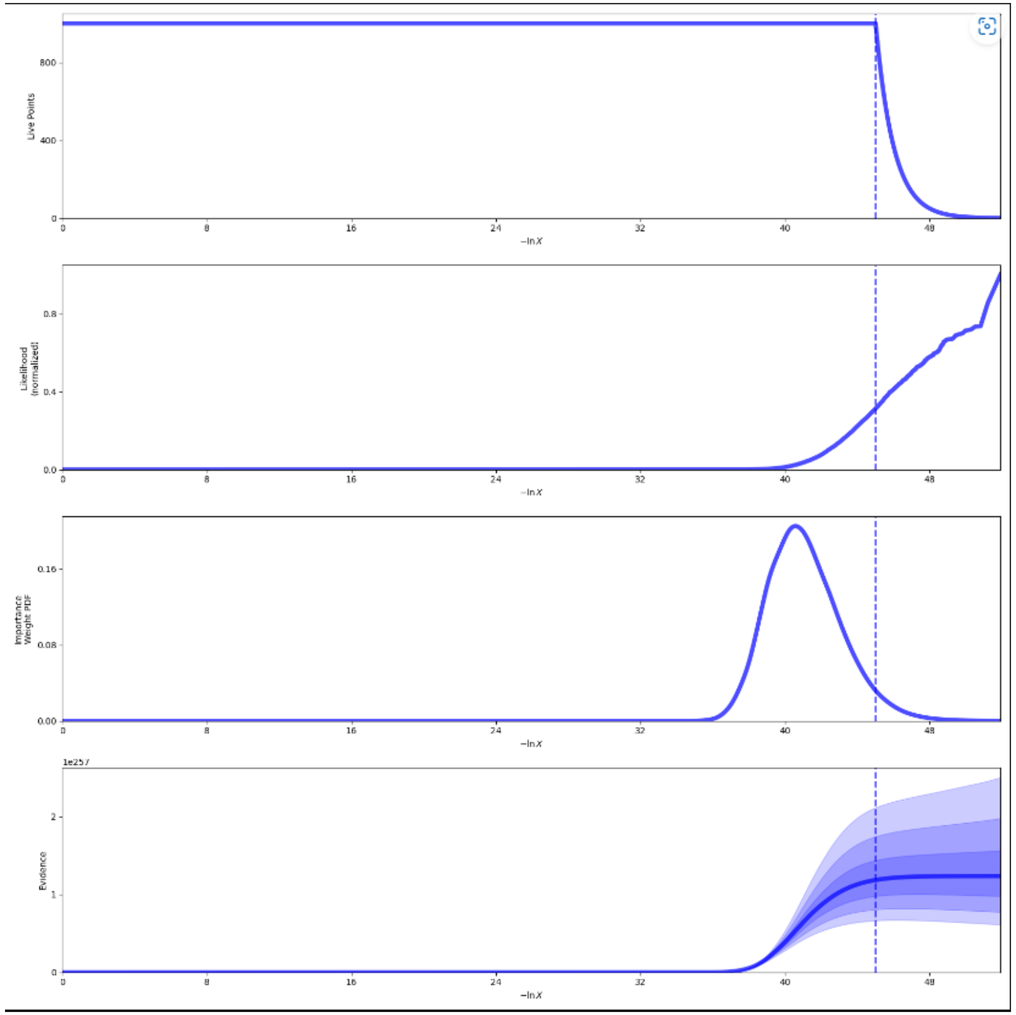
MNRAS 493, 3132(2020)

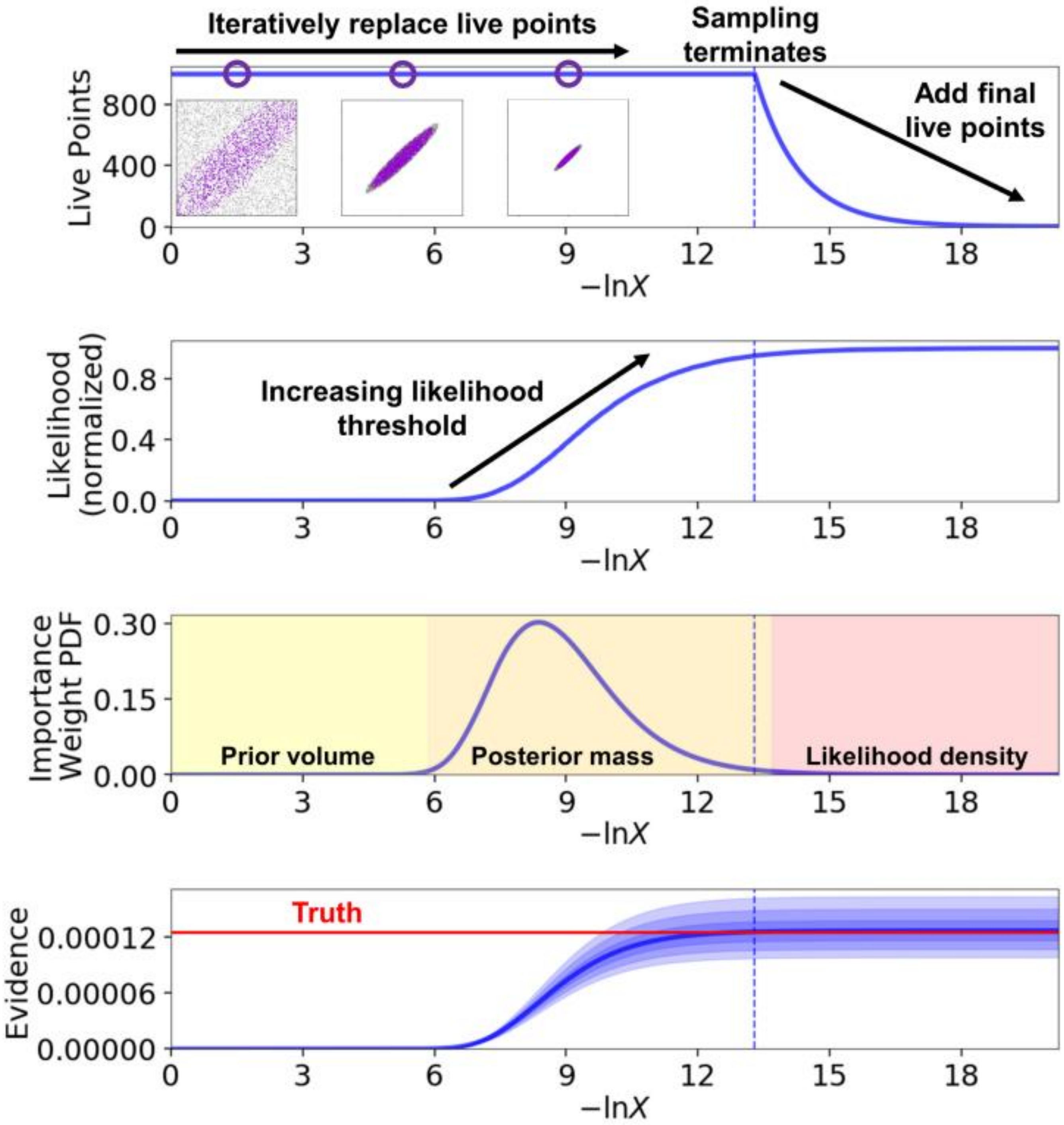
Nested Sampling



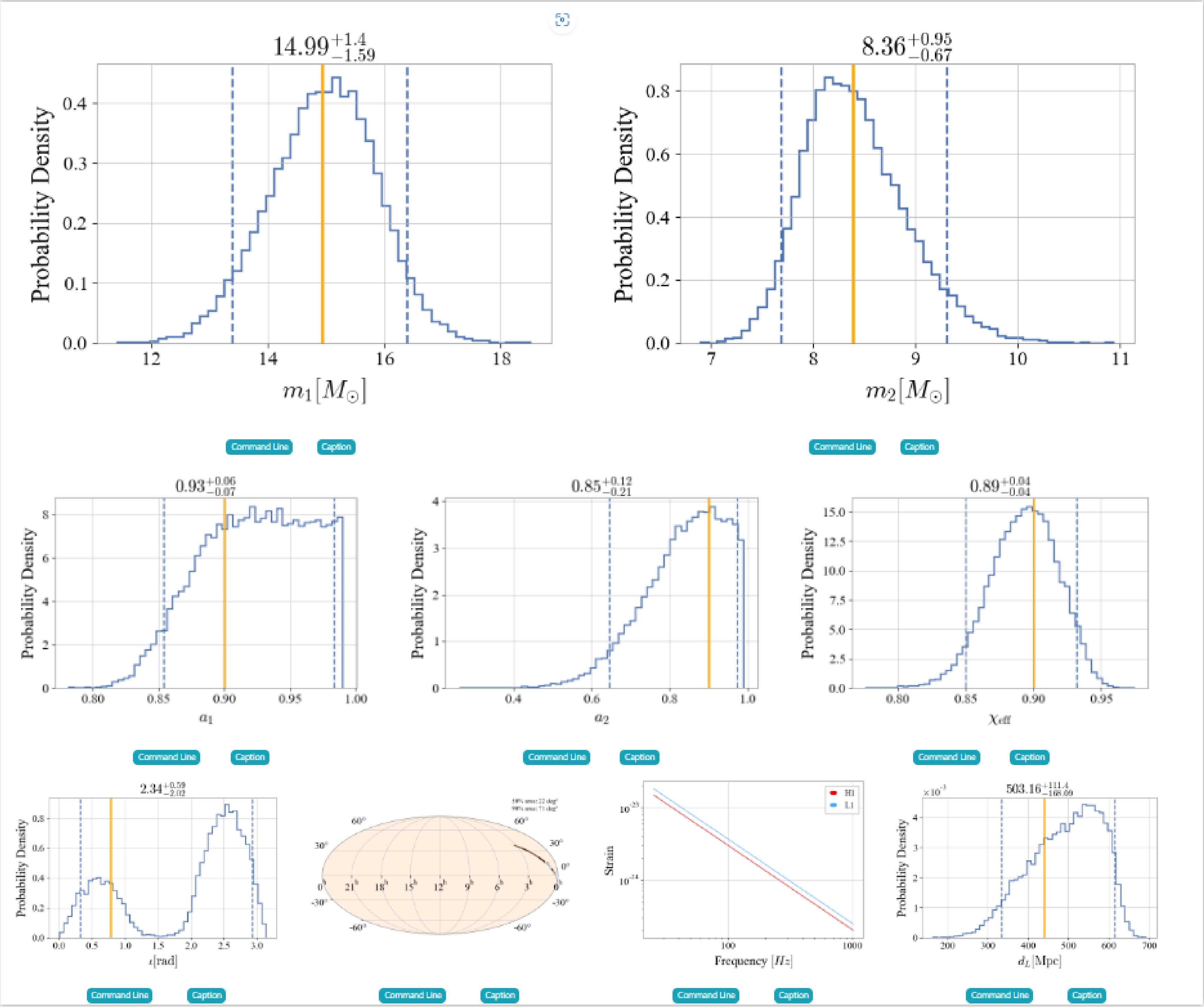
Arxiv:2101.09675

계산이 잘 되었나?




Iteratively replace live points
Sampling terminates
Add final live points
Live Points
−lnX
Likelihood (normalized)
Increasing likelihood threshold
Importance Weight PDF
Prior volume
Posterior mass
Likelihood density
Evidence
Truth

계산이 잘 되었나?



2024-07-31

분석도구

LALSuite(LALSuite: Main Page (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):

- !FrameL- LIGO/Virgo Frame library (needed for LALFrame)
- !MetaIO - 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 rebust:

```
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 managament 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))

lalinference_mcmc
lalinference_nest

Documentation

Here is a list of all modules:

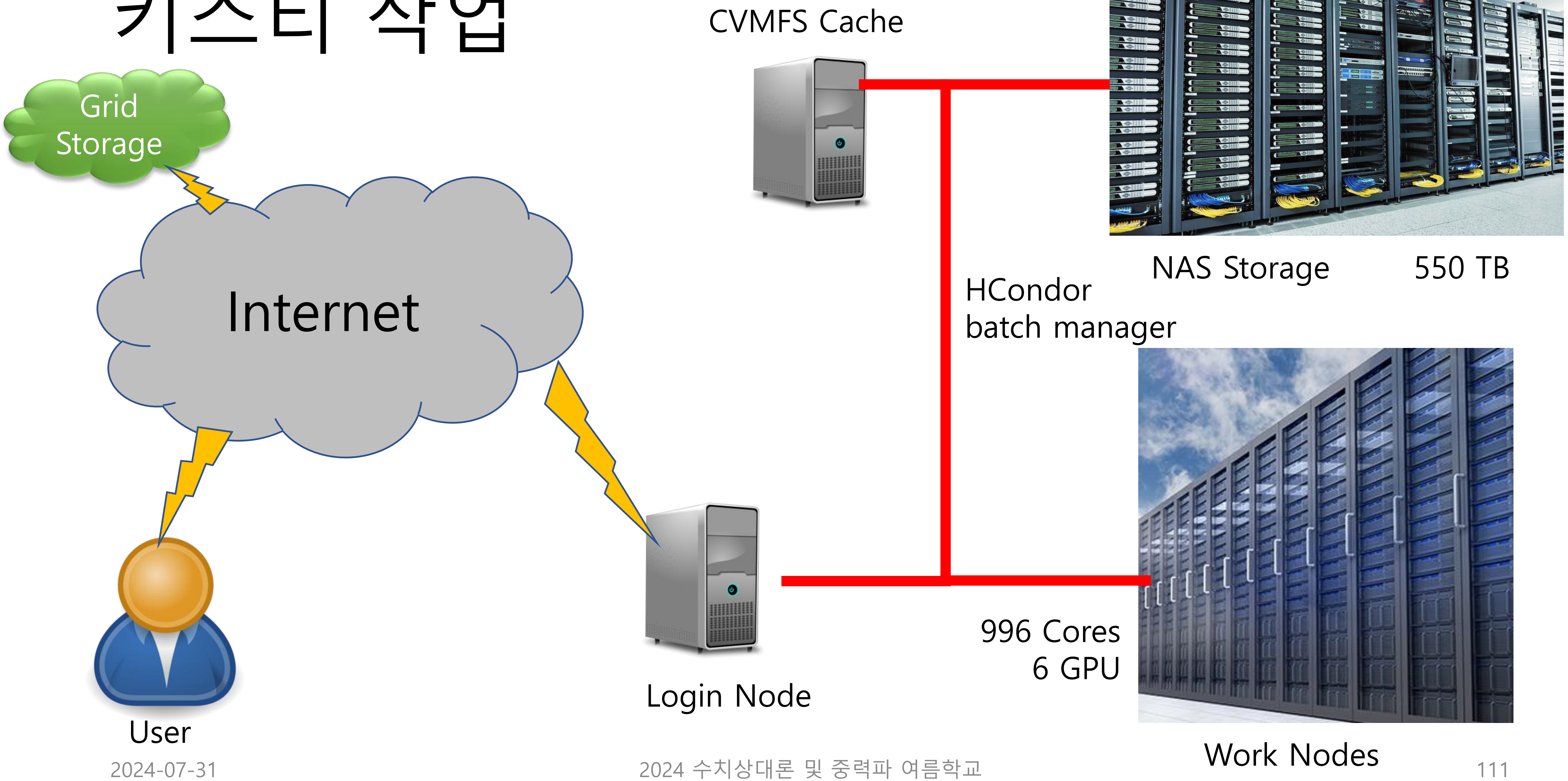
▼ General Packages	
Header LALInference.h	Main header file for LALInference common routines and structures
Header LALInferenceLikelihood.h	Header file for likelihood functions used by LALInference codes
Header LALInferenceNestedSampler.h	Nested sampler written for LALInference
Header LALInferencePrior.h	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 *before* the LALInference headers
Interface SWIGLALInferenceOmega.i	SWIG code which must appear *after* 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.

software freedom conservancy

키스티 작업


CVMFS Cache
Grid
Storage
Internet
NAS Storage
550 TB
HCondor
batch manager
User
Login Node
996 Cores
6 GPU
Work Nodes

작업 수행

[screen 0: bash] hwlee@ldg-ui01:/data/ligo/scratch/hwlee/eccwork/gw151226/ecc-ecc-0.04

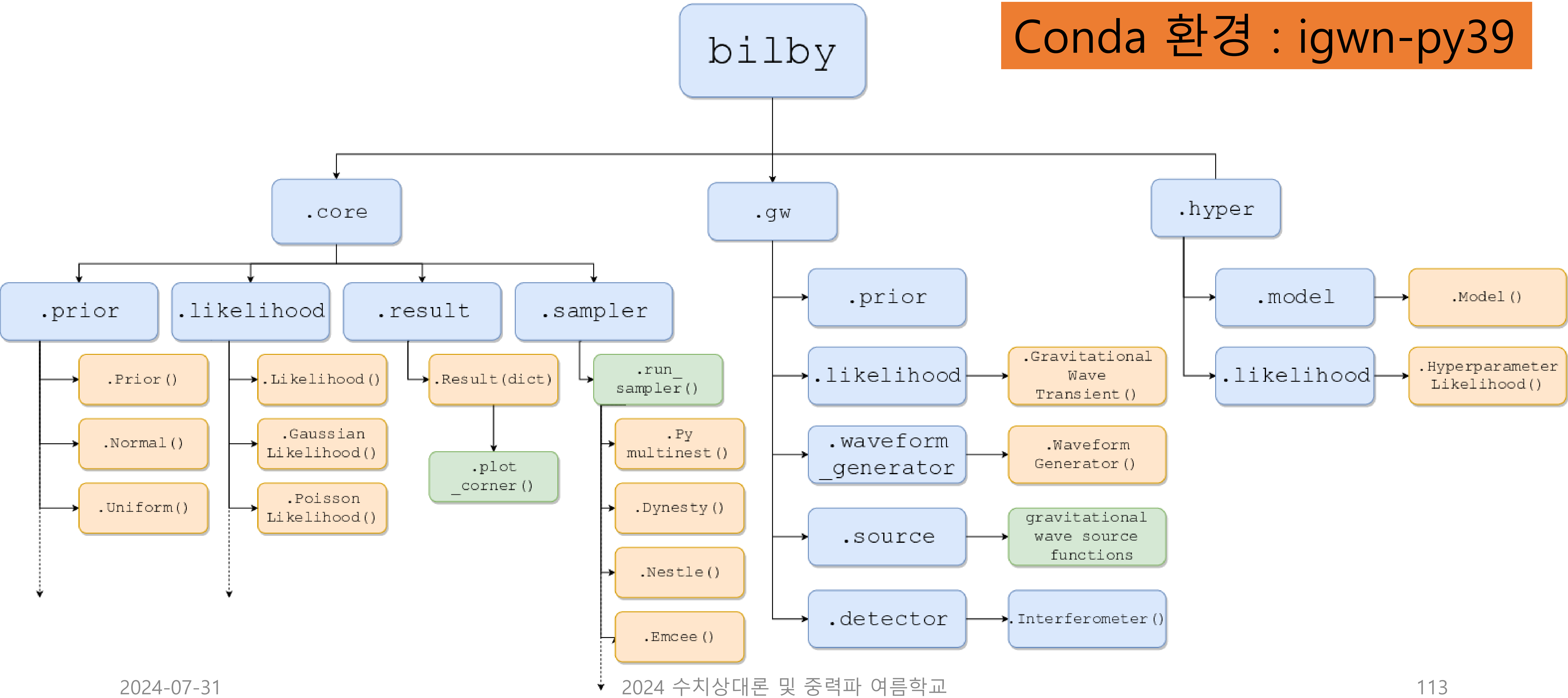
```
#!/bin/sh

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 1.1 documentation (ligo.org))

Conda 환경 : igwn-py39



Installation

Conda   Pip

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

Supported python versions: 3.6+.

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.

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.

Quickstart and output

To use the `bilby_mcmc` sampler, we call

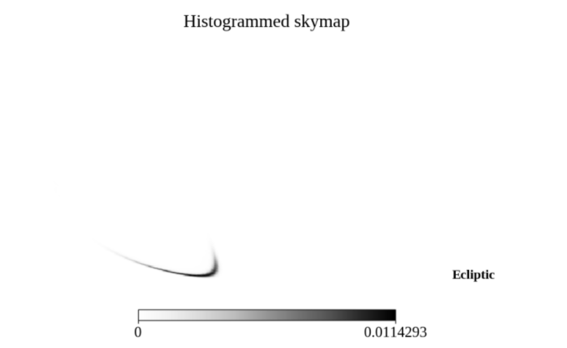
```
>>> bilby.run_sampler(likelihood, priors, sampler="bilby_mcmc", nsamples=1000)
```

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

후처리 도구

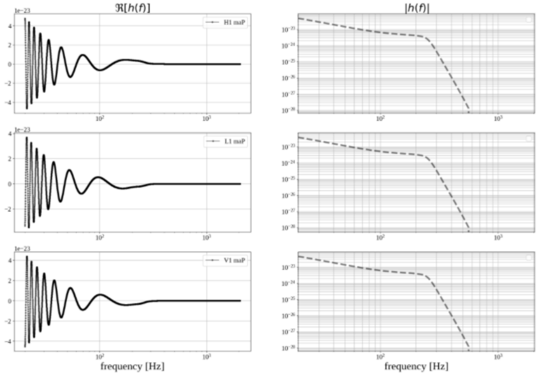
CBCBayesPostProc

SkyMap

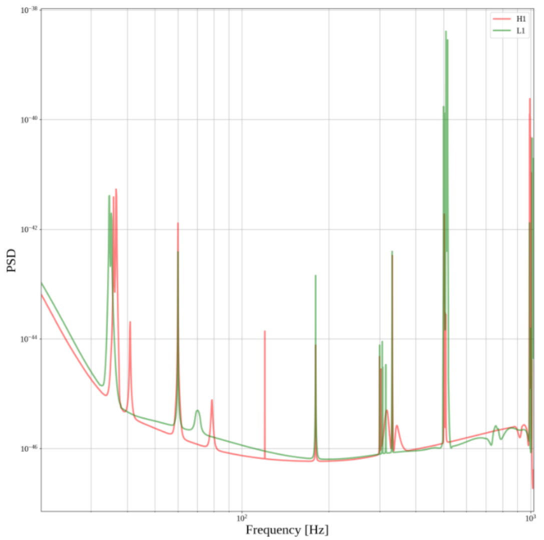


Confidence region	size (sq. deg)
0.67	93.4763
0.9	196.342
0.95	274.344
0.99	666.714

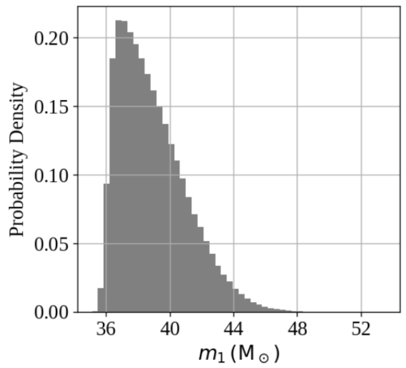
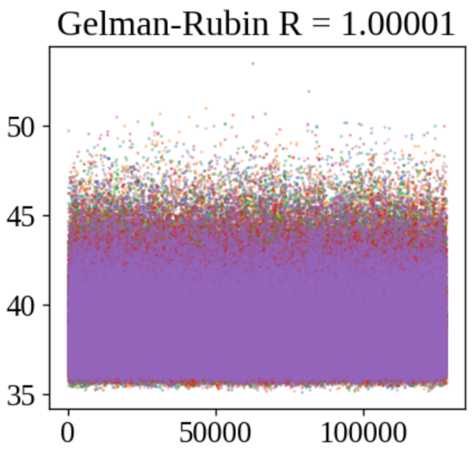
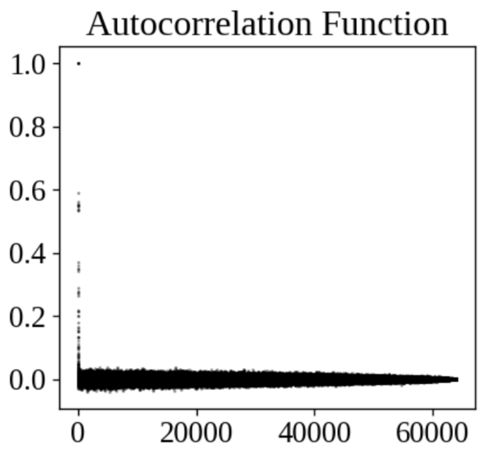
Waveforms



PSDs

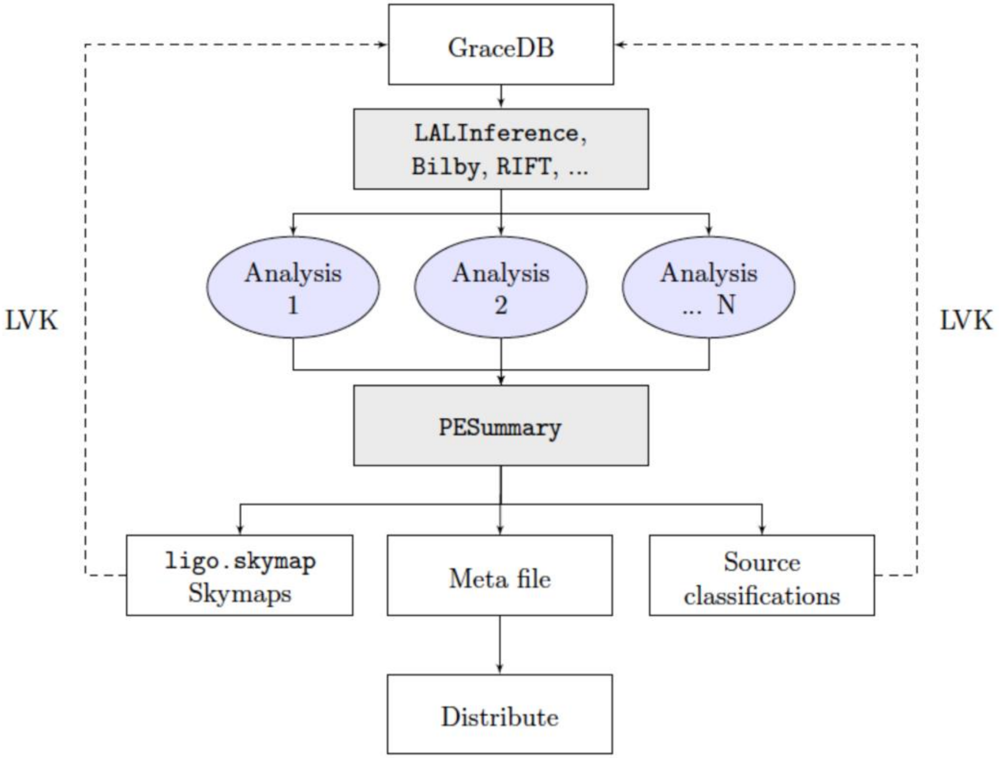


Top | **1D marginal posterior PDFs (Masses)** | [-] Collapse

Histogram and Kernel Density Estimate	Samples used	Autocorrelation
		

PESummary(PESummary (ligo.org))

- 모수추정 후처리 결과 생성 라이브러리



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
```

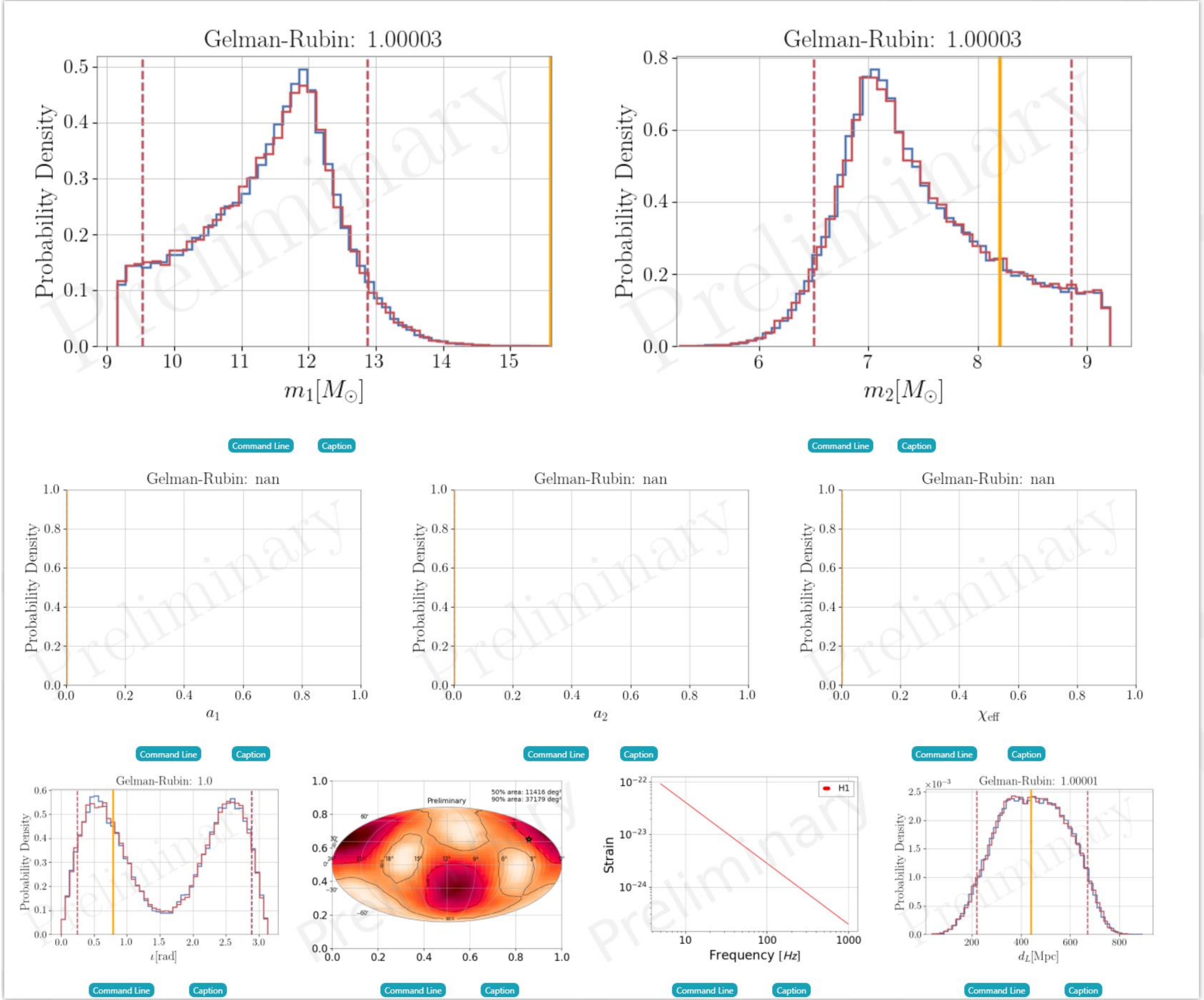
Pulling the PESummary docker image

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

```
$ docker pull 08hoyc/pesummary
```

PESummary 출력

- Bootstrap css
- Interactive

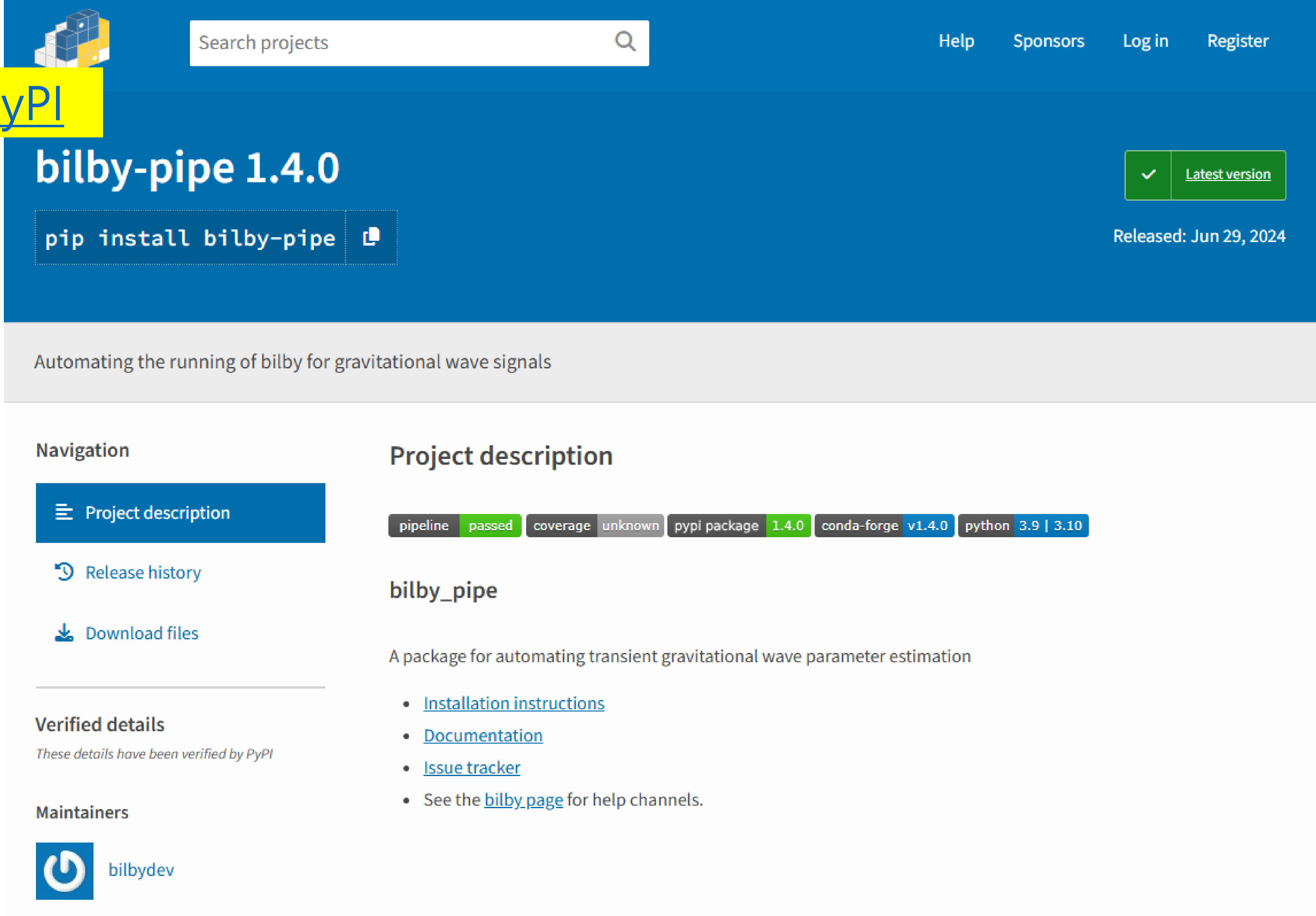


bilby_pipe

[lscsoft / bilby_pipe · GitLab (ligo.org)]

conda activate igwn

[bilby-pipe · PyPI]



How bilby_pipe works?

Data Generation →

- Reading strain Data
- PSD

Data Analysis →

- Nested Sampling
- Merge Results

Post Process

- PESummary
- PDF plots
- Webpages

How to Run

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

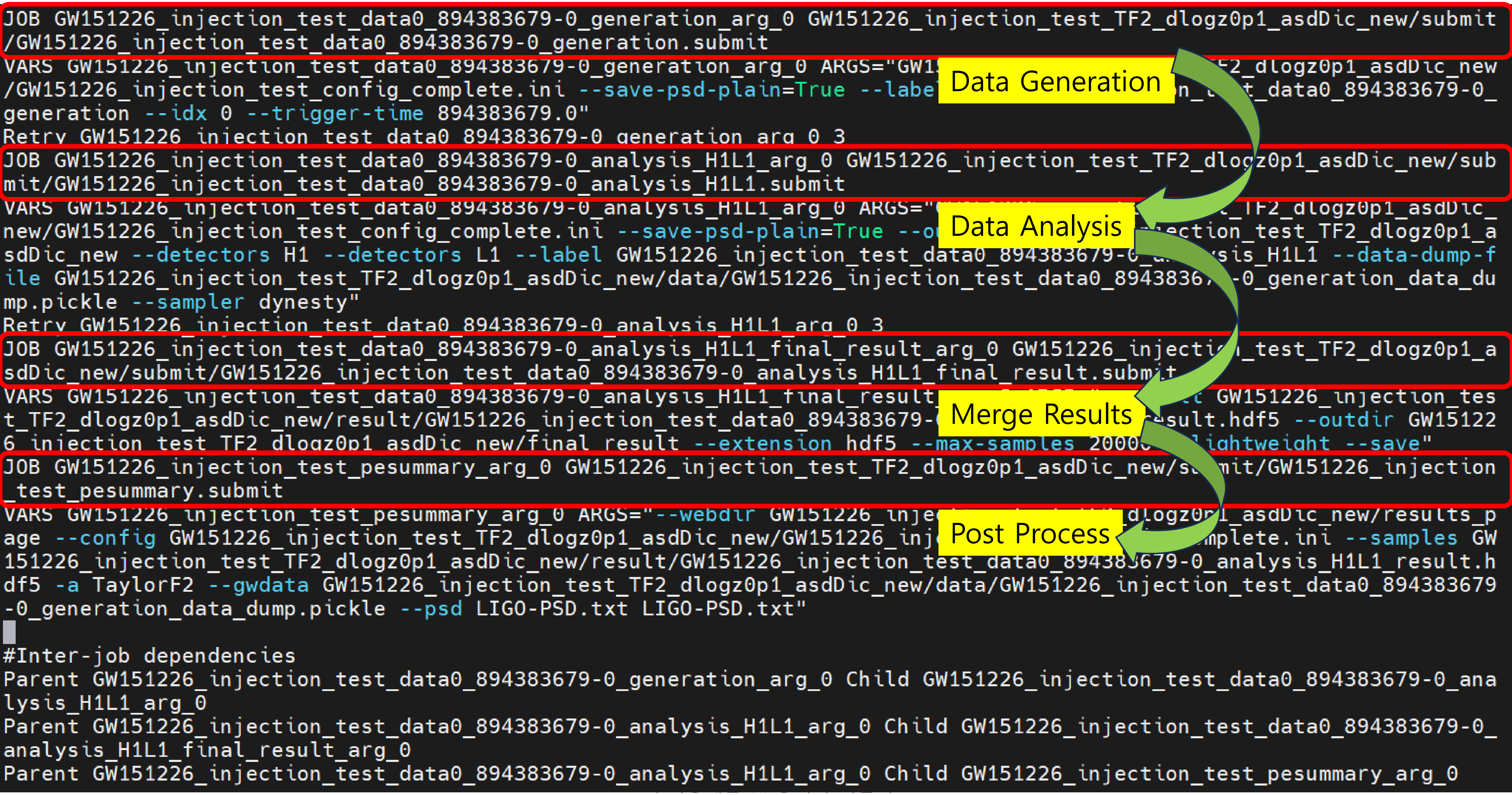
```
my-run.ini
outdir/
  -> data/
  -> log_data_analysis/
  -> log_data_generation/
  -> log_results_page/
  -> result/
  -> results_page/
  -> submit/
```

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-kwargs = {'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="GW15                  F2_dlogz0p1_asdDic_new
/GW151226_injection_test_config_complete.ini --save-psd-plain=True --labe                  n_t  t_data0_894383679-0_
generation --idx 0 --trigger-time 894383679.0"
Retry 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/sub
mit/GW151226_injection_test_data0_894383679-0_analysis_H1L1.submit
VARS GW151226_injection_test_data0_894383679-0_analysis_H1L1_arg_0 ARGS="                 _TF2_dlogz0p1_asdDic_
new/GW151226_injection_test_config_complete.ini --save-psd-plain=True --o                 jection_test_TF2_dlogz0p1_a
sdDic_new --detectors H1 --detectors L1 --label GW151226_injection_test_data0_894383679-0_a    ysis_H1L1 --data-dump-f
ile GW151226_injection_test_TF2_dlogz0p1_asdDic_new/data/GW151226_injection_test_data0_8943836  -0_generation_data_du
mp.pickle --sampler dynesty"
Retry 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_injecti n_test_TF2_dlogz0p1_a
sdDic_new/submit/GW151226_injection_test_data0_894383679-0_analysis_H1L1_final_result.subm t
VARS GW151226_injection_test_data0_894383679-0_analysis_H1L1_final_result                  t GW151226_injection_tes
t_TF2_dlogz0p1_asdDic_new/result/GW151226_injection_test_data0_894383679-                  esult.hdf5 --outdir GW15122
6_injection_test_TF2_dlogz0p1_asdDic_new/final_result --extension hdf5 --max-samples 2000     lightweight --save"
JOB GW151226_injection_test_pesummary_arg_0 GW151226_injection_test_TF2_dlogz0p1_asdDic_new/s  mit/GW151226_injection
_test_pesummary.submit
VARS GW151226_injection_test_pesummary_arg_0 ARGS="--webdir GW151226_inje                  dlogz0p1_asdDic_new/results_p
age --config GW151226_injection_test_TF2_dlogz0p1_asdDic_new/GW151226_inj                  mplete.ini --samples GW
151226_injection_test_TF2_dlogz0p1_asdDic_new/result/GW151226_injection_test_data0_89438 679-0_analysis_H1L1_result.h
df5 -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_ana
lysis_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
```

https://ldas-jobs.ligo.caltech.edu/~hyungwon.lee/pe/O4/S230522n/home.html

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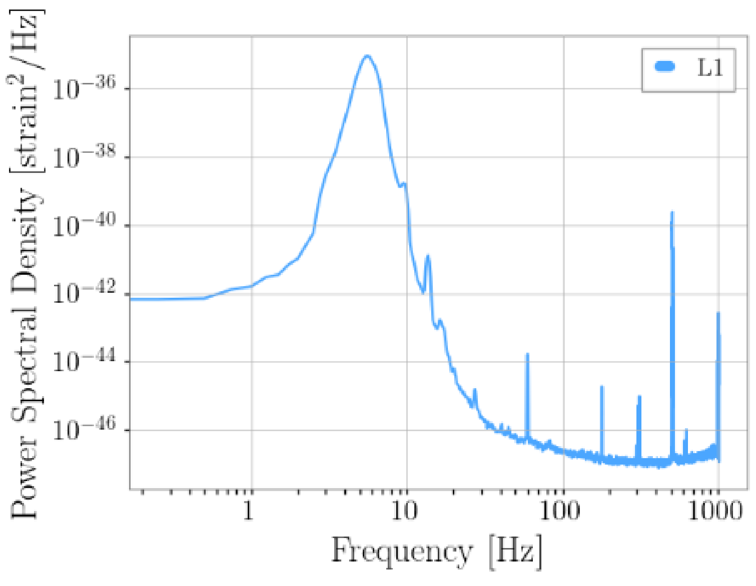
Summary for G407786

PESummary output

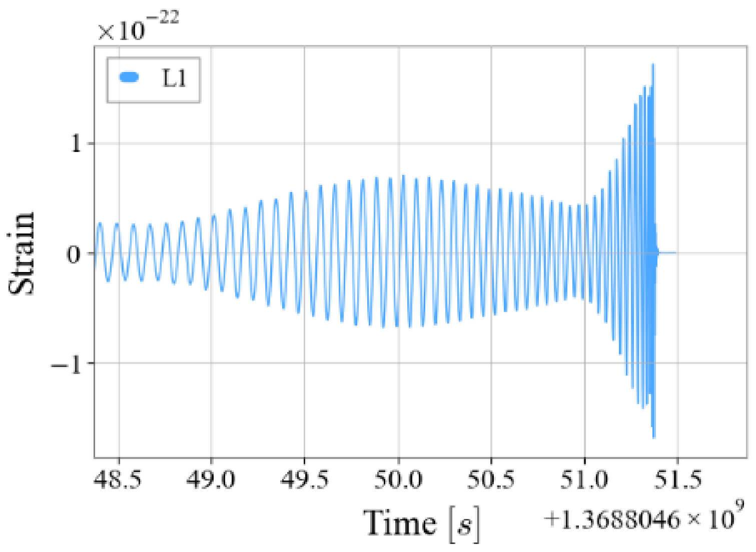
The figures below show the summary plots for the run

G407786_Online_Ecc

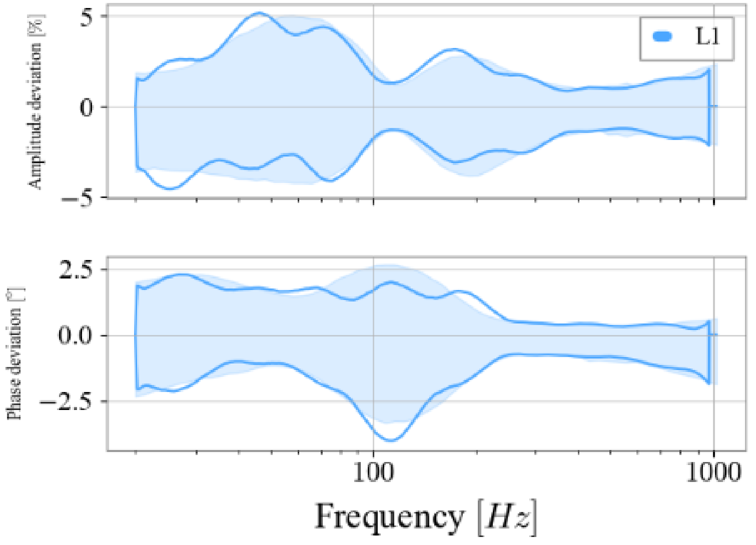
The figures below show the plots for G407786_Online_Ecc



Caption



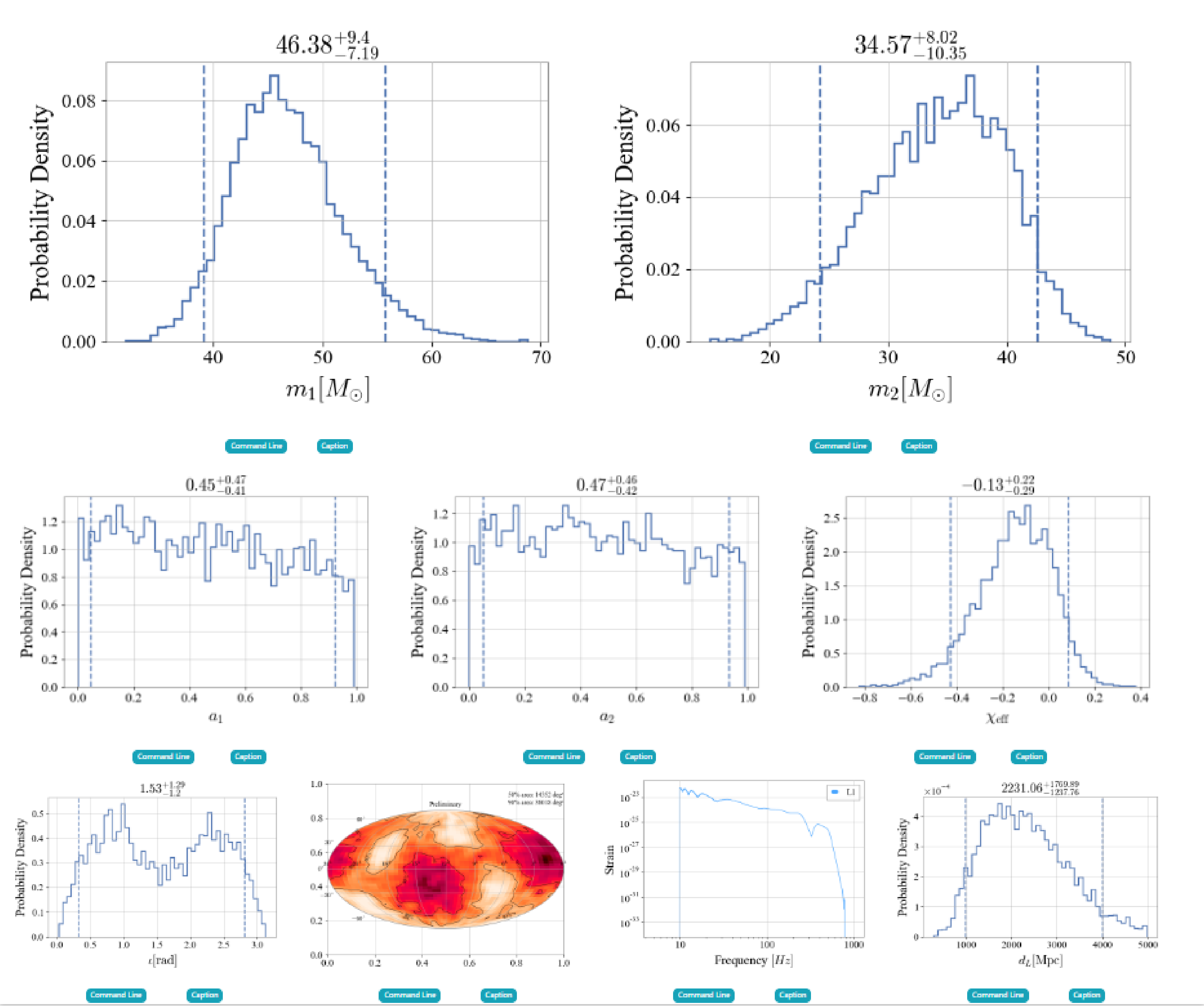
Caption



Caption

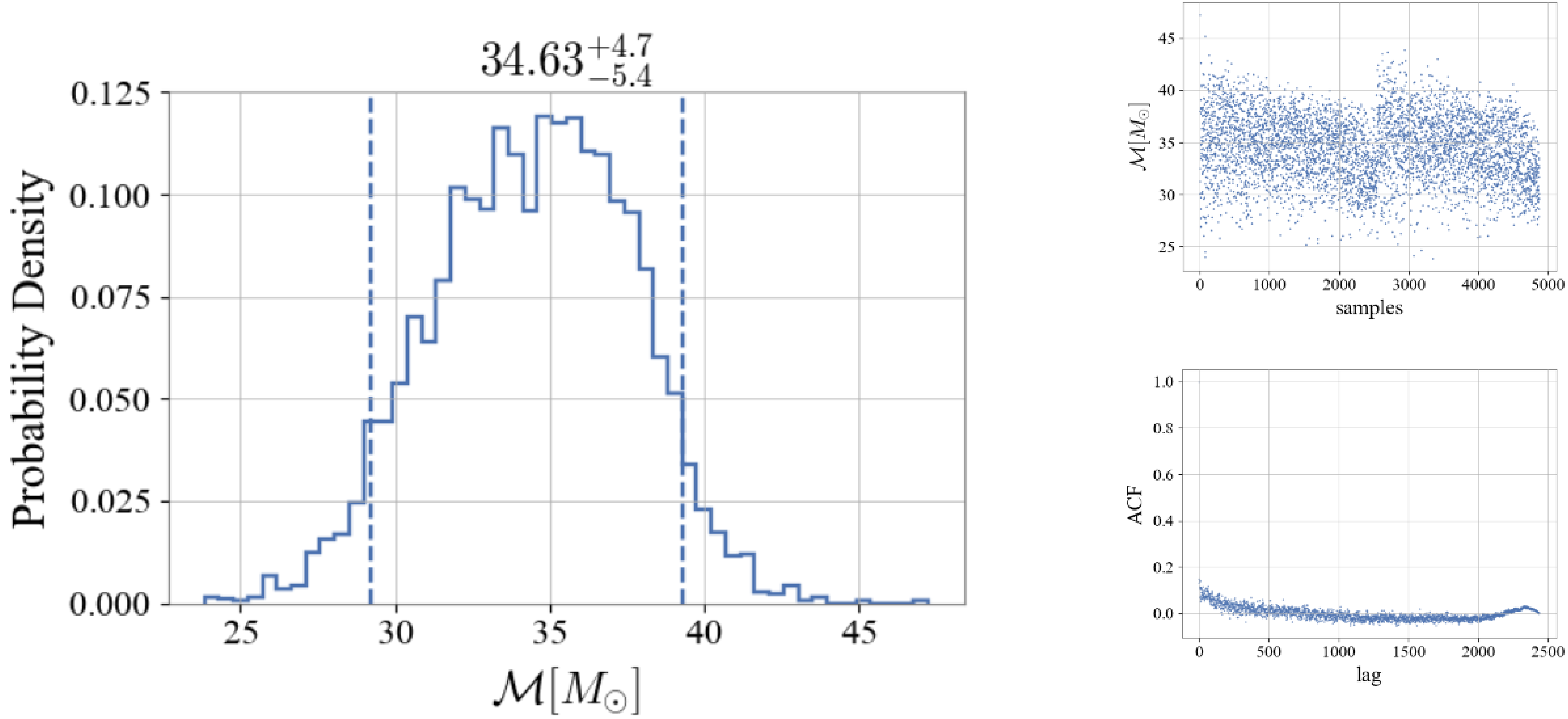
G407786_Online_Ecc

The figures below show the plots for G407786_Online_Ecc



chirp_mass

The figures below show the summary plots for the run



맺음 말

질문

감사합니다