중력파의 중력렌징

Gravitational Lensing of Gravitational Waves

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강의 내용

1. 중력렌징 개요 Gravitational lensing in a nutshell

2. 빛의 중력렌징 Gravitational lensing of lights

3. 중력파의 중력렌징 Gravitational lensing of gravitational waves

1. 중력렌징 개요

Gravitational lensing in a nutshell

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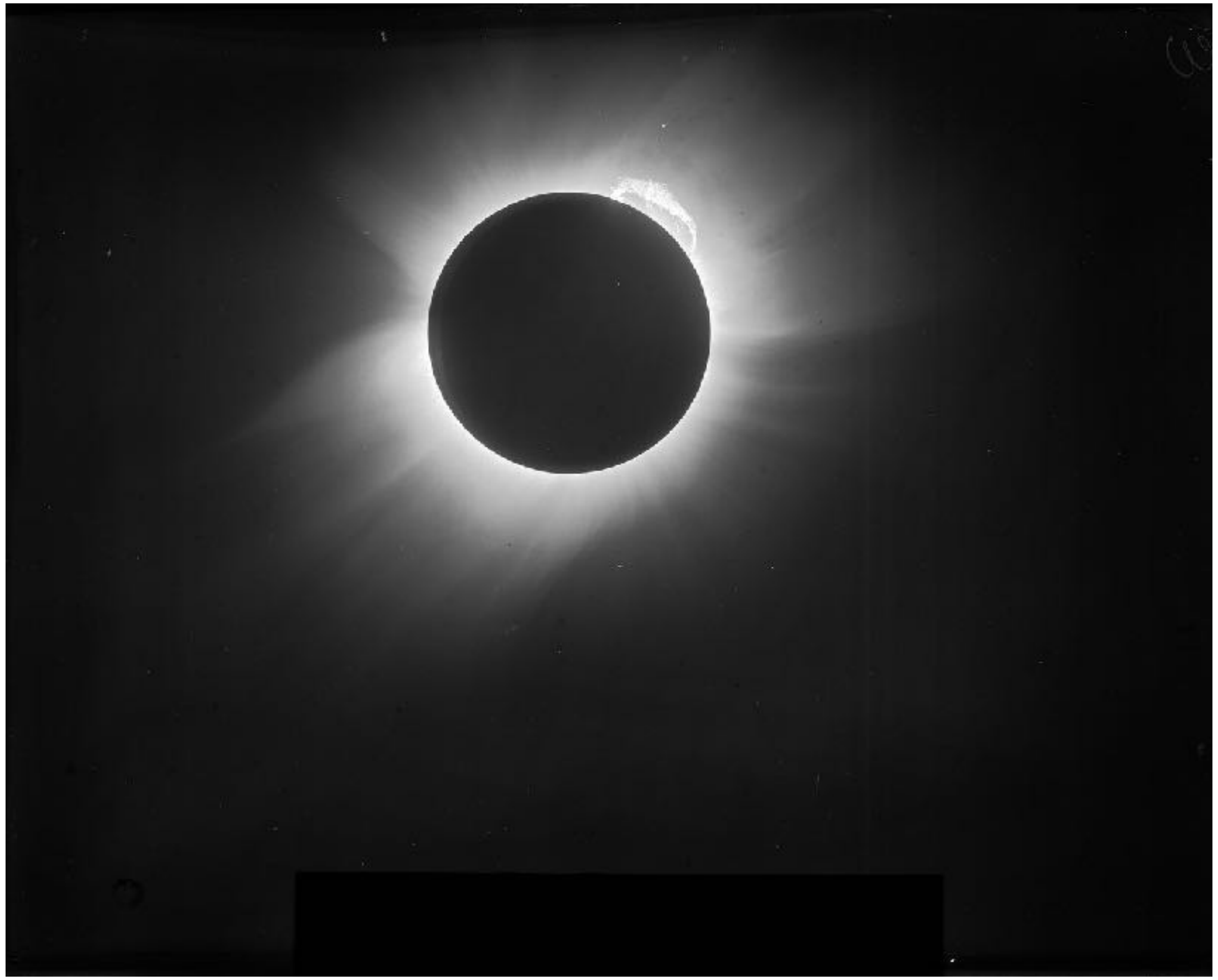

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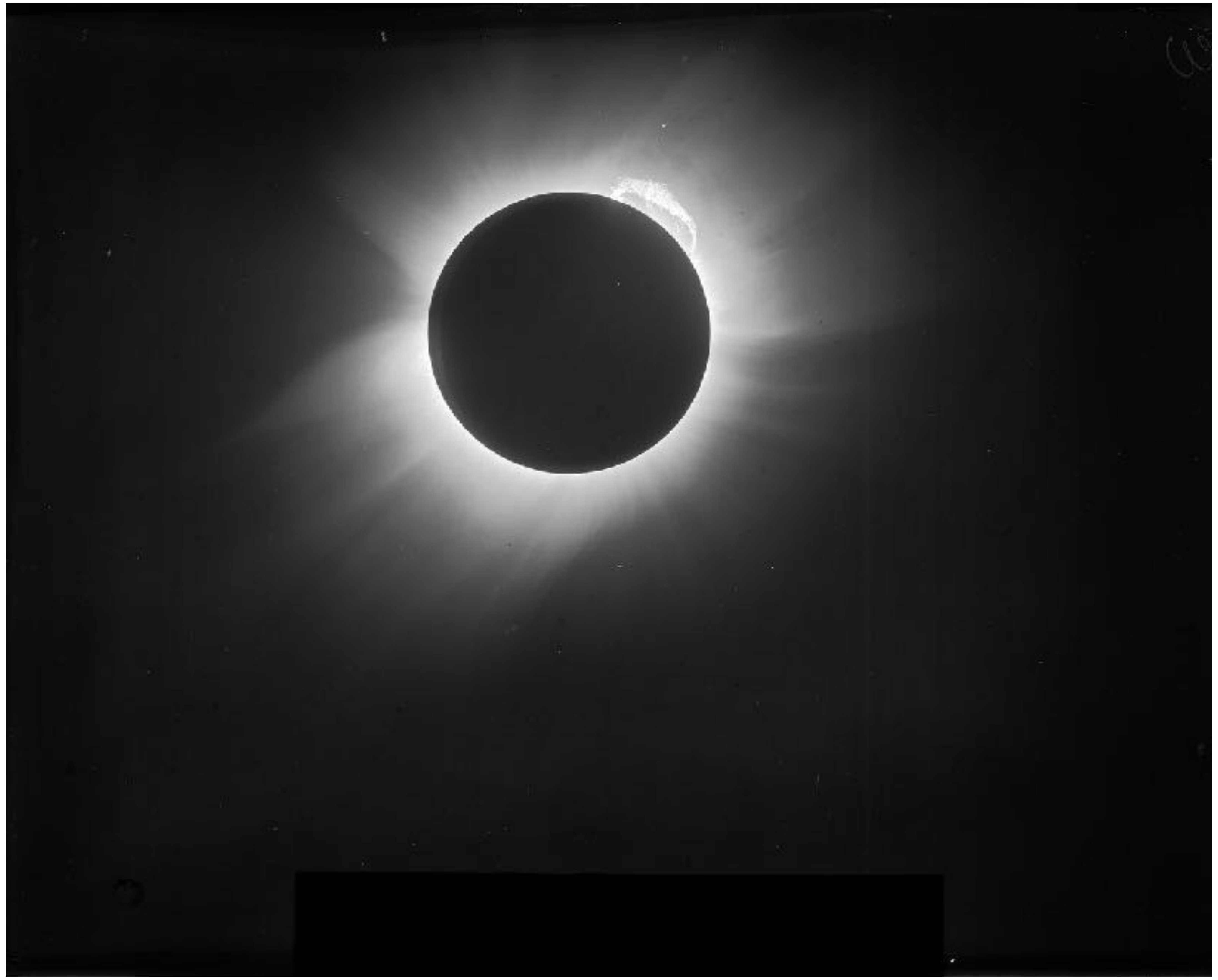


브라질 Sobral에서 관측한
개기일식 (1919년)

source:
ESO/Landessternwarte
Heidelberg-Königstuhl/
F. W. Dyson, A. S. Eddington,
& C. Davidson

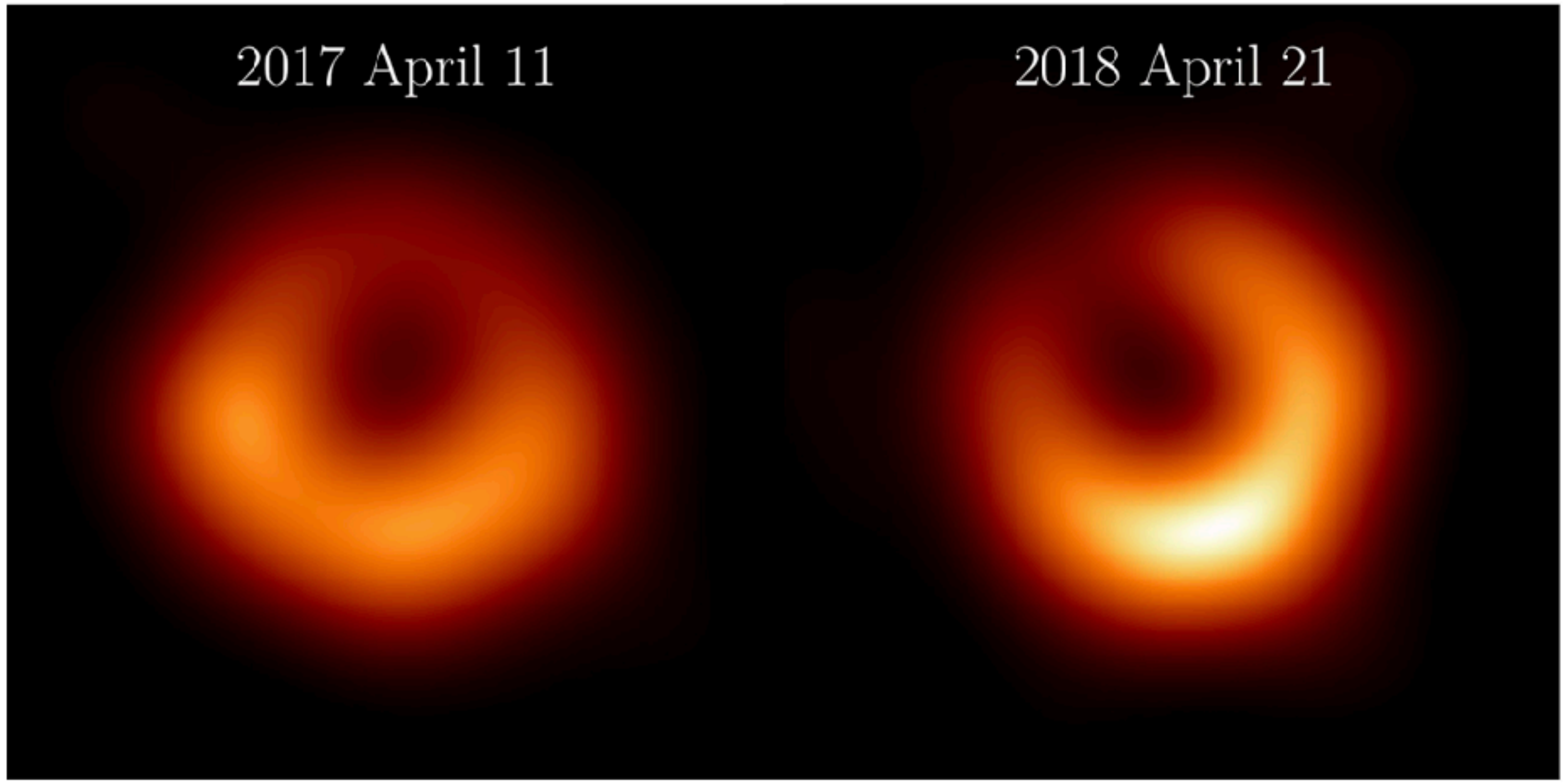
Do you know what this picture is?

Do you know what this picture is?

SMACS 0723 은하단 (galaxy cluster)

source:
제임스 웹 우주 망원경
(James Webb Space Telescope)

Do you know what this picture is?



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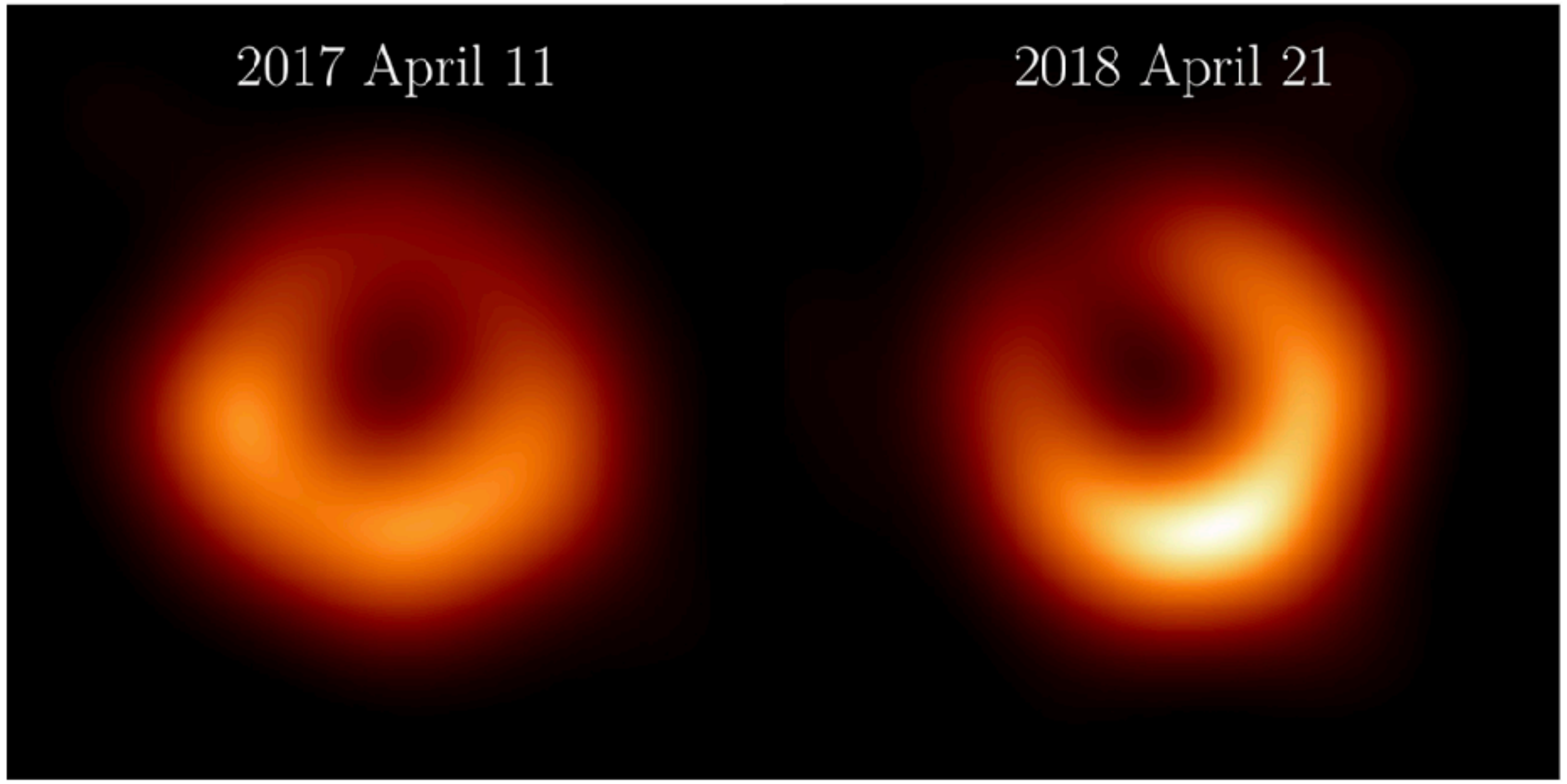
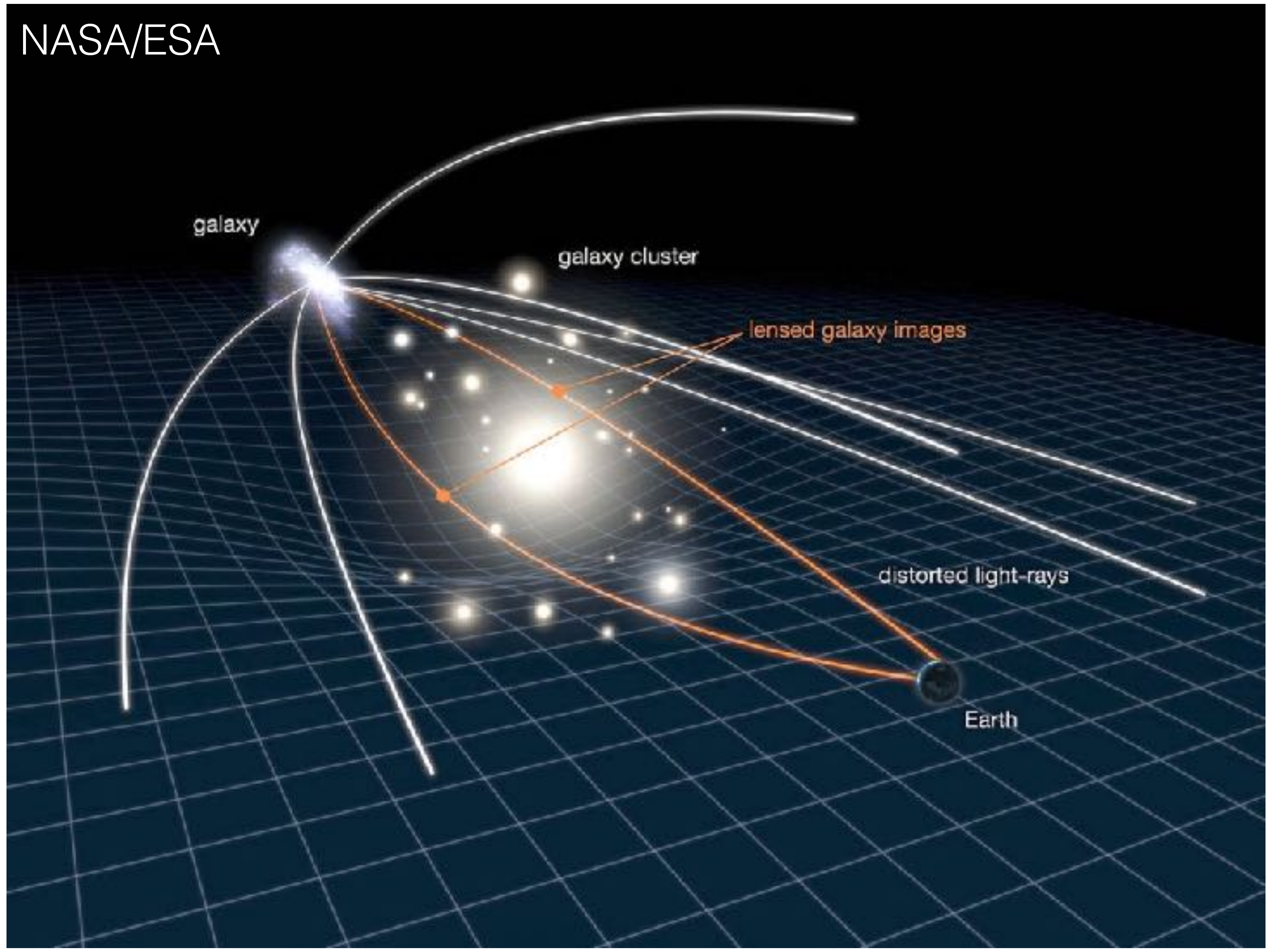


M87 은하 중심의 초거대질량 블랙홀
(Supermassive BH in M87)

source:
이벤트 호라이즌 망원경
(Event Horizon Telescope)

Gravitational lensing phenomena

- The deflection of light by massive bodies and the phenomena resulting therefrom.



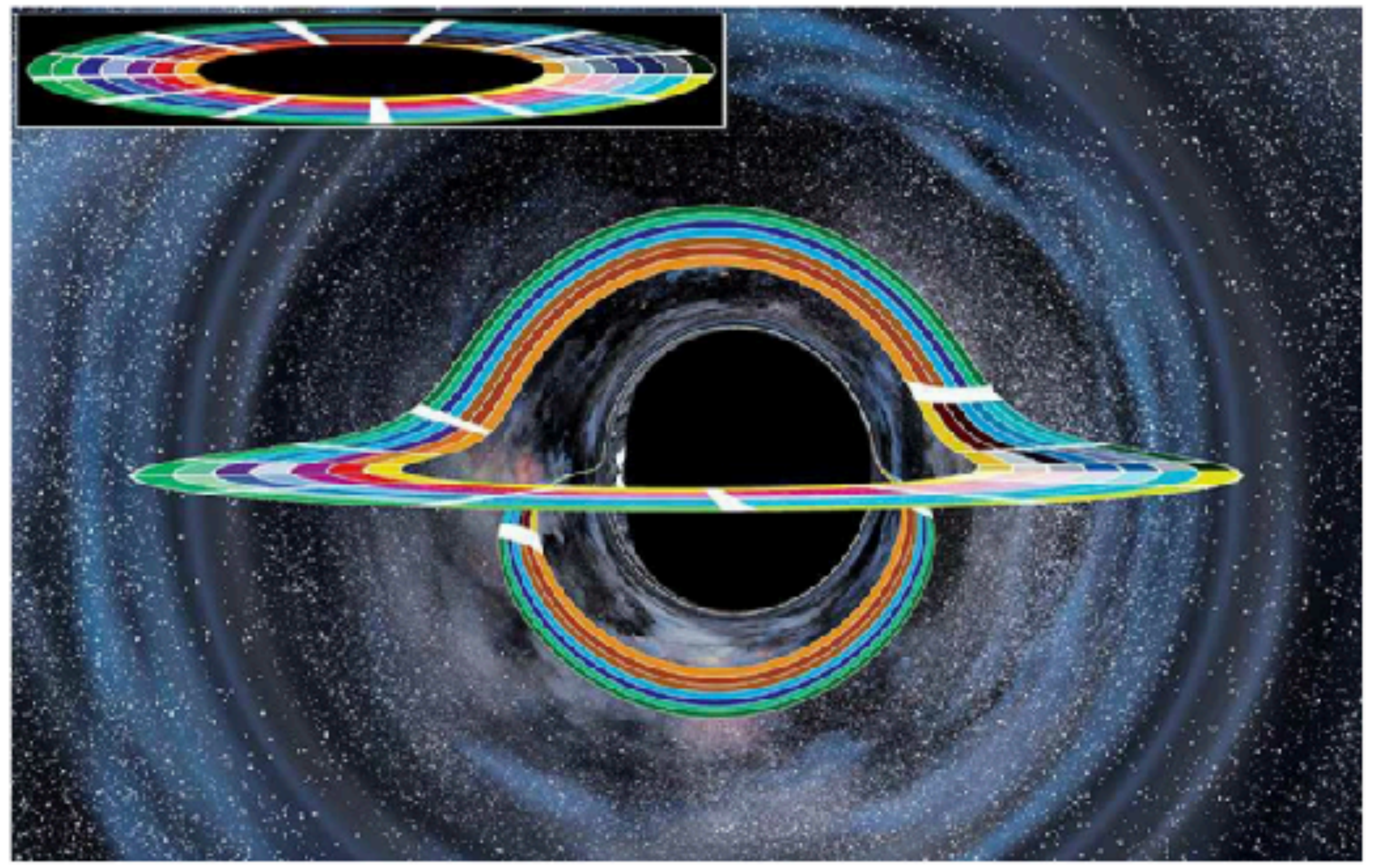


Fig. 9.7. An infinitesimally thin disk in Gargantua's equatorial plane, gravitationally lensed by Gargantua's warped space and time. Here Gargantua spins very fast. *Inset:* The disk in the absence of the black hole. *[From Eugénie von Tunzelmann's artistic team at Double Negative.]*

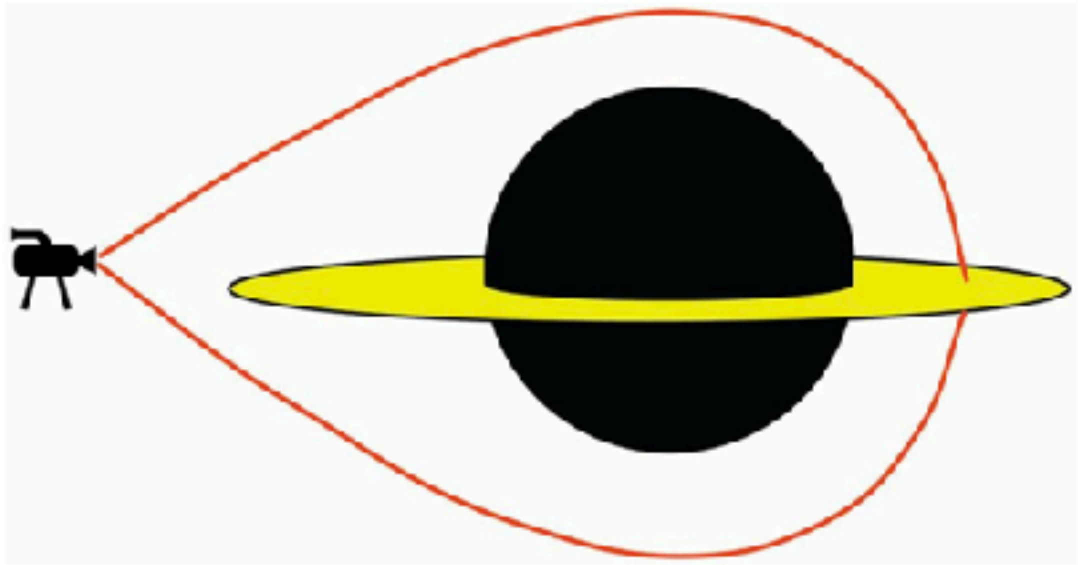
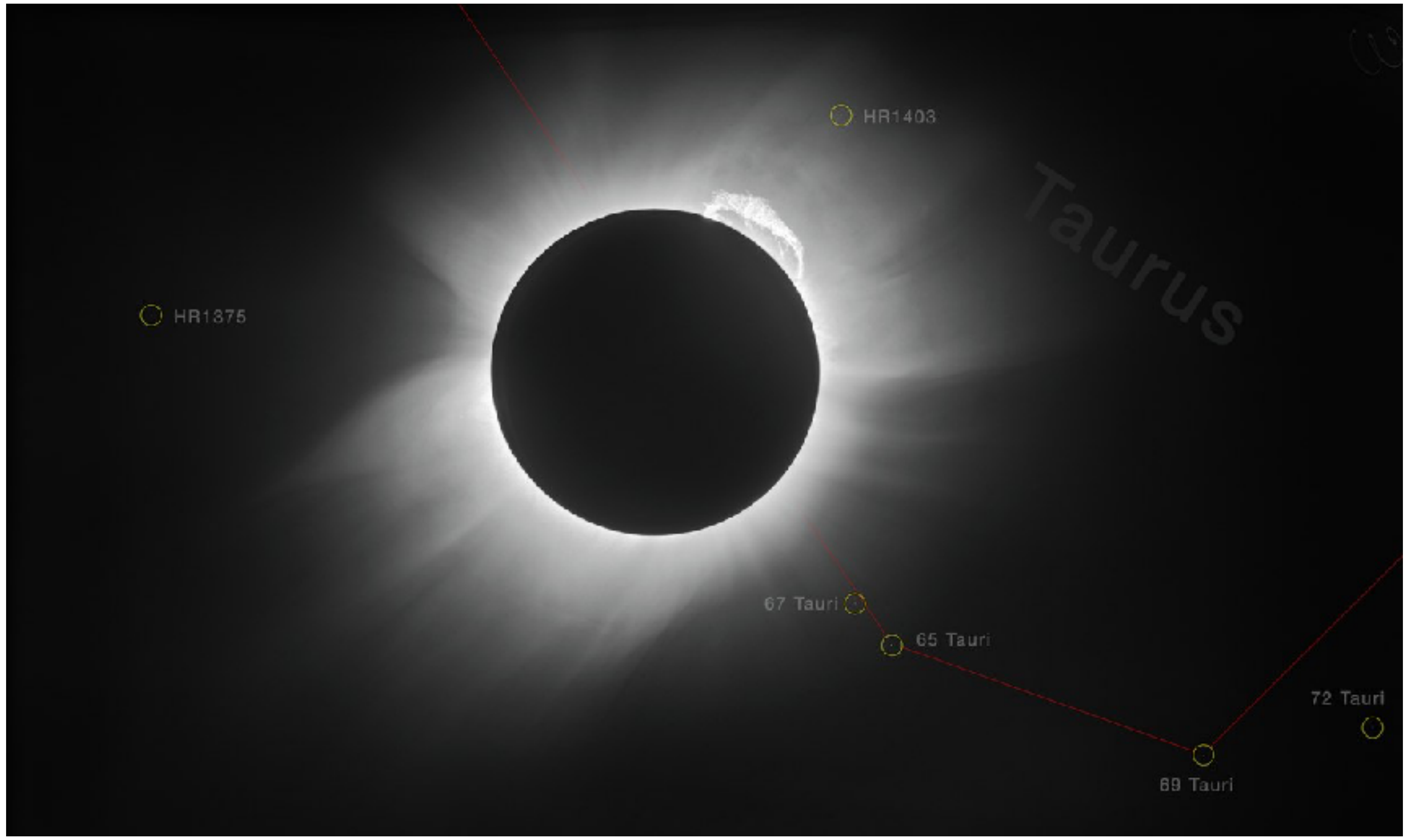


Fig. 9.8. Light rays (*red*) bring to the camera images of the back part of the accretion disk, behind Gargantua: one image above the hole's shadow, the other below the hole's shadow.

Kip Thorne (2014)
"The Science of Interstellar"

Gravitational lensing phenomena

- One of the consequences of Einstein's General Theory of Relativity.
- Confirmed with a ray of light passing close to the limb of the Sun (1919).



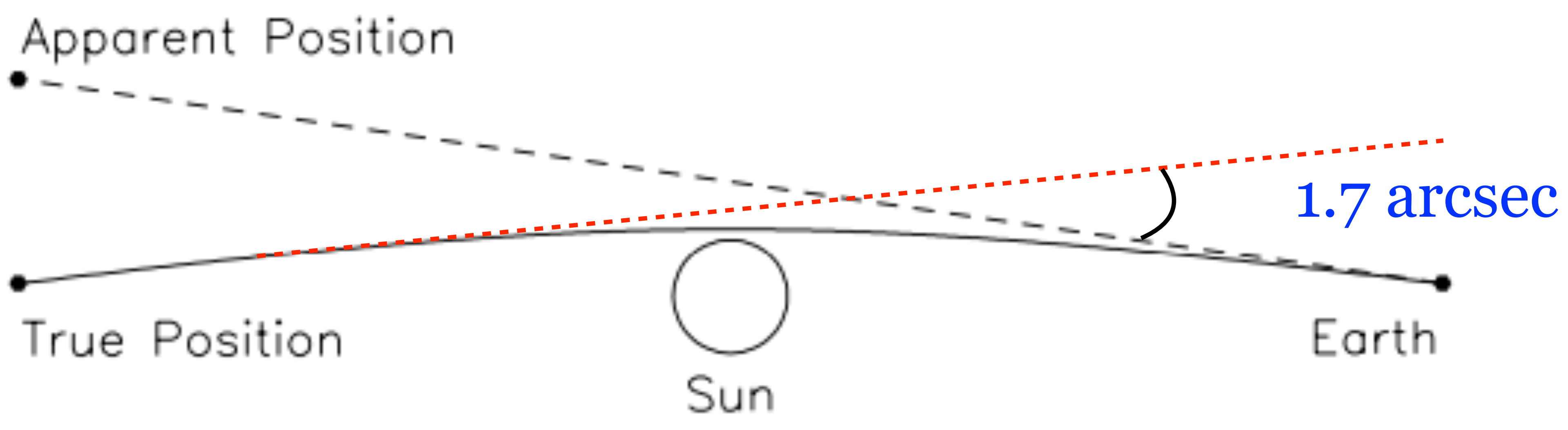


FIG. 1.—Angular deflection of a ray of light passing close to the limb of the Sun. Since the light ray is bent toward the Sun, the apparent positions of stars move away from the Sun.

[figure & caption from Narayan & Bartelmann '96]

- Magnify light from distant sources which would otherwise remain undetected (Zwicky 1937).

2. 빛의 중력렌징

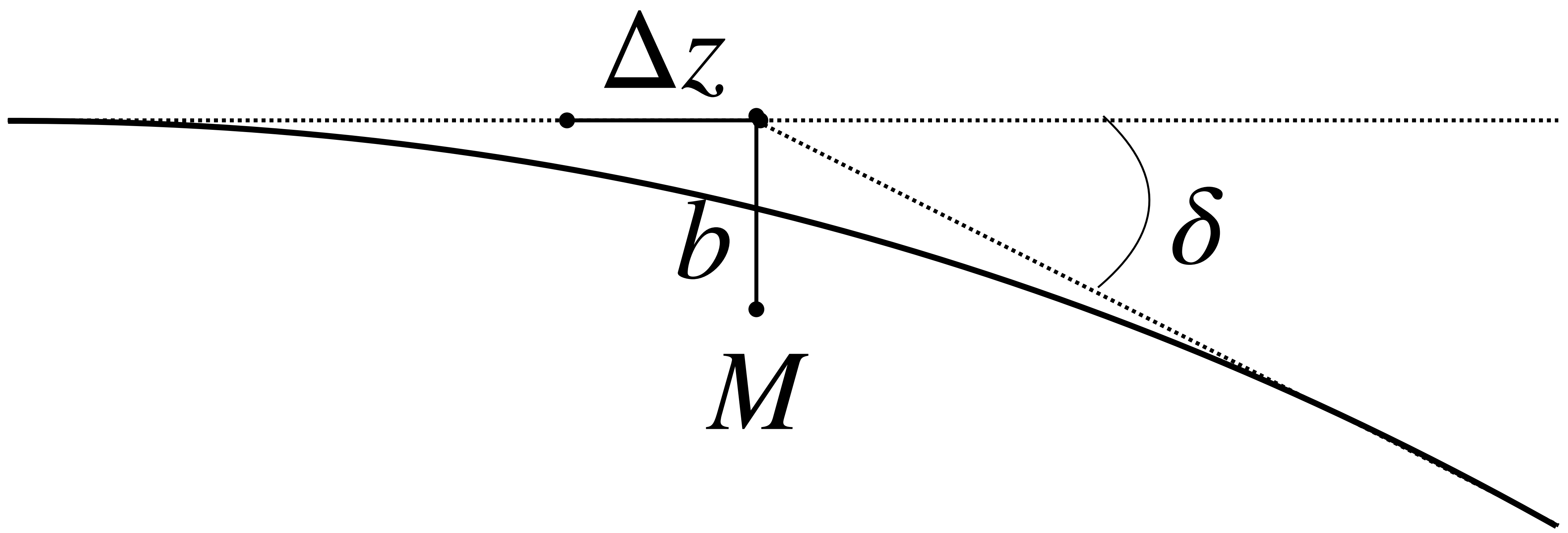
Gravitational lensing of lights

Further reading: textbooks
such as
"***Introduction to Gravitational Lensing with Python Examples***"
by Massimo Meneghetti

Lensing by a point mass

Narayan & Bartelmann
(astro-ph/9606001)

- **Let's suppose a lensing by a point mass** M
  - deflection angle, $\delta = \frac{2}{c^2} \int \vec{\nabla}_\perp \Phi dz$, where
    - b: impact parameter
    - z: distance along the original light path
    - $\Phi = -GM/(b^2 + z^2)^{1/2}$: Newtonian potential

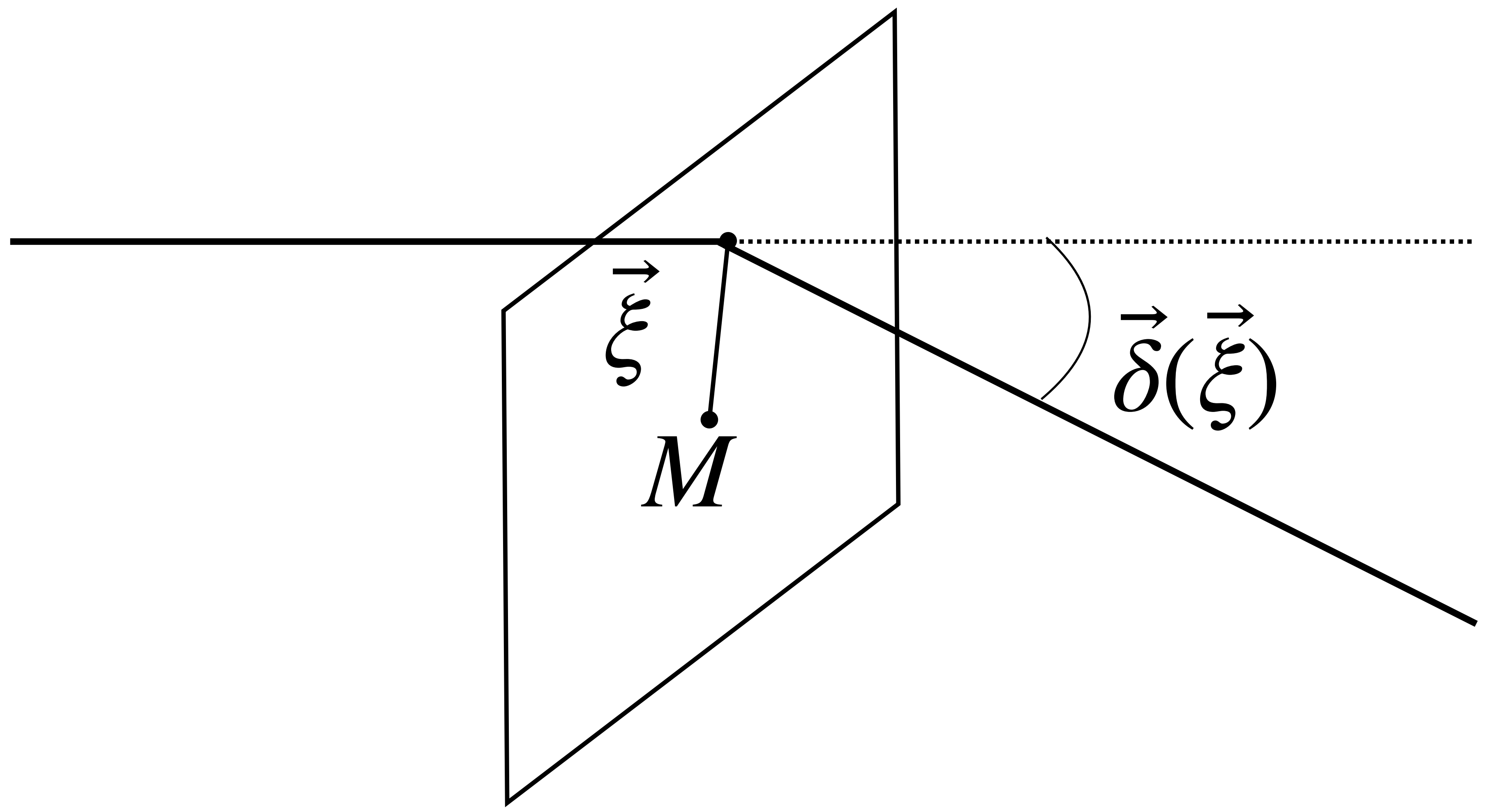


- most of light deflection occurs within $\Delta z \sim \pm b$ of the point of closest encounter between the light ray and the point mass.
  - Δz is typically much smaller than the distances between (the observer and lens) and between (lens and source).
    → thin lens (screen) approximation!

Thin lens approximation

Narayan & Bartelmann
(astro-ph/9606001)

- deflection angle $\vec{\delta}(\vec{\xi}) = \frac{4G}{c^2}\int \frac{(\overrightarrow{xi} - \vec{\xi}')\Sigma(\vec{\xi}')}{|\vec{\xi} - \vec{\xi}'|^2} d^2\xi'$, where
  - $\Sigma(\vec{\xi}) = \int \rho(\vec{\xi}, z)dz$: surface mass density
  - $\vec{\xi}$: a two-dimensional vector in the lens plane



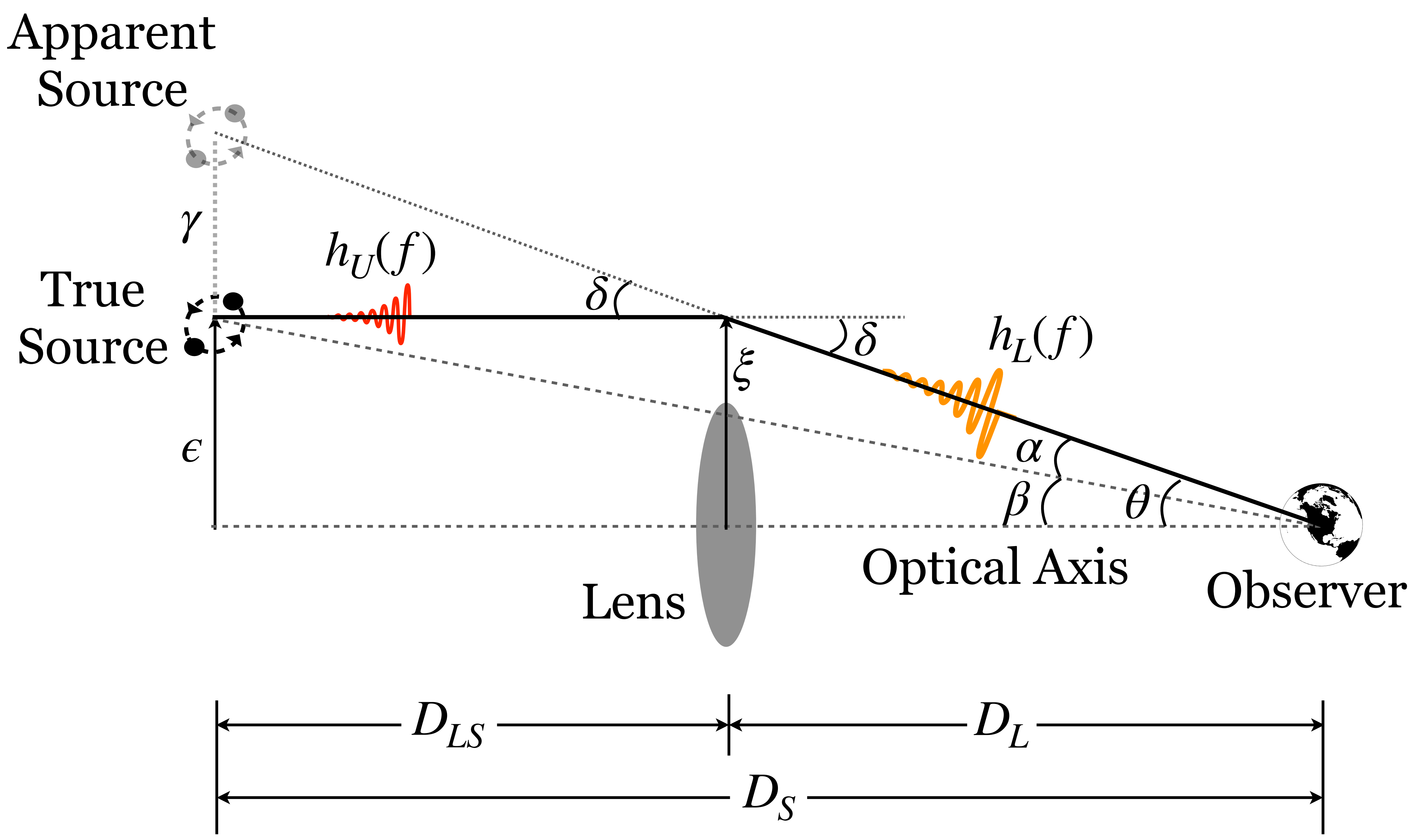
- for a circularly symmetric lens, deflection angle becomes $\delta(\xi) = \frac{4GM(\xi)}{c^2\xi}$, where
  - ξ: distance from the lens center
  - $M(\xi) = 2\pi\int_0^{\xi} \Sigma(\xi')\xi' d\xi'$: mass enclosed within radius ξ

Lensing geometry and lens equation

Narayan & Bartelmann (astro-ph/9606001)

- reduced deflection angle $\vec{\alpha} = \frac{D_{LS}}{D_S}\vec{\delta}$
- We see that $\theta D_S = \beta D_S + \delta D_{LS}$ from the schematic.

  $\rightarrow \vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta})$: lens equation
  (or, equivalently, ray-tracing equation)



Einstein radius

Narayan & Bartelmann
(astro-ph/9606001)

- With the deflection angle for a circularly symmetric lens and its reduced deflection angle, the lens equation reads

$$\beta(\theta) = \theta - \frac{D_{LS}}{D_L D_S}\frac{4GM(\theta)}{c^2\theta}$$

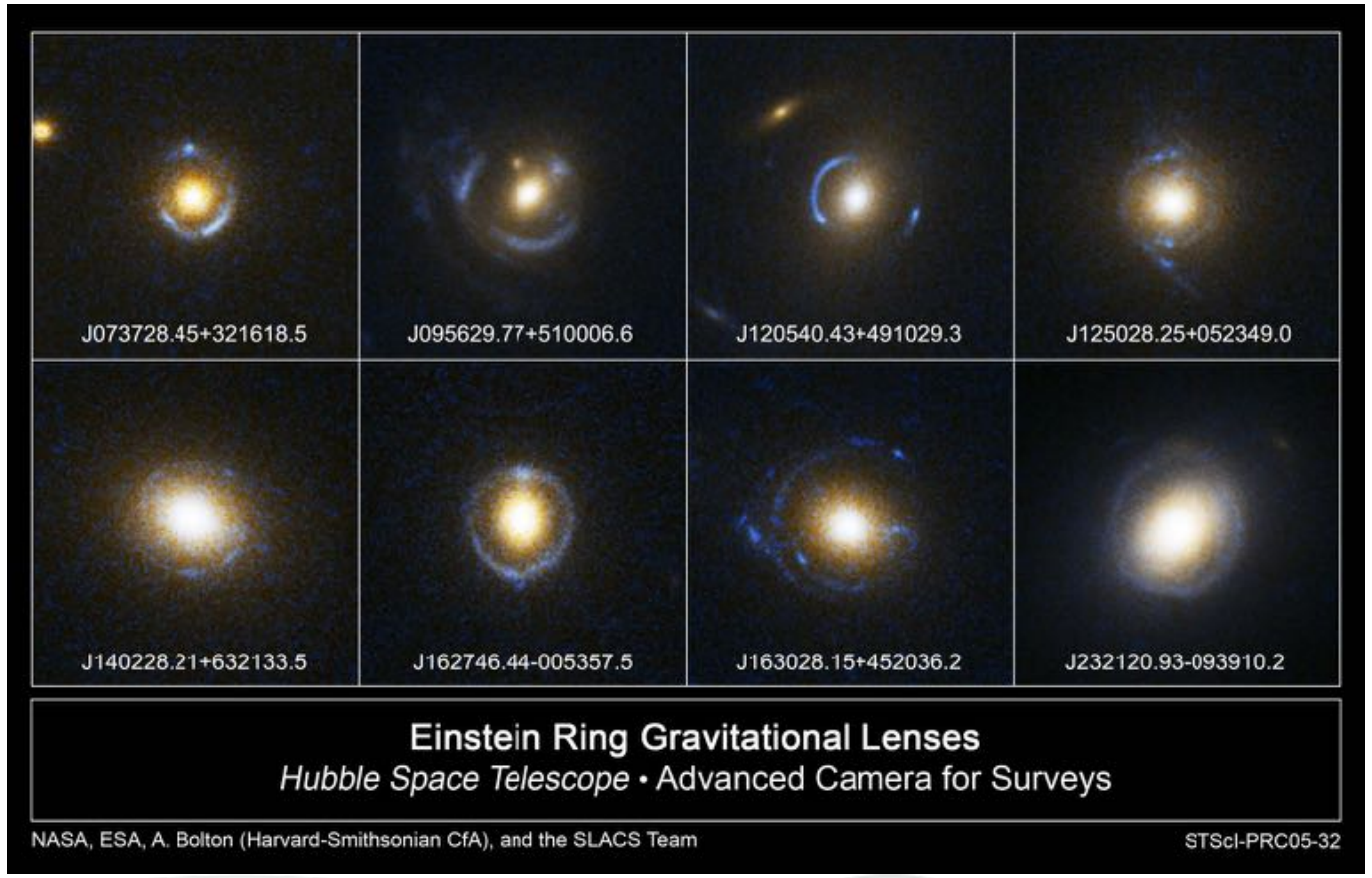
- Due to the rotational symmetry of the lens system, a source which lies exactly on the optic axis ($\beta = 0$) is imaged as a ring having the radius ξ_E such as

$$\xi_E = \left[\frac{4GM(\theta_E)}{c^2}\frac{D_{LS}}{D_L D_S}\right]^{1/2},$$

that is referred to as the Einstein radius.

  - For a point mass M, it becomes

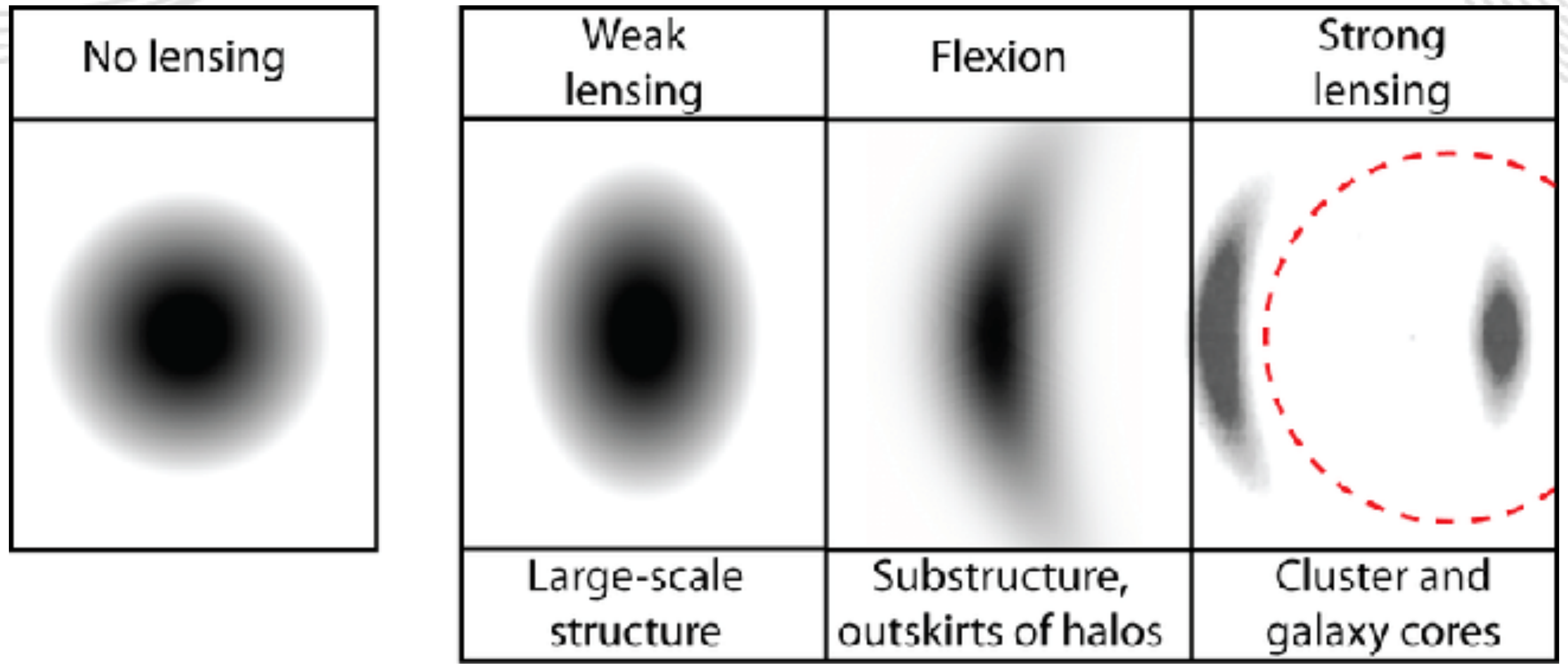
$$\xi_E = \left[\frac{4GM}{c^2}\frac{D_{LS}}{D_L D_S}\right]^{1/2}$$



Types of gravitational lensing

- weak lensing
  - distortion of background source such as galaxy
  - typically produces a single distorted image.
- strong lensing
  - occurs when source, lens, and observer are well positioned.
  - 2+ distorted images
- microlensing
  - occurs by small stellar objects
  - observable by changes in the brightness

[credit: ESA]



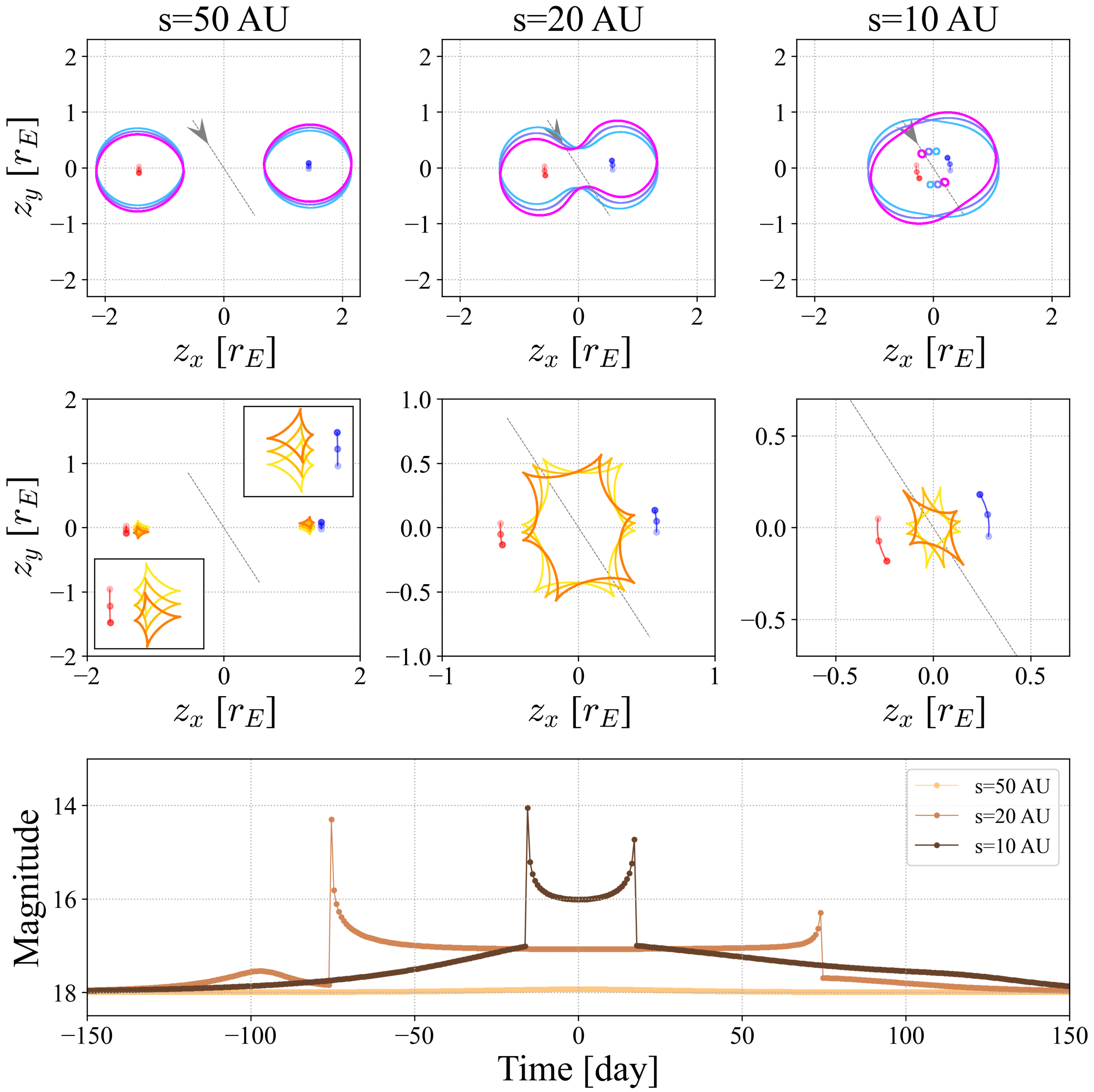
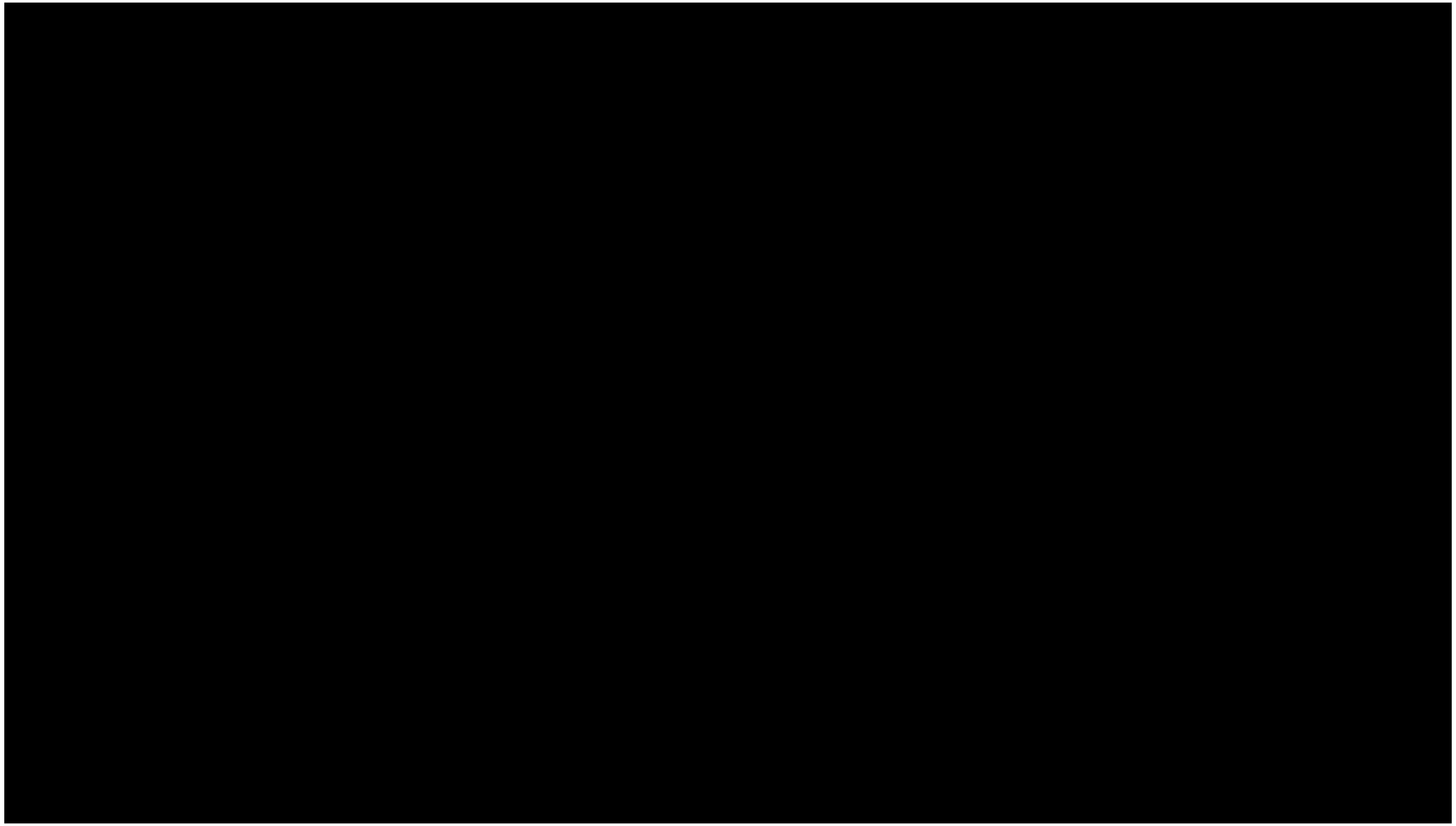
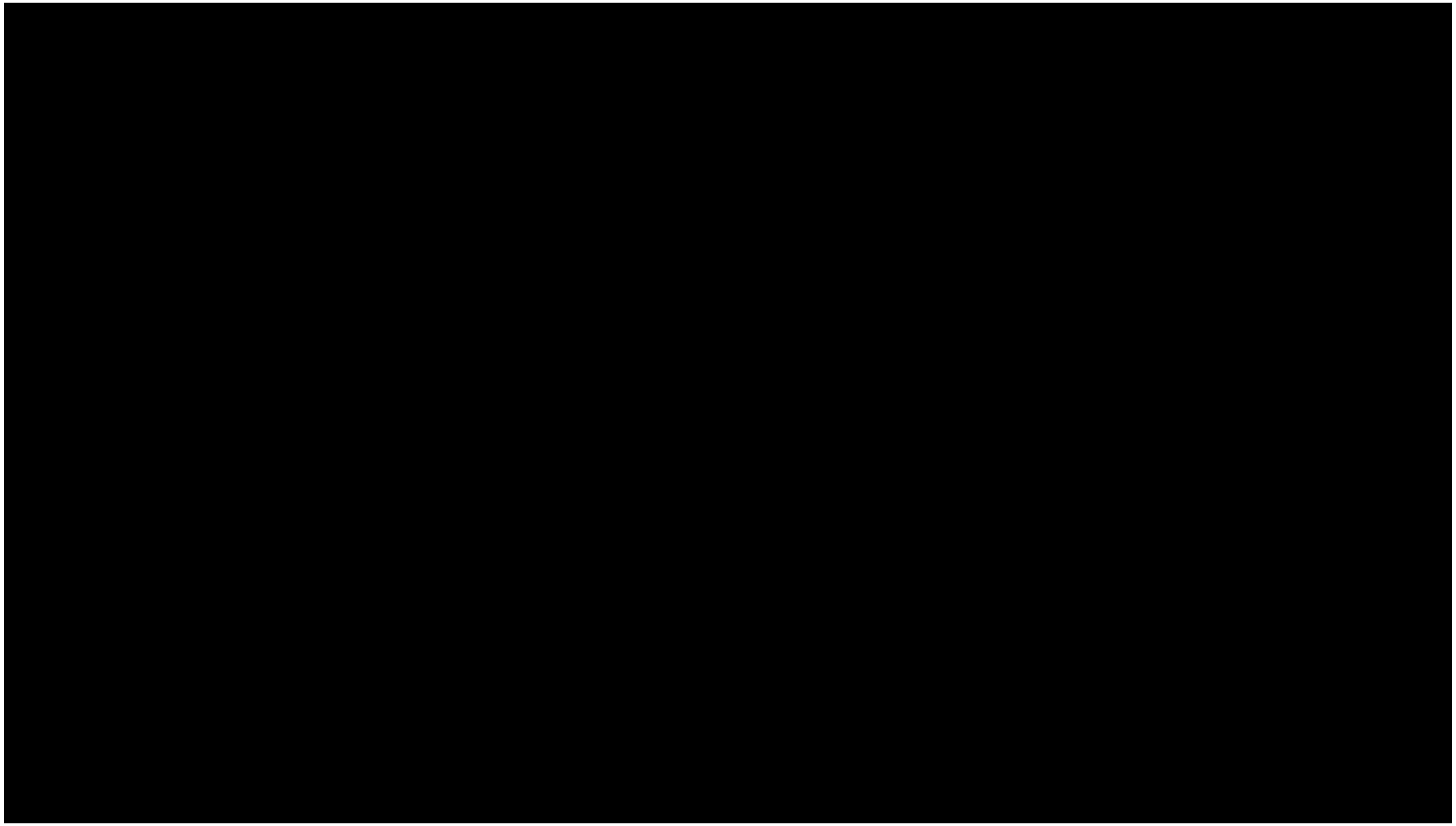


Table-top gravitational lensing of lights



[credit: Perimeter Institute for Theoretical Physics / source: YouTube]

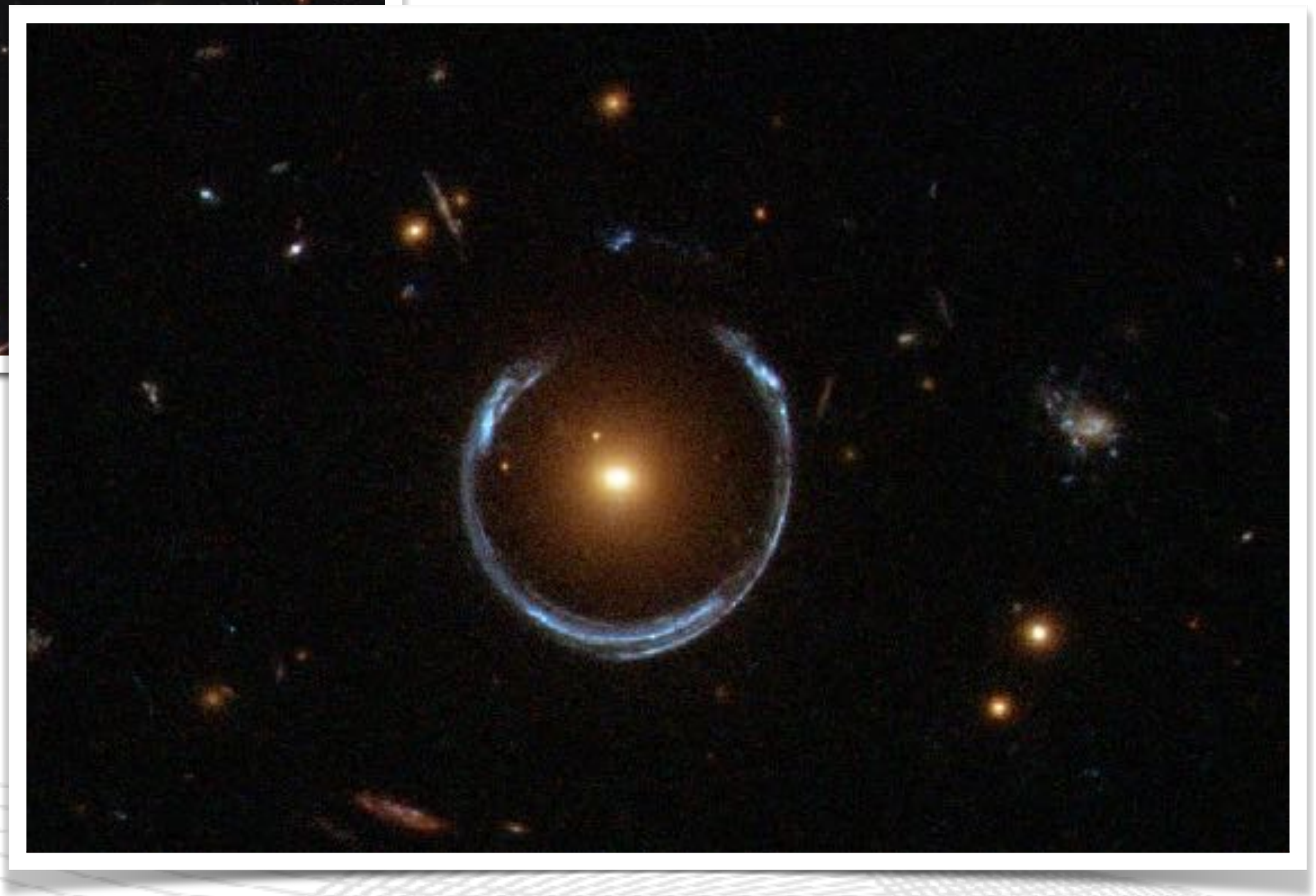
Table-top gravitational lensing of lights



[credit: Perimeter Institute for Theoretical Physics / source: YouTube]

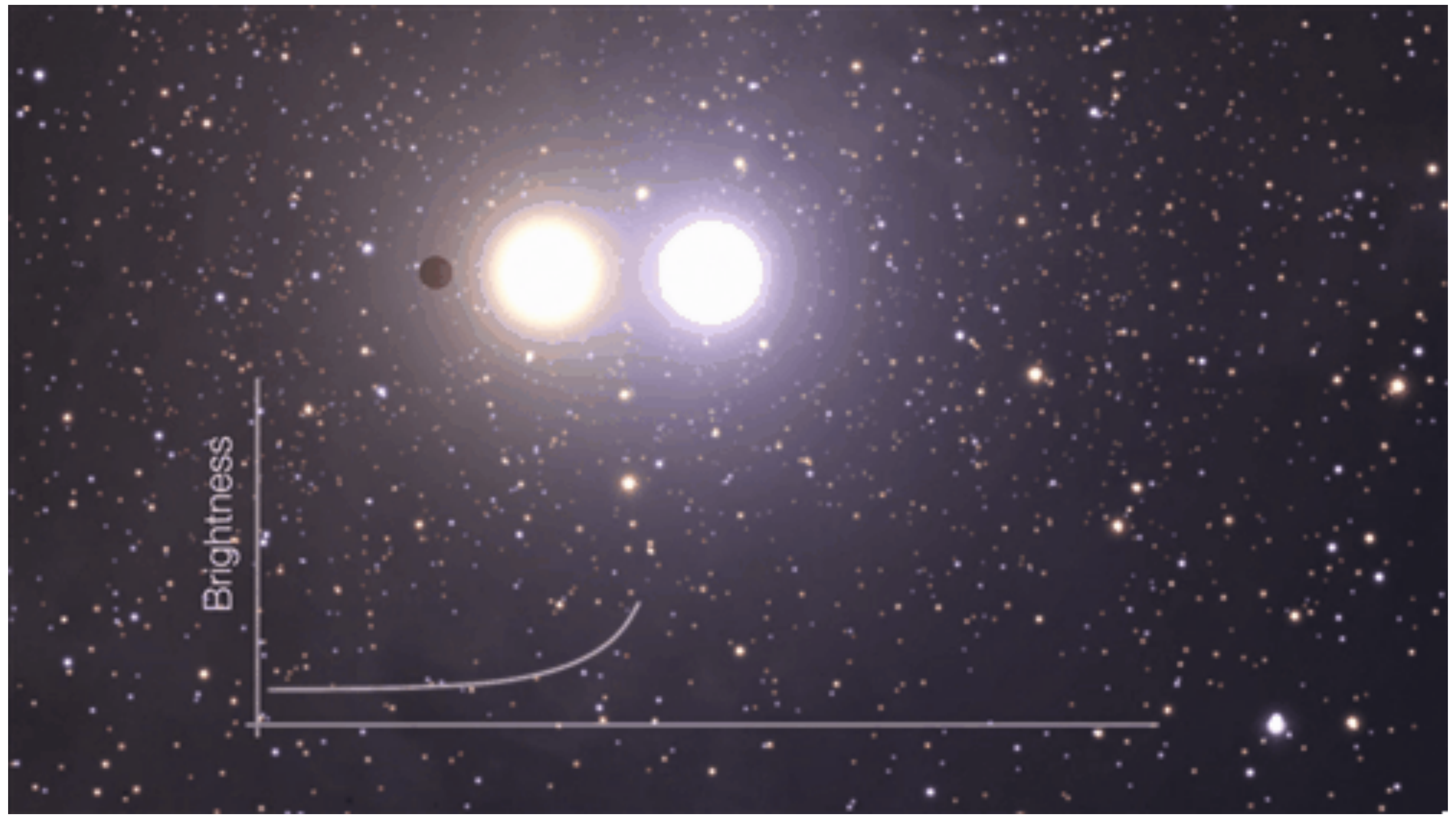
Examples of gravitational lensing of lights

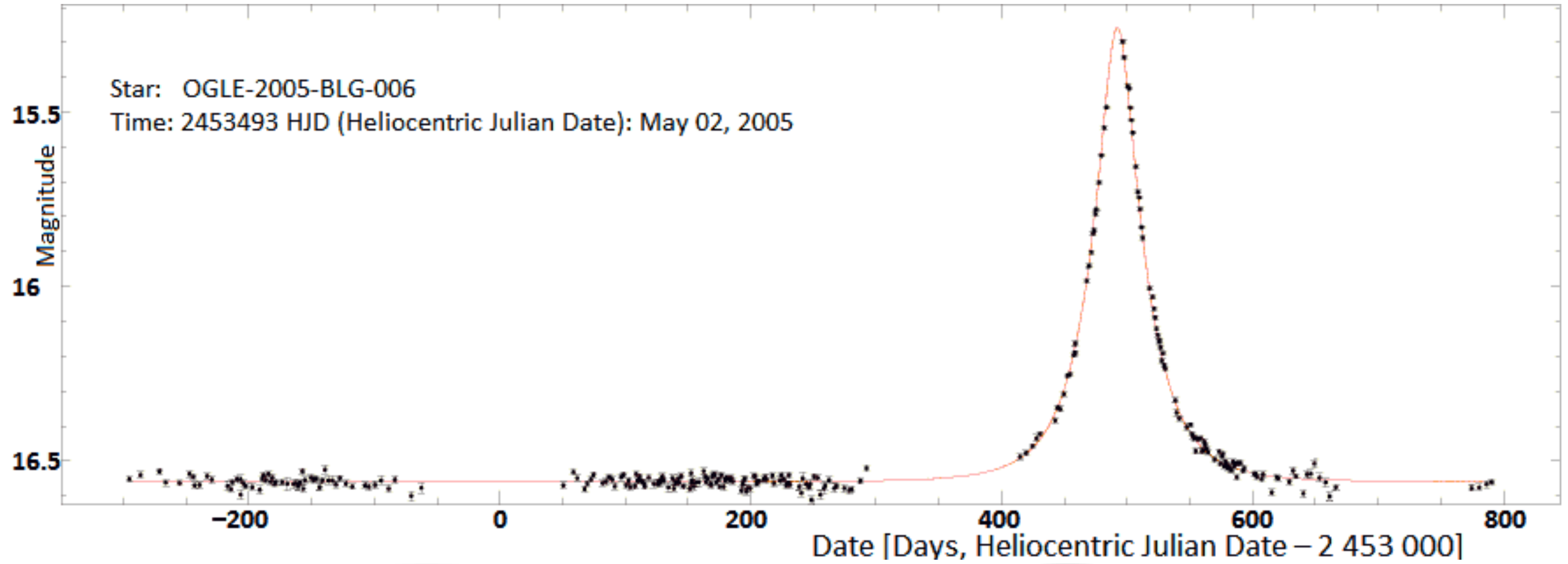
- **Lensing by galaxies/galaxy clusters (strong/weak lensing)**
  - A major sub-discipline of gravitational lensing
  - Cosmic telescope effect of gravitational lenses enables us to study faint and distant galaxies which happen to be strongly magnified by galaxy clusters.
  - The statistics of gravitational lensing events lensed by galaxies offers one of the promising ways of inferring cosmological parameters.



Examples of gravitational lensing of lights

- **Lensing by stellar objects (microlensing)**
  - Another sub-discipline of gravitational lensing
  - Stellar objects bend the light of a background object.
  - Microlensing enables the study of the population of faint or dark objects such as brown/red/white dwarfs, (exo)planets, and so on.





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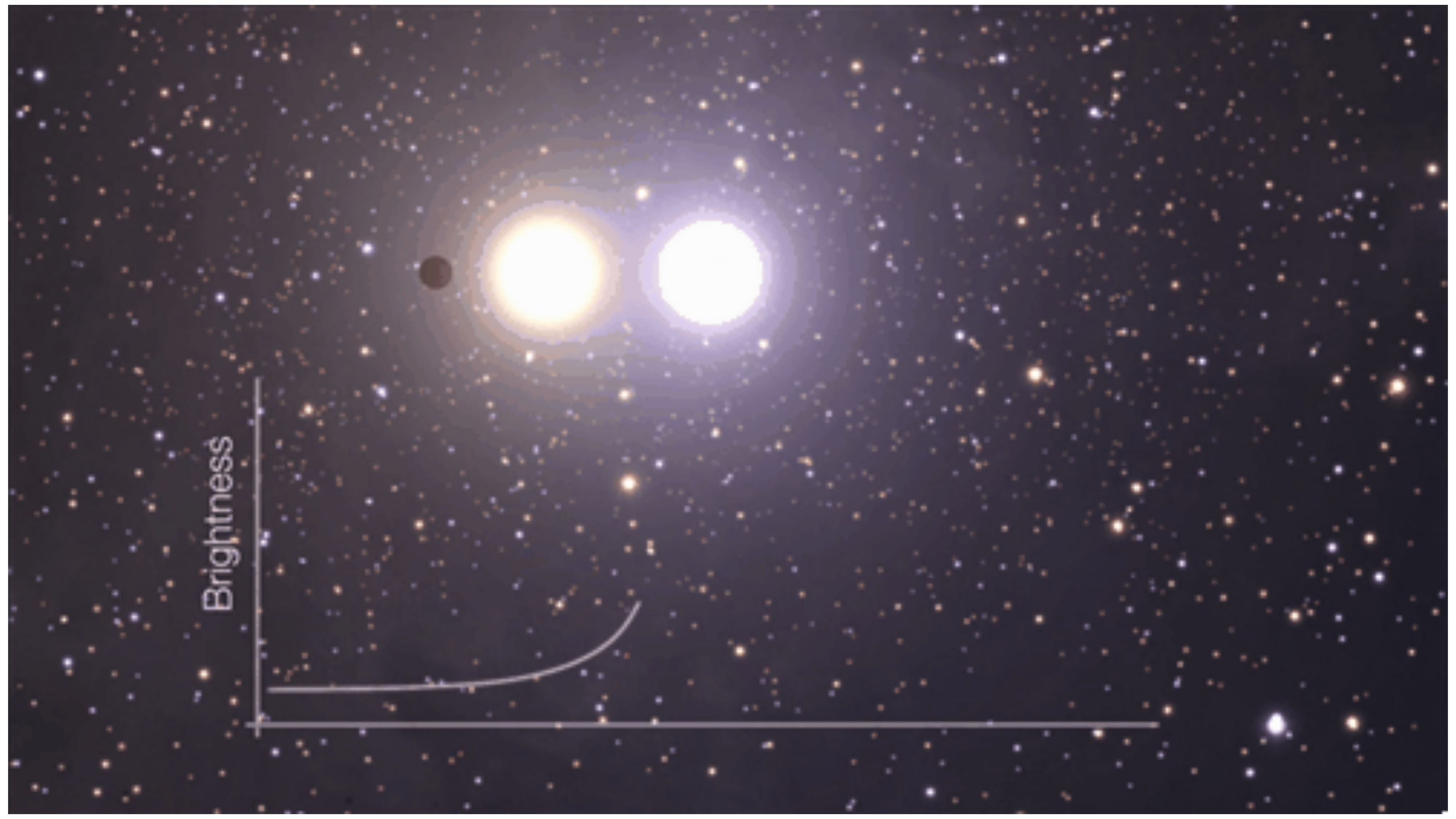
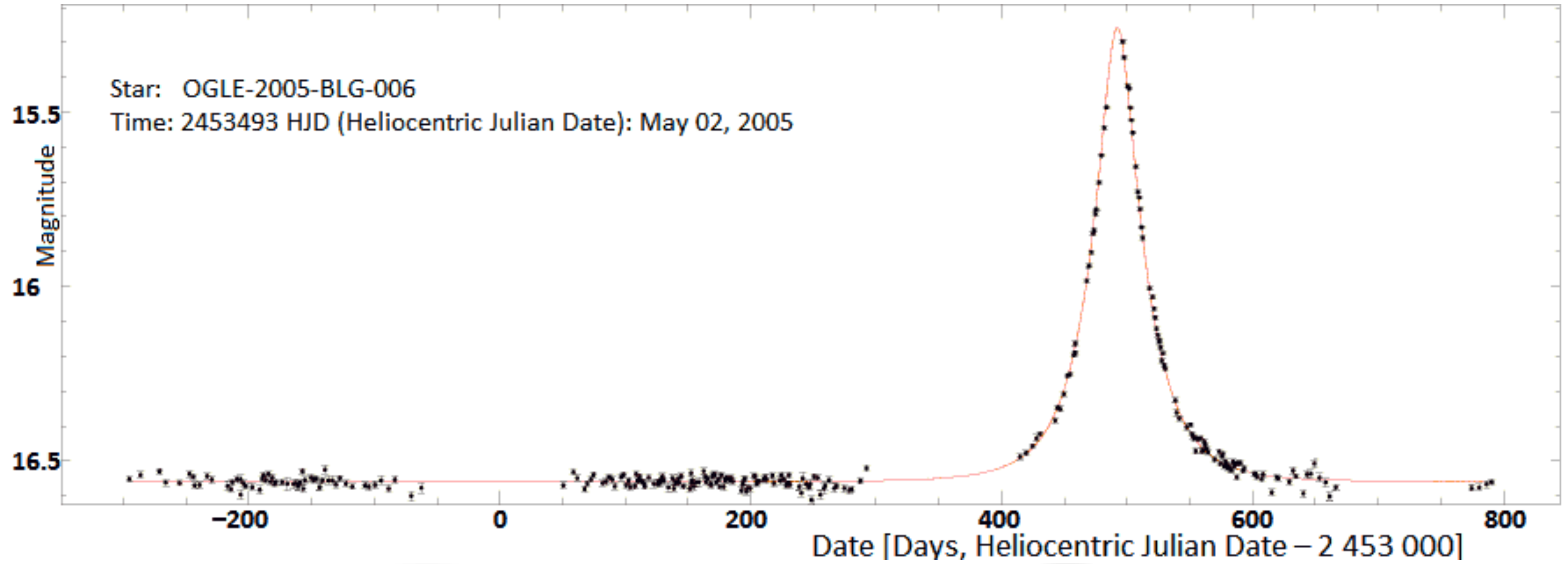
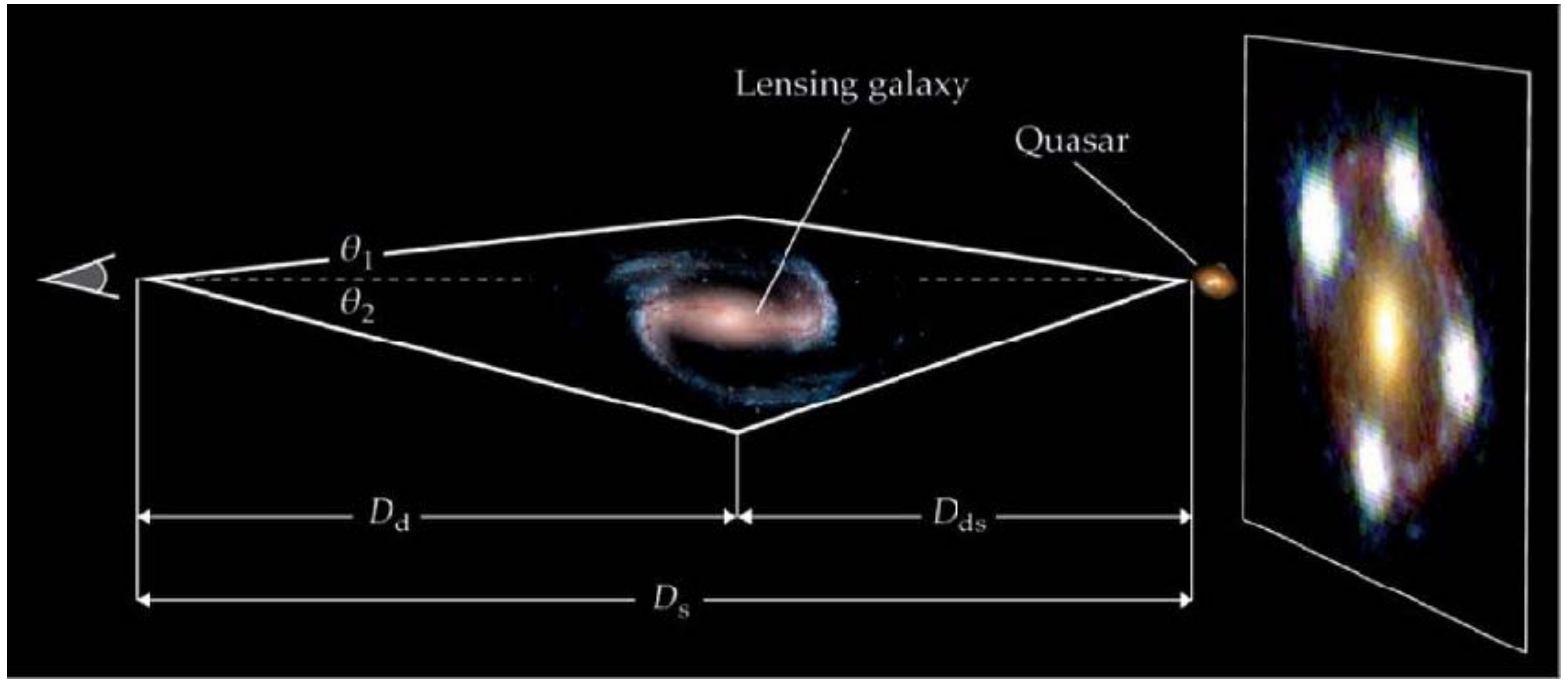




Gravitational lensing for cosmology

- **Measurement of the Hubble constant H_0 w/ gravitational lensing** (Refsdal 1964)
  - Hubble—Lemaître law: $v = H_0 D$ (v: recessional velocity; D: proper distnance)
    → Unit of H_0: $[\mathrm{km} \cdot \mathrm{s}^{-1} \cdot \mathrm{Mpc}^{-1}]$
  - Key: time delay between lensed images
  - Time delay ∝ the difference in the absolute lengths of the light paths ∝ H_0^{-1}
  - If the time delay is measured and if an accurate model of a lensed source is provided, H_0 could be measured.



[credit: EO Portal]

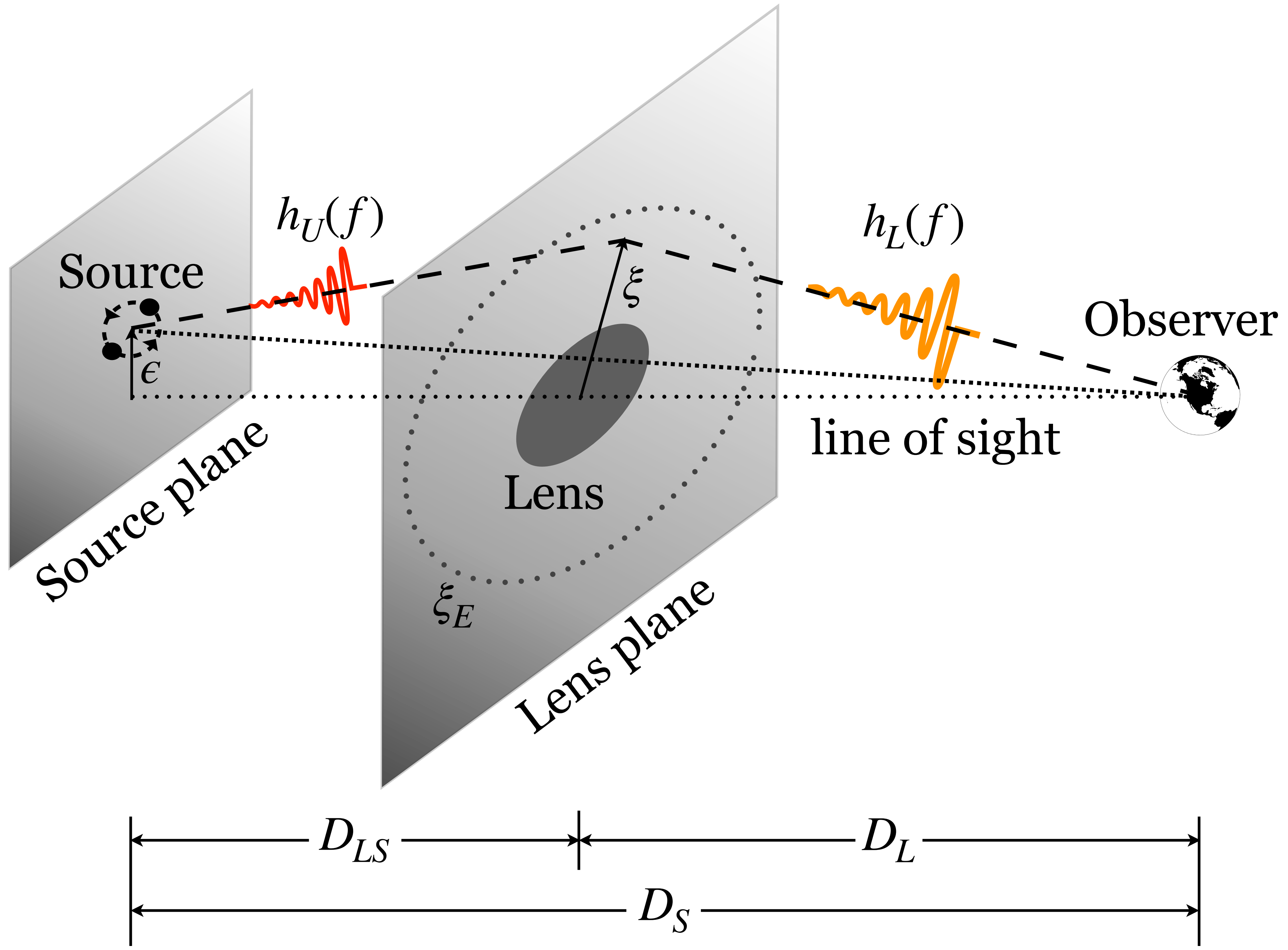
3. 중력파의 중력렌징

Gravitational lensing of gravitational waves

Lensing configuration

- Define the amplification factor as $F(f) \equiv \dfrac{h_L(f)}{h_U(f)}$ $(\rightarrow h_L(f) = F(f)h_U(f))$

  where $h_L(f)$ and $h_U(f)$ are the lensed and unlensed GWs in the frequency domain.



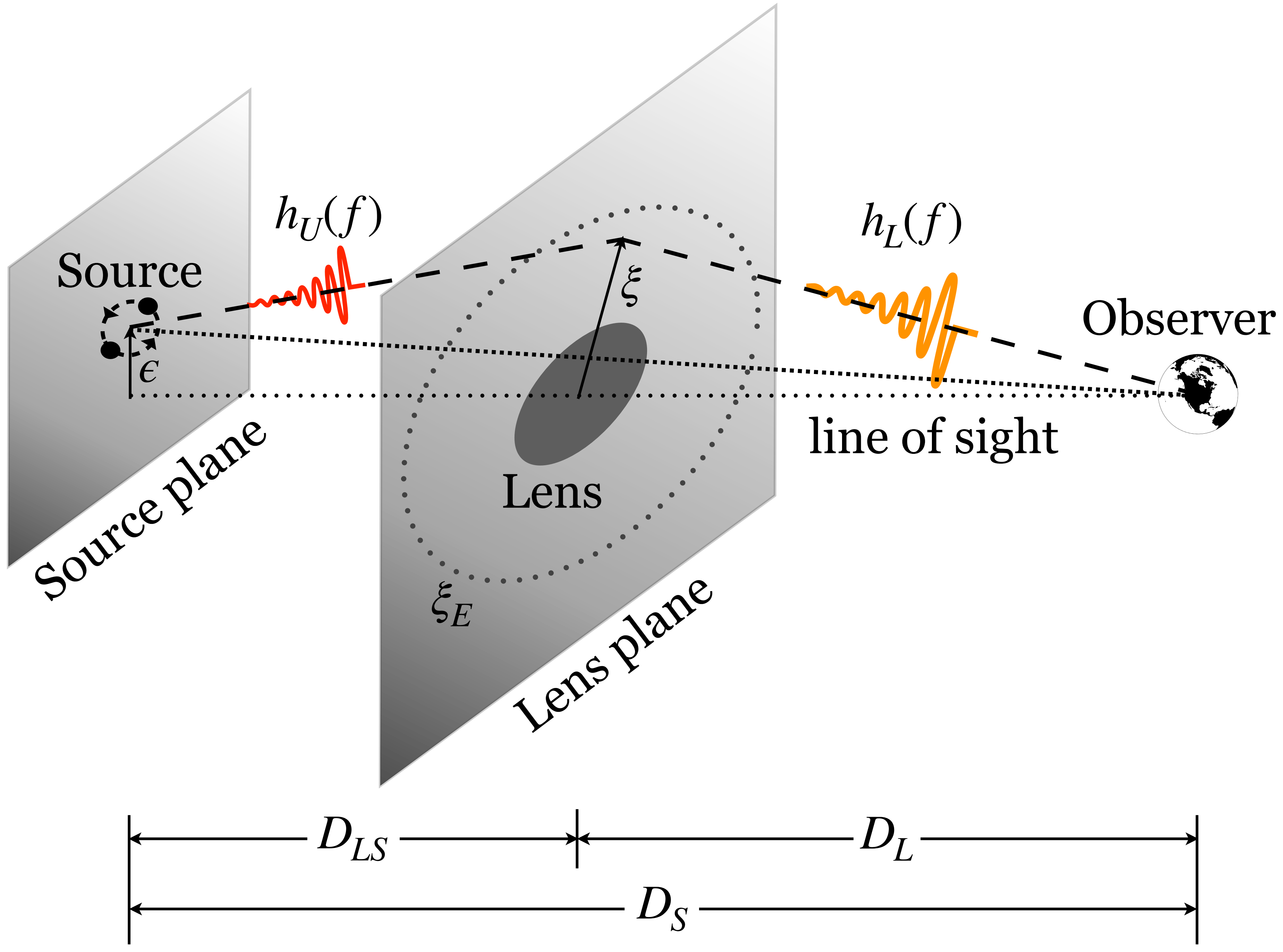
Lensing configuration (cont'd)

- With adopting the thin-lens approximation, we get

$$F(f) = \frac{D_S \xi_0^2 (1+z_L)}{D_L D_{LS}} \frac{f}{i} \int d^2\mathbf{x} \exp[2\pi i f t_d(\mathbf{x}, \mathbf{y})],$$

where

- $\mathbf{x} = \xi/\xi_0$, $\mathbf{y} = \epsilon D_L/\xi_0 D_S$: the position of image and source, respectively
  - ξ is the impact parameter in the lens plane
  - ϵ is the position vector of the source in the source plane
- ξ_0 is an arbitrary normalization constant of the length
  - For convenience, $\xi_0 = \xi_E$, where ξ_E is the Einstein radius of a lens system.
- t_d is the arrival time at the observer from the source
- F is normalized such that $|F| = 1$ in the no-lens limit



Arrival time

- The arrival time t_d at the observer from the source position ϵ through ξ is given by

$$t_d(\mathbf{x}, \mathbf{y}) = \frac{D_S \xi_0^2 (1 + z_L)}{D_L D_{LS}} \left[\frac{1}{2} |\mathbf{x} - \mathbf{y}|^2 - \psi(\mathbf{x}) + \phi_m(\mathbf{y}) \right],$$

  where

  - $\psi(\mathbf{x})$ is the dimensionless deflection potential
  - $\phi_m(\mathbf{y})$ is an arbitrary constant to be chosen to make the minimum value of t_d is 0

Lens models in geometrical optics limit

Takahashi & Nakamura
(ApJ, 2003)
with $c = G = 1$

- **Point-mass lens**: describe lens mass as a 2-dim Dirac delta function on lens plane

$$F(f) = |\mu_+|^{1/2} - i|\mu_-|^{1/2} e^{2\pi i f \Delta t_d},$$

where

- $\mu_\pm = \dfrac{1}{2} \pm \dfrac{(y^2+2)}{(2y\sqrt{y^2+4})}$: magnification factor for the 1st image (+) and 2nd image (-), respectively

- $$\Delta t_d = 4M_{Lz}\left[\frac{y\sqrt{y^2+4}}{2} + \ln\left(\frac{\sqrt{y^2+4}+y}{\sqrt{y^2+4}-y}\right)\right]$$: time delay between 1st and 2nd images

- $M_{Lz} = M_L(1+z)$: redshifted lens mass

Lens models in geometrical optics limit

Takahashi & Nakamura
(ApJ, 2003)
with $c = G = 1$

- **Singular Isothermal Sphere**: circular and symmetric mass distribution on lens plane

$$F(f) = \begin{cases} |\mu_+|^{1/2} - i|\mu_-|^{1/2} e^{2\pi i f \Delta t_d} & \text{if } y < 1, \\ |\mu_+|^{1/2} & \text{if } y \geq 1 \end{cases},$$

where

- $\mu_\pm = \dfrac{1}{y} \pm 1$: magnification factor for the 1st image (+) and 2nd image (-), respectively
- $\Delta t_d = 8 M_{Lz} y$: time delay between 1st and 2nd images
- $M_{Lz} = M_L(1+z)$: redshifted lens mass

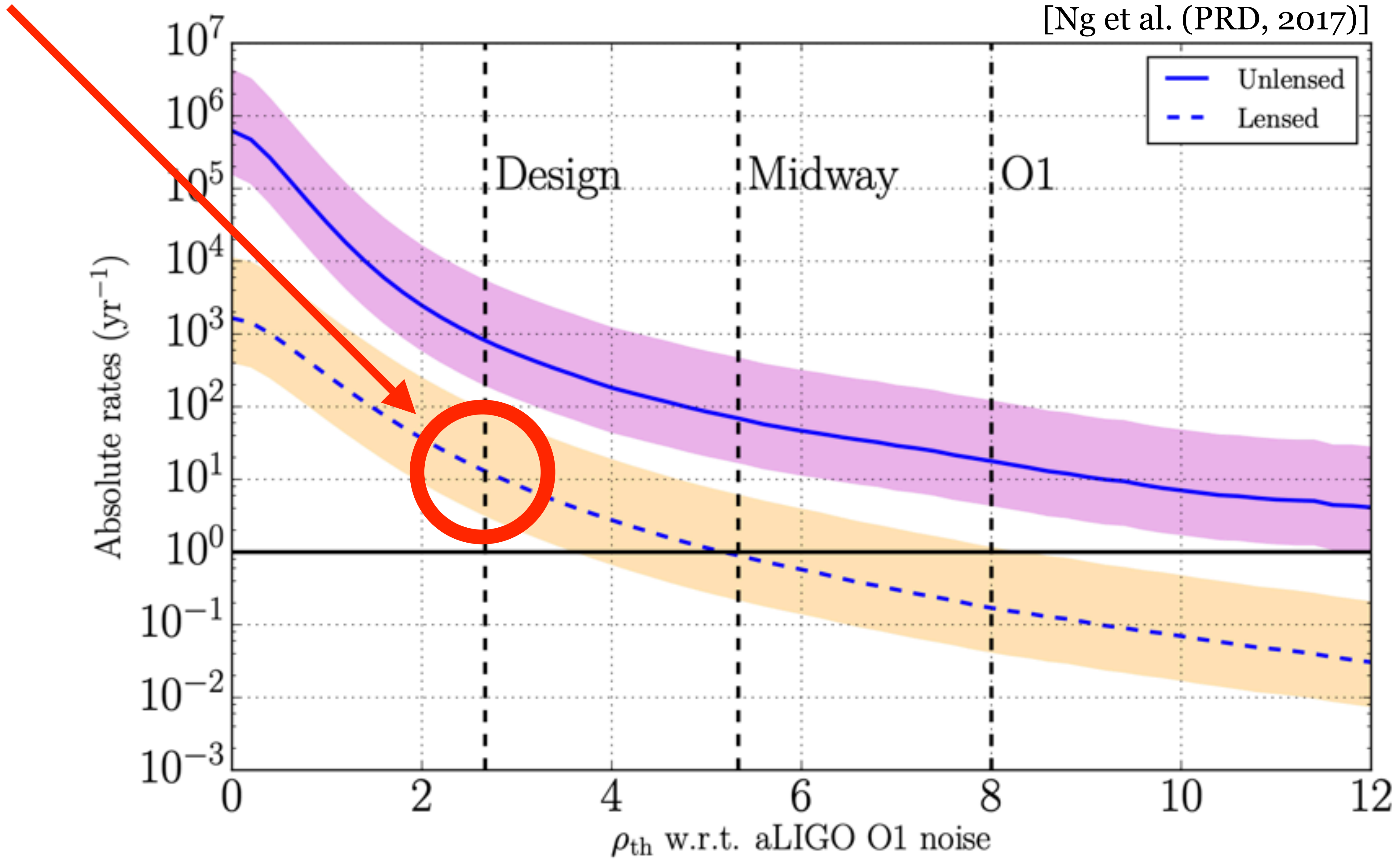
Light Lensing vs GW Lensing

	Light Lensing	GW Lensing
Optics	Geometrical optics	Wave optics (Geometrical optics limit if $\lambda_{\rm GW} \ll 2GM_L/c^2$)
Categories by scale	Strong, Weak, Micro	Strong, Weak*, Phenomenological**, Micro
Angular resolution	Good	Poor
Time resolution	Fair	Precise
Analysis	Solved using the lens equation	Solved using the amplification factor

*: not considered in the current searches
**: considered from O4 search

Why is GW lensing exciting now?

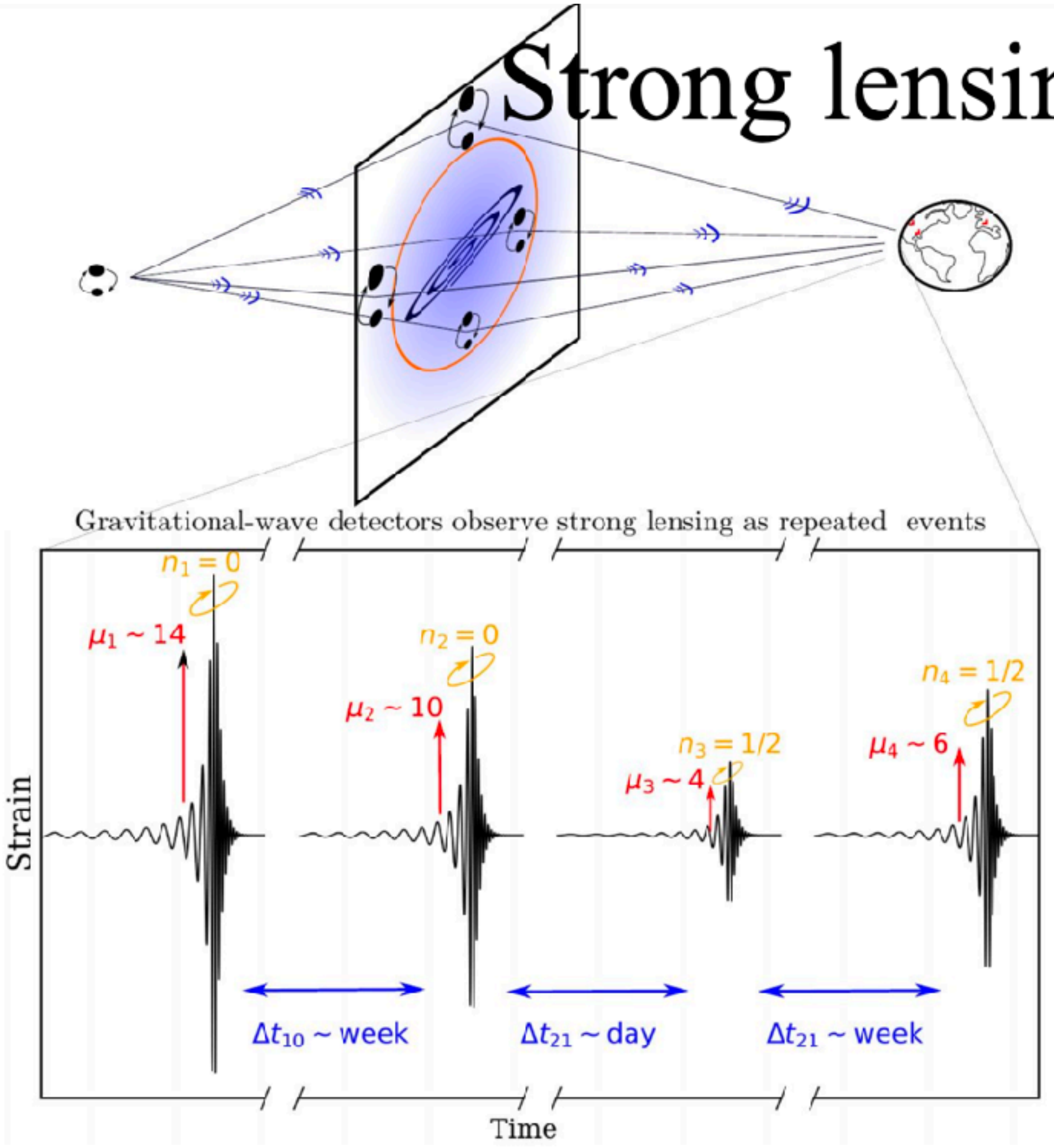
- Forecasts predict strong lensing at a reasonable rate
  Ng et al. (2017), Li et al. (2018), Oguri (2018), Wierda et al. (2021), Xu et al. (2021)



- Can probe new studies of astrophysics, cosmology, and fundamental physics
  - **Study the origin of black holes**
    Hannuksela et al. (2020)
  - **Tests of fundamental physics**
    Collet & Bacon (2017; speed of GWs), Liu & Kim (2024; millilensed GWs vs precessing GWs)
  - **Study the expansion of the Universe**
    Baker & Trodden (2017), Liao et al. (2017), Hannuksela et al. (2020), Seo & Kim (in prep.)
  - **Study microlens populations** *Lai et al. (2018), Jung et al. (2019)*
  - **Study wave optics** *Cheung et al. (2020)*

Search for strong lensing of gravitational waves

Strong lensing challenge



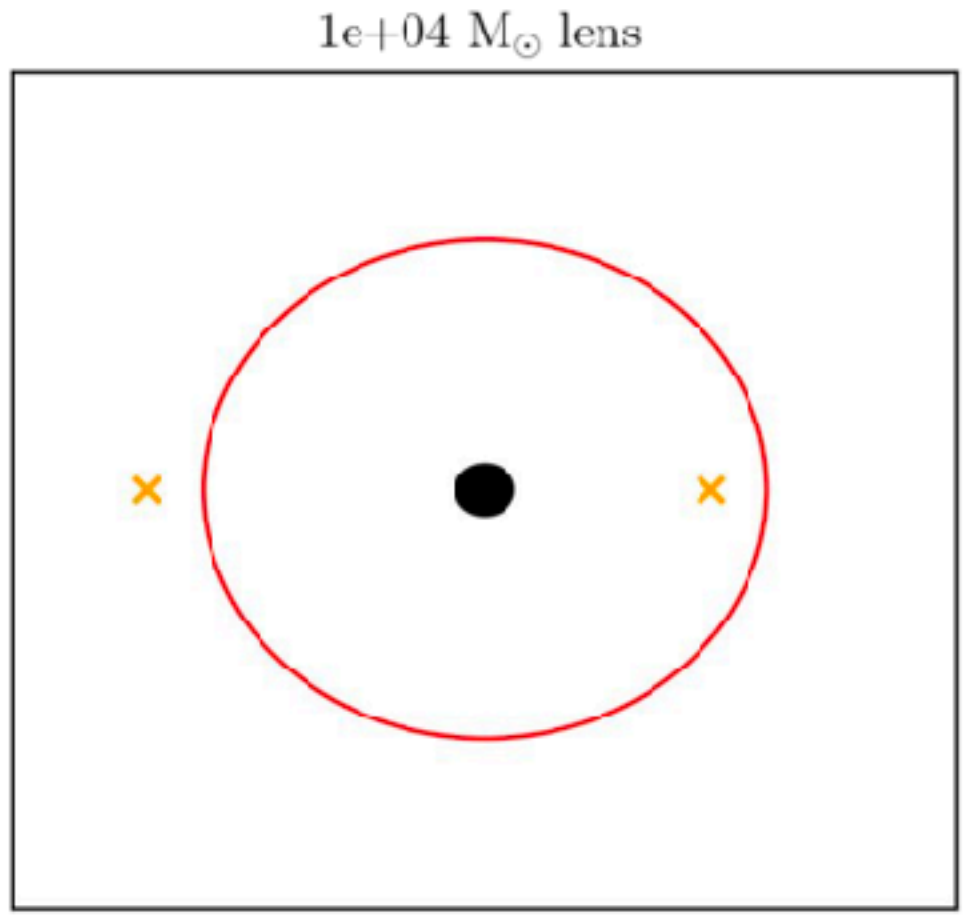
Strong lensing:

- Identify "repeated events" in the data
- Targets: Galaxies, galaxy clusters

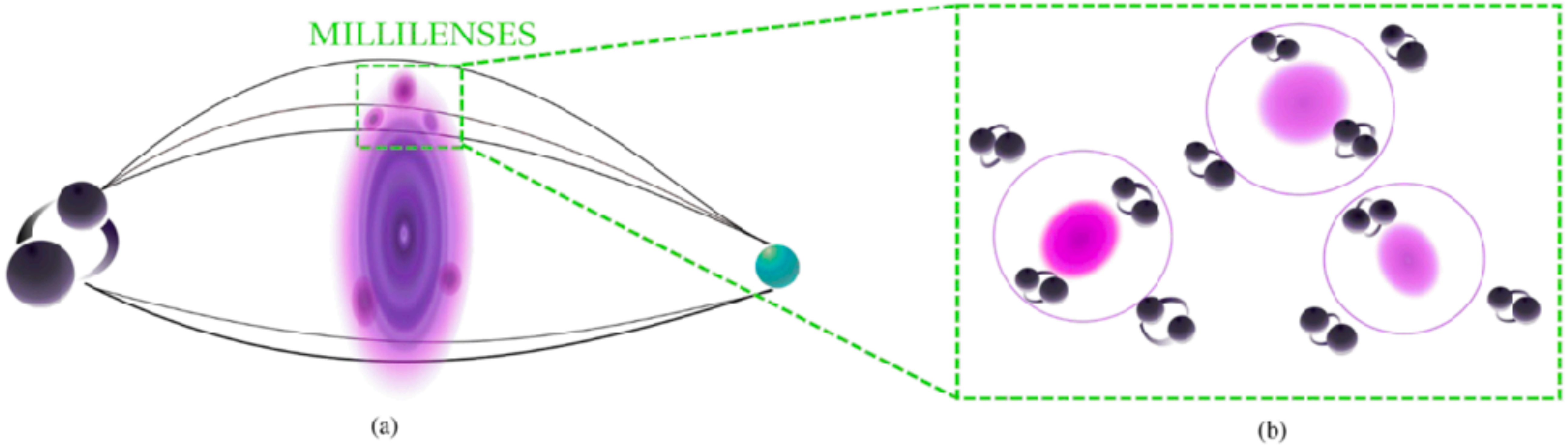
Precise measurement of gravitational-wave image properties

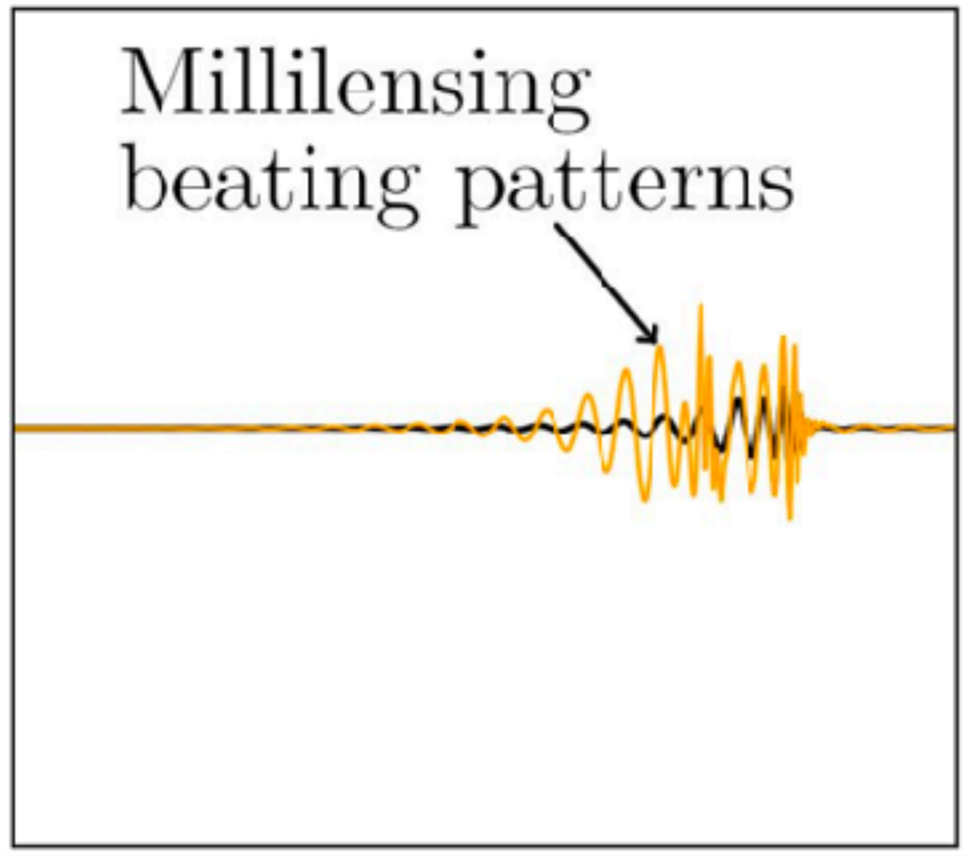
[credit: Otto Hannuksela]

Search for millilensing of graviational waves



Millilensing challenge



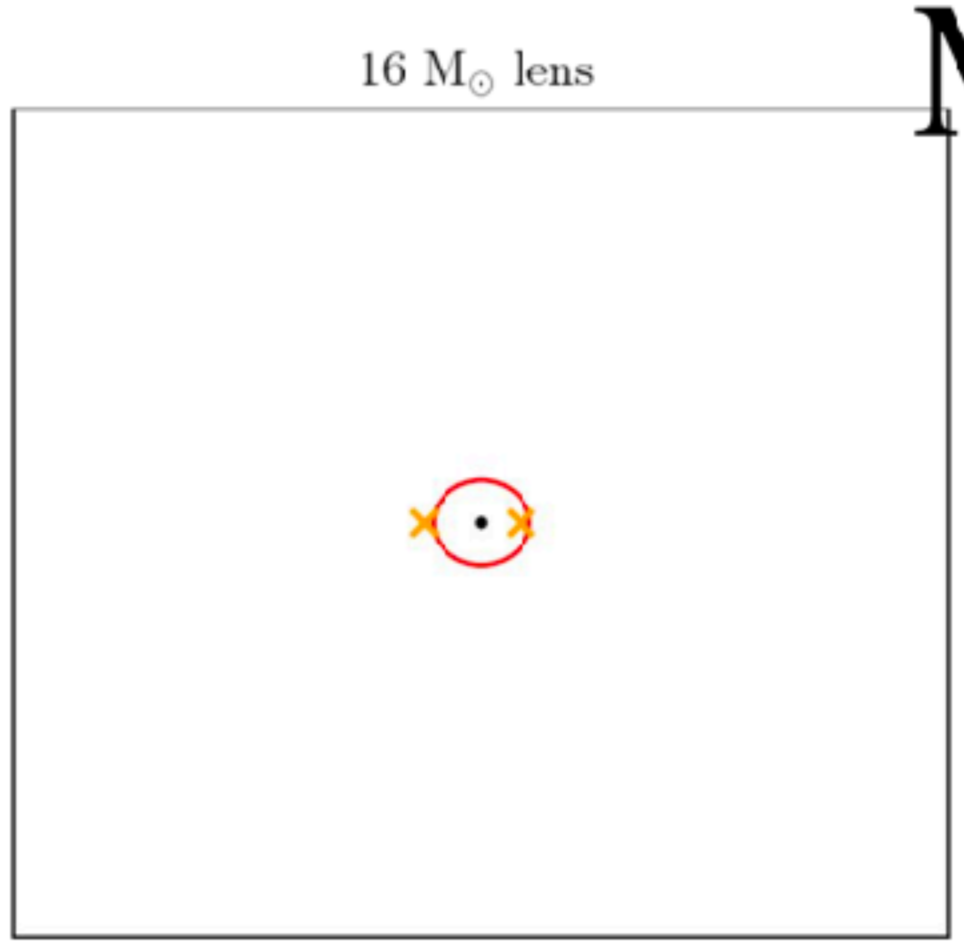


Millilensing:
- Modify gravitational-wave templates to identify millilensing “beating patterns”
- Targets: Subhalos, massive black holes

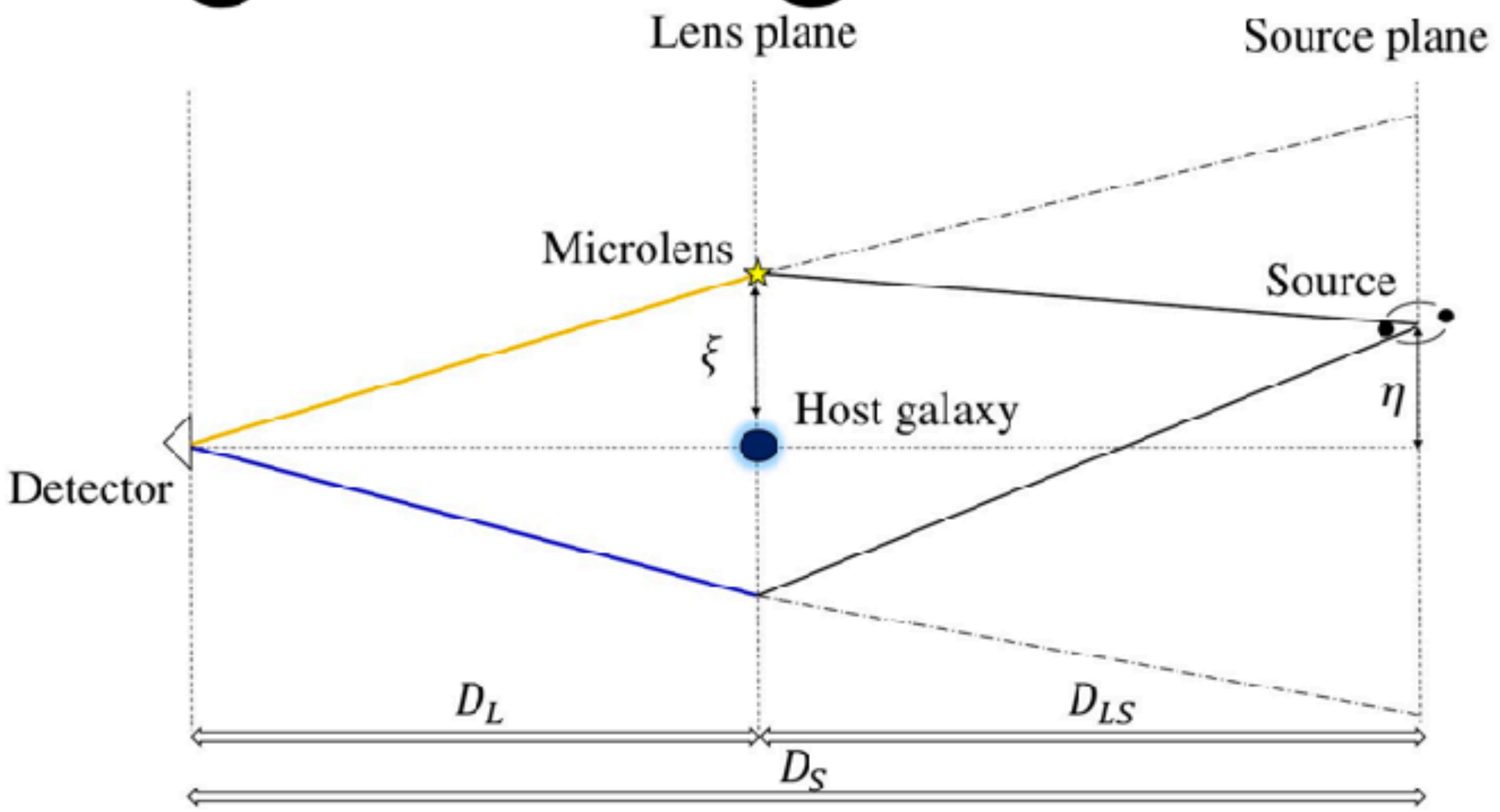
Measurement of the millilens **mass** and source position

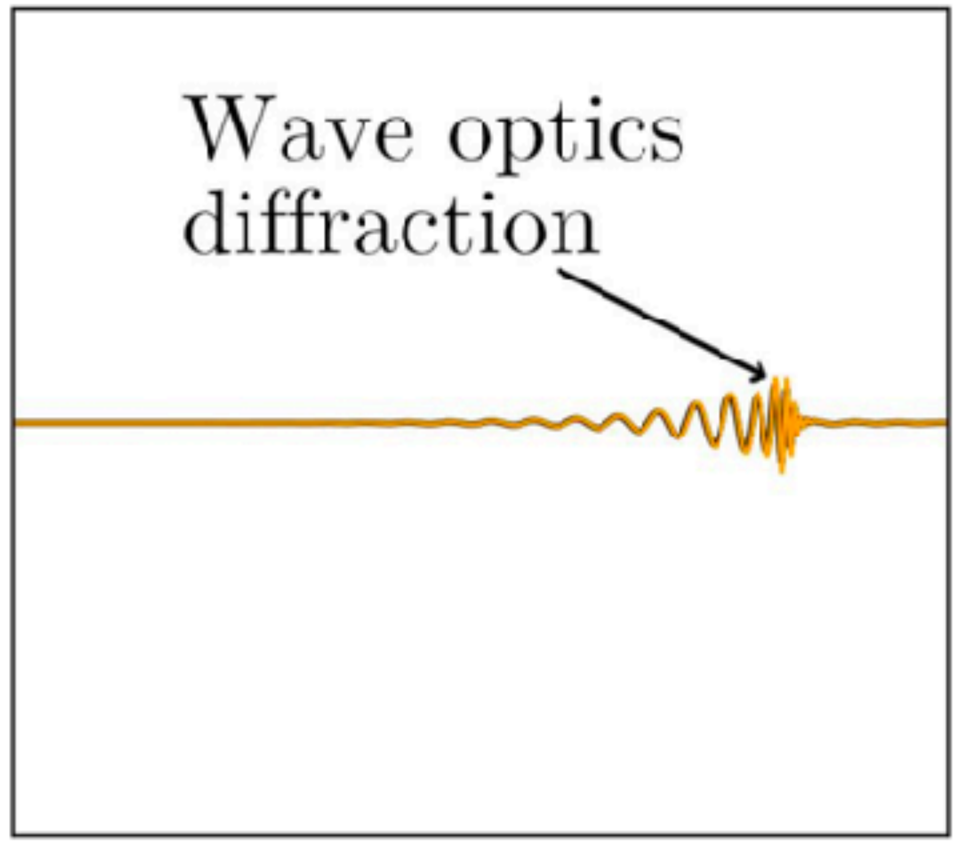
[credit: Otto Hannuksela]

Search for microlensing of gravitational waves



Microlensing challenge





Microlensing:

- Modify gravitational-wave templates to identify microlensing wave optics effects
- Targets: Stars, stellar-mass black holes and primordial black holes

Measurement of the microlensing **mass** and source position

[credit: Otto Hannuksela]

Search results (selected)

(O4a CBCs)

THE ASTROPHYSICAL JOURNAL LETTERS (O1 & O2 BBHs)

Search for Gravitational Lensing Signatures in LIGO-Virgo Binary Black Hole Events

O. A. Hannuksela[1], K. Haris[2], K. K. Y. Ng[3,4], S. Kumar[2,5,6], A. K. Mehta[2], D. Keitel[7], T. G. F. Li[1], and P. Ajith[2,8]

Published 2019 March 19 •
The Astrophysical Journal Letters, Volume 874, Number 1
Citation O. A. Hannuksela *et al* 2019 *ApJL* **874** L2
DOI 10.3847/2041-8213/ab0c0f

THE ASTROPHYSICAL JOURNAL (O3a CBCs)

Search for Lensing Signatures in the Gravitational-Wave Observations from the First Half of LIGO–Virgo's Third Observing Run

R. Abbott[1], T. D. Abbott[2], S. Abraham[3], F. Acernese[4,5], K. Ackley[6], A. Adams[7], C. Adams[8], R. X. Adhikari[1], V. B. Adya[9], C. Affeldt[10,11] Show full author list

Published 2021 December 10 •
The Astrophysical Journal, Volume 923, Number 1
Citation R. Abbott *et al* 2021 *ApJ* **923** 14
DOI 10.3847/1538-4357/ac23db

THE ASTROPHYSICAL JOURNAL (O1 & O2 BBHs; microlensing → millilensing → phenomenological lensing)

OPEN ACCESS

Deep Learning–based Search for Microlensing Signature from Binary Black Hole Events in GWTC-1 and -2

Kyungmin Kim[1,2], Joongoo Lee[3], Otto A. Hannuksela[4], and Tjonnie G. F. Li[4,5,6]

Published 2022 October 24 •
The Astrophysical Journal, Volume 938, Number 2
Citation Kyungmin Kim *et al* 2022 *ApJ* **938** 157
DOI 10.3847/1538-4357/ac92f3

THE ASTROPHYSICAL JOURNAL (Full O3 CBCs)

OPEN ACCESS

Search for Gravitational-lensing Signatures in the Full Third Observing Run of the LIGO–Virgo Network

R. Abbott, H. Abe, F. Acernese, K. Ackley, S. Adhicary, N. Adhikari, R. X. Adhikari, V. K. Adkins, V. B. Adya, C. Affeldt Show full author list

Published 2024 July 31 •
The Astrophysical Journal, Volume 970, Number 2
Citation R. Abbott *et al* 2024 *ApJ* **970** 191
DOI 10.3847/1538-4357/ad3e83

arXiv

General Relativity and Quantum Cosmology

[Submitted on 18 Dec 2025 (v1), last revised 4 Feb 2026 (this version, v3)]

GWTC-4.0: Searches for Gravitational-Wave Lensing Signatures

The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration: A. G. Abac, I. Abouelfettouh, F. Acernese, K. Ackley, C. Adamcewicz, S. Adhicary, D. Adhikari, N. Adhikari, R. X. Adhikari, V. K. Adkins, S. Afroz, A. Agapito, D. Agarwal, M. Agathos, N. Aggarwal, S. Aggarwal, O. D. Aguiar, I.-L. Ahrend, L. Aiello, A. Ain, P. Ajith, T. Akutsu, S. Albanesi, W. Ali, S. Al-Kershi, C. Alléné, A. Allocca, S. Al-Shammari, P. A. Altin, S. Alvarez-Lopez, W. Amar, O. Amarasinghe, A. Amato, F. Amicucci, C. Amra, A. Ananyeva, S. B. Anderson, W. G. Anderson, M. Andia, M. Ando, M. Andrés-Carcasona, T. Andrić, J. Anglin, S. Ansoldi, J. M. Antelis, S. Antier, M. Aoumi, E. Z. Appavuravther, S. Appert, S. K. Apple, K. Arai, A. Araya, M. C. Araya, M. Arca Sedda, J. S. Areeda, N. Aritomi, F. Armato, S. Armstrong, N. Arnaud, M. Arogeti, S. M. Aronson, G. Ashton, Y. Aso, L. Asprea, M. Assiduo, S. Assis de Souza Melo, S. M. Aston, P. Astone, F. Attadio, F. Aubin, K. AultONeal, G. Avallone, E. A. Avila, S. Babak, C. Badger, S. Bae, S. Bagnasco, L. Baiotti, R. Bajpai, T. Baka, A. M. Baker, K. A. Baker, T. Baker, G. Baldi, N. Baldicchi, M. Ball, G. Ballardin, S. W. Ballmer, S. Banagiri, B. Banerjee, D. Bankar, T. M. Baptiste, P. Baral, M. Baratti, J. C. Barayoga, B. C. Barish, D. Barker et al. (1669 additional authors not shown)

Gravitational waves can be gravitationally lensed by massive objects along their path. Depending on the lens mass and the lens--source geometry, this can lead to the observation of a single distorted signal or multiple repeated events with the same frequency evolution. We present the results for gravitational-wave lensing searches on the data from the first part of the fourth LIGO--Virgo--KAGRA observing run (O4a). We search for strongly lensed events in the newly acquired data by (1) searching for an overall phase shift present in an image formed at a saddle point of the lens potential, (2) looking for pairs of detected candidates with consistent frequency evolution, and (3) identifying sub-threshold counterpart candidates to the detected signals. Beyond strong lensing, we also look for lensing-induced distortions in all detected signals using an isolated point-mass model. We do not find evidence for strongly lensed gravitational-wave signals and use this result to constrain the rate of detectable strongly lensed events and the merger rate density of binary black holes at high redshift. In the search for single distorted lensed signals, we find one outlier: GW231123_135430, for which we report more detailed investigations. While this event is interesting, the associated waveform uncertainties make its interpretation complicated, and future observations of the populations of binary black holes and of gravitational lenses will help determine the probability that this event could be lensed.

- No strong evidence has been found from the events of the three observing runs.
- The results of O4b+c data will appear soon.

이쯤되면... 고민의 시작?

이쯤되면... 고민의 시작?


GW theory, simulation, experiment, search pipeline, parameter estimation, lunar exploration, ...
me
GW Lensing

하지만, 북산고 안선생님은 말씀하셨지요...

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뭘 믿고???

[한국시간 **2015**년 **2**월 **12**일 **00:30**]

뭘 믿고???

[한국시간 **2015**년 **2**월 **12**일 **00:30**]

Thesis for the degree of Doctor of Philosophy

Search for Gravitational Waves Associated with Short Gamma-Ray Bursts

Kyungmin Kim

Hanyang University Graduate School

February 2015

뭘 믿고???

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February 2015

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For the two recent CBC-GRB searches [6, 32], a search pipeline, which is called *coherent search pipeline*, was used. The pipeline imposes a ranking method, *detection statistic* [10], to pick and to classify a significant candidate for gravitational-wave signal among the *triggers* generated by *matched filtering* [39]. However, in this thesis, the machine learning algorithm (MLA) will be considered as an alternative method for ranking triggers. Application of MLAs to many problems including several gravitational-wave related analyses have shown good classification performances for their nonlinear multi-dimensional data [40–43] by using various MLAs such as artificial neural networks [44, 45], random forests of bagged

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뭘 믿고???

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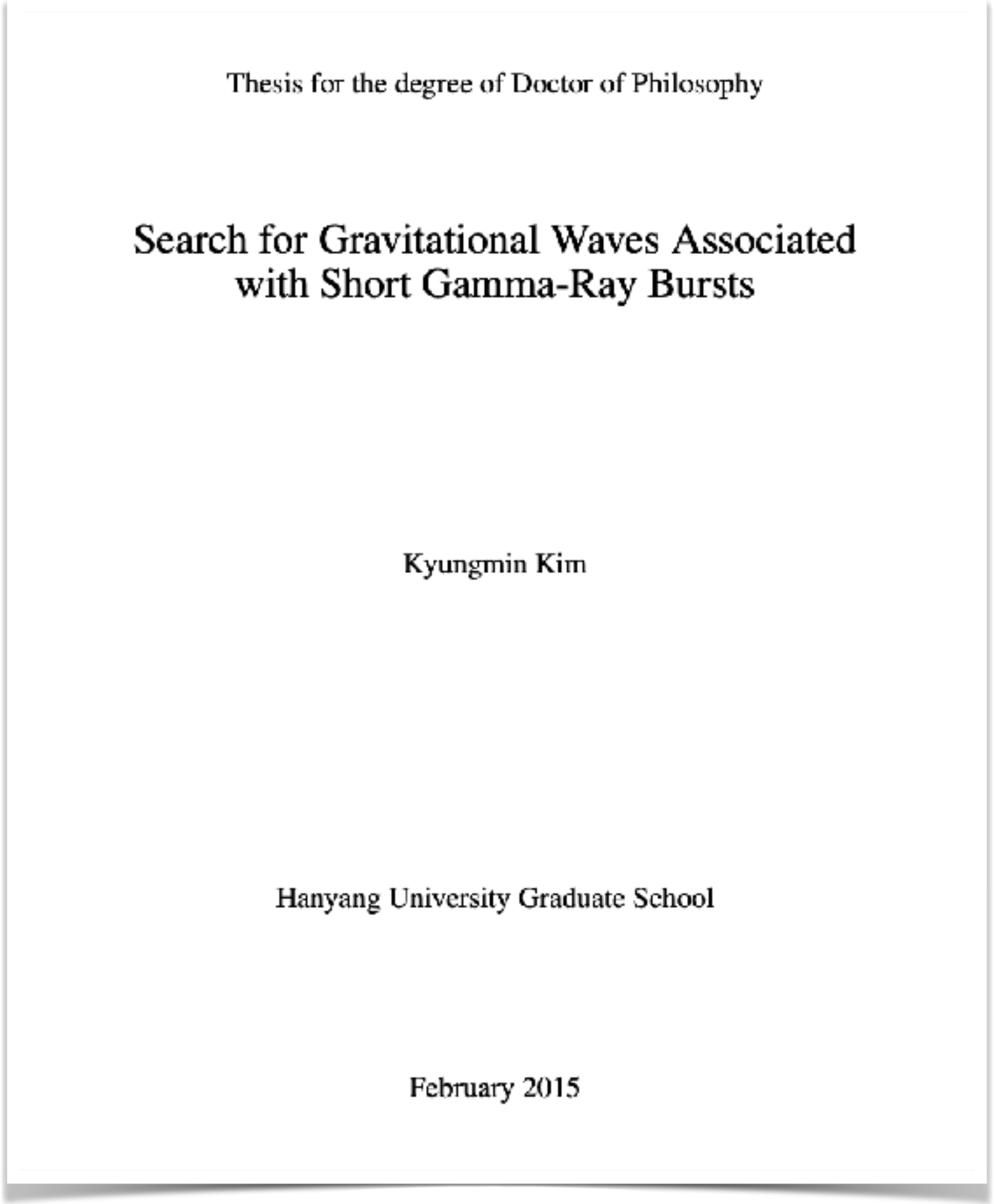
[한국시간 2015년 2월 12일 00:30]

뭘 믿고???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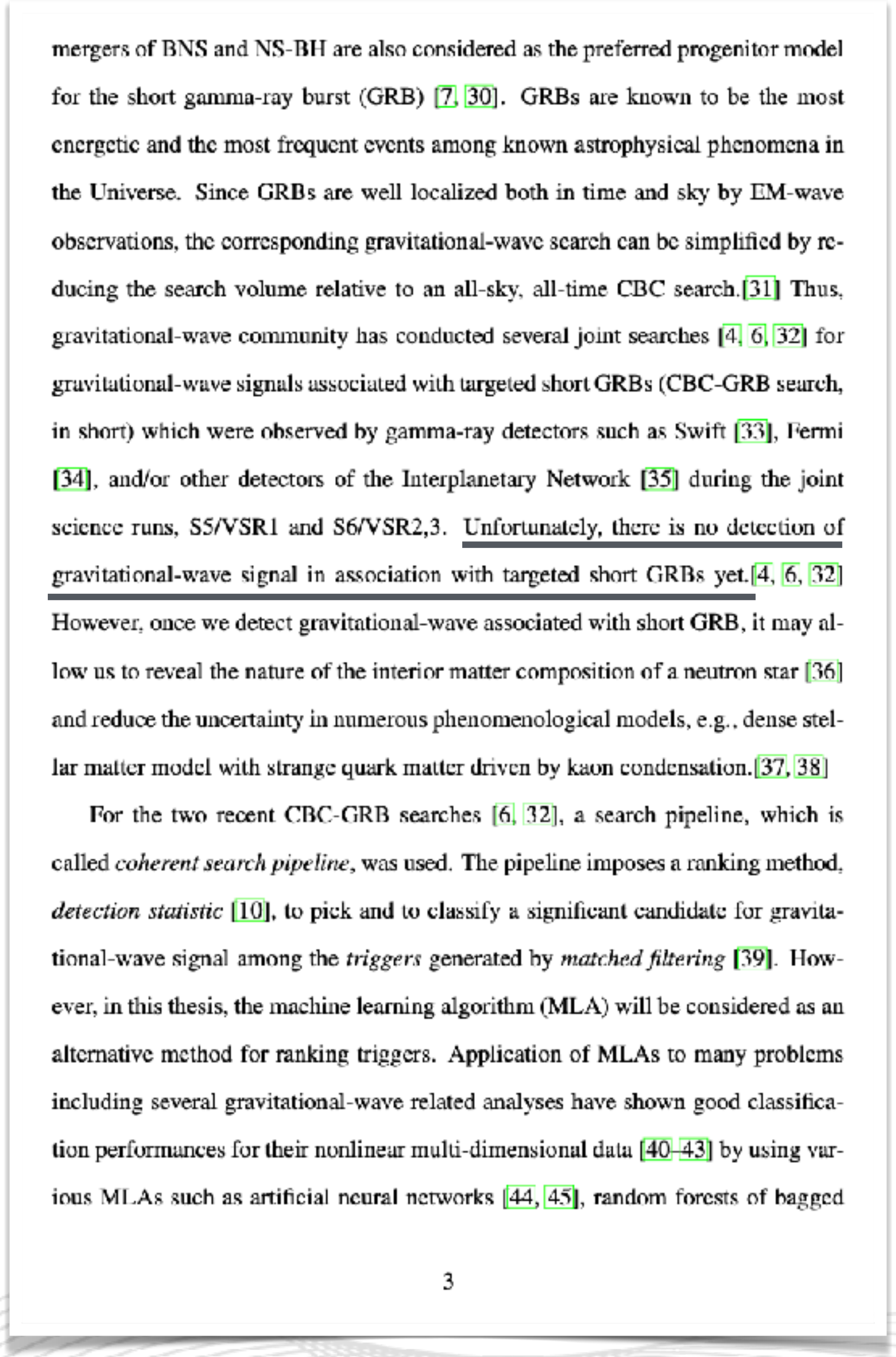
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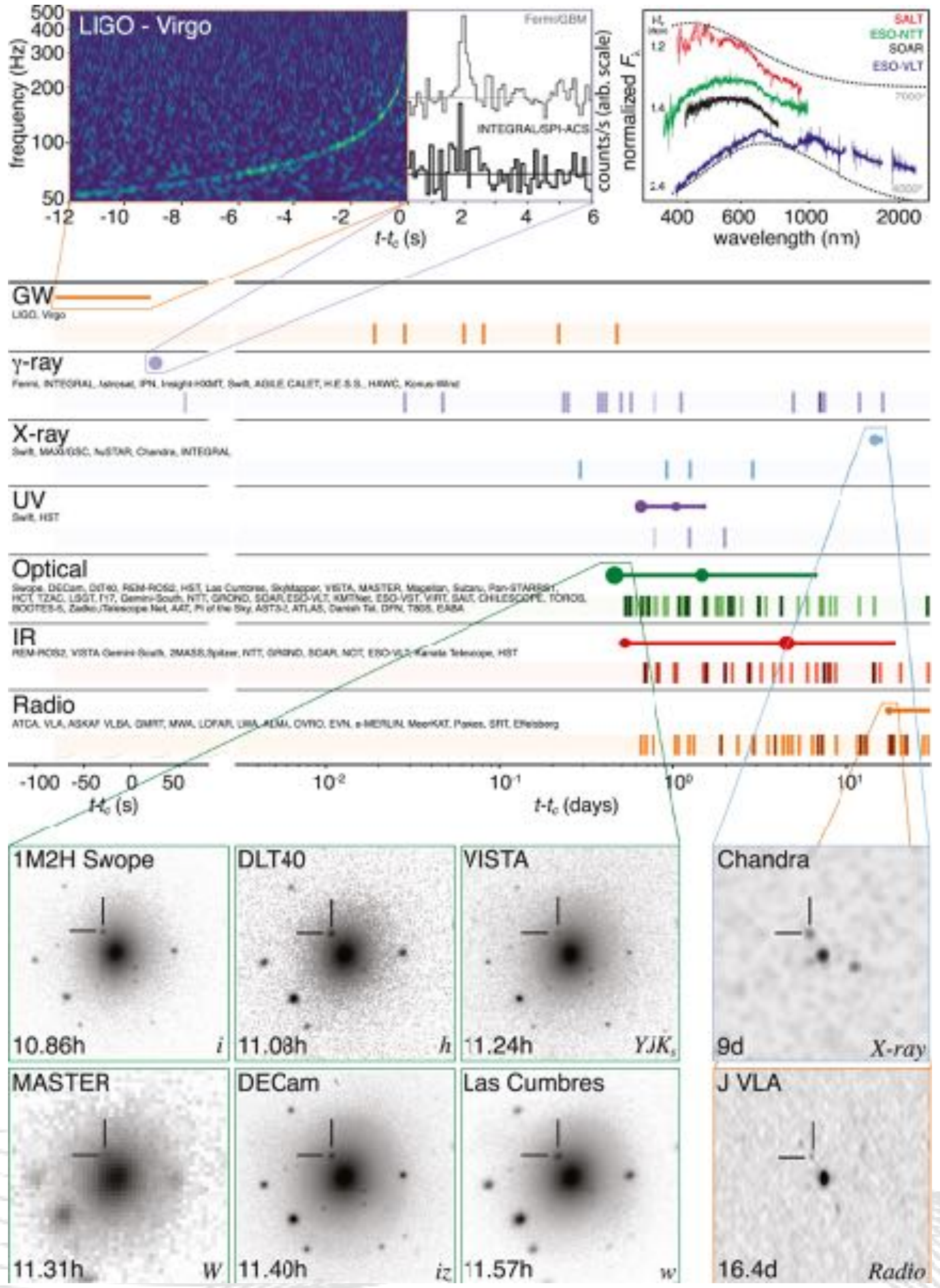
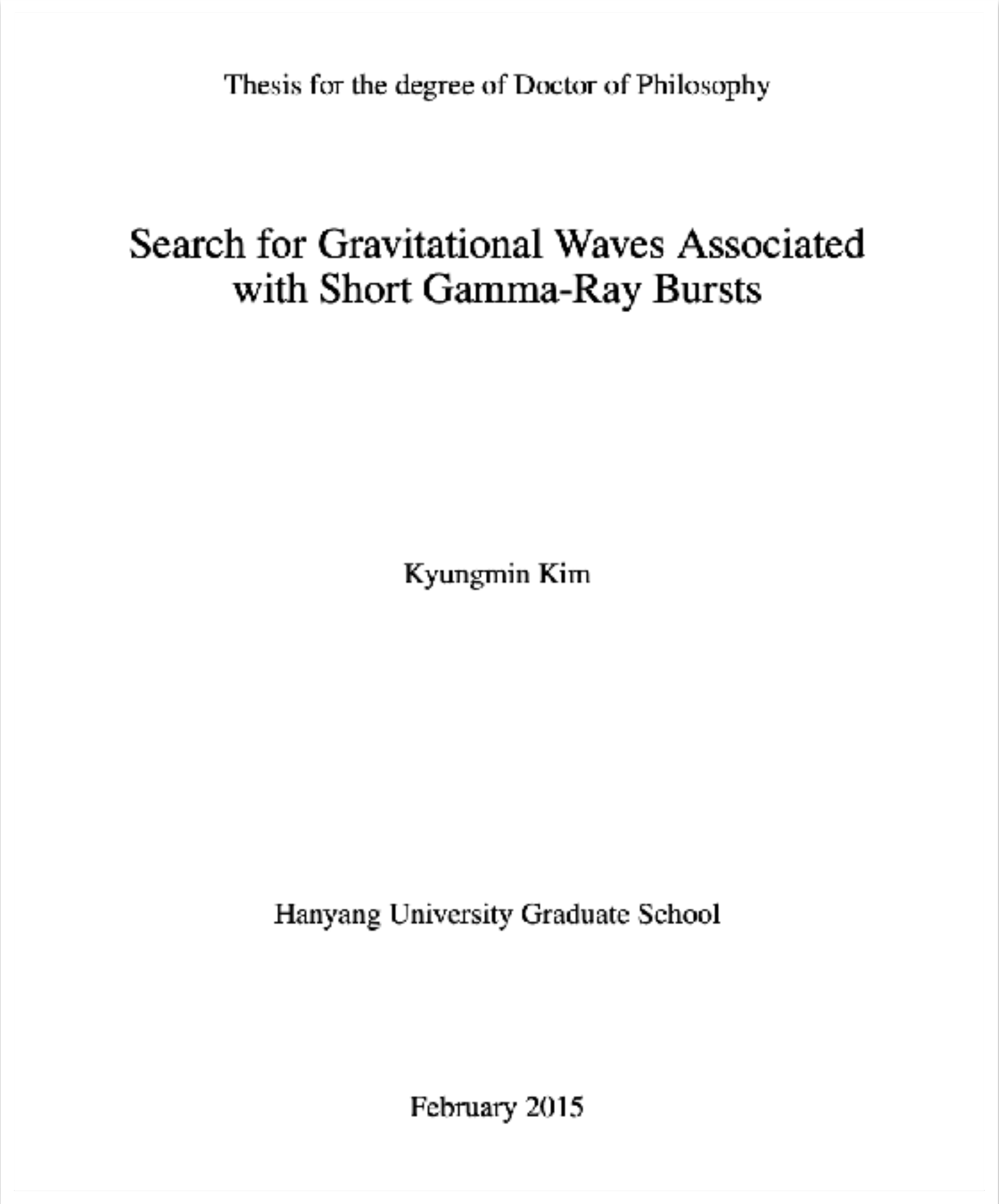


[Abbott+2017b]

뭘 믿고??? 일단 준비 해보자!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Kyungmin Kim

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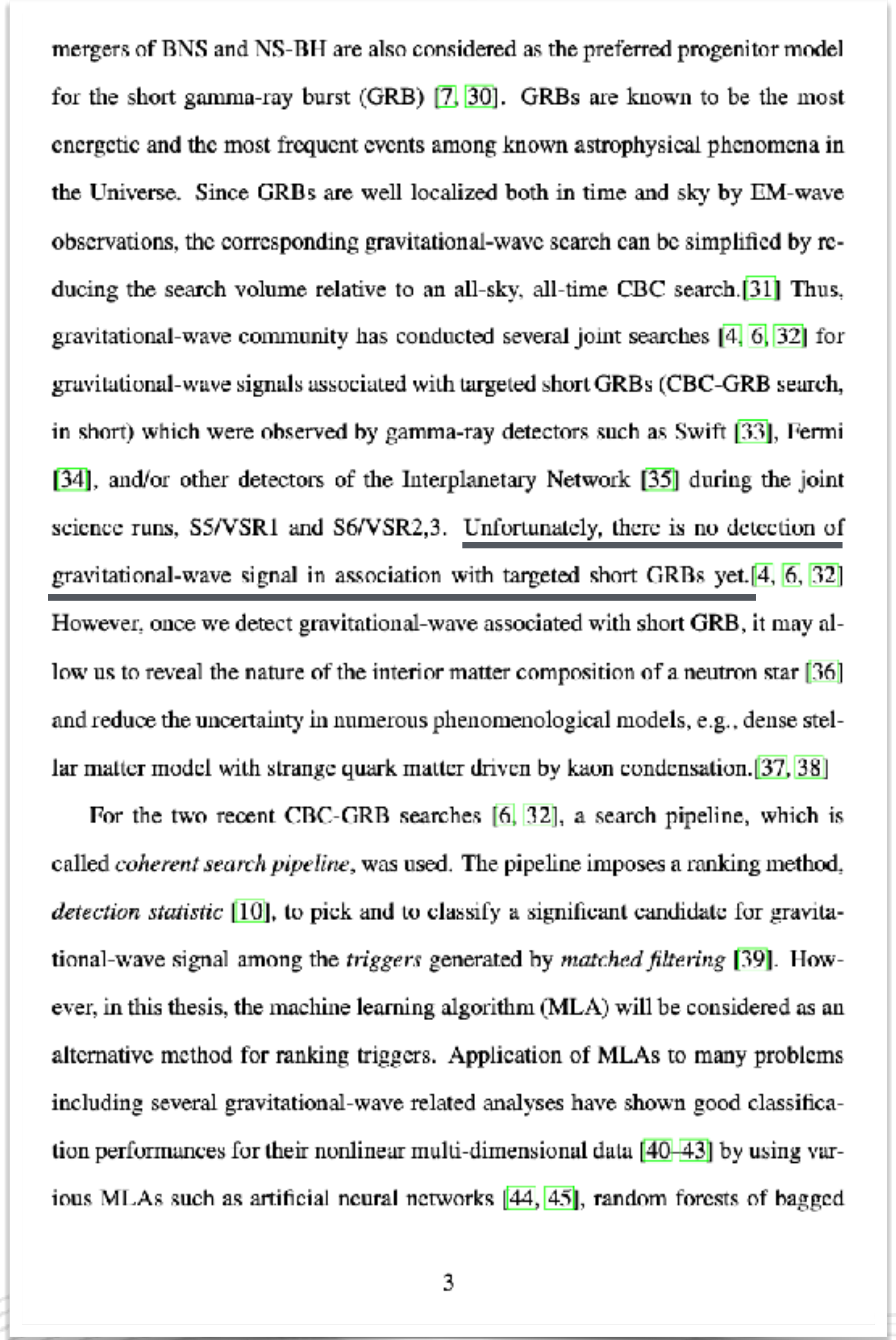
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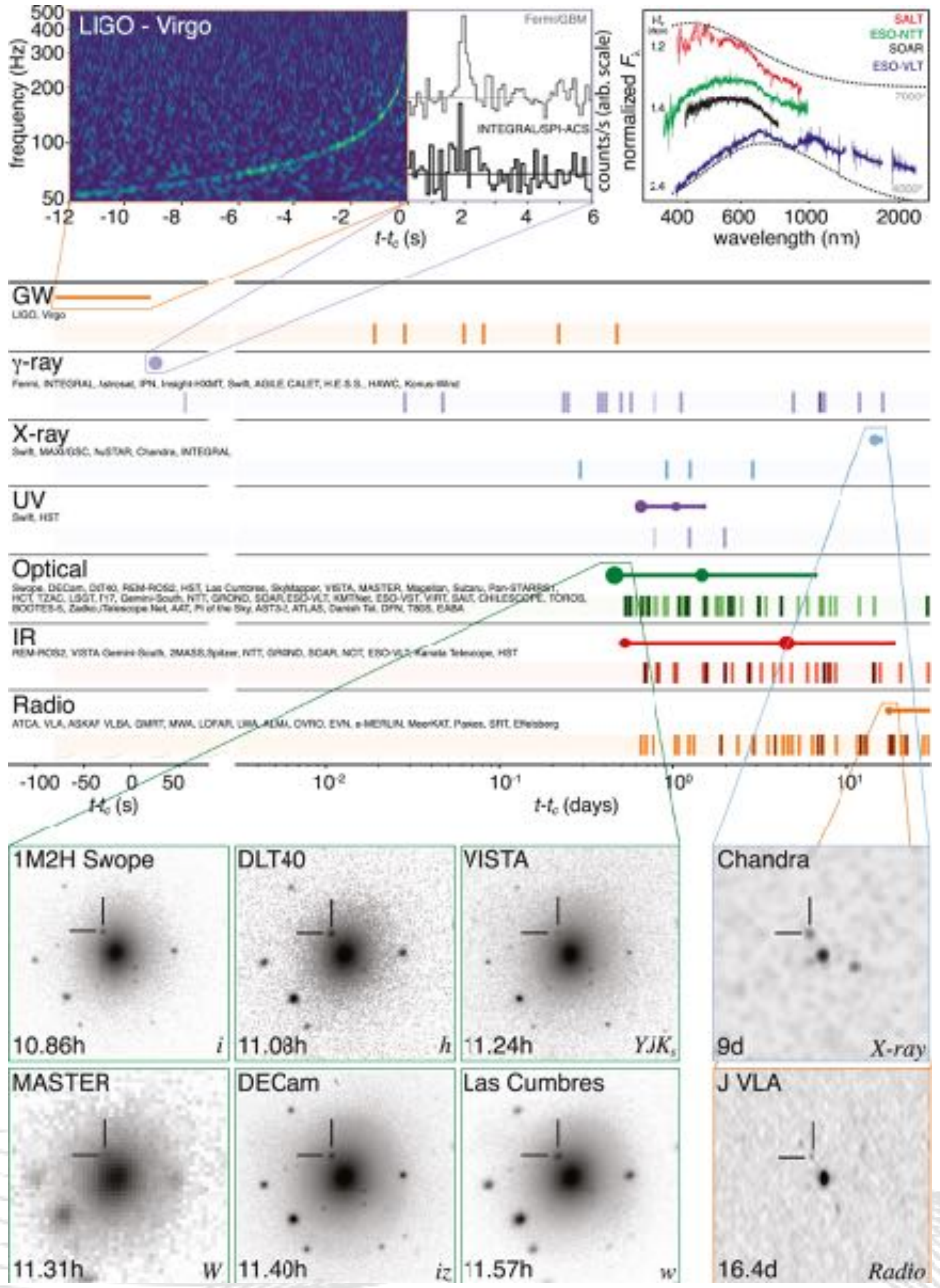
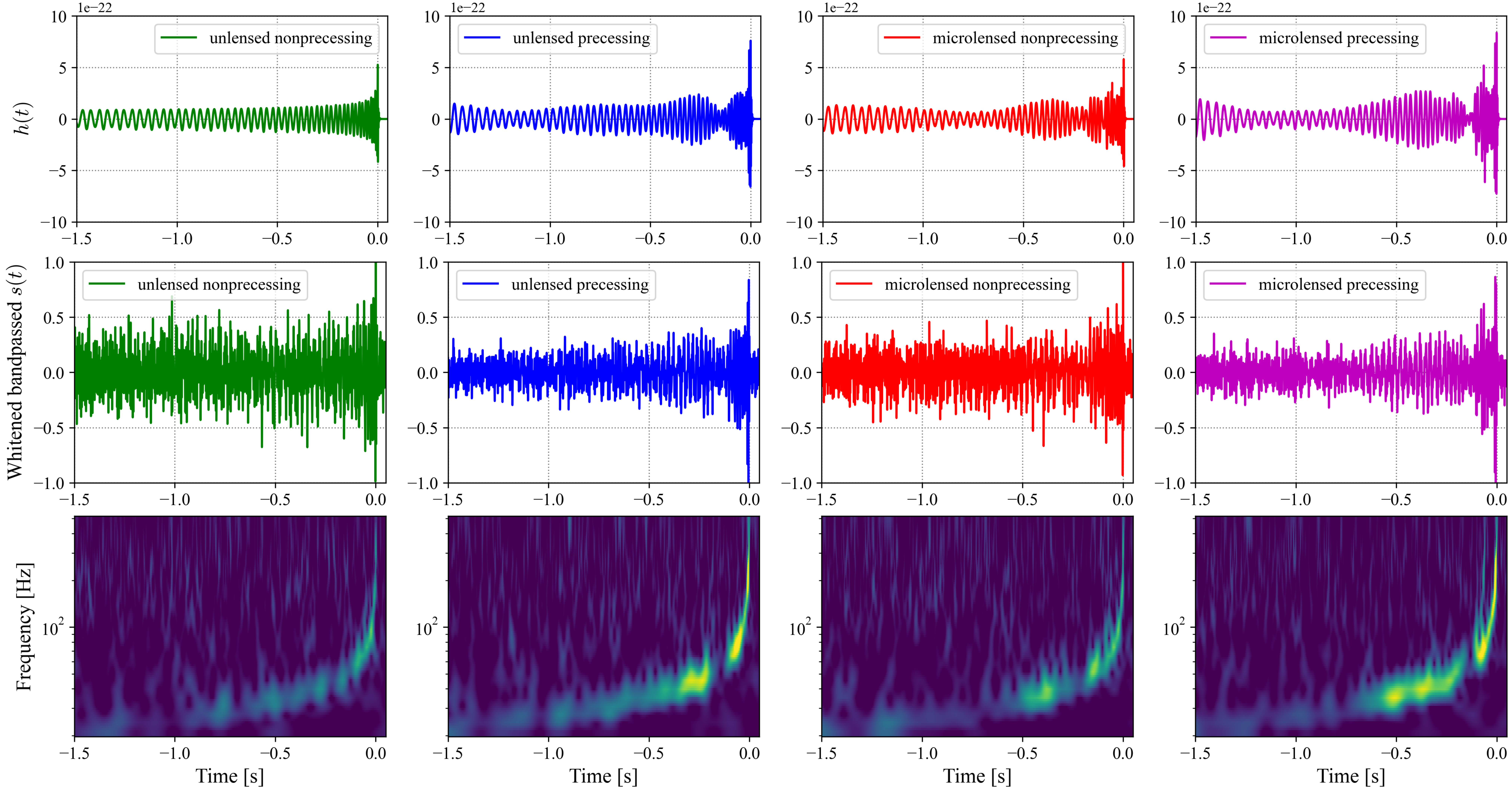


[Abbott+2017b]

Can we discern millilensed GW signals from signals produced by precessing binary black holes

[A. Liu, KK (PRD, 2024)]

- Morphological similarity between millilensed GWs and GWs from precessing binaries



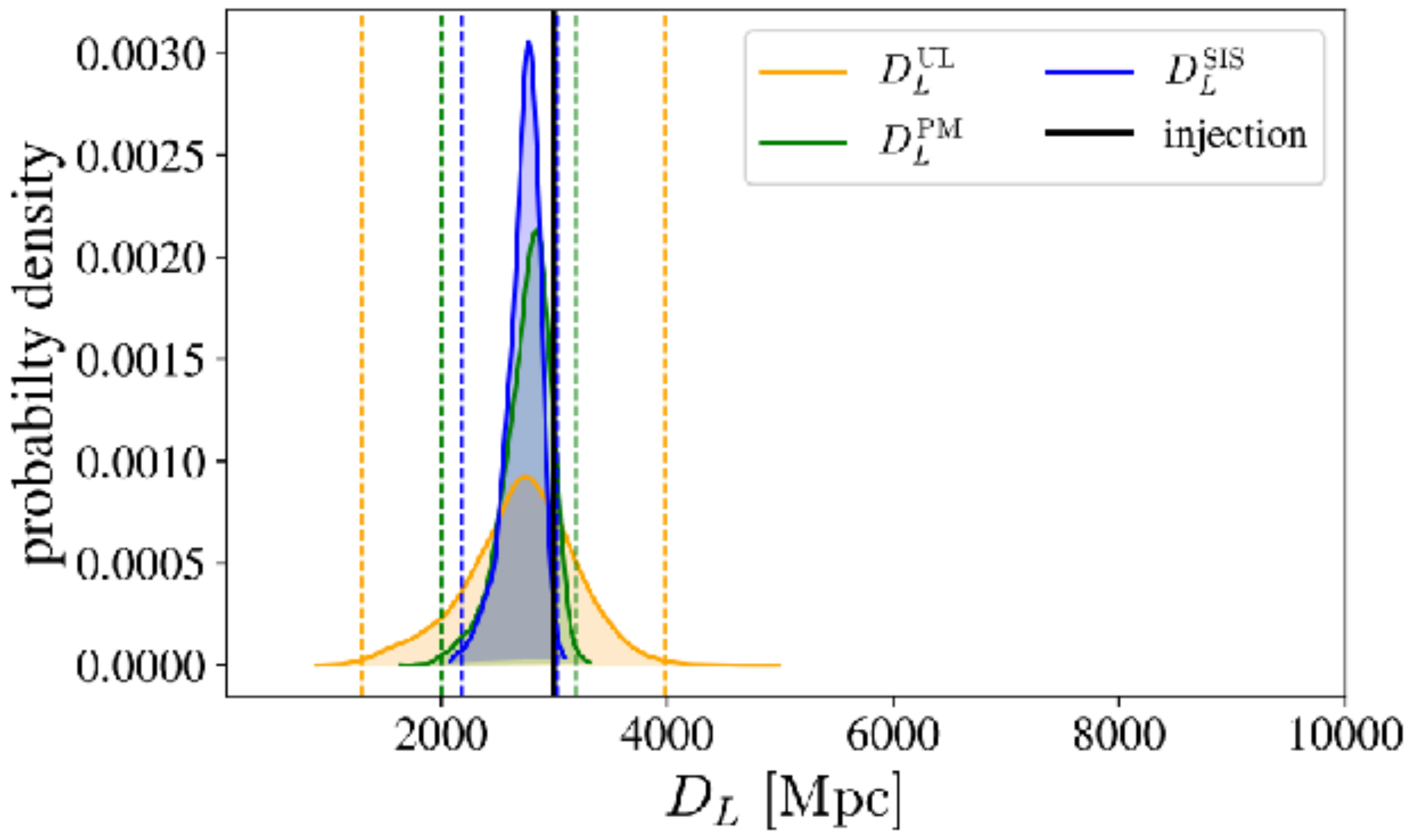
Luminosity distance estimation for Binary black holes with strongly lensed GWs

[KK, E. Seo, C. Kim (PRD, 2024)]

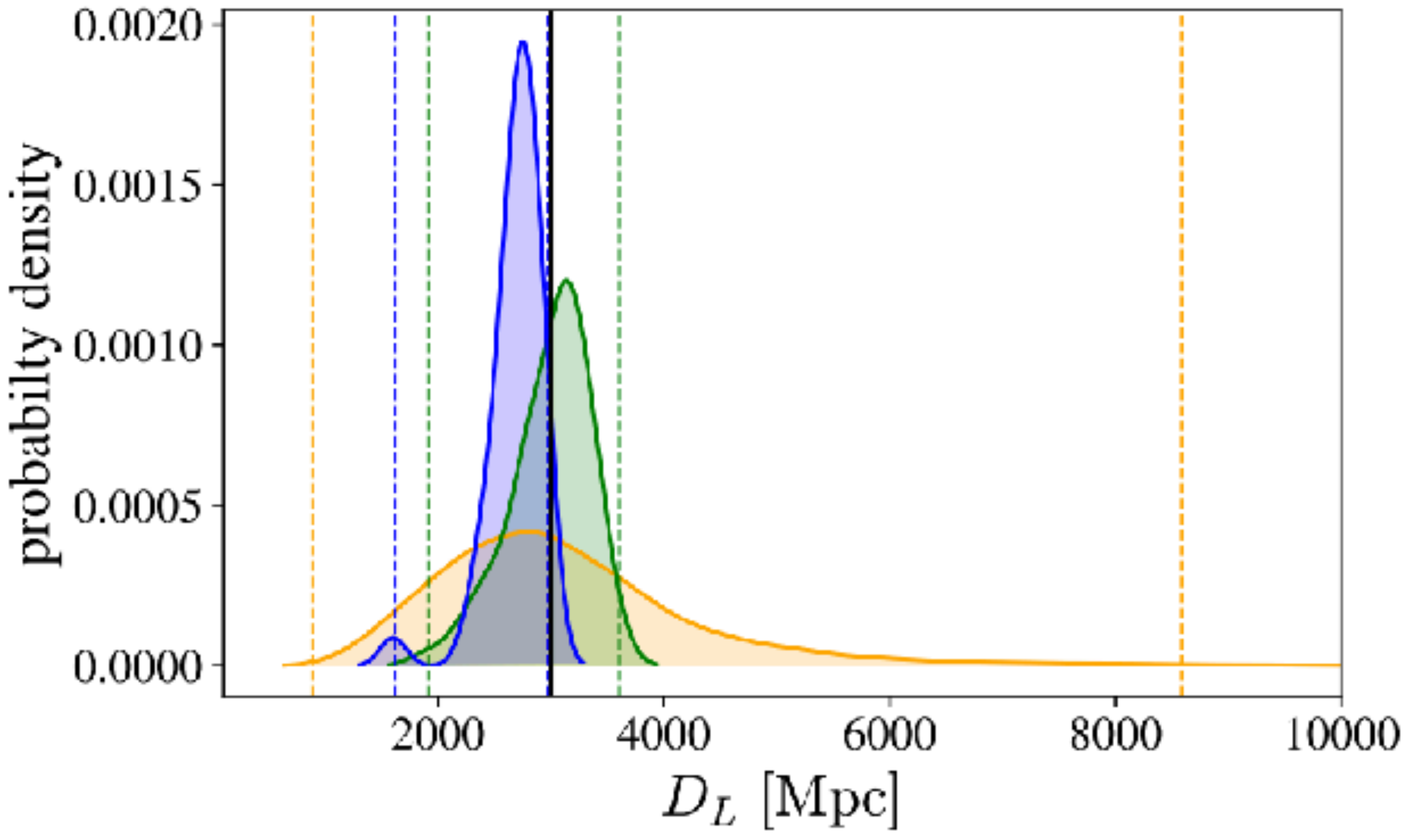
- Luminosity distance d_L: a direct observable of GW observations
- Time delay of strongly lensed GWs: days—months depending on lens mass and alignment
  - likely to identify multiple lensed GW events as independent events.

- Demonstrate estimating d_L to BBHs with strongly lensed GW signals.
  - Combine results from parameter estimations on two individual lensed GWs.

- Conclude about ***a factor of a few better precision*** compared to that can be expected without lensing.



(a) HLV design PSDs with zero noise



(b) HLV O3a PSDs with a Gaussian noise realization

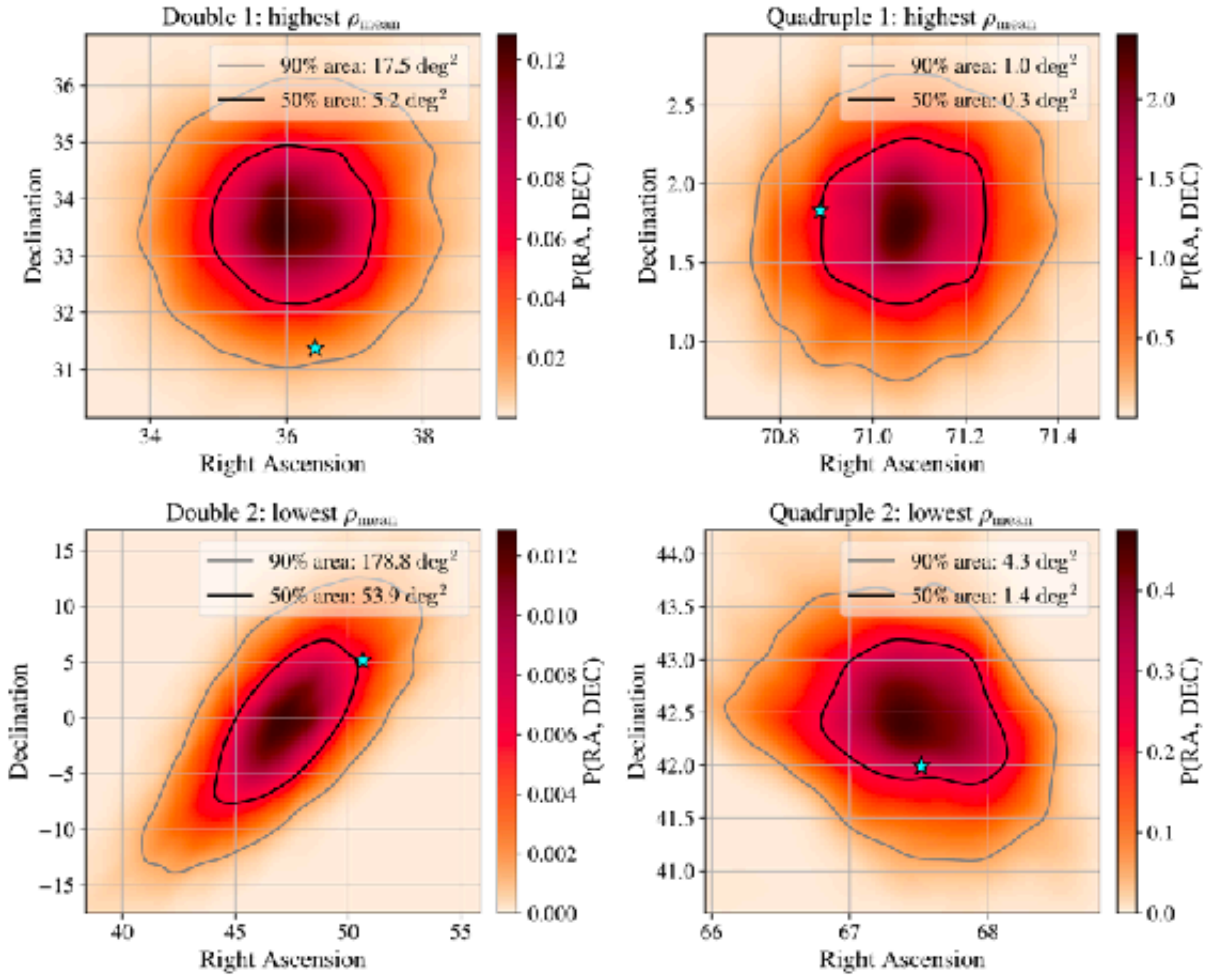
Case A: HLV design PSDs with zero-noise				
Signal	$\mathcal{W}_{99}$ [Mpc]	$\mathcal{R}_{99}$	$\mathcal{W}_{67}$ [Mpc]	$\mathcal{R}_{67}$
Unlensed	2,688	1.00	923	1.00
Lensed (PM)	1,193	2.25	405	2.28
Lensed (SIS)	845	3.18	286	3.23

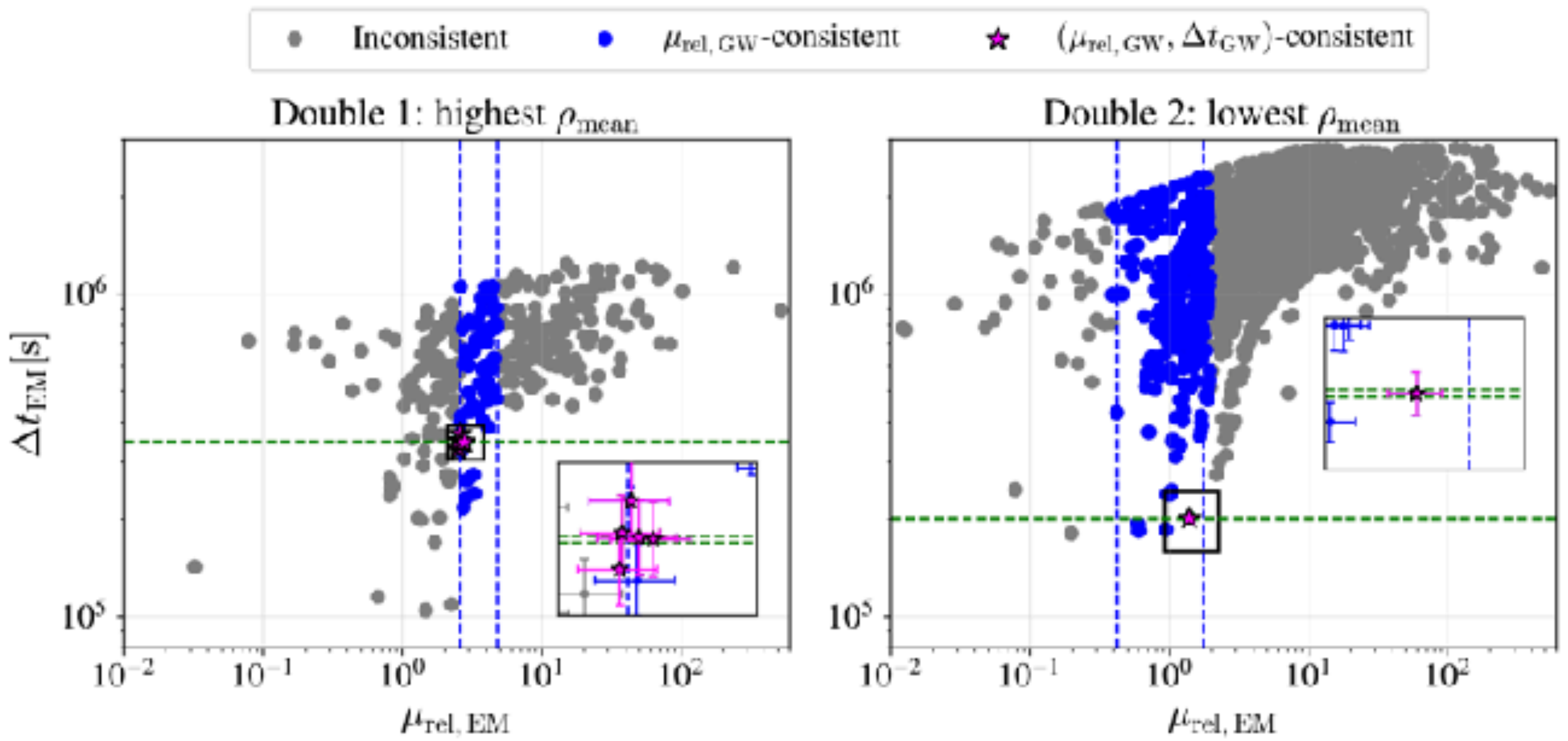
Case B: HLV O3a PSDs with a Gaussian noise				
Signal	$\mathcal{W}_{99}$ [Mpc]	$\mathcal{R}_{99}$	$\mathcal{W}_{67}$ [Mpc]	$\mathcal{R}_{67}$
Unlensed	7,700	1.00	2,074	1.00
Lensed (PM)	1,689	4.56	637	3.26
Lensed (SIS)	1,354	5.69	348	5.95

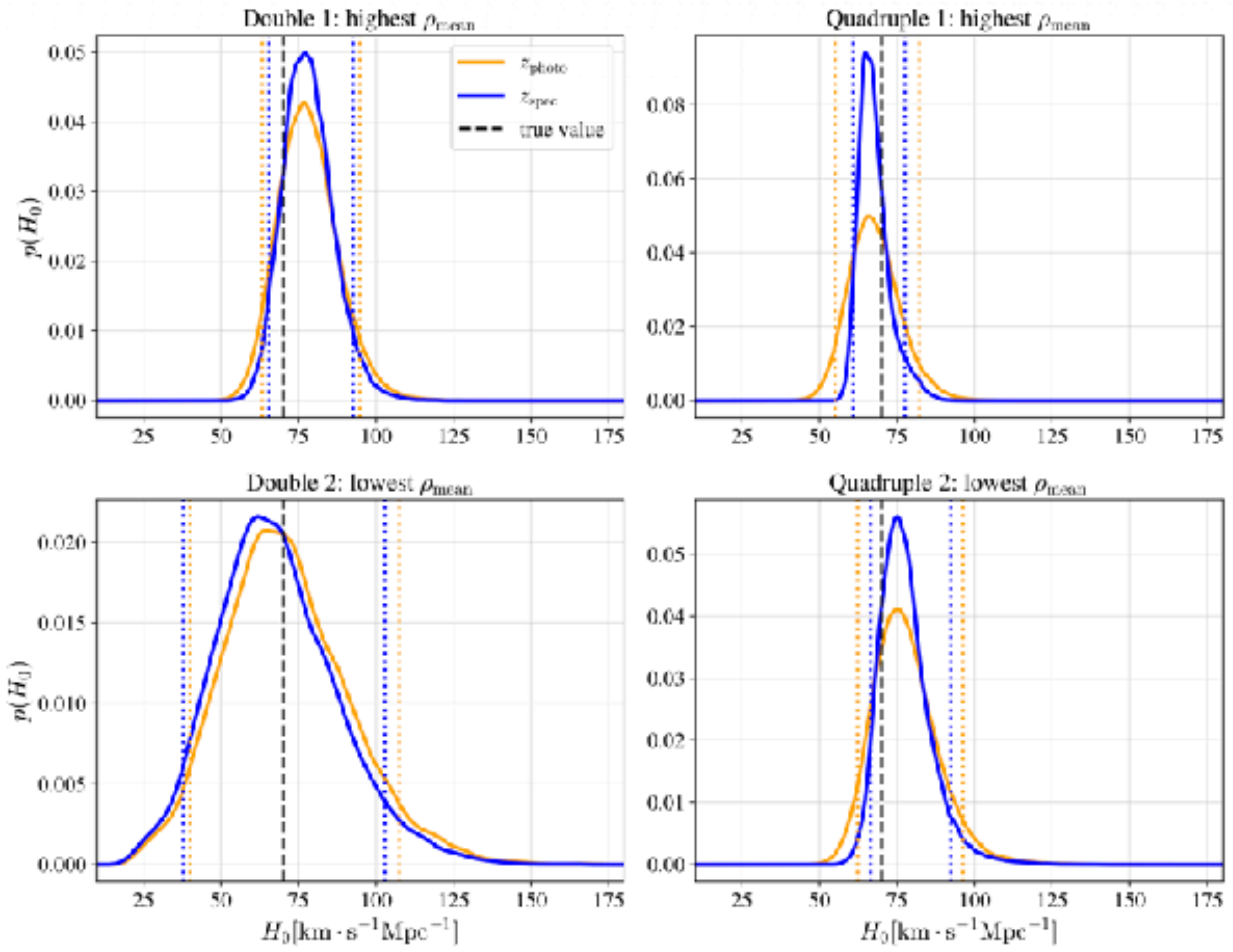
The impact of strong lensing on Hubble constant measurements w/ GW dark sirens

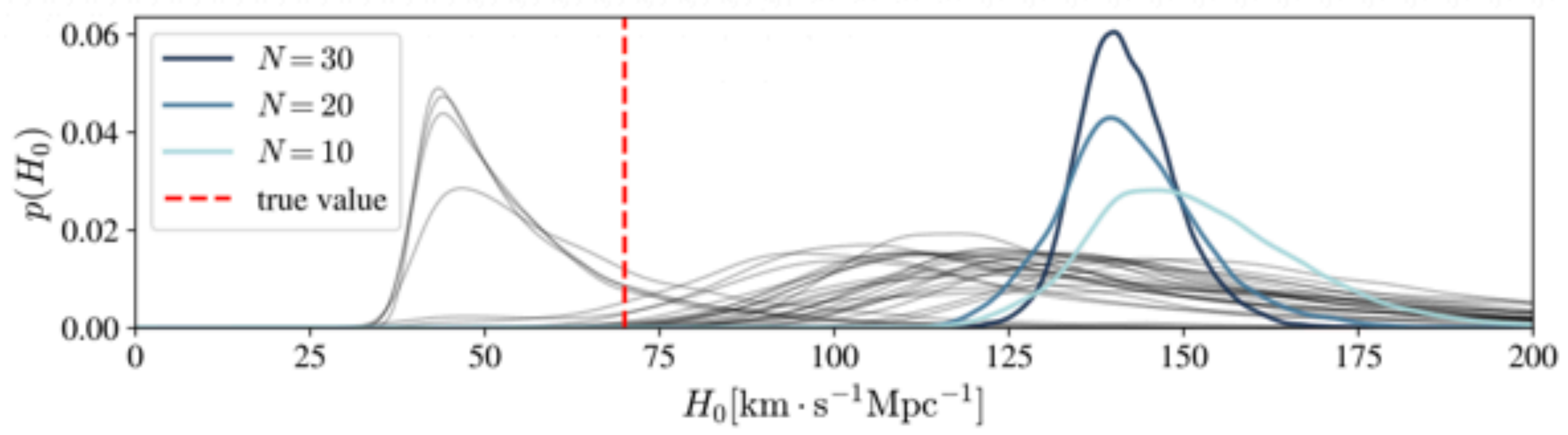
[E. Seo, KK, et al. (ApJS, 2026)]

- Better precision on the Hubble constant measurements is obtainable via joint observations of GW and EM strong lensings..

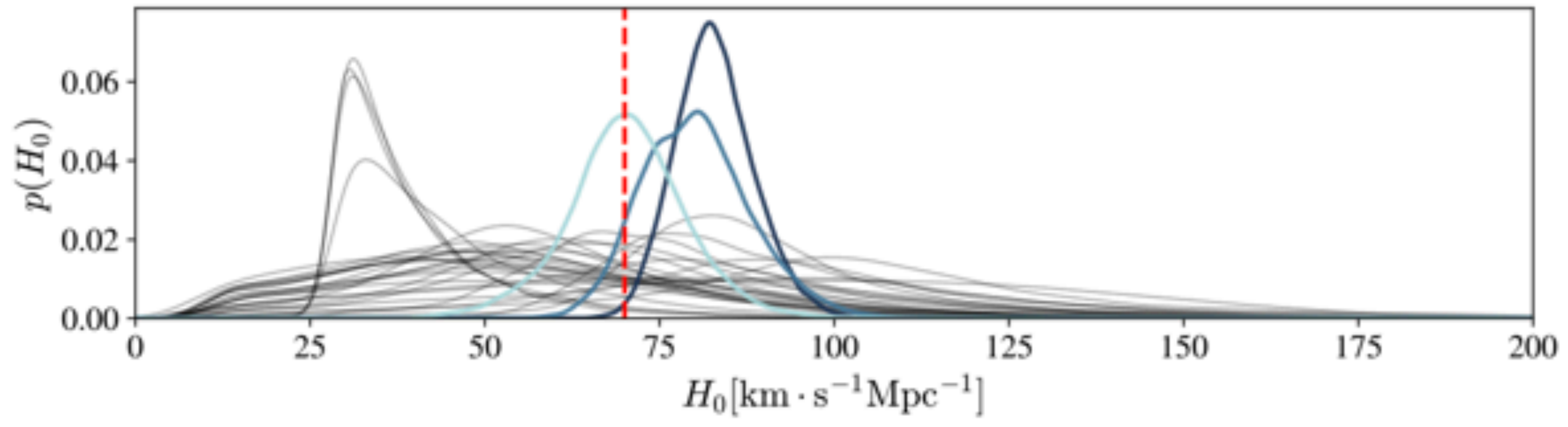




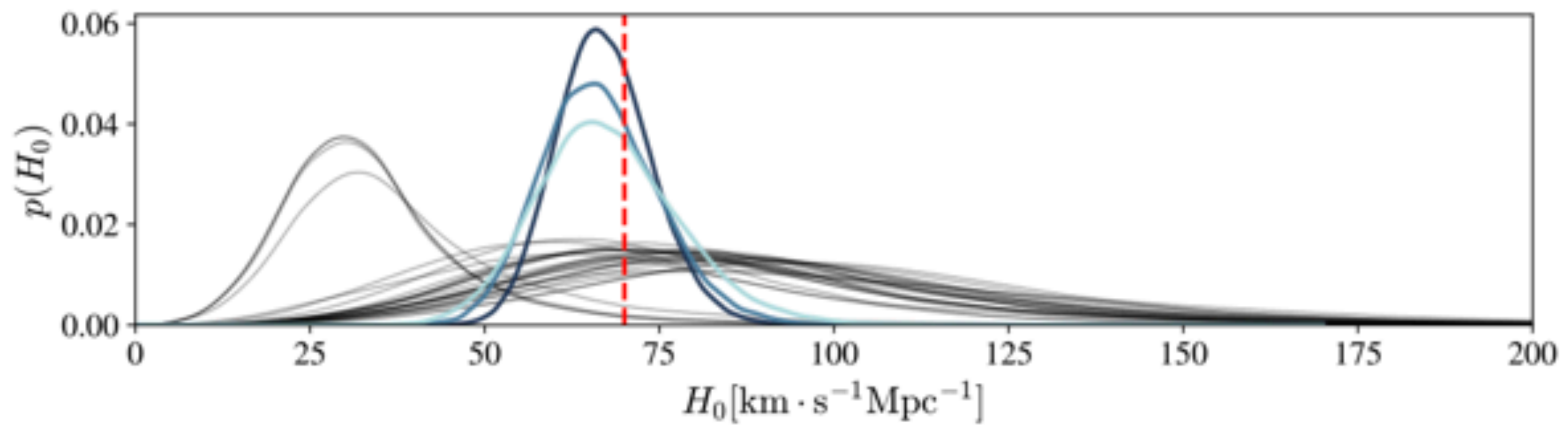




(a) No delensing applied



(b) Delensing with SIS model

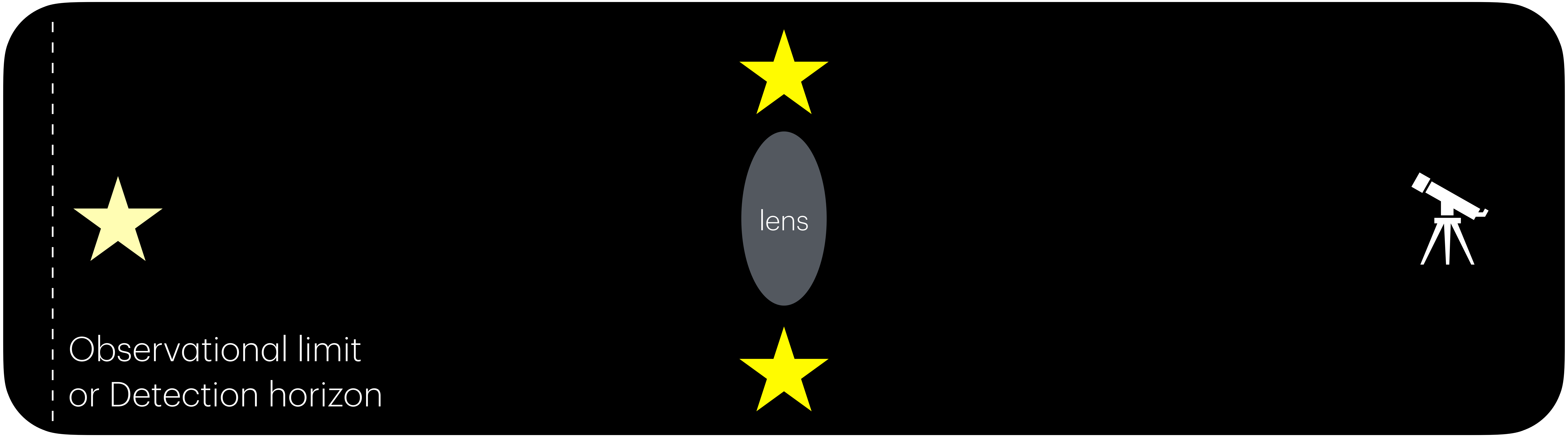


(c) Delensing with SIE model

In short, gravitational lensing is...

- An efficient tool for detecting distant and/or faint events, even beyond the limits of current telescopes and detectors.

  - Faint events: via magnification in brightness/amplitude



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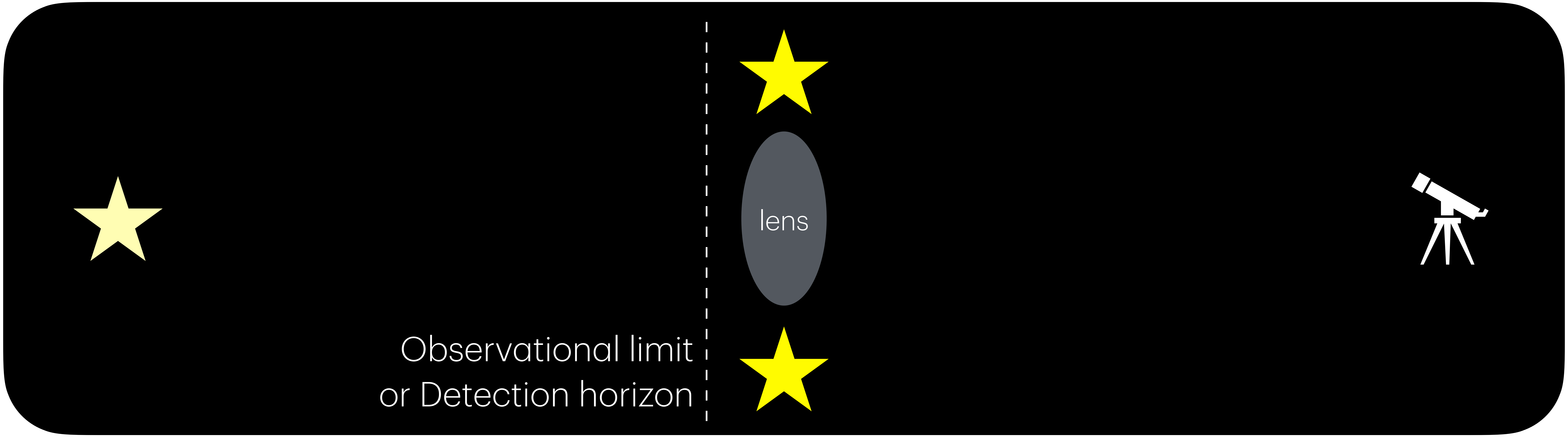
- An efficient tool for detecting distant and/or faint events, even beyond the limits of current telescopes and detectors.

  - Distant events: via images around lens objects

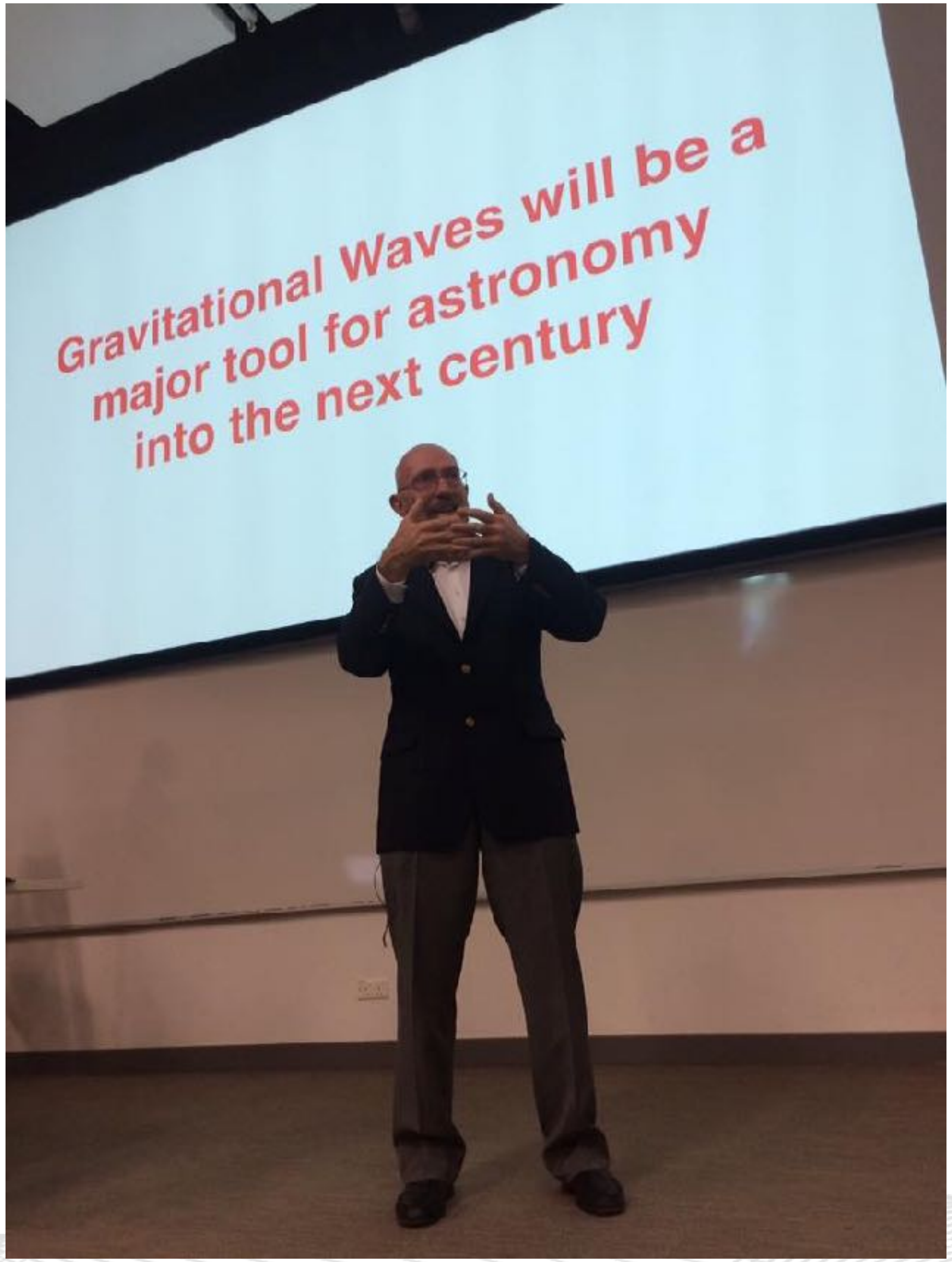


In short, gravitational lensing is…

- An efficient tool for detecting distant and/or faint events, even beyond the limits of current telescopes and detectors.
- One of powerful tools for understanding our Universe more deeply.
  - population of astrophysical objects
  - cosmological parameters
- Stay tuned! ;)

Kip Thorne prophesied...

September 30, 2016
Public lecture by Kip Thorne & Rainer Weiss
@ CUHK, Hong Kong



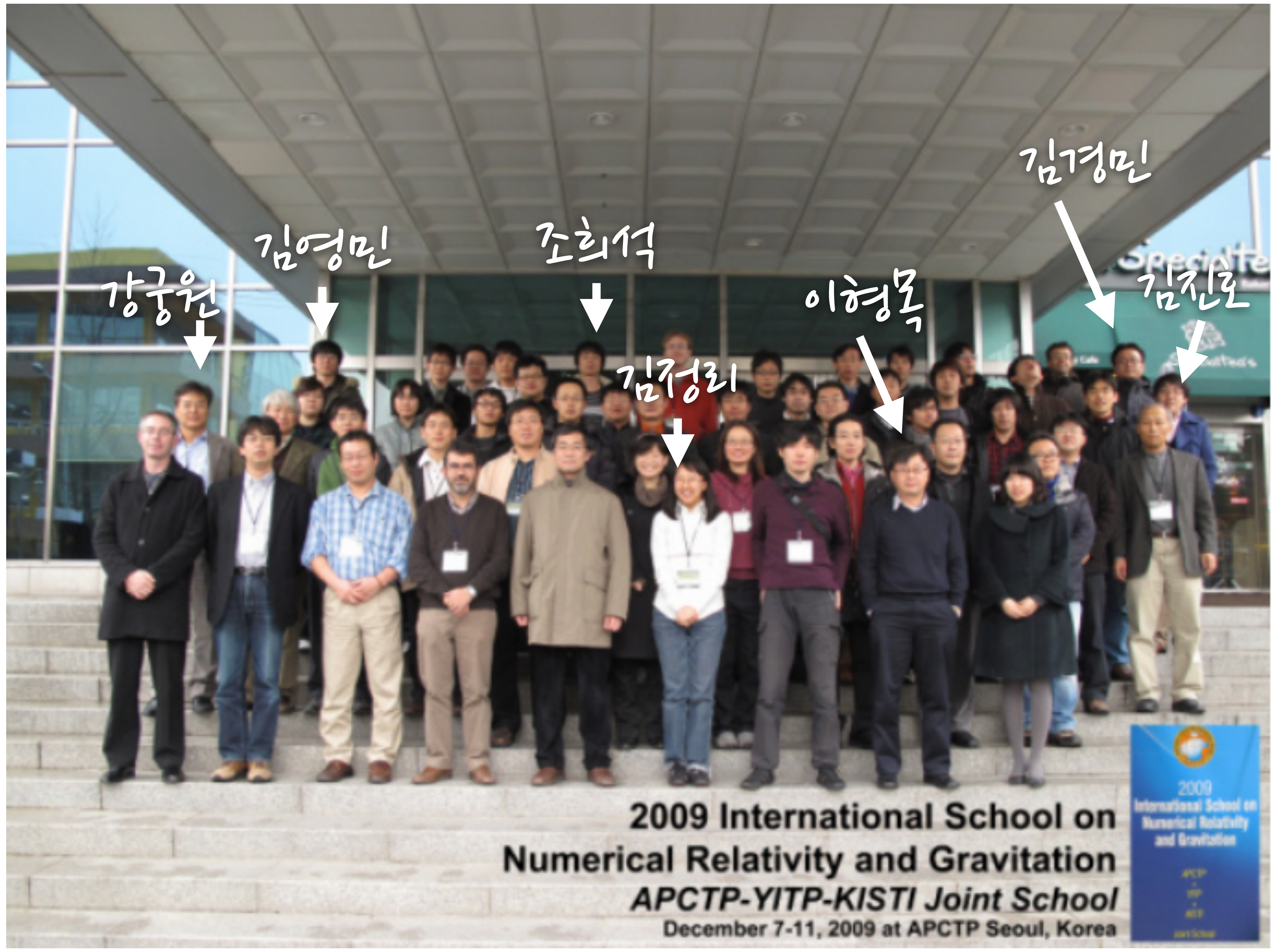
Once upon a time...

"2005"

"2006"

Once upon a time…

“2008”



“2009”

Once upon a time…

"2011"

For future schools...

끝이 아닌 시작!

- From my publication list and ongoing works …

1. “Application of machine learning algorithms to the study of noise artifacts in gravitational-wave data”, PRD (2013) w/ Y.-M. Kim
2. “Application of artificial neural network to search for gravitational-wave signals associated with short gamma-ray bursts”, CQG (2015) w/ Y.-M. Kim
3. “Neutron star structure in Horava-Lifshitz gravity”, PRD (2021) w/ C. Park
4. “Deep learning model on gravitational waveforms in merging and ringdown phases of binary black hole coalescences”, PRD (2021) w/ J. Lee
5. “Identification of lensed gravitational waves with deep learning”, ApJ (2021) w/ J. Lee
6. “Deep learning-based search for microlensing signature from binary black hole events in GWTC-1 and -2”, ApJ (2022) w/ J. Lee
7. “Gravitational lensing aided luminosity distance estimation for compact binary coalescences”, PRD (2024) w/ E. Seo and C. Kim
8. “The impact of strong lensing on Hubble constant measurements with gravitational-wave dark sirens”, ApJS (2026) w/ E. Seo
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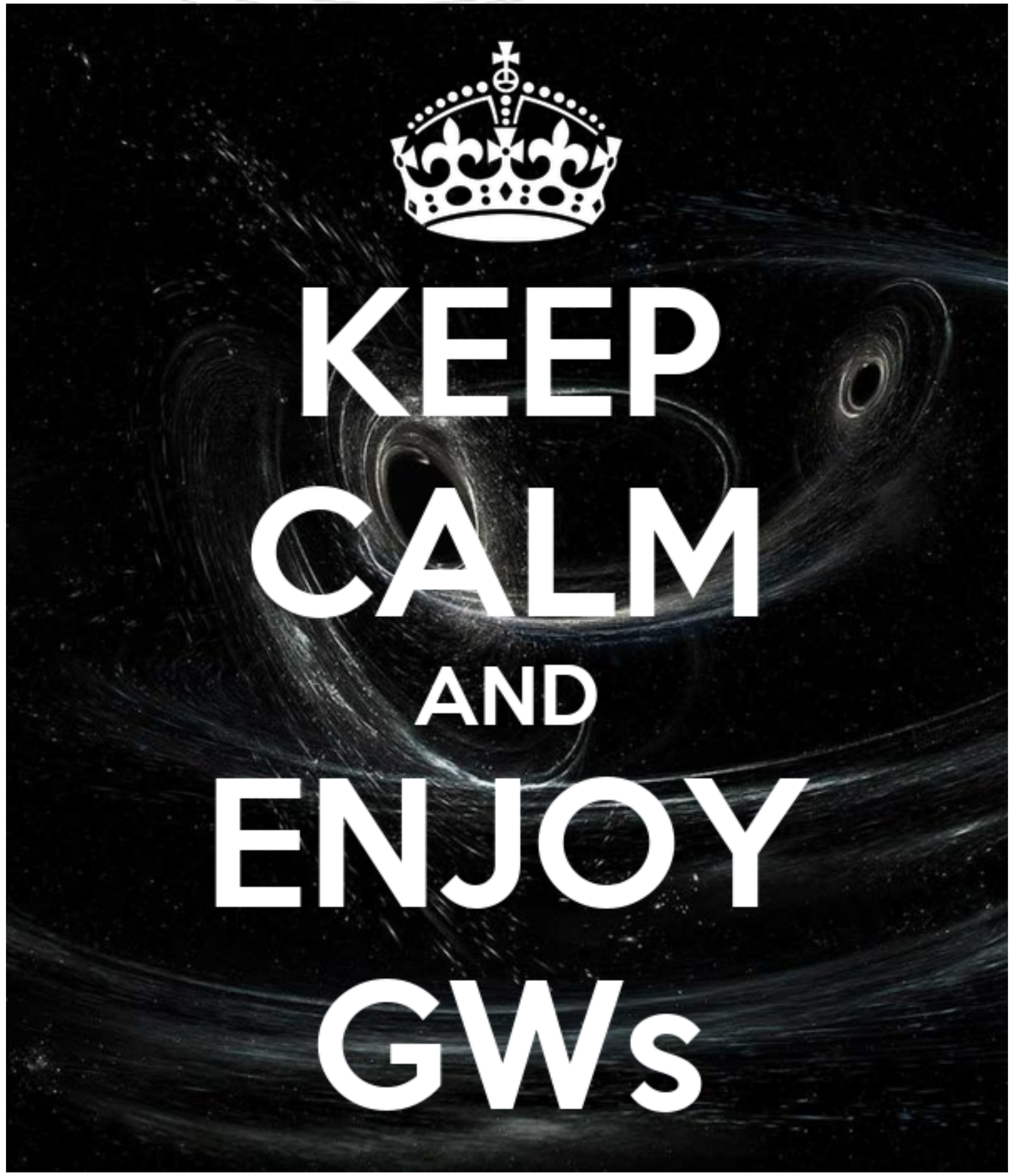

Thank you!