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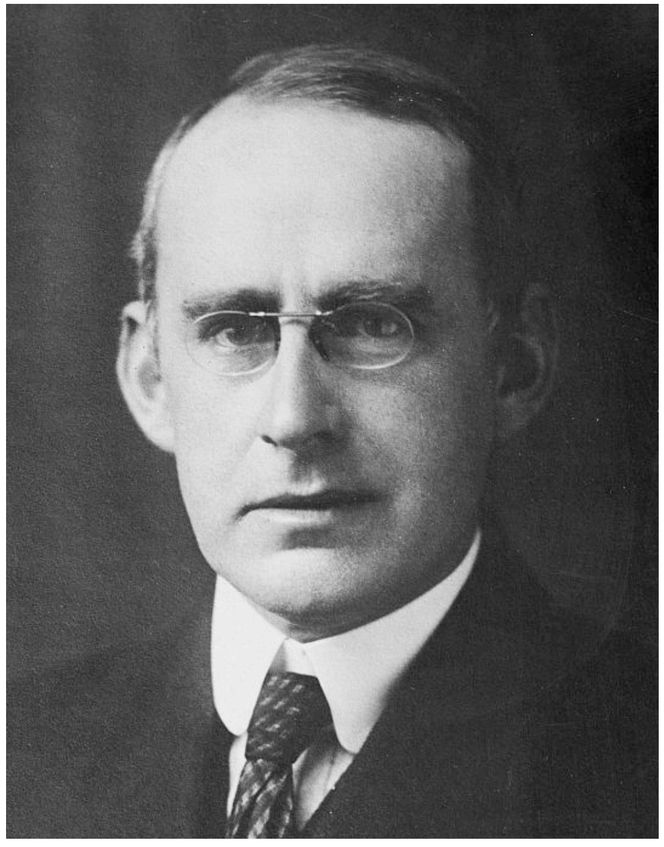
GRAVITATIONAL LENSING OF GRAVITATIONAL WAVES

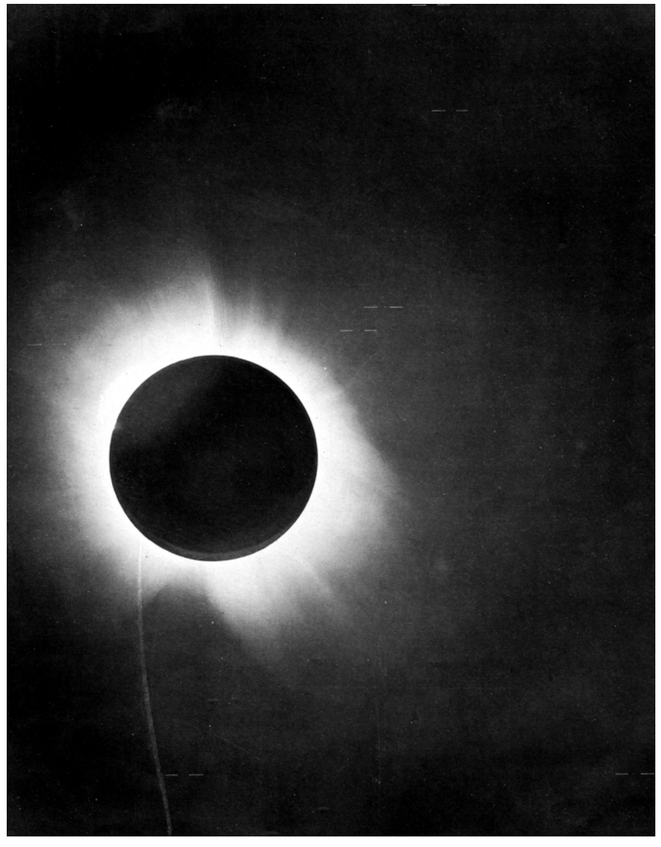
Parameswaran Ajith
International Centre for Theoretical Sciences, TIFR, Bangalore

Chennai Symposium on Gravitation and Cosmology | IIT Madras | 23 Jan 2020

1919: Eddington’s observation of gravitational light bending



Arthur Eddington



Eddington's photograph of the total solar eclipse of 29 May 1919

Triumph of Einstein's theory

TIME AND SPACE

THE NEW SCIENTIFIC THEORY

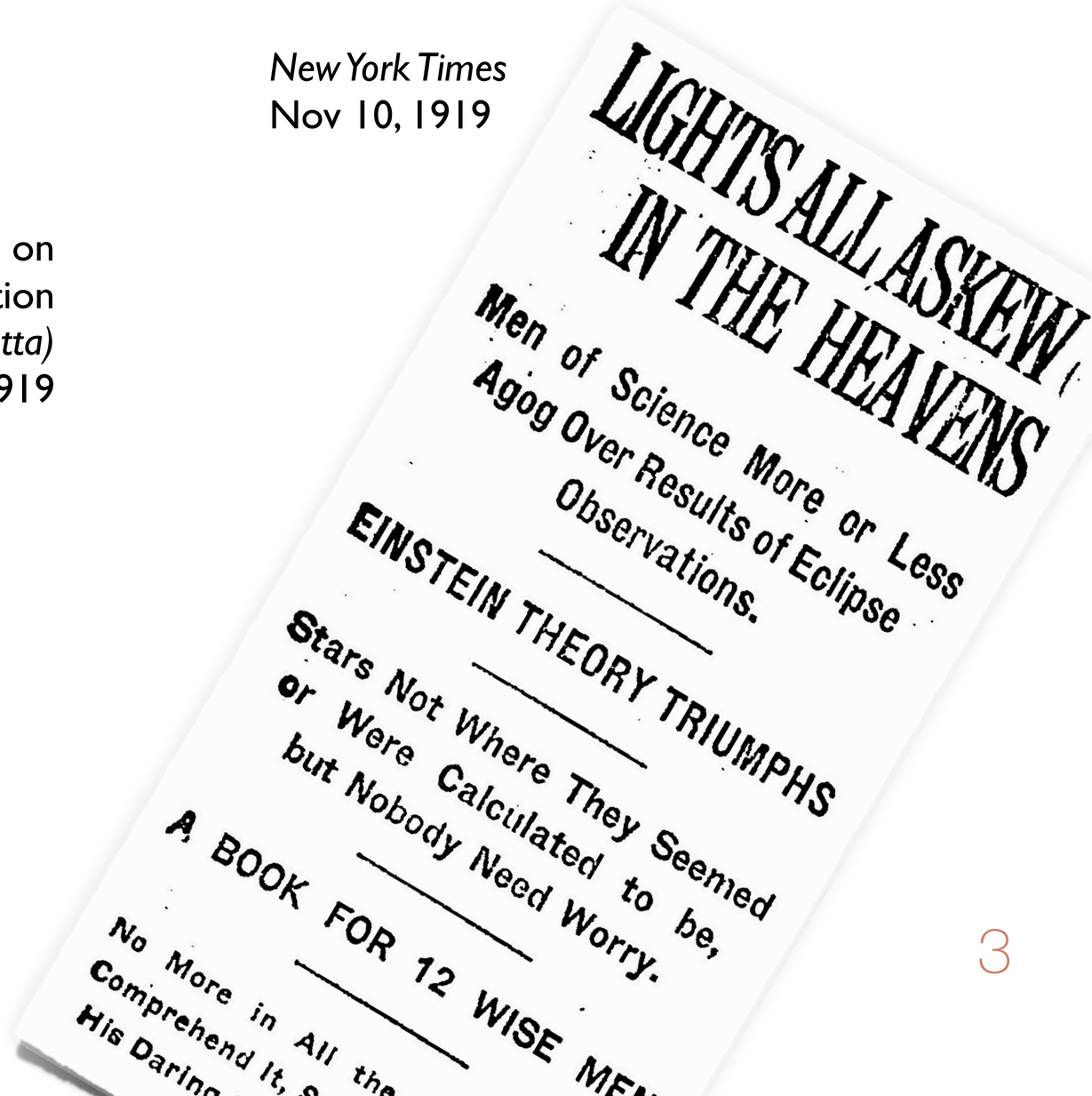
(FOR 'THE STATESMAN.')

DR. N. N. SAHA, Lecturer on Physics at the Calcutta University, writes as follows:—

The announcement conveyed in yesterday's Reuter's cable that Professor Einstein's theory of the equivalence of Time and Space has at last been verified by observations made during the last total solar eclipse will be hailed with joy by scientific circles all over the world. If the announcement be true, then the time-honoured dogma, time and space are quite in-

Saha's article on
Eddington's observation
The Statesman (Calcutta)
13 Nov 1919

New York Times
Nov 10, 1919



LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

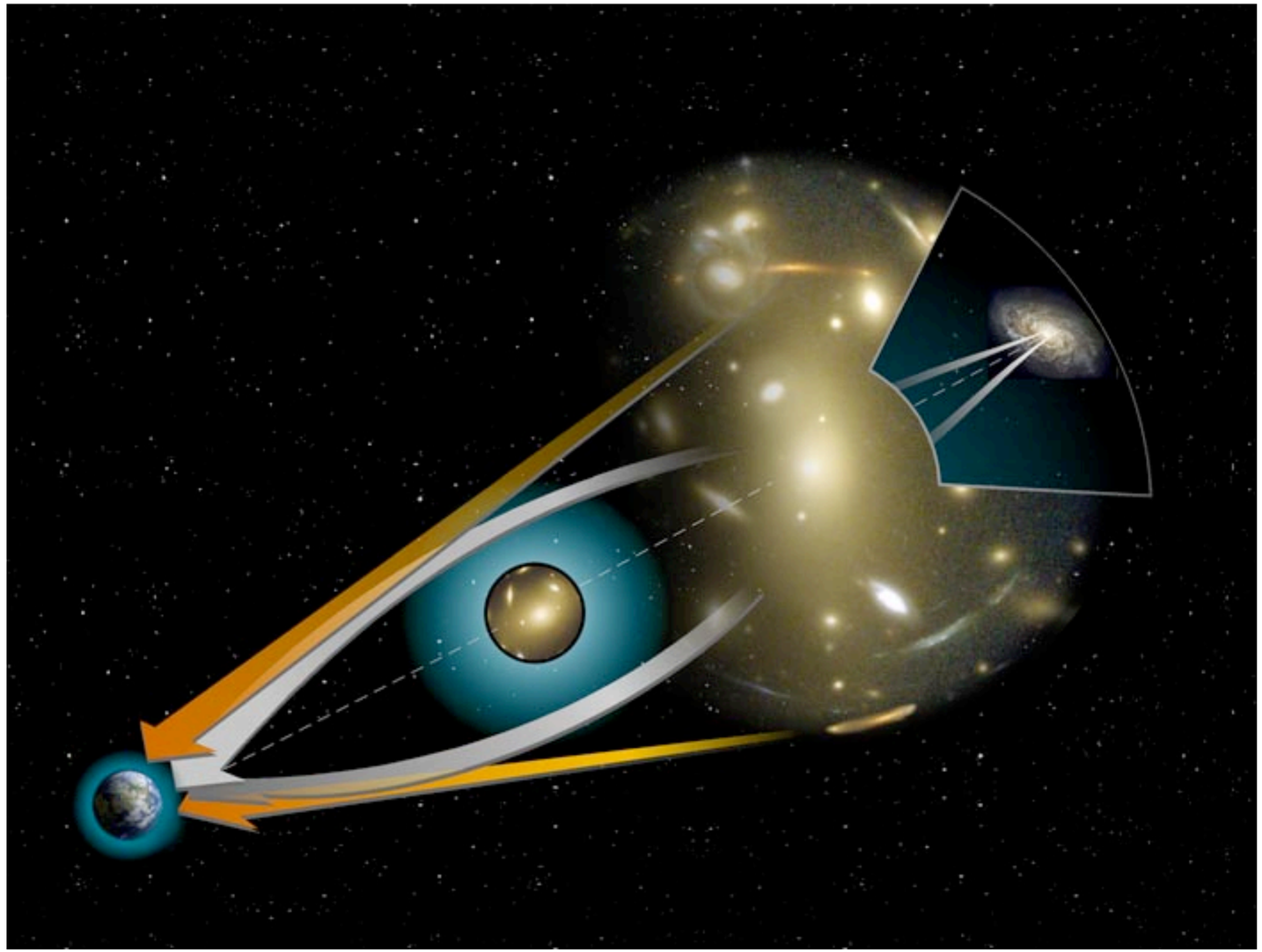
EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

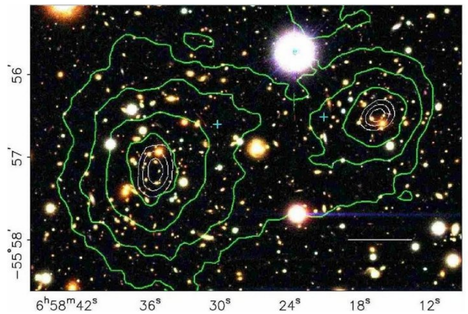
No More in All the Comprehend It, S His Daring

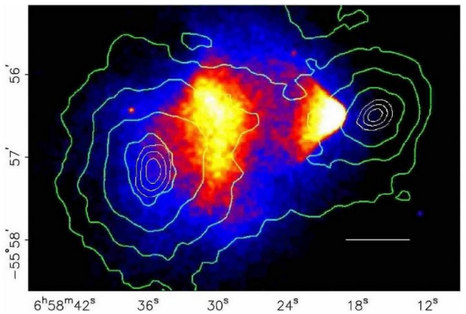
Gravitational lensing

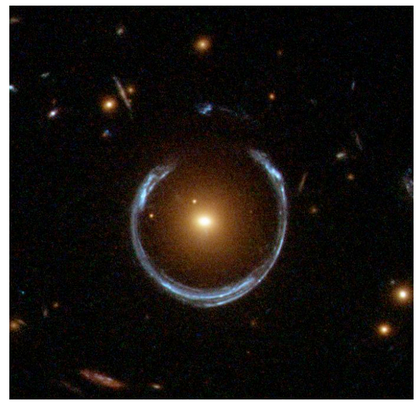


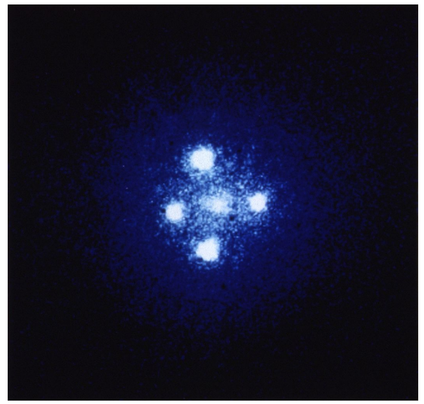
Gravitational lensing: A powerful tool for astronomy

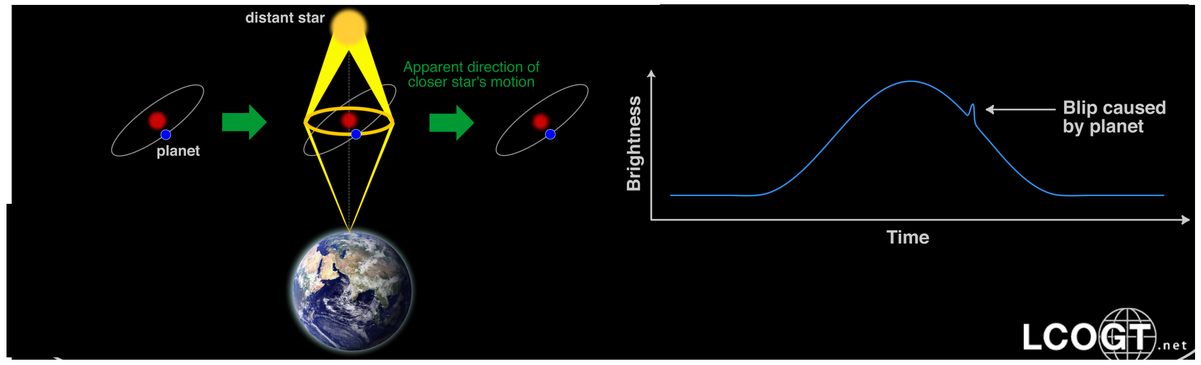
- Evidence of dark matter.
- Mapping out dark matter distributions.
- Constraining the fraction of compact dark matter (MACHOs).
- Detection of exoplanets.
- Estimation of cosmological parameters.
- ….



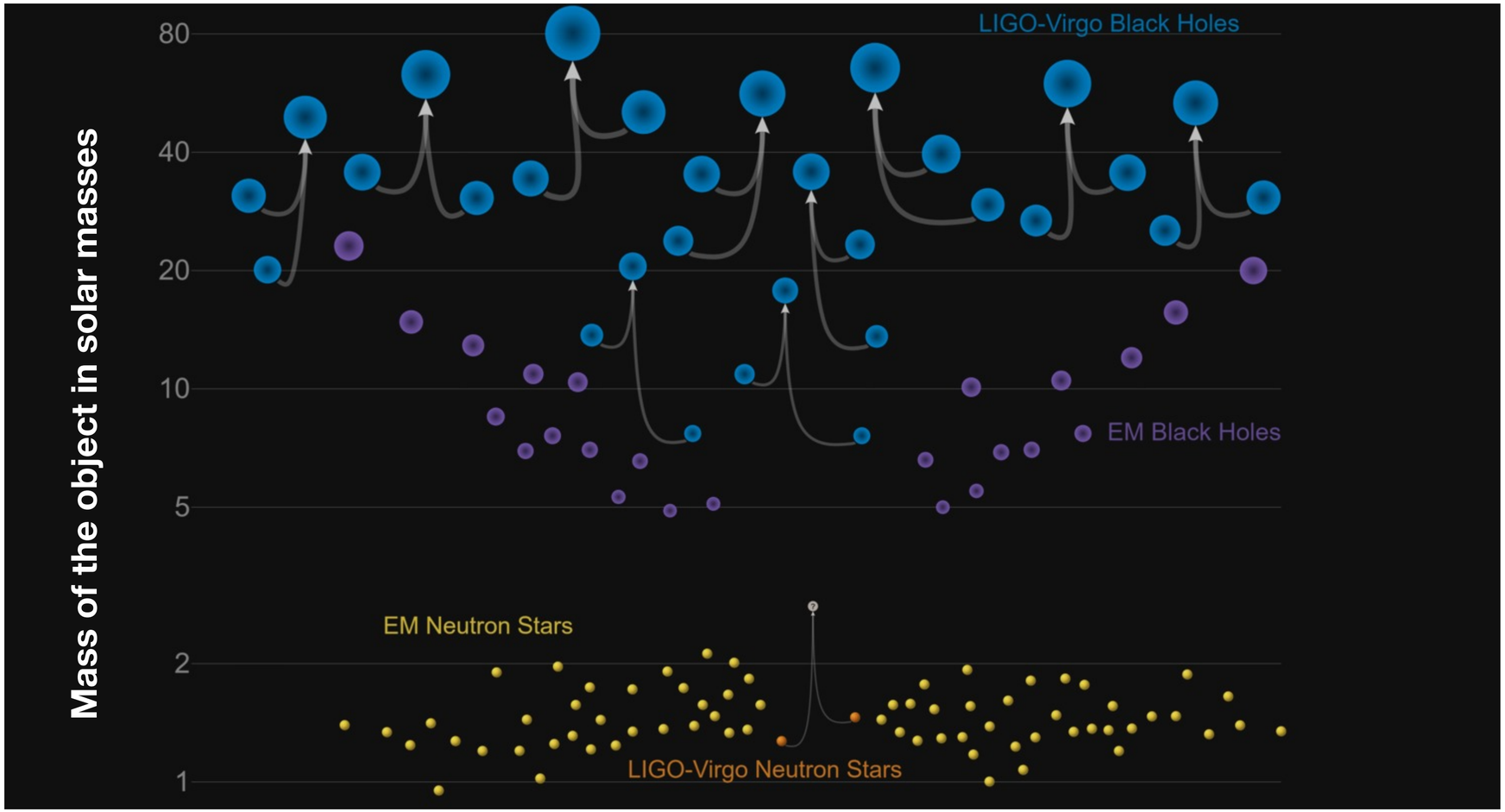








2015: Birth of gravitational-wave astronomy

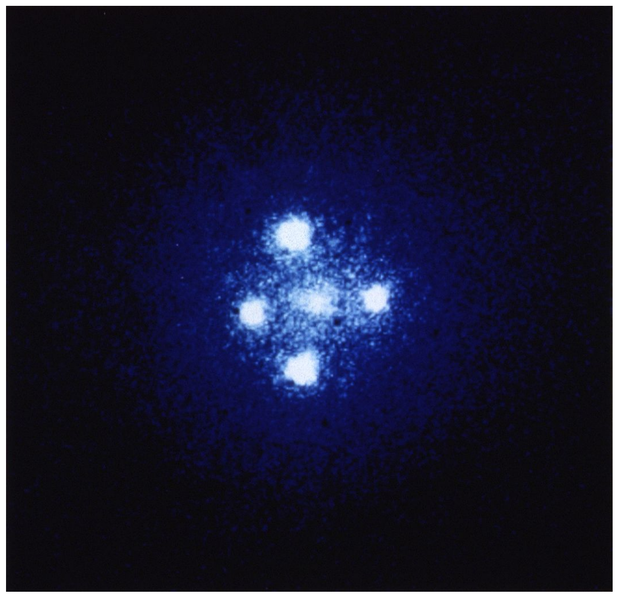


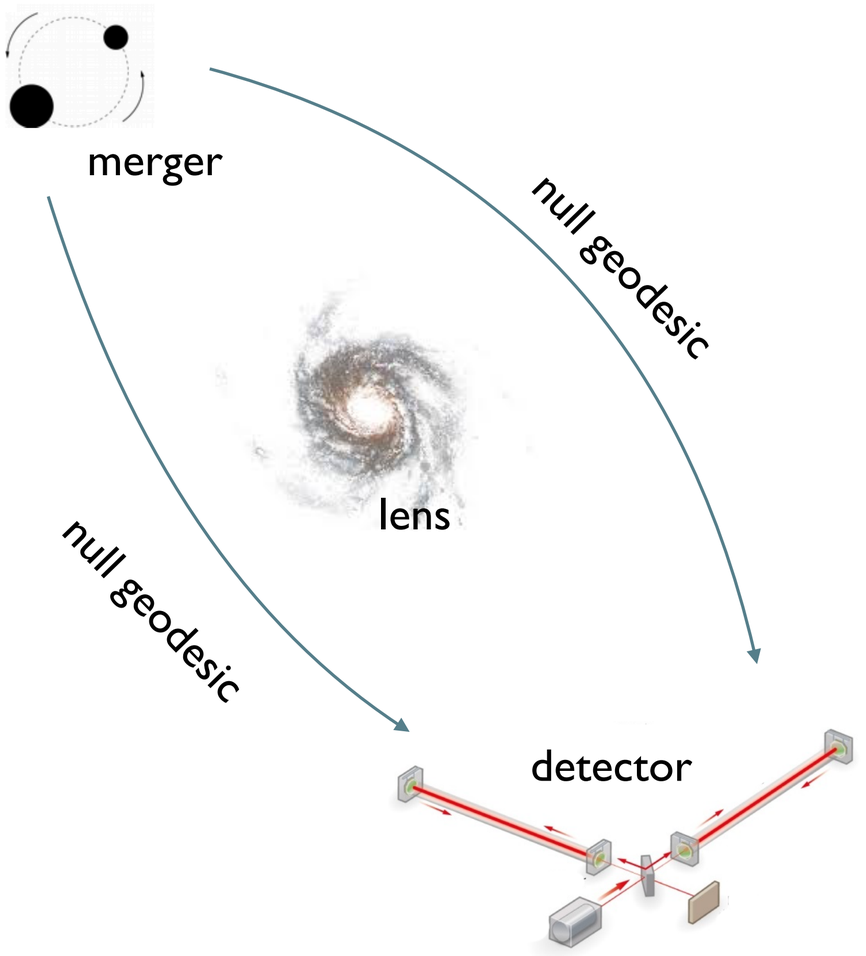
[LIGO-Virgo/Frank Elavsky/Northwestern]

10 BBH + 1 BNS detections from the first two observing runs (LVC analysis)
Additional events from independent analyses of the data.
~50 BBH, BNS and NSBH candidates from the ongoing third observing run (1 BNS published)

Gravitational lensing of GWs: A new frontier

- Small fraction (~0.4%) of detectable BBH mergers could be strongly lensed by intervening galaxies ⟹ multiple images, separated by hours to weeks.





Gravitational lensing of GWs: A new frontier

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A hundred years after Eddington's observation of the bending of light, we are in the verge of detecting the gravitational bending of GWs!

Identifying lensed images is challenging

- Need to identify pairs of lensed events among thousands of unrelated events.

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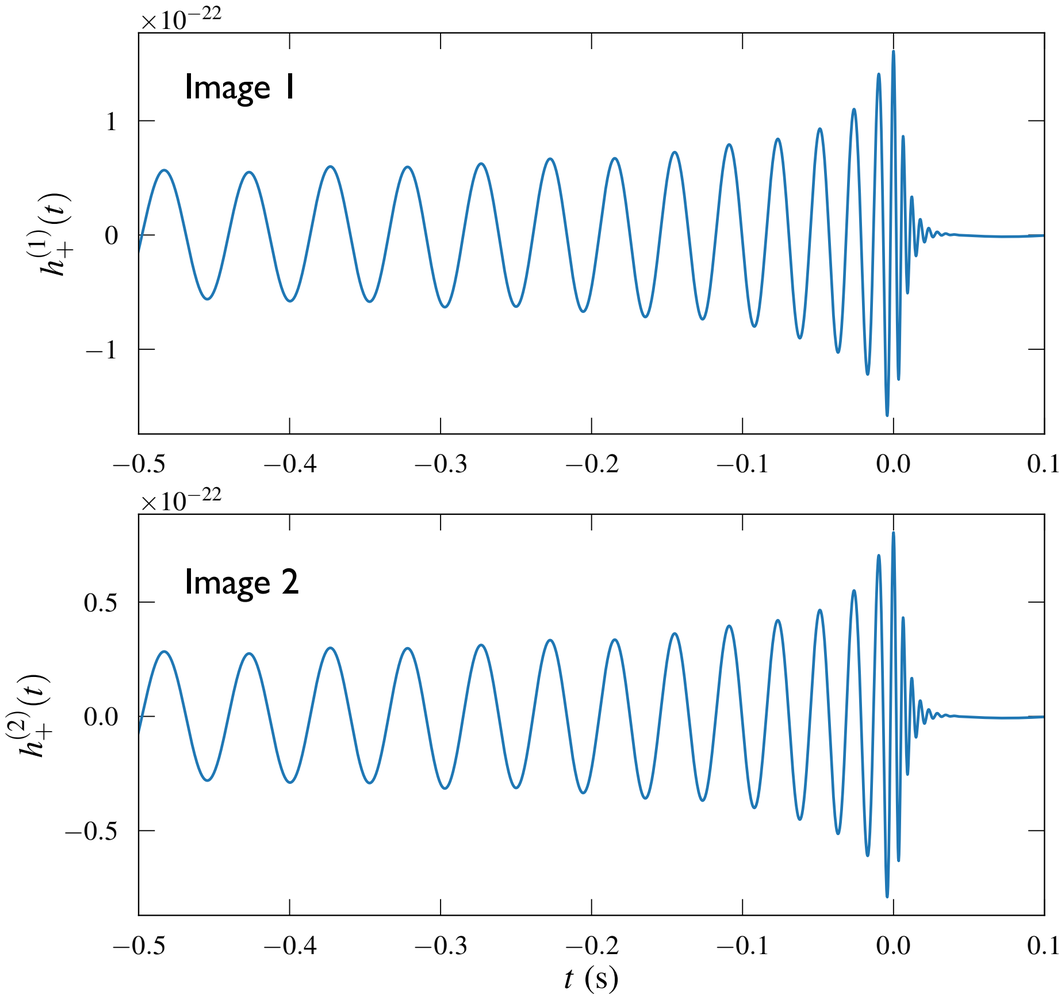
- Galaxies are the dominant lenses. Geometric optics regime $(\lambda_{\rm GW} \ll M_{\rm lens})$. Signals are only magnified; without affecting their shape.

$$h^i_{+,\times}(t) = \sqrt{\mu^i}\; h_{+,\times}(t)$$

Lensed polarizations from multiple images

Lensing magnification

Original polarizations



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$$h^i_{+,\times}(t) = \sqrt{\mu^i}\ h_{+,\times}(t)$$

Distance is degenerate with magnification. Estimated distance will be biased; so will be the estimated redshift and source-frame masses.

$$d_{\rm obs} = \frac{d_L}{\sqrt{\mu}}$$

$$z_{\rm obs} = z(d_{\rm obs})$$

$$M_{\rm obs} = \frac{M^z}{1 + z_{\rm obs}}$$

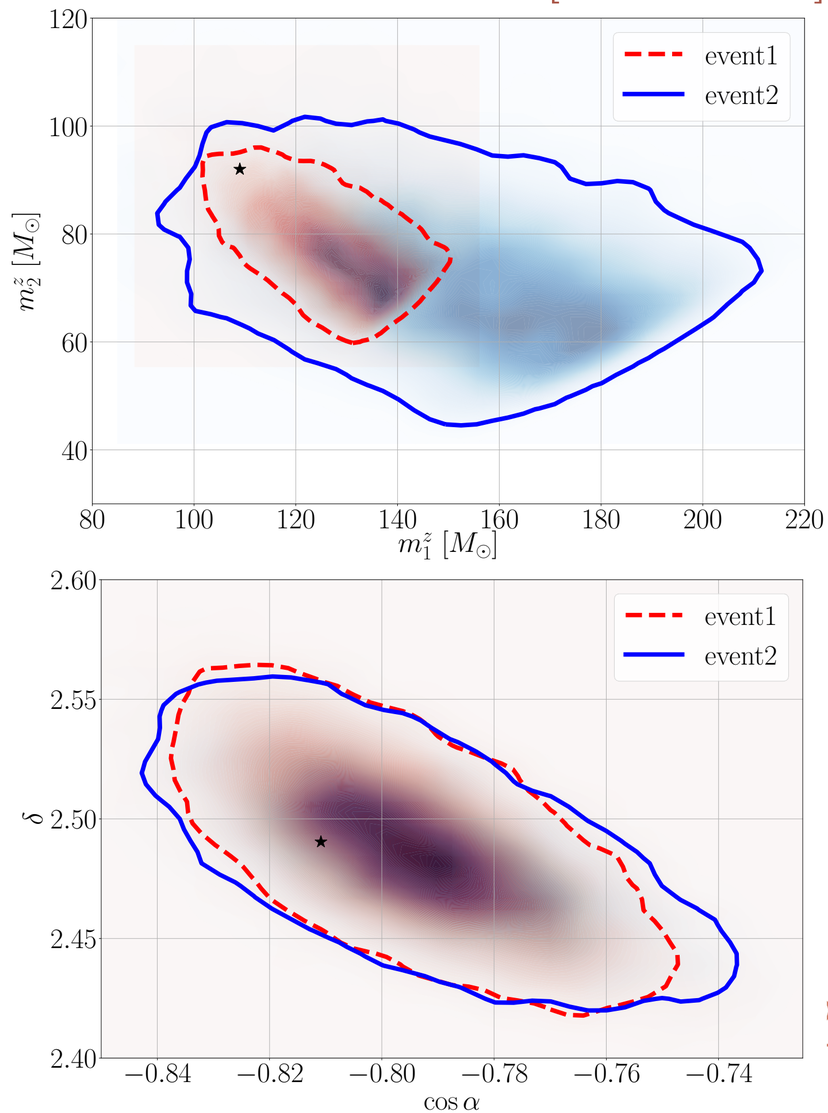
Identifying lensed images is challenging

- Bayesian model selection: From a pair of events compute the odds ratio of the two hypotheses (lensed vs unlensed)

$$\mathcal{O}^{\mathrm{L}}_{\mathrm{U}} := \underbrace{\frac{P(\mathcal{H}_{\mathrm{L}})}{P(\mathcal{H}_{\mathrm{U}})}}_{\text{Prior odds}} \underbrace{\int d\vec{\theta}\, \frac{P(\vec{\theta}|d_1)\, P(\vec{\theta}|d_2)}{P(\vec{\theta})}}_{\text{Lensing Bayes factor}}$$

Posterior distributions of binary parameters (except the distance) estimated from lensed images will be consistent

[Haris et al 2018]

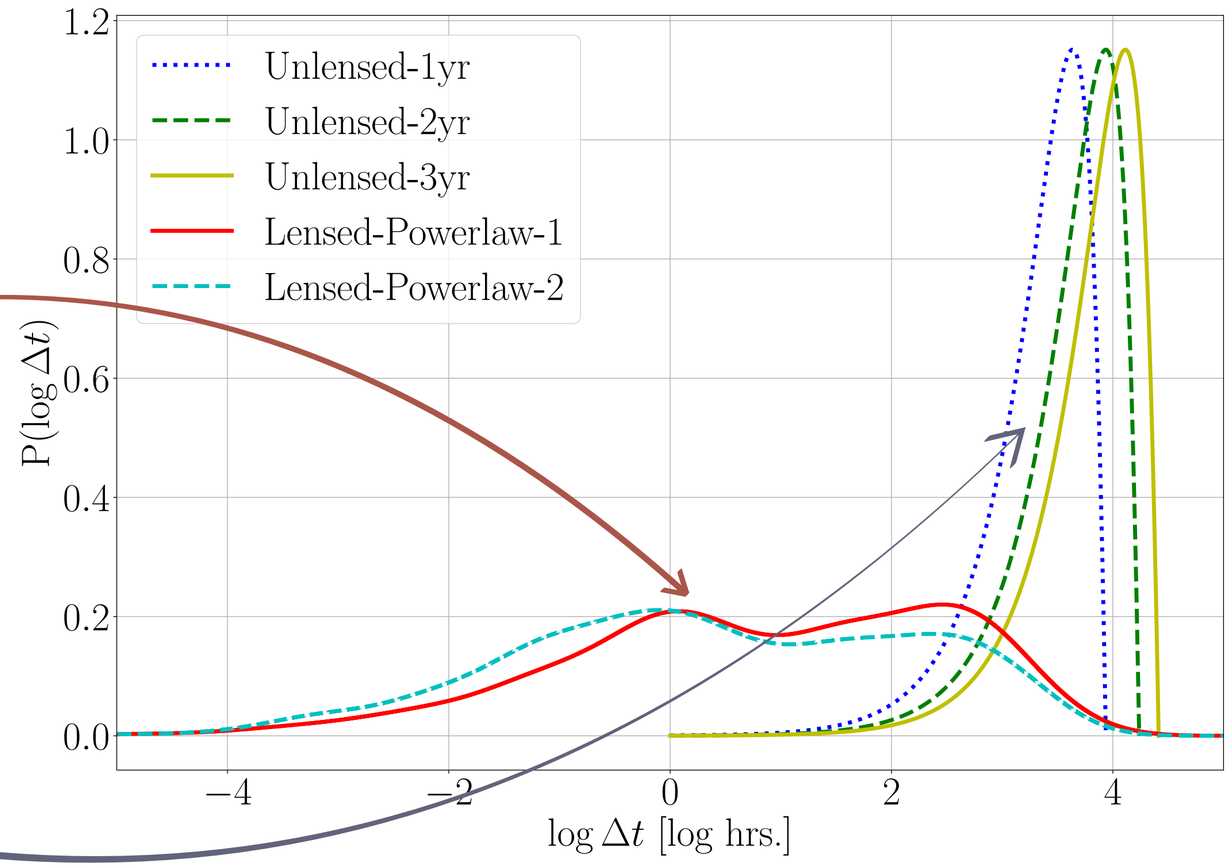


Identifying lensed images is challenging

- Bayesian model selection: Additional information from the time delay between events.

$$\mathcal{R}^{\mathrm{L}}_{\mathrm{U}} = \frac{P(\Delta t_0|\mathcal{H}_{\mathrm{L}})}{P(\Delta t_0|\mathcal{H}_{\mathrm{U}})}$$

[Haris et al 2018]

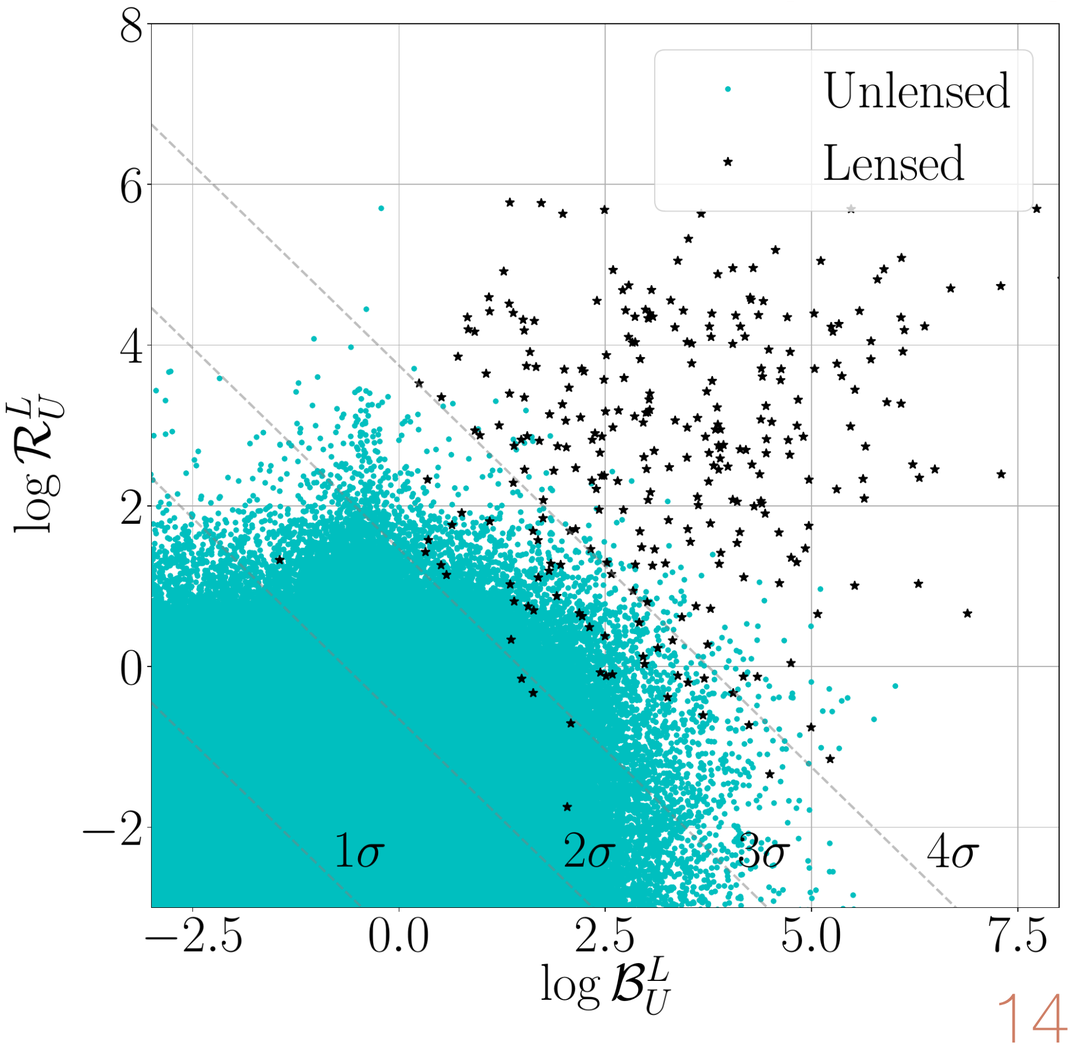


Prior distributions of time delay expected from lensed and unlicensed events.

Identifying lensed images is challenging

- Combine the Bayes factors to discriminate between lensed & unlicensed events.
  - ~66% of the lensed events can be identified with a false alarm probability of 10^{-5}.

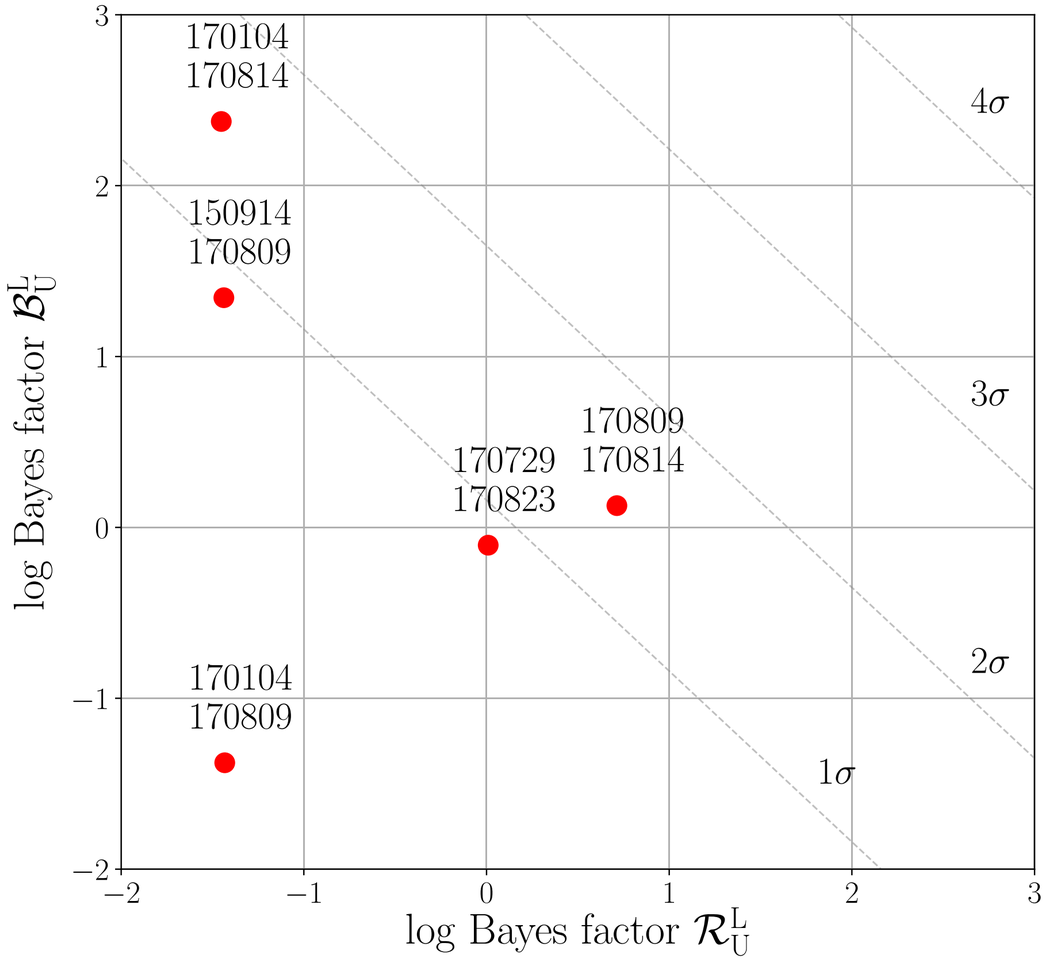
[Haris et al 2018]



No evidence of lensing… yet.

- Performed the first search for lensing effects in the binary BH observations during the first 2 observing runs.
- No evidence of multiple images.

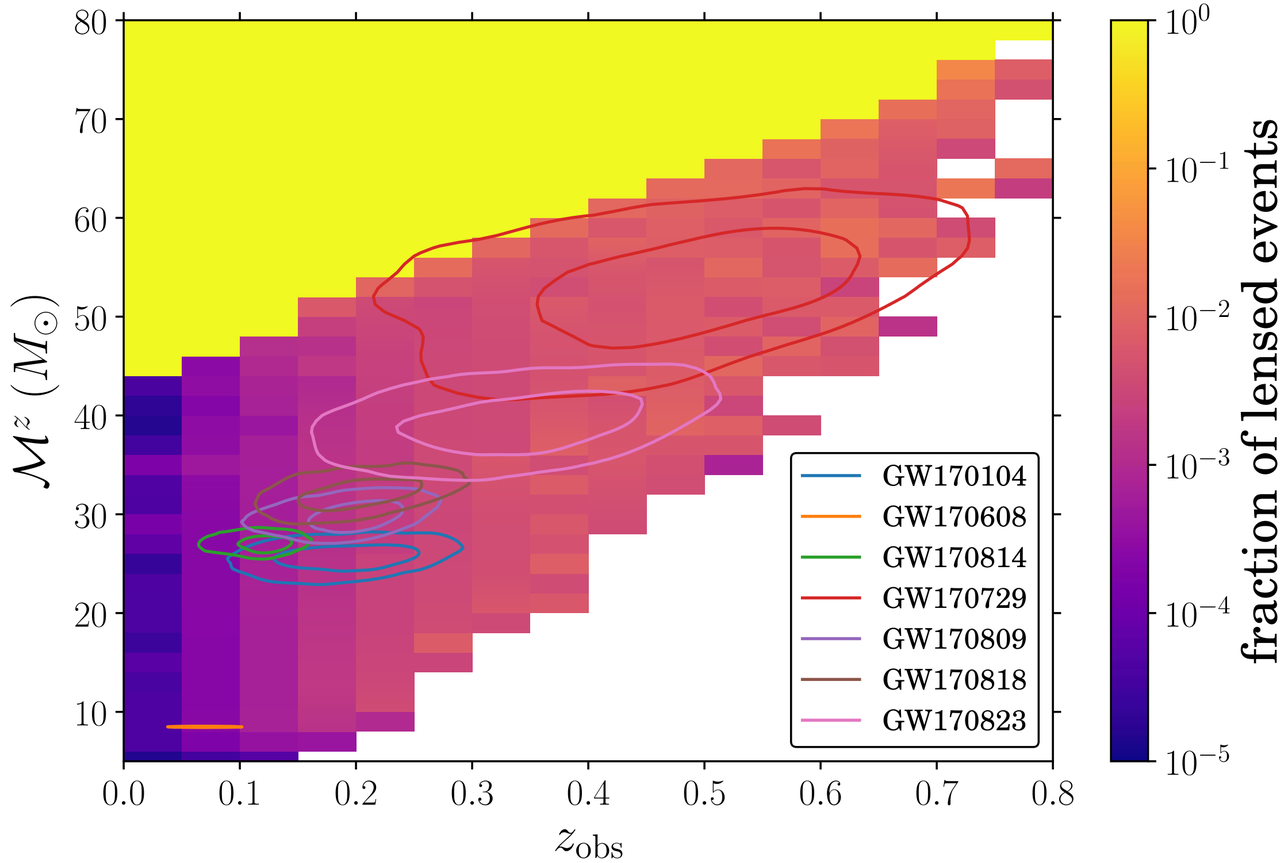
[Hannuksela et al ApJ. Lett. 874:L2, 10 (2019)]



No evidence of lensing… yet.

- Performed the first search for lensing effects in the binary BH observations during the first 2 observing runs.
- Observed source properties are consistent with expectations without invoking lensing magnification.

[Hannuksela et al ApJ. Lett. 874:L2, 10 (2019)]



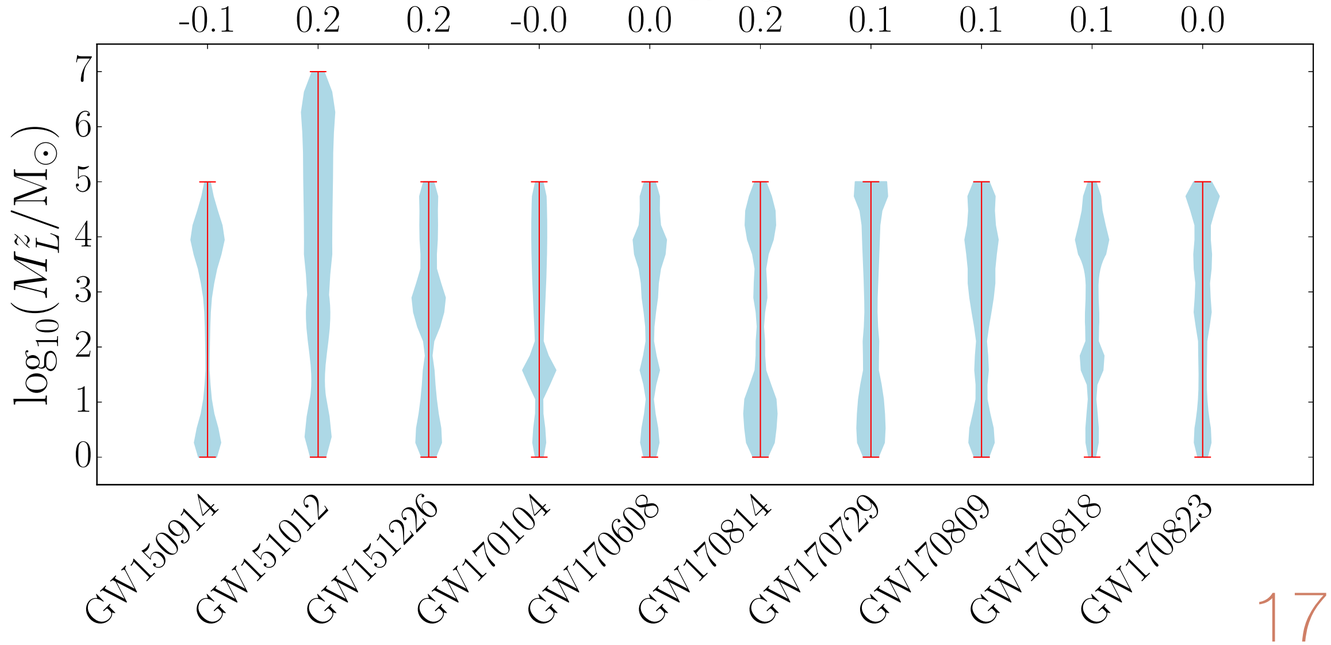
No evidence of lensing… yet.

- Performed the first search for lensing effects in the binary BH observations during the first 2 observing runs.
- No evidence of wave optics effects due to lensing in the observed signals.

[Hannuksela et al ApJ. Lett. 874:L2, 10 (2019)]

When $\lambda_{\rm GW} \sim M_{\rm lens}$ lensing can produce wave optics effects. Expected deformation in the GW signals can be modeled for simple lens models (e.g point mass).

Lensing Bayes factor $\log_{10} \widetilde{\mathcal{B}}^{L}_{U}$



No evidence of lensing… yet.

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  effects in the binary BH observations
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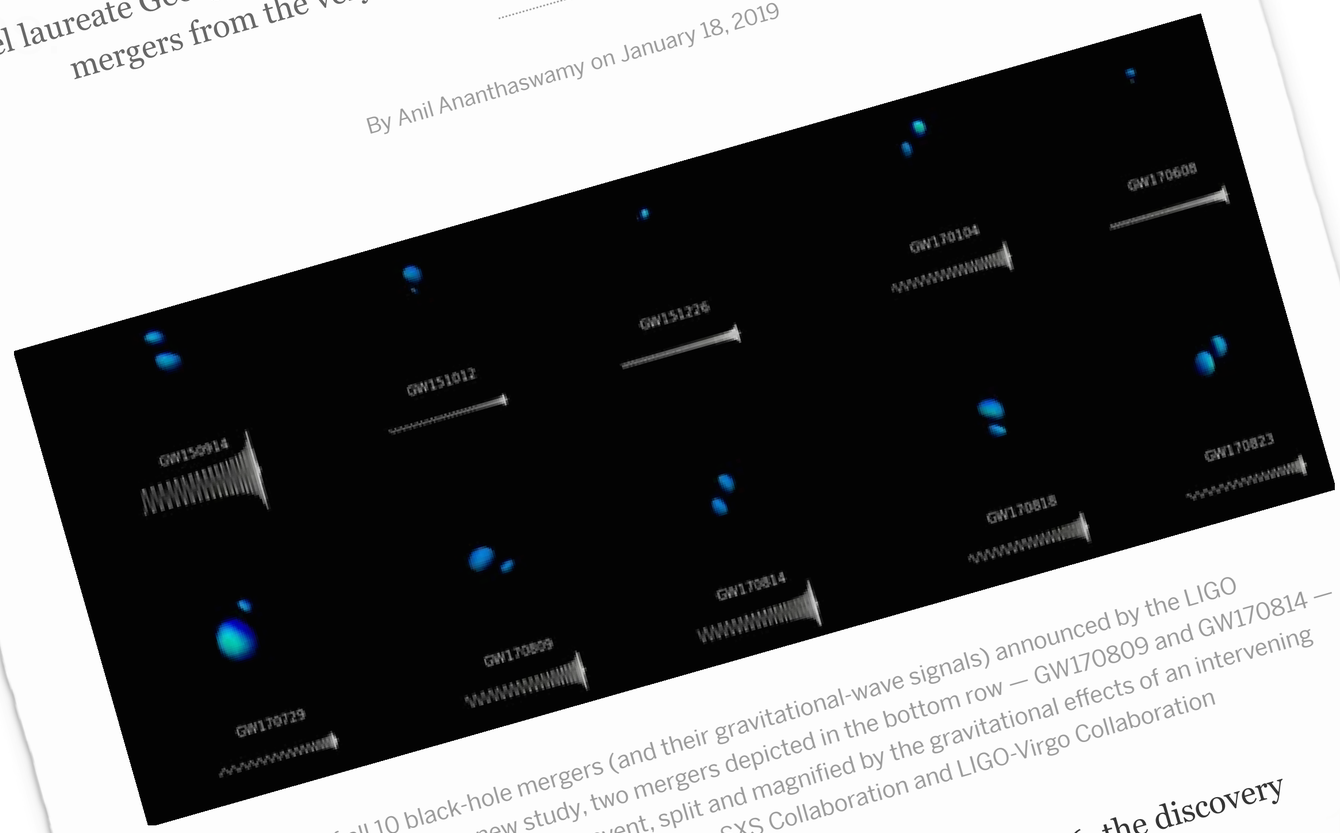
SPACE

Has LIGO Seen Galaxy-Warped Gravitational Waves?

Nobel laureate George Smoot claims LIGO has observed amplified signals of black hole mergers from the very distant universe, but LIGO scientists disagree

By Anil Ananthaswamy on January 18, 2019



A visualization of all 10 black-hole mergers (and their gravitational-wave signals) announced by the LIGO collaboration. According to a new study, two mergers depicted in the bottom row — GW170809 and GW170814 — may actually be twin images of a single event, split and magnified by the gravitational effects of an intervening galaxy. Credit: Teresita Ramirez, Geoffrey Lovelace, SXS Collaboration and LIGO-Virgo Collaboration

the LIGO collaboration in February 2016, the discovery
n as gravitational waves was momentous
hysics. Now, another Nobel
tacular

Gravitational lensing of GWs: A new frontier

- LIGO-Virgo expected to detect 100s of mergers in the next few years. First detection of lensed GWs around the corner.

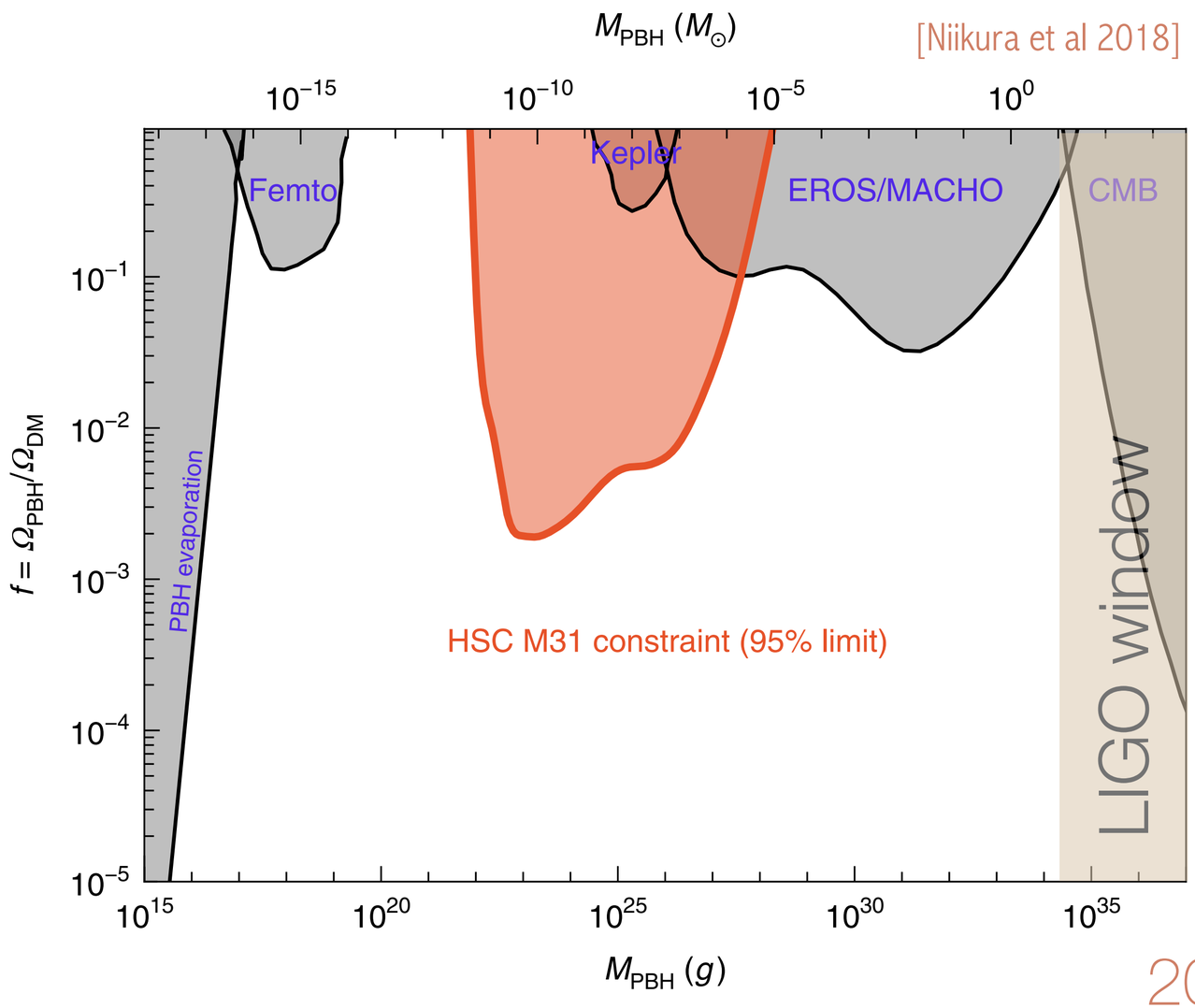
- Precise (sub-galaxy) localization of mergers from lensed images from the observed time delay and magnification ratio [Mehta et al, In prep]

- Accurate extraction of the polarizations. Are polarizations consistent with GR predictions? [Goyal et al, In prep]

Gravitational lensing of GWs: A new frontier

- If the lens mass is comparable to the GW wavelength (10-10^5 $M_\odot$) $\Longrightarrow$ wave optics signatures in the observed signal.

- Constrain the fraction of dark matter in the form of compact objects (even from null observations) [Ganguly et al, In prep]



Summary

- Gravitational lensing observations begun as a means of testing the validity of GR.
- Eventually it became a powerful probe of astrophysics and cosmology.
- Similar story of GWs. Now becoming a unique branch of astronomy.
- More fascinating observations are expected in the near future, e.g., the gravitational lensing of GWs — doubly Einstein!