Inferring Astrophysical Channels with Neutron Star-Black Hole Mergers

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Northwestern University

N3AS Annual Meeting– August 6, 2025

Network for Neutrinos, Nuclear Astrophysics, and Symmetries

PHYSICS FRONTIER CENTER

Research Interests

Using simulated and observed gravitational-wave events for

- Forecasting the multi-messenger capabilities of next-generation observatories
- Inference of astrophysical formation scenarios
- Cosmological inference with binary mergers
- Inferring neutron star properties
- Testing general relativity

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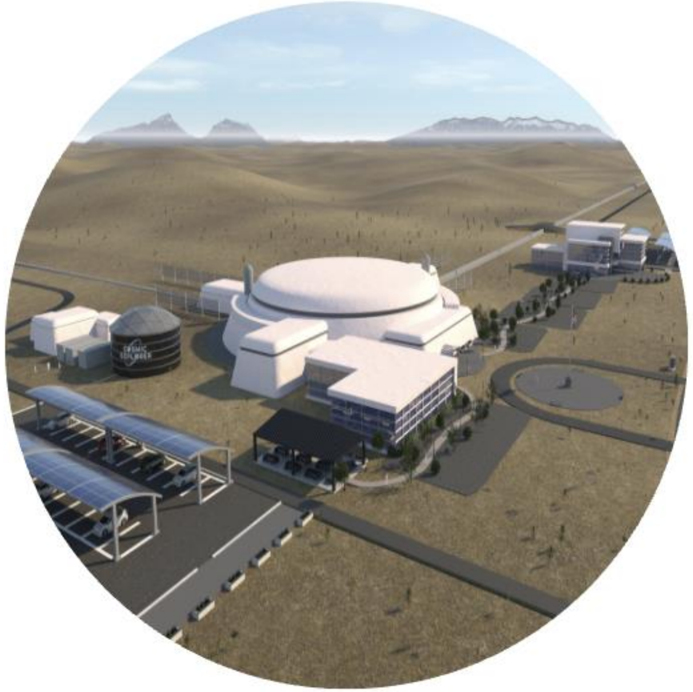

Neutron star-black hole mergers in next generation gravitational-wave observatories
Gupta et al., Phys.Rev.D 107 (2023) 12, 124007.

Characterizing Gravitational Wave Detector Networks: From A♯ to Cosmic Explorer
Gupta et al., CQG 41 (2024).

The Critical Role of LIGO-India in the Era of Next-Generation Observatories
Pandey, Gupta et al., Accepted in ApJL, 2025.

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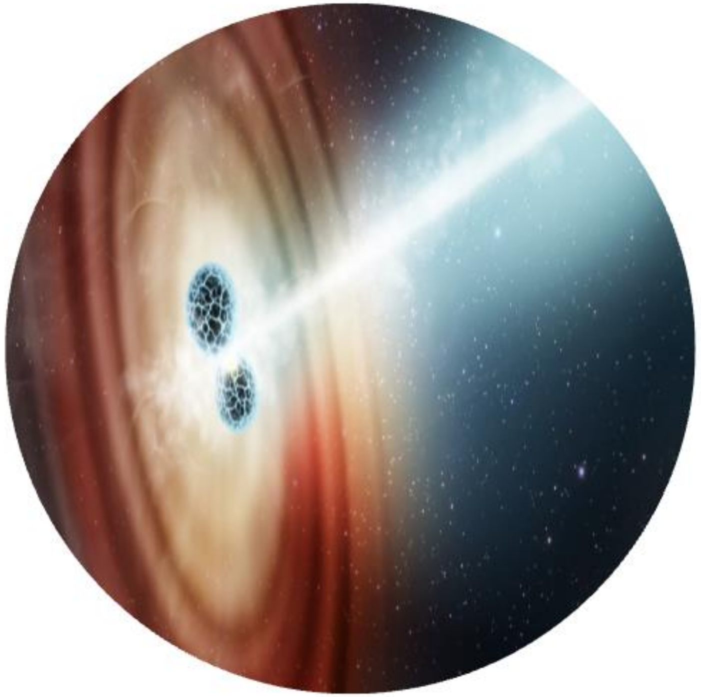

Measuring the neutron star spin with neutron star-black hole mergers.
Gupta. Astrophys J. 970 (2024)

On the Origins, Remnant, and Multimessenger Prospects of the Compact Binary Merger GW230529
Chandra, Gupta, et al., Astrophys J. (2025)

Foreground signals minimally affect inference of high-mass binary black holes in next generation gravitational-wave detectors
Gupta et al., Submitted to PRD, 2025.

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Using Gray Sirens to Resolve the Hubble-Lemaître Tension
Gupta. Mon.Not.Roy.Astron.Soc. 524 (2023) 3, 3537-3558

Cosmography with XG gravitational wave detectors
Gupta, Chen and Ezquiaga. Class. Quantum Grav. 41, 125004 (2024).

Effect of precession on golden dark siren measurements
In preparation. (2025)

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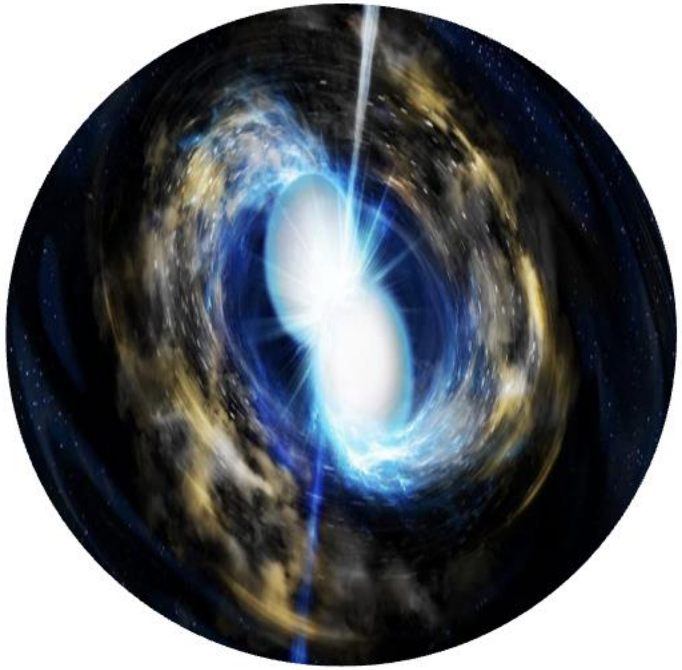


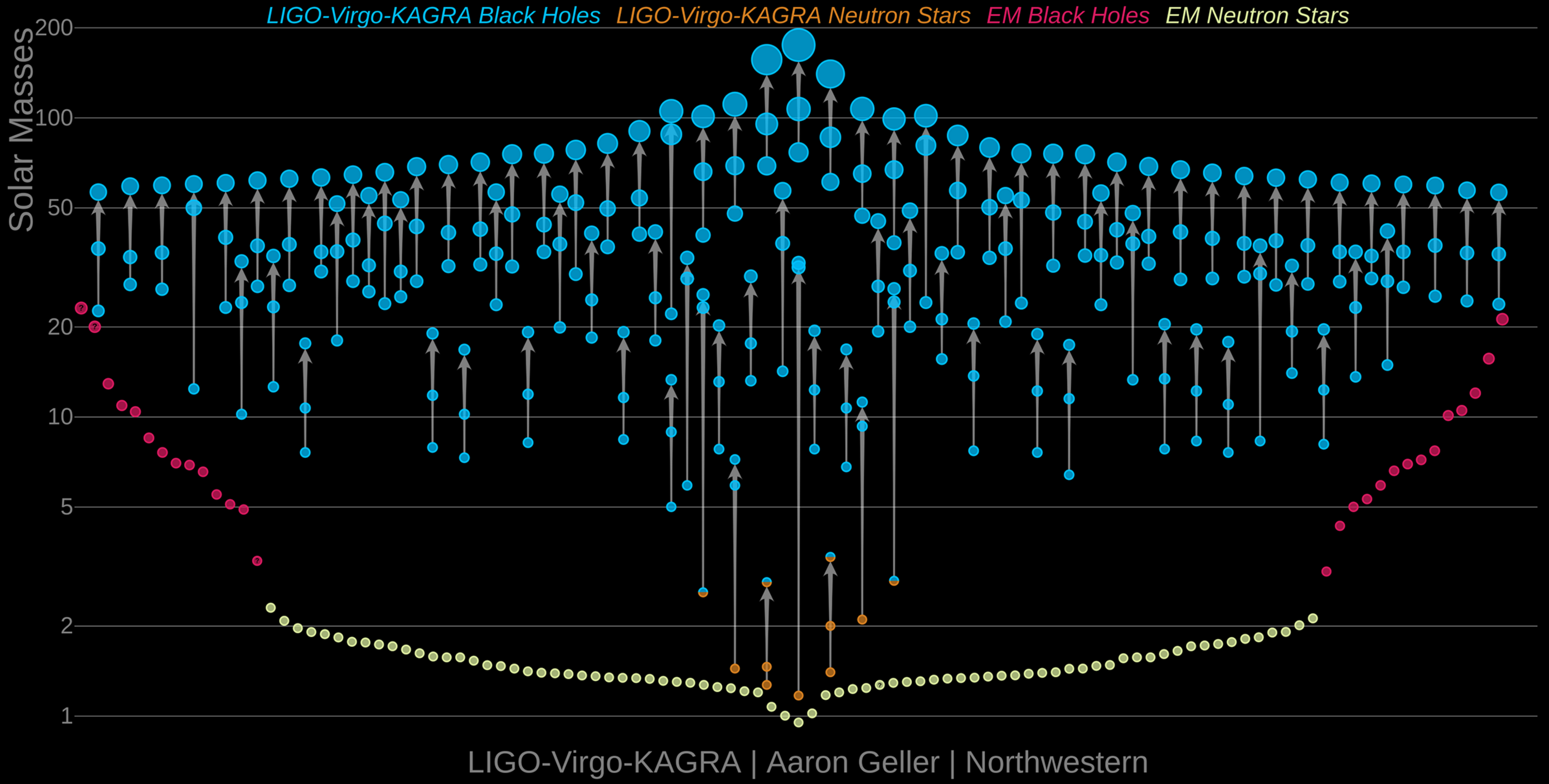
Detectability of QCD phase transitions in binary neutron star mergers
Prakash, Gupta, et al., Phys. Rev. D 109, 103008 (2023)

Cosmic Calipers: Precise and Accurate Neutron Star Radius Measurements with Next-Generation Gravitational Wave Detectors
Khadkikar, Gupta et al., Submitted to PRD, 2025.

Optimizing Bayesian model selection for equation of state of cold neutron stars
Kashyap, Gupta et al., Submitted to PRD, 2025.

Testing general relativity with sub-dominant mode amplitudes
Gupta, et al., In preparation. (2025)

Masses in the Stellar Graveyard



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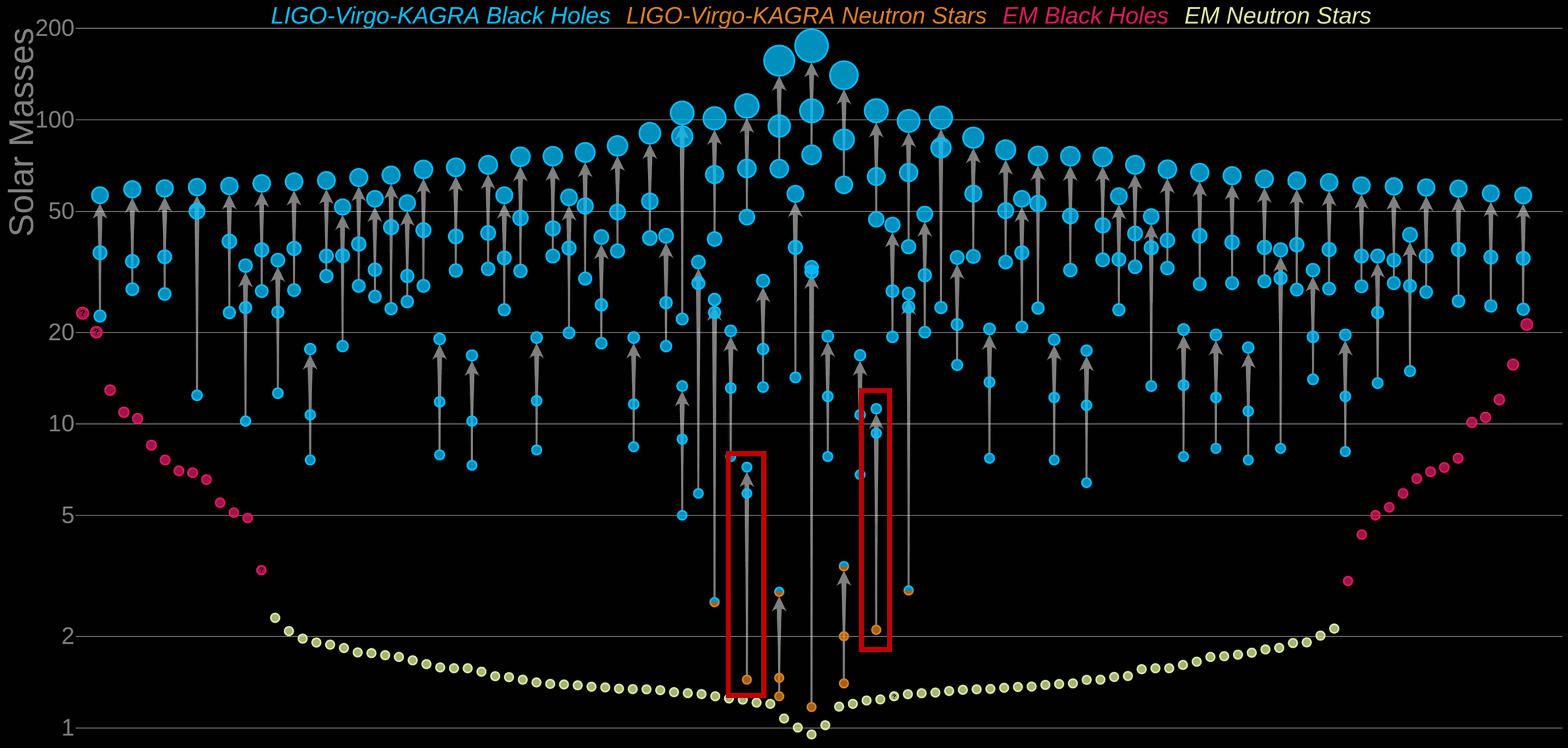
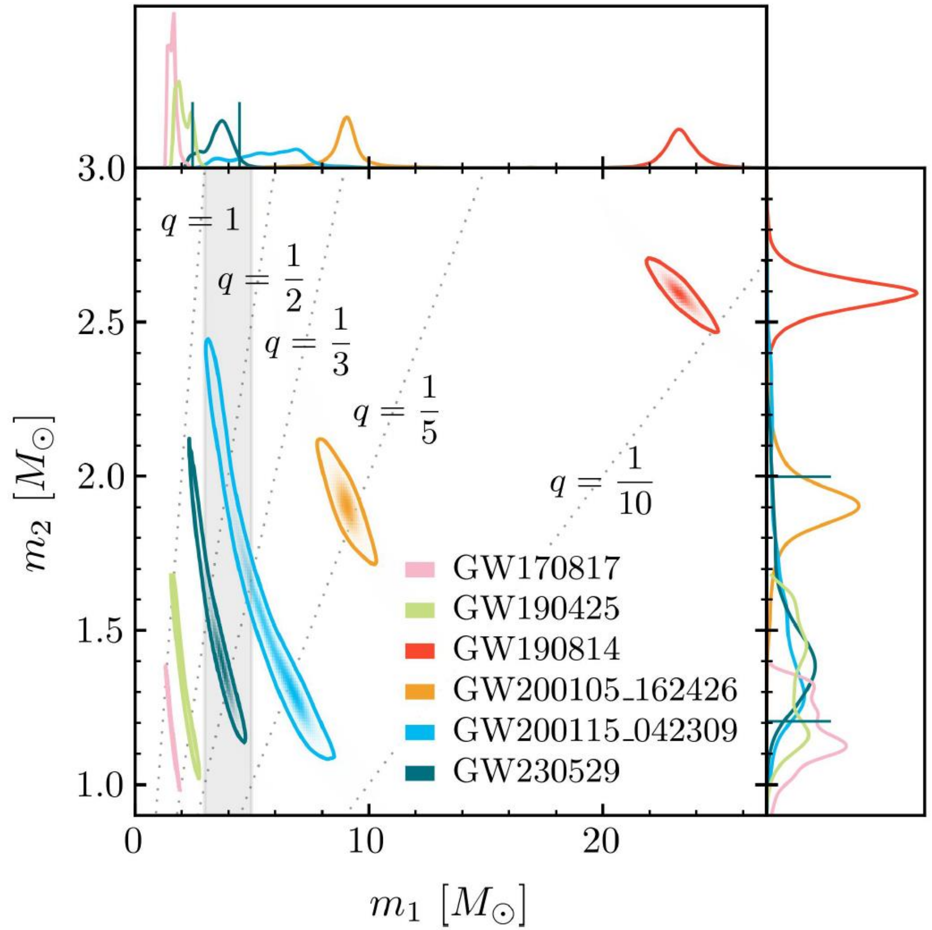
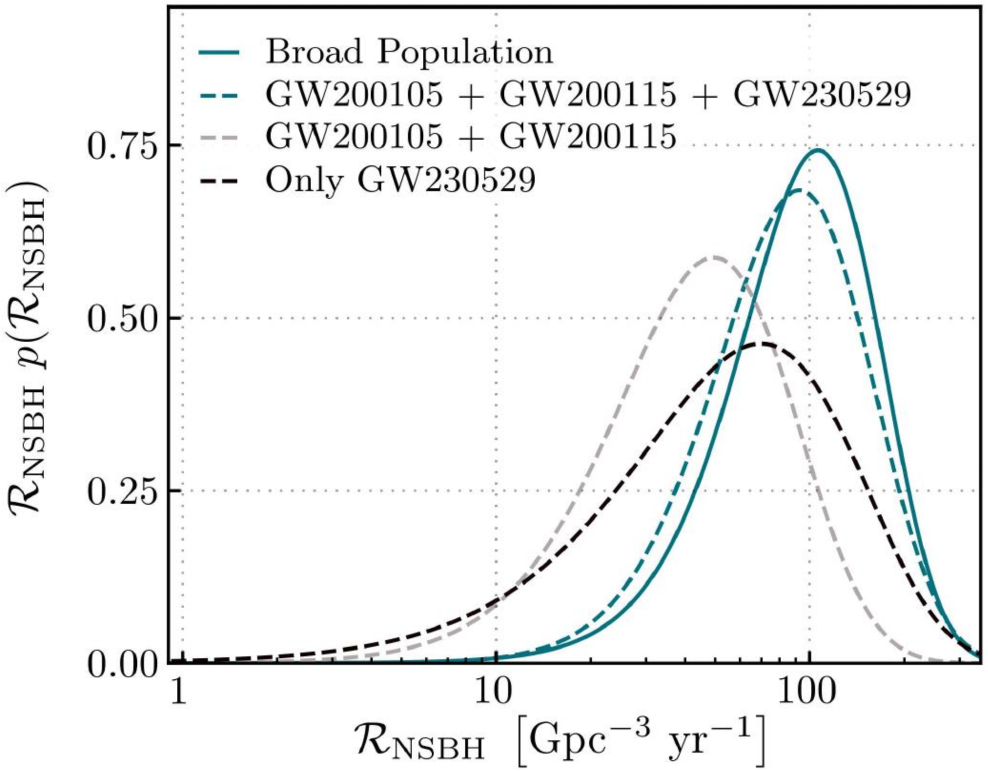


LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

The observed population





Abbott+, *arXiv:2404.04248 (2024)*

Usefulness of neutron star-black holes

$$h(t) = \sum_{l=2}^{\infty} \sum_{m=-l}^{l} h_{lm}(t, \lambda) Y_{lm}^{-2}(\iota, \phi_0)$$

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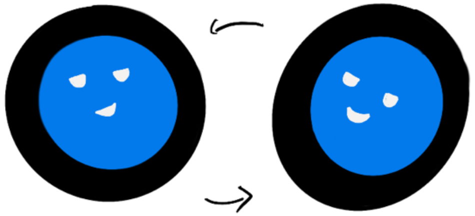
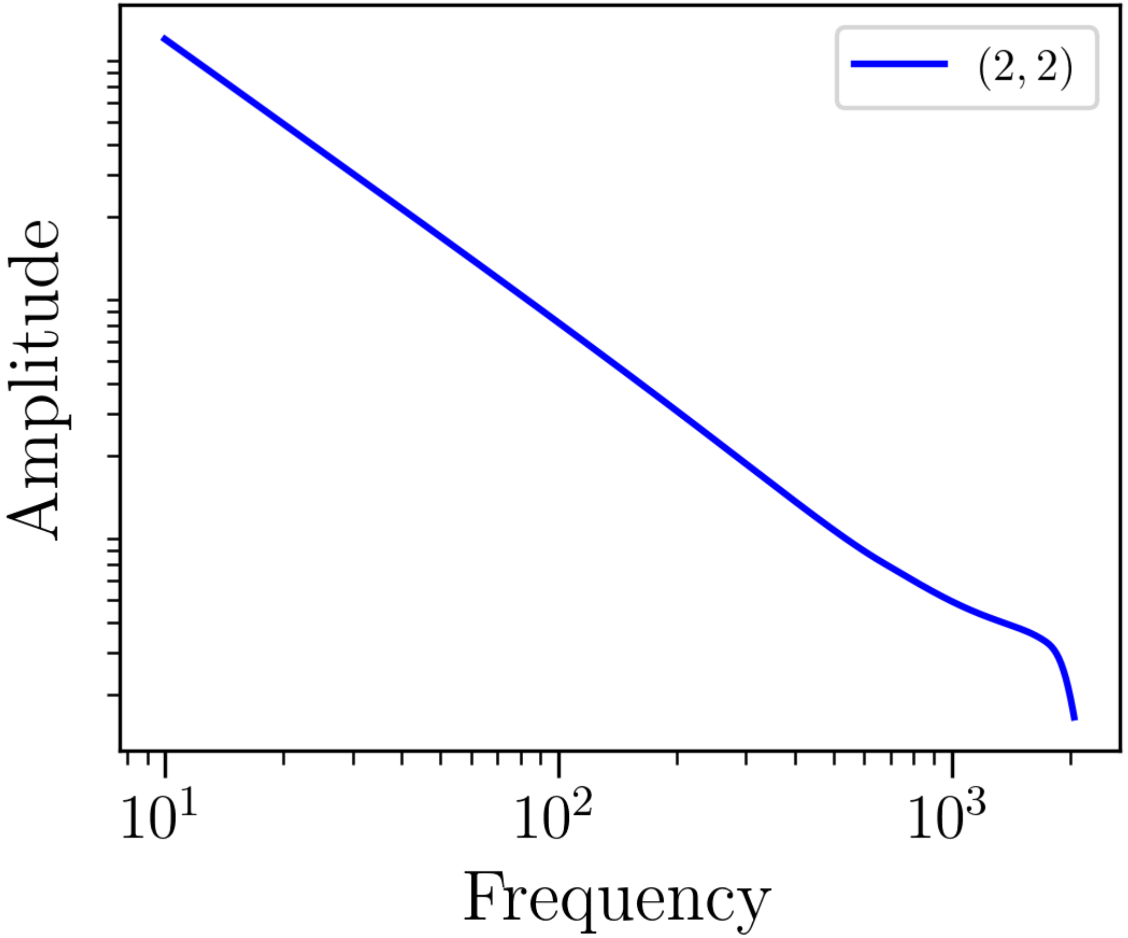


Mass symmetric

$$(2, \pm 2)$$



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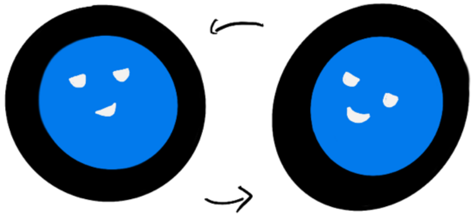
$$h(t, \boldsymbol{\lambda}) \rightarrow f(m, \boldsymbol{S}, D_L)$$

$(2, \pm 2)$



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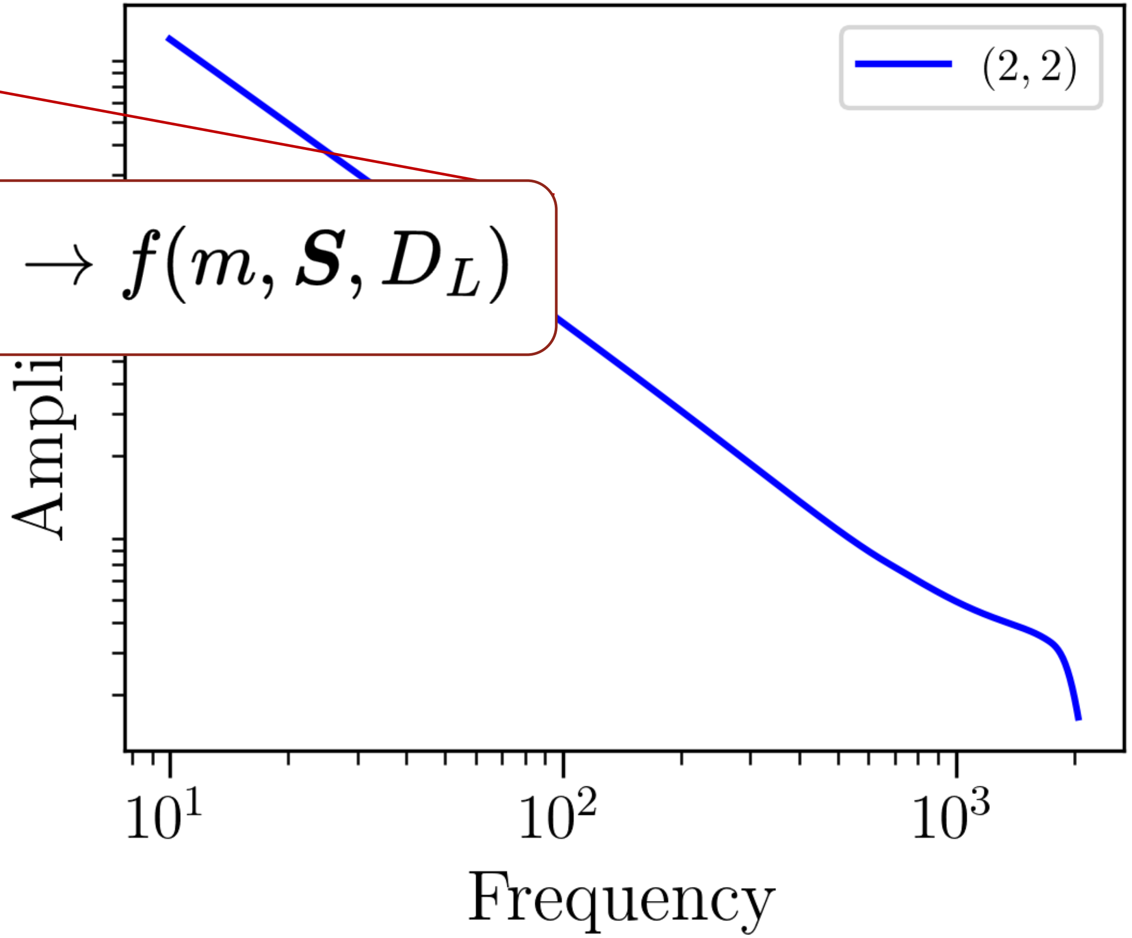

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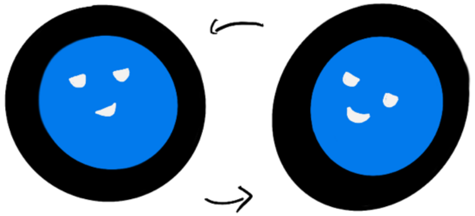

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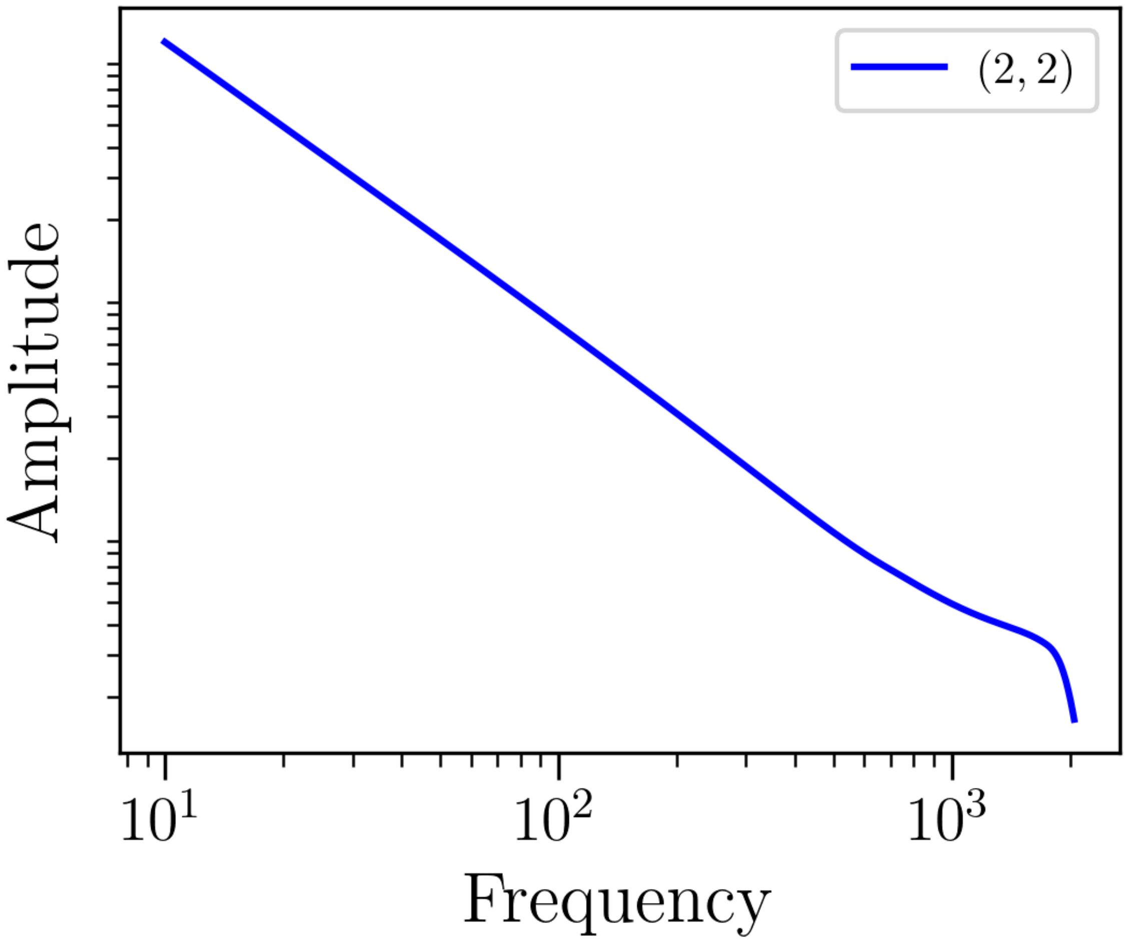

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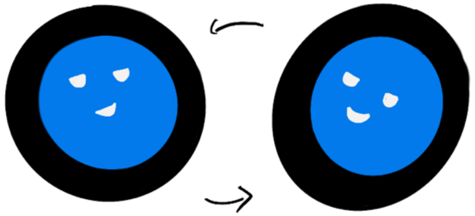

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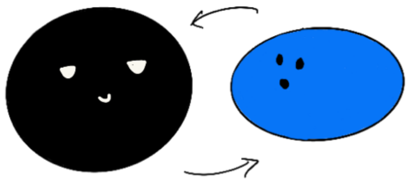
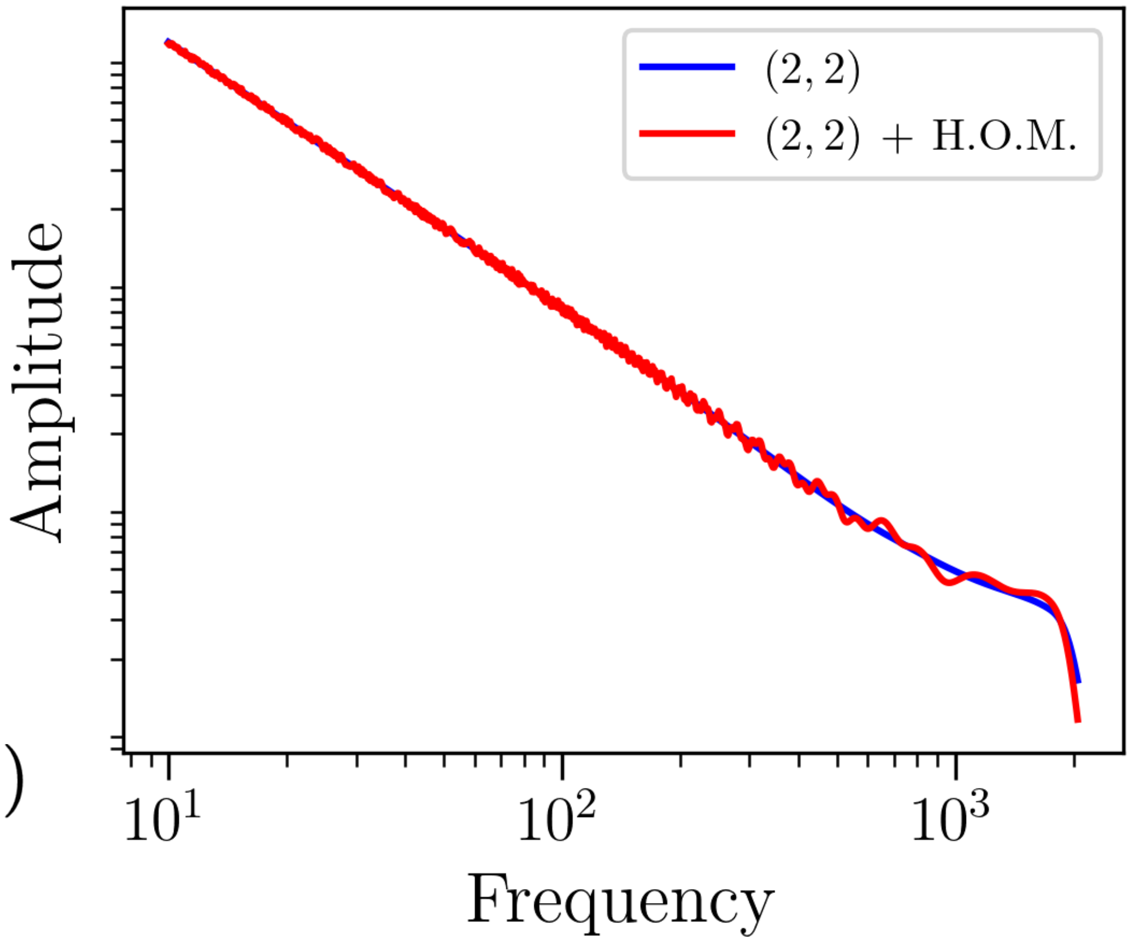


Mass asymmetric

$$(2, \pm 2)\ (3, \pm 3)\ (2, \pm 1)$$
$$(4, \pm 4)\ (3, \pm 2)\ \ldots$$



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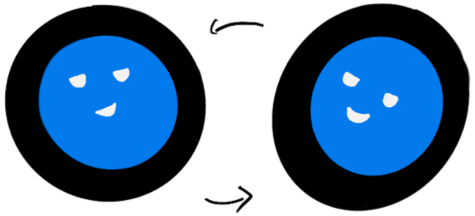

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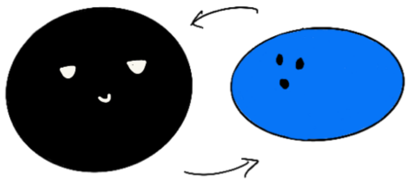

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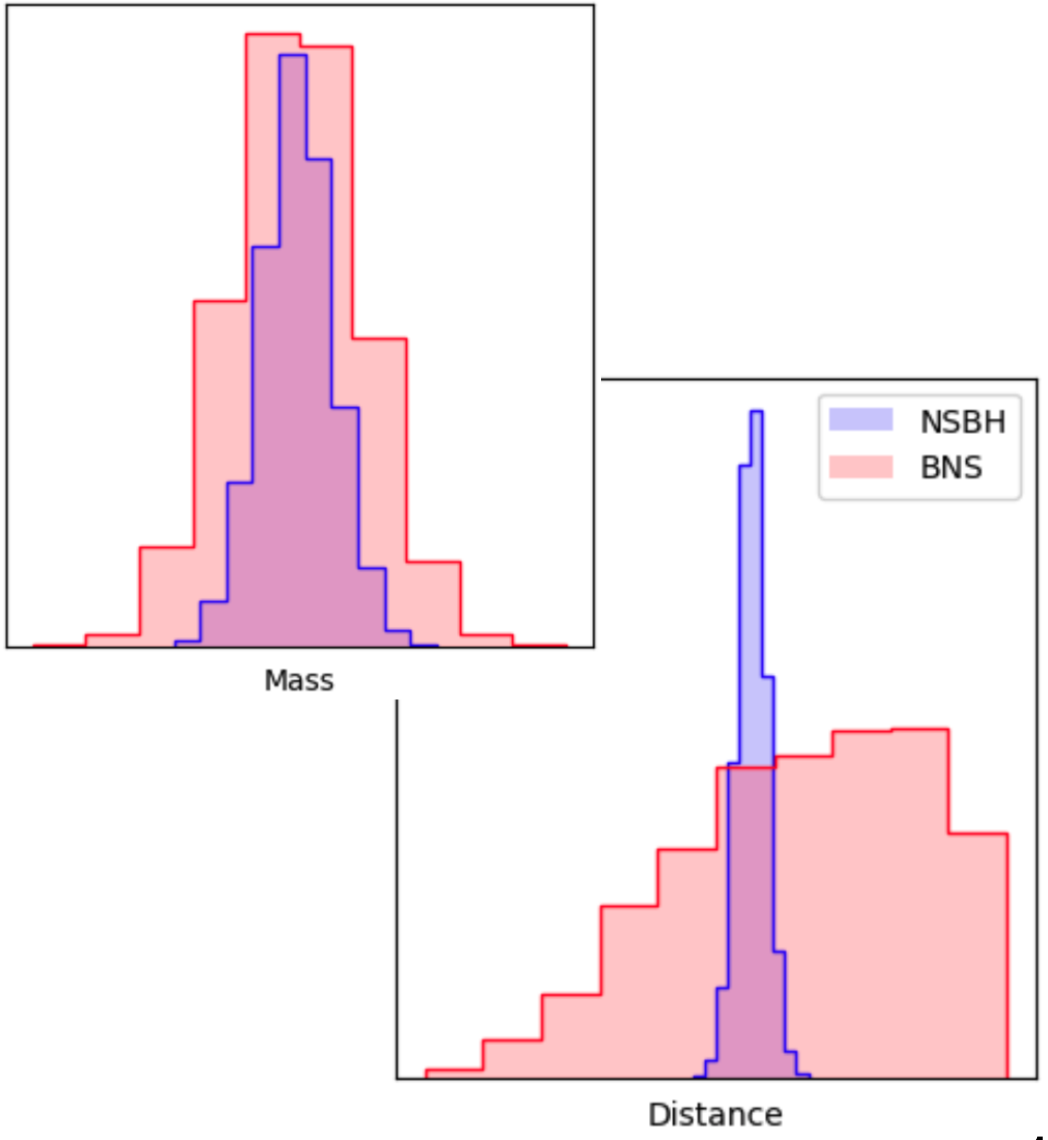
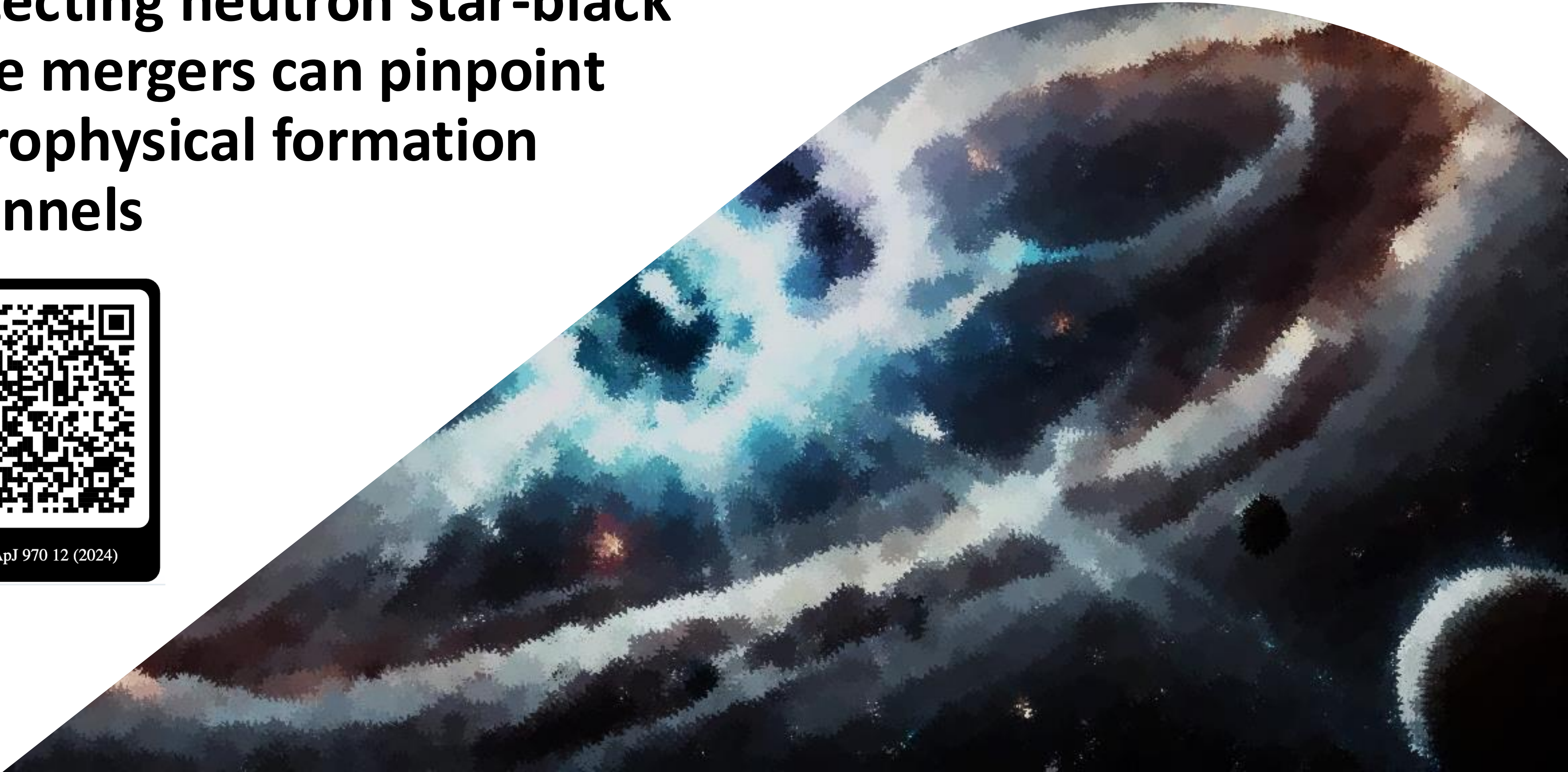


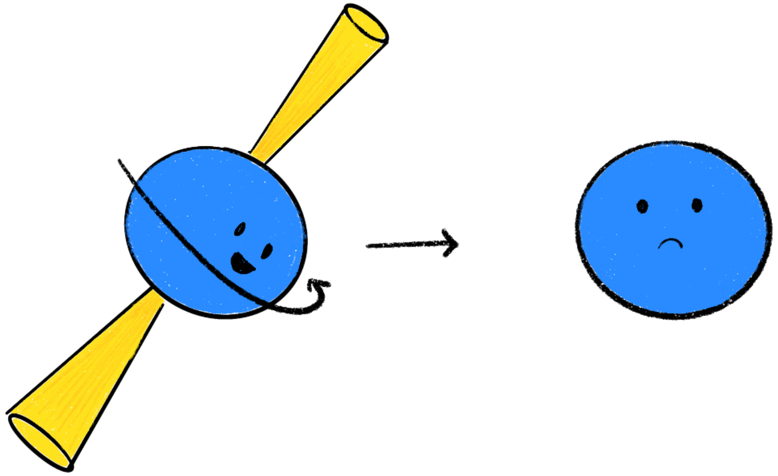
Detecting neutron star-black hole mergers can pinpoint astrophysical formation channels

Gupta, ApJ 970 12 (2024)



Why don't we measure neutron star's spin?

Astrophysically speaking...

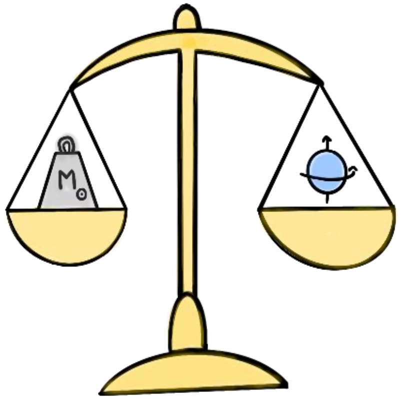


Neutron stars that are born as rapidly spinning pulsars radiate away their energy and angular momentum, slowing down.

Theoretically speaking...

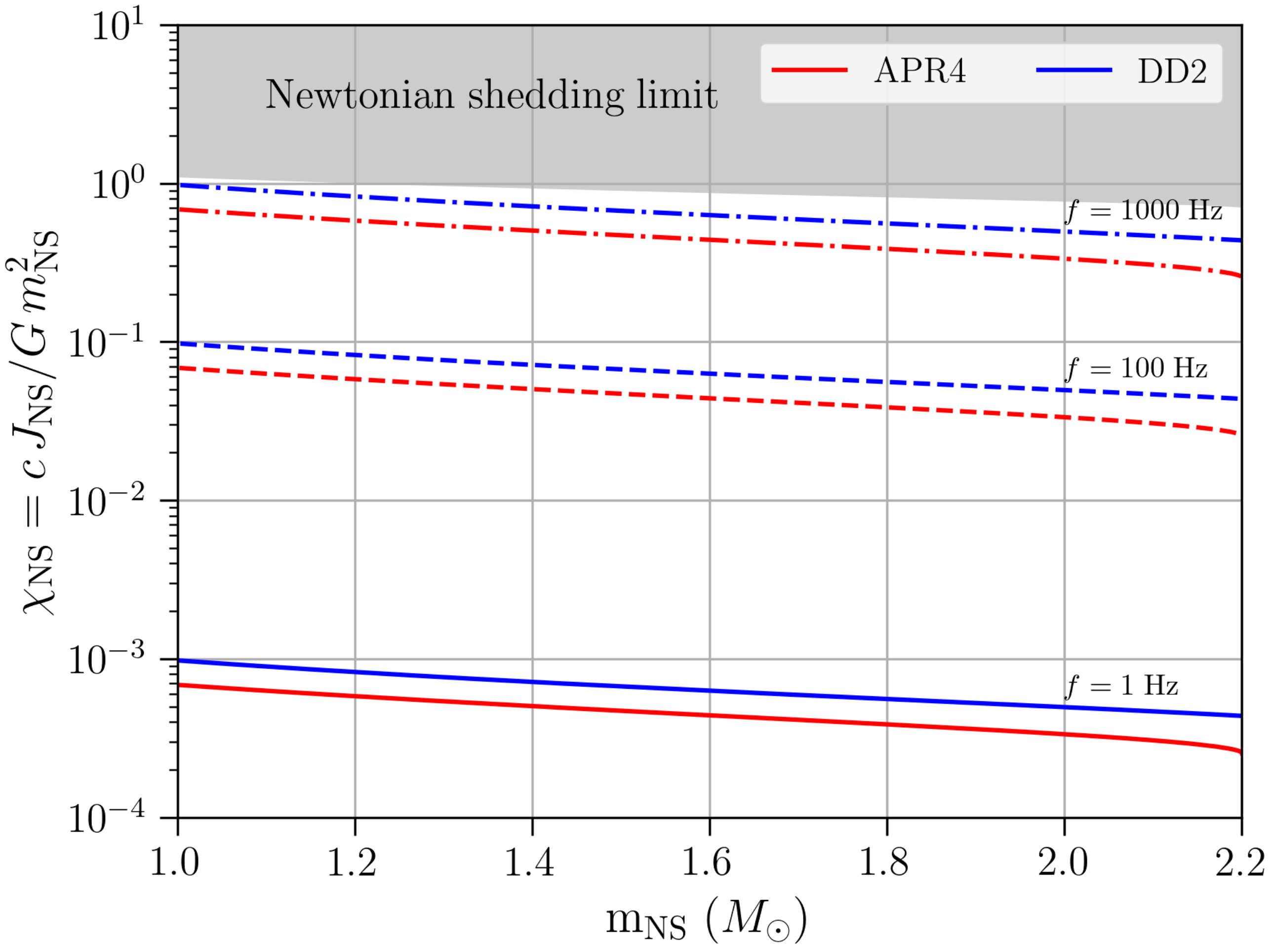
$$\Delta\Psi \approx \frac{55}{9}\eta + \frac{113\nu}{3}\chi_{\mathrm{PN}}$$

$$\chi_{\mathrm{eff}} = \frac{\chi_1 + q\,\chi_2}{1+q}$$

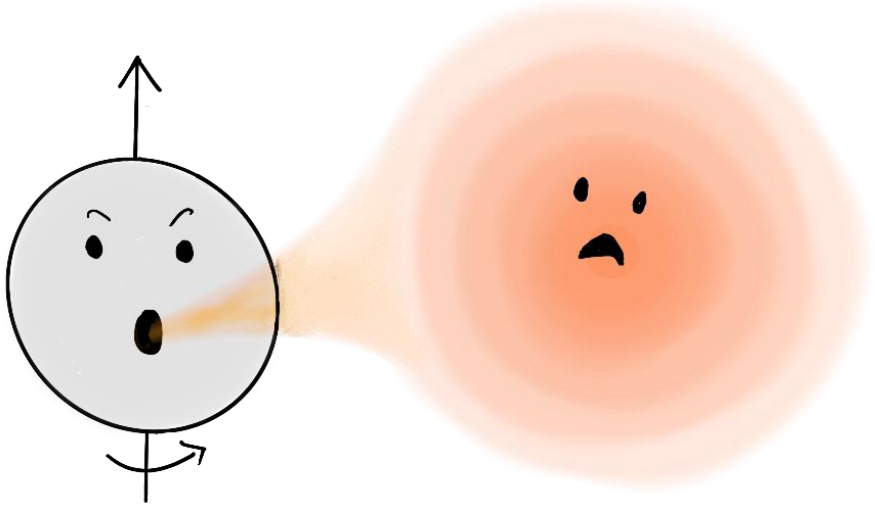


In the gravitational wave phase, the degeneracy between mass and spin parameters makes it difficult to measure component spins.

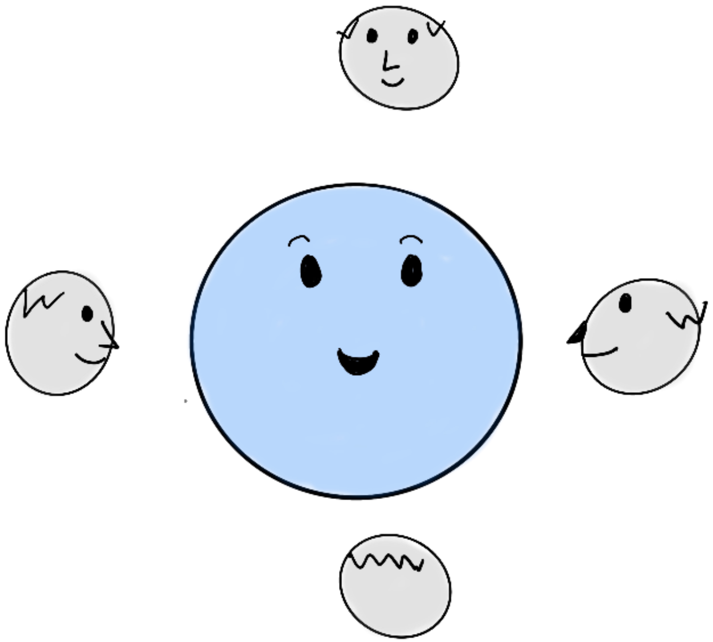
Why don't we measure neutron star's spin?



Can the universe form such systems?



The first-born accretes mass from the companion Helium star and spins up.



The second-born can get spun-up by tidal synchronization.

Under the constraints of the isolated binary formation, a limited number of scenarios have been proposed that can lead to a rapidly spinning neutron star at merger.

Higher order modes to the rescue!

Higher order modes to the rescue!

Mode	Leading order spin terms
$(2,1)$	$\frac{4i}{R}\sqrt{\frac{\pi}{5}}\,\eta M\,\tilde{\chi}$
$(2,2)$	$\frac{32}{3R}\sqrt{\frac{\pi}{5}}\,\eta M\,(\chi_{\rm eff}-\eta\chi_s)$
$(3,2)$	$\frac{32}{3R}\sqrt{\frac{\pi}{7}}\,\eta^2 M\,\chi_s$
$(3,3)$	$\frac{3i}{2R}\sqrt{\frac{6\pi}{7}}\,\eta M\,((4-5\eta)\tilde{\chi}-14\eta\chi_a)$
$(4,4)$	$\frac{256}{9R}\sqrt{\frac{\pi}{7}}\,\eta M\left[\left(-\frac{2}{3}+\frac{13}{5}\eta\right)\chi_{\rm eff}+\frac{2\eta}{5}\left(\frac{1}{3}-7\eta\right)\chi_s\right]$

Positive spin combinations

$$\chi_{\rm eff}=\frac{\chi_1+q\,\chi_2}{1+q}$$

$$\chi_s=\frac{\chi_1+\chi_2}{2}$$

Higher order modes to the rescue!

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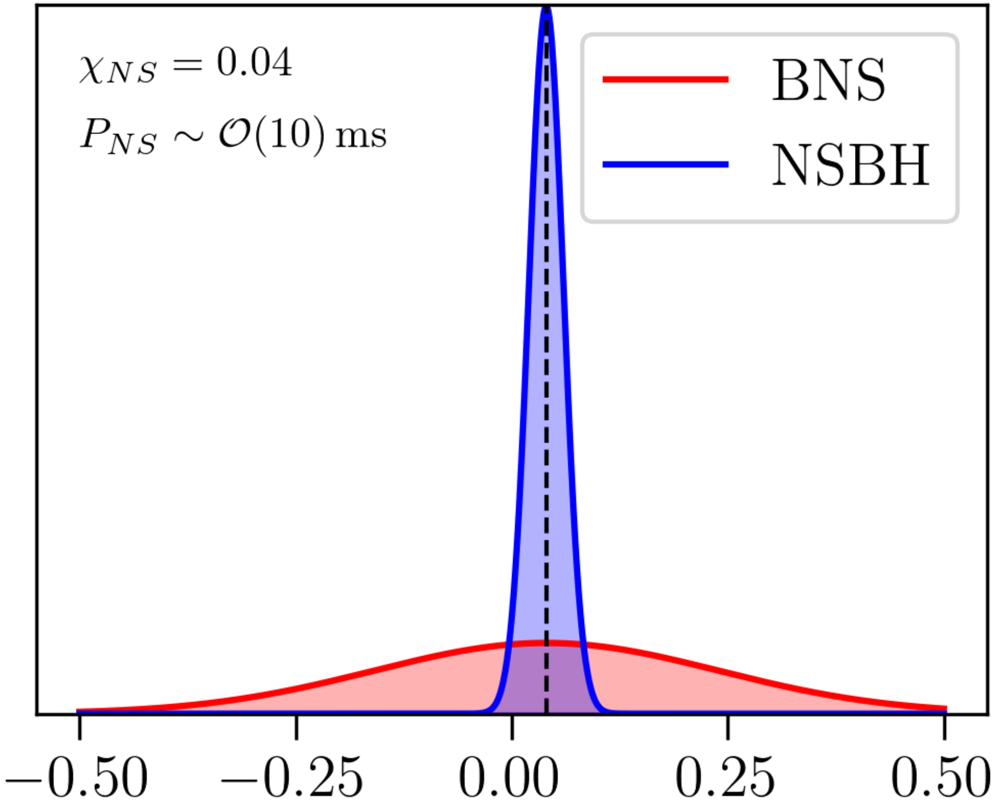
$(3,2)$	$\frac{32}{3R}\sqrt{\frac{\pi}{7}}\,\eta^2 M\,\chi_s$
$(3,3)$	$\frac{3i}{2R}\sqrt{\frac{6\pi}{7}}\,\eta M\,((4-5\eta)\tilde{\chi} + 14\eta\chi_a)$
$(4,4)$	$\frac{256}{9R}\sqrt{\frac{\pi}{7}}\,\eta M\left[(-\frac{2}{3} + \frac{13}{5}\eta)\chi_{\rm eff} + \frac{2\eta}{5}\left(\frac{1}{3} - 7\eta\right)\chi_s\right]$

Negative spin combinations

$$\tilde{\chi} = \frac{\chi_1 - q\,\chi_2}{1+q}$$

$$\chi_a = \frac{\chi_1 - \chi_2}{2}$$

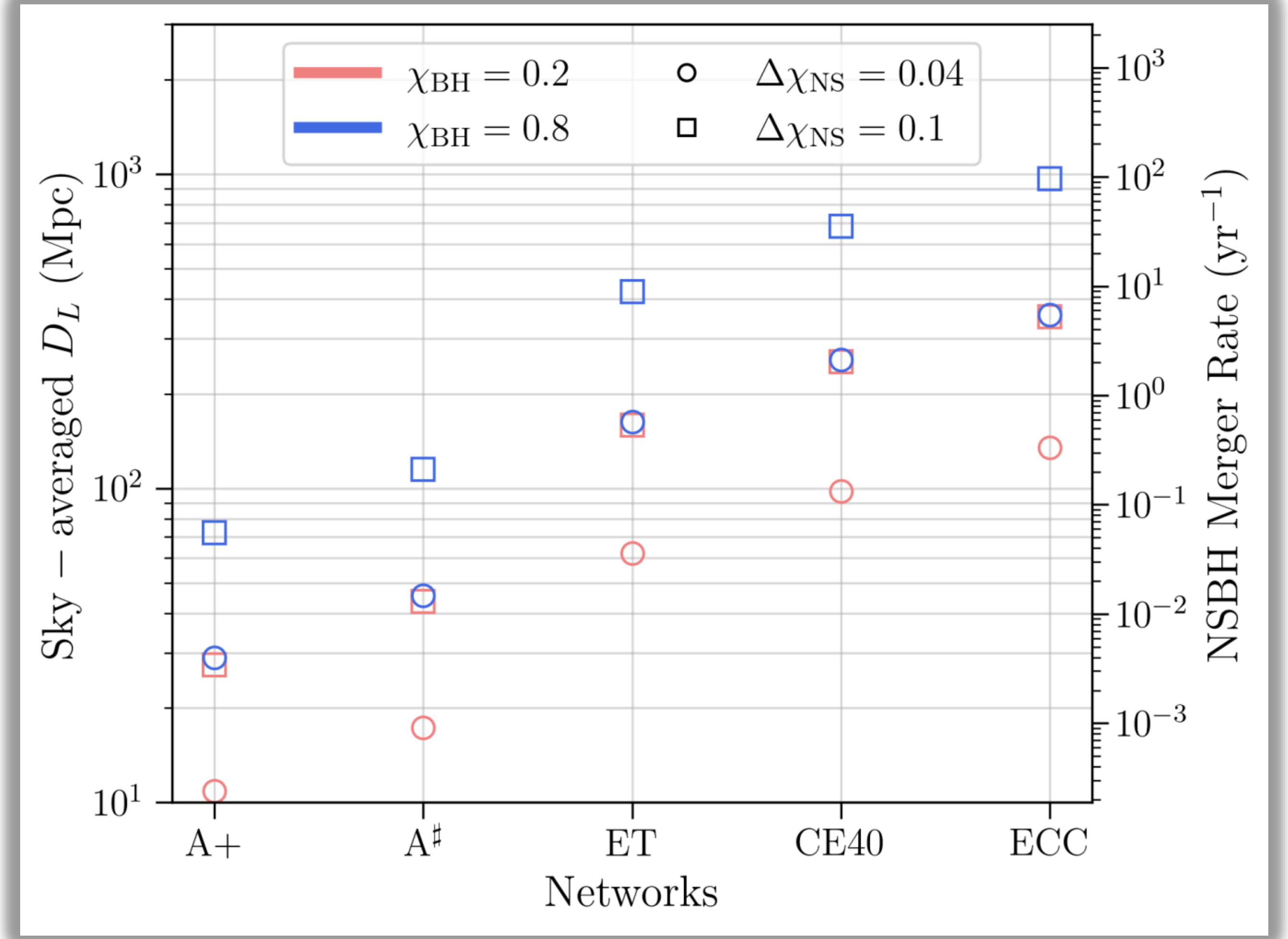
Can we measure it?



The spin of a neutron star is much more precisely measured with a neutron star-black hole merger detection compared to a binary neutron star detection.

Gupta, ApJ 970 (2024)

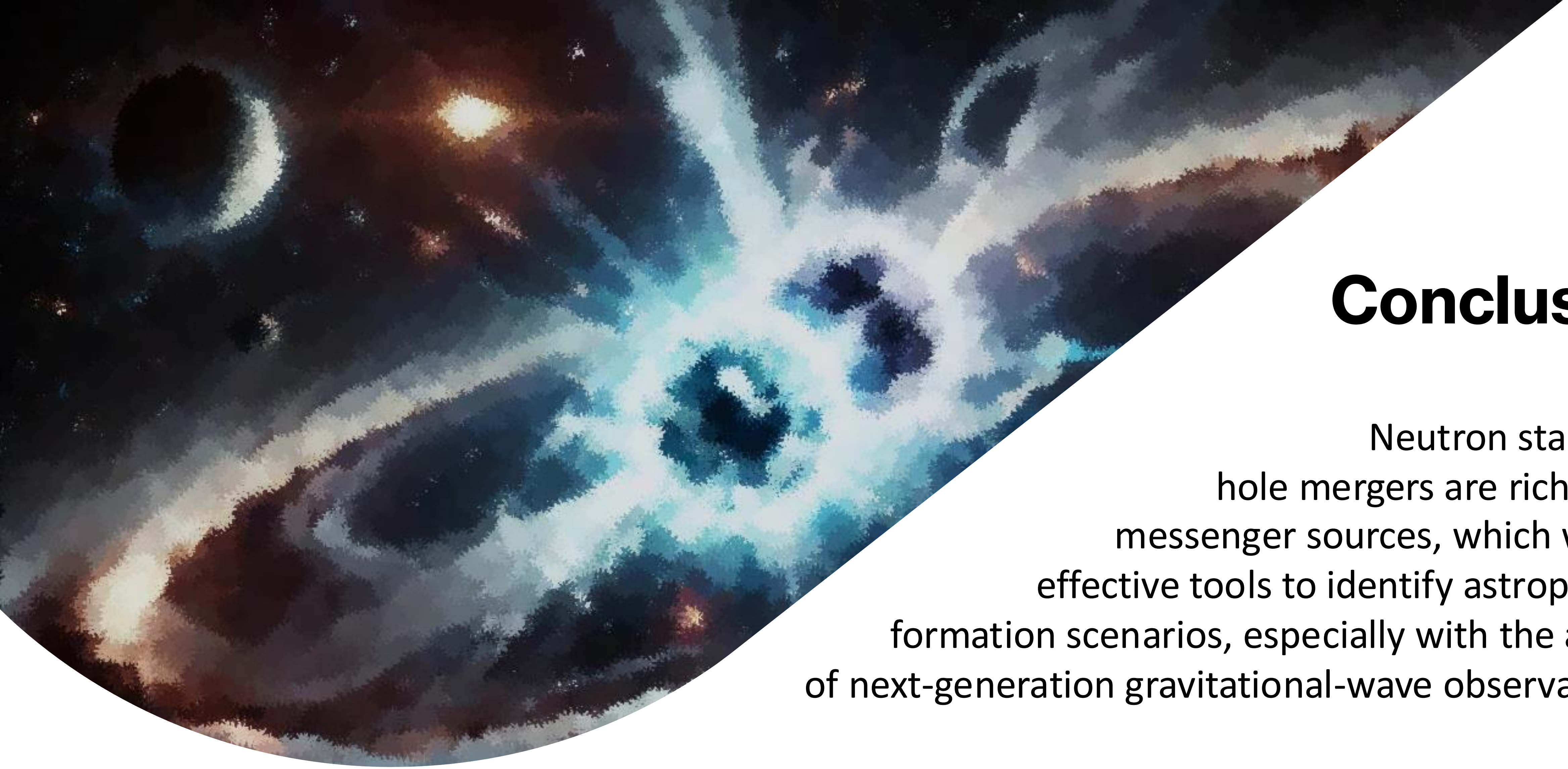
Can we measure it?



Next-generation observatories can precisely measure the spin of a neutron star with neutron star-black hole mergers, even if they were to happen a Gpc away.

Gupta, ApJ 970 (2024)

Conclusion



Conclusion

Neutron star-black hole mergers are rich multi-messenger sources, which will act effective tools to identify astrophysical formation scenarios, especially with the advent of next-generation gravitational-wave observatories.

Let's not sleep on neutron star-black hole mergers!

Extra slides

Using gravitational-wave detections

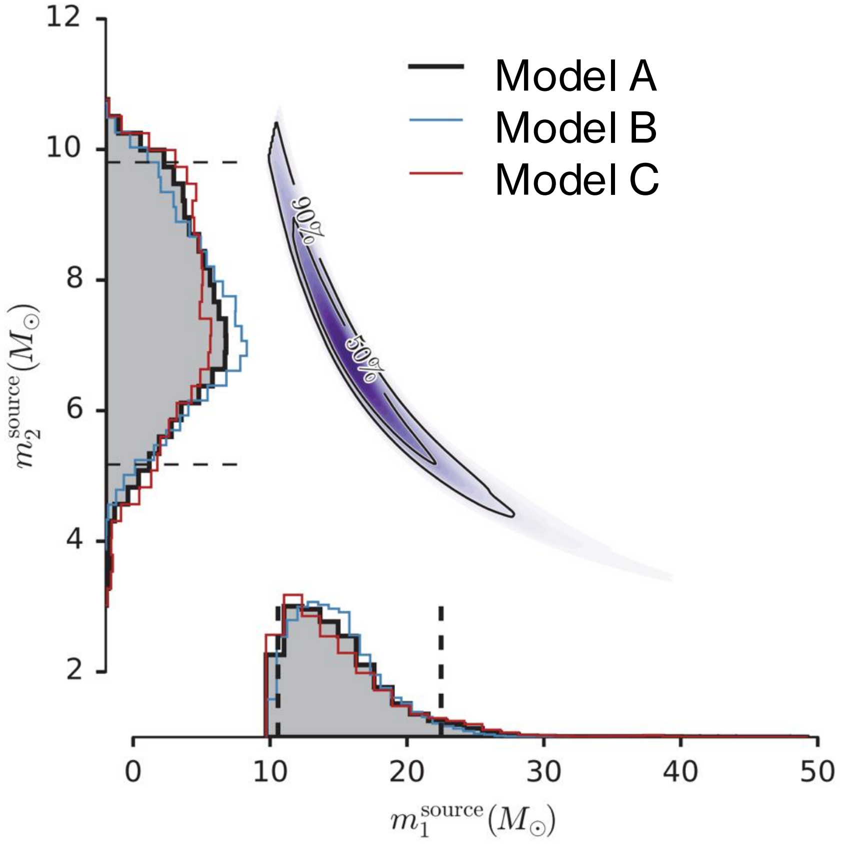
Likelihood

Prior

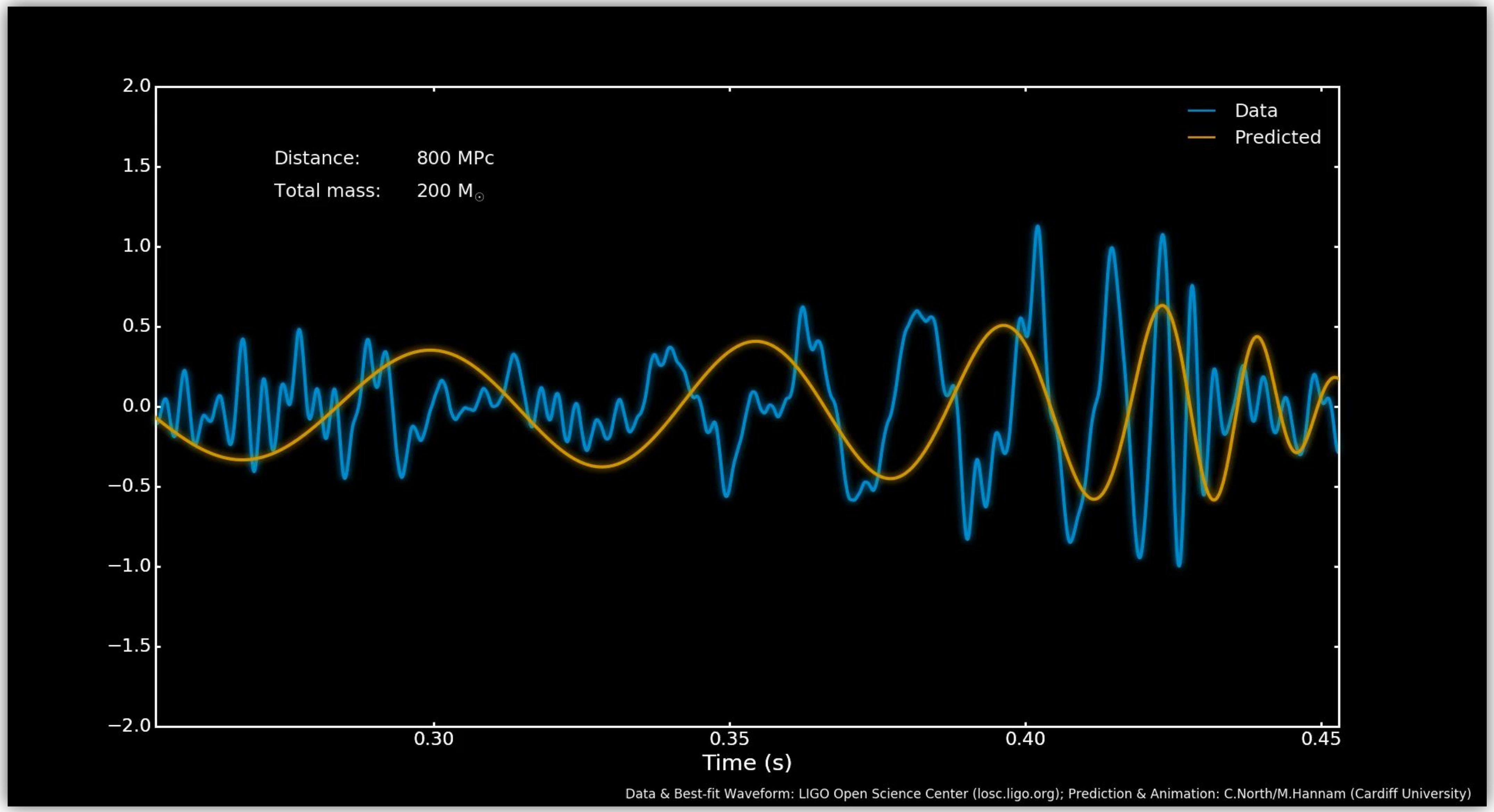
$$p(\boldsymbol{\theta} \mid \mathbf{d}, H) = \frac{p(\mathbf{d} \mid \boldsymbol{\theta}, H)\, p(\boldsymbol{\theta} \mid H)}{p(\mathbf{d} \mid H)}$$

Posterior

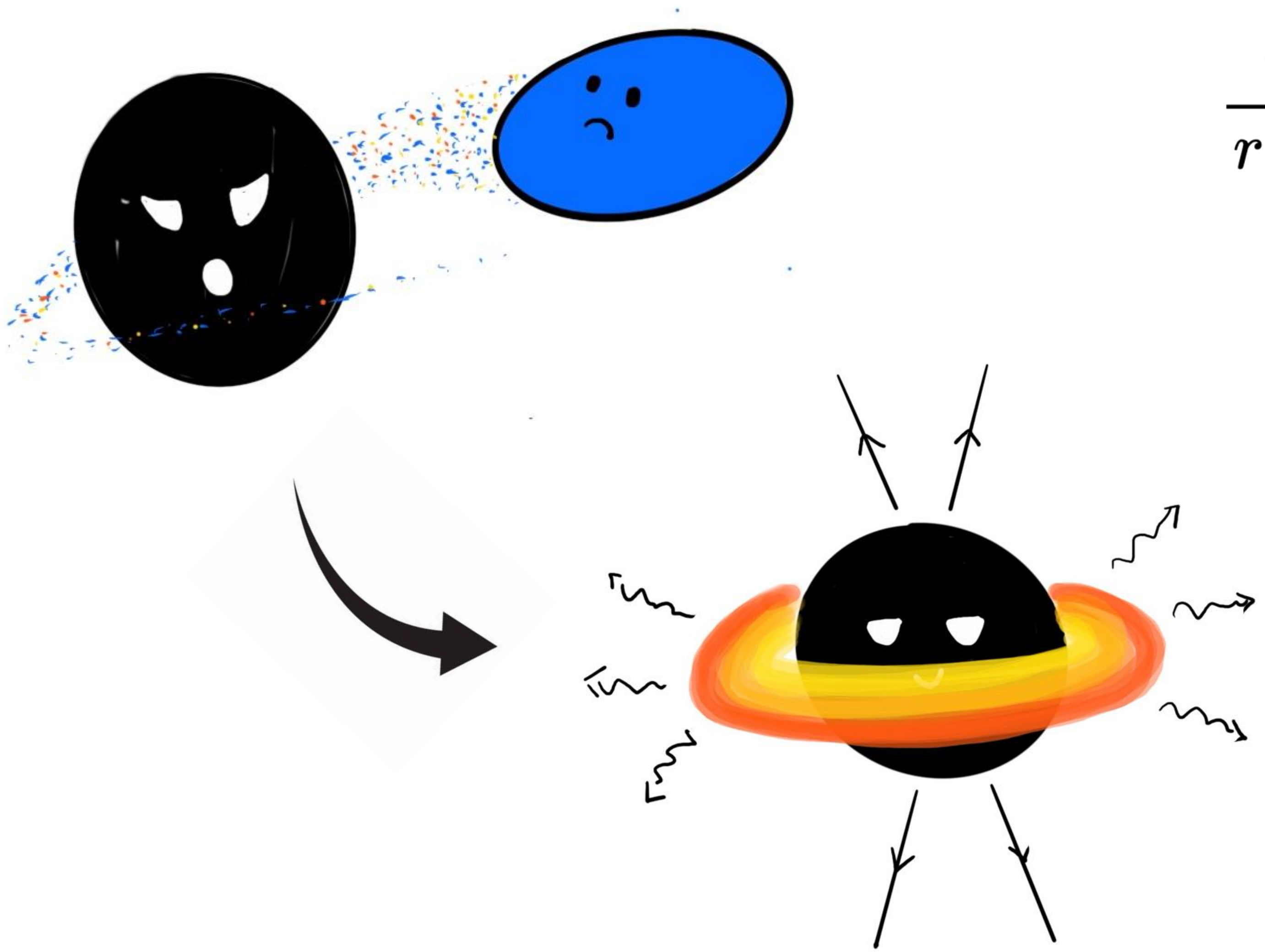
Evidence



Using gravitational-wave detections



Usefulness of neutron star-black holes

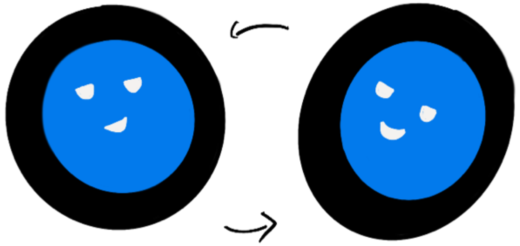


$$\frac{r_{ms}}{r_{ISCO}} \propto q^{-2/3}\, C^{-1}\, \hat{r}_{ISCO}^{-1}(\chi)$$

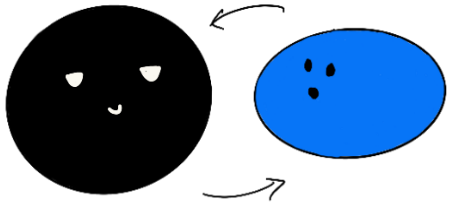
$$q = \frac{m_{\rm BH}}{m_{\rm NS}}$$

$$C = \frac{G m_{\rm NS}}{c^2 R_{\rm NS}}$$

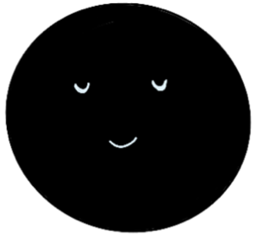
Usefulness of neutron star-black holes

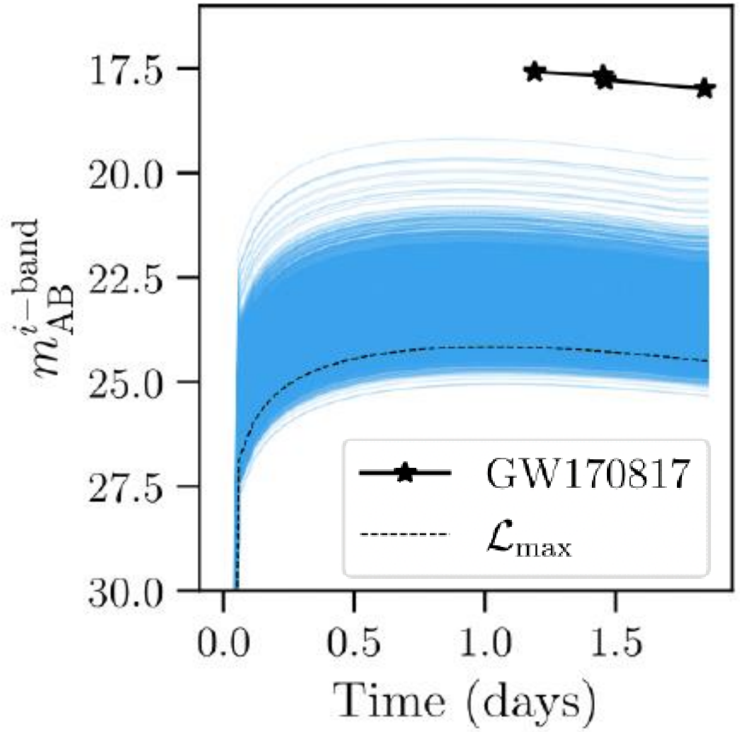


Mass symmetric



Mass asymmetric





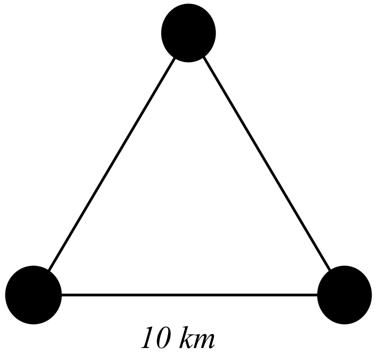
The probably i-band kilonovae light curves for GW230529. (Chandra, ***Gupta,*** *et al. ApJ 977, 2024)*

Looking toward the future

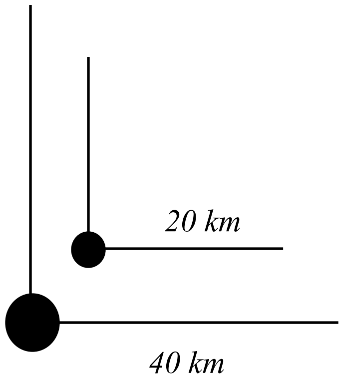
More observations

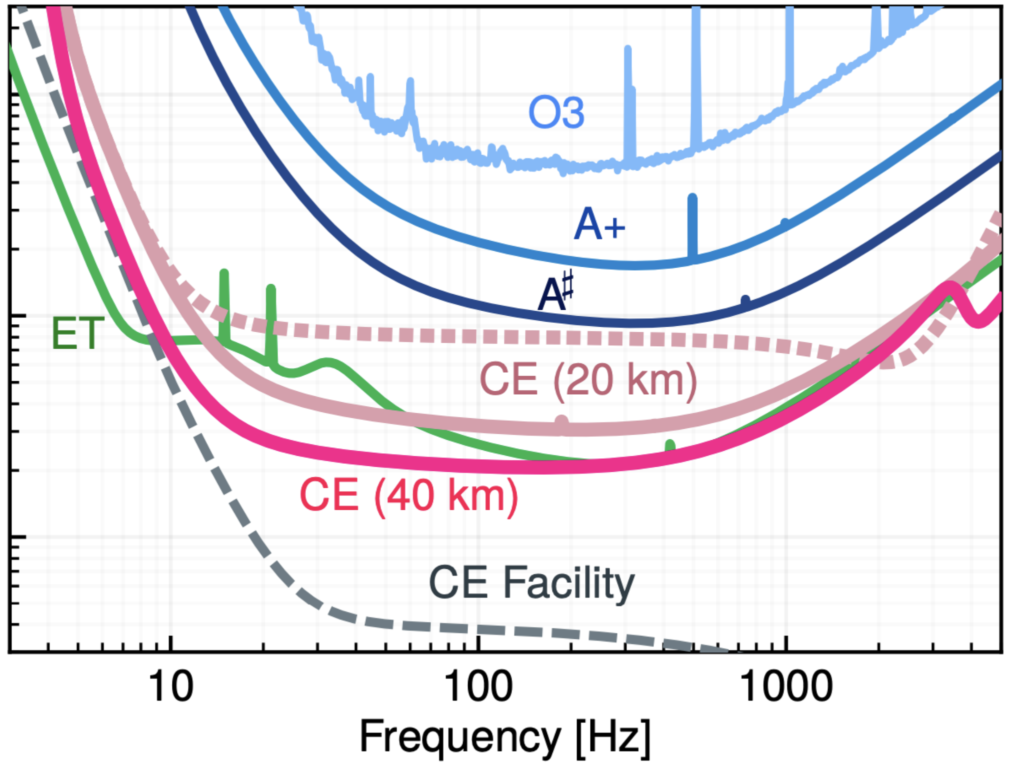
Louder signals

ET EINSTEIN TELESCOPE



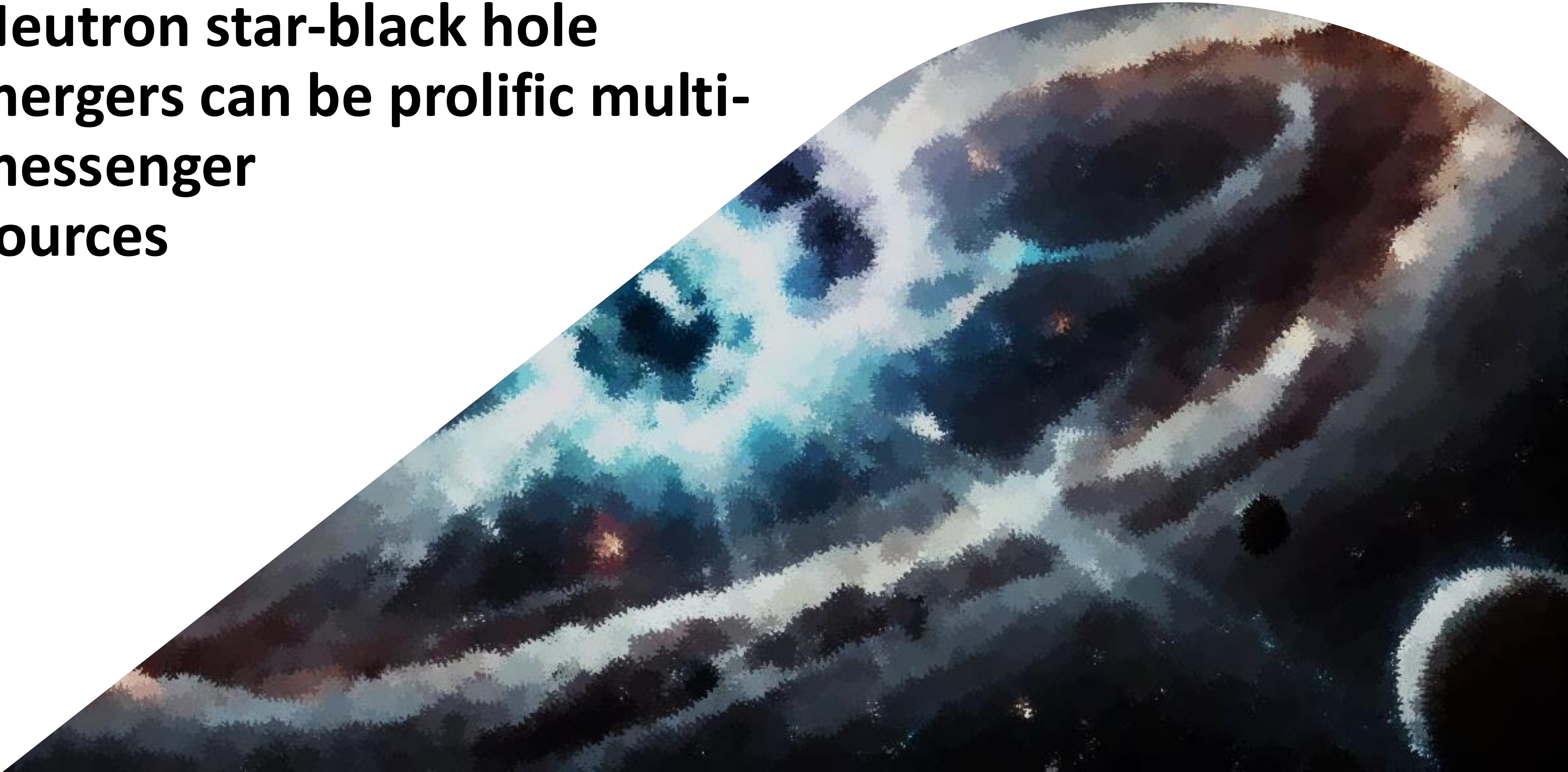
COSMIC EXPLORER



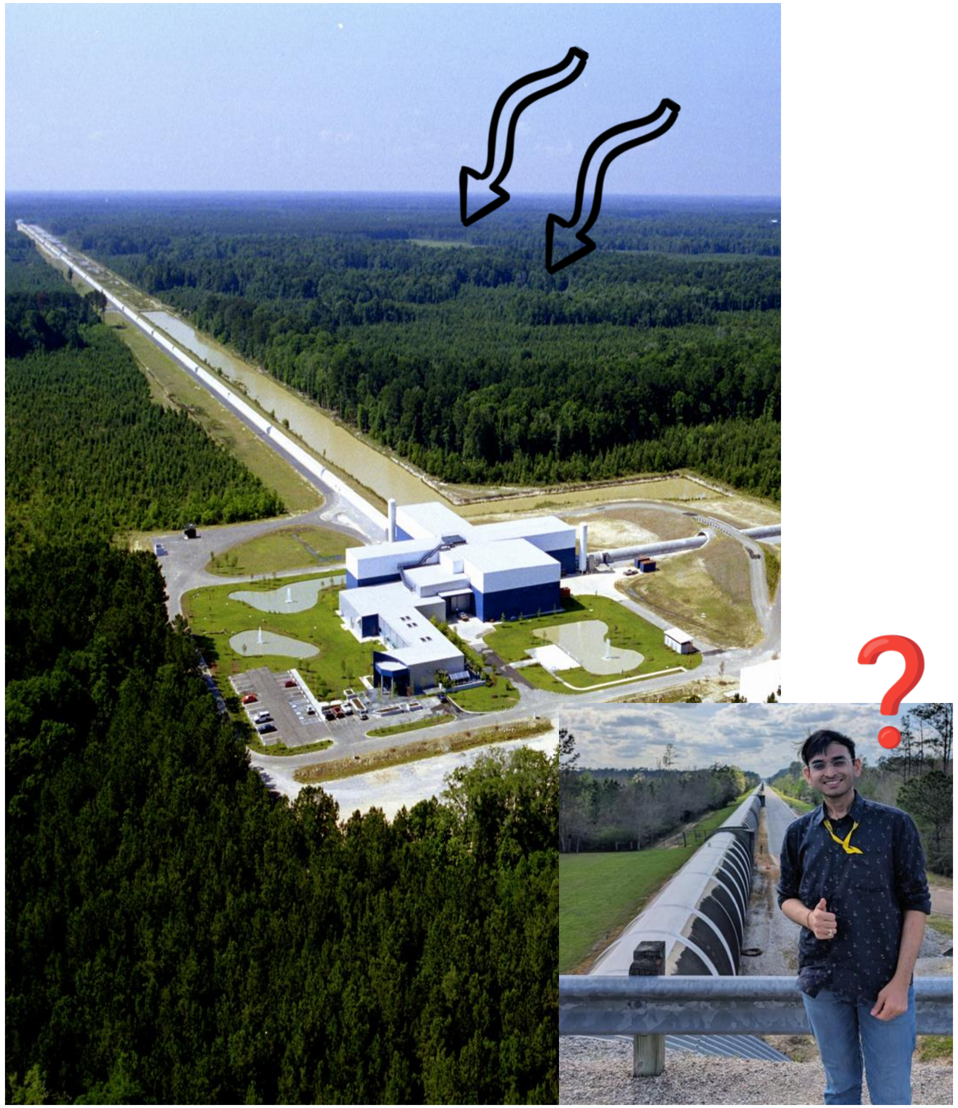


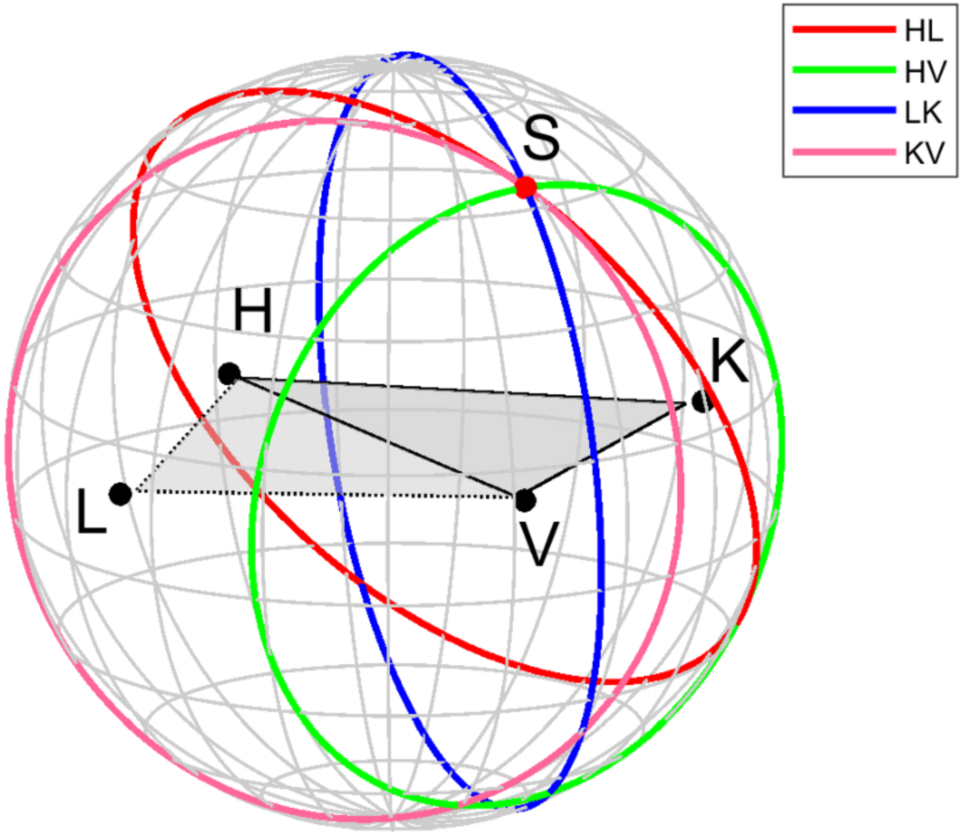
*The sensitivity curves of different detectors. (**Gupta** et al. CQG 41, 2024)*

Neutron star-black hole mergers can be prolific multi-messenger sources



Localization of events in the sky





LVK, Liv. Rev. Rel. 23(1), 2020

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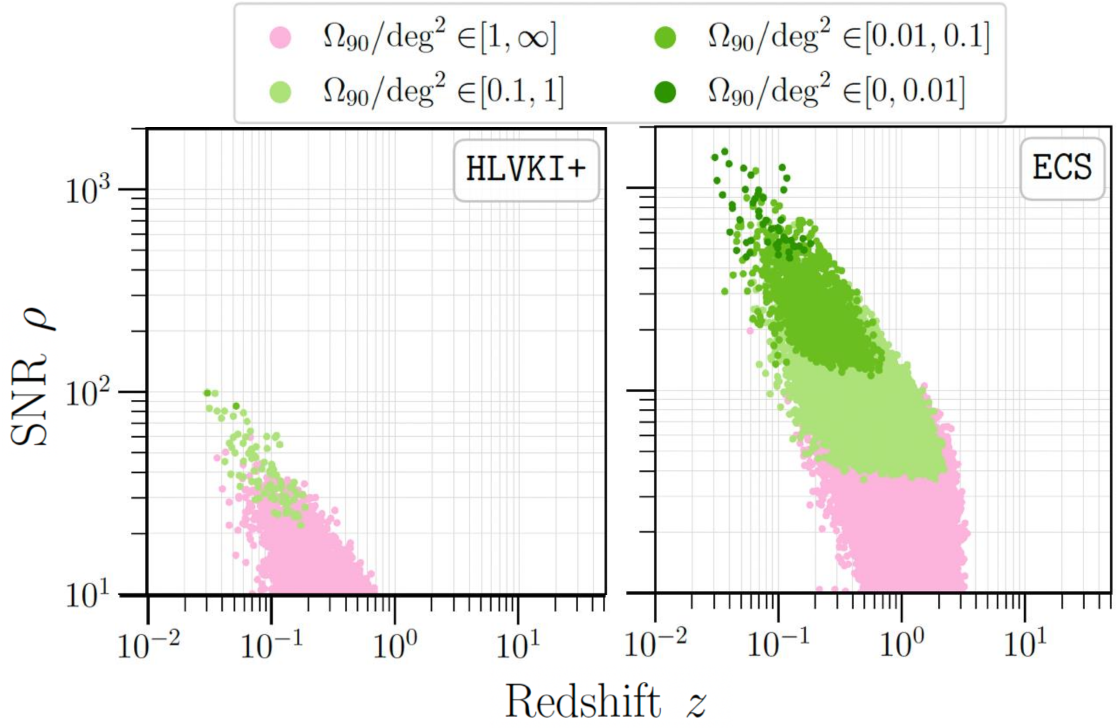
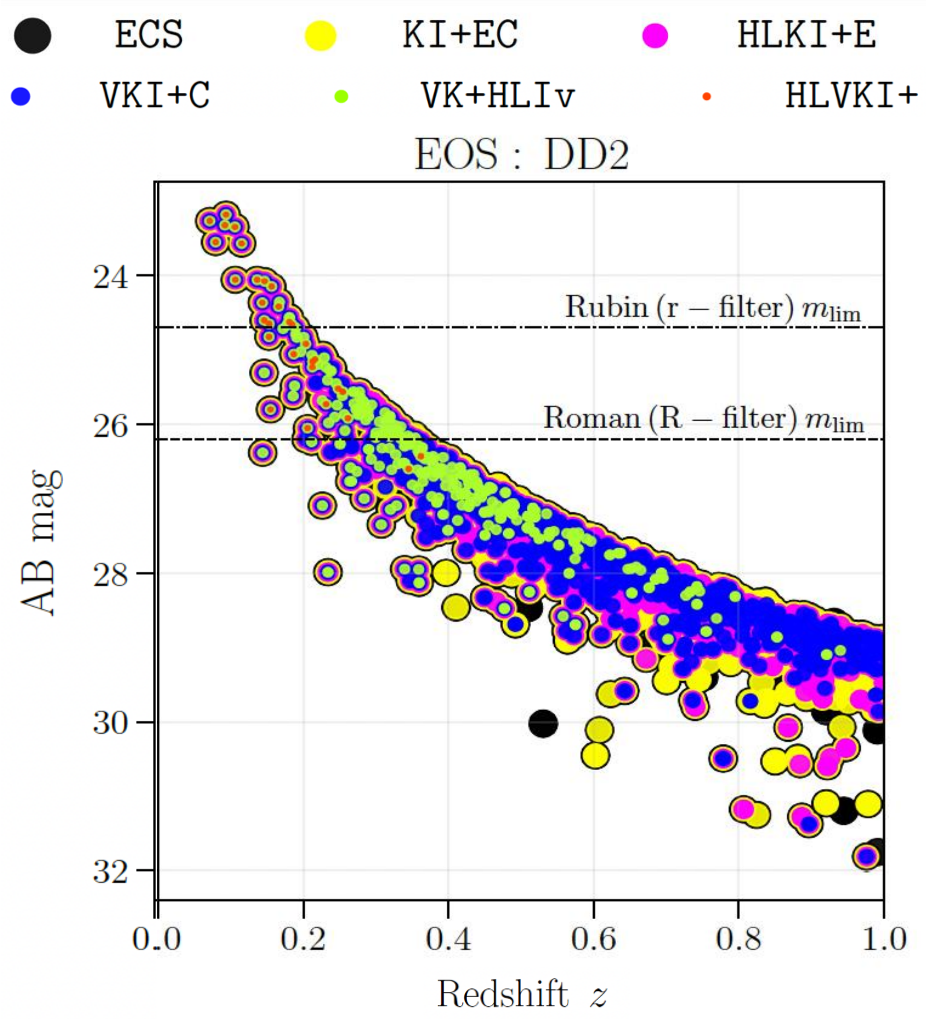




Gupta+, *Phys. Rev. D 107, 124007 (2023)*

Measuring the cosmic expansion

Gravitational waves already provide distance, all we need is redshift.

$$D_L = \frac{1+z}{H_0} \int_{1/(1+z)}^{1} \frac{dx}{x^2 \sqrt{\Omega_\Lambda + \Omega_m x^{-3}}}$$

Planck 2018

$$H_0 = 67.4 \pm 0.5 \ \mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Using cosmic microwave background measurements

TENSION

SH0ES

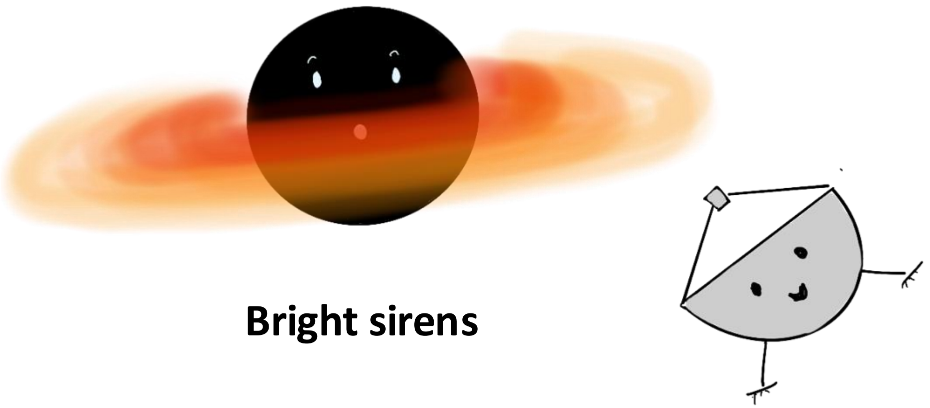
$$H_0 = 73.30 \pm 1.04 \ \mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Using Type 1A supernovae

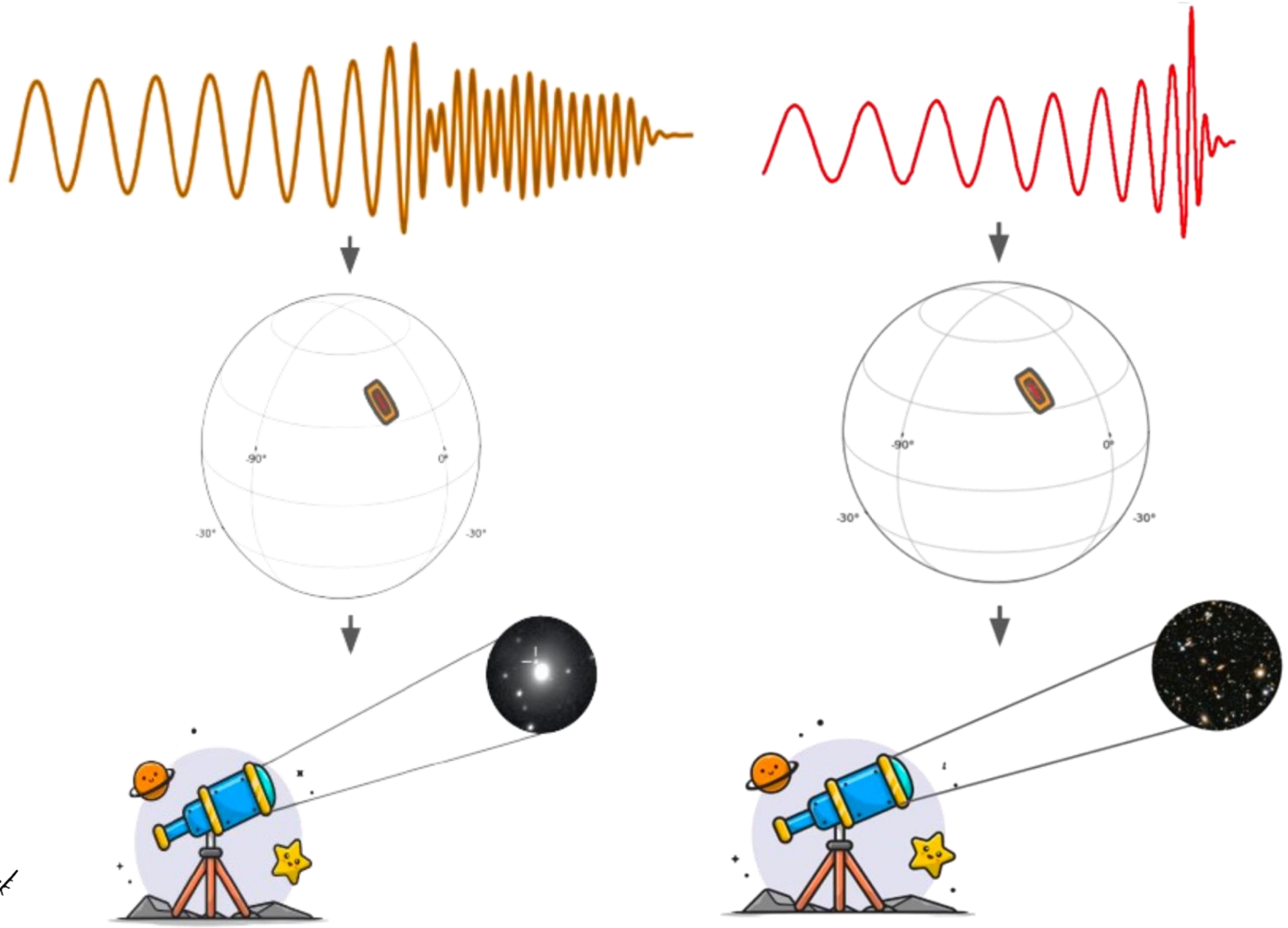
Gravitational waves can provide an independent measure of H_0 and resolve the Hubble tension.

Gravitational-wave sirens

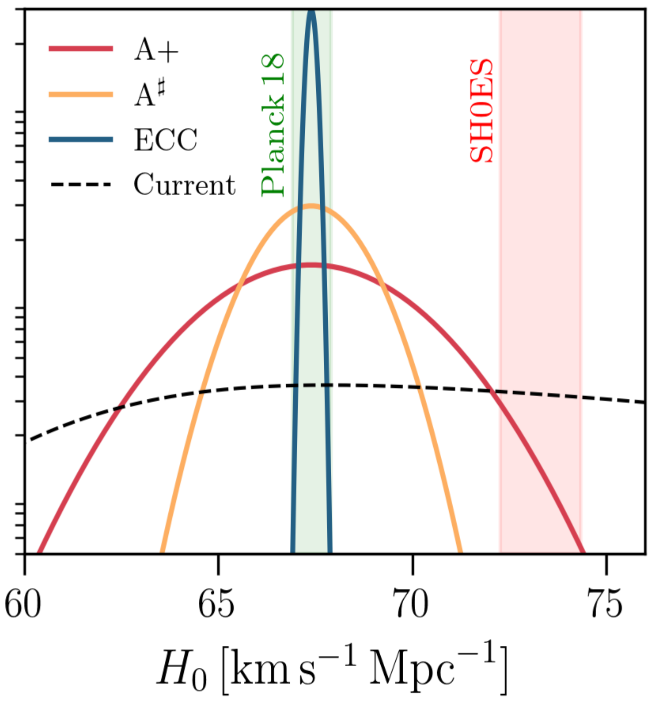
Dark sirens



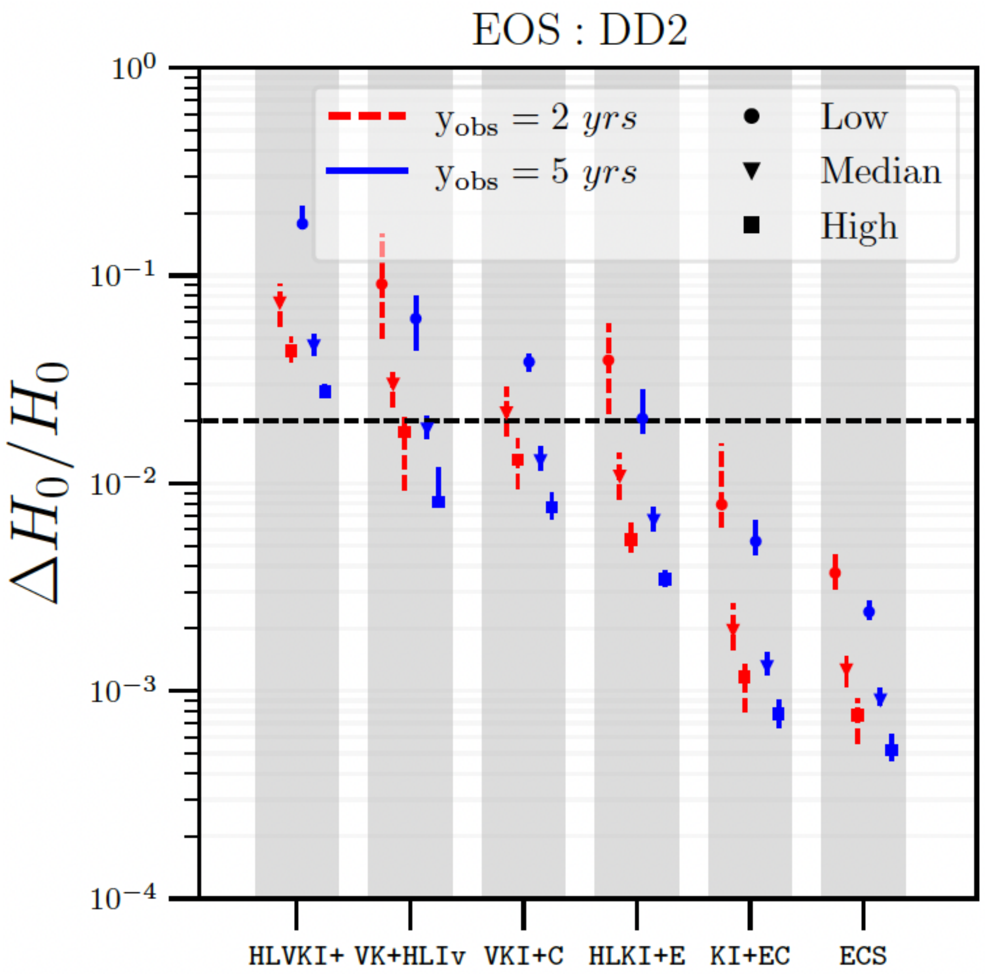
Bright sirens



Resolving the Hubble tension

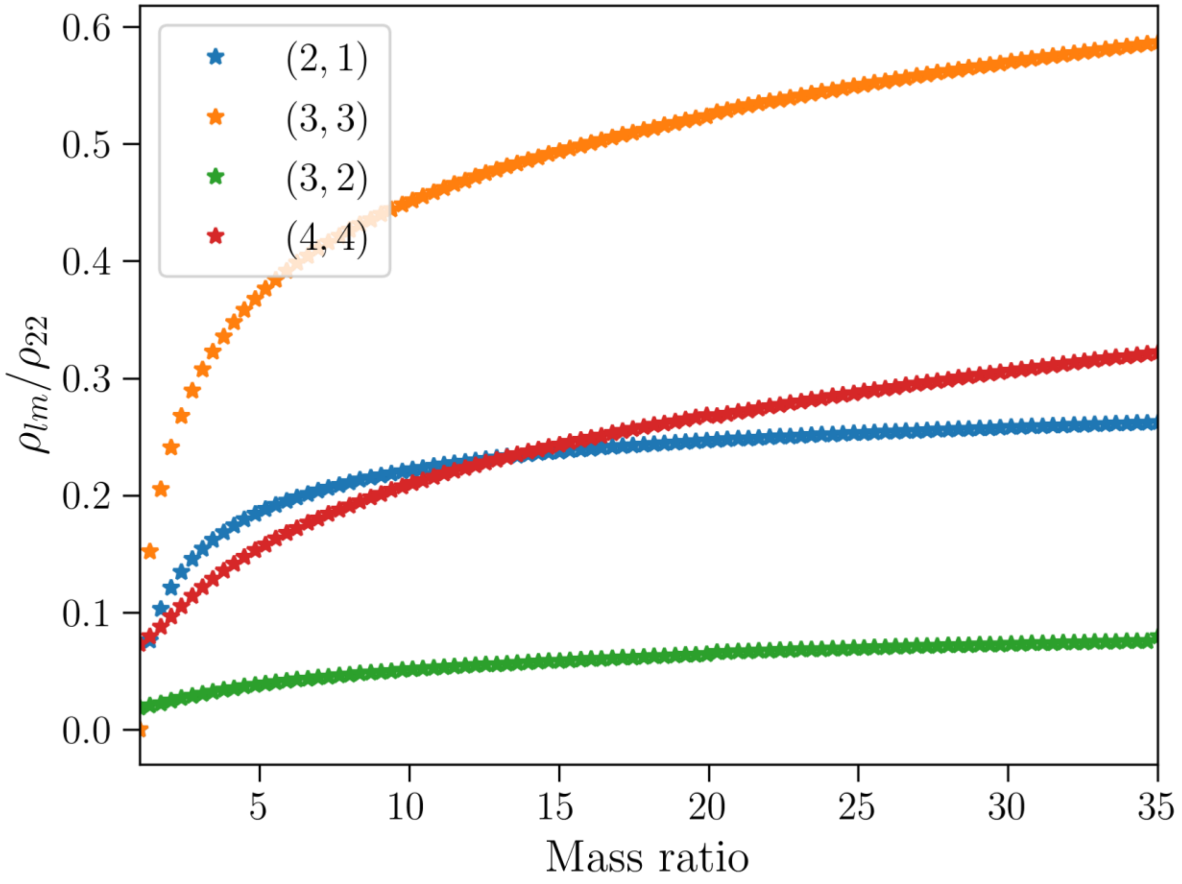


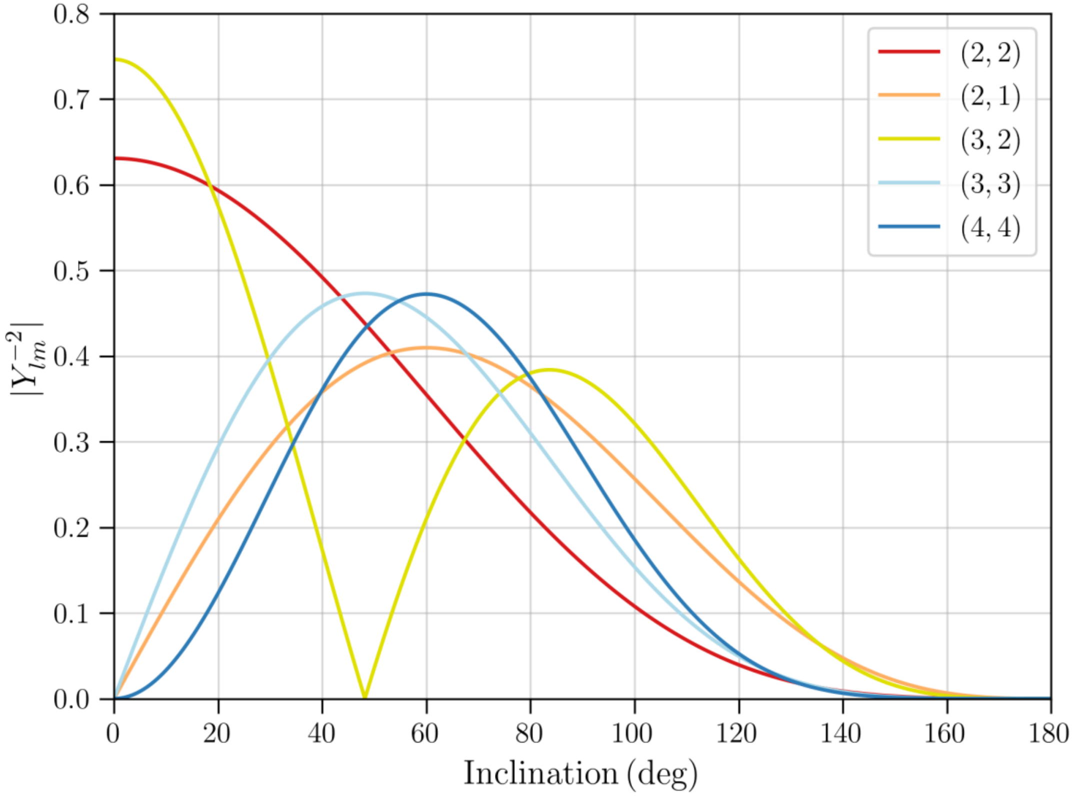
Neutron star-black hole mergers make excellent cosmological probes.



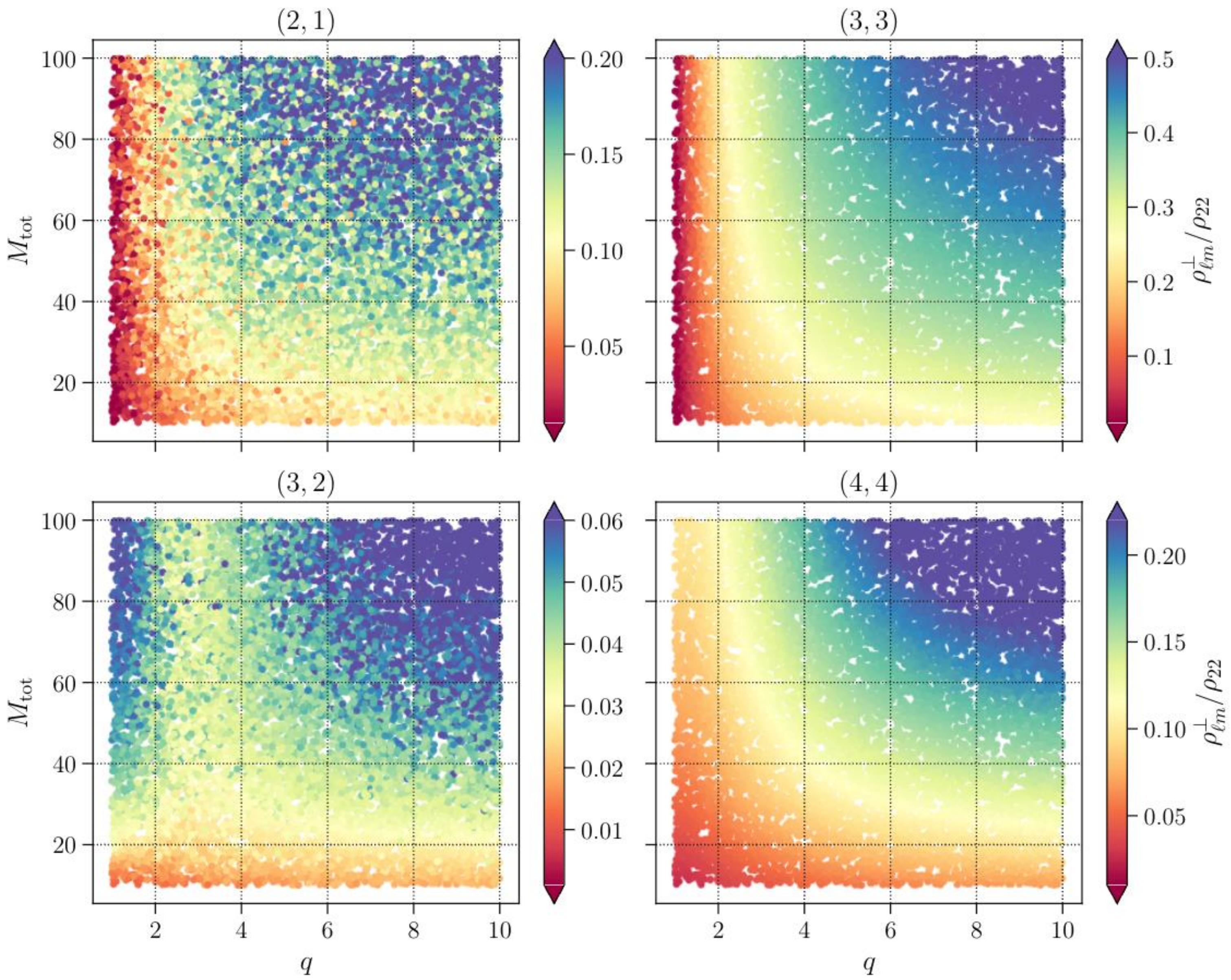
Gupta, MNRAS 524, 2023

Higher order modes

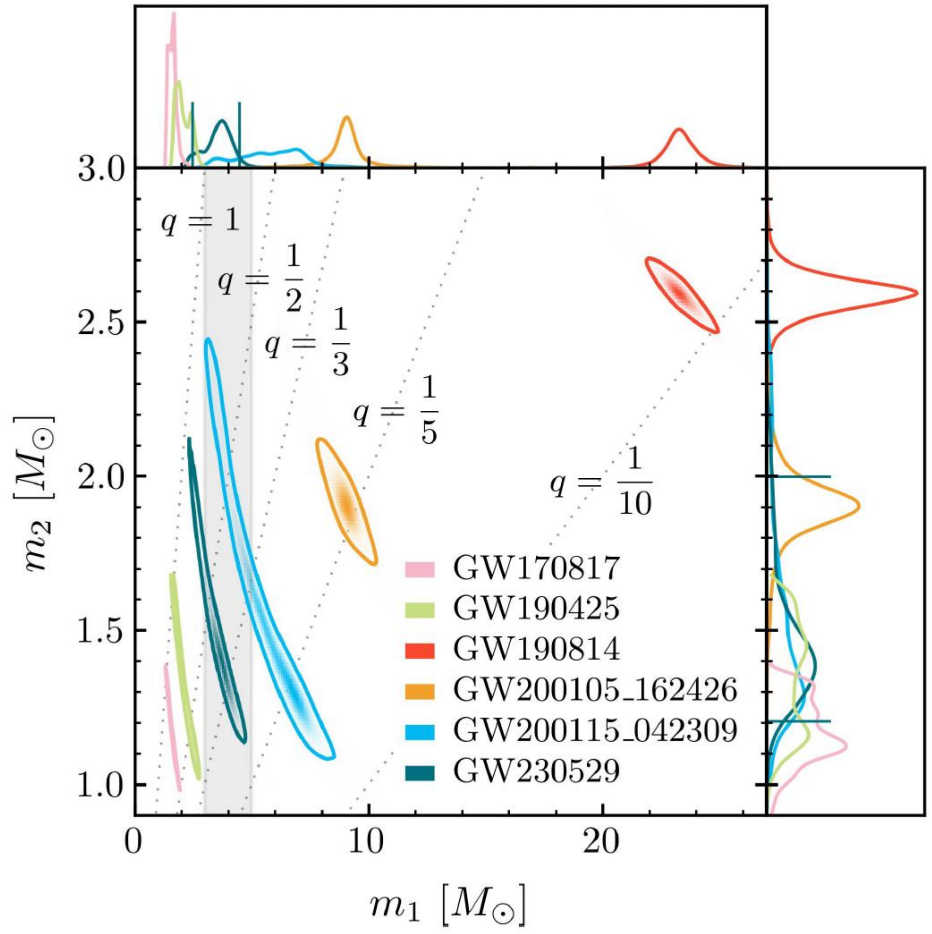


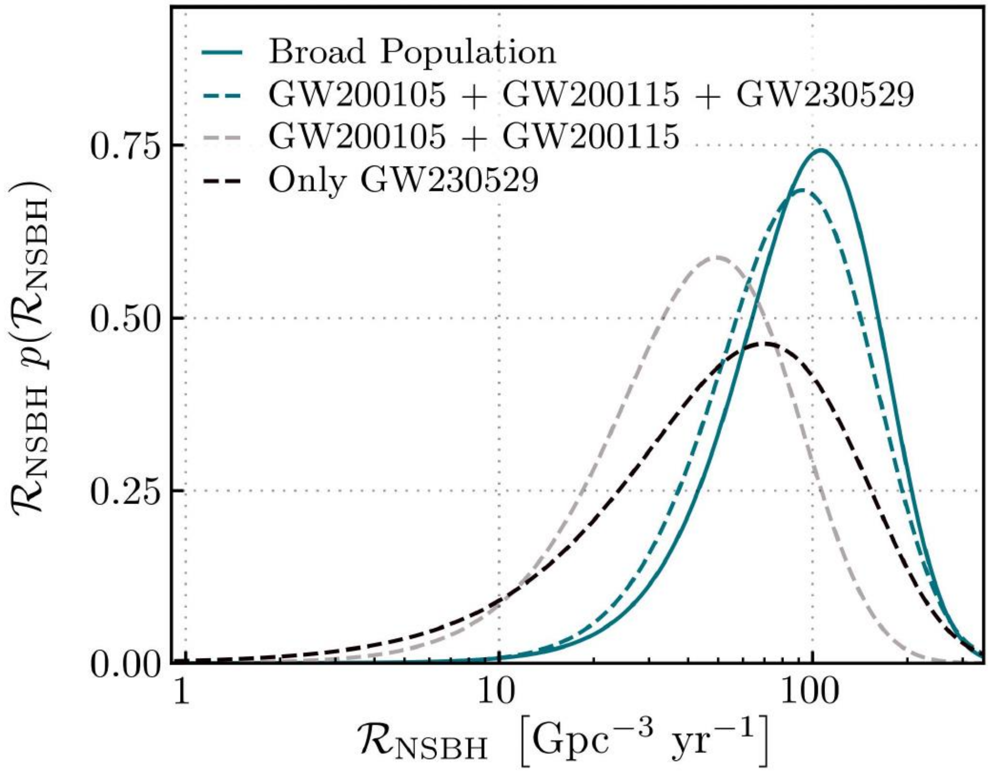


Higher order modes



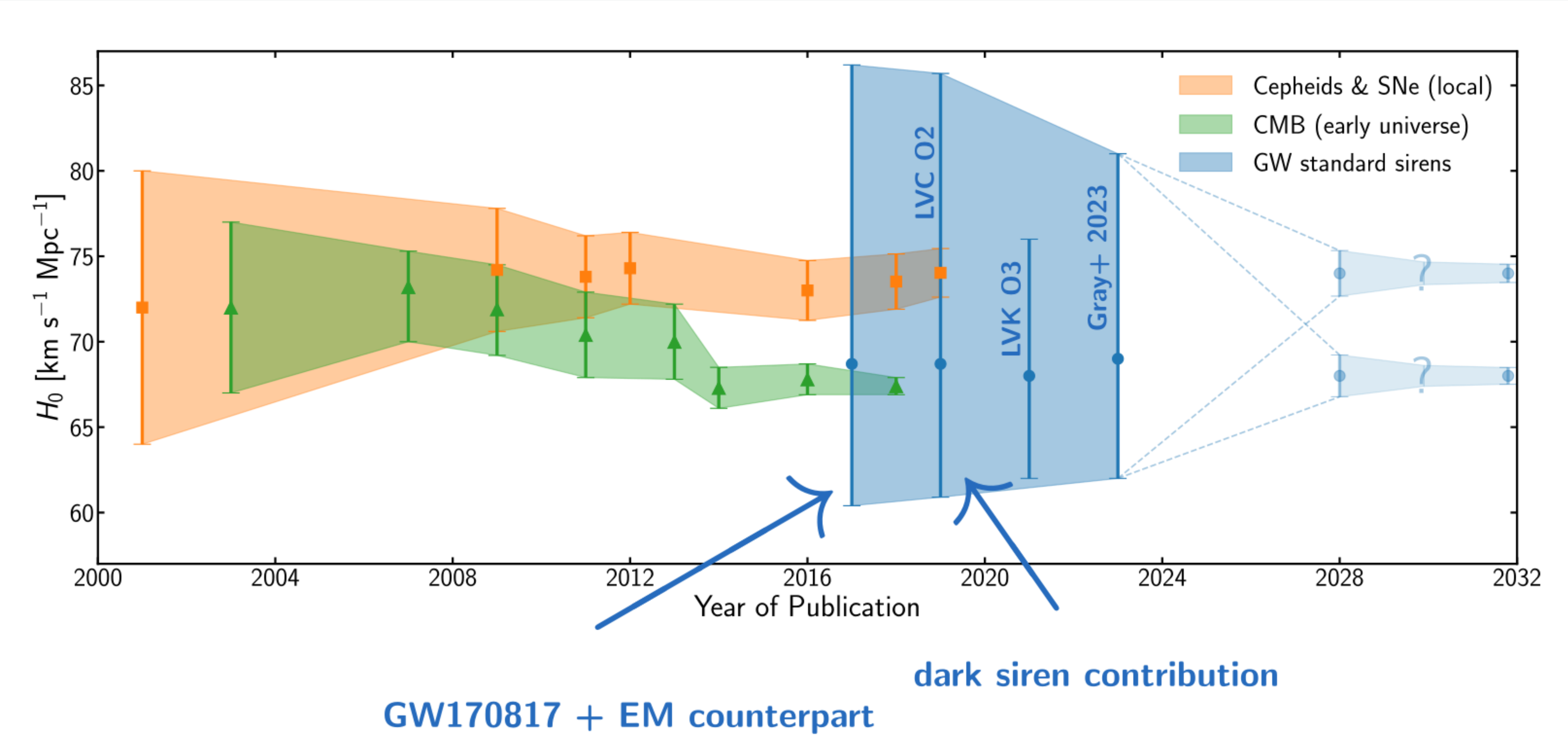
Observed NSBH population





Abbott+, *arXiv:2404.04248 (2024)*

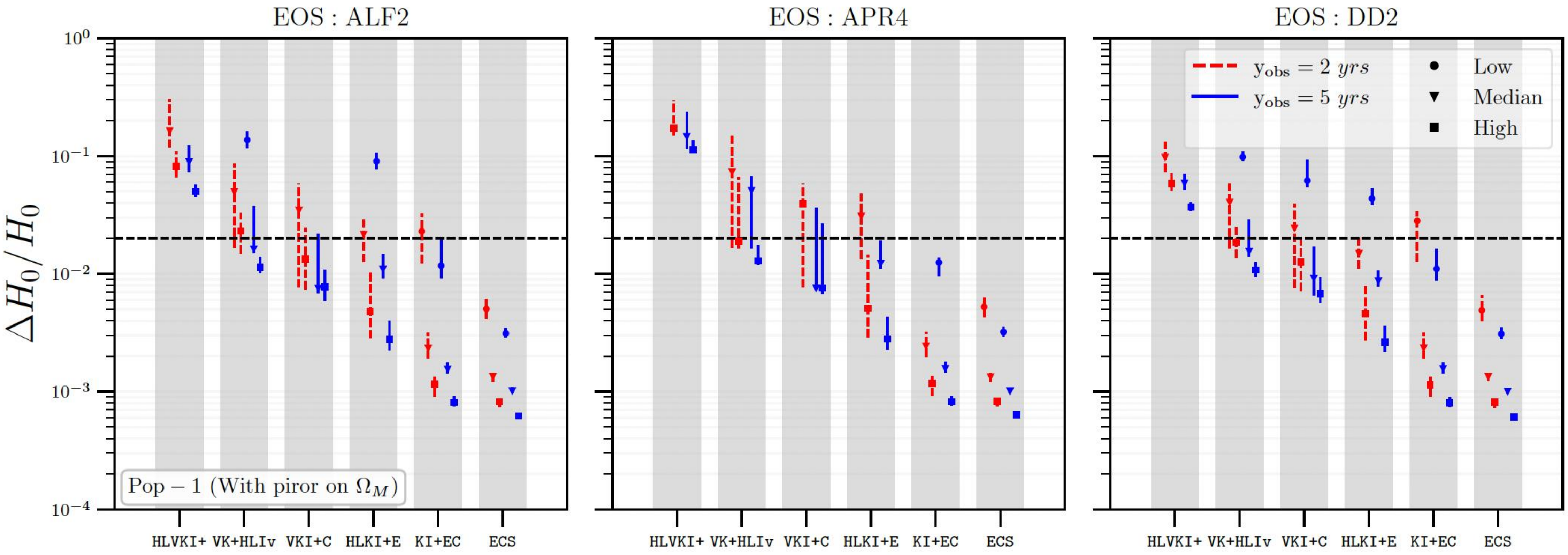
Gravitational-wave sirens



Bright sirens

Current constraints on the Hubble constant with gravitational sirens.

Resolving the Hubble tension



Neutron star spin measurements

Mode	Leading order spin terms
$(2,1)$	$\frac{4i}{R}\sqrt{\frac{\pi}{5}}\,\eta M\,\tilde{\chi}$
$(2,2)$	$\frac{32}{3R}\sqrt{\frac{\pi}{5}}\,\eta M\,(\chi_{\rm eff} - \eta\chi_s)$
$(3,2)$	$\frac{32}{3R}\sqrt{\frac{\pi}{7}}\,\eta^2 M\,\chi_s$
$(3,3)$	$\frac{3i}{2R}\sqrt{\frac{6\pi}{7}}\,\eta M\,((4-5\eta)\tilde{\chi} - 14\eta\chi_a)$
$(4,4)$	$\frac{256}{9R}\sqrt{\frac{\pi}{7}}\,\eta M\left[\left(-\frac{2}{3}+\frac{13}{5}\eta\right)\chi_{\rm eff} + \frac{2\eta}{5}\left(\frac{1}{3}-7\eta\right)\chi_s\right]$

Positive spin combinations

$$\chi_{\rm eff} = \frac{\chi_1 + q\,\chi_2}{1+q}$$

$$\chi_s = \frac{\chi_1 + \chi_2}{2}$$

Neutron star spin measurements

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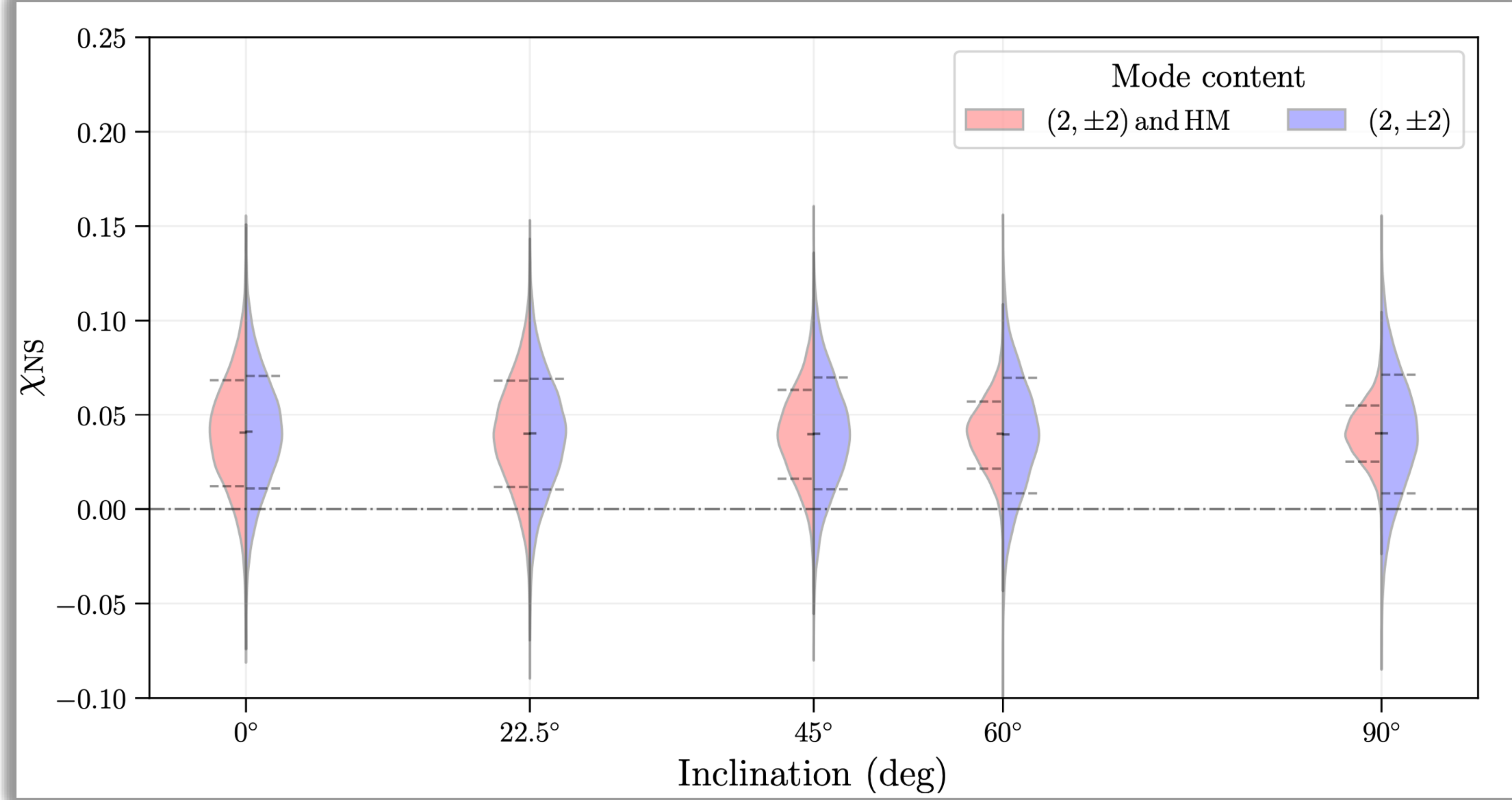
Negative spin combinations

$$\tilde{\chi} = \frac{\chi_1 - q\,\chi_2}{1+q}$$

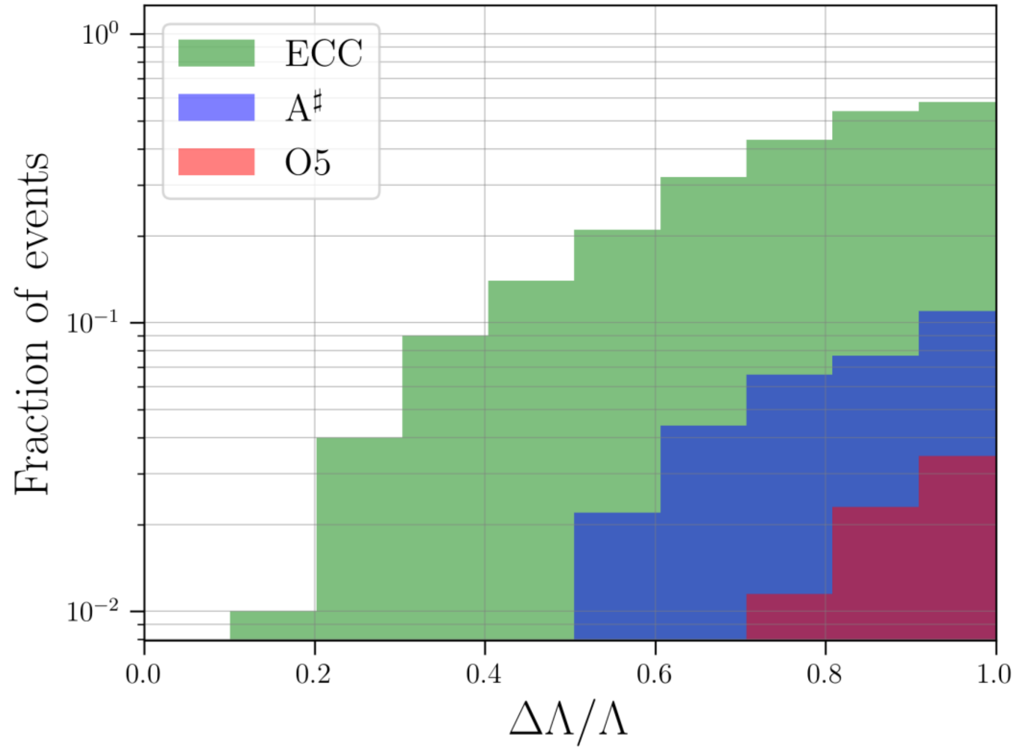
$$\chi_a = \frac{\chi_1 - \chi_2}{2}$$

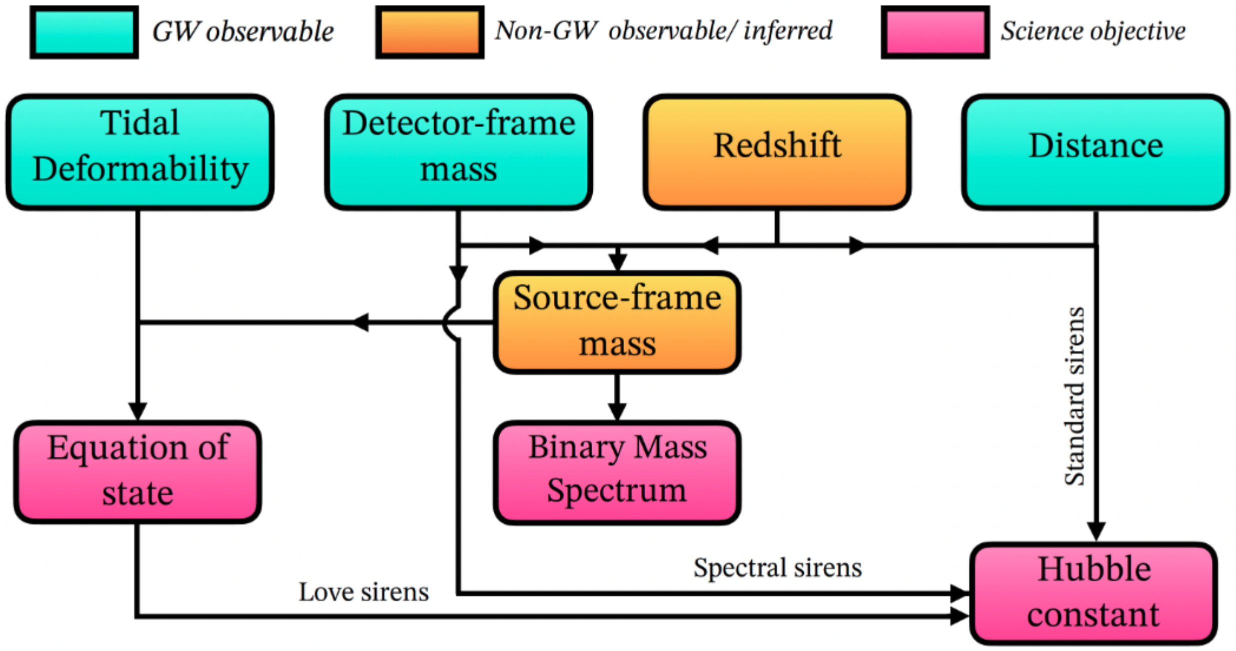
Neutron star spin measurements



Comprehensive utilization of neutron star-black hole mergers

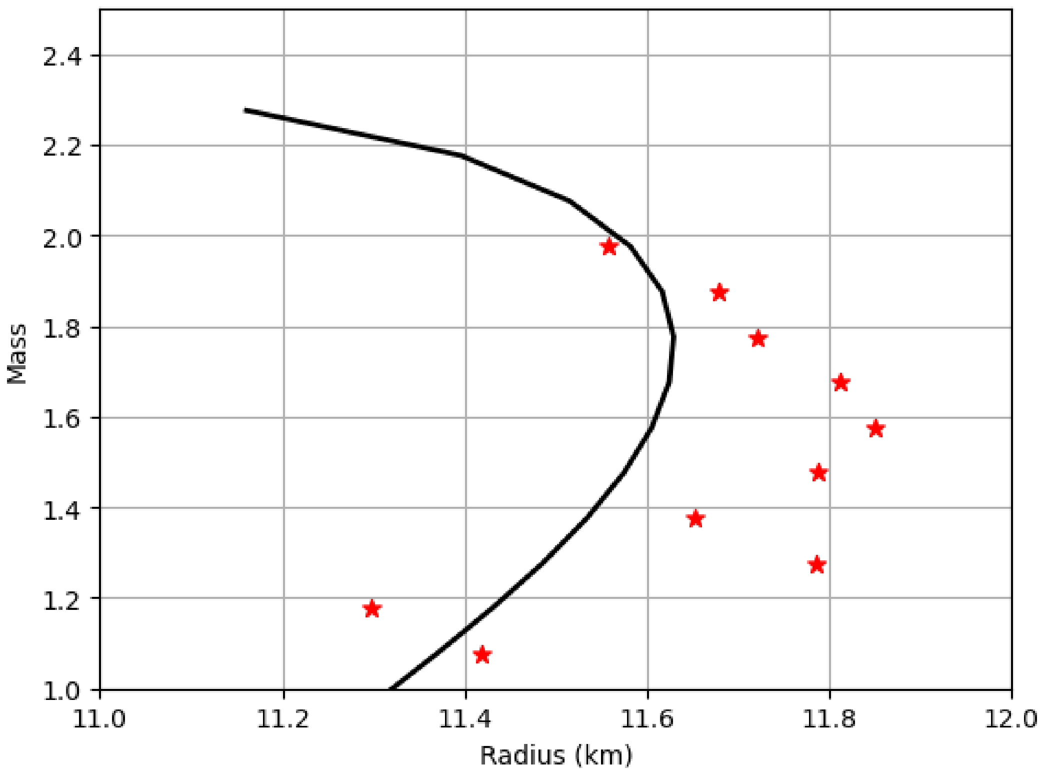
Build an infrastructure that jointly infers the binary mass spectrum, the equation of state, and the Hubble constant.

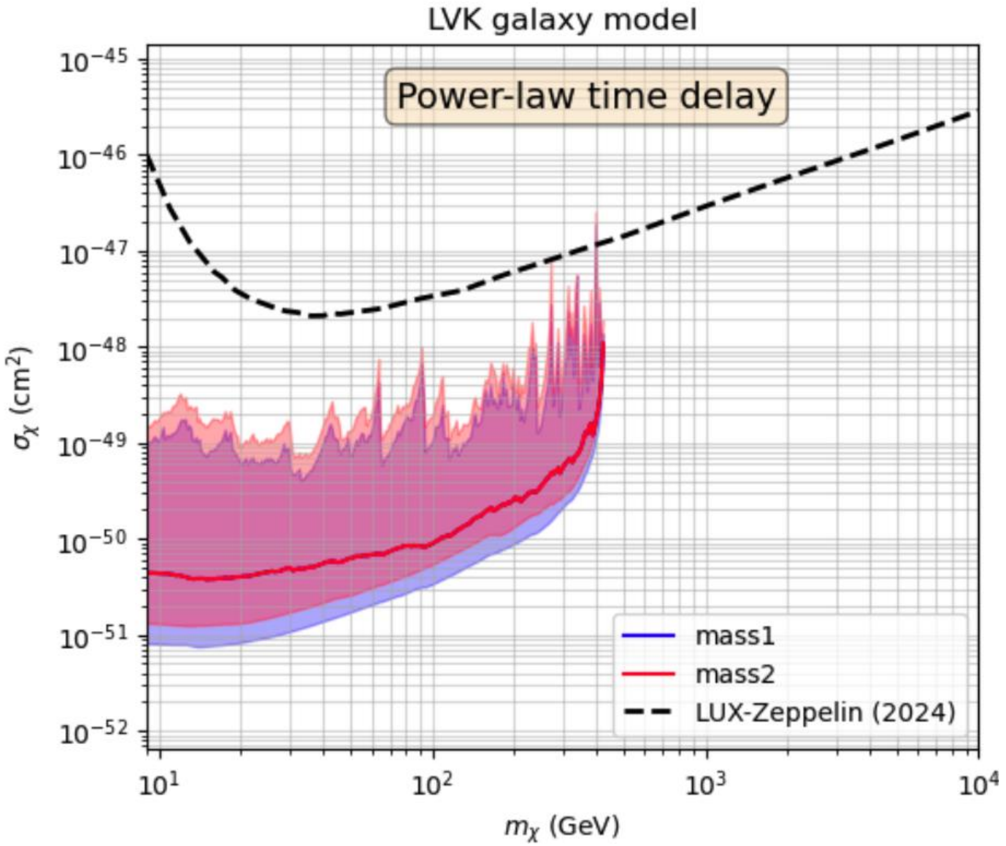




Neutron stars as dark matter detectors

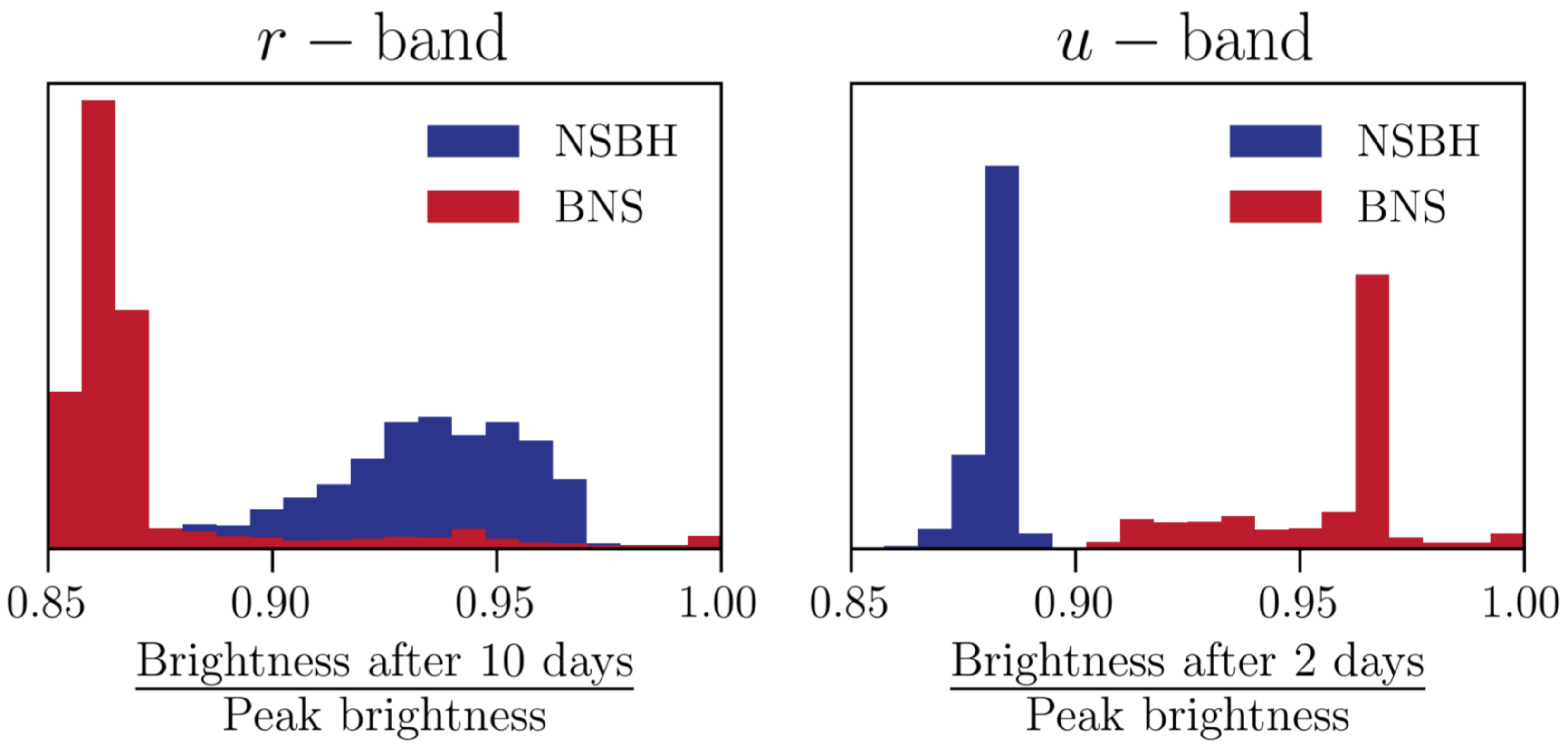
Model realistic levels of dark matter contamination in neutron stars and apply Bayesian model selection.





The origins of observed kilonovae

Develop a formalism to distinguish between kilonovae from binary neutron stars and neutron star-black hole mergers.

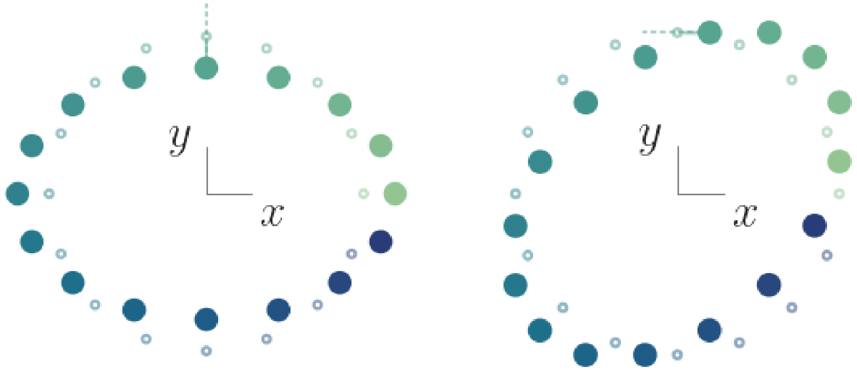


Gravitational waves

$$h_{ij} = \frac{2G}{c^4}\frac{1}{d}\frac{d^2Q_{ij}}{dt^2}$$

$$|h_{ij}| = \frac{\Delta L}{L}$$

$$\approx 10^{-22}\left(\frac{100\ \mathrm{Mpc}}{d}\right)\left(\frac{M}{1\,\mathrm{M}_\odot}\right)^{5/3}\left(\frac{\omega}{100\ \mathrm{Hz}}\right)^{2/3}$$

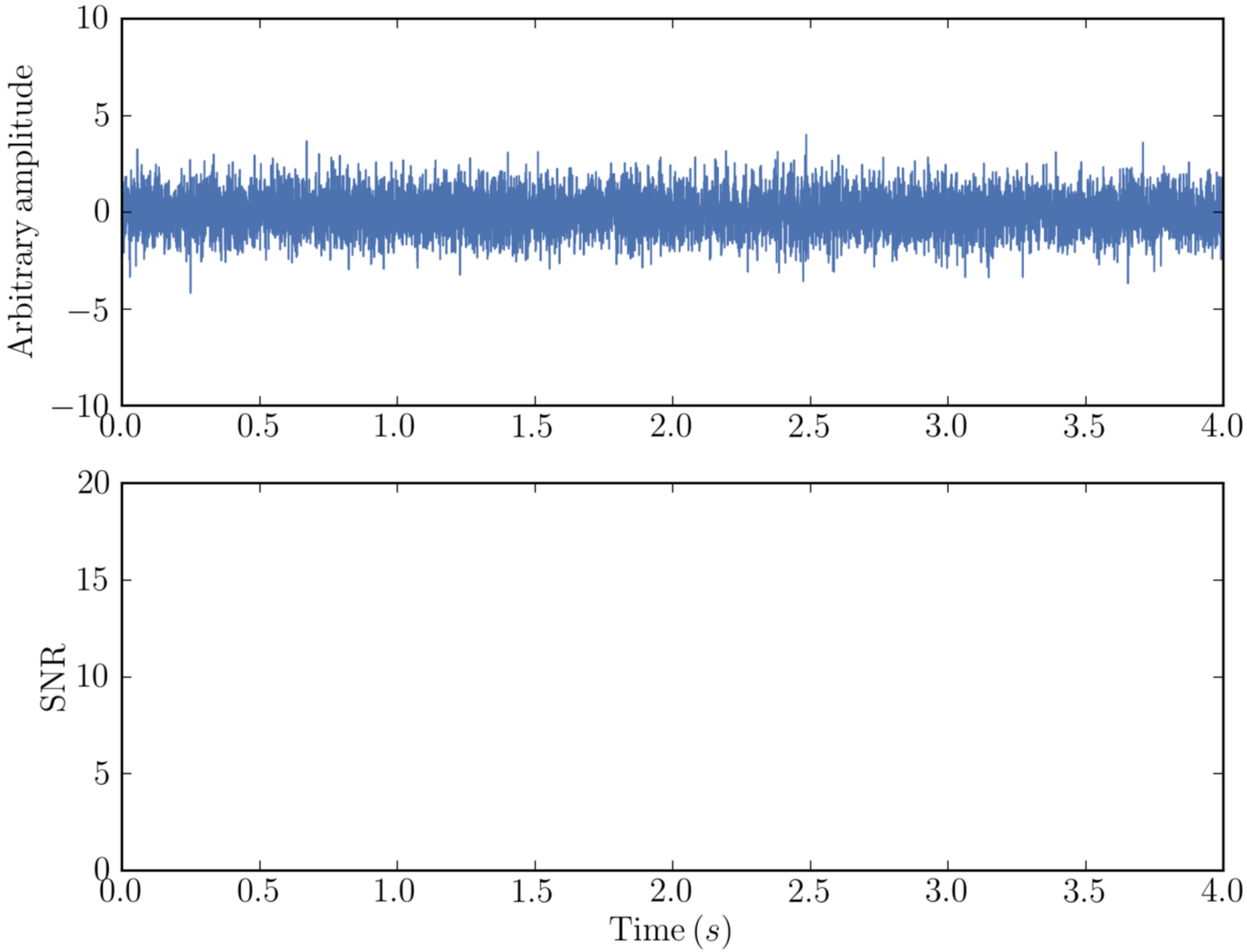


Credit: Max Isi

Credit: SXS

Credit: AAS NOVA

Detecting gravitational waves



Credit: Ryan Magee