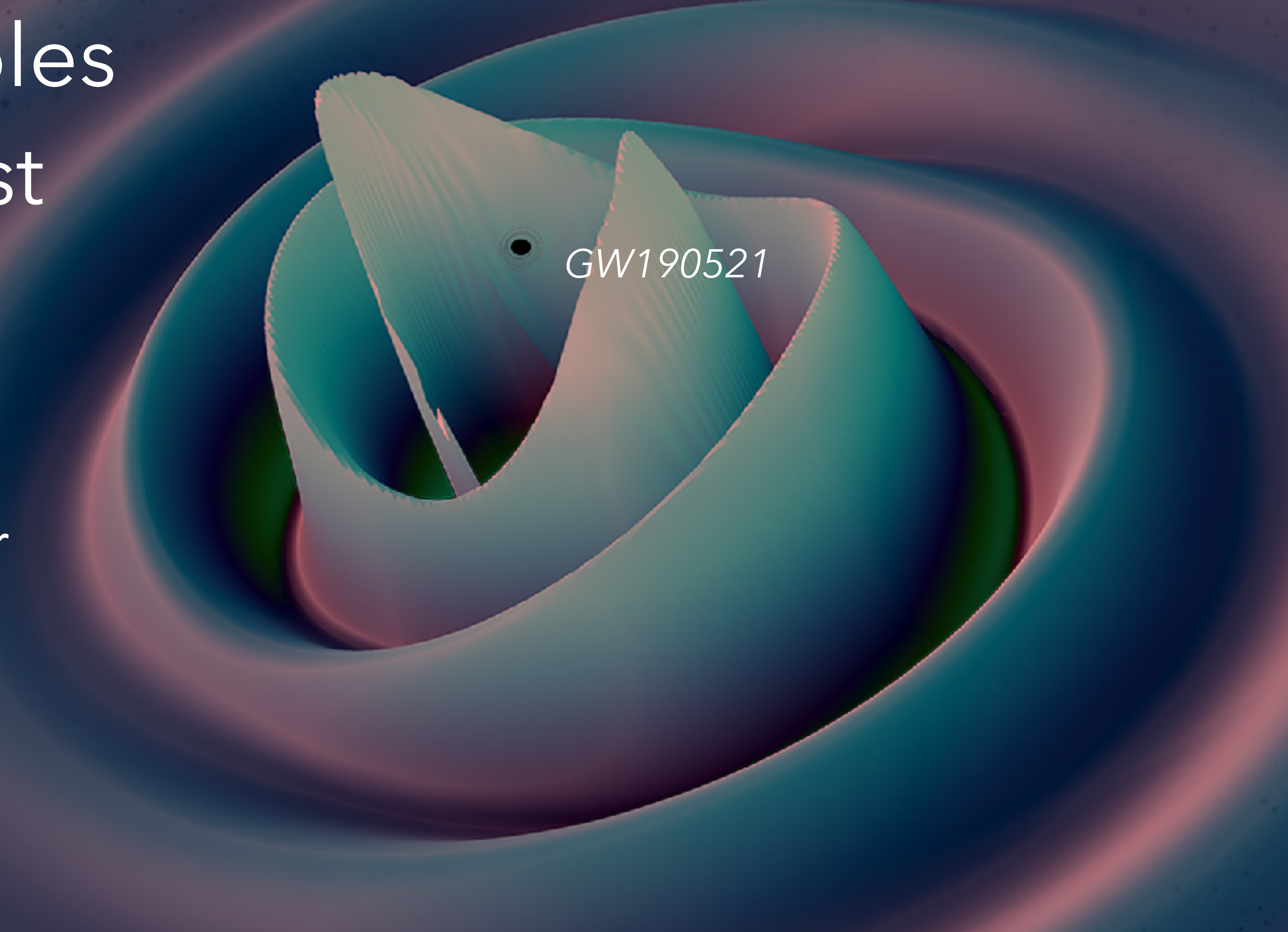
Discovery of Black Holes that Should Not Exist



Fermilab, "Wine & Cheese" Seminar
October 23, 2020

Karan Jani
Vanderbilt | LIGO Collaboration
@astrokpj

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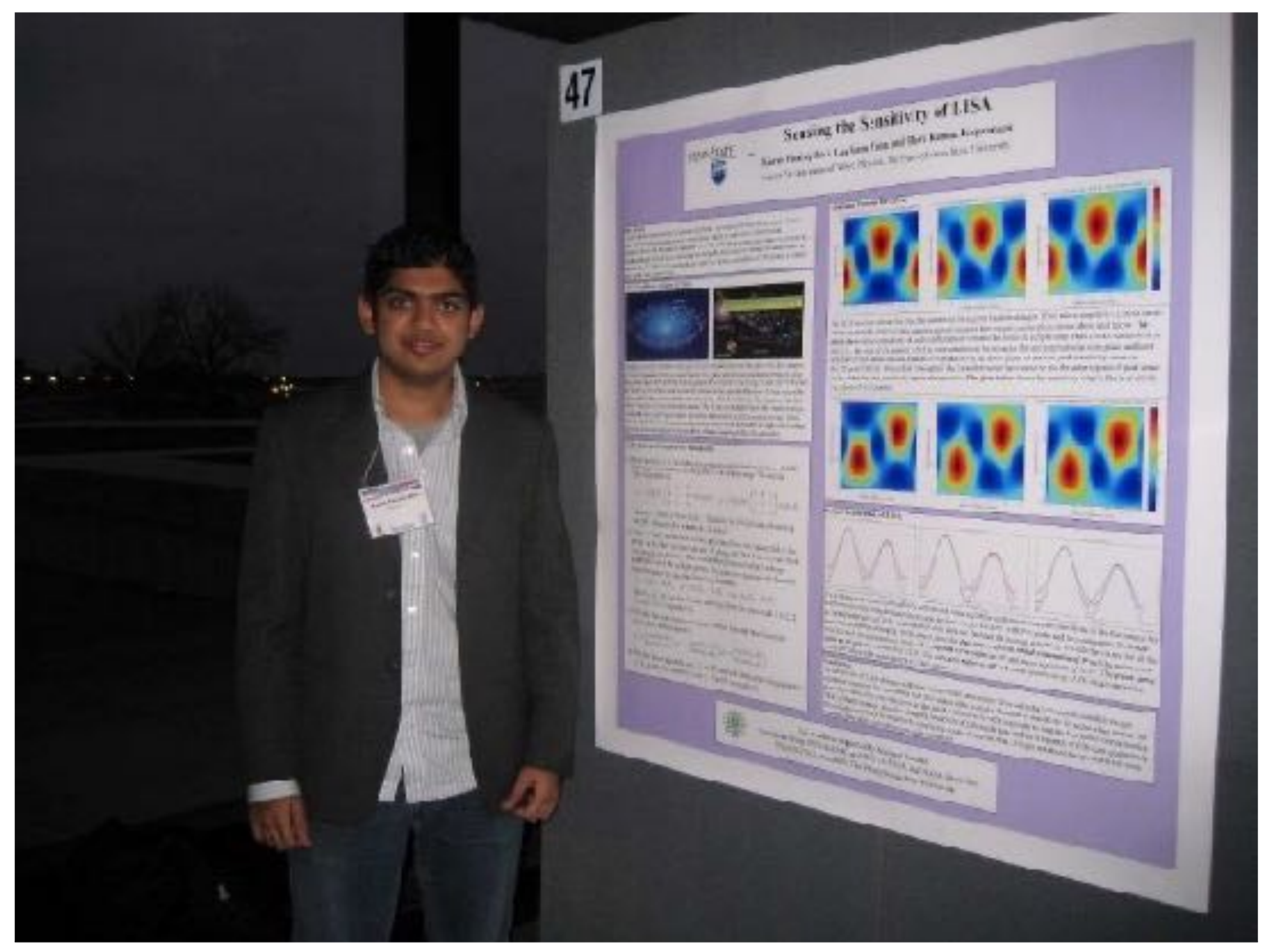


Fermilab, Sigma Pi Sigma Congress
November, 2008

Leon M. Lederman
Physics Nobel Laureate; Director Emeritus, Fermilab;
Pritzker Professor of Science, Illinois Institute of Technology; Resident Scholar, Illinois Mathematics and Science Academy

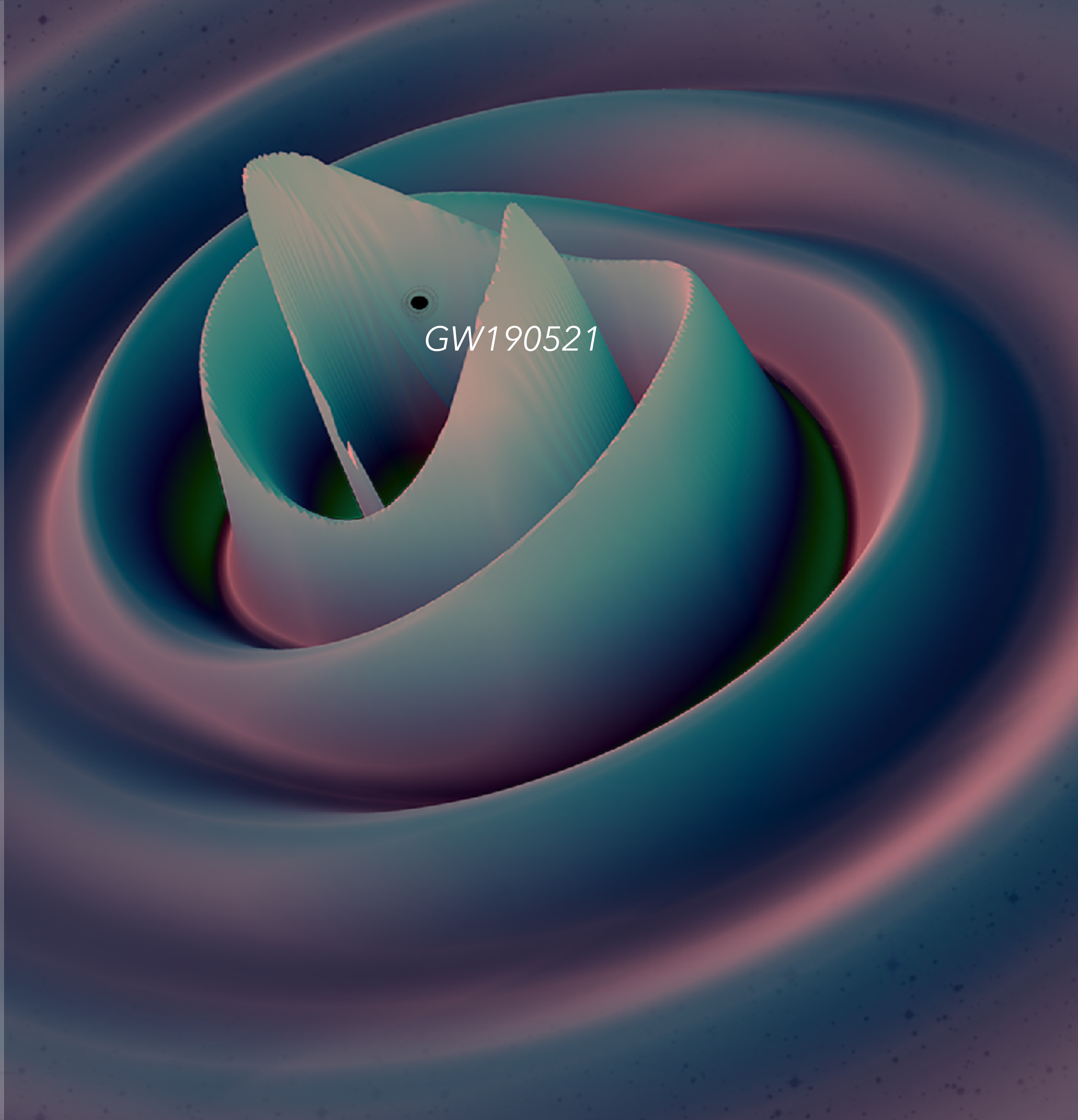
Plenary Lecture: What Presidents and Physicists Need to Know About Science

Abstract

As we plunge deeper into the 21st century, we find that our nation and our planet confronting an extraordinary number of challenges. Ticking off a few, we have global climate change, the complexity of globalization entwined with technological advances, the growing affluence of populations, and the simultaneous persistence of grinding poverty, a world-wide food problem as energy competes with agriculture. All of these have science and technology aspects as well as social, economic and political sides. My plan is to stress two features in the life of physicists: (1) the wonder and joy of doing physics and (2) the societal obligations of physicists.

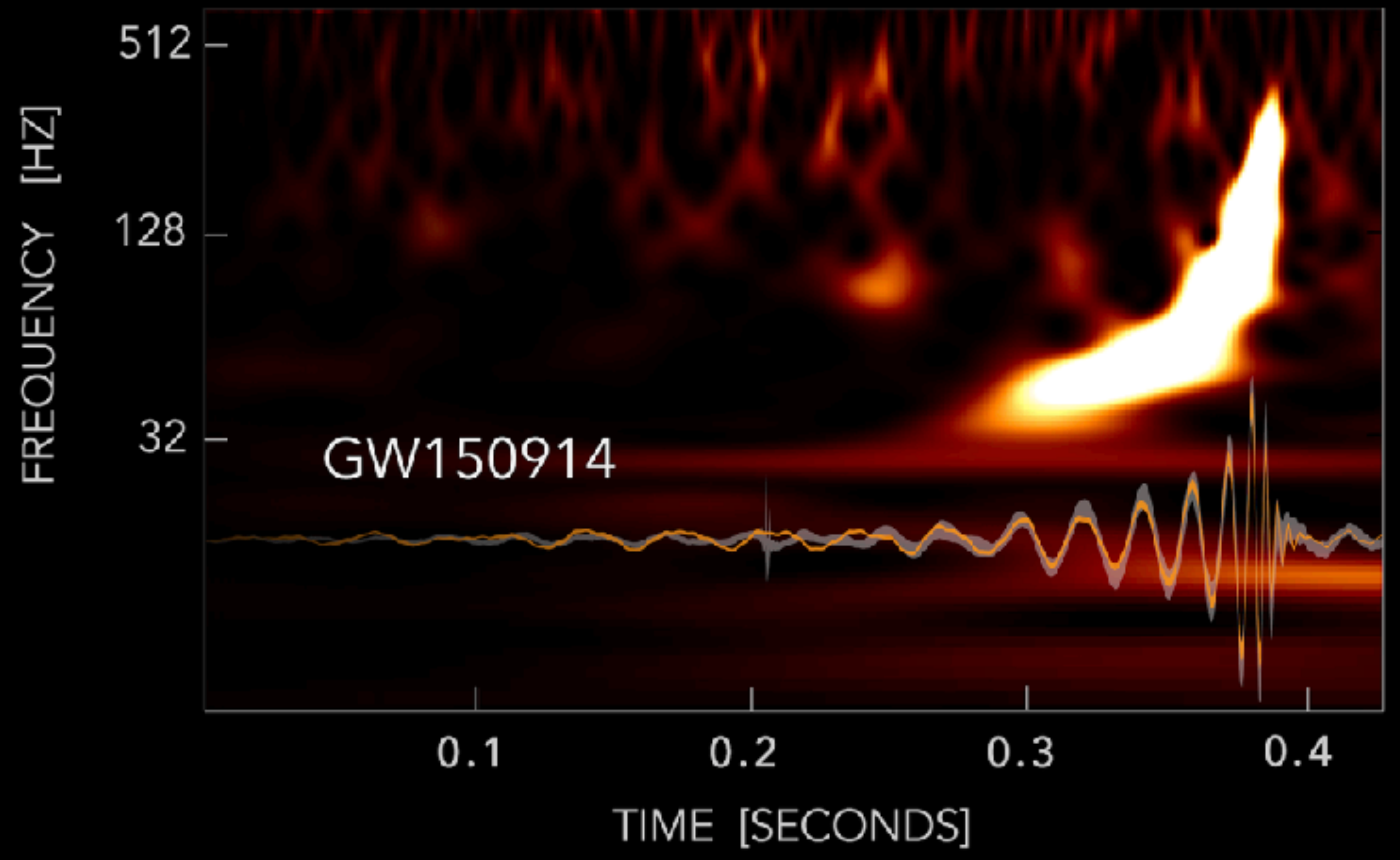
Outline

- What makes this discovery so unique?
- Implications to astrophysics & cosmology
- Science-case for next-gen. gravitational-wave (GW) experiments



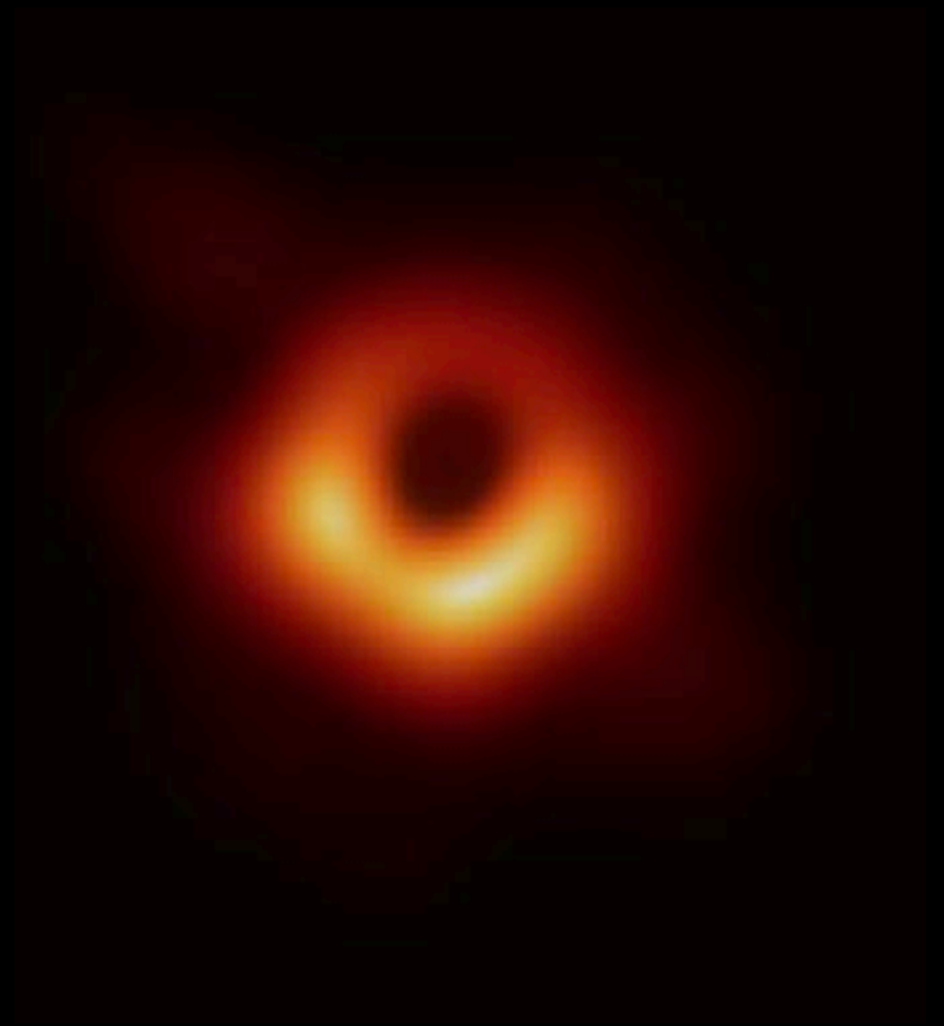
Measuring a Black Hole

LIGO-Virgo Collaboration



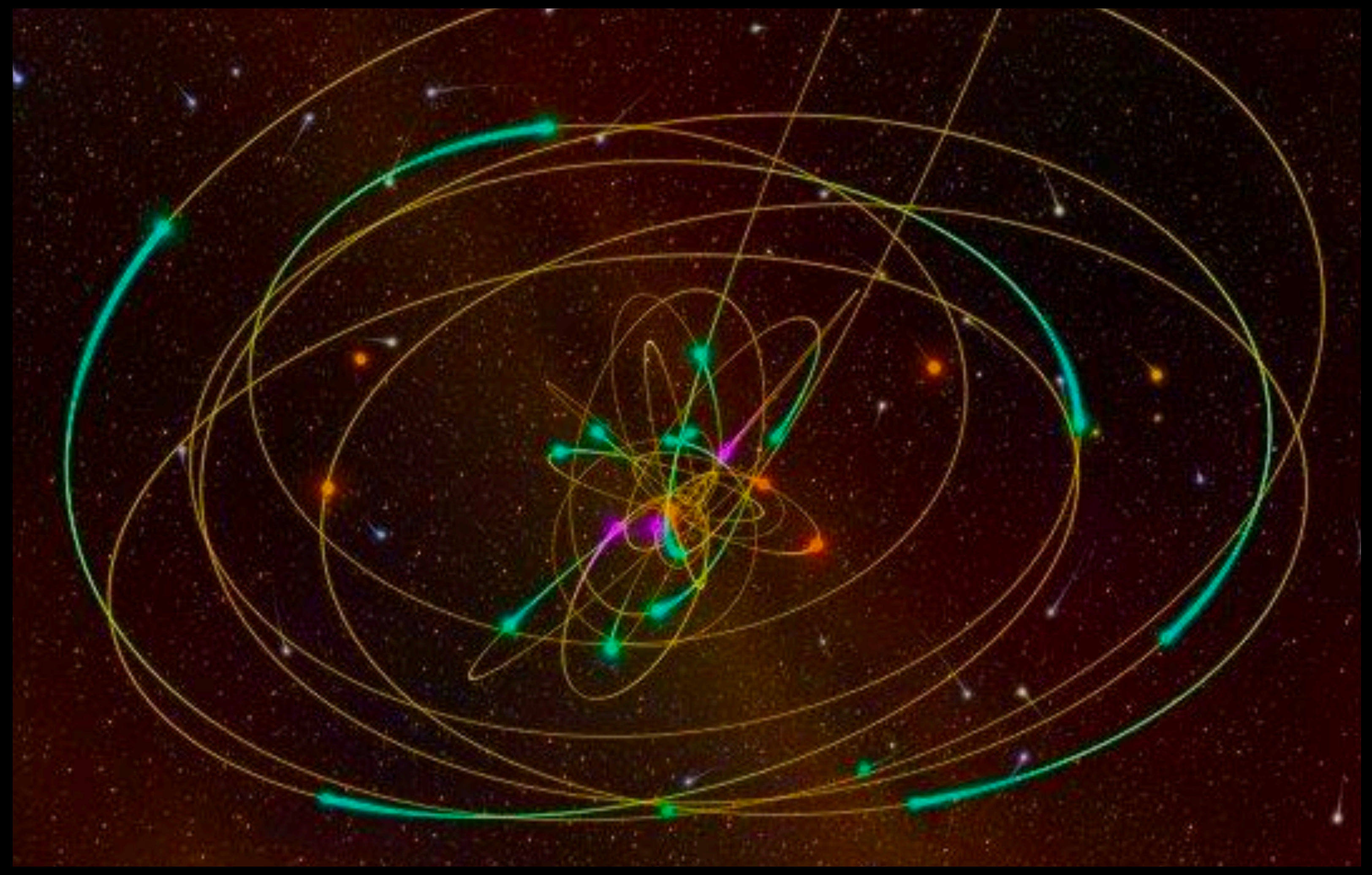
2017 - Nobel Prize

EHT Collaboration



2020- Breakthrough Prize

Ghez et al., Genzel et al.



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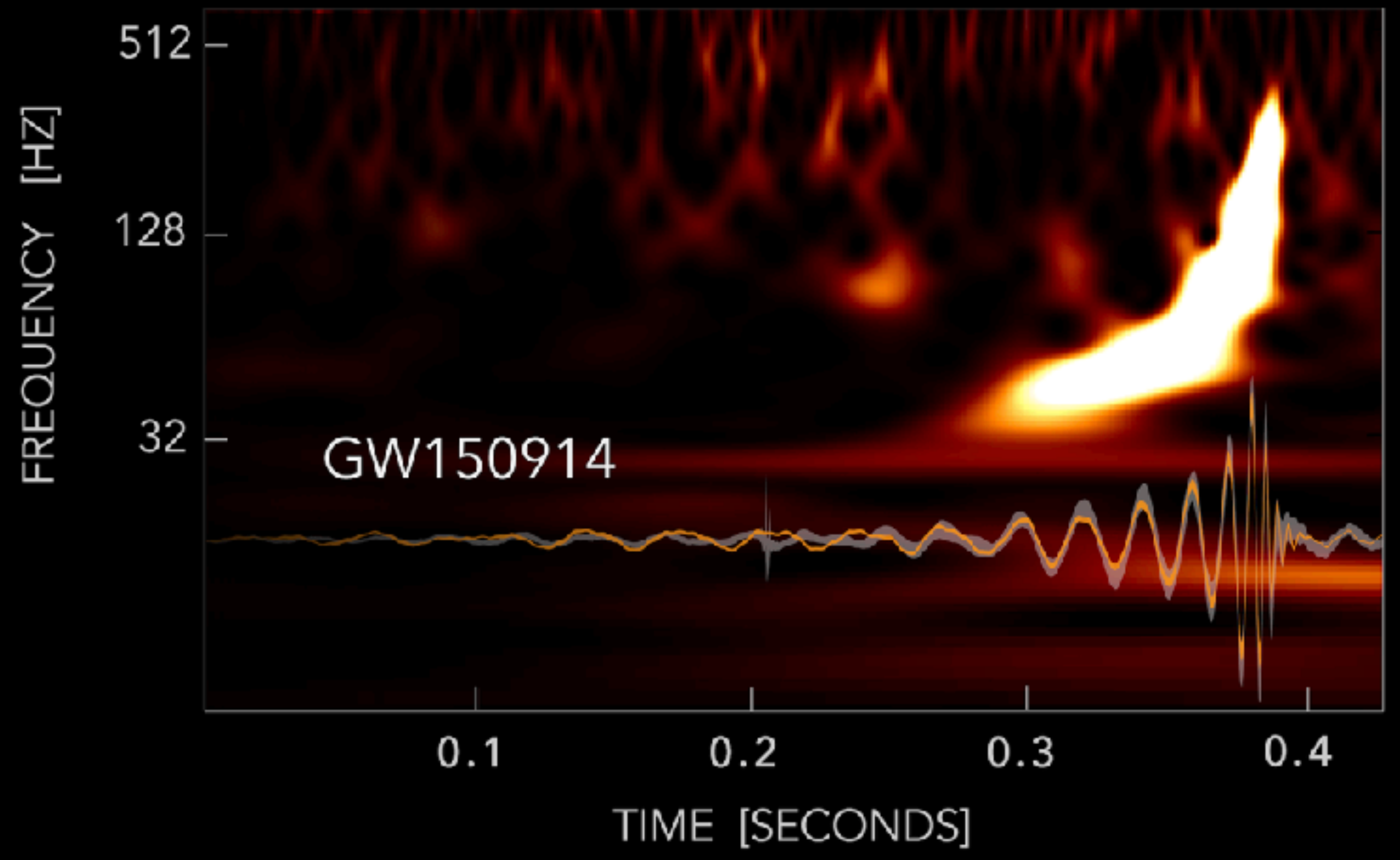
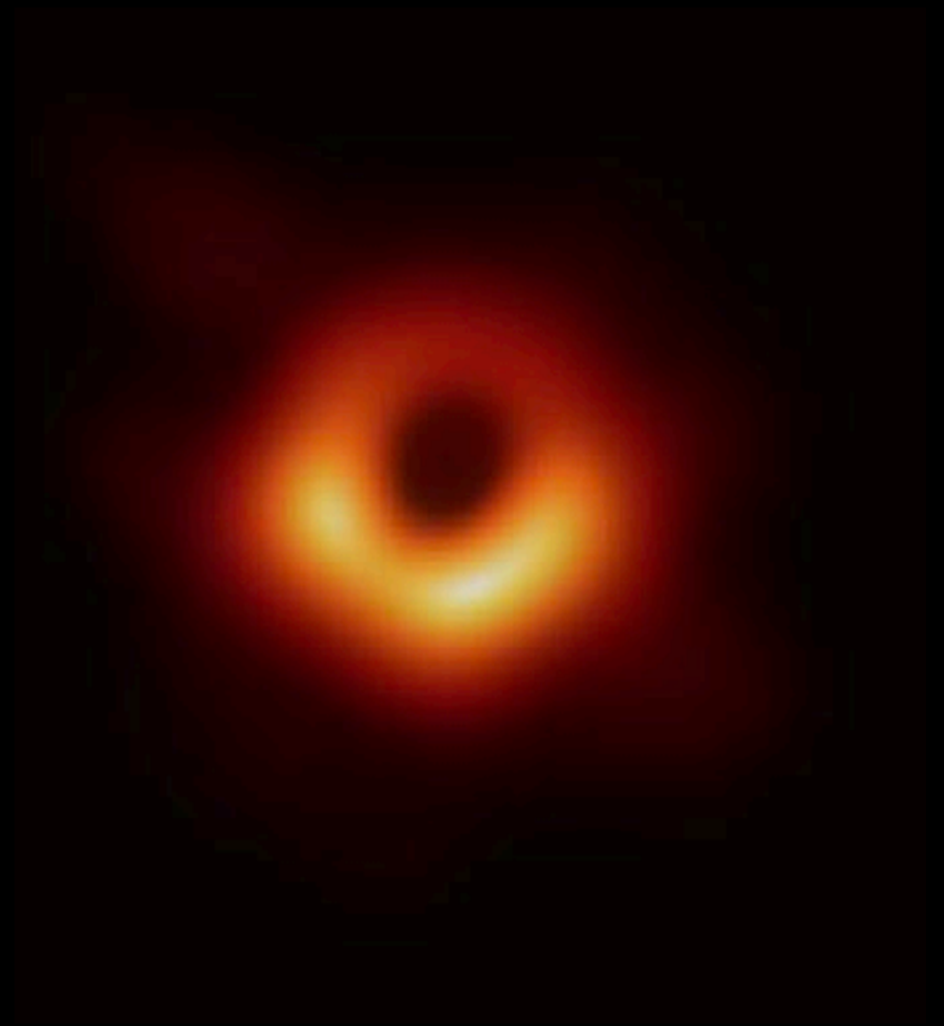
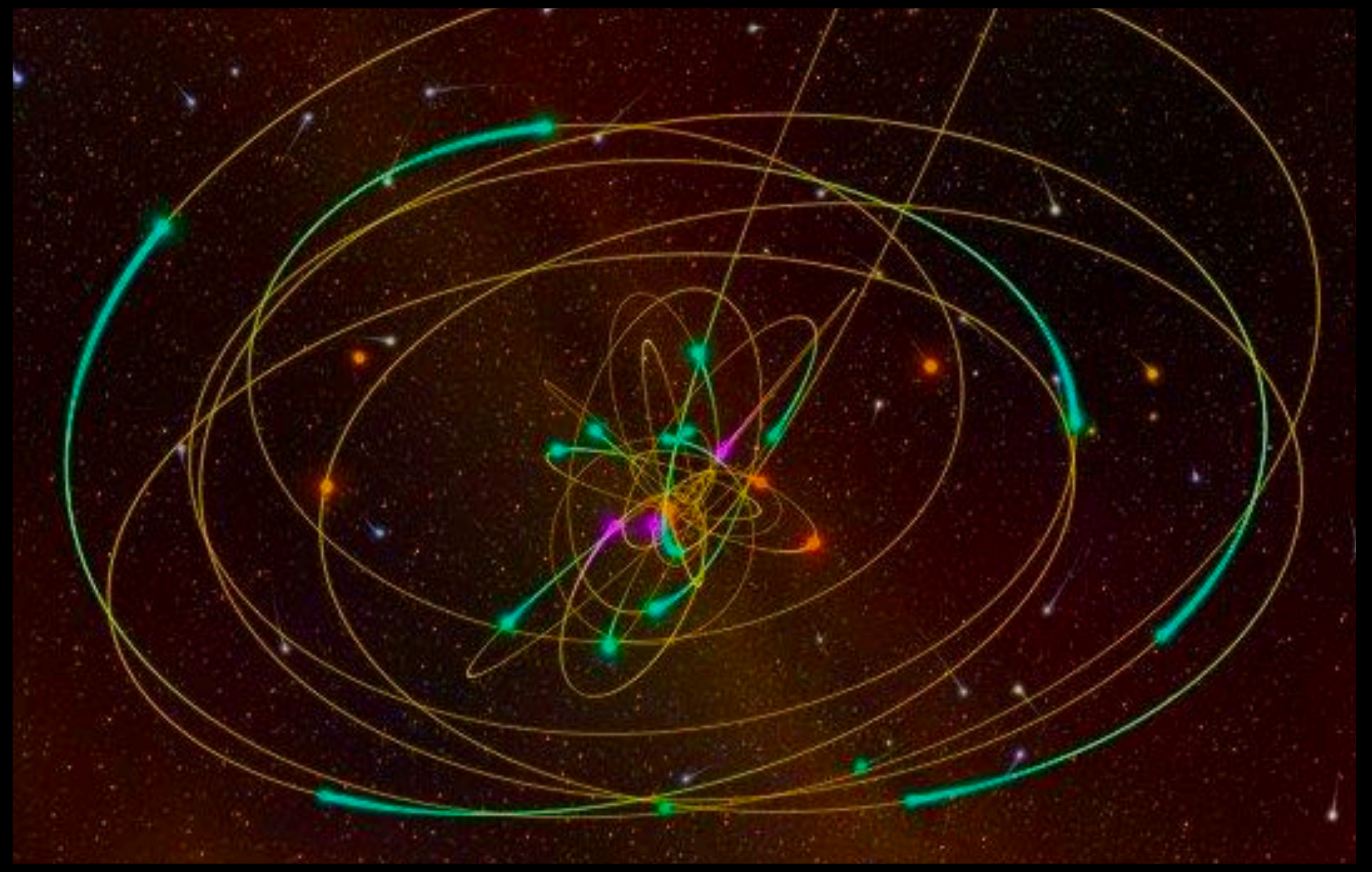


EHT Collaboration



Ghez et al., Genzel et al.



Direct

Indirect

(X-ray binaries)

GRAVITATIONAL-WAVE TRANSIENT CATALOG-1 (2015-2017)

KJ with LIGO-Virgo - Phys. Rev. X (2019)

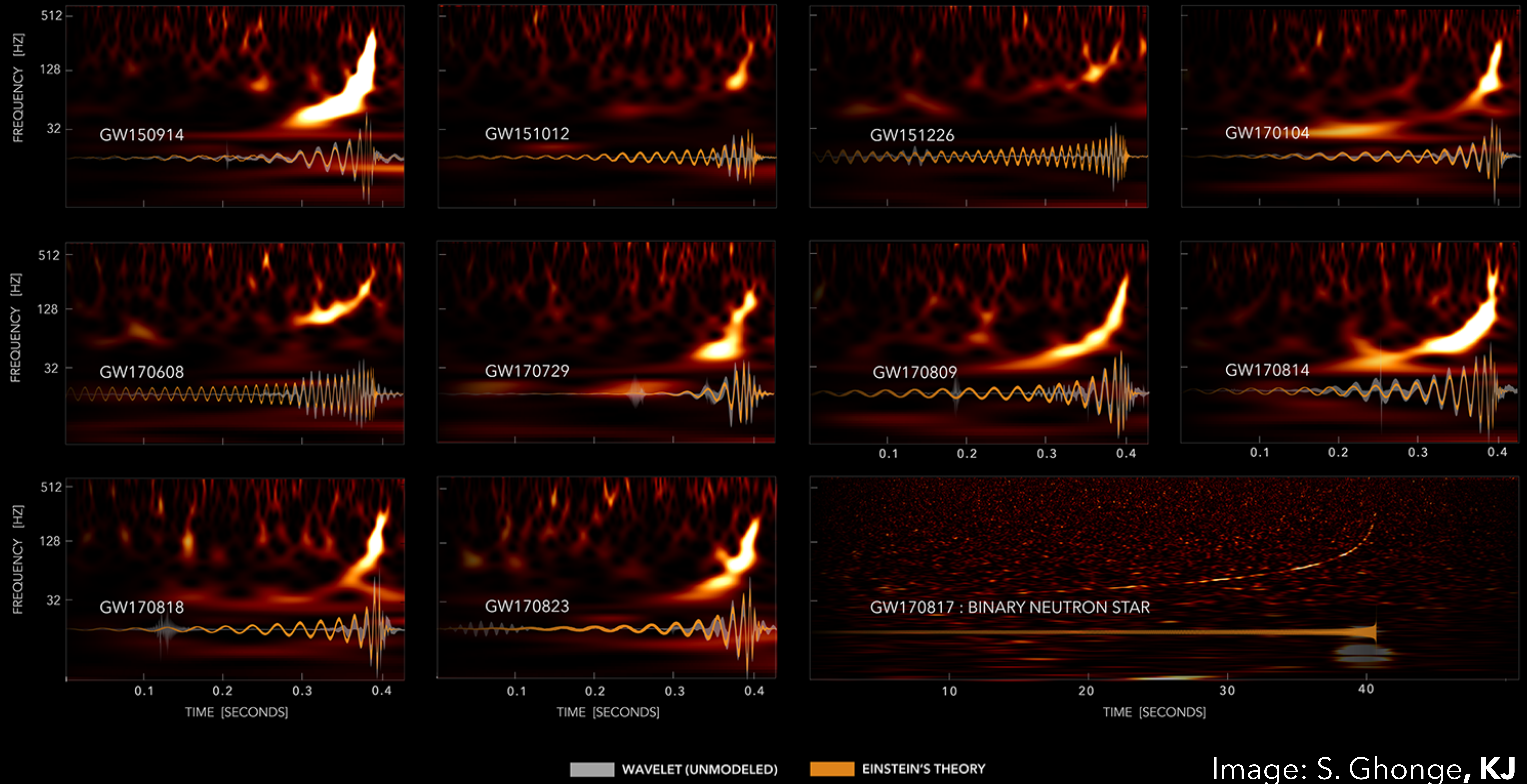
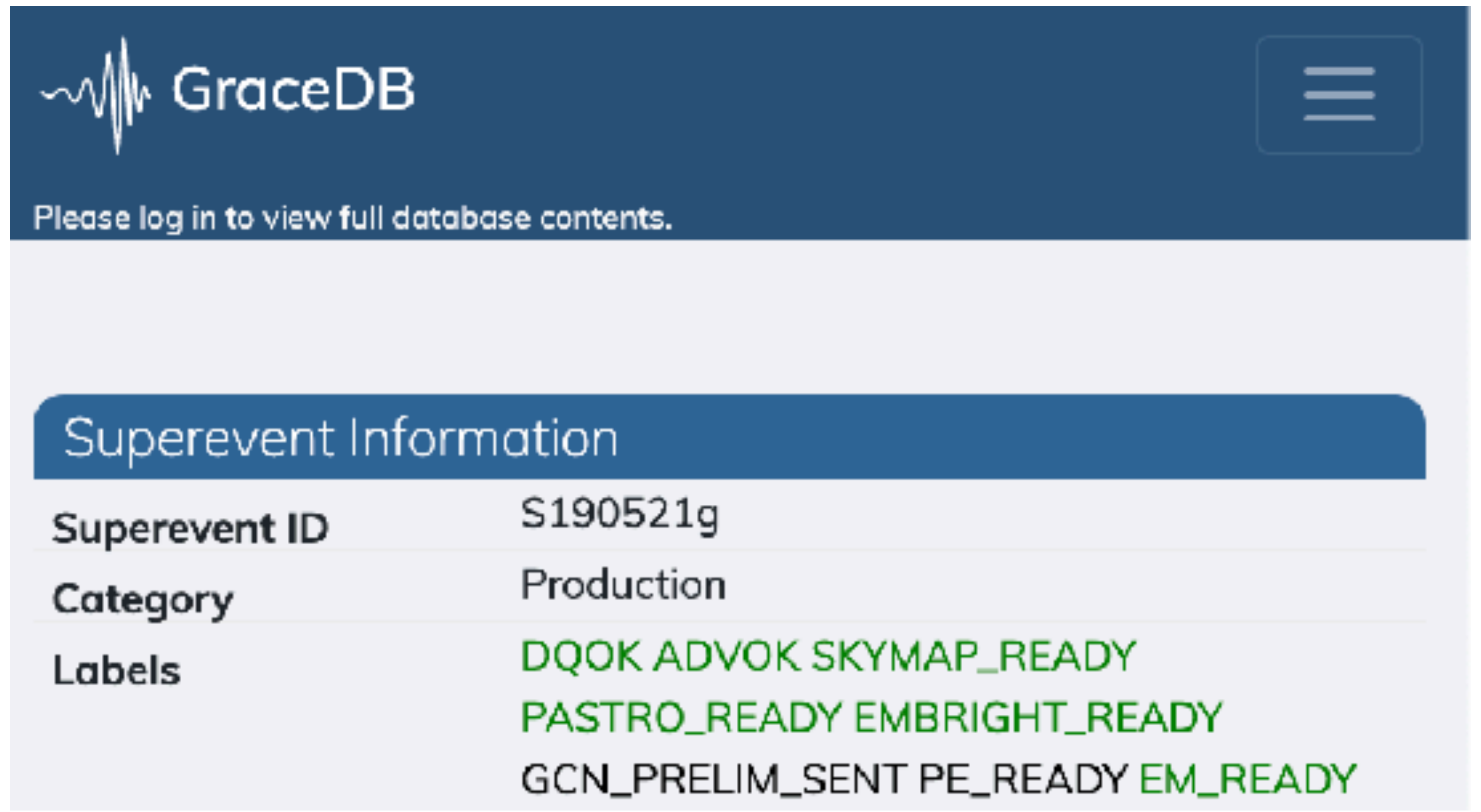
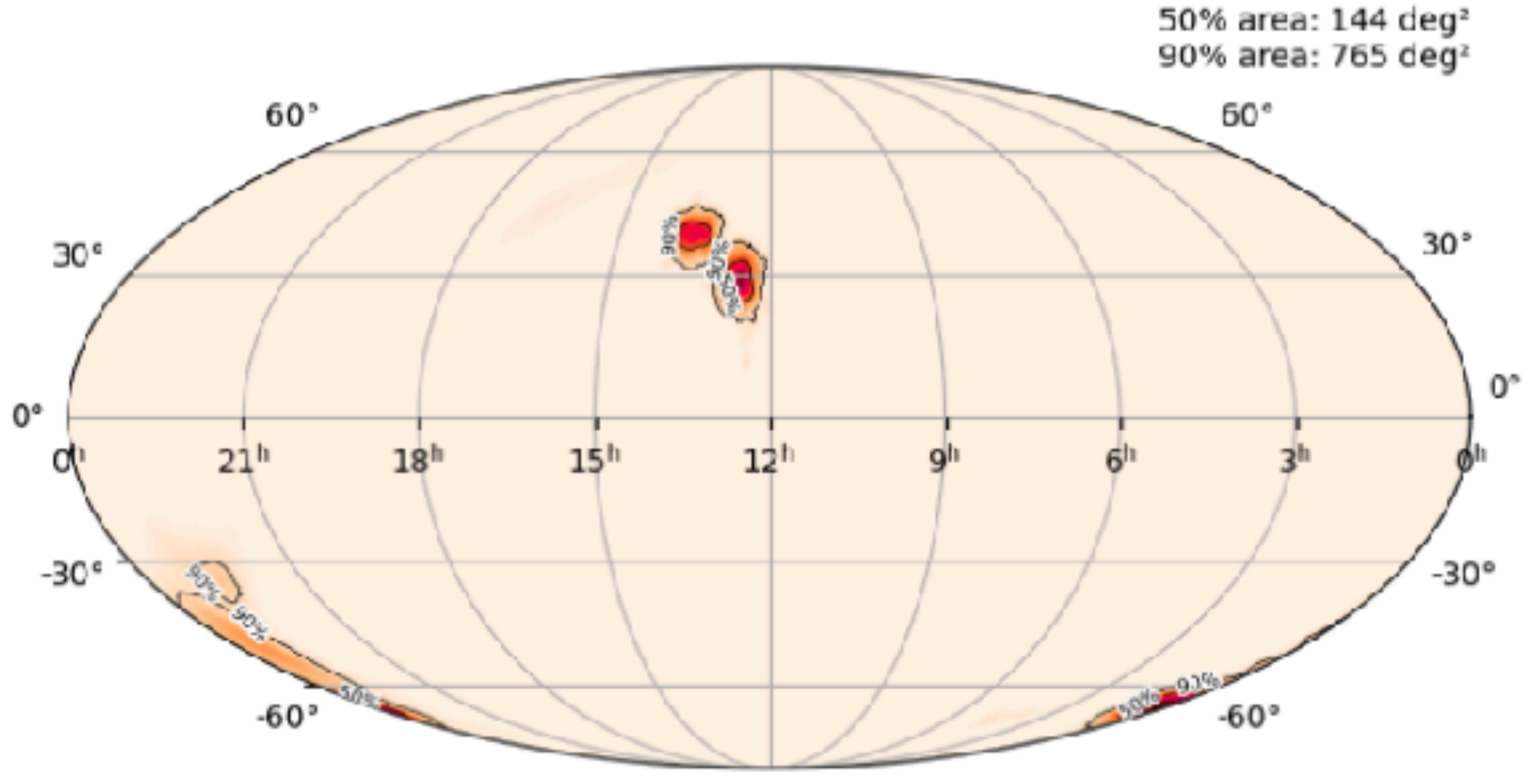


Image: S. Ghonge, **KJ**

May 21, 2019
Signal in LIGO-Virgo





Sept. 2, 2020
GW190521 Press Conference

(15th confirmed GW event)

Two papers from the LIGO-Virgo Collaboration:

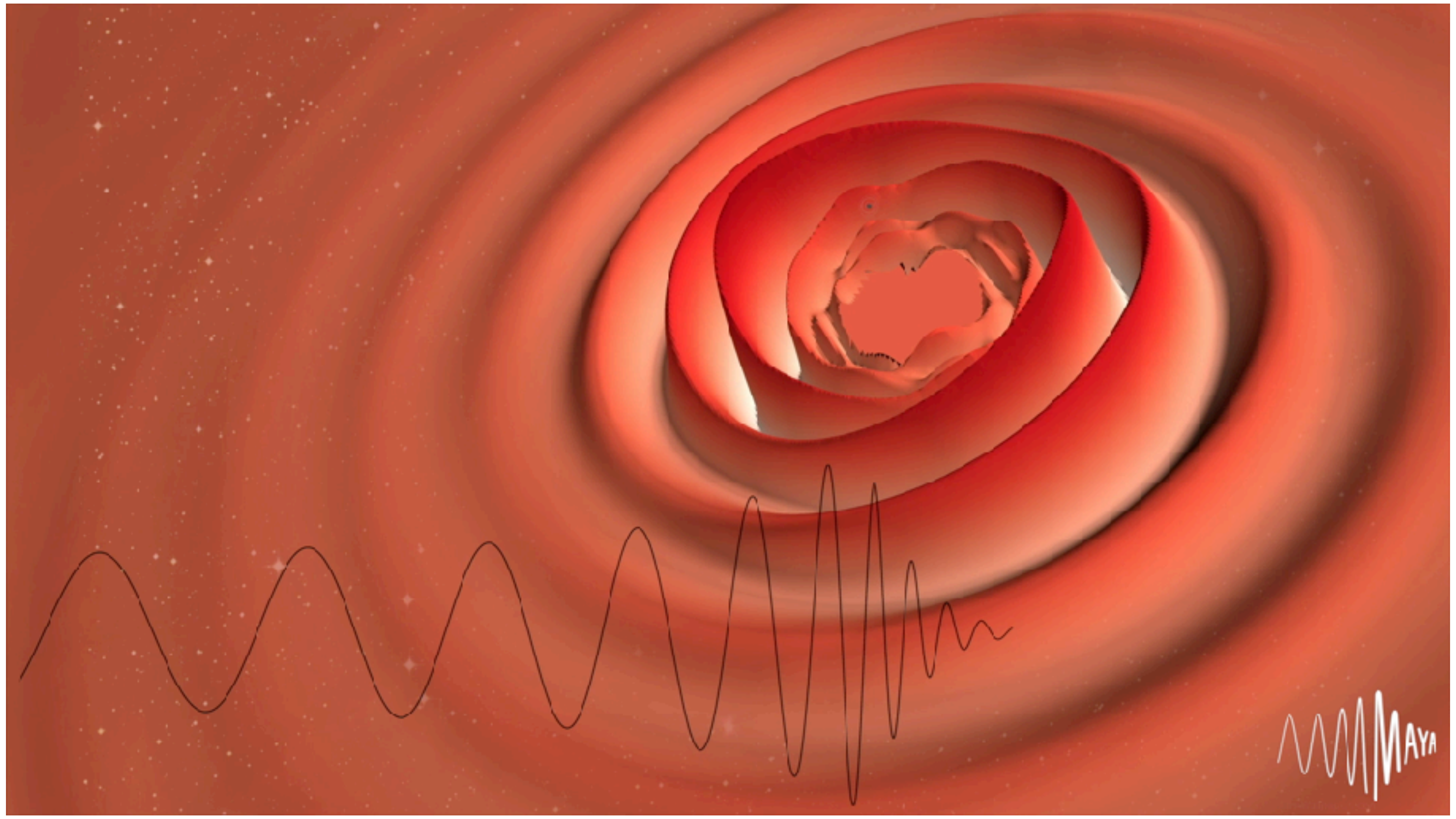
Astrophysical Journal Letters

Physical Review Letters *(Cover, Editor's Suggestion)*

The New York Times

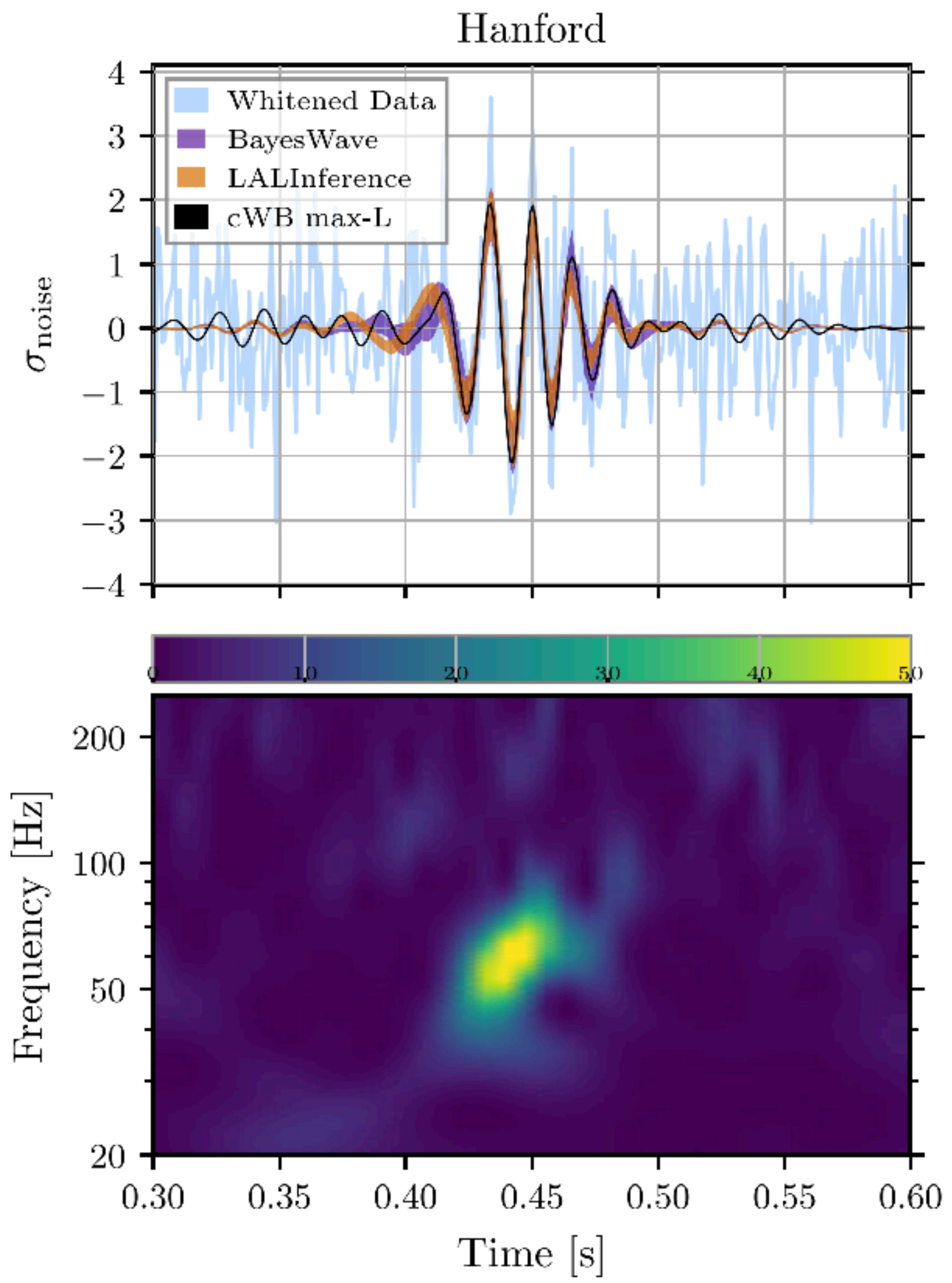
OUT THERE

These Black Holes Shouldn't Exist, but There They Are



Deborah Ferguson, **Karan Jani**, Deirdre Shoemaker, Pablo Laguna
MAYA Collaboration

Shortest signal yet



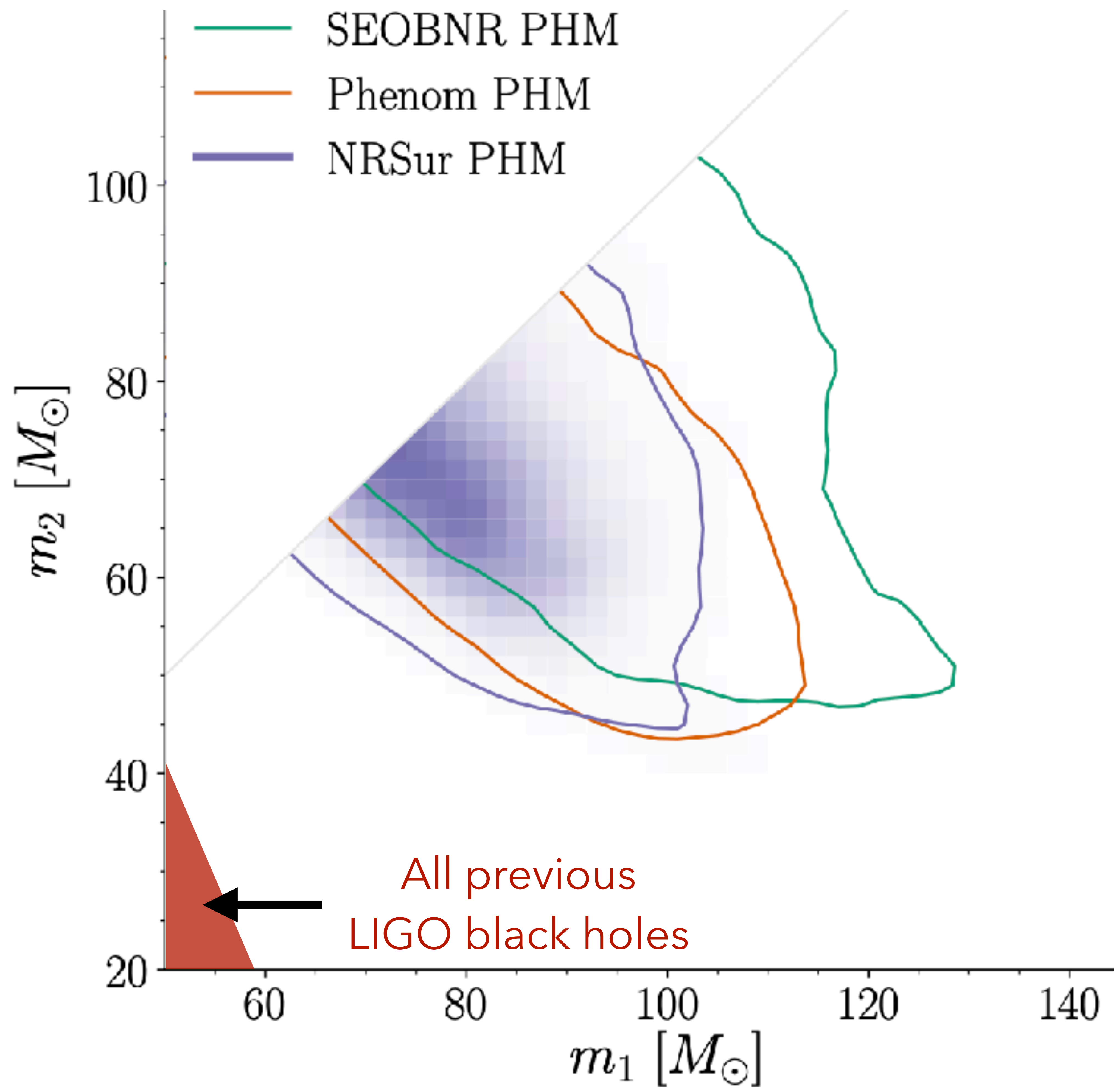
- ~0.1 seconds of data (4 cycles > 30 Hz)
- False-Alarm-Rate ~ 1/5000 years
- Highest detection significance in an "unmodeled burst search"
  - Powerful for hunting **Intermediate-mass Black Holes** (10^2-10^5 Msun)

    KJ with LIGO-Virgo - Phys. Rev. D (2017, 2019)

    KJ - PhD Thesis (2017)
- **Rare event : 1 every 8 years in Gpc^3**
- Two signals that day! (4 hours apart)

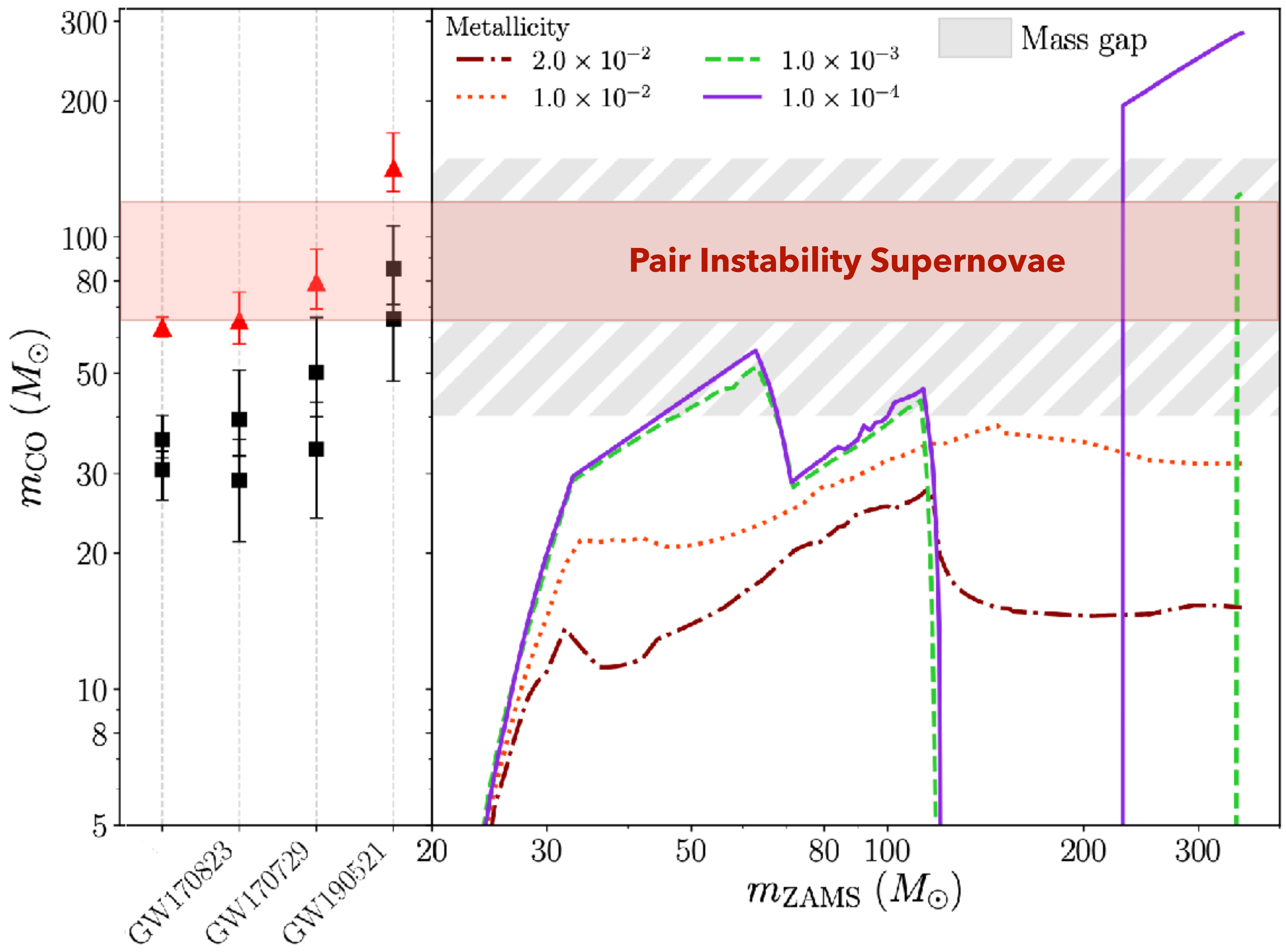
Unusually high masses

$$85\ M_\odot + 66\ M_\odot$$



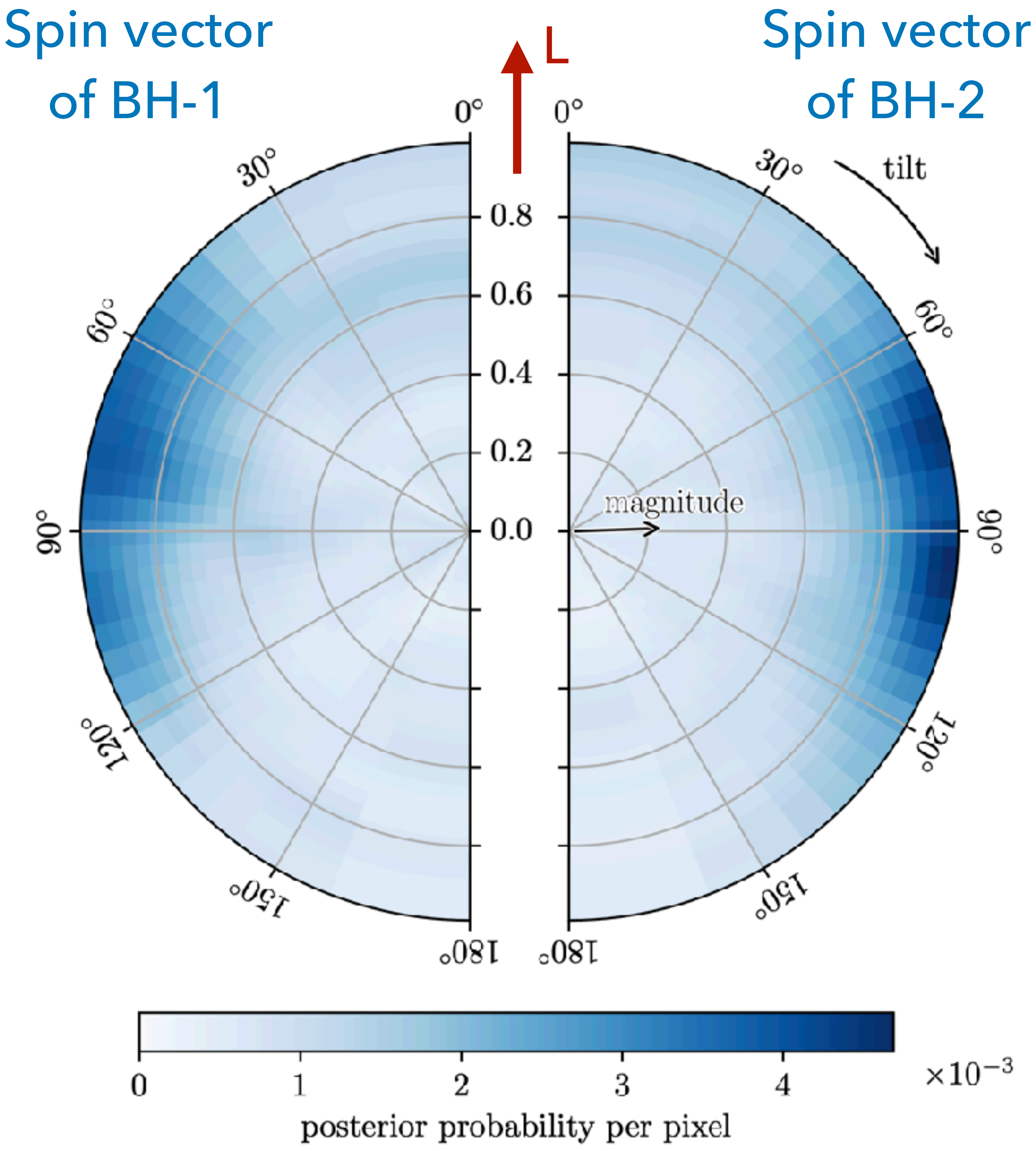
- 3 distinct state-of-the-art General Relativity (GR) signal models for Binary Black Hole (BBH) coalescence
- Compared with 3400+ numerical relativity simulations of BBH mergers
  KJ et al. (MAYA Catalog) - Classical & Quant. Grav. (2016)
  Boyle et al. (SXS Catalog), Healy et al. (RIT Catalog)
- **Both primary (BH-1) and secondary (BH-2) heavier than any previous GW binary**
- Merger produces an **IMBH** ~ 150 Msun

Mind the (black hole) gap!



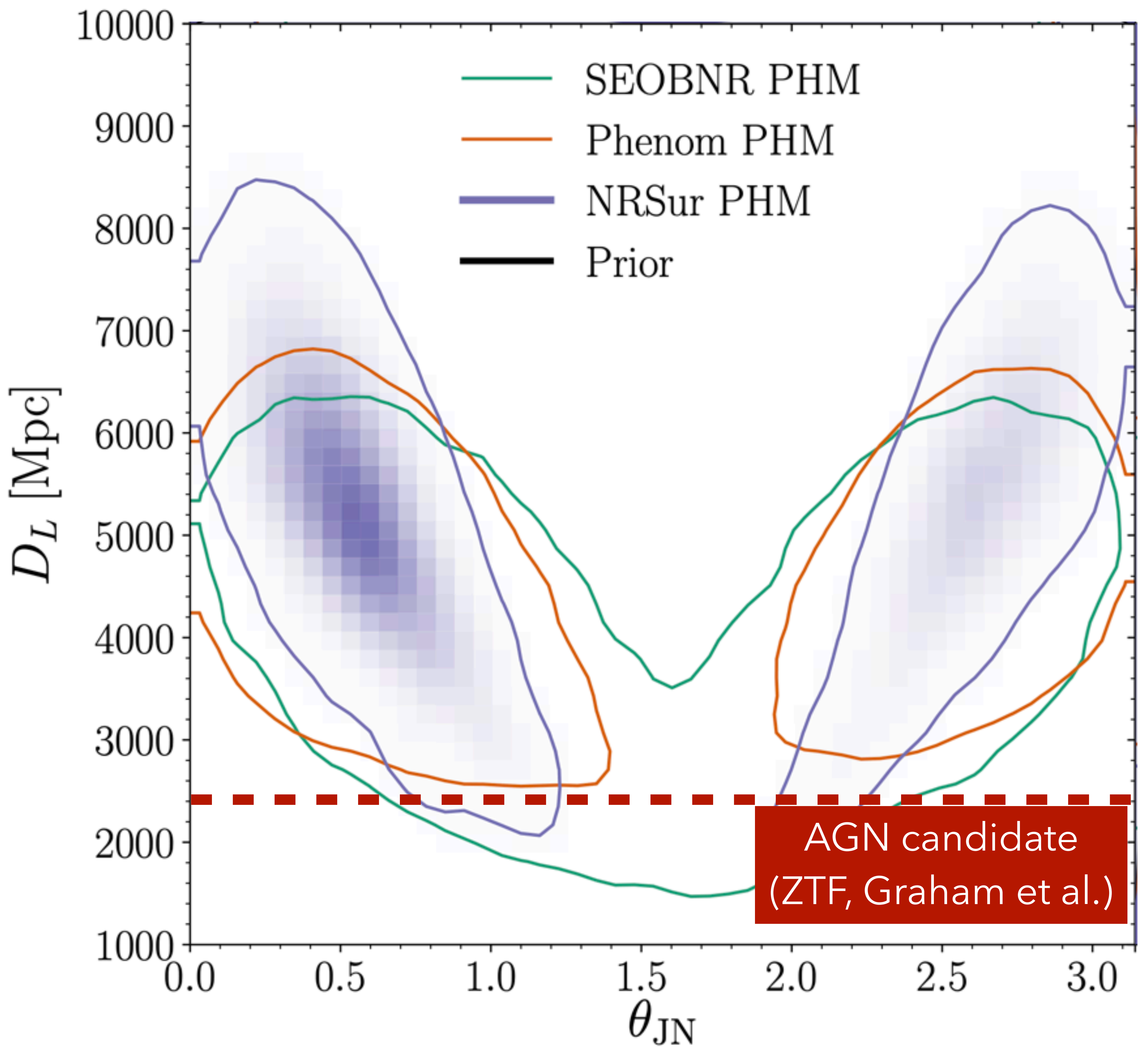
- PISN mass-gap: $\sim 65 - 120\ M_\odot$
- BH-1: **0.1 - 0.3%** probability outside gap
- BH-2: **6 - 46 %** probability outside gap

Black holes were wobbling



- Mild, but consistent evidence that the BBH exhibited spin-orbit precession just before the merger
- Both BH spins have little projection with orbital angular momentum axis - **evidence for dynamical capture**
- P(spins vs. no-spins) = 8.3 : 1
- P(precessing vs. aligned-spin) = 11.5 : 1

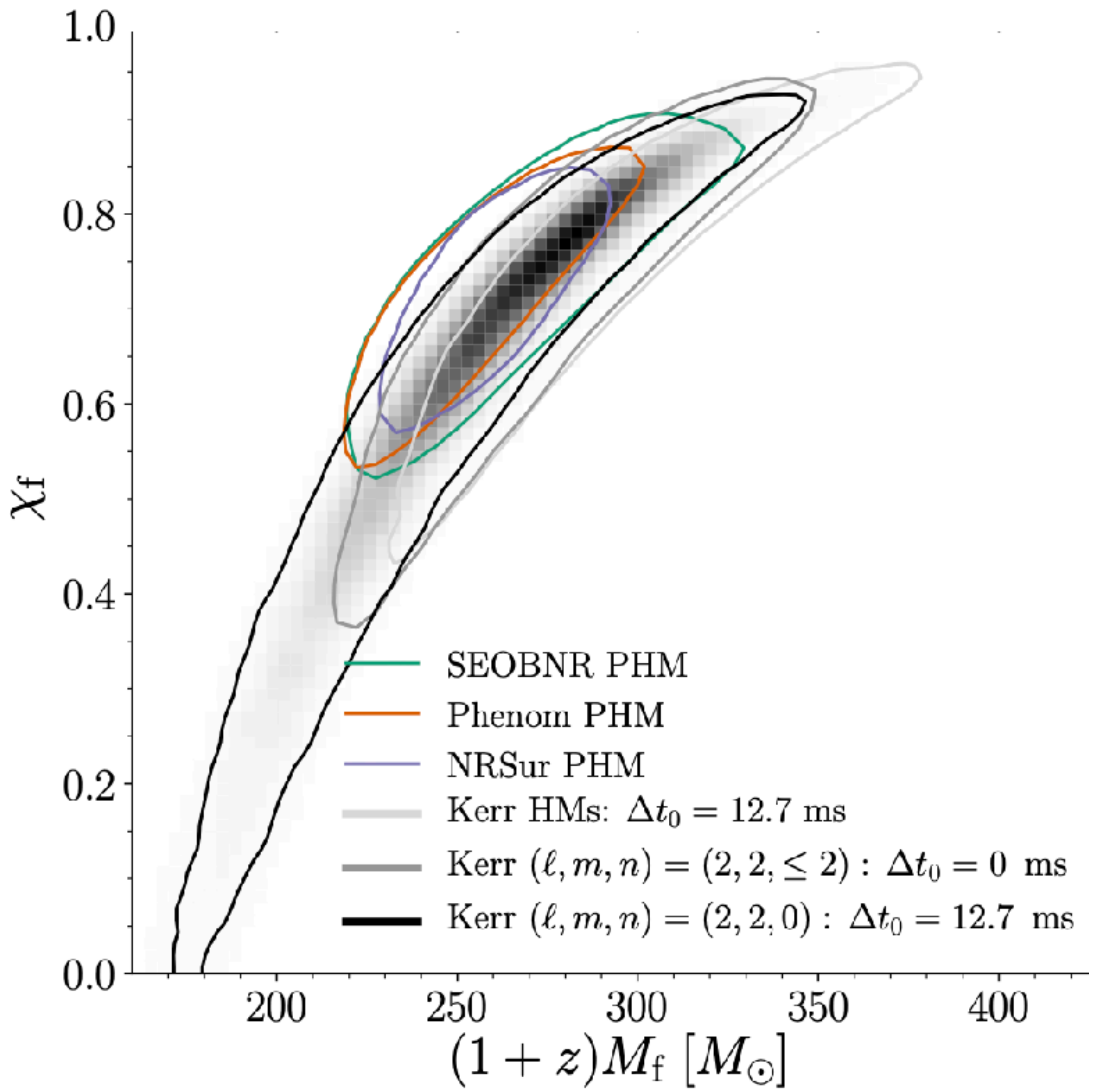
Farthest GW event yet



- **Redshift z ~ [0.5, 1.1]**
- Strong impact on luminosity distance estimation from radiation beyond the quadrupole term
  (tighter constraints on inclination)
  Calderón Bustillo, **KJ+**- Phys. Rev. D. (2018)
- Almost twice the distance than low-latency alert and EM-counterpart claim
  (mild support for lower-distance from one model)

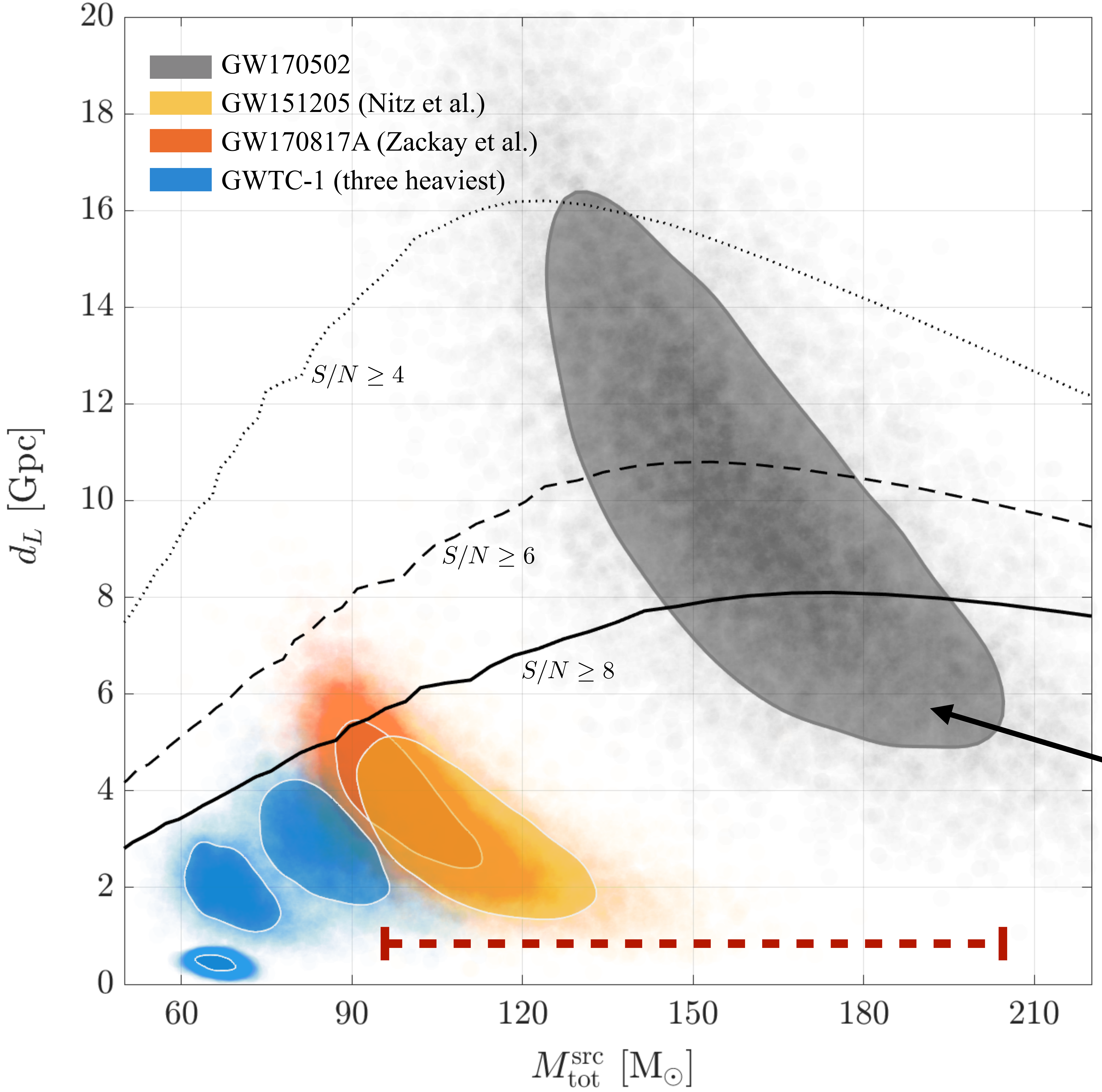
PAUSE

Consistency with GR



- **Residual tests**
  subtracting GR solutions from data leaves residual that is consistent with typical LIGO noise
- **Black hole ringdown**
  consistency in the properties of final black hole from pre- and post-merger analysis

More "Lite" IMBHs



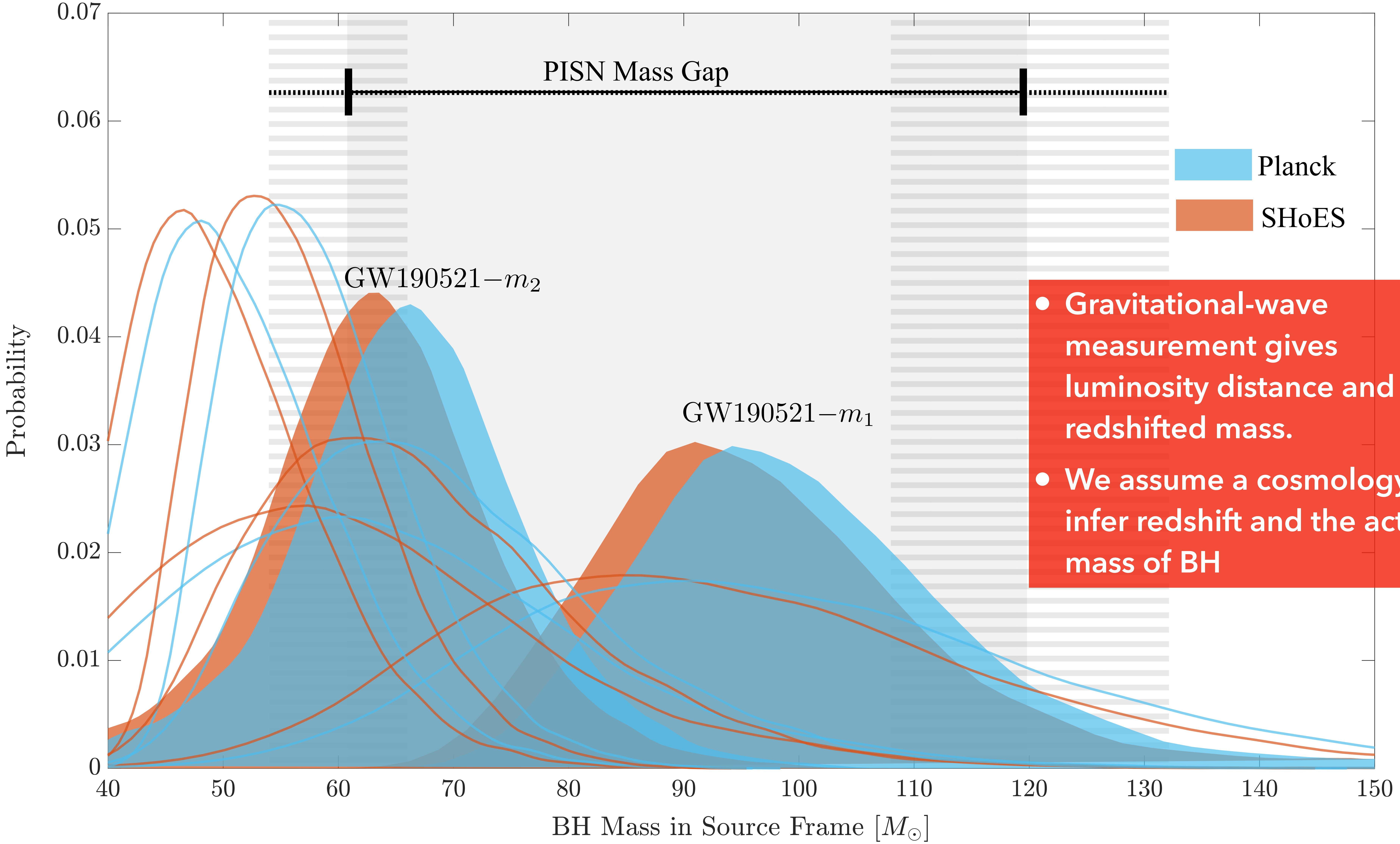
- Emerging population from the public GW data analysis
- **GW170502**

  Udall, **KJ, KHB+**- Astrophysical Journal (2020)

  KJ with LIGO-Virgo - Phys. Rev. D (2019)

Primary BH mass, $m_1^{\rm src}$ ($M_\odot$)	94^{+44}_{-28}
Secondary BH mass, $m_2^{\rm src}$ ($M_\odot$)	62^{+30}_{-25}
Total mass, $M_{\rm tot}^{\rm src}$	157^{+55}_{-41}
Redshift, z	$1.37^{+0.93}_{-0.64}$

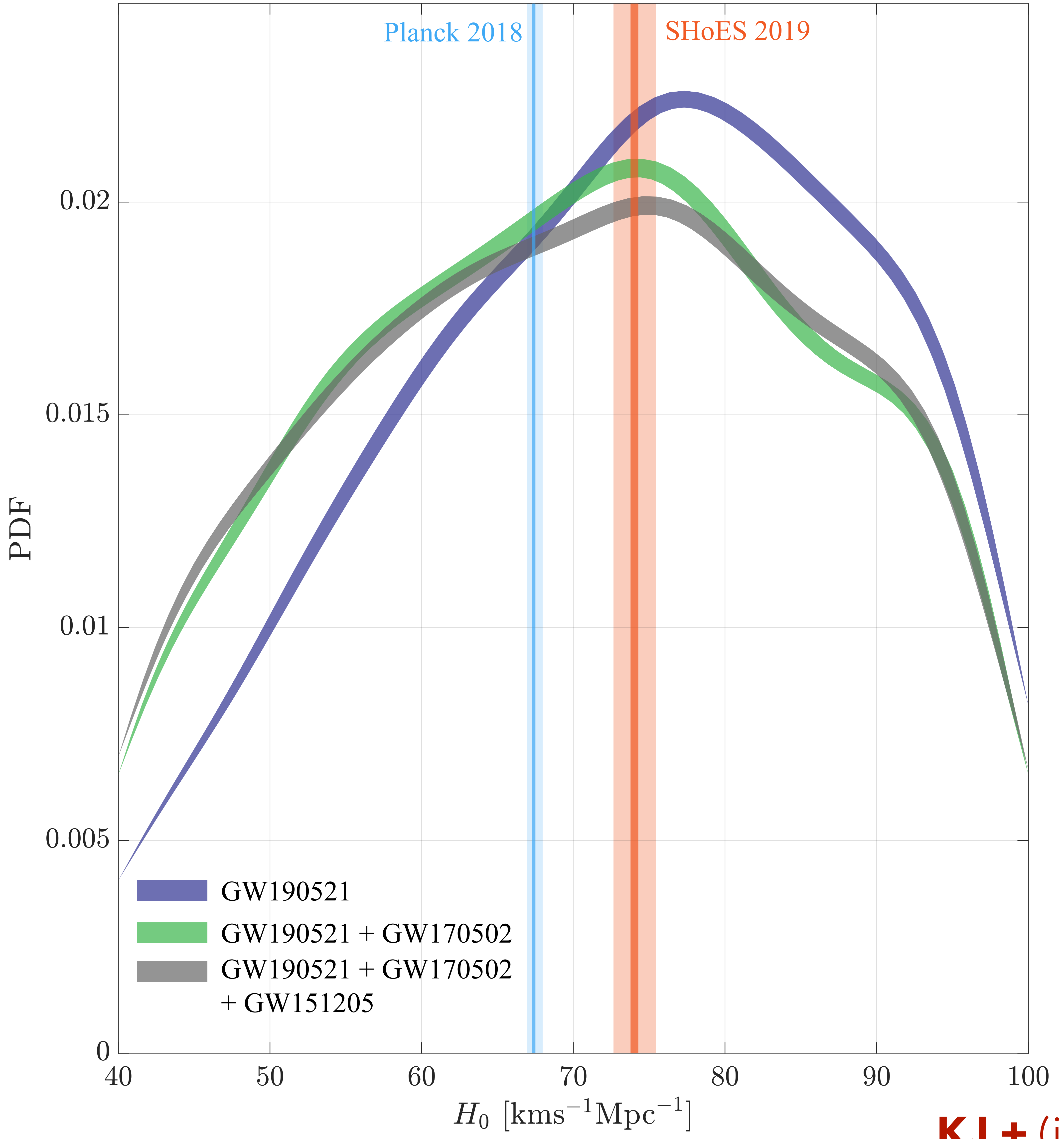
Hubble Constant & Mass-Gap



- Gravitational-wave measurement gives luminosity distance and redshifted mass.
- We assume a cosmology to infer redshift and the actual mass of BH

KJ + (in-prep)

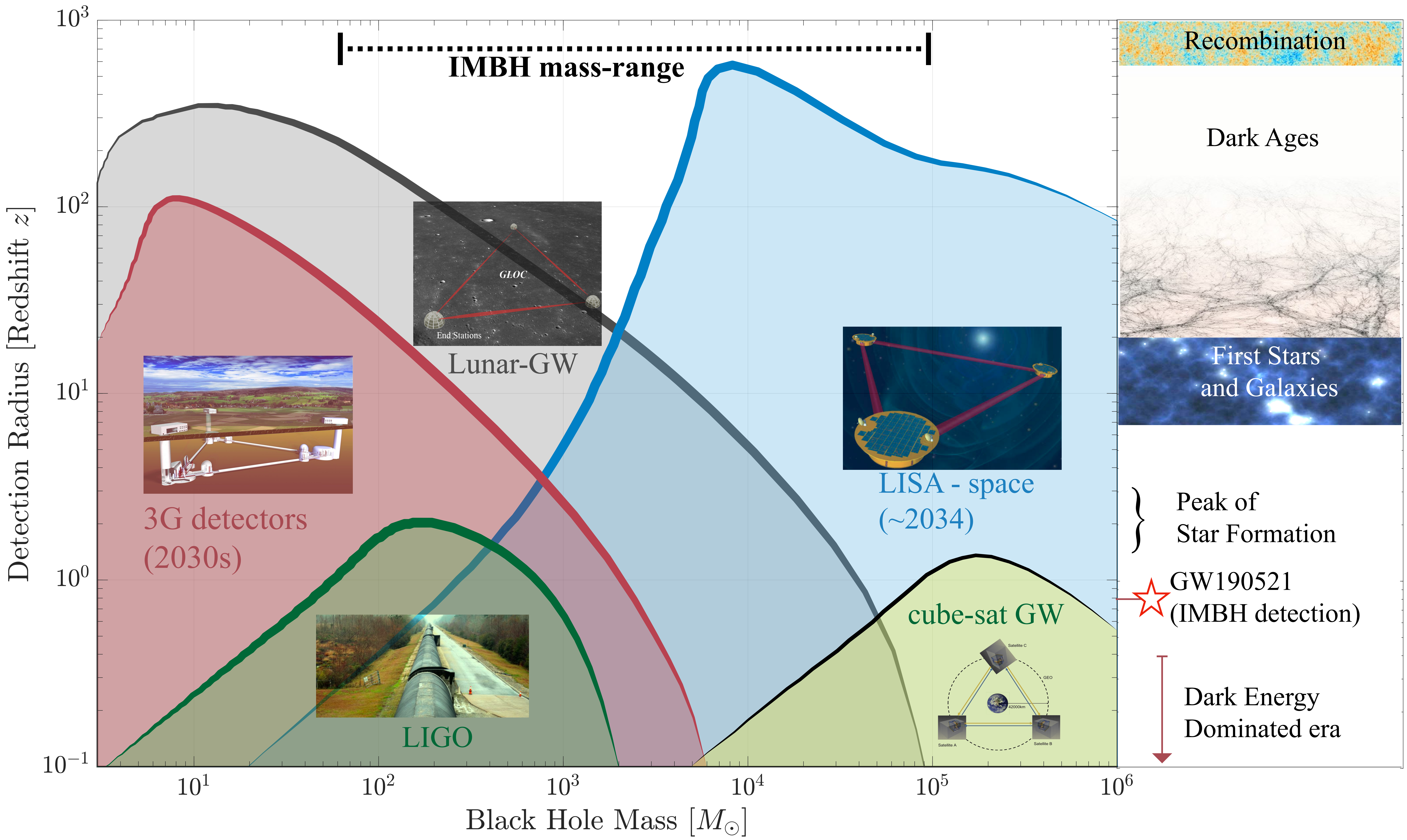
Hubble Constant & Mass-Gap

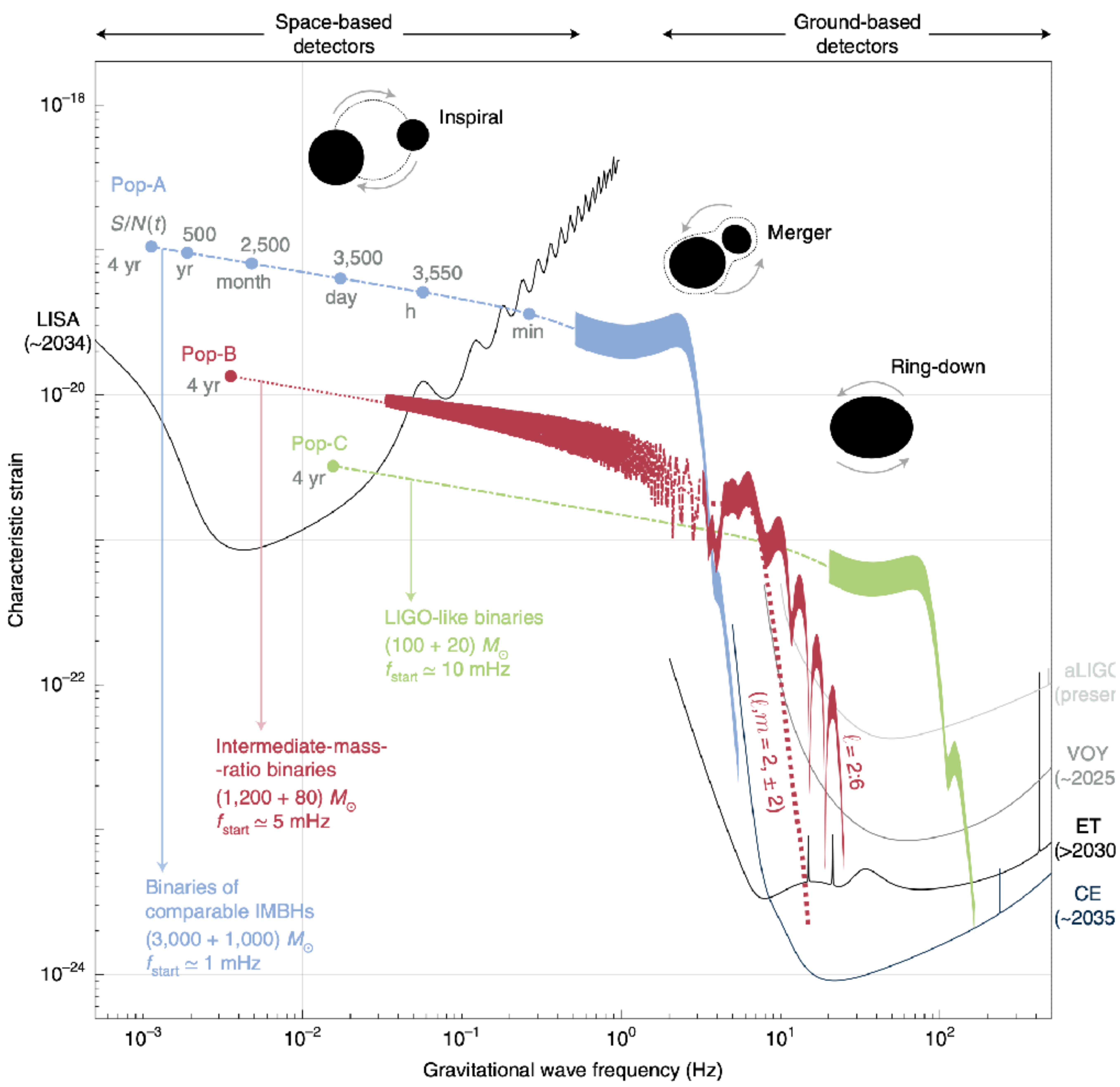


KJ + (in-prep)

- Assuming mass-gap starts from 60 solar masses
- **Slight preference from SNe cosmology**
- No need for galaxy association, EM counterparts
- High redshift events (z~1)

A new era for IMBHs

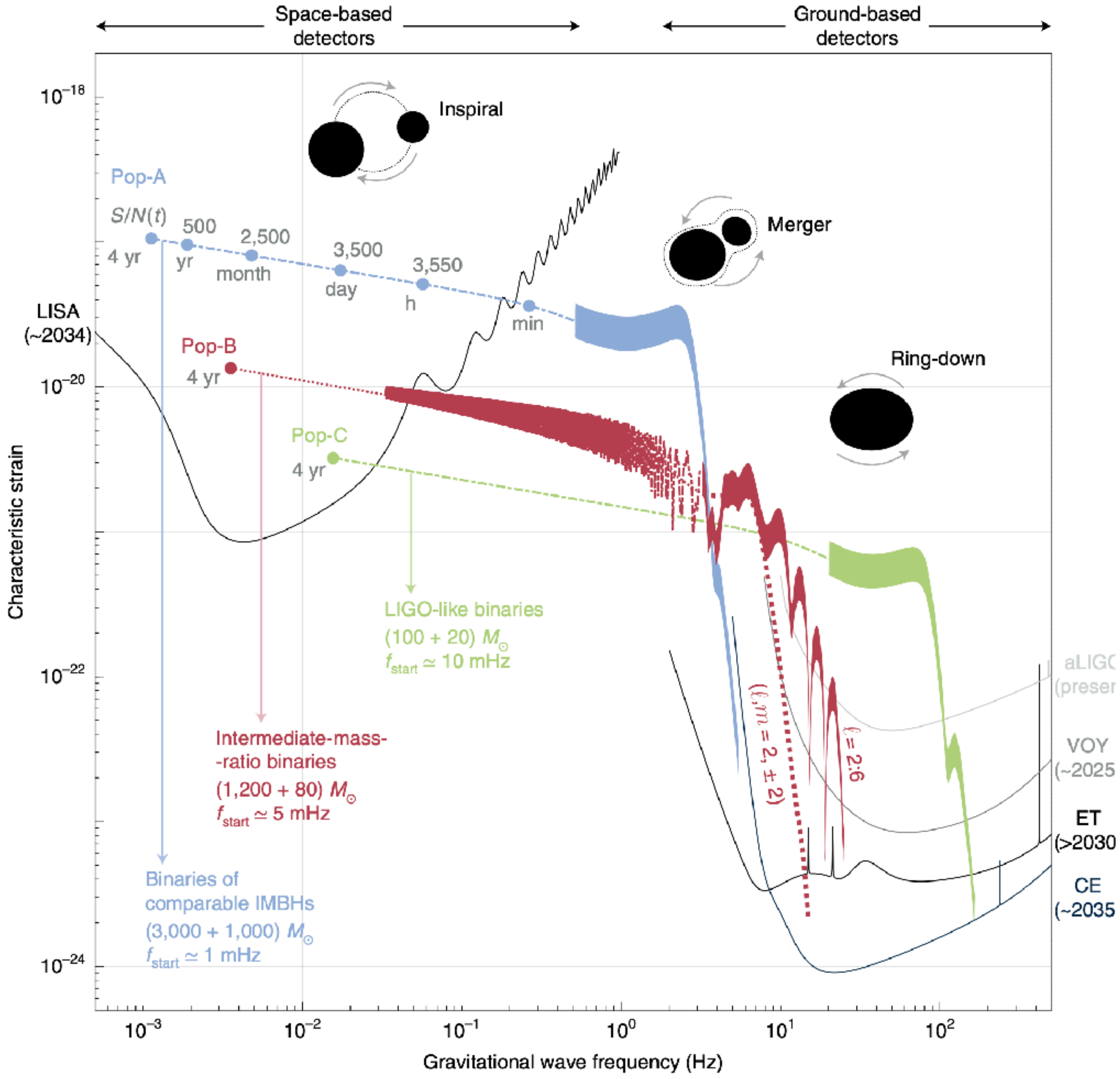


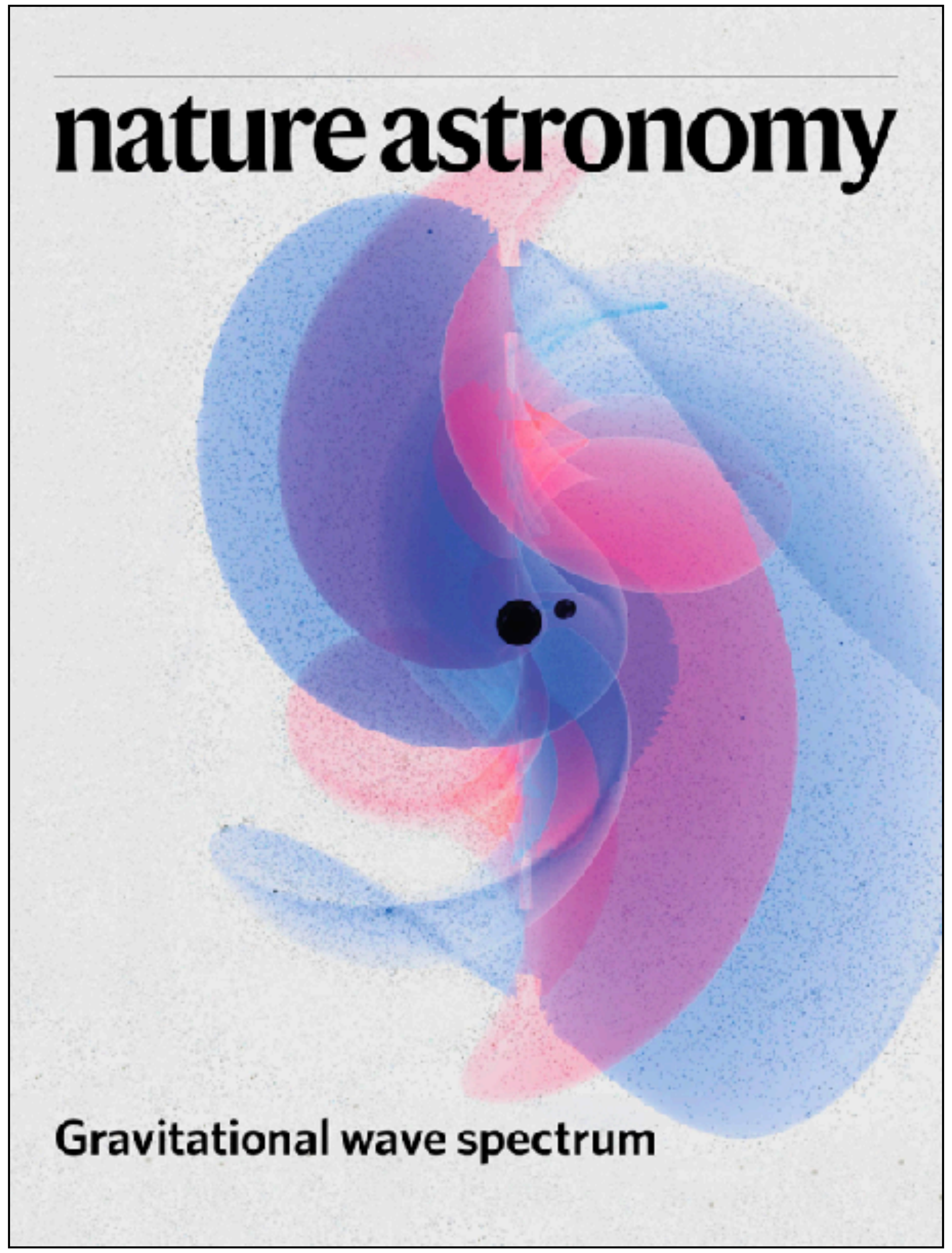


Multi-Band Astronomy

- IMBH binaries would be observed by the **LISA mission** (ESA/NASA) 4-10 years before merger
- Final stages (merger) will be observed by ground network *(Einstein Telescope, Cosmic Explorer, LIGO-A+)*
- **New era of multi-wavelength GW observations to study single astrophysical source**

Multi-Band Astronomy

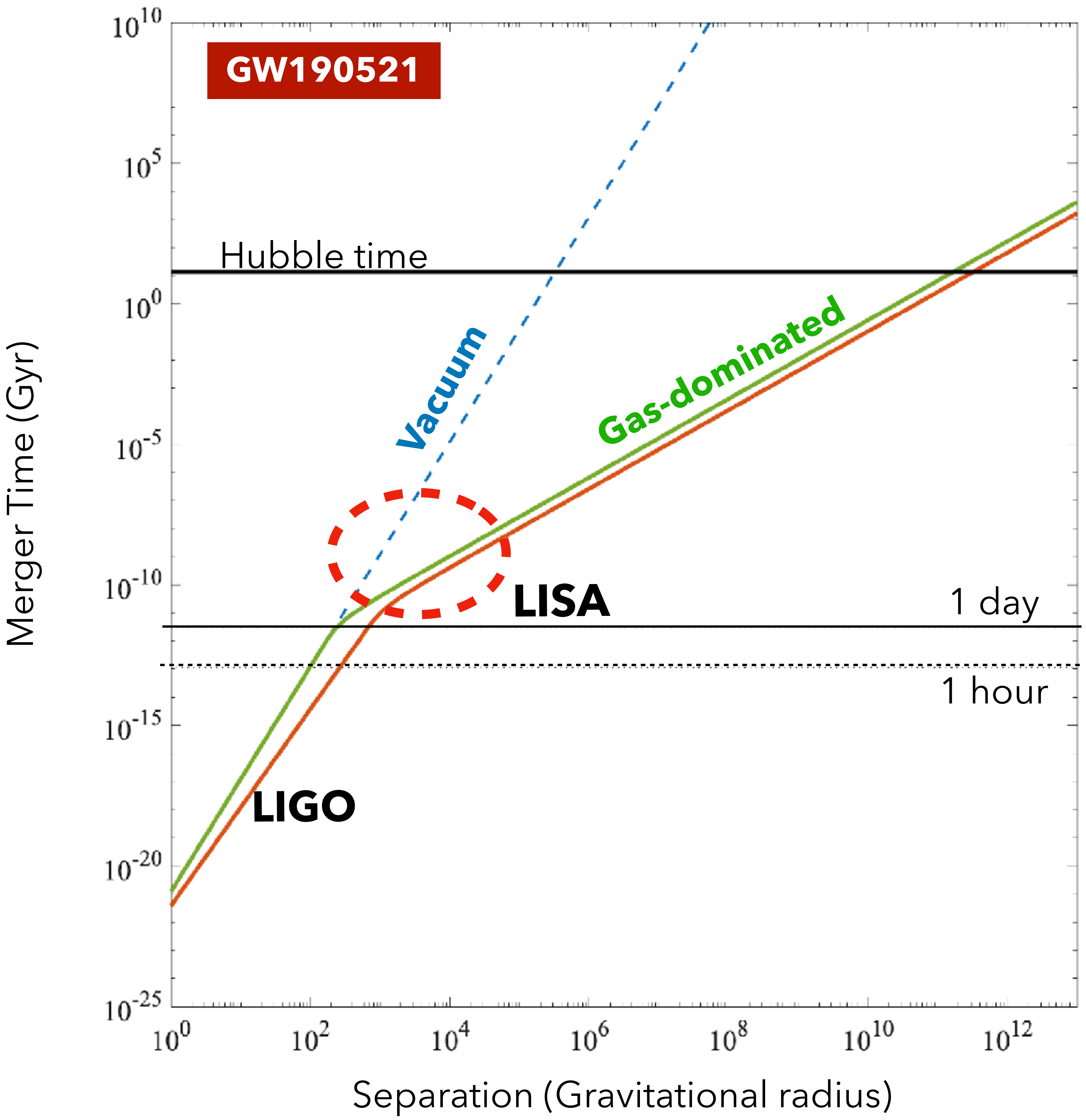




Jani et al.

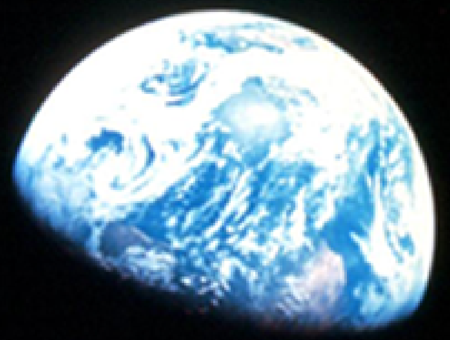
Nature Astronomy Cover Story

(March 2020 Issue)



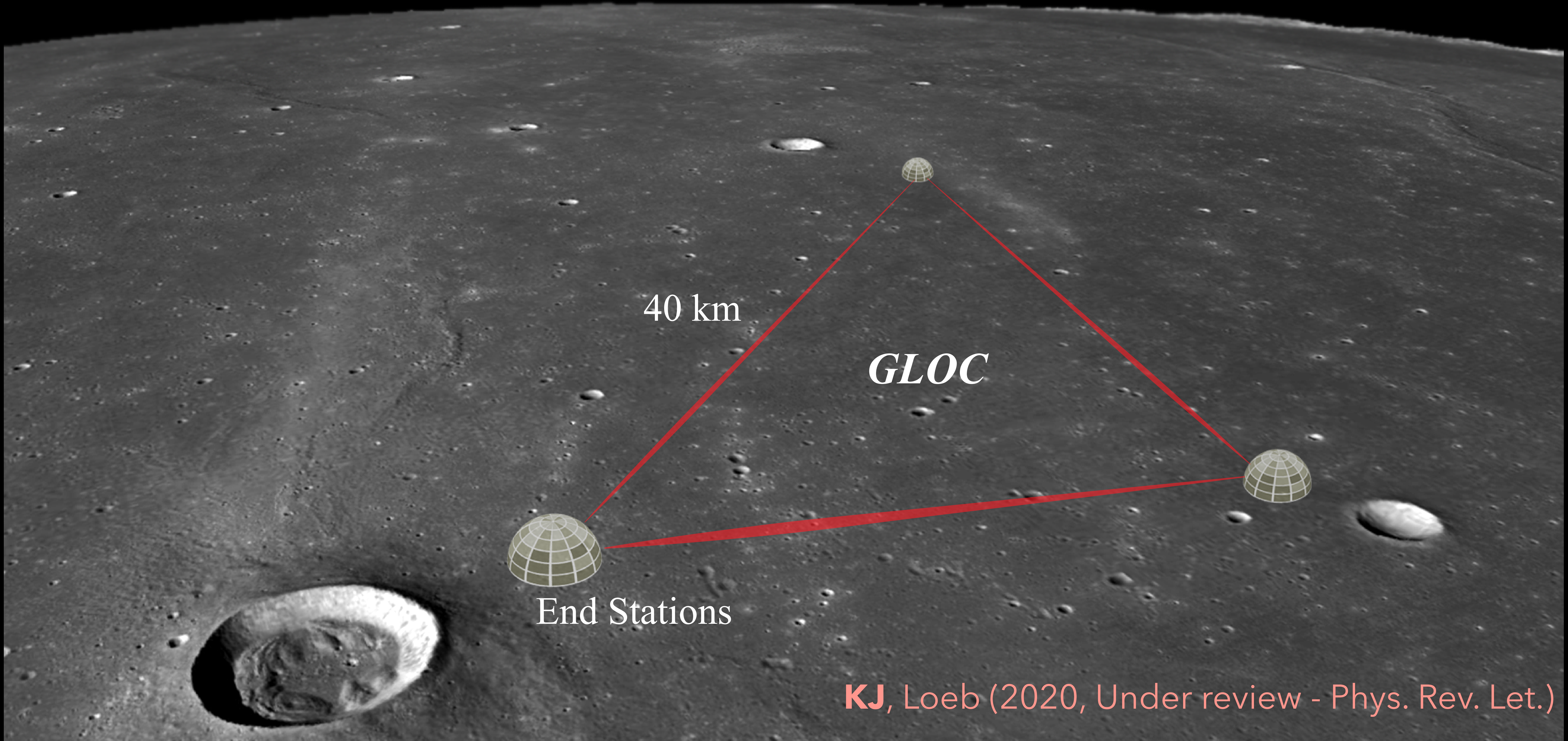
Multi-Messenger Astronomy

- **If** GW190521 originated in AGN disk, the **gas+radiation will speed up merger**
  KJ, Bogdanovic+ (in-prep)
- GW signature at low-frequencies will be different, but in LIGO they would appear as vacuum BBHs
  Toubiana et al. (with **KJ**) - submitted to PRL
- LISA observations can rule out IMBH-AGN connection



IMBHs on Moon

the deci-Hz case



KJ, Loeb (2020, Under review - Phys. Rev. Let.)

IMBHs on Moon

Snowmass2021 - Letter of Interest

A deci-Hz Gravitational-Wave Lunar Observatory for Cosmology

>70+ co-authors

DOE / NSF perspectives from yesterday

- Jim Siegrist (DOE):
  - Bickering scientists get nothing.
  - Let 1000 flowers bloom!
  - Particular need for $30-100M scale projects
  - Use imagination – partner with NASA for moon-based experiments?
  - Cover as much dark matter parameter space as possible.

From slides of Aaron Chou, Marcelle Soares-Santos, Tim Tait *(CF conveners)*

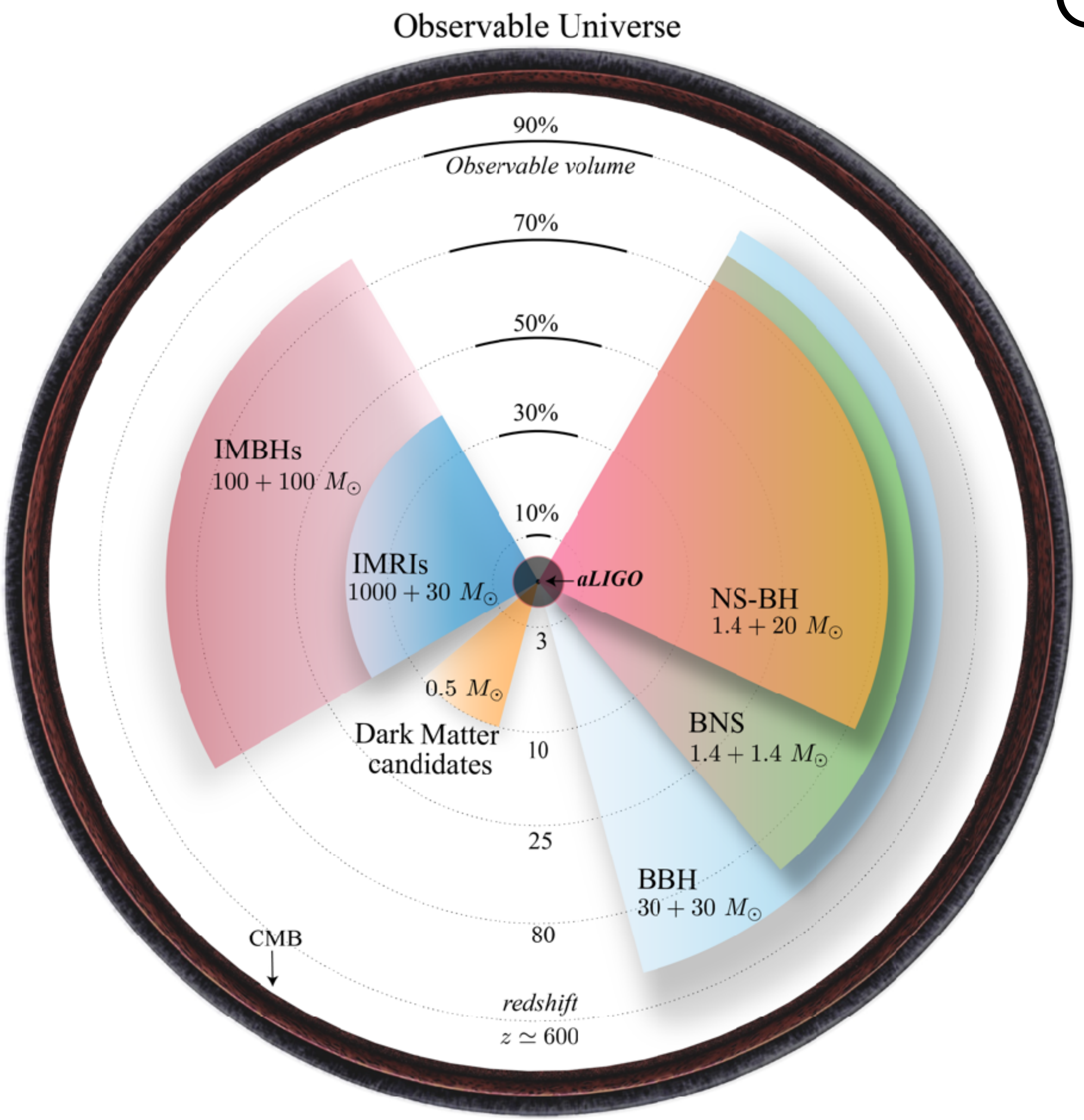
IMBHs on Moon

Call for Artemis Science White Papers

GRAVITATIONAL-WAVE LUNAR OBSERVATORY FOR FUNDAMENTAL PHYSICS

K. Jani*, Vanderbilt U.; A. Loeb, Harvard U.; K. Holley-Bockelmann, Vanderbilt U.; A. J. Ruiter, U. of New South Wales; A. Palmese, Fermi National Accelerator Laboratory; B. L. McKernan, American Museum of Nat. History; G. Congedo, Institute for Astronomy, U. of Edinburgh; J. Harms, GSSI, Italy; K. E. S. Ford, American Museum of Nat. History; M. Arca Sedda, Heidelberg U., Germany; M. Branchesi, Gran Sasso Science Institute, Italy; M. Gill, Stanford; M. Ruiz, U. of Illinois-Urbana-Champaign; N. Schmerr, U. of Maryland; O. Birnholtz, Bar-Ilan U., Israel; P. Jetzer, U. of Zurich; P. Lognonné, IPGP, France; R. Fisher, U. Mass.-Dartmouth; S. Katsanevas, European Gravitational Obs.; S. Marka, Columbia U.; S. Shandera, Pennsylvania State U. | **contact person:* karan.jani@vanderbilt.edu

Parallel proposal to ESA's European Large Lander -
Stavros Katsanevas et al (GW+geosciences)



Cosmology & Fundamental Physics on Moon

- Largest cosmological survey across all experiments
- Measurement of Hubble constant with dark sirens up to redshift ~ 3
- Calibration of Type Ia SNe
- Dark matter constraints
- **IMBHs**

Please do reach out for more science cases!

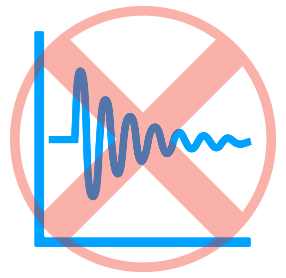
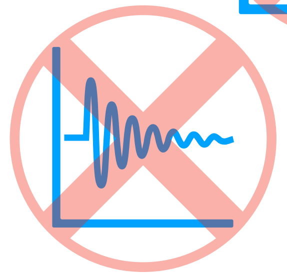
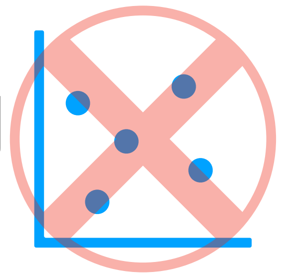
KJ, Loeb (2020, Under review - Phys. Rev. Letters)

Present world- GW190521 Origins?

Astrophysical

- Stellar origins *(<0.8% stars will contribute)*
  KJ, Loeb - ApJ Letters (2019)
- GC: Hierarchical BBH mergers *(spin sensitive)*
  Kimbal+ (2019), Gerosa+ (2020)
- **GC:** Stellar mergers *(~2% of BHs in gap)*
  Spera, Di Carlo, Mapelli+ (2019)
- **NSC:** accretion *(can reach any IMBH mass)*
  Natarajan (2020)
- **AGN disk** *(hierarchical, EM counterparts)*
  Bartos, McKernan, Ford + (>2017)

Exotic

- Core Collapse Supernovae 
- Cosmic Strings 
- Beyond GR 
- Strong Gravitational Lensing 
- **Primordial/Pop-III BH Mergers**
- **Highly Eccentric Collisions**
  Gayathri+ (2020), Romero-Shaw+ (2020)

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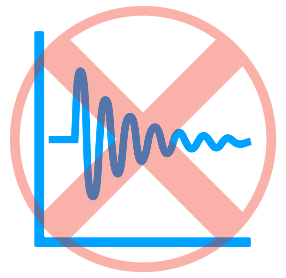
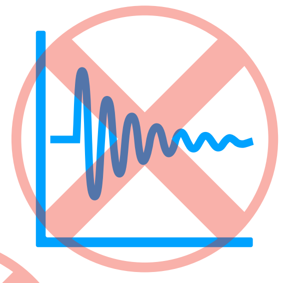
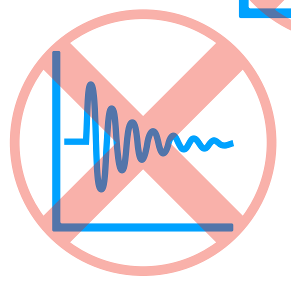
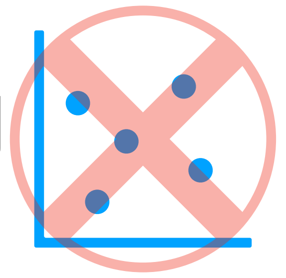
- Core Collapse Supernovae 
- Cosmic Strings 
- Beyond GR 
- Strong Gravitational Lensing 
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Conclusion : 100-1000 solar mass “Lite” IMBHs are the most exciting GW sources for this decade

GW190521

Detection of an intermediate-mass black hole

Thank you!

Follow-up discussions

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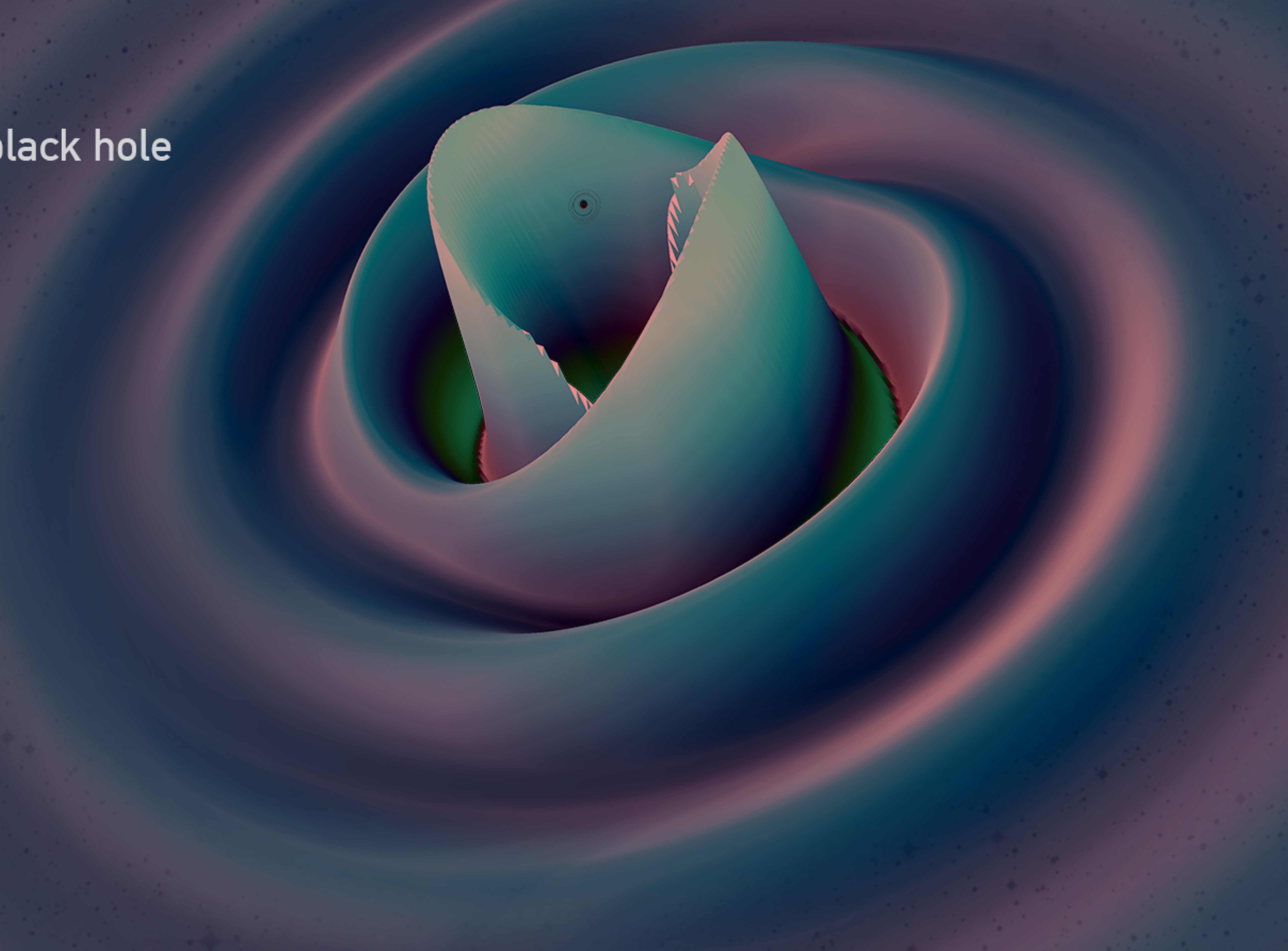
@astrokpj



NSF LIGO VIRGO

Deborah Ferguson | Karan Jani | Deirdre Shoemaker | Pabla Laguna