Title: GW190521 - Discovery of Black Holes that Should Not Exist

Speakers: Karan Jani

Series: Cosmology & Gravitation

Date: October 27, 2020 - 11:00 AM

URL: http://pirsa.org/20100010

Abstract: The new gravitational-wave signal GW190521in LIGO and Virgo marks the first observational detection of the elusive intermediate-mass black holes. The detection also confirms there exist a new class of black holes in the mass gap predicted by the pair-instability supernovae theory. In this talk, I will discuss the process that went behind inferring the astrophysical properties of this historic discovery. I would briefly address the alternative scenarios we looked into for a possible exotic origin of this signal, including any violation of General Relativity. For the upcoming ESA/NASA space mission LISA, I would highlight how this discovery opens a unique epoch of multi-band, multi-messenger astronomy.

Jani-Perimeter-talk-Oct-2020

GW190521 - Discovery of Black Holes that Should Not Exist

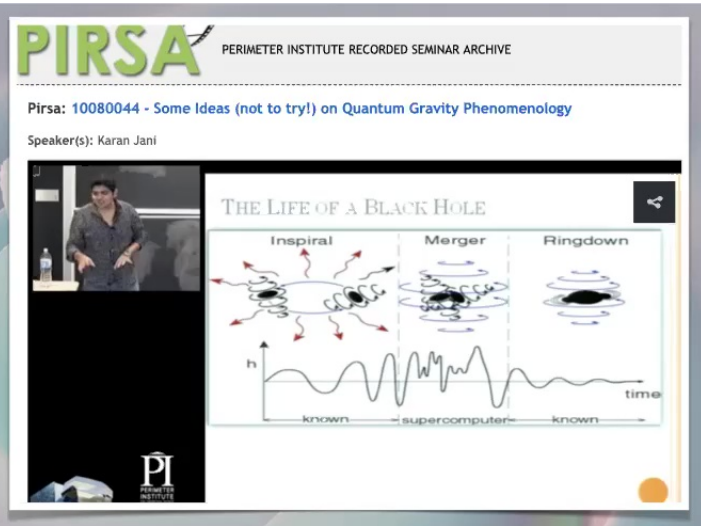
Perimeter Institute
Cosmology & Gravitation Seminar
October 27, 2020

Karan Jani
Vanderbilt | LIGO Collaboration
@astrokpj

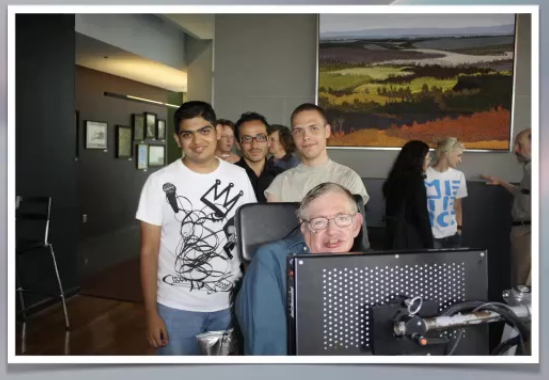
GW190521 - Discovery of Black Holes that Should Not Exist

Perimeter Institute
Cosmology & Gravitation Seminar
October 27, 2020

Karan Jani
Vanderbilt | LIGO Collaboration
@astrokpj

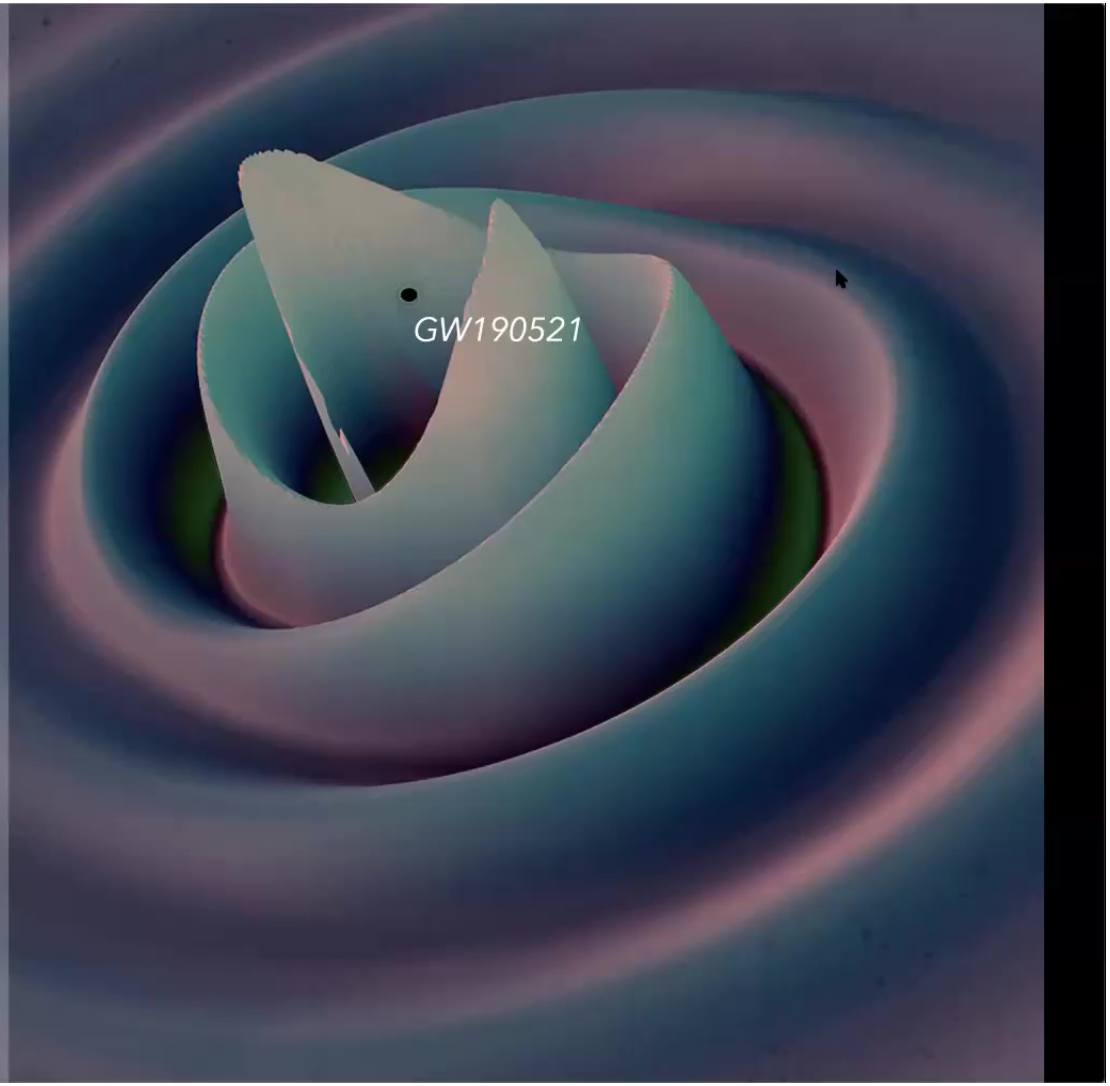


Perimeter Institute (Summer **2010**)



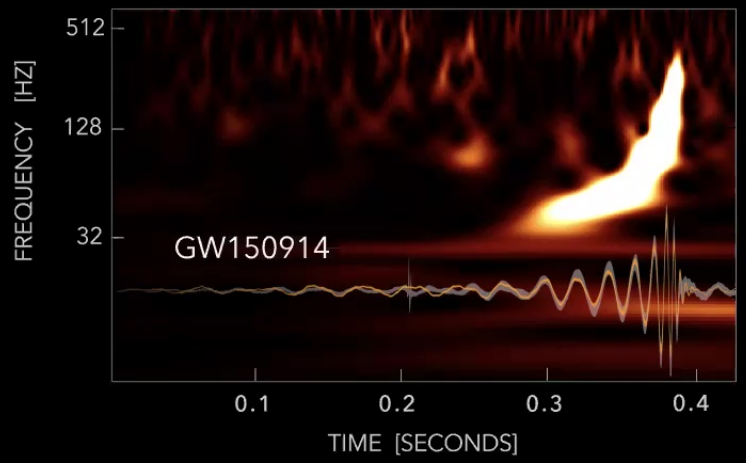
Outline

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



Measuring a Black Hole

LIGO-Virgo Collaboration

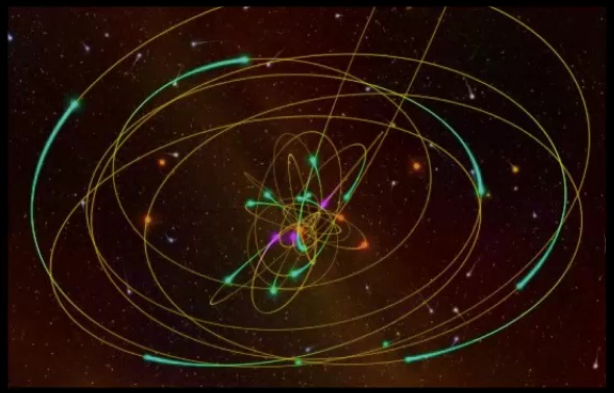


2017 - Nobel Prize

EHT Collaboration

2020- Breakthrough Prize

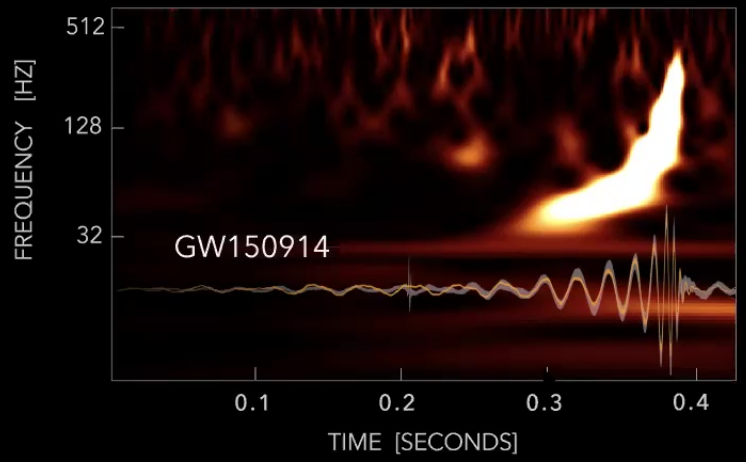
Ghez et al., Genzel et al.



2020 - Nobel Prize

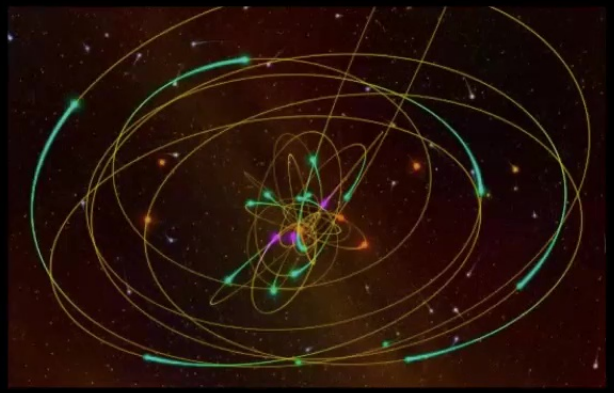
Measuring a Black Hole

LIGO-Virgo Collaboration



EHT Collaboration

Ghez et al., Genzel et al.



Direct → Indirect

(X-ray binaries)

5

Gravitational-Wave Transient Catalog-1 (2015-2017)

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

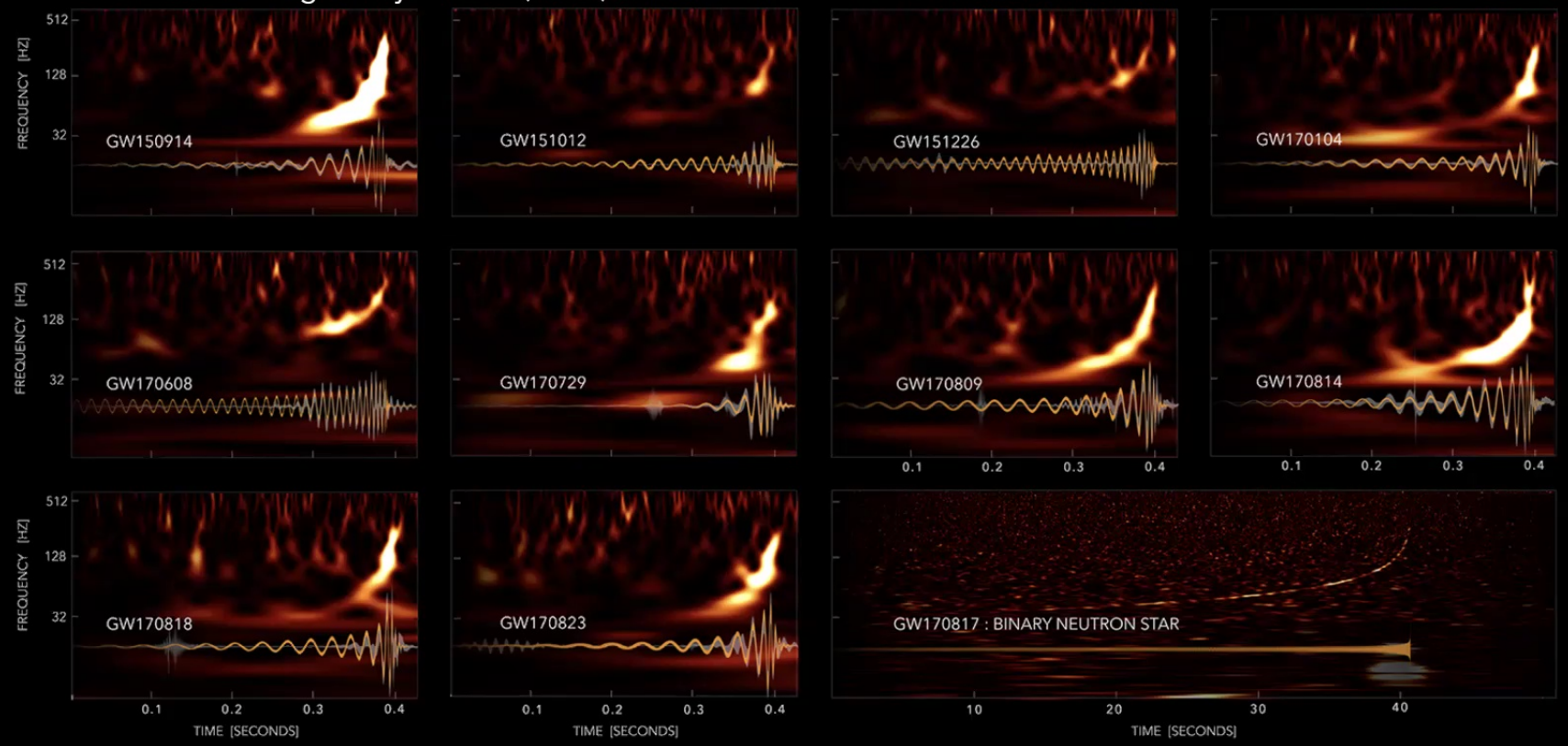
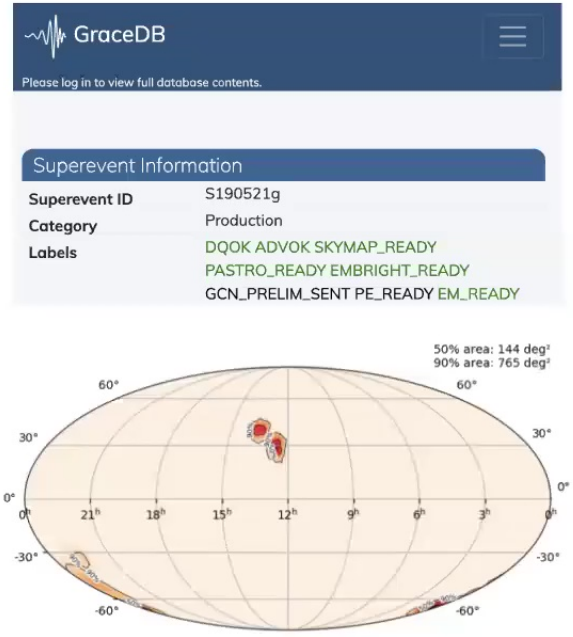


Image: S. Ghonge, **KJ**

May 21, 2019
Signal in LIGO-Virgo



Sept. 2, 2020
GW190521 Press Conference

(15th confirmed GW event)

Two papers from the LIGO-Virgo Collaboration:

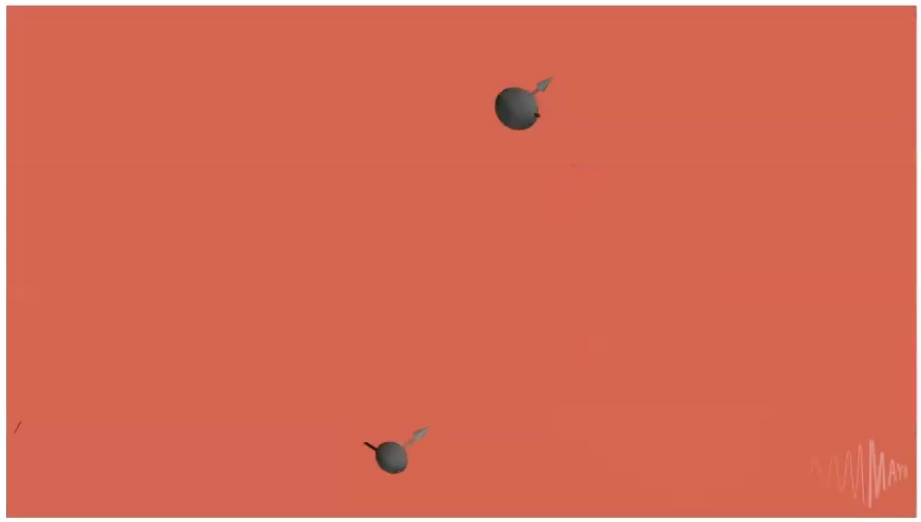
Astrophysical Journal Letters

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

The New York Times

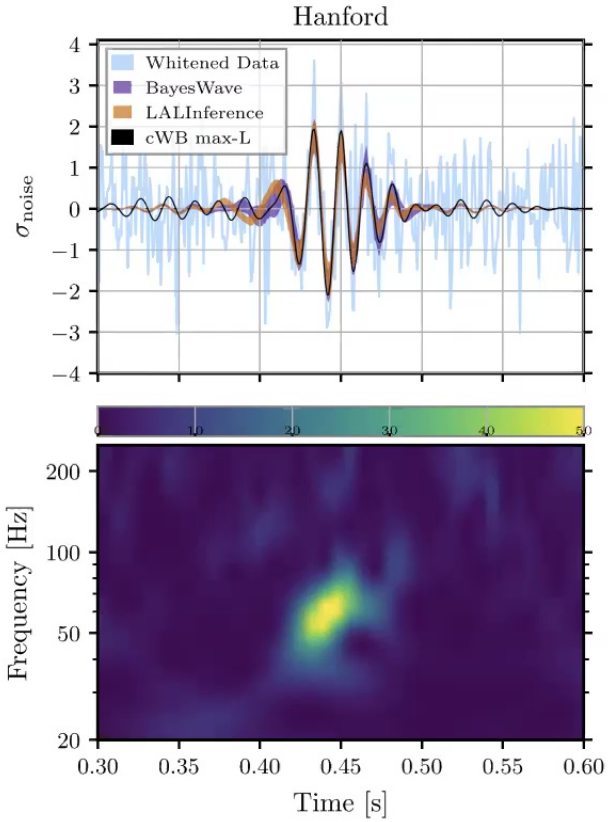
OUT THERE

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



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

Shortest signal yet



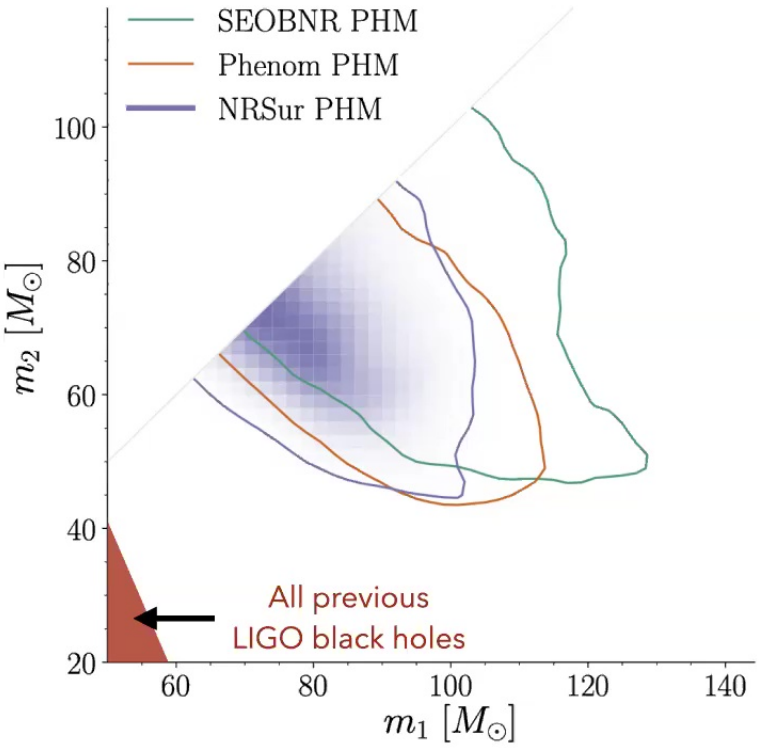
- ~0.1 seconds of data (4 cycles > 30 Hz)
- False-Alarm-Rate ~ 1/5000 years
- Highest detection significance in an "unmodeled burst search"
  - Ideal for hunting **Intermediate-mass Black Holes** (10^2-10^5 Msun)

    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)

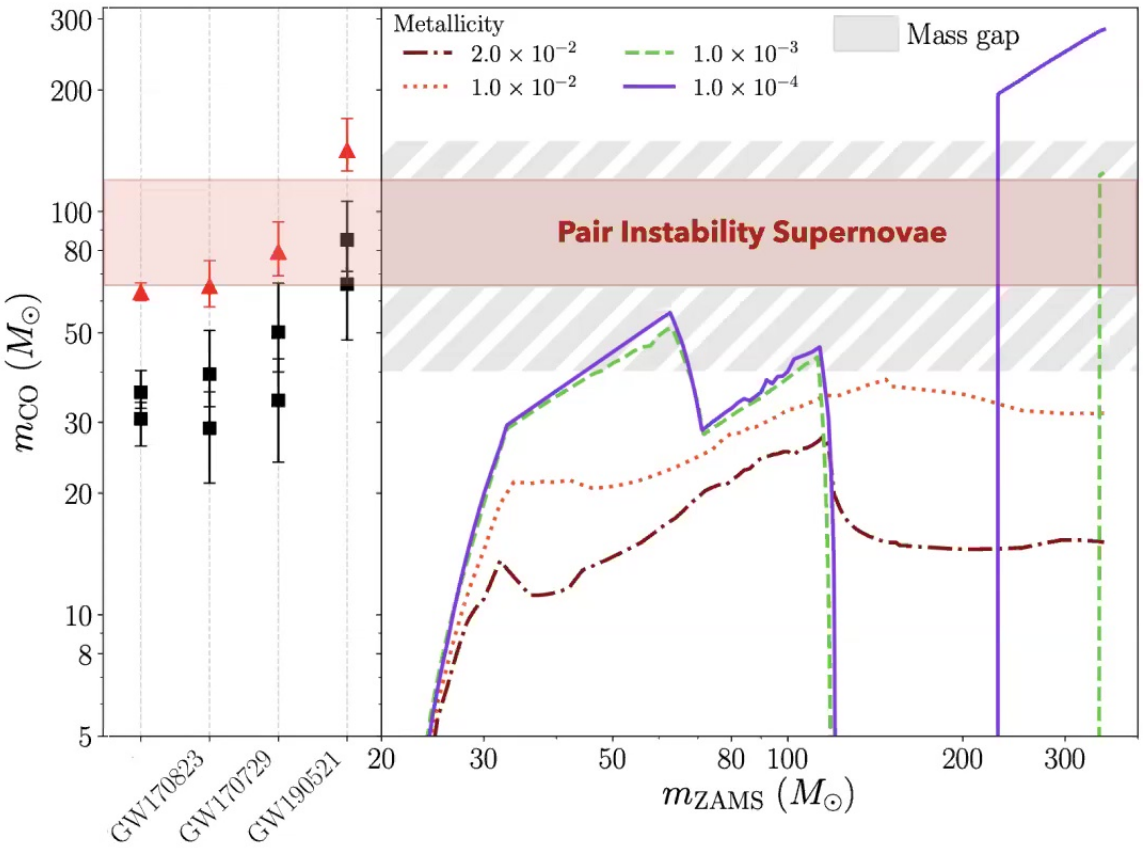
Unusually high masses

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



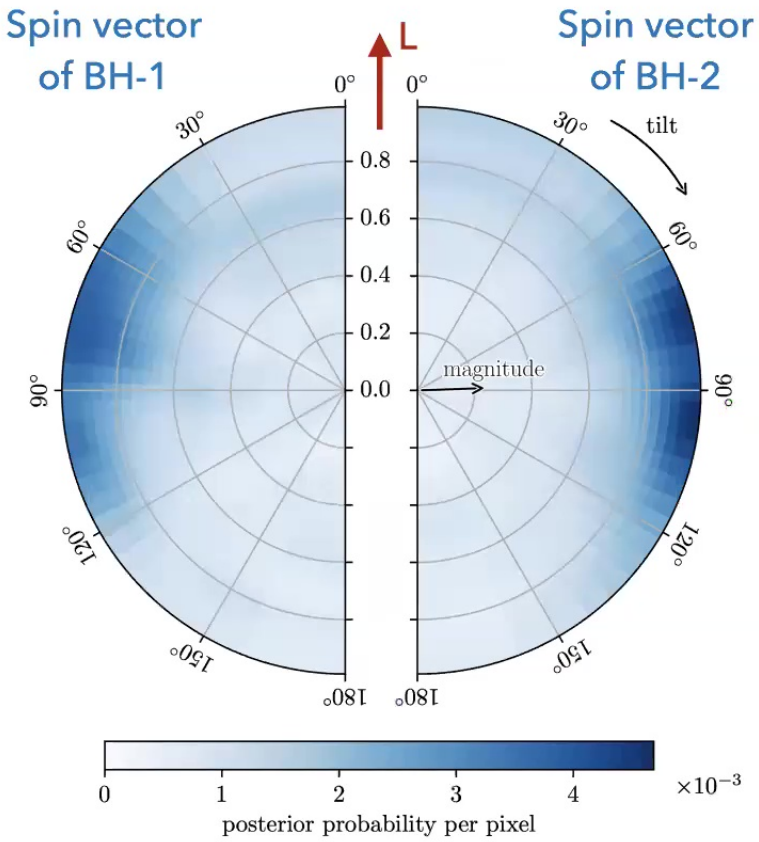
- 3 distinct state-of-the-art General Relativity (GR) signal models for Binary Black Hole (BBH) coalescence
- Compared with 3400+ numerical relativity simulations of BBH mergers
  KJ et al. (MAYA Catalog) - Classical & Quant. Grav. (2016)
  Boyle et al. (SXS Catalog), Healy et al. (RIT Catalog)
- **Both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

Mind the (black hole) gap!



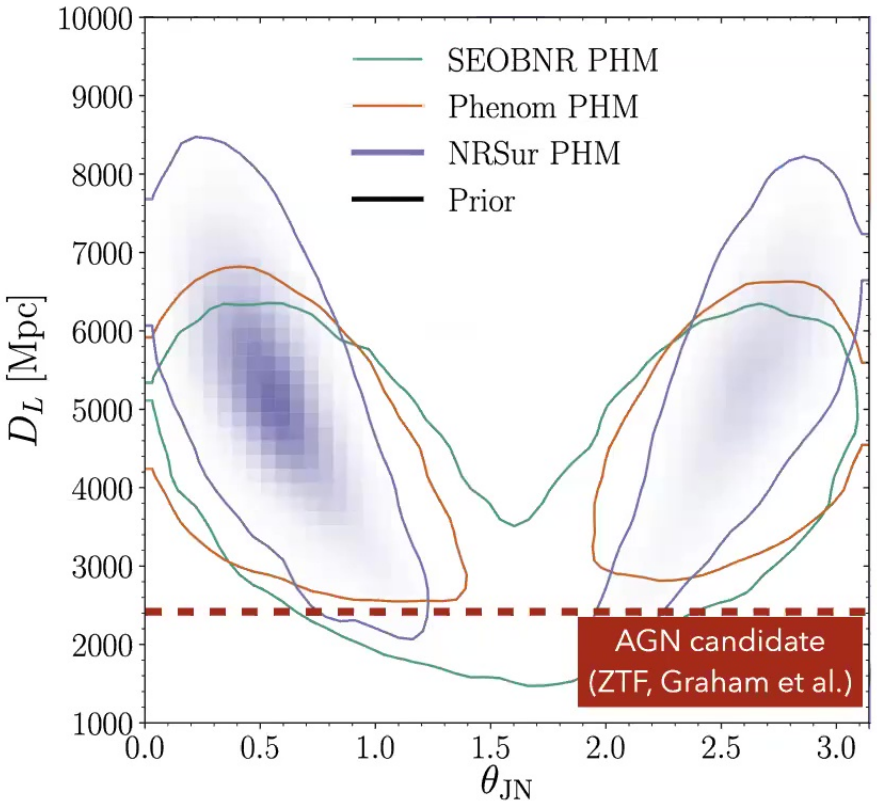
- BH mass-gap: $\sim 65 - 120\ M_\odot$
- Pair-Instability SNe: leaves no remnant
- BH-1: **0.1 - 0.3%** probability outside gap
- BH-2: **6 - 46 %** probability outside gap

Black holes were wobbling



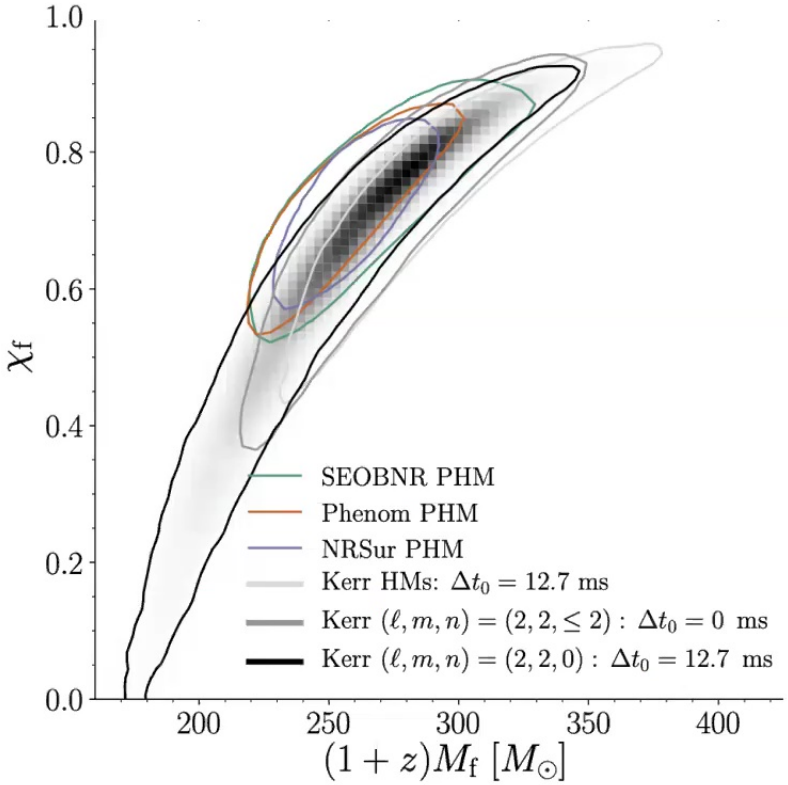
- Mild, but consistent evidence that the BBH exhibited spin-orbit precession just before the merger
- Both BH spins have little projection with orbital angular momentum axis - **evidence for dynamical capture**
- P(spins vs. no-spins) = 8.3 : 1
- P(precessing vs. aligned-spin) = 11.5 : 1

Farthest GW event yet



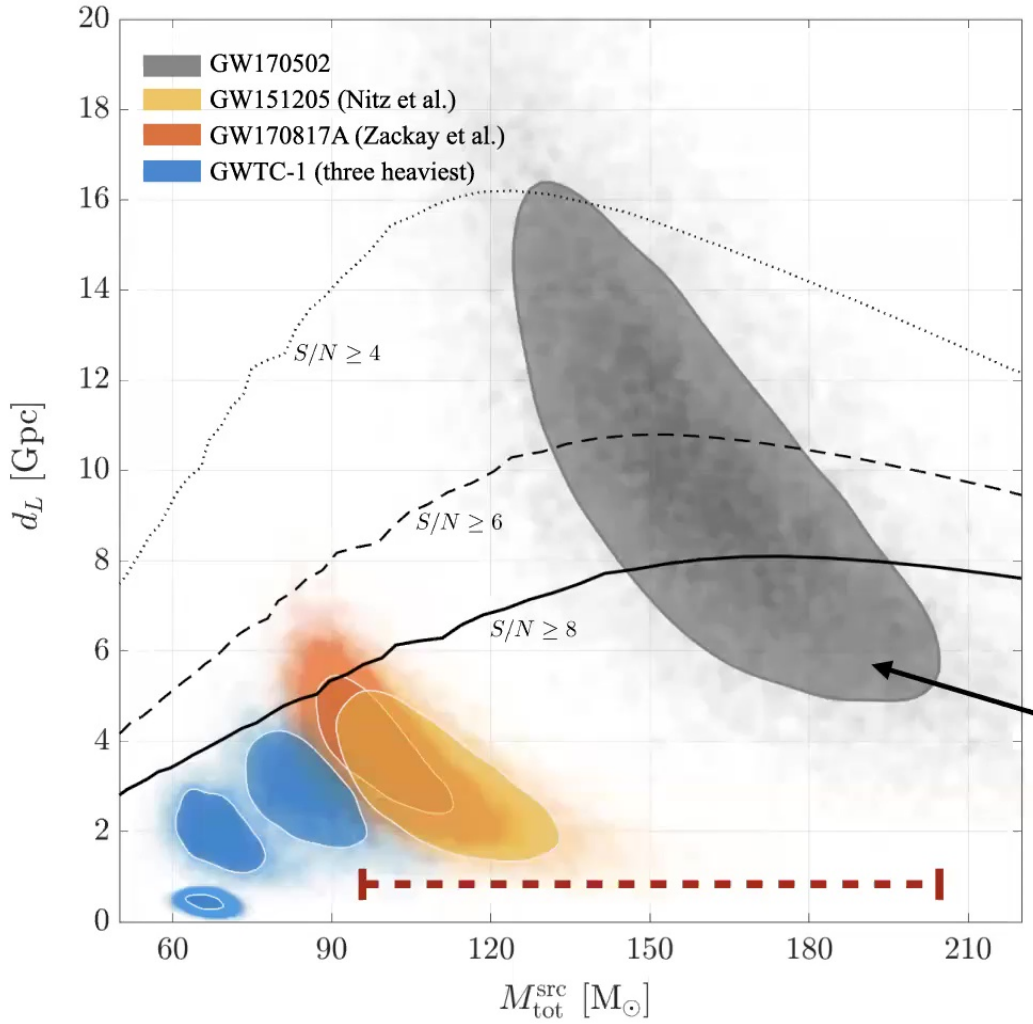
- **Redshift z ~ [0.5, 1.1]**
- Strong impact on luminosity distance estimation from radiation beyond the quadrupole term
  (tighter constraints on inclination)
  Calderón Bustillo, **KJ+**- Phys. Rev. D. (2018)
- Almost twice the distance than low-latency alert and EM-counterpart claim
  (mild support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

Consistency with GR



- **Residual tests**
  subtracting GR solutions from data leaves residual that is consistent with typical LIGO noise
  (No tests of 'echoes' so far for this event)
  Abedi, Afshordi +

- **Black hole ringdown**
  consistency in the properties of final black hole from pre- and post-merger analysis



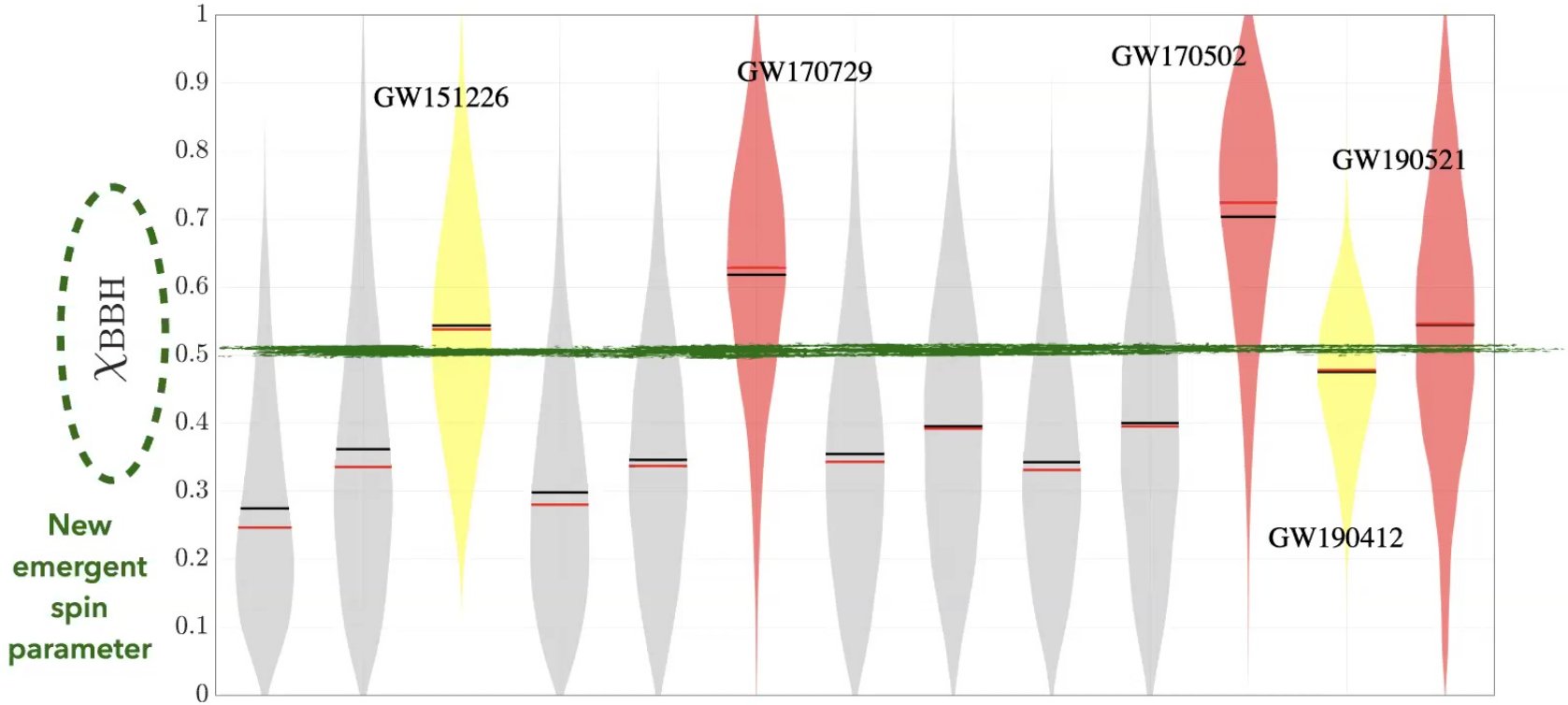
More "Lite" IMBHs

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

Udall, **KJ, KHB+**- Astrophysical Journal (2020)
KJ with LIGO-Virgo - Phys. Rev. D (2019)

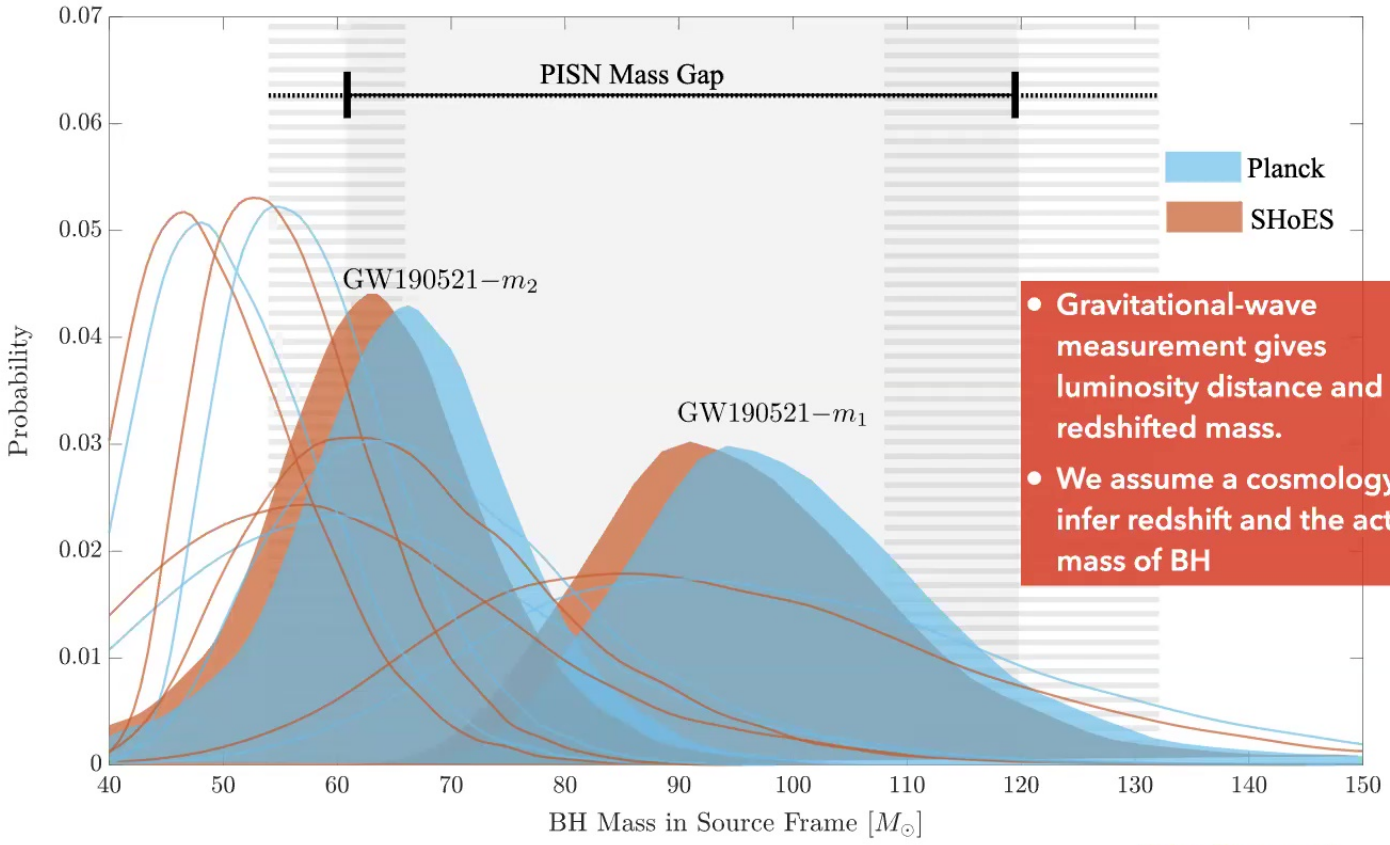
Primary BH mass, $m_1^{\rm src}$ ($M_\odot$)	94^{+44}_{-28}
Secondary BH mass, $m_2^{\rm src}$ ($M_\odot$)	62^{+30}_{-25}
Total mass, $M_{\rm tot}^{\rm src}$	157^{+55}_{-41}
Redshift, z	$1.37^{+0.93}_{-0.64}$

Lite-IMBHs = high spin mergers?



KJ, Holley-Bockelmann, O'shaughnessy (in-prep)

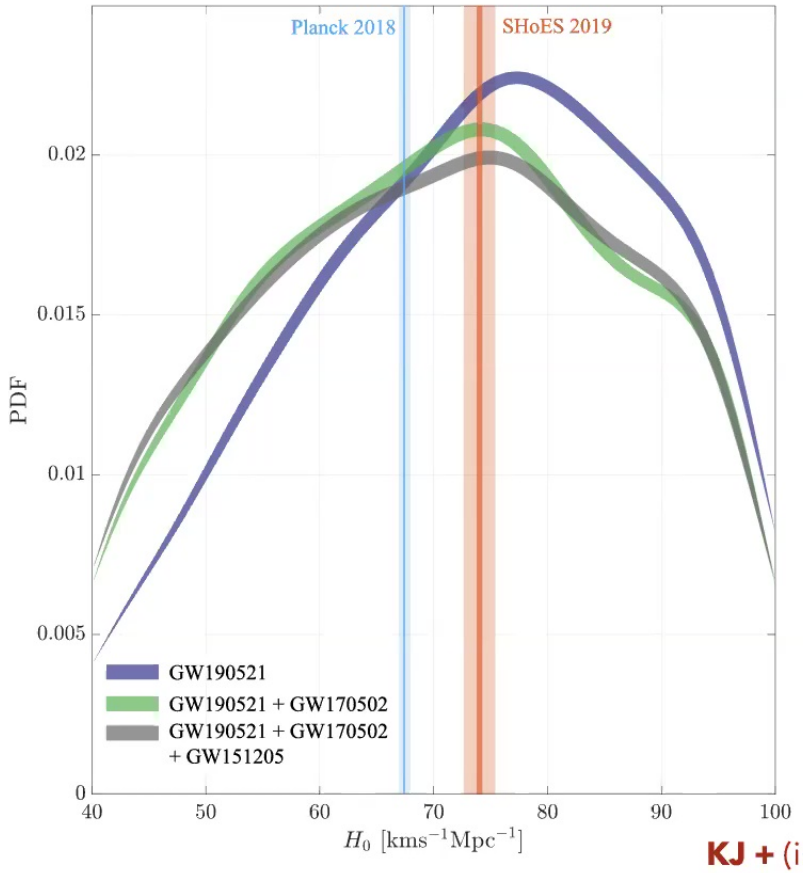
Hubble Constant & Mass-Gap



- 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)

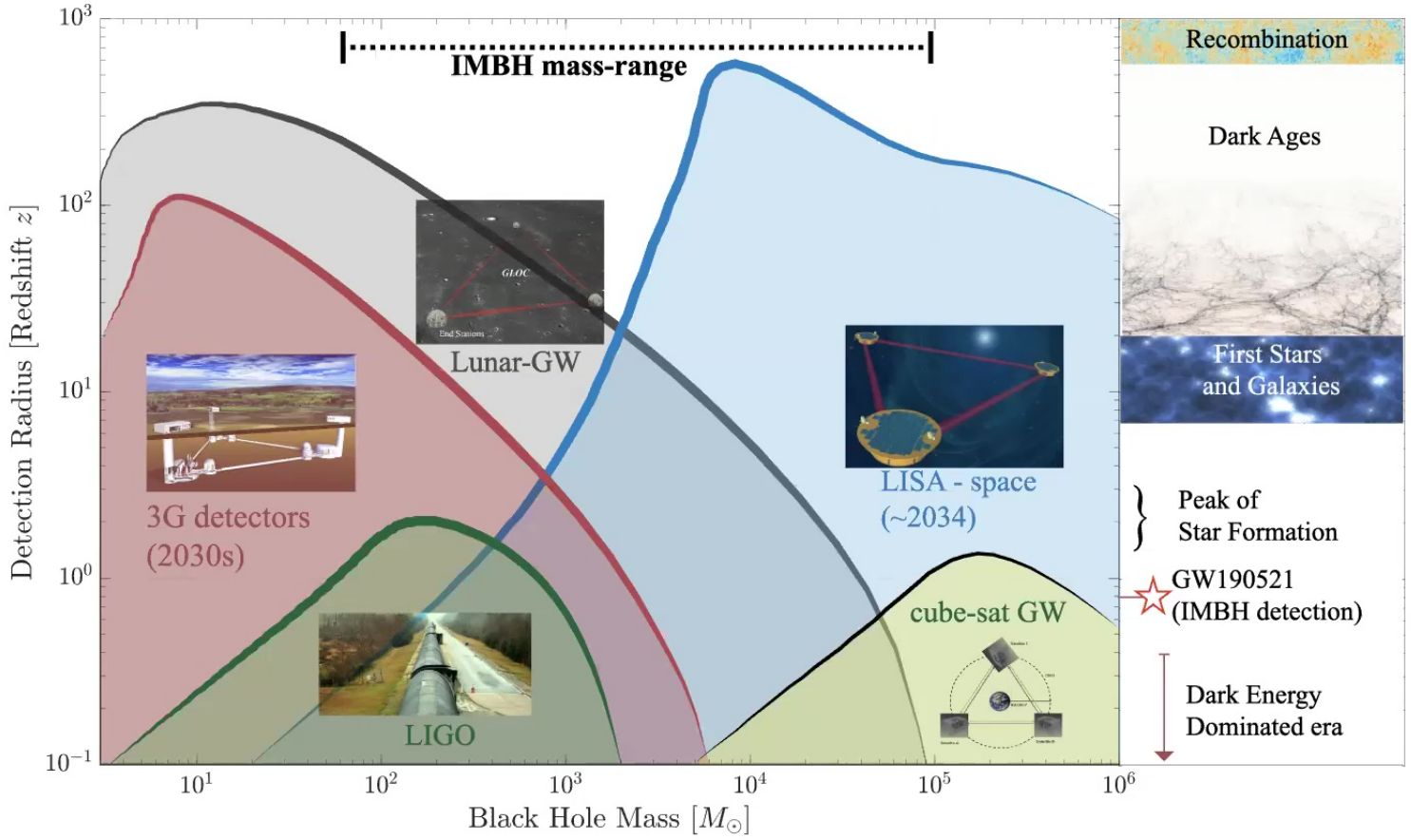
Hubble Constant & Mass-Gap

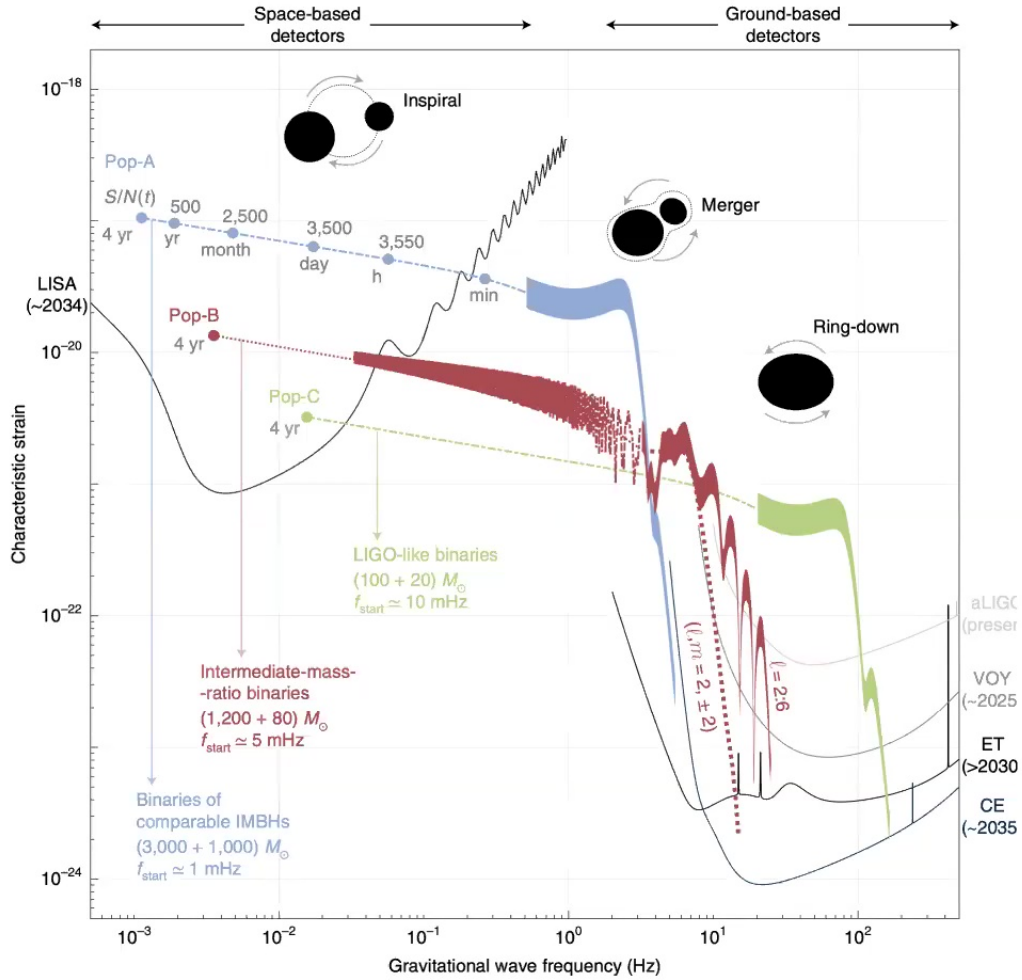


KJ + (in-prep)

- 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)

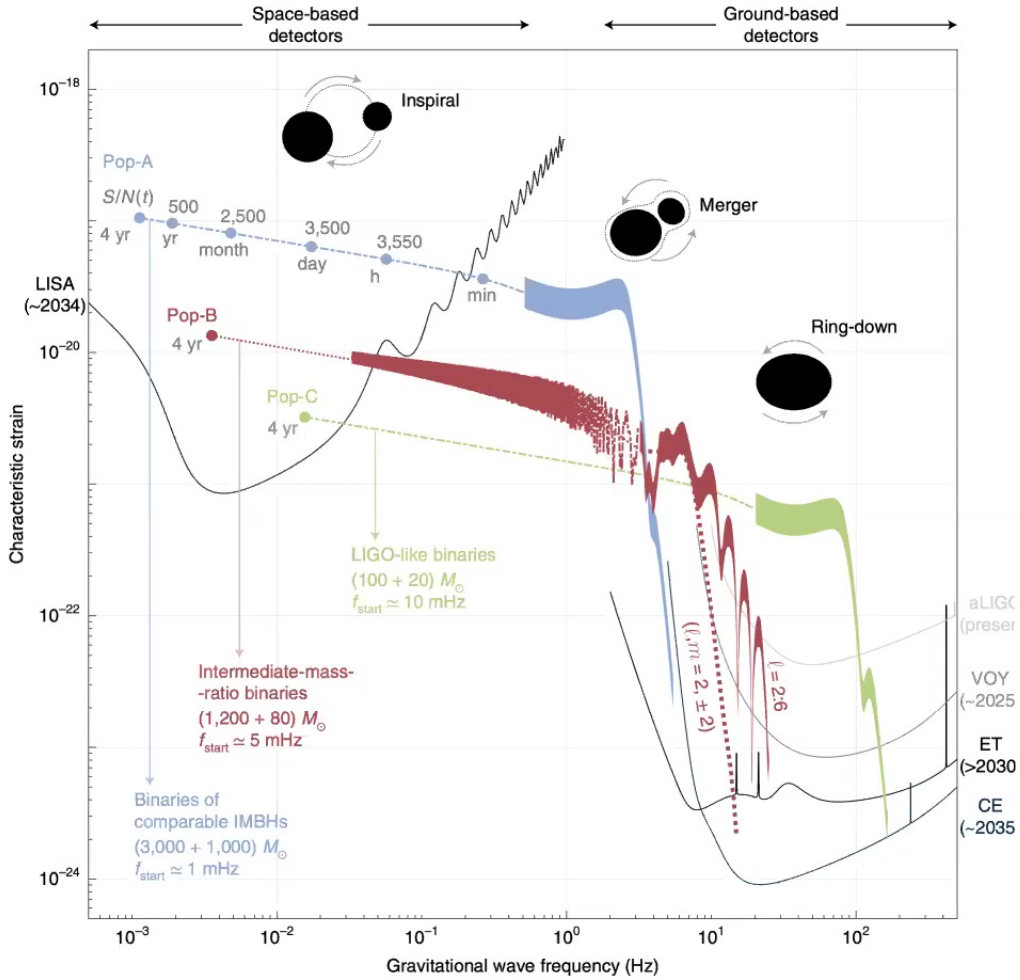
A new era for IMBHs





Multi-Band Astronomy

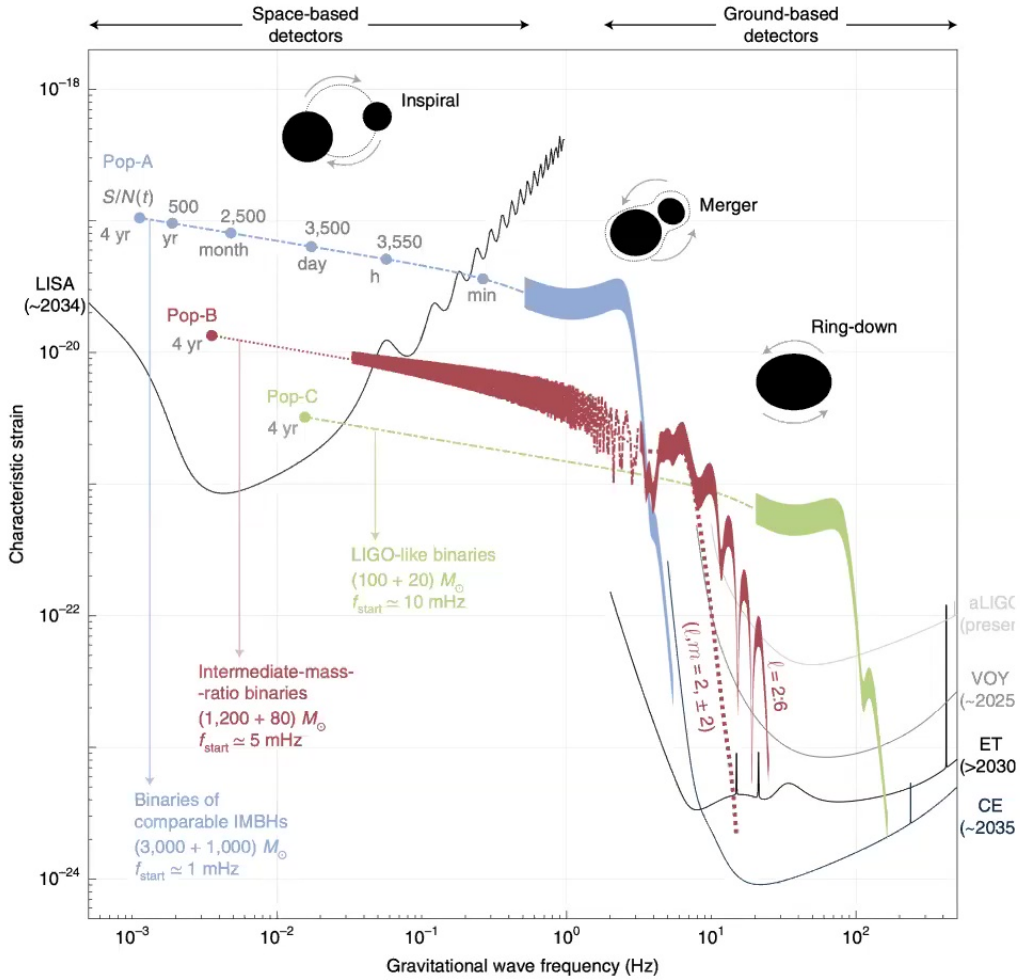
- IMBH binaries would be observed by the **LISA mission** (ESA/NASA) 4-10 years before merger
- Final stages (merger) will be observed by ground network *(Einstein Telescope, Cosmic Explorer, LIGO-A+)*
- **New era of multi-wavelength GW observations to study single astrophysical source**

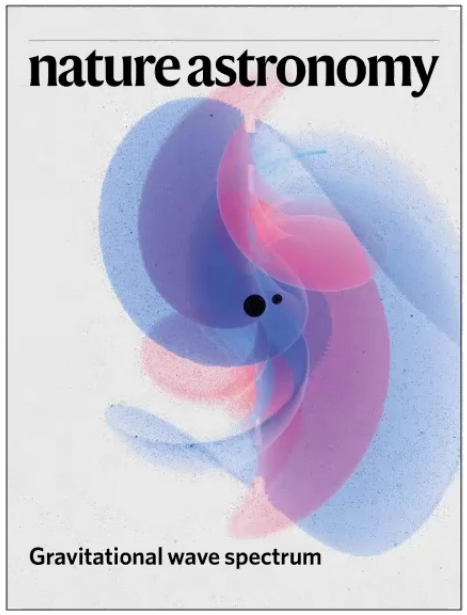


Multi-Band Astronomy

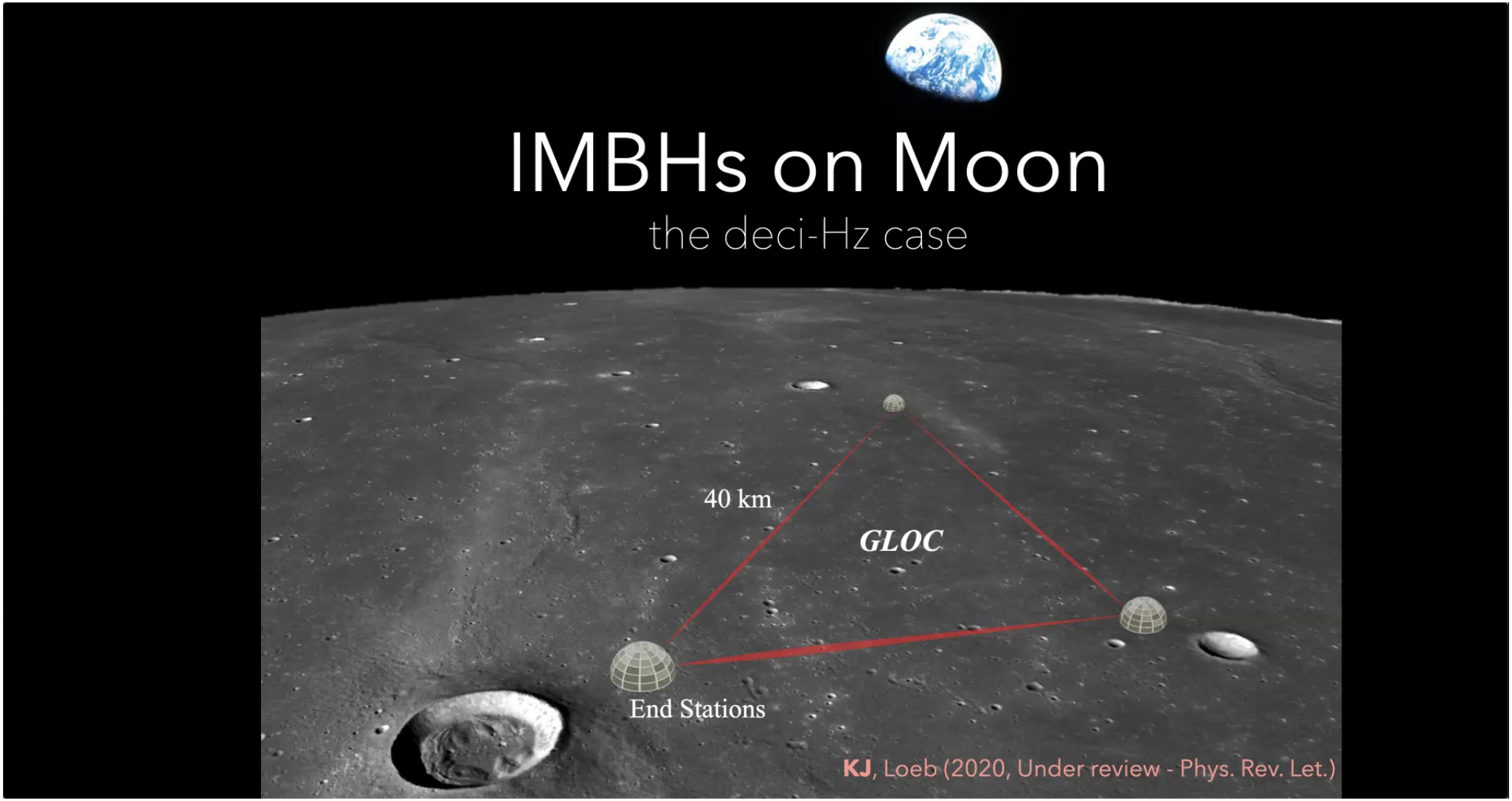
- IMBH binaries would be observed by the **LISA mission** (ESA/NASA) 4-10 years before merger
- Final stages (merger) will be observed by ground network *(Einstein Telescope, Cosmic Explorer, LIGO-A+)*
- **New era of multi-wavelength GW observations to study single astrophysical source**

Multi-Band Astronomy





Jani et al.
Nature Astronomy Cover Story
(March 2020 Issue)


IMBHs on Moon
the deci-Hz case
40 km
GLOC
End Stations
KJ, Loeb (2020, Under review - Phys. Rev. Let.)

IMBHs on Moon

Snowmass2021 - Letter of Interest

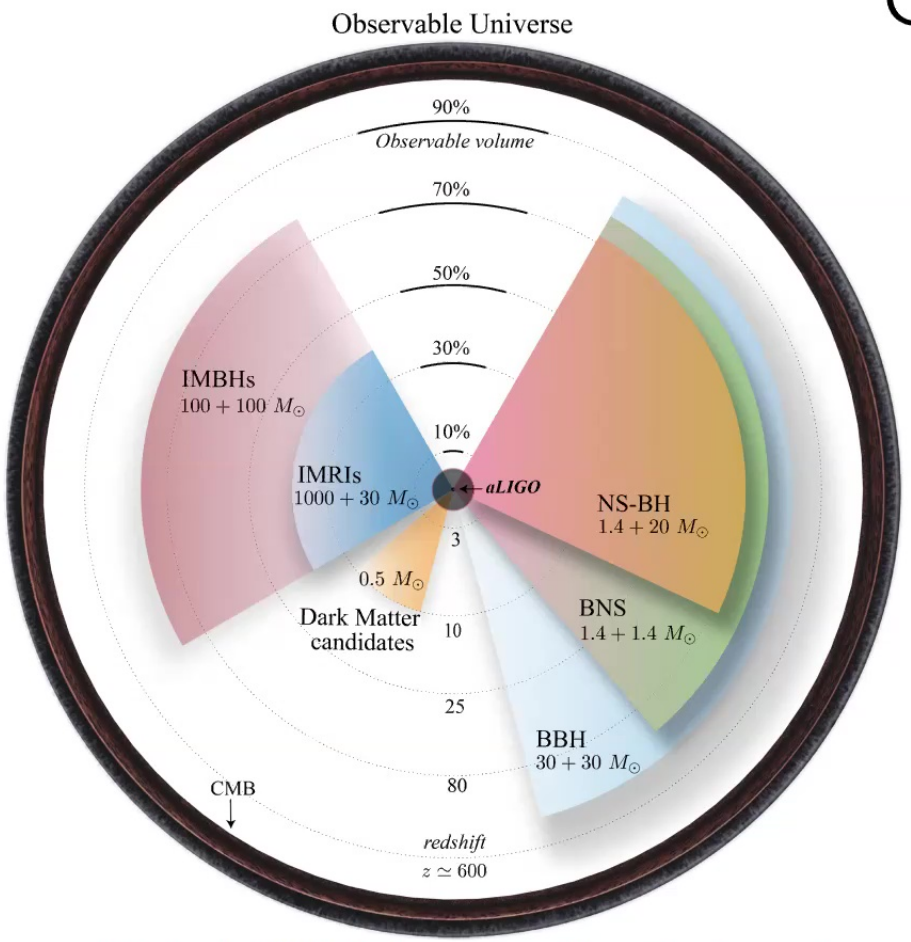
A deci-Hz Gravitational-Wave Lunar Observatory for Cosmology

>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)*



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

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!

Present - 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)
- Mergers of Ultra-Dwarf Galaxies
  Palmese+ (2020)

Exotic

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

Present - GW190521 Origins?

Astrophysical

- Stellar origins *(<0.8% stars will contribute)*
  KJ, Loeb - ApJ Letters (2019)

- **AGN disk** *(hierarchical, EM counterparts)*
  Bartos, McKernan, Ford + (>2017)

Exotic

- Core Collapse Supernovae

- **Highly Eccentric Collisions**
  Gayathri+ (2020), Romero-Shaw+ (2020)

Conclusion : 100-1000 solar mass "Lite" IMBHs are the most exciting GW sources for this decade