Science overview of LIGO/Virgo and LISA

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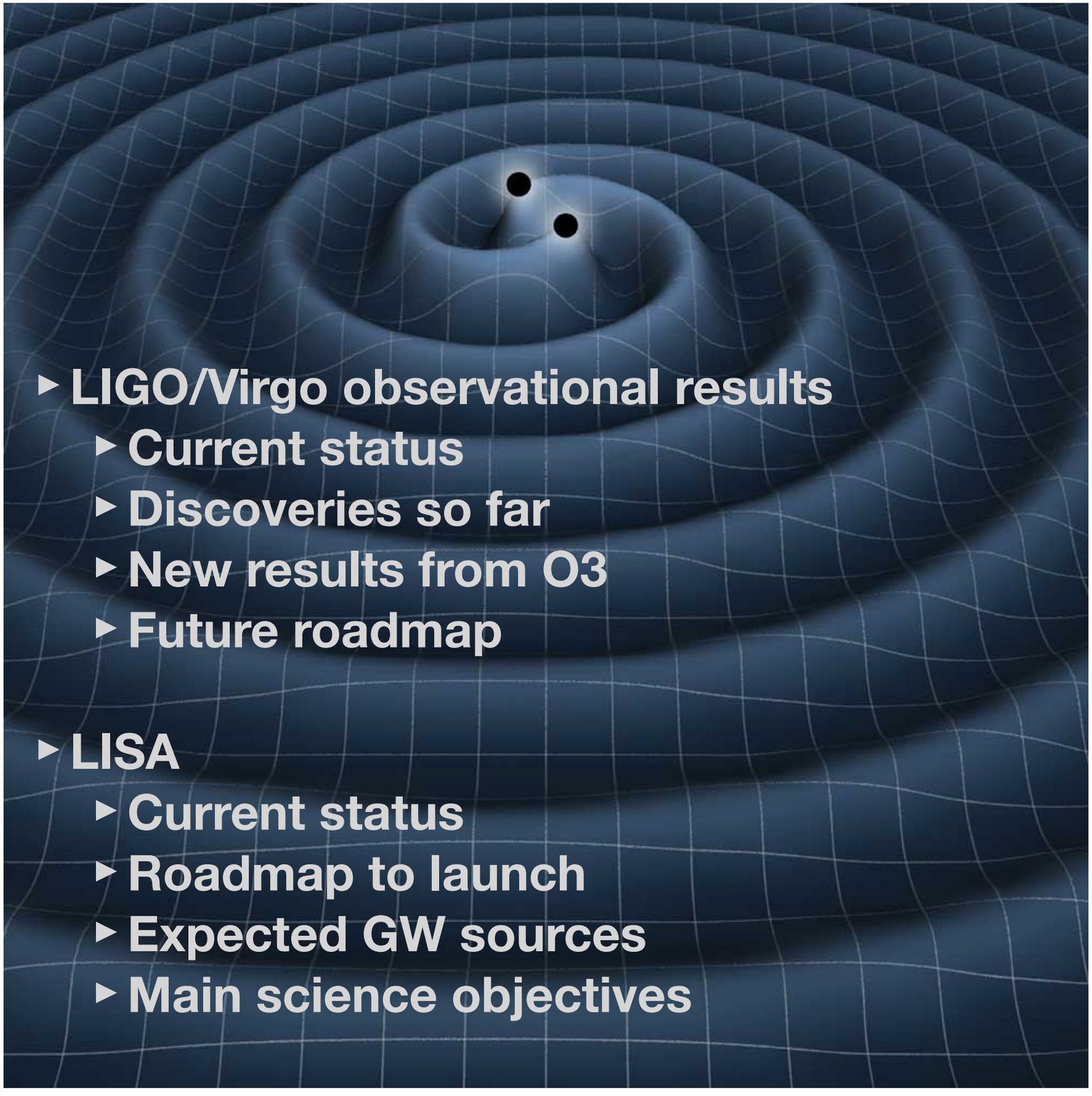
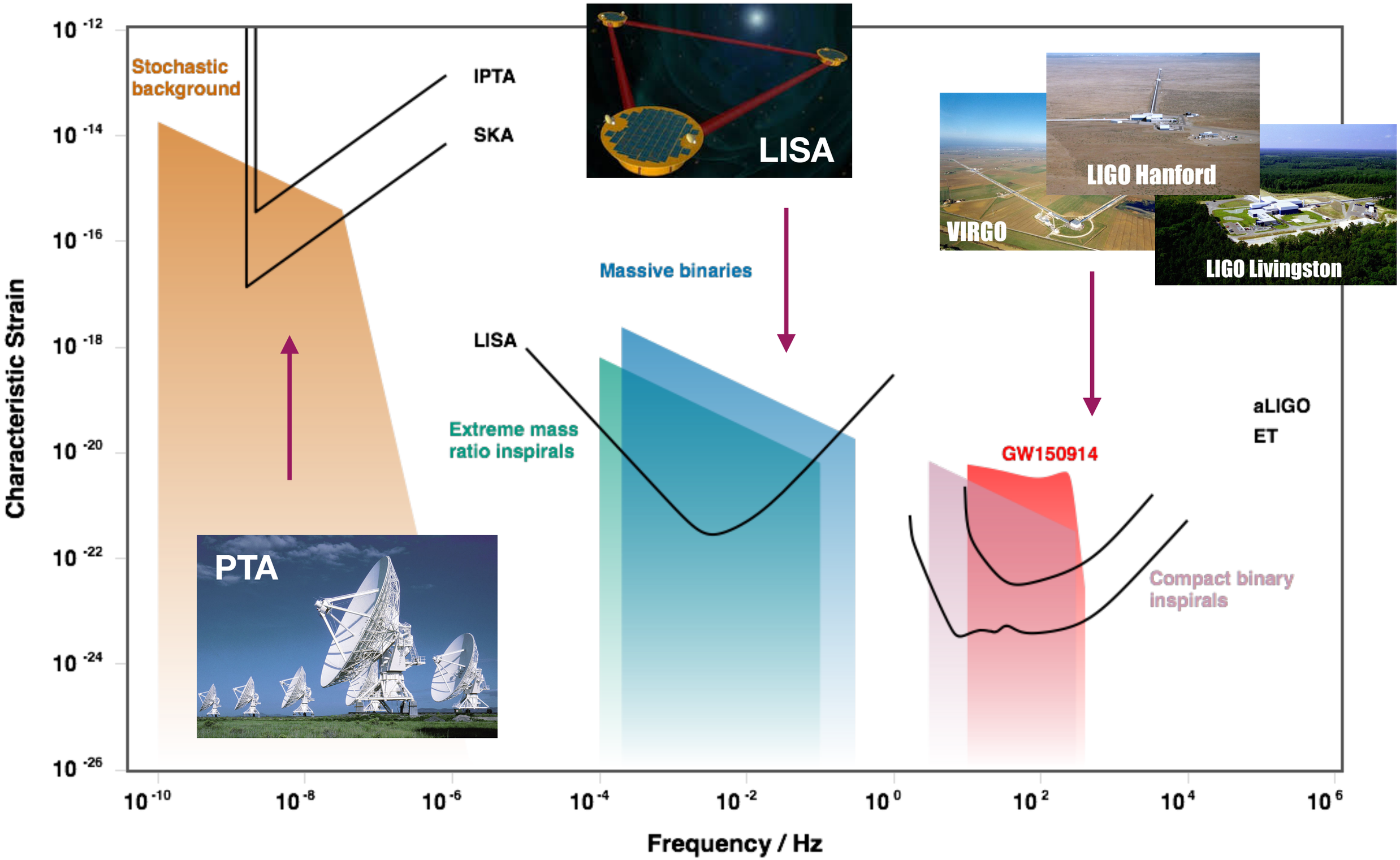
Outline



- LIGO/Virgo observational results
  - Current status
  - Discoveries so far
  - New results from O3
  - Future roadmap
- LISA
  - Current status
  - Roadmap to launch
  - Expected GW sources
  - Main science objectives

GW landscape

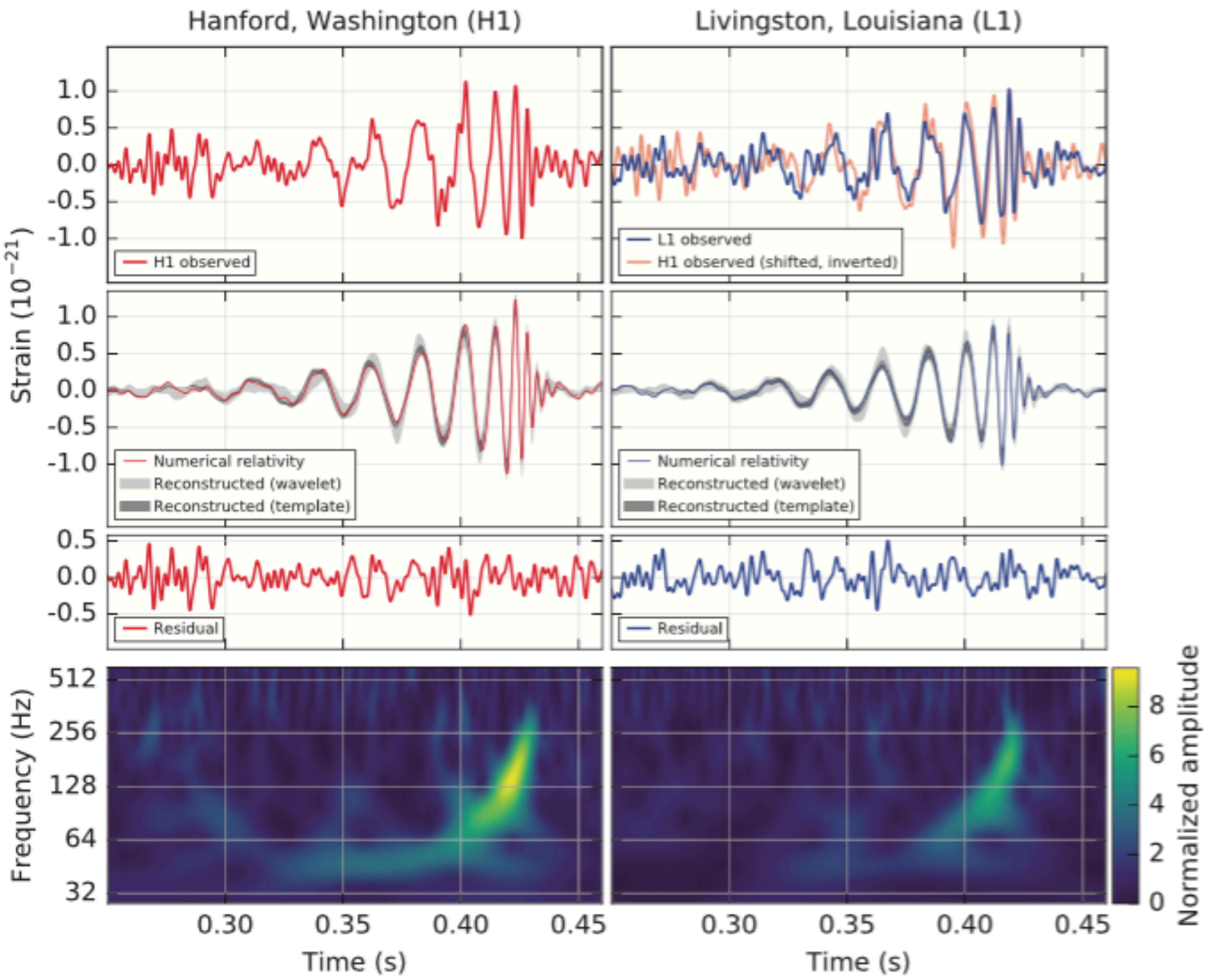


Current detector network

LIGO/Virgo discoveries

Ground-based detector network observational timeline:

- O1: 09/2015 - 01/2016 (4 months), LIGO only (LH BNS range ~80Mpc), 3 BBHs



GW150914

LIGO/Virgo discoveries

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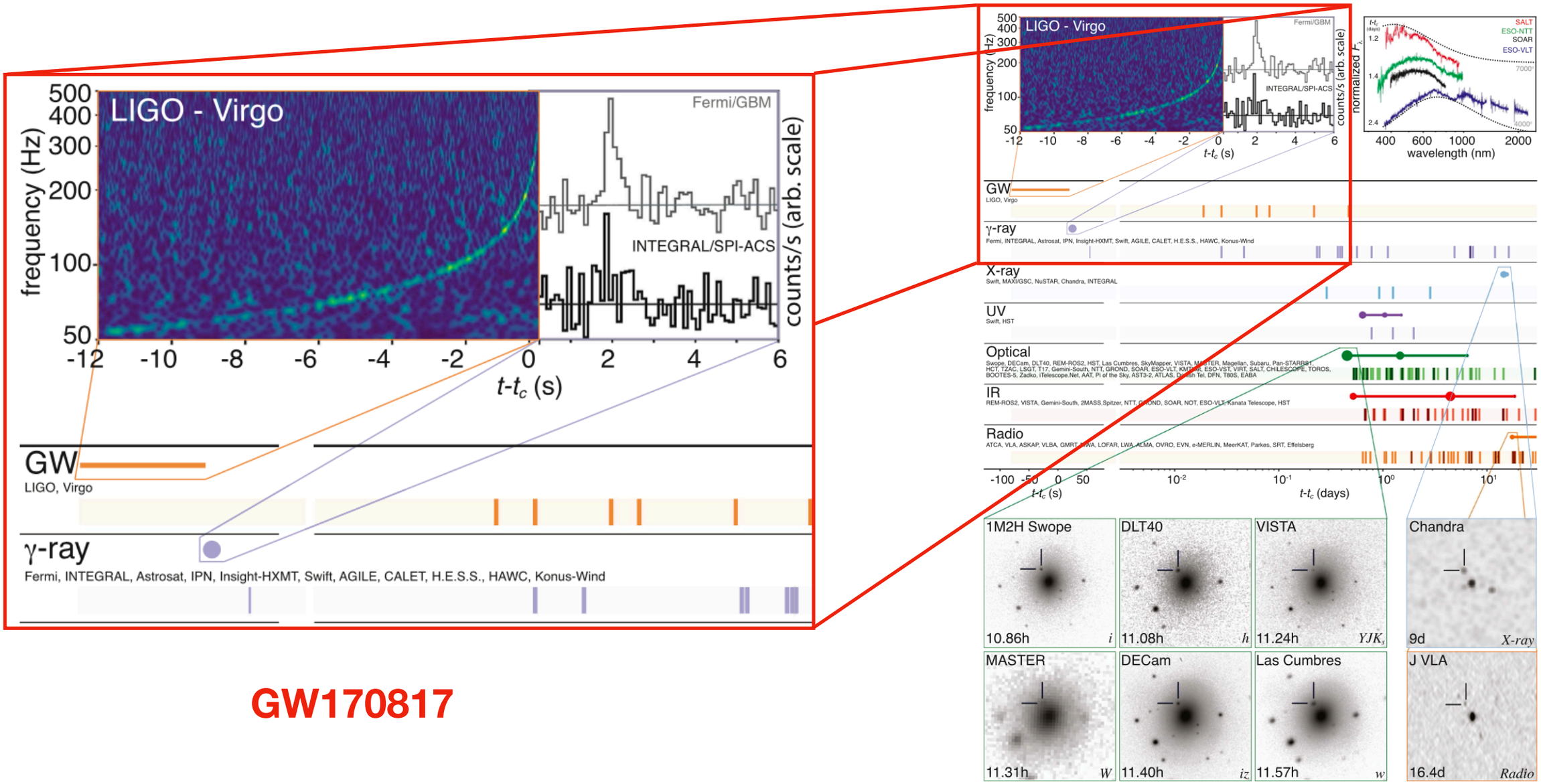

GW170817

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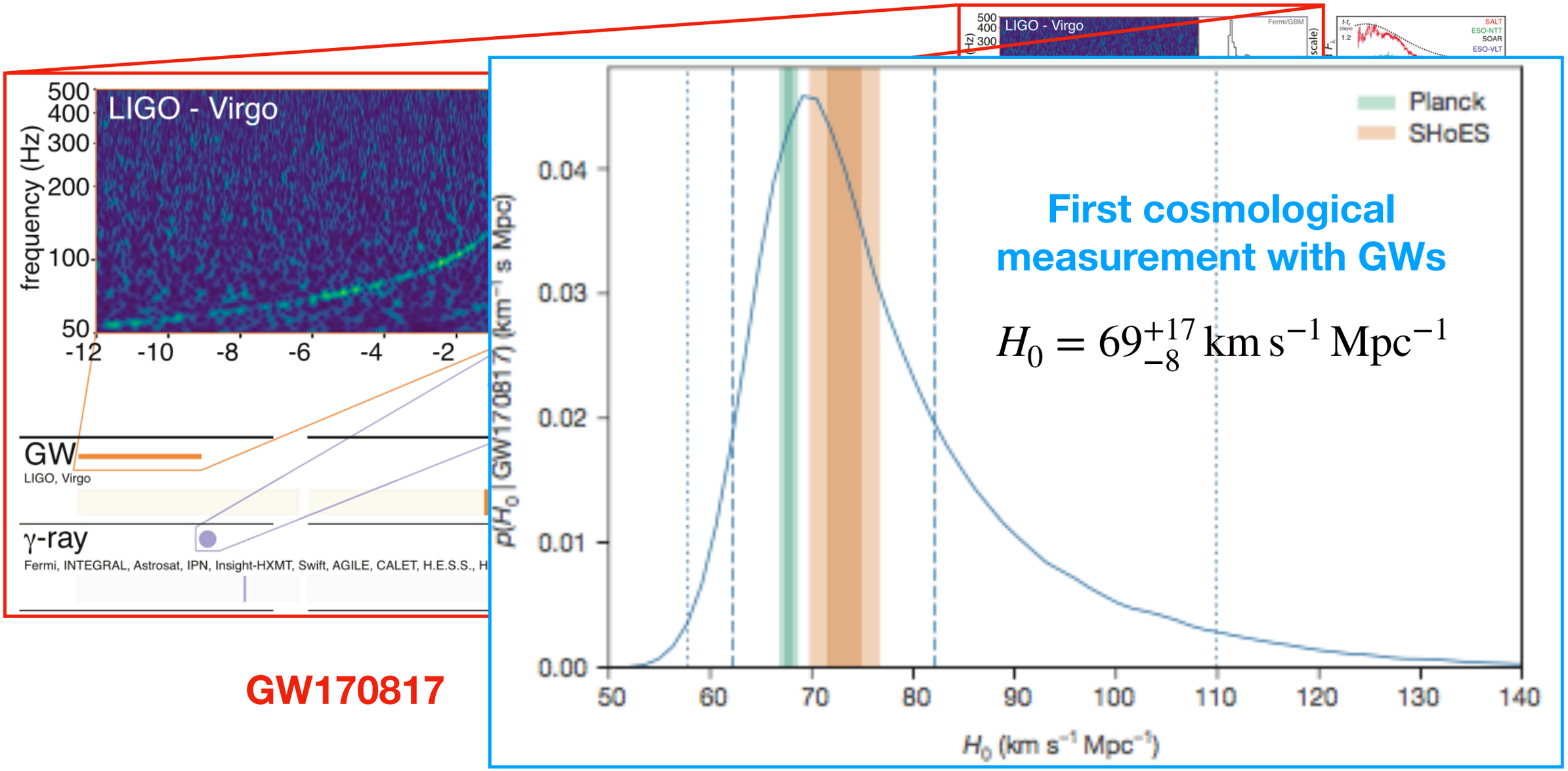

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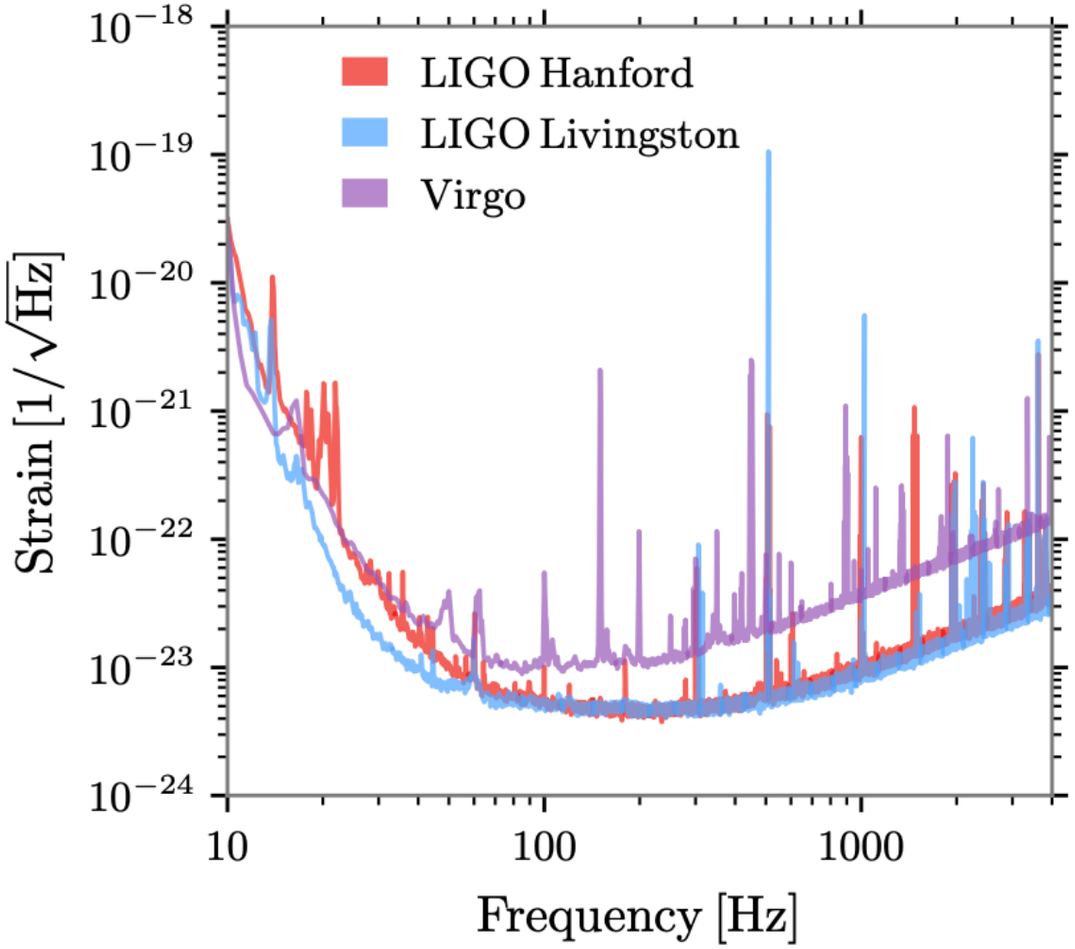
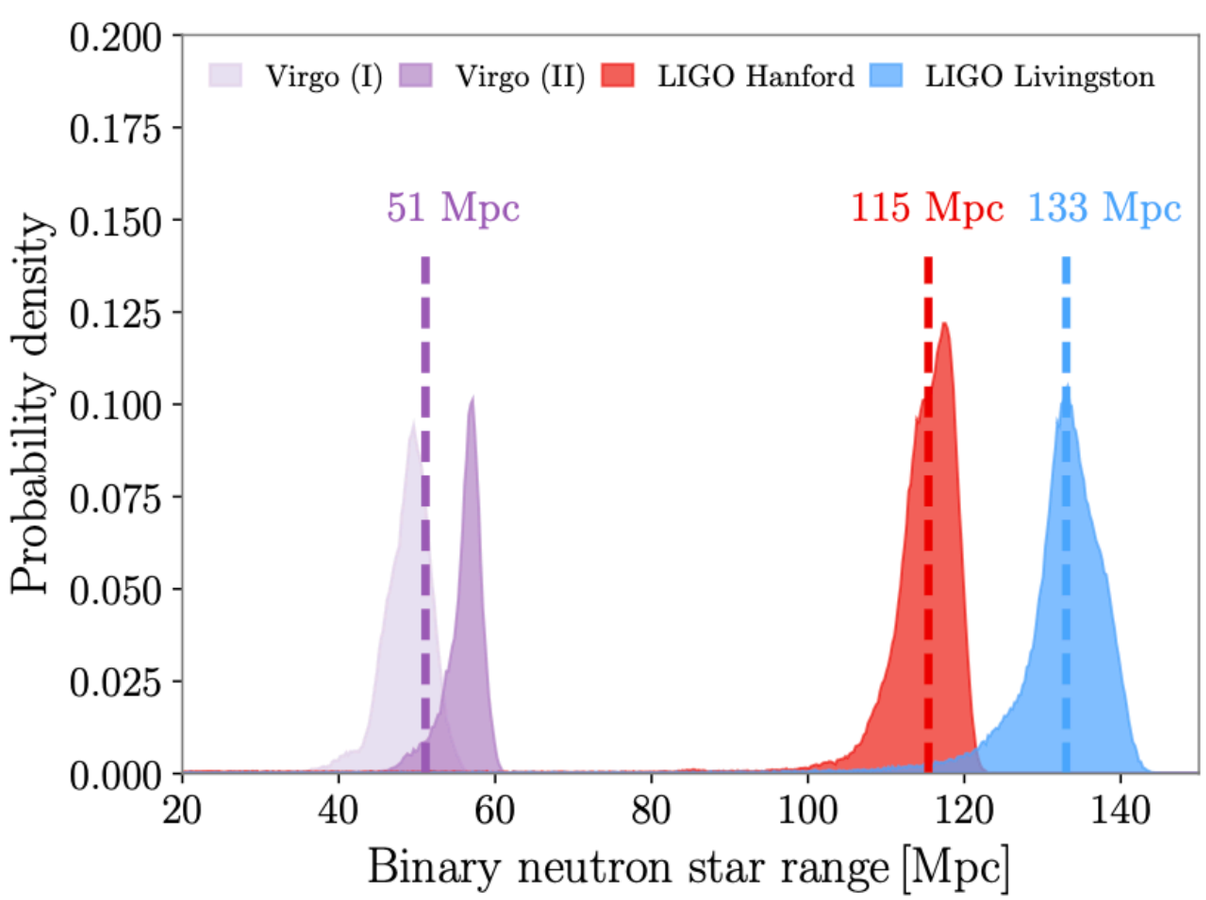
- O3: 04/2019 - 03/2020 (1 year), LIGO (~130Mpc) + VIRGO (~50Mpc), 79 events, 73 BBHs + 2 BNSs + 4 NSBHs [LVK, *PRX* (2020)] [LVK, *ApJL* (2021)] [LVK, *arXiv* (2021)]





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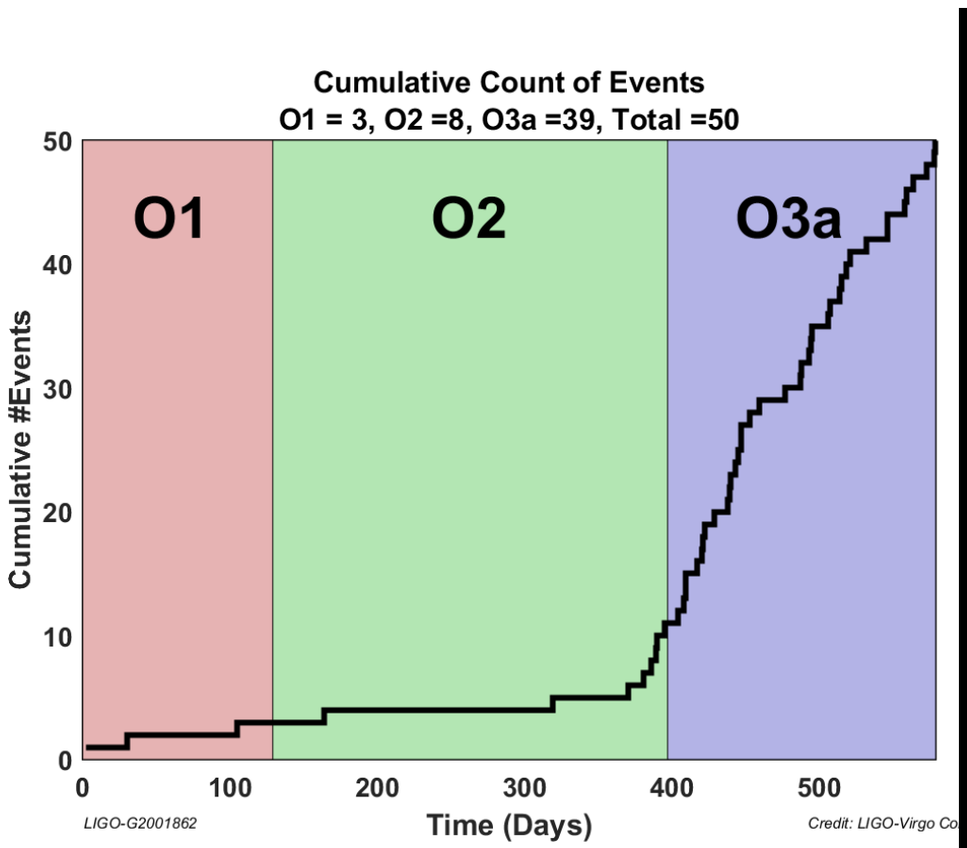

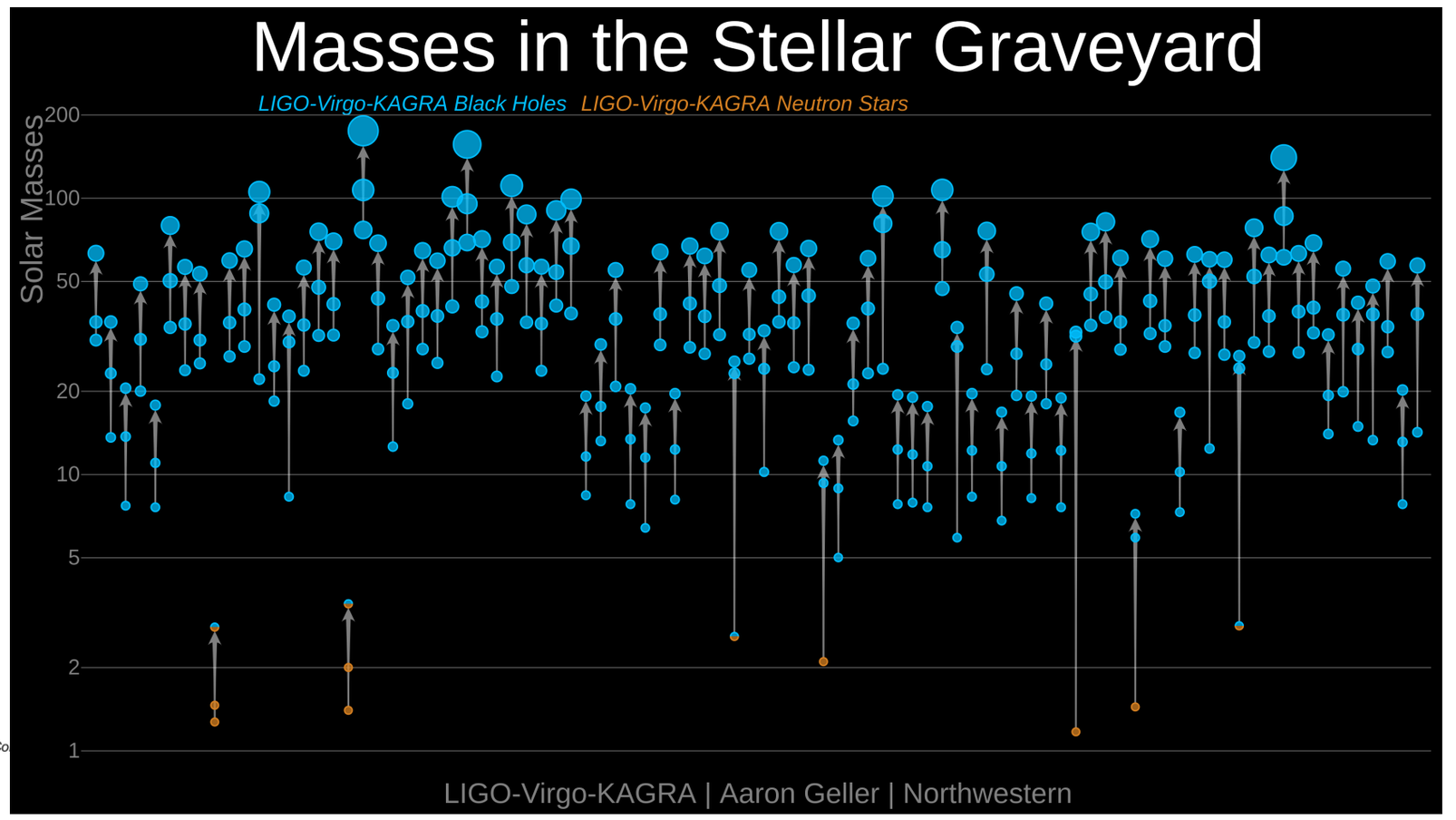

Future roadmap

Ground-based detector network observational timeline:

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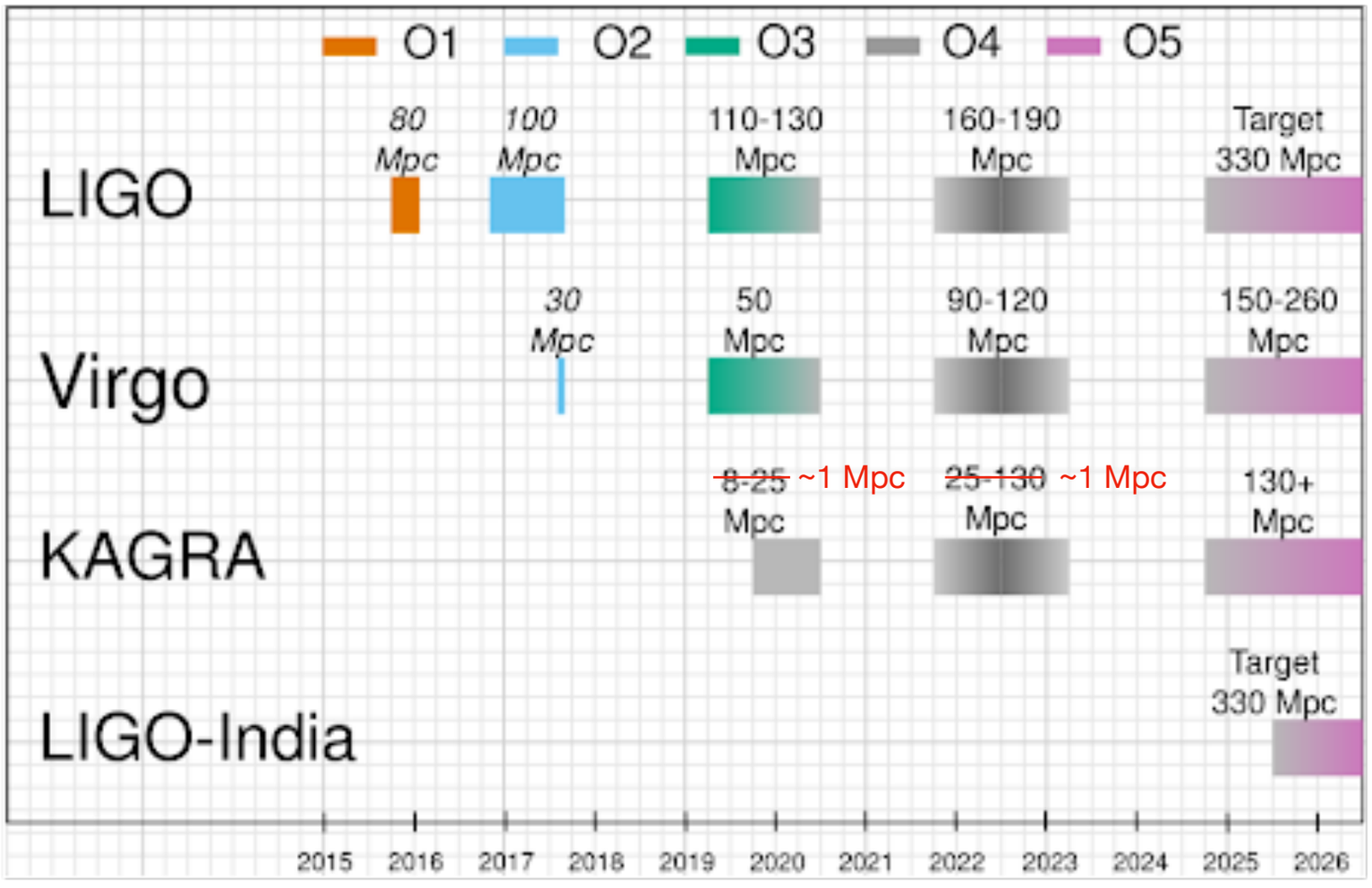
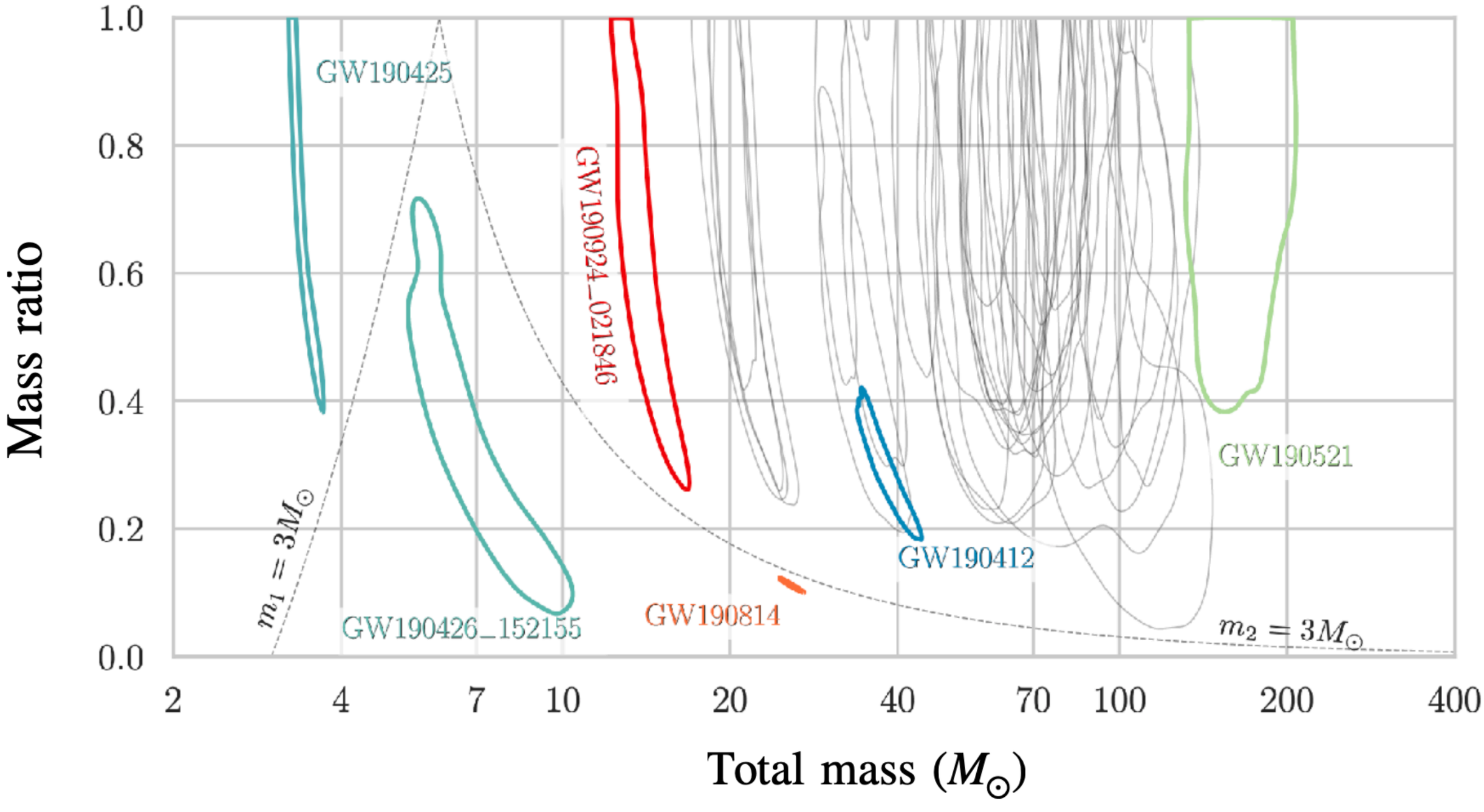
- O4: ~2023
  LIGO+VIRGO+KAGRA(?)
- O5: ~2026?
  LIGO India should join



Some highlights from O3

Remarkable detections:

LVK arXiv:2111.03606



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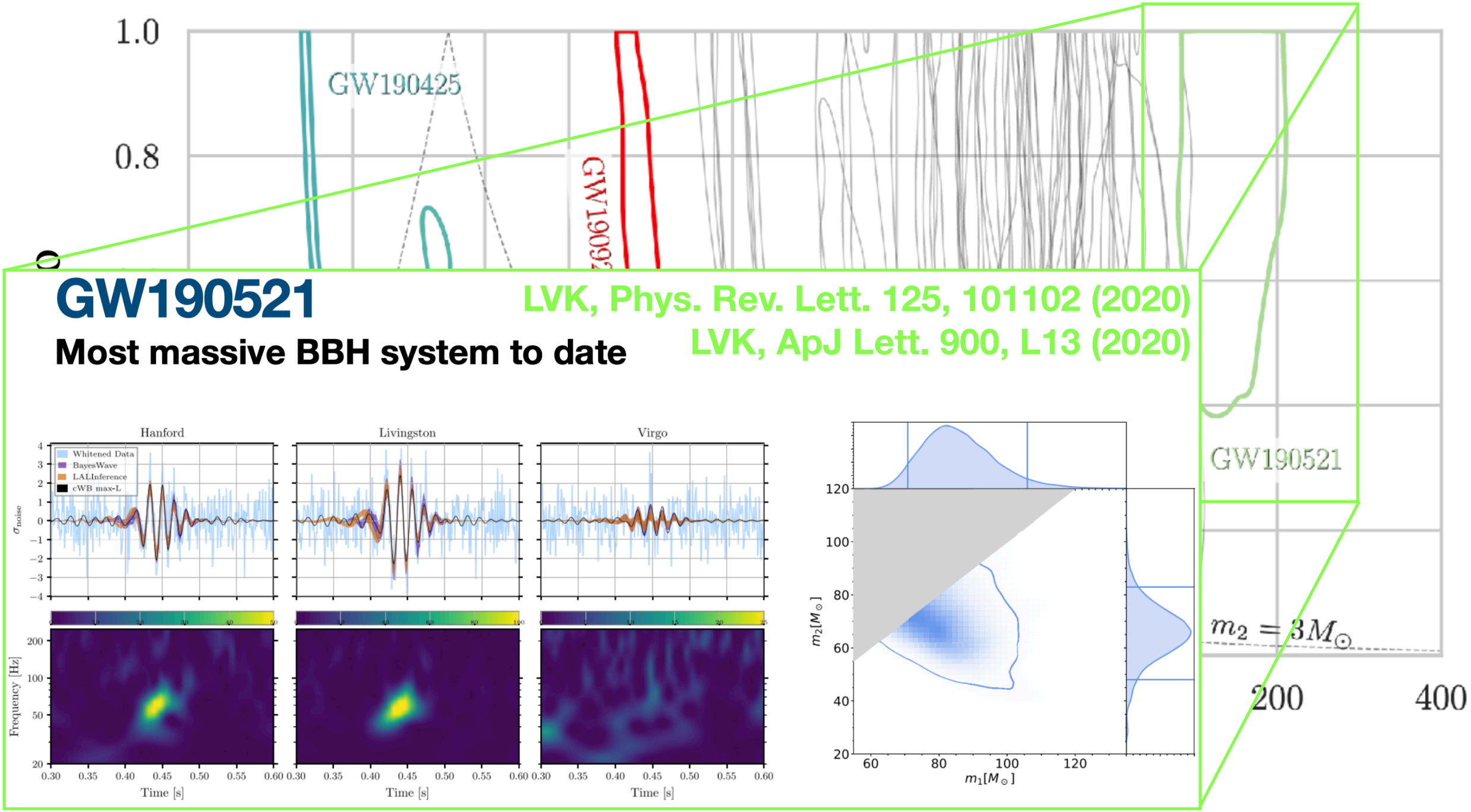

GW190521

Most massive BBH system to date

LVK, Phys. Rev. Lett. 125, 101102 (2020)

LVK, ApJ Lett. 900, L13 (2020)

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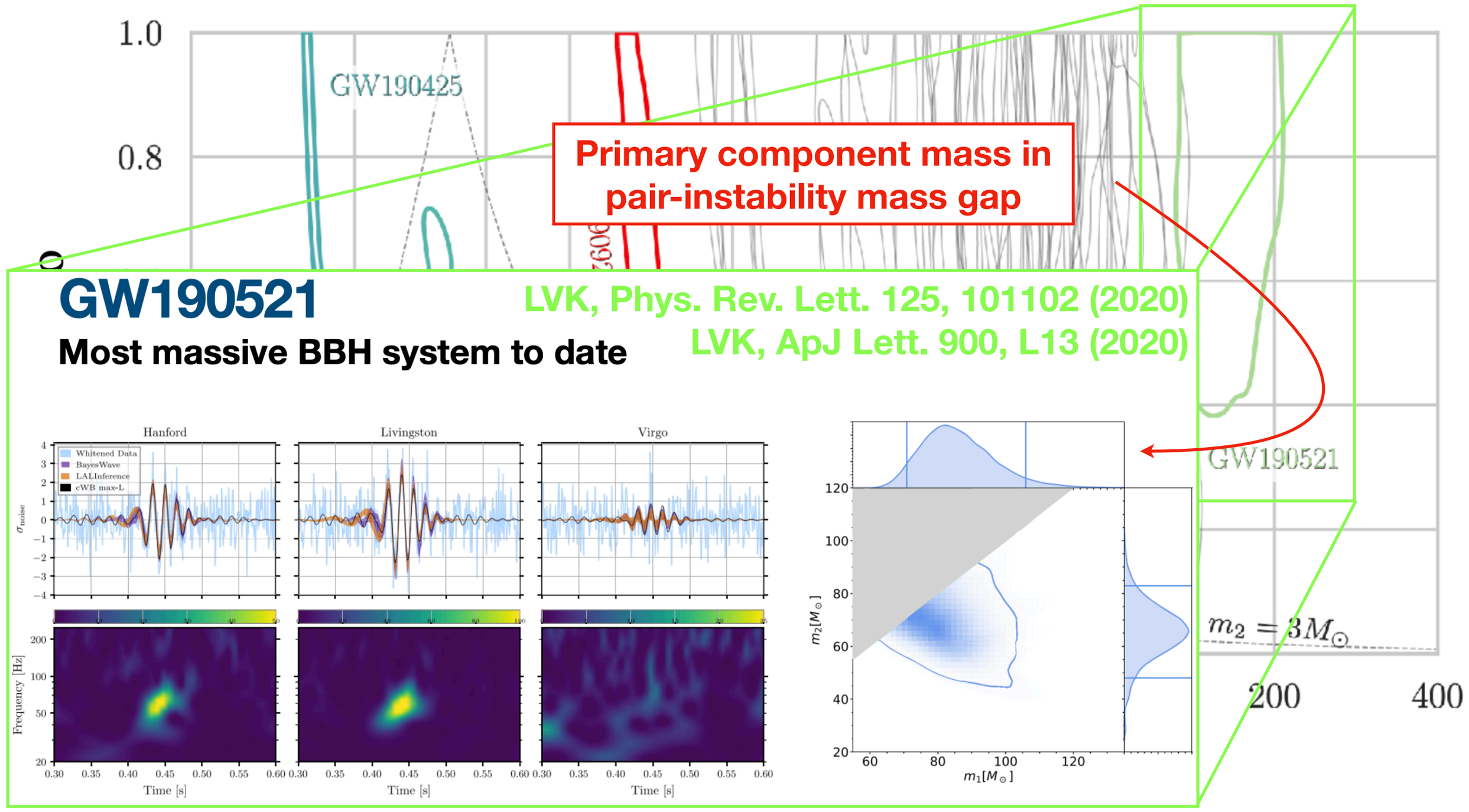

Primary component mass in pair-instability mass gap

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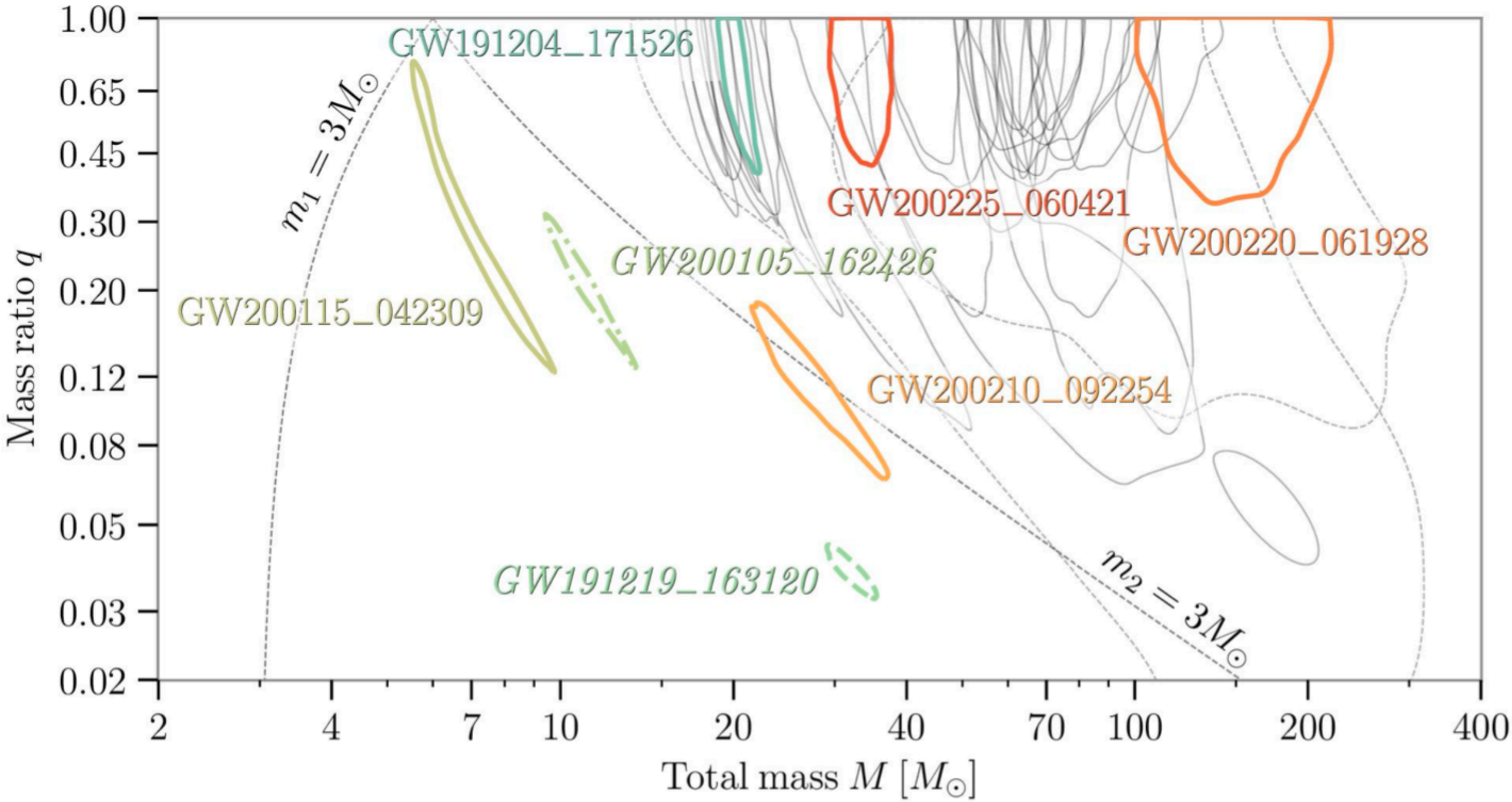

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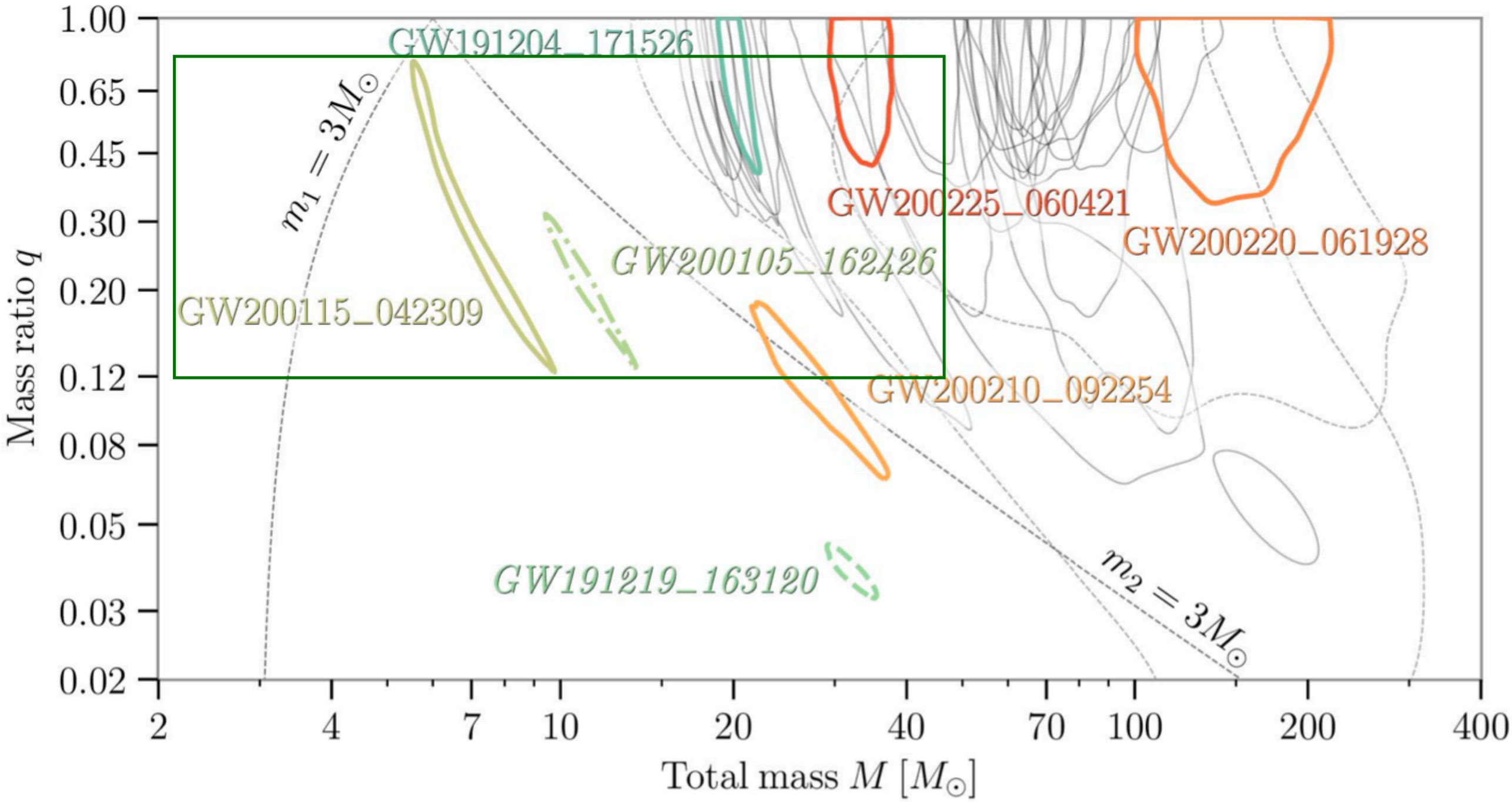


Some highlights from O3

Remarkable detections:

GW200105 and GW200115

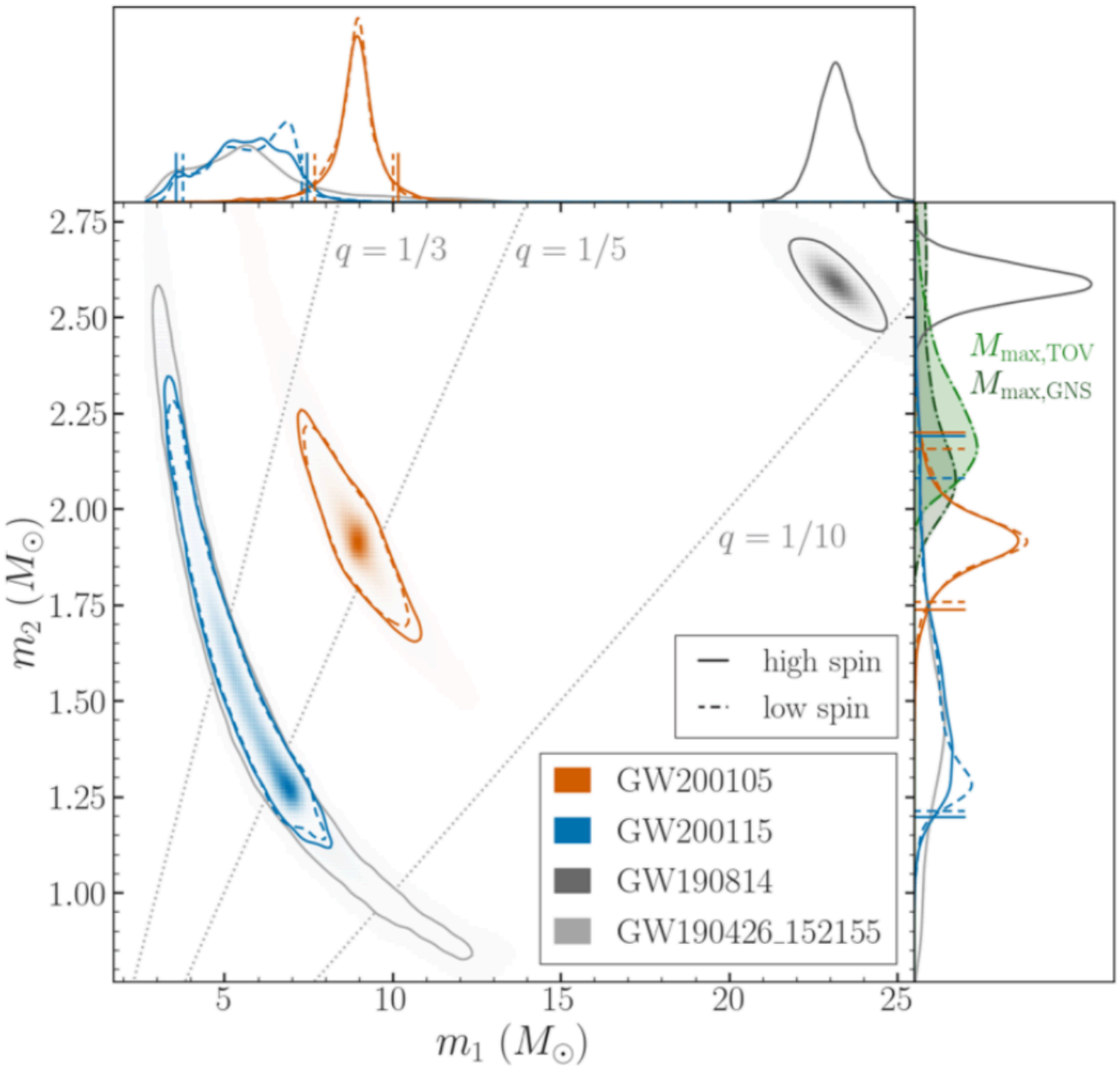
NS-BH Systems

GW200105 $m_1 = 8.9^{+1.2}_{-1.5}$ $m_2 = 1.9^{+0.3}_{-0.2}$

GW200115 $m_1 = 5.7^{+1.8}_{-2.1}$ $m_2 = 1.5^{+0.7}_{-0.3}$

Consistent with known NS masses

No EM counterpart, but not unexpected

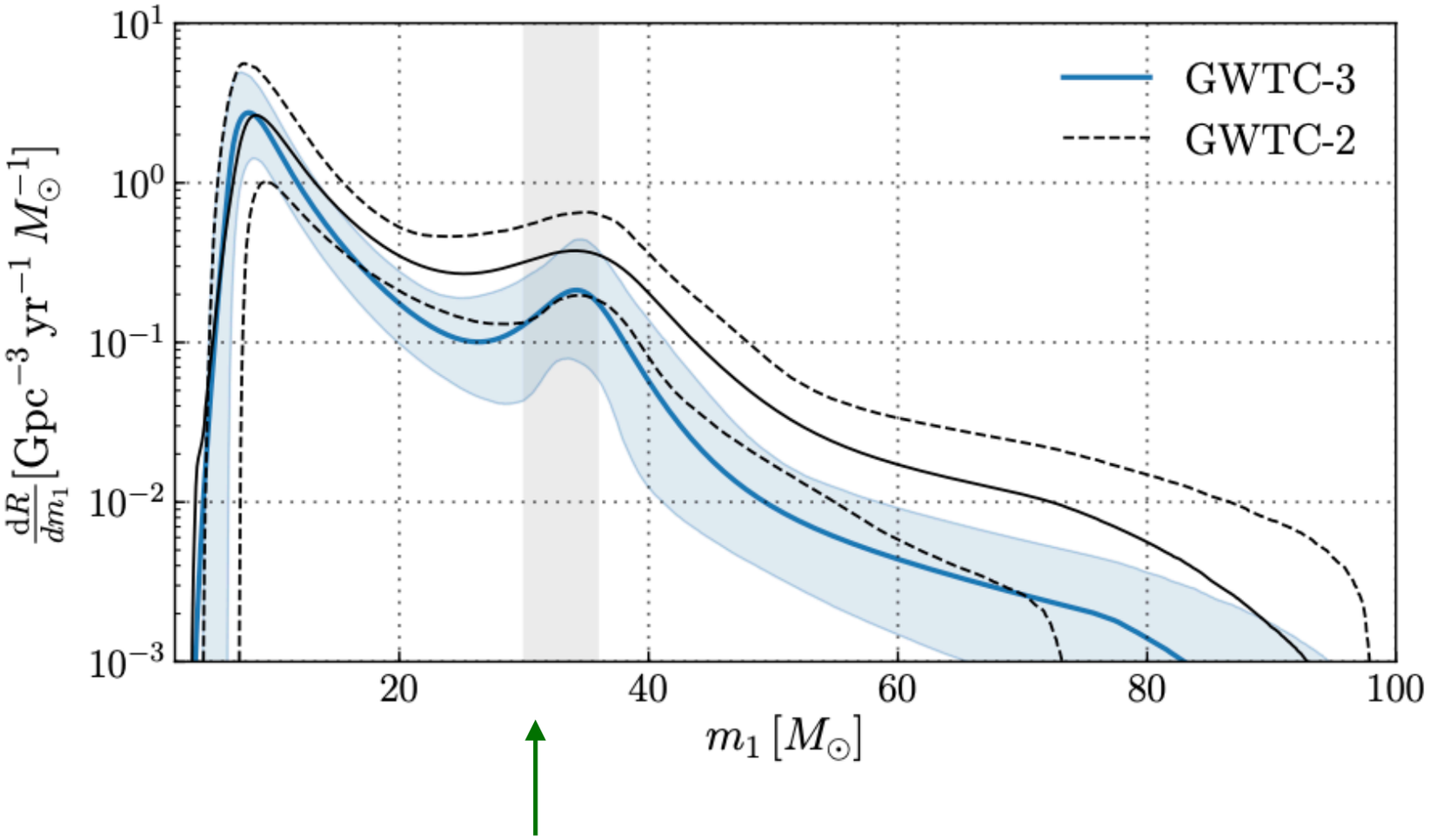


Abbott et al. ApJ Lett. 915 L5 (2021)

Some highlights from O3

Population analyses:

LVK arXiv:2111.03634



Evidence for features in the BBH mass function, but no support for a strong decrease above ~60Msun

Some highlights from O3

Population analyses:

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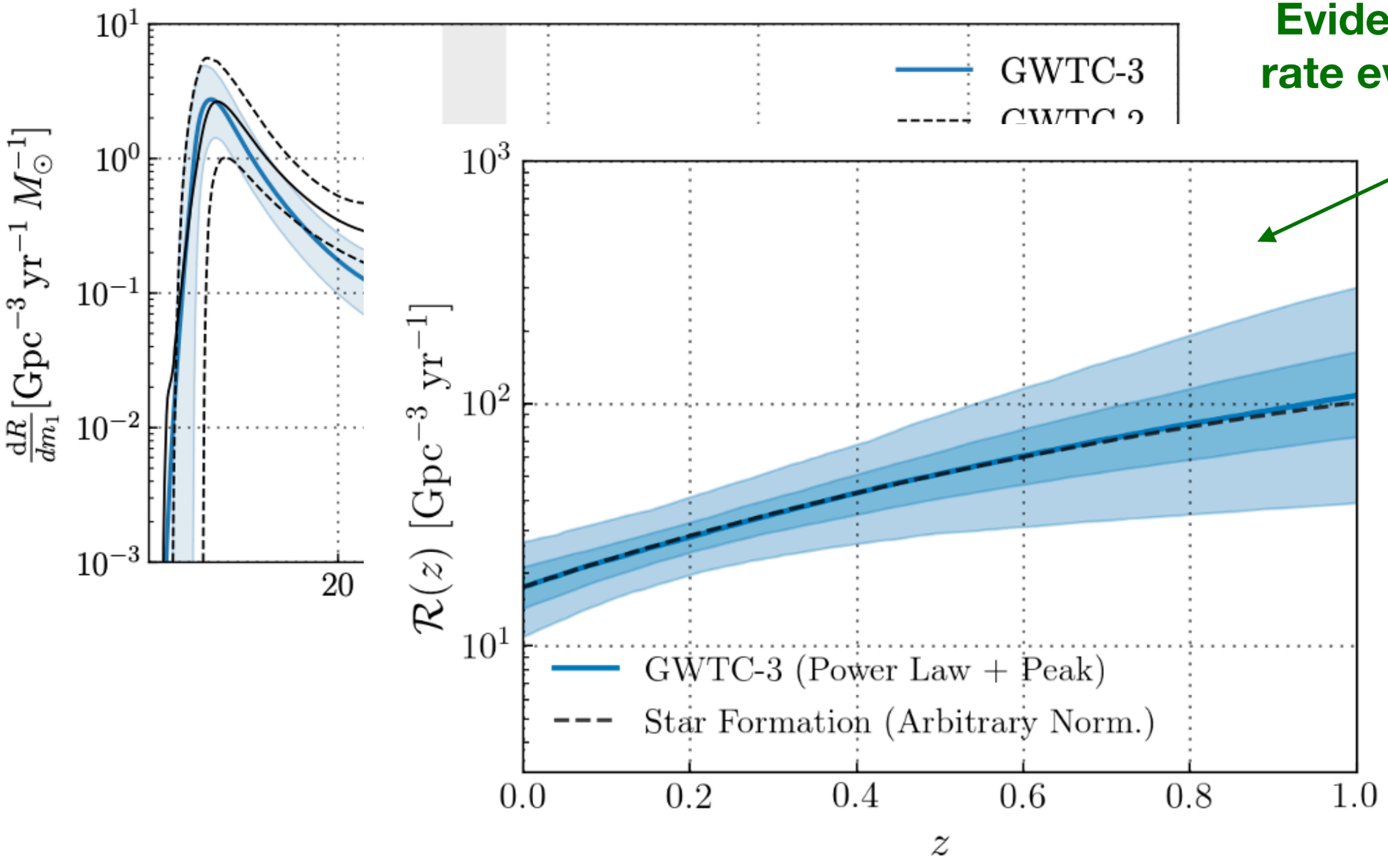
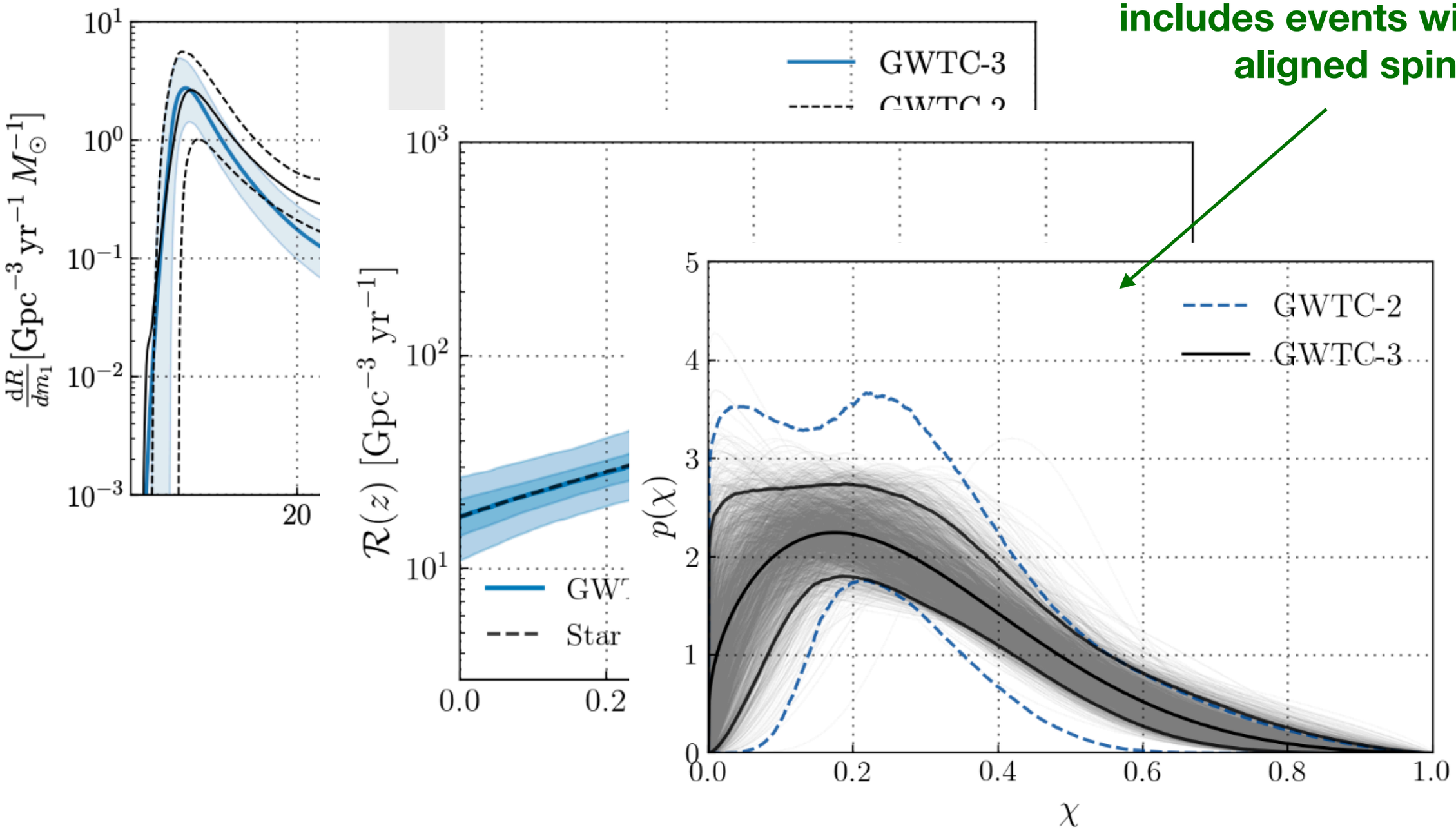


Evidence for BBH merger rate evolution with redshift

Some highlights from O3

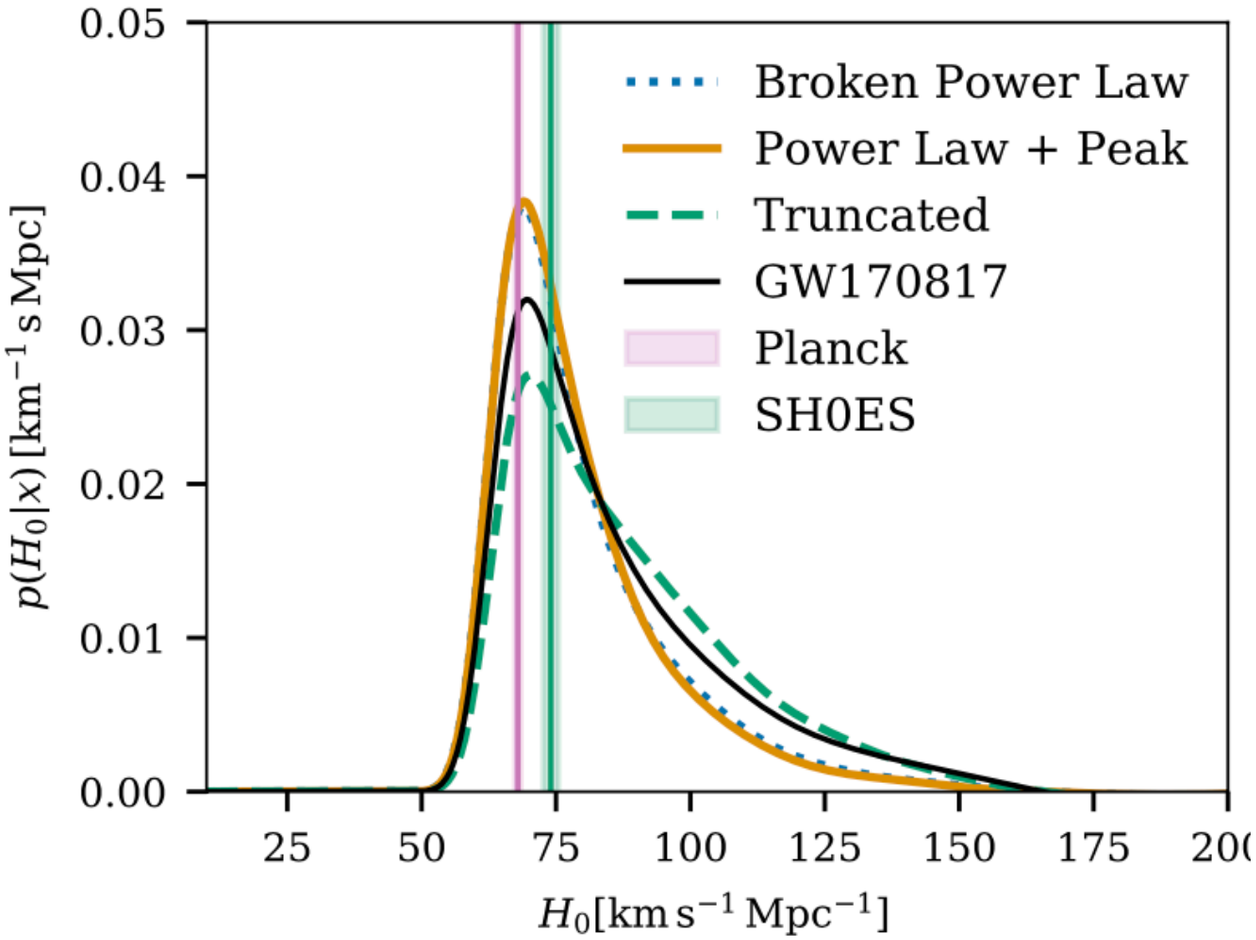
Population analyses:
LVK arXiv:2111.03634

spin distribution requires spin–orbit misalignment and includes events with anti-aligned spins



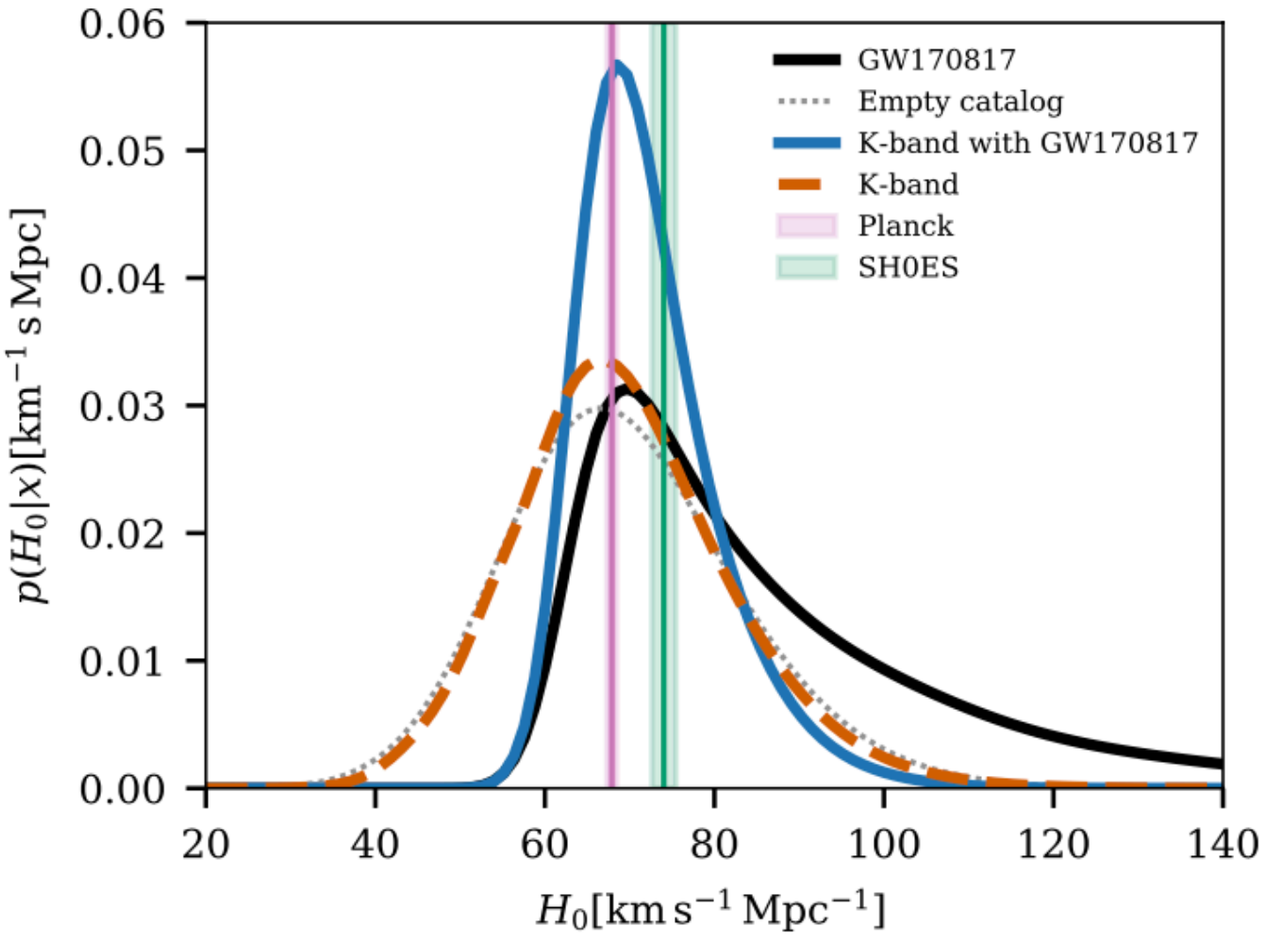
Some highlights from O3

Cosmological analyses:
LVK arXiv:2111.03604



$$H_0 = 68^{+13}_{-7}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Method: redshifted mass function of BBH population

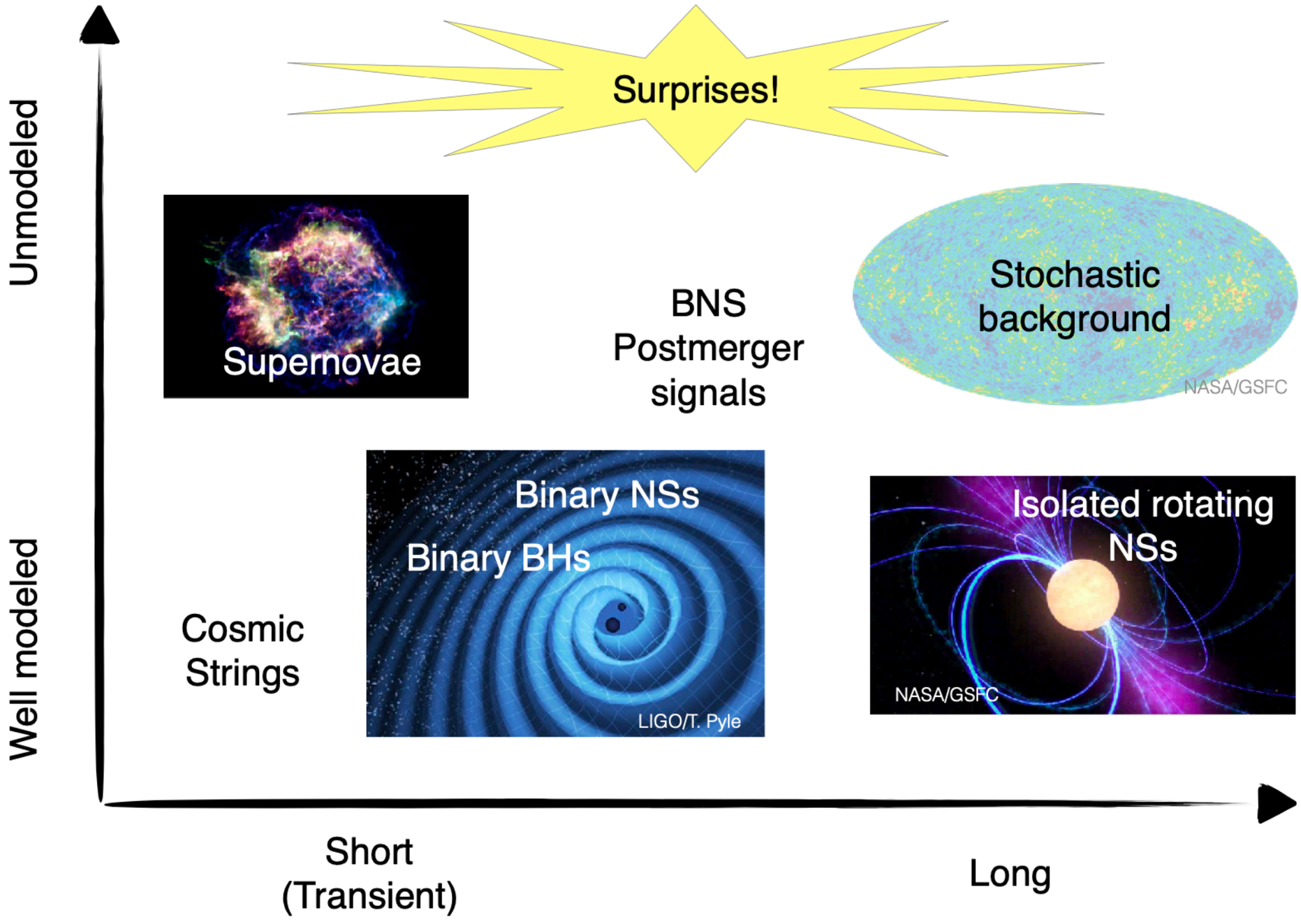


$$H_0 = 68^{+8}_{-6}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Method: cross-correlation with galaxy catalogs

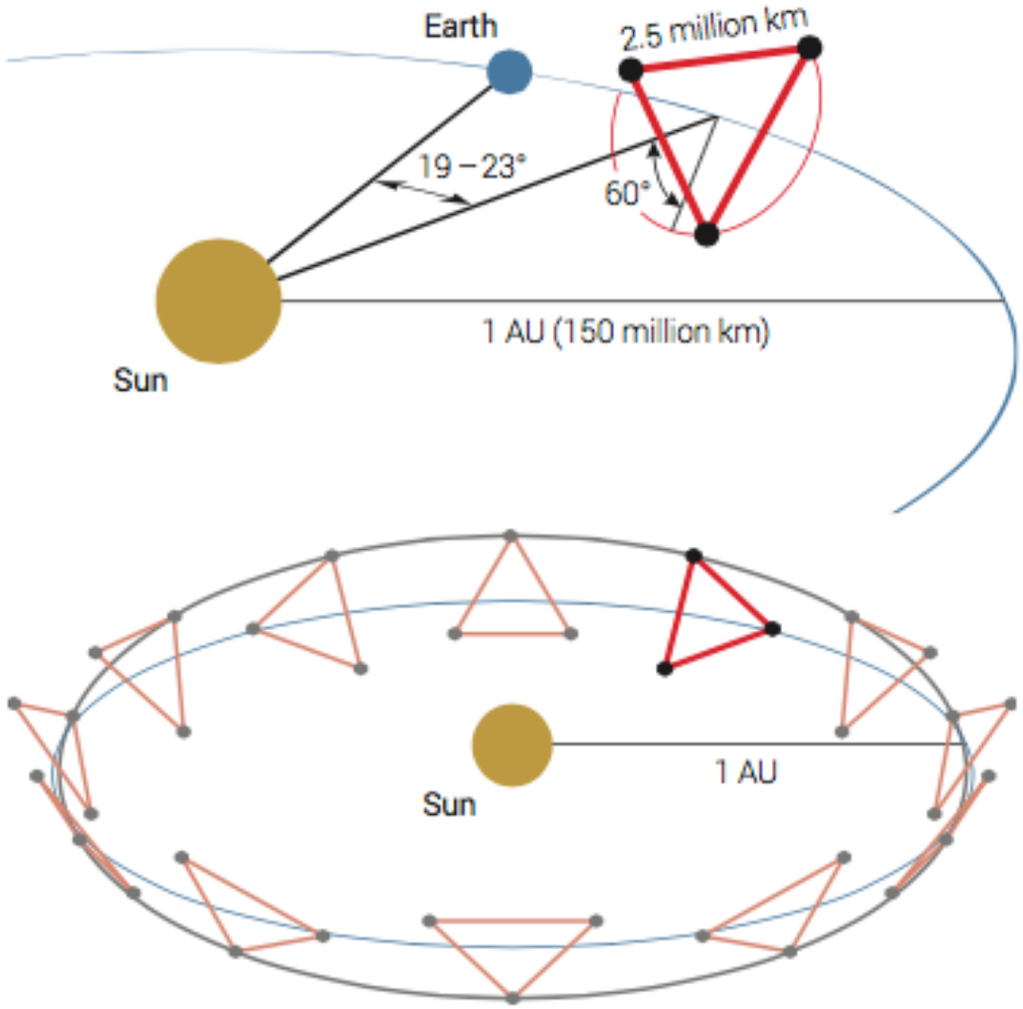
LVK science beyond binaries

Searches for other sources



LISA: mission concept and roadmap

Laser Interferometer Space Antenna



[LISA, *ArXiv* (2017)]

Design:

- Near equilateral triangular formation in heliocentric orbit
- 6 laser links (3 active arms)
- Arm-length: 2.5 million km
- Mission duration: 4 to 10 yrs
- Launch: ~2034

Roadmap to launch:

- 2015-2017 LISA Pathfinder mission
- 2017 ESA Select LISA for L3
- ~2024 Adoption
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- ~2036 Start of science operations

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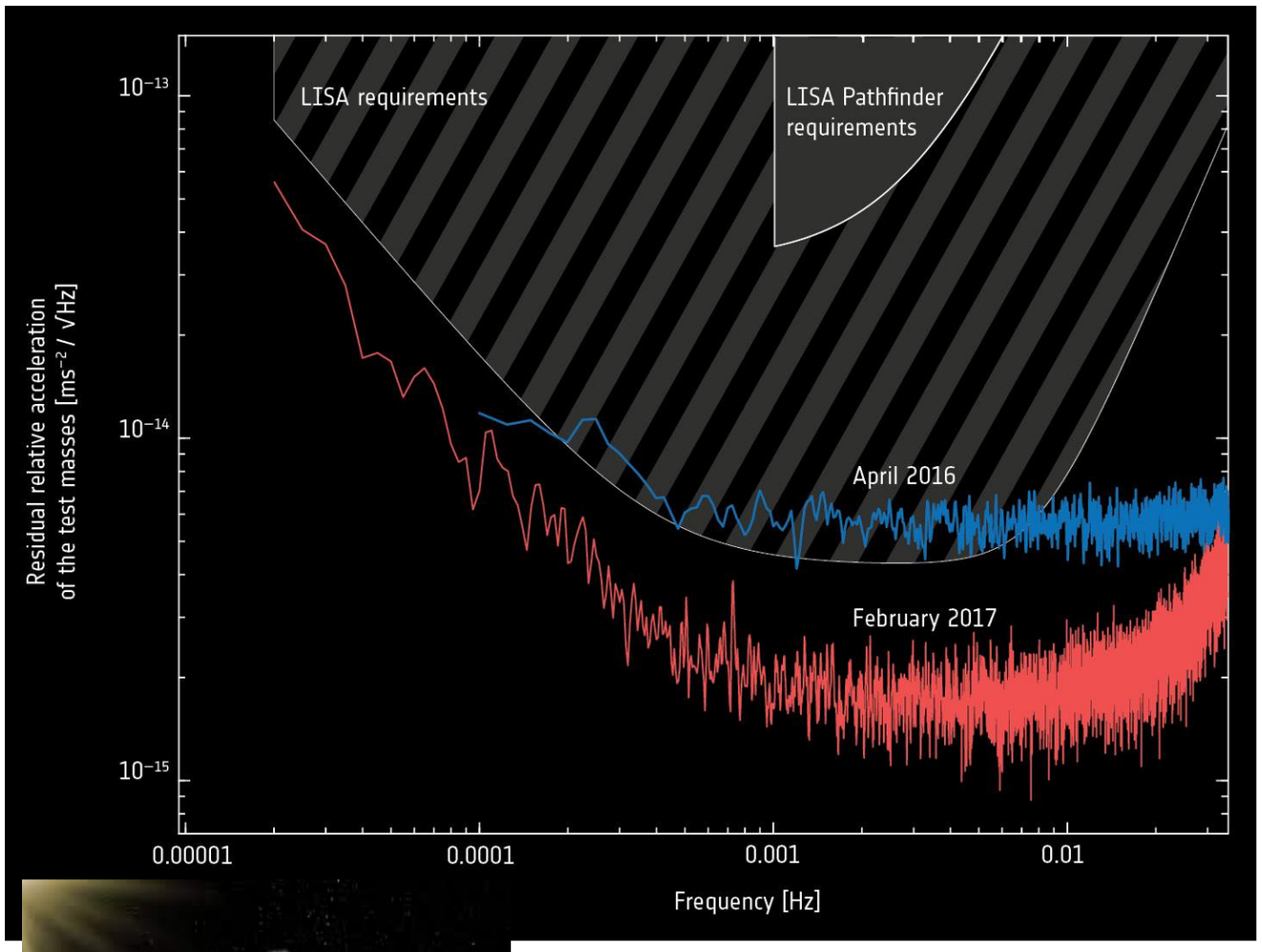

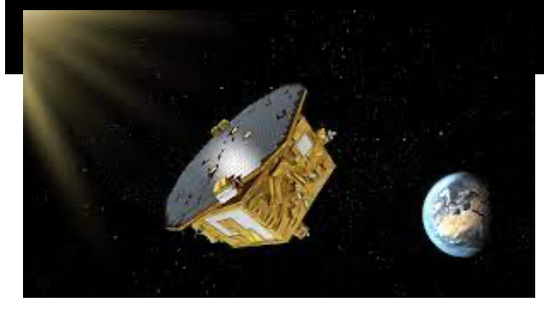

[Armano+, *PRL* (2018)]

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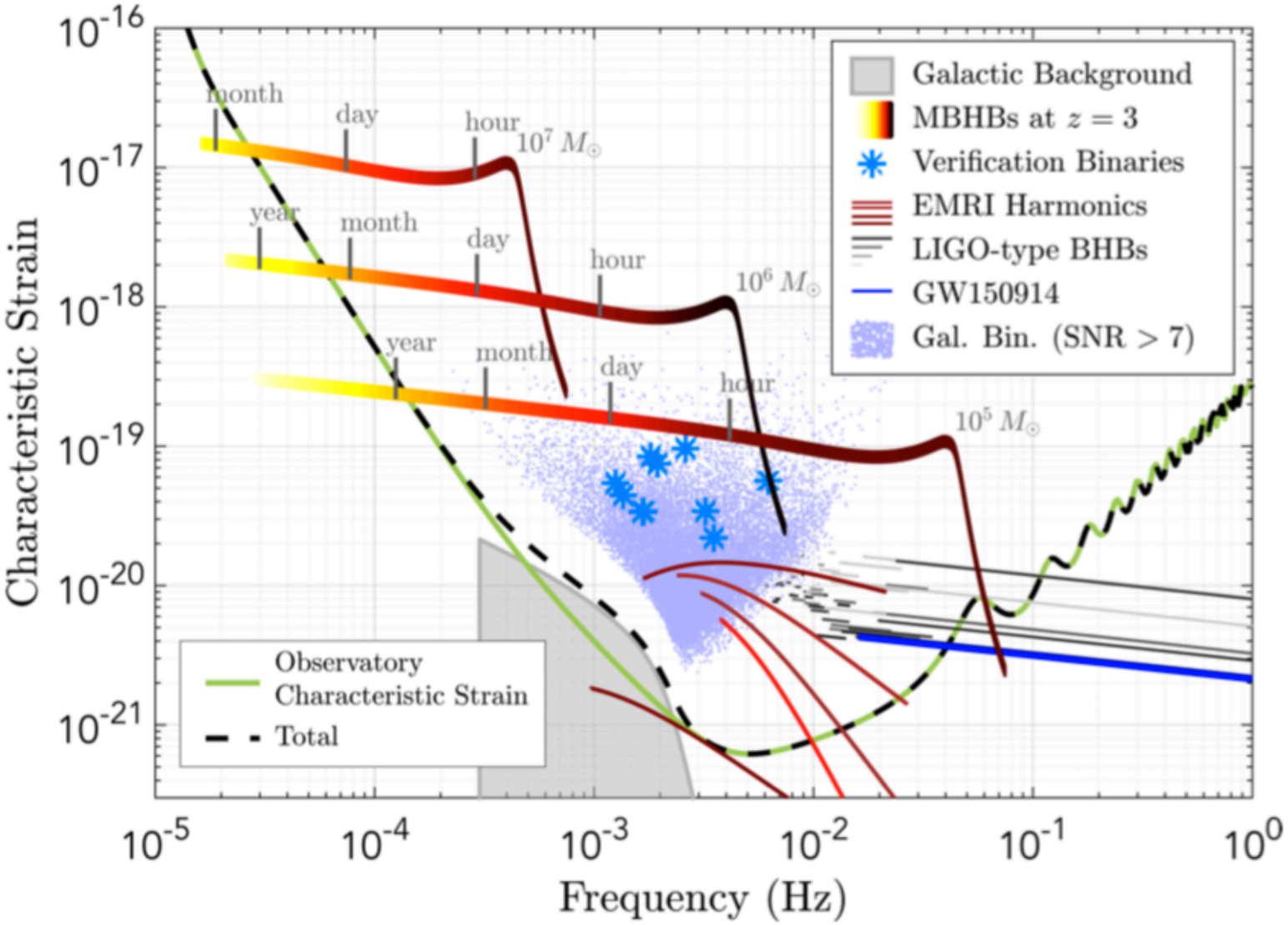
LISA: GW sources and science case



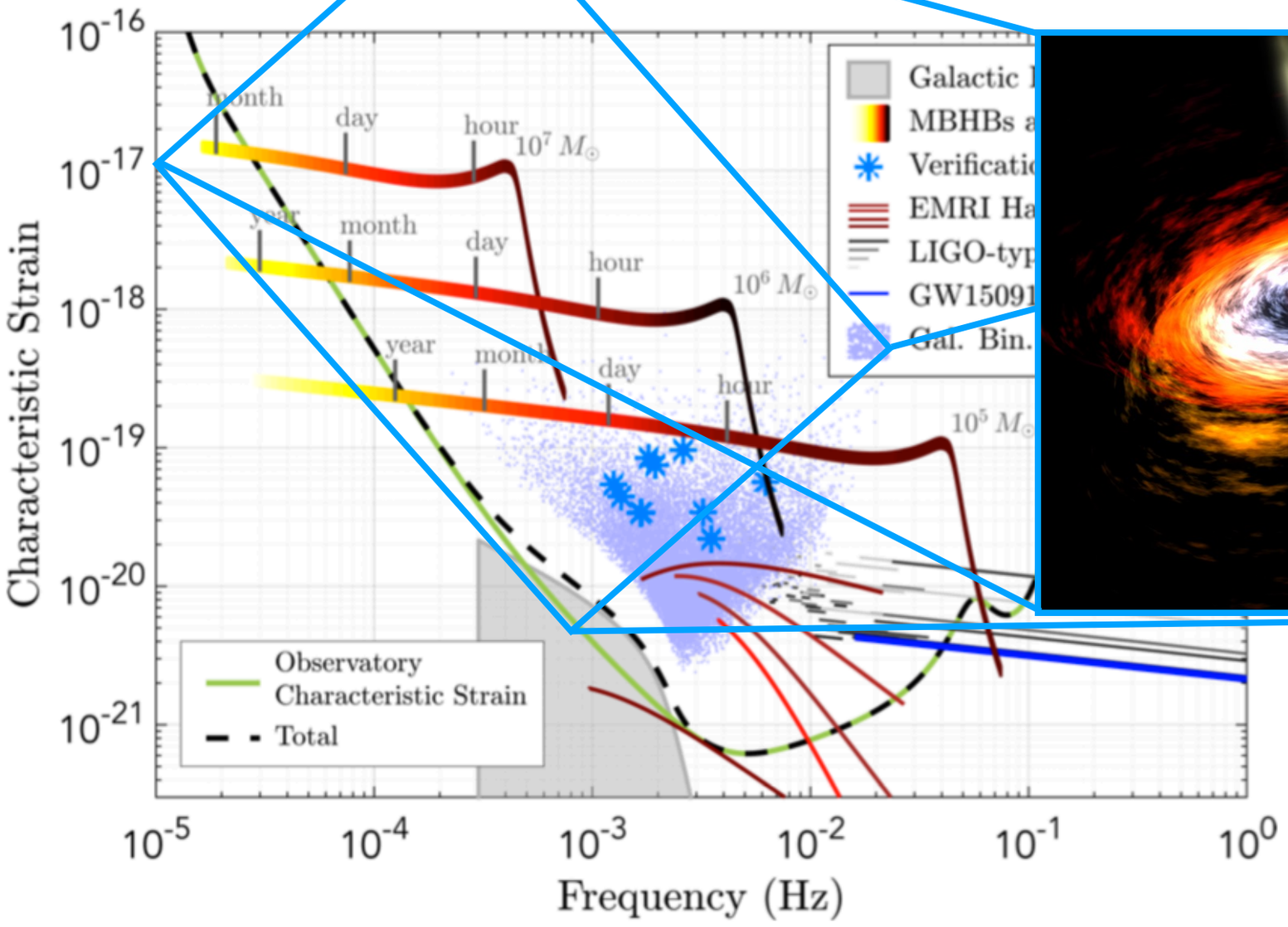
[LISA (2017), arXiv:1702.00786]

LISA GW target sources:

- **Massive BBHs**
- **Extreme mass ratio inspirals**
- **Stellar-mass (and intermediate-mass) BBHs**
- **Galactic binaries/multiples**
- **Stochastic GW backgrounds**

LISA: GW sources and science case

LISA can detect up to <u>hundreds</u> of massive black hole binary mergers up to $z \sim 20$



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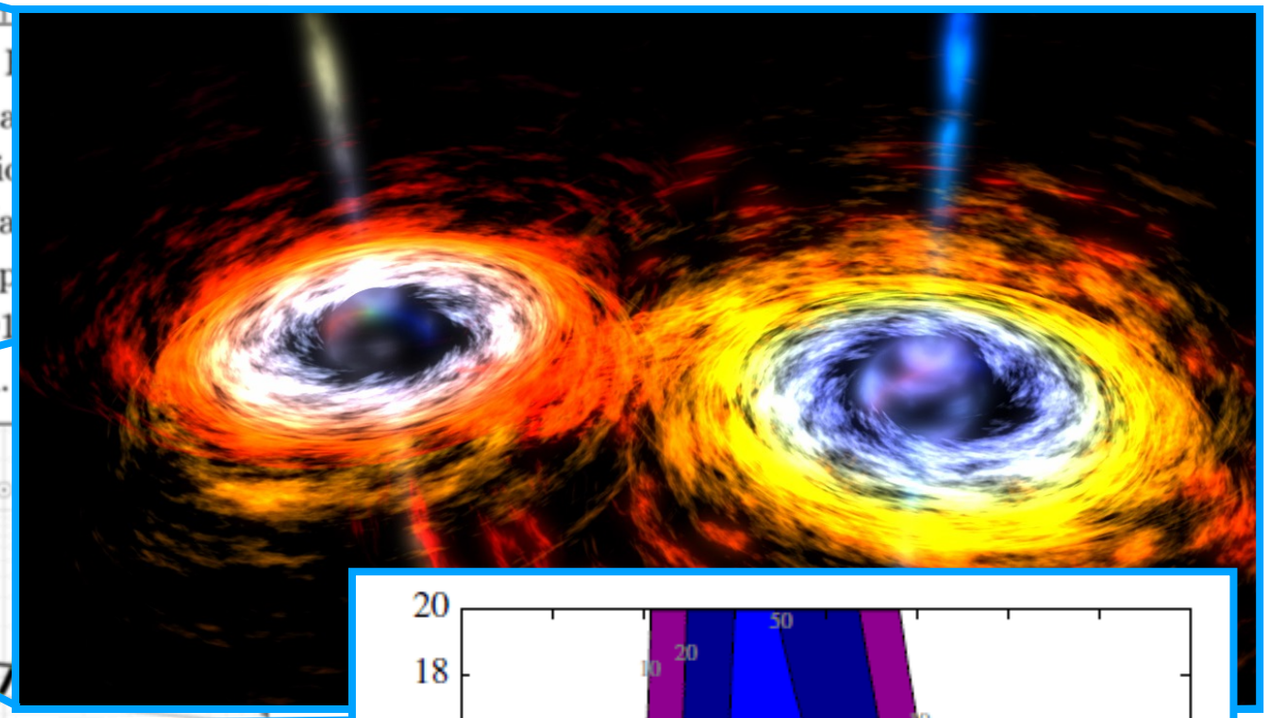

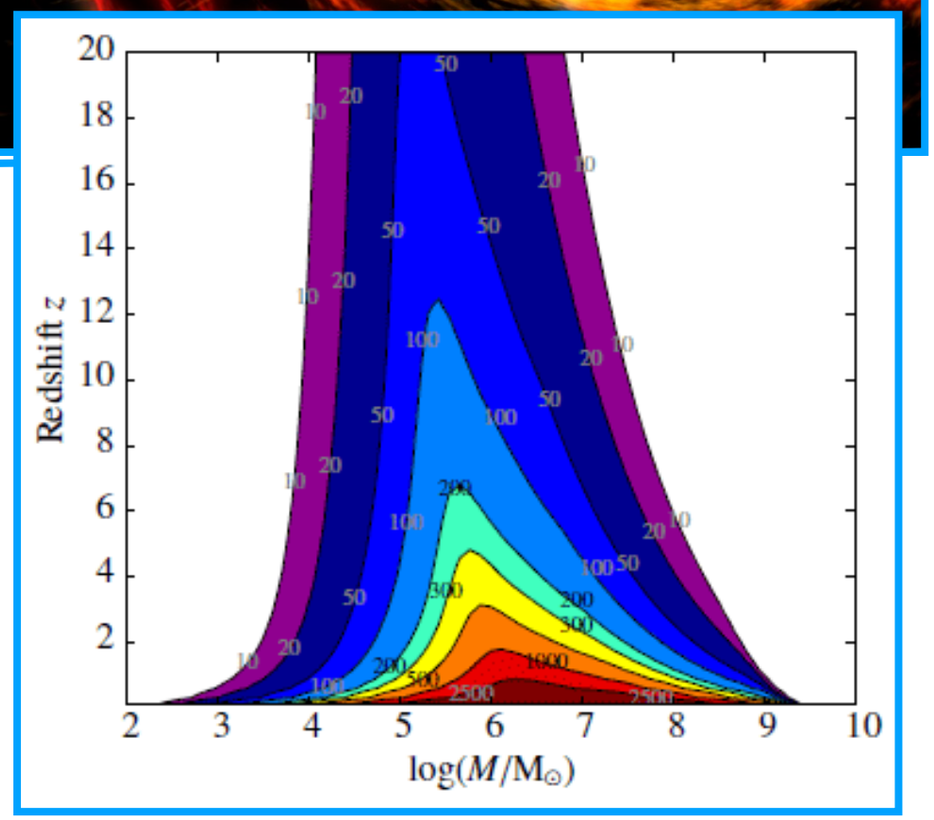

[Klein+, PRD (2016)]

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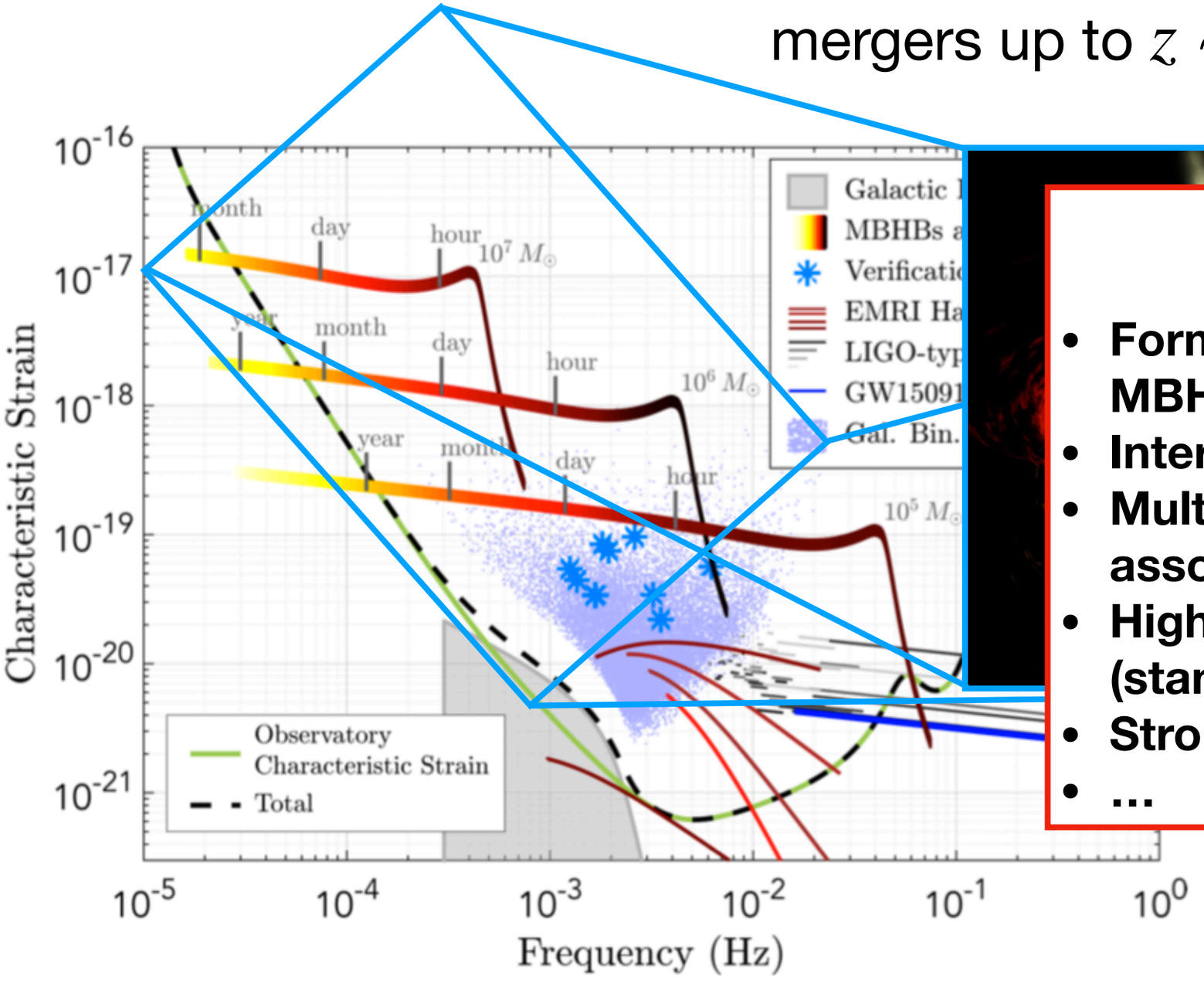
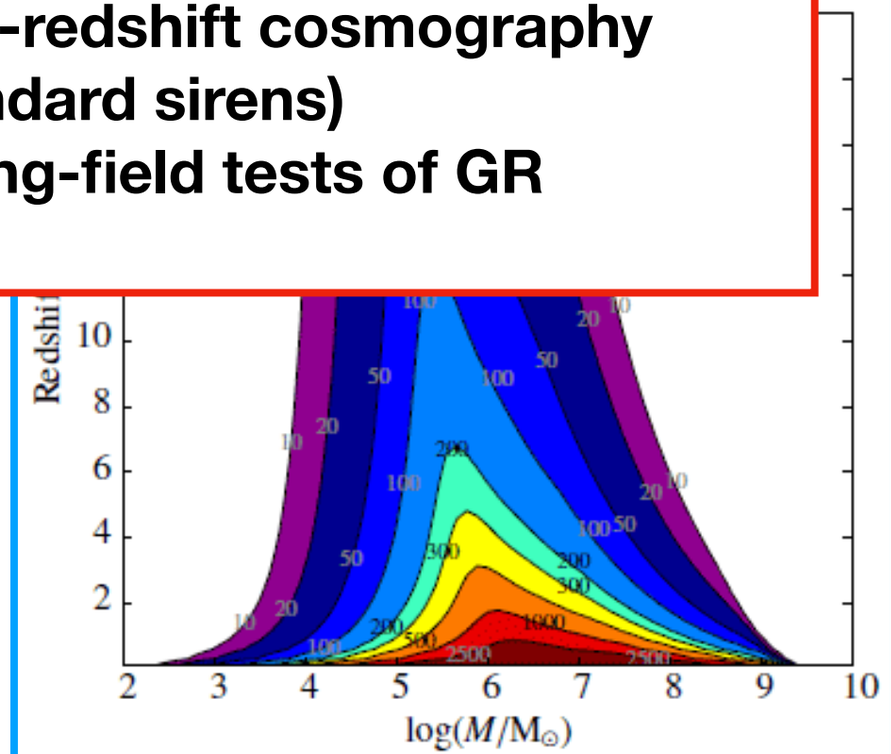


[LISA (2017), arXiv:1702.00786]

Related science:

- **Formation and evolution of MBHs**
- **Interplay with galaxy evolution**
- **Multi-messenger signals and associated physics**
- **High-redshift cosmography (standard sirens)**
- **Strong-field tests of GR**
- **…**



[Klein+, PRD (2016)]

Cosmology with EMRIs

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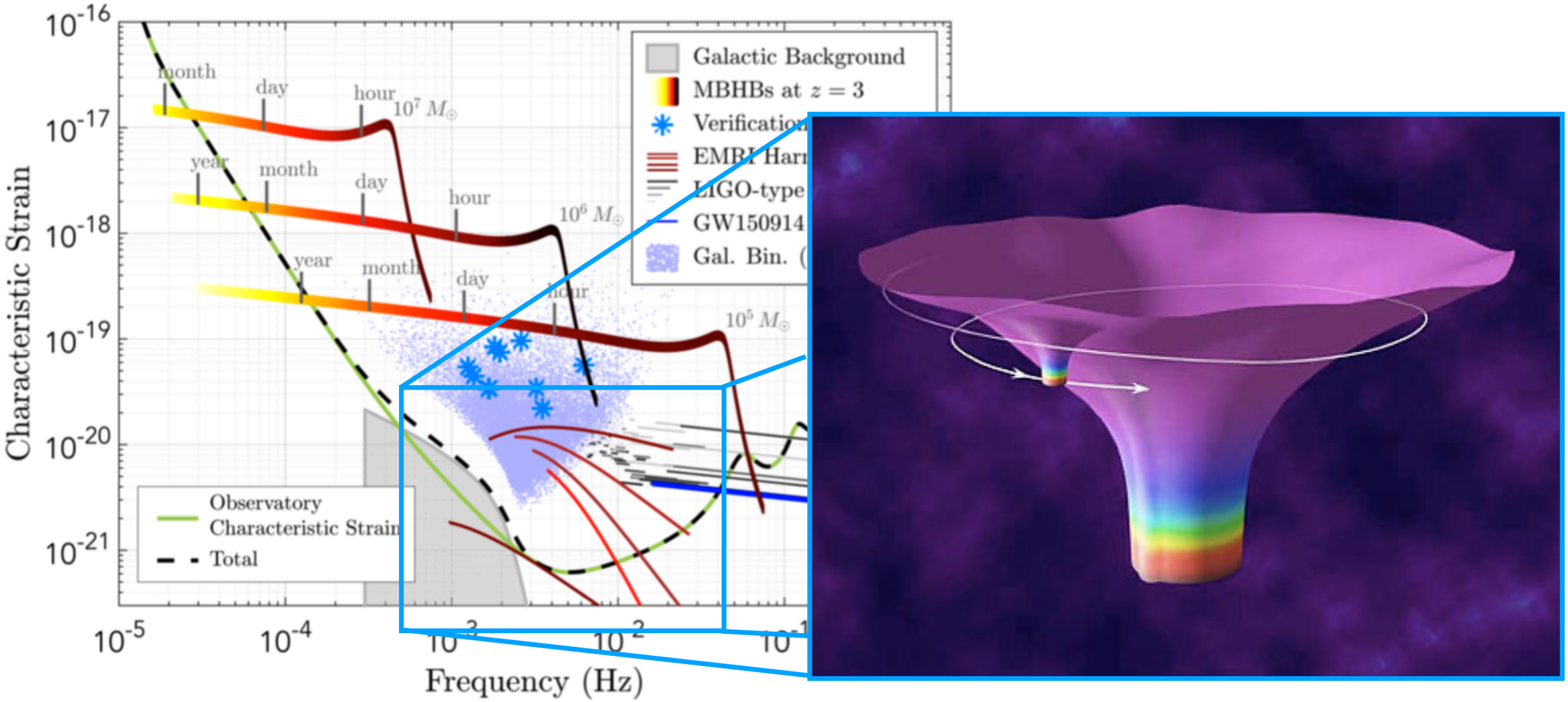

[LISA (2017), arXiv:1702.00786]

[Babak+, PRD (2017), arXiv:1703.09722]

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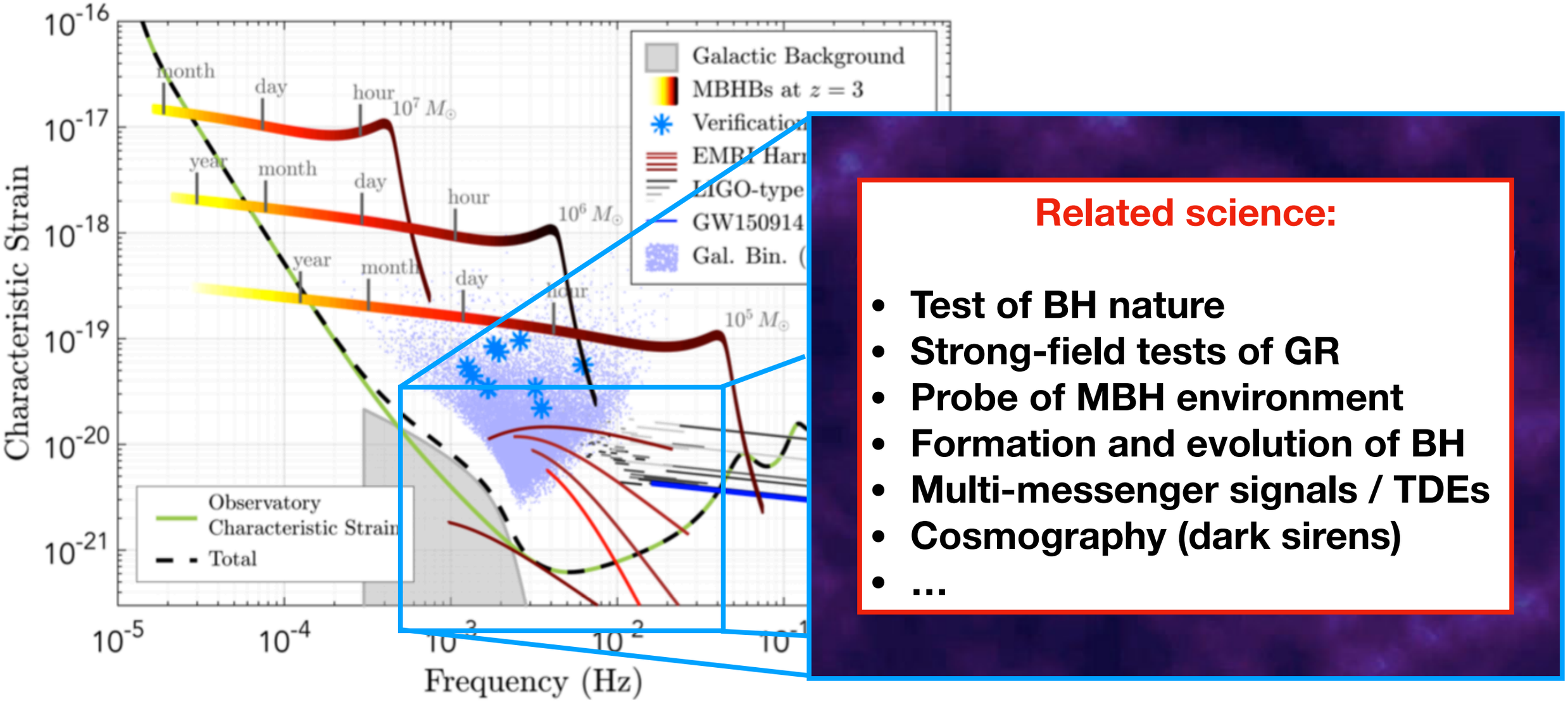

Related science:

- **Test of BH nature**
- **Strong-field tests of GR**
- **Probe of MBH environment**
- **Formation and evolution of BH**
- **Multi-messenger signals / TDEs**
- **Cosmography (dark sirens)**
- **…**

[LISA (2017), arXiv:1702.00786]

[Babak+, PRD (2017), arXiv:1703.09722]

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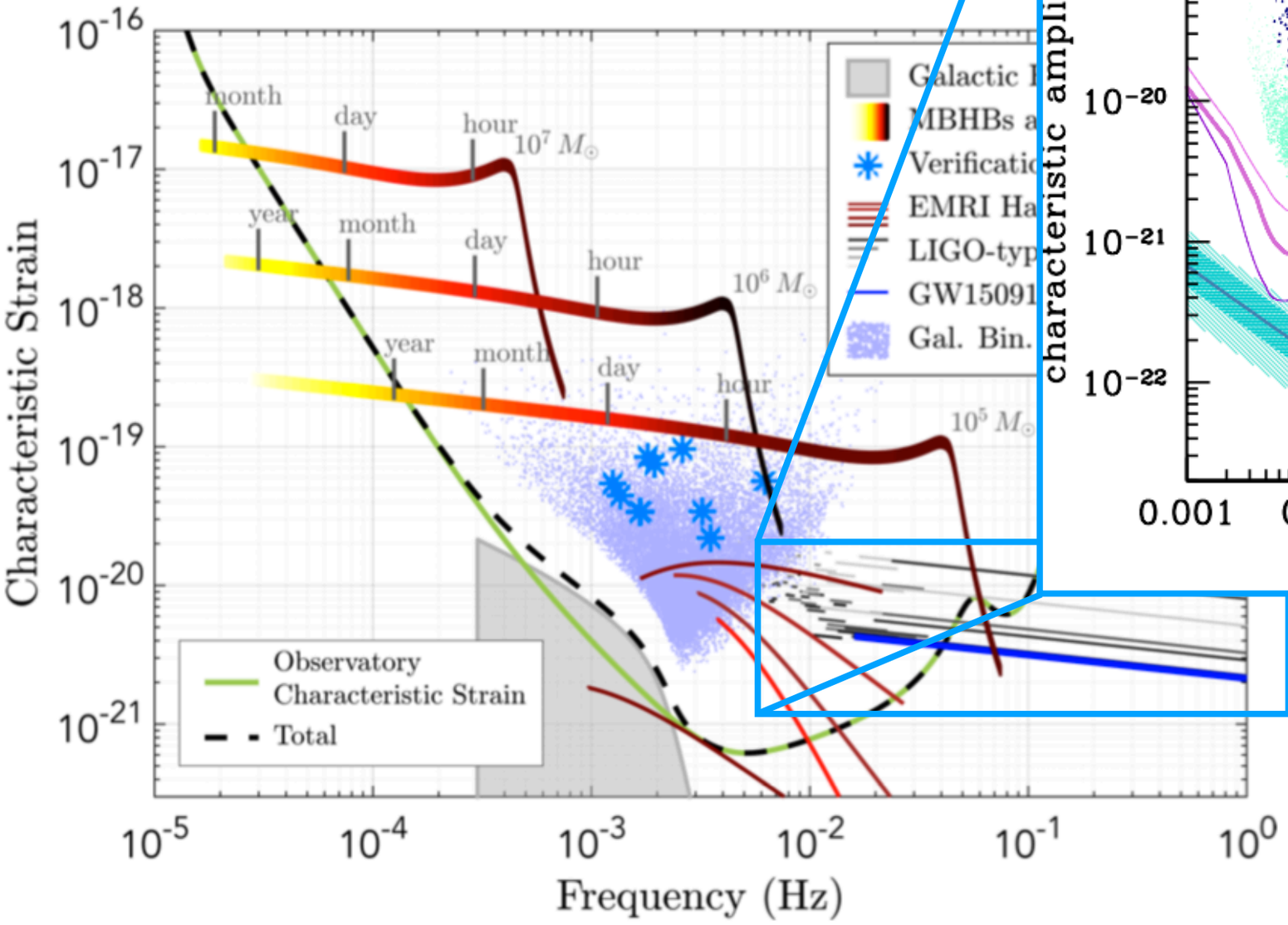
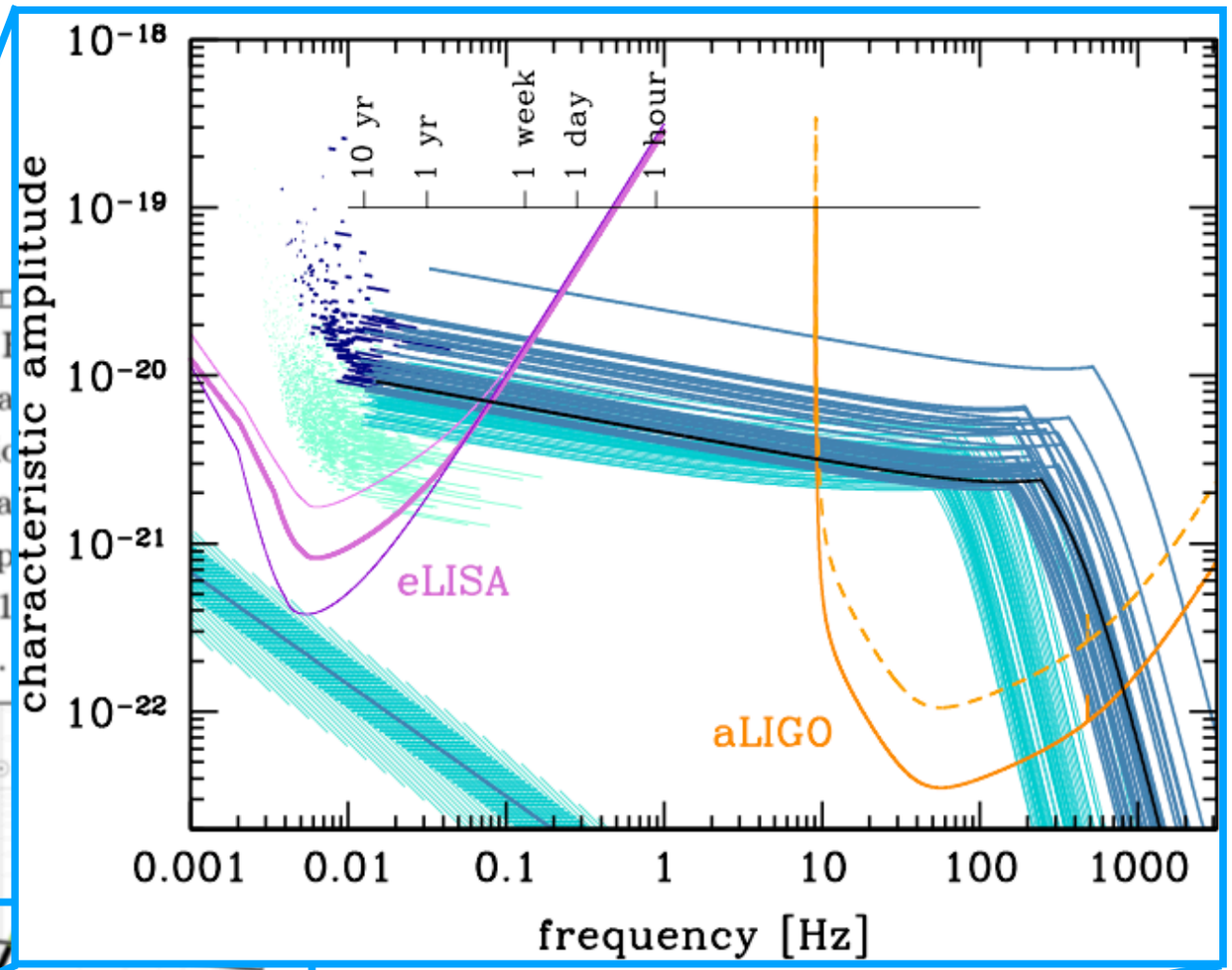
LISA can detect up to <u>tens</u> of stellar-mass BBHs at low-redshift





[LISA (2017), arXiv:1702.00786]

[Sesana, *PRL* (2016)]

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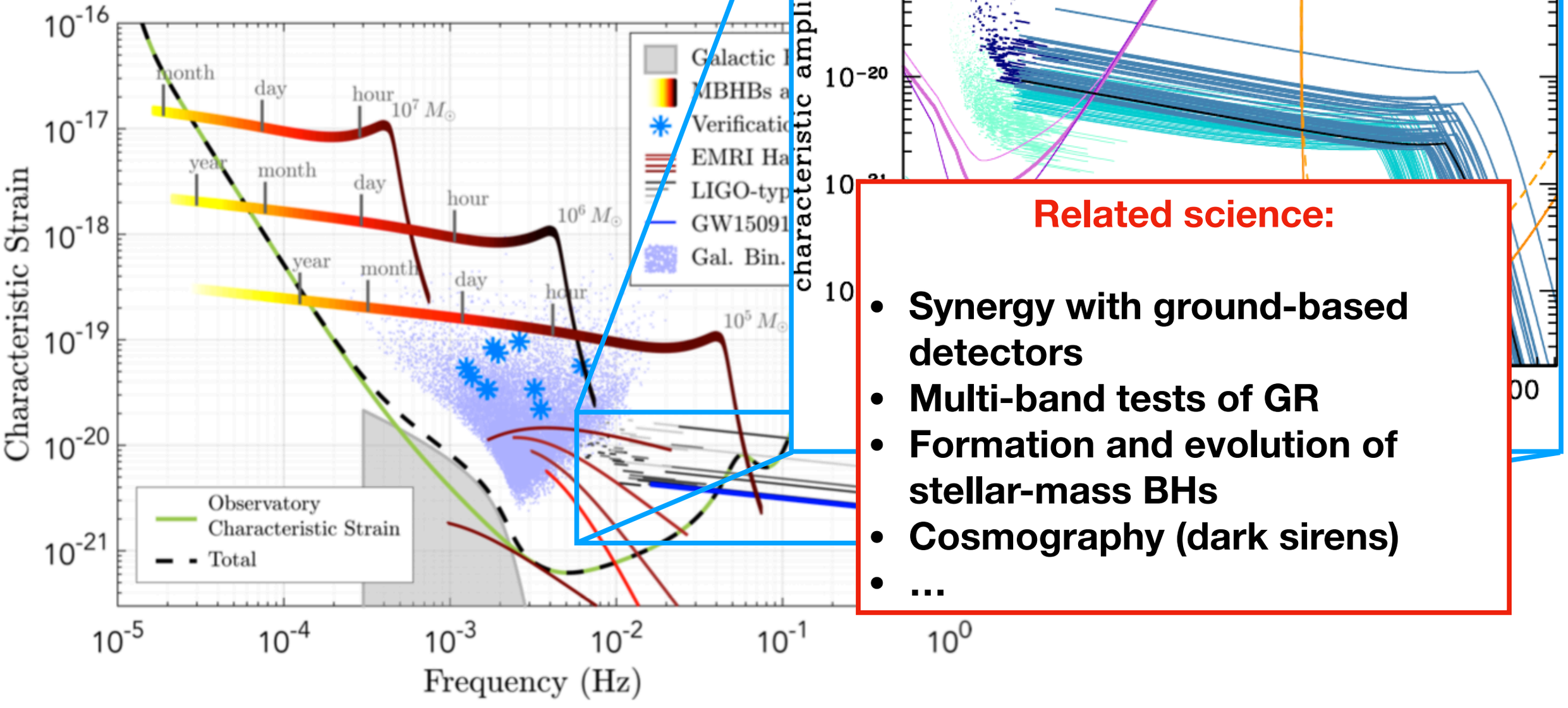


Related science:

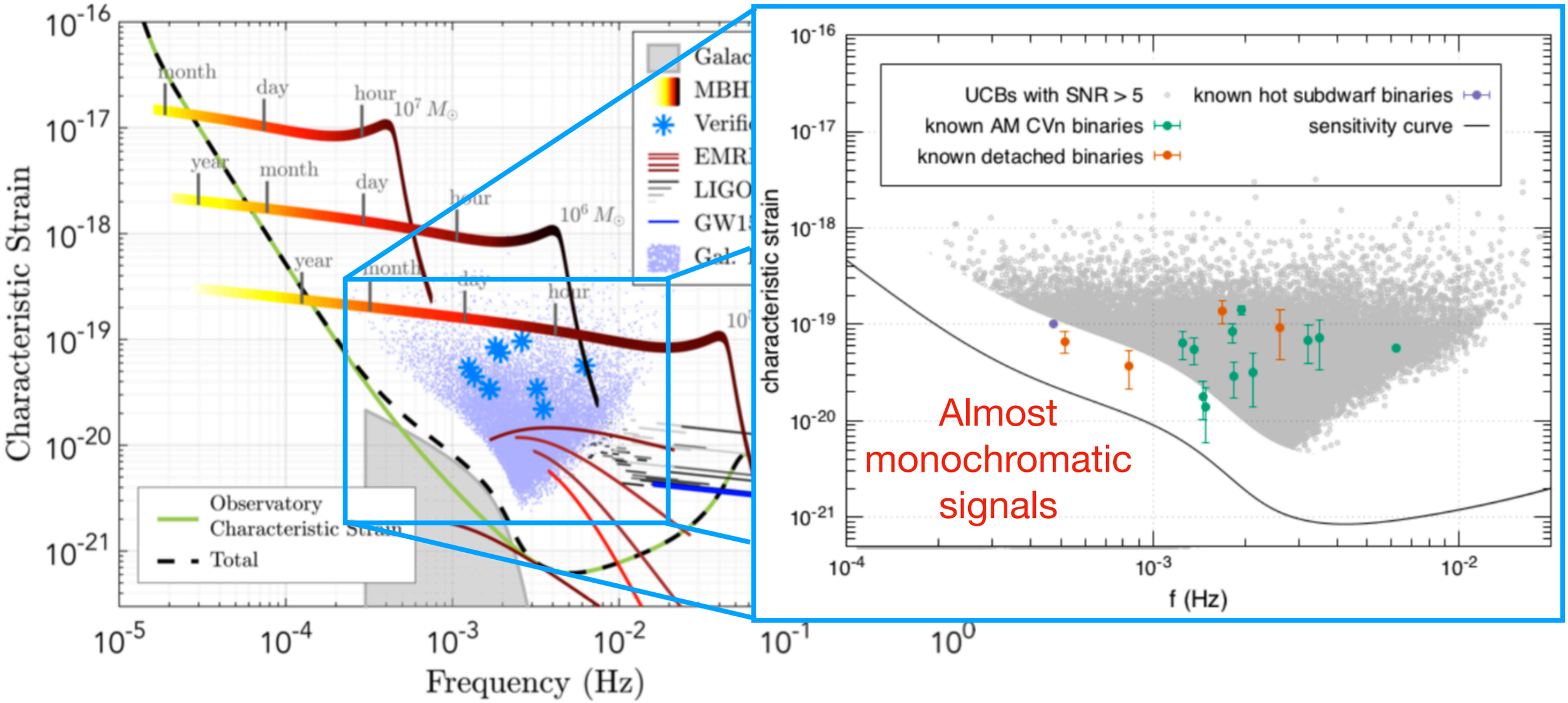
- **Synergy with ground-based detectors**
- **Multi-band tests of GR**
- **Formation and evolution of stellar-mass BHs**
- **Cosmography (dark sirens)**
- **…**

[LISA (2017), arXiv:1702.00786]

[Sesana, *PRL* (2016)]

Exoplanets with LISA

LISA can detect <u>tens of thousands</u> of double white dwarf (DWD) binaries all over the Milky Way and beyond



[LISA (2017), arXiv:1702.00786]

[Littenberg+ (2019), arXiv:1903.05583]
[Kupfer+, *MNRAS*, 480, 302, (2019); arXiv:1805.00482]

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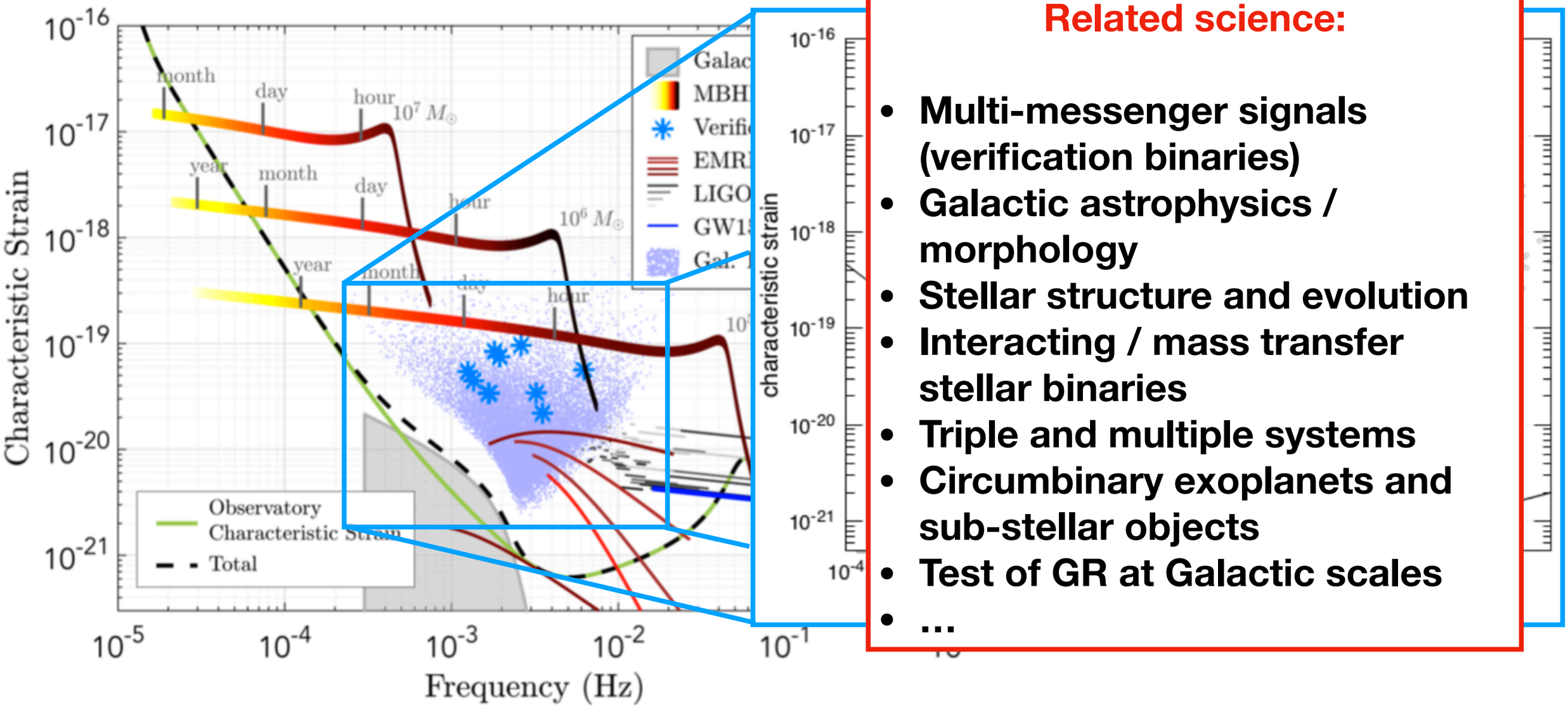

Related science:

- **Multi-messenger signals (verification binaries)**
- **Galactic astrophysics / morphology**
- **Stellar structure and evolution**
- **Interacting / mass transfer stellar binaries**
- **Triple and multiple systems**
- **Circumbinary exoplanets and sub-stellar objects**
- **Test of GR at Galactic scales**
- **…**

[LISA (2017), arXiv:1702.00786]

[Littenberg+ (2019), arXiv:1903.05583]
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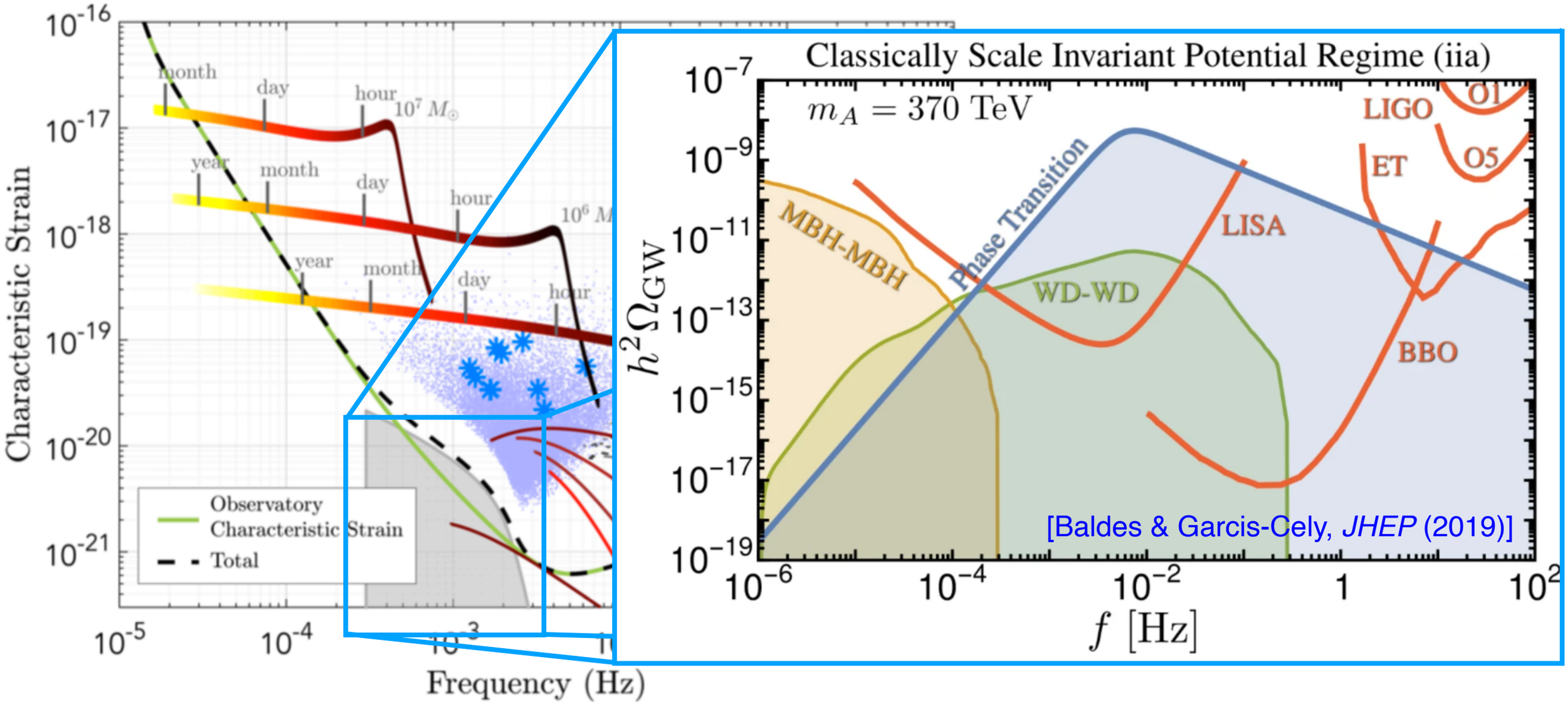
LISA can detect stochastic backgrounds of GW of both astrophysical and cosmological origin

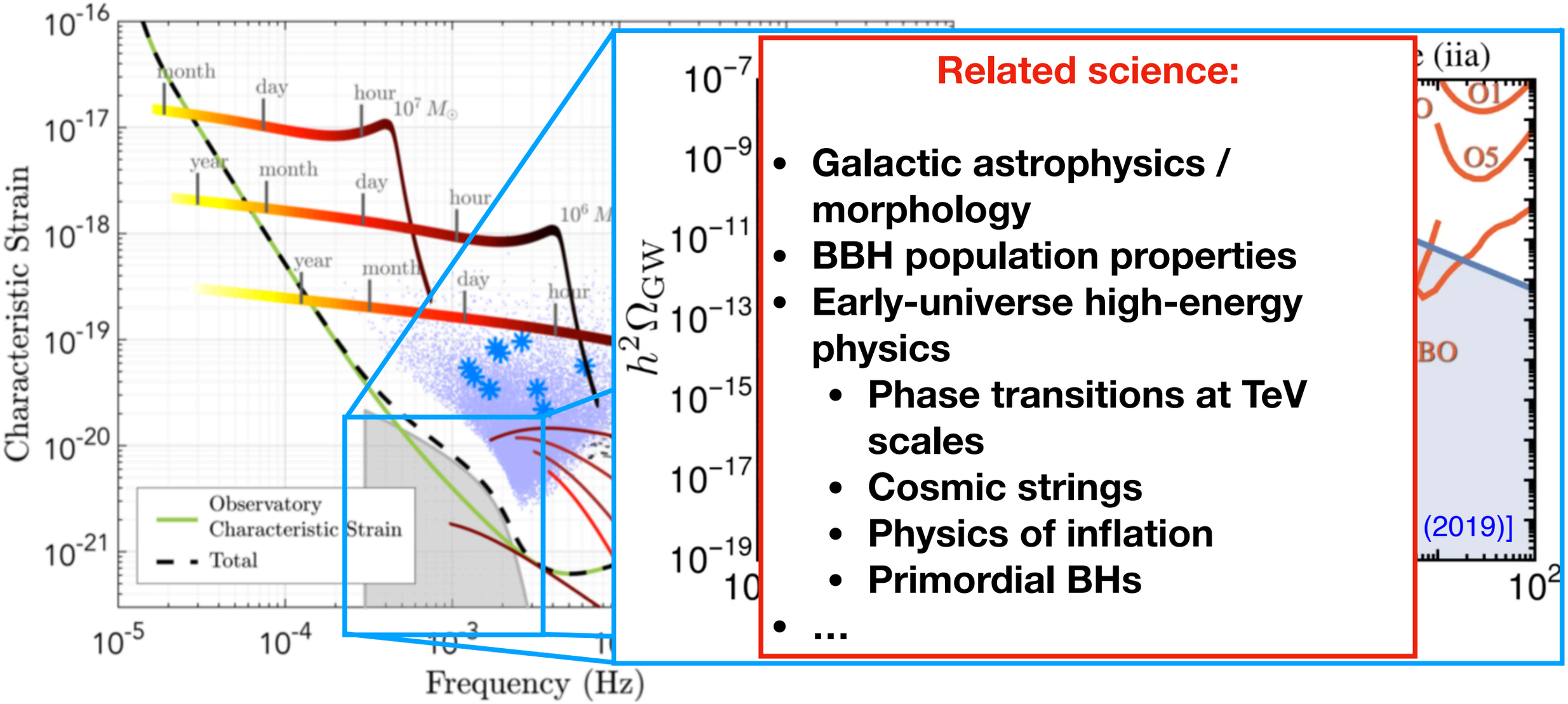


[LISA (2017), arXiv:1702.00786]

[Caprini & Figueroa, *CQG* (2018)]

LISA: GW sources and science case

LISA can detect stochastic backgrounds of GW of both astrophysical and cosmological origin



Related science:

- **Galactic astrophysics / morphology**
- **BBH population properties**
- **Early-universe high-energy physics**
  - **Phase transitions at TeV scales**
  - **Cosmic strings**
  - **Physics of inflation**
  - **Primordial BHs**
- **…**

[LISA (2017), arXiv:1702.00786]

[Caprini & Figueroa, *CQG* (2018)]

Conclusion

LIGO/Virgo

- **Great discoveries and great science**
- **Beginning of GW astronomy and fast transition to data-dominated science**
- **More results/observations soon**

LISA

- **Even greater discoveries await us**
- **Even greater science to be made**
- **Surprises?**