Introduction to CBC Science

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GW Open Data Workshop, May 12 2025

Image: Aurore Simonnet/Sonoma State

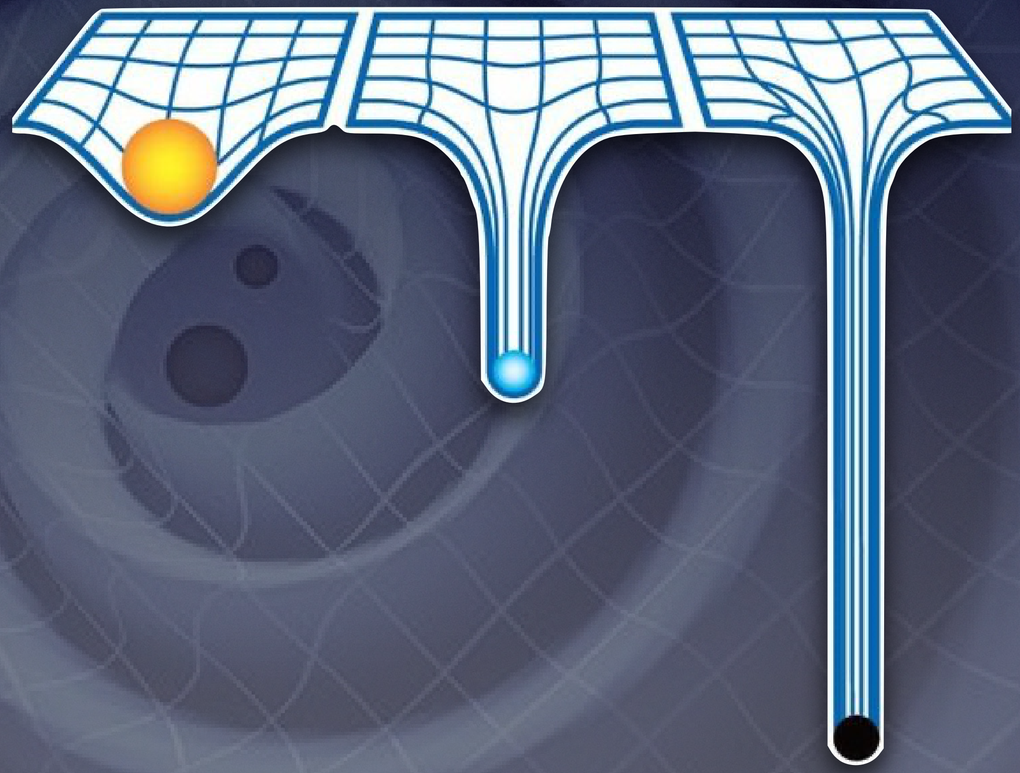
Compact Binary Coalescences

Compact Binary Coalescences

Compact objects: high mass-to-radius ratio

Very compact objects lead to more extreme curvature of space-time

Less compact ⟶ More compact

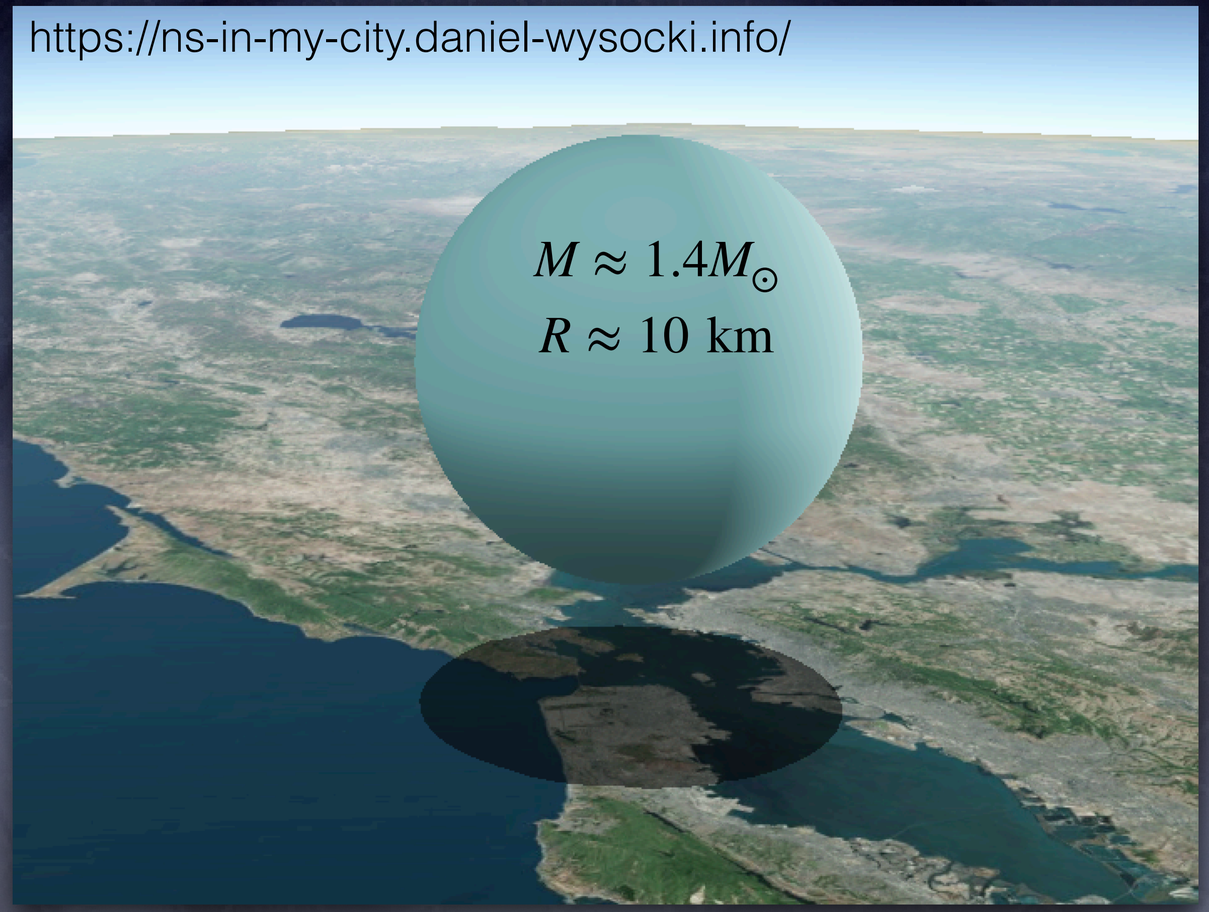


Compact Binary Coalescences

Compact objects: high mass-to-radius ratio

Neutron Stars

- Formed by the collapse of a massive star ($\sim 10 - 20 M_\odot$)
- Density higher than atomic nucleus -> mostly made of neutrons

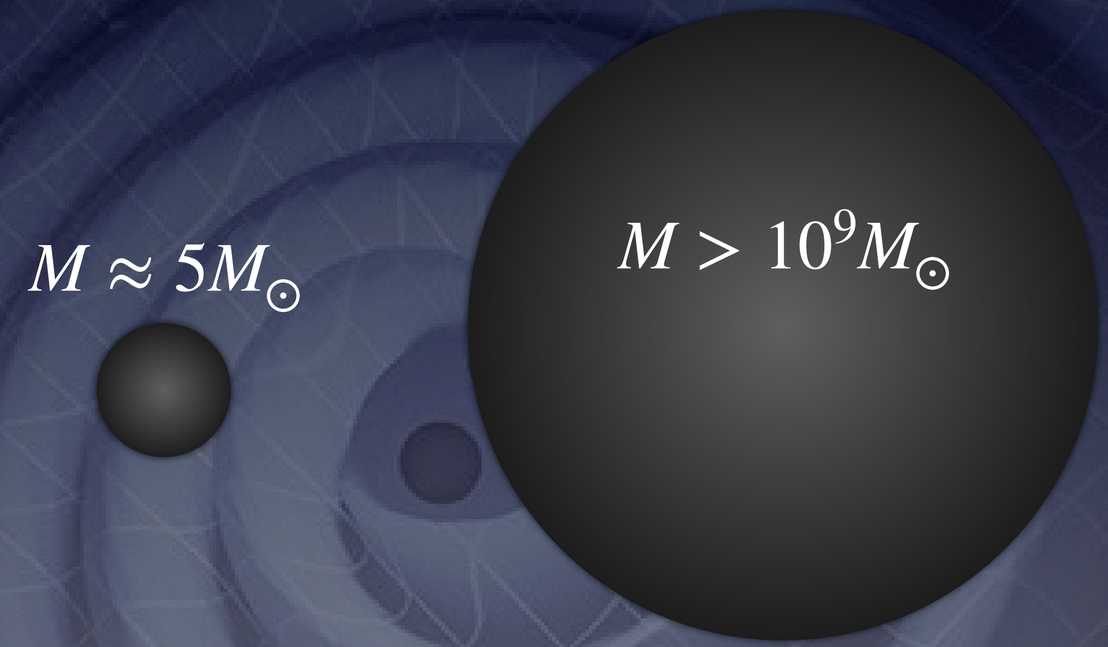


Compact Binary Coalescences

Compact objects: high mass-to-radius ratio

Black holes

- So compact that even light cannot escape the extreme spacetime curvature
- Masses span many orders of magnitude



*radii not to scale

Compact Binary Coalescences

Compact objects: high mass-to-radius ratio

Black holes

- LIGO-Virgo-KAGRA sensitive to *stellar mass* black holes
- Formed from collapse of a massive ($\gtrsim 20\mathrm{M}_{\odot}$) star (mostly!)

*radii not to scale

Compact **Binary Coalescences**

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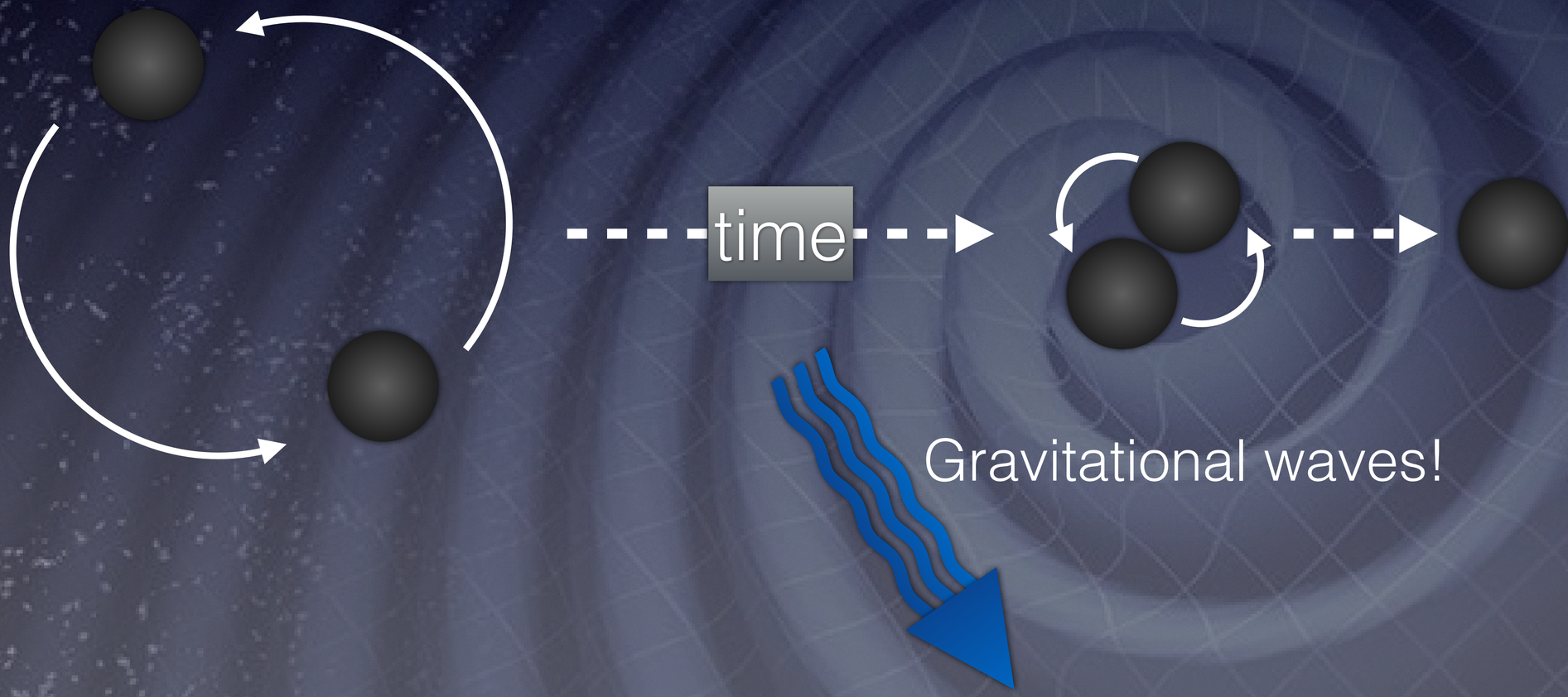
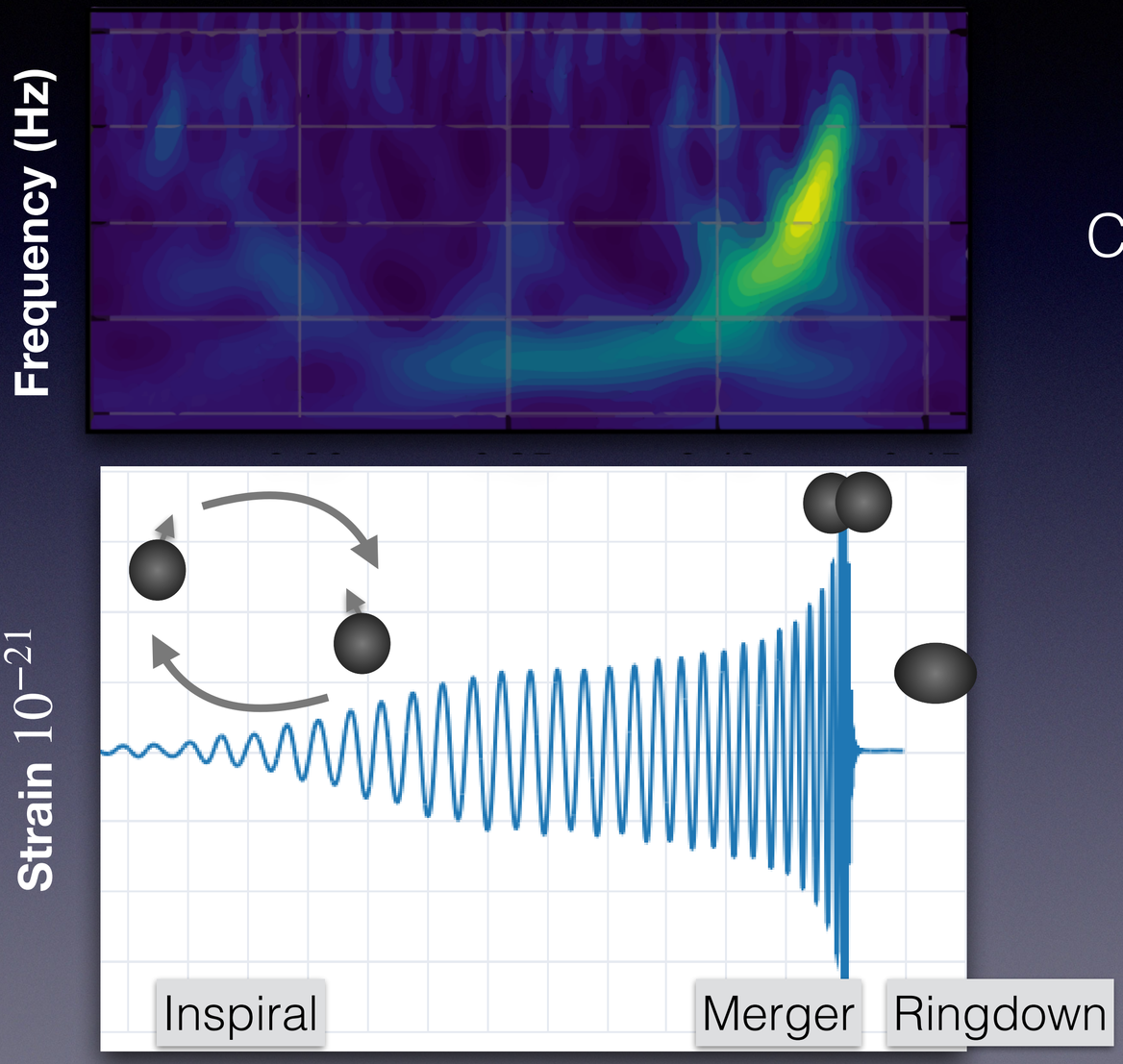


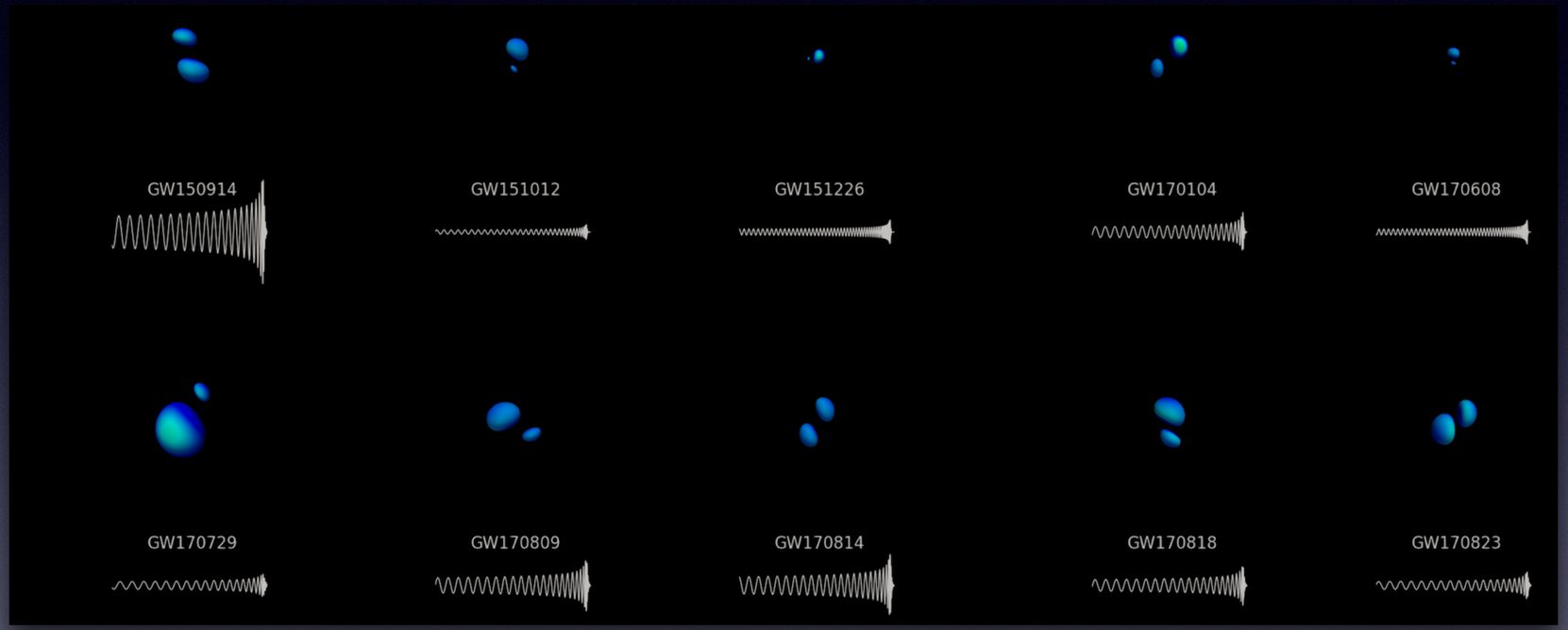
Anatomy of a waveform



Chirp!

Fractional length change

Anatomy of a waveform



Waveform encodes data about:

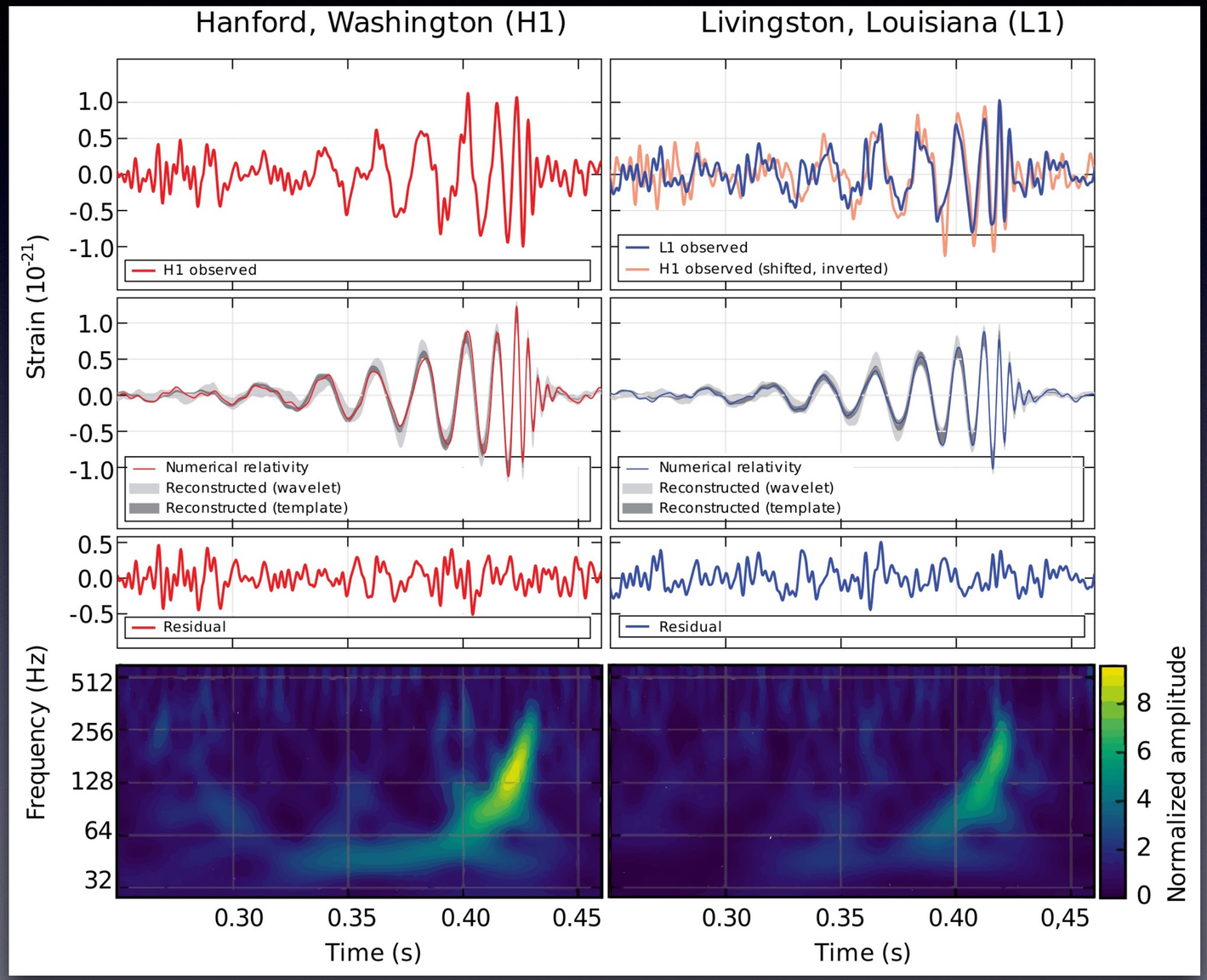
- compact object *masses*
- Compact object *spins*
- NS tidel deformability
- Distance to binary system
- Orientation of orbit

See Daniel's talk tomorrow

Teresita Ramirez/Geoffrey Lovelace/SXS Collaboration/LIGO-Virgo Collaboration

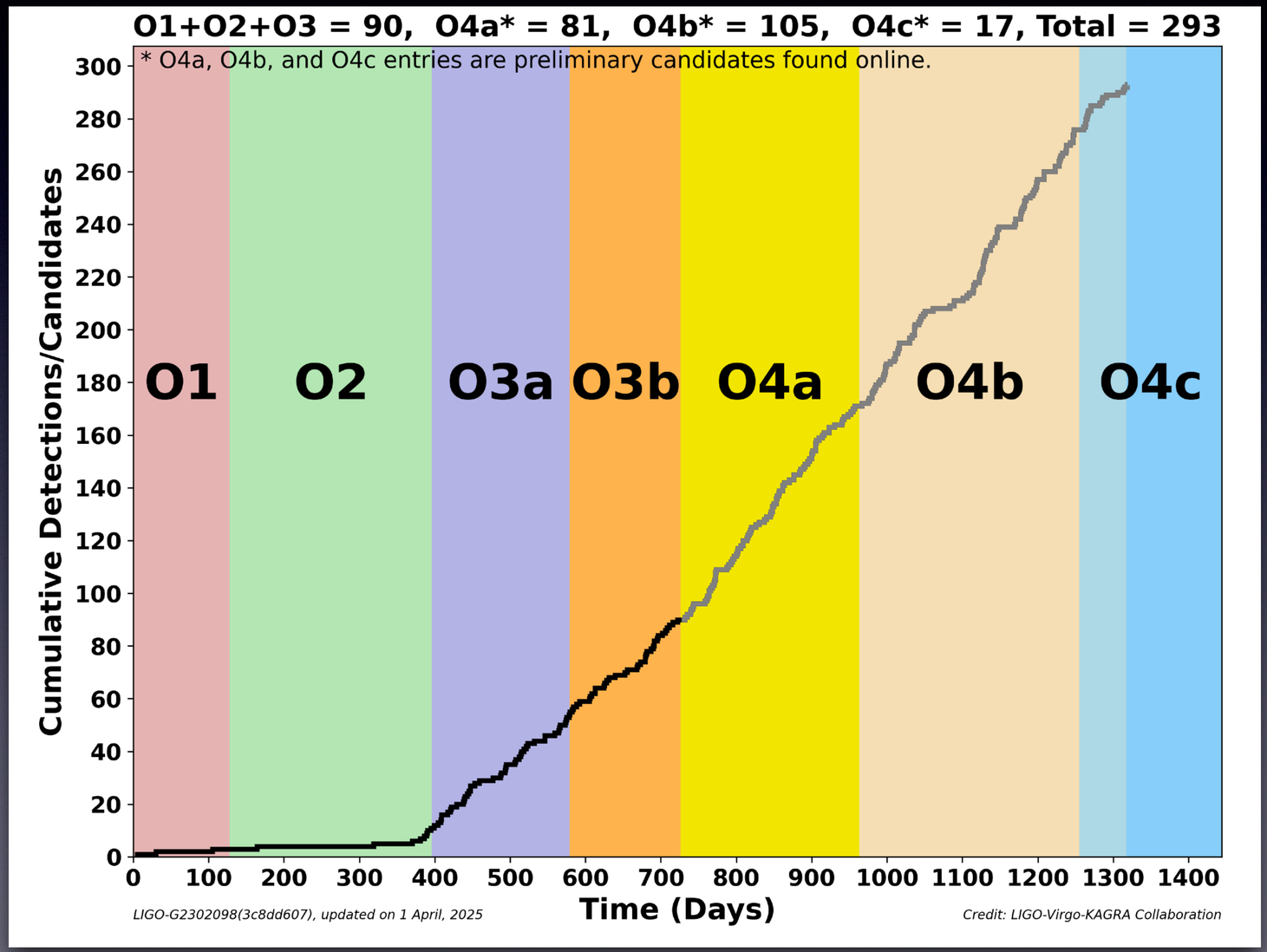
CBC Detections

- GW150914: the very first detection!
  - Hanford and Livingston
  - $36M_\odot - 29M_\odot$ system

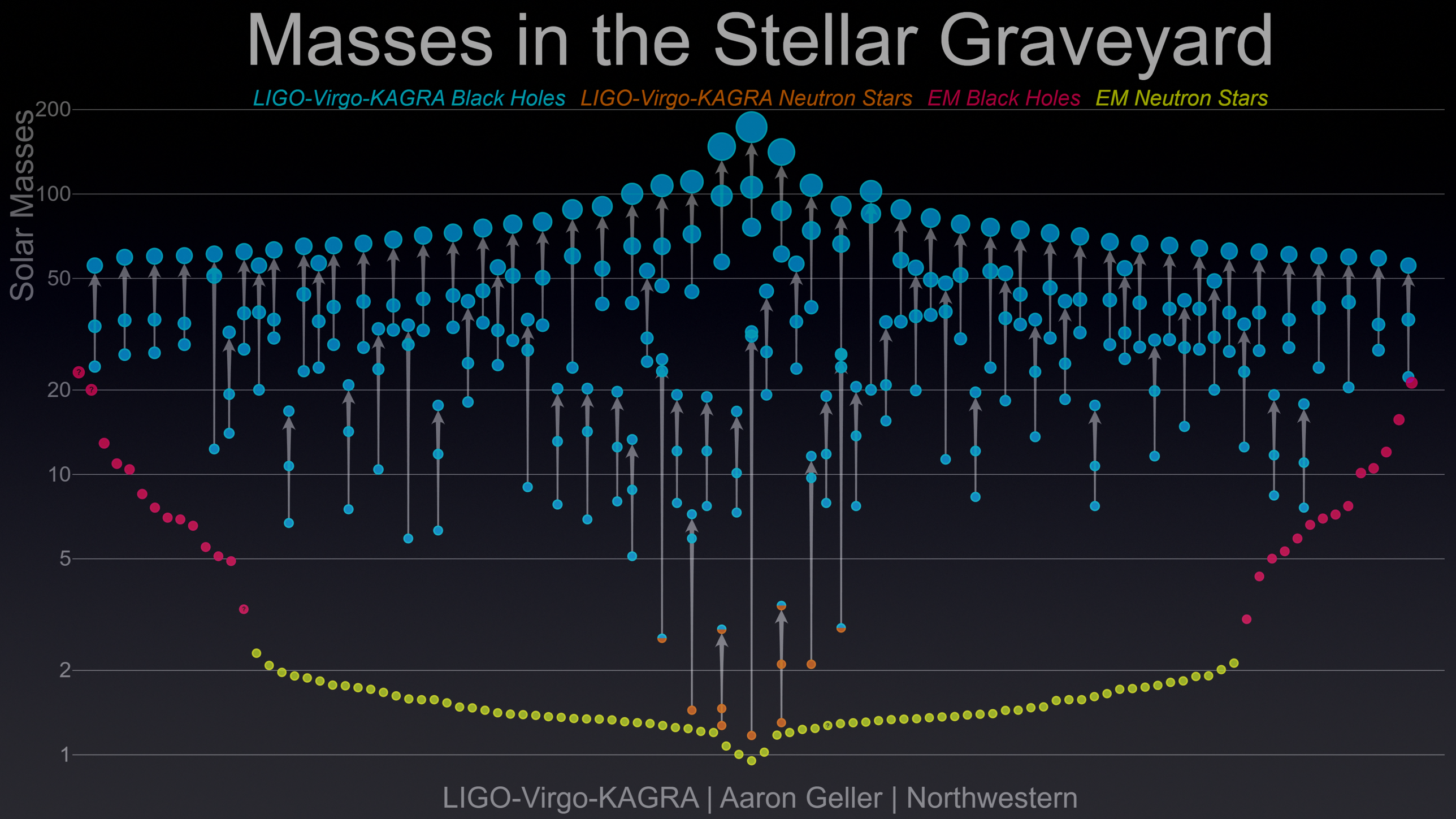


Abbott et al., PRL 116, 061102 (2016)

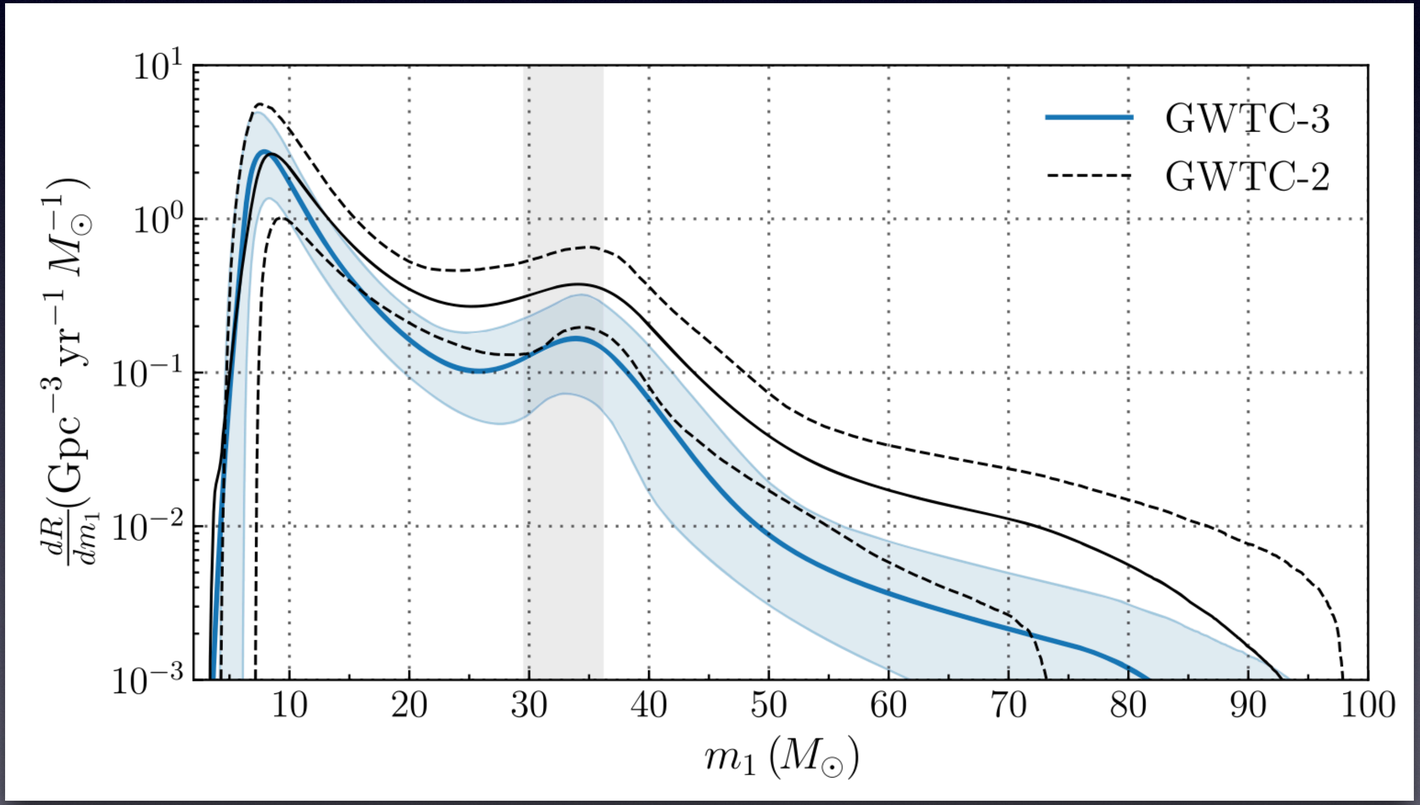
CBC Detections



Masses in the Stellar Graveyard



Population Analysis

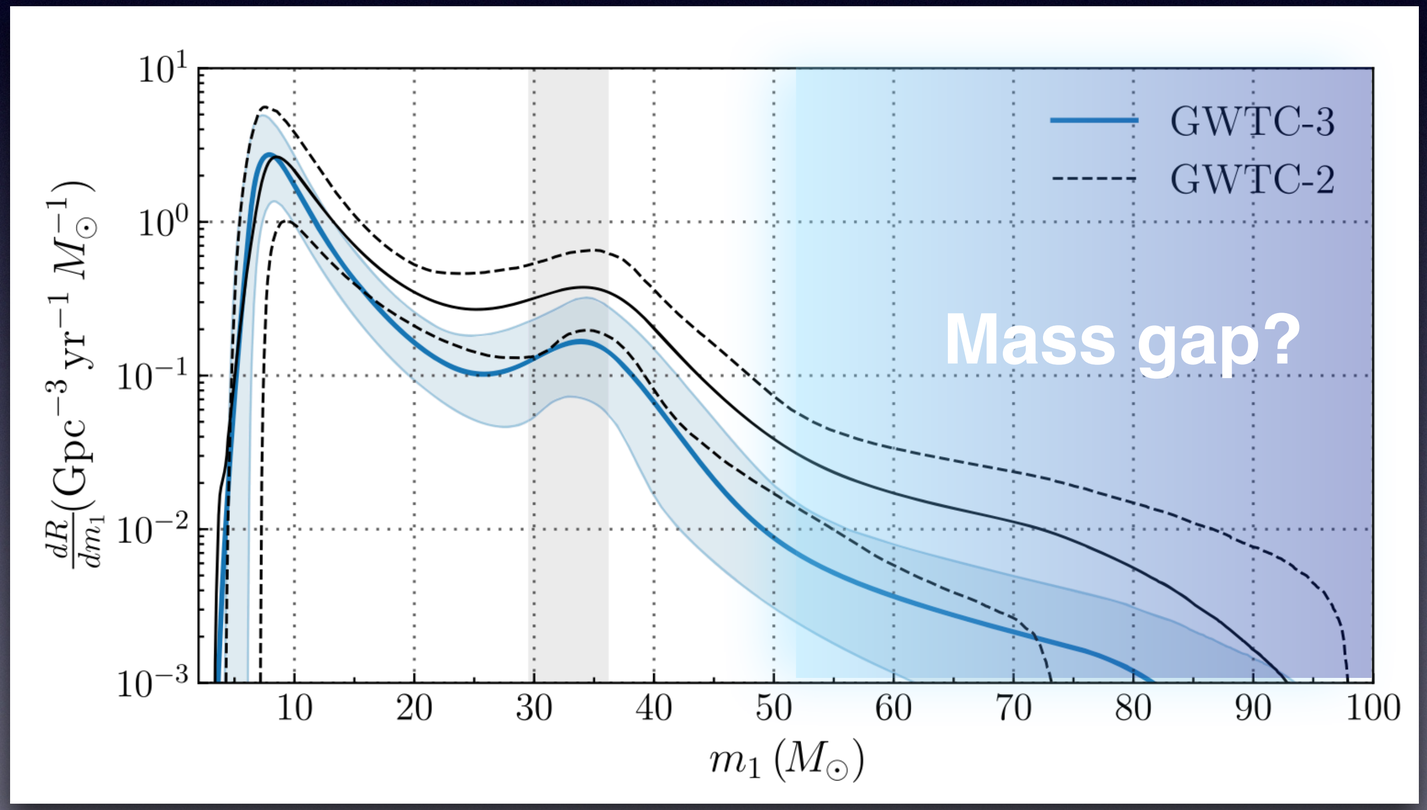


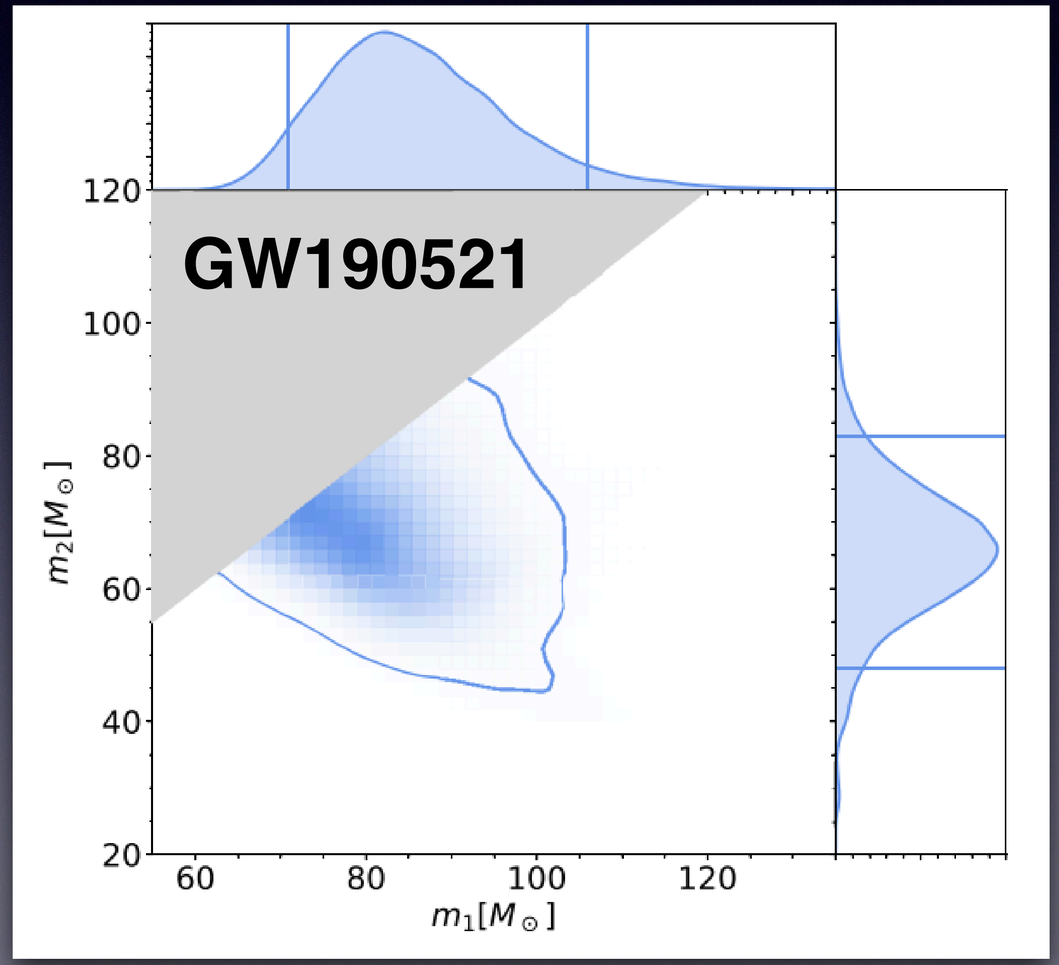
- Find a population model that describes observed masses

LVK Phys. Rev. X 13, 011048 (2023)

Population Analysis

Do we find objects in the theoretical mass gap?

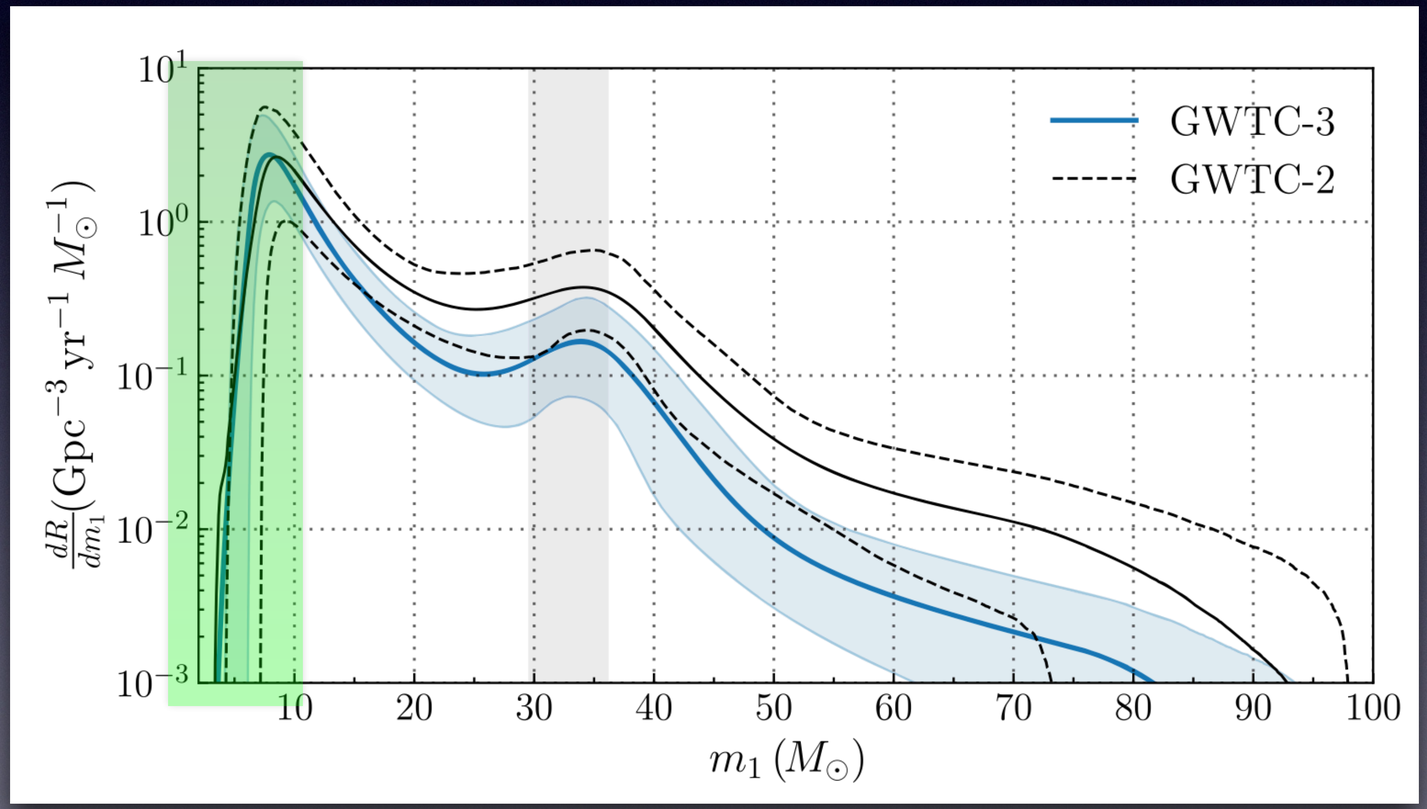


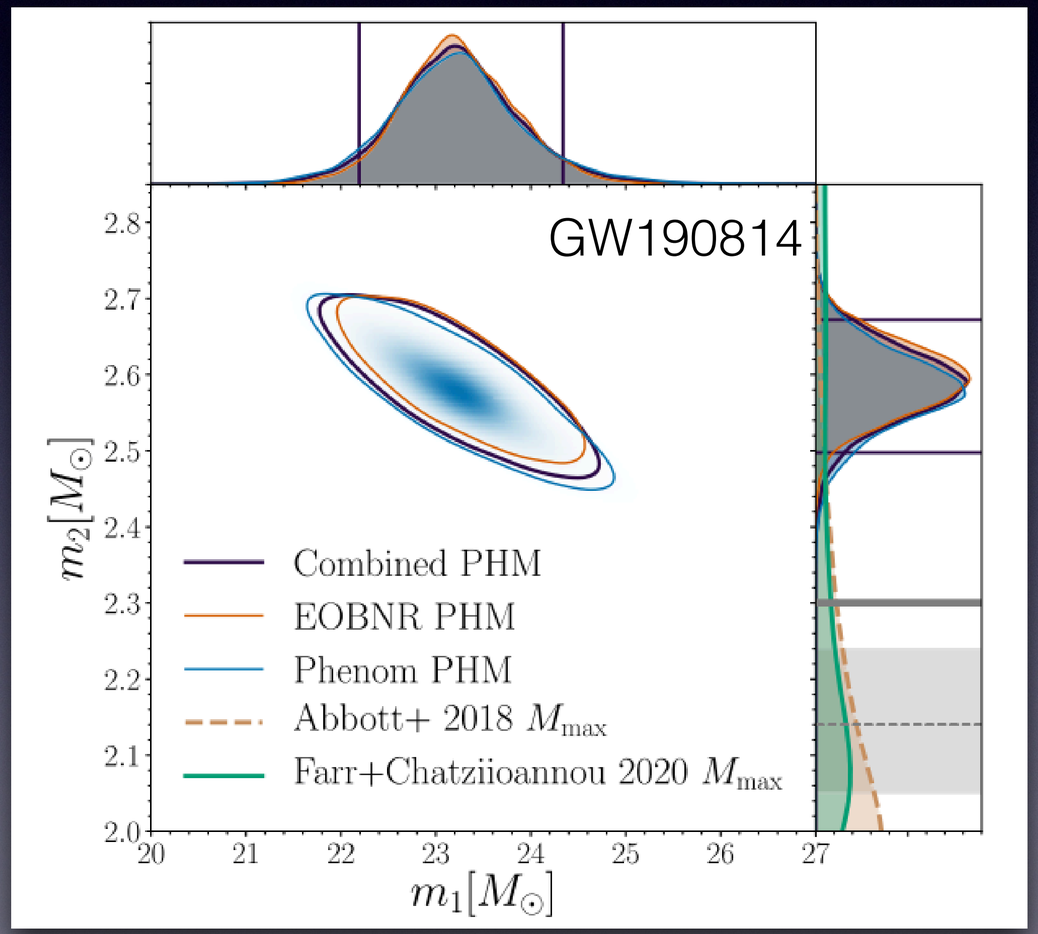


LVK Phys. Rev. Lett. 125, 101102 (2020) and LVK ApJ Lett. 900, L13 (2020)

Population Analysis

Minimum BH mass?





LVK ApJ Lett. 896, L44 (2020)

Population Analysis

How are CBCs formed?

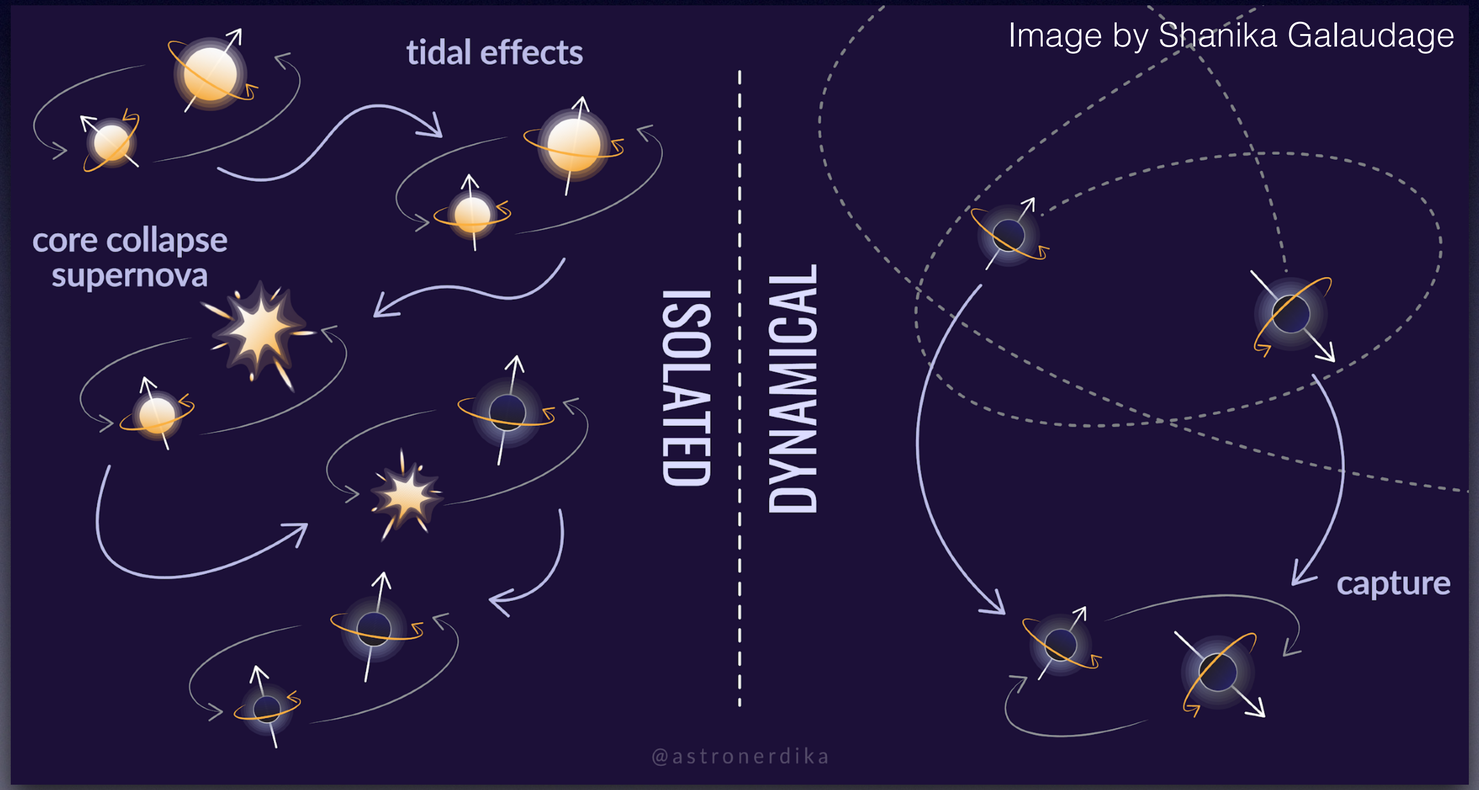
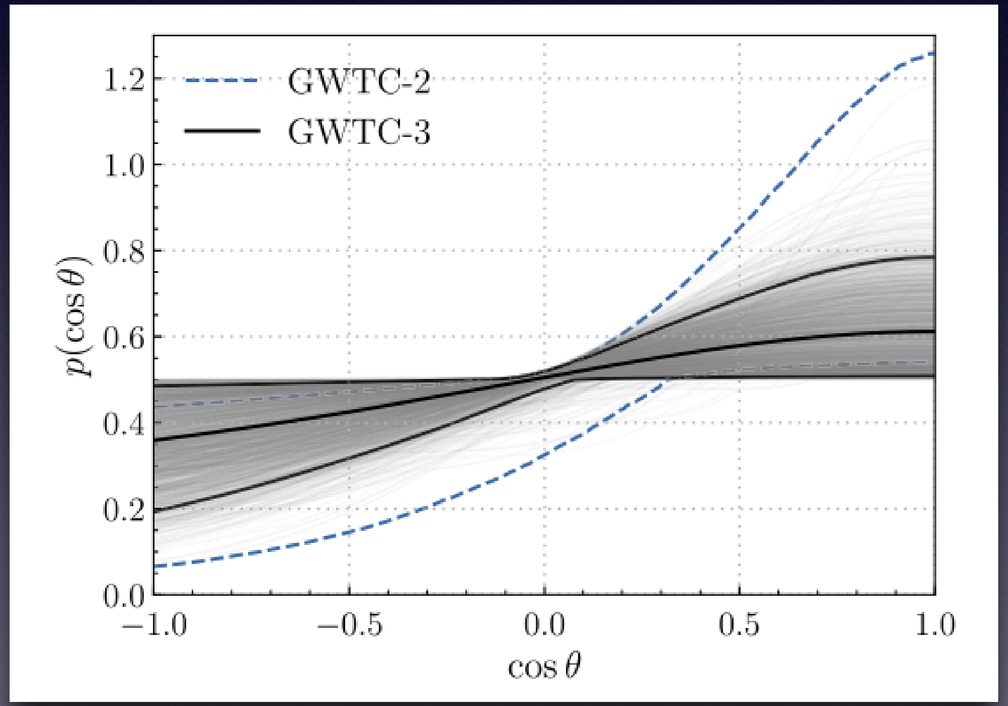


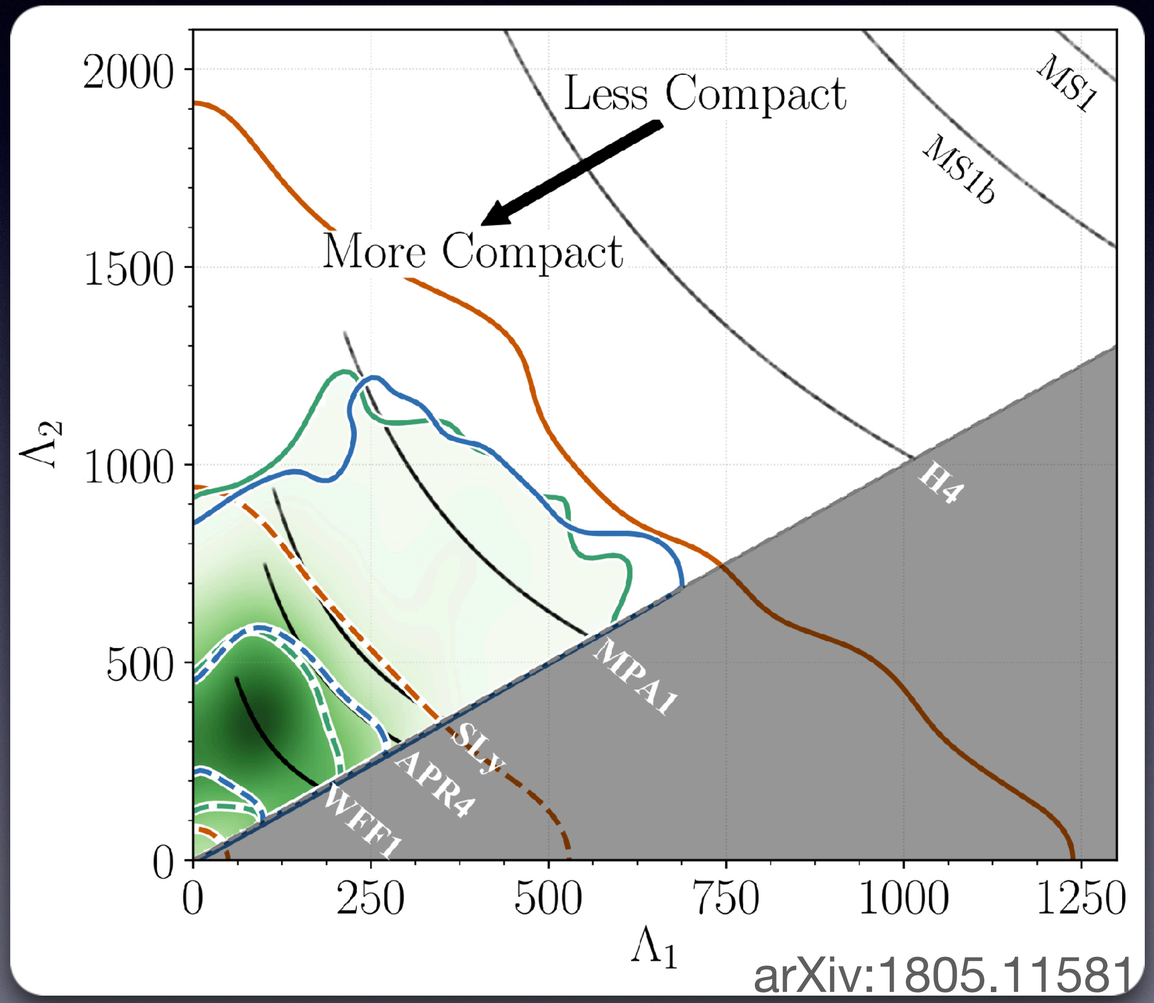
Image by Shanika Galaudage



Spin-orbit misalignment

LVK Phys. Rev. X 13, 011048 (2023)

Extreme Matter

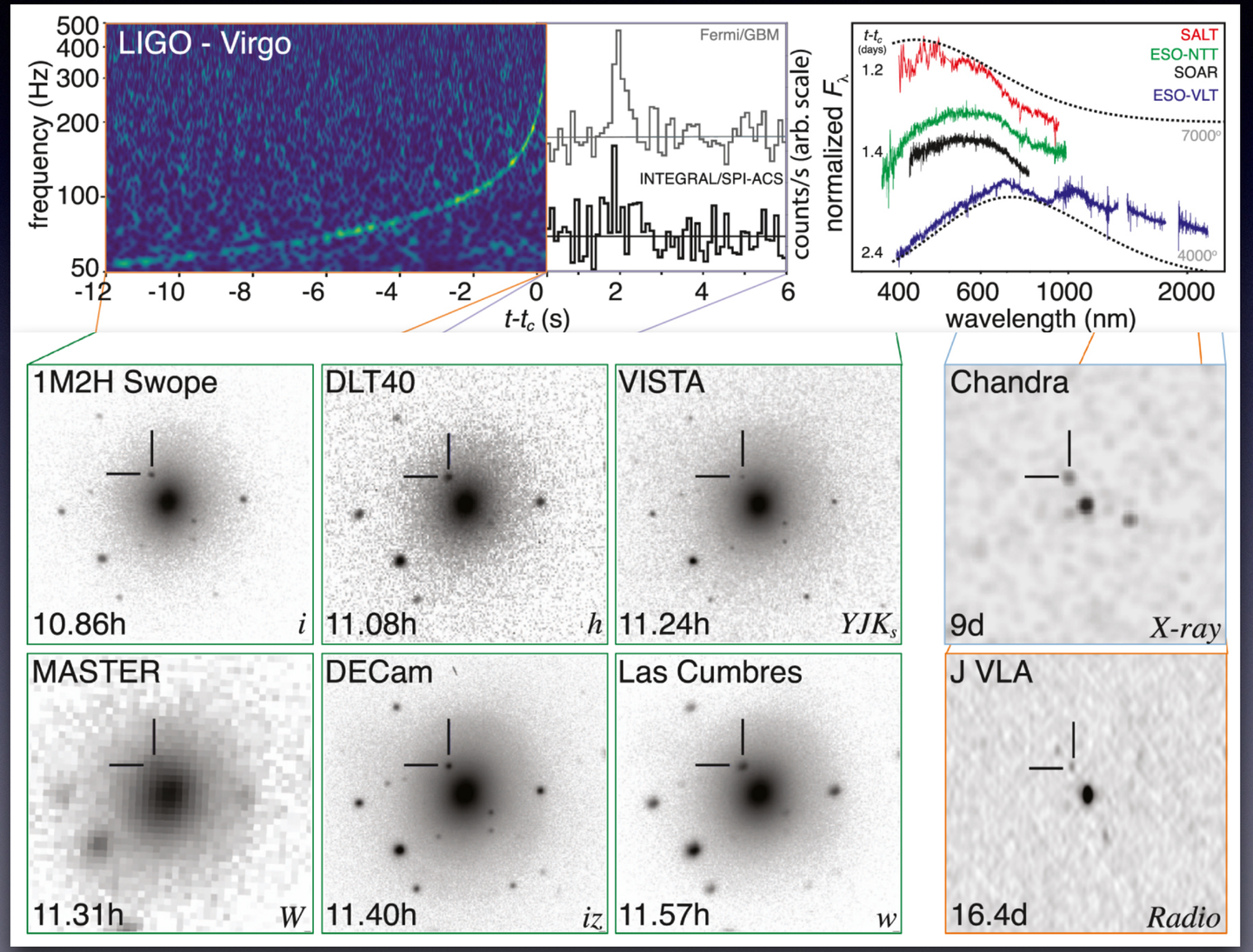


- **Binary neutron stars** offer an opportunity to study how matter behaves at extreme densities
- What is the **equation of state**?
  - *Soft* EoS: smaller radii, less deformable
  - *Stiff* EoS: larger radii, more deformable

Tidal deformation (not to scale!)

Extreme Matter

- Observe EM and GW signals from the same system
- GW170817:
  - Gamma ray burst
  - Kilonova
- Source of many heavy elements!



LVK 2017 *ApJL* **848** L12

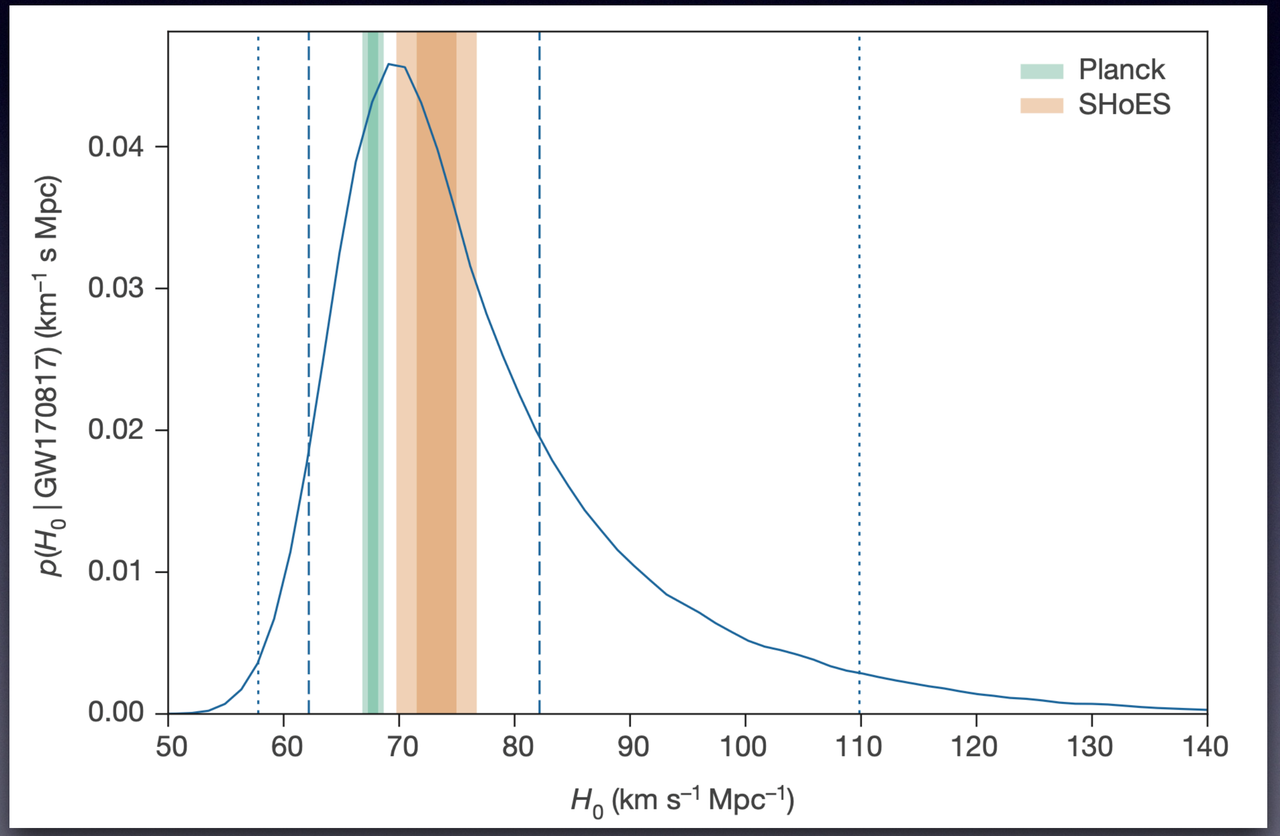
Cosmology

Measure the expansion of the universe with theHubble constant

luminosity distance from GW

$$z = H_0 \frac{d}{c}$$

redshift from EM



LVK, Nature 551, 85–88 (2017)

Tests of General Relativity

Are our GR-based models correct??

- Residual SNR
- Inspiral-merger-ringdown consistency
- Speed of gravity

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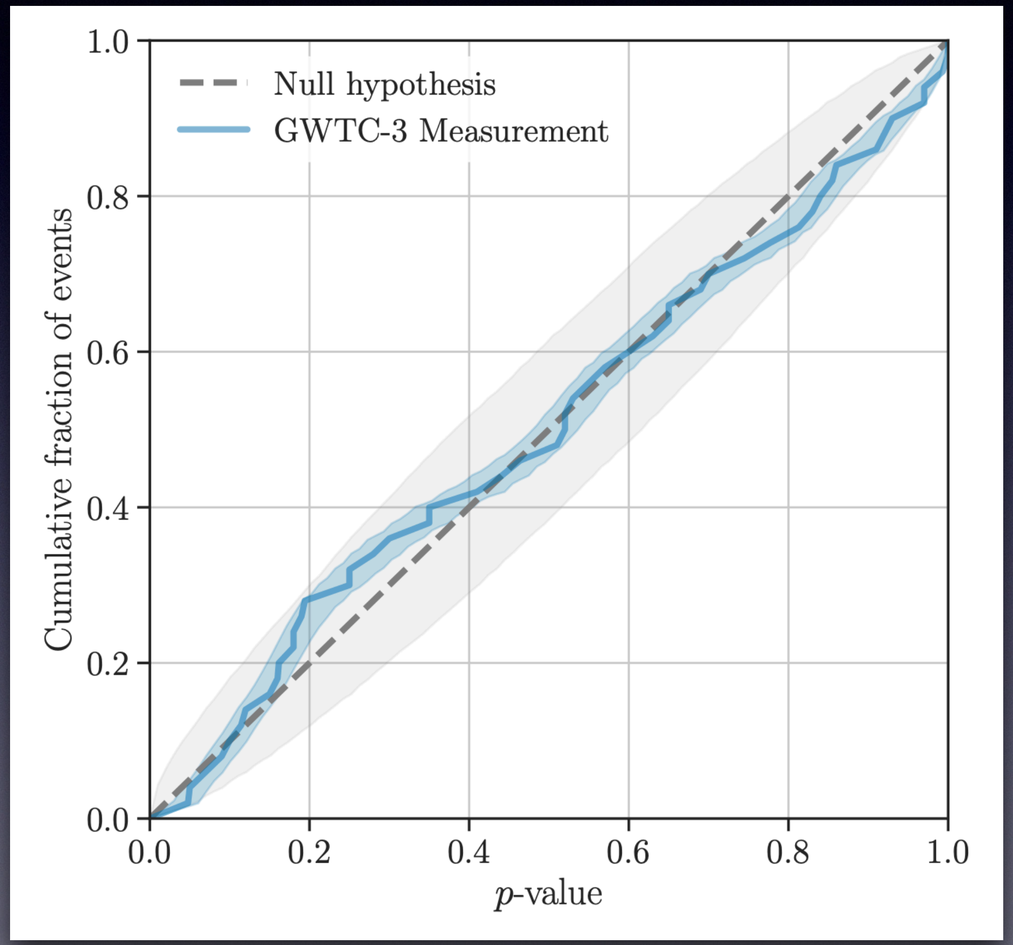

LVK arXiv:2112.06861

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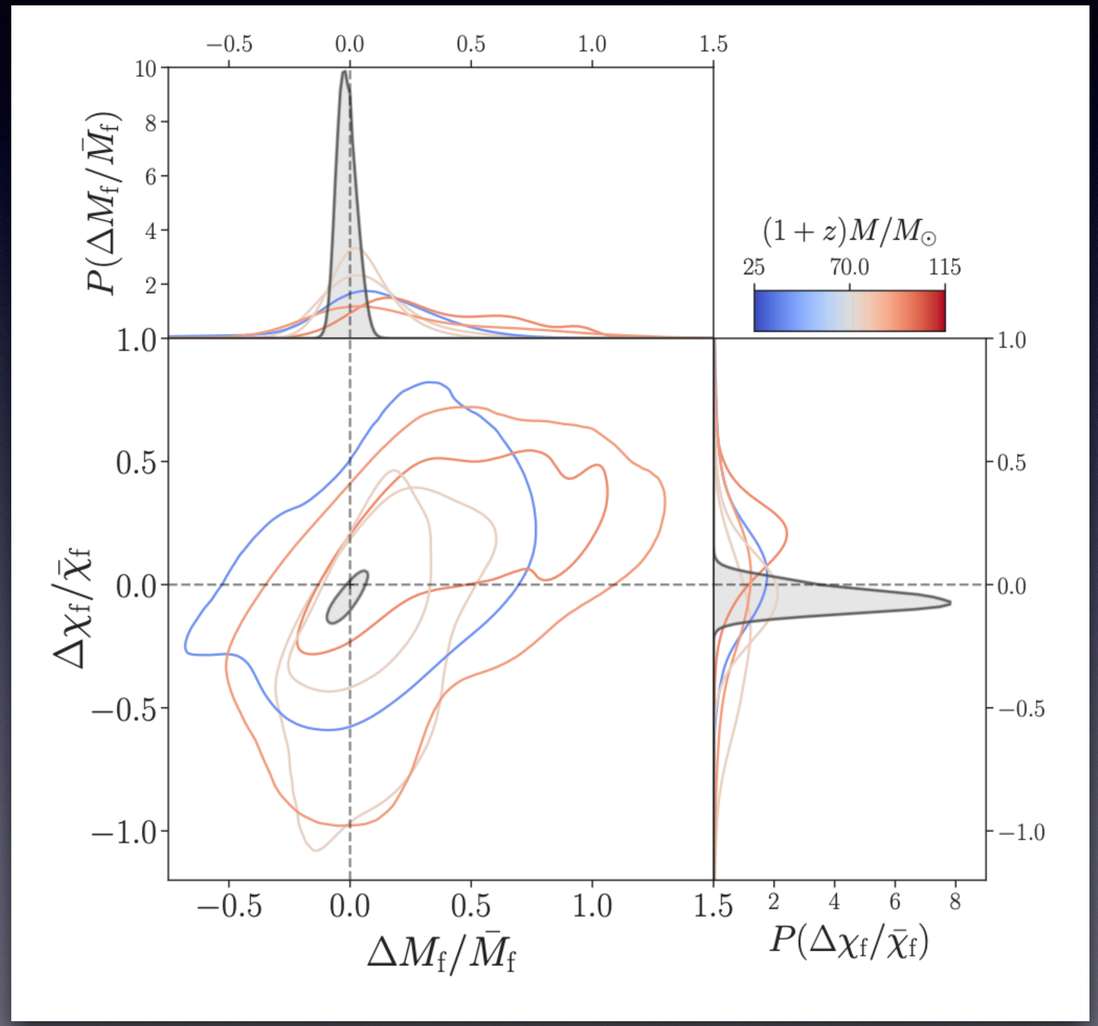

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- Residual power
- Inspiral-merger-ringdown consistency
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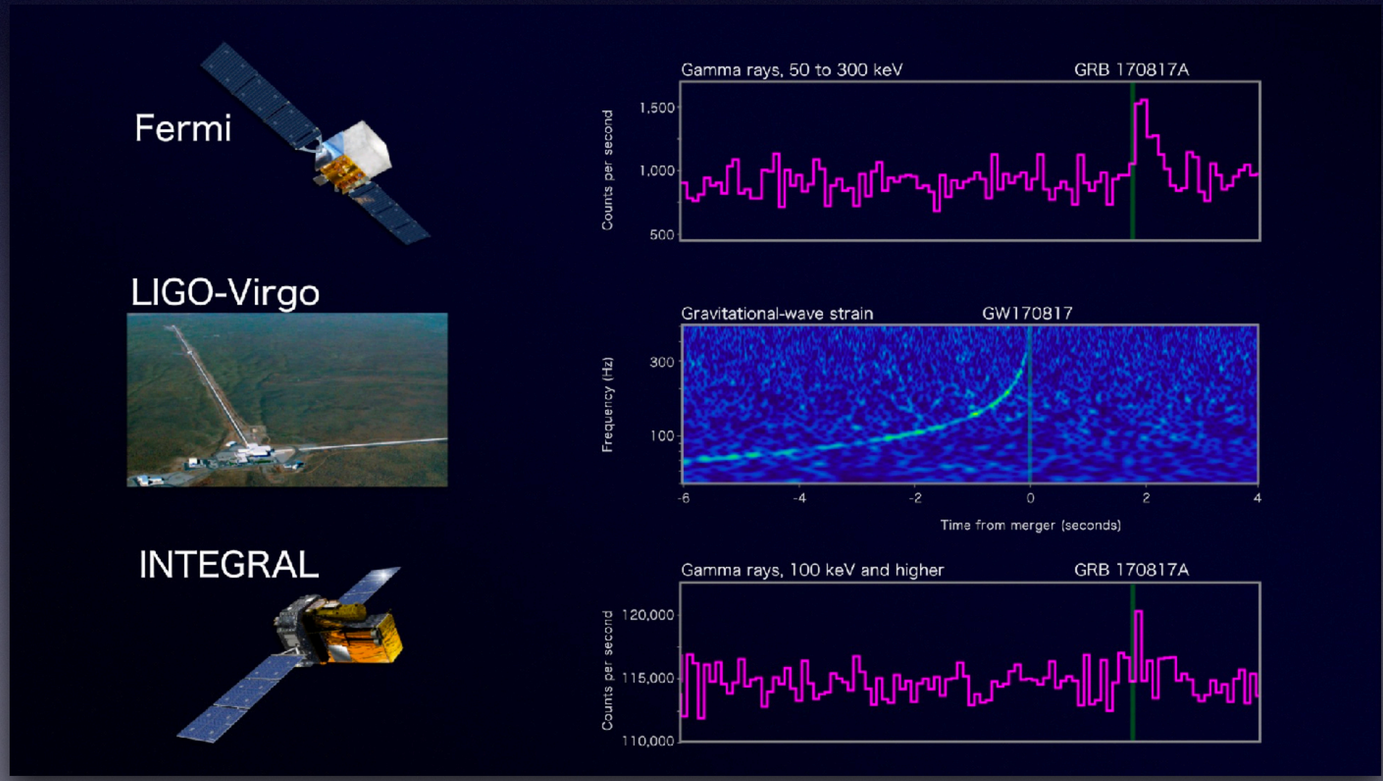

NASA's Goddard Space Flight Center, Caltech/MIT/LIGO Lab and ESA

Bonus: Beyond-CBC Science

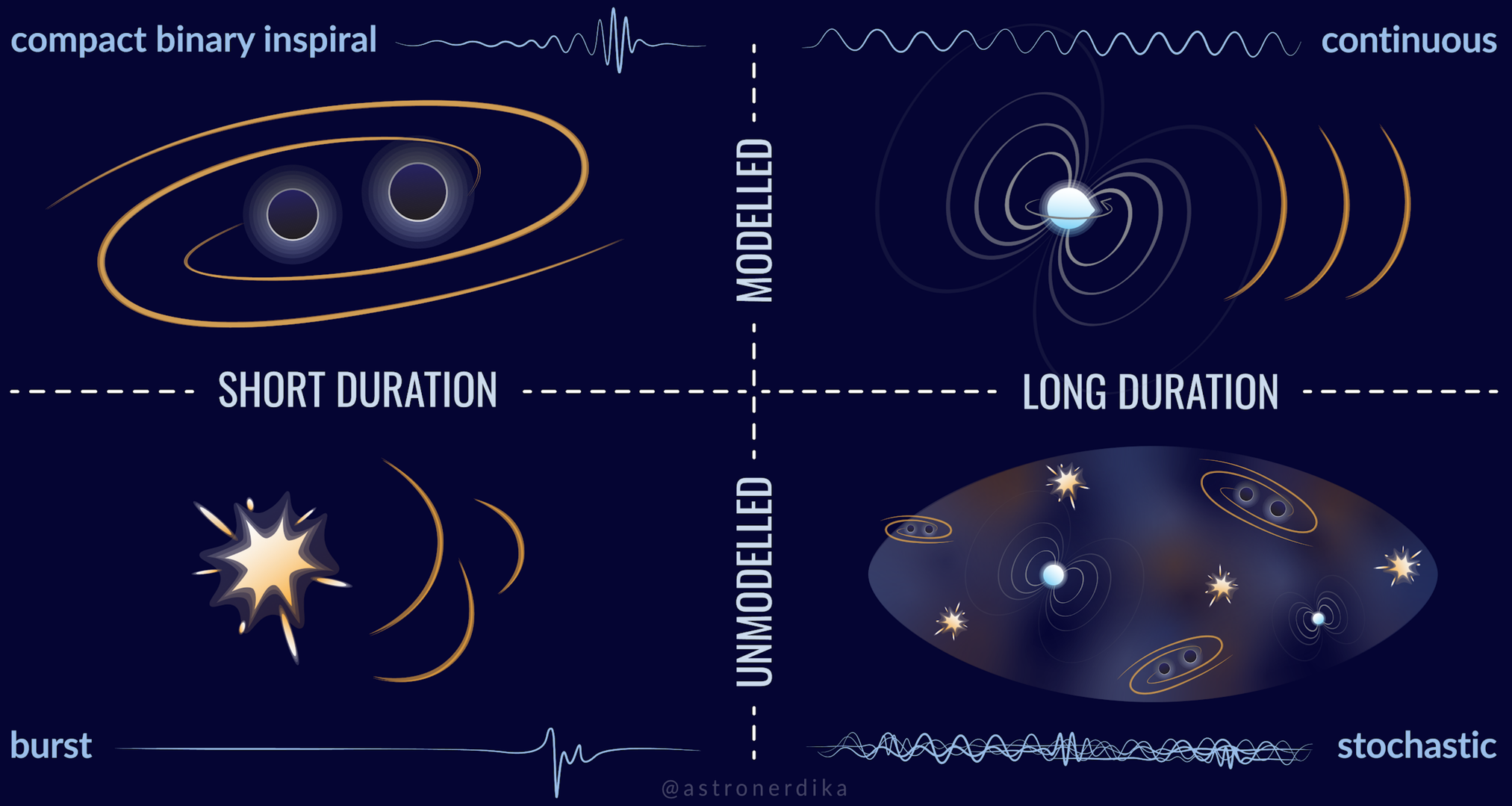

Image by Shanika Galaudage

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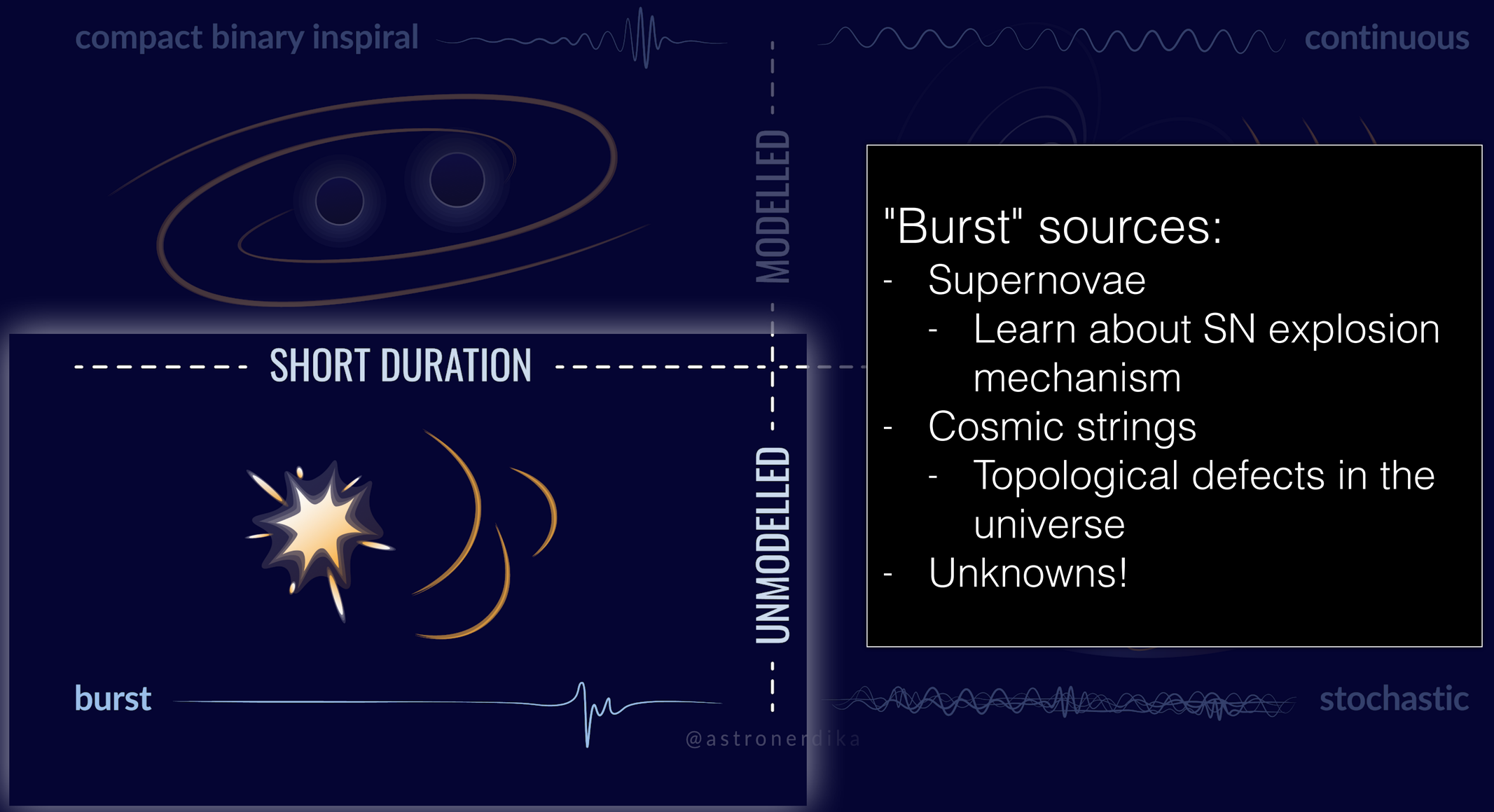

"Burst" sources:

- Supernovae
  - Learn about SN explosion mechanism
- Cosmic strings
  - Topological defects in the universe
- Unknowns!

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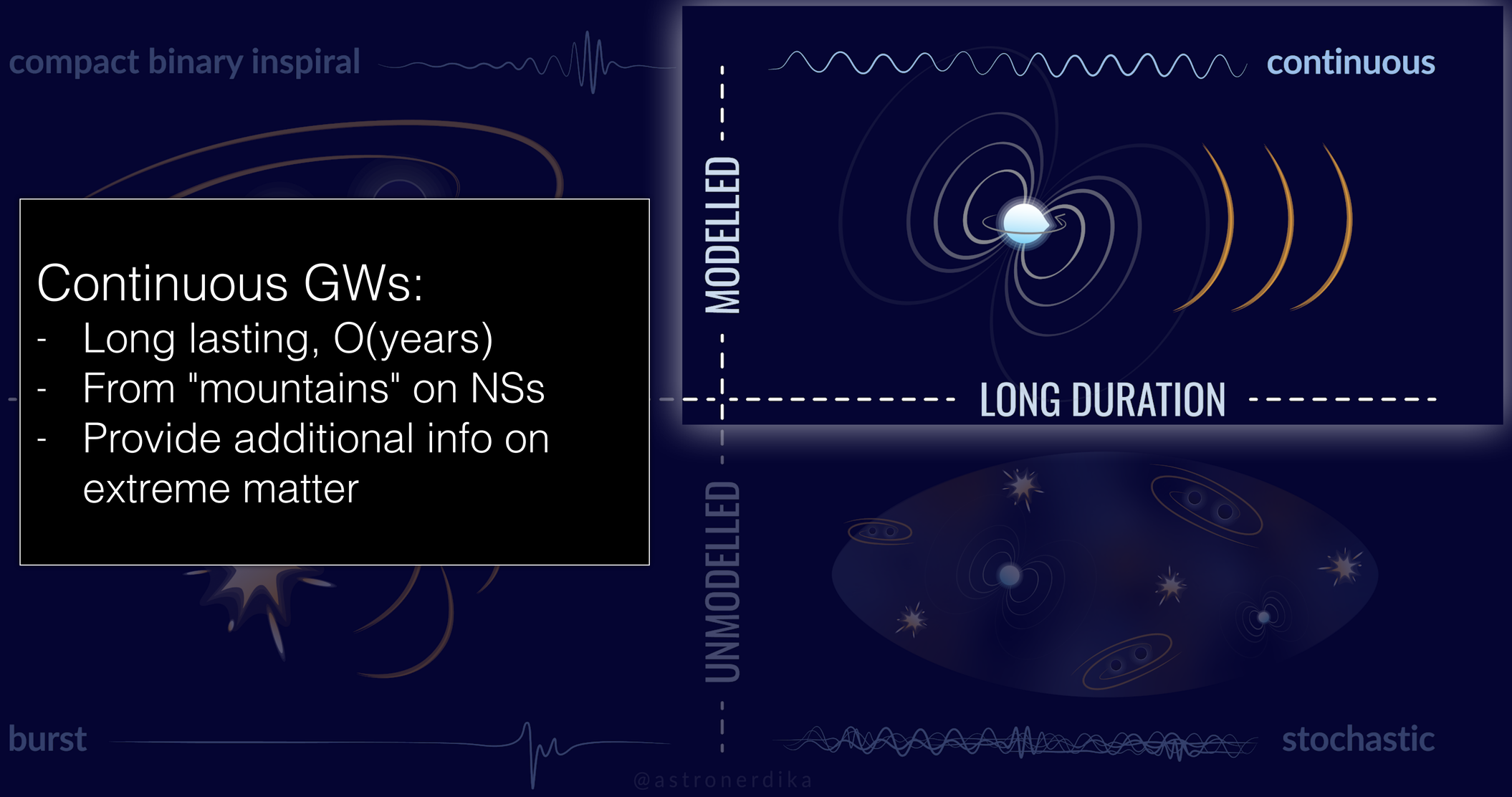

Continuous GWs:

- Long lasting, O(years)
- From "mountains" on NSs
- Provide additional info on extreme matter

Image by Shanika Galaudage

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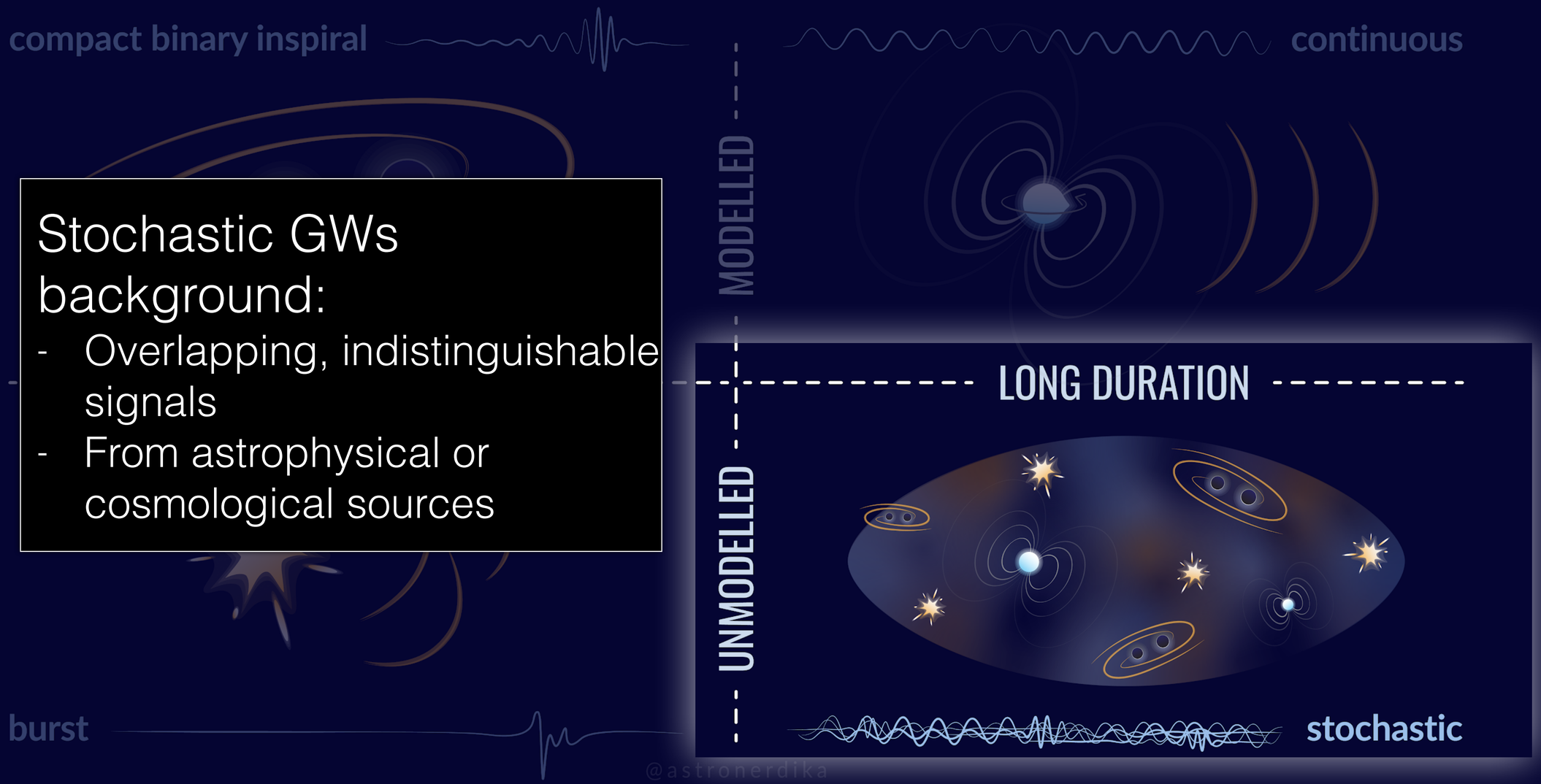

Stochastic GWs background:

- Overlapping, indistinguishable signals
- From astrophysical or cosmological sources

Image by Shanika Galaudage

Summary

- O1 through O3 gave us >90 CBC detections
- Enabled new science including:
  - How stars die and form binaries
  - How matter behaves at the most extreme densities
  - If GR is the correct model of gravity
- O4 ongoing, new results to be reported this year
  - Look forward to more CBCs and more science!