LIGO's Latest Results and Prospects for the Next Run

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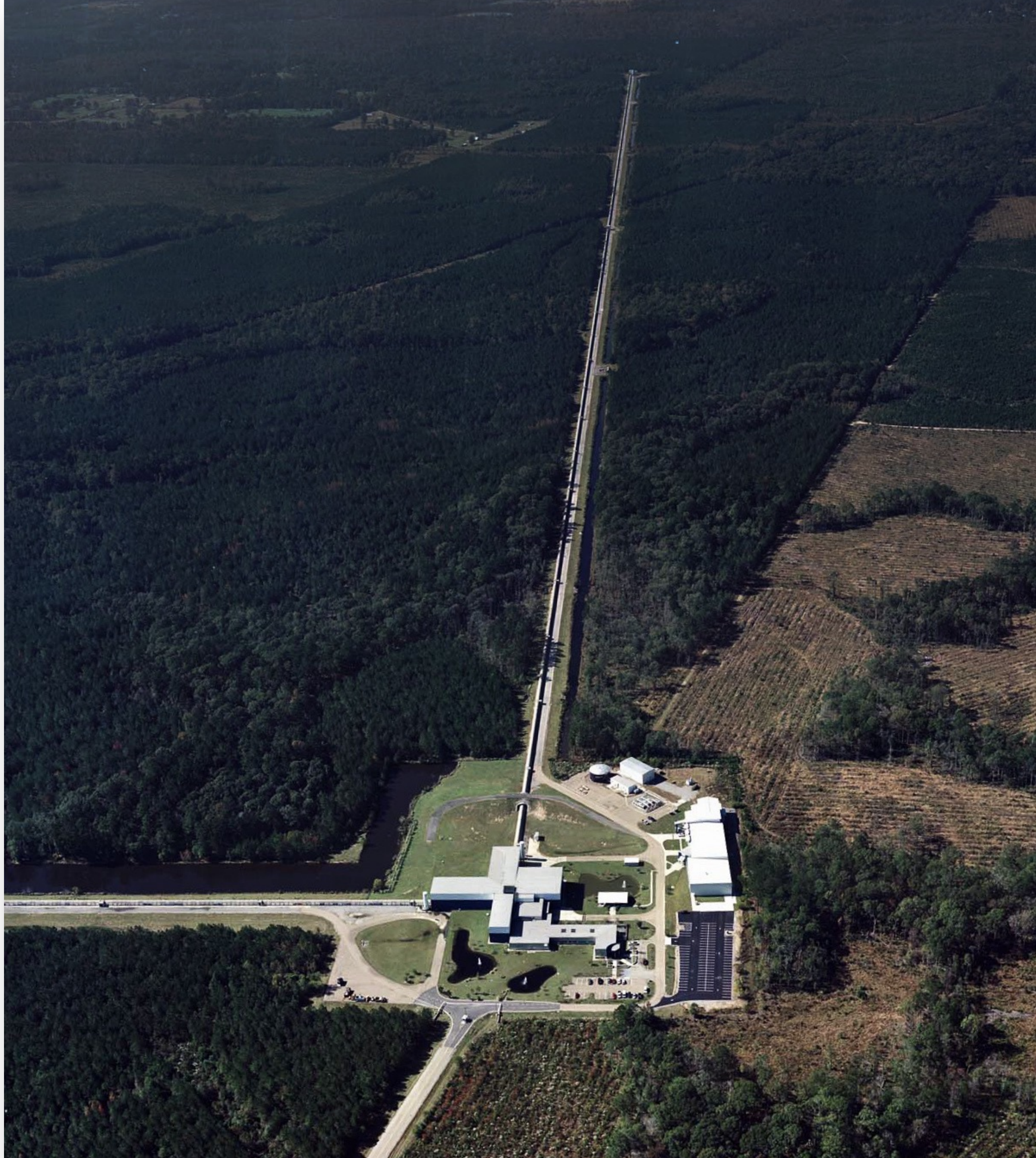


Multi-messenger astrophysics

The Universe is a big laboratory that is continuously sending us information through multiple channels.

Many cosmic “experiments” cannot be reproduced on Earth.

Nature has several cosmic messengers:

radio / optical / X-ray / γ-ray
neutrinos
cosmic rays
gravitational waves

We can learn the most by collecting information from all 4.

We only recently developed the technology to observe all messengers – expect major breakthroughs.

NASA Decadal Survey on Astronomy and Astrophysics 2020

Worlds and Suns in Context

Priority Area: Pathways to Habitable Worlds

Understanding the connections between stars and the worlds that orbit them, from nascent disks of dust and gas through formation and evolution, is an important scientific goal for the next decade. The effort to identify habitable Earth-like worlds in other planetary systems and search for the biochemical signatures of life will play a critical role in determining whether life exists elsewhere in the universe.

KEY RECOMMENDATIONS:

New Messengers and New Physics

Priority Area: New Windows on the Dynamic Universe

Over the next decade, a range of complementary observations—from radio to gamma rays, gravitational waves, neutrinos, and high-energy particles—will enable investigations into the most energetic processes in the universe and address larger questions about the nature of dark matter, dark energy, and cosmological inflation. These growing capabilities will enable close study of neutron stars, white dwarfs, black hole collisions, stellar explosions, and the birth of our universe.

KEY RECOMMENDATIONS:

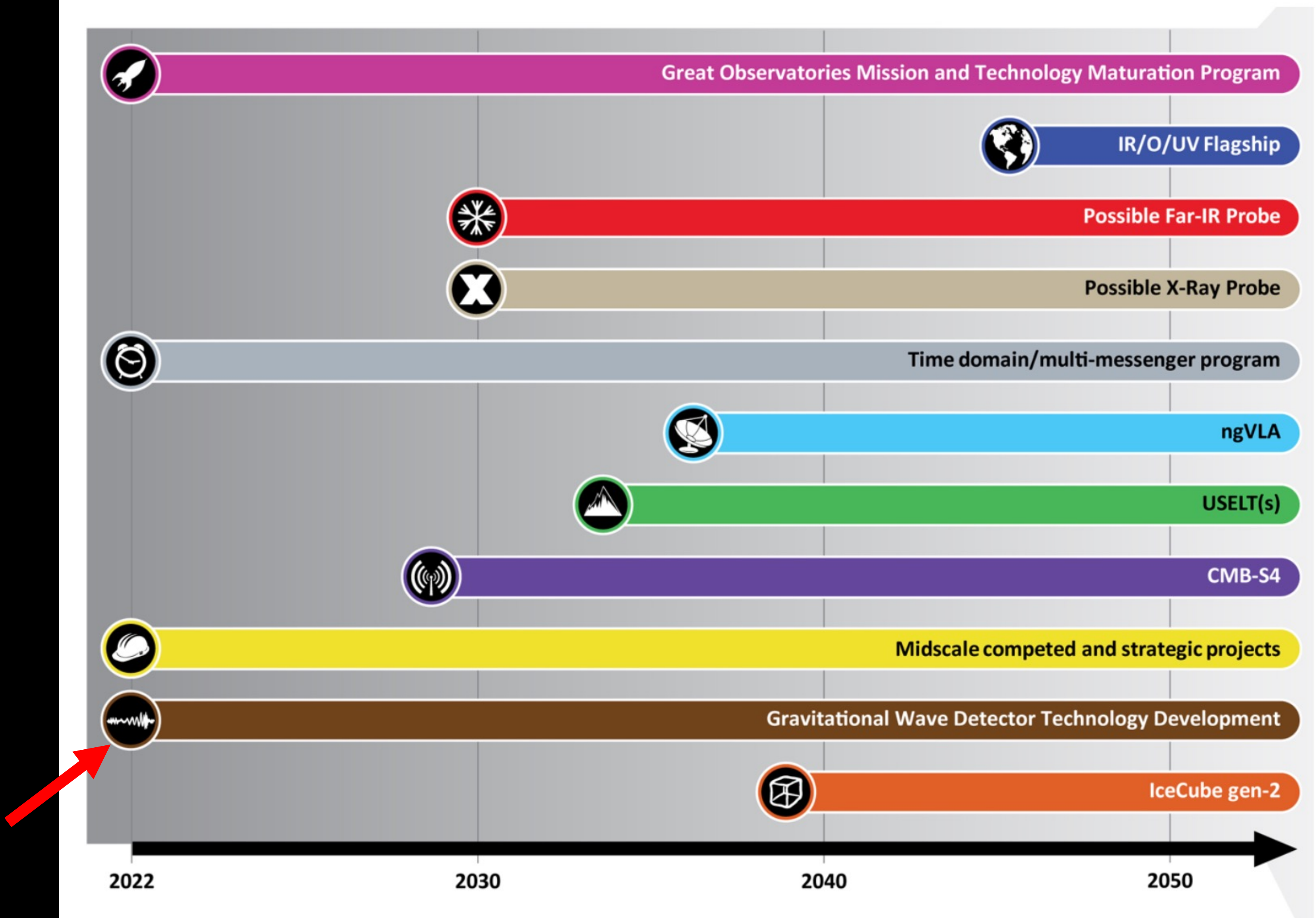
Cosmic Ecosystems

Priority Area: Unveiling the Drivers of Galaxy Growth

Research in the coming decade will revolutionize our understanding of the origins and evolution of galaxies, from the cosmic webs of gas that feed them to the formation of stars. New observational capabilities across the electromagnetic spectrum along with

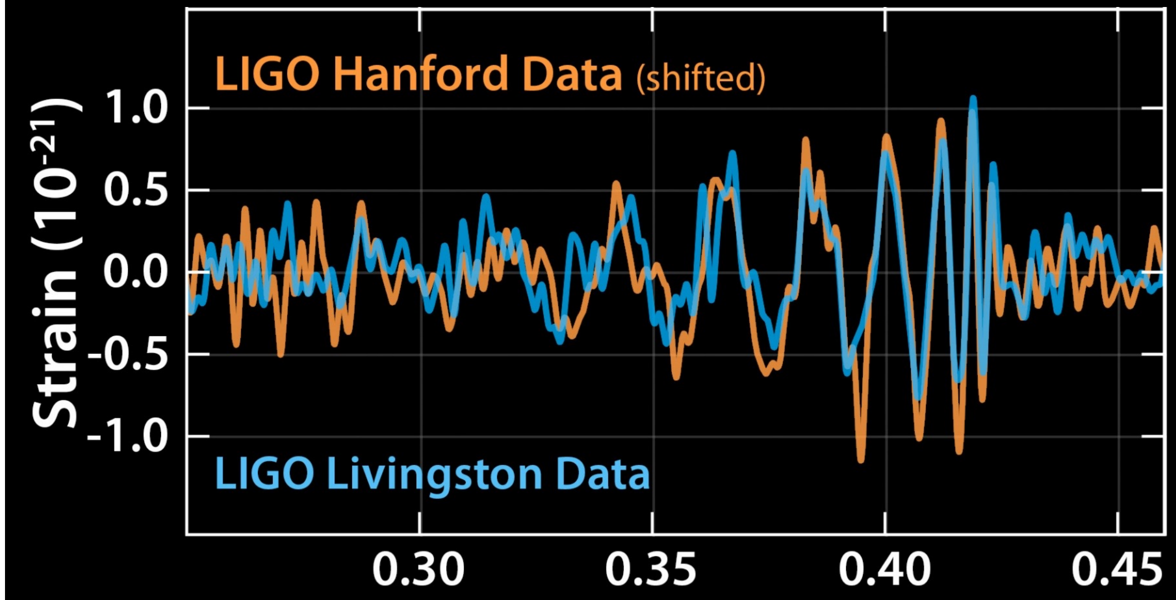
- One of 3 big areas for next decade: **multi-messenger astrophysics**.
- **Gravitational waves** are front and center.
- Next generation gravitational wave observatory, **Cosmic Explorer endorsed as top priority**

Timeline for the medium and large programs and projects recommended and endorsed by the decadal survey



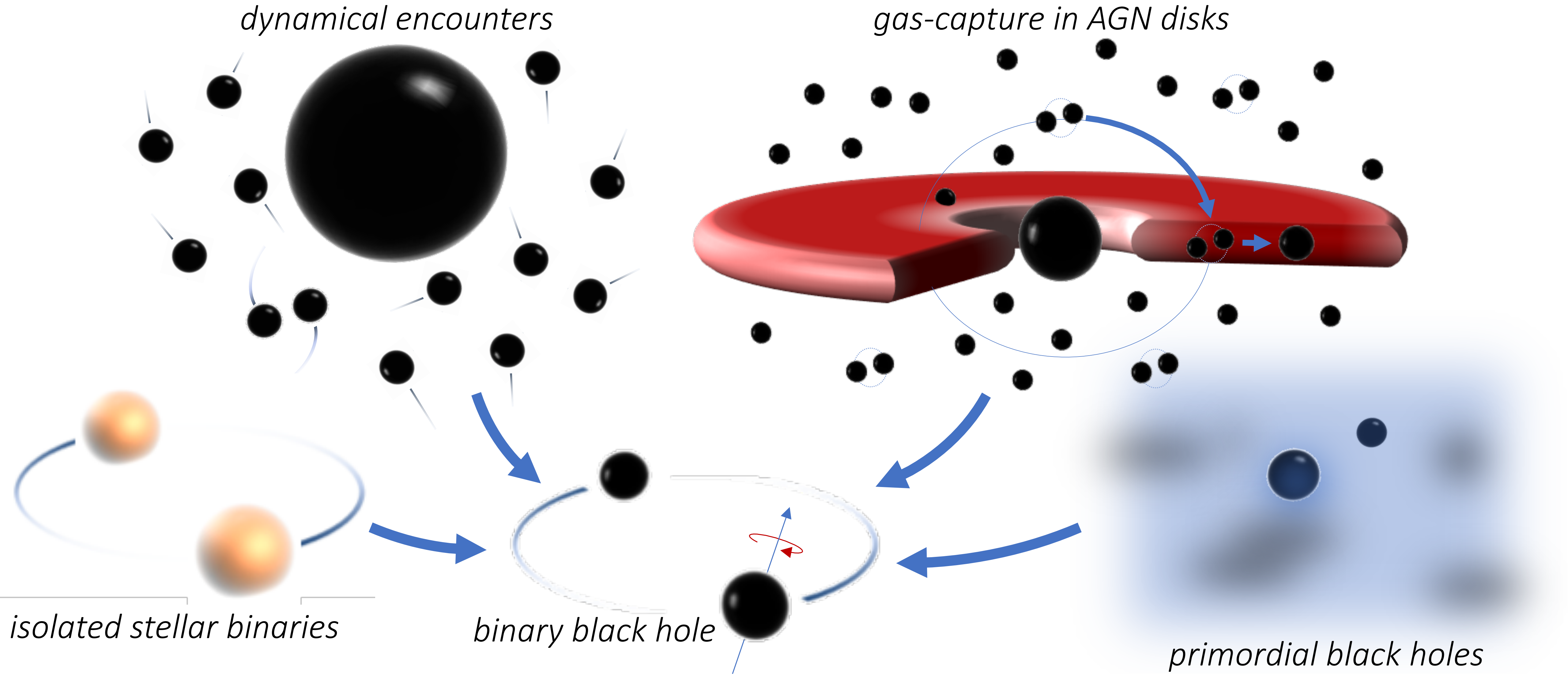
Discovery

- Advanced LIGO completed in 2015 – *discovery within hours!*
- Nobel prize in 2017.
- All information about two black holes (masses, spins, distance, etc.) are encoded in the gravitational waveform.
- Surprises:
  - Black hole merger – not known before
  - Einstein was right (consistent with General Relativity)
  - Speed of gravity $\sim c$ to within 10^{-15}
  - The Universe is full of black hole mergers.
- We now have ~90 discoveries --- much more information.
- **What is the origin of binary black holes?**
- *(Neutron star mergers – see later talks in this session)*



Abbott+ PRL 116, 061102 (2016)

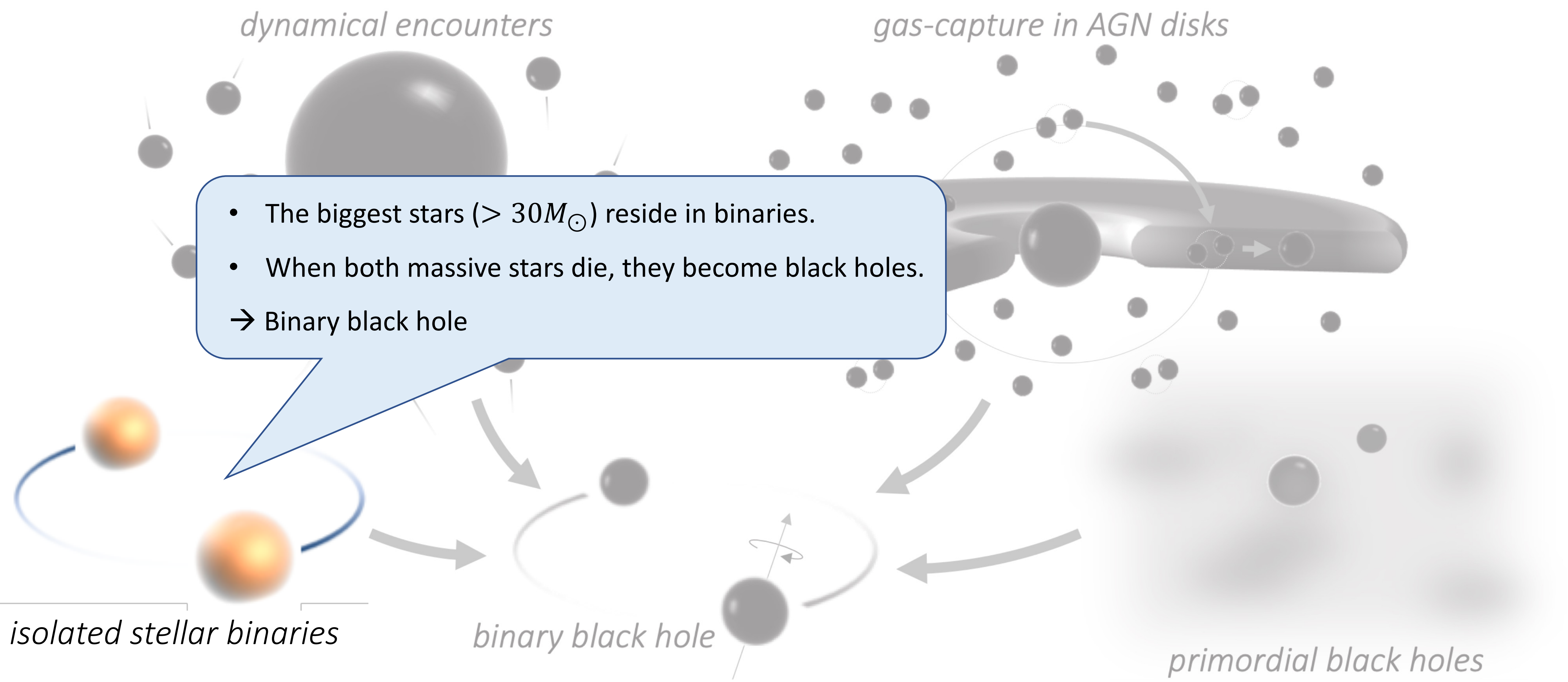
Possible origins of binary black holes



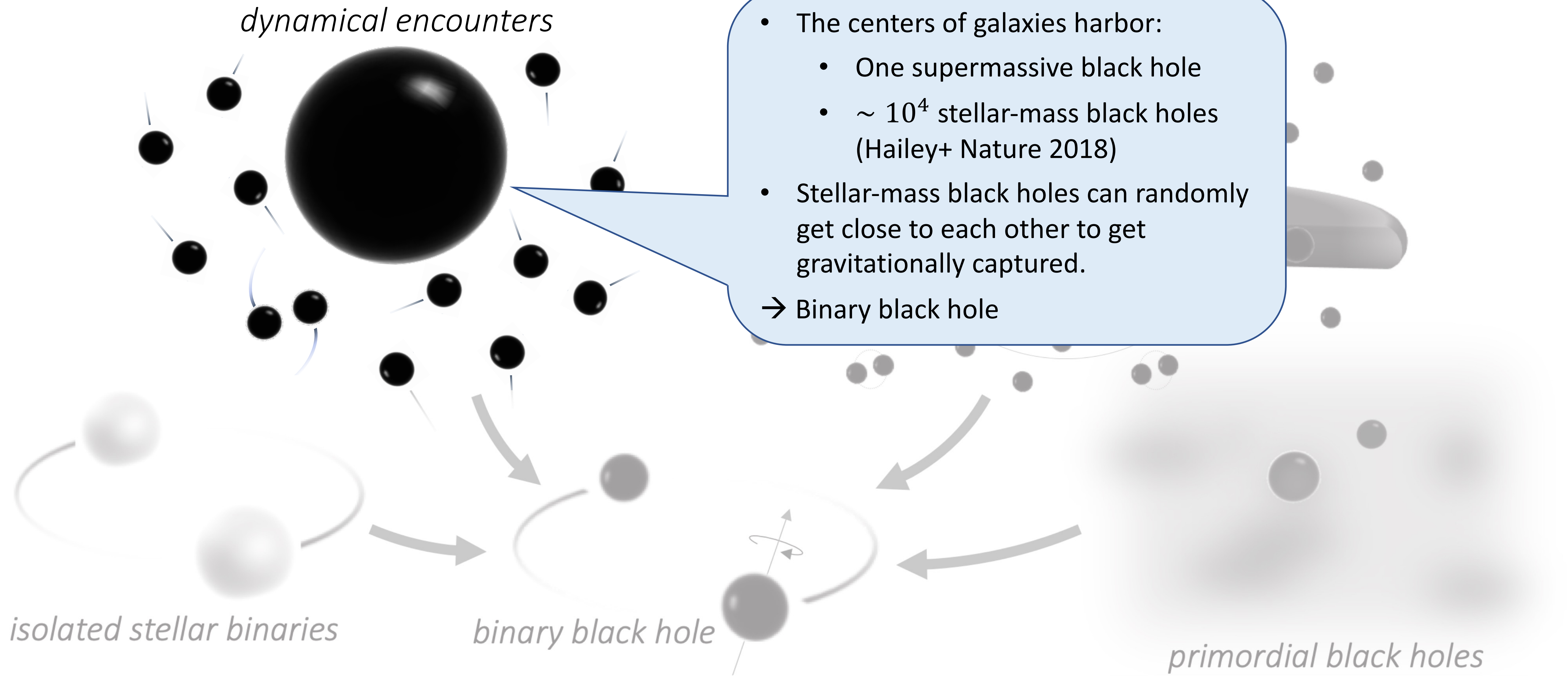
Possible origins of binary black holes

- The biggest stars ($> 30M_{\odot}$) reside in binaries.
- When both massive stars die, they become black holes.

→ Binary black hole



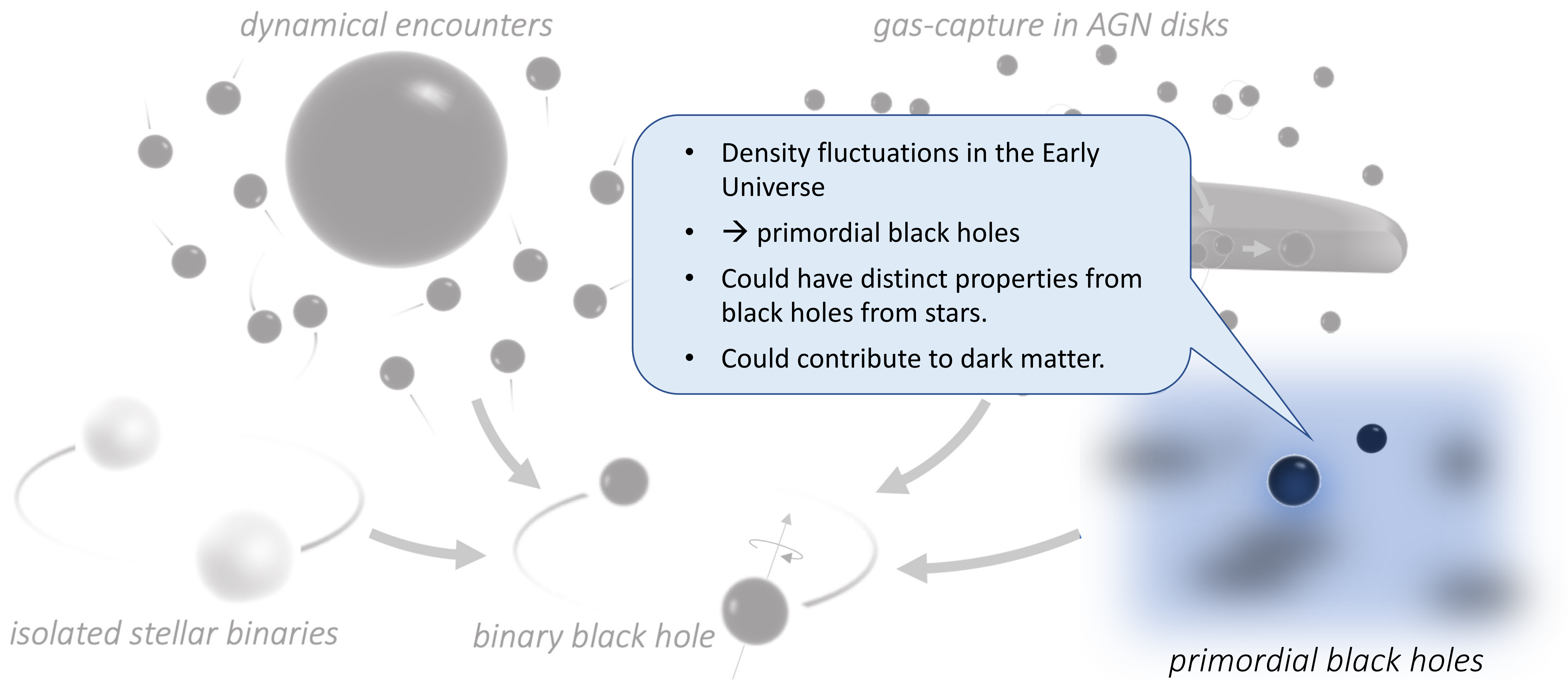
Possible origins of binary black holes



- The centers of galaxies harbor:
  - One supermassive black hole
  - $\sim 10^4$ stellar-mass black holes (Hailey+ Nature 2018)
- Stellar-mass black holes can randomly get close to each other to get gravitationally captured.

→ Binary black hole

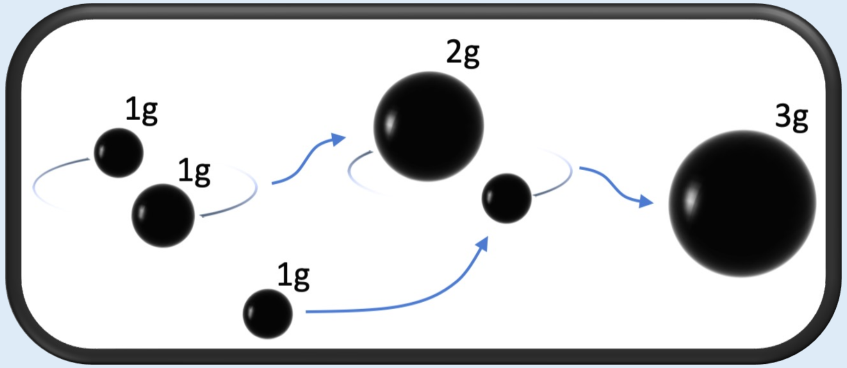
Possible origins of binary black holes

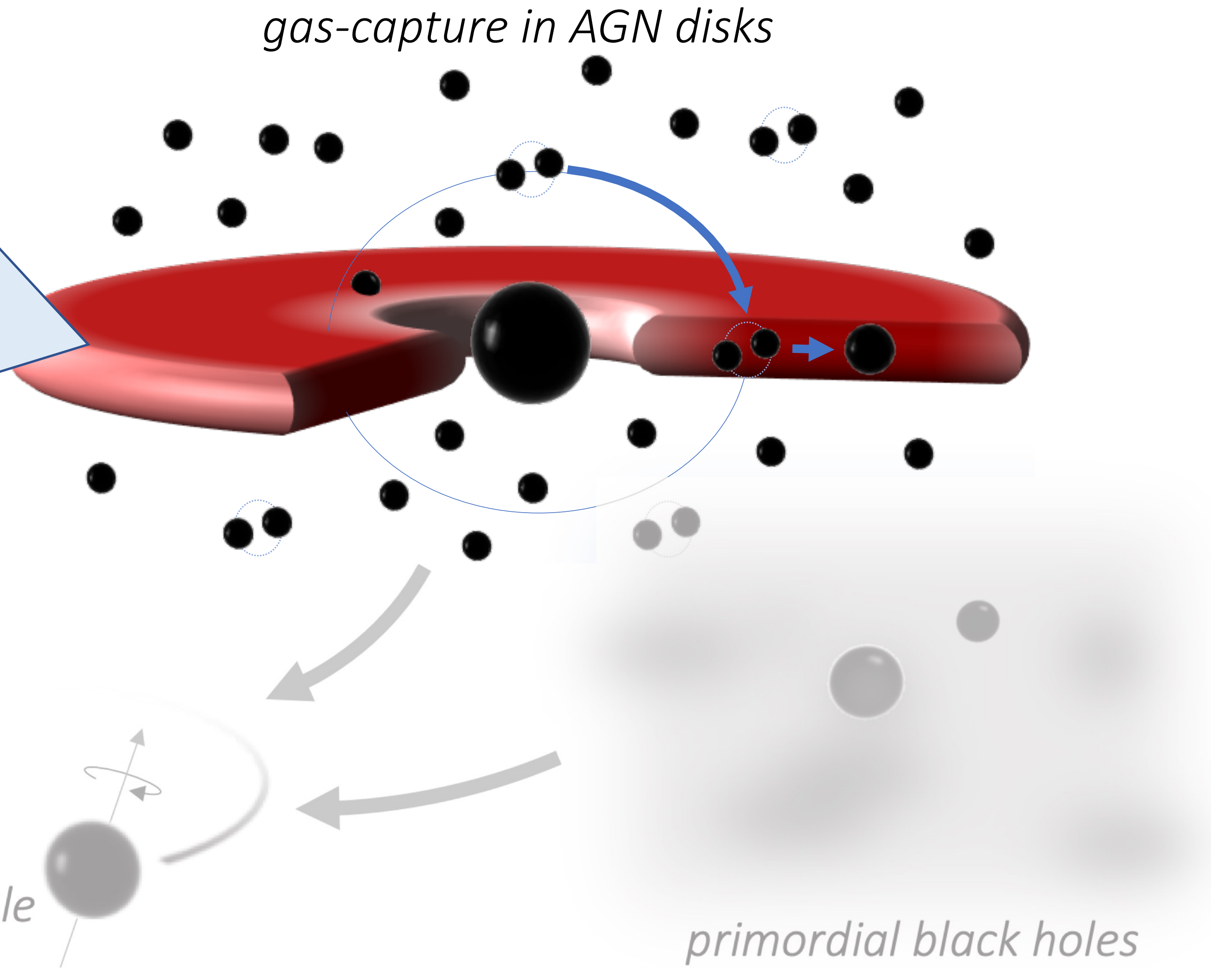


- Density fluctuations in the Early Universe
- → primordial black holes
- Could have distinct properties from black holes from stars.
- Could contribute to dark matter.

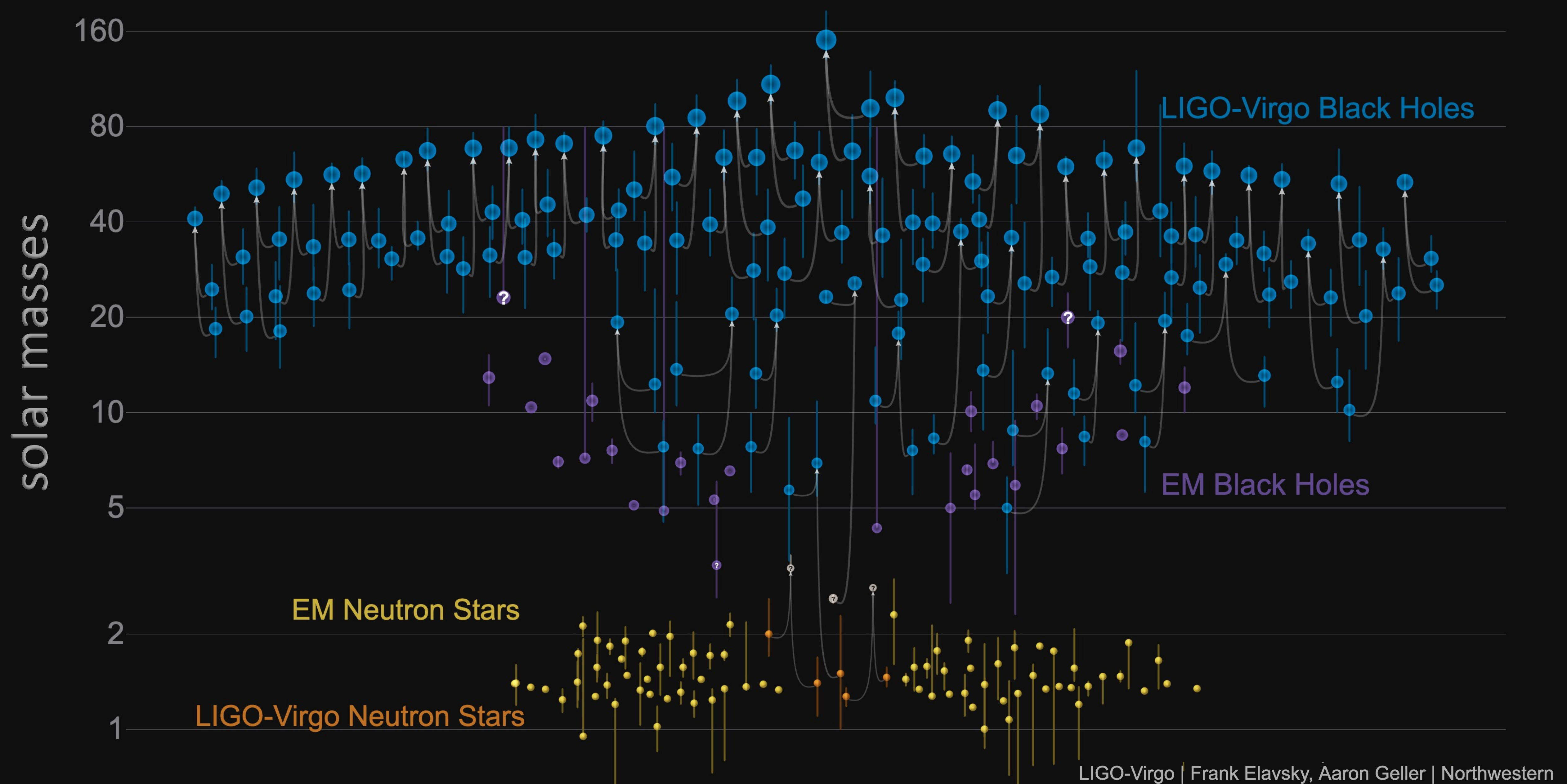
Possible origins of binary black holes

- Gas forms disk around SMBH.
- Disk drags black holes into the disk.
- Black holes migrate inward in disk.
- Black holes inside merge.
  → **multi-messenger emission** due to surrounding gas? (Bartos+ 2017)
- Black holes can **merge multiple times**, creating much heavier black holes (Yang+ PRL 2019).

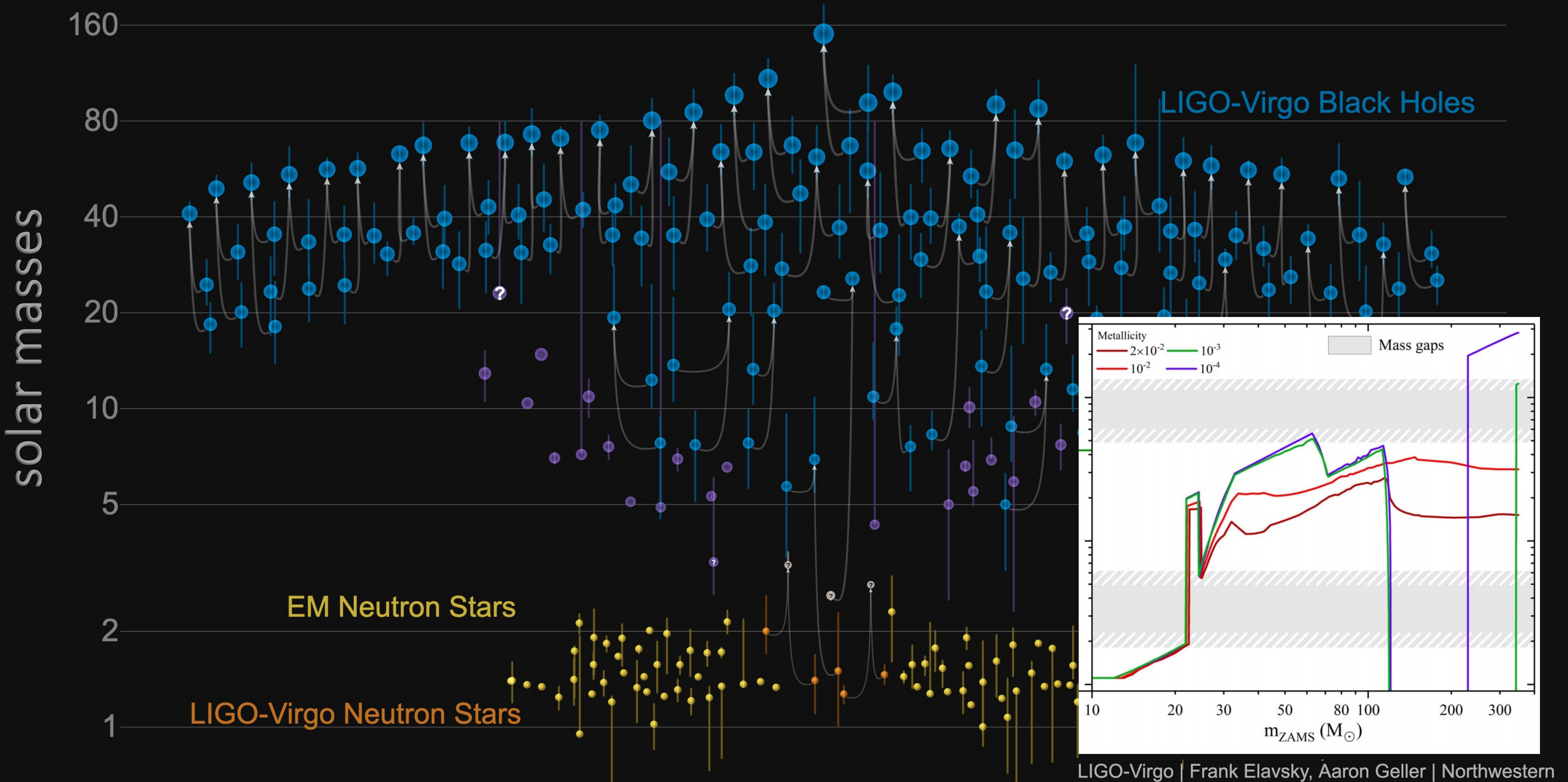




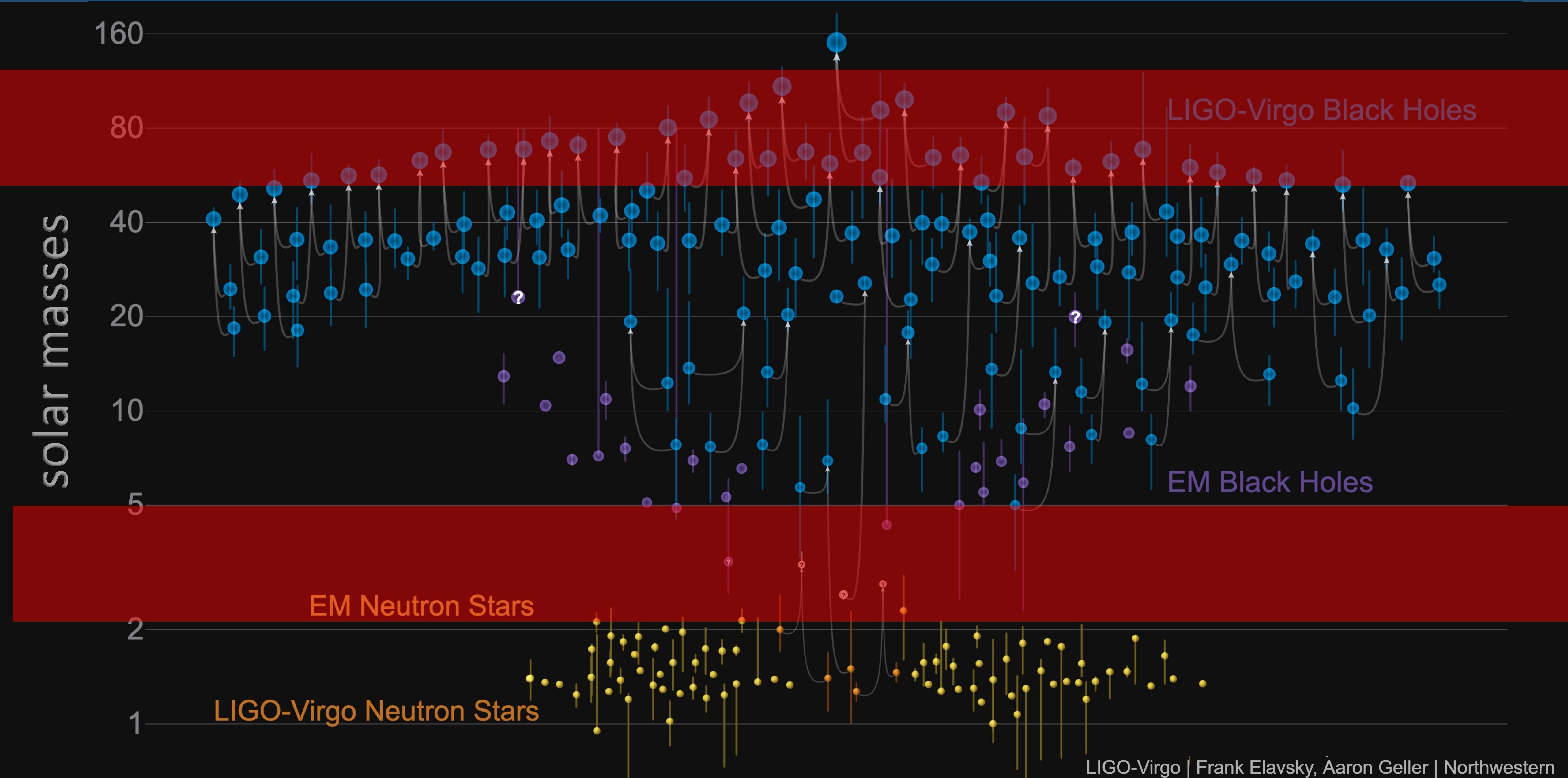
Stellar graveyard



Special events



Special events



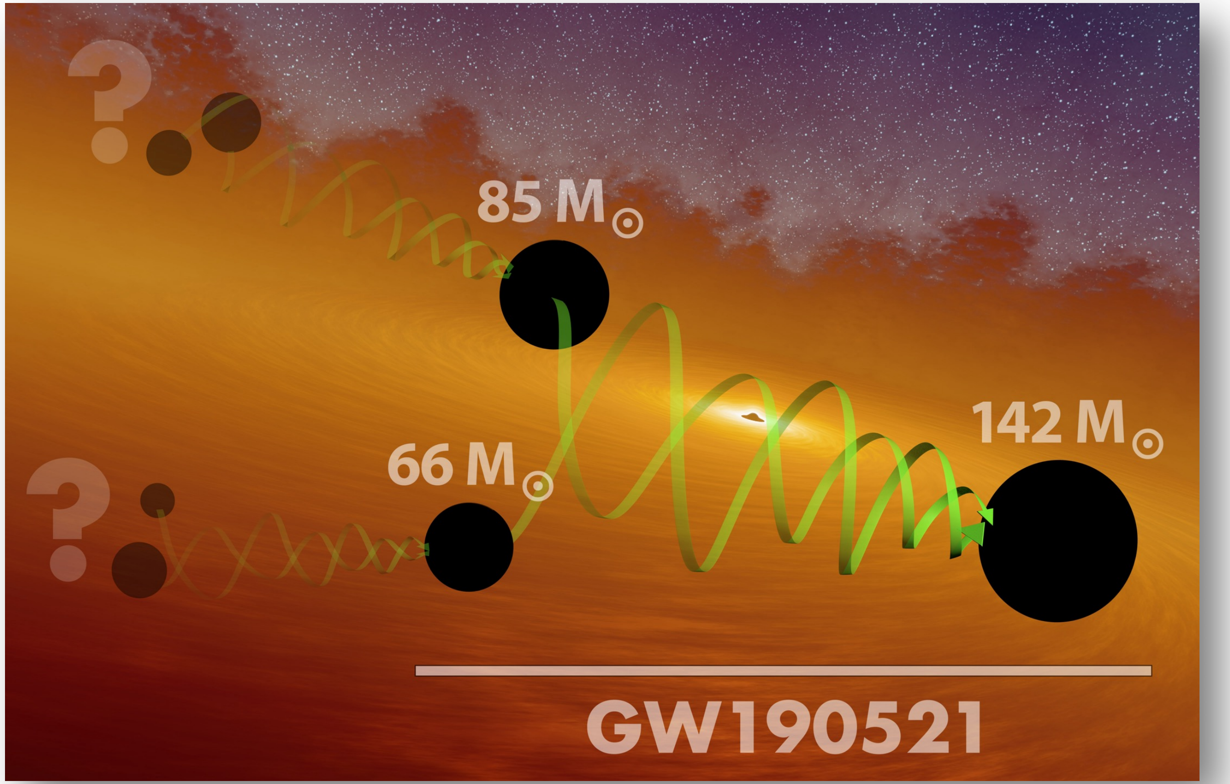
Special events: the black hole that shouldn't exist

- $\boldsymbol{M_1 > 65M_\odot}$: Mass of heavier black hole is difficult to explain with stellar evolution, although uncertainties remain.

  Possible explanation: the black holes are the **remnants of previous mergers?**

- **High spin:** higher than other black hole mergers observed so far. Could have increased through previous mergers or accretion.

- **Misaligned spin from orbit:** also difficult to explain with stellar binaries where spin should be parallel with binary orbit. It is expected if binaries form in chance encounters (such as the case for multiple mergers).



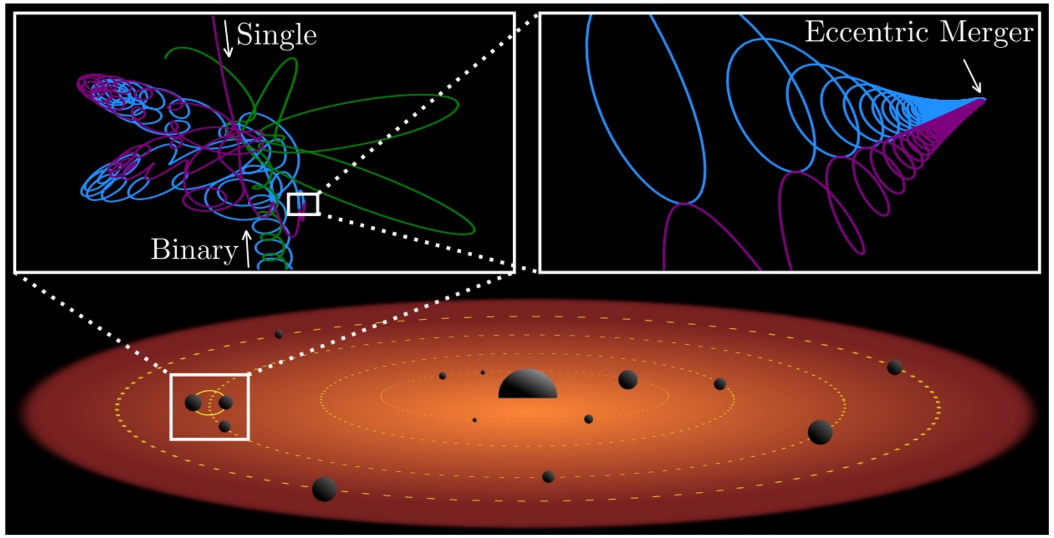
Orbital eccentricity

- Gravitational waves circularize the binary orbit → orbital eccentricity is expected only if:
  (1) binary recently formed or
  (2) external source supplies eccentricity.

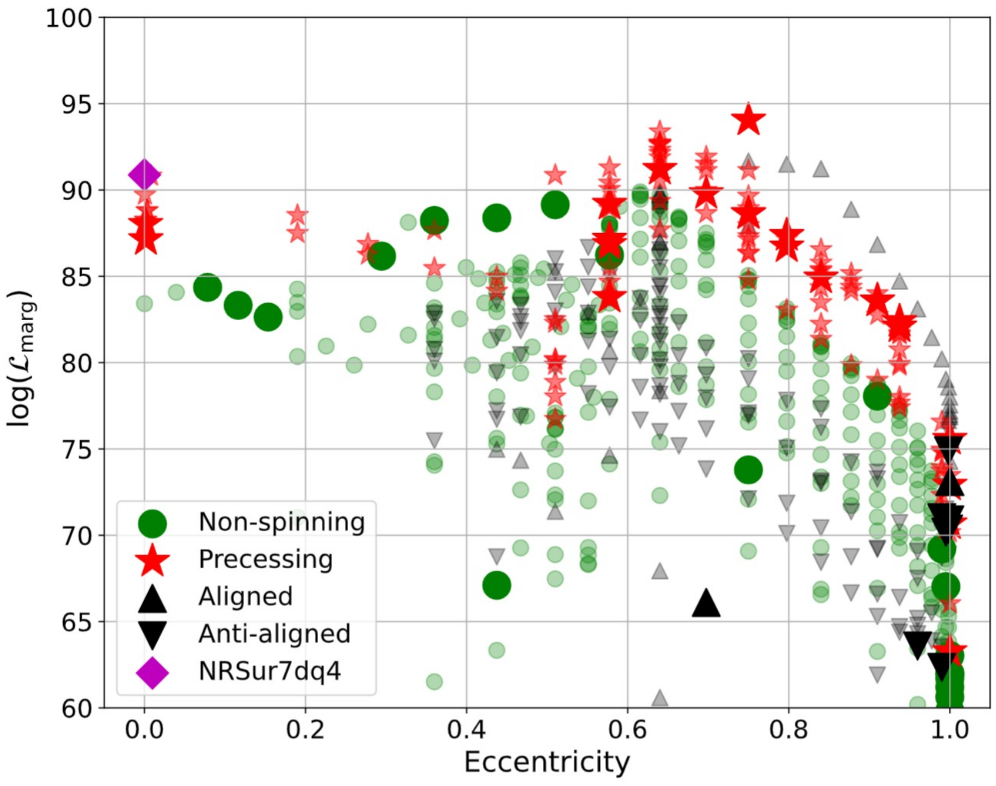
- AGNs could be best sites for high eccentricity mergers. 2D interactions lead to high eccentricity much more often than 3D interactions. (Samsing+ Nature 2022).

- Using a large suite of numerical relativity simulations, we found that GW190521 is most consistent with highly eccentric binary with $\boldsymbol{e \approx 0.7}$. (Gayathri+ Nature Astronomy 2022).
- Using semi-analytic template banks gives similar results (Romero-Shaw 2020, Gamba+ 2021).

- GW190521 is first identified highly eccentric binary.



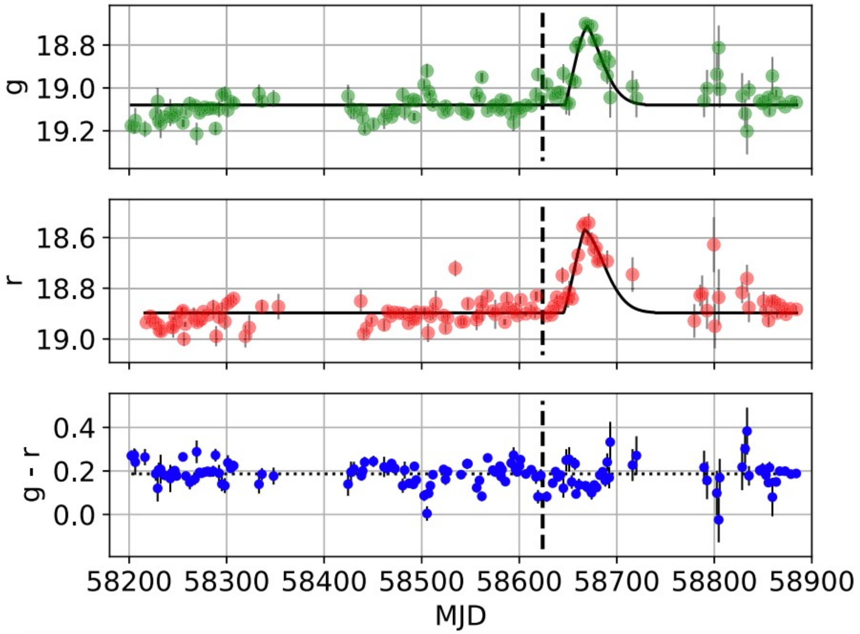
Samsing+ Nature 2022

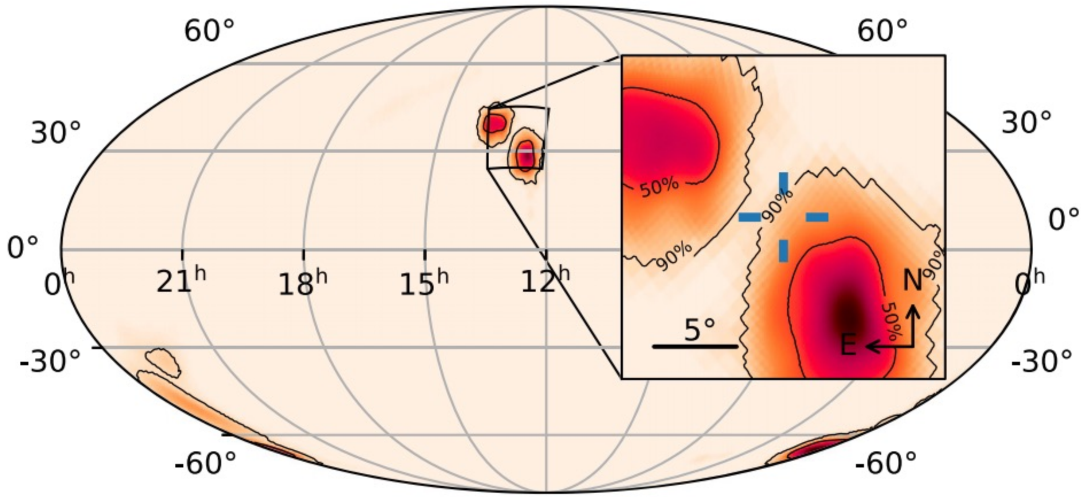


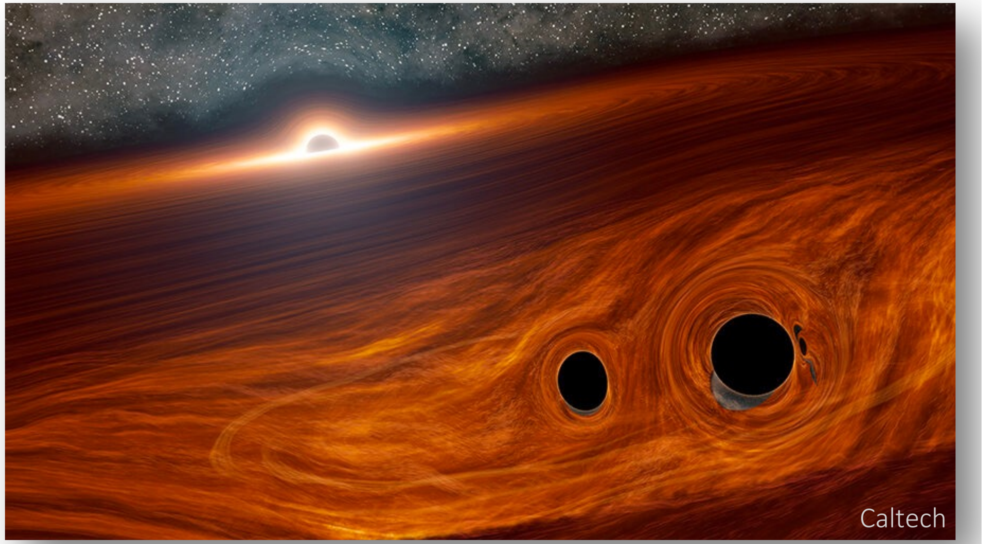
Gayathri+ Nature Astronomy 2022

Possible electromagnetic counterpart to GW190521

- Black hole merger EM follow-up search with ZTF (Graham+ PRL 2020).
- 2-months long transient in the wake of GW190521.
- EM signal consistent with AGN origin.
- Statistical significance depends on Bayesian priors of the GW signal, and it is difficult to fold in other evidence of the AGN origin of GW190521 → more of these will be welcome.

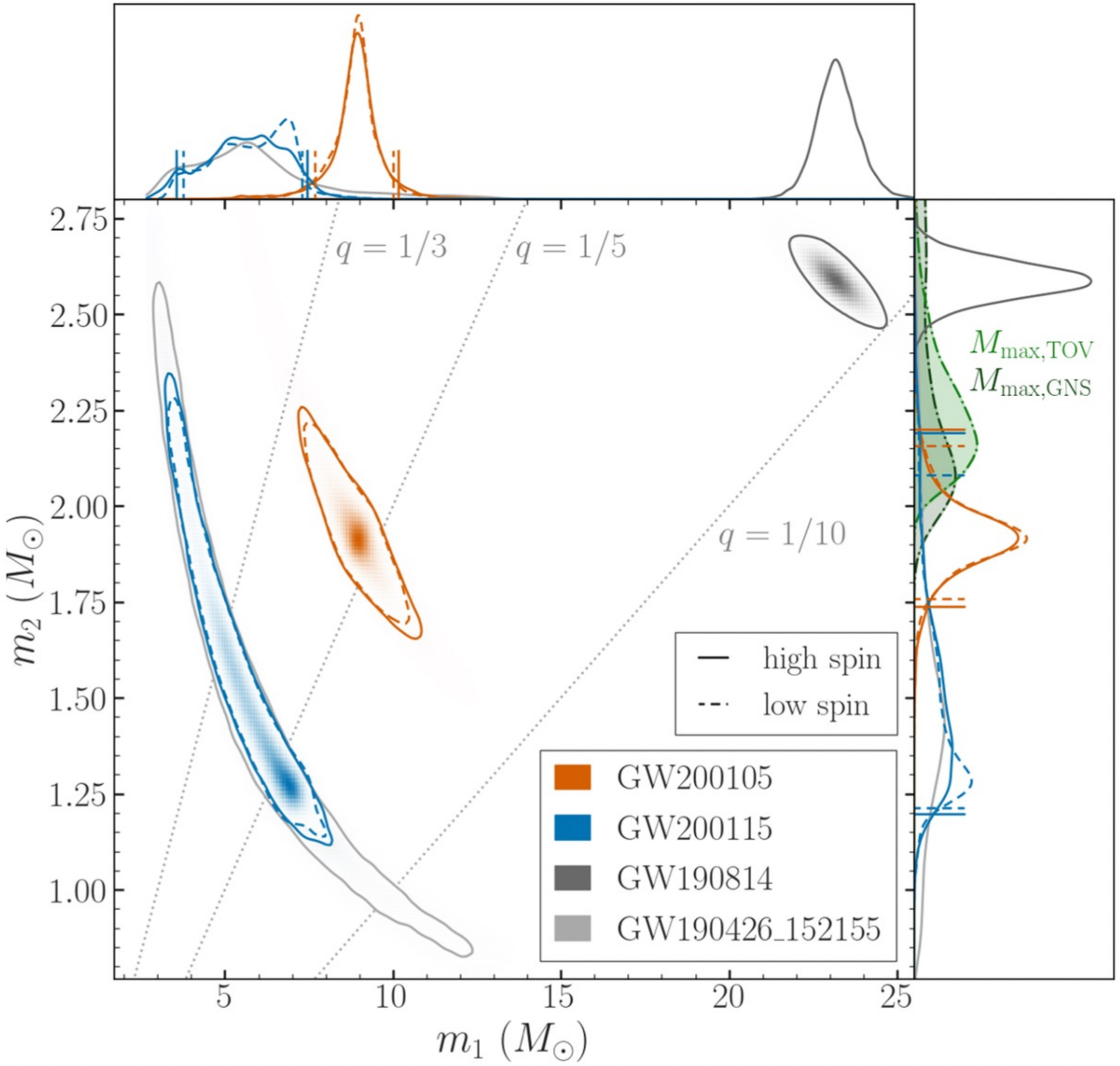






Special events: low-mass companions

- Companion: neutron stars or ??
- Galactic binary NS systems: $M_{NS} \sim 1.3 \pm 0.1\ M_{\odot}$
- Some are consistent with such NSs, but some are not!
- Galactic selection effect? *(equal mass lives longer?)*
- 2.6 $M_{\odot}$ object: could be NS or BH. Suspiciously: mass equal to Galactic NS-NS system mass - triple system (Lu+ 2020, Veske+ 2021)?

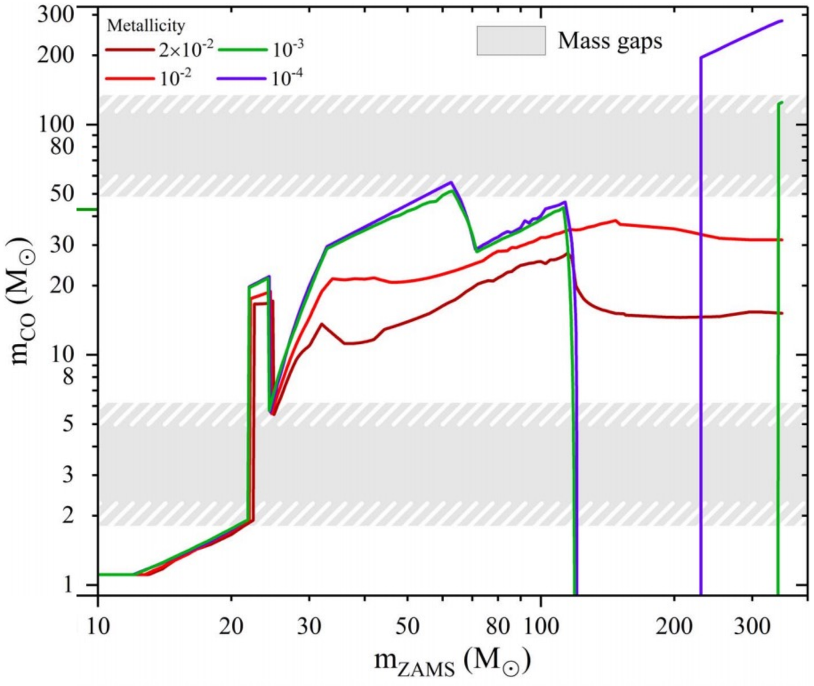


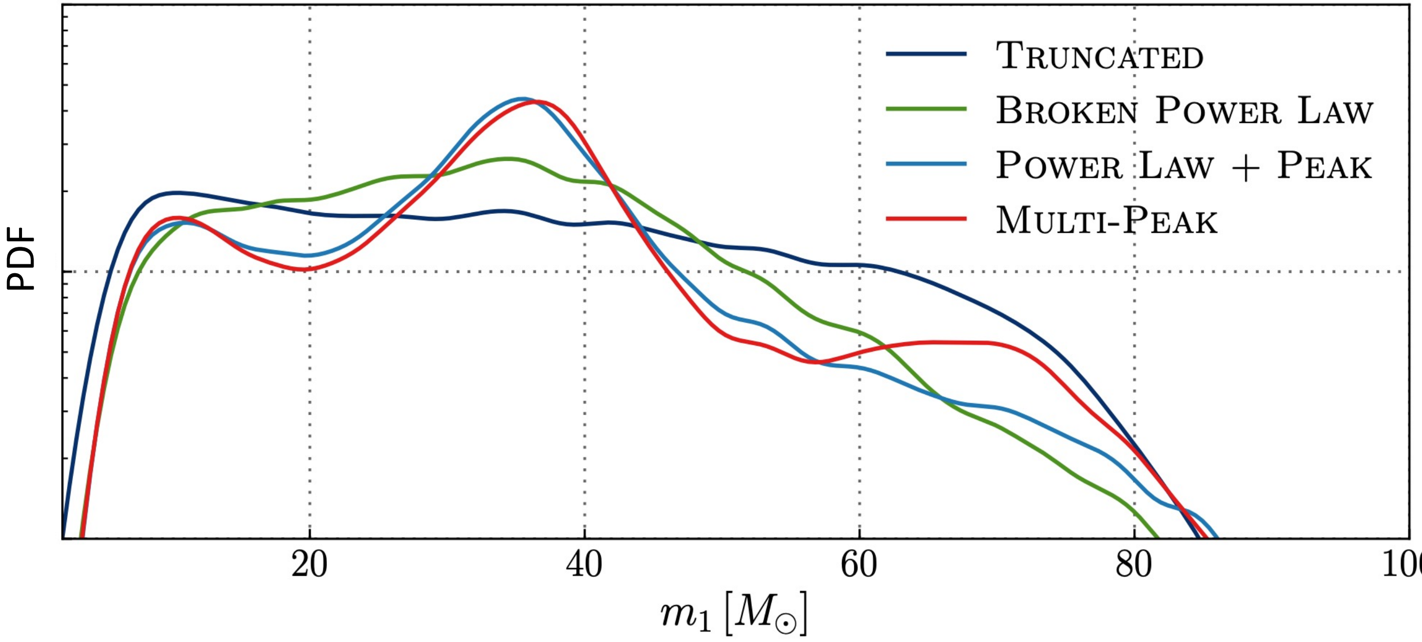
LIGO+Virgo+KAGRA ApJ Lett 2021

What we learned about binary black hole populations?

Mass distribution

- Single power law with max and min cutoff doesn't work.
- Extends to high masses
- Possibly overabundance at $\sim 40 M_{\odot}$, or two components.
- Beyond this, we don't really have enough information to tell.
- Not conclusive regarding origin.



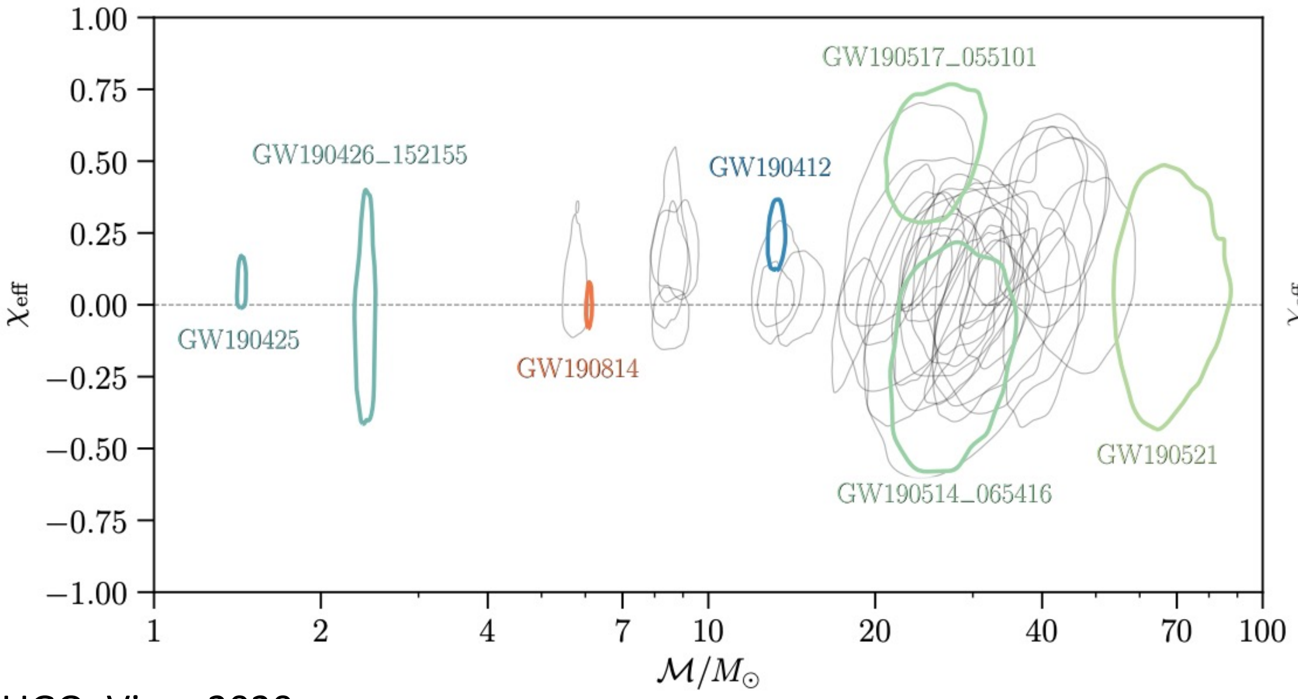


LIGO+Virgo 2020

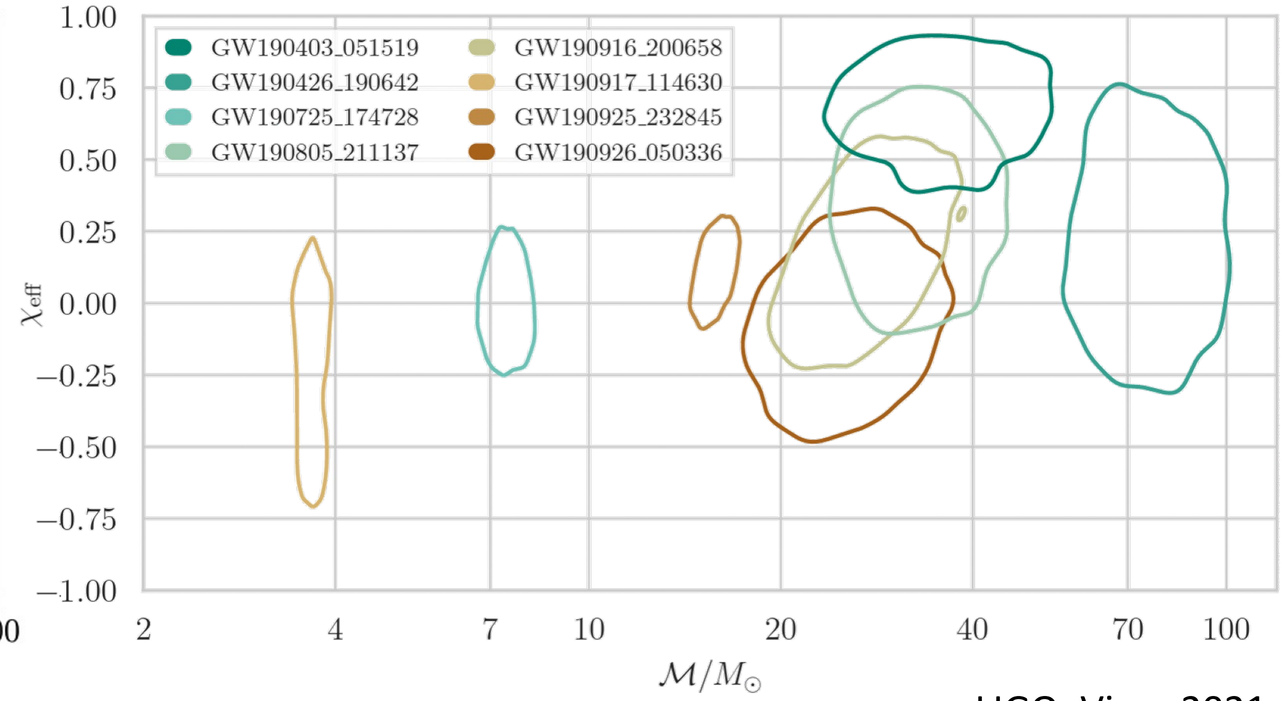
What we learned about binary black hole populations?

Spin distribution

- Significant χ_{eff} (parallel with orbital axis) for some events.
- About a third of BBHs have $\chi_{eff} < 0$.
- Significant χ_p (perpendicular with orbital axis) for some events.
- Both χ_{eff} and χ_p distributions are difficult to reconcile with isolated stellar binary origin, but are consistent with expectations of dynamical / AGN gas-capture origin.
- (more spin-modeling needed on isolated binary side).



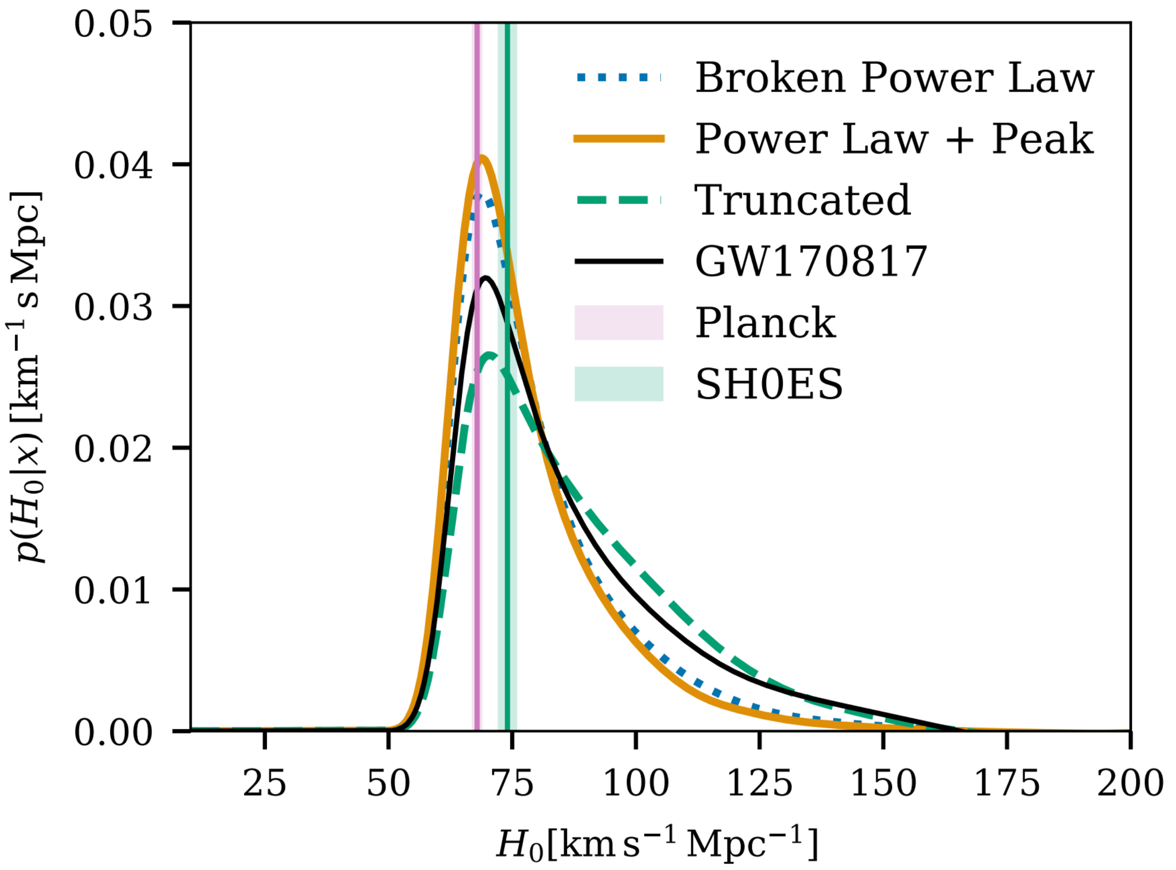
LIGO+Virgo 2020



LIGO+Virgo 2021

Probing cosmic expansion with gravitational waves

- Gravitational waves carry information about source's luminosity distance
- Host galaxy's identification gives redshift / black hole mass distribution can be assumed not to change over cosmic time
  --> cosmic expansion



Neutron star mergers: electromagnetic counterpart helps locate host.

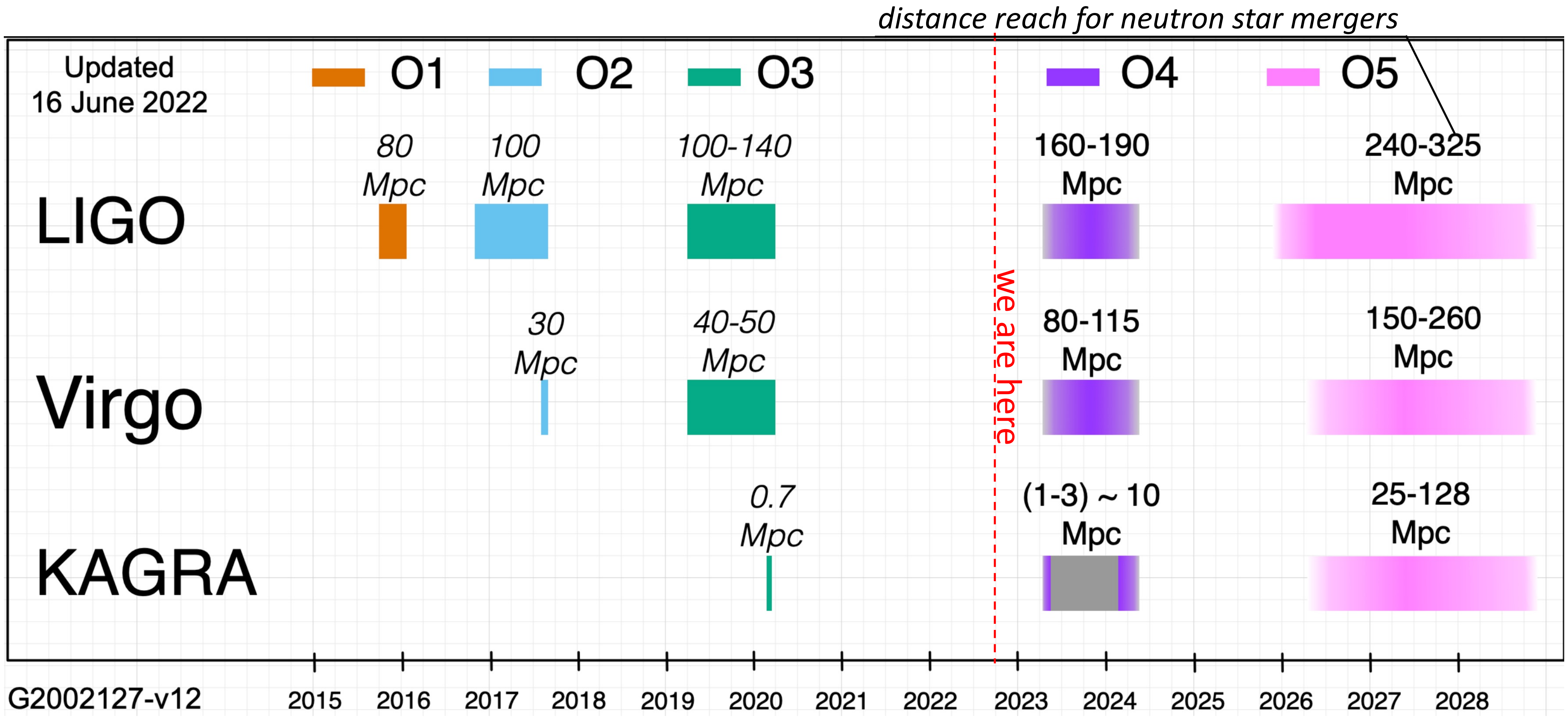
Black hole mergers: larger error radius → statistical approach needs to be taken.

47 detected sources →

$$H_0 = 68^{+12}_{-8}\ \mathrm{km\,s^{-1}\,Mpc^{-1}}\ \text{(68\% credible interval)}$$

LIGO+Virgo+KAGRA 2021

Prospects for the next run(s)



Next observing run (O4) will probably start in March 2023.
Order of magnitude detection rate improvement in next 5 years.

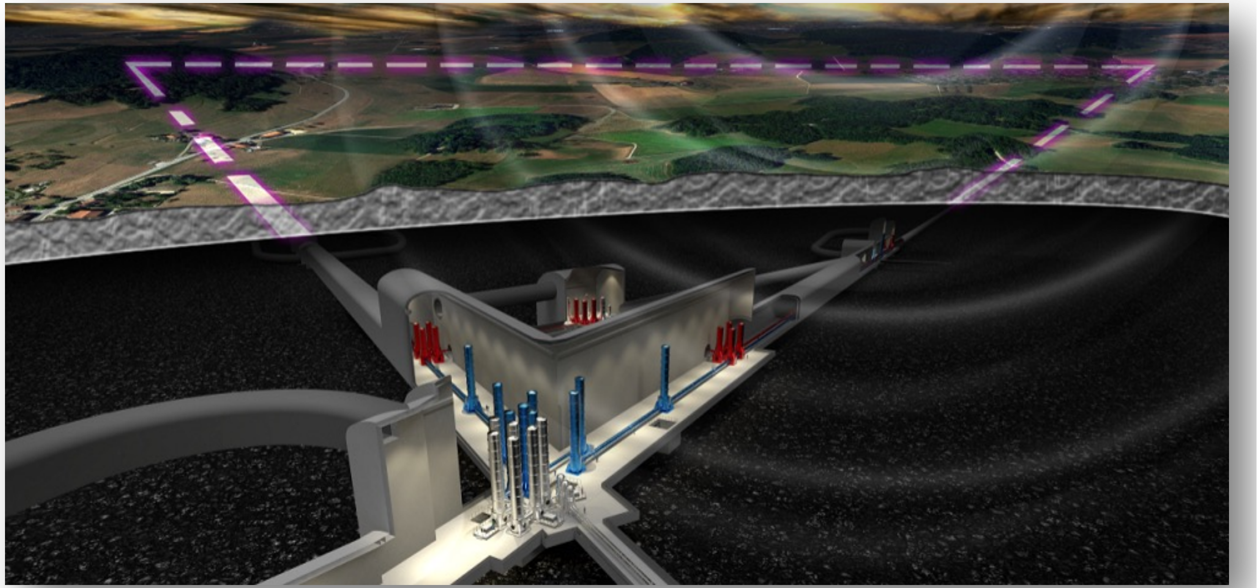
→ **>1000 discoveries** soon…

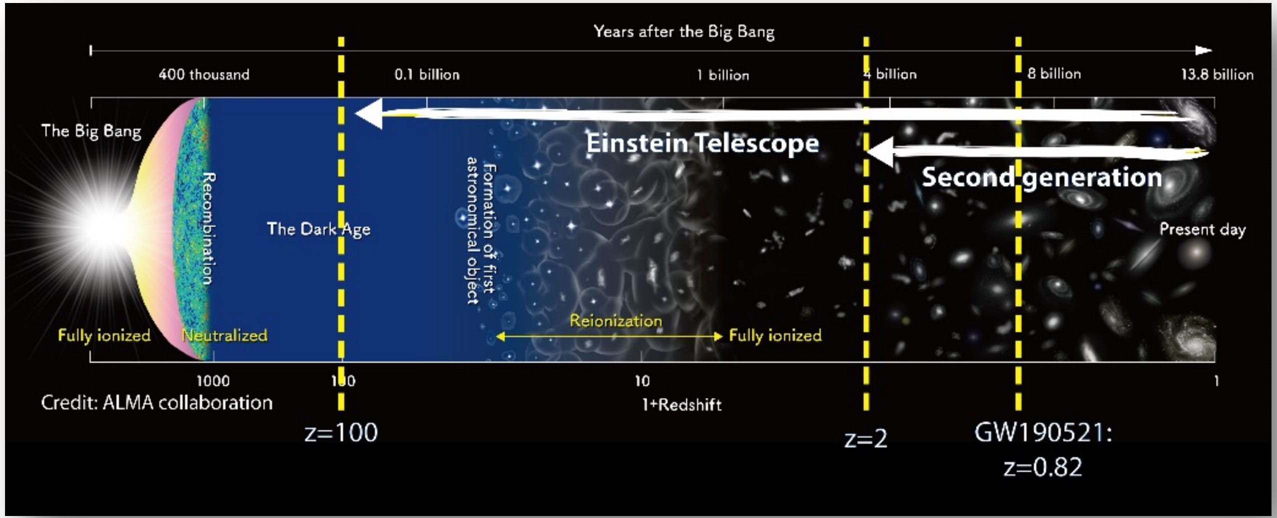
→ Some events will be detected with very high SNR -> "**precision gravity**"

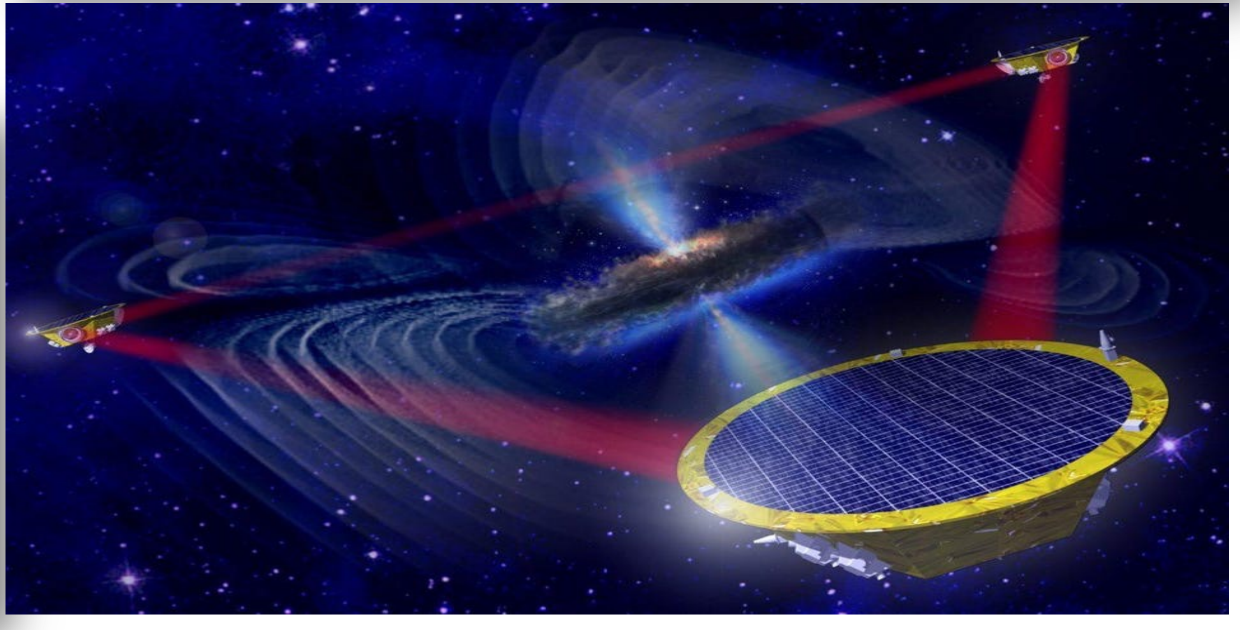
LIGO might deliver major breakthroughs in the next 5 years.

Farther future (~10yr)

- Next generation gravitational wave detectors:
  - **Cosmic explorer** and **Einstein telescope**: LIGO with ~10x sensitivity and lower frequency reach
  - **LISA** space based detector targeting SMBHs
- Black hole mergers from the ~**entire Universe**.
  - Will see the Universe before the first stars were born. If there are black holes they are primordial.
  - Map how the Universe changed since then.
- Precision gravity:
  - Nearby discoveries with extreme SNR → can better probe deviation from General Relativity + vacuum.







Summary

- LIGO and Virgo already delivered close to 100 discoveries.
- Potential for breakthroughs in astrophysics, cosmology and fundamental physics.
- We have an emerging picture of the origin of black hole mergers but there are still many uncertainties.
- <u>Exciting possibilities for the next observing run:</u>
  - ✓ Heavier black holes than GW190521 (would point to hierarchical mergers or very massive (Pop III?) stars)
  - ✓ More objects with $\sim 2.6 M_{\odot}$ (stellar triples or multiple mergers)
  - ✓ Smoking gun multi-messenger sign of black holes in AGN disks *(EM counterpart of merger, micro-TDE, spatial correlation with AGNs)*
  - ✓ High-significance identification of eccentricity *(dynamical/AGN origin)*
  - Surprises!

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