Title: Black hole assembly lines in AGN disks

Speakers: Imre Bartos

Series: Strong Gravity

Date: May 13, 2021 - 1:00 PM

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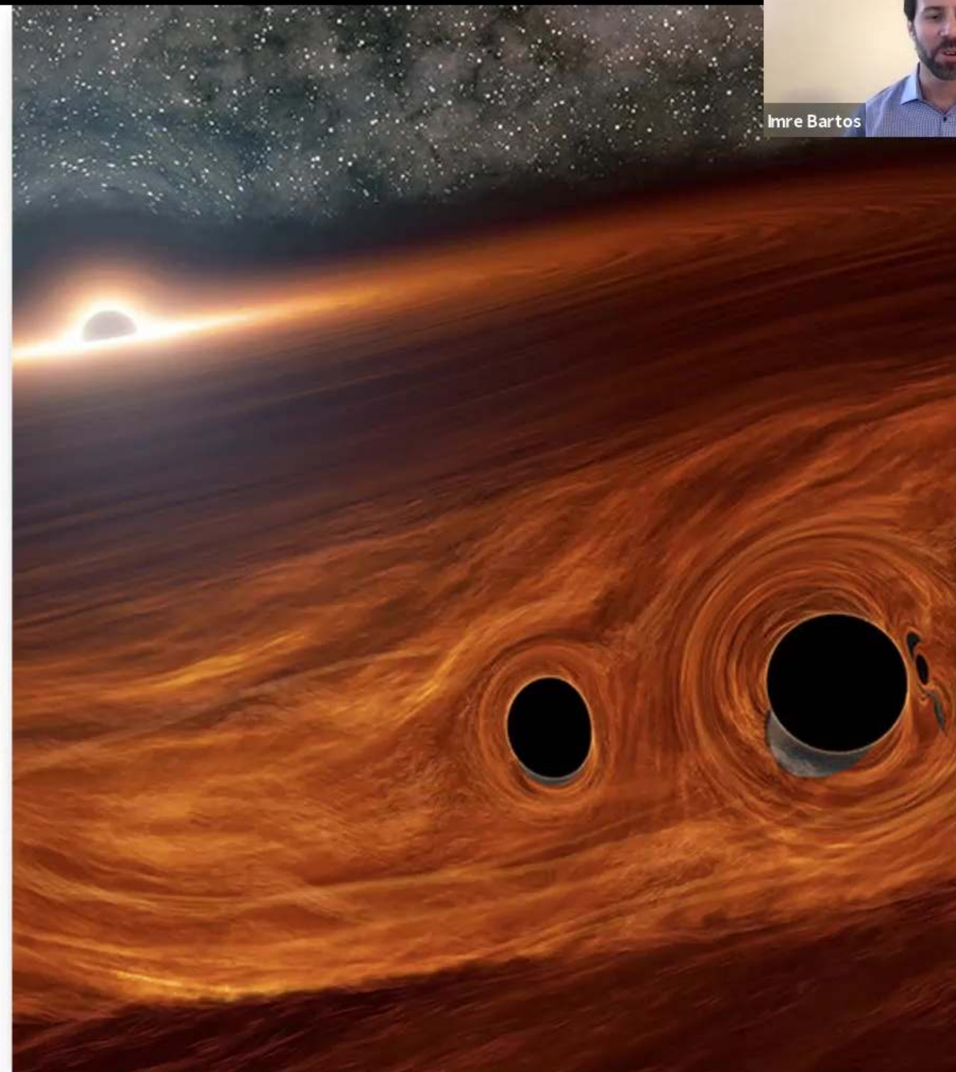
Abstract: Since their first discovery in 2015, gravitational-wave observations yielded several "surprises." The LIGO and Virgo observatories detected more and heavier black holes than anticipated; the first object in the lower mass gap was found; and LIGO announced the discovery of a particularly heavy black hole that could have not come from stellar core collapse. The surprises point to the possibility that some of LIGO/Virgo's black hole mergers occurred in the dense accretion disks of active galactic nuclei (AGNs). AGNs act like black hole assembly lines, resulting in multiple consecutive mergers that create heavier and faster-spinning black holes. I will discuss what we currently know about AGN-assisted mergers and which of LIGO/Virgo's events are suspects. I will finally discuss the prospects of multi-messenger observations from AGN assisted mergers.

Zoom Link: https://pitp.zoom.us/j/93121526365?pwd=c1VCTjBEZnlXYk5HVTFObVBadHlxQT09

Black hole assembly lines *in* AGN disks

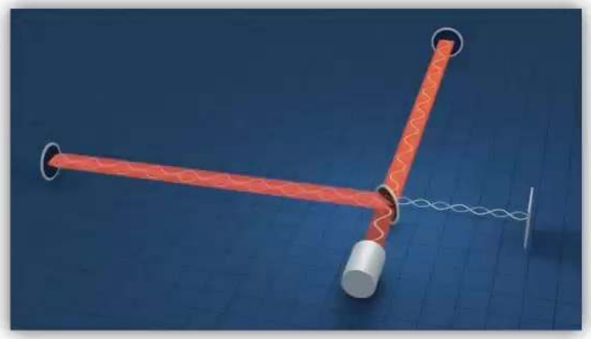
Imre Bartos
University of Florida

Strong Gravity Seminar | Perimeter Institute | 05.13.2021



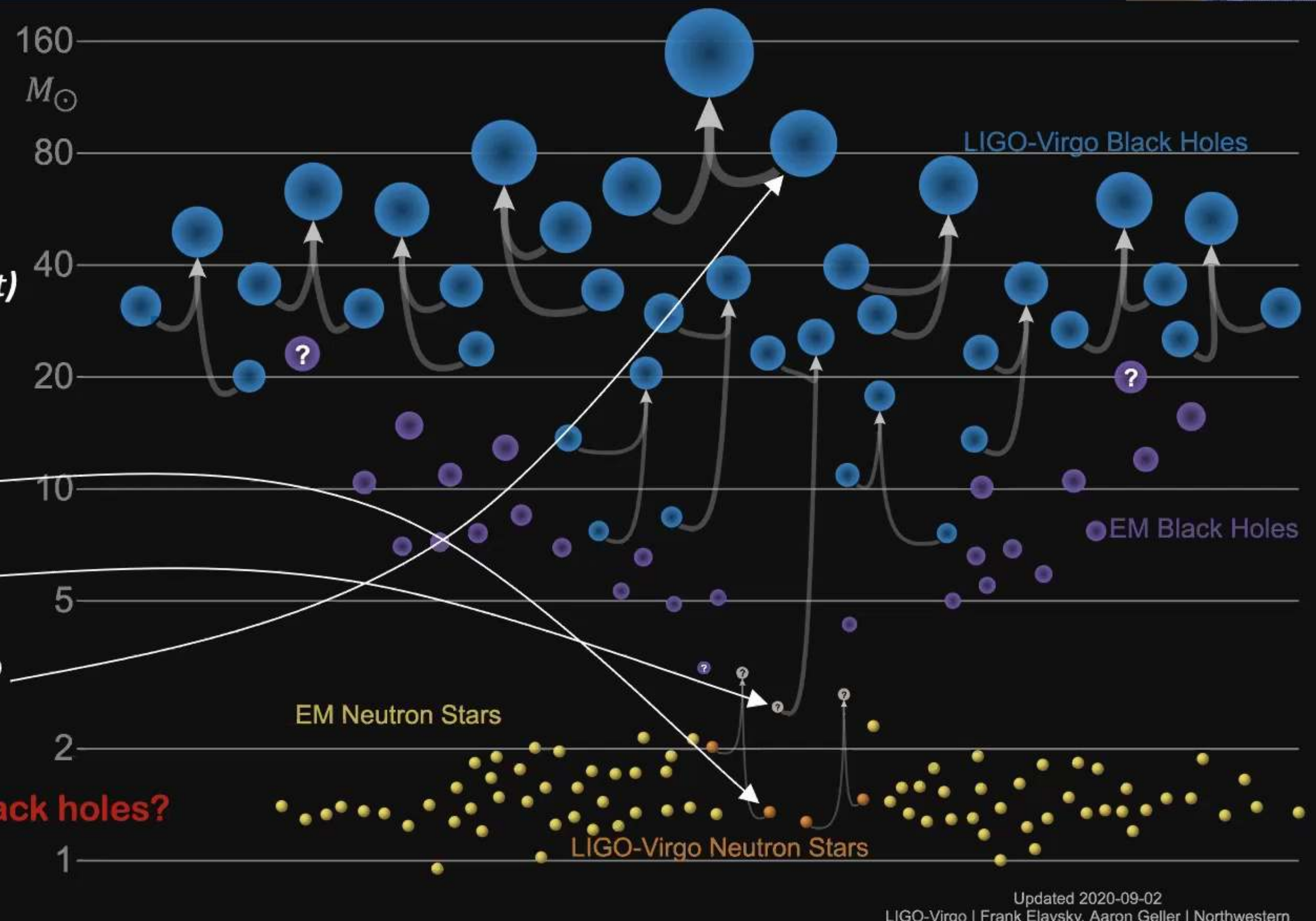
Gravitational-wave detections

- **Advanced LIGO completed in 2015** – *discovery within hours!*
- **All information about two black holes** (masses, spins, distance, etc.) **are encoded in the gravitational waveform.**
- **Each LIGO/Virgo observing run gave us a new source type!**
  - O1: binary black hole merger
  - O2: binary neutron star merger
  - O3: black hole + “???” merger
- **So far the astrophysical mechanism that produced these mergers was not clear.**



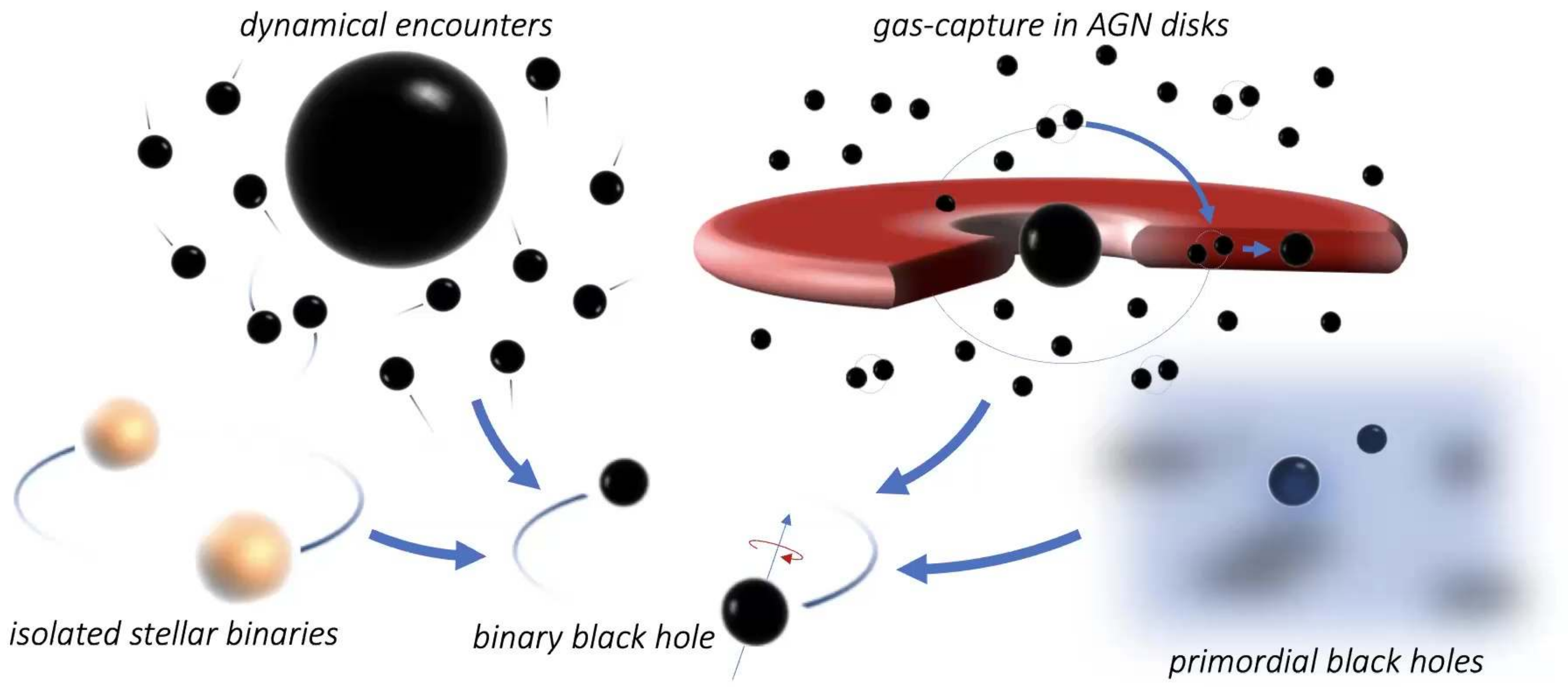
LIGO/Virgo discoveries

- O3 ended in March 2020
- 3 + 7 + 57(?) **GW discoveries** *(special events are published first)*
- Many more black hole mergers
- New neutron star merger, no counterpart ☹
- Object in the lower mass gap
- Black hole in the upper mass gap (beyond what stars can produce)

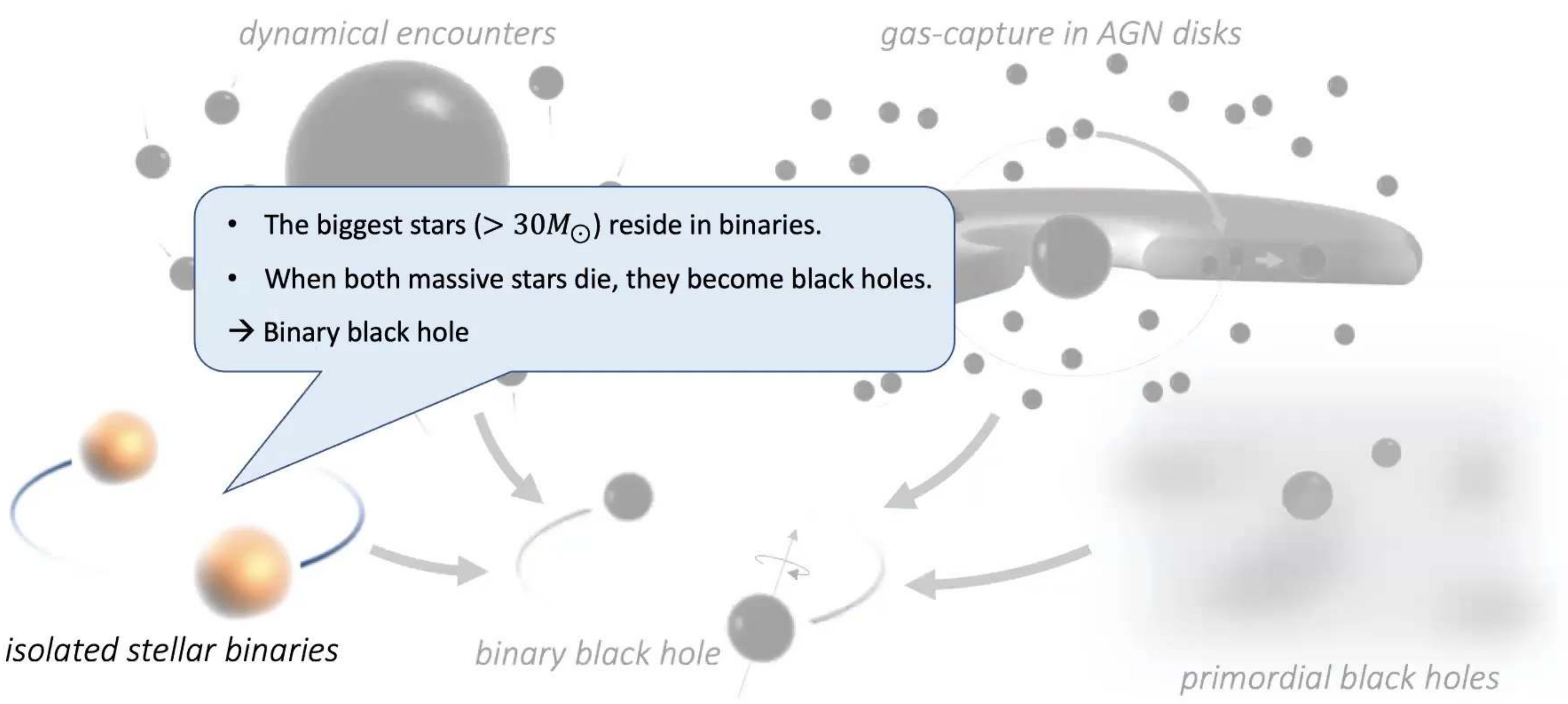


What is the origin of binary black holes?

Possible origins of binary black holes



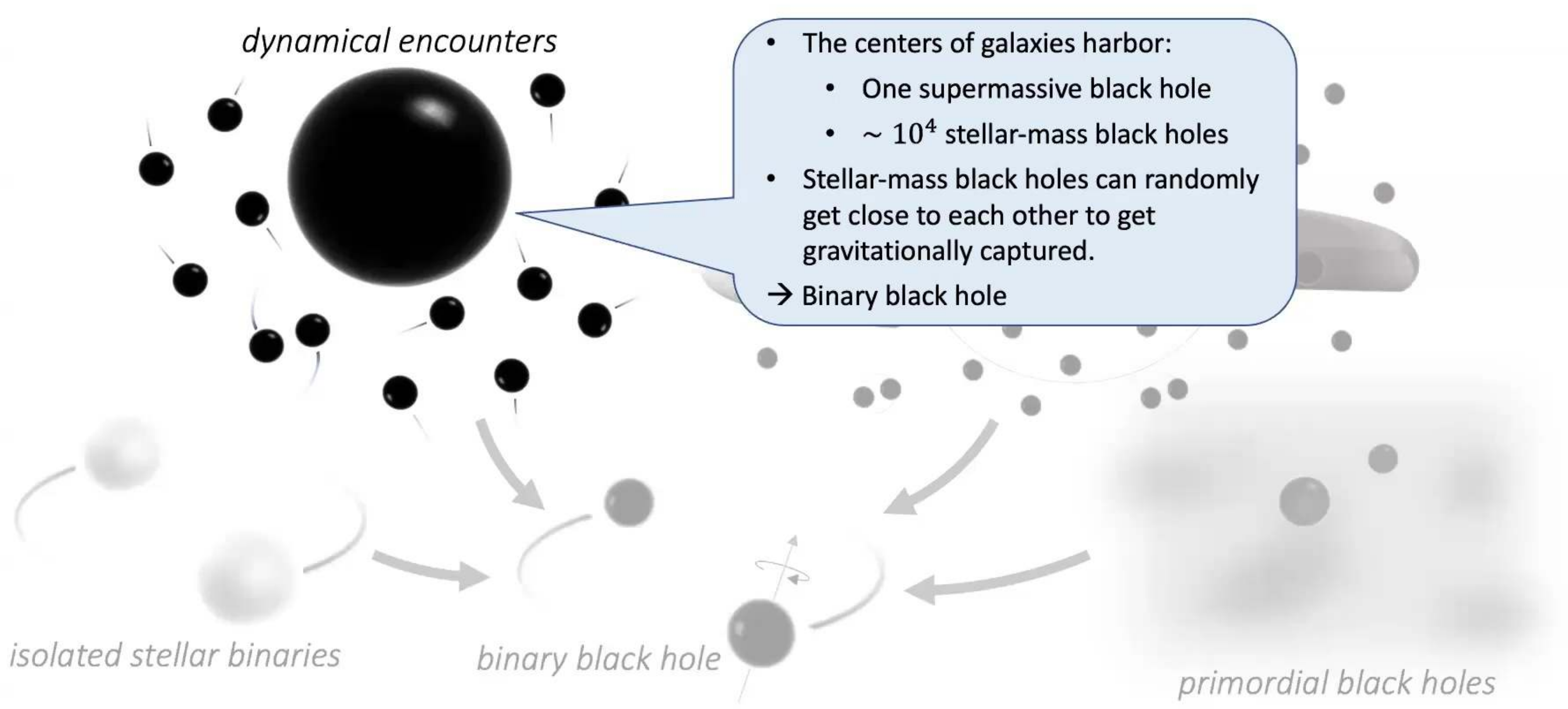
Possible origins of binary black holes



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

→ Binary black hole

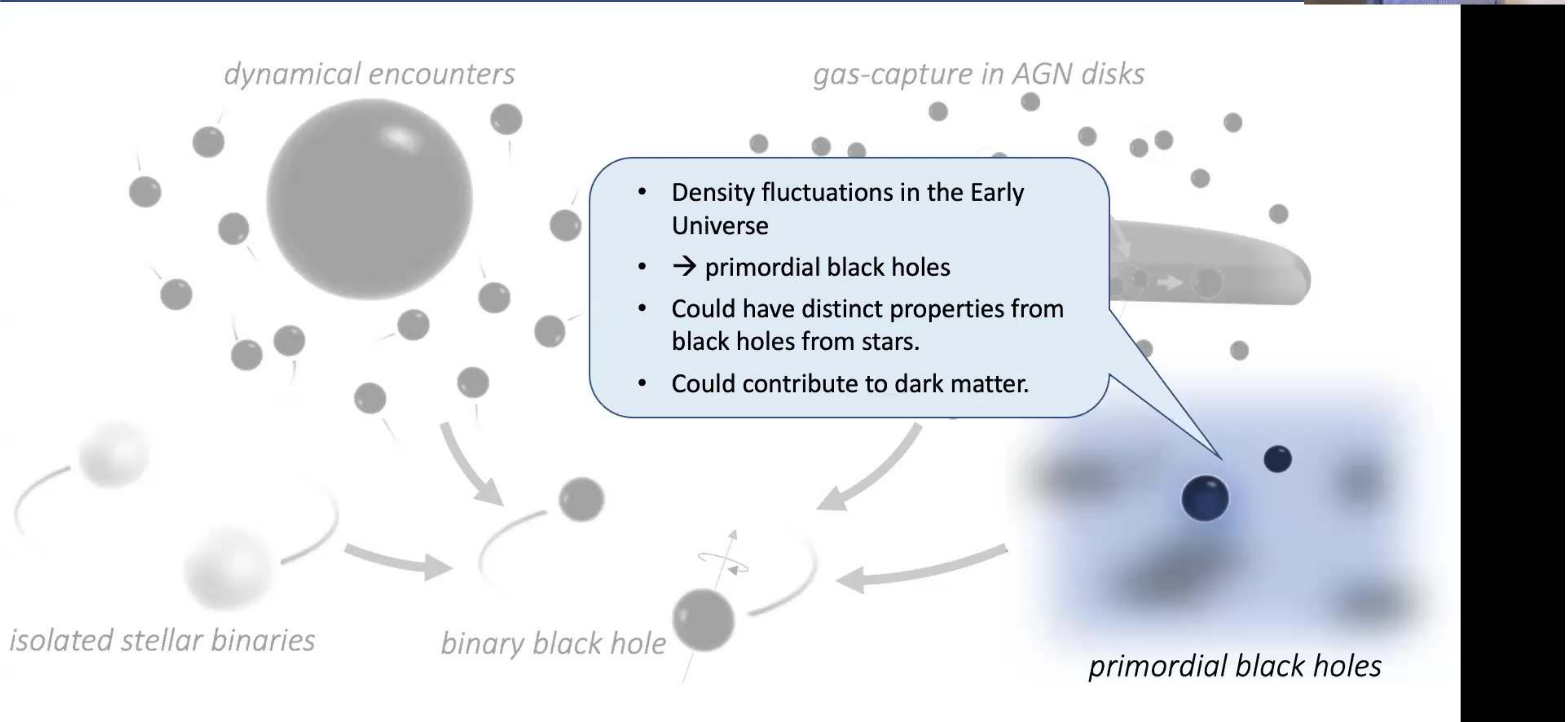
Possible origins of binary black holes



- The centers of galaxies harbor:
  - One supermassive black hole
  - $\sim 10^4$ stellar-mass black holes
- 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.

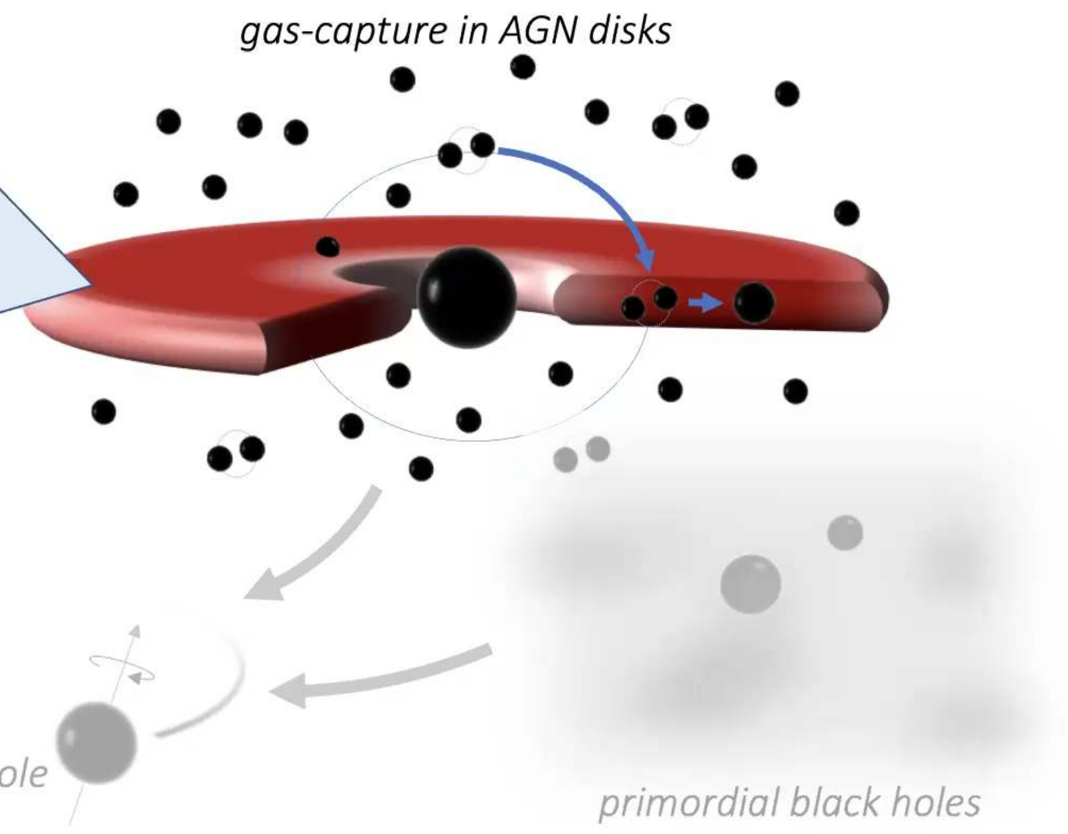
Possible origins of binary black holes

1. Black holes align their orbit with disk
2. Migrate inward in disk
3. Gas capture → form binaries
4. Rapidly merge due to dynamical friction + binary-single interactions
5. Repeat (hierarchical mergers)

Observational signatures:

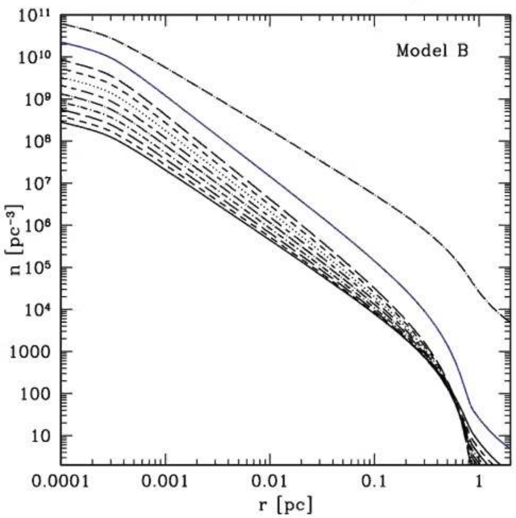
- Heavier black holes
- High spin
- Multi-messenger counterpart
- Eccentricity
- Correlation with AGN locations

Bartos+ ApJ 2017, Stone+ MNRAS 2017, Yang+ PRL 2019, McKernan+ ApJ Lett 2019, Tagawa+ ApJ 2020, Secunda+ ApJ 2019

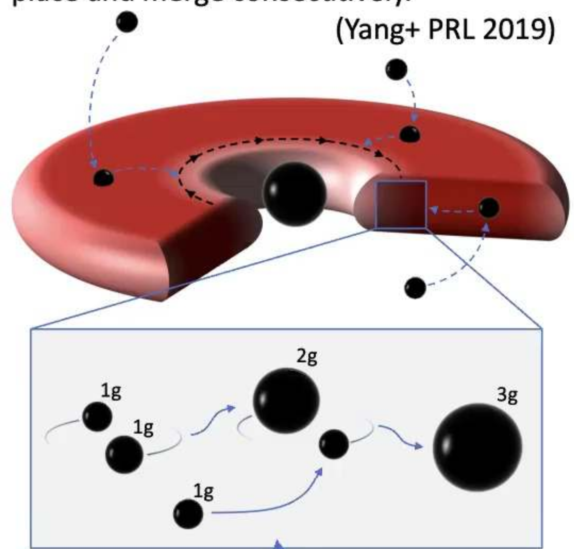


Why are black holes in AGNs heavier?

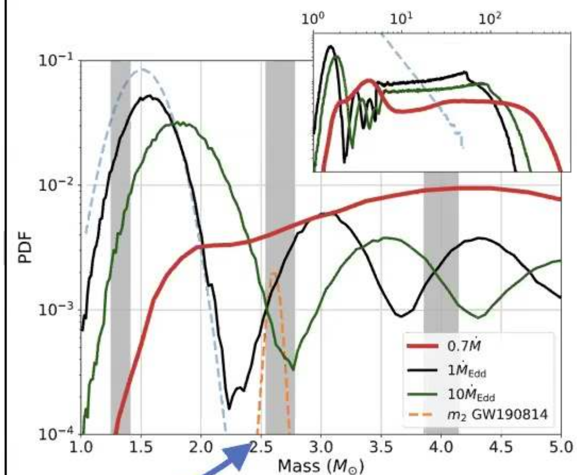
Mass segregation
Heavier objects in galactic center migrate inward, lighter ones move out.
(O'Leary+ 2009)



Hierarchical mergers.
Multiple black holes can migrate to same place and merge consecutively.
(Yang+ PRL 2019)



Accretion
Black holes (and neutron stars) accrete gas inside the AGN disk.
(Yang+ ApJ Lett 2019)

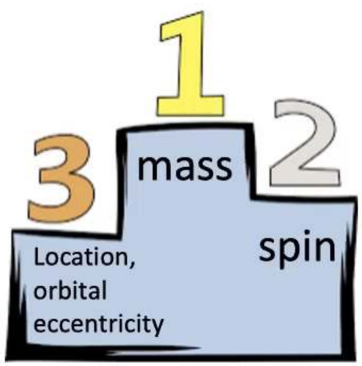


Higher spin

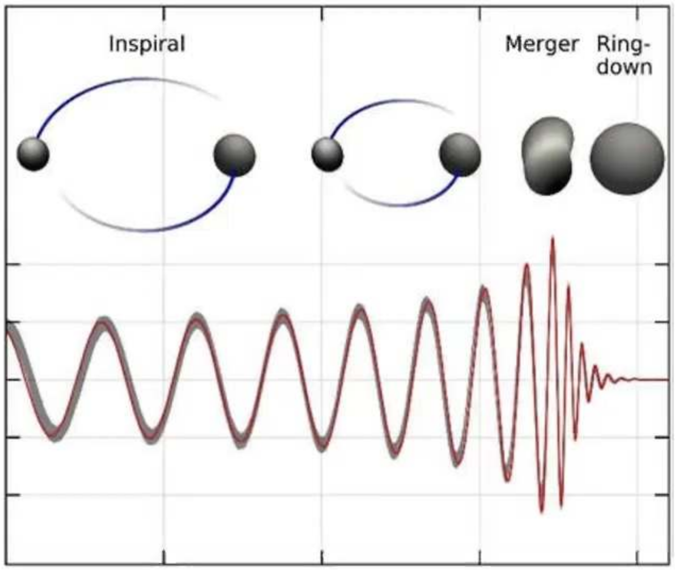
Both <u>mergers</u> and <u>accretion</u> can increase spin.

Information in gravitational wave detections

- A black hole merger can be described by ~ 15 parameters (masses, spins, location, orientation, eccentricity).
- The more information we have the better we can establish the origin of binary mergers. Ideally, we should model all these and compare to observations.
- Not all information is equally accessible.
- It is not just reconstruction uncertainties. Some parameters simply make GW emission less detectable:
  - ➢ Antialigned spin (weaker GW)
  - ➢ Precessing spin (unusual waveform)
  - ➢ Orbital eccentricity (unusual waveform)



Ranking of how well these can be extracted from GWs.



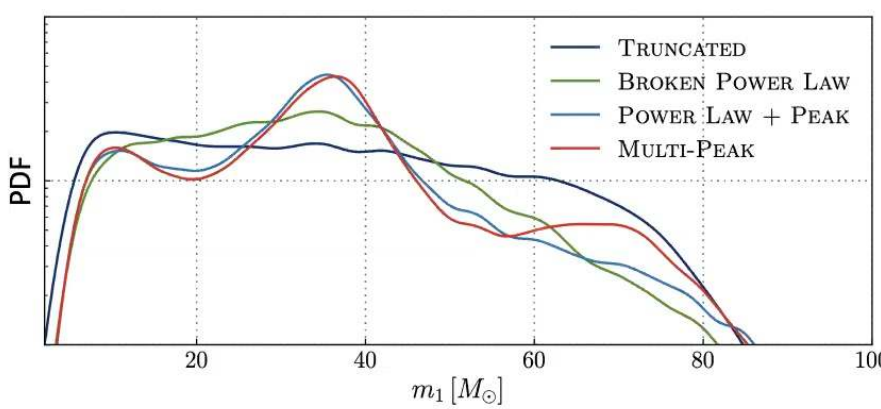
Probing the origin of black hole mergers

<u>We can look at:</u>

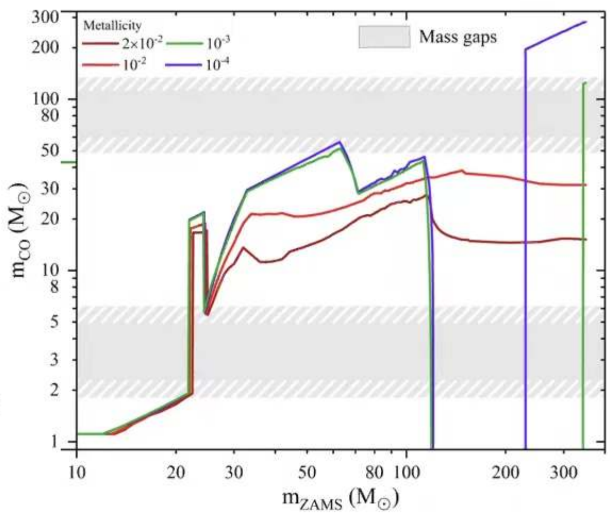
- Populations (where different models make different predictions on distributions)
  - ✓ *e.g. mass, spin distribution*
- Special events (some parameter rules out some of the models)
  - ✓ unusual mass / spin
  - ✓ orbital eccentricity
- Smoking guns (observationally unique even if the event itself is not)
  - host galaxy properties
  - Electromagnetic counterpart

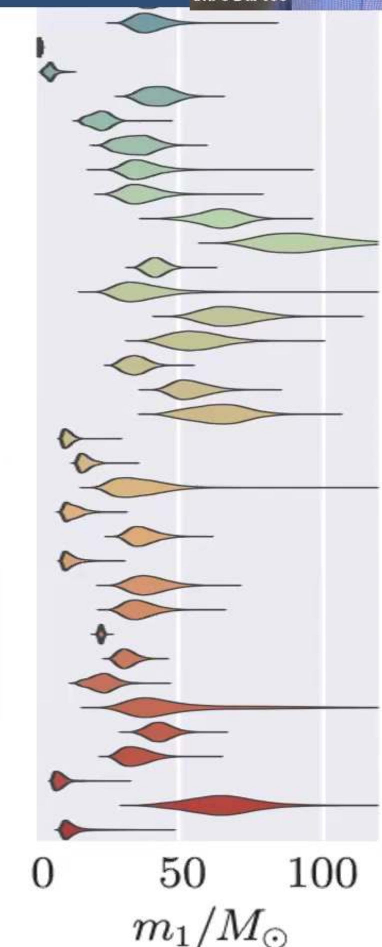
What we learned about binary black hole populati

1. Mass distribution:
   - Single power law with max and min cutoff doesn't work.
   - Extends to high masses
   - Possibly overabundance at $\sim 40M_{\odot}$, or two components (model-based possibilities).
   - Beyond this, we don't really have enough information to tell.
   - General distribution not conclusive regarding origin (other than extreme events).

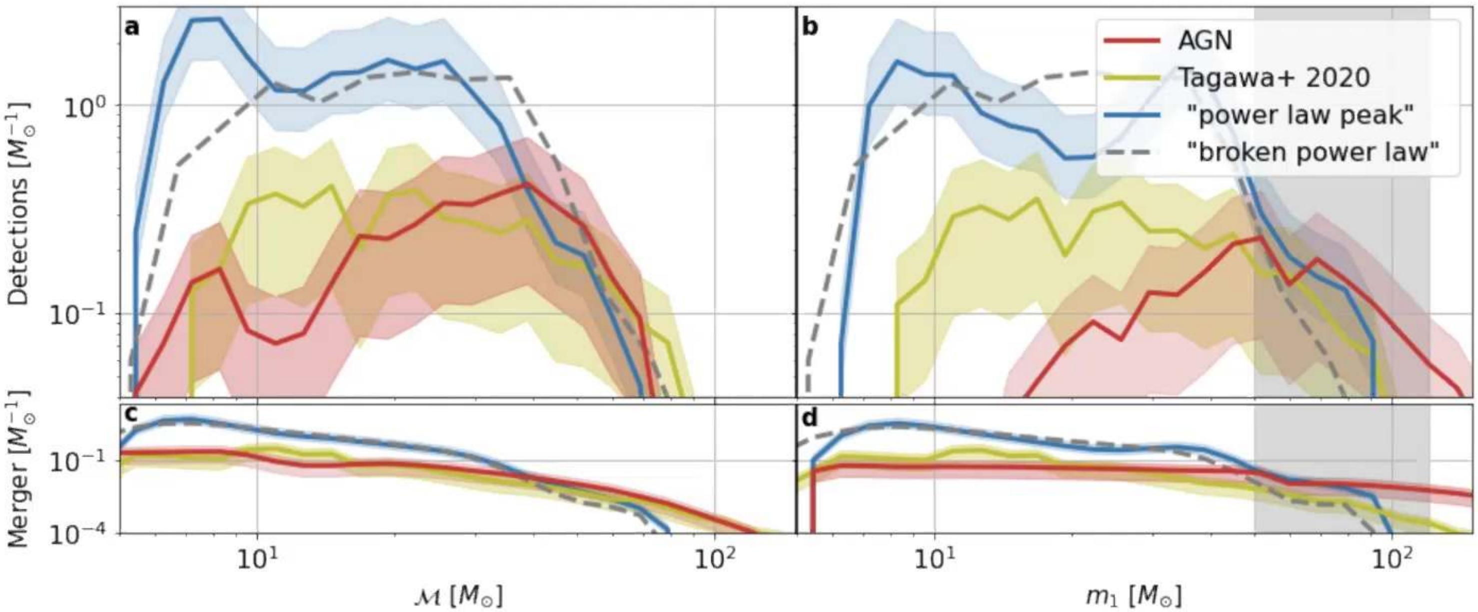


LIGO+Virgo 2020





Expected mass distribution from AGNs?



- Mass distribution at the highest masses consistent with AGN origin.
- 25% of detected events may be from AGNs.
  (smaller fraction of merger rate)

Gayathri+ 2021 (2104.10253)

Imre Bartos

Origin of GW190521

- $\boldsymbol{M_1 > 65M_\odot}$: in tension with stellar binary origin (although some uncertainties remain; Belczynski 2020, Costa+ 2020, Farmer+ 2020).

- **Misaligned spin w.r.t. orbit:** also difficult to explain with stellar binaries where spin should be parallel with binary orbit. Expected in dynamical capture.

- **High spin:** this is the highest so far detected. One possibility: increased through previous mergers or accretion.

Based on these, possible scenario is that these BHs are the remnants of previous mergers. In particular AGNs are an interesting possibility. What could prove this further?

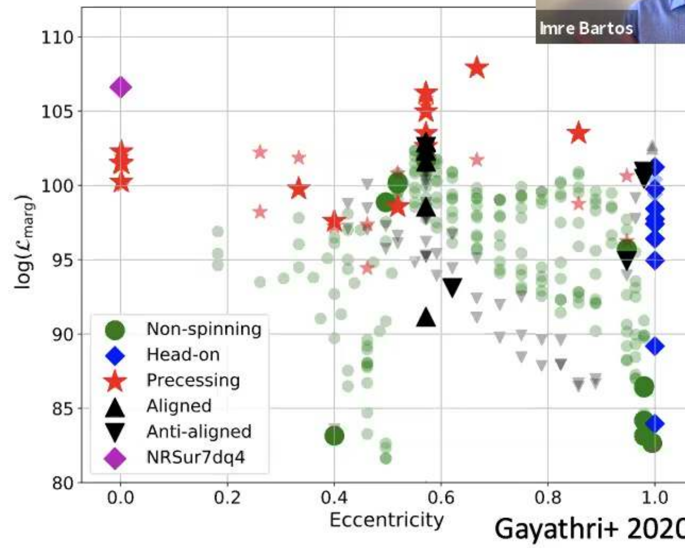
- **Electromagnetic counterpart** (~only in AGNs)

- **Orbital eccentricity** (dynamical encounter origin)

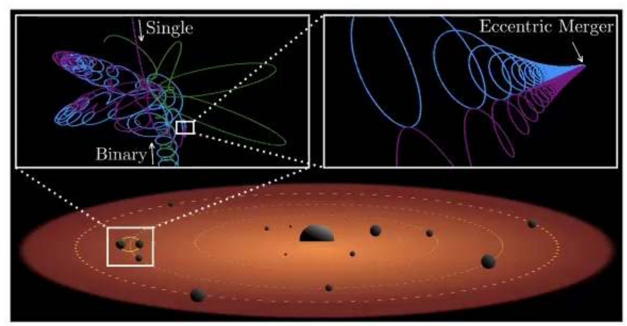
Parameter	
Primary mass	$85^{+21}_{-14}\ M_\odot$
Secondary mass	$66^{+17}_{-18}\ M_\odot$
Primary spin magnitude	$0.69^{+0.27}_{-0.62}$
Secondary spin magnitude	$0.73^{+0.24}_{-0.64}$
Total mass	$150^{+29}_{-17}\ M_\odot$
Mass ratio ($m_2/m_1 \leq 1$)	$0.79^{+0.19}_{-0.29}$
Effective inspiral spin parameter ($\chi_{\rm eff}$)	$0.08^{+0.27}_{-0.36}$
Effective precession spin parameter ($\chi_{\rm p}$)	$0.68^{+0.25}_{-0.37}$
Luminosity Distance	$5.3^{+2.4}_{-2.6}$ Gpc
Redshift	$0.82^{+0.28}_{-0.34}$
Final mass	$142^{+28}_{-16}\ M_\odot$
Final spin	$0.72^{+0.09}_{-0.12}$
P ($m_1 < 65\ M_\odot$)	0.32%
$\log_{10}$ Bayes factor for orbital precession	$1.06^{+0.06}_{-0.06}$
$\log_{10}$ Bayes factor for nonzero spins	$0.92^{+0.06}_{-0.06}$
$\log_{10}$ Bayes factor for higher harmonics	$-0.38^{+0.06}_{-0.06}$

Eccentric GW190521?

- Orbital eccentricity is expected only if the binary formed only recently (dynamical encounters or gas-capture in AGNs) or near supermassive black holes (in galactic centers).
- High eccentricity has been impossible to identify due to lack of sufficient number of appropriate templates.
- Complicated waveforms so analytical solutions are difficult.
- We carried out 300+ numerical relativity simulations, equivalent to ~30,000 templates (typical LIGO/Virgo bank is ~200,000).
- We find that best fit is a highly eccentric binary with $e \approx 0.7$. (Gayathri+ 2009.05461 2020).
- No eccentric binary has been identified before.
- AGNs: likely best sites for high eccentricity mergers.
  2D interactions lead to high eccentricity much more often than 3D interactions. (Samsing+ 2010.09765 2020).



Gayathri+ 2020



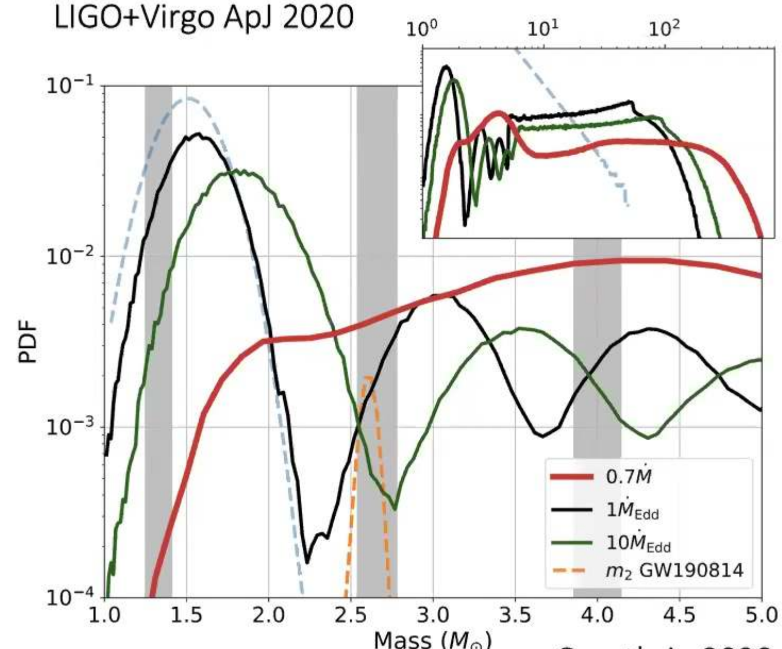
Samsing+ 2020

The lower mass gap (GW190814)

- **Compact object in "lower mass gap" ($2.6 M_\odot$)**
  - Stars are not expected die as $2-5 M_\odot$ compact objects.
  - So there was either
    - A lot of accretion (e.g. in AGNs)
    - Previous merger of neutron stars
  - $2.6 M_\odot =$ final mass of a neutron star merger
  - Accretion possible but not necessary
- **Heavy companion ($23 M_\odot$)**
  - Very asymmetric masses not expected from stellar binaries
  - → more likely the two objects met in a chance encounter in a dense stellar environment.
- **Possible explanation:**
  - Hierarchical merger in a dense stellar environment
  - AGNs: up to few % of detected mergers will have object in lower mass gap (Gayathri+ 2020).
  - Triple system (Lu+ 2020)

Primary mass $m_1/M_\odot$	$23.2^{+1.1}_{-1.0}$
Secondary mass $m_2/M_\odot$	$2.59^{+0.08}_{-0.09}$
Effective inspiral spin parameter $\chi_{\rm eff}$	$-0.002^{+0.060}_{-0.061}$
Upper bound on effective precession parameter $\chi_{\rm p}$	0.07
Luminosity distance $D_{\rm L}/{\rm Mpc}$	241^{+41}_{-45}

LIGO+Virgo ApJ 2020



Gayathri+ 2020

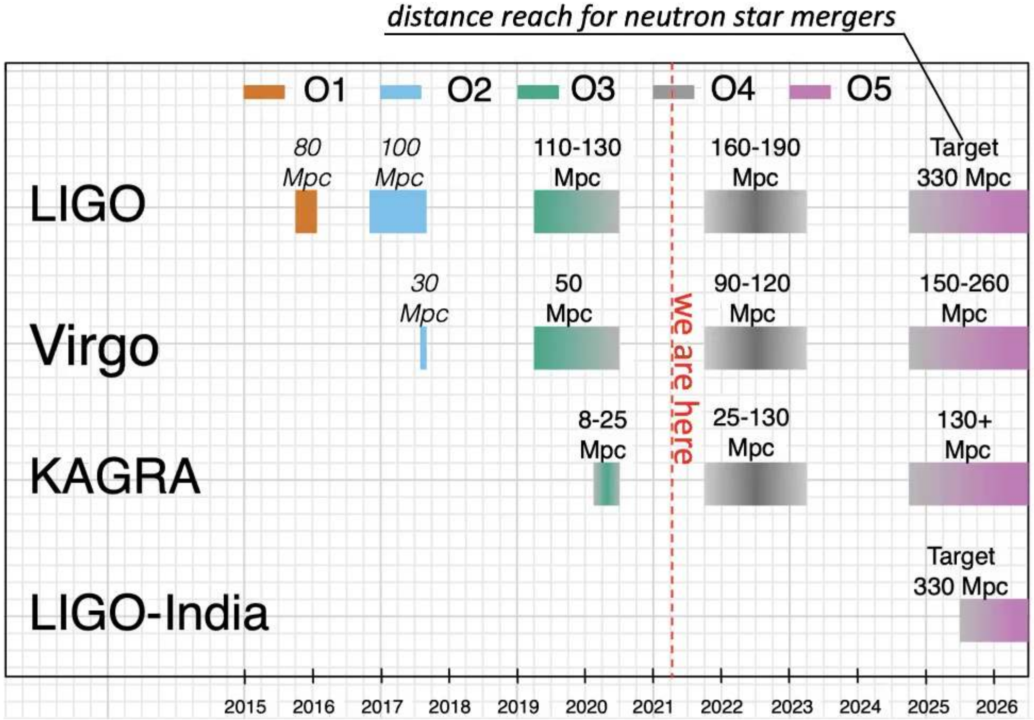
What's next (short-term)

Order of magnitude detection rate improvement from already funded upgrades in next 5 years.

→ **>1000 discoveries** soon…

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

LIGO will deliver major breakthroughs in the next 5 years.



LIGO, Virgo, KAGRA (2020)

Takeaway

- We have a lot more information now than after O1+O2.
- It is becoming difficult to explain observations with the standard isolated binary paradigm:
  - ✓ $\sim 1/3$ of events have negative χ_{eff}.
  - ✓ Many binaries with nonzero χ_p.
  - ✓ Objects in lower and upper mass gap.
  - ✓ Event with mass ratio $q \ll 1$.
  - ✓ Highly eccentric merger.
  - ✓ EM counterpart of a BBH?
- Differentiating between dynamical / AGN channels is more difficult:
  - ✓ Large model uncertainties remain making population comparisons hard.
  - ✓ How much are hierarchical mergers in globular clusters limited by small escape velocities?
  - ✓ High eccentricity favors AGN origin
  - ✓ EM counterpart if true would be smoking gun.
- I am looking forward to:
  - ✓ Are there even more massive BHs than GW190521?
  - ✓ Are there more eccentric binaries?
  - ✓ Are there mass-gap events with masses different from 2 x NS?
  - ✓ Can we localize the host galaxy of some BBHs?

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