Compact object mergers as high-energy multi-messenger sources

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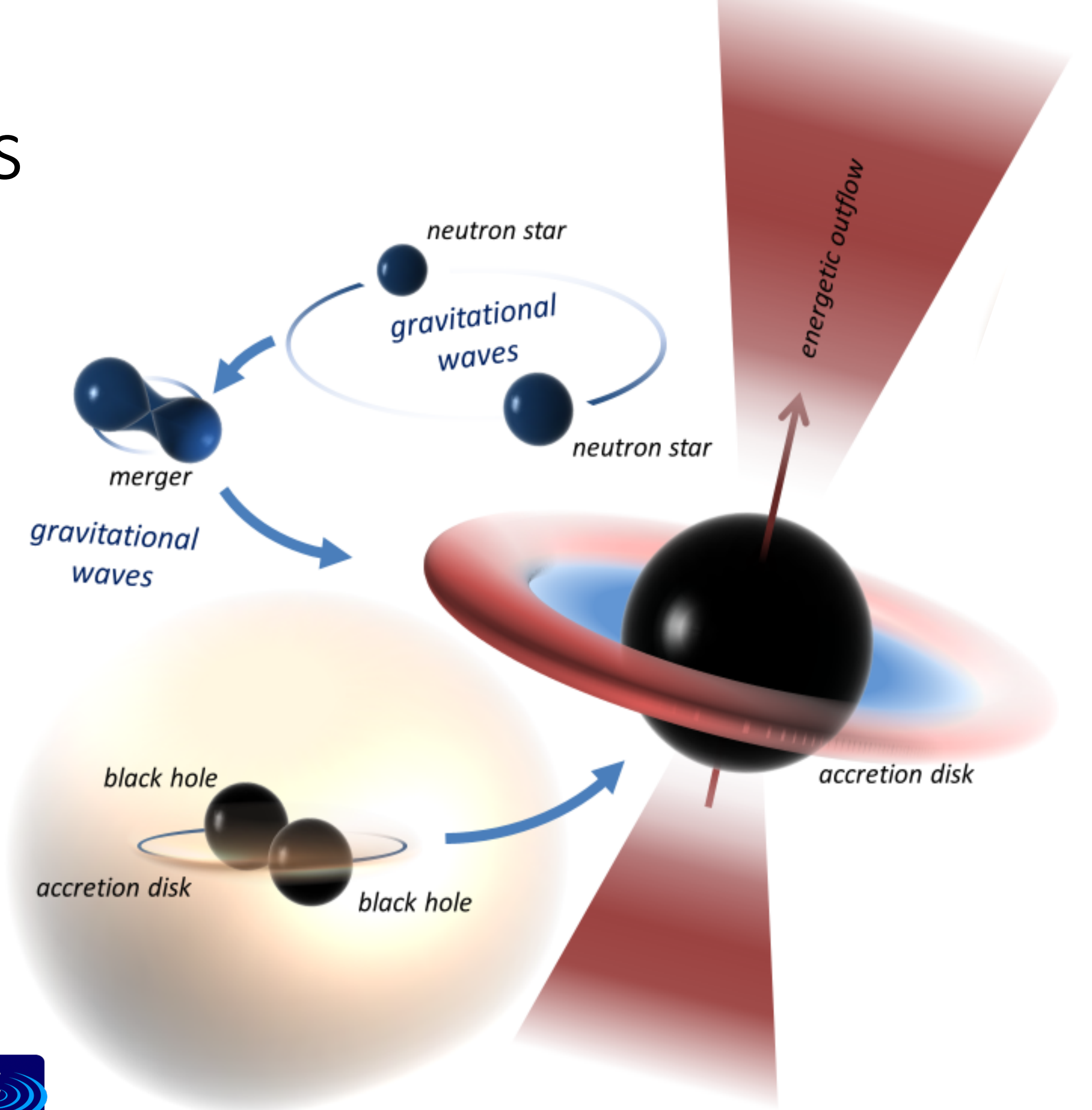
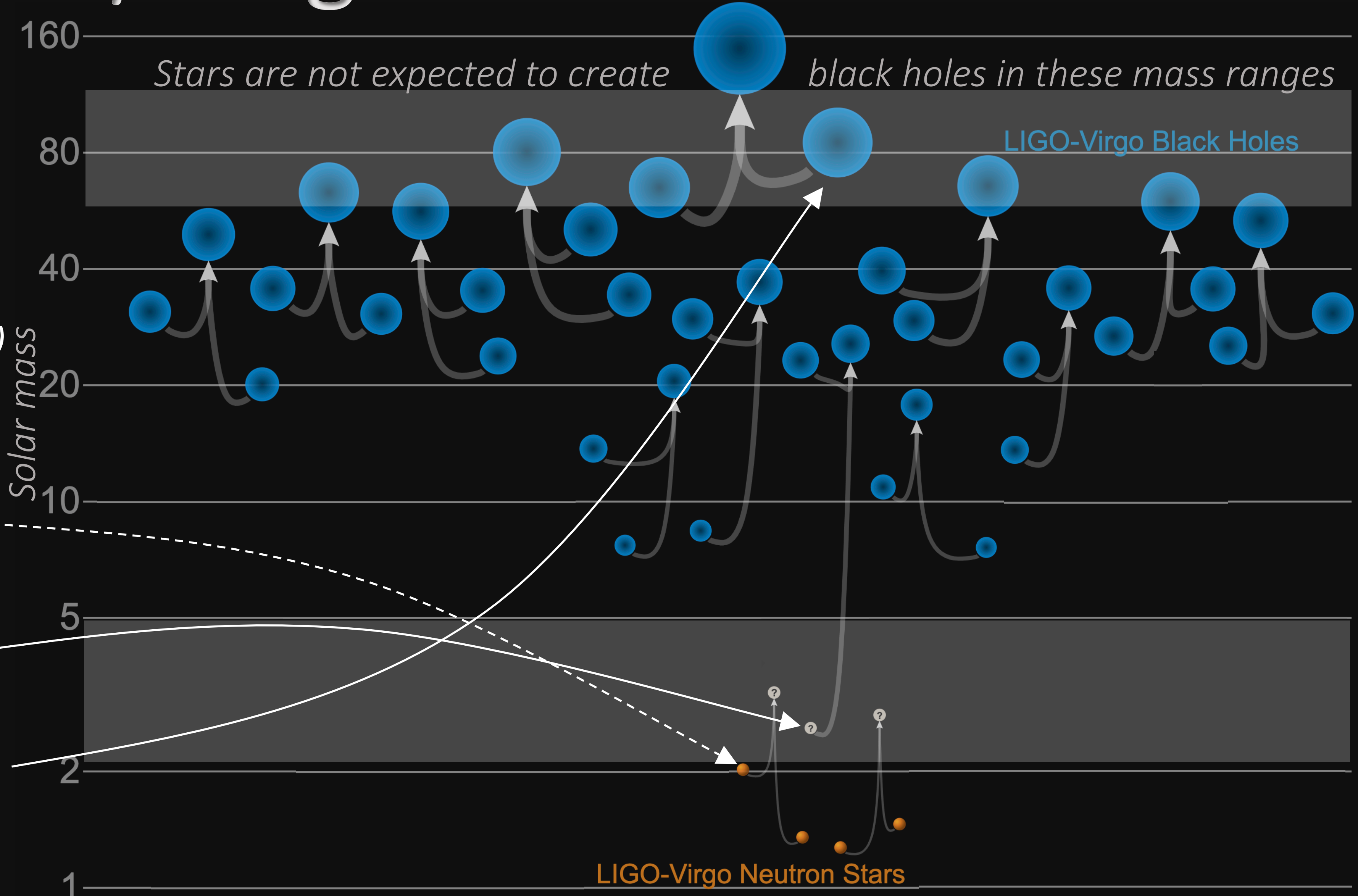
YITP workshop | Kyoto | 12.10.2020



LIGO / Virgo discoveries

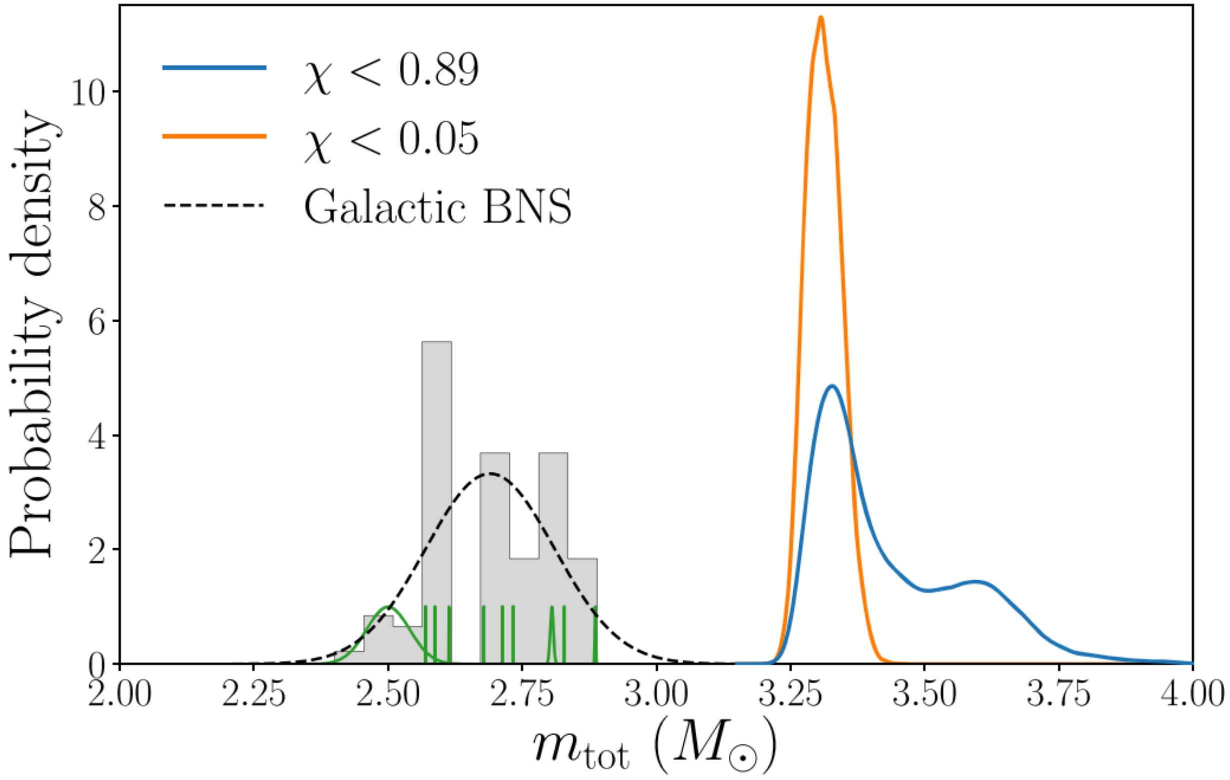
- O3 ended in March 2020
- Next observing run with KAGRA!!
- 3 + 7 + 57(?) **GW discoveries** *(special events are published first)*
- Many more black hole mergers
- New neutron star merger, no counterpart ☹
- Object in the lower mass gap
- Black hole in the upper mass gap (beyond what stars can produce)



Adopted from: LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

A special neutron star merger: GW190425

Primary mass m_1	1.60–1.87 $M_\odot$
Secondary mass m_2	1.46–1.69 $M_\odot$
Effective inspiral spin parameter $\chi_{\rm eff}$	$0.012^{+0.01}_{-0.01}$
Luminosity distance $D_{\rm L}$	159^{+69}_{-72} Mpc



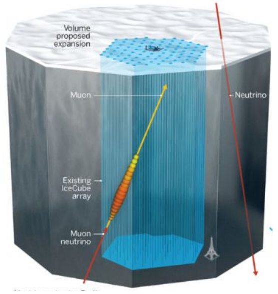
- These neutron stars were much heavier than seen in Galactic binary neutron stars. In the Milky way NSs in BNSs have $\sim 1.33 \pm 0.1\ M_\odot$

i. Possibly due to small orbital separation between stars that resulted in large mass transfer?
ii. Chance encounter? (NSs in other types of binaries are often more massive)

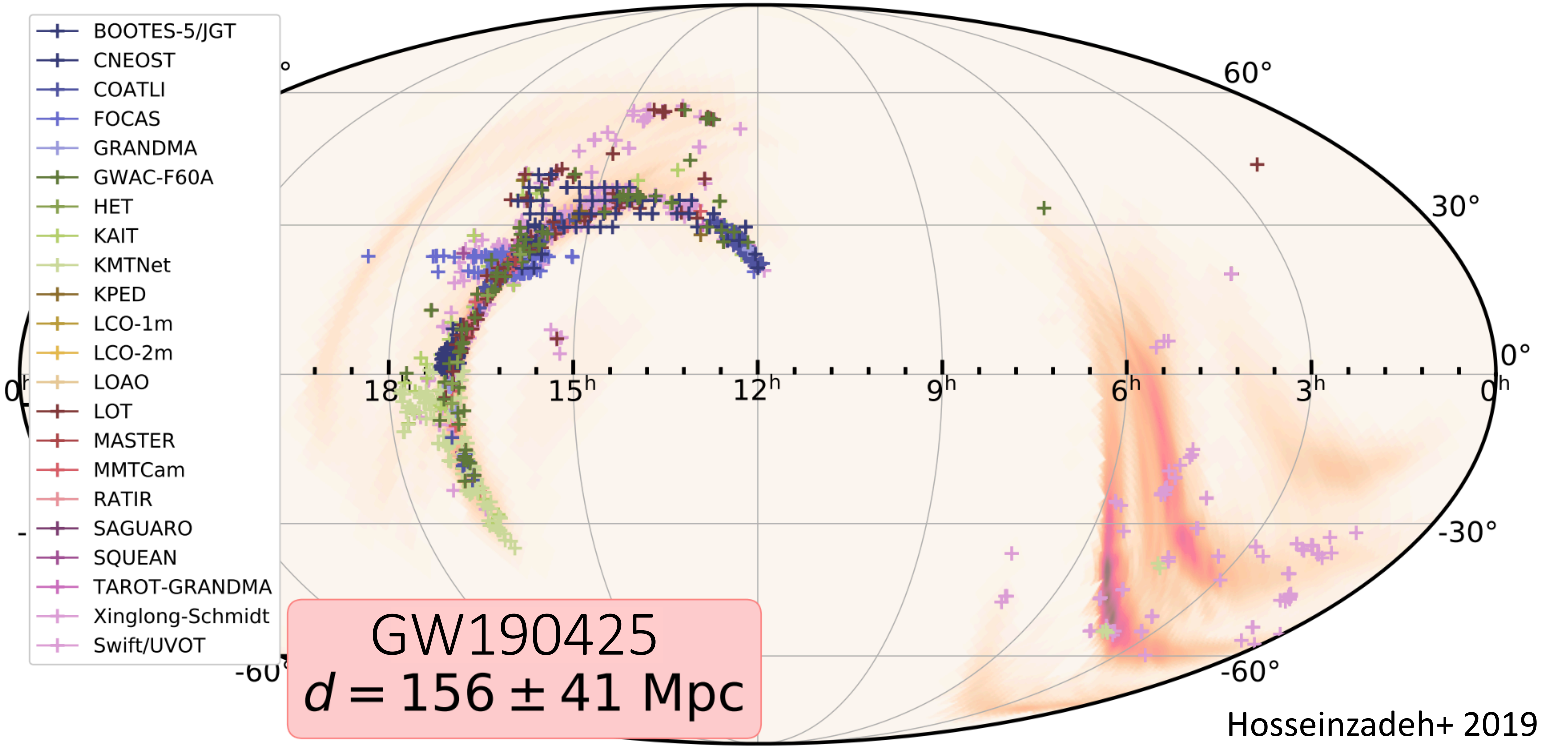
- Possible special EM counterpart?
(e.g. fast ejecta (Most+ 2020))

Electromagnetic follow-up can be difficult

- We were spoiled by GW170817.
- No GRB / high-energy neutrino counterpart.
- Dozens of observatories, 100s of observations (>230 GCN circulars).
- Extensive observation campaign only covered ~50% of volume.
- Many false positives.
- Galaxy targeted searches --- < 1% covered.



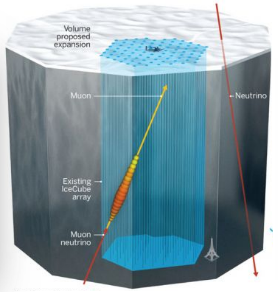
Poor localization is not a problem for neutrino follow-up.
IceCube ApJ Lett. 898:L10 2020

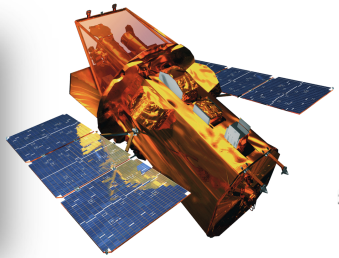


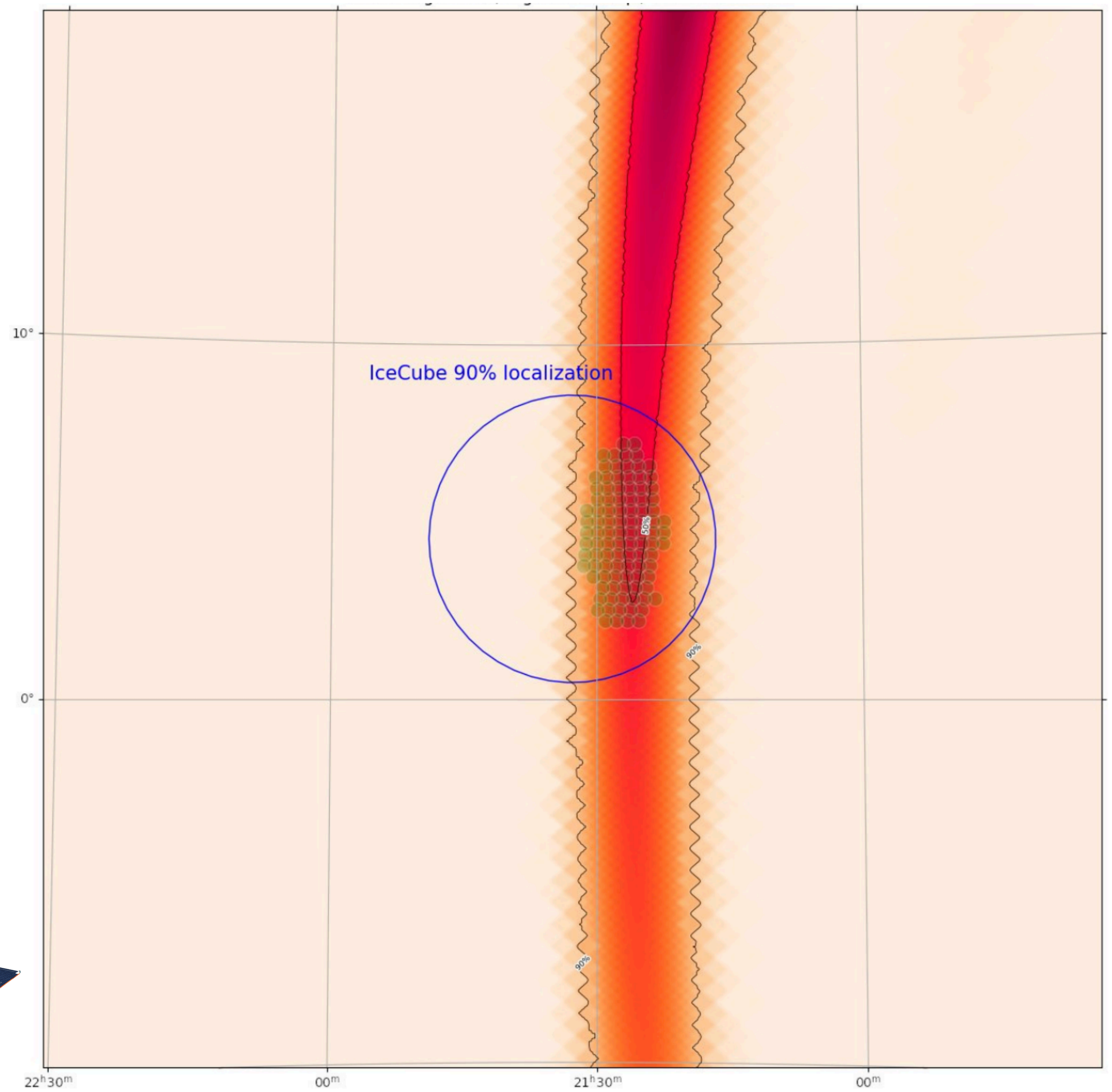
Hosseinzadeh+ 2019

IceCube follow-up of gravitational-wave candidate S191216ap

- IceCube followed up all of LIGO/Virgo's publicly announced candidates.
- Low latency (mostly it was the first detector to report the results of the follow-up).
- One particularly interesting overlap: S191216ap
  - ➢ Classified as "mass gap" by LIGO/Virgo
  - ➢ Bayesian coincidence analysis (Bartos+ PRD 2019) identified overlap significance of 2.5σ.
  - ➢ Coincidence substantially shrunk the error region for follow-up observations.
  - ➢ The HAWC high-energy gamma detector identified an interesting coincident sub-threshold event.
  - ➢ The Swift satellite carried out X-ray follow-ups in the jointly found direction, but did not find any signal.

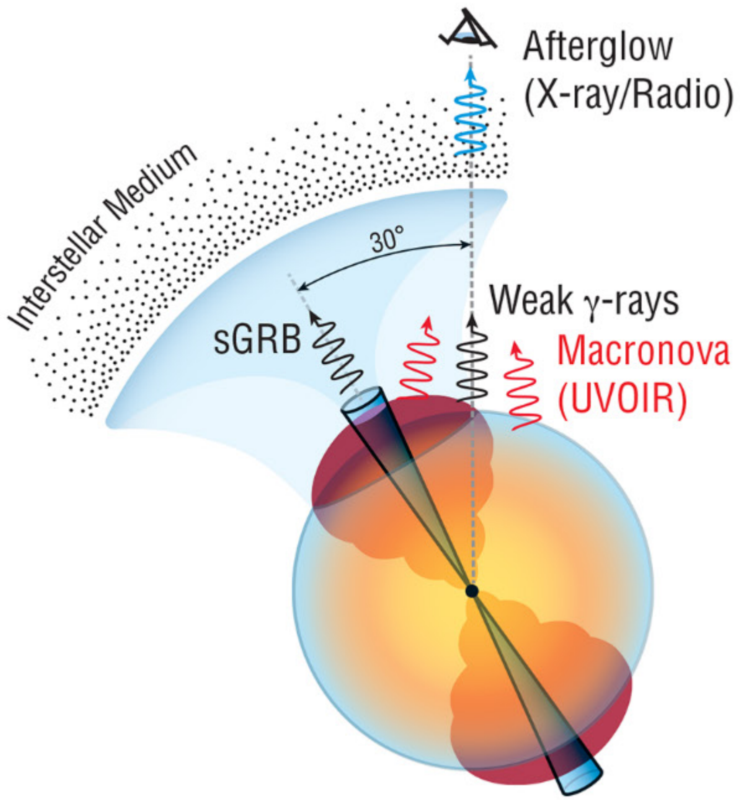




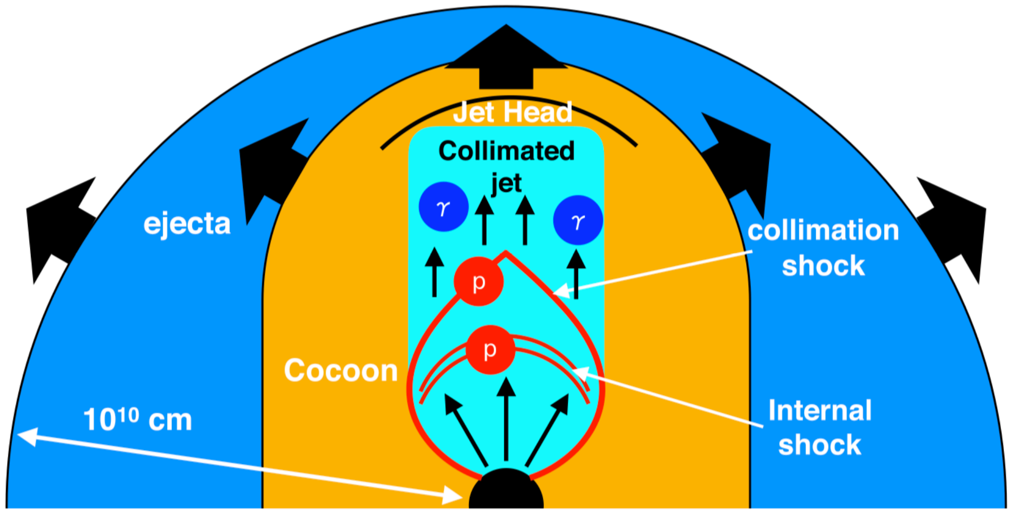


Keivani,…,Bartos+ 2020

Relativistic / dynamical ejecta



- Relativistic outflow interacts with slower ejecta
  → alter neutrino emission
  → attenuate observable gamma-ray flux
- GW170817 was not likely to produce a detectable neutrino flux, but more head-on similar events are promising for IceCube (Kimura+ 2018).



Kimura, Murase, Bartos, Ioka, Heng, Meszaros 2018

GW170817:
- Closest gamma-ray burst ever (by far)
- Off axis (20°-30°)
- Structured outflow (but there was a jet)

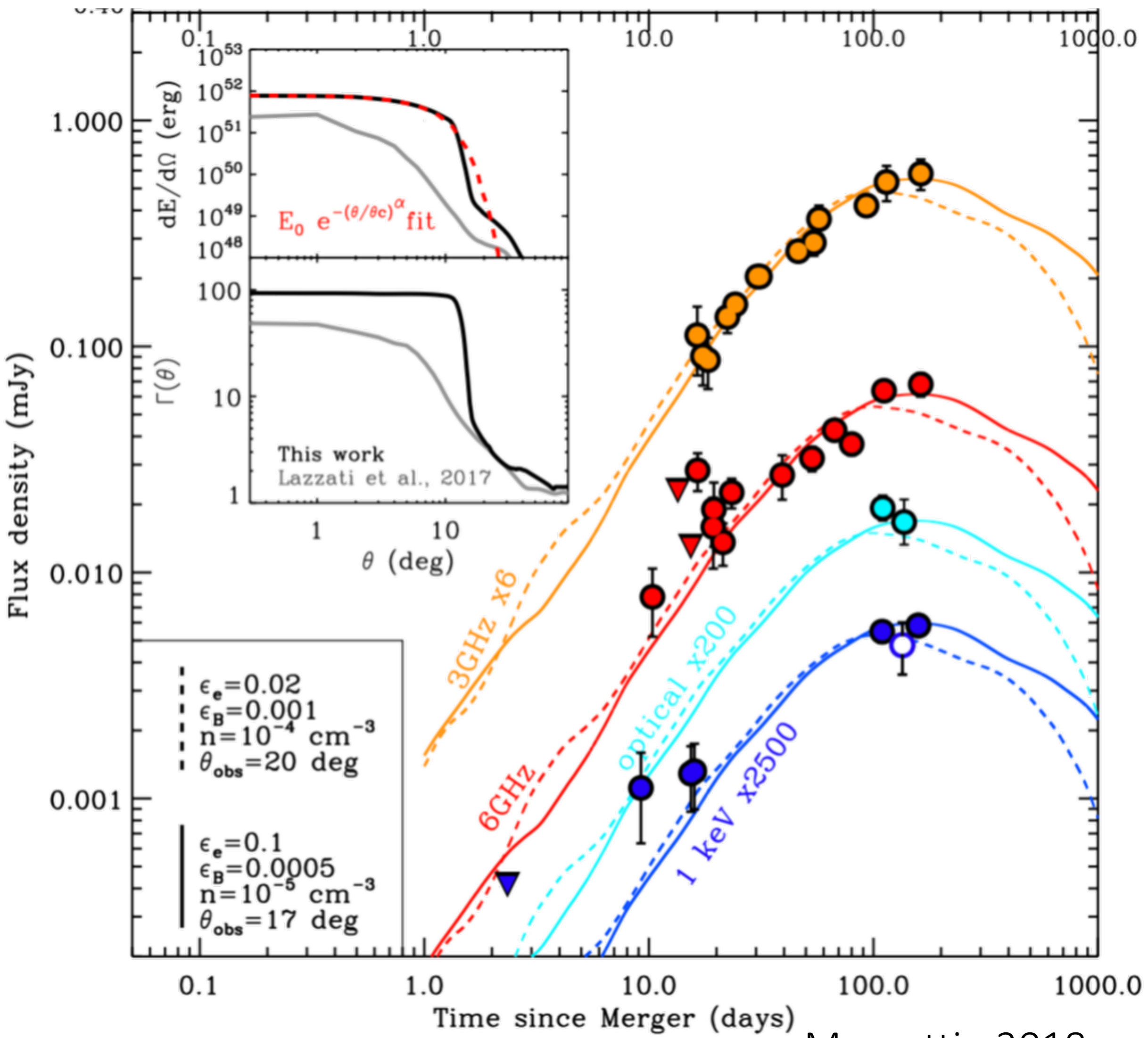
We did not expect this GRB structure…

- Based on cosmological GRB beaming observations, GRB 170817A should be highly atypical (Beniamini+ 2018).

- Joint GW + GRB detection have been mostly considered unlikely.

- But what if <u>GRB 170817A is typical</u>?

- Taking structured jet (Margutti+ 2018) at face value:
  - ✓ <u>up to 30%</u> of GWs from BNS will have GRB counterpart.
  - ✓ Significant fraction (10%) of GRBs should be <u>nearby</u>.



Margutti+ 2018

Can we uncover past neutron star mergers in archival radio surveys?

- No radio flare has been detected from neutron star mergers.

❑ Radio flares are not detectable unless the merger is nearby.

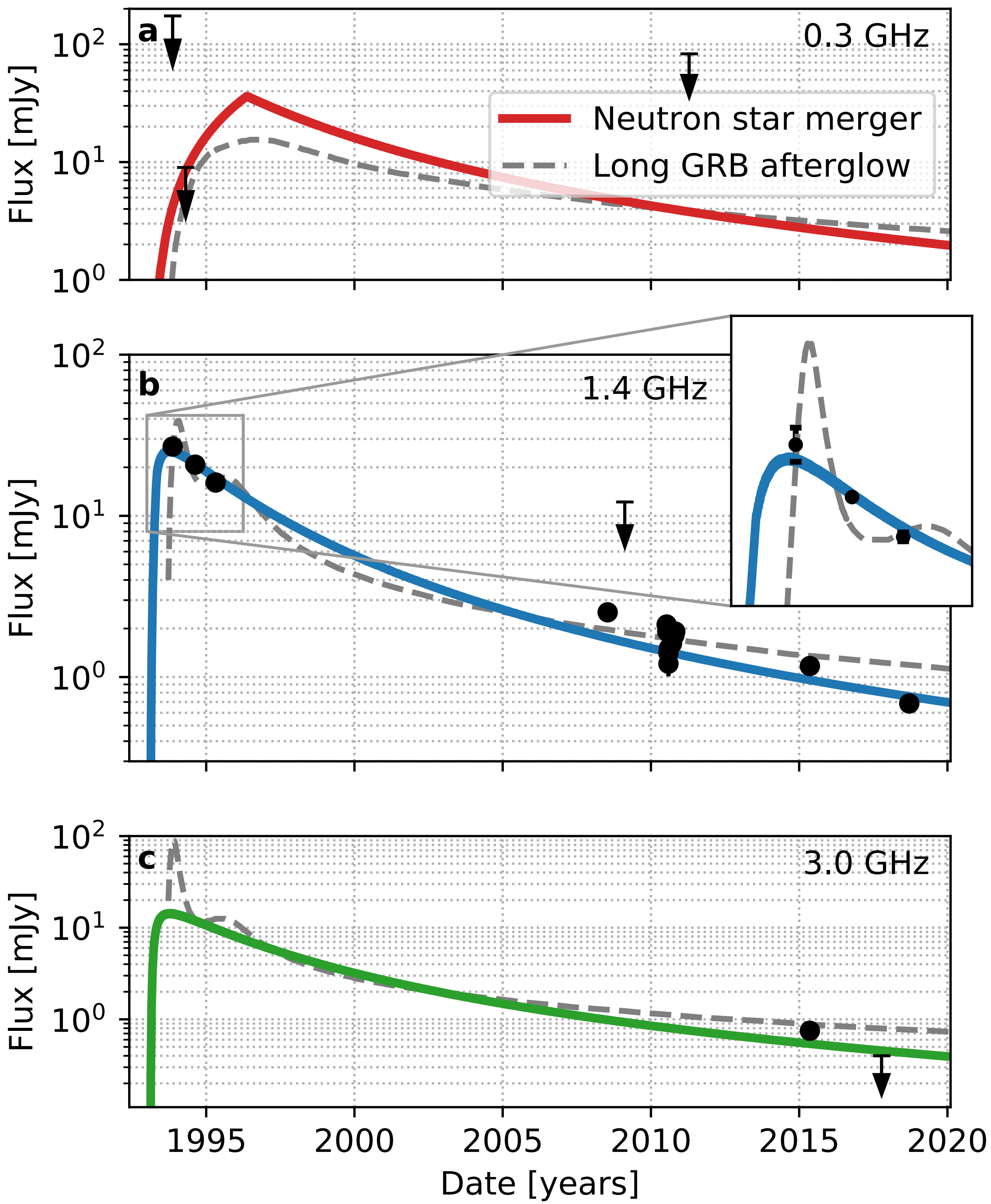
❑ The merger also needs to be in a dense interstellar medium, which is typically not expected (Metzger & Merger 2012). (e.g. GW170817 is close but is in a very sparse medium)

- But: **atypical ≠ never!**

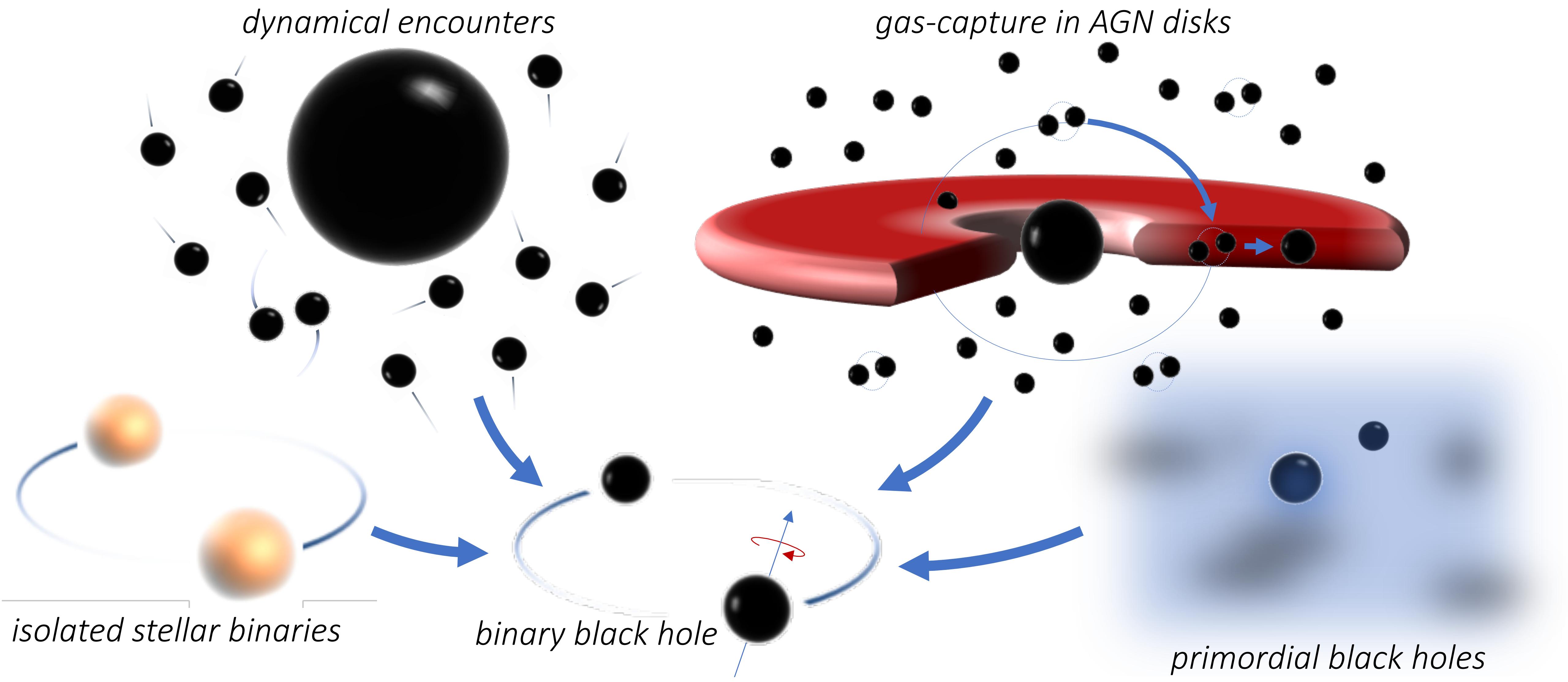
✓ A long-term radio signal (FIRST J1419+3940) 87 Mpcs away is better explained with a merge origin than alternative explanations (afterglow).

✓ Would be first such discovery.

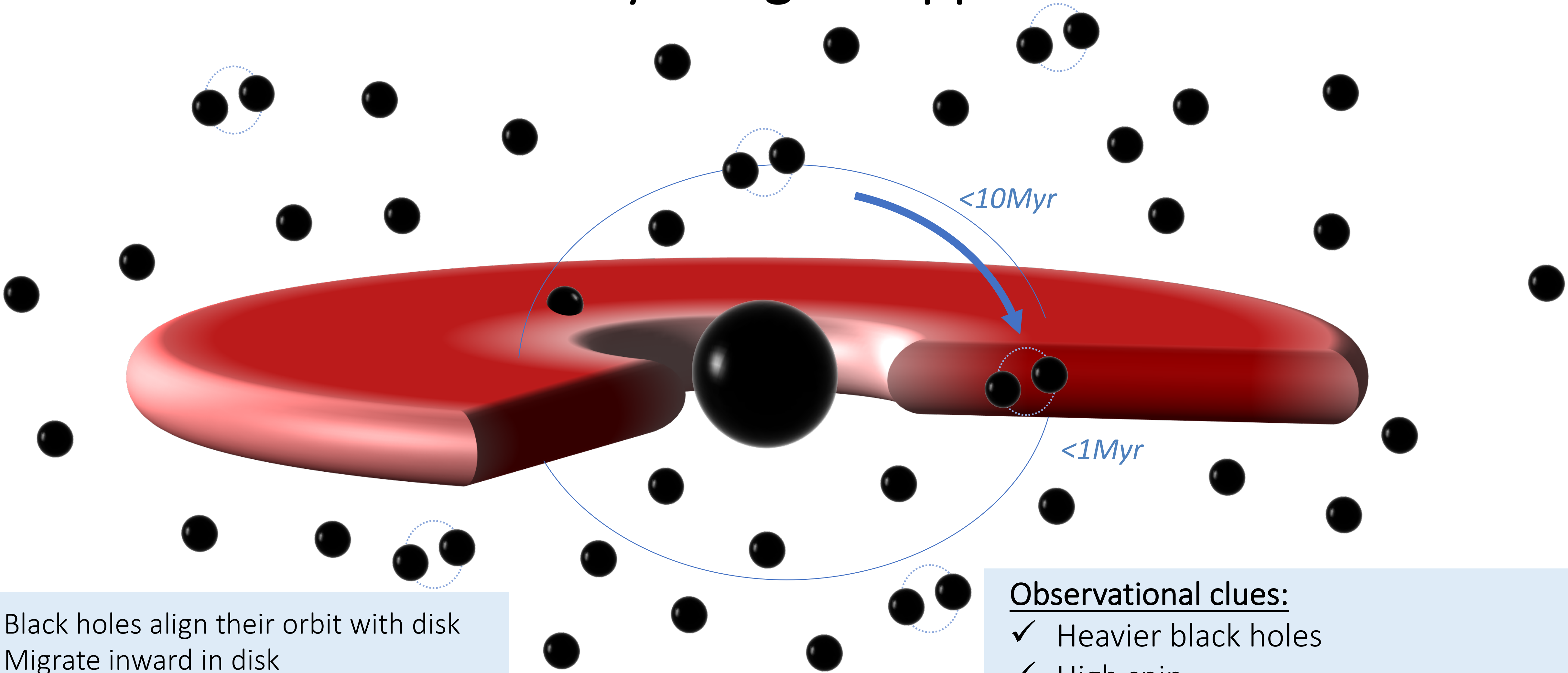
Lee, Bartos+ ApJ Lett 2020



Origin of binary black holes



How do we know if a binary merger happened in an AGN disk?



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)

McKernan+ ApJ 2012
Bartos+ ApJ 2017
Yang+ PRL 2019

<u>Observational clues:</u>

- ✓ Heavier black holes
- ✓ High spin
- ✓ Masses can be highly asymmetric
- ✓ Eccentricity (Gayathri+ 2020)
- ✓ Multi-messenger counterpart?

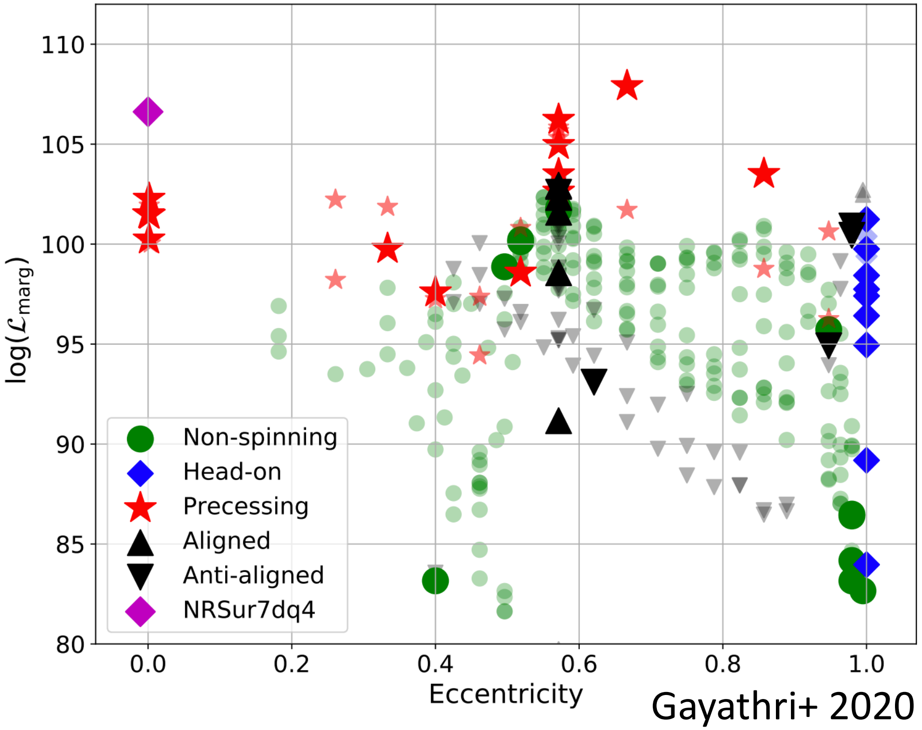
GW190521

- Mass of heavier black hole ($\sim 85M_{\odot}$) difficult to explain with stellar evolution, although uncertainties remain

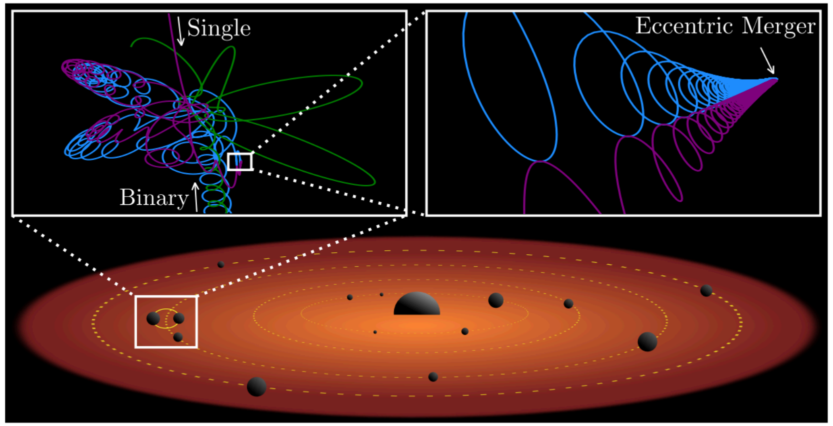
- Spin: likely high and ~perpendicular to orbital angular momentum.
  - ➢ This is difficult to explain with isolated stellar binary.

- Indication of highly eccentric orbit (Gayathri+ 2020)
  - ➢ ~proof of dynamical / AGN origin
  - ➢ AGNs may be optimal sites for high eccentricity (Samsing+ 2020, Tagawa+ 2020)
  - ➢ Lower-mass highly-eccentric mergers are difficult to detect --- no templates for search, lower model-agnostic search sensitivity, weaker GW signal.

➢ If this is indeed a black hole merger in an AGN disk, there can be many more like this that may produce EM counterparts.



Gayathri+ 2020

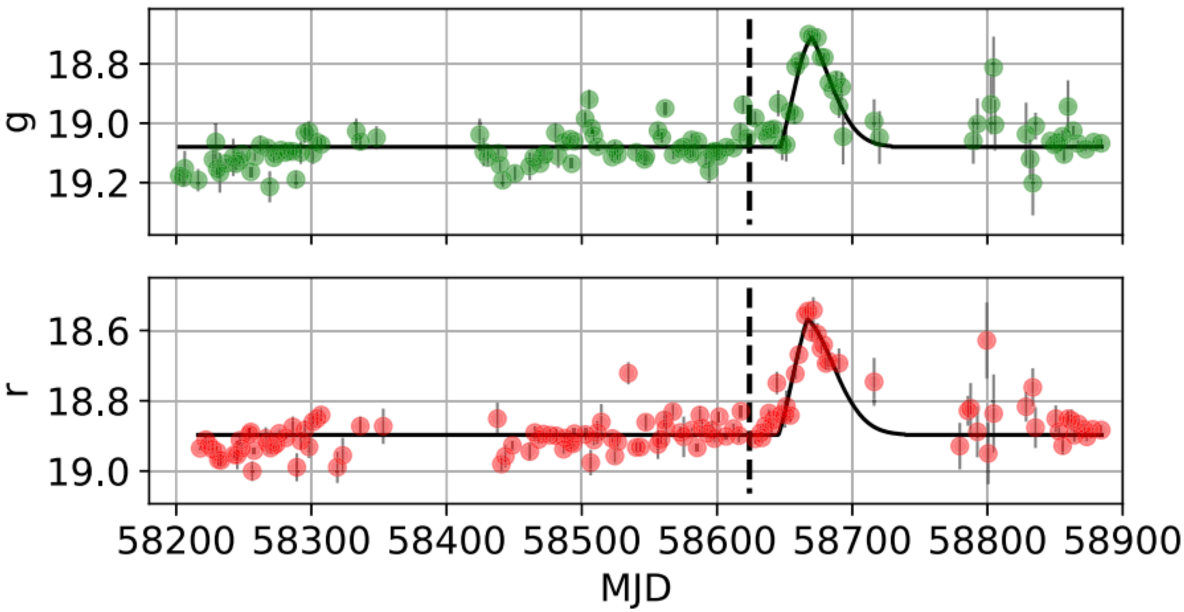


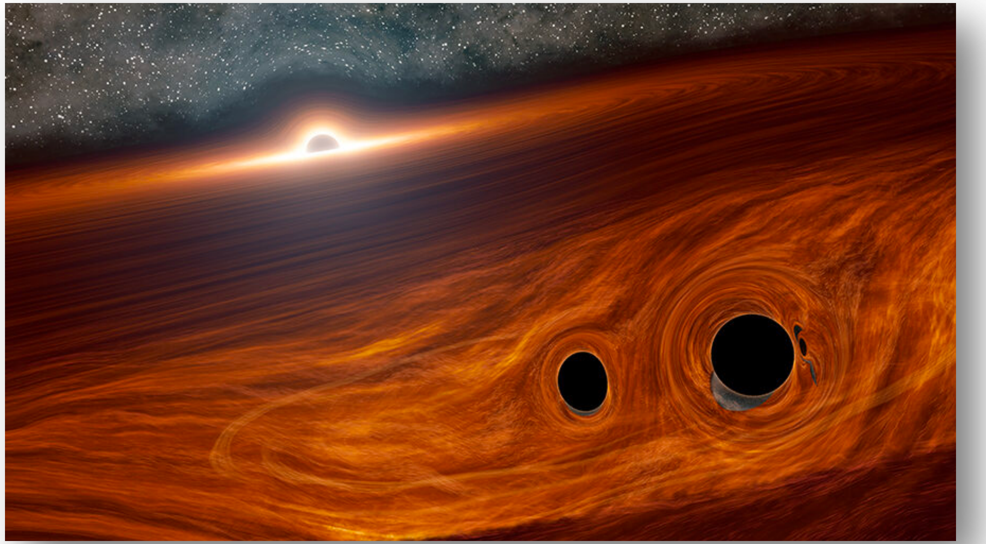
Samsing+ 2020

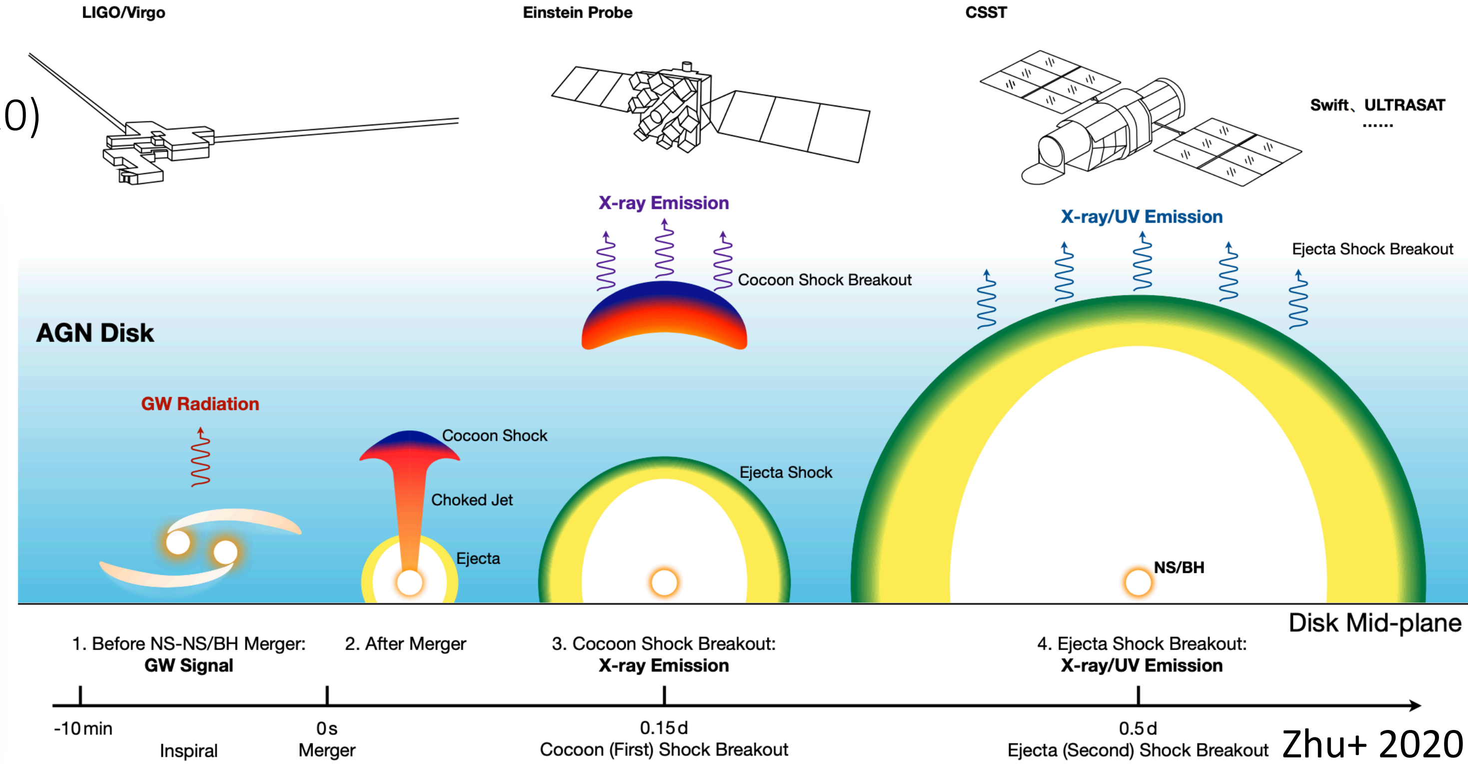
Candidate EM Counterpart to Black Hole Merger GW190521

McKernan+ PRL 2020

- Black hole merger EM follow-up search with ZTF
- 2-months long transient in the wake of S190521g.
- EM signal consistent with AGN origin.
- Other possibilities:
  - Explosions in AGN disks (Perna+ 2020)
  - Neutron star merger in AGN disks (Zhu+ 2020)







Zhu+ 2020

- Summary
  - ✓ A lot of information in the gravitational wave channel.
  - ✓ Difficult to explain with the standard isolated binary paradigm.
  - ✓ Multiple hints of mergers in AGN disks
    → multi-messenger possibilities even with black holes.
  - ✓ Interaction of multiple outflows from neutron stars could substantially alter high-energy output.

- What's your targeted physics in next decade?
  - ✓ We will discover thousands of binary mergers.
  - ✓ We will see back to the Cosmic Dawn ($z \sim 20$).
  - ✓ We have already been completely surprised many times.
  - ✓ I expect to work on something in 10 years I don't know of yet.
  - ➢ Neutron star mergers: interaction of different outflows
  - ➢ Accretion and high-energy emission from binary black holes and their mergers (both stellar-mass and supermassive!)

- What we need to accomplish?
  - ✓ Are there non-GW signatures of binary black holes?
  - ✓ Do black hole mergers meaningfully contribute to the overall radiation in the universe?

- Take-home message
  - ✓ Compact object merger astrophysics is exponentially expanding
  - ✓ We will be awash in sources and problems and we will need to work hard to spend our time on the most interesting ones.

Takeaway

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