Stellar graveyards in AGN disks:

Prospects for multi-messenger transients

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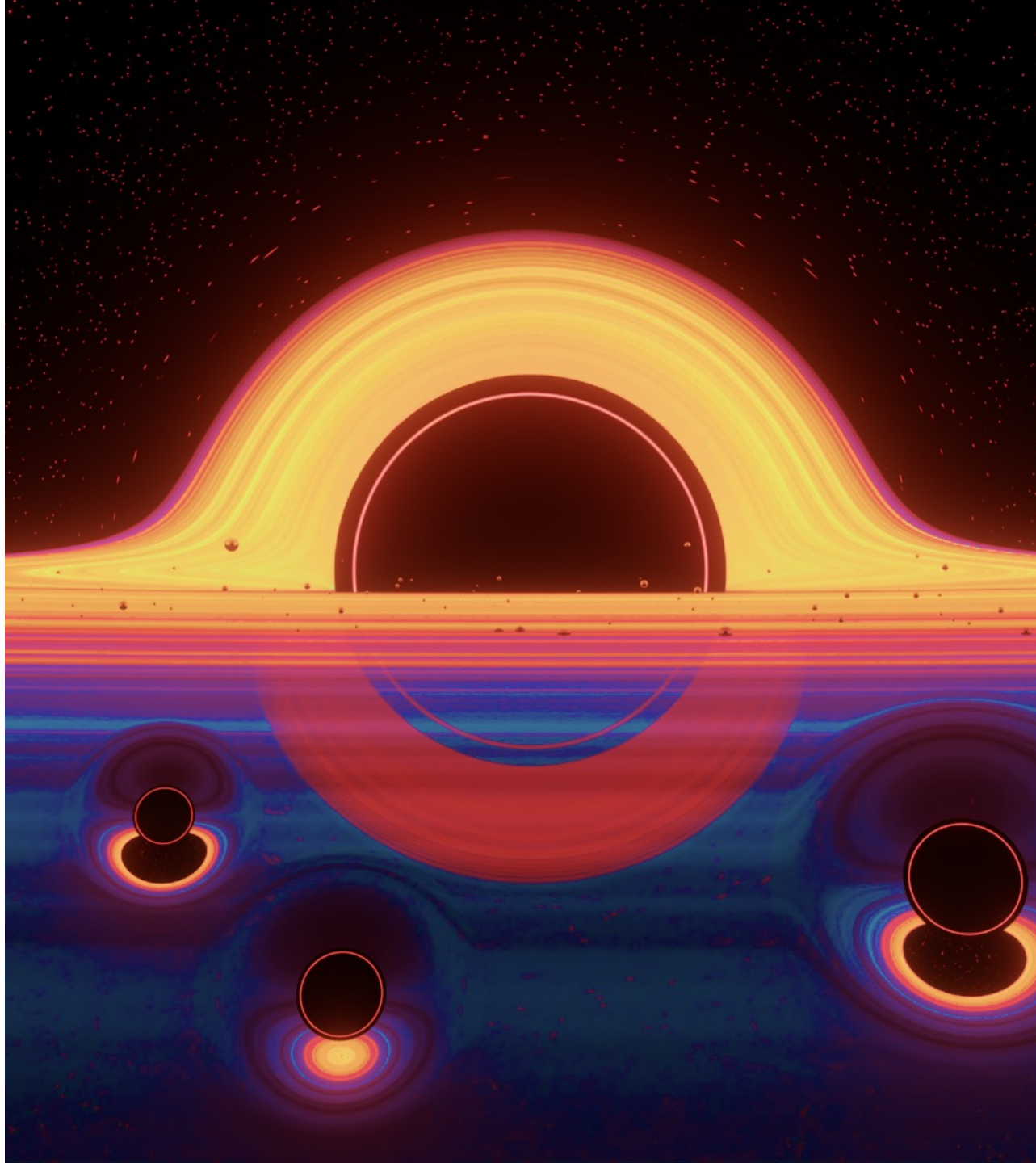
The Restless Nature of AGN | 06.27.2023

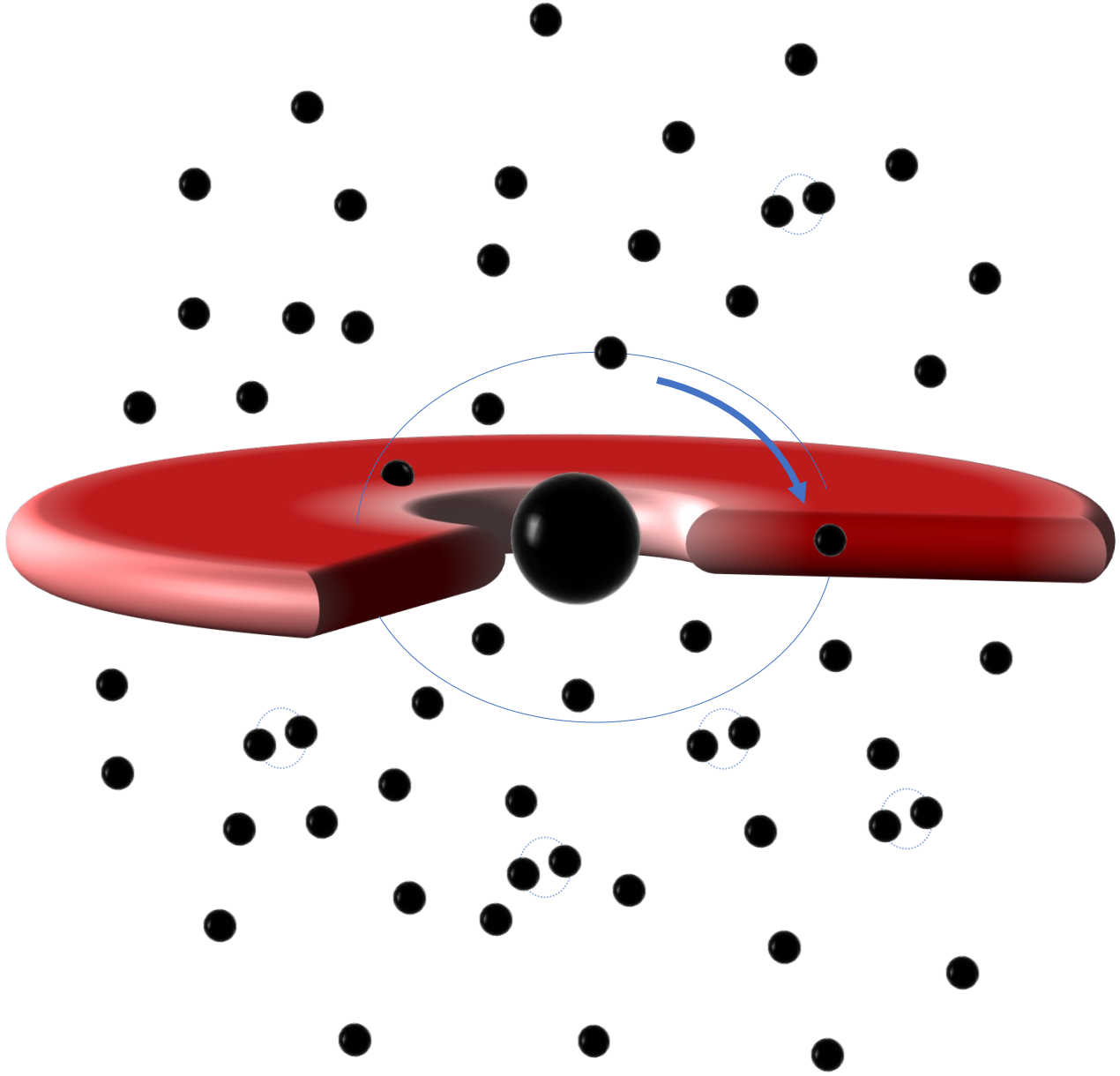


Why are there stellar objects in AGN disks?

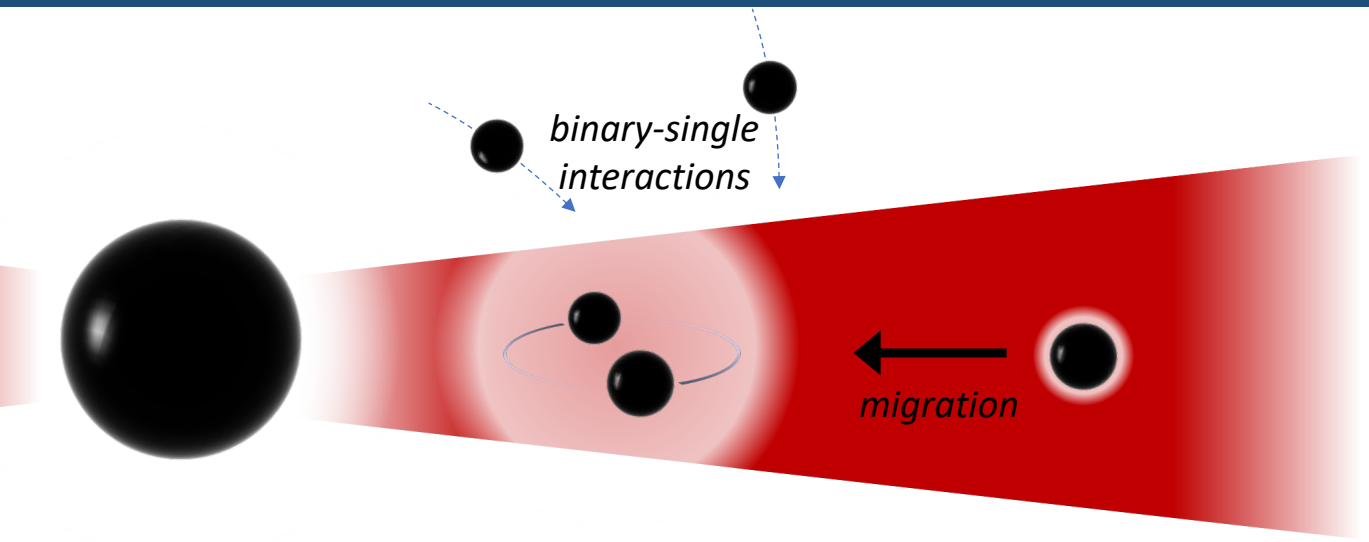
1. **Disk capture.**
   - Mass segregation – heavier objects move closer to the center → O(10^4) black holes in the inner parsec
     - *observed near Sgr A* (Hailey+ 2018).*
   - Periodic disk crossing: – some stellar objects align their orbit with disk plane (Bartos+ 2017).

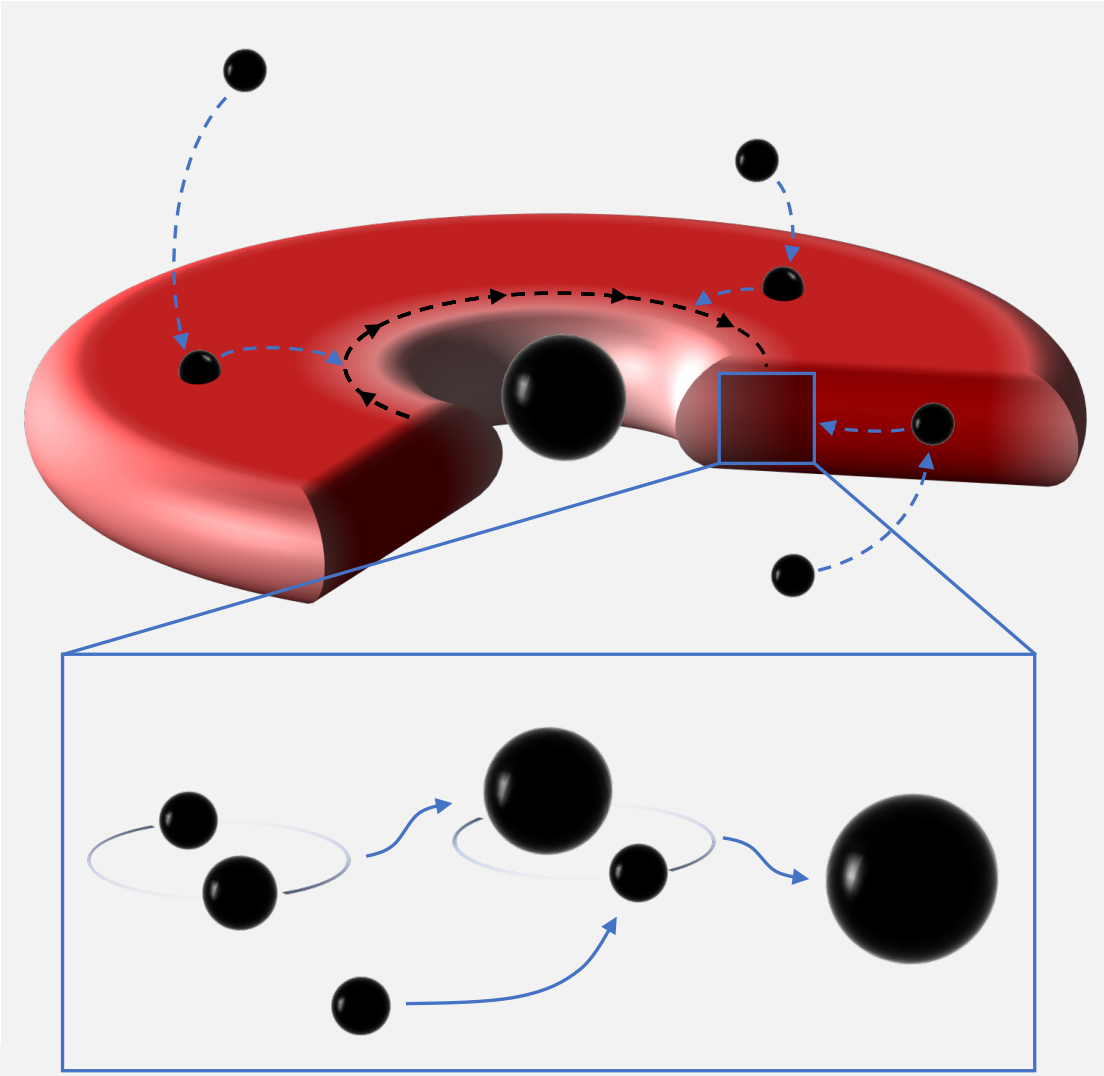
2. **Star formation within the disk.**
   - Stars form due to gravitational clumping.
   - After stellar evolution – leave black holes or neutron stars in disk.

Black holes, neutron stars and stars can be residing within AGN disks.



(Stellar mass) black holes in the disk





1. Migration inwards due to pressure gradient.
   - *Migration trap at few hundred R_S? (Bellovary+ 2016)*
   - *Interaction with stars/BHs in center - $\sim 10^{-2} pc$. (Tagawa+ 2020)*
2. Gas capture – efficient binary formation in gas.
3. Rapid inspiral:
   a. Dynamical friction in gas.
   b. Binary-single interactions with stellar objects outside the disk.
4. Remnant stays in/near disk → can merge with another black hole → hierarchical mergers.

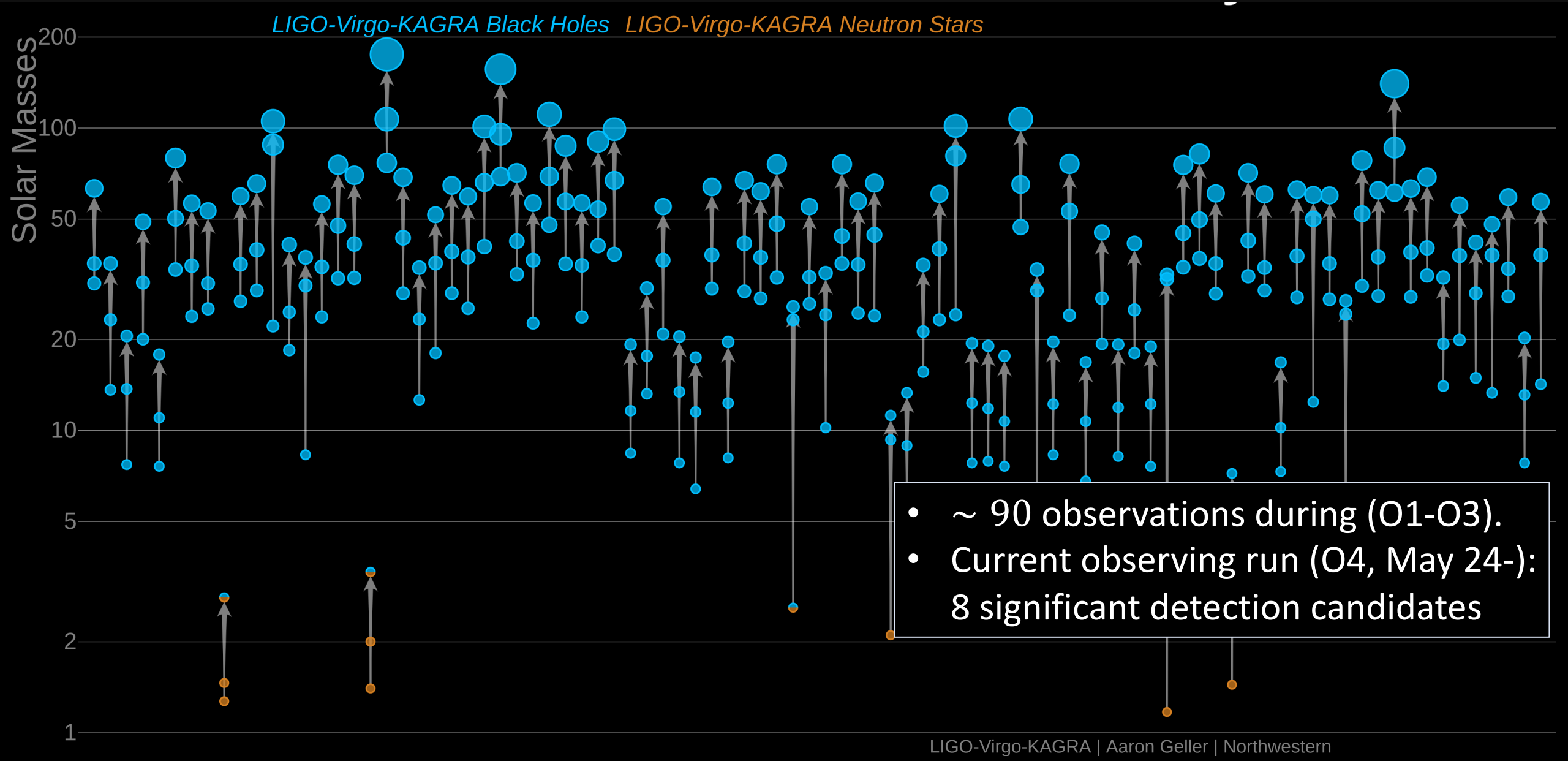

LIGO Hanford


LIGO Livingston

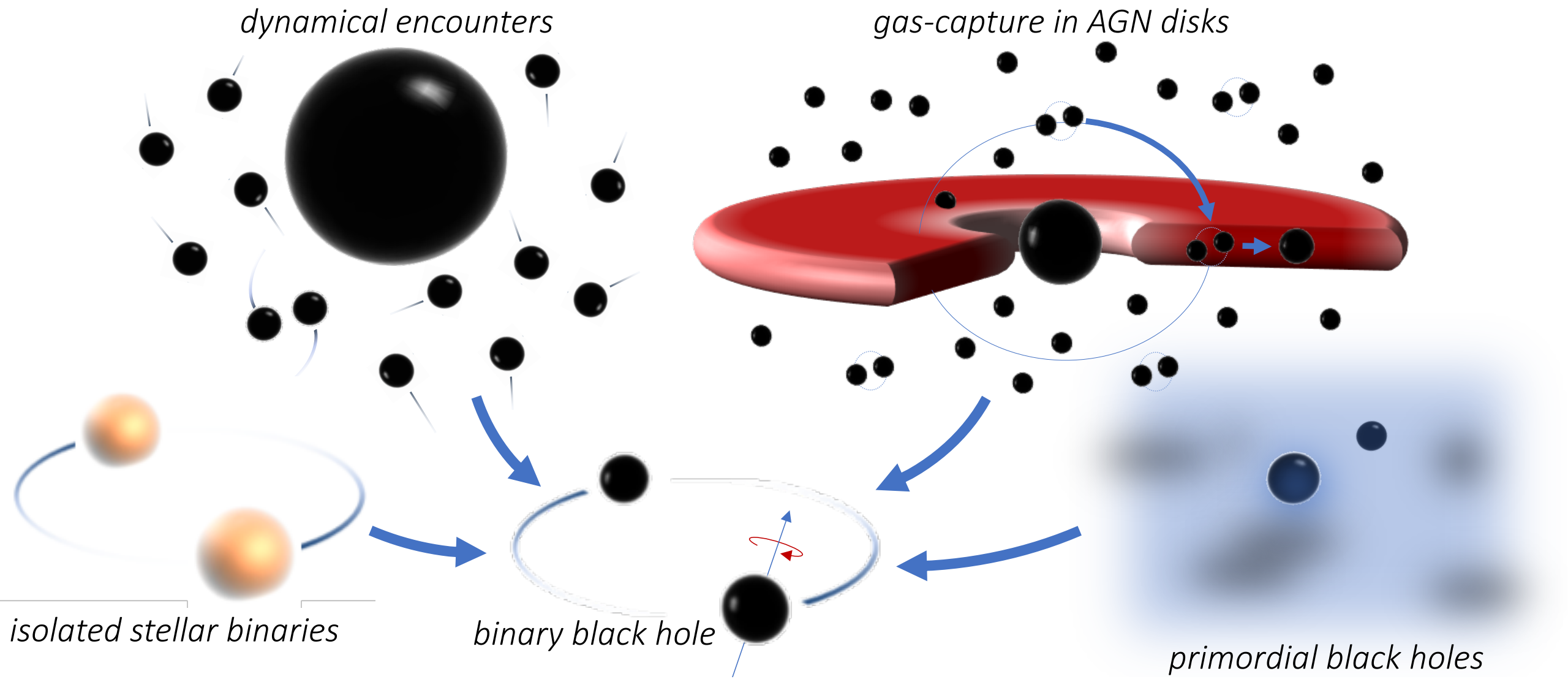

Virgo


KAGRA

Gravitational wave discoveries



Possible origins of binary black holes

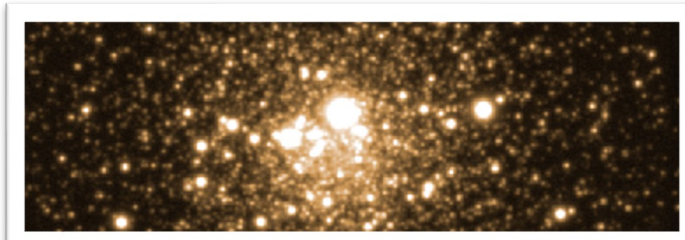


Observational consequences

Higher mass

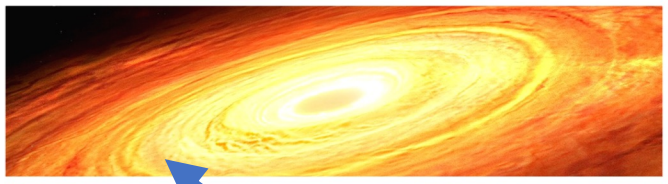
Mass segregation

Heavier objects in GC migrate inward, lighter ones move out. (O'Leary+ 2009)



Accretion

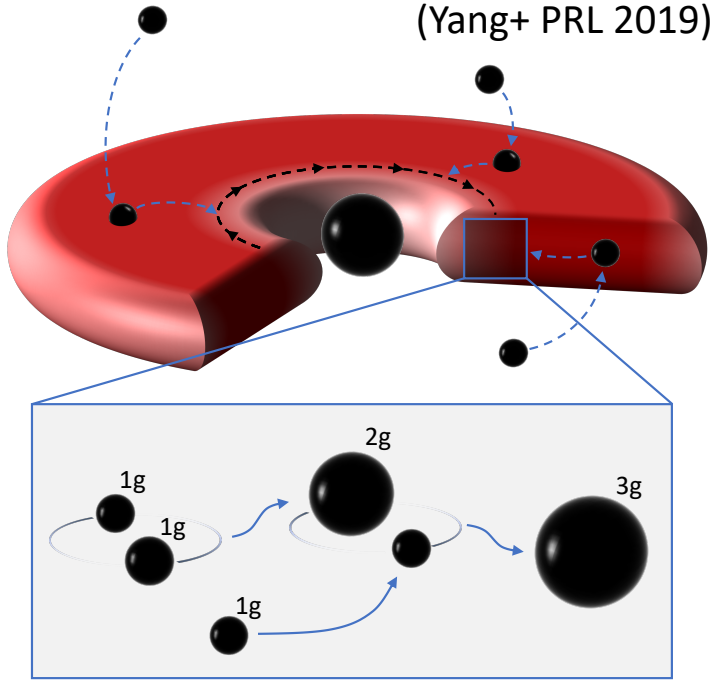
Black holes (and NSs) accrete gas inside the AGN disk (Yang+ ApJ Lett 2019).



Hierarchical mergers.

Multiple black holes can migrate to same place and merge consecutively.

(Yang+ PRL 2019)



Higher spin

Both accretion and mergers can increase spin.

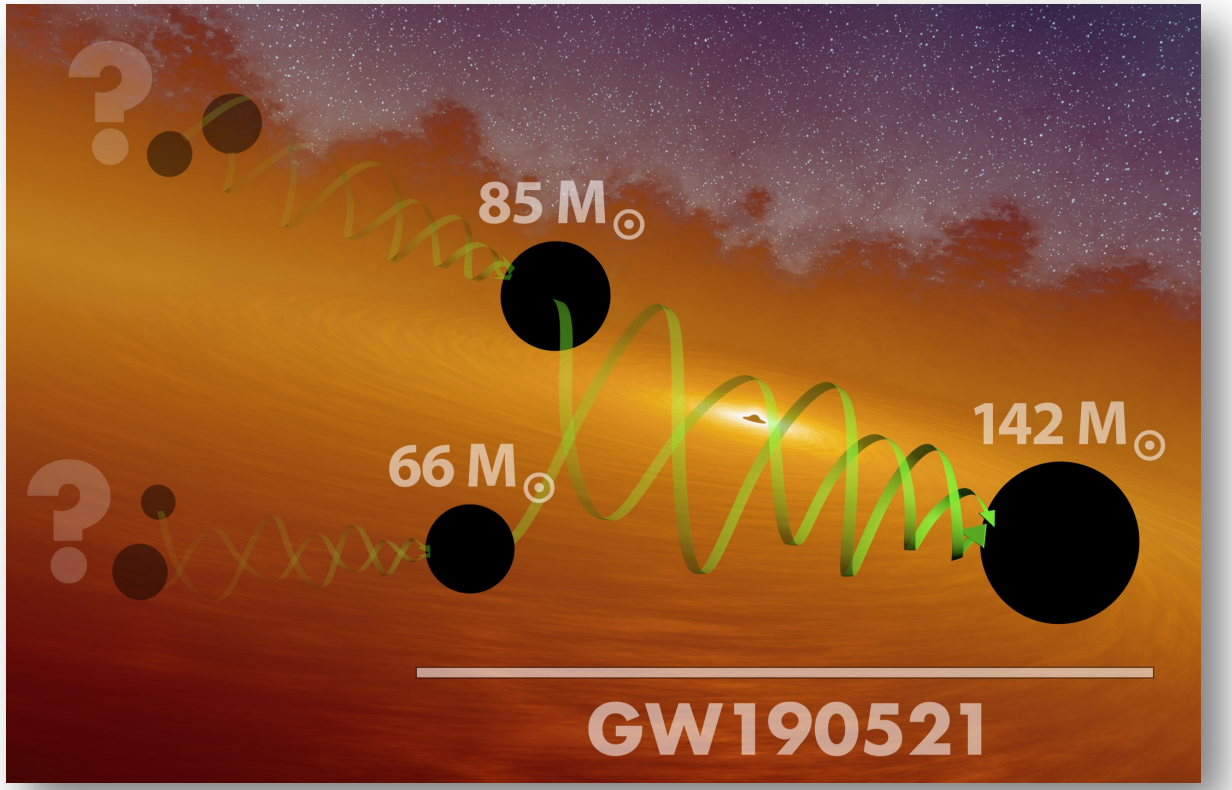
The black hole that shouldn't exist: GW190521

- $M_1 > 65 M_\odot$: 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.

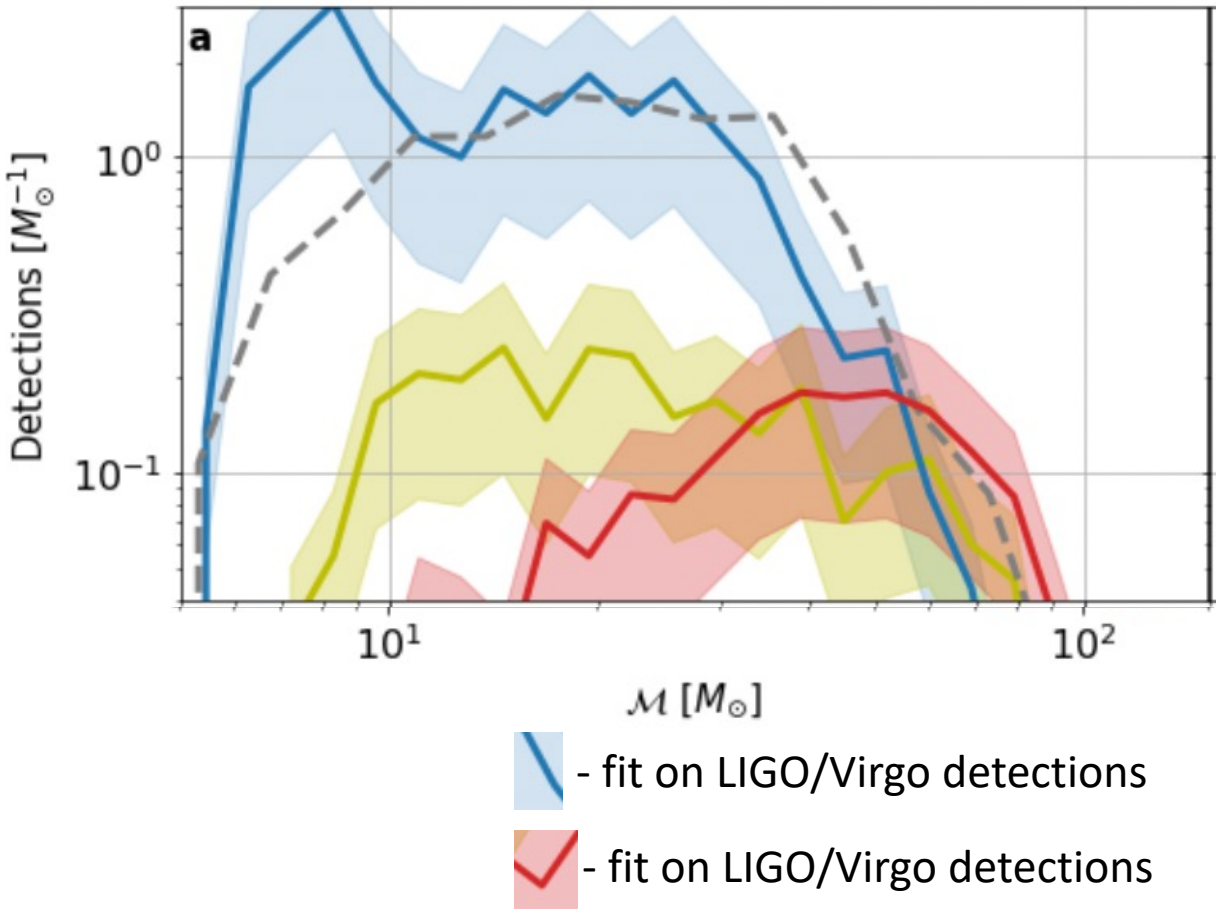
- **Misaligned spin from orbit:** also difficult to explain with stellar binaries where spin should be parallel with binary orbit. It is expected if binaries form in chance encounters (such as the case for multiple mergers).



What fraction of gravitational waves are from AGNs?

Model comparison

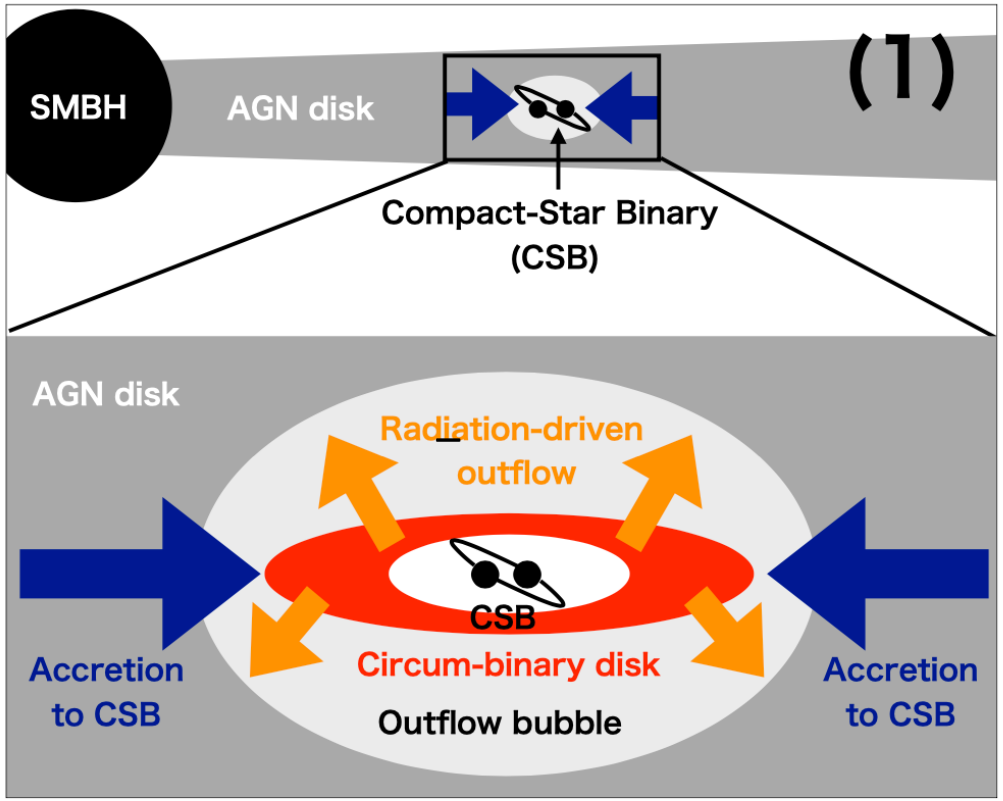
- Compare AGN model vs overall mass+spin fit to all LIGO-Virgo events.
- Determine for each event whether overall mass+spin fit or AGN model works better.
- High-mass ($M_{chirp} > 40\ M_{\odot}$): overwhelmingly of AGN origin
- **20% of LIGO-Virgo detections could come from AGNs**

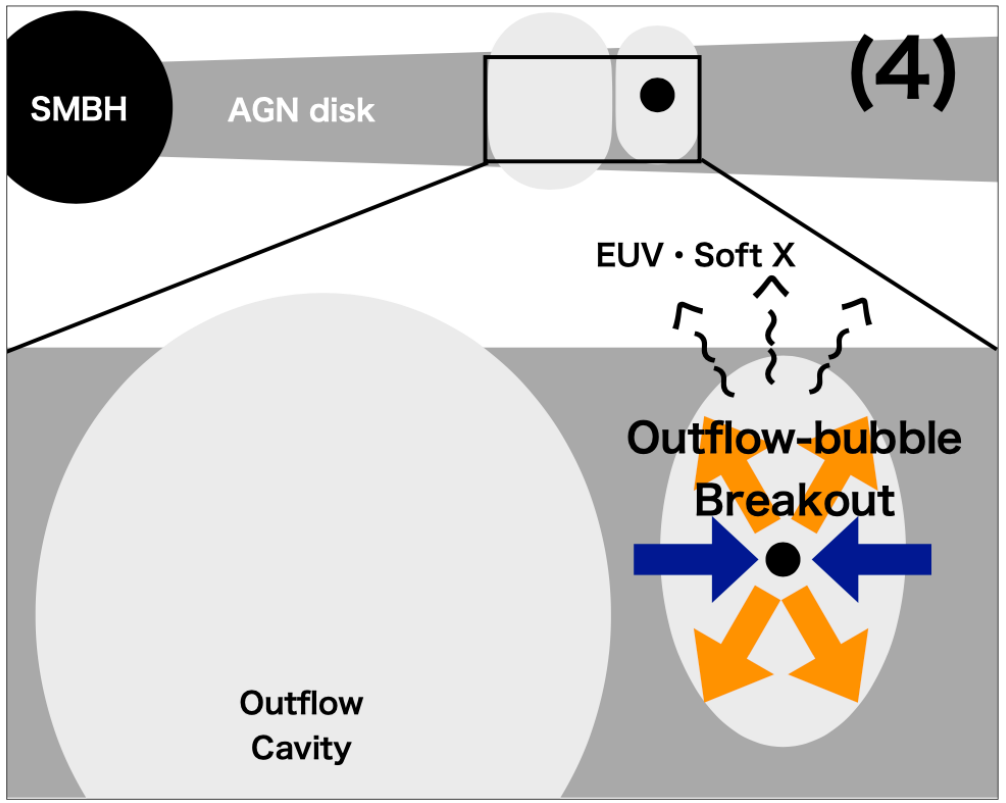


Gayathri, Yang, Tagawa, Haiman, Bartos ApJ Lett 2021

Multi-messenger emission from black hole mergers in AGNs

Kimura, Murase, Bartos 2021

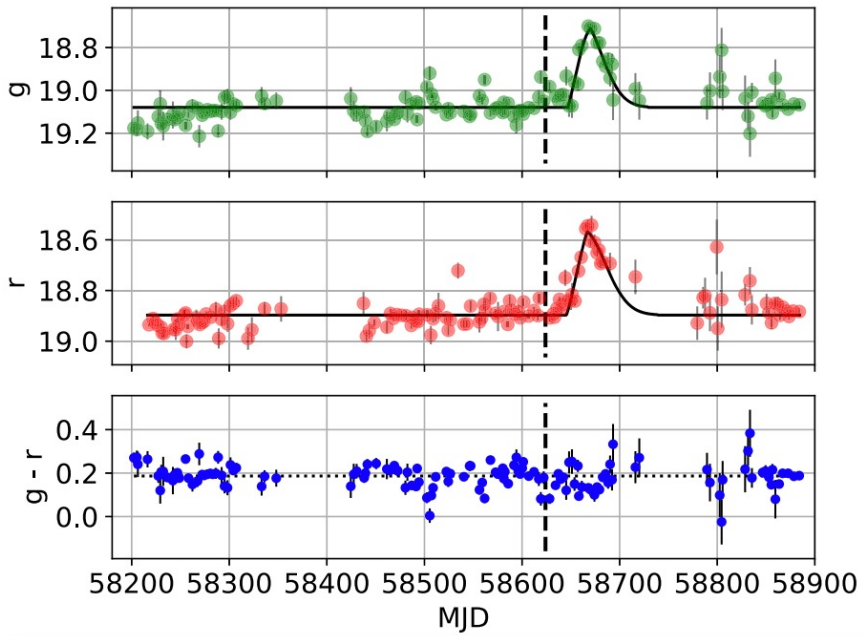


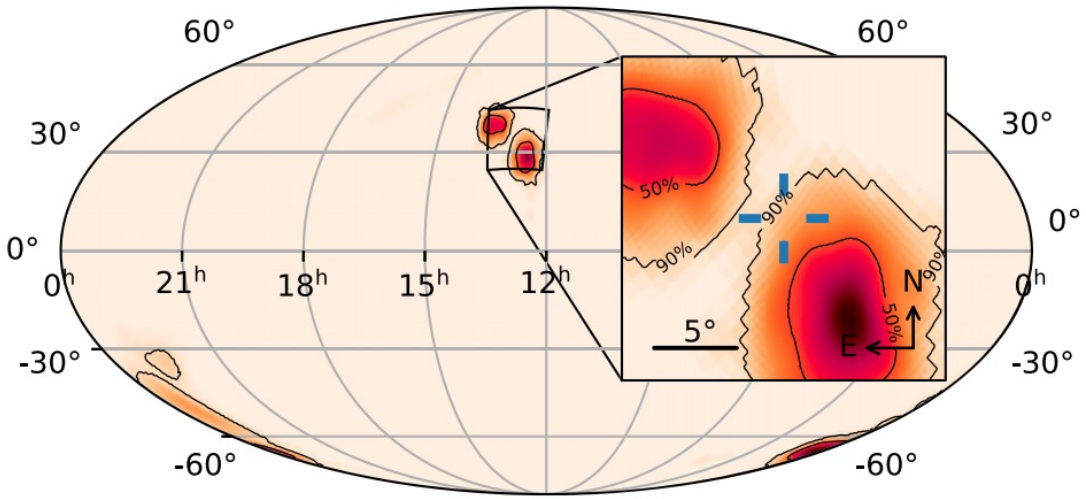


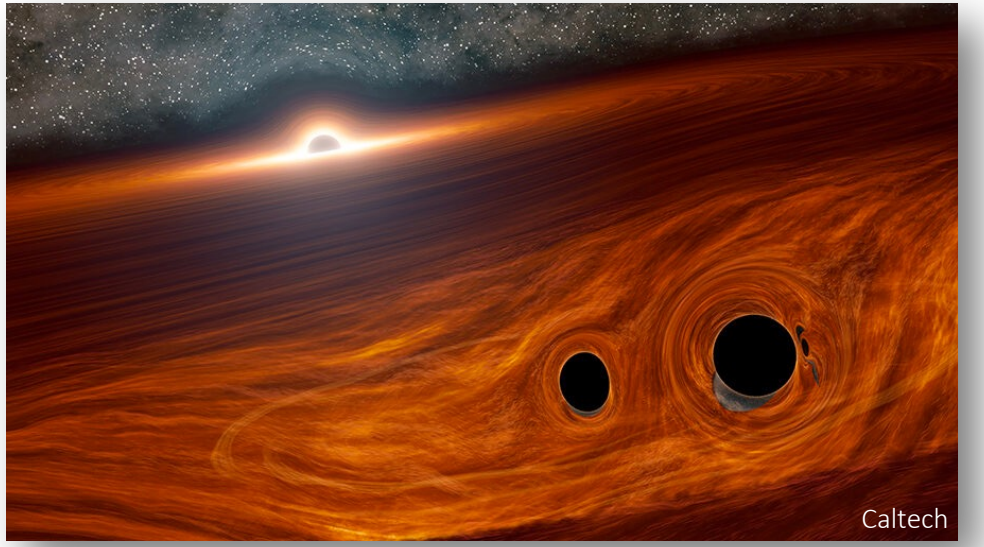
- Radiation driven outflows will balance accretion → **cavity + low accretion**
- Merger → GW recoil → remnant BH enters dense AGN disk → **high accretion**
  → soft X-ray (~500 Mpc with Swift/Chandra) + optical/IR (reprocessing)
- *Is inflow spherical/constant?*

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 is not yet conclusive, more detections needed (8 more candidates: Graham+ 2023).

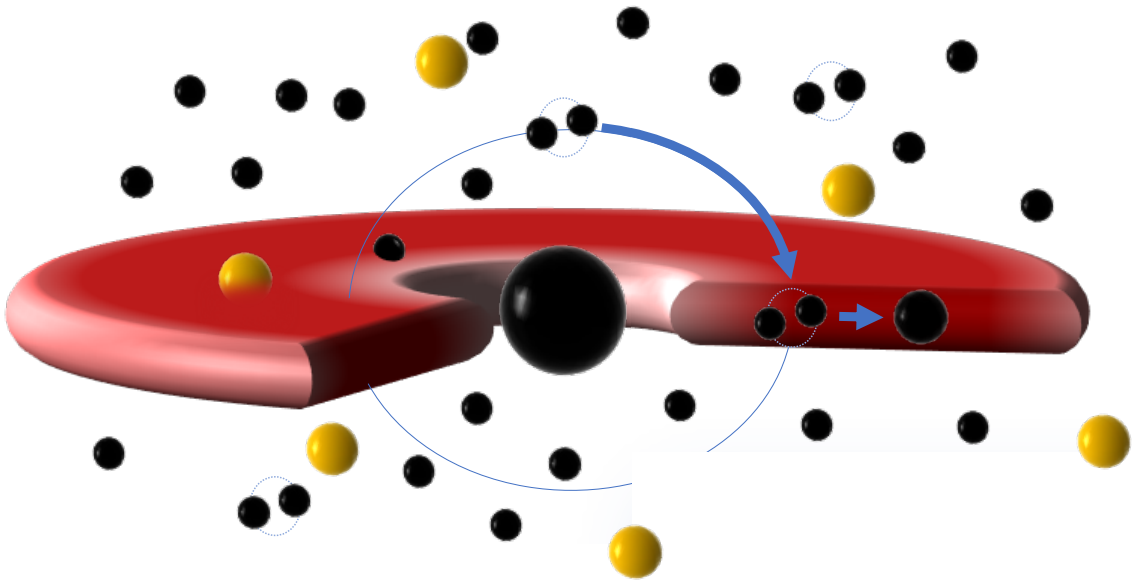






Micro Tidal Disruption Events in AGNs

- Stars and black holes align their orbits with AGN disk
- Gas capture → binaries
- Tidal disruption on stellar-mass black holes
- Possible observational signatures:
  - Ultralong GRBs? (Perets+ 2016)
  - TDEs in AGNs.
    - ➢ TDE on SMBHs has higher rate.
    - ➢ Different emission profile?
    - ➢ SMBH mass $> 10^8 M_\odot$ - solar type stars are not disrupted by SMBH. Candidates:
      - ASASSN-15lh
      - ZTF19aailpwl



Expected Rate Density of Binary Mergers/Disruptions in AGNs

$Gpc^{-3}\ yr^{-1}$	Black Hole	Neutron Star	Star
Black hole	13	1	170
Neutron star		10^{-3}	0.14
Star			20

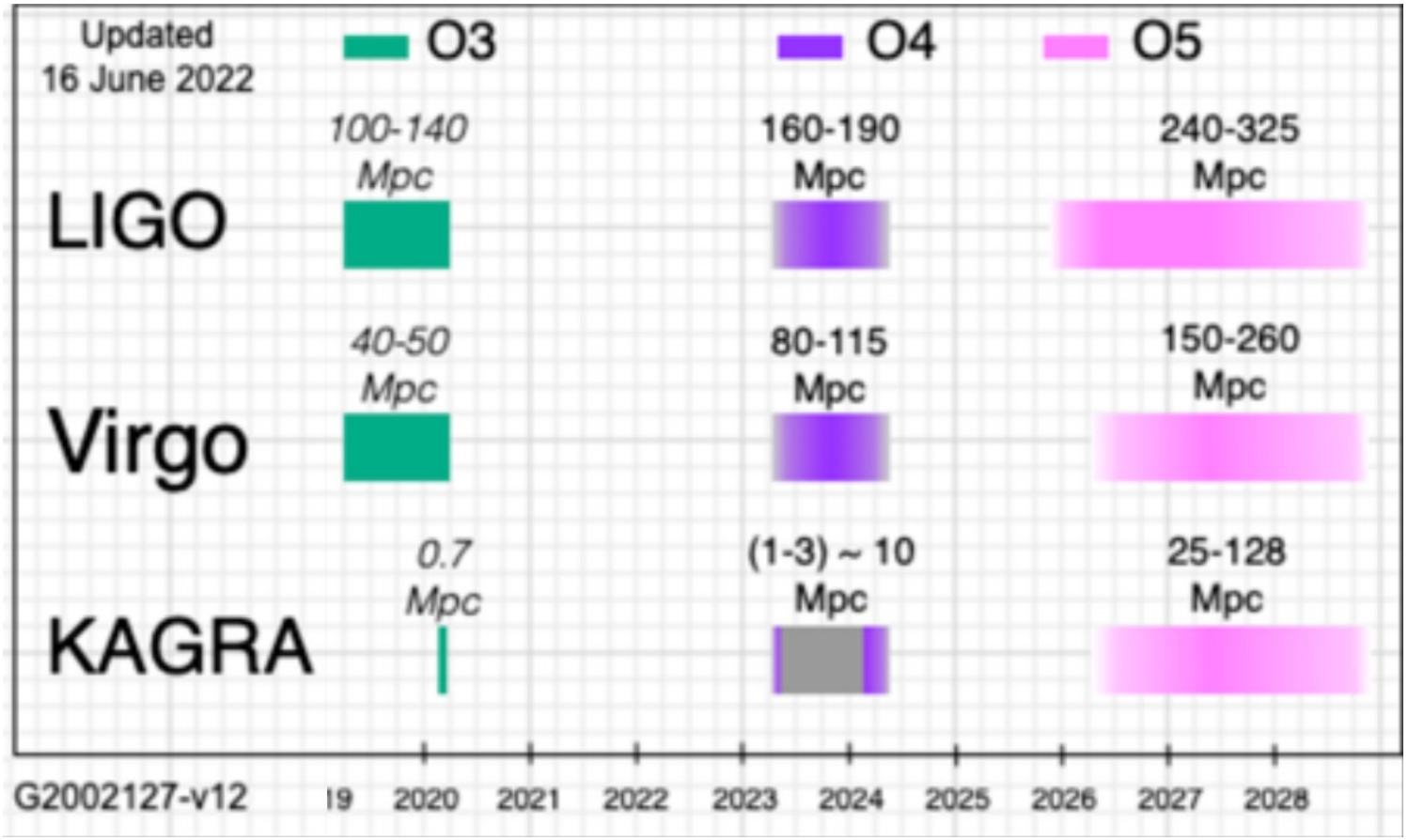
Yang, Bartos, Fragione, Haiman, Kowalski, Marka, Perna, Tagawa+ ApJ Lett 2021

Expected multi-messenger output and prospects for detection in the next 10 years?

Number of gravitational wave observations with LIGO/Virgo/KAGRA will expand significantly in next 10 years (LIGO-G2002127).

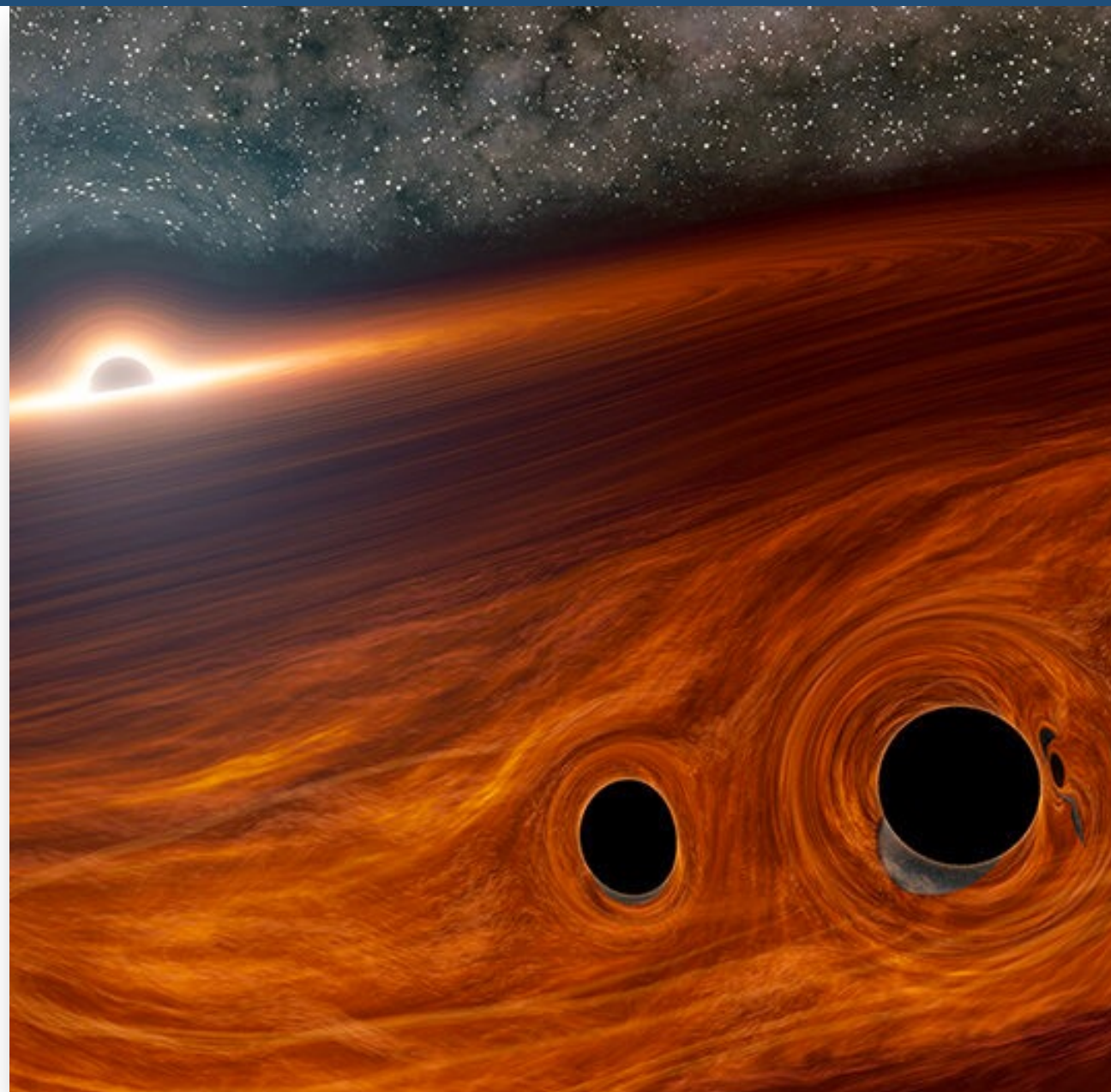
$\sim 20\%$ of black hole mergers might be from AGNs (Gayathri+ ApJ Lett. 2021).

Broad optical/EM follow-up of these events as well as the large number of discovered TDEs will probe what happens in AGNs.



Summary

- AGN disks are expected to collect/produce stellar mass black holes, stars and neutron stars.
- These stellar objects within the disk interact with the disk and each other to produce transients, as well as possibly long-term, multi-messenger emission.
- We may have already detected black hole mergers and micro-TDEs occurring in AGN disks.
- Interference with disk also possible (disk depletion in small SMBH mass AGNs; X-ray quasi periodic eruptions, etc.)
- Exciting multi-messenger possibilities with improving and new facilities.
- Our understanding of stellar graveyards in AGN disks is still in its infancy. Lot of interesting open questions to study.



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