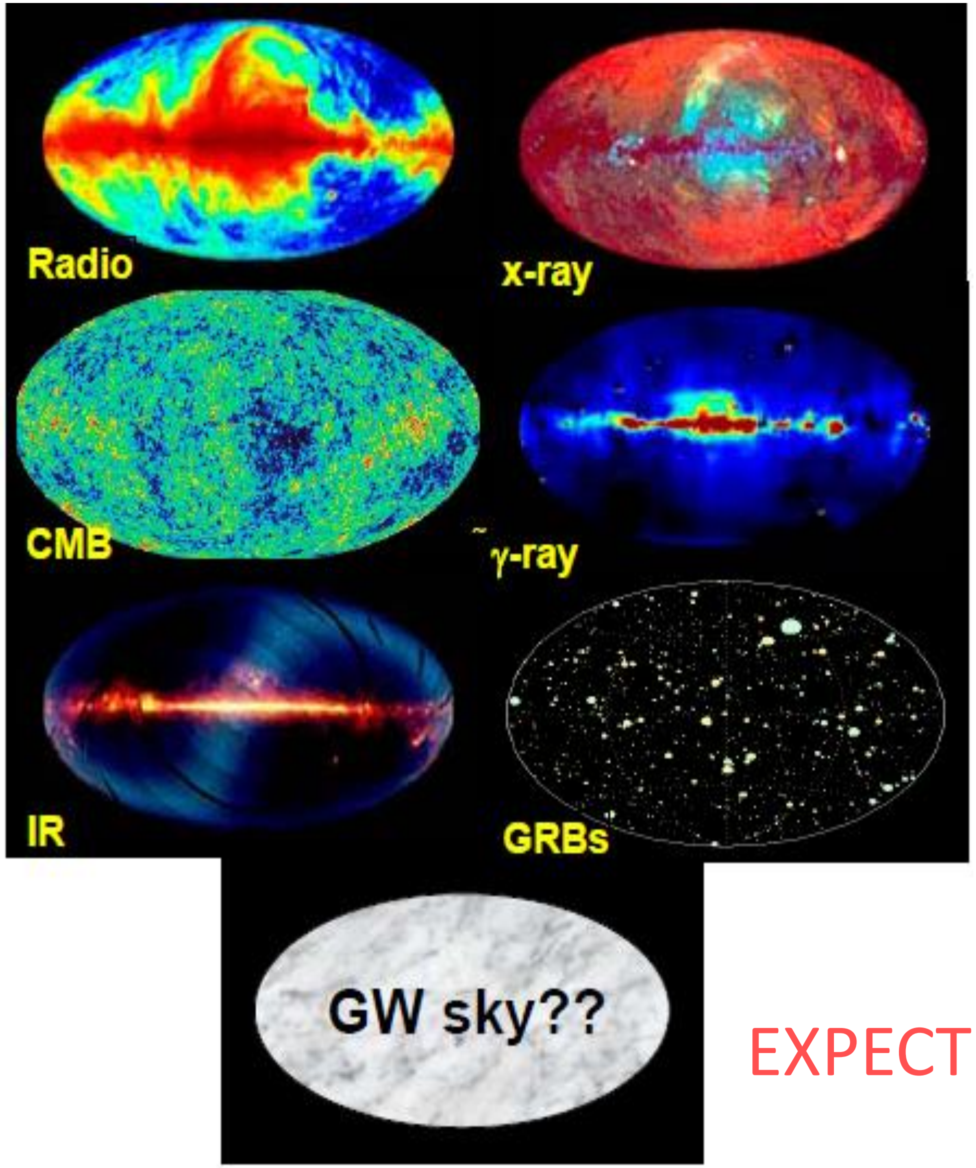
Searching for the origin of black hole mergers in the Universe with gravitational waves

credit: ESA/Hubble/N. Bartmann

Bence Kocsis (University of Oxford)

Morning of Theoretical Physics, Oxford, 28 October 2023

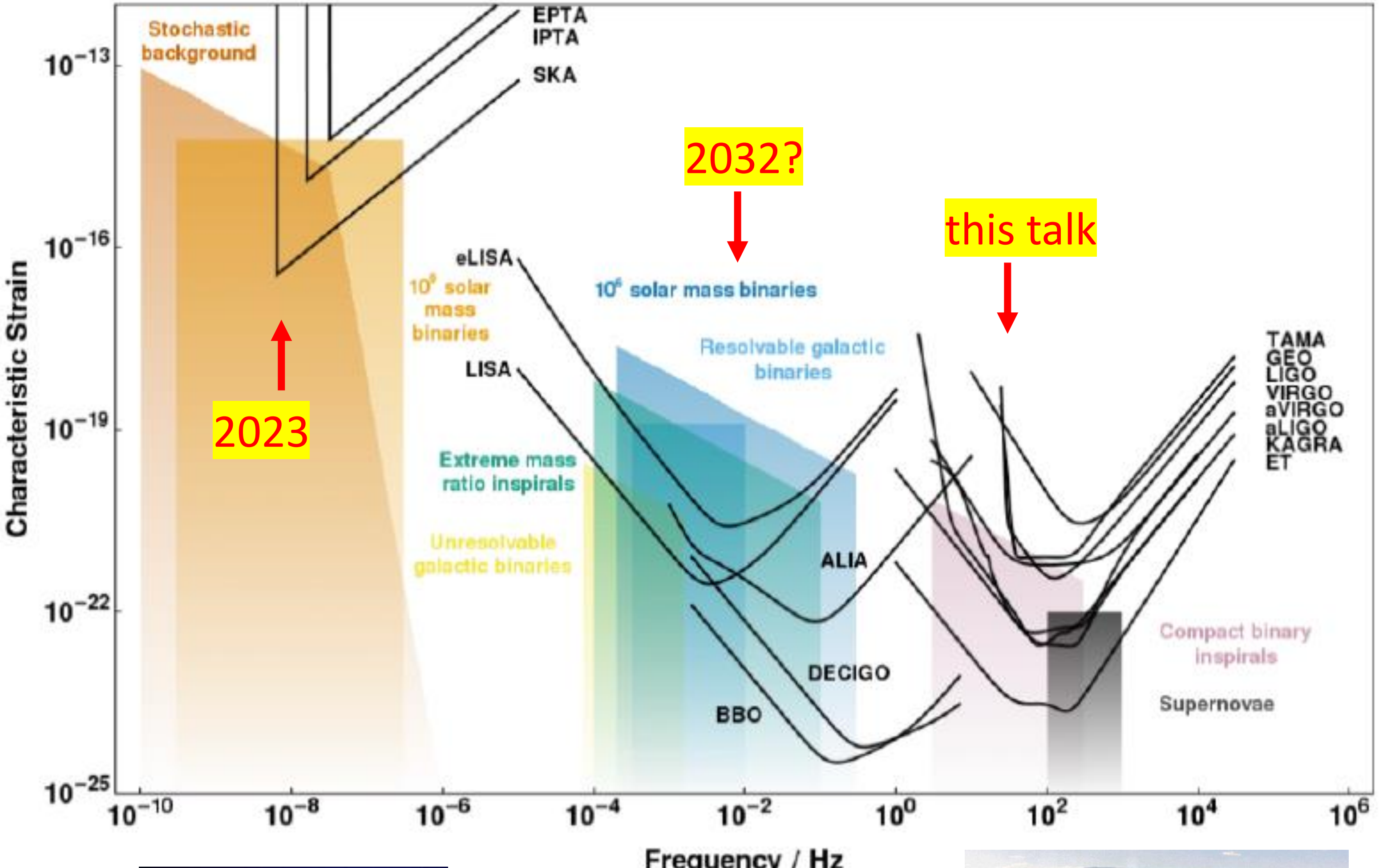
The Dawn of GW astronomy



1. Status of discoveries
2. Astrophysical models for sources
    - with problems
3. New ideas to explain sources

EXPECT THE UNEXPECTED!

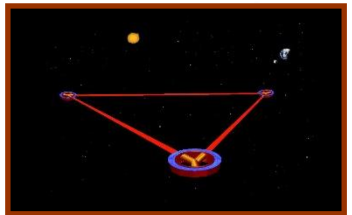
Gravitational wave detectors

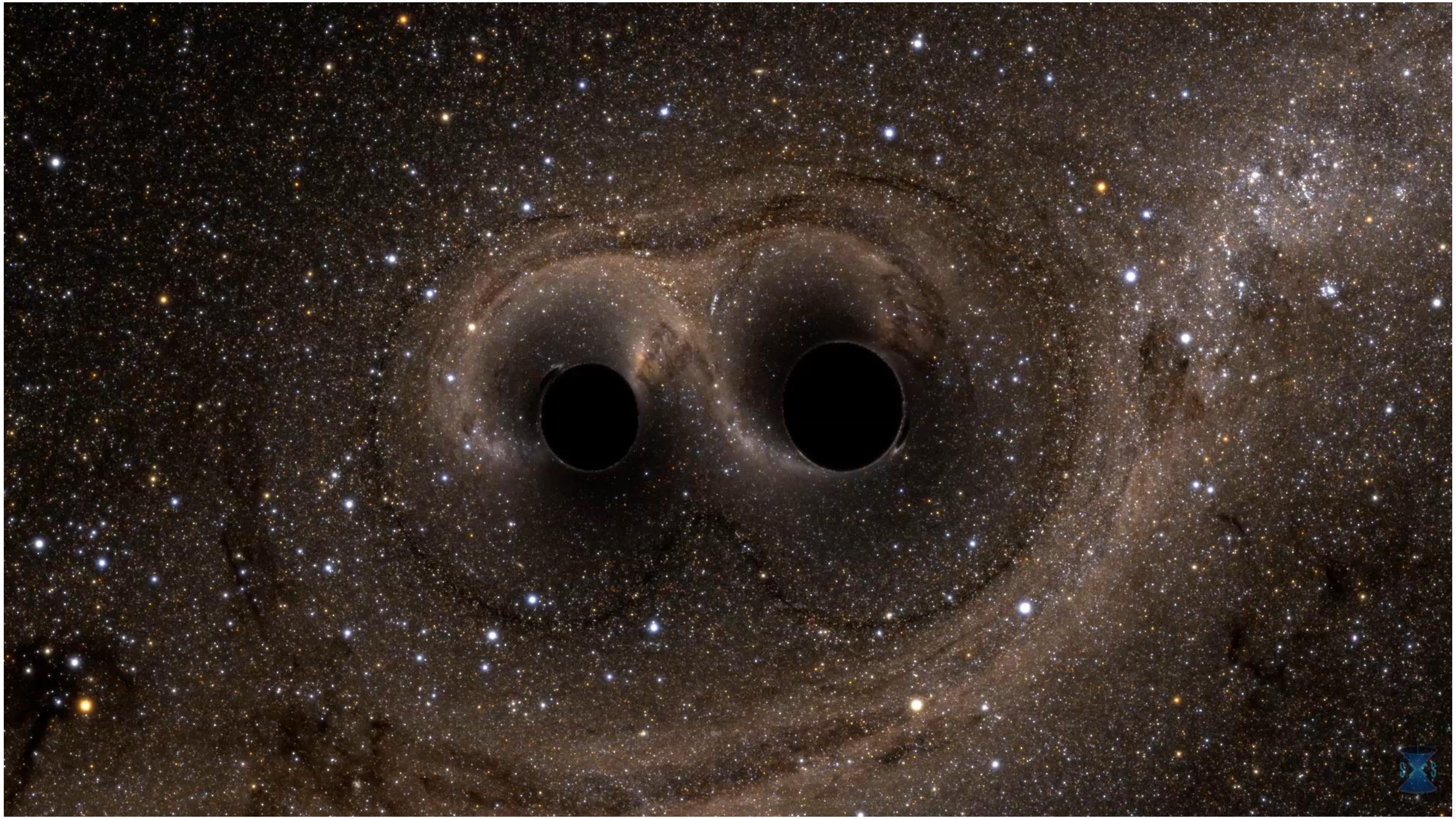


2032?

this talk

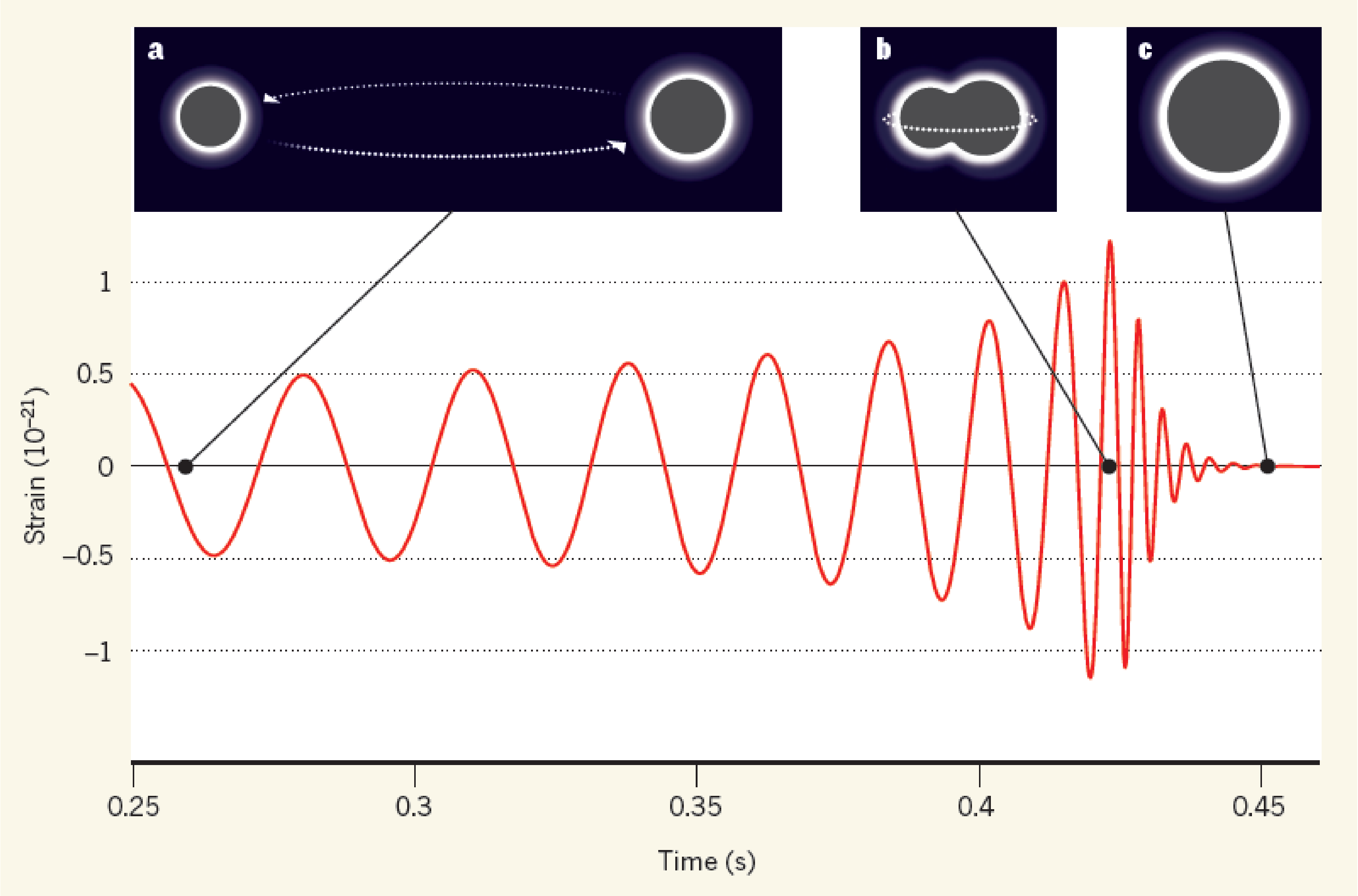
2023

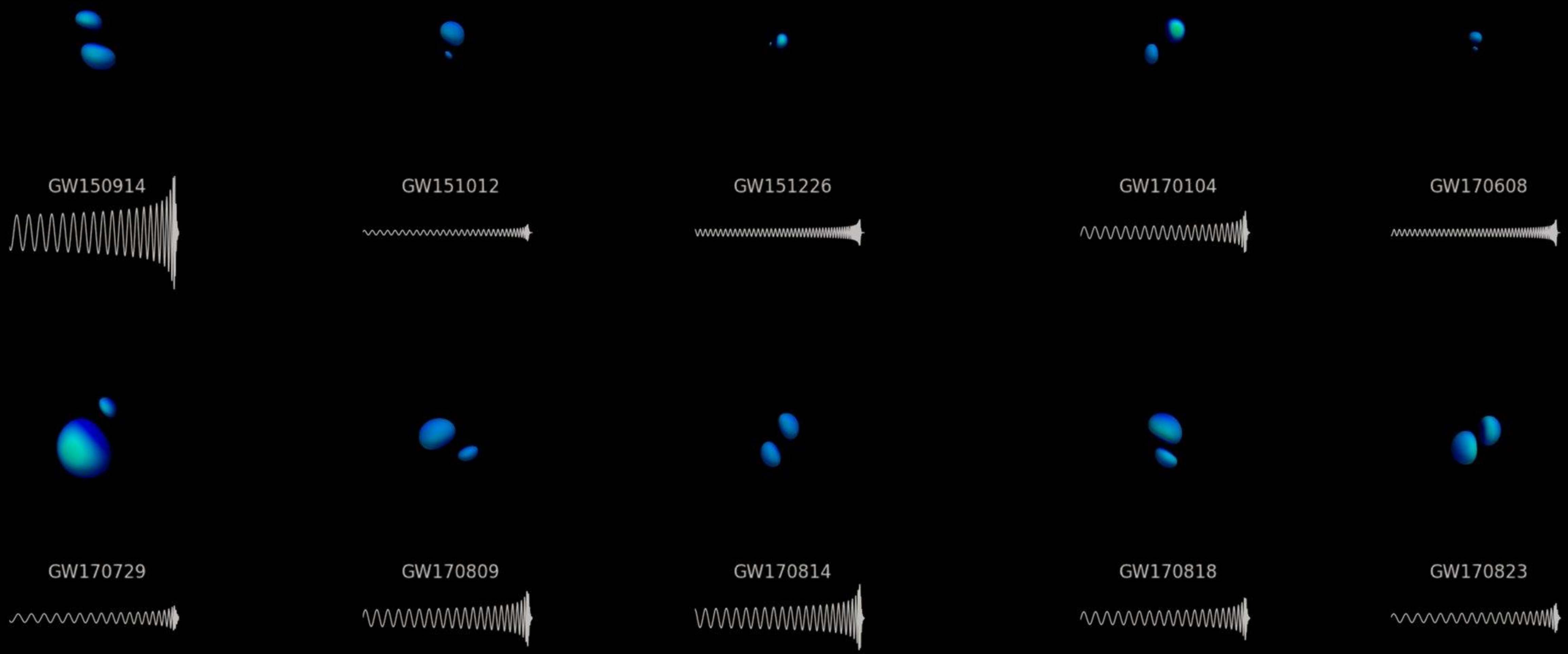
https://www.youtube.com/watch?v=I_88S8DWbcU

Credit: LIGO, Simulating eXtreme Spacetimes

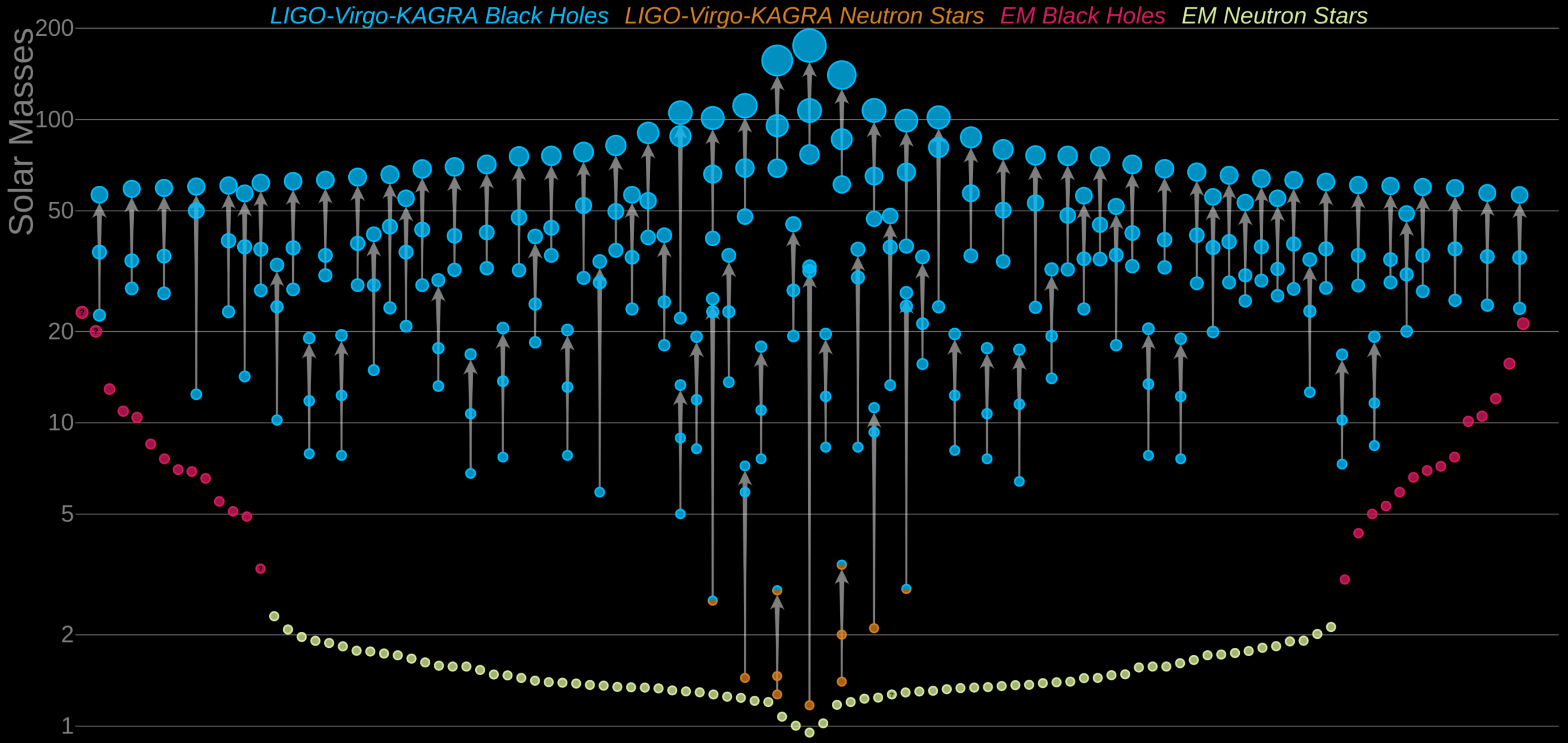


Miller, Nature, 531, 40 (2016)

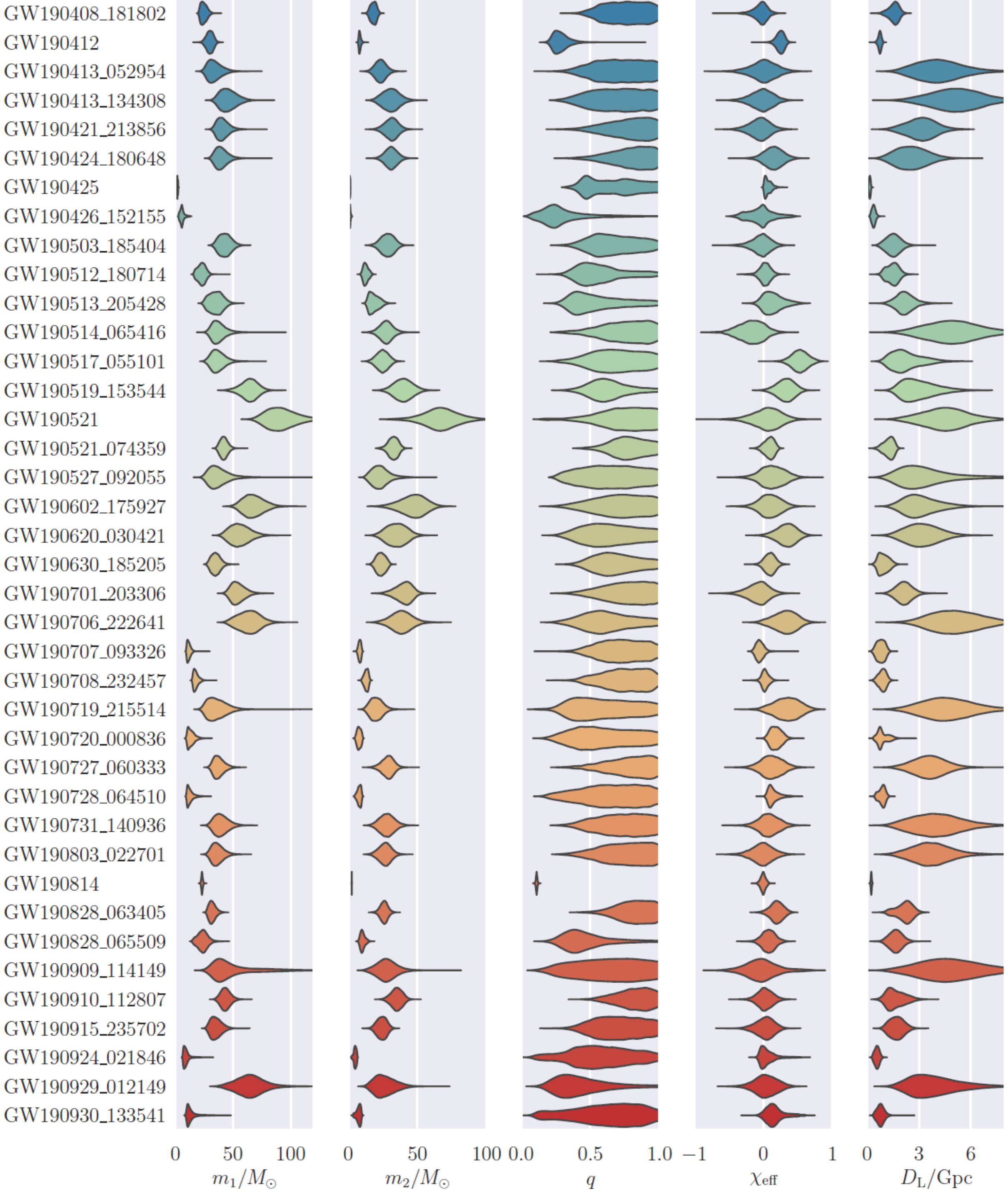
LIGO VIRGO


GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170818
GW170823

Masses in the Stellar Graveyard

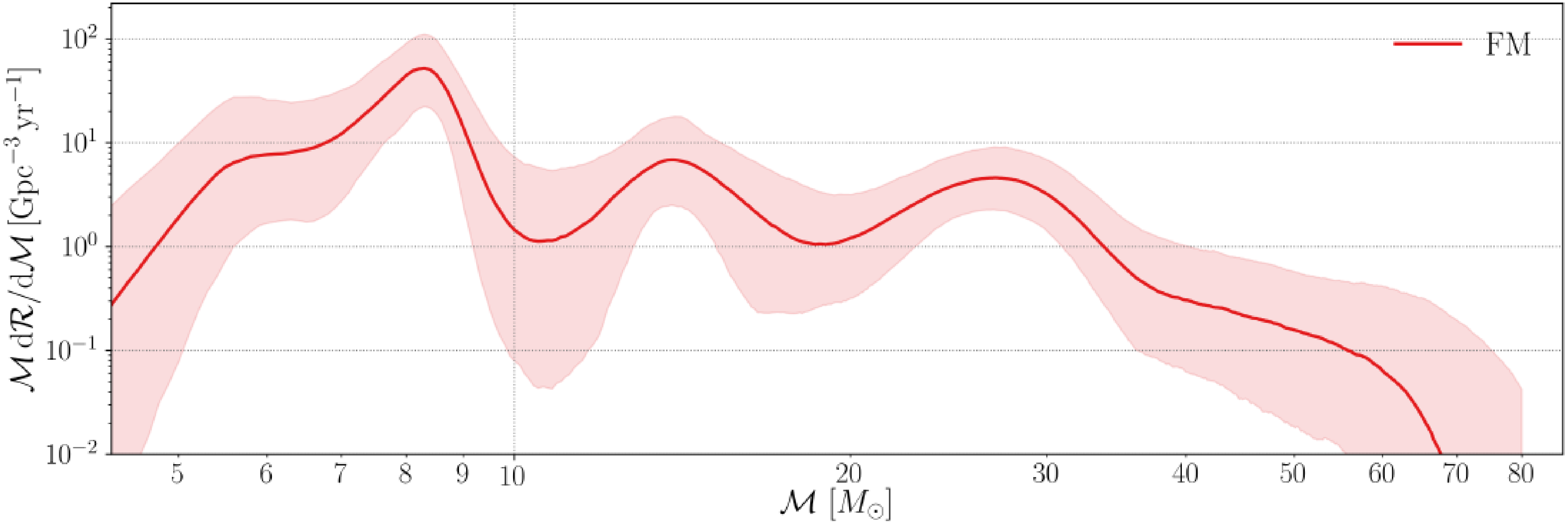


LIGO-Virgo-KAGRA | Aaron Geller | Northwestern



LIGO/VIRGO Collaboration
2111.03634

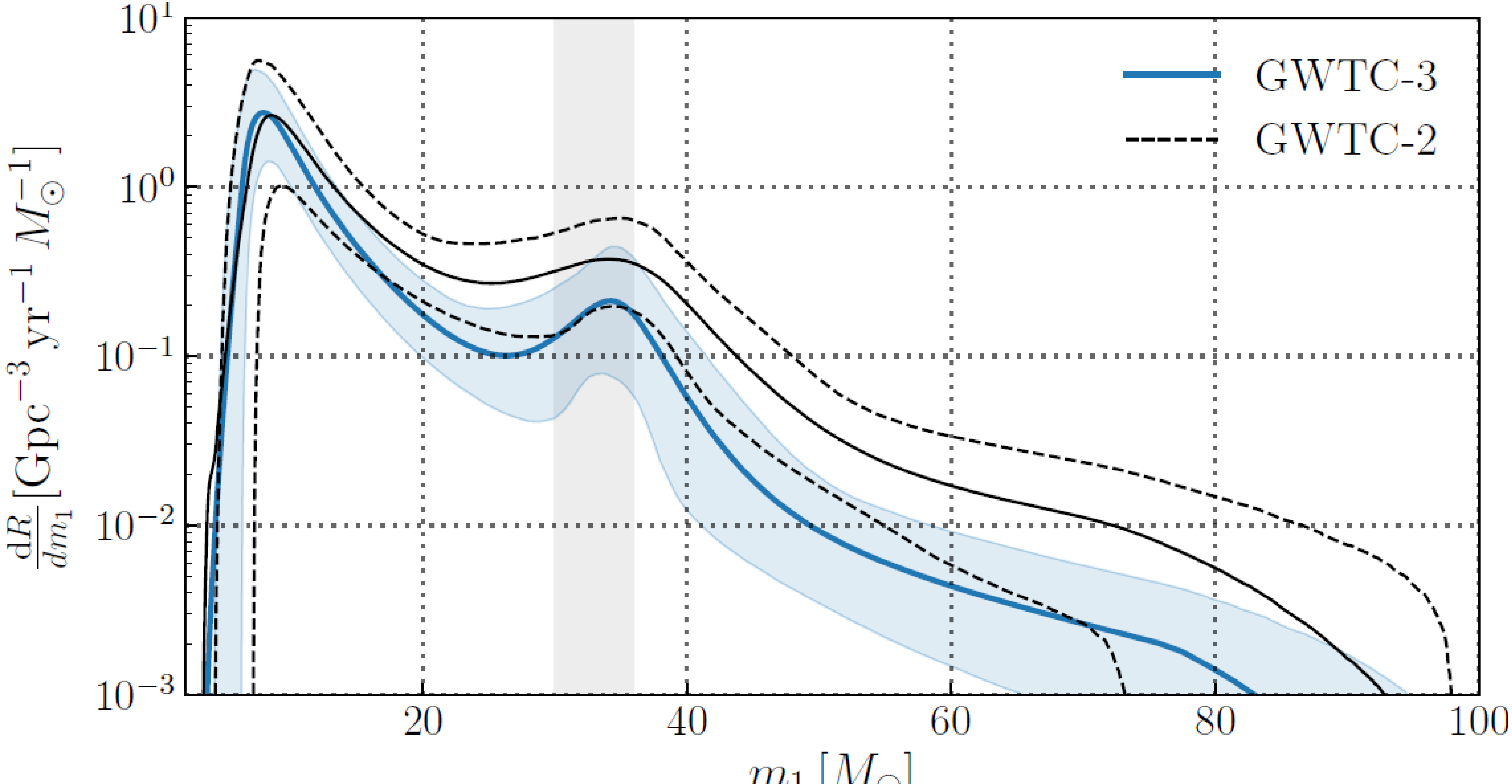
Black hole mass distribution



LIGO/VIRGO Collaboration
arxiv:2111.03634

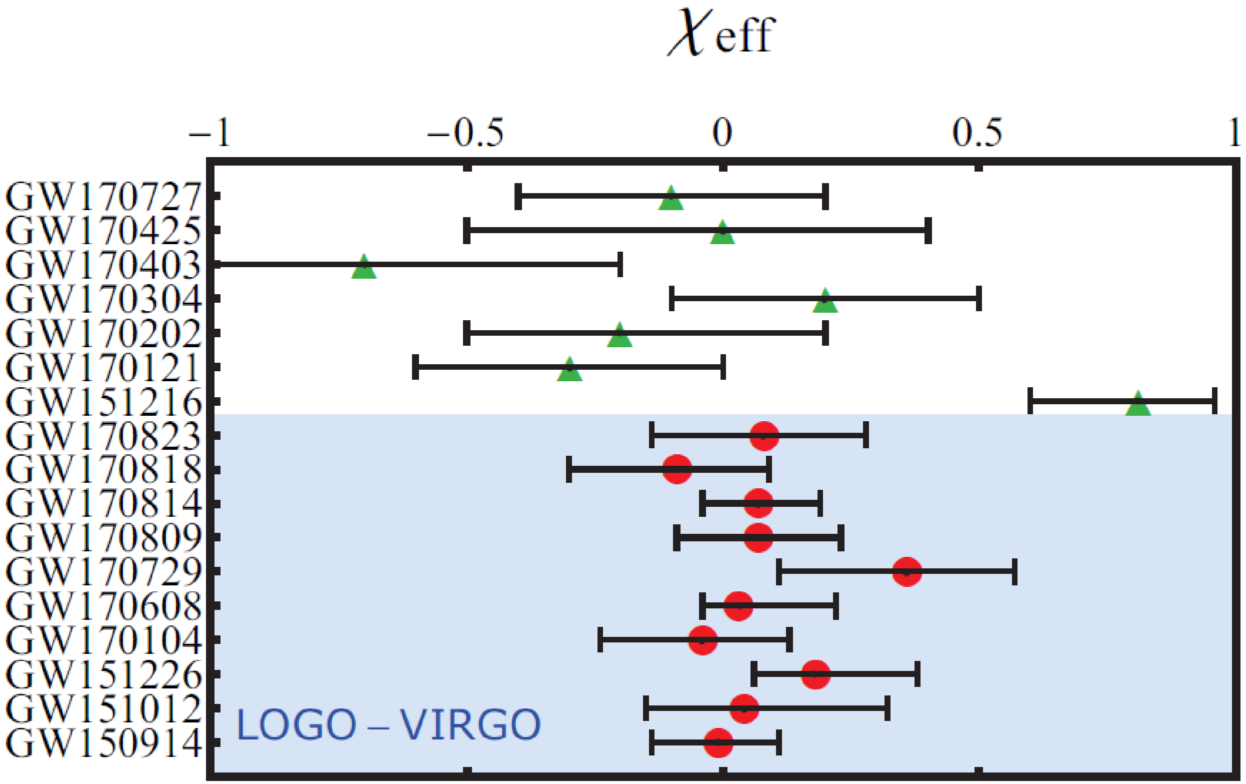
Very top heavy!

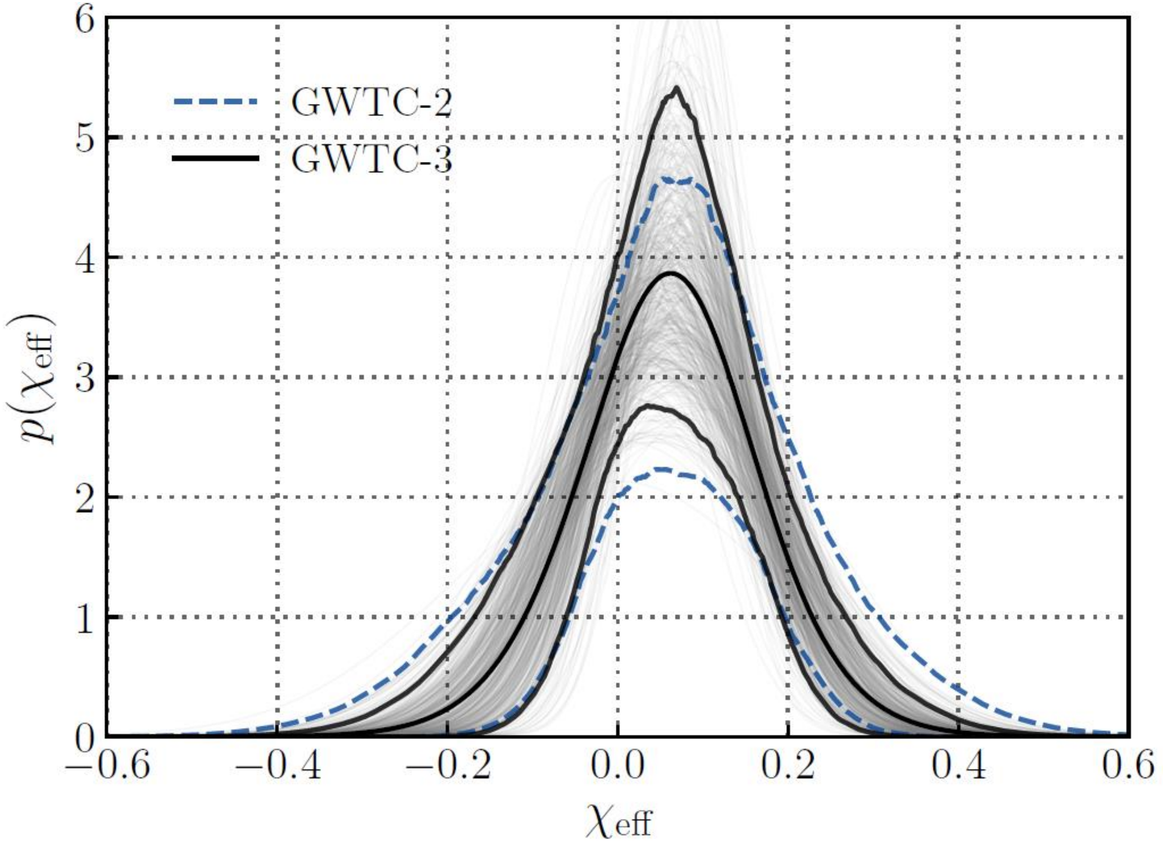
Primary black hole mass



Spins

$$\chi_{\rm eff} = \frac{(m_1\chi_1\cos\theta_1 + m_2\chi_2\cos\theta_2)}{M}$$





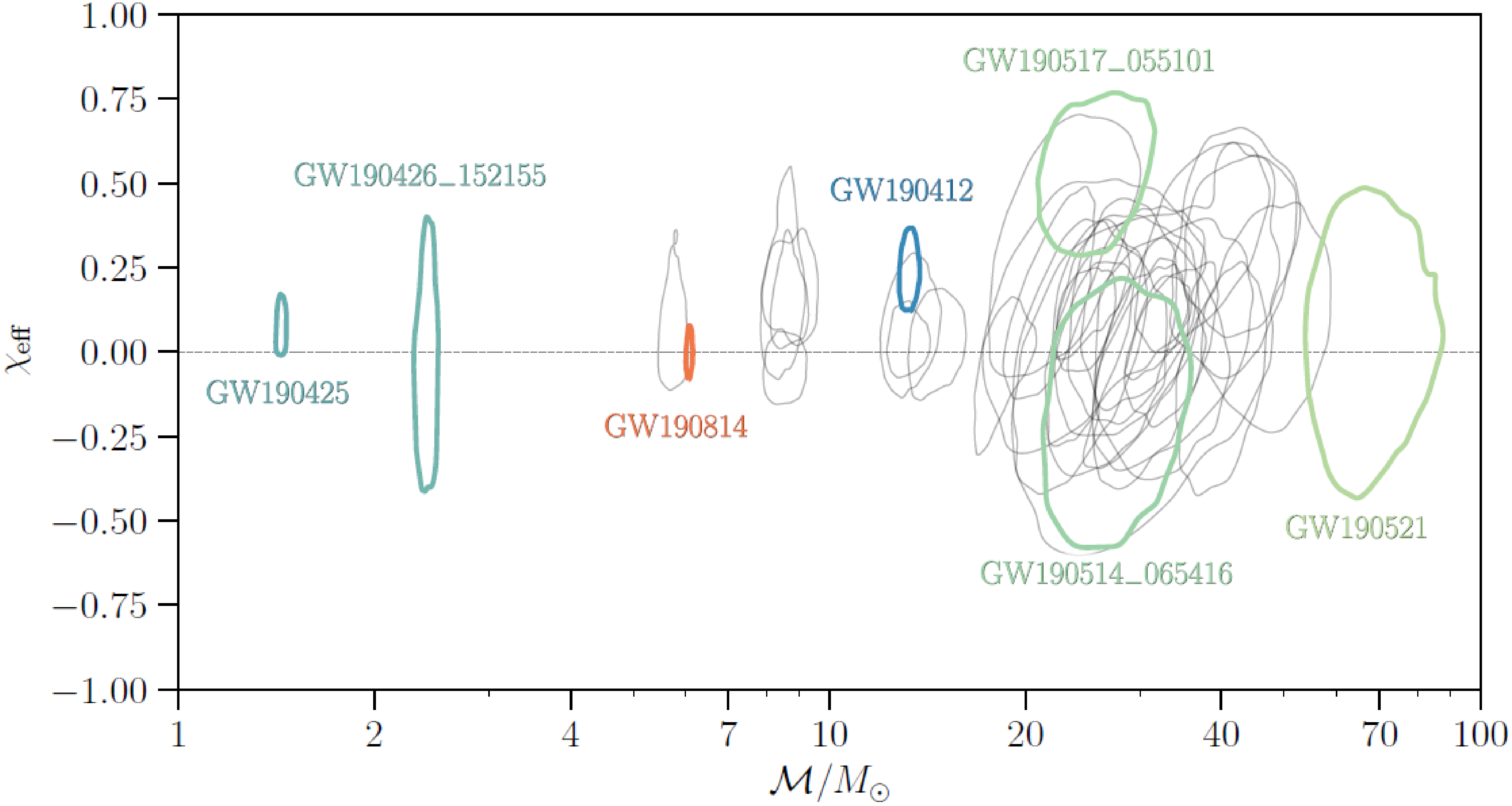
clustered around zero!

LIGO/VIRGO Collaboration 2021;
Zackay+ 2019, Venumadhav+ 2019

LIGO/VIRGO Collaboration
arxiv: 2111.03634

Mass vs. spins

$$\chi_{\mathrm{eff}} = \frac{(m_1\chi_1 \cos\theta_1 + m_2\chi_2 \cos\theta_2)}{M}$$



LIGO/VIRGO Collaboration arxiv:2010.14533

Rate of BH-BH coalescence

GW150914+LVT151012:

2 – 600 Gpc $^{-3}$ yr $^{-1}$

+2 new BH/BH detections (O1)

12 – 213 Gpc $^{-3}$ yr $^{-1}$

+7 new BH/BH detections (O2) :

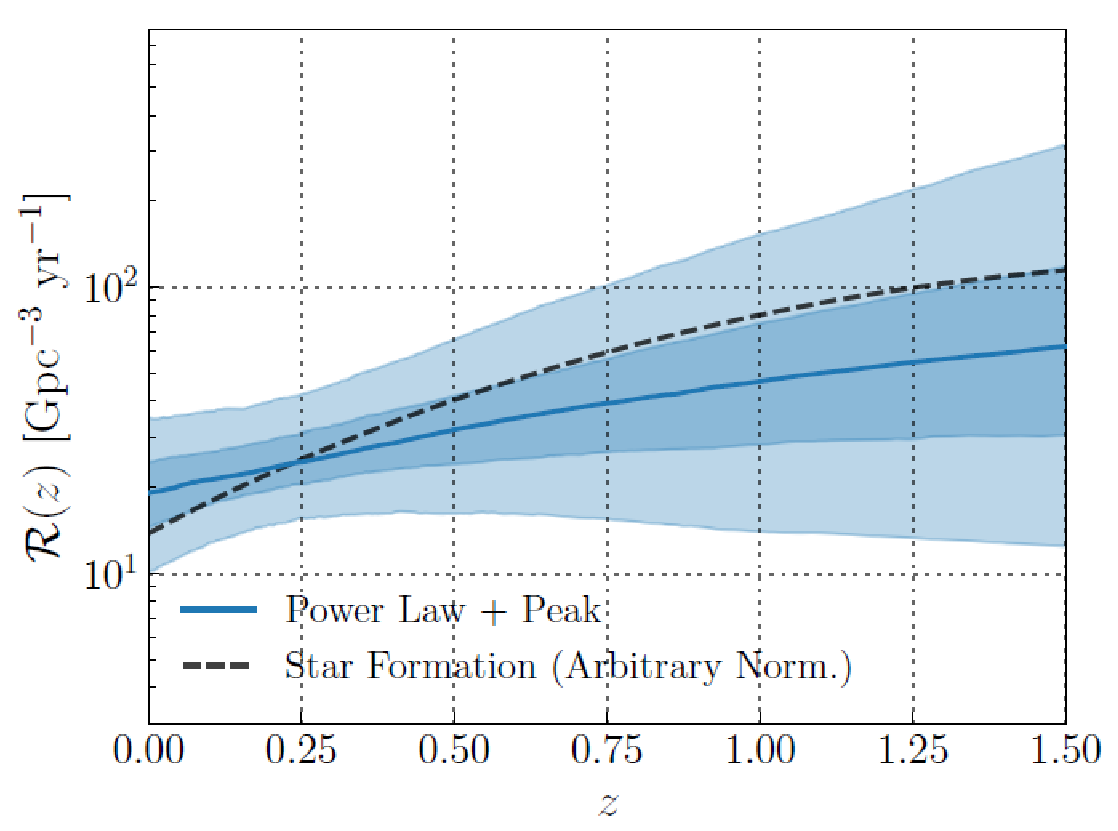
29 – 100 Gpc $^{-3}$ yr $^{-1}$

+37 new BH/BH detections (O3a) :

15 – 39 Gpc $^{-3}$ yr $^{-1}$

+38 new BH/BH detections (O3b) :

17 – 45 Gpc $^{-3}$ yr $^{-1}$



LIGO/VIRGO Collaboration arXiv:2010.14533

Rate of NS-NS coalescence

GW170608 (O2):

300 – 4700 Gpc $^{-3}$ yr $^{-1}$

+GW190425 (O3a) (O3b):

80 – 810 Gpc $^{-3}$ yr $^{-1}$ 13 – 1900 Gpc $^{-3}$ yr $^{-1}$

Rate of BH-NS coalescence

5 events (O3)

7 – 320 Gpc $^{-3}$ yr $^{-1}$

Future prospects

17 – 45 Gpc $^{-3}$ yr $^{-1}$ implies

- **1-3 mergers/day** within **z=0.5**
- **1-3 mergers/hour** within **z=2**

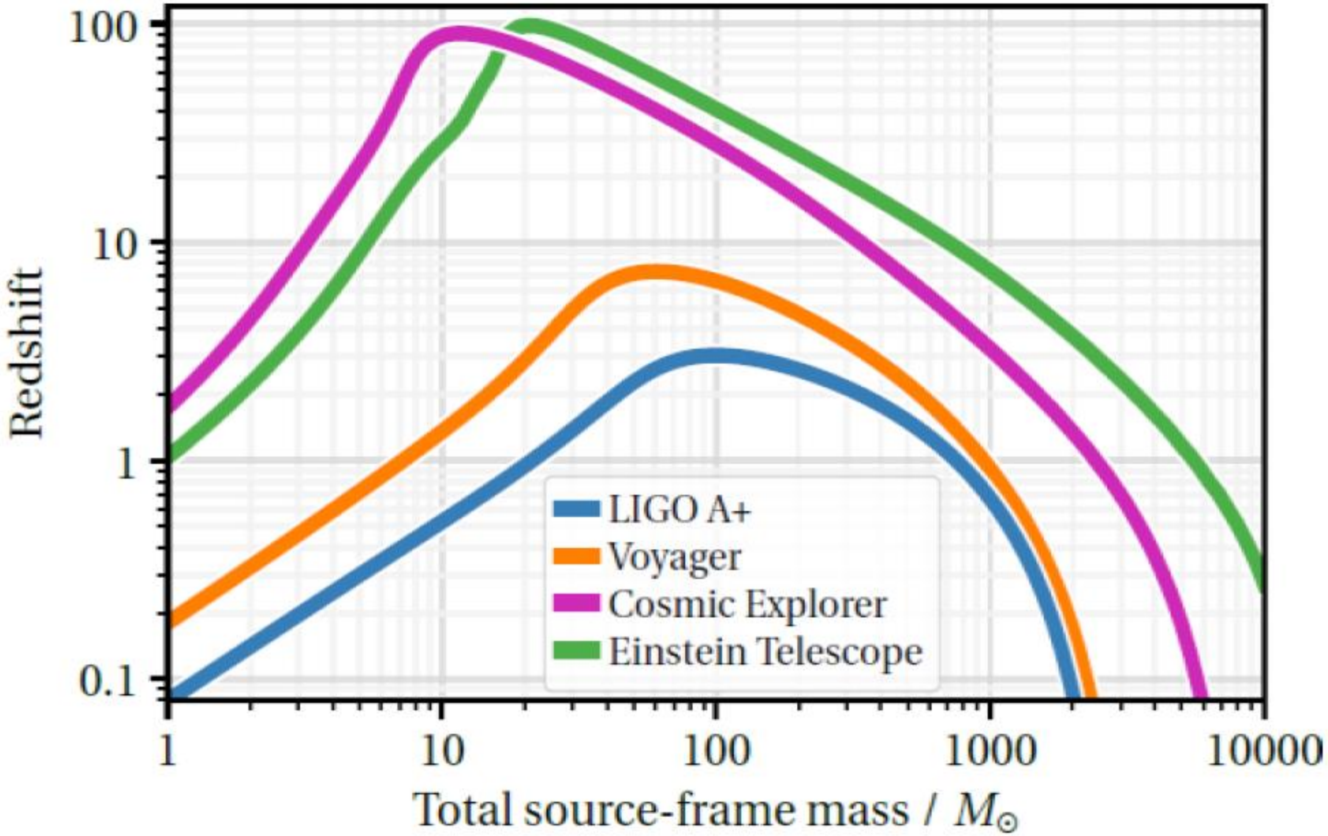
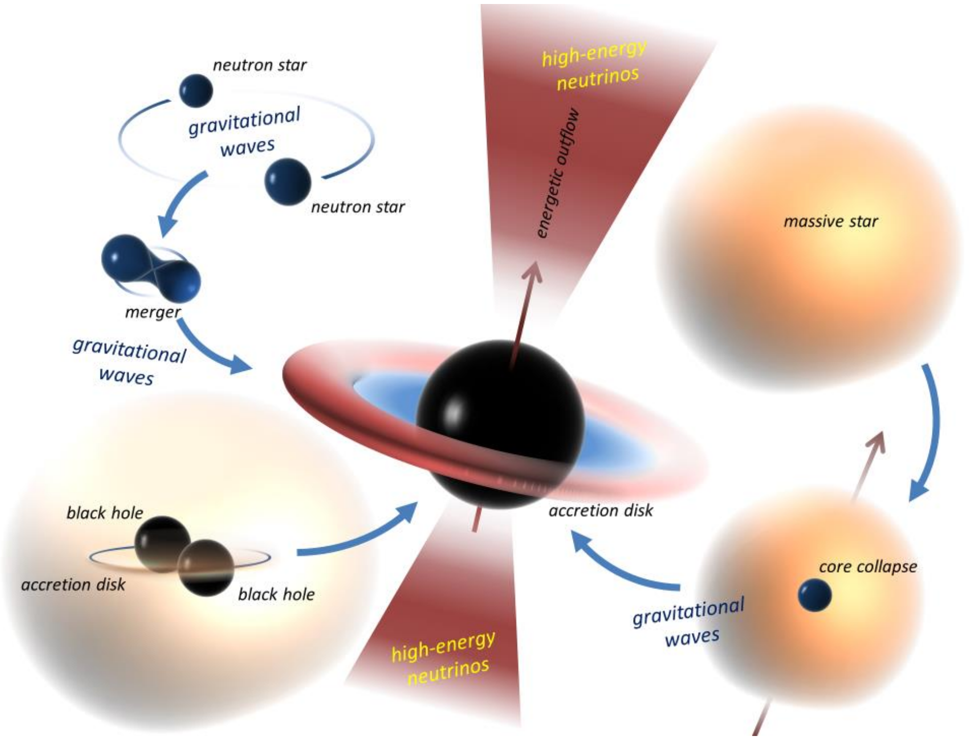
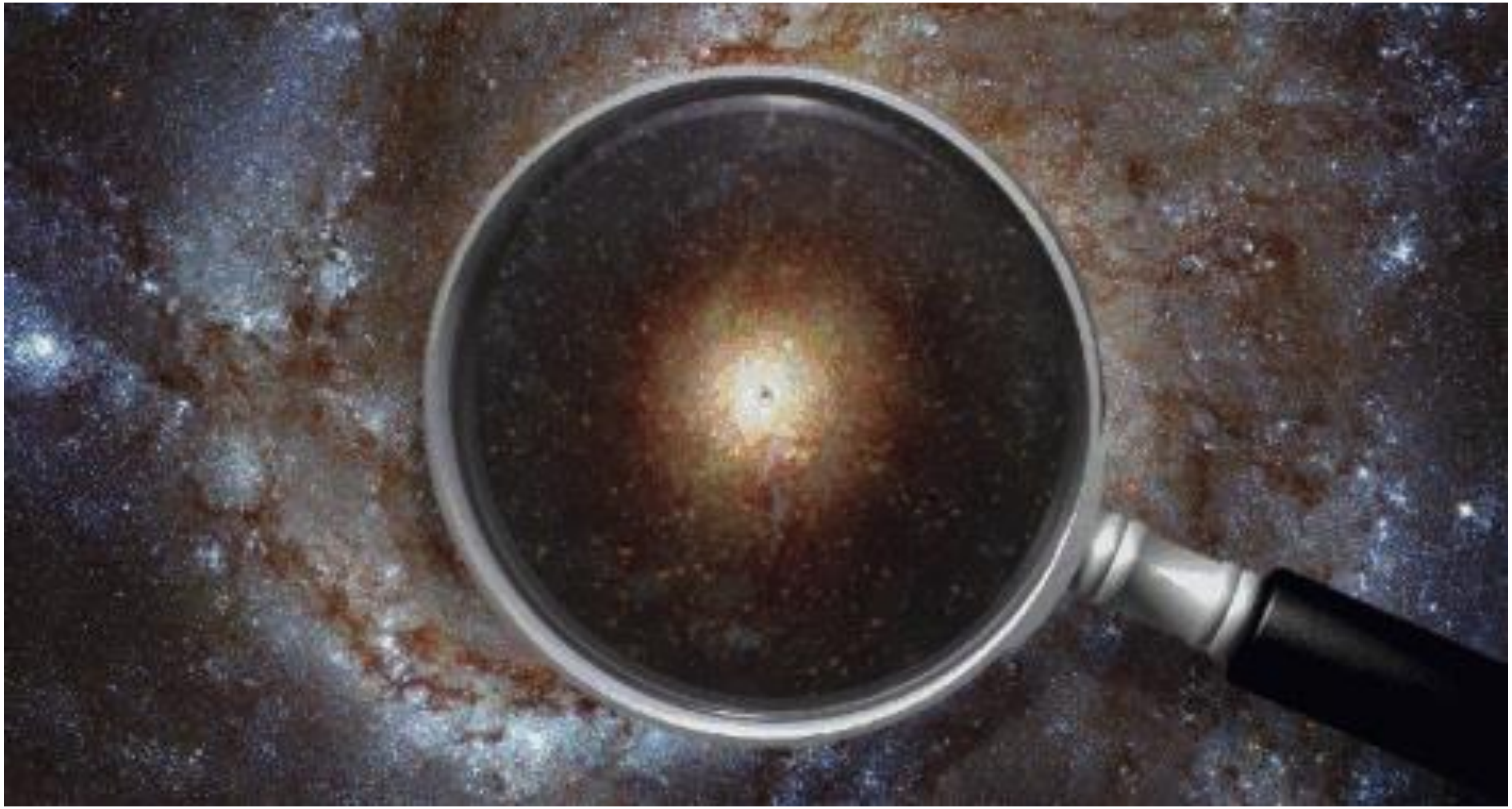


Figure 1: Redshift range of upcoming GW instruments (adapted from Ref. [3]).

Zeroth order questions

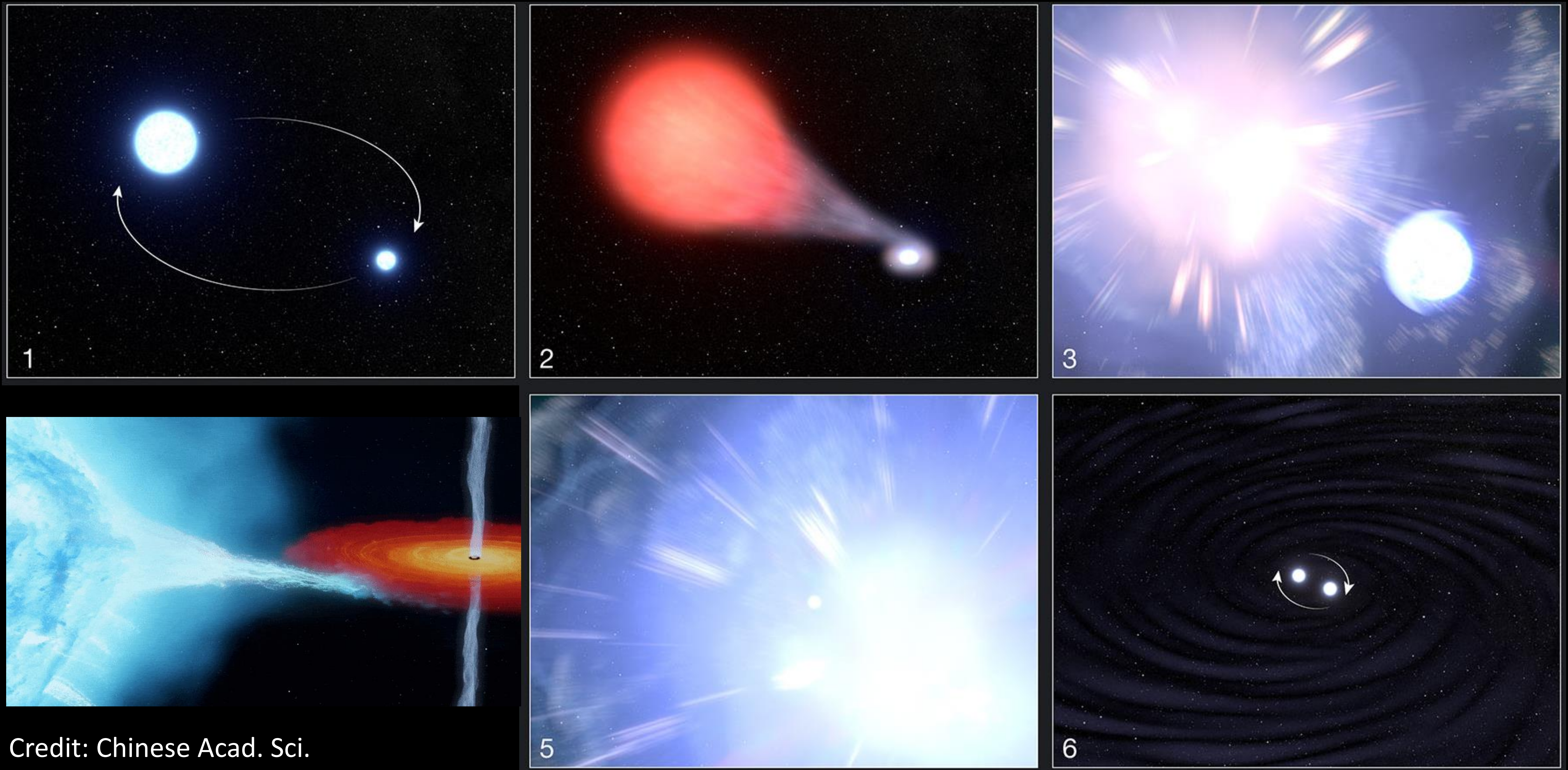
- What astrophysical process is responsible for the observed mergers?
  - How did the black holes form?
  - How did the binary form?
  - How did it reach merger?
  - What are the most likely environments for mergers?
    - Galactic disk, galactic bulge, star clusters (e.g. globular cluster), halo?





Astrophysical origin of mergers

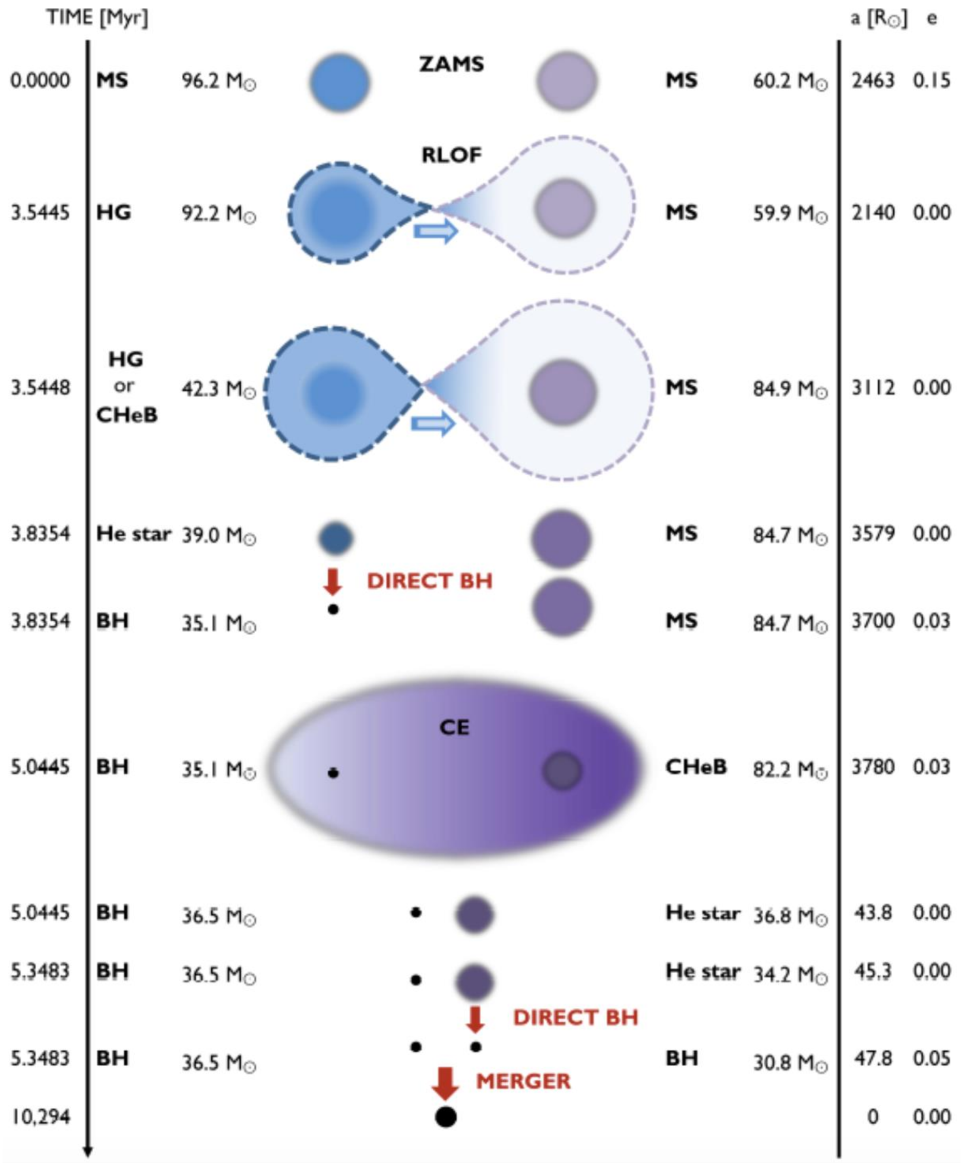
How do black holes form a binary?



Credit: Chinese Acad. Sci.

How do black holes form a binary and merge

Option 1: stellar binary evolution

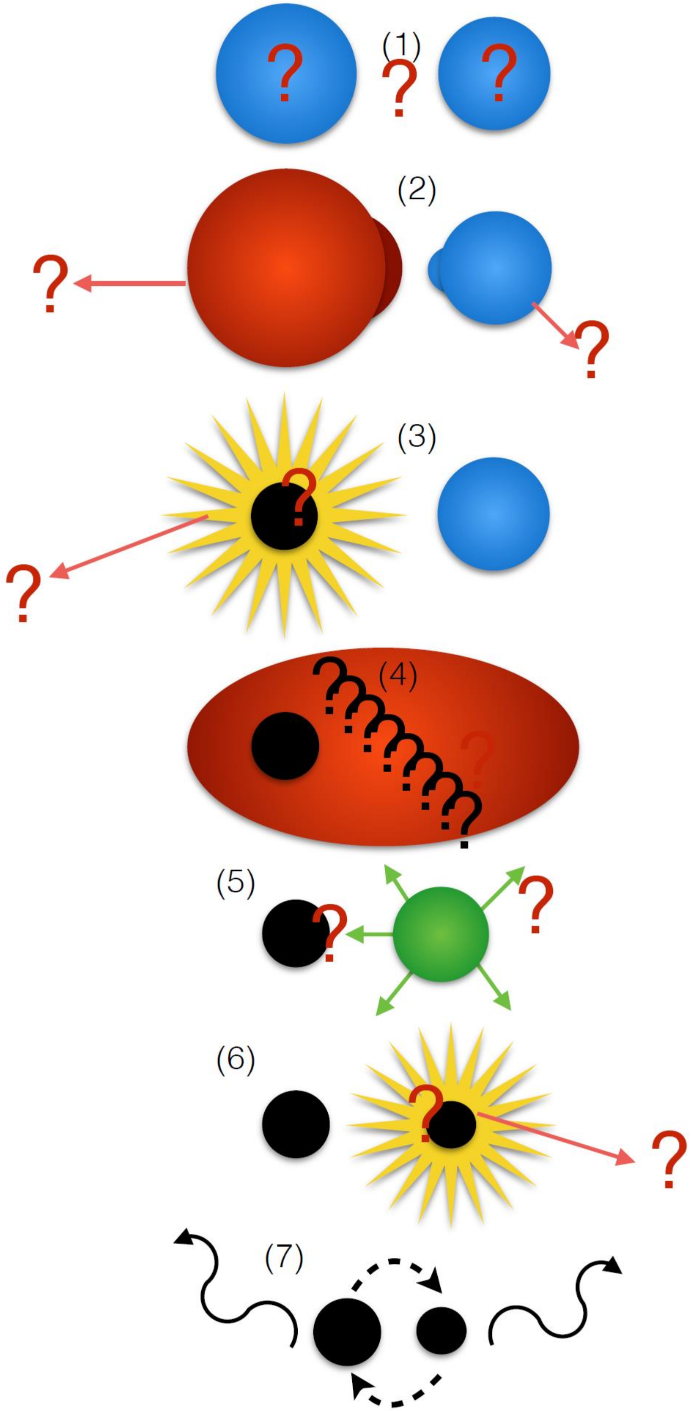


Galactic binaries

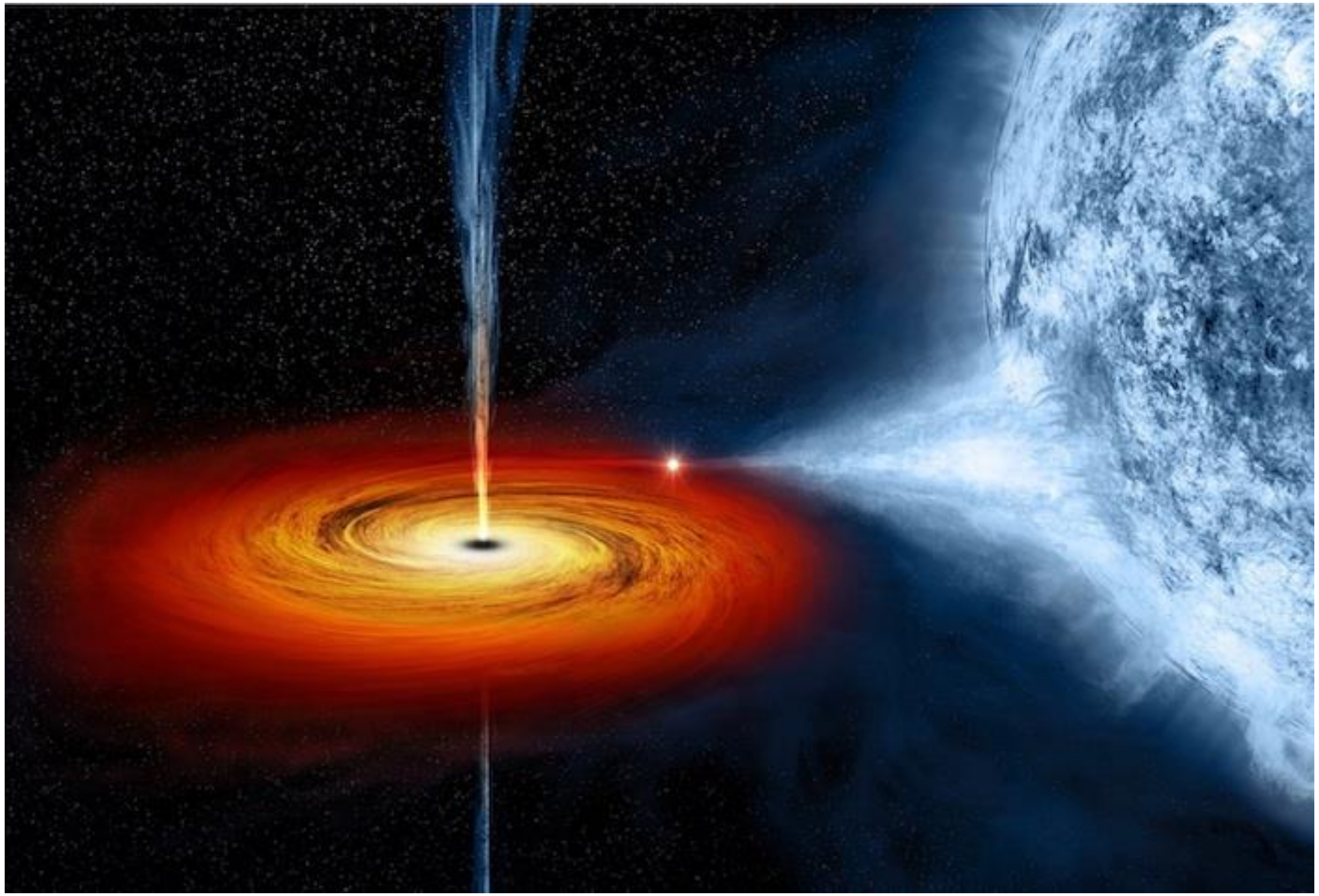
- 10^{11} stars in a Milky Way type galaxy
- 10^{7-8} stellar mass black holes
- Most massive stars are in (wide) binaries
    - 25% in triples

Belczynski+ (2016)

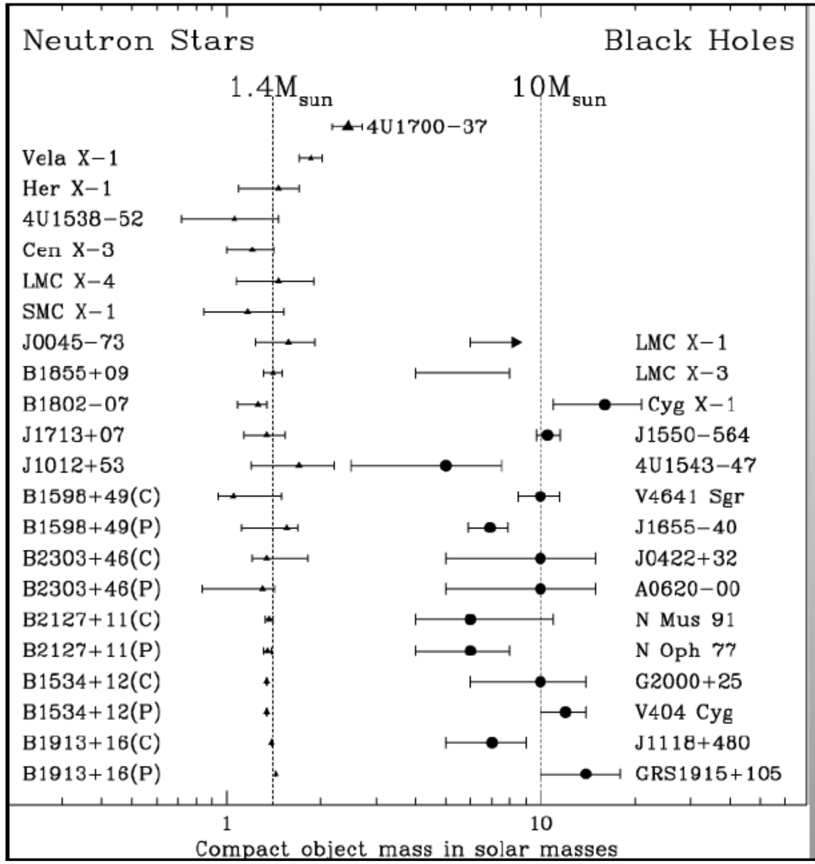
Open questions



Problem 1a: Why are the merging black holes so massive?

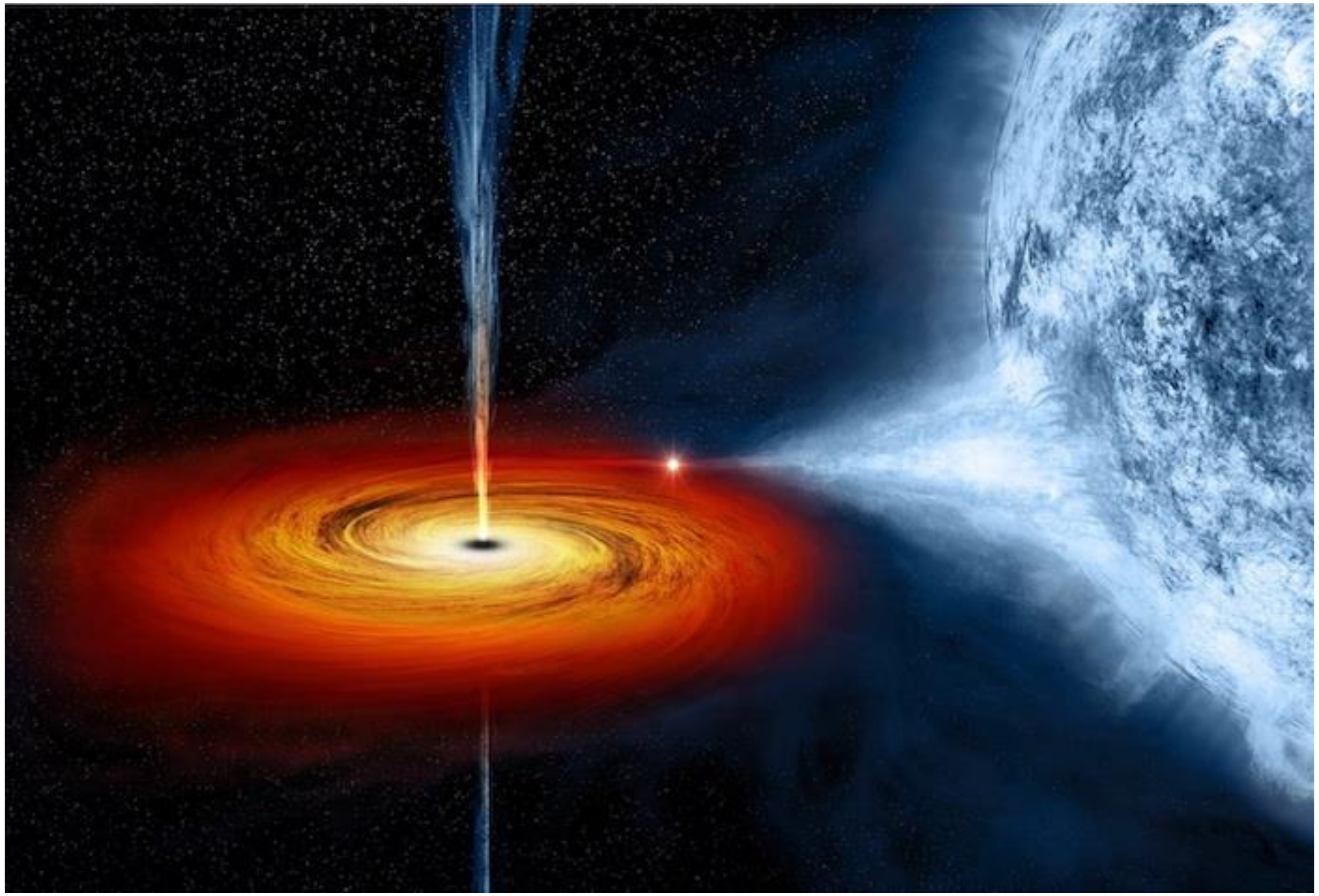


Observed masses in X-ray binaries

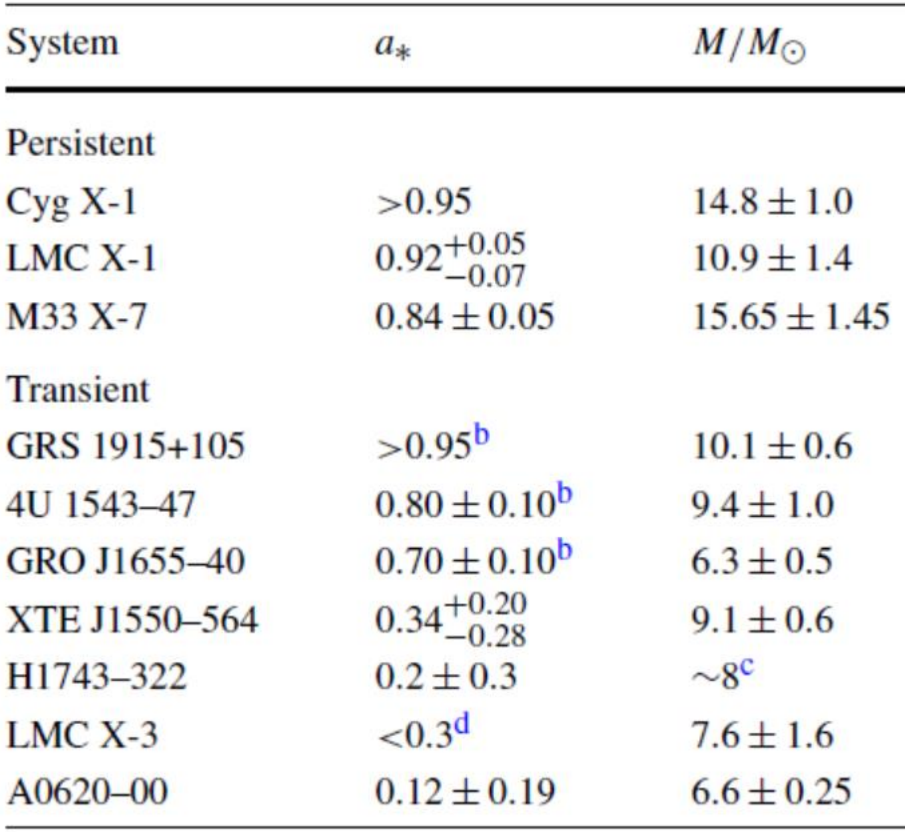


About 20 binaries in our galaxy where the compact object seems to be too massive to be a neutron star

Problem 1b: Why are the merging black holes not spinning?

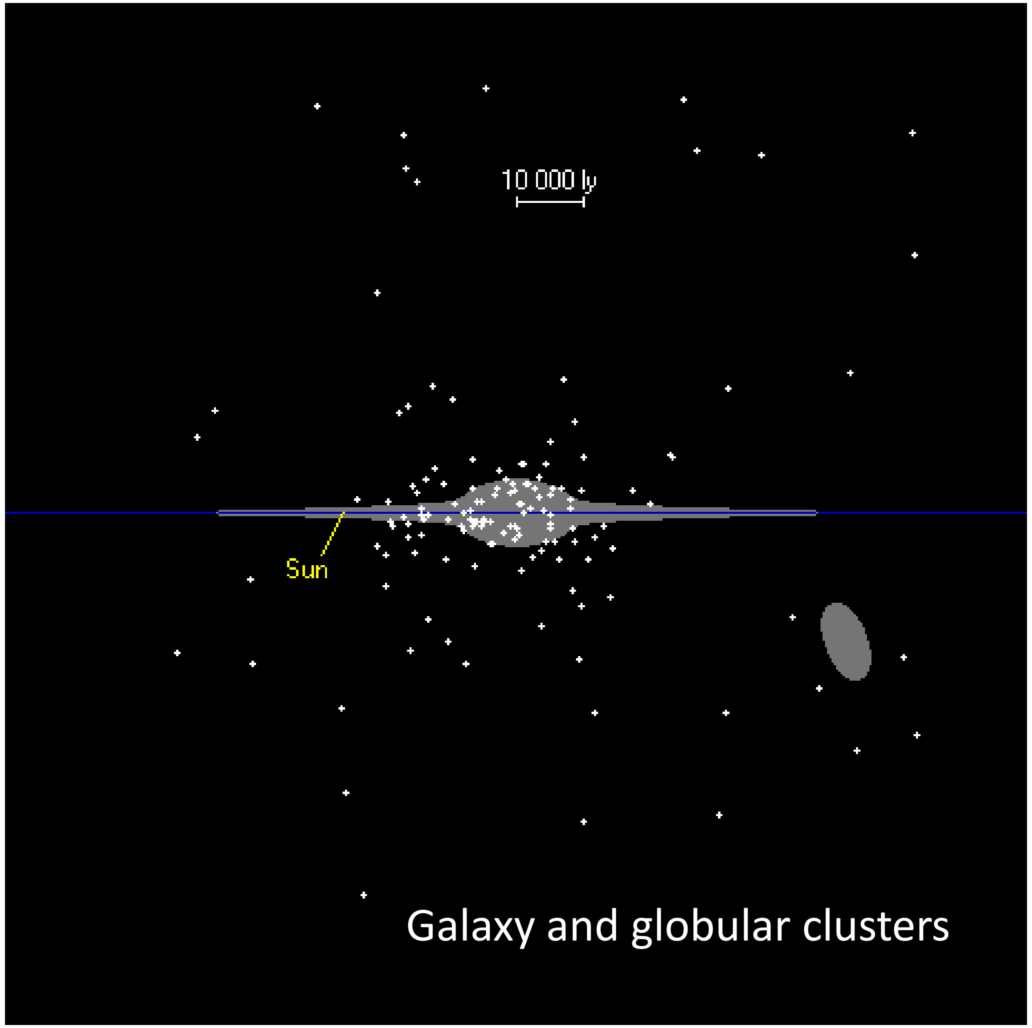


Observed spins in X-ray binaries



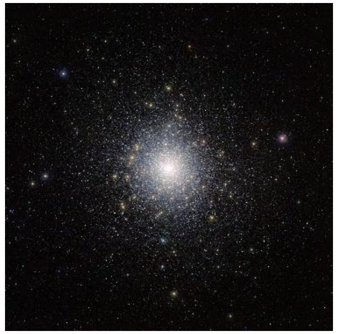
System	a_*	$M/M_\odot$
Persistent		
Cyg X-1	>0.95	14.8 ± 1.0
LMC X-1	$0.92^{+0.05}_{-0.07}$	10.9 ± 1.4
M33 X-7	0.84 ± 0.05	15.65 ± 1.45
Transient		
GRS 1915+105	>0.95[b]	10.1 ± 0.6
4U 1543–47	0.80 ± 0.10[b]	9.4 ± 1.0
GRO J1655–40	0.70 ± 0.10[b]	6.3 ± 0.5
XTE J1550–564	$0.34^{+0.20}_{-0.28}$	9.1 ± 0.6
H1743–322	0.2 ± 0.3	~ 8[c]
LMC X-3	<0.3[d]	7.6 ± 1.6
A0620–00	0.12 ± 0.19	6.6 ± 0.25

Option 2: Dynamical environments



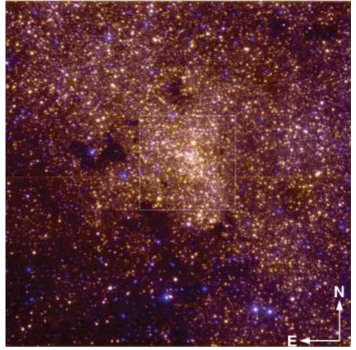
Galaxy and globular clusters

Globular clusters



- 0.5% of stellar mass of the Universe
- 100 per galaxy
- Size: 1 pc – 10 pc
- Density 10^3—10^5 x higher

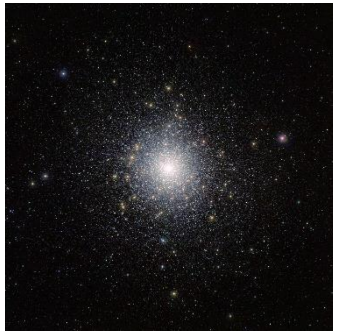
Galactic nuclei



- 0.5% of stellar mass of the Universe
- 10^{6-7} M_{sun} supermassive black hole
- 10^{4-5} stellar mass black holes
- Size: 1 pc – 10pc
- Density 10^6 – 10^{10} x higher

Option 2: Dynamical environments

Globular clusters



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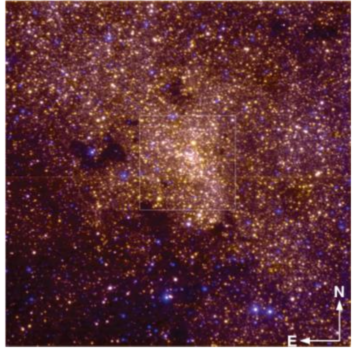

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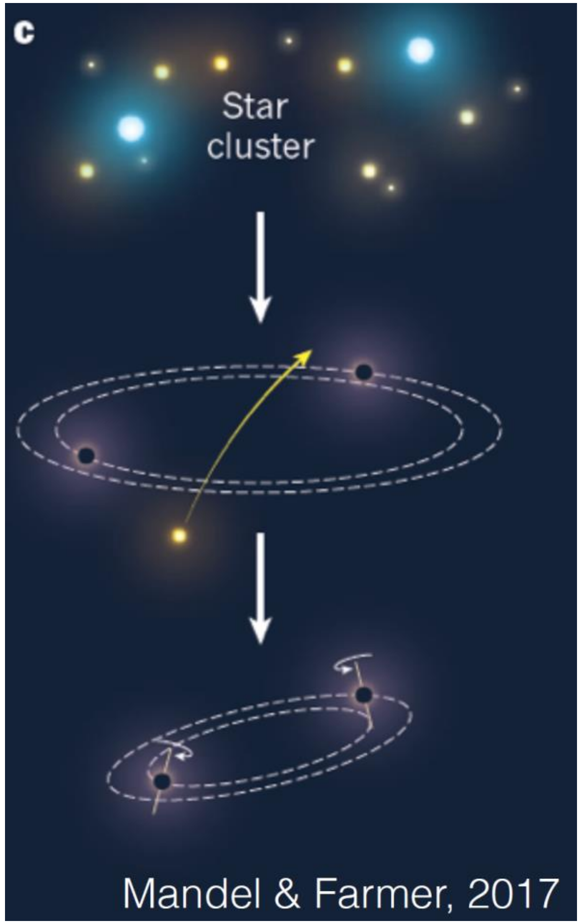
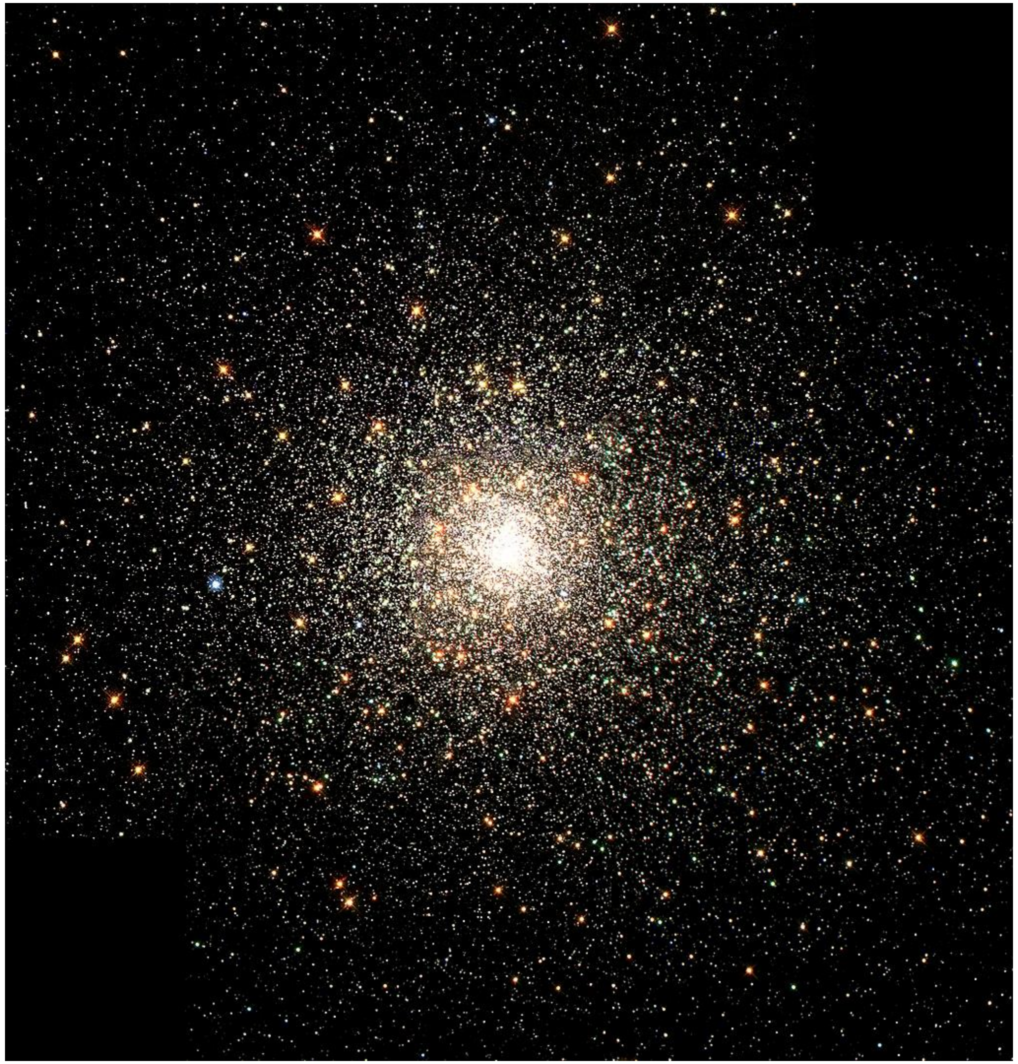


Mandel & Farmer, 2017

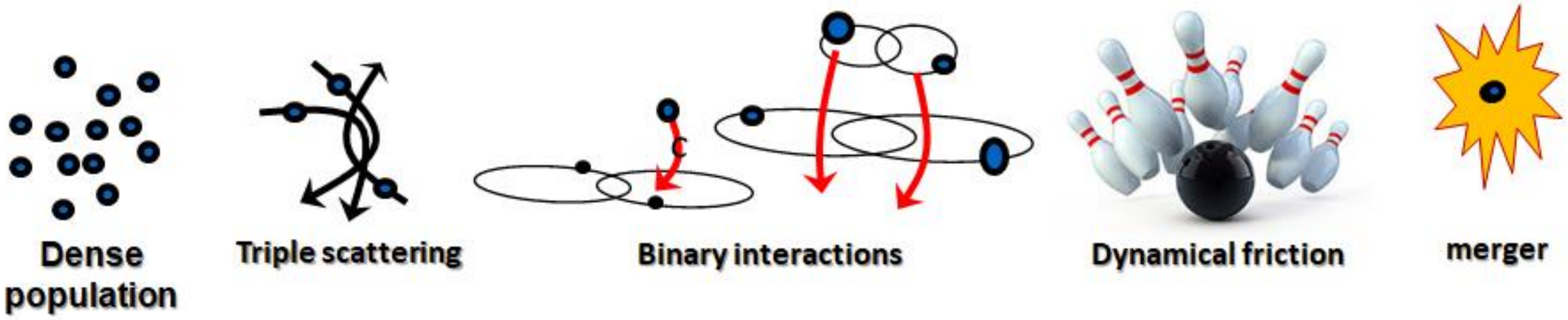
encounter rate ~ density^2

Option 2: dynamical environments

- A theoretically clean problem for N-body simulations



Option 2: dynamical environments



- **binary formation from singles**
- **exchange interactions**
- **mass segregation**

Expectation:

Mergers more likely for heavier objects

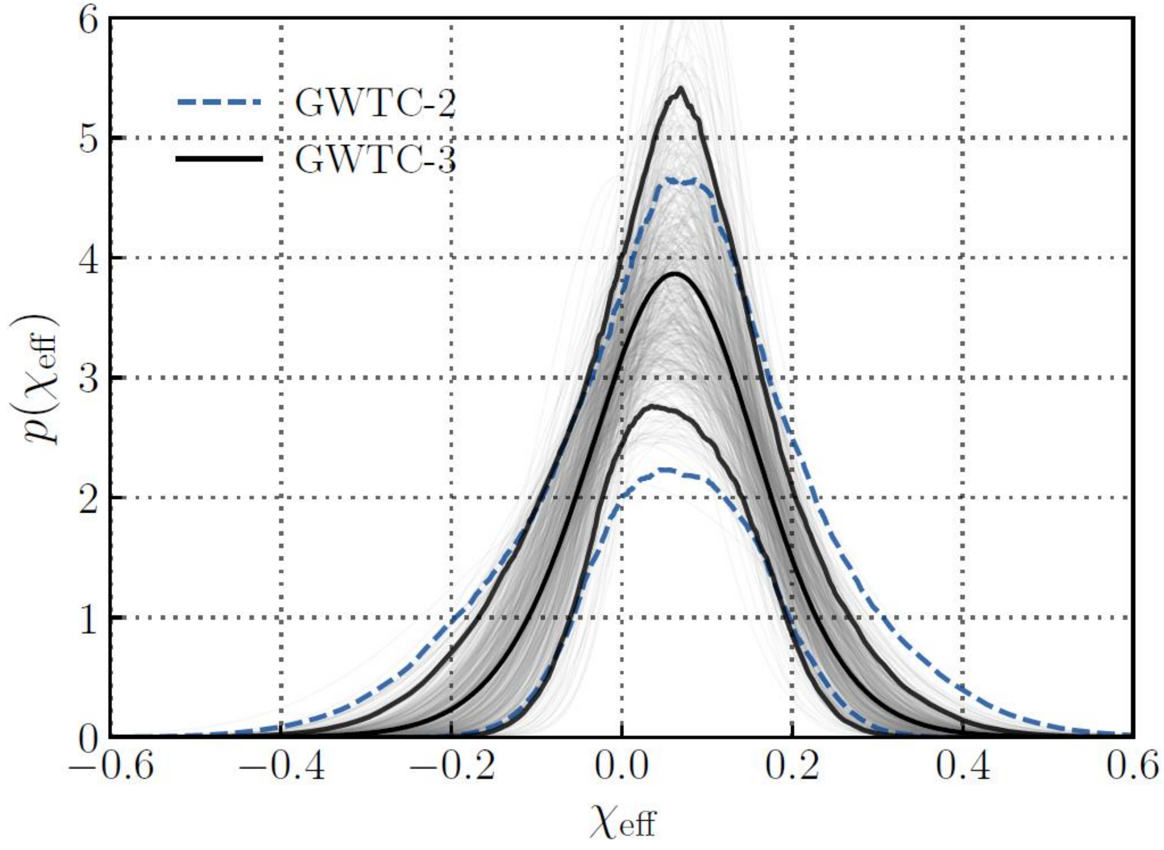
https://youtu.be/ppEviUxRWj8

Option 2: dynamical environments

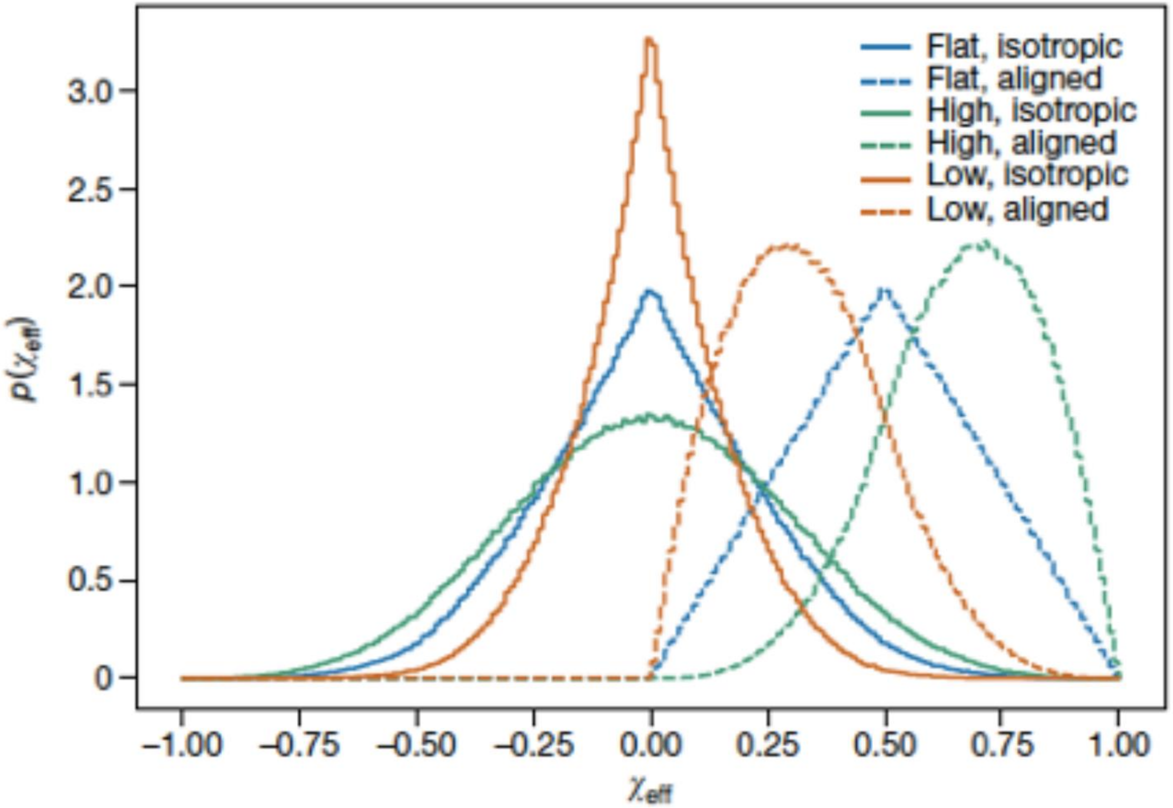
What about spins?

$$\chi_{\rm eff} = \frac{(m_1\chi_1\cos\theta_1 + m_2\chi_2\cos\theta_2)}{M}$$

- LIGO distribution **consistent** with isotropically distributed **spins**



LIGO/VIRGO Collaboration 2021



Farr+ 2017

Problem 2a: Why is the black hole merger rate so high?

Expected rates in MCMC and Nbody simulations of isolated globular clusters: ~ 6 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$

Where does this come from?

- assume **each** BH merges **at most once*** in a Hubble time
- BHs form from stars with $m>20M_{Sun}$, → 0.3% of stars turns into BHs
  - **globular clusters: R < 40 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$**
    - 0.5% of stellar mass, $10^{5.5}$ stars with n ~ 0.8 Mpc^{-3}
  - **galactic nuclei: R < 35 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$**
    - 0.5% of stellar mass, 10^{7} stars with n ~ 0.02 Mpc^{-3}

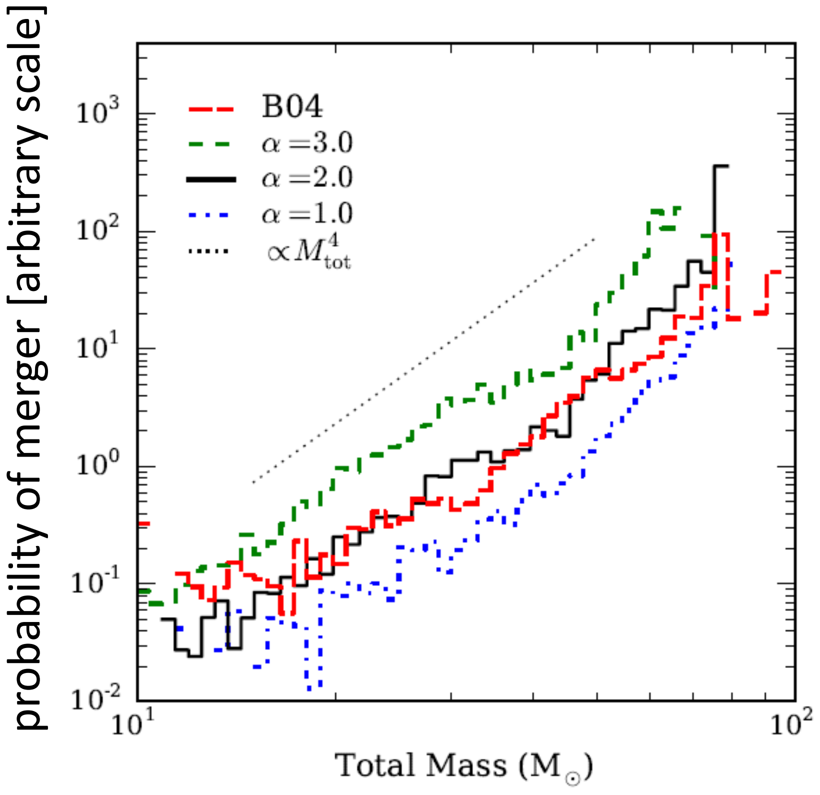
* note: in simulations **20%** of BHs **form binaries** and only **50% of binaries merge**

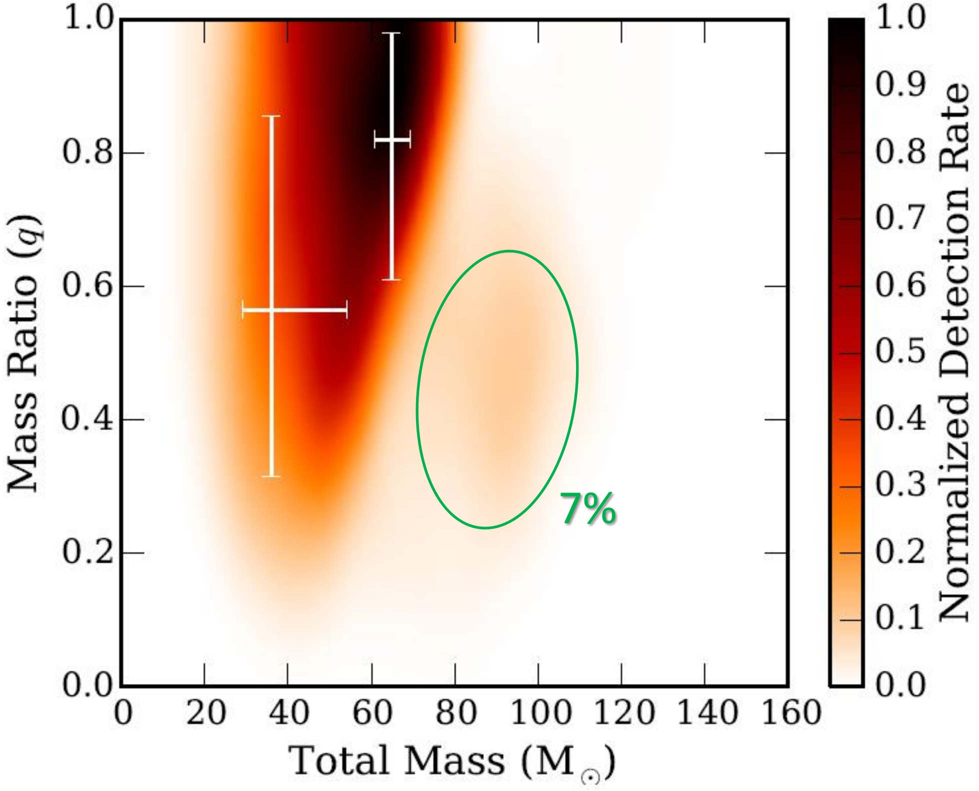
Observed rate: 15 – 39 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$

Mass distribution for globular clusters

Monte Carlo and Nbody simulations

O'Leary, Meiron, Kocsis (2016), Rodriguez+ '19, Askar+ '18





merger probability scales with M^4

2nd generation mergers are possible: 5%-10%
3rd generation mergers are difficult to produce

O'Leary, Meiron, Kocsis 2016

Problem 2b: How can the BHs merge multiple times and not get ejected?

Typical escape speed: 30-60km/s

Gravitational wave kick: 50-5000 km/s

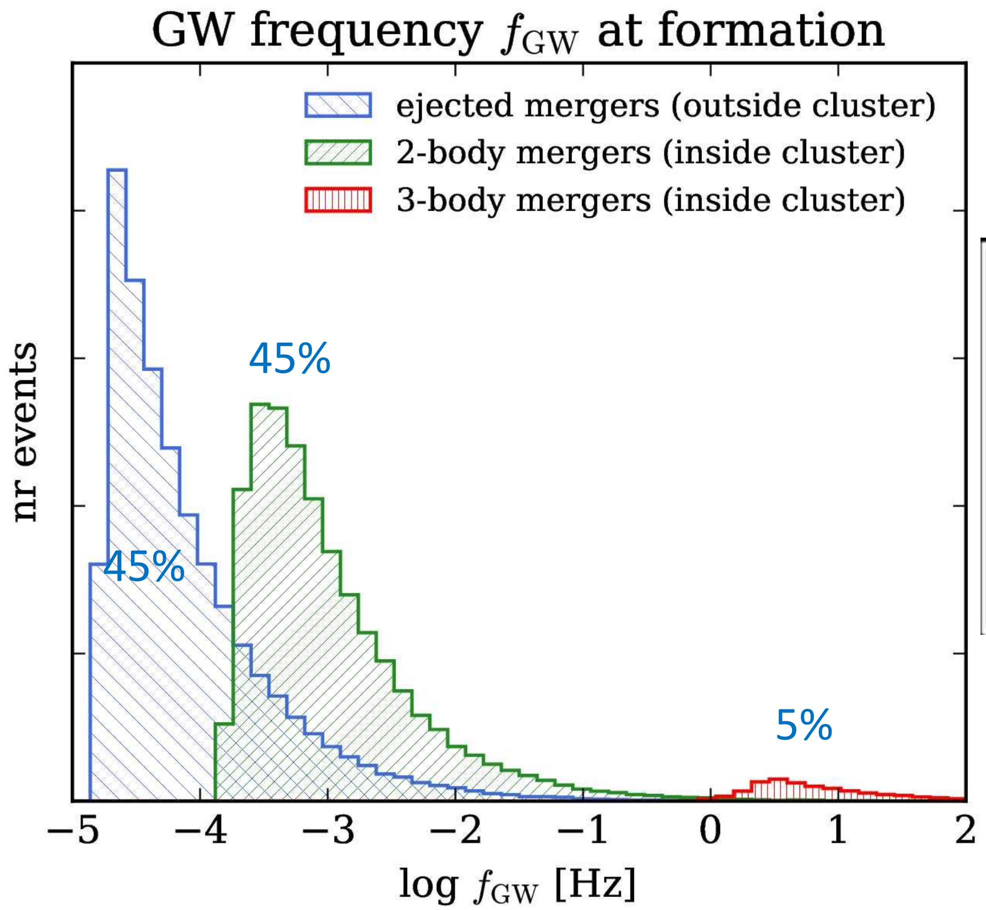
Merger remnants are spinning
→ Kick velocity high for spinning BHs

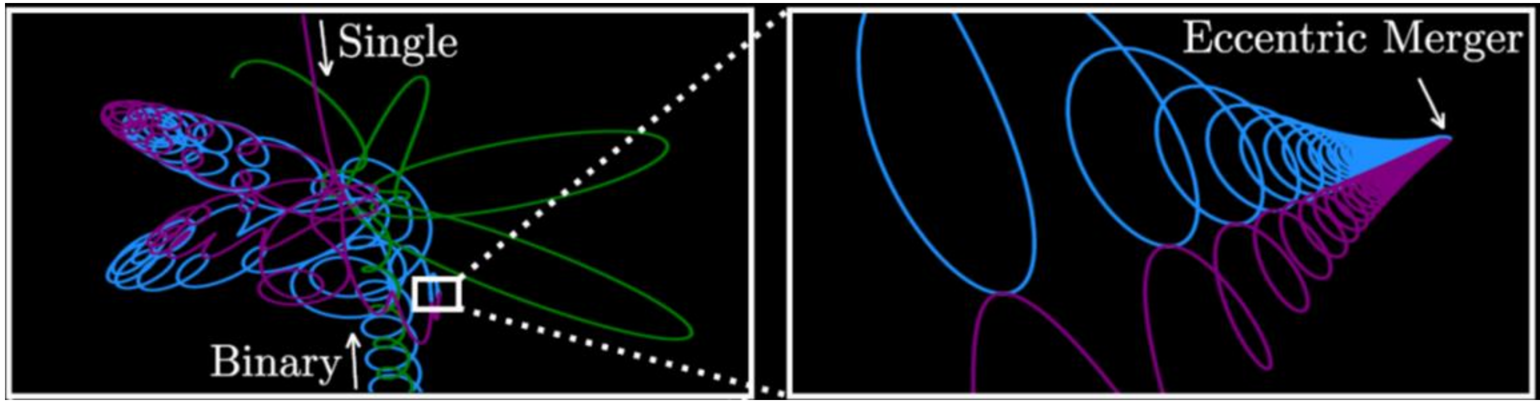
Merger hierarchy in LIGO/VIRGO observations:

1G+1G: (83 events) 95%
1G+2G: (5 events) 5% -- 0.05%
2G+2G: (2 events) 0.1% -- 10^-5 %

Kimball+ arxiv:2011.05332

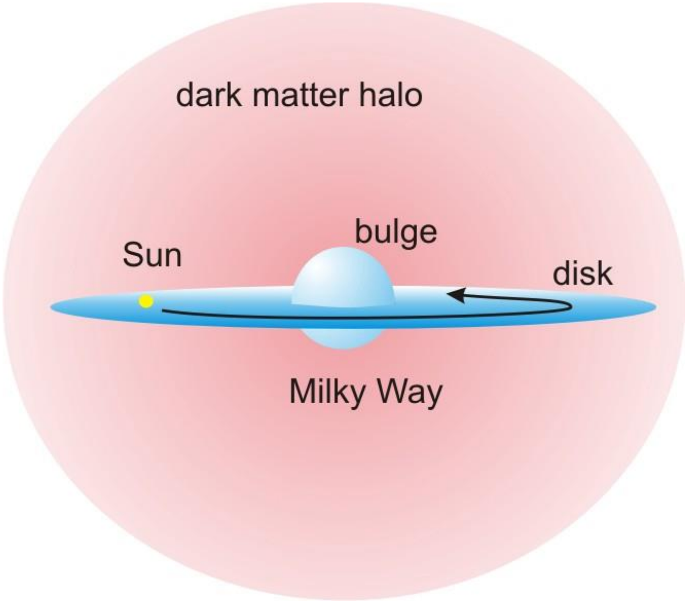
Problem 2c: Why don't some of the mergers have eccentricity?





Samsing, Dorazio 2018

Option 3: Dark matter halo



Dark matter halo

- 10x more mass than in stars
- 10^{10} primordial mass black holes / galaxy?

- **Observational probes:**
  - lack of microlensing events: $m > 20\ M_{Sun}$,
  - survival of stellar binaries $m < 100\ M_{Sun}$
  - CMB excludes the rest (with assumptions)
  - GW detections!

- Rates match if
  - 100% of dark matter is in 30 Msun **single BHs** (Bird et al 2016)
    - RULED OUT BY OBSERVATION OF a GLOBULAR CLUSTER IN A DWARF GALAXY (Brandt et al. 2017)
    - Newer studies: 1% of dark matter in BHs is sufficient (Ali-Haimud et al 2017)
  - 0.1% of dark matter is in primordial **binary BHs** after inflation (Sasaki et al 2016)

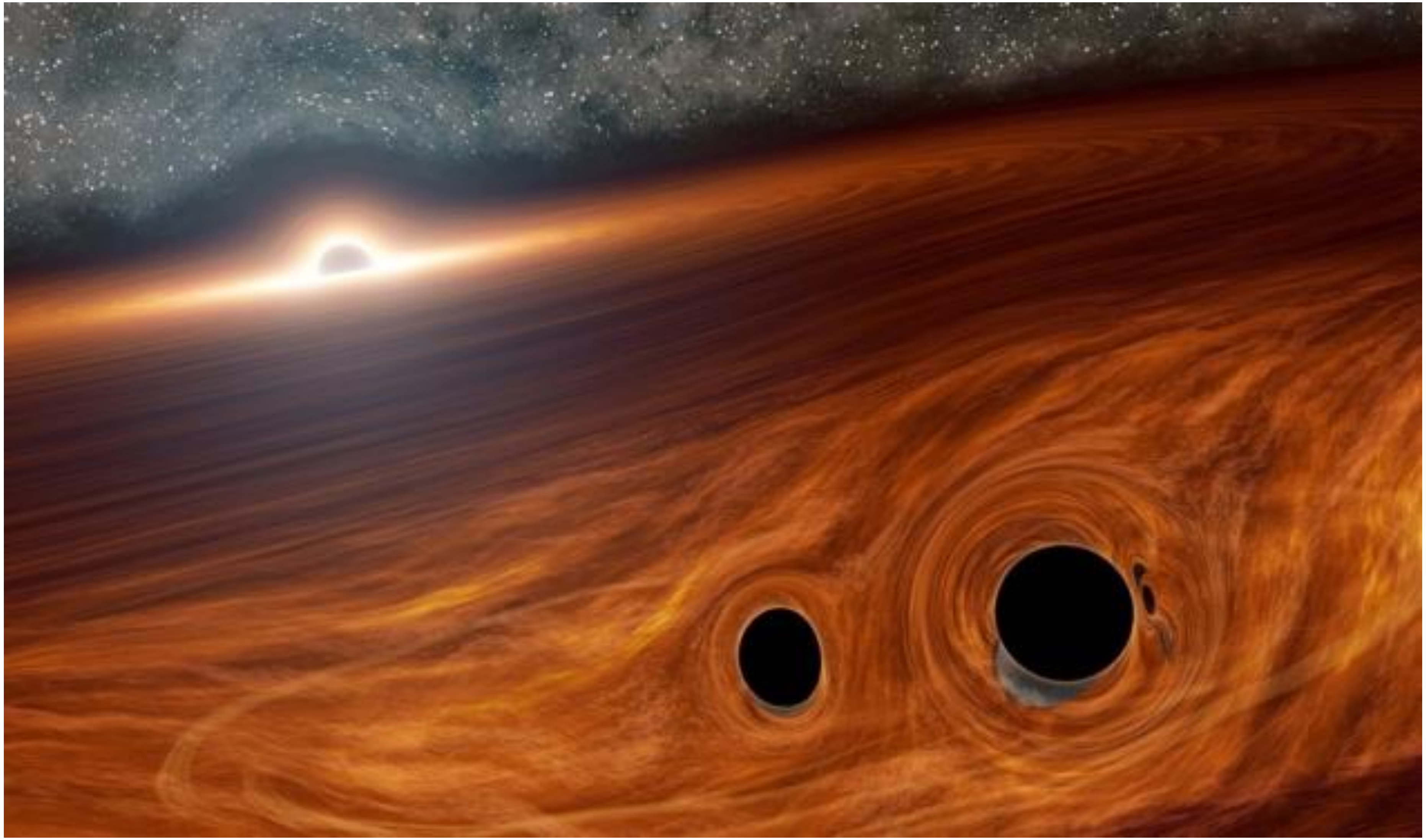
Summary of populations and rates

- galactic field binaries: spins, masses, final au problem, common envelope
- galactic field triples: not enough in the right configuration

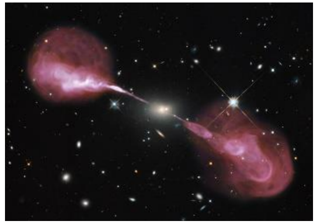
- globular clusters: not enough black holes? why are they not ejected? not enough eccentric?
- galactic nuclei: requires multiple mergers/BH

- dark matter halos: requires primordial black holes (exotic)

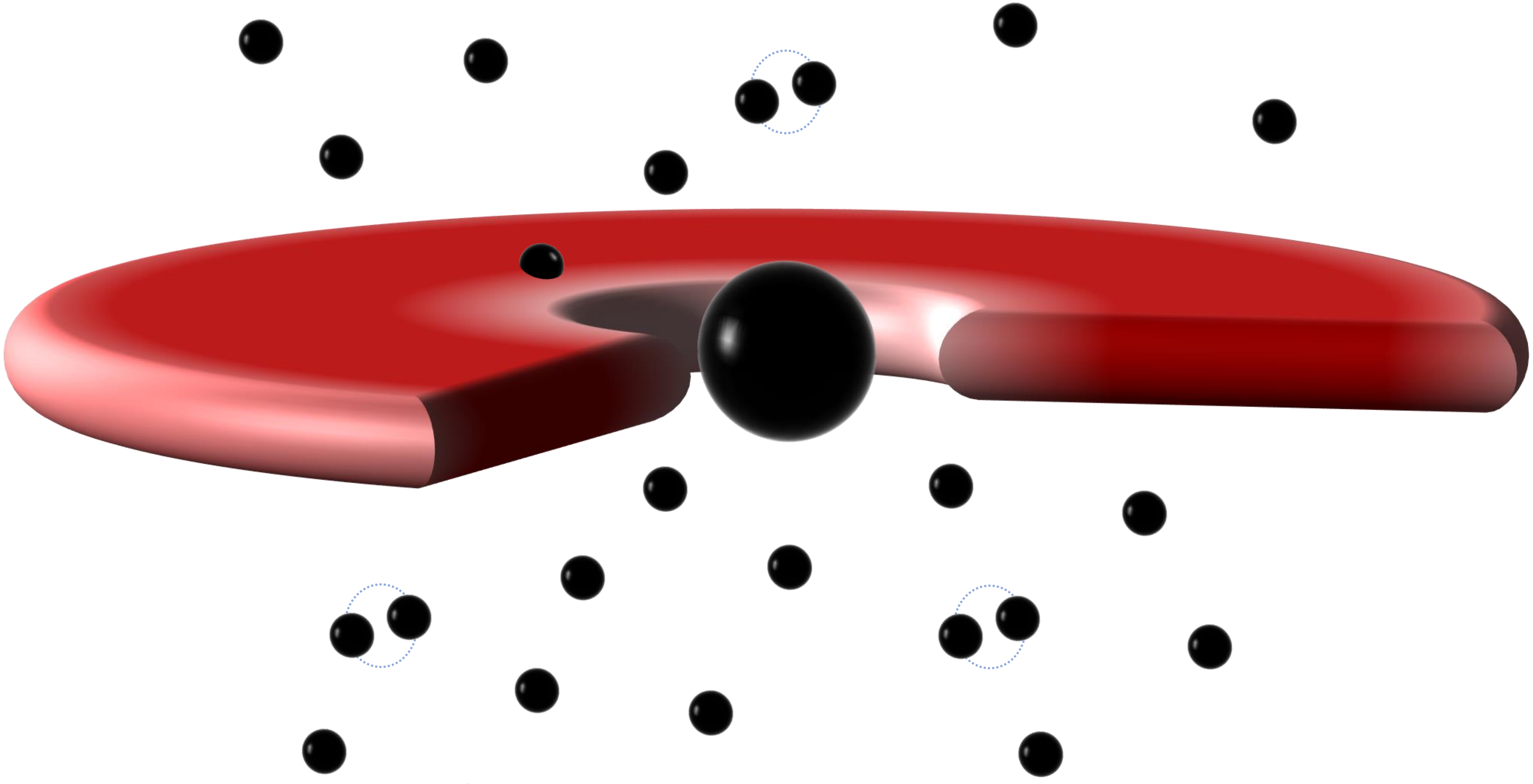
No convincing single theory to explain all observations!



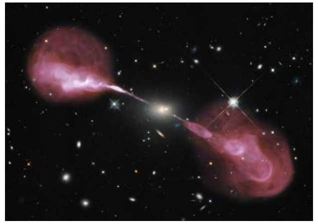
Black hole mergers in active galactic nuclei



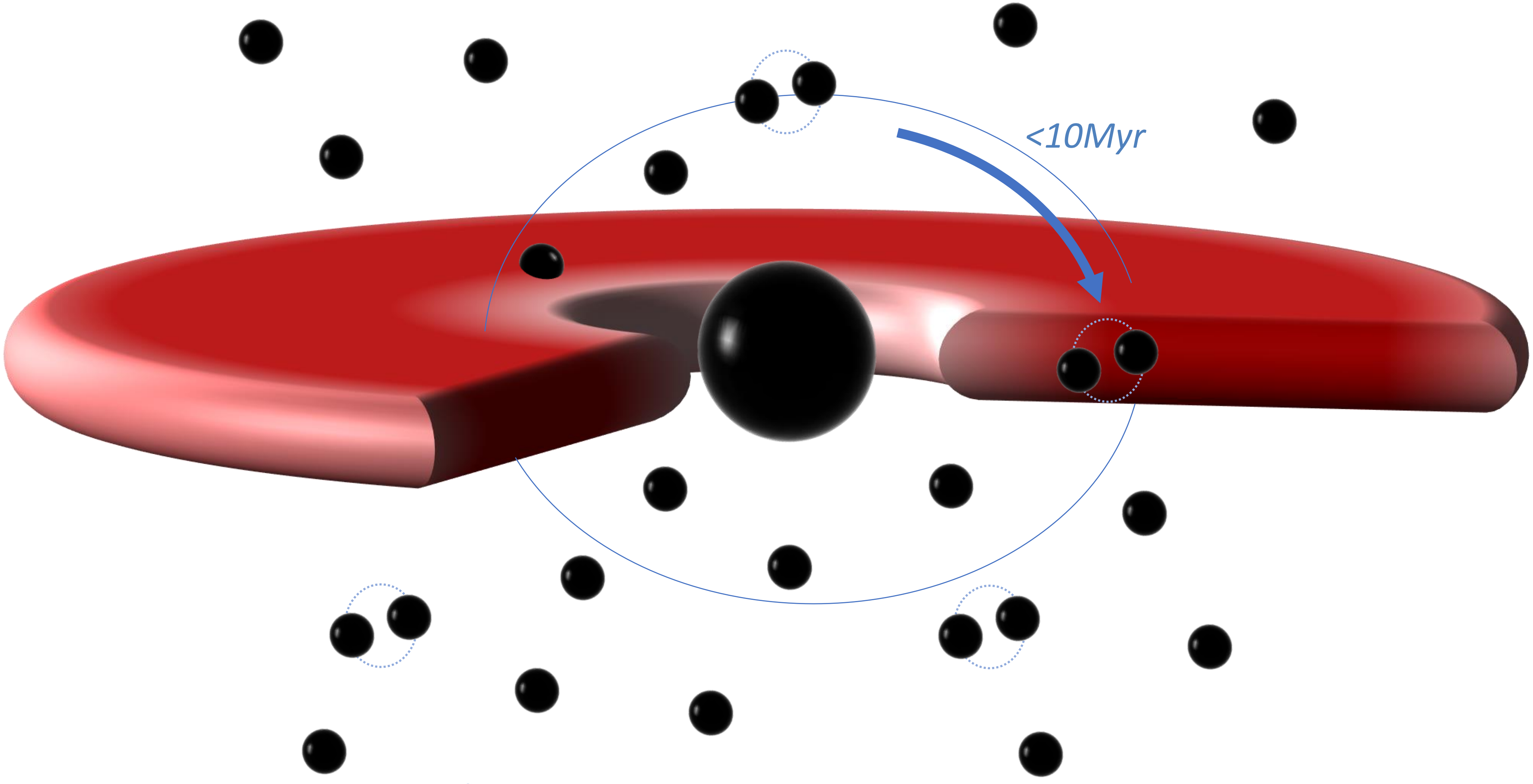
GW sources in active galactic nuclei



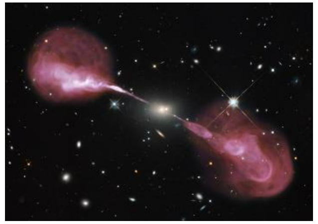
There are large amounts of gas at the centers of 1% of galaxies (AGN).



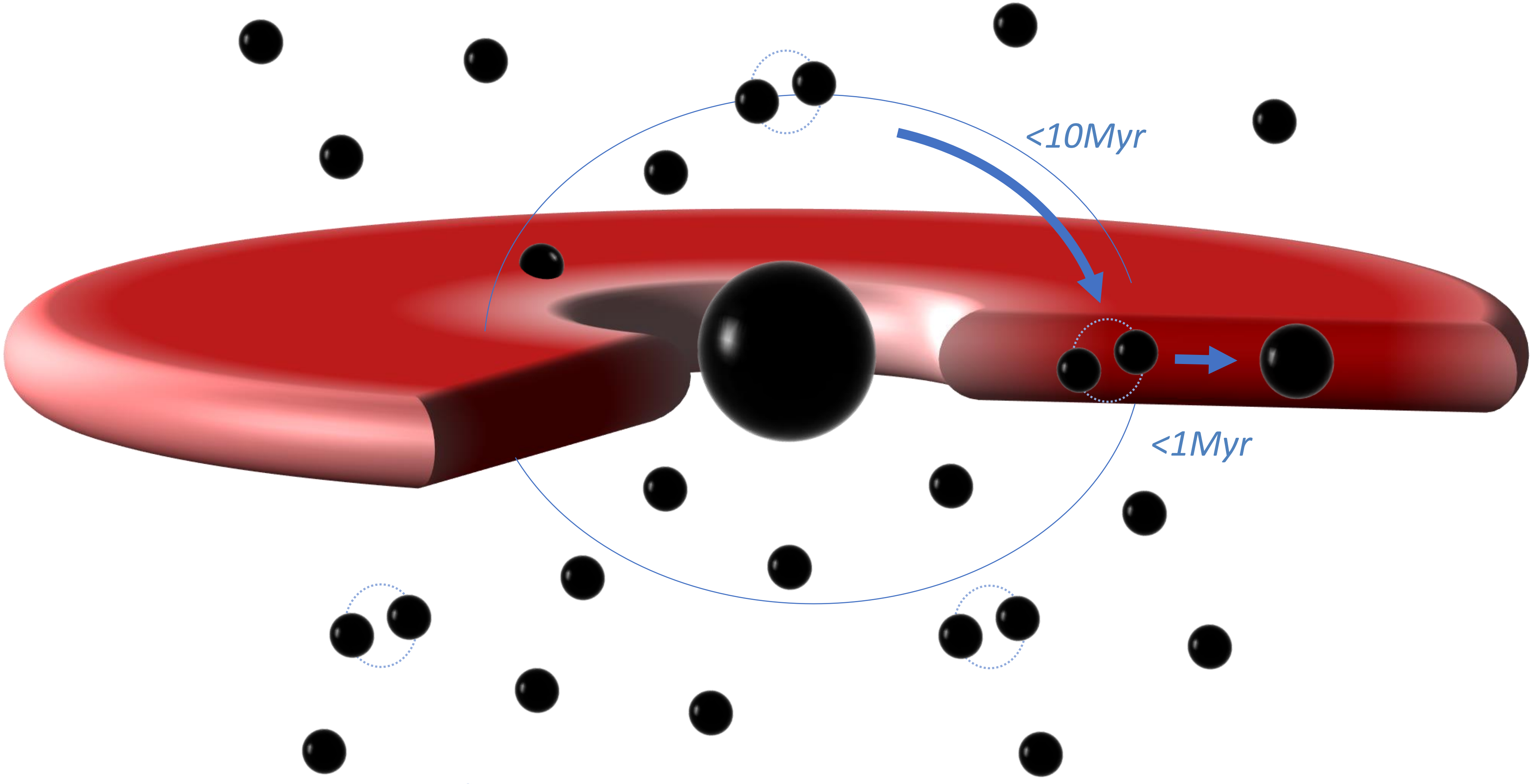
GW sources in active galactic nuclei



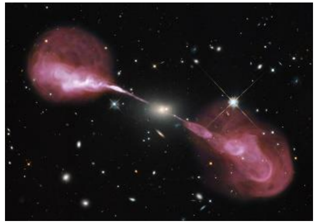
Get captured by the disk…



GW sources in active galactic nuclei



…and then quickly merge due to dynamical friction on the gas



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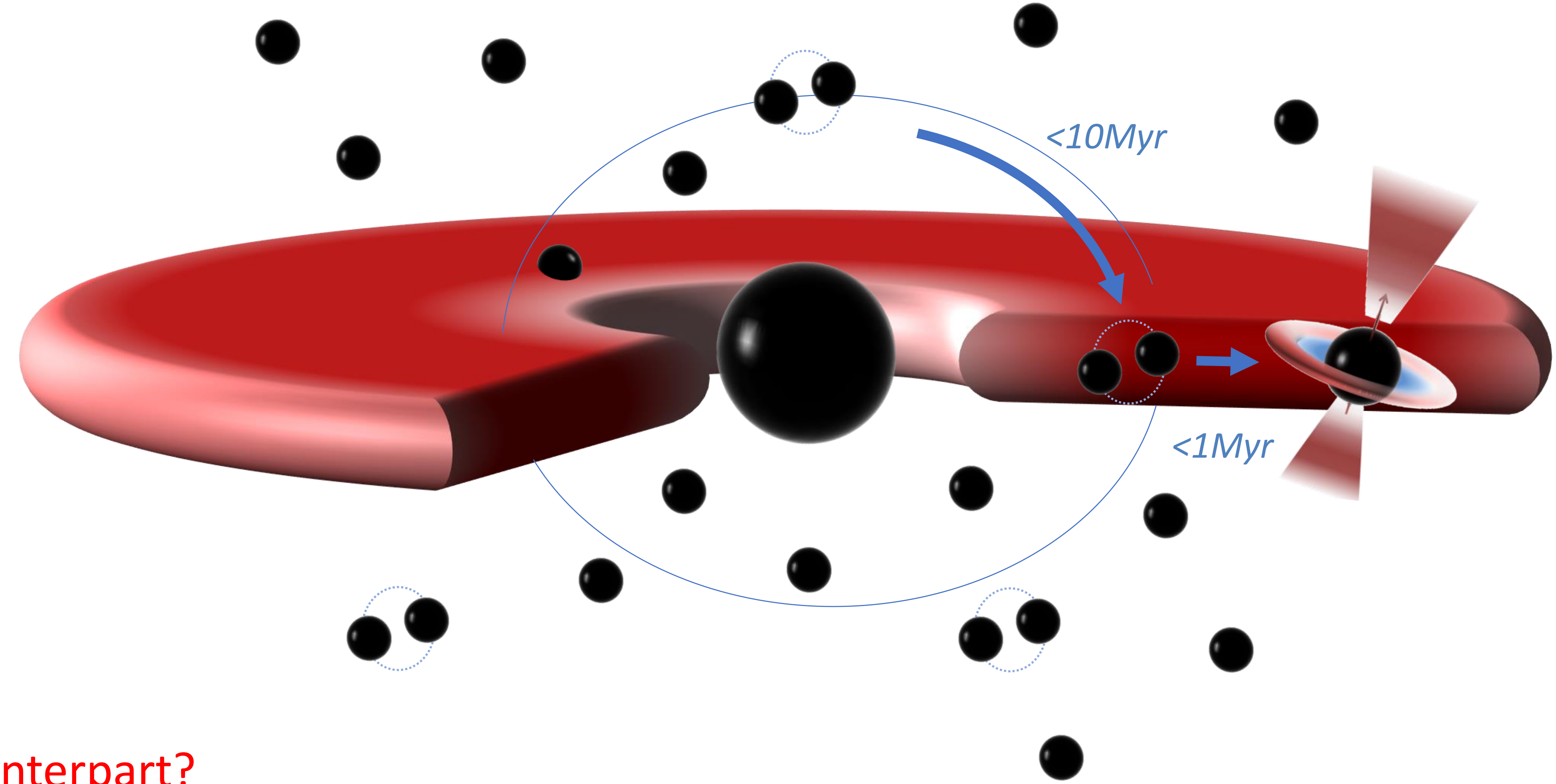
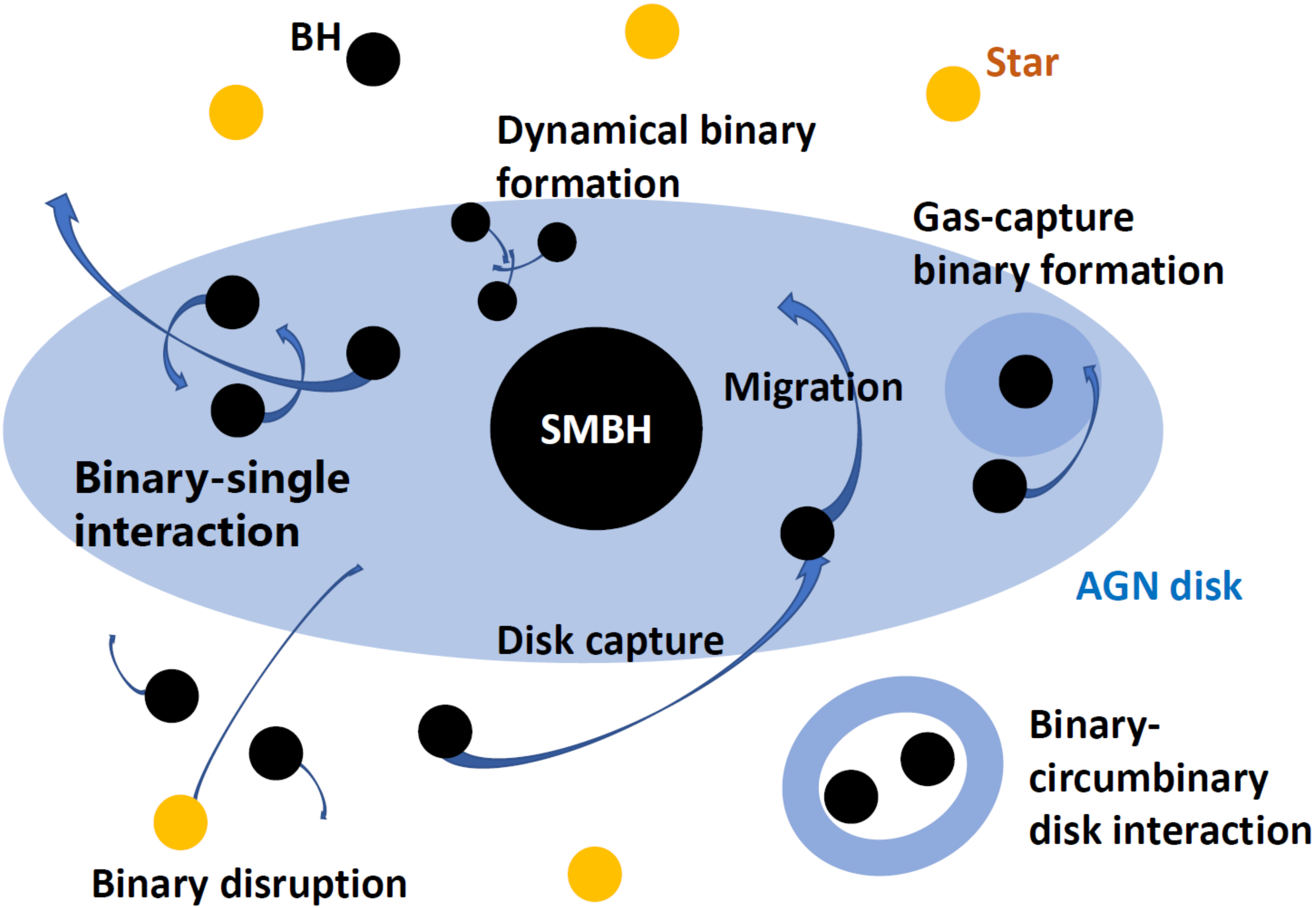


EM counterpart?

Graham+ arXiv:2006.14122

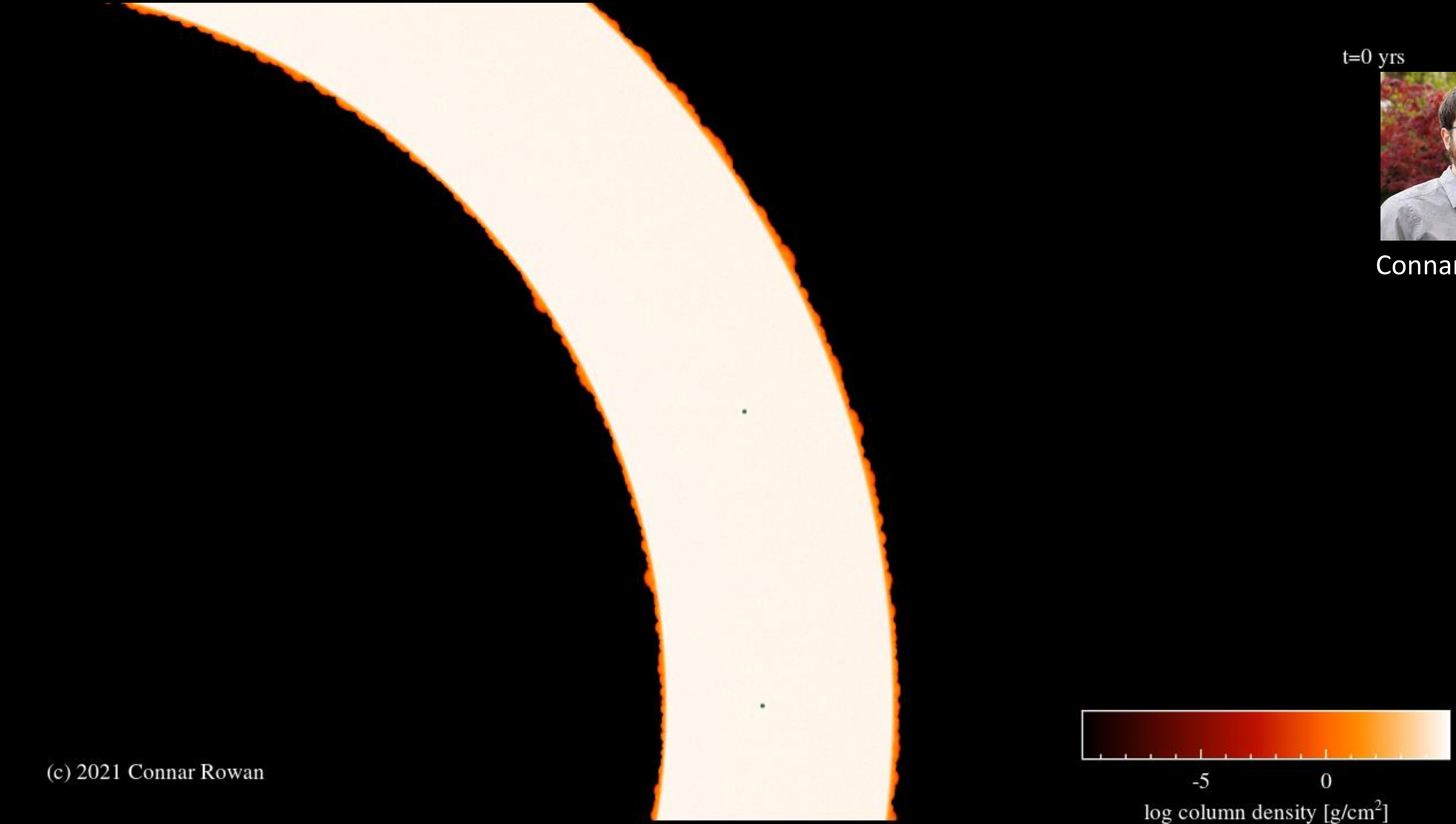
AGN flare 34 days after LIGO event S190521g

Bartos, Kocsis, Haiman, Marka 2017
Stone, Metzger, Haiman 2017

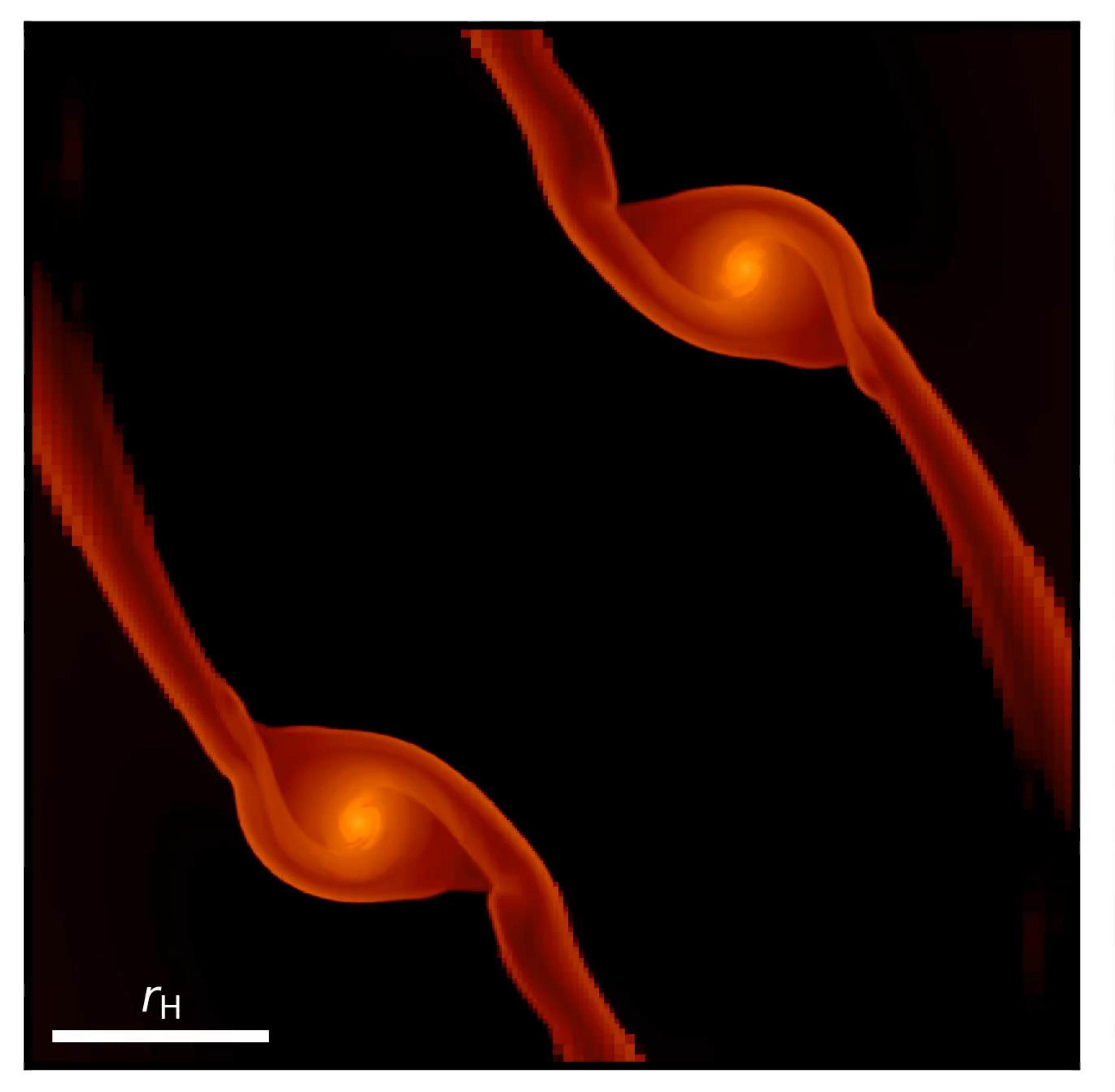


Semi-analytical N-body simulation

Tagawa, Haiman, Kocsis 2020; Tagawa, Haiman, Bartos, Kocsis 2020; Tagawa, Kocsis, et al. (2021a, 2021b), Rowan+ (2022,2023), Whitehead, Rowan, Boekholt, Kocsis (2023)



Connar Rowan




Henry Whitehead

Summary

- 90 BH/BH mergers detected by LIGO and VIRGO
- many astrophysical merger pathways
- distributions of source parameters useful to test theory
  - Mass, mass ratio, spins, eccentricity

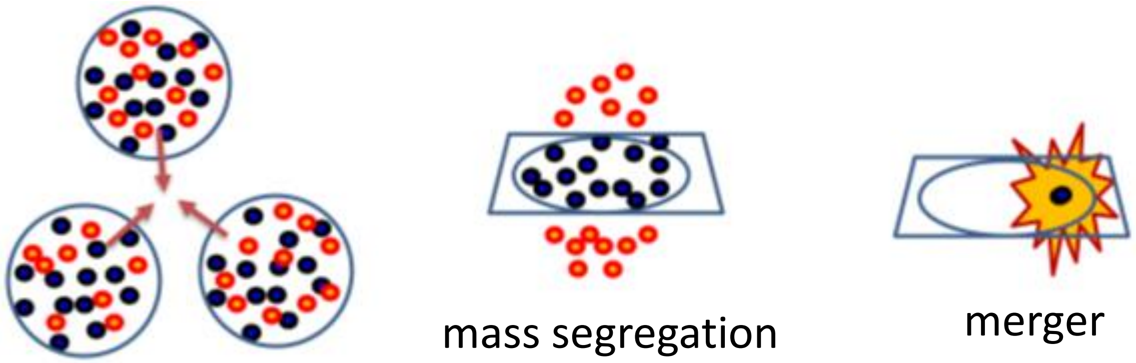
- GWs probe astrophysical systems in new ways
  - globular cluster evolution over cosmic time
  - active galactic nuclei

- Bright future for GW astronomy
  - New instruments: KAGRA, LIGO India
  - Plans for further upgrades: LIGO+, Cosmic Explorer, Einstein Telescope
  - LISA 2034

Extra slides

New ideas

1. Disrupted globular clusters (Fragione & Kocsis, PRL 2018)
2. Black hole disks (Szolgyen & Kocsis PRL 2018)



globlar cluster mergers

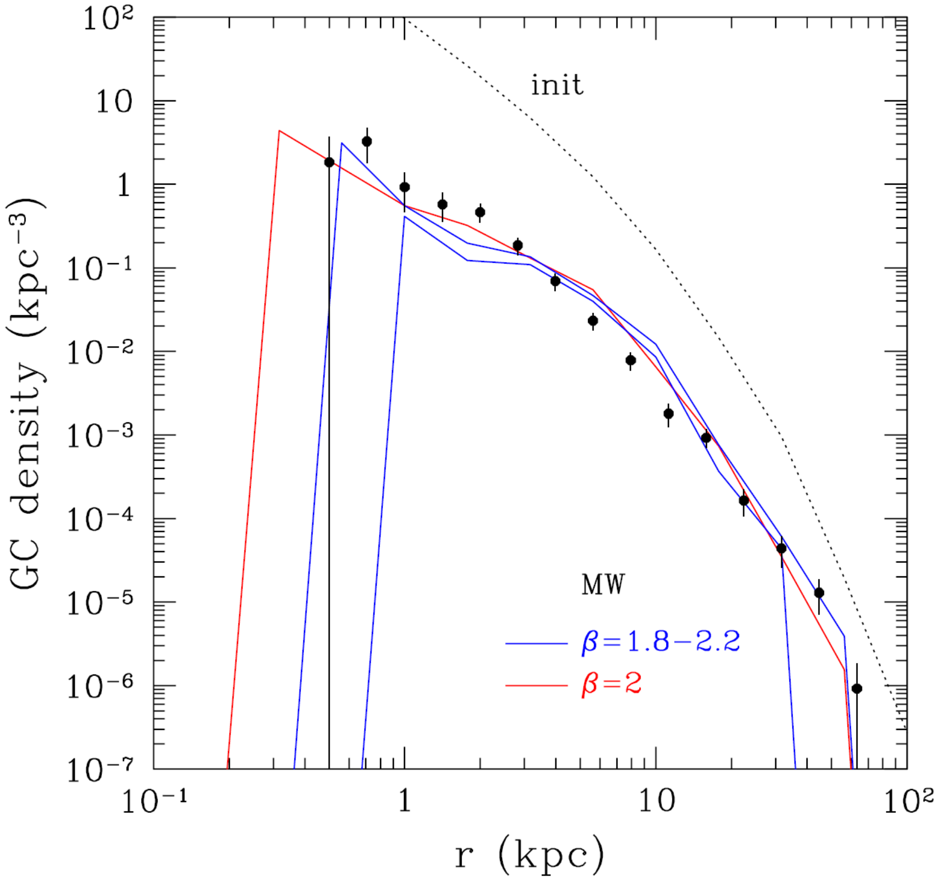
mass segregation

merger

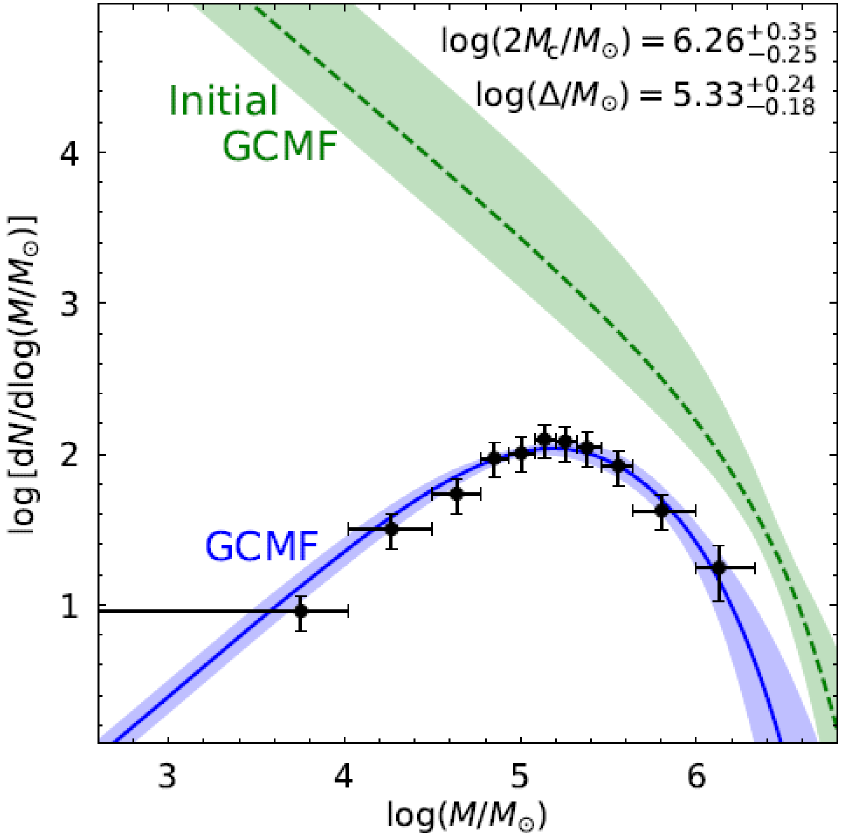
3. Mergers in AGN (Bartos, Kocsis, Haiman 2017; Tagawa, Haiman, Kocsis, 2020.,..)

Disrupted globular clusters

- Globular clusters were much more numerous in the past



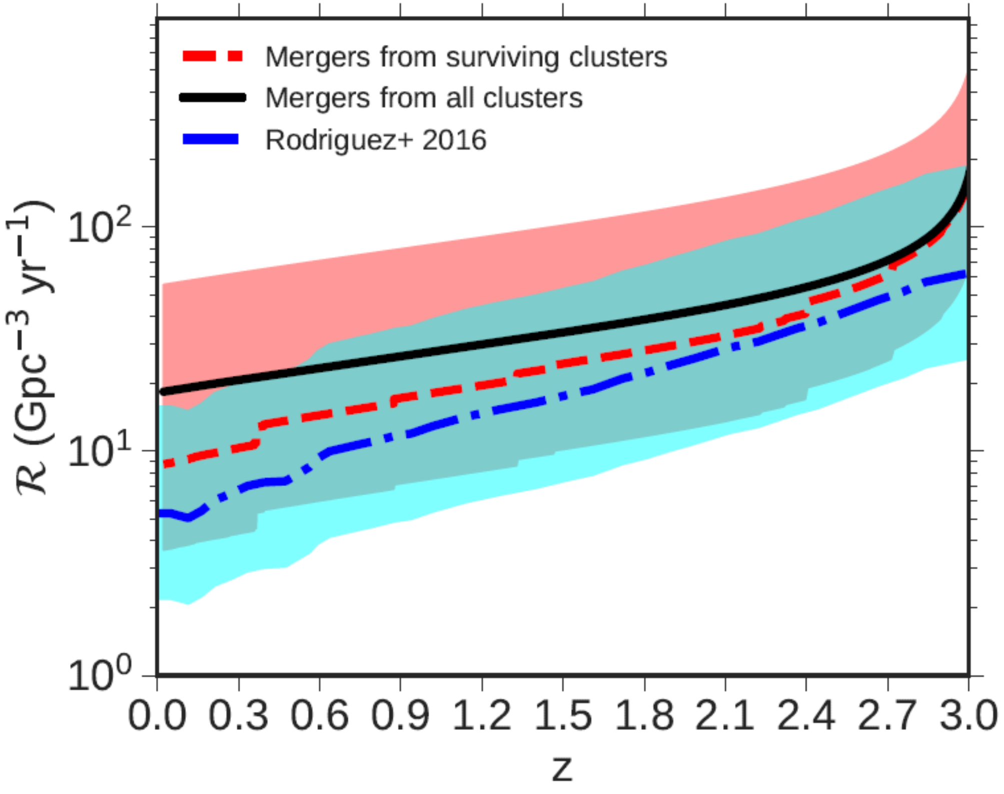
Gnedin, Ostriker, Tremaine (2014)



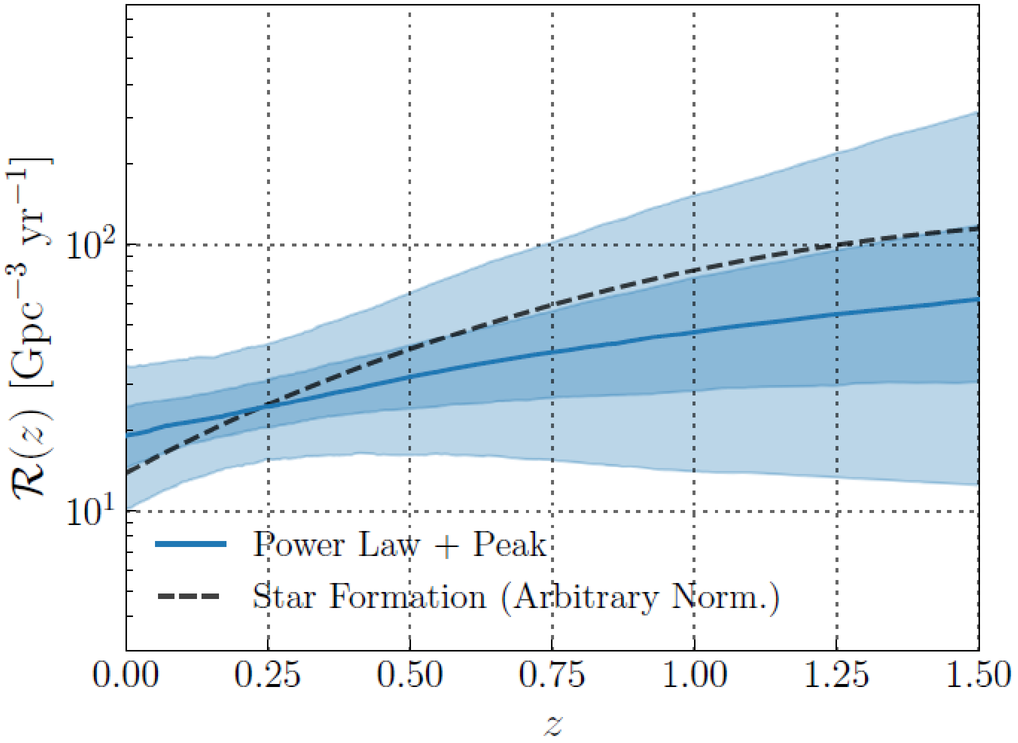
Antonini, Gieles (2020)

Disrupted globular clusters

- Implication: increased merger rate



Fragione & Kocsis (2018) PRL

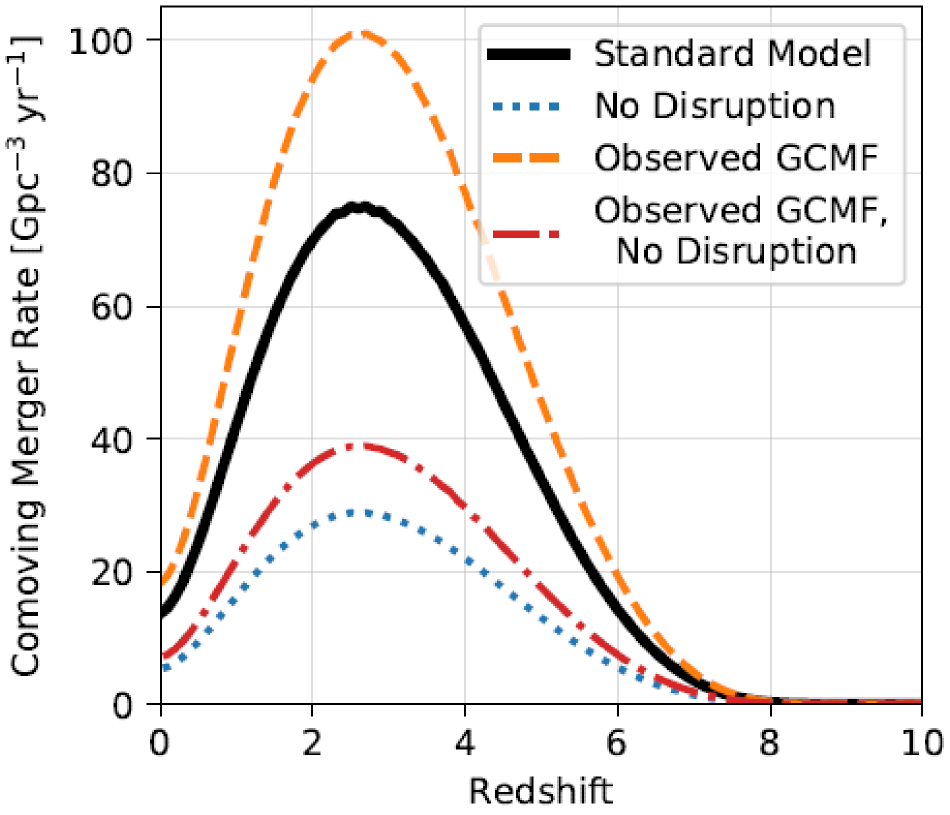


Observed rate

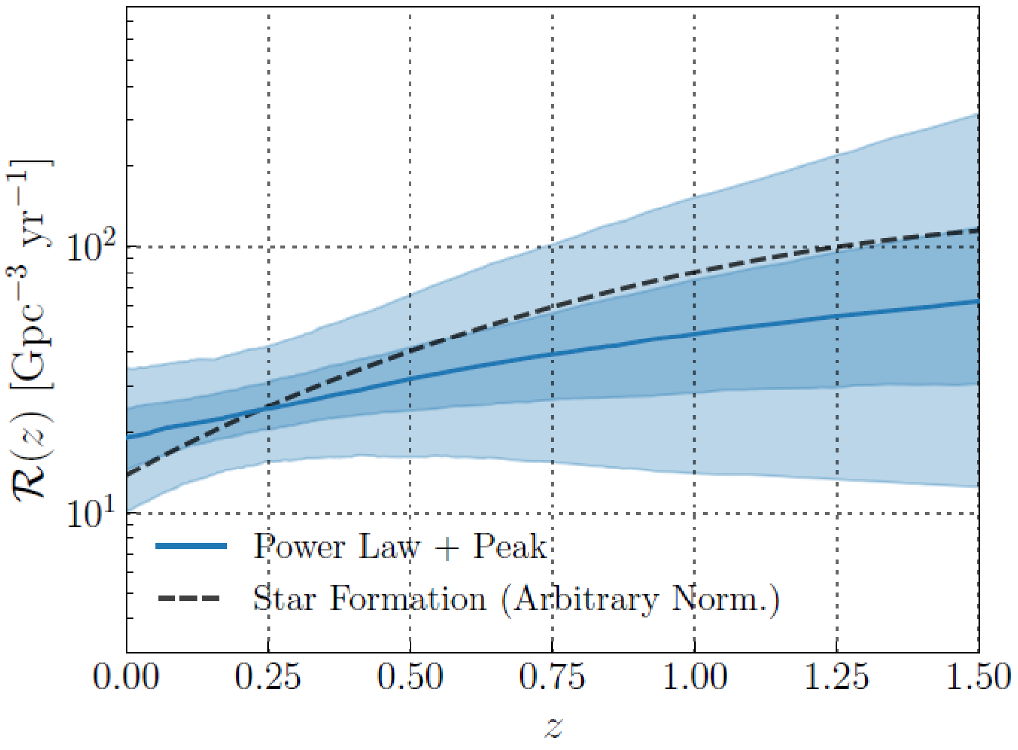
LIGO/VIRGO Collaboration arxiv:2010.14533

Disrupted globular clusters

- Implication: increased merger rate



Rodriguez & Loeb (2018)



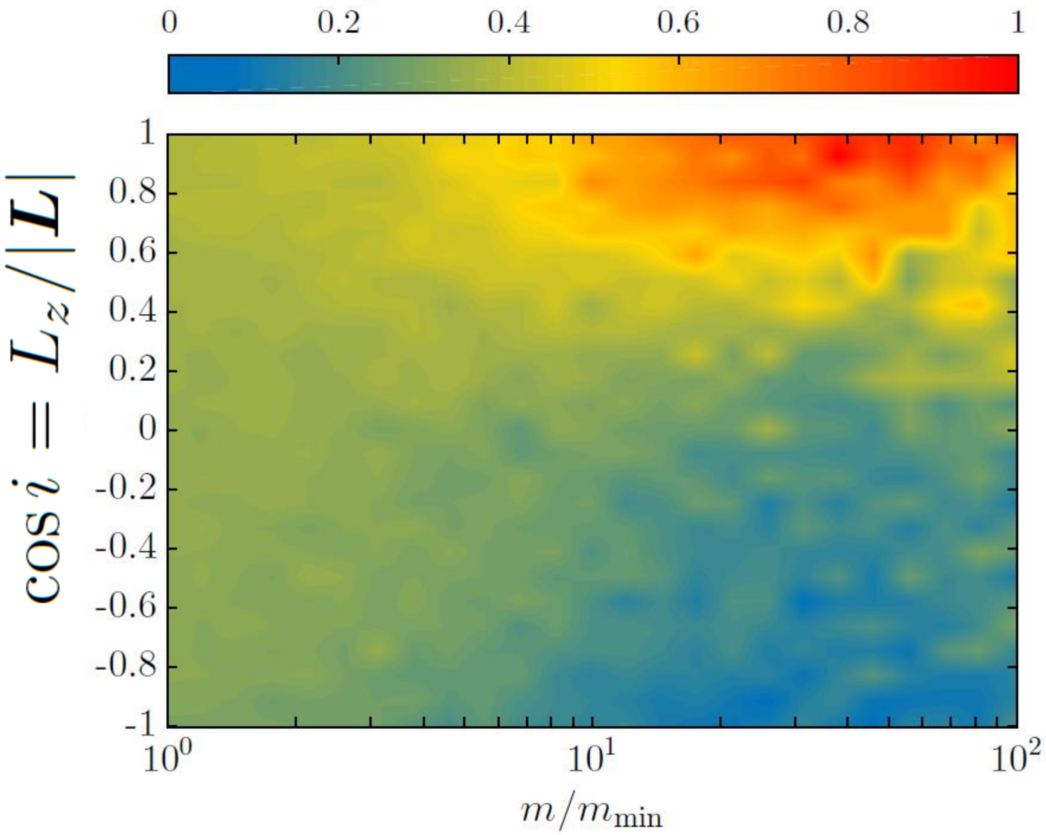
Observed rate

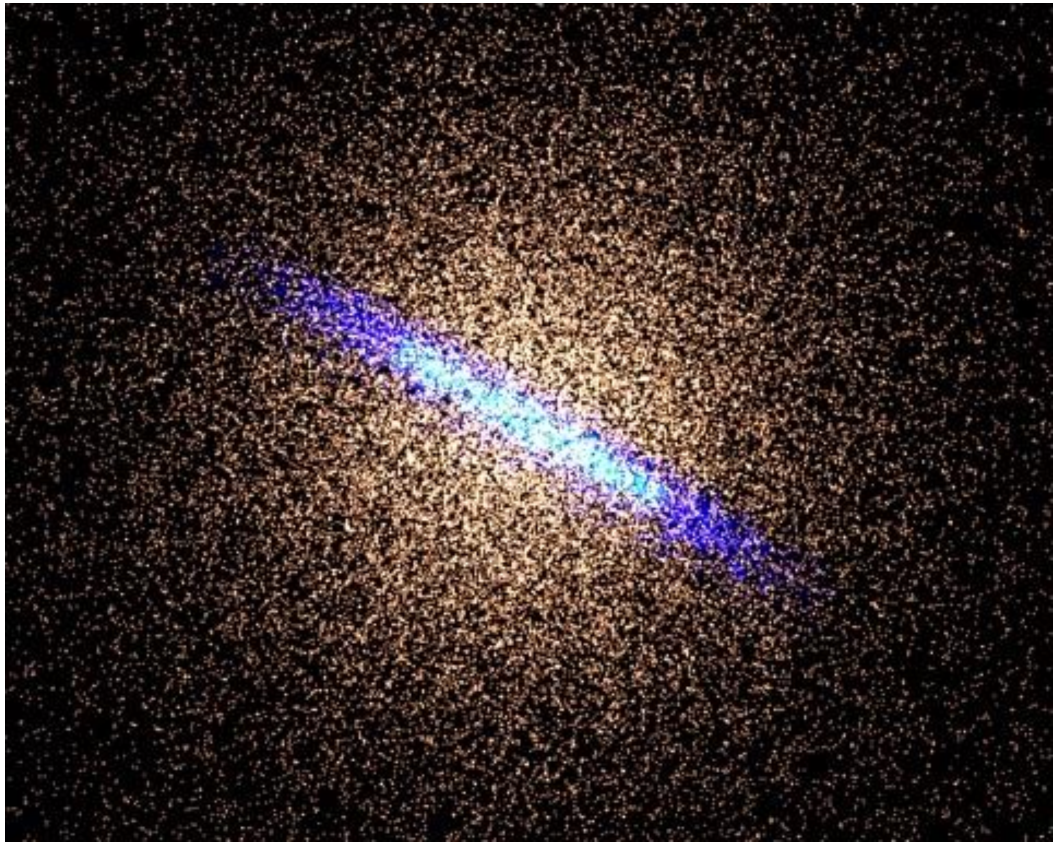
LIGO/VIRGO Collaboration arxiv:2010.14533

Black hole disks in galactic nuclei and globular clusters

Black holes reorient their orbits to form a disk due to resonant relaxation

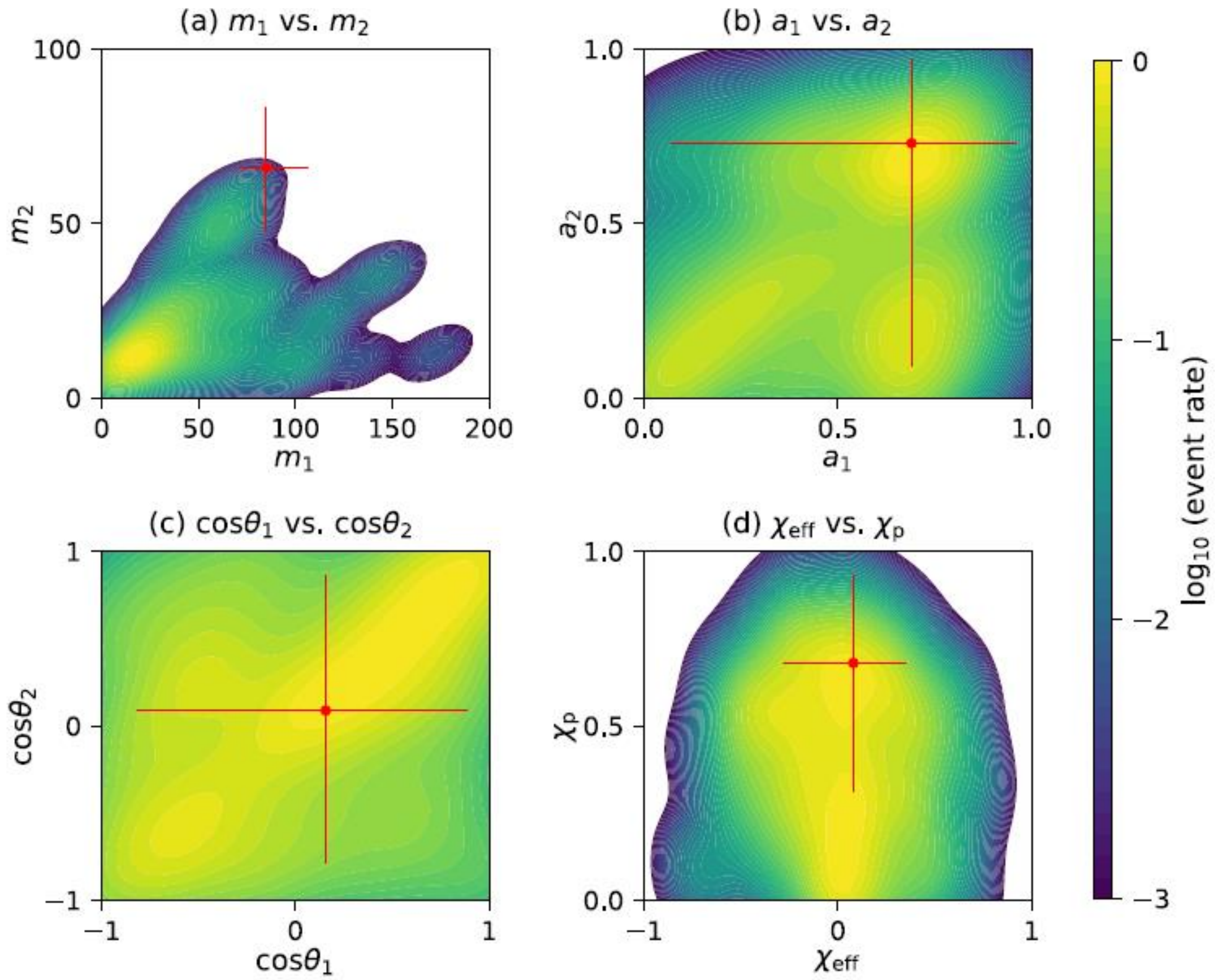
- mergers more likely



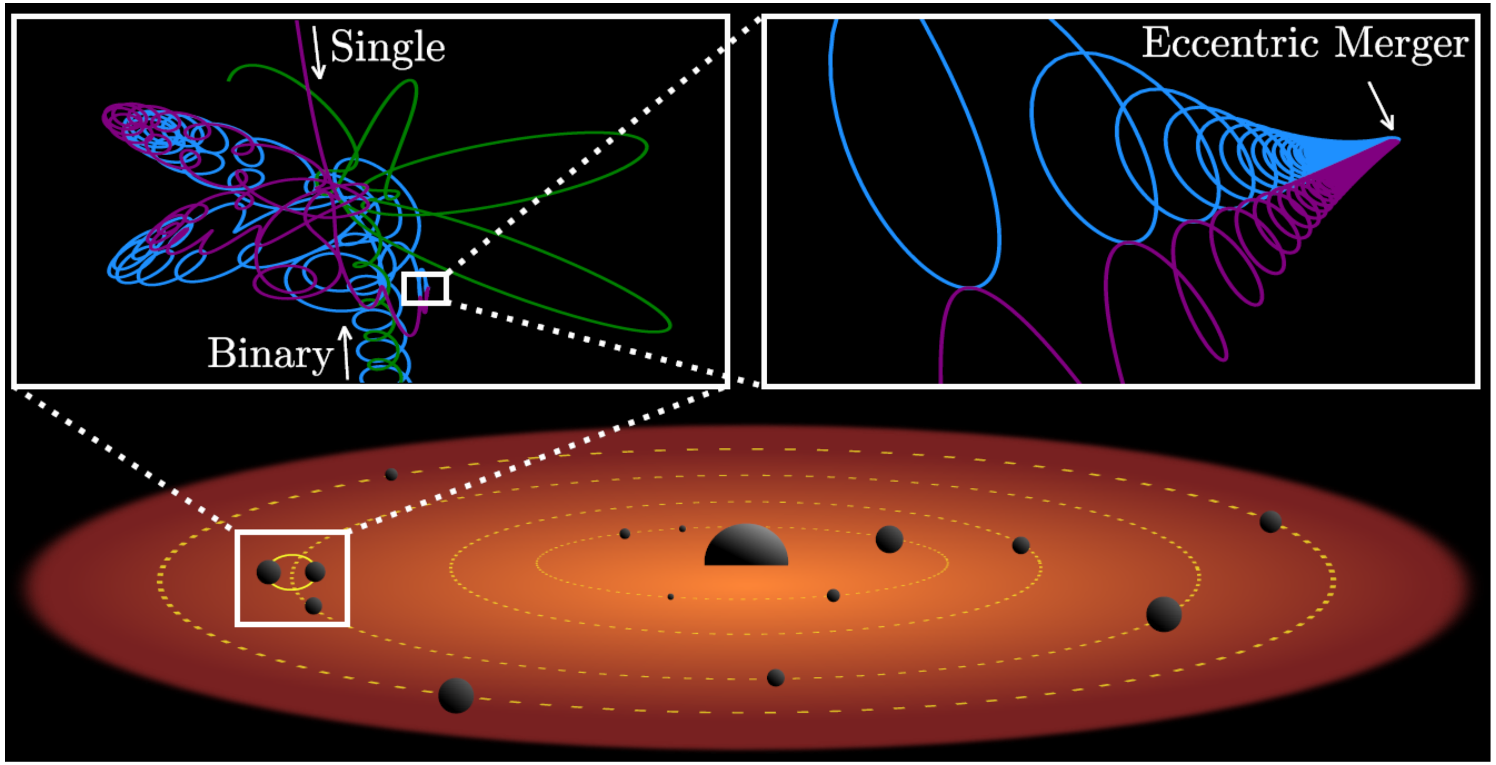


Szolgyen & Kocsis PRL 2018
Szolgyen, Meiron, Kocsis 2019

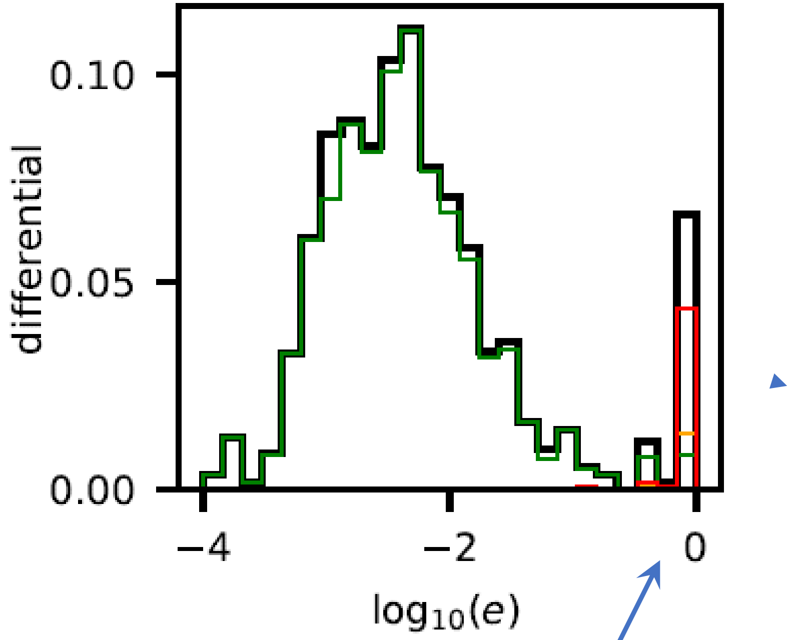
Hierarchical mergers with large spin misalignment



Some of these sources are eccentric



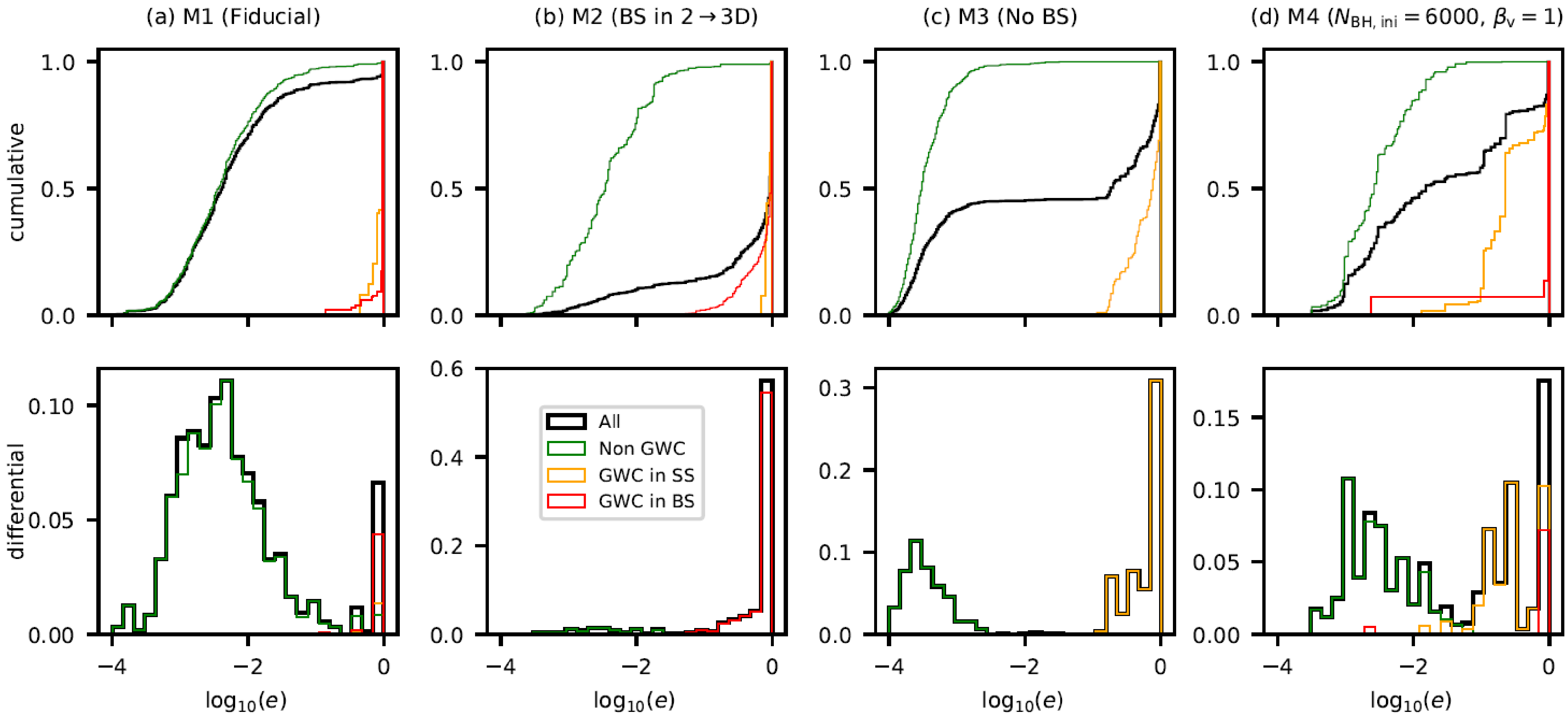
Predicted eccentricity distribution



Samsing, Bartos, D'Orazio, Haiman, Kocsis, et al. (2020)
Tagawa, Kocsis, Bartos, Haiman, Omukai, Samsing (2020)

cf.: GW190521 also has e=0.7 (possibly)
Gayathri+ (2020), Romero-Shaw+ (2020)

Eccentricity distribution in different models



Conclusions/implications for AGN

- Black holes merge frequently in AGN

$$0.02\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1} \lesssim \mathcal{R}_{\mathrm{sBH}} \lesssim 60\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

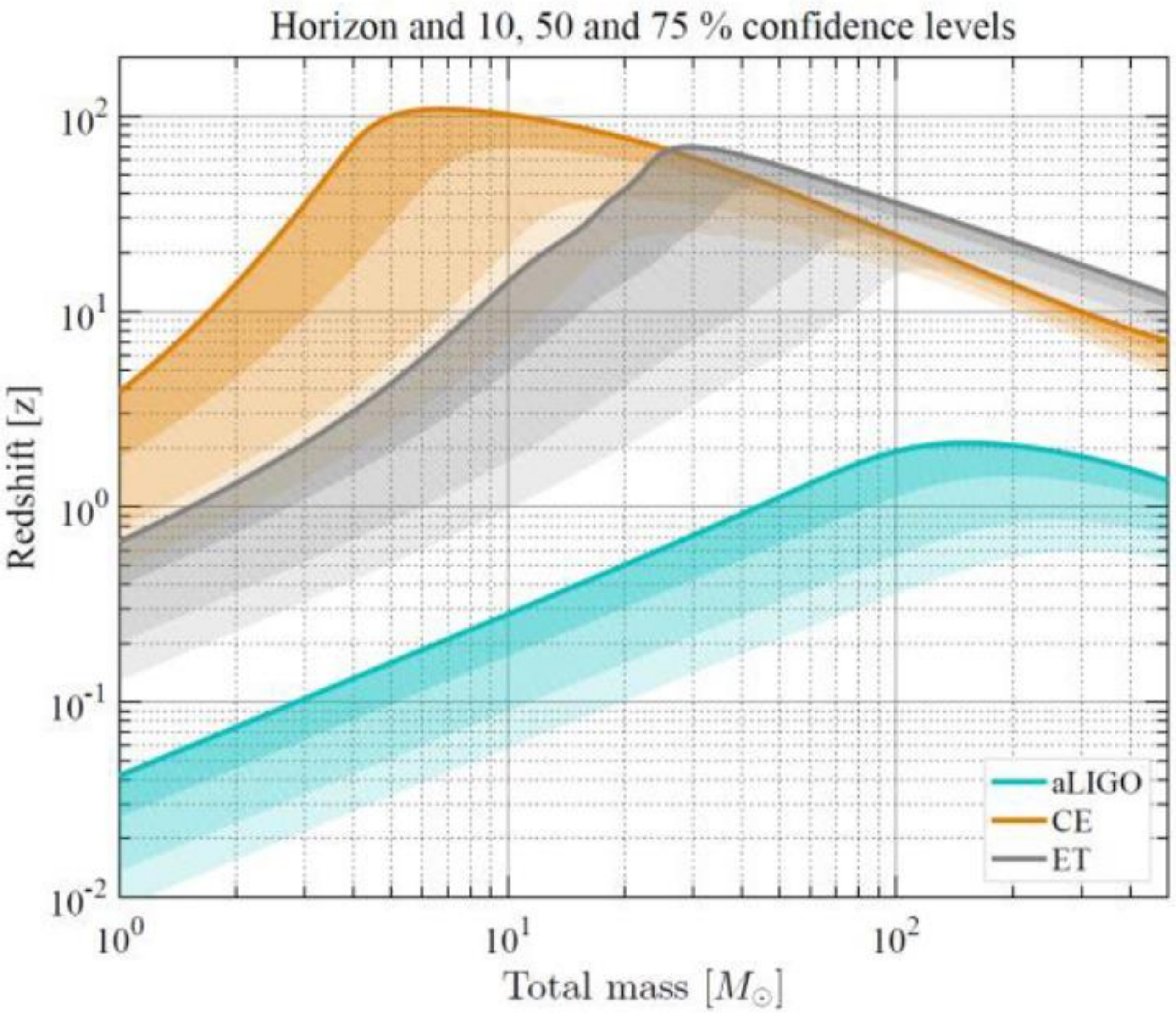
- Distinguishing features:
  - repeated mergers are common
  - mass increases due to mergers
  - since BH spins increase to 0.7 after mergers,

    → statistical correlation between spins and mass
  - BH spins are aligned with each other, but misaligned with orbit

Horizon distance for future Earth-based instruments

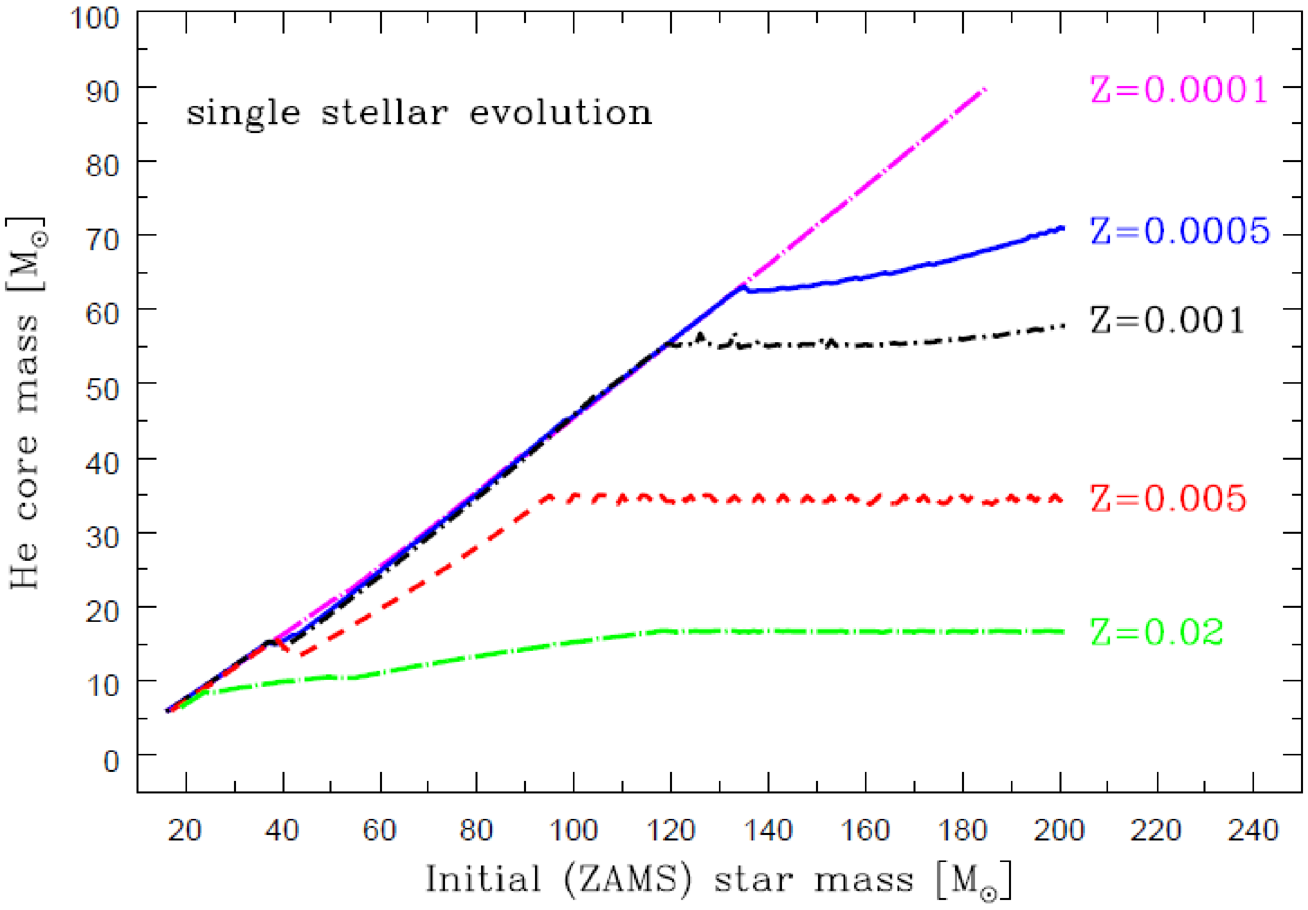
17 – 45 Gpc $^{-3}$ yr $^{-1}$ implies

- **1-3 mergers/day** within **z=0.5**
- **1-3 mergers/hour** within **z=2**



Does the mass distribution make sense?

Theoretical expectations



stellar origin BH can reach: $\sim 100\ M_\odot$
(Zamperi & Roberts 2009; Mapelli et al. 2009)

– updates:

stellar models: $\sim 130\ M_\odot$
(Spera et al. 2015)

IMF extension: $\sim 300\ M_\odot$
(Belczynski et al. 2014)

-(Belczynski et al. 2016):

BH mass down: $\lesssim 50\ M_\odot$
(pair-instability pulsations)

Belczynski et al. 2020 arxiv:2009.13526
BH mass back up: 100 M_{Sun}

3rd observing run (O3) highlights

- GW190412: the first BBH with definitively asymmetric component masses, which also shows evidence for higher harmonics
- GW190425: the second gravitational-wave event consistent with a BNS, following GW170817
- GW190426_152155: a low-mass event consistent with either an NSBH or BBH
- GW190514_065416: a BBH with the smallest effective aligned spin of all O3a events
- GW190517_055101: a BBH with the largest effective aligned spin of all O3a events
- GW190521: a BBH with total mass over 150 times the mass of the Sun, eccentricity favored e = 0.7
- GW190814: a highly asymmetric system of ambiguous nature, corresponding to the merger of a 23 solar mass black hole with a 2.6 solar mass compact object, making the latter either the lightest black hole or heaviest neutron star observed in a compact binary
- GW190924_021846: likely the lowest-mass BBH, with both black holes exceeding 3 solar masses

Rate estimate

- Use the number of black holes from stellar evolution models
- Merger fraction from simulations
- system parameters from observations

$$\mathcal{R}_{\rm sBH} = \int_{M_{\rm SMBH,min}}^{M_{\rm SMBH,max}} \frac{dn_{\rm AGN}}{dM_{\rm SMBH}} \frac{f_{\rm BH,mer} N_{\rm BH,cross}}{t_{\rm AGN}} dM_{\rm SMBH},$$

$$N_{\rm BH,cross} = N_{\rm BH,NSC} \frac{r_{\rm AGN}}{r_{\rm eff,NSC}},$$

$$N_{\rm BH,NSC} = \eta_{\rm n,BH} M_{\rm NSC},$$

$$M_{\rm NSC} = 4.3 \times 10^6 \, M_\odot \left(\frac{\sigma_{\rm Bulge}}{54 \ {\rm km \ s^{-1}}} \right)^{2.11}$$

$$\sigma_{\rm Bulge} = 200 \ {\rm km \ s^{-1}} \left(\frac{M_{\rm SMBH}}{3.1 \times 10^8 \, M_\odot} \right)^{0.228}$$

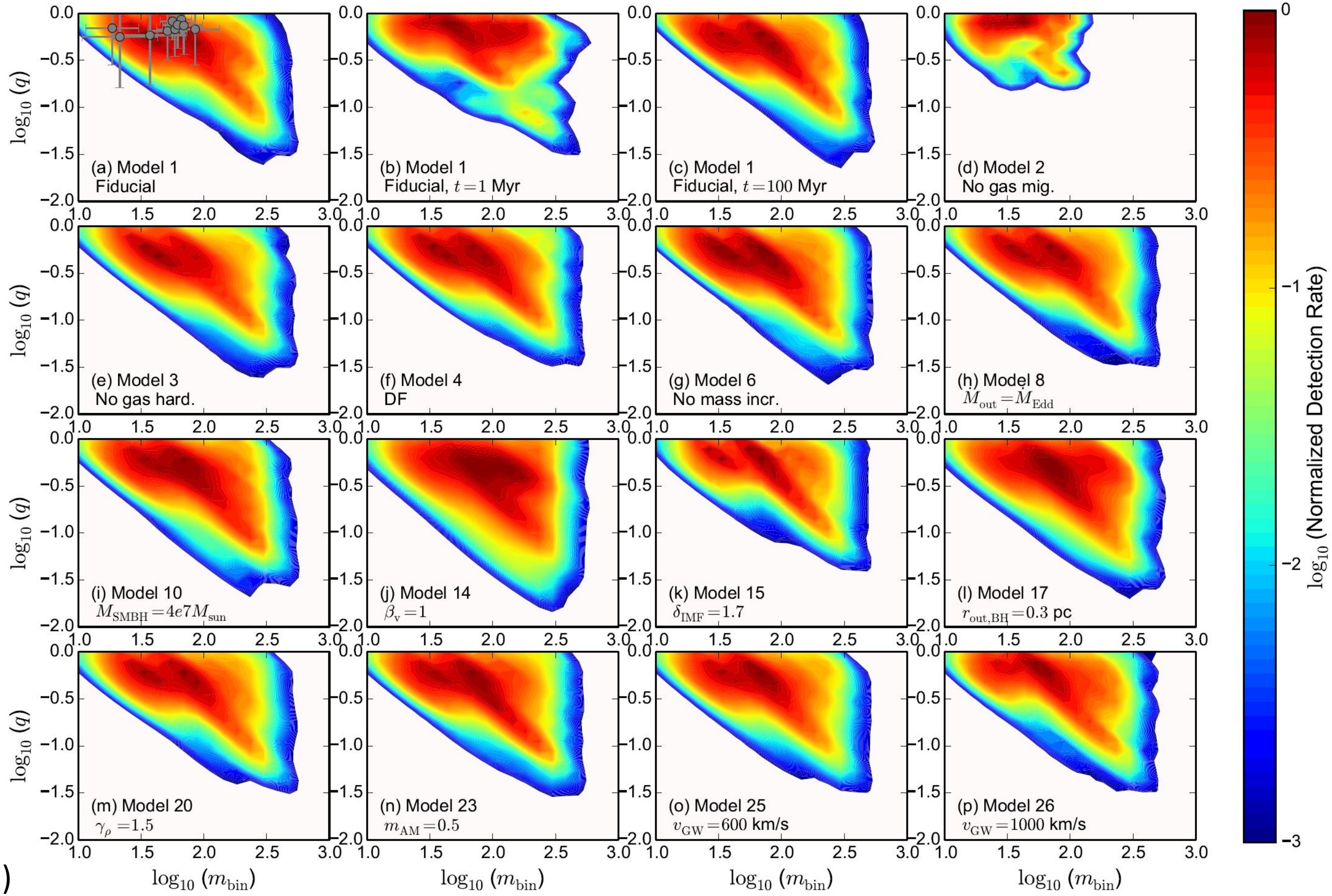
$$r_{\rm AGN} \sim {\rm pc} \left(\frac{L_{\rm bol}}{10^{45} \ {\rm erg}} \right)^{1/2} \sim 0.1 \ {\rm pc} M_{\rm SgrA}^{1/2} \left(\frac{f_{\rm Edd}}{0.03} \right)^{1/}$$

$$r_{\rm eff,NSC} = 3.23 \ {\rm pc} \left(\frac{M_{\rm NSC}}{3.6 \times 10^6 \, M_\odot} \right)^{0.321}$$

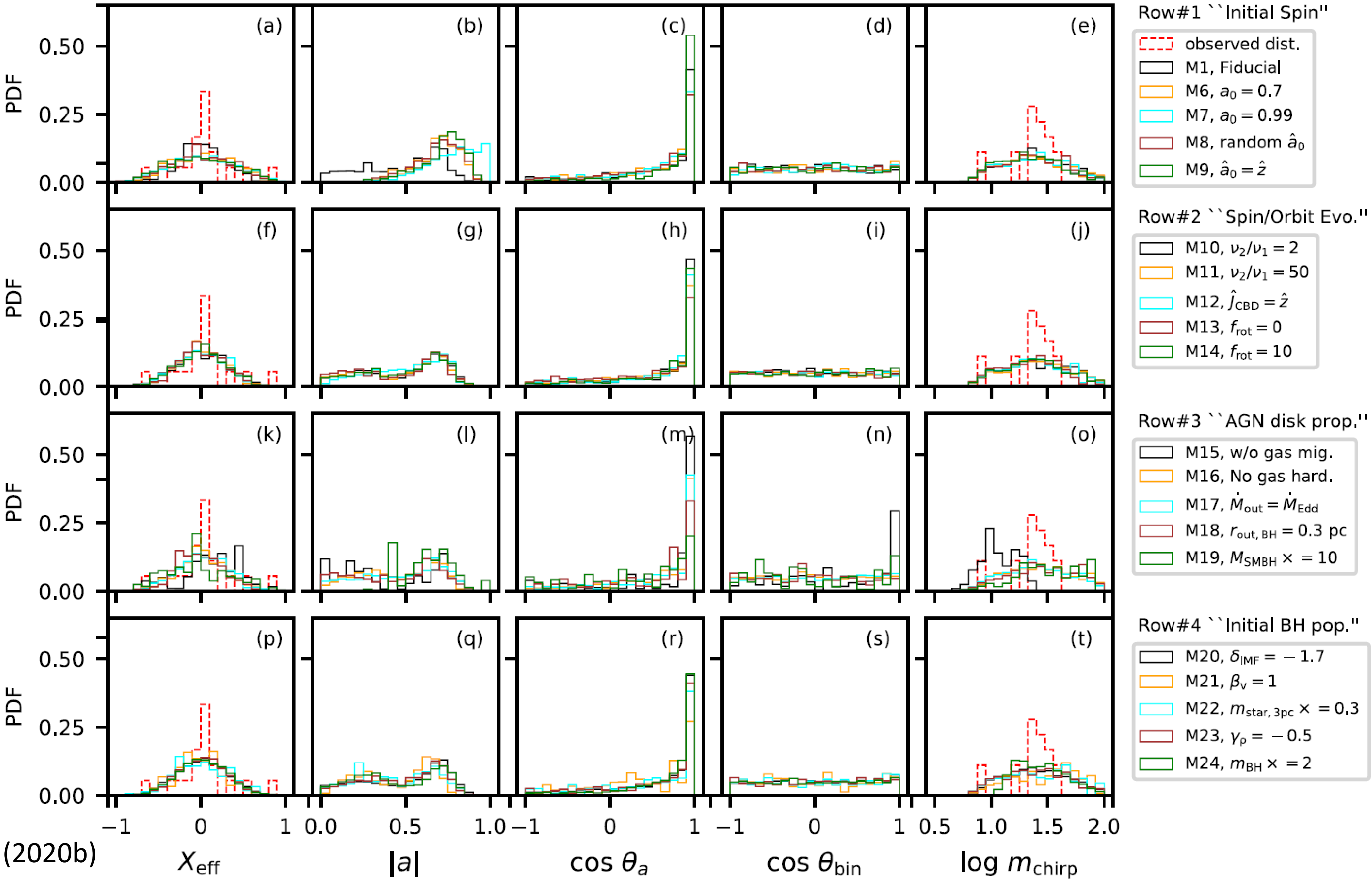
$$\mathcal{R}_{\rm sBH} \sim 3 \ {\rm Gpc^{-3} \ yr^{-1}} \left(\frac{f_{\rm BH,mer}}{0.5} \right) \left(\frac{t_{\rm AGN}}{30 \ {\rm Myr}} \right)^{-1} \left(\frac{r_{\rm AGN,MW}}{0.1 \ {\rm pc}} \right) \left(\frac{\eta_{\rm n,BH}}{0.005 \, M_\odot^{-1}} \right).$$

$$0.02 \ {\rm Gpc^{-3} \ yr^{-1}} \lesssim \mathcal{R}_{\rm sBH} \lesssim 60 \ {\rm Gpc^{-3} \ yr^{-1}}.$$

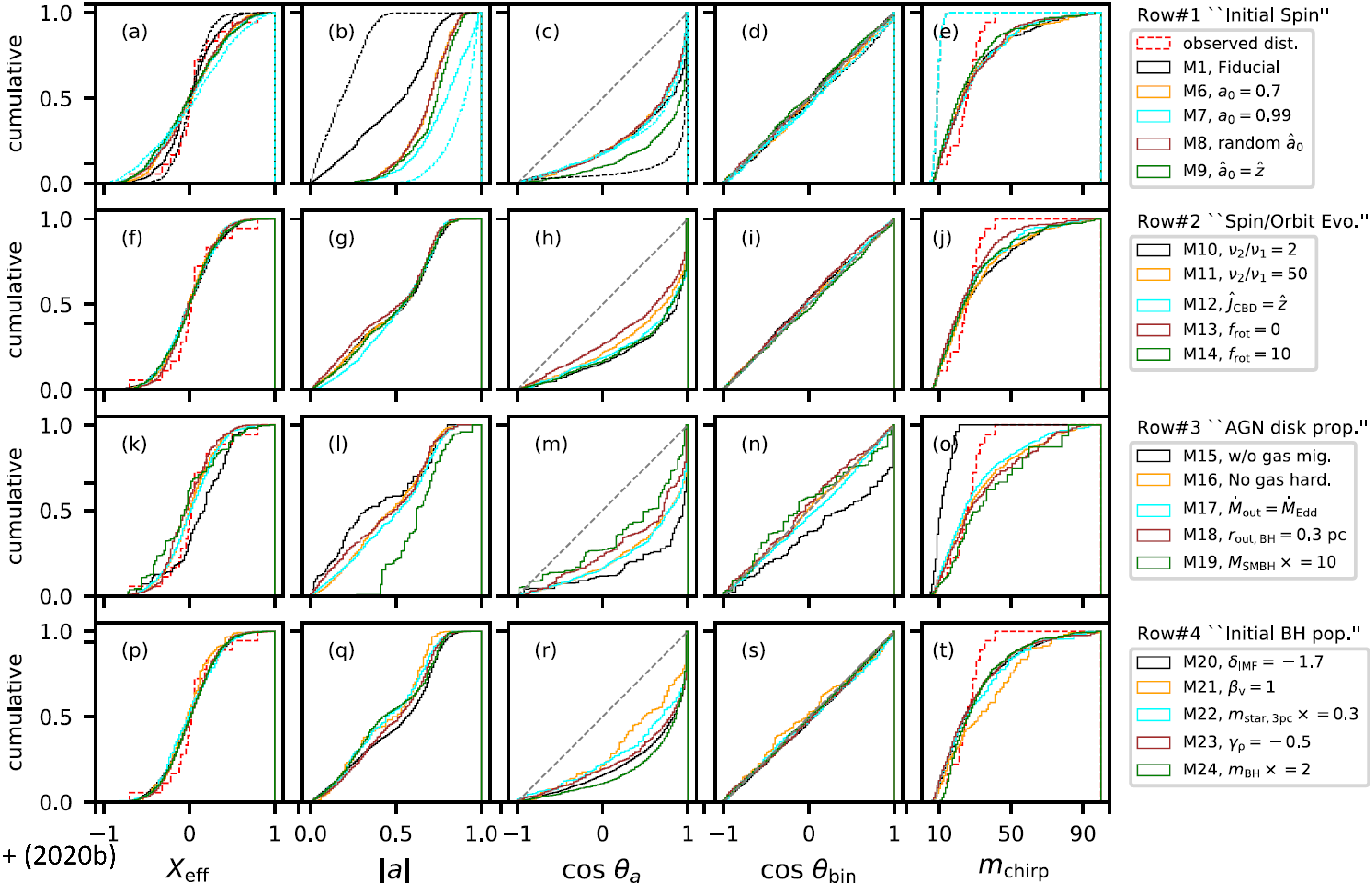
Binary total mass vs. mass ratio distribution



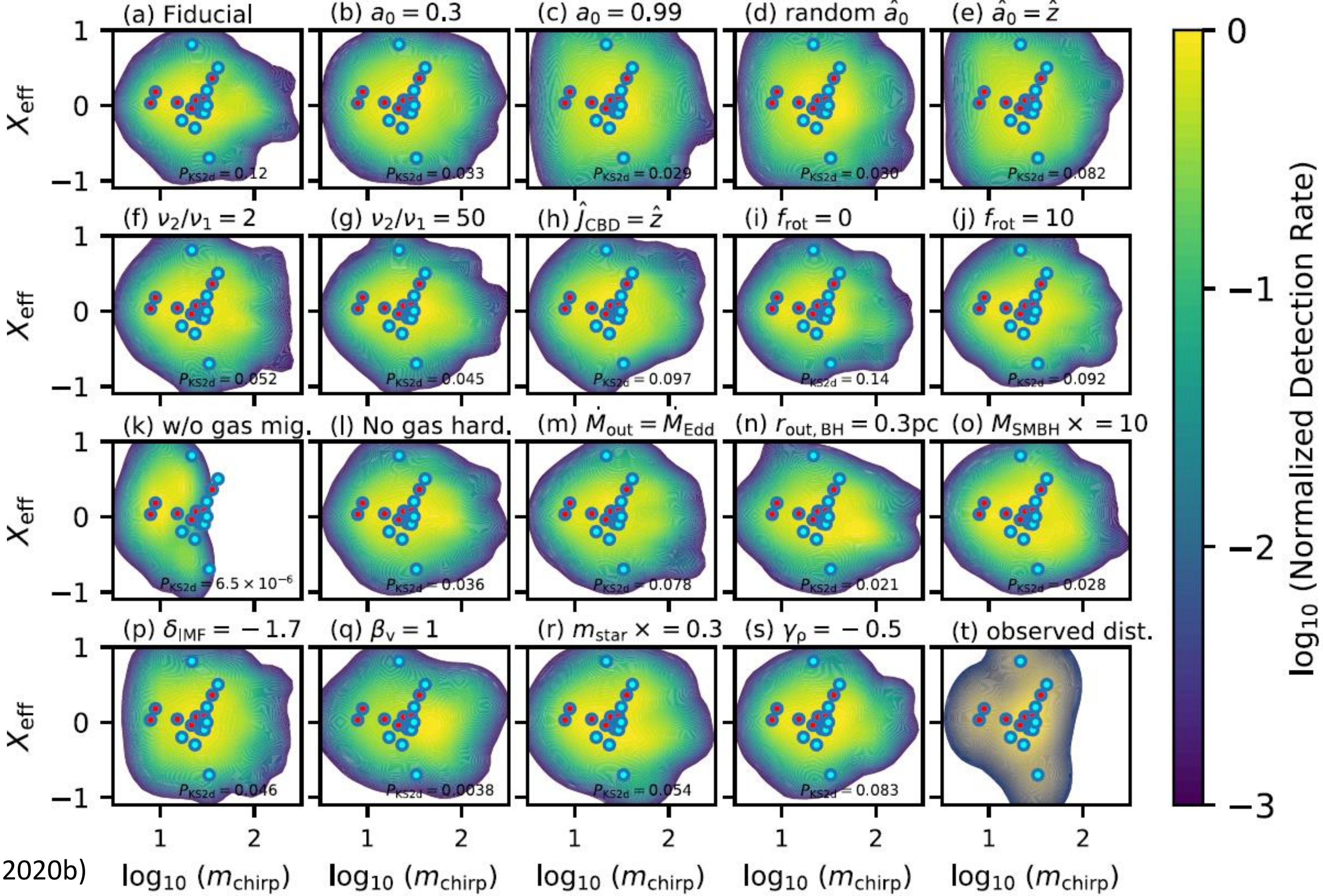
Tagawa+ (2020a)



Tagawa+ (2020b)



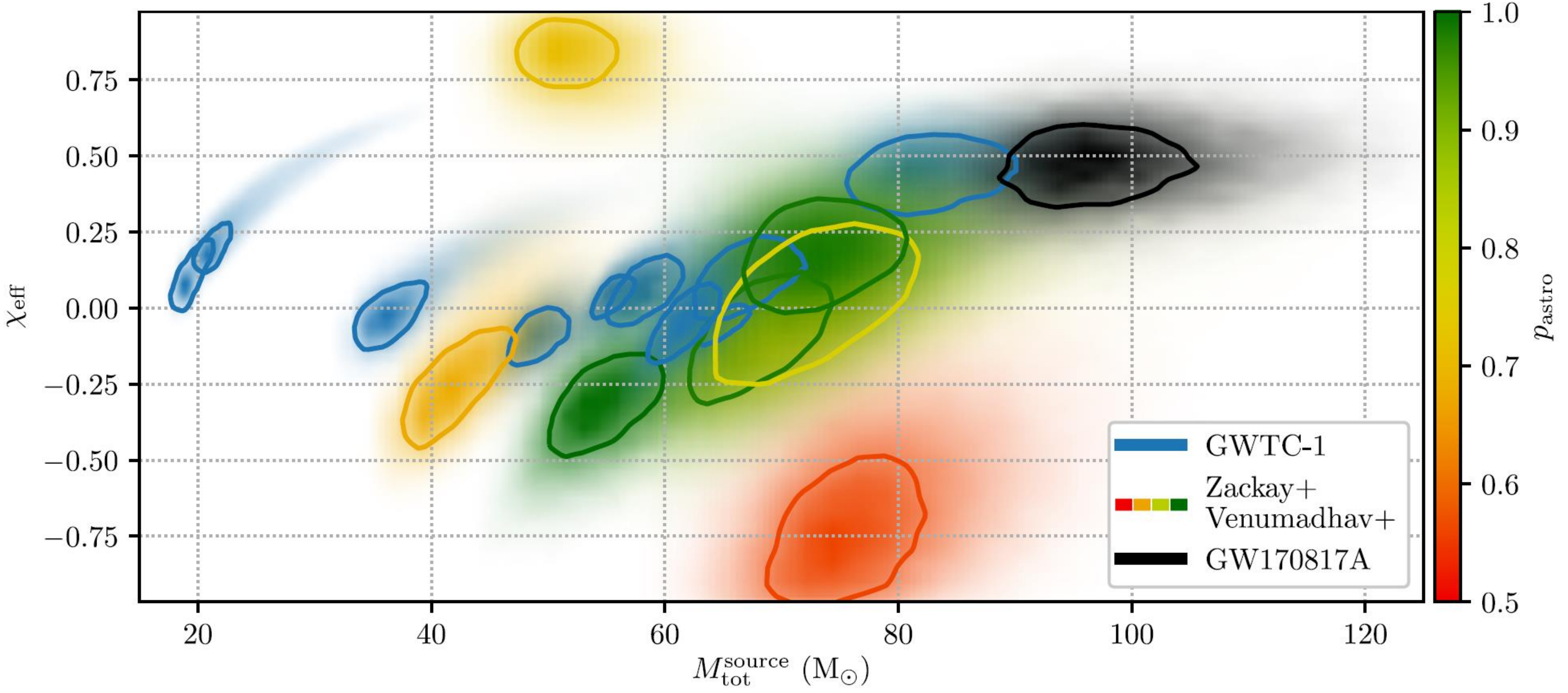
Tagawa+ (2020b)



Tagawa+ (2020b)

Mass vs. spins

$$\chi_{\rm eff} = \frac{(m_1\chi_1\cos\theta_1 + m_2\chi_2\cos\theta_2)}{M}$$



Venumadhav, Zackay, Roulet, Dai, Zaldarriaga, 2019

What about mergers with intermediate mass black holes?

$100\ M_{Sun} - 10^5\ M_{Sun}$

intermediate mass black holes

Theory

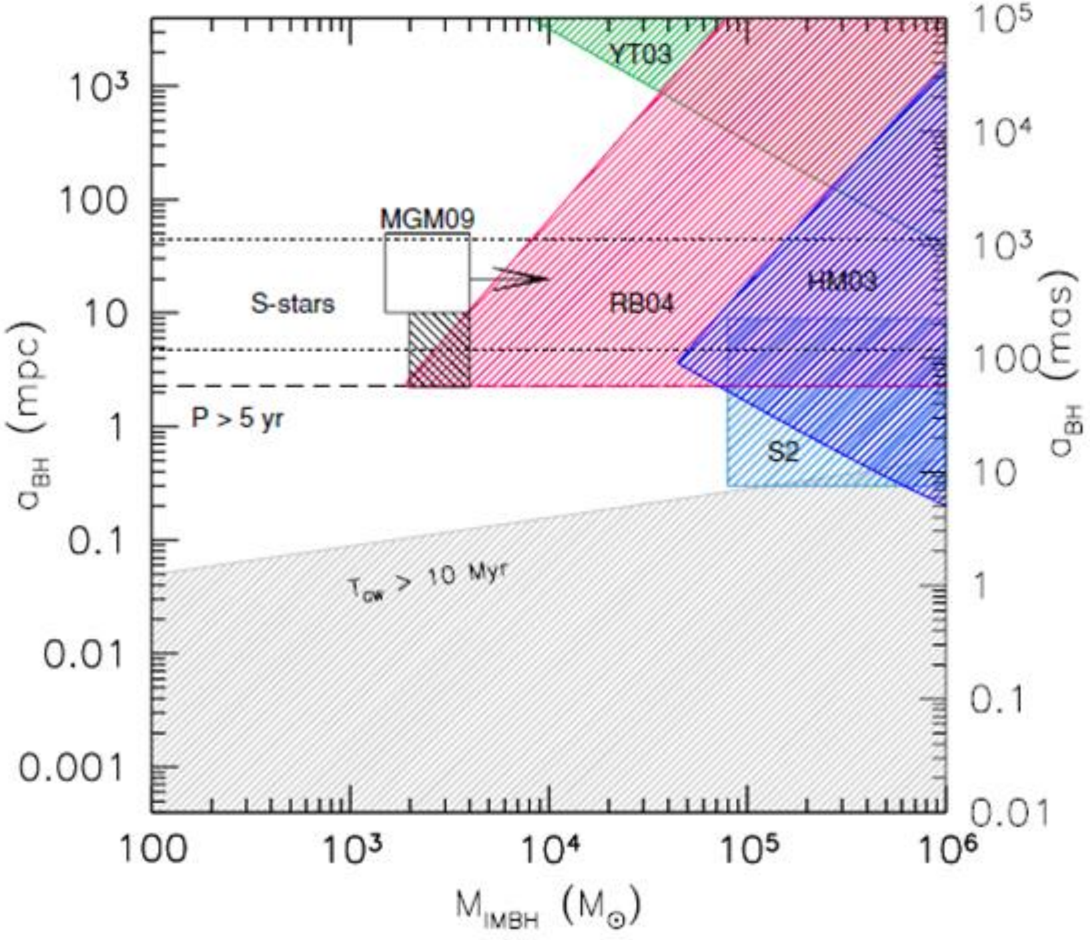
Formation

- Early universe:
  - collapse of the first stars (Madau & Reese ‘01)
- Globular clusters
  - runaway collisions (Portegies Zwart &McMillan ‘02)
  - mergers of stellar mass black holes (Miller & Hamilton ‘02)
  - dynamical friction

    → IMBH deposited in the galactic center
- In accretion disks (Goodman & Tan 04’, McKernan+ ‘12, ’14; Leigh+)

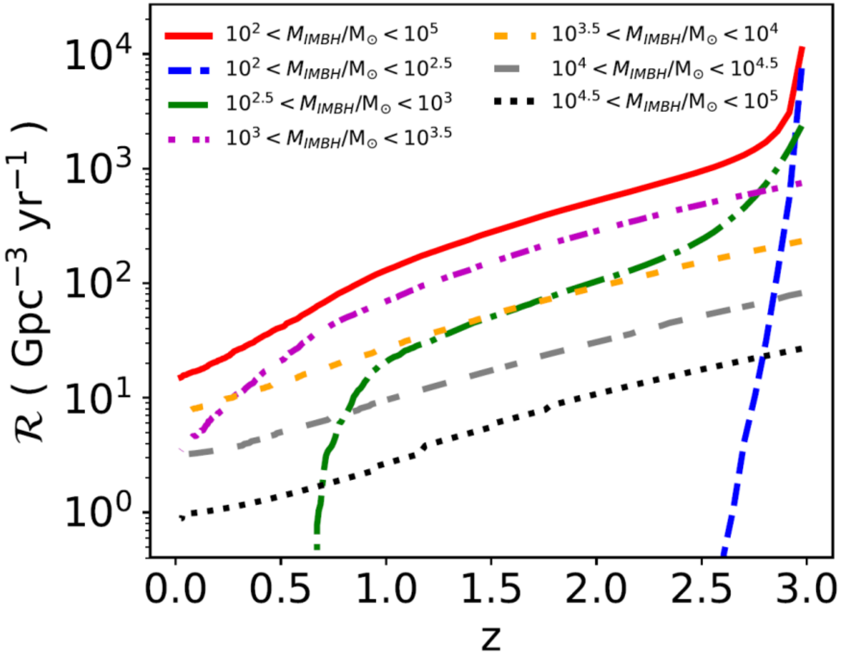
~ 50 IMBHs within 10 pc
~ 8,000 IMBHs within 1kpc

Observational constraints



Yu & Tremaine (2003)
Gualandris & Merritt (2009)

IMBH + BH mergers in globular clusters



current detectors limited to

$M < 300\ M_{sun}$ and $z<1$.

Such low mass IMBHs form in low mass globular clusters and get ejected from host cluster at $z > 2.6$ ☹

Advanced LIGO @ design sensitivity and LISA should see $M>300\ M_{sun}$ mergers at $z>0.6$

Fragione, Ginzburg, Kocsis 2018

BH mergers in AGN (most detailed models at present)

Tagawa, Haiman, Kocsis (2020)

- 1D semianalytical simulation of the evolution of BHs in AGN
  → BHs are followed in radius, inclination, without assumptions on migration traps
- Powerlaw nuclear star cluster with stellar disk and stellar BH components
  - Initial BH masses are limited to <15 Msun if the metallicity is solar
- Thompson+ (2005) thin alpha disk model
  - includes star formation → BH formation
- Gas interactions:
  - dynamical friction,
  - accretion,
  - type I/II migration (both from large scale disk and the minidisk),
  - gas capture binary formation
- Dynamical interactions
  - Binary single interactions -- note: GW captures, eccentricity effects, exchange interactions are neglected
- GW emission

Tagawa, Haiman, Kocsis (2020b)

- Follow-up paper includes BH spins
- Spins change due to BH mergers and accretion
- Orbital ang. mom. changes due to binary-single interactions

Simple models assuming “migration traps”

- AGN disk captures BHs from the nuclear star cluster one-by-one
- transported to migration traps immediately
- merge immediately with the stellar-mass BH already there → hierarchical mergers 1g-1g, 1g-2g, 1g-3g, …

Yang, Bartos, Haiman, Kocsis+ (2019)

- mass powerlaw exponent of mergers is harder by 1.3 than BH IMF
- mass ratio distribution is broad between 0.2 and 1, q=0.2 more likely by a factor 1.4

Yang, Bartos, Haiman, Kocsis+ (2020)

- redshift distribution decreases with z less rapidly until z=1 than for other merger channels

Gayathri, Bartos, Haiman+ (2020) (PRL)

- GW170817A and GW170729– M_{chirp}=40, Xeff=0.5 is explained by a 2g merger, expected for the AGN channel

Yang, Gayathri, Bartos, Haiman+ (2020)

- NS mergers + accretion may populate lower mass gap
- 0.5%-4% in lower mass gap for Eddington-limited to super-Eddington cases (Jiang, Stone, Davis19)

Other recent papers

- McKernan, Ford, Shaughnessy, Wysocki 2020a
  - semi-analytical model in which BHs migrate toward the migration trap on characteristic migration timescale
  - Spins are followed due to accretion (assumed to always be aligned or antialigned with disk)
  - Binaries form if another BHs enters within the Hill's sphere of a BH
  - Binaries are hardened on the migration timescale
  - Dynamical three-body interactions are neglected

  → Conclude that mergers are hierarchical mostly 1g+1g type in the bulk, with 10x less 1g-2g, and 100x less 1g-3g

  → mergers in migration traps are 1g-Ng type and Xeff peaked around 0.4, and -0.4
- McKernan, Ford, Shaughnessy 2020b
  - Same model as previous paper focusing on BH/NS, NS/NS mergers

  → BH/NS rate = 0.1—3 BH/BH rate;

  → NS/NS rate = 0.001—4 BH/BH rate
- Fabj, et al. (McKernan group) arXiv:2006.11229
  - settling of objects into the AGN disk using simple analytical models (same as Bartos+ 2017)

  → Critical density for capture is 10^{-11} g/cm^3
- Gröbner, Ishibash, Tiwari, Haney, Jetzer arXiv:2005.03571
  - disk-binary interaction including eccentricity evolution (toy model)
  - rate increases due to eccentricity
- Ishibash, Gröbner arXiv:2006.07407
  - Same model as in the previous paper, focusing on eccentricity evolution
  - Eccentricity significant for LISA but negligible for LIGO

Possible AGN counterpart – (controversial)

- Graham+ arXiv:2006.14122
  - AGN flare 34 days after LIGO candidate S190521g
  - they speculate that it could be a counterpart after a merger and GW kick

  ..but:
    - ½ m v_{kick}^2 = 4e49 erg, while flare has 100 times more energy (4e51 erg, 1e45 erg/s for 50 days)
    - false alarm calculation for coincidence with a flare uses a naïve Gaussian model
    - not explained what is special about the merger

      → if BHL accretion plays a role as claimed, then the flare should be larger well before the merger

      → disk crossing by BHs should be very common in all AGN which do not show flares

- McKernan, Ford, Bartos+ (2019)
  - order of magnitude of estimate for EM energy (ram-pressure stripping)
  - $E = ½\, m_{Hill}\, v_{kick}^2 = 10^{47}$erg, $t = r_{Hill}/v_{kick}$
  - $L=10^{41}$ erg/sec; t= 6 mo for $M_{SMBH} = 10^9$ Msun, v_{kick} = 100 km/s, $T = (m_H/k_B)\, v_{kick}^2 = 10^5$ K (UV)
  - diffusion time may be longer, decreasing the flare luminosity

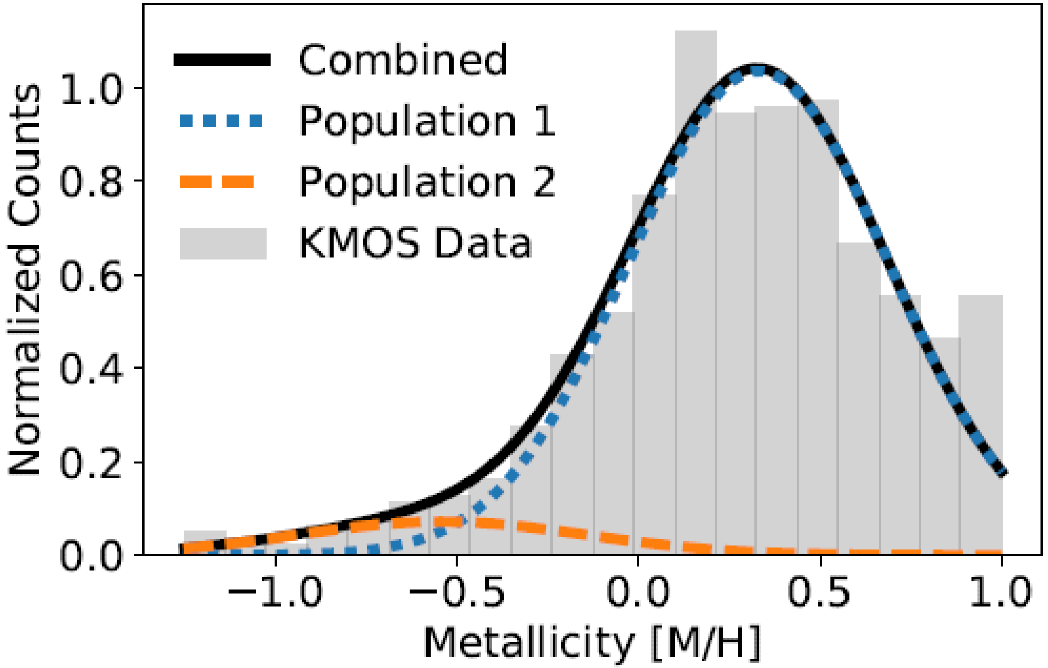
in nuclear star clusters

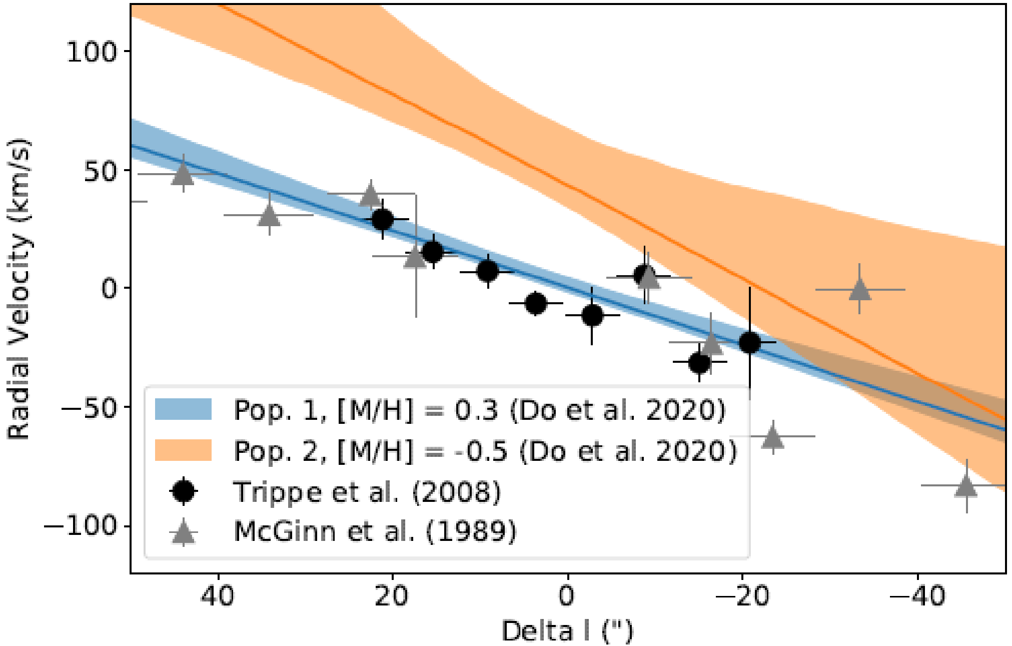
Metallicity is high in the Galactic center

(Do et al. 2015; Feldmeier-Krause et al. 2017a; Rich et al. 2017; Nandakumar et al. 2018; Schultheis et al. 2019)

Most recently

- Schödel+ arXiv:2007.15950
    - >90% of stars are super-solar
    - 7% of stellar mass have low-metallicity
- Do+ arXiv:2009.02335
    - 7% low-metallicity has a stronger rotation, it may be offset
- Arca-Sedda+ arXiv:2009.02328
    - 7% low-metallicy population is a remnant of an infalling globular cluster or a dwarf galaxy
    - >90% is star clusters (globular, young massive, open) that formed within 500 pc or stars that formed in situ





Stars in AGN may be different

Cantiello, Jermyn, Lin arXiv:2009.03936

- solar-type stars become massive by accretion from the AGN
- pollute AGN with metals

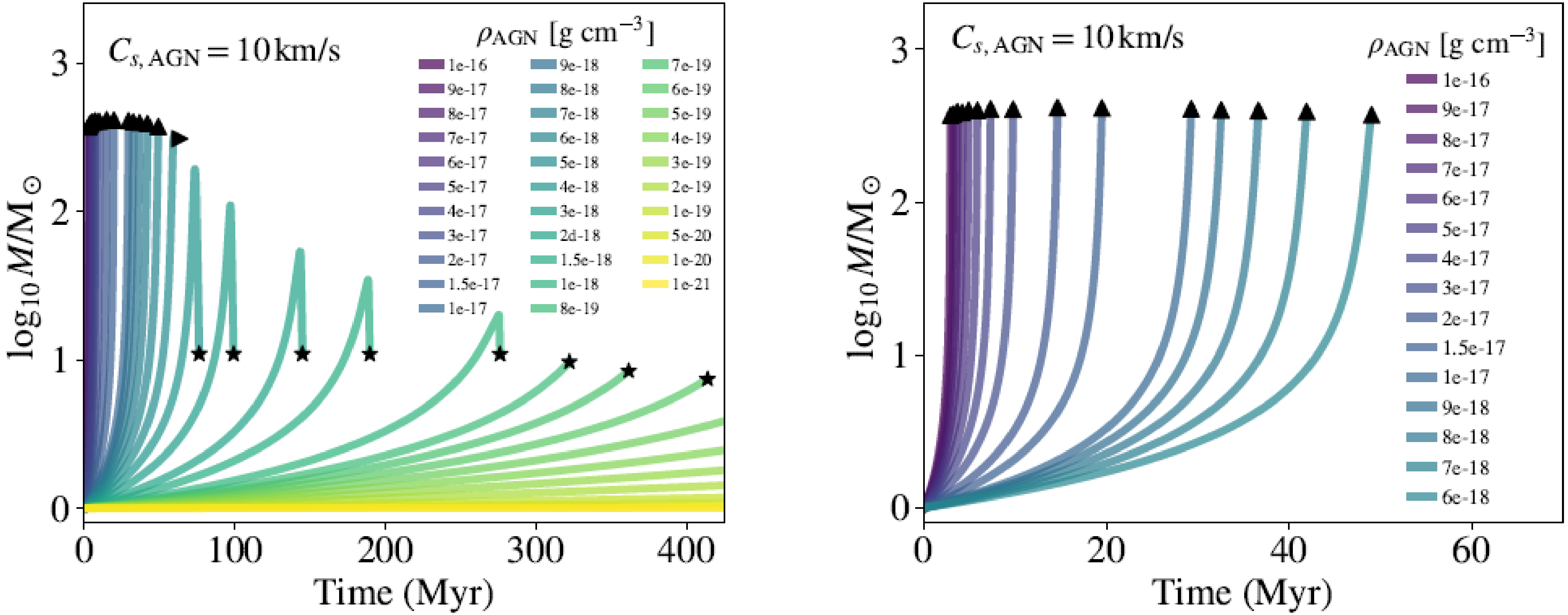
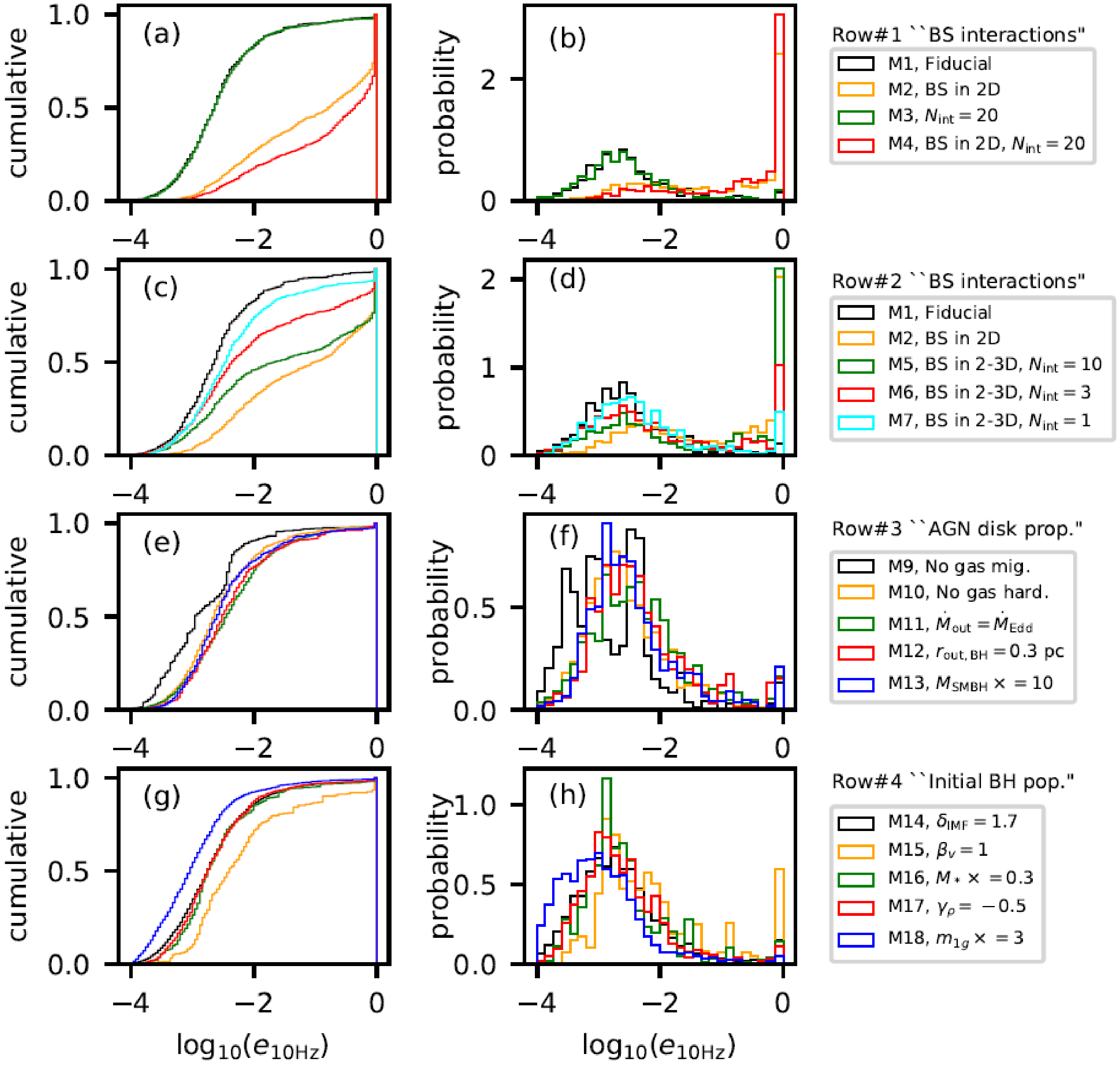


Figure 6. A grid of stellar models is shown after evolving with a fixed AGN sound speed of 10 km s^{-1} and AGN densities ranging from 10^{-16} to 10^{-21} g cm^{-3}. The panels show the evolution of stellar mass as function of time for models starting with $M = 1\mathrm{M}_\odot$.

eccentricity dist.

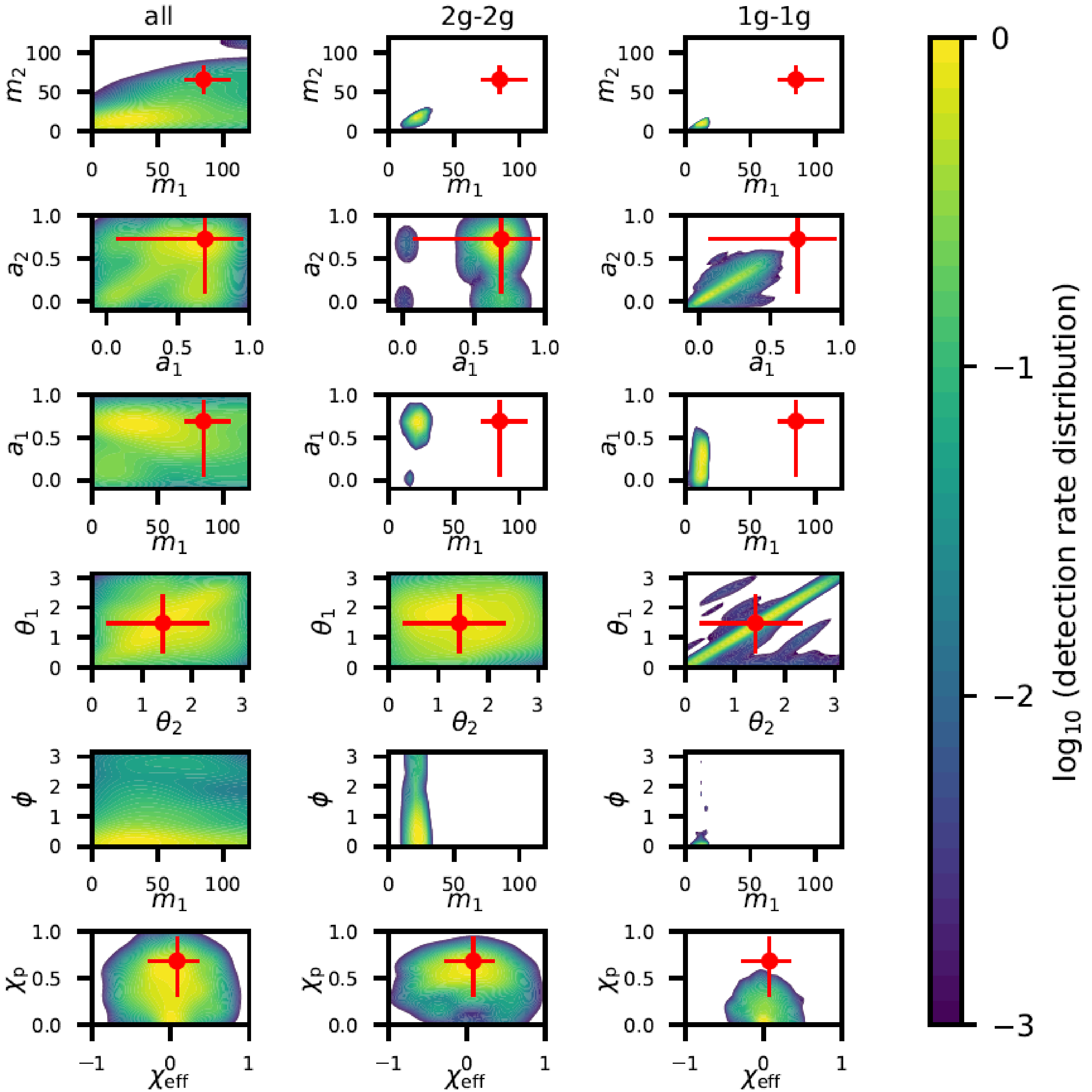


- peaked at e = 10^-3 at 10 Hz in the fiducial model with isotropic binary-single scattering interactions
- but peaked at high e if the binary-single interactions are in 2D

Tagawa+ (2020c) in prep.

Comparison with GW190521

- High BH masses in GW190521 can be explained by mergers in AGN either by
    1. High generation mergers
    2. 2g-2g mergers if the 1g BH masses are high
    3. Super-Eddington accretion



Tagawa+ (2020d) in prep.

Option 3: triples

Tertiary perturber:

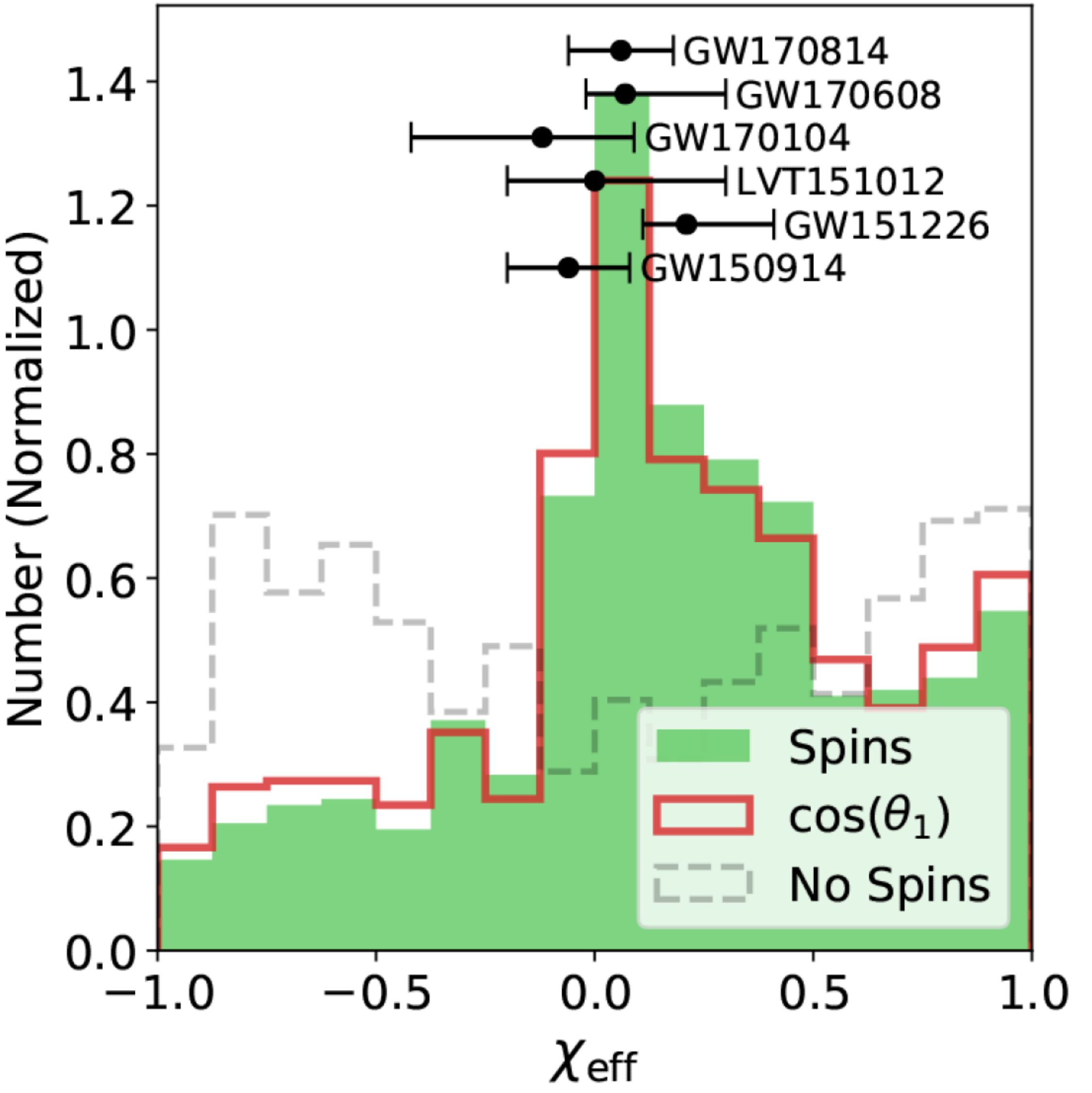
- Kozai-Lidov effect increases eccentricity

  → merger

  - spins **align in the perpendicular** direction at quadrupole order
    but generally do not align

- expected **rates are**

  2 – 25 Gpc^{-3} yr $^{-1}$



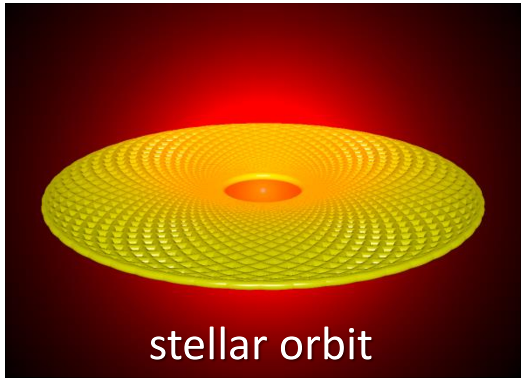
Silsbee & Tremaine 2017; Antonini+ 2017, 2018; Hamers+ 2018; Hoang, Naoz, Kocsis+ 2018; Liu & Lai 2017, 2018, 2018; Liu, Lai, Wang 2019; Fragione, Kocsis 2019, etc.

$$\chi_{\rm eff} = \frac{(m_1\chi_1\cos\theta_1 + m_2\chi_2\cos\theta_2)}{M}$$

Black hole disks

Motion of stars in the galactic disk:

- Elliptic orbit around supermassive black hole
- Precession due to spherical component of star cluster



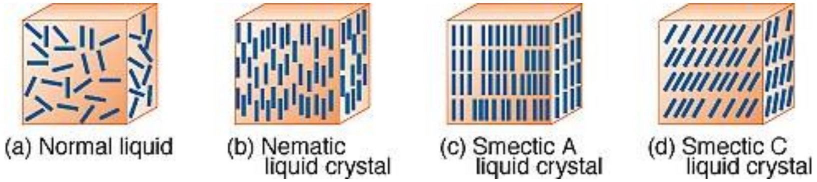
Orbital planes reorient and relax very quickly

Long term gravitational interaction of stellar orbits = Interaction among liquid crystal molecules

(Kocsis+Tremaine 2015, Kocsis+Tremaine in prep., Roupas+Kocsis+Tremaine in prep)

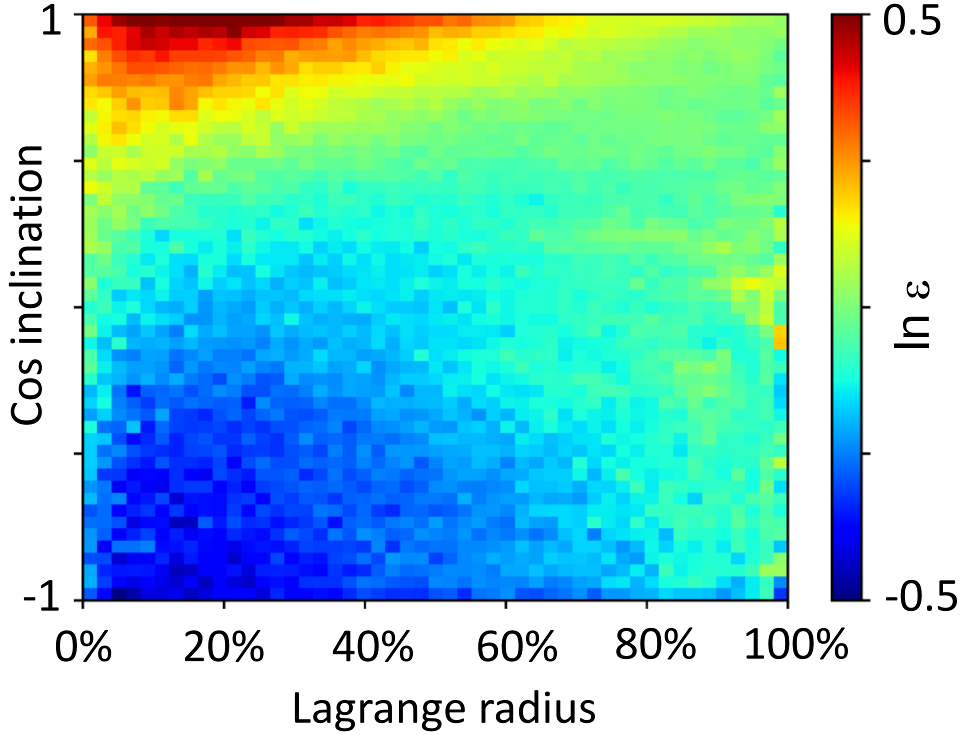
Maximum entropy:

- massive objects: ordered phase
- light objects: spherical phase
- Implication: Black hole disks !



Black hole disks in globular clusters

- Does this happen in globular clusters? – yes!
- Average mass at a given inclination and radius relative to average mass at a given radius



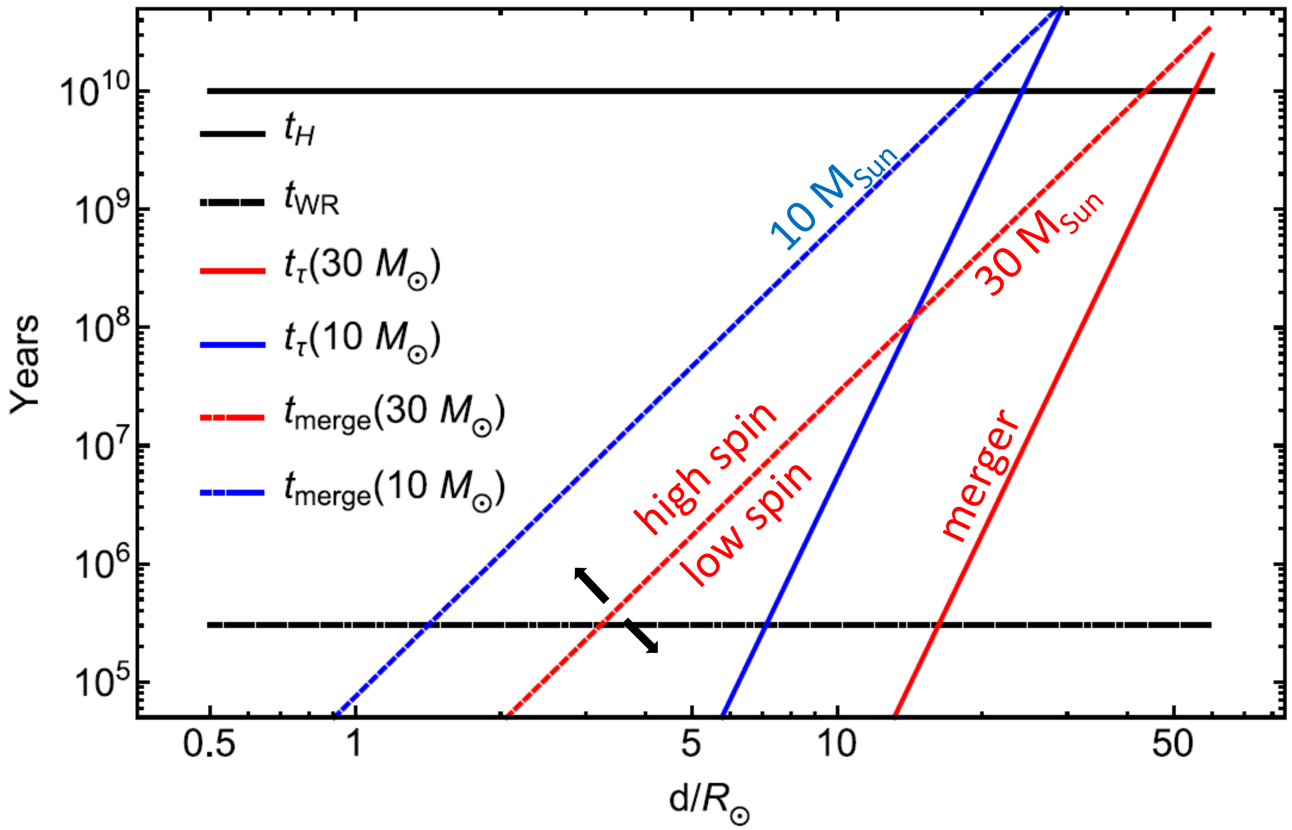
Average mass at a given inclination and radius relative to average mass at given radius

$$\varepsilon(r, \cos i) \equiv \frac{\bar{m}(r, \cos i)}{\bar{m}(r)}$$

Szolgyen, Meiron, Kocsis 2019

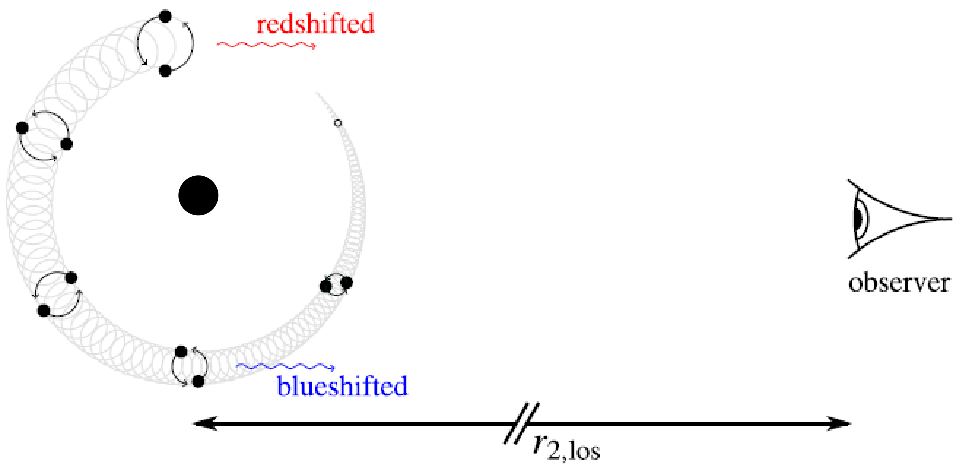
Option 1: stellar binary evolution

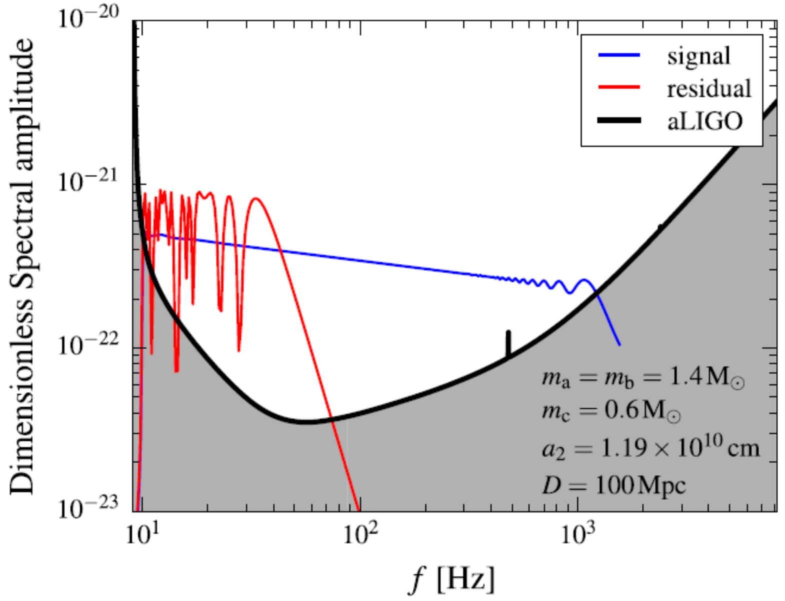
- Progenitor WR star is spun up to high spins?
- What is black hole spin after formation?
- Spin up from accretion?



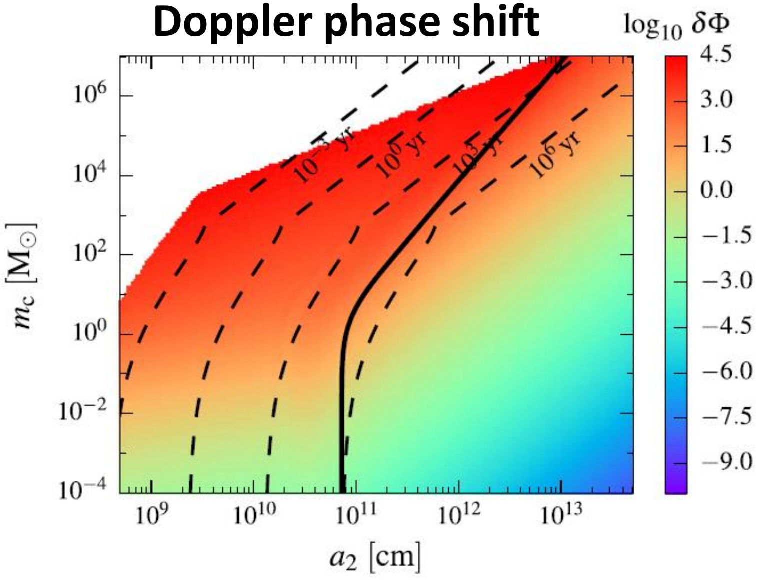
Kushnir+ 2017; Zaldarriaga+ 2018

How to test if sources are in AGN?

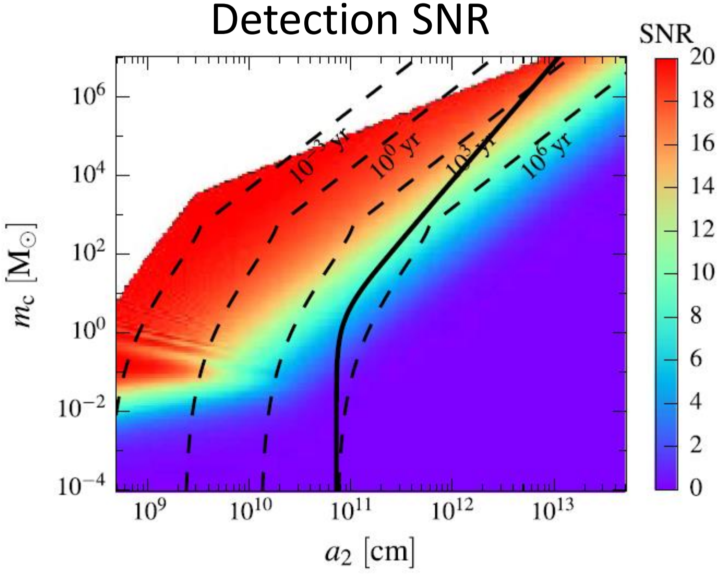




Doppler phase shift



Detection SNR



Meiron, Kocsis, Loeb 2017

Distinguishing sources

from different channels

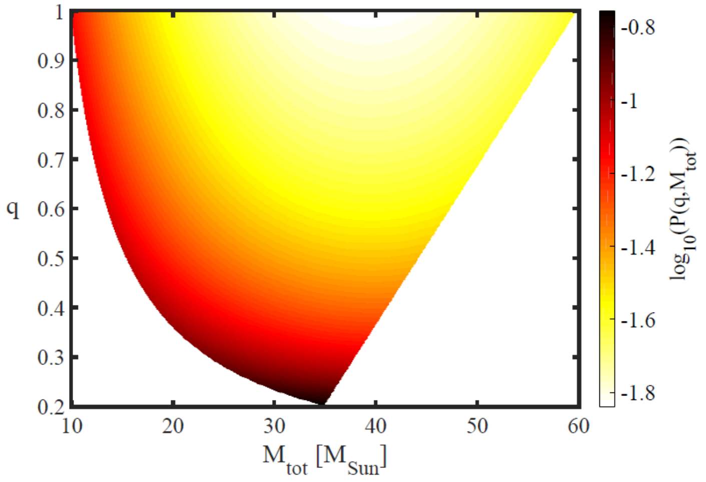
- eccentricity, mass, spin distribution
- electromagnetic counterparts
- intermediate mass black holes

Mass distribution for different processes

universal diagnostic: independent of the mass function

Given: $\mathcal{R}(m_1, m_2) \propto \mathcal{L}(m_1, m_2) f(m_1) f(m_2)$

How can we eliminate the unknown f(m)?



$$\boxed{-(m_1+m_2)^2 \frac{\partial^2}{\partial m_1 \partial m_2} \ln \mathcal{R}(m_1, m_2, t)}$$

$= \mathbf{4}$ in globular clusters (*needs revision)

$= \mathbf{1.4 \ldots -5}$ for GW capture binaries in galactic nuclei

$= \mathbf{1.4}$ for GW capture binaries in collisionless systems

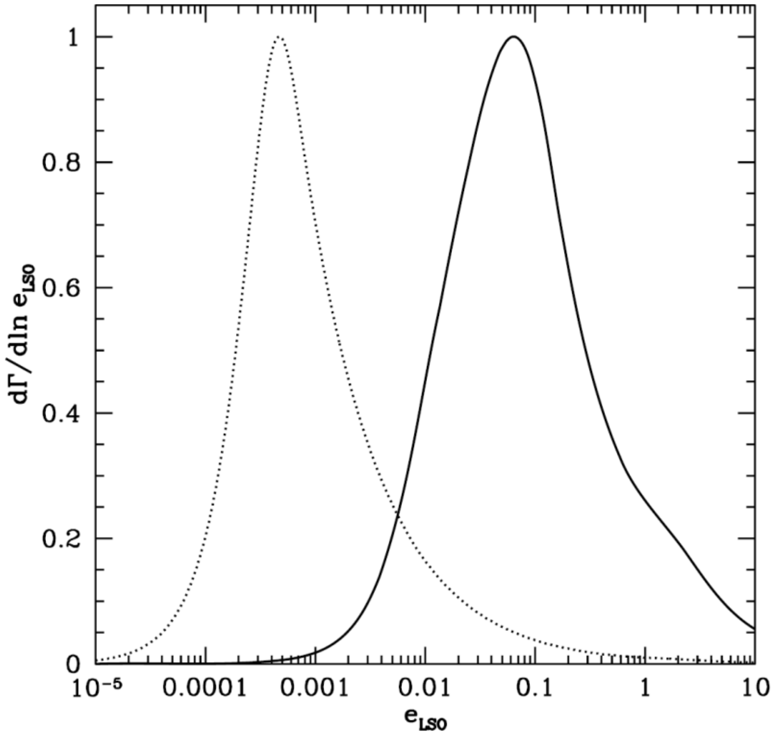
$= \mathbf{1}$ for PBH binaries formed in early universe

Kocsis, Suyama, Takahiro, Yokoyama 2018; Gondan, Kocsis, Raffai, Frei 2018

Eccentricity distribution for GW capture binaries

Velocity dispersion → maximum initial pericenter distance r_p/M → eccentricity at merger

$$\boxed{\sigma \sim 258\,\frac{\mathrm{km}}{\mathrm{s}}\,(4\eta)^{1/2}\left(\frac{e_{\mathrm{LSO,peak}}}{0.01}\right)^{35/32}}$$



O’Leary, Kocsis, Loeb (2009); see also Rodriguez+ 2016, Gondan+ 2018, Samsing 2017

Eccentricity distribution for GW capture binaries

Velocity dispersion → maximum initial pericenter distance r_p/M → eccentricity at merger

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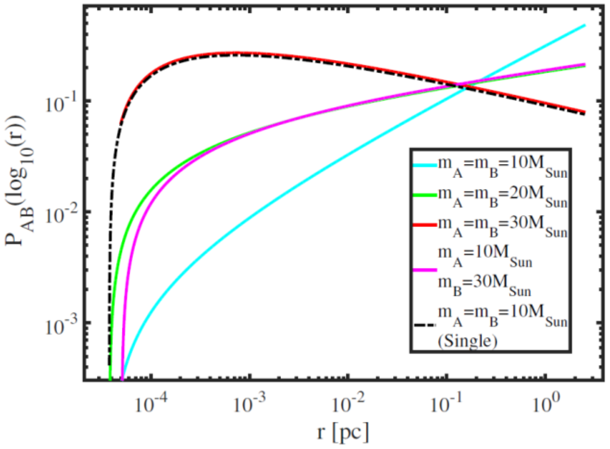
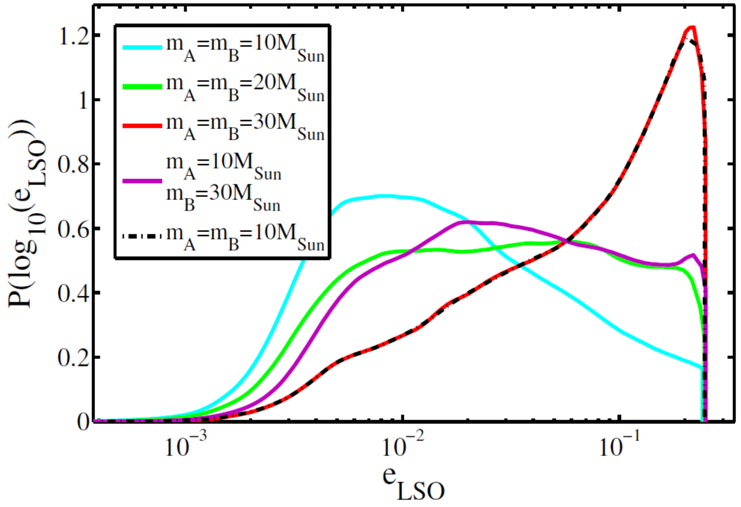


radial distribution of mergers shows mass segregation



→ Eccentricity distribution reveals mass segregation

Gondán, Kocsis, Raffai, Frei (2018b)

Eccentricity distribution
for GW capture binaries

Velocity dispersion → maximum initial pericenter distance r_p/M → eccentricity at merger

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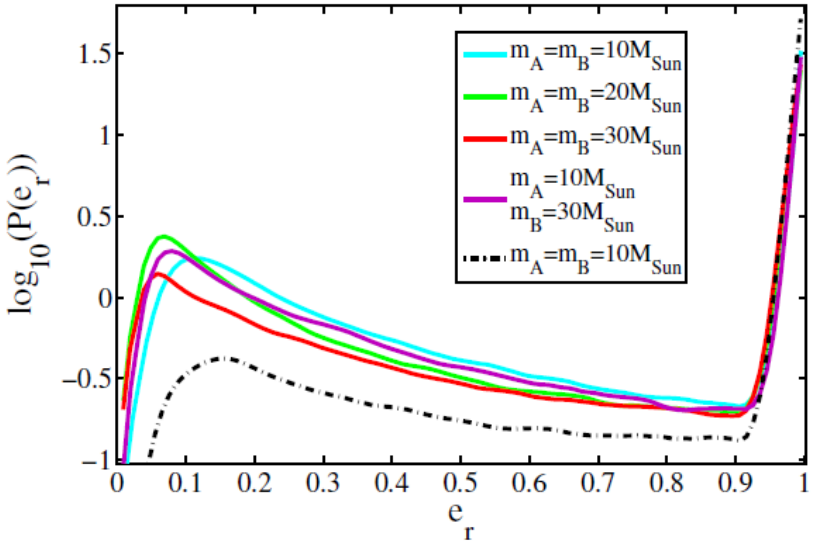
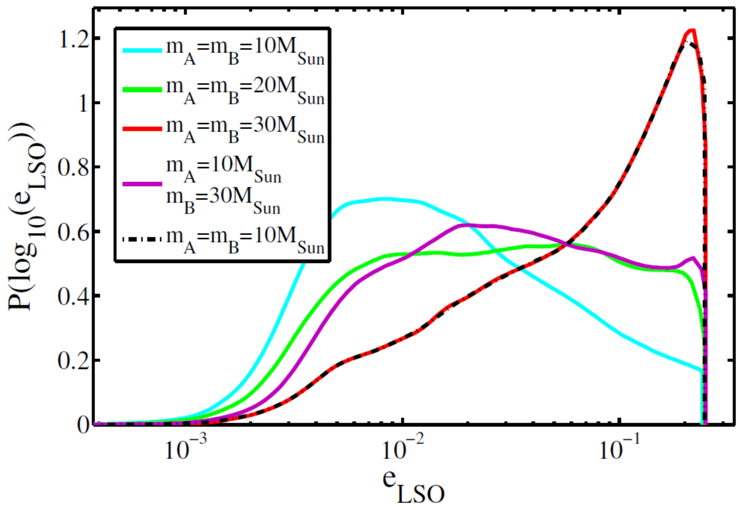


Eccentricty distribution when ALIGO first sees it (design sensitivity)



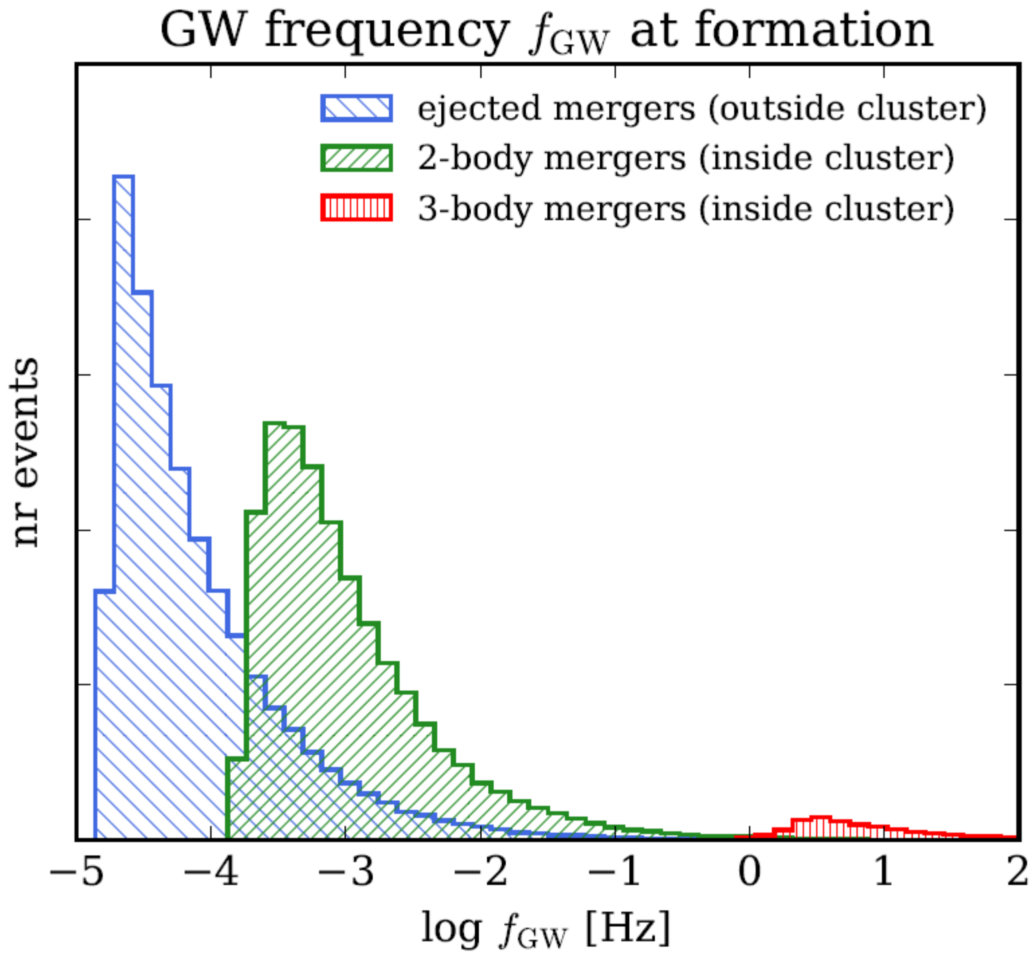
→ Eccentricity distribution reveals mass segregation

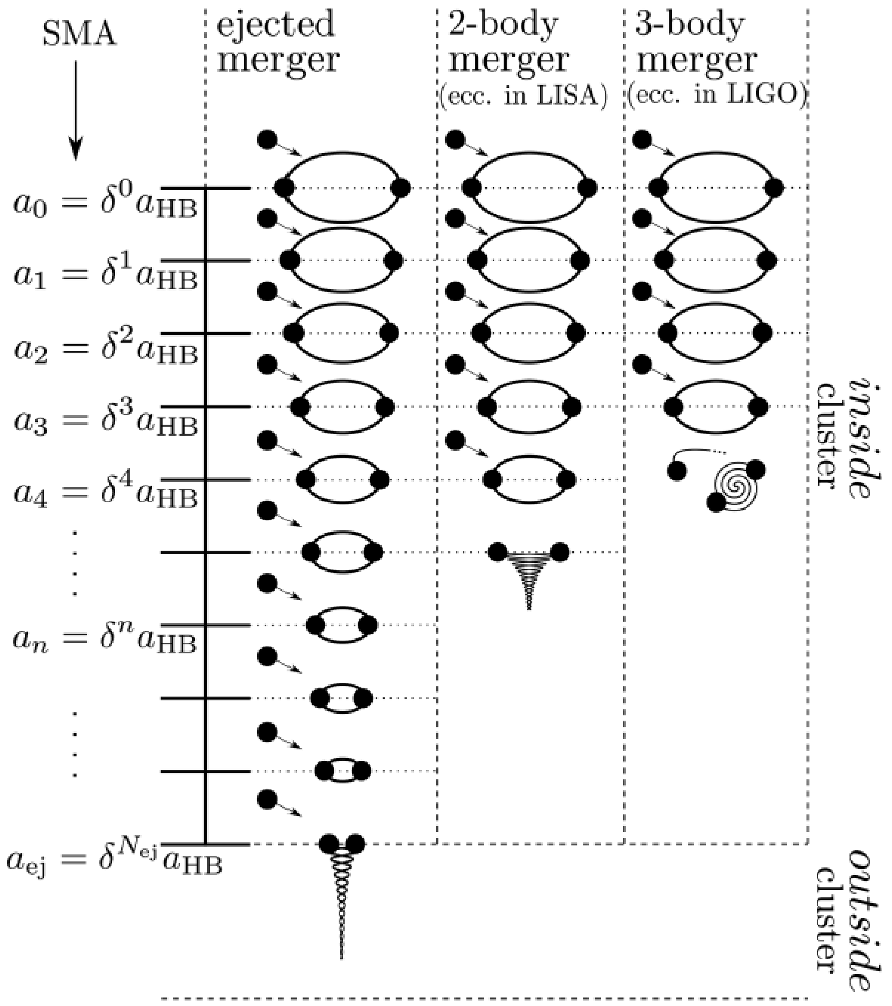
cf. measurement accuracy $\Delta e_{LSO} \sim 10^{-2}$–$10^{-3}$

$30M_{Sun}+30M_{Sun}$ @ 1Gpc

Gondán, Kocsis, Raffai, Frei (2018a,b)

Eccentricity distribution
for merging globular cluster binaries

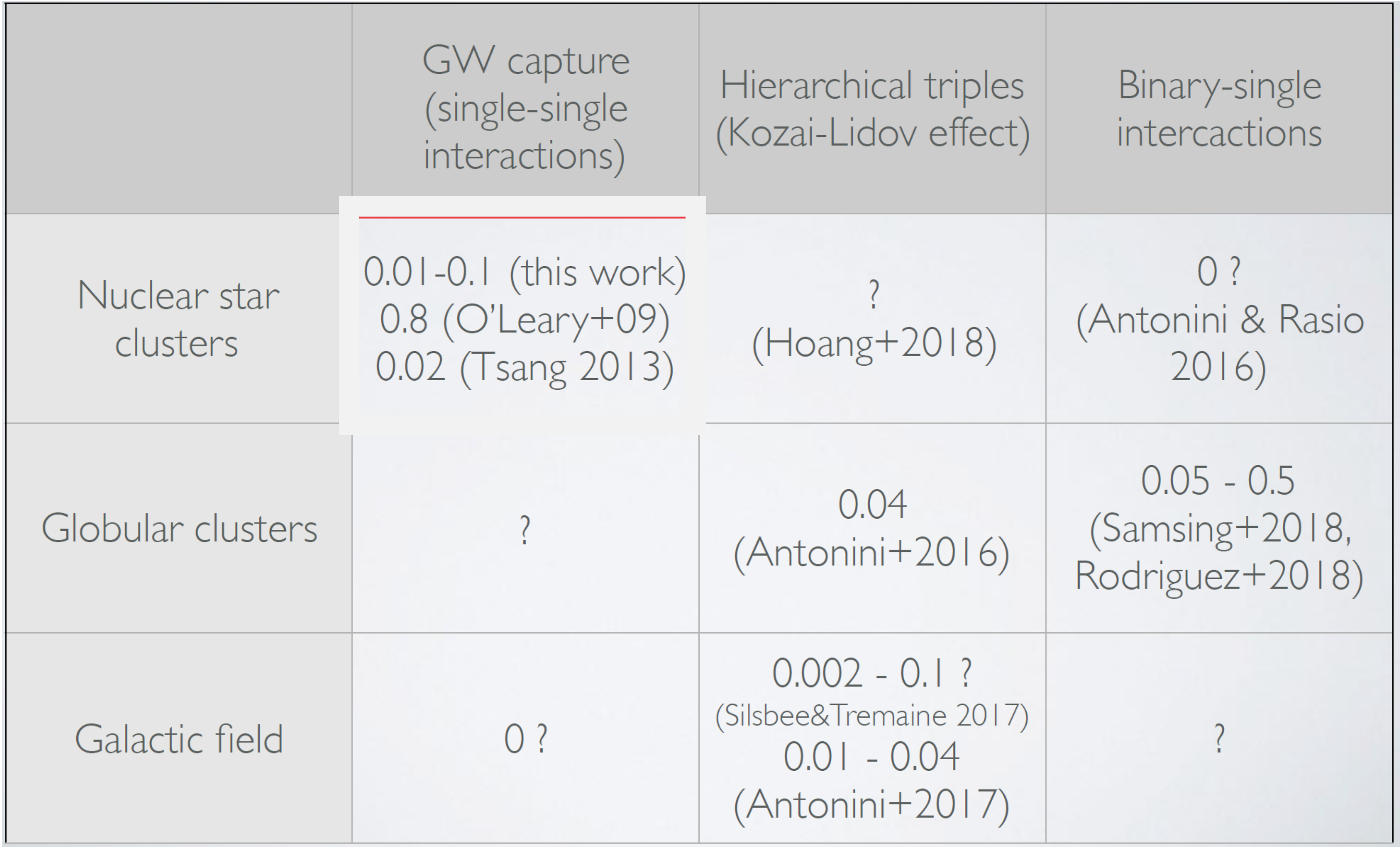




Samsing+ (2018a, 2018b)

Eccentric sources:

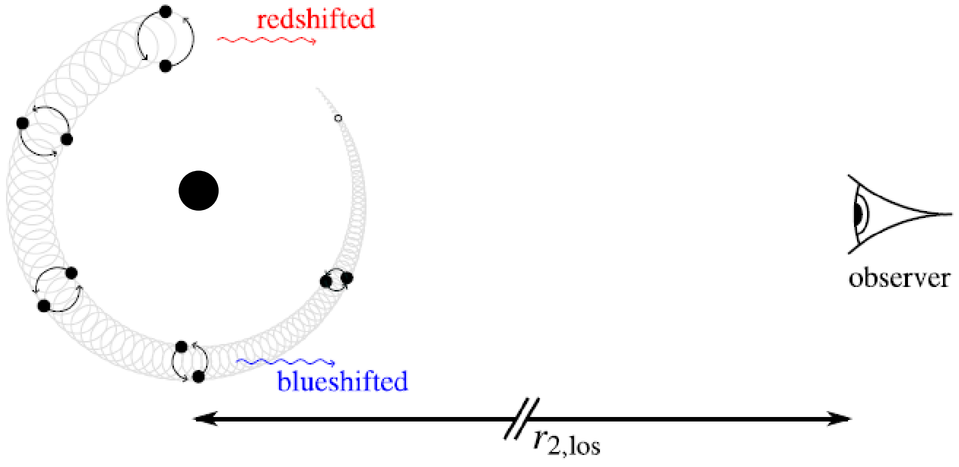
rates from different channels

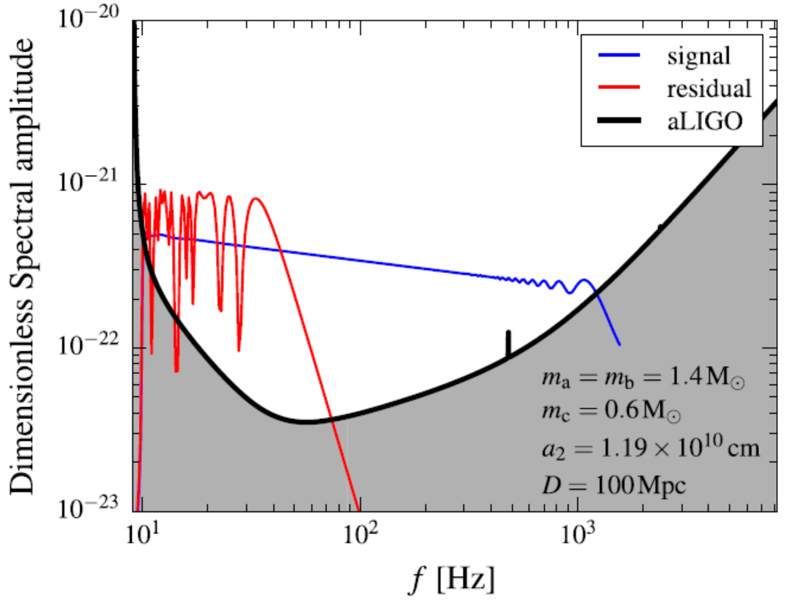


	GW capture (single-single interactions)	Hierarchical triples (Kozai-Lidov effect)	Binary-single intercactions
Nuclear star clusters	0.01-0.1 (this work) 0.8 (O'Leary+09) 0.02 (Tsang 2013)	? (Hoang+2018)	0 ? (Antonini & Rasio 2016)
Globular clusters	?	0.04 (Antonini+2016)	0.05 - 0.5 (Samsing+2018, Rodriguez+2018)
Galactic field	0 ?	0.002 - 0.1 ? (Silsbee&Tremaine 2017) 0.01 - 0.04 (Antonini+2017)	?

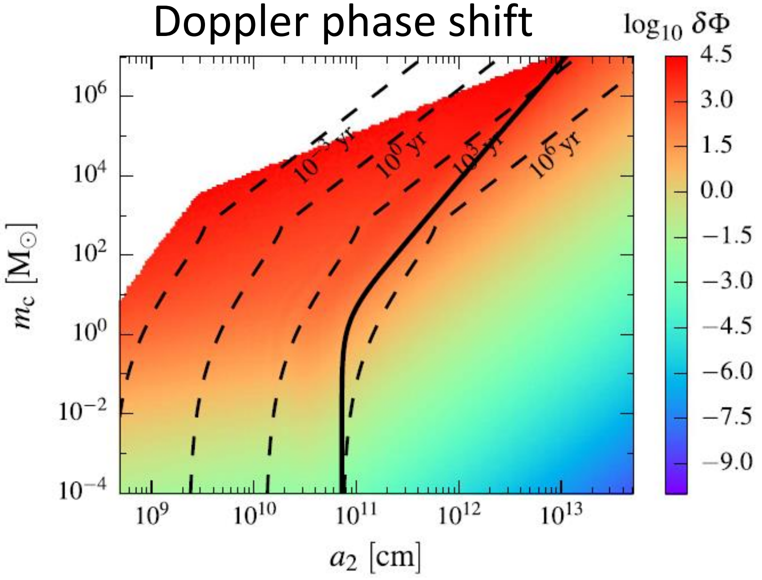
Smoking gun signatures
to identify origin of source

SMBH/AGN source with LIGO

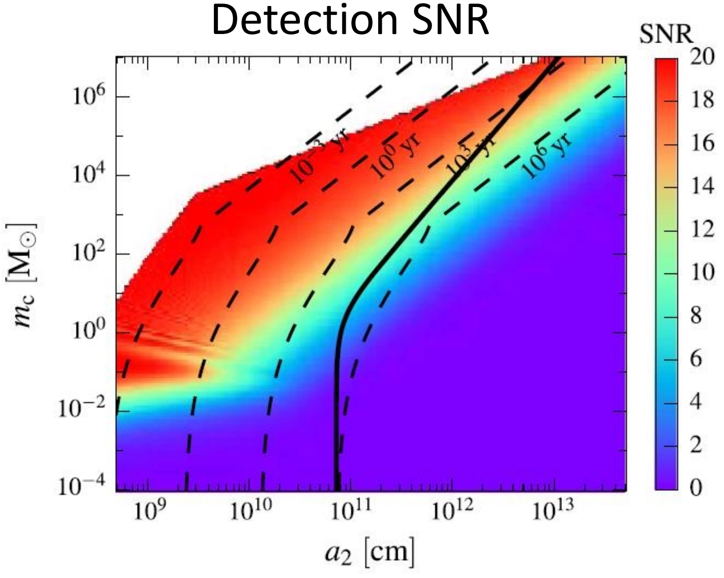




Doppler phase shift

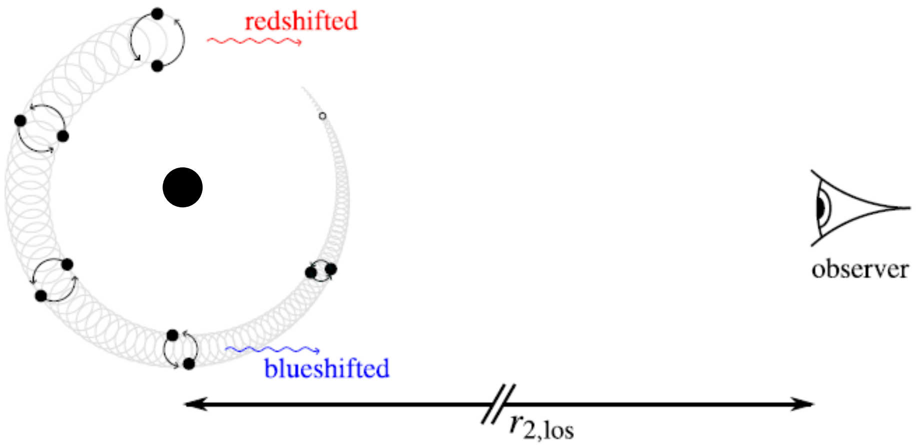


Detection SNR

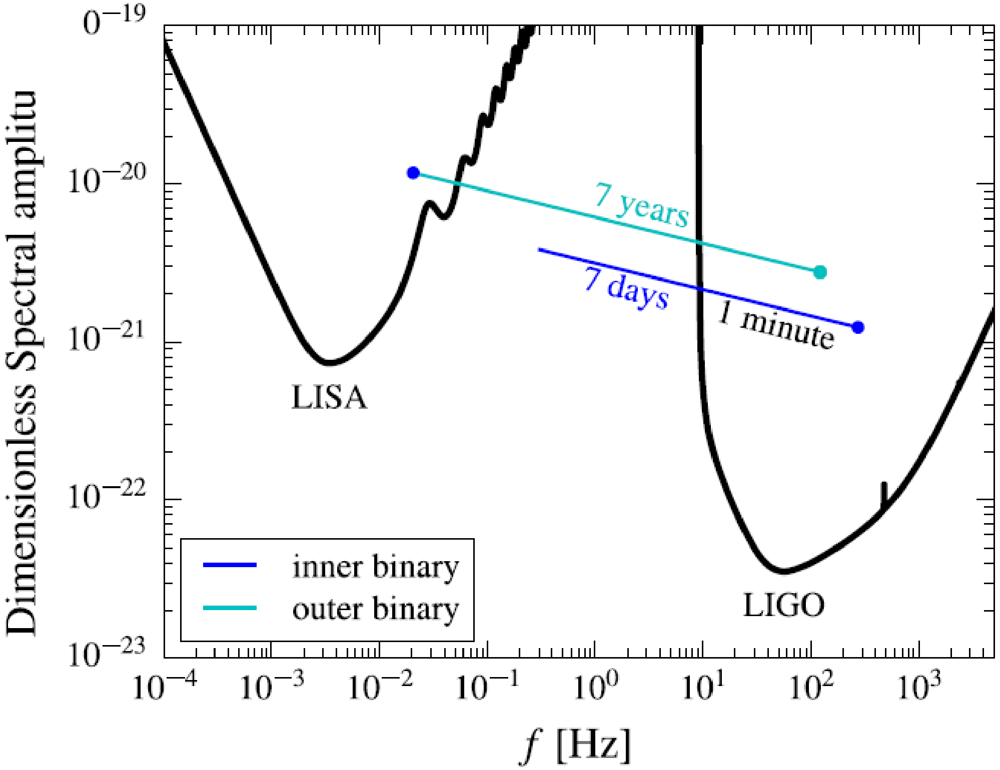


Meiron, Kocsis, Loeb 2017

SMBH/AGN source with LIGO+LISA



see also Sesana (2016), Inayoshi+ (2017)

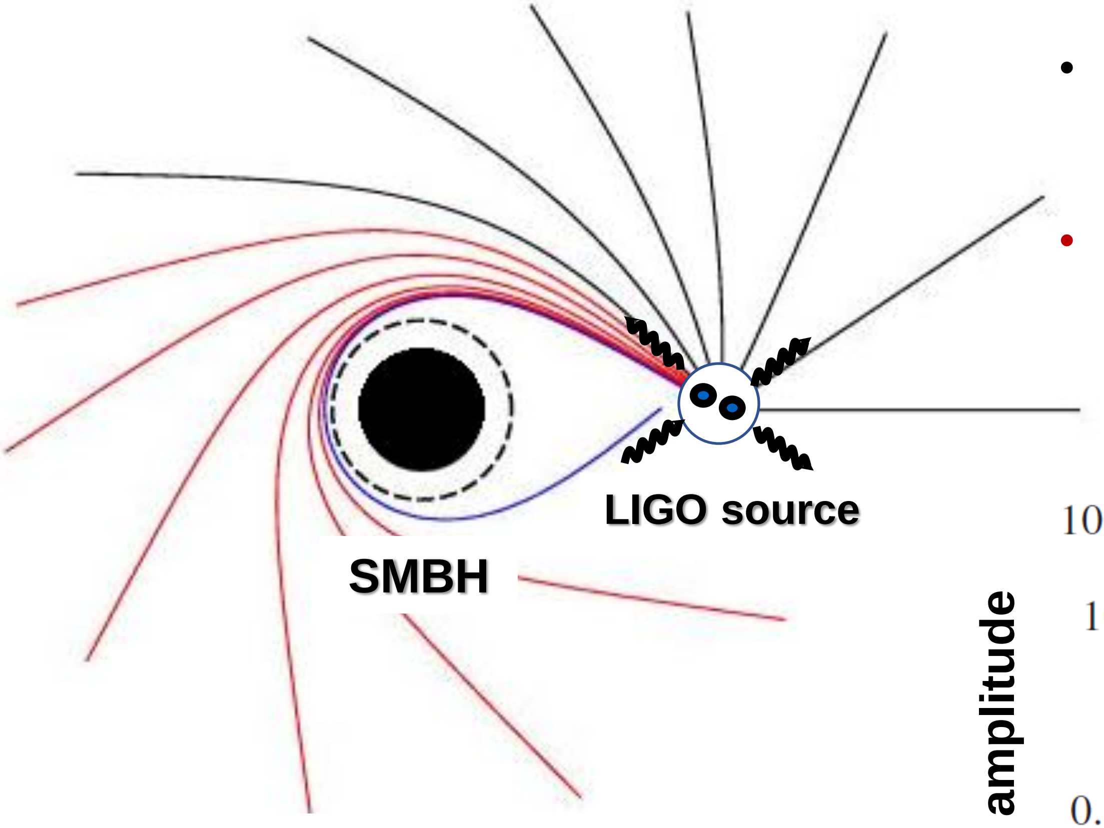


- LISA+LIGO coincident detection of triple inspiral
- LIGO detection of GW mass loss
- LISA detection of GW mass loss
- Later: LIGO detection of merger (if stellar-mass triple)

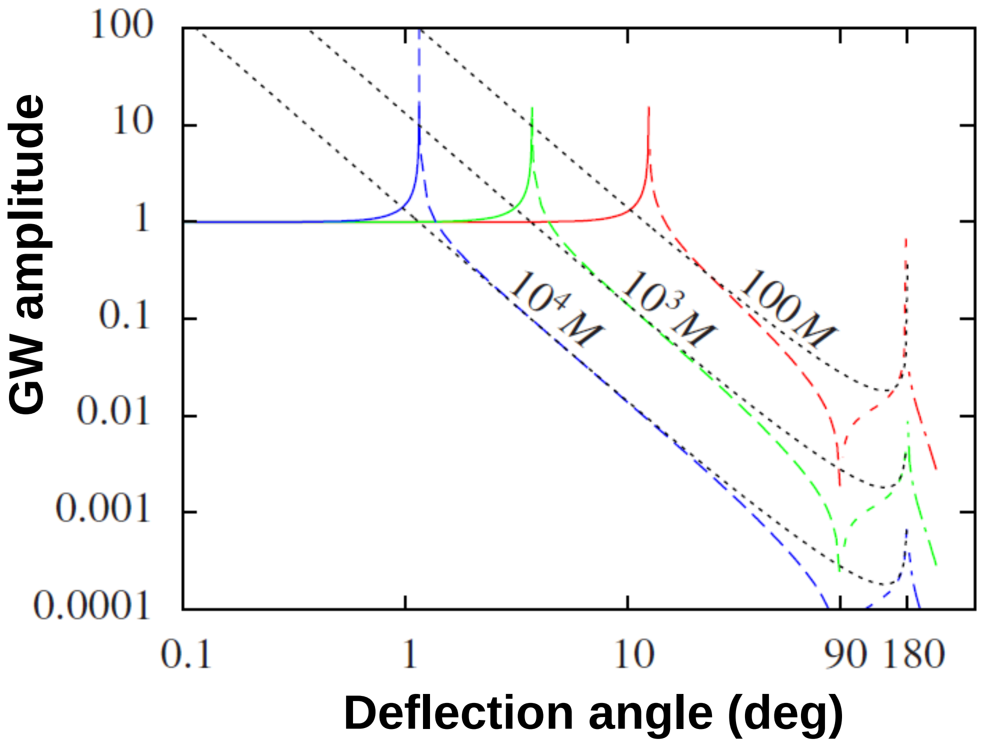
Test of general relativity

Meiron, Kocsis, Loeb 2017

GW echos



- GW rays are deflected around supermassive black holes
- Echo amplitude depends on distance to SMBH and deflection angle



GW echo arrives in

$$14\,\mathrm{h} \times (1-\cos\alpha)M_6(r/10^4 M)$$

Kocsis 2013, Gondan & Kocsis in prep.