On the Origin of Gravitational Wave Sources Observed by LIGO/VIRGO

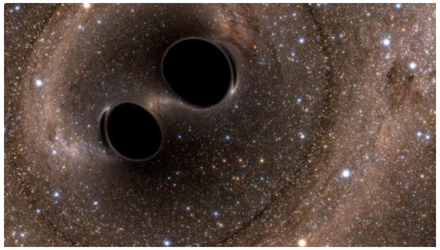
Bence Kocsis Eotvos University

GALNUC team members

- postdoc: Yohai Meiron, Alexander Rasskazov, Hiromichi Tagawa, Zacharias Roupas
- phd: László Gondán, Ákos Szölgyén, Gergely Máthé, Ádám Takács, Barnabás Deme
- msc: Kristóf Jakovác

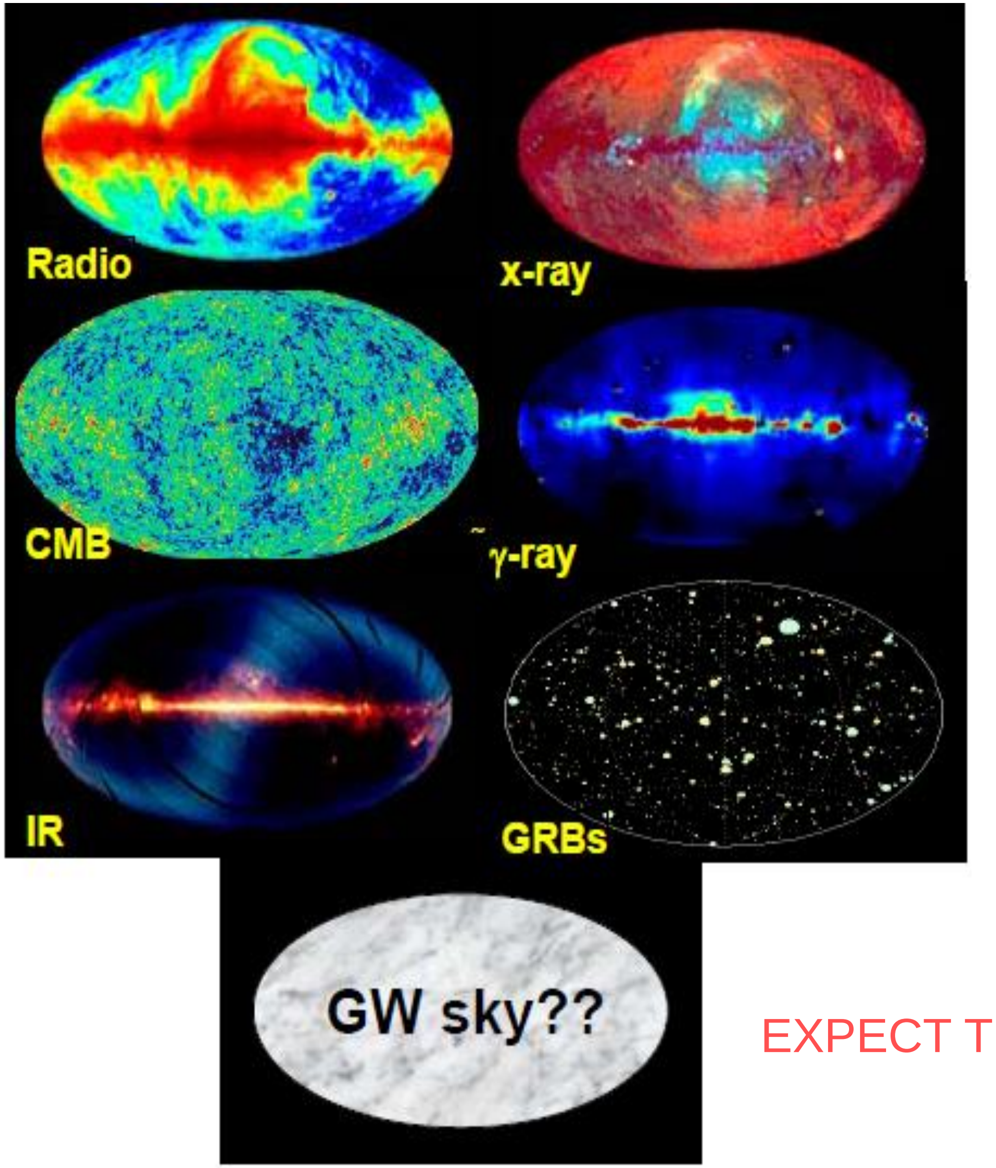
external collaborators:

Ryan O'Leary (Colorado),
Zoltan Haiman, Imre Bartos (Columbia),
Bao-Minh Hoang, Smadar Naoz (UCLA),
Giacomo Fragione (Jerusalem), Idan Ginzburg (CFA), Manuel Arca-Sedda (ZAH)
Teruaki Suyama (Tokyo), Suichiro Yokoyama, Takahiro Tanaka (Kyoto)
Scott Tremaine (IAS)



Bolyai Szeminárium, October 8 2019

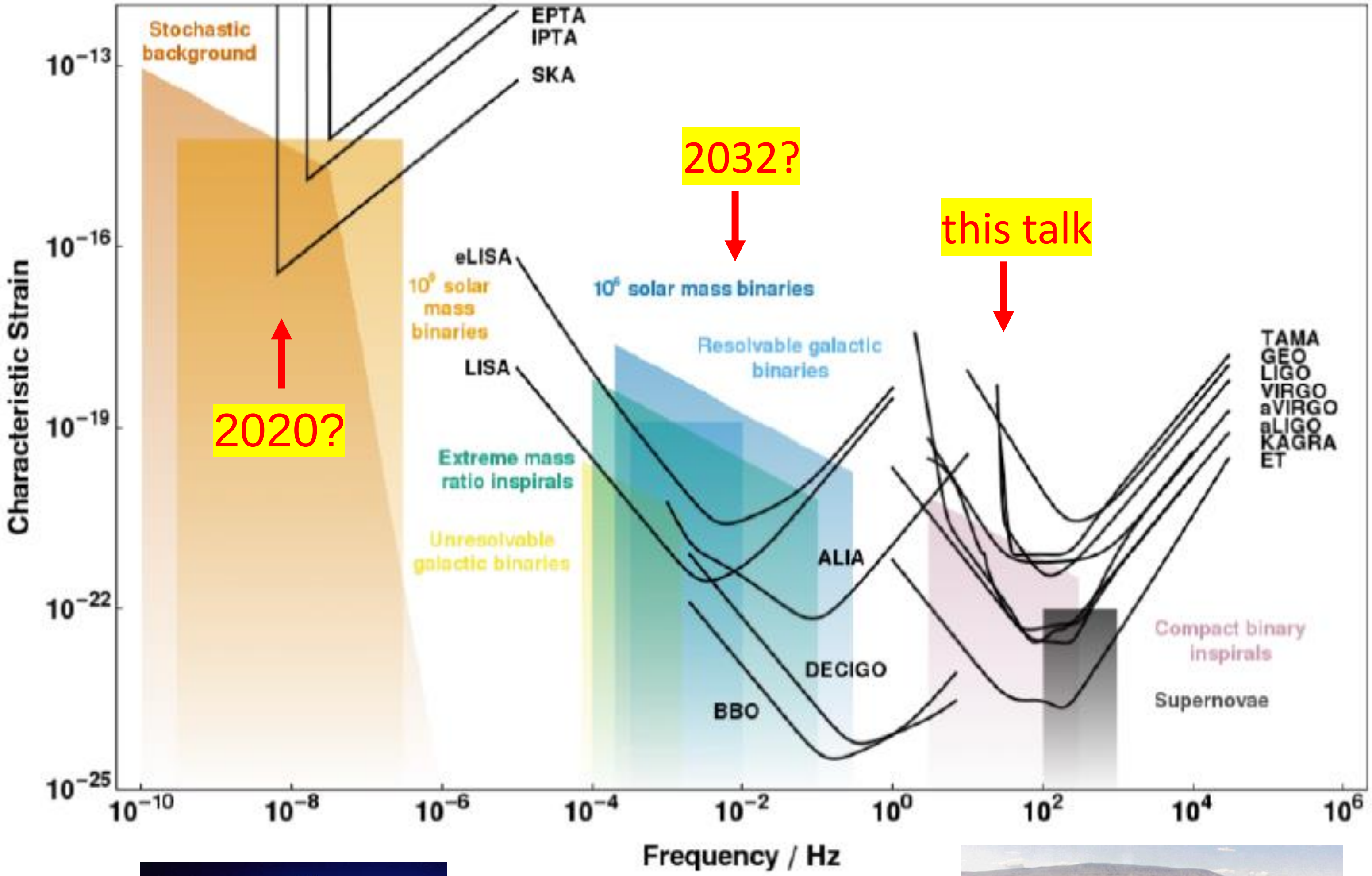
The Dawn of GW astronomy



- 1. Status of discoveries
- 2. Does it make sense?
- 3. Astrophysical channels
  - problems with interpretation
- 4. New ideas
- 5. Distinguishing sources

EXPECT THE UNEXPECTED!

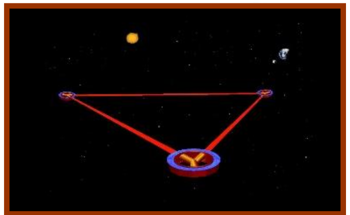
Gravitational wave detectors



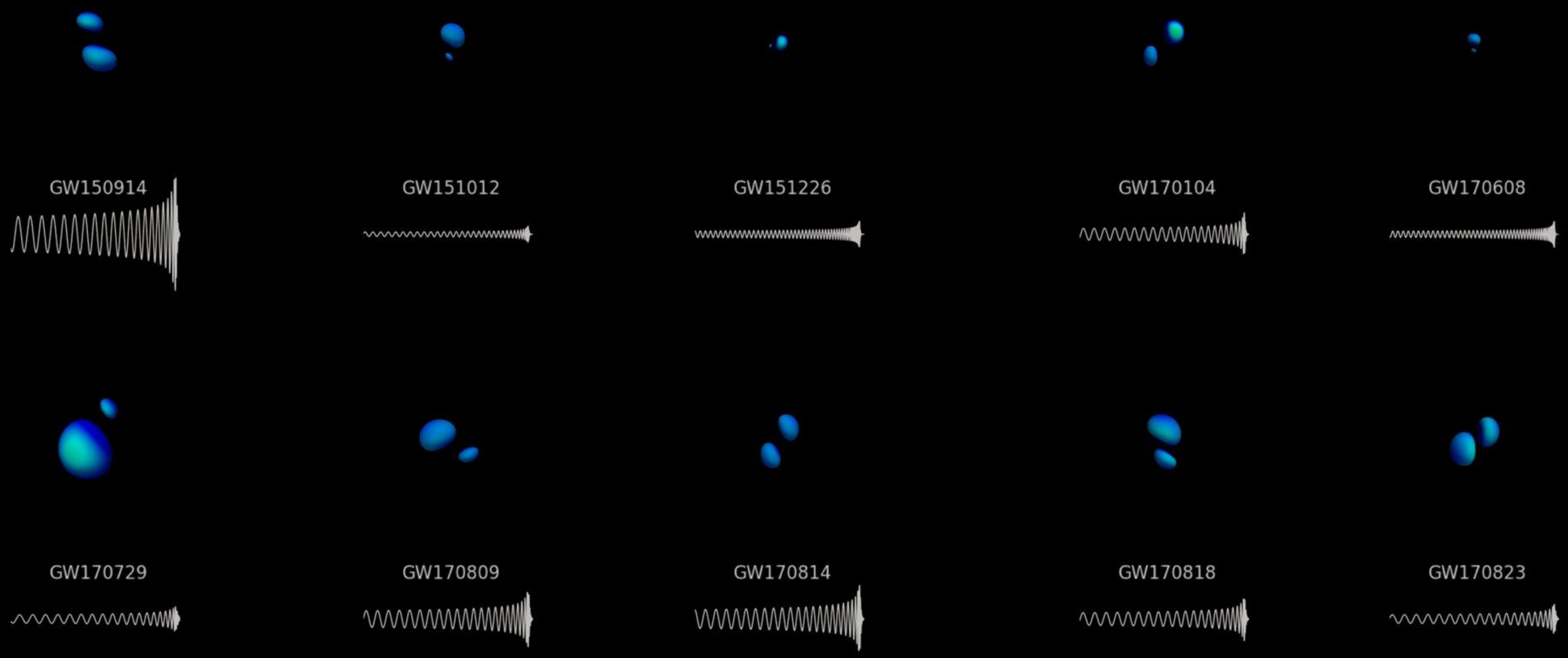
2032?

this talk

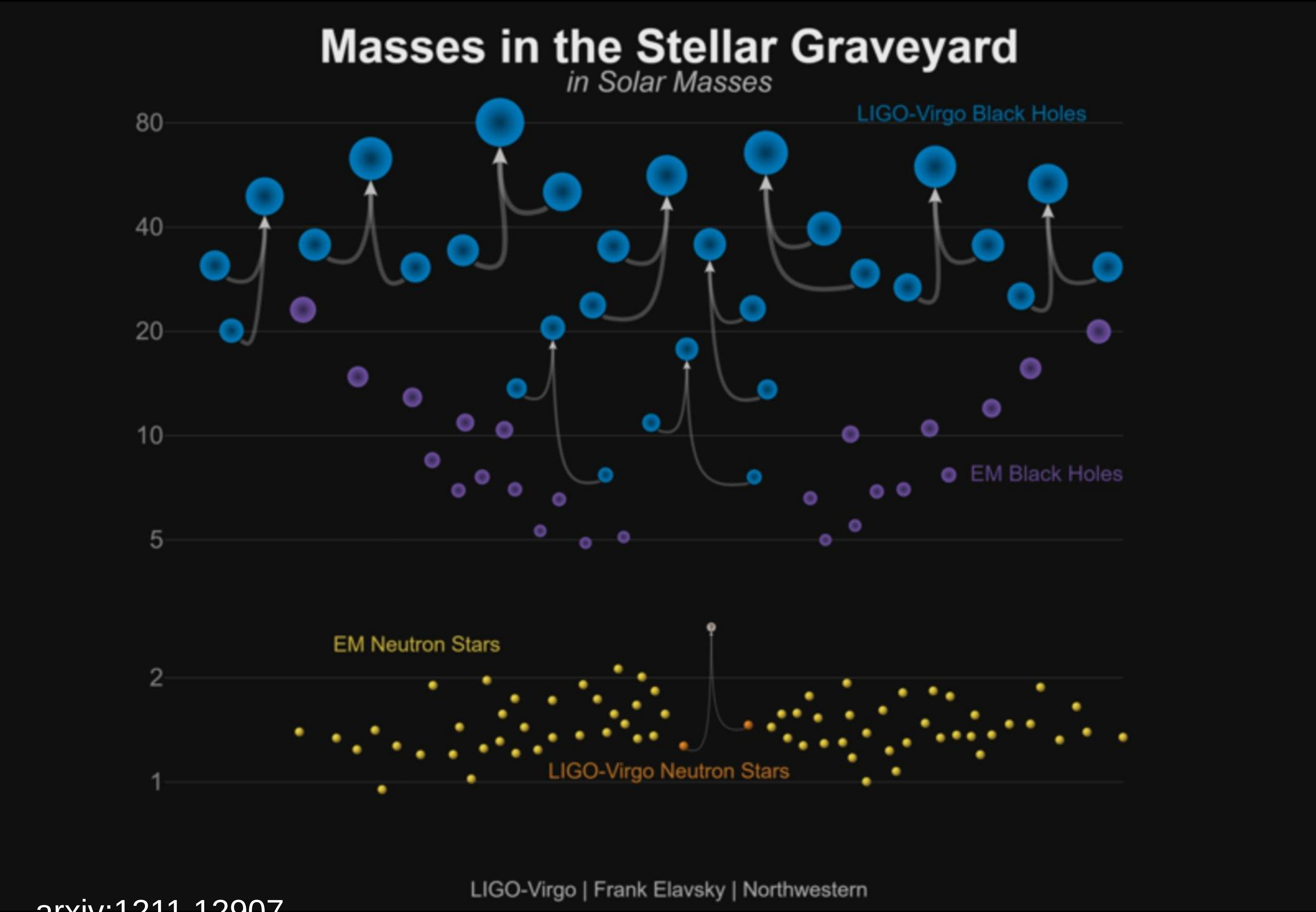
2020?



Gravitational wave detections



arxiv:1211.12907

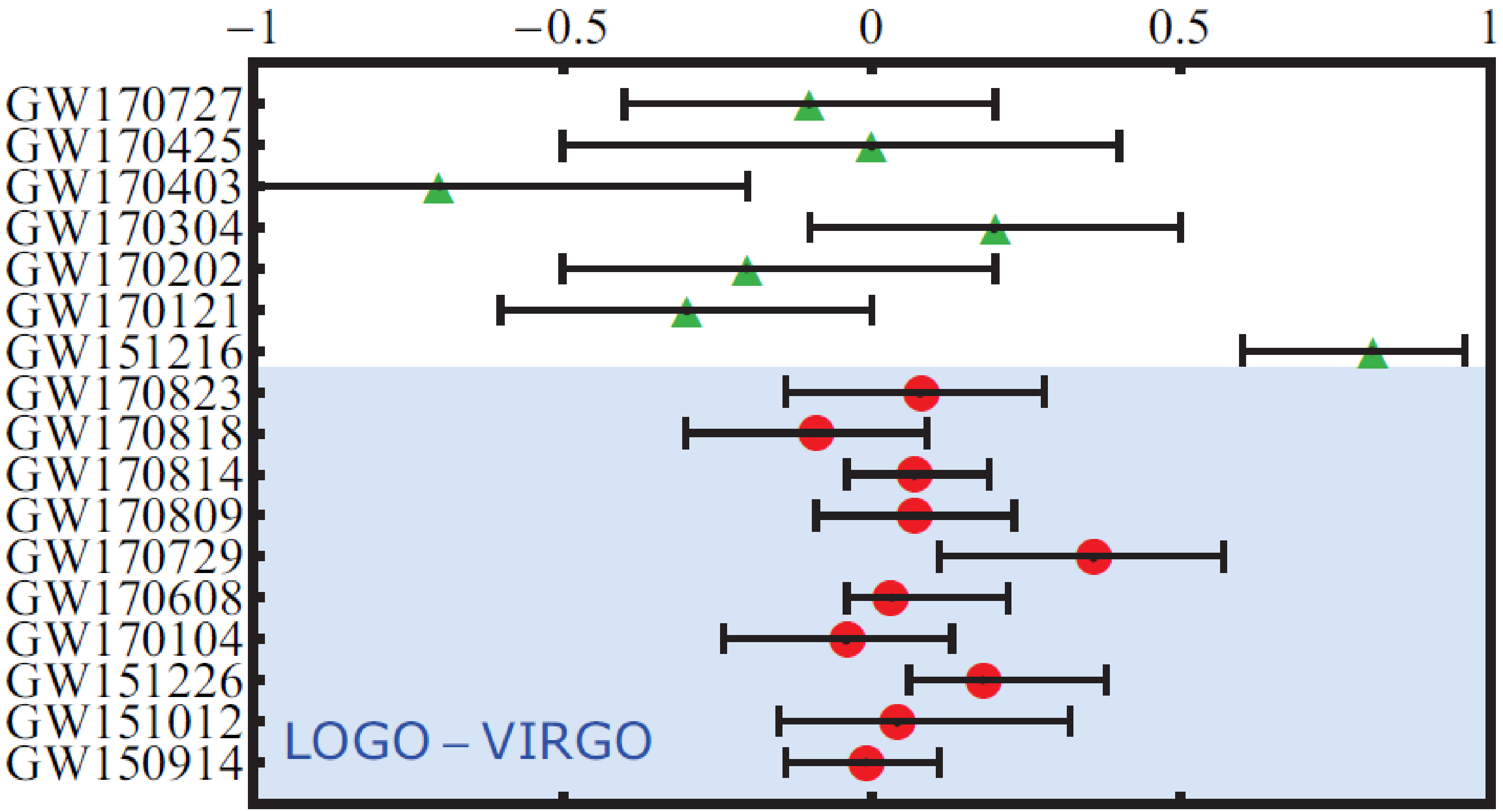


LIGO-Virgo | Frank Elavsky | Northwestern

arxiv:1211.12907

Spins

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



LIGO/VIRGO Collaboration 2018; Zackay+ 2019, Venumadhav+ 2019

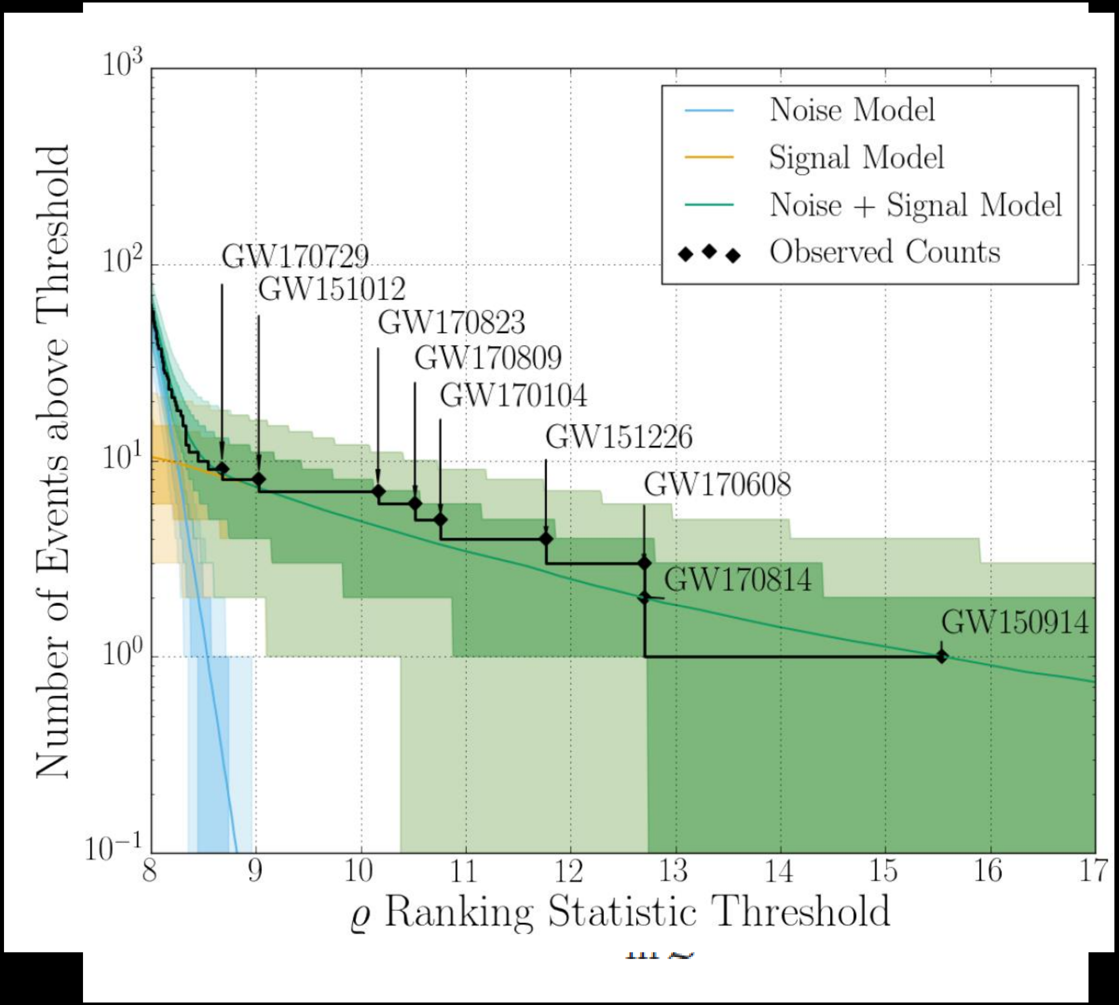
Rate of BBH coalescence

GW150914+LVT151012:
2 – 600 $\text{Gpc}^{-3}\ \text{yr}^{-1}$

+GW151226:
9 – 240 $\text{Gpc}^{-3}\ \text{yr}^{-1}$

+GW170104:
12 – 213 $\text{Gpc}^{-3}\ \text{yr}^{-1}$

+7 new BH/BH detections:
29 – 100 $\text{Gpc}^{-3}\ \text{yr}^{-1}$



Rate of NS coalescence

GW170608:
300 – 4700 $\text{Gpc}^{-3}\ \text{yr}^{-1}$

arxiv:1211.12907

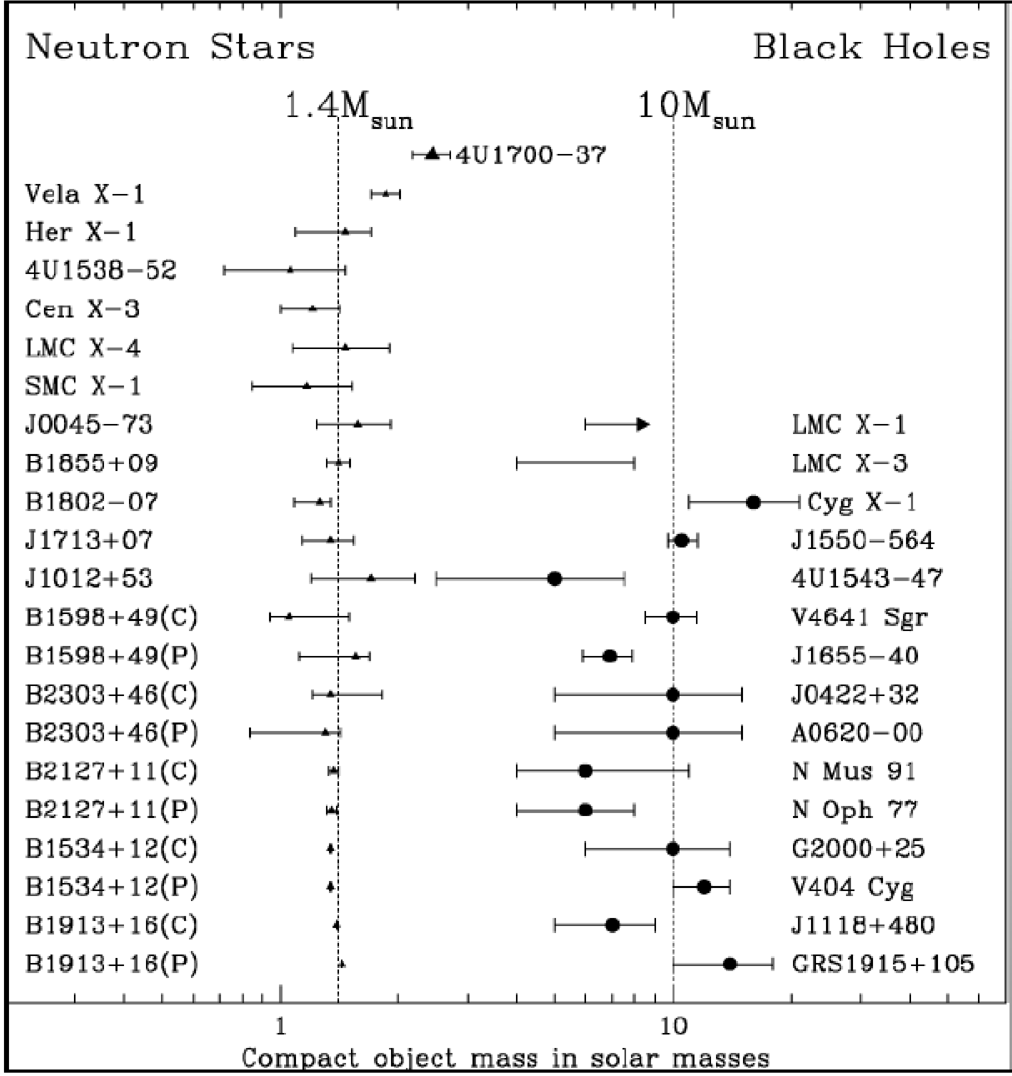
LIGO/VIRGO Collaboration 2018

Basic questions

- Does the mass distribution make any sense?
- Does the spin distribution make any sense?
- How did the black holes get so close?
- Do the rates match expectations?

Does the mass distribution make sense?

Observed masses in X-ray binaries

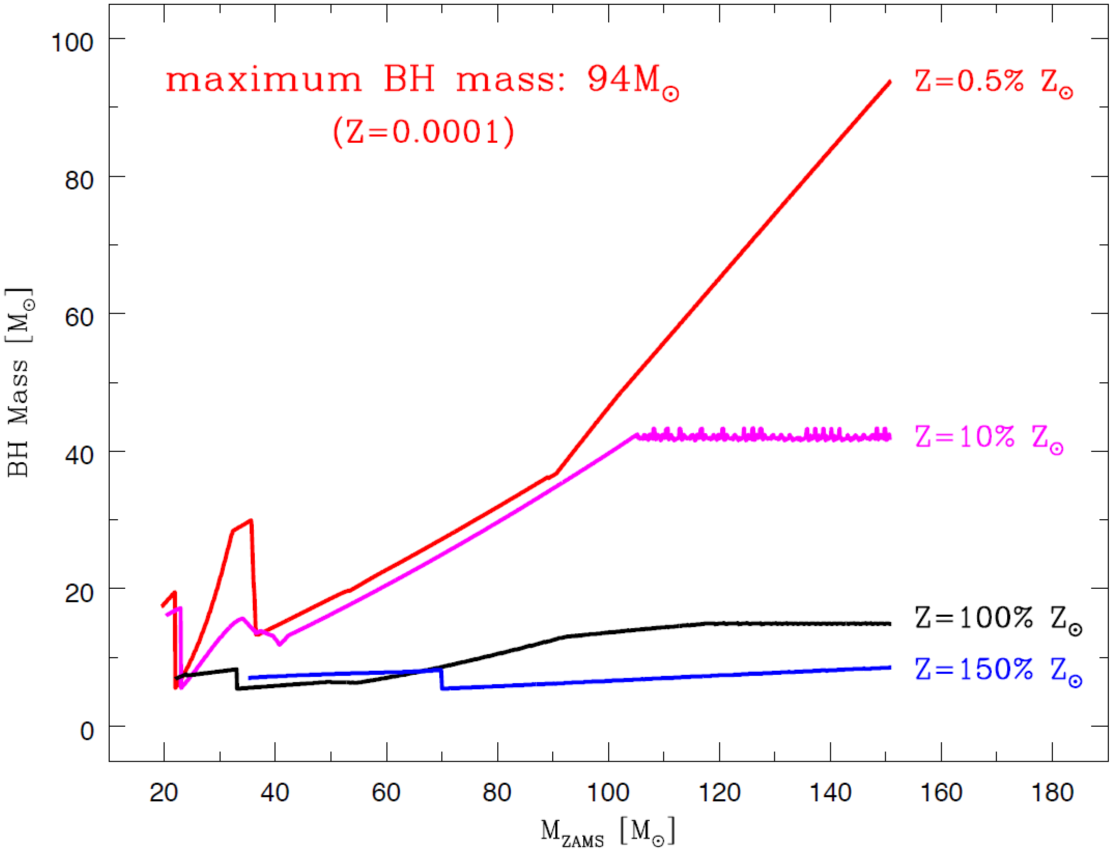


About 20 binaries in our galaxy where the compact object seems to be too massive to be a neutron star

Does the mass distribution make sense?

Theoretical expectations

Belczynski et al. 2010a (ApJ 714, 1217)



– updates:

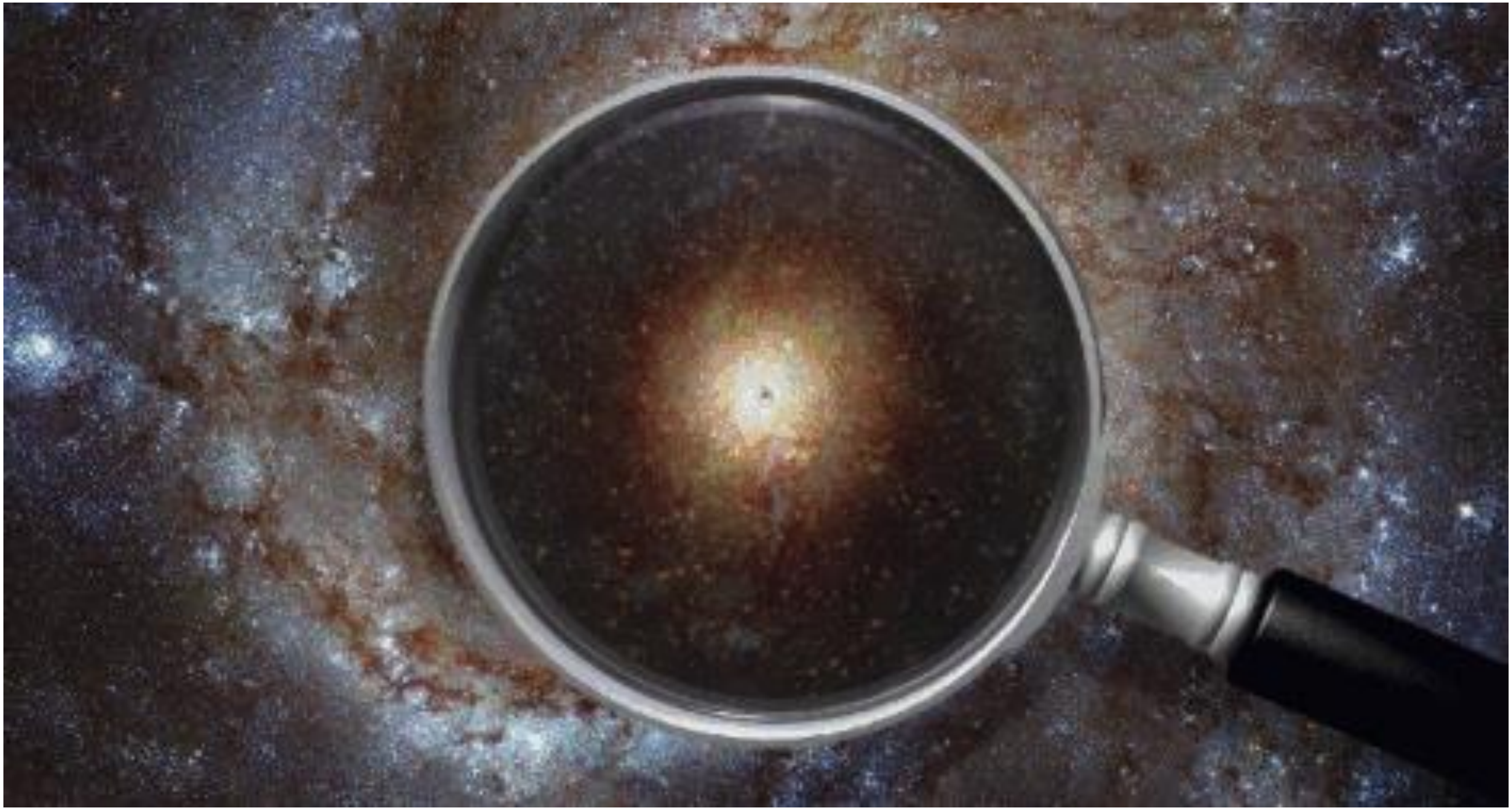
stellar models: $\sim 130\ M_\odot$
(Spera et al. 2015)

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

-(Belczynski et al. 2016):

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

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

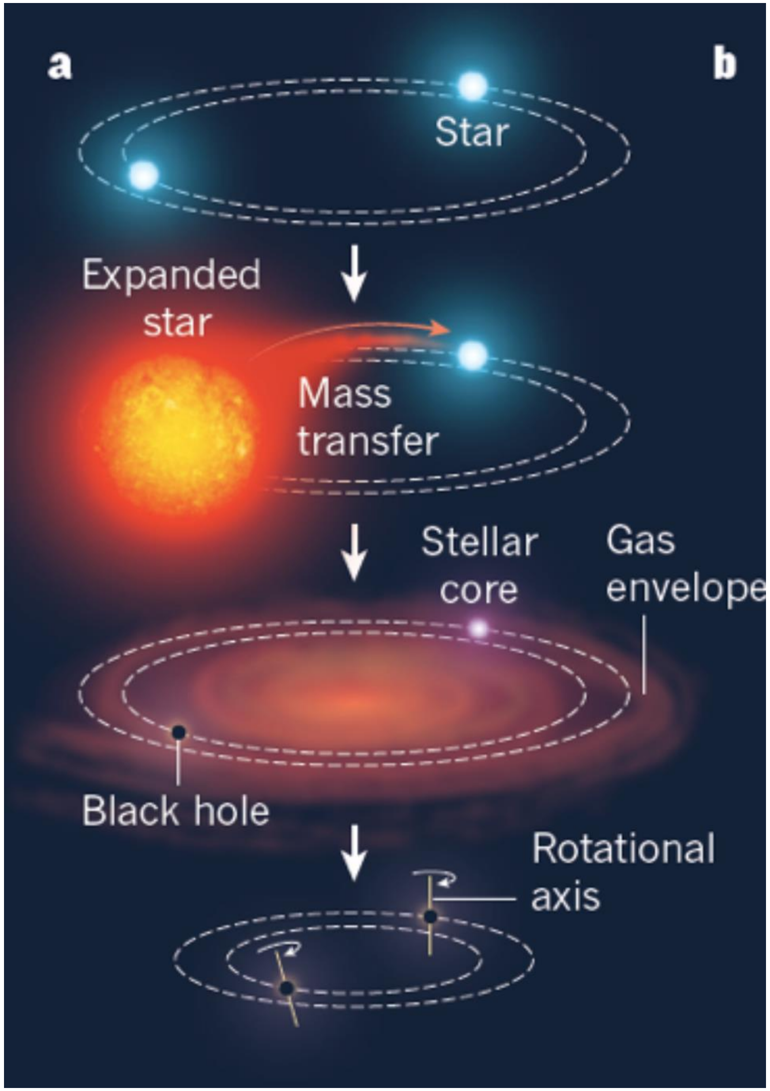


Astrophysical origin of mergers

Option 1: stellar binary evolution

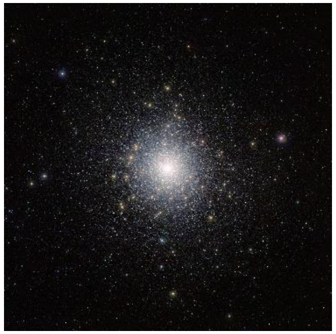
Galactic binaries

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



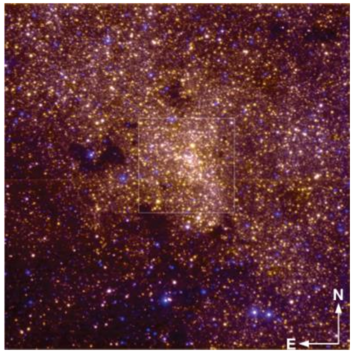
Option 2: Dynamical environments

Globular clusters

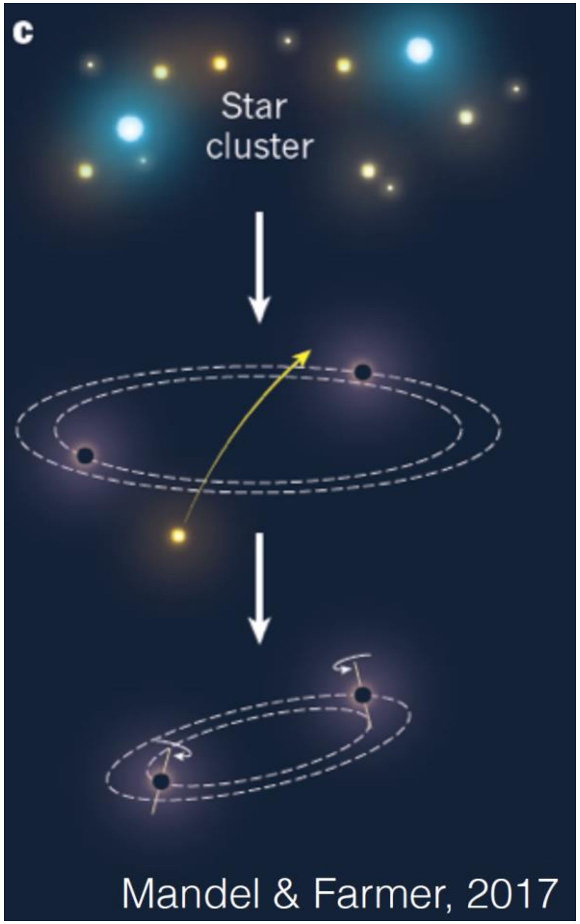


- 0.5% of stellar mass of the Universe
- 100 per galaxy
- Size: 1 pc – 10 pc
- Density 10^3—10^5 x higher

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



Mandel & Farmer, 2017

encounter rate ~ density^2

$$\frac{d}{d\ln r}\Gamma = (4\pi r^3) n_{\bullet}^2 \sigma_{\rm cs} v$$

Option 3: Dark matter halo

Dark matter halo

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

- 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)

- 30 Msun primordial BHs form when T ~ 30 MeV (Carr 1975)
  - standard model does not have any phase transitions at this temperature

Problems

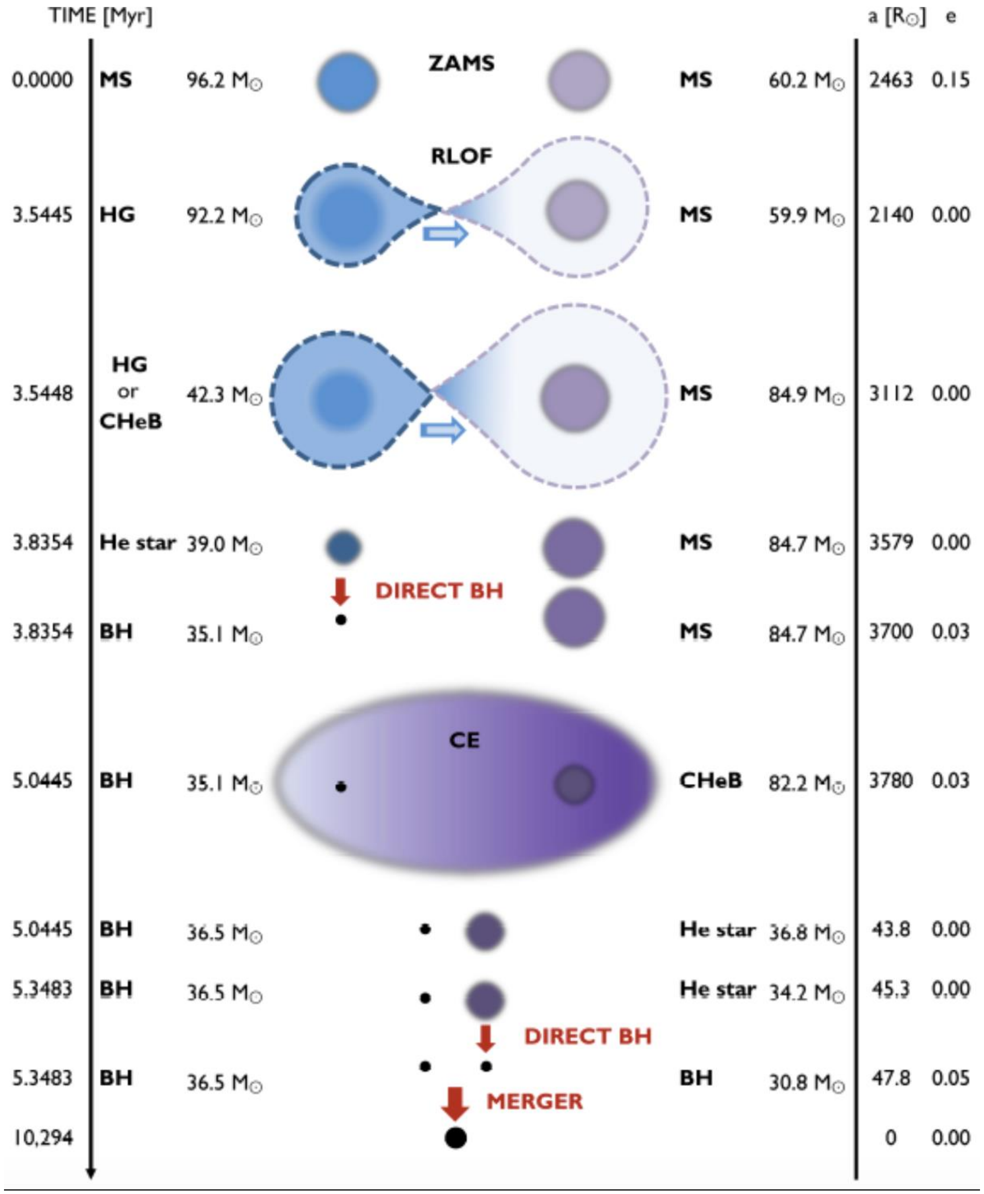
- galactic field binaries: spins, final au problem, common envelope
- galactic field triples: not enough in the right configuration

- globular clusters: not enough black holes
- galactic nuclei: requires multiple mergers/BH, implies spins

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

No convincing theory to explain the observed rates!

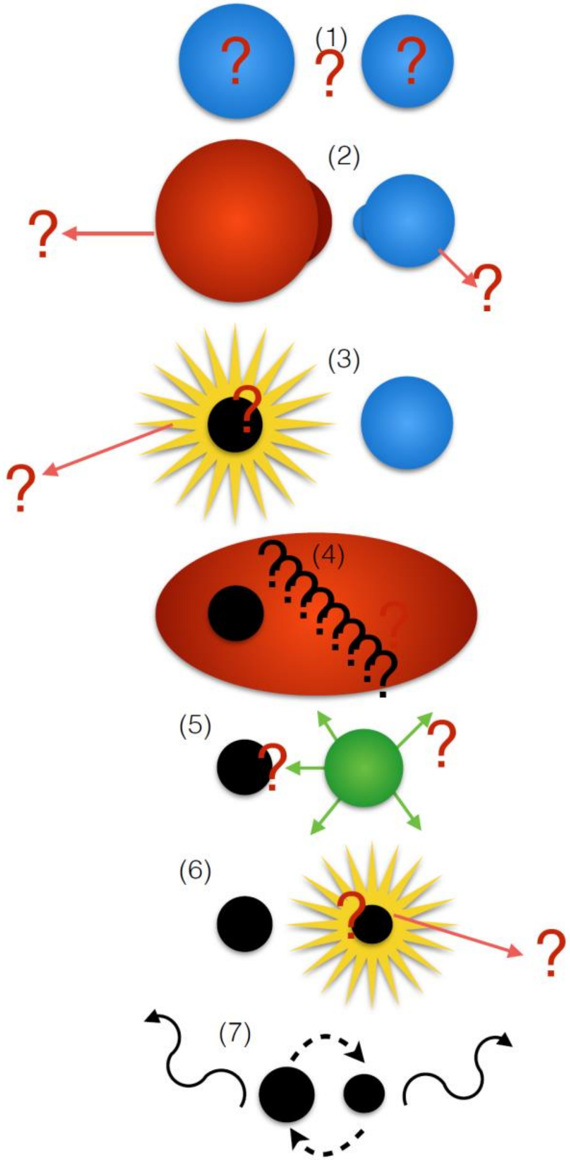
Option 1: stellar binary evolution



Belczynski+ (2016)

Option 1: stellar binary evolution

Open questions



Option 1: stellar binary evolution

What about spins?

- Black hole X-ray binaries show **evidence of high spins**

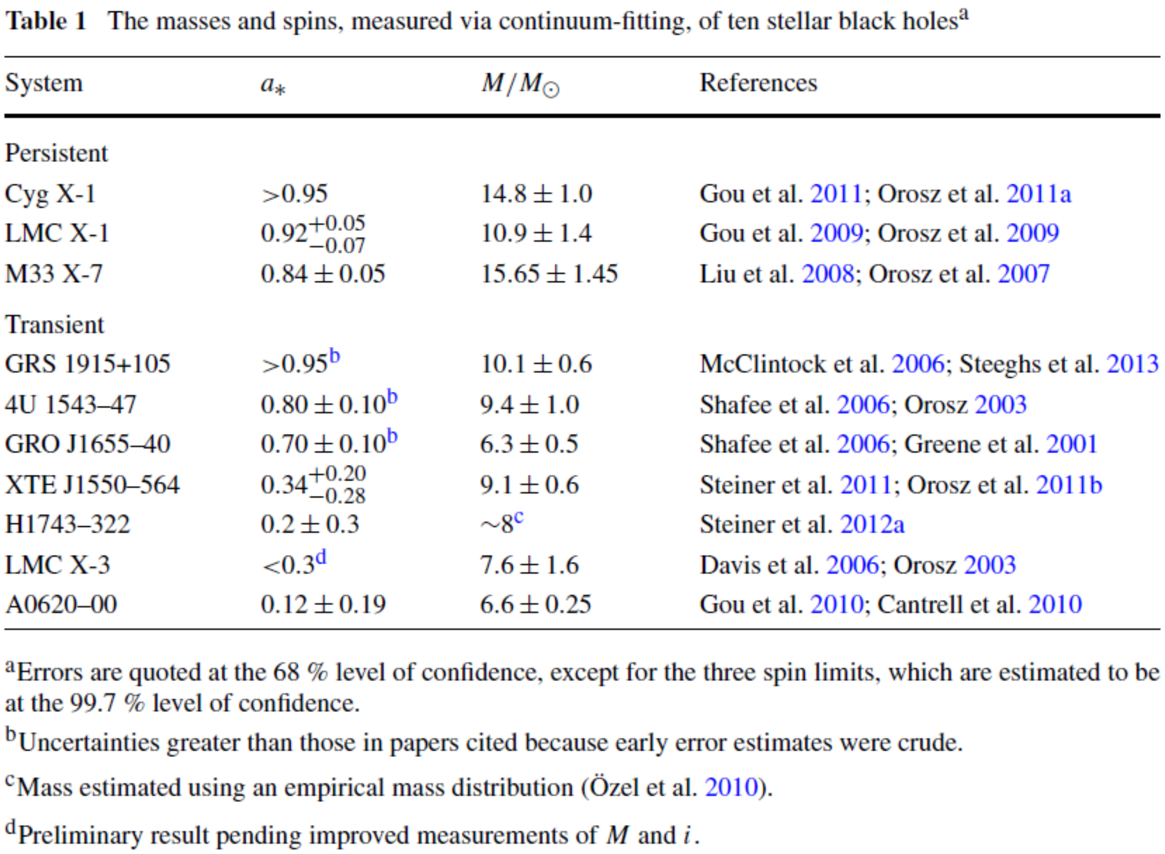


Table 1 The masses and spins, measured via continuum-fitting, of ten stellar black holes[a]

System	a_*	$M/M_\odot$	References
Persistent			
Cyg X-1	>0.95	14.8 ± 1.0	Gou et al. 2011; Orosz et al. 2011a
LMC X-1	$0.92^{+0.05}_{-0.07}$	10.9 ± 1.4	Gou et al. 2009; Orosz et al. 2009
M33 X-7	0.84 ± 0.05	15.65 ± 1.45	Liu et al. 2008; Orosz et al. 2007
Transient			
GRS 1915+105	>0.95[b]	10.1 ± 0.6	McClintock et al. 2006; Steeghs et al. 2013
4U 1543–47	0.80 ± 0.10[b]	9.4 ± 1.0	Shafee et al. 2006; Orosz 2003
GRO J1655–40	0.70 ± 0.10[b]	6.3 ± 0.5	Shafee et al. 2006; Greene et al. 2001
XTE J1550–564	$0.34^{+0.20}_{-0.28}$	9.1 ± 0.6	Steiner et al. 2011; Orosz et al. 2011b
H1743–322	0.2 ± 0.3	~ 8[c]	Steiner et al. 2012a
LMC X-3	<0.3[d]	7.6 ± 1.6	Davis et al. 2006; Orosz 2003
A0620–00	0.12 ± 0.19	6.6 ± 0.25	Gou et al. 2010; Cantrell et al. 2010

[a] Errors are quoted at the 68 % level of confidence, except for the three spin limits, which are estimated to be at the 99.7 % level of confidence.

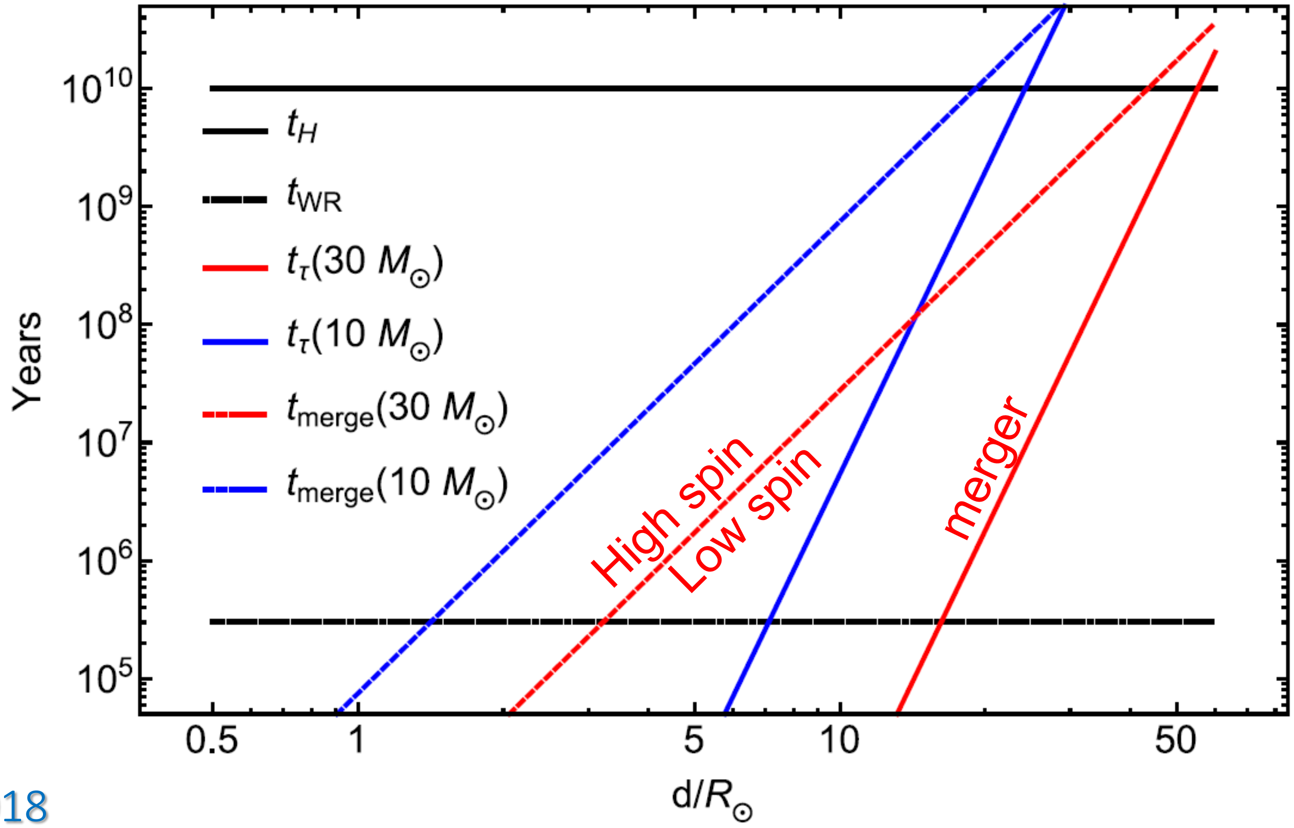
[b] Uncertainties greater than those in papers cited because early error estimates were crude.

[c] Mass estimated using an empirical mass distribution (Özel et al. 2010).

[d] Preliminary result pending improved measurements of M and i.

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?

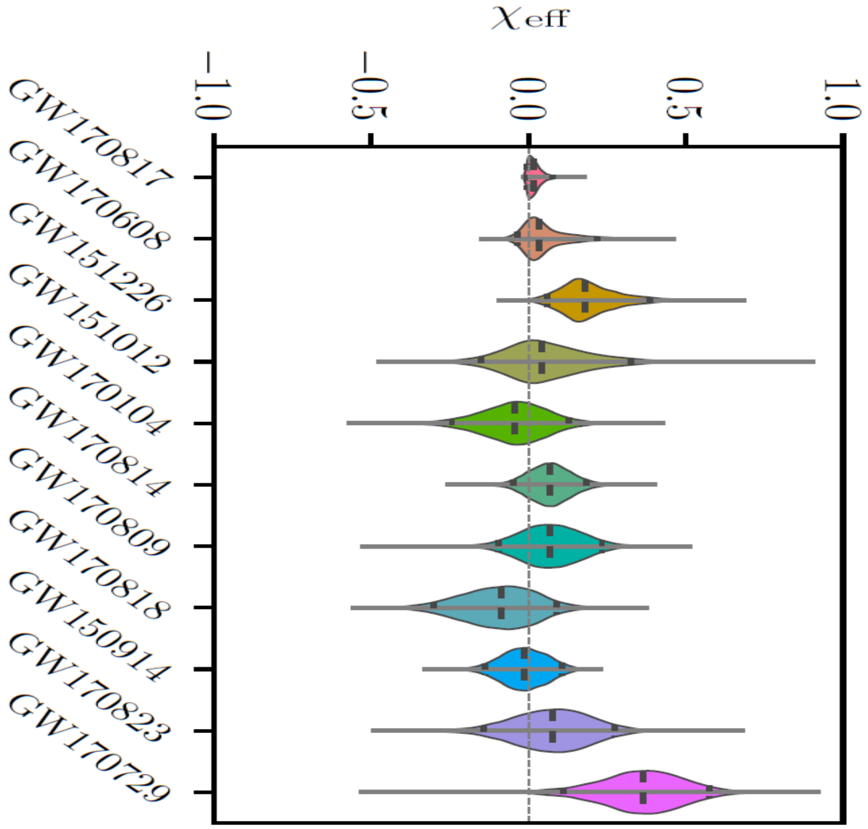


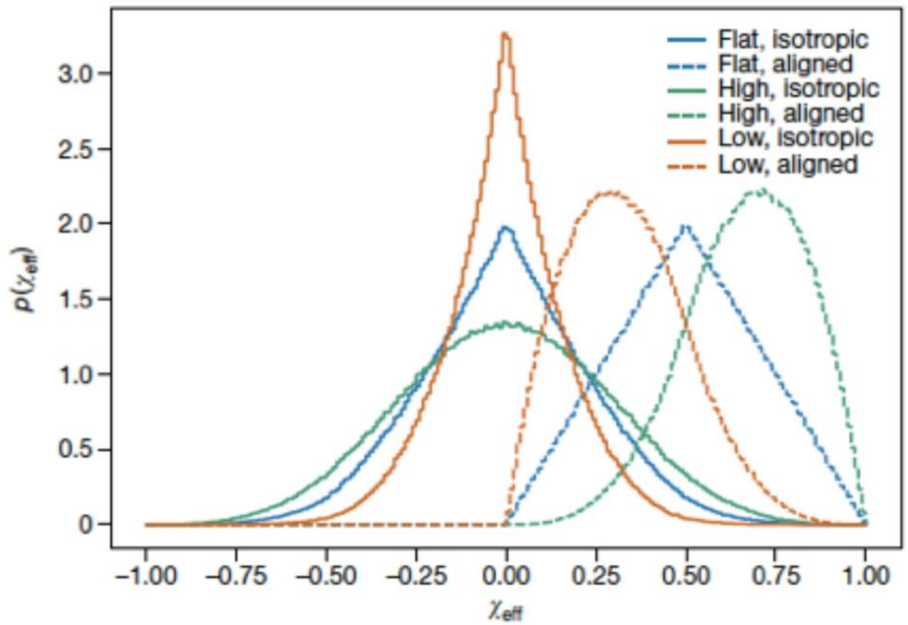
Kushnir+ 2017; Zaldarriaga+ 2018

Option 1: stellar binary evolution

What about spins?

- LIGO distribution **inconsistent** with aligned **high spins**





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

LIGO/VIRGO Collaboration 2018

Farr+ 2017

Option 1: stellar binary evolution

What about the rates?

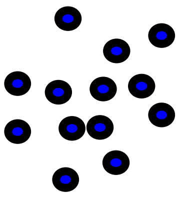
- Theory very uncertain – consistent with observations
- Relative rate of NS/NS mergers vs. BH/BH mergers may be a problem

Option 2: dynamical environments

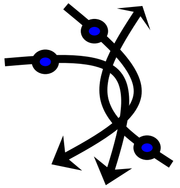
- A theoretically clean problem: N-body

Option 2: dynamical environments

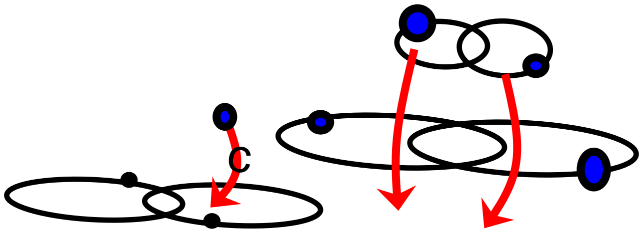
- A theoretically clean problem: N-body



Dense population

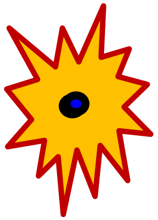


Triple scattering



Binary interactions

Dynamical friction



merger

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

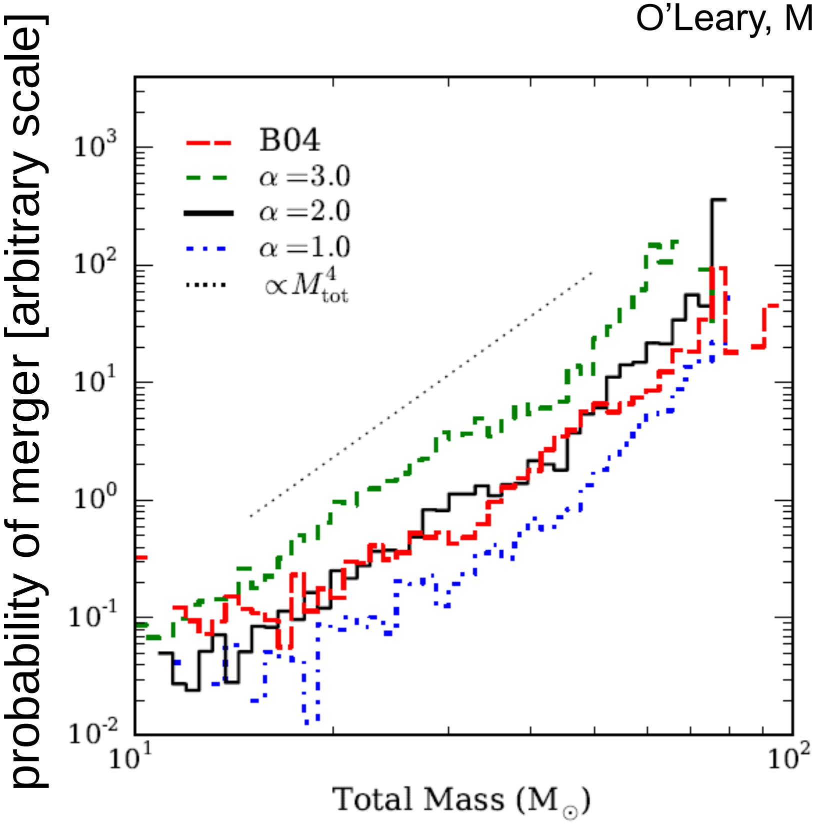
Expectation:

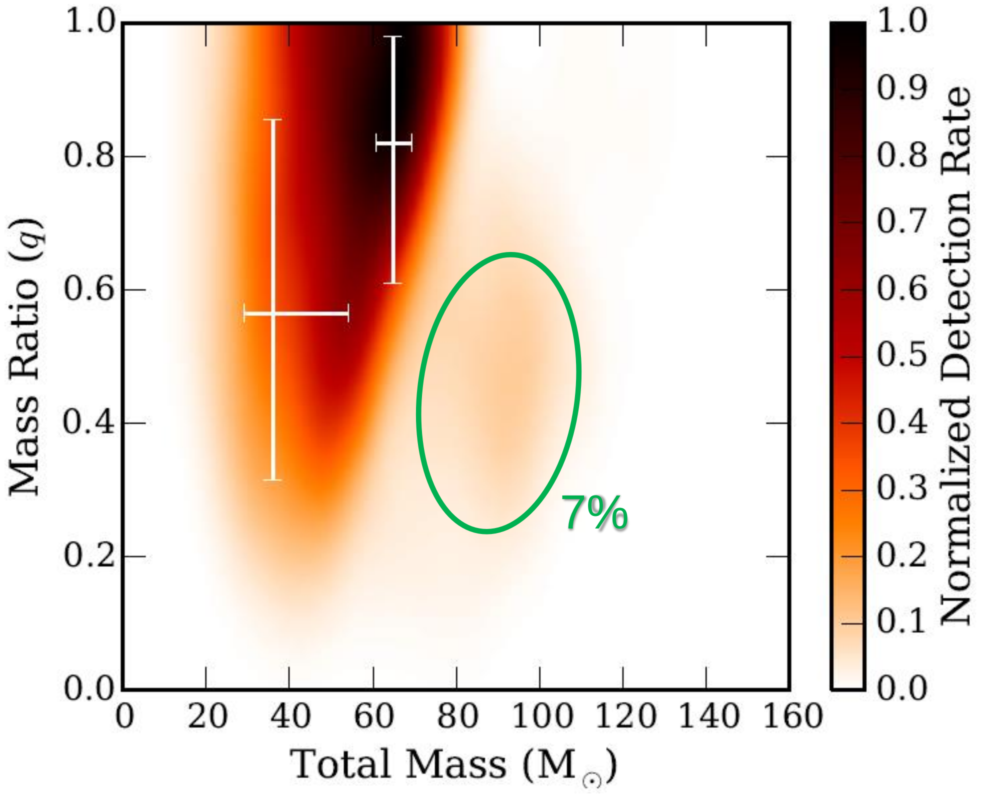
Merger probability larger for heavier objects

Mass distribution for globular clusters

Monte Carlo and Nbody simulations

O’Leary, Meiron, Kocsis (2016) (see also Rodriguez+ ’18, Askar+ ‘18)





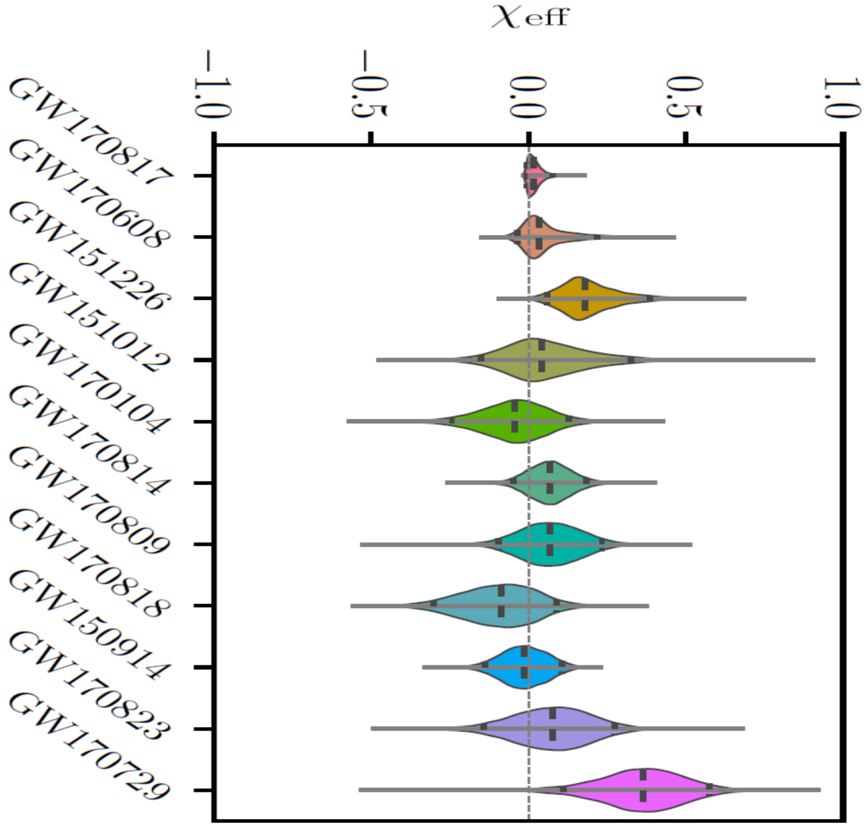
Robust statement (independent of IMF): heavy objects merge more often M^4

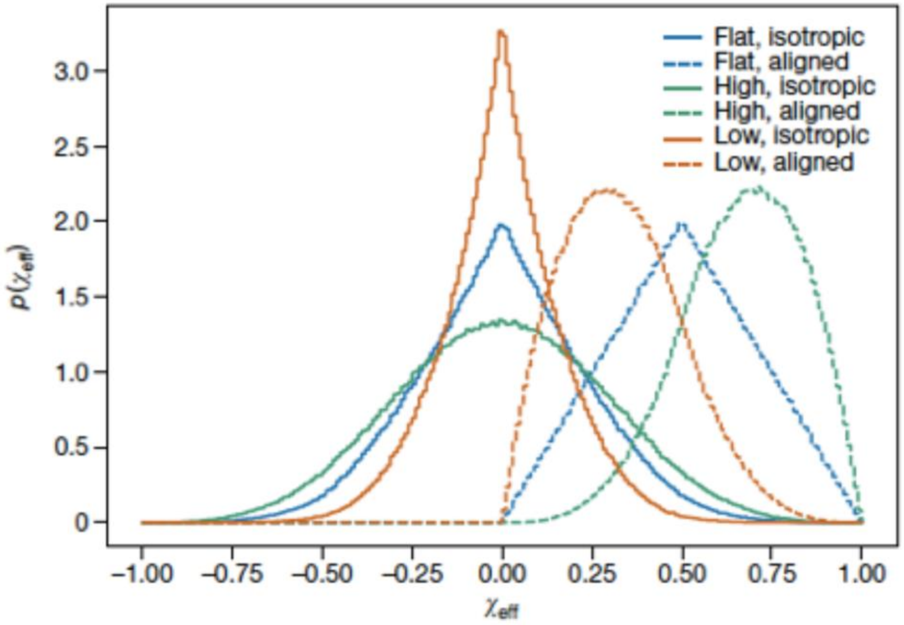
O’Leary, Meiron, Kocsis 2016

Option 2: dynamical environments

What about spins?

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





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

LIGO/VIRGO Collaboration 2018

Farr+ 2017

Option 2: dynamical environments

What about the rates?

Expected rates (MCMC and Nbody simulations): ~ 6 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$

Simple upper limit:

- assume **each** BH merges **at most once*** in a Hubble time
- BHs form from stars with $m > 20M_{Sun}$, $dN/dm \sim m^{-2.35}$

→ 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 $n \sim 0.8\ \mathrm{Mpc}^{-3}$
- **galactic nuclei:** **R < 35 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$**
  - 0.5% of stellar mass, 10^{7} stars with $n \sim 0.02\ \mathrm{Mpc}^{-3}$

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

Observed rate: 29 – 100 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$

(powerlaw mass distribution prior, Abbott+ 2018 arxiv:1811.12907)

Option 3: triples

Tertiary perturber:

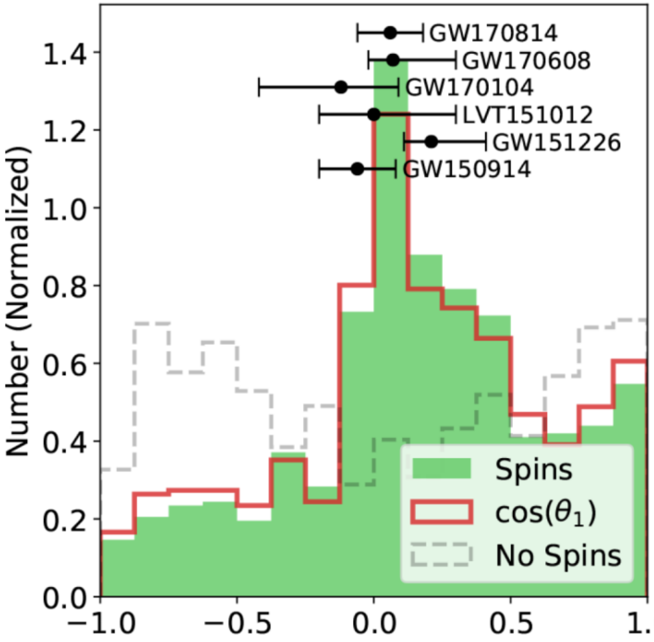
- Kozai-Lidov effect increases eccentricity

  → merger

- Spins **align in the perpendicular** direction

- expected **rates are**

  2 – 25 Gpc^{-3} yr $^{-1}$



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

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

Summary of channels and rates

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

- globular clusters: not enough black holes
- galactic nuclei: requires multiple mergers/BH, implies spins

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

No convincing theory to explain the observed rates!

Problems

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

- globular clusters: not enough black holes
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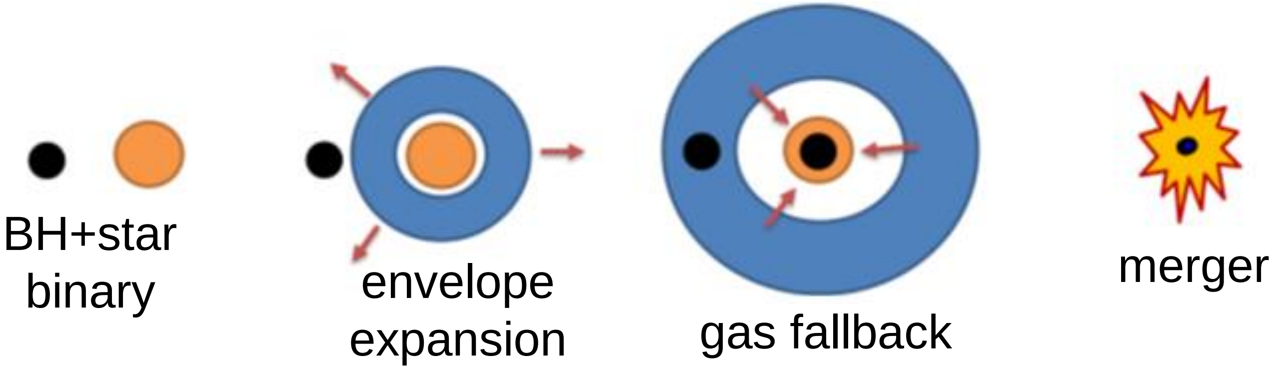
No convincing theory to explain the observed rates!

possible ways forward
I.

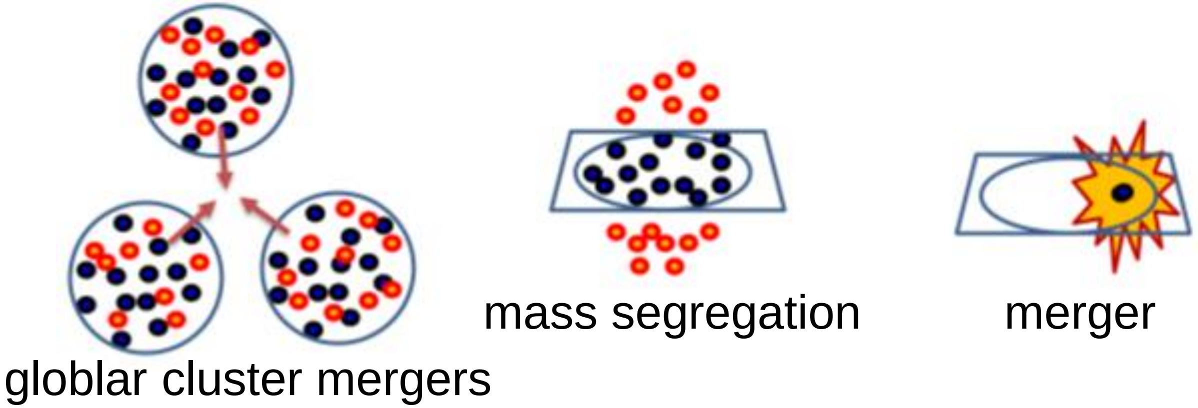
New ideas

1. Gas fallback mergers (Tagawa, Saitoh, & Kocsis, PRL 2018)

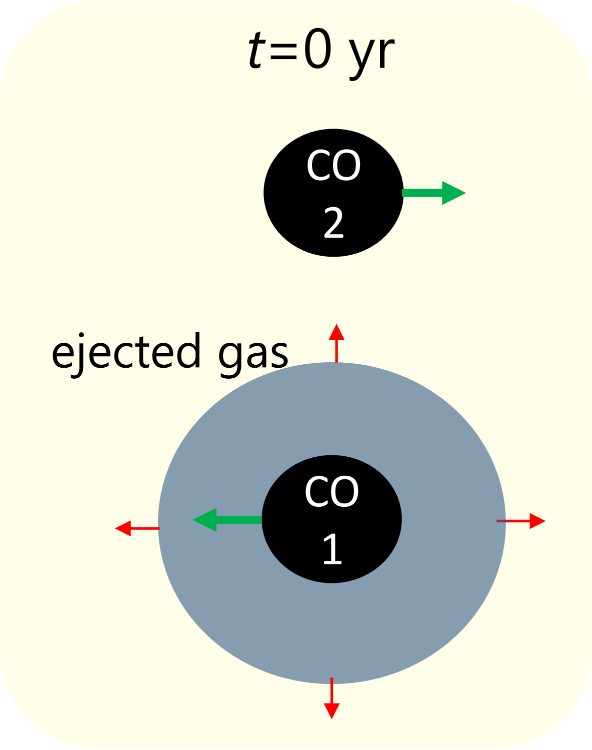


2. Disrupted globular clusters (Fragione & Kocsis, PRL 2018)

3. Black hole disks (Szolgyen & Kocsis PRL 2018)

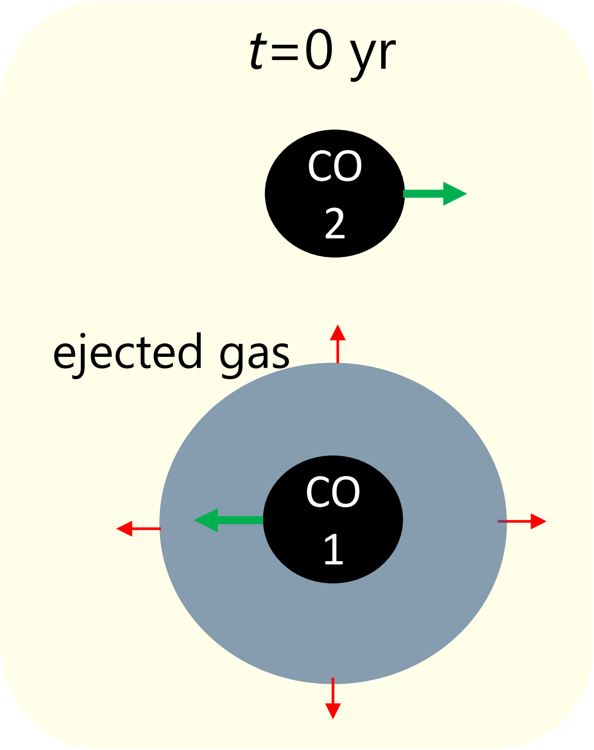


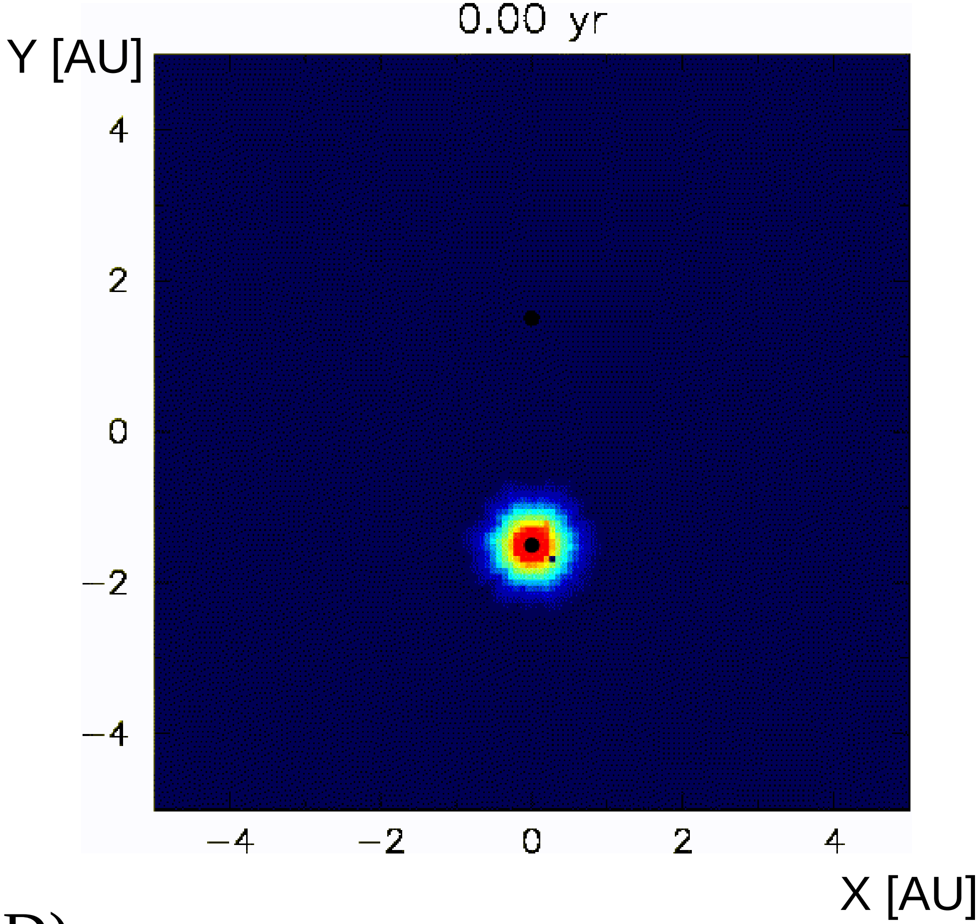
Fallback driven merger



Tagawa, Kocsis, Saitoh, 2018, PRL

Fallback driven merger





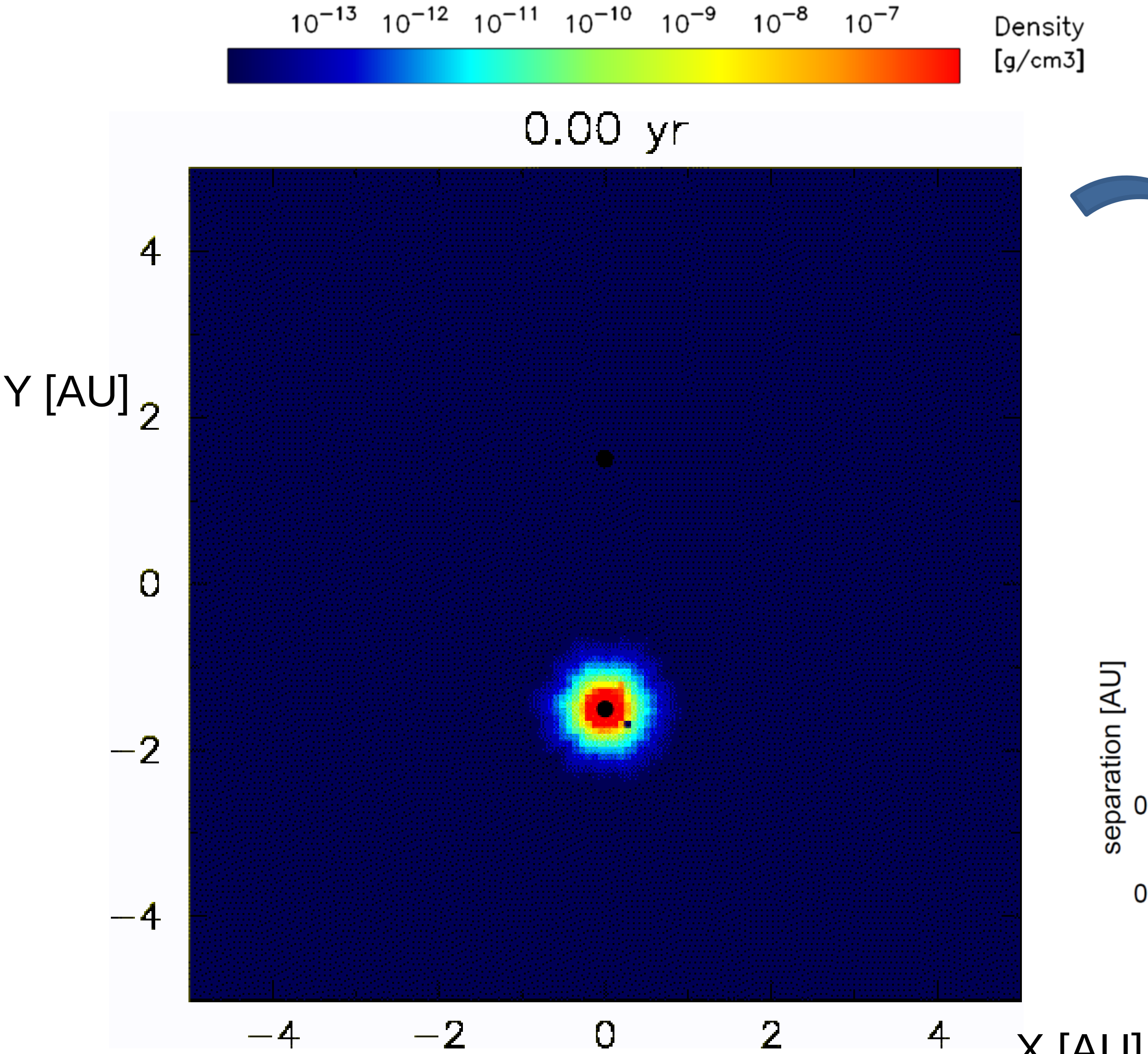
N-body/SPH simulation (3D)
Ideal gas EOS
$v(r)=v_{\max}\ r/r_{\max}$

Initial condition:
studies of fallback accretion
e.g. Zampieri et al. 1998, Batta etal. 2017

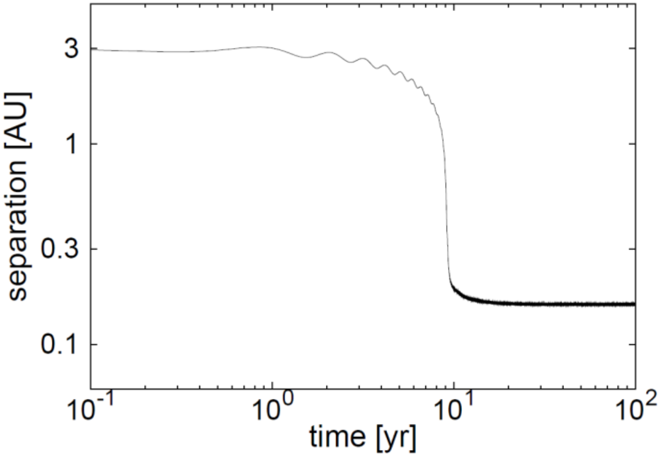
Tagawa, Saitoh, Kocsis 2018, PRL

Fallback driven merger

$M_{\rm CO1}=M_{\rm CO2}=5M_\odot$
$M_{\rm gas,ini}=5.4M_\odot$



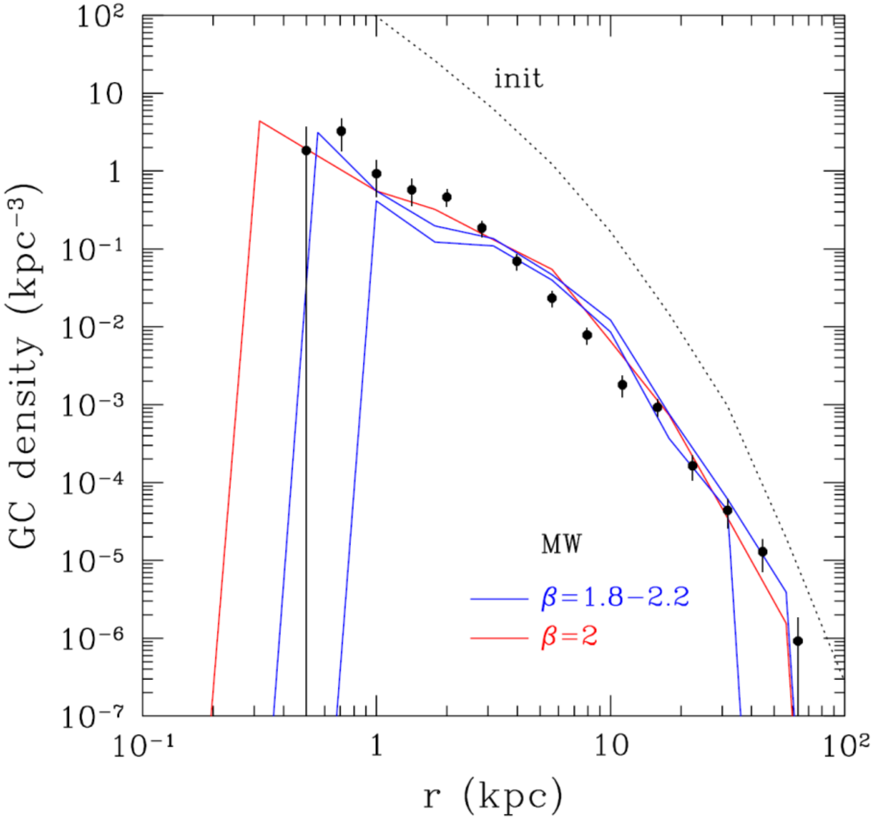
rotating clockwise

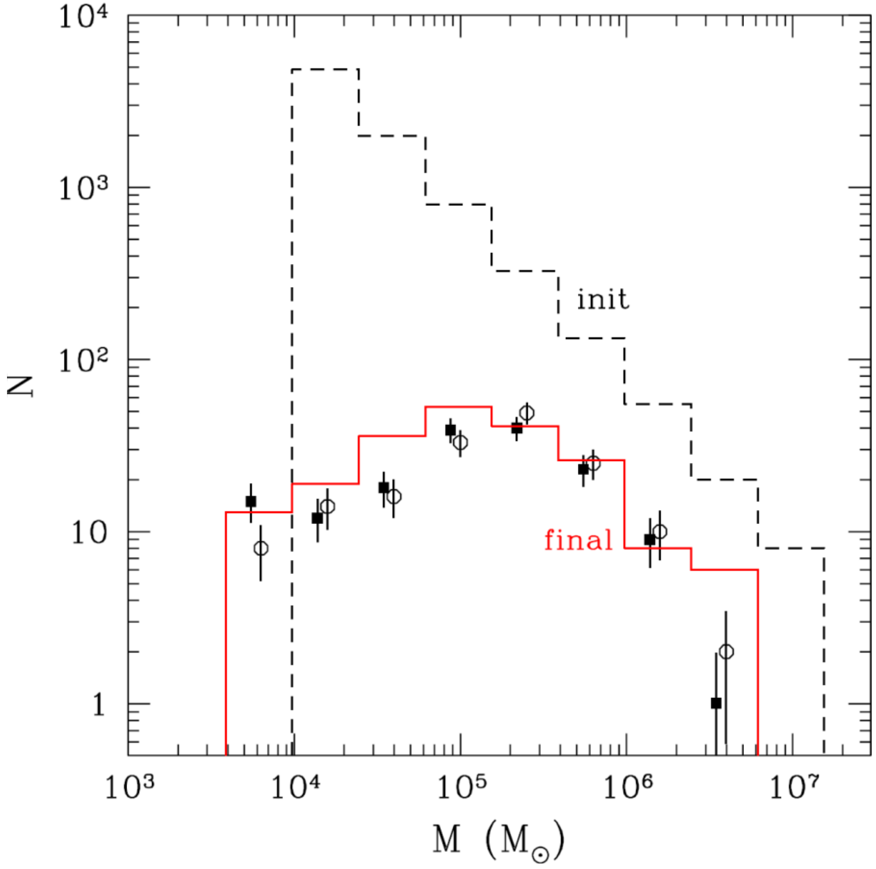


Tagawa, Kocsis, Saitoh, 2018, PRL

Disrupted globular clusters

- Globular clusters were much more numerous in the past

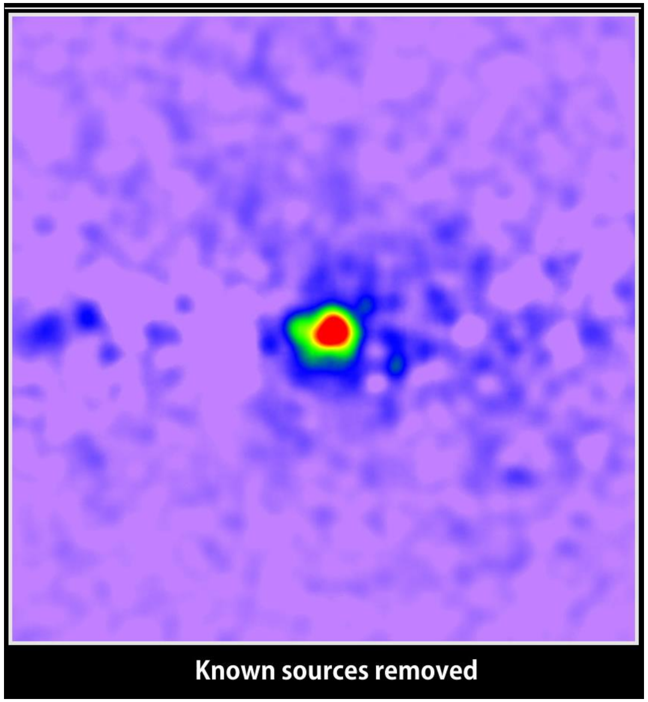


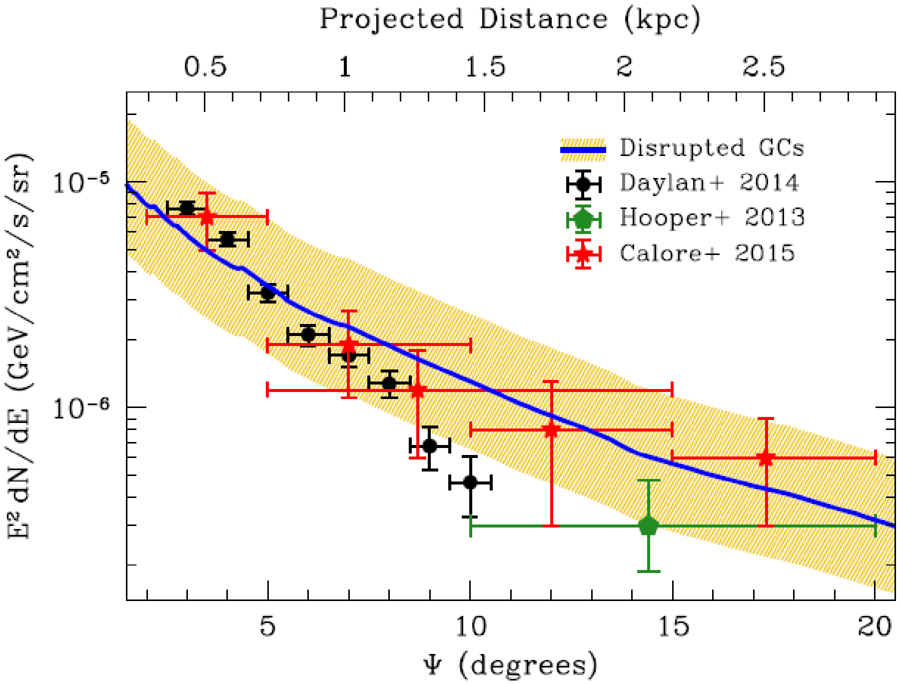


Gnedin, Ostriker, Tremaine (2014)

Disrupted globular clusters

- Gamma rays from disrupted globular clusters explains “Fermi excess”



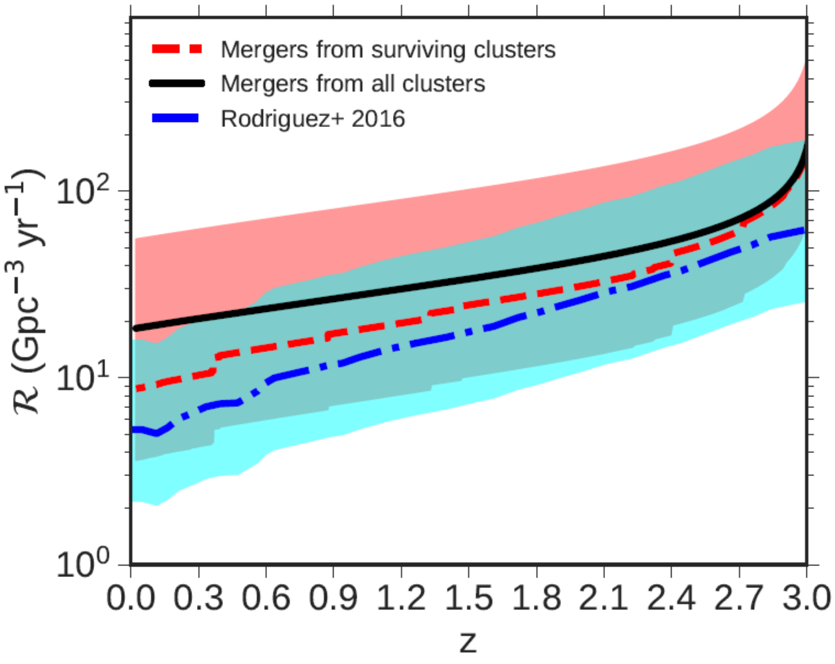


Brandt, Kocsis (2015)

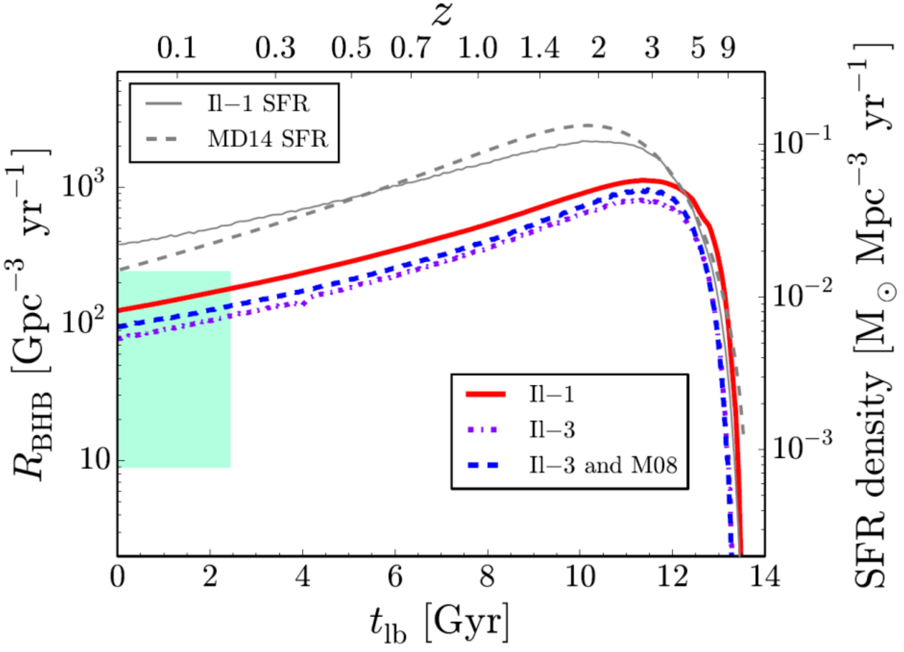
Disrupted globular clusters

- Implications for LIGO
  - High rates from disrupted globular clusters

Globular clusters



Field binaries – star formation rate

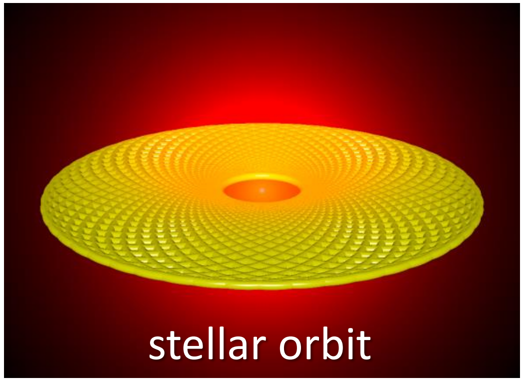


Fragione, Kocsis (2018) PRL

Black hole disks

Motion of stars in the galactic disk:

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



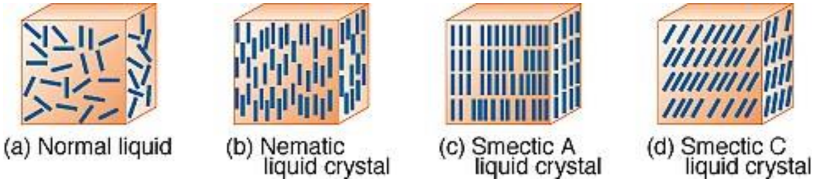
Orbital planes reorient and relax very quickly

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

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

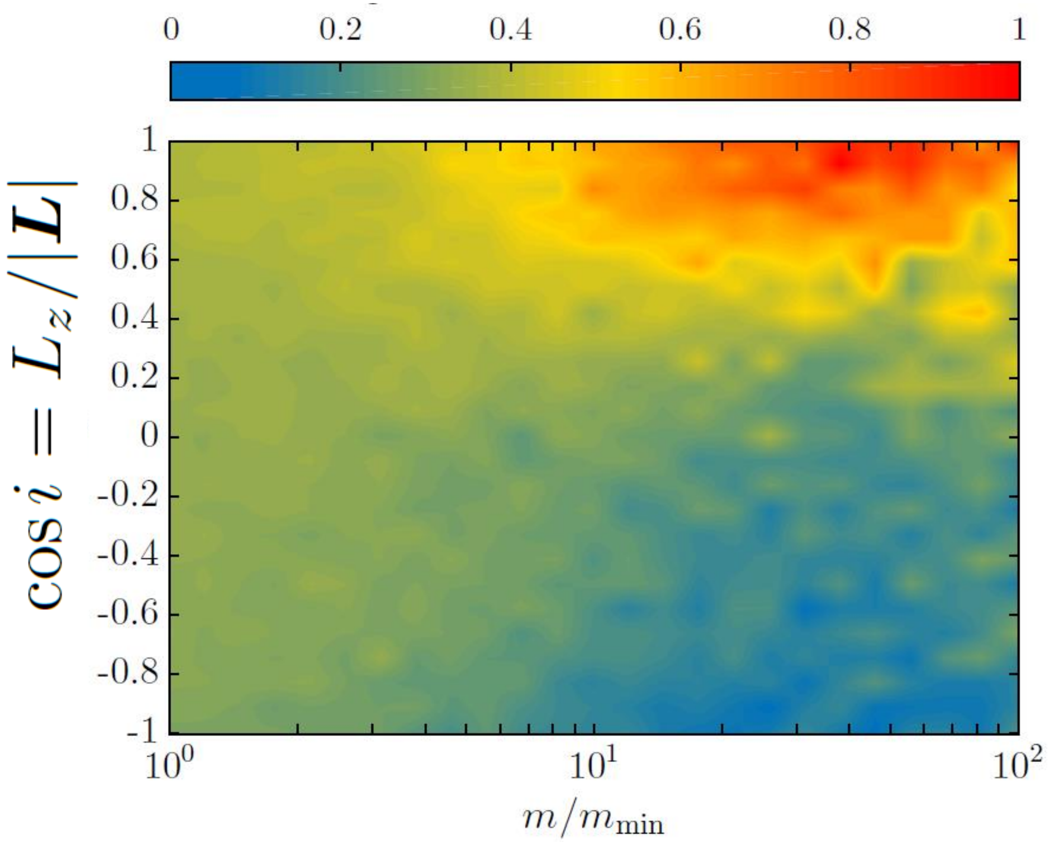
Maximum entropy:

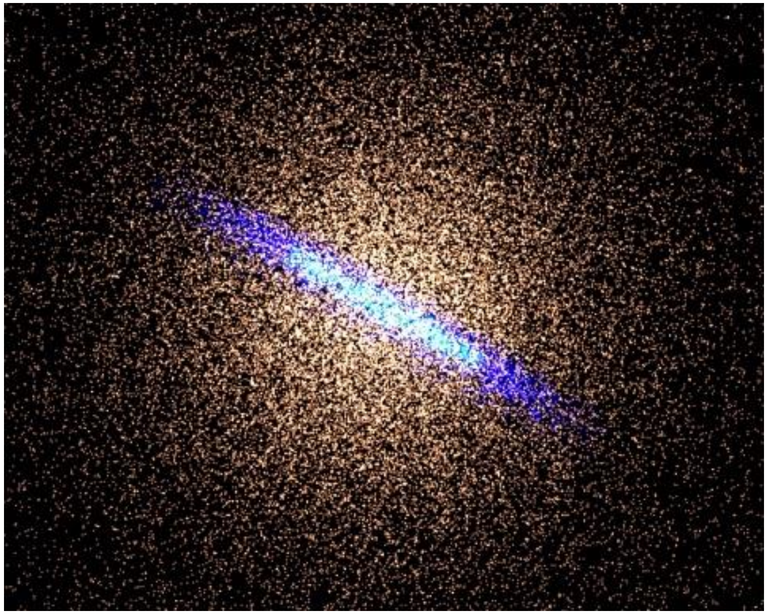
- massive objects: ordered phase
- light objects: spherical phase
- Implication: Black hole disks !



Black hole disks in galactic nuclei

- Massive objects like black holes sink to form a disk
  - mergers more likely

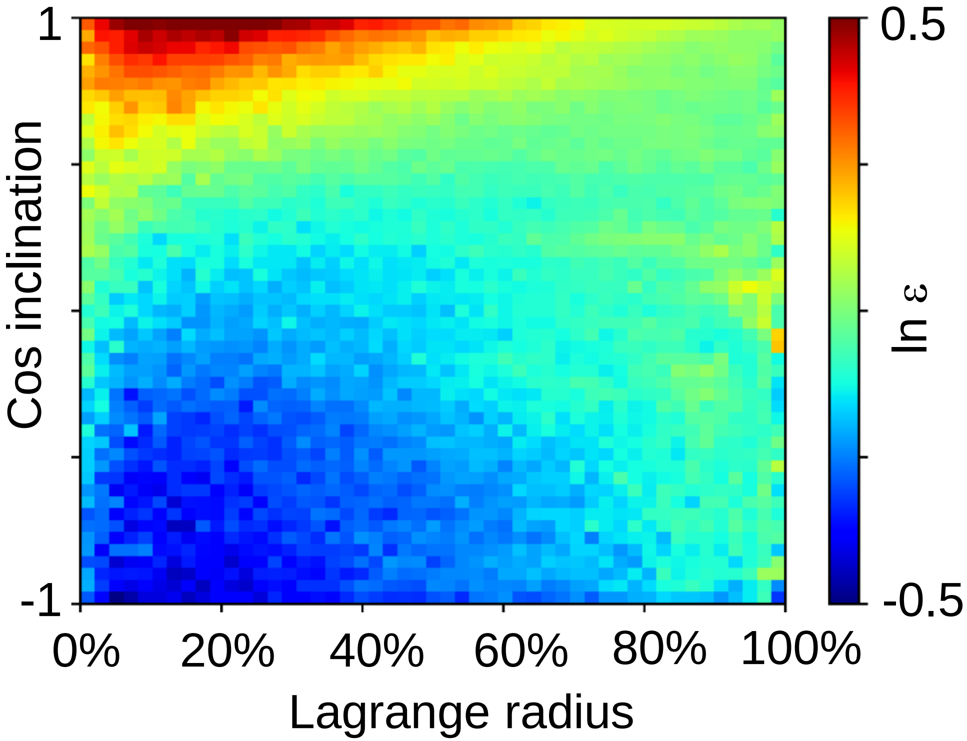




Szolgyen, Kocsis PRL 2018

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

possible ways forward
II.

Distinguishing sources

from different channels

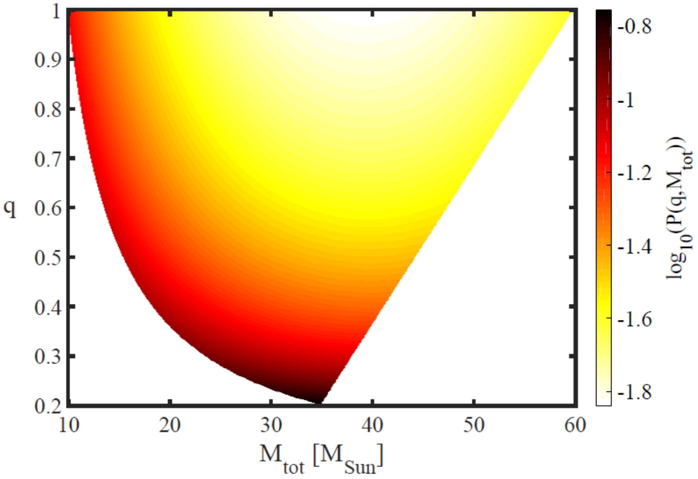
- eccentricity, mass, spin distribution
- electromagnetic counterparts
- intermediate mass black holes

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)?



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

Mass distribution for different processes

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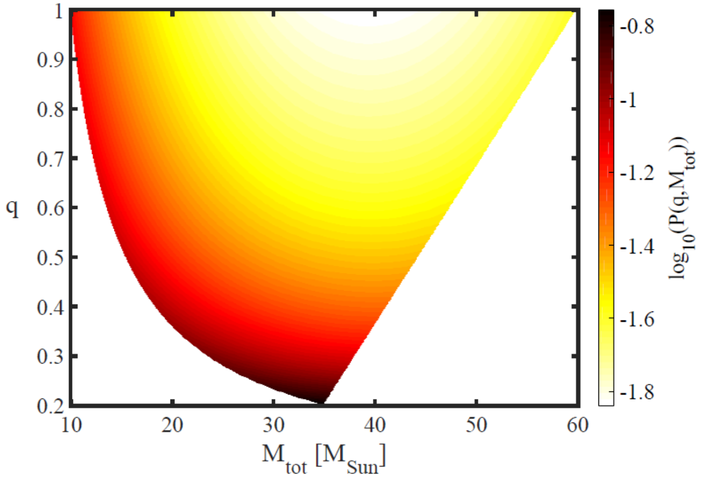


$$\boxed{-(m_1+m_2)^2 \frac{\partial^2}{\partial m_1 \partial m_2} \ln \mathcal{R}(m_1, m_2, t)}$$

$= \mathbf{4}$ 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

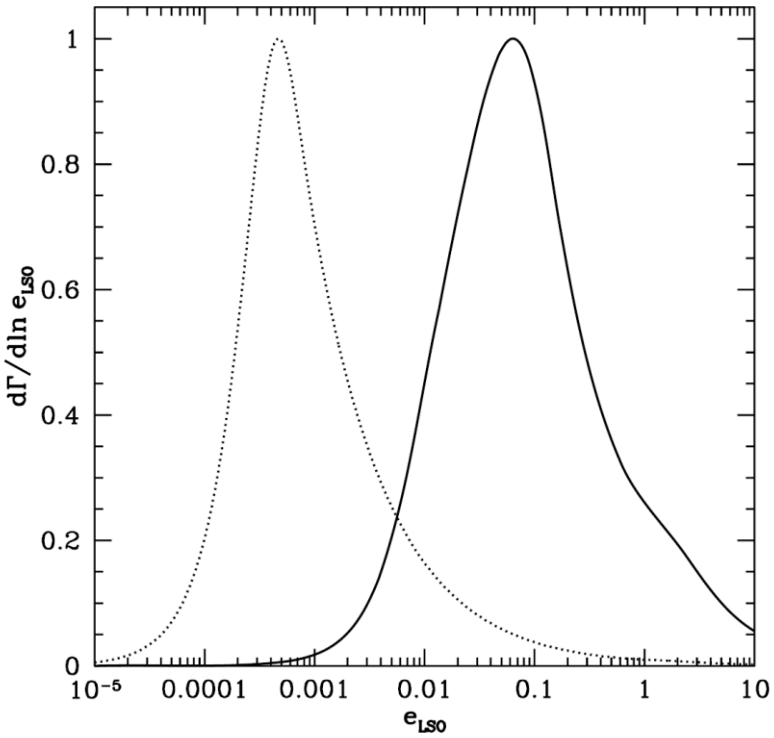
$= \mathbf{1}$ for PBH binaries formed in early universe

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

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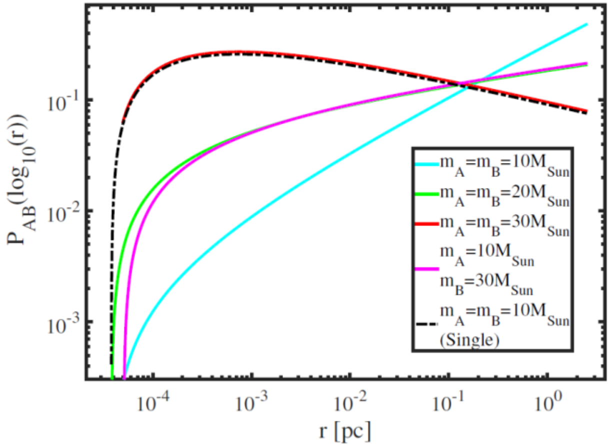
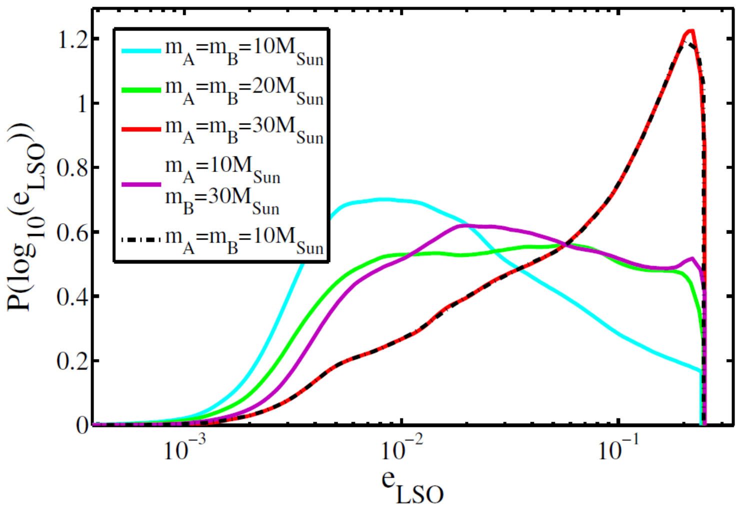


radial distribution of mergers shows mass segregation



→ 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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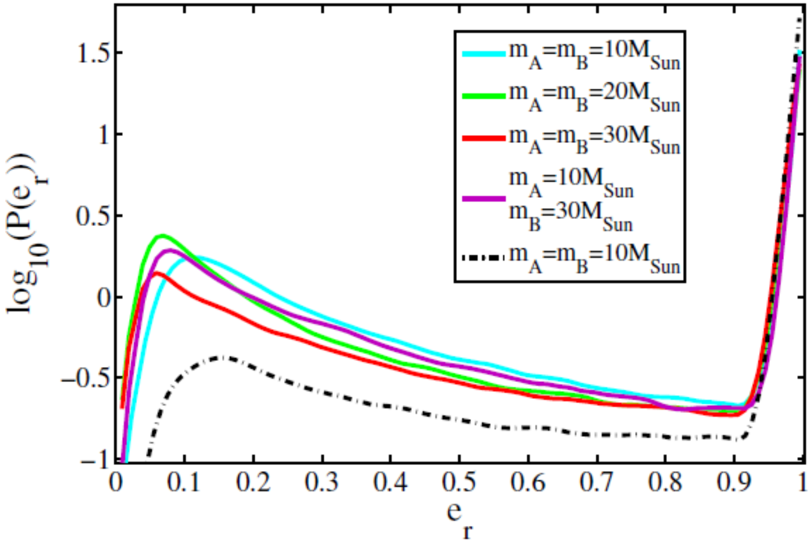
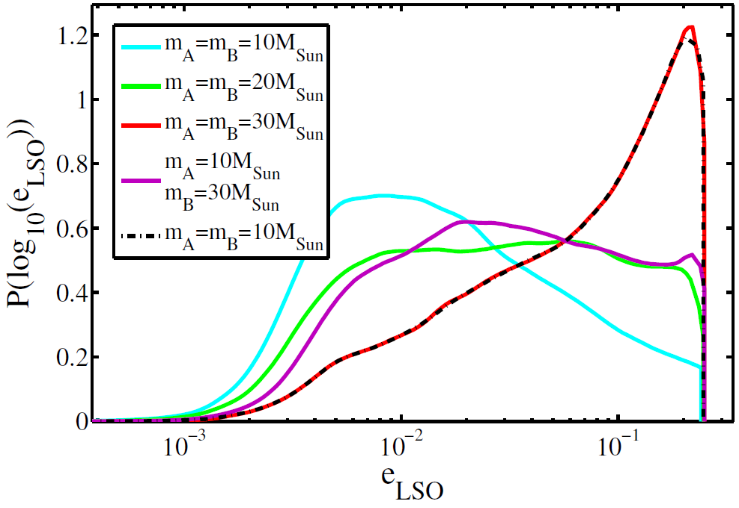


Eccentricty distribution when ALIGO first sees it (design sensitivity)



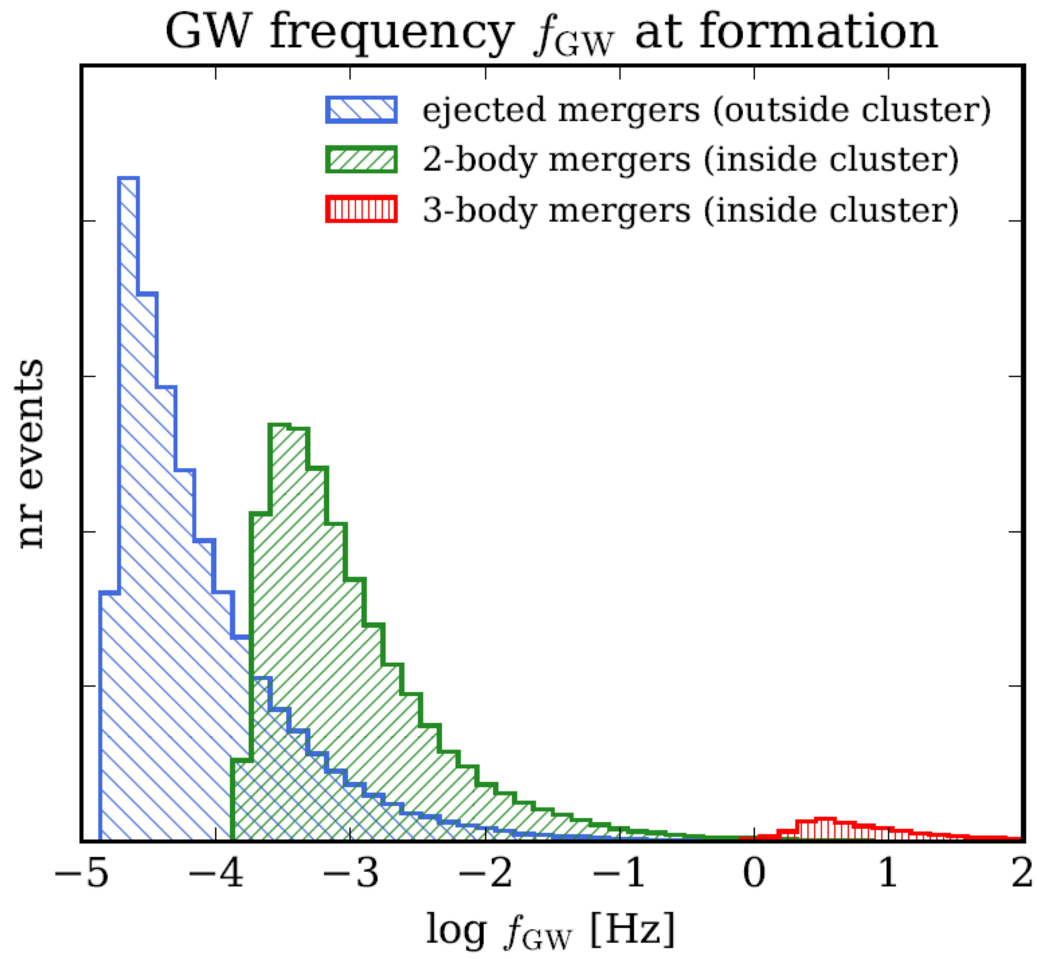
→ Eccentricity distribution reveals mass segregation

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

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

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

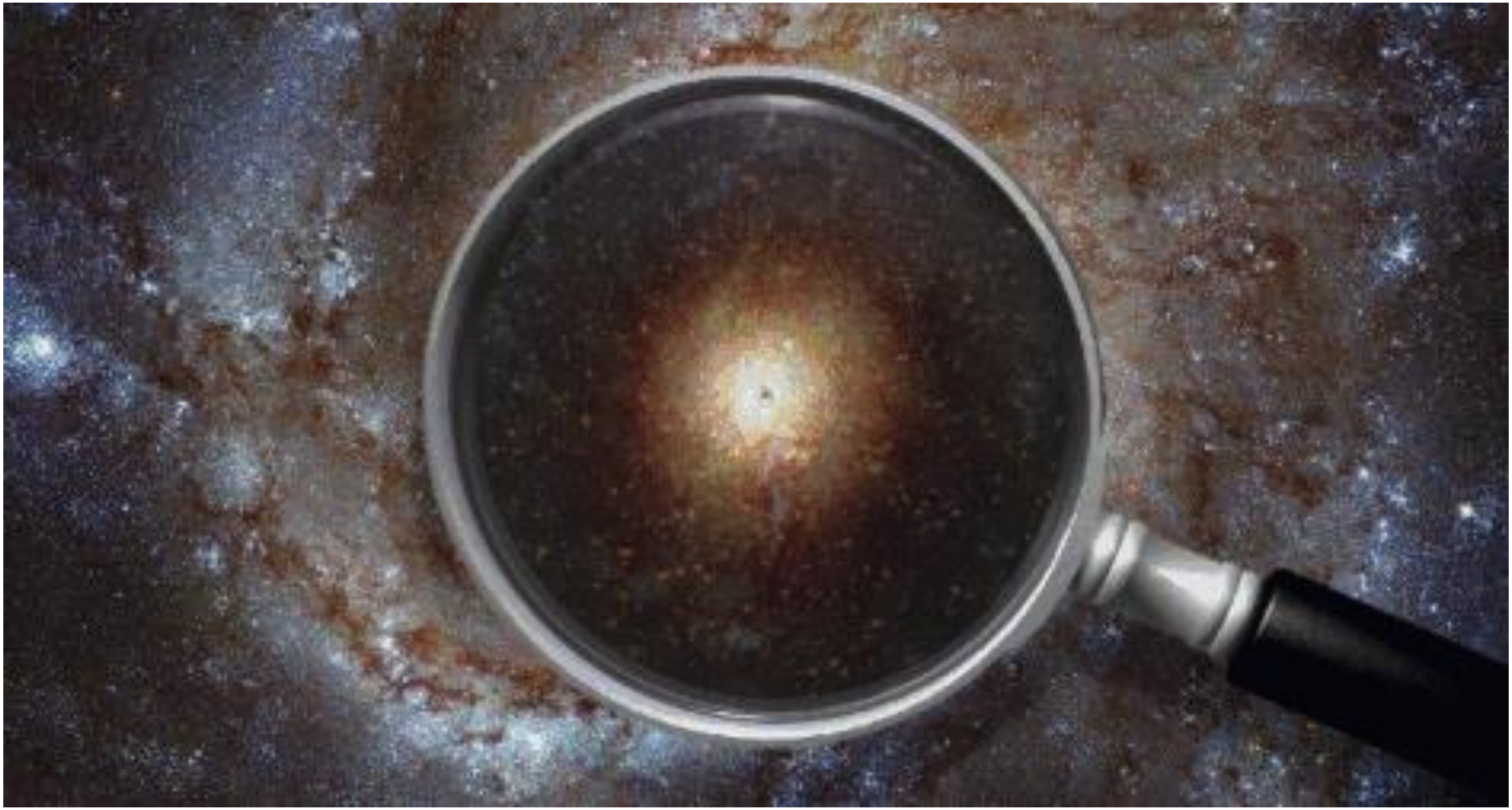
Eccentricity distribution
for merging globular cluster binaries



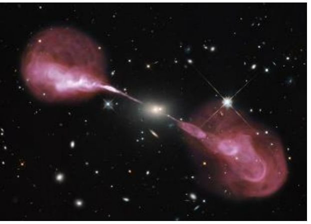
Samsing+ (2018a, 2018b)

Eccentric sources:
rates from different channels

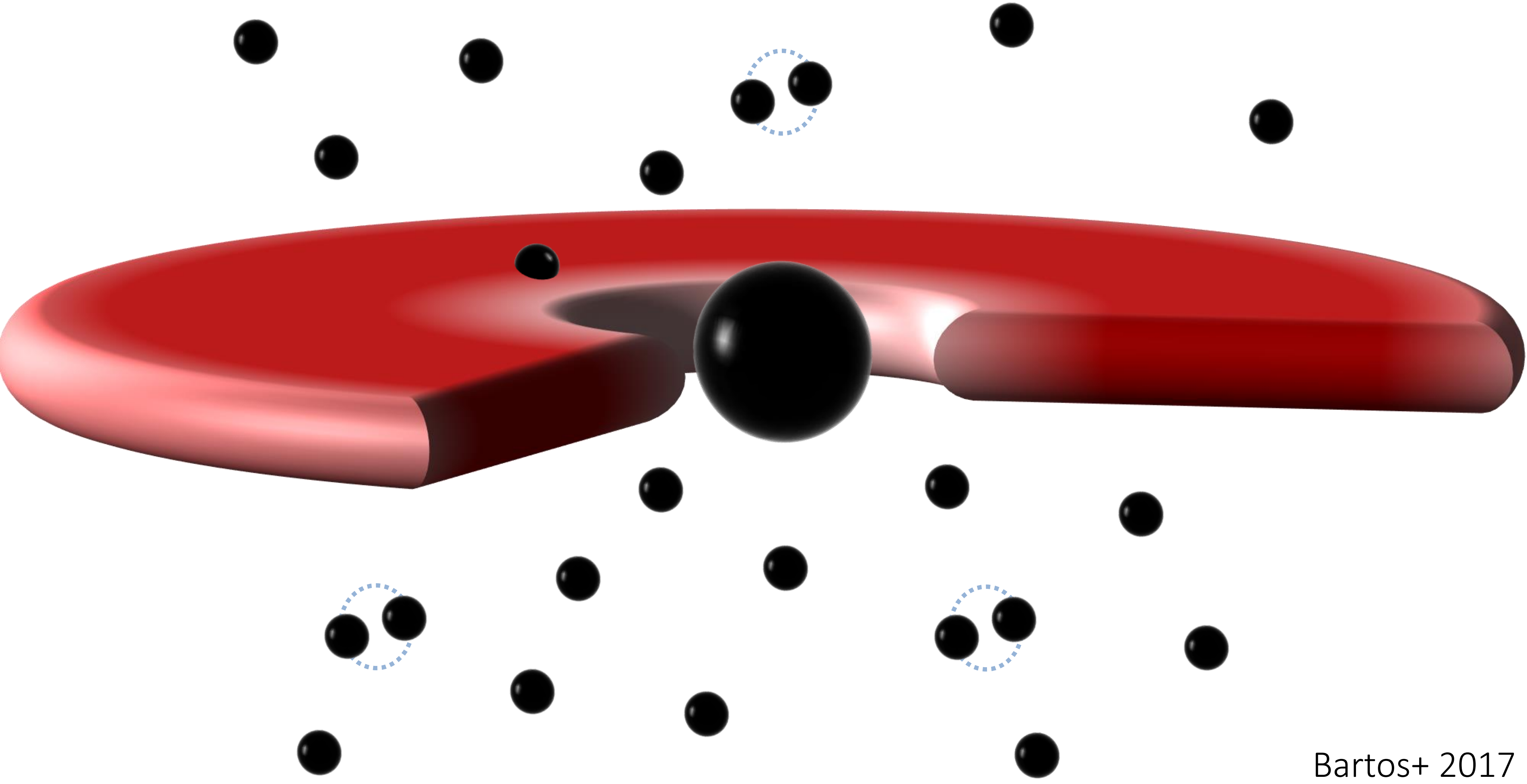
	GW capture (single-single interactions)	Hierarchical triples (Kozai-Lidov effect)	Binary-single intercactions
Nuclear star clusters	0.01-0.1 (this work) 0.8 (O'Leary+09) 0.02 (Tsang 2013)	? (Hoang+2018)	0 ? (Antonini & Rasio 2016)
Globular clusters	?	0.04 (Antonini+2016)	0.05 - 0.5 (Samsing+2018, Rodriguez+2018)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



Mergers with EM counterparts

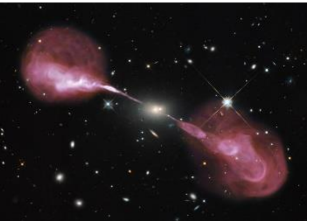


GW sources in active galactic nuclei

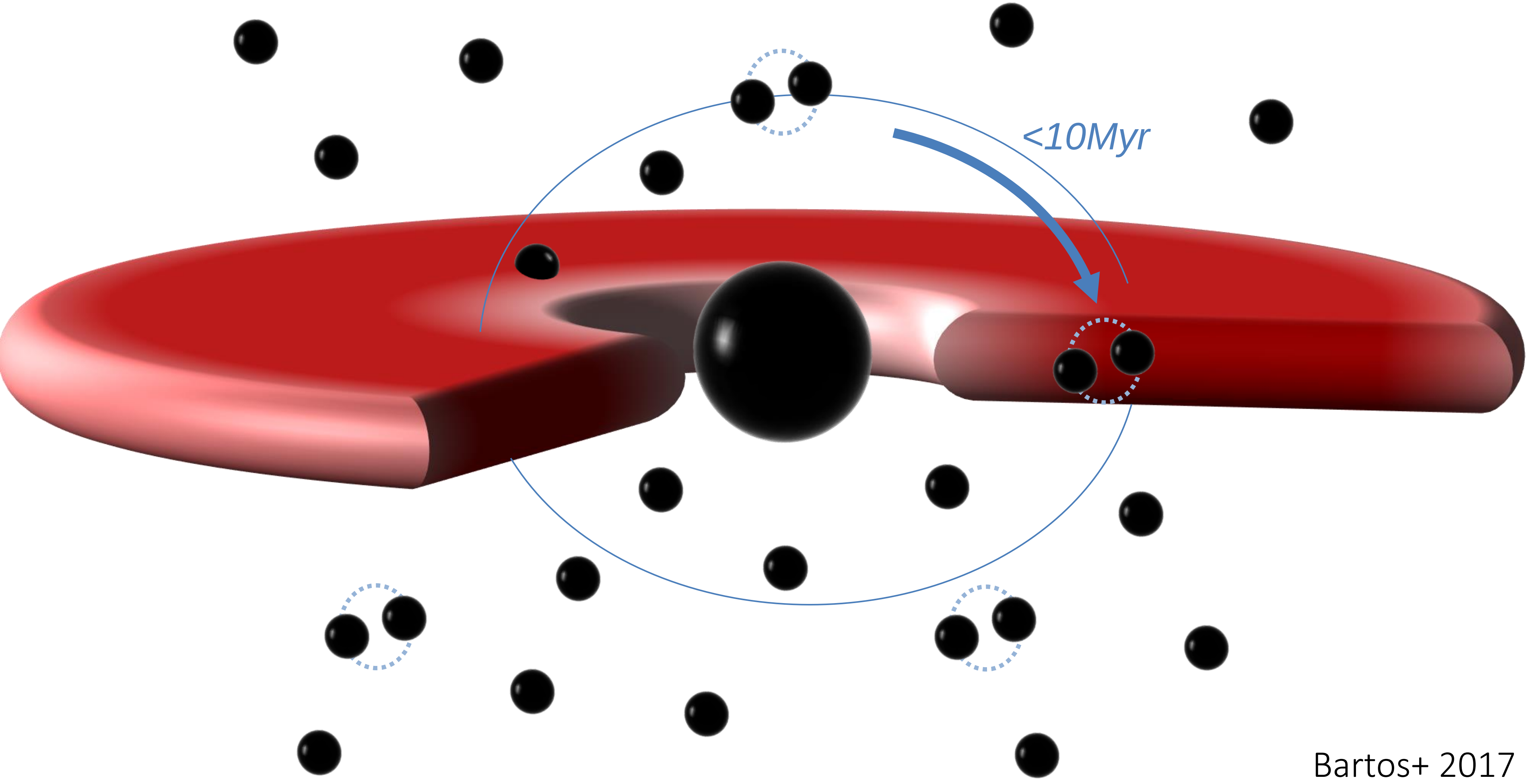


Bartos+ 2017

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

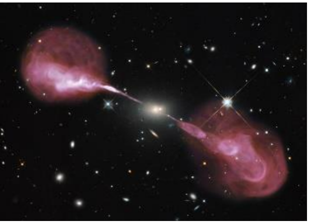


GW sources in active galactic nuclei

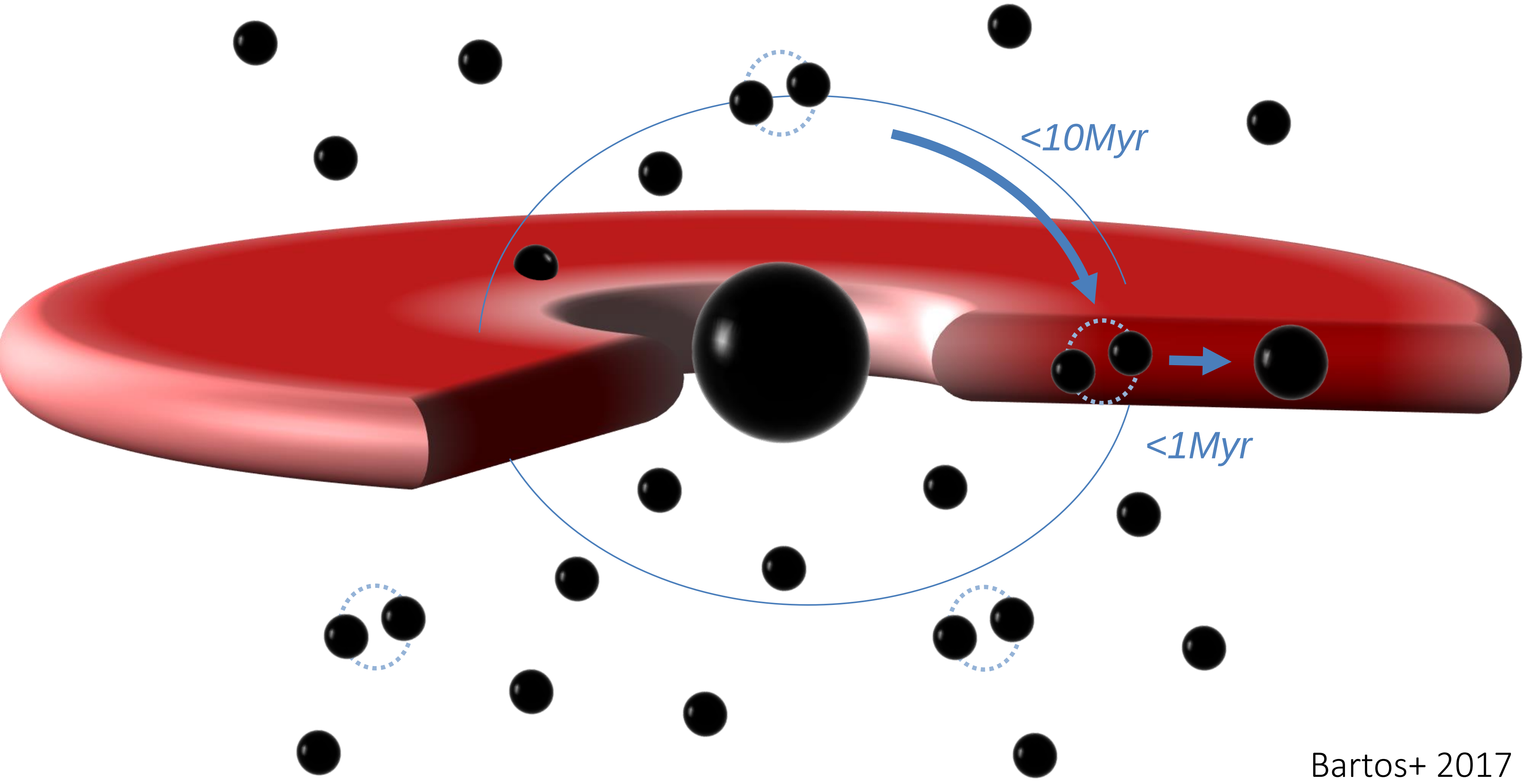


Bartos+ 2017

Get captured by the disk…

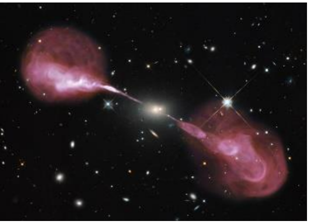


GW sources in active galactic nuclei

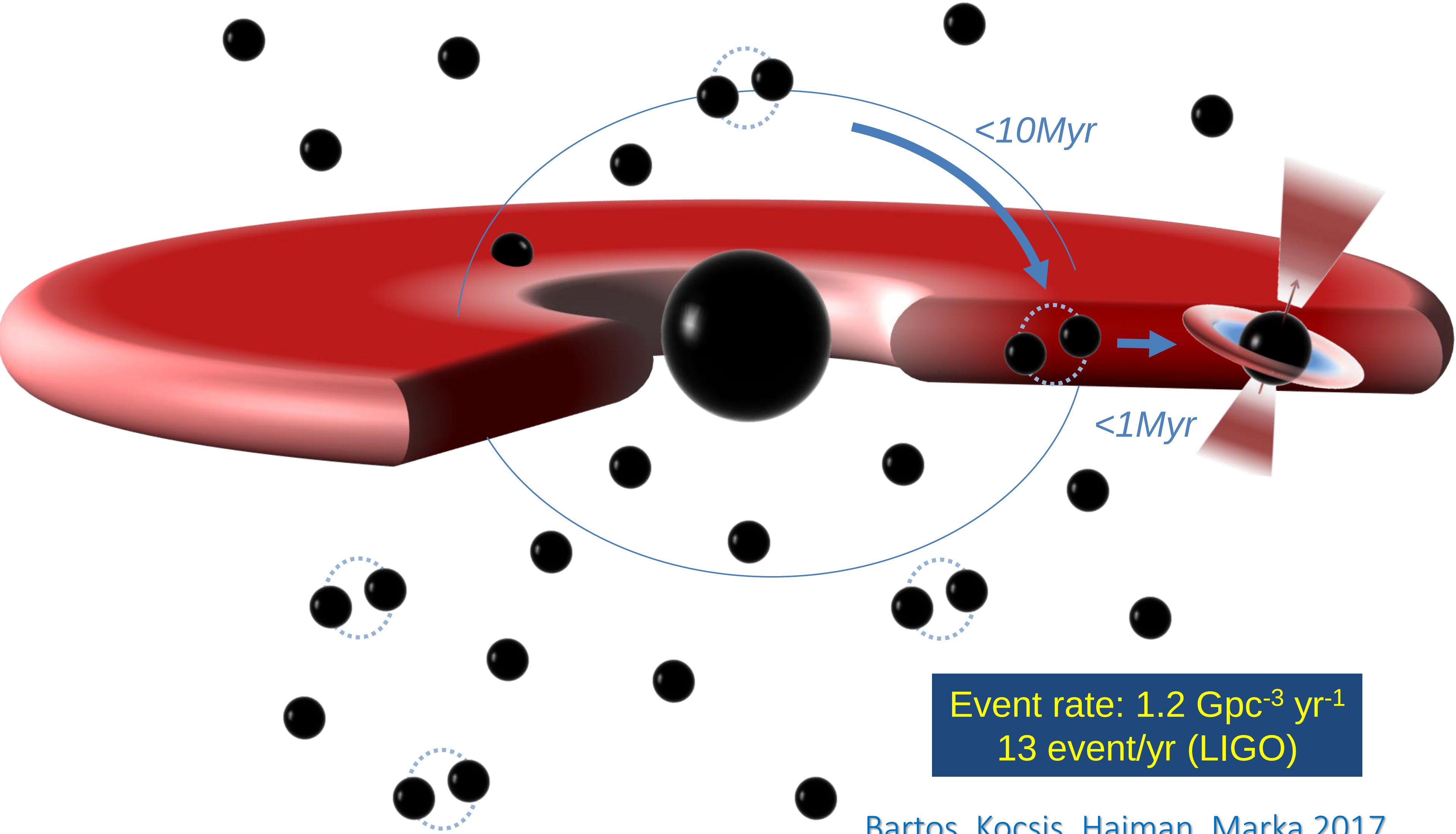


Bartos+ 2017

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



GW sources in active galactic nuclei

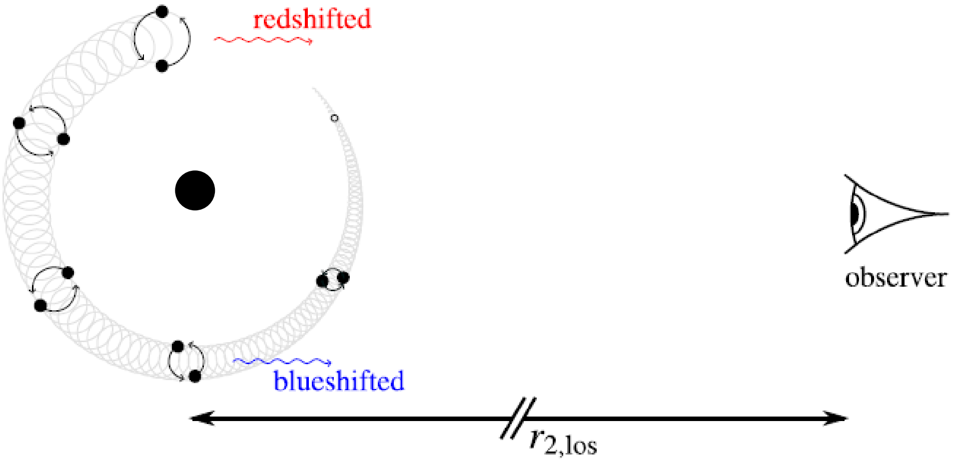


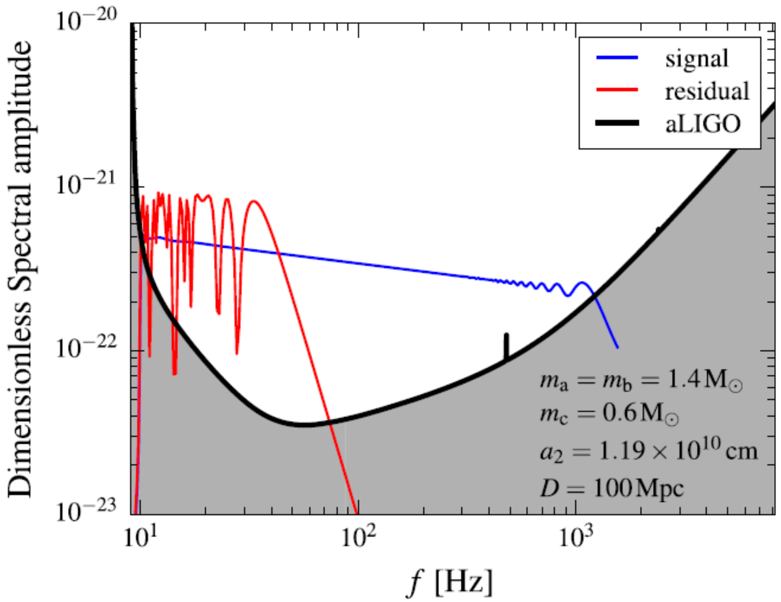
Event rate: 1.2 Gpc^{-3} yr^{-1}
13 event/yr (LIGO)

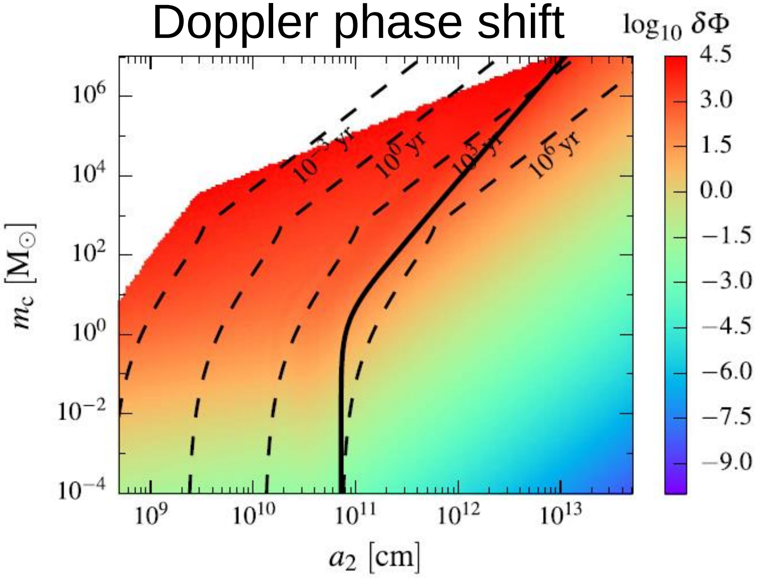
Bartos, Kocsis, Haiman, Marka 2017
Stone, Metzger, Haiman 2017

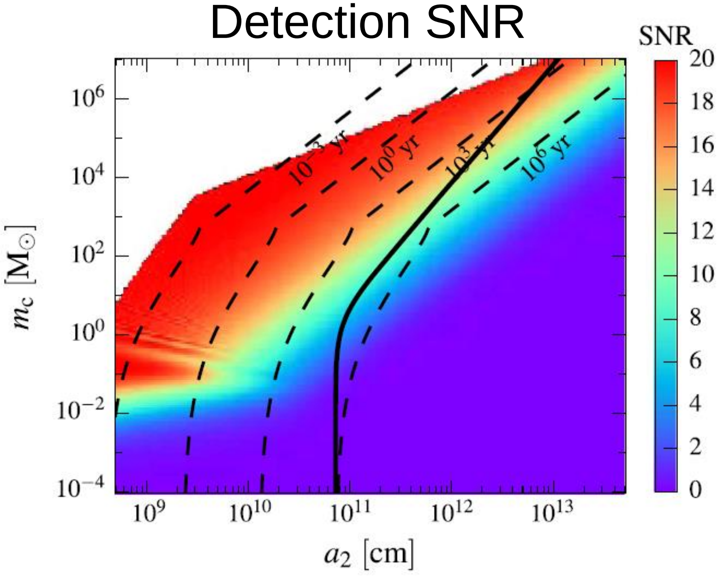
Smoking gun signatures to identify origin of source

SMBH/AGN source with LIGO



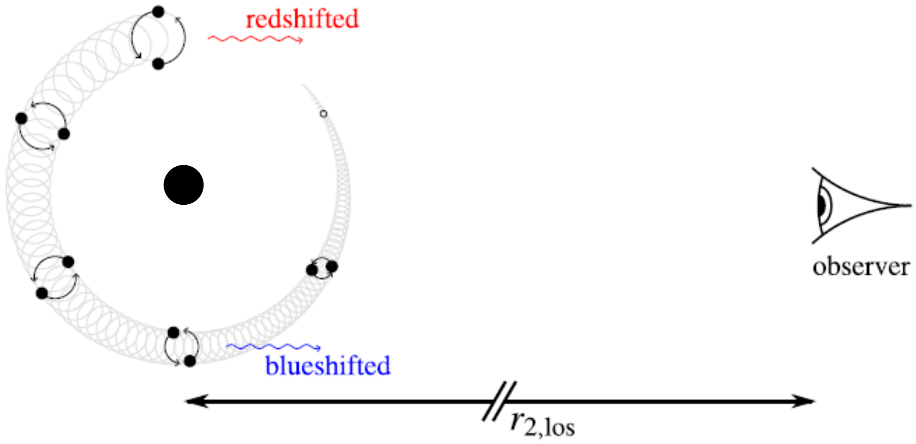



Doppler phase shift

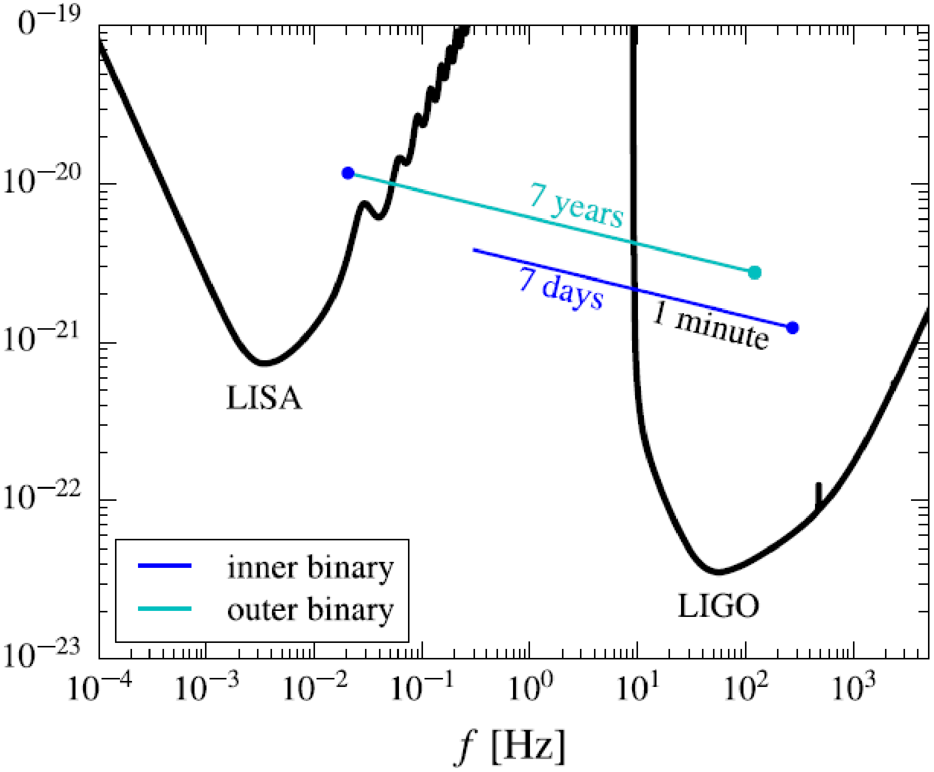

Detection SNR

Meiron, Kocsis, Loeb 2017

SMBH/AGN source with LIGO+LISA



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

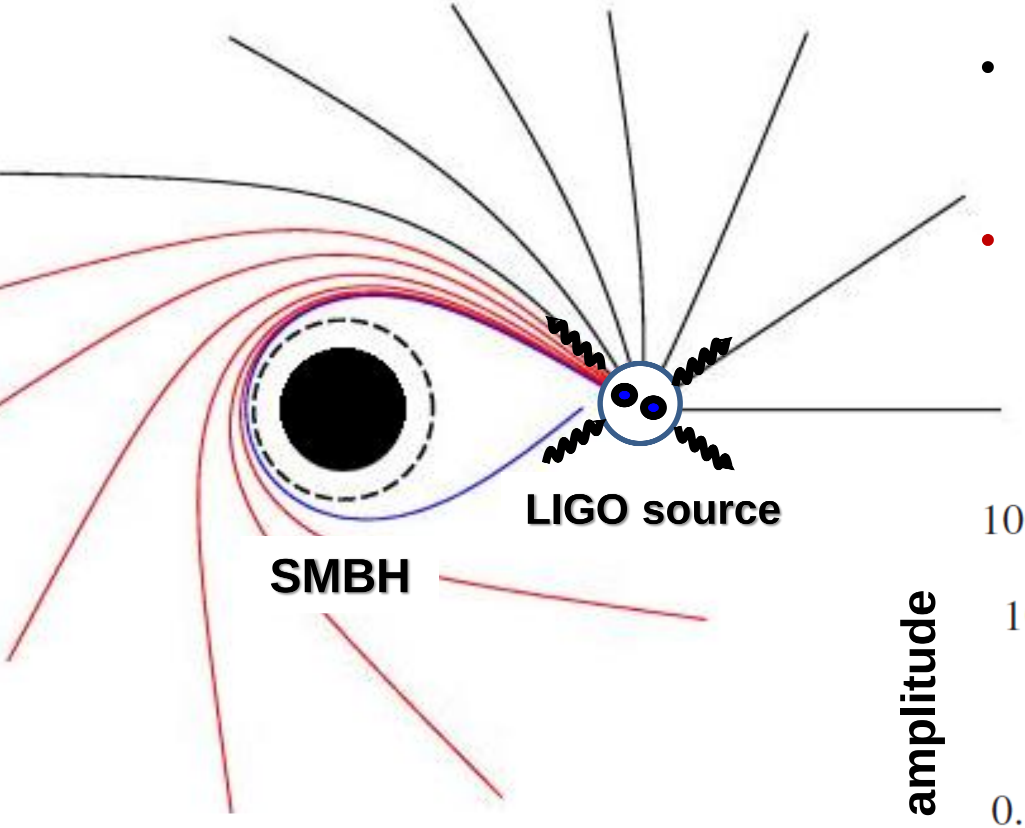


- LISA+LIGO coincident detection of triple inspiral
- LIGO detection of GW mass loss
- LISA detection of GW mass loss
- Later: LIGO detection of merger (if stellar-mass triple)

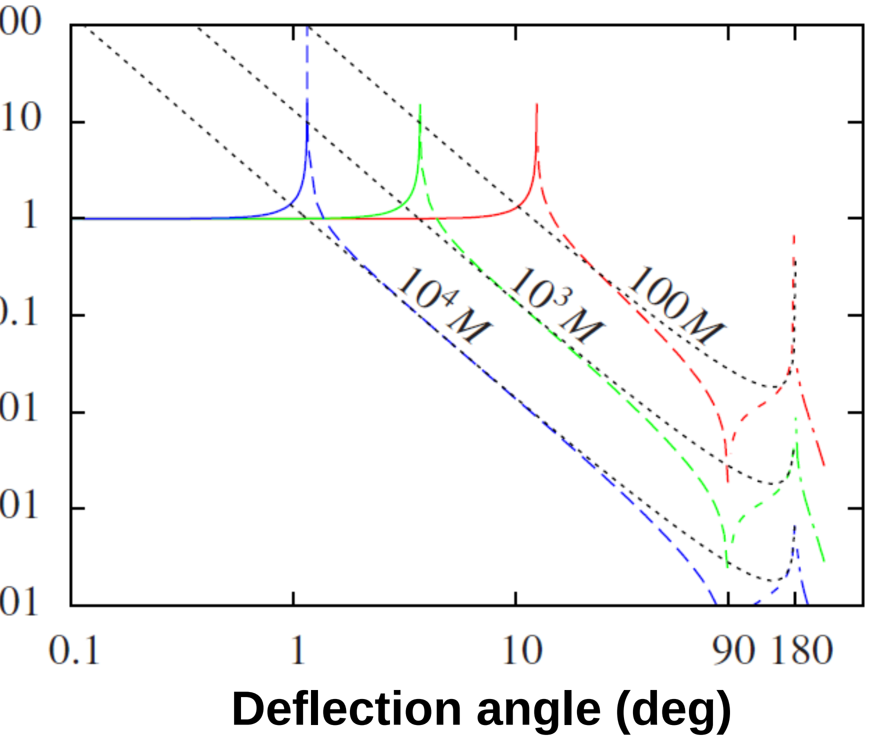
Test of general relativity

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.

What about intermediate mass black holes?

$100\ M_{Sun} – 10^5\ M_{Sun}$

intermediate mass black holes

Theory

Formation

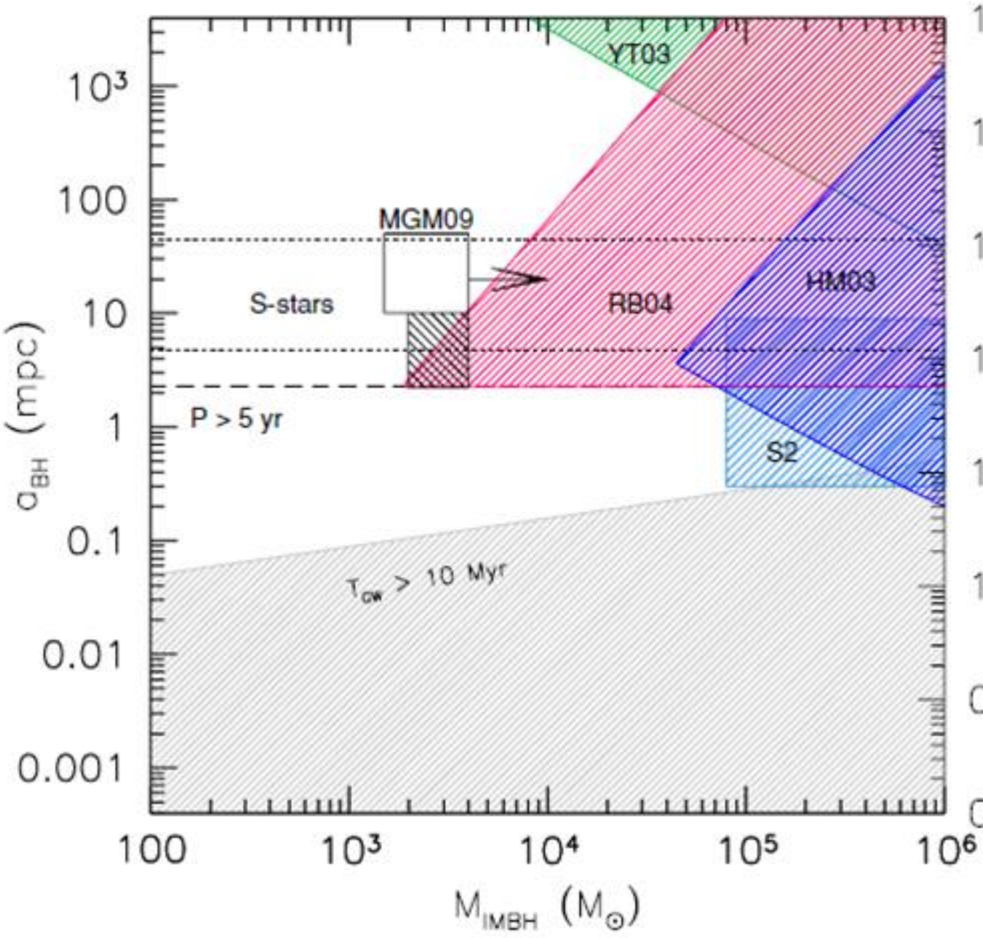
- Early universe:
  - collapse of the first stars (Madau & Reese '01)
- Globular clusters
  - runaway collisions (Portegies Zwart &McMillan '02)
  - mergers of stellar mass black holes (Miller & Hamilton '02)
  - dynamical friction

    → 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

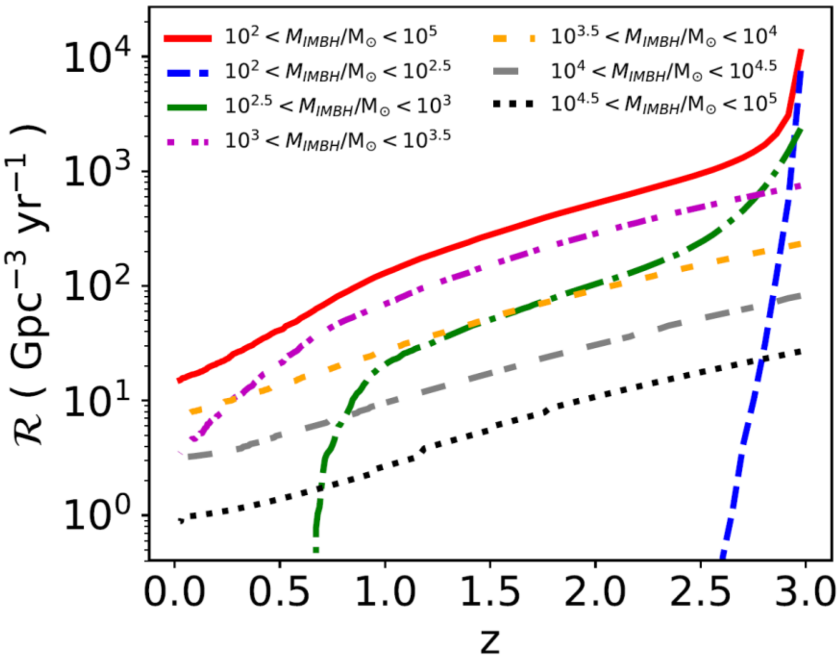
Observational constraints



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

GWs from intermediate mass black holes

IMBH + BH mergers in globular clusters



M < 300 M_{sun} @ z > 2.6 ☹

>300 M_{sun} mergers are closer (z>0.6) but currently not detectable due to low-frequency noise

Advanced LIGO @ design sensitivity and LISA should see them ☺ ☺

Fragione, Ginzburg, Kocsis 2018

Take-away

- **New ideas are needed** to identify the most common source
  - fallback driven mergers ?
  - disrupted globular clusters ?
  - black hole disks?
- Discriminate LIGO sources using **2D mass distribution**
  - 4 for globular clusters
  - 2 for galactic nuclei
  - 1 for primordial black holes

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

- **Eccentricity** measurable at design sensitivity
  - Delta e ~ 0.01
- **Smoking gun signatures** in some cases

  → Doppler phase

  → GW echo for a few percent of these
- **IMBH discovery expected** at LIGO design sensitivity