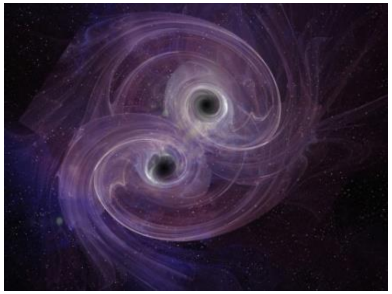
Gravitational Wave Astrophysics

Bence Kocsis Eotvos University



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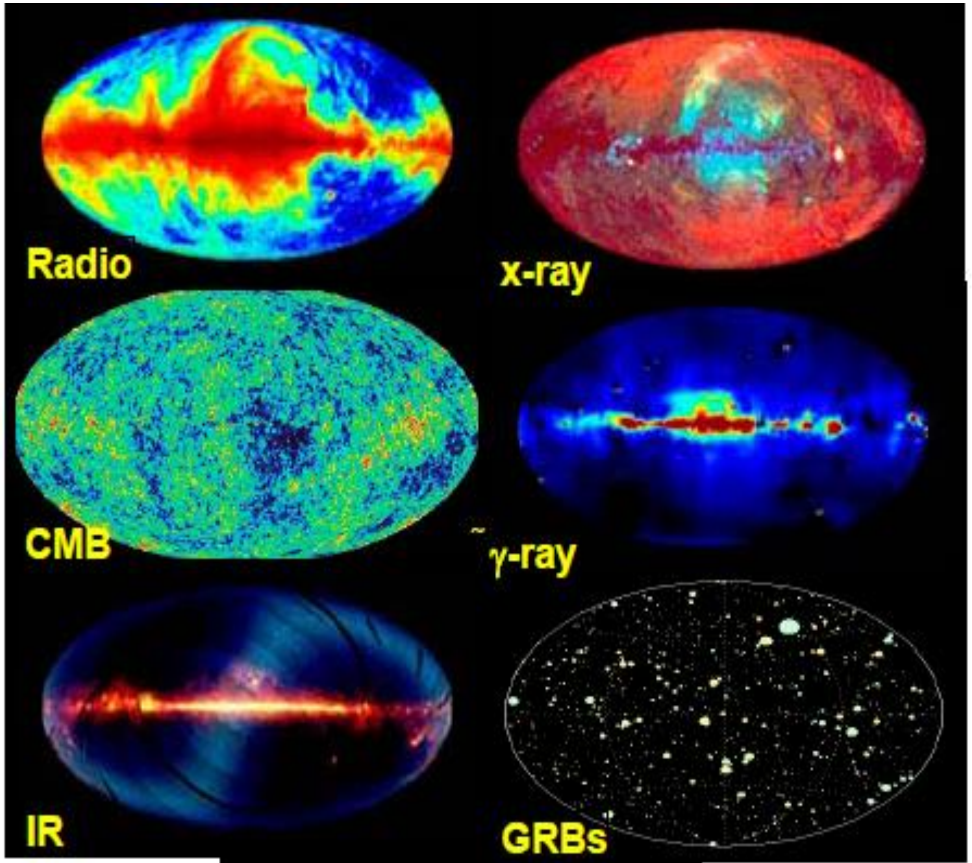
Black Hole Physics, 2018

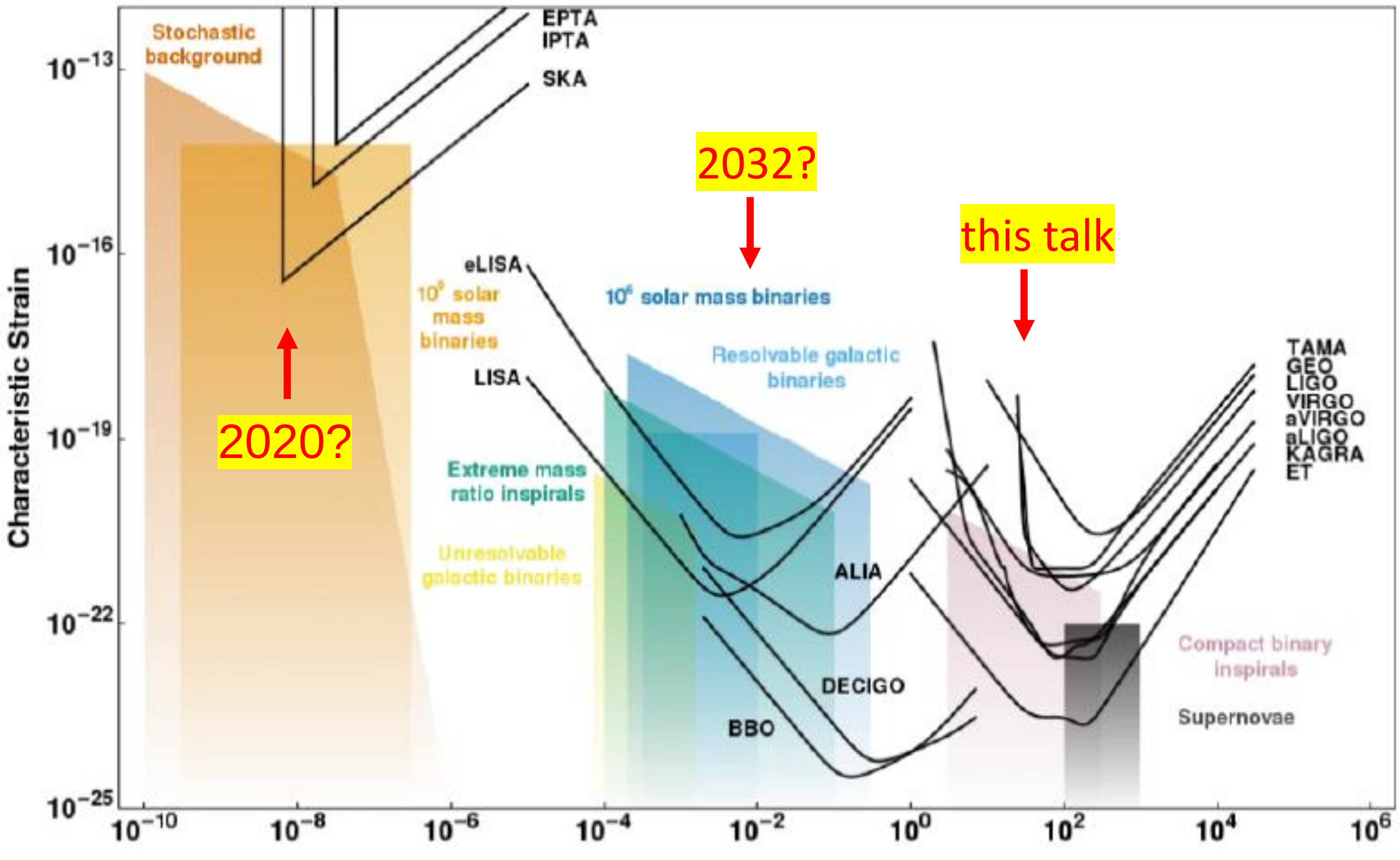
The Dawn of GW astronomy



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

EXPECT THE UNEXPECTED!

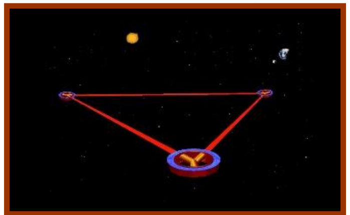
Gravitational wave detectors



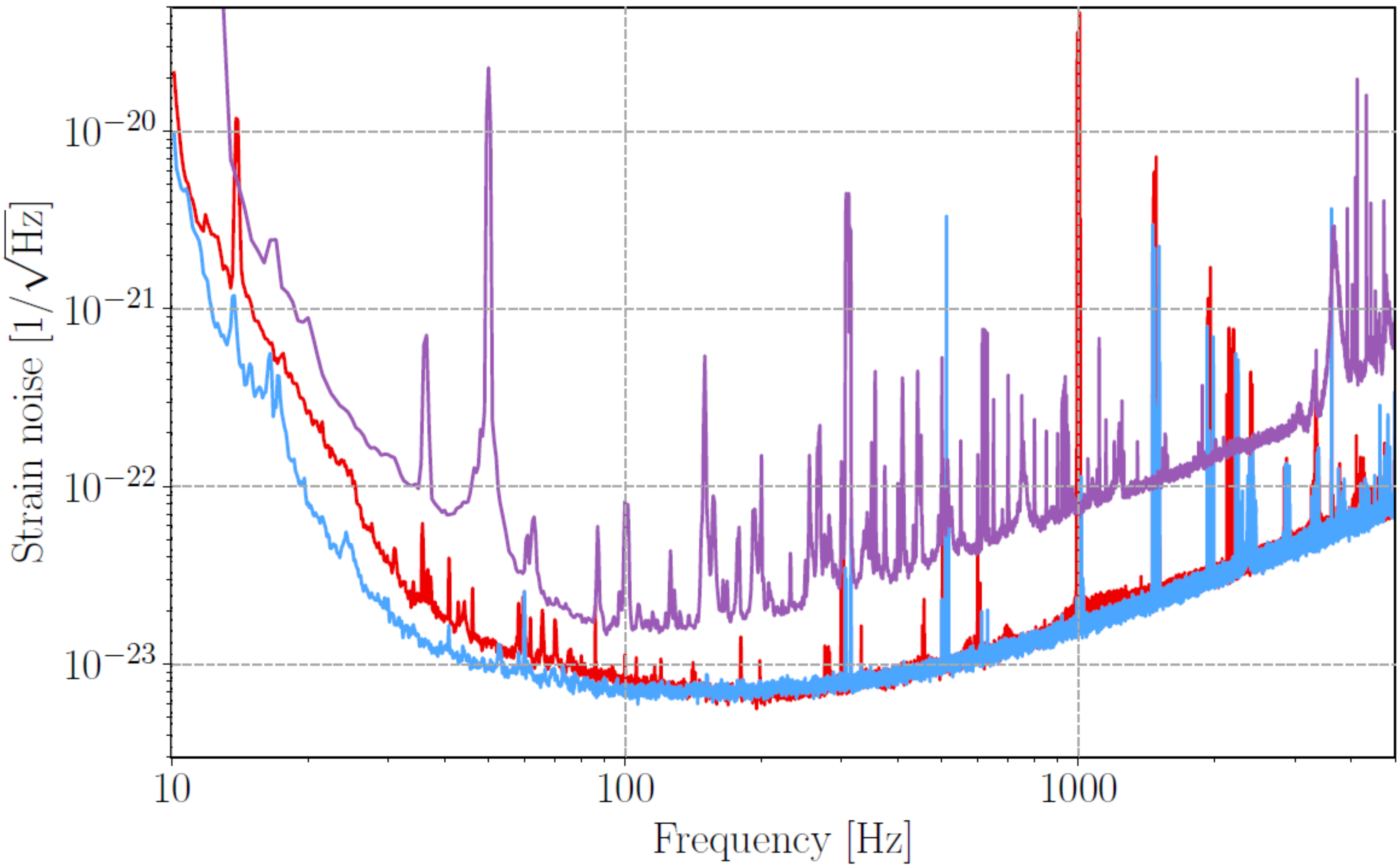
2032?

this talk

2020?

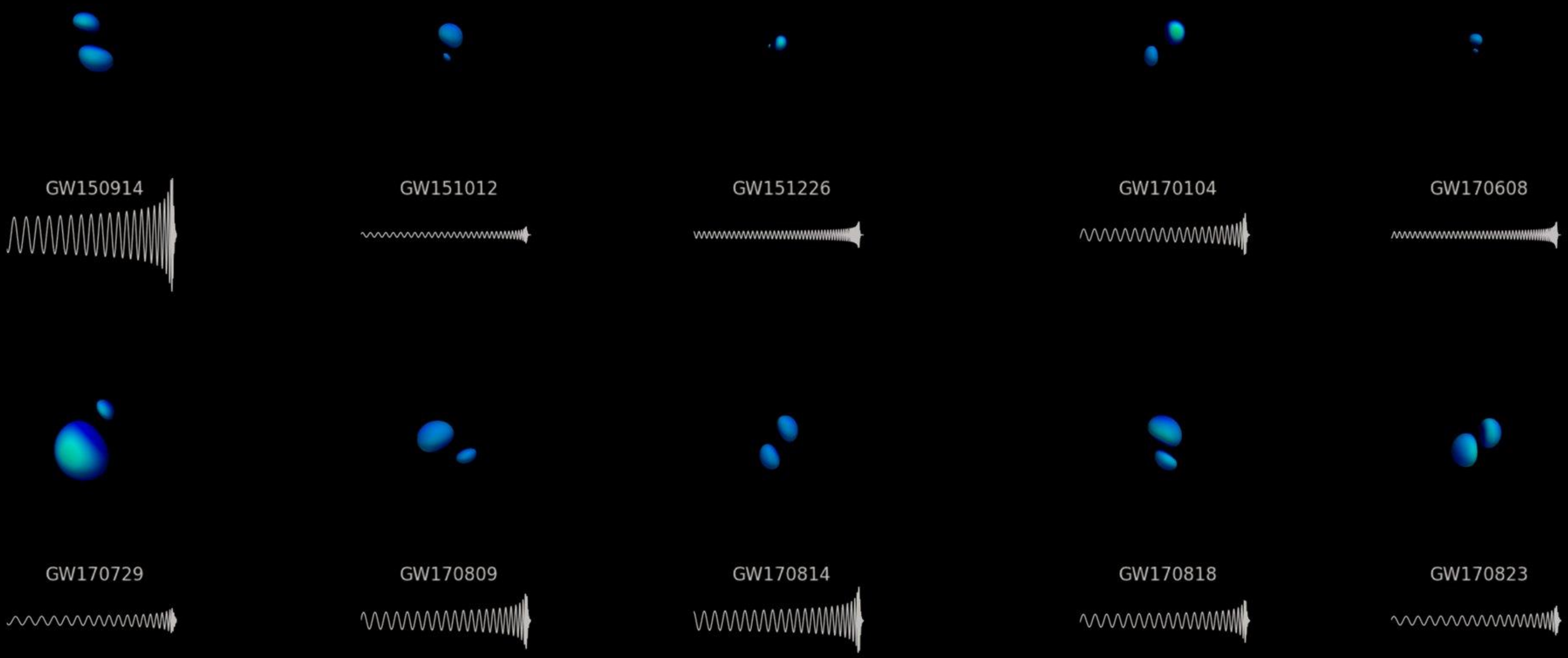


LIGO-H, LIGO-L, VIRGO sensitivity



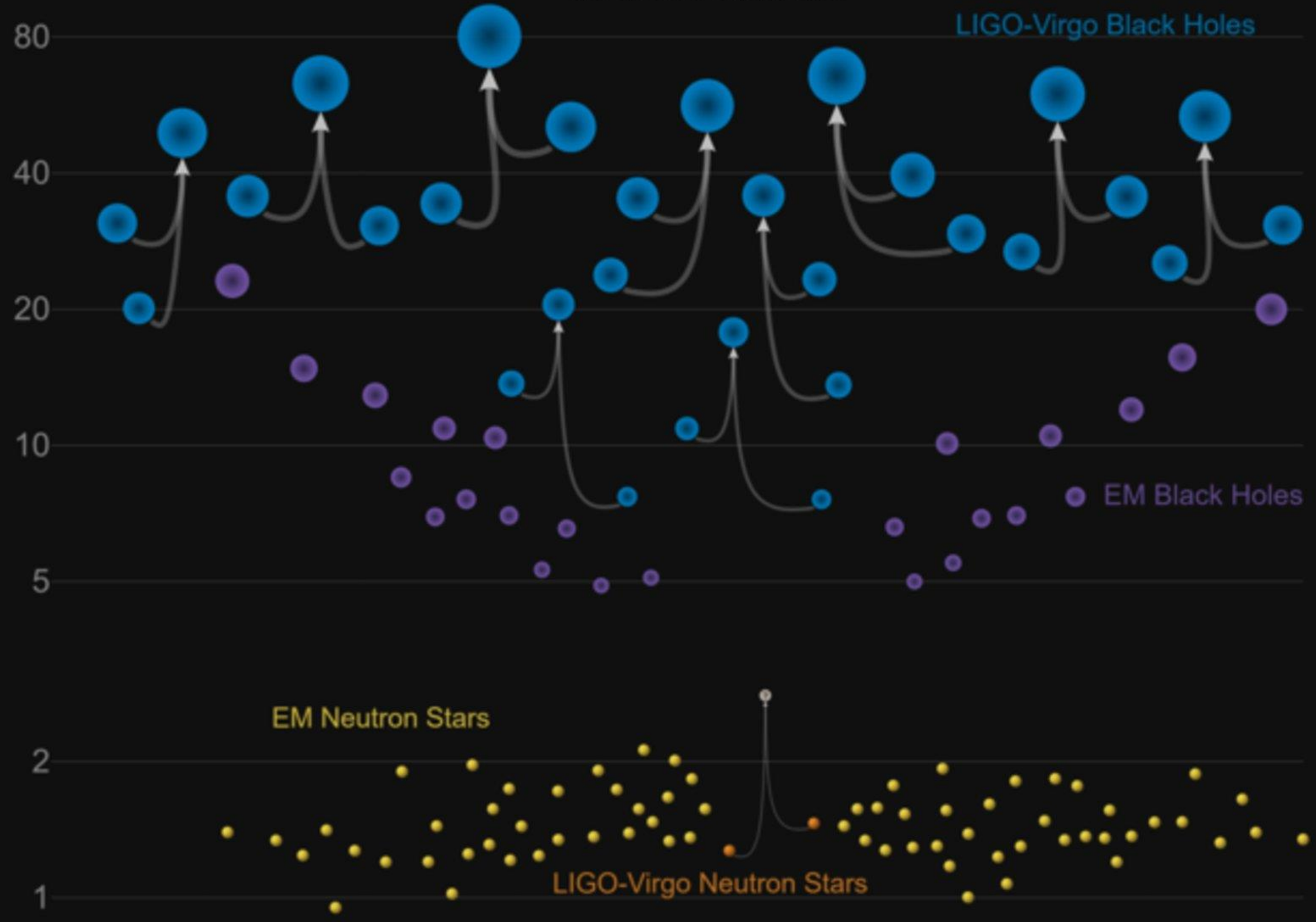
arxiv:1211.12907

Gravitational wave detections



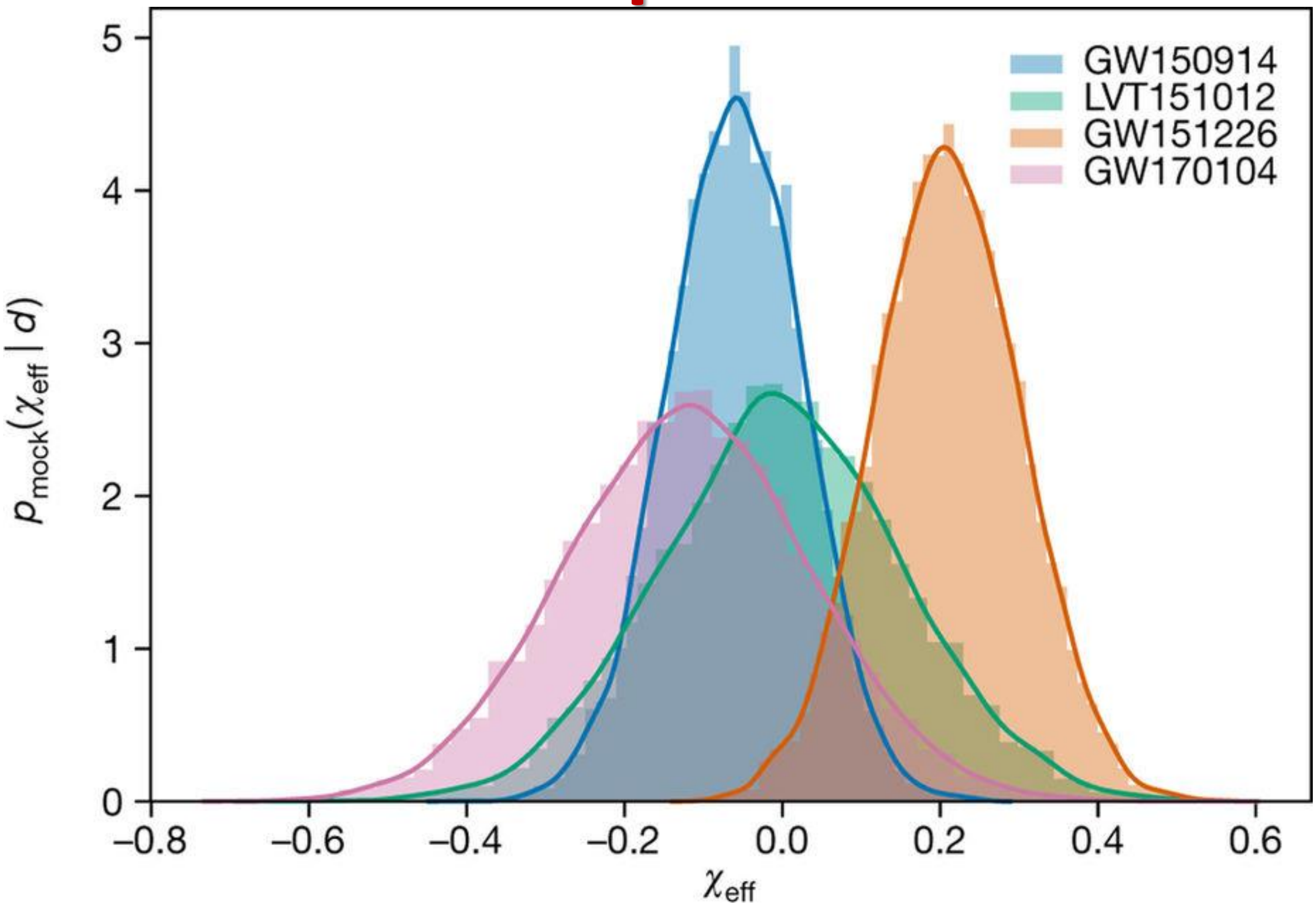
Masses in the Stellar Graveyard

in Solar Masses



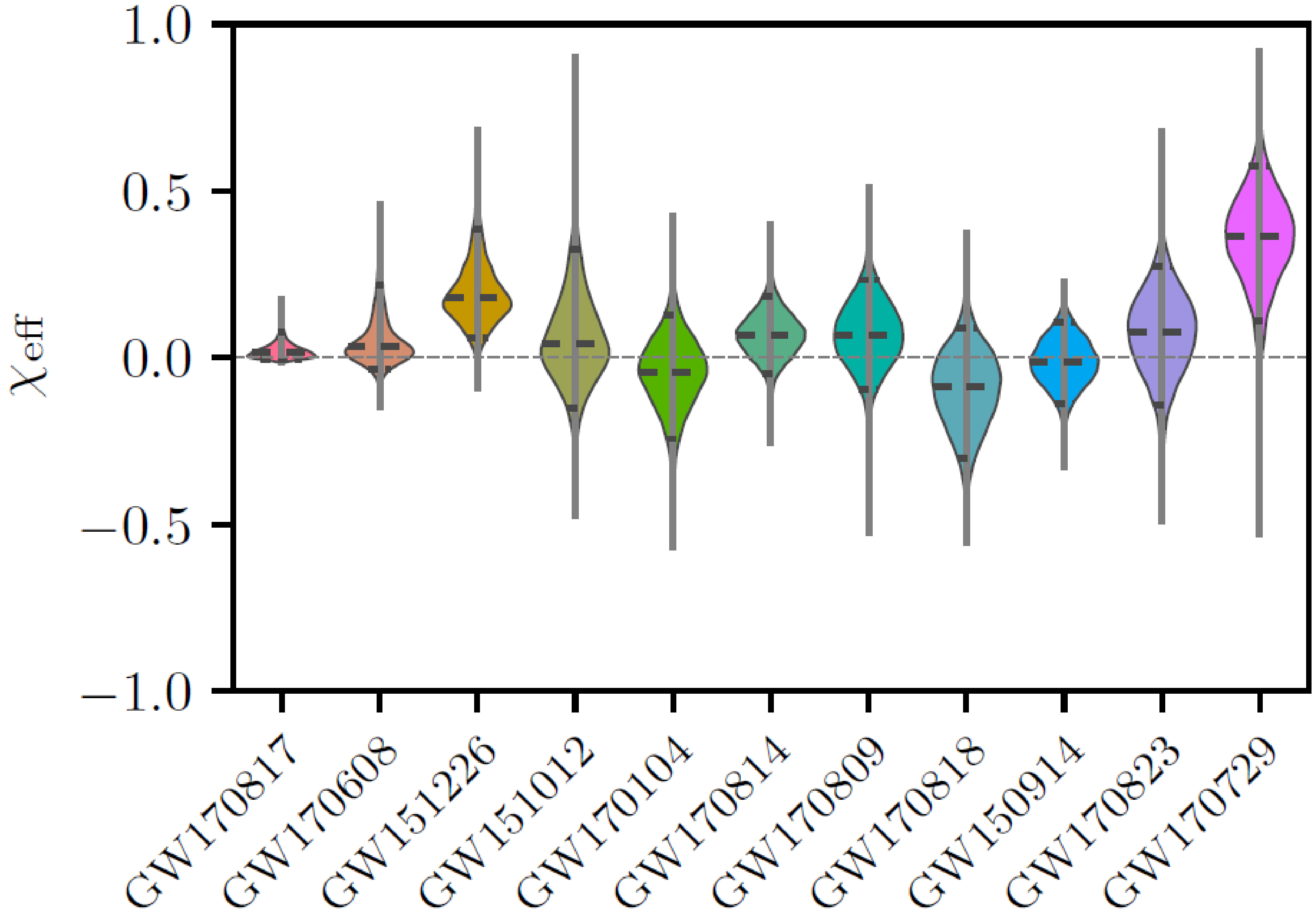
LIGO-Virgo | Frank Elavsky | Northwestern

Spins



Farr+ (2017)

Spins



$\chi_{\rm eff}$
1.0
0.5
0.0
−0.5
−1.0
GW170817
GW170608
GW151226
GW151012
GW170104
GW170814
GW170809
GW170818
GW150914
GW170823
GW170729

Rate of BBH coalescence

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

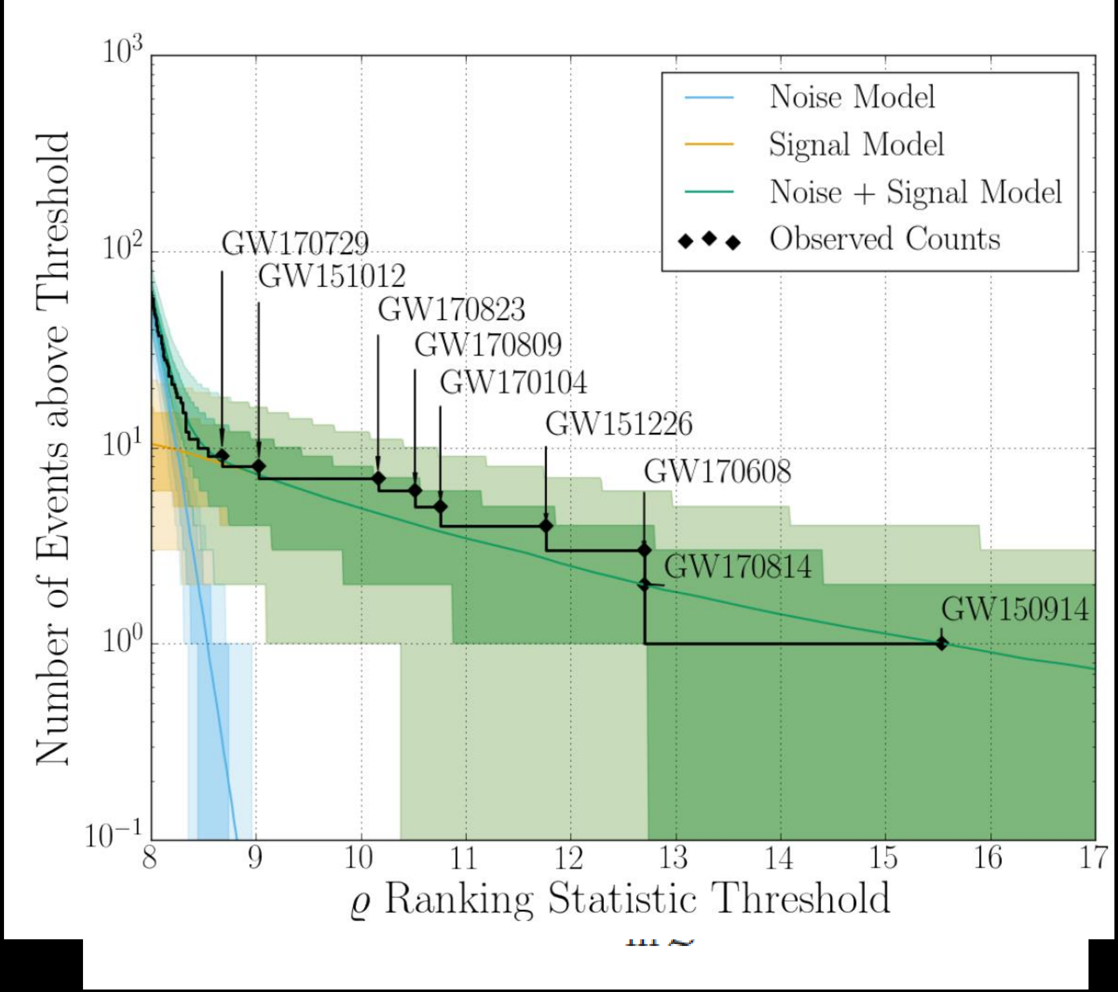
+GW151226:
9 – 240 $\text{Gpc}^{-3}\ \text{yr}^{-1}$

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

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

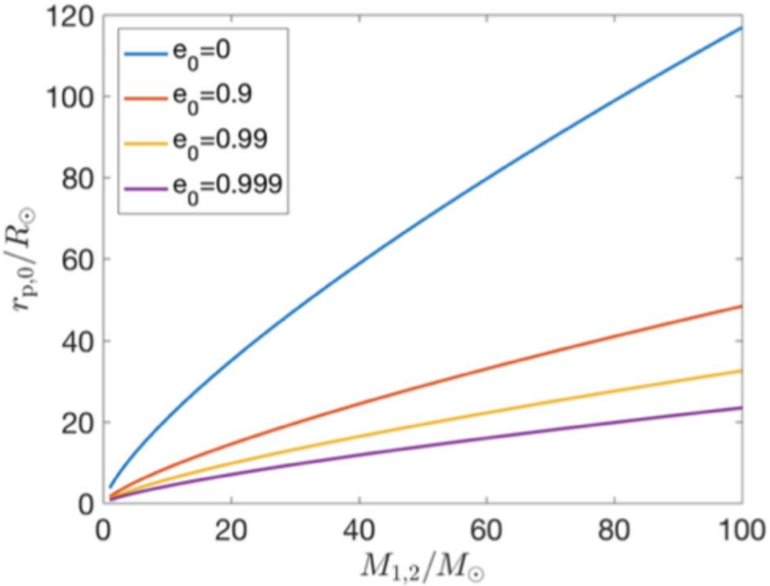
Rate of NS coalescence

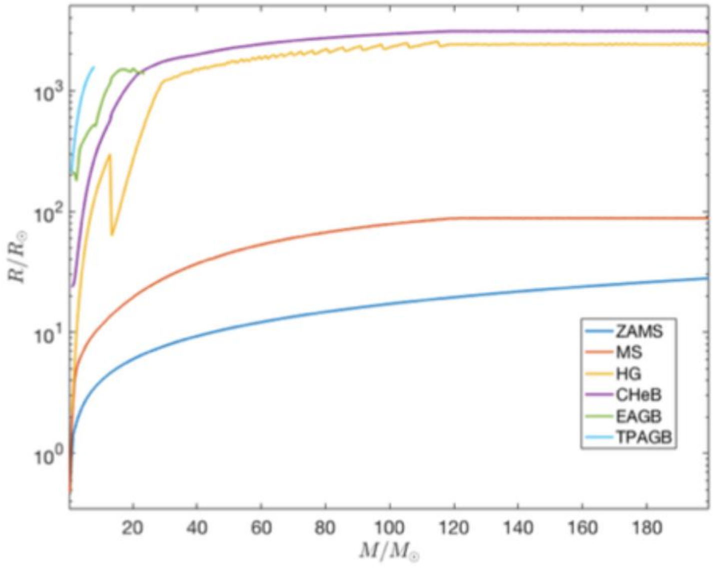
GW170608:
300 – 4700 $\text{Gpc}^{-3}\ \text{yr}^{-1}$



Basic questions

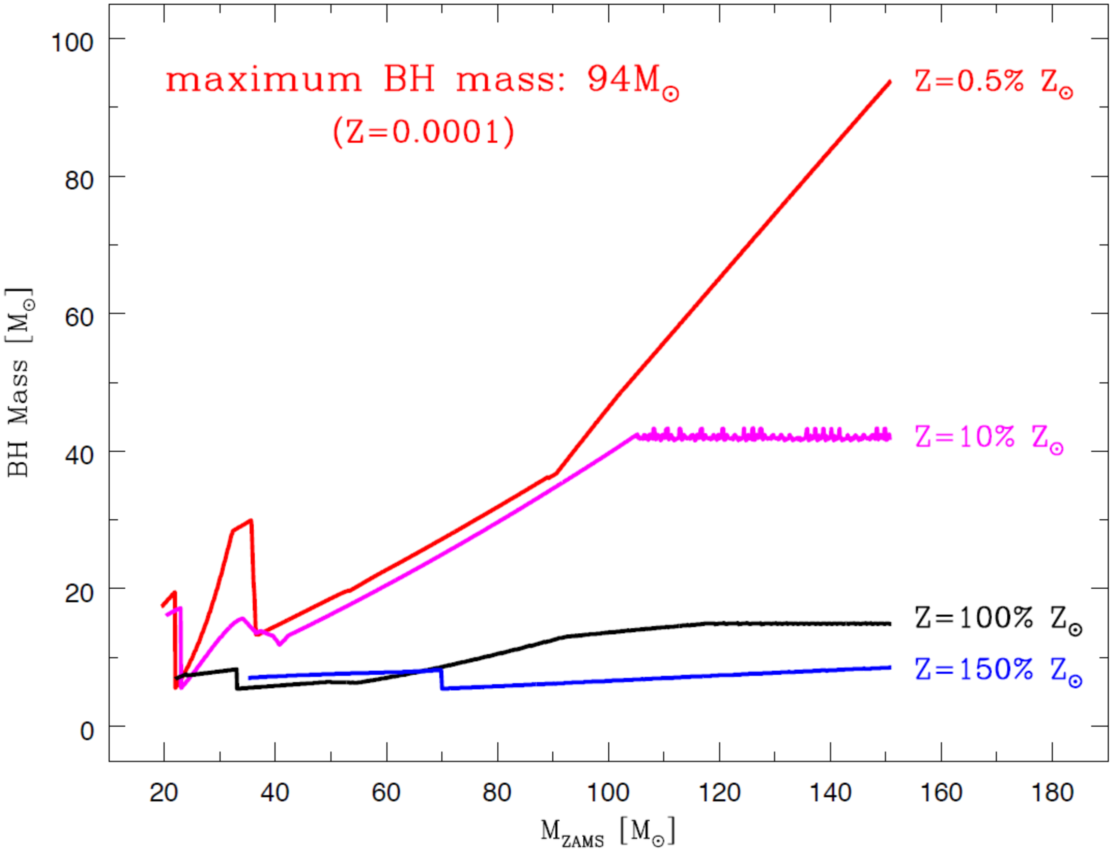
- Does the mass distribution make any sense?
- Does the spin distribution make any sense?
- How did the black holes get so close?
- Do the rates match expectations?





Does it make sense? I.

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



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

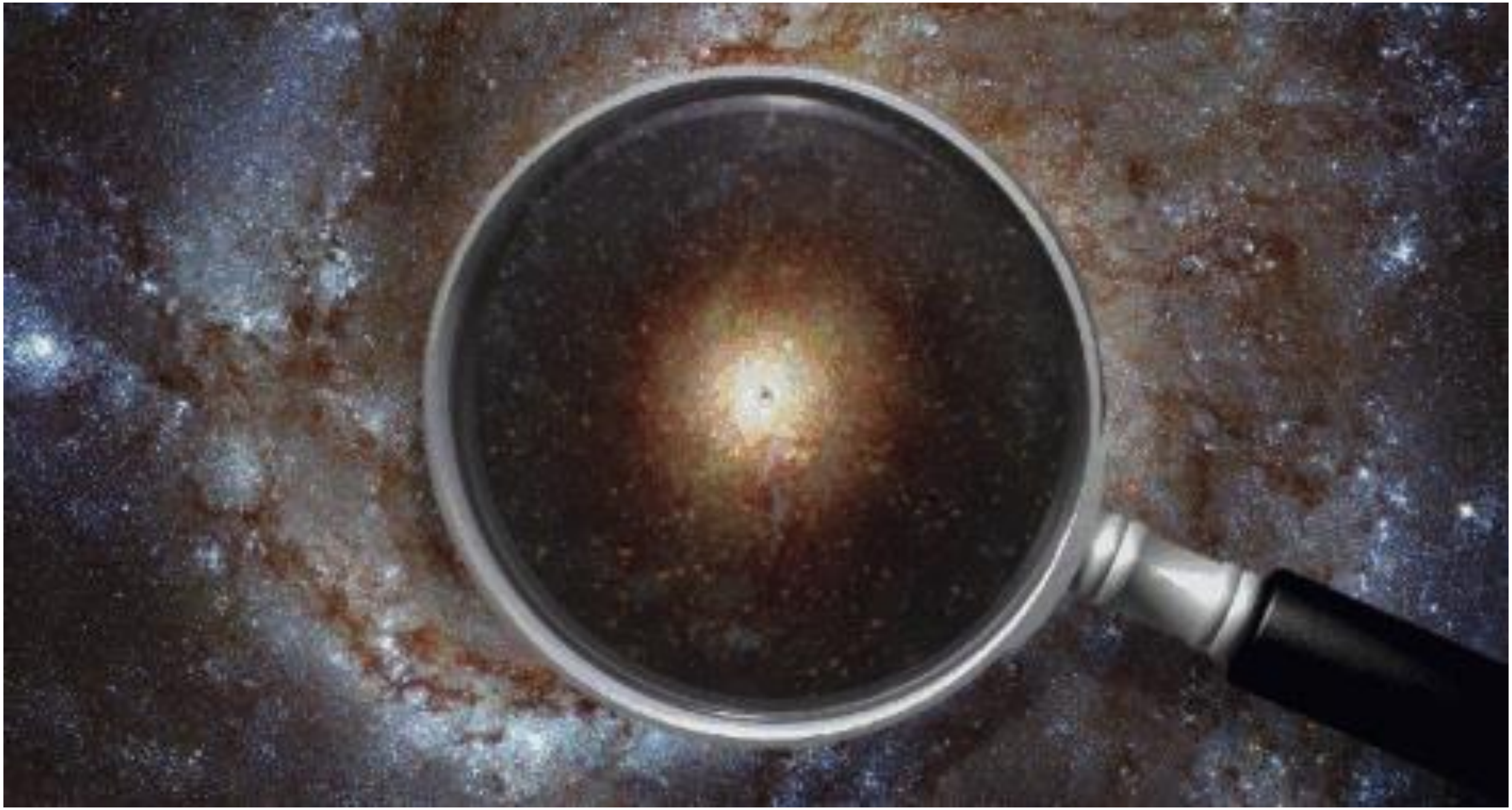
– updates:

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)

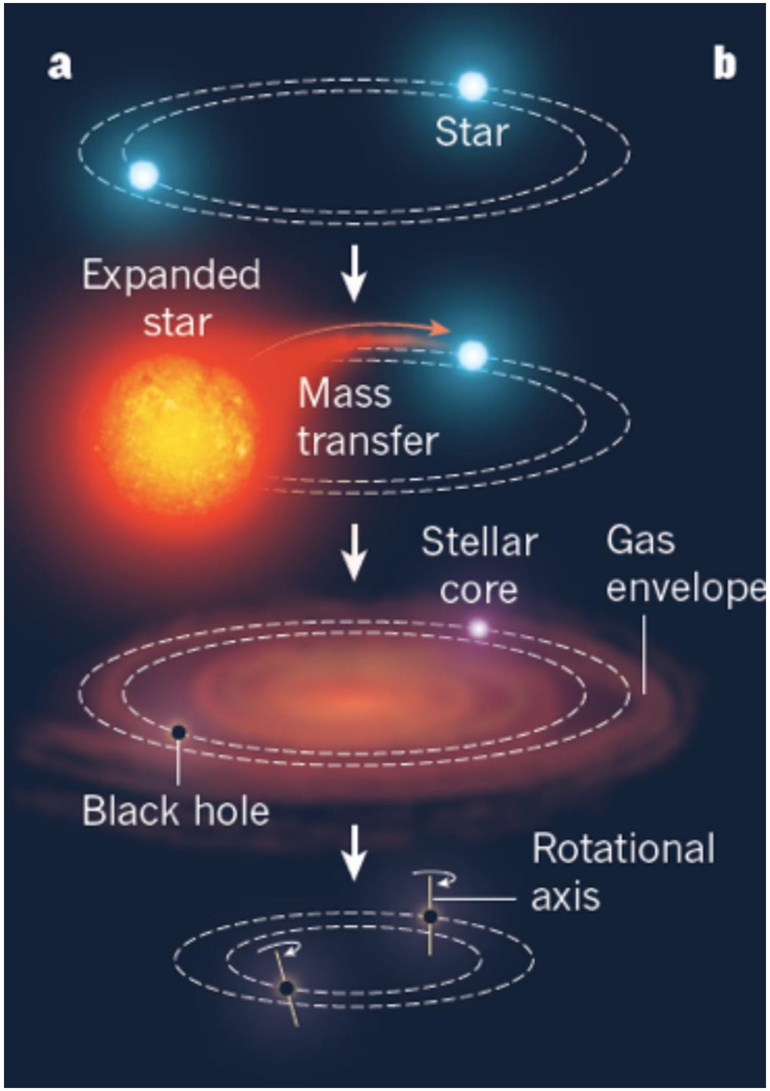


Astrophysical origin of mergers

Option 1: stellar binary evolution

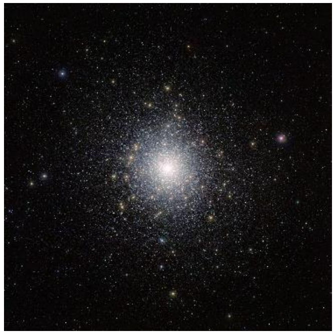
Galactic binaries

- 10^11.5 stars in a Milky Way type galaxy
- 10^{7-8} stellar mass black holes
- Most massive stars are in binaries
  - 25% in triples



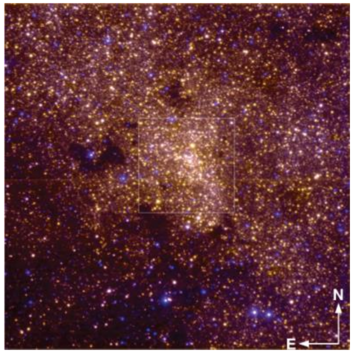
Option 2: Dynamical environments

Globular clusters

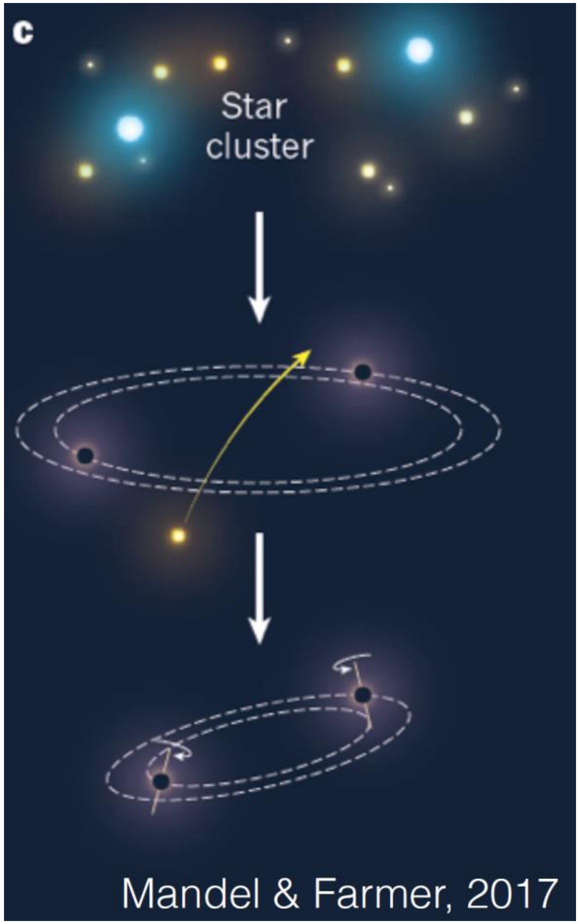


- 200 in a Milky Way type galaxy
- 10^{2-3} stellar mass black holes
- Size: 1 pc – 10 pc
- Density 10^3—10^5 x higher

Galactic nuclei



- 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?

- 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

Summary of channels and rates

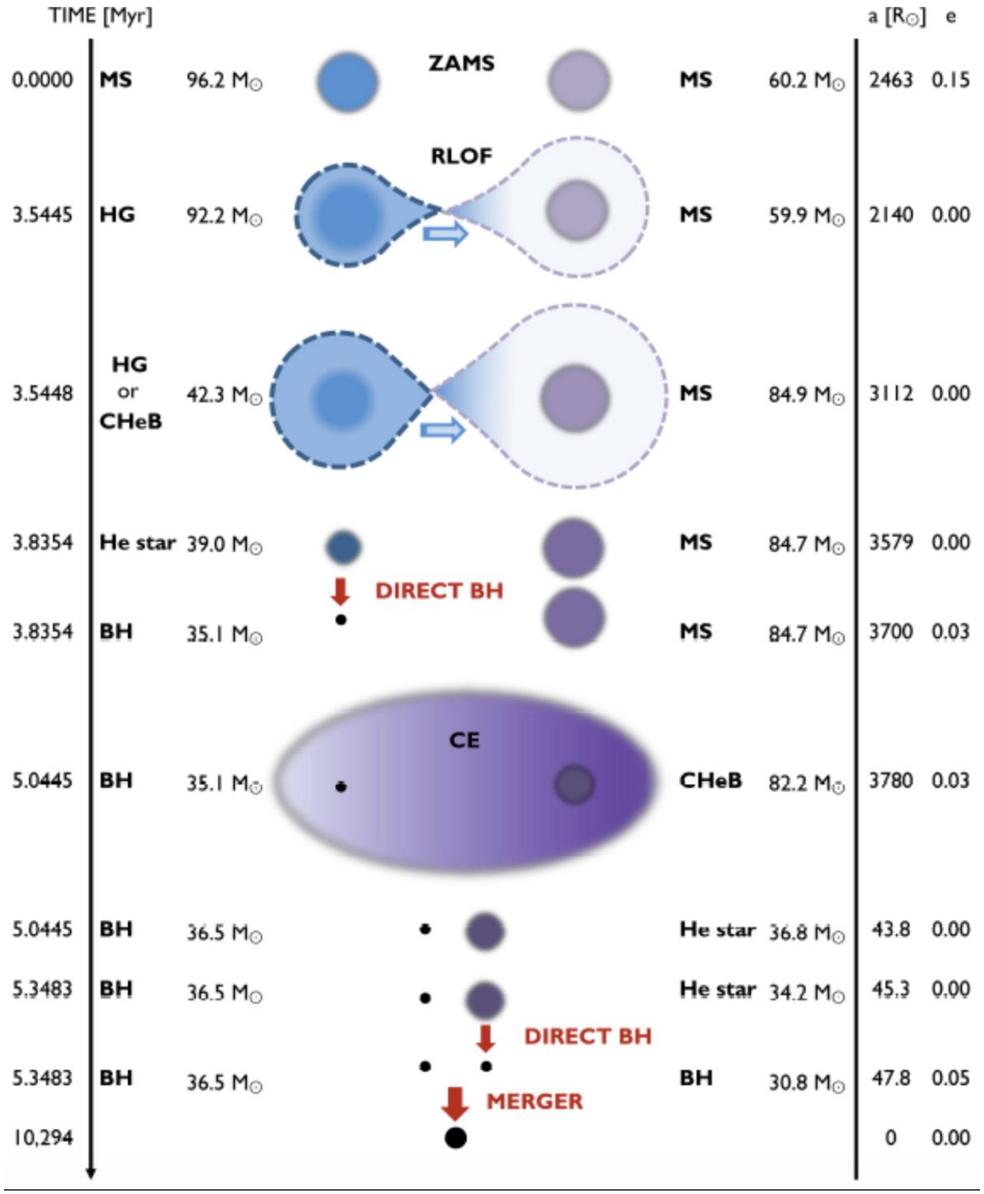
- galactic field binaries: final au problem, common envelope
- galactic field triples: not enough in the right configuration

- 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

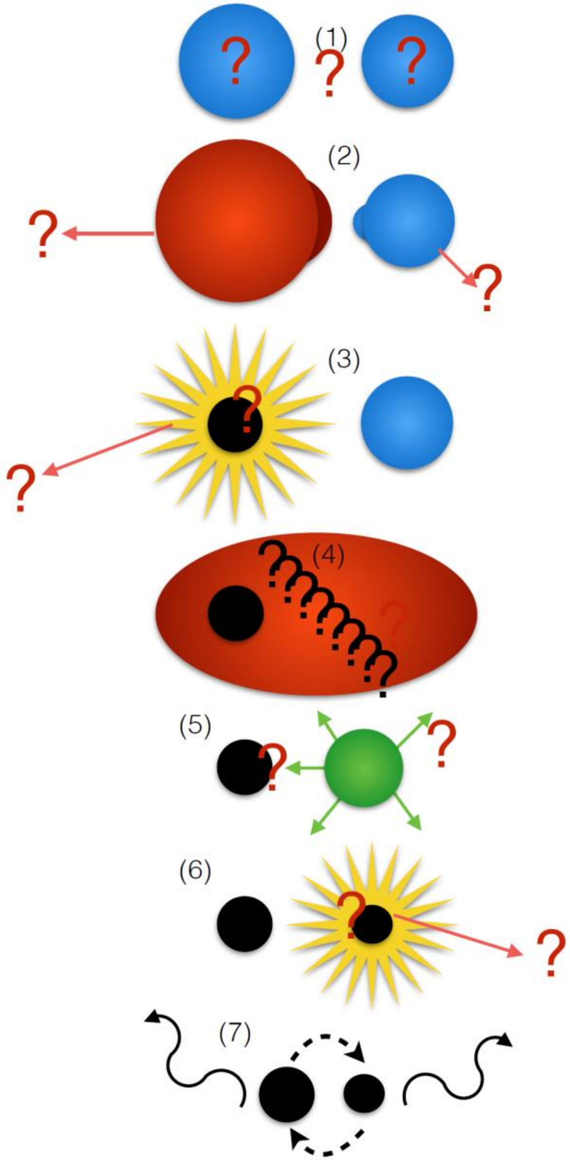


TIME [Myr]						a [$R_\odot$]	e
0.0000	**MS**	96.2 $M_\odot$	**ZAMS**	**MS**	60.2 $M_\odot$	2463	0.15
			RLOF				
3.5445	**HG**	92.2 $M_\odot$		**MS**	59.9 $M_\odot$	2140	0.00
3.5448	**HG** or **CHeB**	42.3 $M_\odot$		**MS**	84.9 $M_\odot$	3112	0.00
3.8354	**He star**	39.0 $M_\odot$		**MS**	84.7 $M_\odot$	3579	0.00
			DIRECT BH				
3.8354	**BH**	35.1 $M_\odot$		**MS**	84.7 $M_\odot$	3700	0.03
5.0445	**BH**	35.1 $M_\odot$	**CE**	**CHeB**	82.2 $M_\odot$	3780	0.03
5.0445	**BH**	36.5 $M_\odot$		**He star**	36.8 $M_\odot$	43.8	0.00
5.3483	**BH**	36.5 $M_\odot$		**He star**	34.2 $M_\odot$	45.3	0.00
			DIRECT BH				
5.3483	**BH**	36.5 $M_\odot$		**BH**	30.8 $M_\odot$	47.8	0.05
			MERGER				
10,294						0	0.00

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**

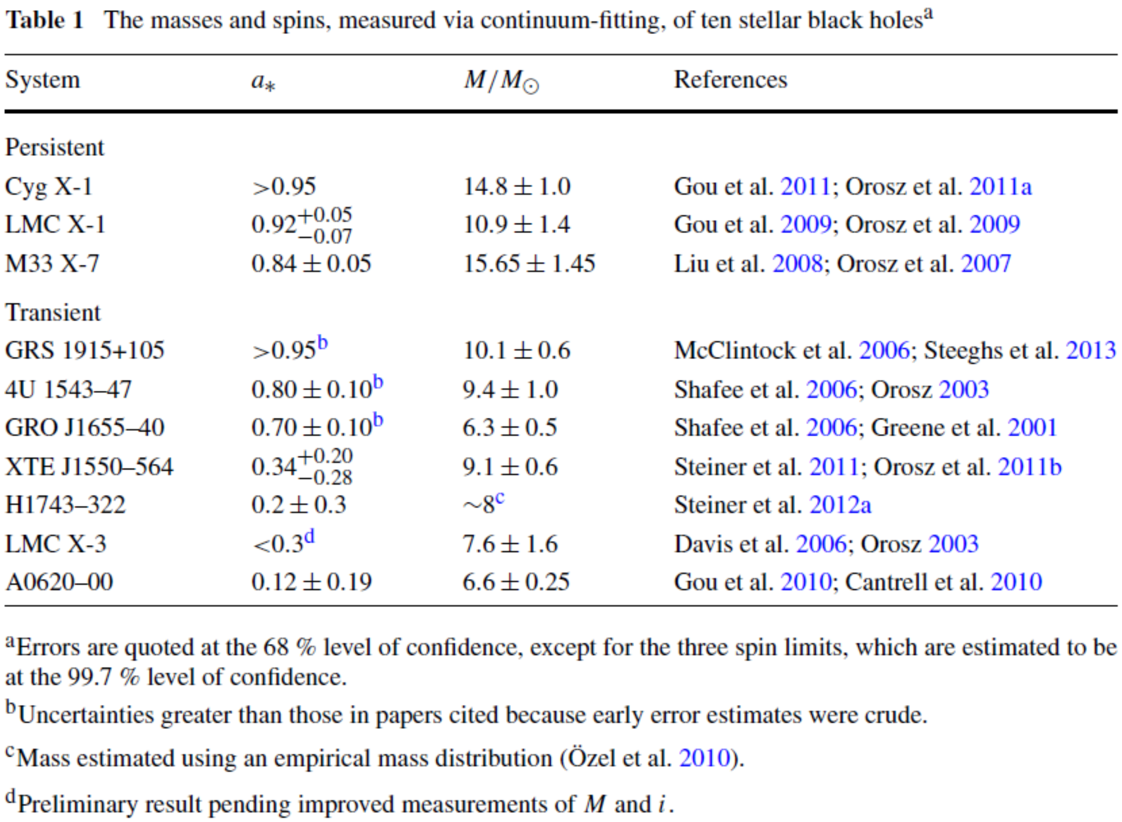


Table 1 The masses and spins, measured via continuum-fitting, of ten stellar black holes[a]

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.

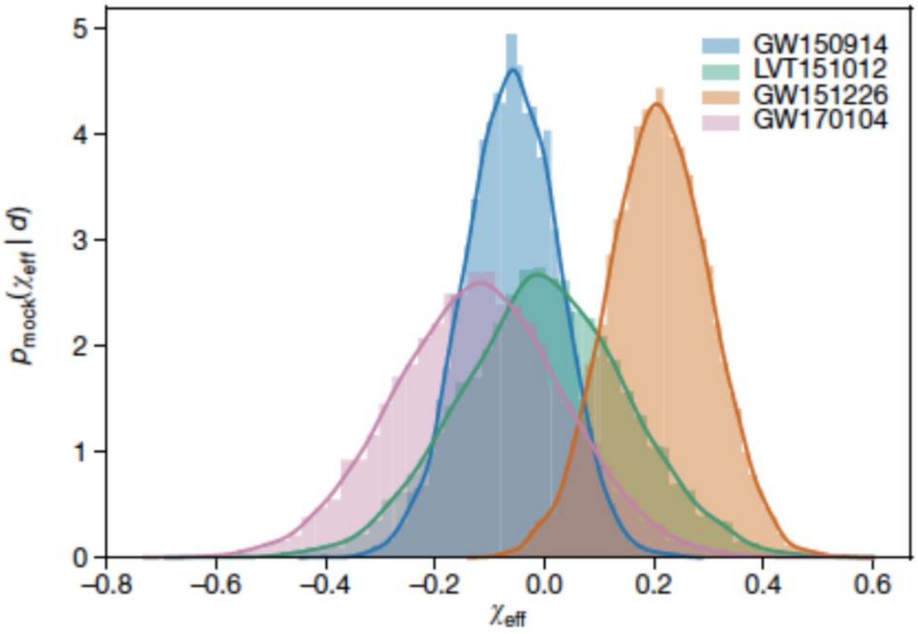
[c] Mass estimated using an empirical mass distribution (Özel et al. 2010).

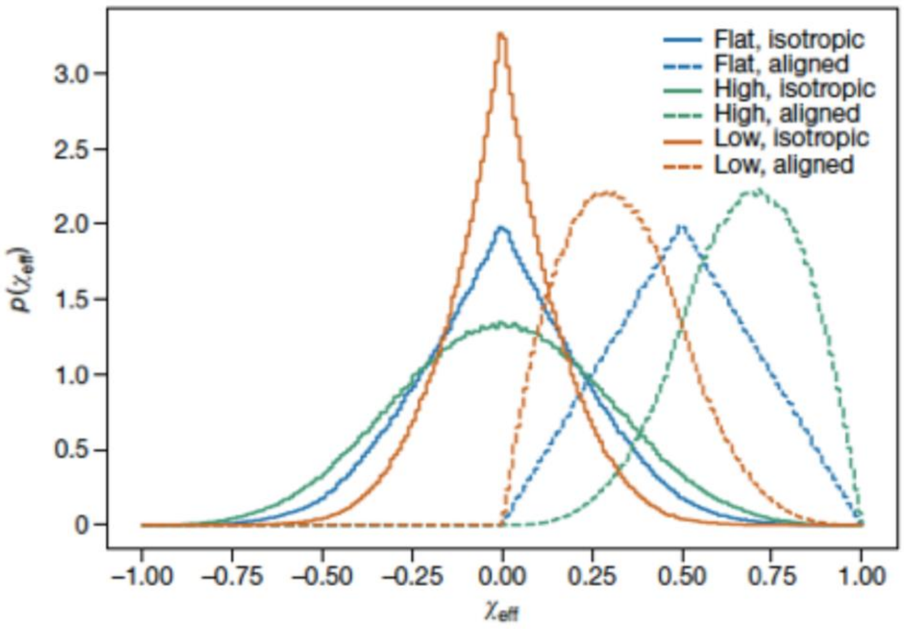
[d] Preliminary result pending improved measurements of M and i.

Option 1: stellar binary evolution

What about spins?

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





Option 1: stellar binary evolution

What about the rates?

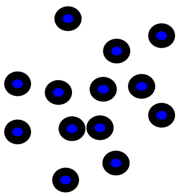
- Theory very uncertain – consistent with observations
- Relative rate of NS/NS mergers vs. BH/BH mergers may be a problem

Option 2: dynamical environments

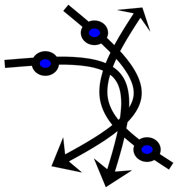
- A theoretically clean problem: N-body

Option 2: dynamical environments

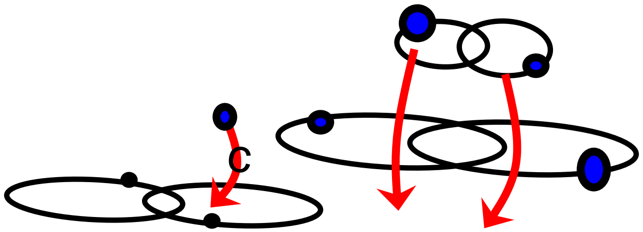
- A theoretically clean problem: N-body



Dense population

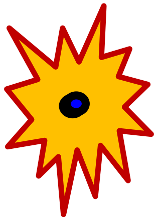


Triple scattering



Binary interactions

Dynamical friction



merger

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

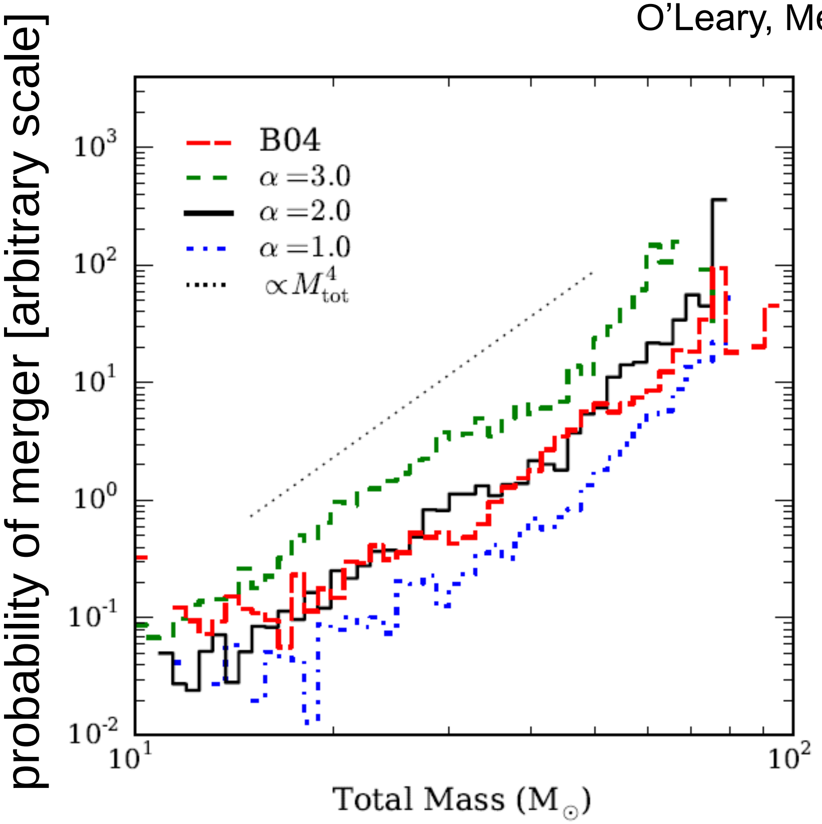
Expectation:

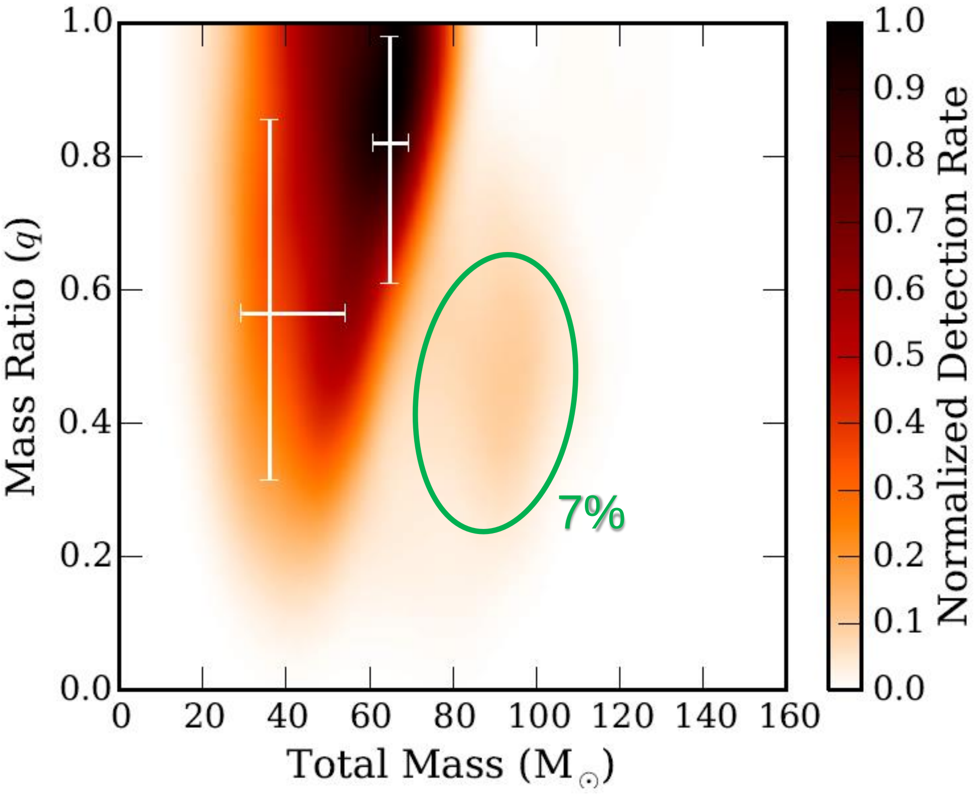
Merger probability larger for heavier objects

Mass distribution for globular clusters

Monte Carlo and Nbody simulations

O'Leary, Meiron, Kocsis (2016) (see also Rodriguez+ '16, Askar+ '17)



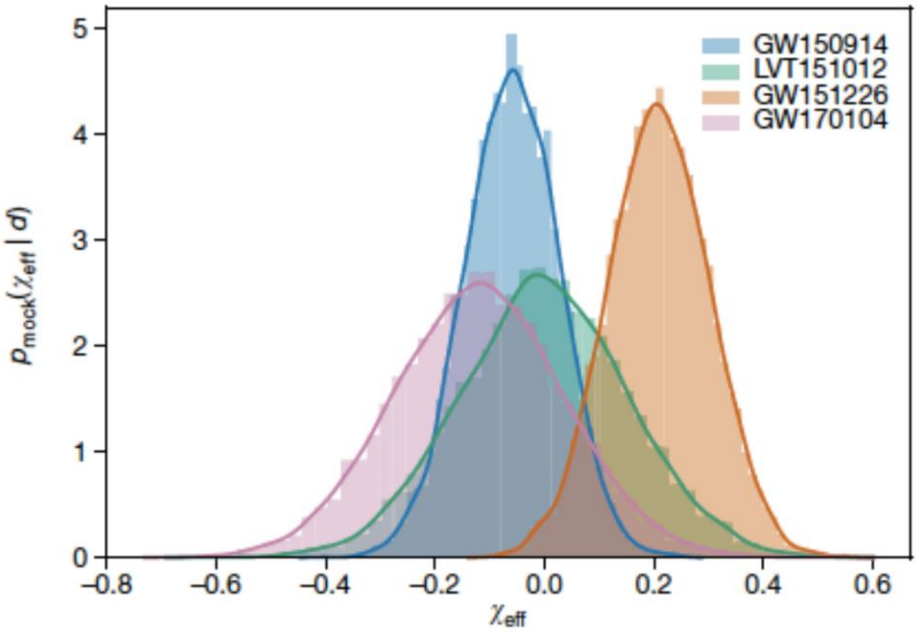


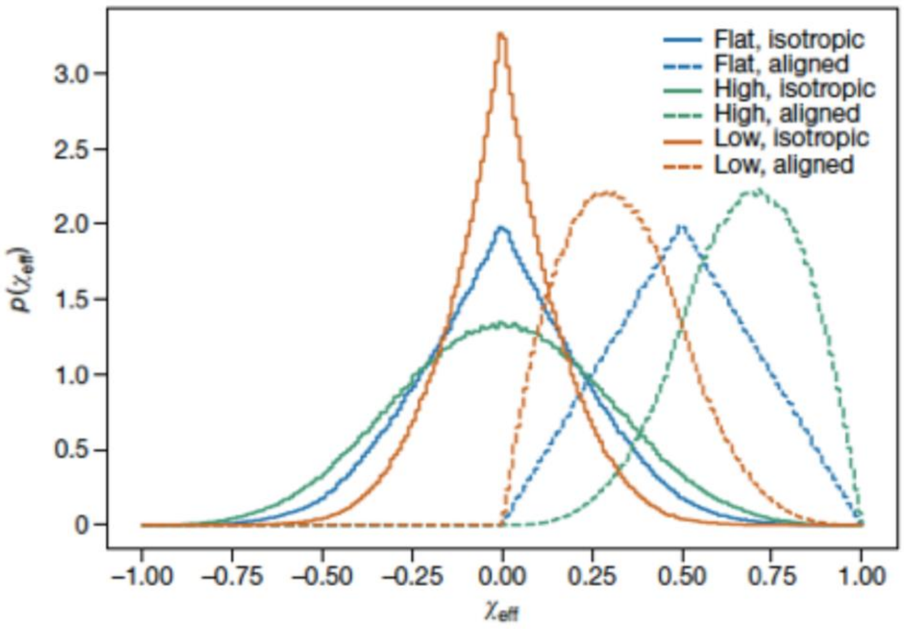
Robust statement (independent of IMF): heavy objects merge more often M^4

Option 2: dynamical environments

What about spins?

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





Option 2: dynamical environments

What about the rates?

it is a problem!

Simple reason:

- 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: $R < 40$ Gpc^{-3} yr^{-1}**
  - 0.5% of stellar mass, $10^{5.5}$ stars with $n \sim 0.8$ Mpc^{-3}
- **galactic nuclei: $R < 35$ Gpc^{-3} yr^{-1}**
  - 0.5% of stellar mass, 10^{7} stars with $n \sim 0.02$ Mpc^{-3}

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

Observed rate: 29 – 100 Gpc^{-3} yr^{-1}

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

Summary of channels and rates

- galactic field binaries: 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)

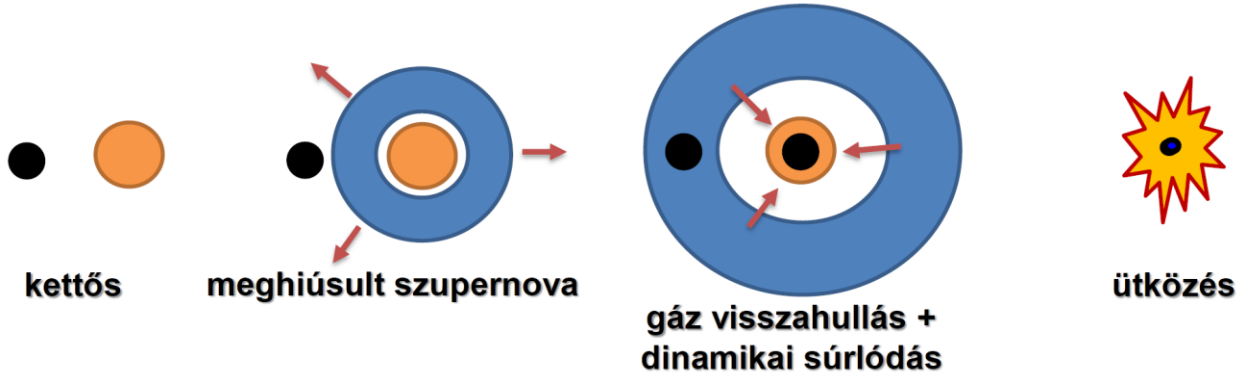
No convincing theory to explain the observed rates!

possible ways forward

I.

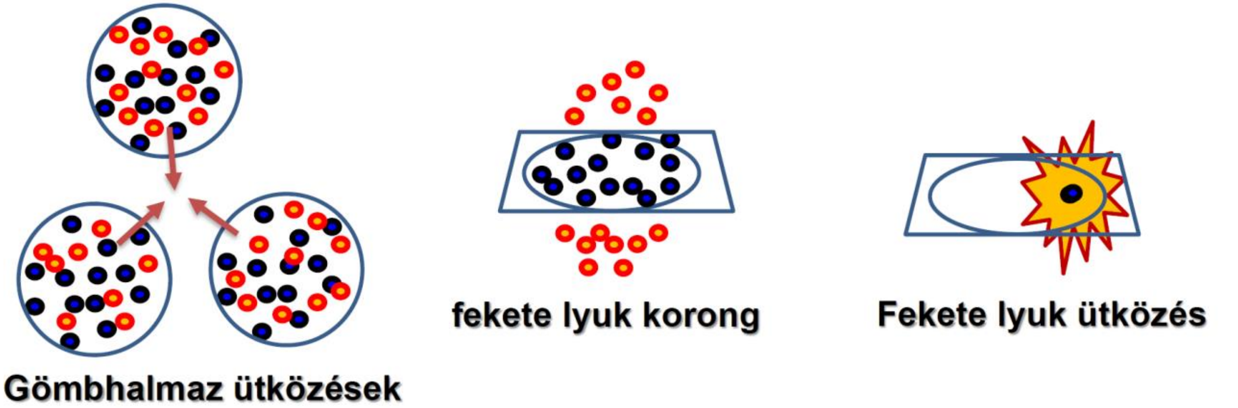
New ideas

1. Fallback mergers (Tagawa, Saitoh, Kocsis, PRL 2018)

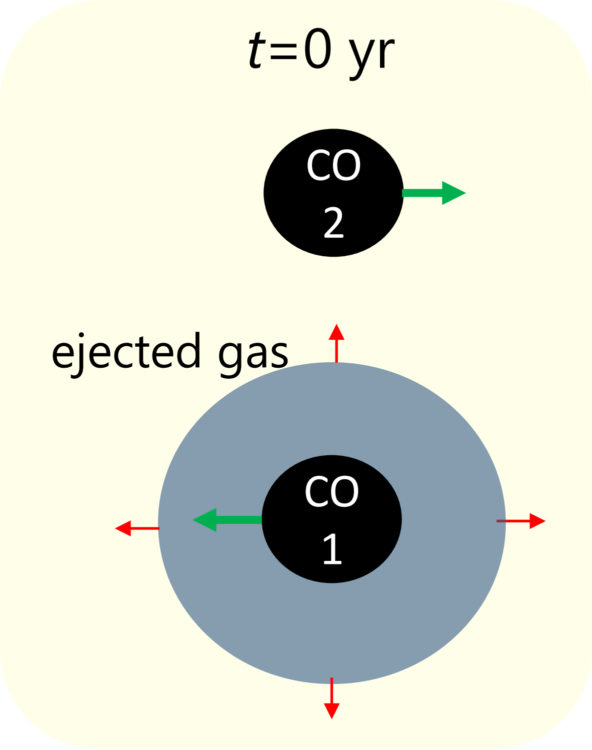


2. Disrupted globular clusters (Fragione, Kocsis, PRL, submitted)

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

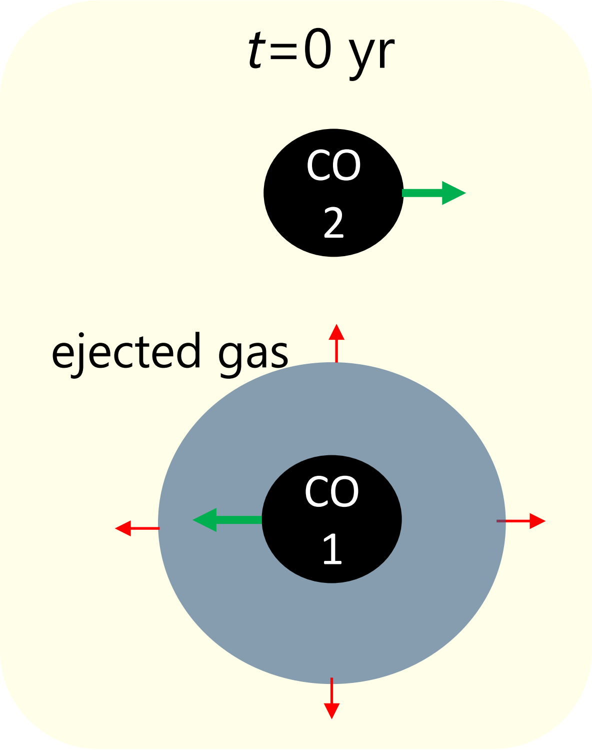


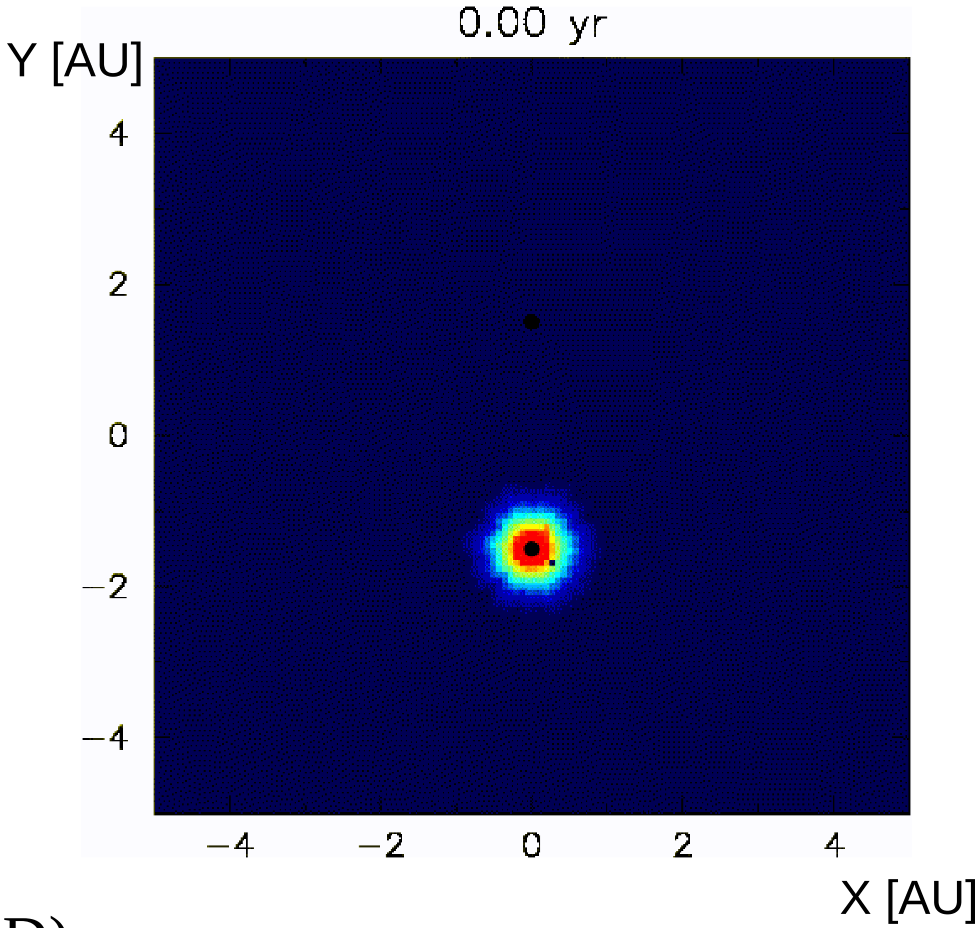
Fallback driven merger



Tagawa, Kocsis, Saitoh, 2018, PRL

Fallback driven merger





N-body/SPH simulation (3D)

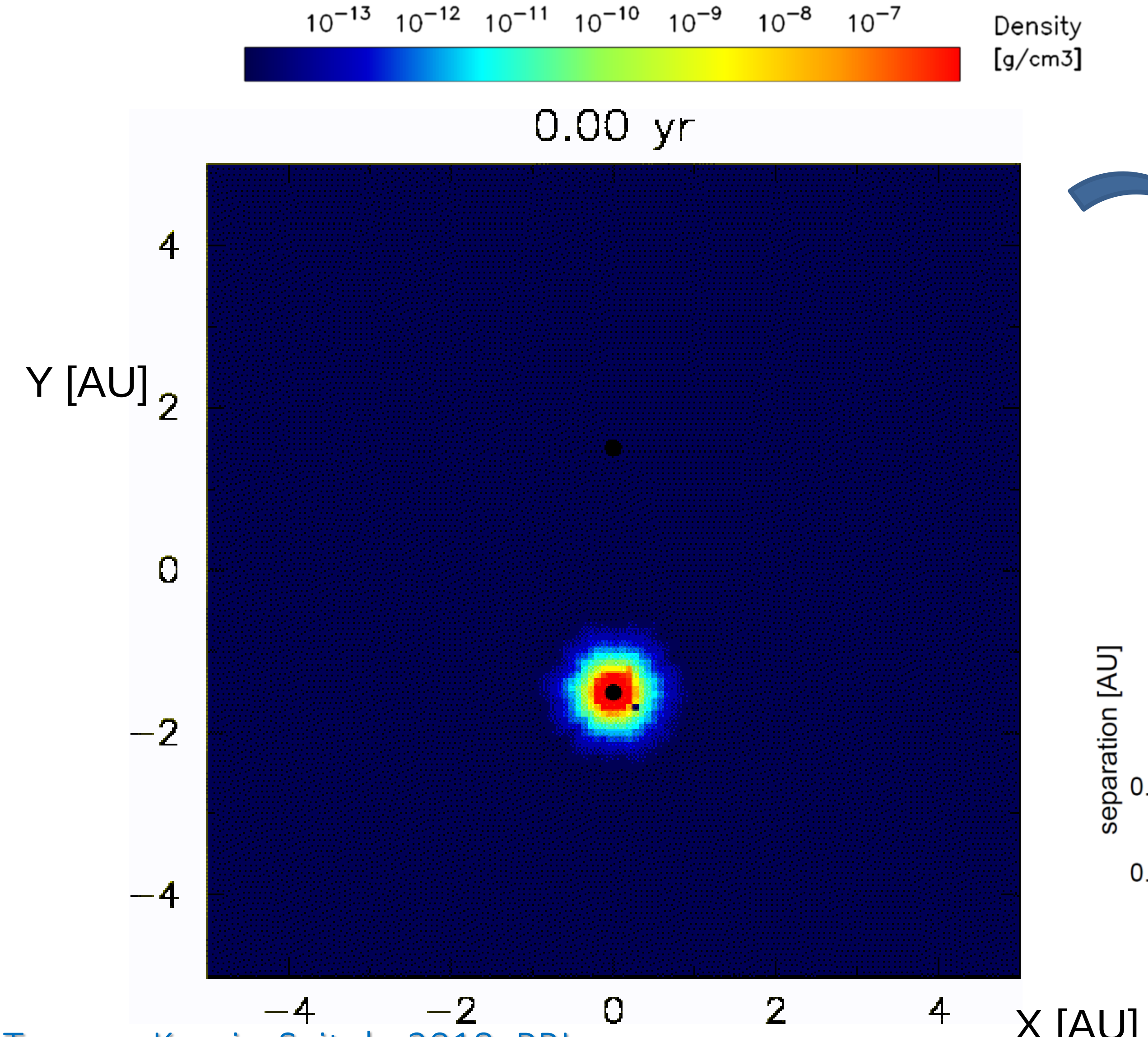
Ideal gas EOS

$v(r) = v_{\max}\, r/r_{\max}$

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

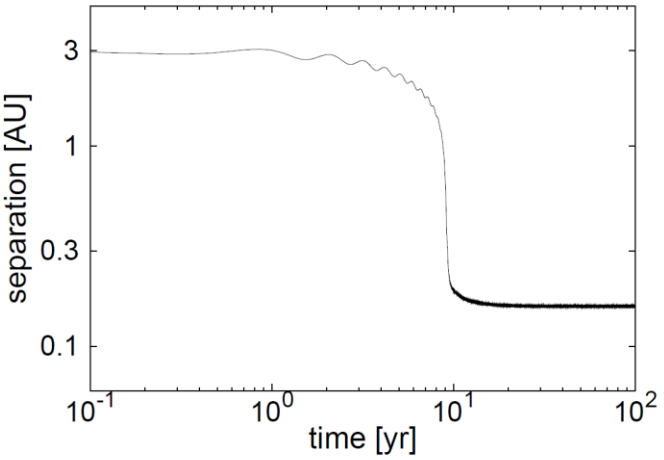
Tagawa, Saitoh, Kocsis 2018, PRL

Fallback driven merger



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

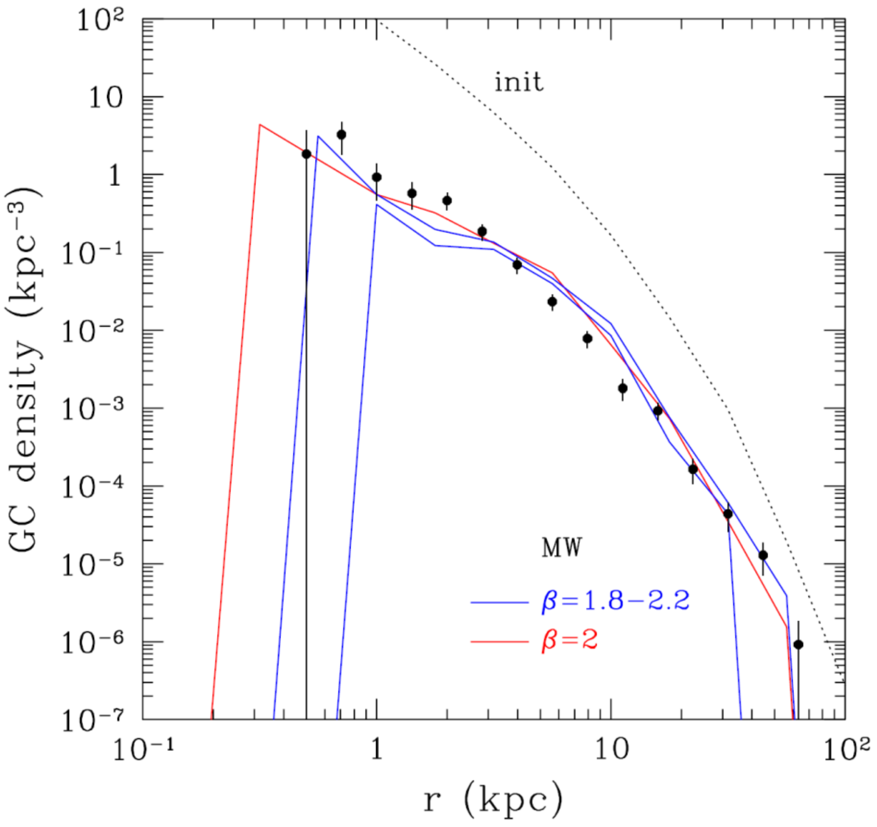
rotating
clockwise

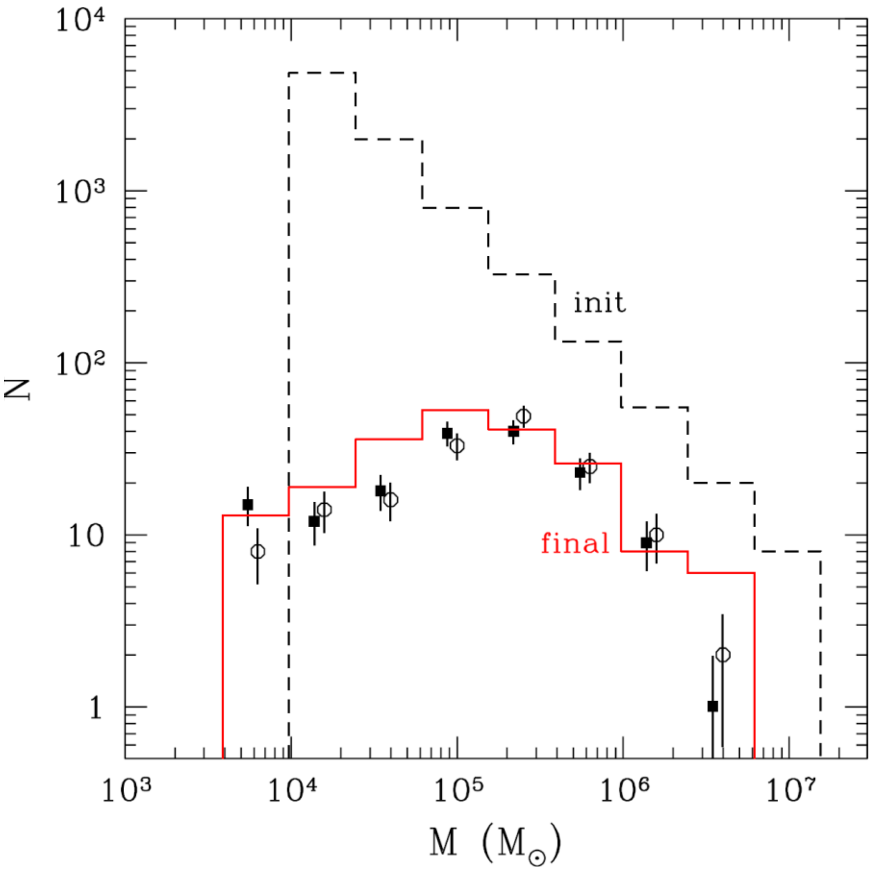


Tagawa, Kocsis, Saitoh, 2018, PRL

Disrupted globular clusters

- Globular clusters were much more numerous in the past

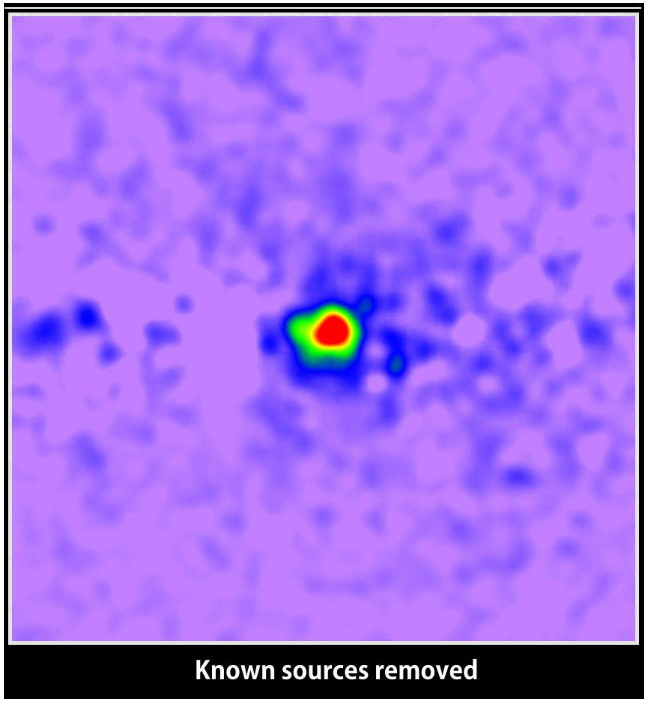


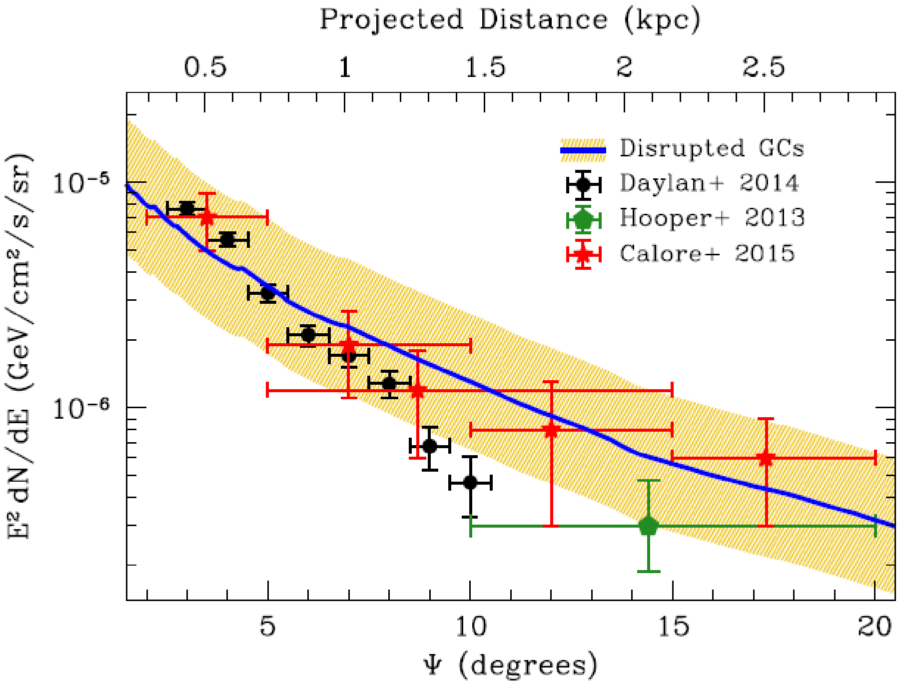


Gnedin, Ostriker, Tremaine (2014)

Disrupted globular clusters

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

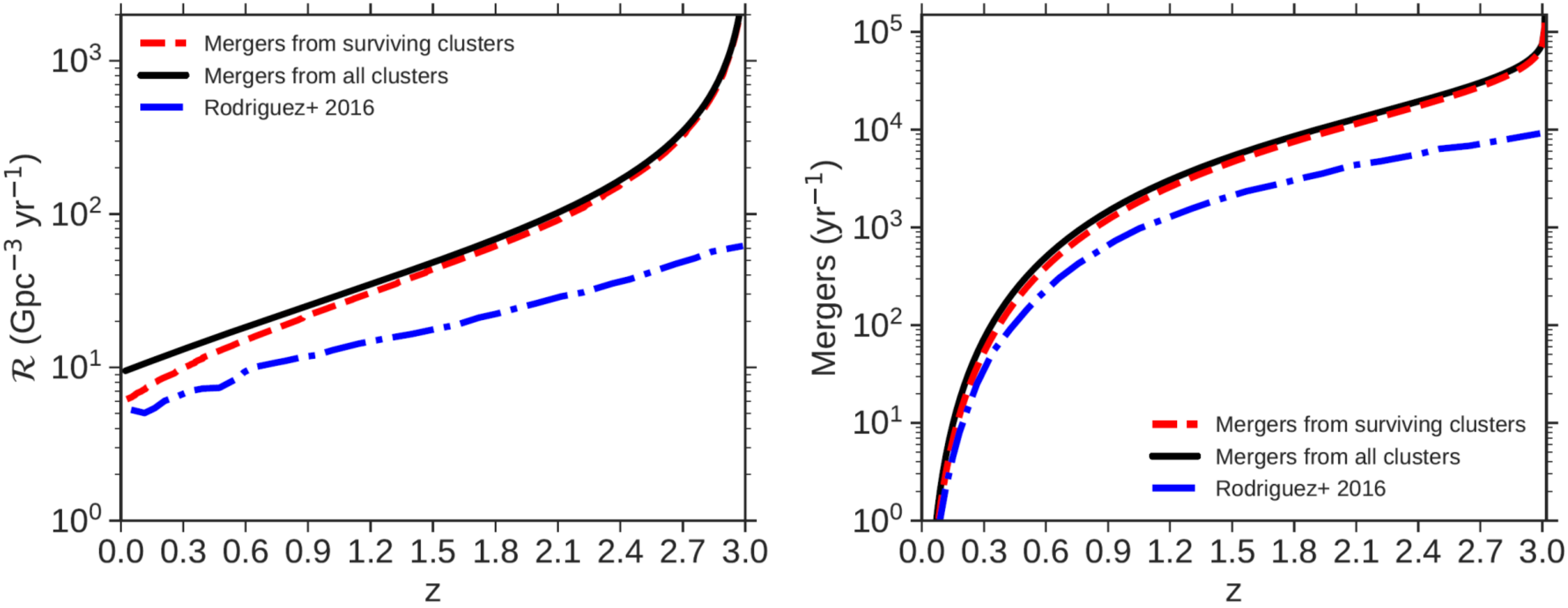




Brandt, Kocsis (2015)

Disrupted globular clusters

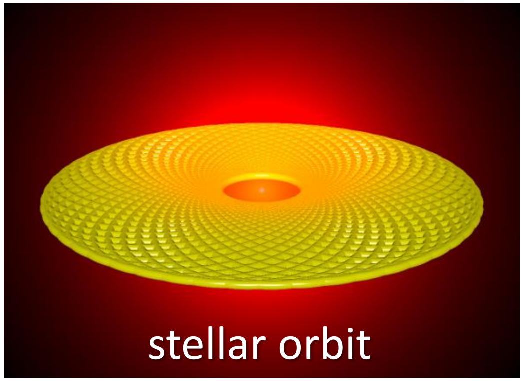
- Implications for LIGO
  - High rates from disrupted globular clusters



Fragione, Kocsis (2018)

Black hole disks

Motion of stars in the galactic disk:



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

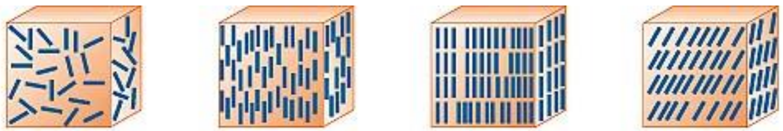
Orbital planes reorient and relax very quickly

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:

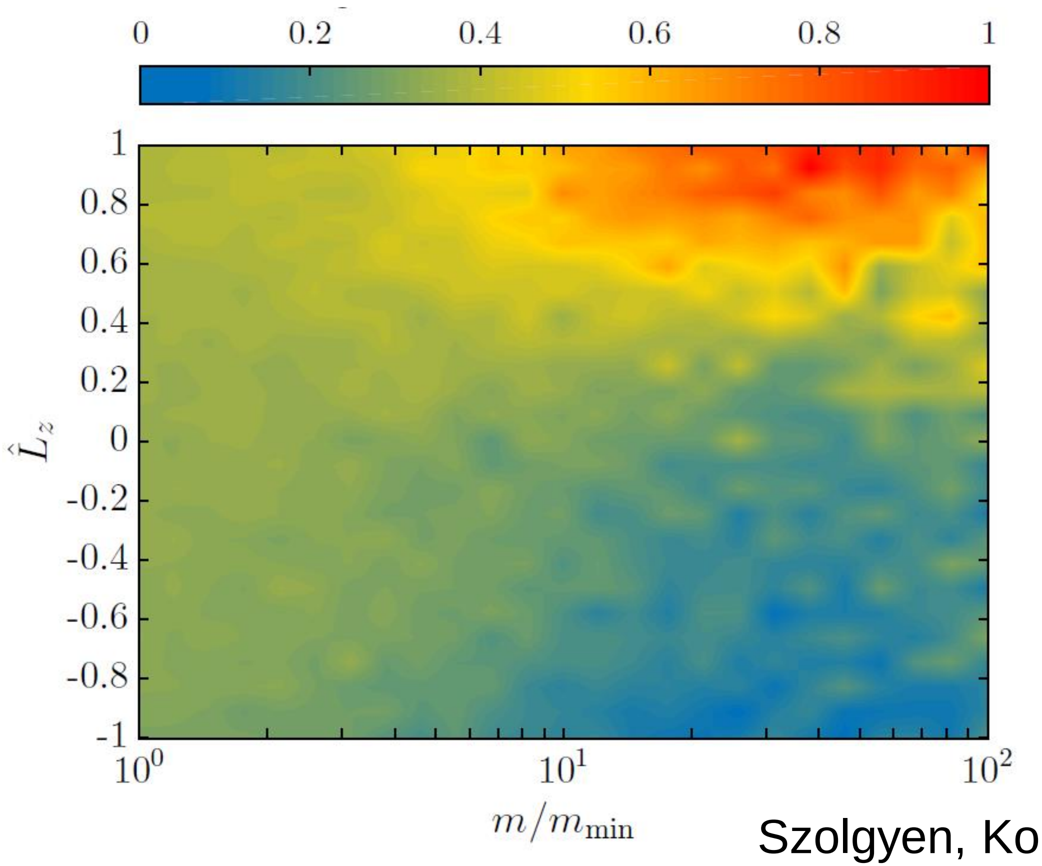
- massive objects: ordered phase
- light objects: spherical phase
- **Implication: Black hole disks !**



(a) Normal liquid (b) Nematic liquid crystal (c) Smectic A liquid crystal (d) Smectic C liquid crystal

Black hole disks

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



Szolgyen, Kocsis PRL 2018 (today)

possible ways forward
II.

Distinguishing sources

from different channels

– eccentricity, mass, spin distribution

– electromagnetic counterparts

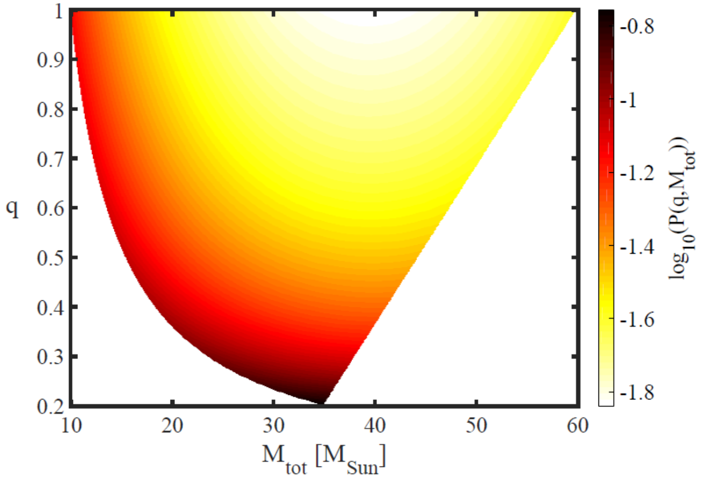
– intermediate mass black holes

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

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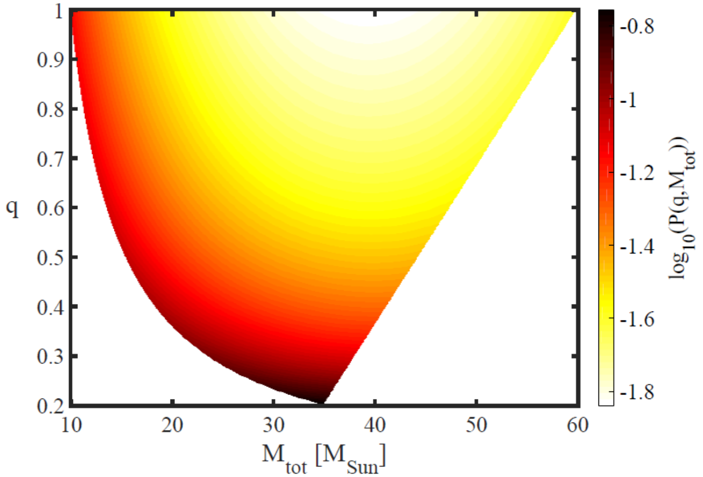


$$\boxed{-(m_1+m_2)^2\frac{\partial^2}{\partial m_1 \partial m_2}\ln\mathcal{R}(m_1,m_2,t)}$$

$= \mathbf{4}$ 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

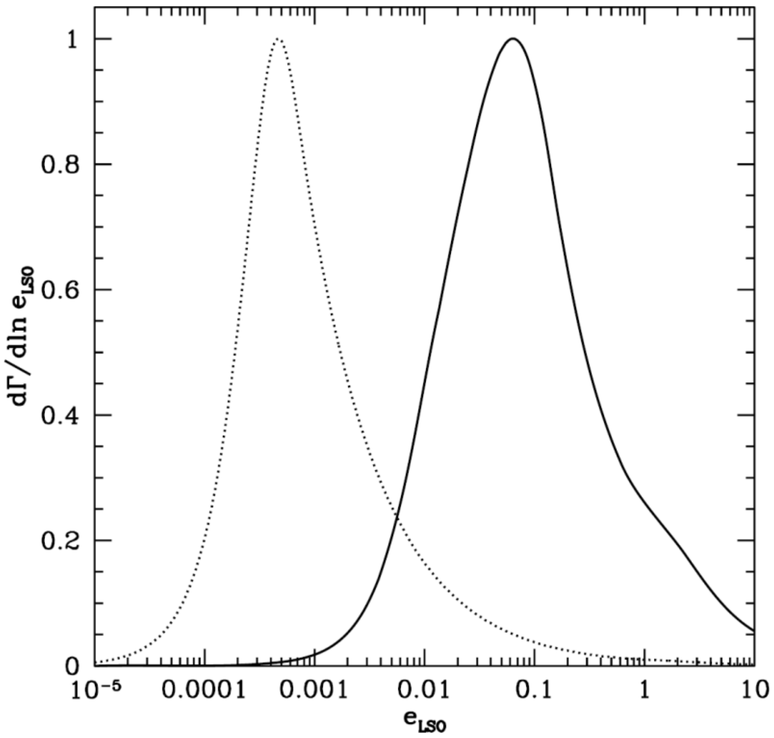
$= \mathbf{1}$ for PBH binaries formed in early universe

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

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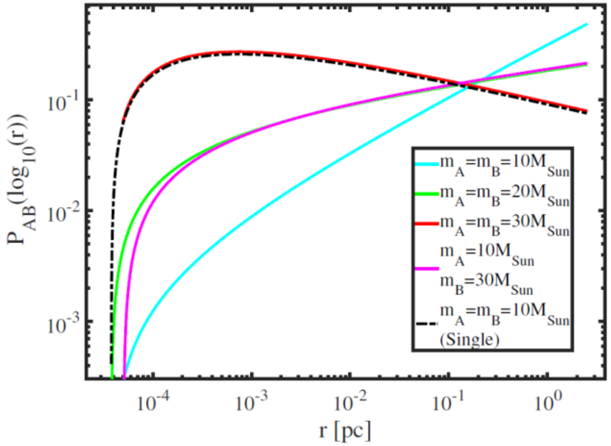
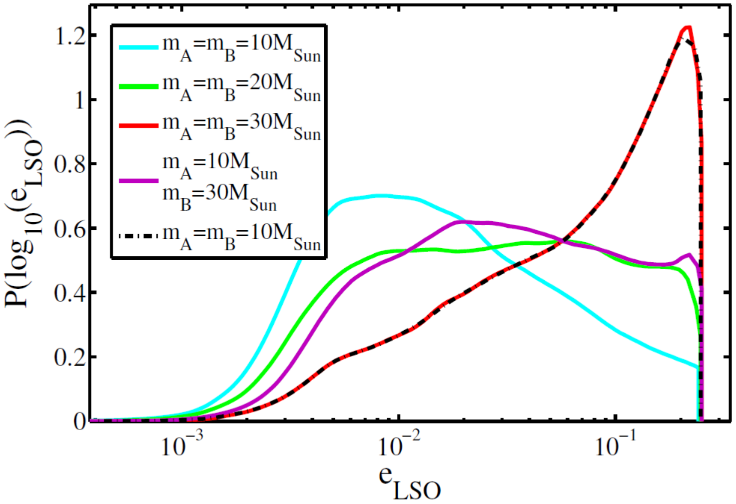


radial distribution of mergers shows mass segregation



→ Eccentricity distribution reveals mass segregation

Gondán, Kocsis, Raffai, Frei (2018b)

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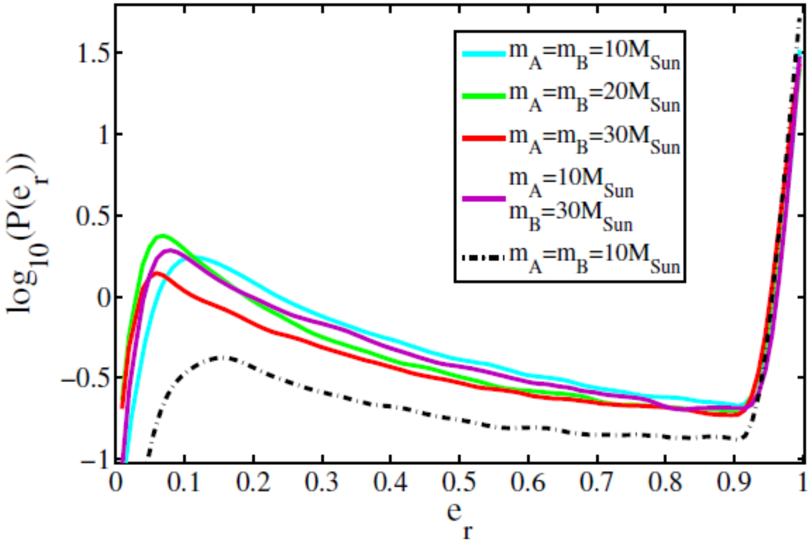
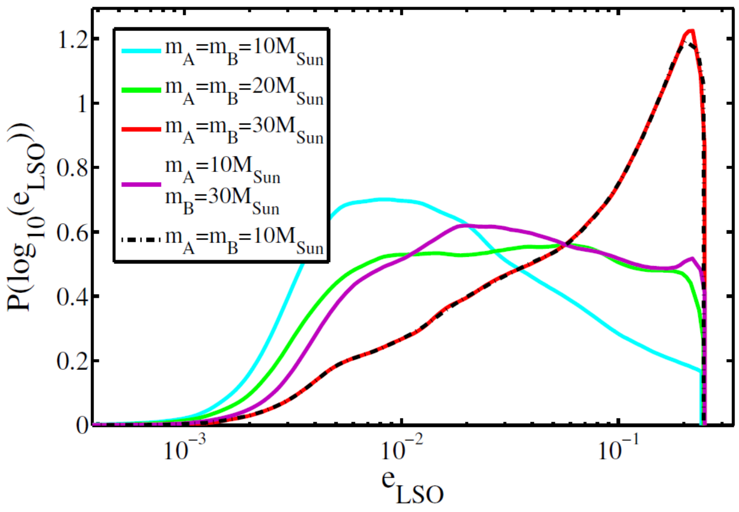


Eccentricty distribution when ALIGO first sees it (design sensitivity)



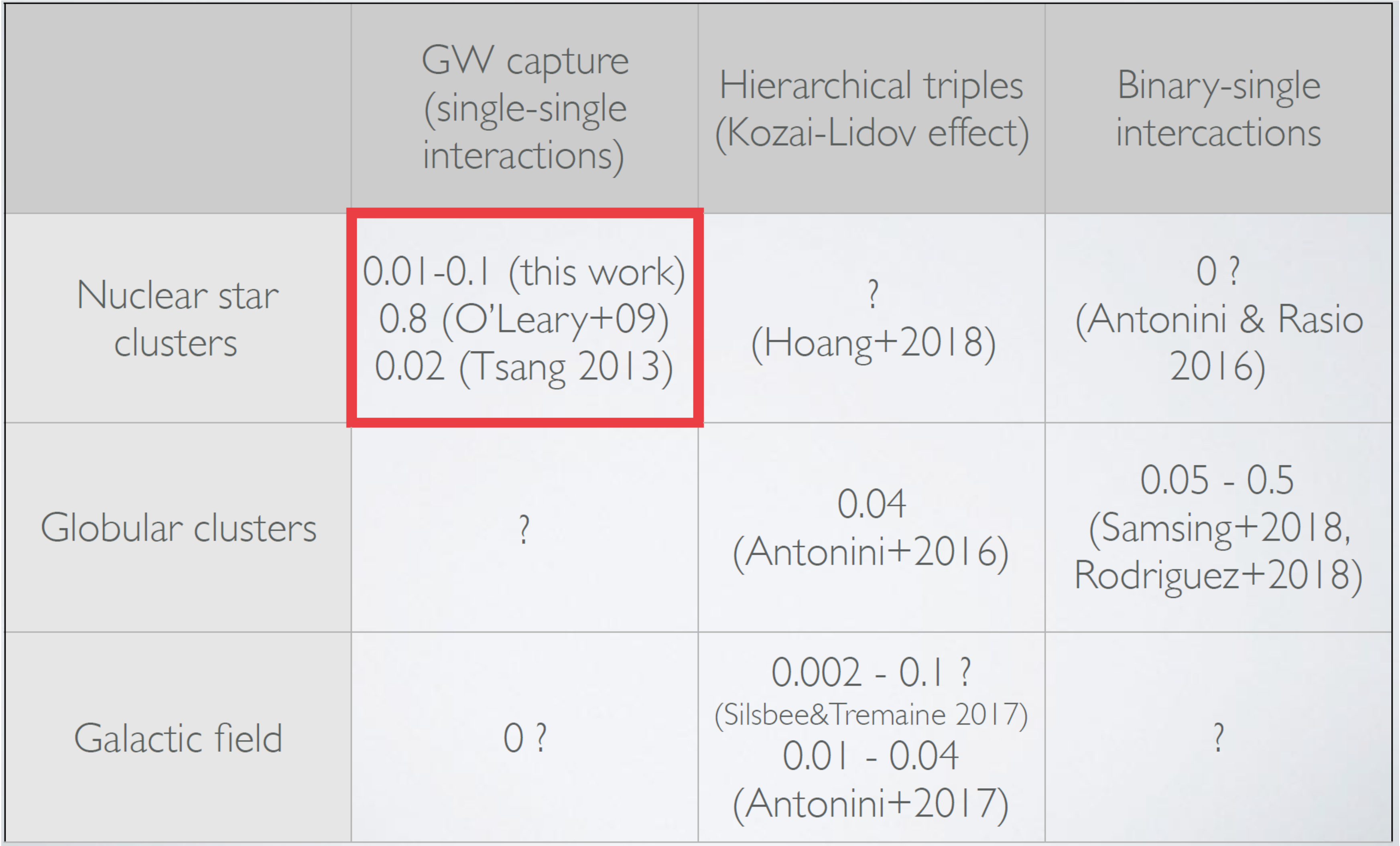
→ Eccentricity distribution reveals mass segregation

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

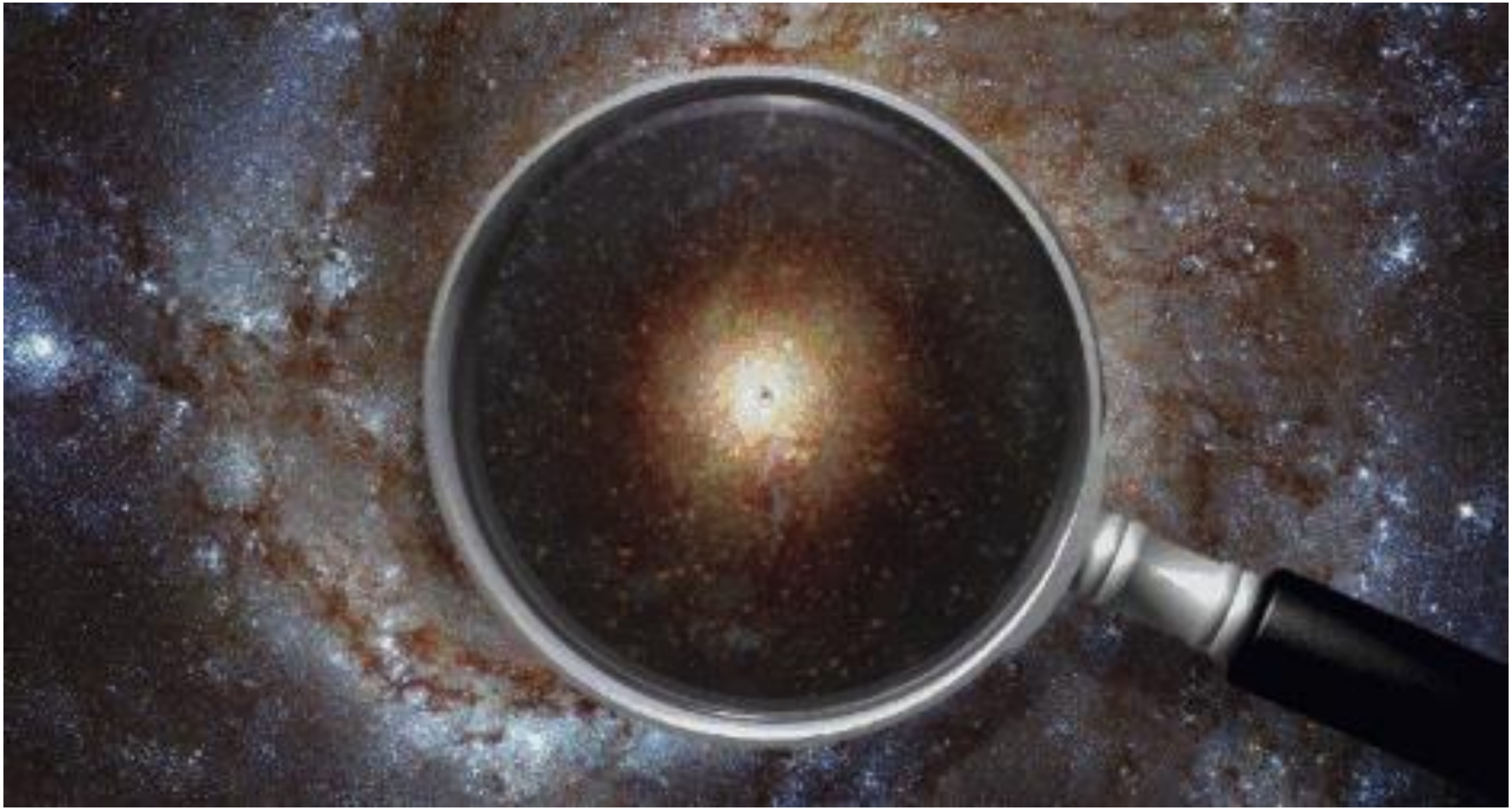
$30M_{\mathrm{Sun}}+30M_{\mathrm{Sun}}$ @ 1Gpc

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

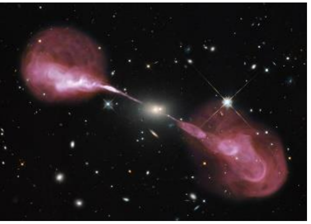
Eccentric sources:
rates from different channels



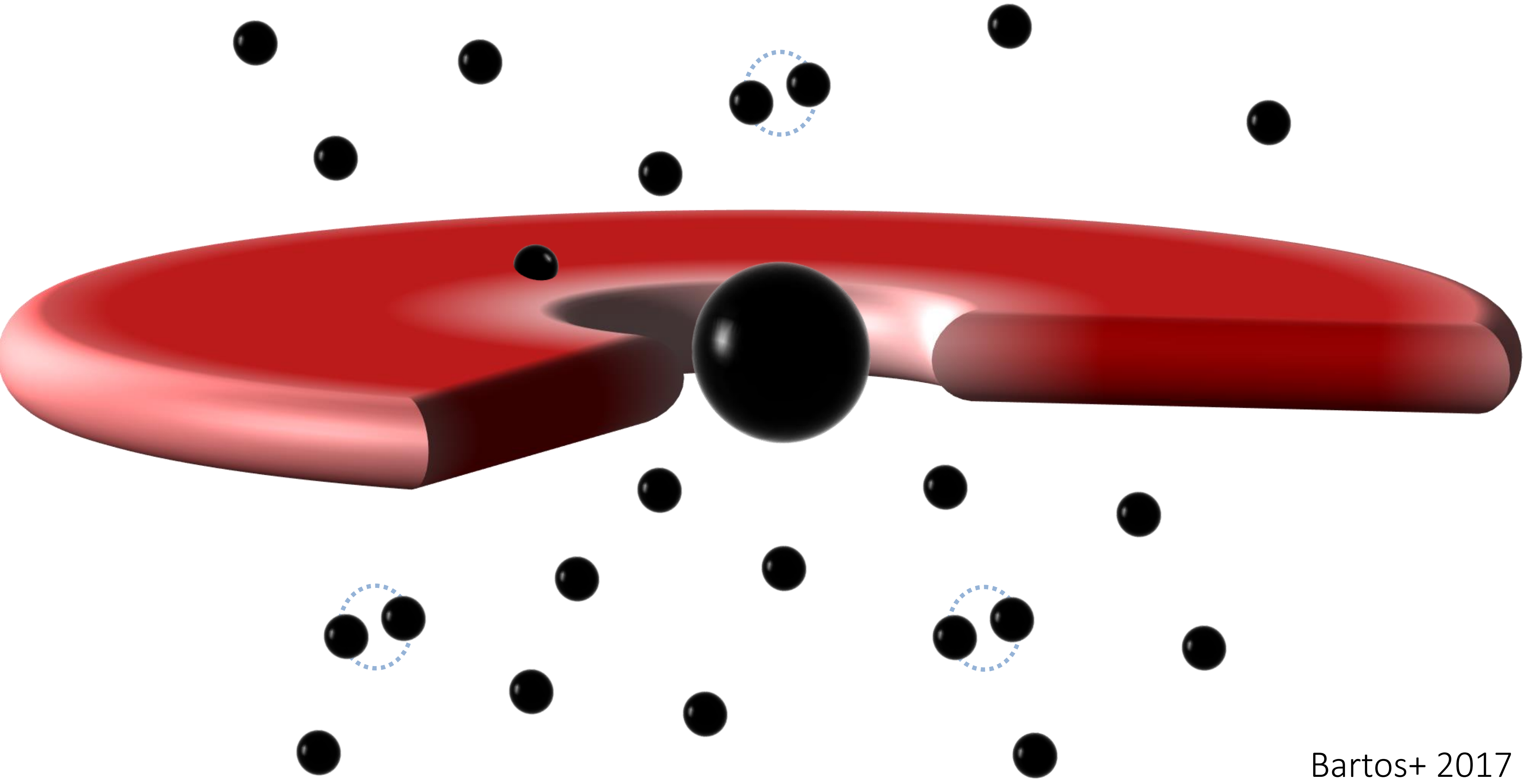
	GW capture (single-single interactions)	Hierarchical triples (Kozai-Lidov effect)	Binary-single intercactions
Nuclear star clusters	0.01-0.1 (this work) 0.8 (O'Leary+09) 0.02 (Tsang 2013)	? (Hoang+2018)	0 ? (Antonini & Rasio 2016)
Globular clusters	?	0.04 (Antonini+2016)	0.05 - 0.5 (Samsing+2018, Rodriguez+2018)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



Mergers with EM counterparts

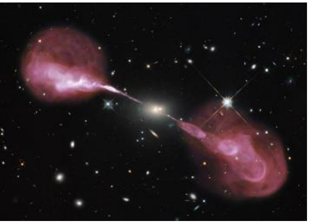


GW sources in active galactic nuclei



Bartos+ 2017

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



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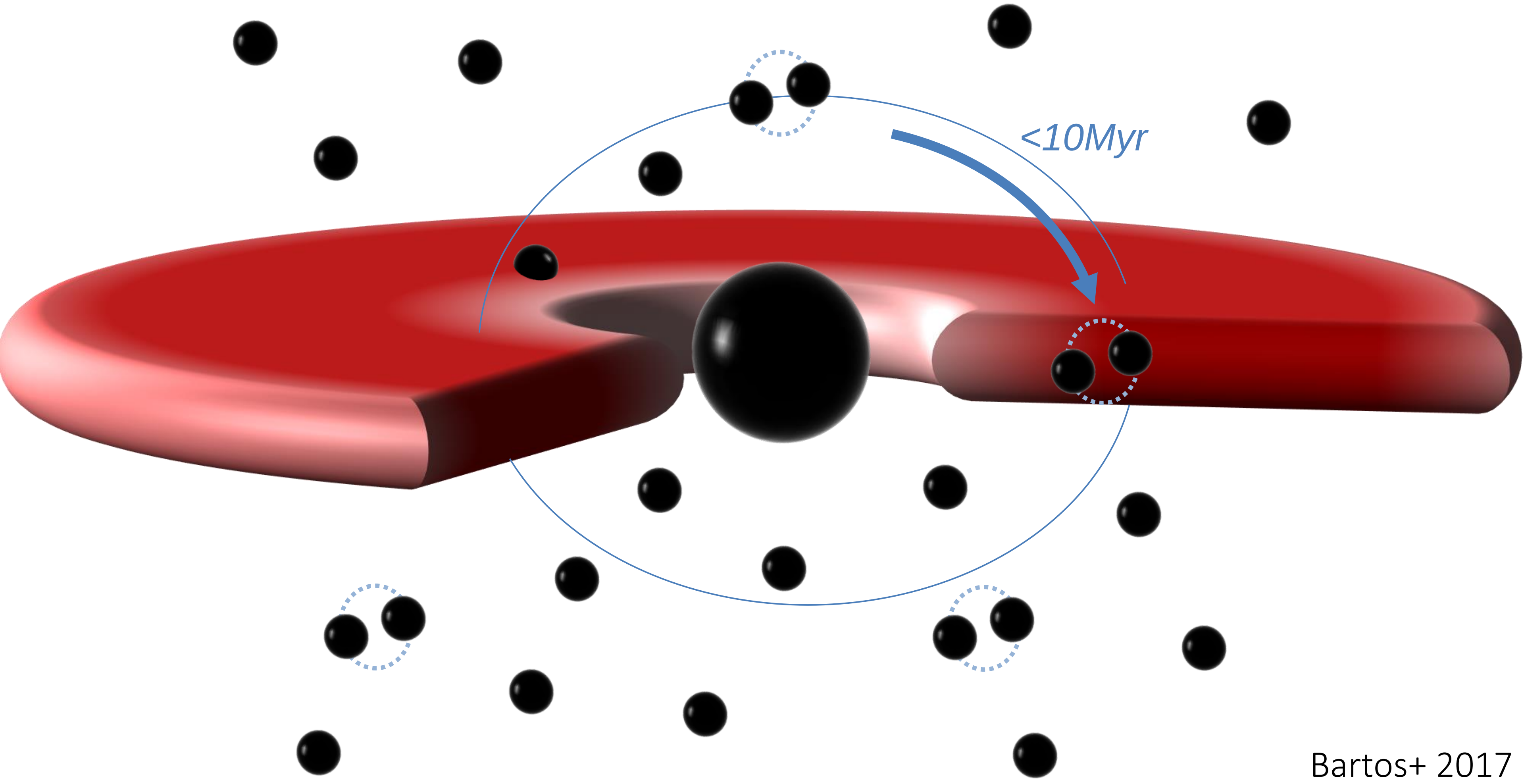
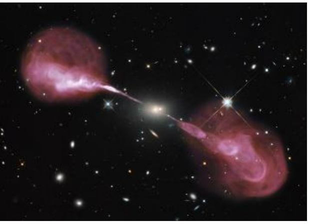
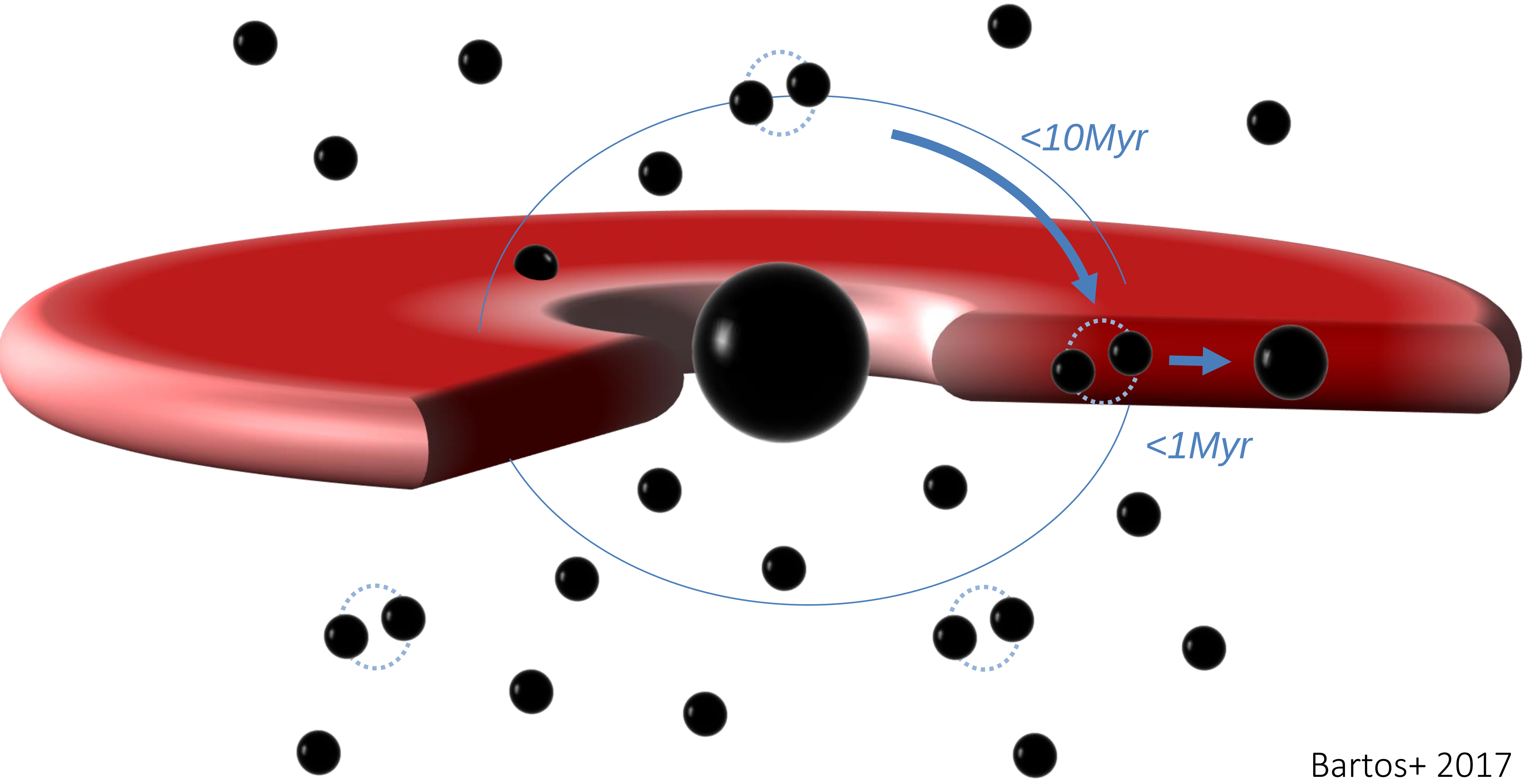


Bartos+ 2017

Get captured by the disk…

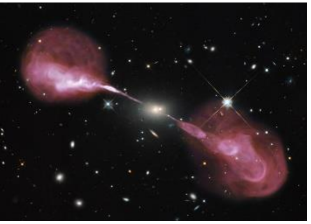


GW sources in active galactic nuclei

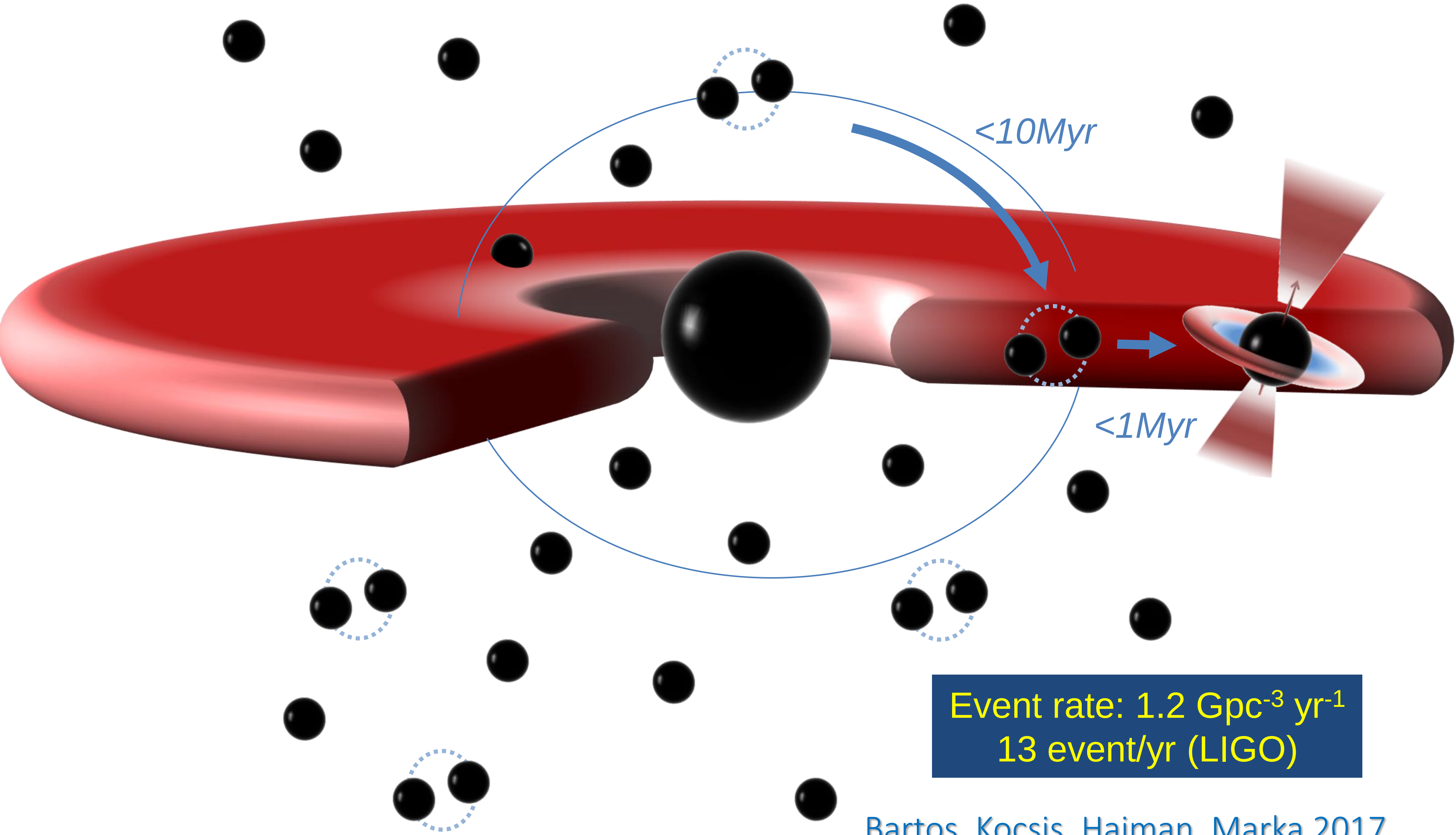


Bartos+ 2017

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



GW sources in active galactic nuclei

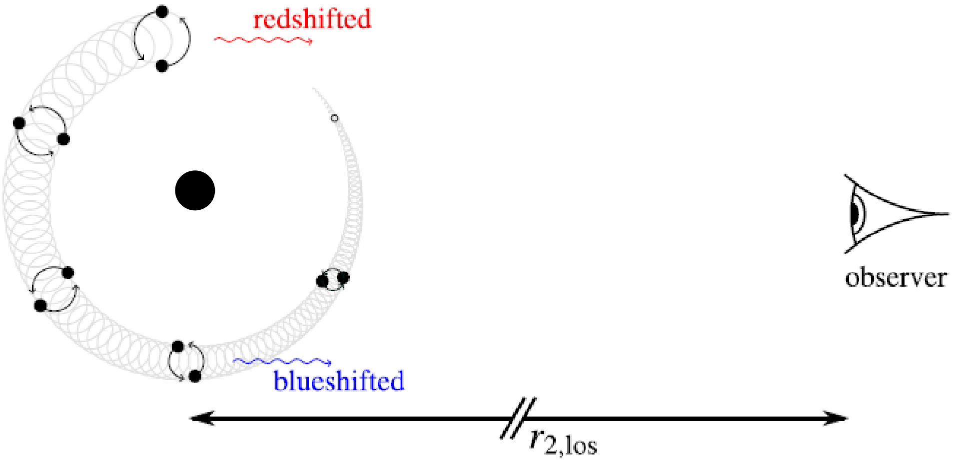


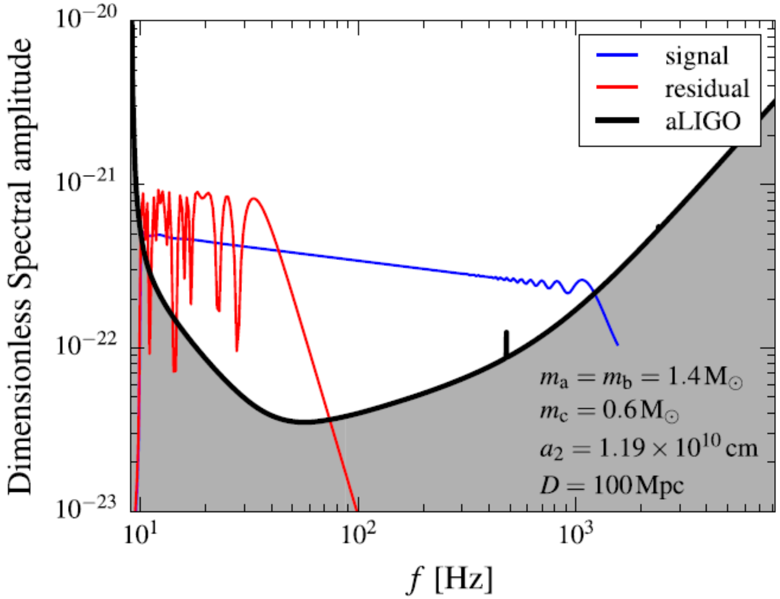
Event rate: 1.2 Gpc^{-3} yr^{-1}
13 event/yr (LIGO)

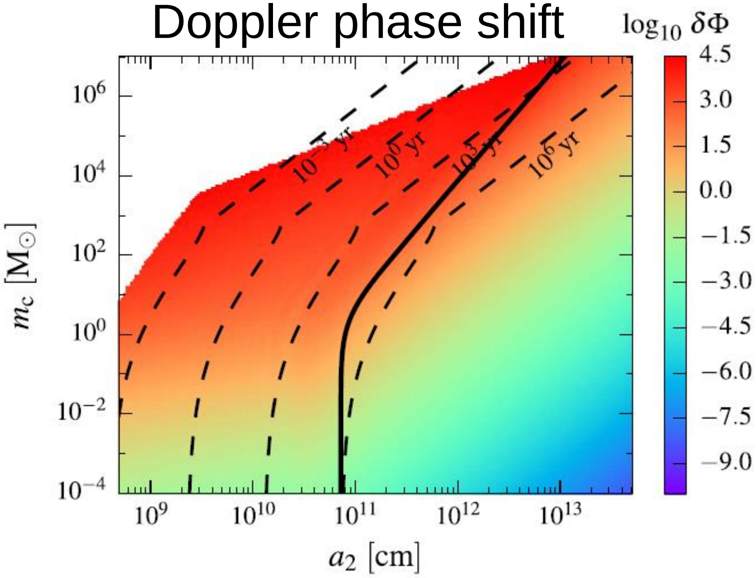
Bartos, Kocsis, Haiman, Marka 2017
Stone, Metzger, Haiman 2017

Smoking gun signatures to identify origin of source

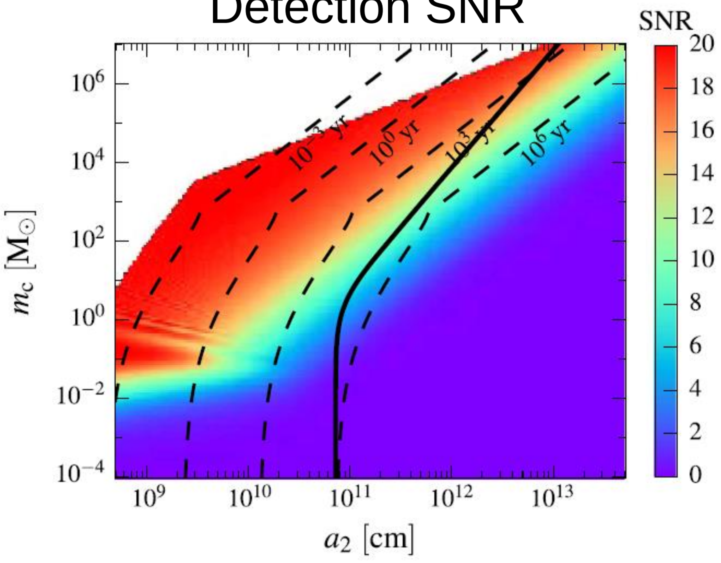
SMBH/AGN source with LIGO







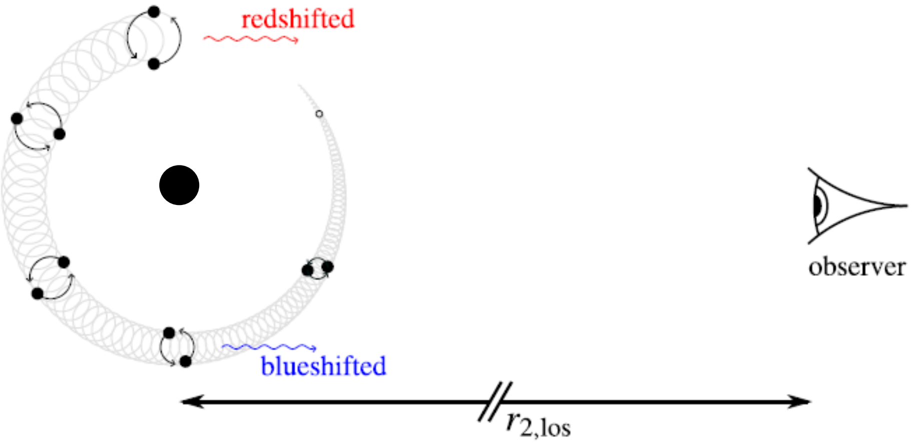
Doppler phase shift



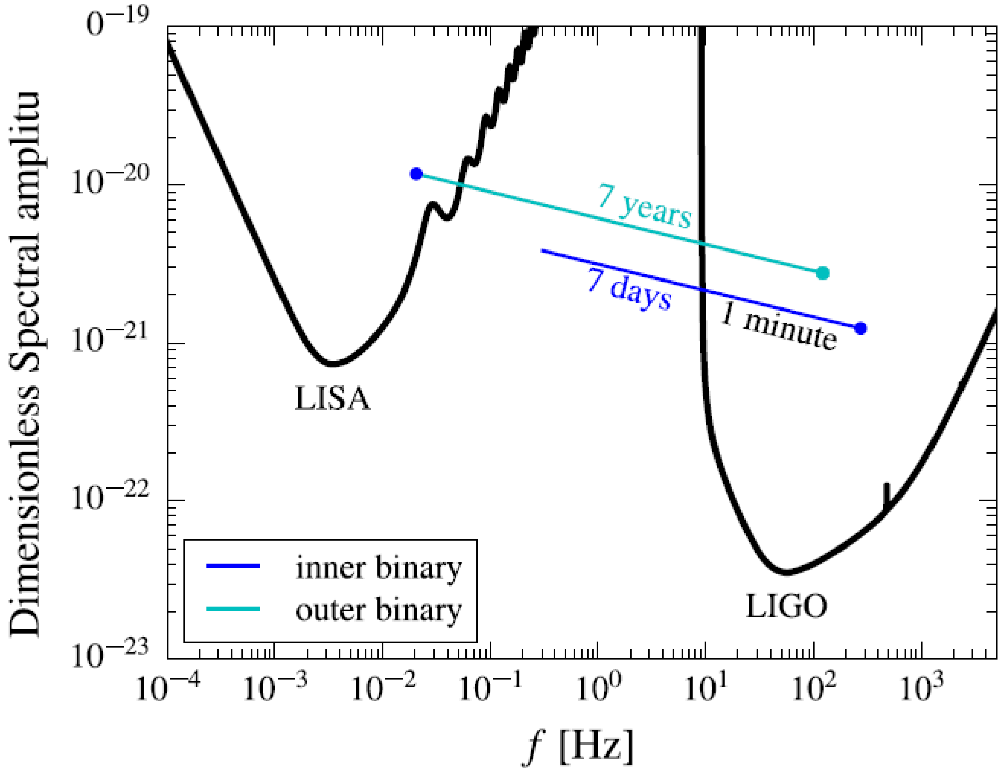
Detection SNR

Meiron, Kocsis, Loeb 2017

SMBH/AGN source with LIGO+LISA



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

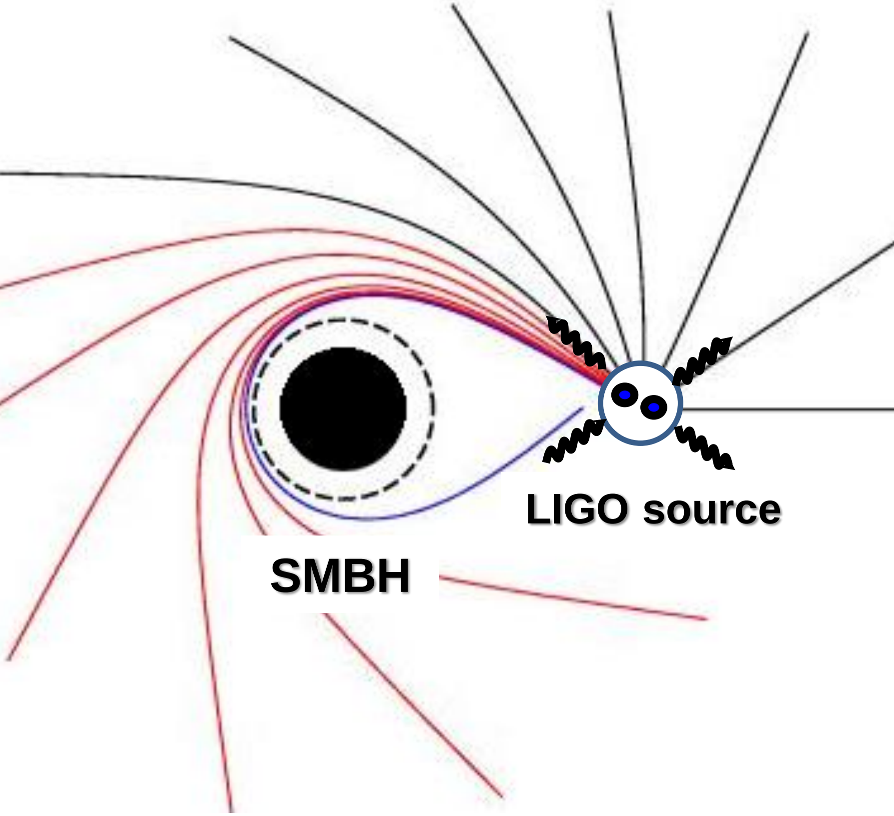


- LISA+LIGO coincident detection of triple inspiral
- LIGO detection of GW mass loss
- LISA detection of GW mass loss
- Later: LIGO detection of merger (if stellar-mass triple)

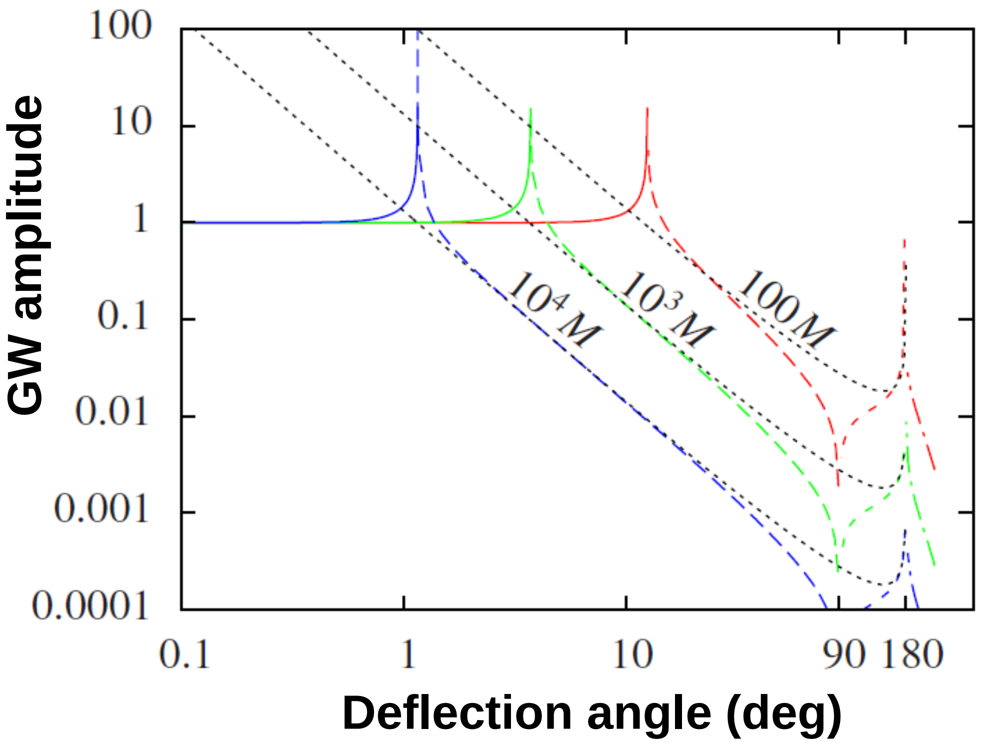
Test of general relativity

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

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

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

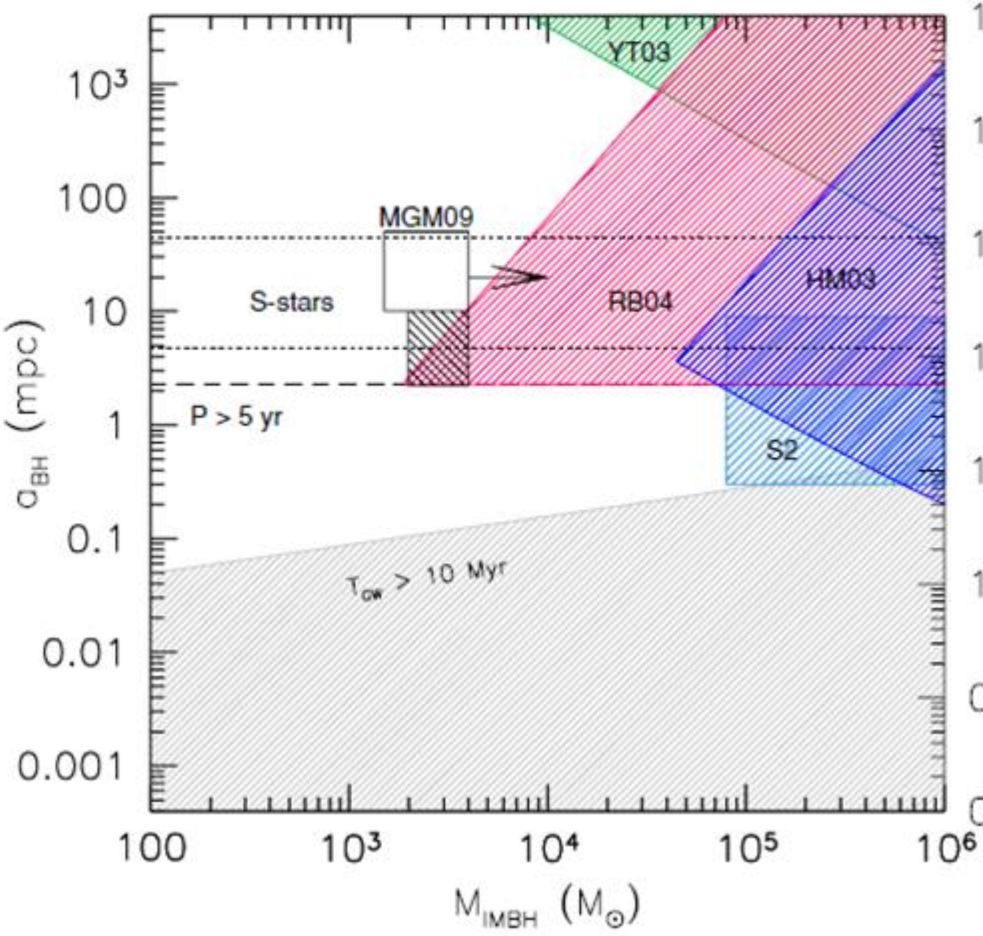
- Early universe:
  - collapse of the first stars (Madau & Reese ‘01)
- Globular clusters
  - runaway collisions (Portegies Zwart &McMillan ‘02)
  - mergers of stellar mass black holes (Miller & Hamilton ‘02)
  - dynamical friction

    → 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

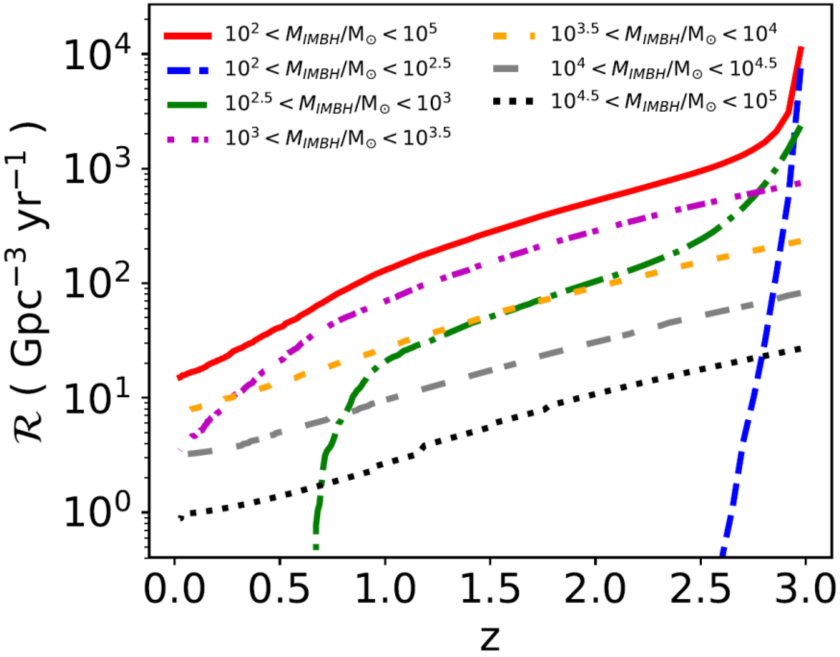


Yu & Tremaine (2003)

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 ☺ ☺

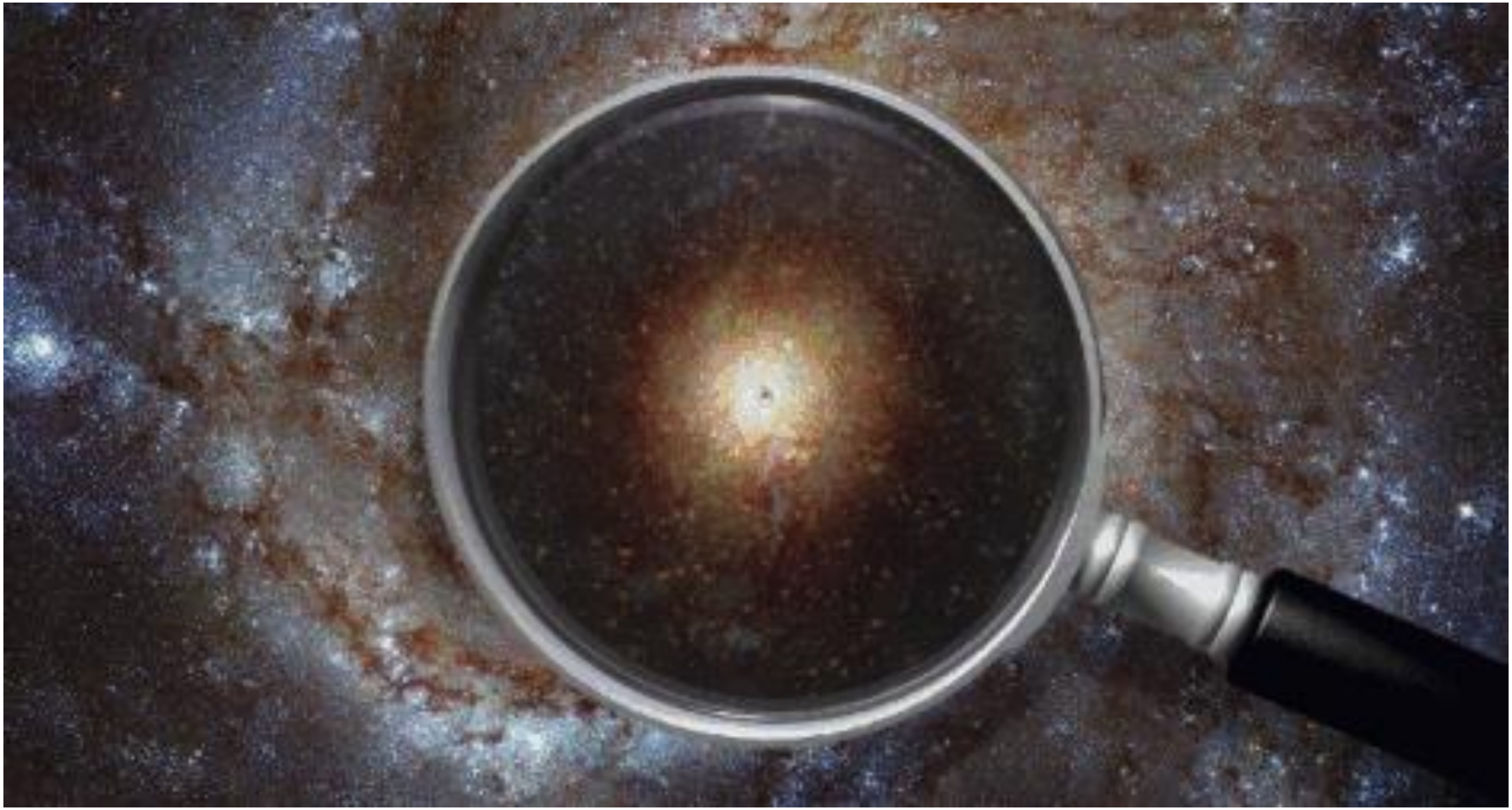
Fragione, Ginzburg, Kocsis 2018

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

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

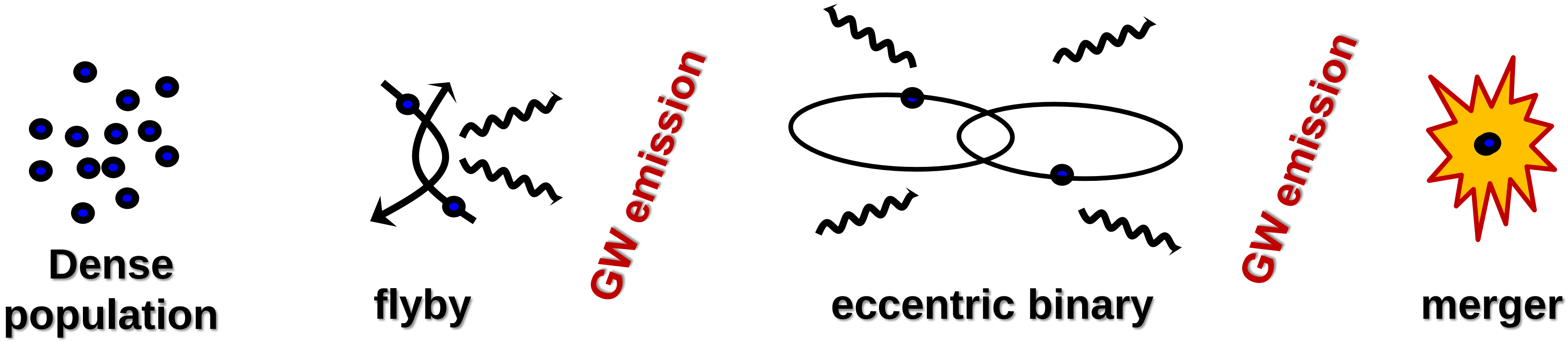
- **Eccentricity** measurable at design sensitivity
  - Delta e ~ 0.01
- **Smoking gun signatures** in some cases
  - → Doppler phase
  - → GW echo for a few percent of these
- **IMBH discovery expected** at LIGO design sensitivity



GW sources in galactic nuclei

4 channels

1. GW captures



Dense population

flyby

GW emission

eccentric binary

GW emission

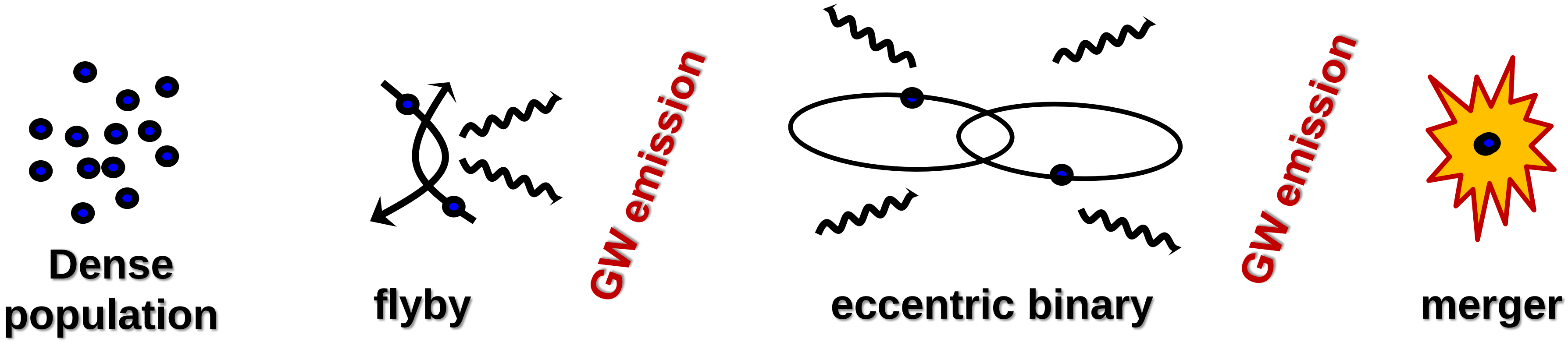
merger

Kocsis, Gaspar, Marka 2006; O'Leary, Kocsis, Loeb 2009; Kocsis & Levin 2012, Gondan, Kocsis+ 2018

BH merger rate:
~1 – 5 / Gpc^3 / yr

- multimass Fokker-Planck model
- secret ingredient

1. GW captures

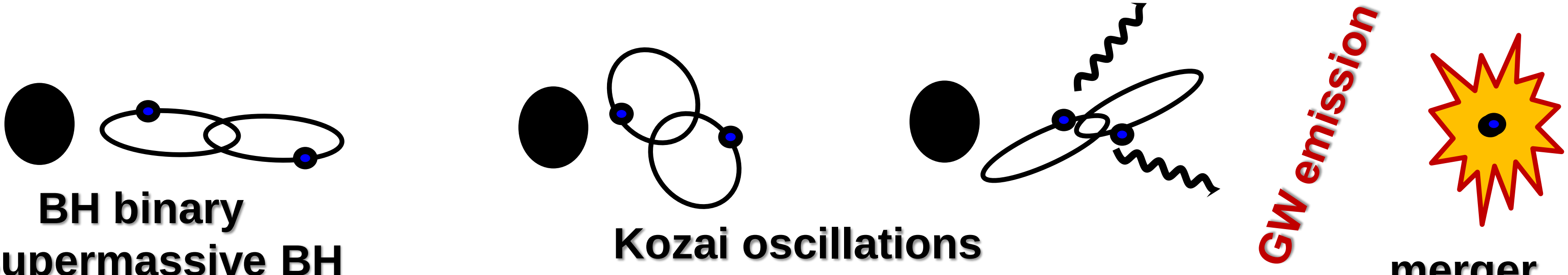


Kocsis, Gaspar, Marka 2006; O'Leary, Kocsis, Loeb 2009; Kocsis & Levin 2012, Gondan, Kocsis+ 2018

BH merger rate:
~ few / Gpc^3 / yr

- multimass Fokker-Planck model
- secret ingredient: **heavy BHs** ($m > 25\ M_{sun}$ needed)
  - sink to center **from far away** within a Hubble time
  - **high number density** at the center $n \sim 10^{10}$ pc^{-3}
  - **retained** due to SMBH
- Merger rate/galaxy ~ $n^2 \sigma v$
  - independent of SMBH mass → **dwarf galaxies contribute**

2. Kozai-Lidov effect



BH binary
+ supermassive BH

Kozai oscillations
(eccentricity and inclination)

GW emission

merger

Wen 2003; Antonini & Perets (2012); Naoz, Kocsis, Loeb, Yunes (2012), Hoang+ (2017)

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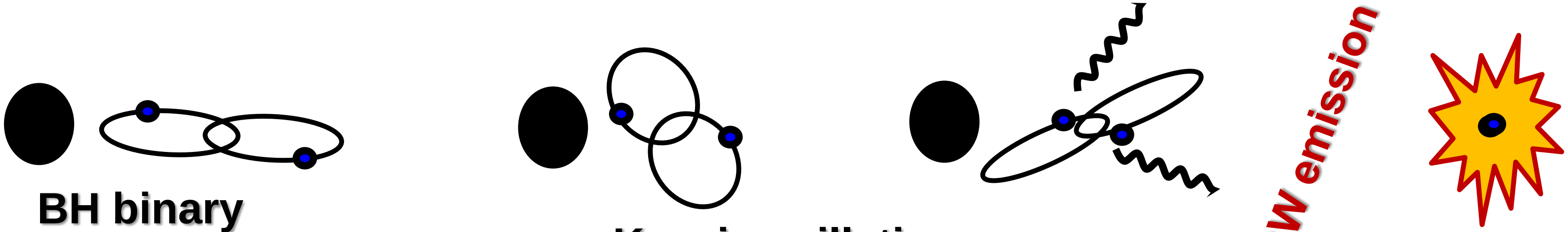

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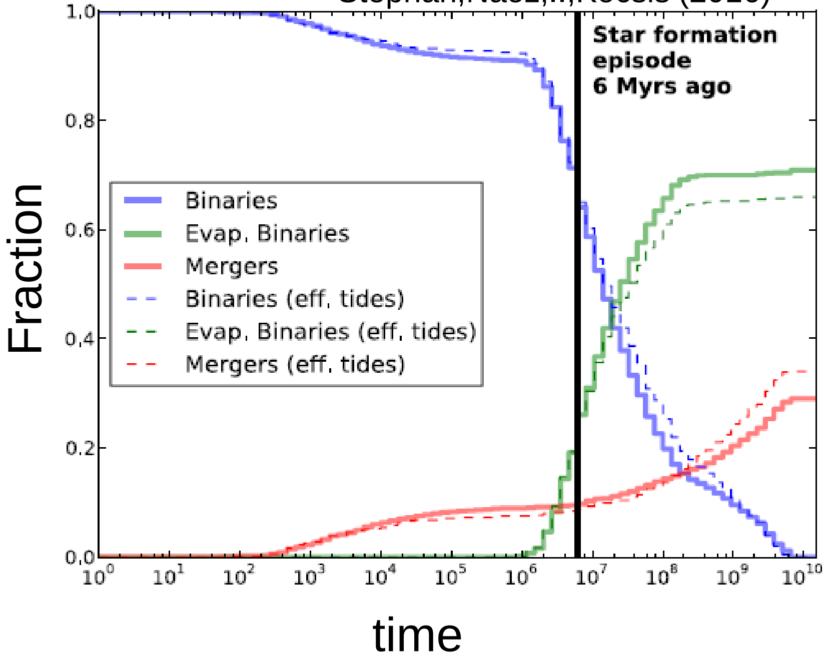
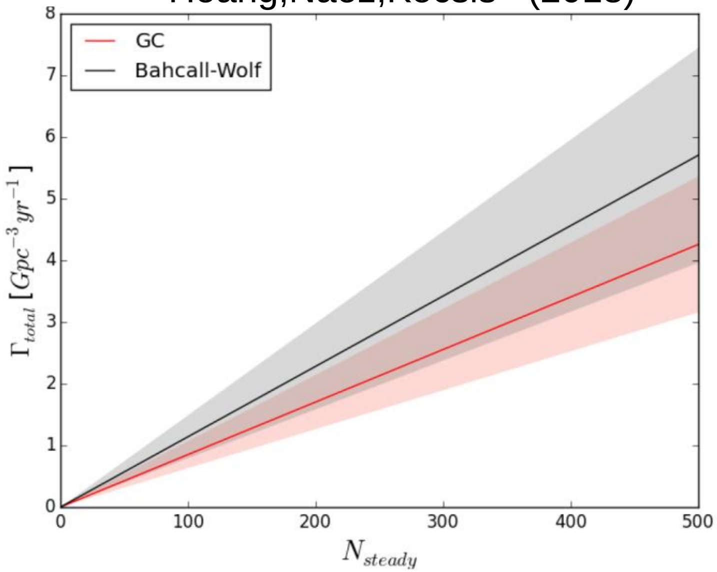
Wen 2003; Antonini & Perets (2012); Naoz, Kocsis, Loeb, Yunes (2012), Hoang+ (2017)

Event rate:
~few/Gpc^{-3}/yr

Stephan,Naoz,..,Kocsis (2016)



Hoang,Naoz,Kocsis+ (2018)



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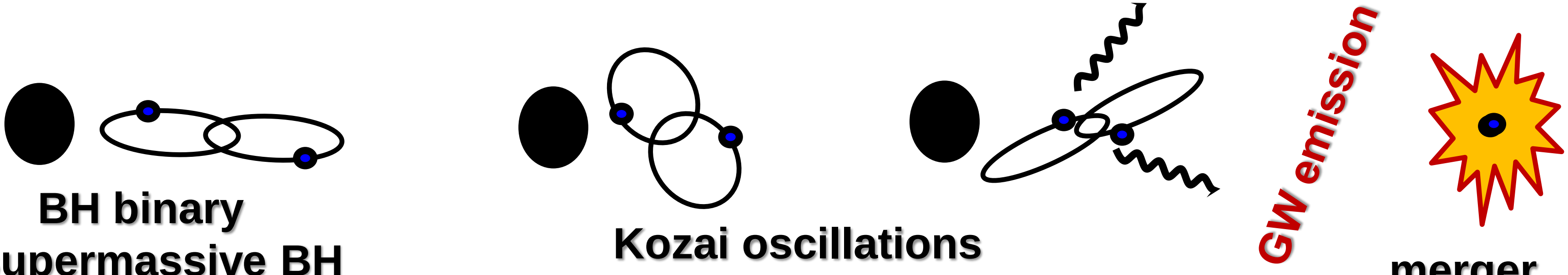

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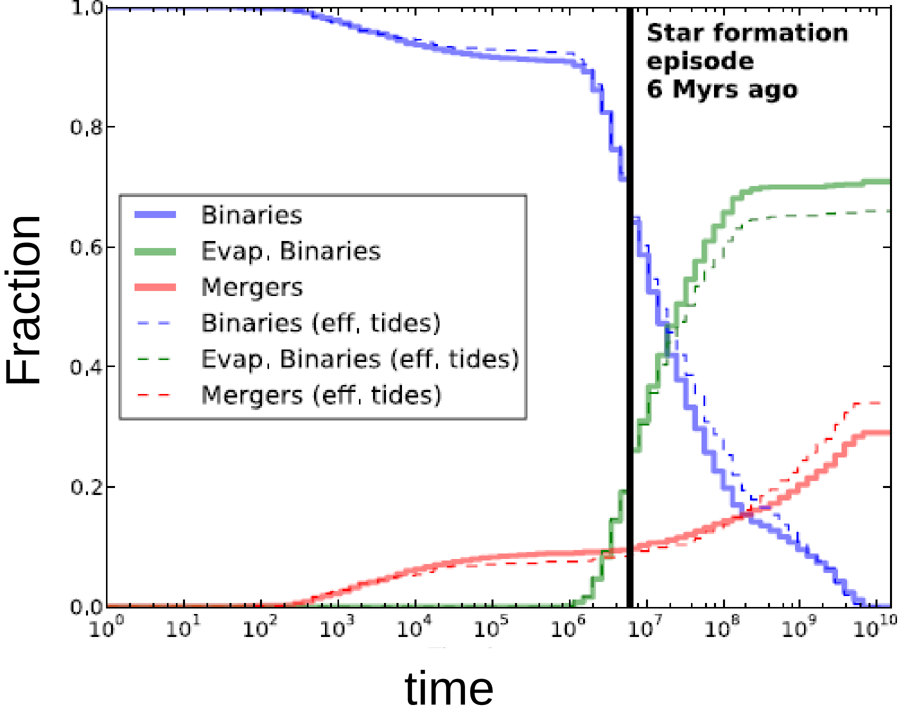
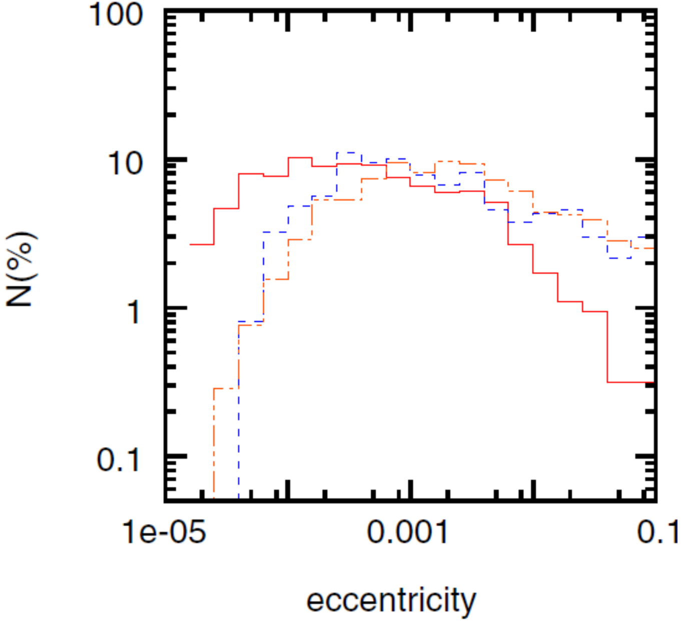
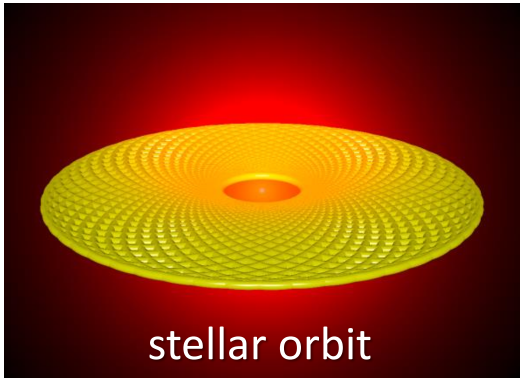


Antonini, Perets (2012)



4. Black hole disks

Motion of stars in the galactic disk:



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

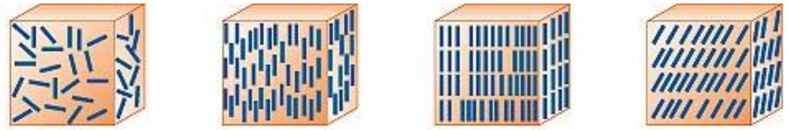
Orbital planes reorient and relax very quickly

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:

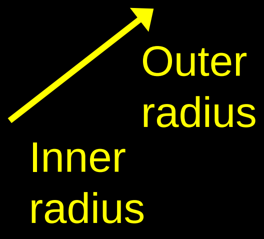
- massive objects: ordered phase
- light objects: spherical phase
- Implication: Black hole disks !

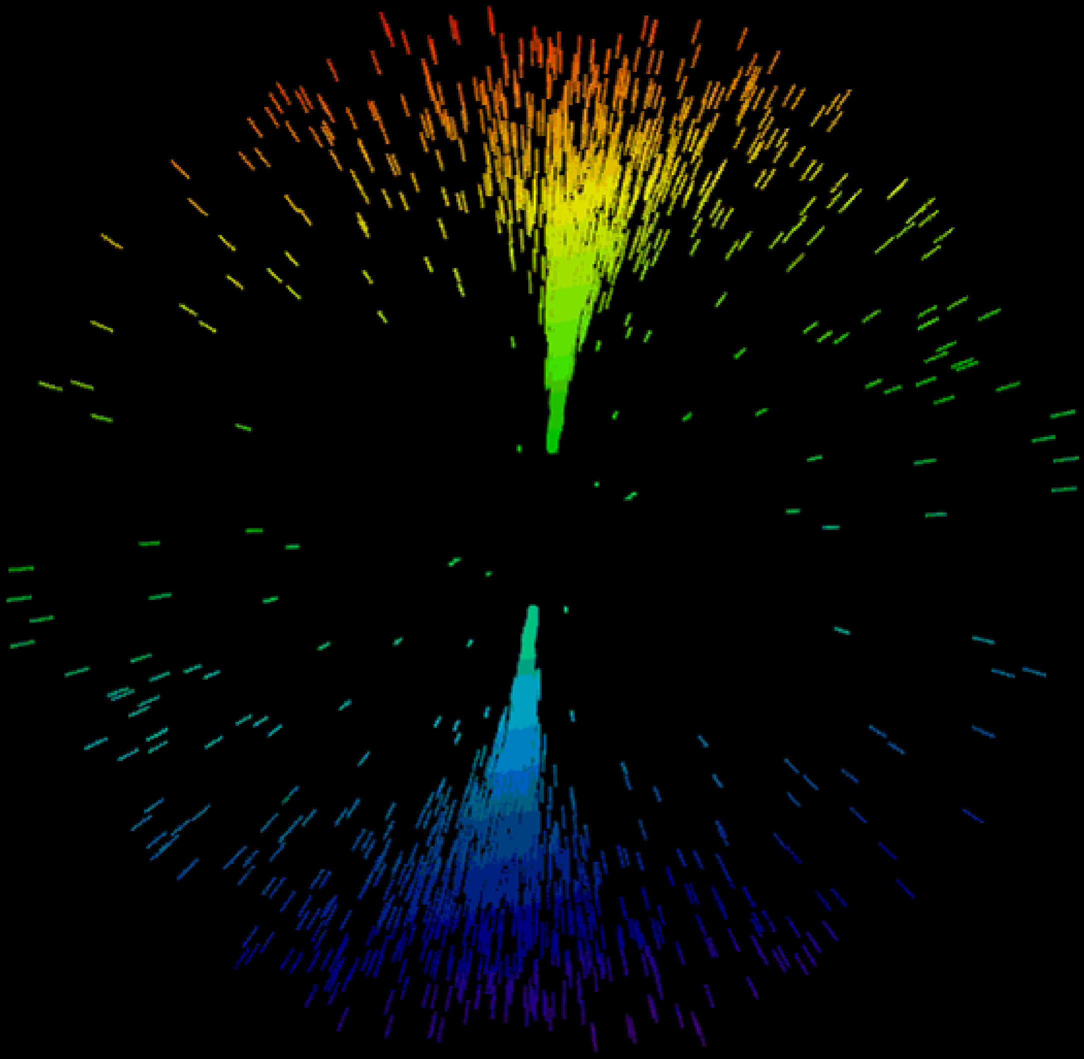


(a) Normal liquid (b) Nematic liquid crystal (c) Smectic A liquid crystal (d) Smectic C liquid crystal

Thermal equilibrium (maximum entropy)

Orbit normal vectors as a function of distance



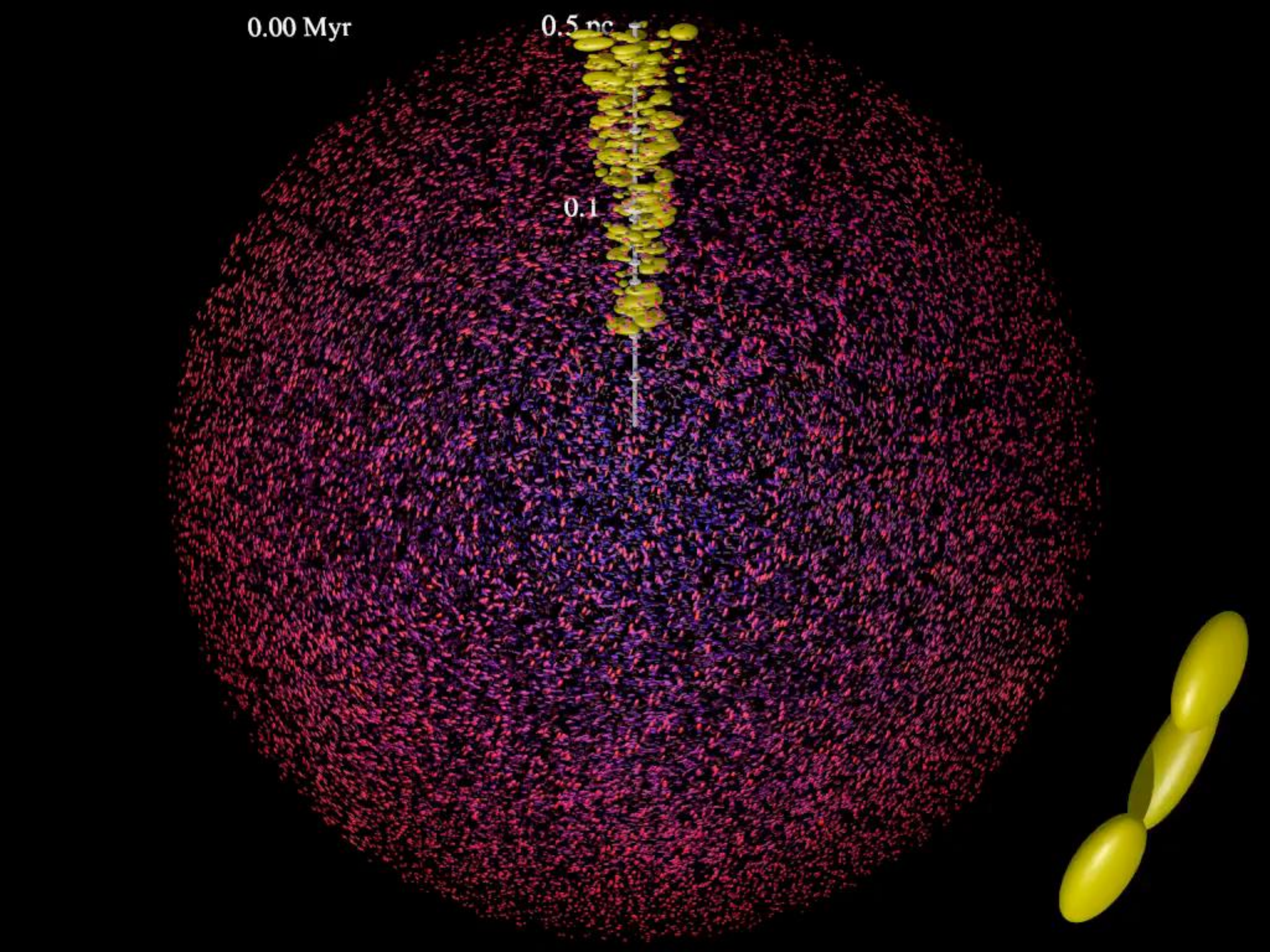


- Stars
  - Same mass and eccentricity

- microcanonical ensemble

Phase transition in orientation

Monte Carlo Markov Chain simulation


0.00 Myr
0.5 pc
0.1

Final state of relaxation

- **Massive objects in a disk inside**
- **Spherical distribution outside**

Three snapshots: