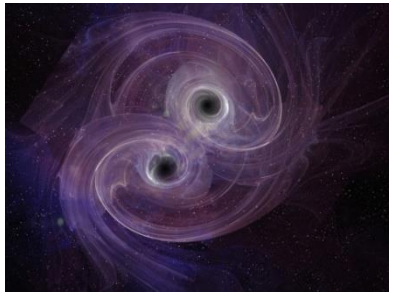
On the Origin of
Gravitational Wave Sources
Observed by LIGO/VIRGO

Bence Kocsis Eotvos University



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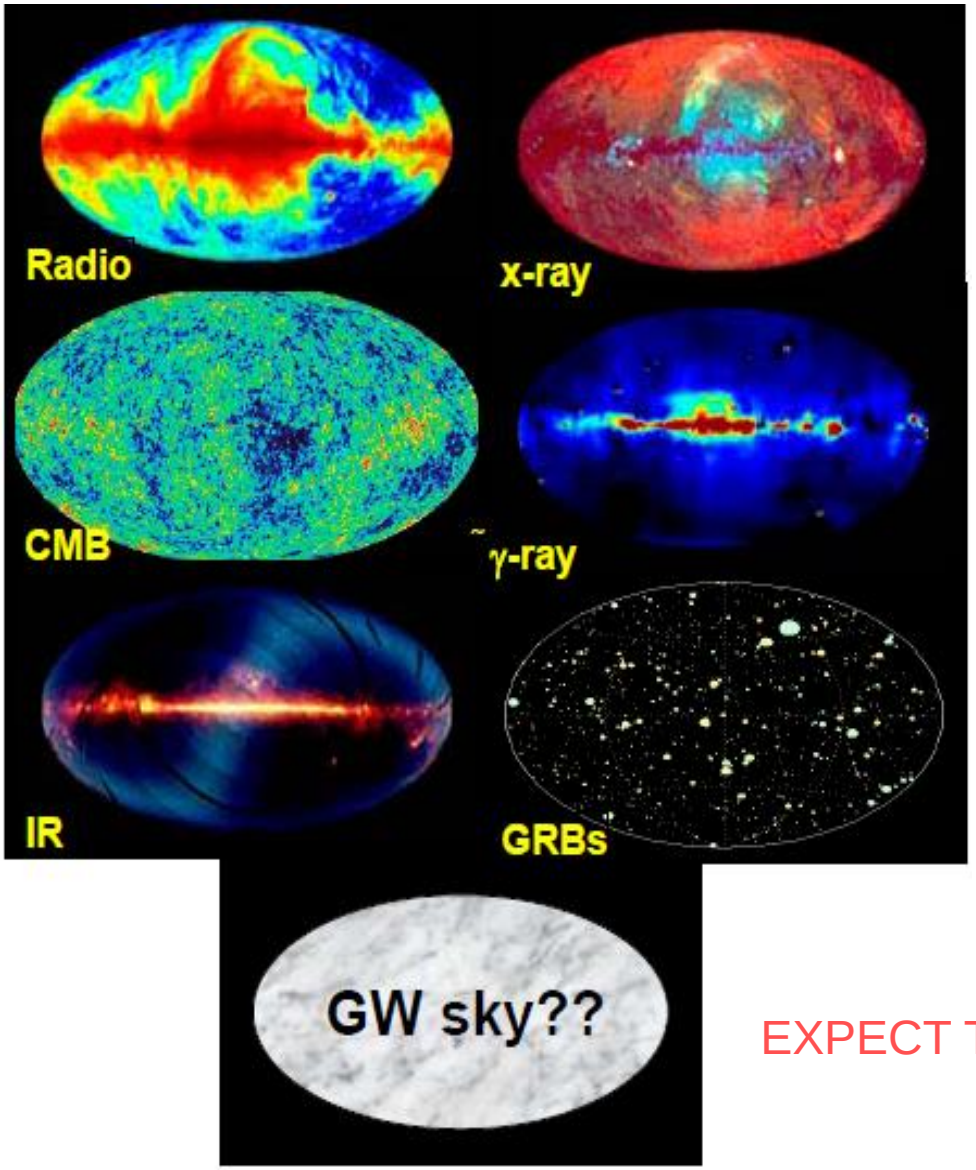
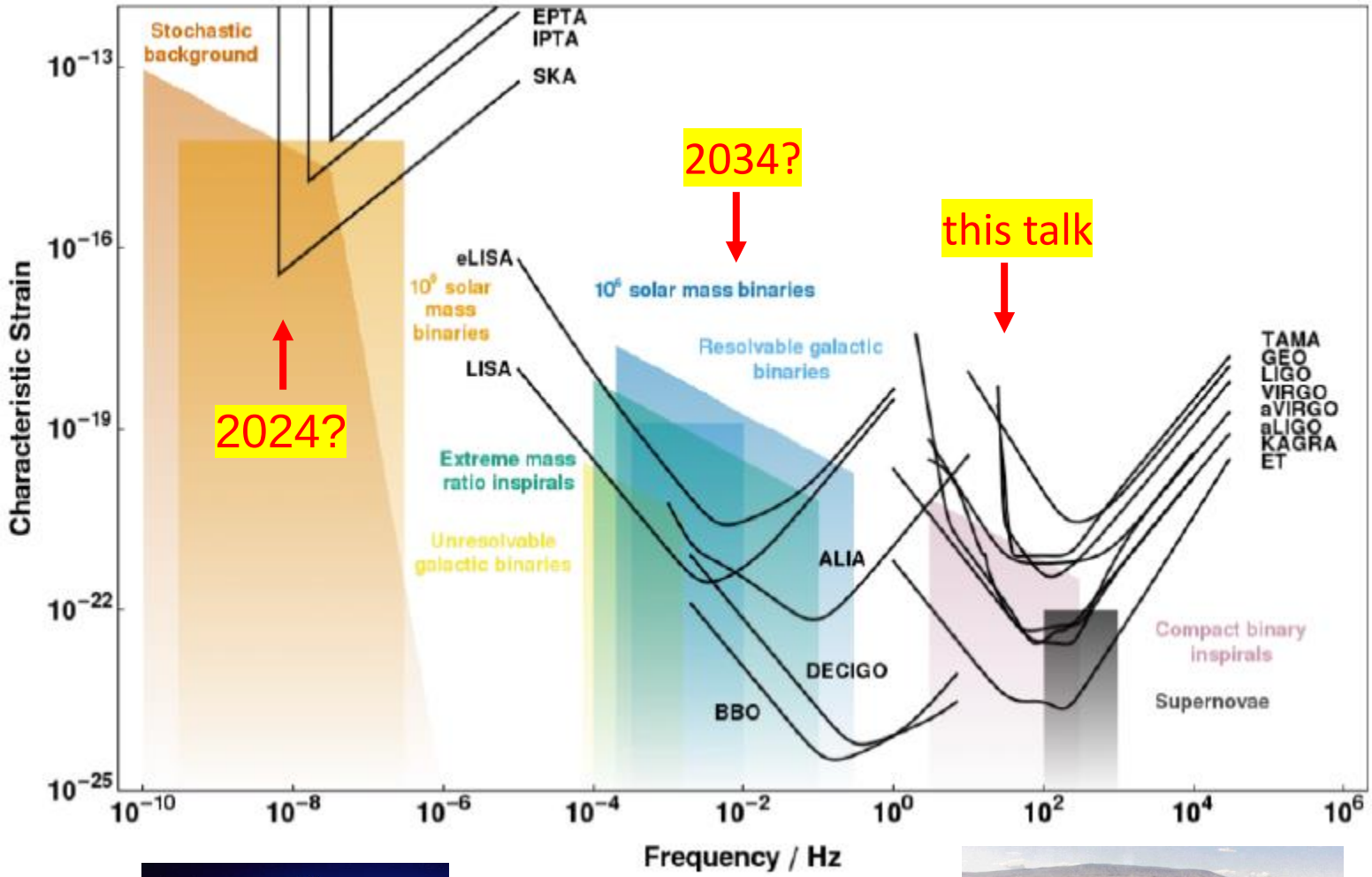
Modern theories of gravity, Hungarian Academy of Sciences, May 8 2019

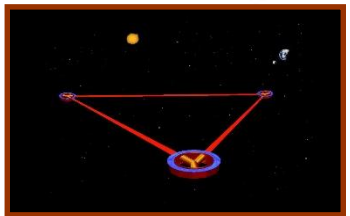
The Dawn of GW astrophysics



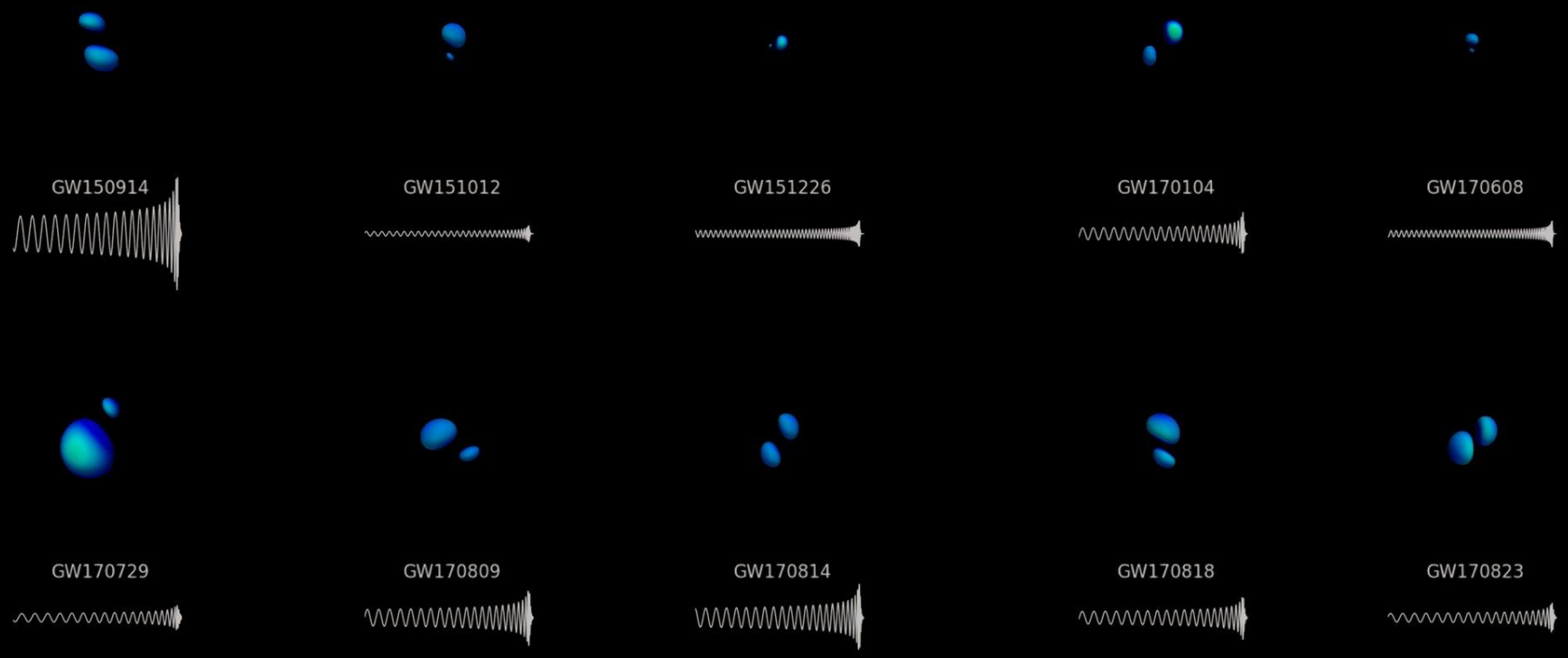
EXPECT THE UNEXPECTED!

Gravitational wave detectors

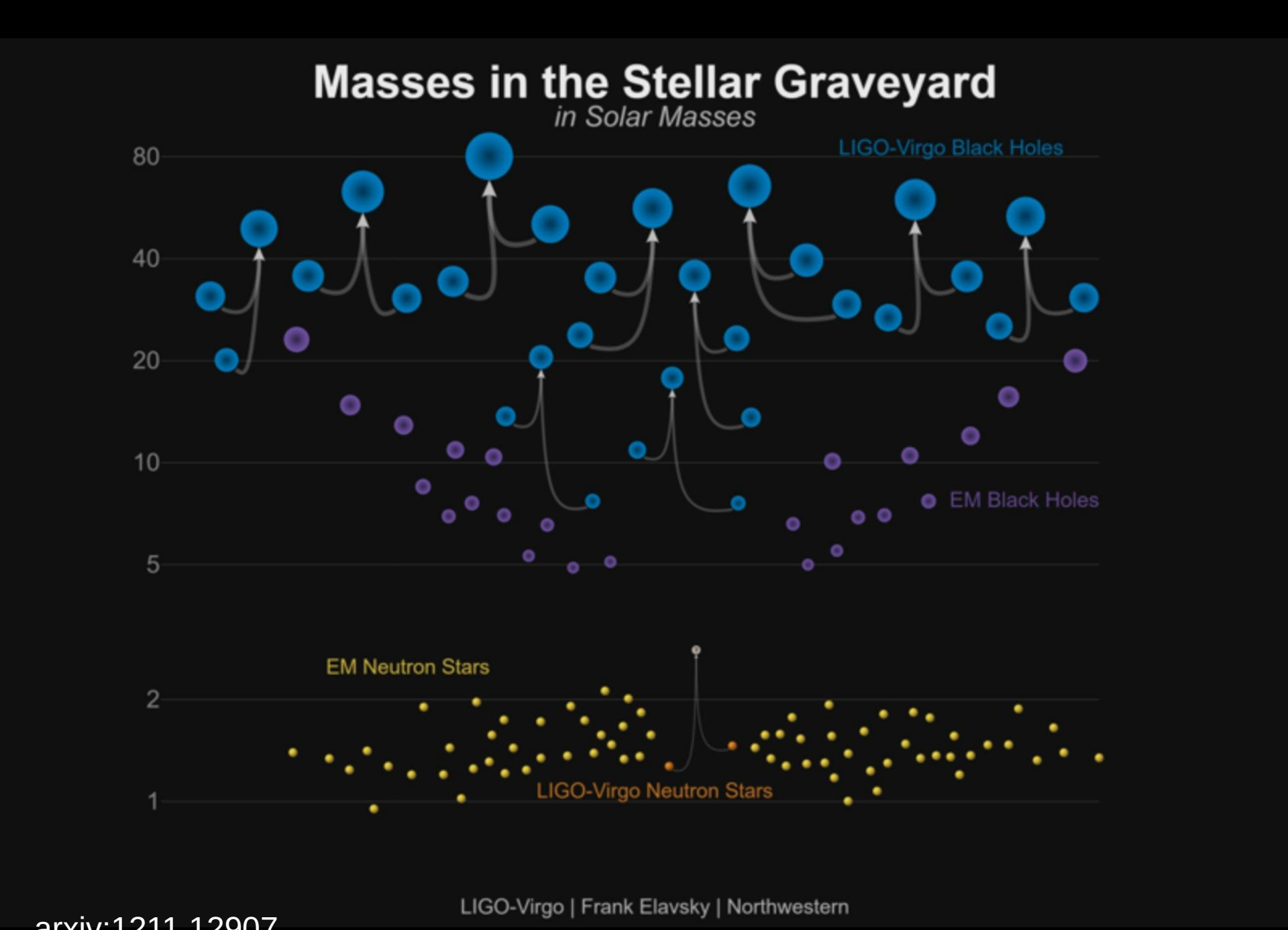




Gravitational wave detections



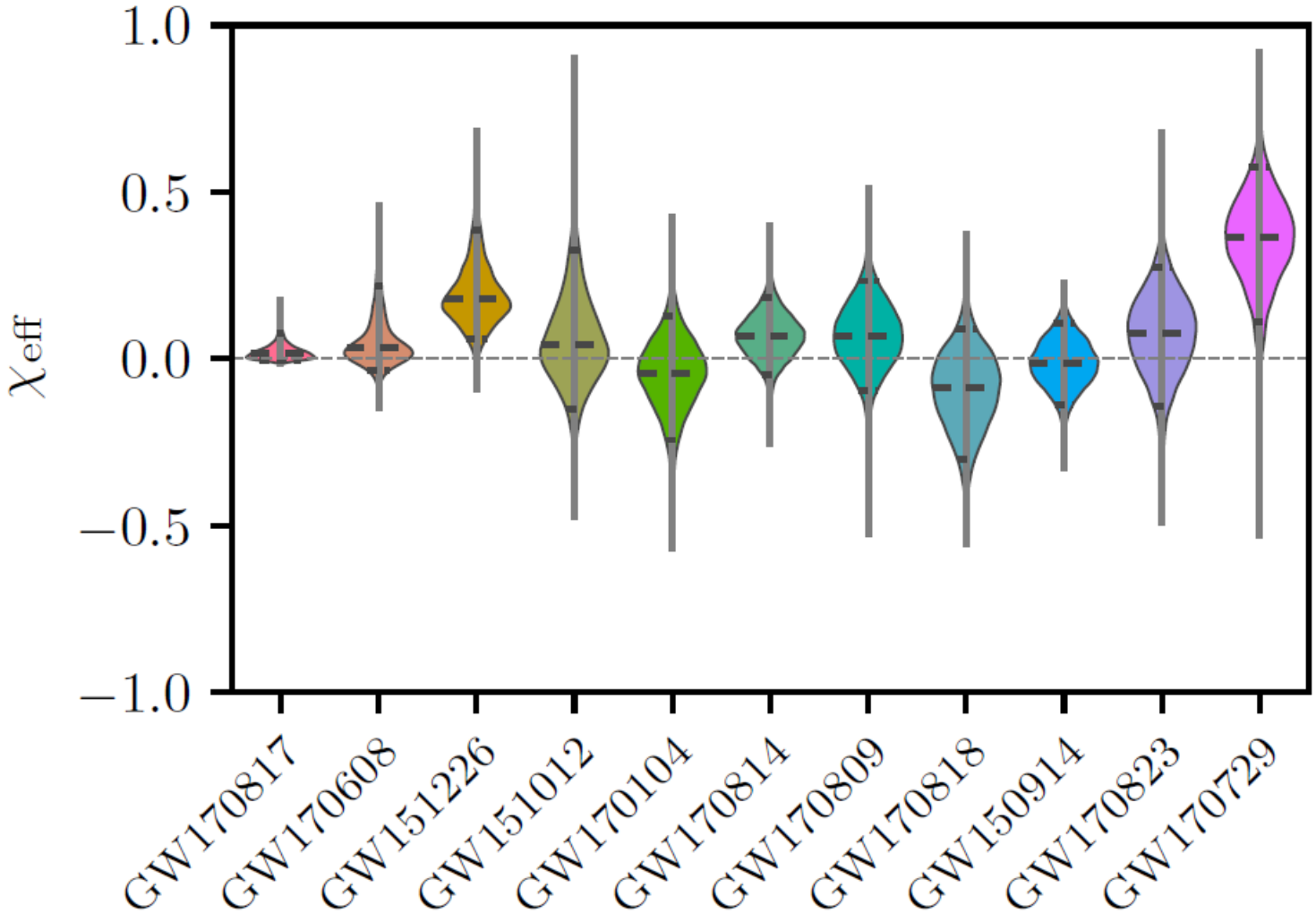
arxiv:1211.12907



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

Rate of BBH coalescence

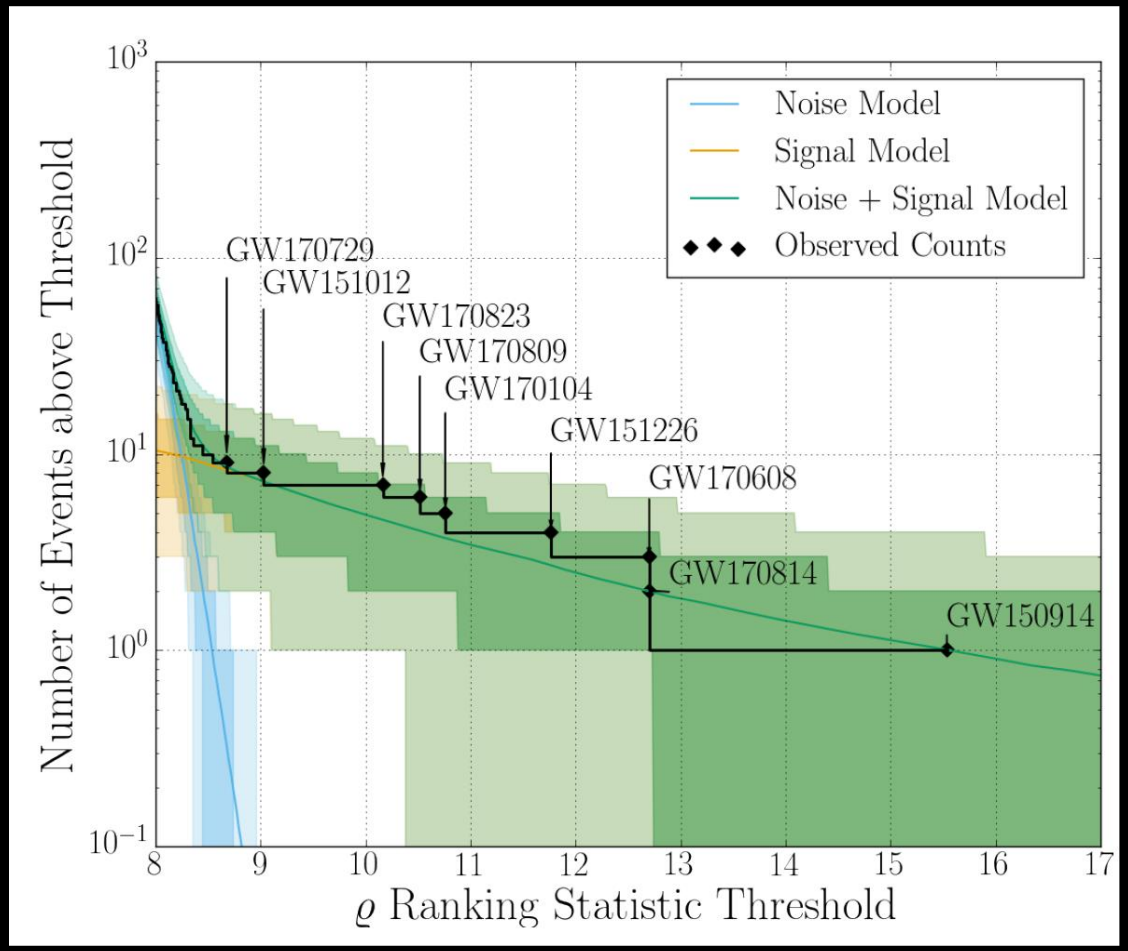
GW150914+LVT151012:
2 – 600 Gpc $^{-3}$ yr $^{-1}$

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

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

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

Rate of NS coalescence
GW170608:
300 – 4700 Gpc $^{-3}$ yr $^{-1}$

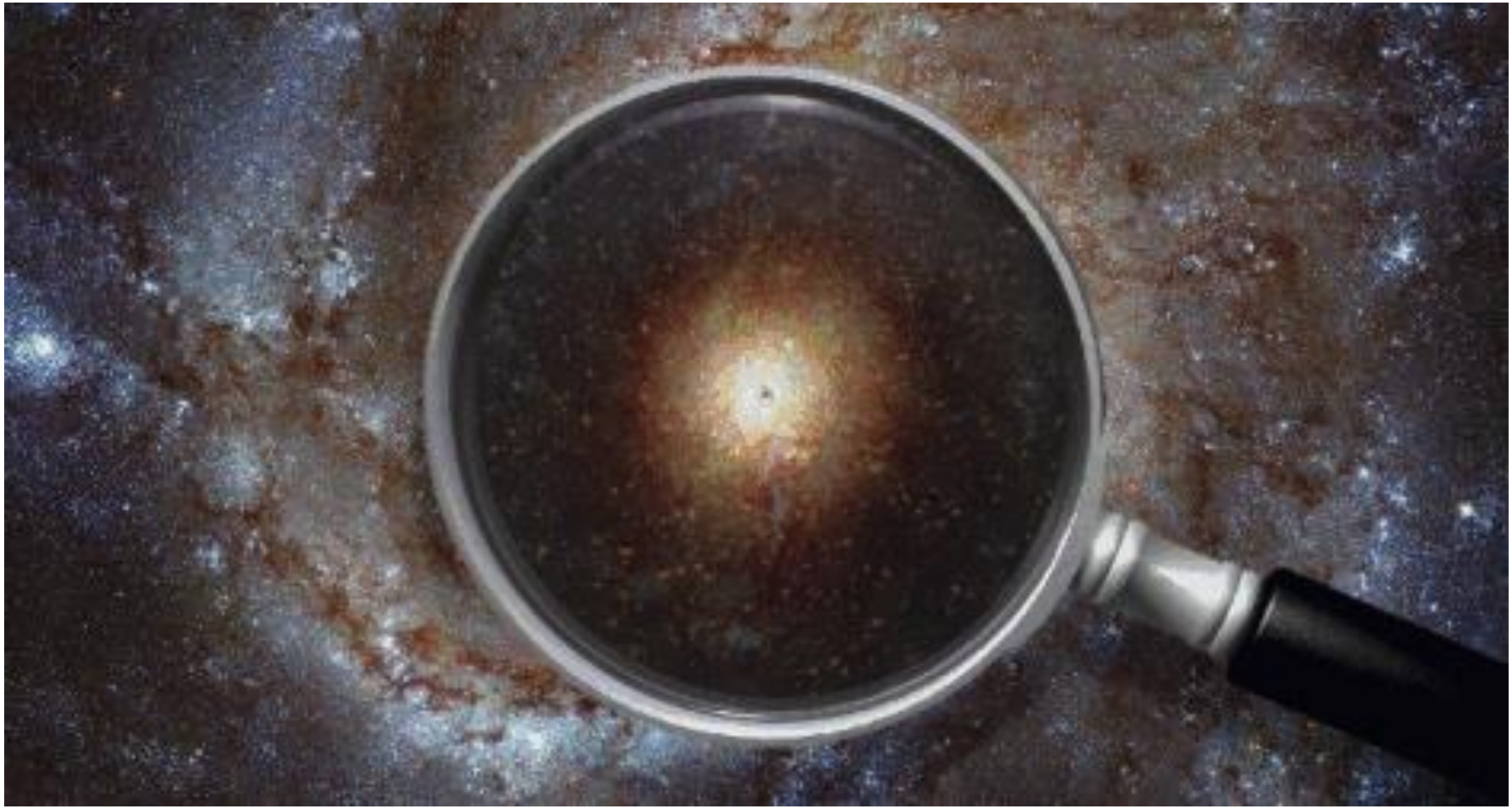


arxiv:1211.12907

LIGO/VIRGO Collaboration 2018

Basic questions

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

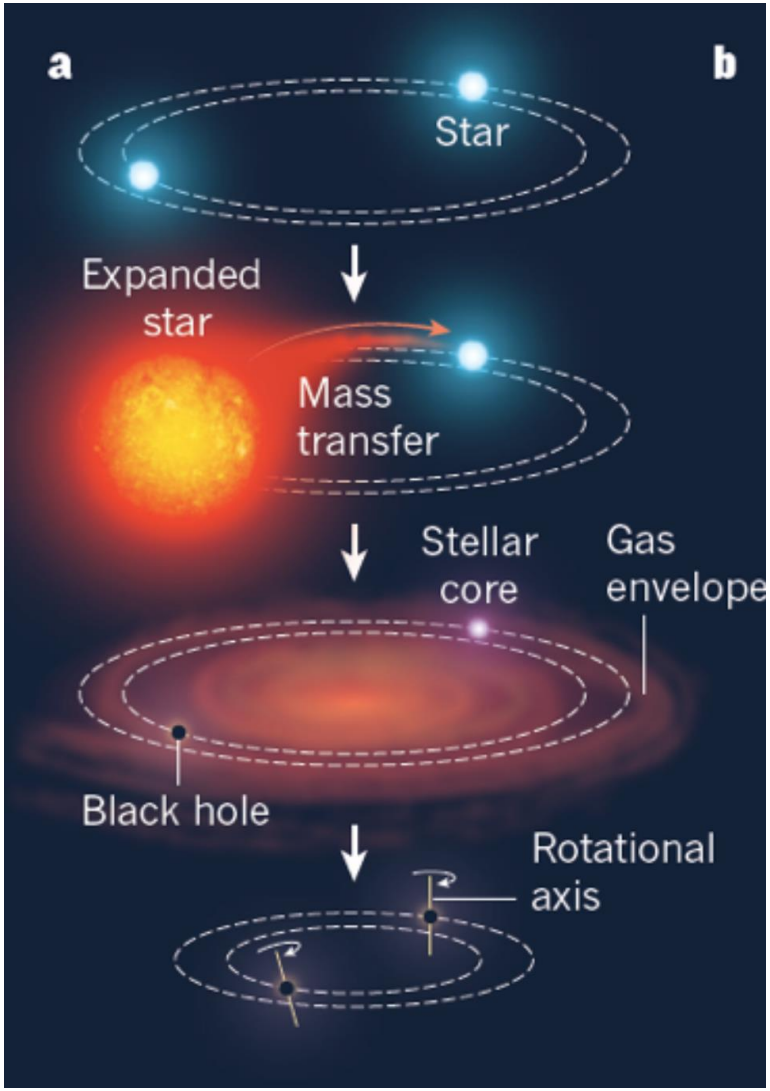


Astrophysical origin of mergers

Option 1: stellar binary evolution

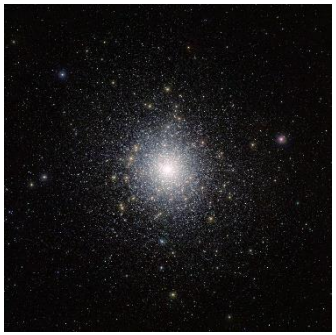
Galactic binaries

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

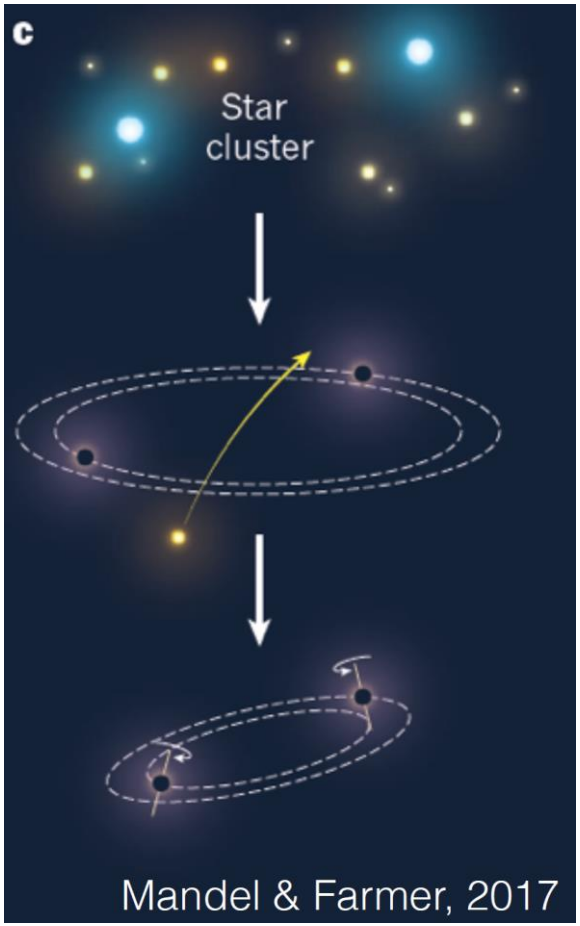


Option 2: Dynamical environments

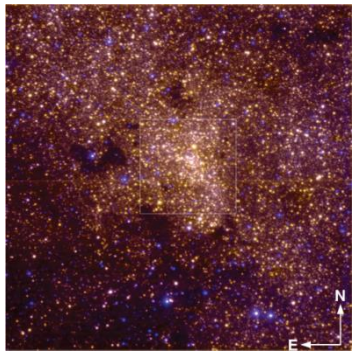
Globular clusters



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

encounter rate ~ density^2

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

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

Summary of channels

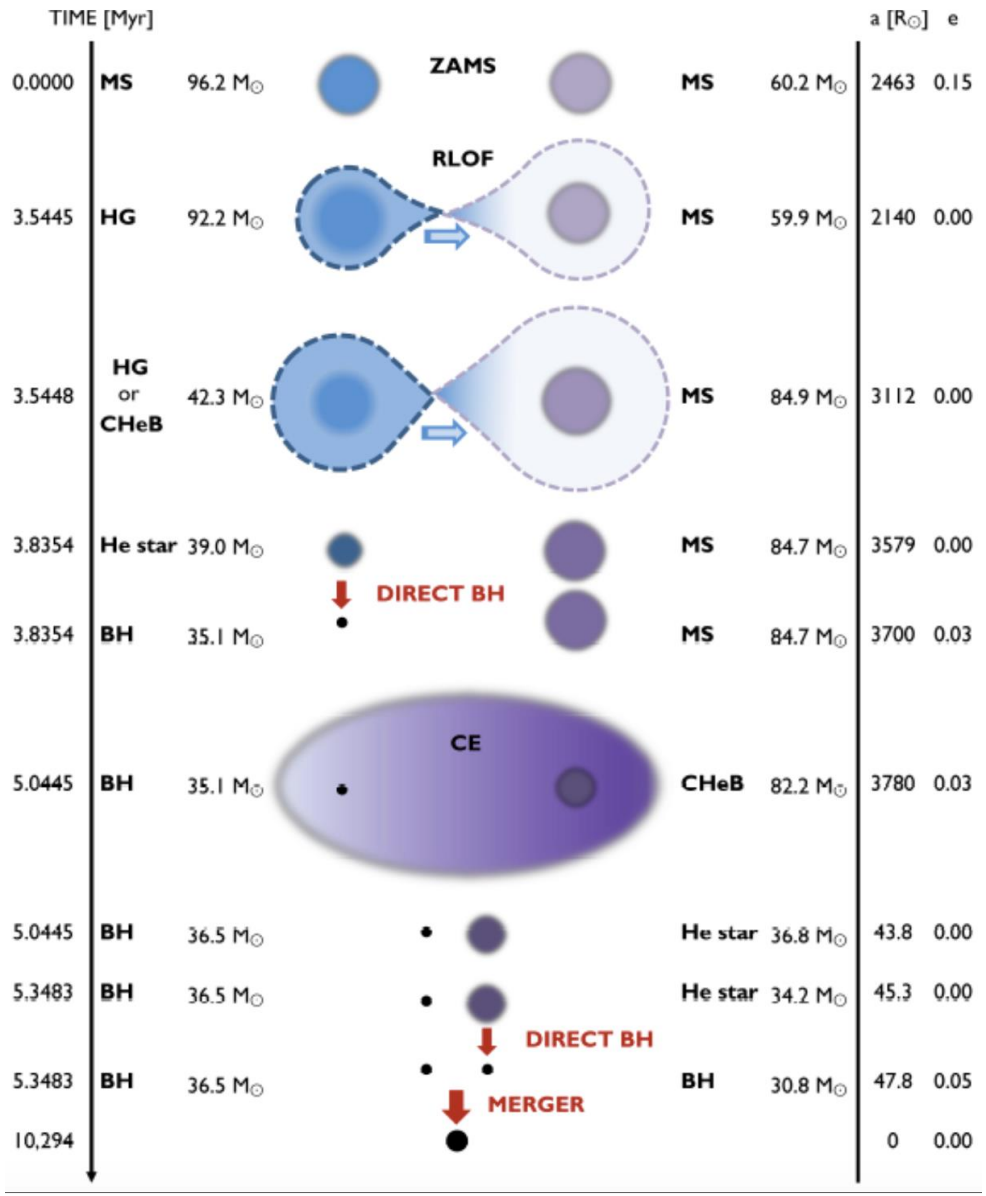
- galactic field binaries: spins, final au problem, common envelope
- galactic field triples: do we have enough in the right configuration?

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

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

All theories have trouble to explain the observed sources!

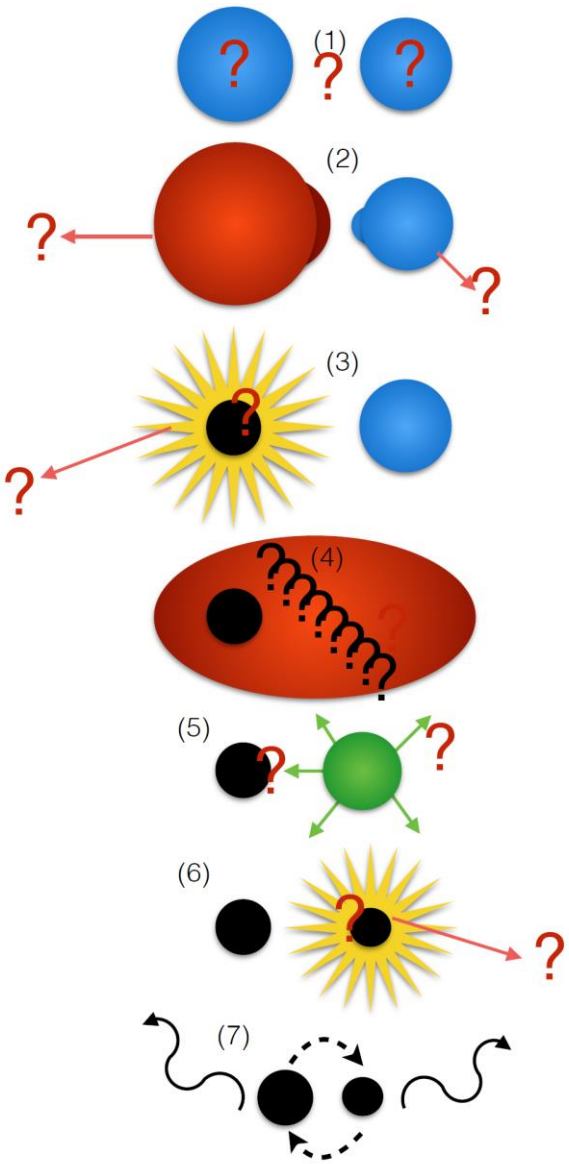
Option 1: stellar binary evolution



Belczynski+ (2016)

Option 1: stellar binary evolution

Open questions



Option 1: stellar binary evolution

What about the rates?

- Theory uncertain 10—1000 Gpc^{-3} yr^{-1} – consistent with observations
- Relative rate of NS/NS mergers vs. BH/BH mergers may be a problem

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.

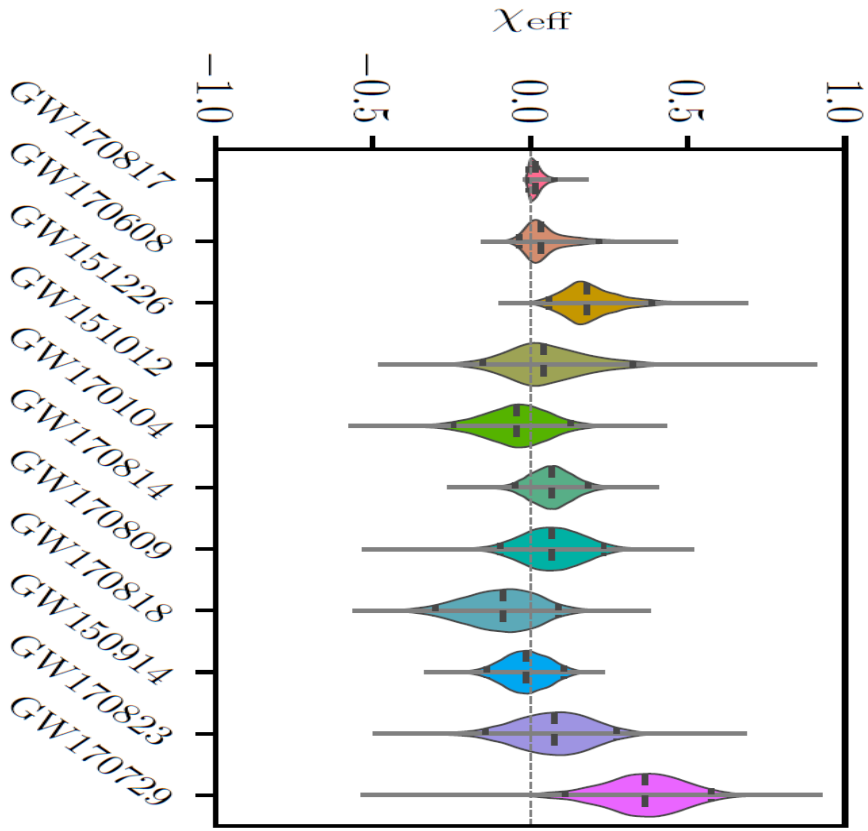
[c]Mass estimated using an empirical mass distribution (Özel et al. 2010).

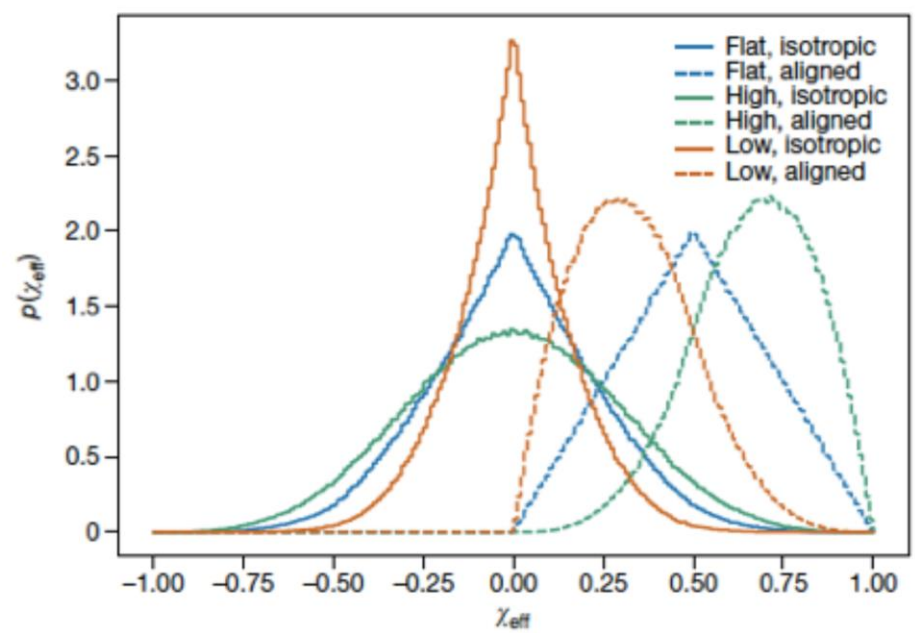
[d]Preliminary result pending improved measurements of M and i.

Option 1: stellar binary evolution

What about spins?

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





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

LIGO/VIRGO Collaboration 2018

Farr+ 2017

Option 2: dynamical environments

- A theoretically clean problem: N-body

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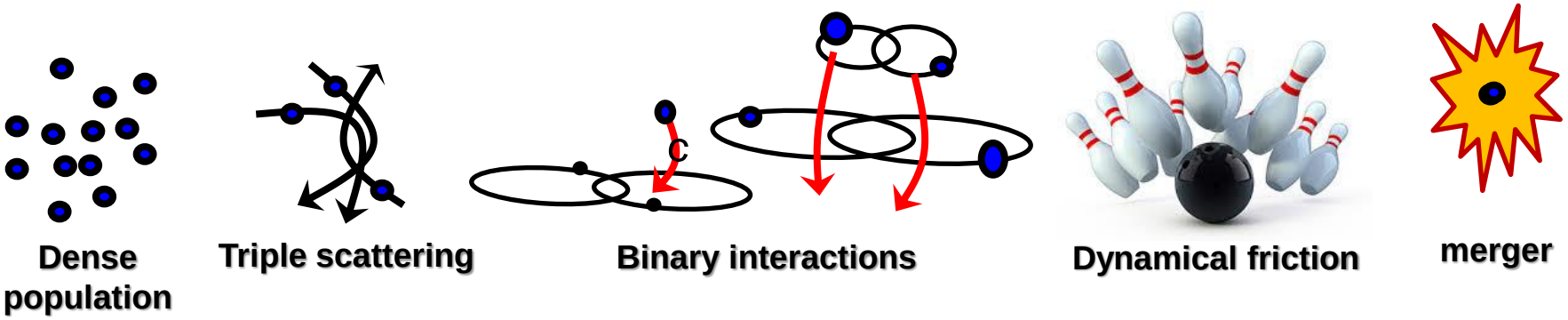
- A theoretically clean problem: N-body



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

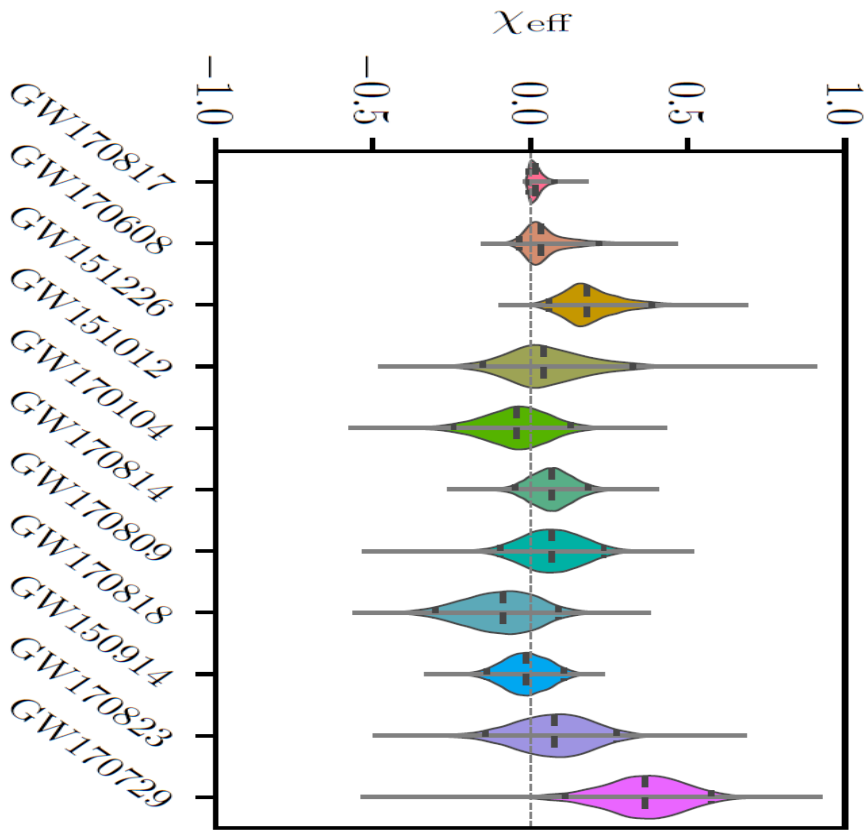
Expectation:

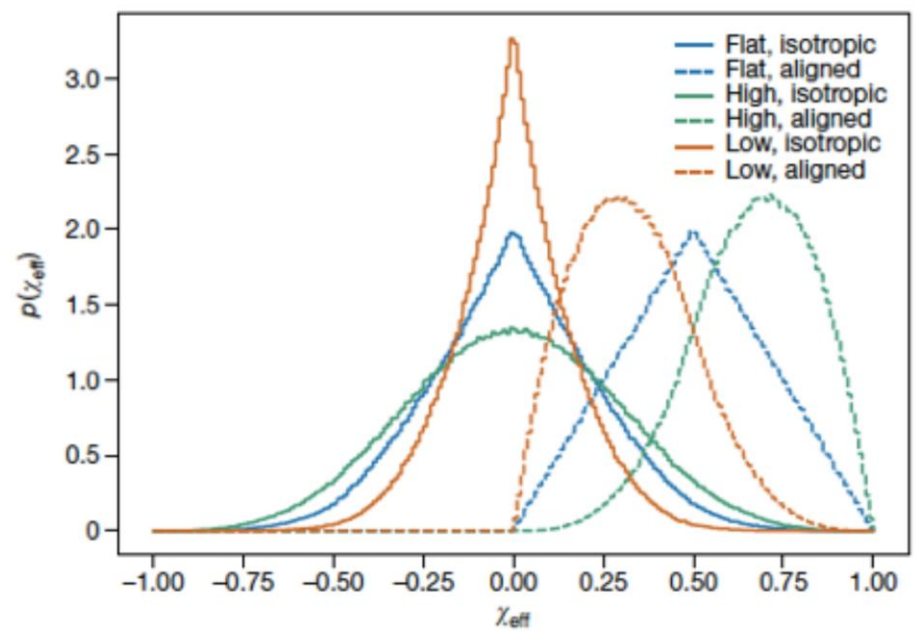
Merger probability larger for heavier objects

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 Gpc^{-3} 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 Gpc^{-3} yr^{-1}**
    - 0.5% of stellar mass, $10^{5.5}$ stars with n ~ 0.8 Mpc^{-3}
  - **galactic nuclei: R < 35 Gpc^{-3} 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: 29 – 100 Gpc^{-3} yr^{-1}
(powerlaw mass distribution prior, Abbott+ 2018 arxiv:1811.12907)

Option 3: triples

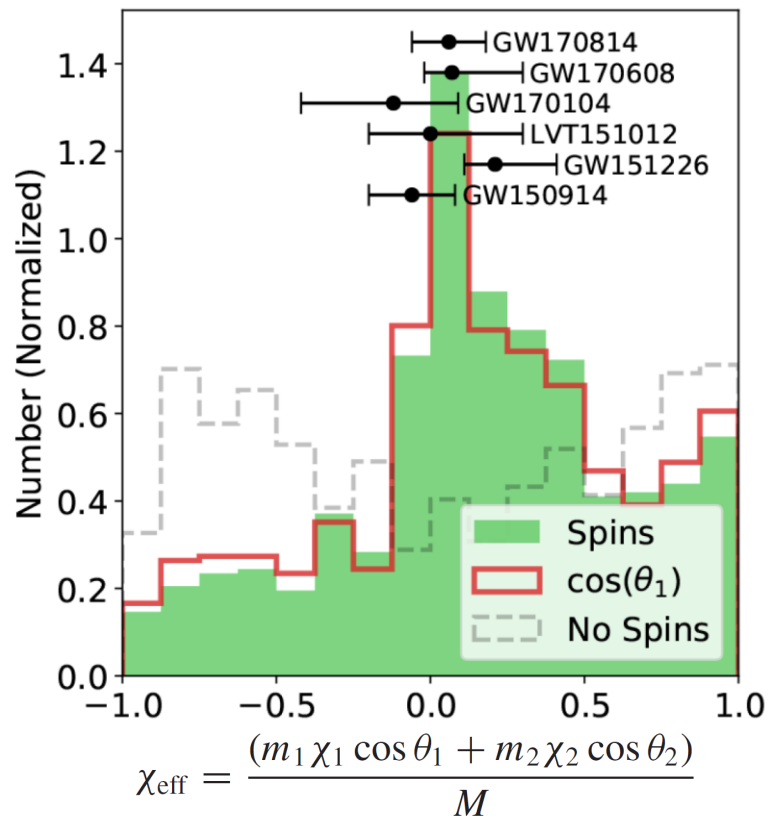
Tertiary perturber:

- Kozai-Lidov effect increases eccentricity to facilitate merger

- Spins **align in the perpendicular** direction

- expected **rates are**

  2 – 25 Gpc^{-3} yr^{-1}



Silsbee & Tremaine 2017; Antonini+ 2017, 2018; Hamers+ 2018; Hoang, Naoz, Kocsis+ 2018

Summary of channels and rates

- galactic field binaries: spins, final au problem, common envelope
- galactic field triples: maybe, but tension with rates

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

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

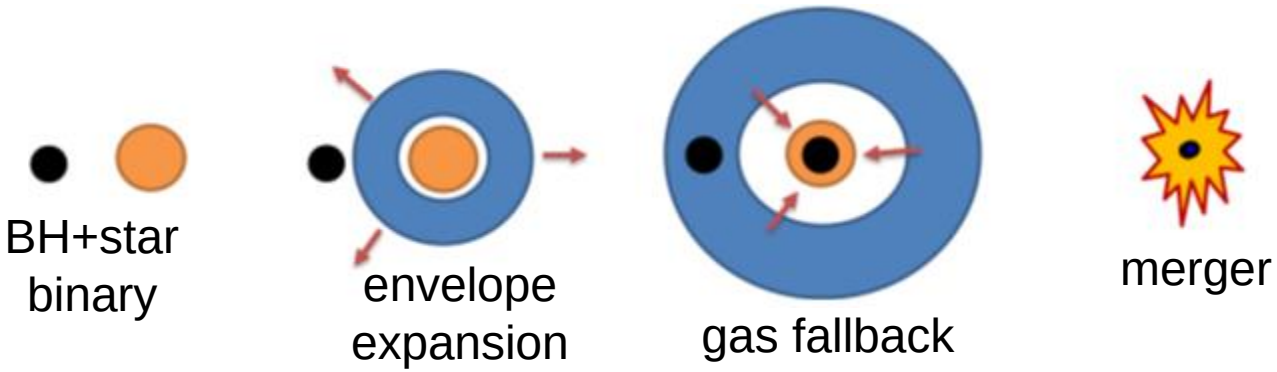
All theories have trouble to explain the observed sources!

possible ways forward

I.

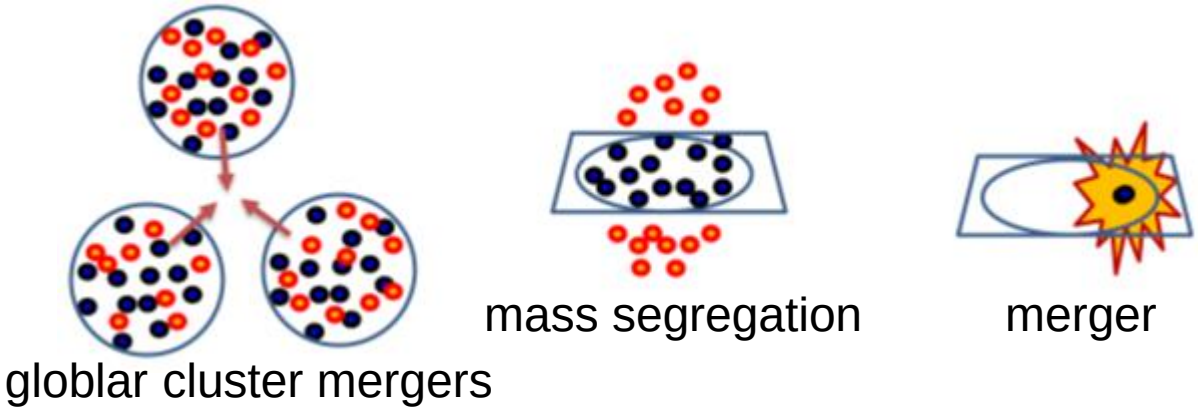
New ideas

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

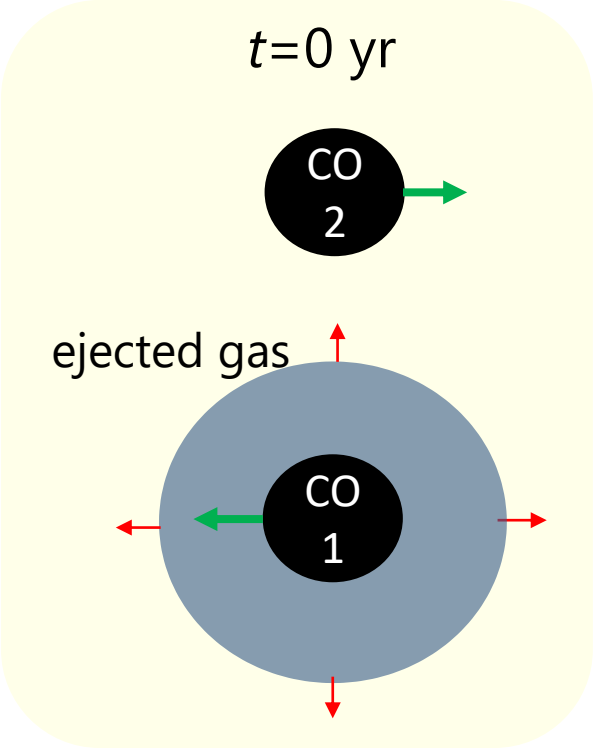


2. Disrupted globular clusters (Fragione & Kocsis, PRL 2018)

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

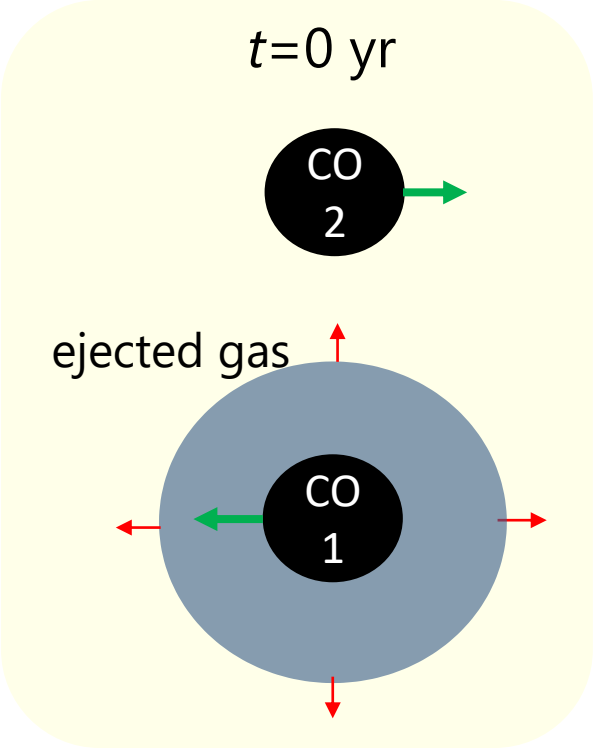


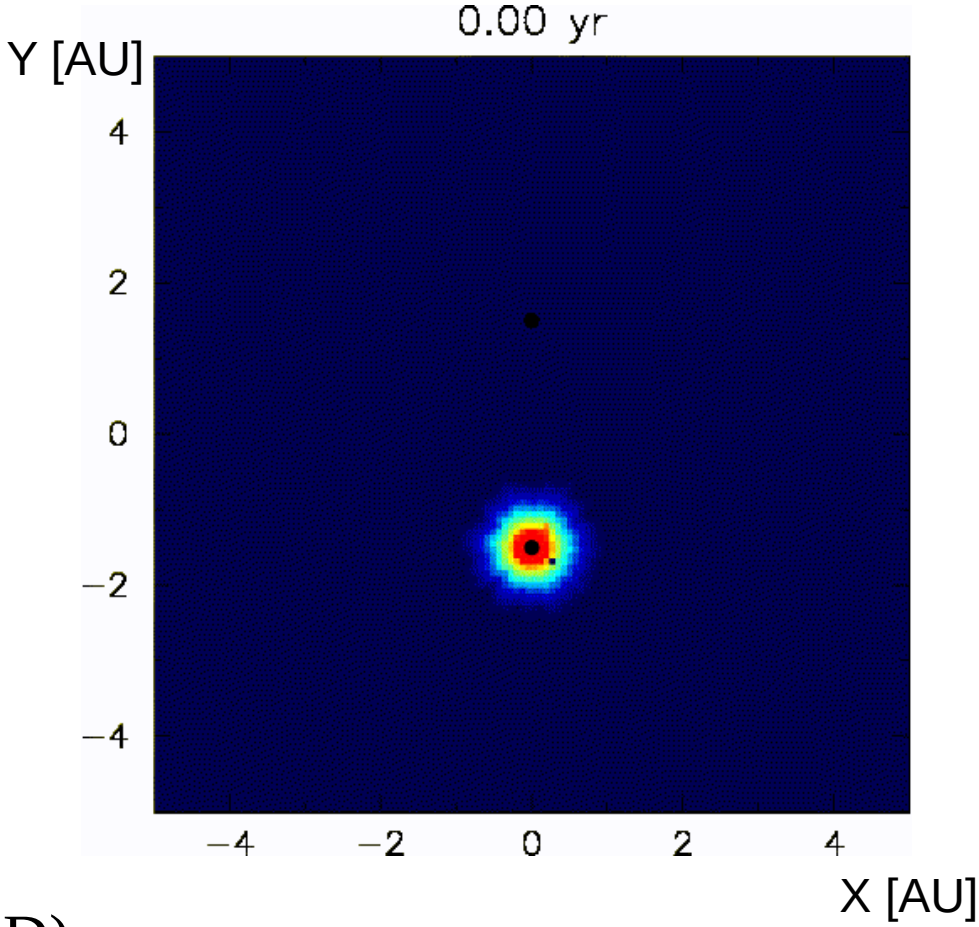
Fallback driven merger



Tagawa, Kocsis, Saitoh, 2018, PRL

Fallback driven merger



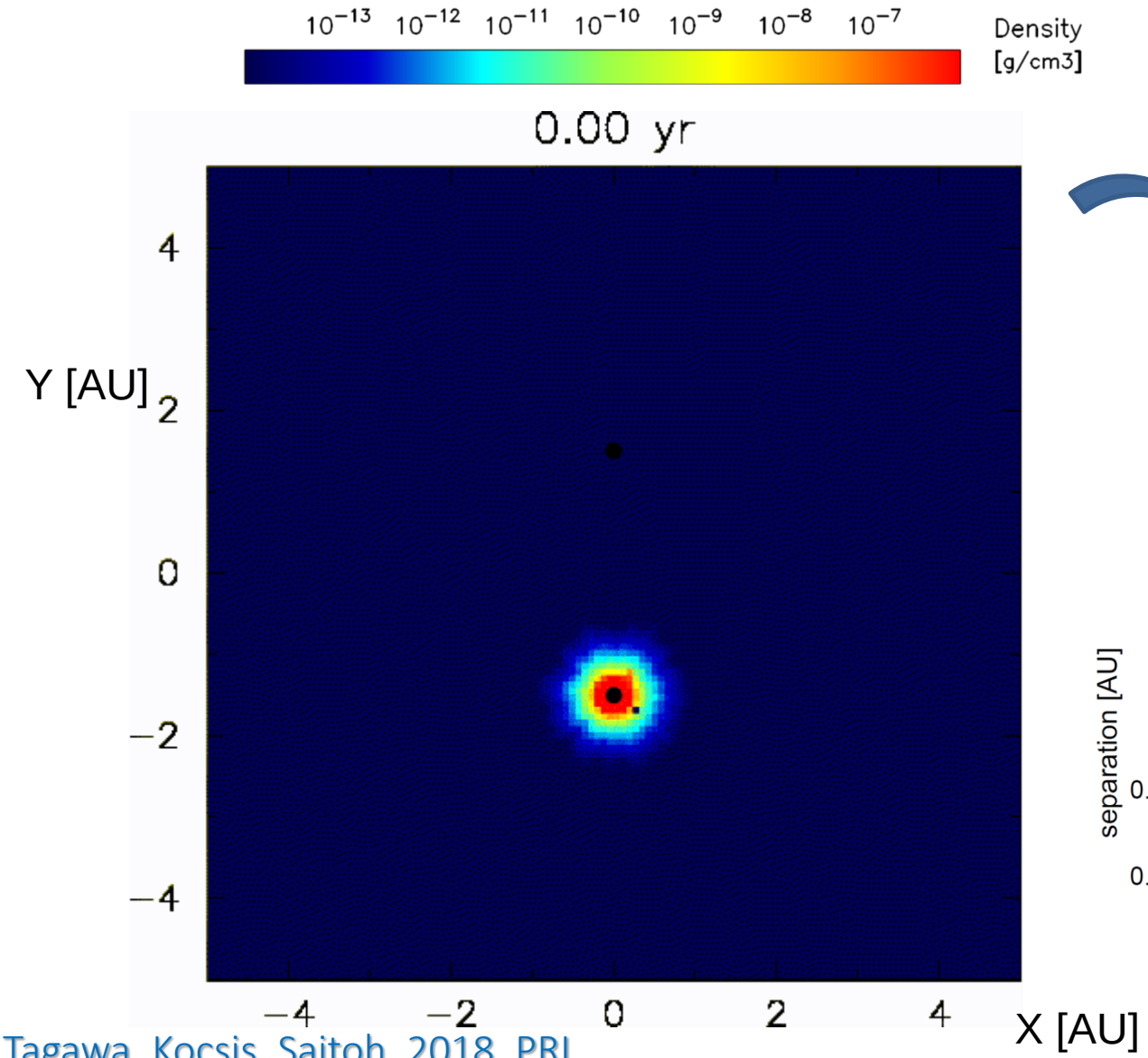


N-body/SPH simulation (3D)
Ideal gas EOS
$v(r)=v_{\max}\ r/r_{\max}$

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

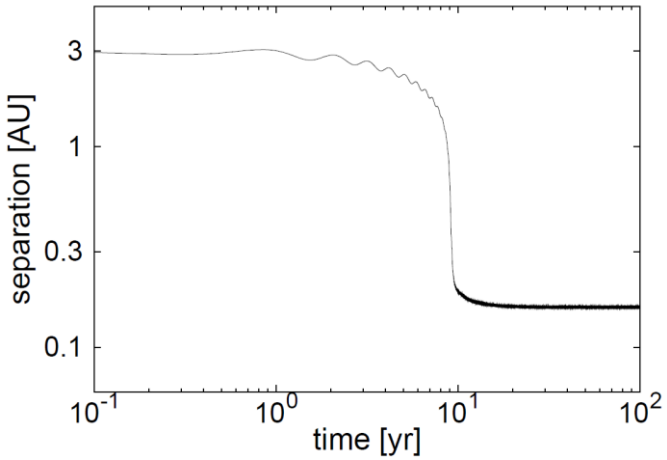
Tagawa, Saitoh, Kocsis 2018, PRL

Fallback driven merger



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

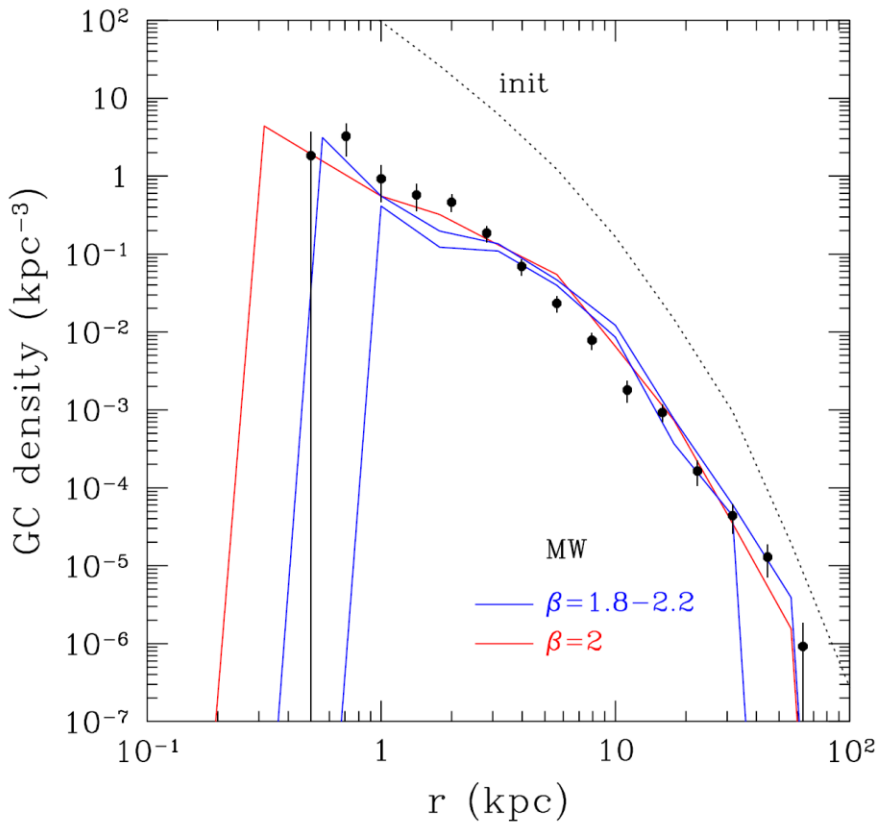
rotating clockwise

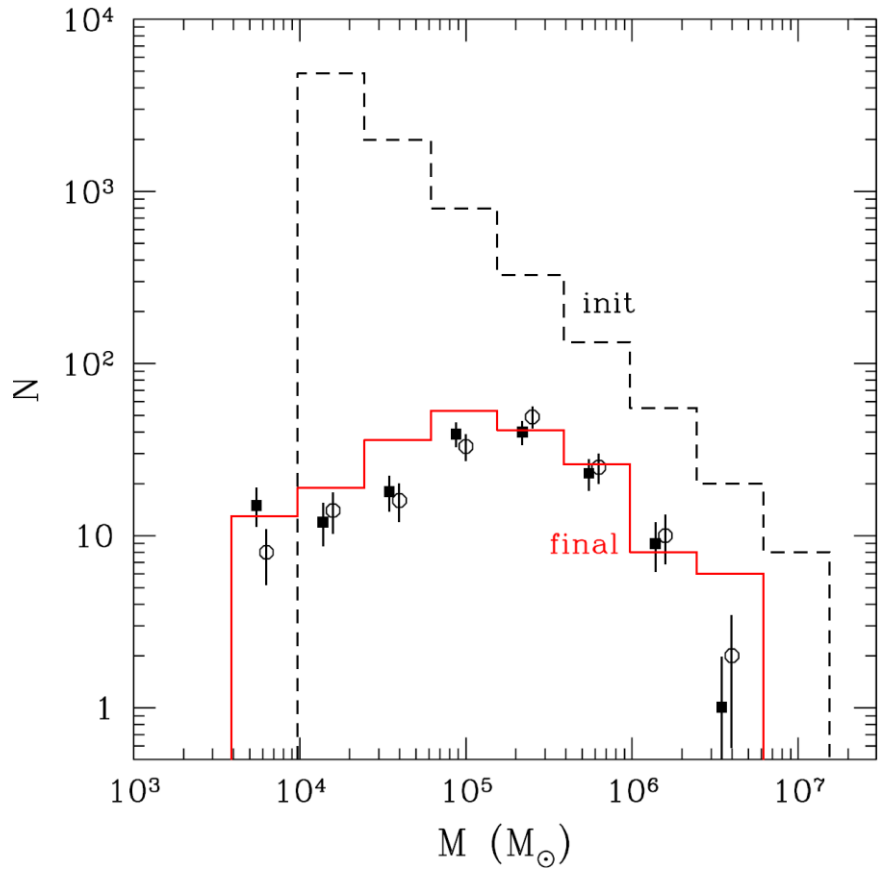


Tagawa, Kocsis, Saitoh, 2018, PRL

Disrupted globular clusters

- Globular clusters were much more numerous in the past

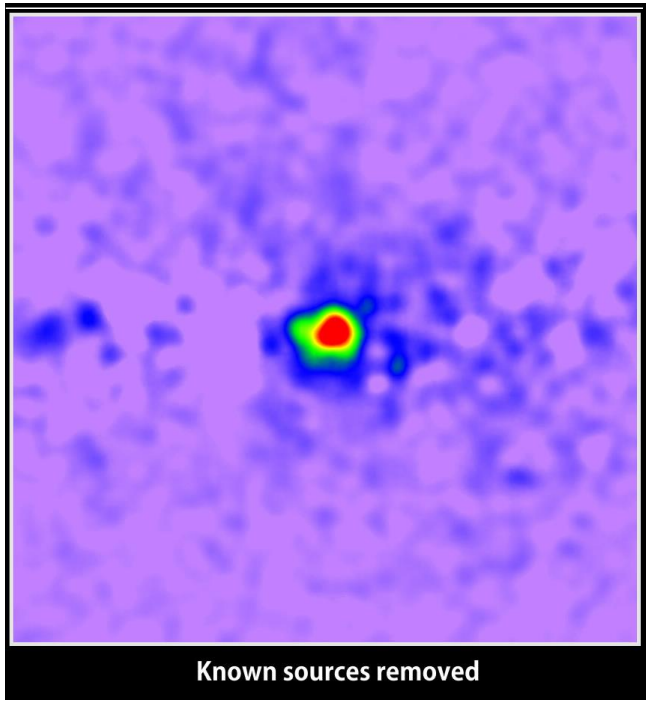


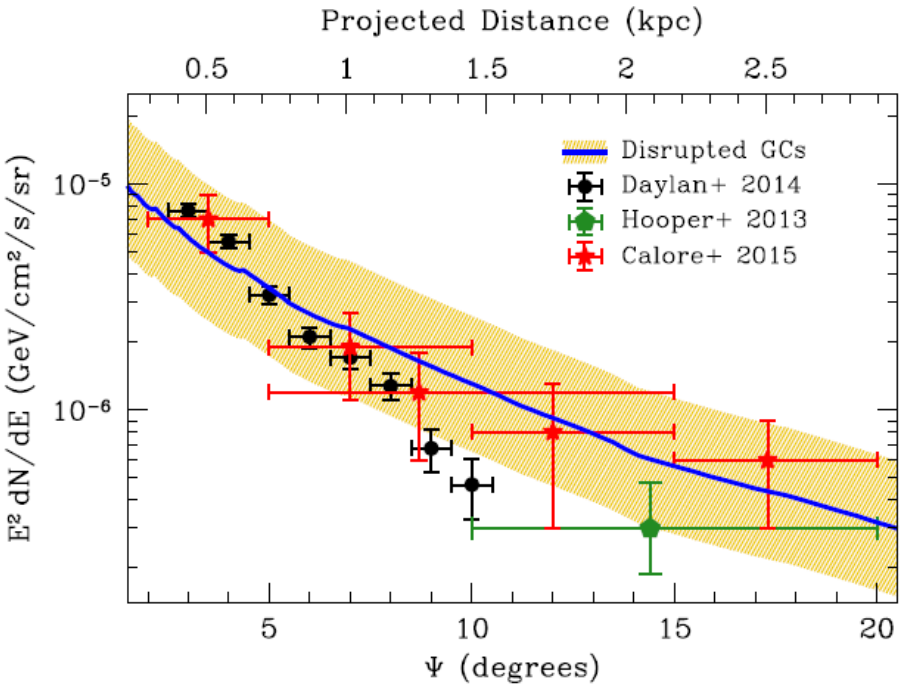


Gnedin, Ostriker, Tremaine (2014)

Disrupted globular clusters

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



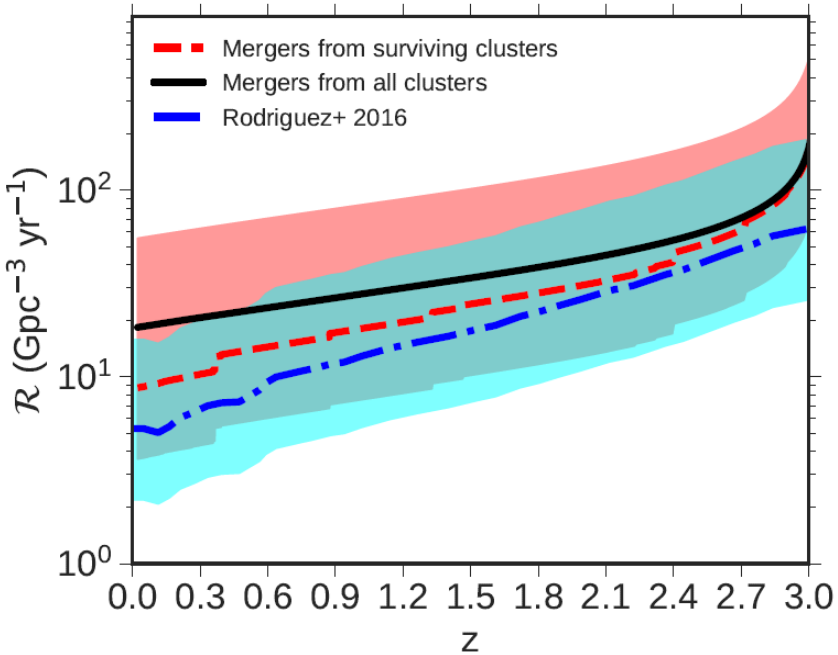


Brandt, Kocsis (2015)

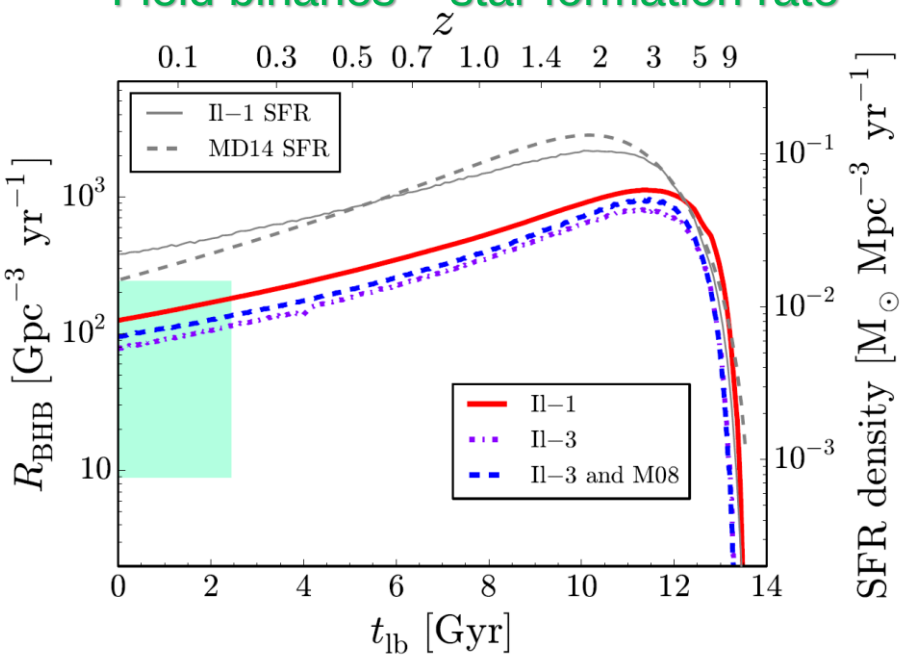
Disrupted globular clusters

- Implications for LIGO
  - Higher rates from disrupted globular clusters

Globular clusters



Field binaries – star formation rate

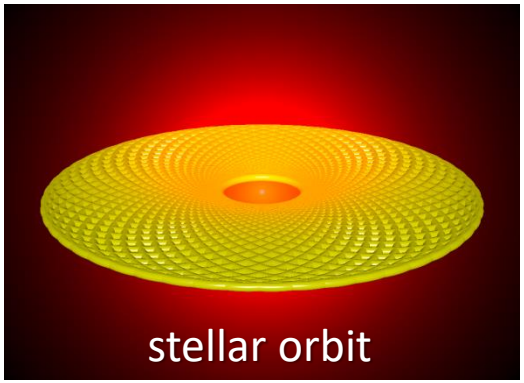


Fragione, Kocsis (2018) PRL

Black hole disks

Motion of stars in the galactic disk:

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



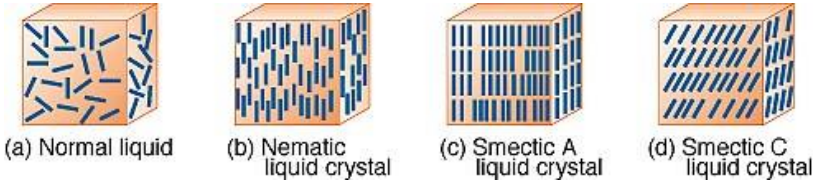
Orbital planes reorient and relax very quickly

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

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

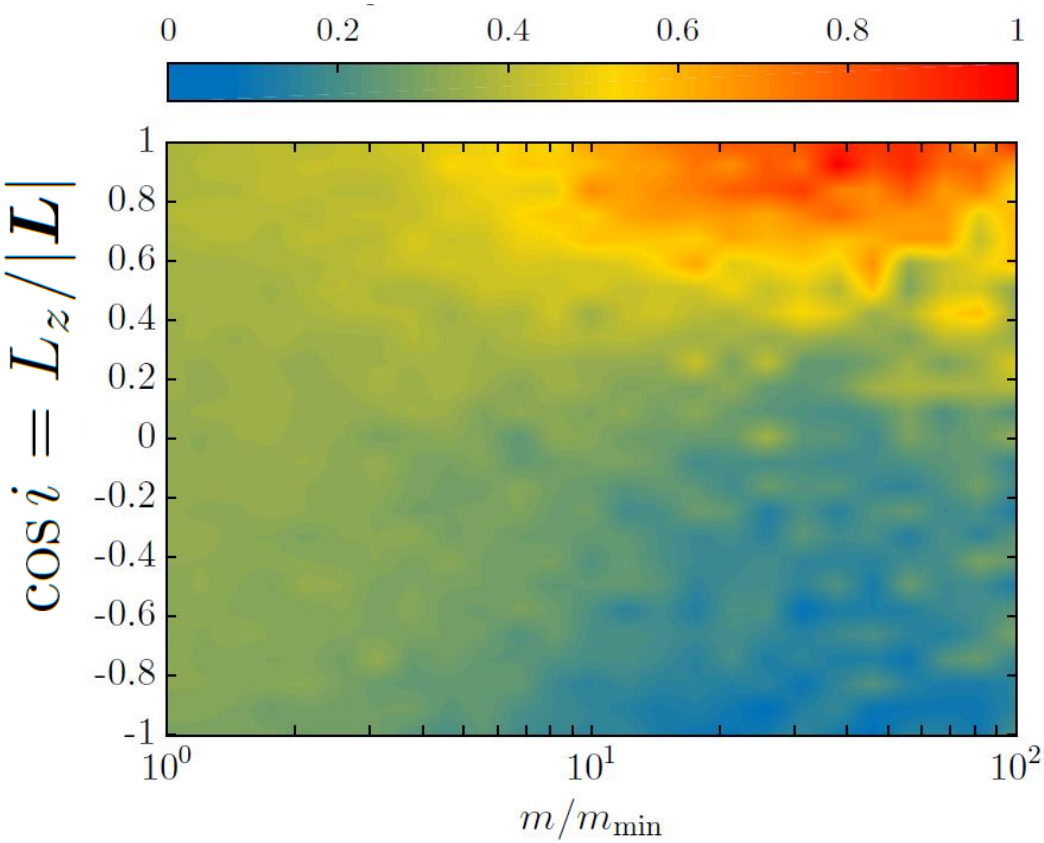
Maximum entropy:

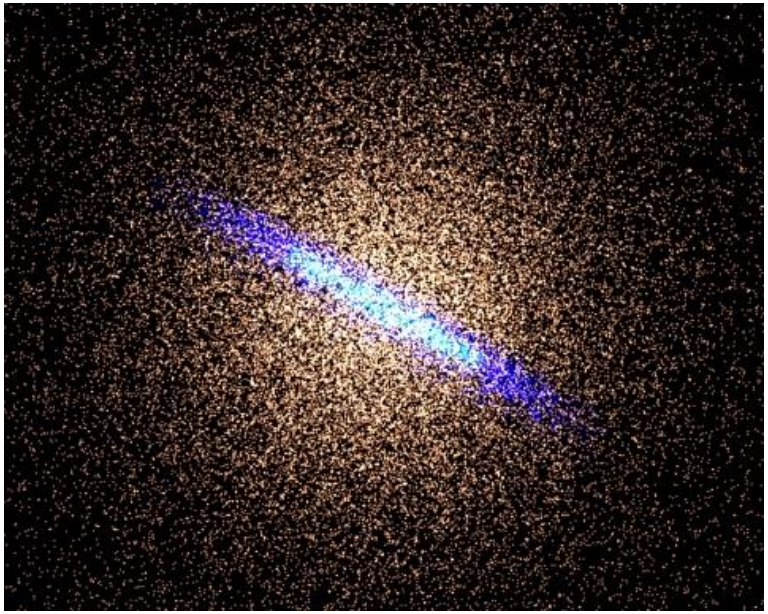
- massive objects: ordered phase
- light objects: spherical phase
- Implication: Black hole disks !



Black hole disks in galactic nuclei

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

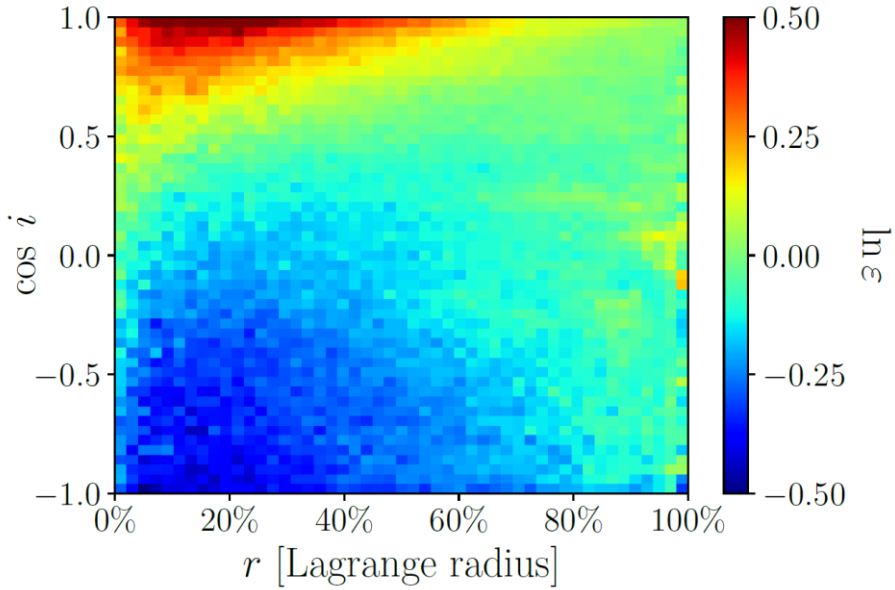




Szolgyen, Kocsis PRL 2018

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



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

Szolgyen, Meiron, Kocsis 2019

possible ways forward
II.
distinguishing sources

from different channels

– eccentricity, mass, spin distribution

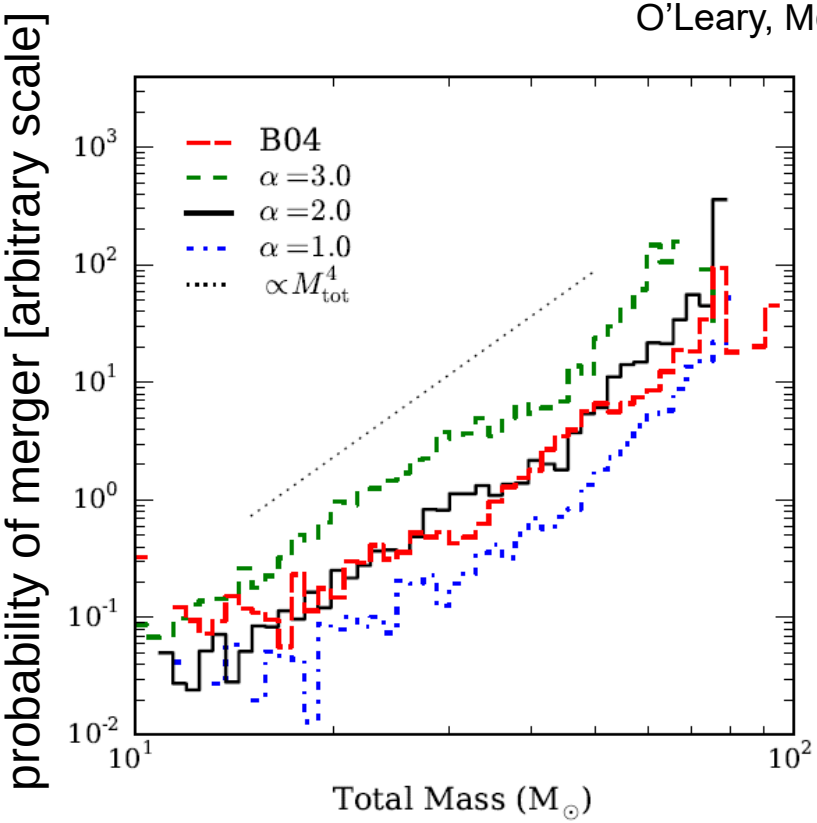
– electromagnetic counterparts

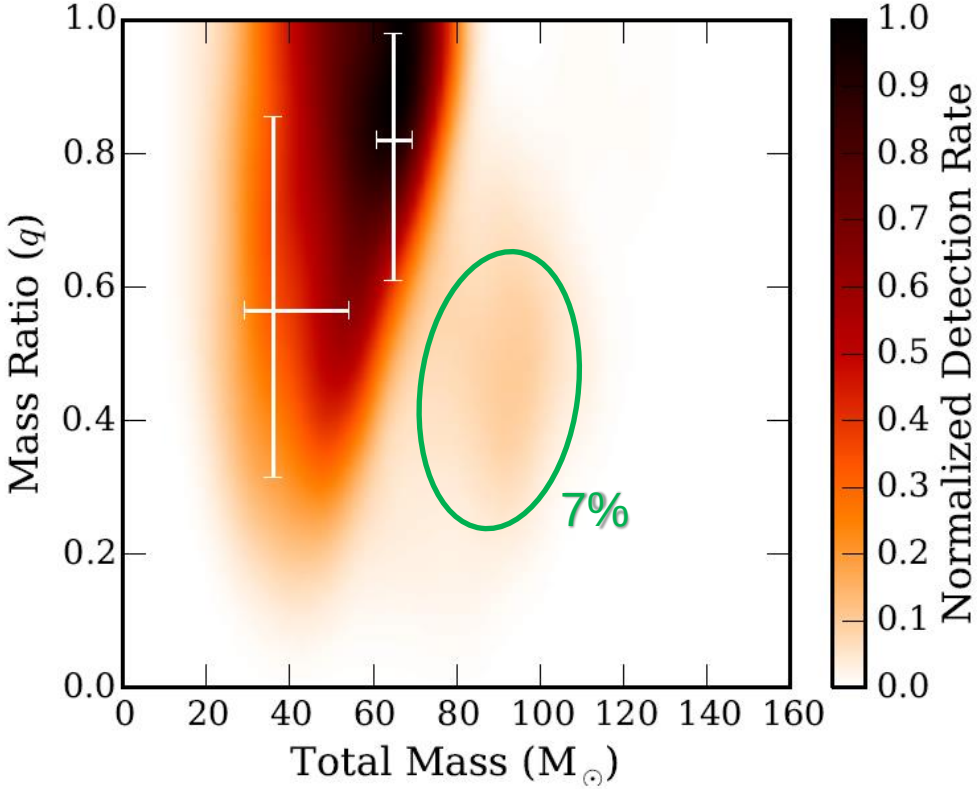
– intermediate mass black holes

Mass distribution for 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

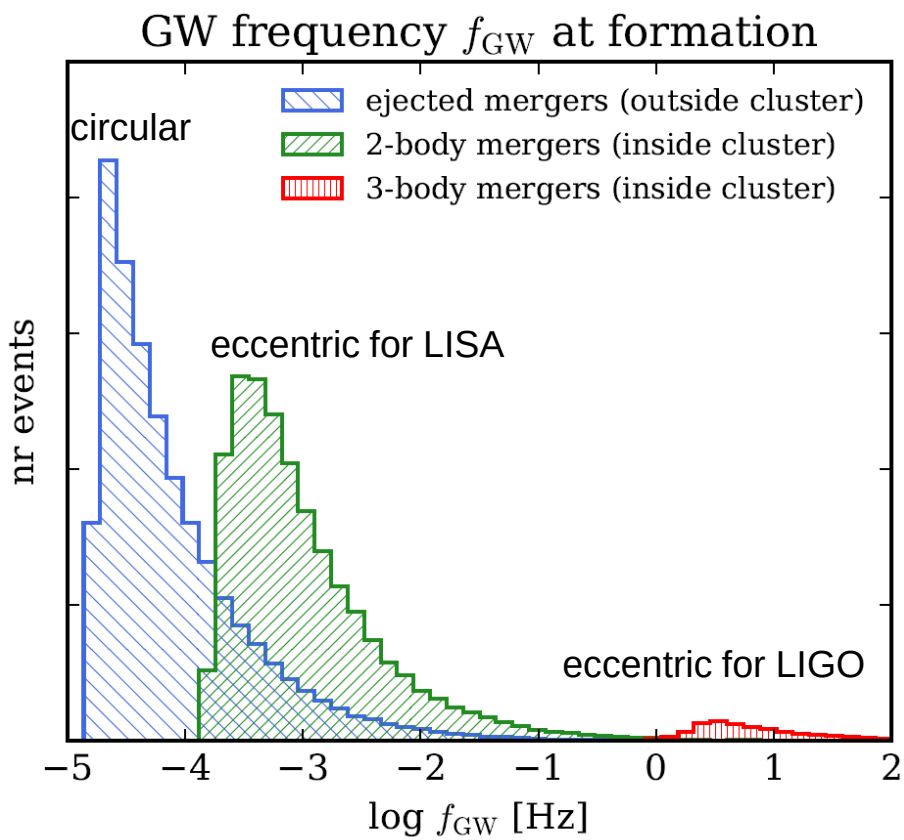
O'Leary, Meiron, Kocsis 2016

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)	?

Alexander & Kocsis (2019)

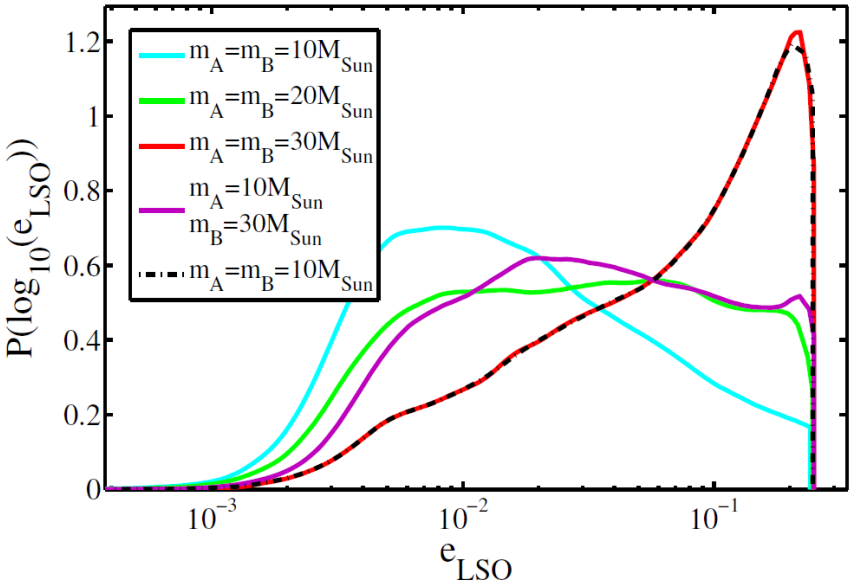
Eccentricity distribution
for merging globular cluster binaries



O'Leary, Kocsis, Loeb (2009); Samsing+ (2018a, 2018b); Takatsy, Bécsi, Raffai (2019);

Eccentricity – mass correlation for GW capture binaries

Heavy objects sink due to mass segregation and merge with higher eccentricity.



cf. measurement accuracy

$\Delta e_{LSO} \sim 10^{-2}$–$10^{-3}$

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

Gondán, Kocsis, Raffai, Frei (2018a); Gondan, Kocsis (2019)

Conclusions

- **Tension with black hole merger formation theories**
- **New ideas may be needed** to explain observed sources
  - fallback driven mergers ?
  - disrupted globular clusters ?
  - black hole disks?
- Discriminate LIGO sources using correlations among parameters
- **Eccentricity** measurable at design sensitivity
    - Delta e ~ 0.06