Electromagnetic counterparts for LISA +LIGO sources cont'd

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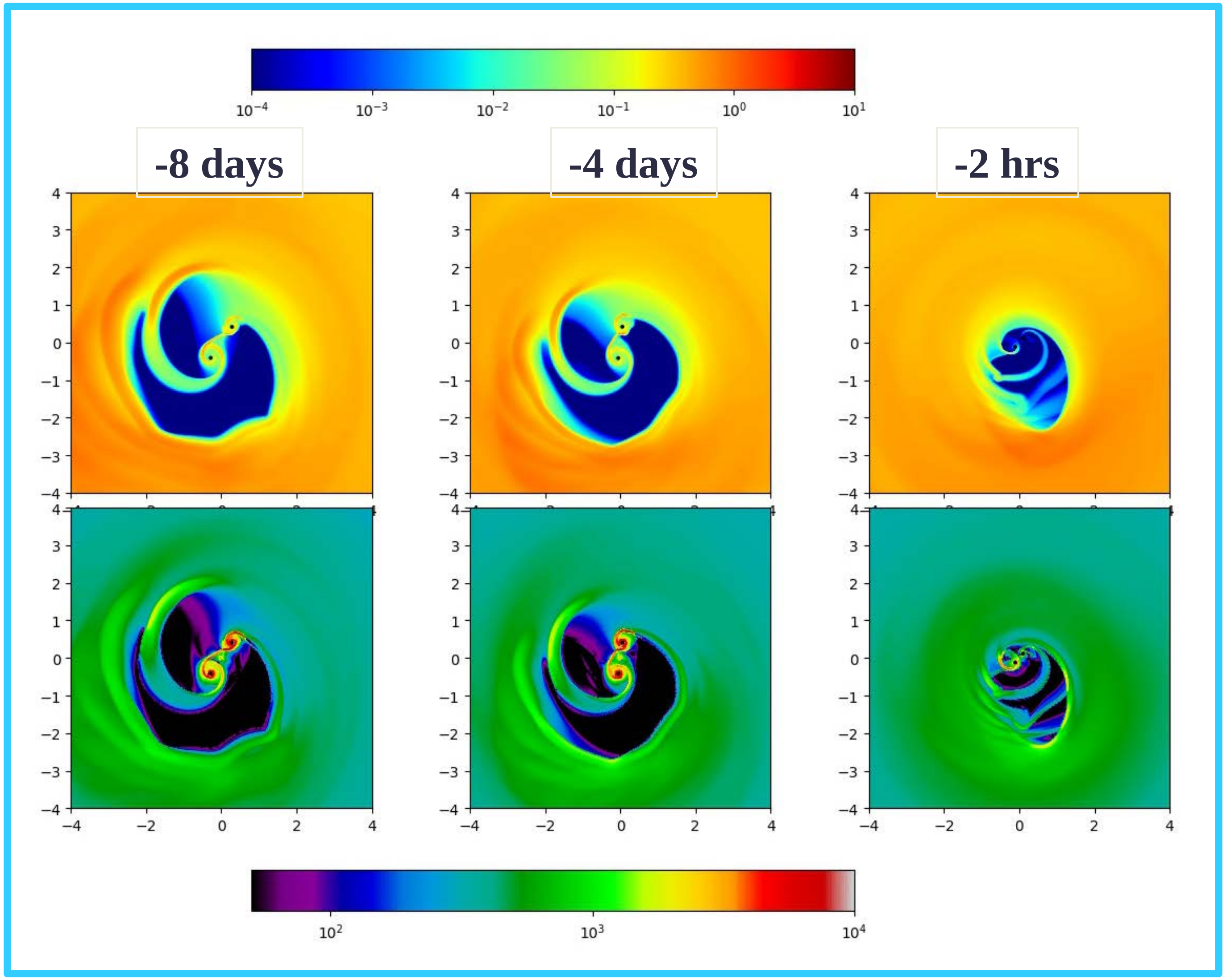
Scott Tremaine (IAS)

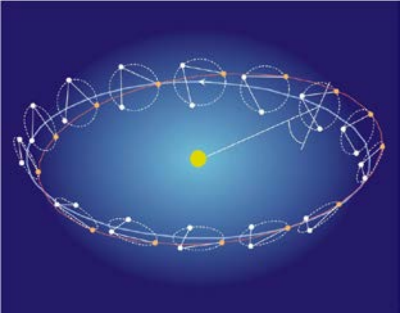
Harvard Sackler Conference: Gravitational Wave Astrophysics, Cambridge, May 9, 2018

EM counterparts for SMBH binaries

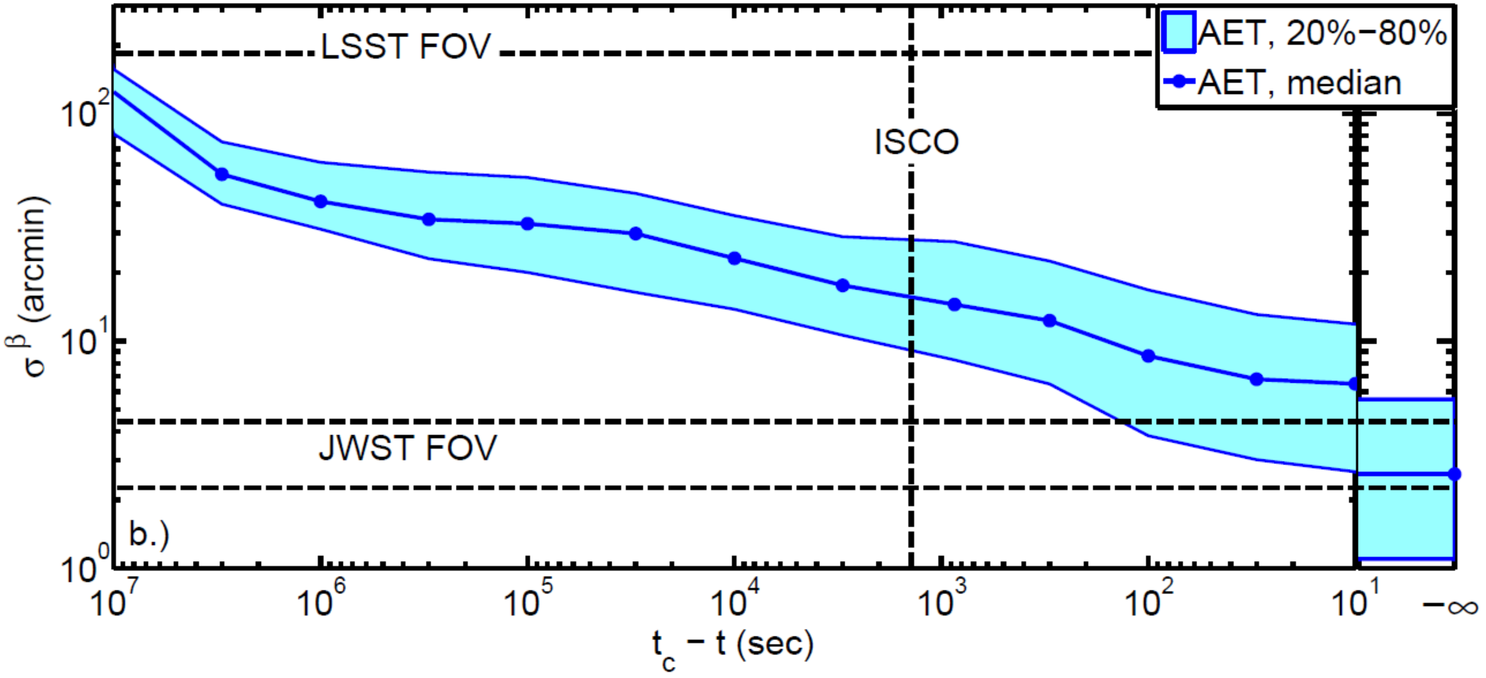
Zoltan Haiman 12:45 @ CFA/Phillips



Tang et al. 2018

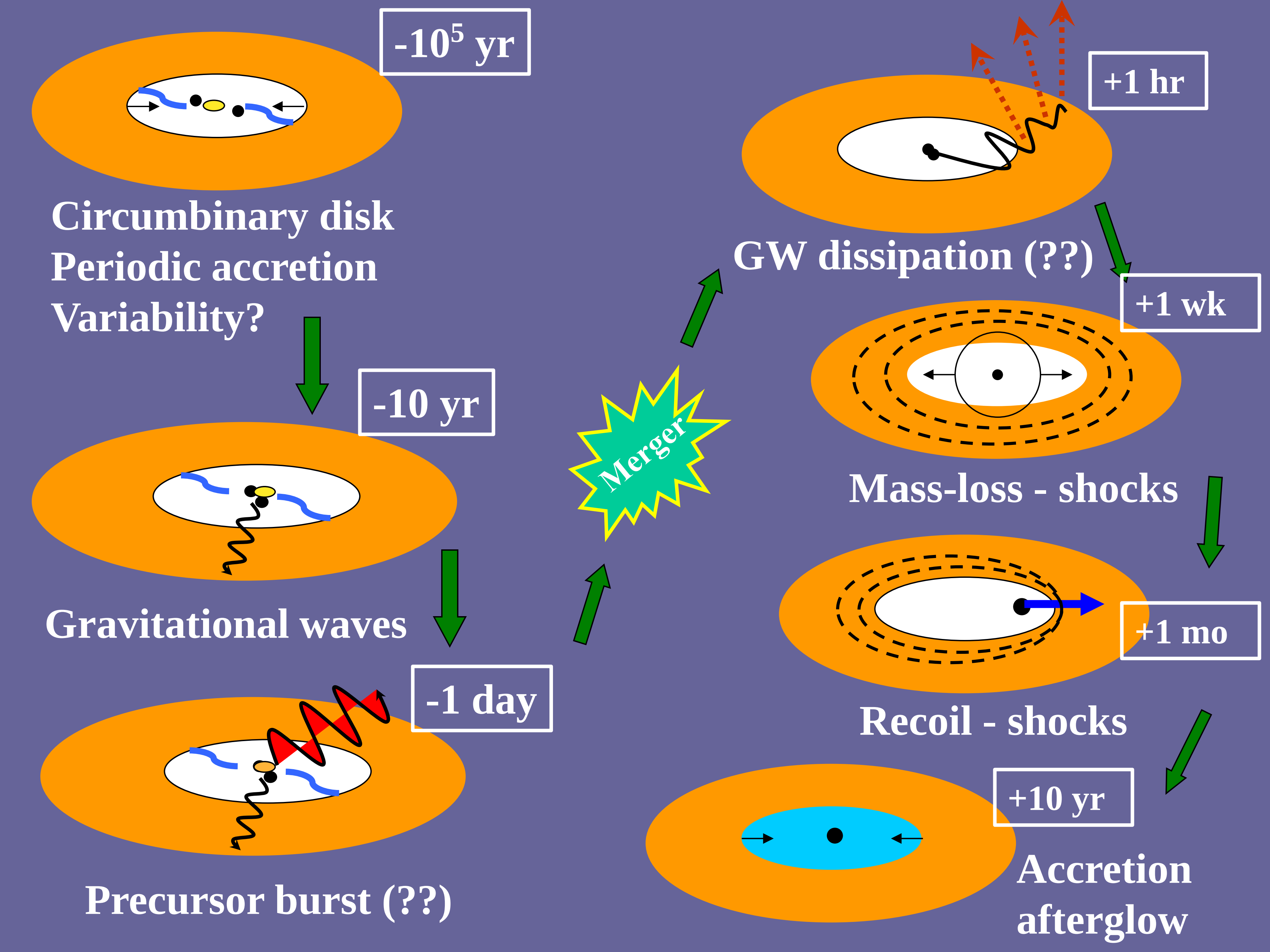


Localization before merger



Search this volume for variability (~24-27 mag)

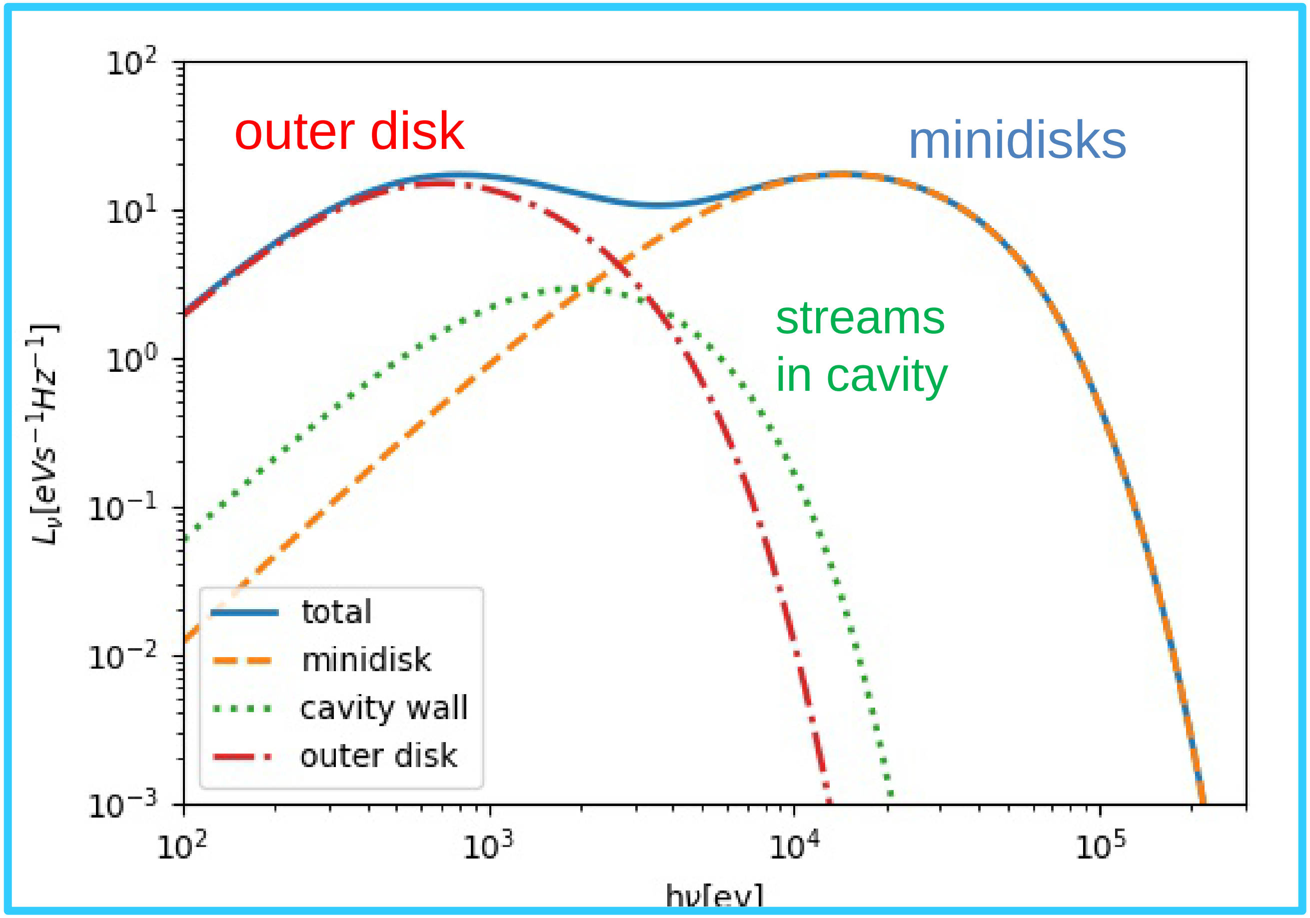
Kocsis+(2007,2008), Lang & Hughes (2008), McWilliams+ (2010,2011)



-10^5 yr
Circumbinary disk
Periodic accretion
Variability?
-10 yr
Gravitational waves
-1 day
Precursor burst (??)
Merger
+1 hr
GW dissipation (??)
+1 wk
Mass-loss - shocks
+1 mo
Recoil - shocks
+10 yr
Accretion
afterglow

Spectrum

Thermal emission extends to hard X-rays from inner regions around each BH



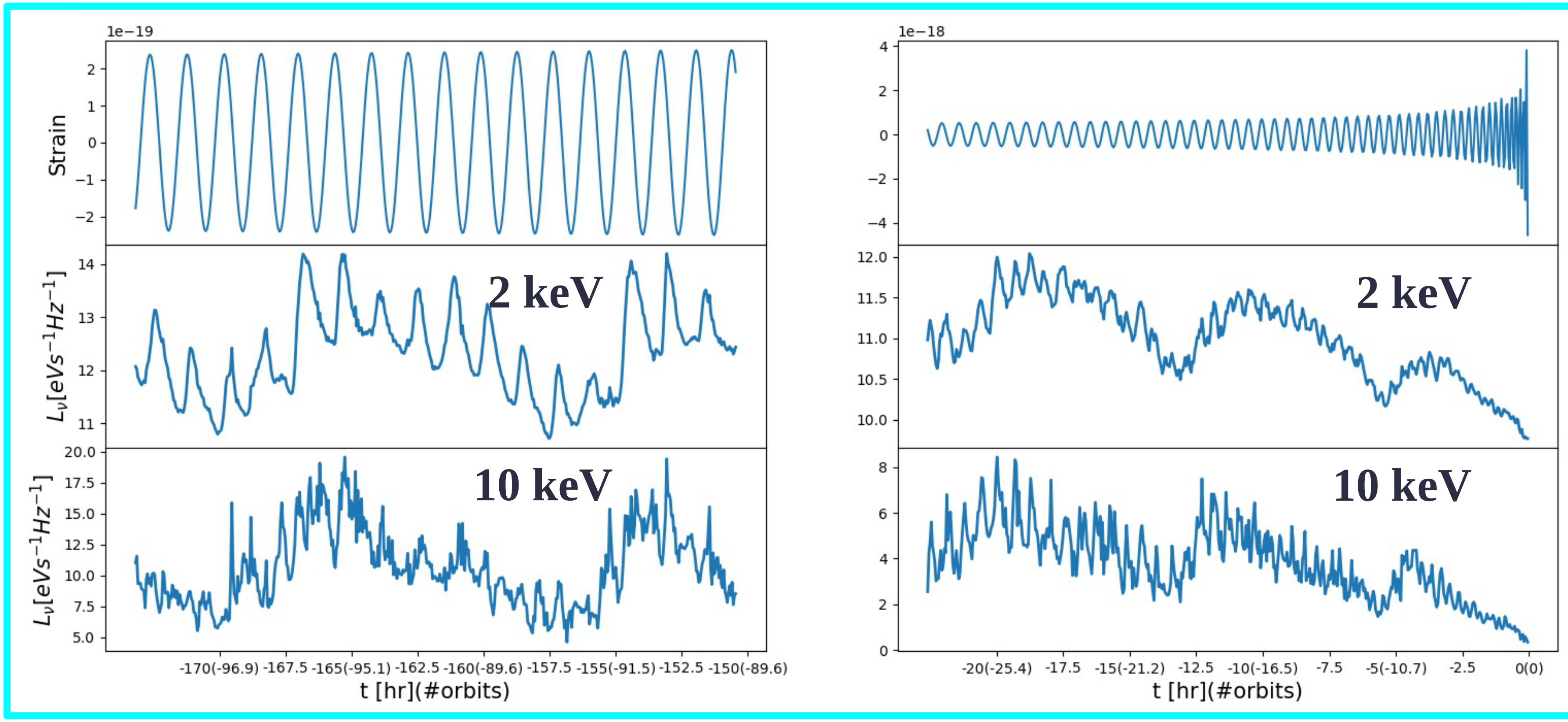
$q = M_2/M_1 = 1$

Tang et al. (2017)

Can GW-driven binaries shine ?

$q = M_2/M_1 = 1$

strong accretion all the way to merger: binary remains luminous & periodic

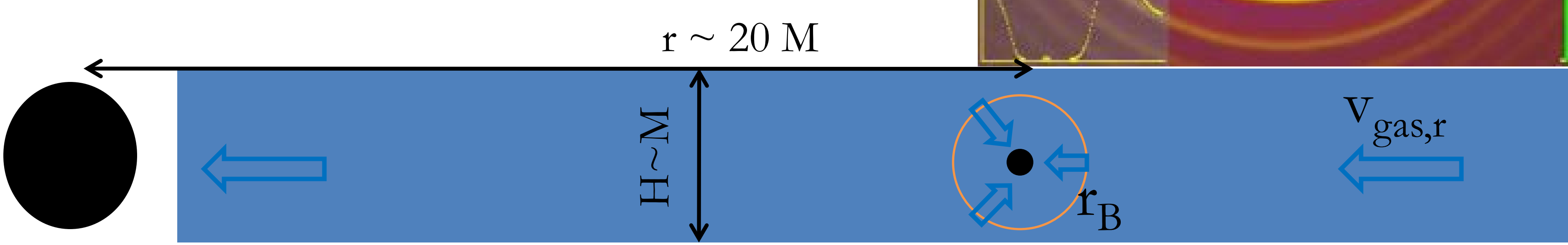


LAST 7 DAYS **LAST 1 DAY**

Tang et al. (2017)

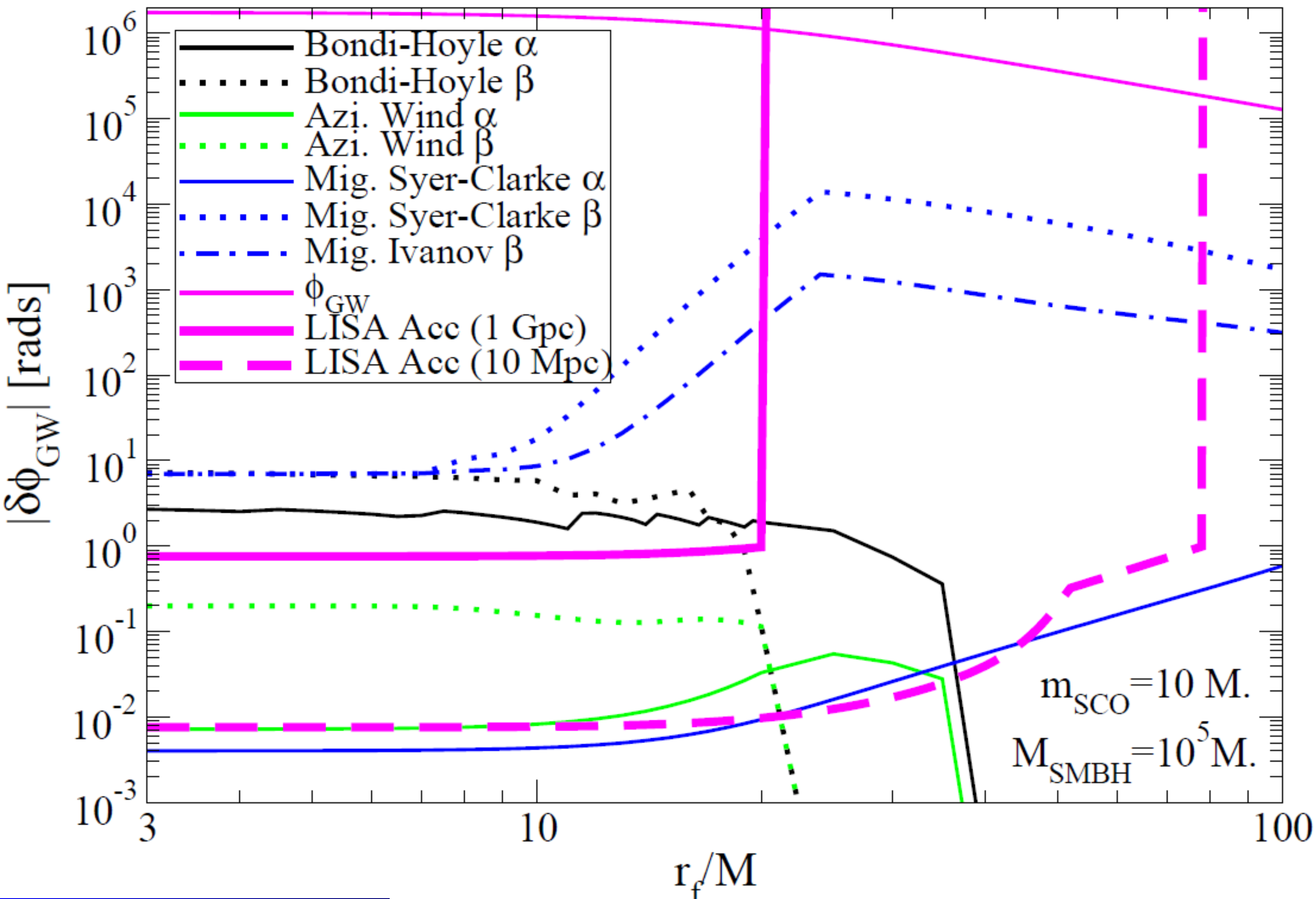
Effects on the GW signal

- Primary black hole mass increase
  - Limited by radiation pressure (Eddington limit)
- Secondary compact object mass increase
  - Spherical accretion (Bondi-Hoyle)
- Wind effects (hydrodynamic drag)
  - Primarily azimuthal
- Axisymmetric disk gravity
- Tidal torque
  - Spiral density wave
  - Gap opening
  - Migration

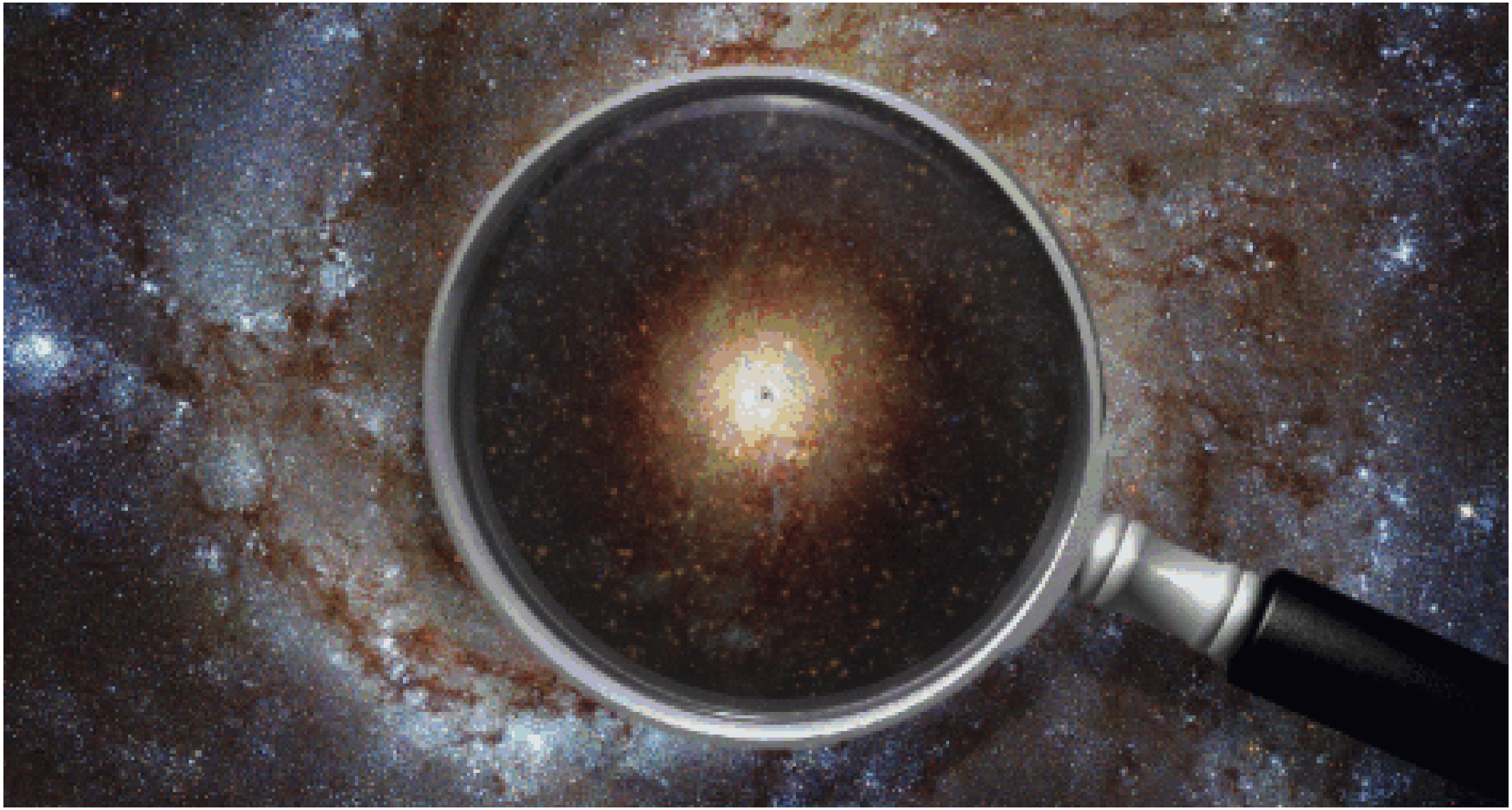


Yunes, Kocsis, Loeb, Haiman (2011); Kocsis, Yunes, Loeb (2011)

Effects on the GW signal



Kocsis, Yunes, Loeb (2011)



..now back to some puzzles about LIGO

Questions on rates

Observed value: 40 – 213 Gpc^{-3} yr^{-1}
(powerlaw mass distribution prior, Abbott+ 2017 PRL 221101)

- 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 < 30 Gpc^{-3} yr^{-1}**
    - 0.5% of stellar mass, $10^{5.5}$ stars with n ~ 0.8 Mpc^{-3}
  – **galactic nuclei: R < 25 Gpc^{-3} yr^{-1}**
    - 0.5% of stellar mass, 10^{7} stars with n ~ 0.02 Mpc^{-3}

Questions on rates

Observed value: 40 – 213 Gpc^{-3} yr^{-1}
(powerlaw mass distribution prior, Abbott+ 2017 PRL 221101)

- galactic field binaries: **final au problem, common envelope?**

  → talks by Ilya Mandel, Selma de Mink

- globular clusters: **low rates even if 100% of BHs merge?**

  → talk by Fred Rasio

- galactic nuclei: **low rates even if 100% of BHs merge?**

  → talk by Smadar Naoz

- galactic field triples: **not enough in the right configuration?**

  → Silsbee & Tremaine (2017), Antonini, Toonen, Hamers (2017)

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

  → Bird+ (2016), Sasaki+ (2016)

Option 5: Dark matter halo

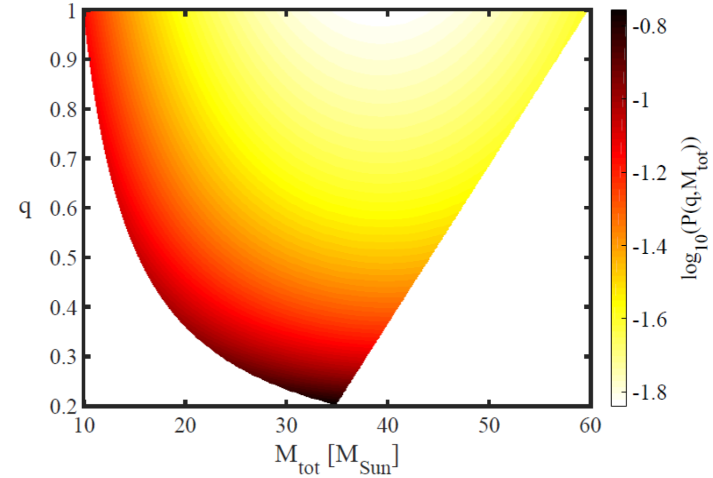
- 10x more mass than in stars
- 10^{10} primordial mass black holes?
- Rates match if
  - 100% of dark matter is in 30 Msun **single BHs** (Bird et al 2016)
    - **RULED OUT BY OBSERVATION OF a GLOBULAR CLUSTER IN A DWARF GALAXY (Brandt+17)**
  - 0.1% of dark matter is in primordial **binary BHs** after 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

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

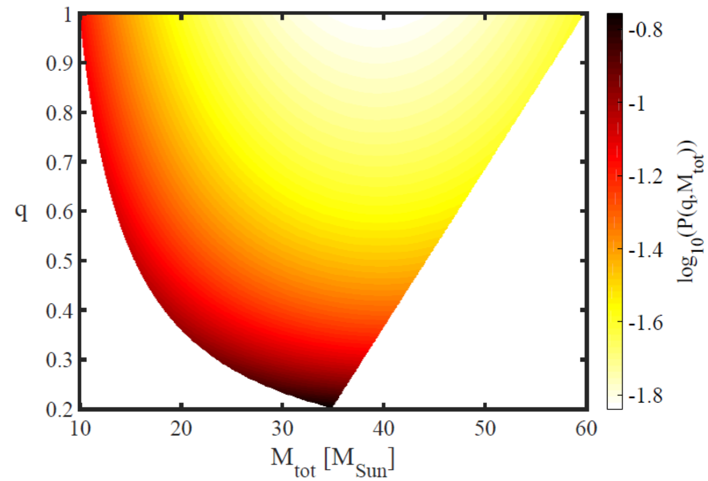
Mass distribution for different processes

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)?

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



$= \mathbf{4}$ 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

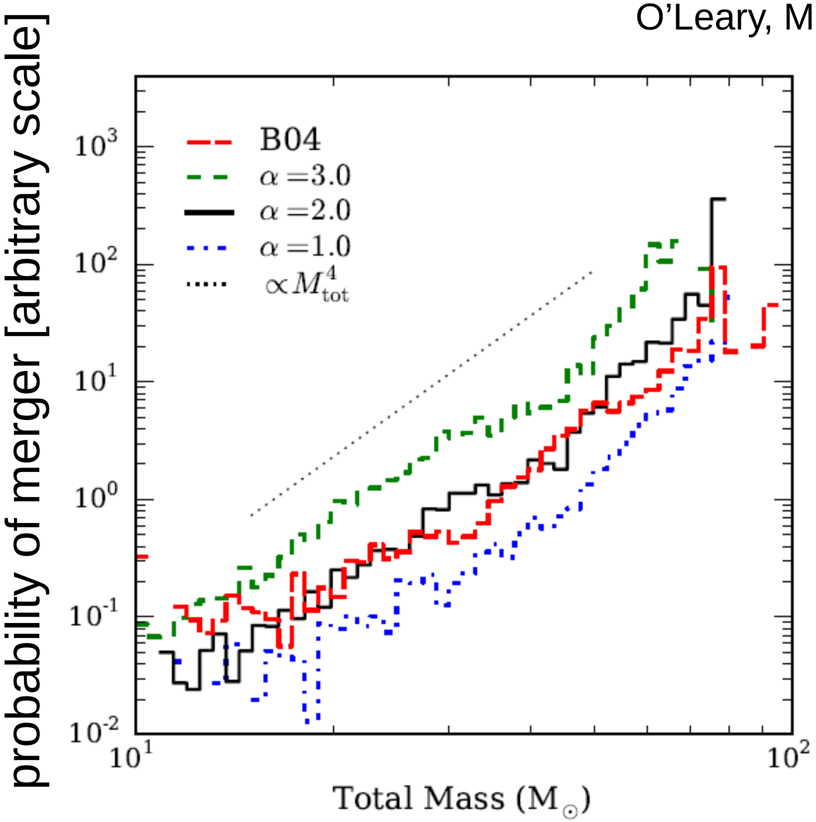
$= \mathbf{1}$ for PBH binaries formed in early universe

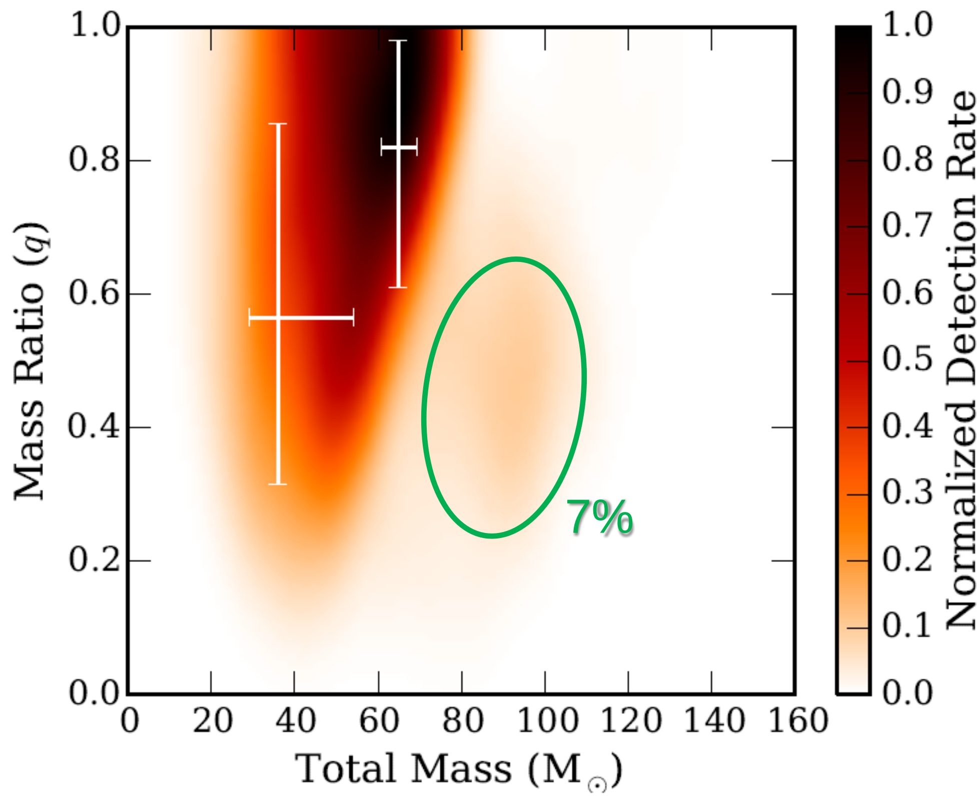
Kocsis, Suyama, Takahiro, Yokoyama 2018; Gondan, Kocsis, Raffai, Frei 2018

Mass distribution for globular clusters

Monte Carlo and Nbody simulations

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



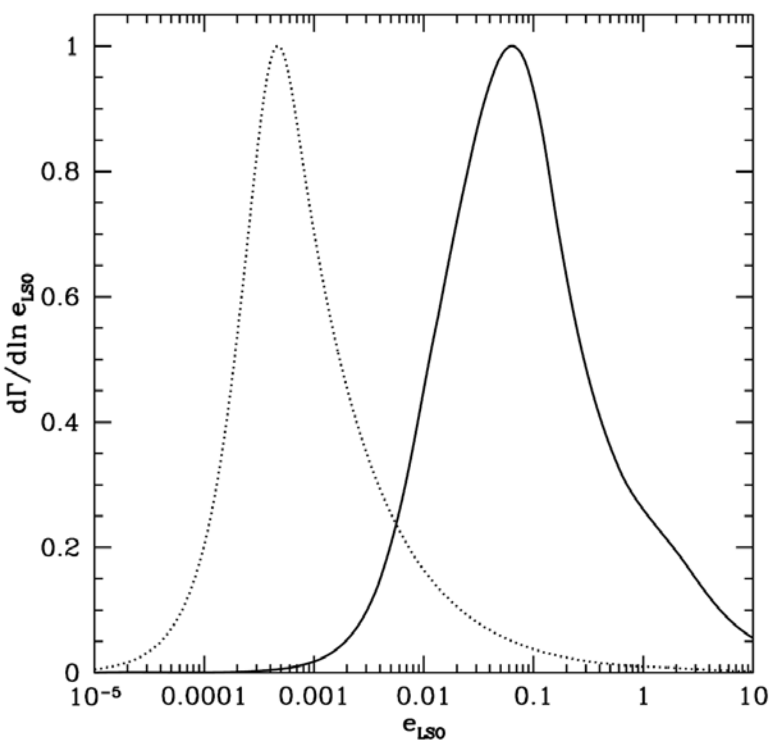


Robust statement (independent of IMF): heavy objects merge more often M^4

Eccentricity distribution
for GW capture binaries

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

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



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

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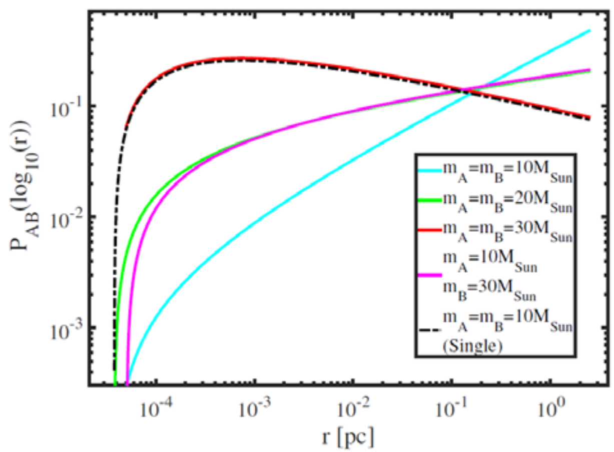
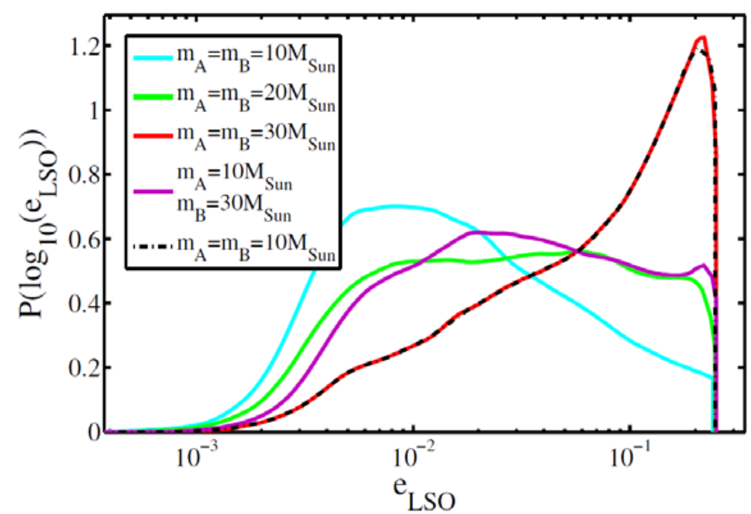


radial distribution of mergers
shows mass segregation



→ Eccentricity distribution
reveals mass segregation

Gondán, Kocsis, Raffai, Frei (2018b)

Eccentricity distribution for GW capture binaries

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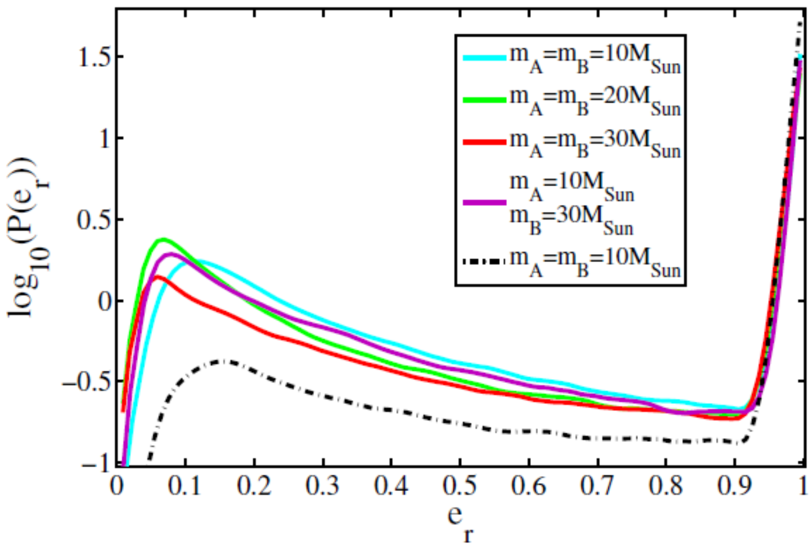
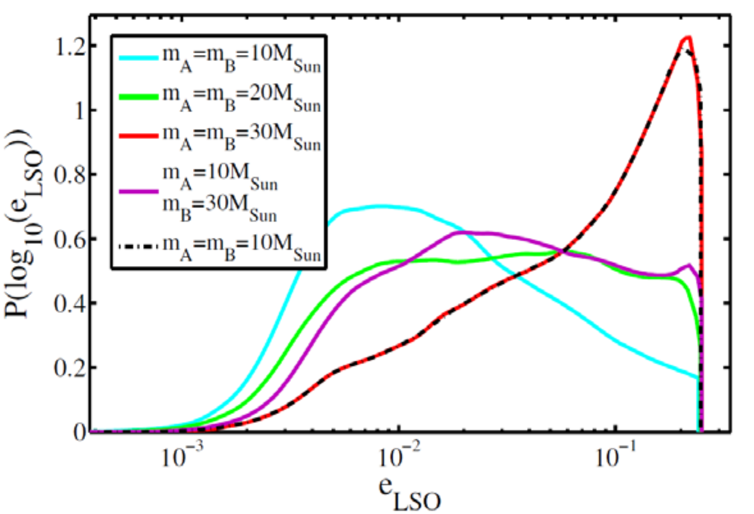


Eccentricty distribution when ALIGO first sees it (design sensitivity)



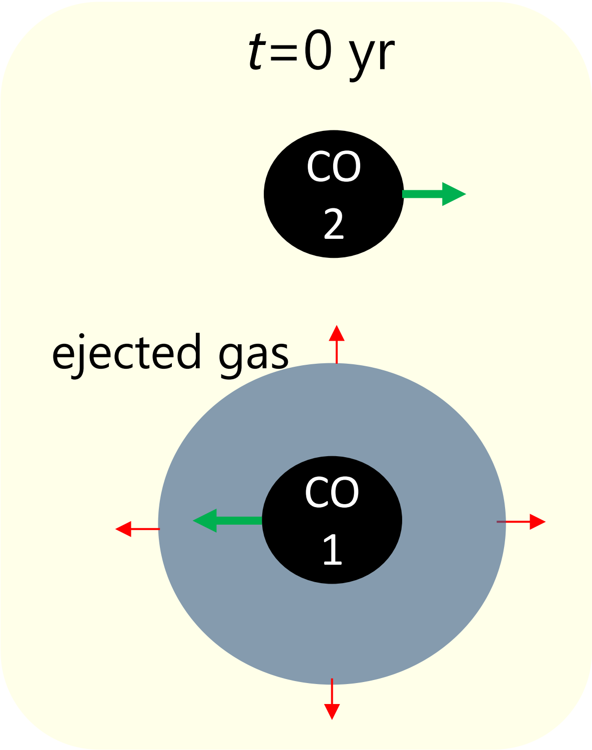
→ Eccentricity distribution reveals mass segregation

cf. measurement accuracy $\Delta e_{LSO} \sim 10^{-2}$–$10^{-3}$
$30M_{Sun}+30M_{Sun}$ @ 1Gpc

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

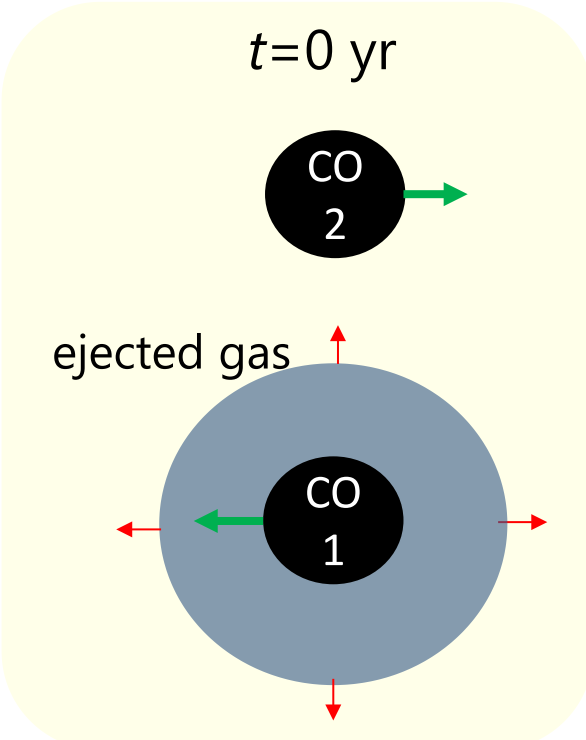
How else can BH binaries merge?

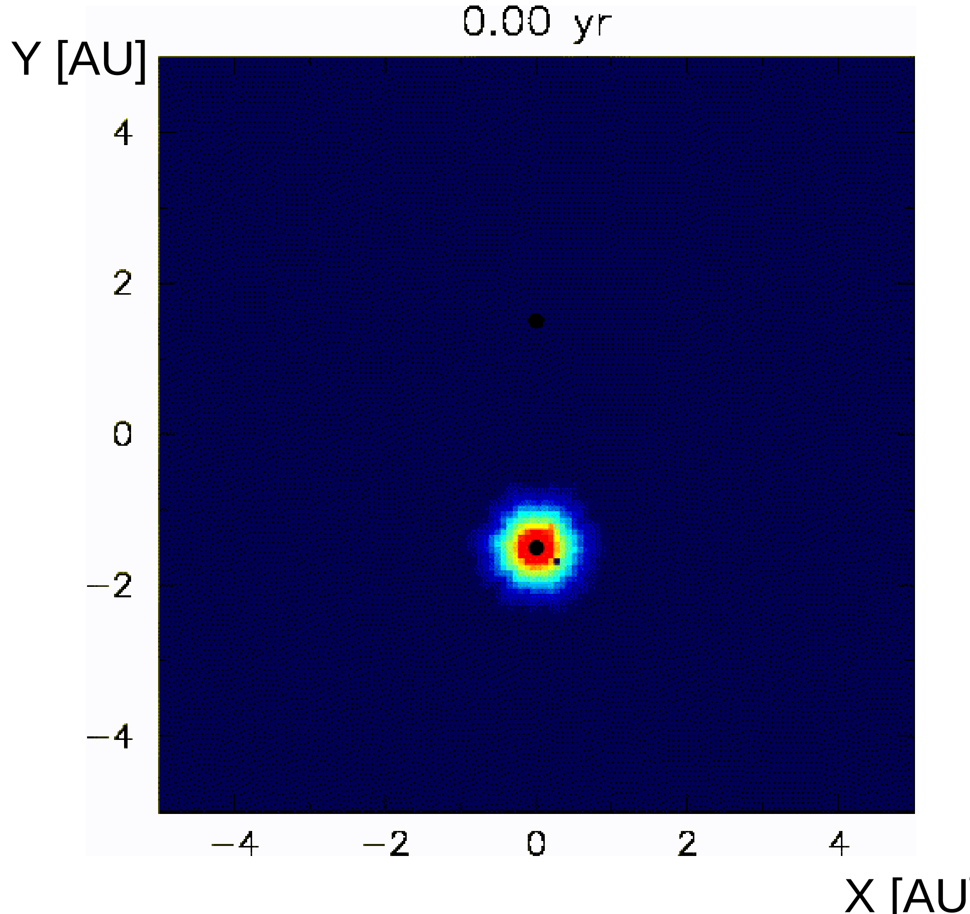
Fallback driven merger



Tagawa, Kocsis, Saitoh, 2018, PRL

Fallback driven merger





N-body/SPH simulation (3D)

Ideal gas EOS

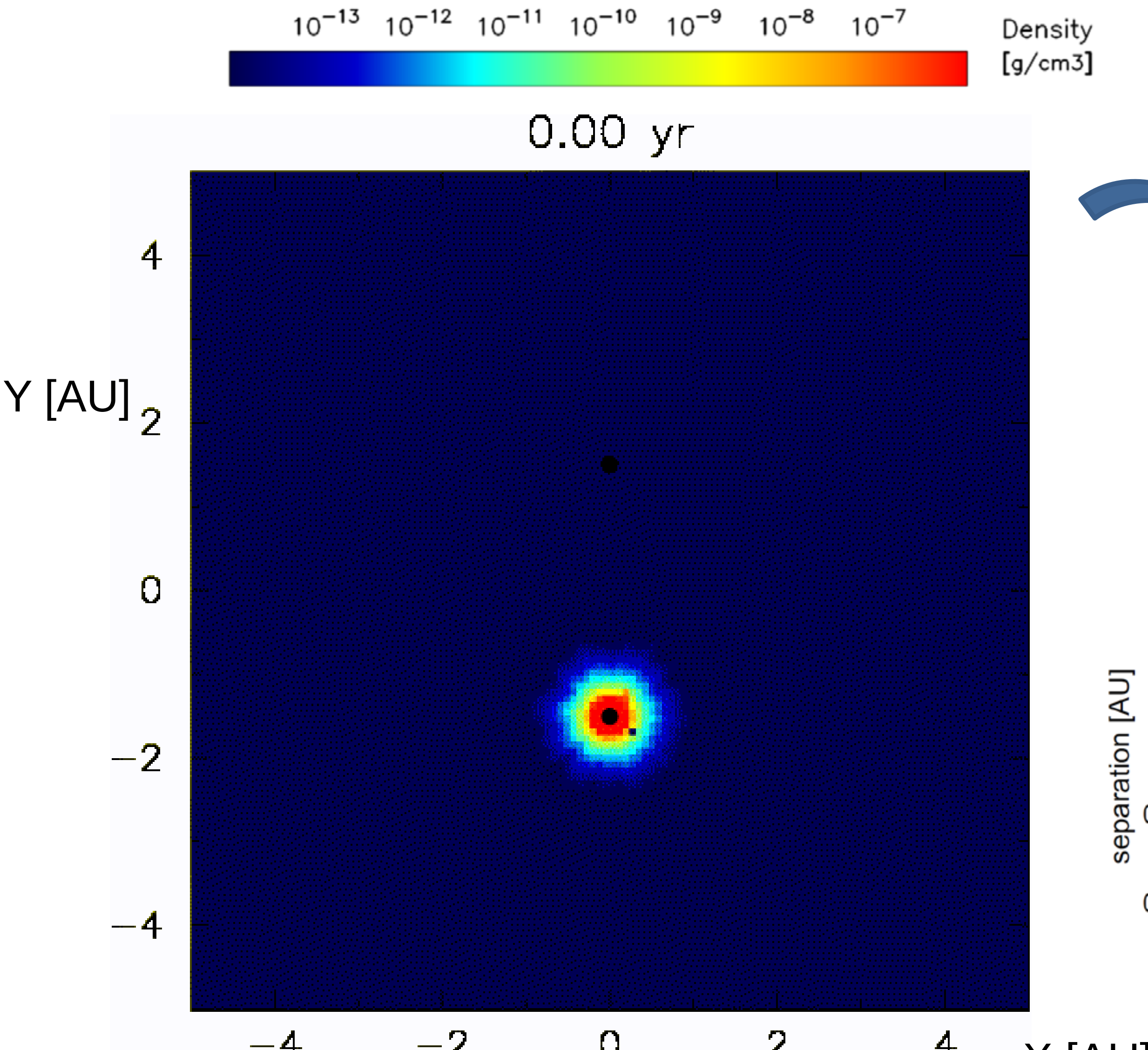
$v(r) = v_{max}\ r/r_{max}$

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

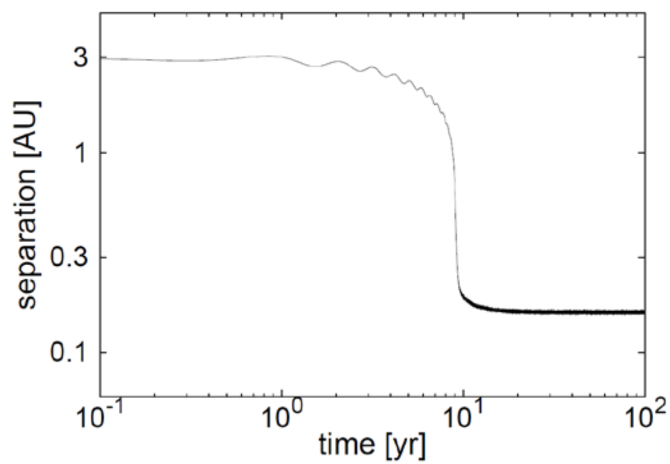
Tagawa, Kocsis, Saitoh, 2018, PRL

Fallback driven merger

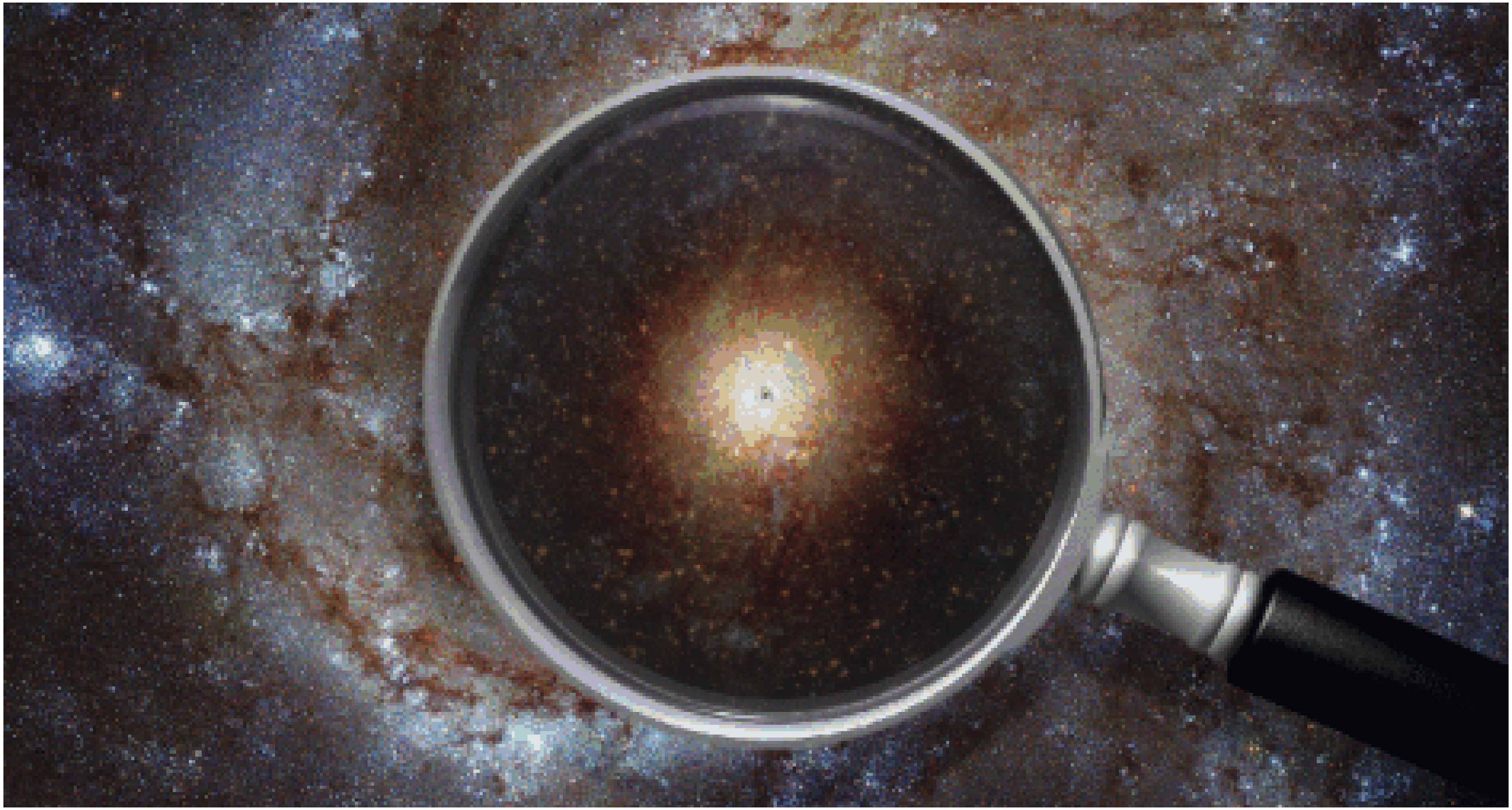
$M_{CO1}=M_{CO2}=5M_{\odot}$
$M_{gas,ini}=5.4M_{\odot}$



rotating clockwise

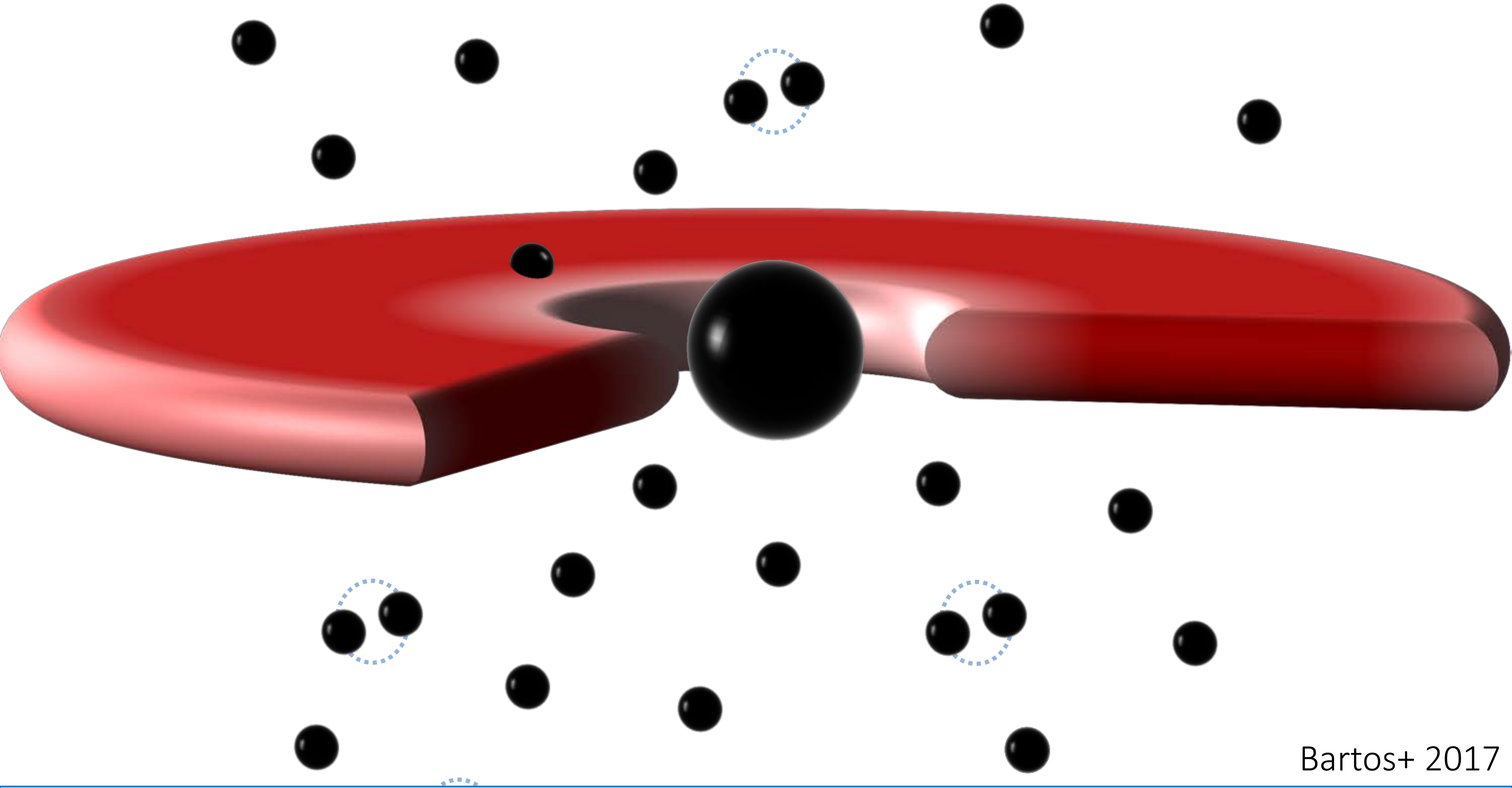


Tagawa, Kocsis, Saitoh, 2018, PRL



Mergers with EM counterparts

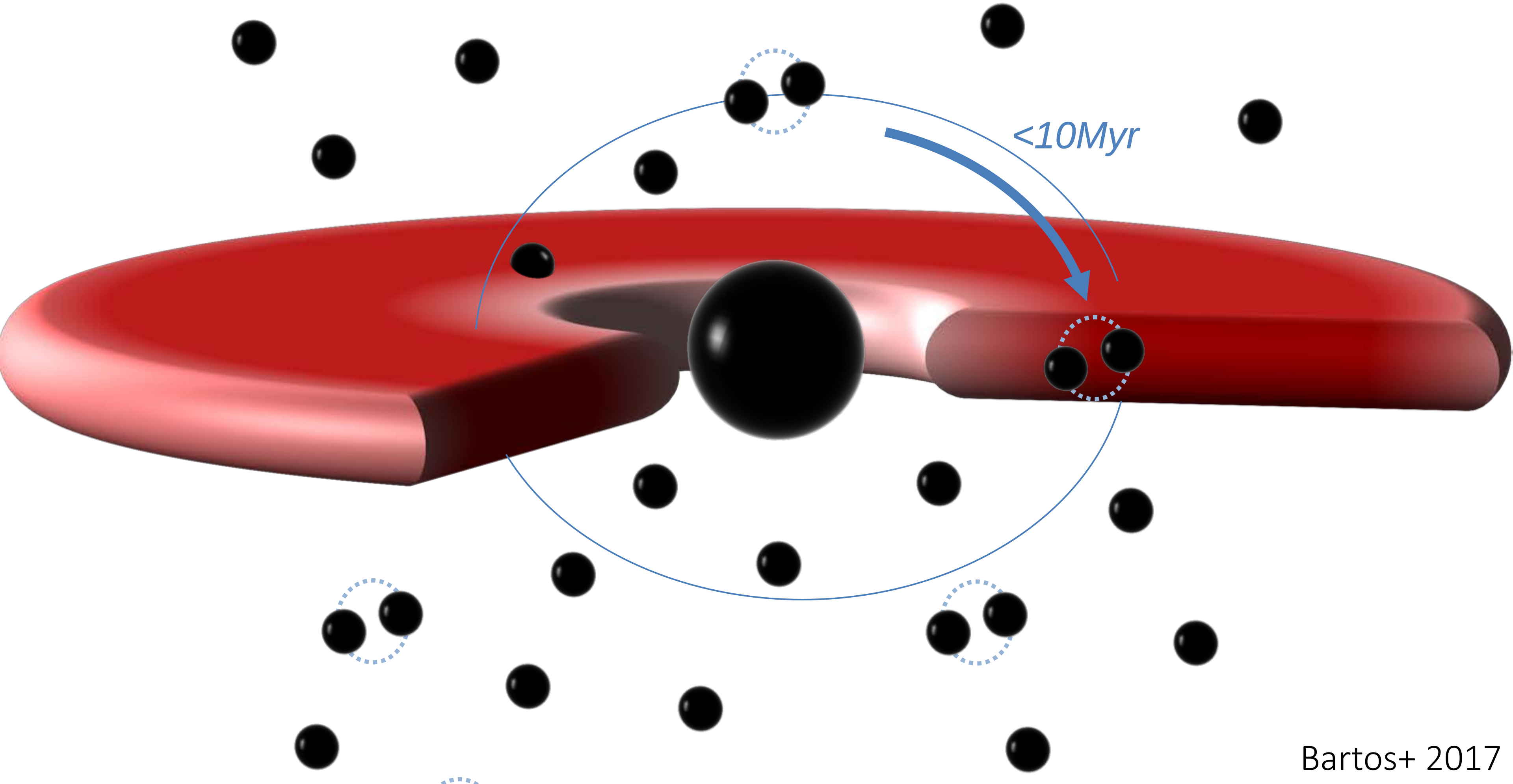
3. GW sources in active galactic nuclei



Bartos+ 2017

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

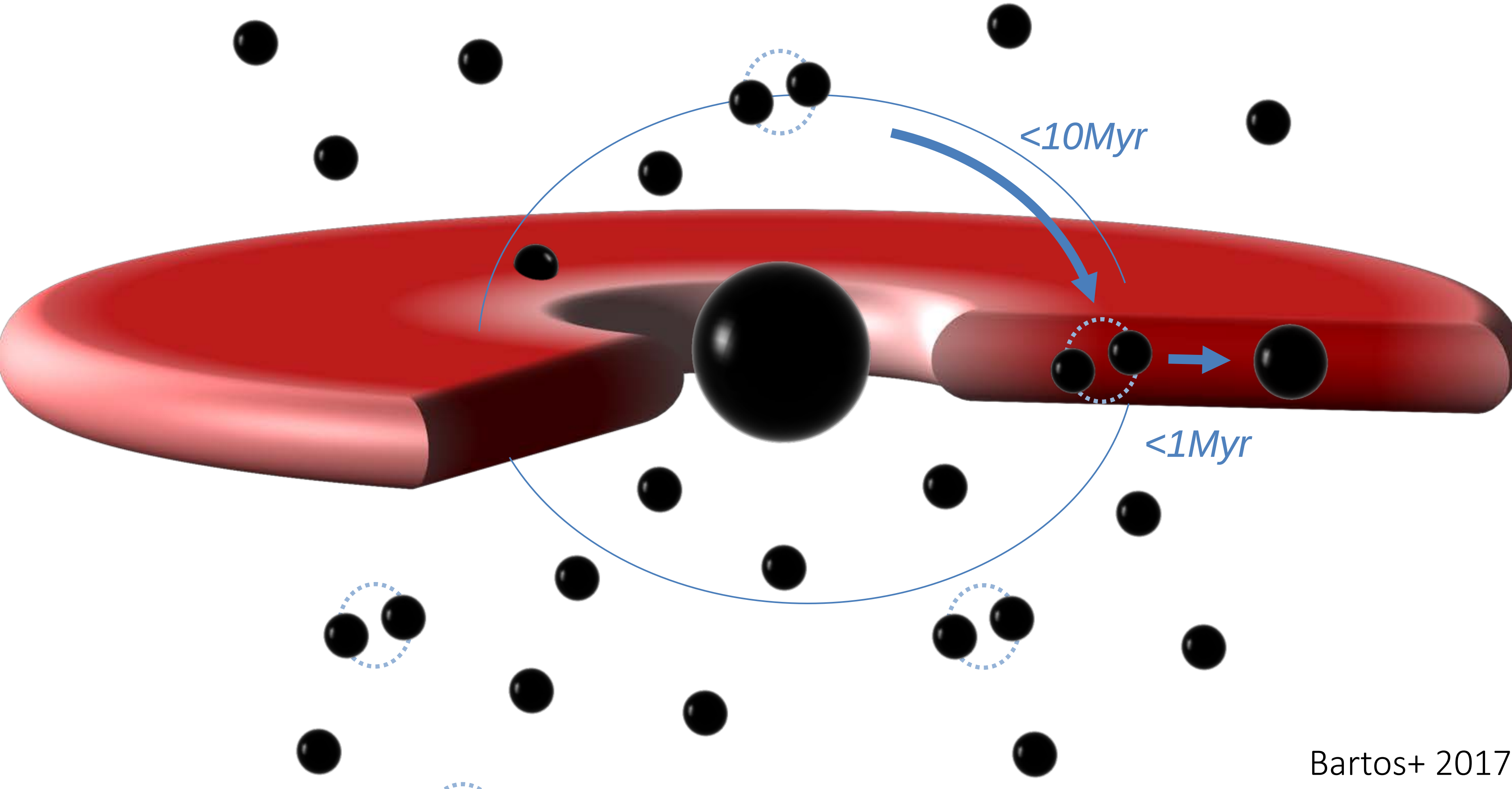
3. GW sources in active galactic nuclei



Bartos+ 2017

Get captured by the disk…

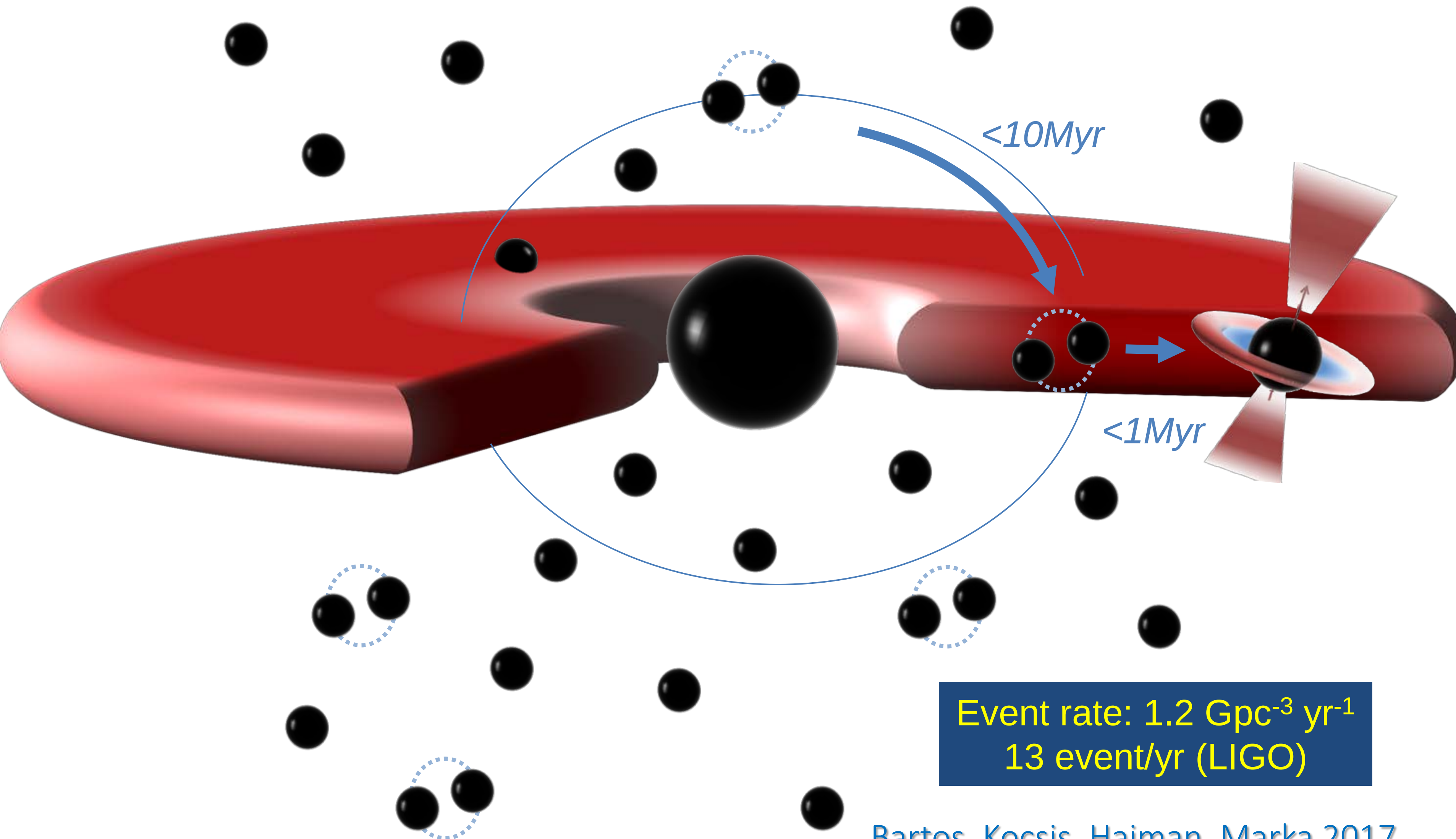
3. GW sources in active galactic nuclei



Bartos+ 2017

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

3. GW sources in active galactic nuclei

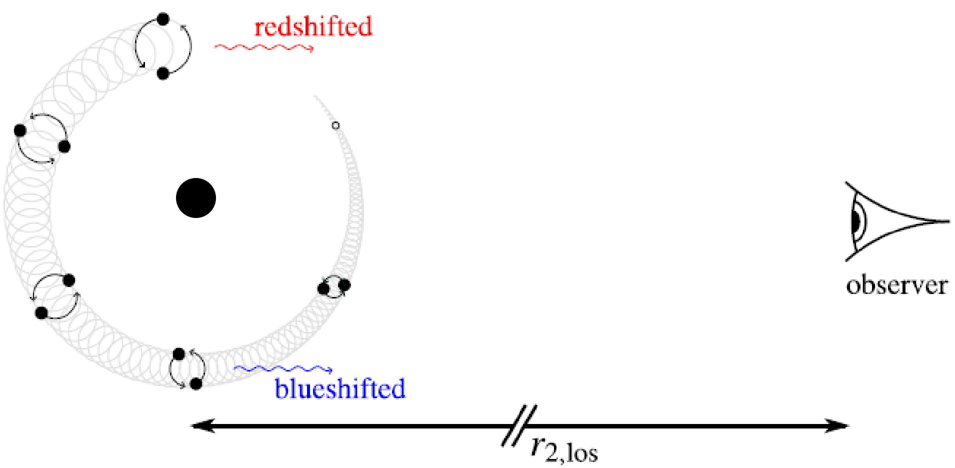


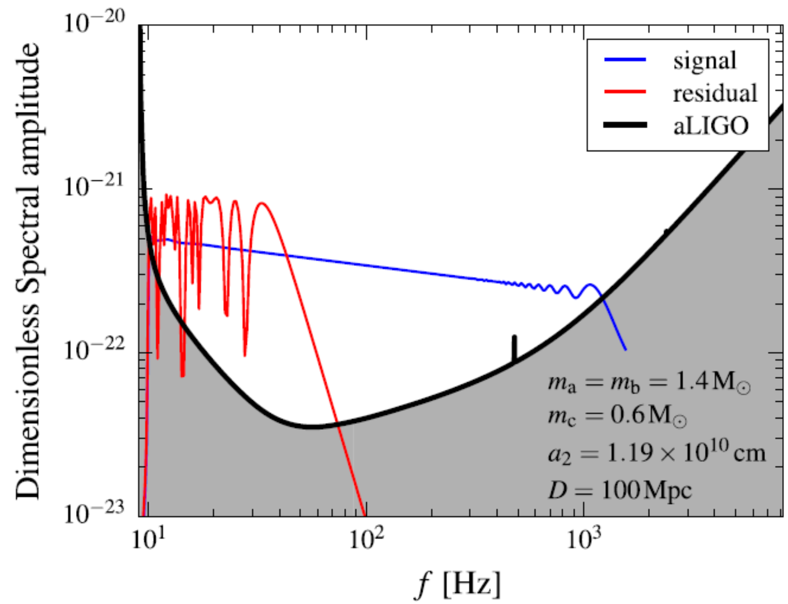
Event rate: 1.2 Gpc^{-3} yr^{-1}
13 event/yr (LIGO)

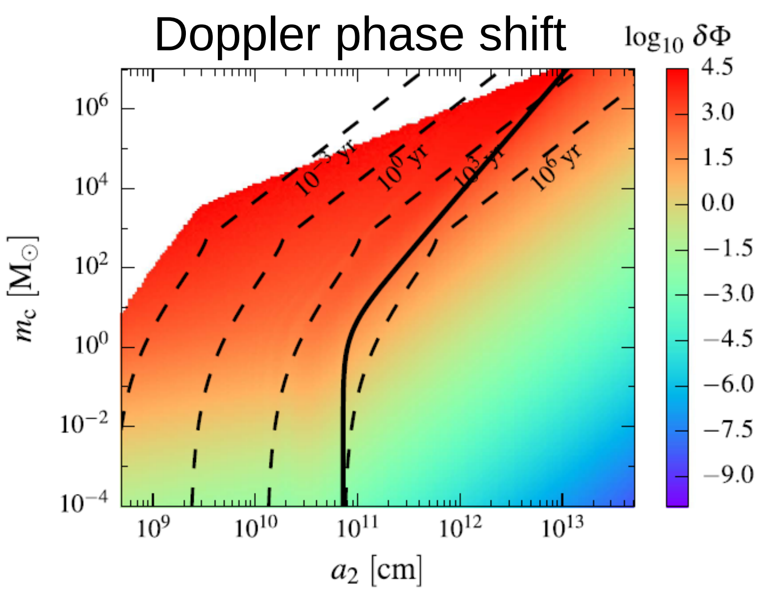
Bartos, Kocsis, Haiman, Marka 2017
Stone, Metzger, Haiman 2017

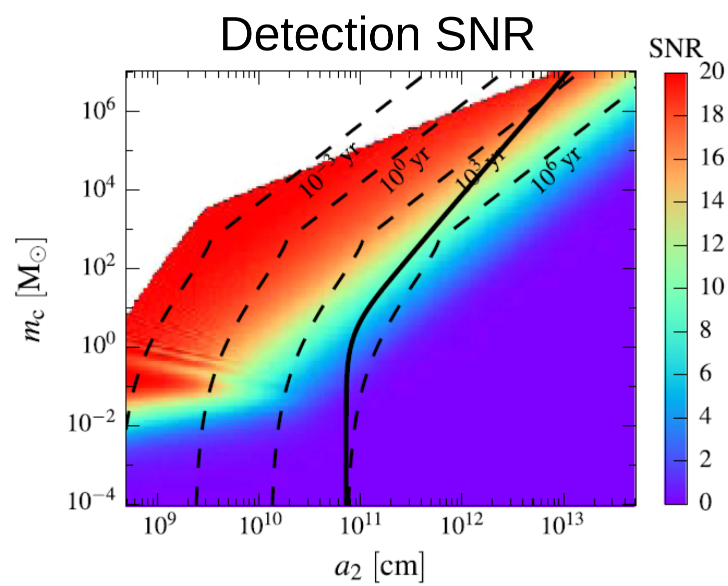
Smoking gun signatures to identify origin of source

SMBH/AGN source with LIGO



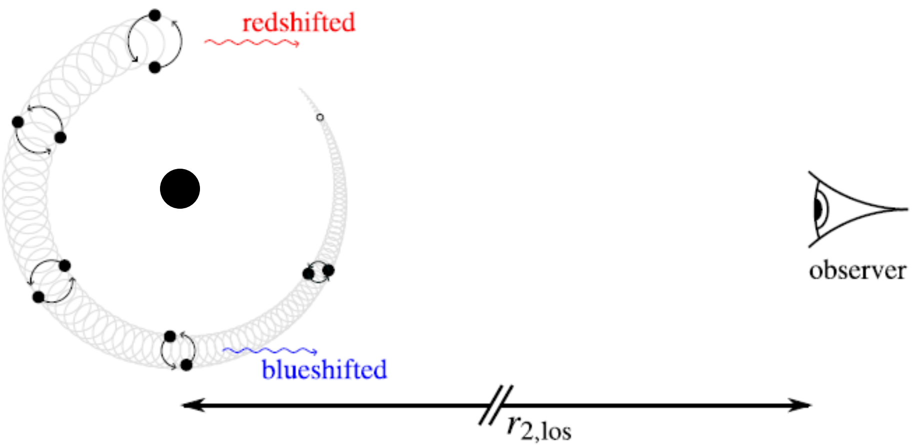




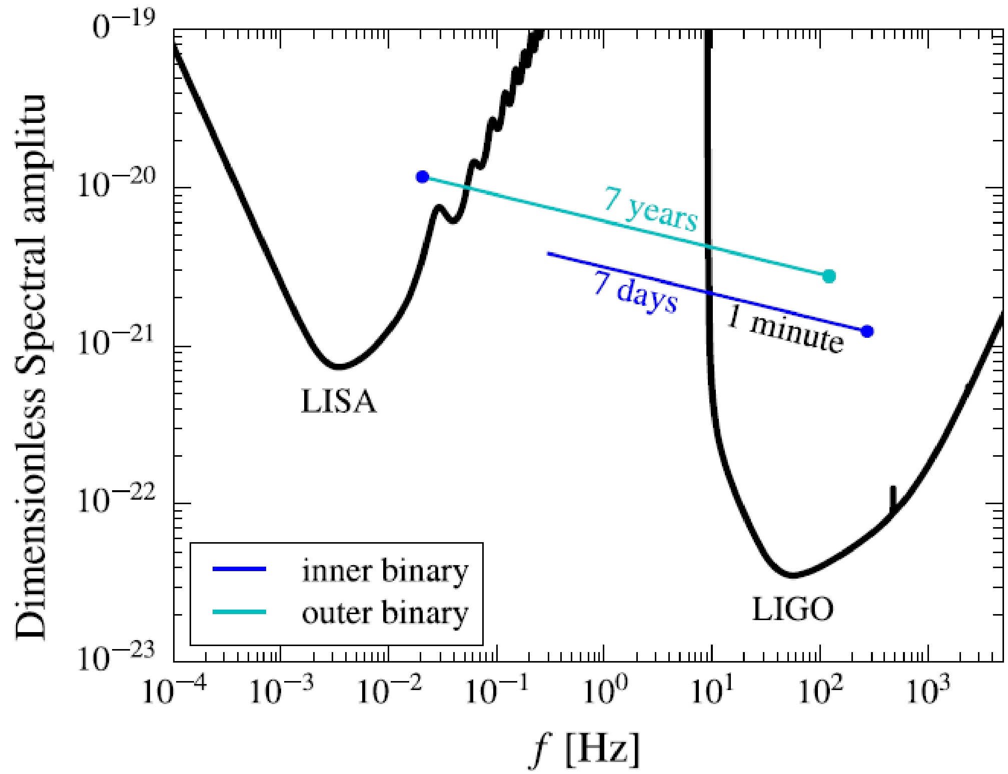


Meiron, Kocsis, Loeb 2017

SMBH/AGN source with LIGO+LISA



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

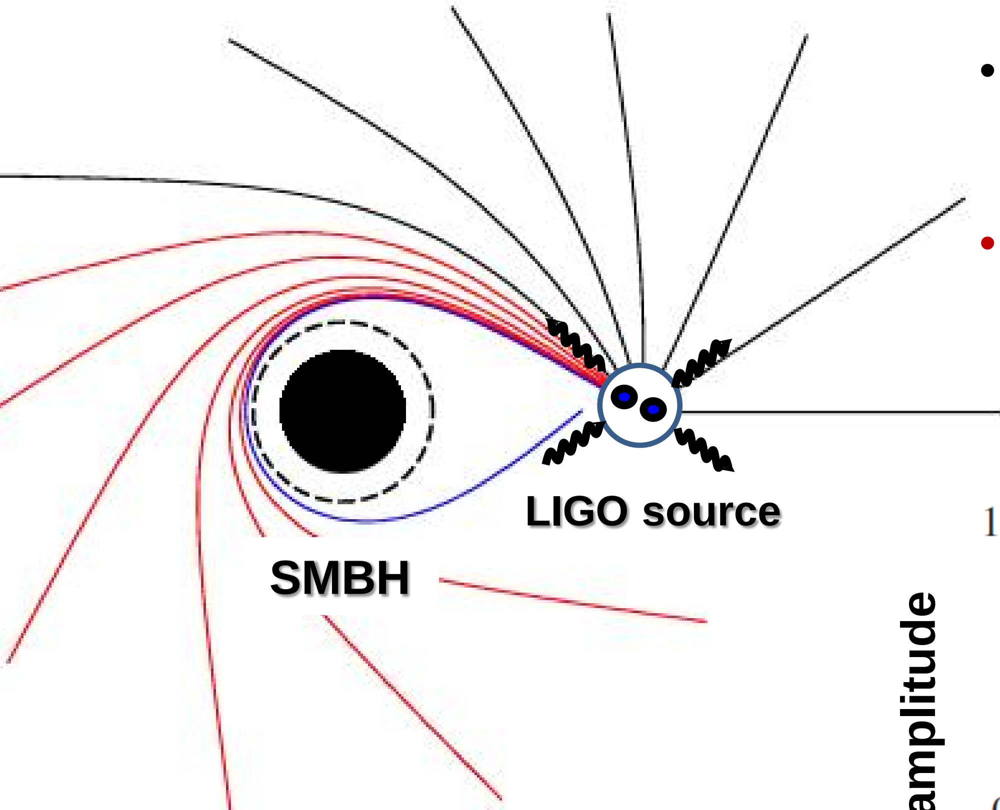


- LISA+LIGO coincident detection of triple inspiral
- LIGO detection of GW mass loss
- LISA detection of GW mass loss
- Later: LIGO detection of merger (if stellar-mass triple)

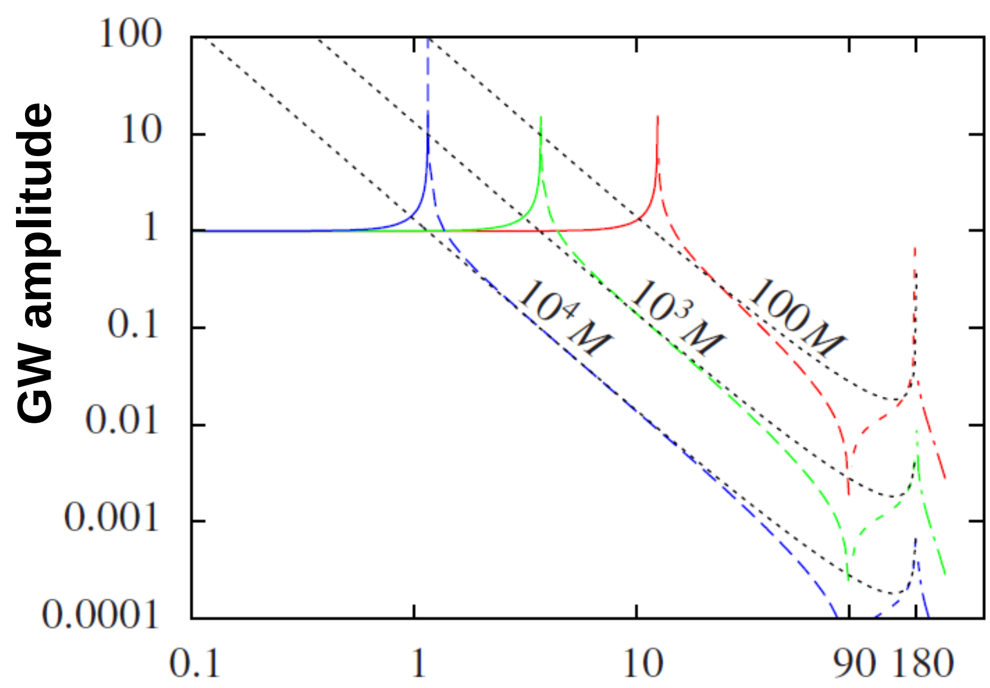
Test of general relativity

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

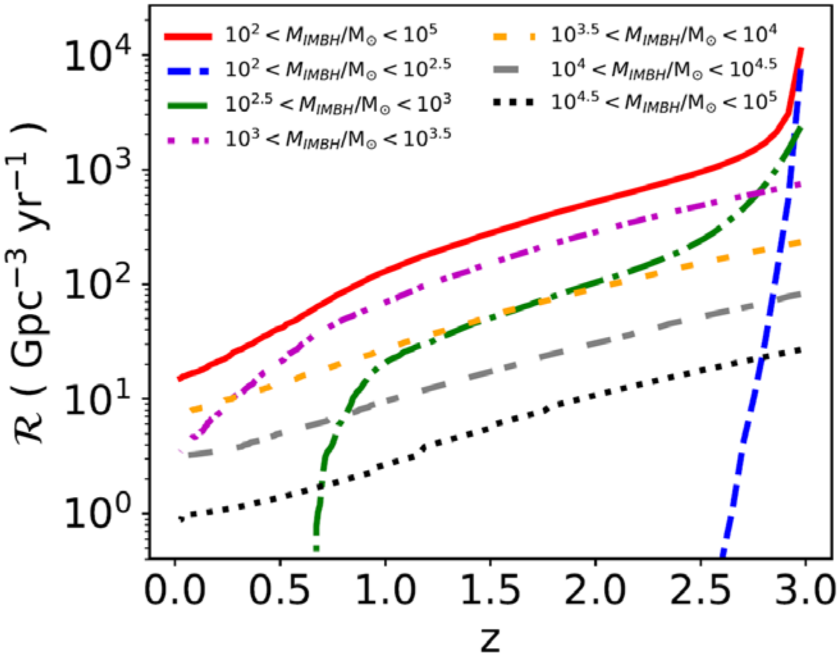
$$14\,\mathrm{h} \times (1-\cos\alpha) M_6 (r/10^4 M)$$

Kocsis 2013, Gondan & Kocsis in prep.

What about
intermediate mass black holes?

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 2017

Take-away

- Zoltan Haiman gives a talk on EM counterparts at 12:45
- 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** to identify sources in galactic nuclei

    → Doppler phase

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

intermediate mass black holes

Theory

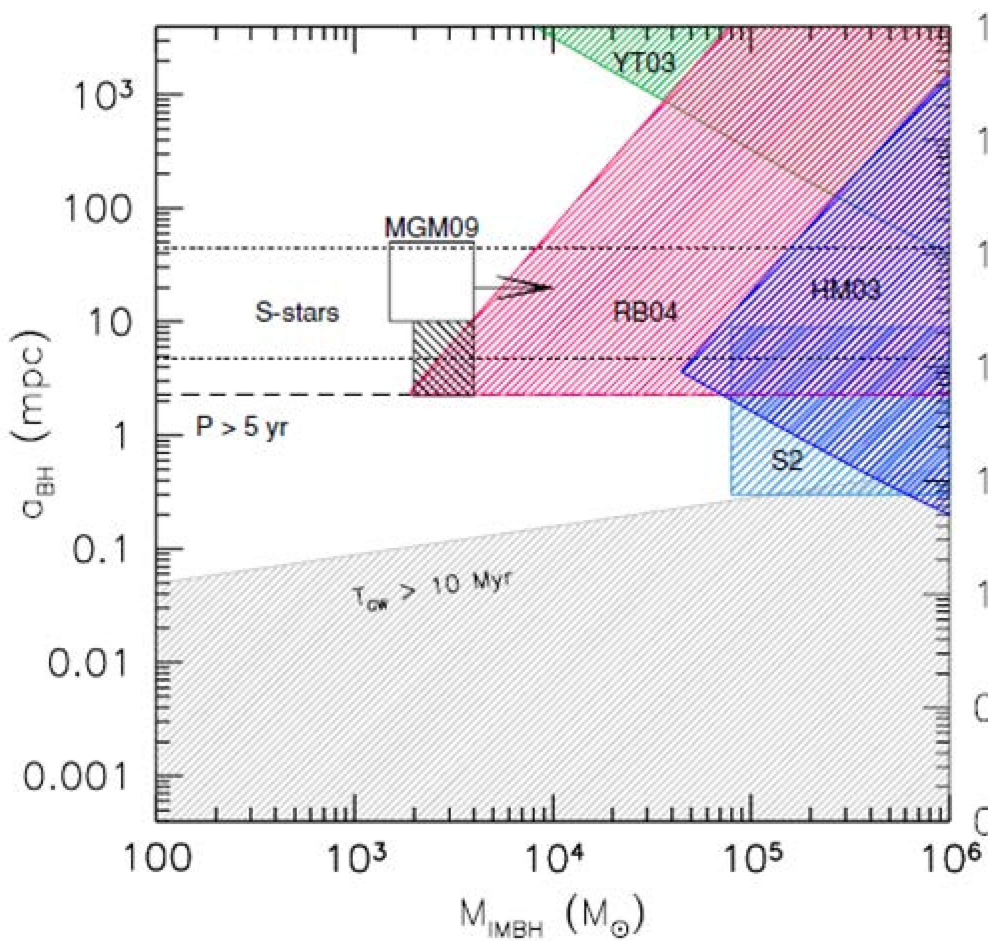
Formation

- 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

Fragione, Ginzburg, Kocsis 2017

Observational constraints



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