Doing Gravitational Wave Astronomy

with binaries of compact objects

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Thessaloniki, October 2018

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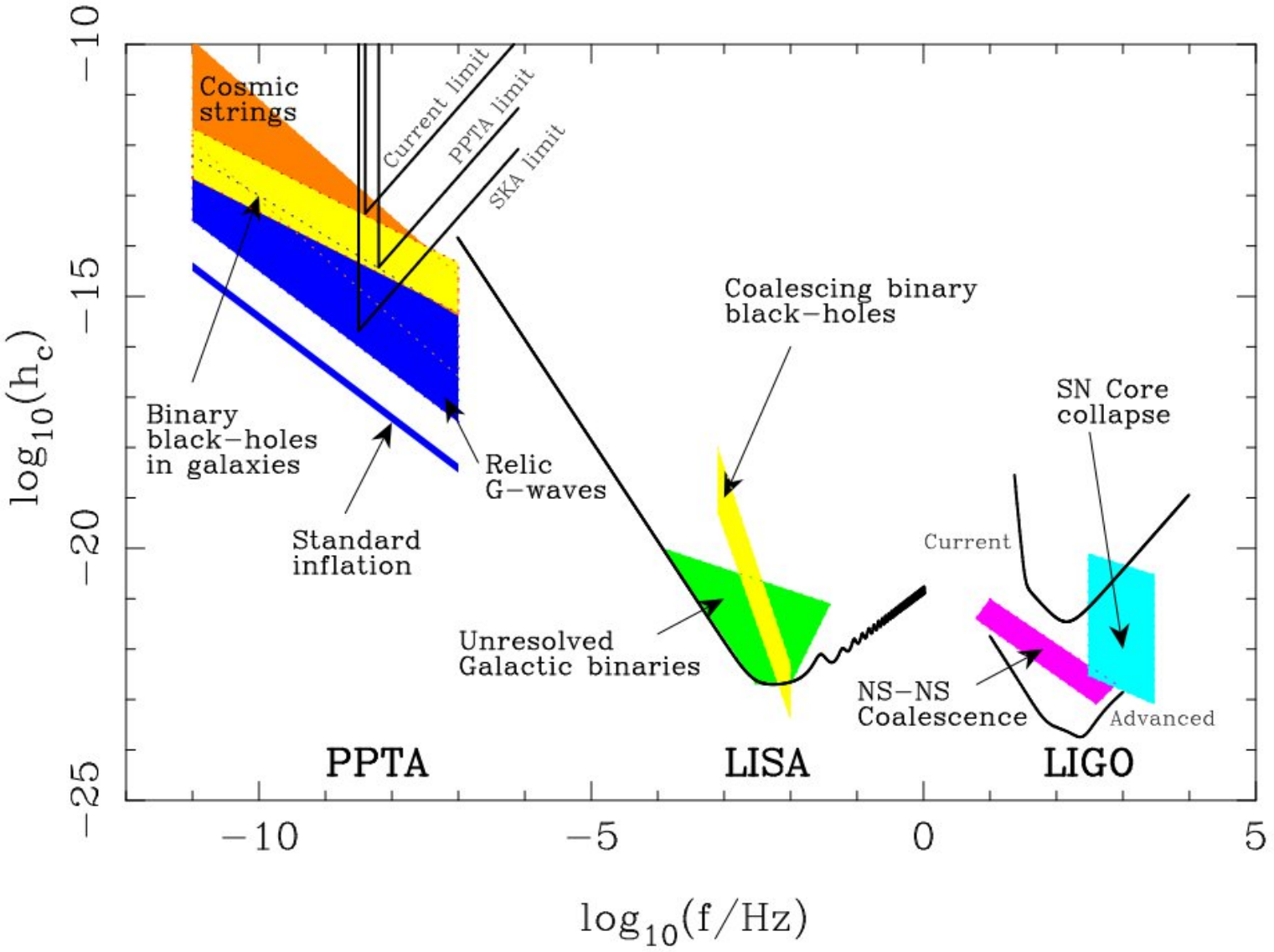
Frequencies

The different windows in GW Astronomy



[Hobbs 2008]

A universe of black holes

Black holes come in different flavors

[Warner Bros, Entertainment Inc. and Paramount Pictures Corporation. Author: double negative, http://www.dneg.com]

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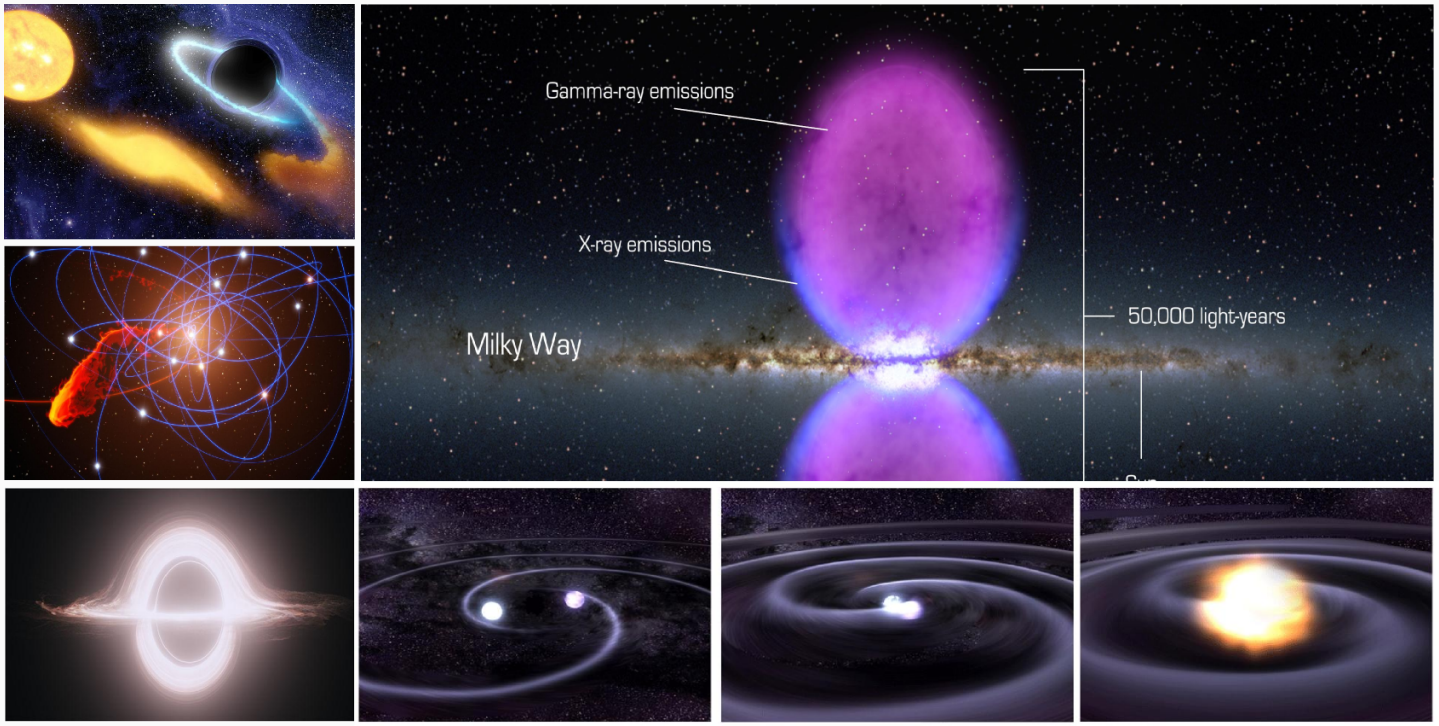
Black holes: Do they exist?

Do black holes exist?



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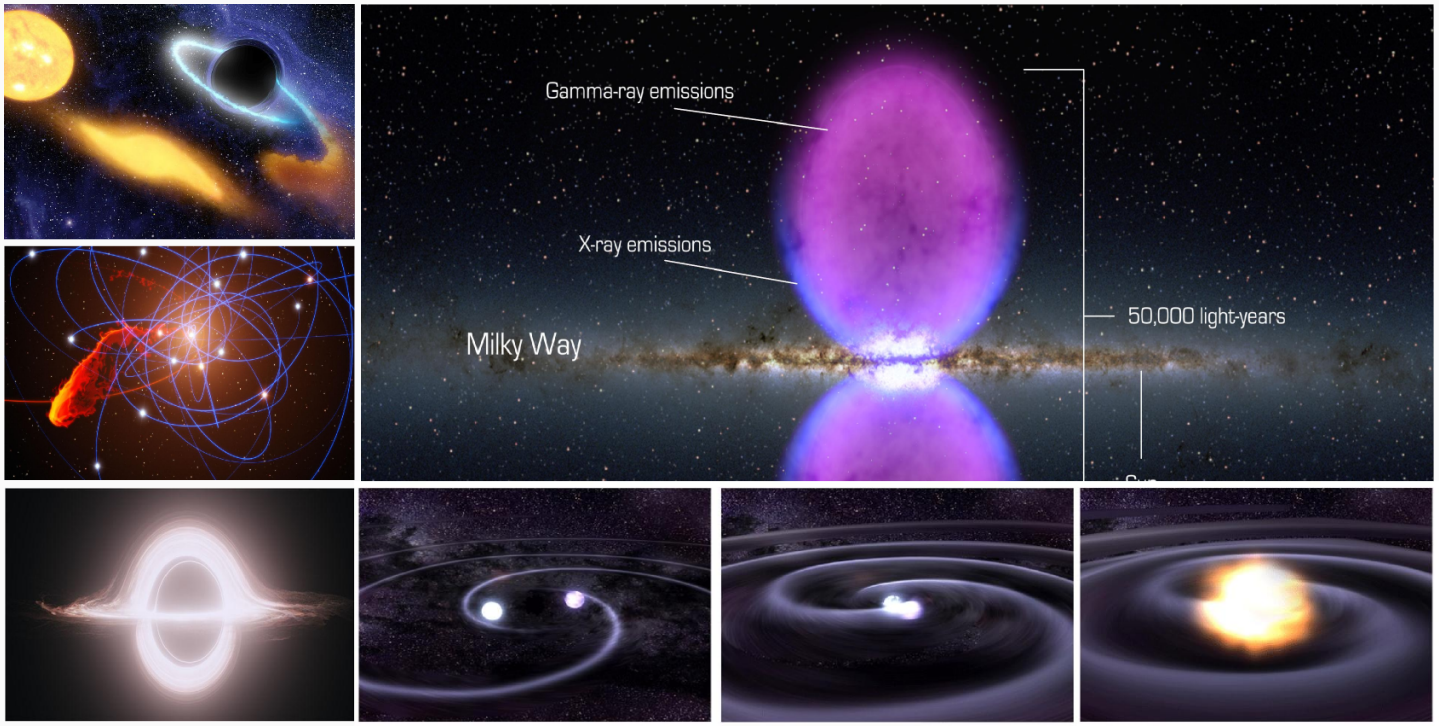

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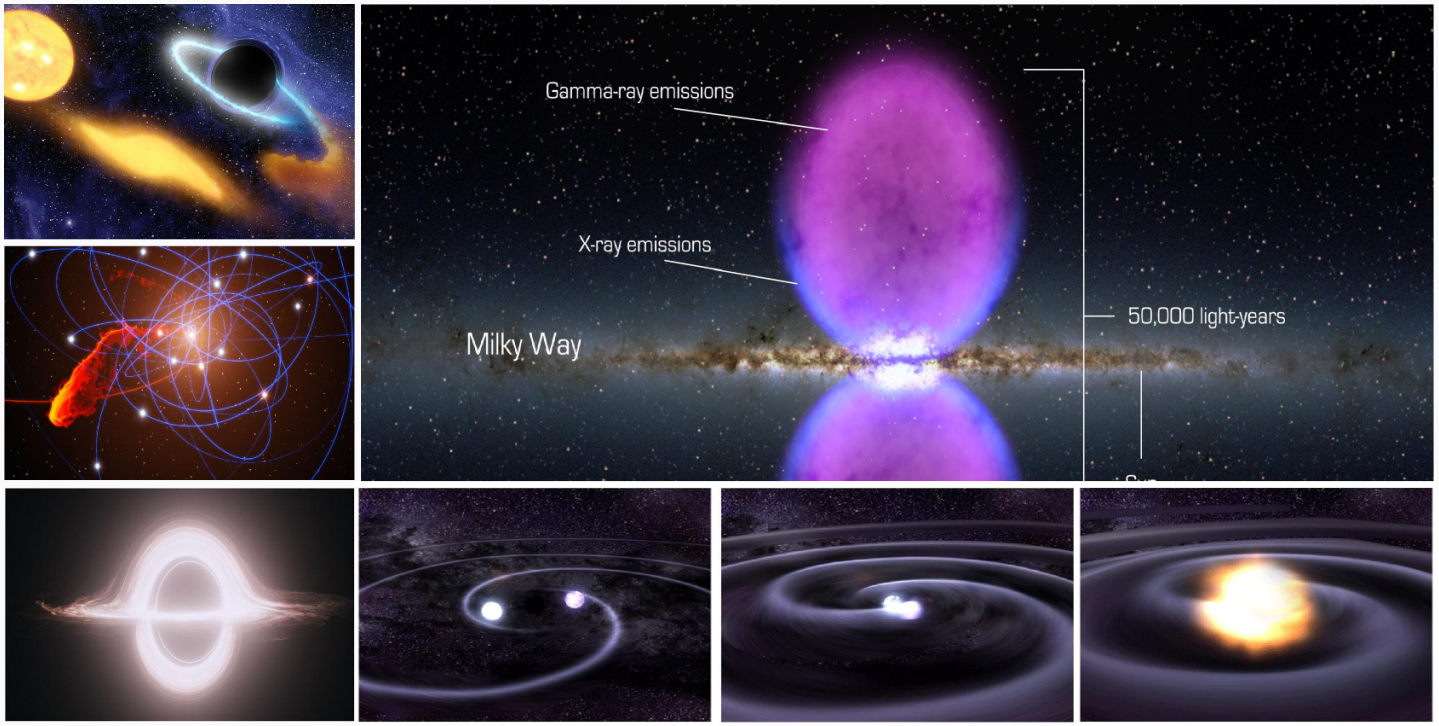

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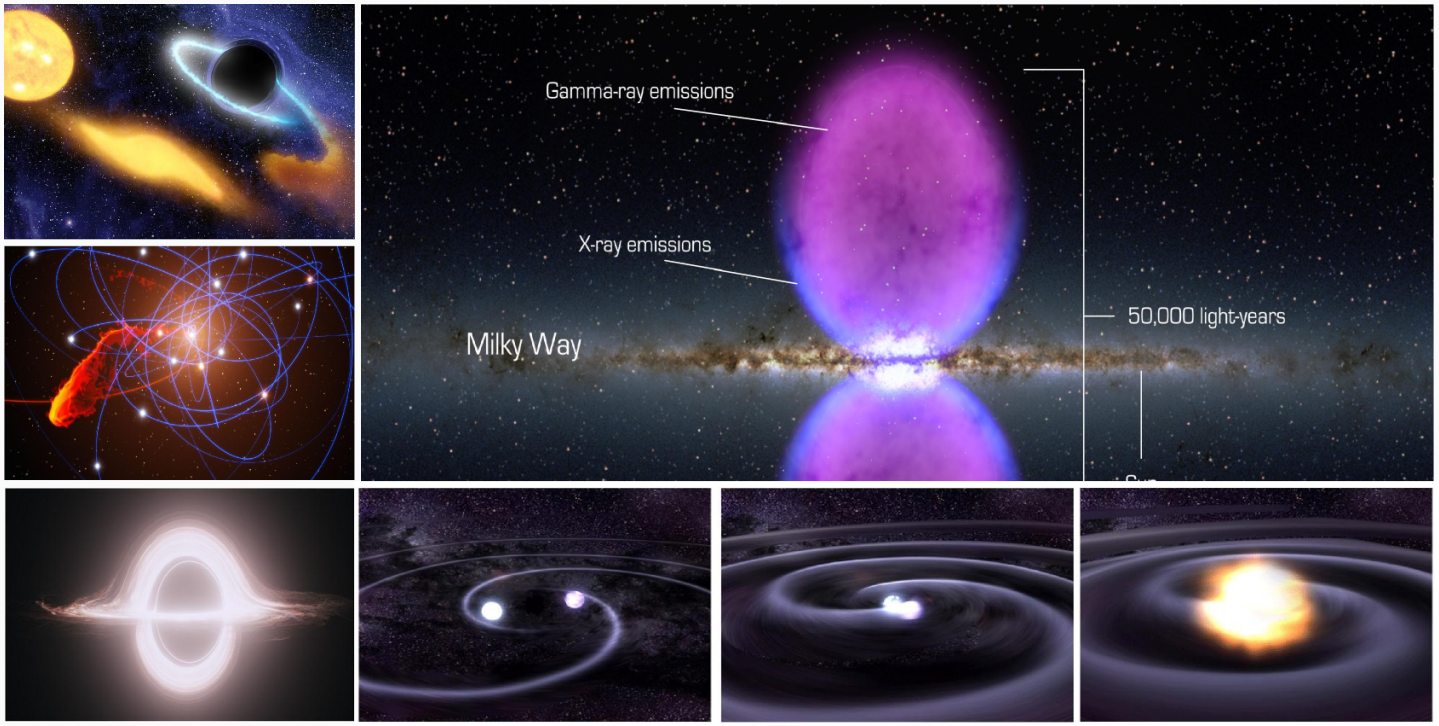

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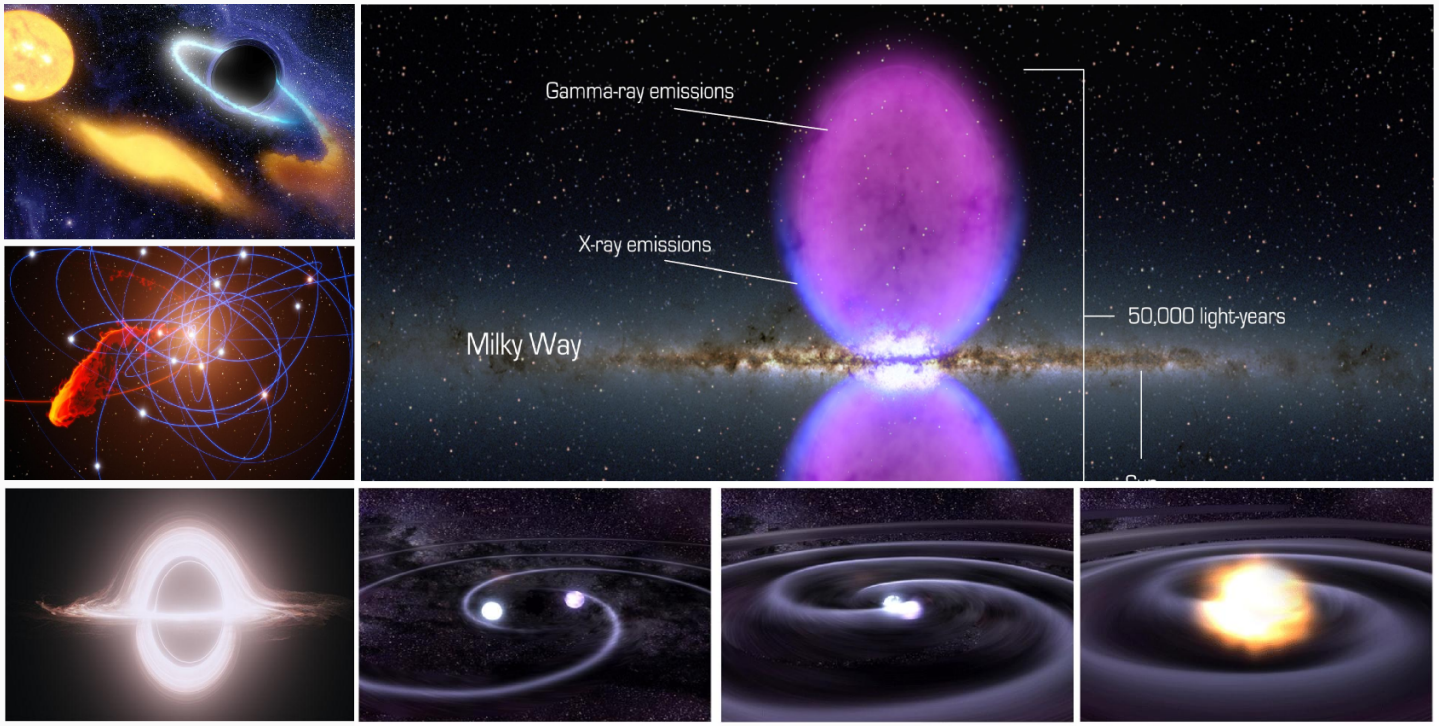

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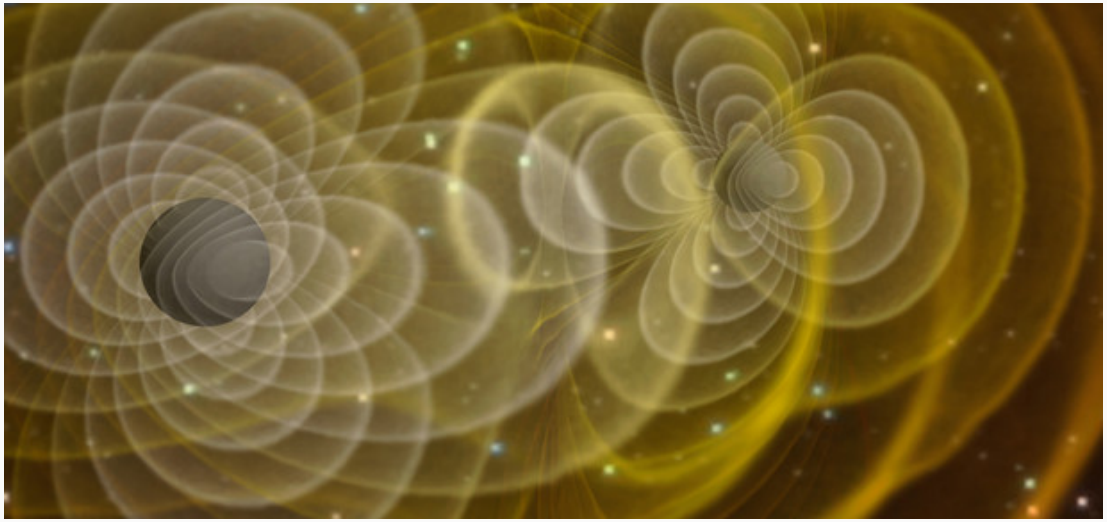
  Gravitational waves

An excellent probe: Gravitational Waves



[Henze, NASA]

- Predicted in 1918 by Albert Einstein
- Electromagnetic waves produced by accelerated charged particles
- Gravitational Waves produced by accelerated masses

What are they good for?

[ESO/L. Calçada]

- Slow decay: Propagate to very long distances

[Vídeo: Jungle and galaxy (w+j, w+0)]

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- Pristine probe: They contain very detailed information about space and time

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Stellar-mass black holes

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Wait… We do have direct proofs now!

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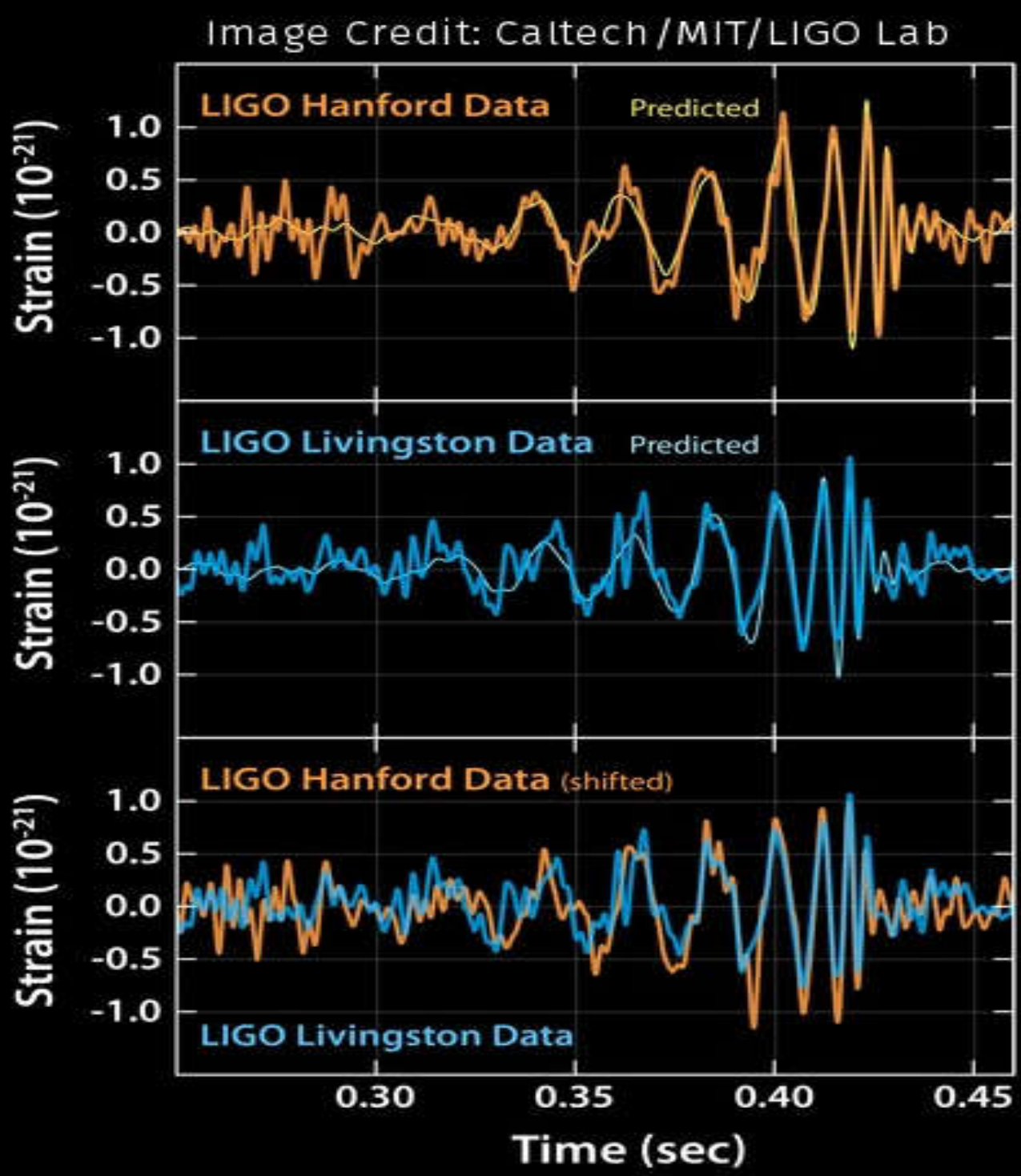
Image Credit: Caltech/MIT/LIGO Lab
LIGO Hanford Data
Predicted
LIGO Livingston Data
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LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10-21)
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0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)

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Do supermassive black holes exist?

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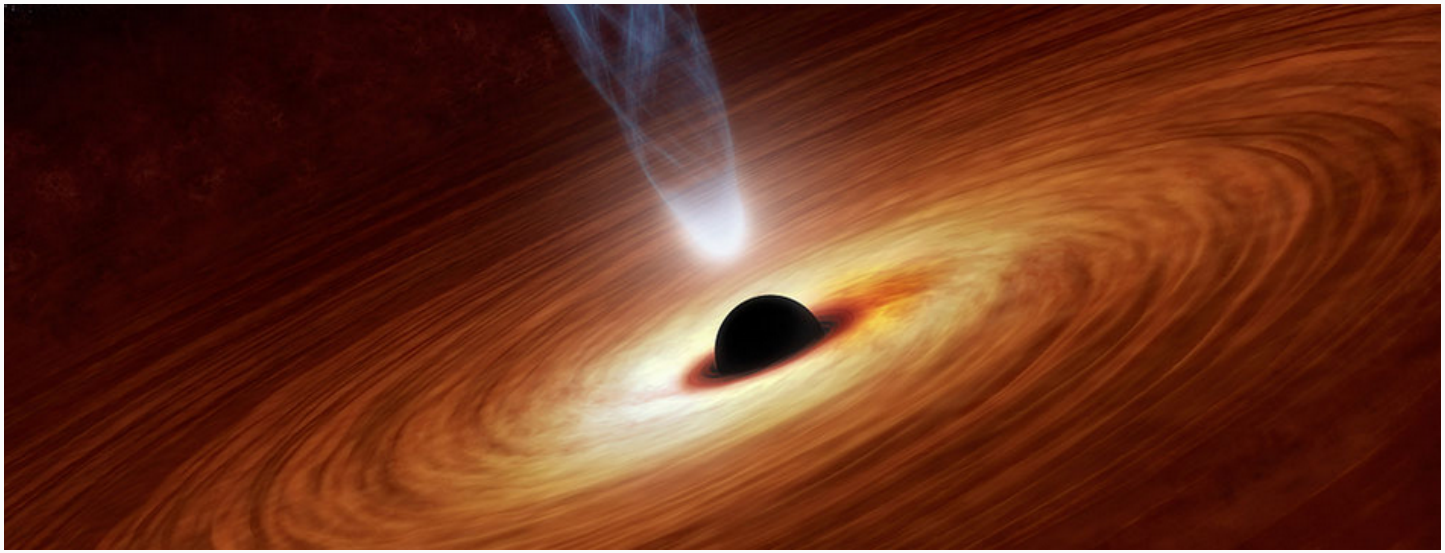
- How do you create a luminosity of 10^{40} W??

Accretion



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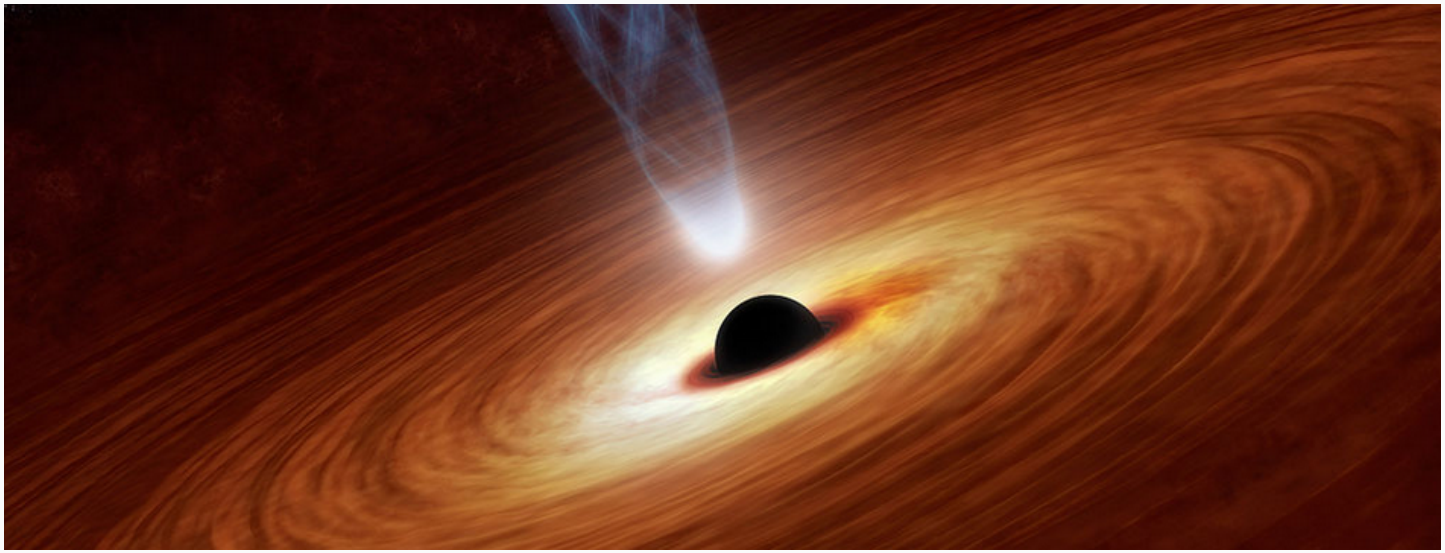

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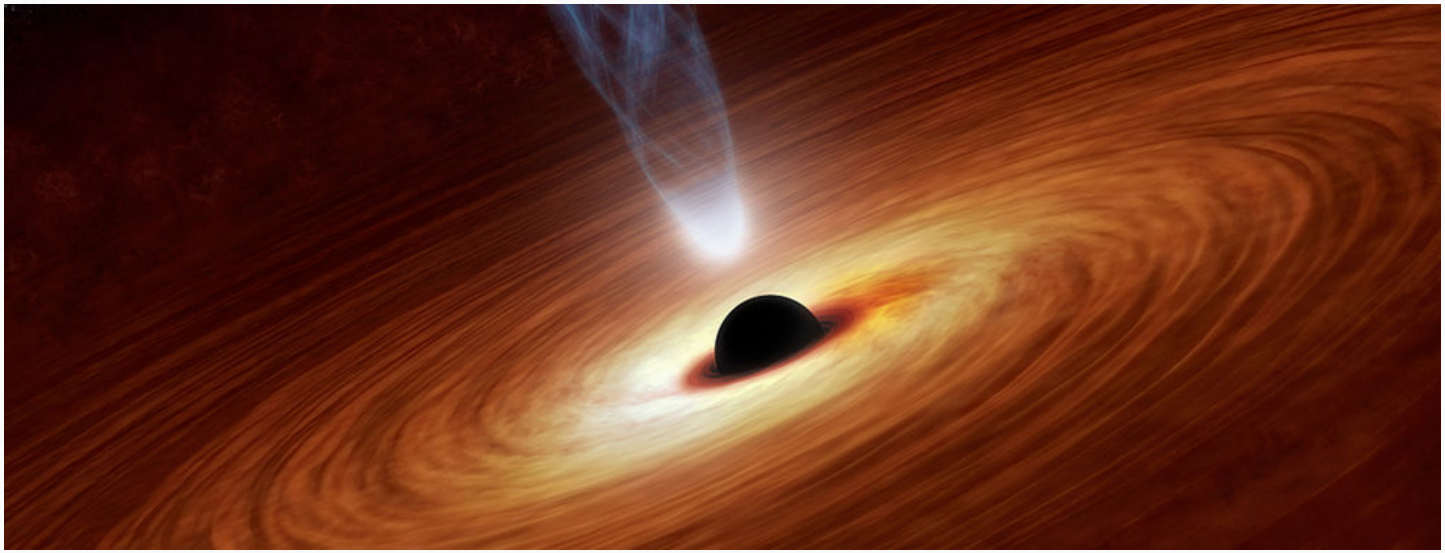

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- The largest one known devours 600 Earths per minute

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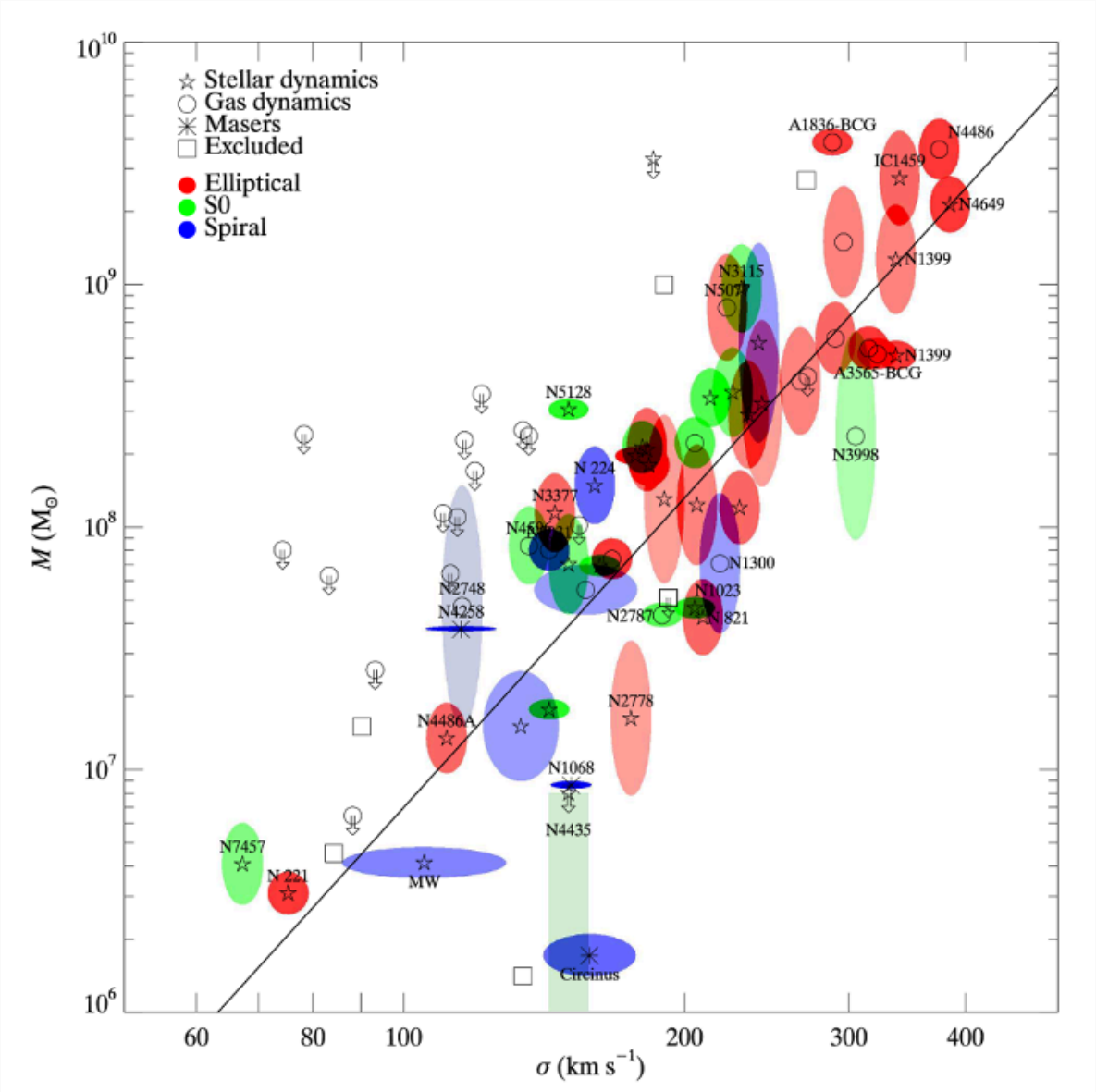
- Within a radius of 22 millions of km, enclosed in $\sim 1/3$ times the distance to the Sun

[Vídeo: S-Stars]

Correlations



[Guelketin et al 2009]

Capture of compact objects: A unique probe

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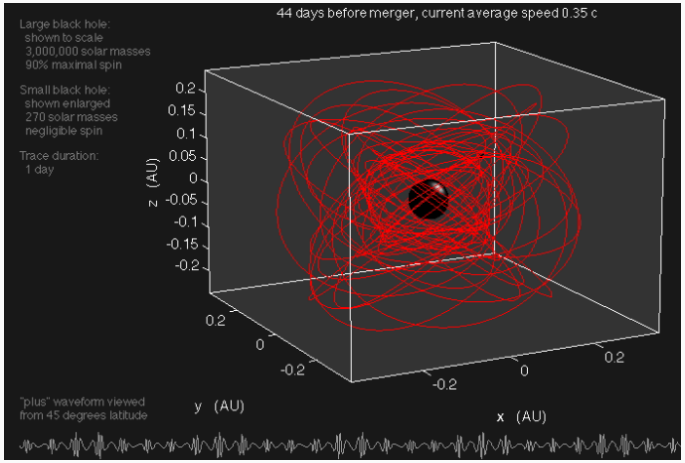

[Vídeo: Extreme-mass ratio inspiral, by S. Drasco]

- ✘ Stellar mass object spiraling into $10^4 - 10^6$ $M_\bullet$
- ✘ This range of masses corresponds to relaxed nuclei (!)
- ✘ Only compact objects – extended stars disrupted early
- ✘ With LISA $z \sim 1$

[Amaro-Seoane et al 2012a b]

Four important points

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4. Measures mass and spin with unprecedent precision

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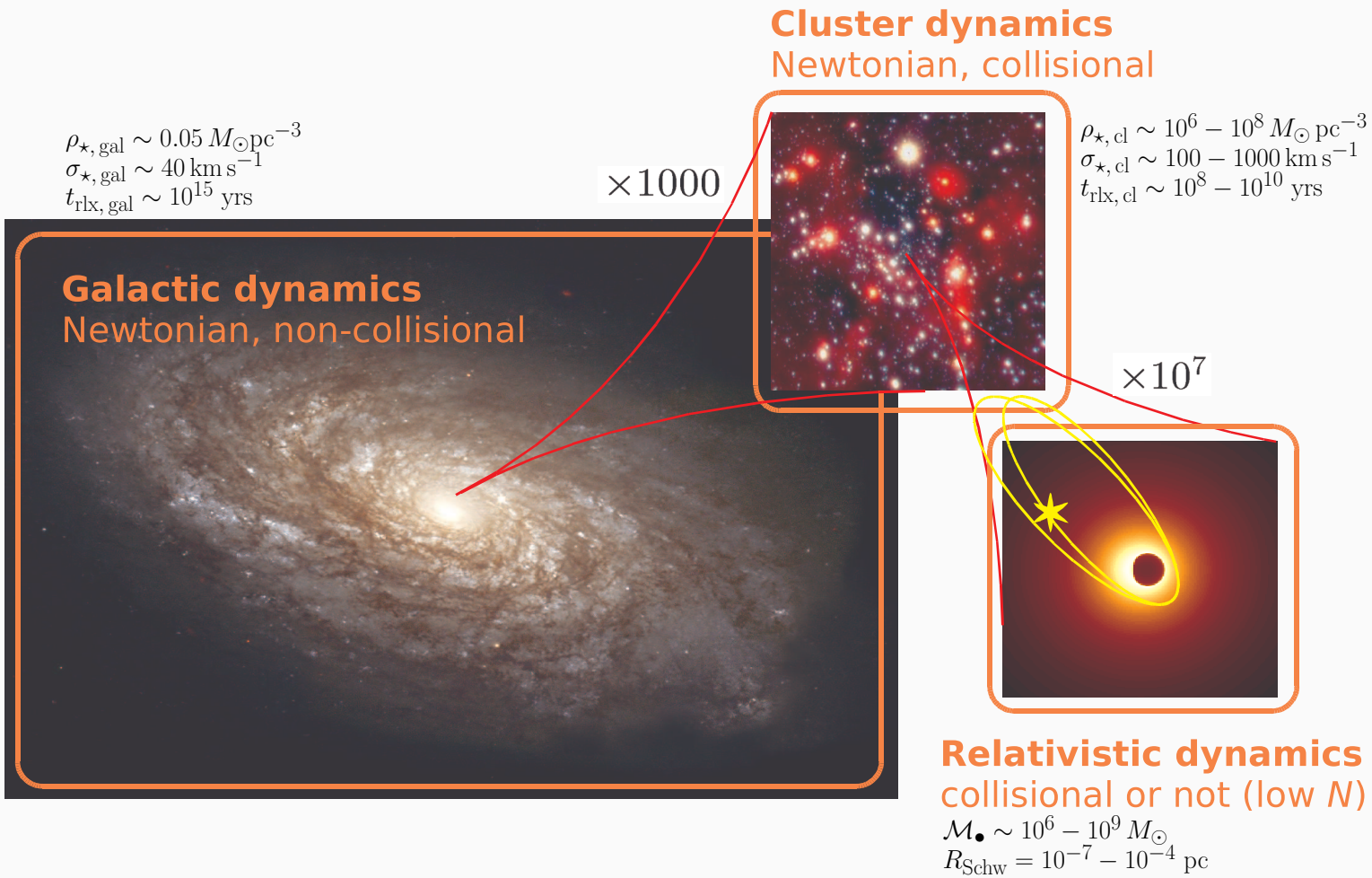
A problem of 10 orders of magnitude



Note: 1pc $\sim$ 3 light years

[Amaro-Seoane 2012]

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  We are already making completely new discoveries many years before LISA

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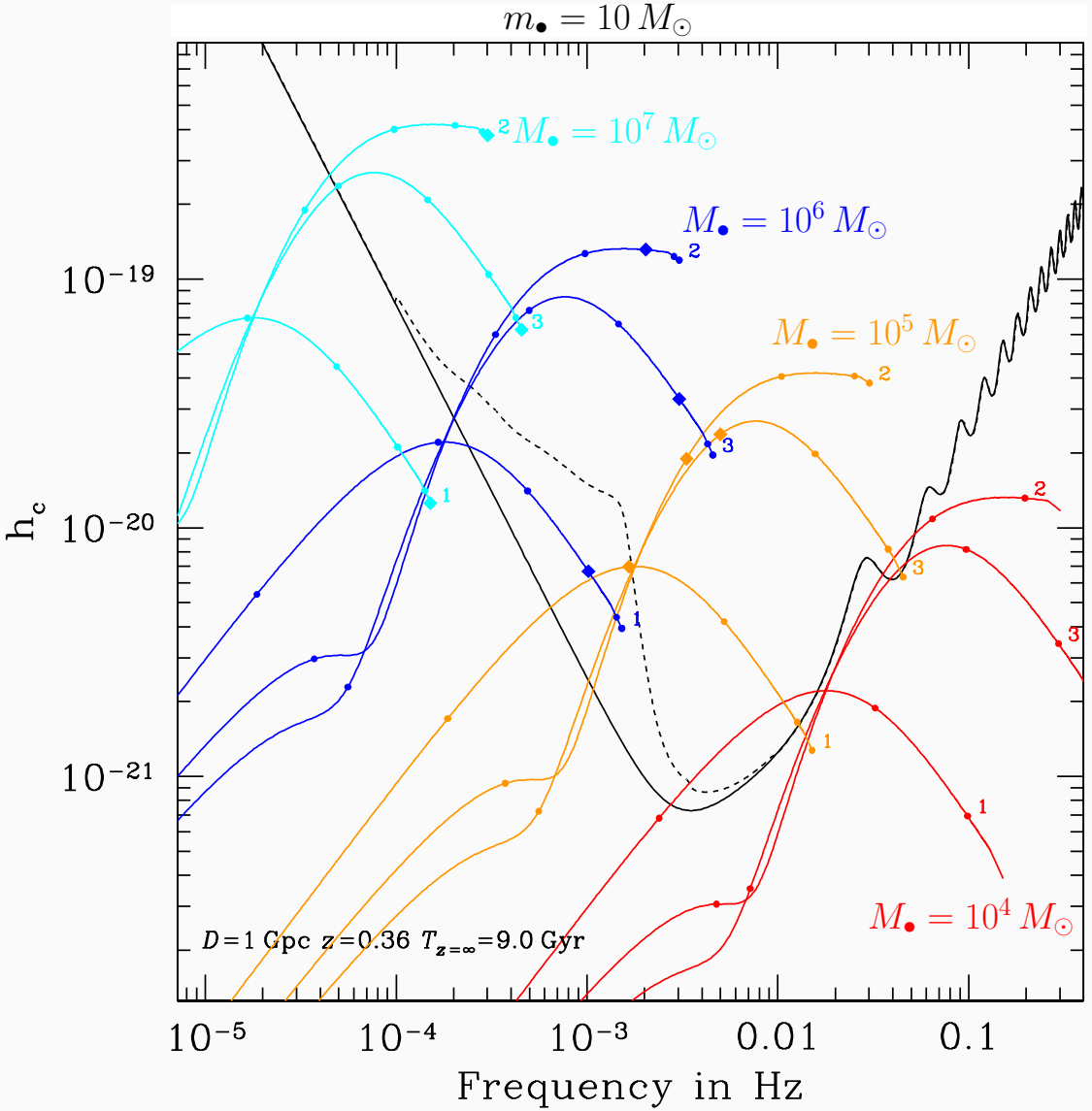
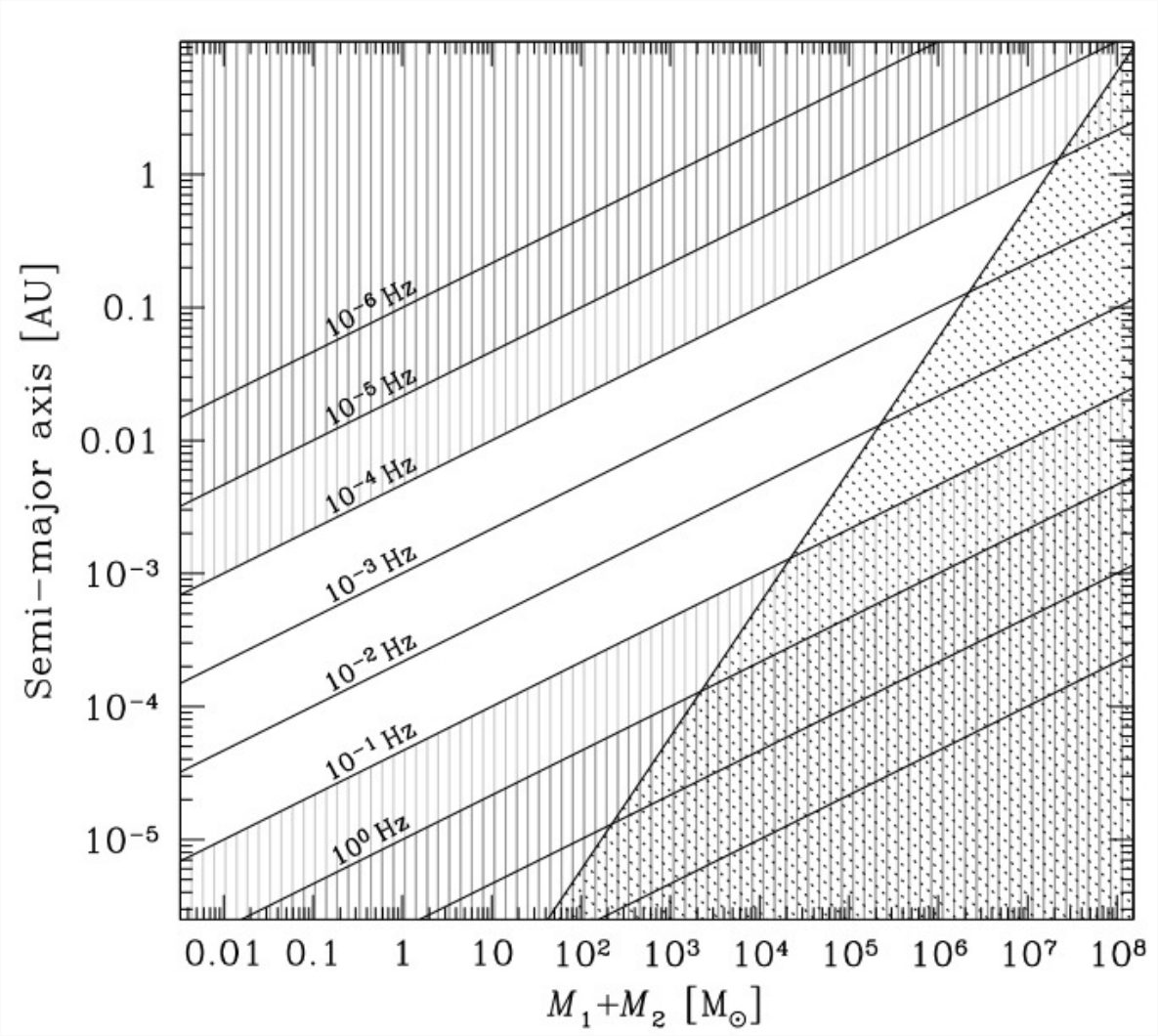
Range of masses



[Amaro-Seoane 2012]

Another way of looking at it



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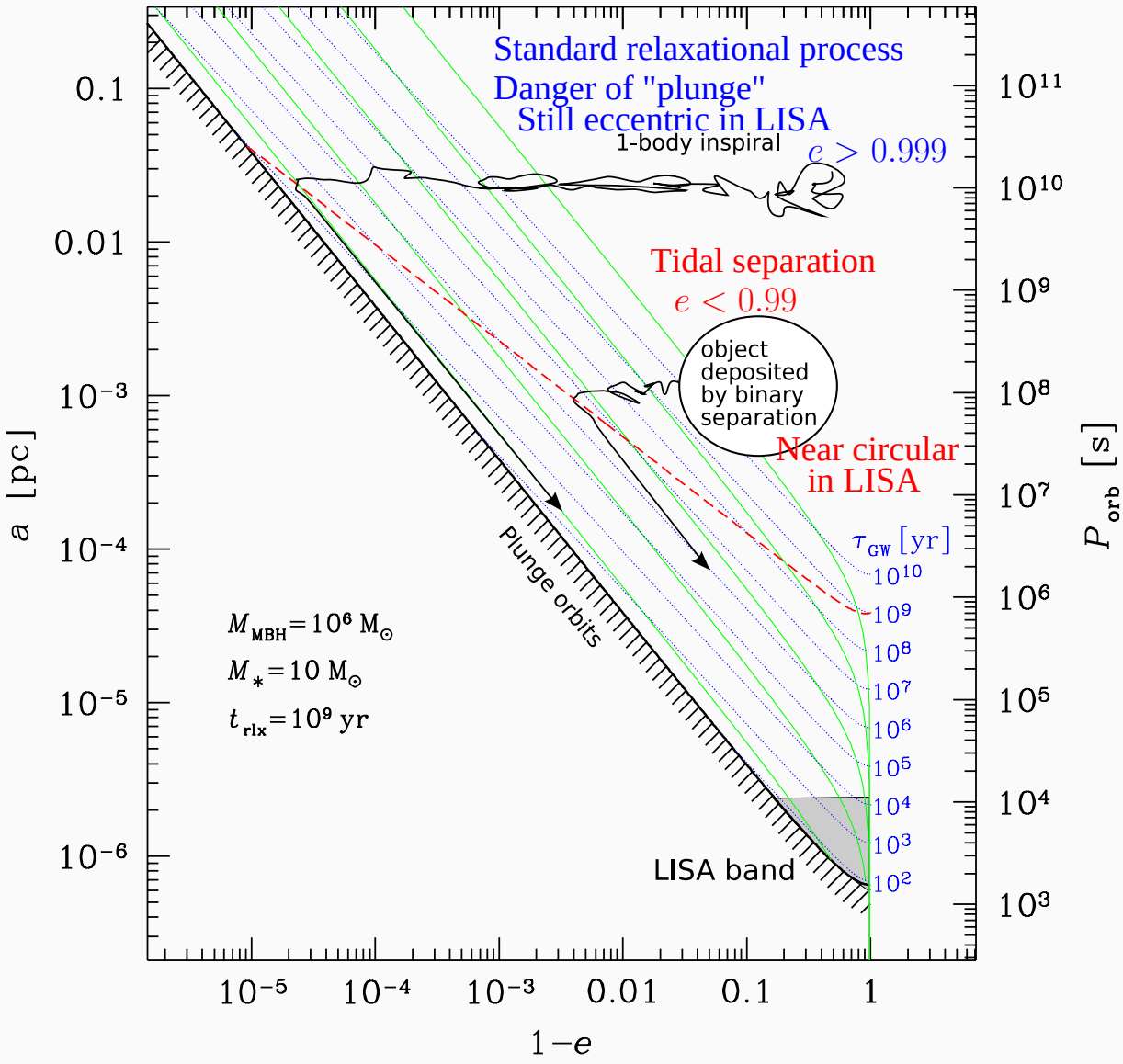
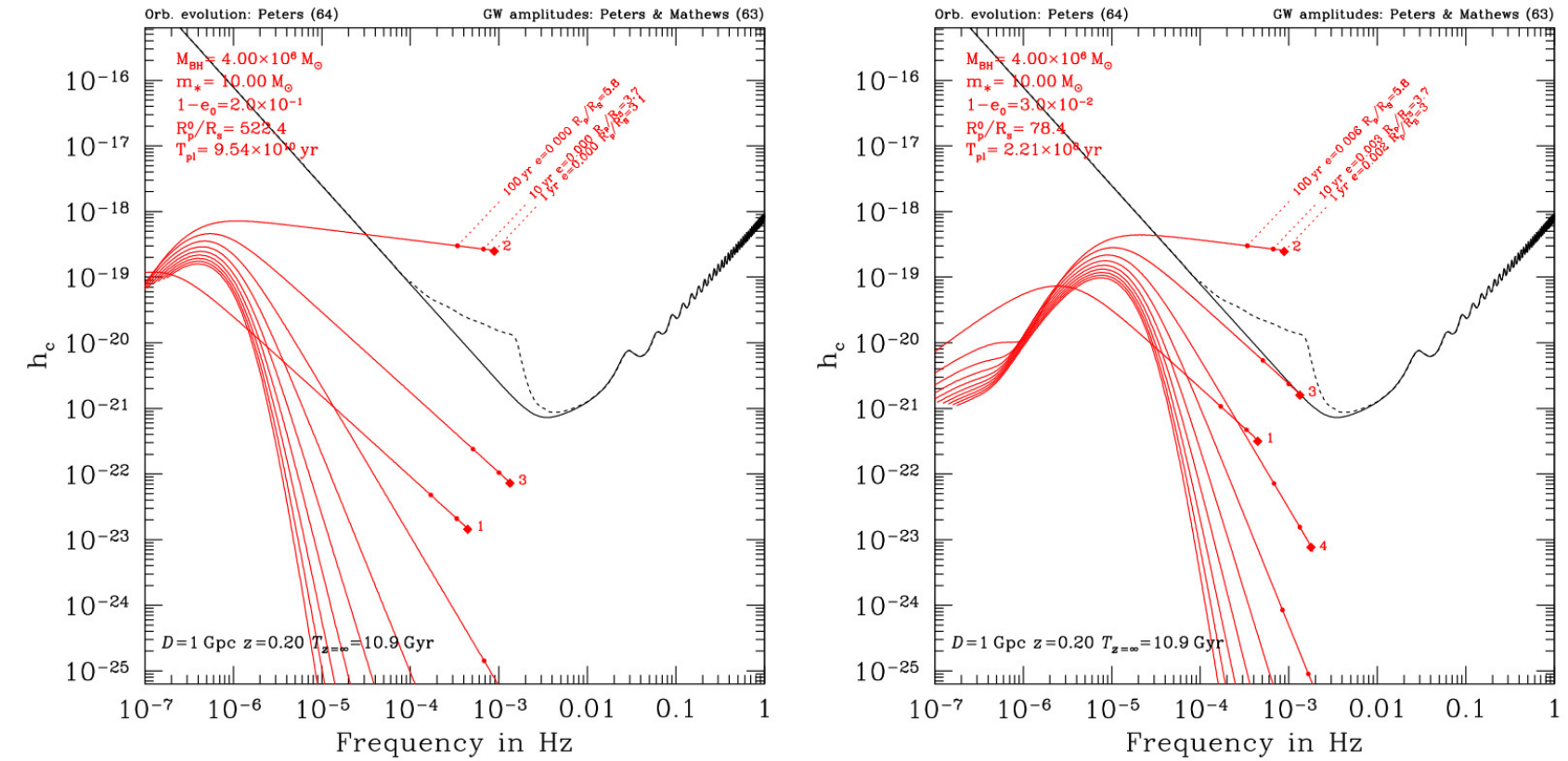
Dichotomizing an EMRI

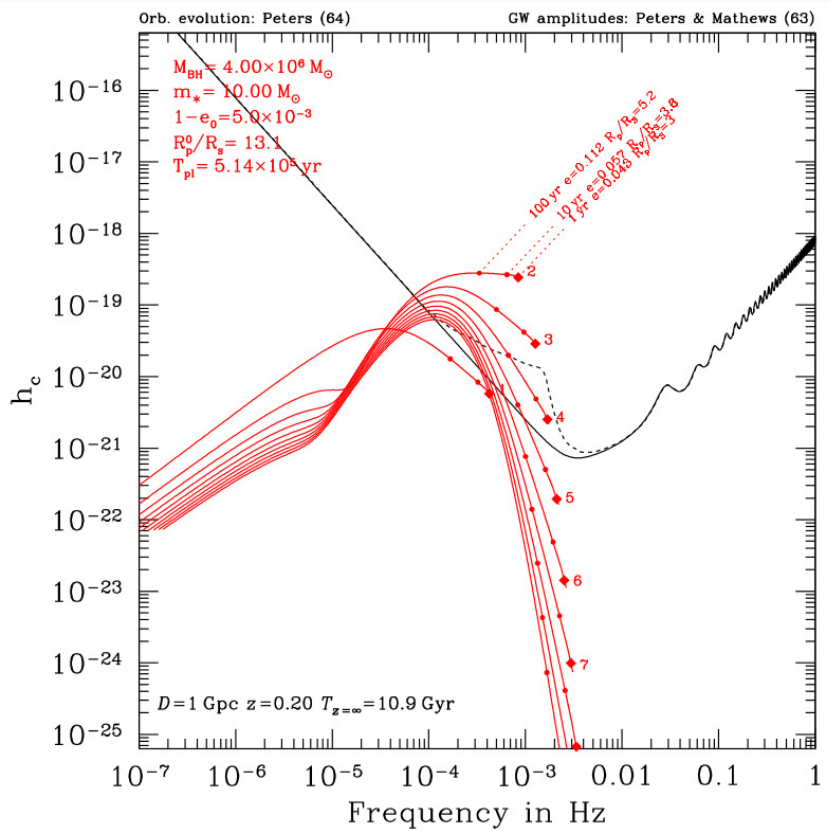


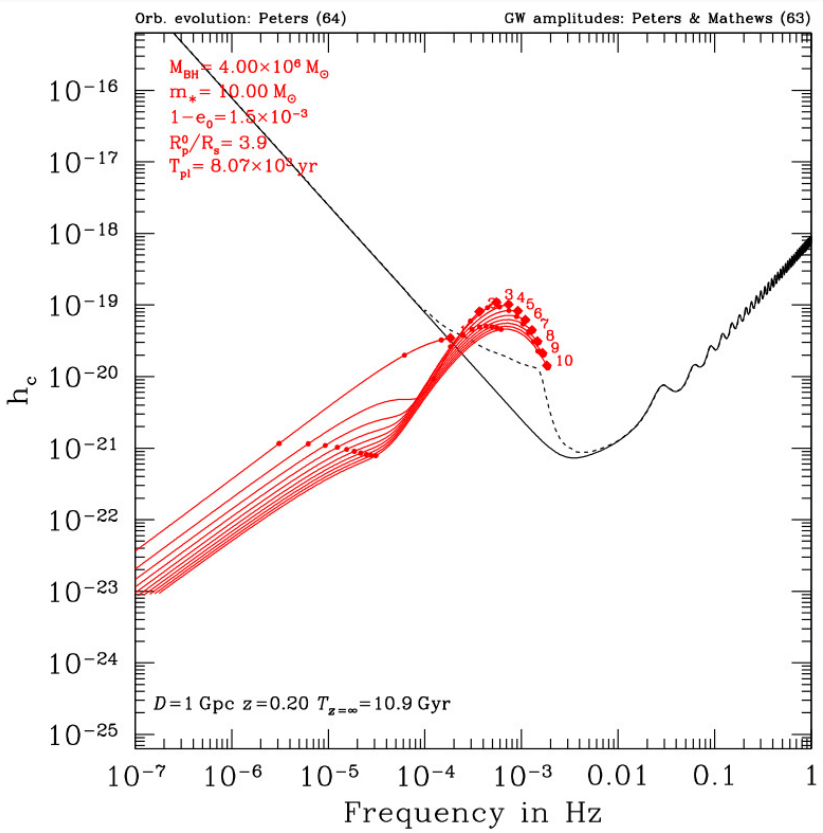
[Amaro-Seoane 2012]

Low eccentricity, 0.8, 0.97



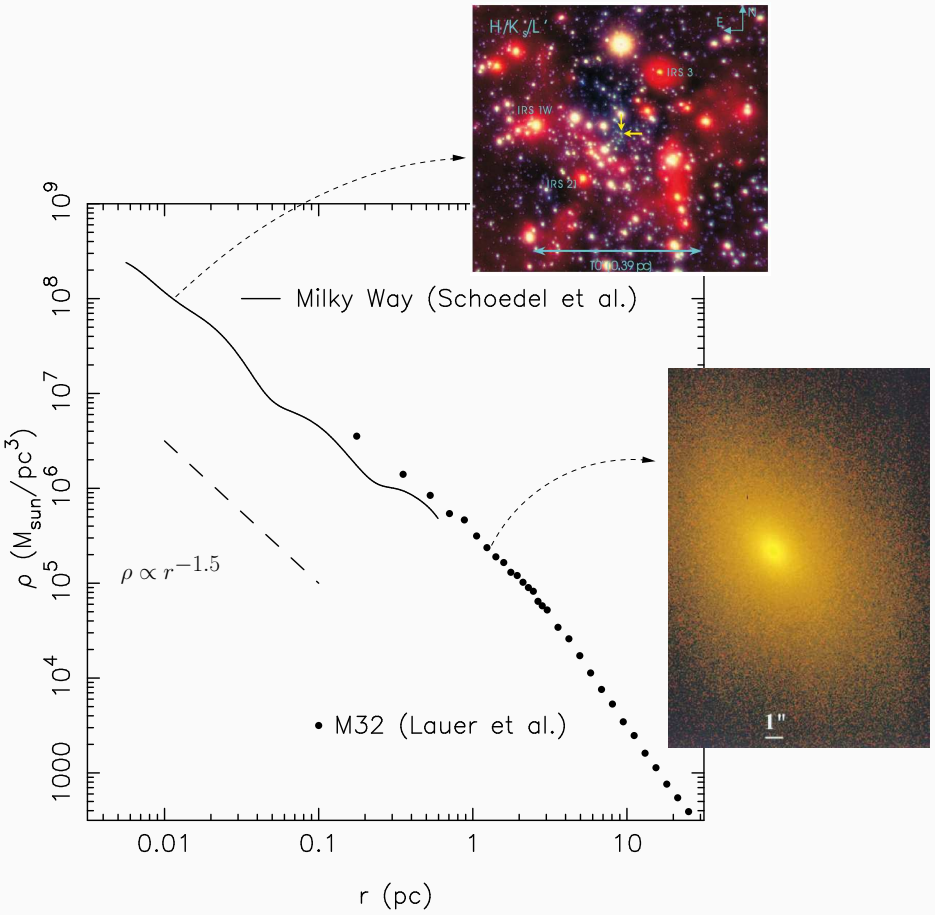
High eccentricity, 0.995, 0.9985





Do we expect these things to exist?

Do we have compact objects close to the massive black hole?



[Adapted from Merritt 2006]

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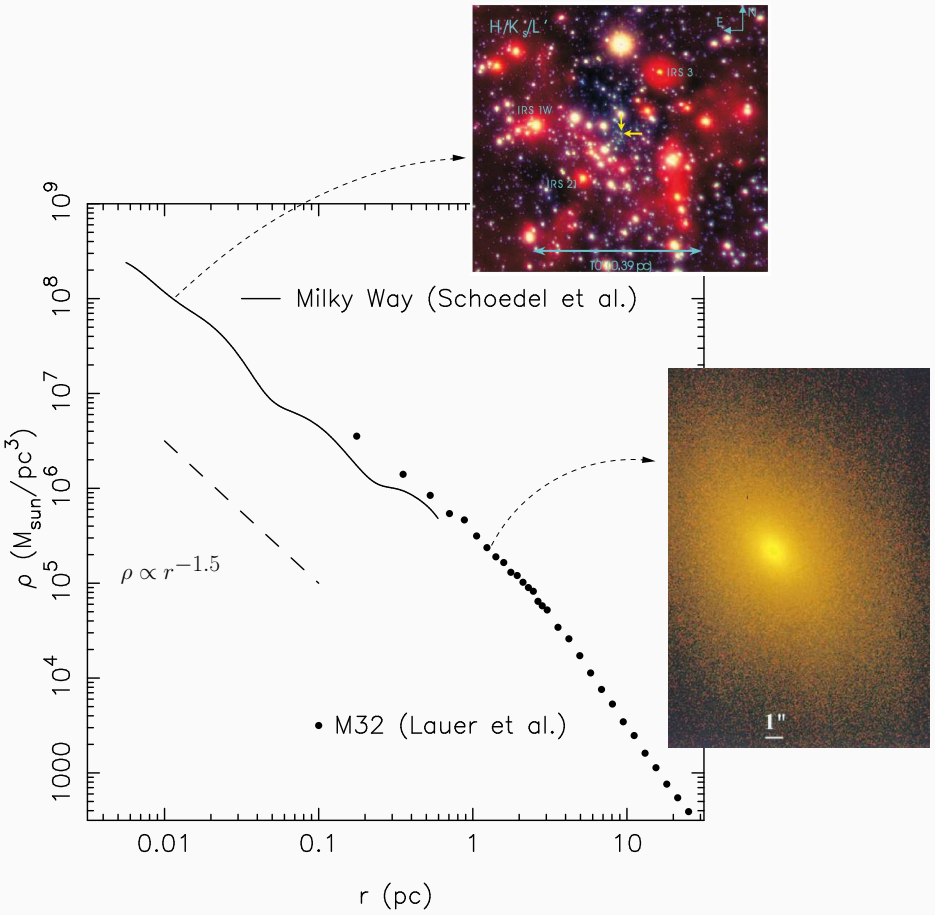

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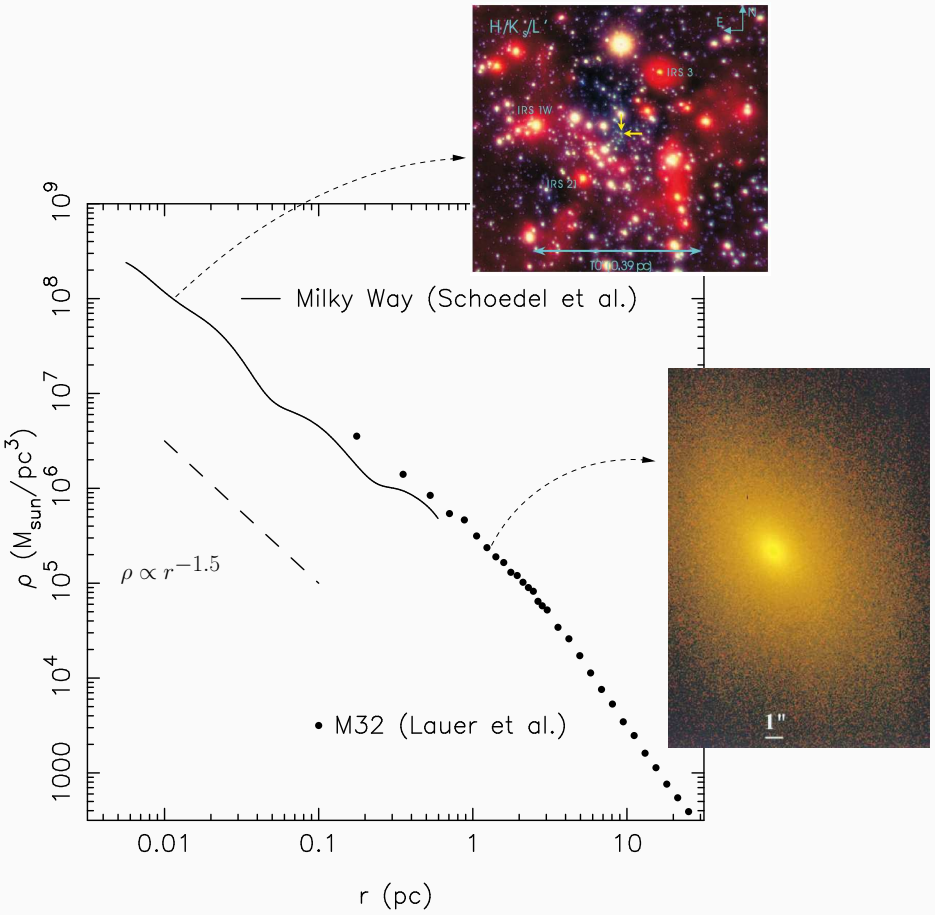

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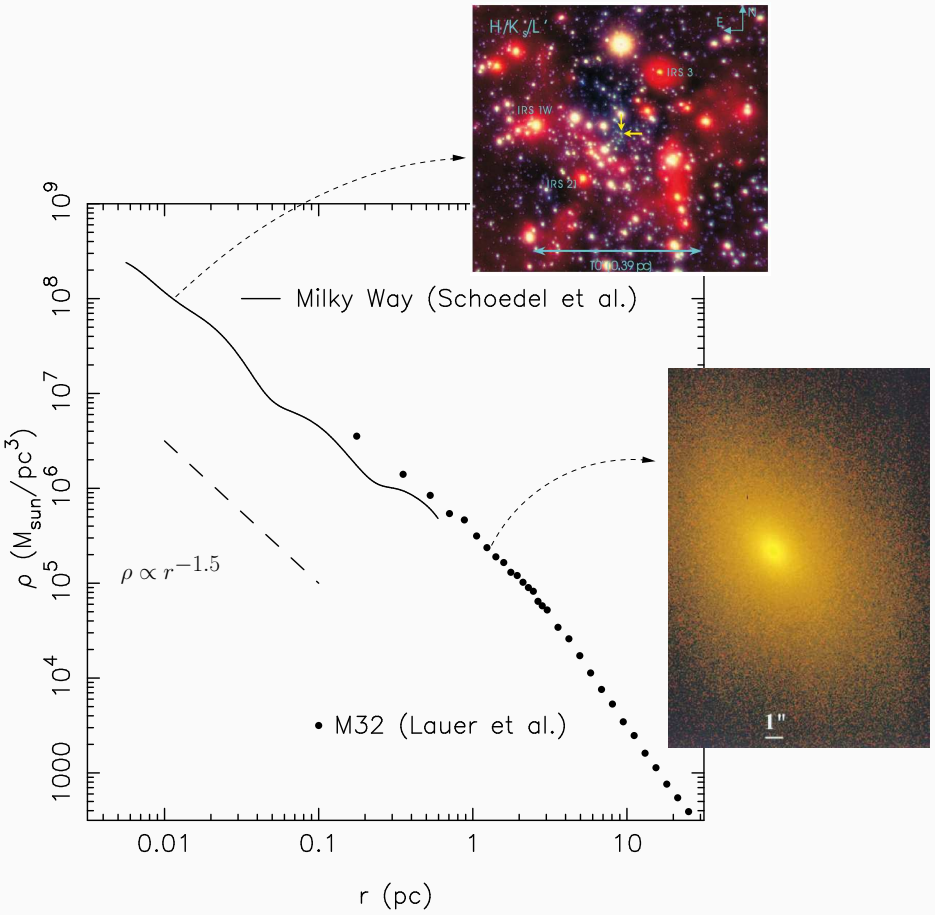

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- Considerable amount of modelling: Are these profiles a coincidence?

Mass segregation

- Classical problem in stellar dynamics: Statistical thermal equilibrium $f(E) \propto e^{-E/\sigma^2}$ must be violated close to the MBH (R_t, R_{Schw}, R_{coll})

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- Confirmed later with a detailed kinematic treatment for single-mass [Bahcall & Wolf 1976]: $\gamma = 7/4$ and $p = \gamma - 3/2 = 1/4$

Strong mass segregation

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- Two branches for the solution: A "weak" (unrealistic) branch and a "strong" branch

  [Hopman & Alexander 2009, Preto & Amaro-Seoane 2010, Amaro-Seoane & Preto 2011]

Impact on rates

$$\Gamma_{\rm EMRI} = f_\bullet \int_{E_{\rm GW}}^{+\infty} dE \, \frac{n(E)}{\ln(J_c(E)/J_{\rm lc})\, T_{\rm rlx}(E)}$$

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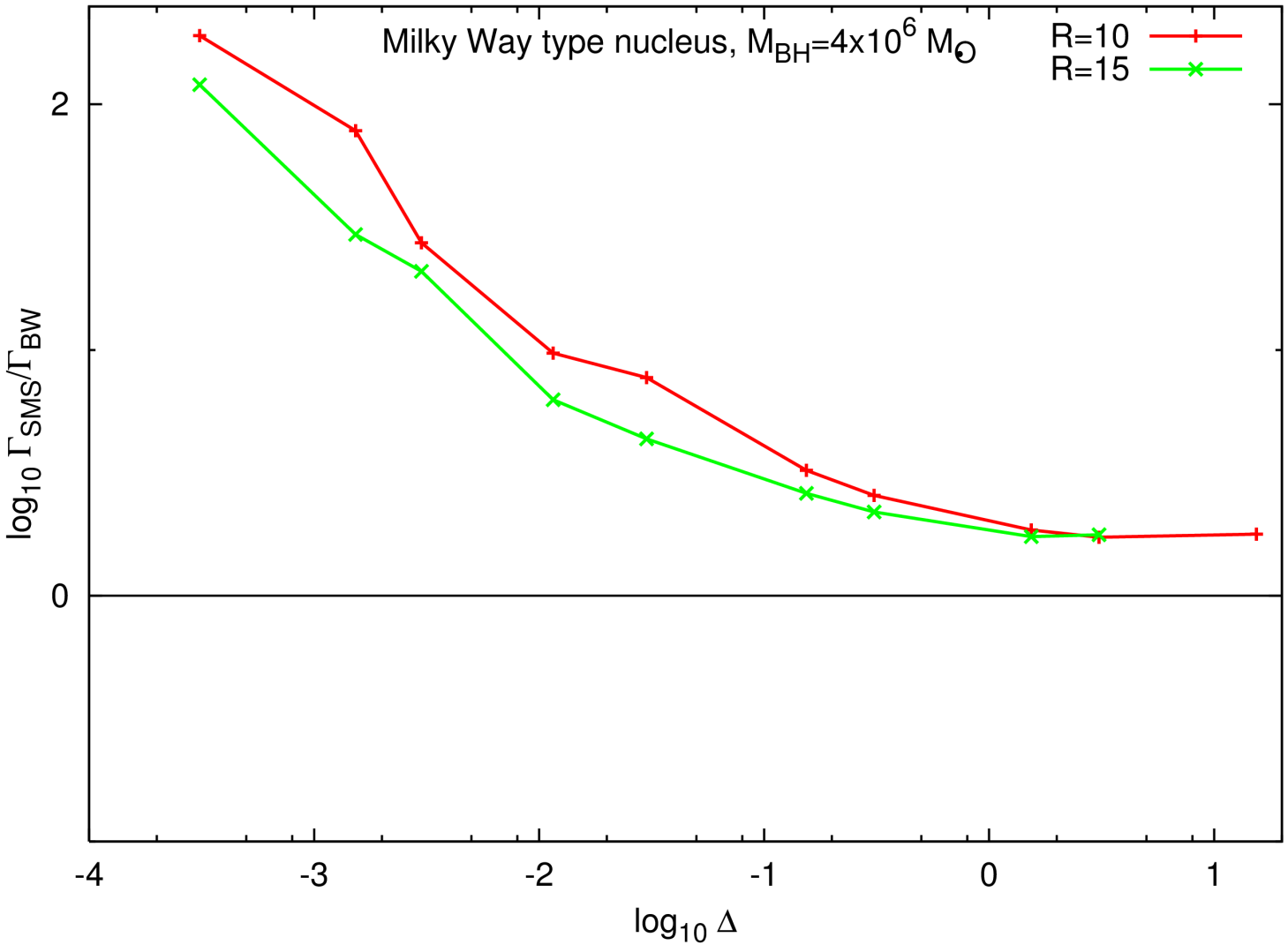
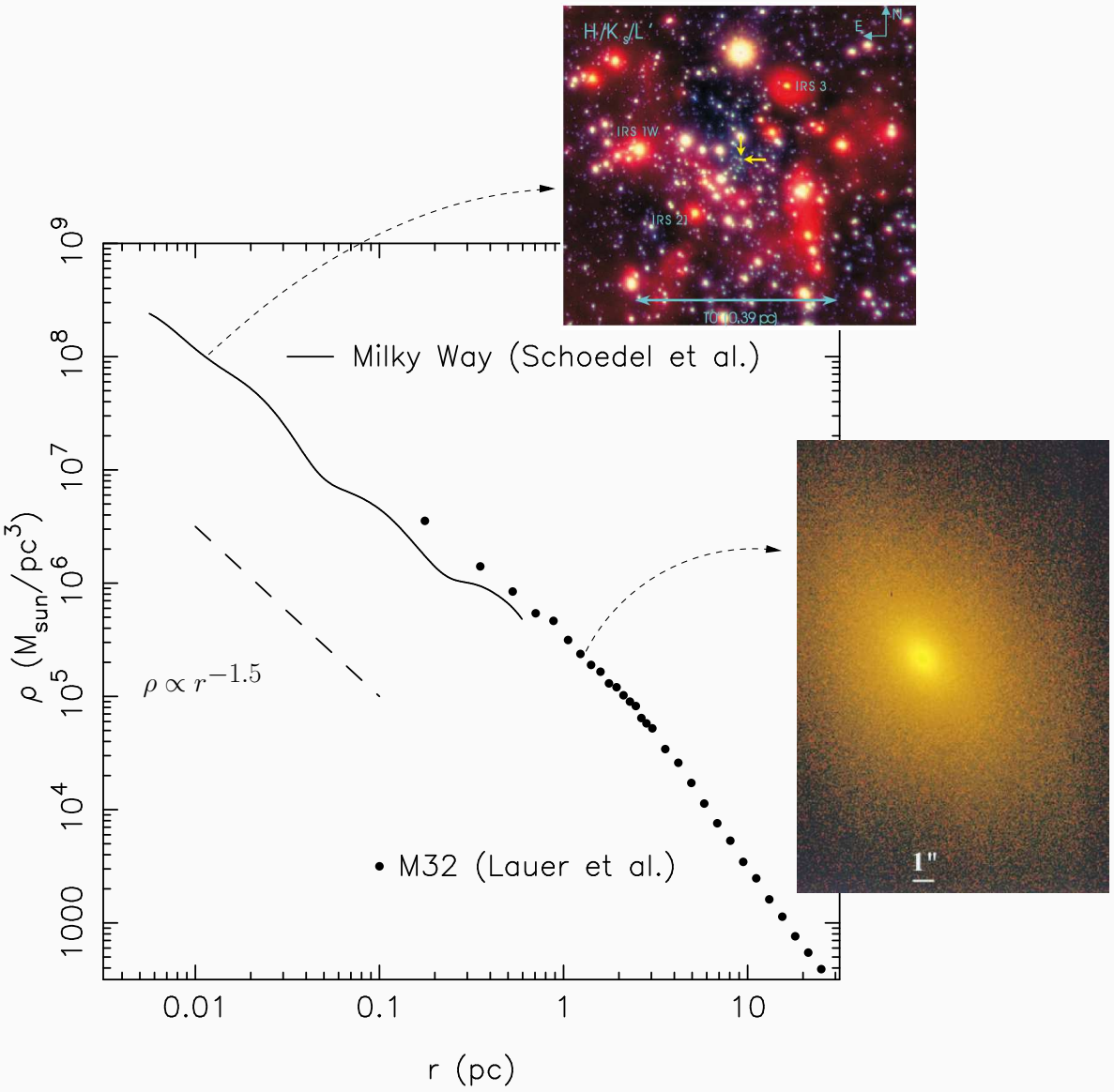
- a_{GW}, or energy E_{GW}, for EMRIs is: $a_{GW} = 0.01 r_h$

Boost on rates



Cusps - Observers: You got it right

Old times



[Adapted from Merritt 2006]

Cusps - Observers: No, you got it wrong

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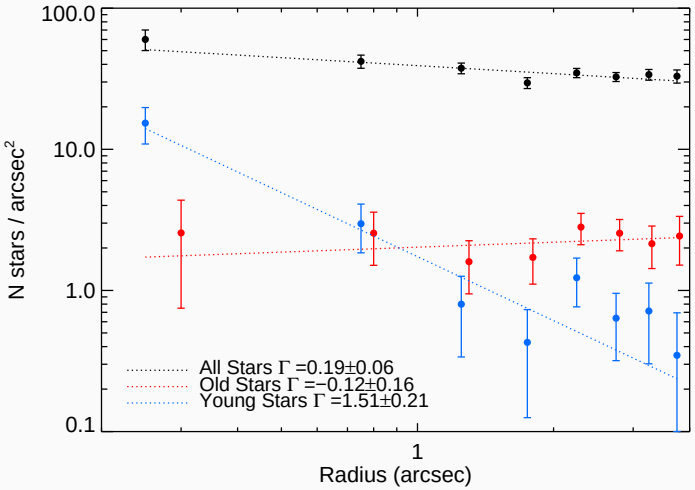

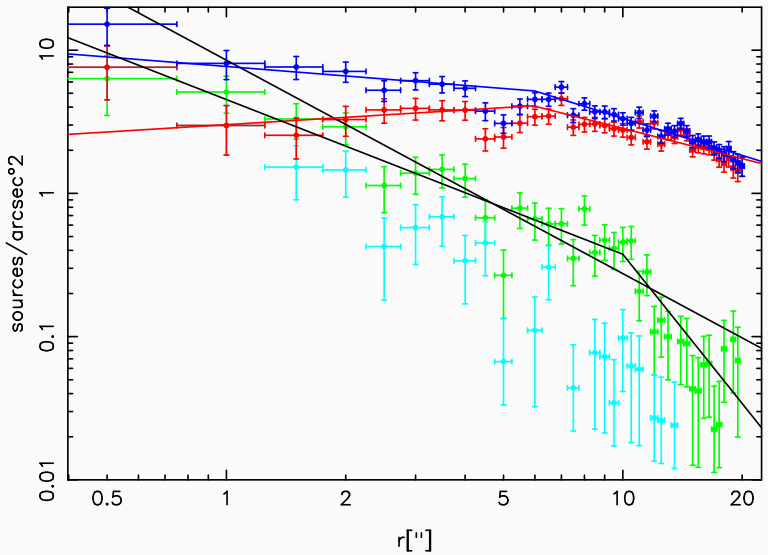

- We can distinguish the young and old population and see a deficit of old stars

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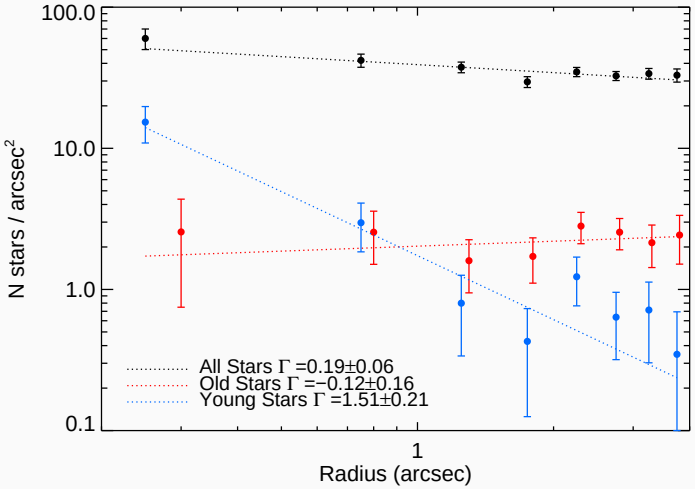

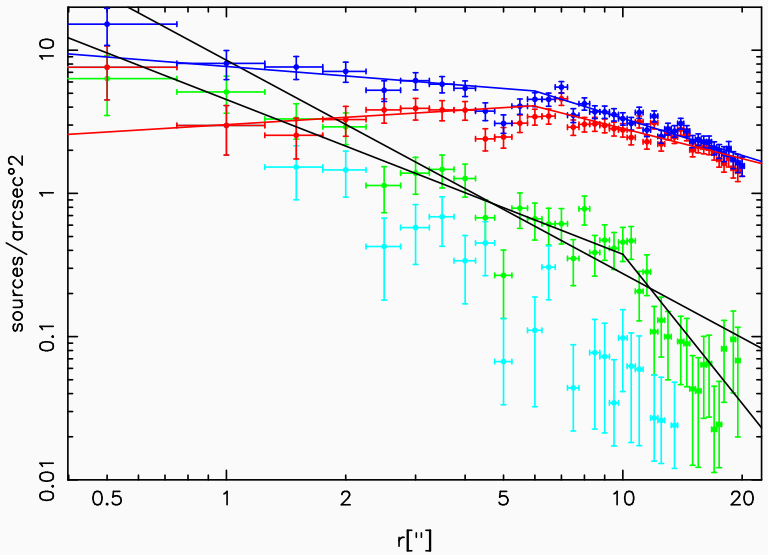

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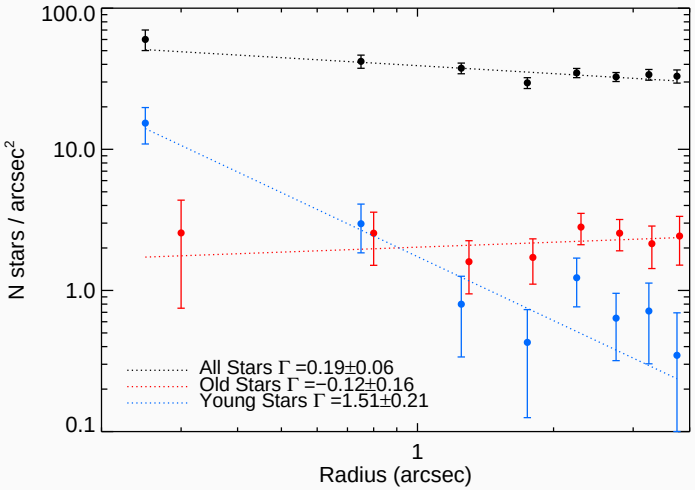

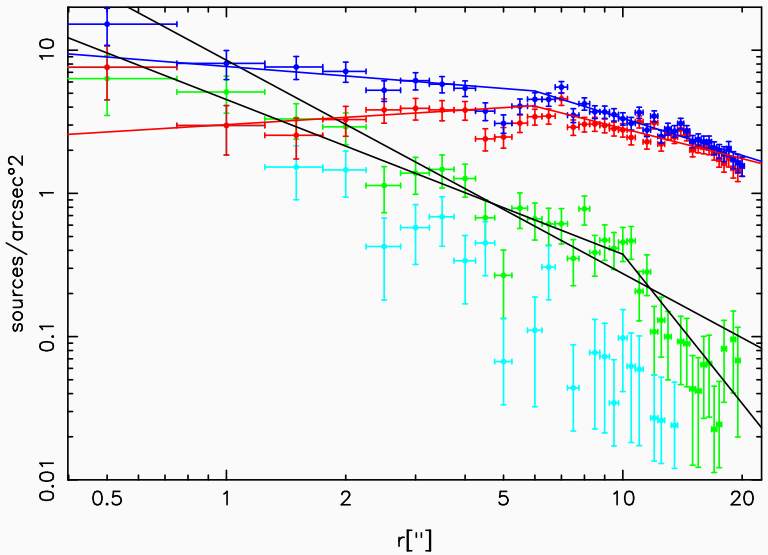

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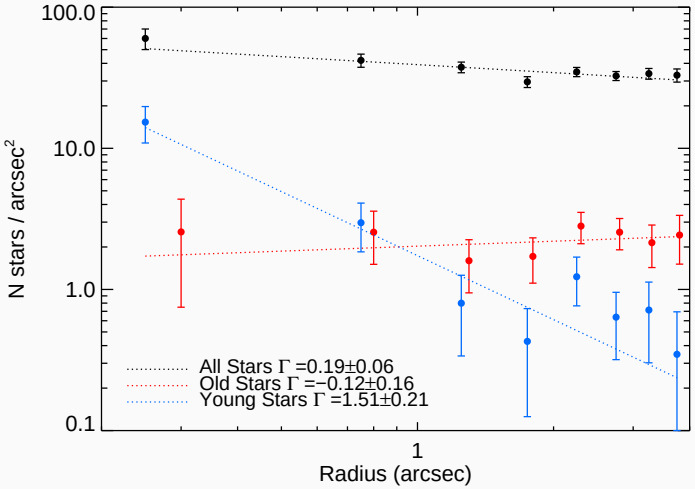

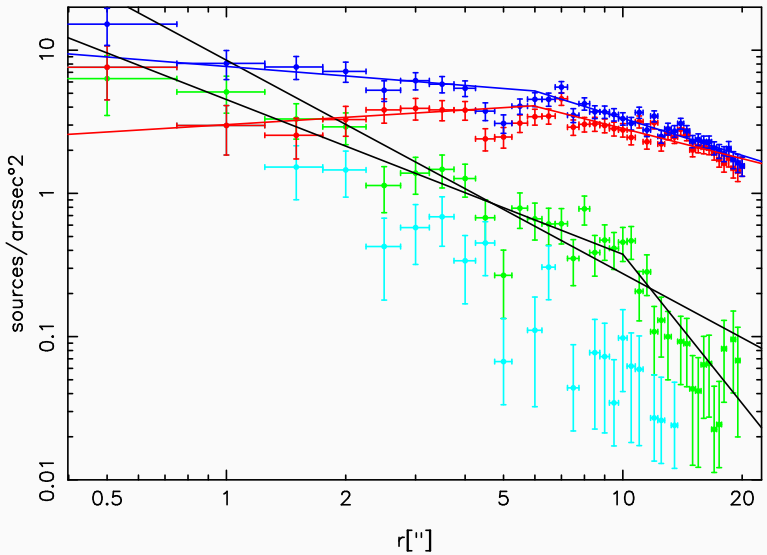

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- Possibility of a core with $\rho_\star$ decreasing, looks like someone carved a hole
- This is old news We know that the problem is not that acute

[Schödel+ and Pau Amaro-Seoane, 2016, Baumgardt, Amaro-Seoane & Schödel 2016]

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③ If by extrapolation this is typical of many galaxies, cosmic rate drops

How do you carve a hole at the Galactic Center?

1. Infalling clusters carve a hole – But need a steady inflow of one at roughly every 10^7 years

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- ▷ With the correct solution of mass segregation, it's short ... about 1/4 of T_{rlx}

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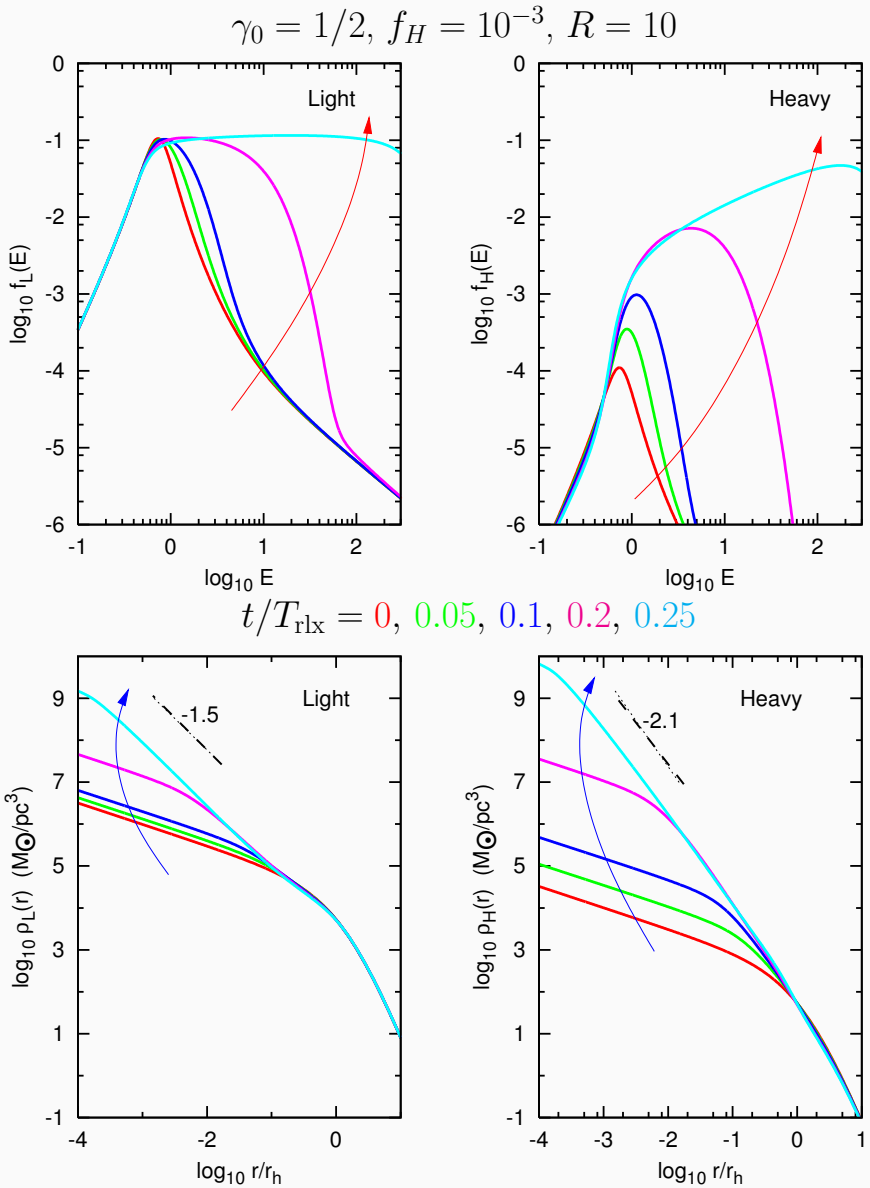
Isocore ... regrowth



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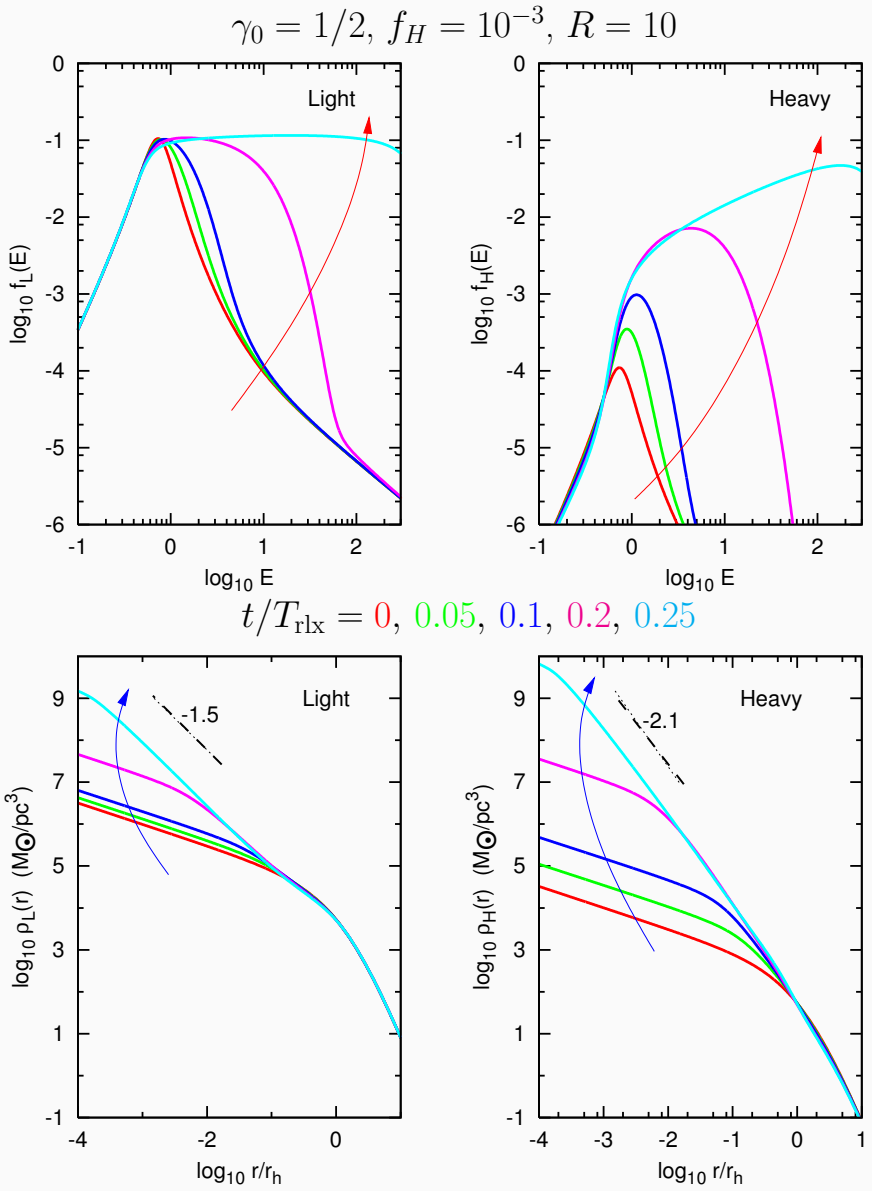

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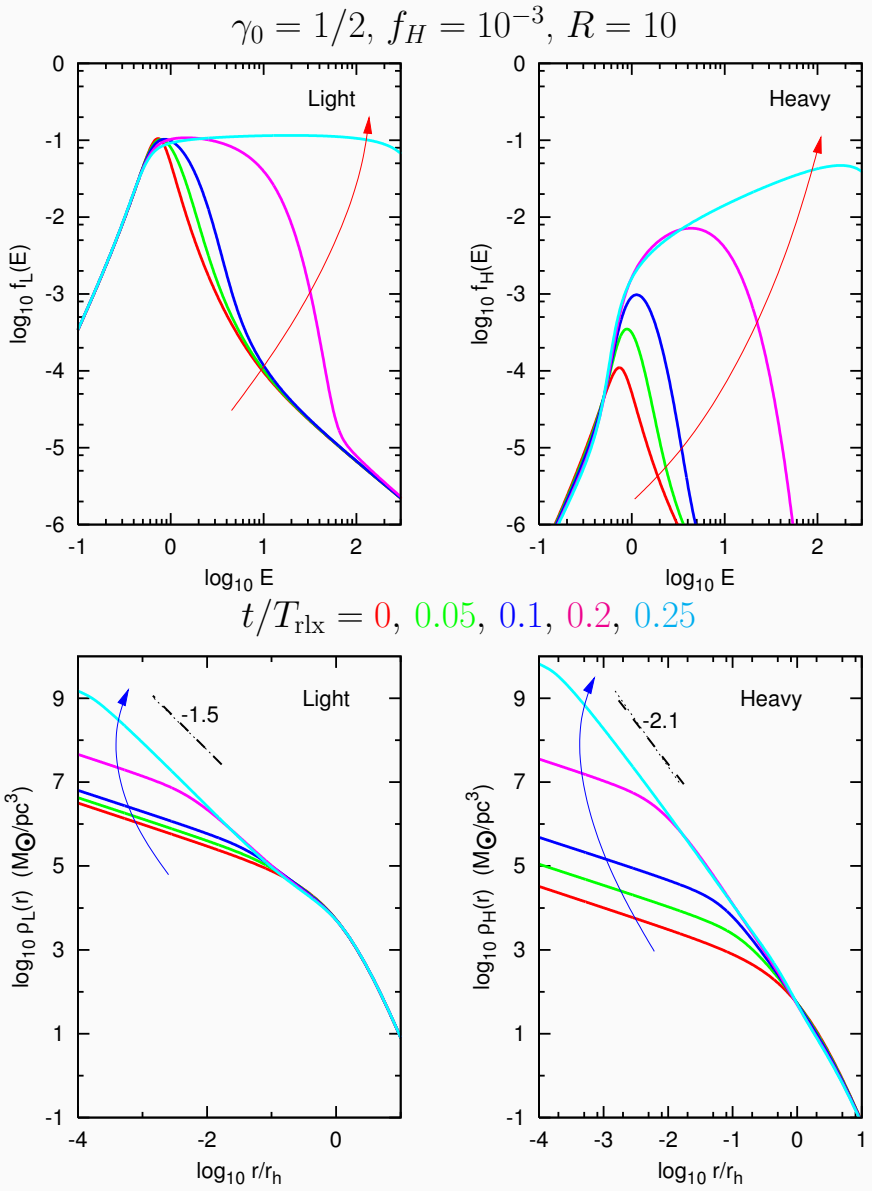

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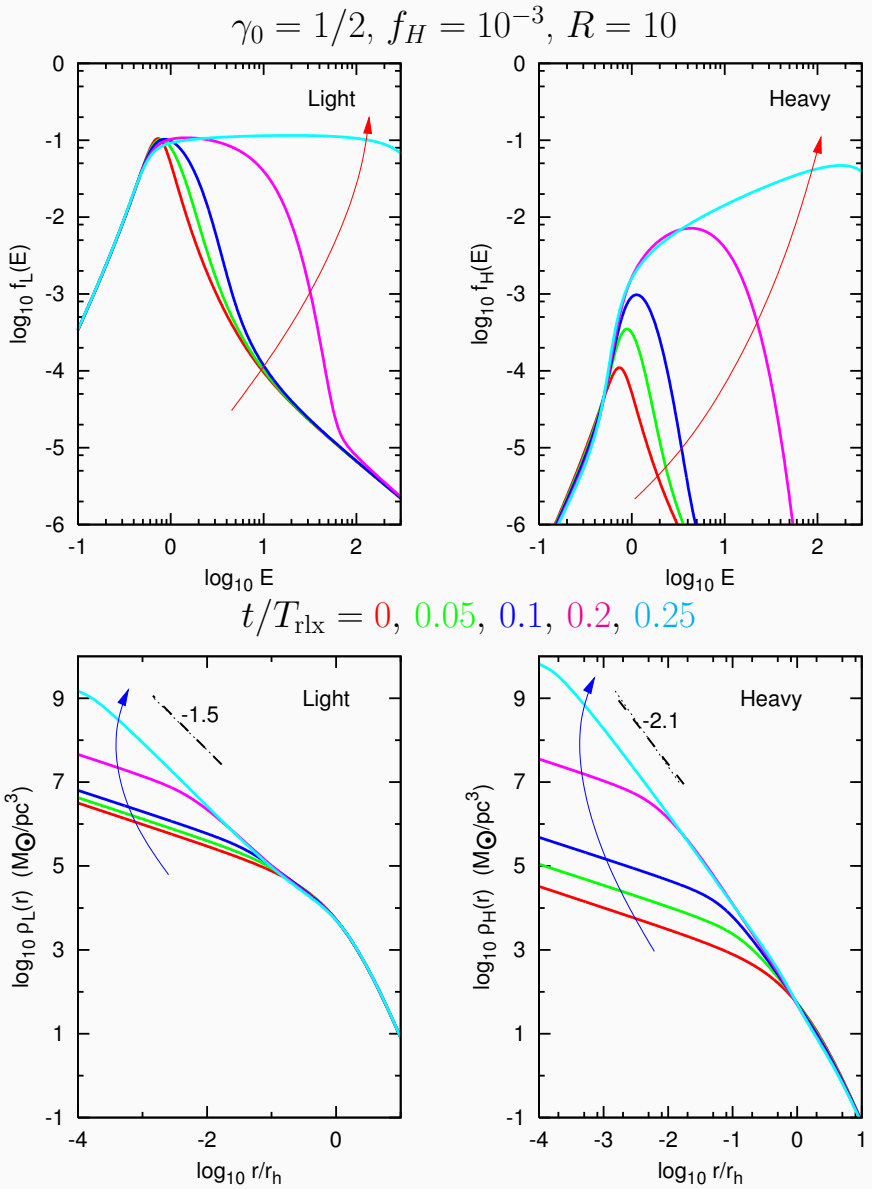

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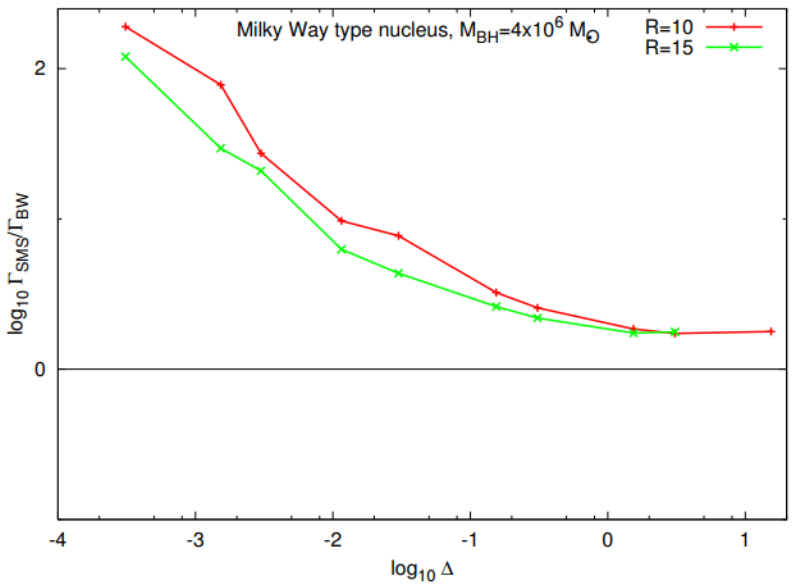
- The Milky Way nucleus is not necessarily the prototype of the nucleus from which LISA detections will be more frequent
- We still expect that a substantial fraction of EMRI events will originate from segregated stellar cusps, in particular with our new solution of mass segregation

So: Stellar-mass black holes pile up in galactic nuclei

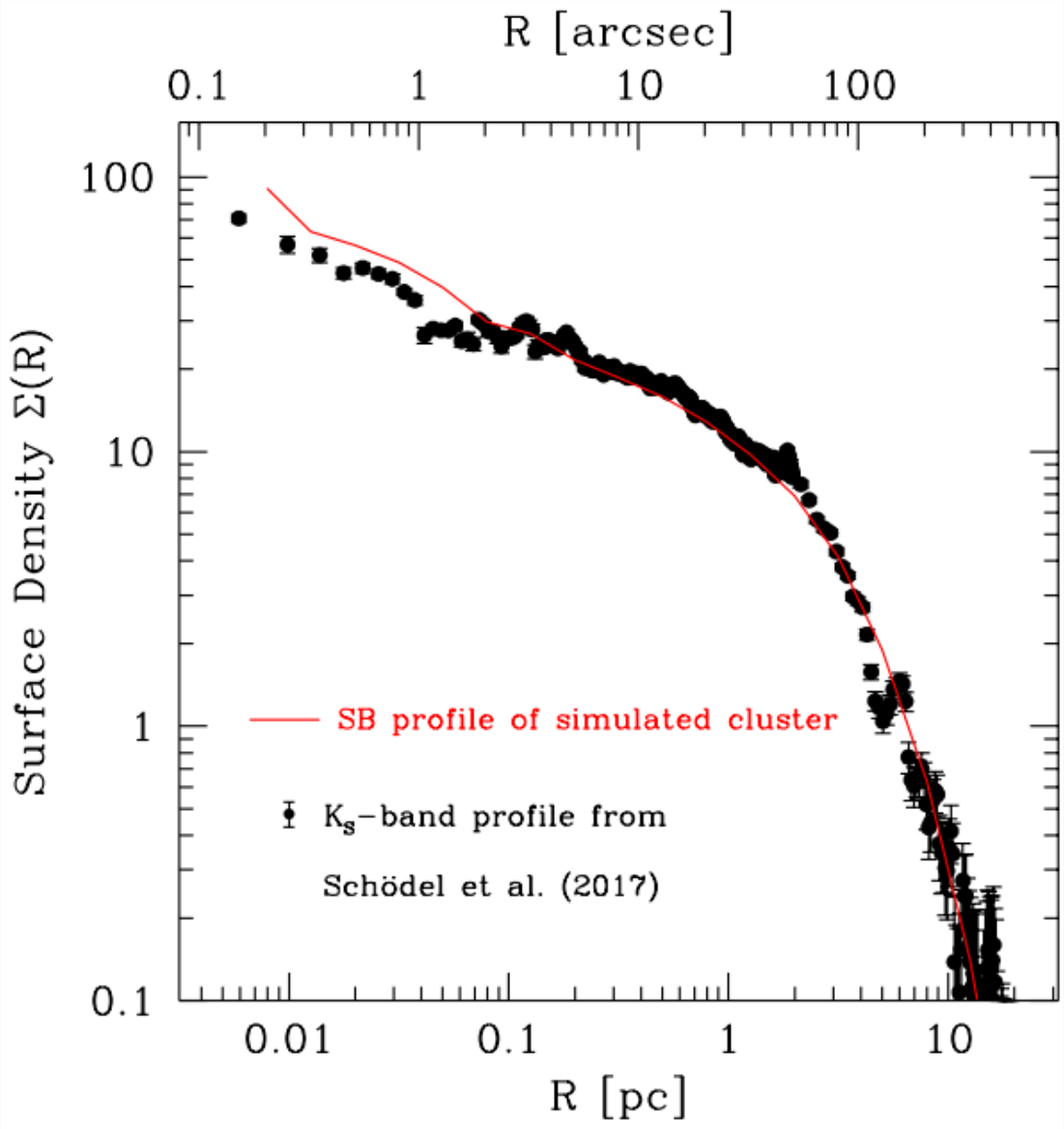


Stars and stellar-mass black holes distribute in the galactic nucleus trying to reach an equipartition of energy in such a way that compact objects (stellar-mass black holes) will dominate in mass density close to the density center of the nucleus.

[PAS et al 2004, Khalisi, PAS & Spurzem 2006, PAS & Preto 2010, Preto & PAS 2010]

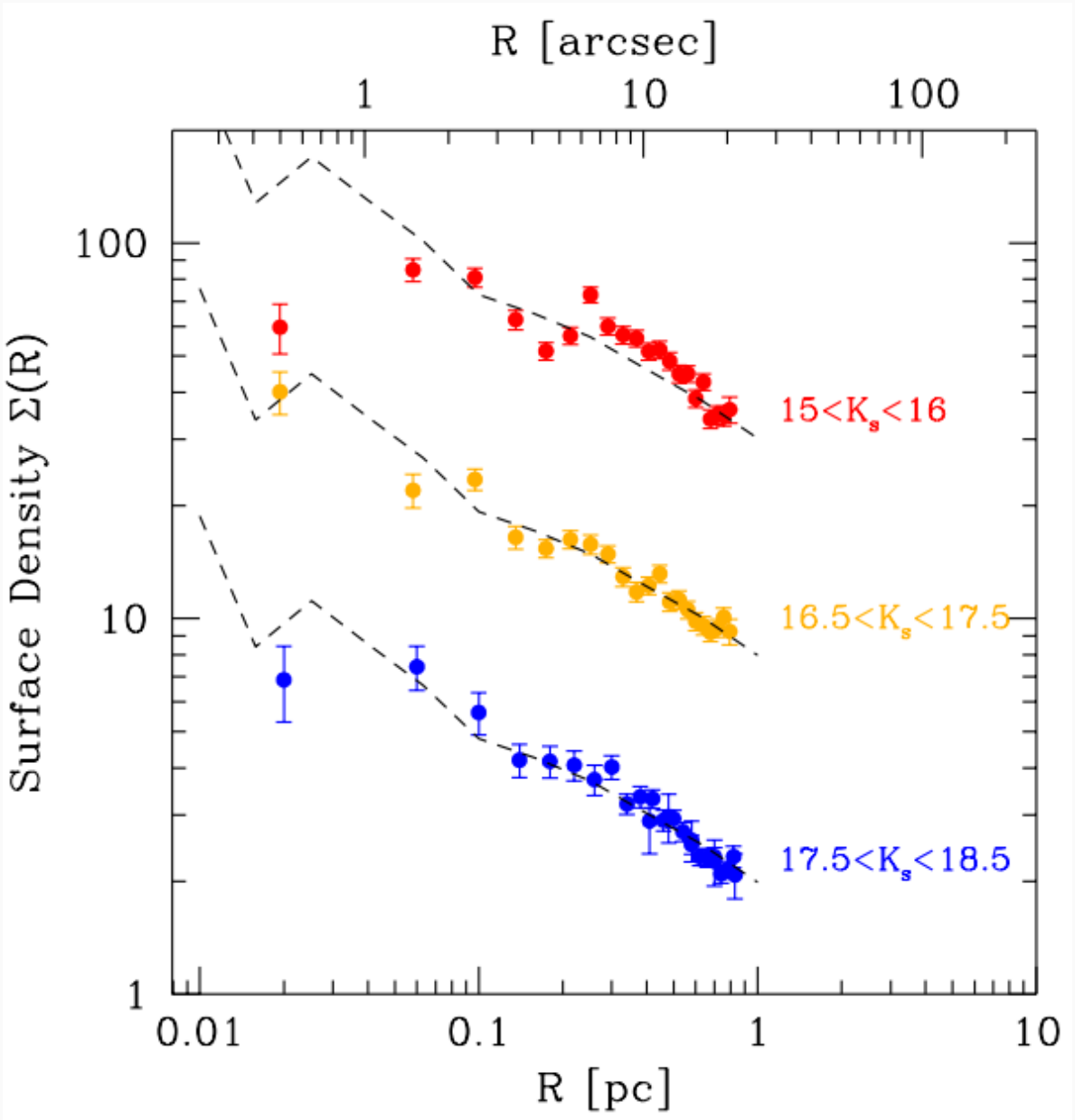
Cusps - Observers and theoreticians: We got it right

Things are just fine



[Baumgardt, Amaro-Seoane & Schödel 2018, and data from Schödel et al + Gallego et al, including PAS 2018]

Observations confirmed with simulations confirm our model



Binaries of supermassive black holes

Merging galaxies

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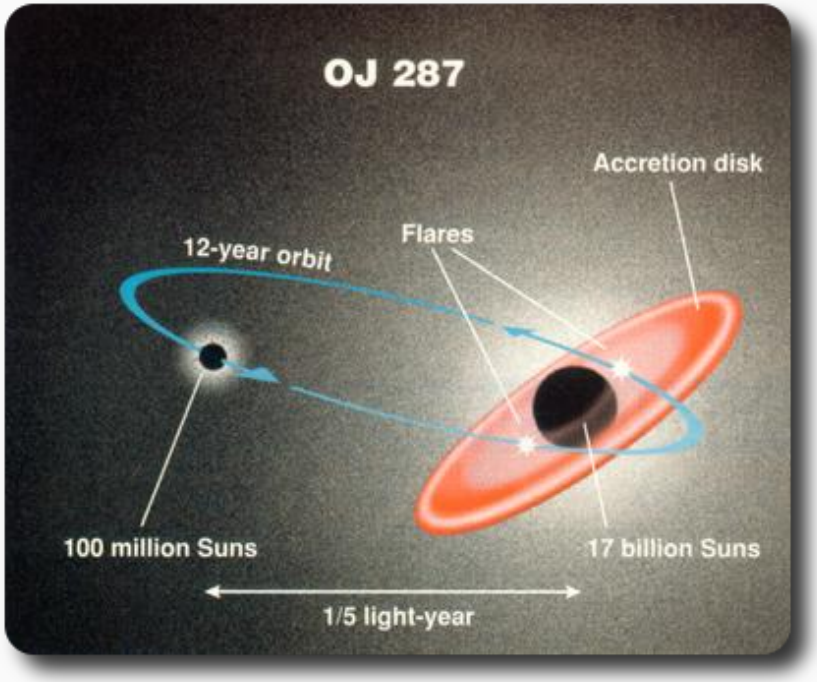
  How many have we seen?

Observed binaries of MBHs



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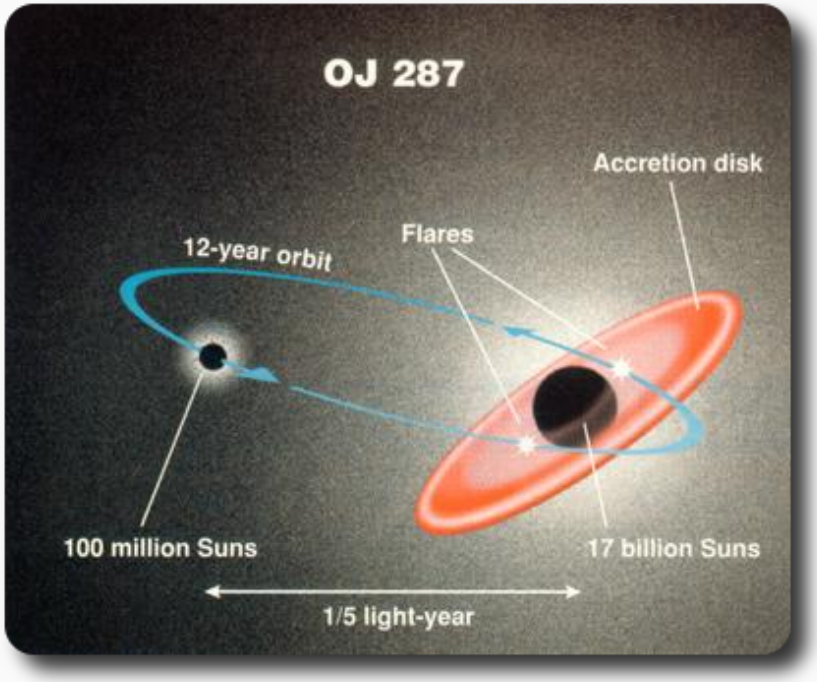

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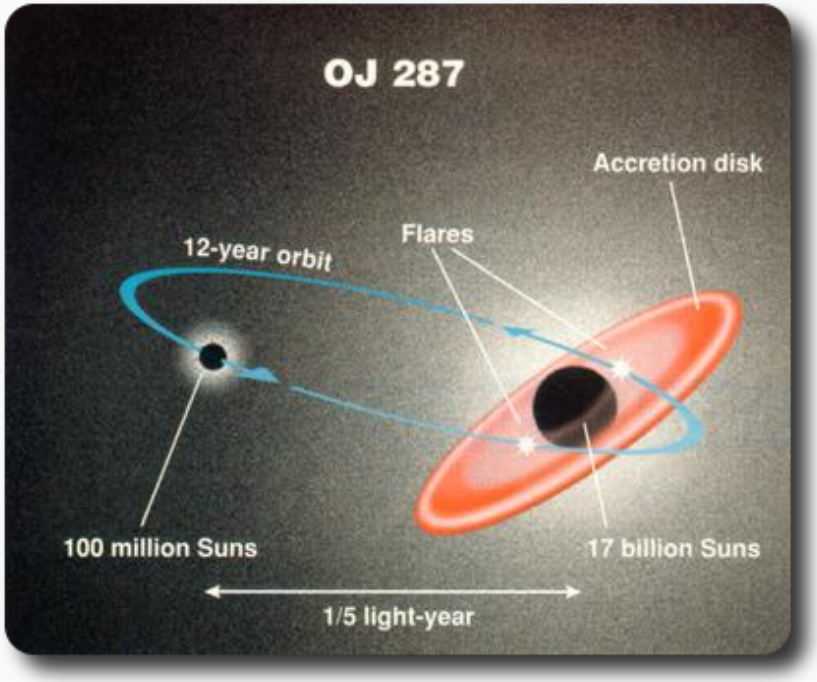

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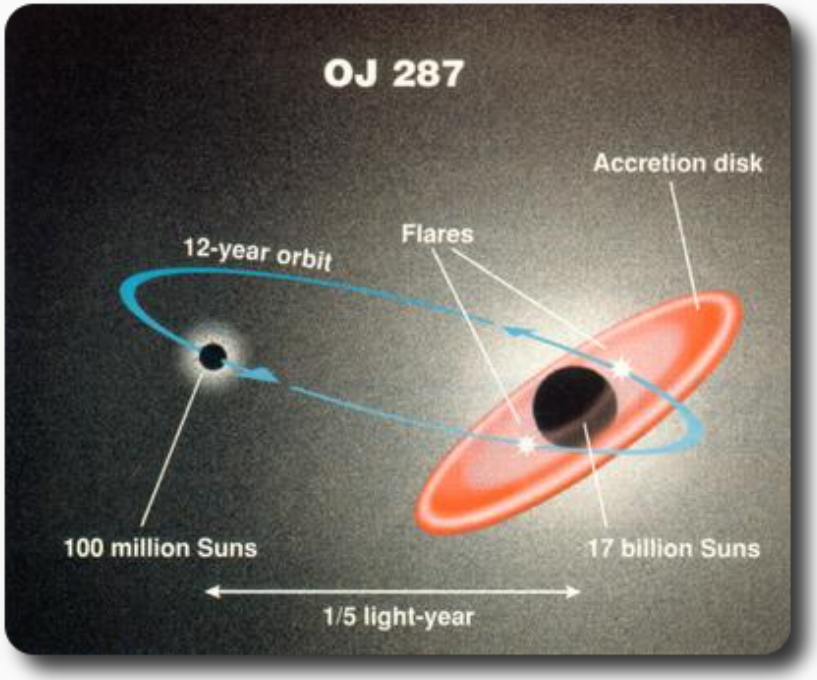

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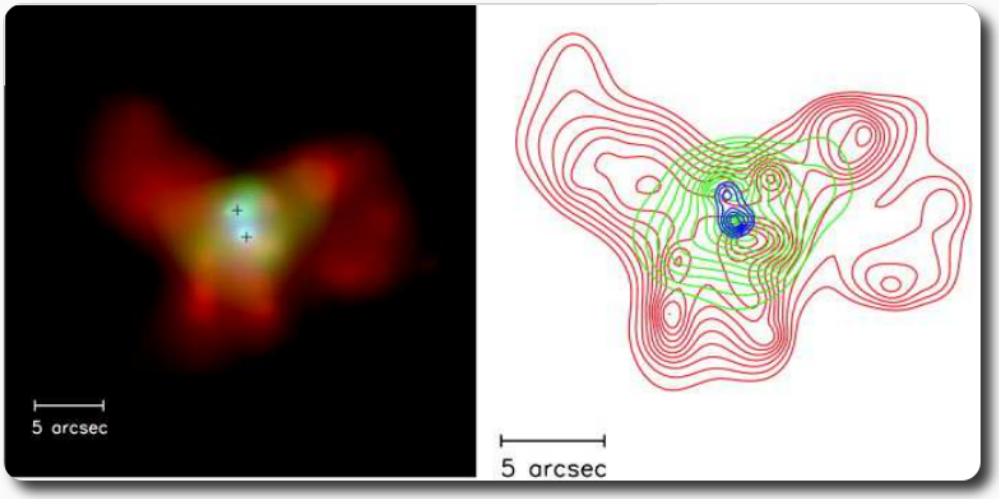
  OJ287 – or not? It's a blazar! BL Lac

Alternatives



[Komossa et al. 2003]

✓ Observations can be explained with other alternatives

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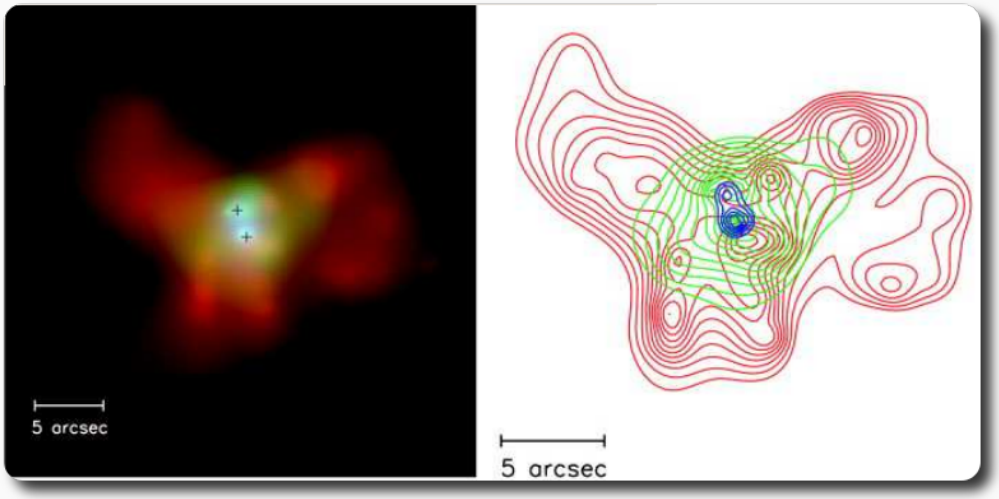

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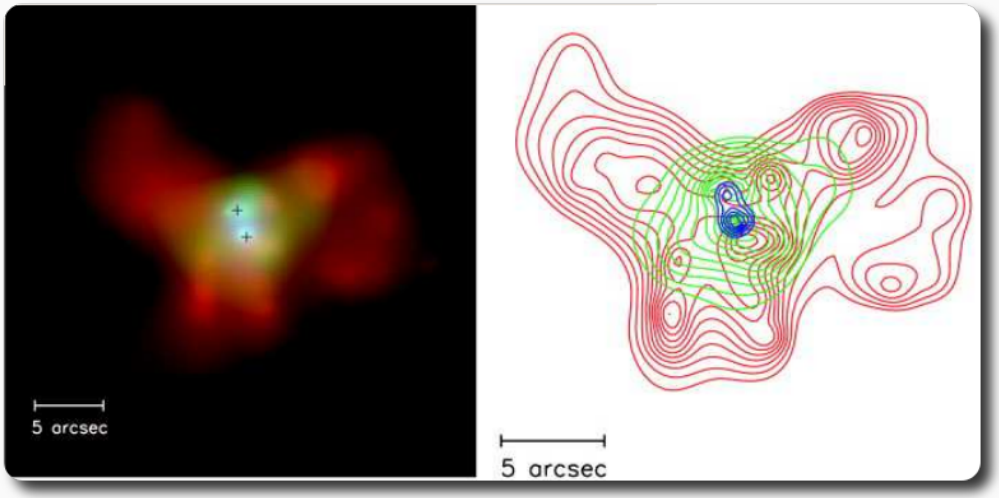

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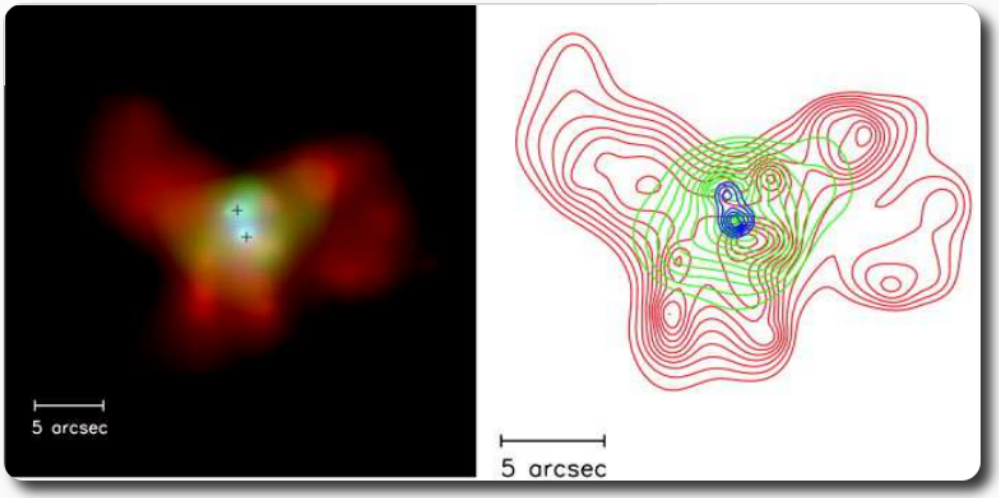

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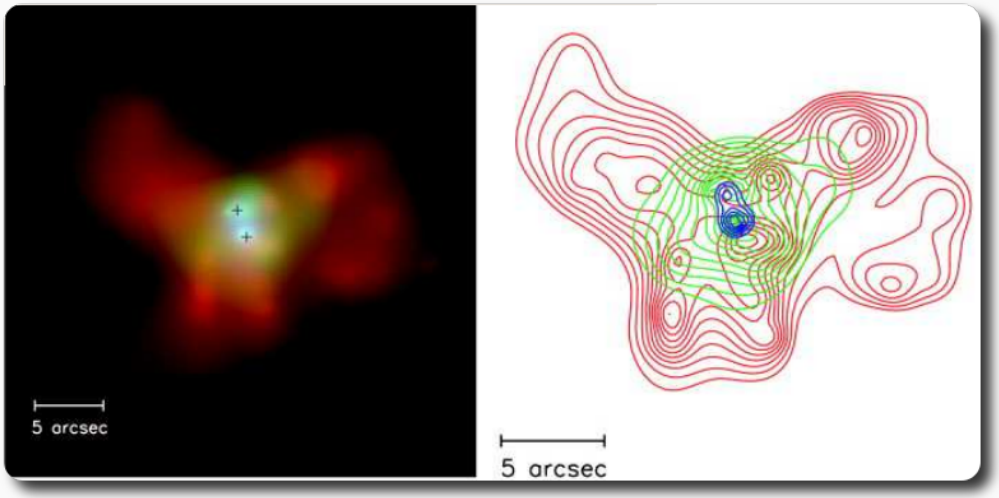

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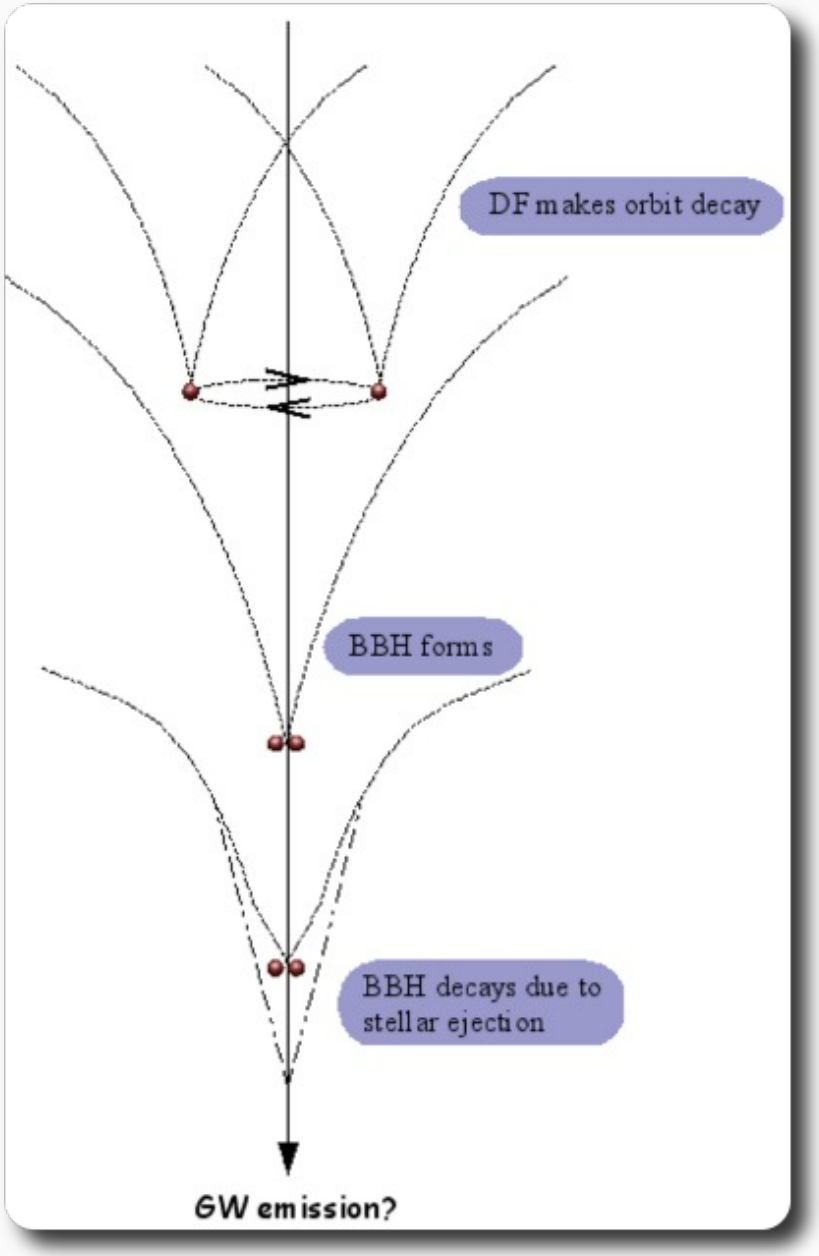
- ✓ Another example: NGC6240 - Note: 1 arcsec = 700 pc

No observed systems

Reference	Object	Feature	M_1, M_2 $(10^9 M_\odot)$	Separation (pc)
Sillanpaa et al. 1988	OJ 287	Optical light curve	5, 0.02	0.1
Kaastra & Roos 1992	3C 273	Wiggly jet	>1, ?	0.01
Roos et al. 1993	1928 +738	Wiggly jet	0.1, 0.01	0.01
Conway & Wrobel 1995	Mrk 501	Jet mis-alignment	0.1, 0.01	0.01
Gaskell 1990	3C390.3	$H\beta$ radial velocity changes	4, 2	0.3

Forming binaries of SMBHs

Formation of binaries of MBHs



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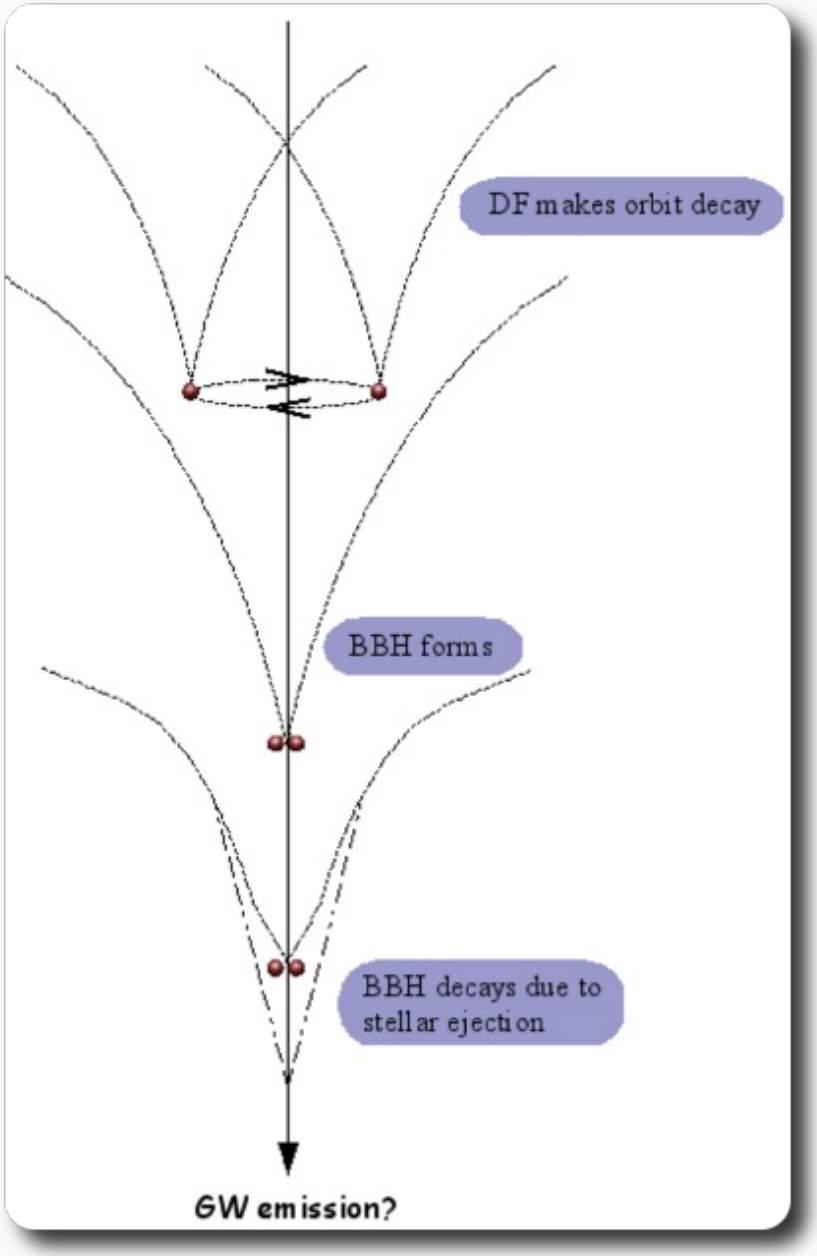

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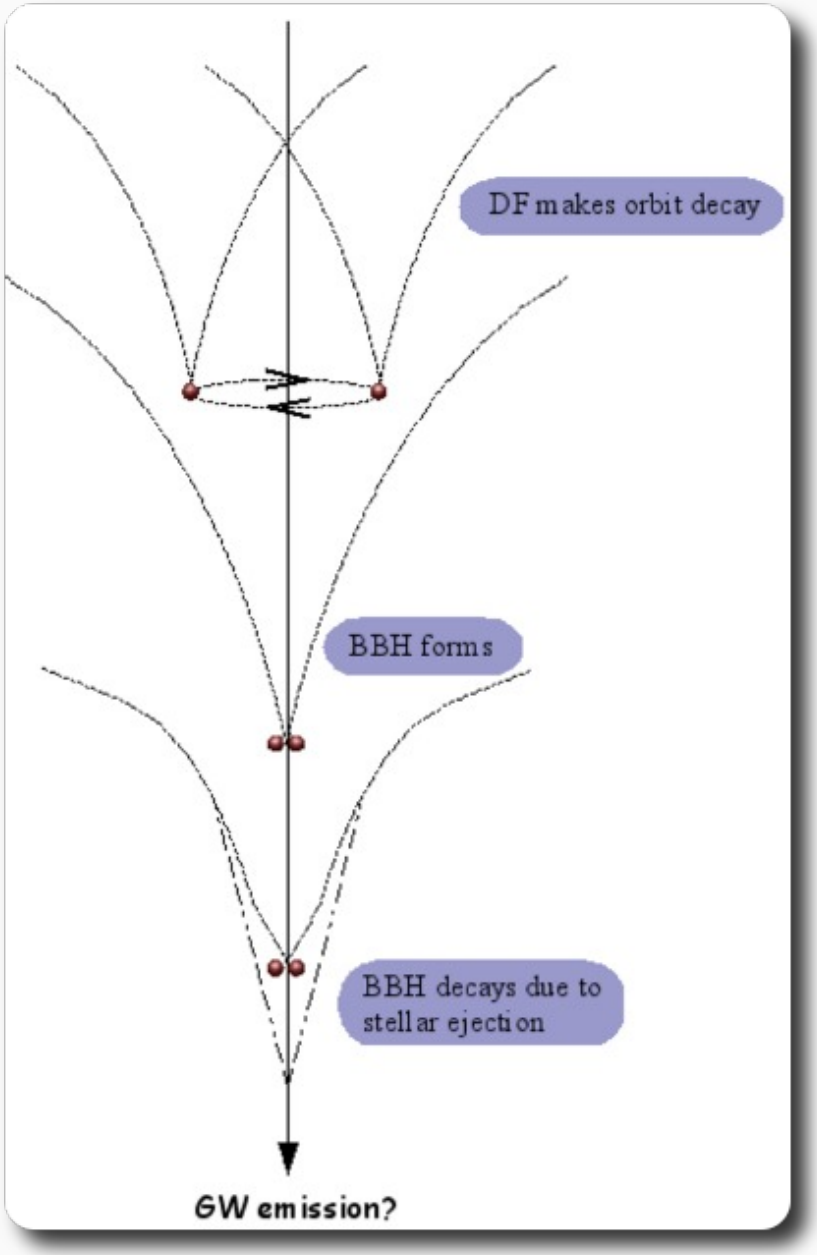

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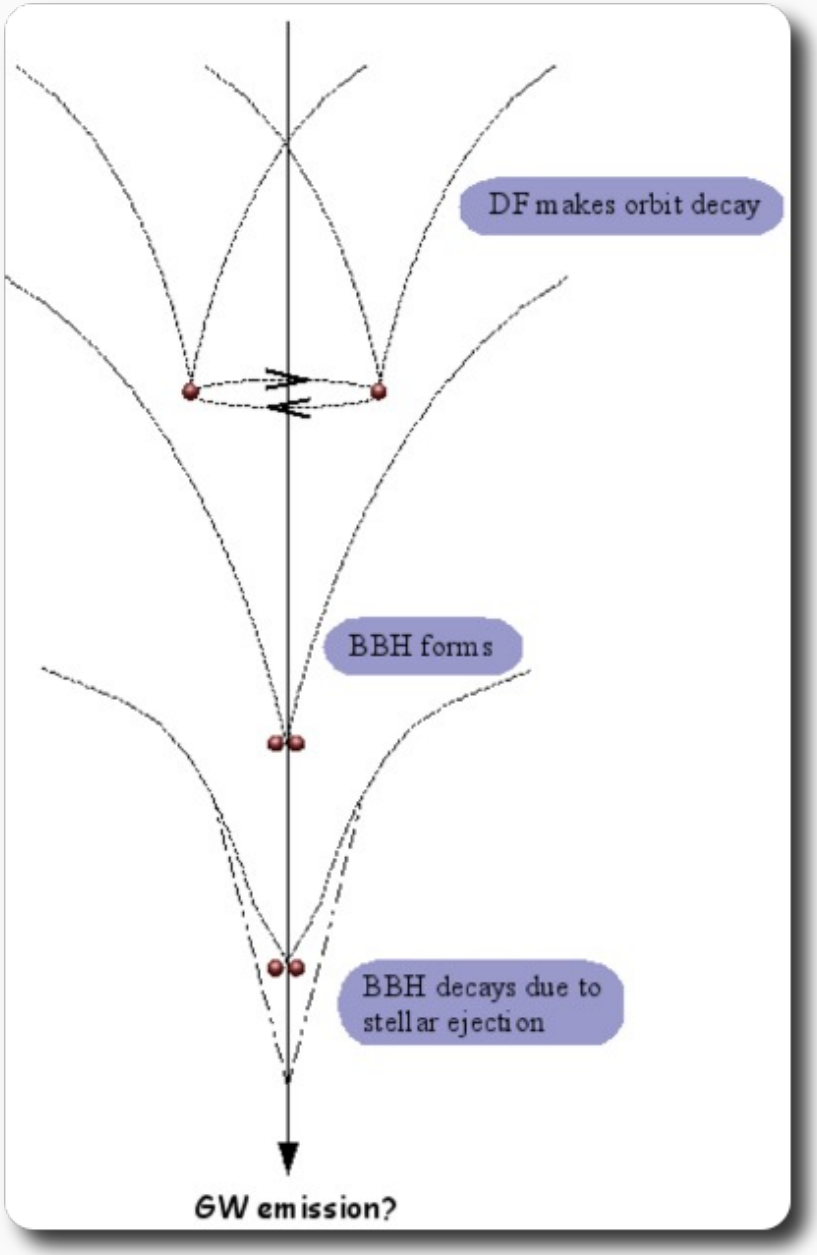

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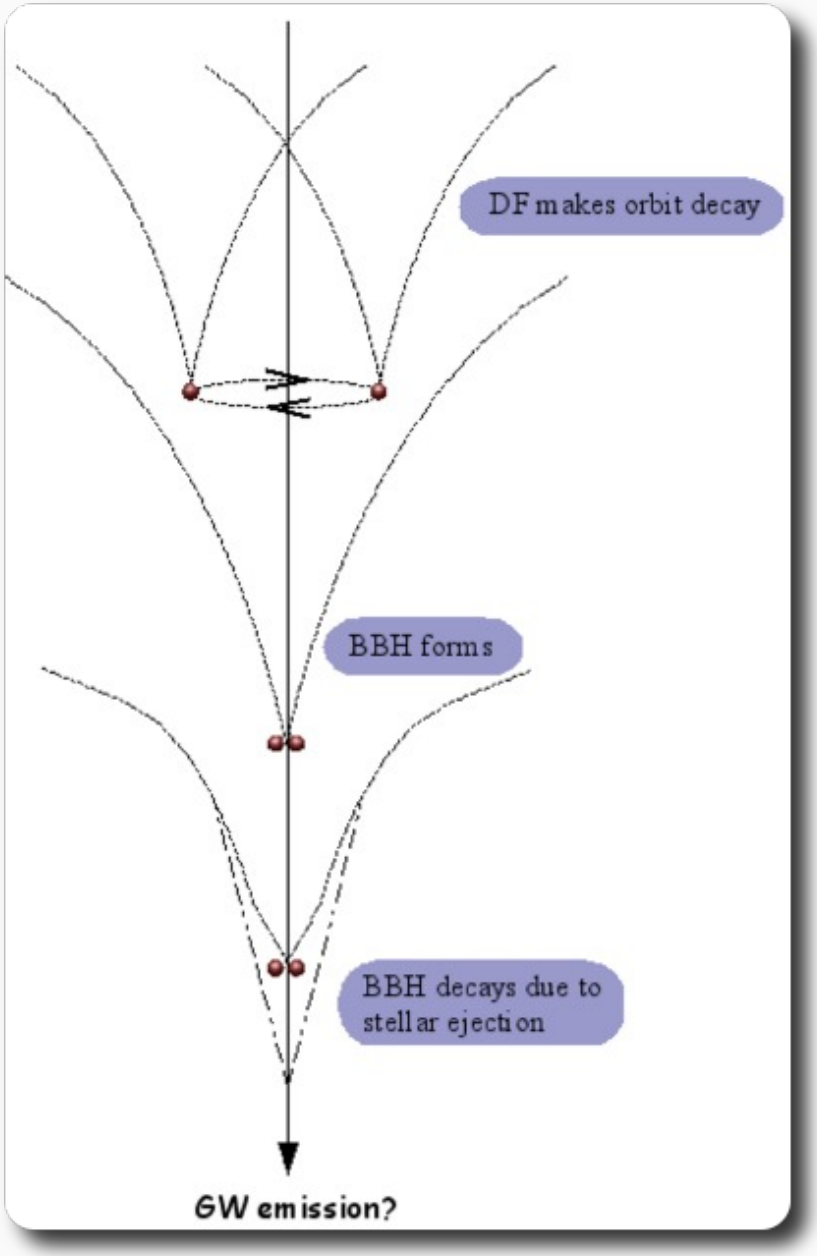

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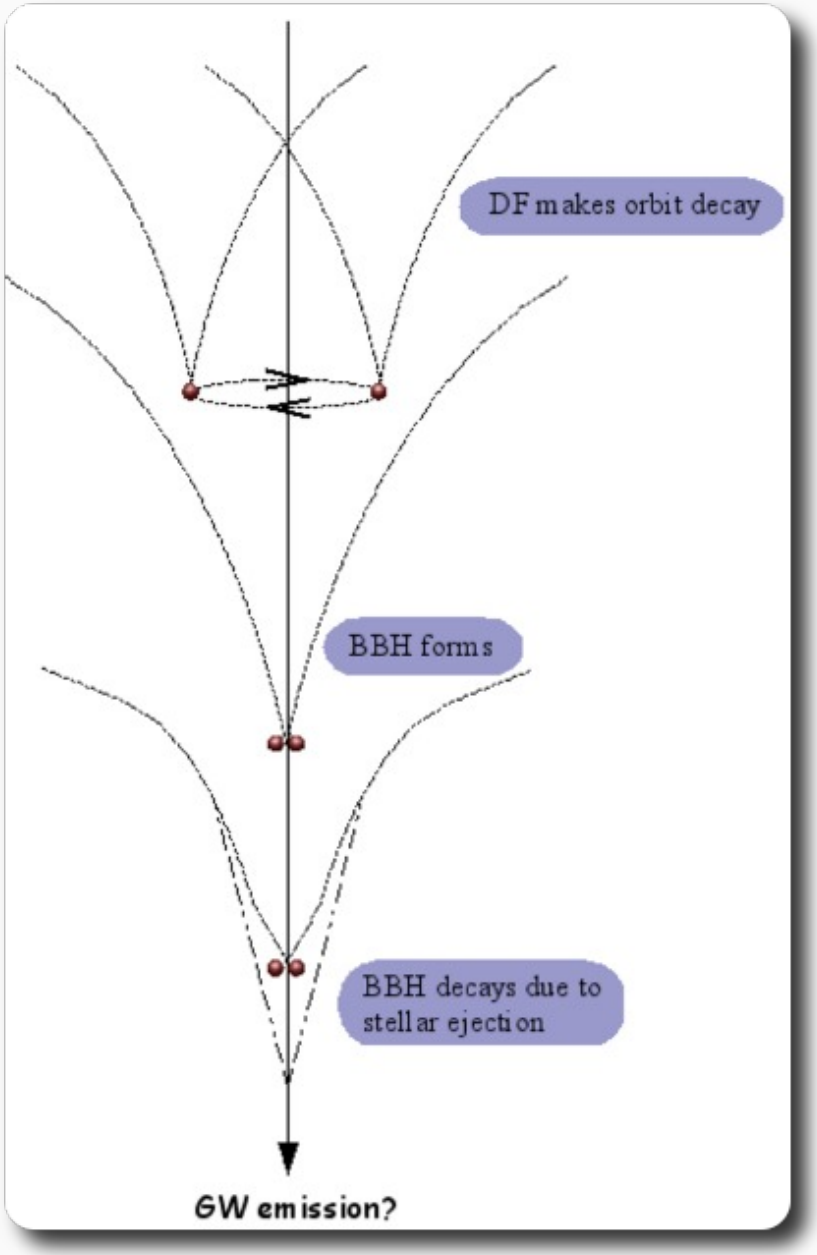

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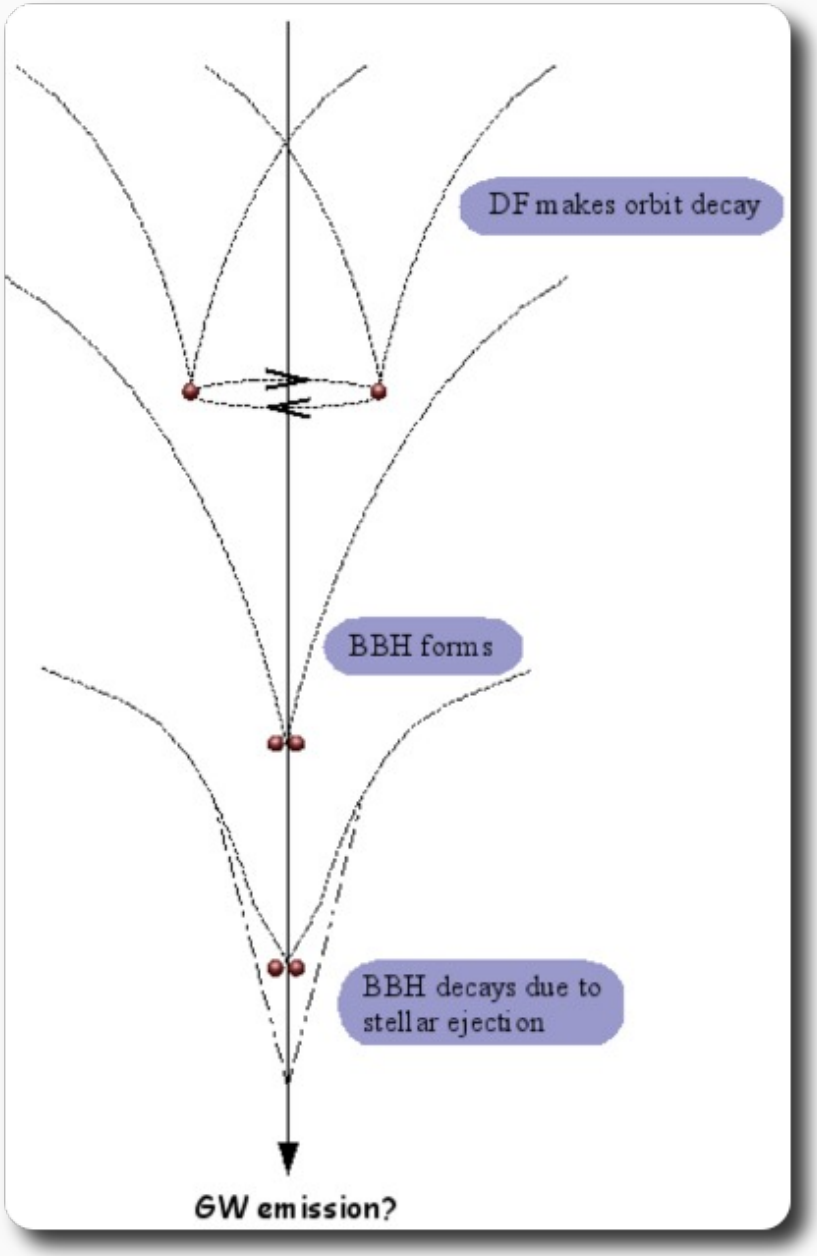

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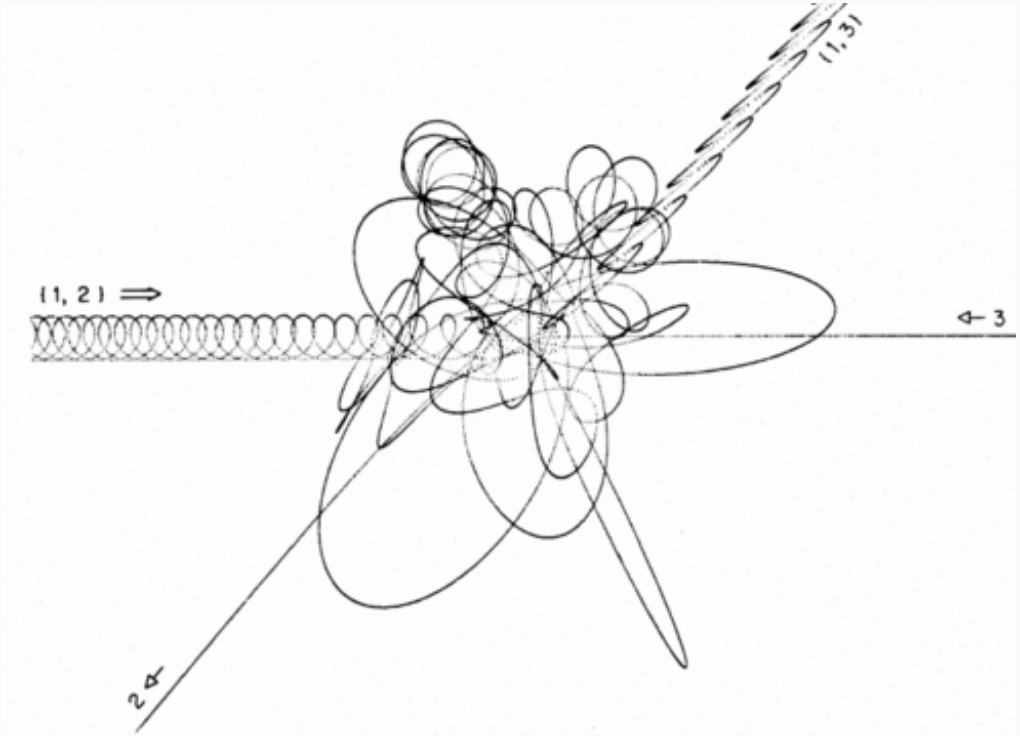

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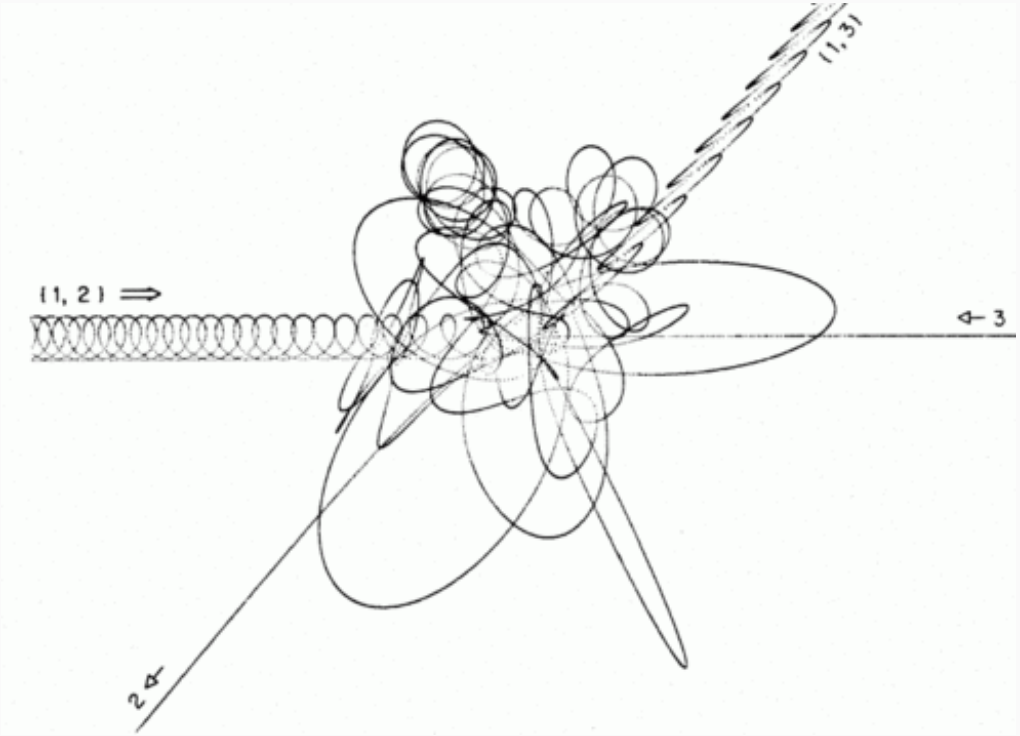

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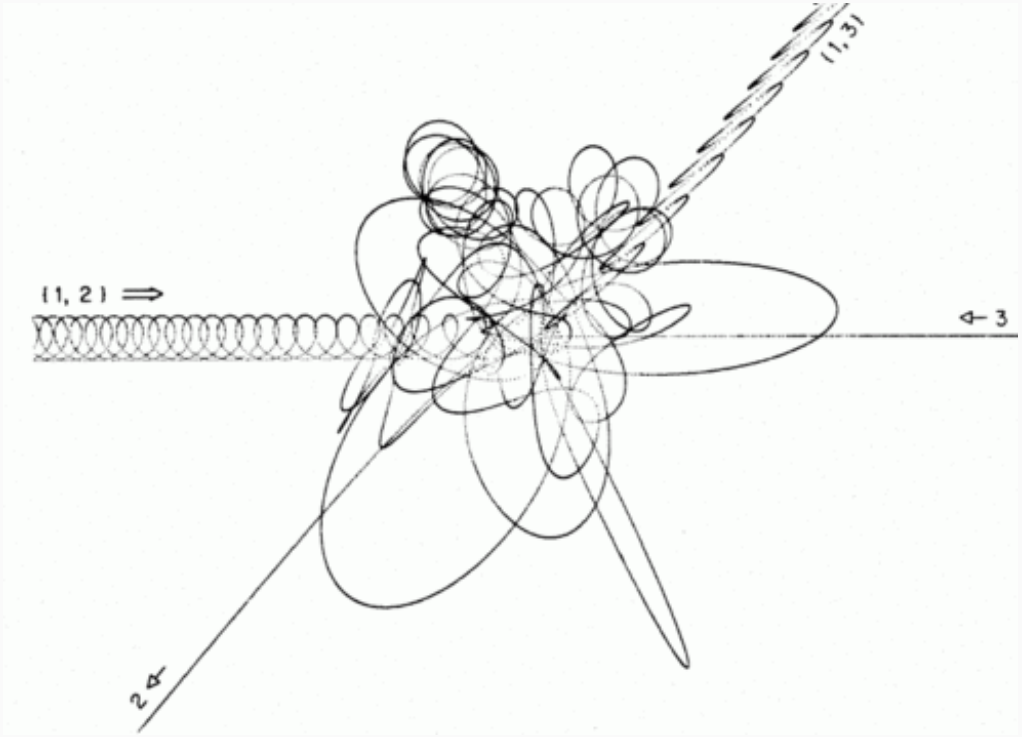

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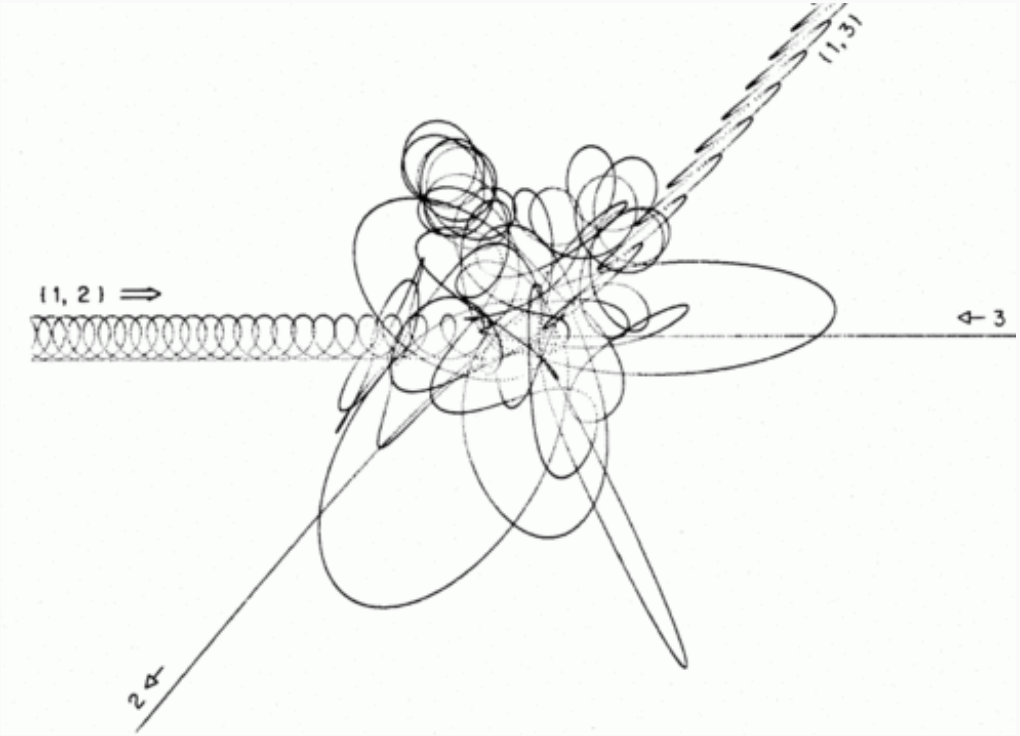

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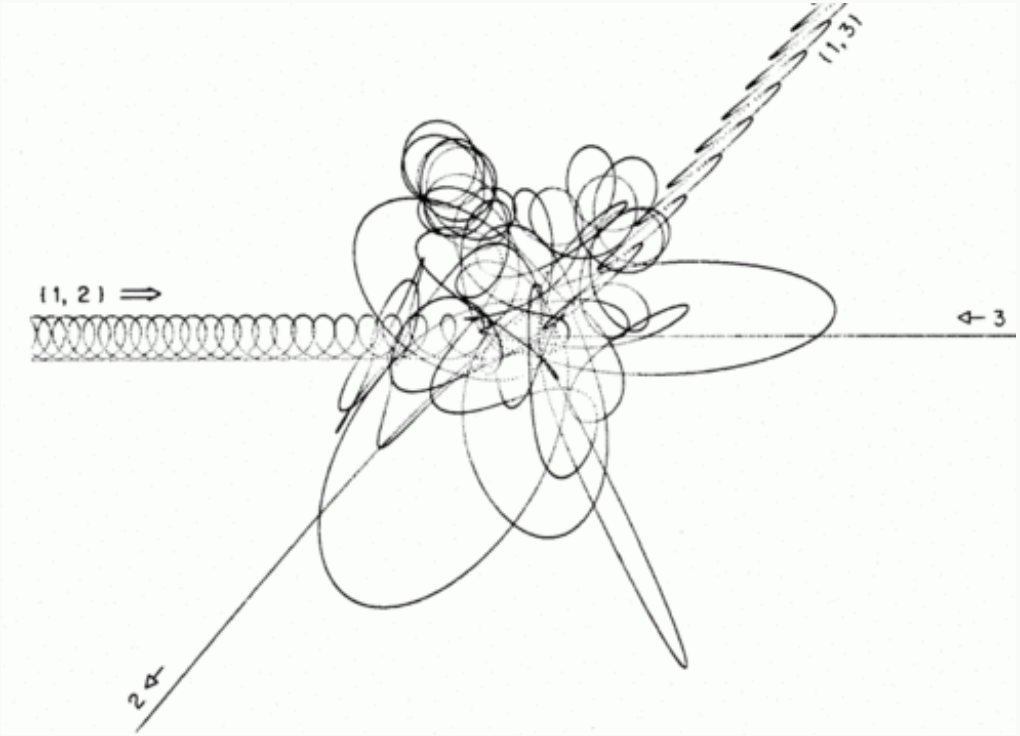

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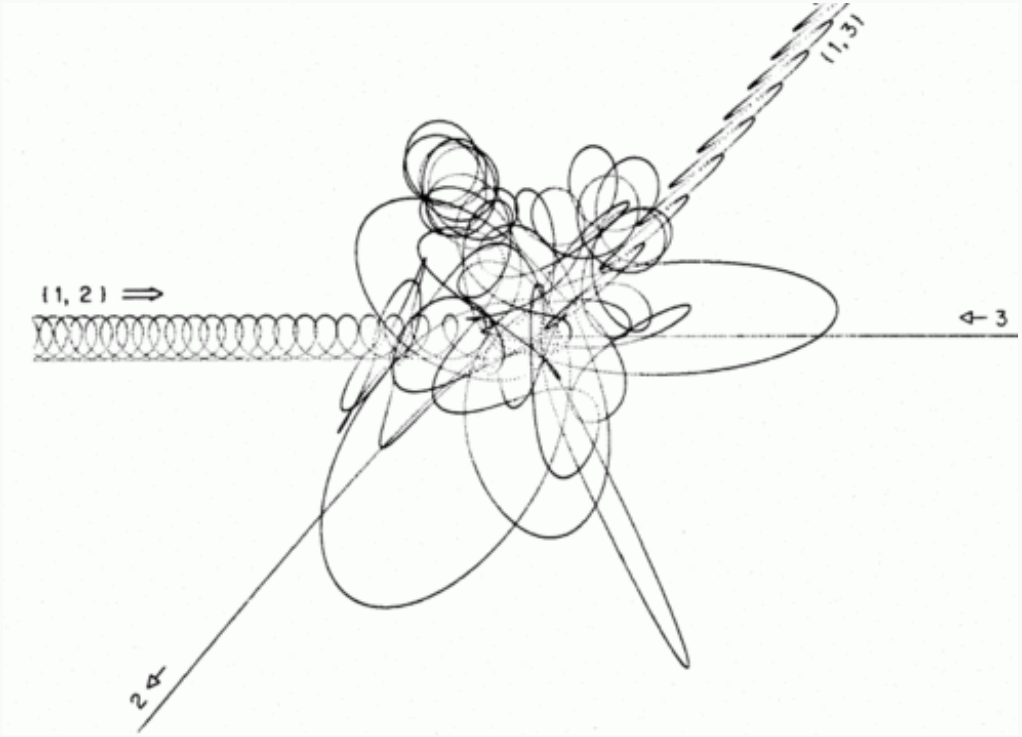

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- It seems we are preparing an instrument that will see nothing

The role of eccentricity

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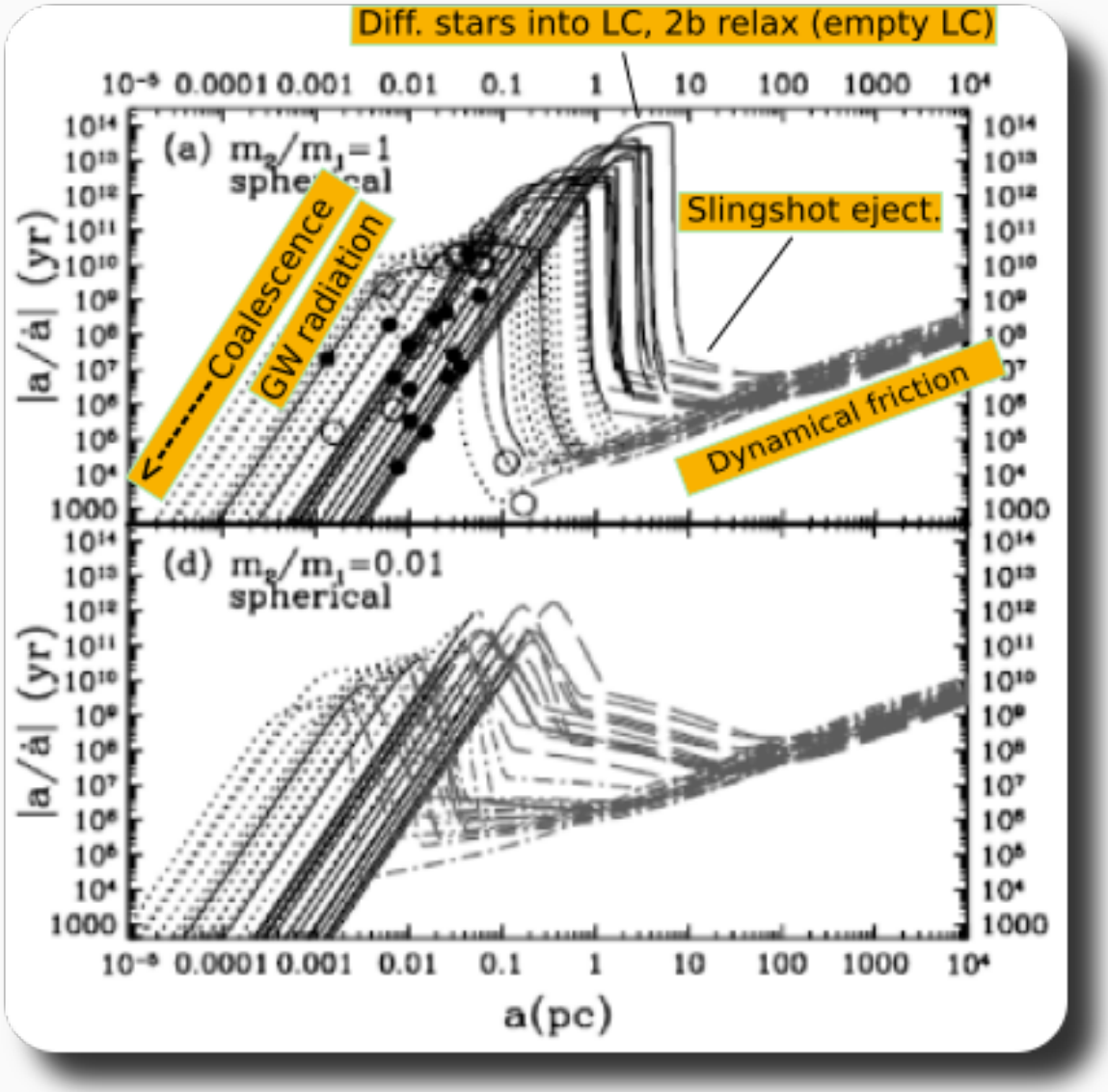
  Inducing a binary of SMBHs to decay from $a \approx a_h \approx 1$ pc to a separation $t_{gr} \lesssim 10^{10}$ yrs

The last parsec problem



Some possible ways to overcome the last pc problem

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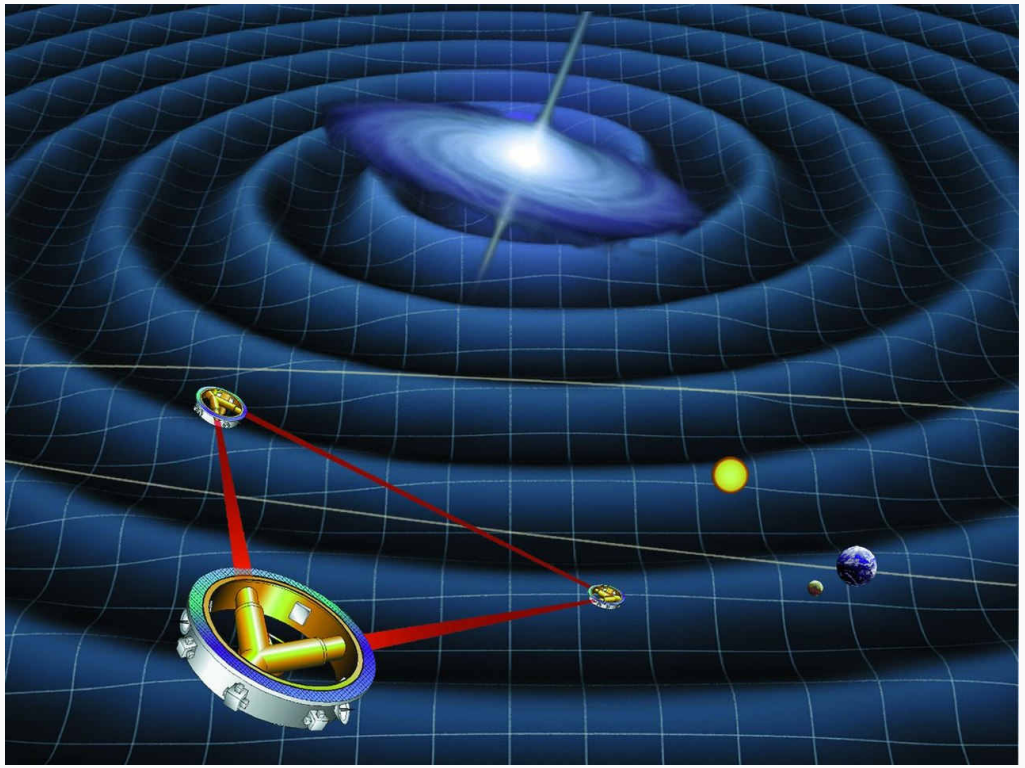
- IMBHs would play a similar role, and we expect within the innermost central 10 pc some 50 IMBHs [Portegies Zwart et al. 2006]

Can we detect them?

The Laser Interferometer Space Antenna



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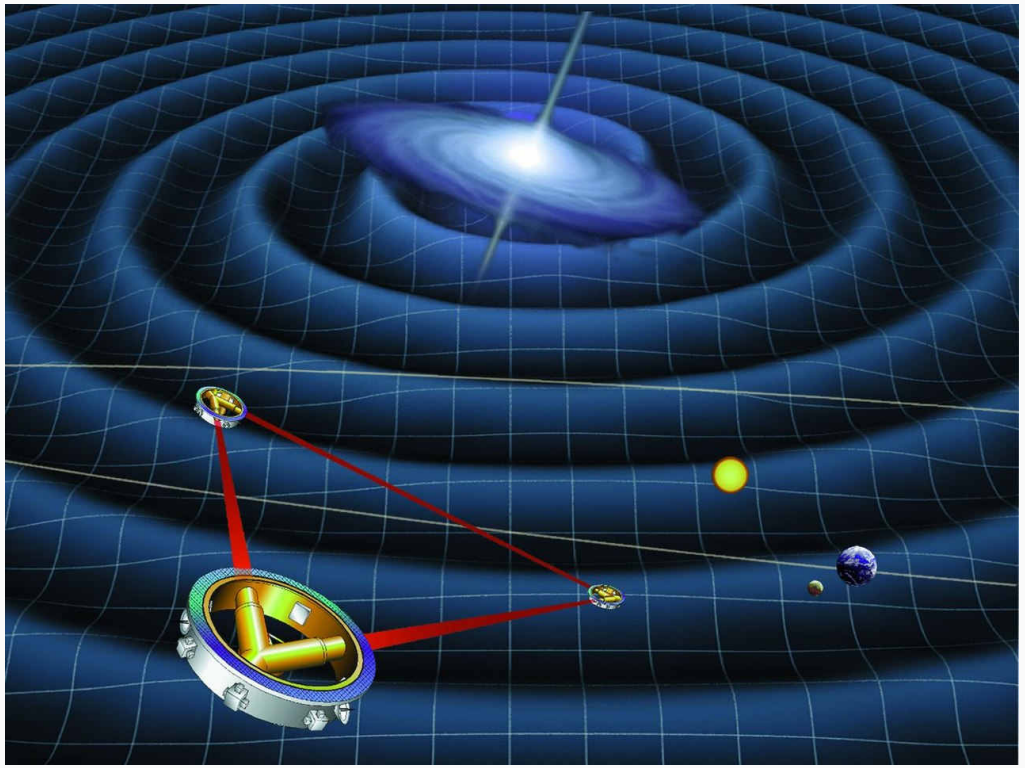

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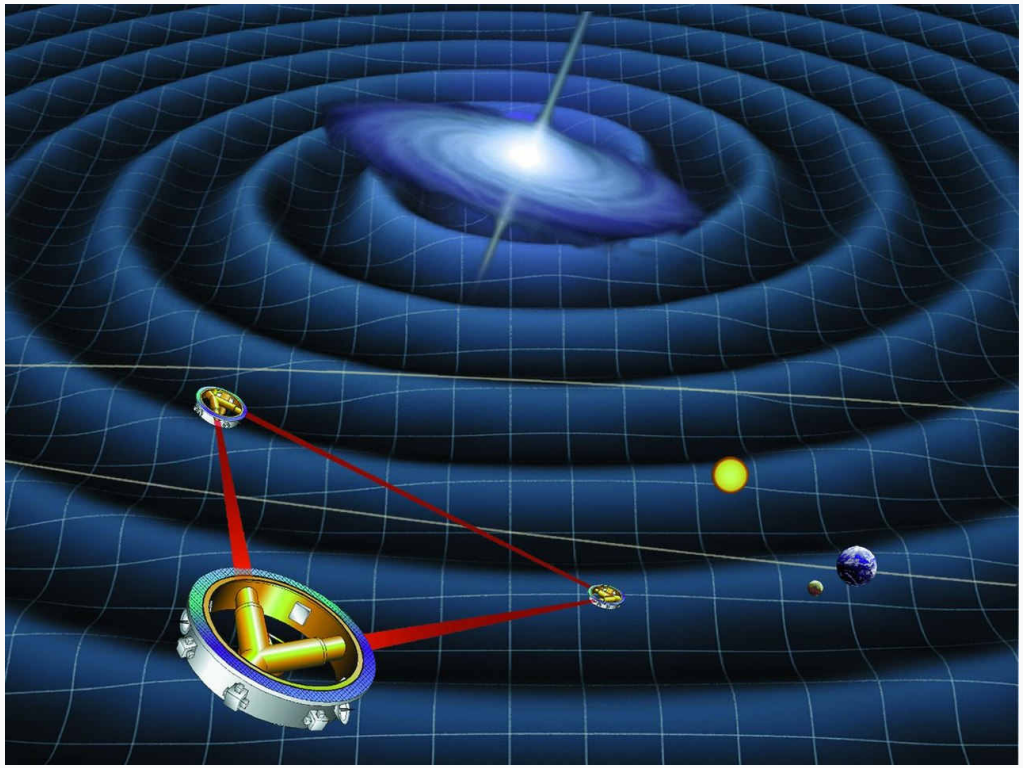

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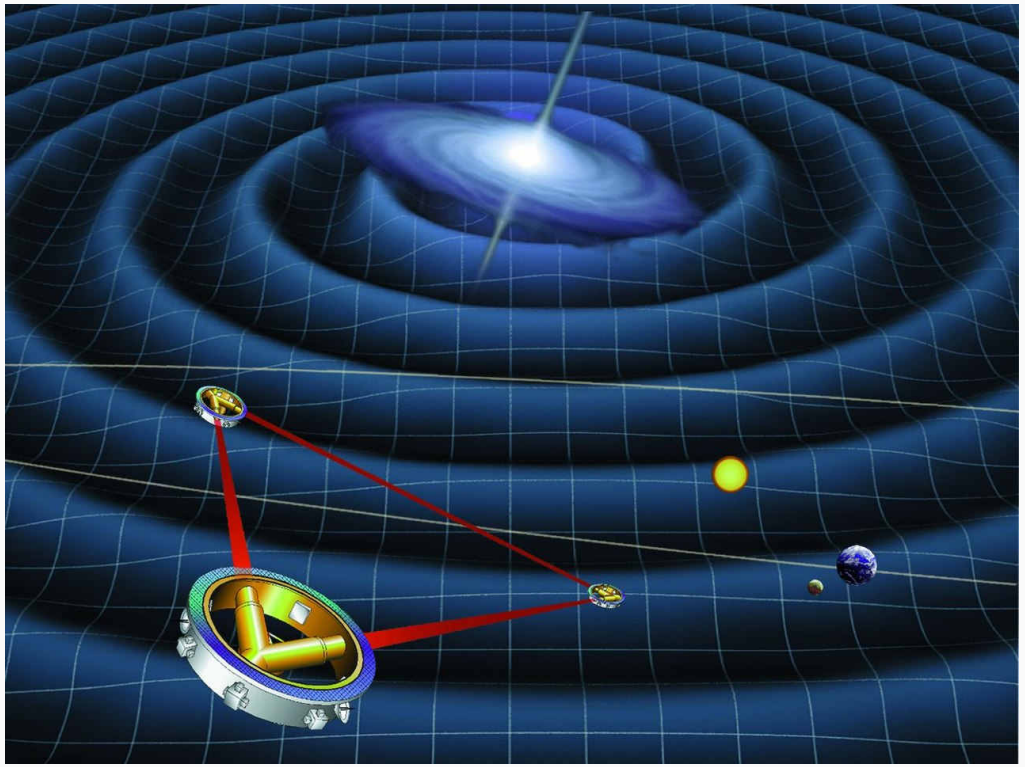

★ On June 20, 2017 the suggested mission received its clearance goal from ESA, and was approved as one of the main research missions

[Amaro-Seoane et al 2017, arXiv170200786A]

[Vídeo: LISA, win+L]

Is this sci-fi?

No, it is not

["LISA Pathfinder mission logo" by the European Space Agency, URL

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- ★ We approached LISA design requirements, we did 10-100 times better than ESA required

Intermediate-mass black holes

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[IMBH in NGC 3783, Credit: ESO/M. Kornmesser]

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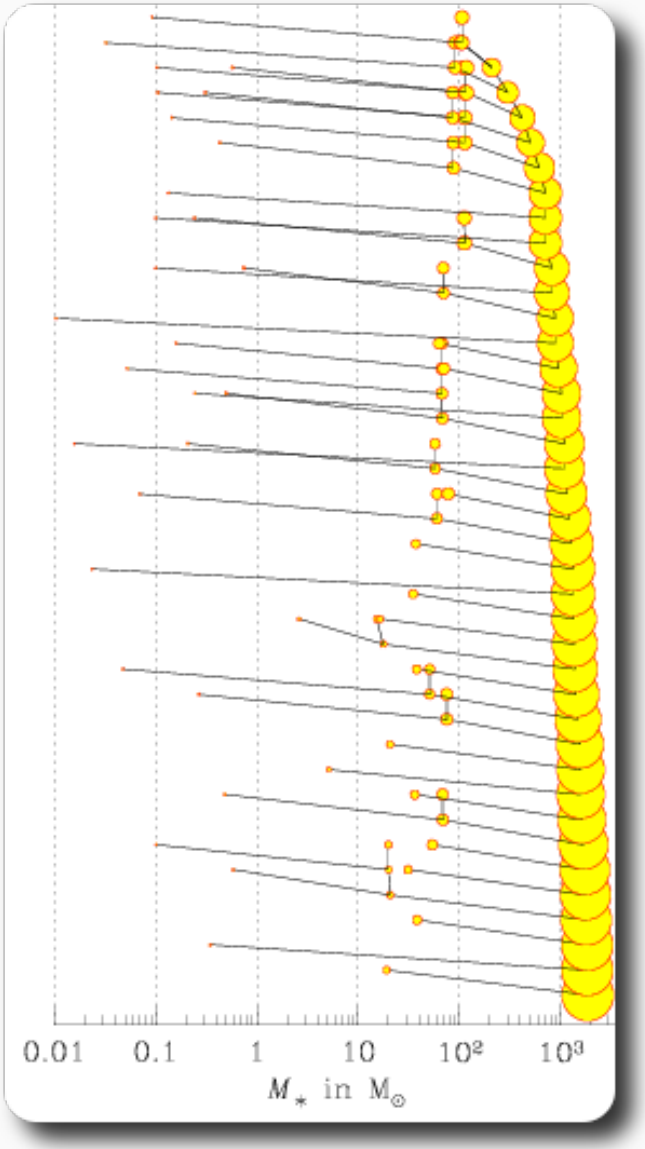

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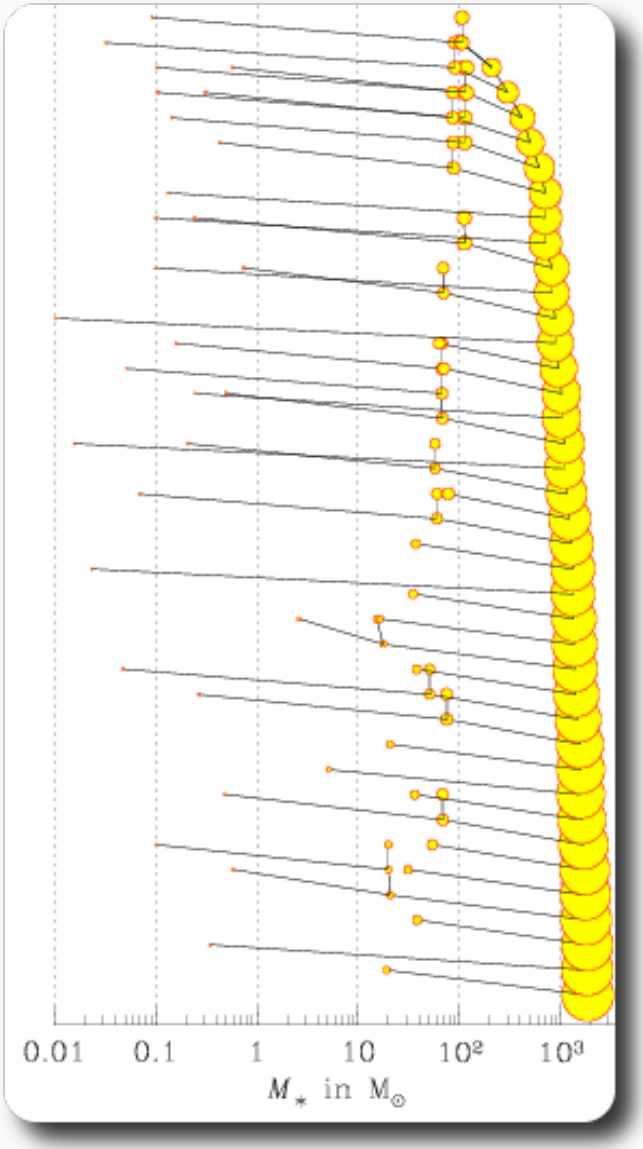

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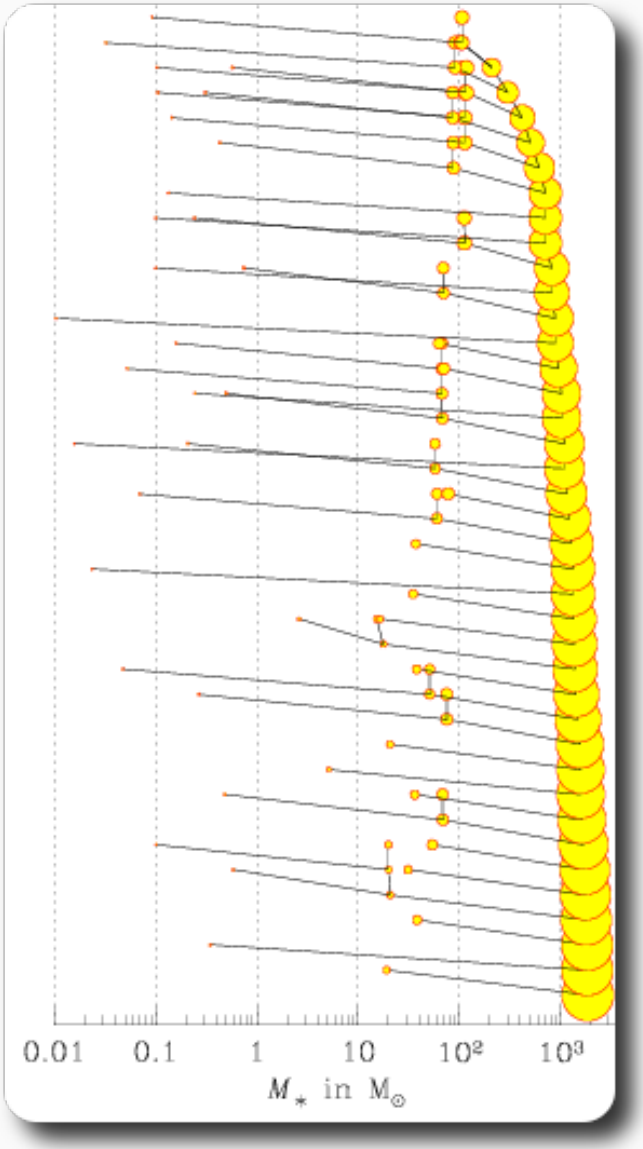

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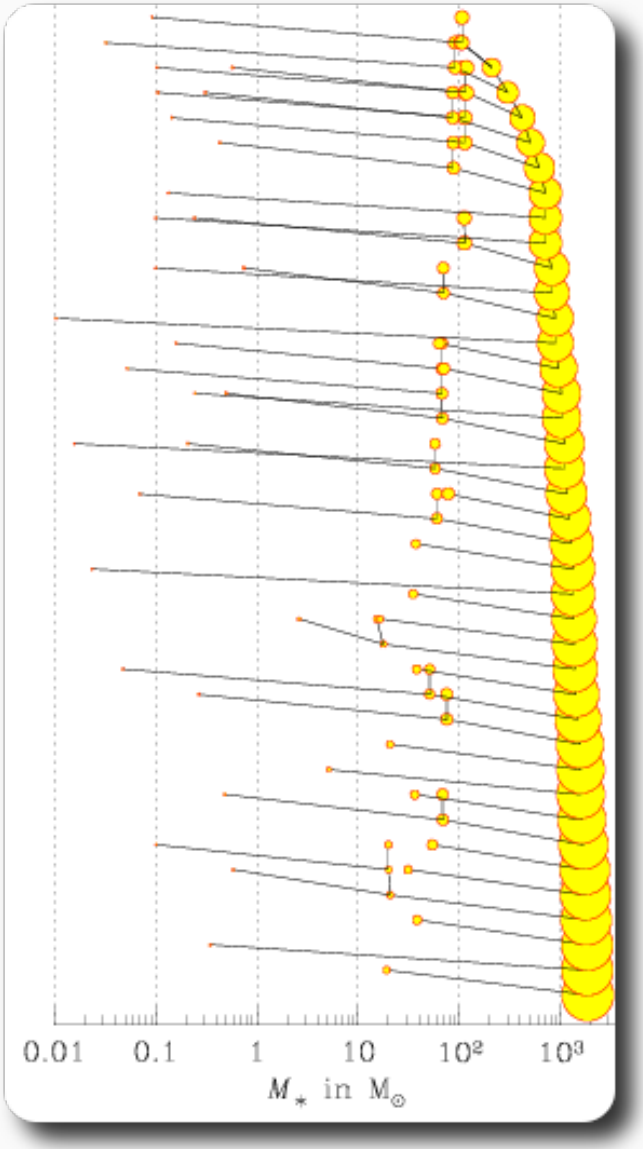

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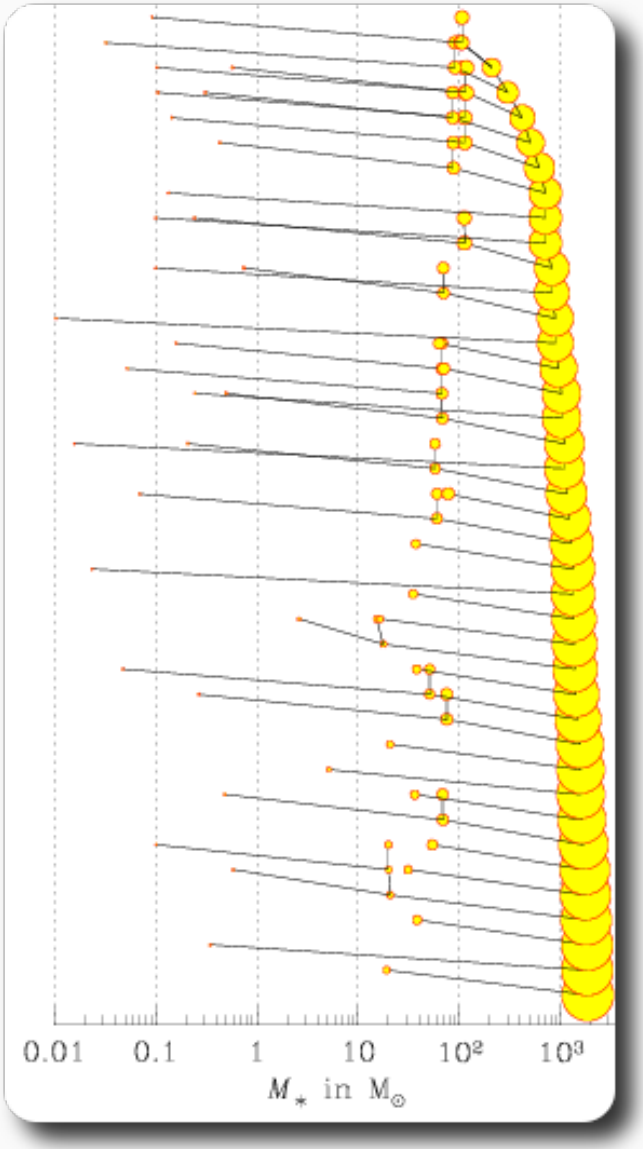

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- We see a growing star, the right "trunk"

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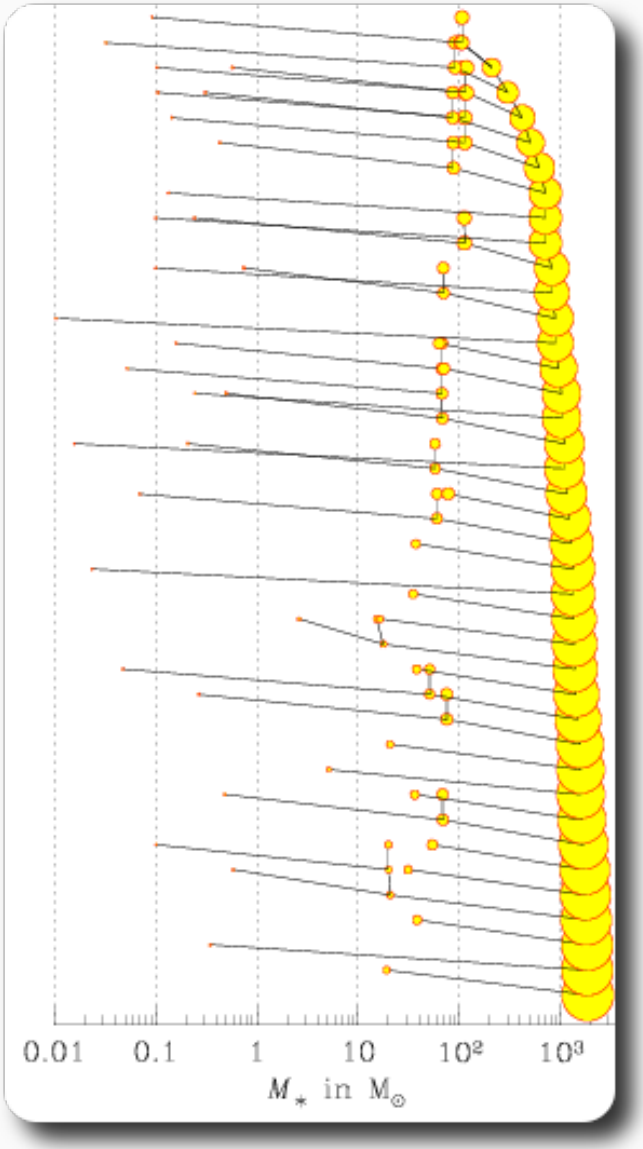

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- We see a growing star, the right "trunk"
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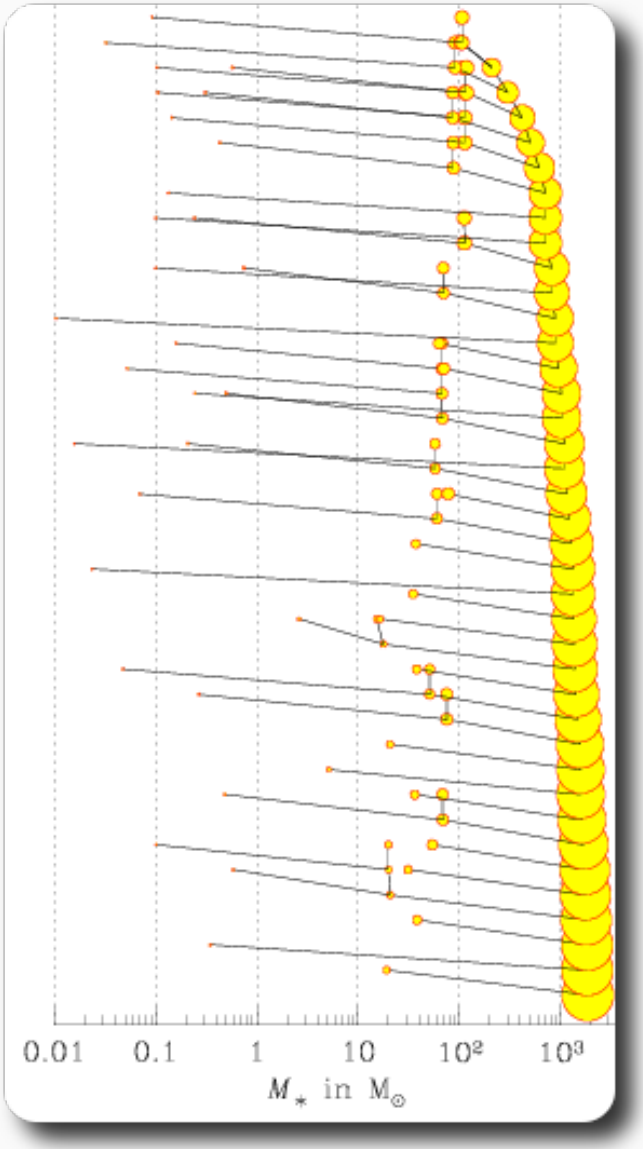
Formation of IMBHs



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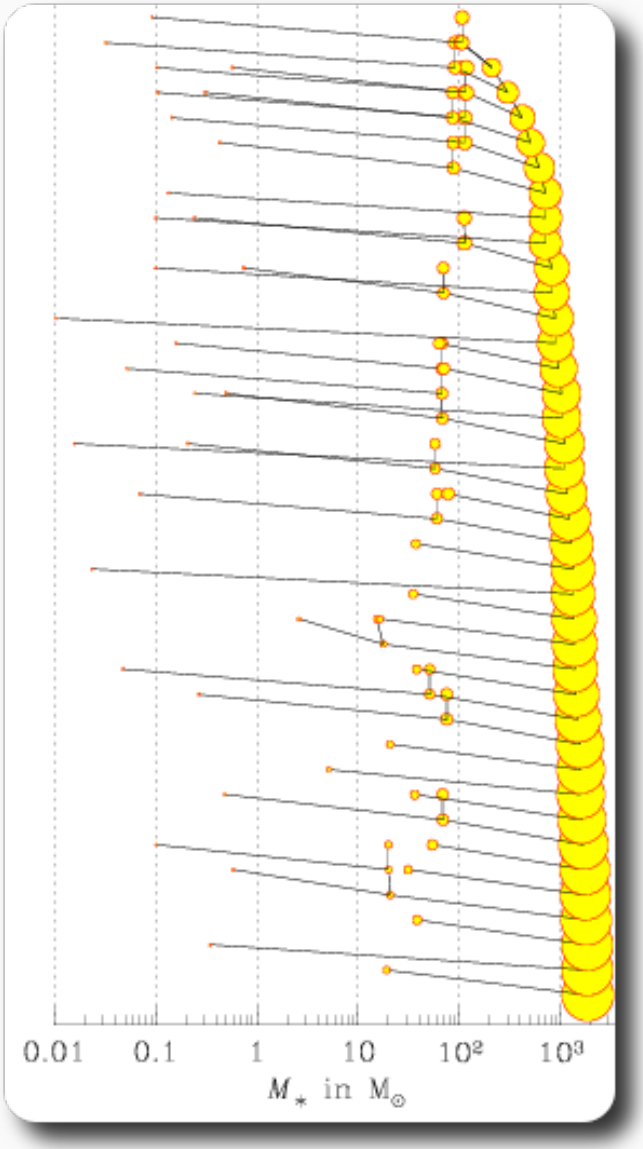

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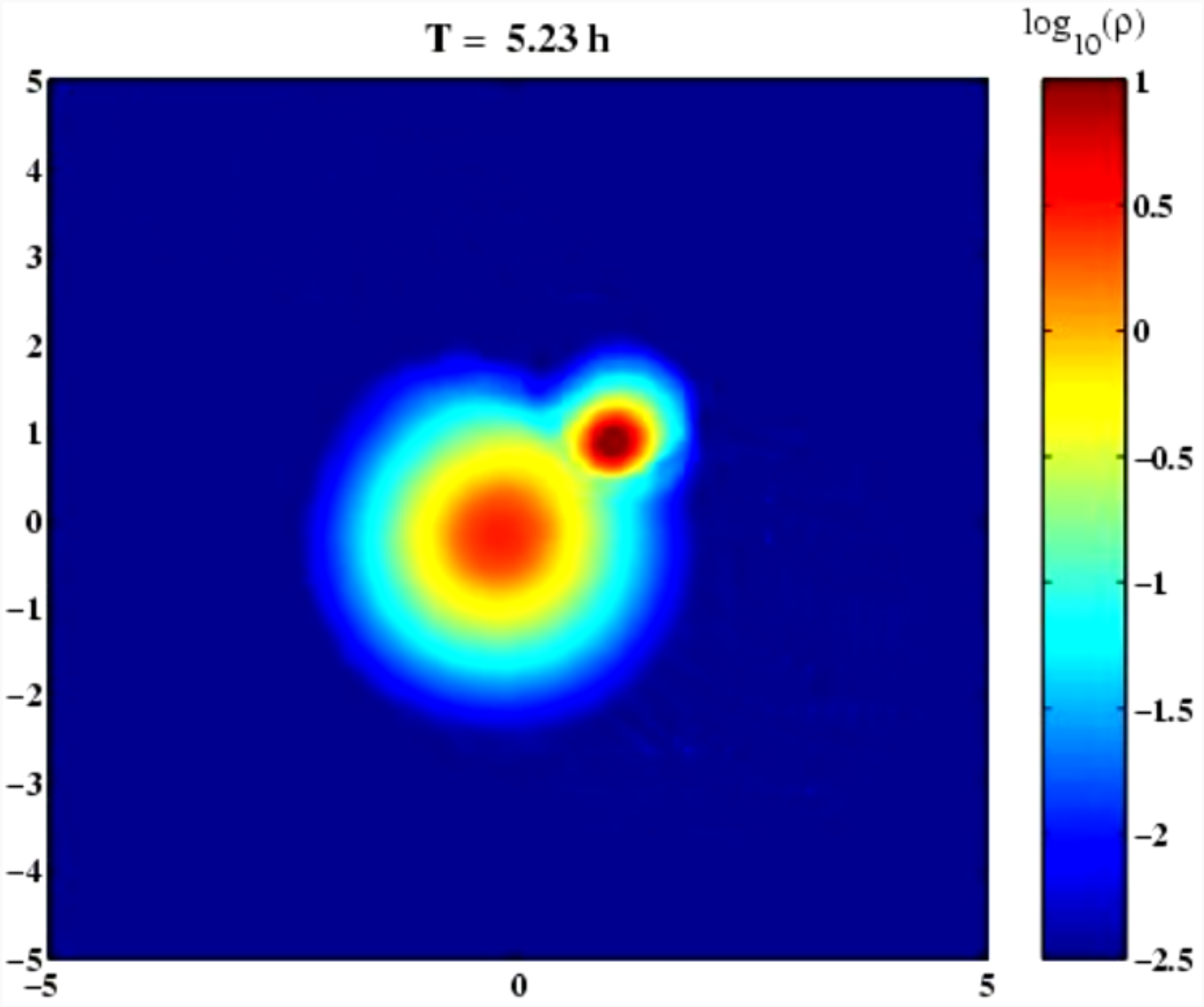
  (Stellar winds, sticky spheres)



[Vídeo: Stellar collisions]

Binaries of intermediate-mass black holes

[Author ALMA (ESO/NAOJ/NRAO). Visible light image: the NASA/ESA Hubble Space Telescope.]

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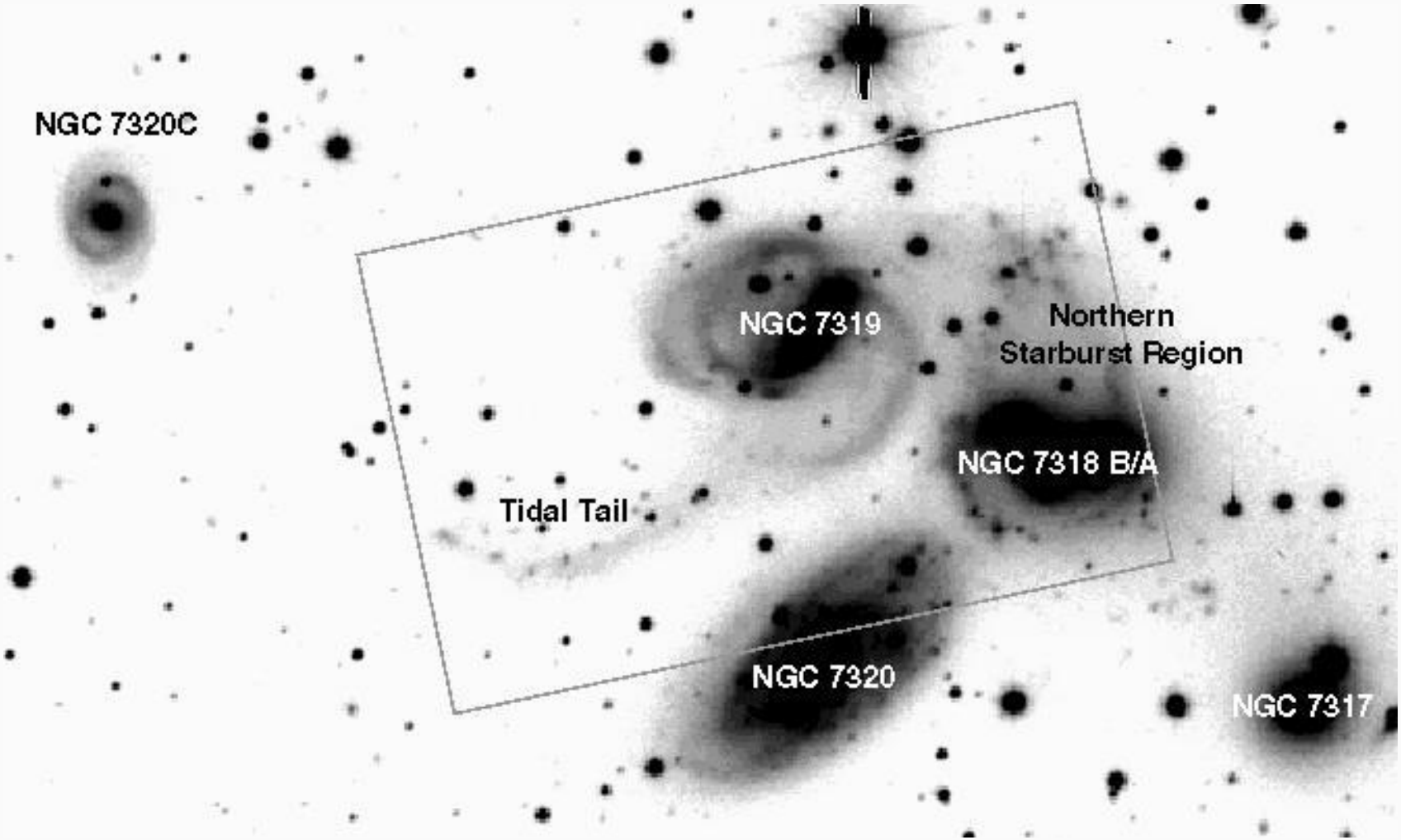
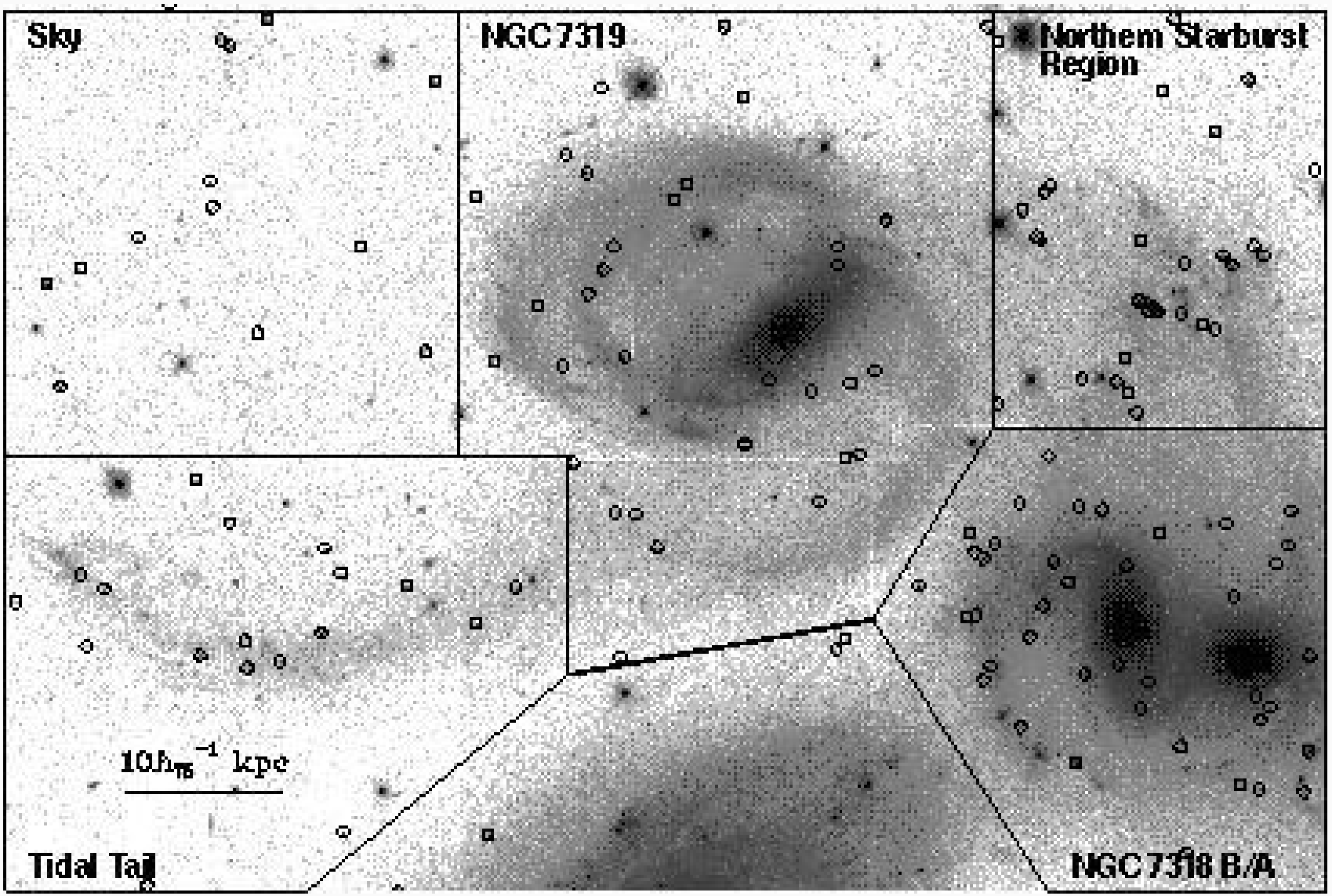
- Star formation: clusters of clusters, many of which bound



Stephan's Quintet, [Gallagher et al. 2005]



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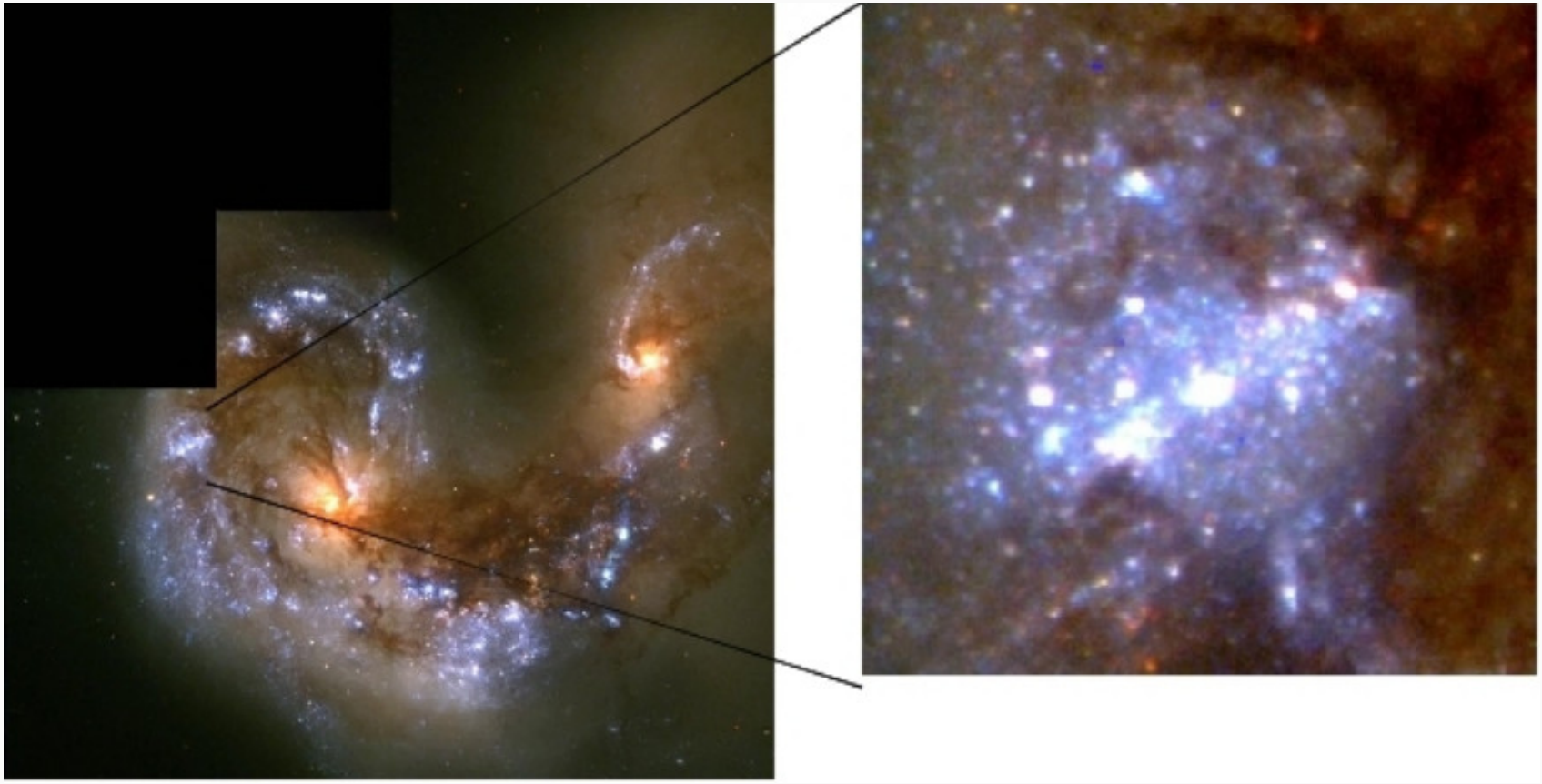
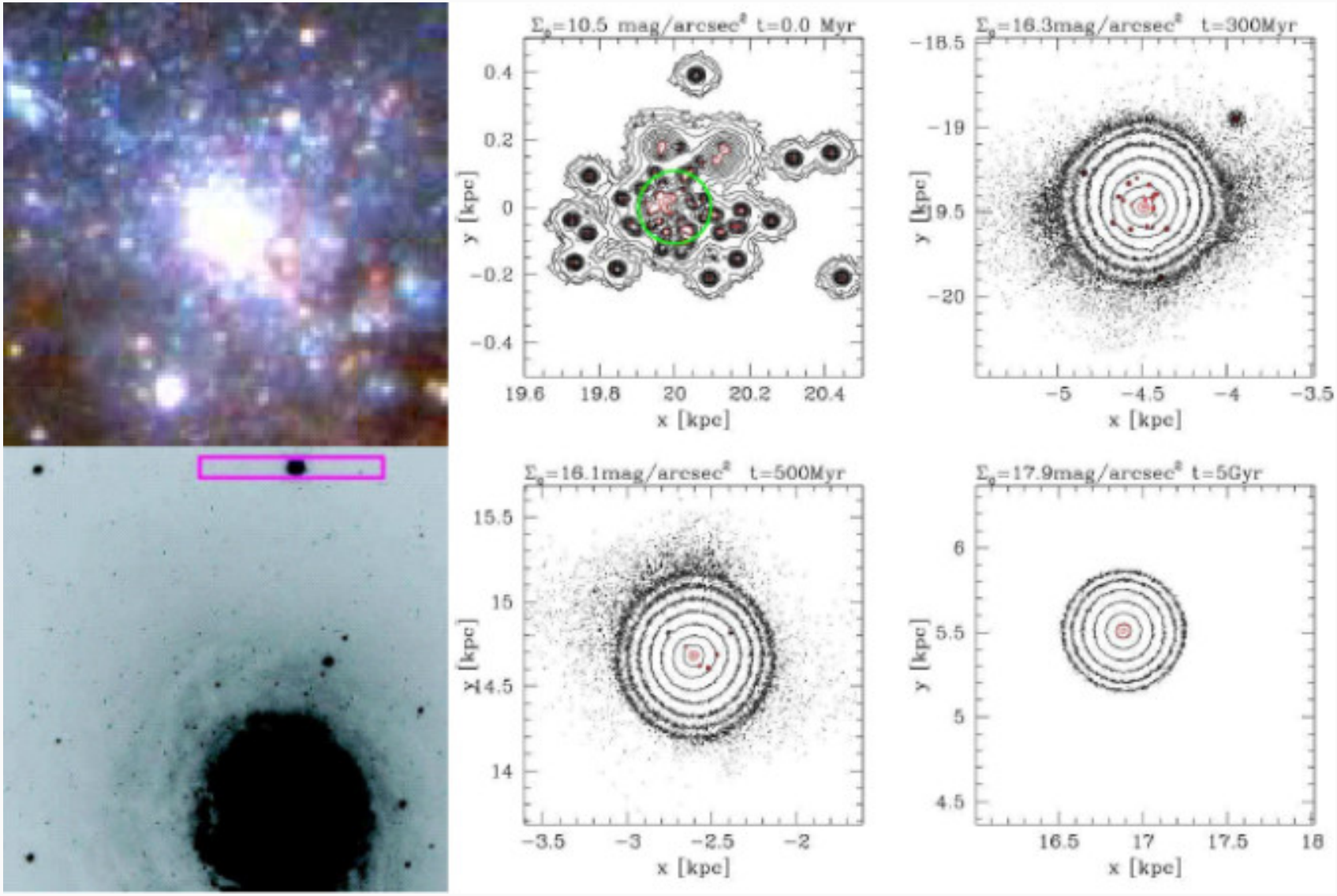
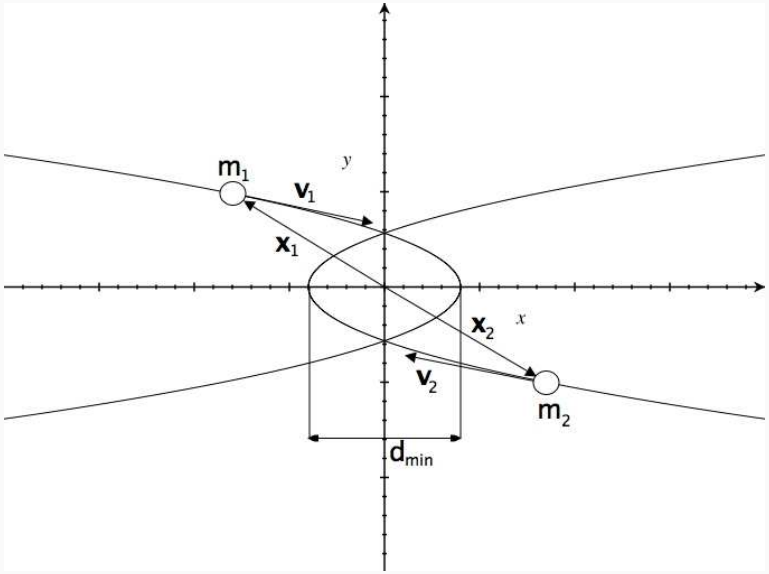


[Vídeo: Clusters of clusters]



Possible formation of W3 in NGC7252 [Fellhauer & Kroupa 2002]

Numerical experiments



- The most accurate thing we can do Direct summation of all forces, N-body

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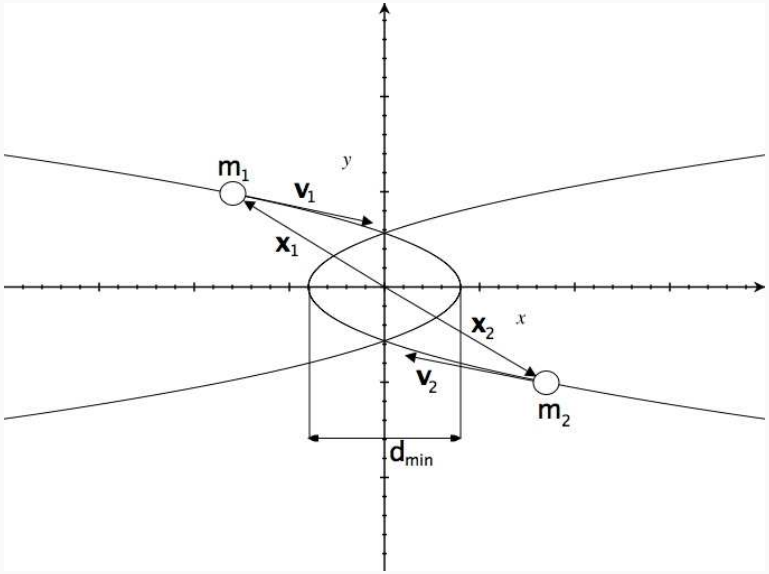

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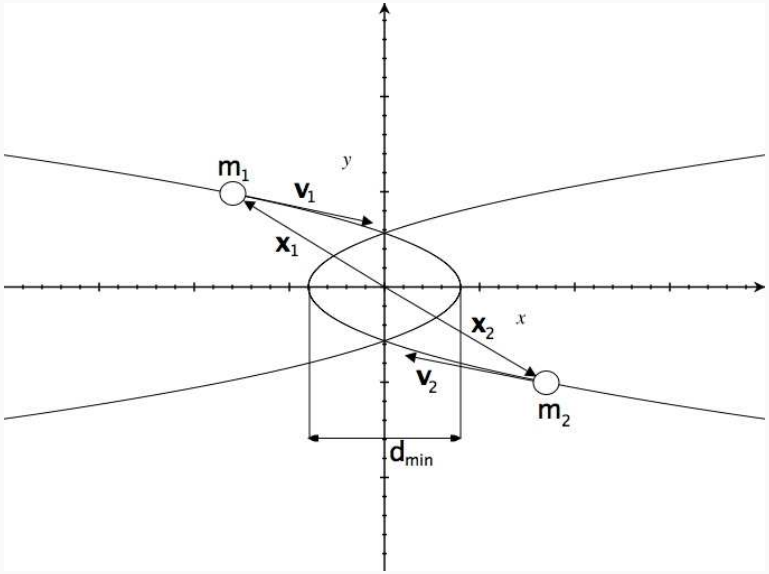

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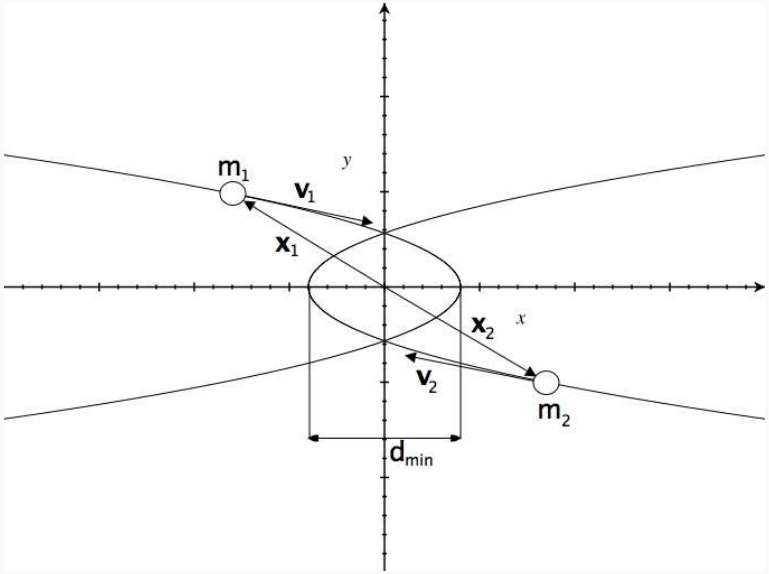

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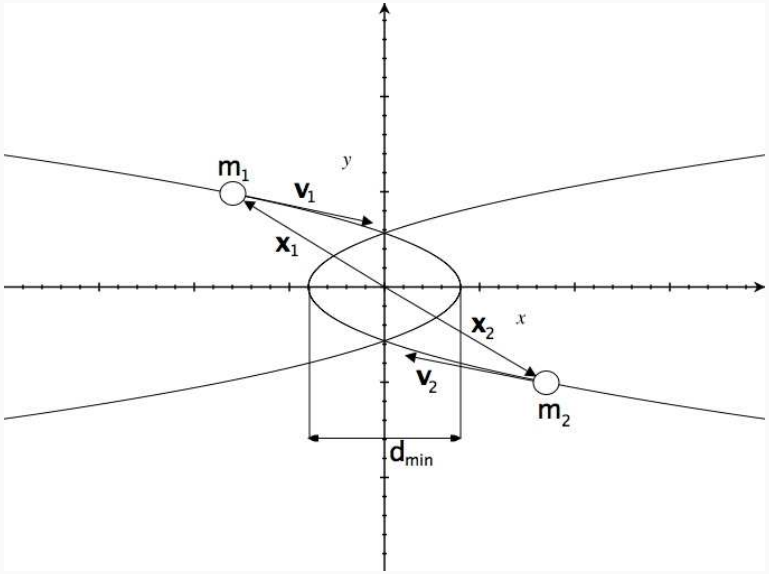

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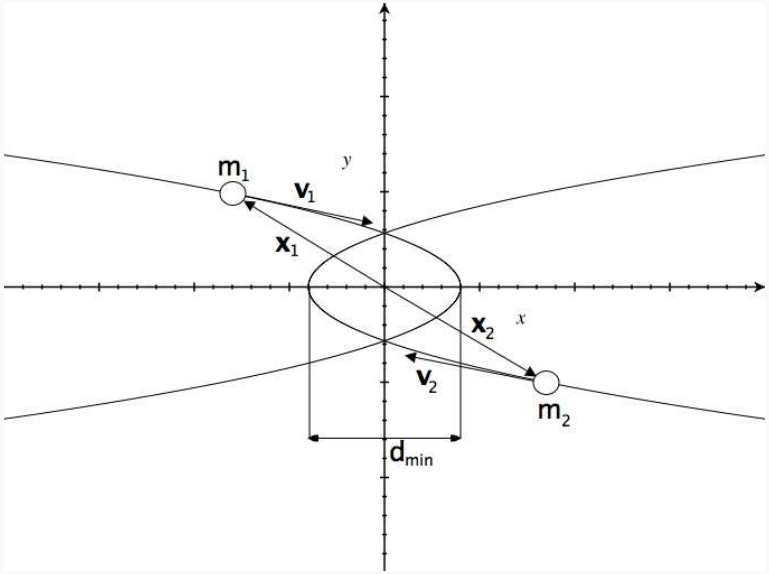

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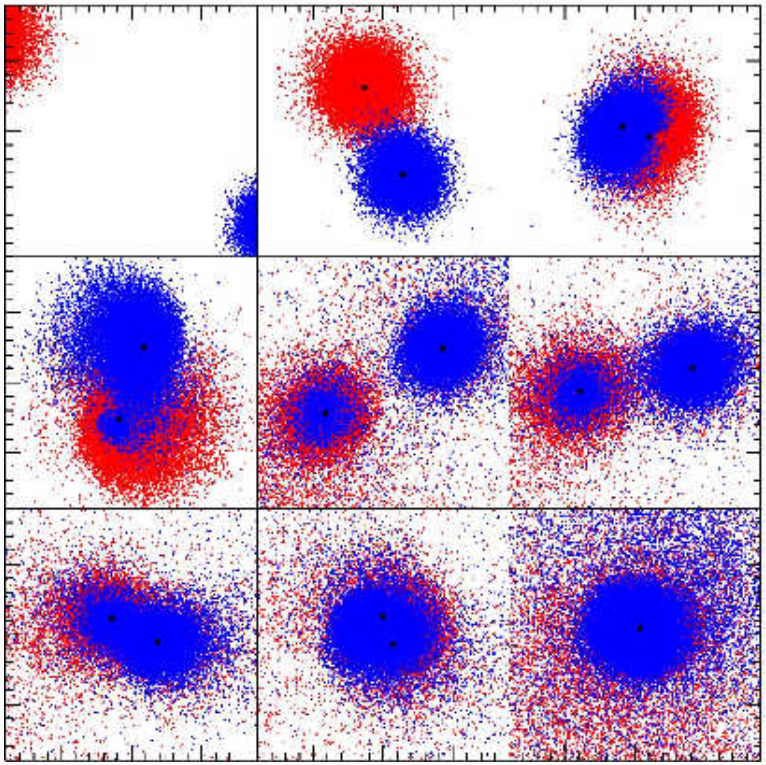
- Only early evolution, impossible to simulate down to GW regime

Merging clusters



- As with massive black holes, IMBHs can form binaries

[Vídeo: Crash of two clusters]

[Amaro-Seoane & Freitag 2006, Amaro-Seoane et al 2009, 2010, Amaro-Seoane & Santalucía 2010]

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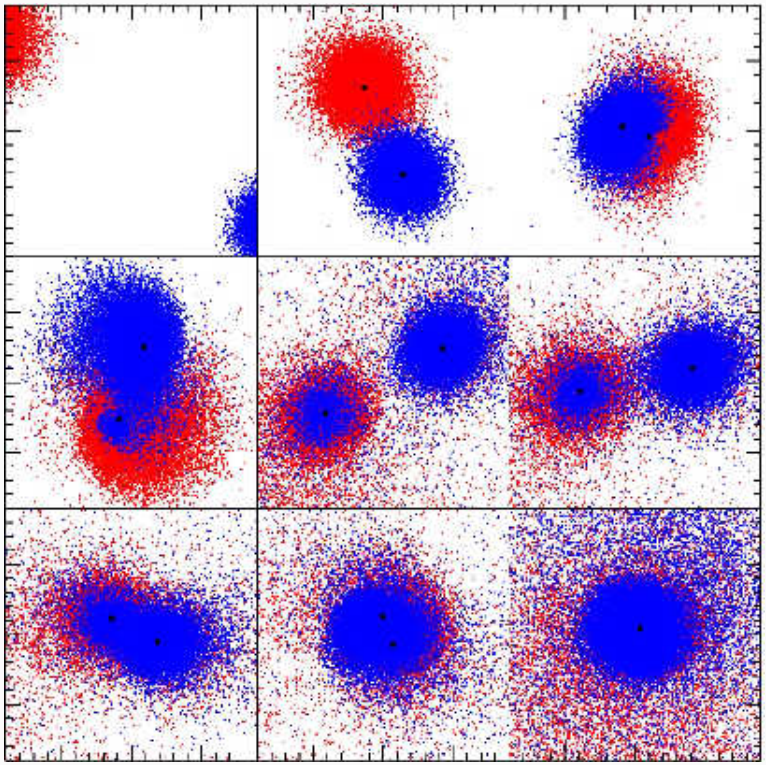

- As with massive black holes, IMBHs can form binaries
- This constitutes a powerful source of GW for LIGO and LISA

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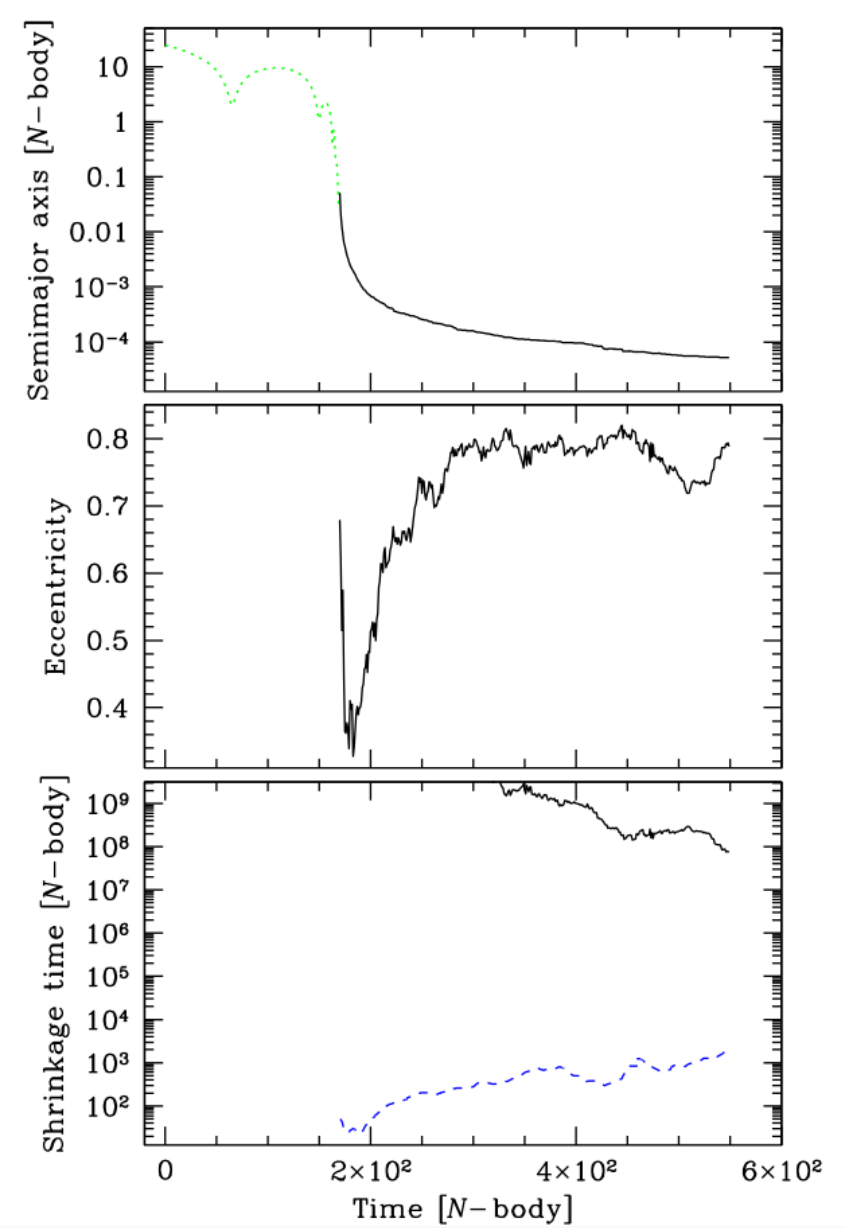
Evolution of the binary



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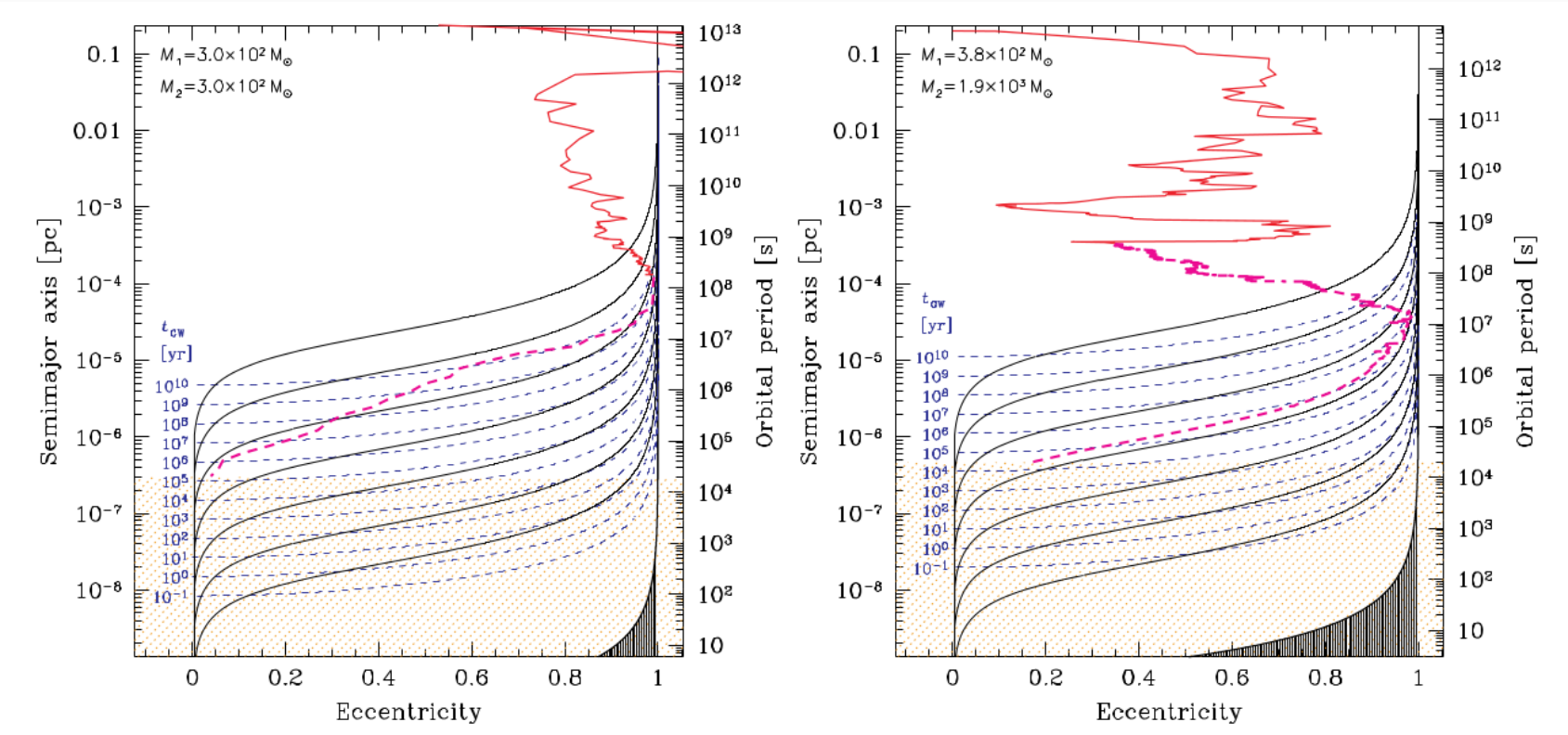
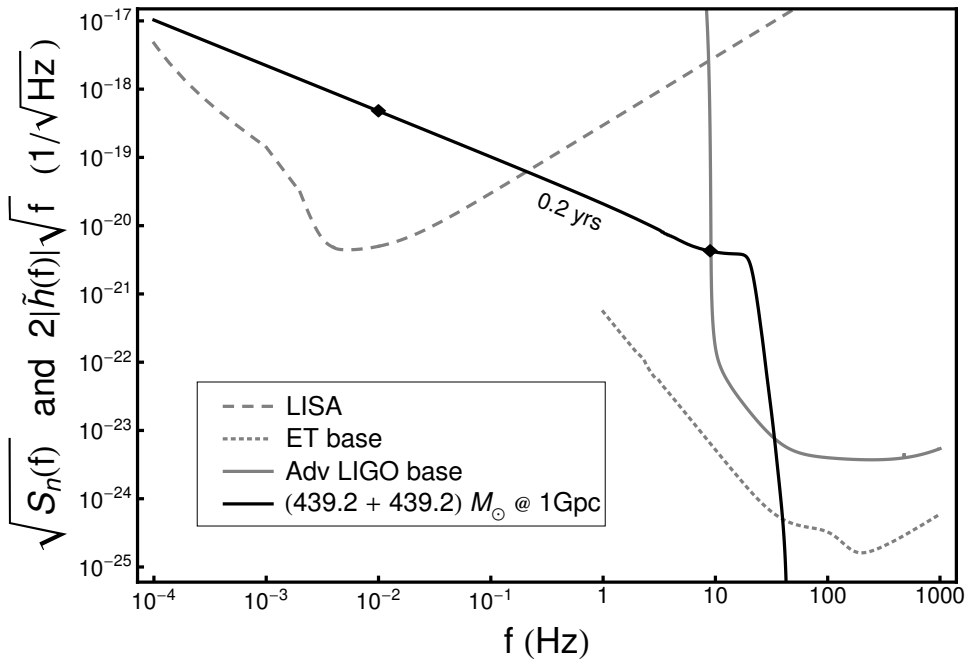


[Amaro-Seoane & Freitag 2006]

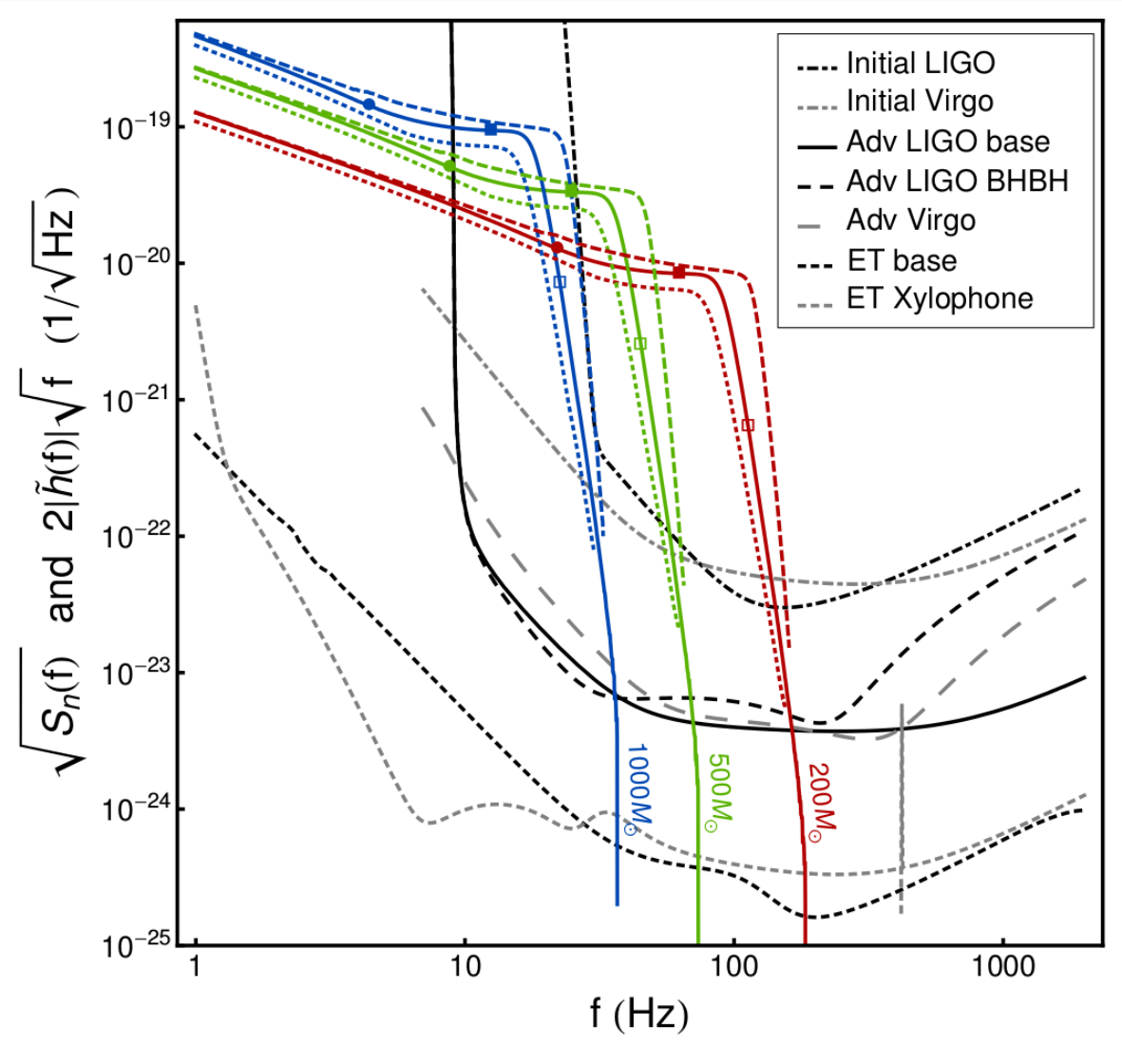
And ground-based? Multi-band Gravitational Wave Astronomy



Enough massive binaries can be seen from the bandwidth of space-borne detectors to ground-based ones: Detailed evolution of inspiral, merger and ringdown, crucial to assess the black hole hypothesis.

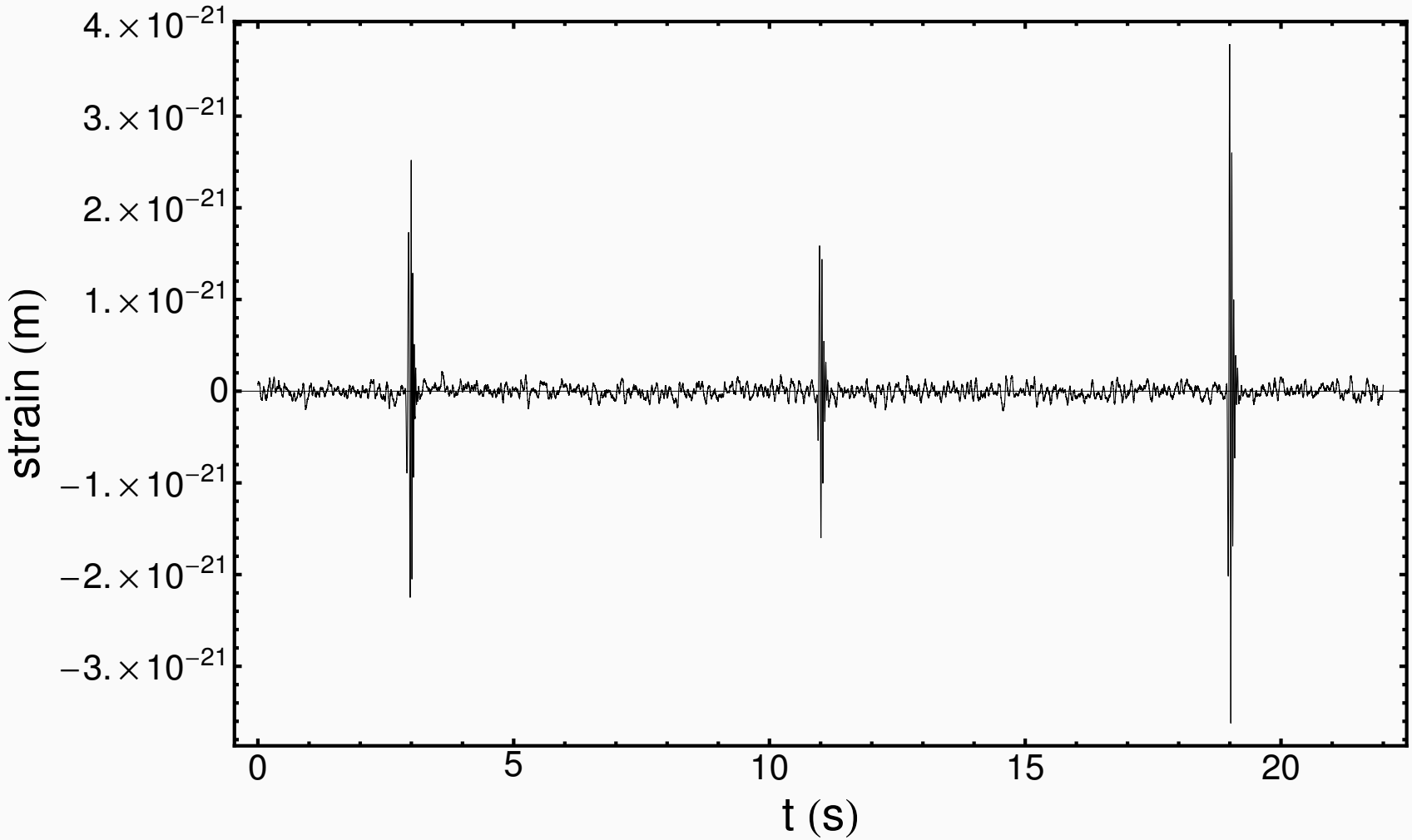
[Amaro-Seoane & Santamaría 2010]

Different masses



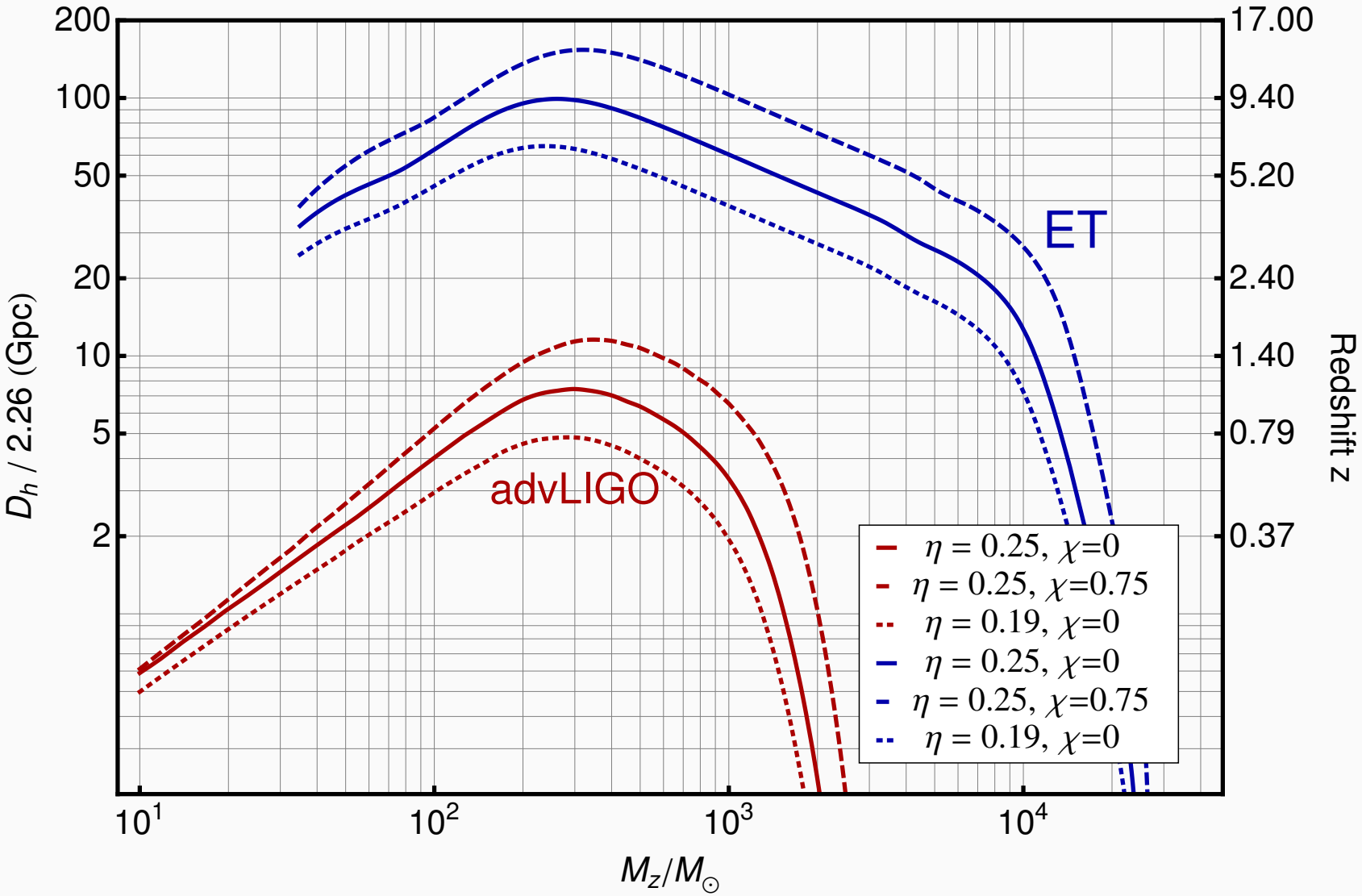
[Amaro-Seoane & Santamaría 2010]

Three hidden IMBH binaries in LIGO simulated noise



[Amaro-Seoane & Santamaría 2010]

Cosmology with IMBH binaries



[Amaro-Seoane & Santamaría 2010]

Conclusions

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GW Jackets

Seen at the Gangnam Station Underground Shopping Center, next to line 2, Seoul, 23/Dec/2017

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- ✖ "Unfortunately" we do science and such words (probably, strange, etc) don't matter – We must prove their existence

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- We've just started: The Gravitational Wave Astronomy era is now

Questions?