Doing Gravitational Wave Astronomy

with one or more neutron stars

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  I will not talk about binaries from the point of view of stellar evolution

Outline

Wednesday 05/July

✓ *Very* succinct introduction to GWs

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- ✓ Applications to the formation of NS binaries, and mixed binaries

Friday 07/July

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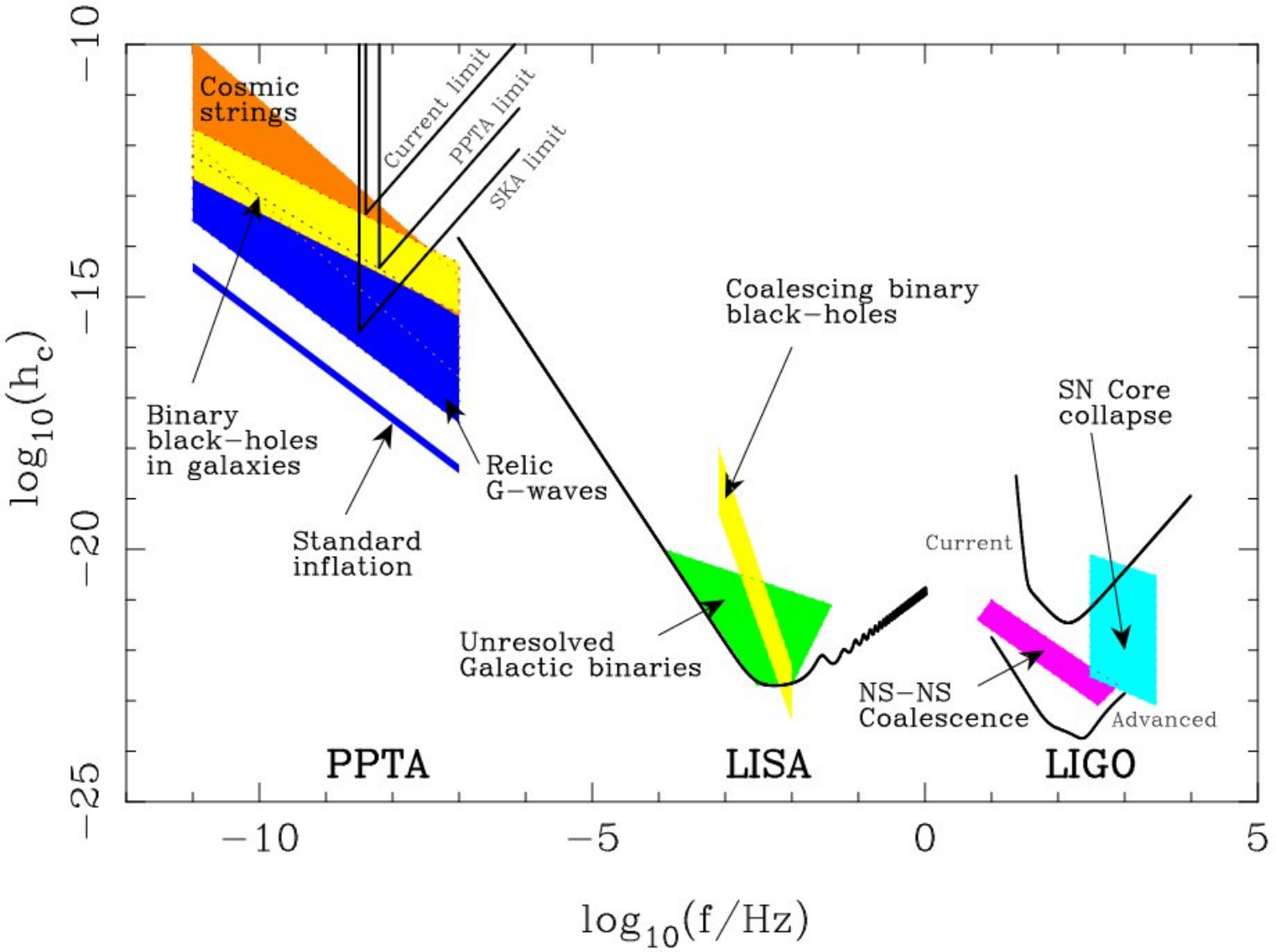
- ✓ What are SMBHs and IMBHs?
- ✓ Prospects of GW Astronomy thanks to neutron stars

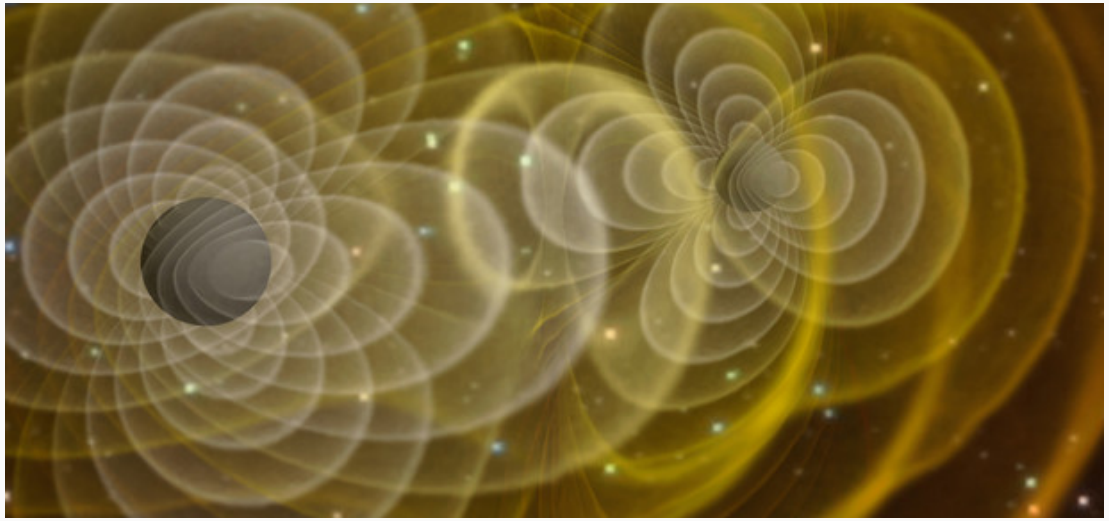
The different windows in GW Astronomy

Ground-based and space-borne detectors



[Hobbs 2008]

Gravitational Waves



[Henze, NASA]

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

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[ESO/L. Calçada]

- Slow decay: Propagate to very long distances

[Film: Jungle and galaxy, win+j, win+0]

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- ▷ Slow decay: Propagate to very long distances
- ▷ Difficult to detect: Almost do not interact with matter
- ▷ Pristine probe: They contain very detailed information about space and time

[Film: Jungle and galaxy, win+j, win+0]

How to form binaries of neutron stars, and mixed binaries, with stellar dynamics

The equation

The Almighty Equation

$$\ddot{\mathrm{r}}_i = -G \sum_{j=i,\, j\neq i}^{j=N} m_j \frac{(\mathrm{r}_i - \mathrm{r}_j)}{\left|\mathrm{r}_i - \mathrm{r}_j\right|^3}$$

- r_i position vector of jth star at t, m its mass, G a constant
- Recognize it?
- Good approximation to solve
  - ✓ solar system ...300 yrs later we also do
  - ✓ star clusters
  - ✓ whole galaxies as well as
  - ✓ clusters of galaxies
- Not bad for a single equation

Gravity is weird

- Gravity = attractive long-range force
- Electromagnetism too, but positive and negative charges tend to screen each other
- Short-range forces (gas pressure) only important on small scales (interior stars)
- Stellar dynamics is <u>simple</u> (but not easy), contrary to plasma astrophysics, radiative transfer, or nuclear astrophysics (complex and not easy)
- If you care about GWs: GR

Stellar dynamics

Stellar dynamics := studying the consequences of
"The Equation" in astrophysical contexts

- Historically: Planets, celestial mechanics
- Solar system is a very regular system
- Planets move in orbits close to the ecliptic
- All revolve in the same direction
- Orbits are well-separated
- No close encounters take place
- Not true for stars in the galactic plane, or in globular clusters
- Very irregular systems: Computer needed
- Still: (semi-) analytical approaches important

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- ✓ Collisionless = the heat flow due to pairwise interactions of stars is neglected

What kind of system?

Some globular clusters from the MW (from

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- Some systems in nature can be approximated well
- For instance globular clusters
- 2011: 157 Milky Way globular clusters
- One of the main topics of the lectures

Perfect testbeds? Ha!

Stellar swarm M80 (NGC 6093)

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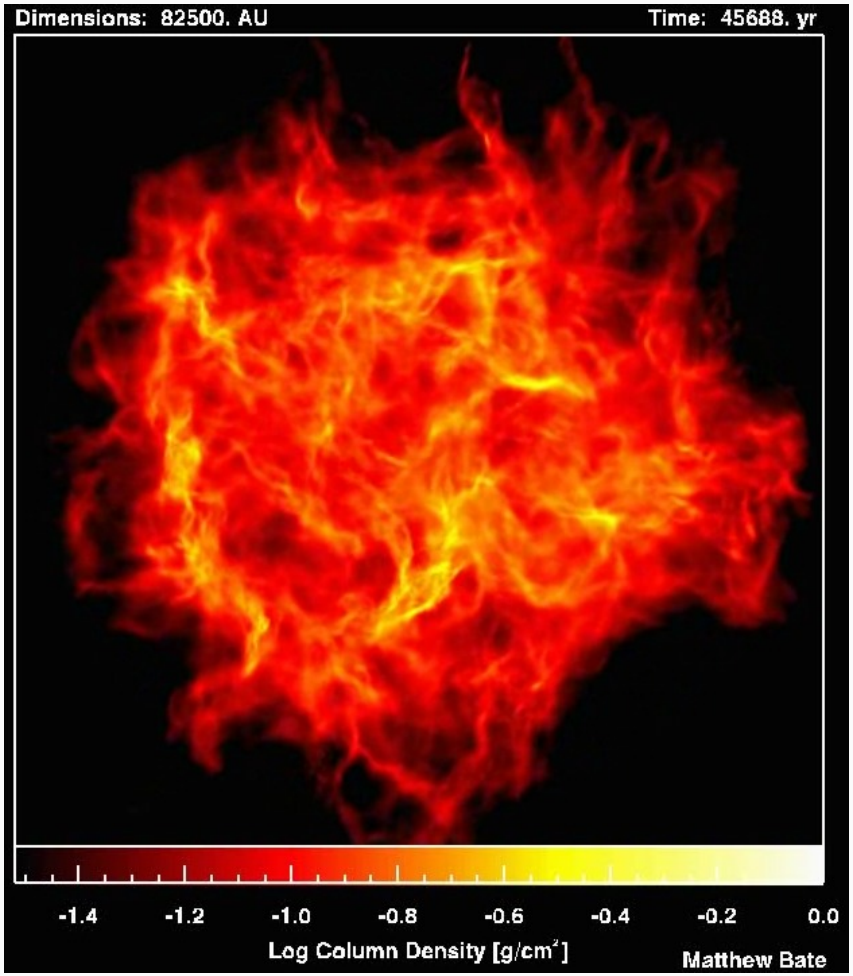
- Factor 10^6 higher than in our neighbourhood

Formation of globular clusters



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[Film: Forming cluster, win+c]

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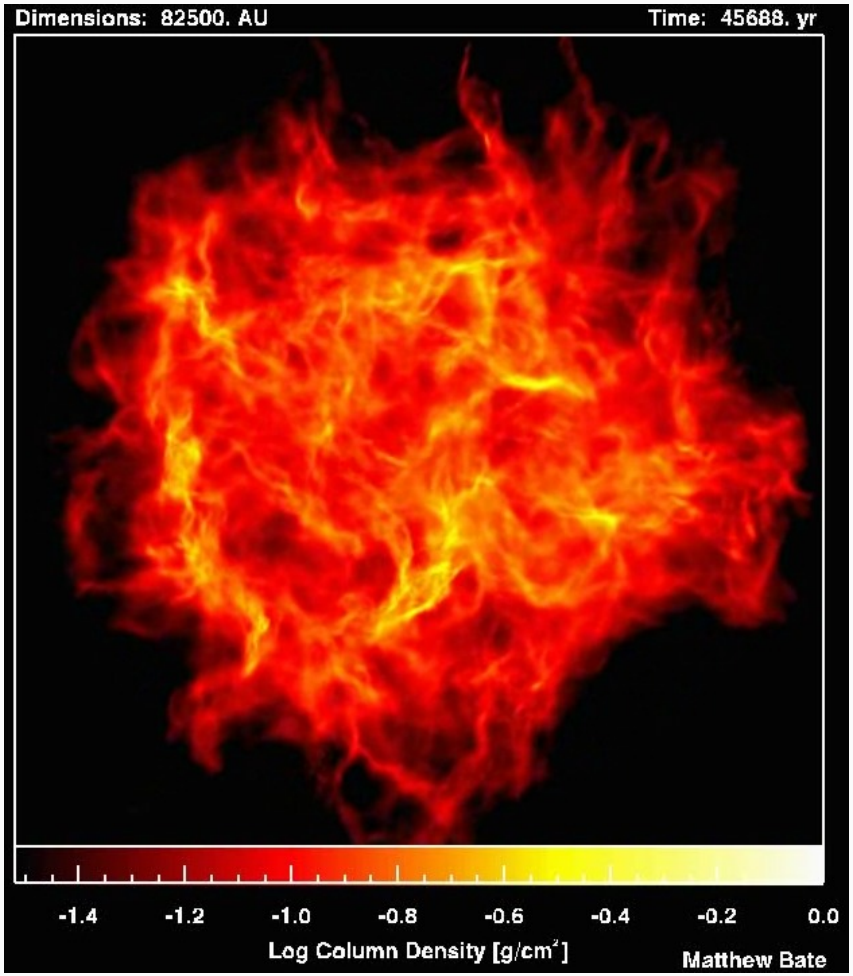

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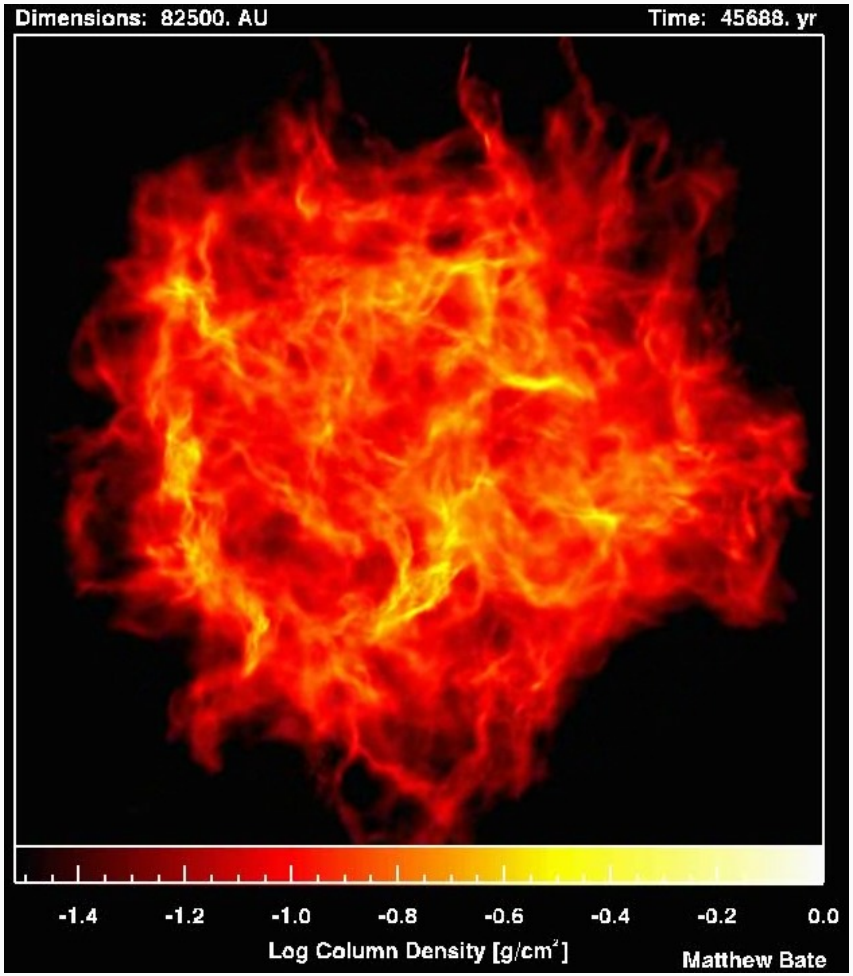

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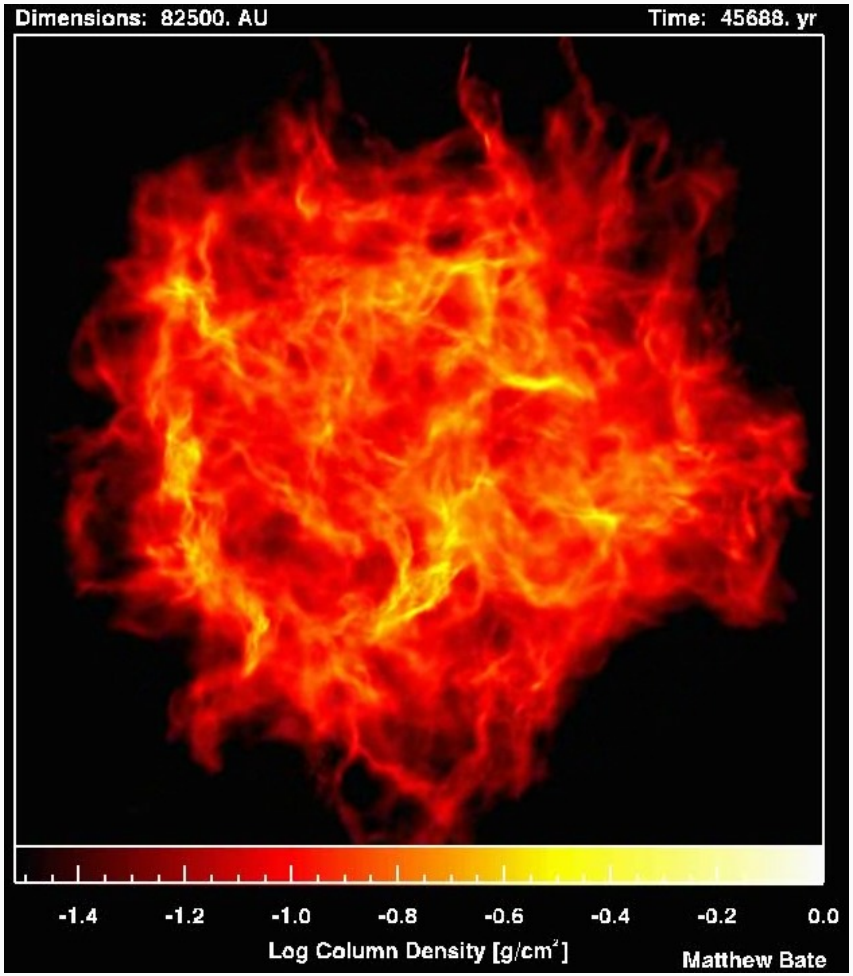

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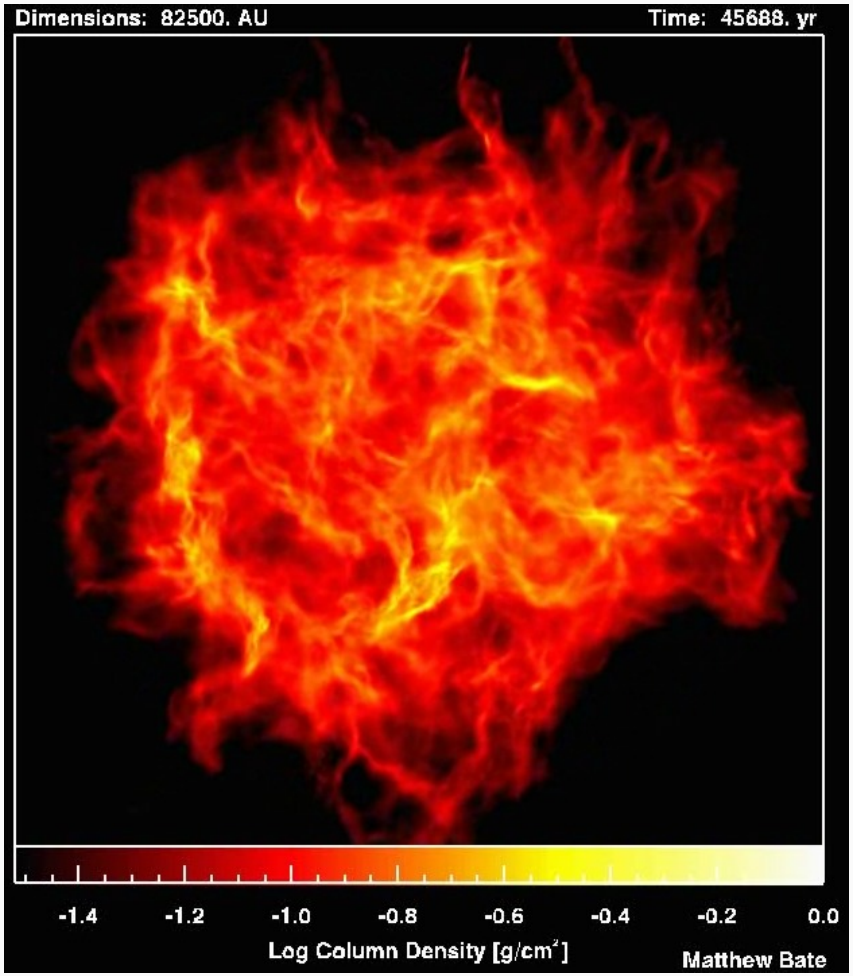

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- Simulation M. Bate, Visualisation R. West

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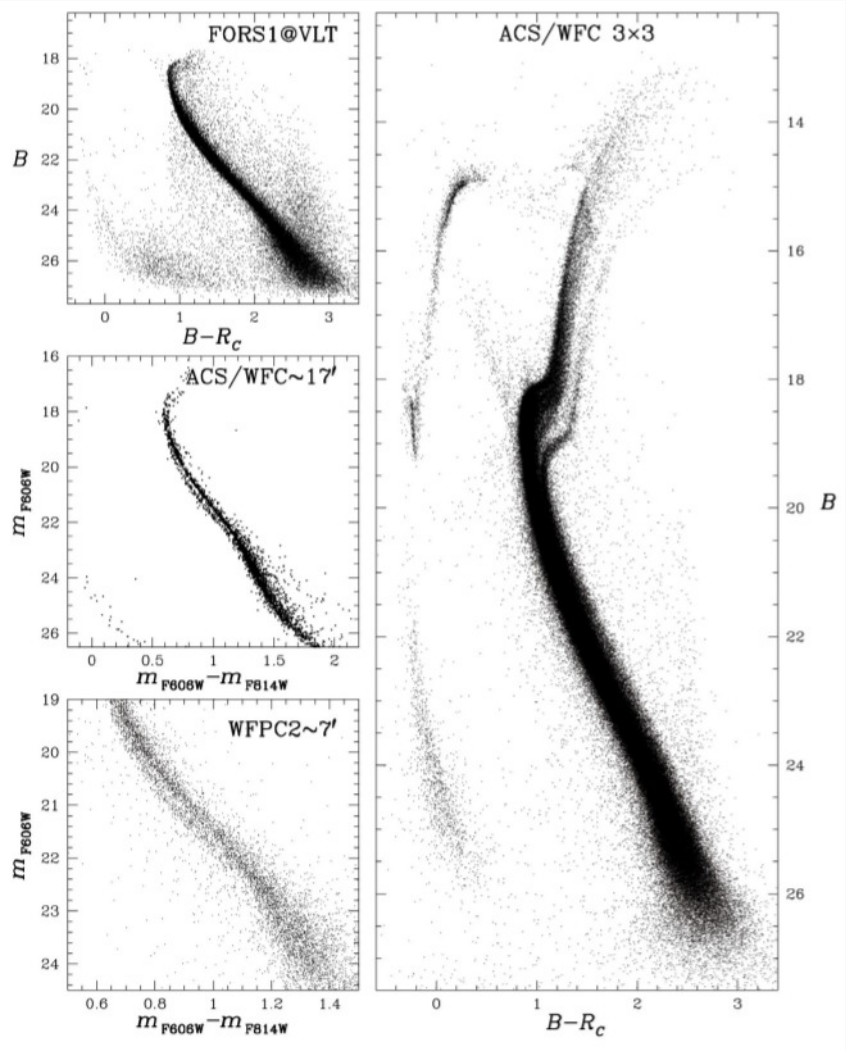
Free parameters

> "I remember my friend Johnny von Neumann used to say, with four parameters I can fit an elephant,and with five I can make him wiggle his trunk." *Enrico Fermi*

- The formation of GCs is not well-understood *[Brodie & Strader 2006]*
- Some clues: gas-rich merging galaxies contain large numbers of young massive star clusters *[Schweizer 1987; Whitmore & Schweizer 1995]*
- Physical processes related to star formation are very complex
- Single or multiple generations over a period of several 10^8 years?

Multiple populations



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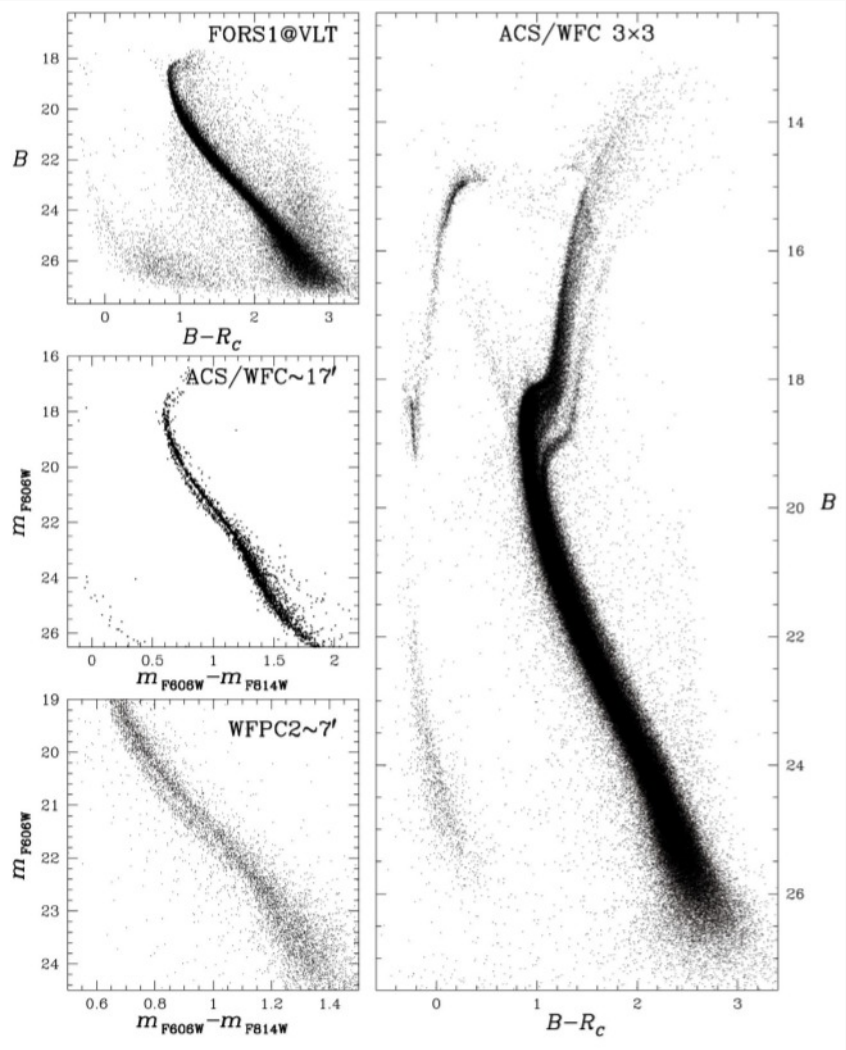

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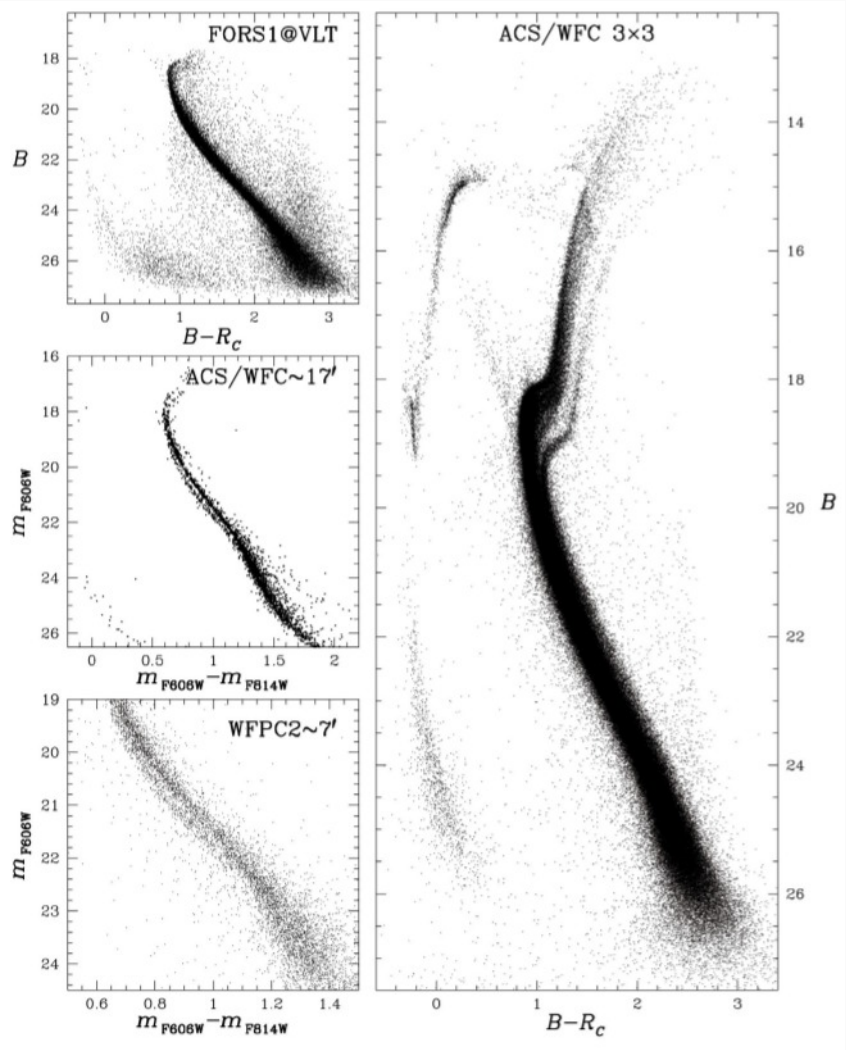

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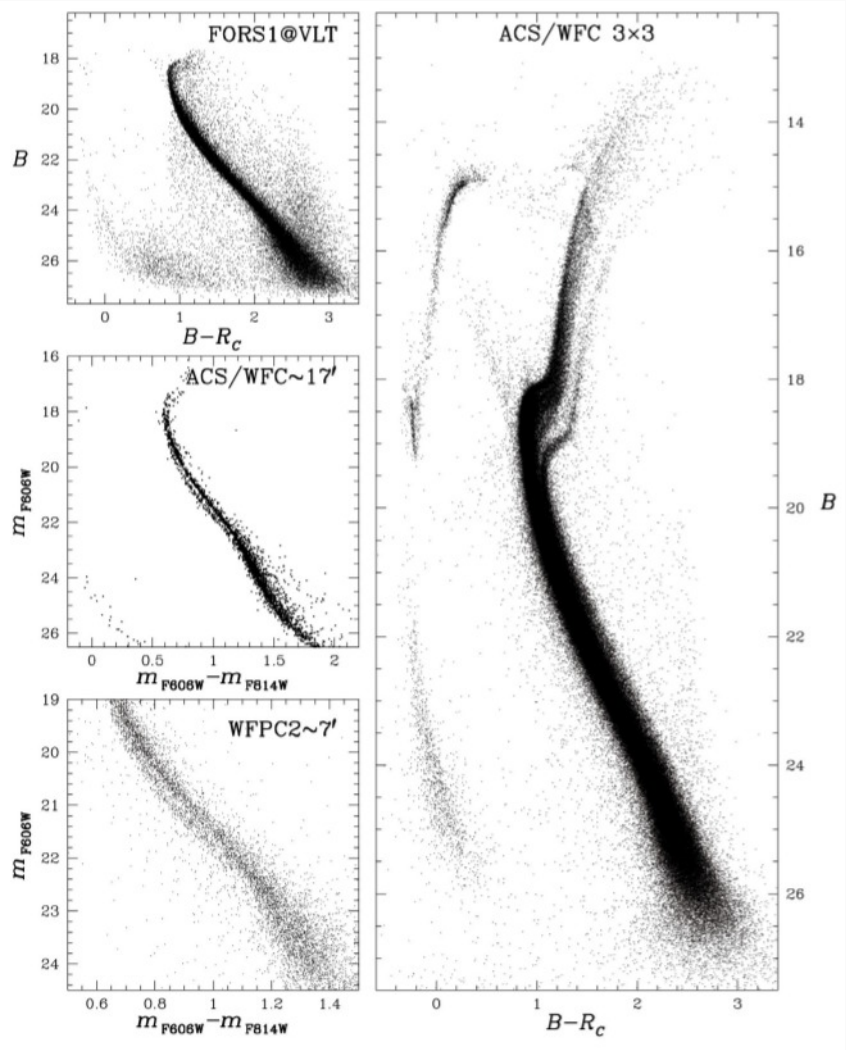

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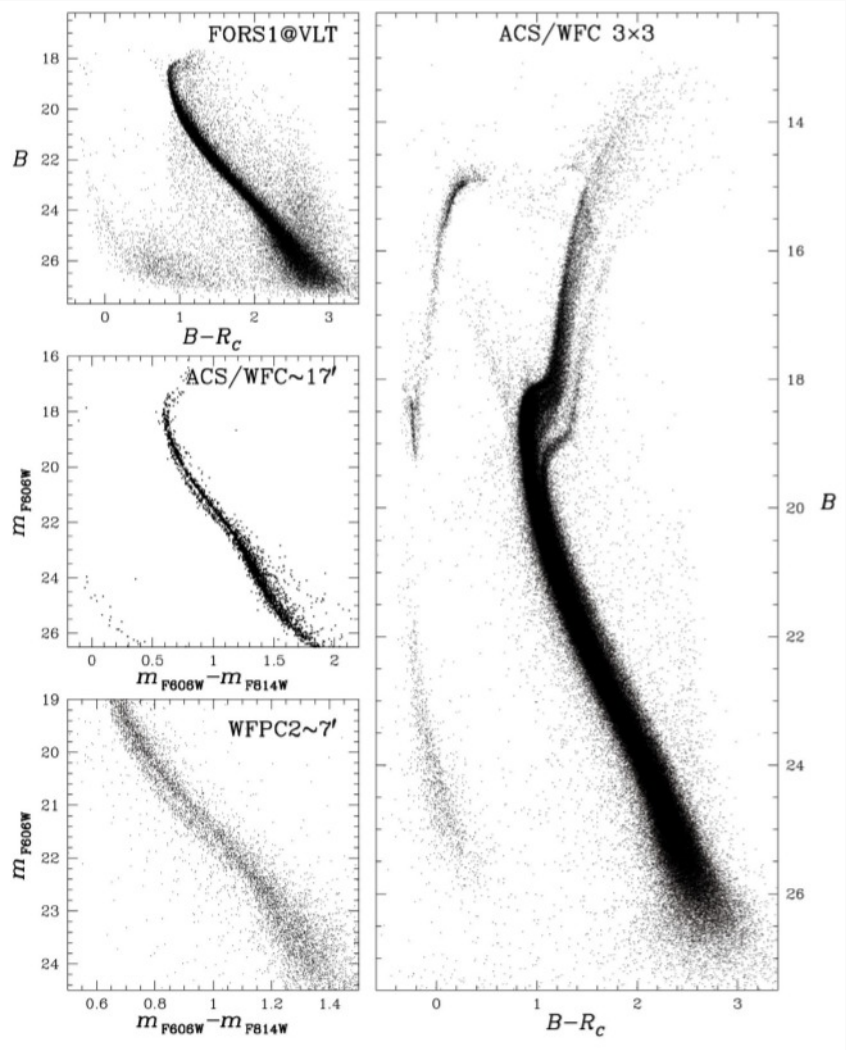

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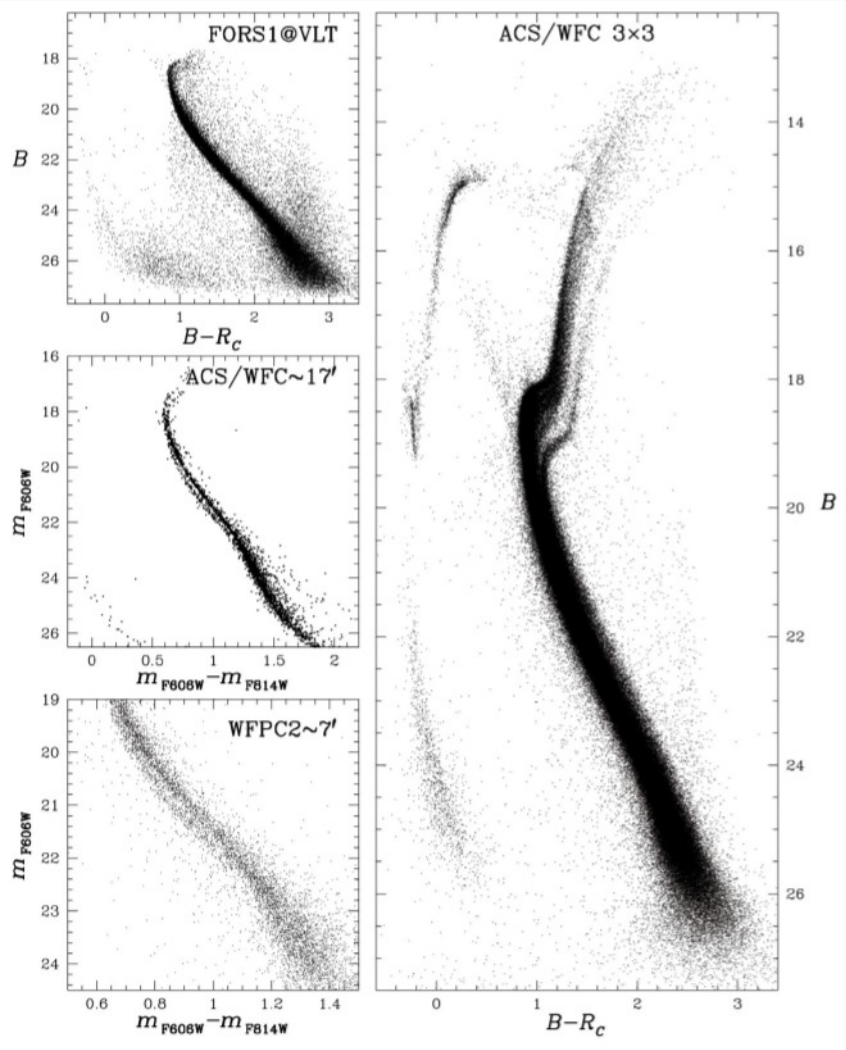

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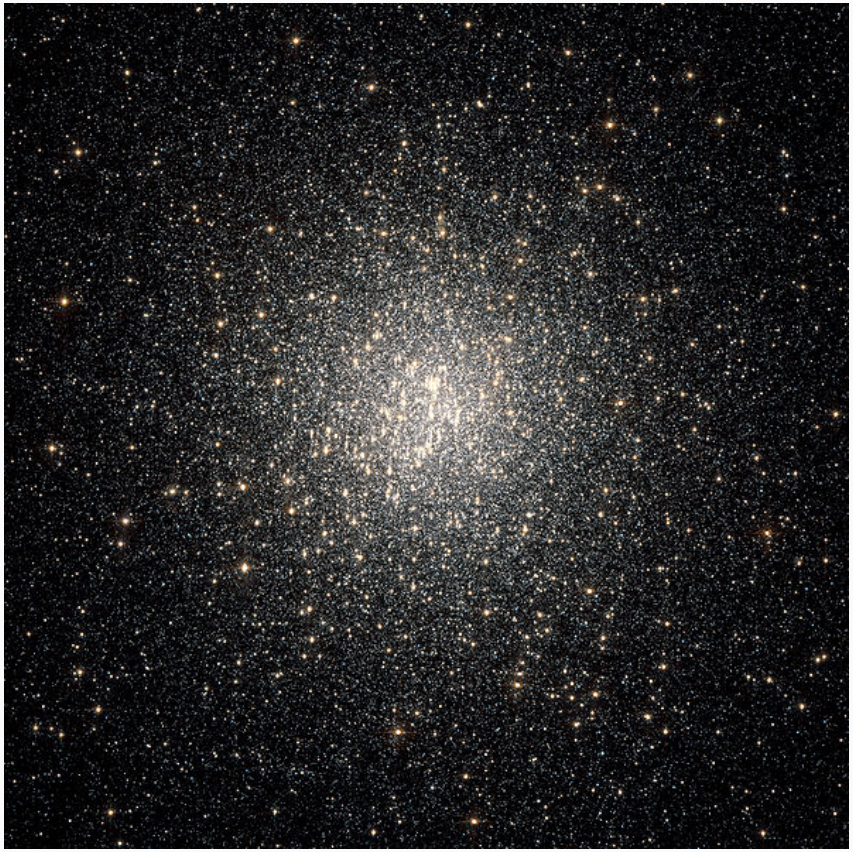
- Split of different evolutionary sequences

Globular clusters: Tracers of MBH and galaxy growth



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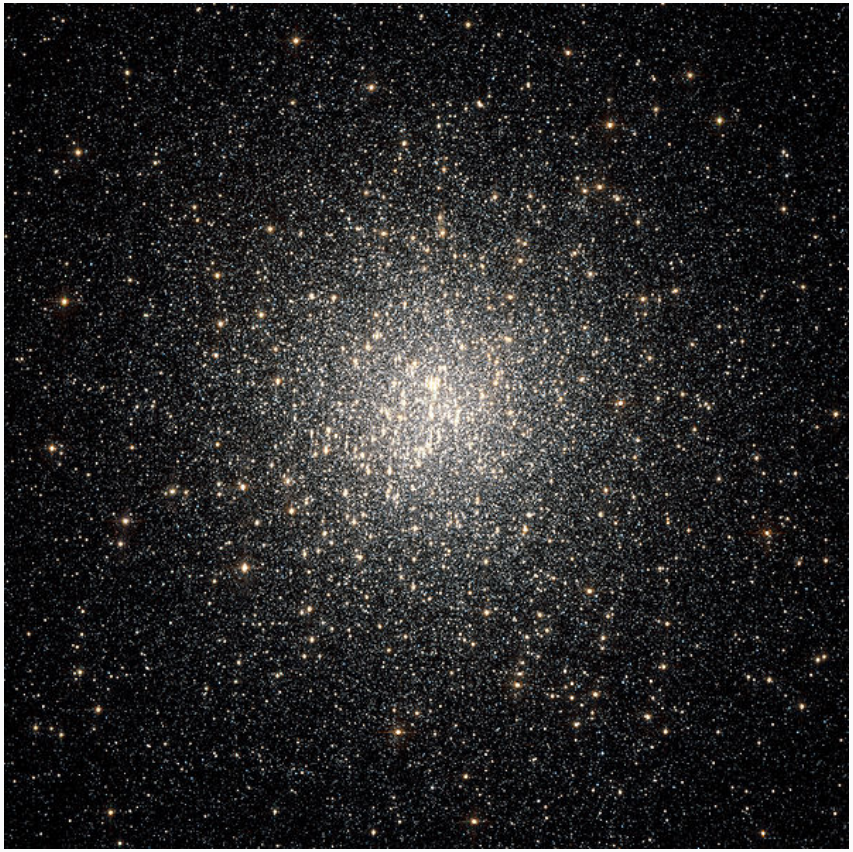

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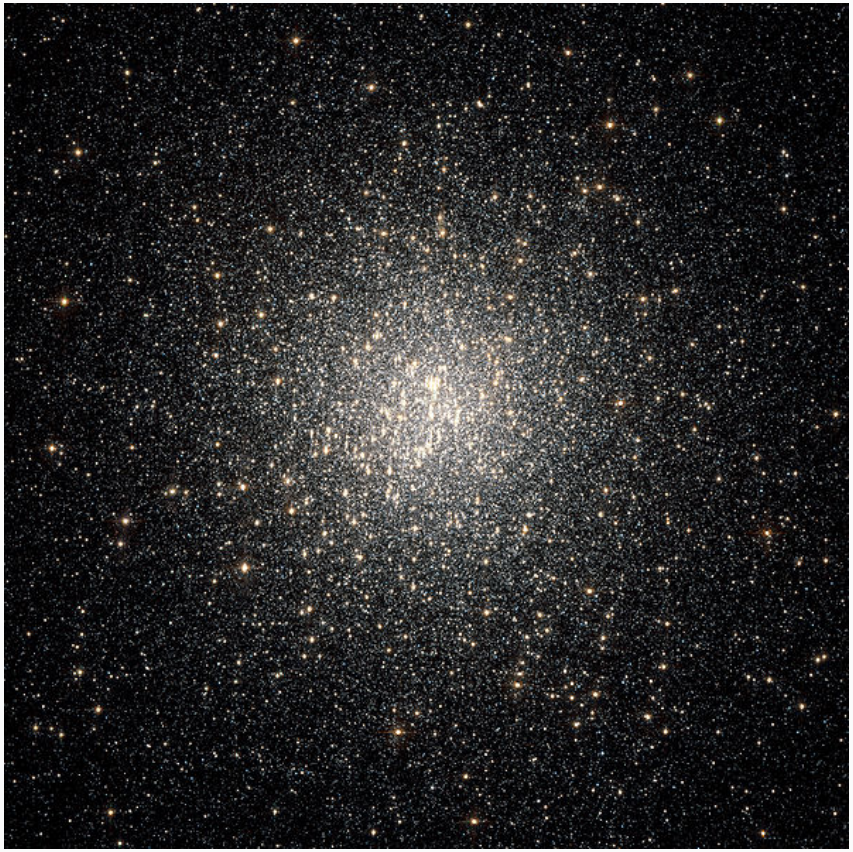

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- S_N the specific globular cluster frequency := # of GCs per unit absolute visual magnitude $M_V = -15$

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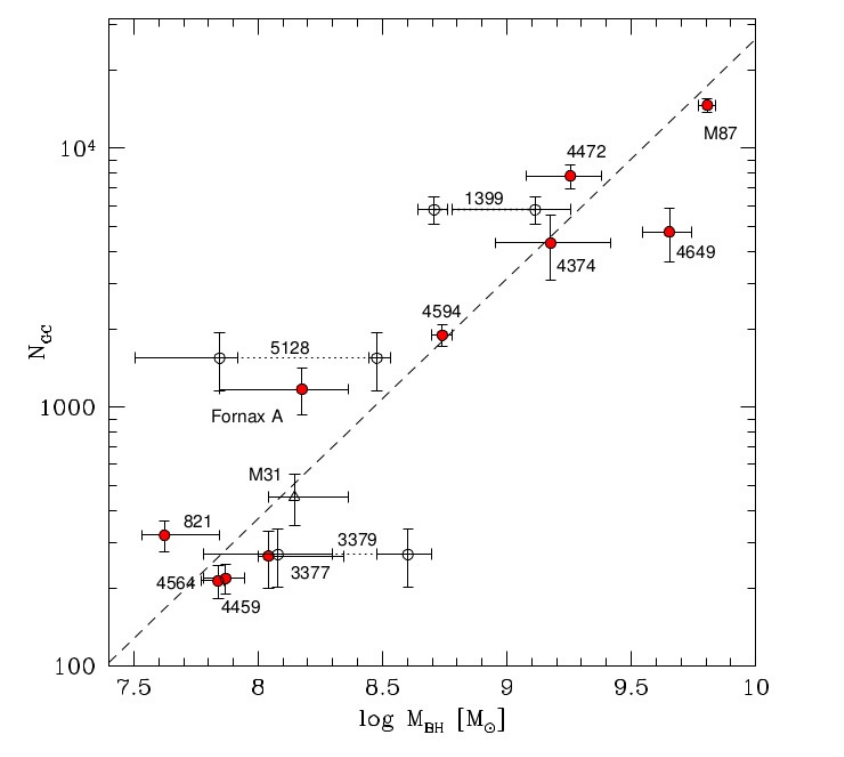

Number of GS vs. mass of central $M_\bullet$ for 13 giant elliptical, lenticular and early-type spiral galaxies *[Burkert & Tremaine 2010]*

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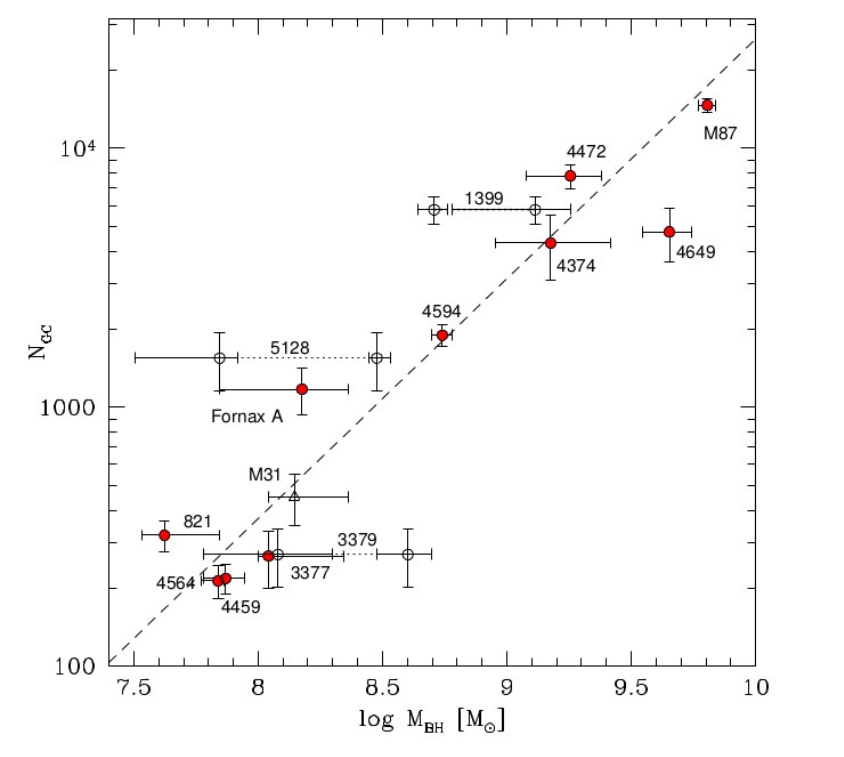

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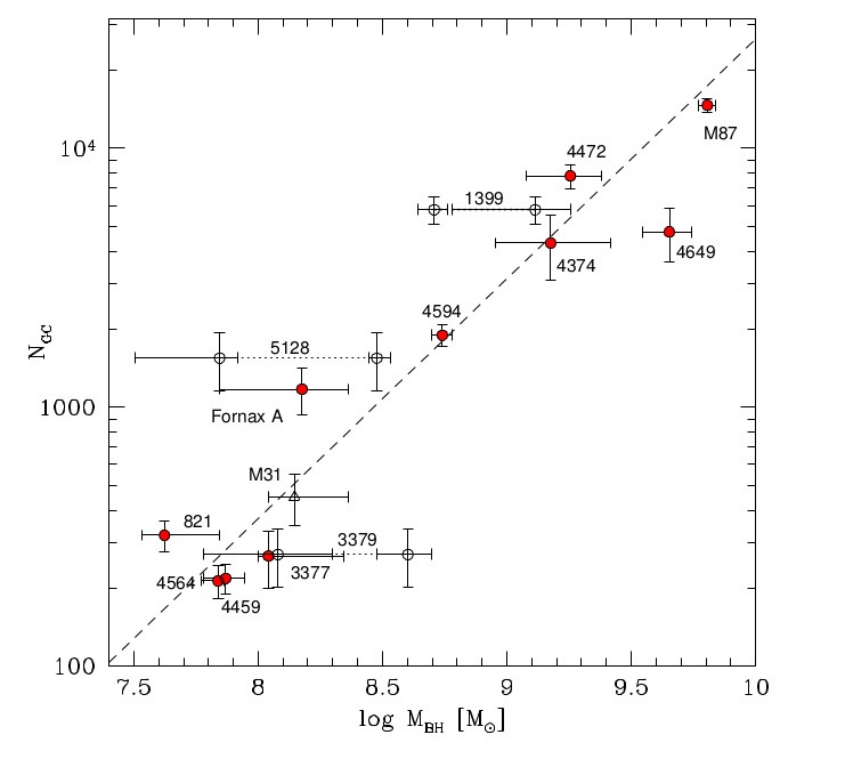

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- Set of 13 galaxies
- $M_\bullet = 1.7\,10^5\,N_{\rm GC}^{1.08\pm0.04}\,M_\odot$

Thermodynamics

A constant

The Coupling Constant

$$G = 6.67 \times 10^{-8} \mathrm{cm}^3 \mathrm{g}^{-1} \mathrm{sec}^2$$

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- *One single coupling constant*
- No decoupling of scales
- Cannot separate *local* and *global* aspects
- Only freedom: # bodies, N

N governs...

- Granularity of the system

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- Speed of internal heat transport and evolution

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- Rate of exponential divergence of nearby trajectories

We can solve

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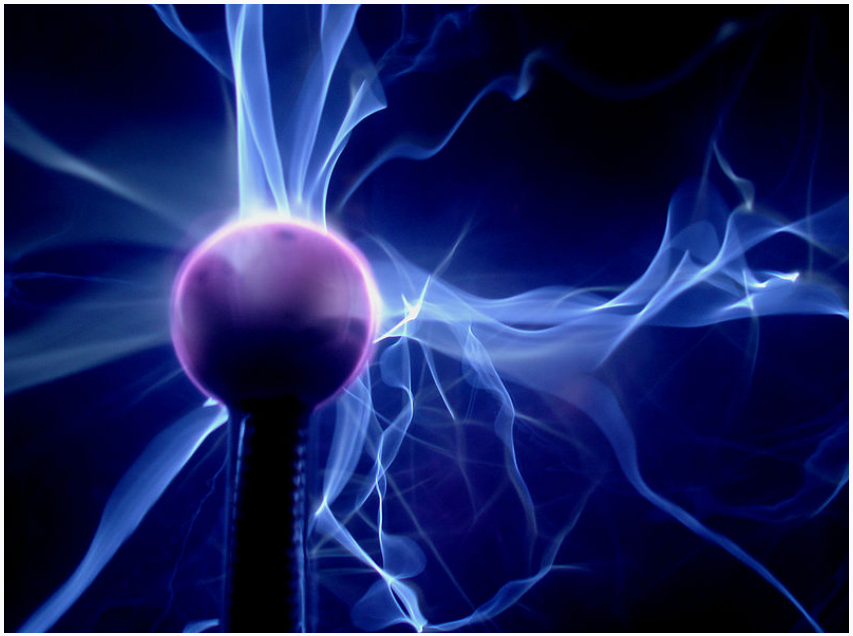
- $N \to \infty$?

Analogies



Interior of plasma ball (credit: Ruy Lestrade)

- Important analogues to the $N \to \infty$ problem

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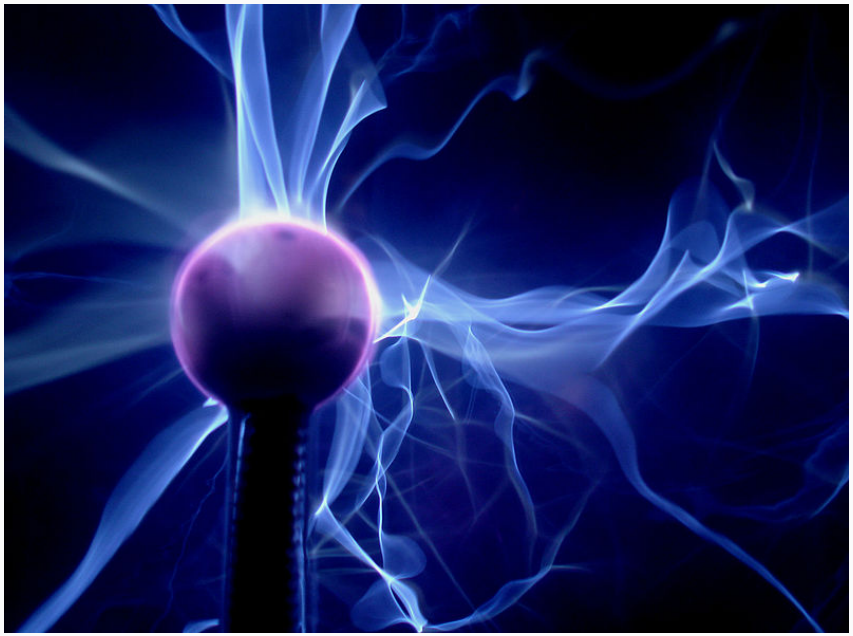

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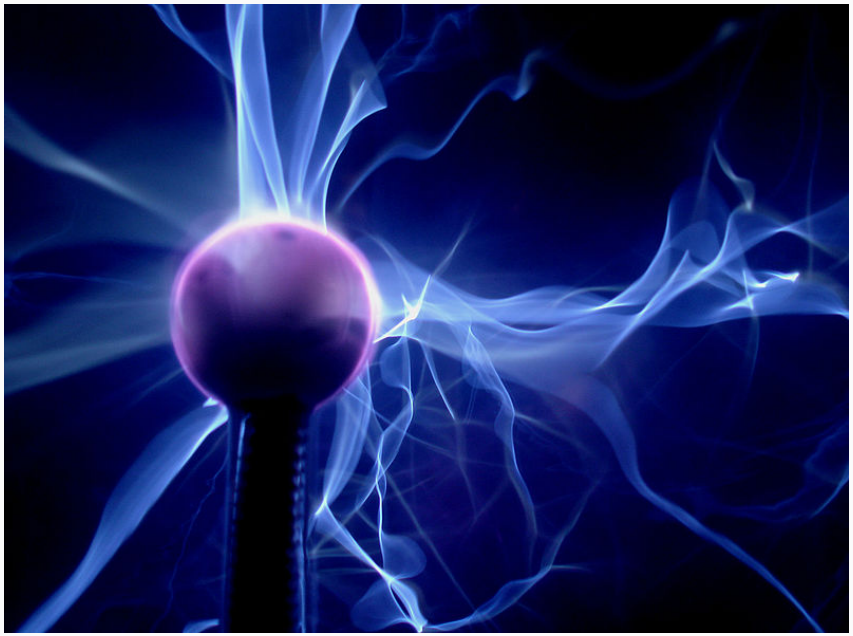

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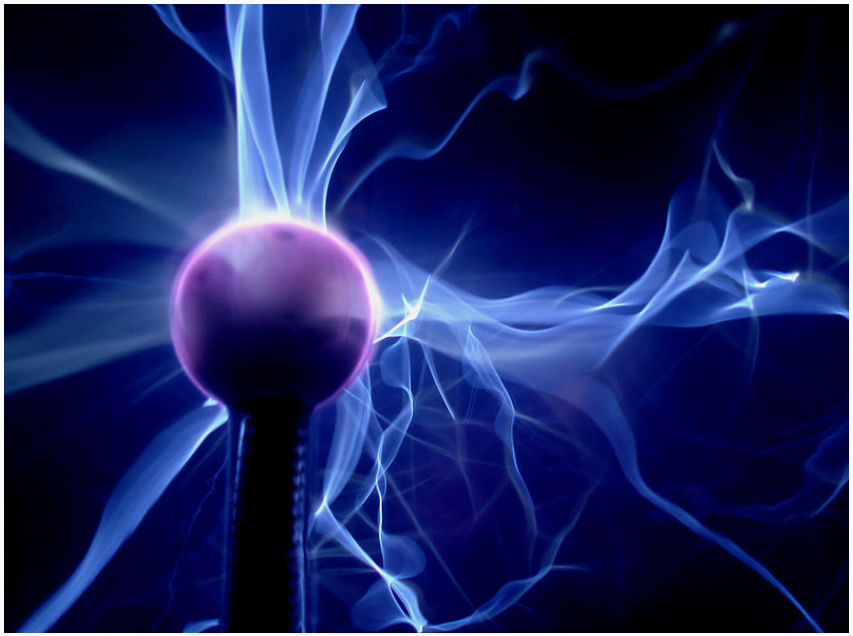

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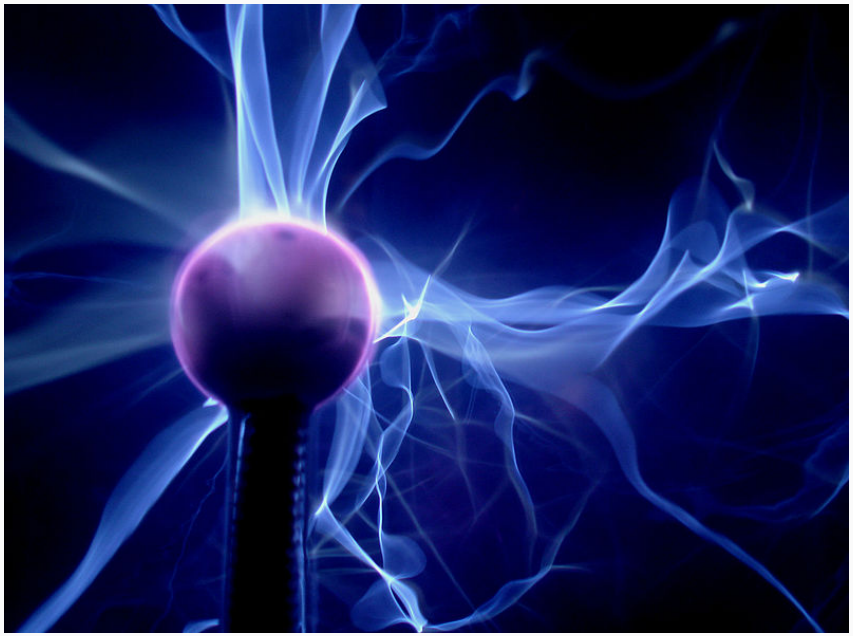

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- ★ Gravitational long-range forces violate the notion of an asymptotic thermodynamic limit
- ★ Physical quantities must be either intensive or extensive
- ★ In gravity we cannot ignore the effect of long-range interactions

Can we use thermodynamics?

- ★ Thermodynamics excludes a description of self-gravitating systems
- ★ Gravitational long-range forces violate the notion of an asymptotic thermodynamic limit
- ★ Physical quantities must be either intensive or extensive
- ★ In gravity we cannot ignore the effect of long-range interactions
- ★ No, we cannot! But let's do it anyway...

A box of stars

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- We cannot reach an asymptotic thermodynamic limit
- Equilibrium thermodynamics ruled out

Cheating ...This is physics, after all

The *formal* inability to apply traditional thermodynamic concepts does not seriously hinder us from thinking and working with them.

Puzzling thermodynamics

Thinking NGC 6752 out of the box

- Let's play with a cluster

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- What happens?

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- What happens?
- Meet negative heat capacity

Cheating with thermodynamics

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- Place it in a colder box: It heats up without limits
- Want to cool it down? Place it in an even hotter one
- *"stars act like donkeys slowing down when pulled forwards and speeding up when held back."*

[Lynden-Bell and Kalnajs (1972)]

The power of binaries

Thinking NGC 6752 outside of the box

- If we wait “long enough” a simultaneous close three-body encounter will produce a tightly bound pair

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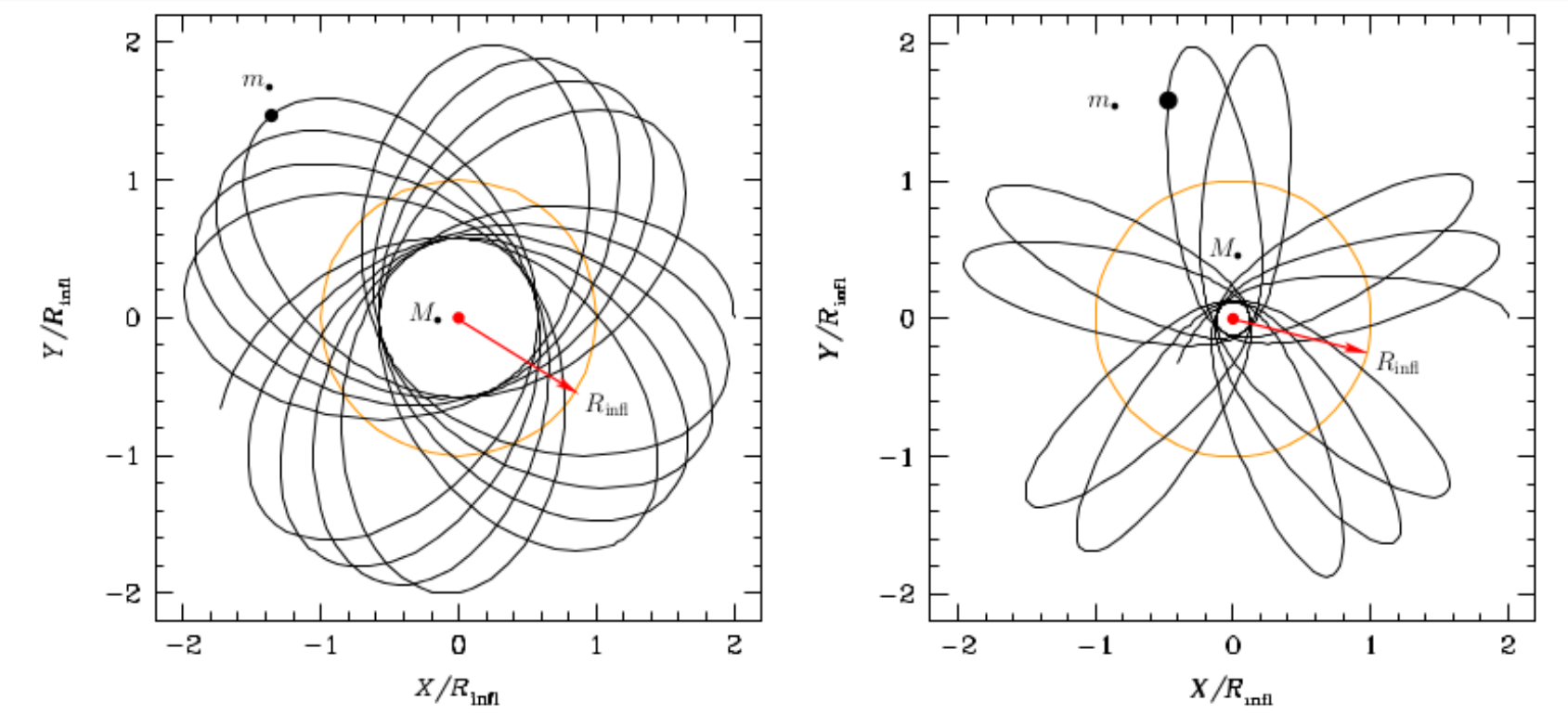
- E_{bin} arbitrarily large: Unlimited amount of $+E$ to the rest of the system

Potentials

Spherical potentials



- Two orbits differing in eccentricity

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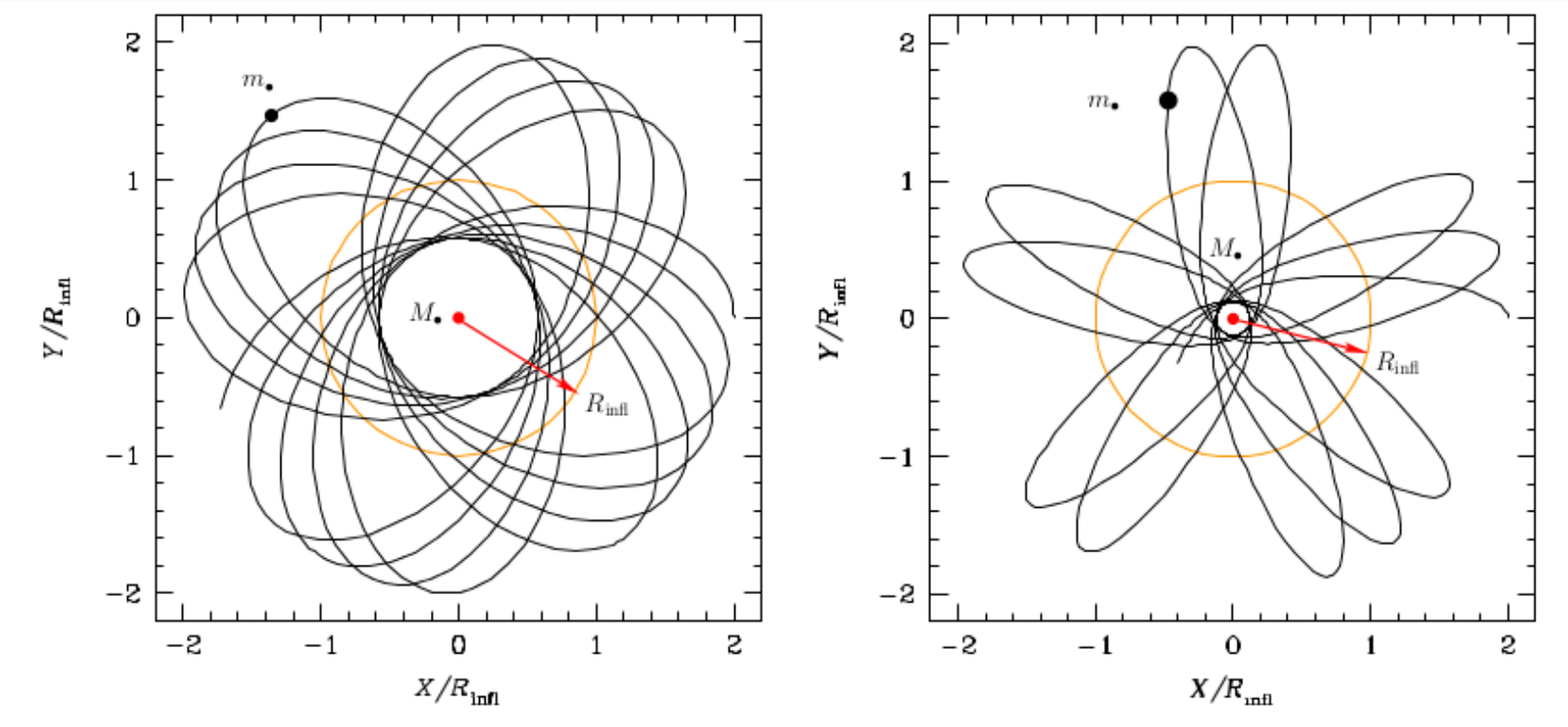

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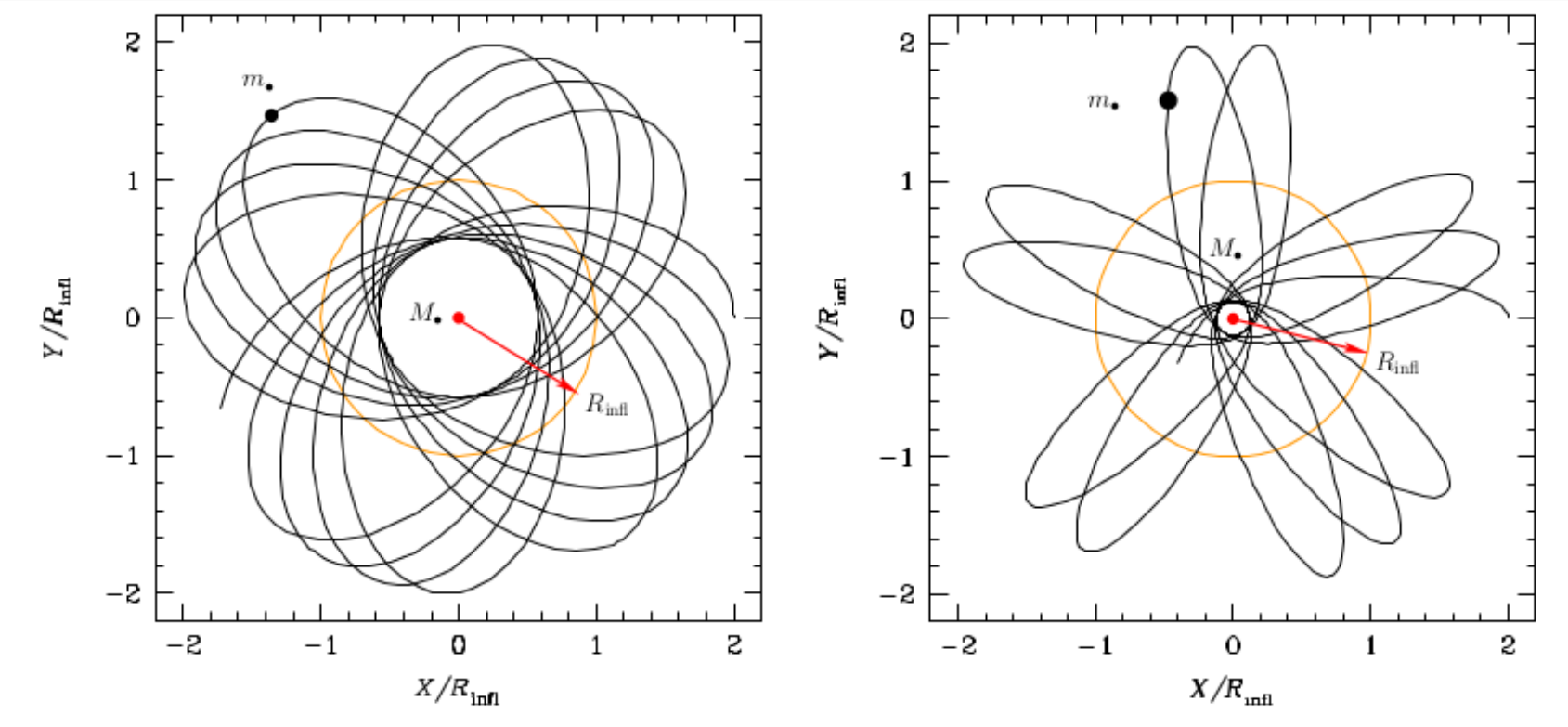

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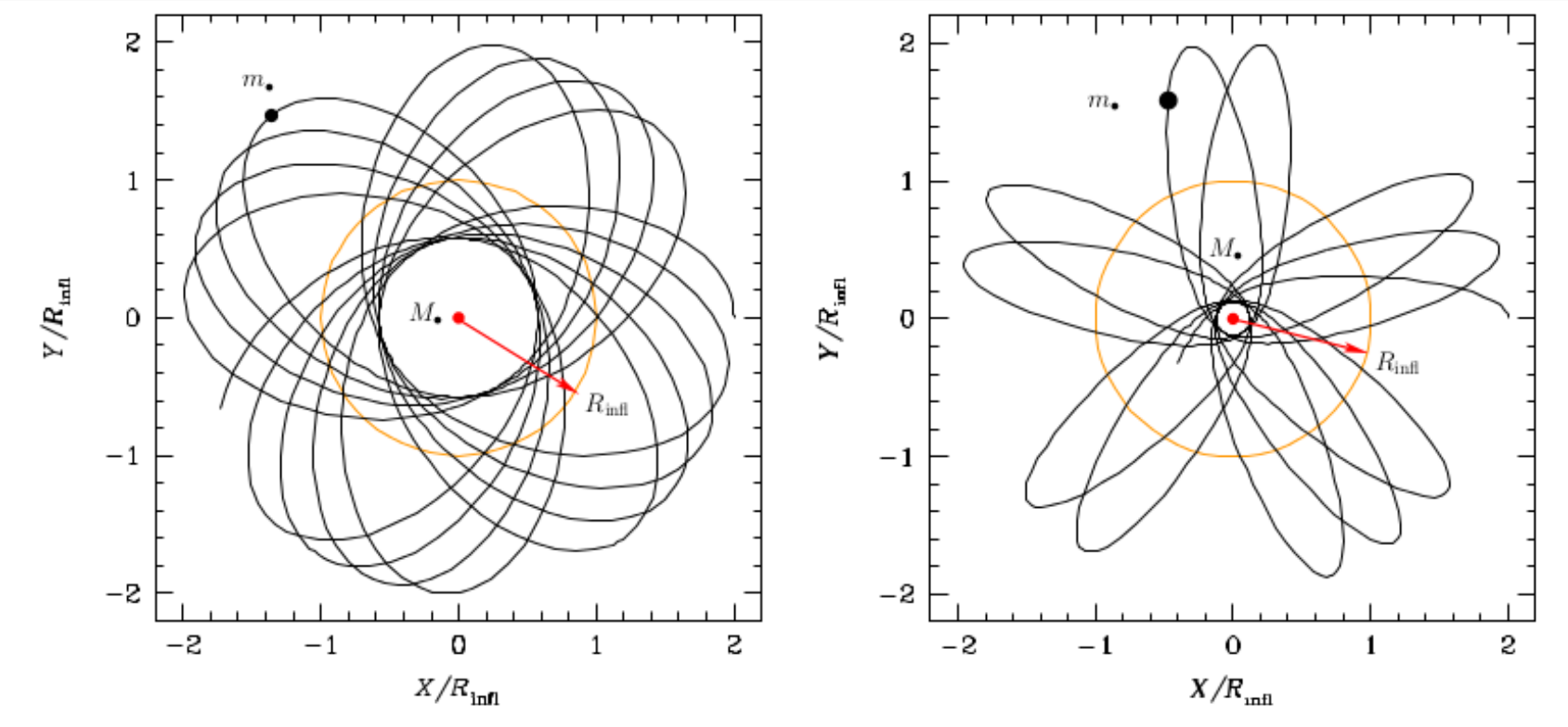

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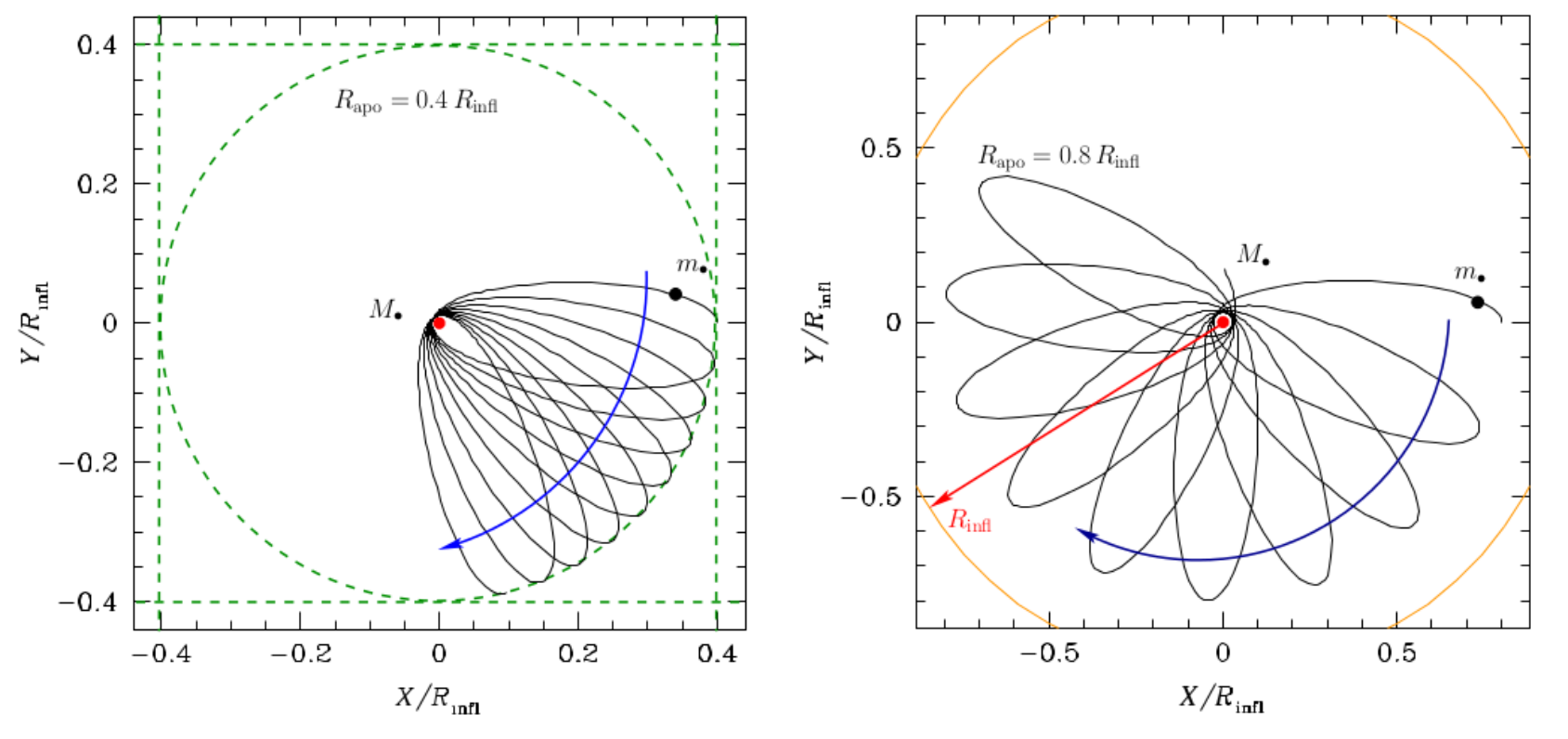
  J conserved: Fixed periapsis, cannot come arbitrarily close to MBH: Need perturbations

Newtonian periapsis retard



- Orbit within $R_{\rm infl}$

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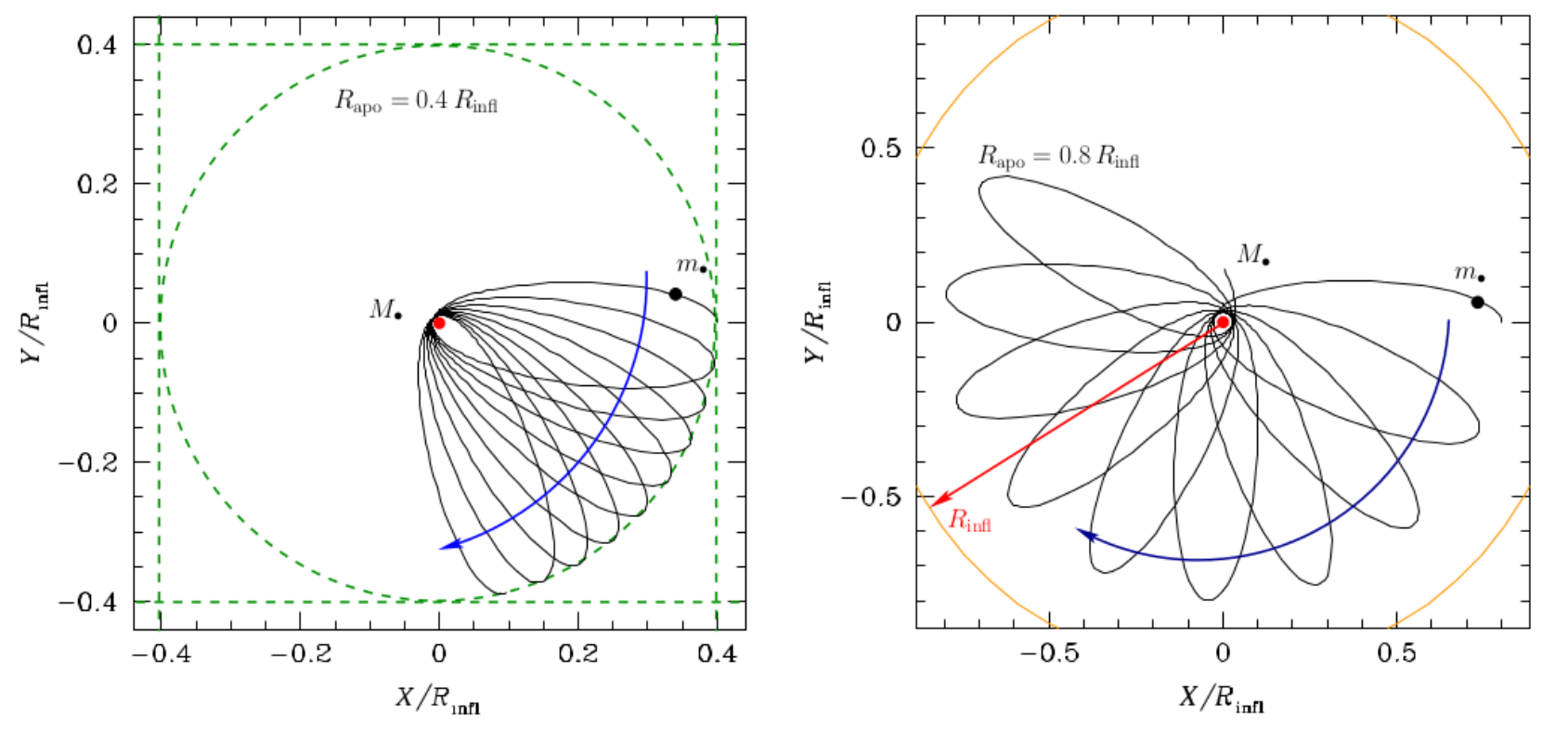

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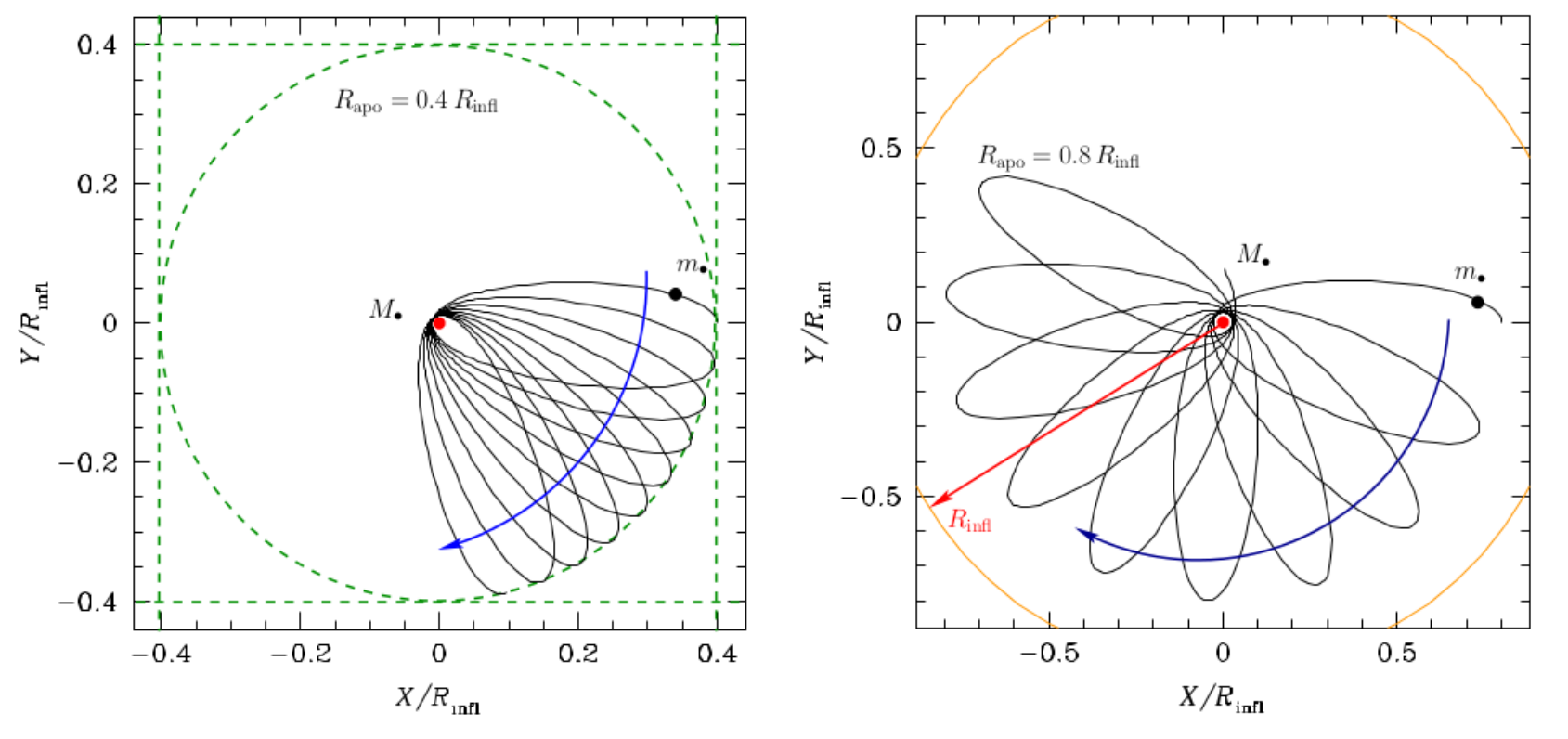

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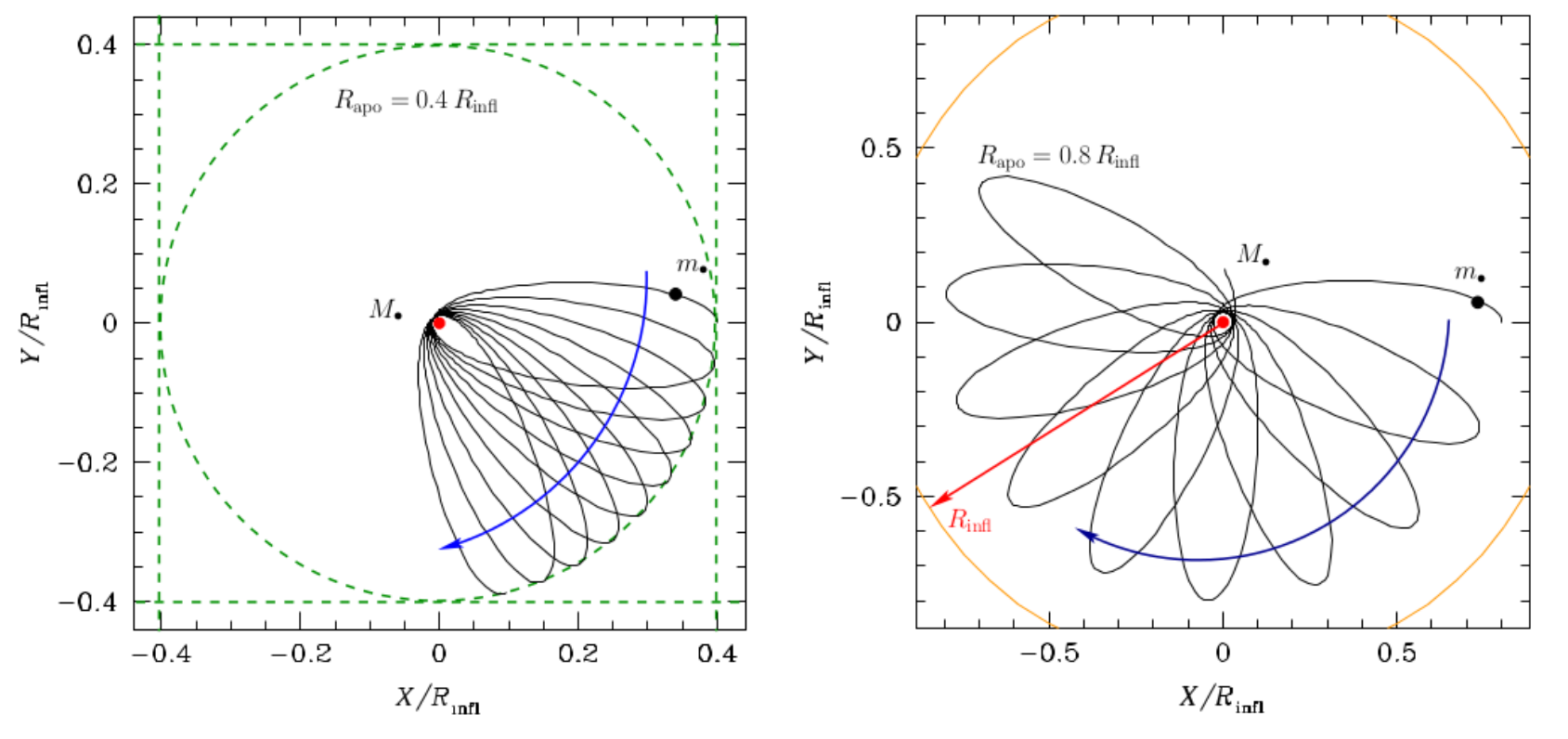

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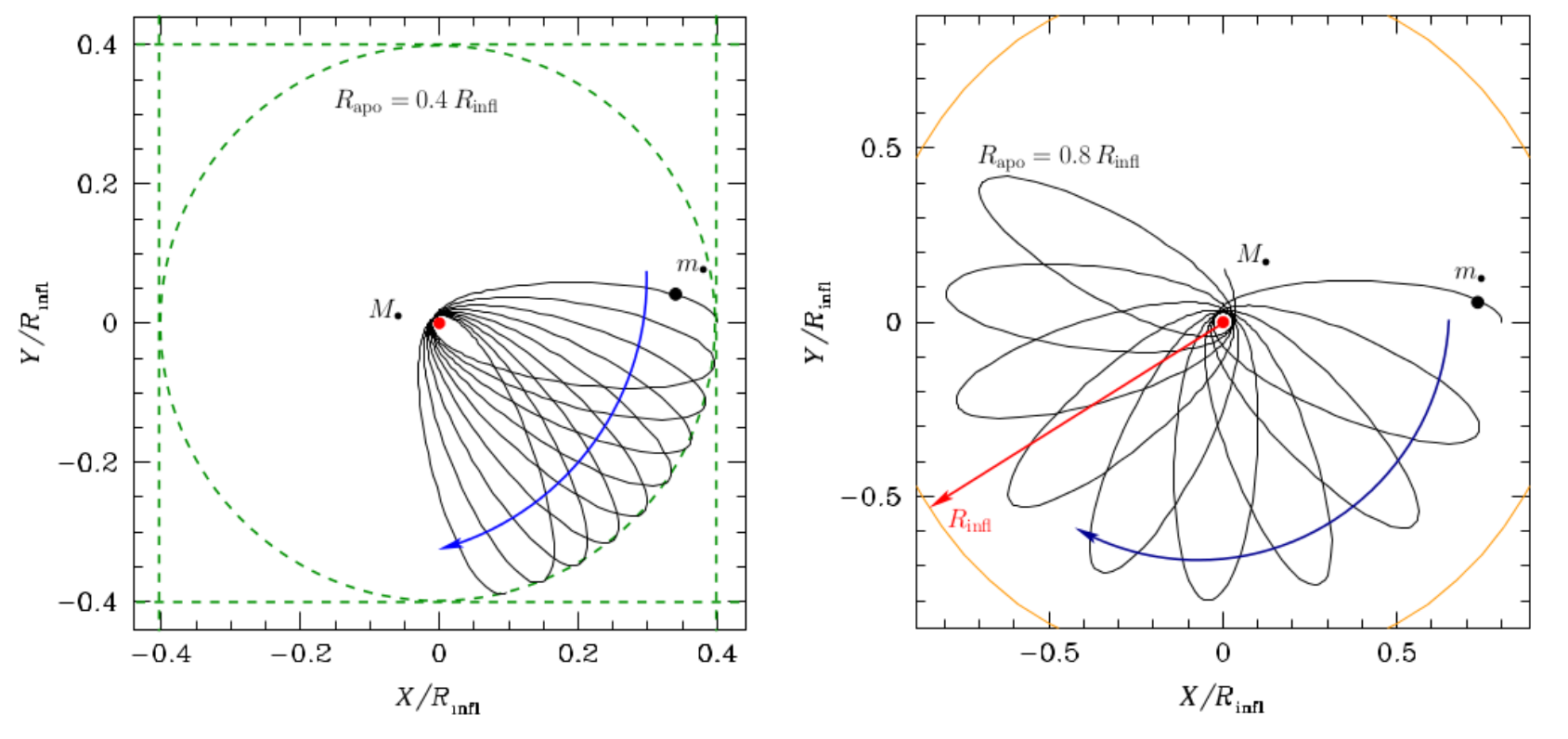

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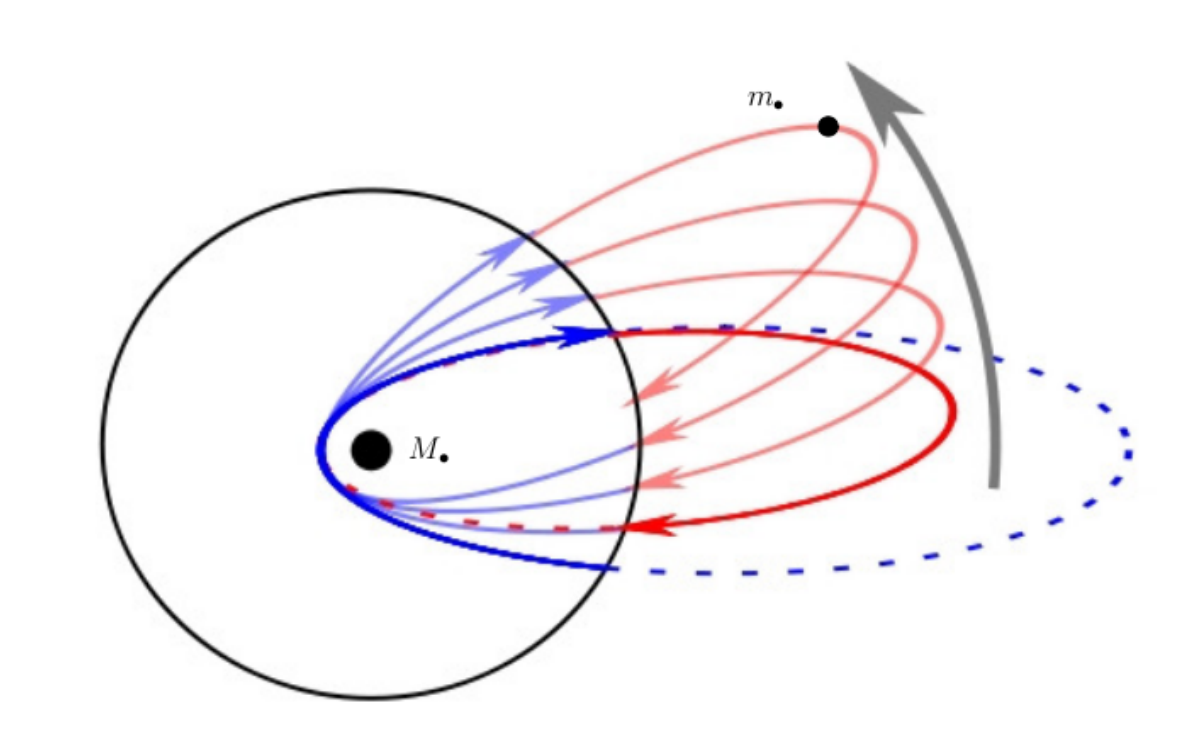

- The star feels more mass far away than closer to the centre

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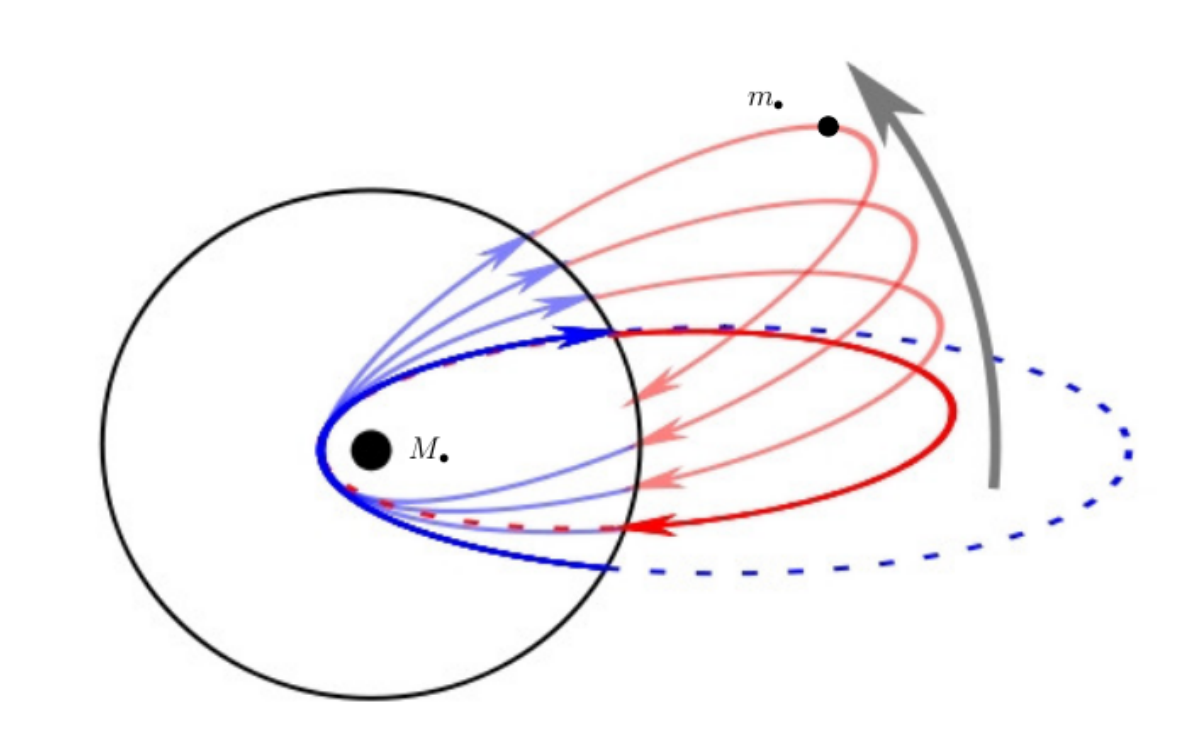

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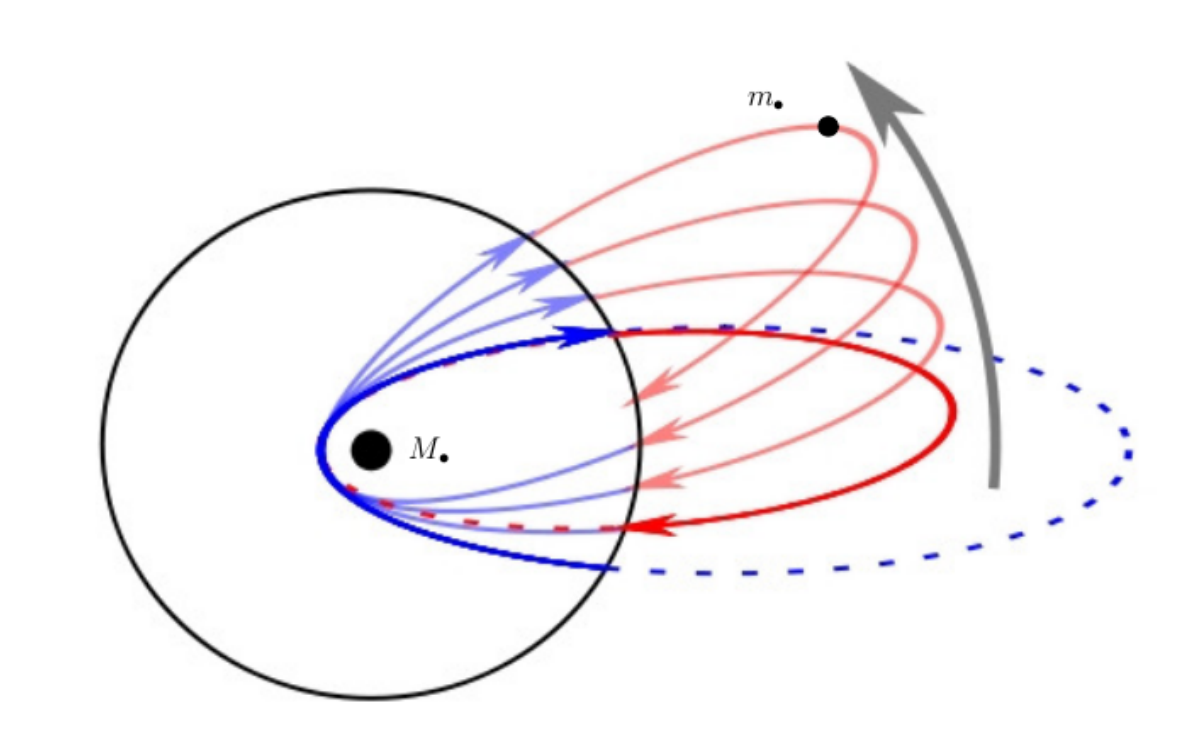

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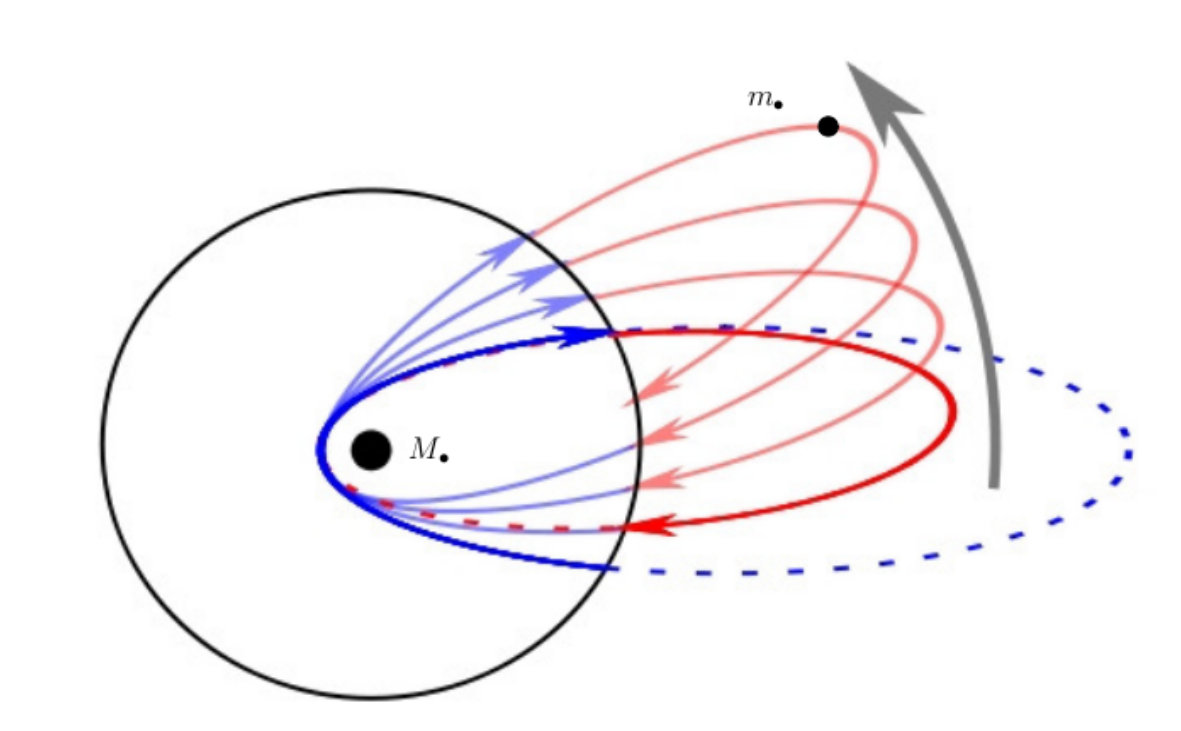

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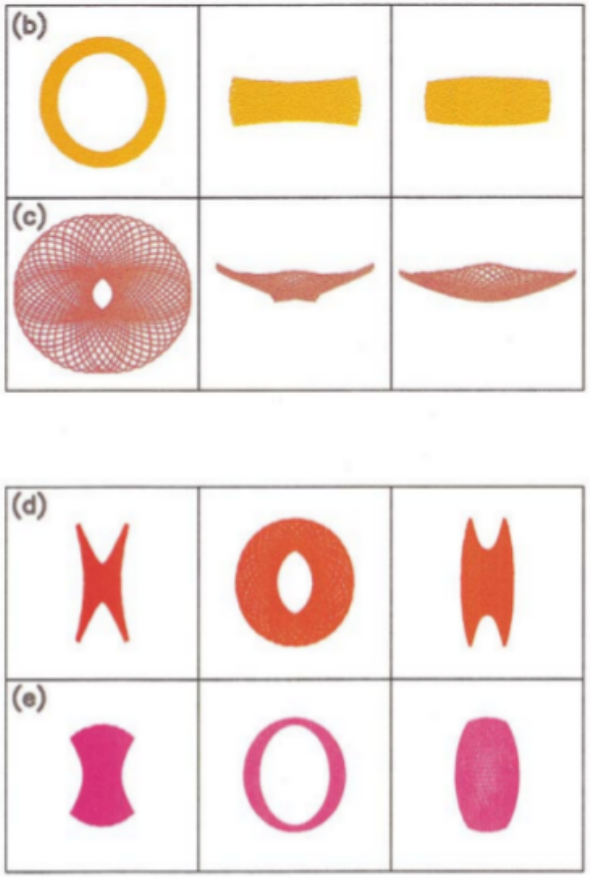
- The orbit precesses in the opposite direction to the orbital one

Non-spherical potentials



Centrophobic orbits - Never reach centre

[Poon & Merritt 2001]

- Most general case: Triaxial potential

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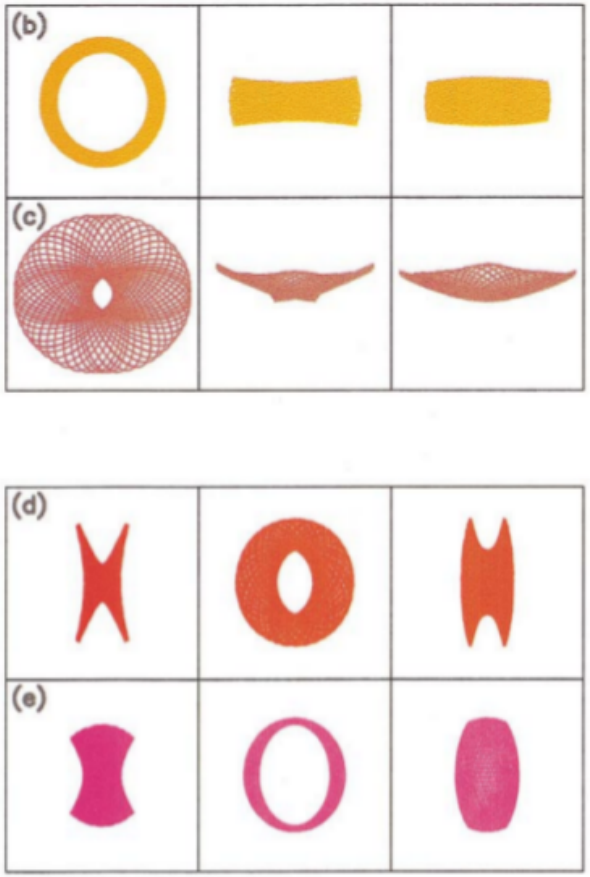

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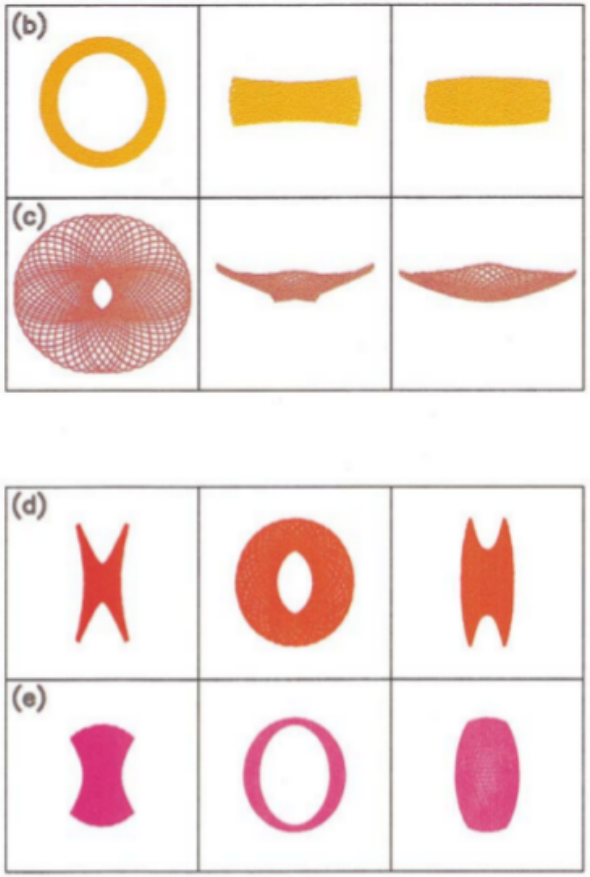

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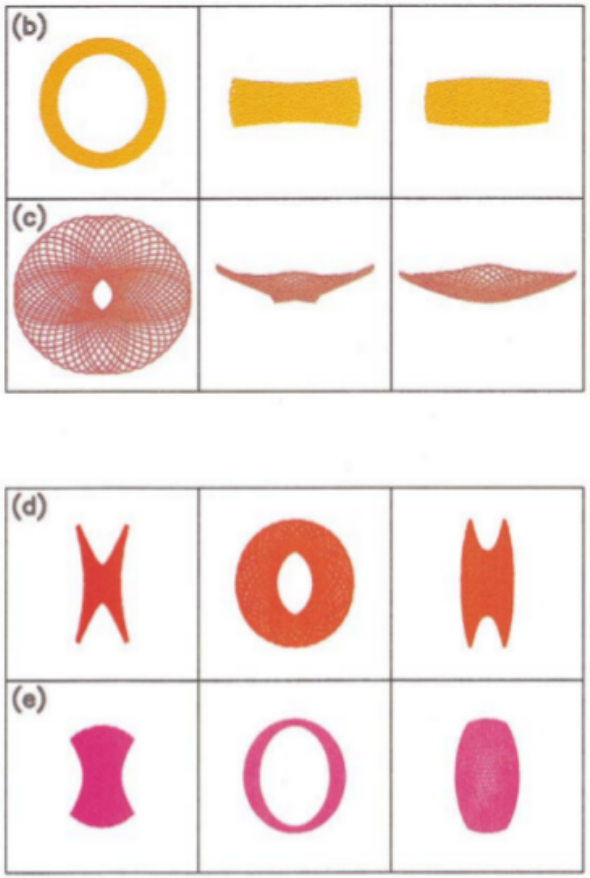

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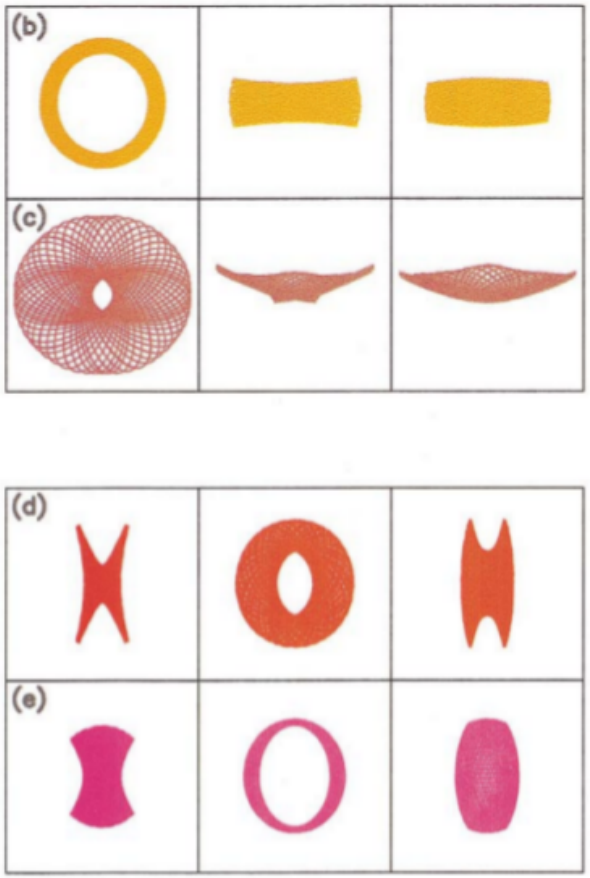

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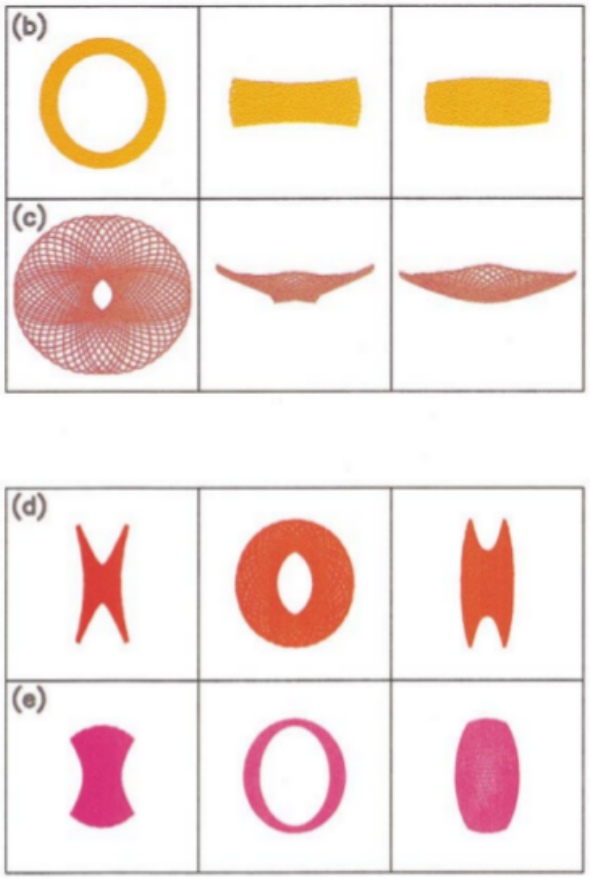

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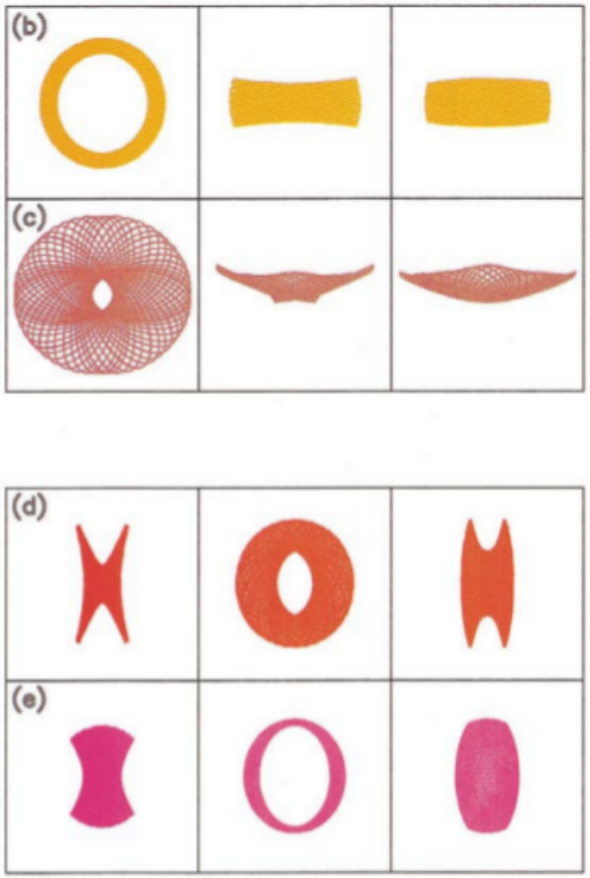

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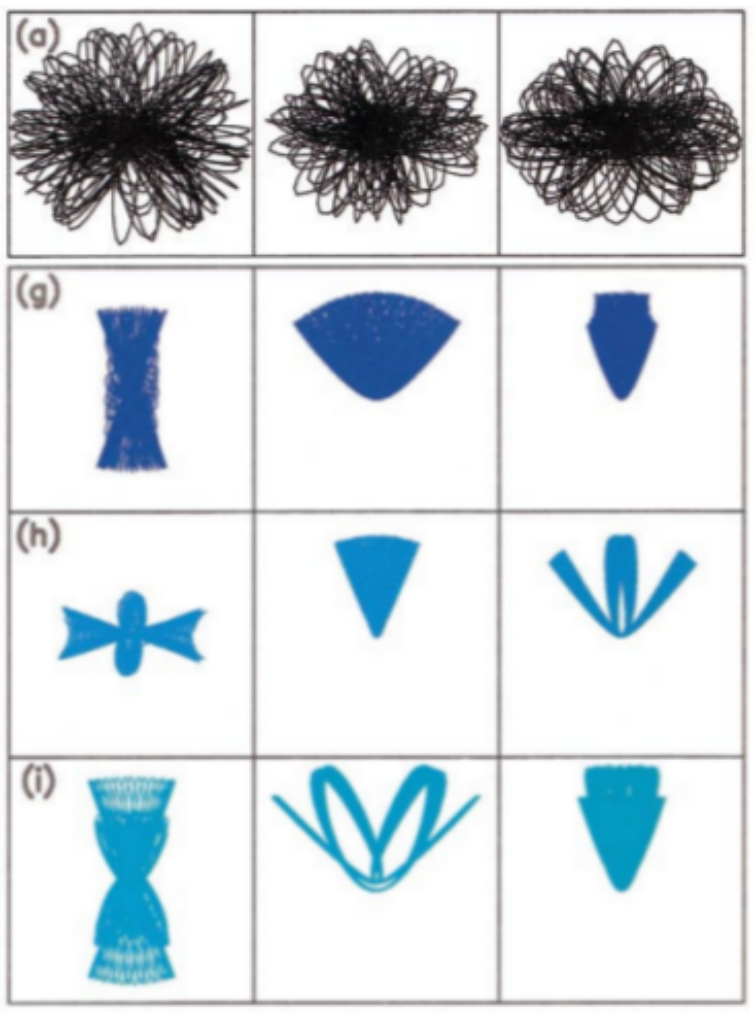

Centrophilic orbits - Get very close centre

- Pyramid or box orbits: Regular, and can get very close

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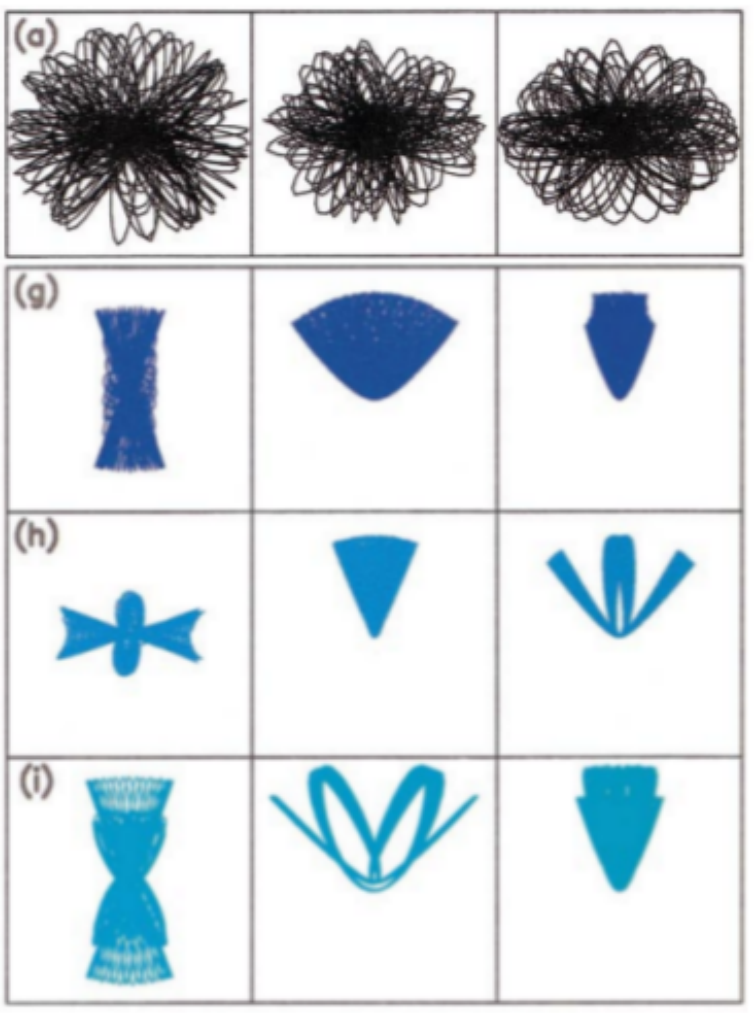

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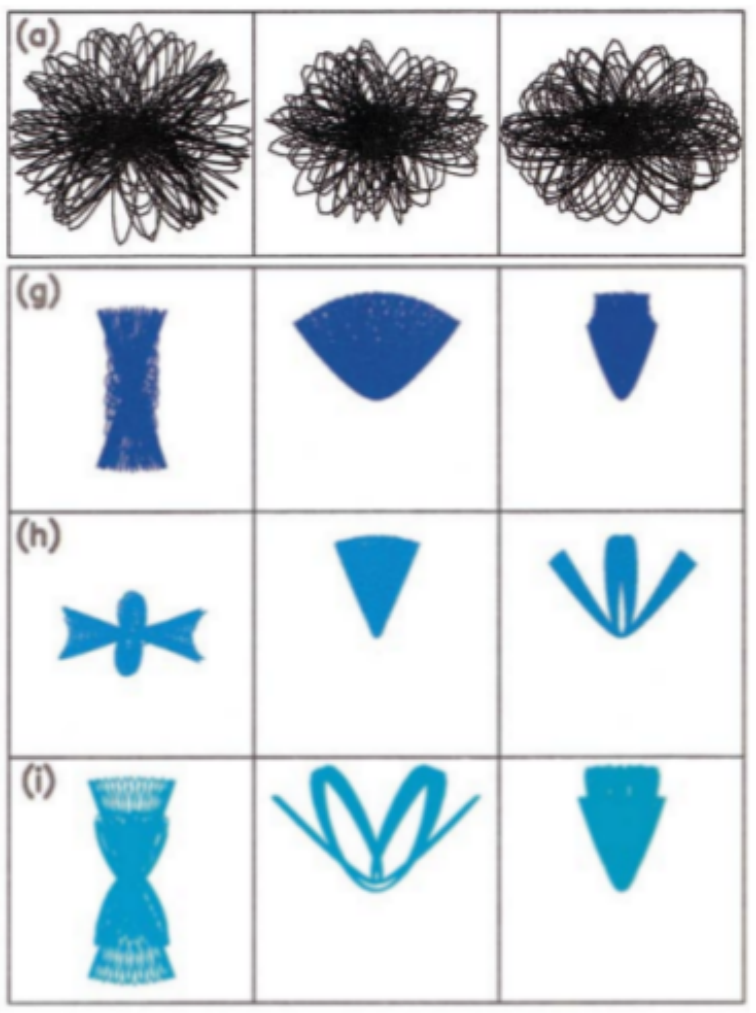

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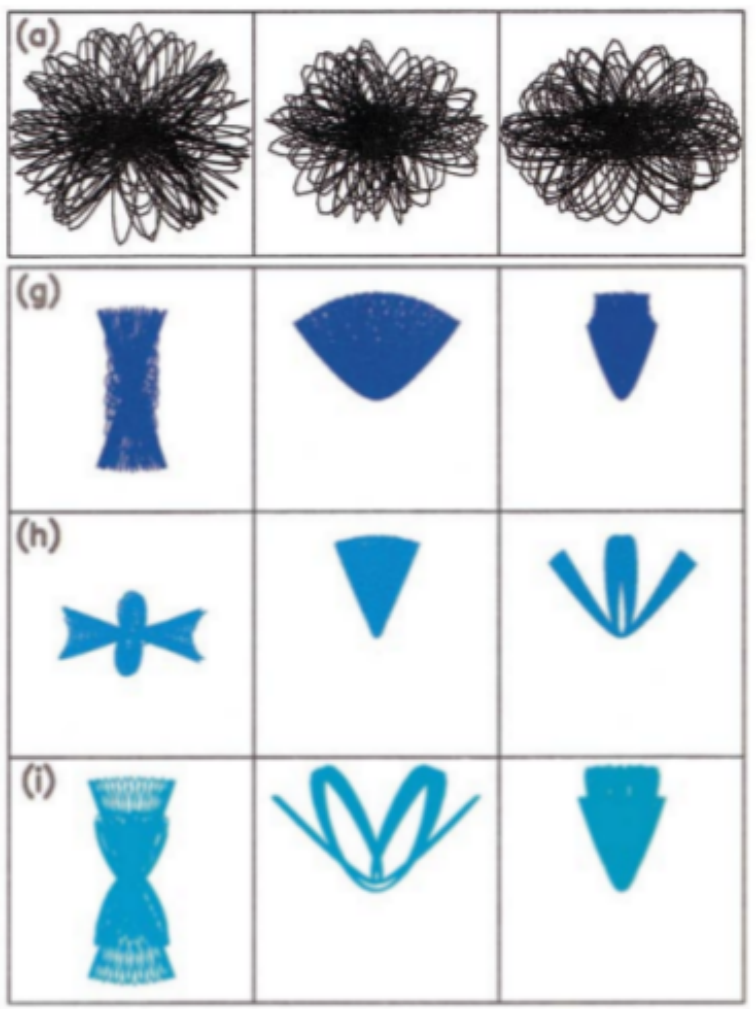

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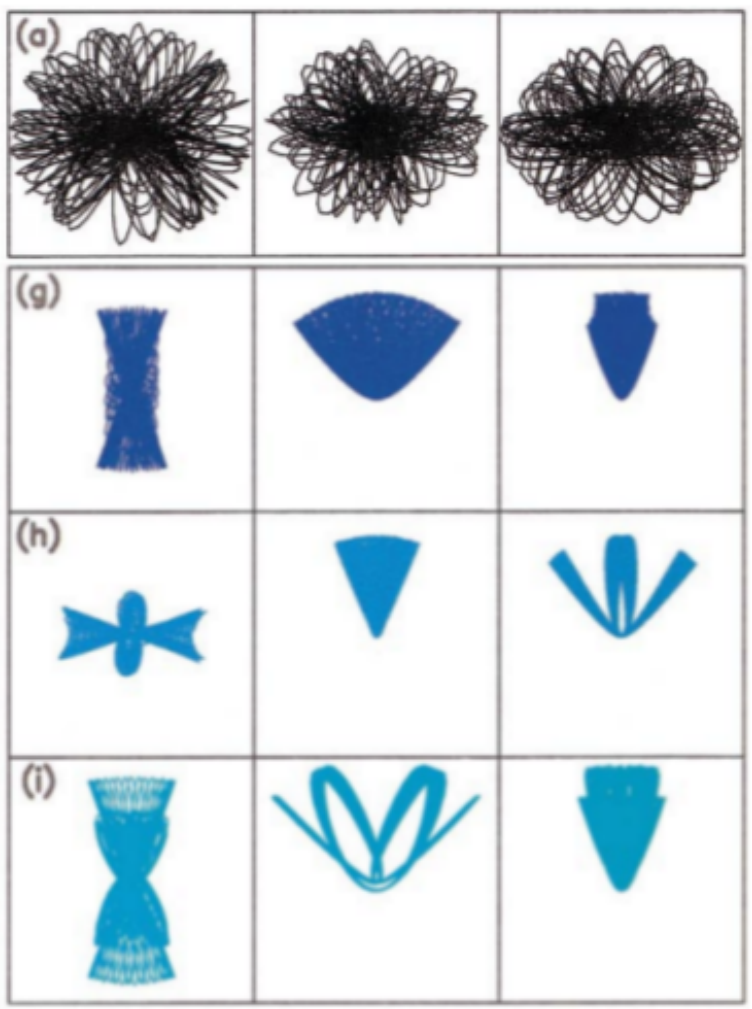

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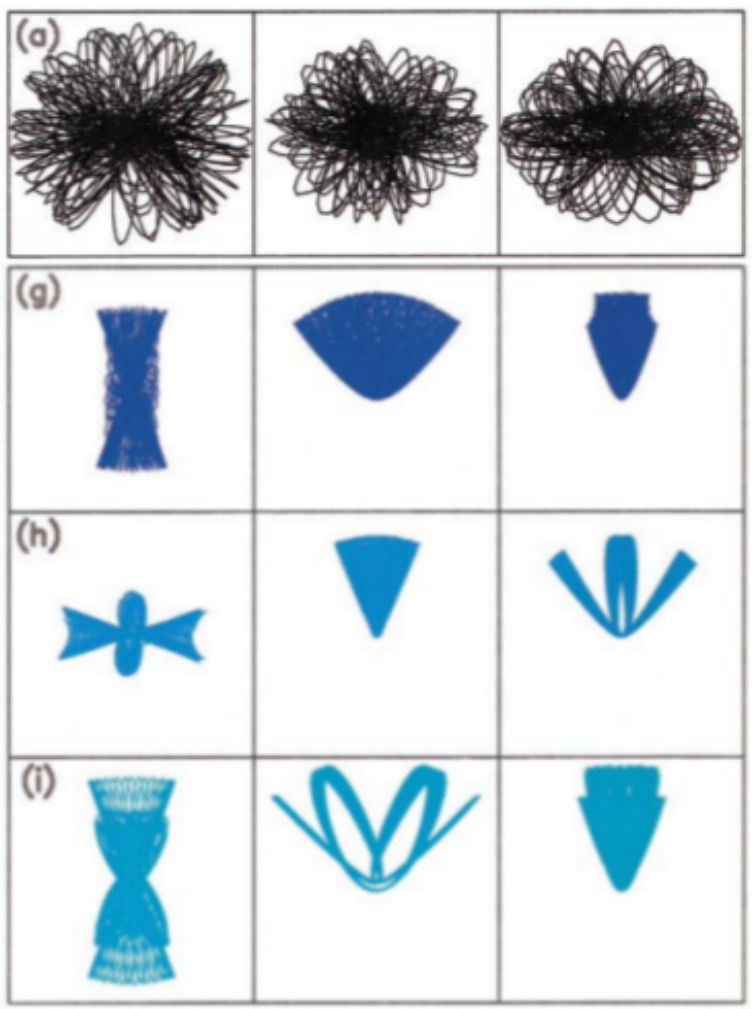

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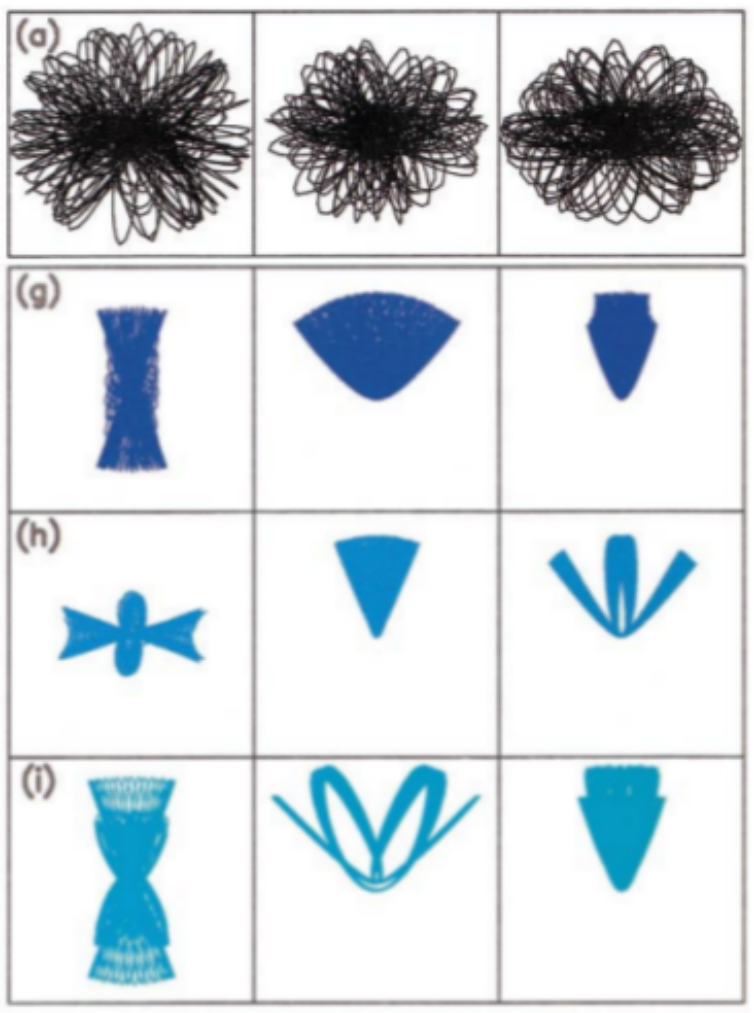

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- The projectile is attracted by the target

[Poon & Merritt 2001]

Relaxation

Two-body relaxation

- Back to a spherical system world

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  Decrease $J \rightarrow$ increase e

Two-body relaxation

- **Relaxation** (This is *not* the transition of an atom)

  For very dense stellar systems as galactic nuclei, one cannot suppose any longer that stars are moving under the influence of the mean potential generated by all other particles (which is what we call a *collision-less* system, related to the Boltzmann equation).

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  Gravitational encounters between stars gradually perturb from the trajectories they would have if the matter distribution were perfectely smooth

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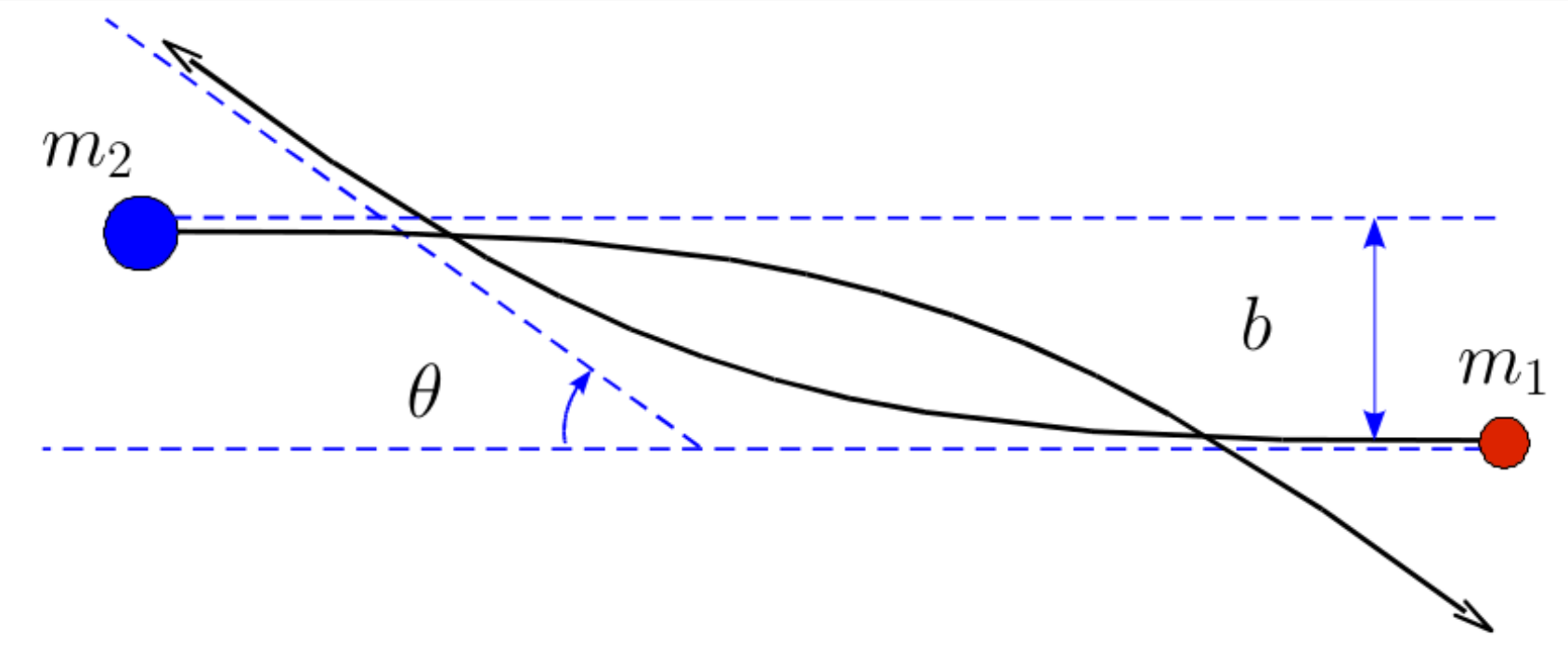
  Time-scale: T_{relax}

The kernel of relaxation



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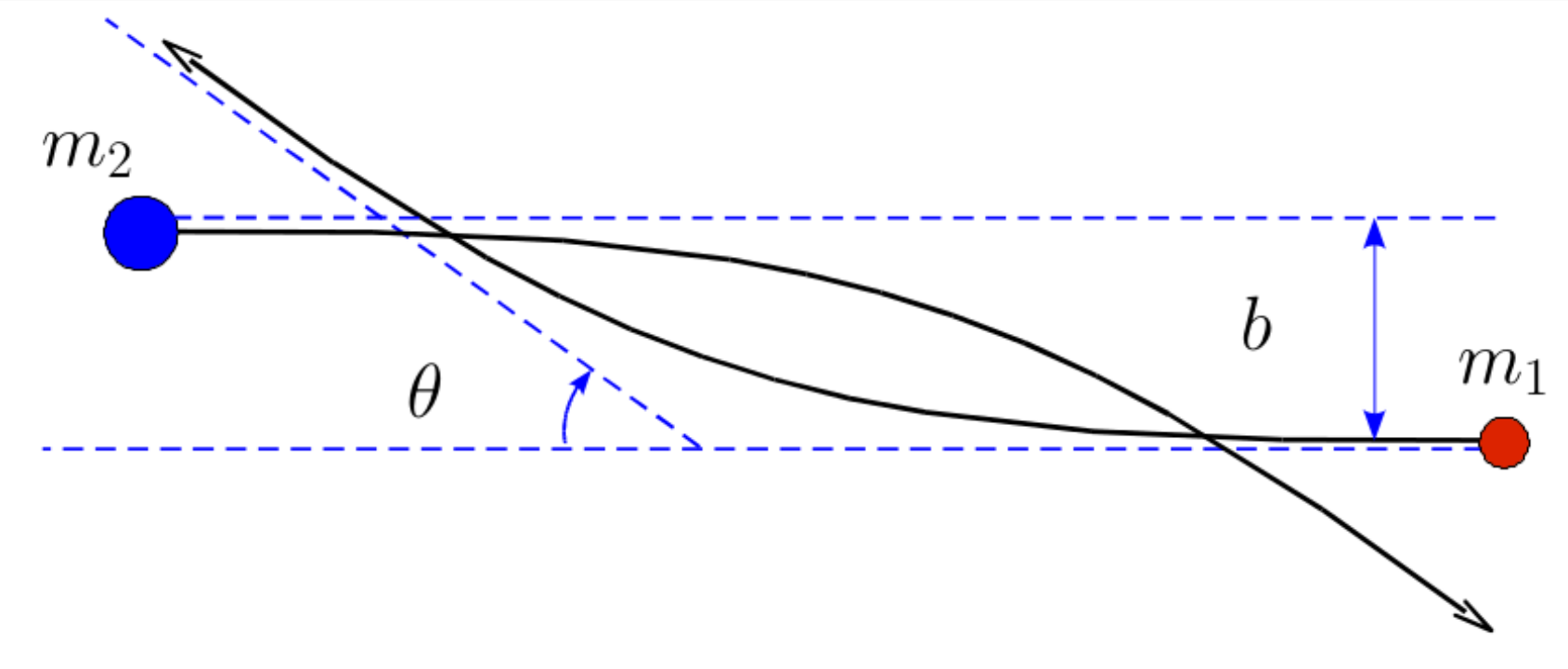

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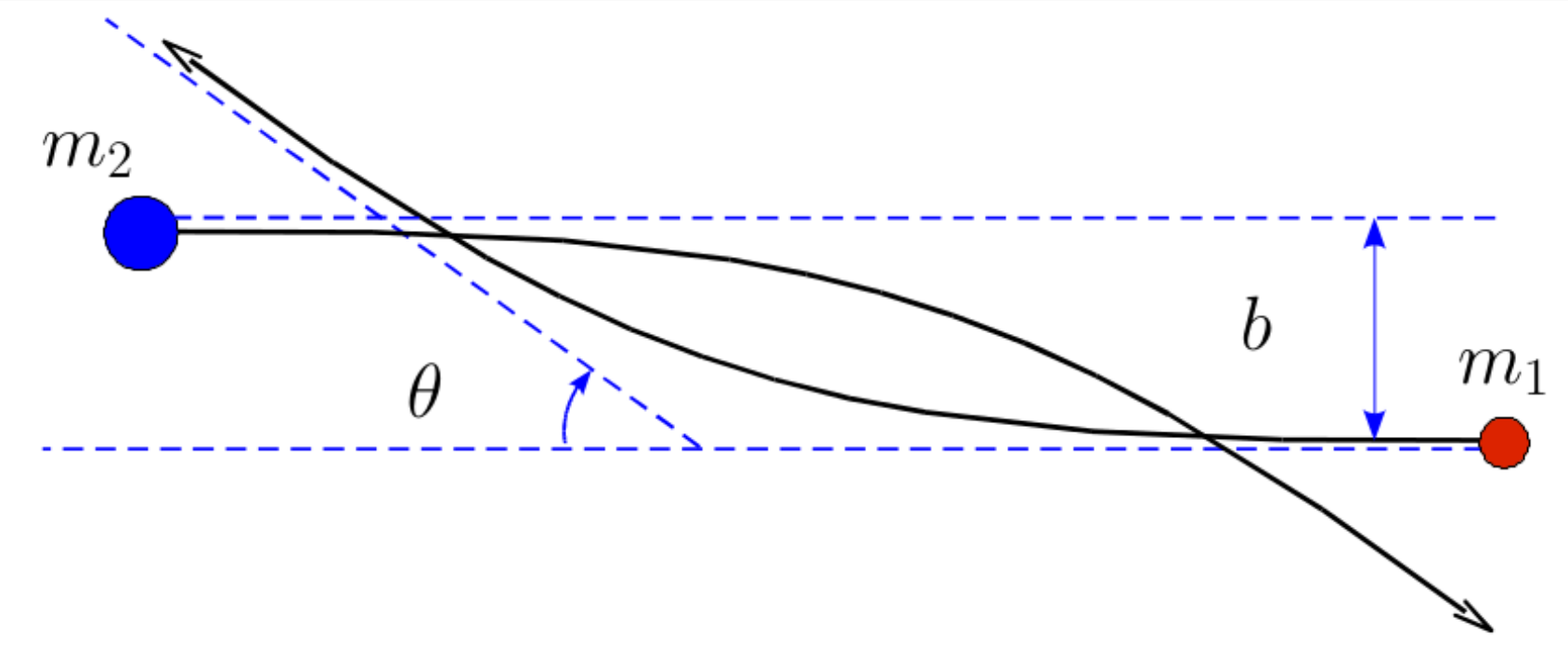

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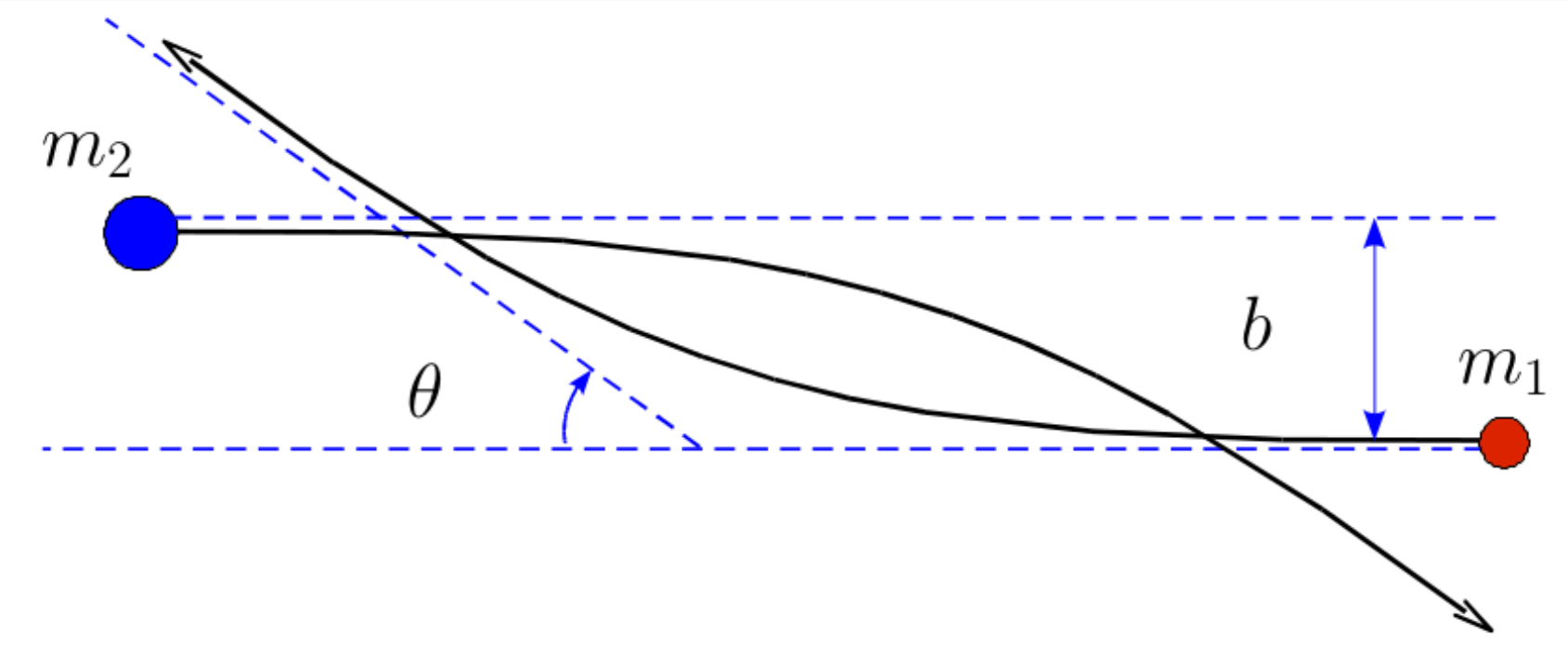

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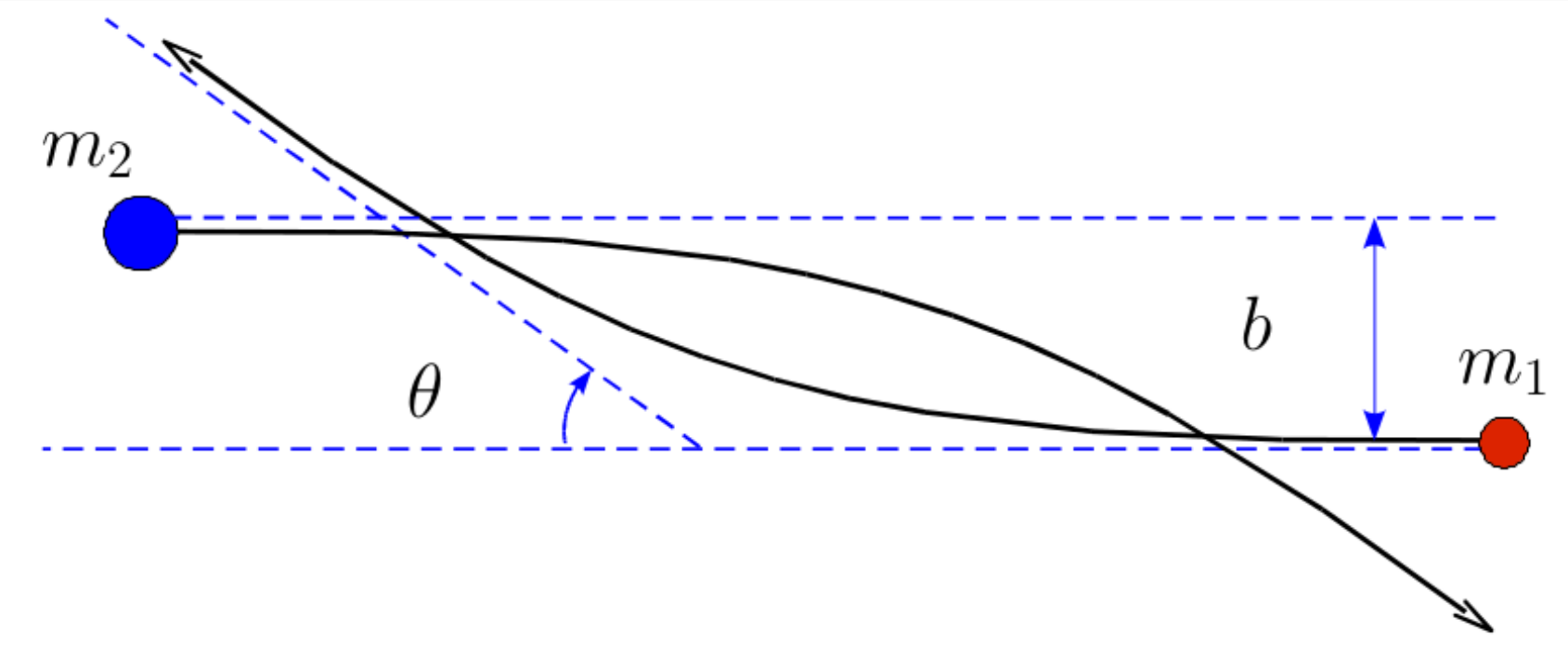

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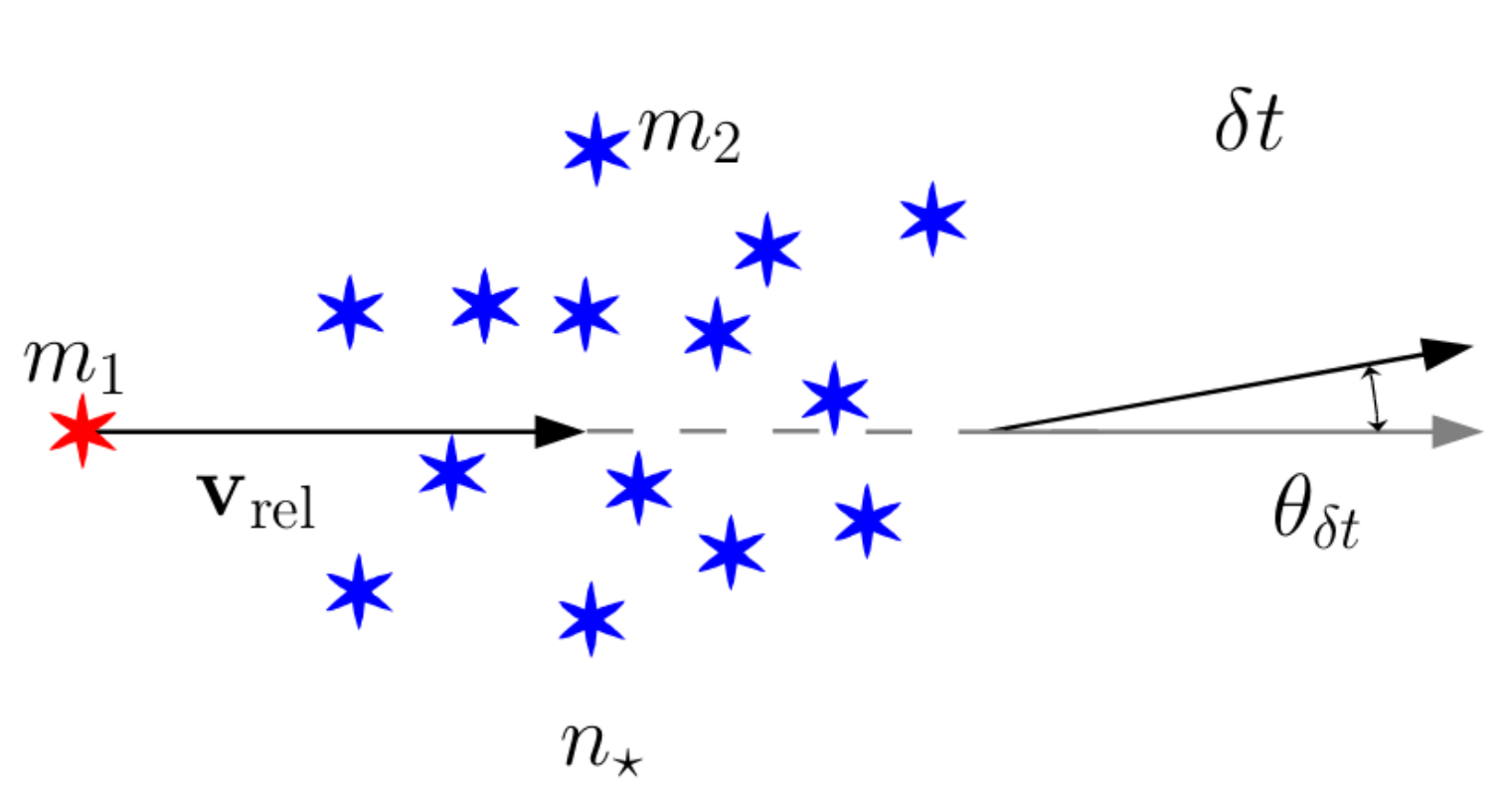
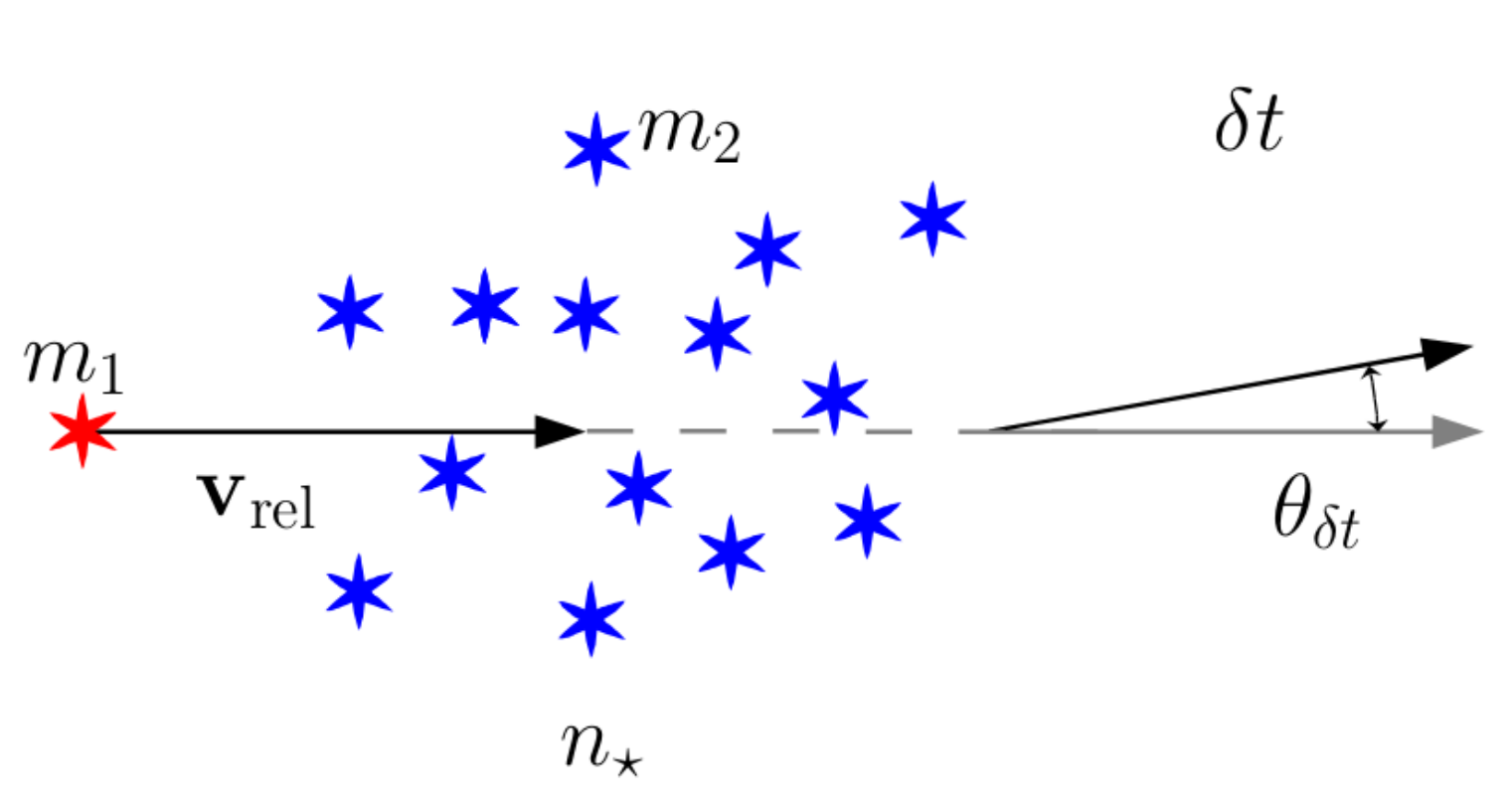


- Integrate b, keep v_{rel} and the masses fix

Integrate over all *b*



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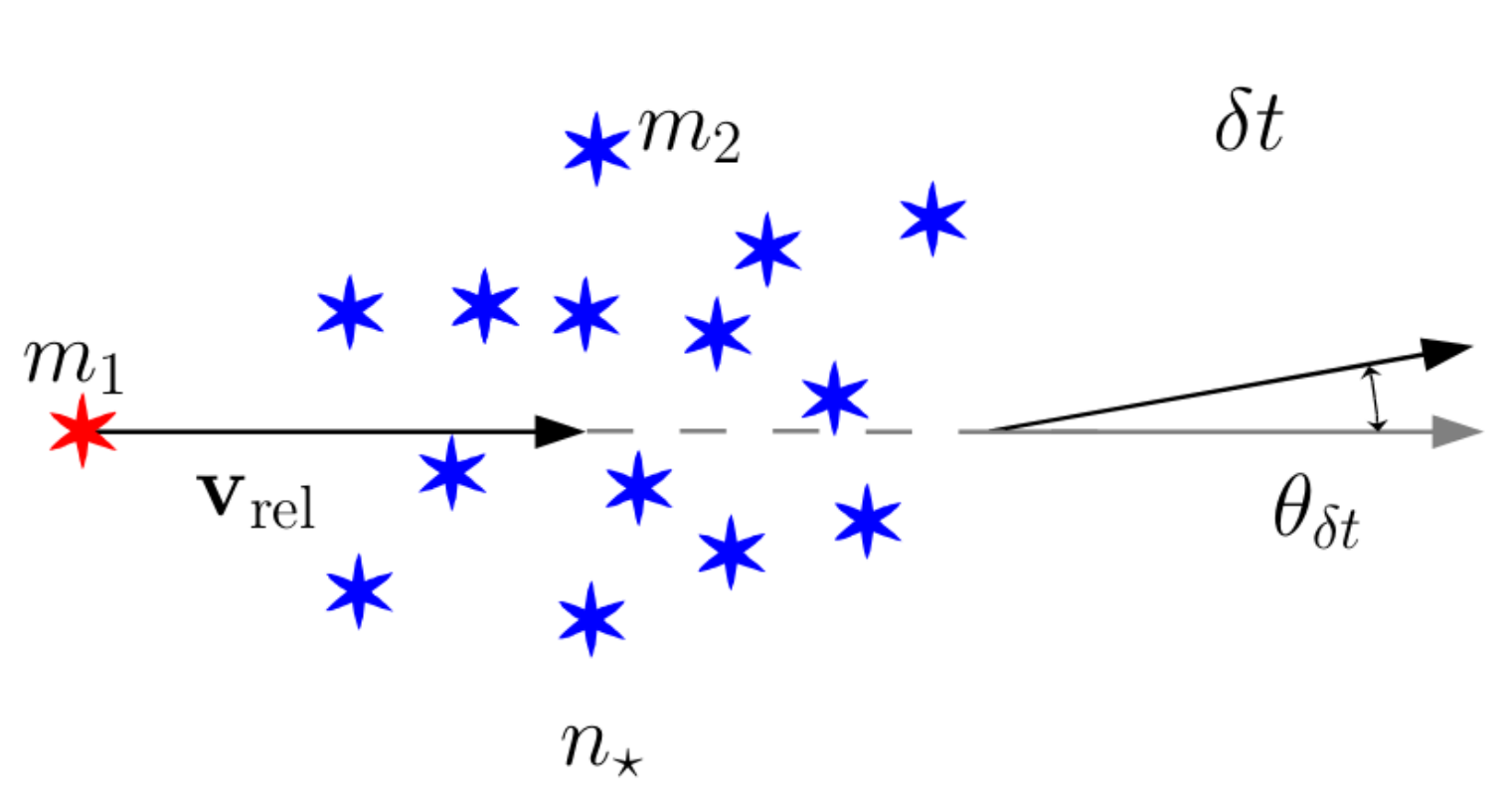

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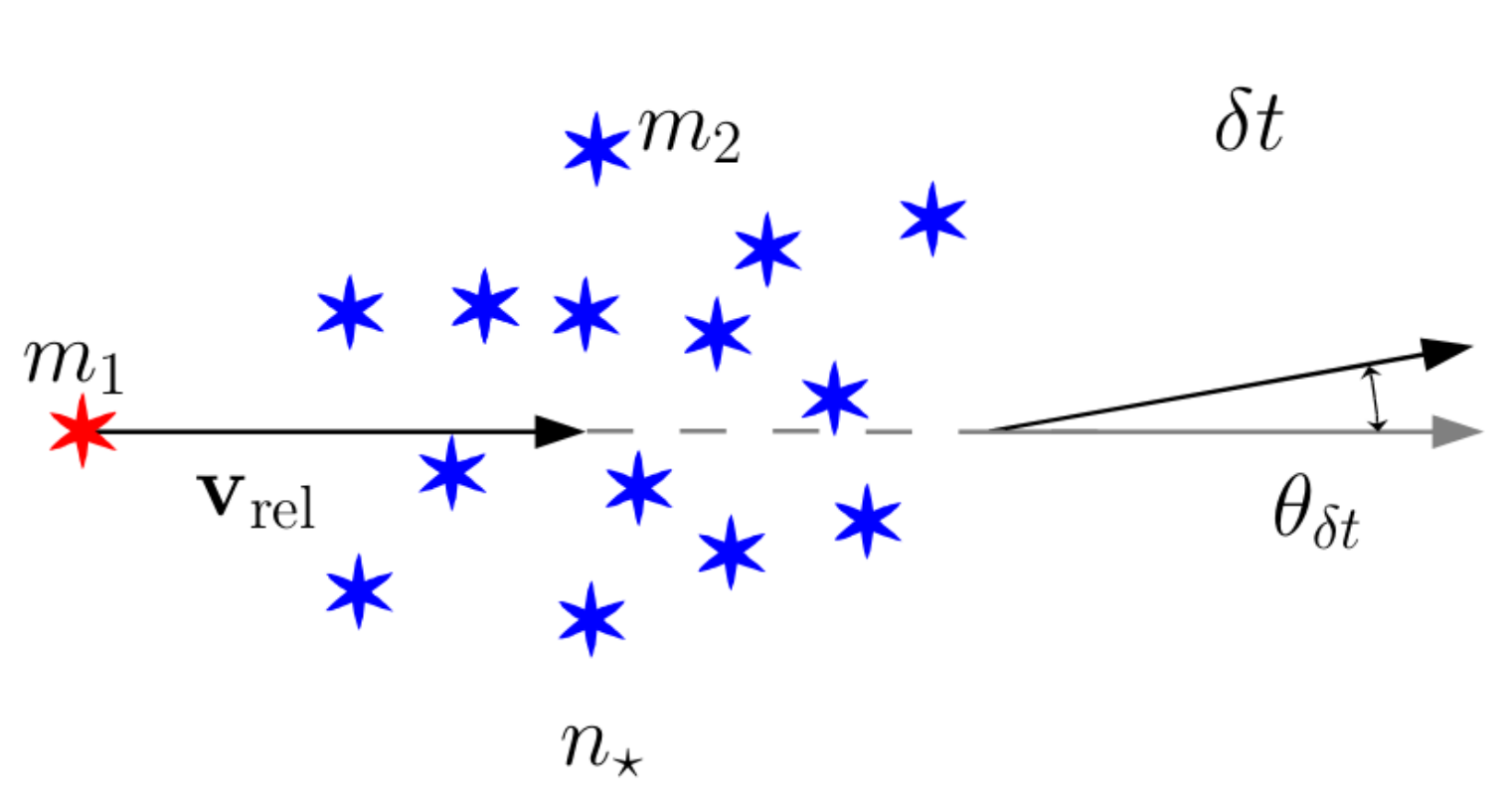

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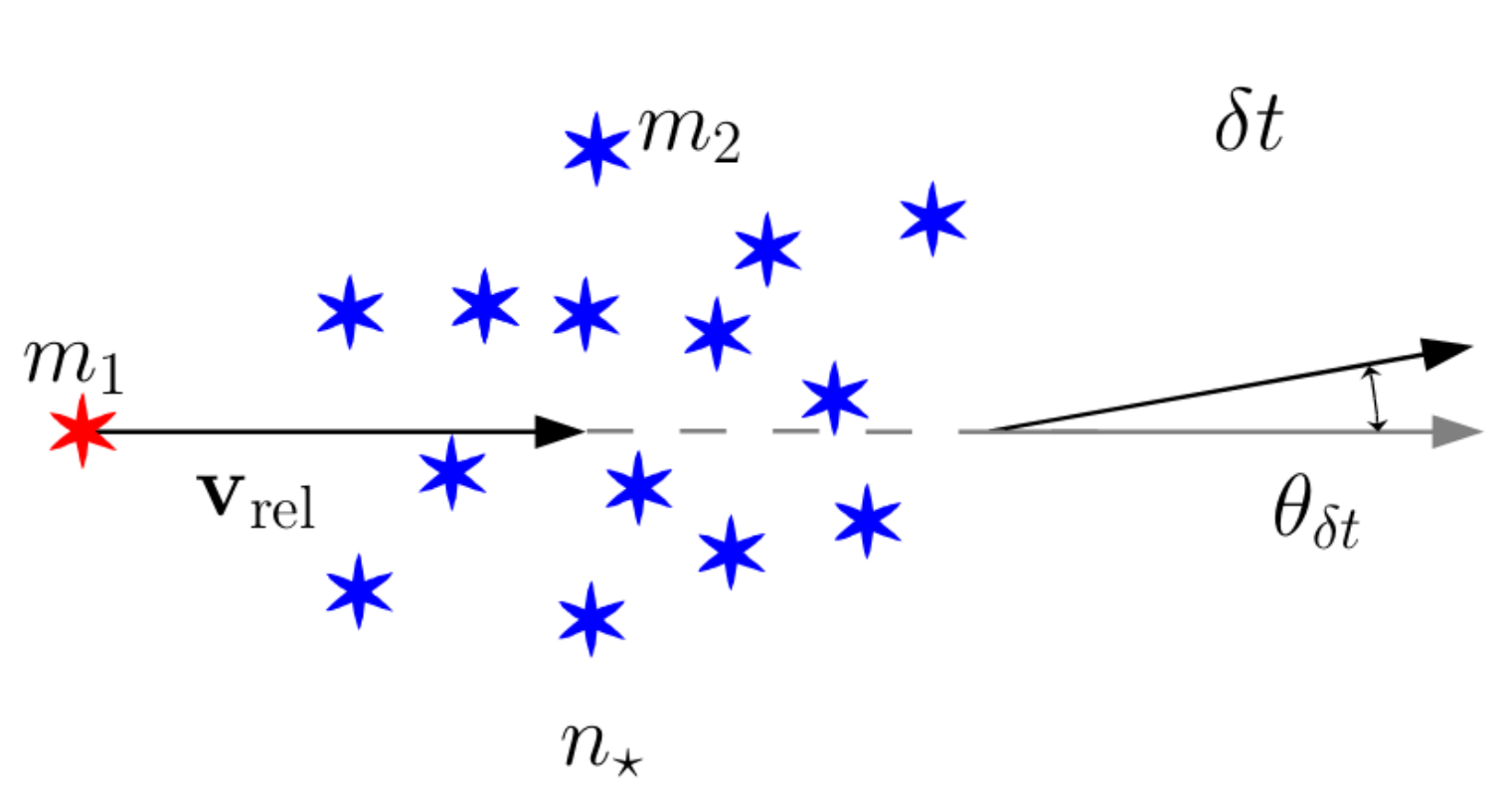

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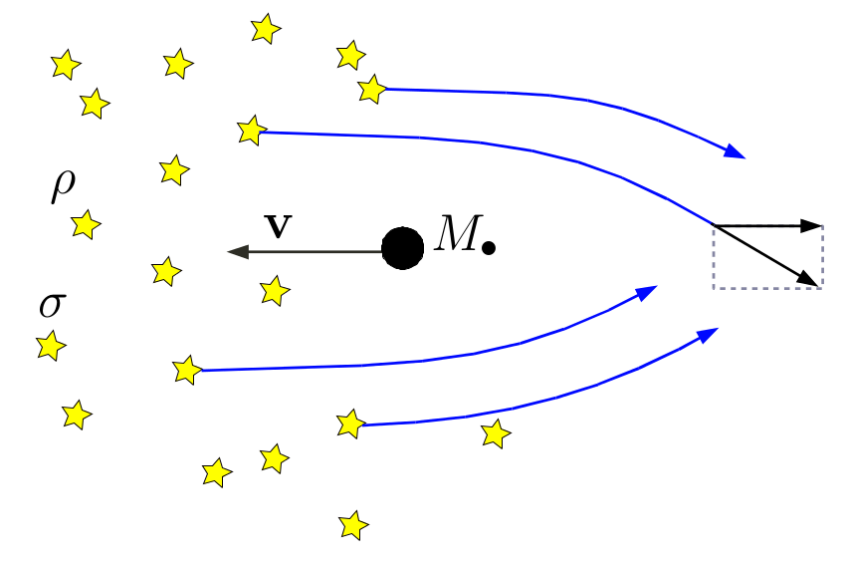
- If mass 10 times smaller, timescale also 10 times shorter

Dynamical friction in action I



★ Massive intruder: Stellar BH in a homogeneous sea of stars

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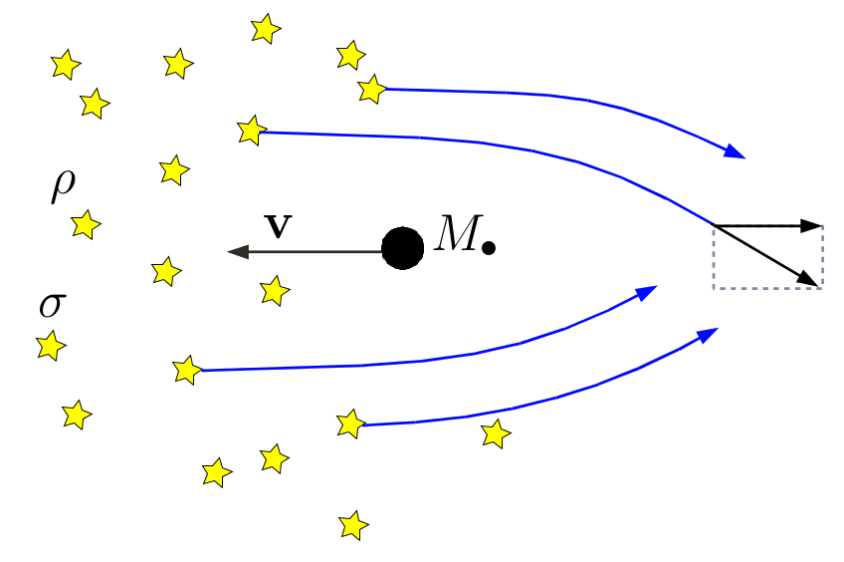

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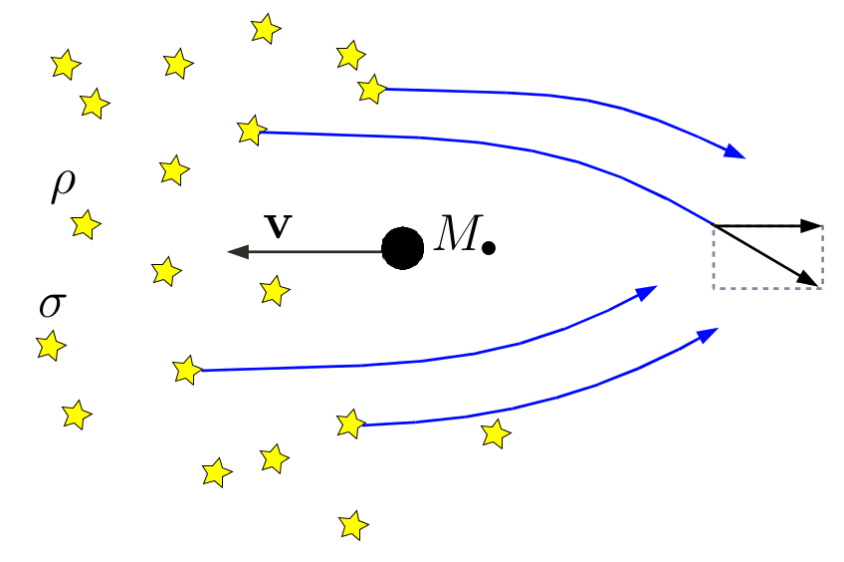

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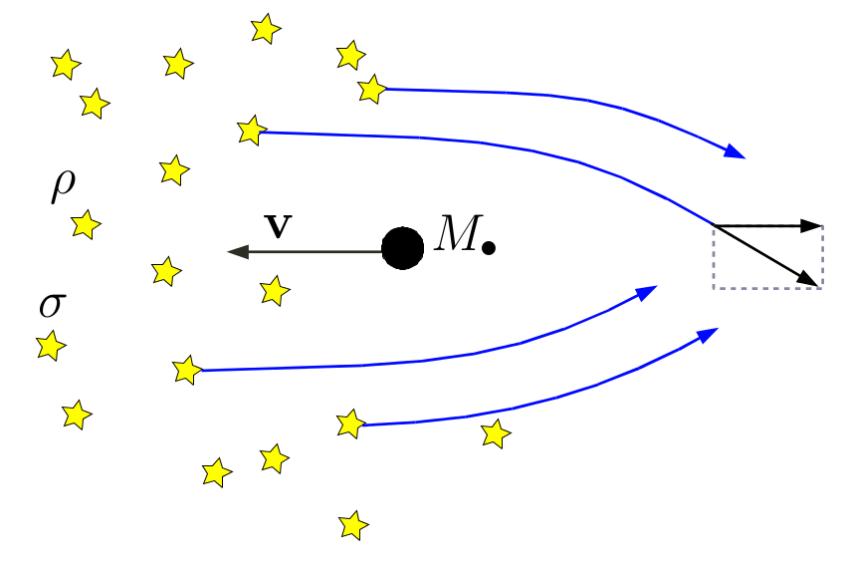

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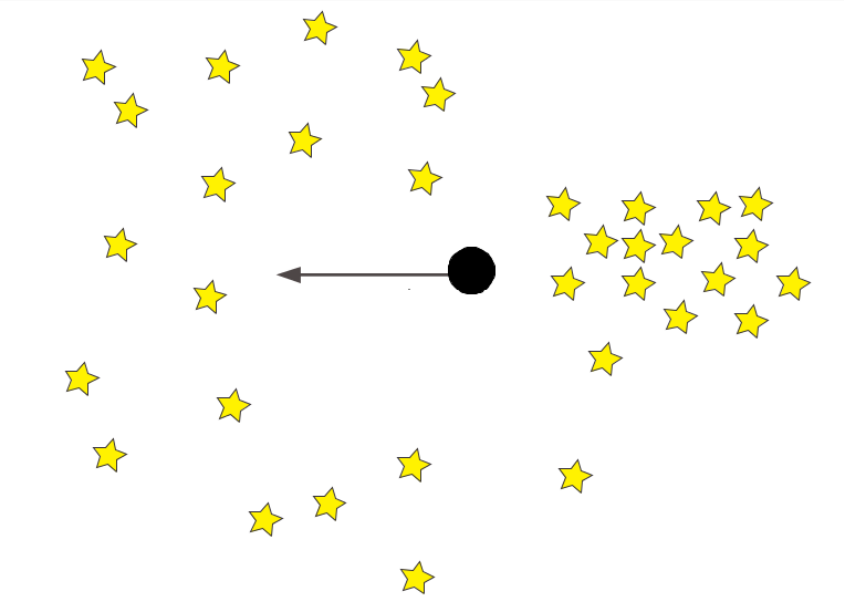
  Velocity vector of perturber almost unmodified in direction, cancel out on average

Dynamical friction in action II



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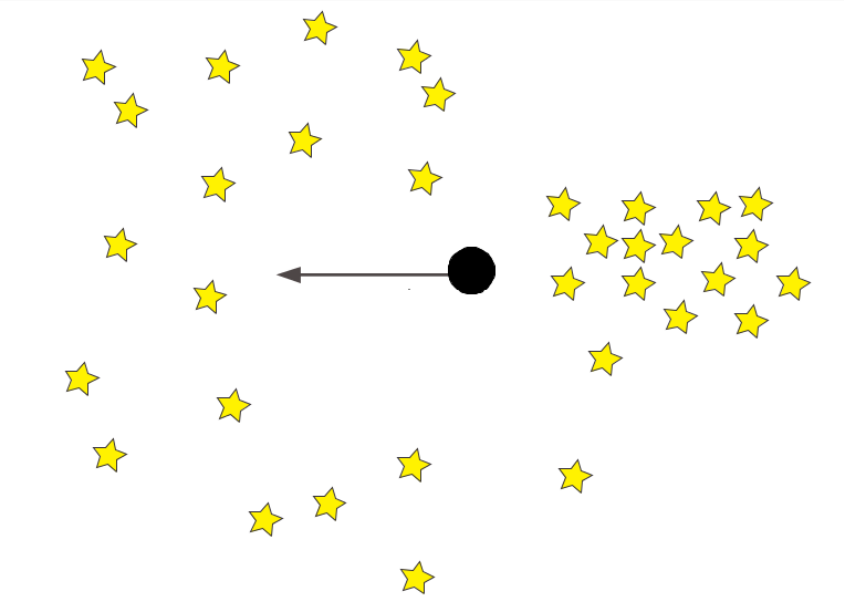

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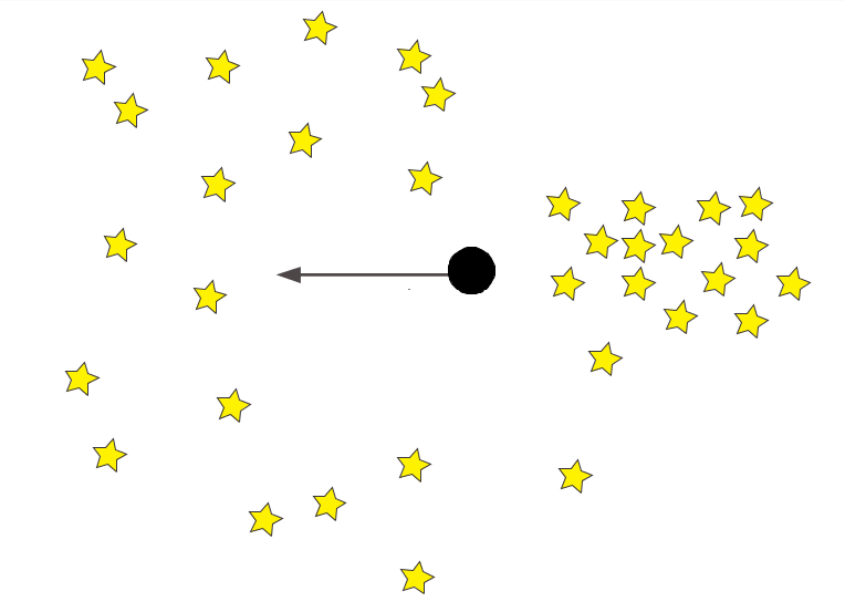

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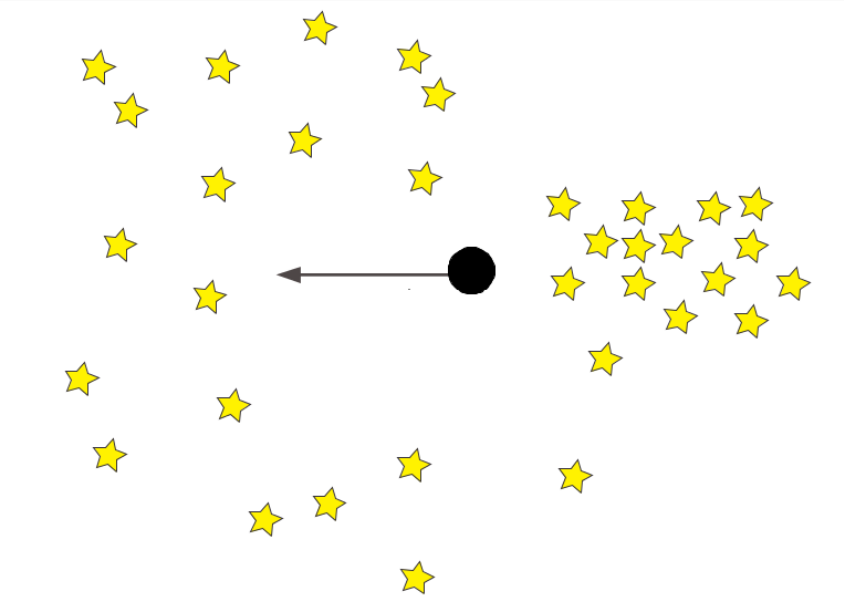

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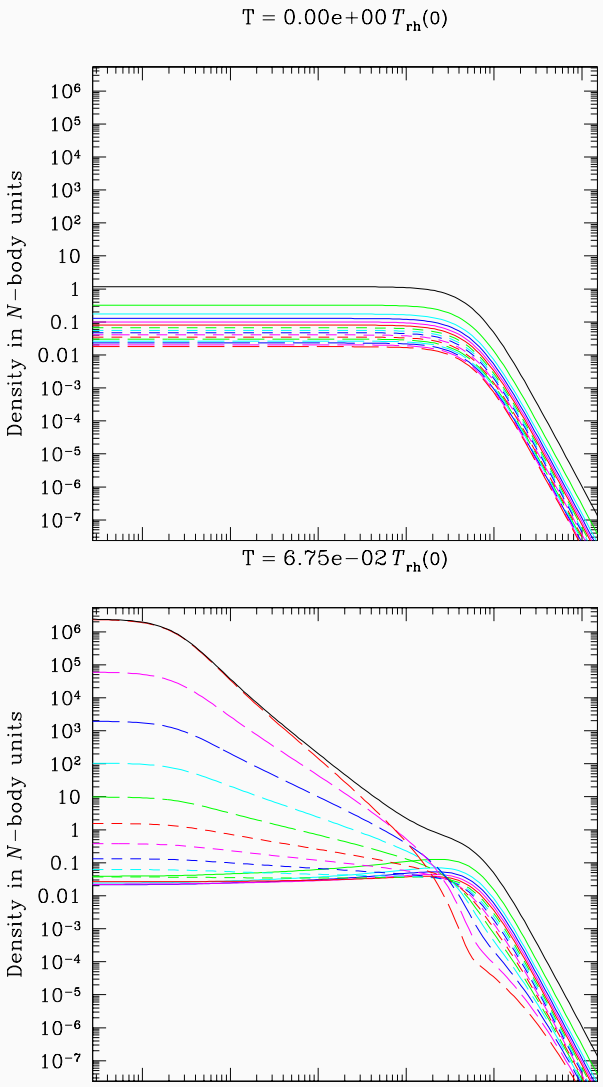
  The bigger $\mathcal{M}_\bullet$, the bigger DF effects are, in spite of bigger inertia

Mass segregation without a MBH



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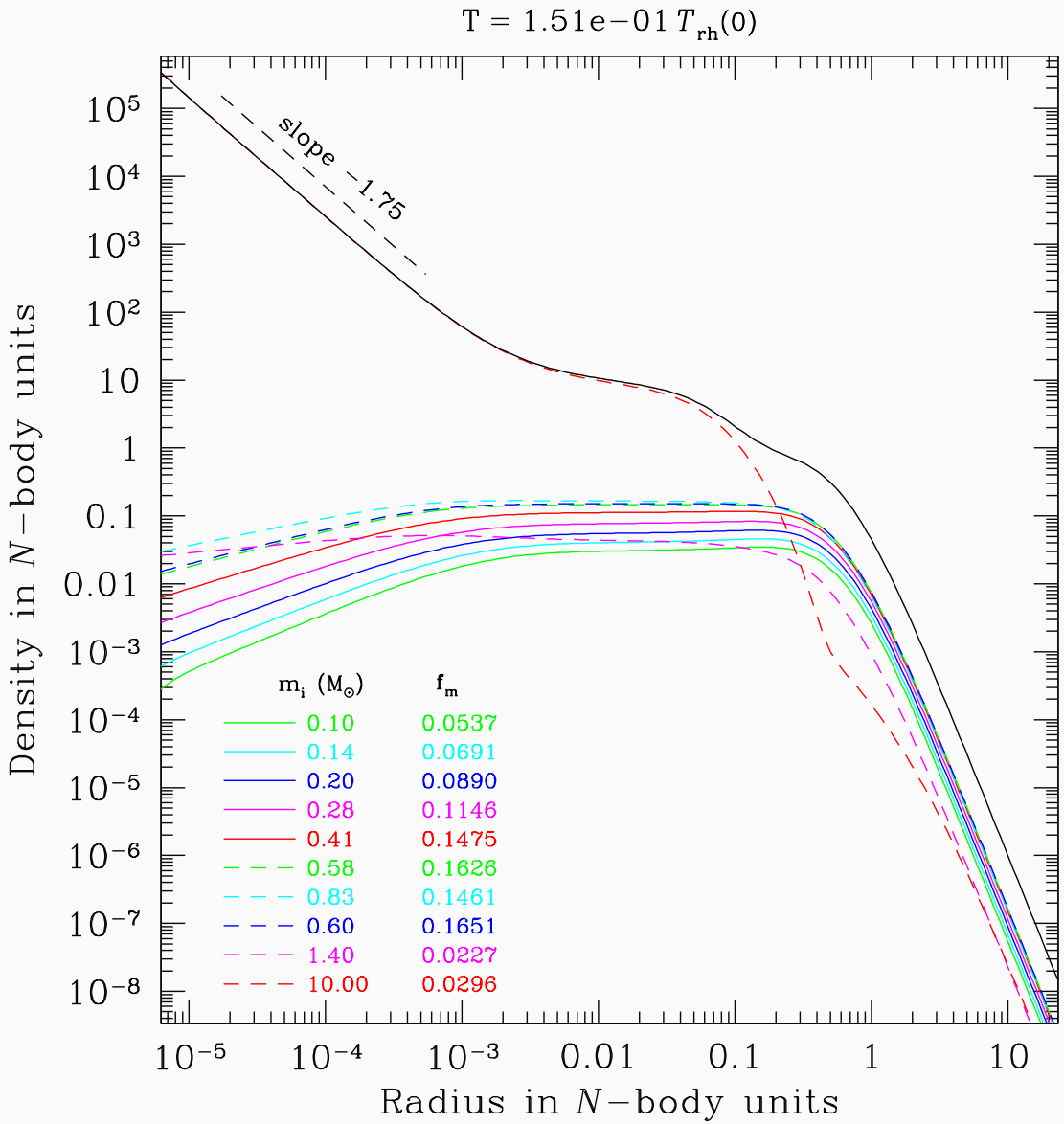
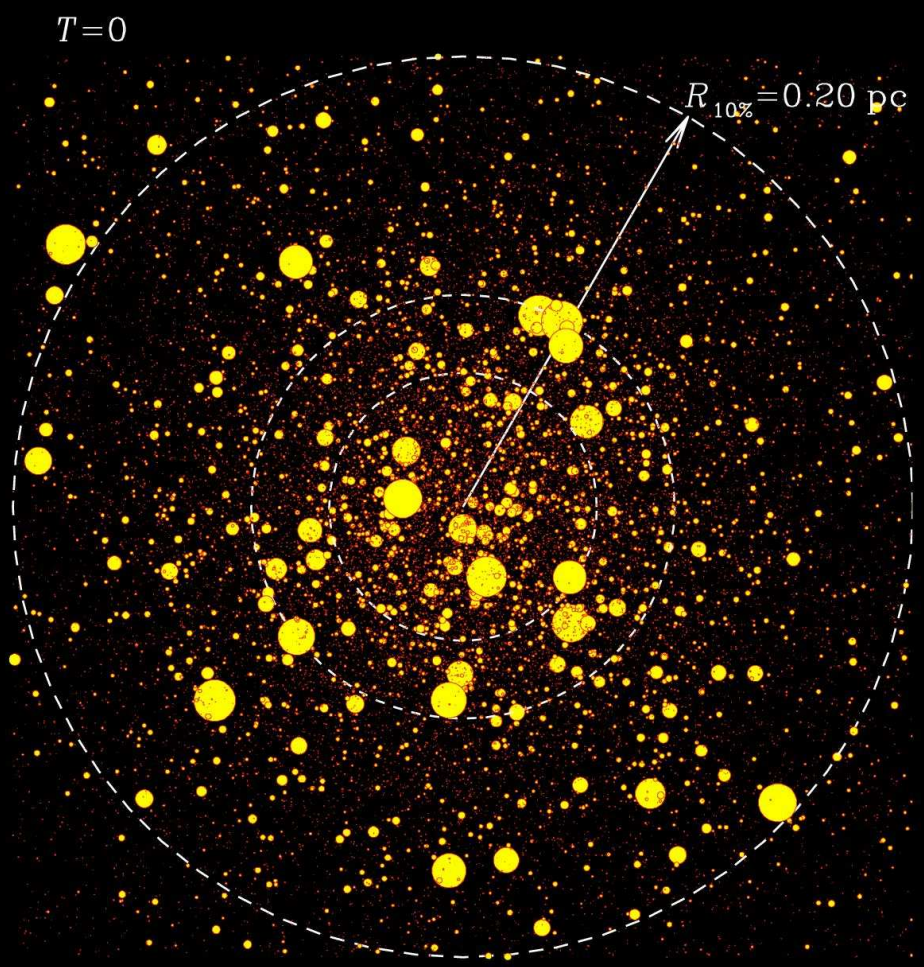
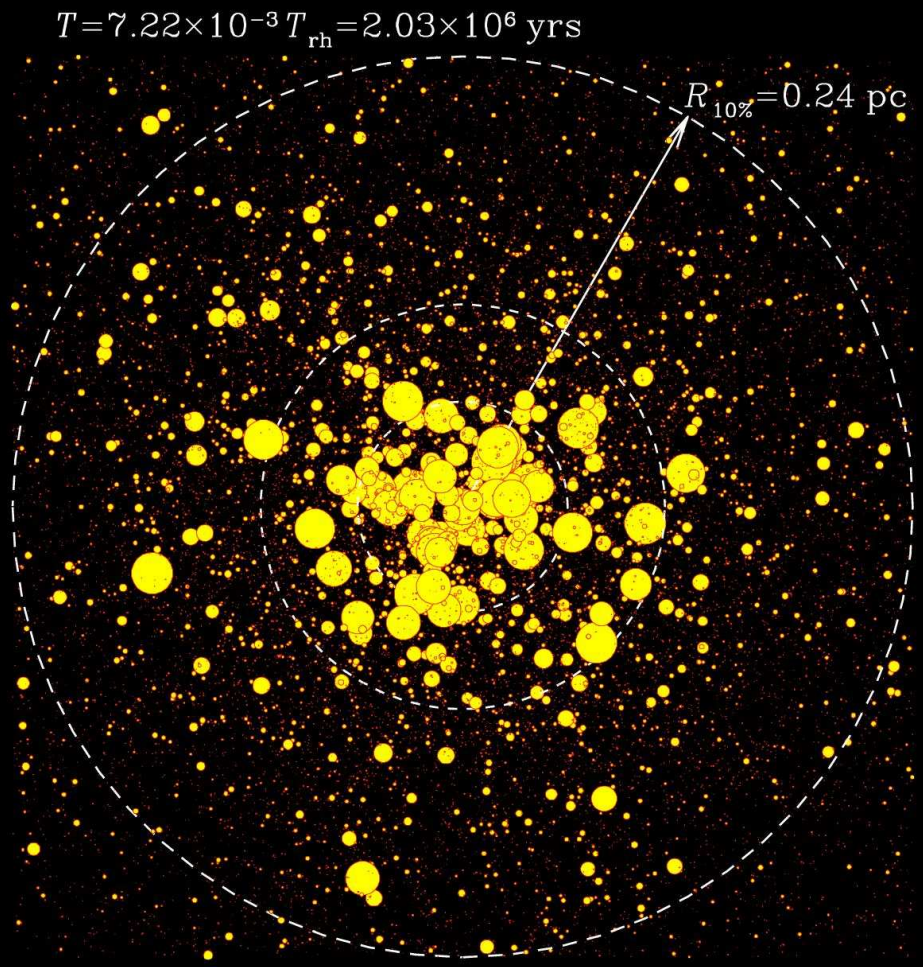


Core collapse

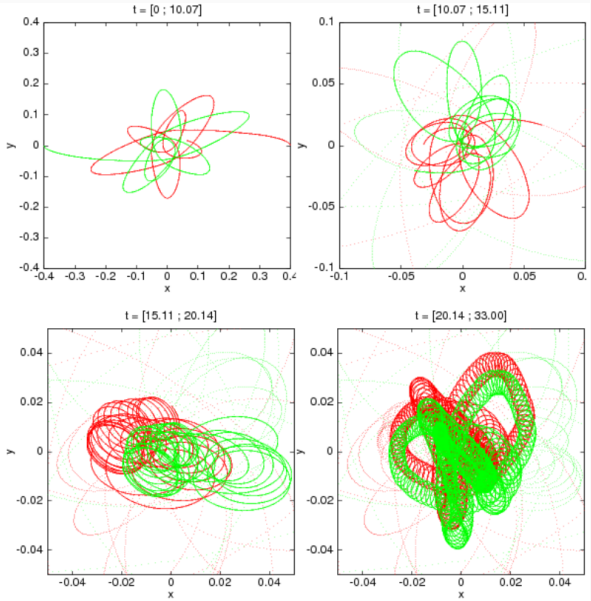


Stellar radii magnified 1.6×10^4 times



Stellar radii magnified 2.0×10^4 times

NS form binaries



- NS sink to the centre and increase in number density

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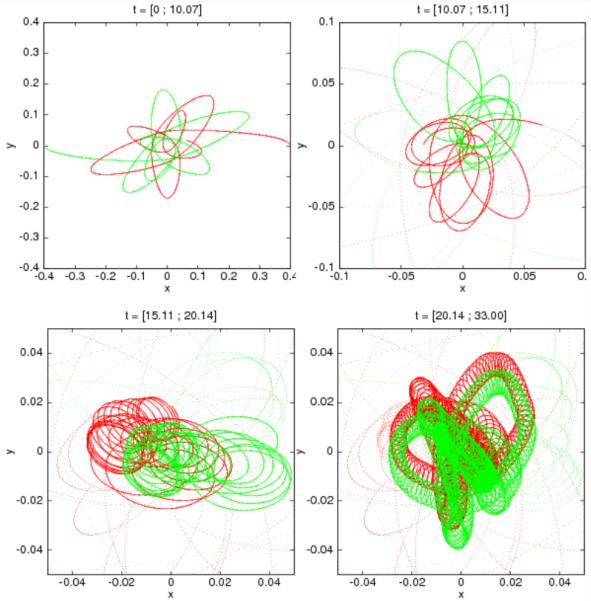

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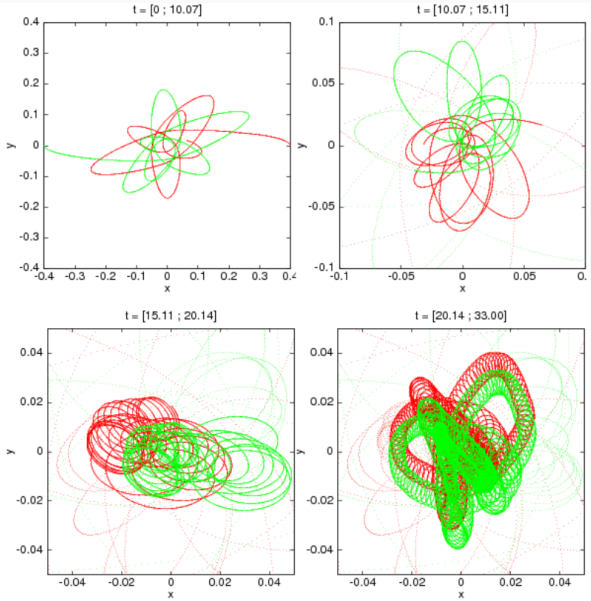

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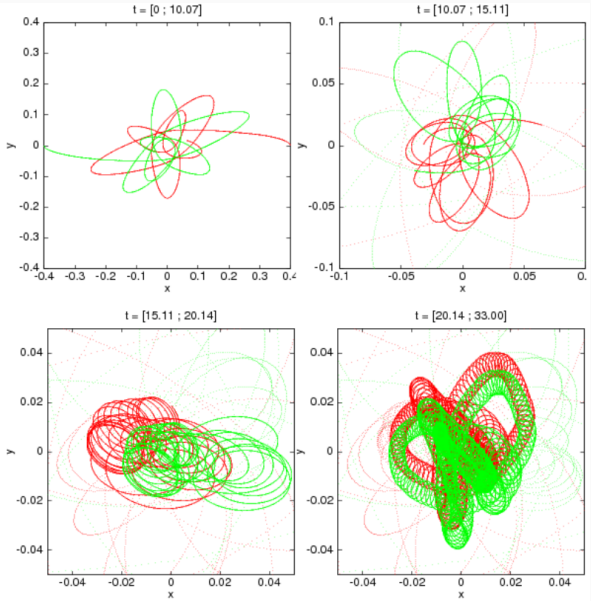

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- They form a NS binary and a source of GWs which will merge or not in a Hubble time depending on their orbital properties

Binaries with massive 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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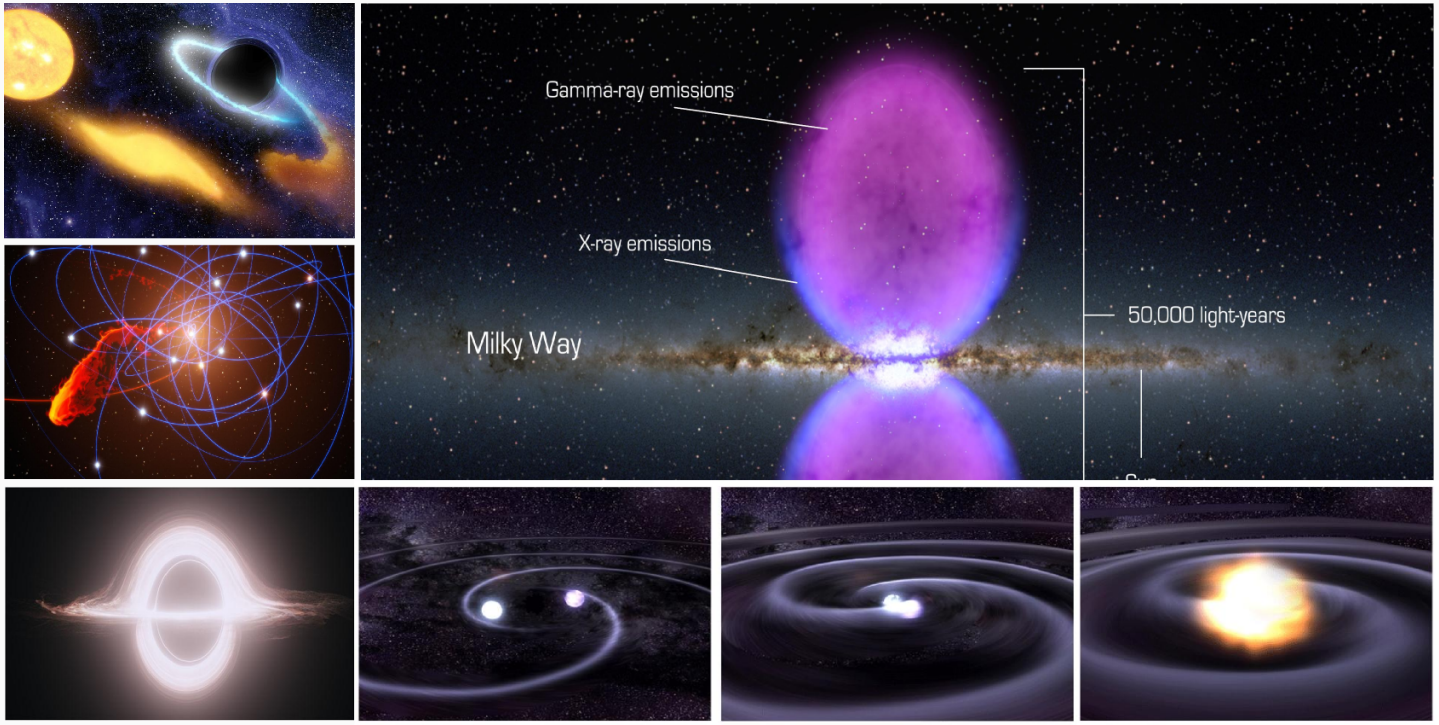
- Intermediate-mass black holes:
  Formation unclear, $100 \lessapprox M_{\rm IMBH}/M_\odot < 10^5$, probably in clusters

Black holes: Do they exist?

Do black holes exist?



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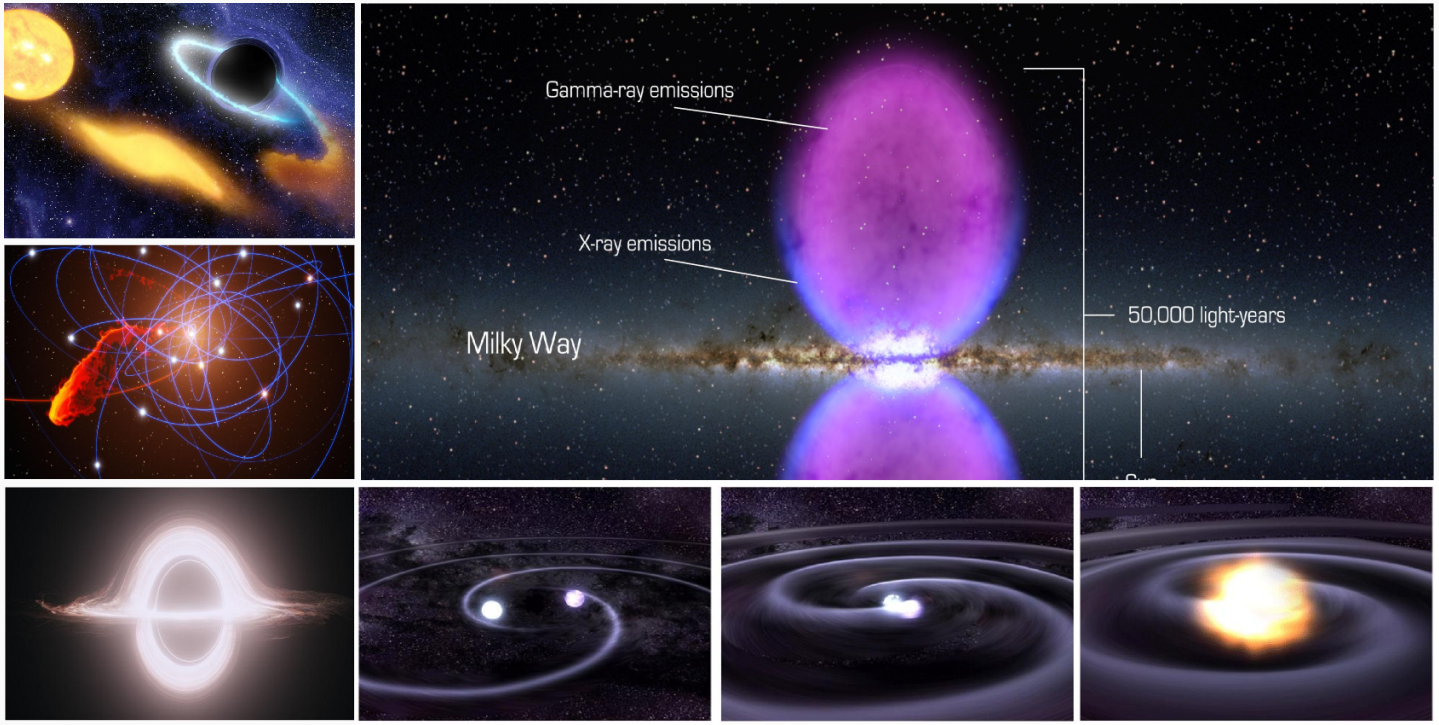

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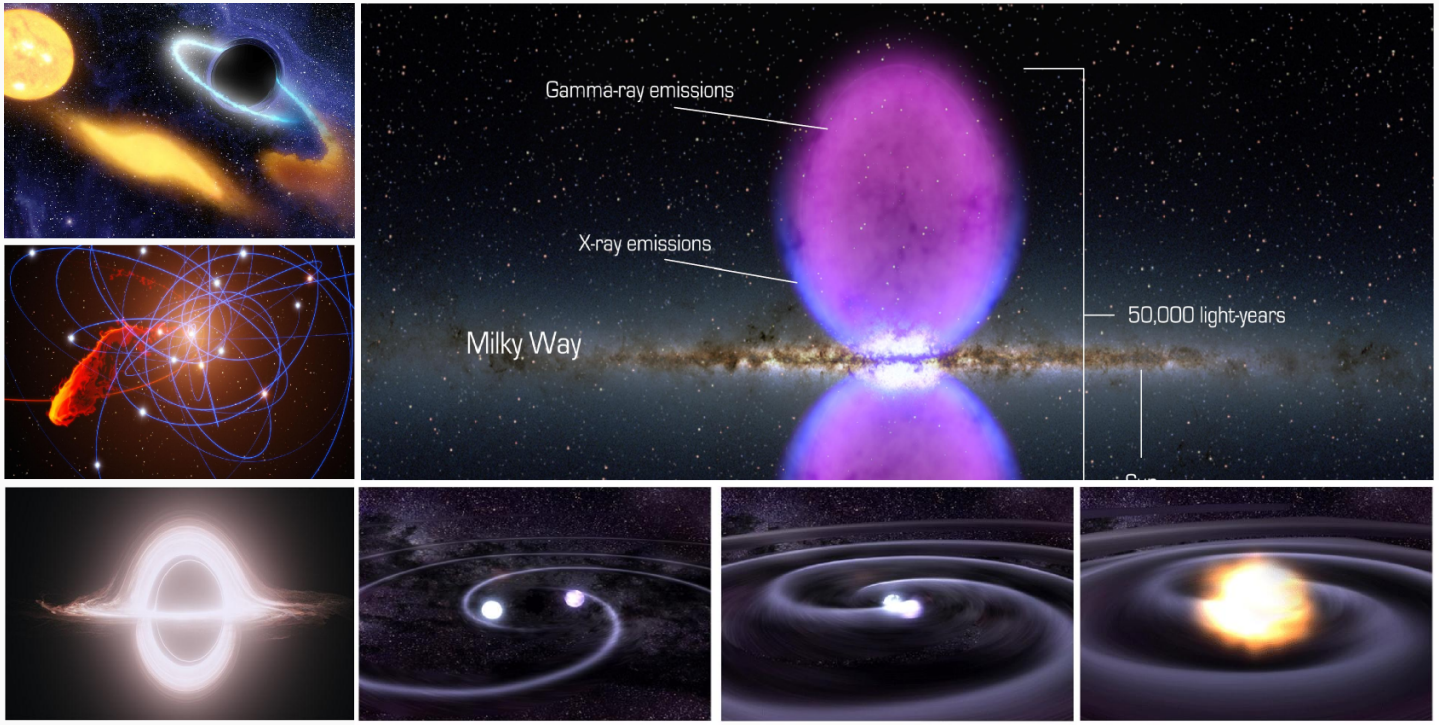

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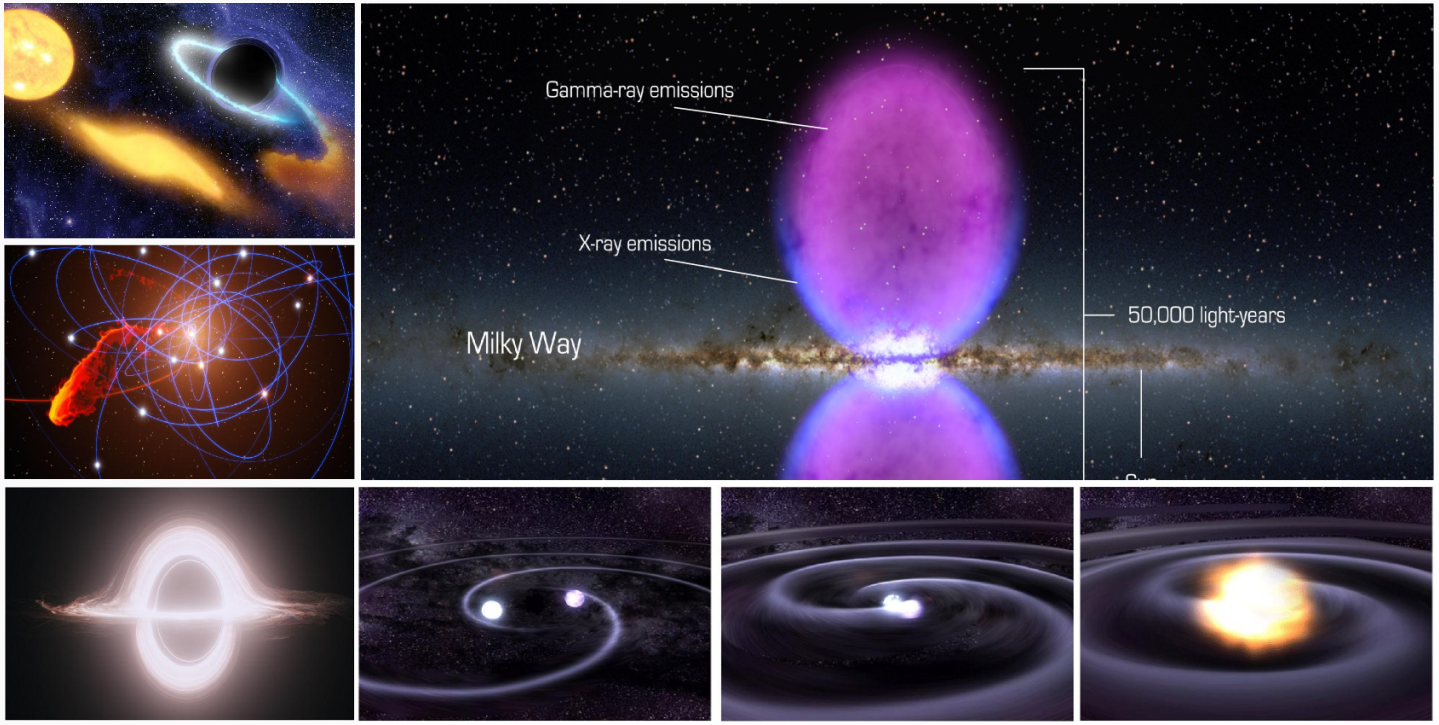

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Facts about black holes

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Wait… We do have direct proofs now!

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GW140915

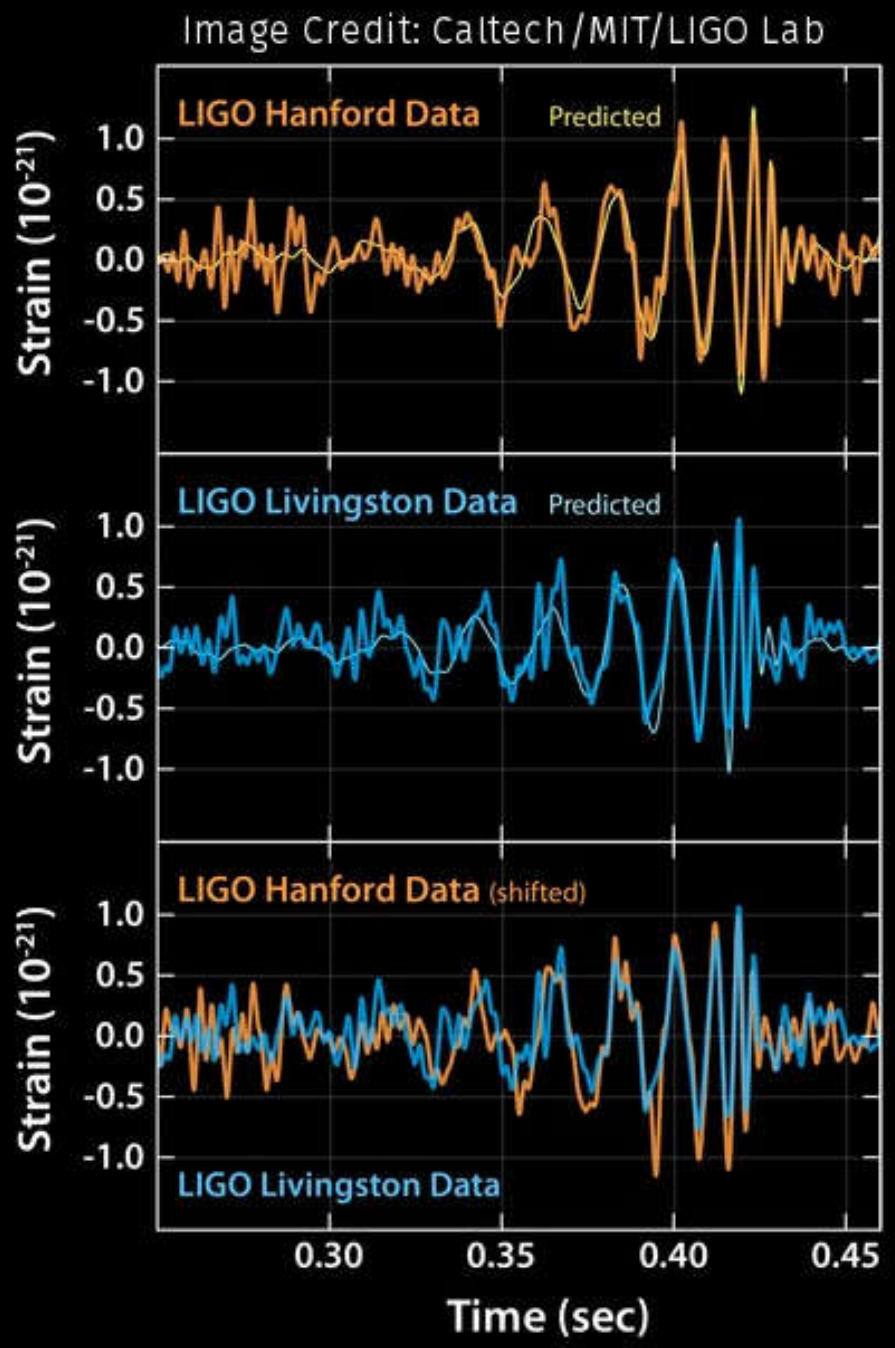
Image Credit: Caltech/MIT/LIGO Lab
LIGO Hanford Data
Predicted
LIGO Livingston Data
Predicted
LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)

Why is this so important?

★ From the point of view of fundamental physics:

1. Waves GW150914 and GW151226 are a prediction of general relativity in the strong regime ... read "GR is correct"

★ From the point of view of astrophysics:

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NS as probes of supermassive black holes

Quasars

[ESO/M. Kornmesser]

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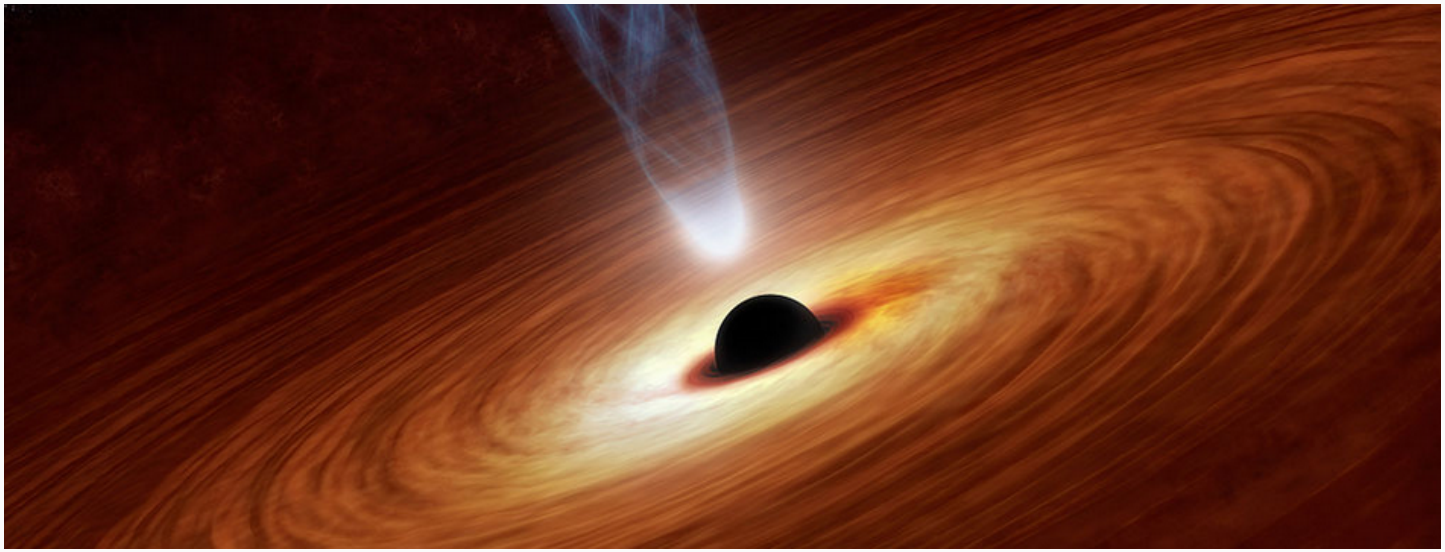
- How do you create a luminosity of 10^{40} W??

Accretion



[NASA/JPL-Caltech]

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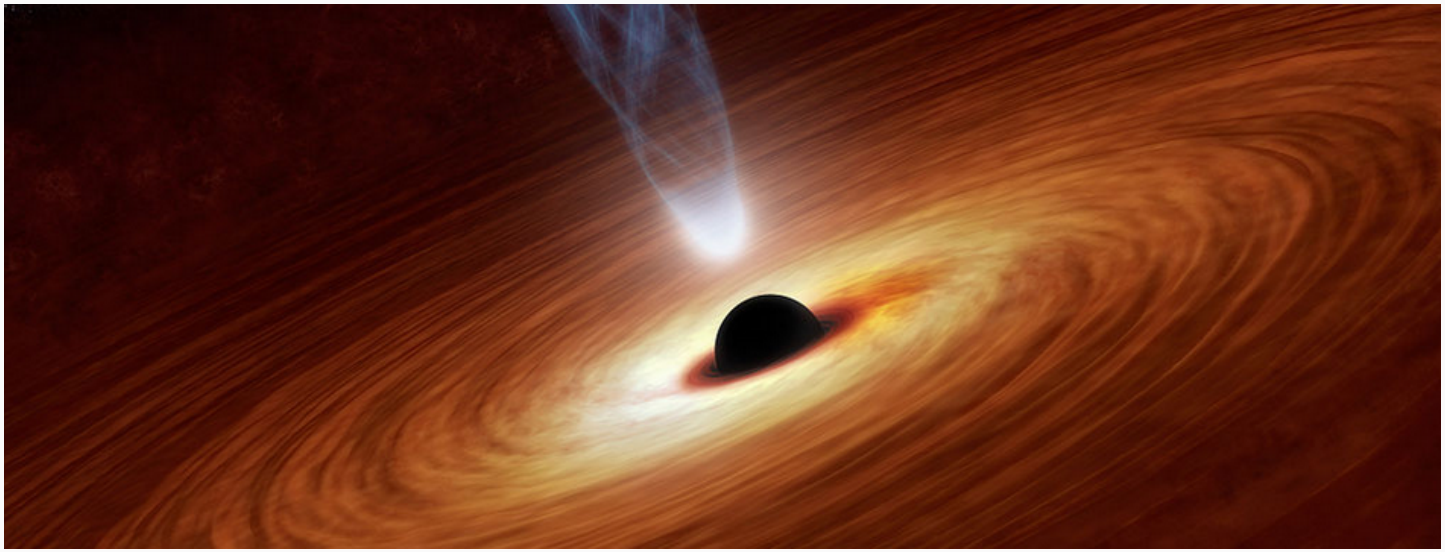

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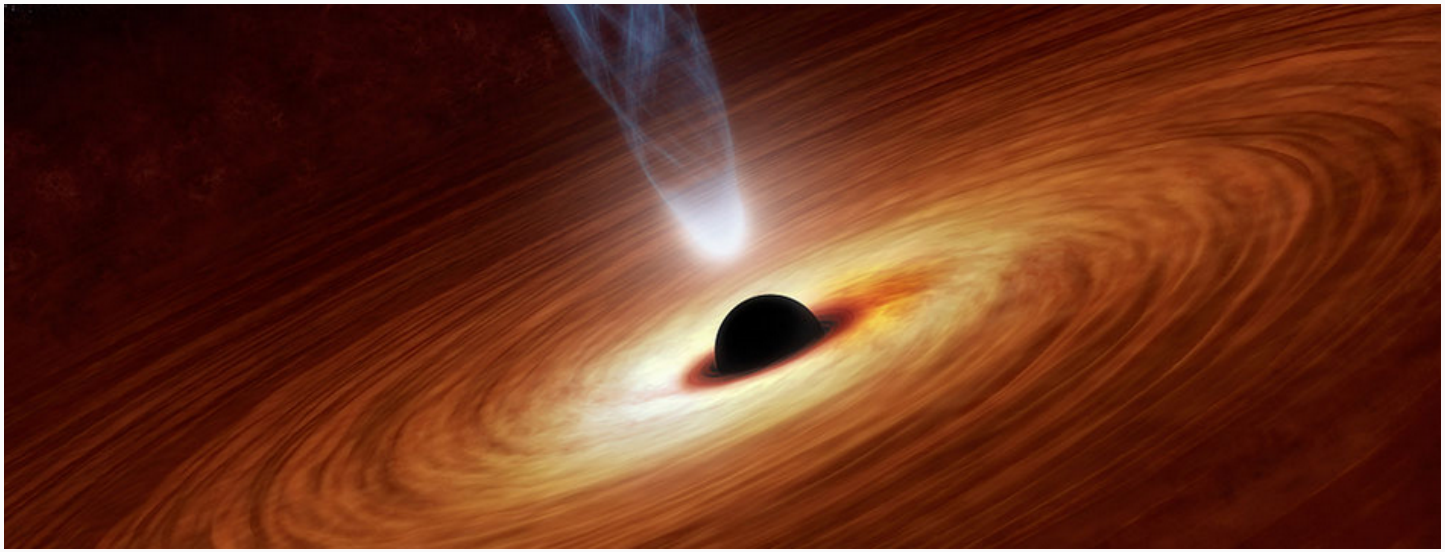

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The SMBH in our Galaxy: Our best candidate

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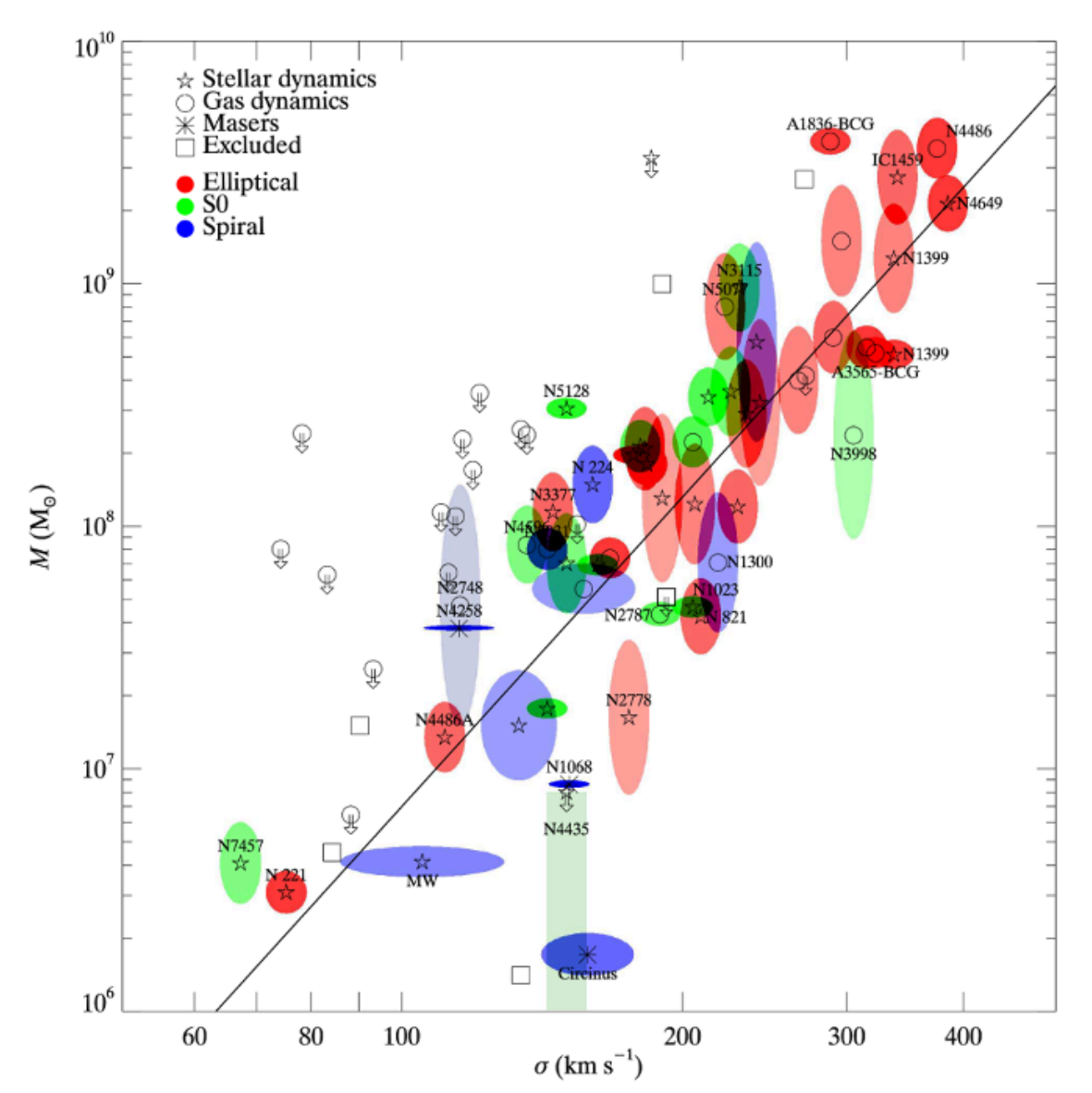
- ★ Within a radius of 22 millions of km, enclosed in $\sim 1/3$ times the distance to the Sun

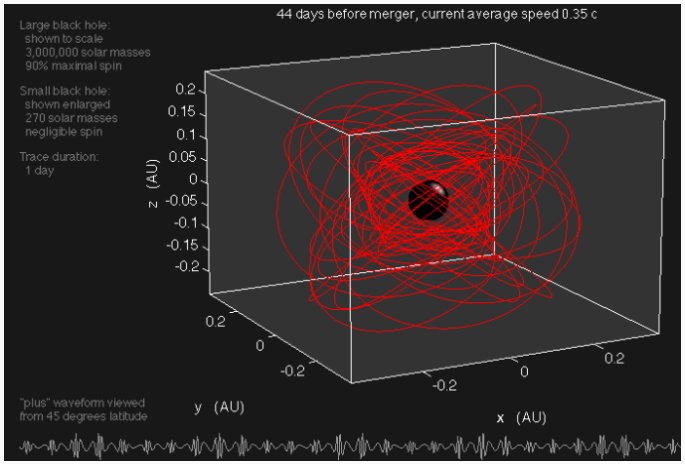
[Film: S-Stars, win+1]

Correlations



[Guelketin et al 2009]

NS and GWs: A unique probe of MBHs



[Film: Extreme-mass ratio inspiral, S. Drasco, win+2 and Natalia Amaro, win+3]

- ✘ 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

1. Extreme-mass ratio inspirals: There has not been any other mission conceived, planned or even thought of ever that can do the science that we can do with them

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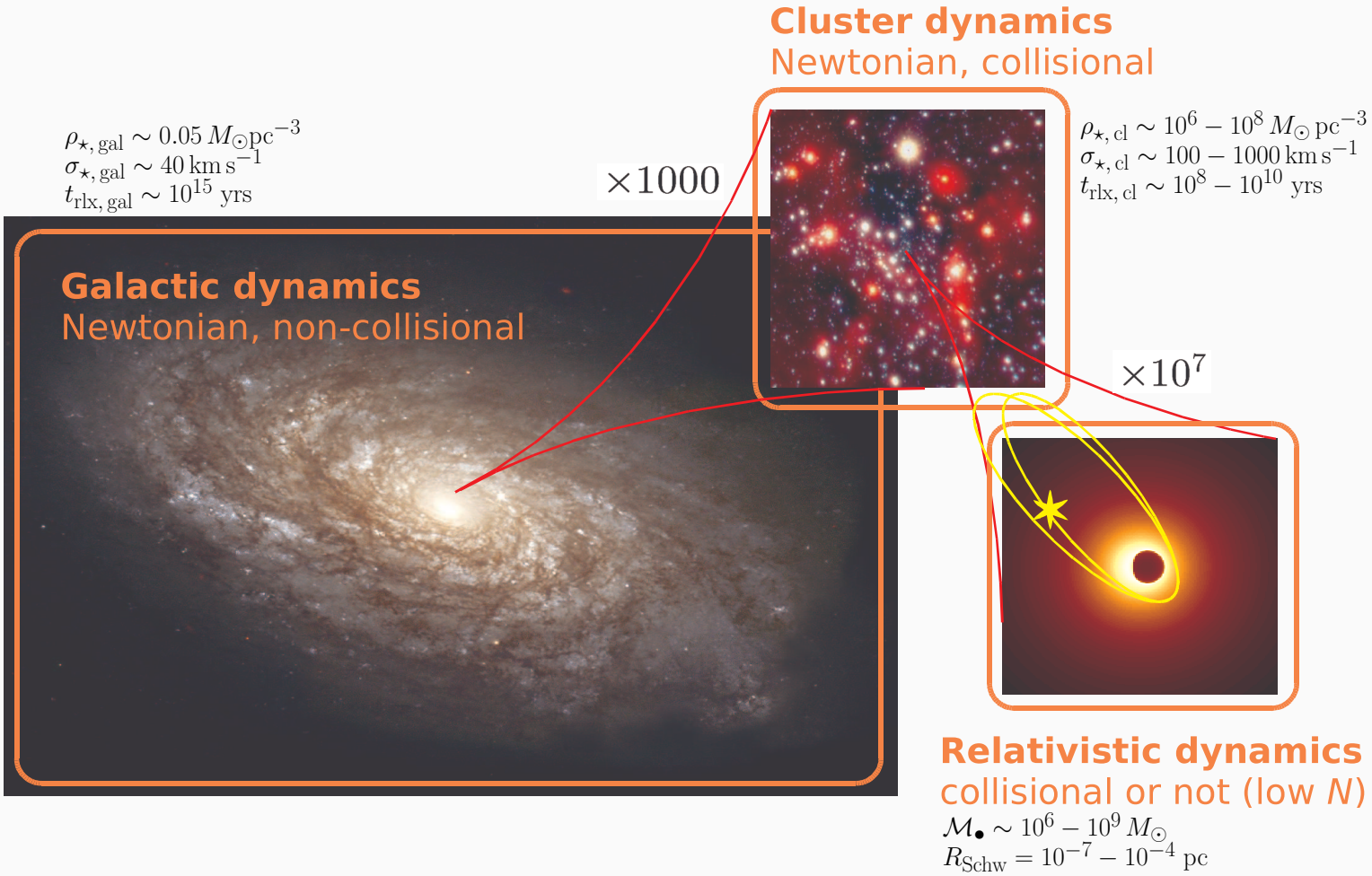
A problem of 10 orders of magnitude



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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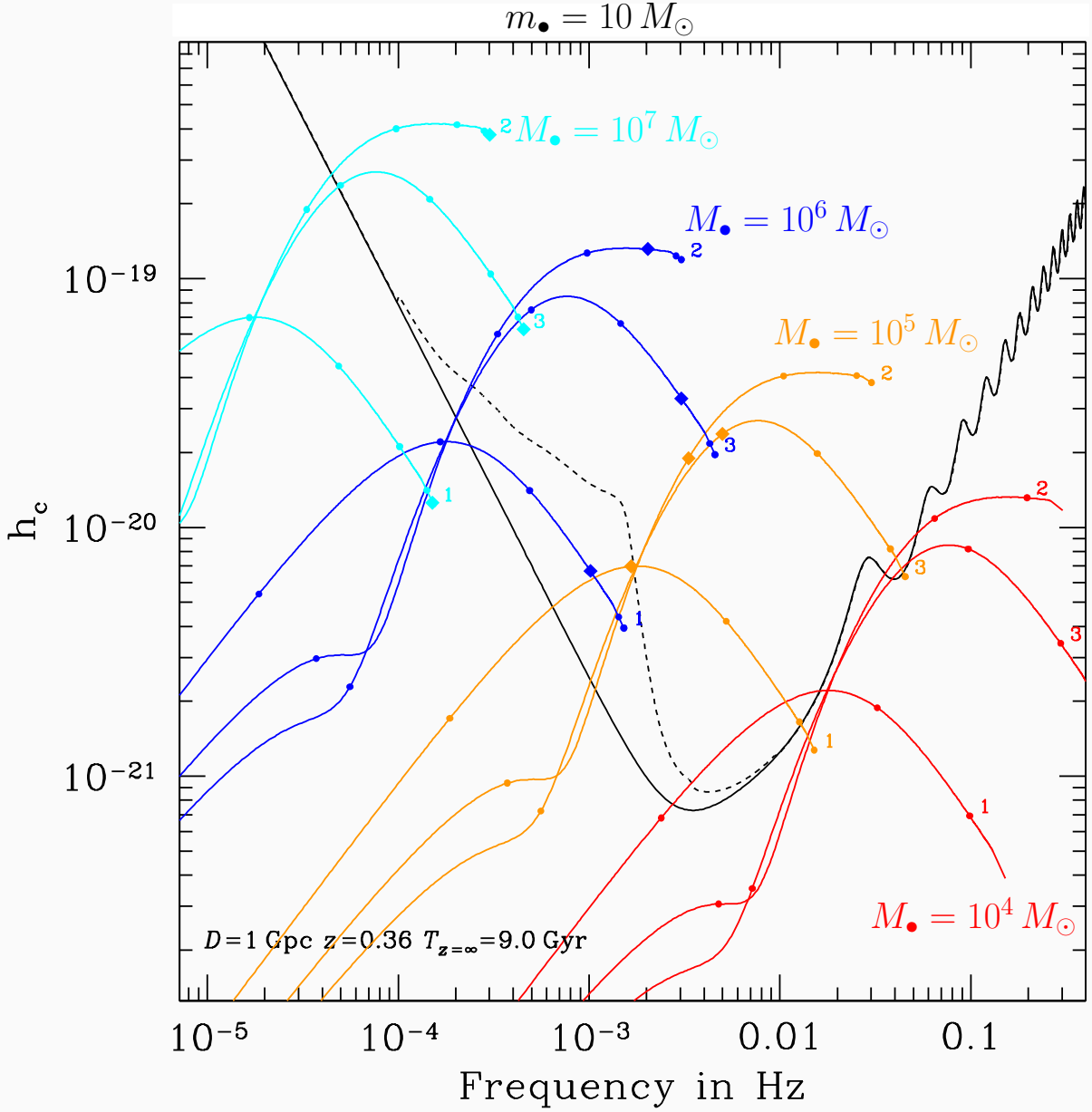
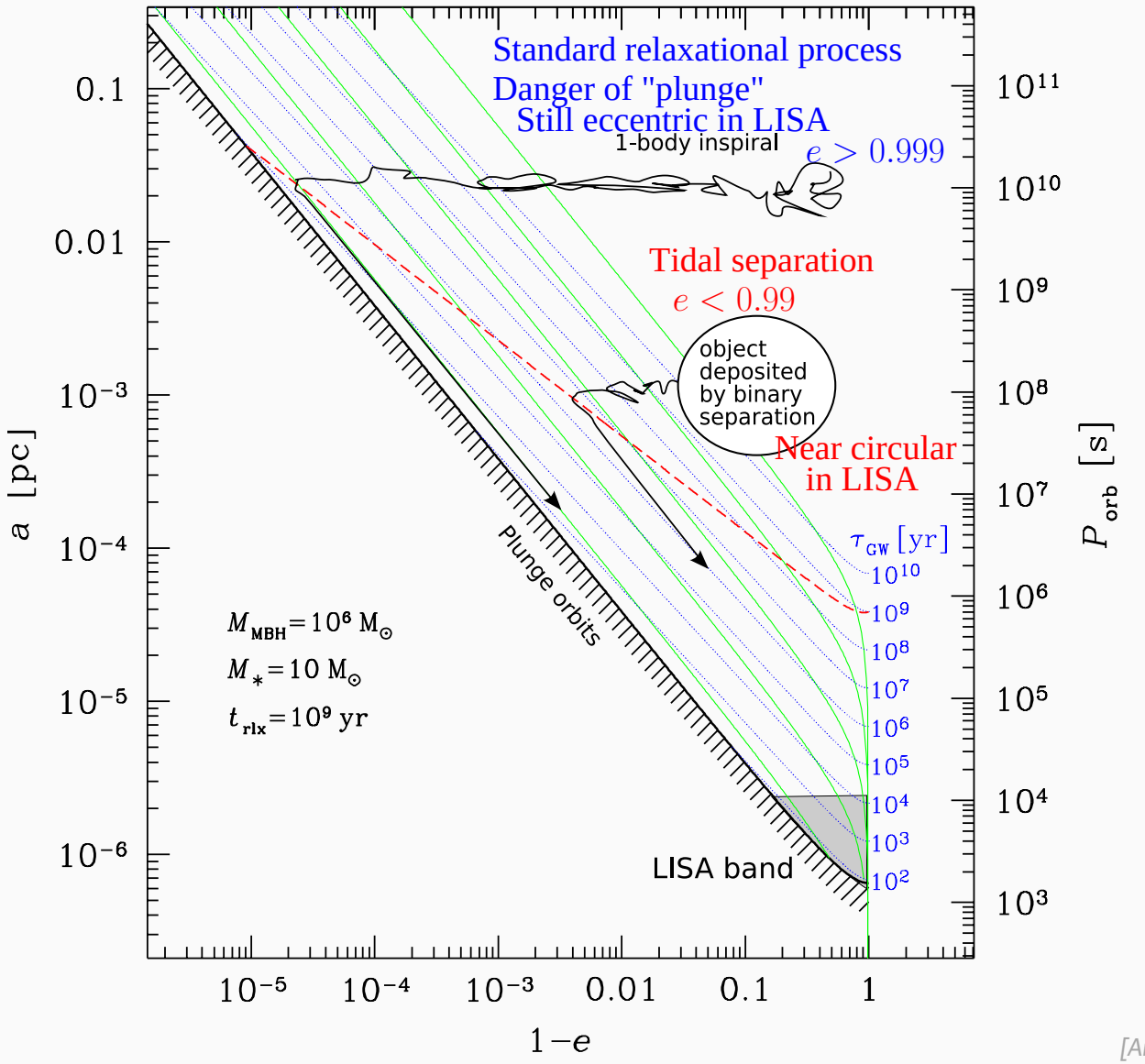
Range of masses



[Amaro-Seoane 2012]

Dichotomizing an EMRI



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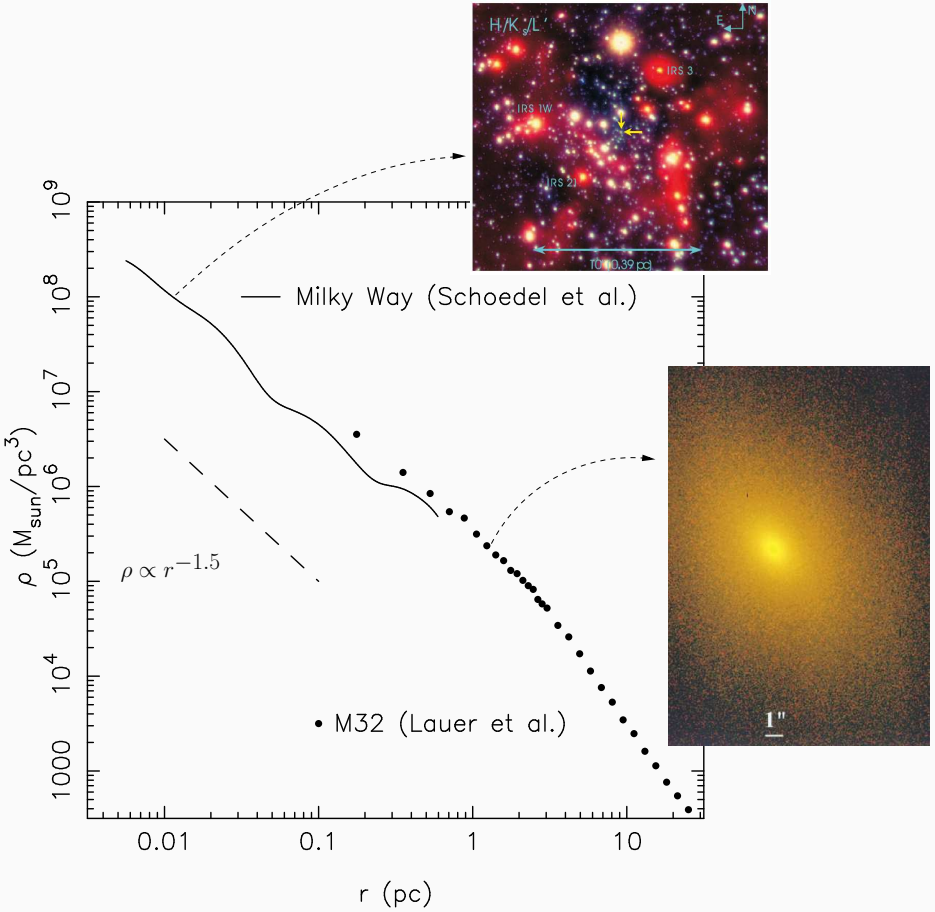
Do we expect these things to exist?

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



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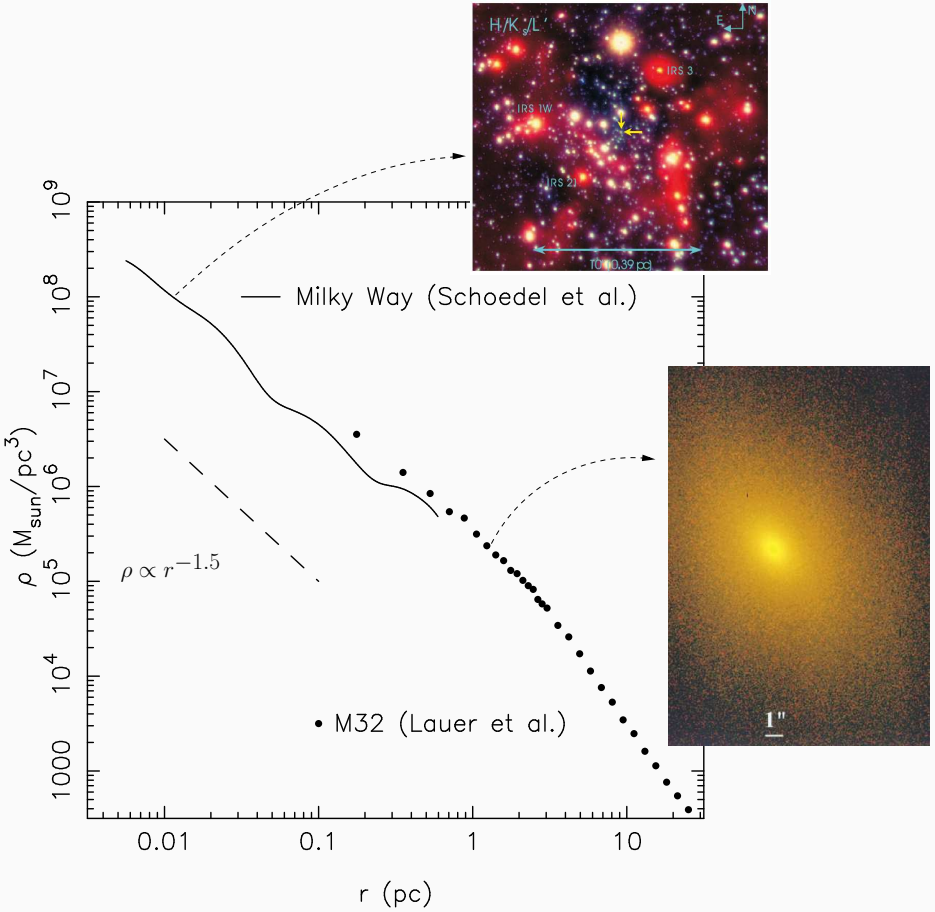

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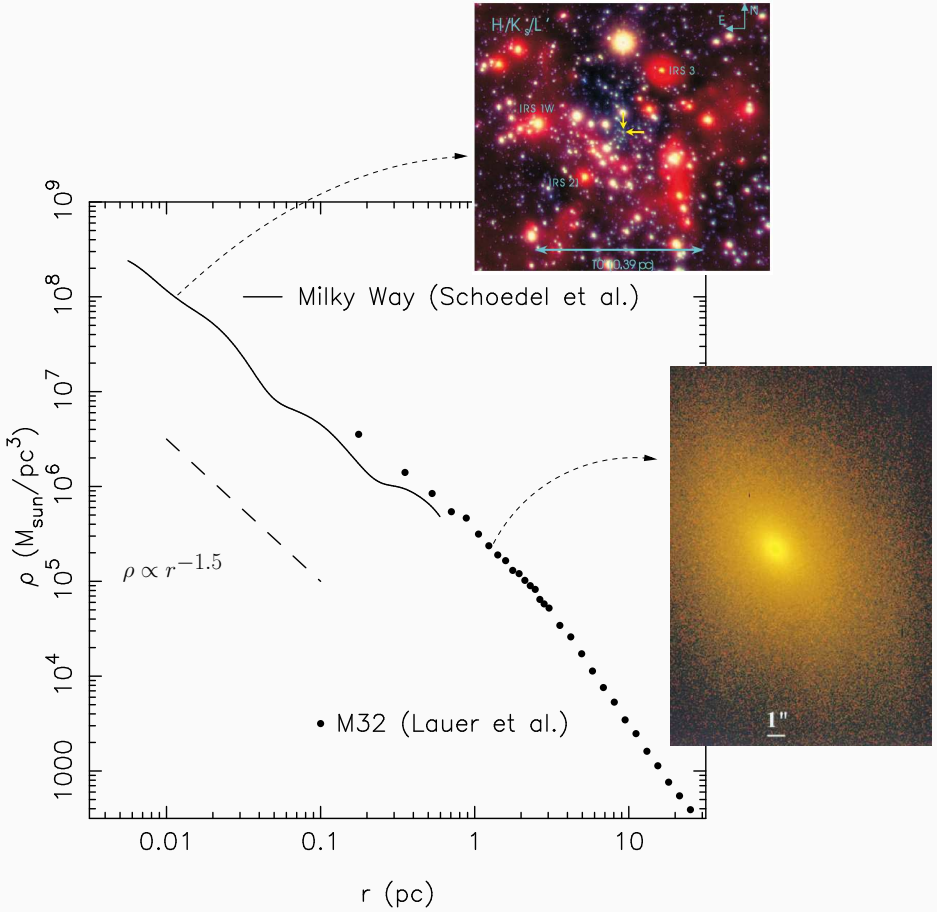

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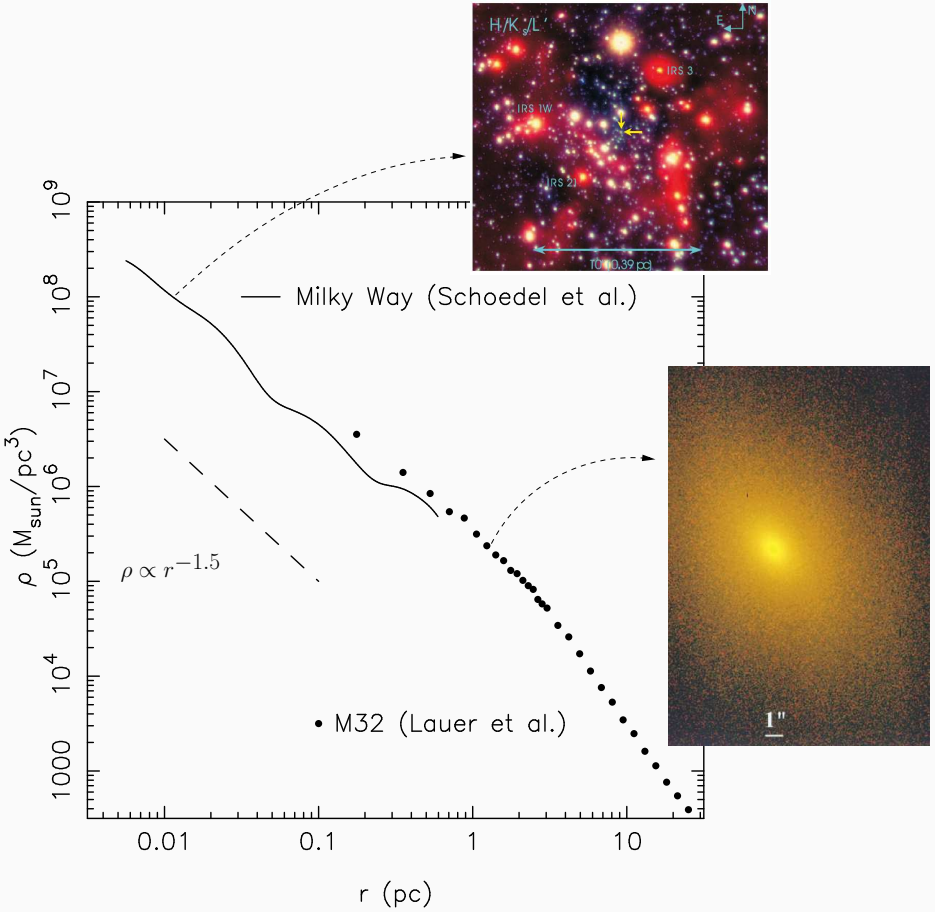

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- Confirmed later with a detailed kinematic treatment for single-mass

  [Bahcall & Wolf 1976]: $\gamma = 7/4$ and $p = \gamma - 3/2 = 1/4$

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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

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

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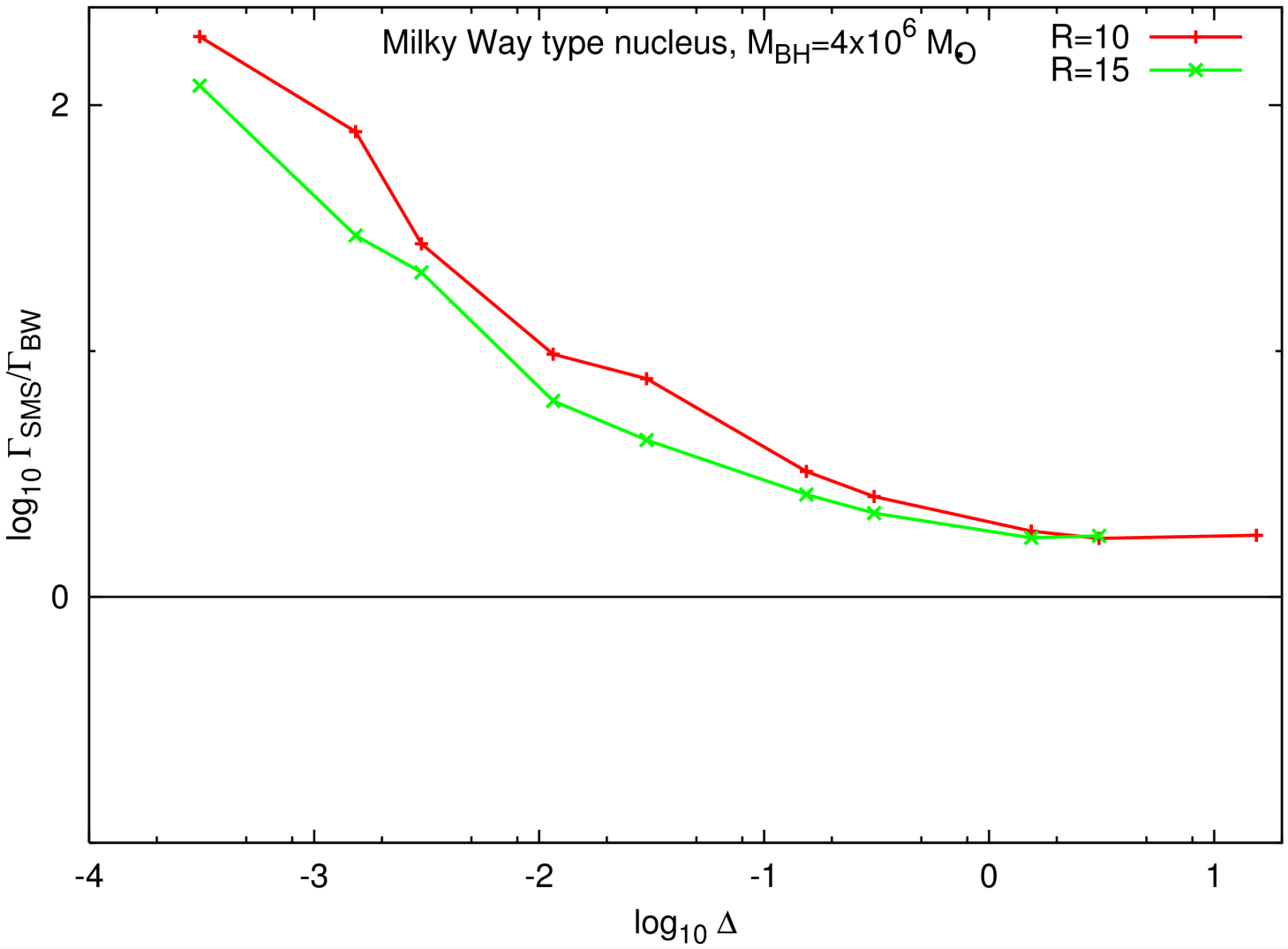
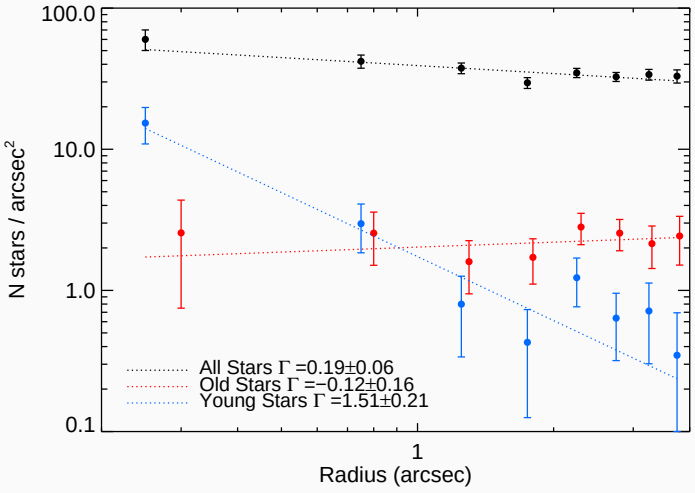
- $J_c(E)$ is the specific angular momentum of a circular orbit of energy E
- a_{GW}, or energy E_{GW}, for EMRIs is: $a_{GW} = 0.01 r_h$

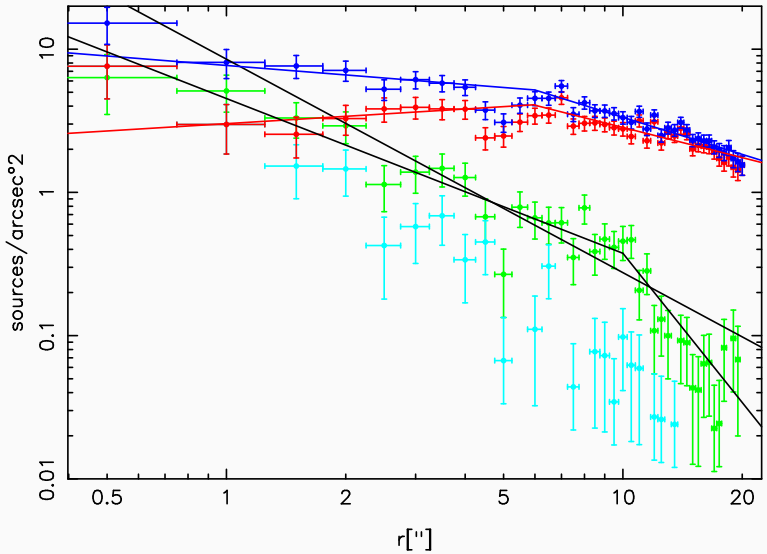
Boost on rates



Cusps in distress

A problem in our Galactic Center?





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

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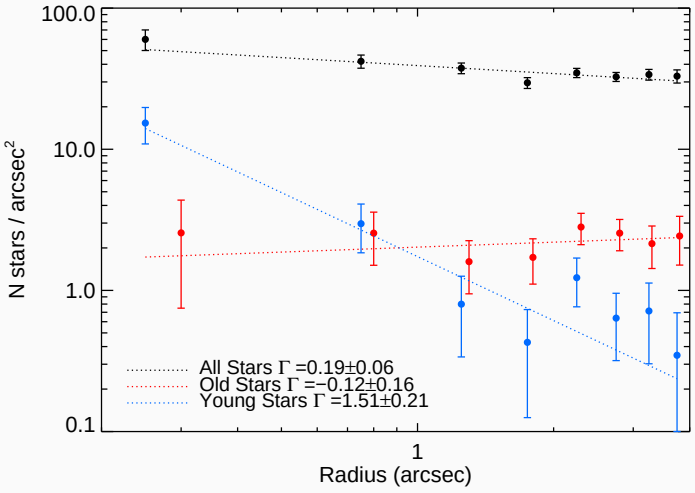

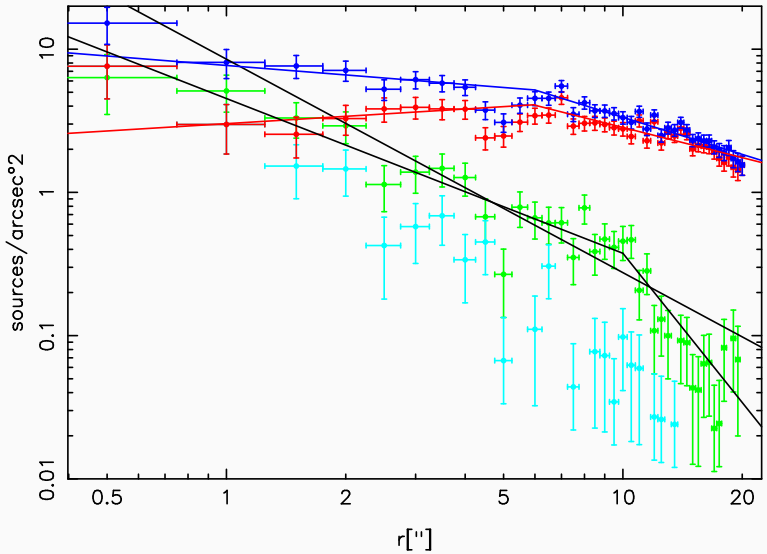

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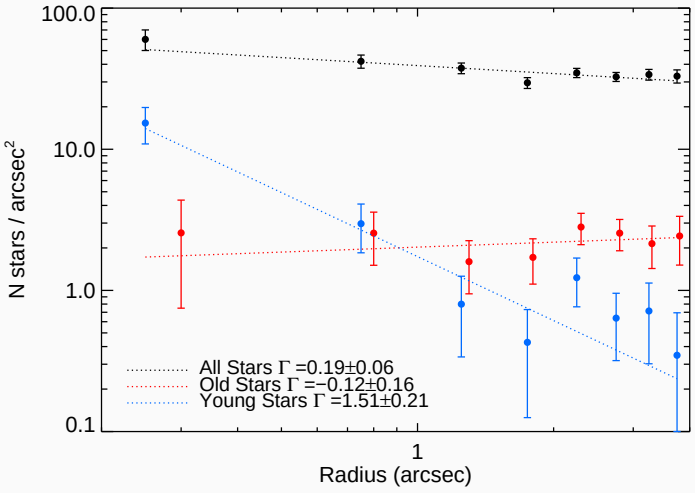

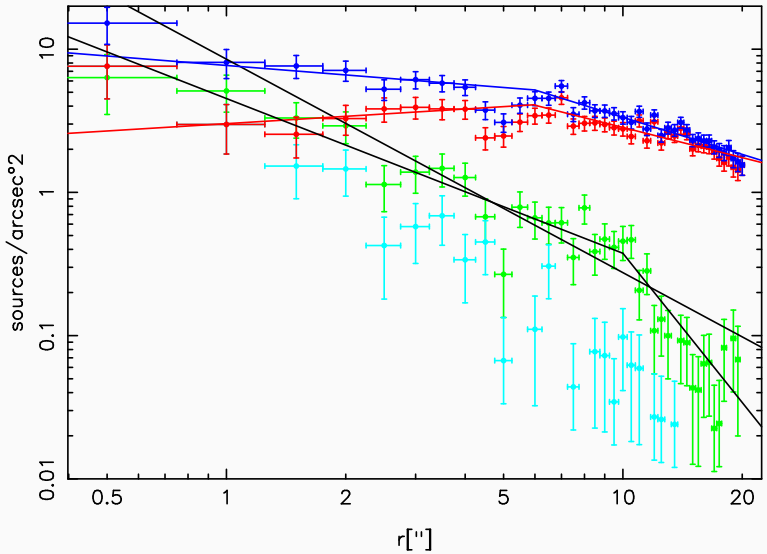

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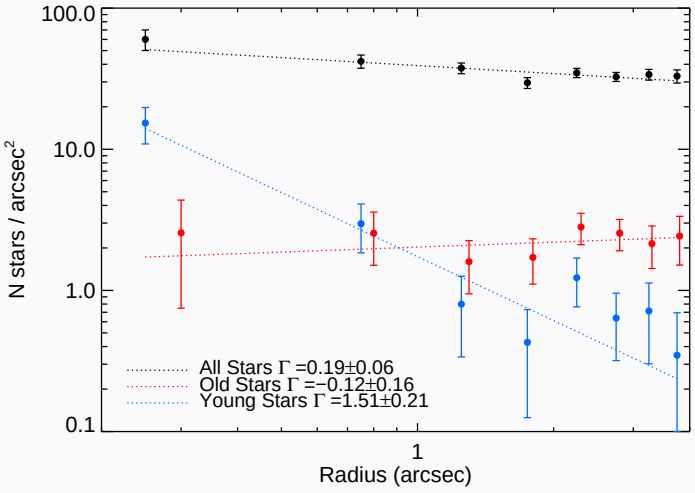

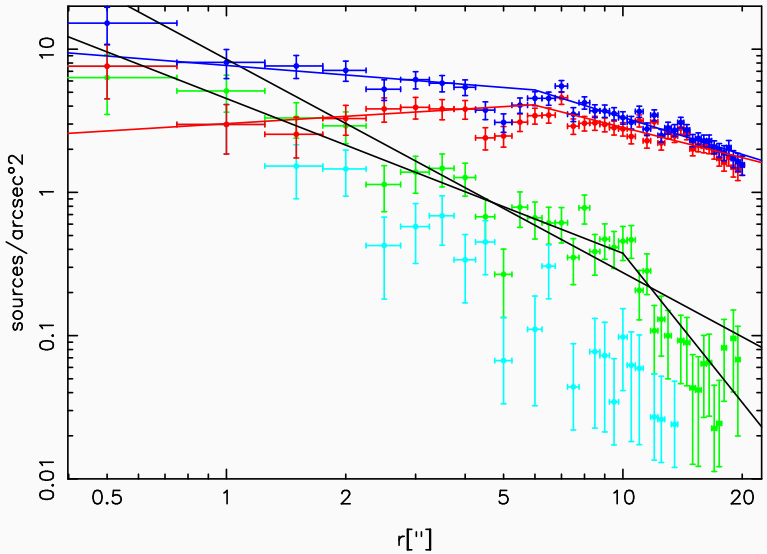

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- This is old news We know that the problem is not that acute

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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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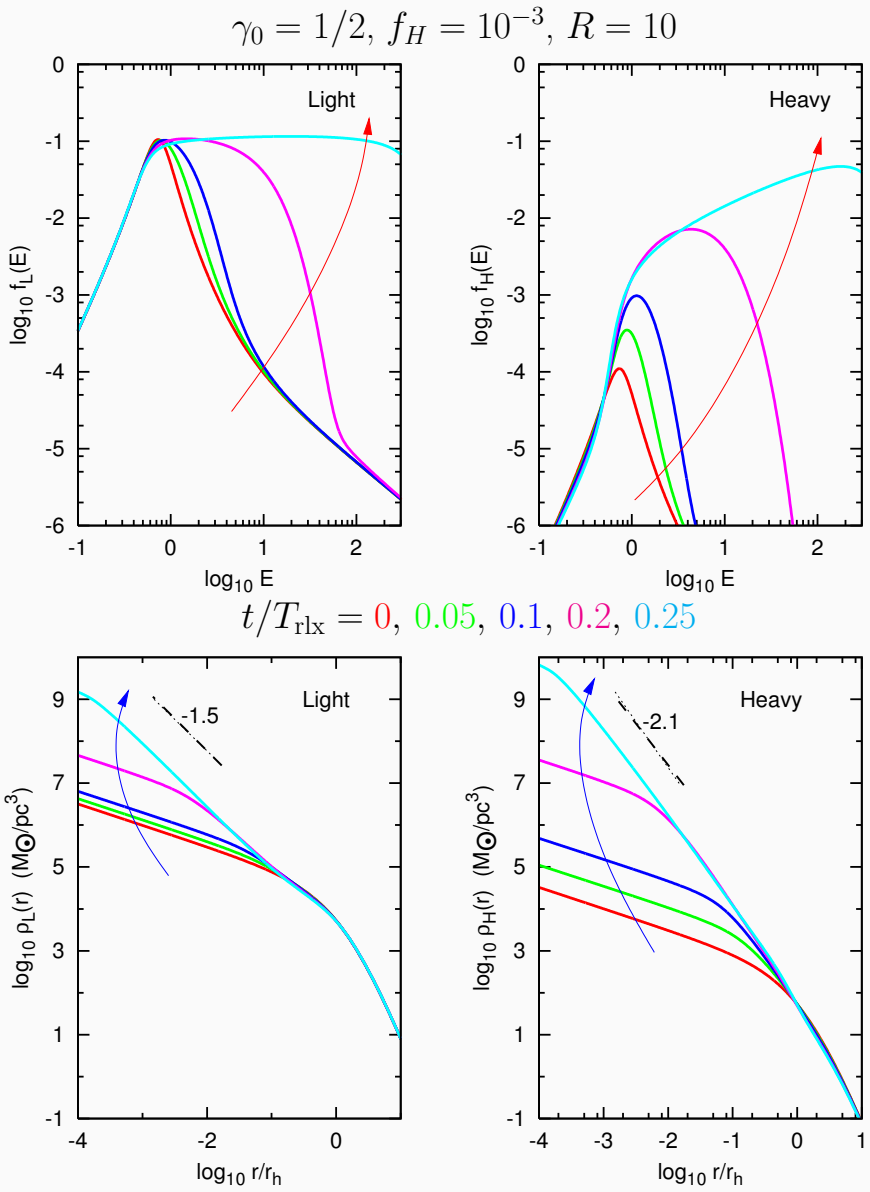
Isocore … regrowth



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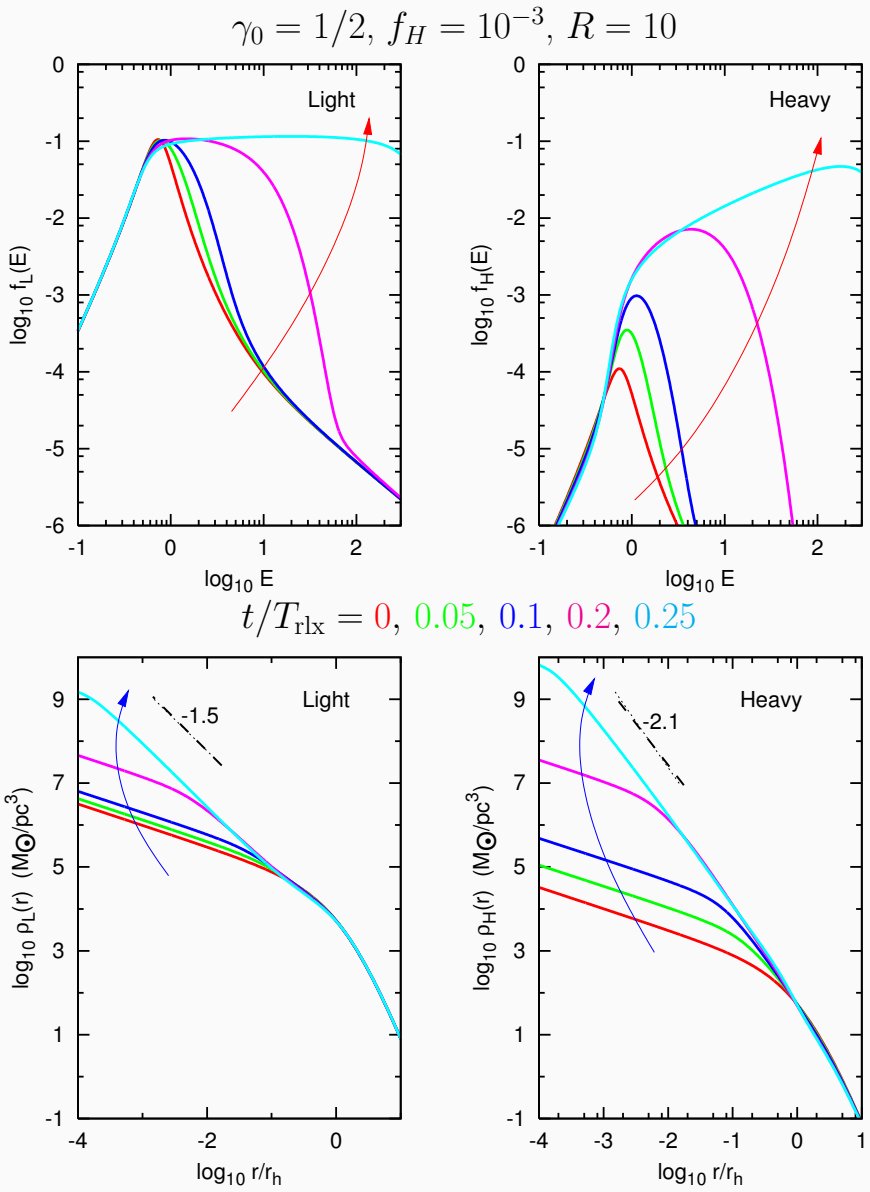

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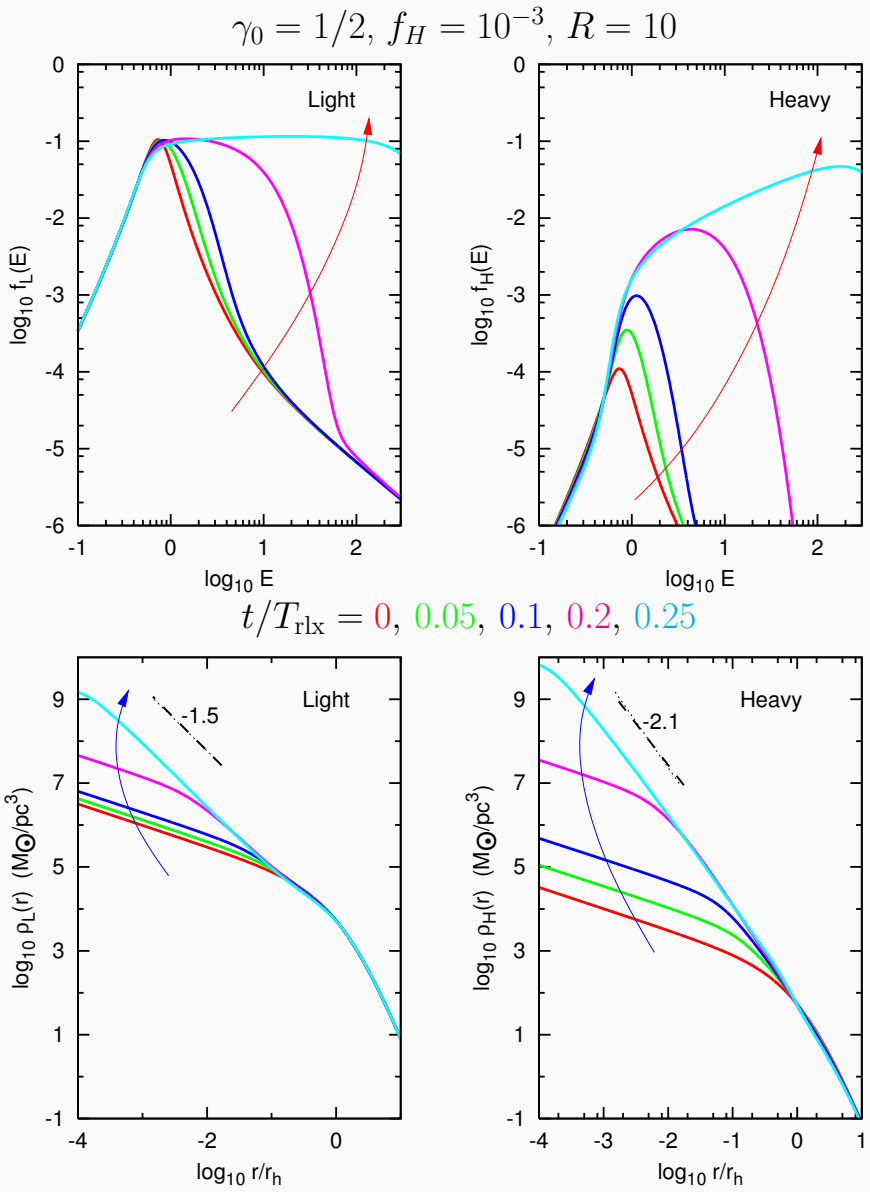

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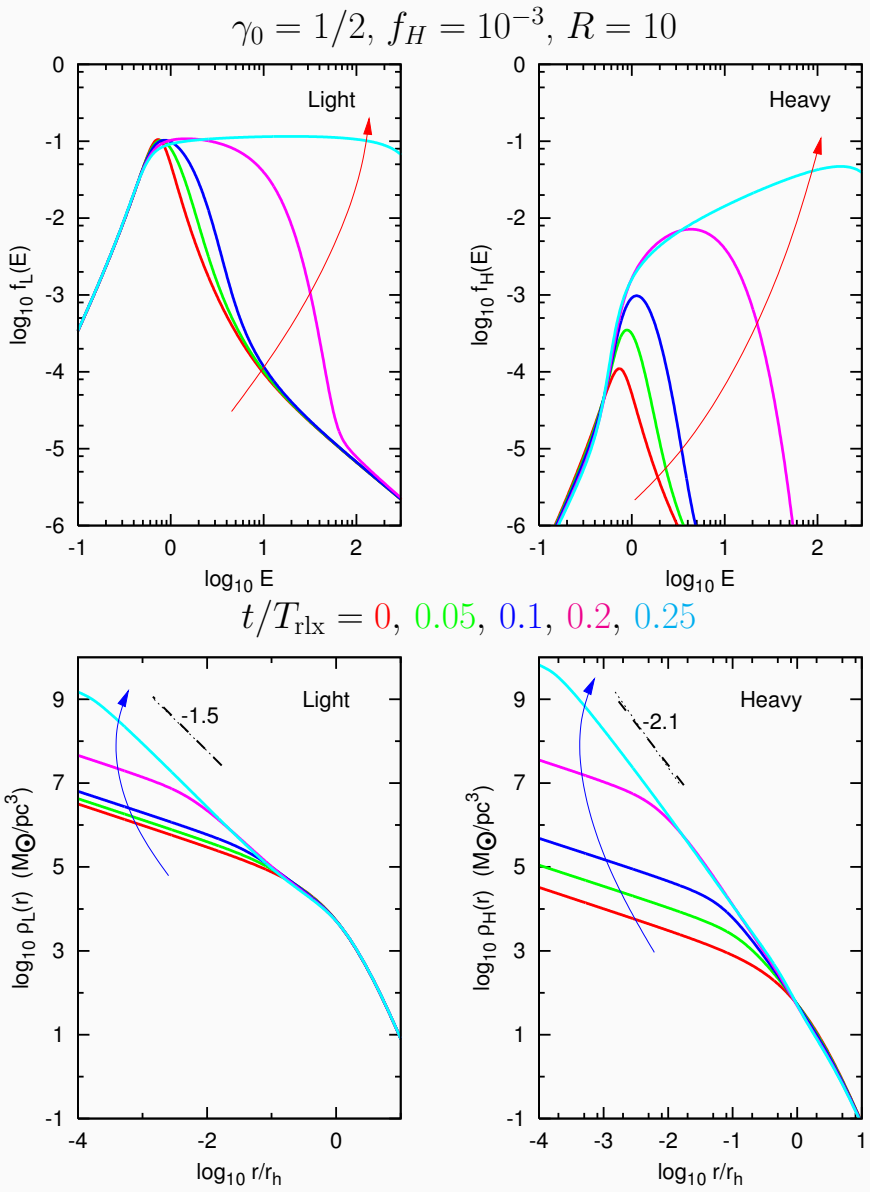

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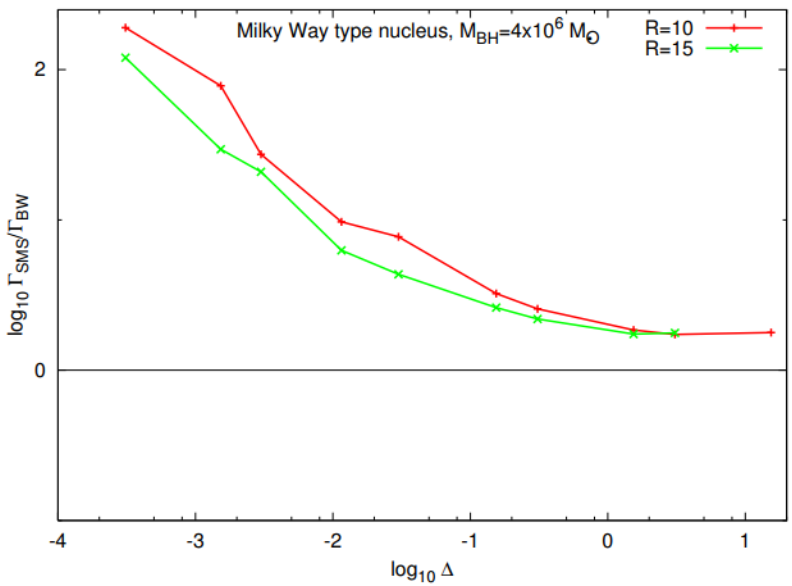
- The Milky Way nucleus is *not* necessarily the prototype of the nucleus from which e-LISA detections will be more frequent
- We still expect that a substantial fraction of EMRI events will originate from segregated stellar cusps, in particular with our new solution of mass segregation

Stellar-mass compact objects pile up in galactic nuclei



Stellar-mass compact objects distribute in the galactic nucleus trying to reach an equipartition of energy in such a way that they 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]

Intermediate-mass black holes

IMBHs

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

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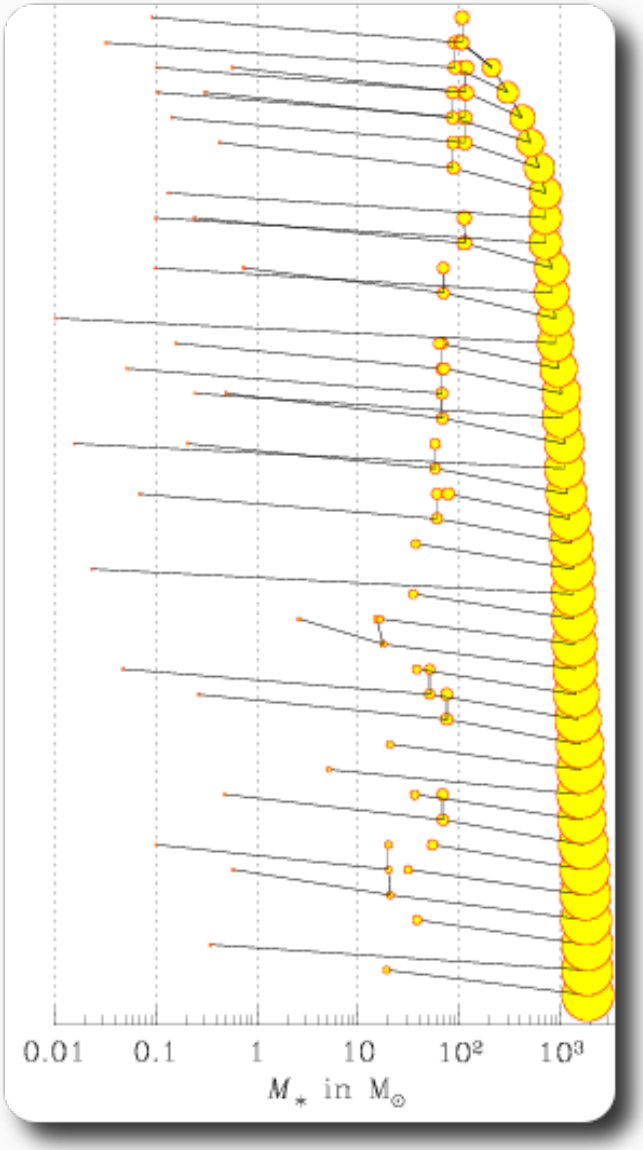

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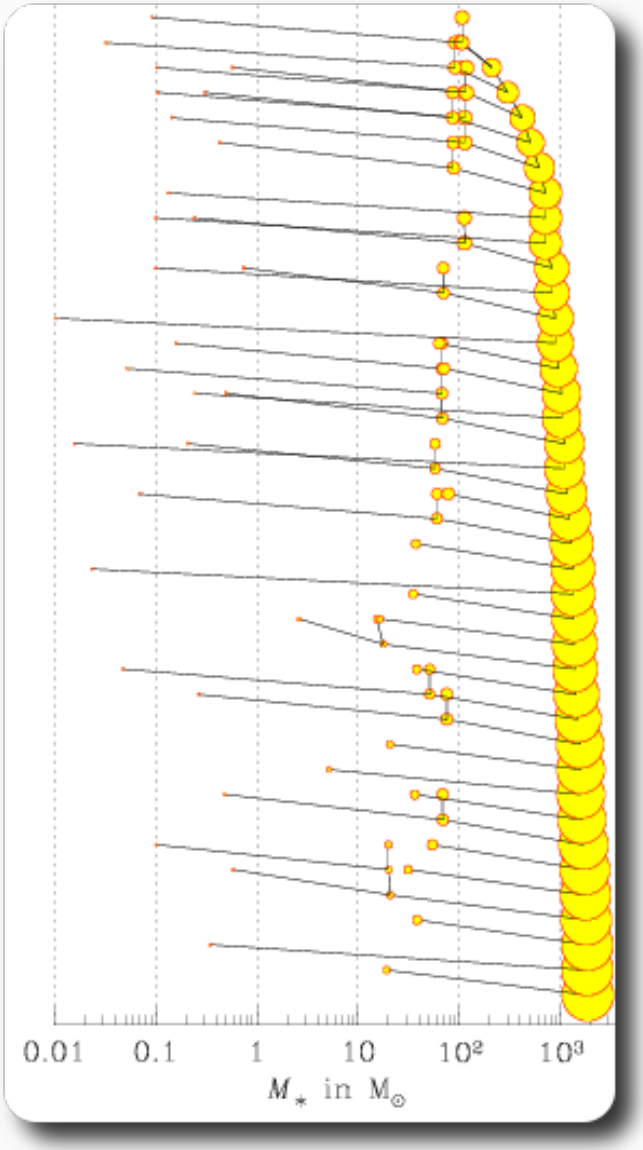

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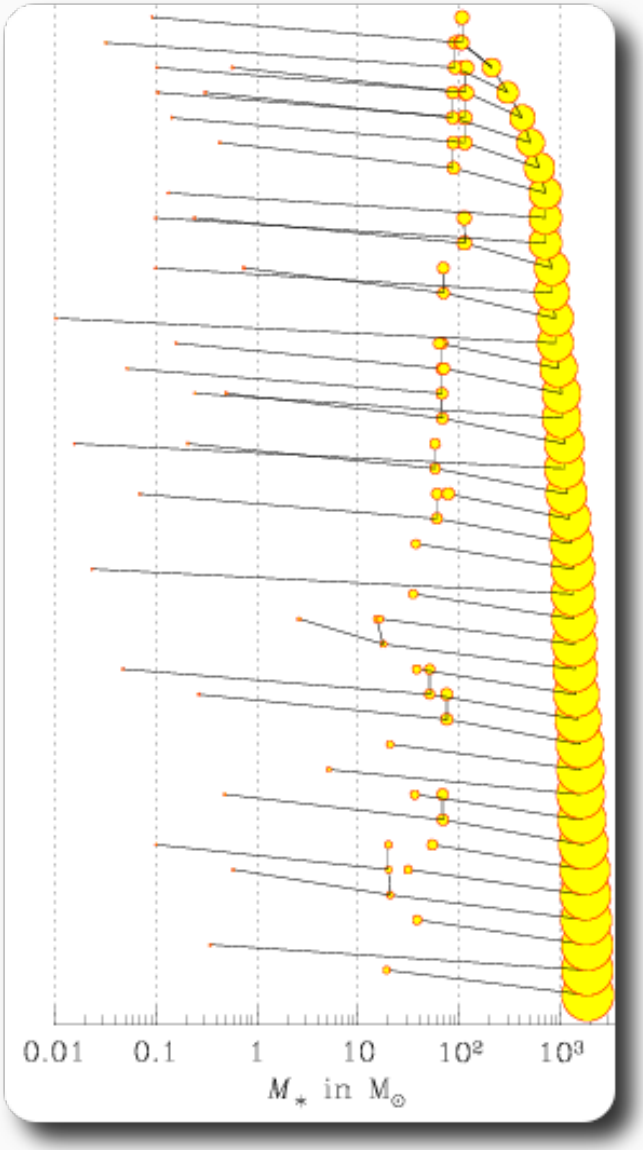

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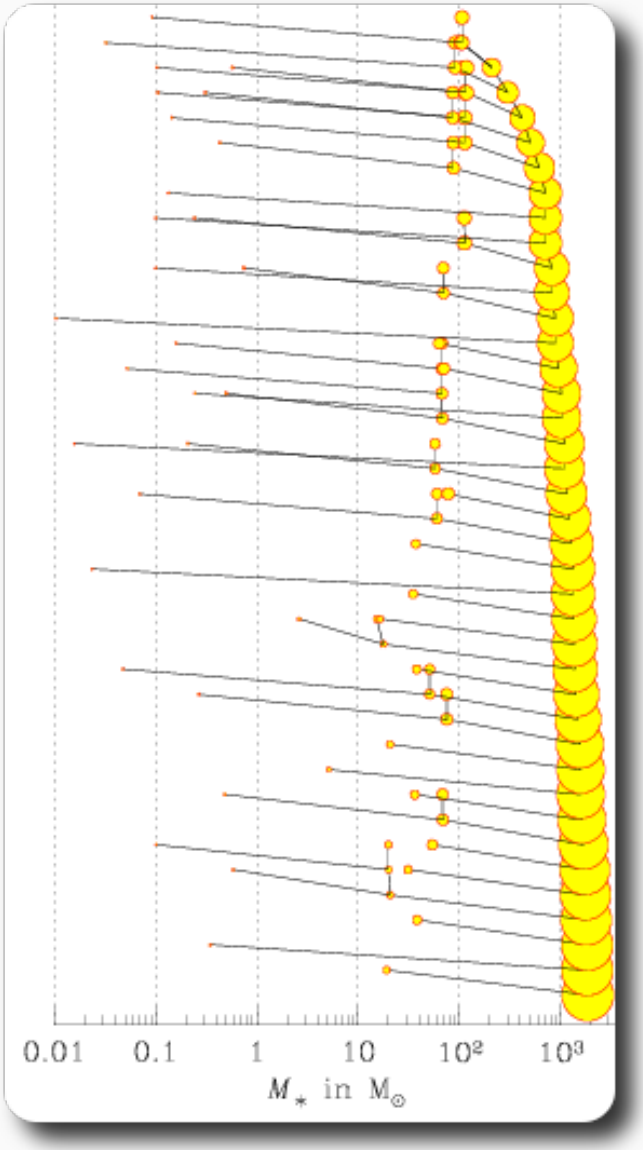

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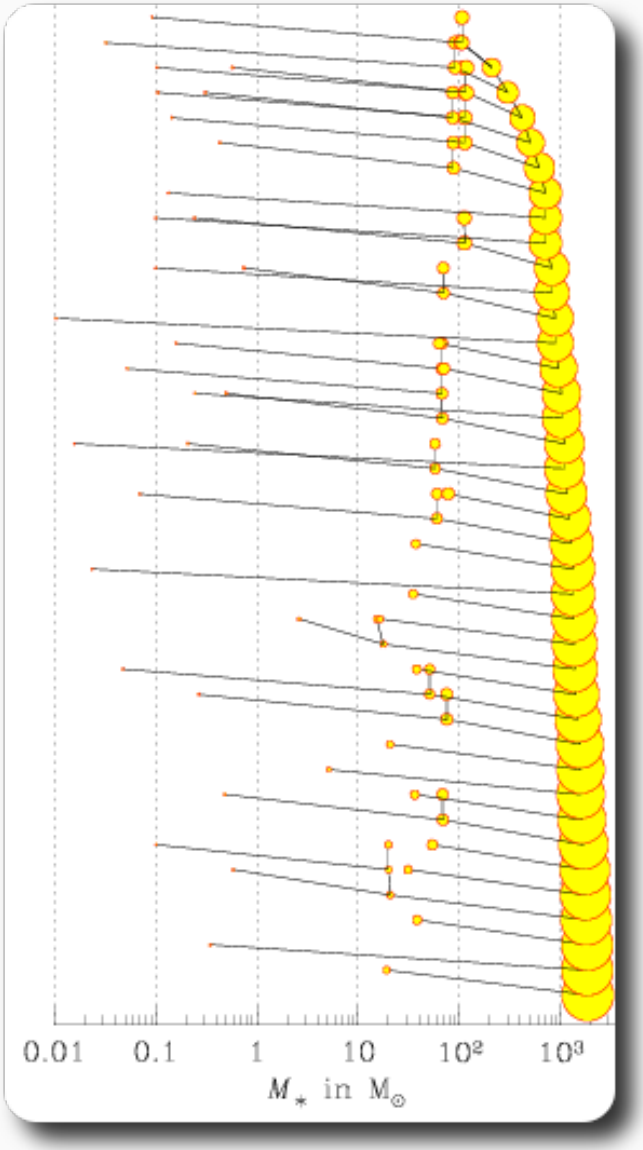

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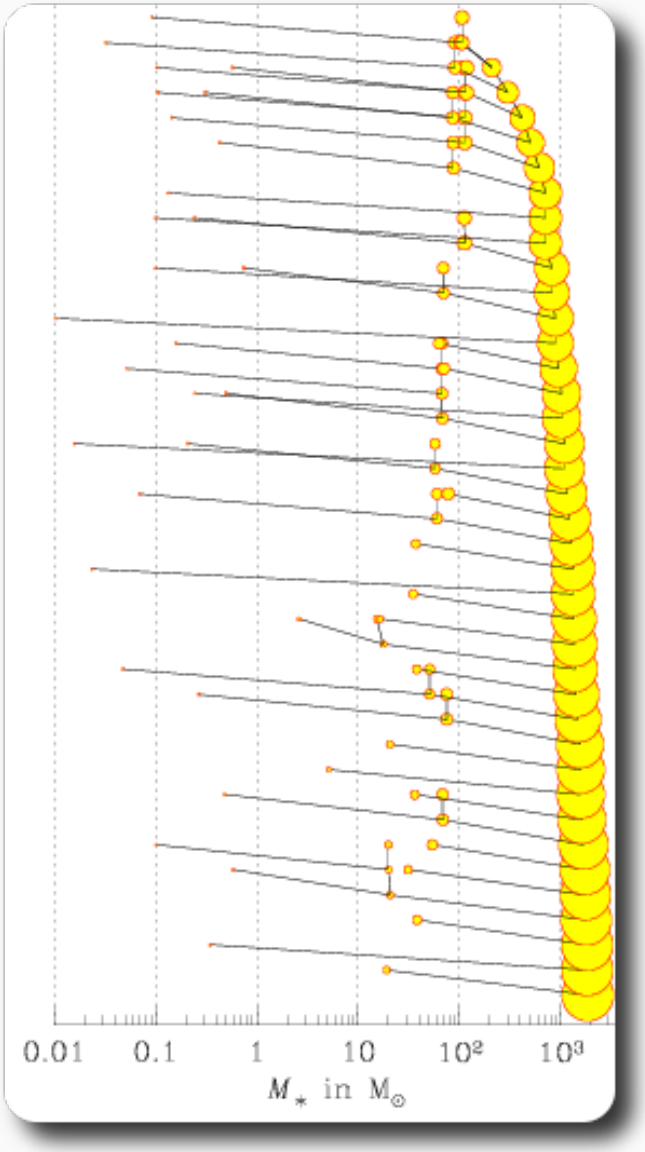

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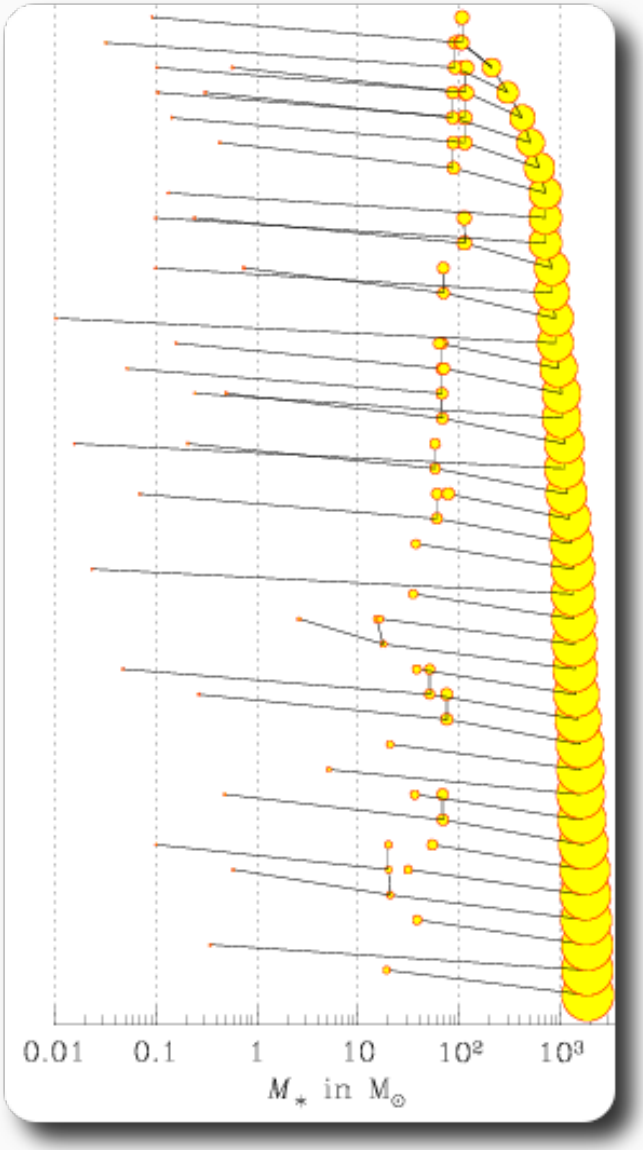

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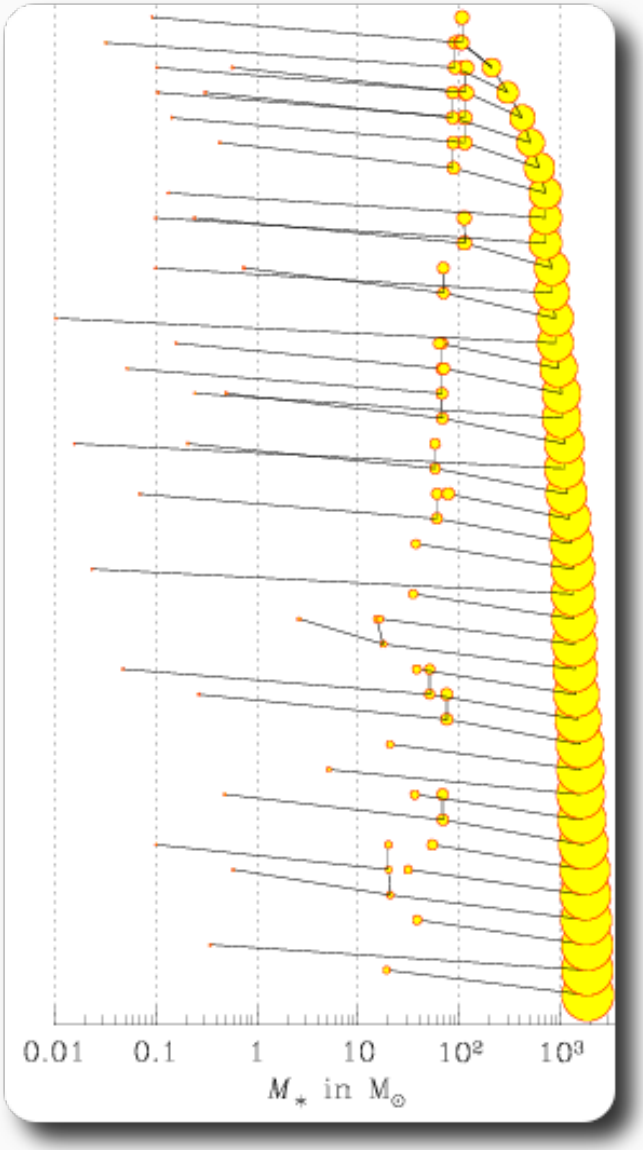

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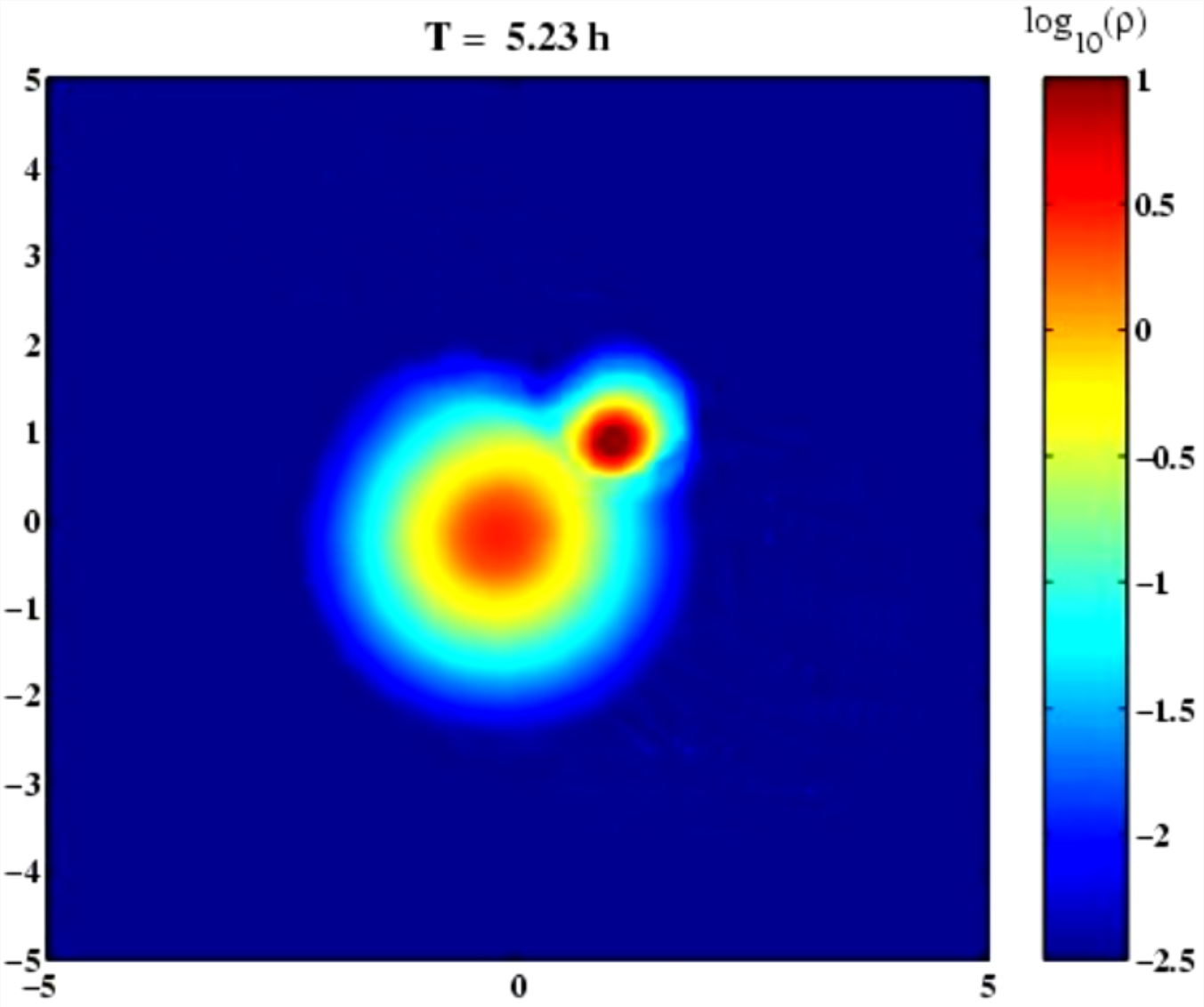

[Film: Stellar collisions, win+r]

NS as probes of IMBHs with GWs

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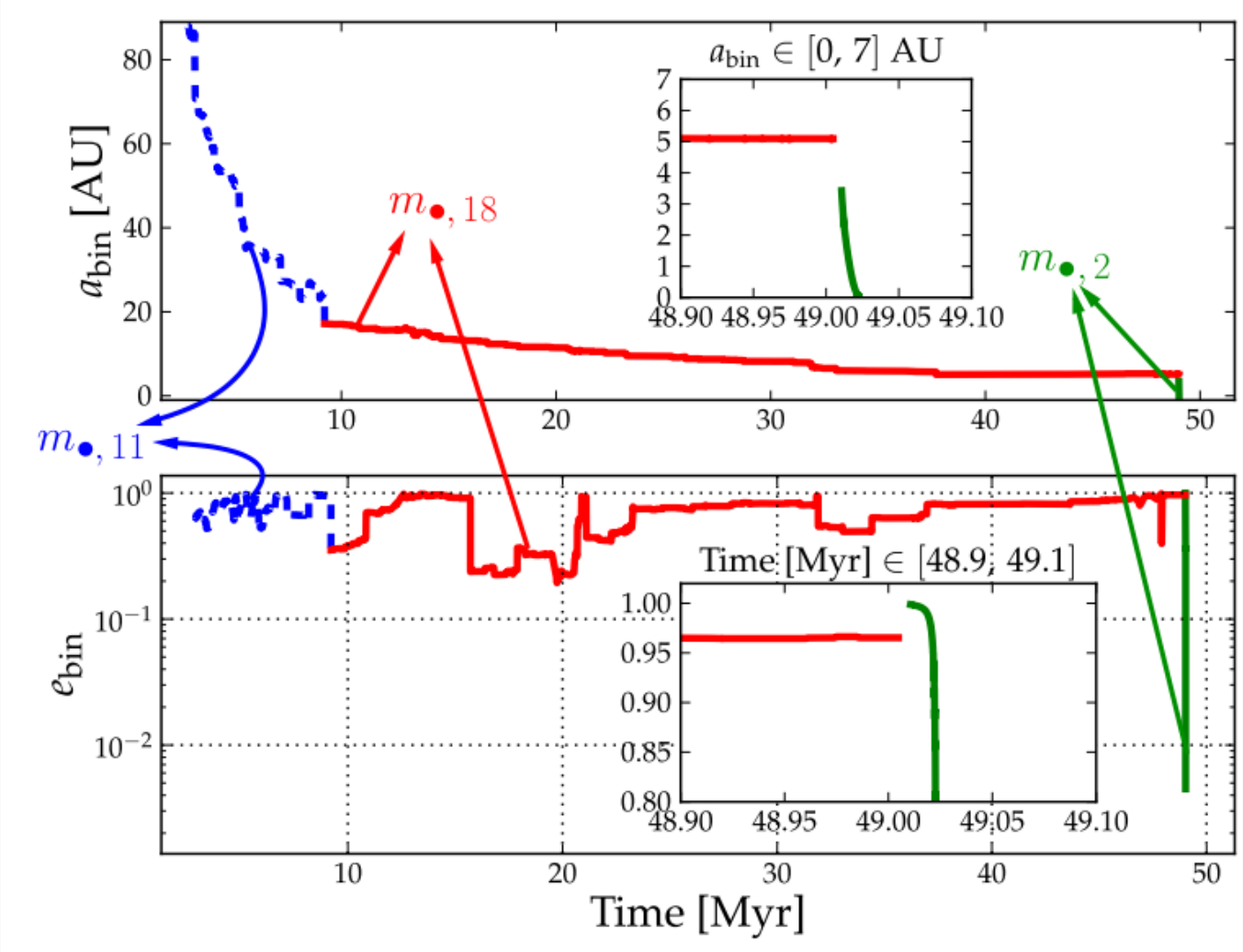
- ✔ IMBHs are likely to be found at the centres of dense stellar systems and we know that NS should segregate there, too

Live formation of an IMRI



Conclusions

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  ...and a specific torture to you

Questions?