The role of dark matter in supermassive black hole mergers

Gonzalo Alonso-Álvarez

Based on [2401.14450] with Caitlyn Dewar & Jim Cline

Physics
UNIVERSITY OF TORONTO

Supermassive black holes

Jets (M87)

Image credit: HST

AGNs (3C 273)

Image credit: SDSS

Stellar dynamics (Sgr A*)

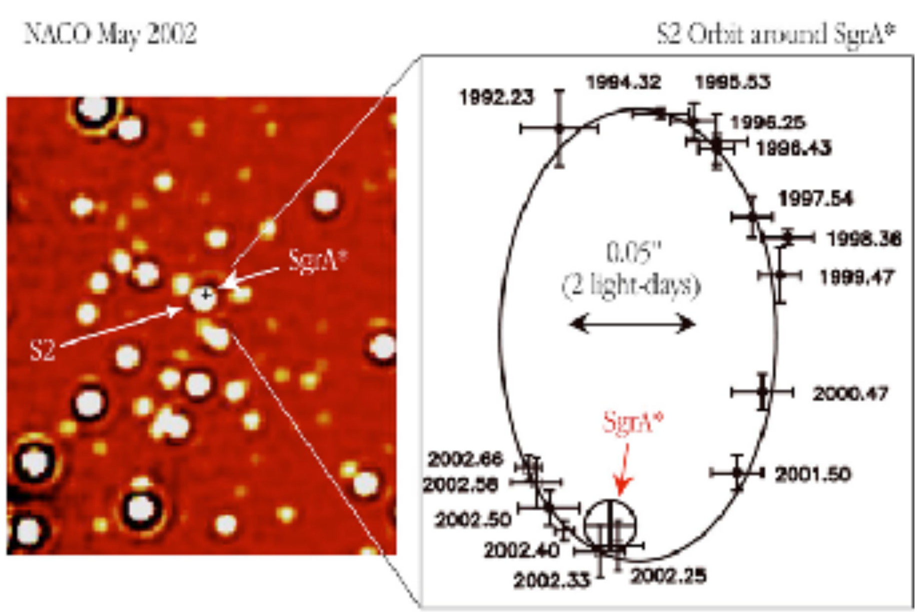


Image credit: ESO

Direct imaging (Sgr A*)

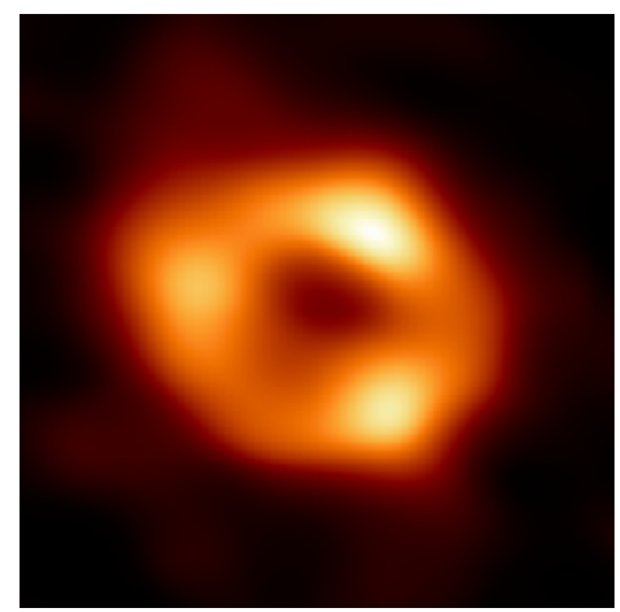


Image credit: EHT

Galaxies are built via mergers

Structure formation

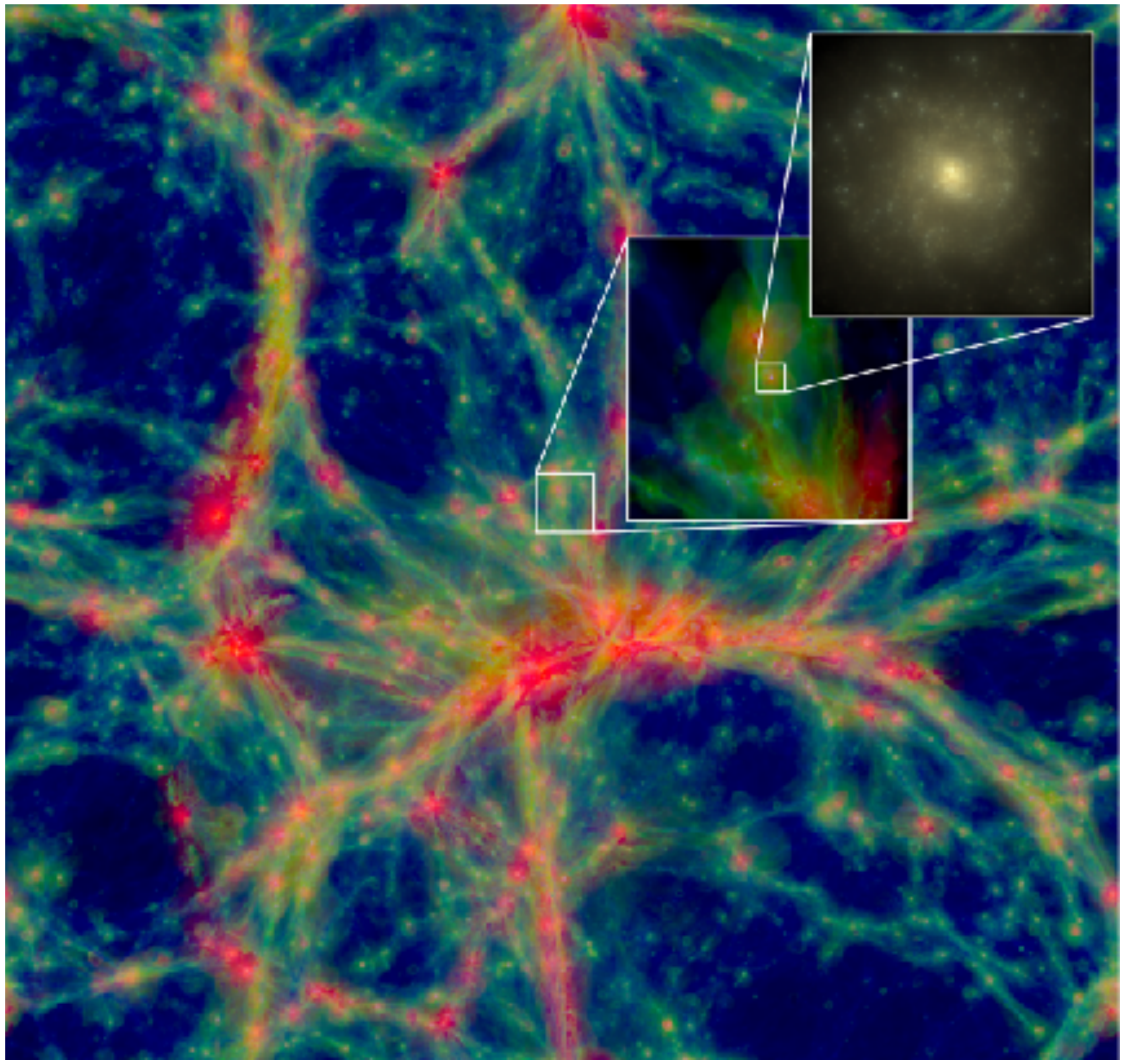
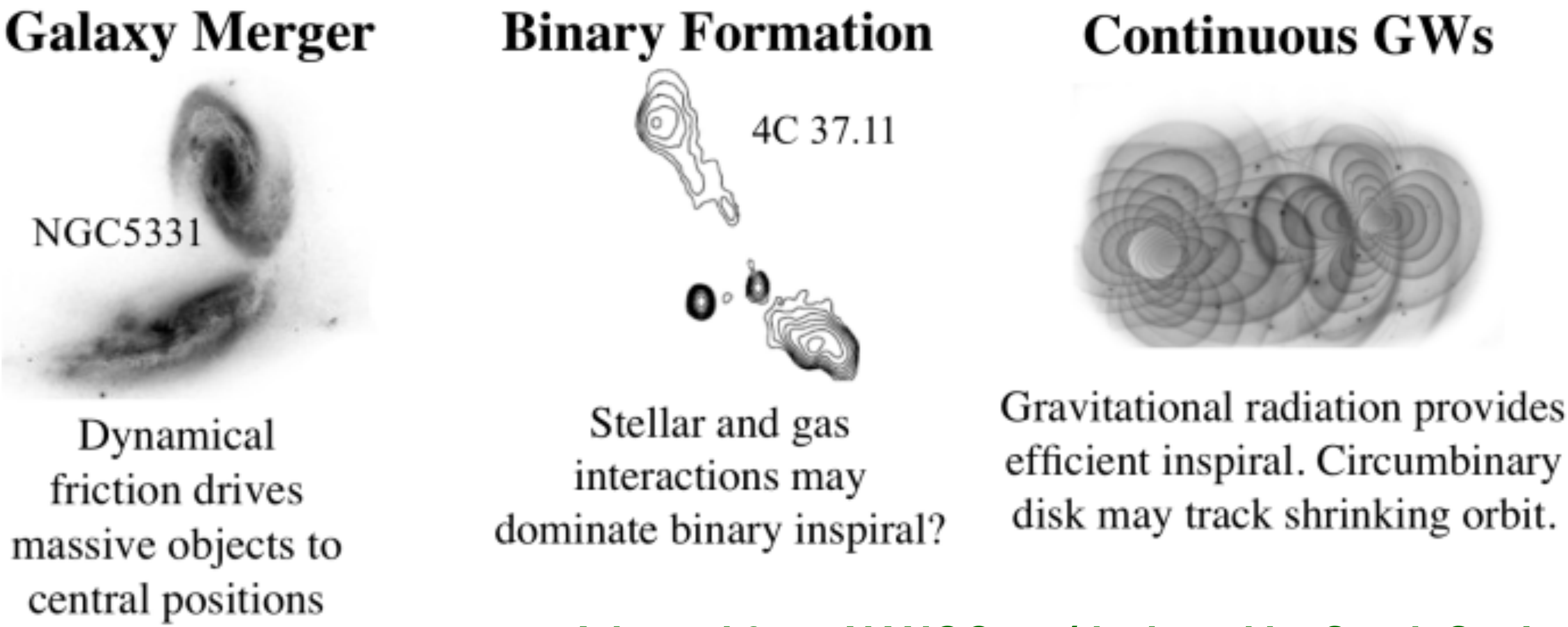


Image credit: EAGLE simulations

Galaxy merger

Image credit: HST

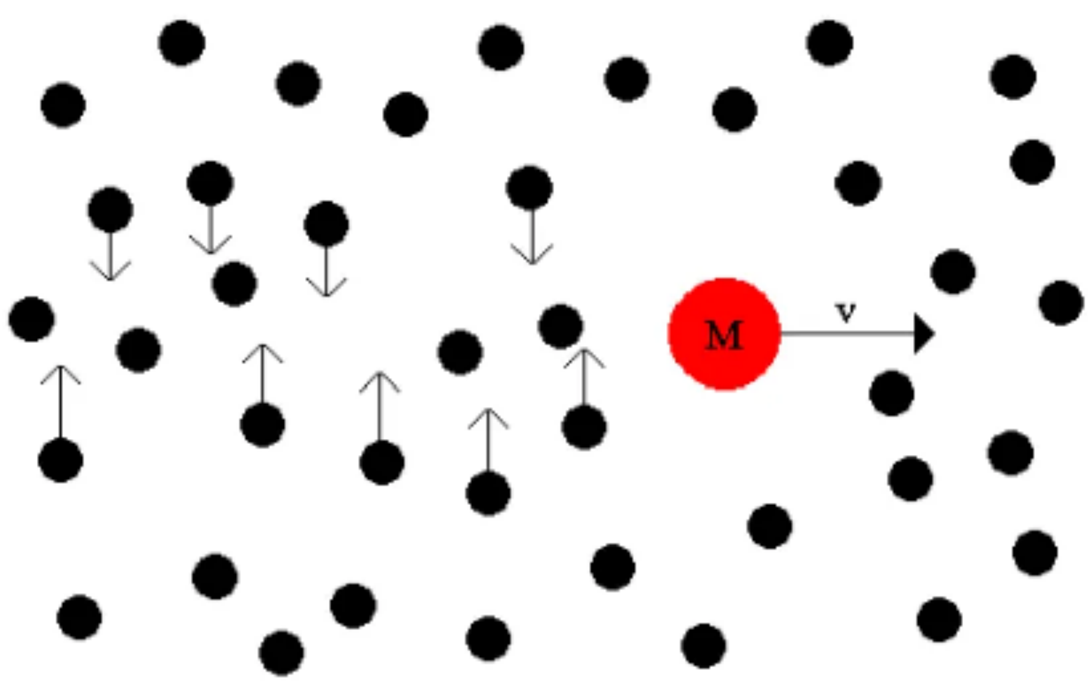
Supermassive black holes mergers



Adapted from NANOGrav (designed by Sarah Spolaor)

Dynamical friction

SMBH creates stellar/gas overdensity behind it



Gravitational pull of the wake slows down SMBH

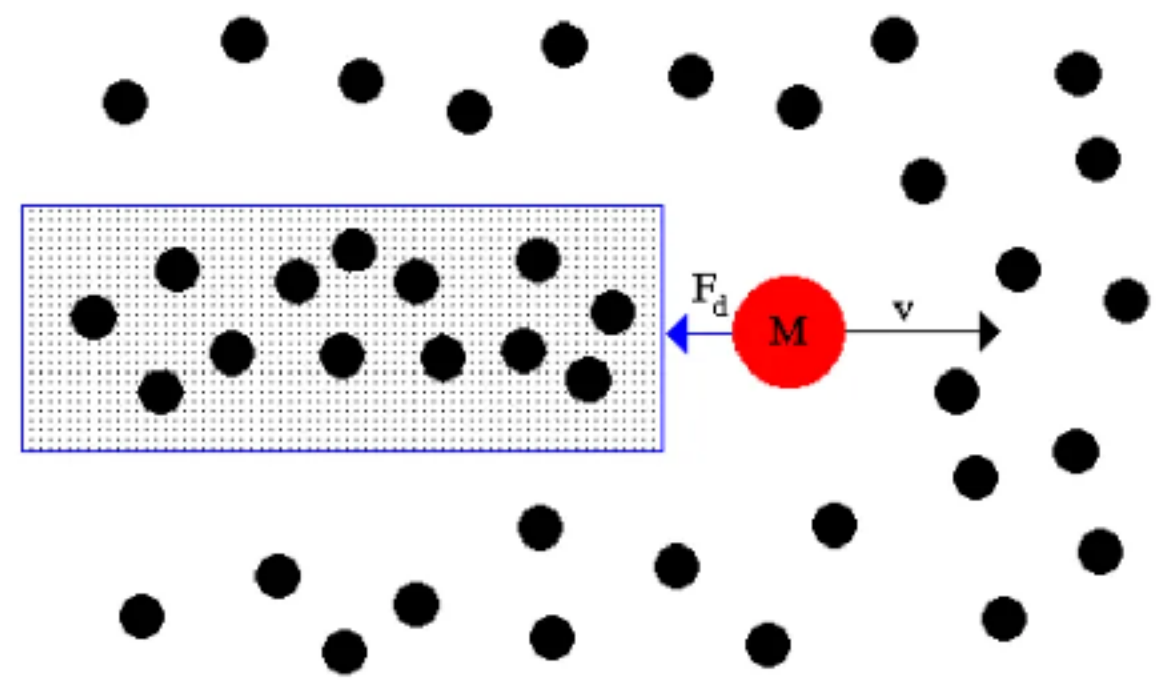
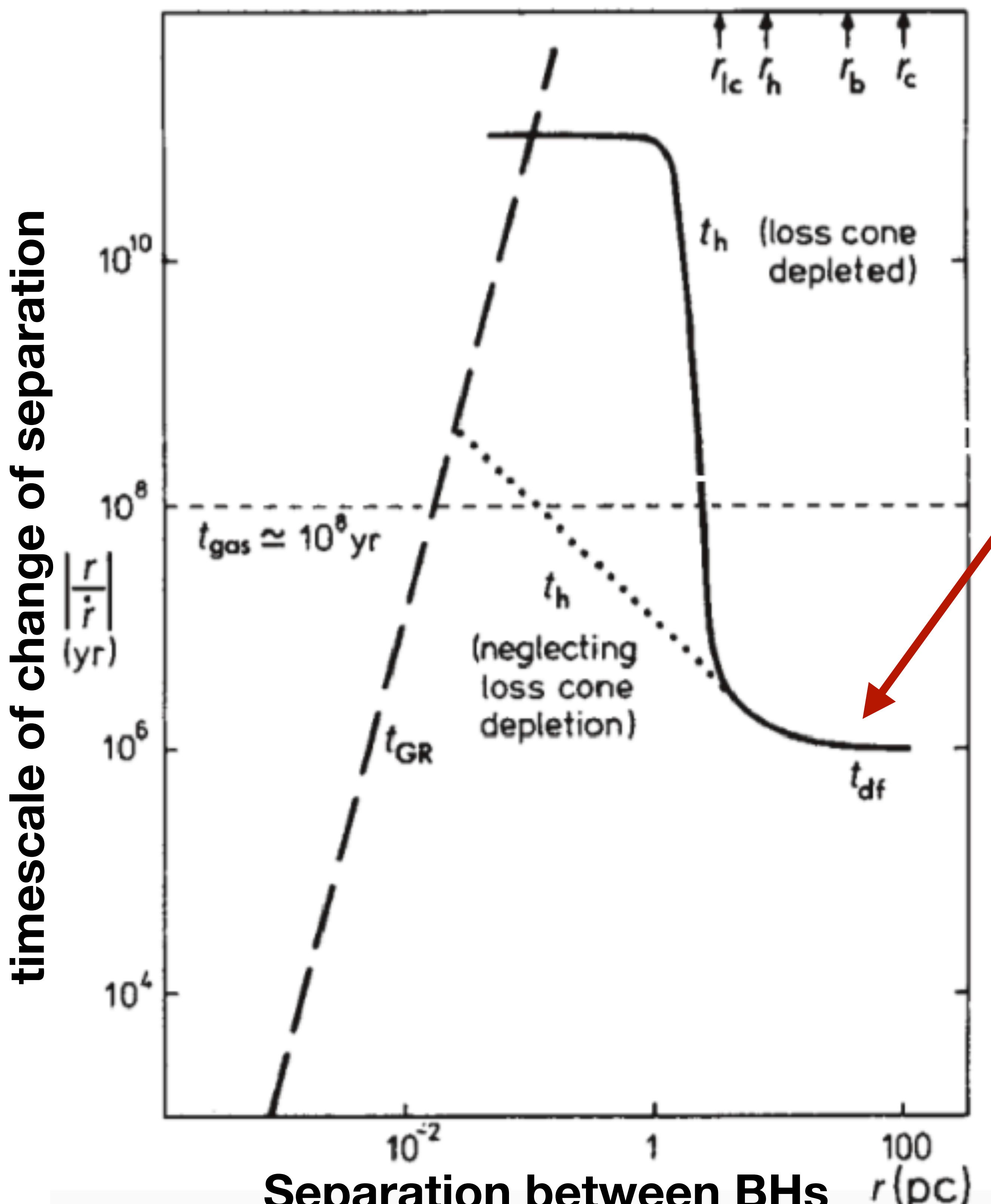


Image credit: J. Schombert (adapted)

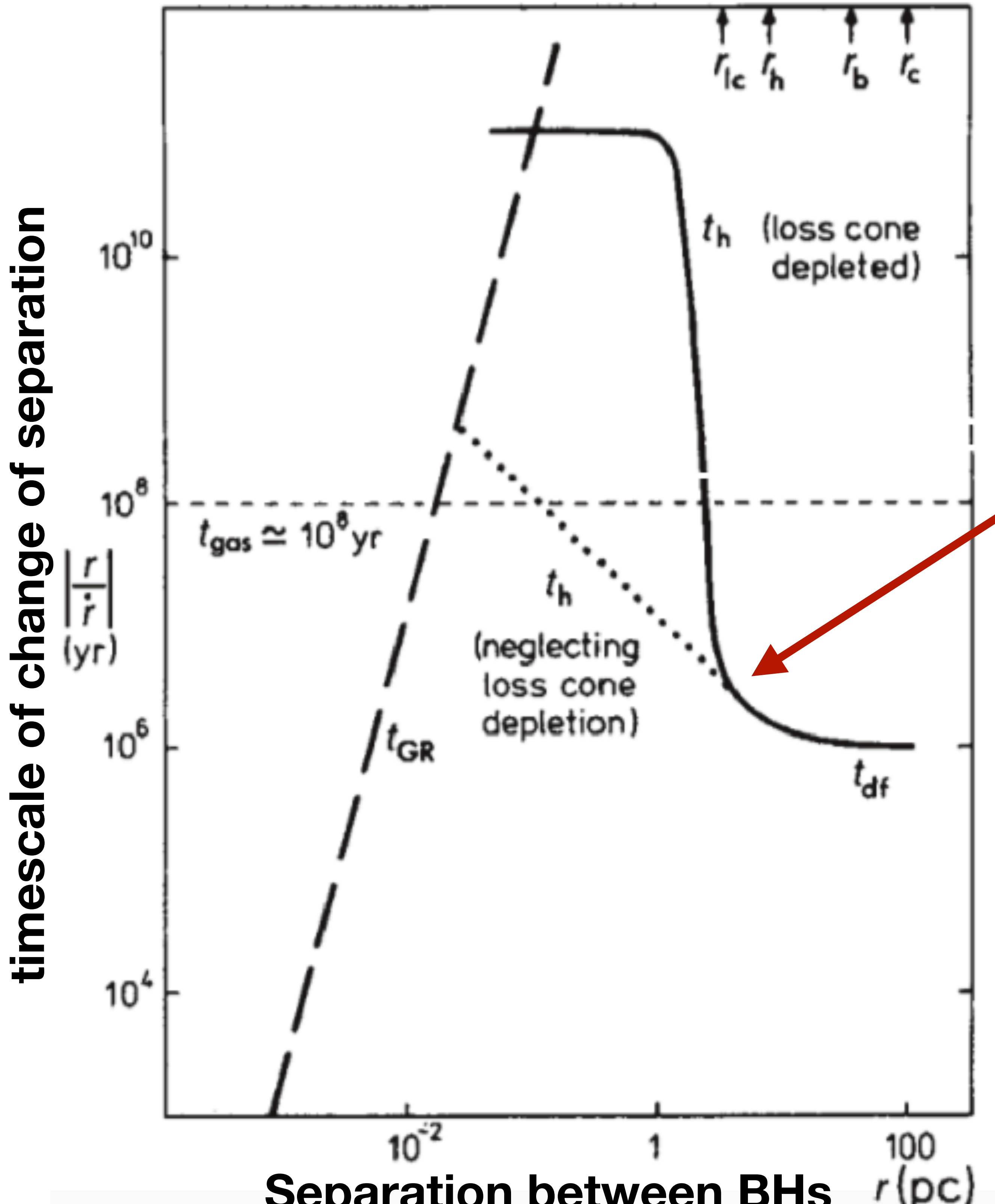
The final parsec problem



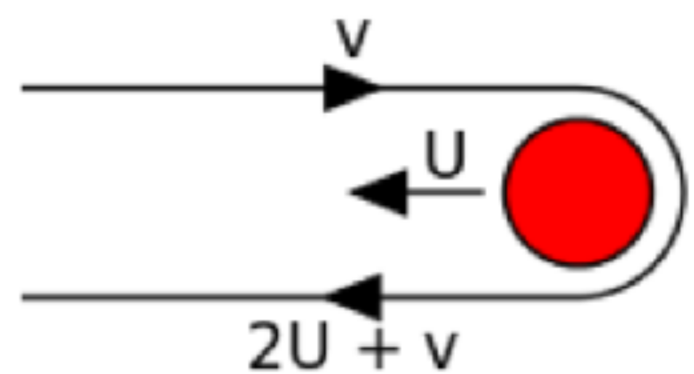
1. Dynamical friction shrinks binary

Begelman, Blandford & Rees (1980)

The final parsec problem

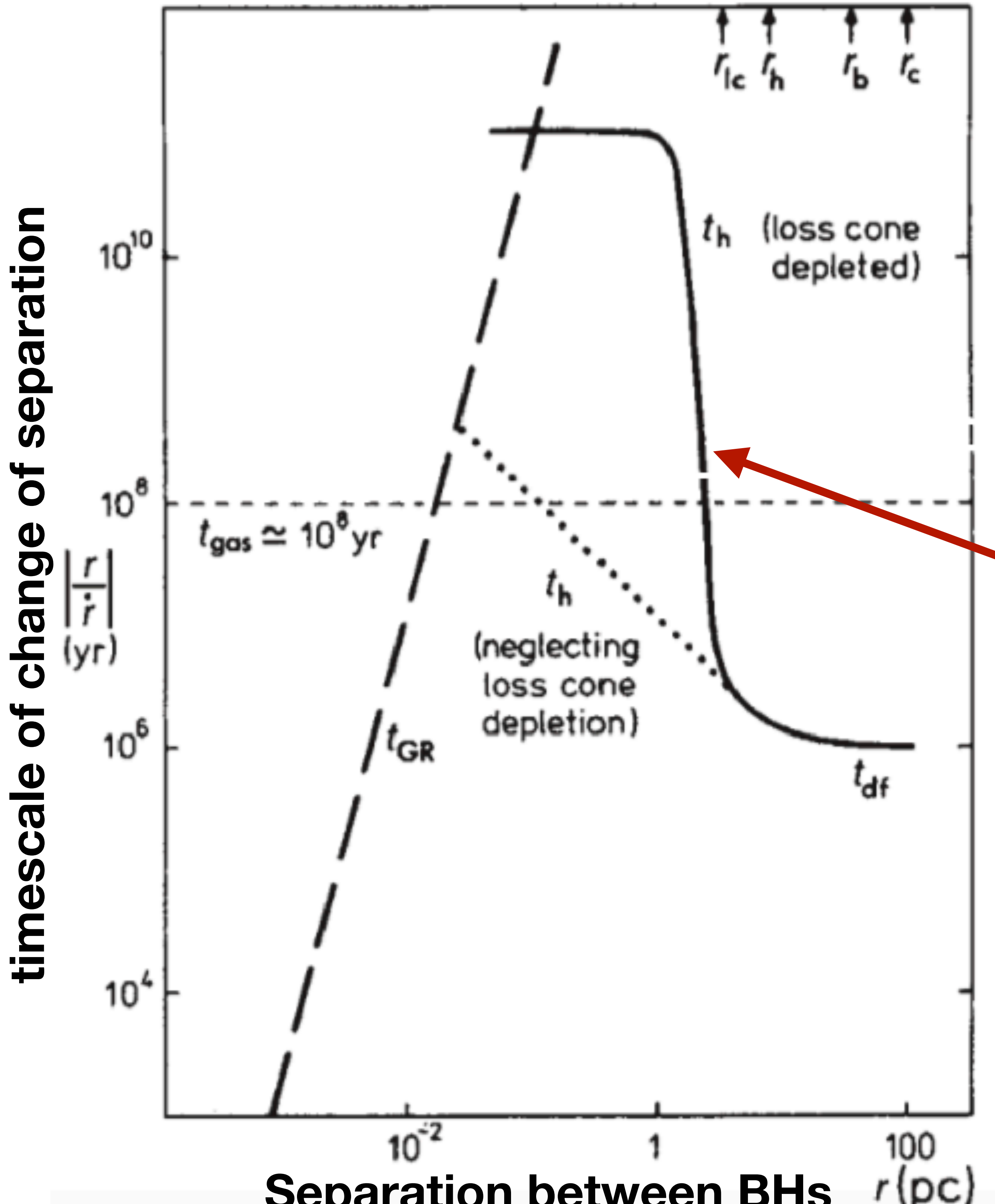


1. Dynamical friction shrinks binary
2. Decay only through close encounters



Begelman, Blandford & Rees (1980)

The final parsec problem

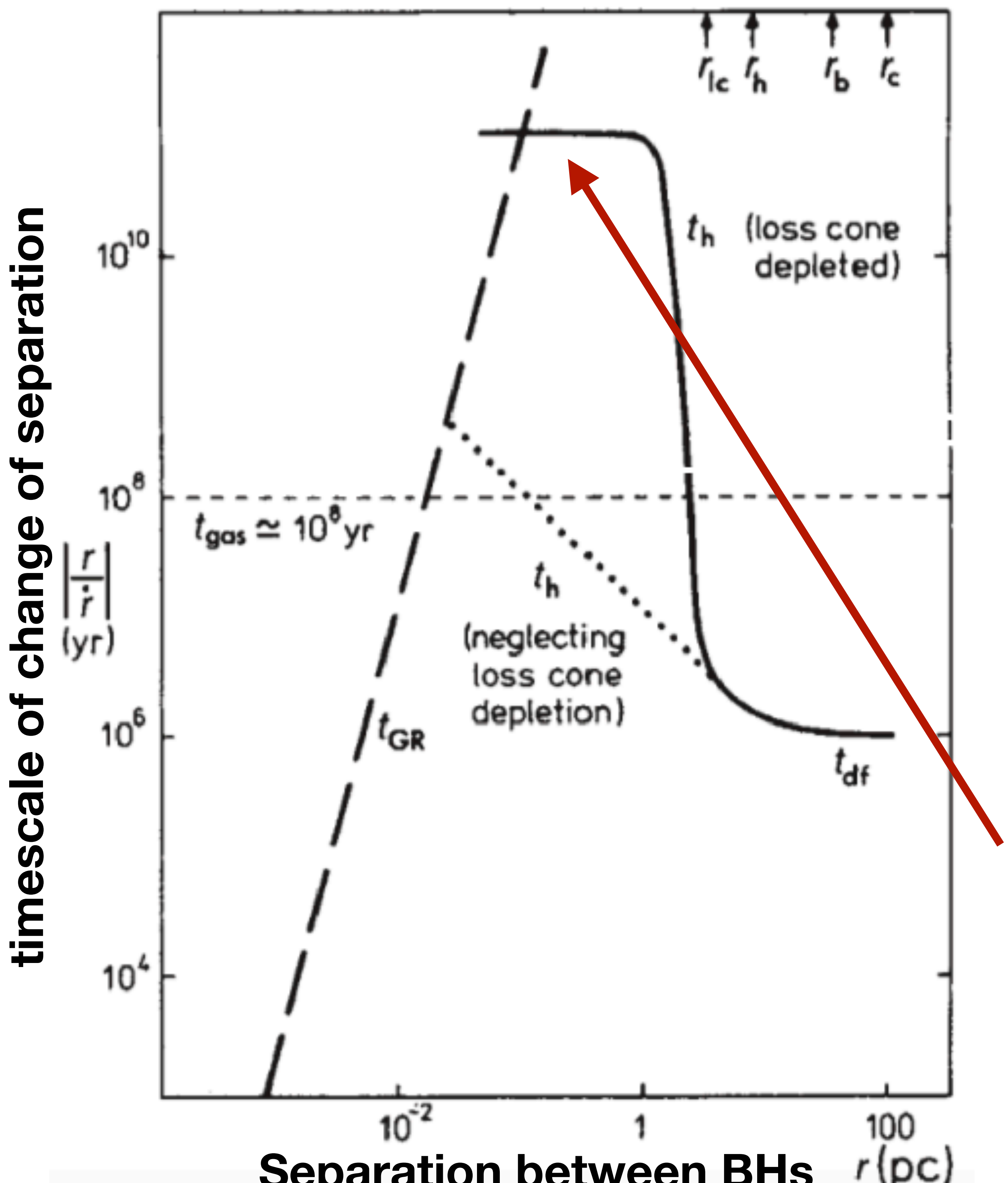


1. Dynamical friction shrinks binary
2. Decay only through close encounters
3. "Loss cone" depleted

Loss cone: region of phase space in which stars have close encounters with the binary black hole

Begelman, Blandford & Rees (1980)

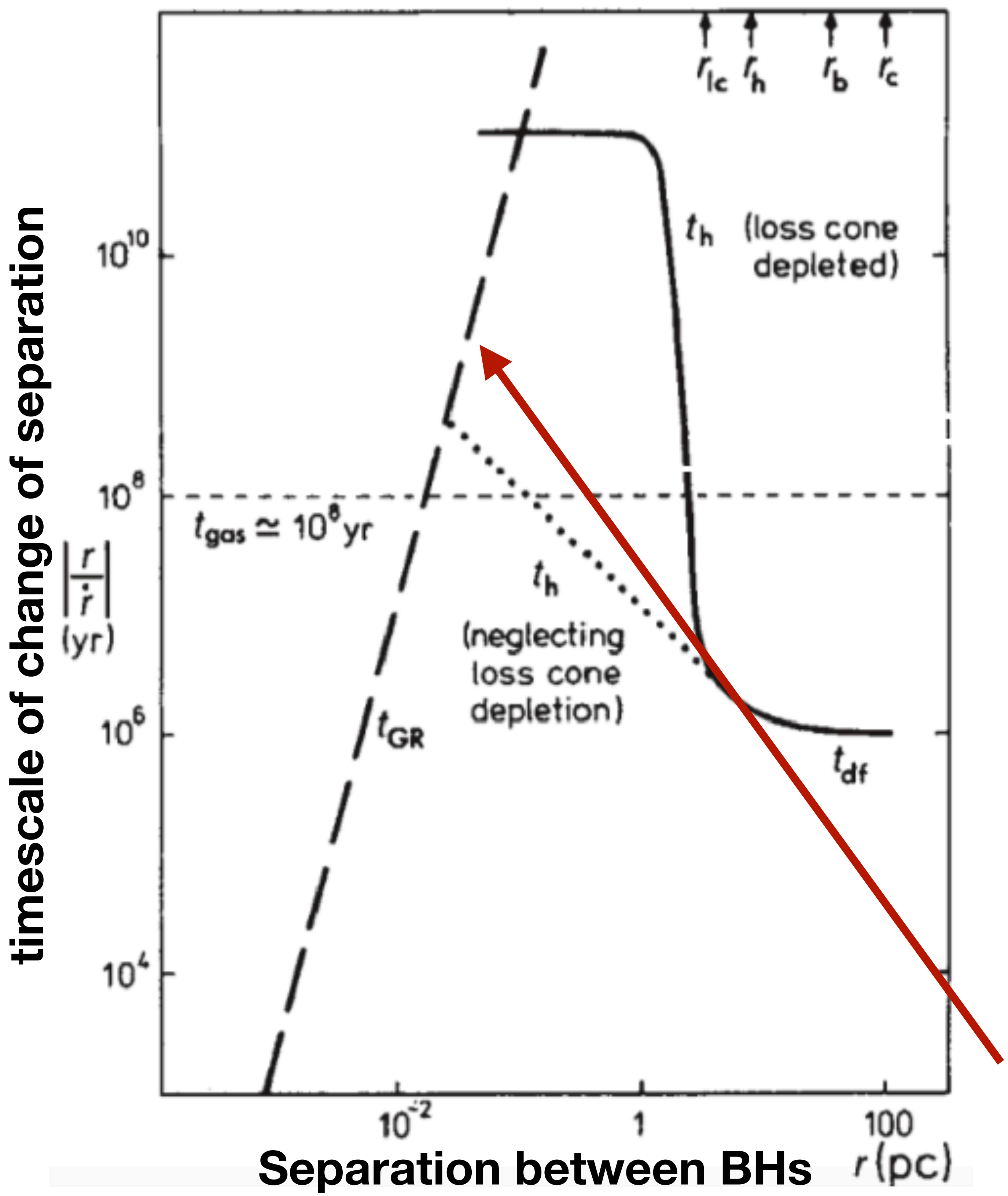
The final parsec problem



1. Dynamical friction shrinks binary
2. Decay only through close encounters
3. “Loss cone” depleted
4. Bottleneck: slow refilling of loss cone

Begelman, Blandford & Rees (1980)

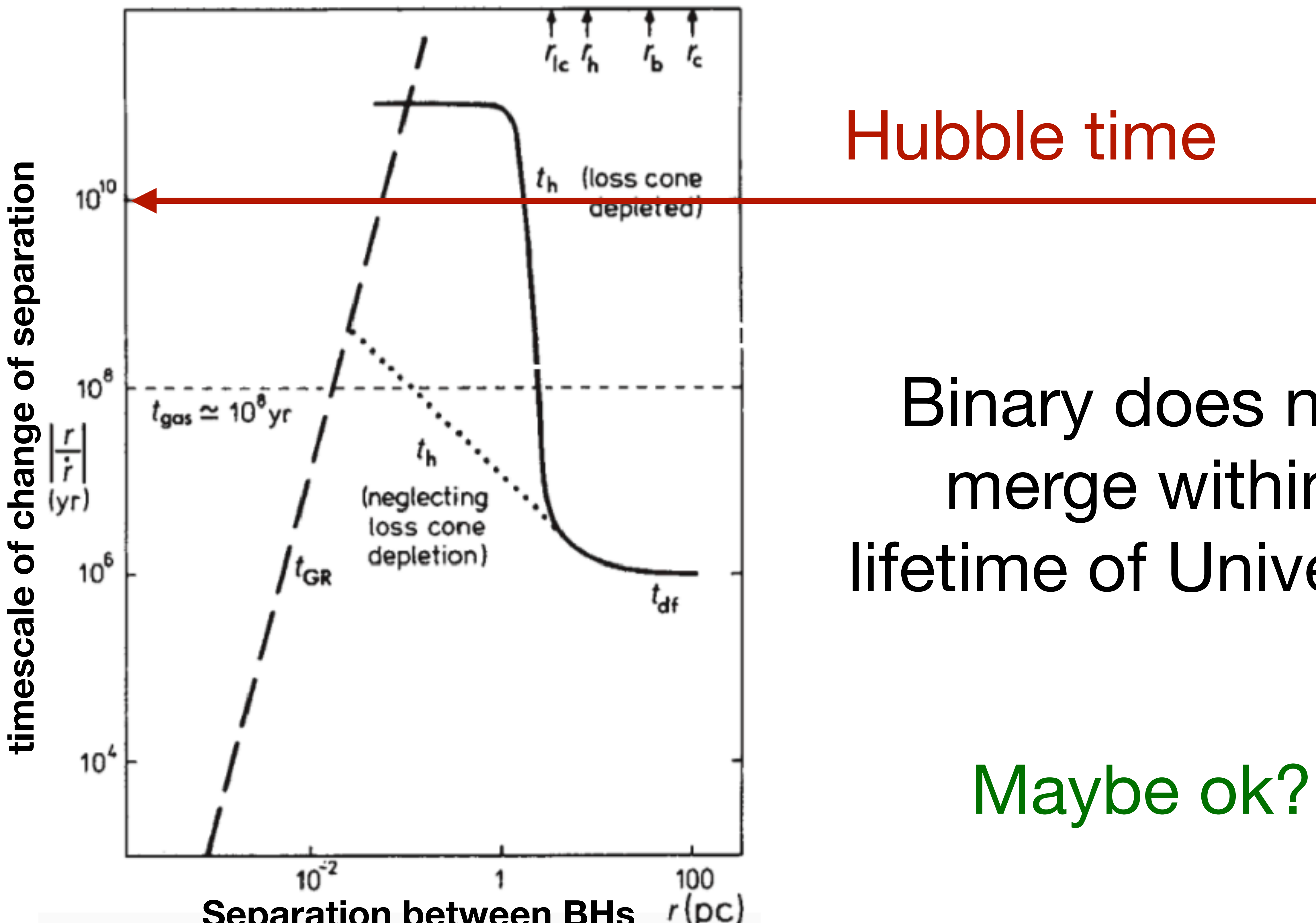
The final parsec problem



1. Dynamical friction shrinks binary
2. Decay only through close encounters
3. "Loss cone" depleted
4. Bottleneck: slow refilling of loss cone
5. GW radiation

Begelman, Blandford & Rees (1980)

The final parsec problem



Hubble time

Binary does not merge within lifetime of Universe

Maybe ok?

Begelman, Blandford & Rees (1980)

Gravitational wave astronomy

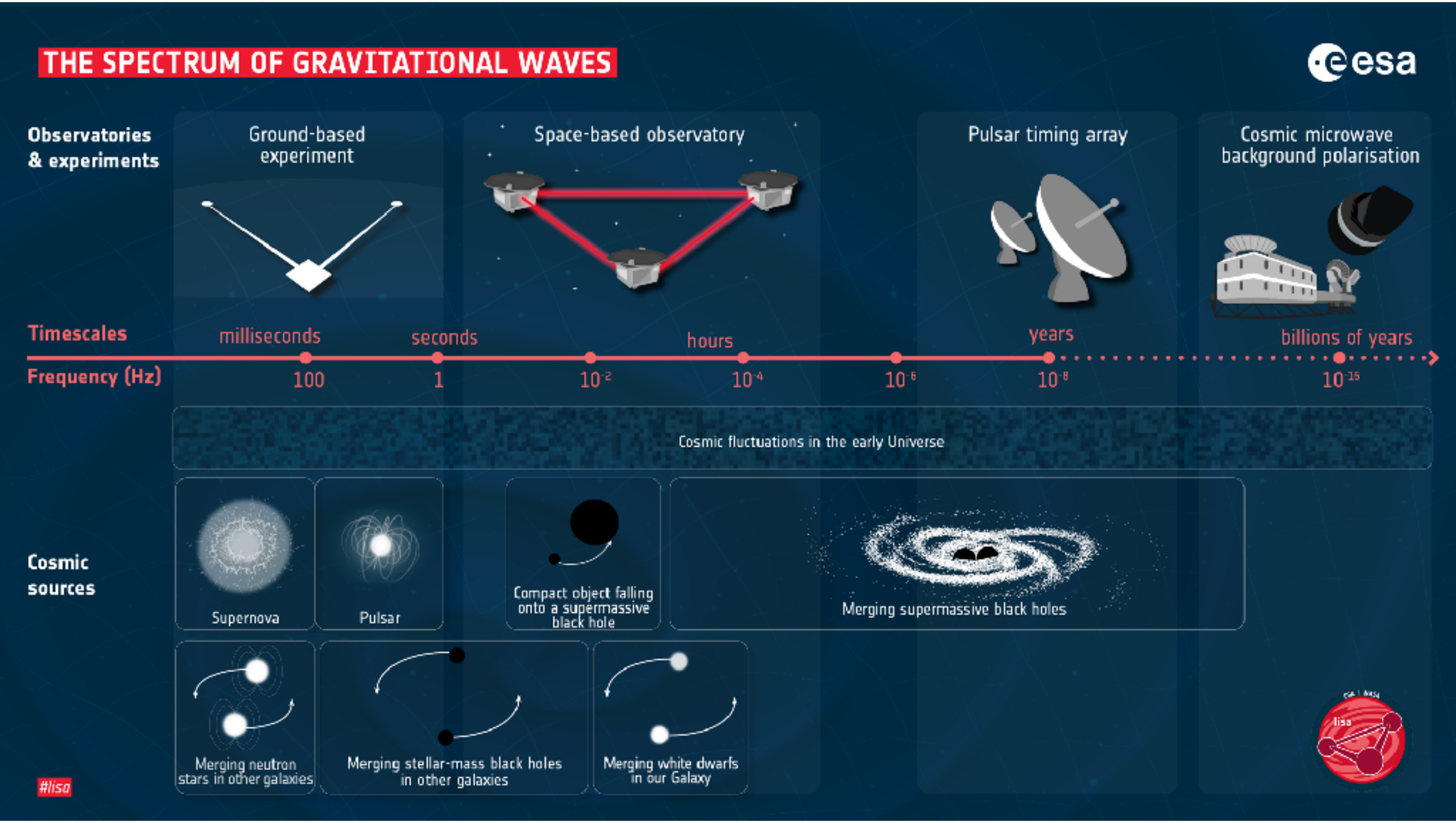
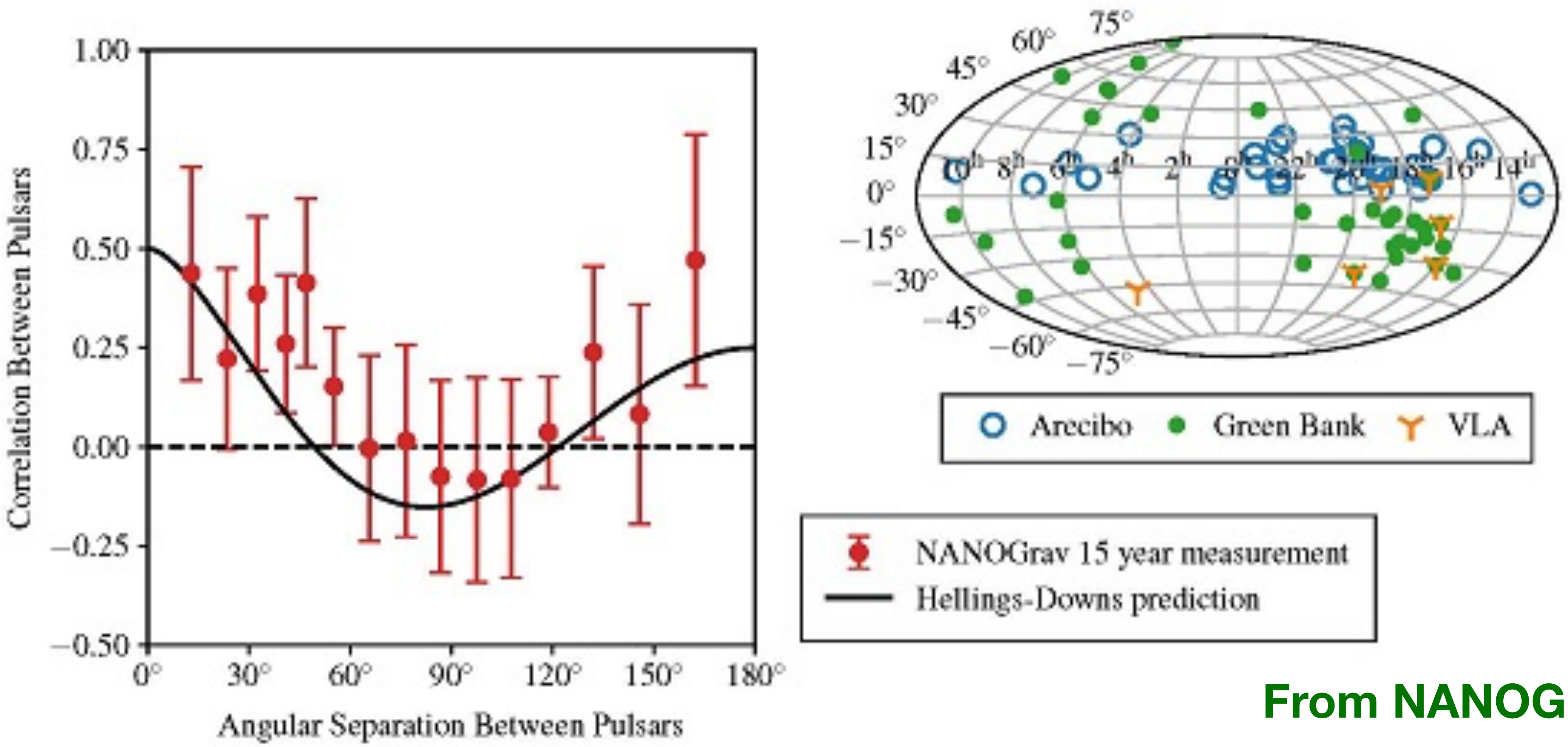


Image credit: ESA

June 2023: Evidence for GW signal



From NANOGrav

Agreement between 4 main PTA collaborations:

- NANOGrav
- Parkes Pulsar Timing Array
- European + Indian Pulsar Timing Array
- Chinese Pulsar Timing Array

Astrophysical explanation: SMBH mergers

Supermassive black holes DO merge

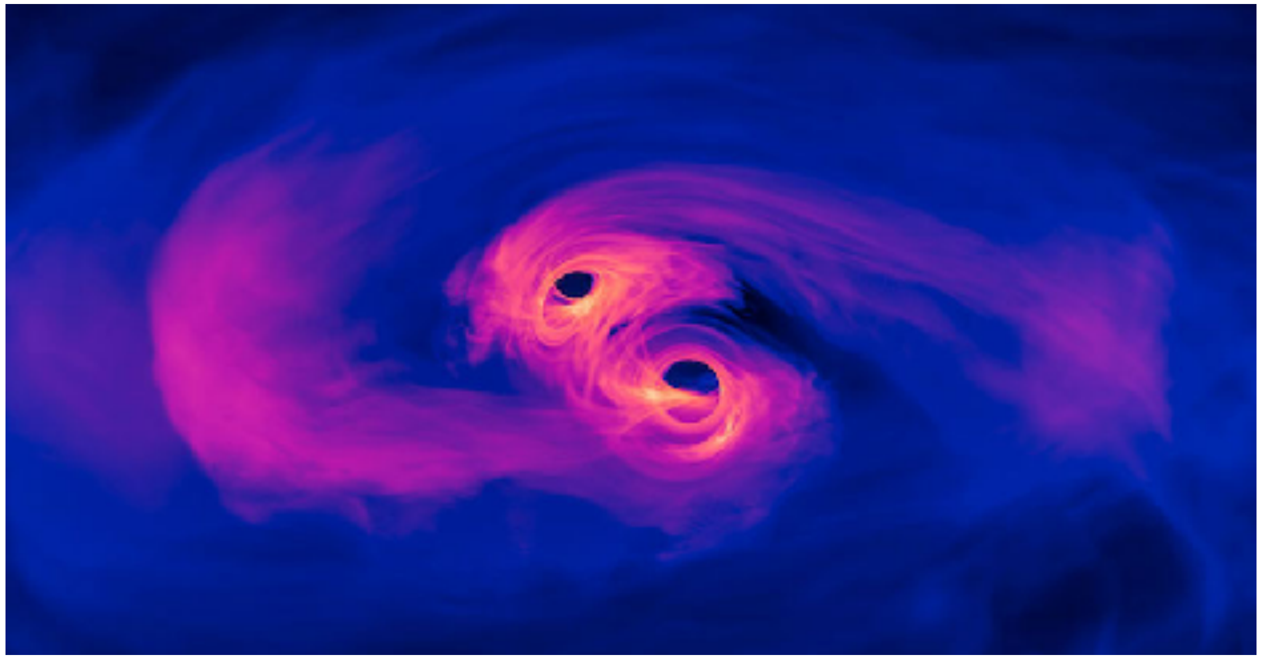


Image credit: NASA

Final parsec problem must be addressed

- Axisymmetry of galactic halo
- Accretion disk
- Multiple black holes
- **… what else is in the BHs environment?**

Dark matter spikes around SMBH

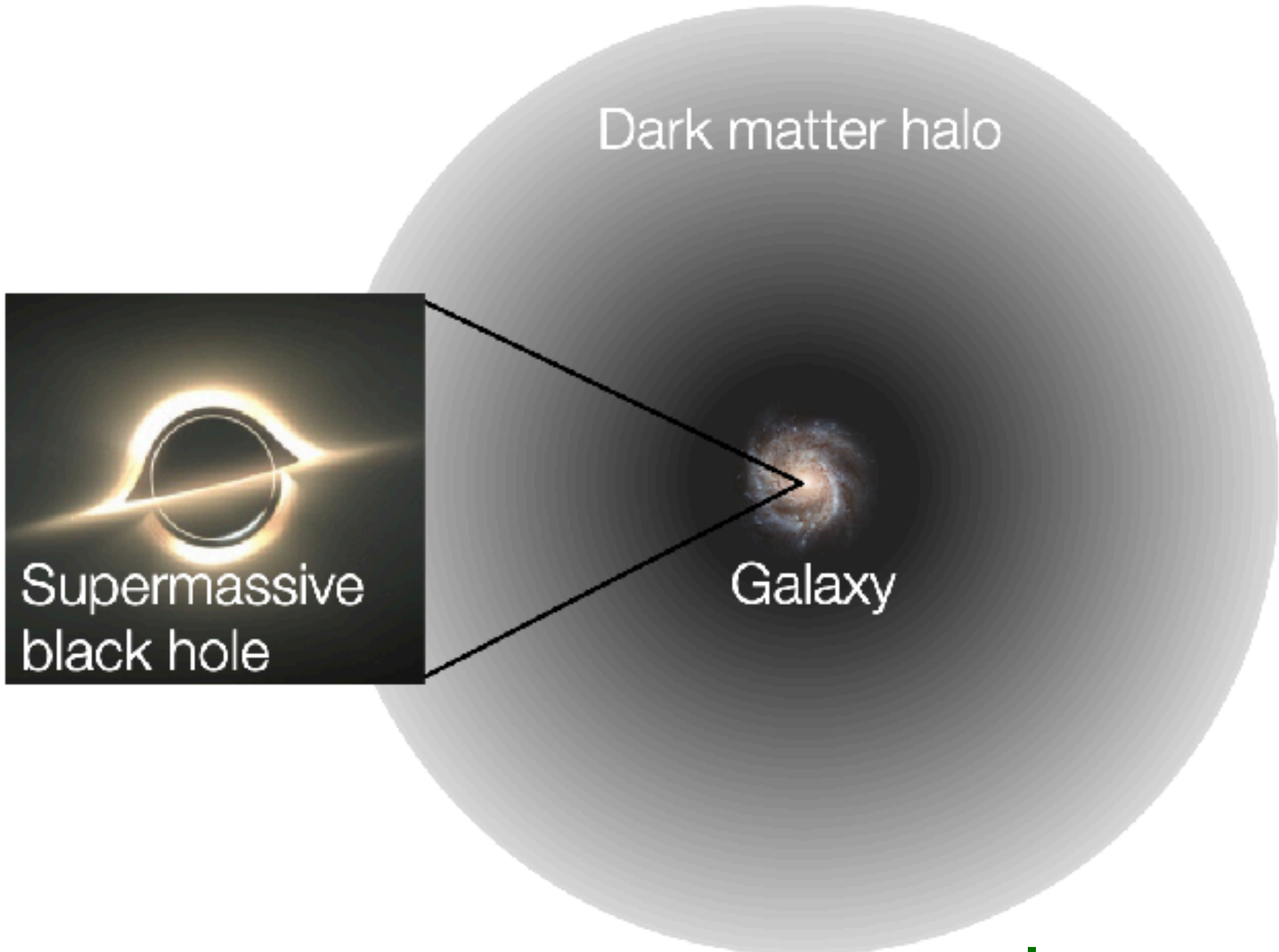
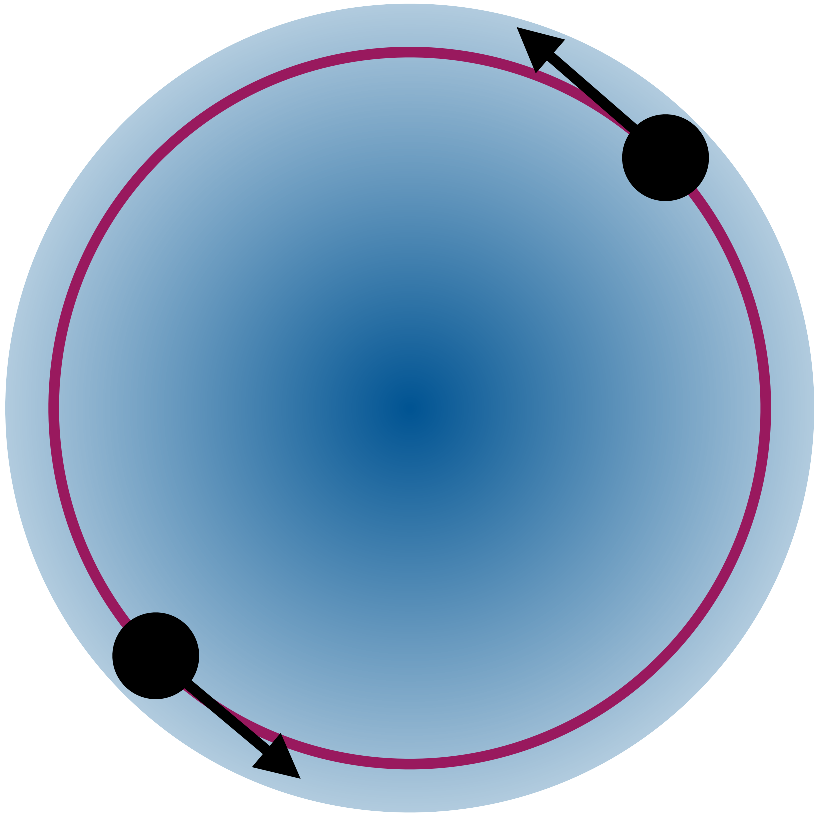


Image credit: M. Powell

DM density enhanced by gravity of SMBH

SMBH orbit decay & Cold Dark Matter

DM-BH dynamical friction shrinks binary



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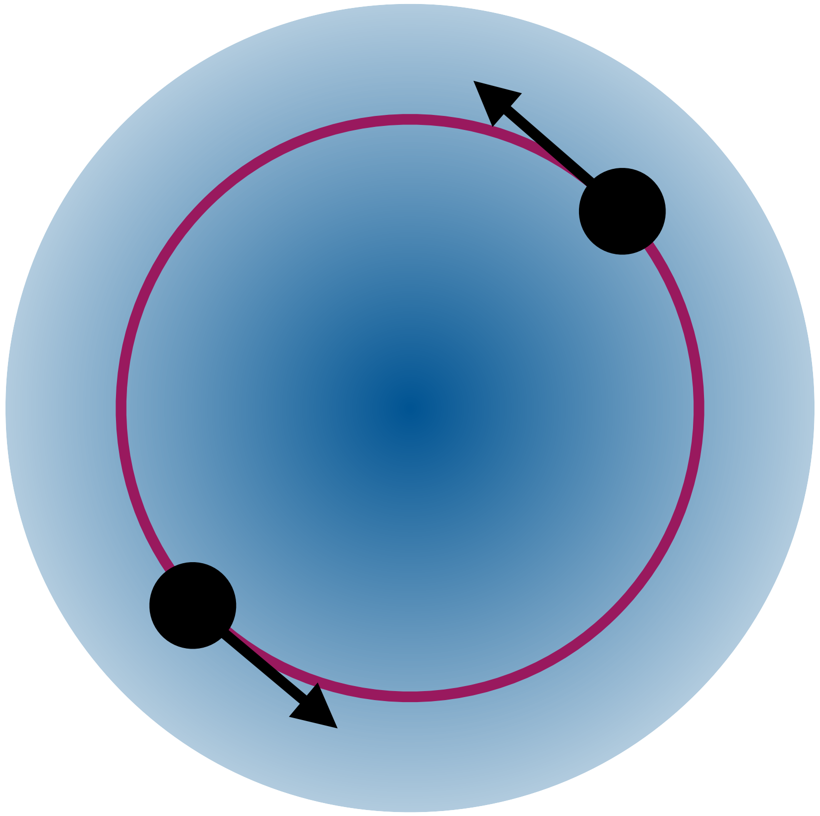

SMBH orbit decay & Cold Dark Matter

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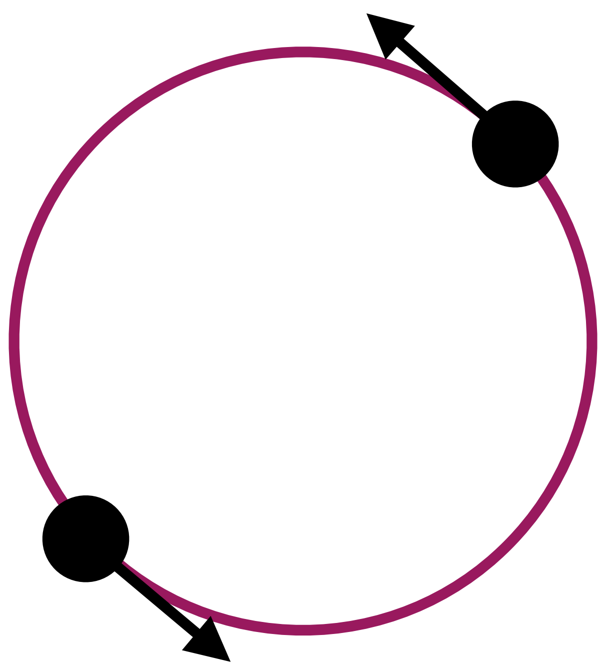
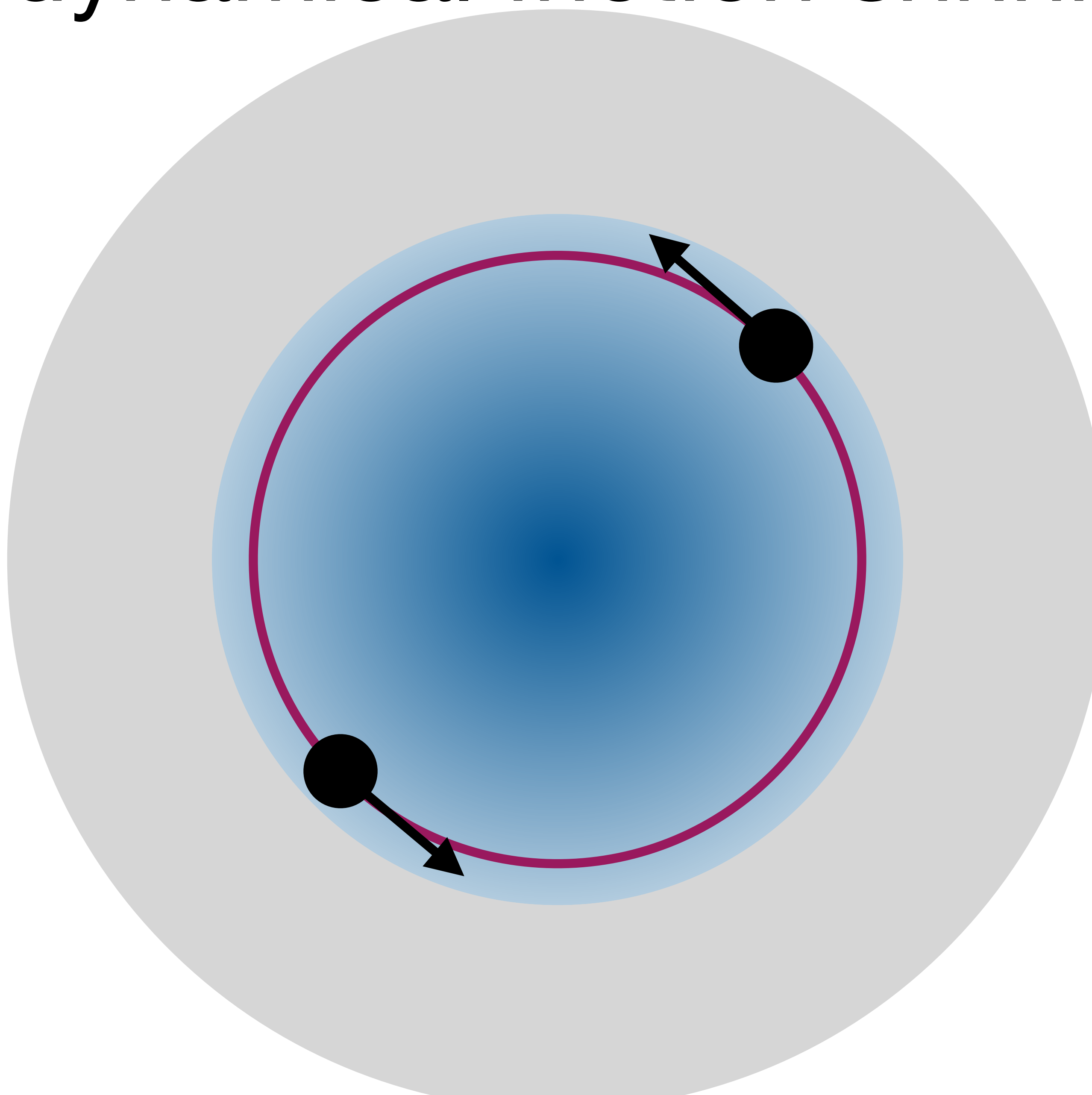


Injected heat evaporates DM spike: binary stalls

Self-interacting Dark Matter

DM-BH dynamical friction shrinks binary



Self-interactions prevent dispersion: BHs coalesce

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Self-interacting Dark Matter

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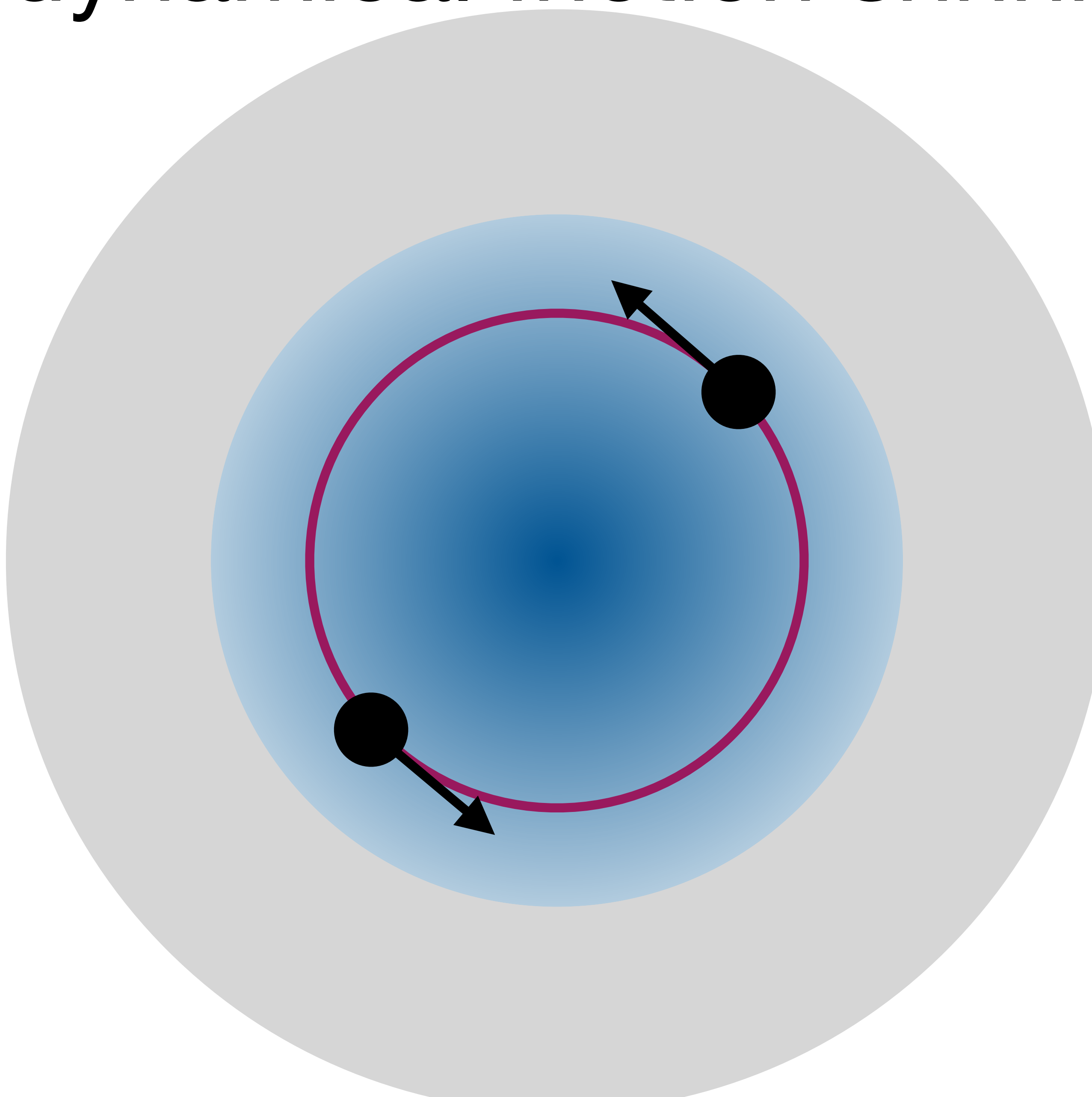

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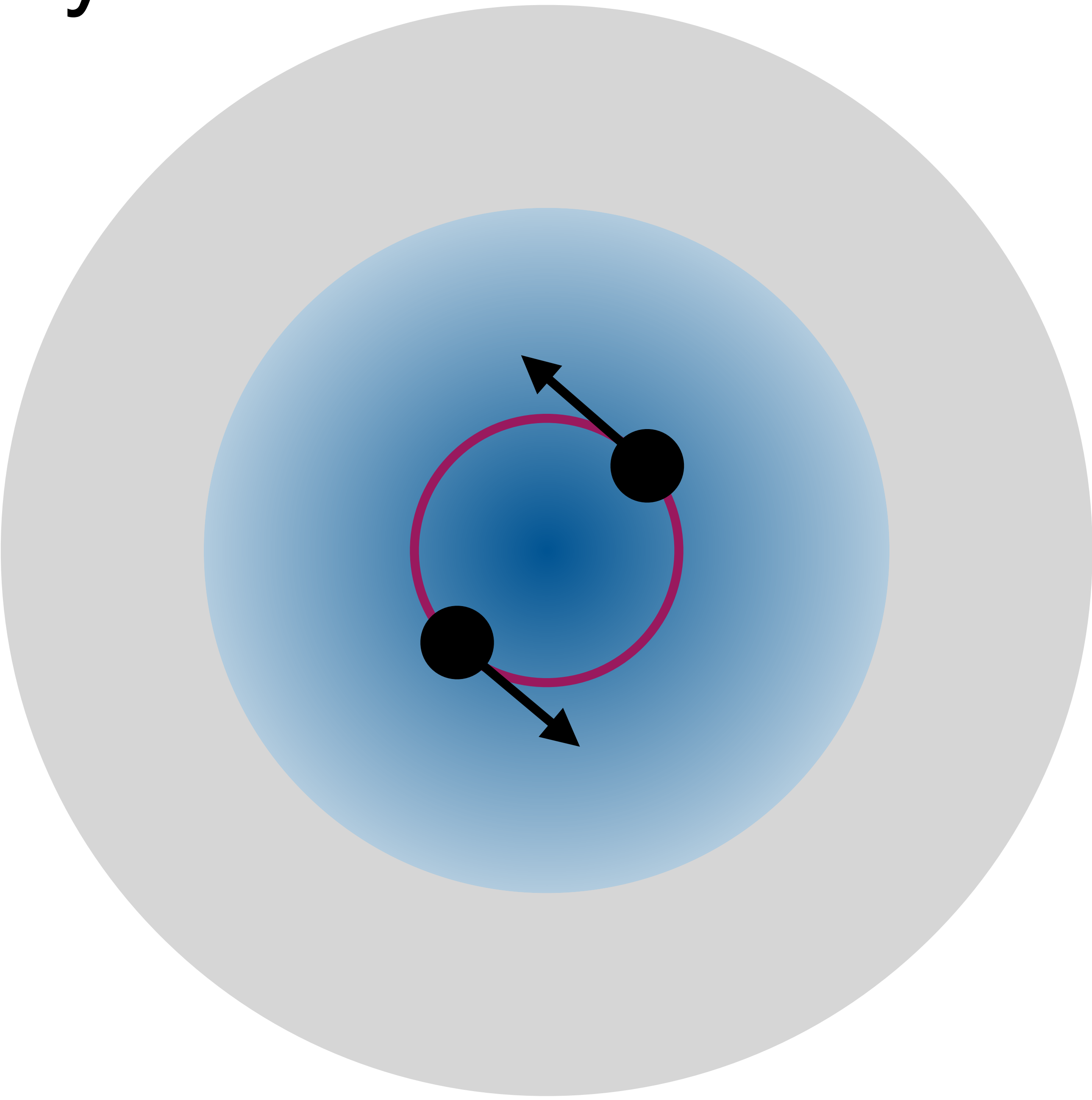

Self-interactions prevent dispersion: BHs coalesce

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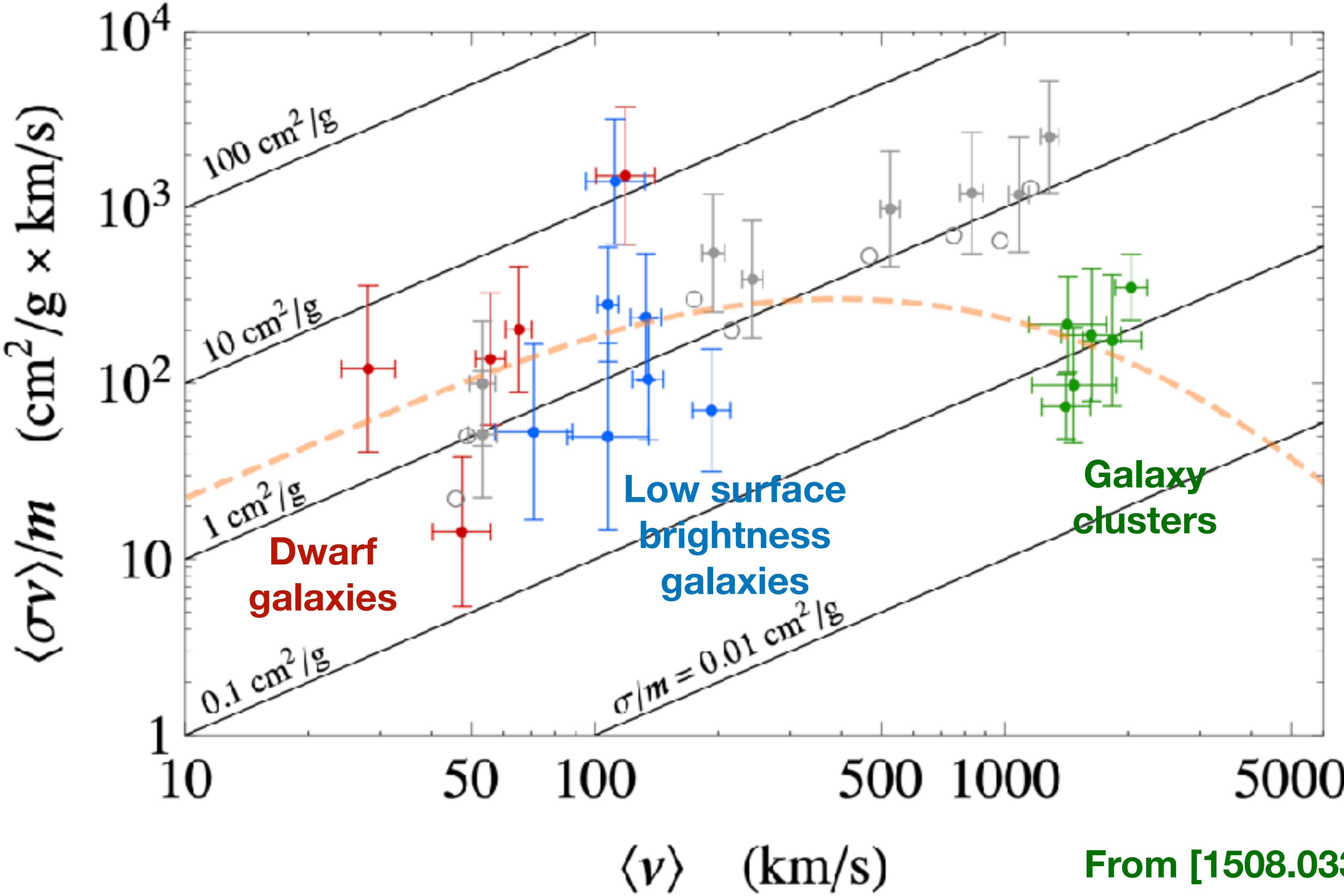
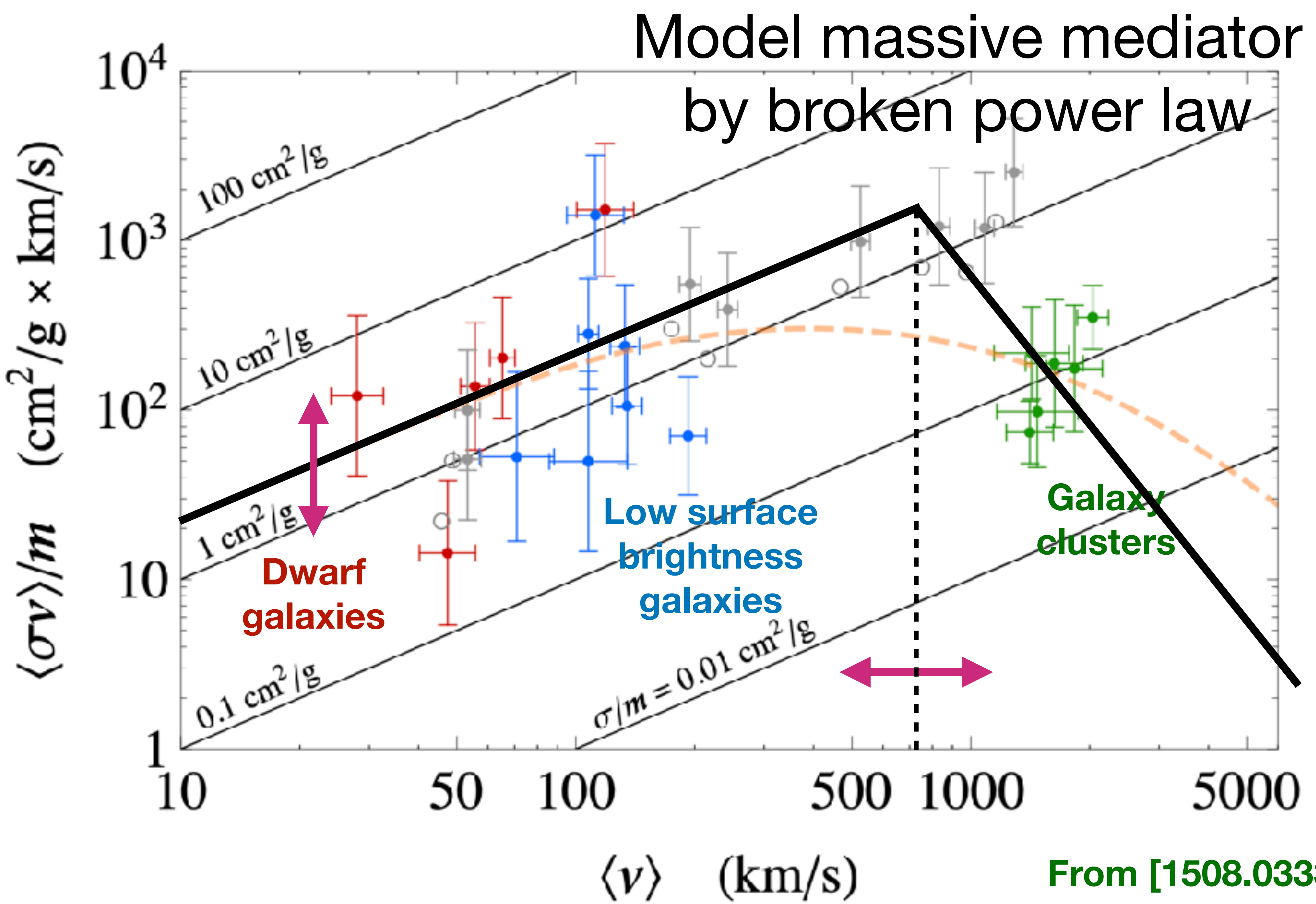
Velocity-dependent self interactions



From [1508.03339]

Velocity-dependent self interactions



From [1508.03339]

OUTLINE

1. Reconstruct the spike profile

2. Calculate BH merger dynamics

3. Predict the GW spectrum

OUTLINE

1. **Reconstruct the spike profile**

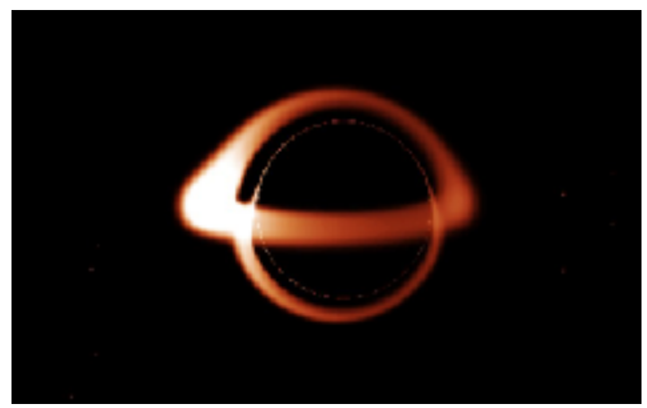
2. Calculate BH merger dynamics

3. Predict the GW spectrum

Observational & semi-analytical correlations

NFW parameters

DM halo mass

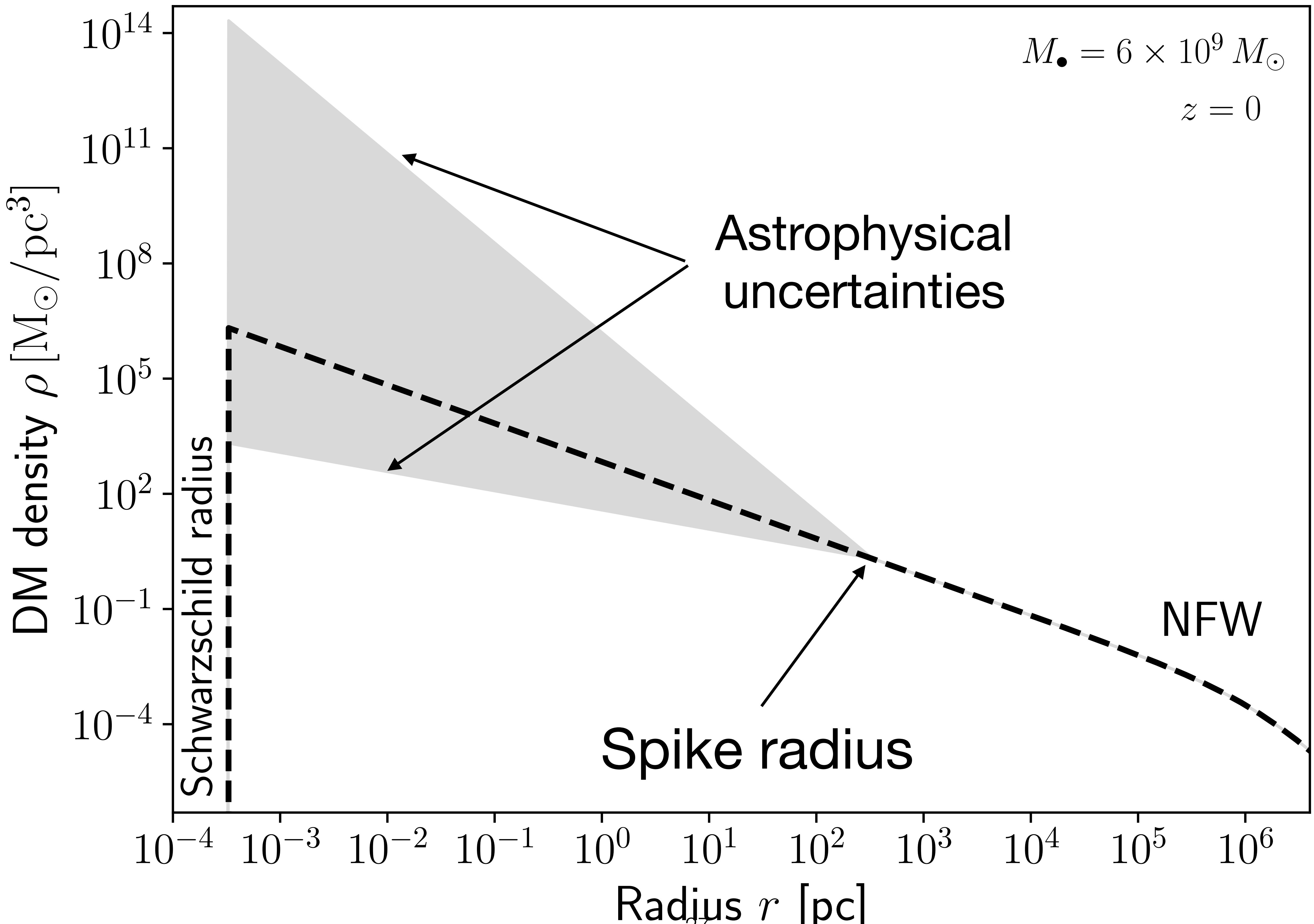


Black hole mass

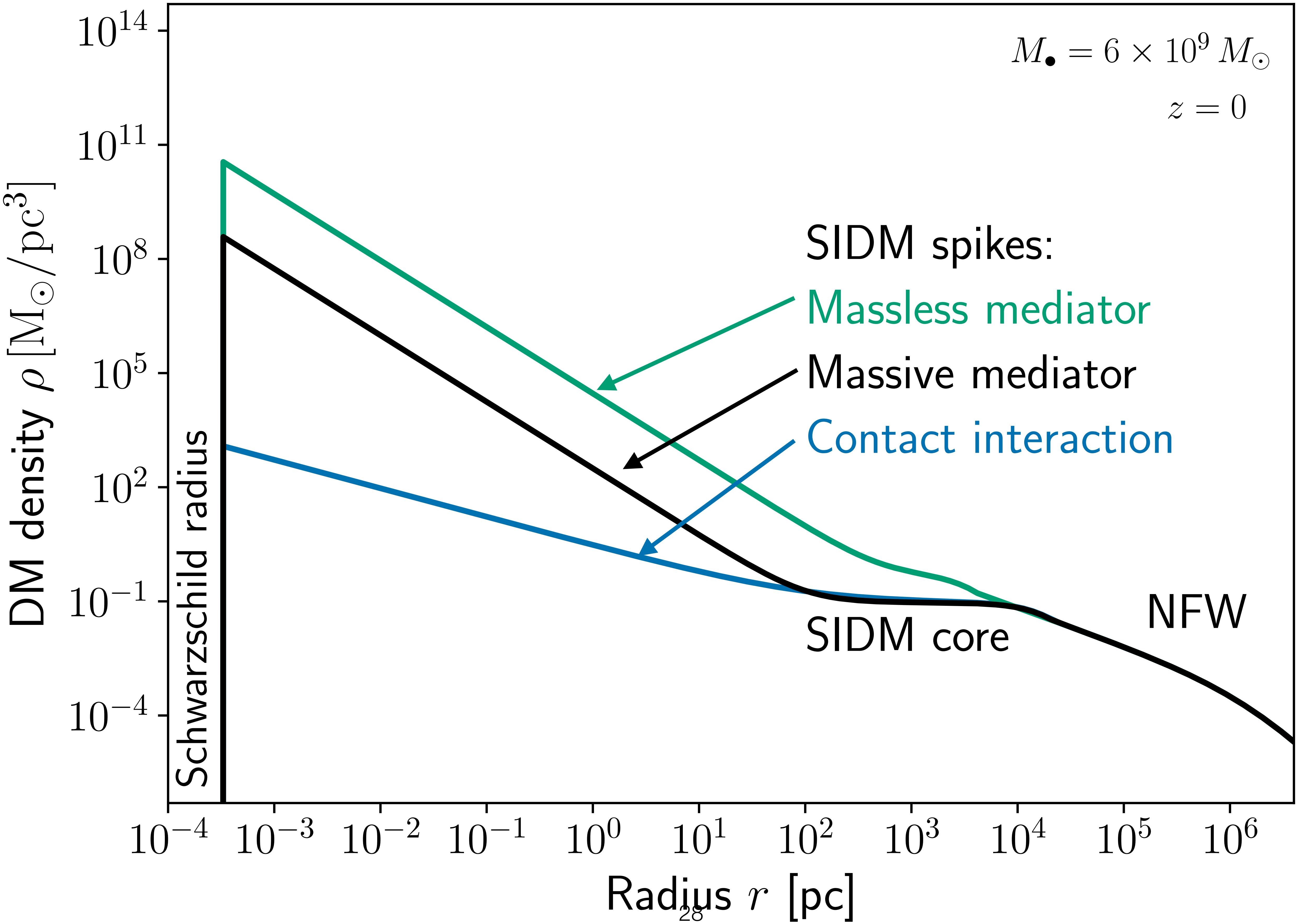
Stellar bulge mass

Stellar mass

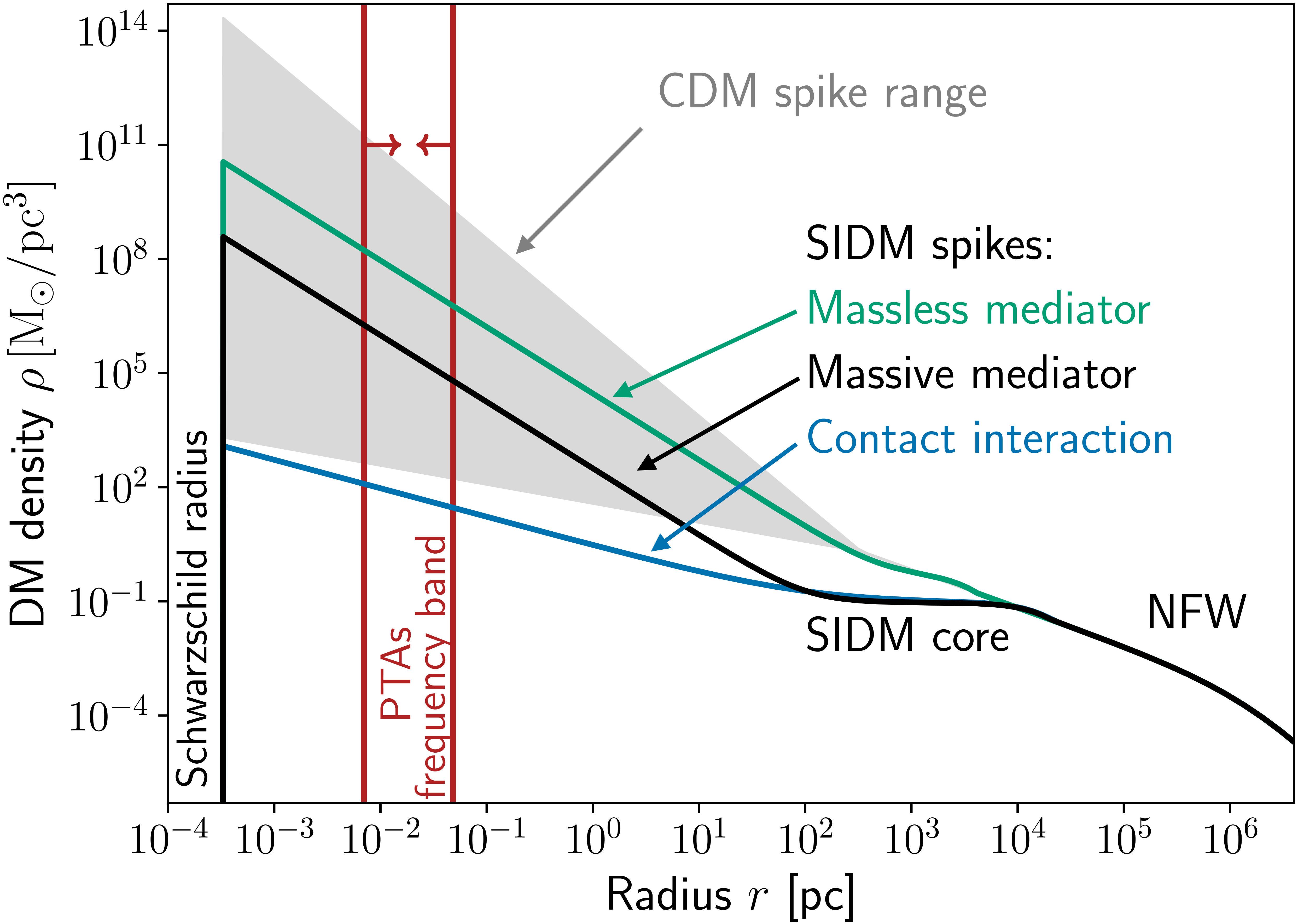
Cold DM spike



Self Interacting DM spike



CDM & SIDM spikes



OUTLINE

1. Reconstruct the spike profile

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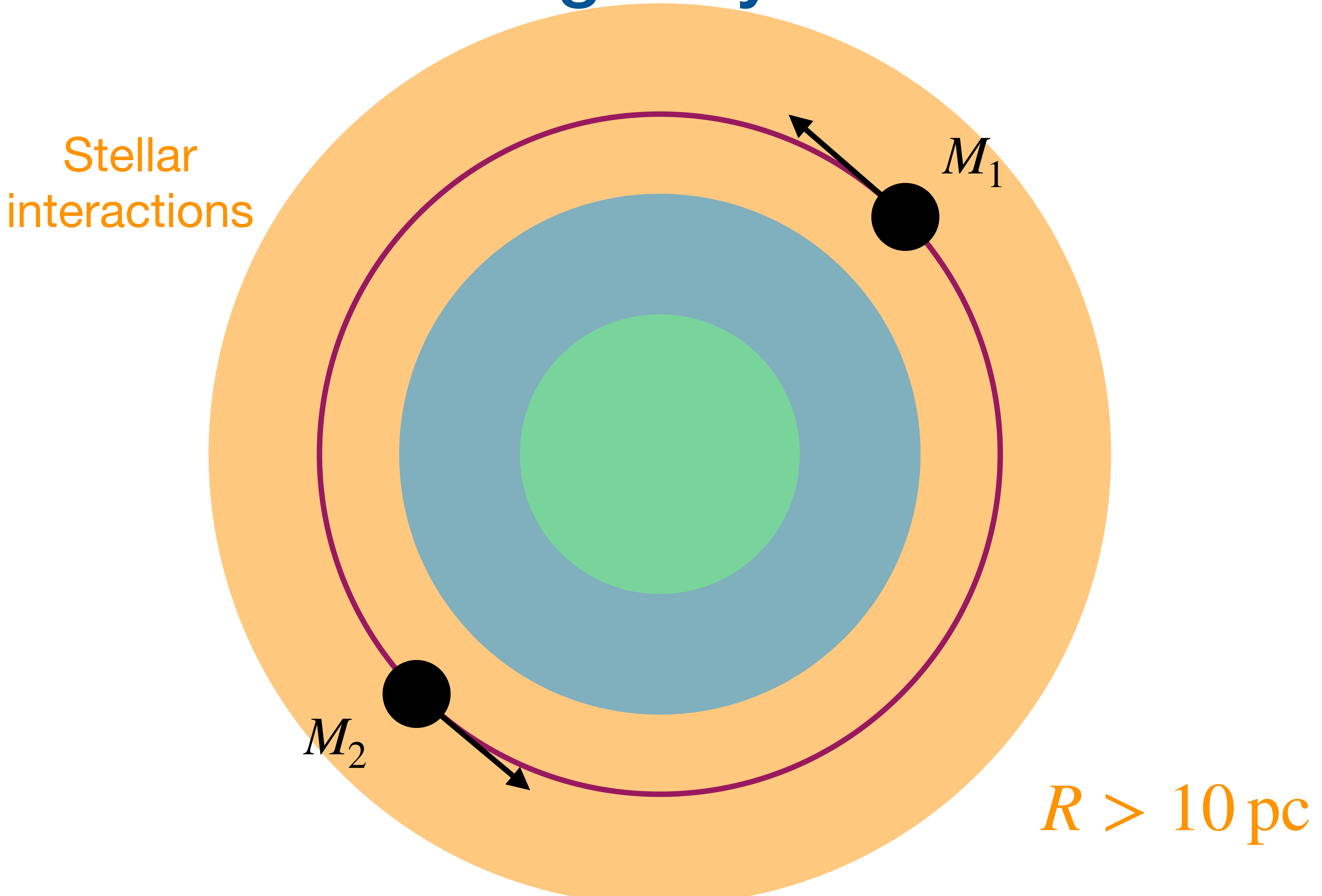
3. Predict the GW spectrum

BH merger dynamics



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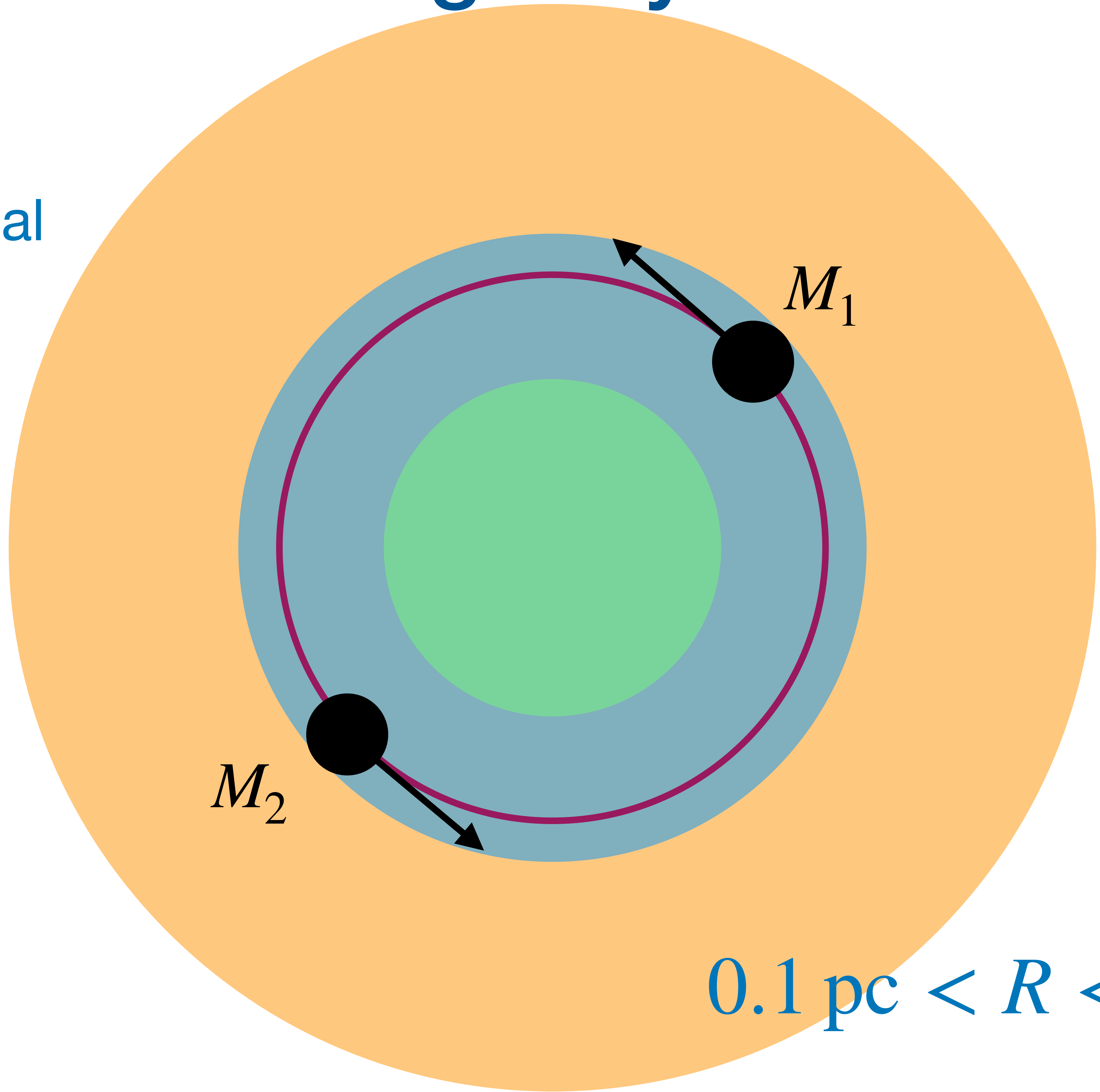
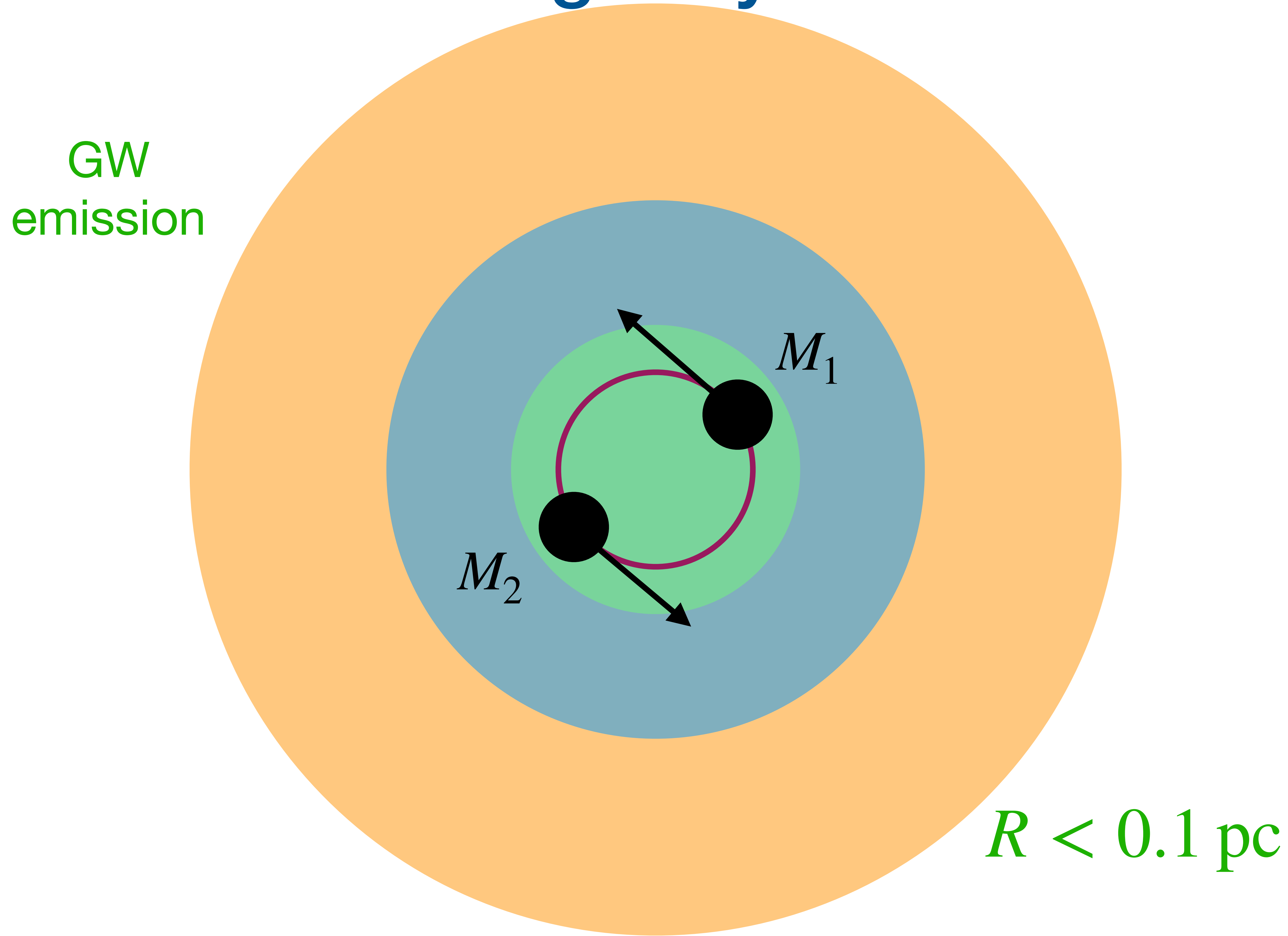
BH merger dynamics

DM
dynamical
friction



$0.1\,\mathrm{pc} < R < 10\,\mathrm{pc}$

BH merger dynamics



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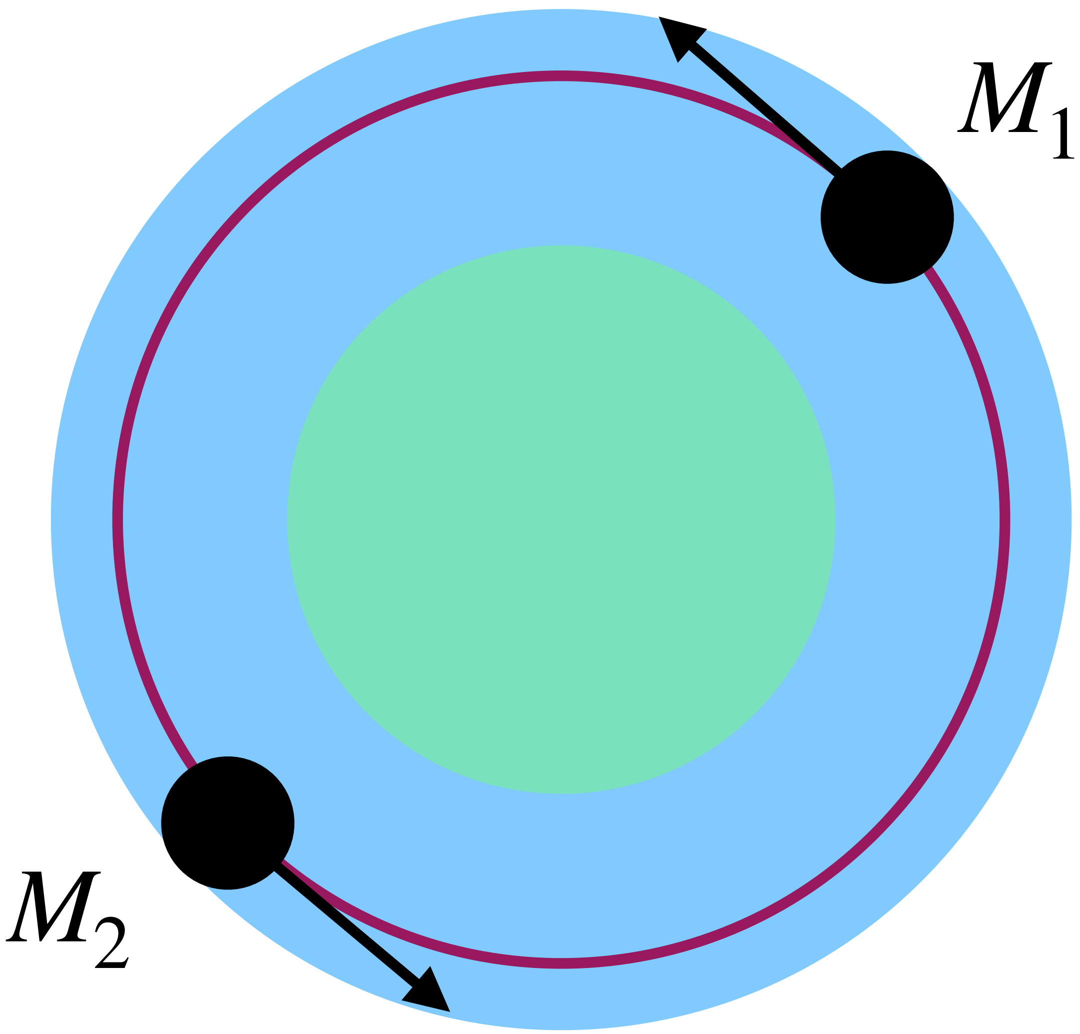
Dynamical friction timescale

DM dynamical friction + GW emission



Binary *hardens* (shrinks) due to dynamical friction

$$t_{\rm DF} = \Delta t\,(10\,{\rm pc} \to 0.1\,{\rm pc})$$
$$\propto 1/\rho_{\rm spike}$$

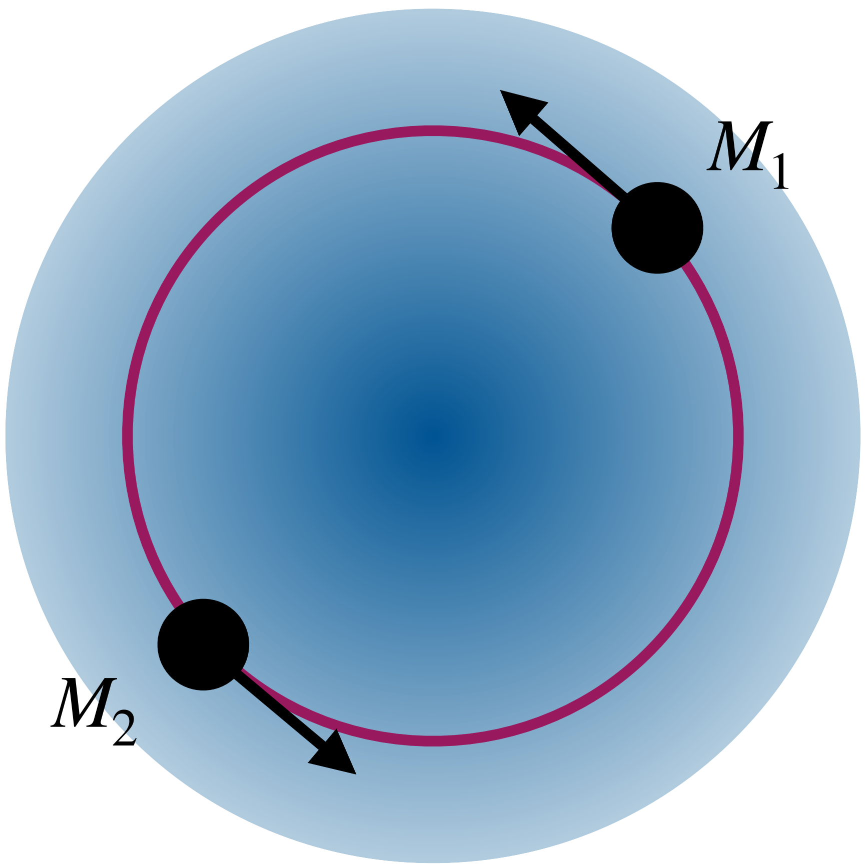
Favours dense spikes

Demand $t_{\rm DF} < 1\,{\rm Gyr}$ **—> Upper limit on** σ_0/m

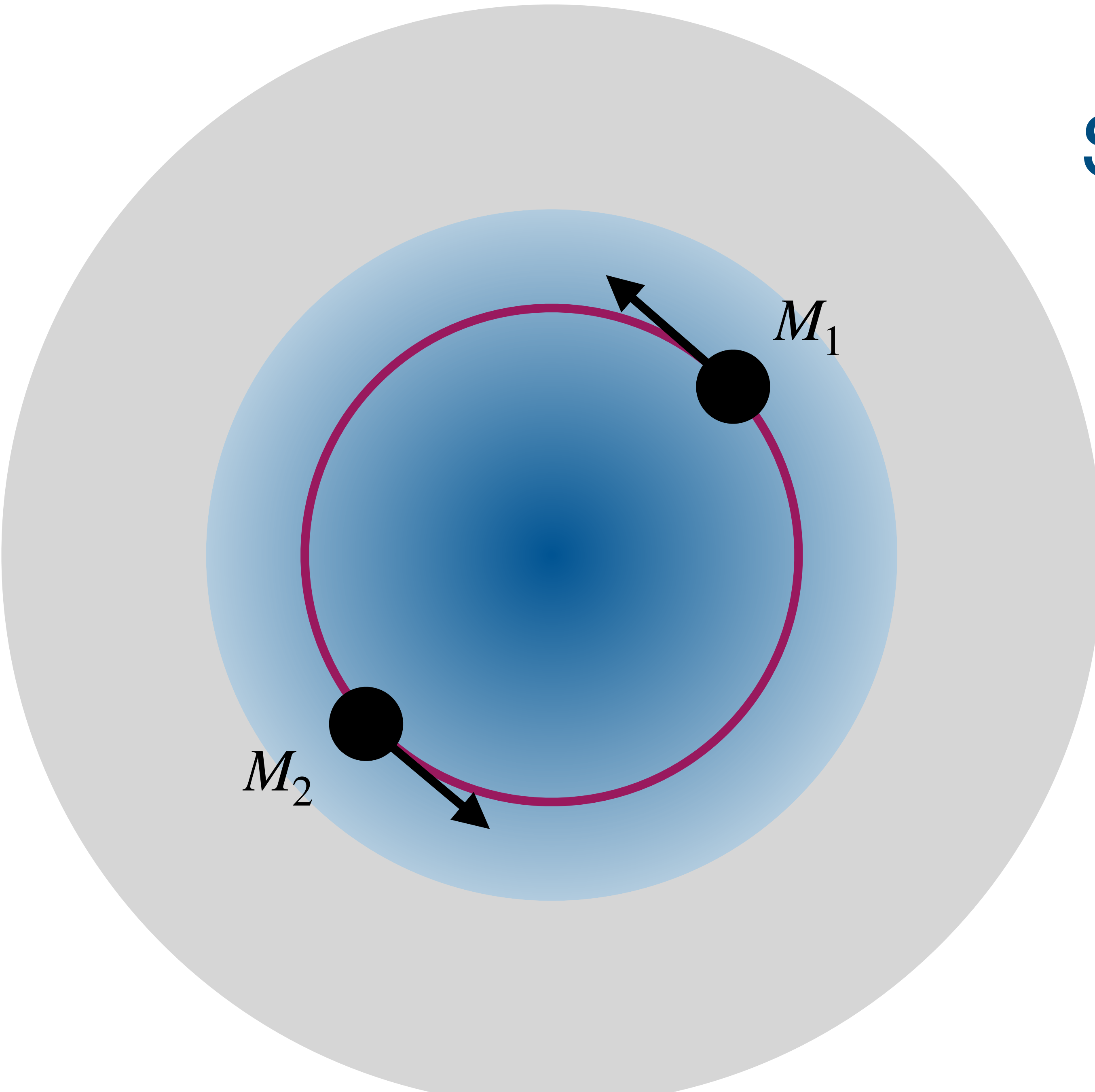
Back-reaction destroys CDM spike

CDM: $\Delta E_{\rm orbit} \gg U_{\rm spike}$

Spike evaporates and only replenished gravitationally



Self interactions replenish SIDM spike



CDM: $\Delta E_{\rm orbit} \gg U_{\rm spike}$

Spike evaporates and only replenished gravitationally

SIDM:

Whole core is in equilibrium with spike

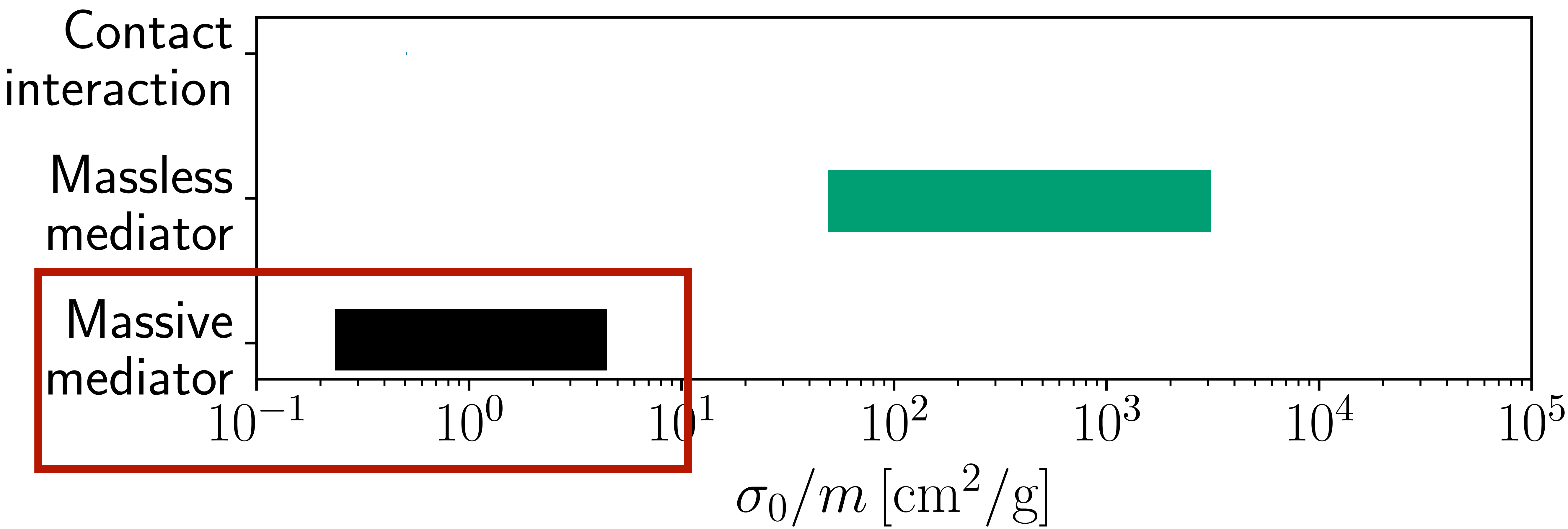
$$U_{\rm core} \gg U_{\rm spike}$$

The core acts as a particle & energy reservoir

Minimum size of core —> lower limit on σ_0/m

Dark matter self-interaction cross section

- Lower limit: large enough core
- Upper limit: fast enough merger



OUTLINE

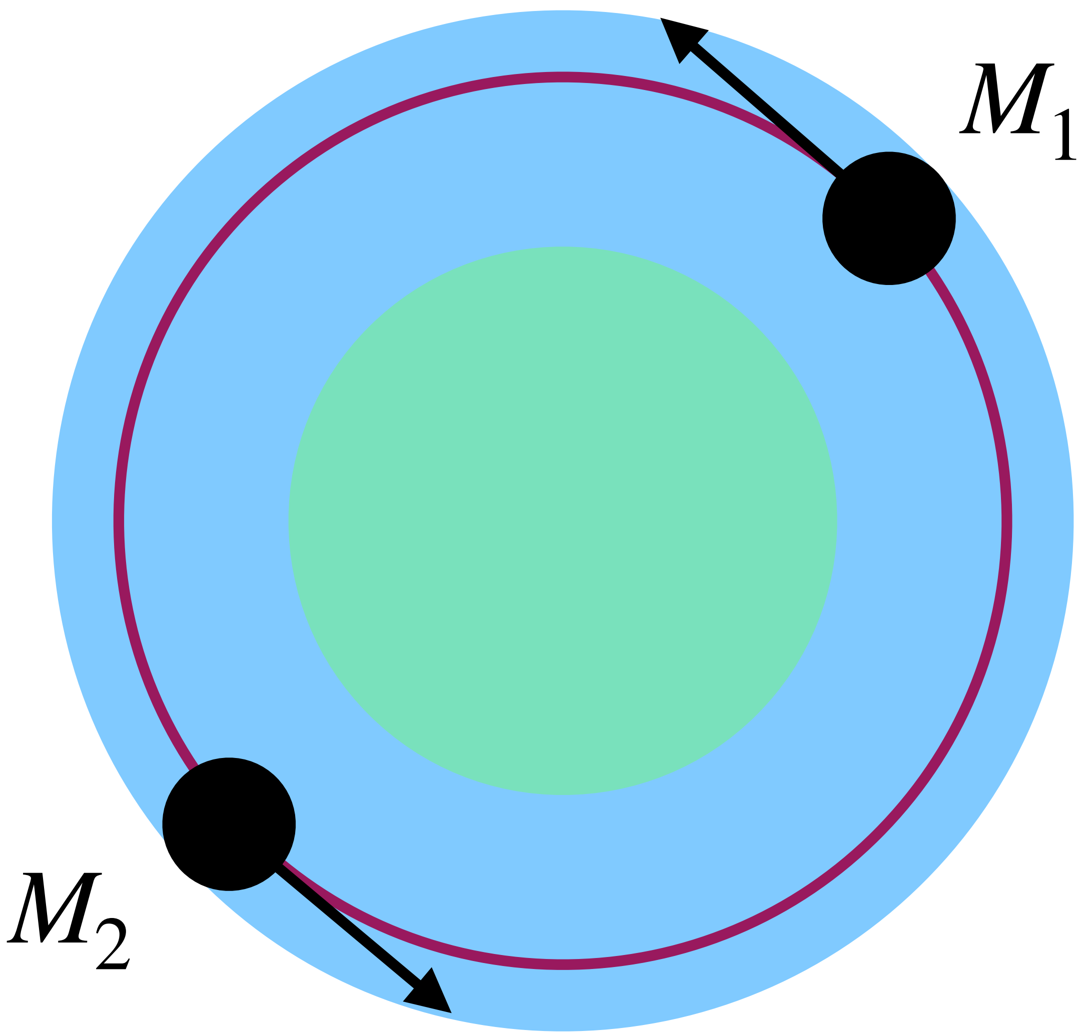
1. Reconstruct the spike profile

2. Calculate BH merger dynamics

3. **Predict the GW spectrum**

Single-merger GW spectrum

GW frequency is twice the orbital frequency



$$f \propto R^{-3/2}$$

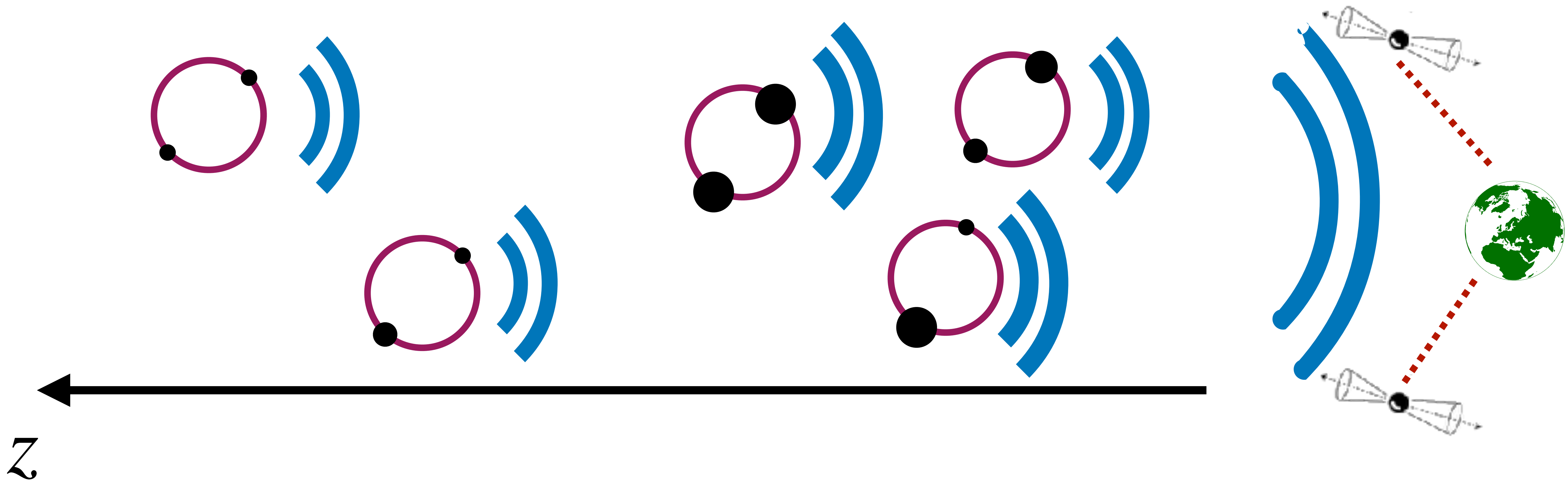
GW energy per unit frequency:

$$\frac{dE_{\rm GW}}{df} \propto \frac{P_{\rm GW}(R)}{P_{\rm GW}(R) + P_{\rm DF}(R)}$$

"Branching ratio" of orbital energy into GW / DF

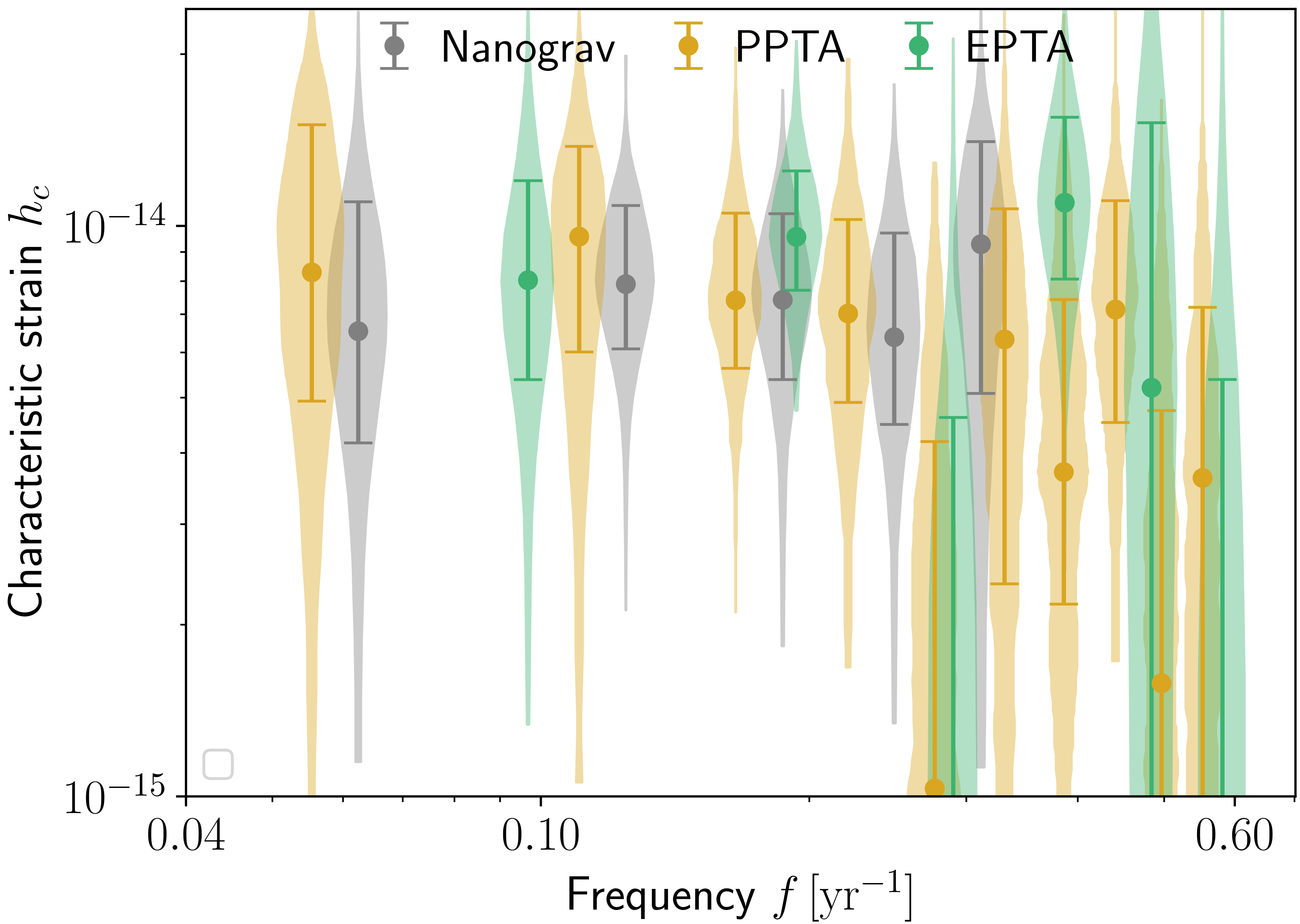
Stochastic gravitational wave spectrum

Add contributions from all SMBH mergers:



Merger rate: observational + semi analytical models

GW spectrum at PTAs



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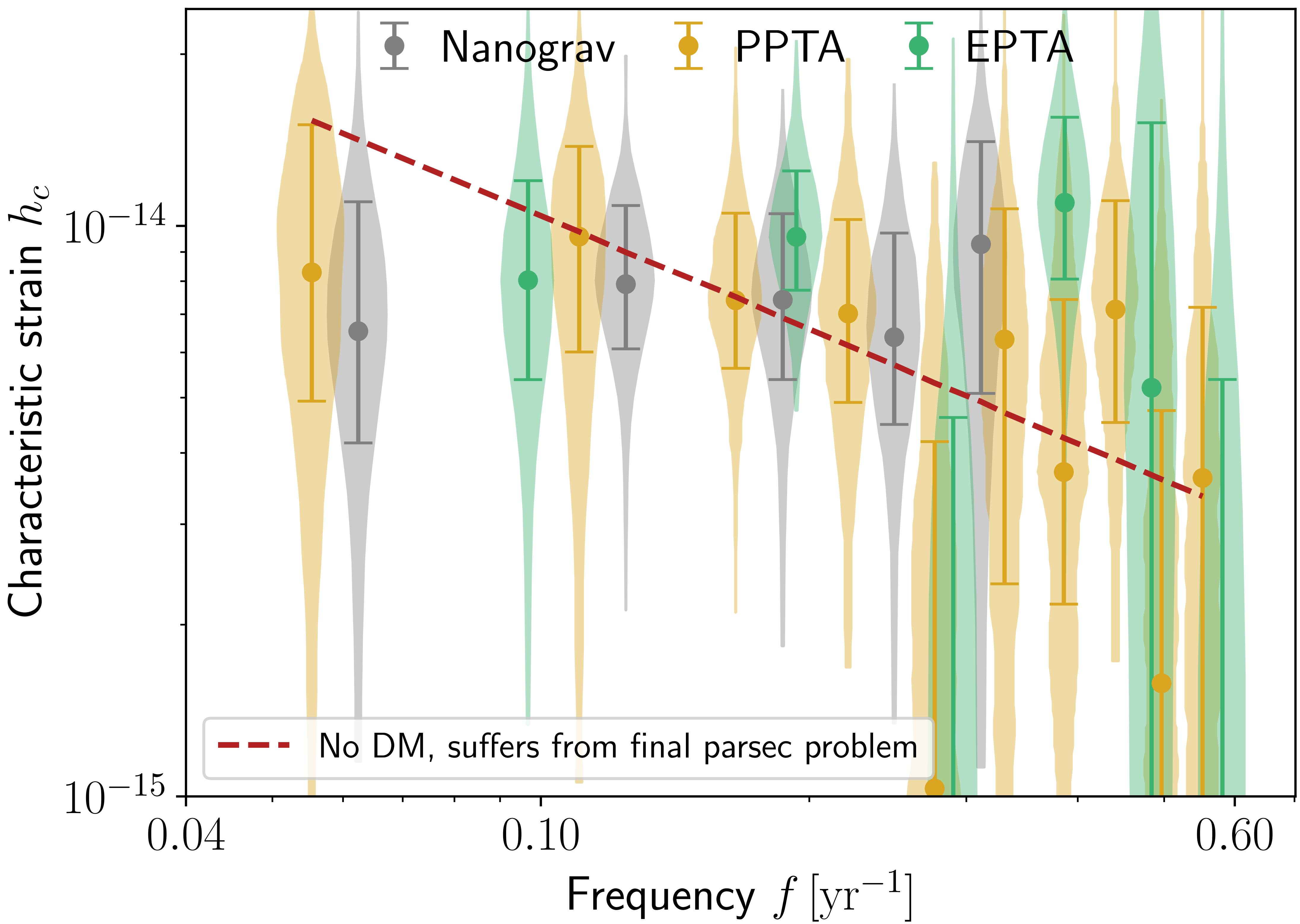
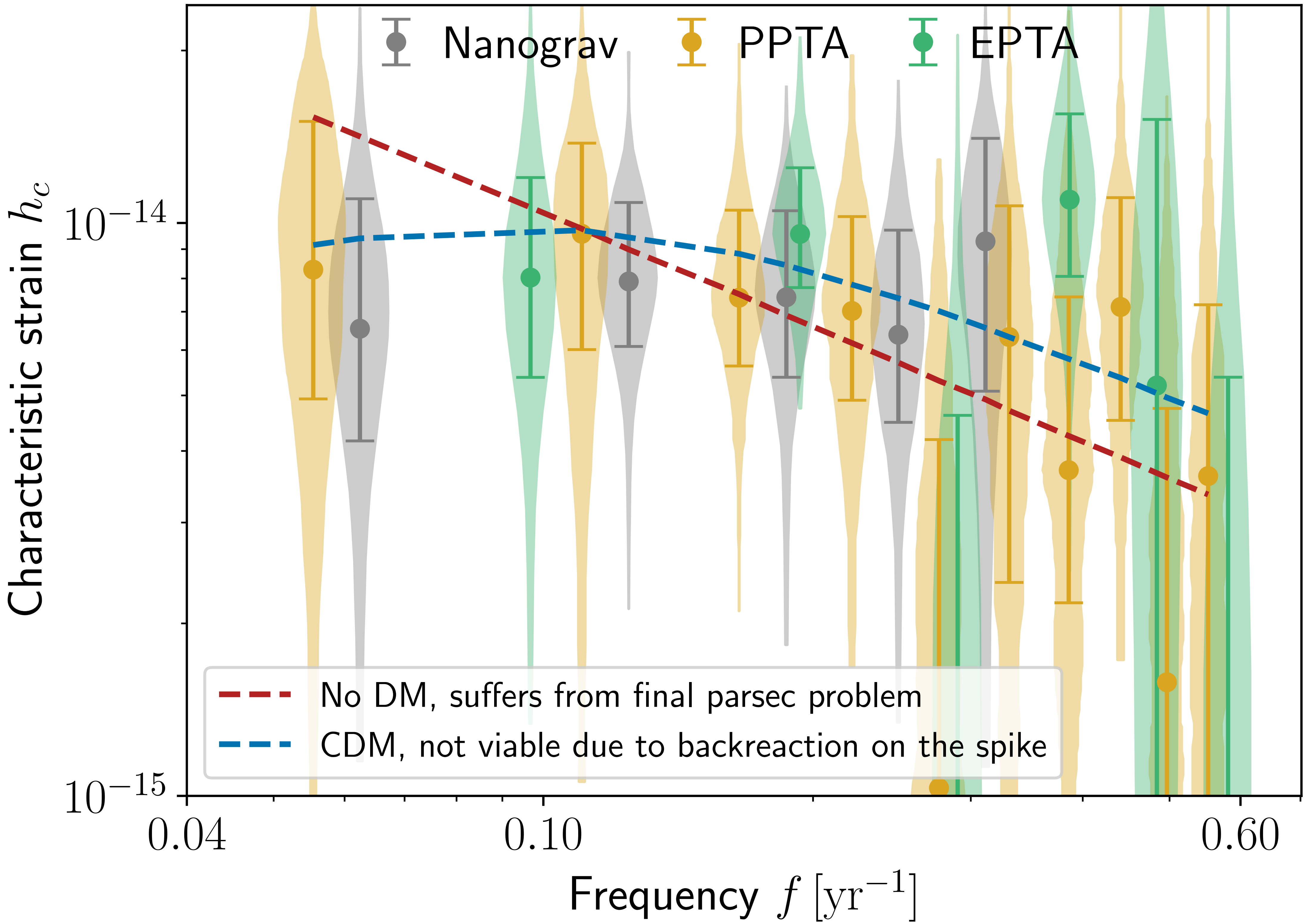
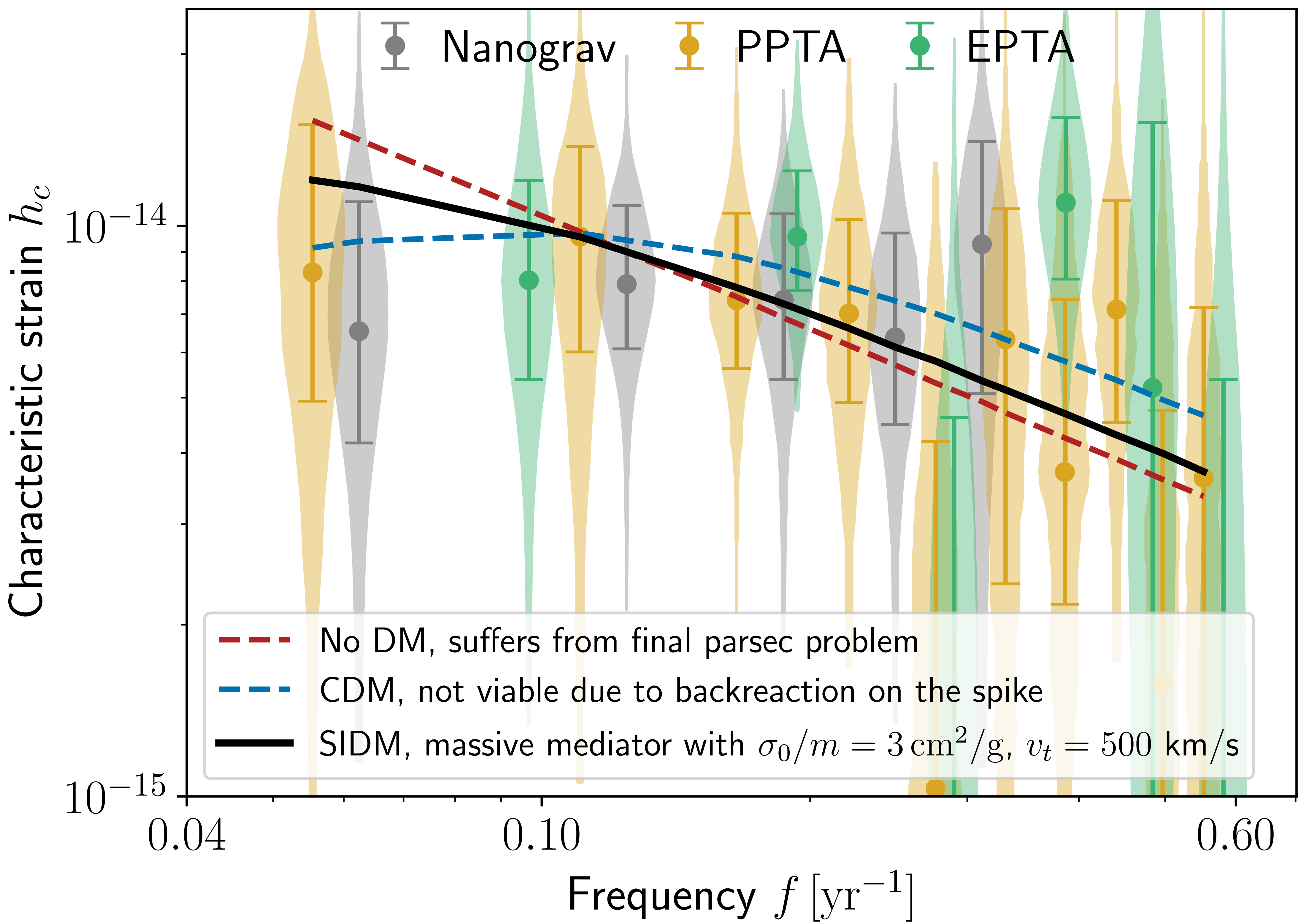


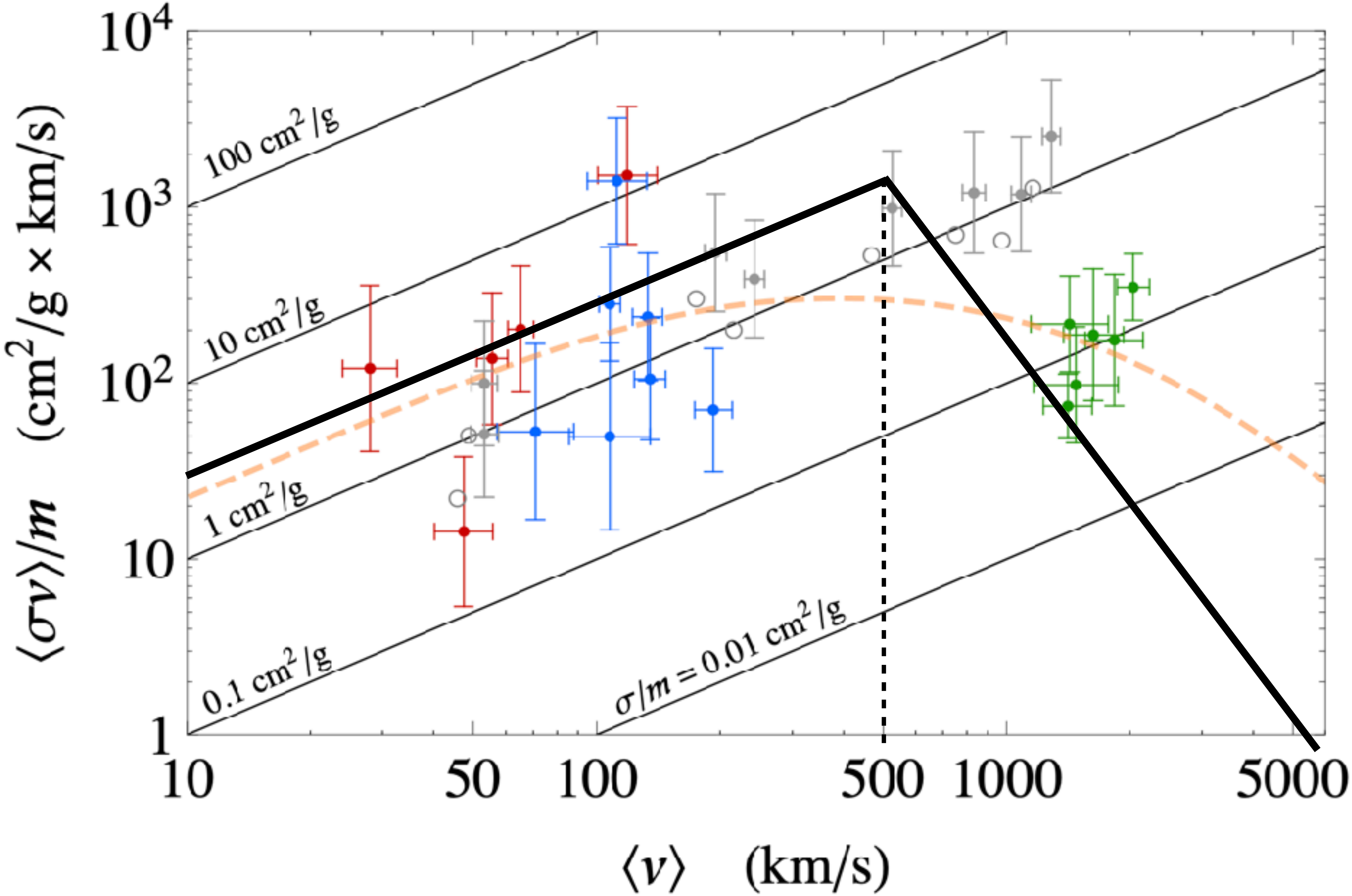
GW spectrum at PTAs



GW spectrum at PTAs



Compatible with small-scale structure



Conclusions

- Self-interacting dark matter solves the final parsec problem of supermassive black holes.

- Correlated softening of the gravitational wave spectrum at pulsar timing arrays.

- Compatible with small scale structure hints.

Work in progress

- Gravothermal simulation of merger & back-reaction on spike.
- Upgraded characteristic strain calculation including finite inspiral duration.
- Improved statistical analysis of PTA data.

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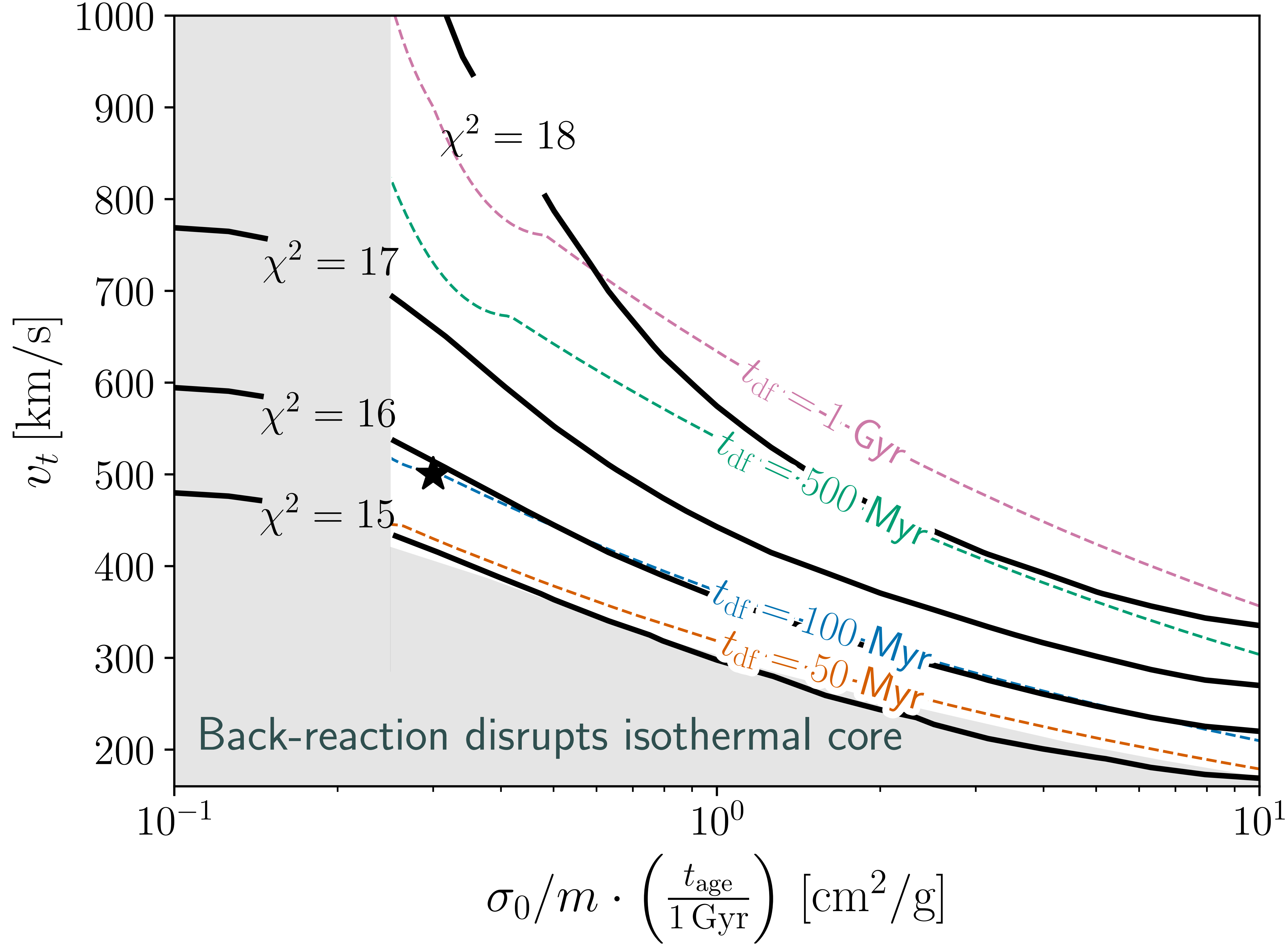
Thanks!

Backup material

SIDM massive mediator



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Pulsar timing arrays

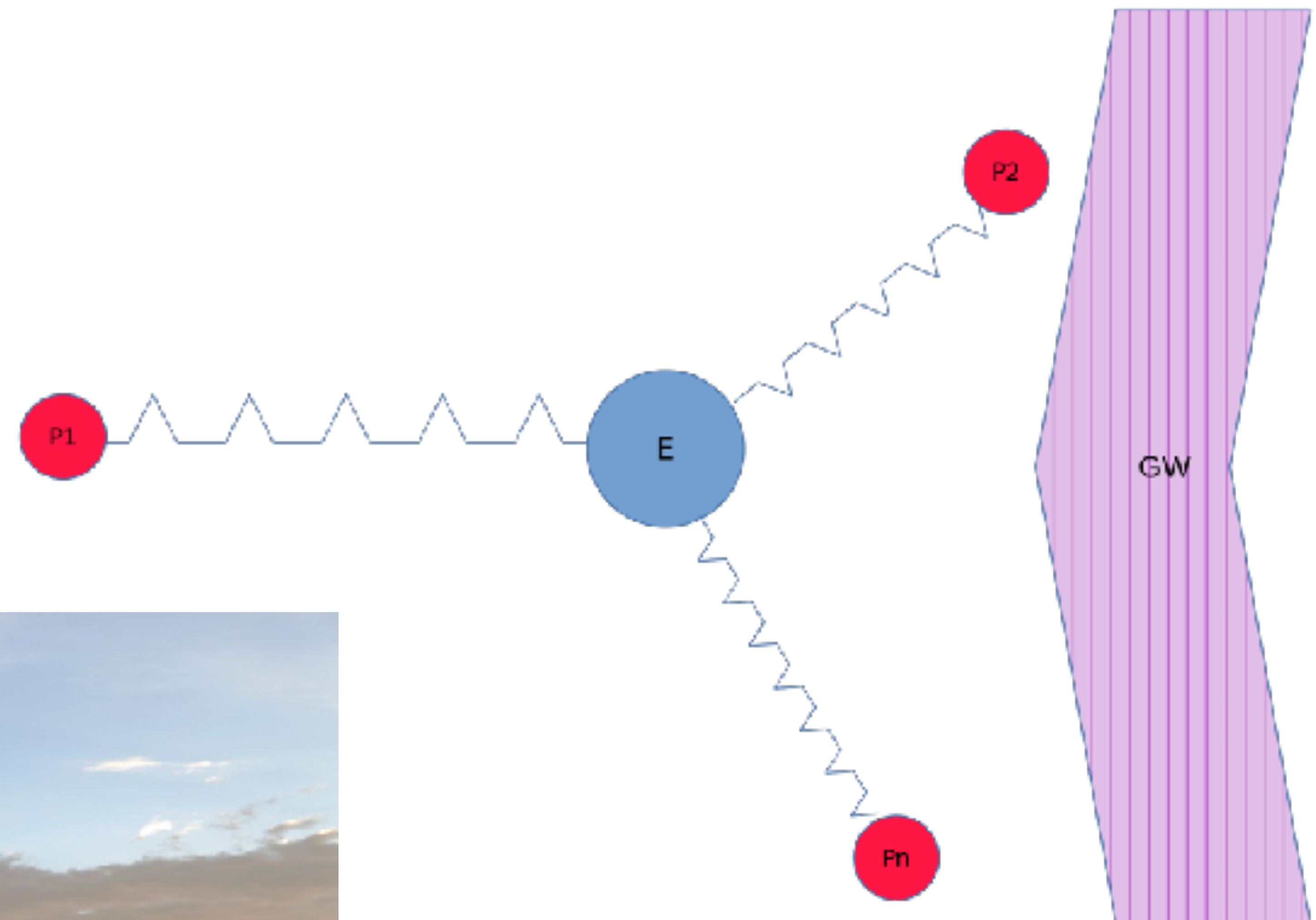


Image credit: Wikipedia

Very Large Array radio telescope

New physics explanations

Inflationary GW

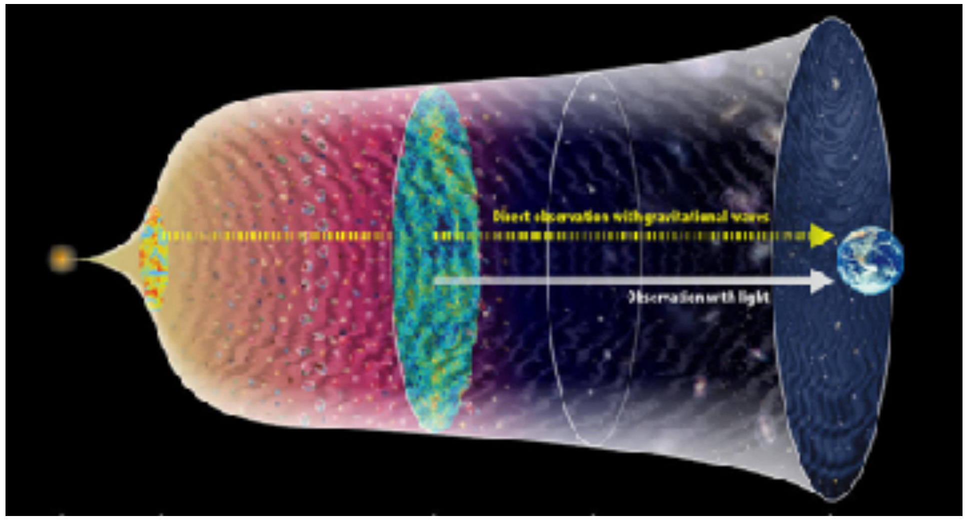


Image credit: NAOJ

Phase transitions

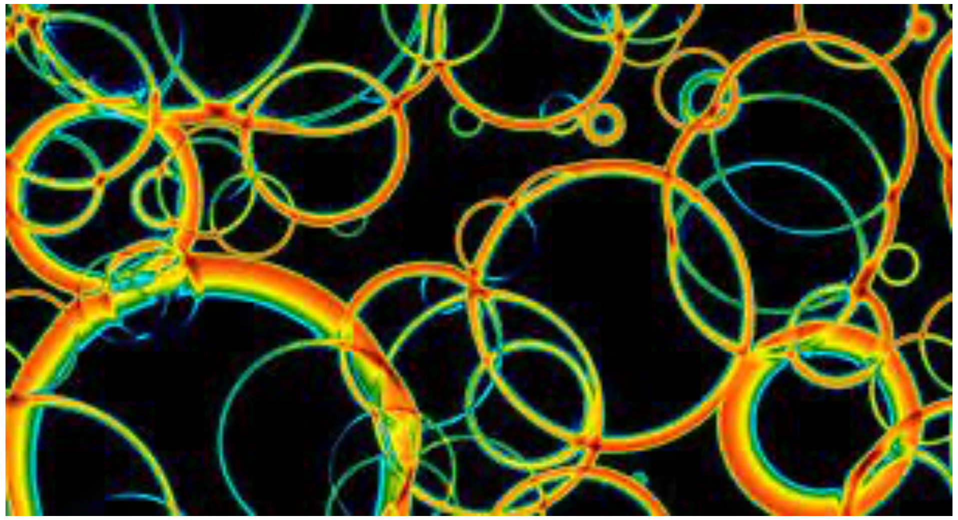


Image credit: Weir et al (2016)

Cosmic strings

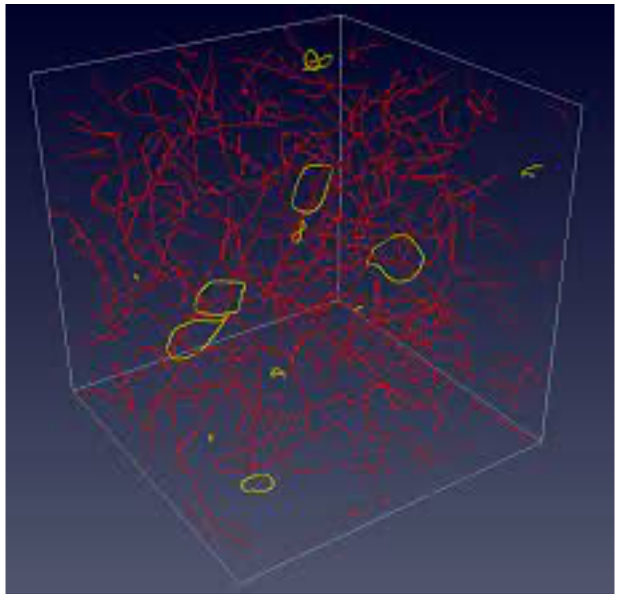


Image credit: Kitajima et al (2023)

Domain Walls

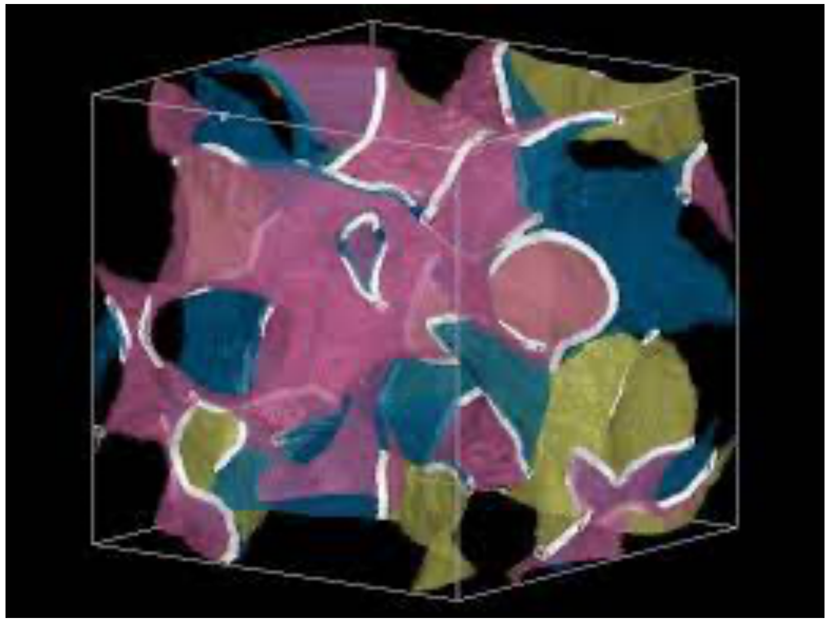
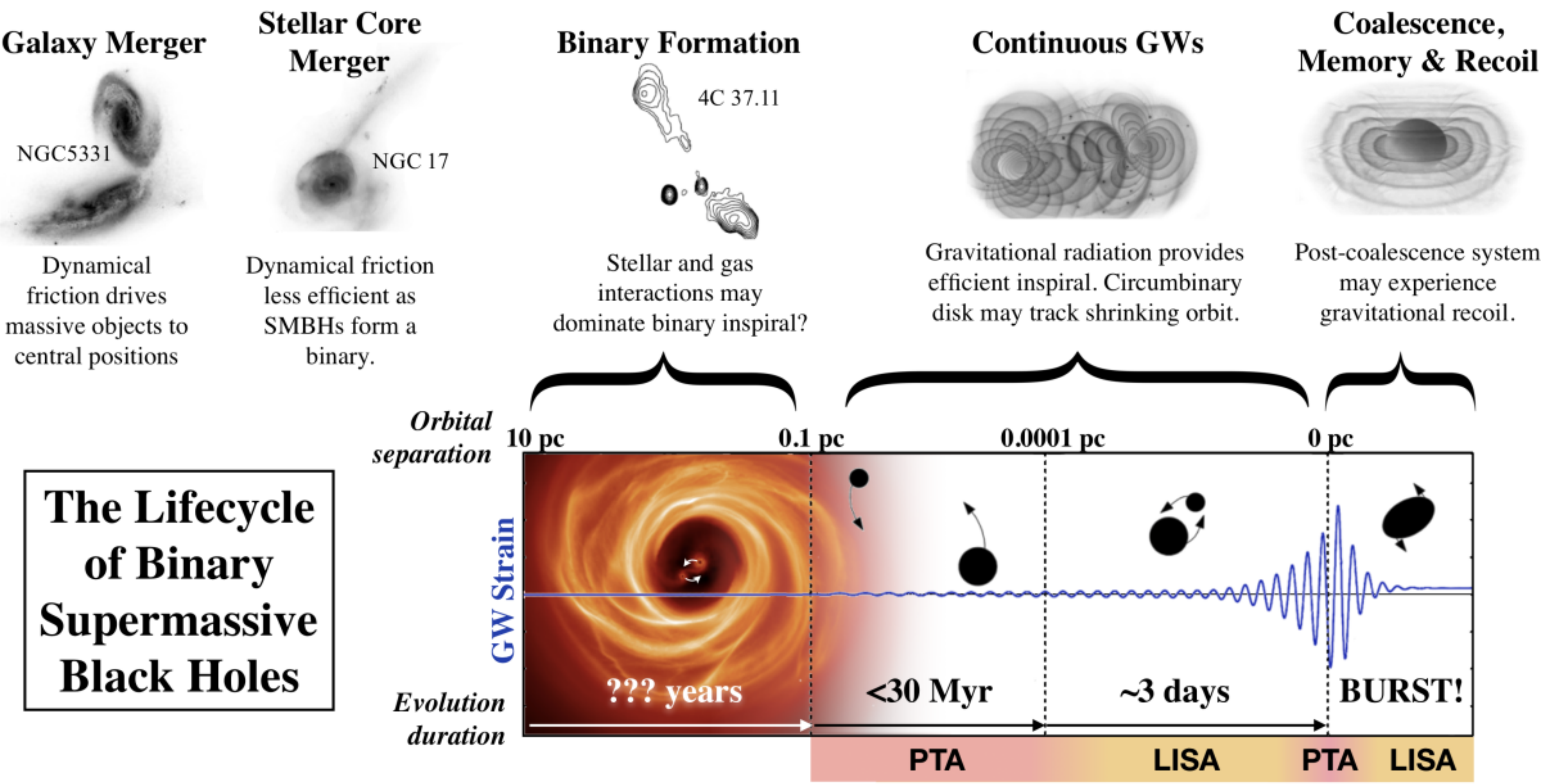


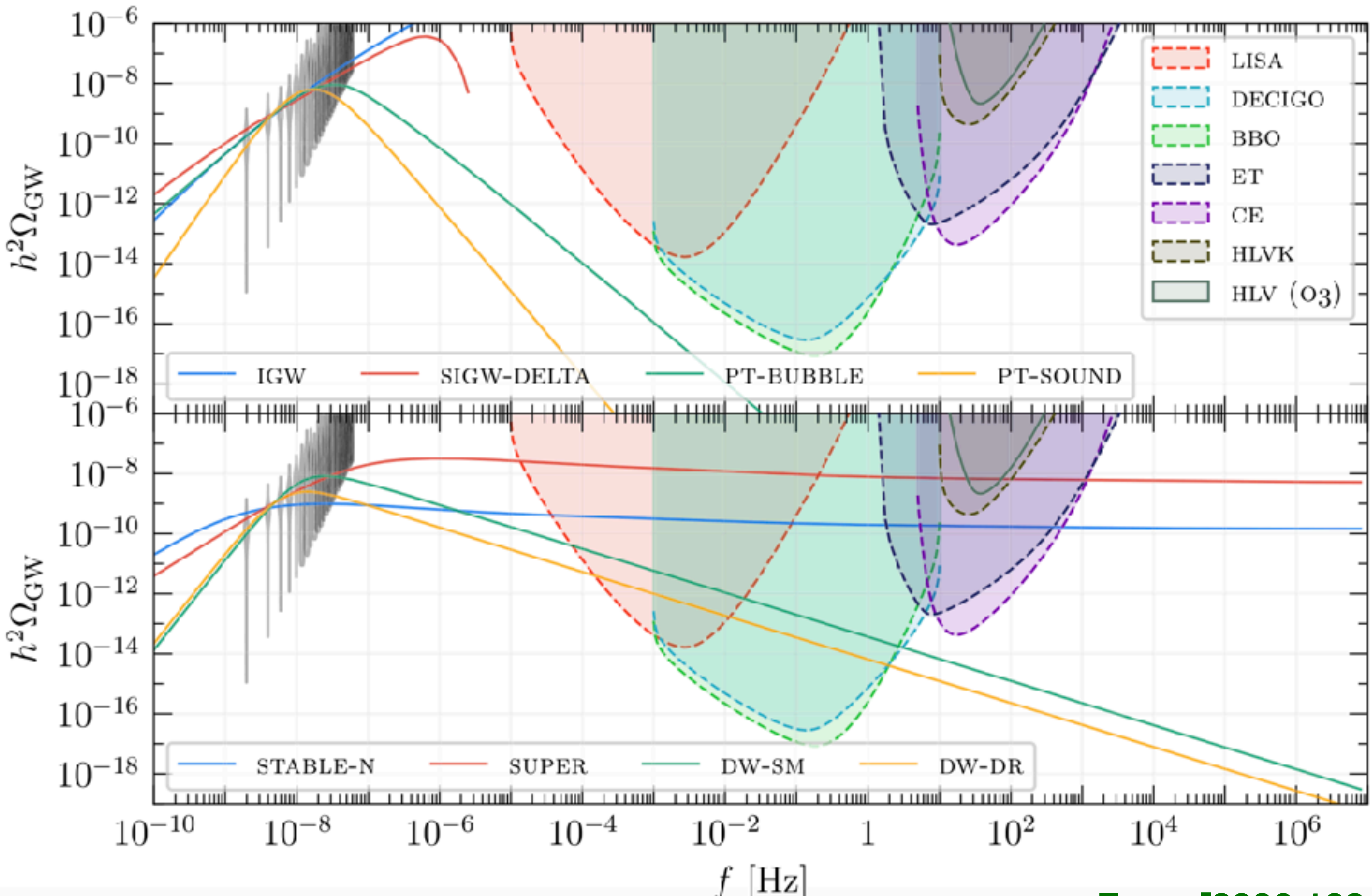
Image credit: Hiramatsu et al (2013)

SMBH mergers



From NANOGrav (designed by Sarah Spolaor)

New physics explanations

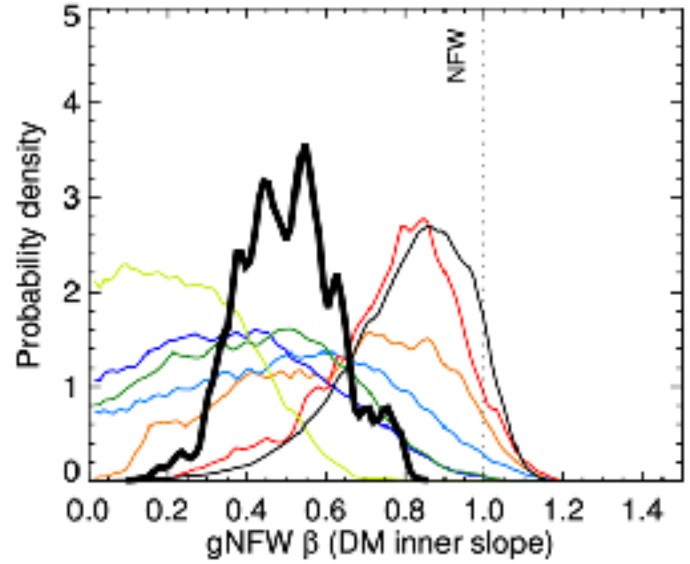


From [2306.16219]

Self-interacting dark matter

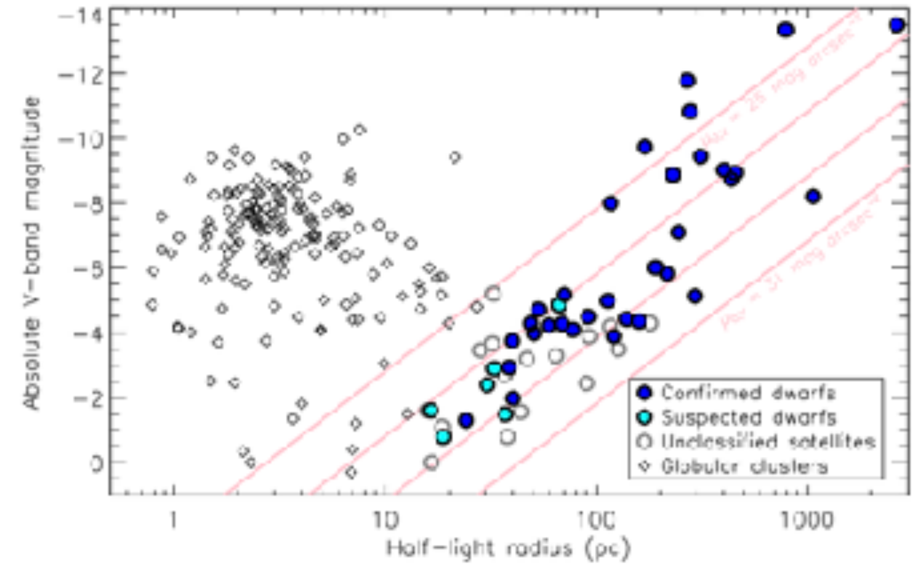
- **Hints**

Core vs cusp



[1209.1392]

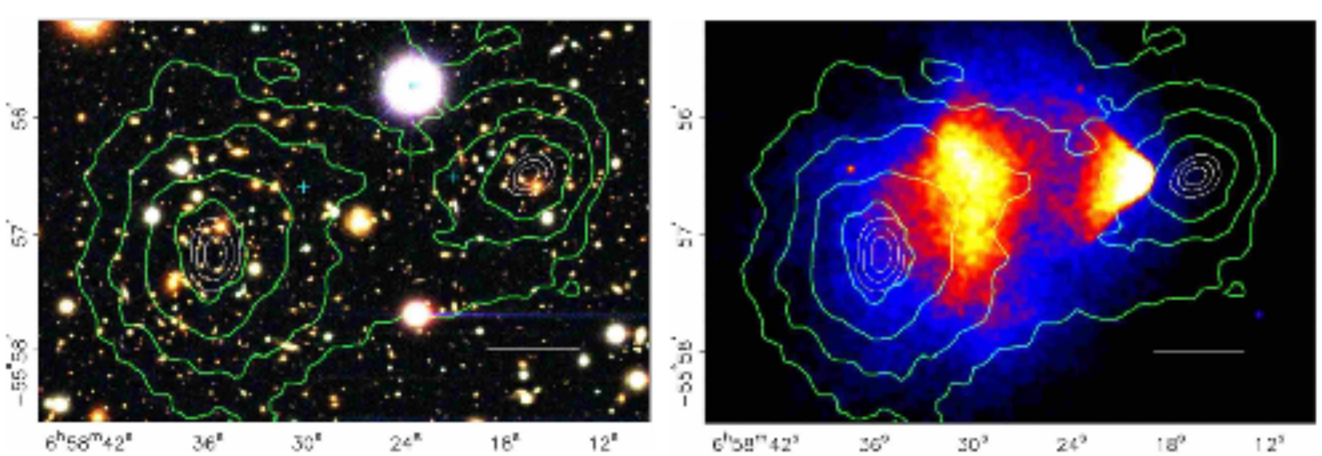
Missing satellites (?)



[1901.05465]

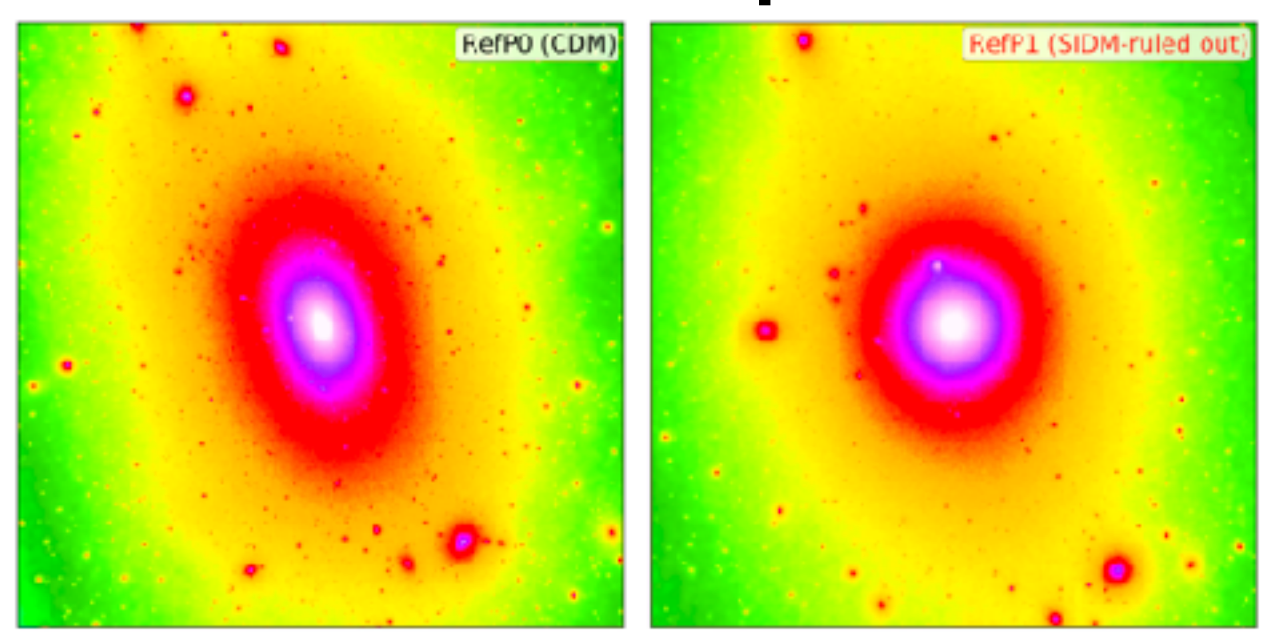
- **Constraints**

Galaxy cluster mergers



[astro-ph/0608407]

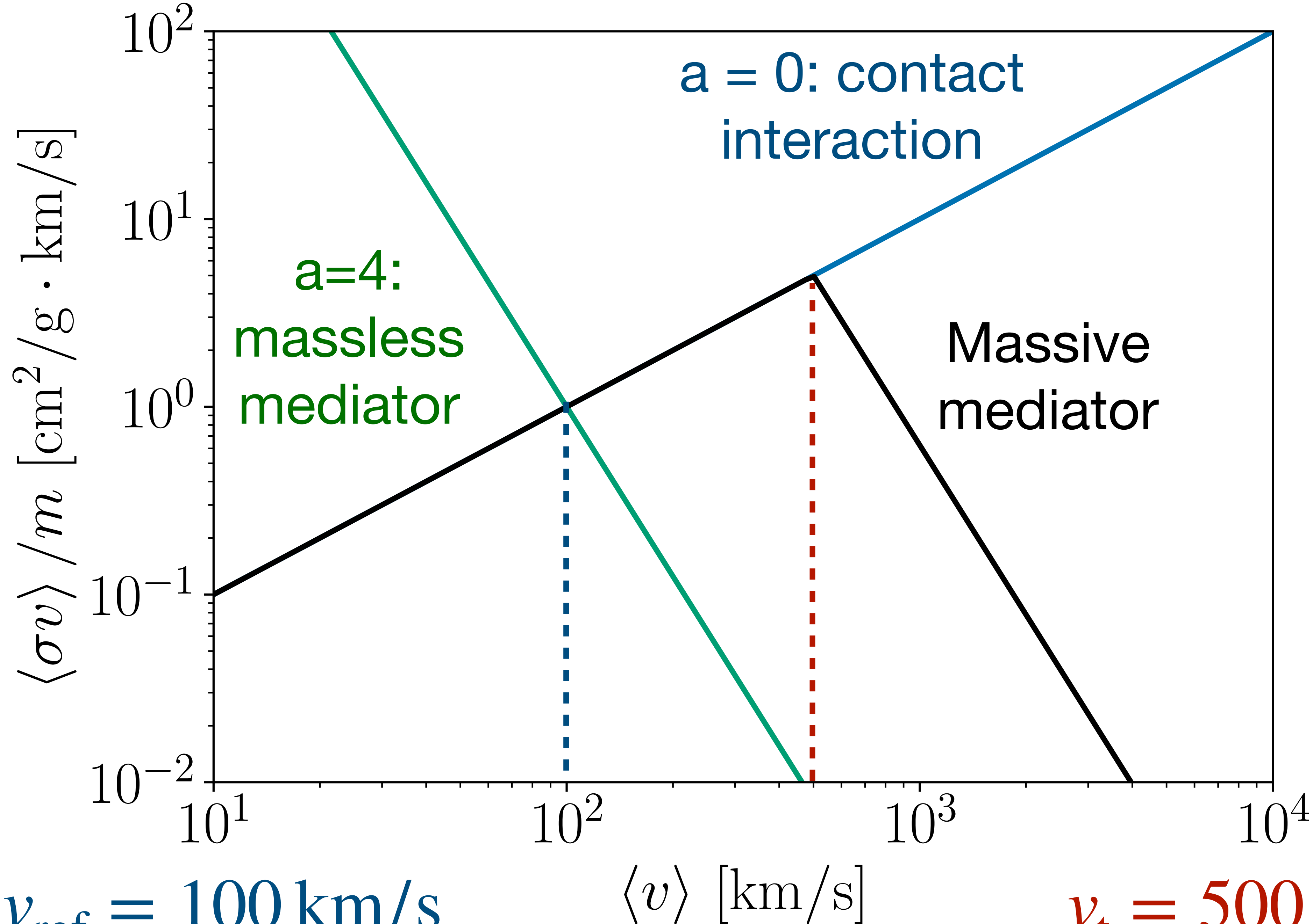
Halo shape



[1201.5892]

SIDM parametrization

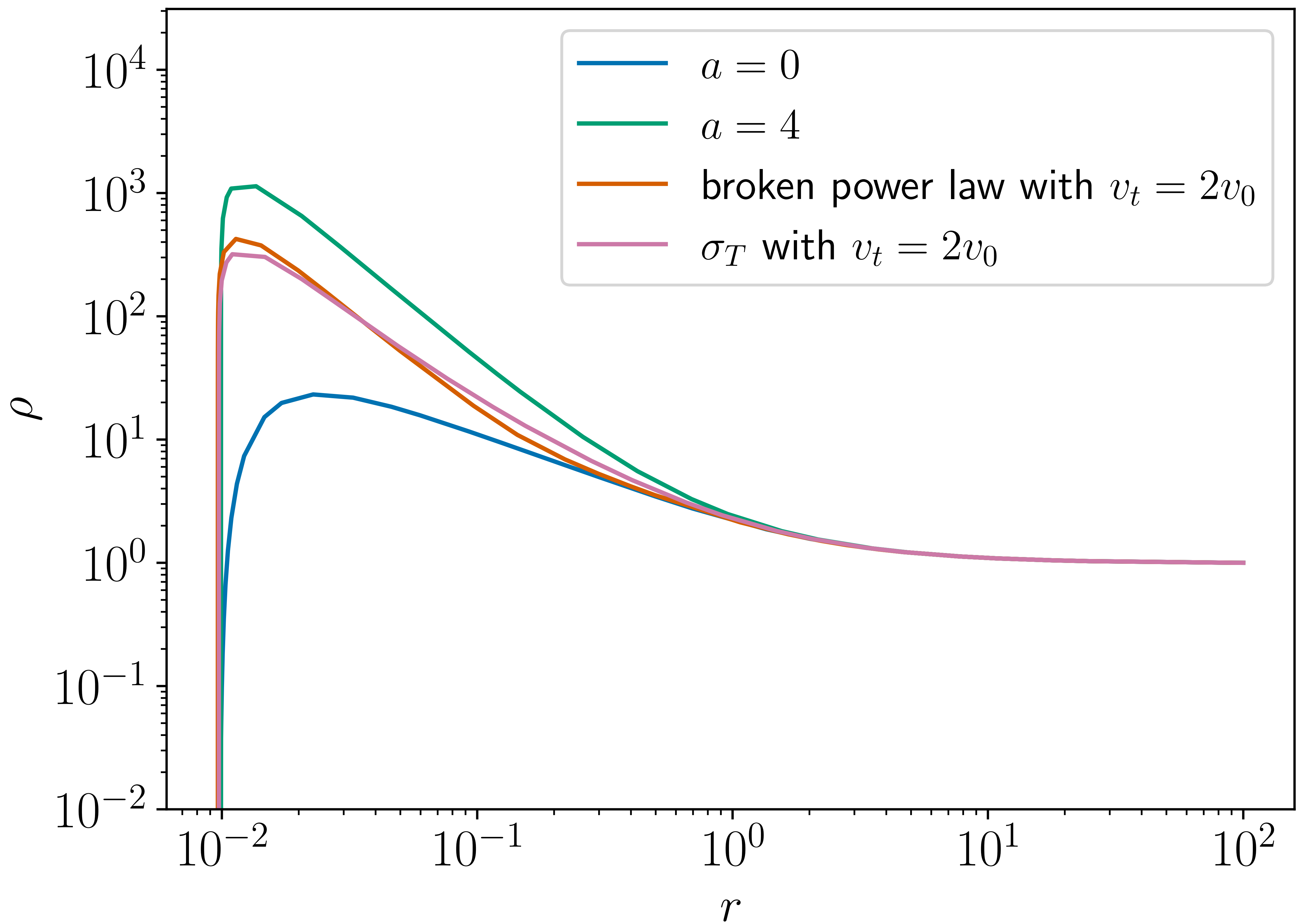
$$\frac{\langle \sigma v \rangle}{m} = \frac{\sigma_0}{m} \left(\frac{v_{\rm ref}}{v} \right)^a v$$



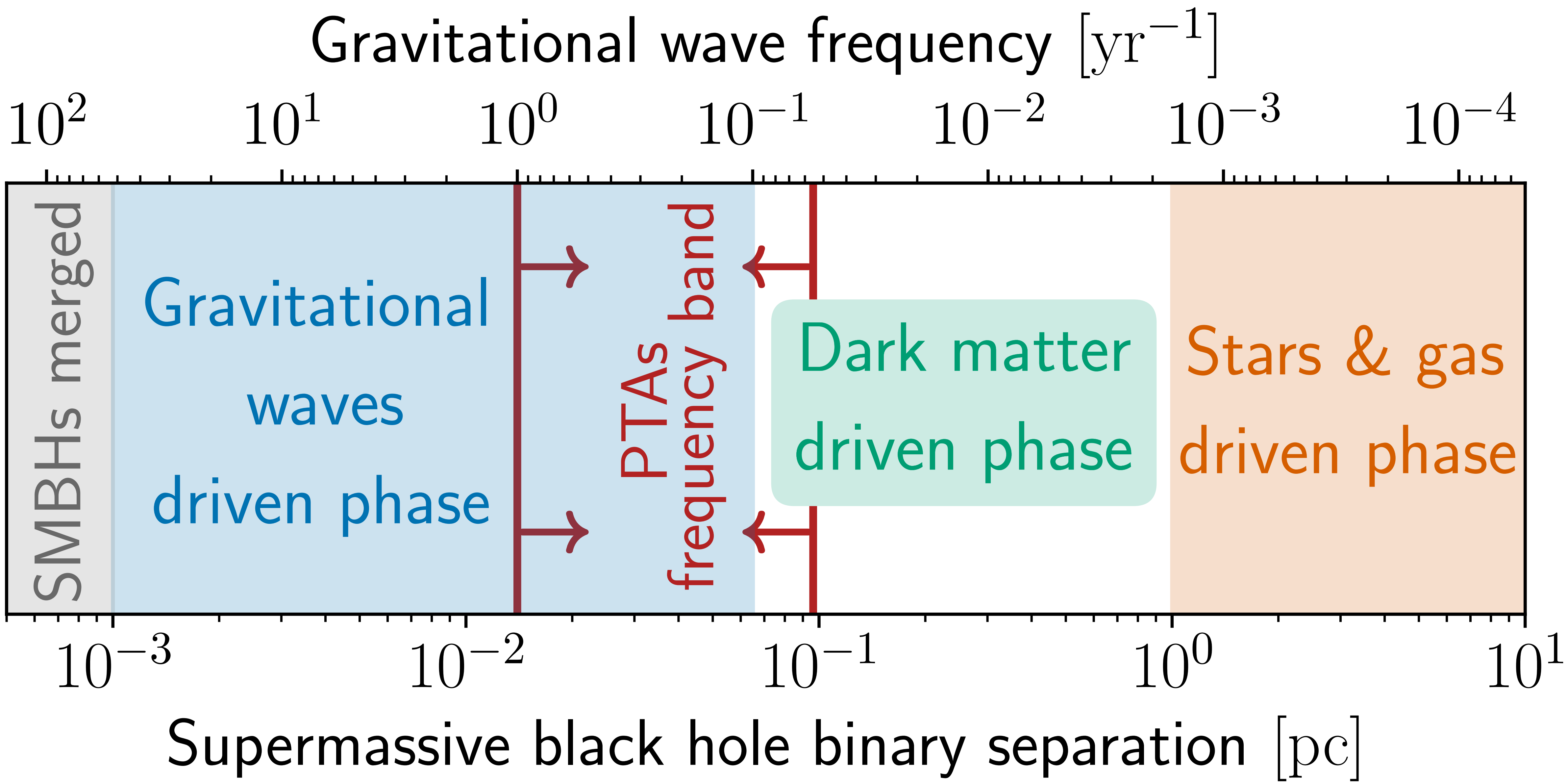
$v_{\rm ref} = 100\,{\rm km/s}$

$v_{\rm t} = 500\,{\rm km/s}$

Power law vs. velocity transfer cross section

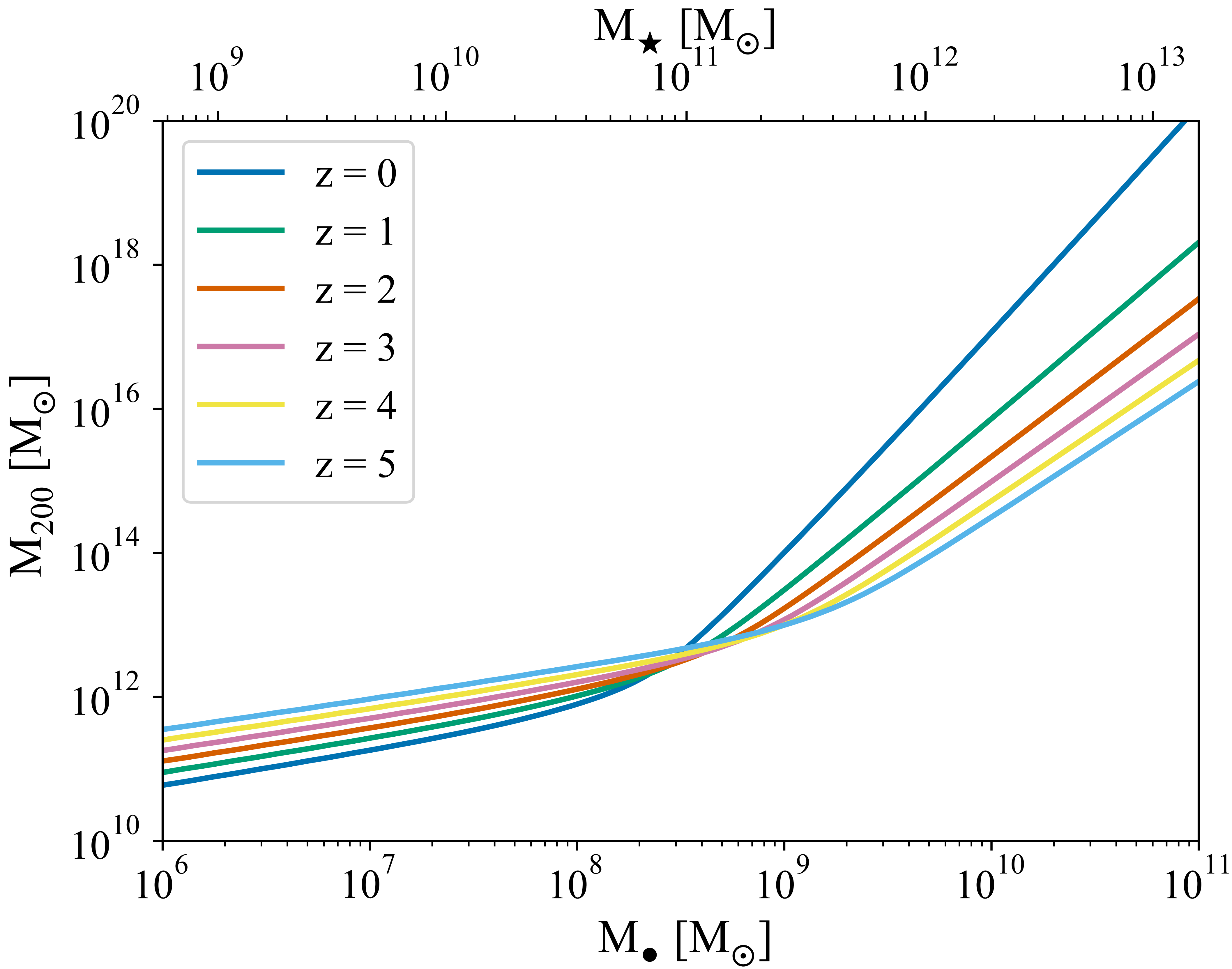


DM spike dynamical friction



Crucial impact on SMBH binary evolution

BH-to-halo mass relation



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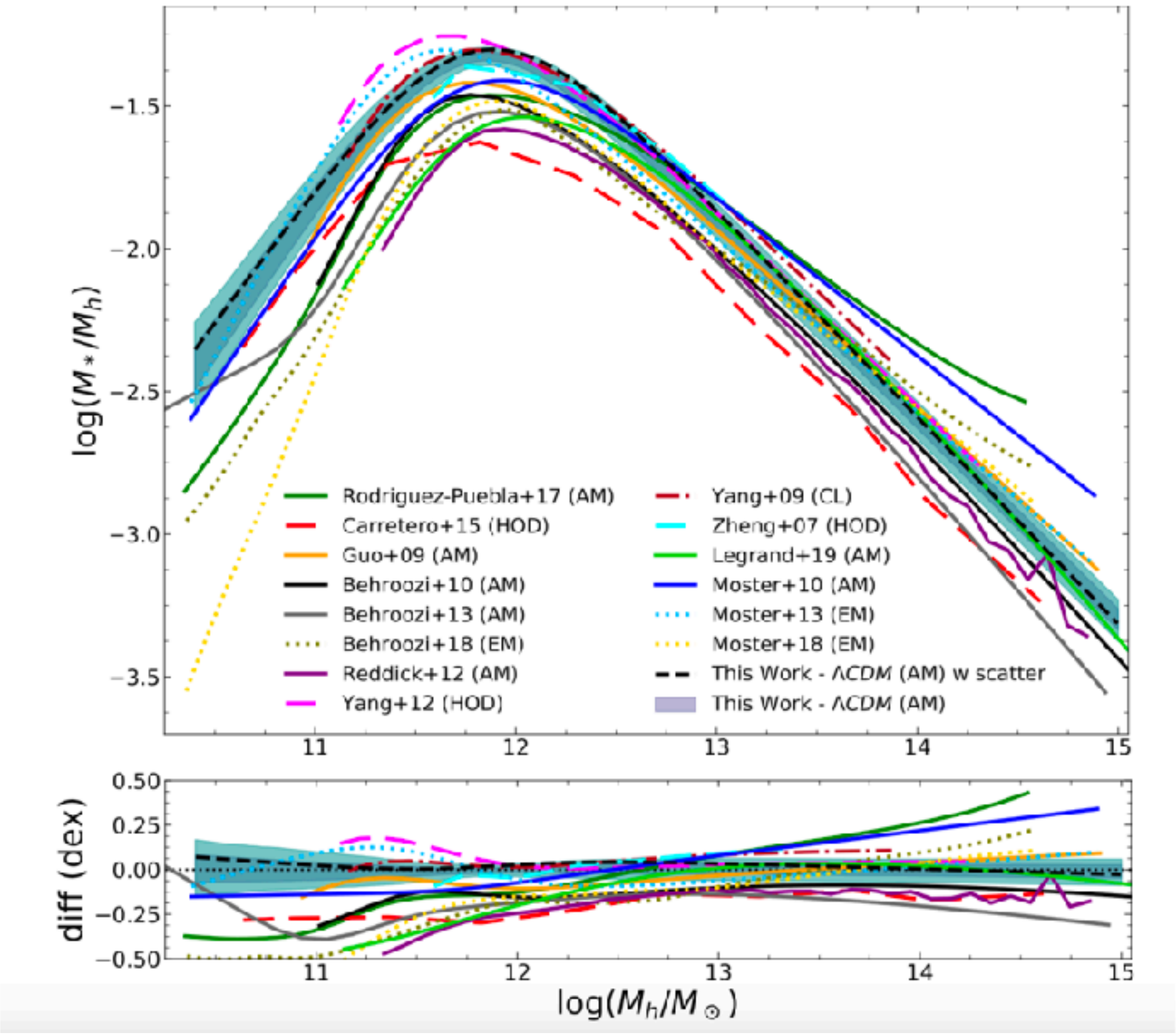
Stellar-to-halo mass relations



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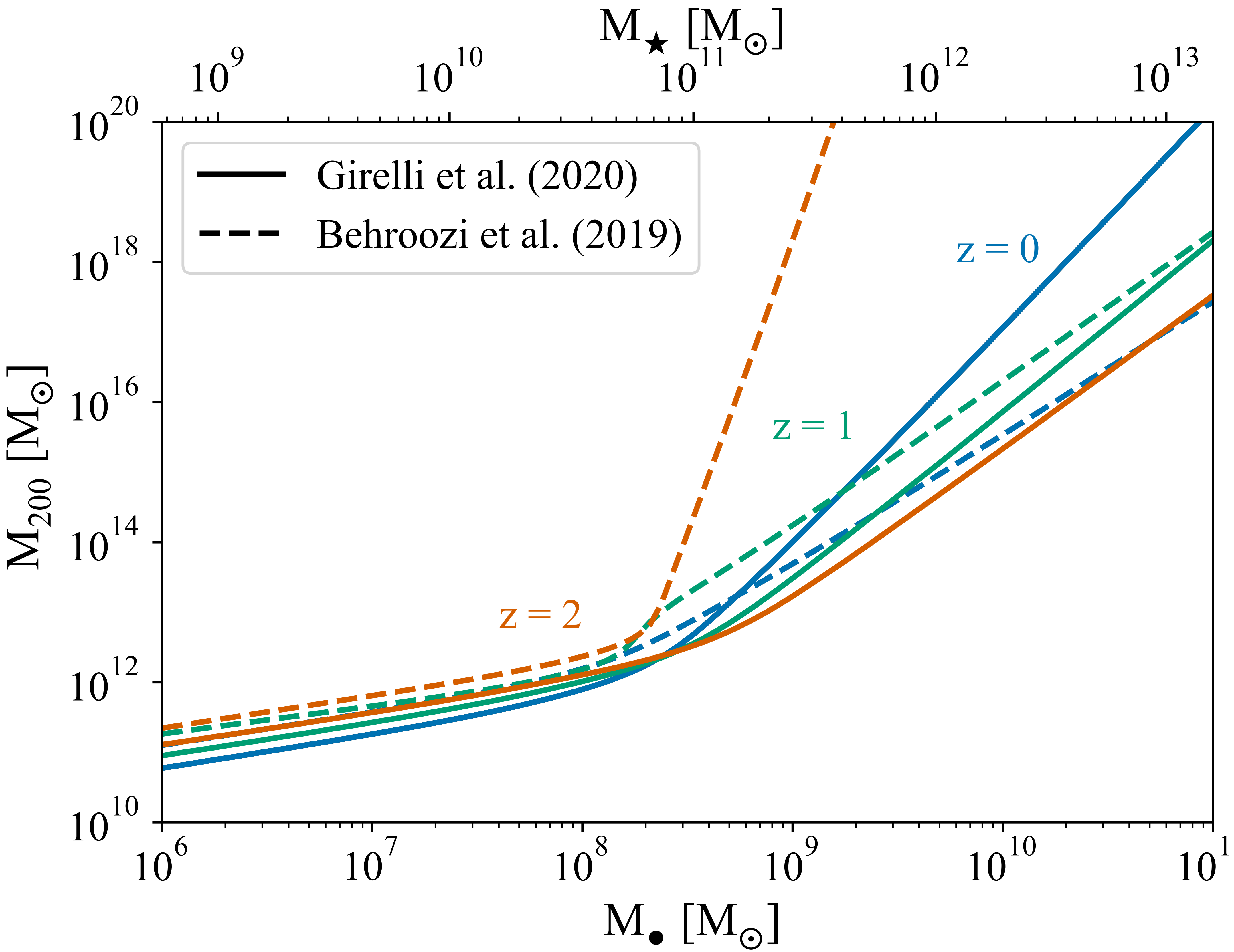
Stellar-to-halo mass relations



Stellar-to-halo mass relations

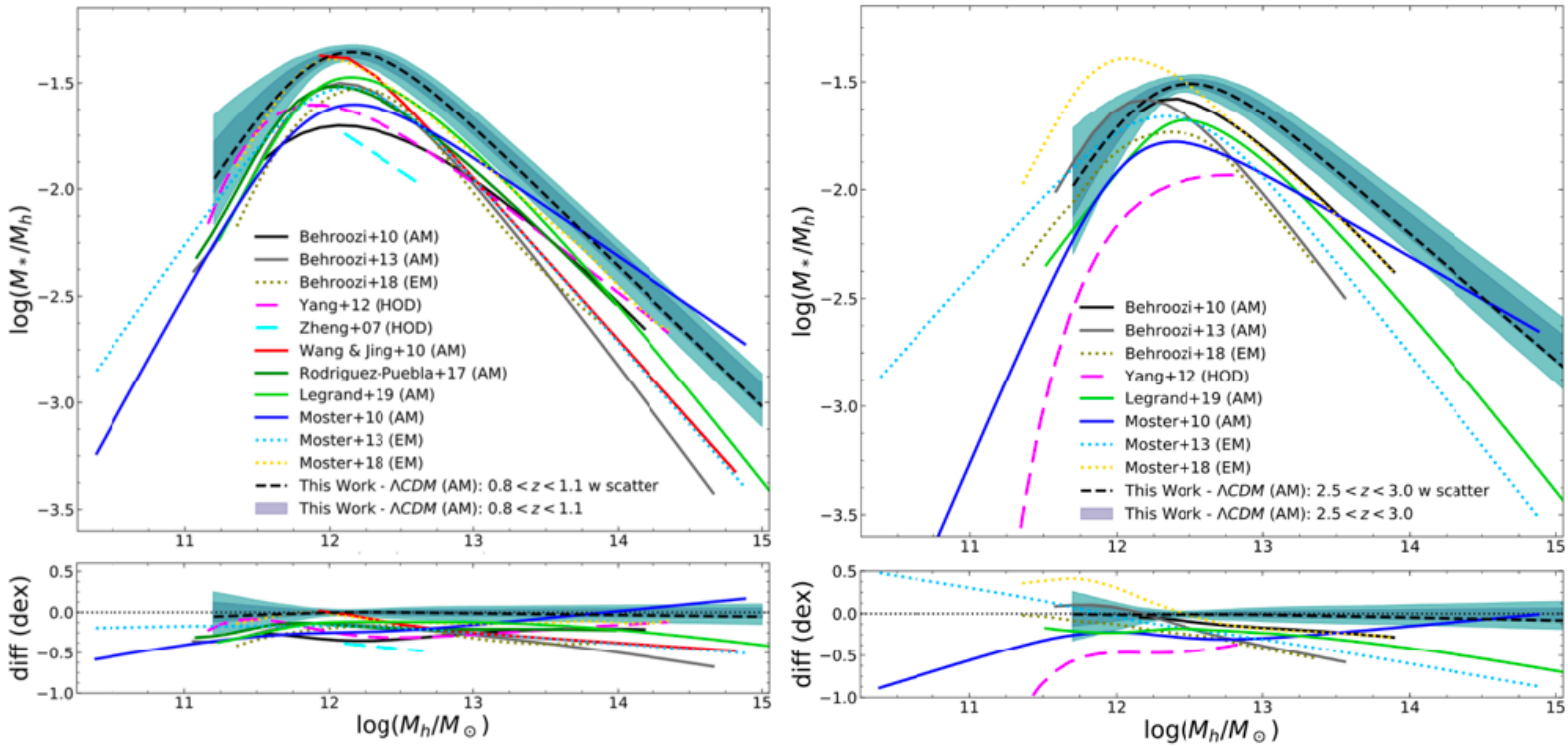
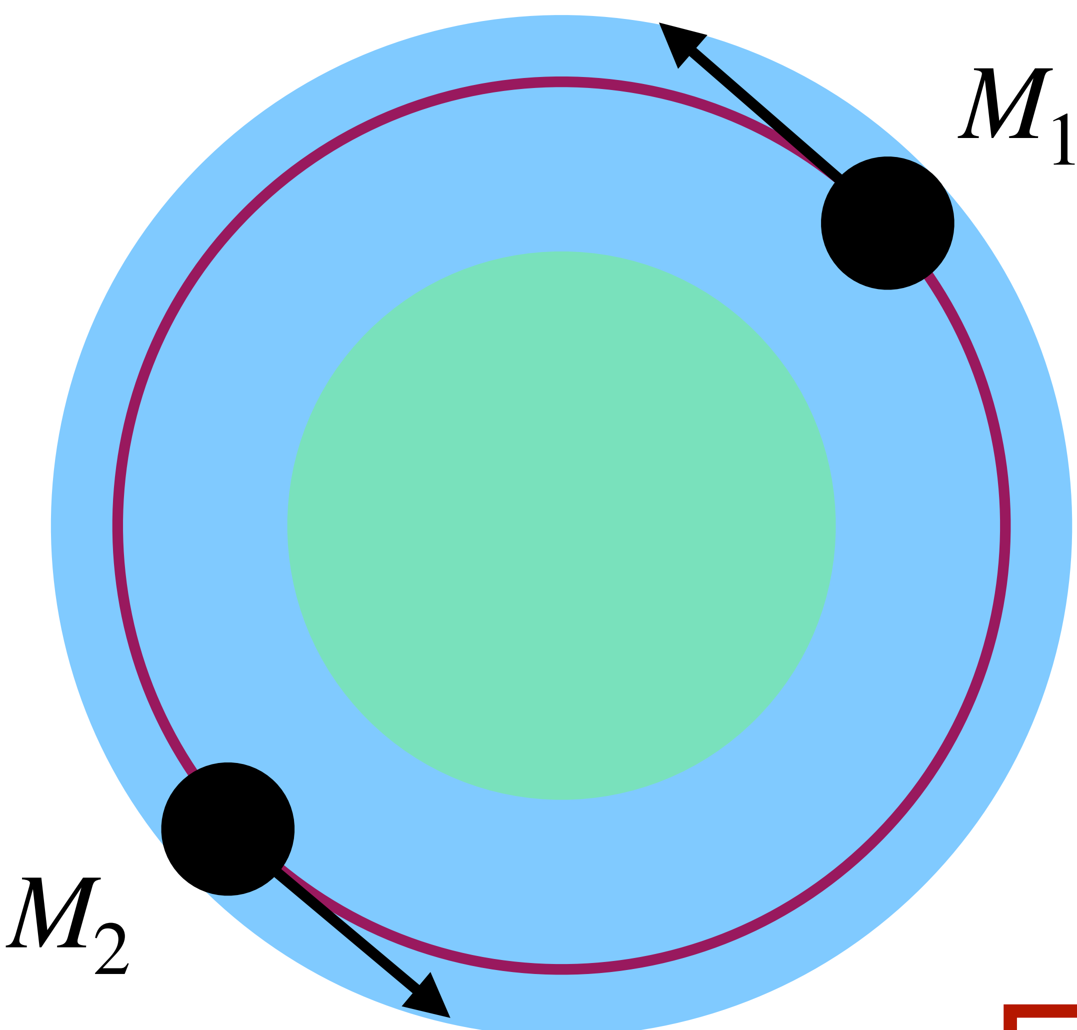


Fig. 10. Best-fit SHMR compared to previous results at $z \sim 1$(left) and $z \sim 3$ (right). Symbols are the same as in Fig. 9.

Orbital radius evolution

DM dynamical friction + GW emission



$$R < 10\,\mathrm{pc}$$

Power lost by the binary

$$P_{\mathrm{gw}} \propto R^{-5}$$

$$P_{\mathrm{df}} \propto R^{1/2} \rho_{\mathrm{spike}}(R)$$

Relate to orbital energy loss

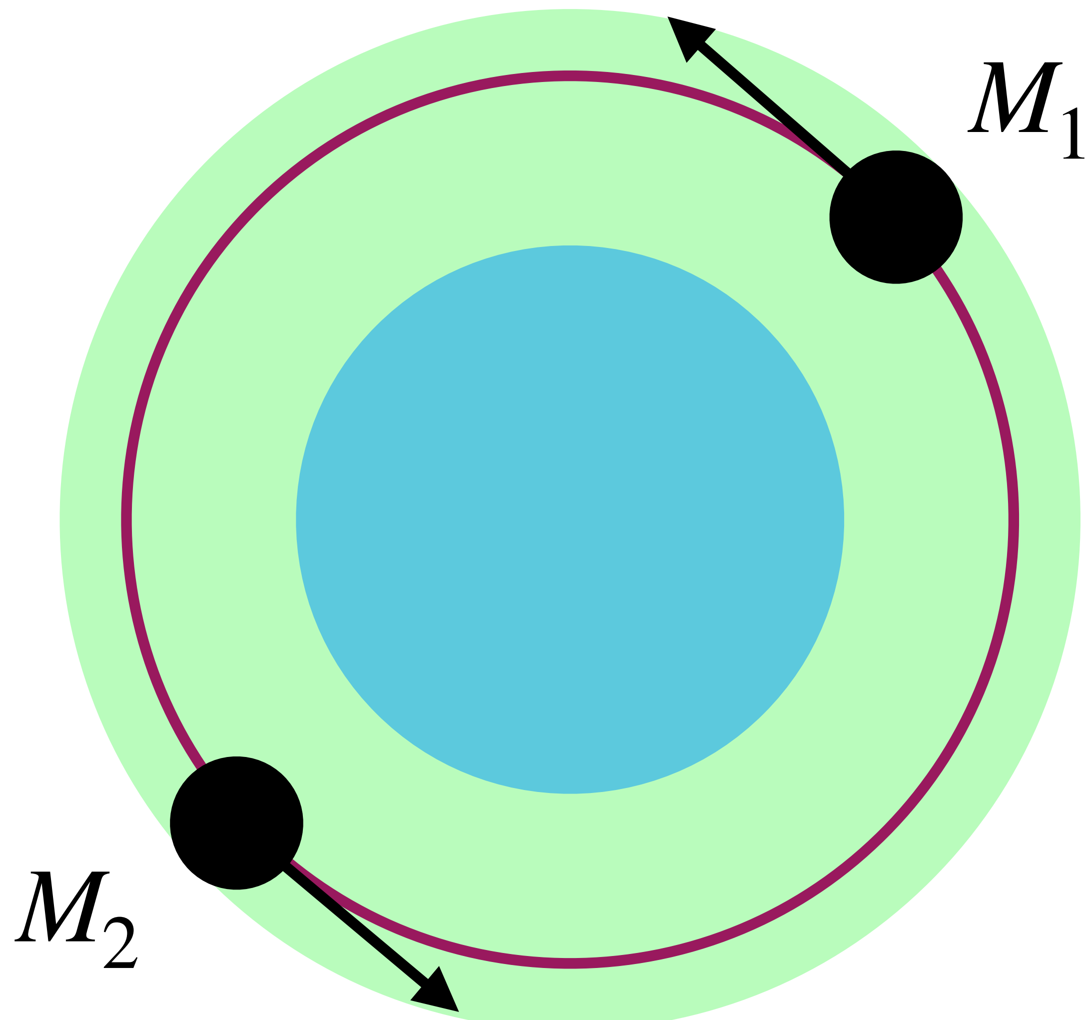
$$\dot{E}_{\mathrm{orbit}} \propto \frac{\dot{R}}{R^2}$$

$$\dot{E}_{\mathrm{orbit}} = P_{\mathrm{gw}} + P_{\mathrm{df}} \rightarrow R(t)$$

Orbital radius evolution

DM dynamical friction + GW emission

$$P_{\rm gw} = \frac{32}{5} q^2 (1+q)\, G^4 \frac{M_1^5}{R^5}$$



$$P_{\rm df} = 12\pi^2 q^2 \sqrt{(1+q)}(GM_1)^{3/2} \times R^{1/2} \left(N_2 \rho(r_2) + N_1 \frac{\rho(r_1)}{q^3} \right)$$

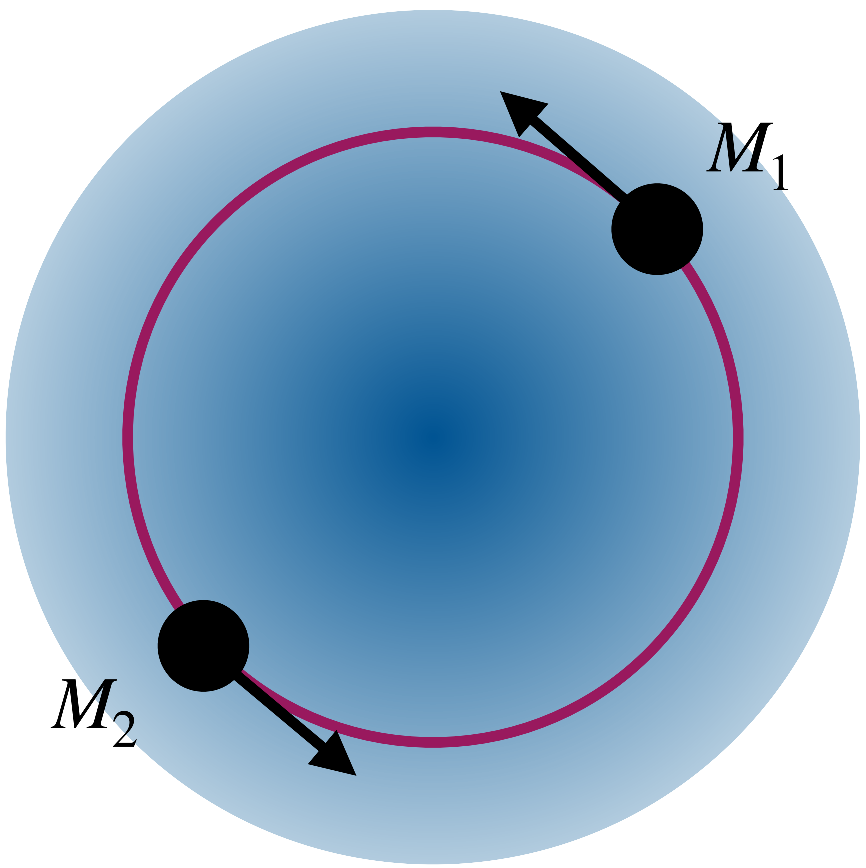
$$\dot{E}_{\rm orb} = q\, G\, M_1 \frac{\dot{R}}{2R^2}$$

$R < 10\,\mathrm{pc}$

$$\dot{E}_{\rm orb} = P_{\rm gw} + P_{\rm df} \quad \rightarrow \quad R(t)$$

Back-reaction on the spike

$$M_{\rm spike} \sim M_1 + M_2$$



Orbital energy lost:

$$\Delta E_{\rm orbit} \sim \frac{G\,M_1^2}{R_{\rm gw}}$$

Binding energy of spike:

$$U_{\rm spike} \sim \frac{G\,M_1^2}{r_{\rm spike}}$$

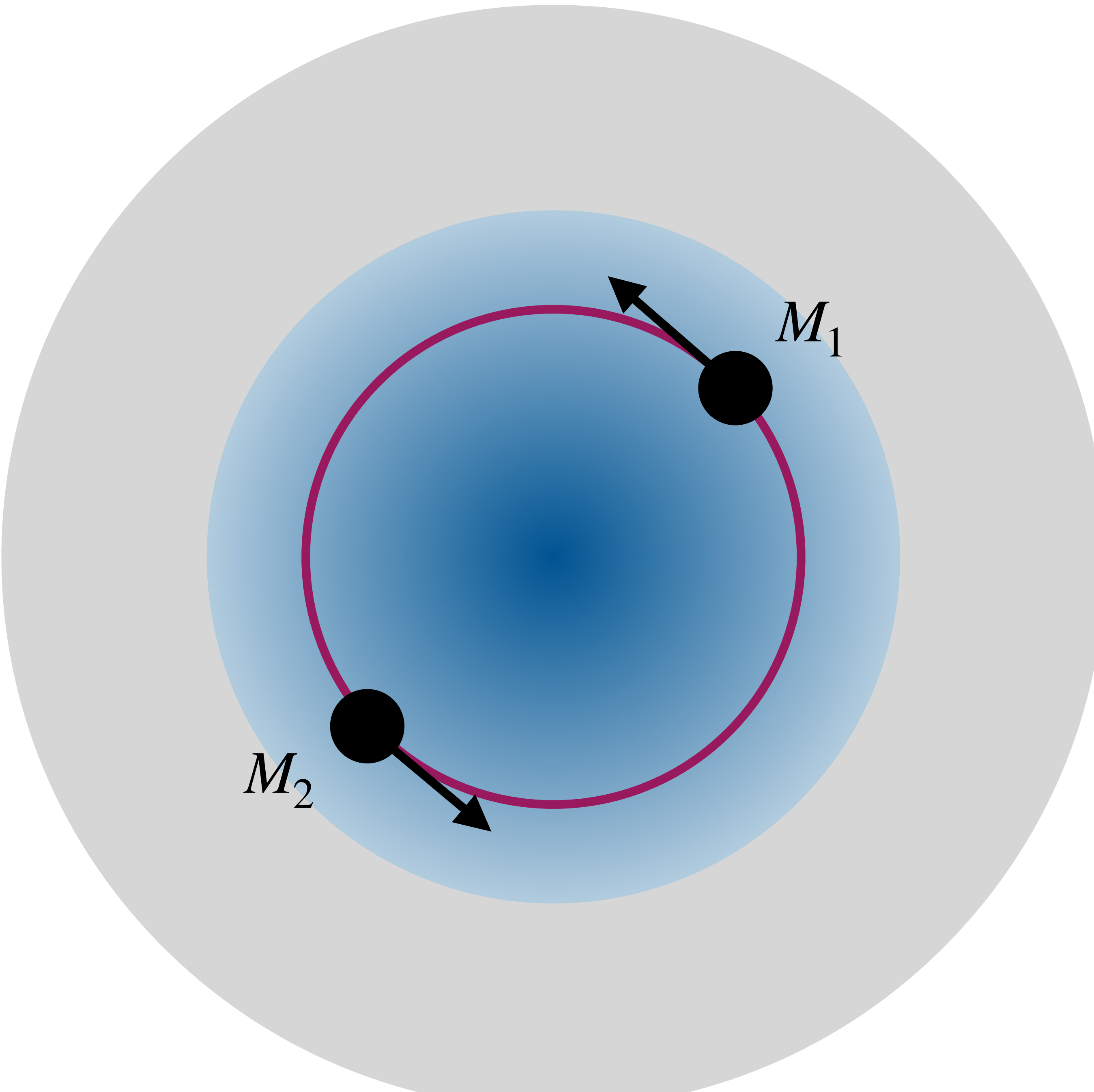
Since $r_{\rm spike} \gg R_{\rm gw}$:

$$\Delta E_{\rm orbit} \gg U_{\rm spike}$$

Spike is quickly disrupted

SIDM core absorbs orbital energy

$$M_{\rm core} \gg M_1 + M_2$$



Orbital energy lost:

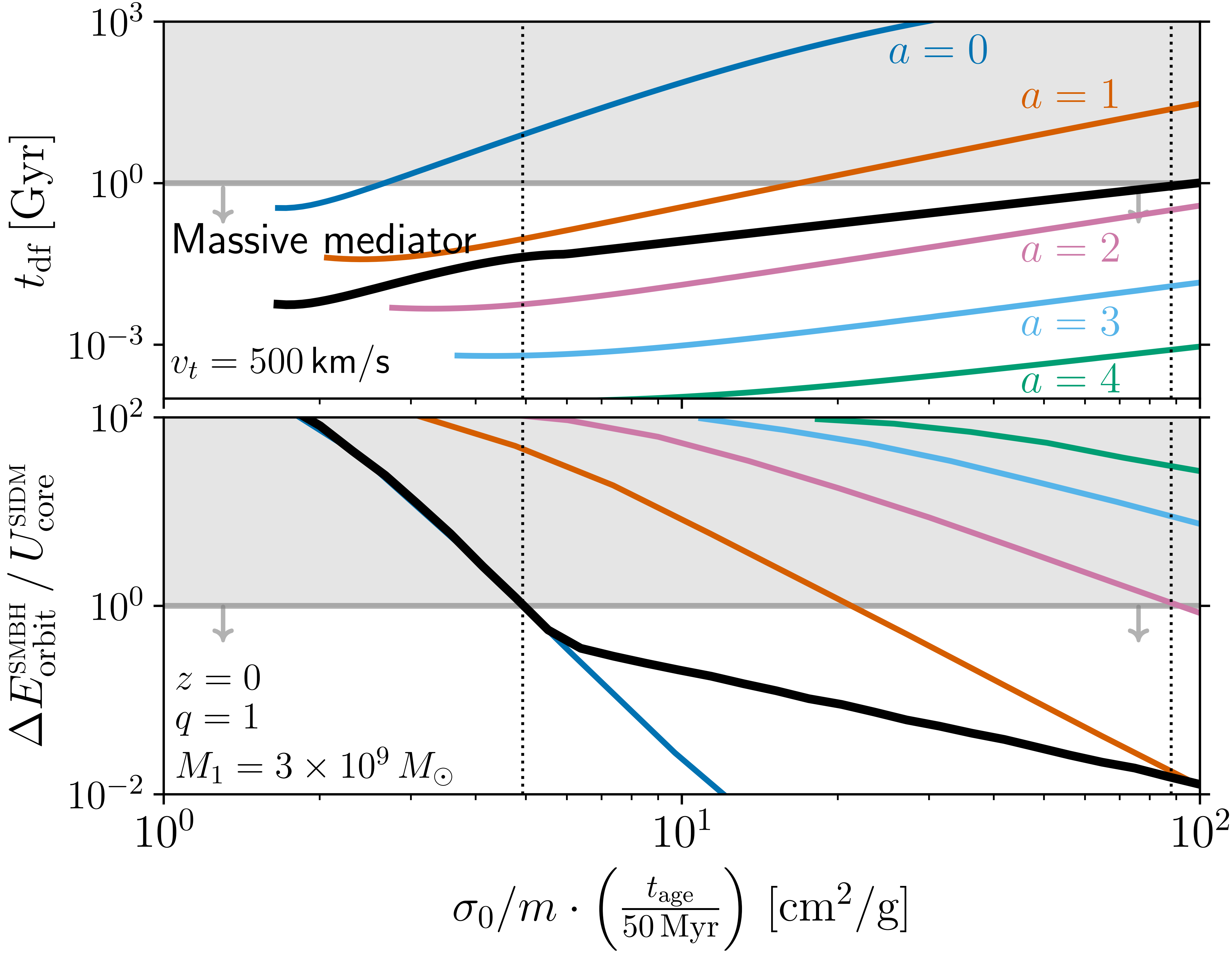
$$\Delta E_{\rm orbit} \sim \frac{G\,M_1^2}{R_{\rm gw}}$$

Binding energy of the core:

$$U_{\rm core} \sim \frac{G\,M_{\rm core}^2}{r_{\rm core}}$$

Minimum size of core —> lower limit on σ_0/m

DF timescale & energy ratio



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Core relaxation timescale

Timescale at which the SIDM spike is replenished

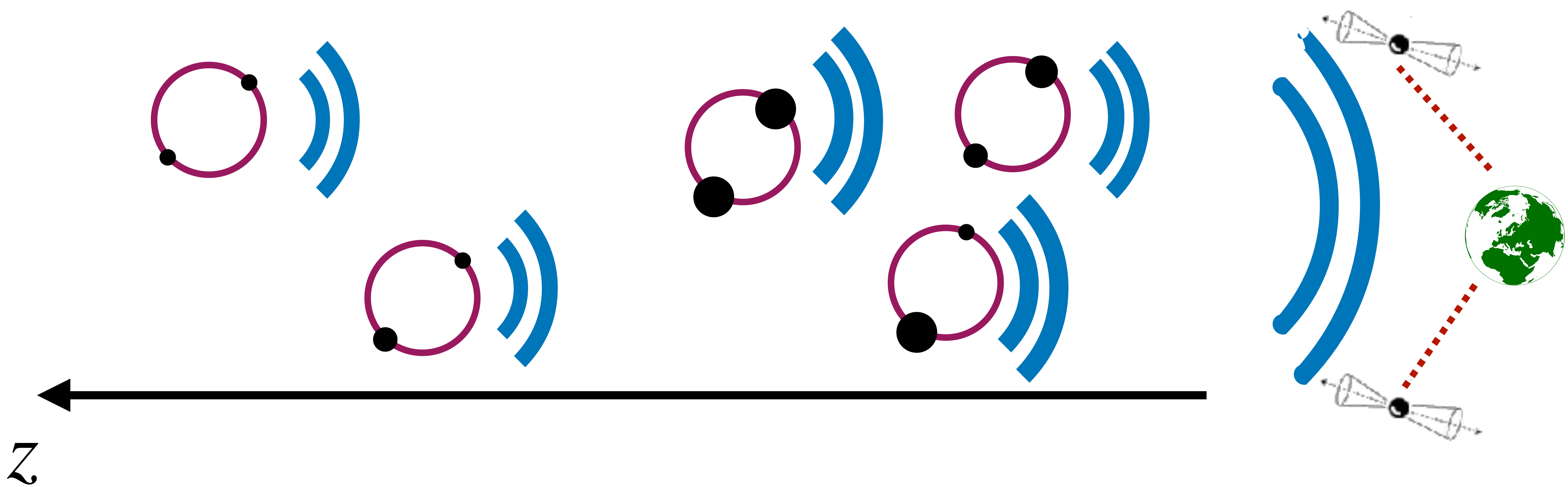
$$t_{\rm r} \sim \left(\rho_c \frac{\sigma\, v_0}{m}\right)^{-1} \cong t_{\rm age}$$

- Must be $t_{\rm r} \lesssim t_{\rm df}$ for spike in equilibrium
- The core is at least that old: $t_{\rm age} \gtrsim t_{\rm df}$

Demand $t_{\rm age} = t_{\rm df}$

Characteristic strain

Add contributions from all SMBH mergers:



Characteristic strain at detection

$$q = \frac{M_2}{M_1}$$

$$h_c^2(f) = \frac{4G}{\pi f} \int dz\, dM_1\, dq\, \frac{d^3 n}{dz\, dM_1\, dq} \frac{dE}{df_s}$$

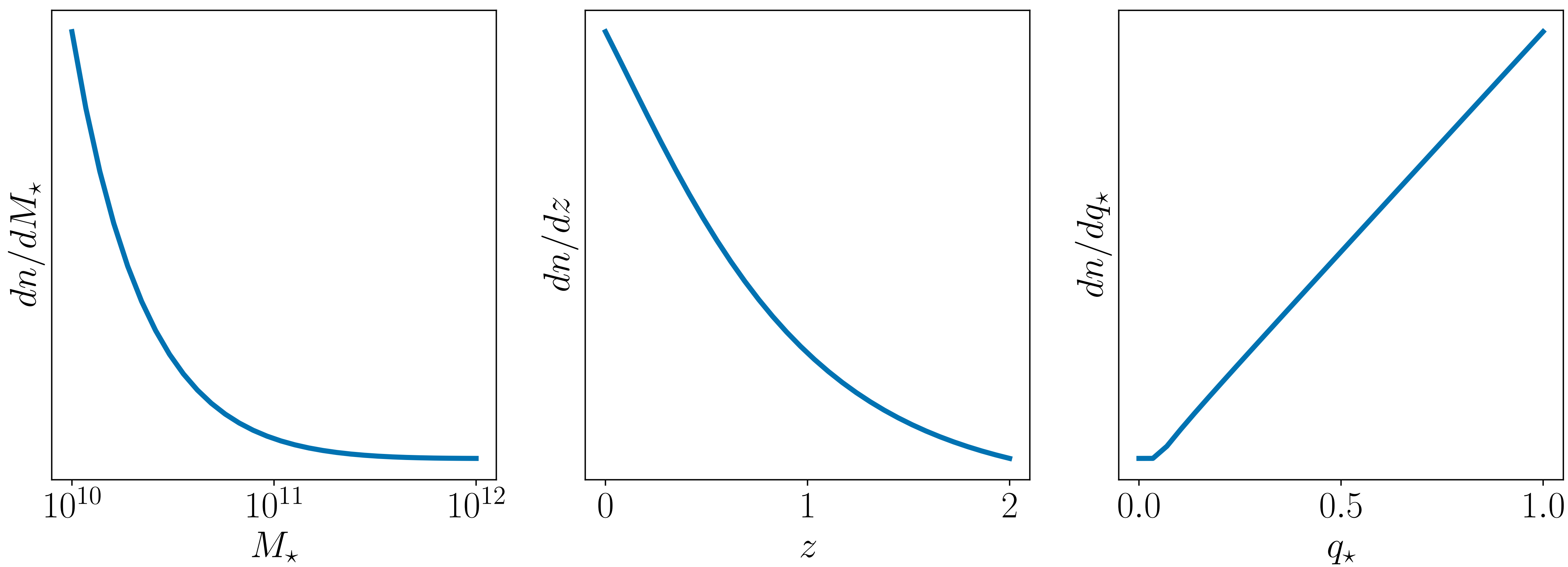
$$f = \frac{f_s}{1+z}$$

SMBH merger rate

Relate to galaxy merger rate

$$\frac{d^3 n}{dz\, dM\, dq} = \frac{d^3 n_{\rm g}}{dz\, dM_\star\, dq_\star} \frac{dM_\star}{dM} \frac{dq_\star}{dq}$$

Input: observational + semi analytical models



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