Self-interacting dark matter impact on pulsar timing array observations

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arXiv:2401.14450

Cosmology in the Alps, 20 March, 2024

Image credit: Simons Foundation

Radio Pulsar Timing Arrays

Numerous PTAs are measuring pulsar timing delays: NanoGRAV, Parkes PTA, European PTA, Chinese PTA . . .

images: NANOGrav

Gravitational Wave Detection

Gravitational waves create correlated timing delays between different pulsars:

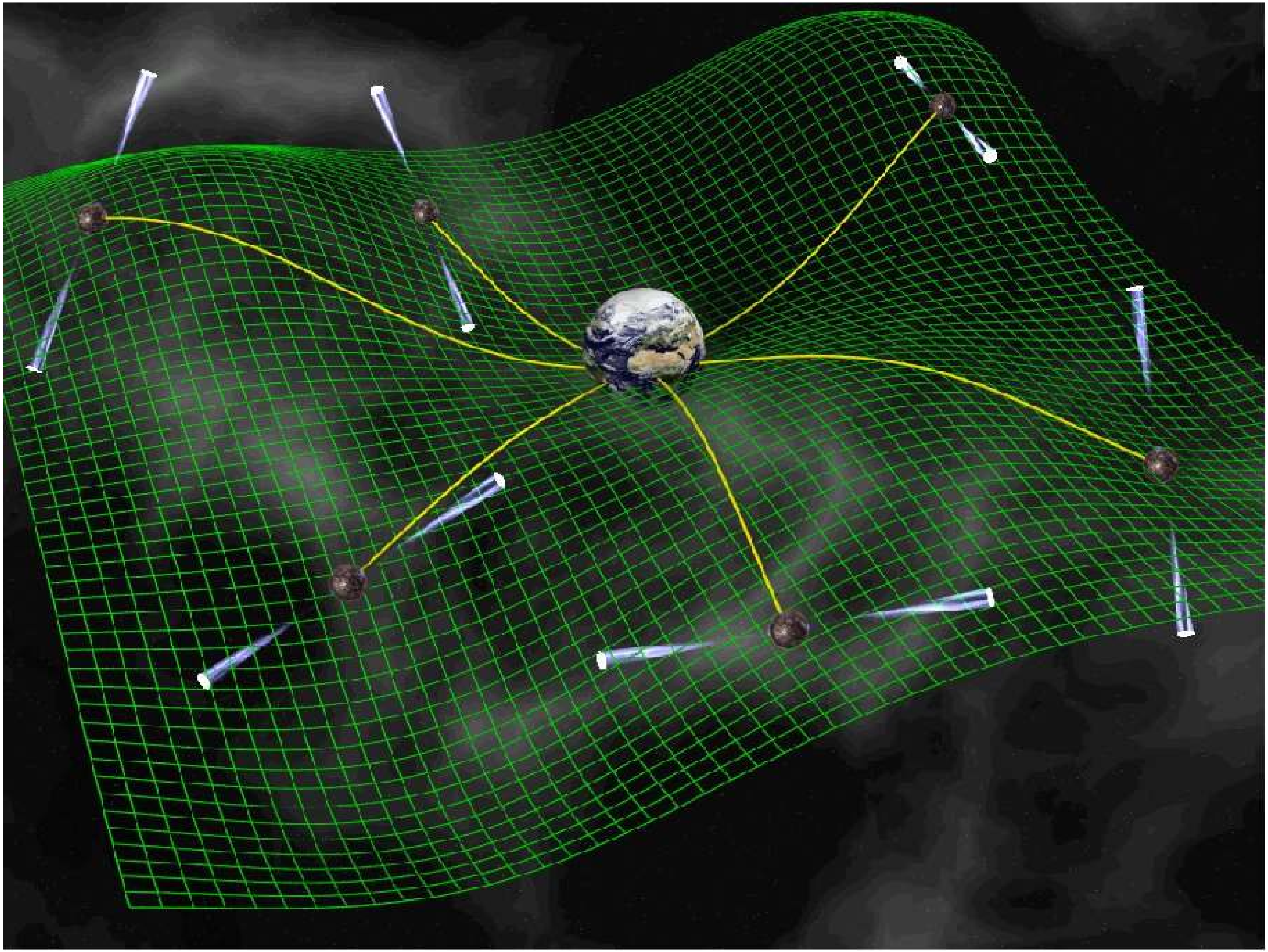
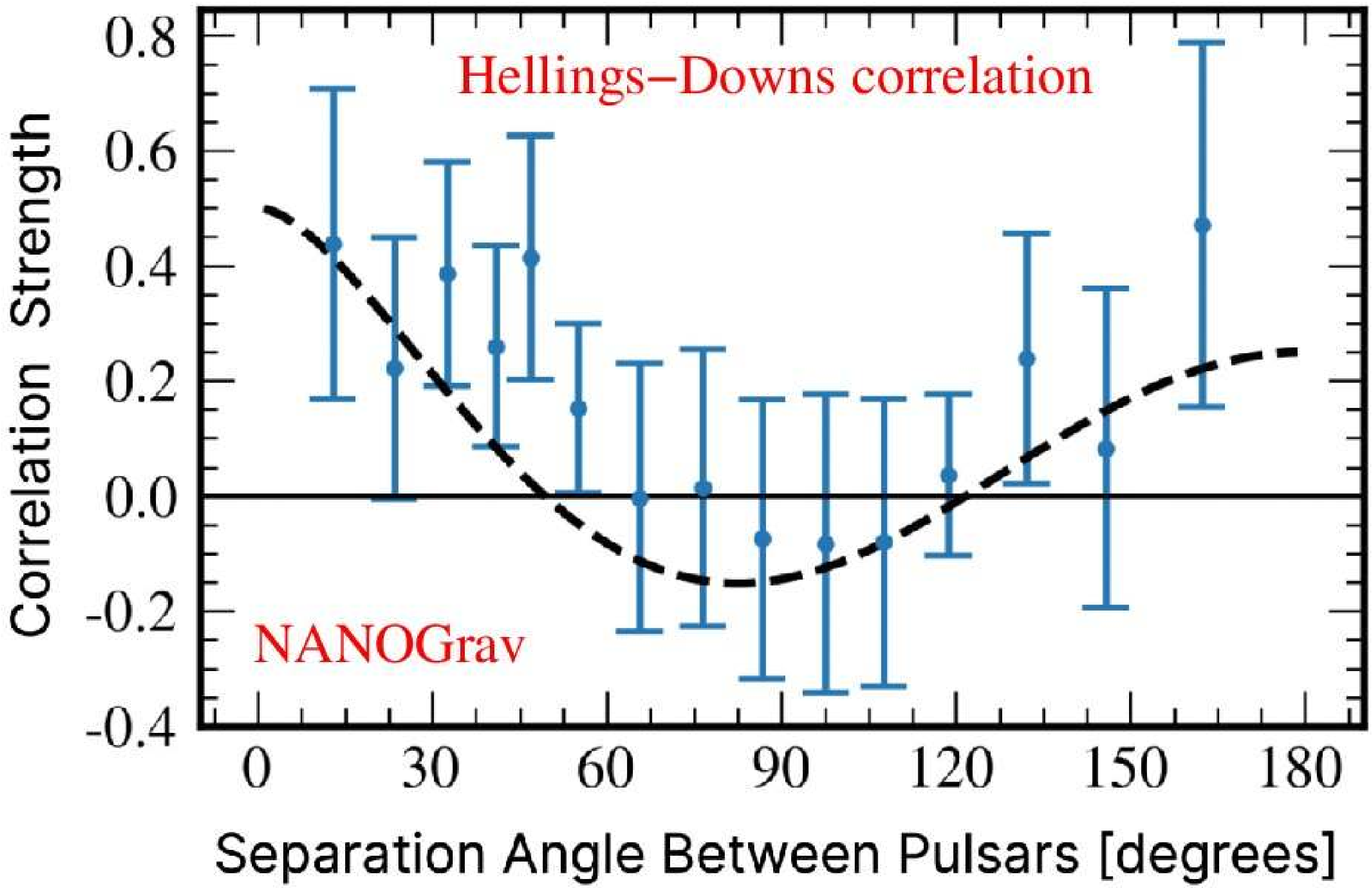


image: David J. Champion

Angular correlation power spectrum

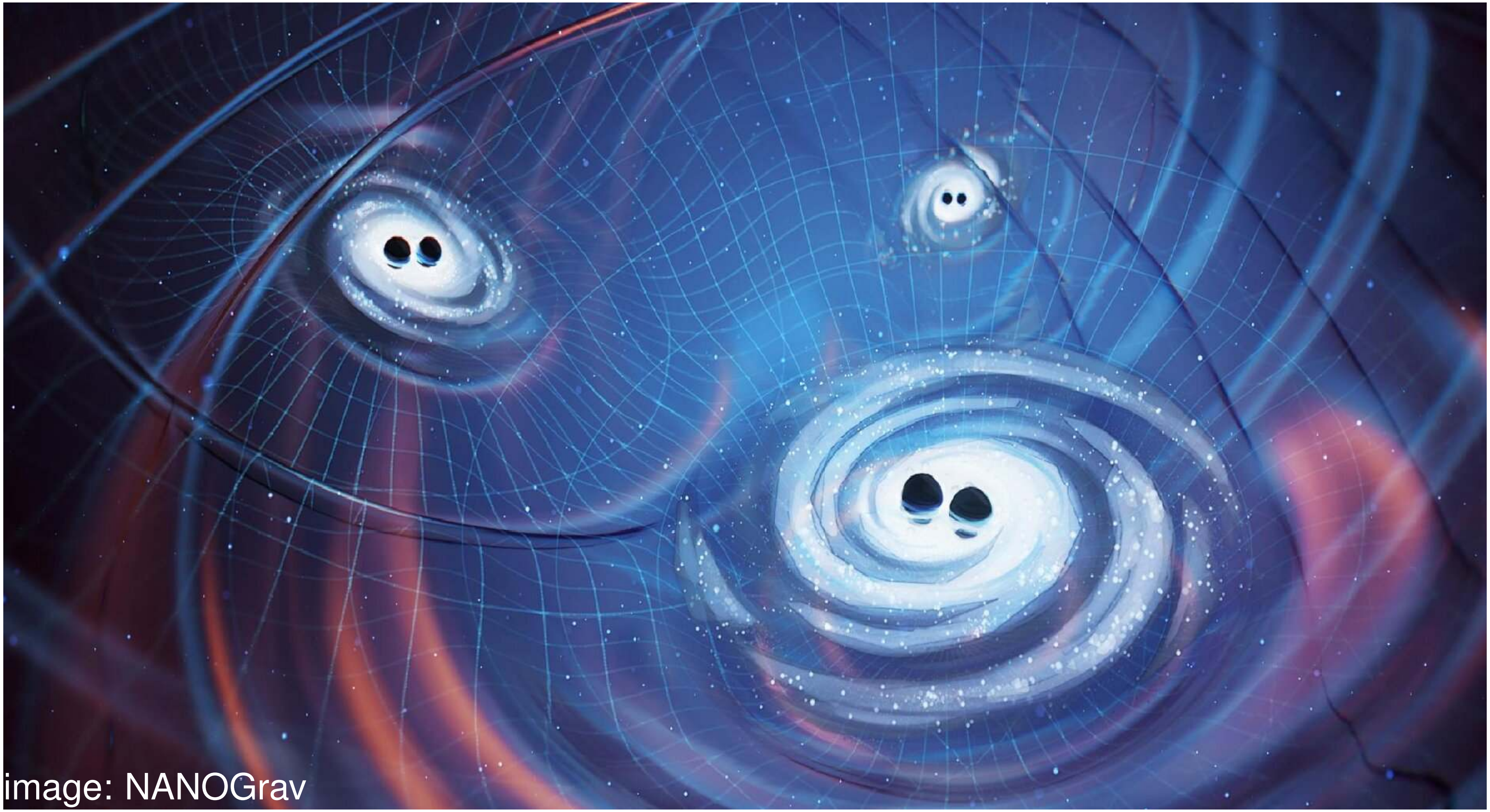
Proof of GW origin comes from angular correlations of timing delays
(Hellings & Downs, 1983)



NanoGRAV confirmed this signal in June 2023 (arXiv: 2306.16213)

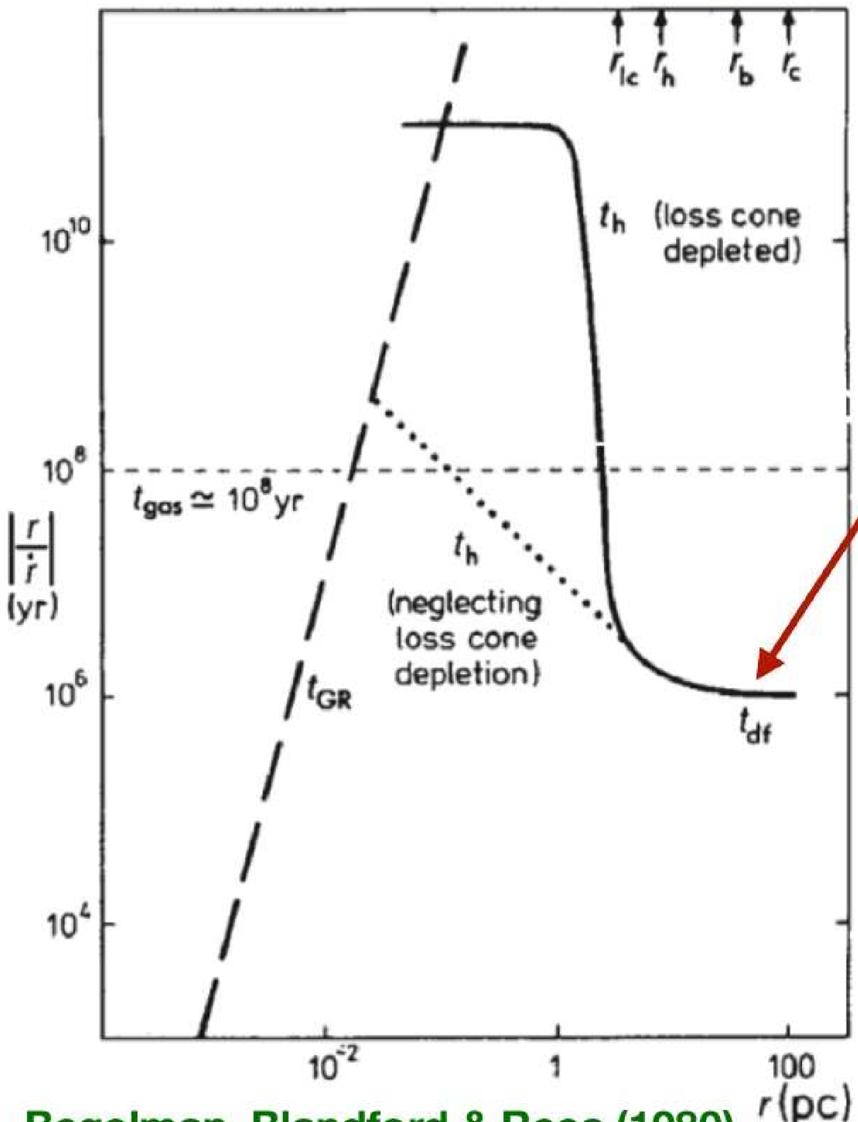
Origin of gravitational waves

Favorite astrophysical explanation is mergers of supermassive black holes (SMBHs) from galaxy mergers



But there is a problem: merger rate is not high enough to explain signal!

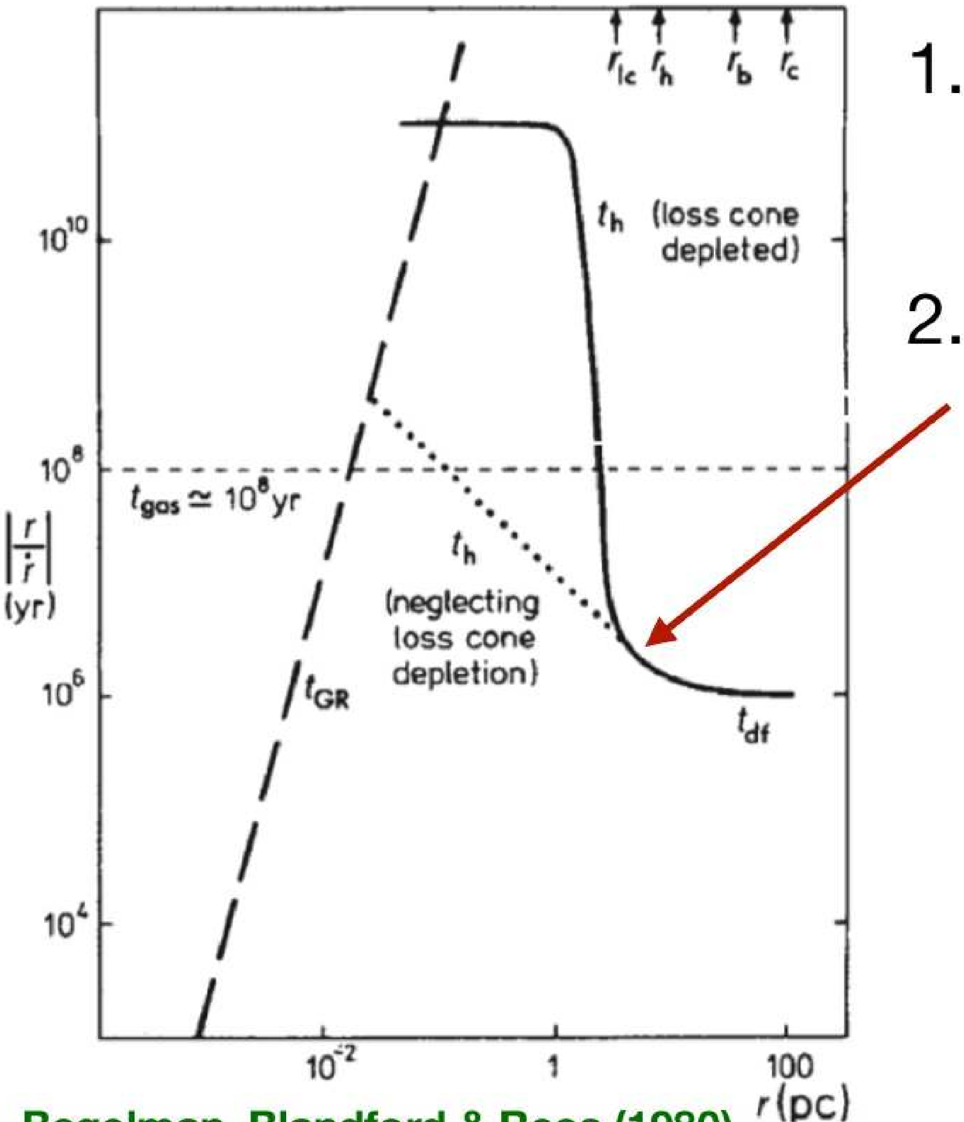
The final parsec problem



1. Dynamical friction shrinks binary

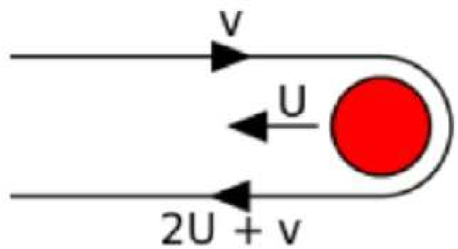
Begelman, Blandford & Rees (1980)

The final parsec problem

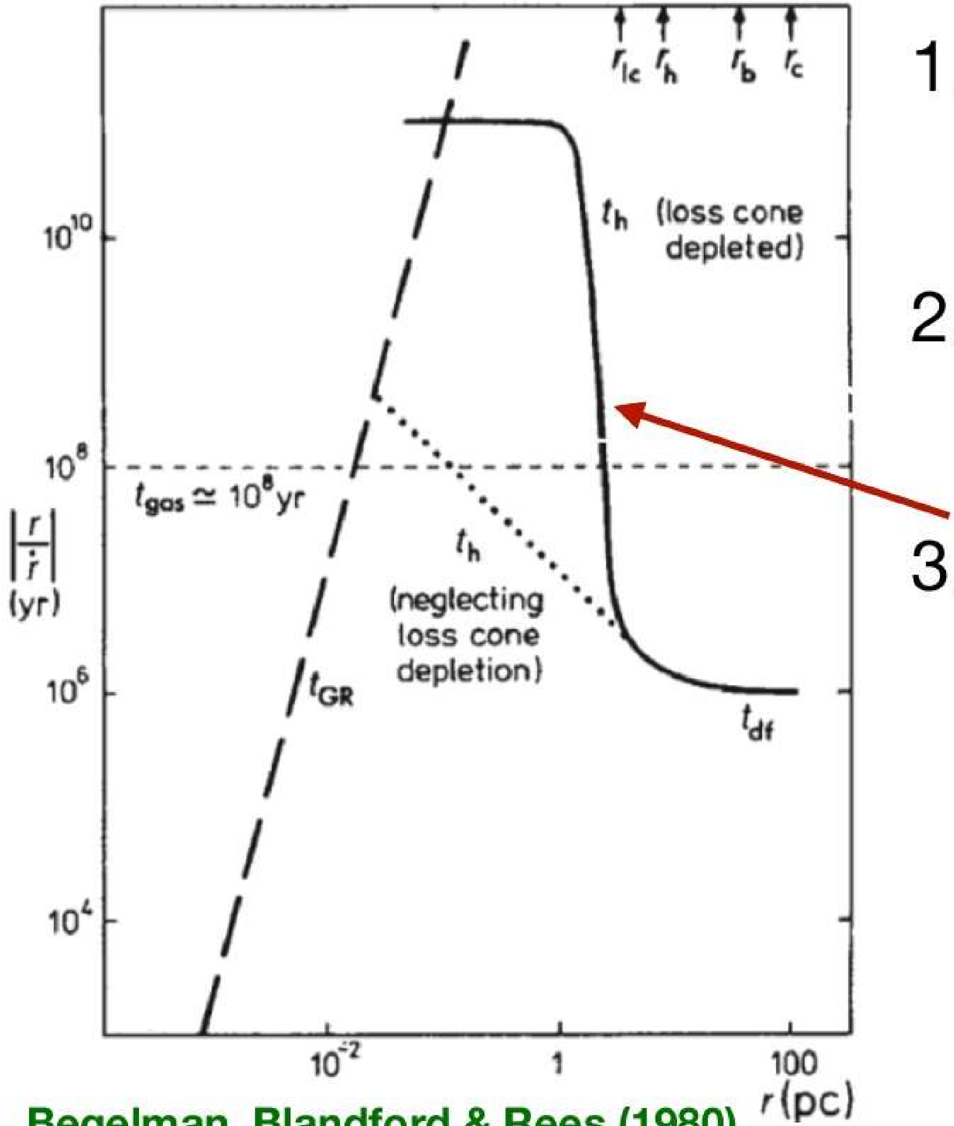


Begelman, Blandford & Rees (1980)

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



The final parsec problem



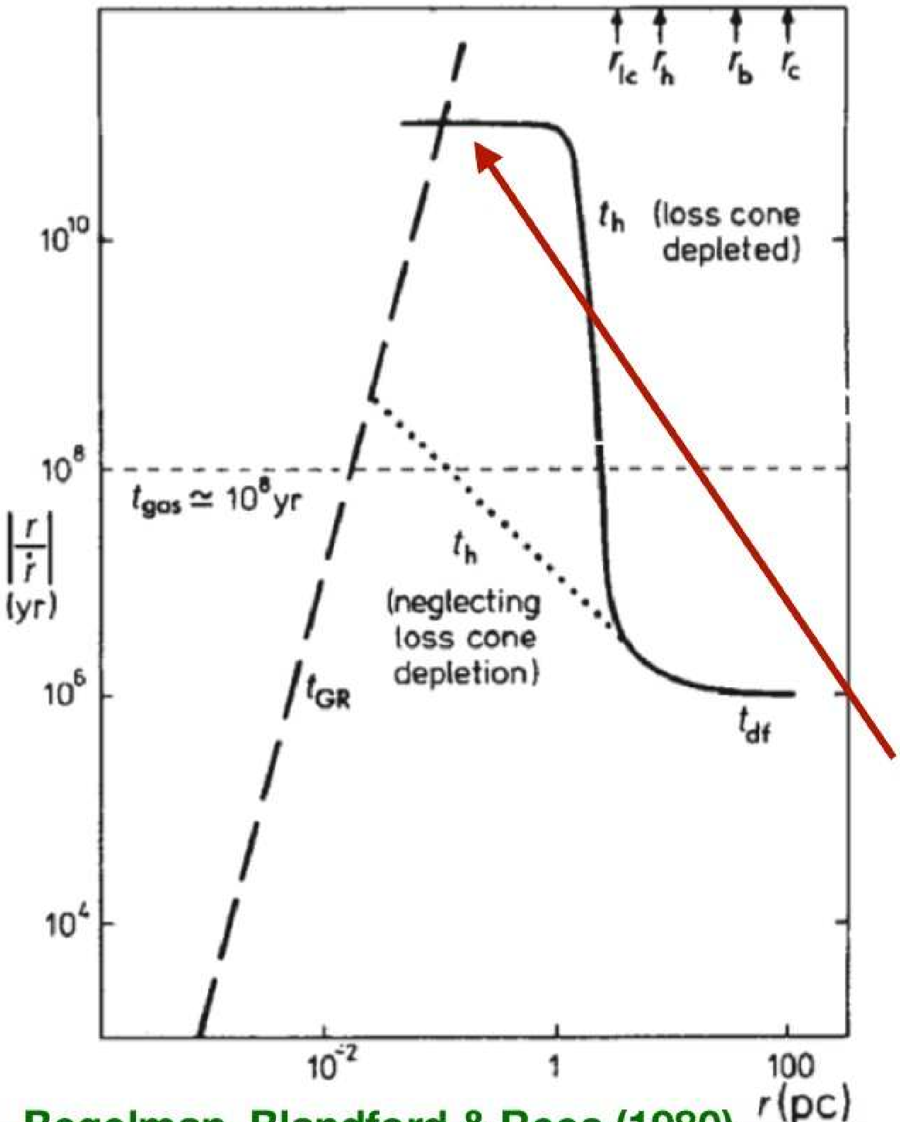
Begelman, Blandford & Rees (1980)

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

Gonzalo Alonso-Álvarez 8 Cornell THEP seminar

The final parsec problem



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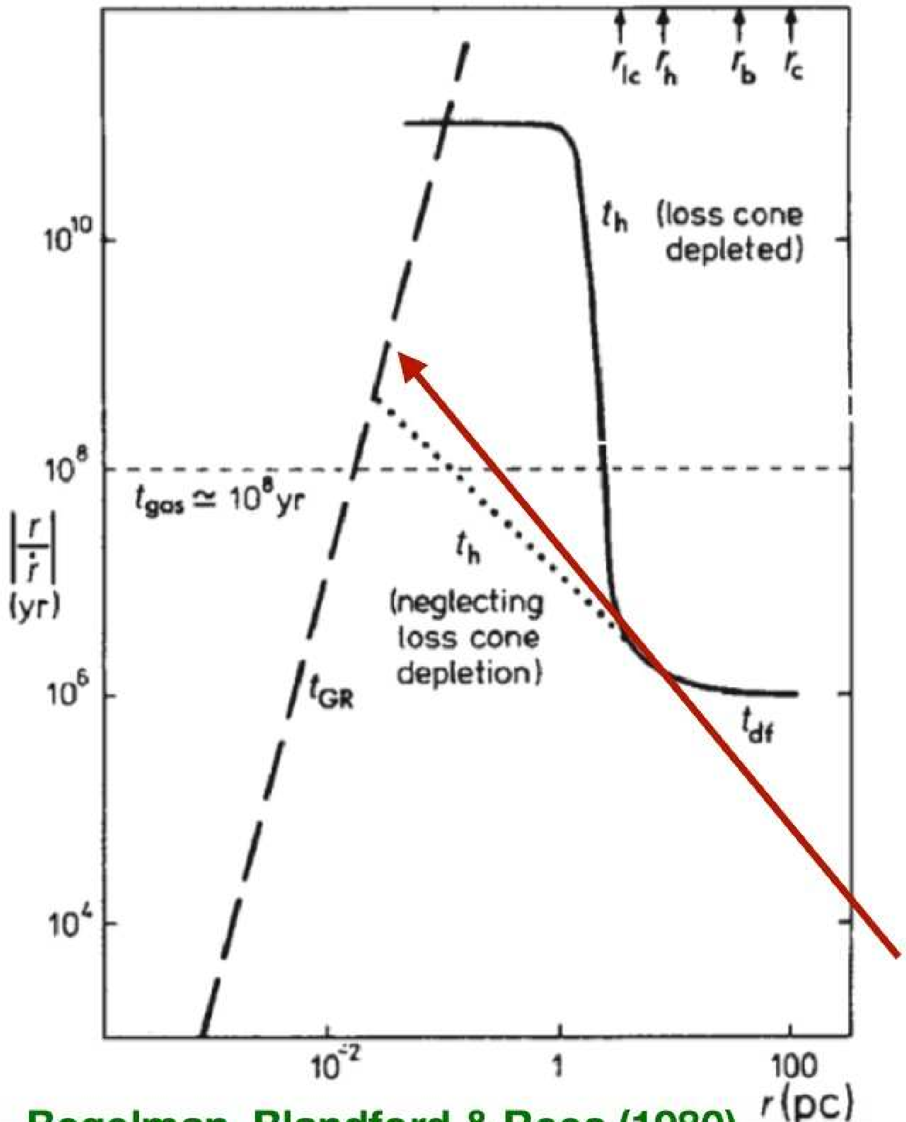
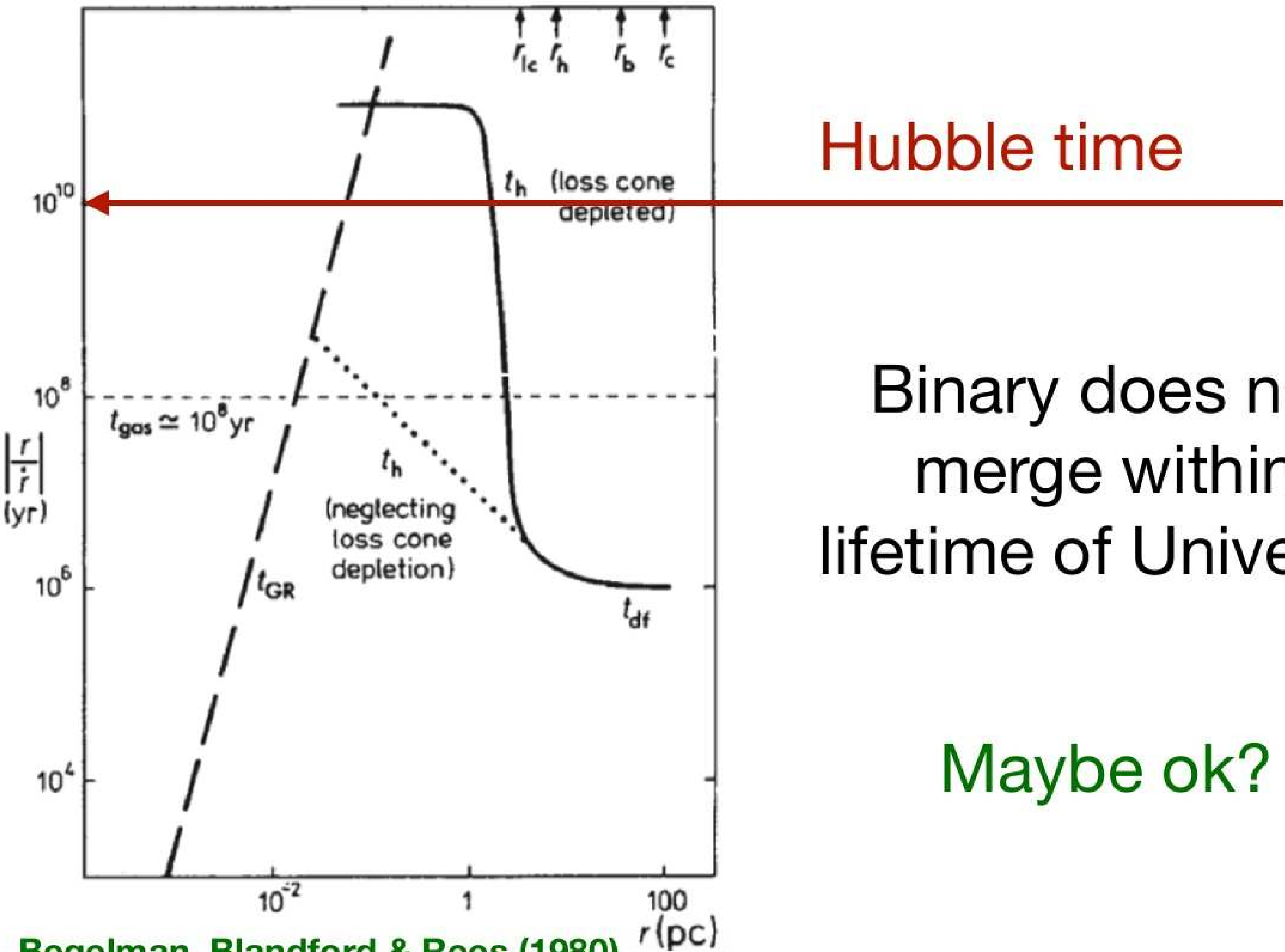


Begelman, Blandford & Rees (1980)

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

The final parsec problem



Binary does not merge within lifetime of Universe

Maybe ok?

Begelman, Blandford & Rees (1980)

New physics origins for GWs?

Beyond astrophysics, theorists have proposed other possible GW origins:

Inflationary GW

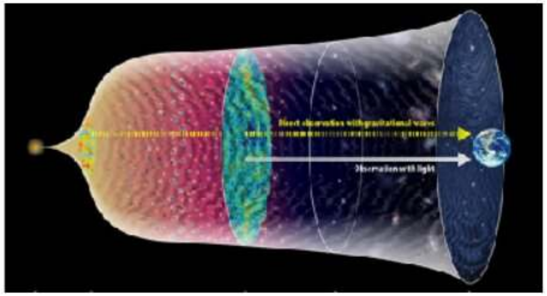


Image credit: NAOJ

Phase transitions

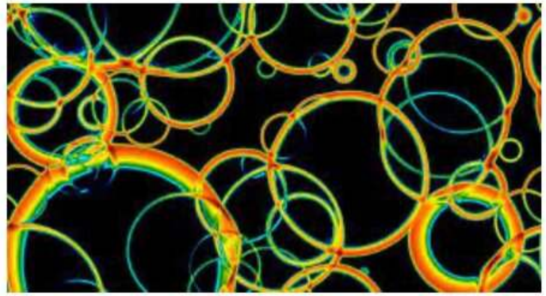


Image credit: Weir et al (2016)

Cosmic strings

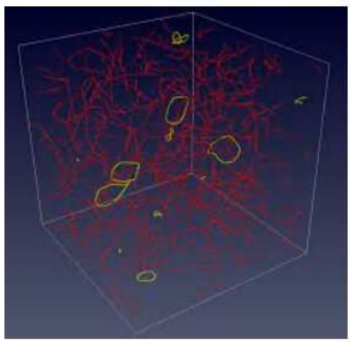


Image credit: Kitajima et al (2023)

Domain Walls

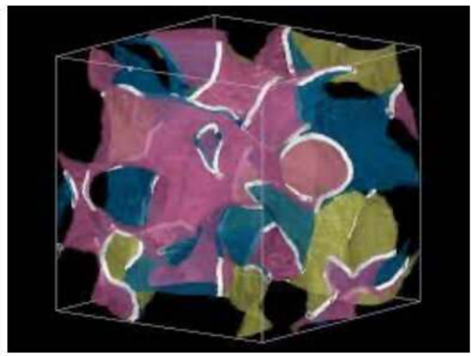


Image credit: Hiramatsu et al (2013)

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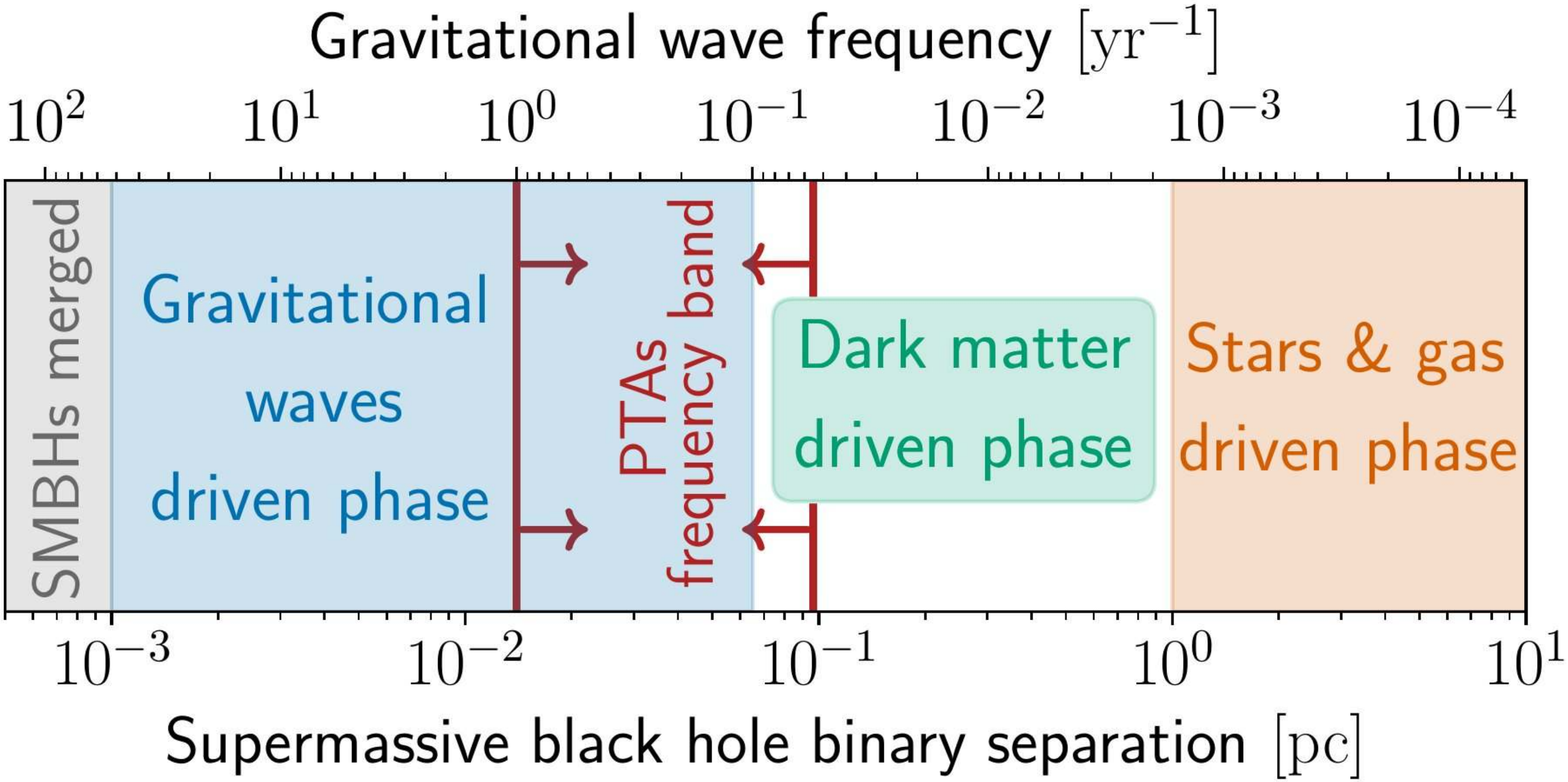
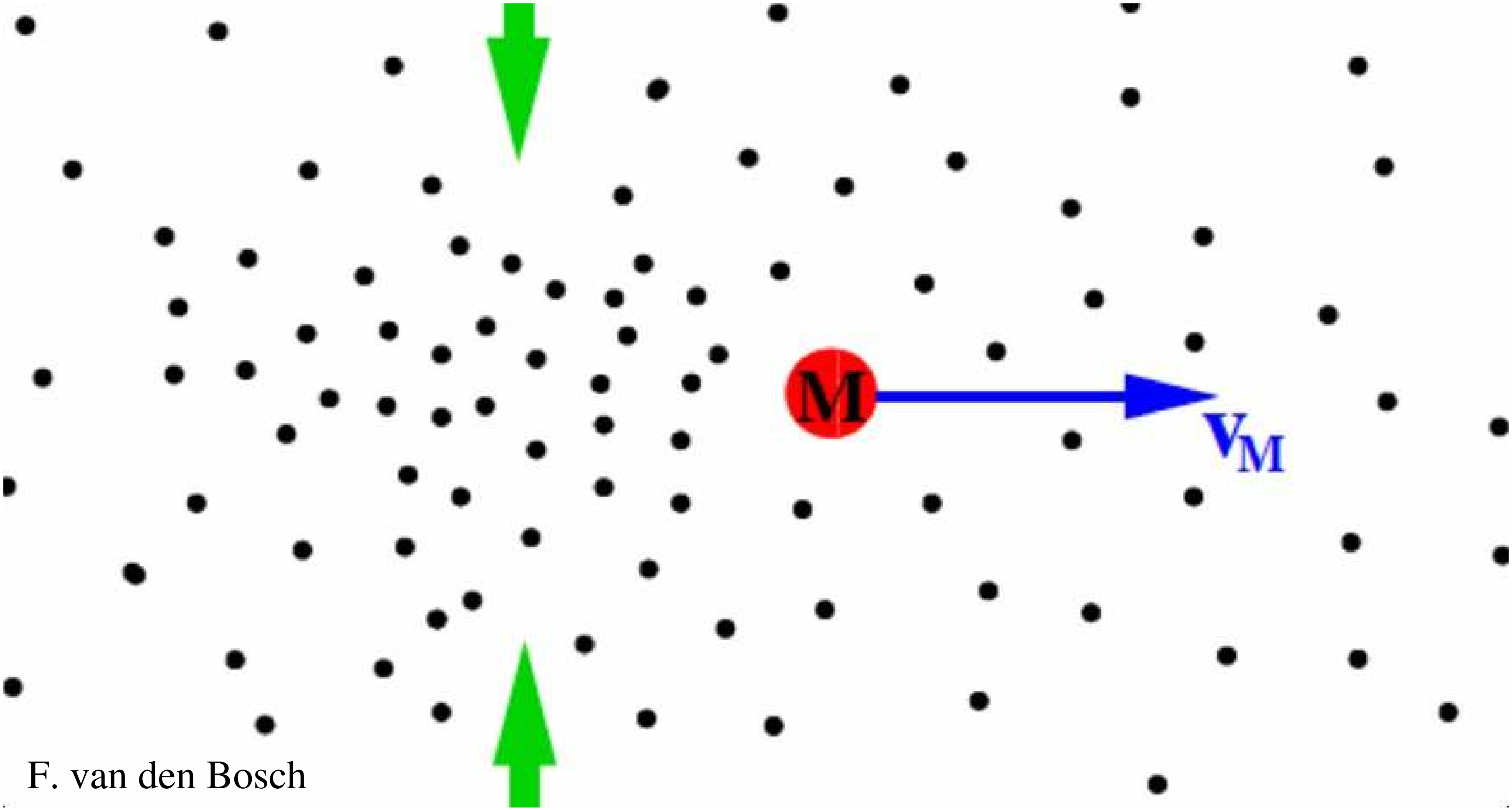
Instead, we propose that dark matter dynamical friction could solve the final parsec problem for SMBHs

Our proposal



Dynamical friction

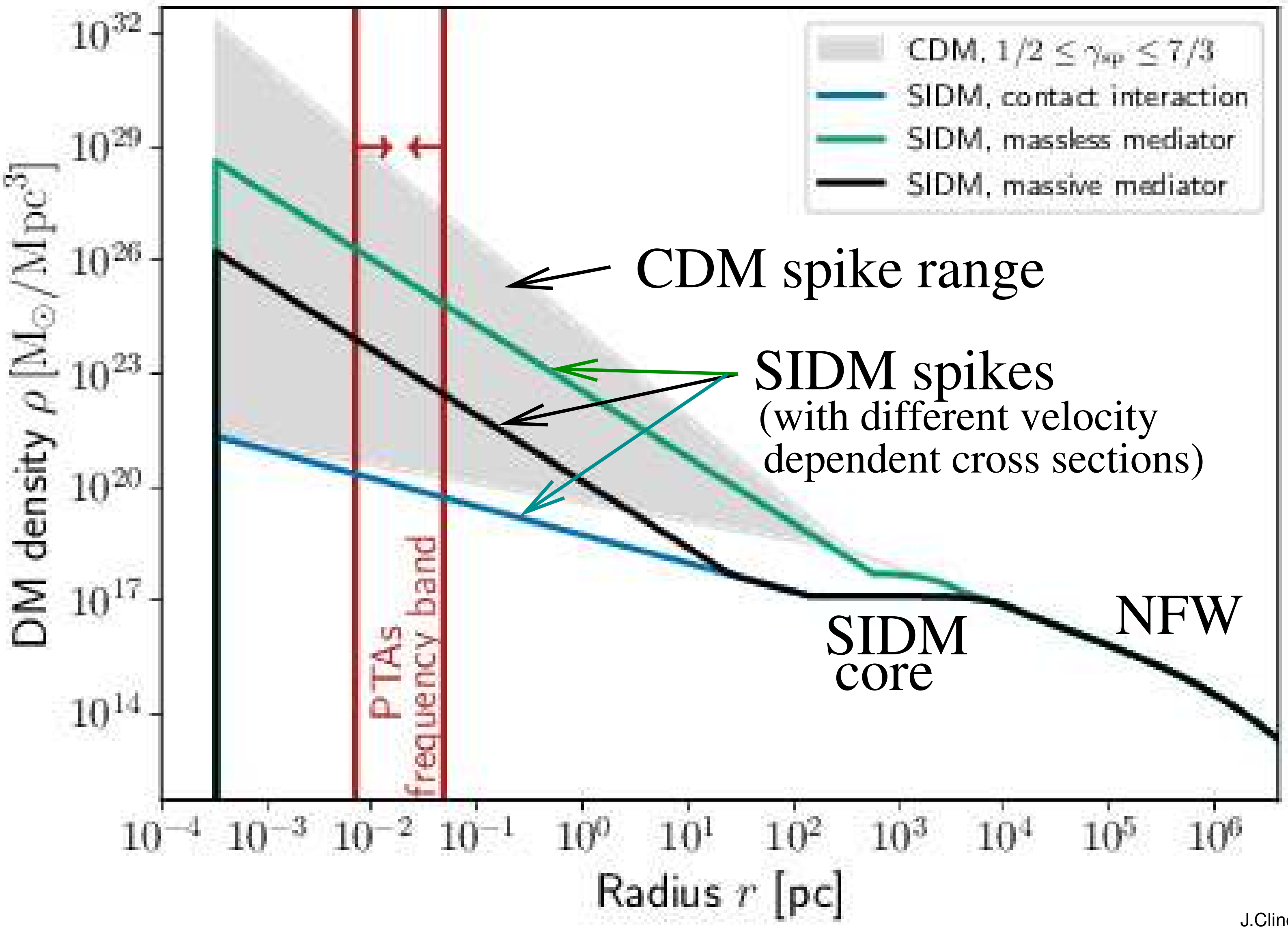
Chandrasekhar (1943) showed that a heavy body moving through cloud of lighter particles experiences gravitational drag force:



SMBHs move through a cloud of dark matter; can this provide enough friction to solve final parsec problem?

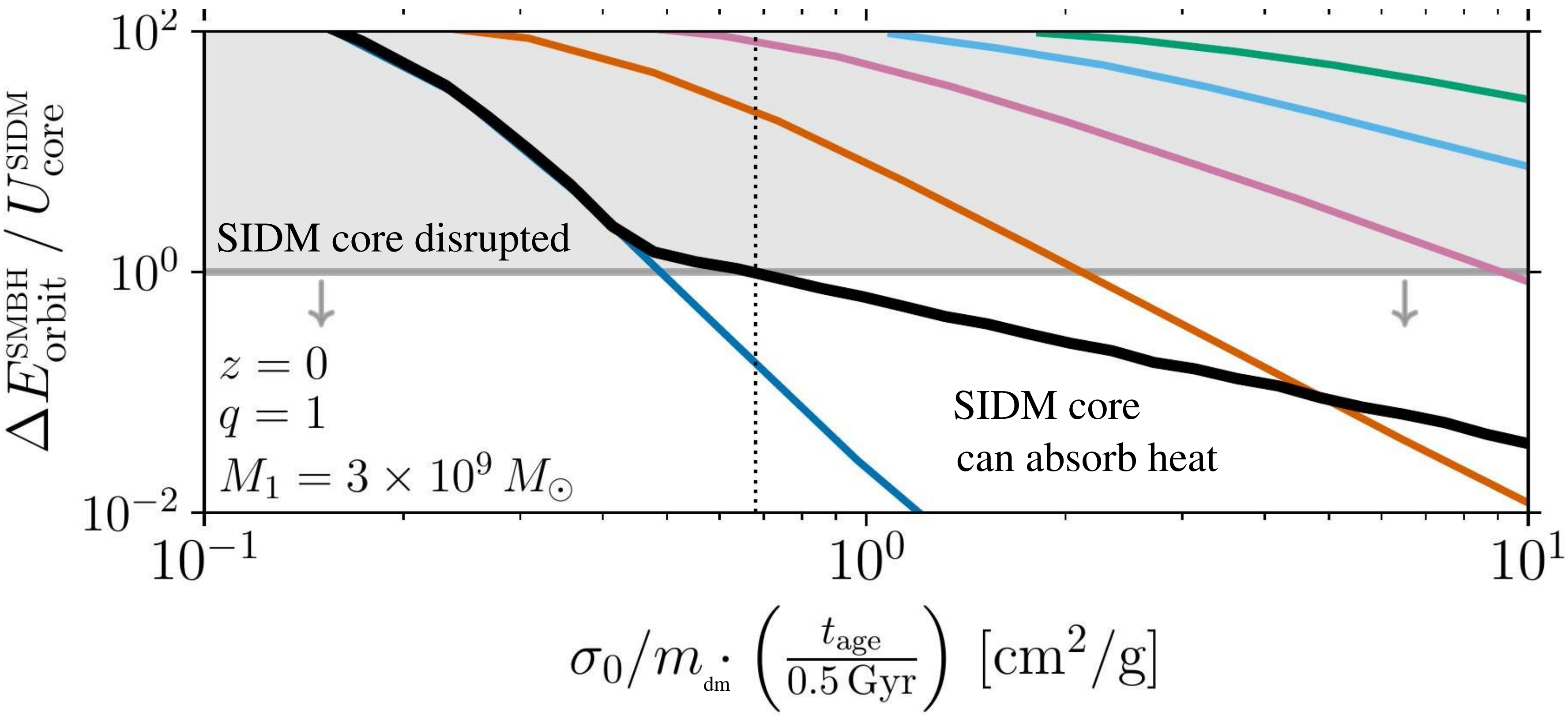
DM "spike" around SMBHs

Dark matter density is enhanced near black holes. The spike profile depends on properties of the DM: noninteracting (CDM) or self-interacting (SIDM).



Can spike absorb the heat produced?

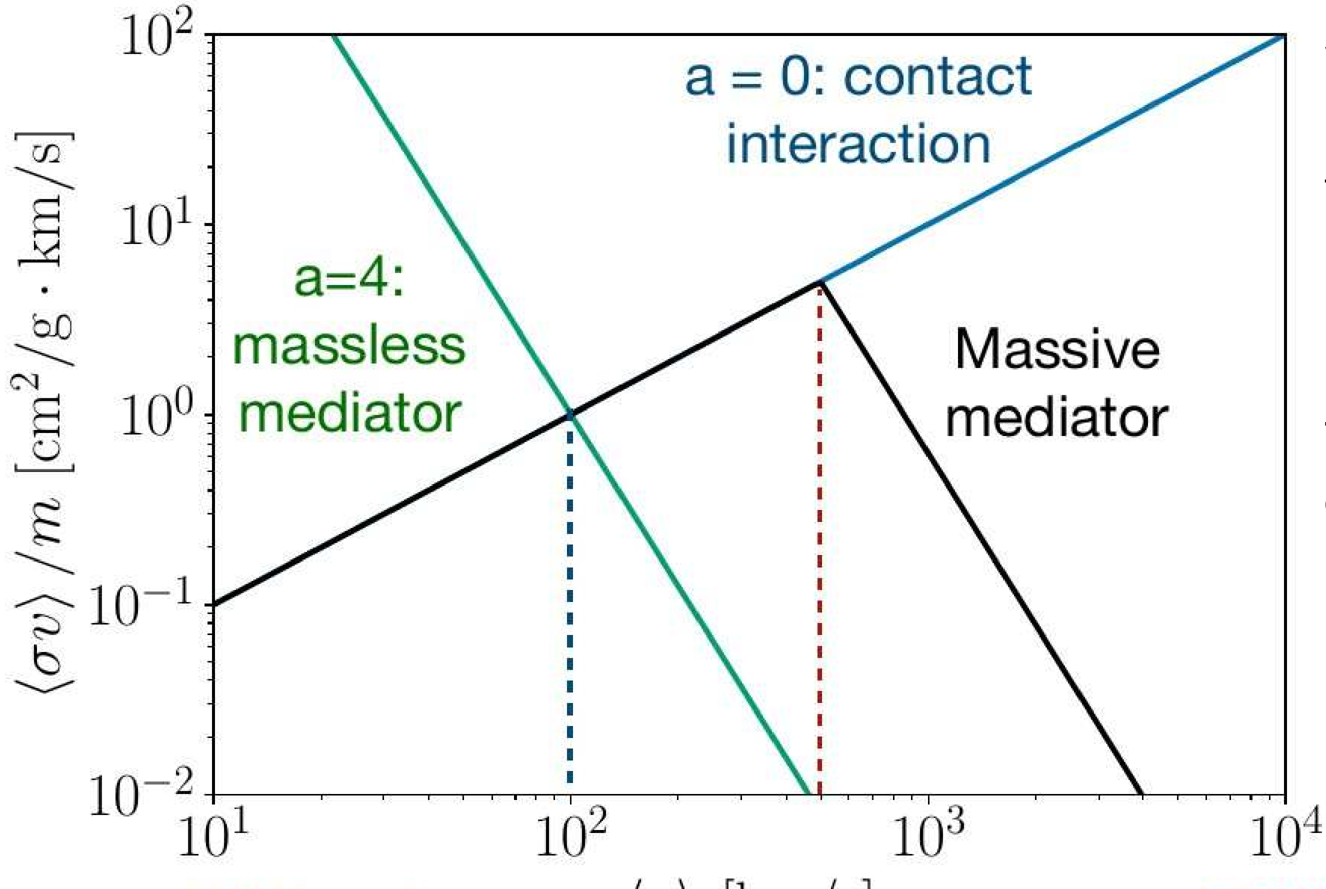
The SMBHs must lose $\sim GM_1M_2/(0.1\,\mathrm{pc})$ of energy to merge.
Compare to binding energy of spike, $\sim G\int\rho(x_1)\rho(x_2)/|\vec{x}_1-\vec{x}_2|$.
The spikes are blown apart, but the SIDM core may survive.



DM Self-interaction cross section

The SIDM cross section may depend on relative velocity of DM particles,

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



$v_{\rm ref} = 100\,\mathrm{km/s}$ $v_{\rm t} = 500\,\mathrm{km/s}$

We model massive mediator exchange by the black line:

$a = 0$ for $v < v_t$,

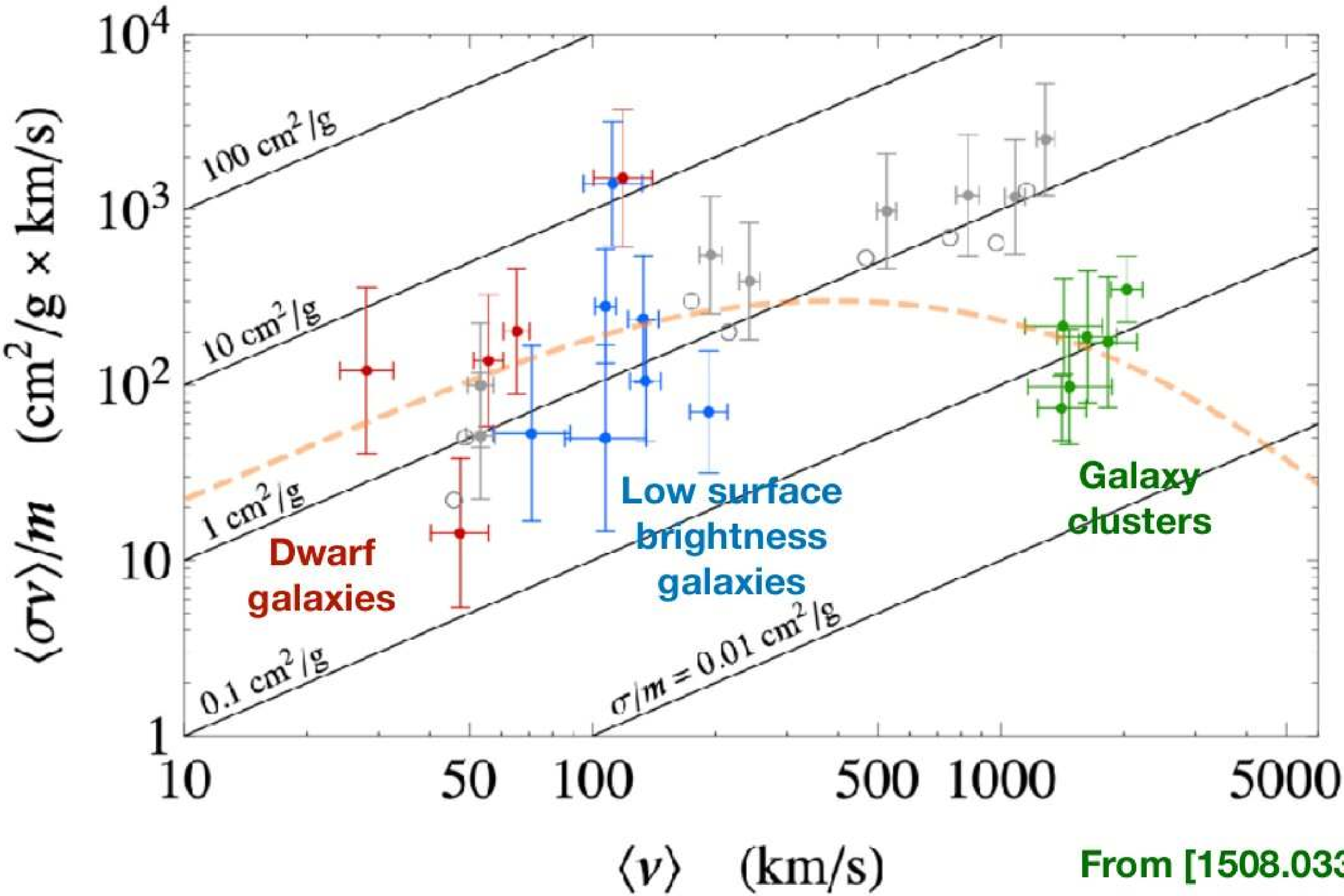
$a = 4$ for $v > v_t$.

Transition speed v_t goes as (mediator mass / DM mass) $\times c$.

Mediator could be "dark photon"

Velocity-dependent self-interactions

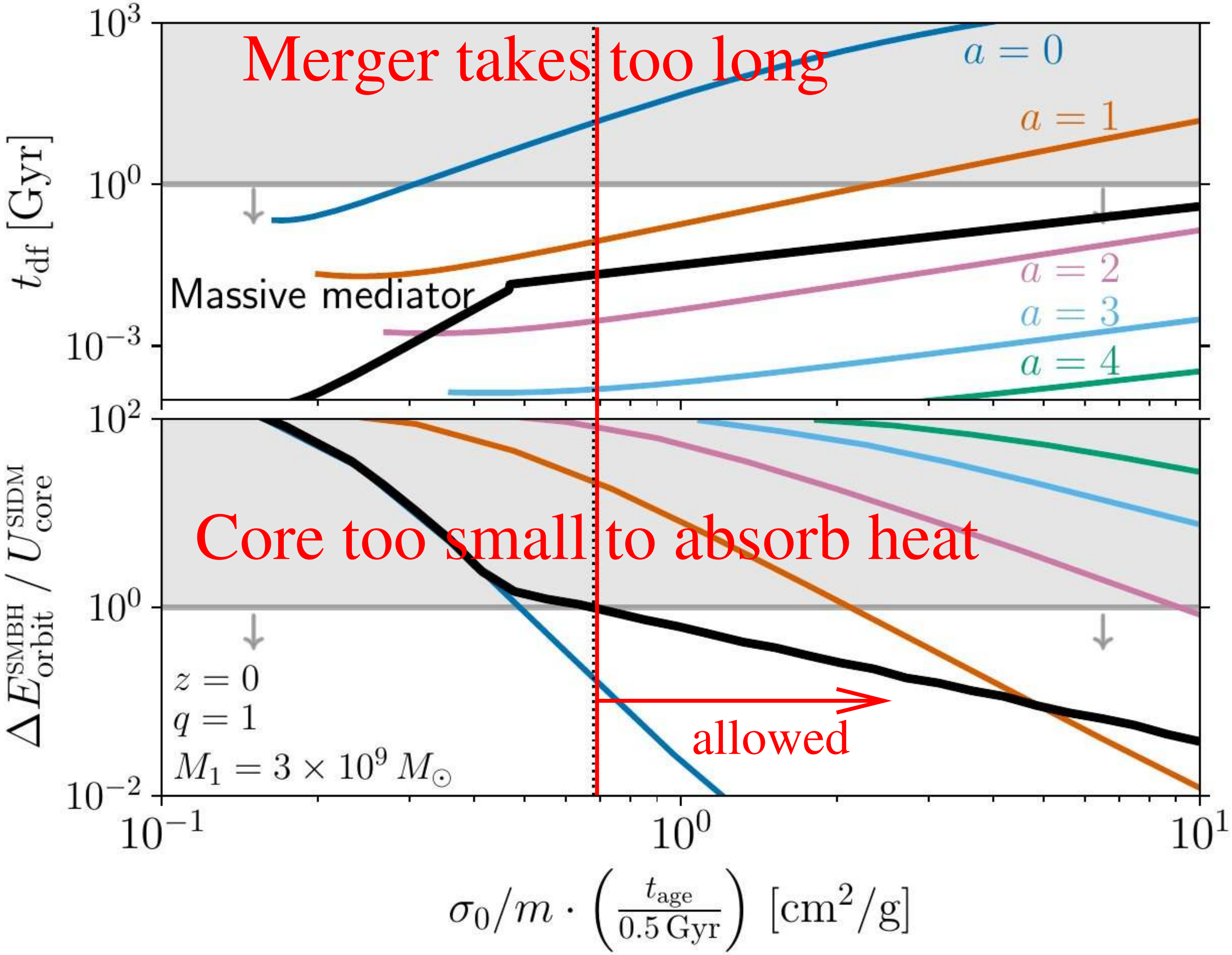
Velocity-dependent SIDM scattering is favored for solving small-scale structure problems of cold DM,



From [1508.03339]

Dark photon model resolves tensions

Tension: absorbing the frictional heat favors $a = 0$, while solving the final parsec problem favors $a > 0$:



Massive mediator (dark photon) reconciles the two requirements

Gravitational wave signal

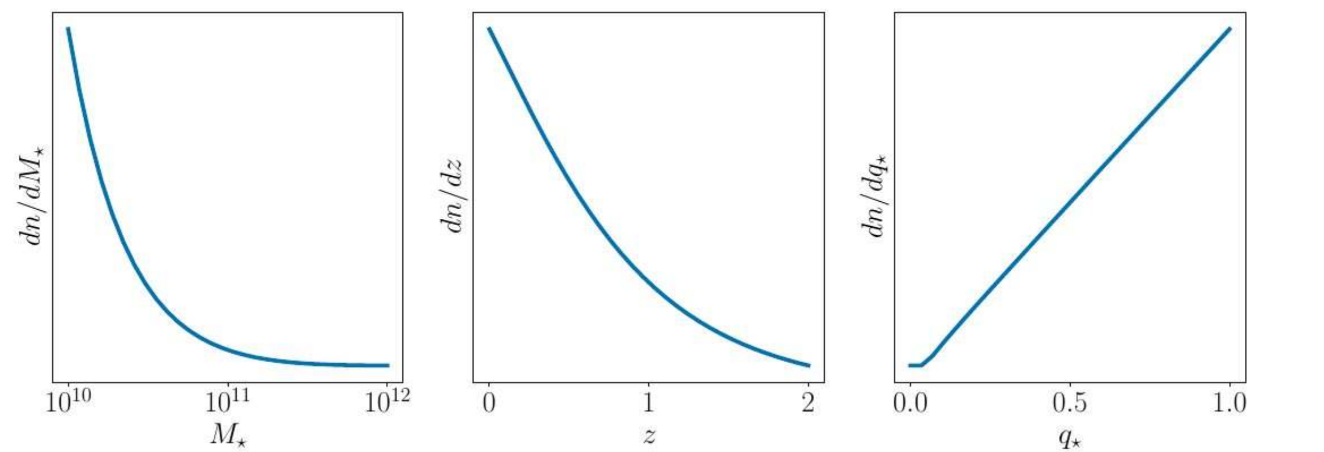
Energy spectrum of GWs emitted in a merger with separation R:

$$\frac{dE}{df} = \frac{GqM_1^2}{3fR} \times \frac{P_{\rm gw}}{P_{\rm gw} + P_{\rm df}}$$

where $R \propto f^{-2/3}$, $q = M_2/M_1 \leq 1$, $P_{\rm gw} =$ power emitted in GWs, $P_{\rm df} =$ power lost to dynamical friction.

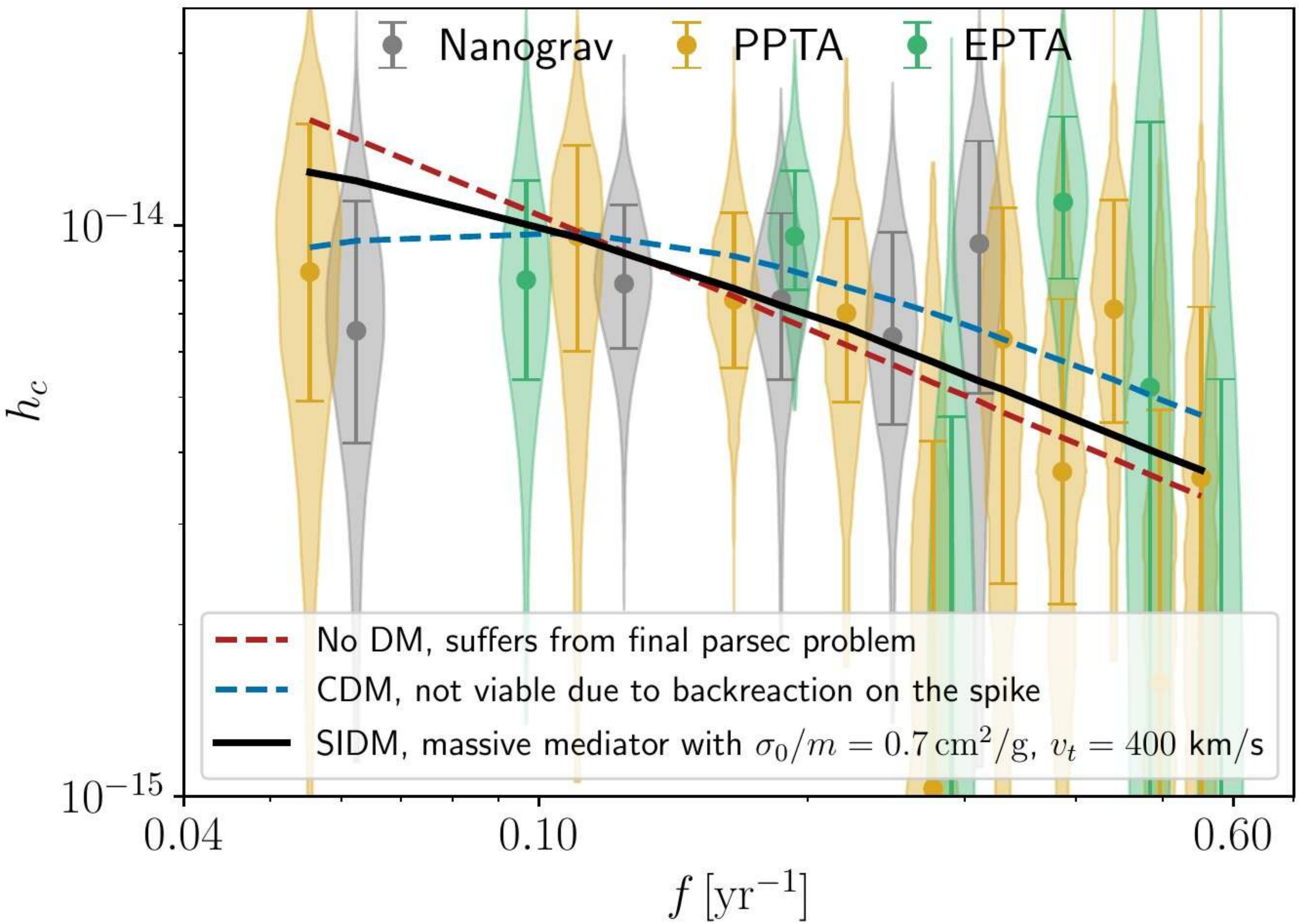
Must integrate over cosmological SMBH population; characteristic strain is

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



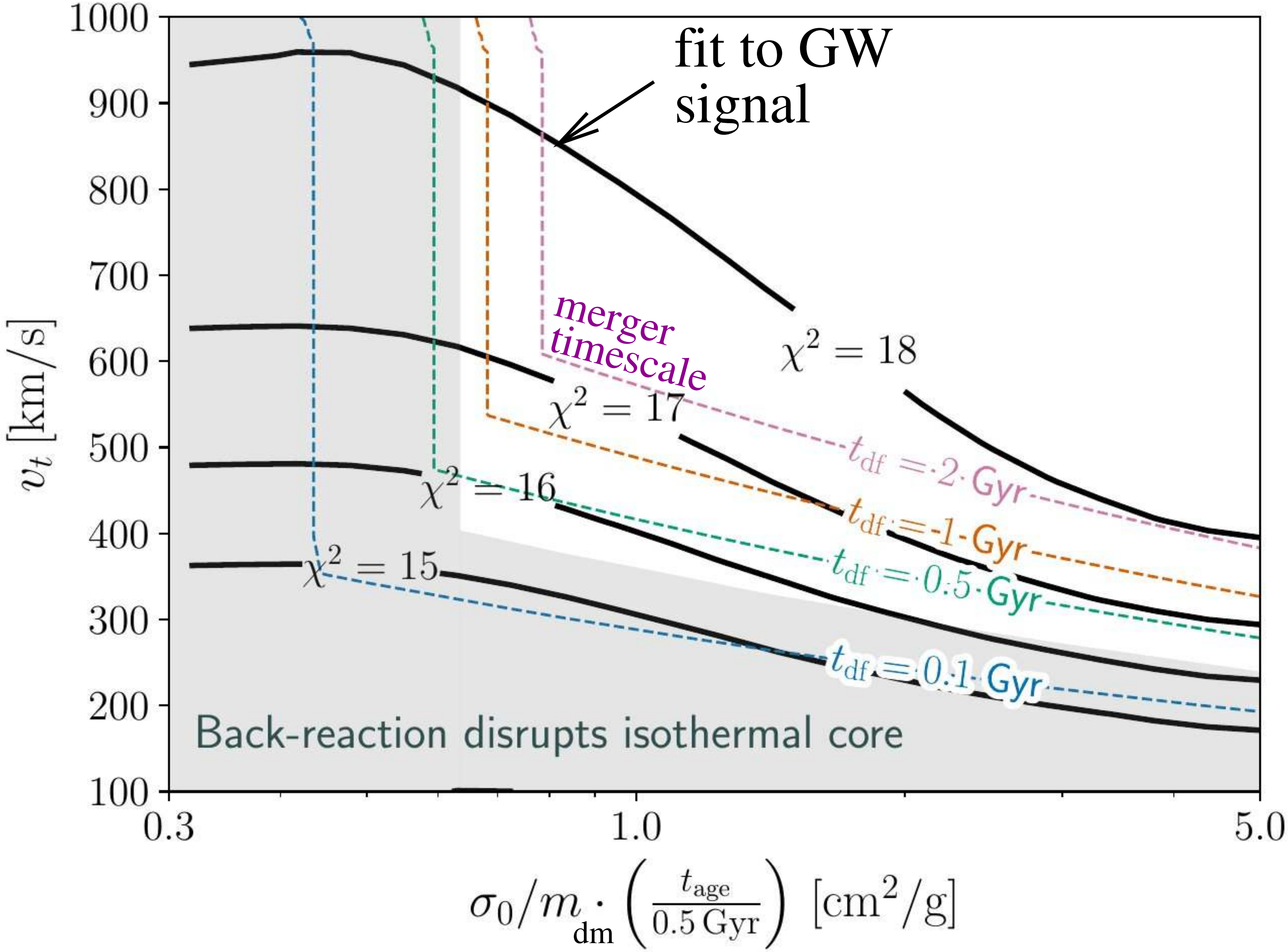
Characteristic strain spectrum

Characteristic strain versus frequency; DM friction softens spectrum at low f



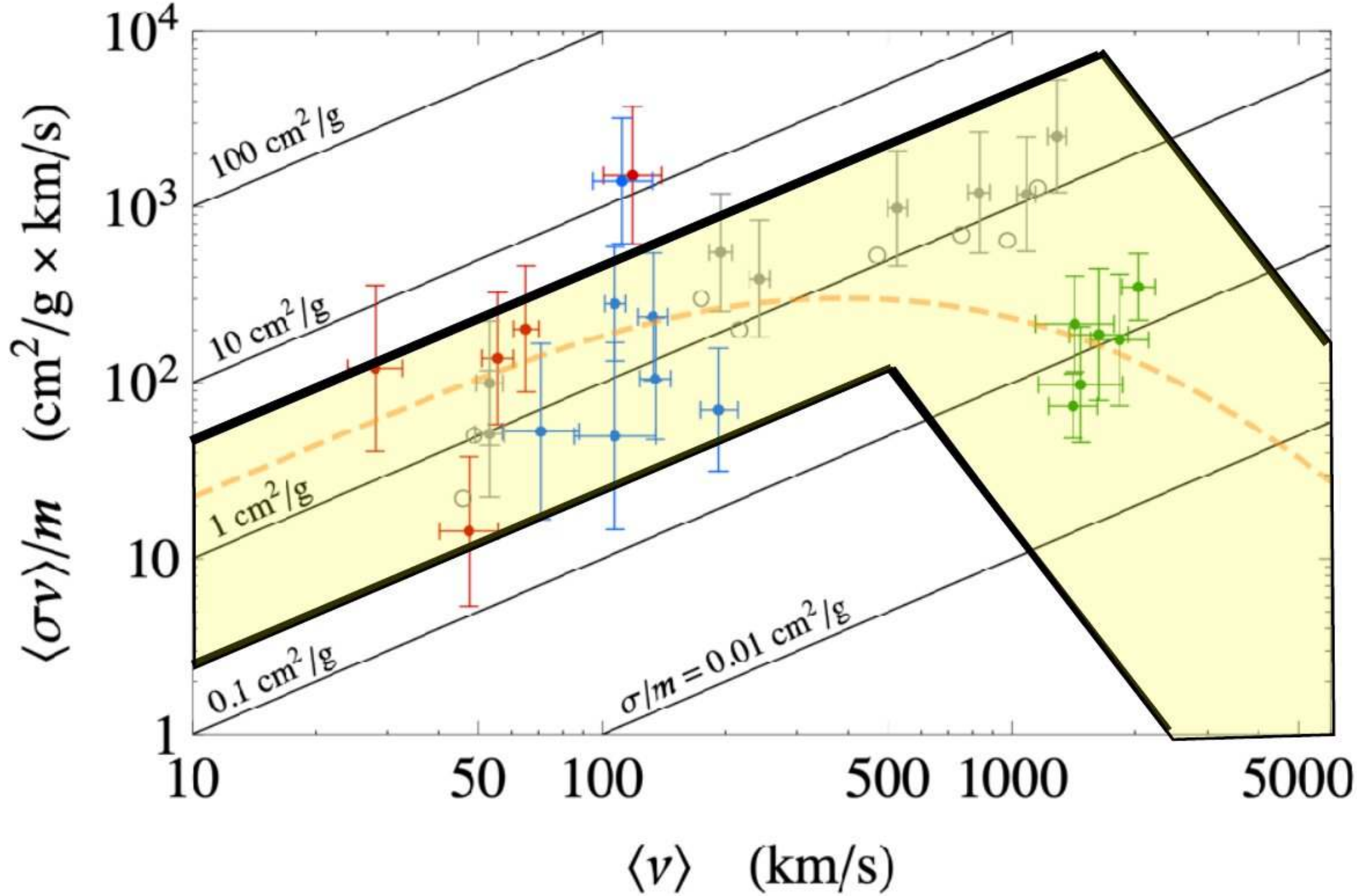
Fit to GW signal

Best fits prefers maximum possible DM friction



Compatibility w/ small scale structure

GW allowed cross sections overlap with small scale structure determinations (shaded region)



Conclusions

Pulsar timing observes stochastic GW background

Supermassive black holes are favored astrophysical source

But they suffer from decades-old final parsec problem

Self-interacting dark matter can provide dynamical friction to solve the problem

Required parameters agree with those already suggested to solve small-scale structure problems of cold dark matter

Simulations may be required to confirm the picture

Backup: GW versus DF power

Power in GW emission:

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

Power in dynamical friction:

$$\begin{aligned} P_{\rm df} &= 12\pi\, q^2 \sqrt{1+q}\, (GM_1)^{3/2} R^{1/2} \\ &\times \left[\frac{N_1(q)}{q^3} \rho_{\rm sp}\left(\frac{qR}{1+q}\right) + N_2(q) \rho_{\rm sp}\left(\frac{R}{1+q}\right) \right] \end{aligned}$$

$N_i =$ fraction of DM particles in spike with speed less than ith BH.