Supermassive Black Hole Binaries in Ultralight Dark Matter

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Rice University

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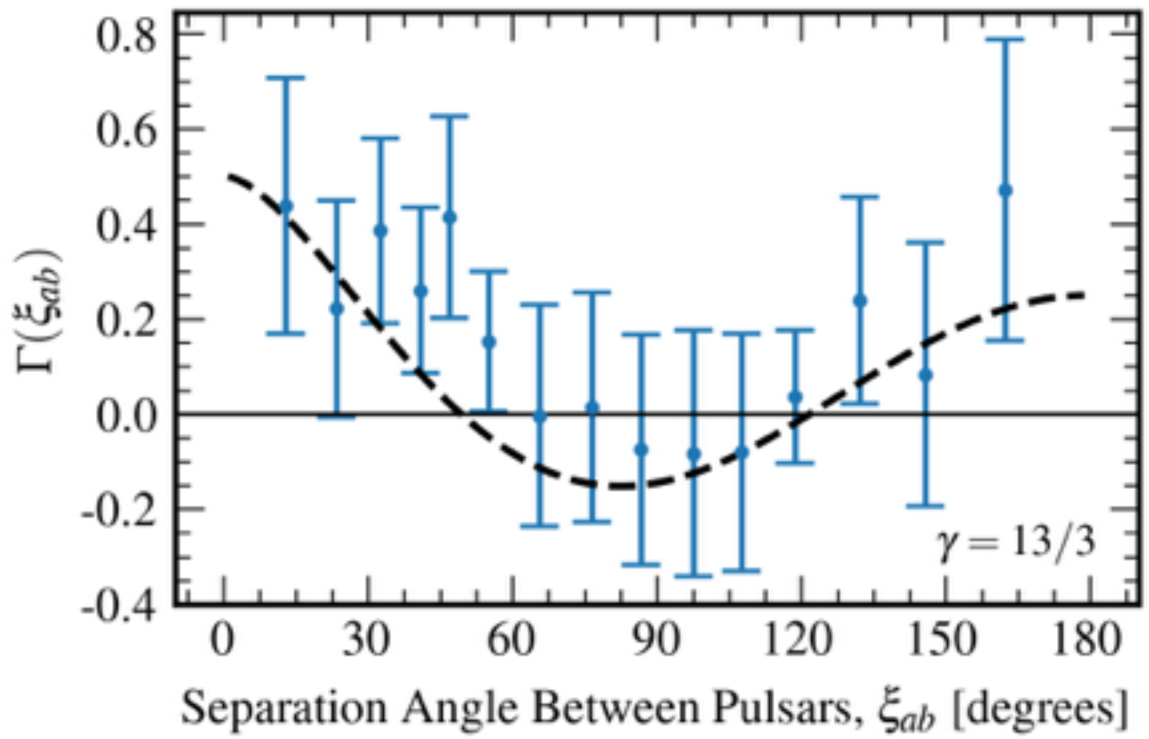
15-year pulsar-timing data:
A stochastic gravitational wave signal correlated among 67 pulsars



G. Agazie *et al.* (NANOGrav), 2023

Source:

Exotic sources:

Inflation
Scalar induced gravitational waves
Domain walls
Cosmic strings
First-order phase transitions

or,
A population of supermassive black hole (SMBH) binaries

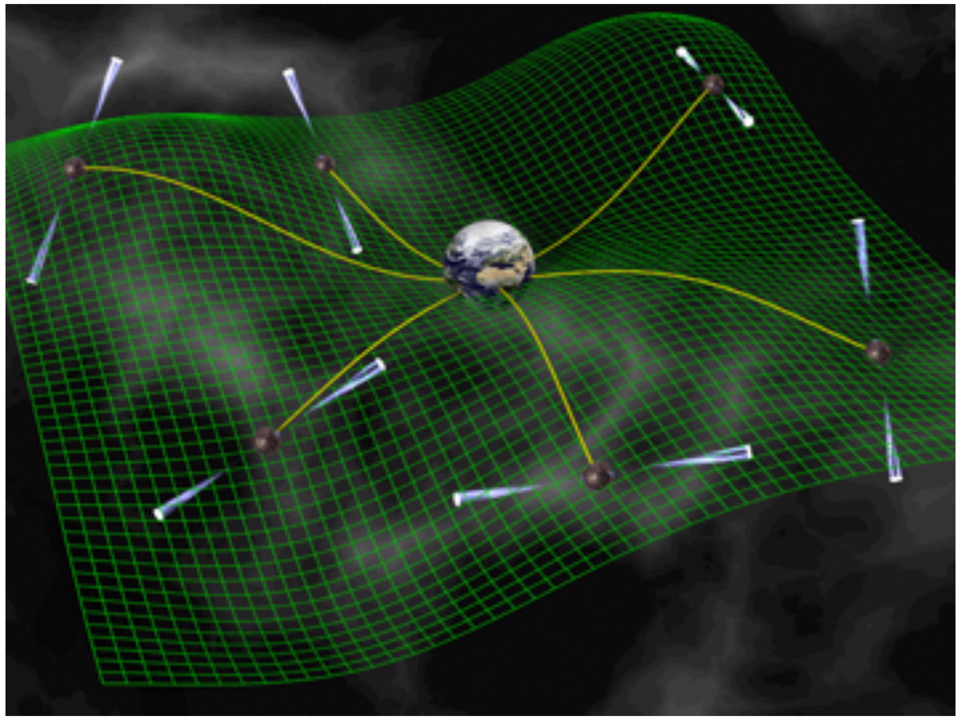
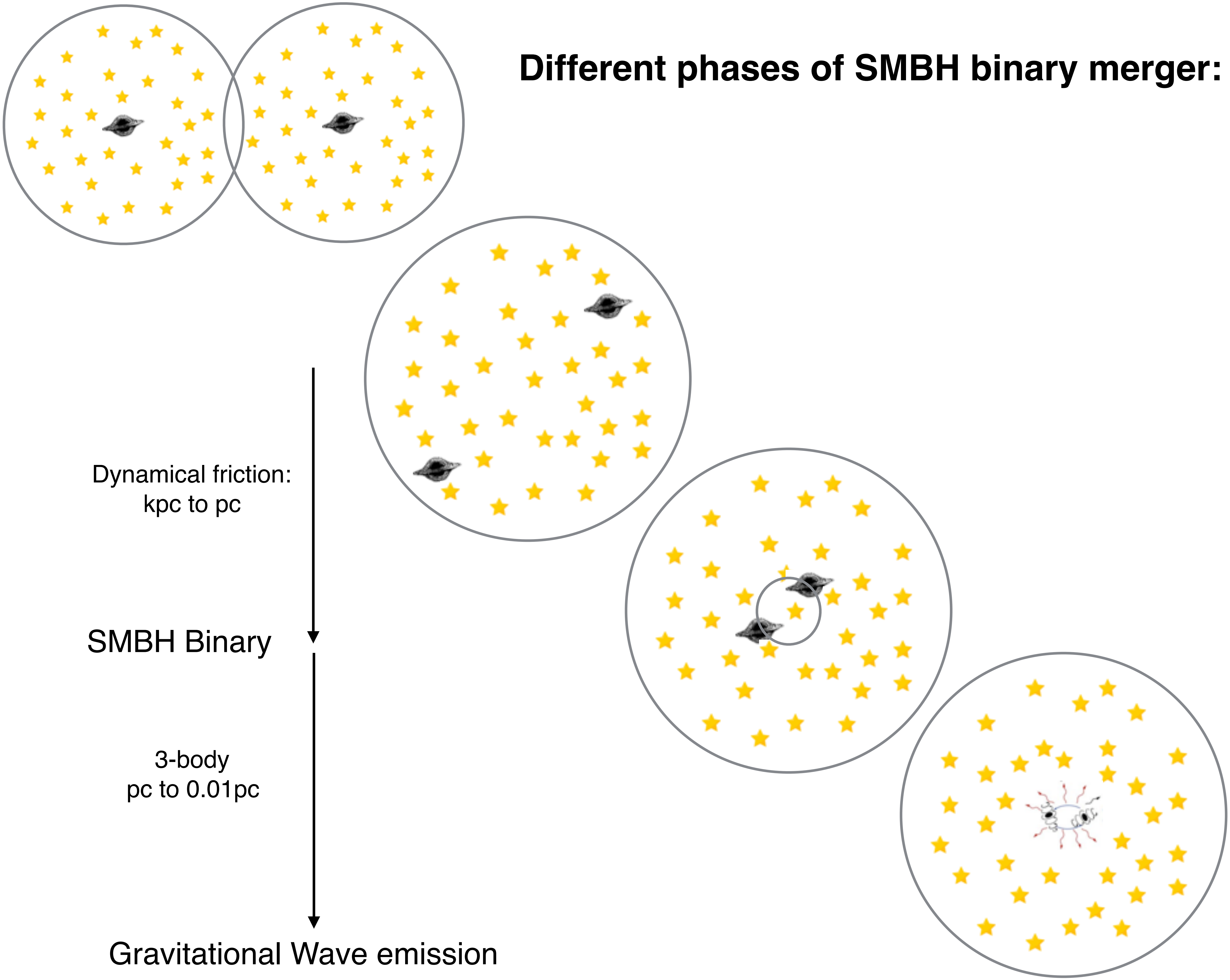


Image credit: David J. Champion

Different phases of SMBH binary merger:

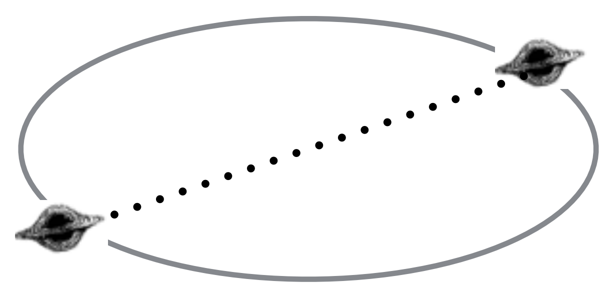


Dynamical Friction:

$$\mathbf{F}_{\mathrm{DF}} \sim -4\pi G^2 M^2 \rho \ln \Lambda \frac{\mathbf{v}_M}{v_M^3}$$

$$\tau_{\mathrm{DF}} \sim \mathrm{Gyr}$$

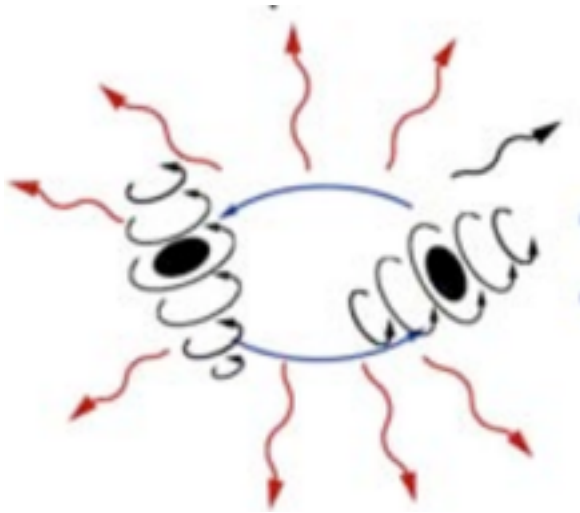
form kpc down to pc



binary forms: $a_h \sim \frac{GM}{8\sigma^2}$

an encounter lasts longer than one orbital period

3-body interactions

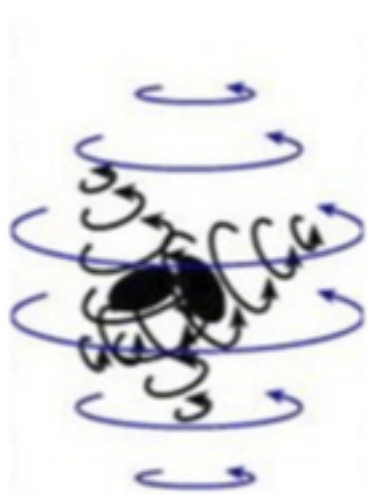


Emission of Gravitational Waves:

$$da/dt \sim -a^{-3}$$

$$t_{\rm gr} = \frac{5}{256F(e)}\frac{c^5}{G^3}\frac{a^4}{2M^3}$$

$$\sim \frac{10^7{\rm yr}}{F(e)}\frac{M}{10^8M_\odot}\left(\frac{\sigma}{200{\rm km\,s^{-1}}}\right)^{-8}\left(\frac{a}{10^{-2}a_h}\right)^4$$



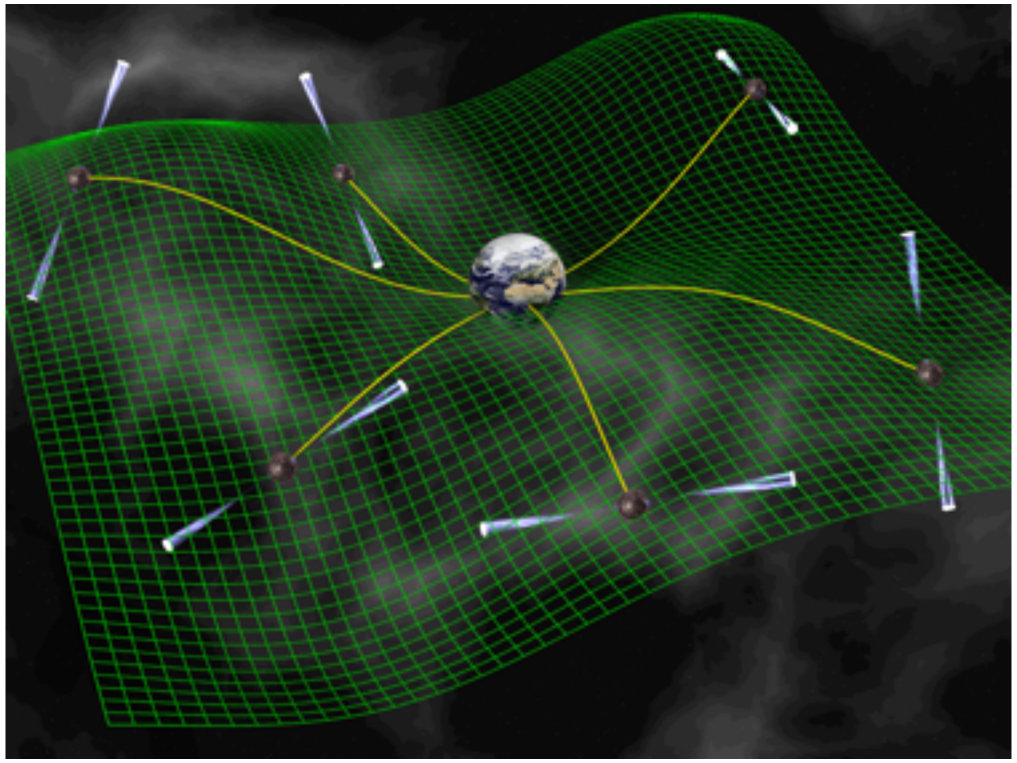


Image credit: David J. Champion

Hardening phase

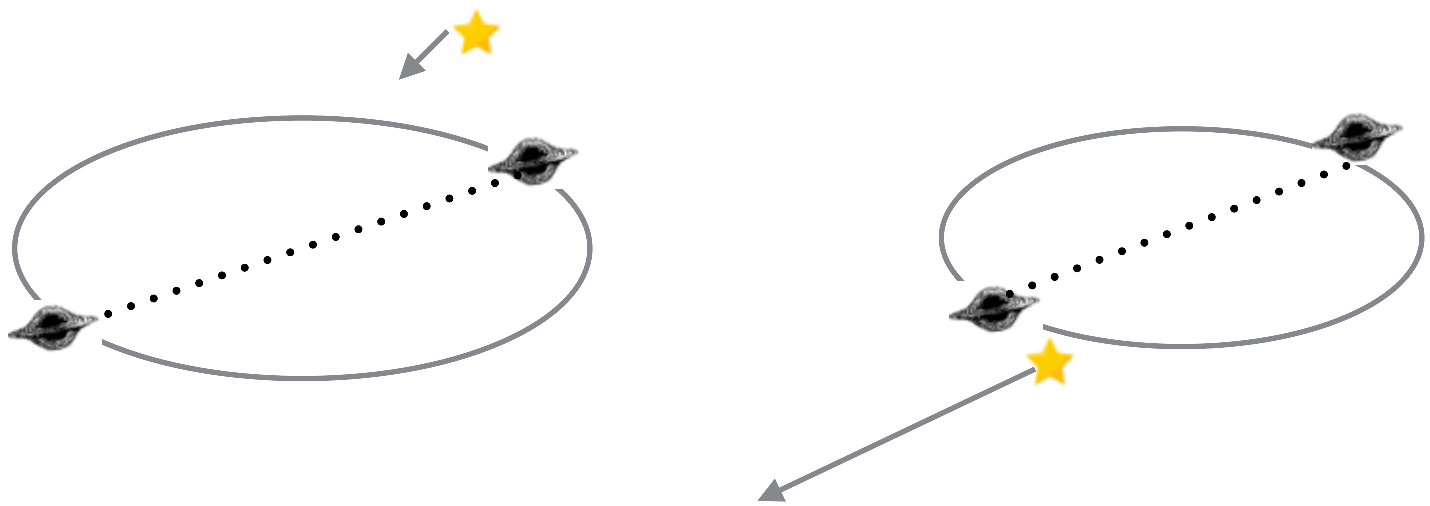


image credit: Zhang, 2001.09385

$$\frac{da}{dt} \sim -\frac{G\rho_\star}{\sigma} a^2$$

successful merger: ejected stellar mass ~ mass of binary

$$\tau_{\rm hard} \sim \frac{\sigma}{G\rho_\star a}$$

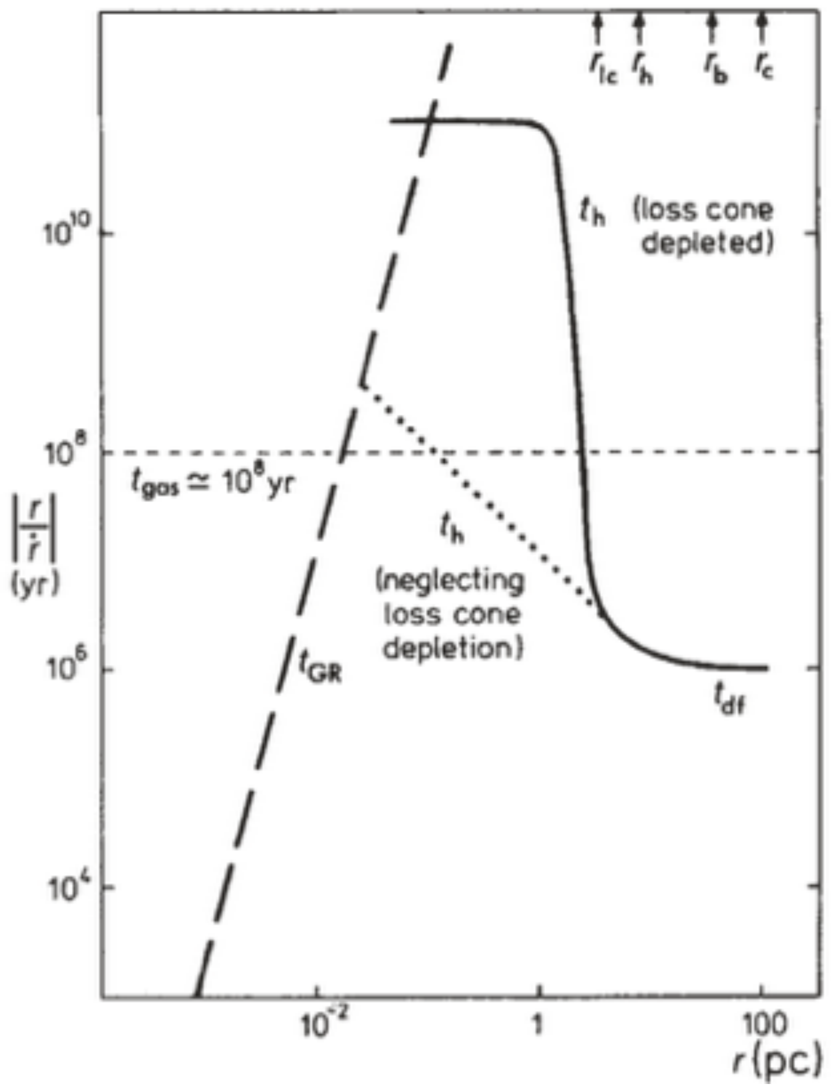
for a fixed background can happen
on a reasonable time scale

but hardening depletes the center of galaxy from stars (the loss cone)

The Final parsec problem

(Spherically symmetric, gas-poor systems)

Begelman, Blandford, Rees 1980
Milosavljevic, Merritt, 2003



possible solution:

Gas:
Begelman, Blandford, and Rees 1980
Escala, Larson, Coppi, 2005

Brownian motions of SMBHs:
Quinlan, Hernquist 1997

Axisymmetric and Triaxial galaxies:
Yu, 2002
Holley-Bockelmann, Sigurdsson, 2006
Berczik, Merritt, Spurzem, Bischof, 2006
Khan, Just, Merritt, 2011
Vasiliev, Antonini, Merritt, 2015
Gualandris, Read, Dehnen, Bortolas 2017

Massive perturbers:
Perets, Hopman, Alexander, 2007
Perets, Alexander, 2008

In the light of NANOGrav 15-year data:
any new (universal) mechanism is interesting!

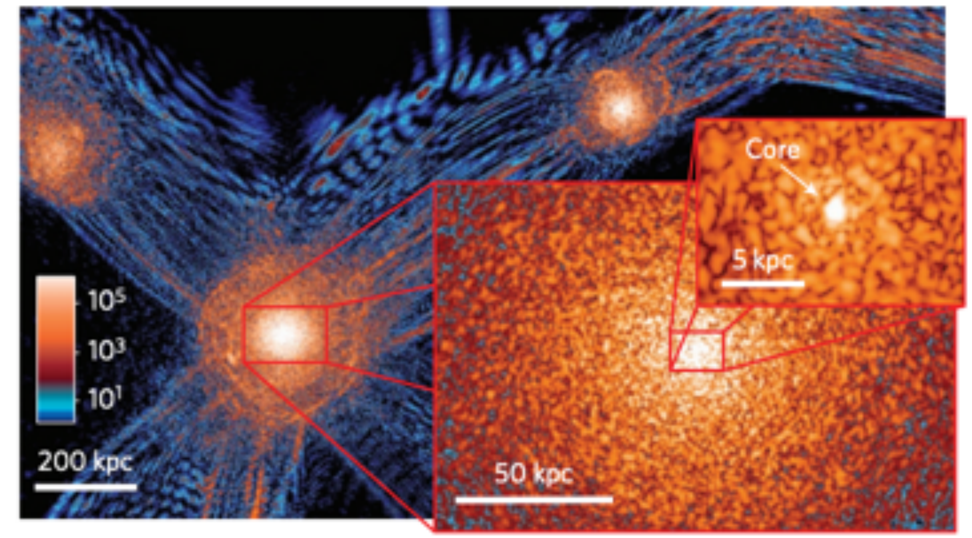
new possible solution:
Ultra Light Dark Matter (ULDM)

ULDM:

Schrodinger-Poisson Equation: $$i\hbar\partial_t\psi = \left[-\frac{\hbar^2\nabla^2}{2m} + m(U_\psi + U_{\rm sat})\right]\psi$$

$$\nabla^2 U_\psi = 4\pi G m|\psi|^2$$

very light boson, astrophysically large de Broglie wavelength:
a huge occupation numbers of the density field.
a classical wave

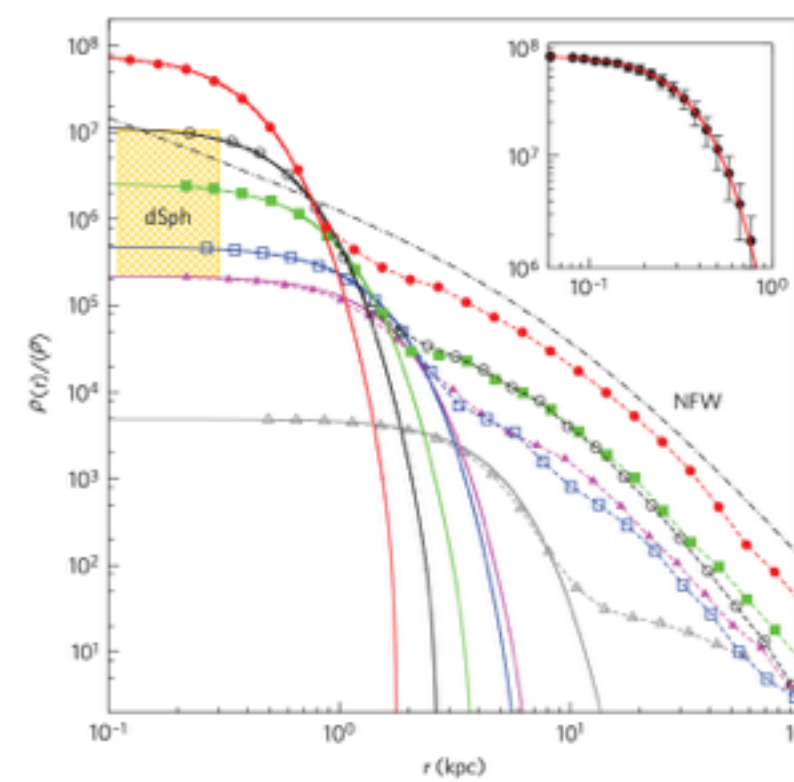


$$\lambda_\sigma = \frac{\hbar}{m\sigma} = 0.2\,{\rm kpc}\left(\frac{10^{-22}\,{\rm eV}}{m}\right)\left(\frac{100\,{\rm km/s}}{\sigma}\right)$$

solitonic core: the ground state
granular envelope (density fluctuations):
interference pattern

core-like density profile

Schive, Chiueh, and Broadhurst 2014



quasiparticles:

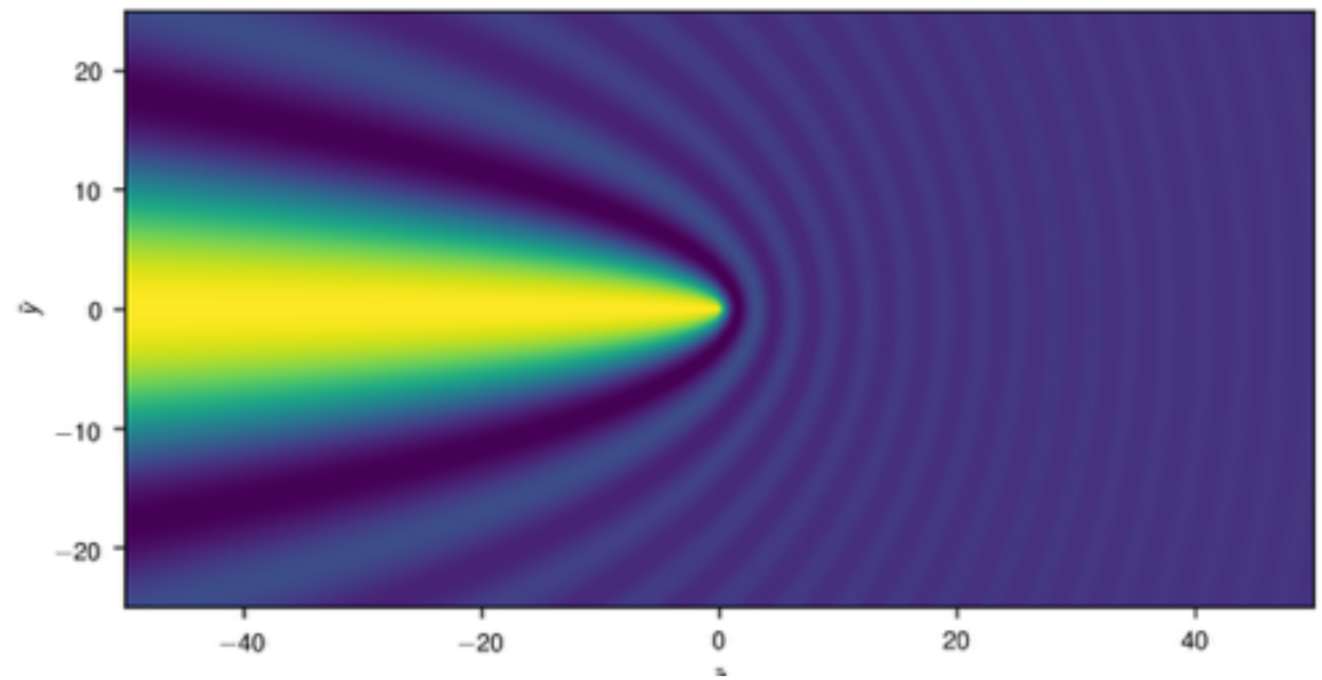
$$m_{\rm eff} \sim \rho\lambda_\sigma^3 = \frac{\sigma^2}{2\pi G r^2}\left(\frac{\hbar}{m\sigma}\right)^3 \simeq 2.6\times10^6\,M_\odot\left(\frac{10^{-22}\,{\rm eV}}{m}\right)^3\left(\frac{1\,{\rm kpc}}{r}\right)^2\left(\frac{100\,{\rm km/s}}{\sigma}\right)$$

new time scale: coherence time (lifetime of quasiparticles)

$$\tau_c \equiv 2\pi\frac{\lambda_\sigma}{\sigma} = \frac{\hbar}{m\sigma^2} \simeq 6\times10^6\,{\rm yr}\left(\frac{10^{-22}\,{\rm eV}}{m}\right)\left(\frac{100\,{\rm km/s}}{\sigma}\right)^2$$

Different phases of merger in ULDM (no stars):

Dynamical friction:



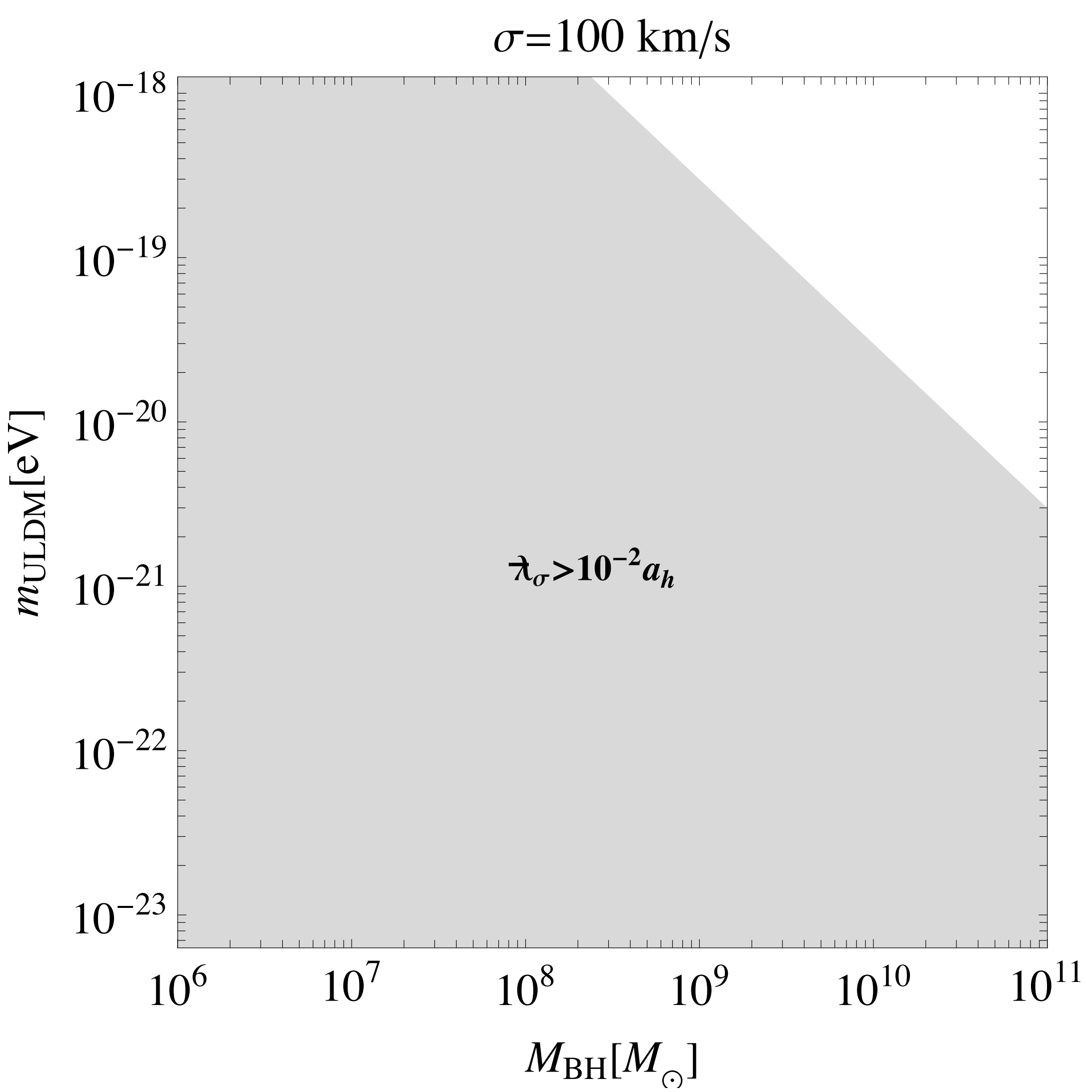
Lancaster, et al., 2020

$$\mathbf{F}_{\mathrm{DF}} = -4\pi\rho G^2 M^2 \frac{\mathbf{v}_{\mathrm{rel}}}{v_{\mathrm{rel}}^3} \begin{cases} \mathrm{Cin}\,(2b/\lambda_\sigma) + \frac{\sin(2b/\lambda_\sigma)}{2b/\lambda_\sigma} - 1 & b \ll \lambda_\sigma, \\ \ln\left[b/(\lambda_\sigma/2)\right]\left[\mathrm{erf}\left(\frac{v_{\mathrm{rel}}}{\sqrt{2}\sigma}\right) - \sqrt{\frac{2}{\pi}}\frac{v_{\mathrm{rel}}}{\sigma} e^{-\frac{1}{2}\left(\frac{v_{\mathrm{rel}}}{\sigma}\right)^2}\right] & b \gg \lambda_\sigma. \end{cases}$$

size of the binary smaller than the de Broglie scale:
smoothing the tail of the particles in the wake,
suppresses dynamical friction

Hardening just by dynamical friction

dynamical friction is still efficient $10^{-2} a_h \gtrsim \lambda_\sigma$



challenge:

$$t_{\mathrm{merger}} \lesssim 10\,\mathrm{Gyr}$$

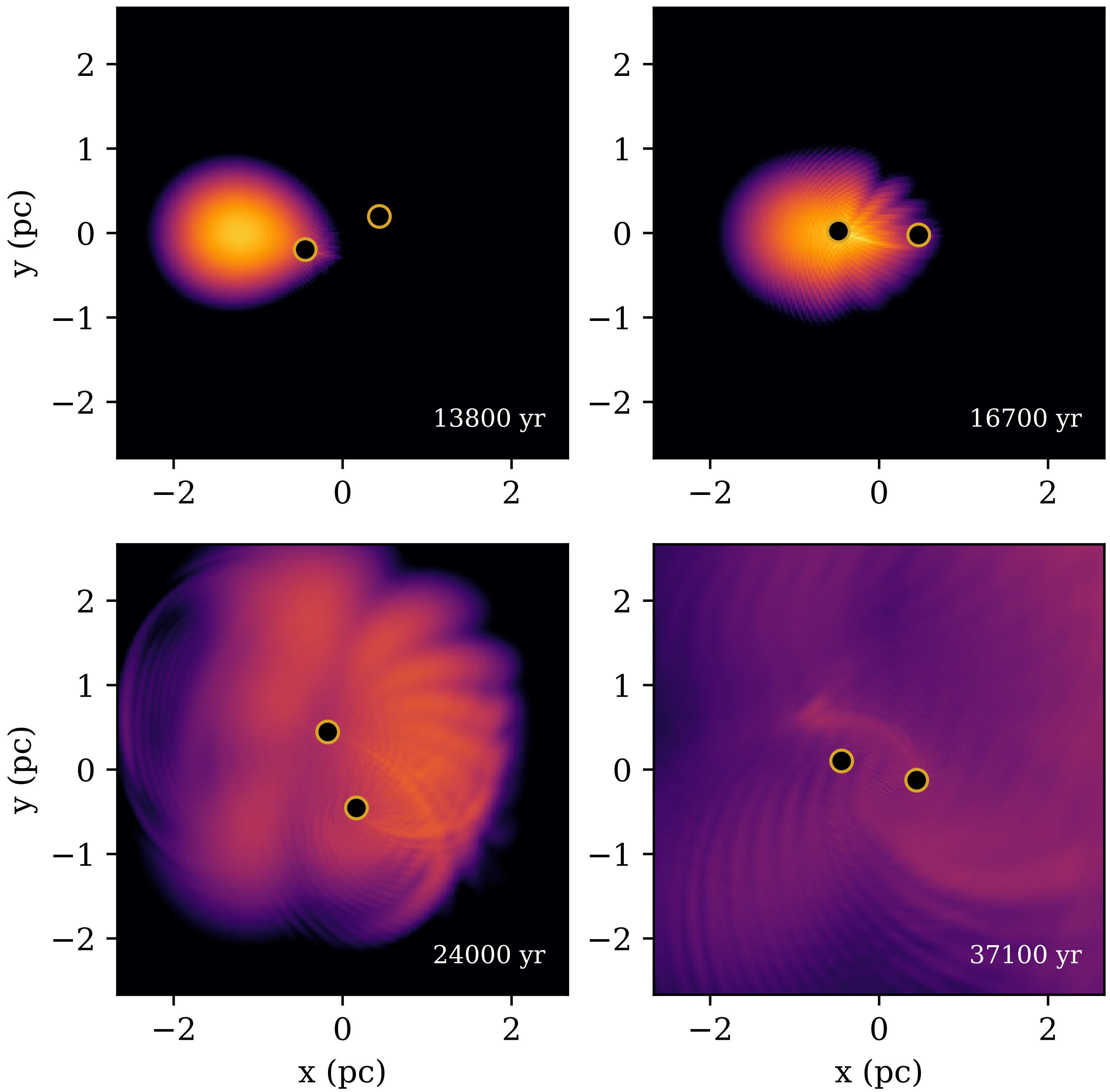
$$a_h \sim \frac{GM}{8\sigma^2}$$

Hardening by quasiparticles:

stars: $$\frac{da}{dt} \sim -\frac{G\rho_\star}{\sigma} a^2$$ **successful merger: ejected stellar mass ~ mass of binary**

ULDM: better/worse than stars?

still in progress …

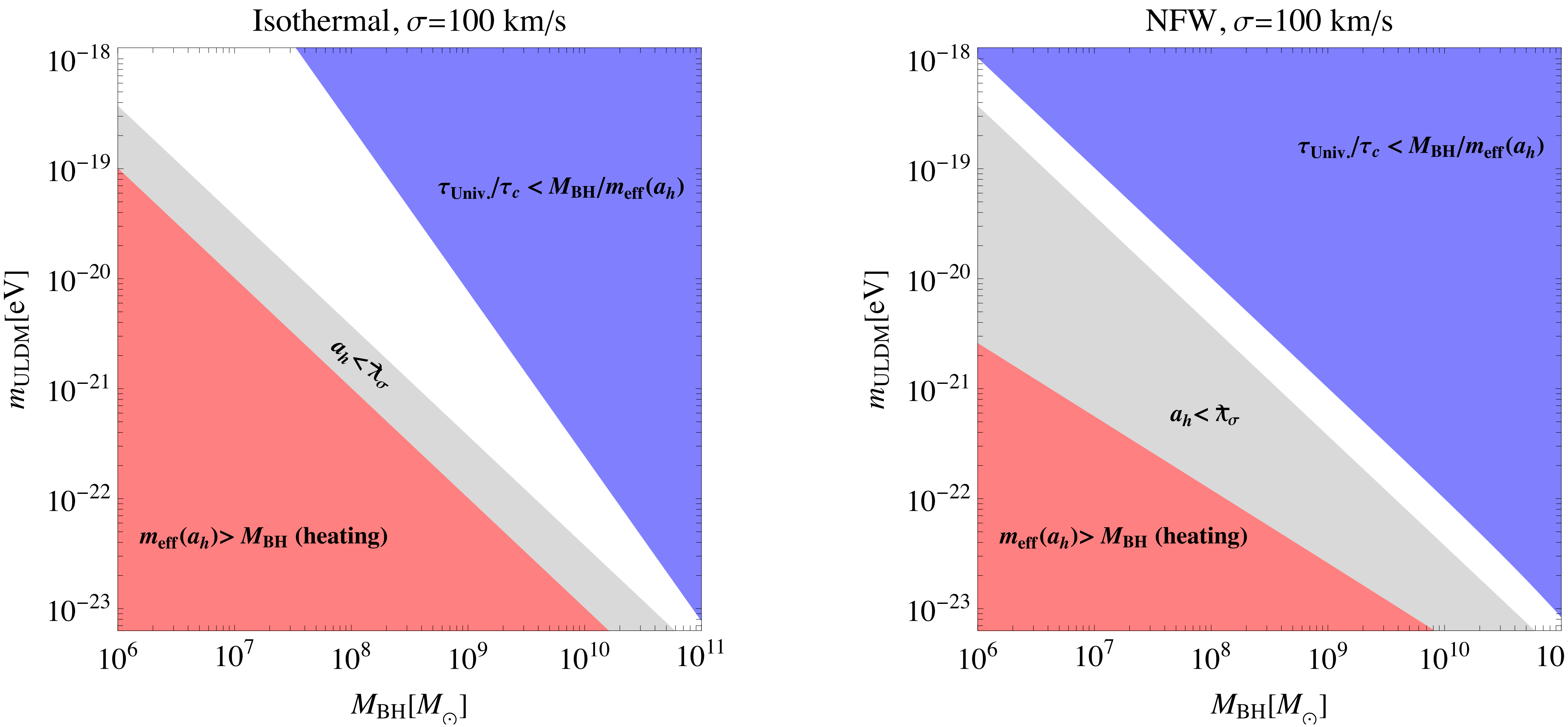


naively, successful merger: interact with quasiparticles ~ mass of binary

binary forms while dynamical friction is not suppressed. outside of the solitonic core $\quad a_h > \lambda_\sigma$

to avoid heating up the binary $\quad m_{\rm eff}(a_h) < M$

refill the loss cone efficiently $\quad \frac{\tau_{\rm Univ.}}{\tau_c} \gtrsim \frac{M}{m_{\rm eff}(a_h)}$



Hardening by stars in the presence of ULDM:

massive perturbers can scatter stars back to the loss cone:
accelerate the stellar relaxation by some orders of magnitude

Perets, Hopman, Alexander, 2007
Perets, Alexander, 2008

giant molecular clouds

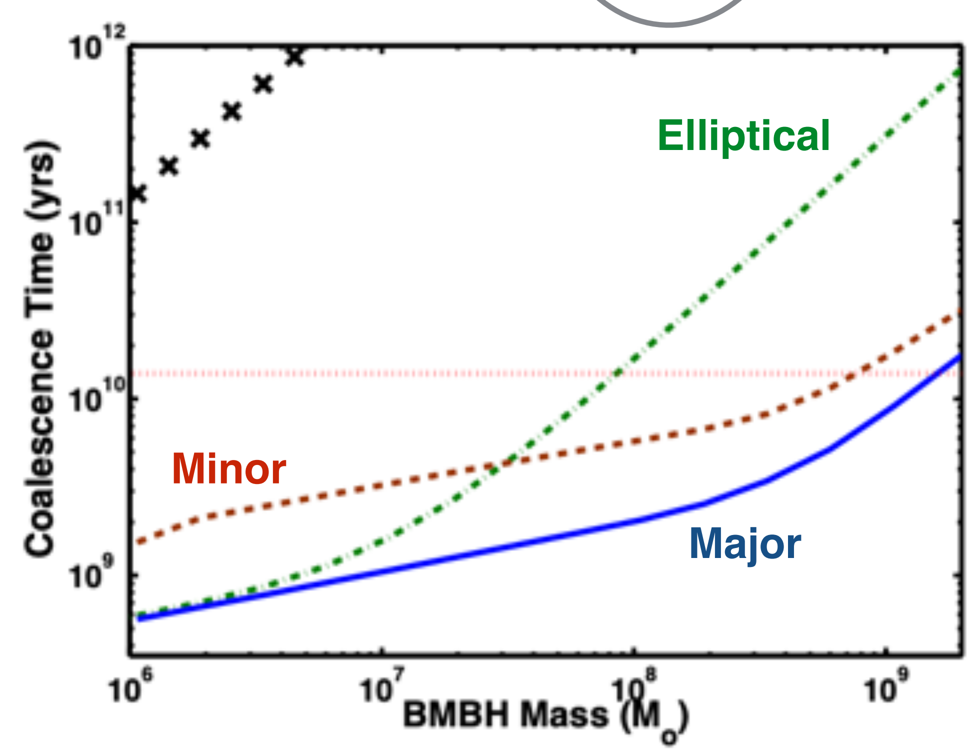
globular cluster

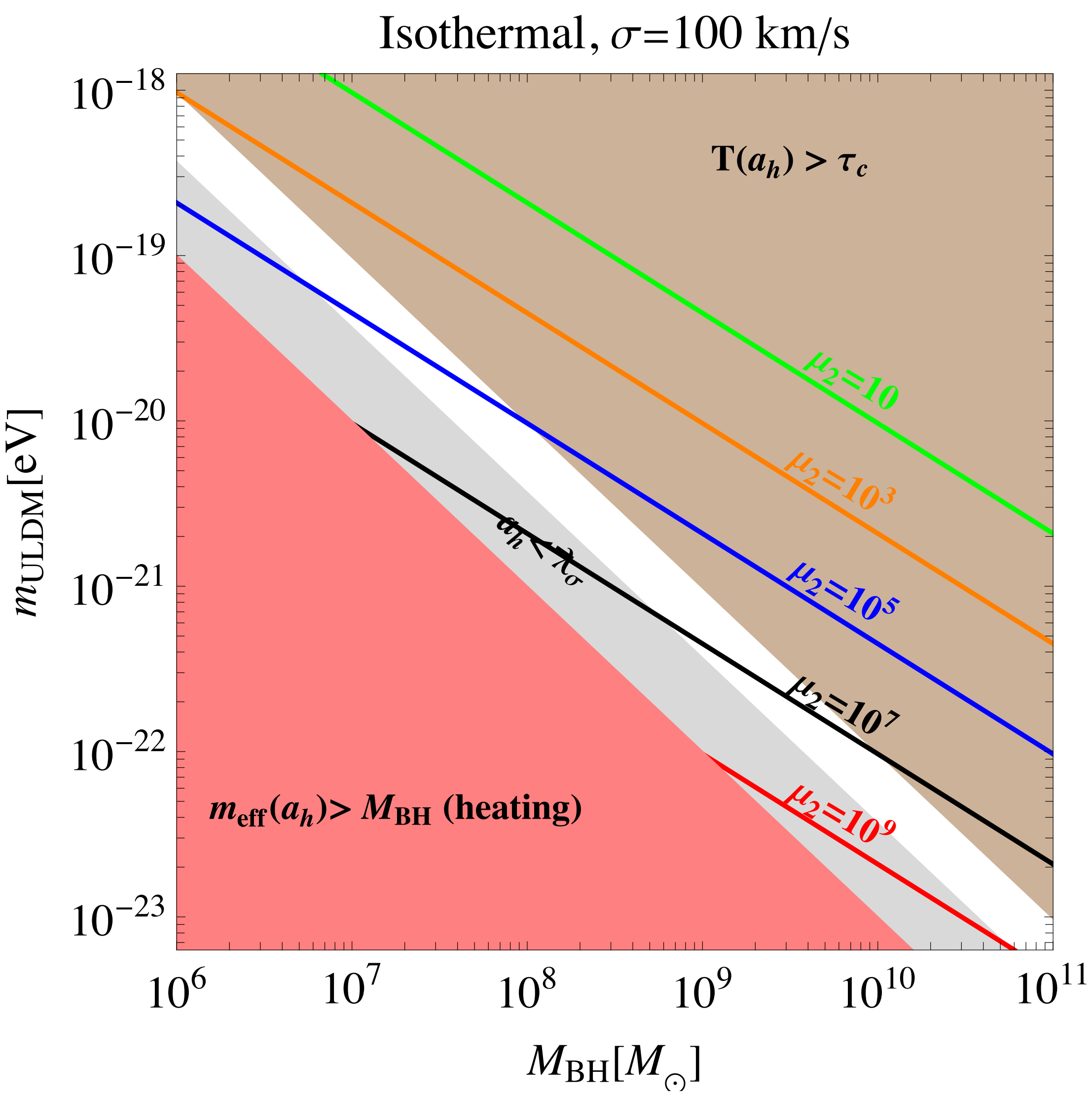
$$\Gamma_{p\star} \sim n_p v \sigma_{p\star} \sim n_p v r_c^2 \sim n_p v (G M_p / v^2)^2$$

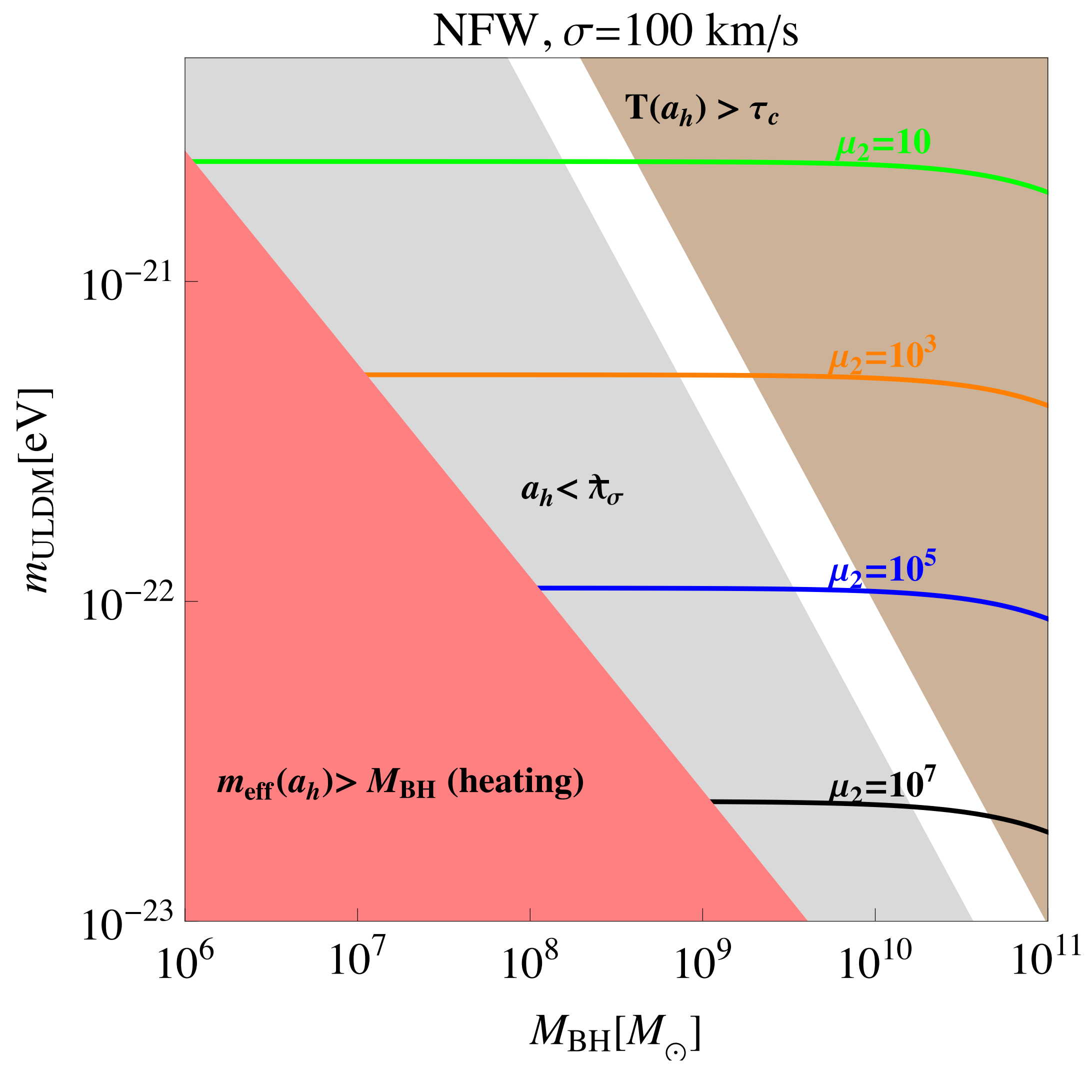
Merger model	Q	r/r_h [a]	$M_p^{tot}/M_{\rm dyn}^{tot}$	$M_p(M_\odot)$	β [b]	R_p (pc)	μ_2 [c]
Major	1	2–30	1/2	5×10^4–1×10^7	1.2	5	3×10^7
Minor	0.05	2–30	1/3	5×10^4–1×10^7	1.2	5	5×10^6
Elliptical	1	2–30	1/5	1×10^5–1×10^7	2	3	5×10^5
Stars	—	1–30	1	1	—	0	1

figure of merit:
the second moment of the mass distribution

$$\frac{t_{r,\star}}{t_{r,p}} \sim \mu_2 \equiv \frac{n_p M_p^2}{n_\star M_\star^2}$$







giant molecular clouds: common in spiral galaxies, but do not survive in **elliptical galaxies** as a result of a history of major mergers.

conclusion

NANOGrav data can be explained by a population of SMBH binaries.

The final parsec problem may not be a problem anymore,
but is still interesting to be explored!

Merger of SMBH binaries just by interacting with ULDM looks challenging:
requires a better understanding of binary evolution close to the core.

ULDM quasiparticles can be treated as massive perturbers to
refill stellar loss cone efficiently.

Back up

lower limits on ULDM mass:

Amin, Mirbabayi, 2022 $10^{-18}\,\mathrm{eV}$

ultra faint dwarf galaxies

Dalal, Kravtsov, 2022 $10^{-19}\,\mathrm{eV}$