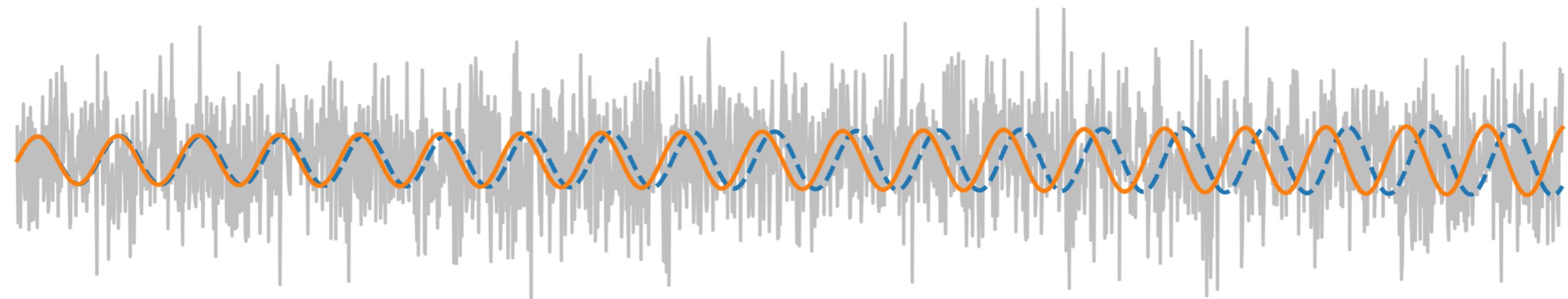


# Dark Matter, Black Holes, Gravitational Waves and Werewolves



Bradley J Kavanagh  
GRAPPA, University of Amsterdam

IFCA, 7th October 2019

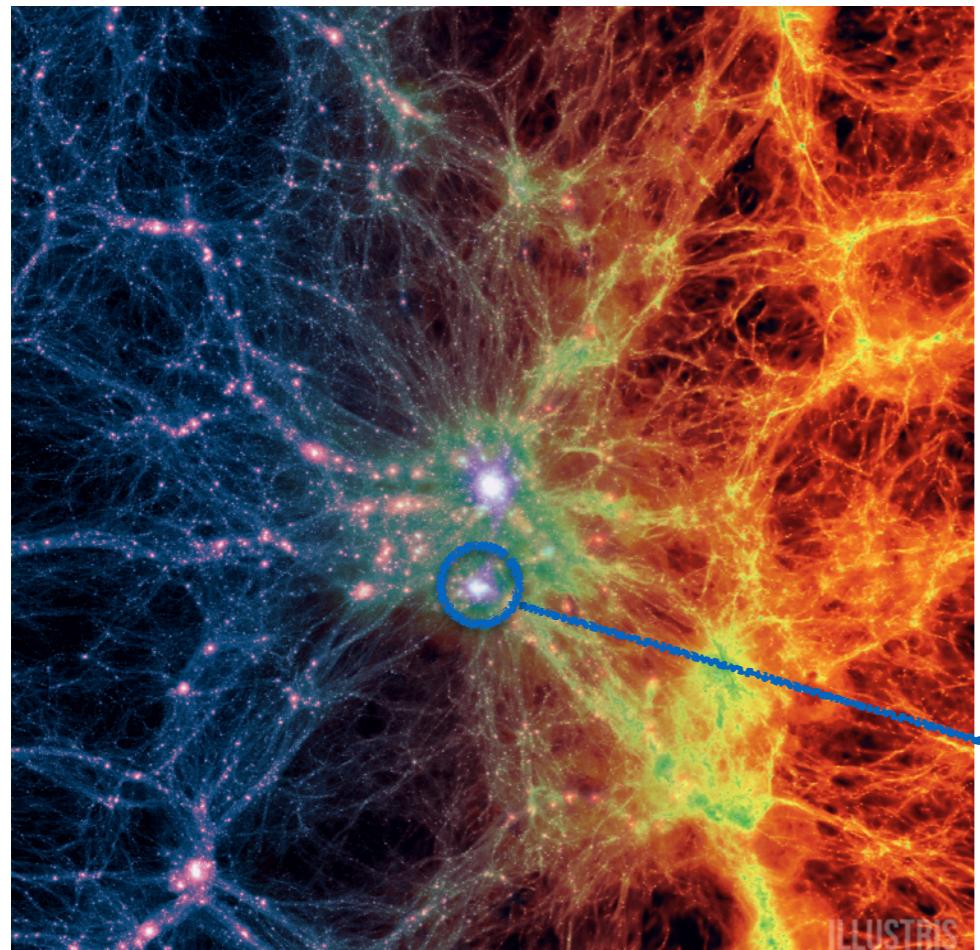
# Werewolves

---

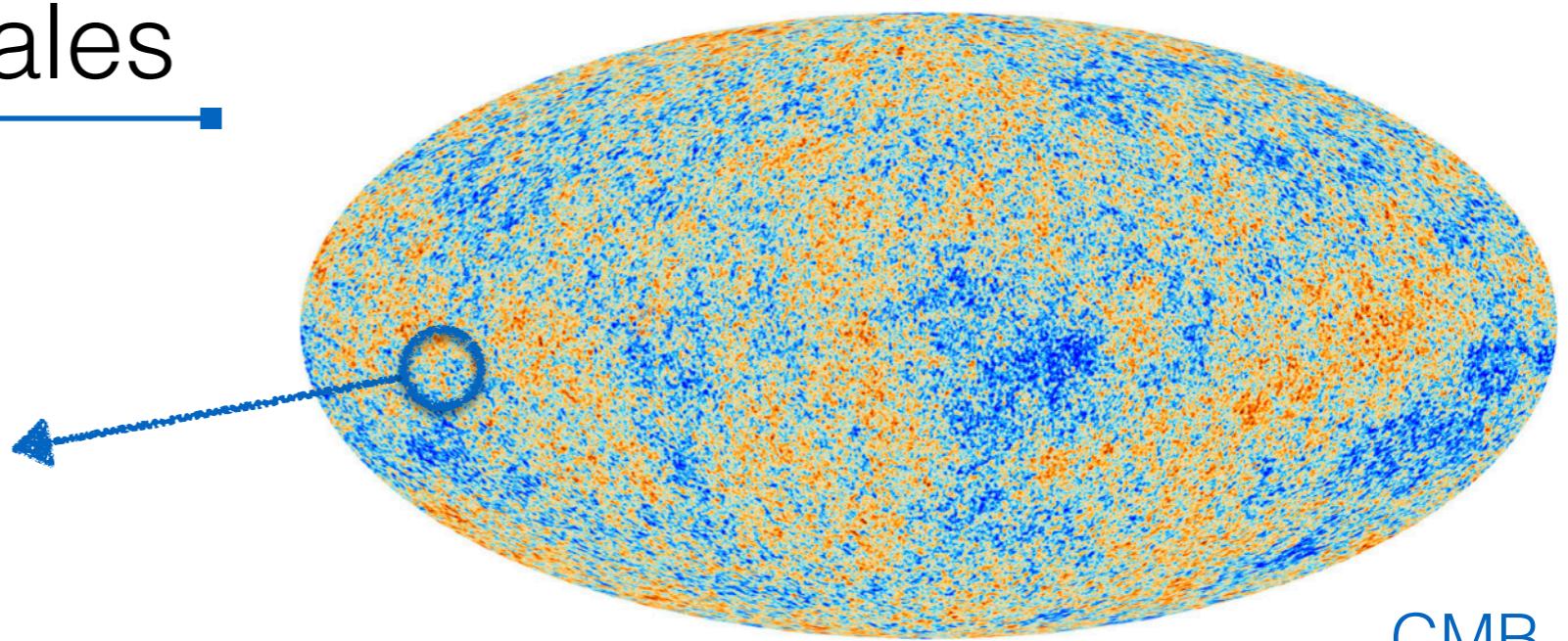
Werewolves: humans with the ability to shapeshift into a wolf, which are notoriously hard to kill



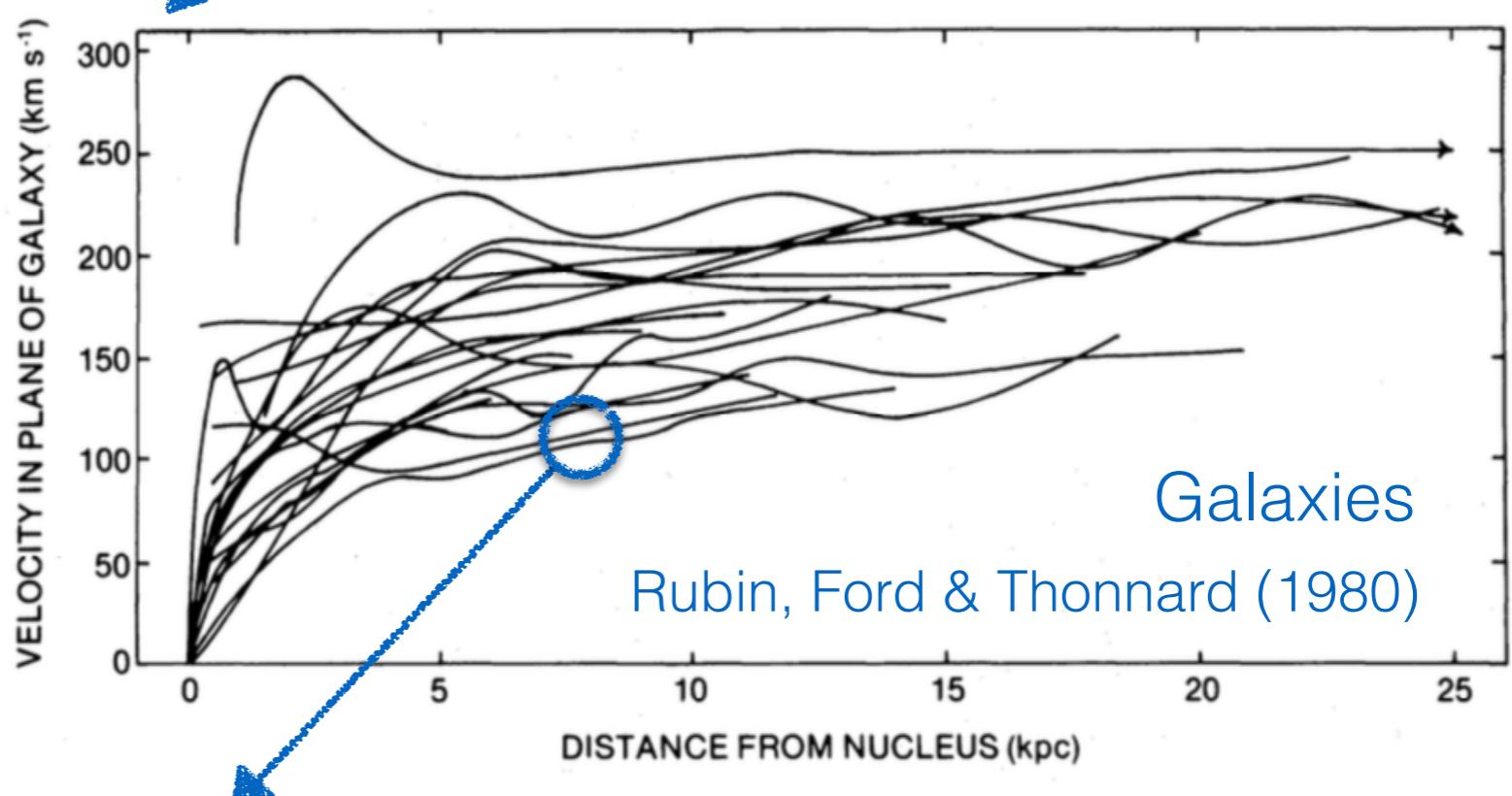
# Dark Matter on all scales



Galaxy clusters  
[Illustris, 1405.2921]  
[astro-ph/0006397]



CMB  
Planck [1502.01589]



Galaxies  
Rubin, Ford & Thonnard (1980)

# Dark Matter at Earth

NOT TO SCALE

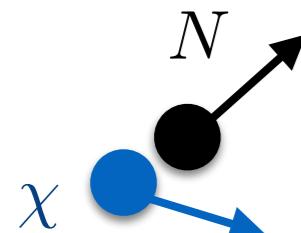
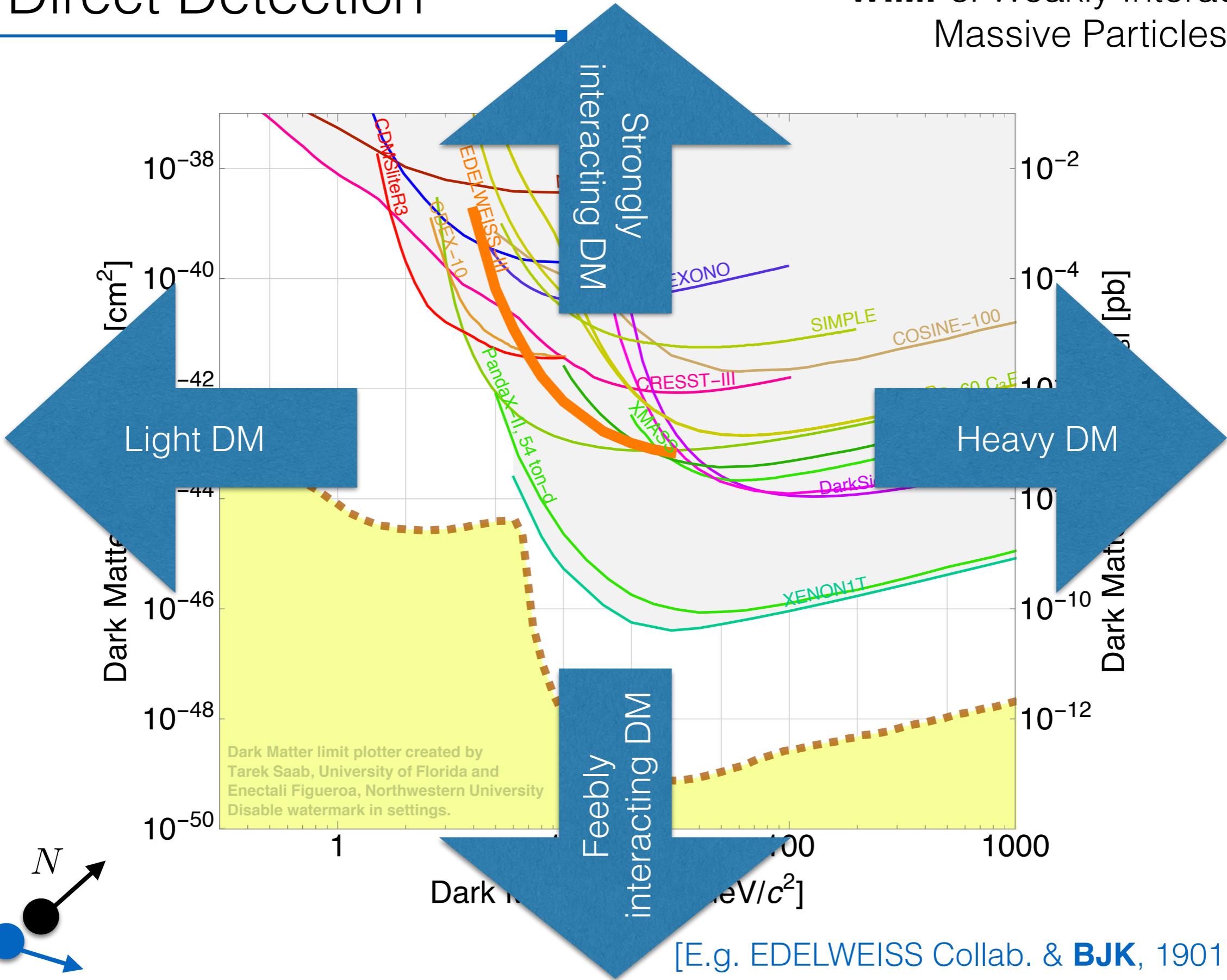


Global and local estimates of  
DM at Solar radius give:  $\rho_\chi \sim 0.2 - 0.8 \text{ GeV cm}^{-3}$

E.g. Iocco et al. [1502.03821],  
Garbari et al. [1206.0015],  
Read [1404.1938]

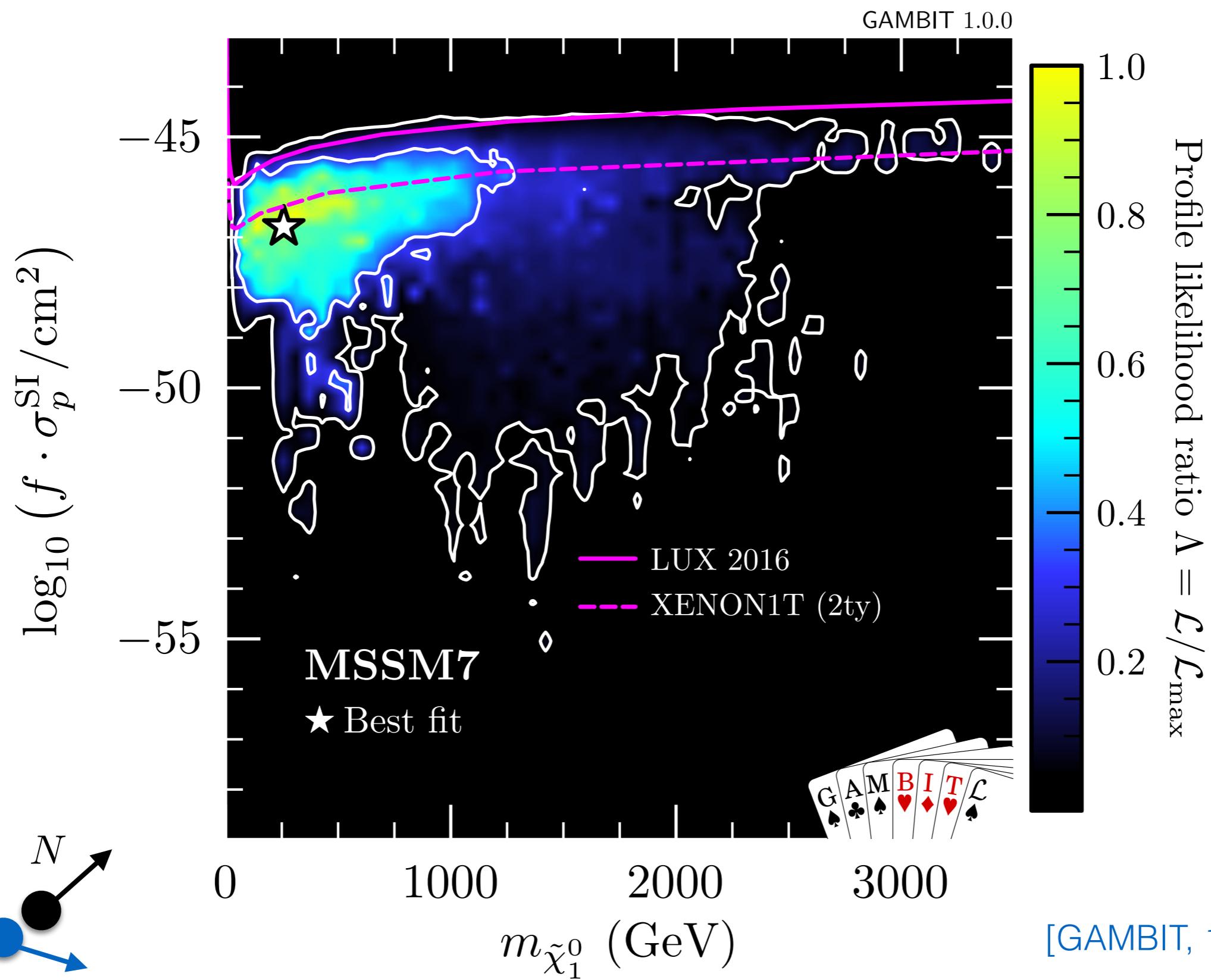
# DM Direct Detection

**WIMPs:** Weakly Interacting Massive Particles



# DM Direct Detection

**WIMPs:** Weakly Interacting  
Massive Particles

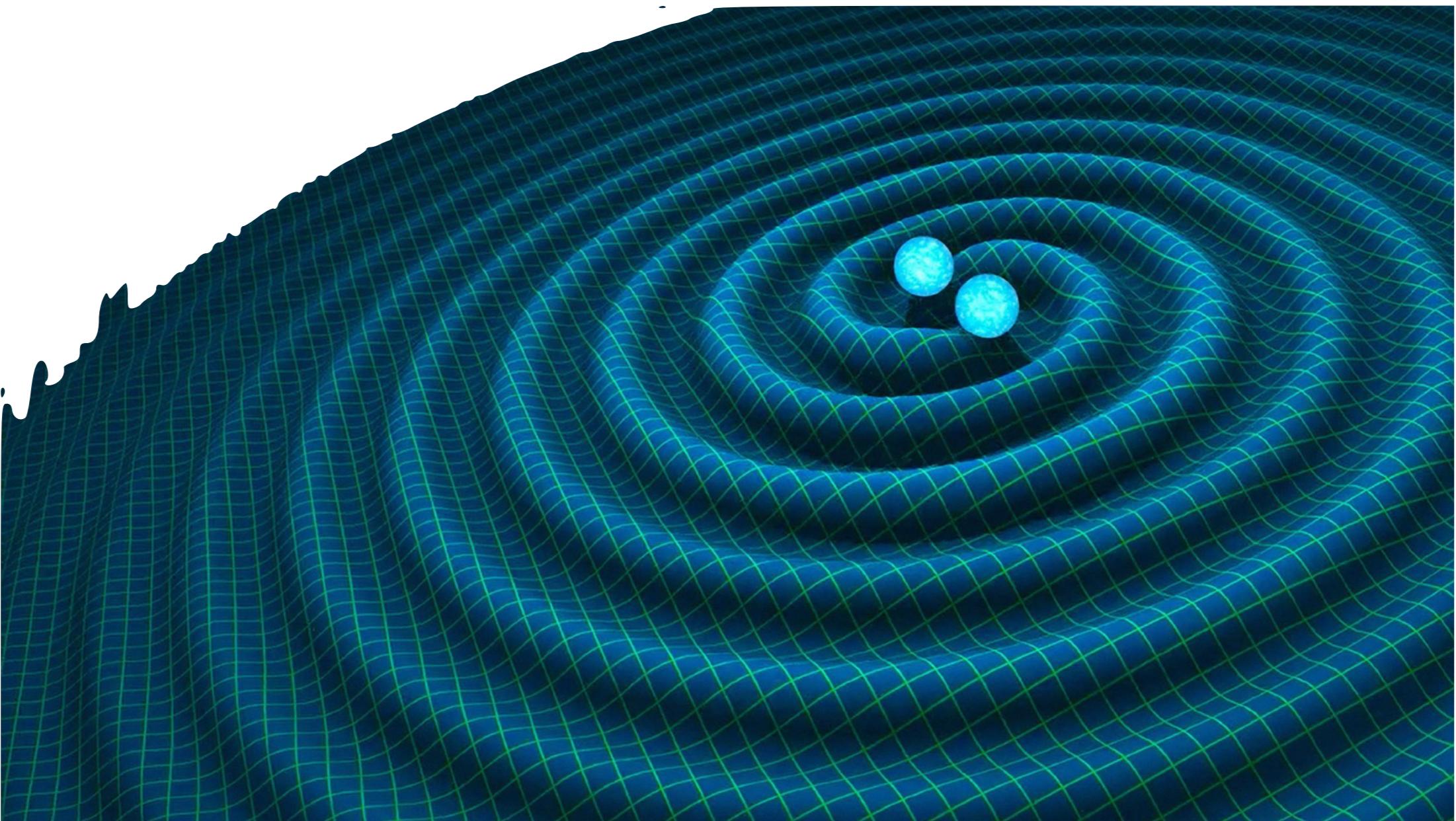


# Gravitational Waves

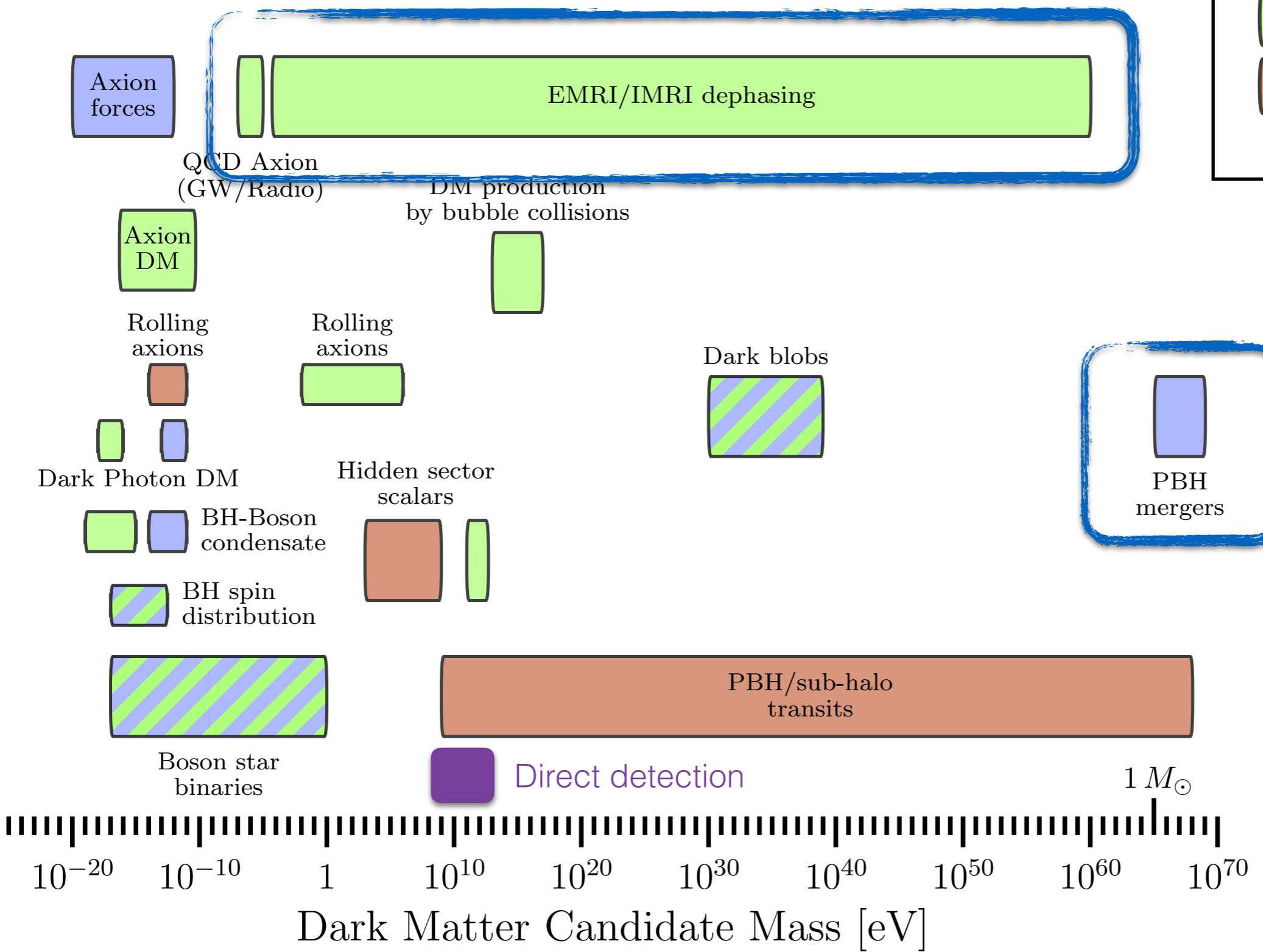
---

Waves in space-time, generated by a changing mass quadrupole moment

R. HURT / CALTECH-JPL / HANDOUT/ ESA

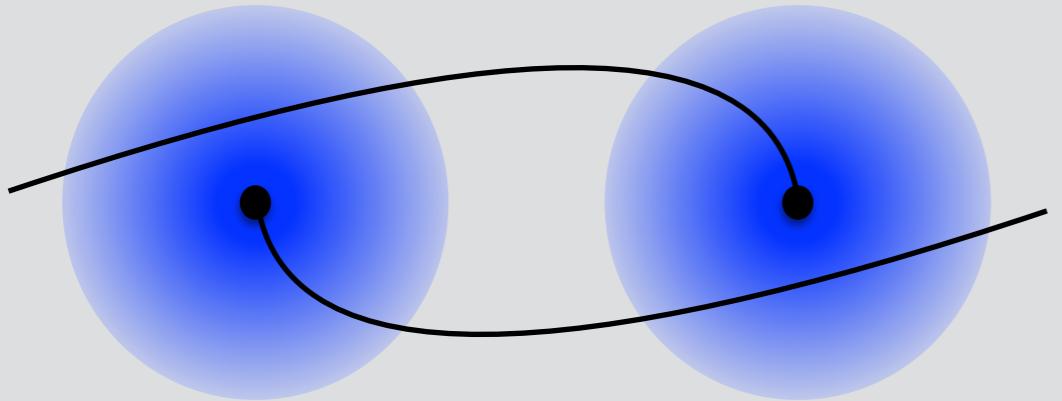


# GW probes of DM



[1907.10610]

# Overview

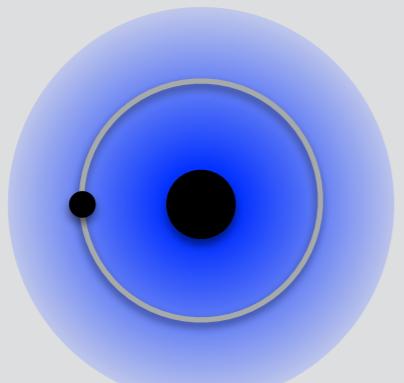
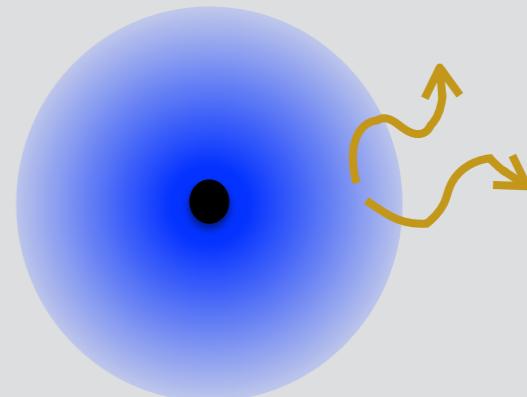


## Merging Primordial Black Holes (PBHs)

[**BJK**, Gaggero & Bertone, 1805.09034]

## DM Annihilation around PBHs

[Bertone, Coogan, Gaggero, **BJK** & Weniger, 1905.01238]



## Intermediate Mass-Ratio Inspirals (IMRIs)

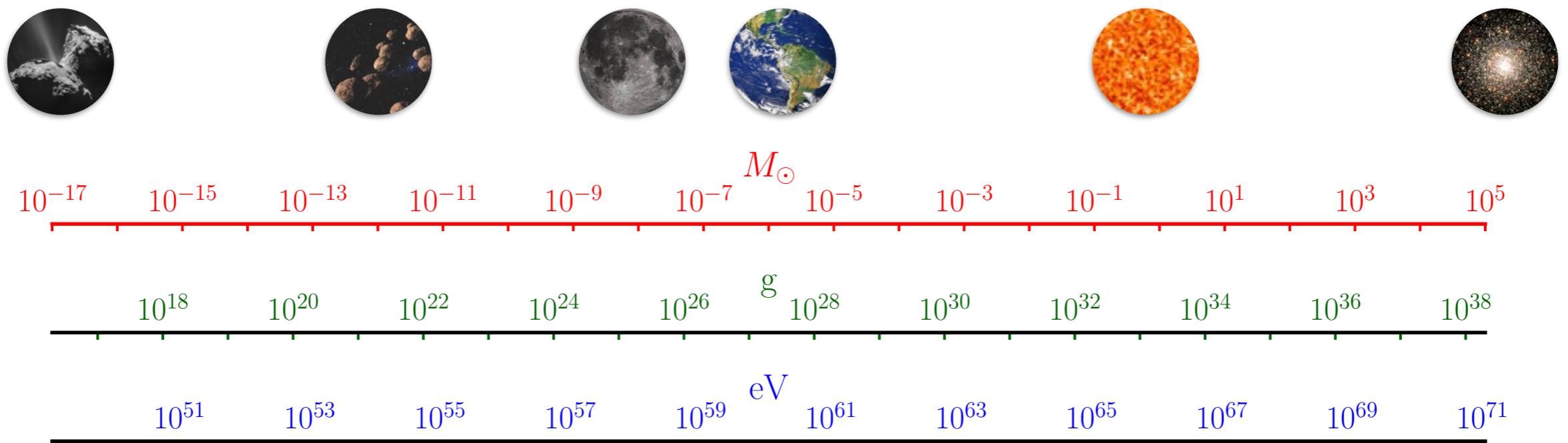
[Edwards, Chianese, **BJK**, Nissanke & Weniger, 1905.04686]

# Primordial Black Holes

Primordial Black Holes (PBHs) *could* form in the early Universe ( $z \gg 10^8$ ) from large over-densities

Mass roughly given by mass inside horizon at time of formation:

[Green & Liddle, astro-ph/9901268]



[Y. B. Zel'dovich and I. D. Novikov, Soviet Astronomy 10, 602 (1967)]

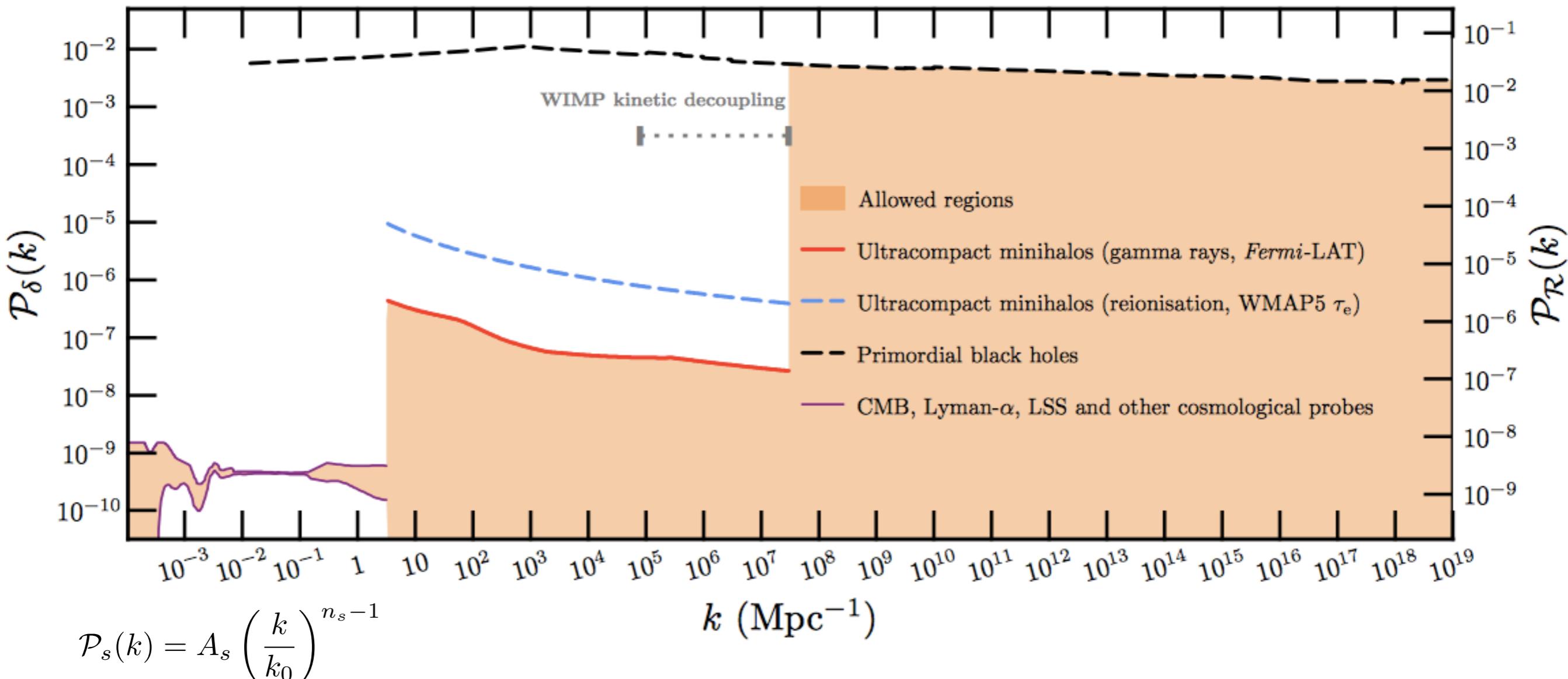
[S. Hawking, Mon. Not. R. Astron. Soc. 152, 75 (1971)]

[Carr and Hawking, MNRAS 168 (1974); Carr, Astrophys. J. 201, 1 (1975)]

# Primordial Black Holes

Extrapolating the primordial power spectrum from Planck, fluctuations big enough to produce PBHs should be negligible...

[1110.2484]



...but small scale power spectrum is largely unconstrained.

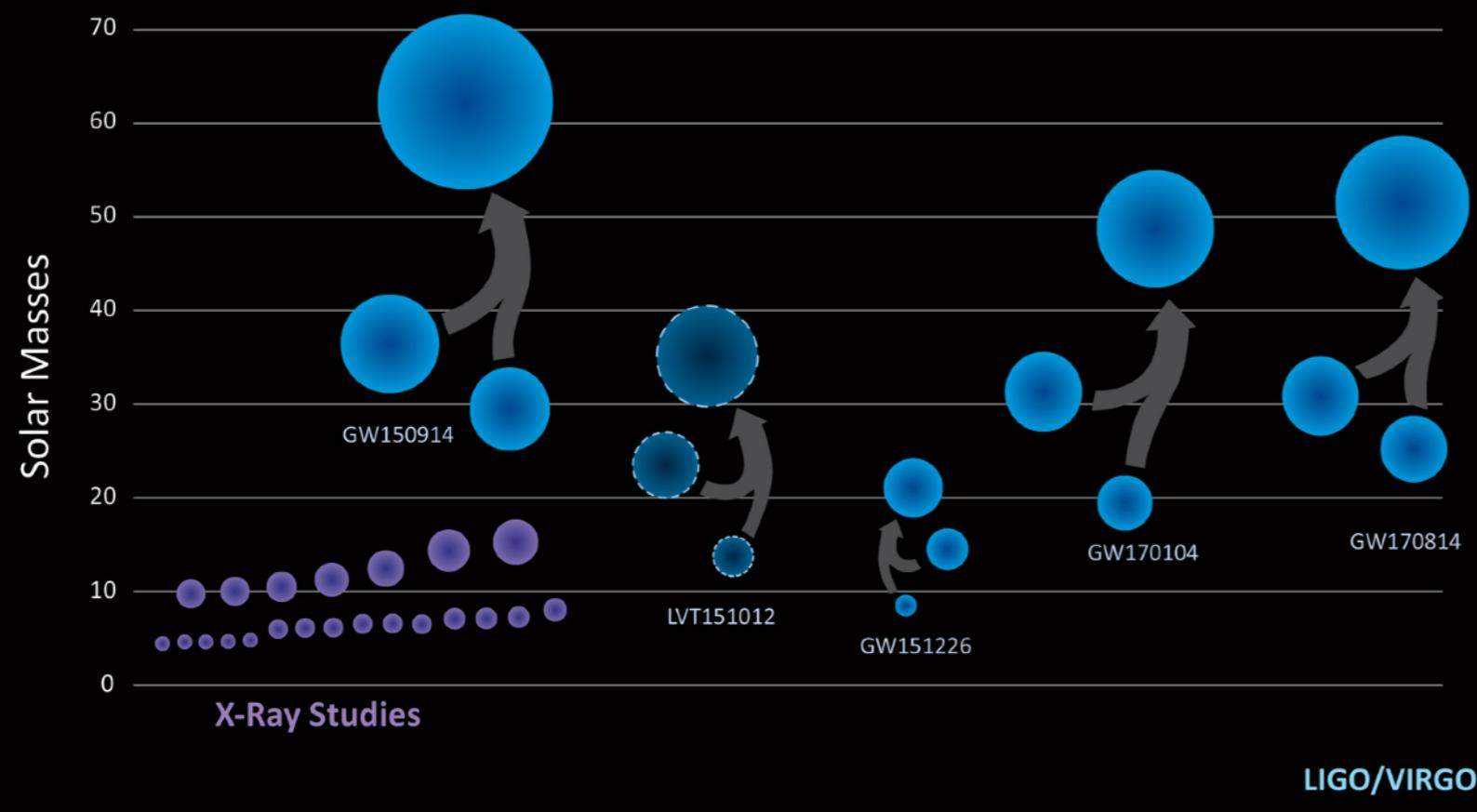
# LIGO/Virgo Mergers

LIGO/Caltech/Sonoma State (Aurore Simonnet)



2018

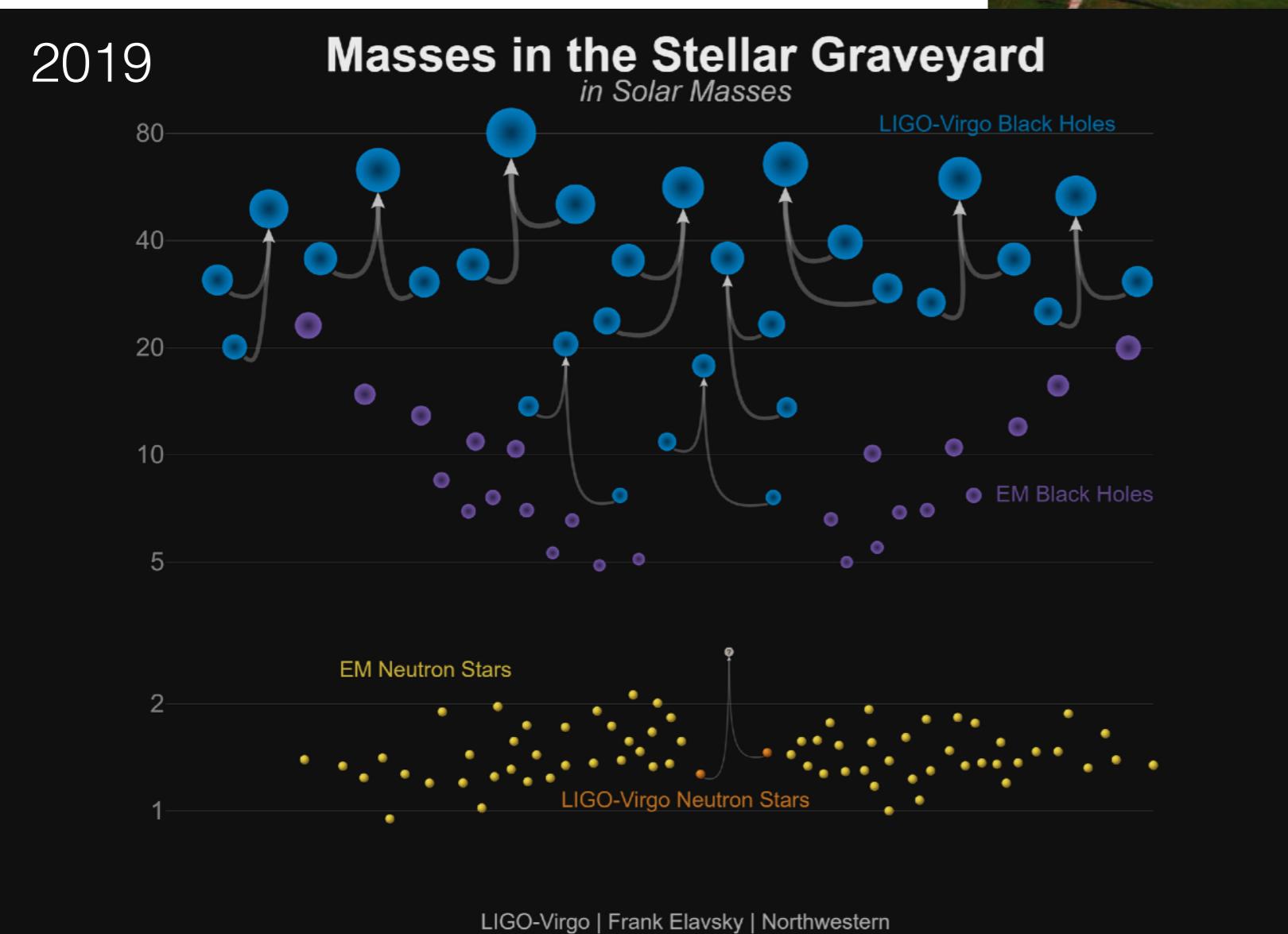
## Black Holes of Known Mass



The Virgo collaboration/CCO 1.0

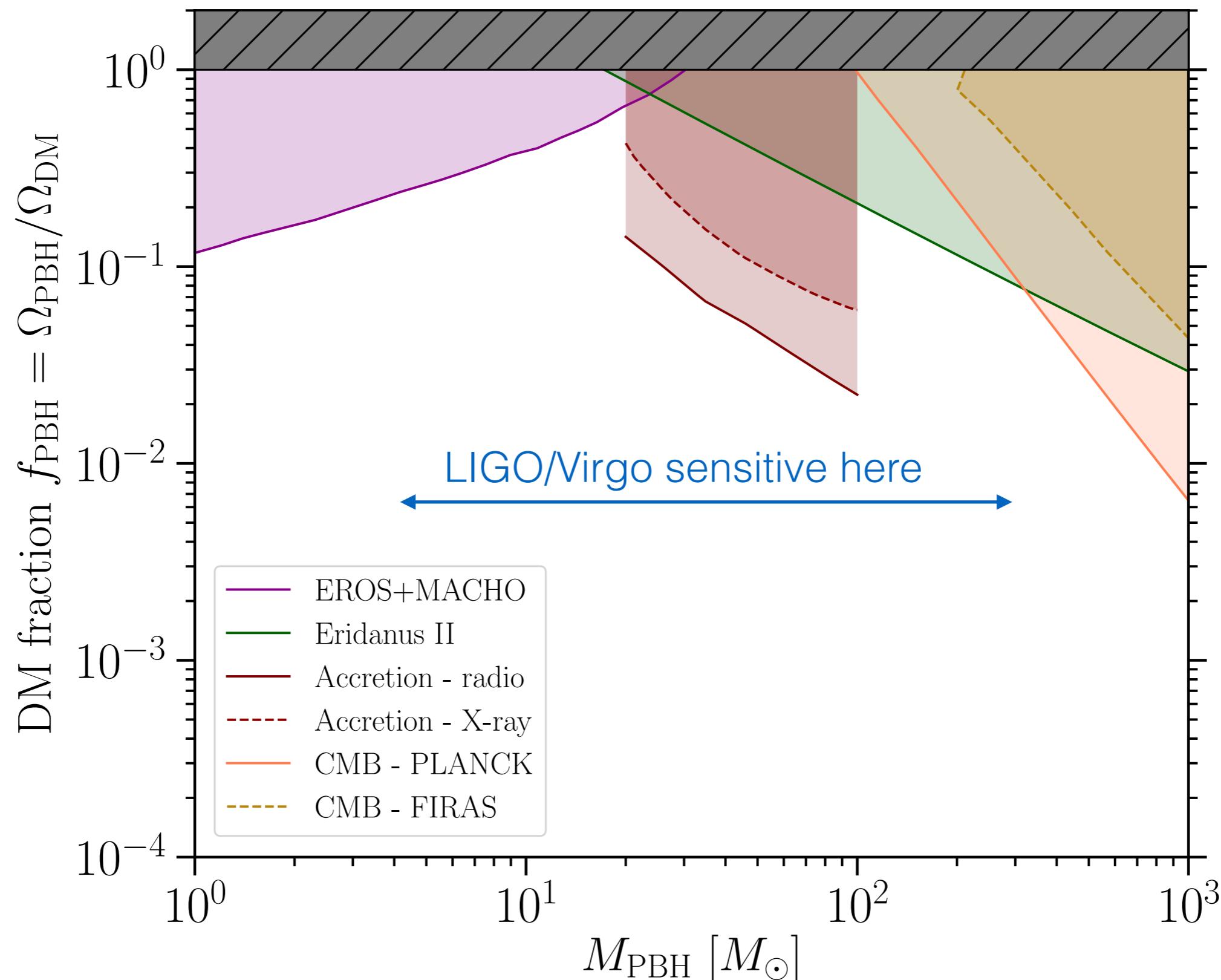
# LIGO/Virgo Mergers

LIGO/Virgo/Northwestern Univ. (Frank Elavsky)



The Virgo collaboration/CCO 1.0

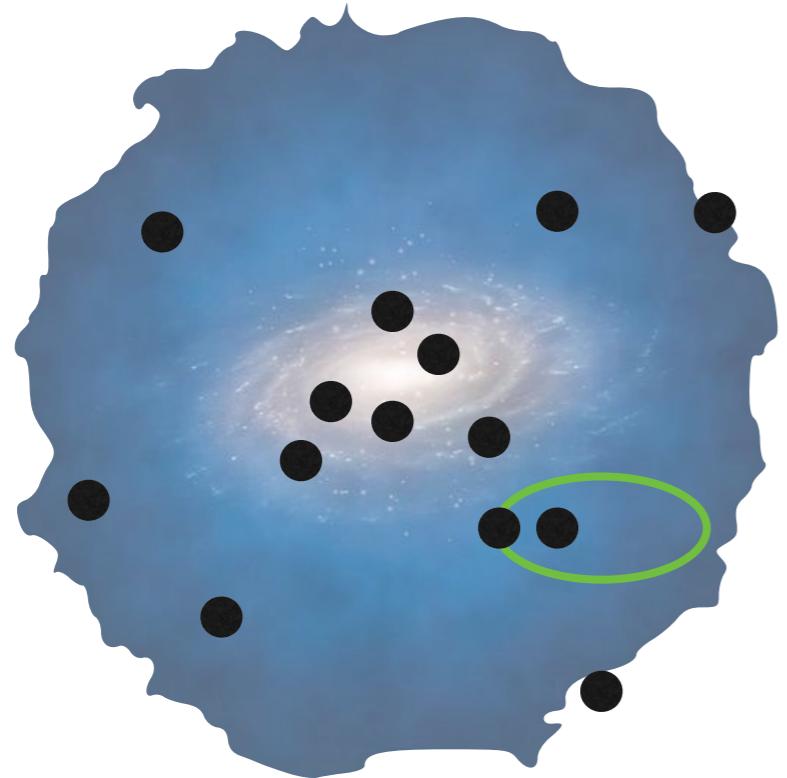
# PBHs as Dark Matter



# A tale of two binaries

A) Binaries formed after close encounters

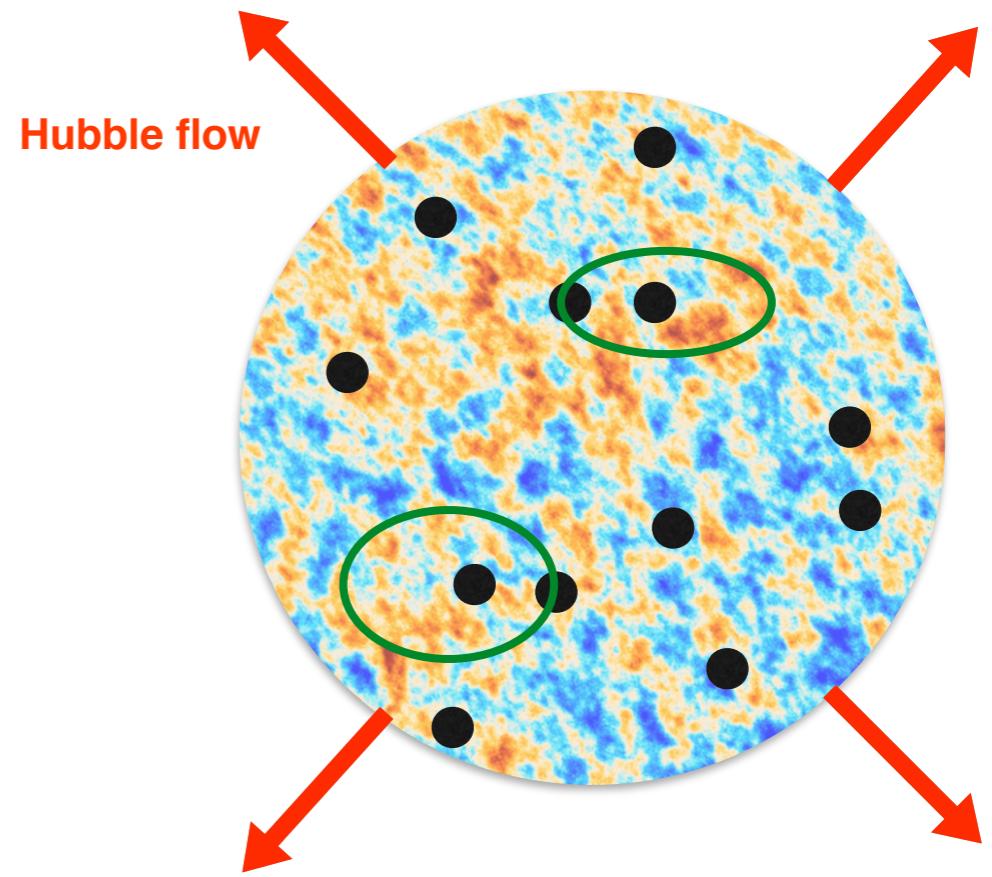
[Bird et al., 1603.00464]



$$\sigma = \pi \left( \frac{85\pi}{3} \right)^{2/7} R_s^2 \left( \frac{v_{\text{pbh}}}{c} \right)^{-18/7}$$
$$= 1.37 \times 10^{-14} M_{30}^2 v_{\text{pbh}-200}^{-18/7} \text{ pc}^2$$

B) Binaries formed in the early Universe

[Sasaki et al, 1603.08338]

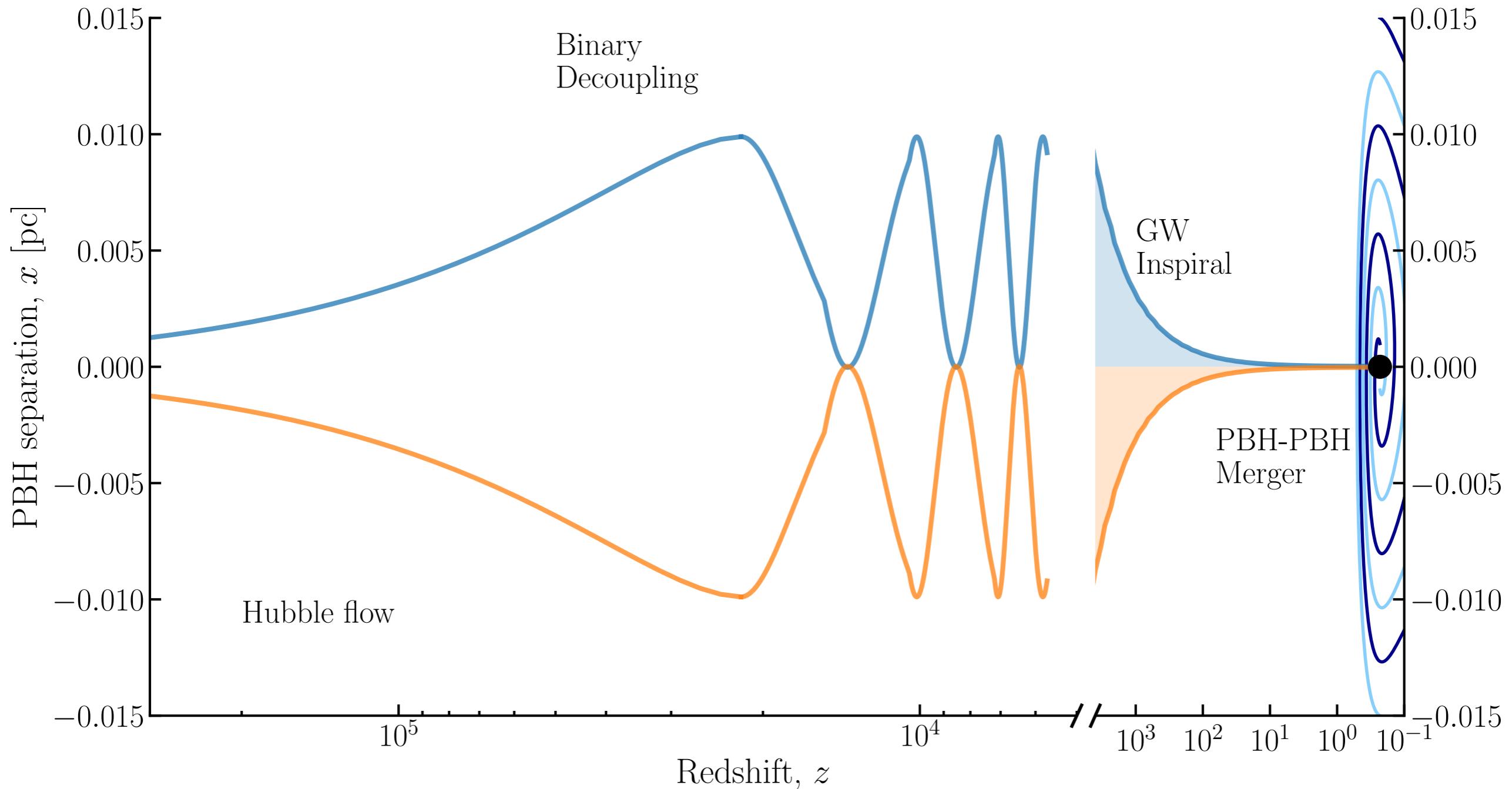


Require:

$$M_{\text{BH}} R^{-3} > \rho(z) \text{ before } z_{\text{eq}}$$

[Daniele Gaggero, UCI 20/02/2018]

# Life of a PBH binary



$$a = 0.01 \text{ pc}$$

$$e = 0.995$$

# PBH Binary Population

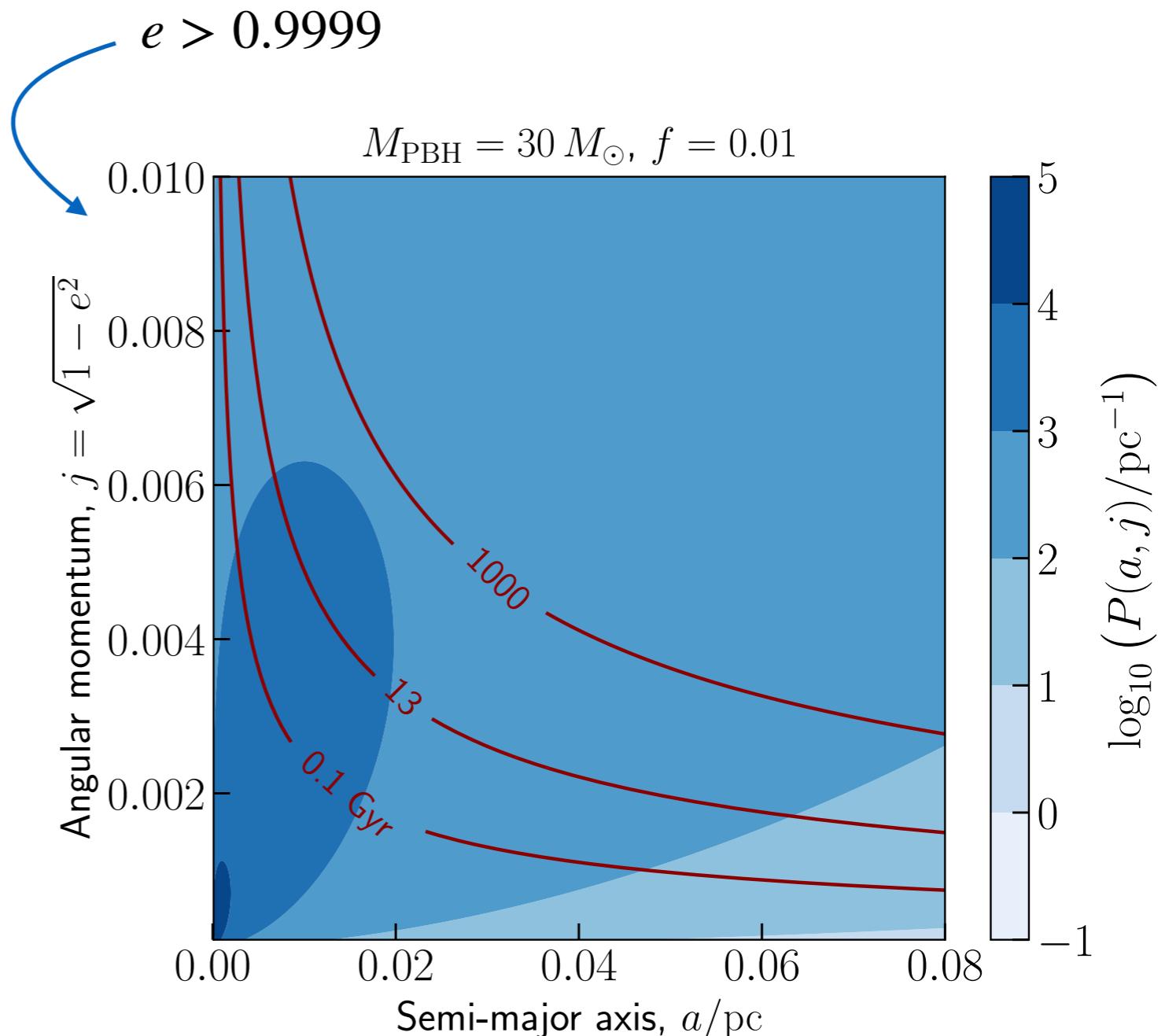
$$j = \sqrt{1 - e^2}$$

Randomly distributed  
(unclustered) PBHs

Angular momentum set by  
torques from smooth density  
perturbations and *all other PBHs*

Close, eccentric binaries  
merge today:

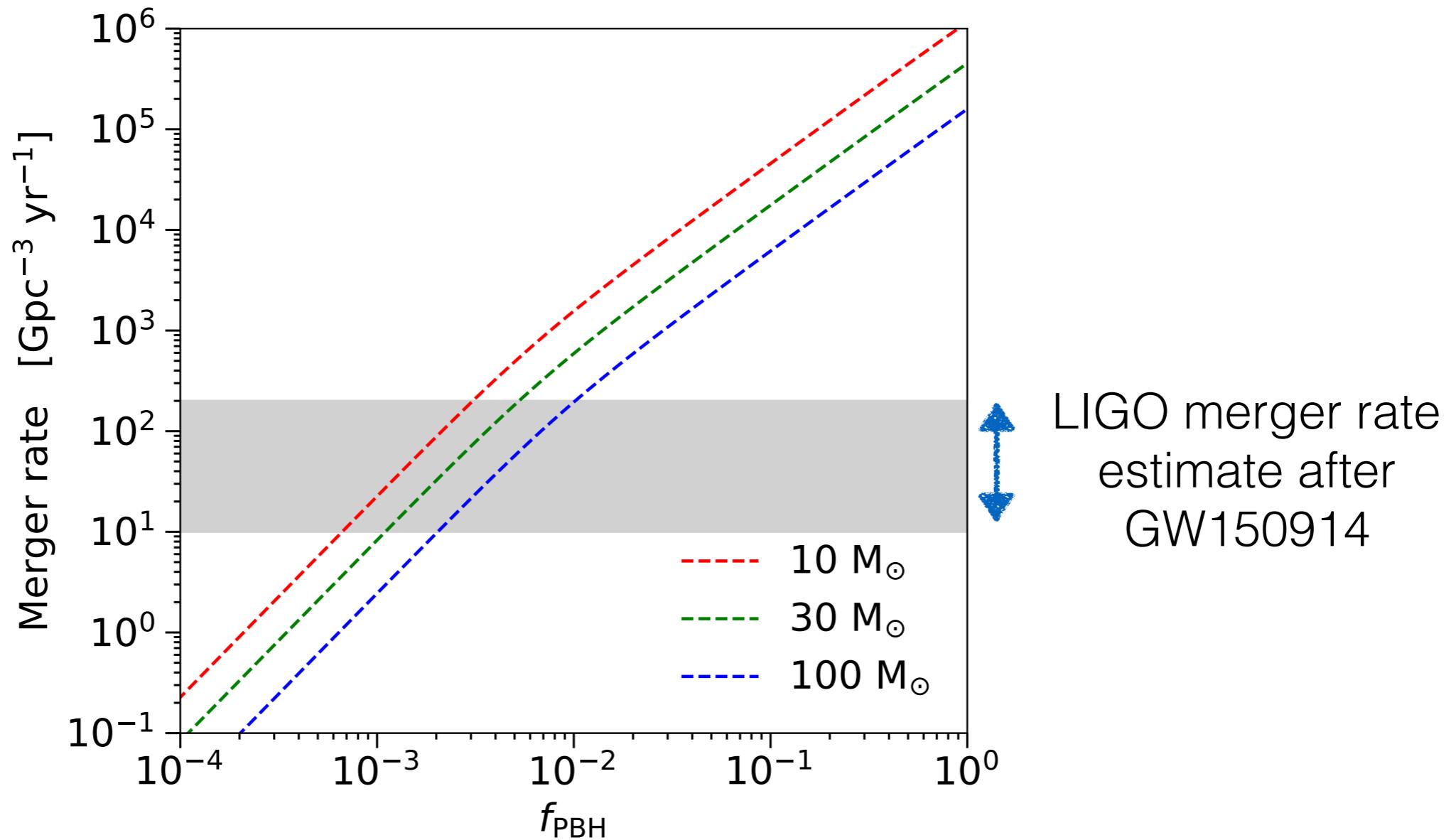
$$t_{\text{merge}} = \frac{3 c^5}{170 G_N^3} \frac{a^4 j^7}{M_{\text{PBH}}^3}$$



[Ali-Haïmoud et al., 1709.06576,  
**BJK**, Gaggero & Bertone, 1805.09034]

# Merger Rate Estimate

$$\mathcal{R}(t_{\text{merge}}) = \frac{1}{2} n_{\text{PBH}} P_{\text{binary}} P(t_{\text{merge}})$$

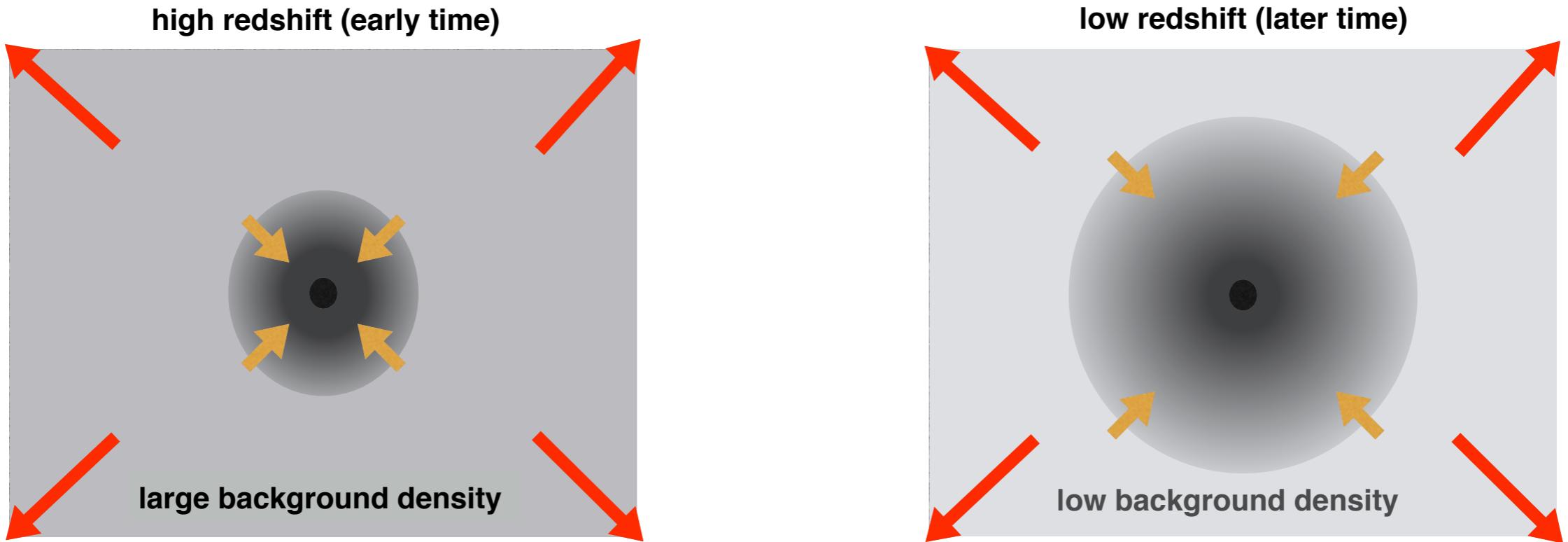


Solar mass PBHs should only be a *sub-dominant* (%-level) contribution to the DM density in the Universe

[Ali-Haïmoud et al., 1709.06576,  
**BJK**, Gaggero & Bertone, 1805.09034,  
and many many others]

# Black Holes' Dark Dress

PBHs seed the formation of 'local' DM halos:



$$R_{\text{tr}}(z) = 0.0063 \left( \frac{M_{\text{PBH}}}{M_{\odot}} \right) \left( \frac{1 + z_{\text{eq}}}{1 + z} \right) \text{ pc}$$

$$\rho(r) \propto r^{-9/4}$$

By matter-radiation equality,  $M_{\text{halo}} \sim M_{\text{PBH}}$

[Bertschinger (1985)]  
[0706.0864, 1901.08528]

Slide shamelessly ripped off from Daniele Gaggero

# Impact of Dark Dresses

[Chandrasekhar, 1943]

*Dynamical friction* due to DM  
exerts a force on the PBHs

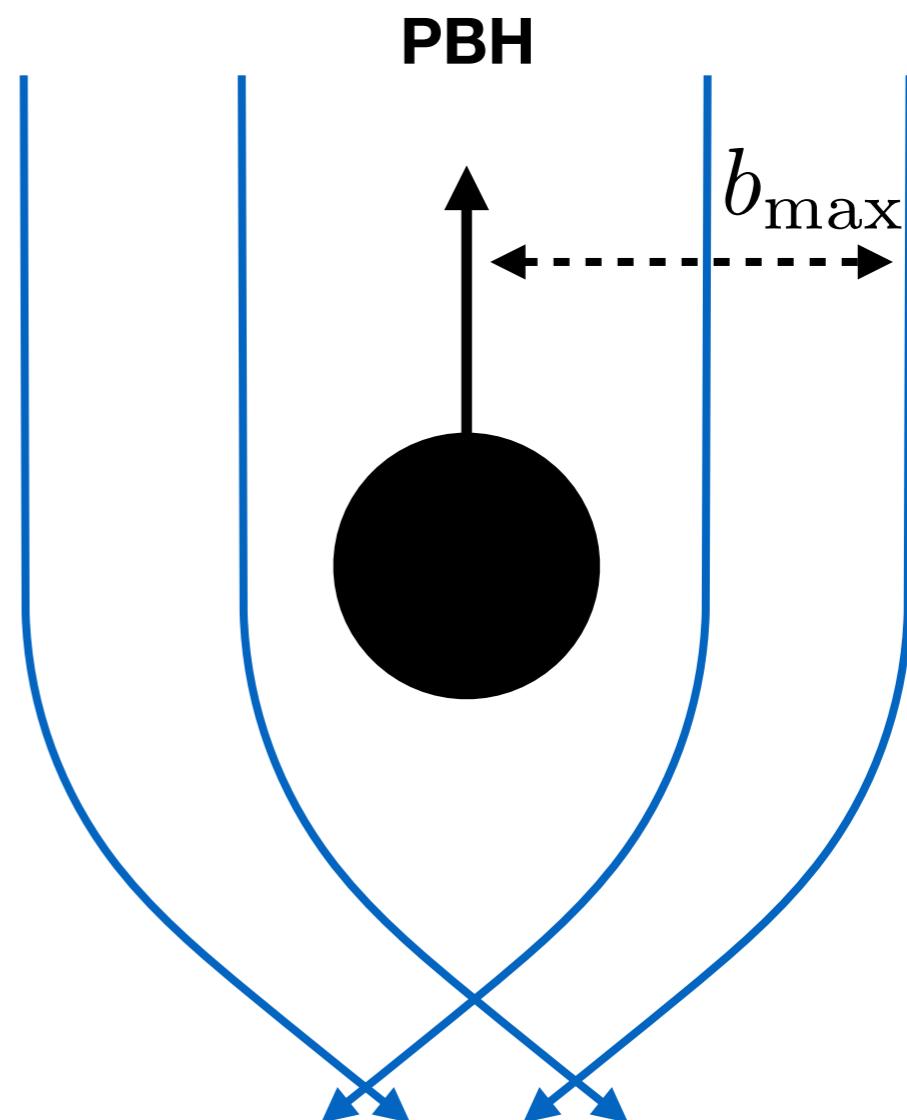
Study the binaries self-consistently  
using N-body simulations:



**GADGET - 2**

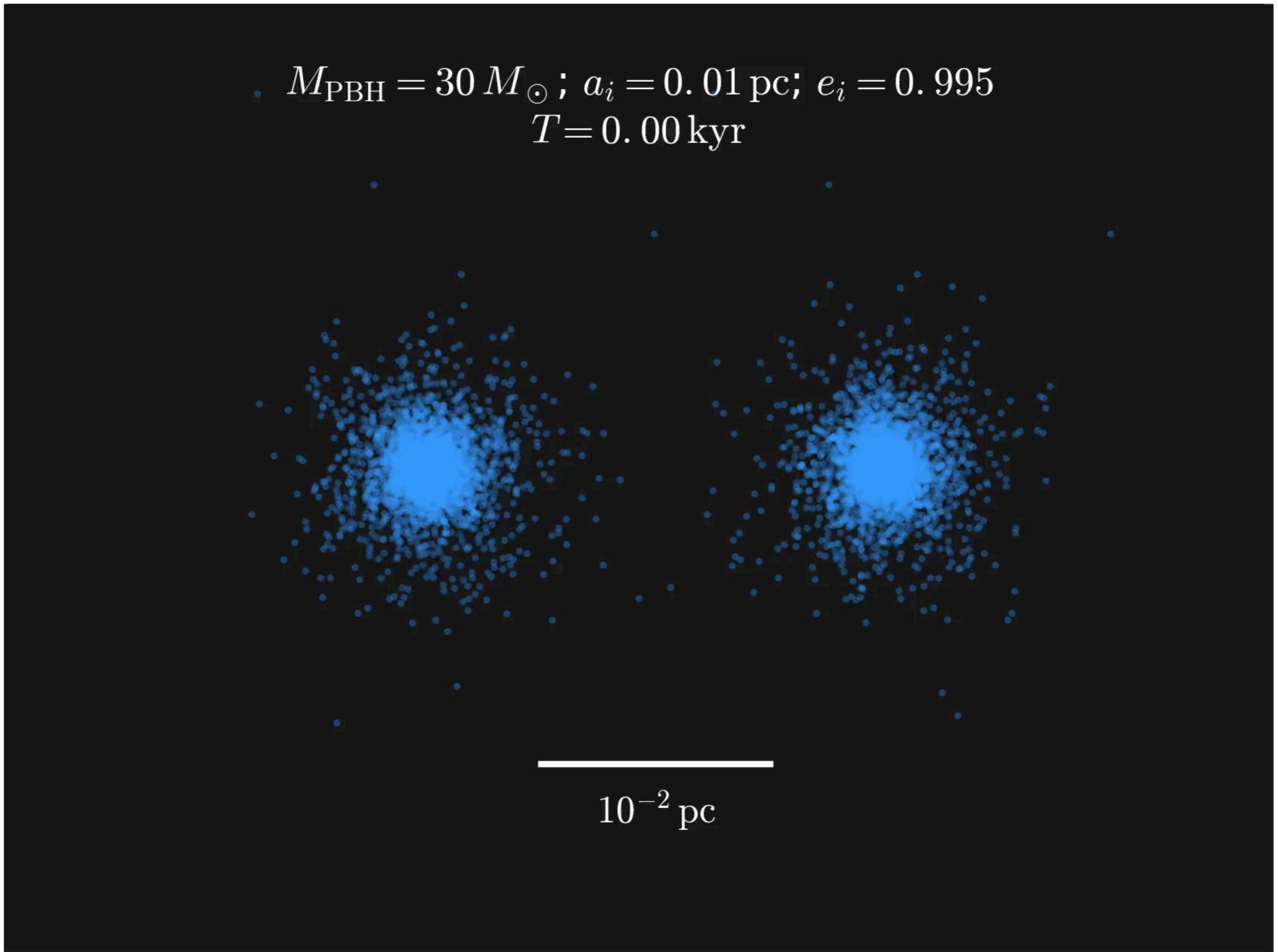
A code for cosmological simulations of structure formation

[astro-ph/0505010]

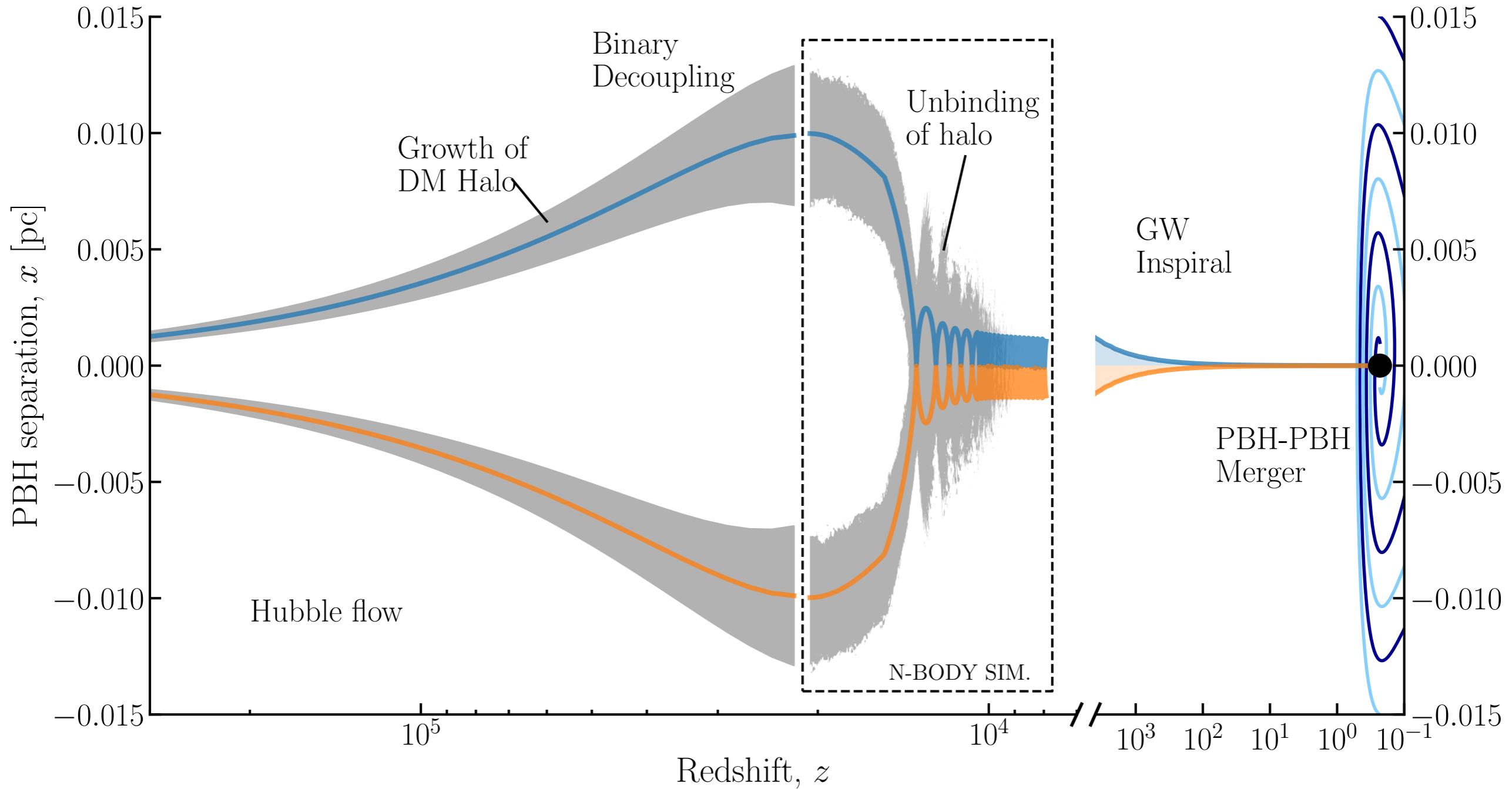


$$\dot{E}_{\text{DF}} \sim \frac{4\pi G_N^2 M_{\text{NS}}^2 \rho_{\text{DM}}(r)}{v_{\text{NS}}} \ln \Lambda$$

- $M_{\text{PBH}} = 30 M_{\odot}$ ;  $a_i = 0.01 \text{ pc}$ ;  $e_i = 0.995$   
 $T = 0.00 \text{ kyr}$



# Life of a ‘dressed’ PBH binary



$$a_i = 0.01 \text{ pc}$$

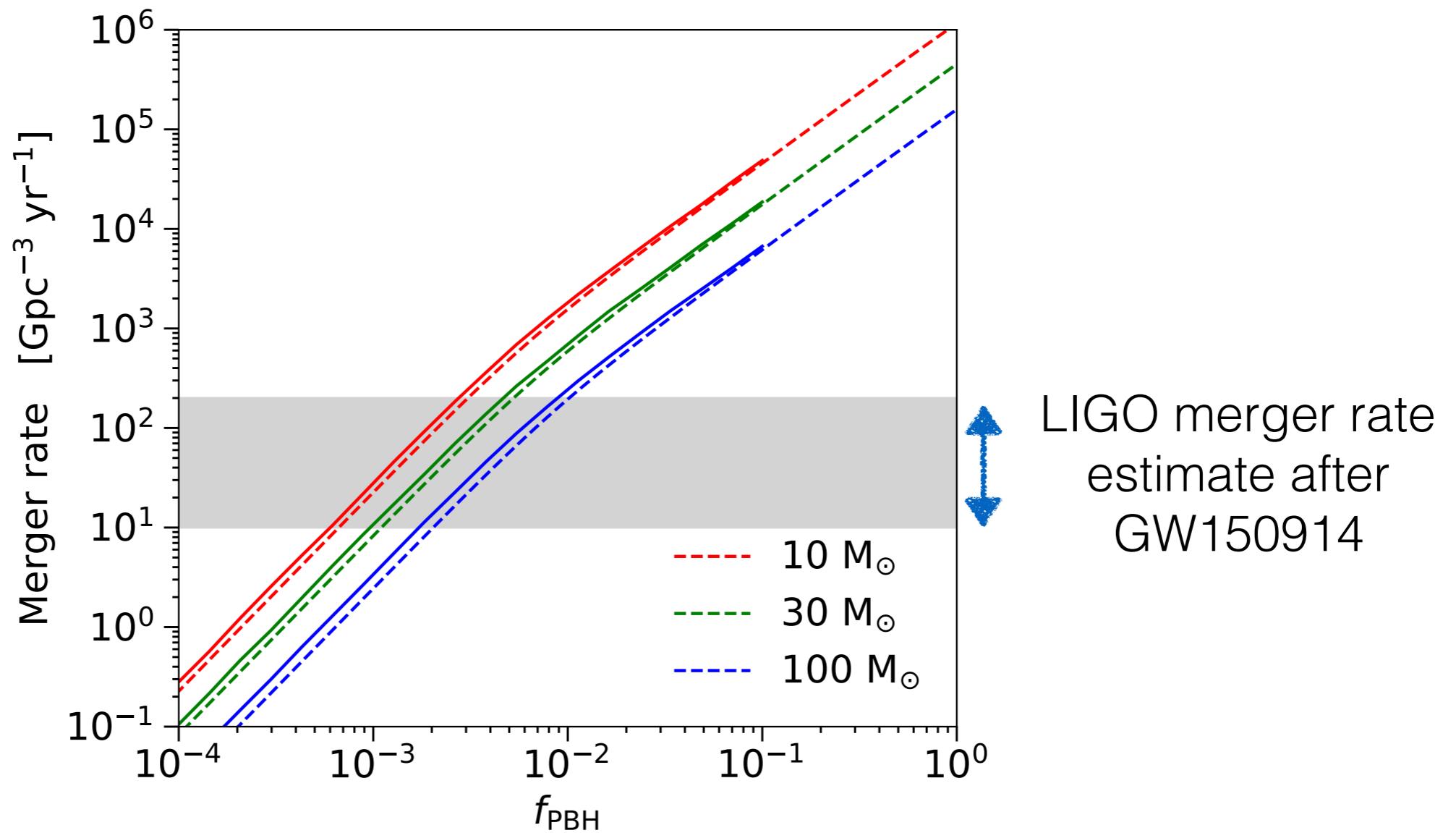
$$e_i = 0.995$$

# Final Merger Rate

$$j = \sqrt{1 - e^2}$$

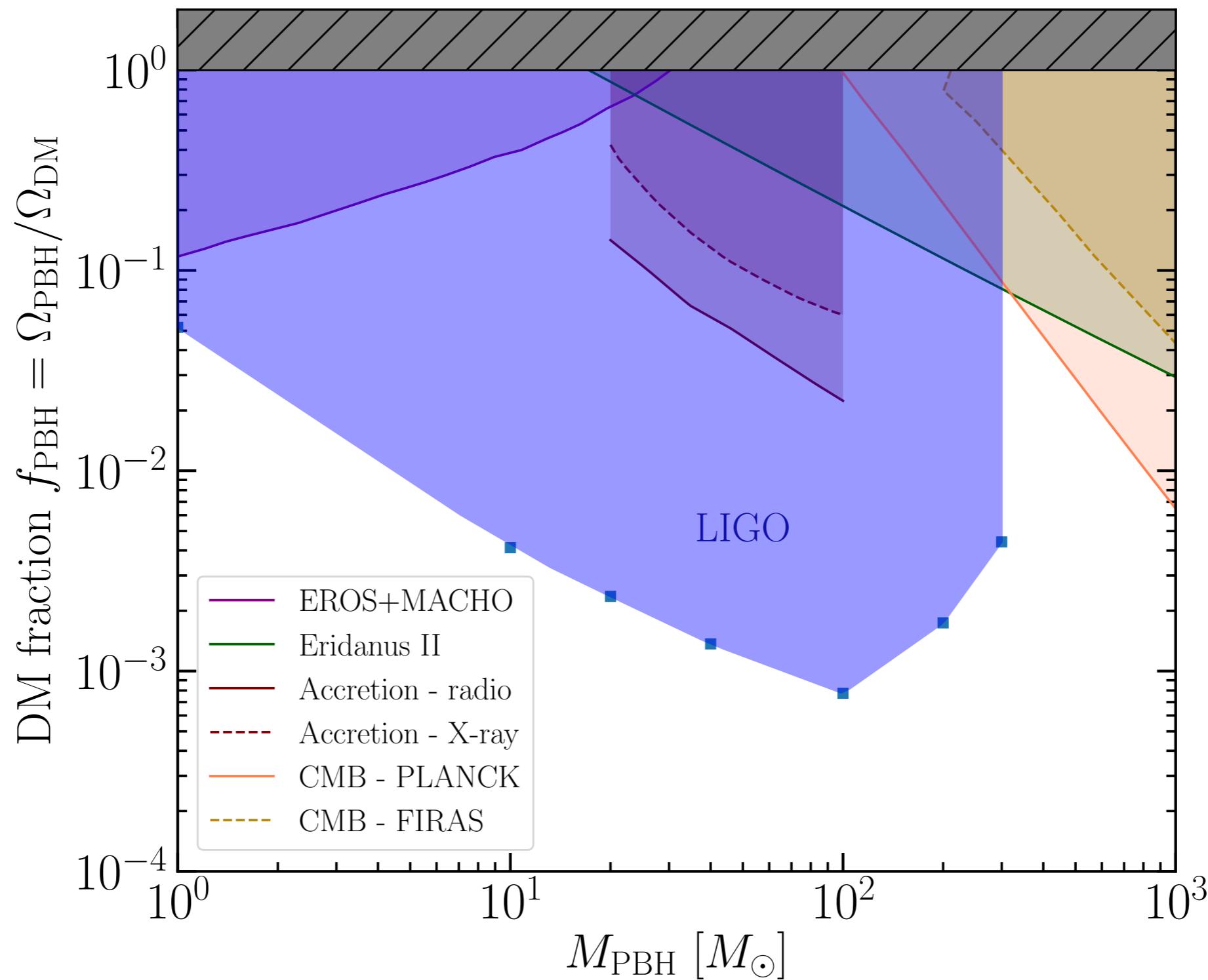
Guided by the simulations, map  $(a_i, e_i) \rightarrow (a_f, e_f)$

Merger time  $t_{\text{merge}} = \frac{3c^5}{170G_N^3} \frac{a^4 j^7}{M_{\text{PBH}}^3}$  is almost conserved:  $t_f = \sqrt{\frac{a_i}{a_f}} t_i$



# Limits from LIGO

[BJK, Gaggero & Bertone, 1805.09034]



*But what if we discover primordial black holes?*

# Detection prospects

**GW detection of  
sub-solar mass BHs**

(LIGO O3,  
now!)

**GW detection of high  
redshift BHs ( $z > 40$ )**

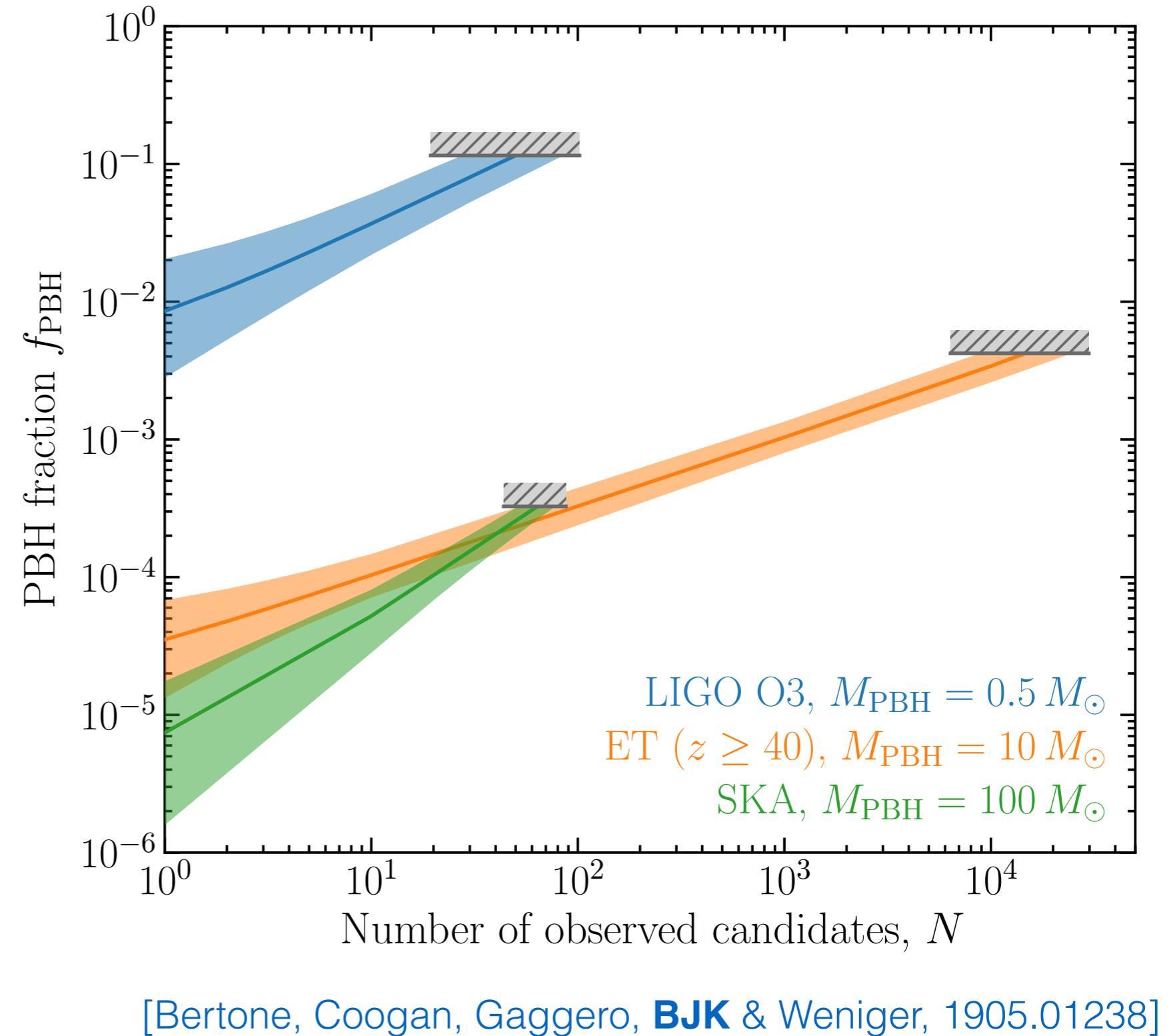
(Einstein Telescope,  
mid-late 2020s)

[1708.07380]

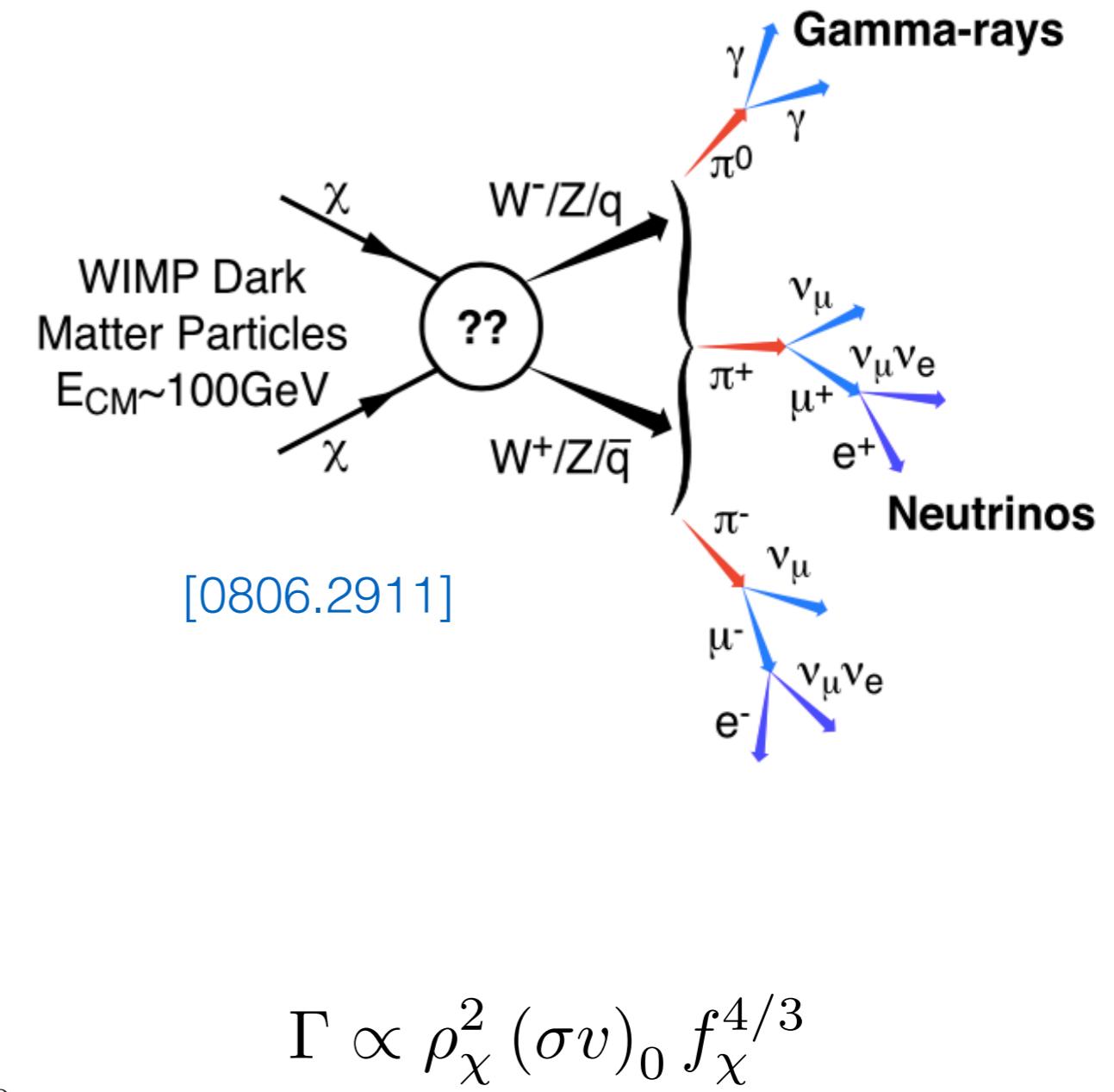
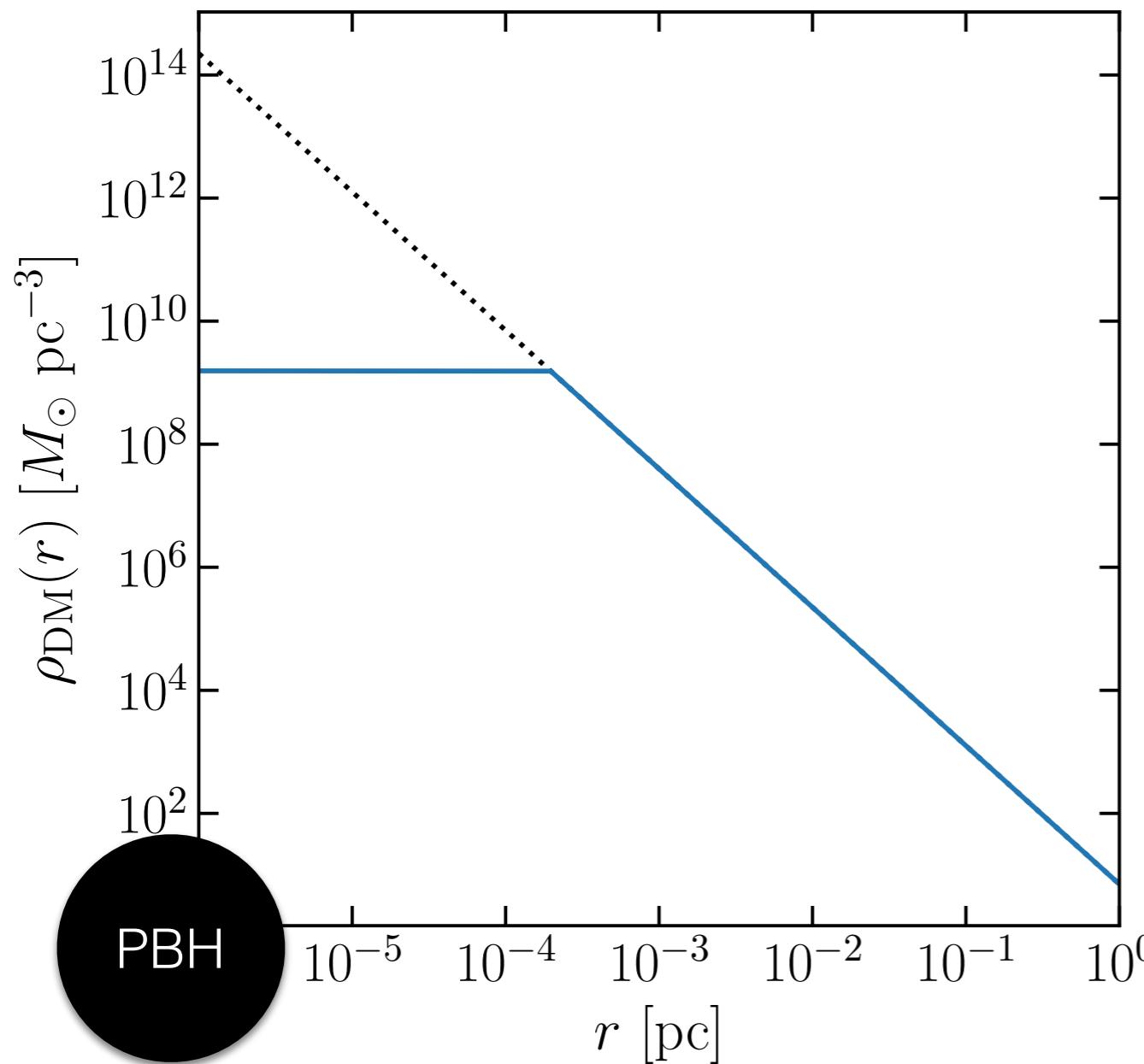
**Radio detection of  
accreting galactic PBHs**

(Square Kilometre Array,  
late 2020s)

[1812.07967]



# DM annihilation

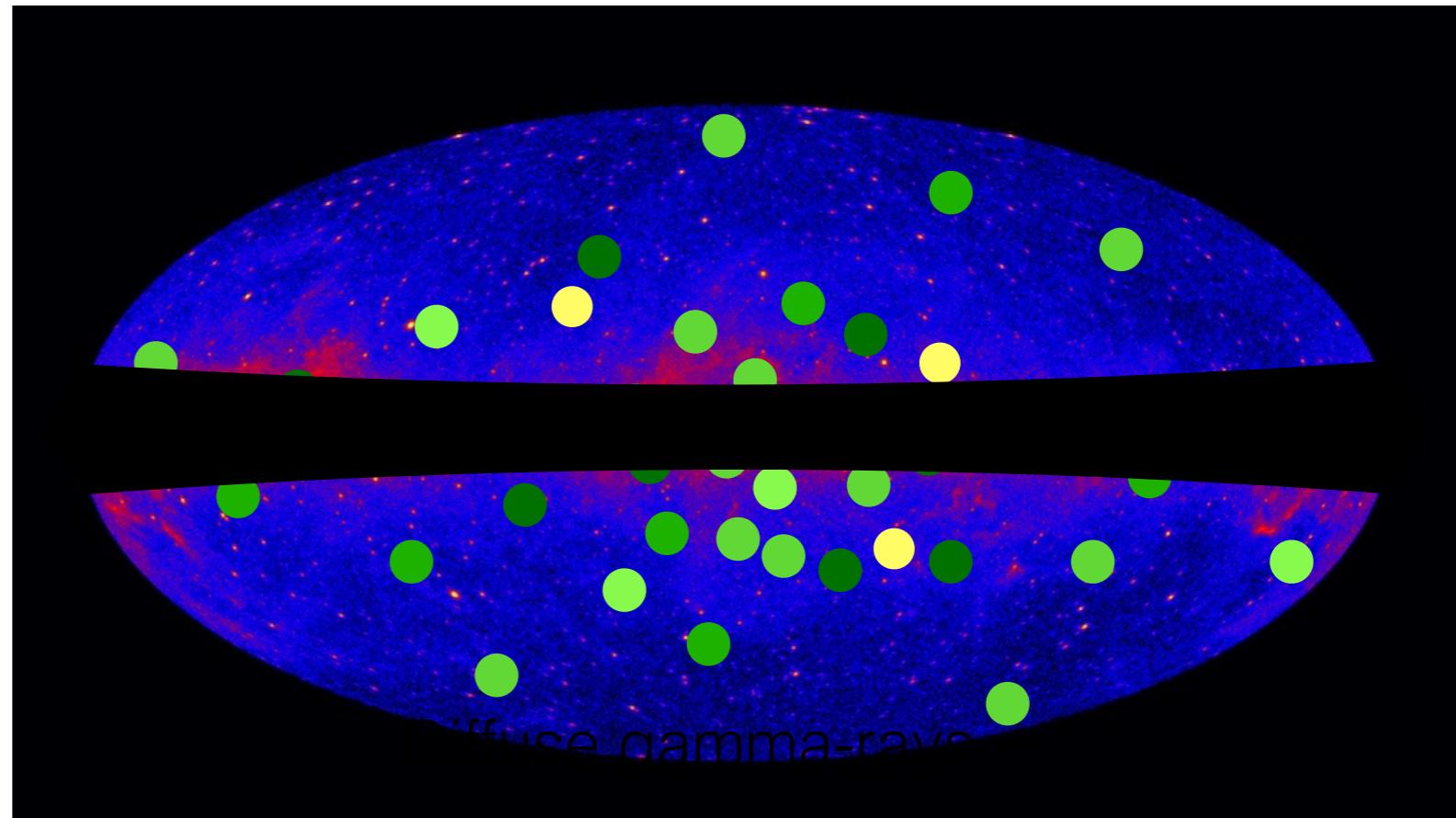


PBH population would act as bright *gamma-ray sources*

# Gamma-ray constraints

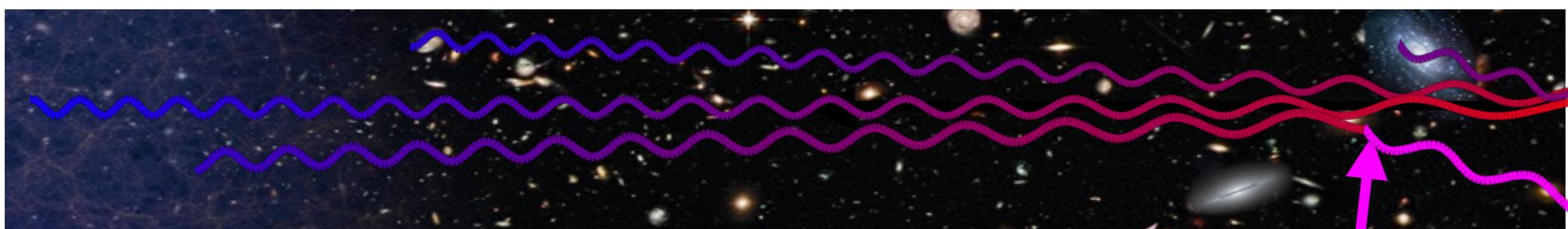
[Credit: Adam Coogan]

## Point Sources in the Milky Way:



Fermi/NASA

## Diffuse (cosmological) background:



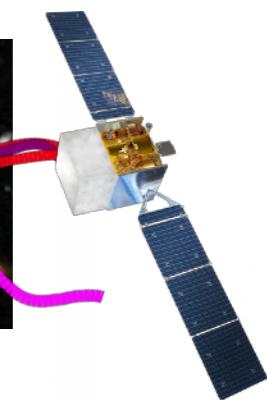
UCO/Lick

Gamma rays from DM ann.

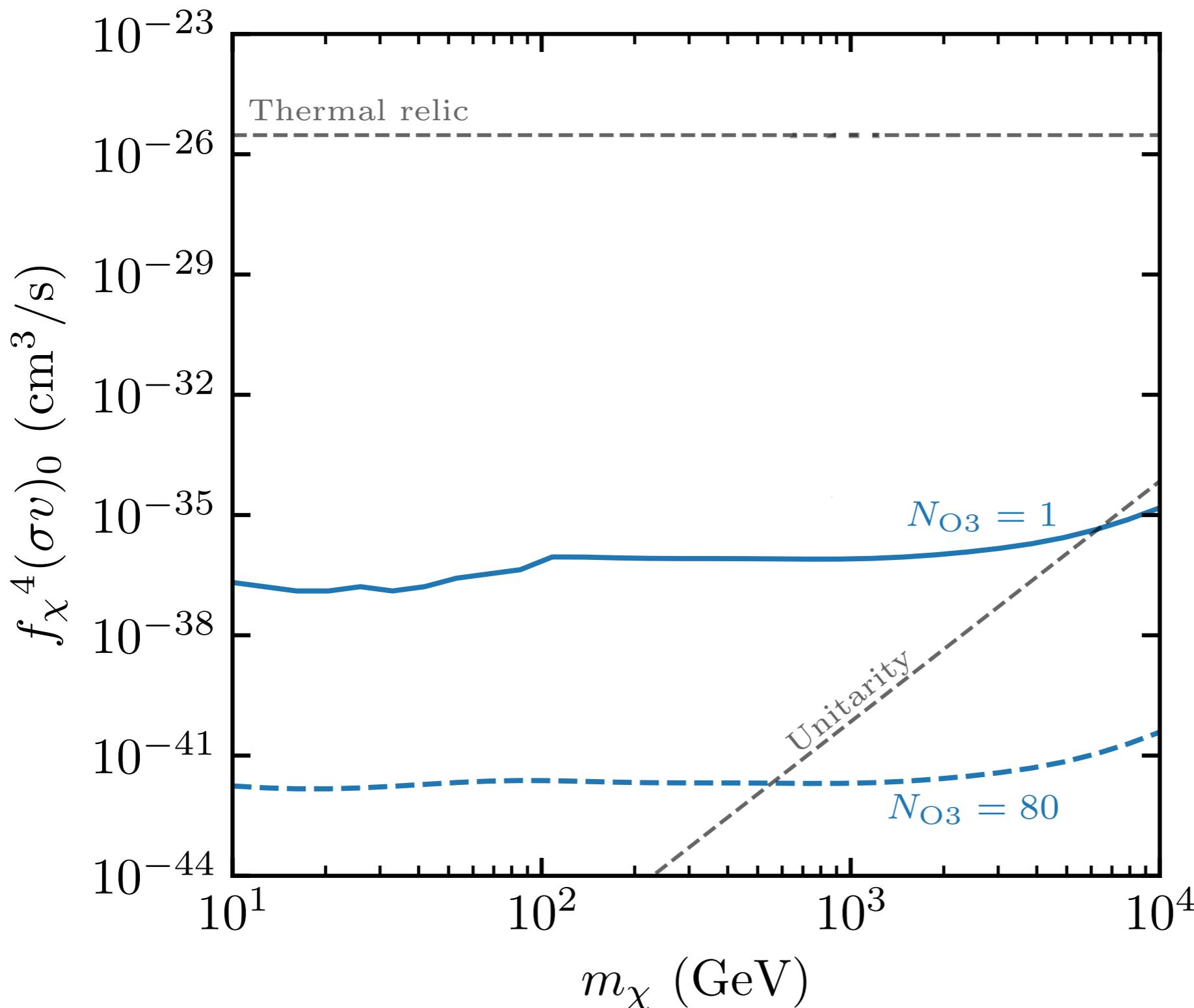
Redshifting

Attenuation

NASA



# Cross section constraints



**GW detection of  
sub-solar mass BHs**  
(LIGO O3,  
now!)

[Bertone, Coogan, Gaggero, **BJK** & Weniger, 1905.01238]

# Werewolves

---

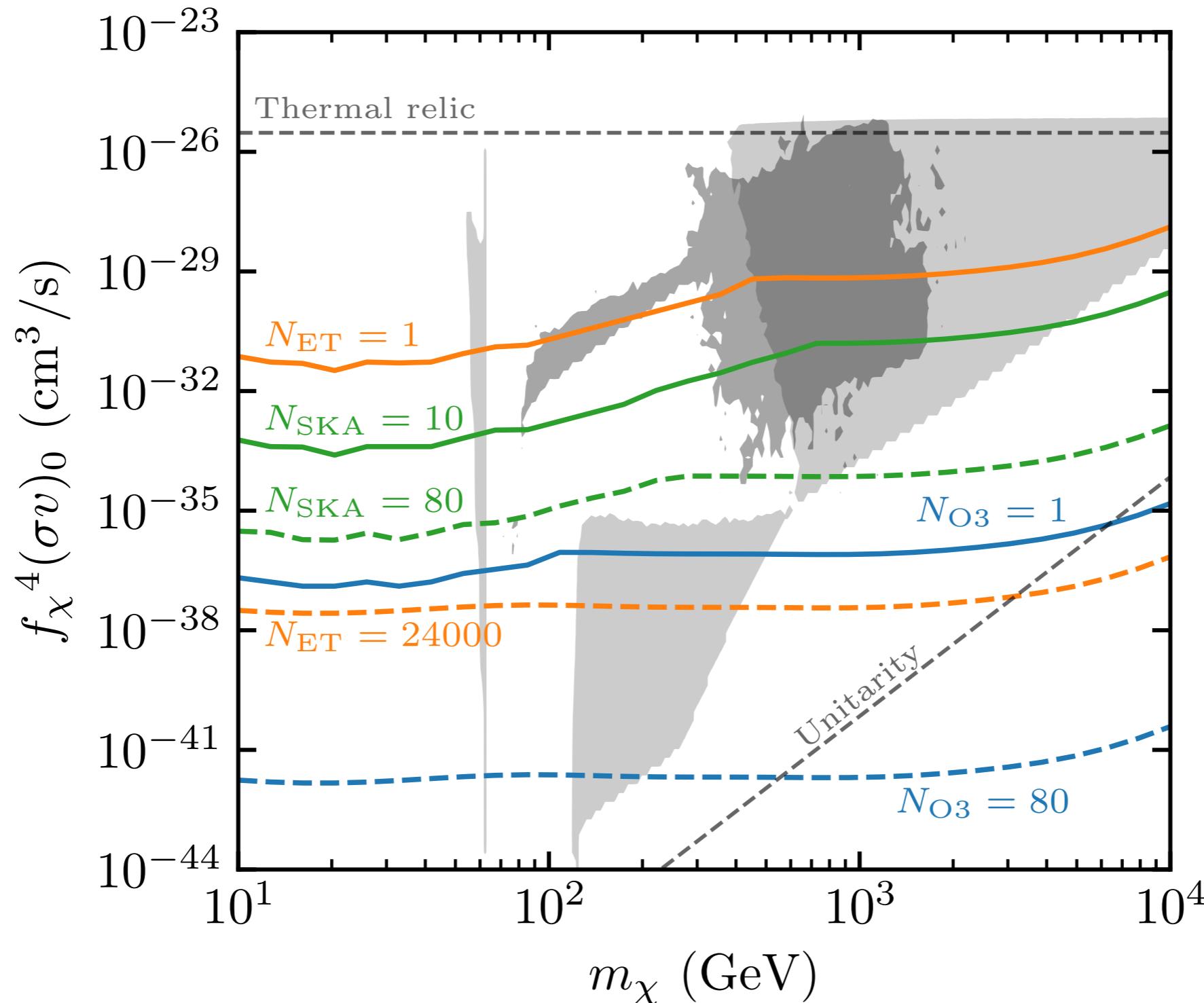
Werewolves: humans with the ability to shapeshift into a wolf, which are notoriously hard to kill



Can be killed with **Silver Bullets**

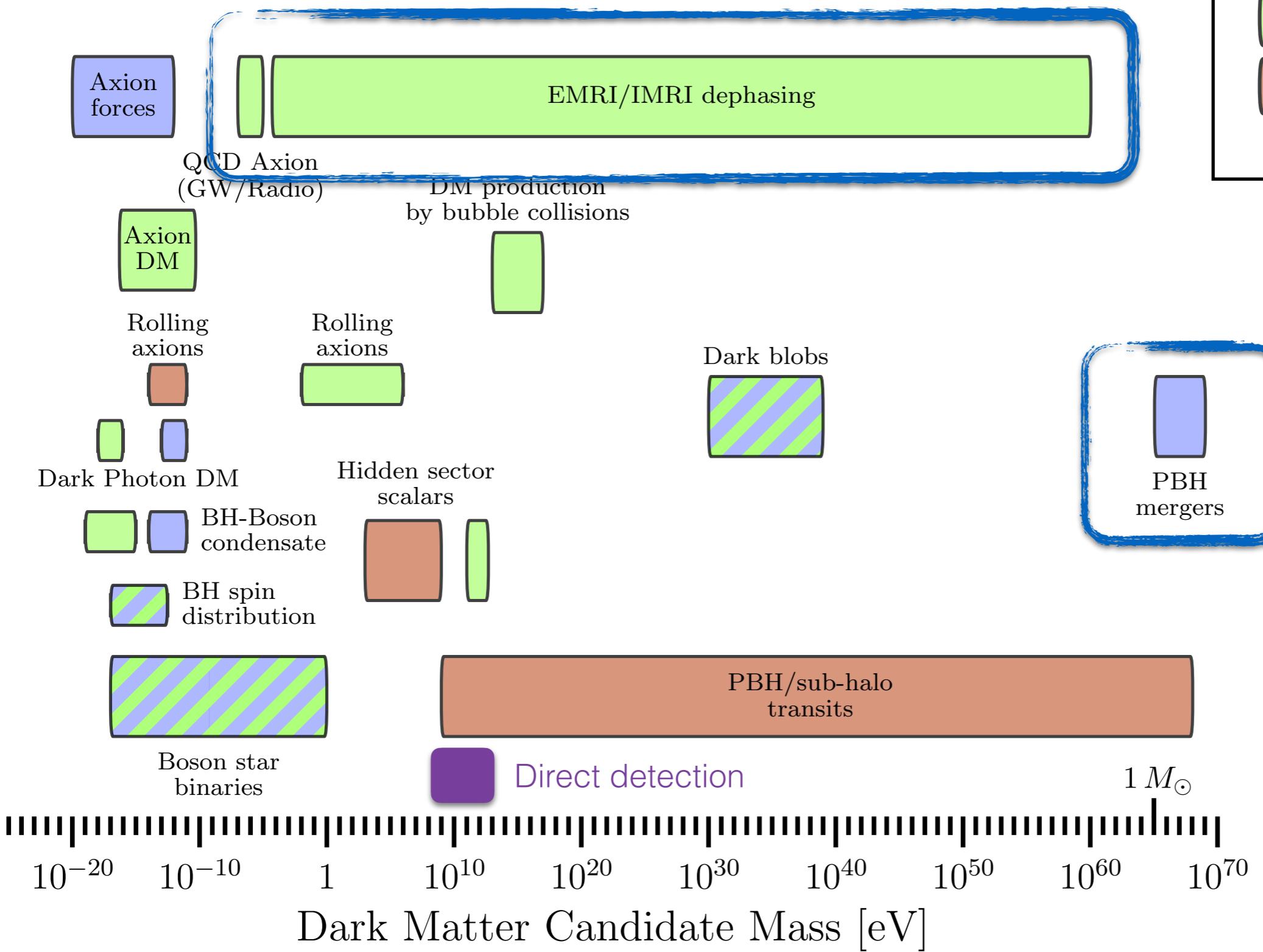
# Silver Bullets

WIMPs: Weakly Interacting Massive Particles,  
which are notoriously hard to kill



Primordial Black Holes as '**Silver Bullets**' for New Physics at the Weak Scale  
[Bertone, Coogan, Gaggero, **BJK** & Weniger, 1905.01238]

# GW probes of DM



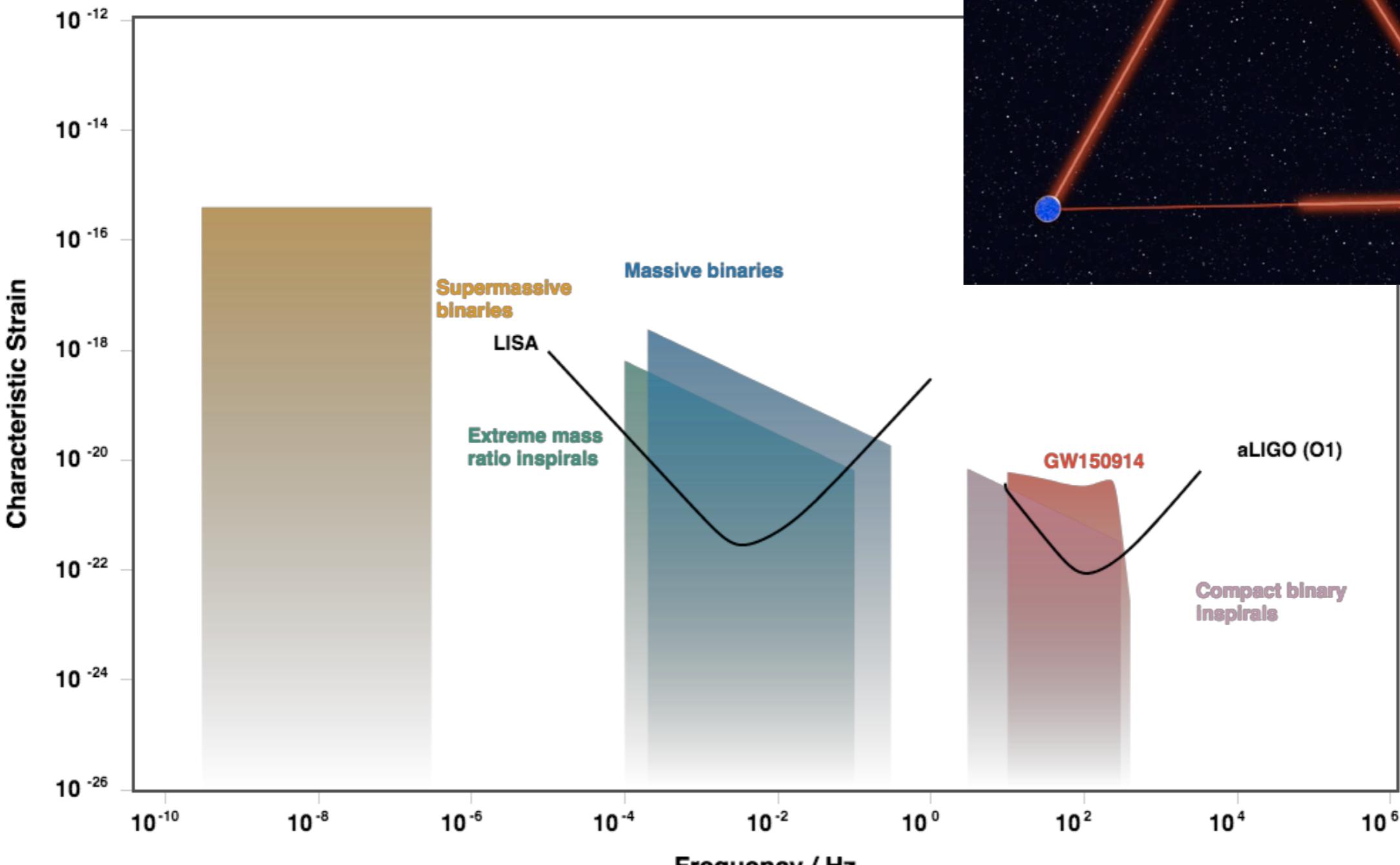
[1907.10610]

# LISA: GWs in Space

© AEI / MM / exozet

Laser Interferometer Space Antenna  
(planned for the 2030s)

[1702.00786]

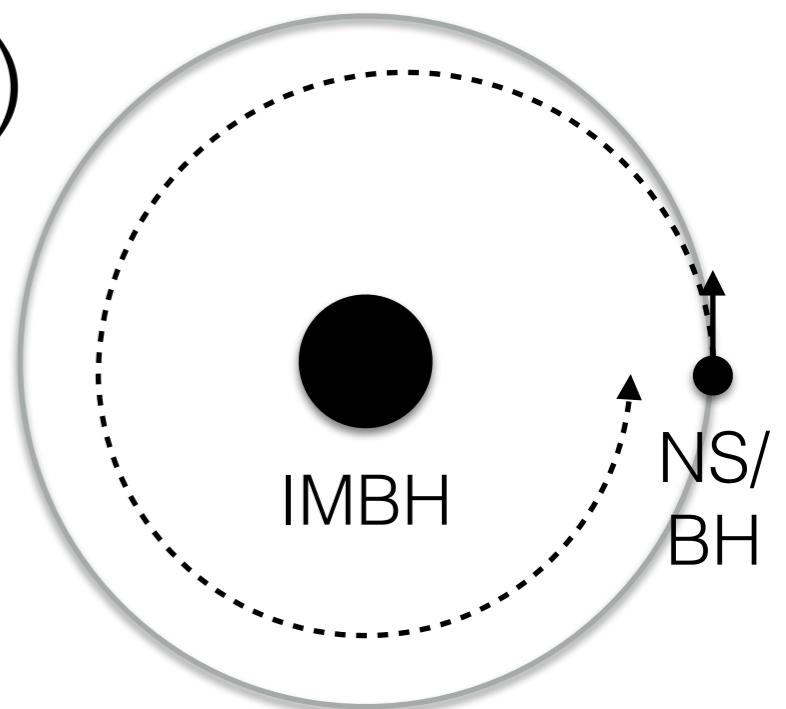


[gwplotter.com]

# Intermediate Mass Ratio Inspiral (IMRI)

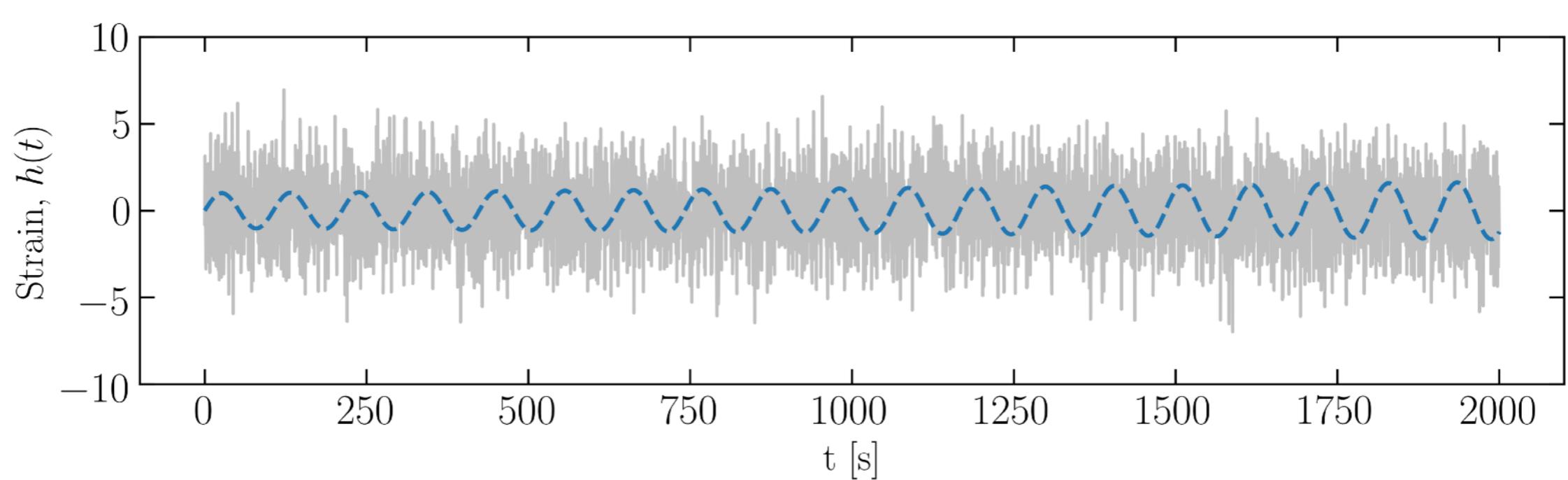
Stellar mass compact object (NS/BH) inspirals towards intermediate mass black hole (IMBH)

$$M_{\text{IMBH}} \sim 10^3 - 10^5 M_\odot$$



GW emission causes long, slow inspiral:

$$\dot{E}_{\text{GW}} \approx \frac{32G^4}{5c^5} \frac{M_{\text{IMBH}}^3 M_{\text{NS}}^2}{r^5} \propto (f_{\text{GW}})^{10/3}$$



LISA should detect  $\sim 3 - 10$  IMRIs per year

[1711.00483]

# Dark Matter ‘Mini-spikes’

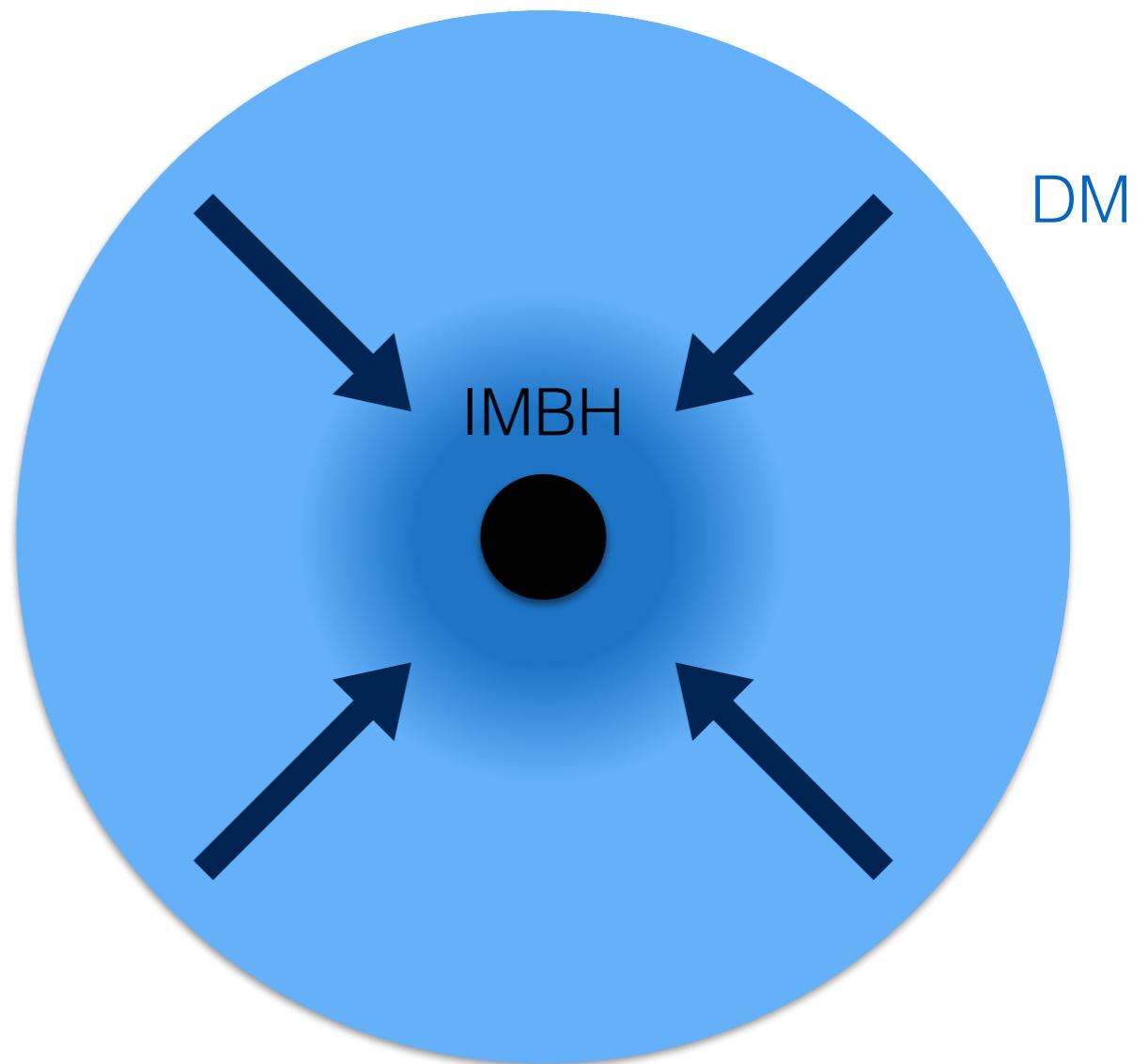
Depending on the formation mechanism of the IMBH,  
expect an over-density of DM:

$$\rho_{\text{DM}}(r) = \rho_{\text{sp}} \left( \frac{r_{\text{sp}}}{r} \right)^{\gamma_{\text{sp}}}$$

For BH forming in an NFW halo,  
from adiabatic growth expect:

$$\gamma_{\text{sp}} = 7/3$$

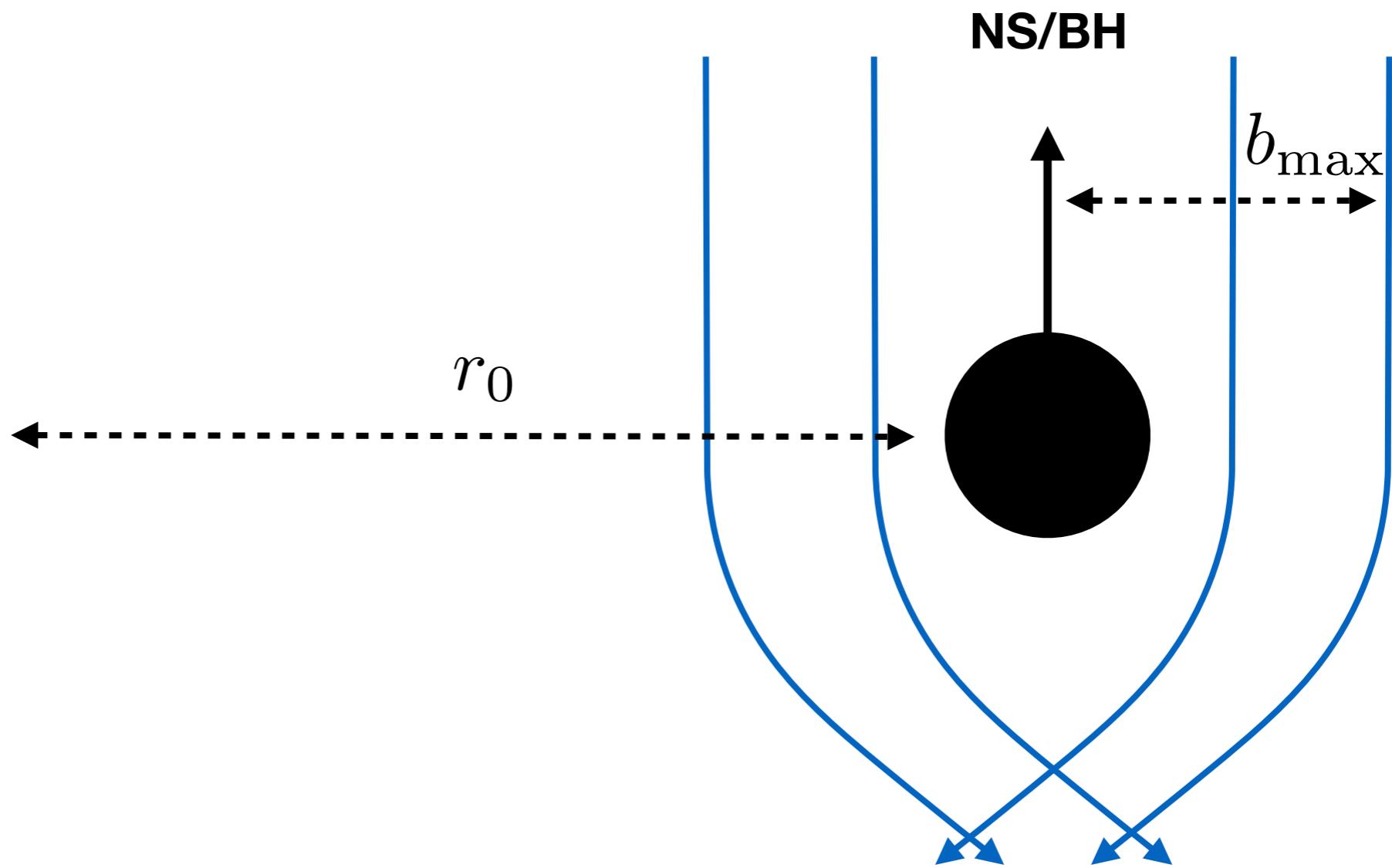
Density can reach  $\rho \sim 10^{24} M_{\odot} \text{ pc}^{-3}$   
( $\sim 10^{24}$  times larger than local density)



[astro-ph/9906391, astro-ph/0501555, astro-ph/0501625, astro-ph/0509565, 0902.3665, 1305.2619]

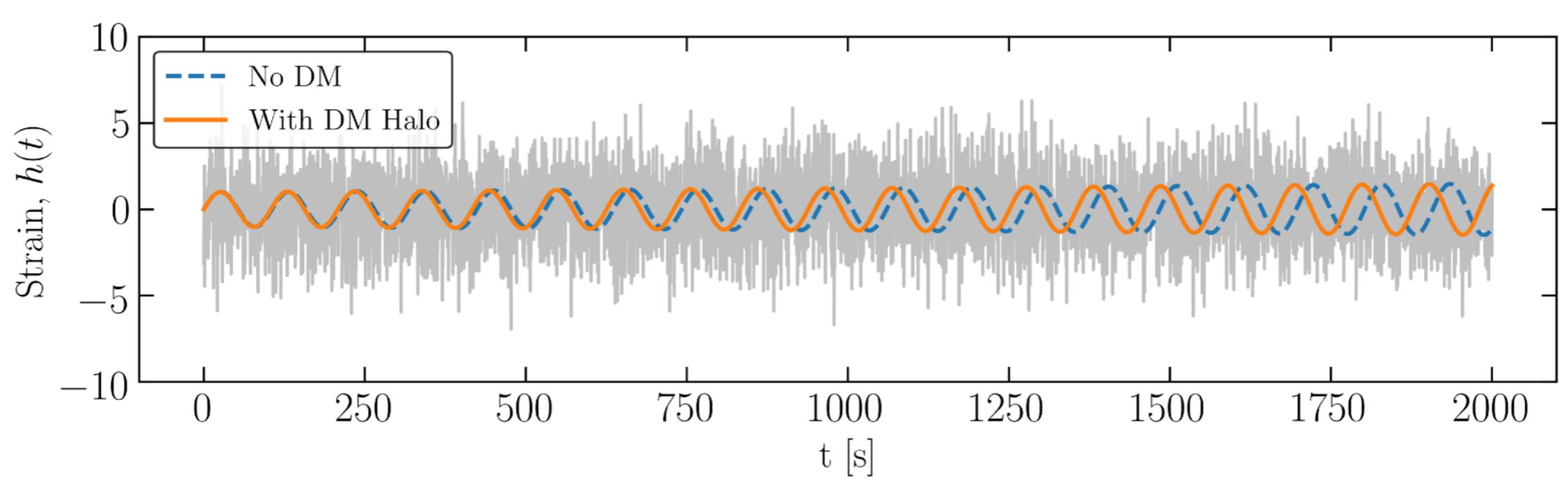
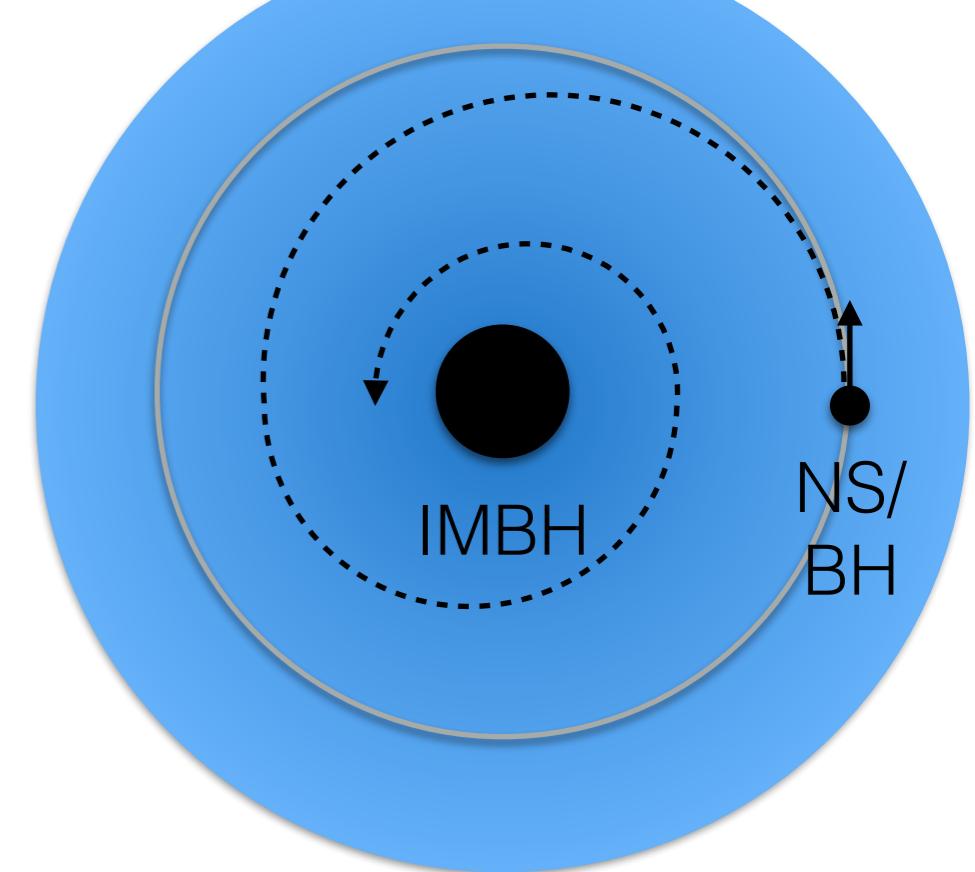
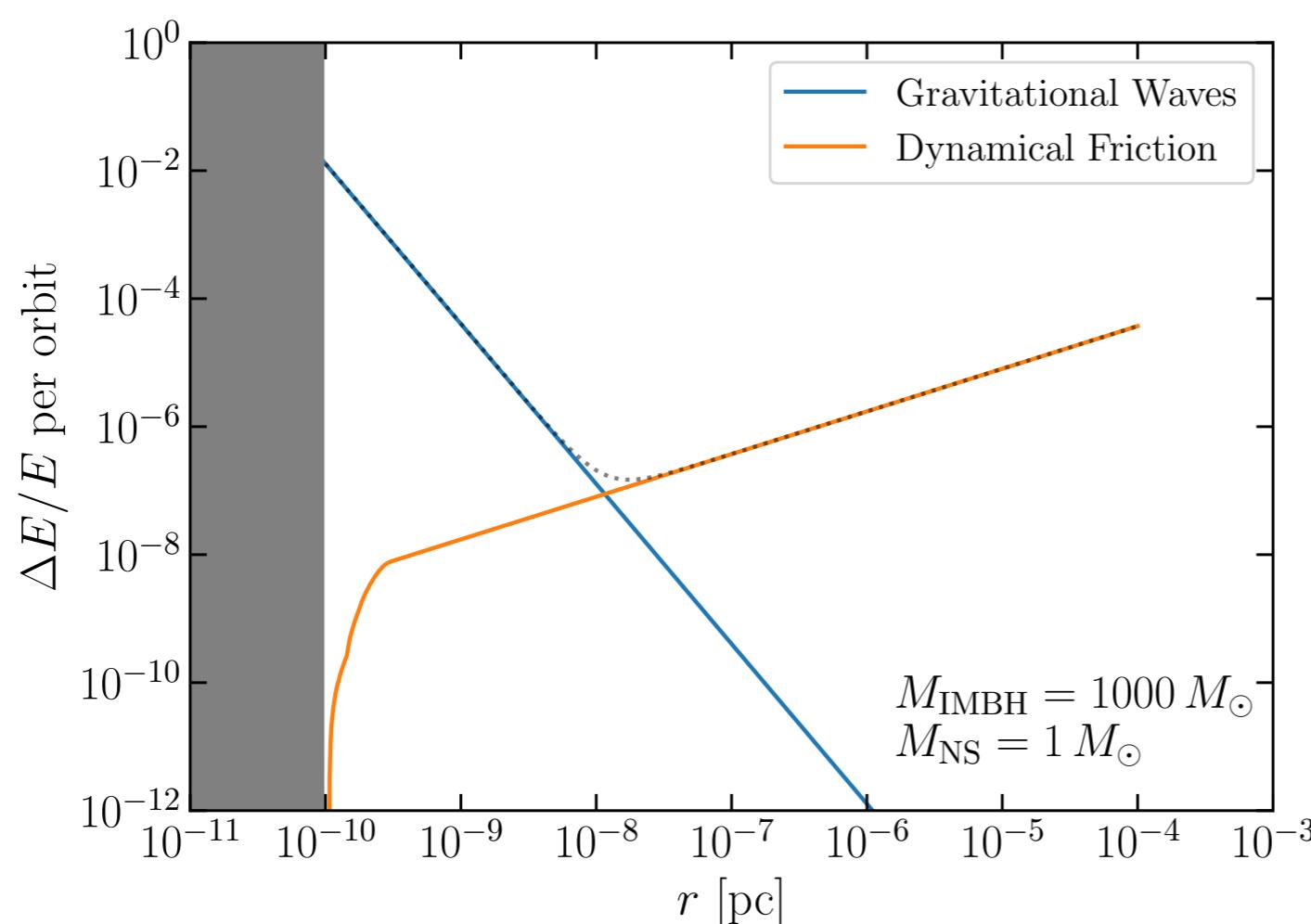
# Dynamical Friction

[Chandrasekhar, 1943]



$$\dot{E}_{\text{DF}} \sim \frac{4\pi G_N^2 M_{\text{NS}}^2 \rho_{\text{DM}}(r)}{v_{\text{NS}}} \ln \Lambda \propto (f_{\text{GW}})^{\frac{2}{3}\gamma - 3}$$

# IMRI + Dark Matter



# 'De-phasing' signal

Benchmark:

$$M_{\text{IMBH}} = 10^3 M_{\odot}$$

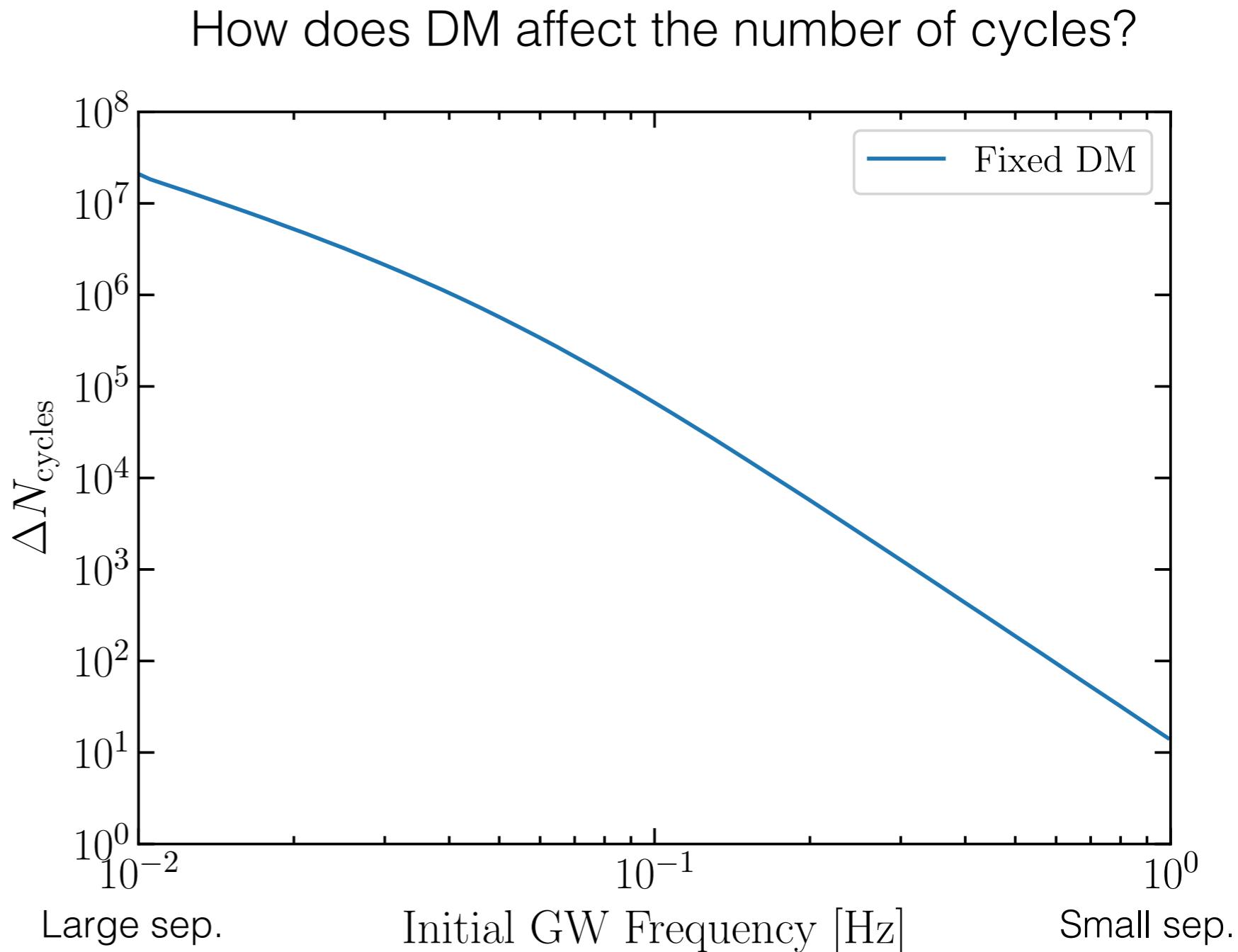
$$M_{\text{NS}} = 1 M_{\odot}$$

$$r_{\text{ini}} \sim 10^{-8} \text{ pc}$$



$$t_{\text{merge}} \sim 5 \text{ yr}$$

$$N_{\text{cycles}}^{\text{vacuum}} \sim 2 \times 10^7$$

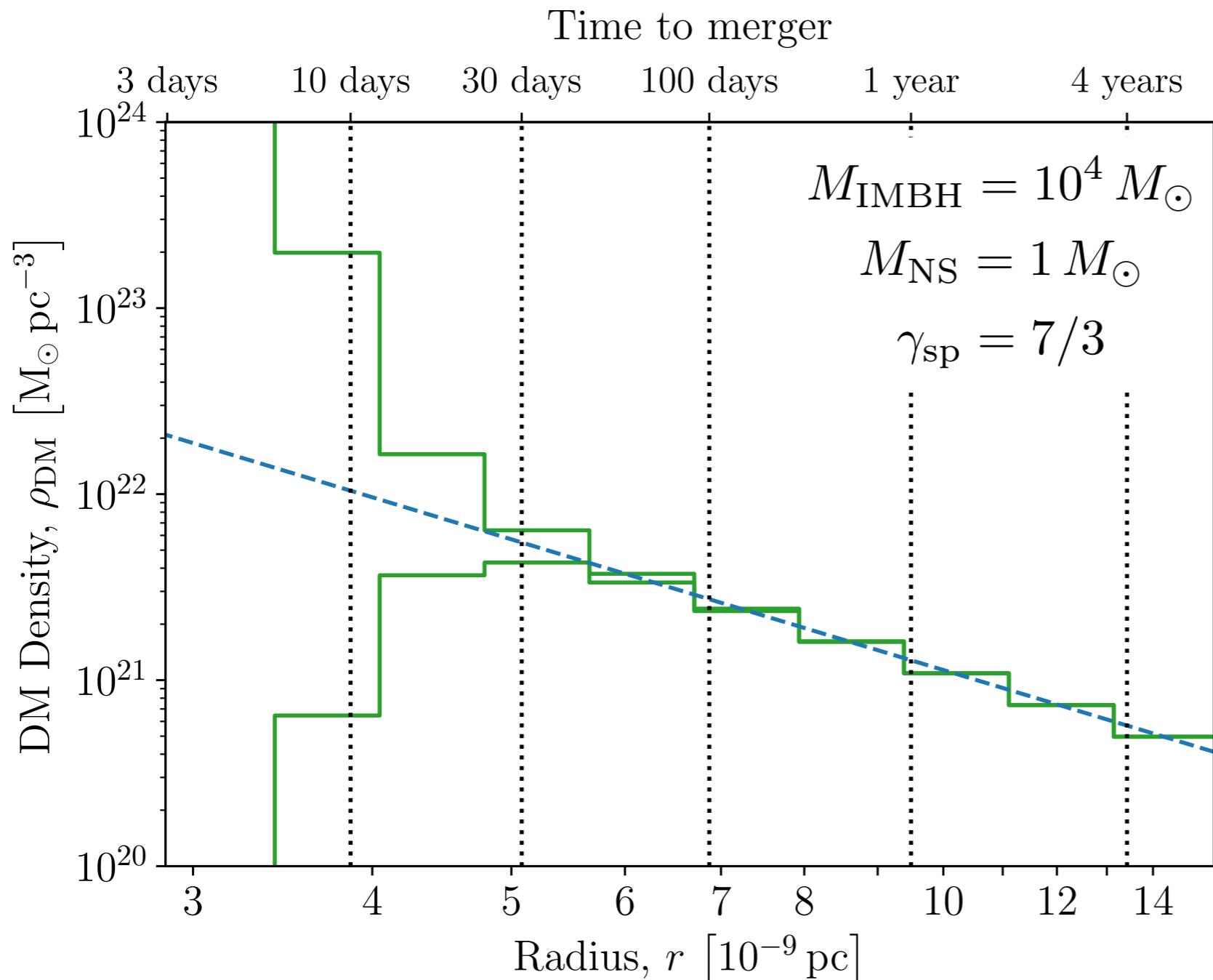


*Need to know the signal to better  
than  $\sim 1$  part in  $10^6$ !*

[Eda et al. 1301.5971, 1408.3534]

[See also 1302.2646, 1404.7140, 1404.7149]

# DM Density Reconstruction



Would allow us to:

Detect DM in GWs  
[1909.05870]

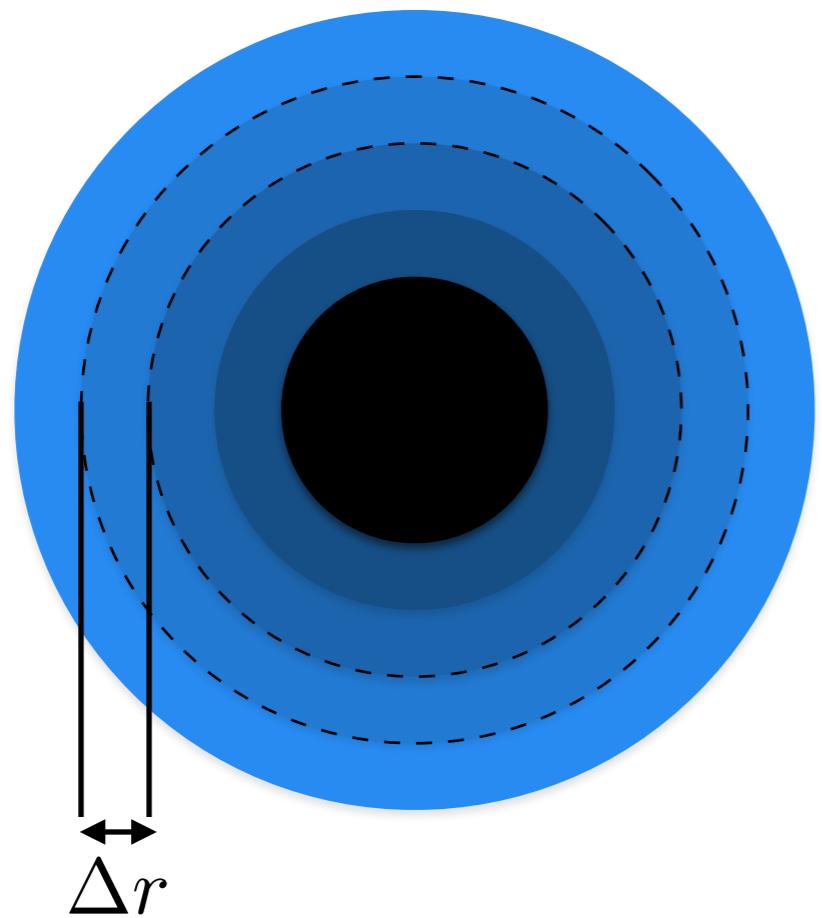
Probe DM nature  
[1906.11845]

Predict EM  
signals from DM  
[1905.04686]

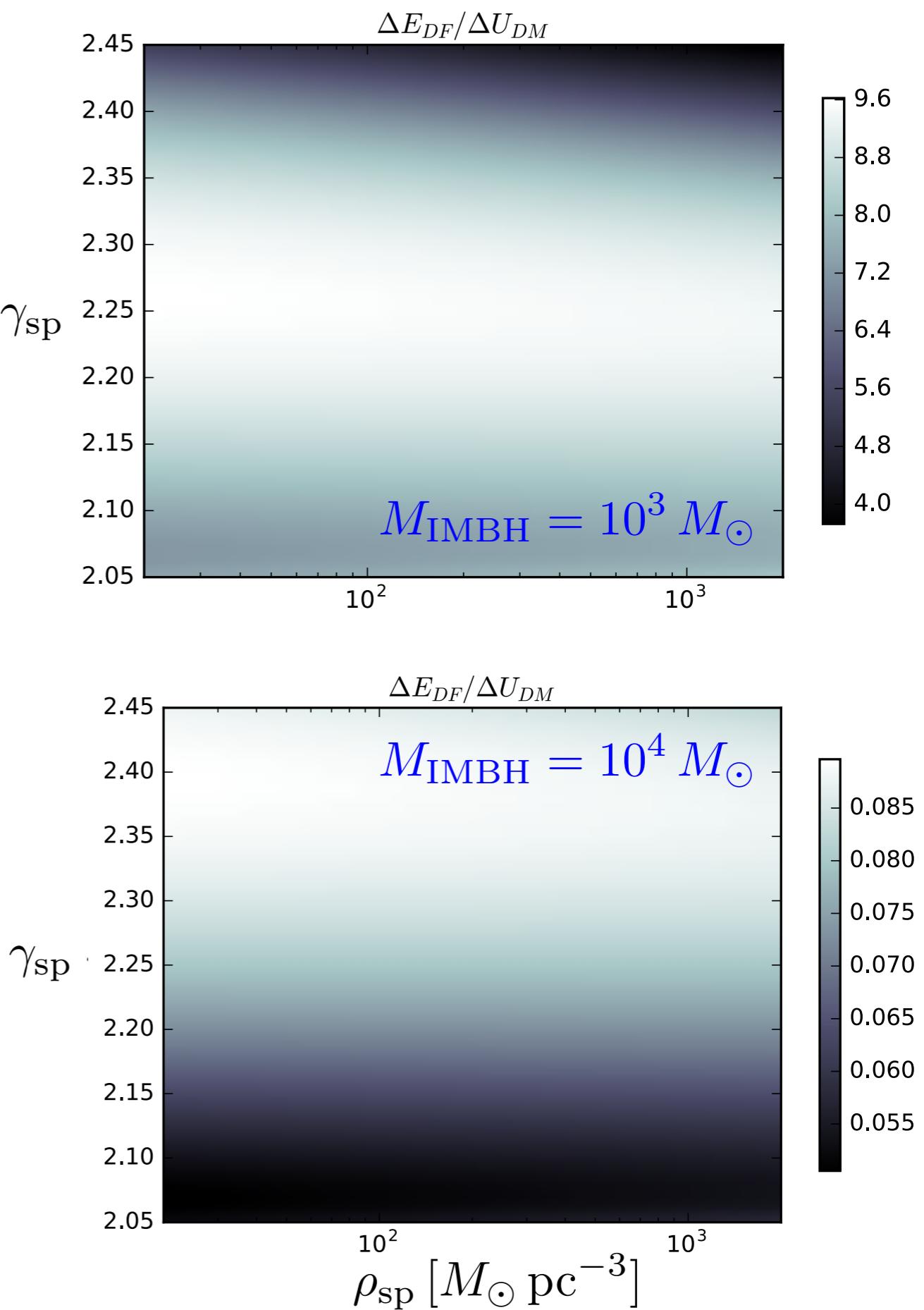
[Edwards, Chianese, **BJK**, Nissanke & Weniger, 1905.04686]

# Energy Budget

Q: How much energy is *available* for dynamical friction?

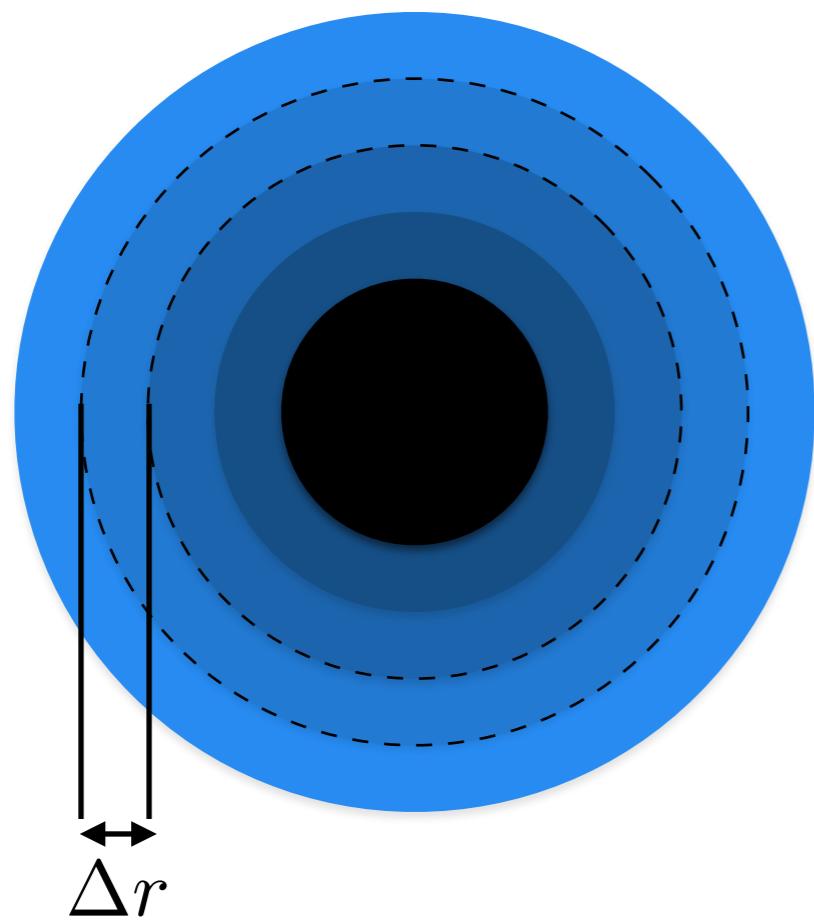


A: Binding energy of DM  $\Delta U_{\text{DM}}$  over radius  $\Delta r$



# Energy Budget

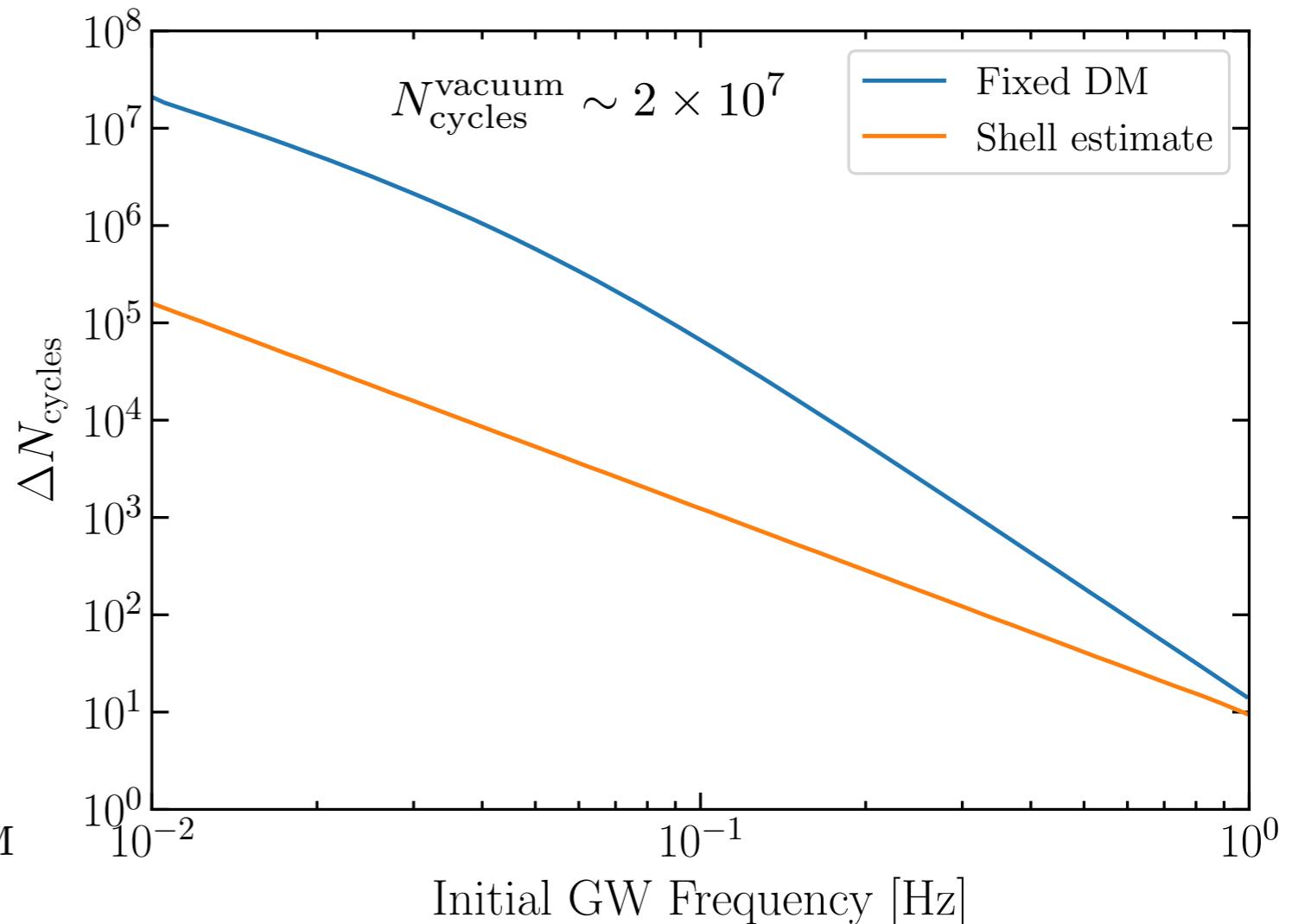
Q: How much energy is *available* for dynamical friction?



A: Binding energy of DM  $\Delta U_{\text{DM}}$  over radius  $\Delta r$

Evolve the system by fixing the dynamical friction force to extract *all* binding energy from a shell at a given radius:

$$\dot{E}_{\text{DF}} = \dot{r} \frac{dU_{\text{DM}}}{dr}$$



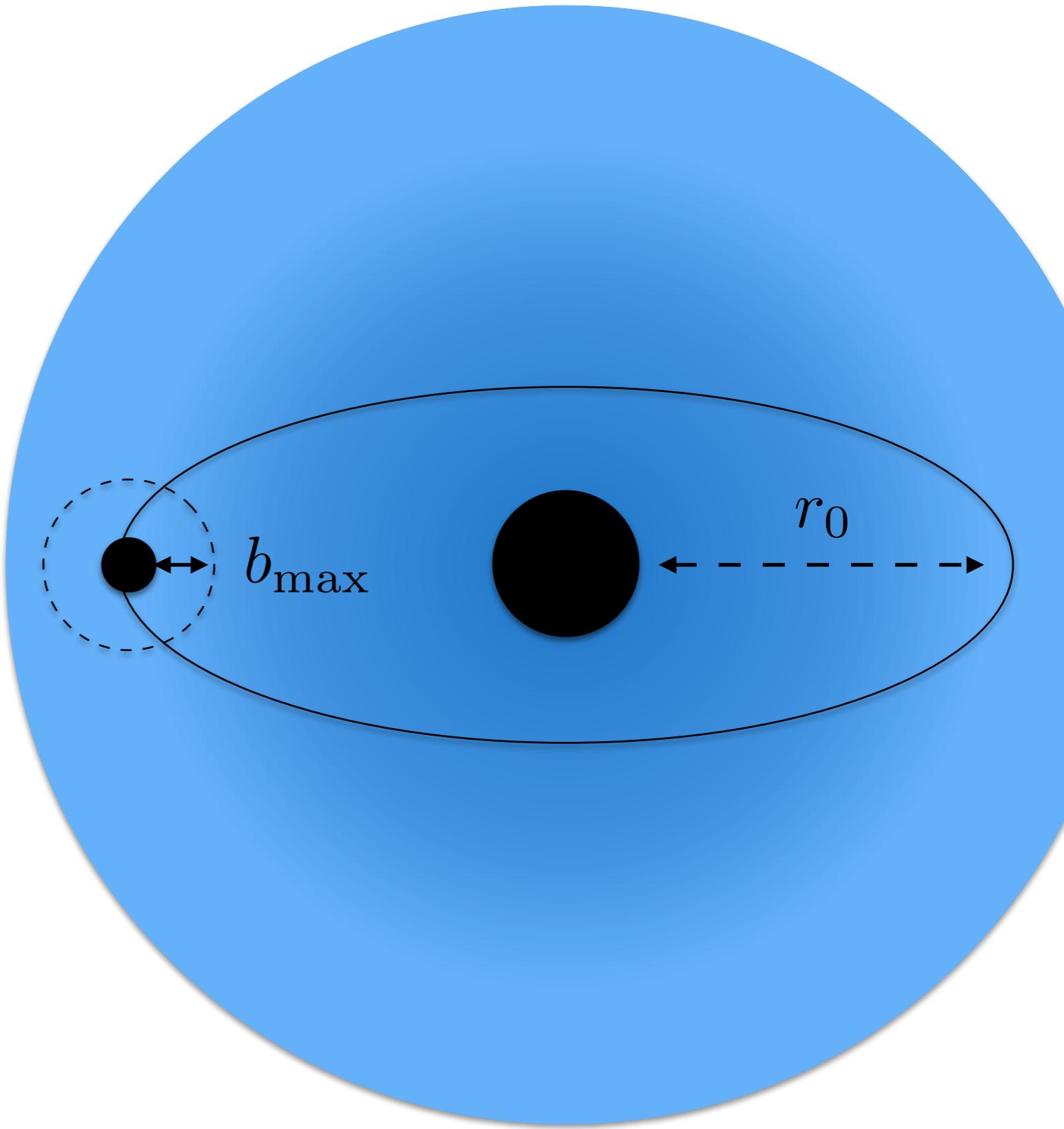
# Self-consistent evolution

*Current focus:*

Follow phase-space  
evolution of the DM halo as  
energy is injected by the  
orbiting compact object

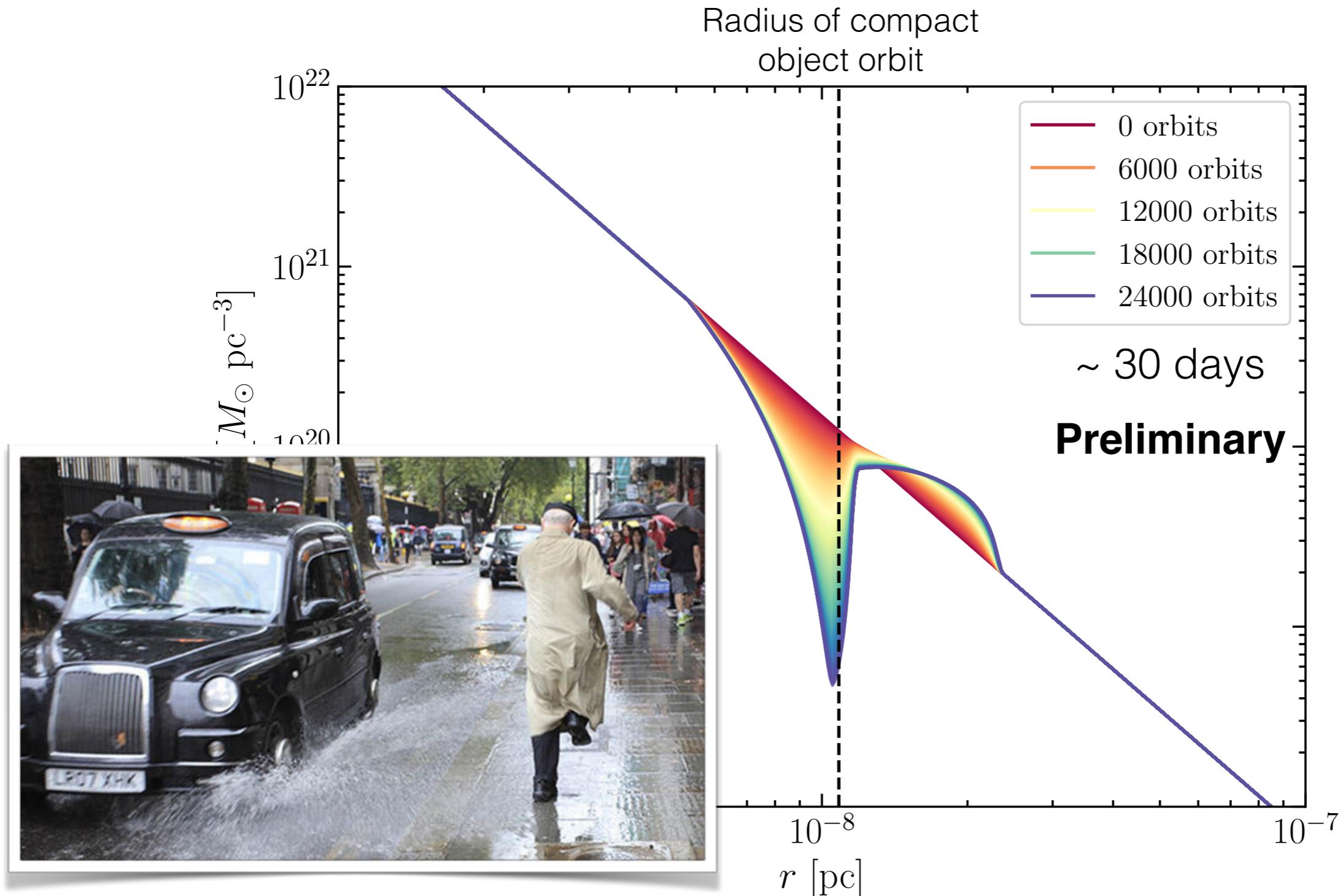
Check and calibrate with  
N-body simulations

Build ‘template banks’ of  
LISA GW waveforms

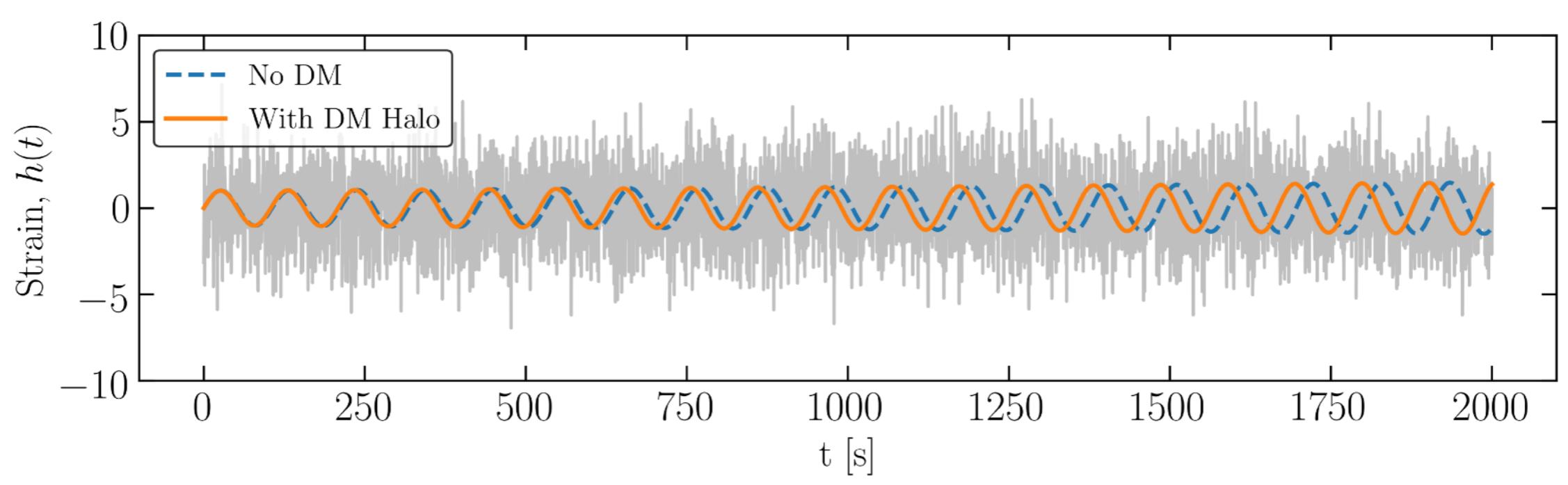
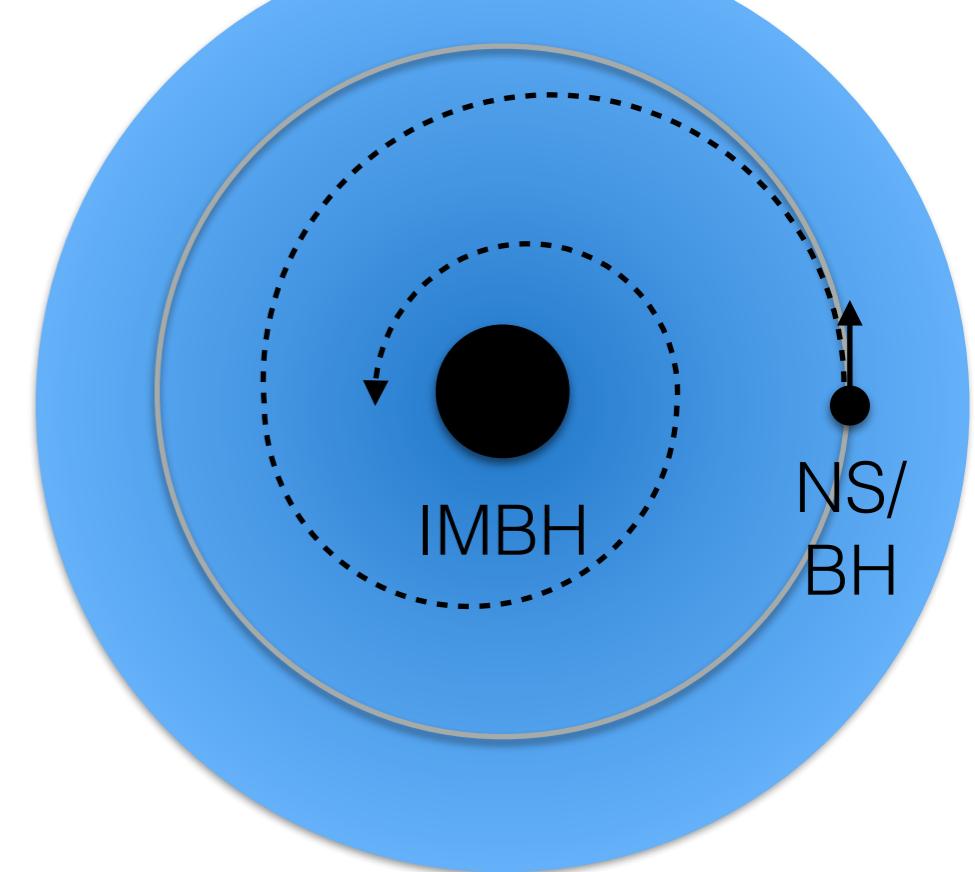
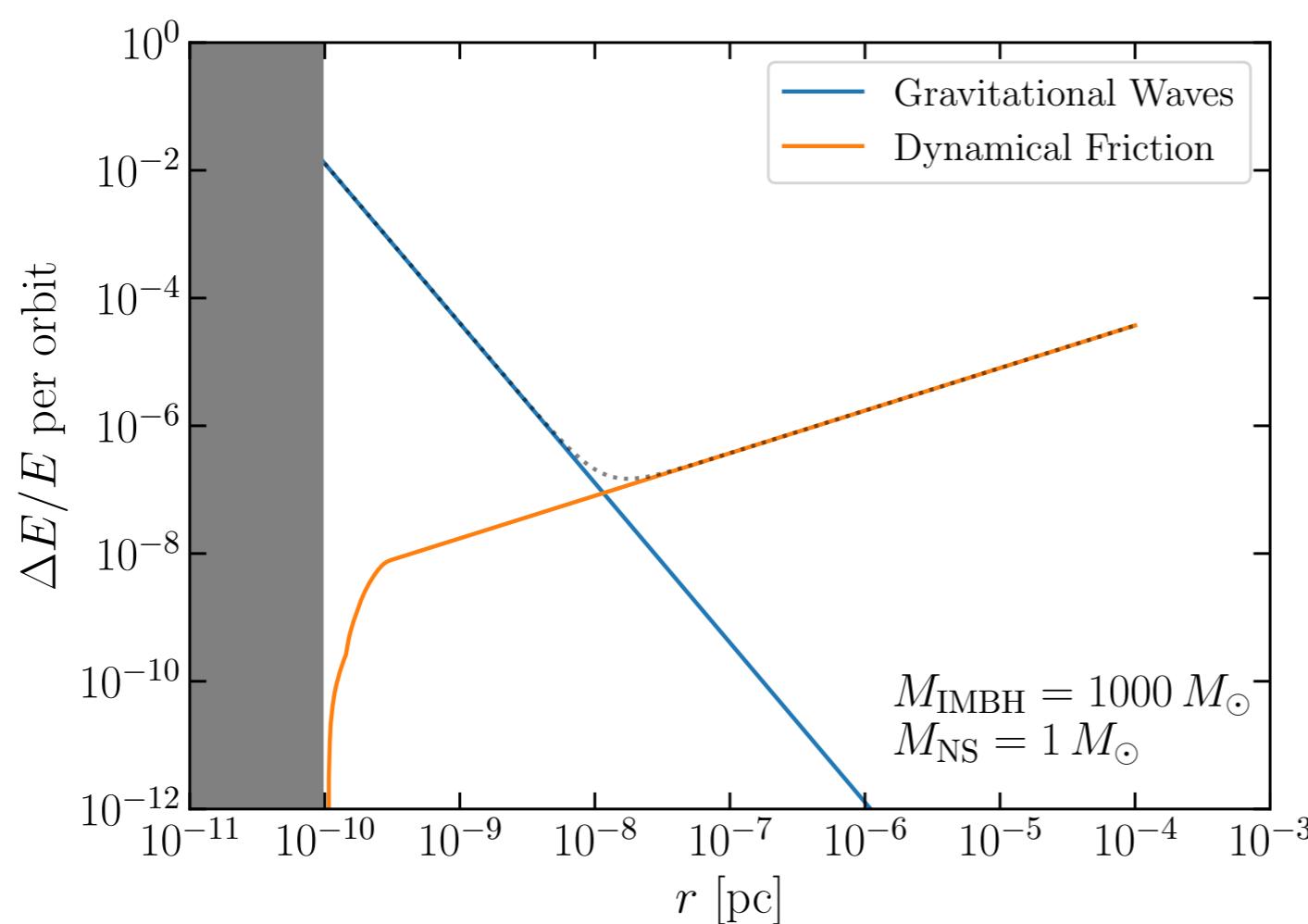


# Evolution of density profile

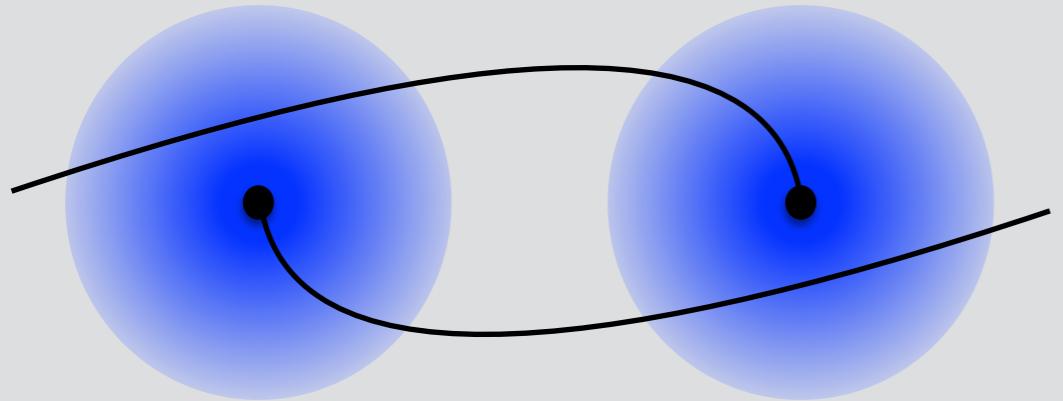
How does the DM halo ‘react’ to the orbiting compact object?



# IMRI + Dark Matter



# Conclusions

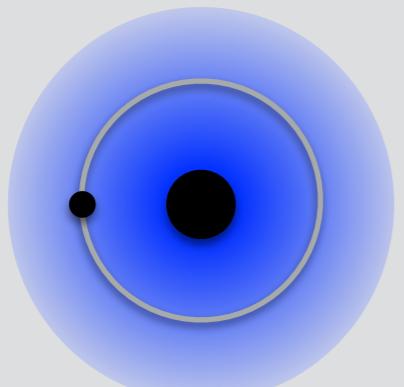
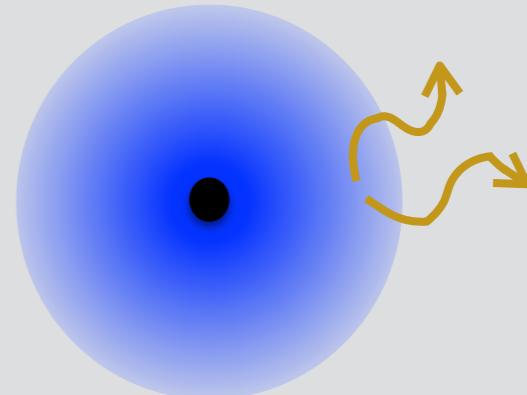


## Merging Primordial Black Holes (PBHs)

[**BJK**, Gaggero & Bertone, 1805.09034]

## DM Annihilation around PBHs

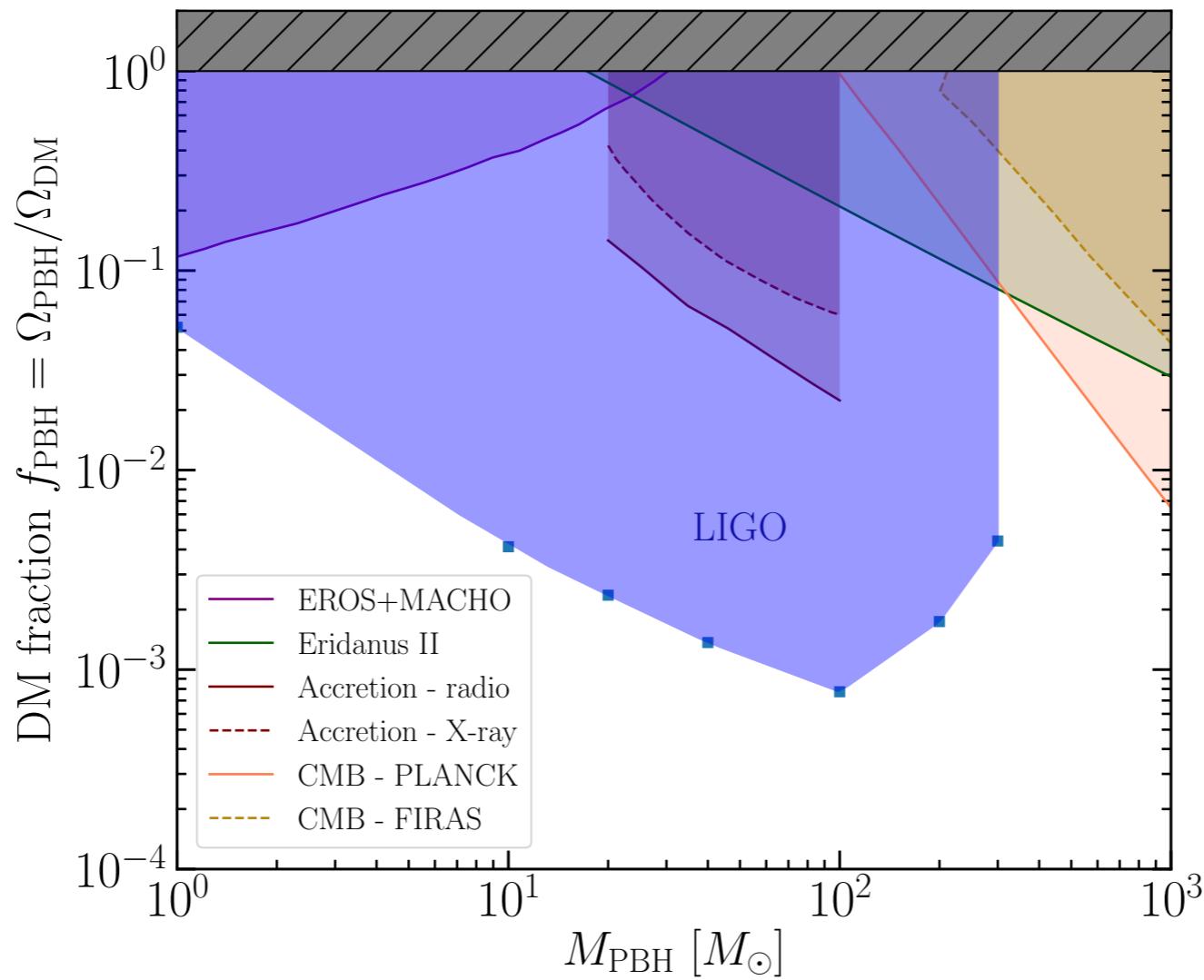
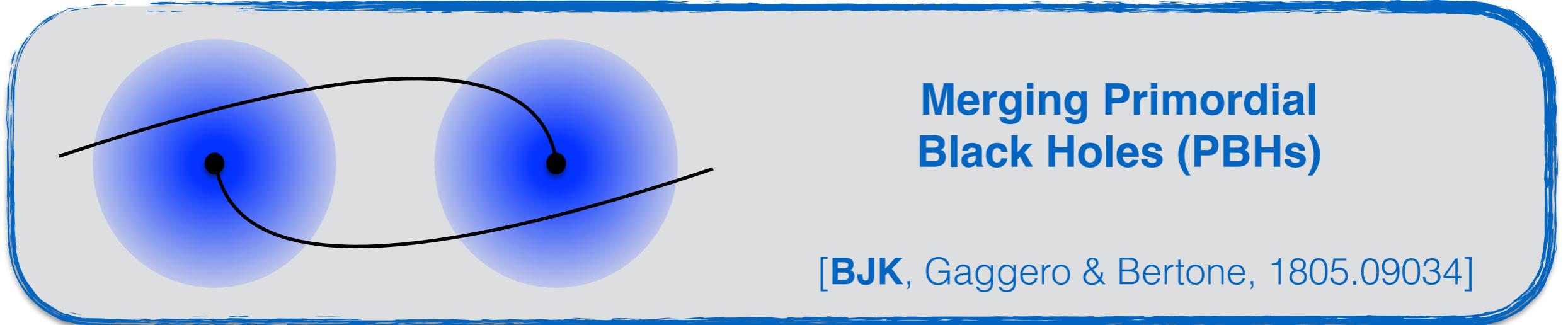
[Bertone, Coogan, Gaggero, **BJK** & Weniger, 1905.01238]



## Intermediate Mass-Ratio Inspirals (IMRIs)

[Edwards, Chianese, **BJK**, Nissanke & Weniger, 1905.04686]

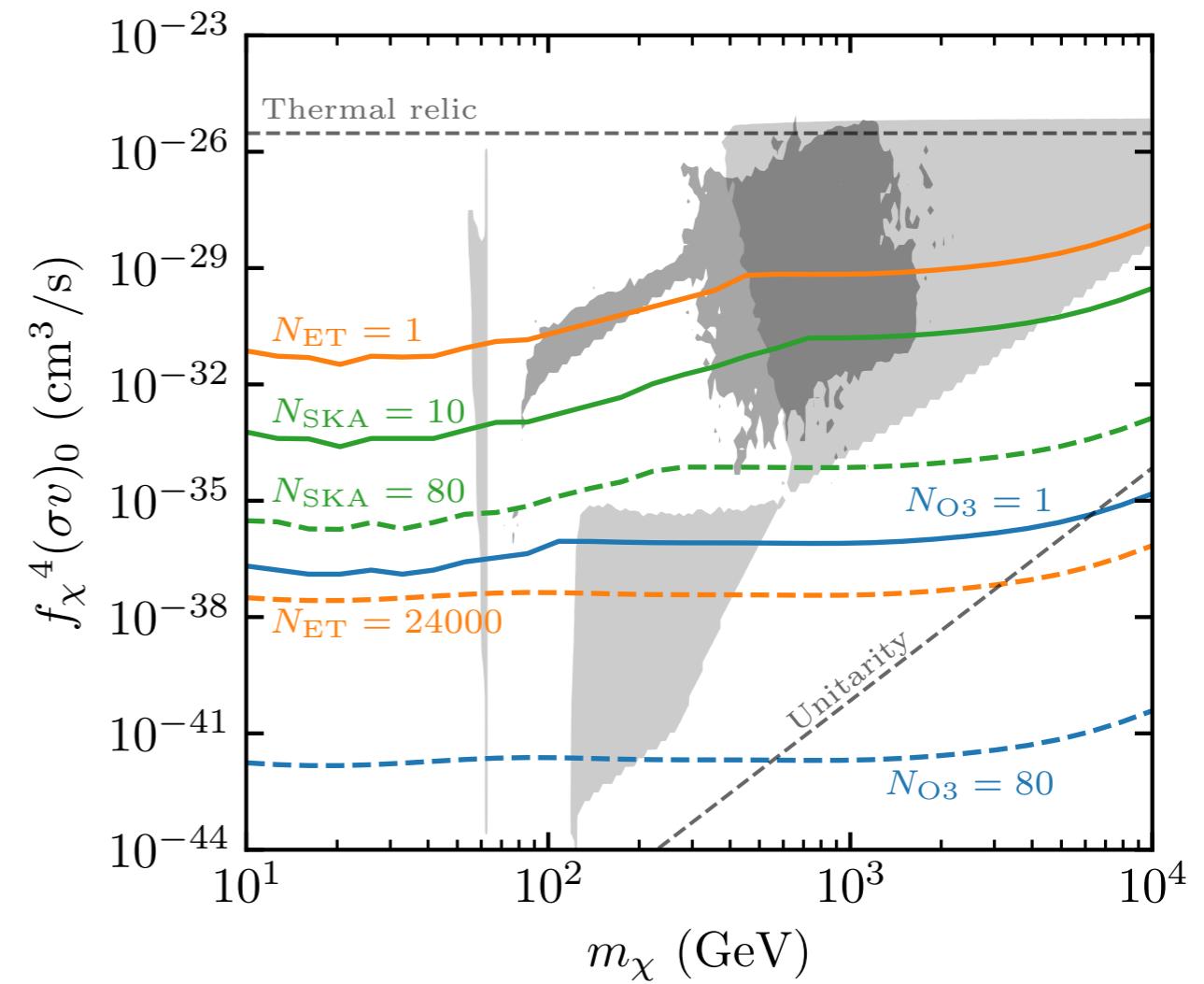
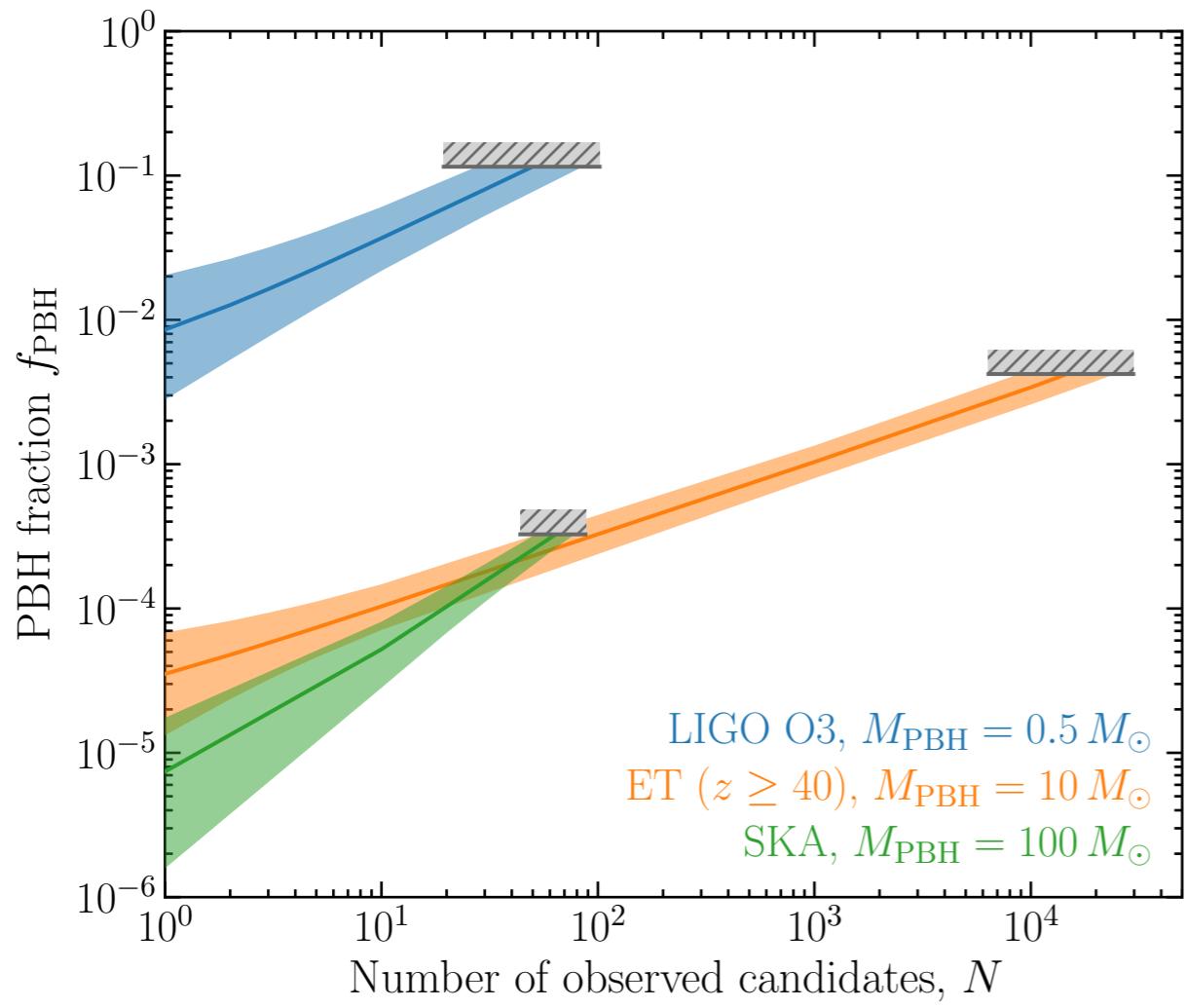
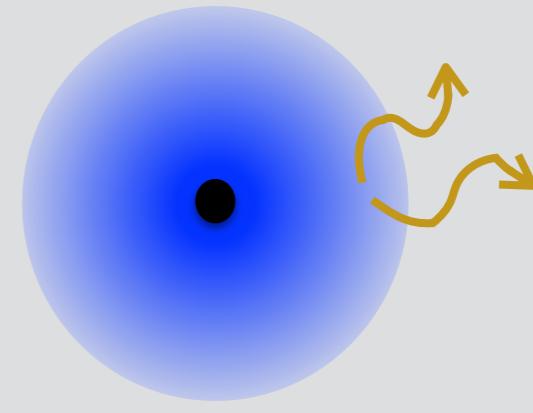
# Conclusions



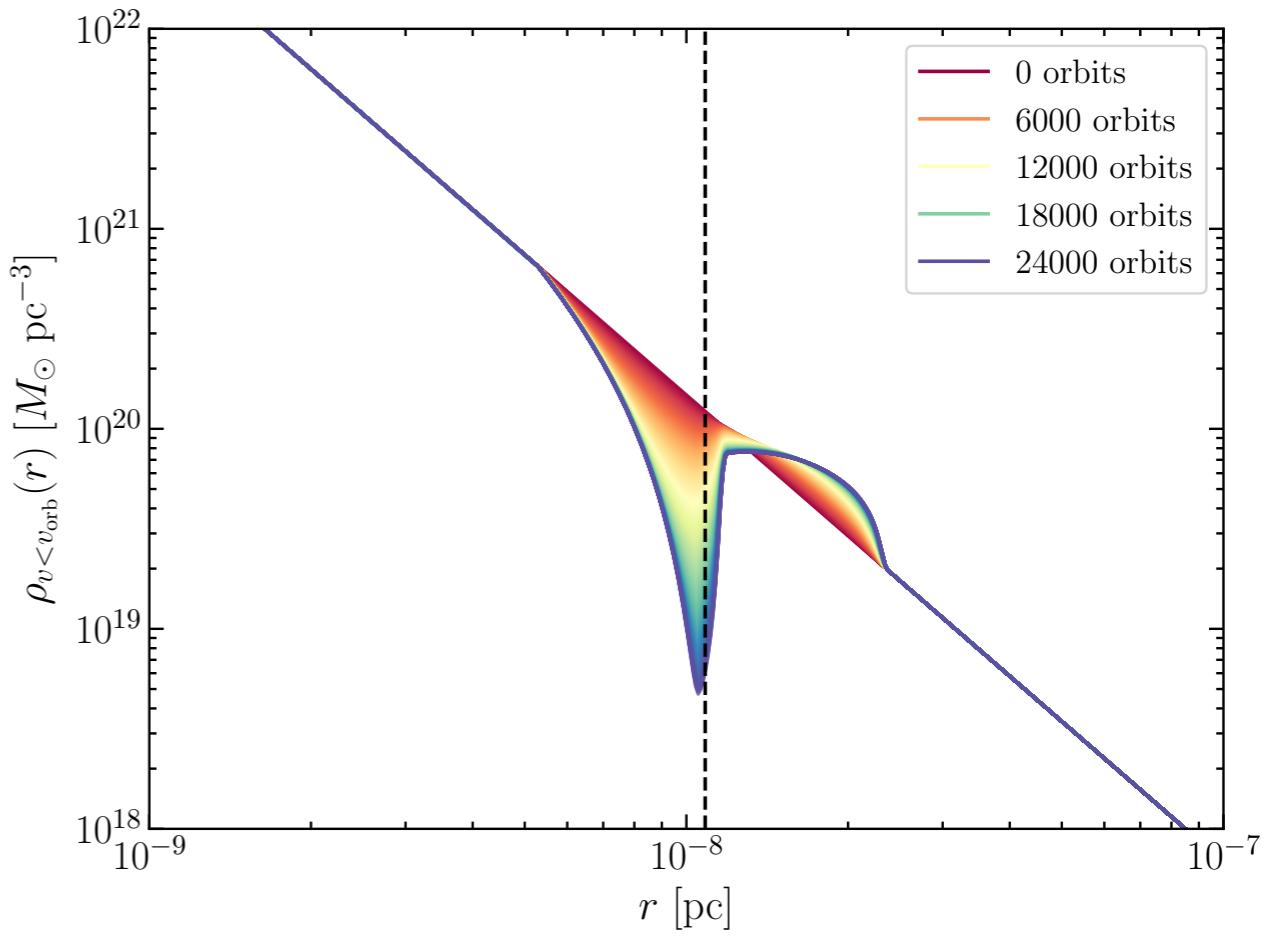
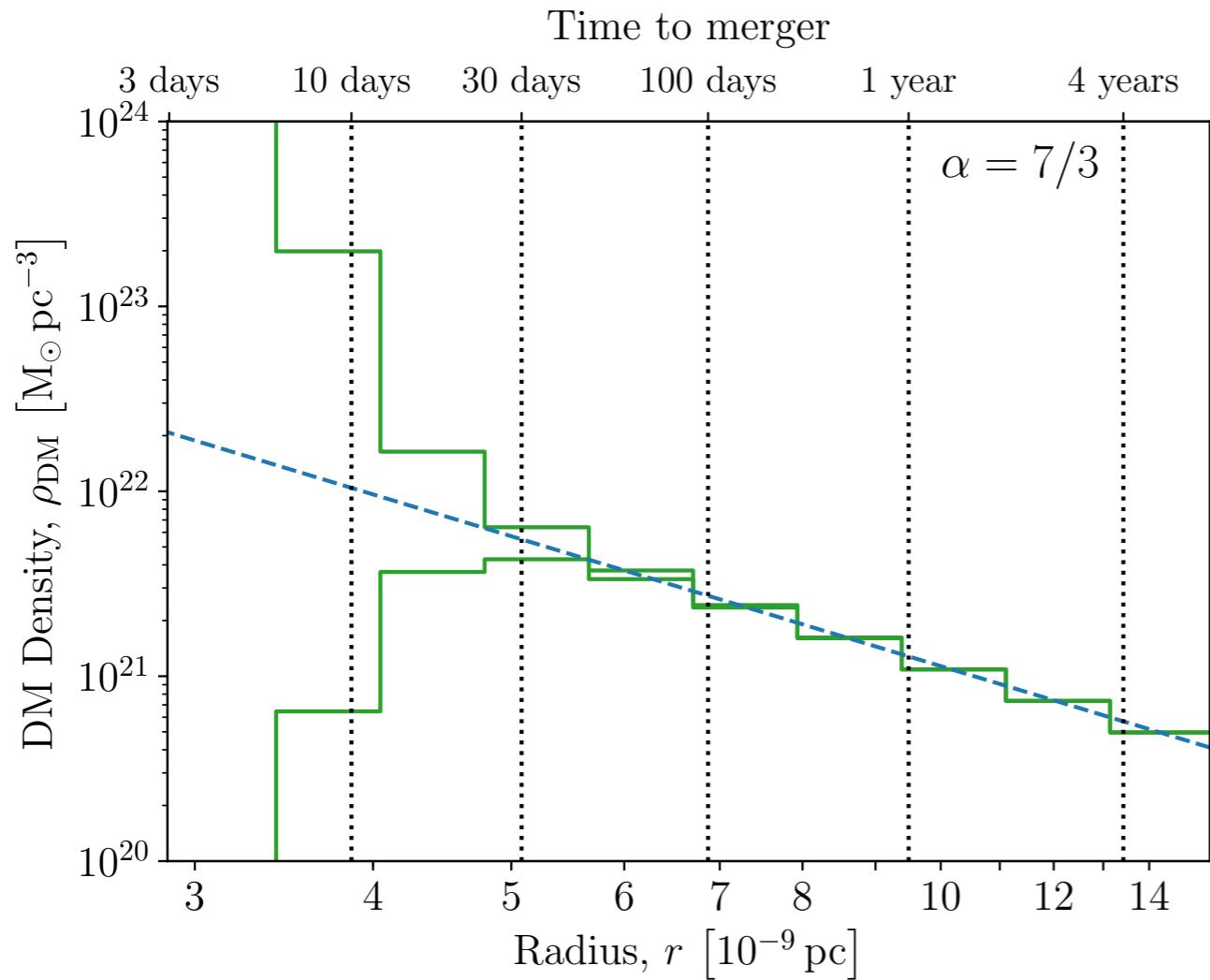
# Conclusions

## DM Annihilation around PBHs

[Bertone, Coogan, Gaggero, **BJK** & Weniger, 1905.01238]

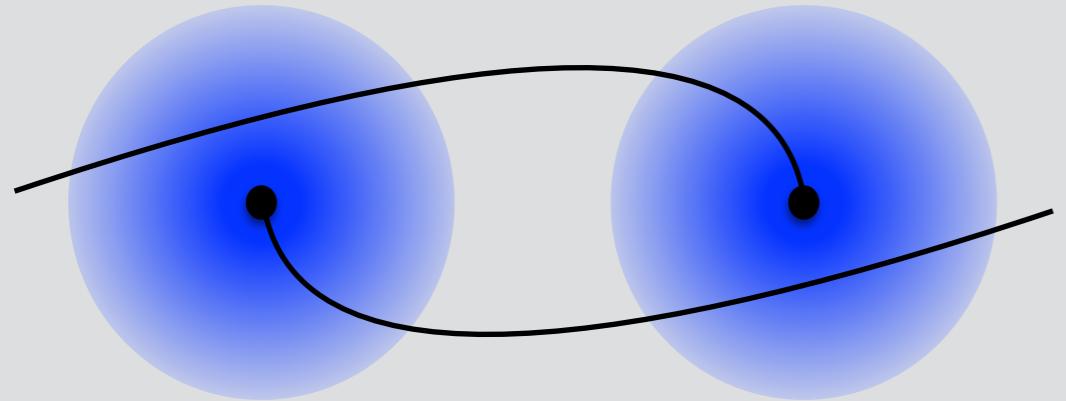


# Conclusions



# Conclusions

**Thank you!**

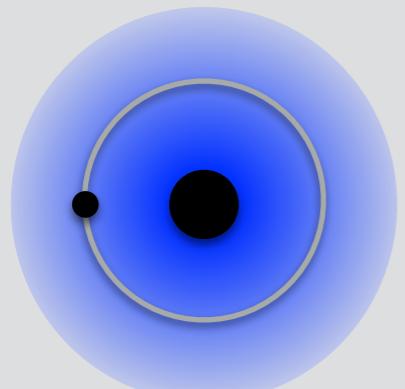
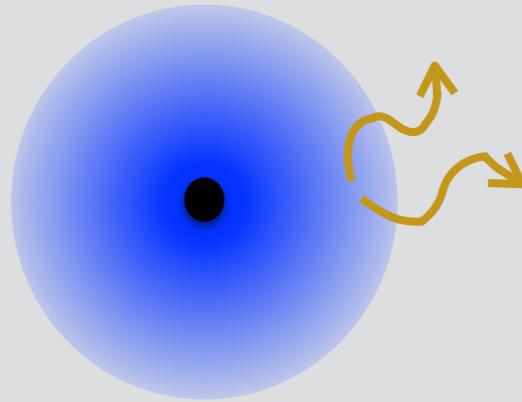


## Merging Primordial Black Holes (PBHs)

[**BJK**, Gaggero & Bertone, 1805.09034]

## DM Annihilation around PBHs

[Bertone, Coogan, Gaggero, **BJK** & Weniger, 1905.01238]



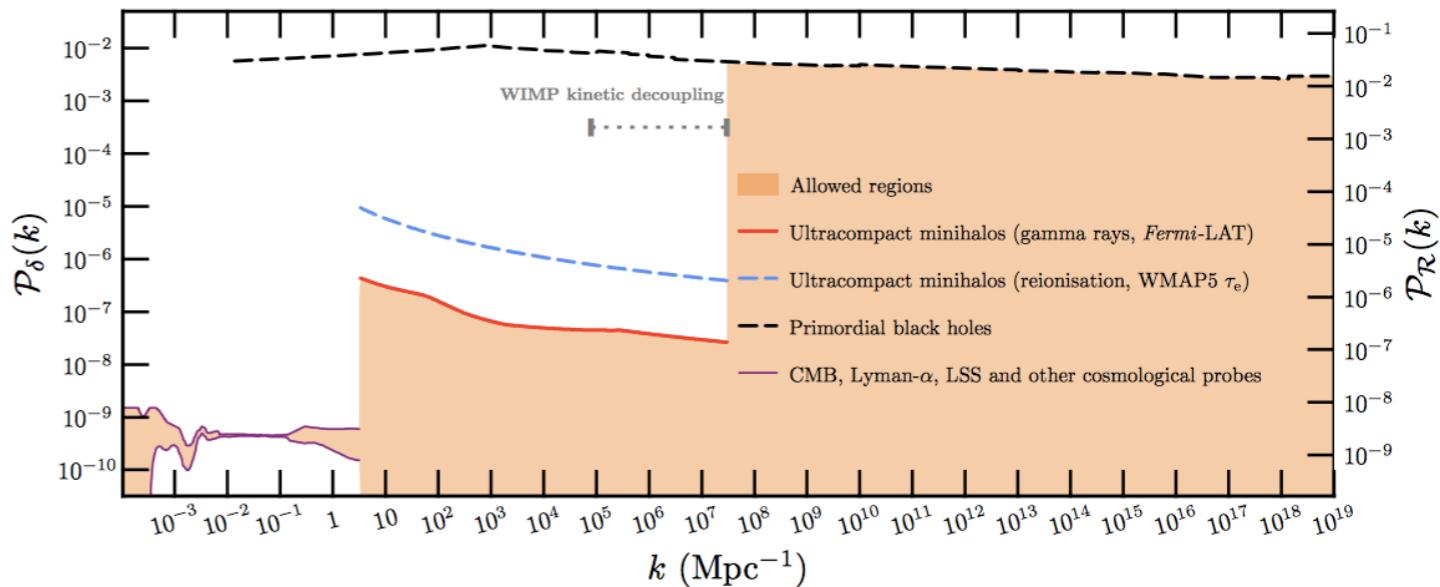
## Intermediate Mass-Ratio Inspirals (IMRIs)

[Edwards, Chianese, **BJK**, Nissanke & Weniger, 1905.04686]

# Backup Slides

# PBH formation

How then could we make PBHs?



- Enhancement/feature in power spectrum

[[astro-ph/9509027](#), [astro-ph/9605094](#), [hep-ph/9710259](#), [1206.4188](#), [1709.05565](#)]

- Cosmic String Loops

[[Hawking \(1987\)](#), [Polnarev & Zembowicz \(1991\)](#), [Caldwell & Caspar \(1996\)](#)]

- Bubble collisions

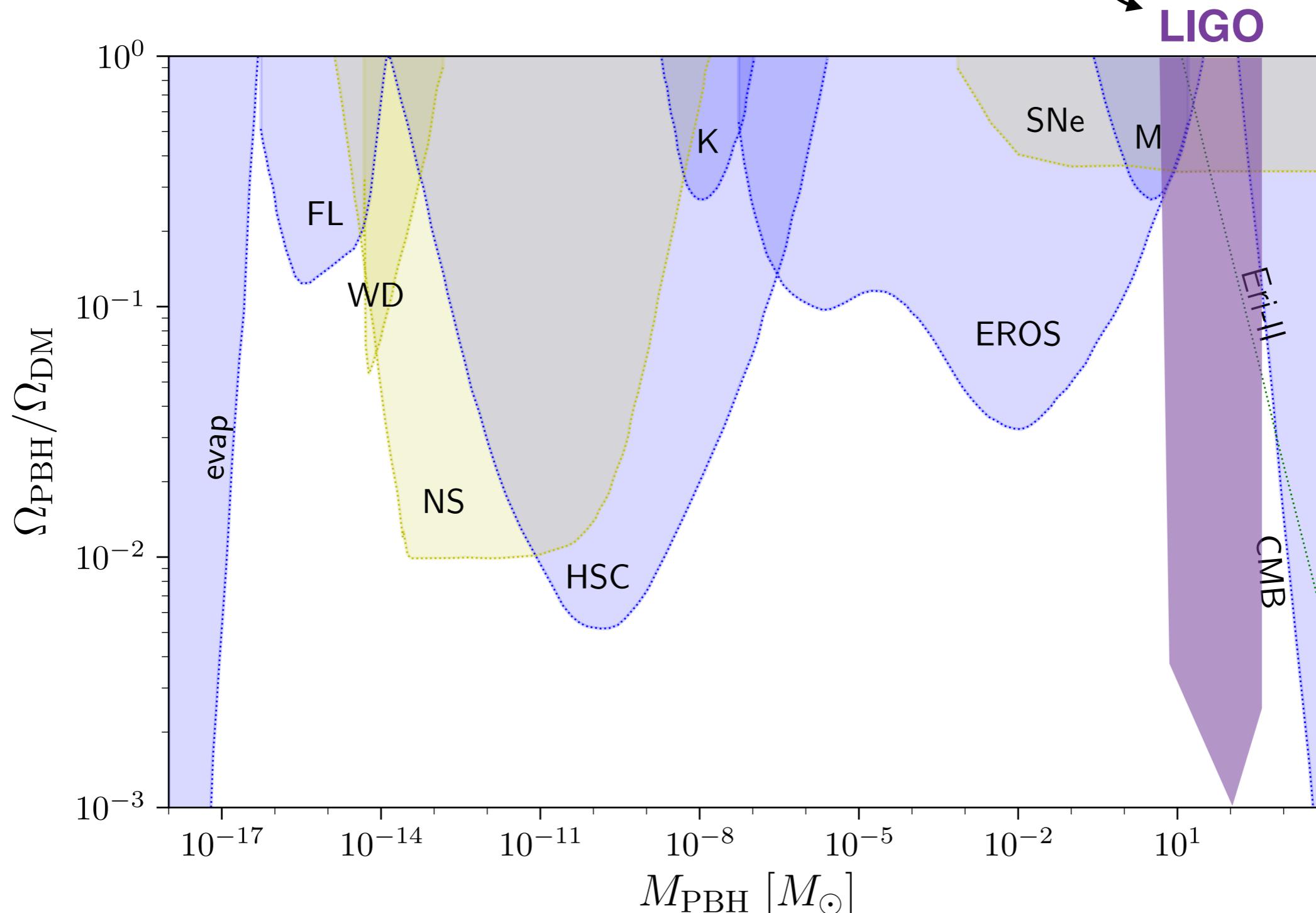
[[Hawking, Moss & Stewart \(1982\)](#); [La & Steinhardt \(1989\)](#)]

PBHs would be a sign of New Physics and a probe of the early universe.

[[Green, 1403.1198](#); [Sasaki et al, 1801.05235](#)]

# PBHs as Dark Matter

[LIGO Bound from  
**BJK**, Gaggero & Bertone, 1805.09034]



[See 1607.06077, 1806.05195 and references therein]

# A peculiar coincidence

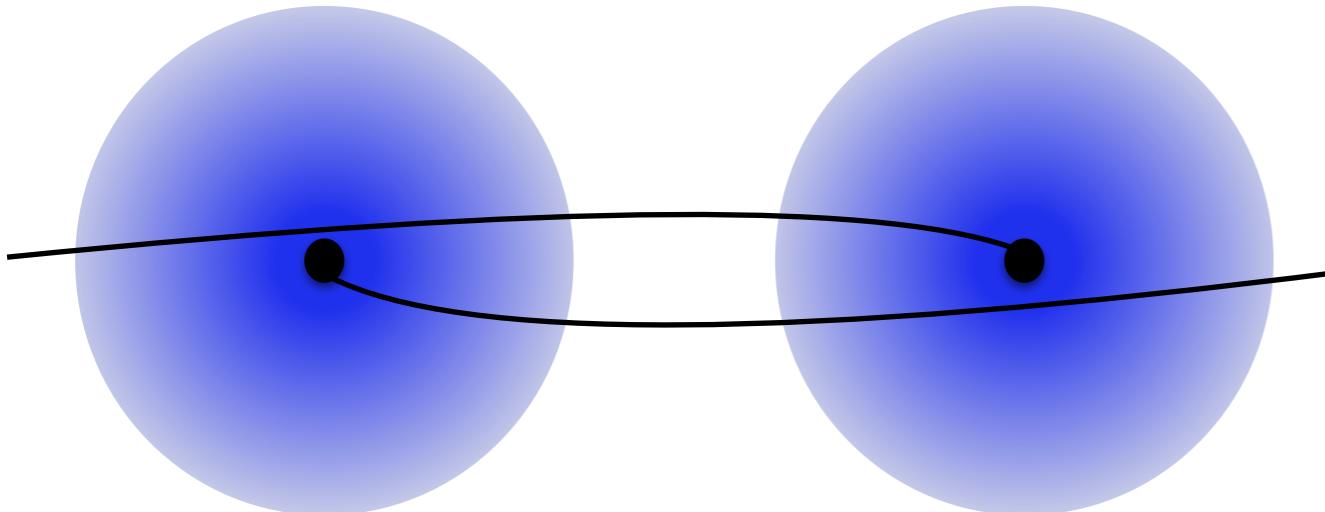
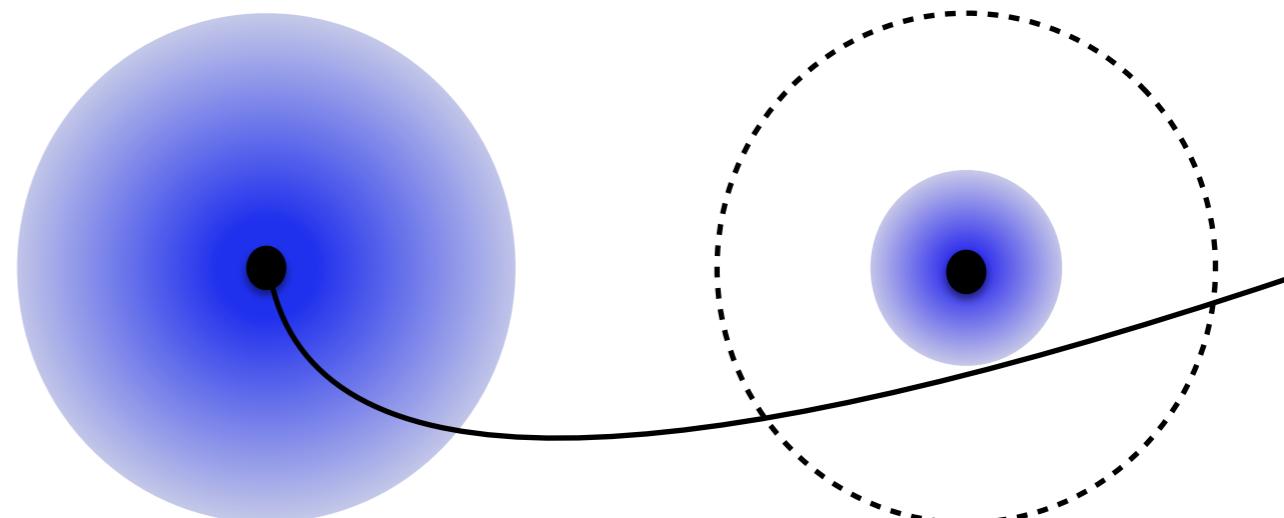
Binaries shrink...

...and circularise

Conservation of energy:

$$E_i^{\text{orb}} + 2U^{\text{bind}} = E_f^{\text{orb}}$$

fixes semi-major axis,  $a$



Conservation of angular momentum:

$$L_i^{\text{PBH}} = L_f^{\text{PBH}}$$

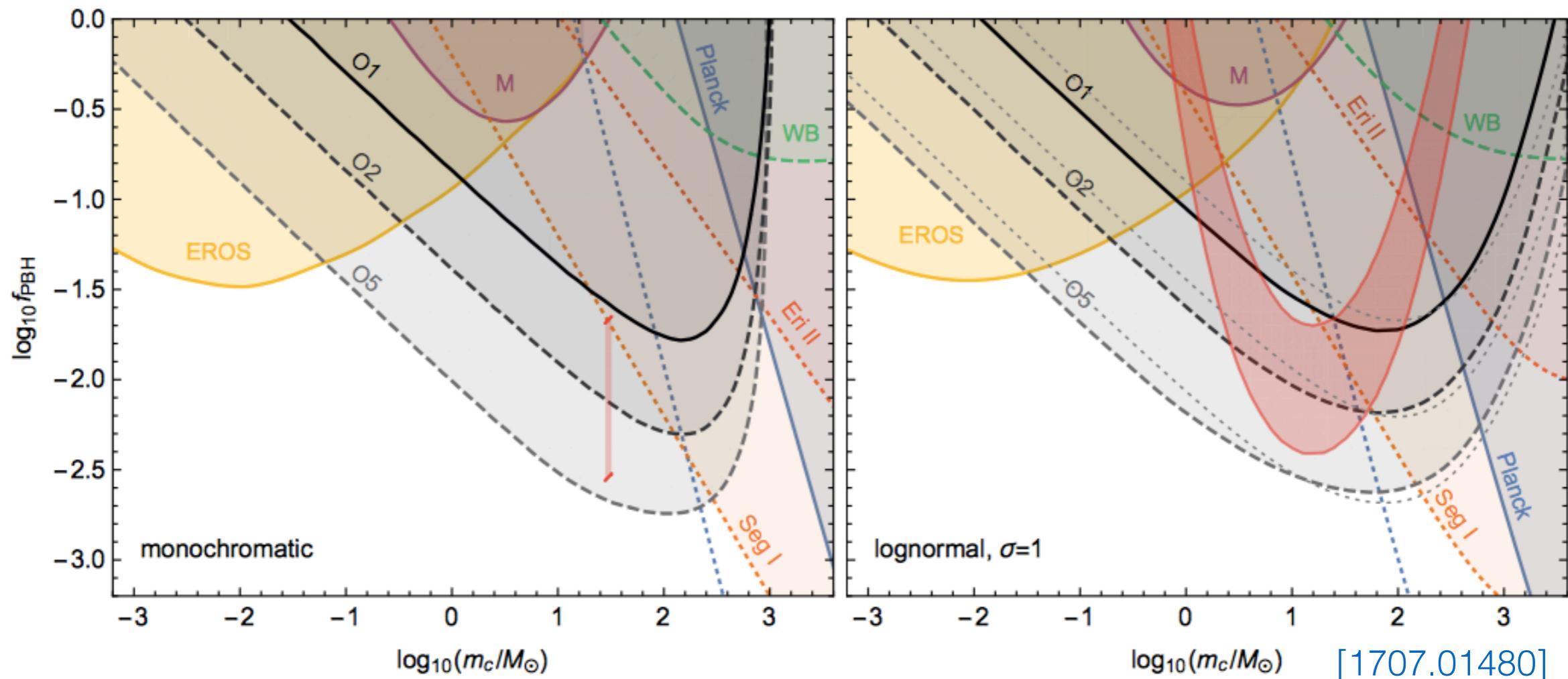
$$L_i^{\text{halo}} = L_f^{\text{halo}}$$

fixes  $j_f = j_i \sqrt{a_i/a_f}$

Merger time  $t_{\text{merge}} = \frac{3c^5}{170G_N^3} \frac{a^4 j^7}{M_{\text{PBH}}^3}$  is almost conserved:  $t_f = \sqrt{\frac{a_i}{a_f}} t_i$

# Extended Mass Function

LIGO O1 Limit



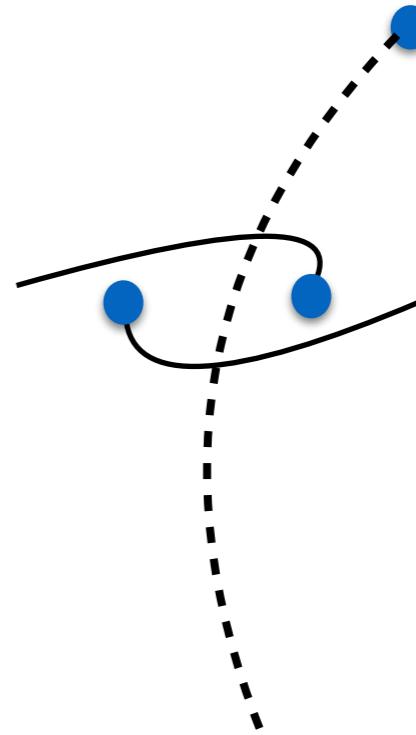
“Old” merger rate calculation à la Sasaki et al.,  
but picture doesn’t change too much...

[See also 1801.10327]

# Caveats

---

- Survival
- Clustering
- Baryons
- Dark Matter



Do these binaries survive for the age of the Universe?

Smooth density perturbations and close encounters  
are unlikely to disrupt the binaries

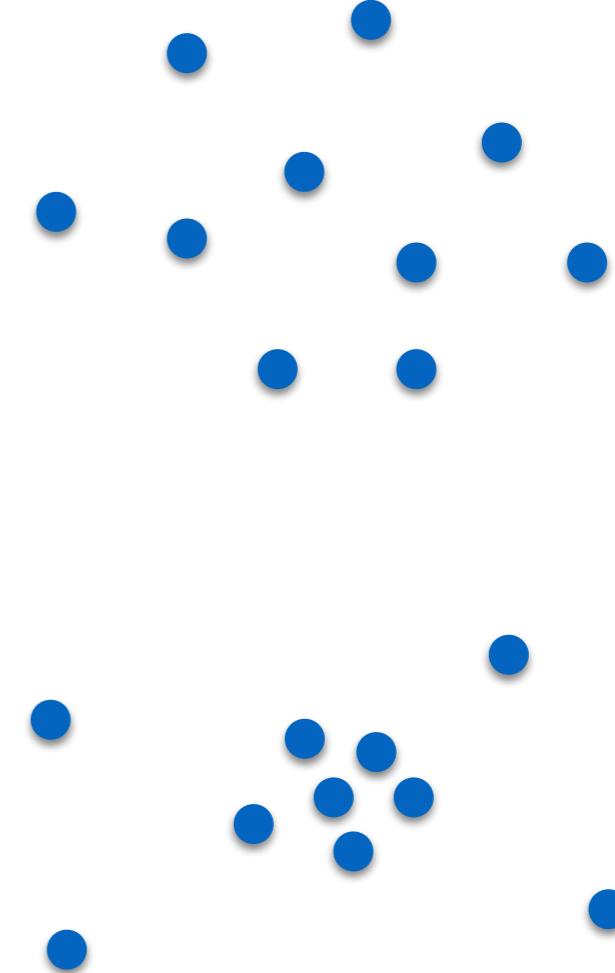
$$a \lesssim 10^{-2} \text{ pc}$$

[Ali-Haïmoud et al., 1709.06576]

# Caveats

---

- Survival
- Clustering
- Baryons
- Dark Matter



How does the distribution of PBHs affect the merger rate?

Clustering could substantially enhance the merger rate ('cascade' mergers) but PBHs are unlikely to form in clusters...

[1808.05910]

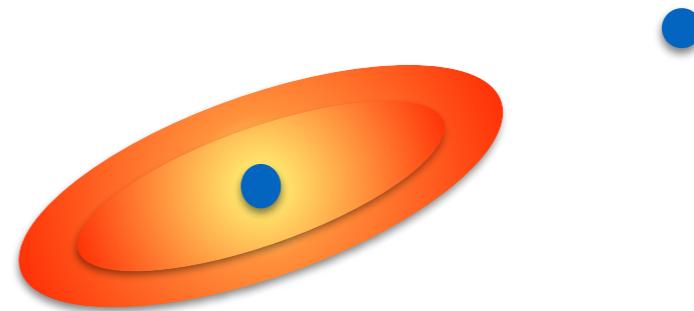
[1807.02084]

[See also 1805.05912, 1806.10414 and others]

# Caveats

---

- Survival
- Clustering
- Baryons
- Dark Matter



Does baryonic accretion disrupt the binary?

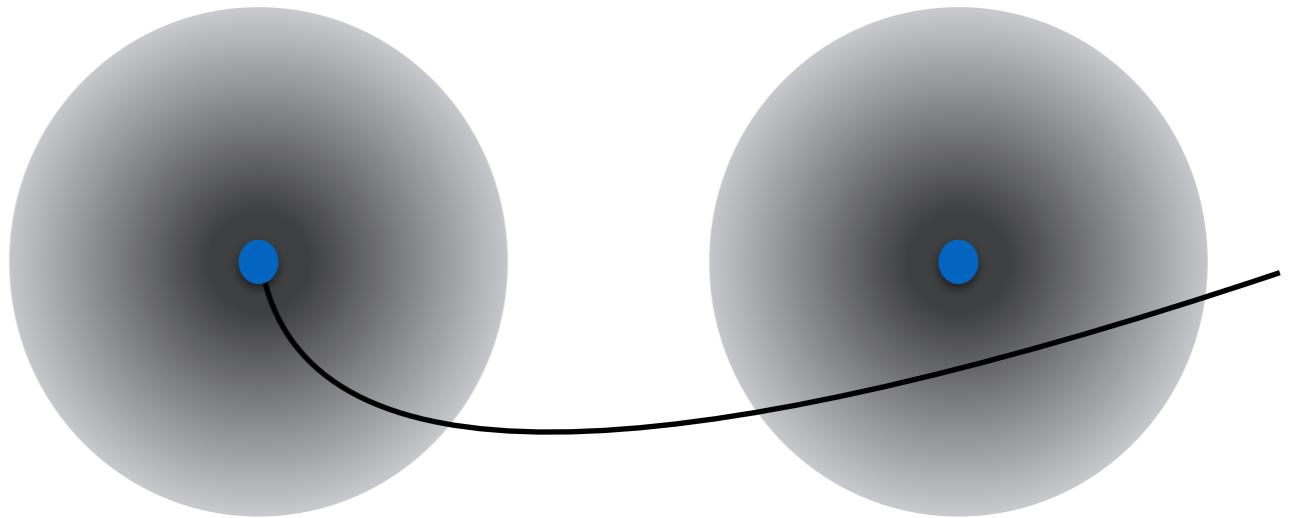
Some simulations have been performed, but the effects are still unclear (especially for highly eccentric binaries)

[0909.1738, 0805.3408, astro-ph/0607467, 1703.03913]

# Caveats

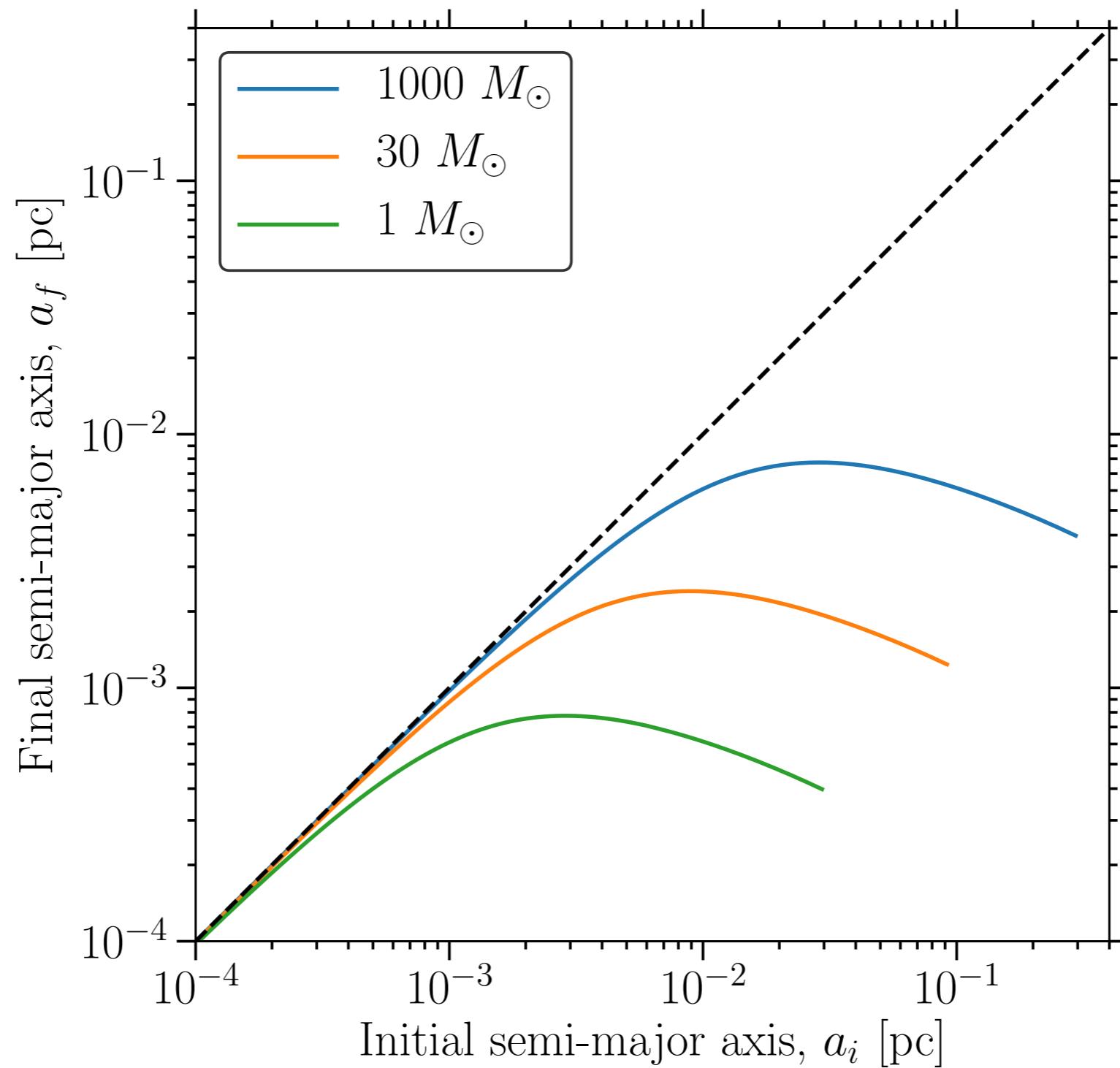
---

- Survival
- Clustering
- Baryons
- **Dark Matter**



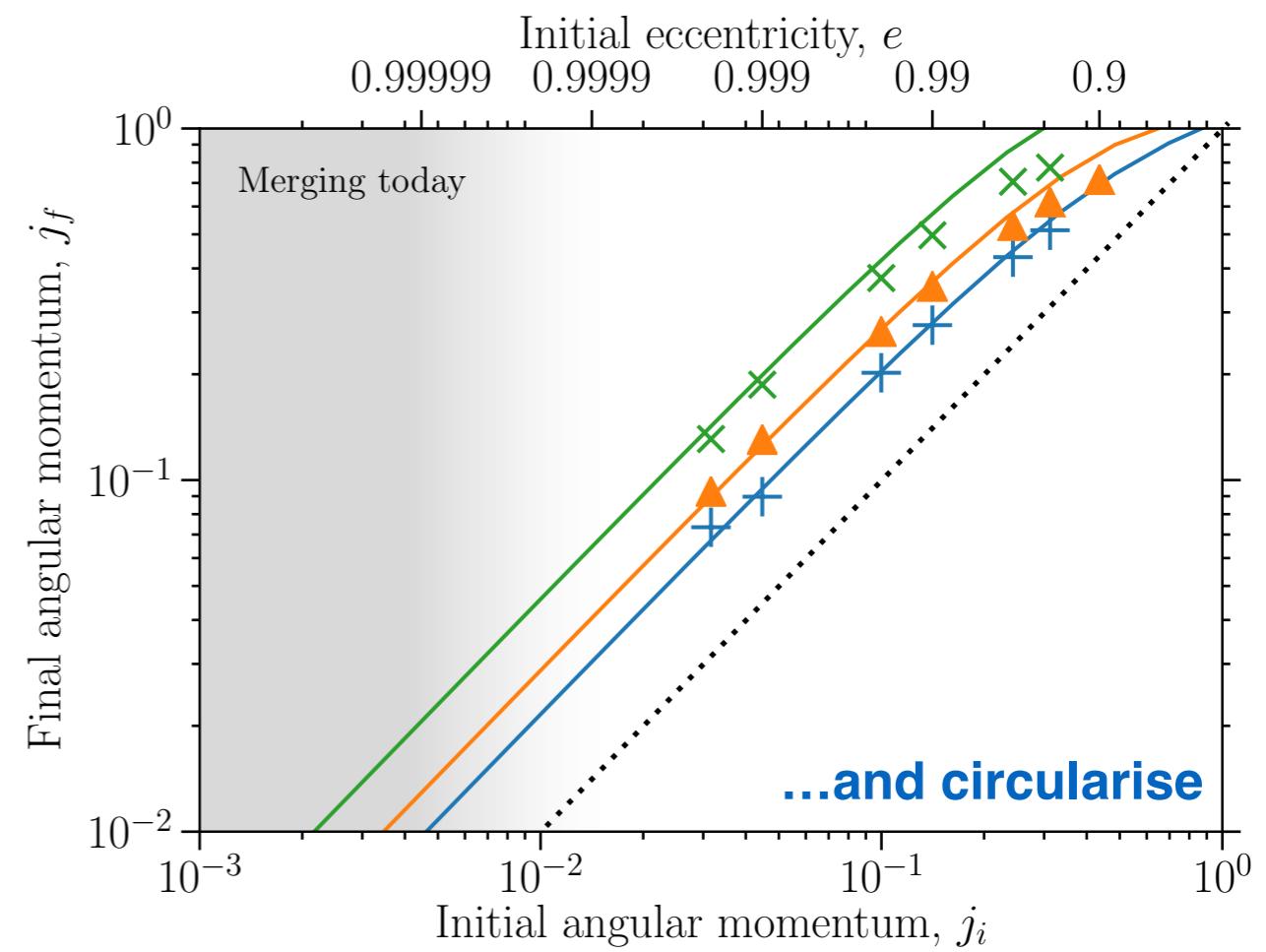
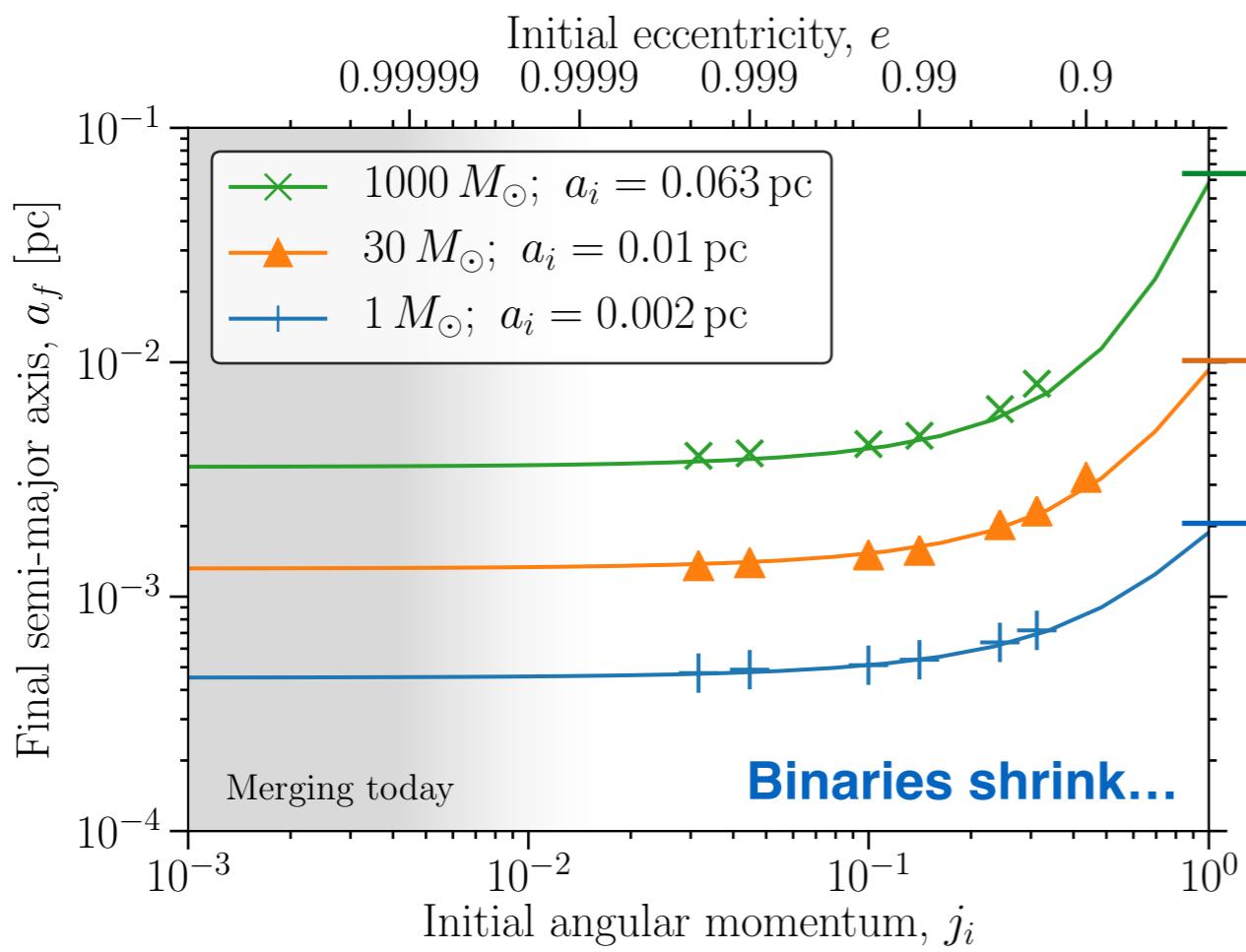
Do *local* Dark Matter halos disrupt PBH binaries?

# PBH Binaries: semi-major axis



$$t_f = \sqrt{\frac{a_i}{a_f}} t_i$$

# PBH Simulation Results



# High precision N-body sims

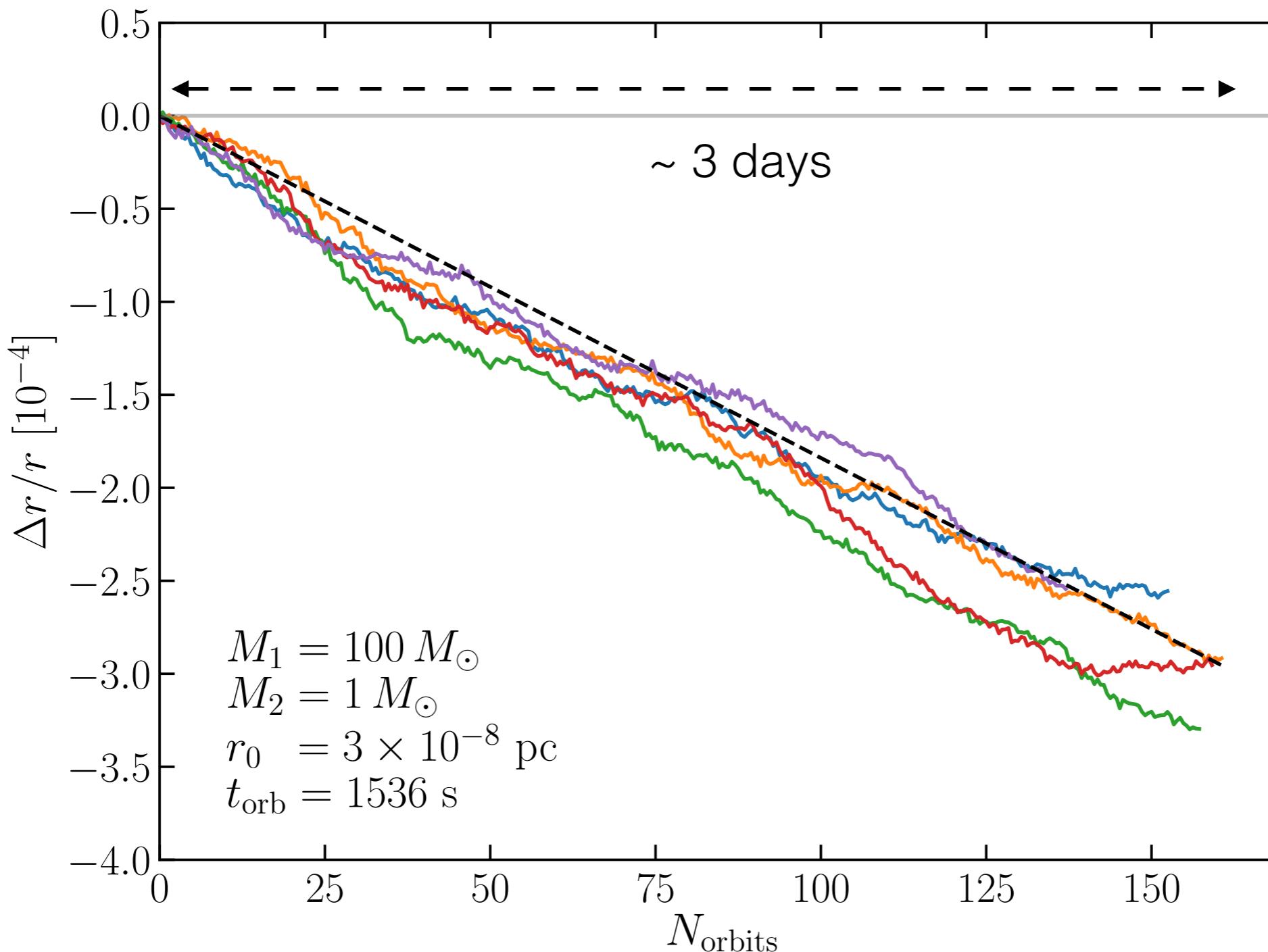
Gadget-II code:

```
58
59  /* Some physical constants in cgs units */
60
61 #define GRAVITY      6.672e-8    /*!< Gravitational constant (in cgs units) */
62 #define SOLAR_MASS   1.989e33
63 #define SOLAR_LUM    3.826e33
64 #define RAD_CONST    7.565e-15
65 #define AVOGADRO    6.0222e23
66 #define BOLTZMANN   1.3806e-16
67 #define GAS_CONST   8.31425e7
68 #define C           2.9979e10
69 #define PLANCK      6.6262e-27
70 #define CM_PER_MPC  3.085678e24
71 #define PROTONMASS  1.6726e-24
72 #define ELECTRONMASS 9.10953e-28
73 #define THOMPSON    6.65245e-25
74 #define ELECTRONCHARGE 4.8032e-10
75 #define HUBLEE     3.2407789e-18    /* in h/sec */
76
```

The Universe:

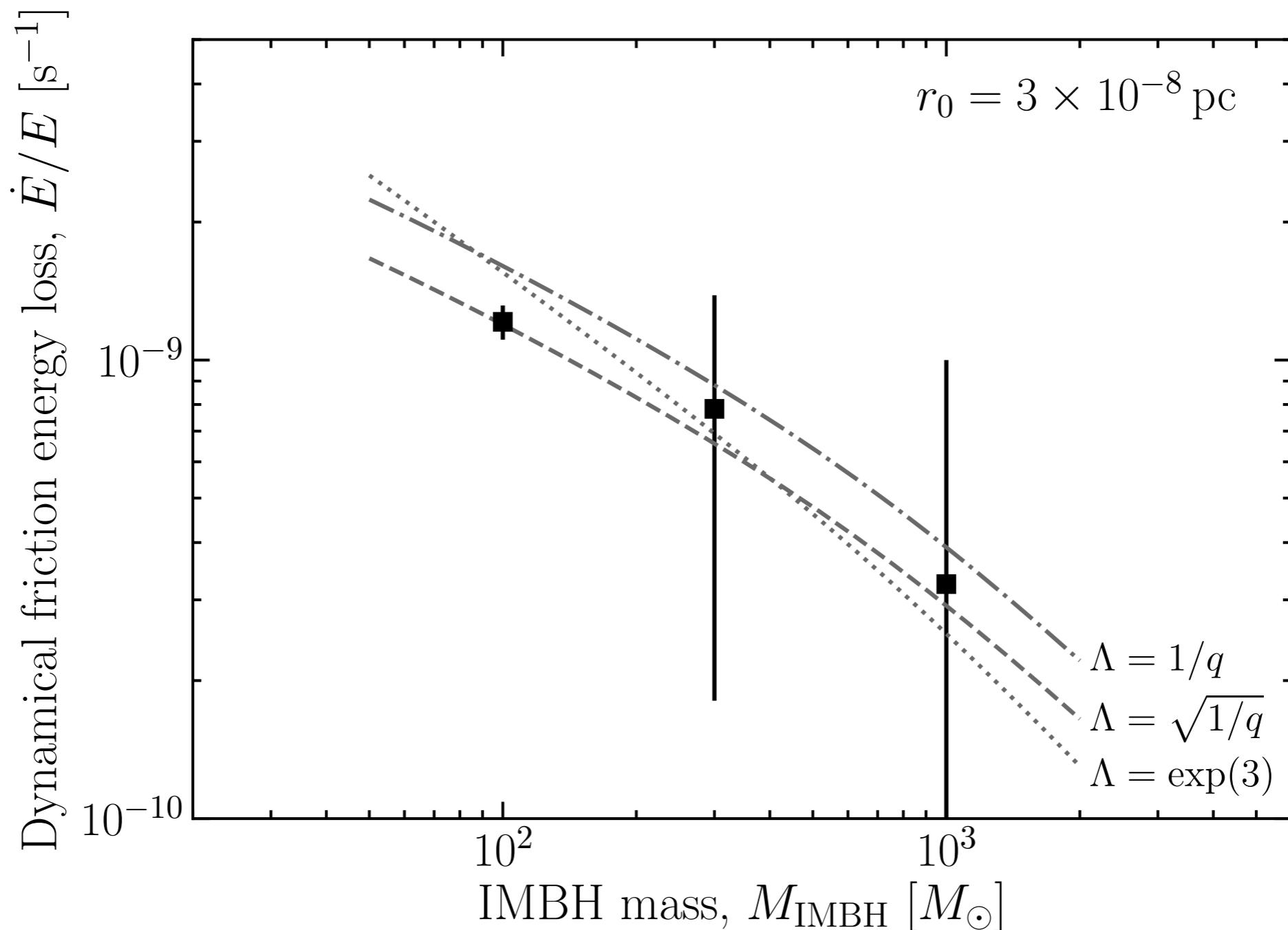
$$G_N = 6.674 \times 10^{-8} \text{ m}^3 \text{ g}^{-1} \text{ s}^{-2}$$

# N-body simulations



Allows us to check assumptions and fix normalisation of DF force ( $\ln \Lambda$ ),  
but can't simulate the whole 5 year inspiral!

# N-body results



NS only scatters with particles where its gravity dominates over the IMBH's

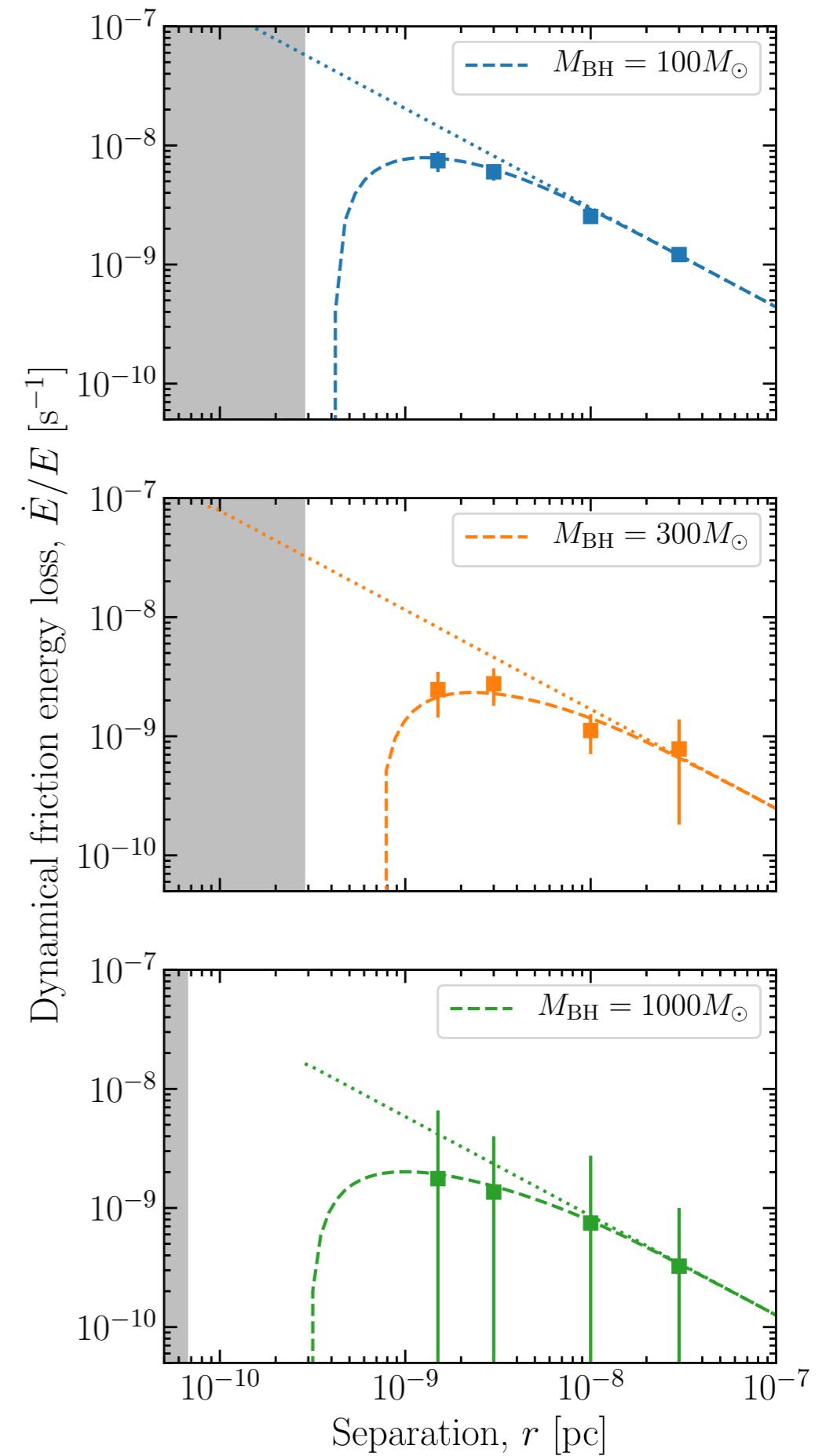
Fix 'Coulomb factor':  $\Lambda = \sqrt{M_{\text{IMBH}}/M_{\text{NS}}} \sim 20 - 60$

# N-body results

Dependence of dynamical friction force on mass and separation matches expectations

Dynamical friction traces local DM density (to better than 1%)

Drop off in DF force at small separations due to softening of simulations



# Self-consistent evolution

---

Assuming orbit evolves slowly compared to the orbital period:

$$T_{\text{orb}} \frac{df(\mathcal{E})}{dt} = -f(\mathcal{E}) P_{\text{scatter}}(r_0, \mathcal{E}) + \left( \frac{\mathcal{E}}{\mathcal{E} + \Delta\mathcal{E}} \right)^{5/2} f(\mathcal{E} - \Delta\mathcal{E}) P_{\text{scatter}}(r_0, \mathcal{E} - \Delta\mathcal{E})$$

$P_{\text{scatter}}(r_0, \mathcal{E})$  - roughly the fraction of DM particles with energy  $\mathcal{E}$  which lie within a distance  $b_{\max}$  from the NS orbit

Density profile (and therefore dynamical friction force) can then be determined self-consistently from the distribution function

# Self-consistent evolution

Assuming orbit evolves slowly compared to the orbital period:

$$T_{\text{orb}} \frac{df(\mathcal{E})}{dt} = -f(\mathcal{E}) P_{\text{scatter}}(r_0, \mathcal{E})$$

Particles scattering from  
 $\mathcal{E} \rightarrow \mathcal{E} + \Delta\mathcal{E}$

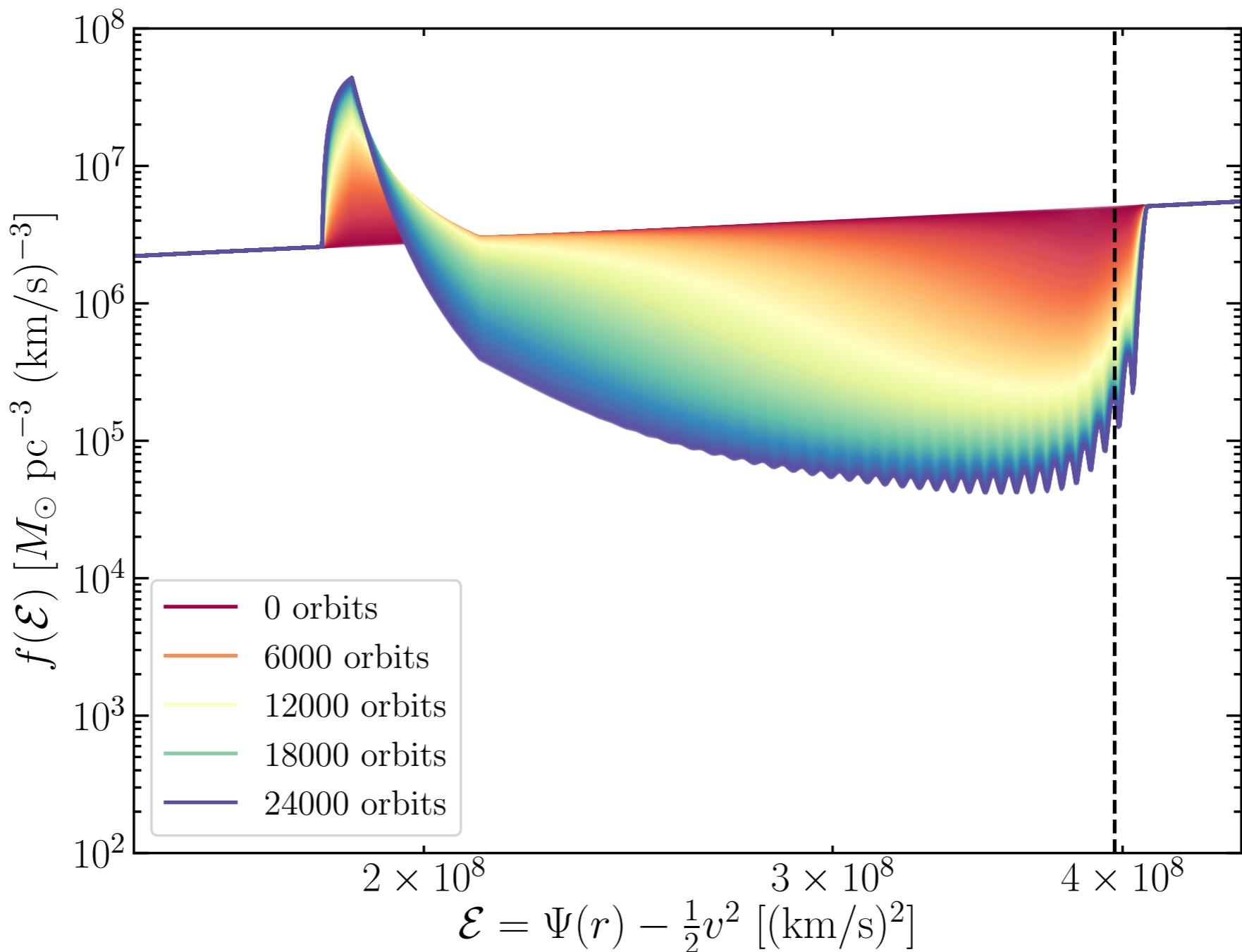
$$+ \left( \frac{\mathcal{E}}{\mathcal{E} + \Delta\mathcal{E}} \right)^{5/2} f(\mathcal{E} - \Delta\mathcal{E}) P_{\text{scatter}}(r_0, \mathcal{E} - \Delta\mathcal{E})$$

Particles scattering from  
 $\mathcal{E} - \Delta\mathcal{E} \rightarrow \mathcal{E}$

$P_{\text{scatter}}(r_0, \mathcal{E})$  - roughly the fraction of DM particles with energy  $\mathcal{E}$  which lie within a distance  $b_{\max}$  from the NS orbit

Density profile (and therefore dynamical friction force) can then be determined self-consistently from the distribution function

# Distribution function



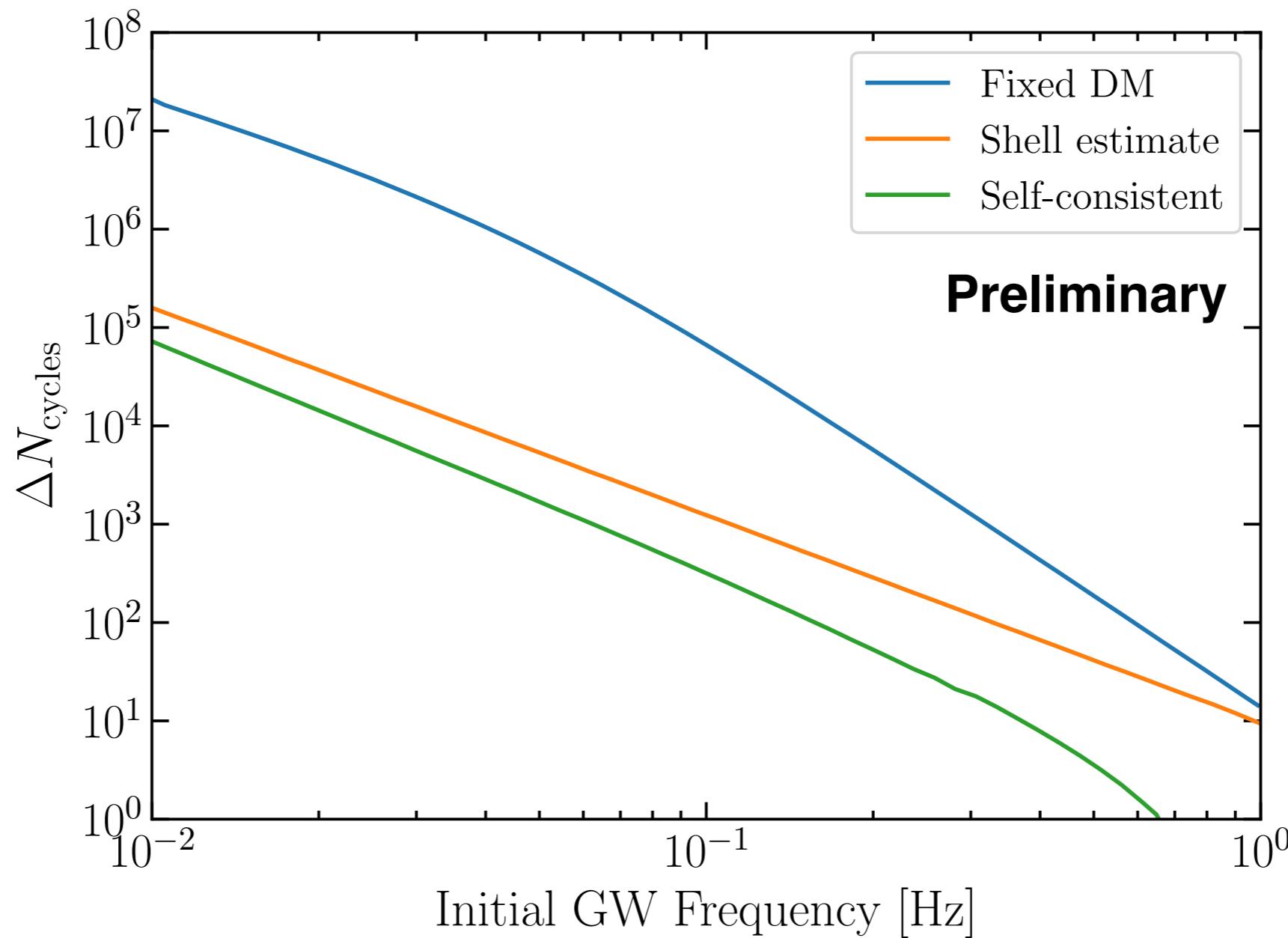
Self-consistently reconstruct density from distribution function:

$$\rho(r) = 4\pi \int_0^{v_{\max}(r)} v^2 f(\mathcal{E}) dv$$

# Impact on de-phasing

$N_{\text{cycles}}^{\text{vacuum}} \sim 2 \times 10^7$

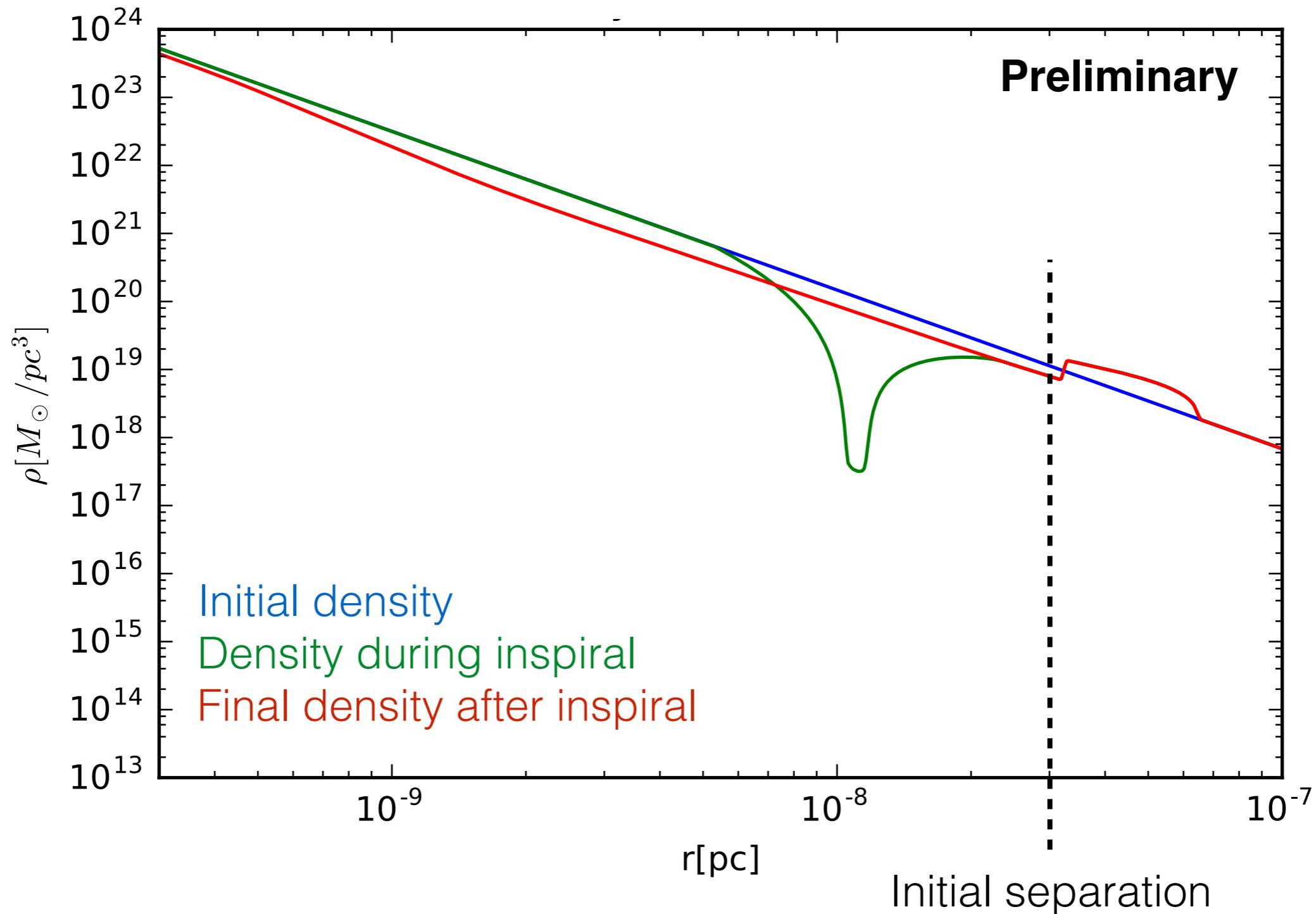
How much shorter is the inspiral compared  
to the ‘vacuum’ case (with no DM?)



De-phasing drastically reduced - *but still detectable!*

# Survival of density profile

How does the density profile evolve during and after the inspiral?



# Assumptions

---

- ▶ Spherical symmetry and isotropy of the DM halo
- ▶ DM particles only scatter within an impact parameter

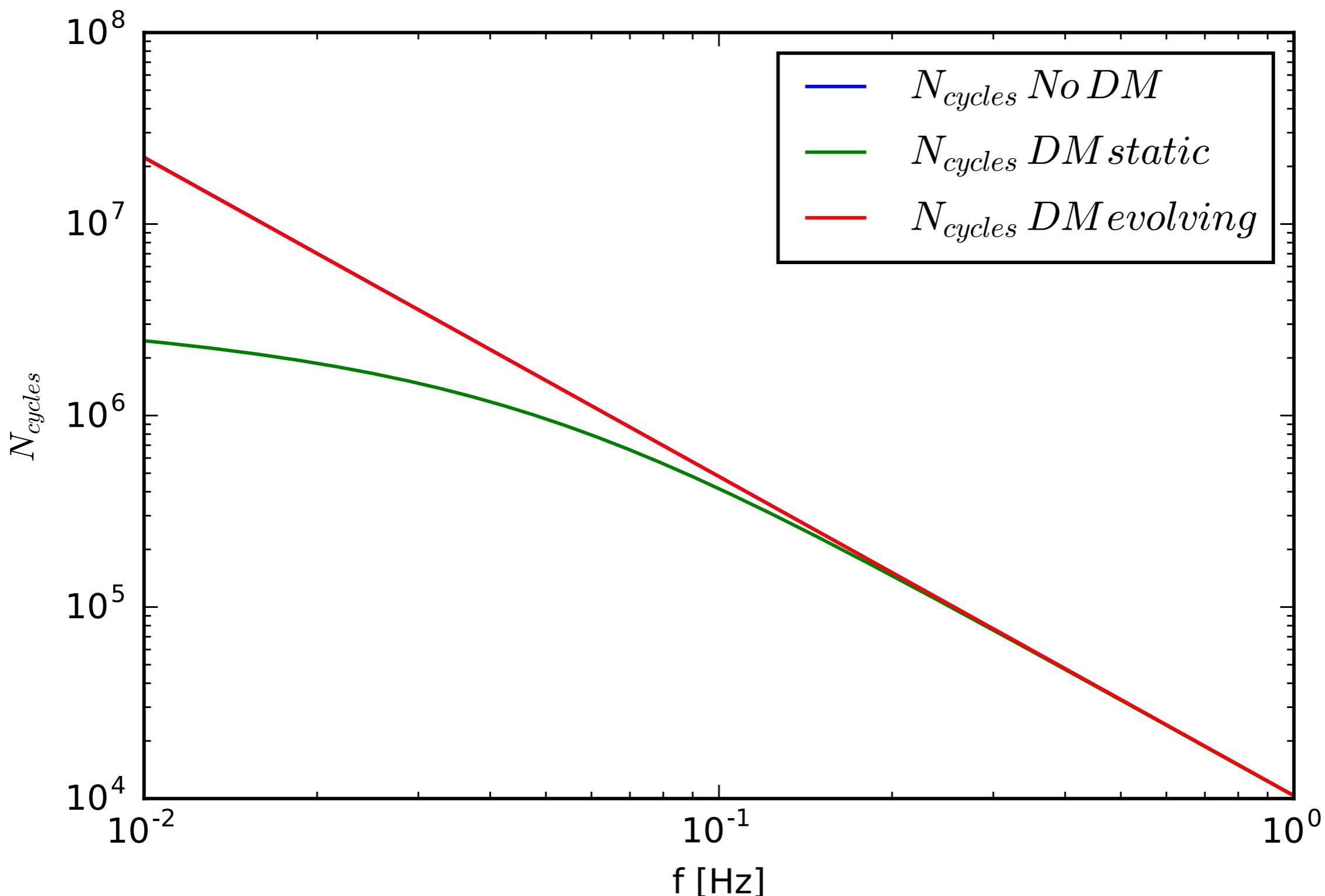
$$b < b_{\max} = \Lambda \times G_N M_{\text{NS}} / v_{\text{NS}}^2$$

- ▶ DM distribution is ‘locally’ uniform

$$b_{\max} \ll r_0$$

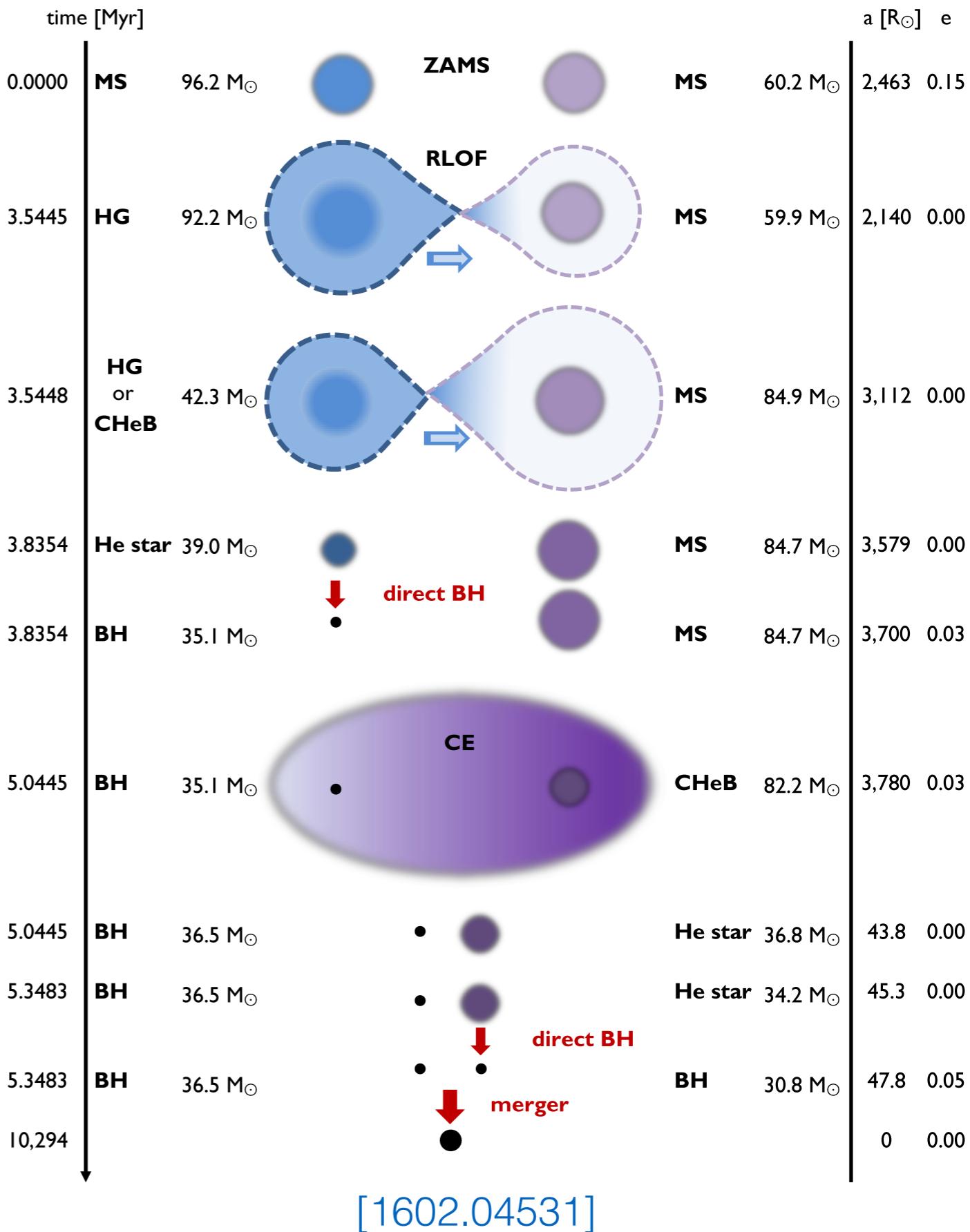
- ▶ Halo ‘relaxation’ is instantaneous
- ▶ Orbital properties evolve slowly compared to the orbital period

# Total number of cycles



# Astrophysical BH binaries

Astrophysical BH binaries could be formed dynamically, or through e.g. common envelope evolution:



[Banerjee, 1611.09357,  
LIGO-Virgo, 1602.03846,  
Elbert et al., 1703.02551,  
Stevenson et al., 1704.01352,  
and many others...]