Primordial Black Holes, Gravitational Waves and Werewolves

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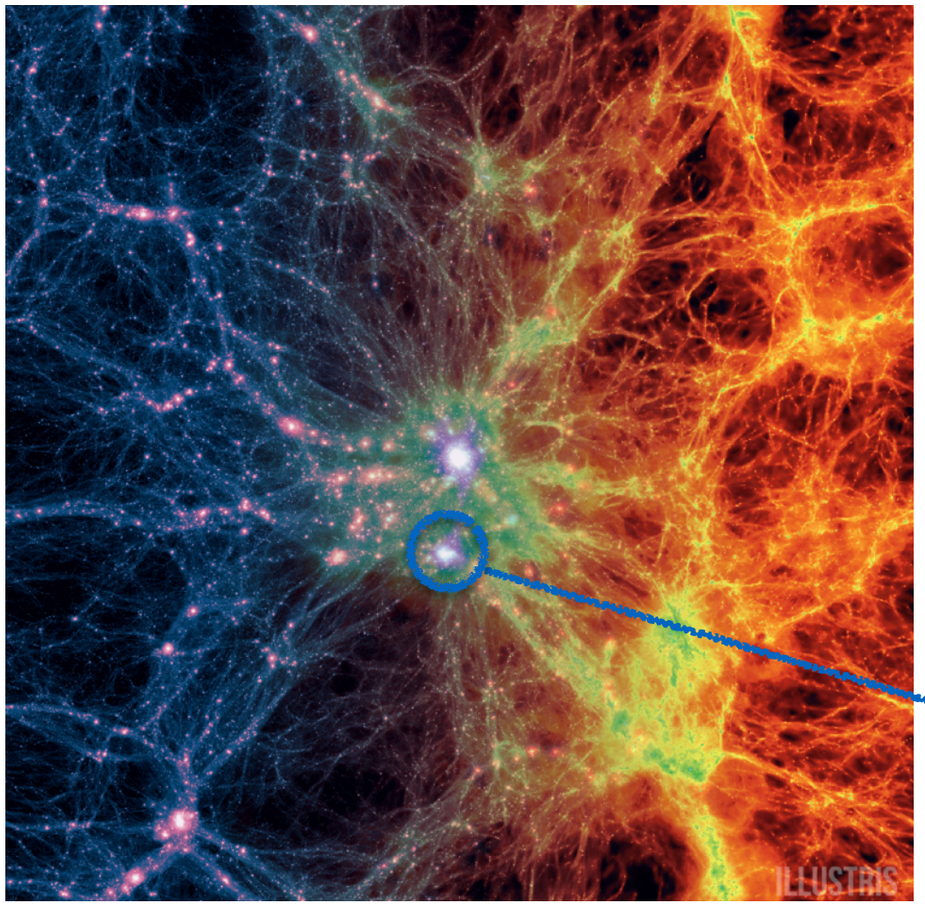
Werewolves

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

aaronsimscompany

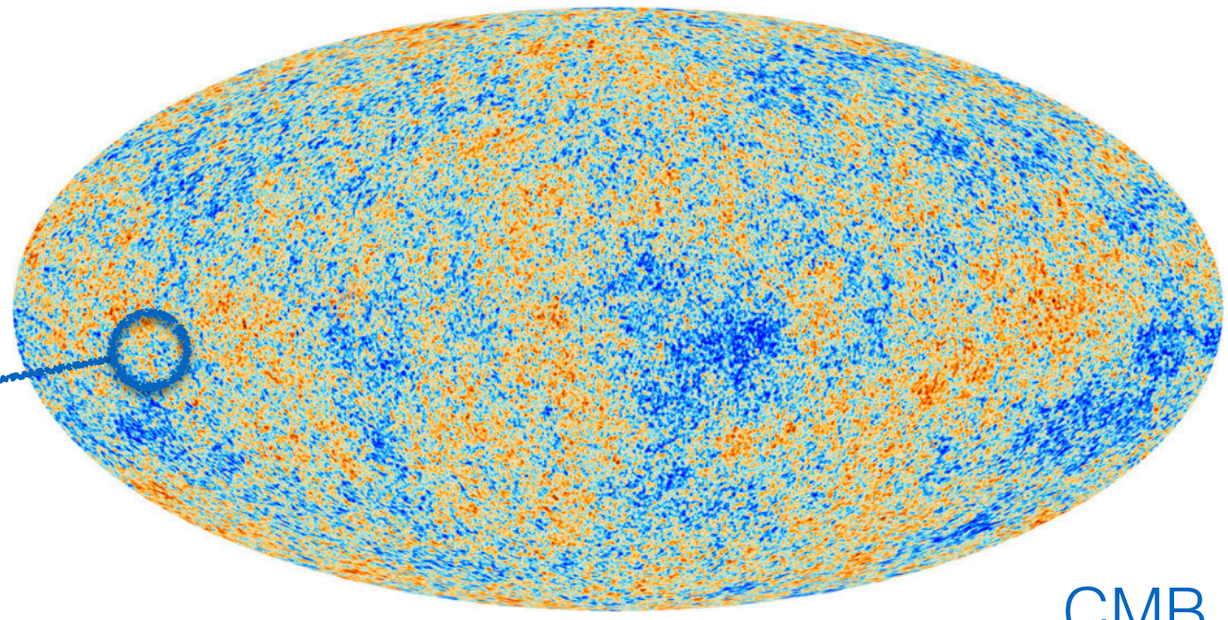
Dark Matter on all scales



Galaxy clusters

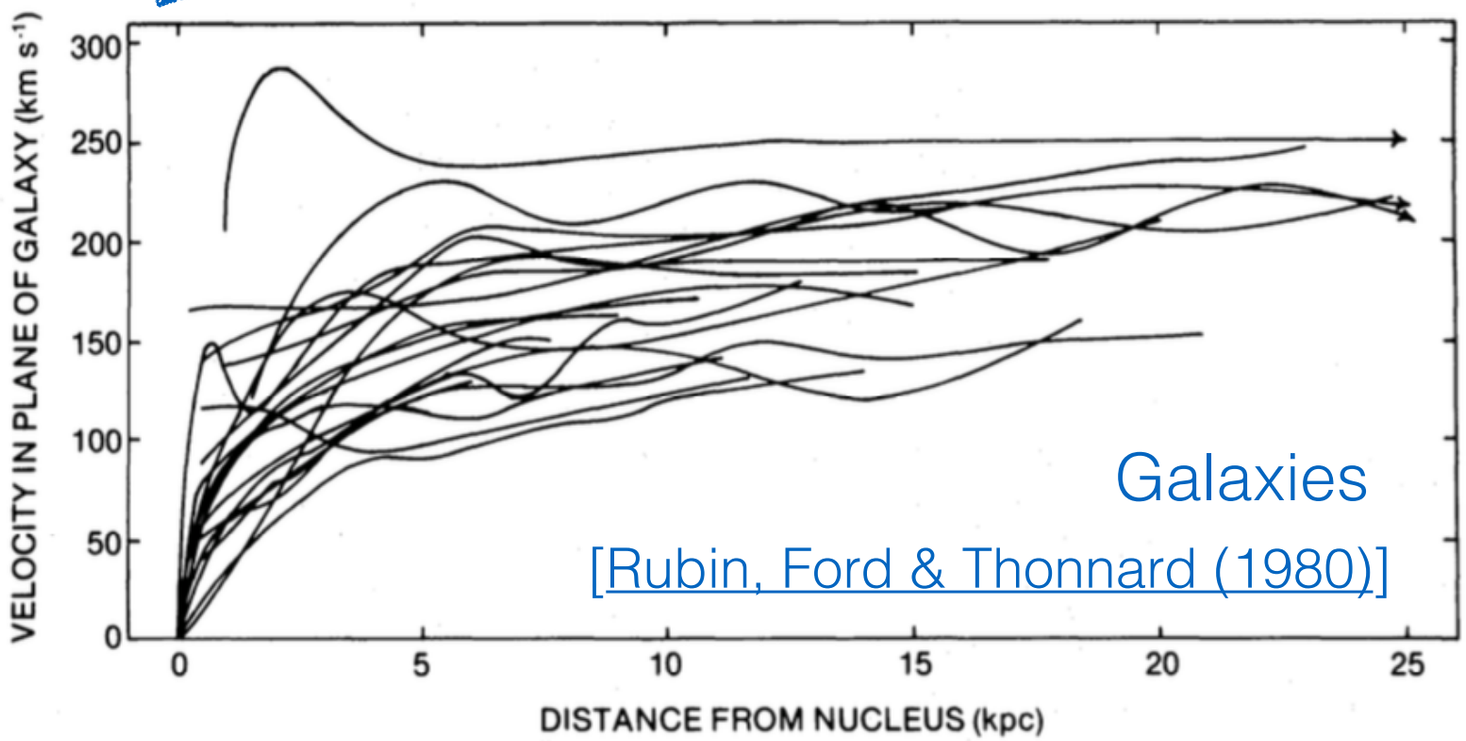
[Illustris, 1405.2921]

[astro-ph/0006397]



CMB

Planck [1502.01589]

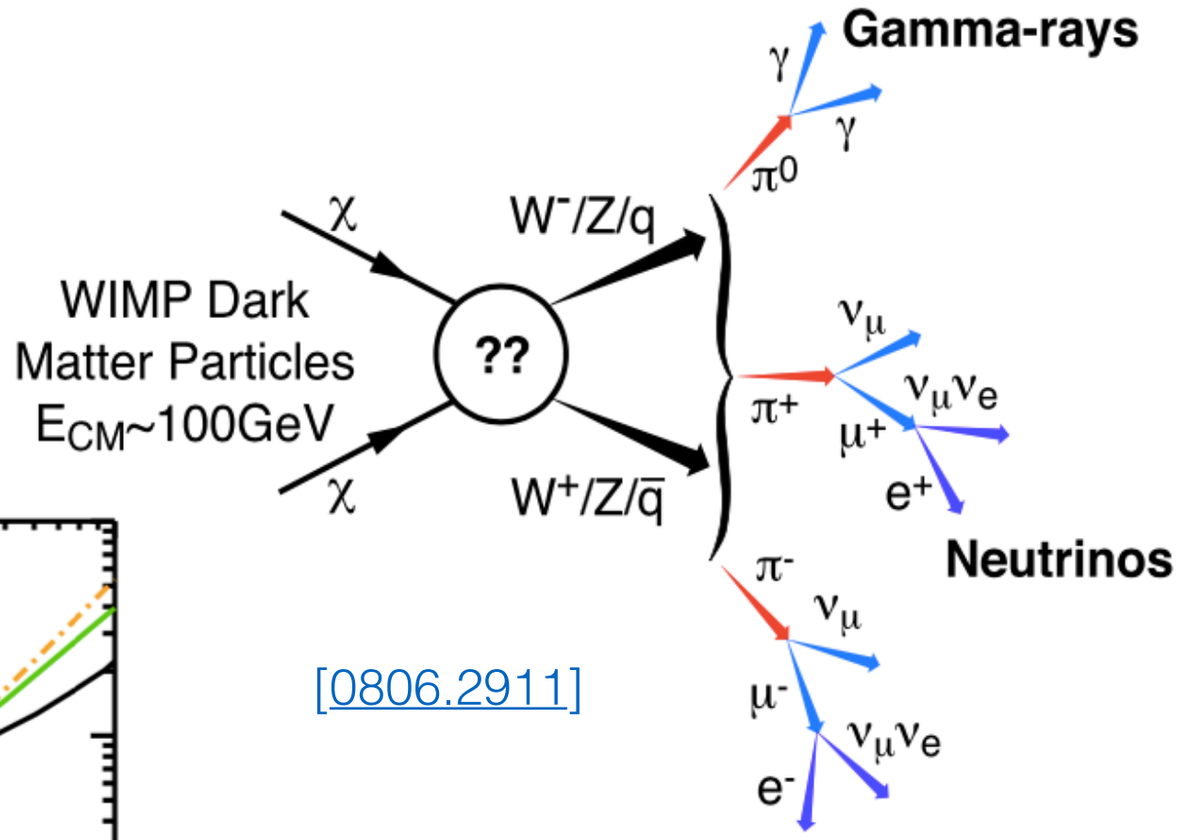


Galaxies

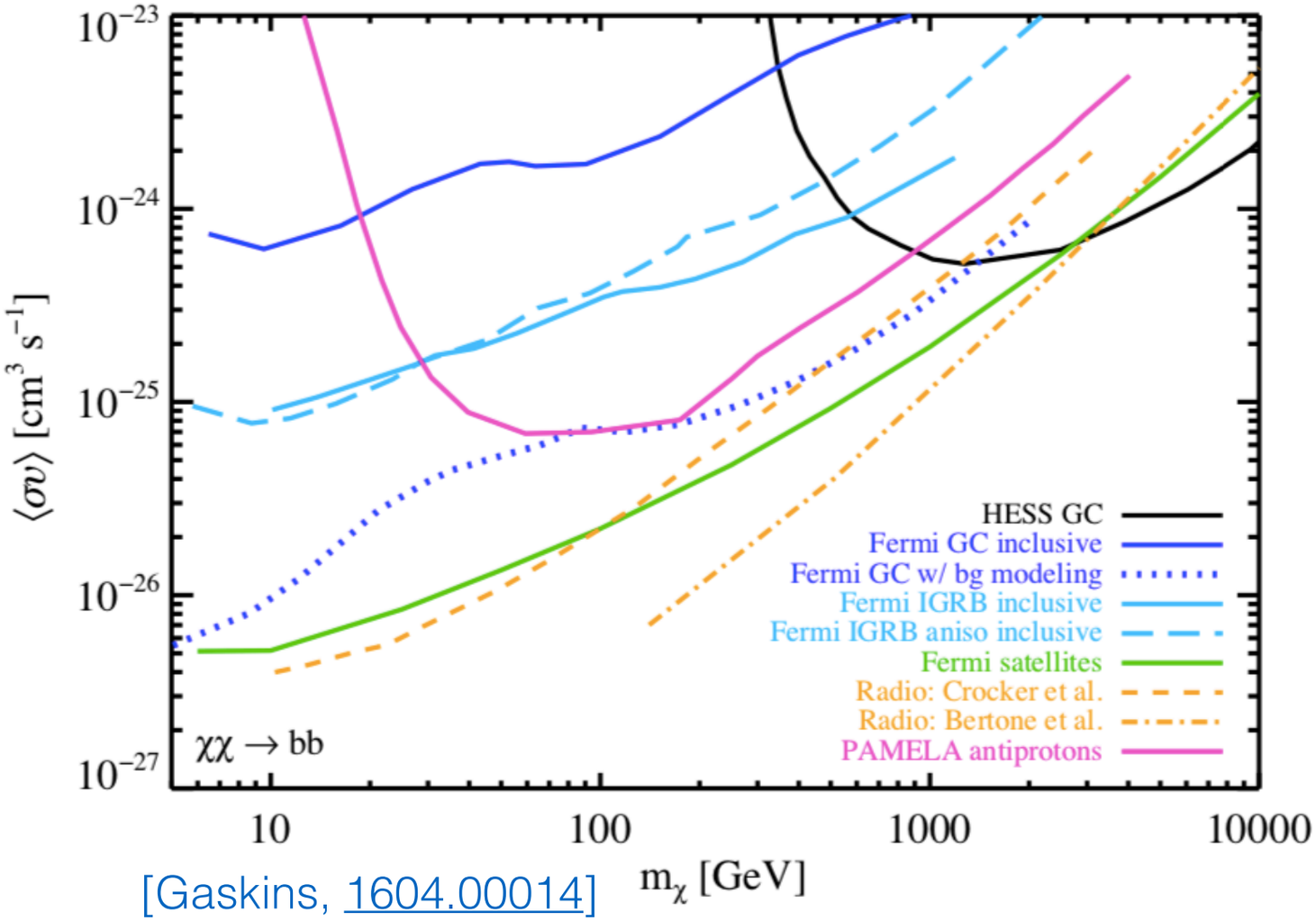
[Rubin, Ford & Thonnard (1980)]

DM Indirect Detection

WIMPs: Weakly Interacting Massive Particles



[0806.2911]

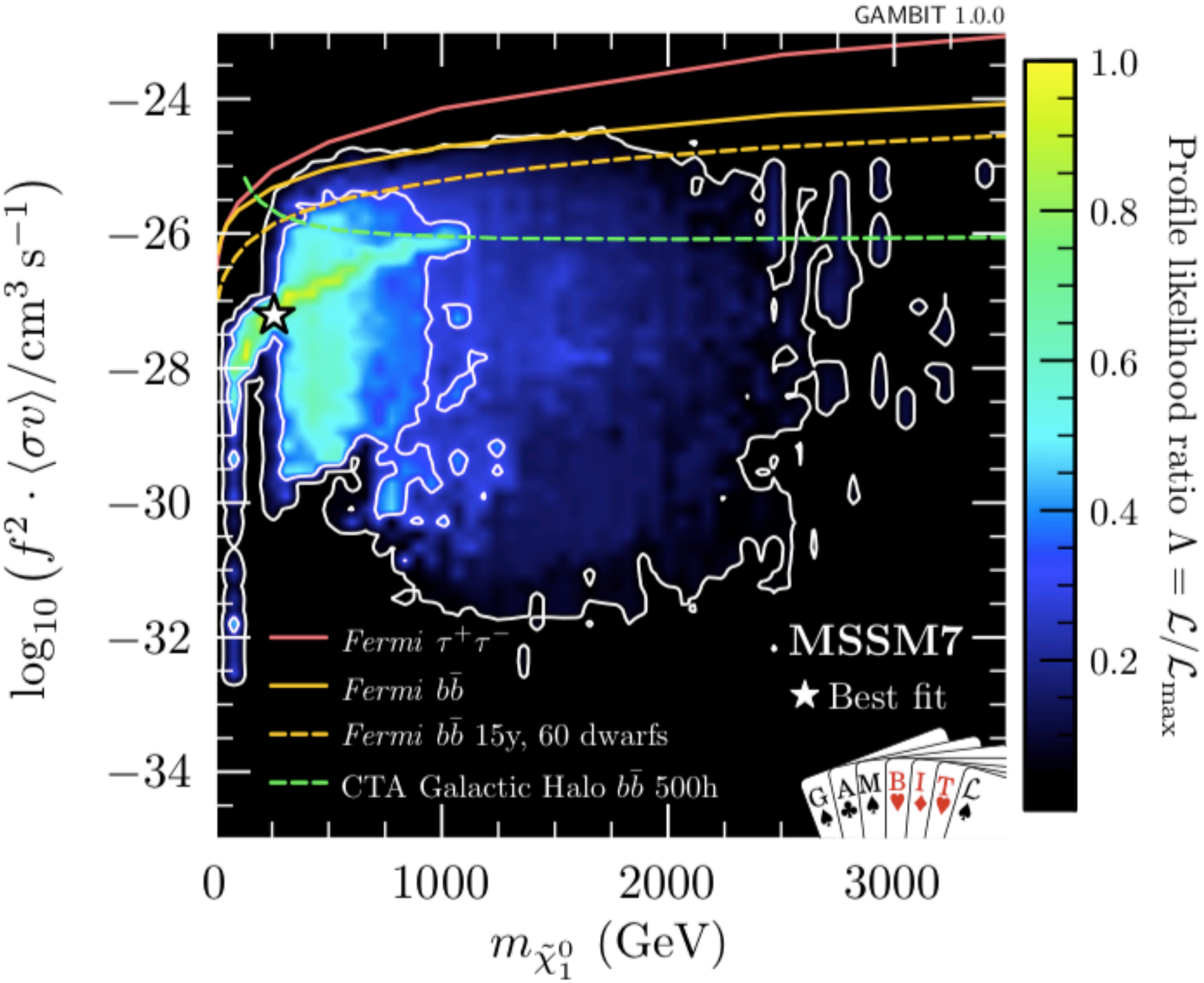


[Gaskins, 1604.00014]

[See recent developments in 2002.11956]

DM Indirect Detection

WIMPs: Weakly Interacting Massive Particles

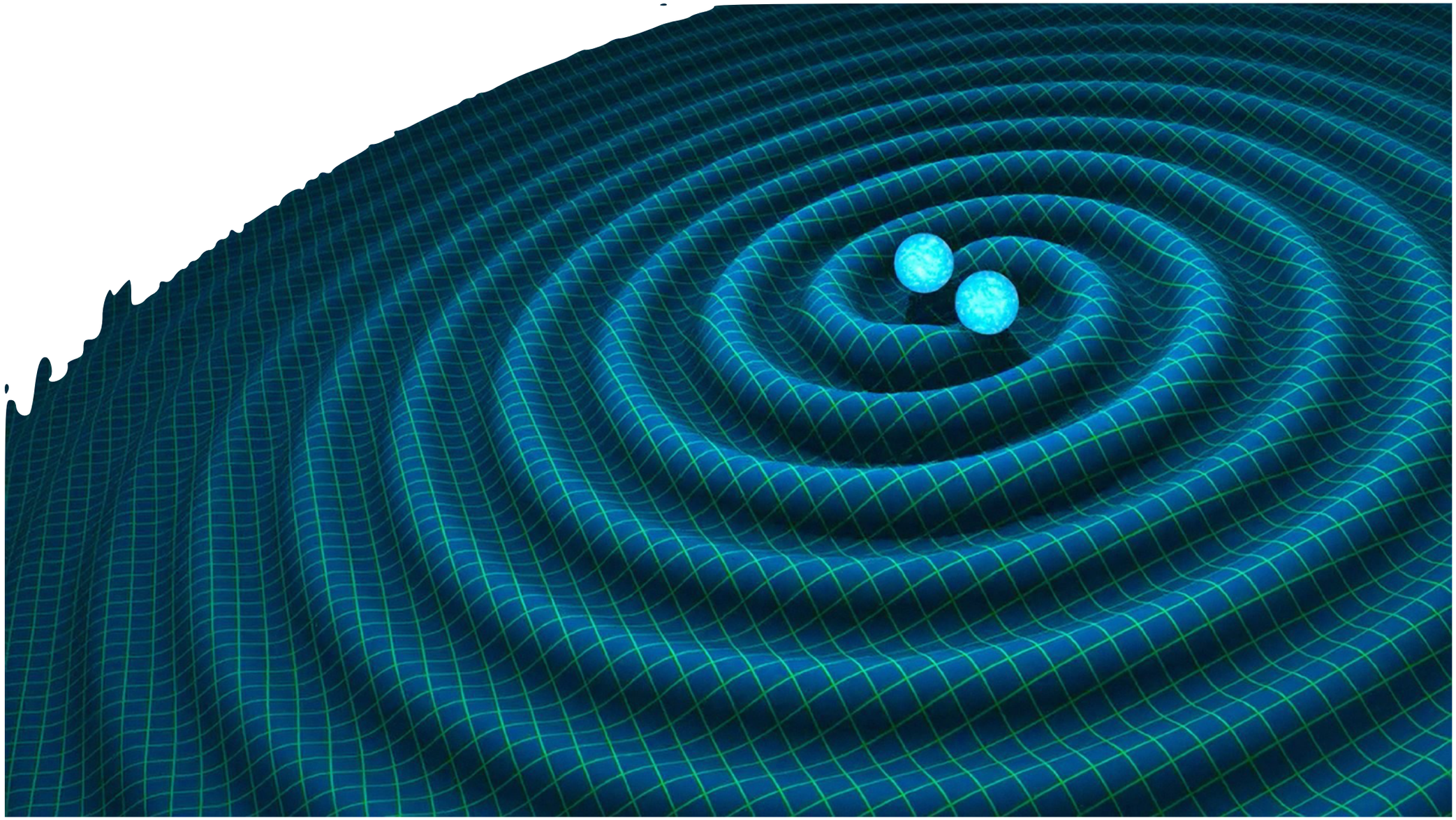


[GAMBIT, 1705.07917]

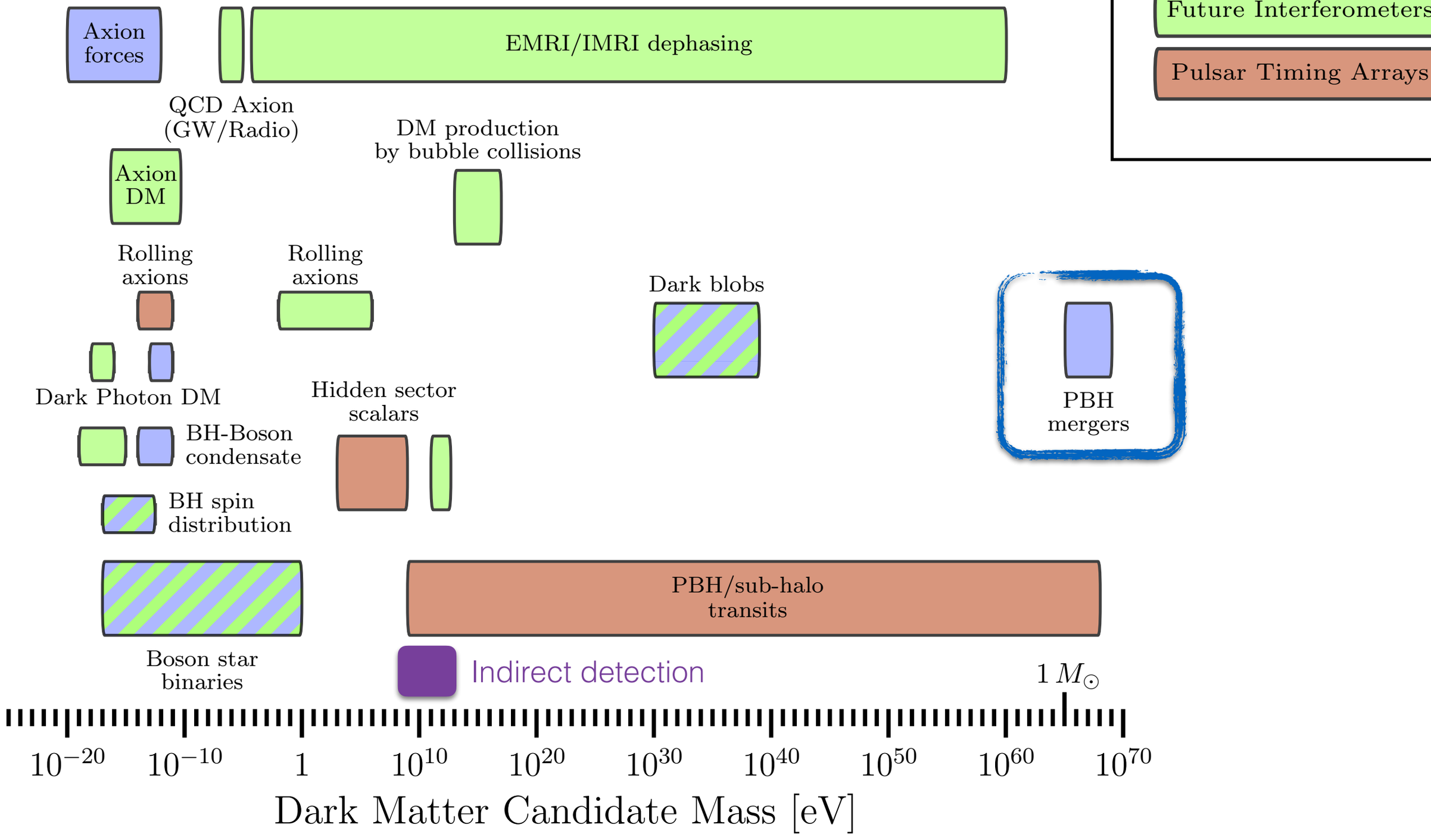
Gravitational Waves

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

R. HURT / CALTECH-JPL / HANDOUT/ ESA

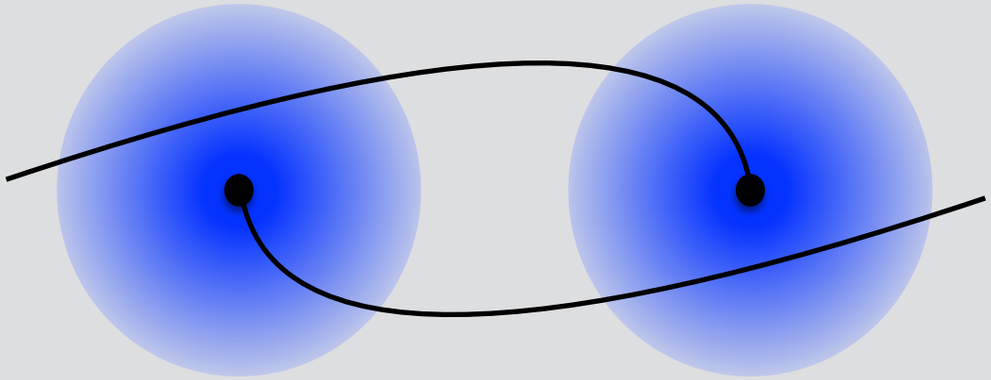


GW probes of DM



[Bertone, Croon, Amin, Boddy, **BJK**, Mack, Natarajan, Opferkuch, Schutz, Takhistov, Weniger, Yu, SciPost Phys. Core 3, 007 (2020), 1907.10610]

Overview

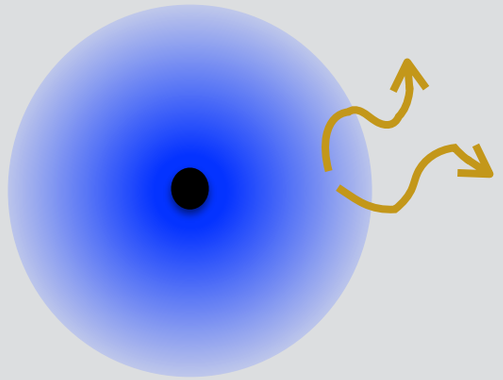


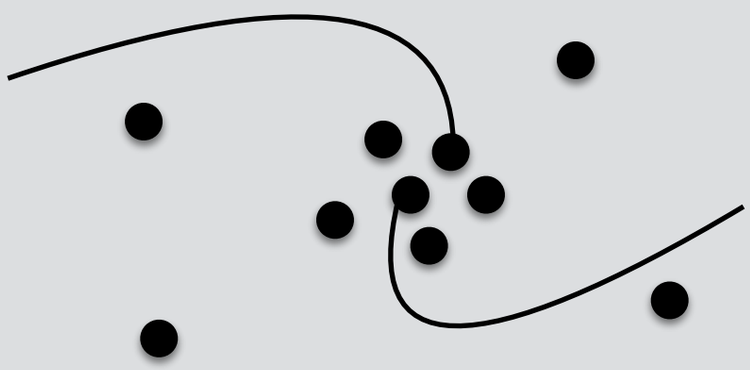
Merging Primordial Black Holes (PBHs)

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

DM Annihilation around PBHs

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





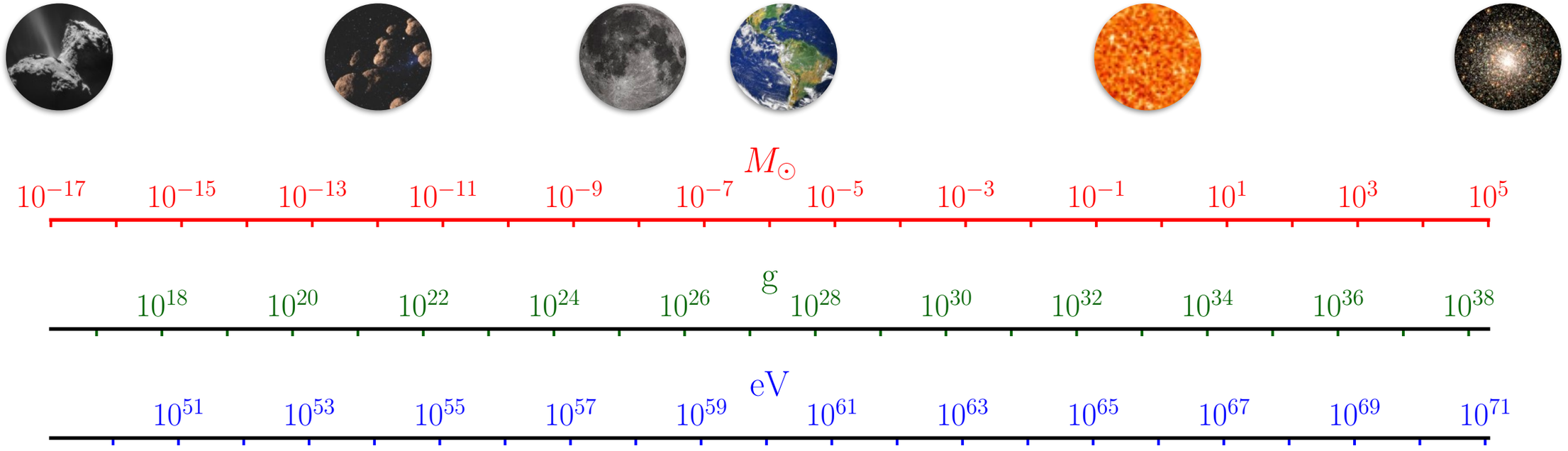
The ever-changing field of PBH mergers…

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]

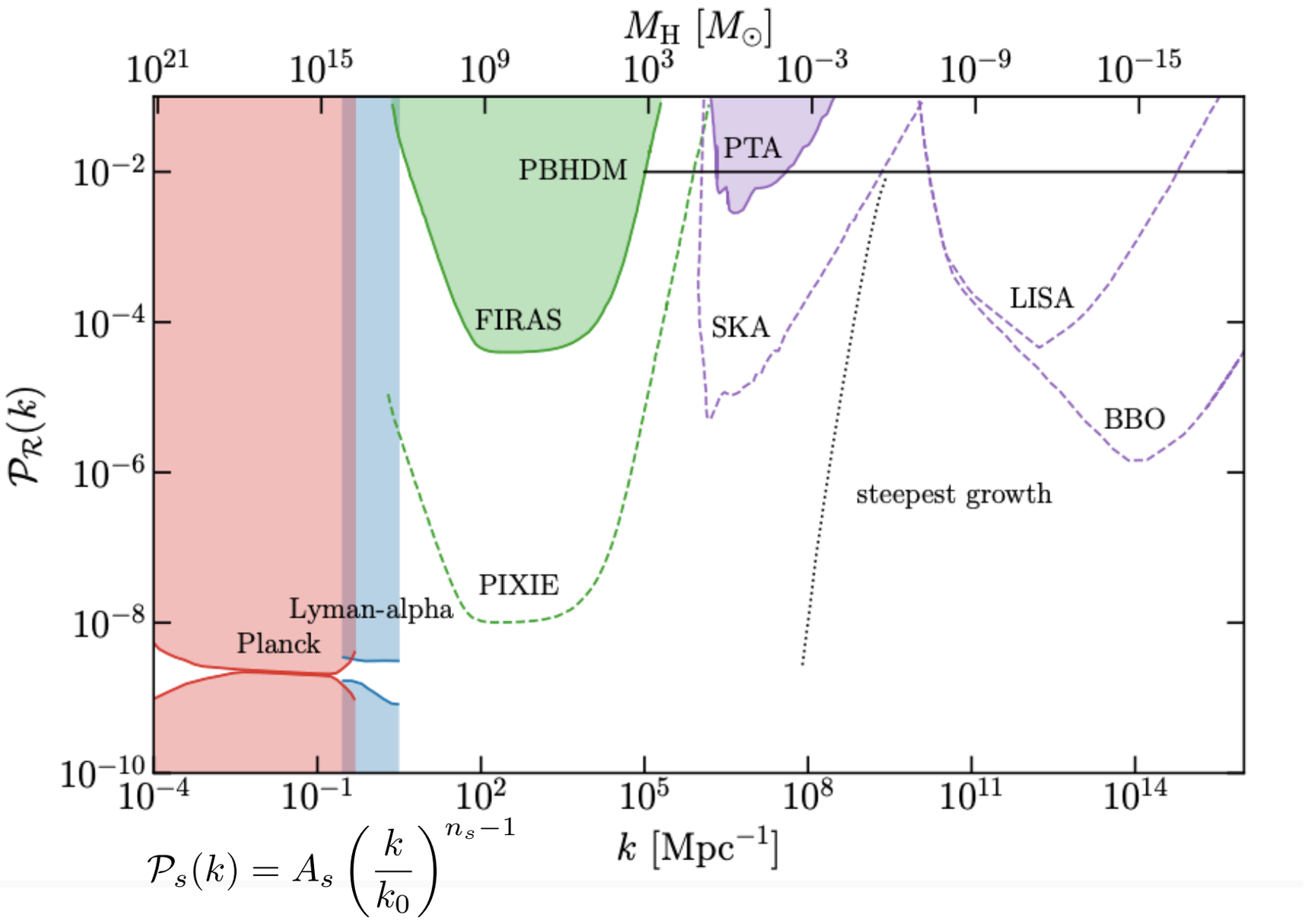


[Zel'dovich & Novikov (1967), Hawking (1971), Carr & Hawking (1974), Carr (1975)]

Primordial Black Holes

[1811.11158]
[Green & **BJK,** 1709.06576]

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

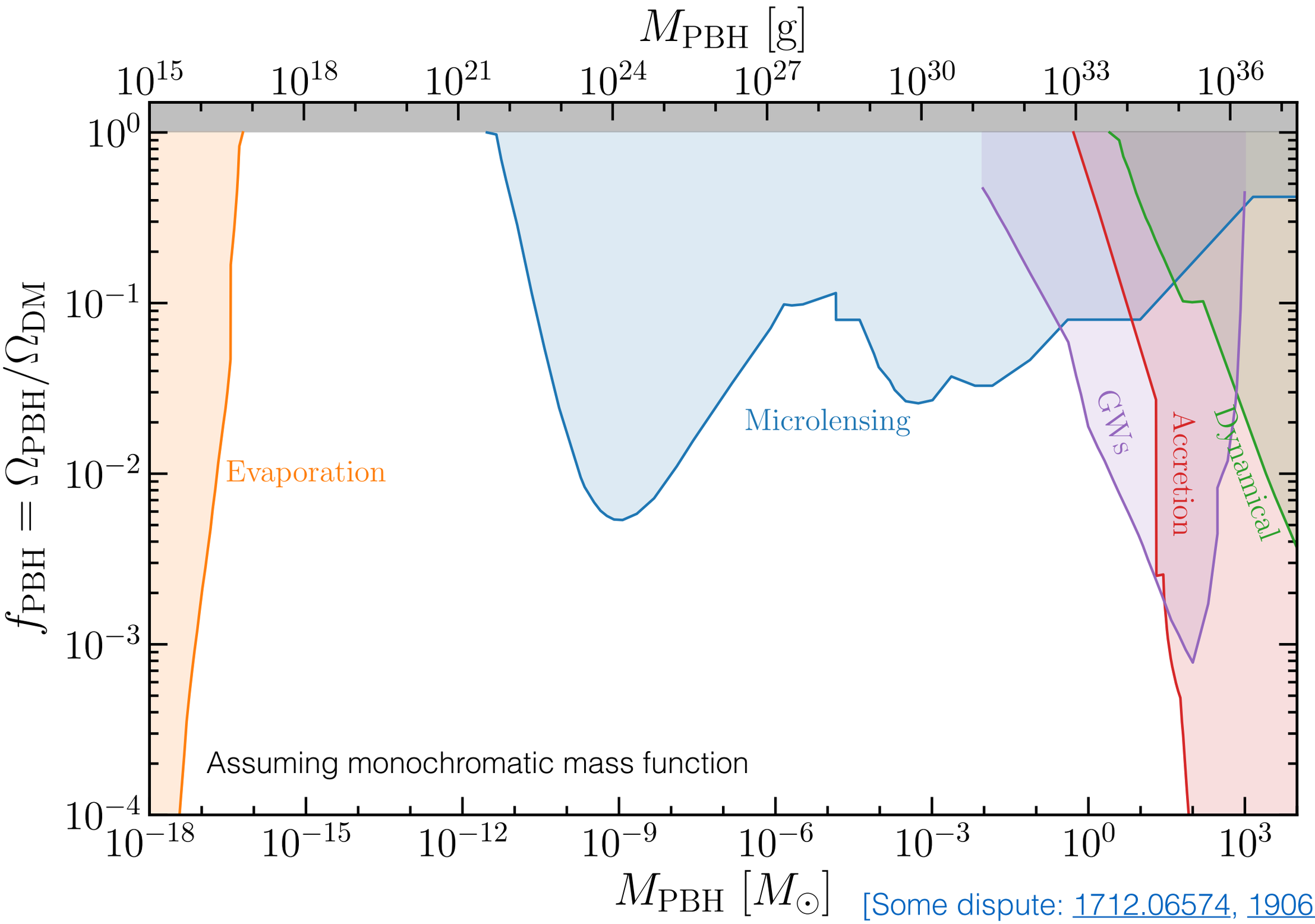


…but small scale power spectrum is largely unconstrained.

PBH bounds

[Green & **BJK**, 1709.06576]

[Code online: github.com/bradkav/PBHbounds]

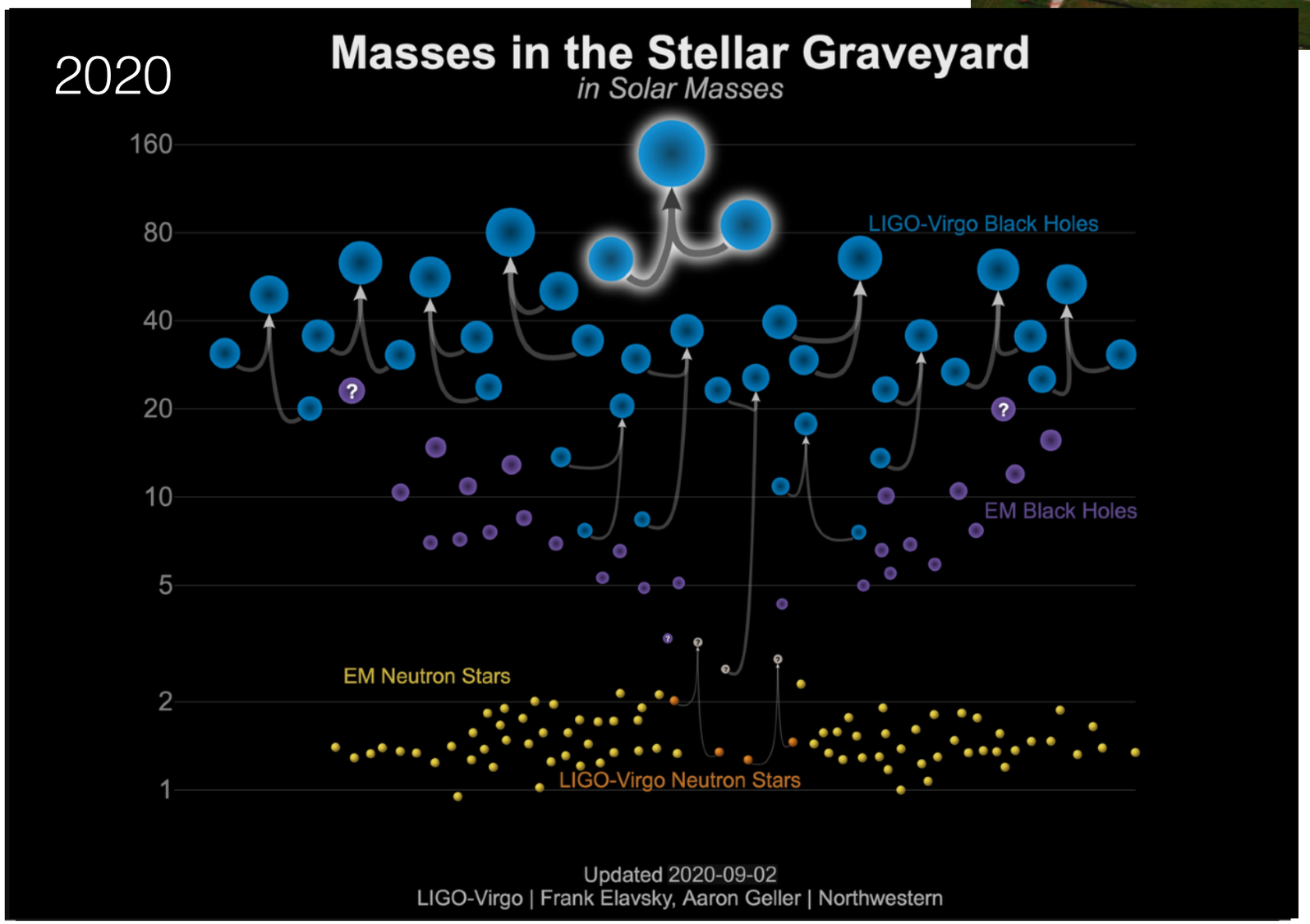


[Some dispute: 1712.06574, 1906.05950]

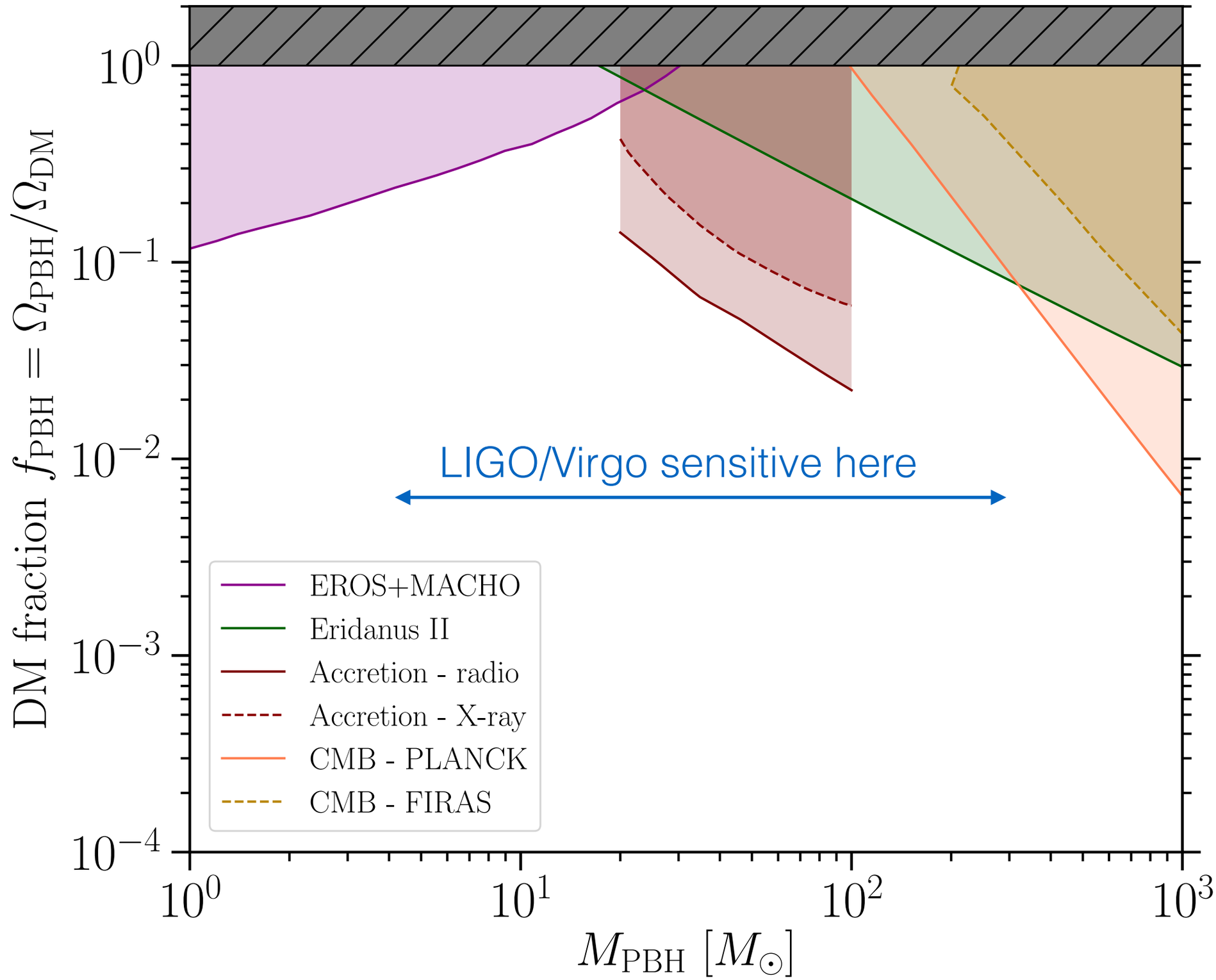
LIGO/Virgo Mergers

The Virgo collaboration/CCO 1.0

LIGO/Caltech/Sonoma State (Aurore Simonnet)



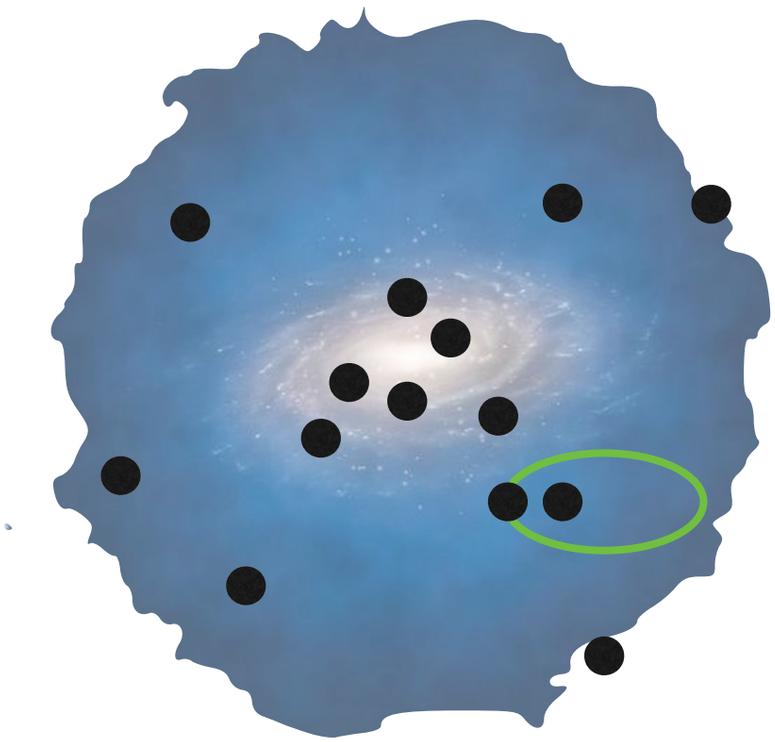
PBHs as Dark Matter



A tale of two binaries

A) Binaries formed after close encounters

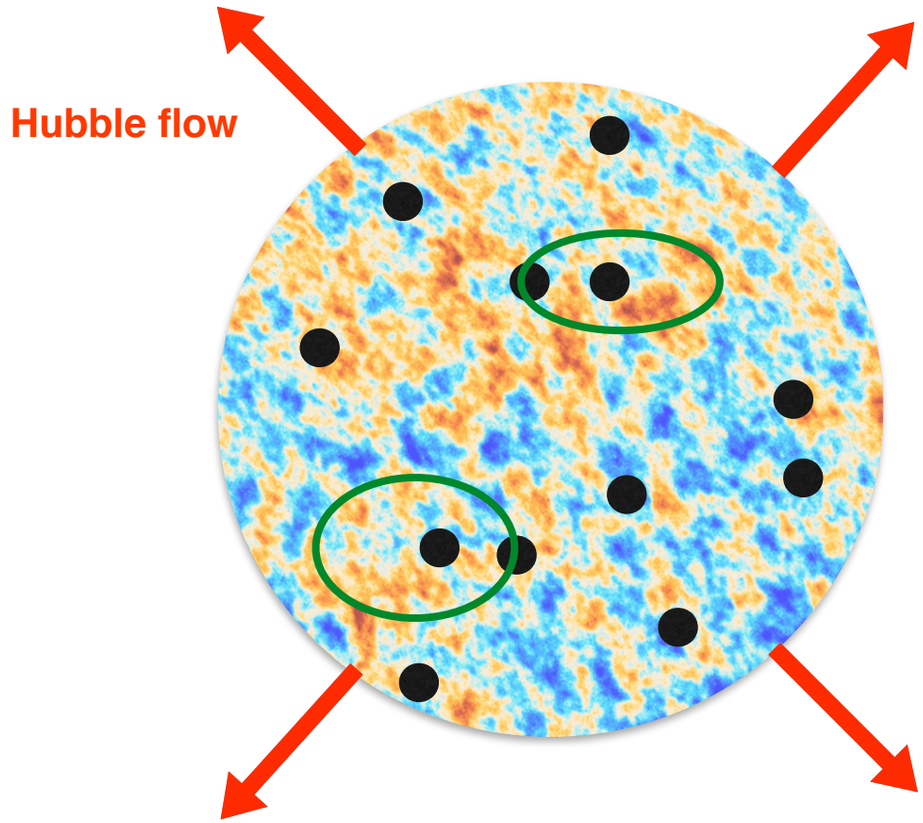
[Bird et al., 1603.00464]



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

B) Binaries formed in the early Universe

[Sasaki et al, 1603.08338]



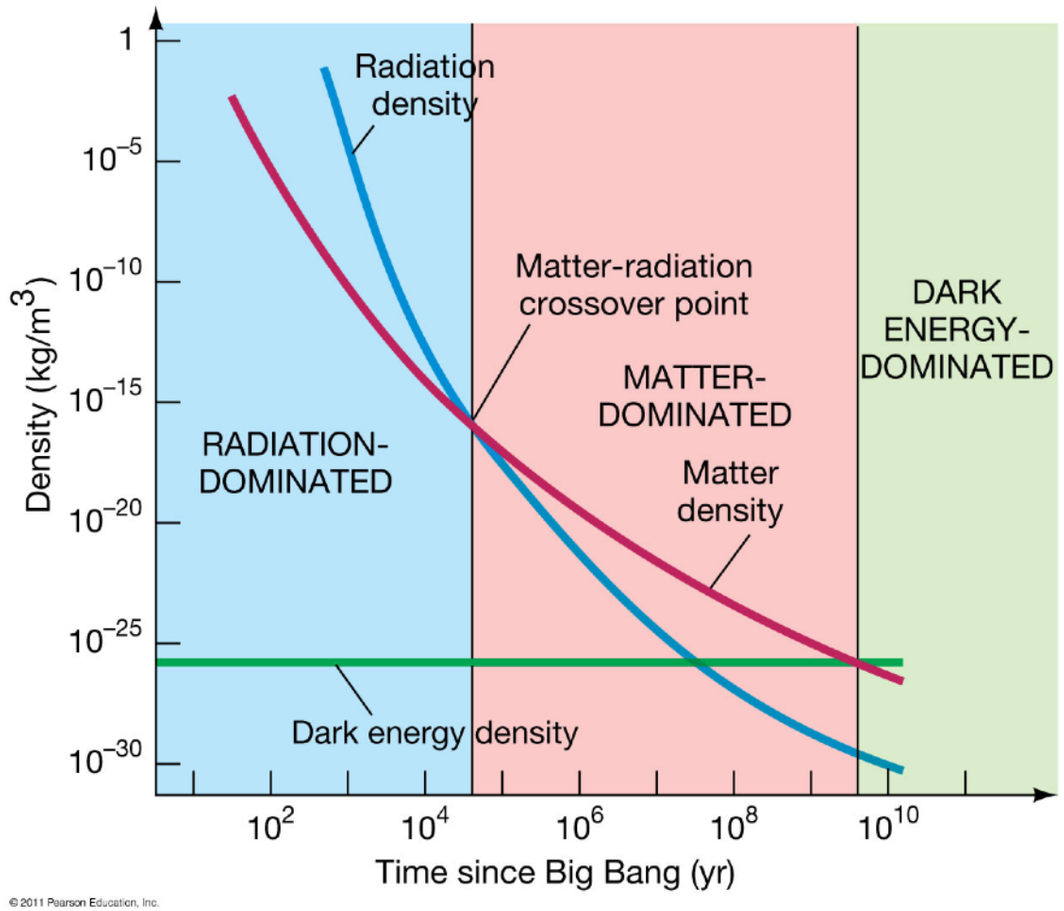
Require:

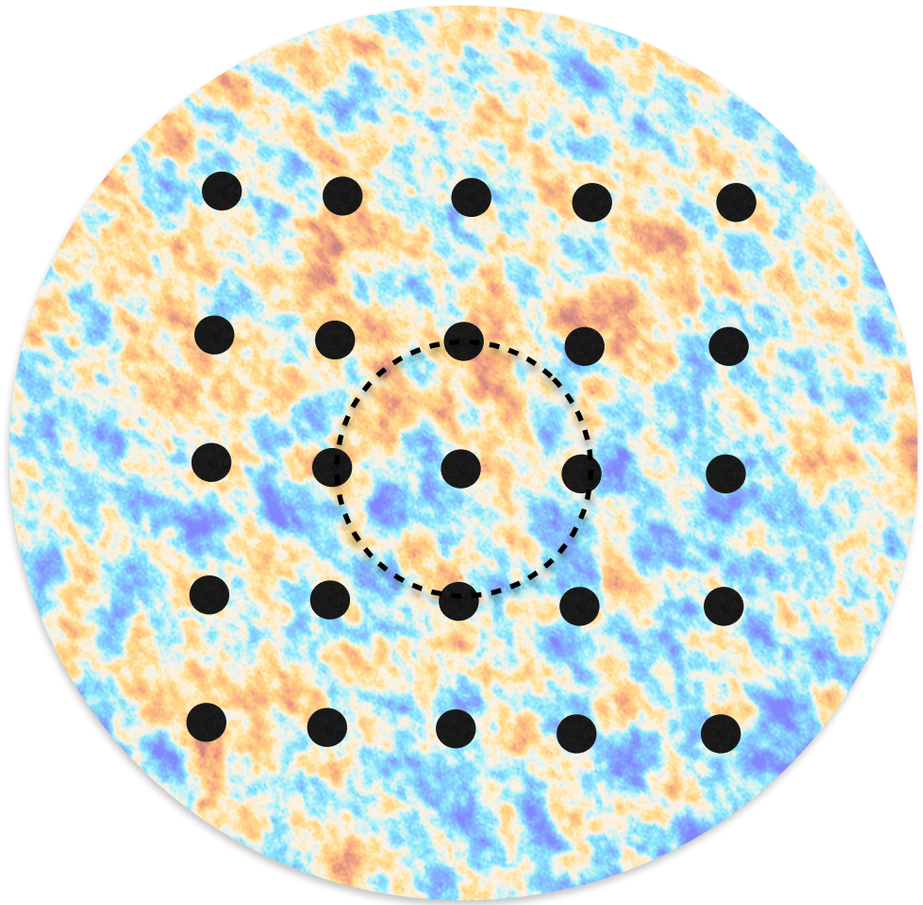
$$M_{\rm BH} R^{-3} > \rho(z) \text{ before } z_{\rm eq}$$

[Daniele Gaggero, UCI 20/02/2018]

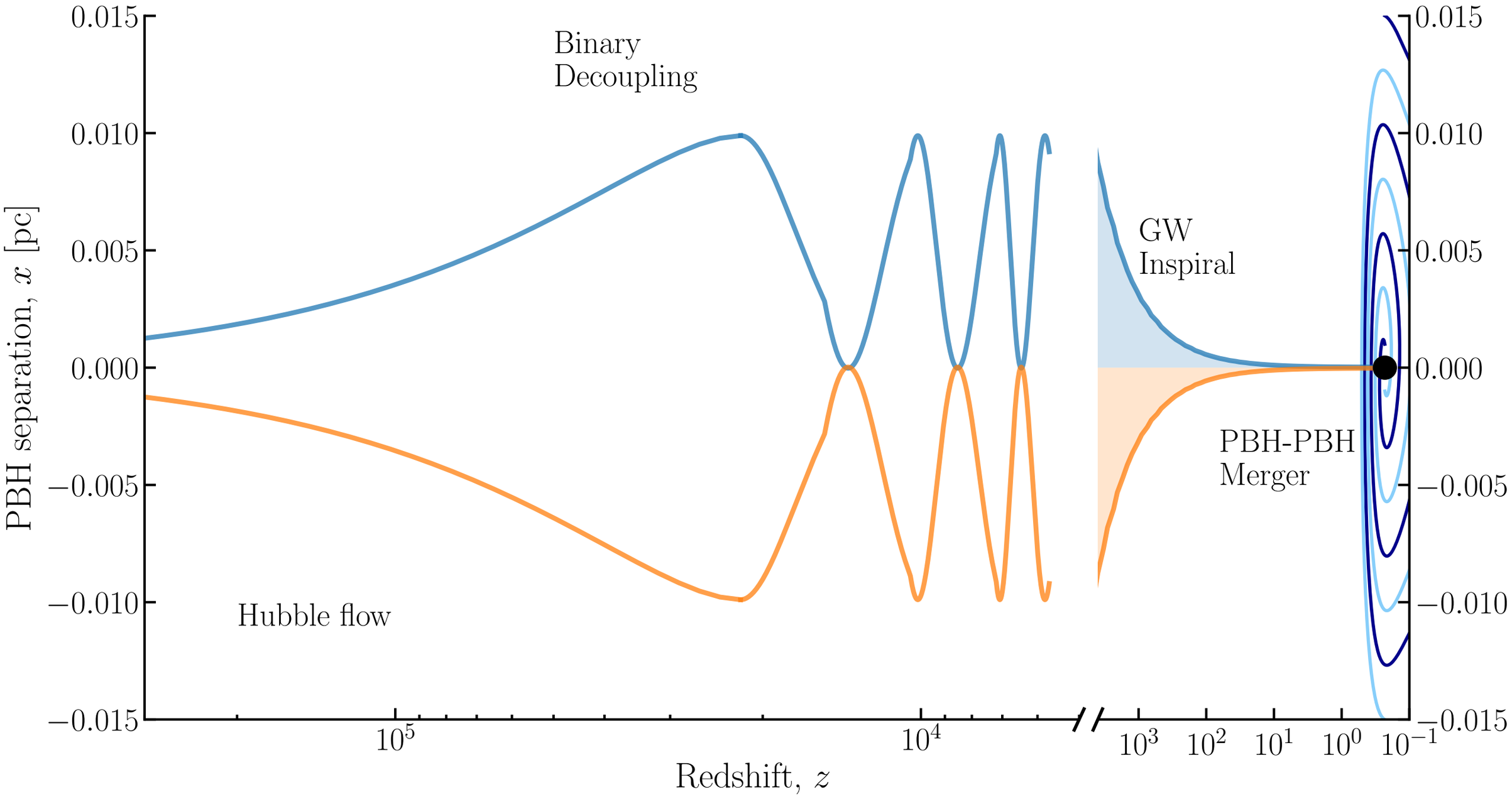
Early Universe Binaries

If $f_{PBH} \sim 1$, the relative density of PBHs *equals* the background radiation density at matter-radiation equality.
(Almost) all PBHs form binaries…





Life of a PBH binary



$a = 0.01\,\mathrm{pc}$

$e = 0.995$

PBH Binary Population

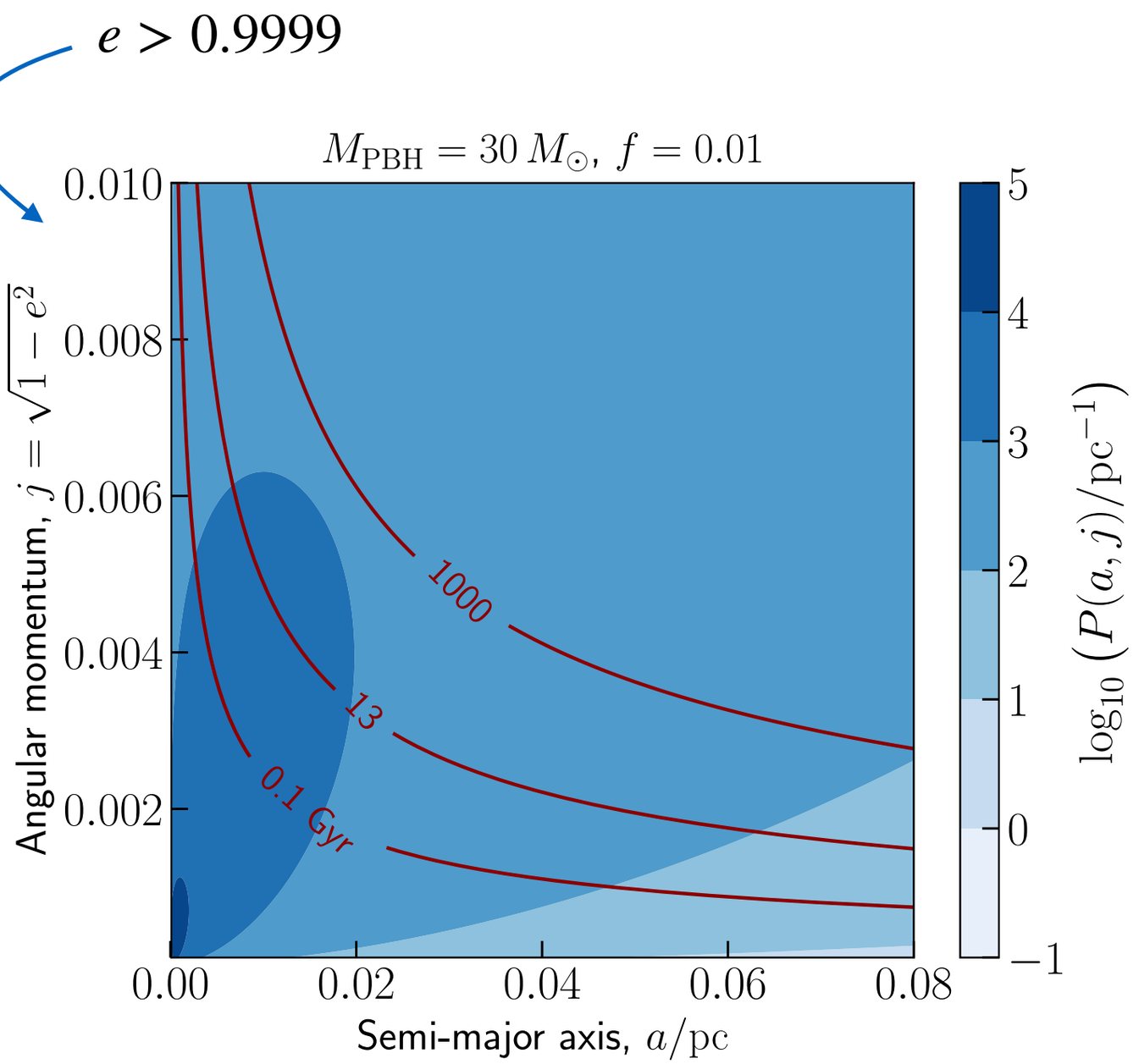
$$j = \sqrt{1 - e^2}$$

Randomly distributed (unclustered*) PBHs

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

Close, eccentric binaries merge today:

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

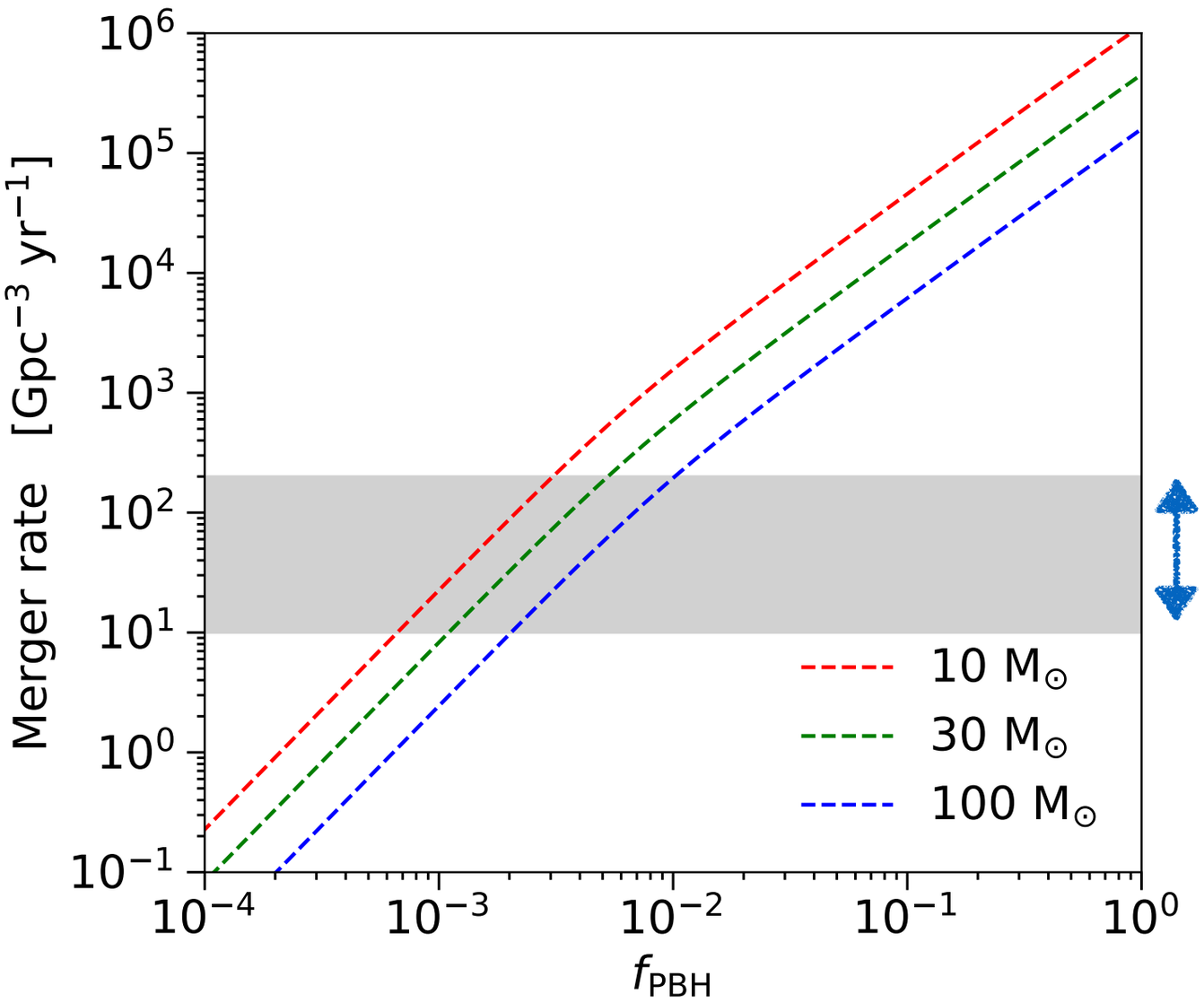


[**BJK**, Gaggero & Bertone, 1805.09034]

[0909.1738, 1606.07437, 1707.01480, **1709.06576**, 1907.01455, and many others.]

Merger Rate Estimate

$$\mathcal{R}\left(t_{\rm merge}\right) = \frac{1}{2} n_{\rm PBH} P_{\rm binary}\, P\left(t_{\rm merge}\right)$$



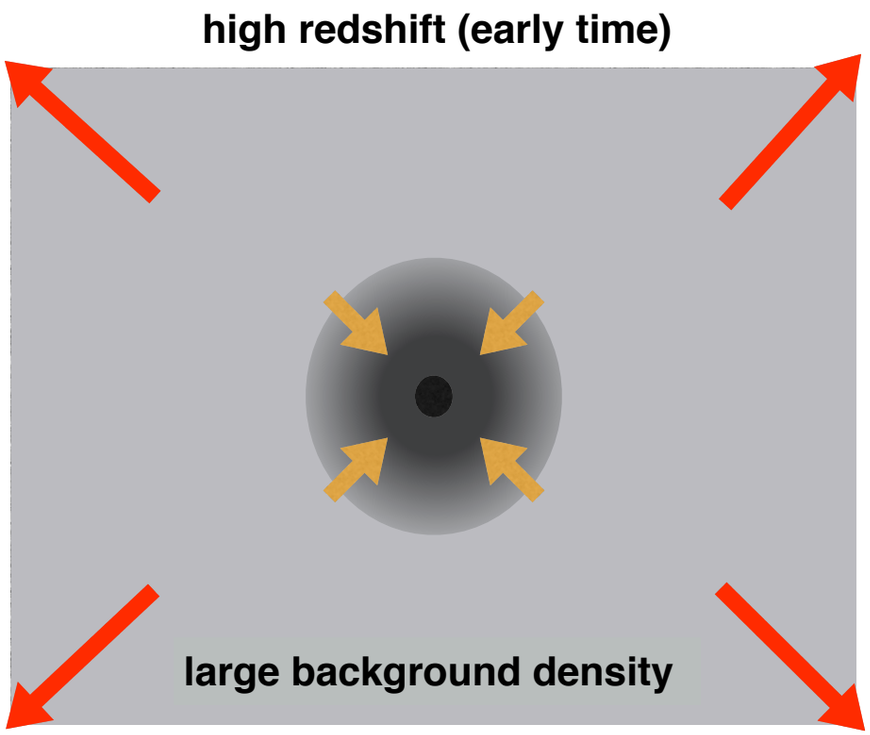
LIGO merger rate estimate after GW150914

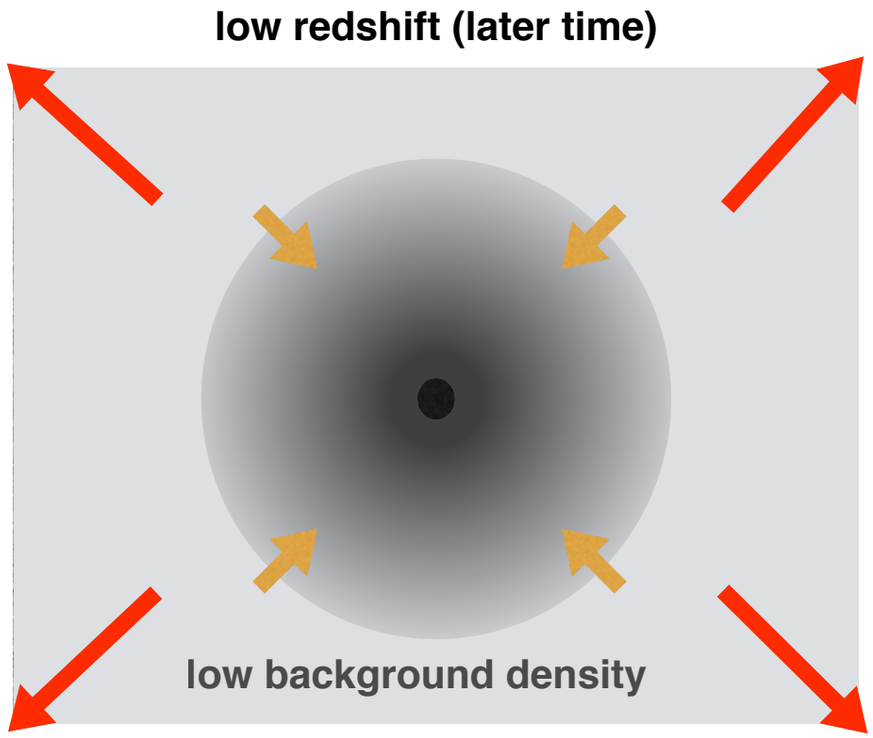
Solar mass PBHs should only be a *sub-dominant* (%-level) contribution to the DM density in the Universe

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

Black Holes' Dark Dress

PBHs seed the formation of 'local' DM halos:





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

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

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

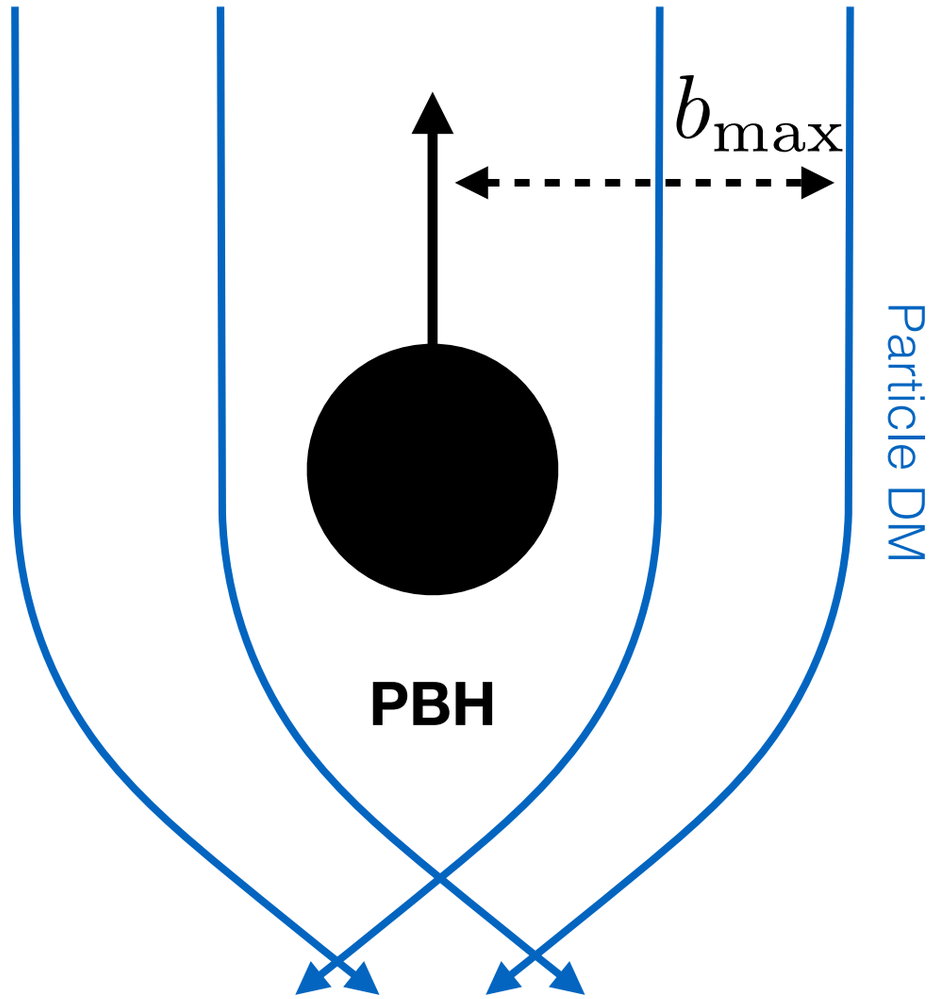
Slide shamelessly ripped off from Daniele Gaggero

[Bertschinger (1985)]
[0706.0864, 1901.08528]

Impact of Dark Dresses

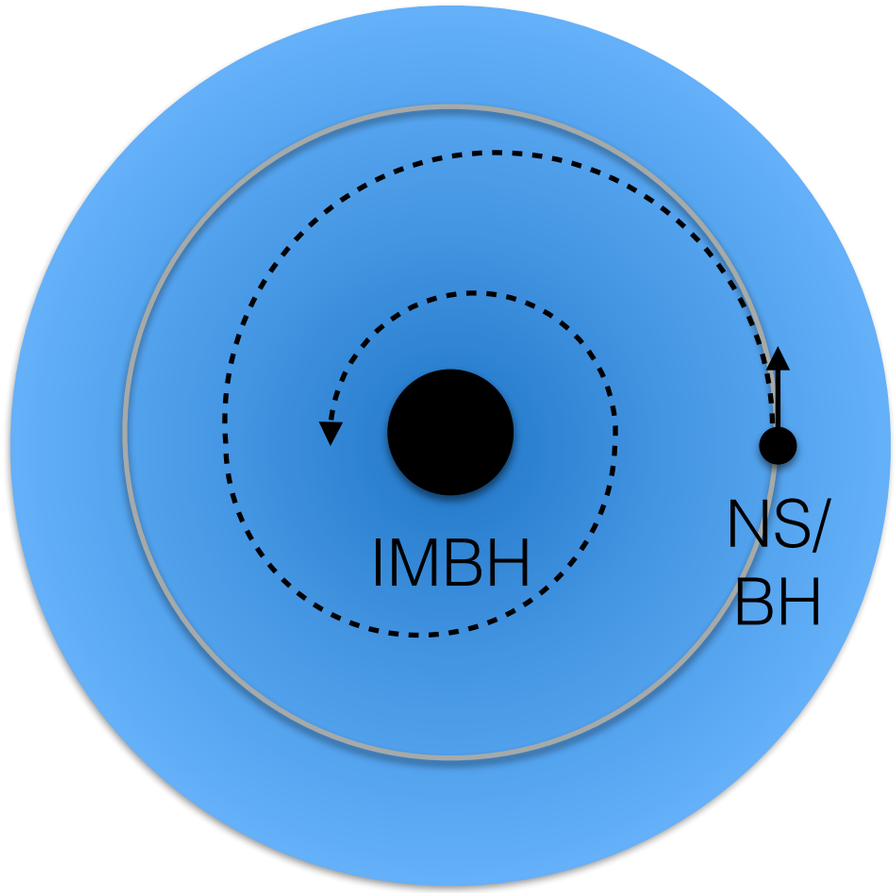
[Chandrasekhar, 1943]

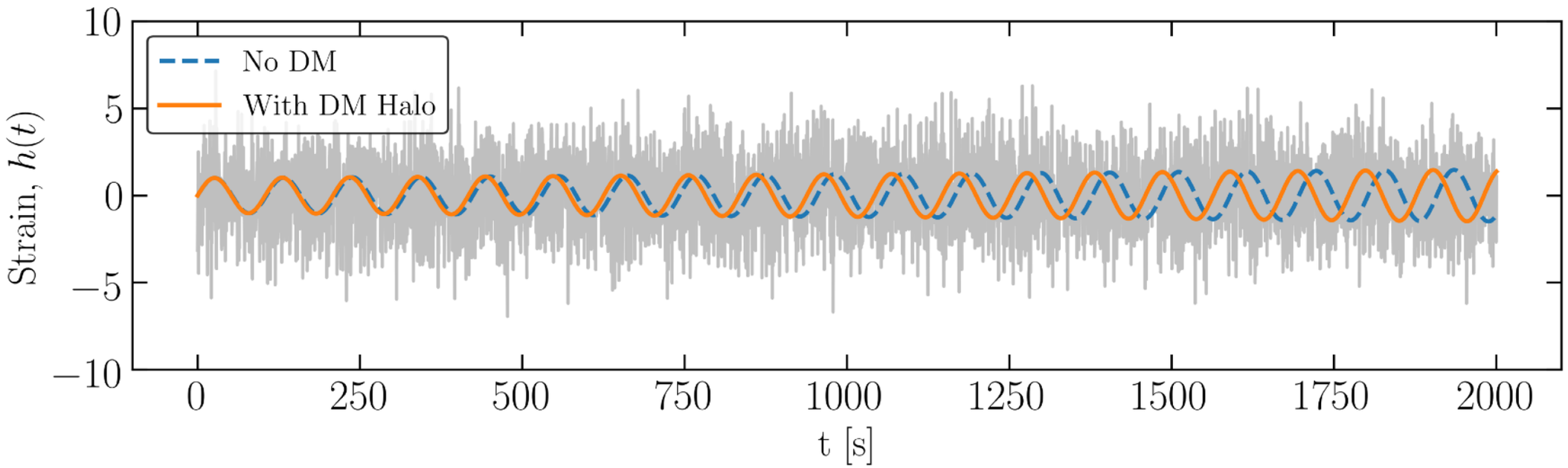
Dynamical friction due to DM exerts a force on the PBHs



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

Dark Dresses in IMRIs

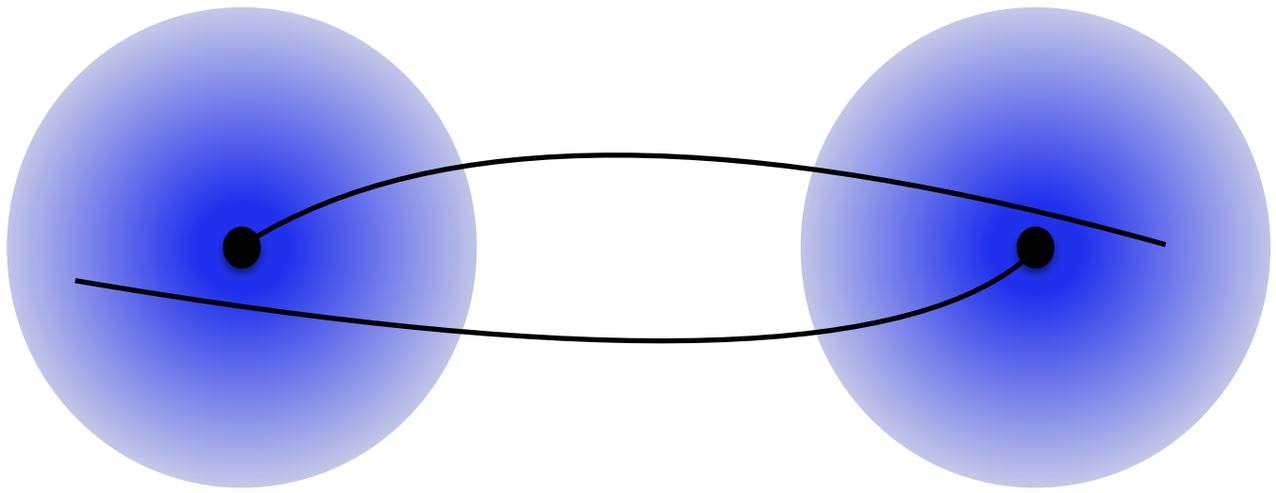




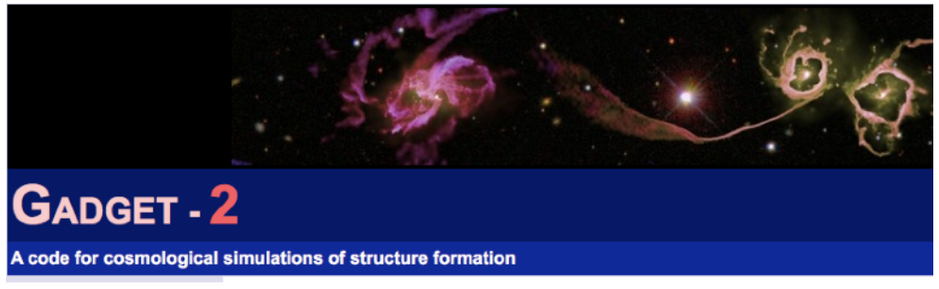
[Edwards, Chianese, **BJK**, Nissanke & Weniger, 1905.04686]

[**BJK**, Nichols, Gaggero, Bertone, 2002.12811]

‘Dressed’ PBH binaries



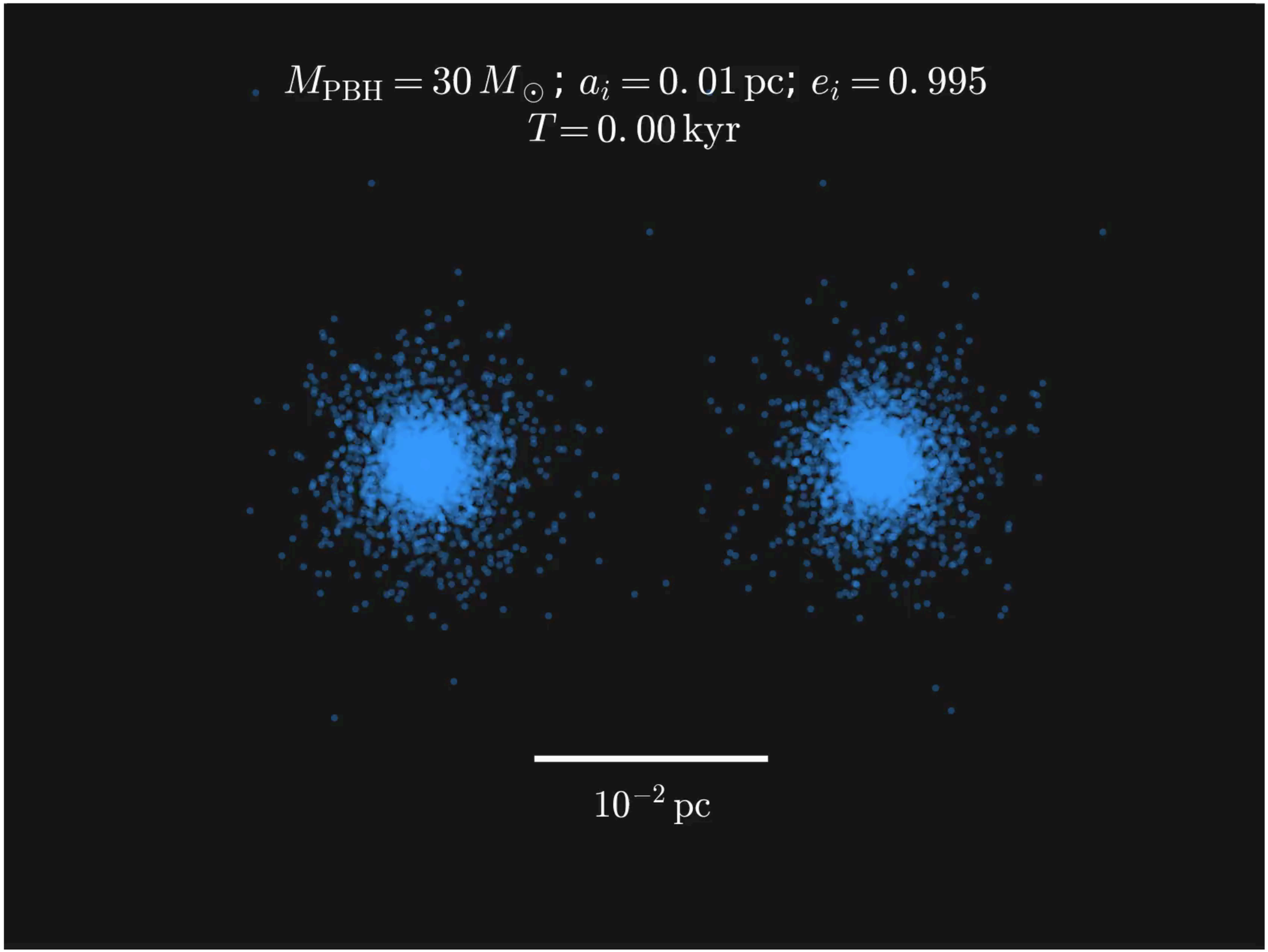
Study the binaries self-consistently using N-body simulations:



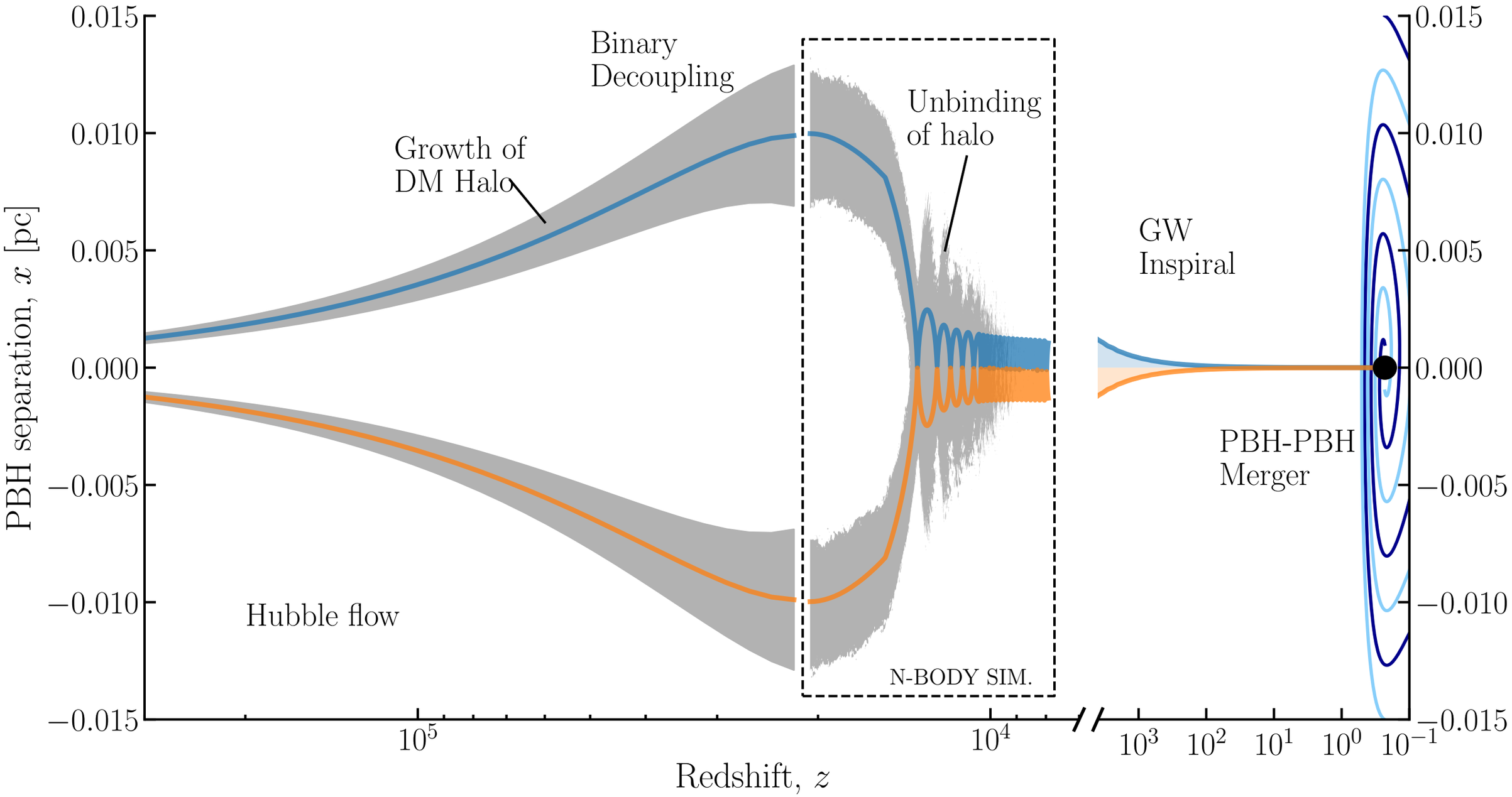
[GADGET-II, astro-ph/0505010]

[github.com/bradkav/BlackHolesDarkDress]

Movies at tinyurl.com/BlackHolesDarkDress



Life of a ‘dressed’ PBH binary



$a_i = 0.01\,\mathrm{pc}$

$e_i = 0.995$

A peculiar coincidence

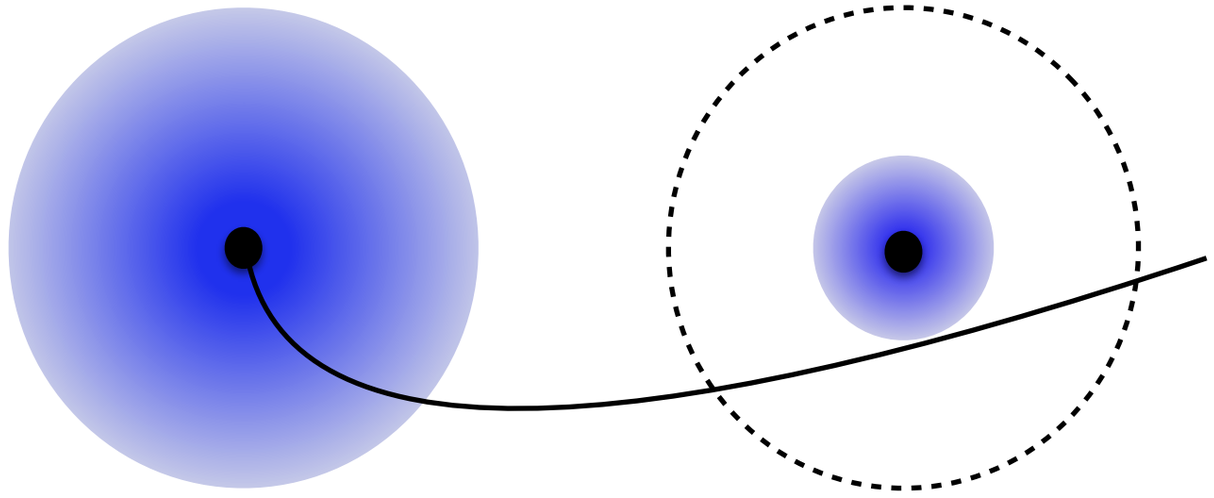
Binaries shrink…

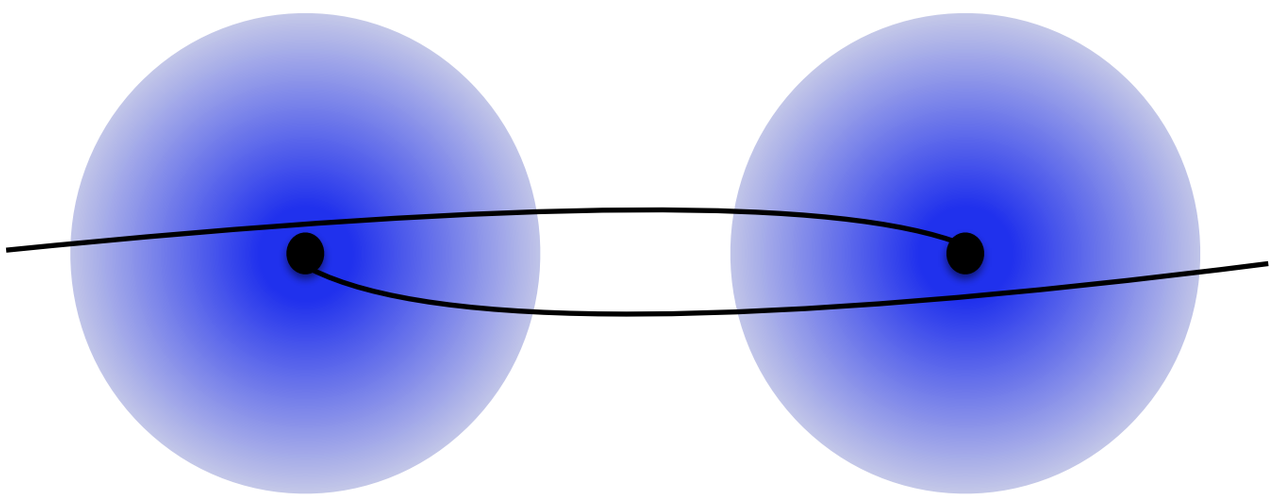
…and circularise

Conservation of energy:

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

fixes semi-major axis, a





Conservation of angular momentum:

$$L_i^{\rm PBH} = L_f^{\rm PBH}$$
$$L_i^{\rm halo} = L_f^{\rm halo}$$

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

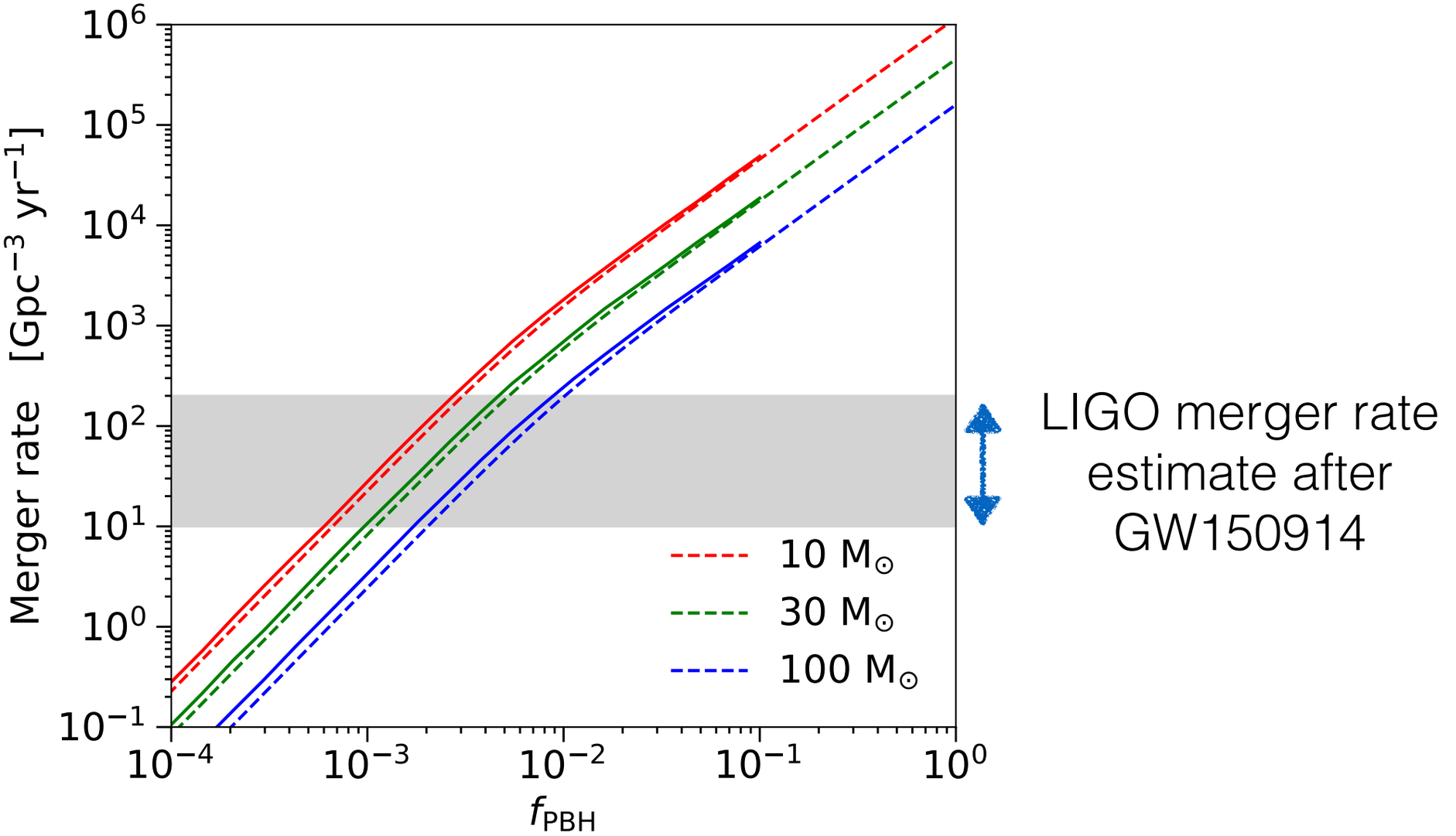
Merger time $t_{\rm merge} = \dfrac{3\,c^5}{170\,G_N^3}\,\dfrac{a^4 j^7}{M_{\rm PBH}^3}$ is almost conserved: $t_f = \sqrt{\dfrac{a_i}{a_f}}\,t_i$

Final Merger Rate

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

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

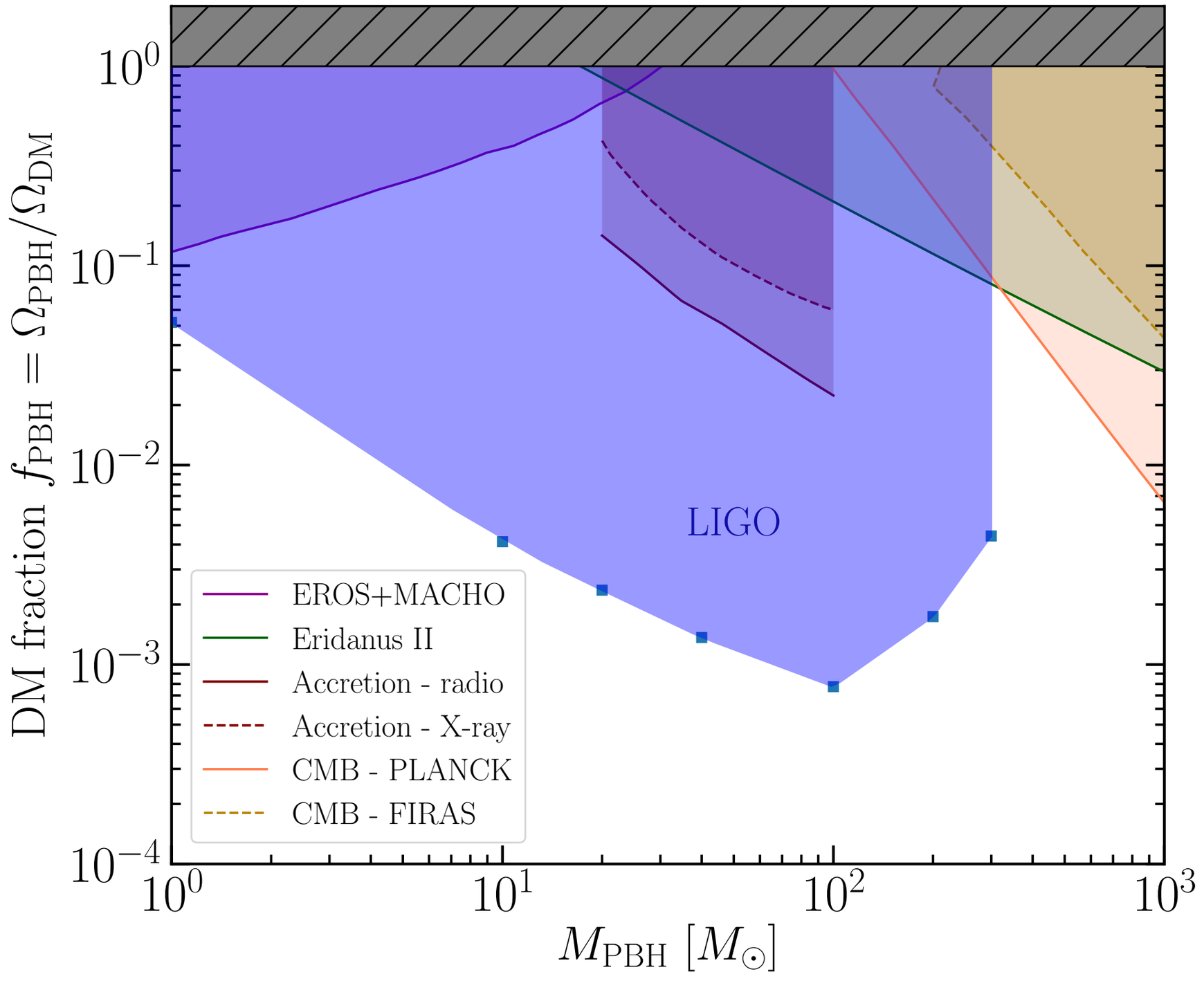
Merger time $t_{\rm merge} = \dfrac{3\,c^5}{170\,G_N^3}\,\dfrac{a^4 j^7}{M_{\rm PBH}^3}$ is almost conserved: $t_f = \sqrt{\dfrac{a_i}{a_f}}\,t_i$



LIGO merger rate estimate after GW150914

Limits from LIGO

[**BJK**, Gaggero & Bertone, 1805.09034]
[LIGO/Virgo, 1904.08976]



But what if we discover primordial black holes?

Detection prospects

[See also 2007.00021]

GW detection of sub-solar mass BHs

(LIGO O3, now!)

GW detection of high redshift BHs (z > 40)

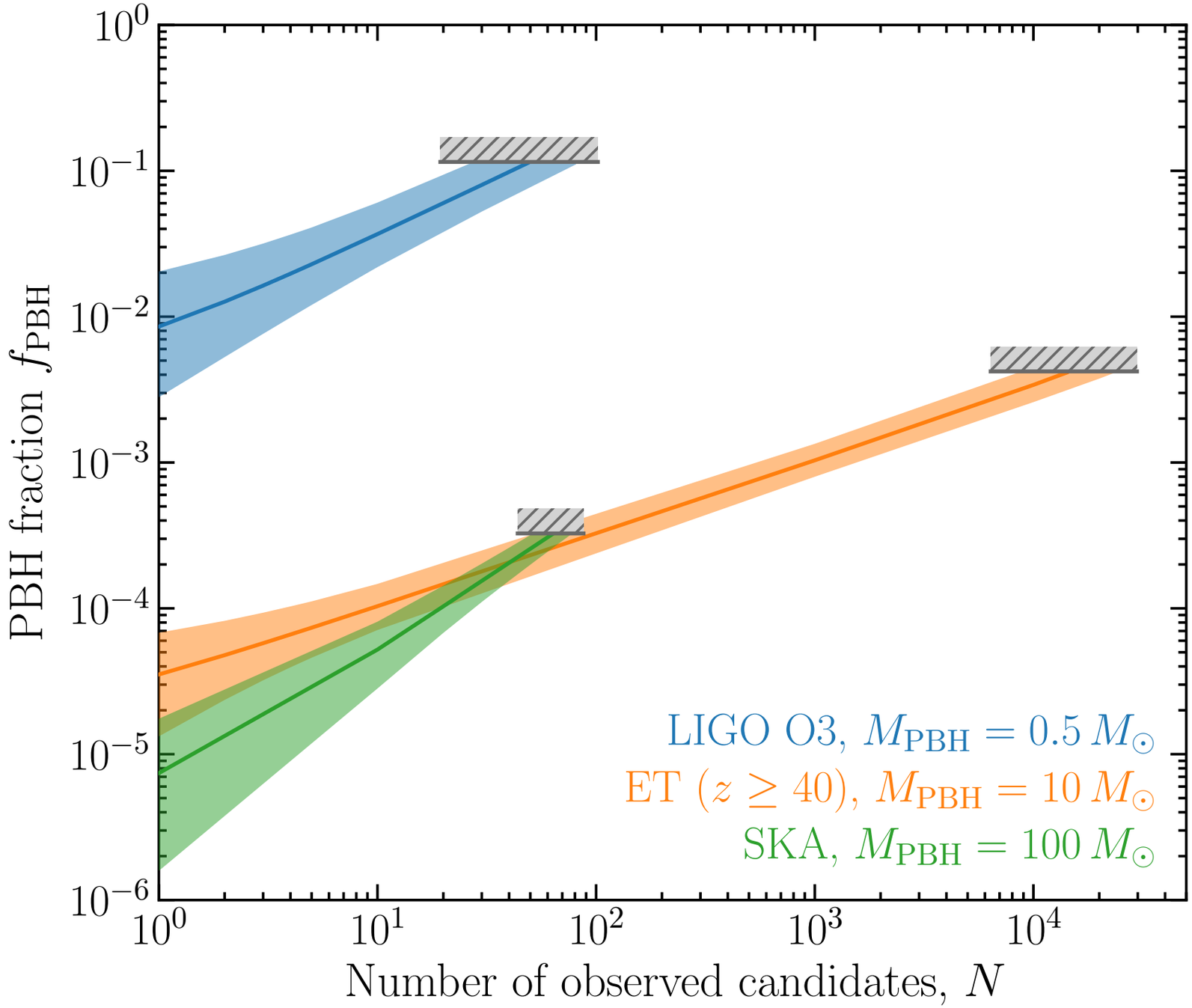
(Einstein Telescope, mid-late 2020s)

[1708.07380]

Radio detection of accreting galactic PBHs

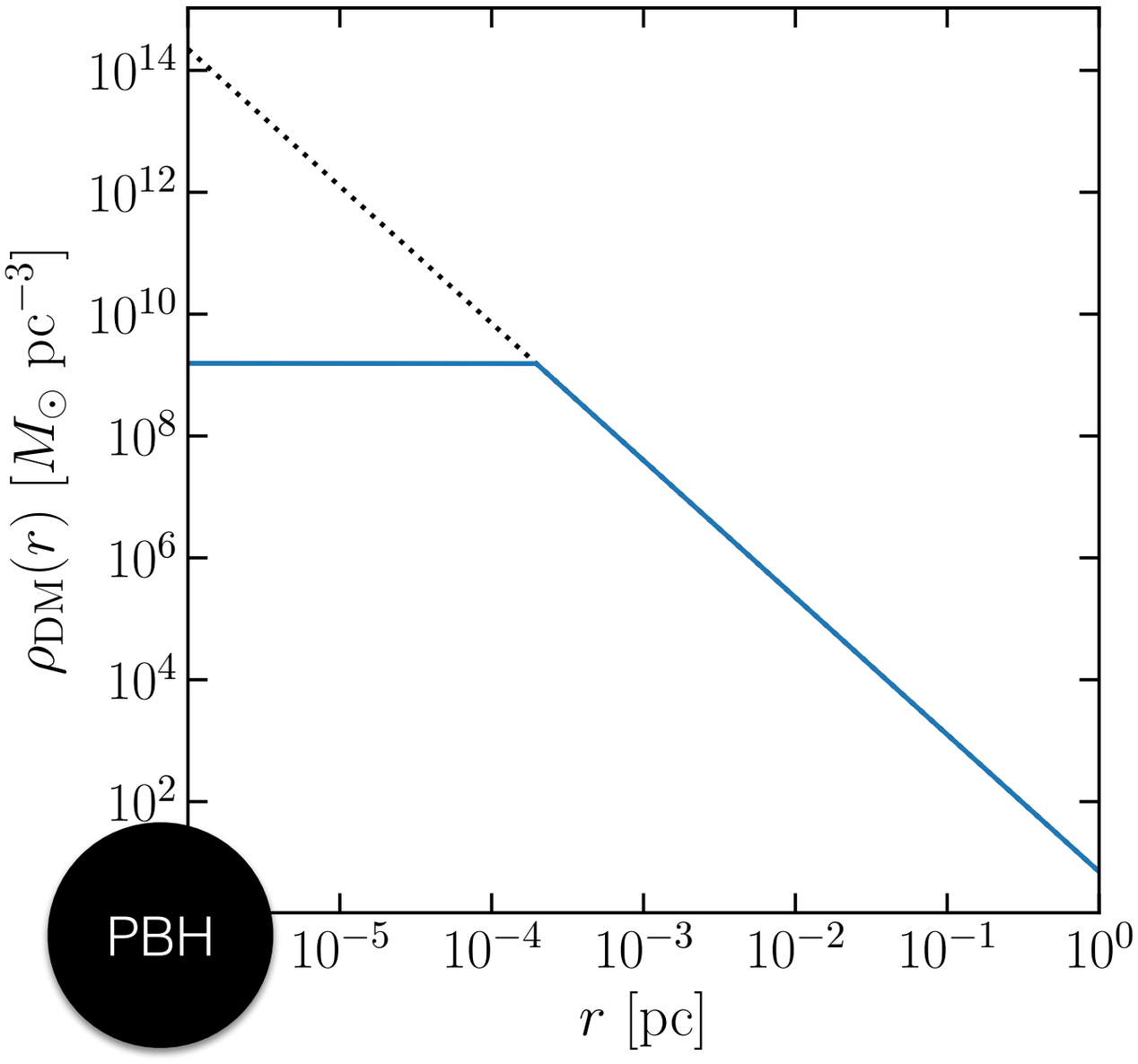
(Square Kilometre Array, late 2020s)

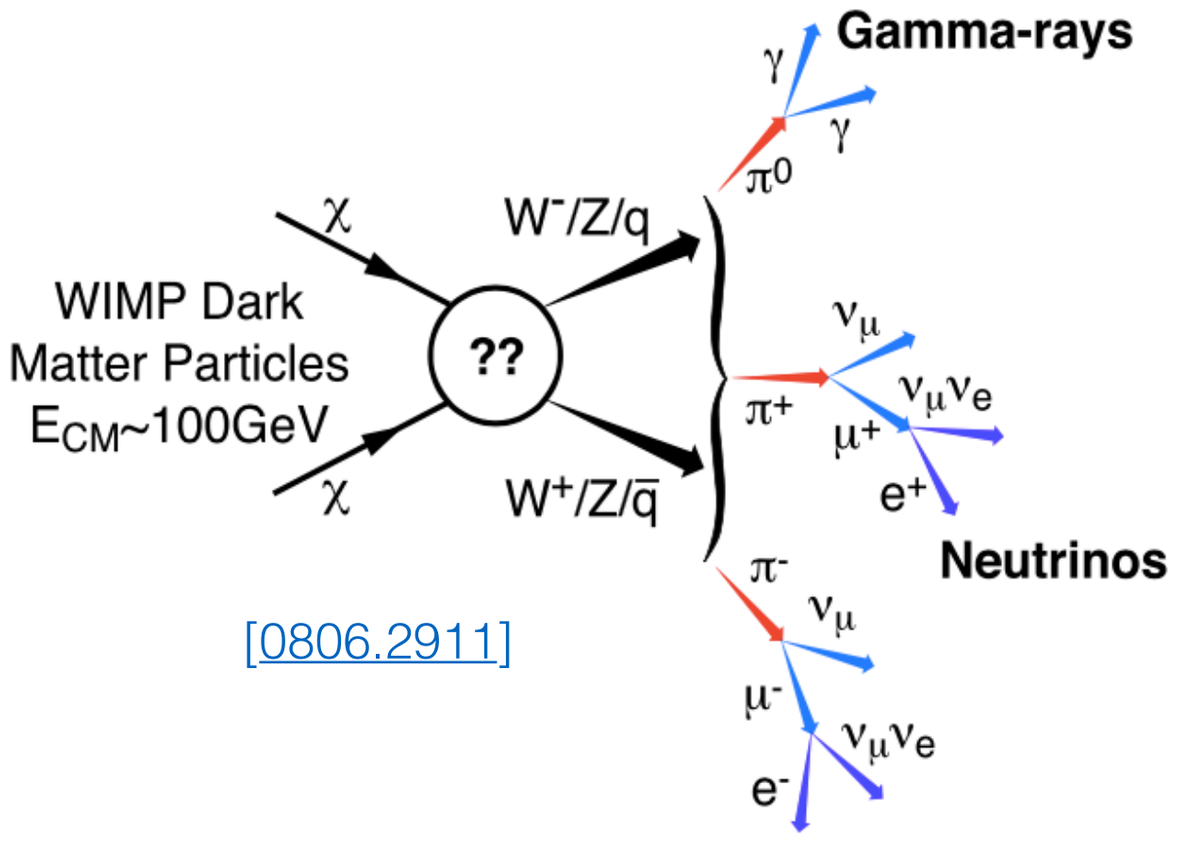
[1812.07967]



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

DM annihilation





[0806.2911]

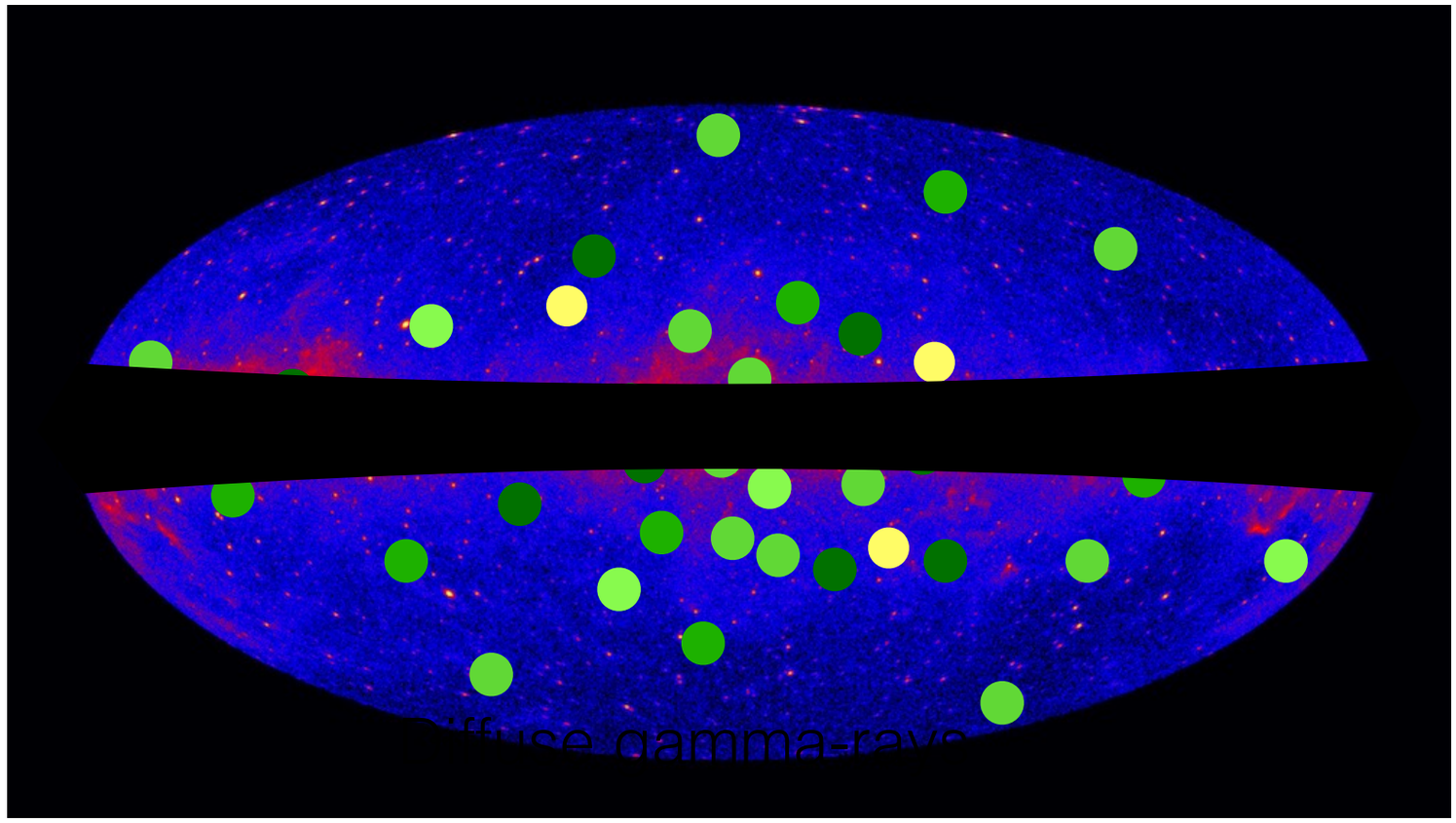
$$\Gamma \propto \rho_\chi^2 \, (\sigma v)_0 \, f_\chi^{4/3}$$

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

Gamma-ray constraints

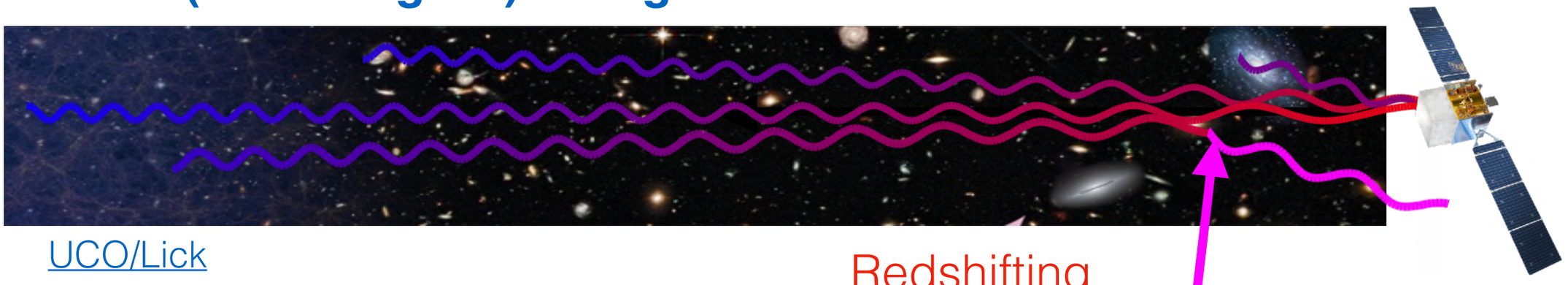
[Credit: Adam Coogan]

Point Sources in the Milky Way:



Fermi/NASA

Diffuse (cosmological) background:

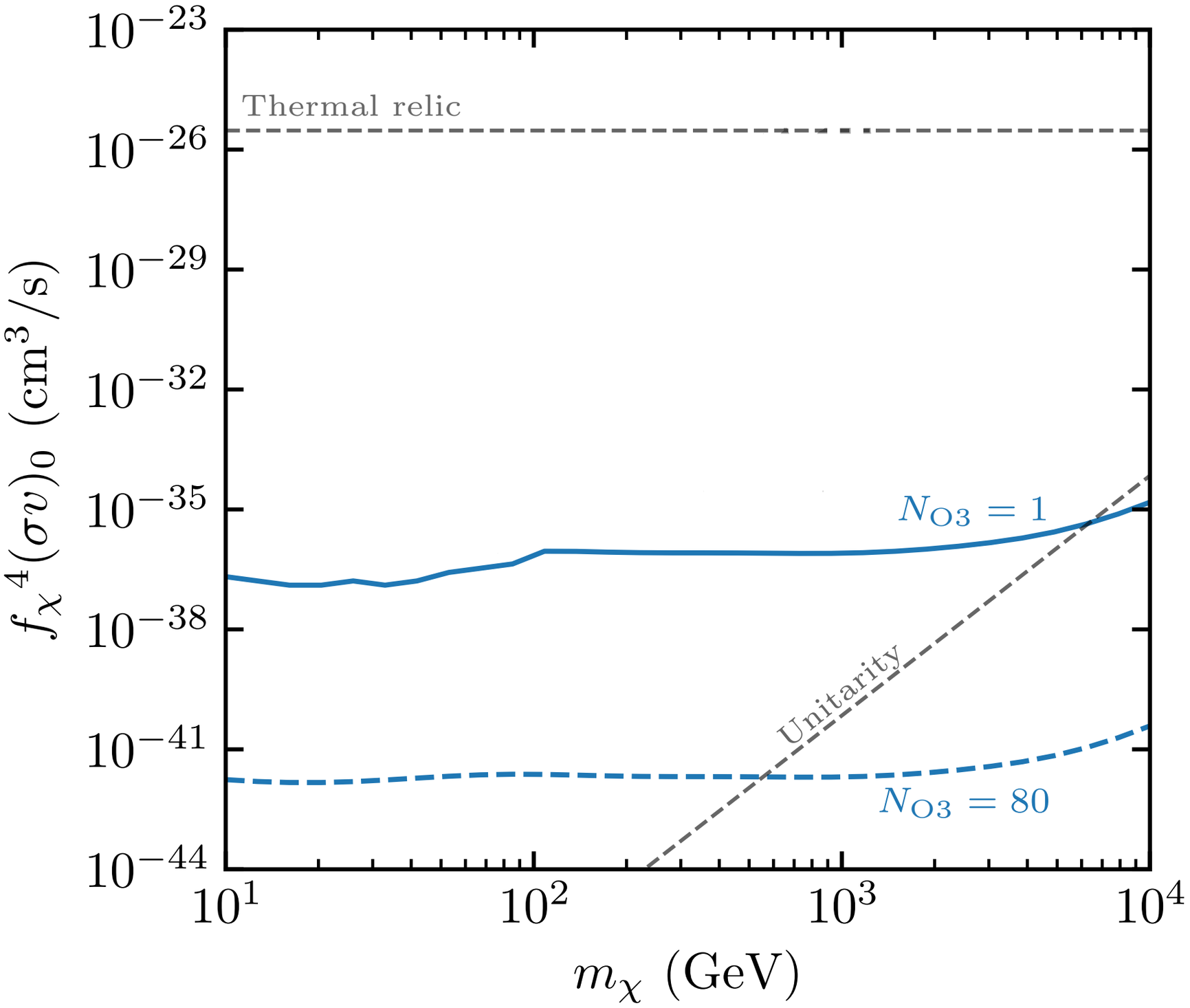


UCO/Lick

Gamma rays from DM ann.

Cross section constraints

[See also - 1003.3466, 1901.08528]



GW detection of sub-solar mass BHs

(LIGO O3, now!)

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

Werewolves

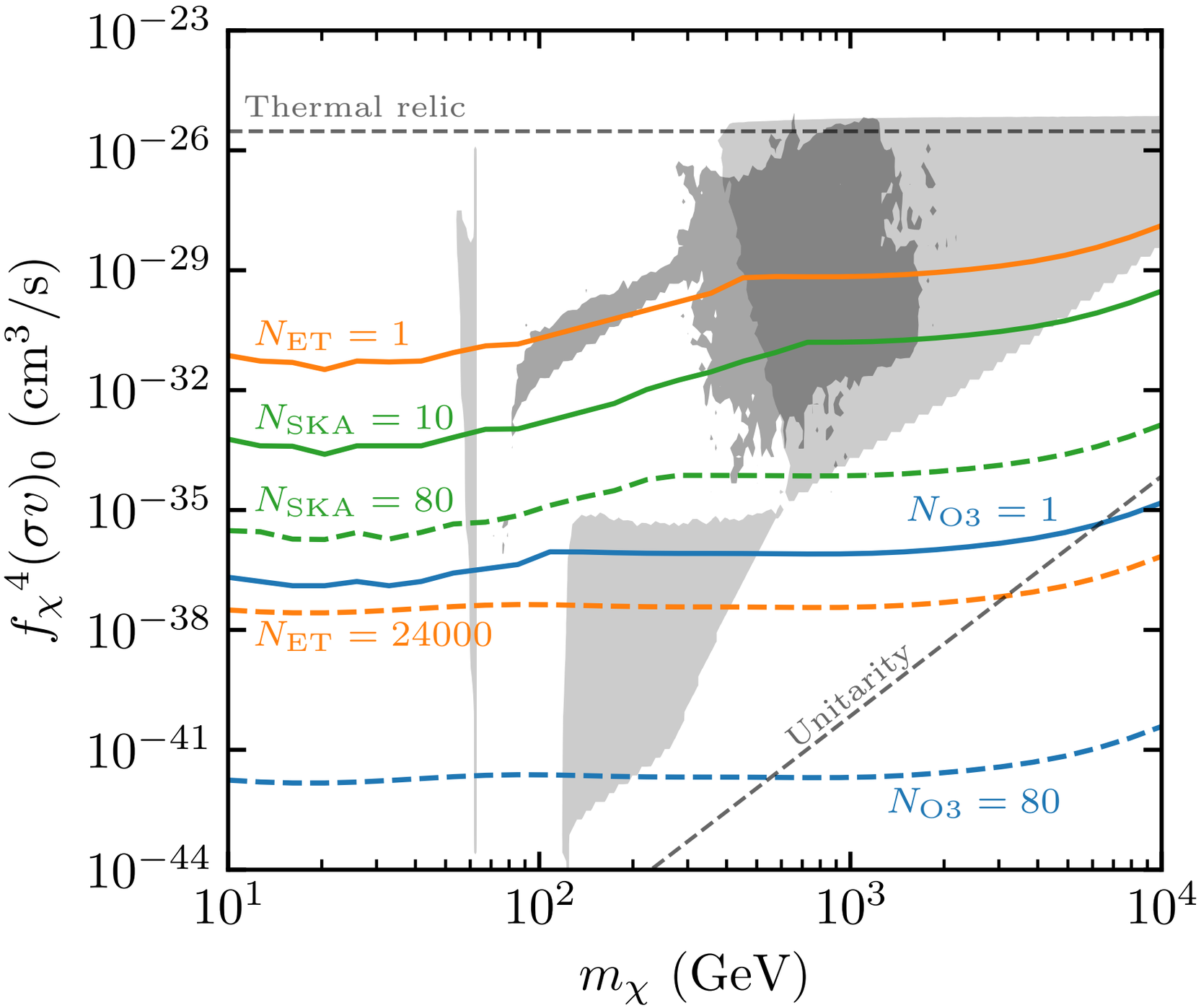
Werewolves: humans with the ability to shapeshift into a wolf, which are notoriously hard to kill

aaronsimscompany

Can be killed with **Silver Bullets**

Silver Bullets

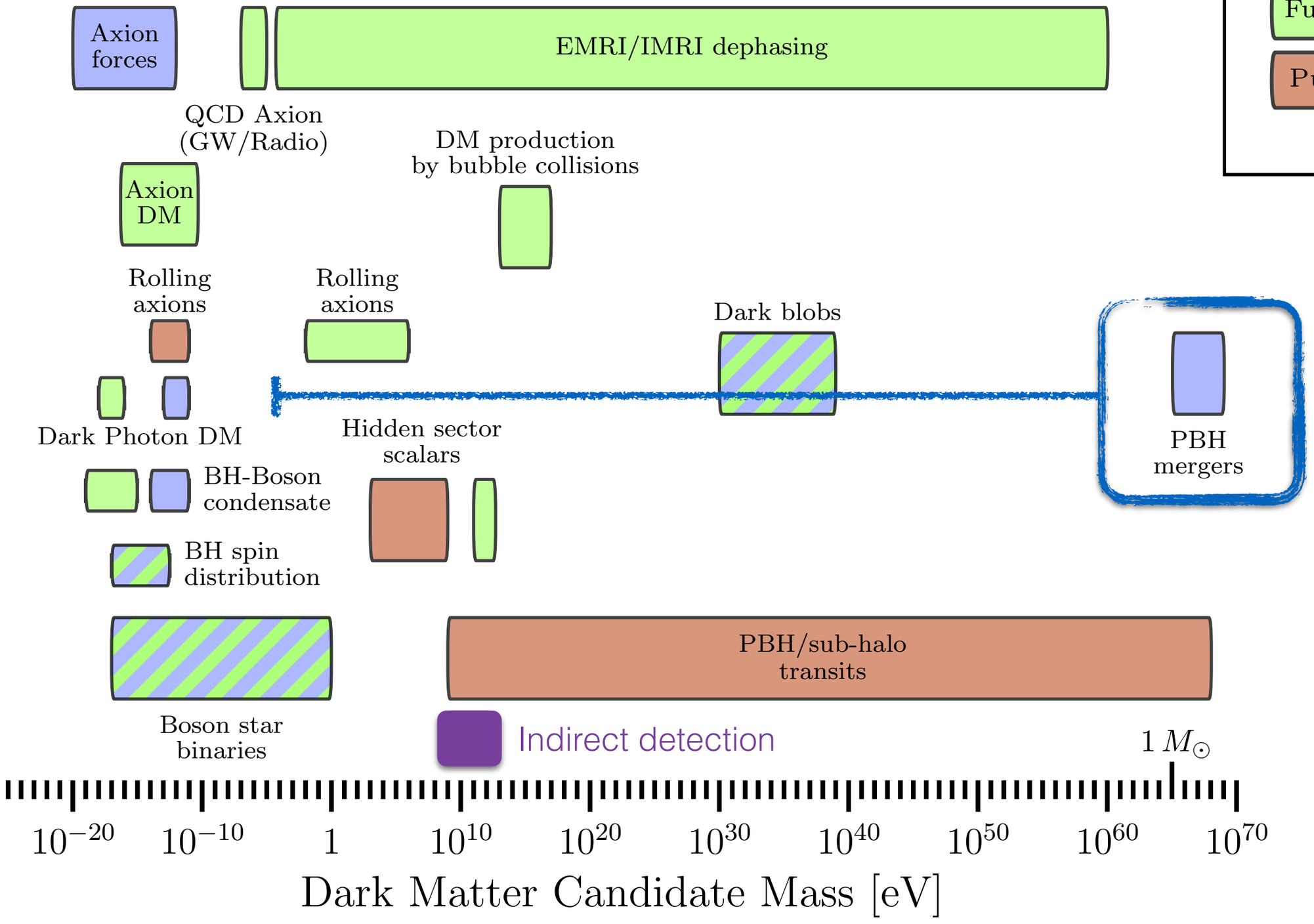
WIMPs: Weakly Interacting Massive Particles, which are notoriously hard to kill



*Primordial Black Holes as '**Silver Bullets**' for New Physics at the Weak Scale*

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

GW probes of DM



Current Interferometers

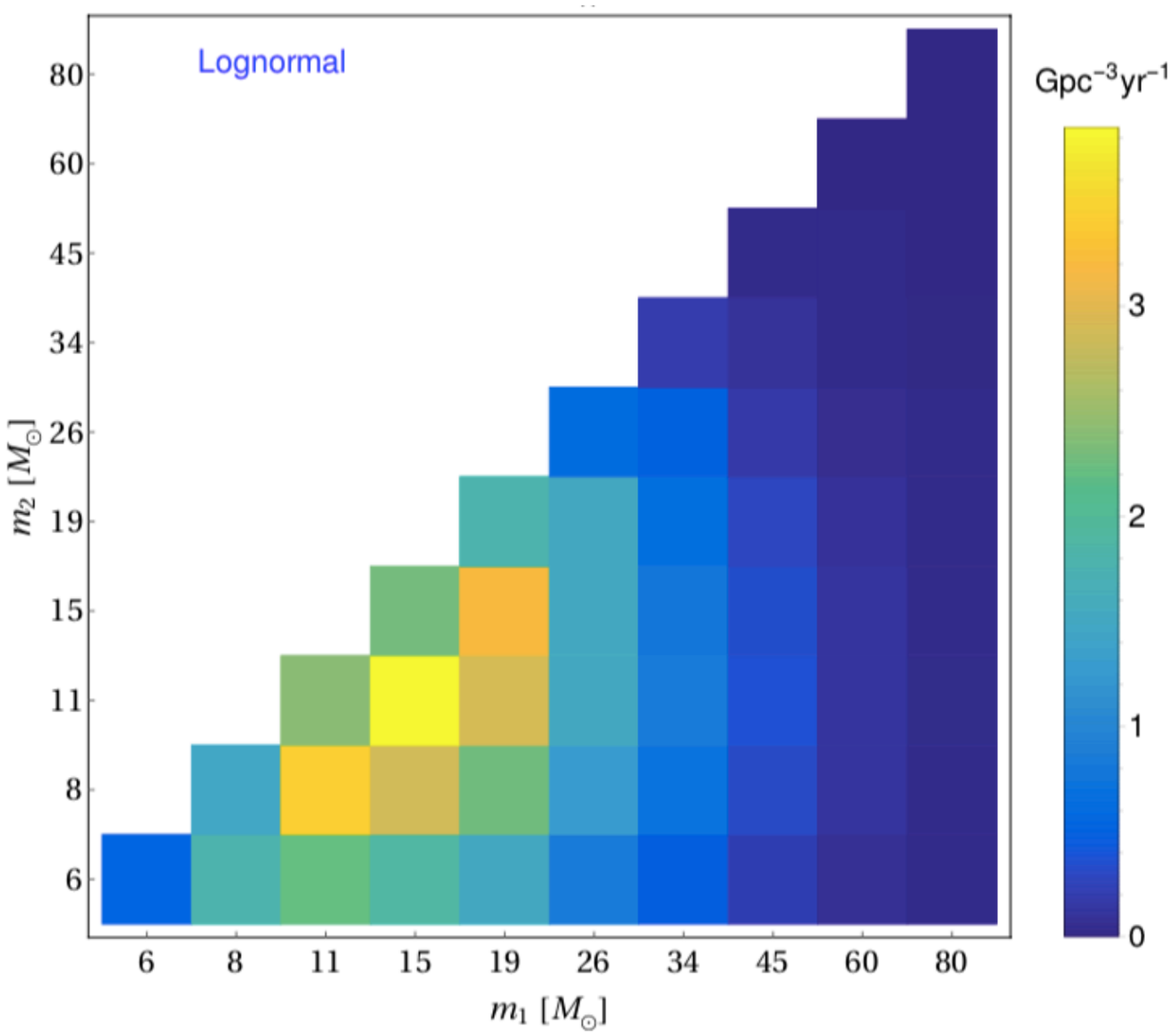
Future Interferometers

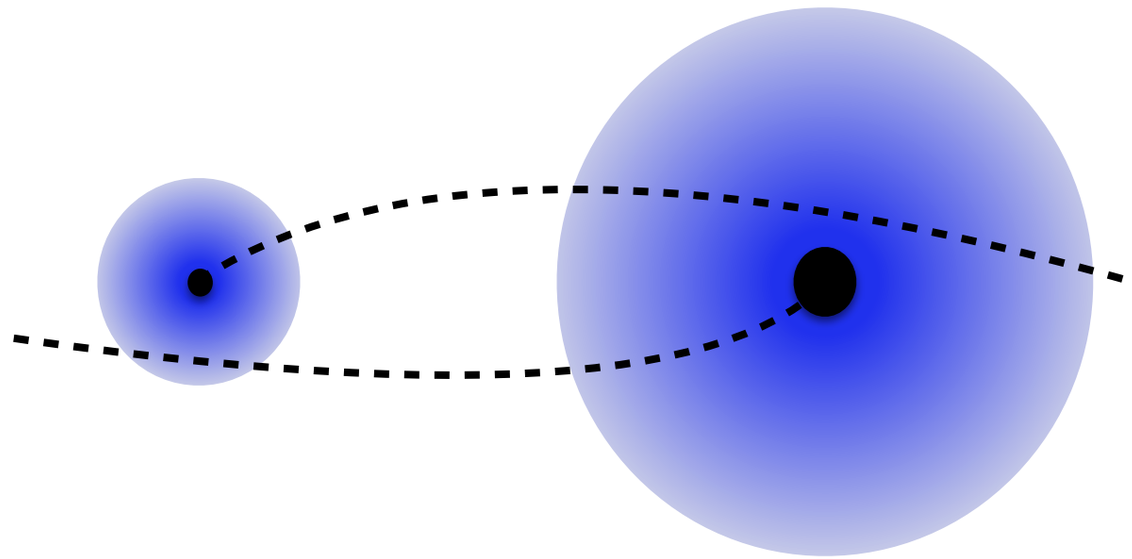
Pulsar Timing Arrays

[Bertone, Croon, Amin, Boddy, **BJK**, Mack, Natarajan, Opferkuch, Schutz, Takhistov, Weniger, Yu, SciPost Phys. Core 3, 007 (2020), 1907.10610]

What next?

Extending the ‘Dark Dress’ formalism to extended mass functions:

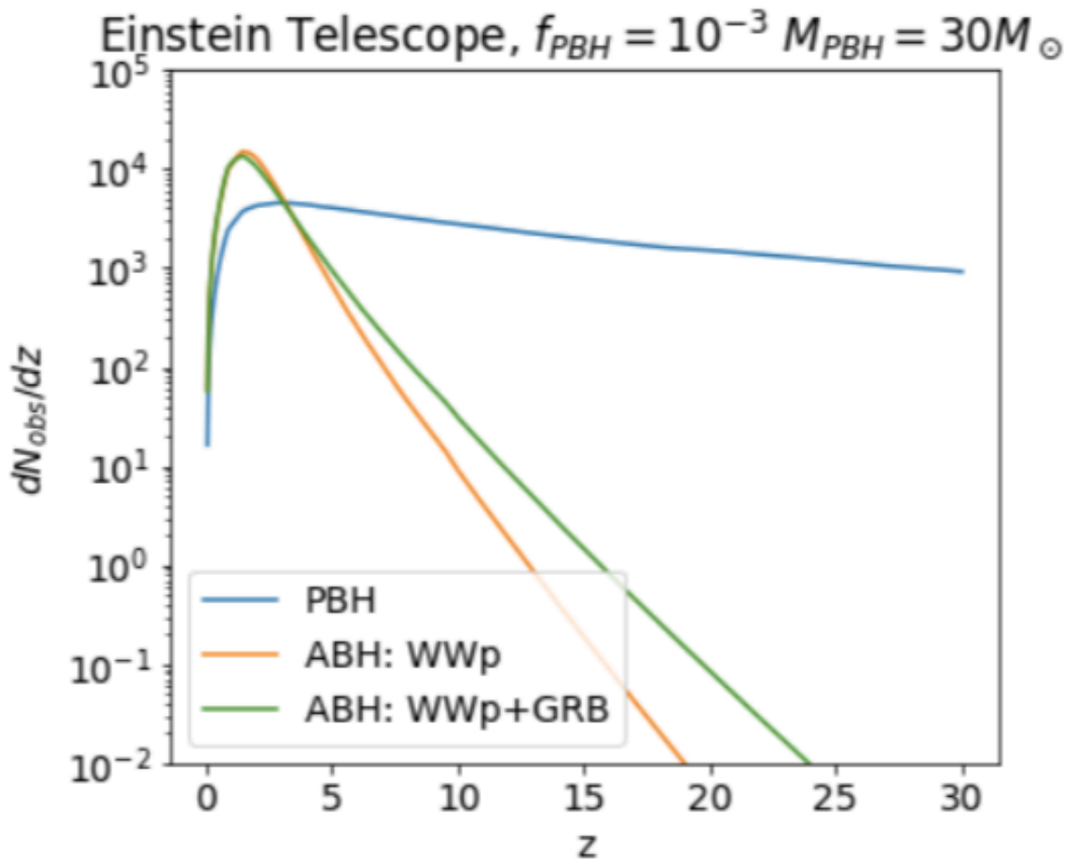


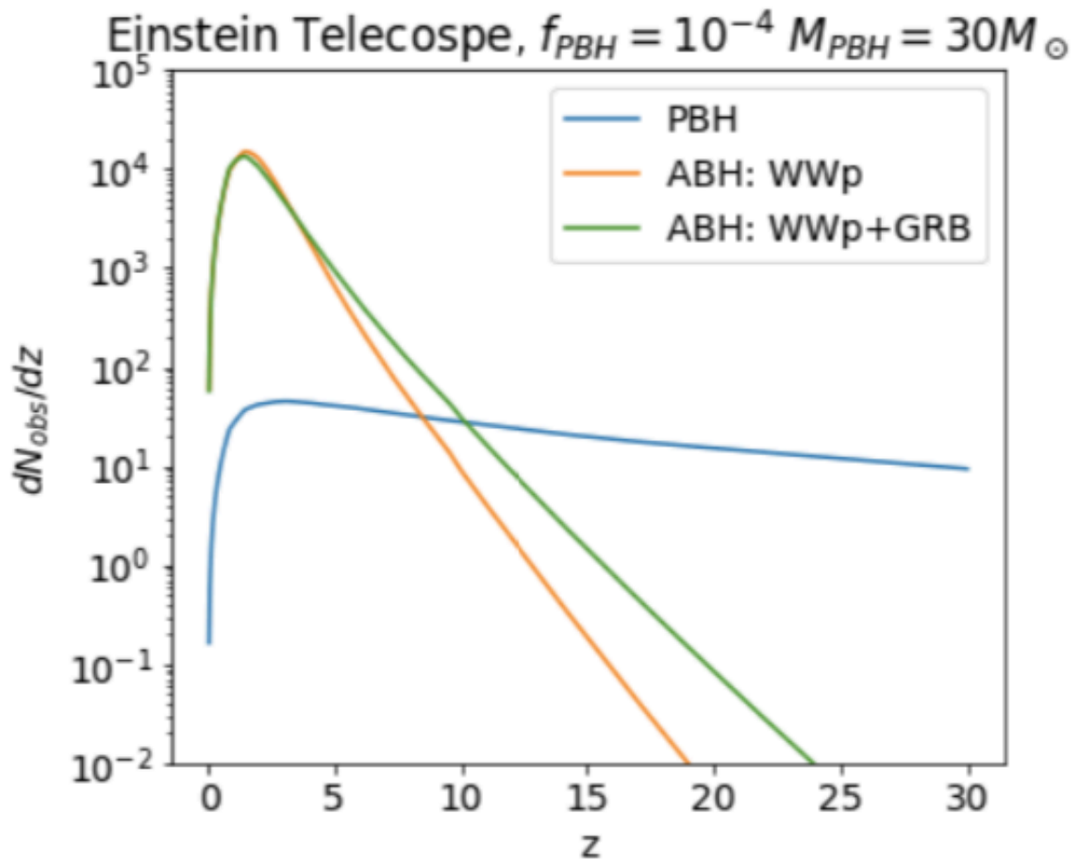


[In collaboration with Pratibha Jangra]

What next?

Distinguishing a population of PBH mergers from astrophysical BHs using their cosmic merger history…

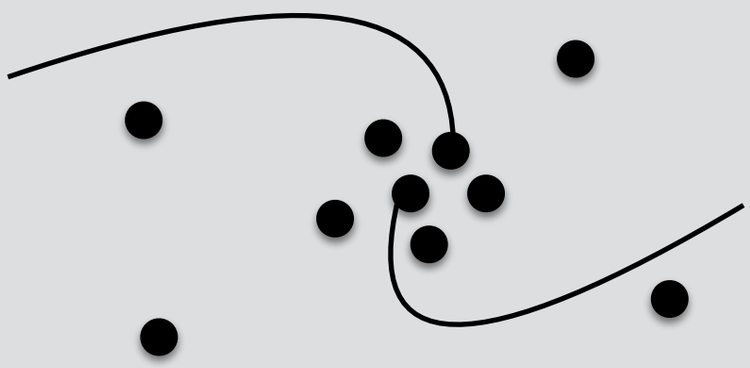




[In collaboration with Tania Muñoz, Francesca Scarcella & Daniele Gaggero]

Can we also look at the stochastic background of mergers to help distinguish?

[See also 1705.09182, 1904.02396, 2008.13704]



The ever-changing field of PBH mergers…*

*Does not cover controversy over choices of metric…
[Boehm et al., 2008.10743; De Luca et al., 2009.04731]

Clustering of PBHs

Even a distribution of PBHs which is initially Poisson distributed will cluster at late times

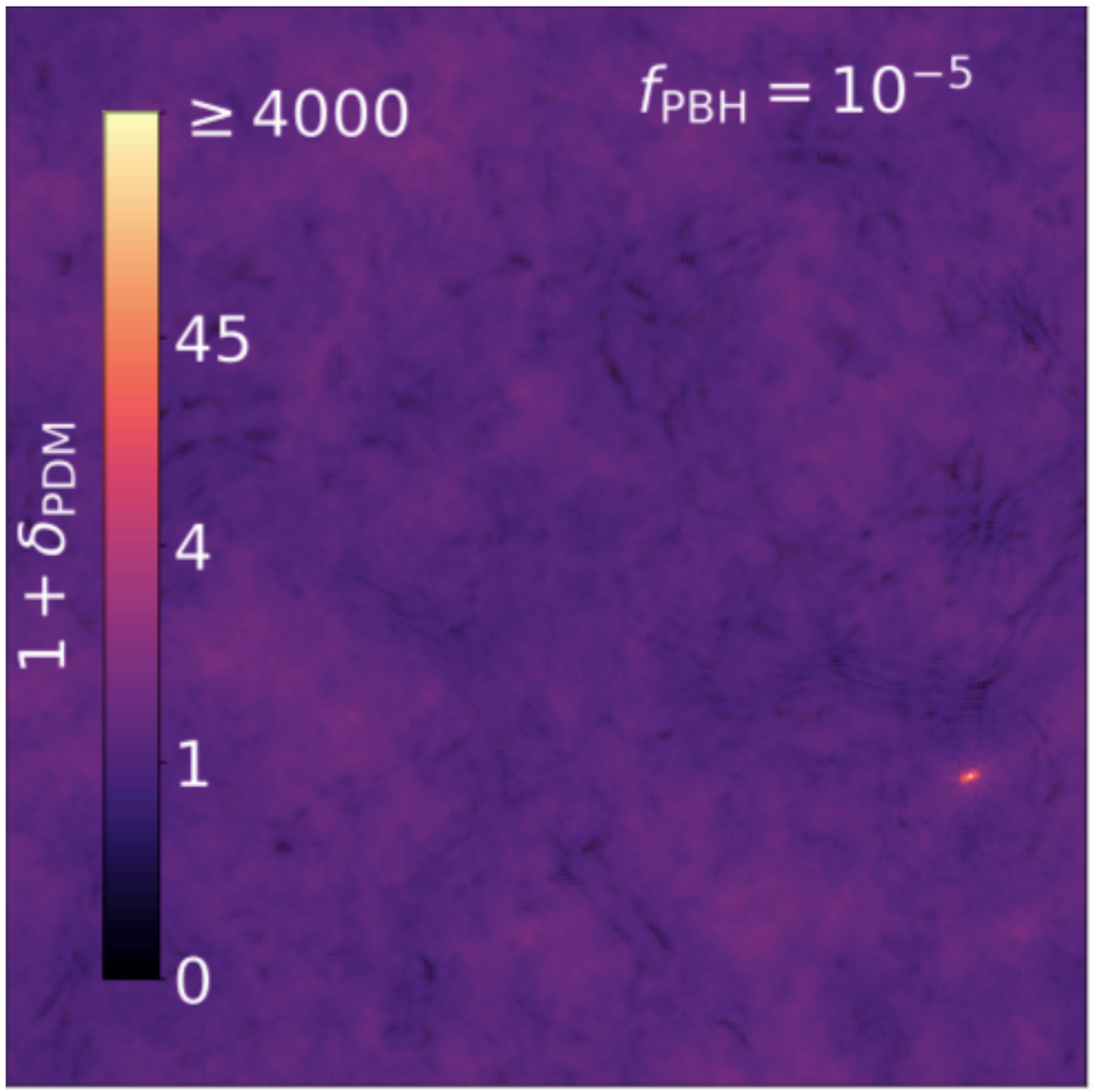
$z \gg 10^4$ $z \lesssim 100$

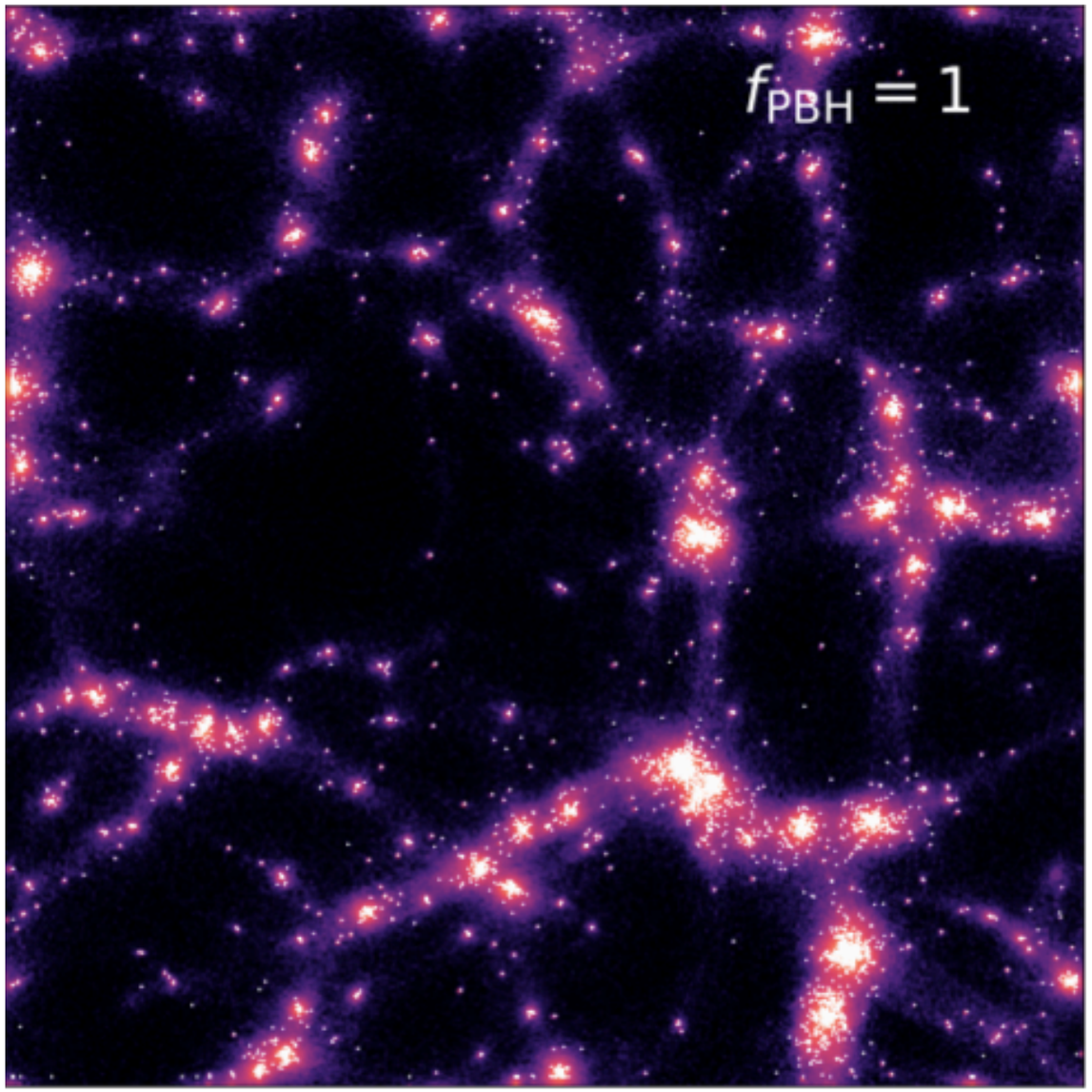
A cluster of N PBHs is expected to form around $z_c \sim z_{\rm eq} f_{\rm PBH}/\sqrt{N}$

[Chisholm - astro-ph/0509141, 1110.4402]

ΛPBH Cosmology

Simulate PBHs + Particle DM down to z ~ 99…



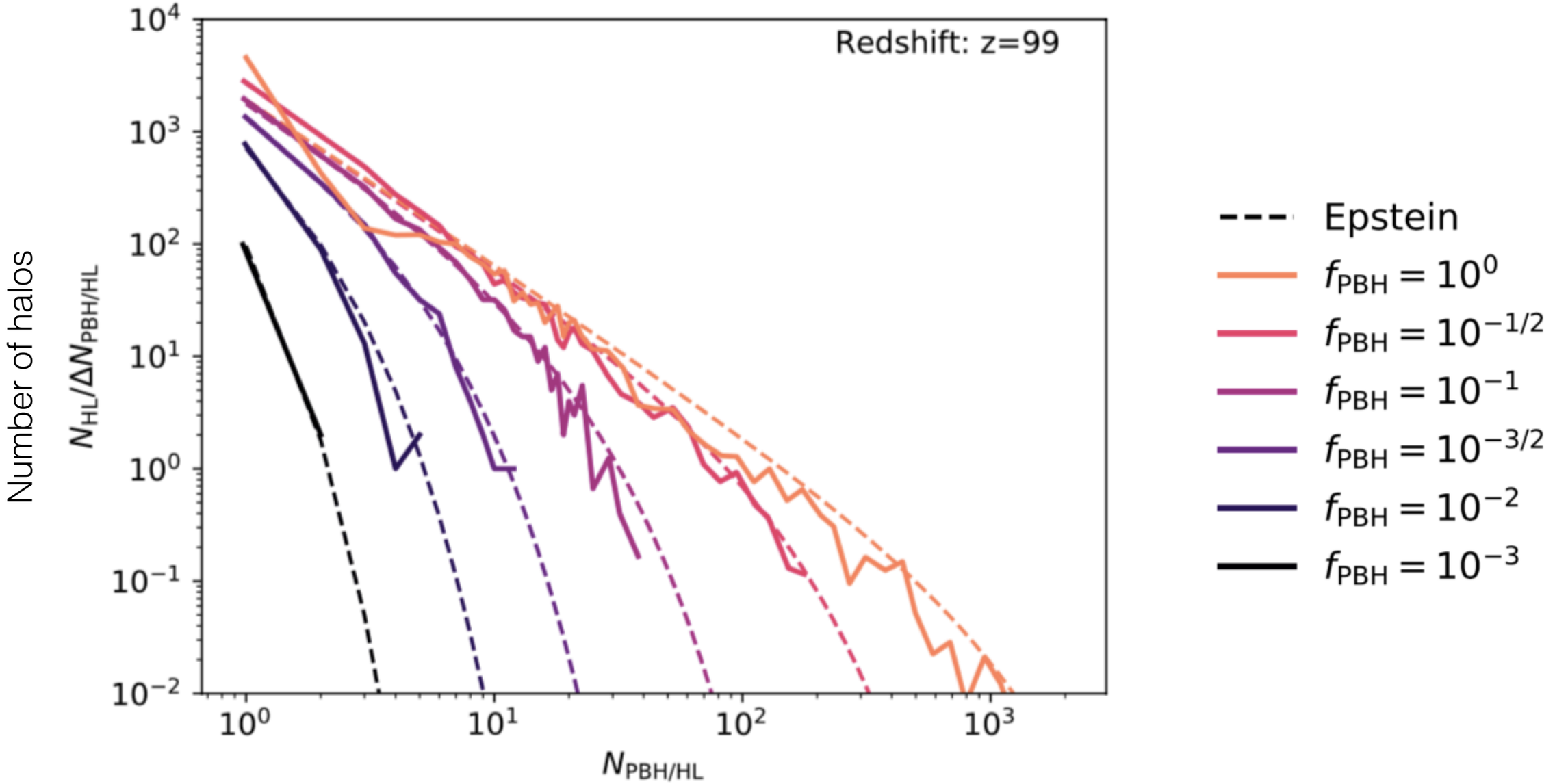


[Inman & Ali-Haïmoud, 1907.08129]

ΛPBH Cosmology

$$N_{\rm HL}(N) \propto \frac{\delta_*}{\sqrt{2\pi}N^{3/2}} {\rm e}^{-N/N_*}$$

$$N_* \equiv \left(\log\left(1+\delta_*\right) - \frac{\delta_*}{1+\delta_*}\right)^{-1}$$



Note: PBH halos are expected to evaporate/collapse by late times…

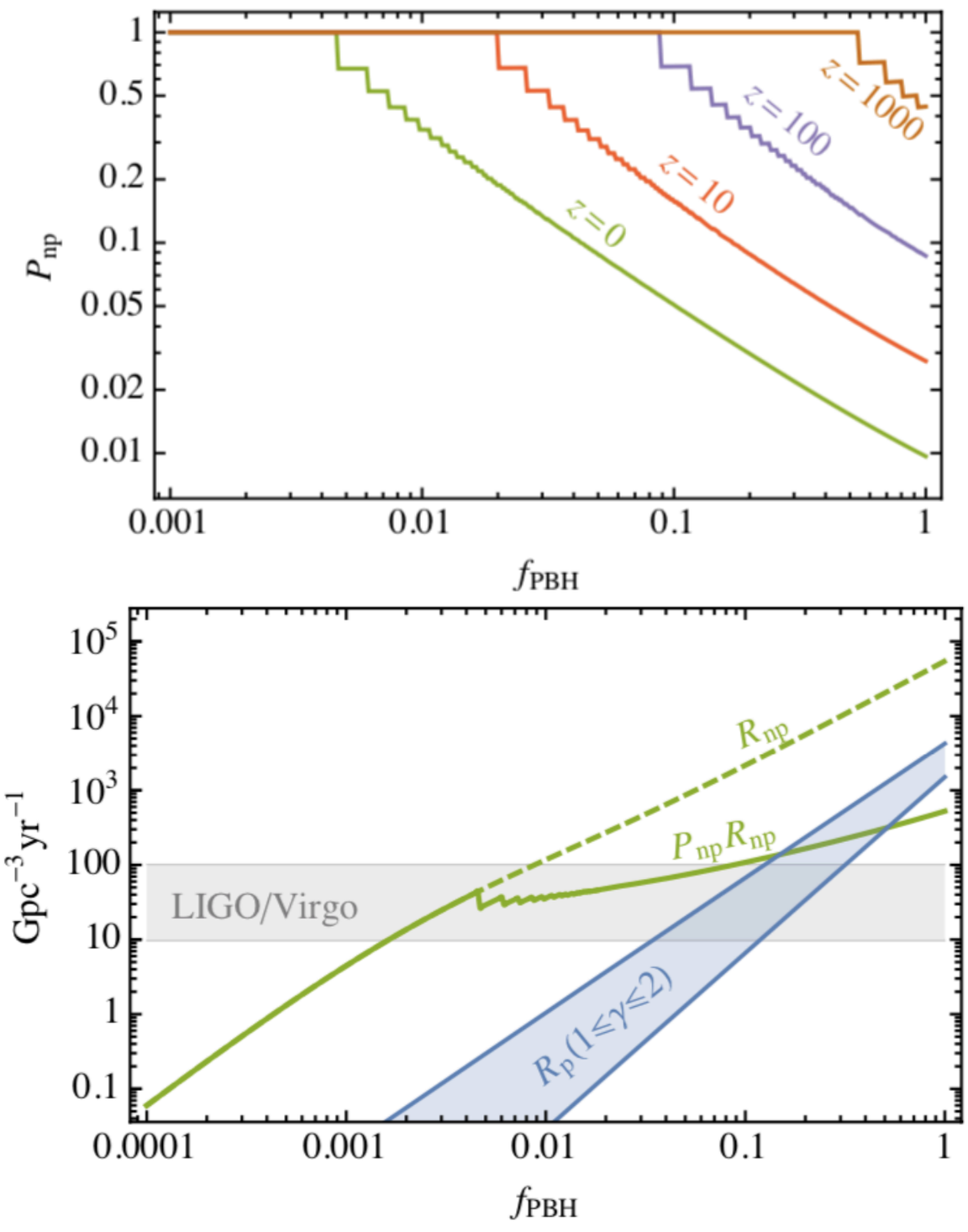
[Inman & Ali-Haïmoud, 1907.08129]

Disruption in clusters

[Raidal+ - 1812.01930]
[Vaskonen & Vermae - 1908.09752]

Dense clusters can lead to perturbations (and even disruption) of the binaries:

Estimate ‘survival probability’ P_{np} as fraction of binaries in clusters which have *not* collapsed by redshift z:

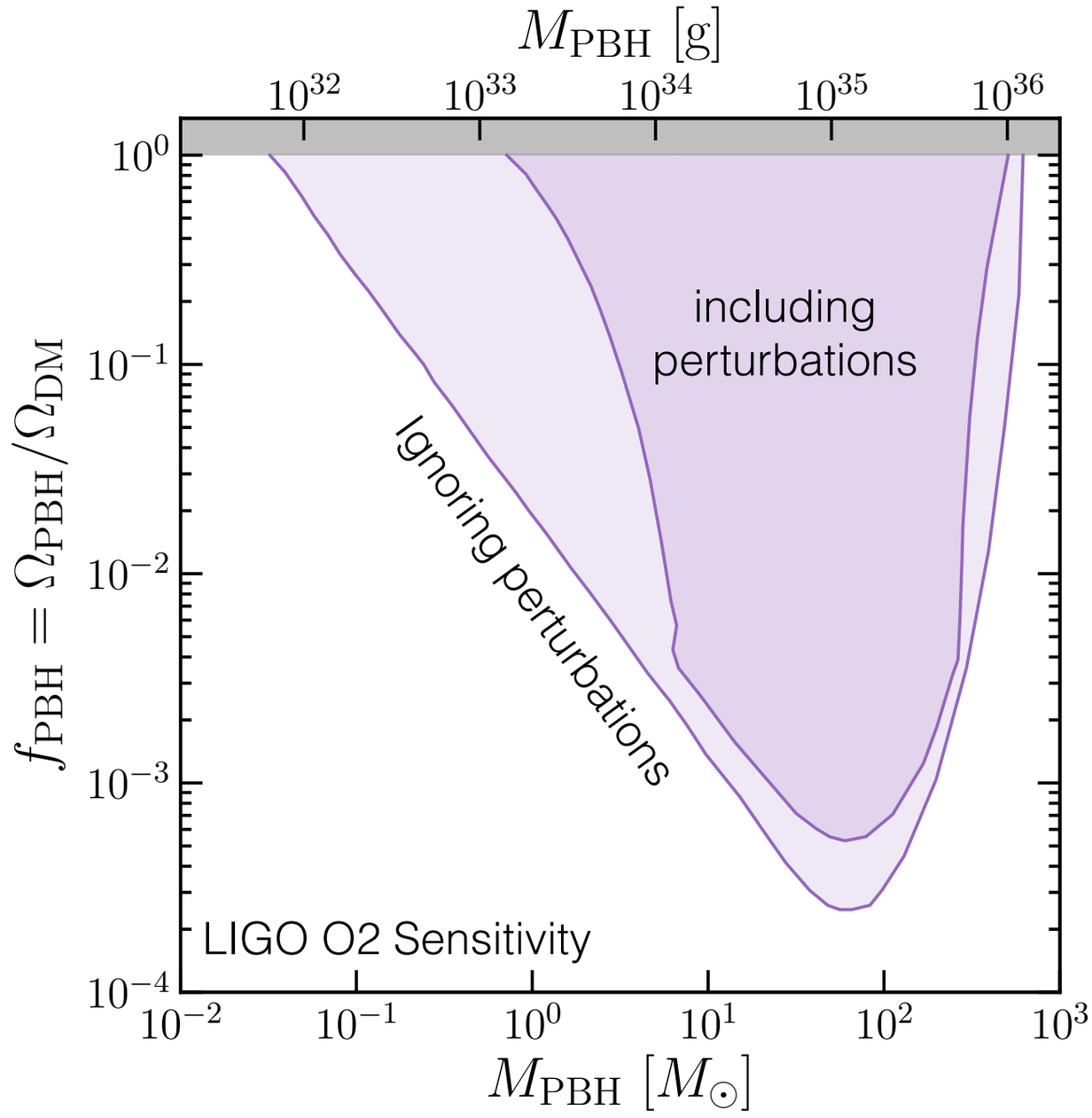


Apply this ‘suppression factor’ to obtain (conservative) merger rate of non-perturbed binaries:

Bounds with disruption

[Vaskonen & Vermae - 1908.09752]
[See also 2007.07212, 2009.04731]

Expect a correction to the bounds - though only at large f_{PBH}:

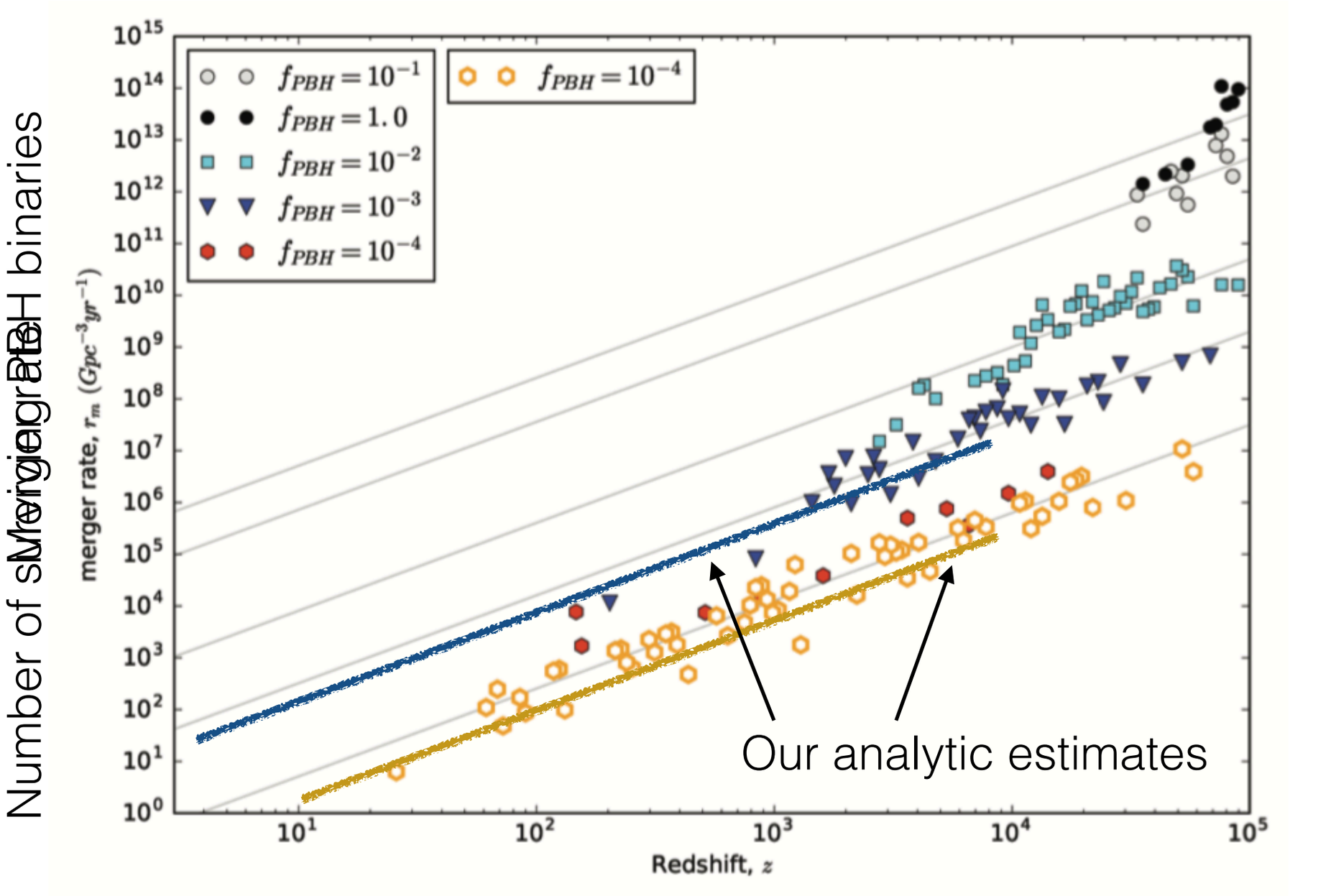


But it would be nice to test these conservative, analytic estimates…

Simulations (1)

[Tkachev, Pilipenko & Yepes - 2009.07813]

Cosmological PBH-only simulations,
using 10^4-10^6 PBHs, *with ad-hoc GW emission*

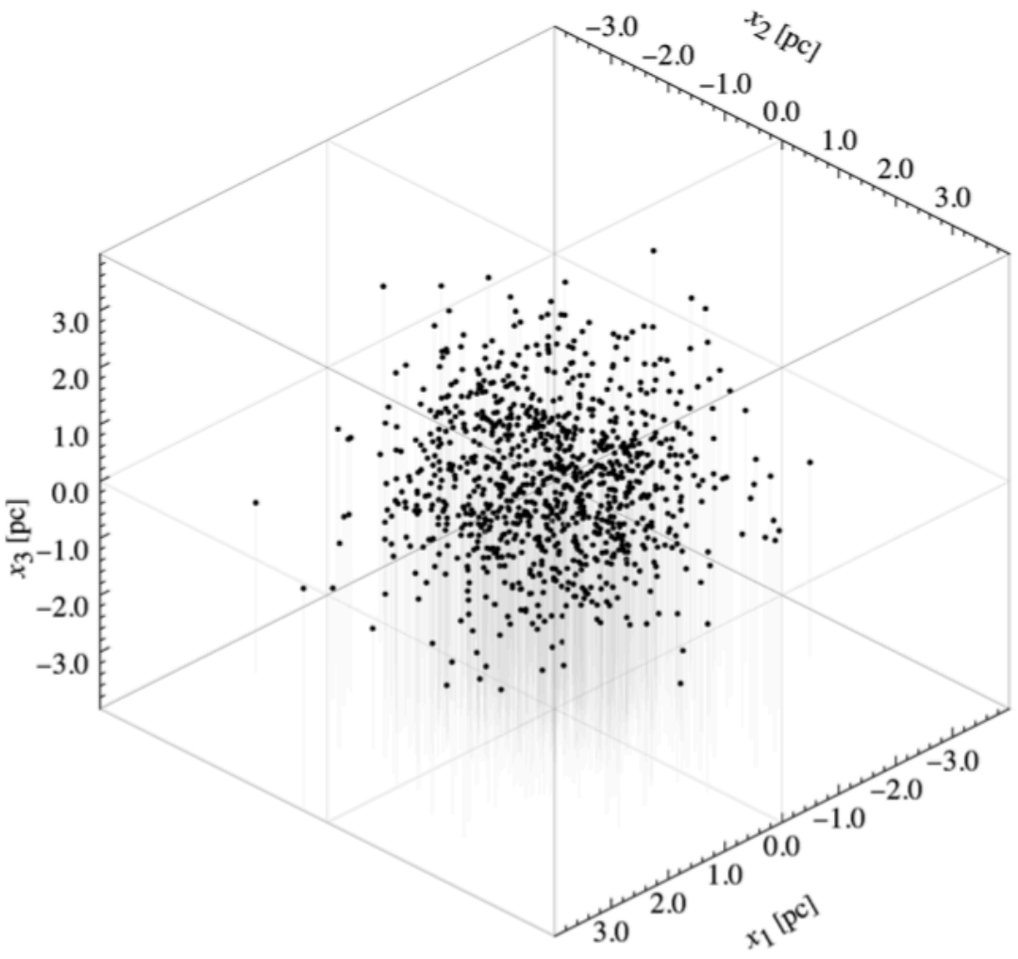


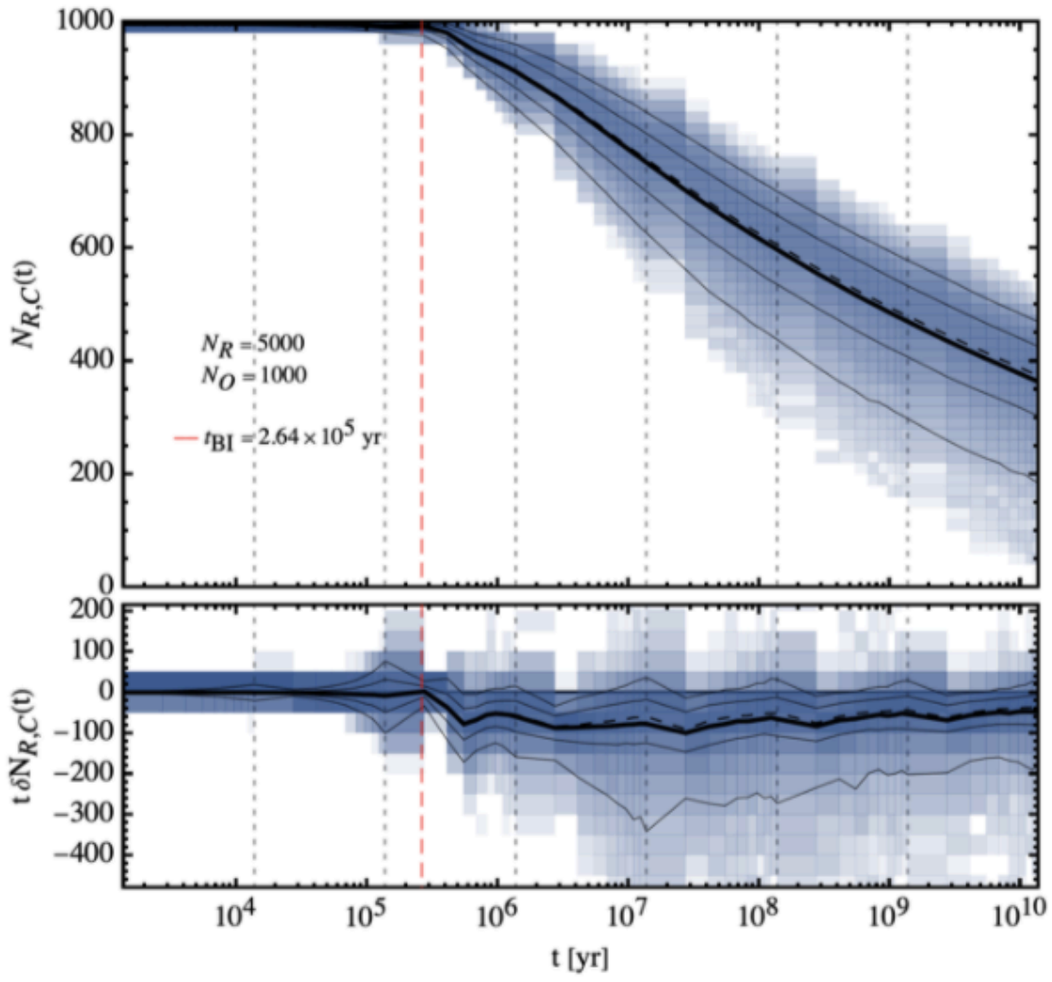
Although these simulations can't yet resolve mergers down to z ~ 0…

Simulations (2)

[Trashorras, García-Bellido & Nesseris, 2006.15018]

Assuming that PBHs form clusters at early times,
simulate many *isolated* N_{PBH} = 1000 clusters, *without GW emission*





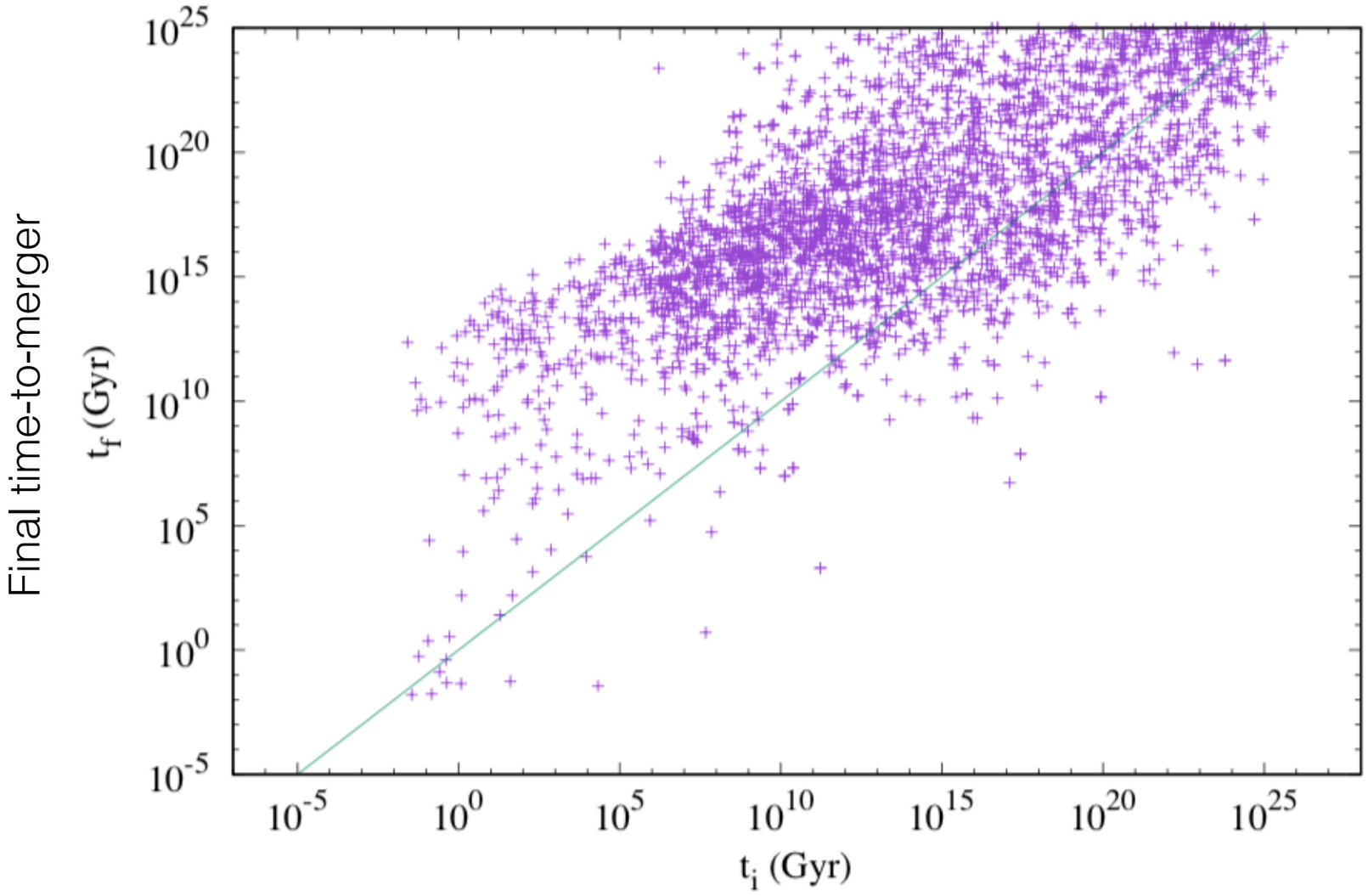
Assuming $f_{PBH} = 1$, estimate the merger rate to be: $\mathcal{R} = 1340 \pm 40\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$

(compare to LIGO observed rate of O(100) $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$)

Simulations (3)

[Jedamzik - 2006.11172, 2007.03565]

Sampling the effects of individual 3-body encounters in N = 1300 clusters, suggests that the *binary* merger rate today should be negligible

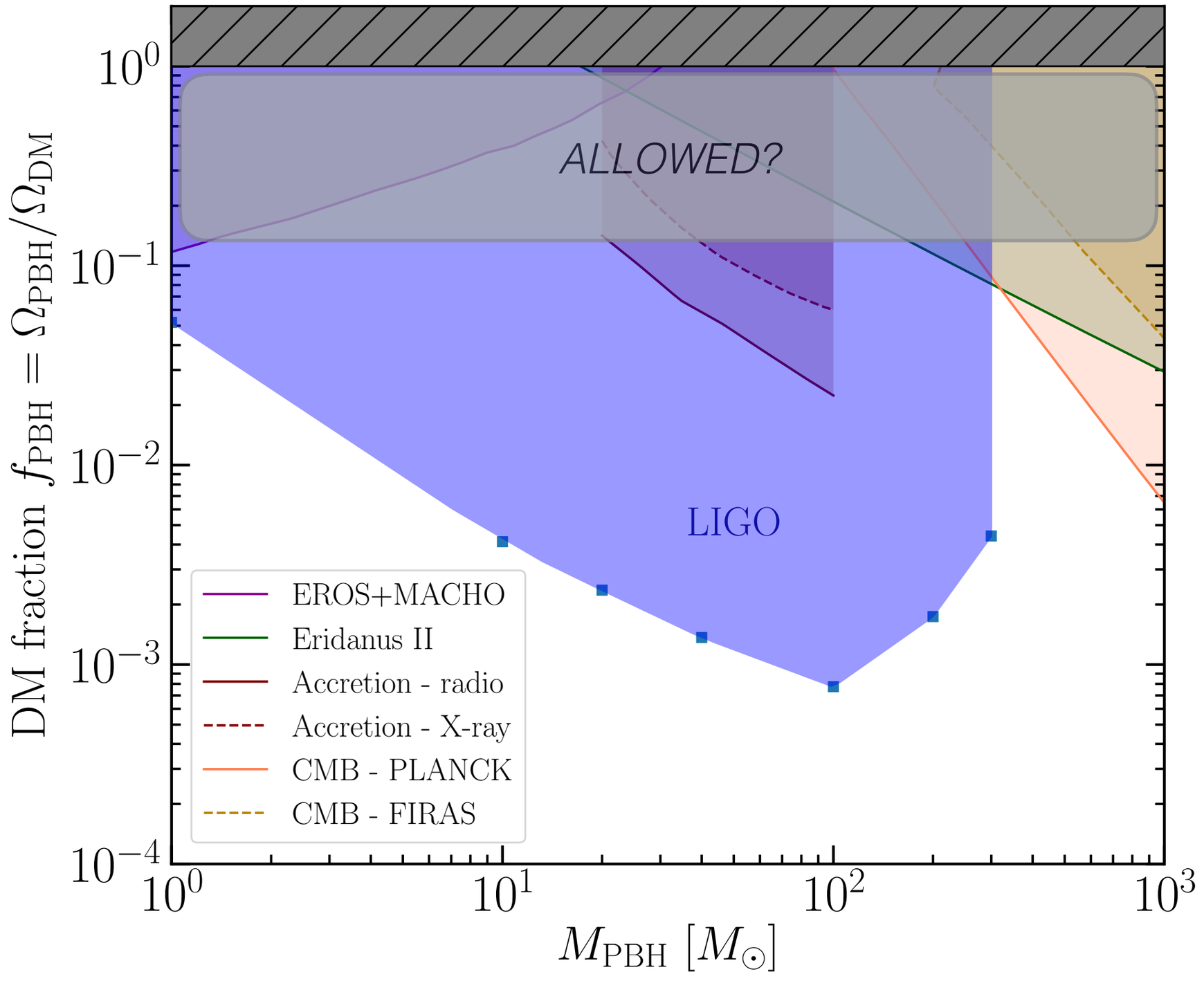


Initial time-to-merger

For f_{PBH} = 1, suggest rate dominated instead today by *direct* mergers!

$$\mathcal{R}_{\rm direct} \approx 108\,{\rm Gpc}^{-3}\,{\rm yr}^{-1}$$

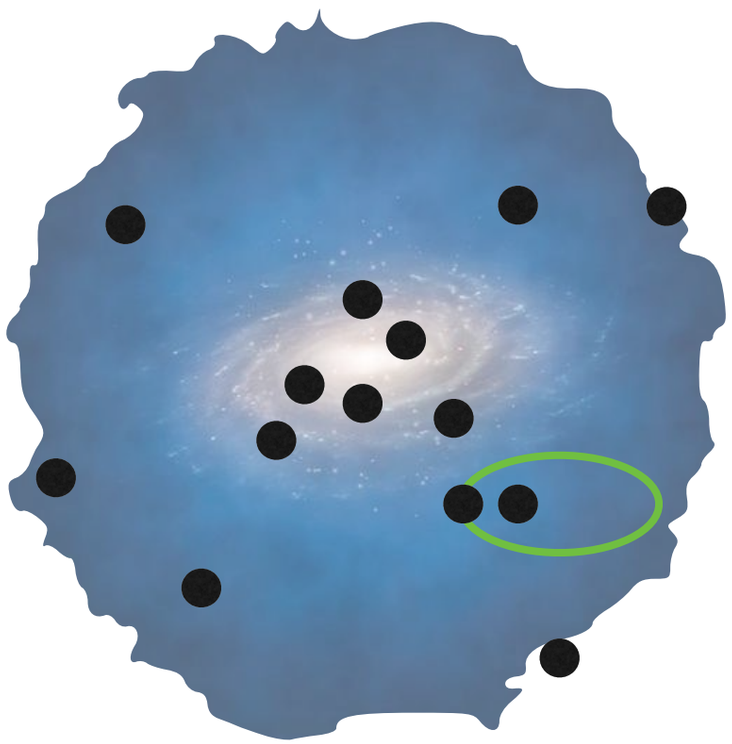
Complicated constraints?



The three ring circus

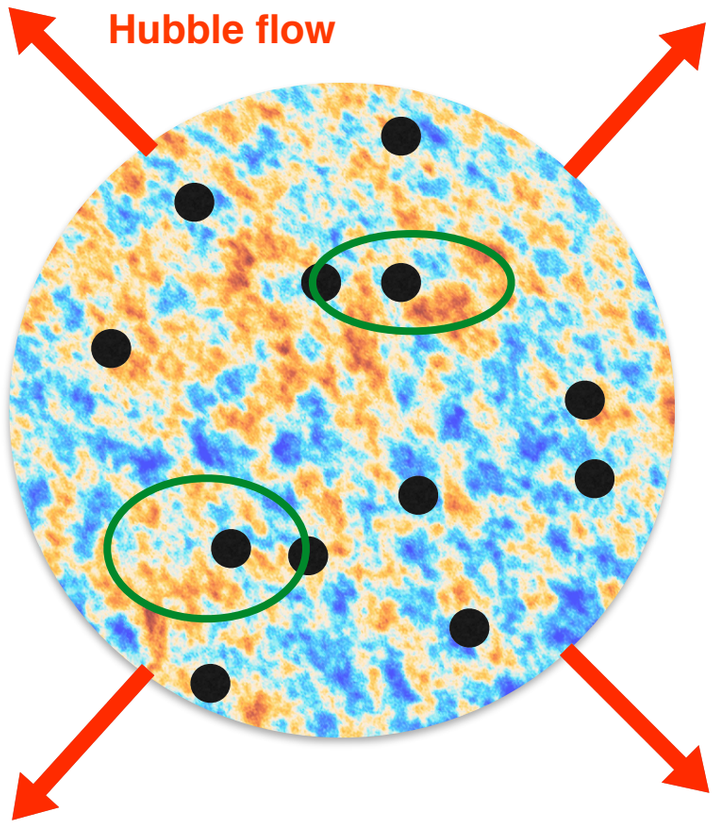
A) Binaries formed after close encounters

[Bird et al., 1603.00464]



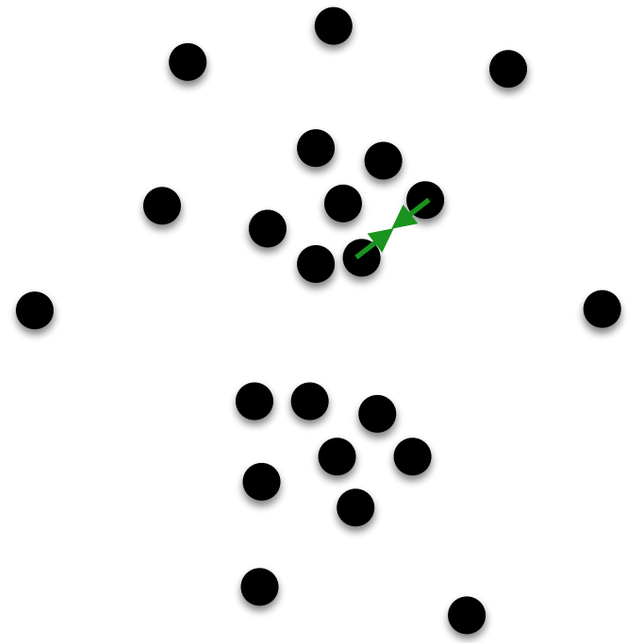
B) Binaries formed in the early Universe

[Sasaki et al, 1603.08338]



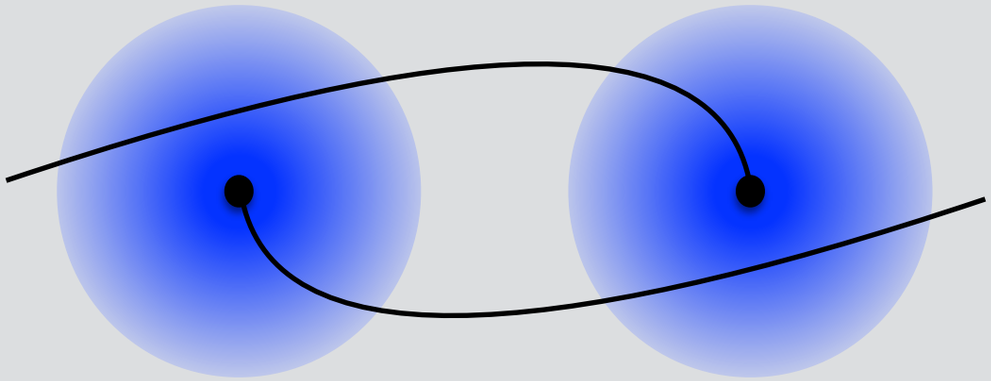
C) Direct mergers in late-time clusters

[Jedamzik, 2007.03565]



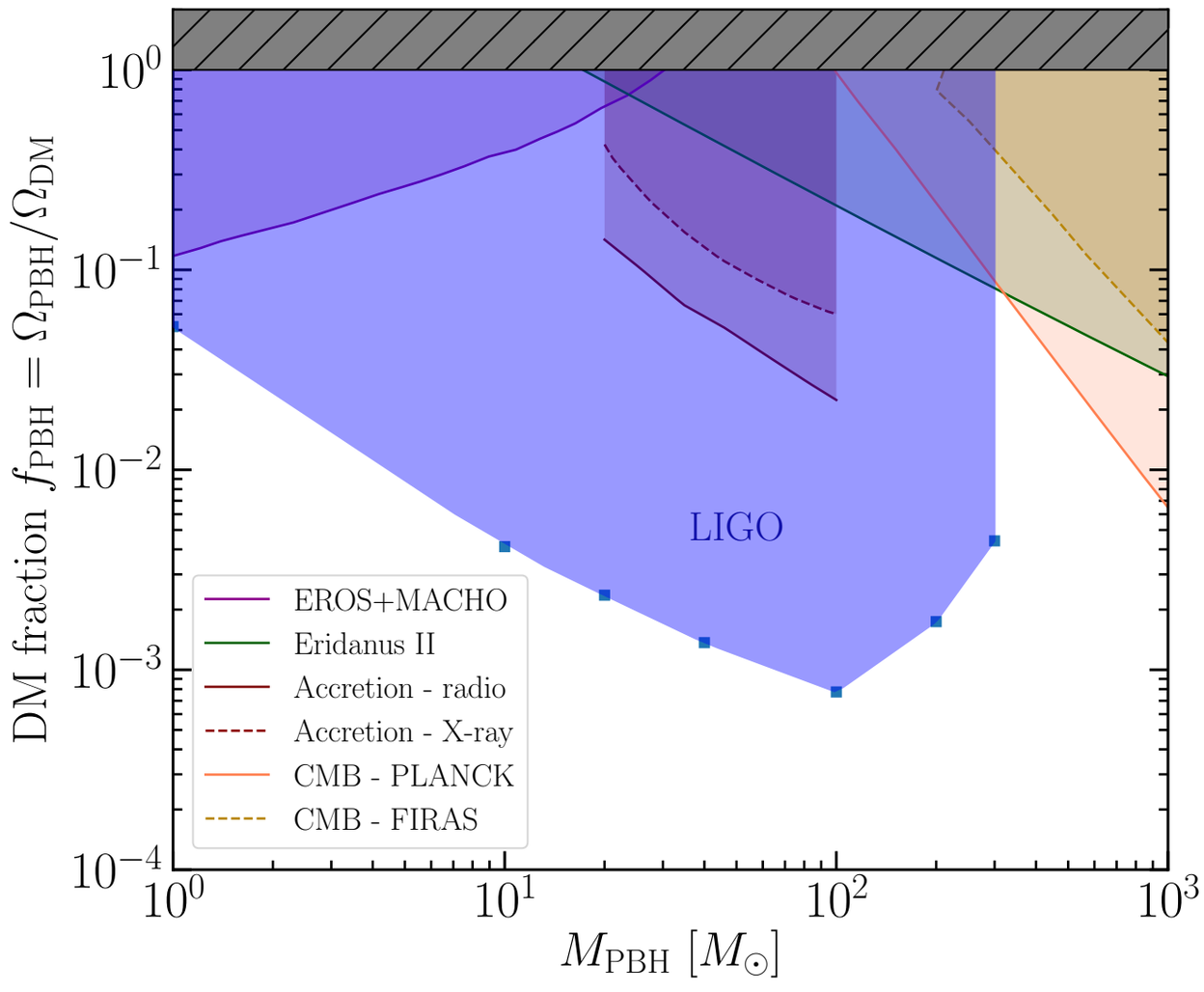
Need careful, multi-scale simulations to capture all the physics…

Conclusions



Merging Primordial Black Holes (PBHs)

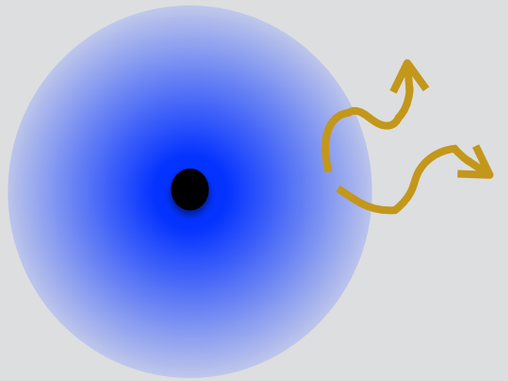
[**BJK**, Gaggero & Bertone, 1805.09034]

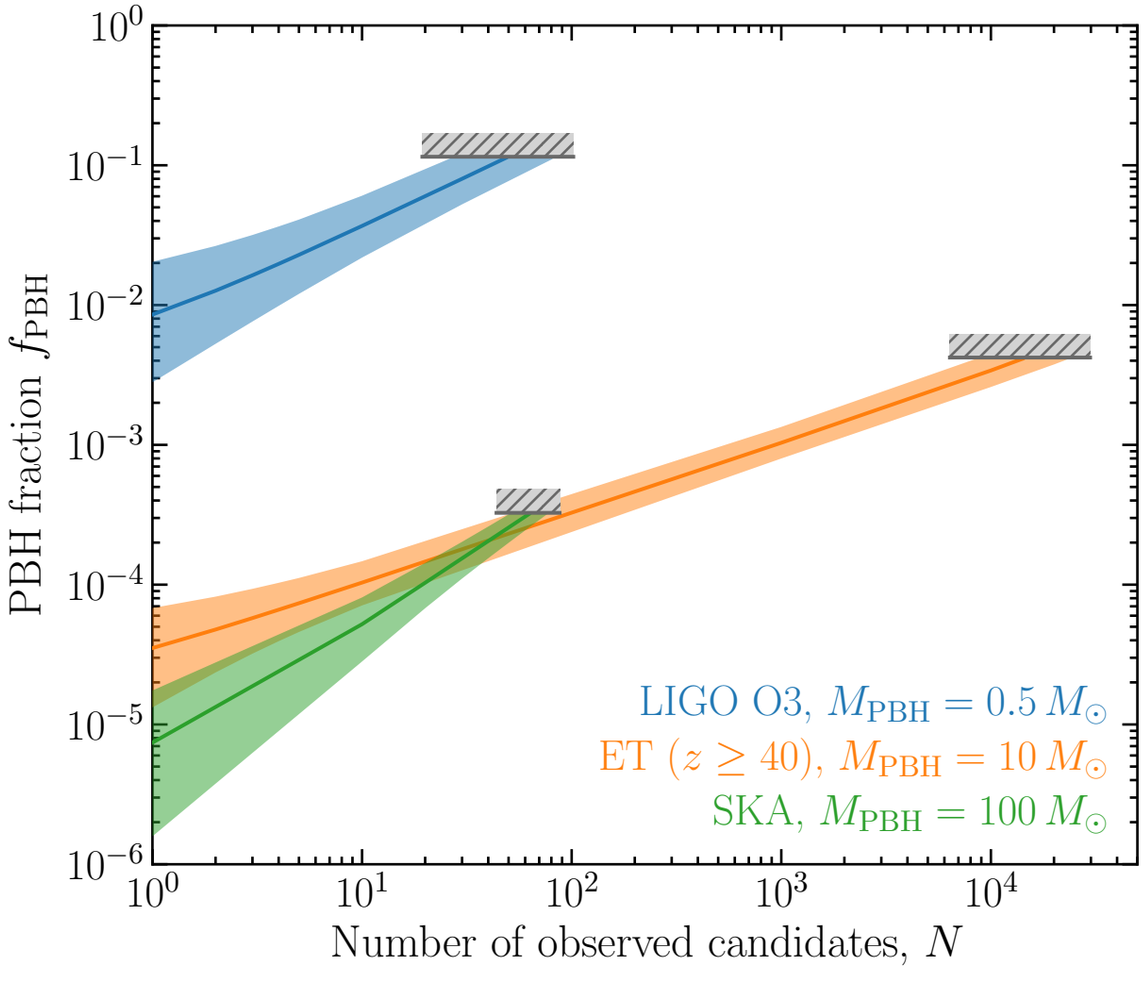


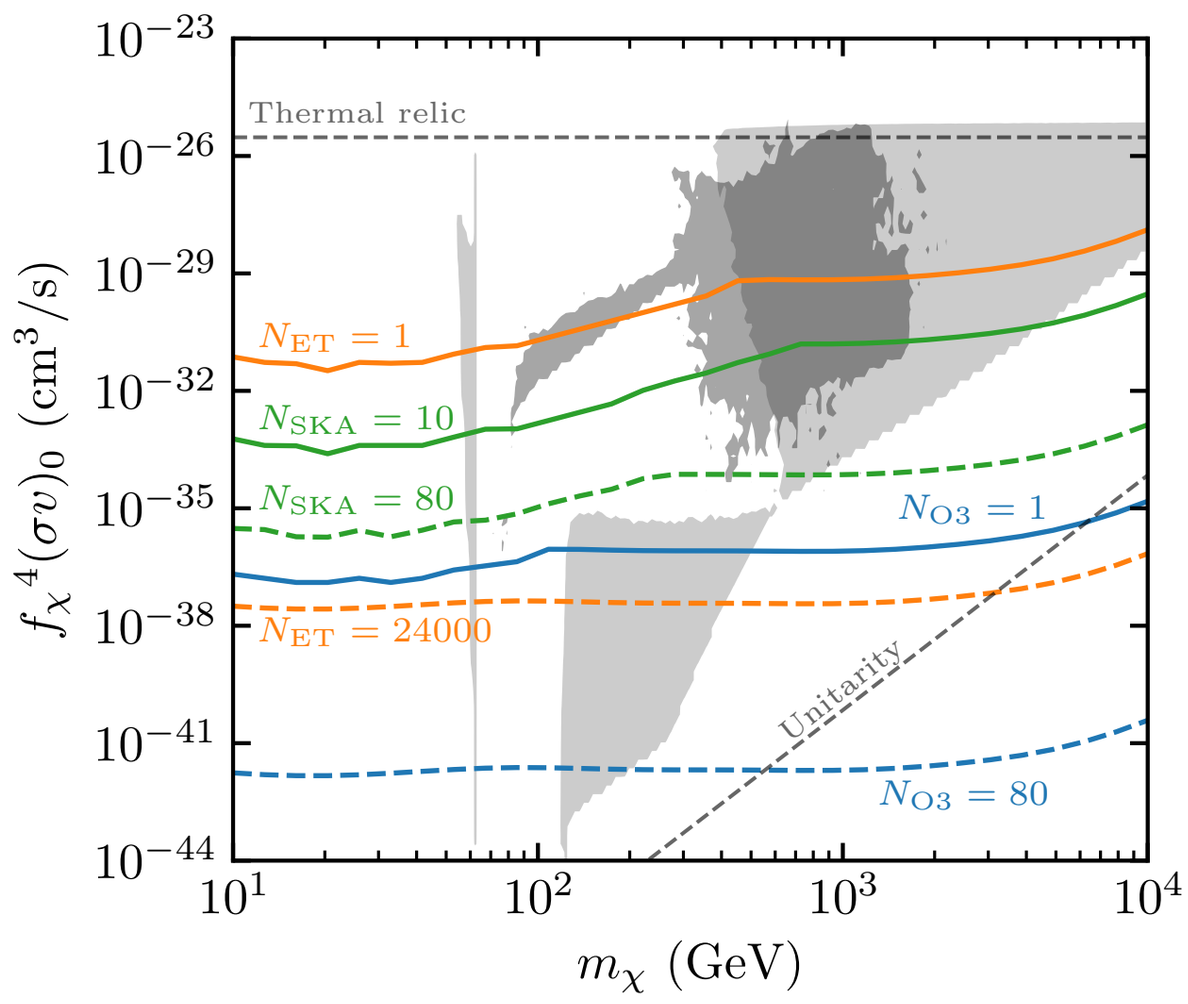
Conclusions

DM Annihilation around PBHs

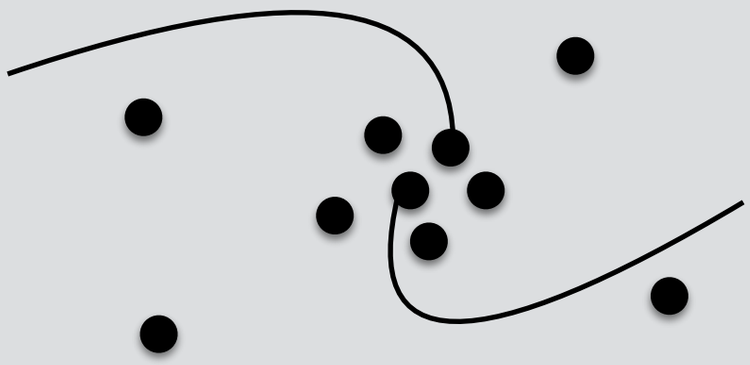
[Bertone, Coogan, Gaggero, **BJK** & Weniger, 1905.01238]







Conclusions

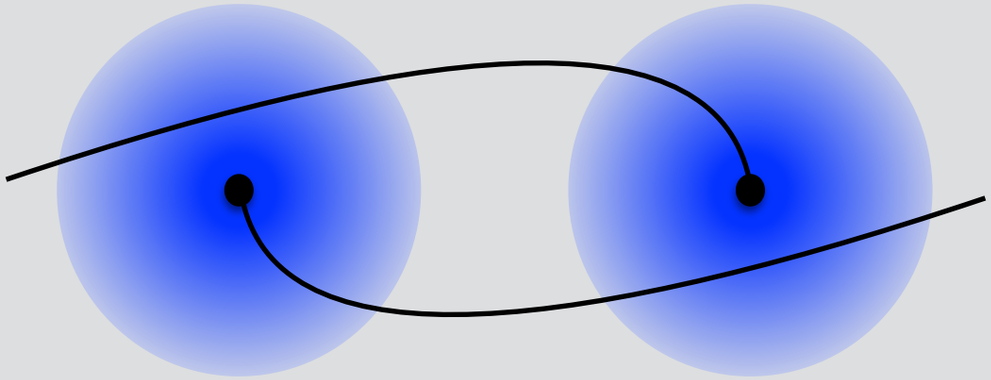


The ever-changing field of PBH mergers…

?

Conclusions

Thank you!

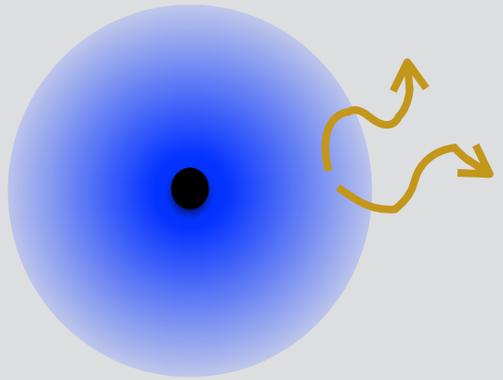


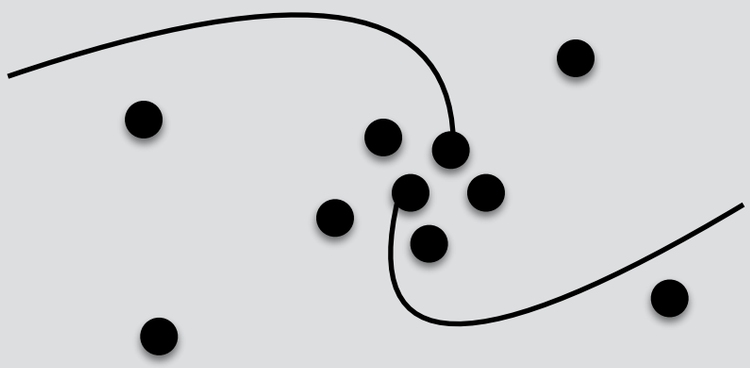
Merging Primordial Black Holes (PBHs)

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

DM Annihilation around PBHs

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





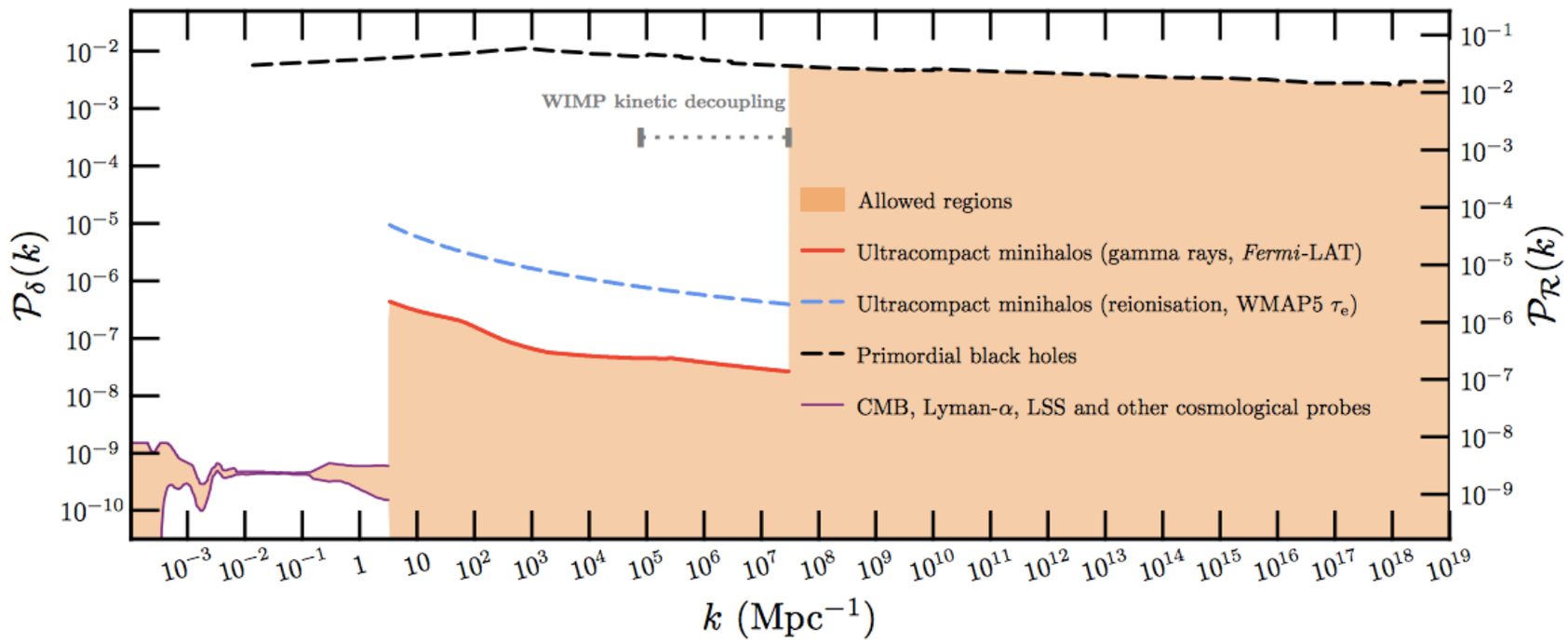
The ever-changing field of PBH mergers…

Backup Slides

PBH formation

How can we make a PBH?

[1110.2484]



- Enhancement/feature in power spectrum

  [e.g. astro-ph/9509027, astro-ph/9605094, hep-ph/9710259, 1206.4188, 1709.05565]

- Cosmic String Loops

  [e.g. Hawking (1987), Polnarev & Zembowicz (1991), gr-qc/9509012]

- Bubble collisions

  [e.g. Hawking, Moss & Stewart (1982); La & Steinhart (1989)]

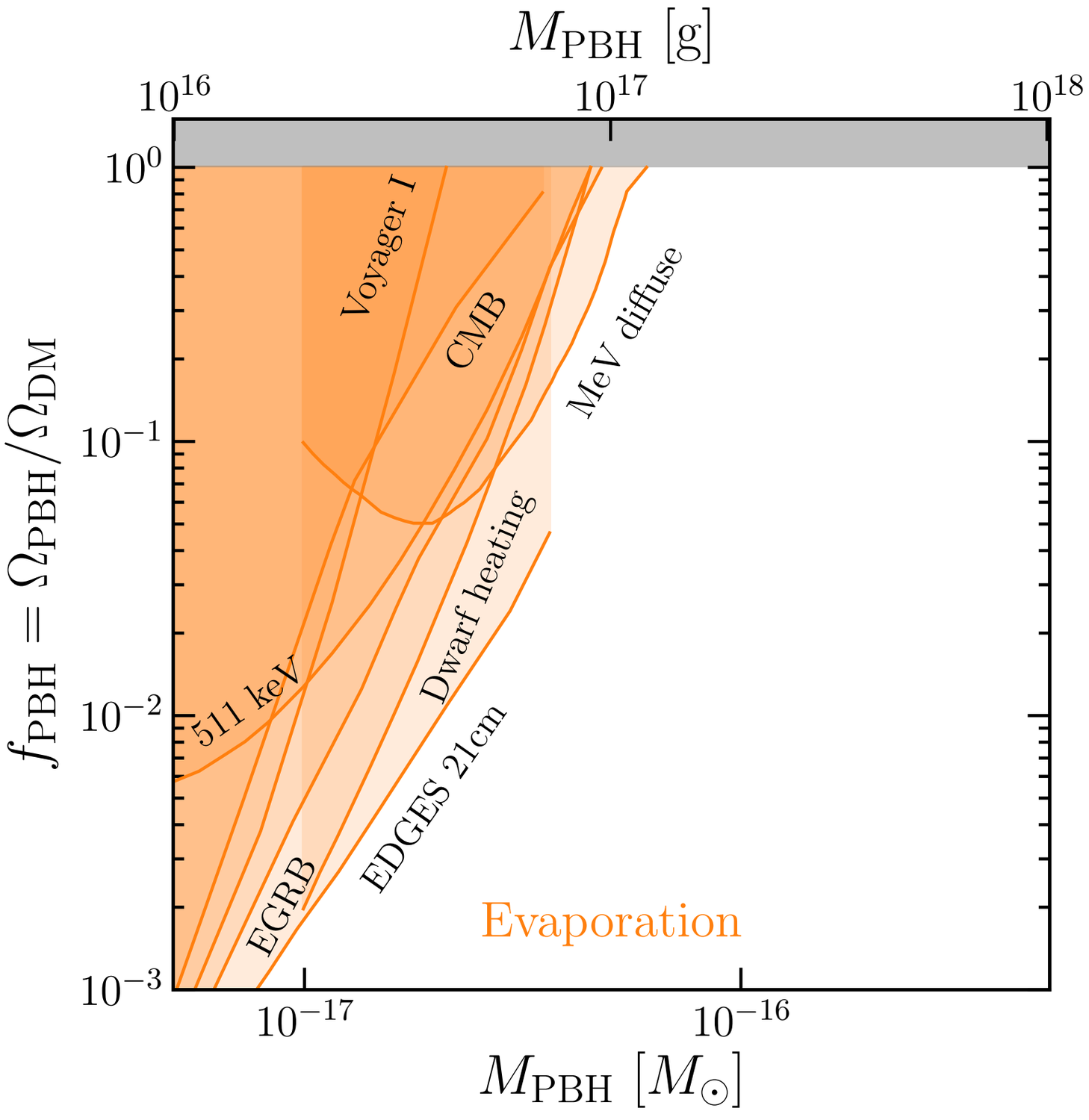
Primordial Black Holes are a probe of the physics of the early Universe:

"**Sirens** of the early Universe" [Green, 1403.1198]

Evaporation bounds

[Code online: github.com/bradkav/PBHbounds]

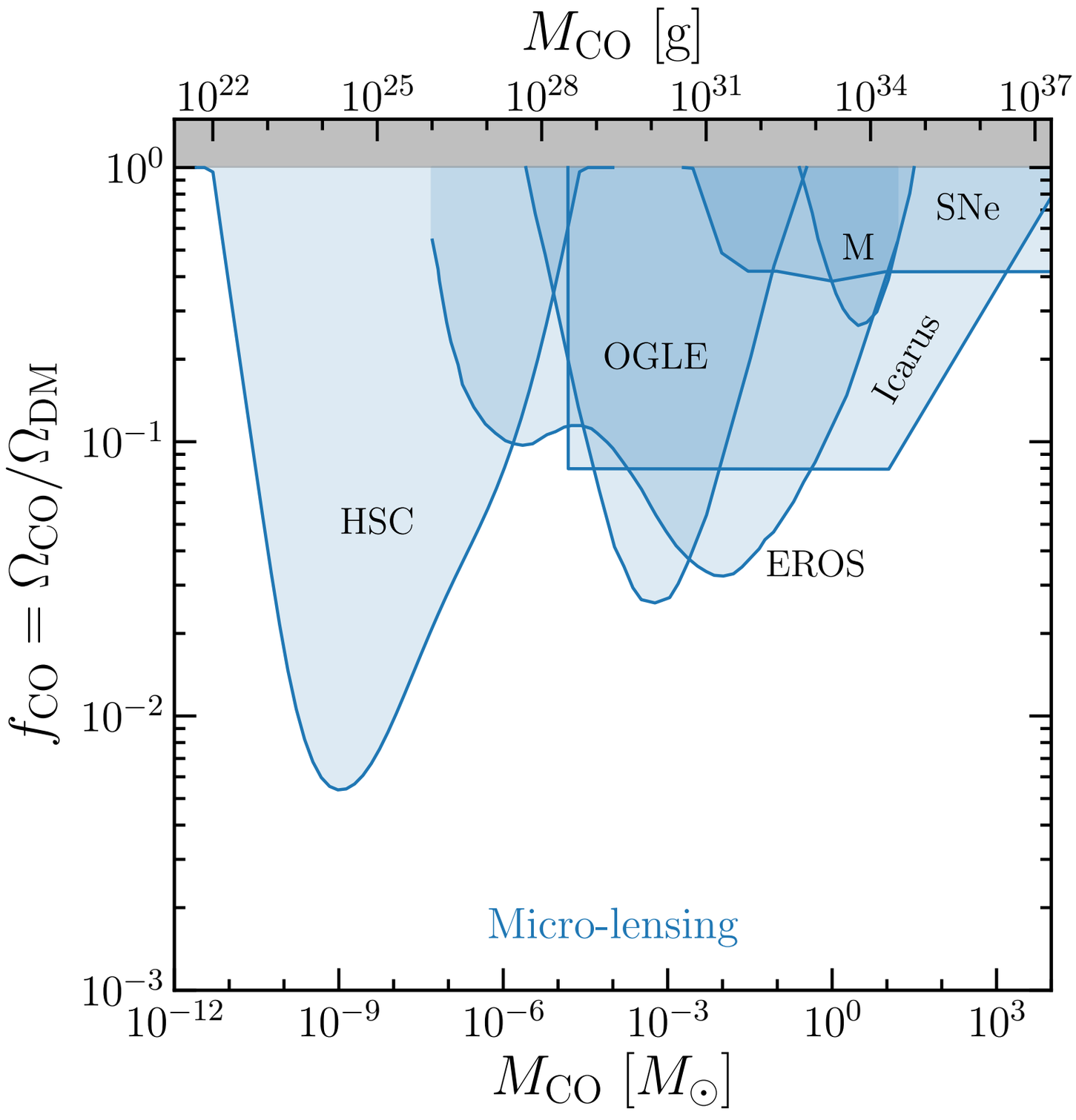
[Green & **BJK**, 1709.06576]



Microlensing bounds

[Code online: github.com/bradkav/PBHbounds]

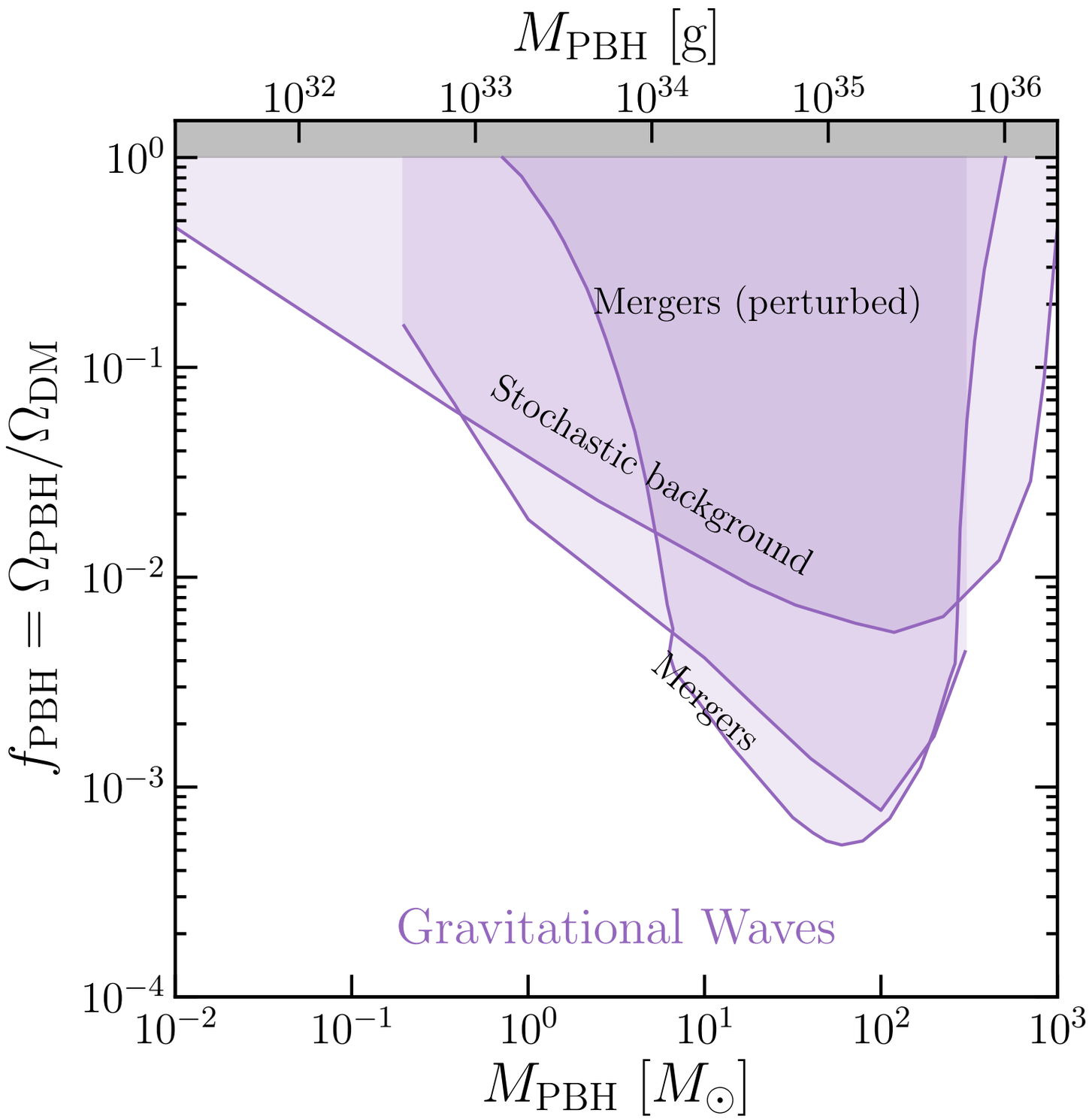
[Green & **BJK**, 1709.06576]



GW bounds

[Code online: github.com/bradkav/PBHbounds]

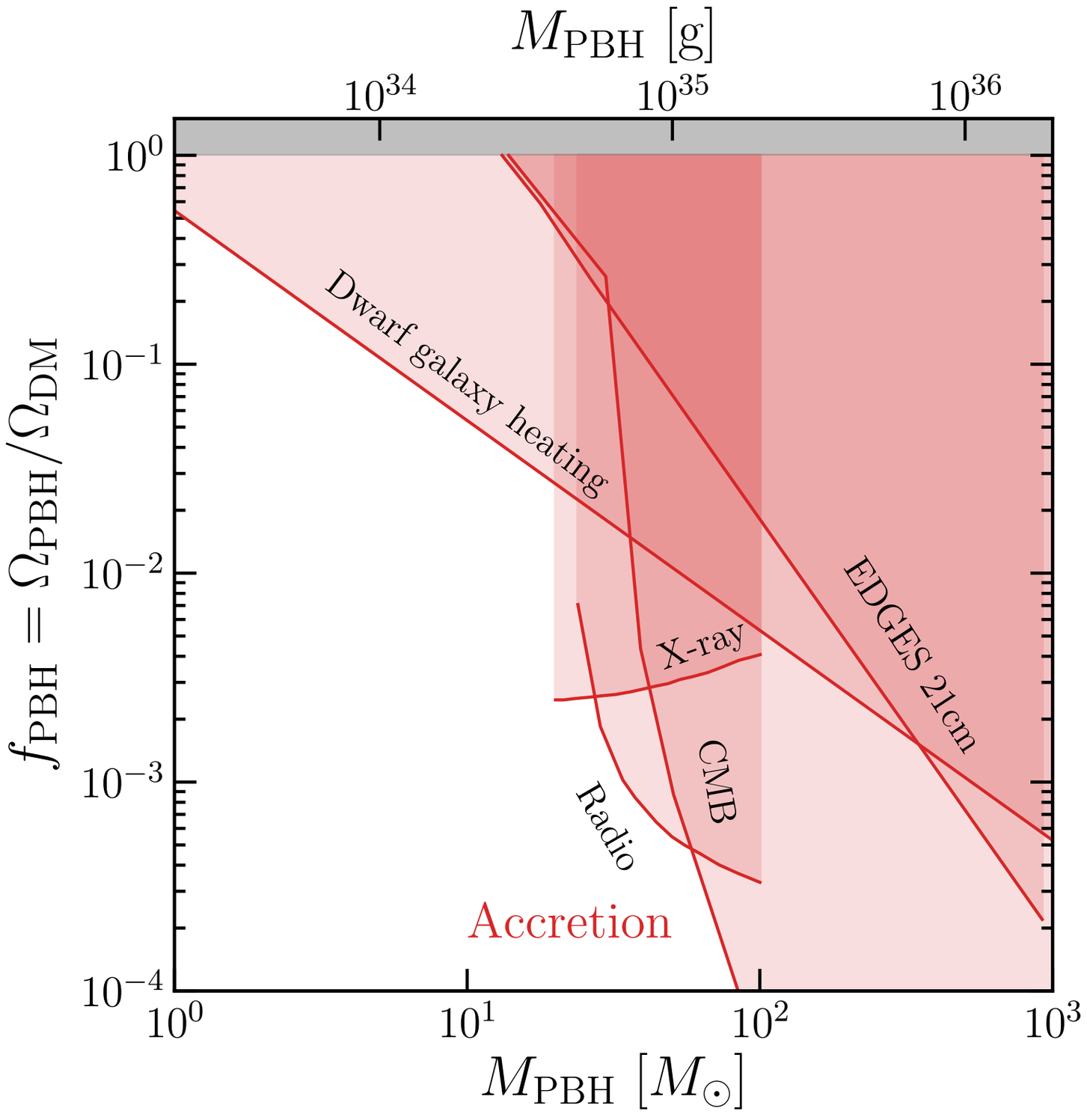
[Green & **BJK**, 1709.06576]



Accretion bounds

[Code online: github.com/bradkav/PBHbounds]

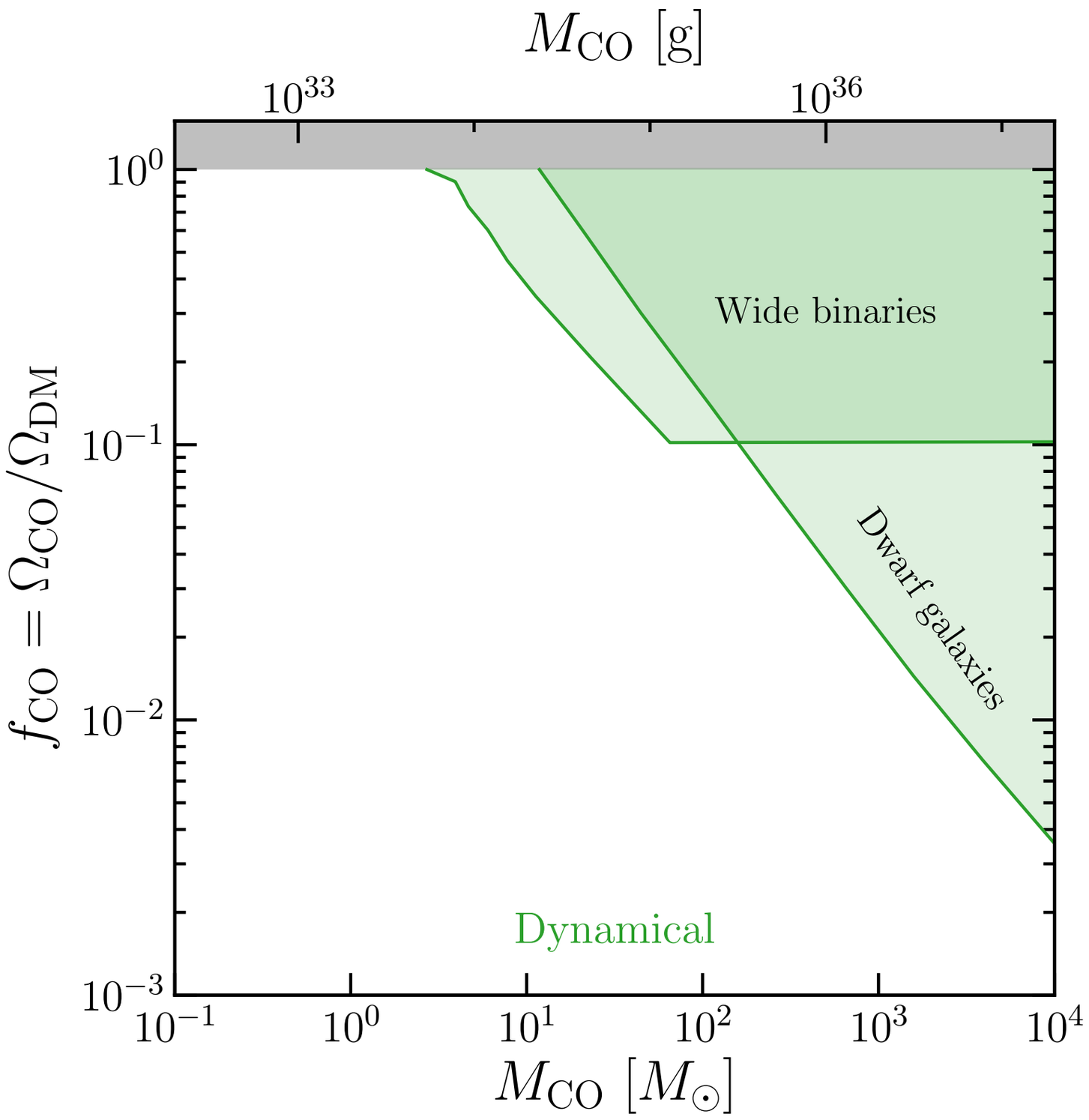
[Green & **BJK**, 1709.06576]



Dynamical bounds

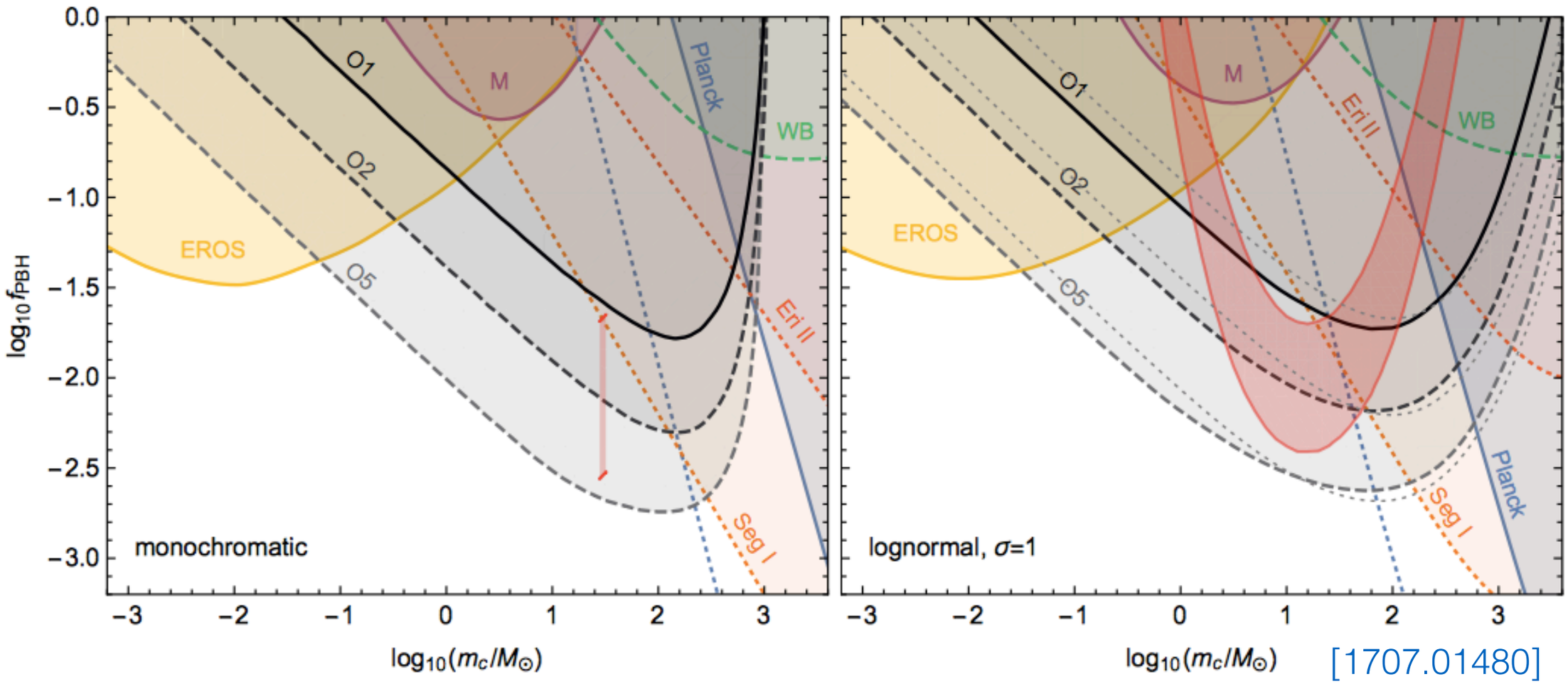
[Code online: github.com/bradkav/PBHbounds]

[Green & **BJK**, 1709.06576]



Extended Mass Function

LIGO O1 Limit



[1707.01480]

"Old" merger rate calculation *à la* Sasaki et al.,
but picture doesn't change too much…

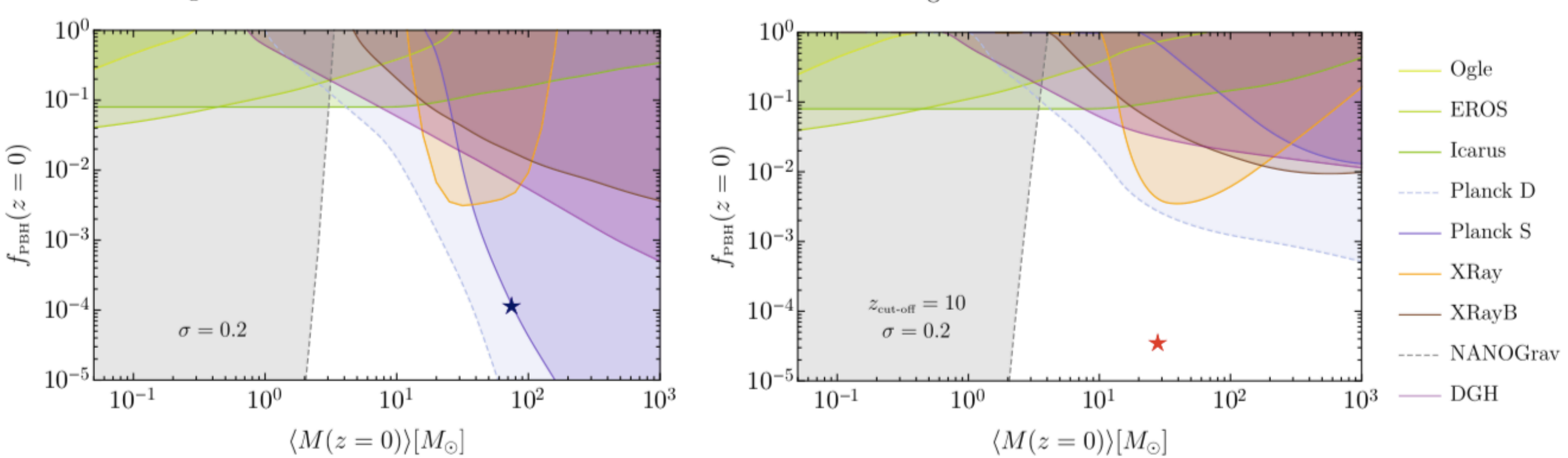
[See also 1801.10327]

GW190521

TABLE I. Parameters of GW190521 according to the NRSur7dq4 waveform model. We quote median values with 90% credible intervals that include statistical errors.

Parameter	
Primary mass	$85^{+21}_{-14}\ M_\odot$
Secondary mass	$66^{+17}_{-18}\ M_\odot$
Primary spin magnitude	$0.69^{+0.27}_{-0.62}$
Secondary spin magnitude	$0.73^{+0.24}_{-0.64}$
Total mass	$150^{+29}_{-17}\ M_\odot$

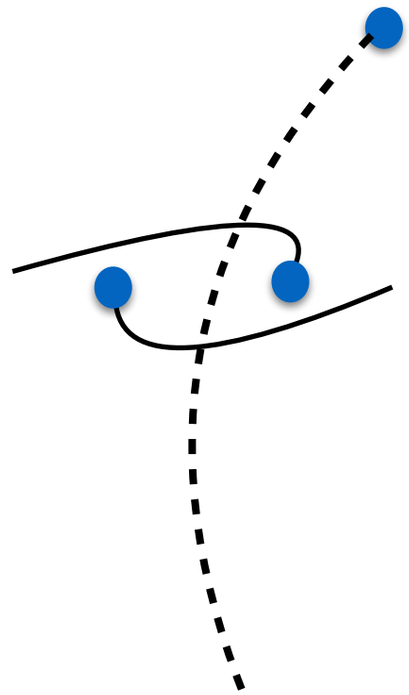
[LVC (GW190521), arXiv:2009.01075]



[De Luca et al., arXiv:2009.01728]

Caveats

- Survival
- Clustering
- Baryons
- Dark Matter



Do these binaries survive for the age of the Universe?

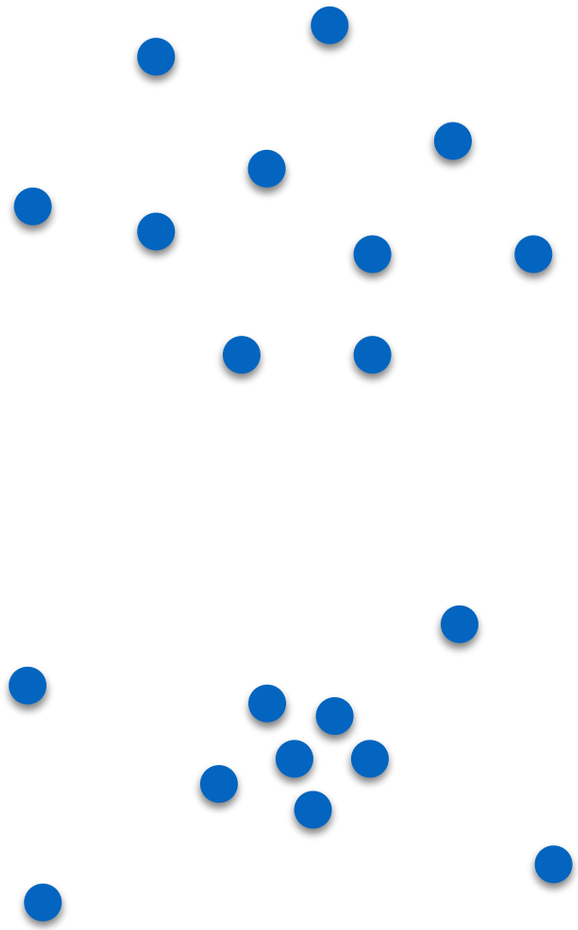
Smooth density perturbations and close encounters are unlikely to disrupt the binaries

$$a \lesssim 10^{-2}\,\mathrm{pc}$$

[Ali-Haïmoud et al., 1709.06576]

Caveats

- Survival
- Clustering
- Baryons
- Dark Matter



How does the distribution of PBHs affect the merger rate?

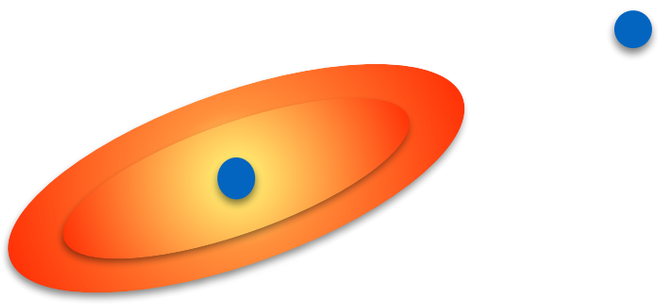
Clustering could substantially enhance the merger rate ('cascade' mergers) but PBHs are unlikely to form in clusters…

[1808.05910] [1807.02084]

[See also 1805.05912,1806.10414 and others]

Caveats

- Survival
- Clustering
- Baryons
- Dark Matter



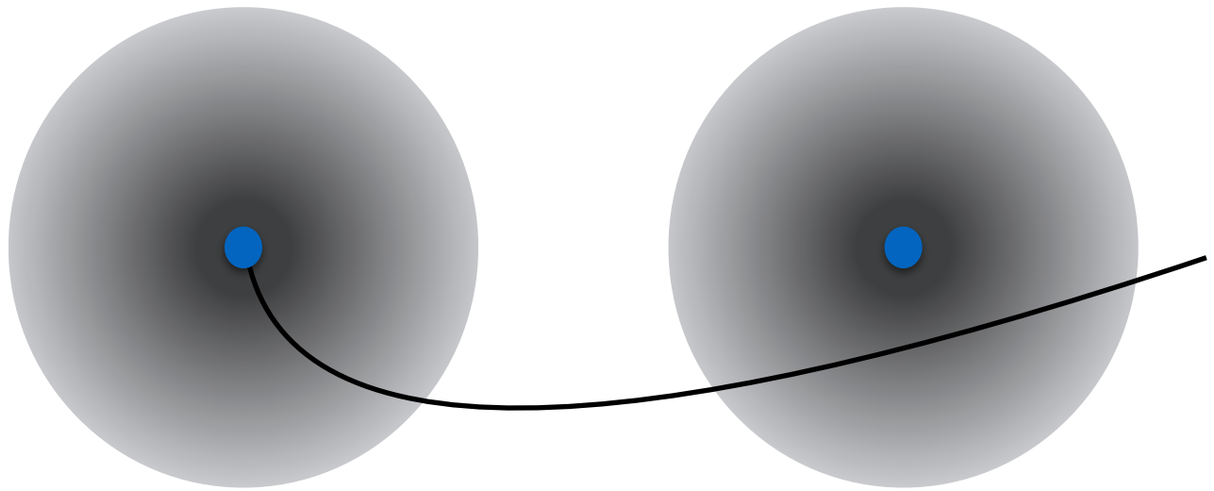
Does baryonic accretion disrupt the binary?

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]

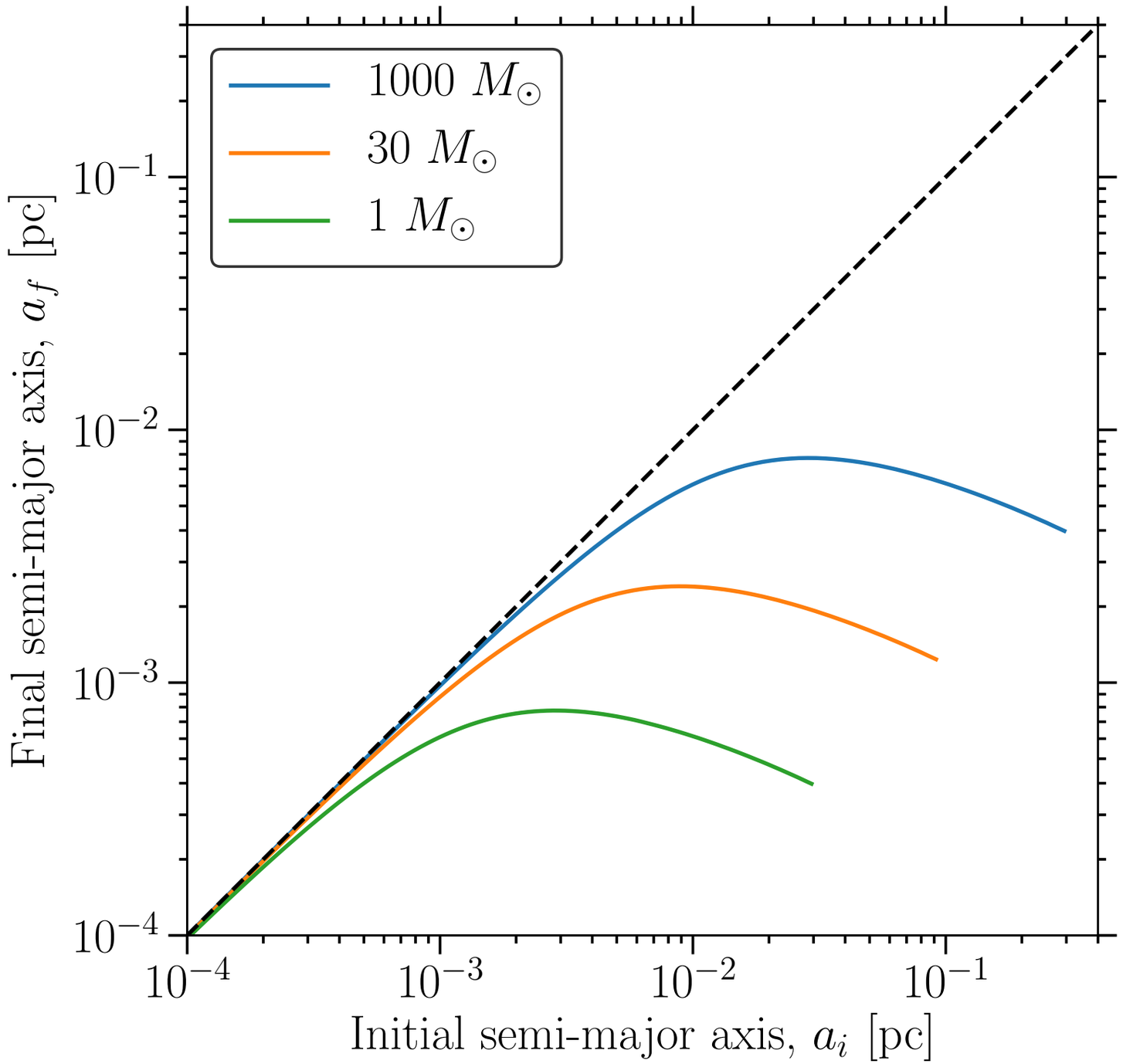
Caveats

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



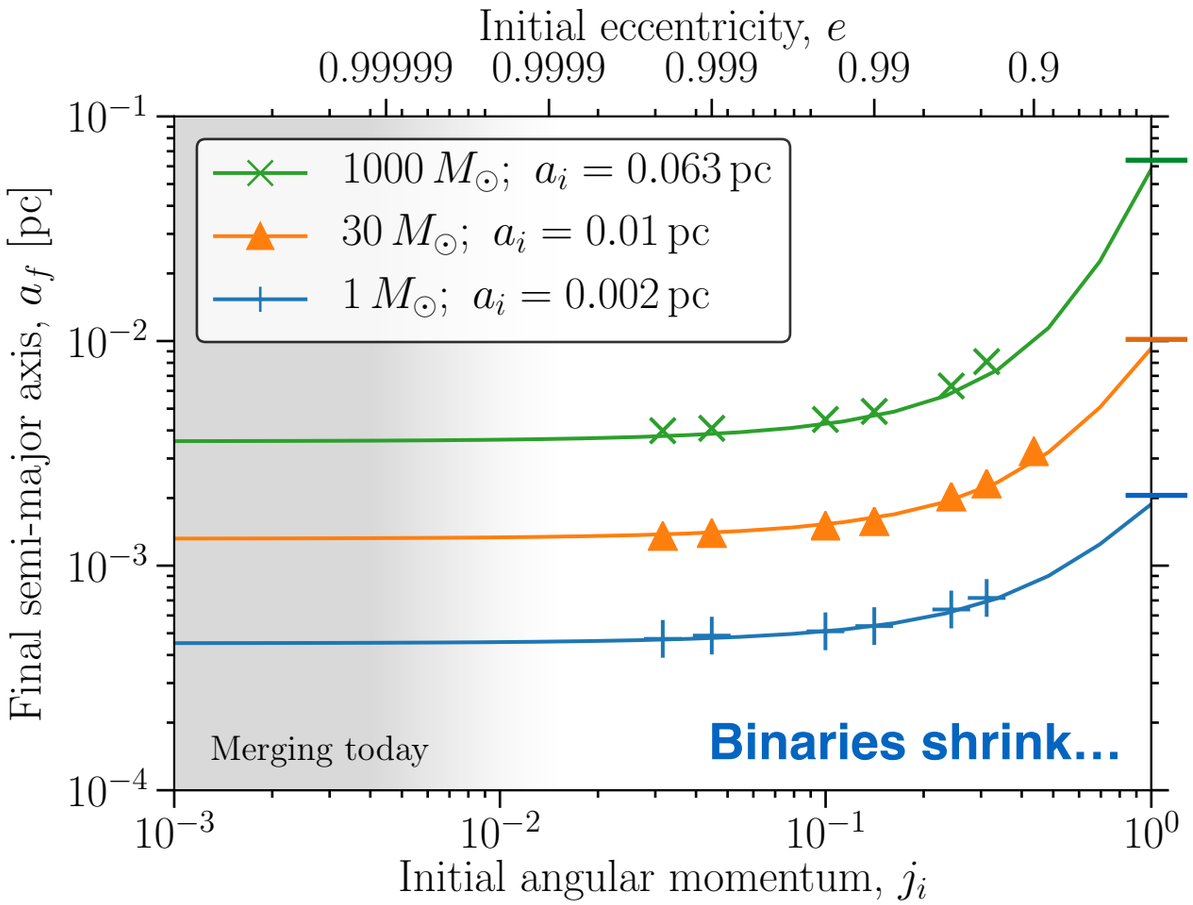
Do *local* Dark Matter halos disrupt PBH binaries?

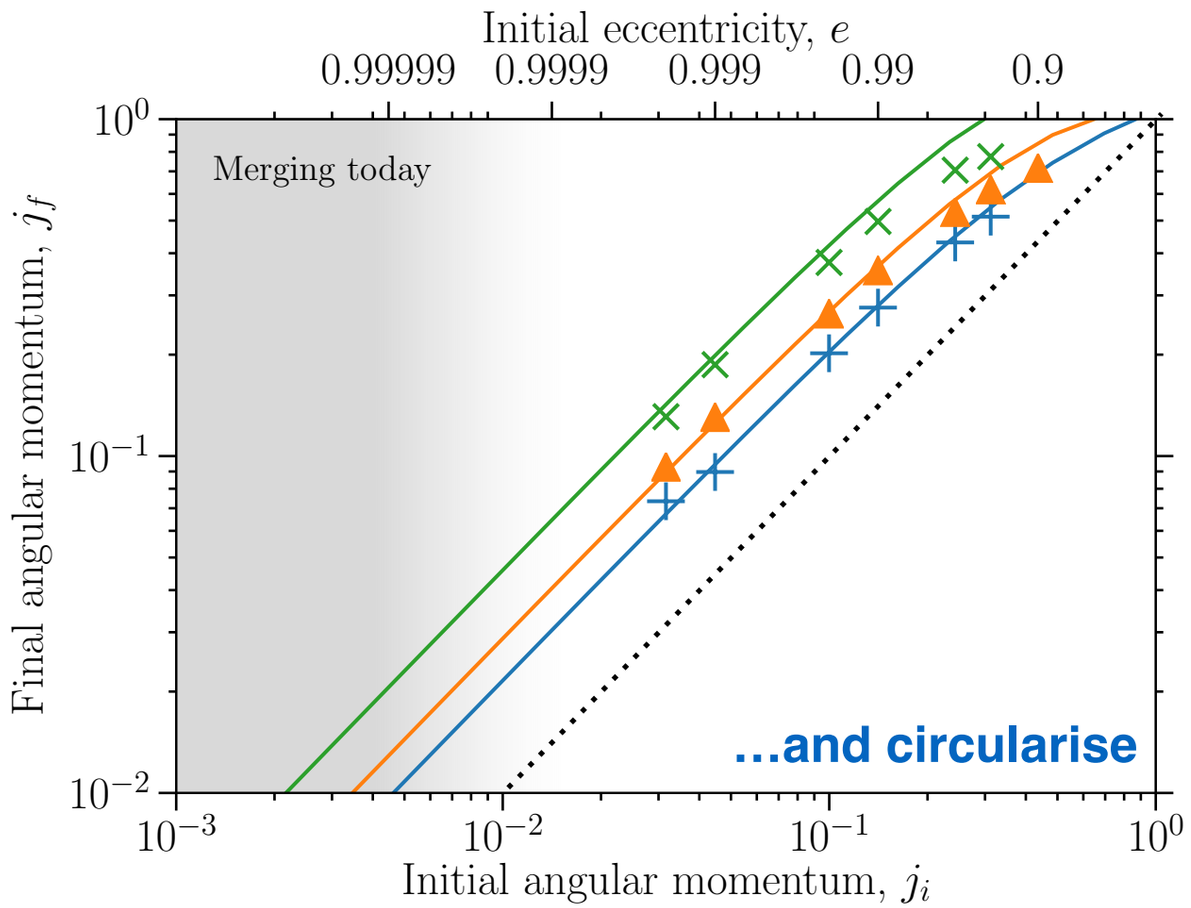
PBH Binaries: semi-major axis



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

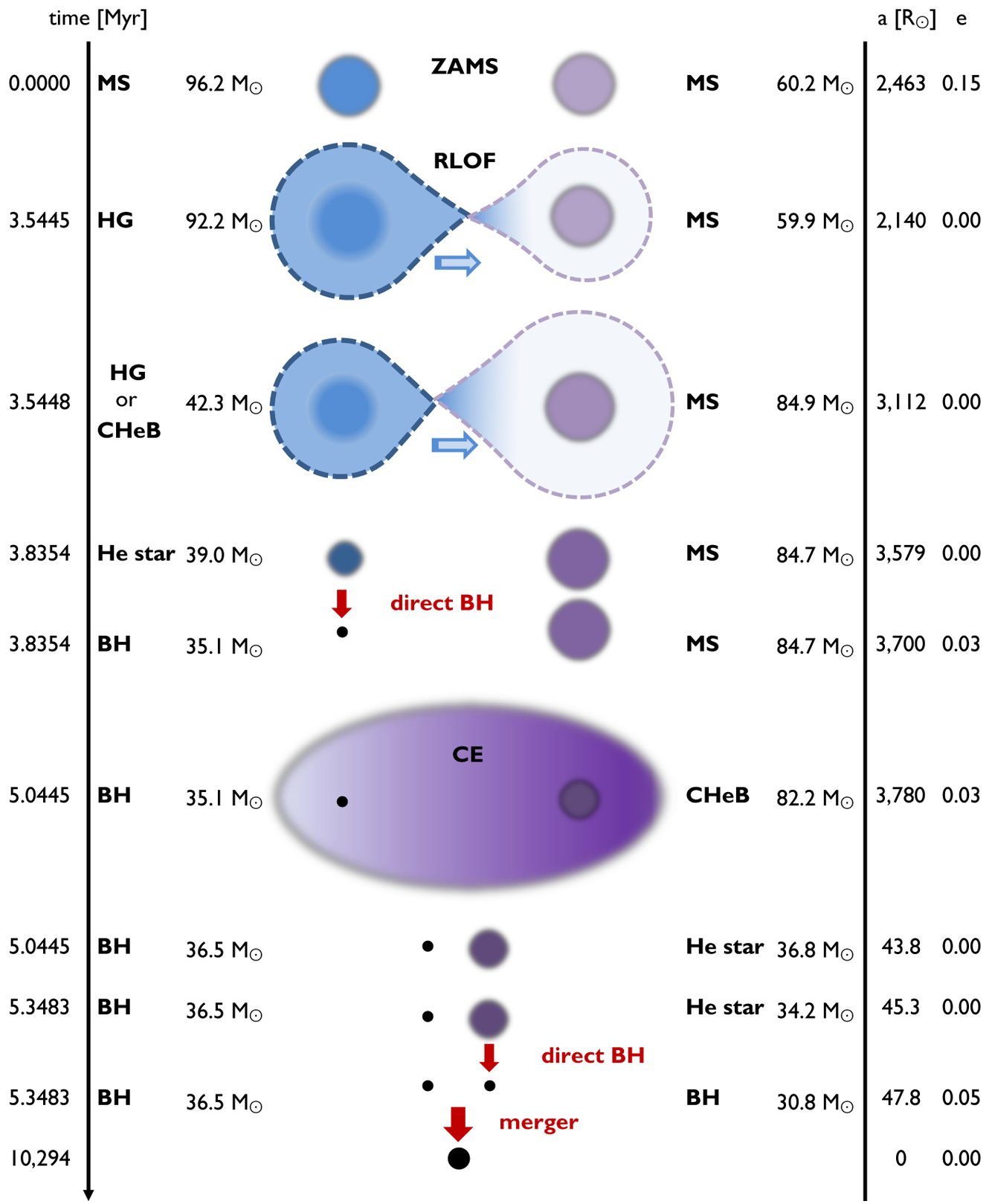
PBH Simulation Results





Astrophysical BH binaries

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



[1602.04531]

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