Fundamental Physics with LISA - Dark matter and PBHs

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IV. Dark Matter and Primordial BHs

A. Low mass particles $m < eV$

B. High mass particles $m > eV$

C. PBHs $m < M_\odot$

D. PBHs $m > M_\odot$

E. Exotic Compact Objects

F. Signatures from self-interactions

G. Multi-messenger signatures

H. Burning Questions

SEE ALSO: Nature of Black Holes (ECOs)

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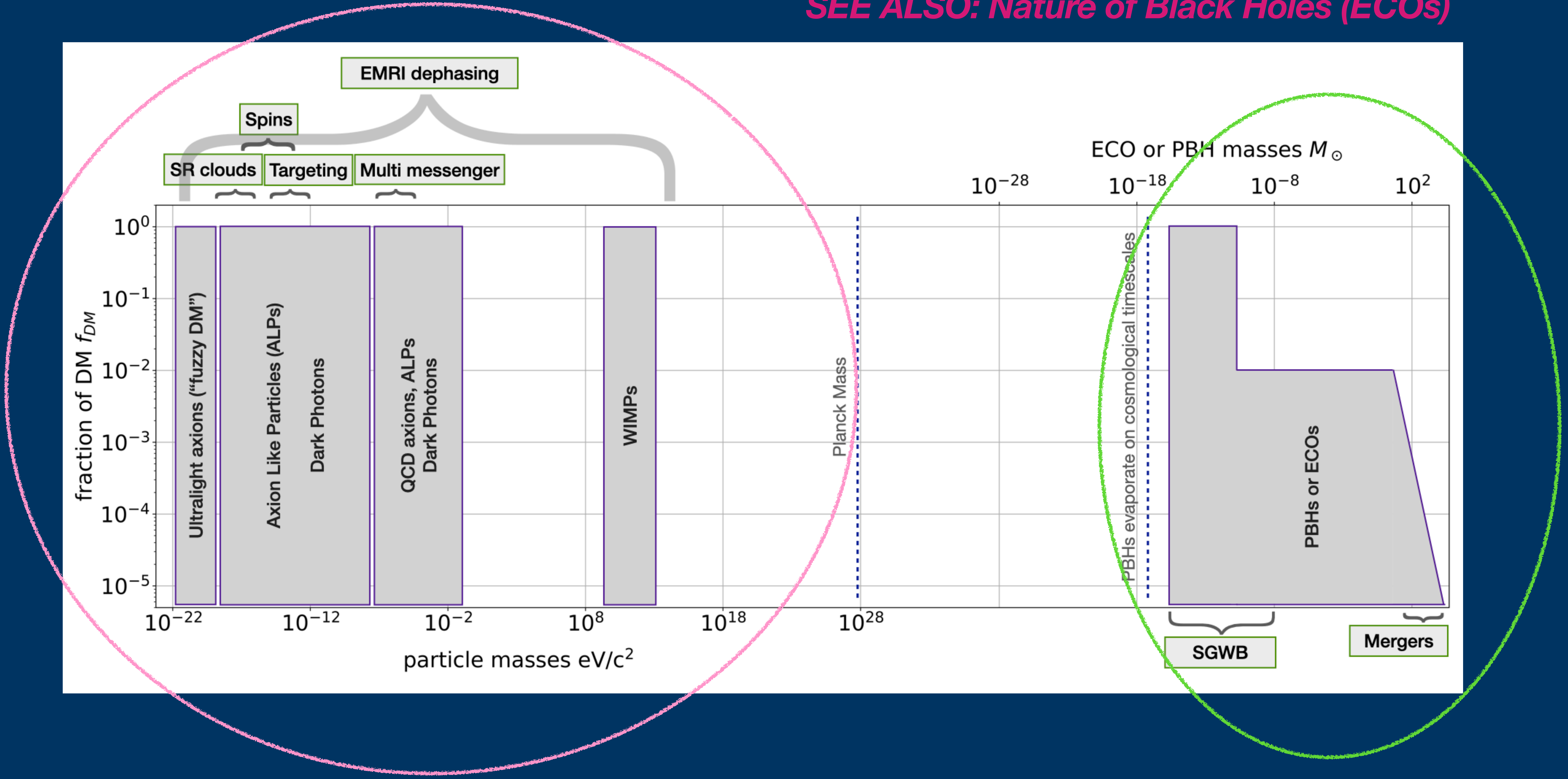


Self
interaction

Particle dark matter parameters

Mass

Fraction of
total DM
(locally/
globally)

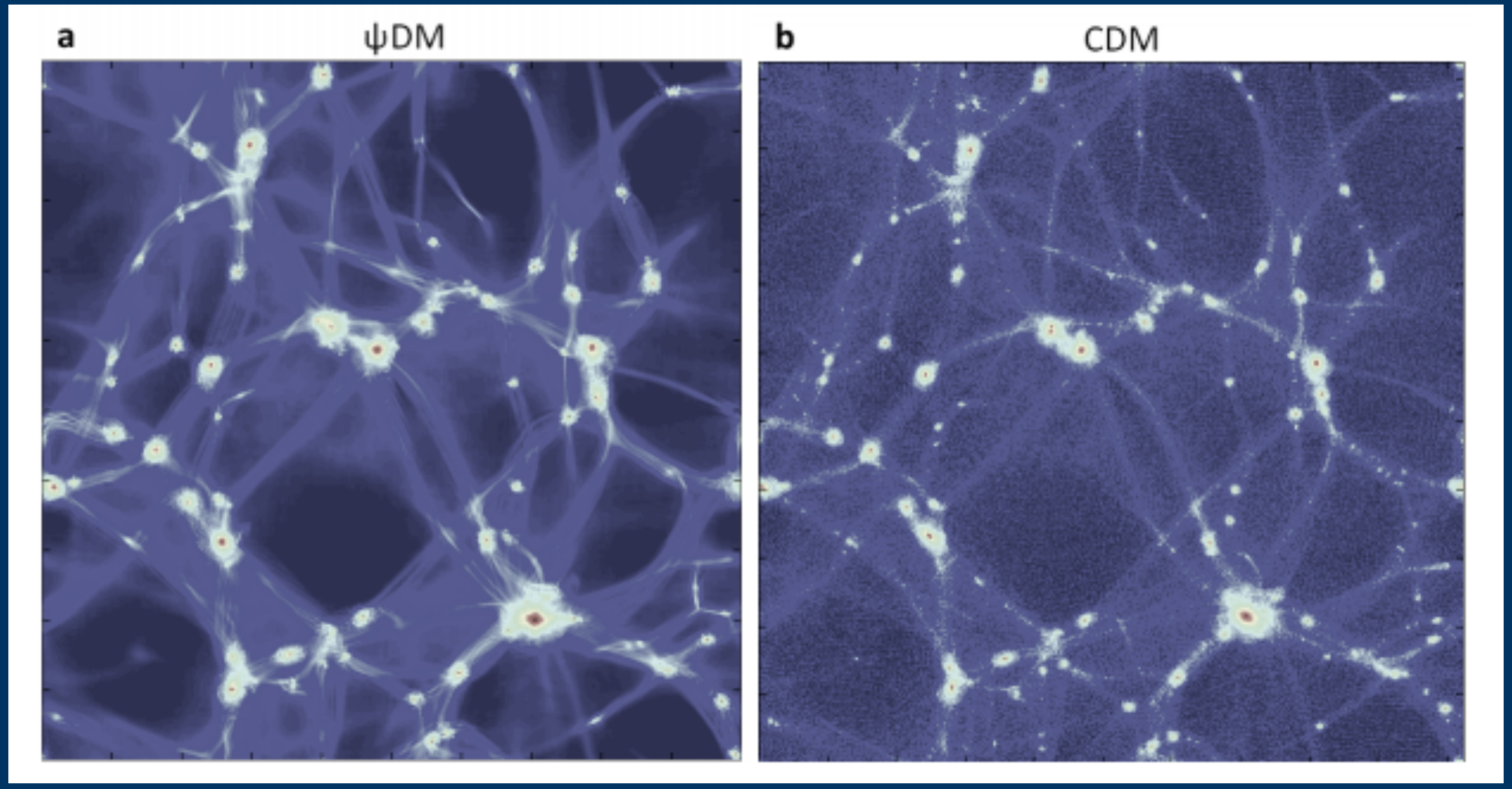
Standard
model
interactions

A vast range of potential masses

Mass

Particle dark matter parameters

Wave DM
e.g. axions
10^{-23} eV - 1 eV



Particle DM
e.g. WIMPS
1 eV - 10^{13}eV

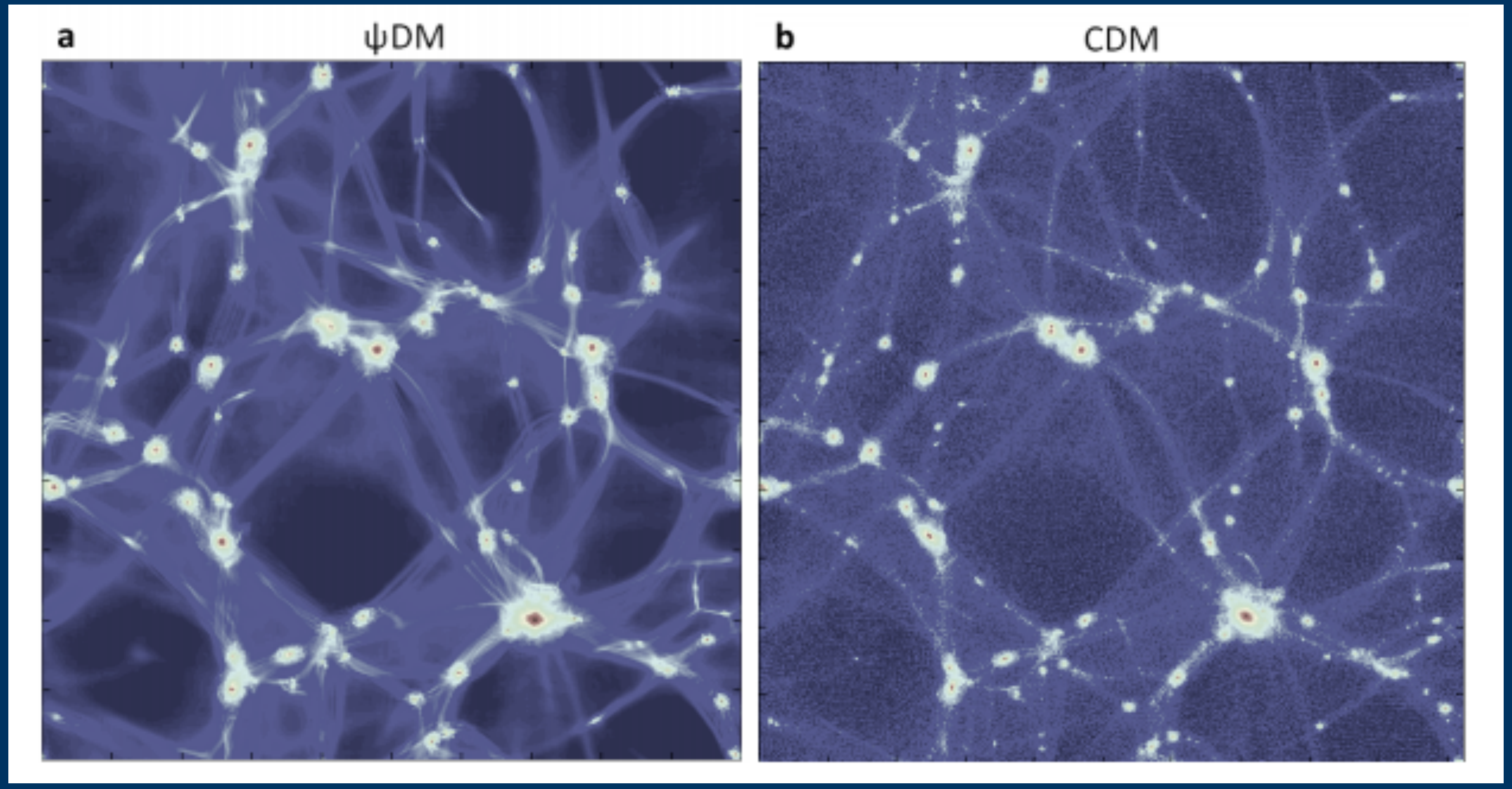
Schive et al. 2014
Cosmic structure as the quantum interference of a coherent dark wave

A useful distinction is between wave-like and particle DM

Mass

Particle dark matter parameters

Wave DM
e.g. axions
10^{-23} eV - 1 eV



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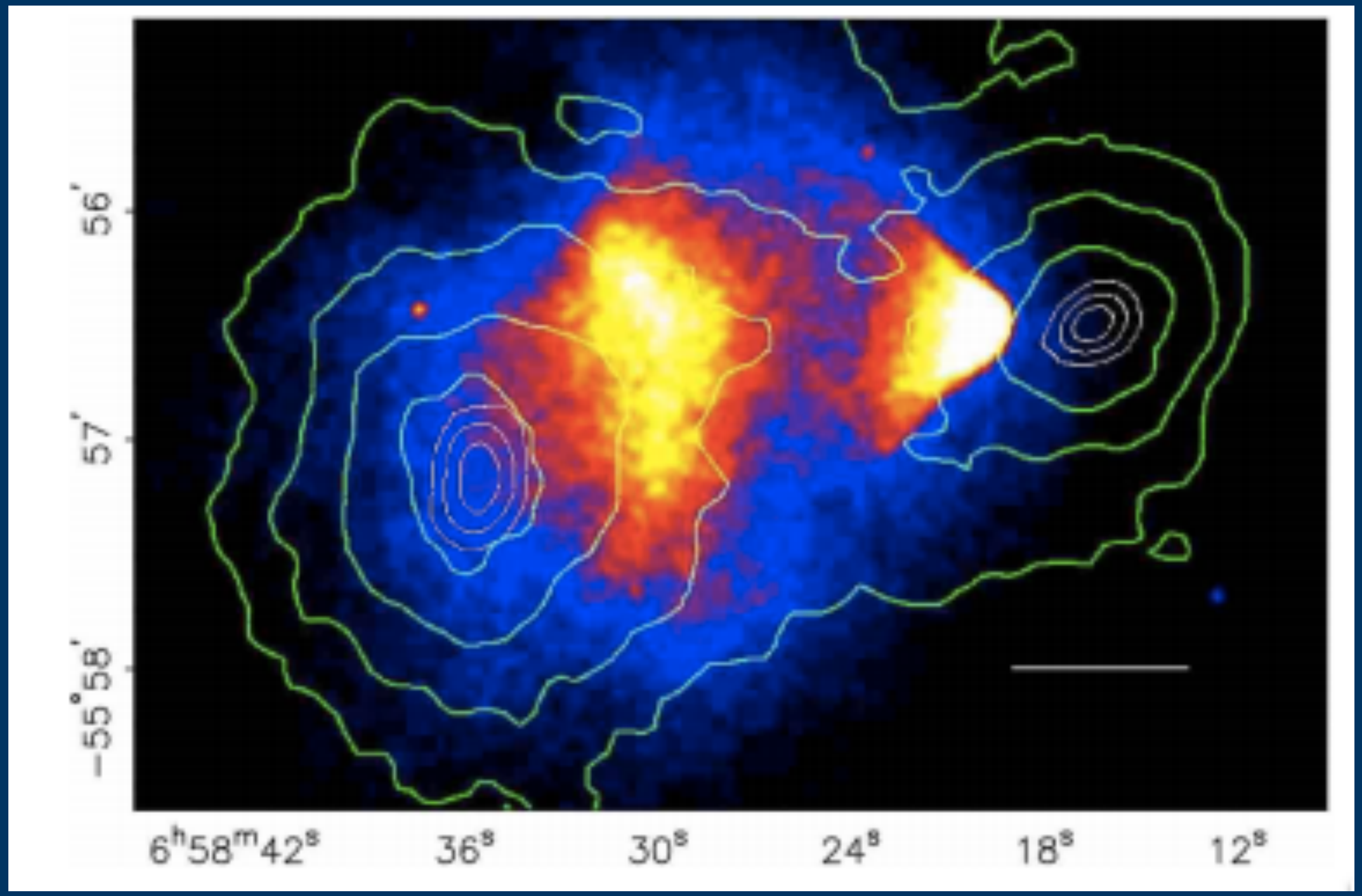
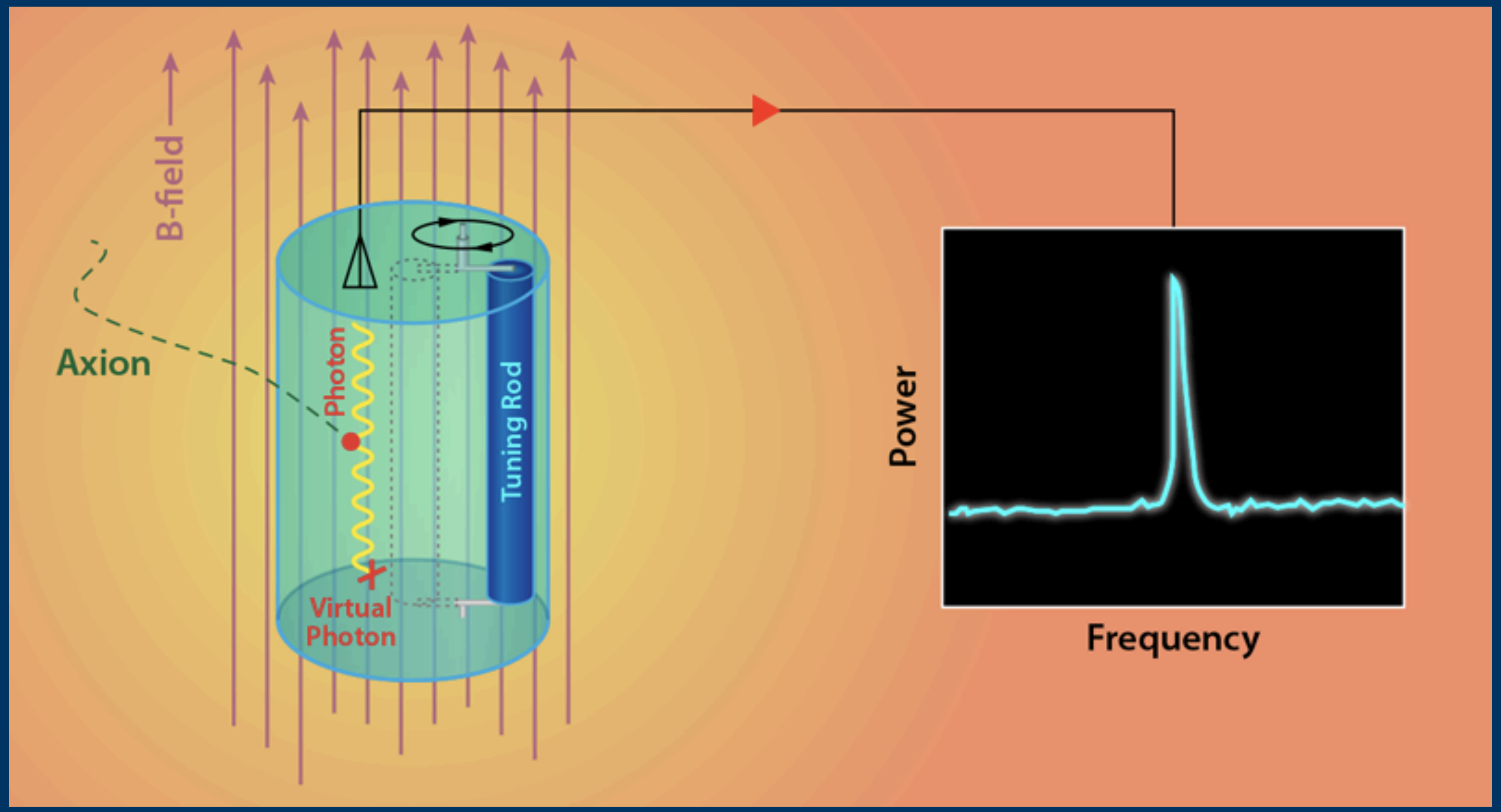


Clowe et. al. 2006
A direct empirical proof of the existence of dark matter

Small - could be zero

Small - could be zero

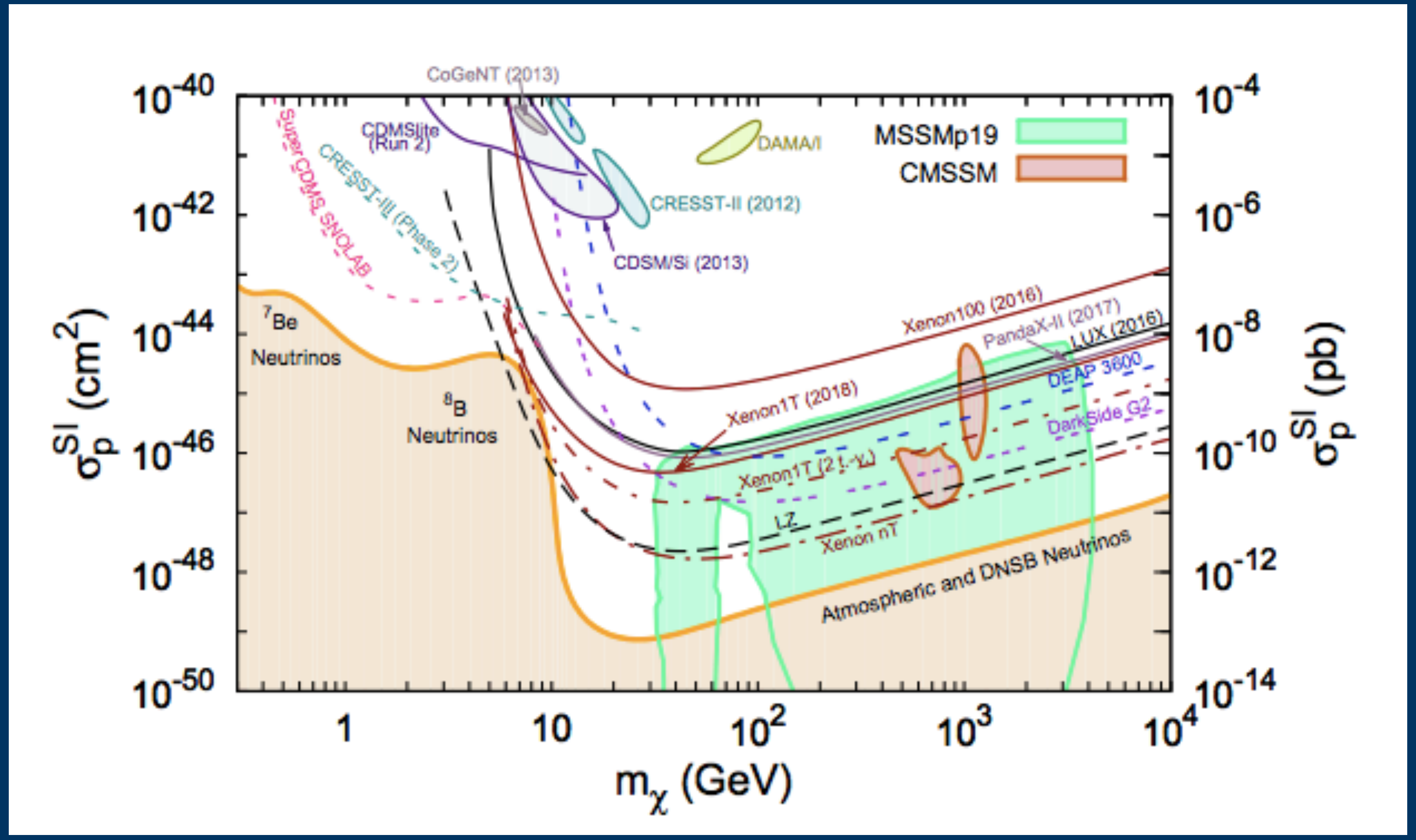
Particle dark matter parameters

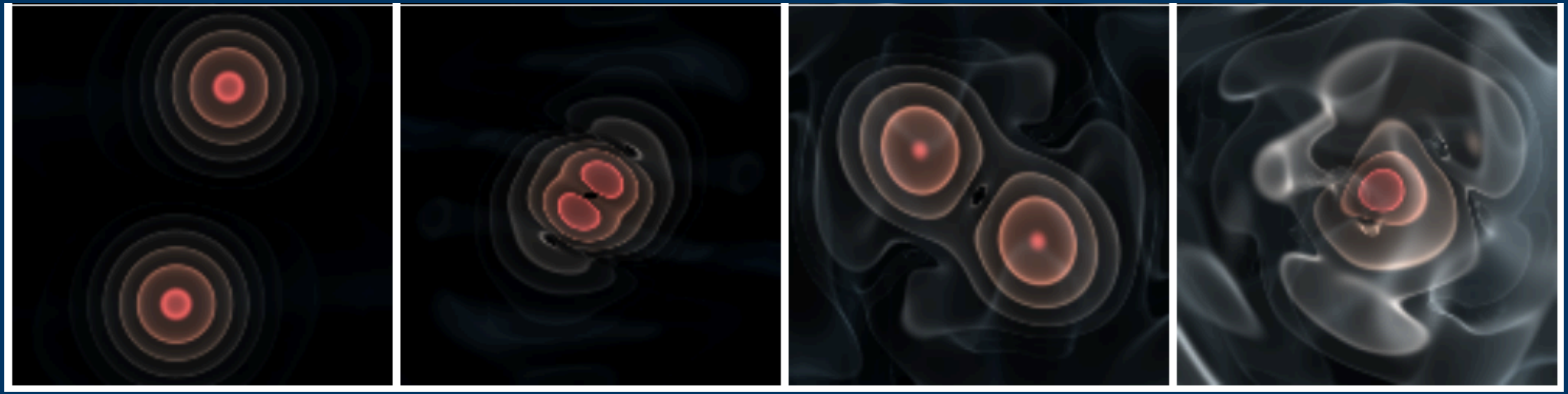


ADMX experiment
C. Boutan/Pacific Northwest National Laboratory

Standard model interactions

Roszkowski et al, 2018
Rept.Prog.Phys. 81 (2018) no.6, 066201





Schwabe et al, 2016
Simulations of solitonic core mergers in ultralight axion dark matter cosmologies

Particle dark matter parameters

Fraction of total DM (locally/ globally)

Constraints rely heavily on fraction of DM composed by the candidate, and its distribution (uniform/clumpy)

1. In what situations is DM likely to have a *significant* GW imprint in LISA observations?

2. Can we measure that imprint *independently* of other factors?

3. Can we use LISA measurements to learn more about the *nature* of DM?

Good news: DM (almost certainly) is a real thing that exists in nature :-)

Good news: DM (almost certainly) is a real thing that exists in nature :-)

Bad news: average DM density is very low :-(

Barausse et al. 2014
Can environmental effects spoil precision gravitational-wave astrophysics?

(Answer: No)

What do you mean “low”?

$\rho \sim 1\ \mathrm{GeV/cm^3}$ **or** $1\ \mathrm{M_\odot/pc^3}$

What do you mean "low"?

$$\frac{\rho}{1/R_s^2} \sim 10^{-30} \left(\frac{M_{BH}}{10^6 M_\odot} \right)^2$$

1. In what situations is DM likely to have a *significant* GW imprint in LISA observations?

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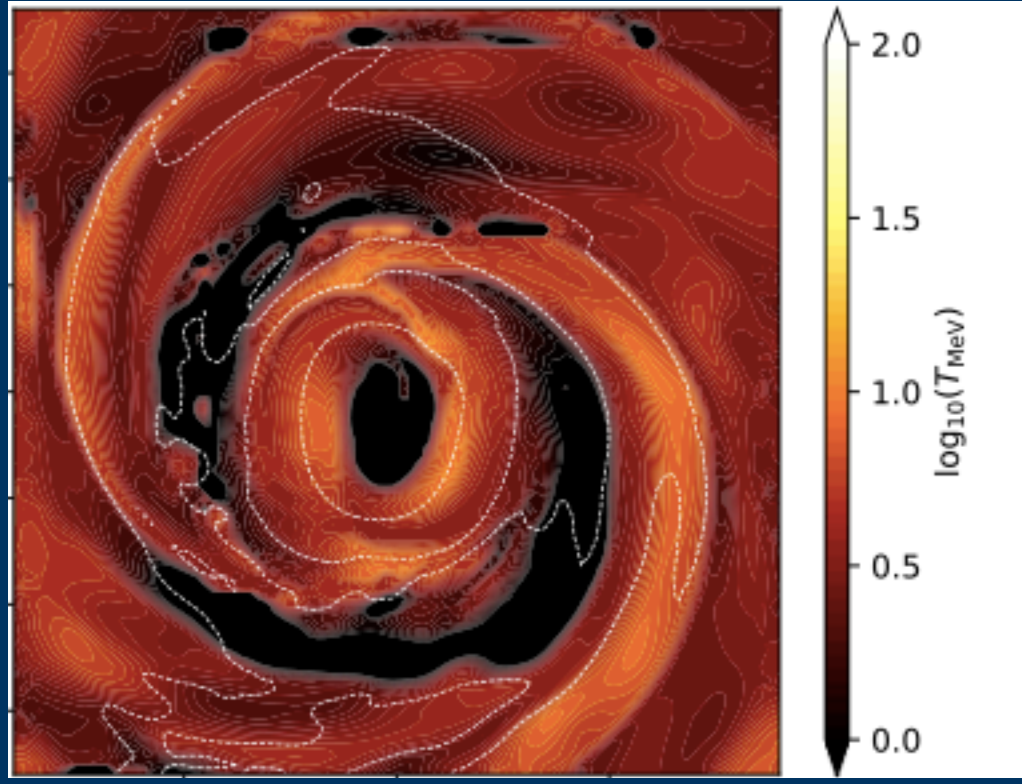
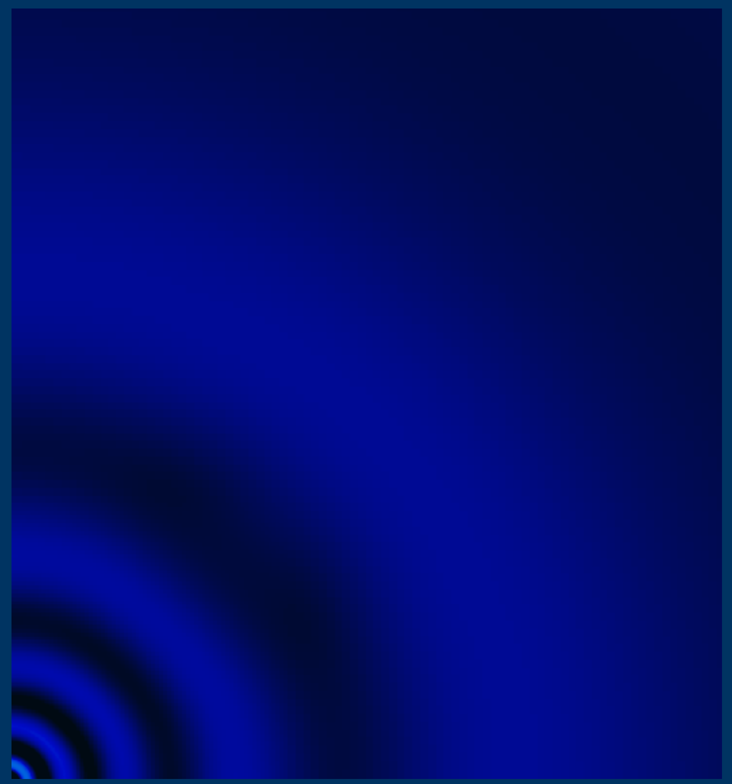
1. What DM density enhancement is required to have an observable impact on LISA signals? Do such enhancements arise naturally?



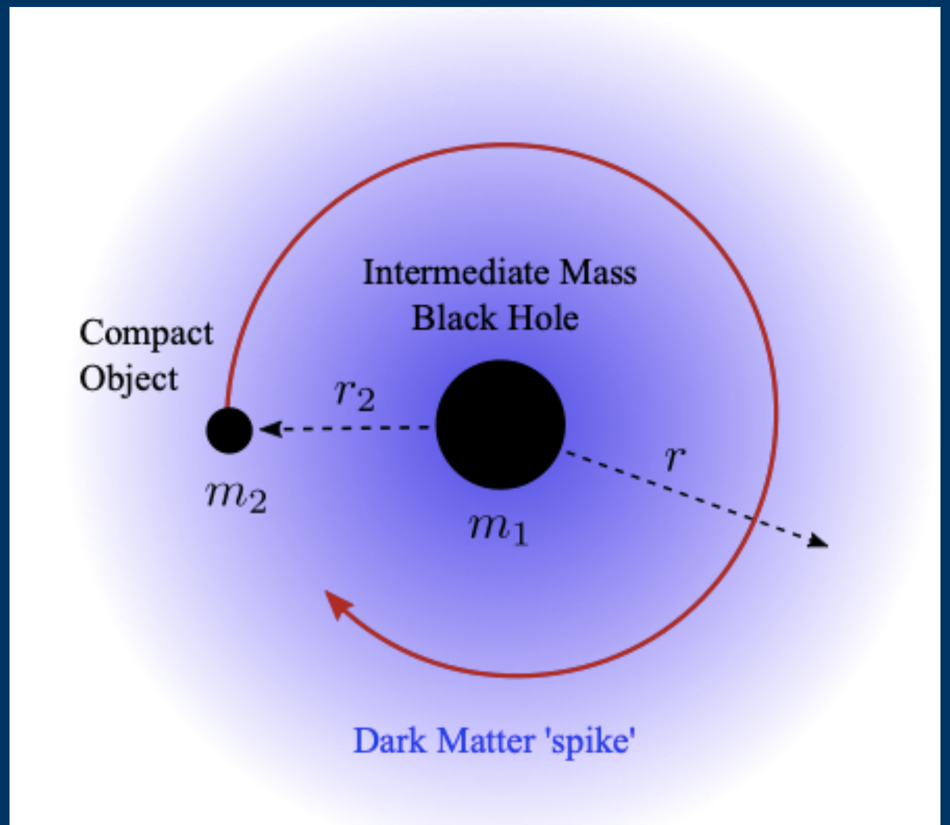
Dietrich et. al. 2019
Cooling binary neutron star remnants via nucleon-nucleon-axion bremsstrahlung

Interactions e.g. bremsstrahlung, or attractive self interactions

Bamber et. al. 2021
Growth of accretion driven scalar hair around Kerr black holes



Kavanagh et. al. 2020, Coogan et. al. 2022
Measuring the dark matter environments of black hole binaries with gravitational waves



Dark matter minispikes (adiabatic growth, accretion)

Dark matter overdensity scenarios

Superradiance

Review by Brito et. al. (updated 2020)
Superradiance: New Frontiers in Black Hole Physics

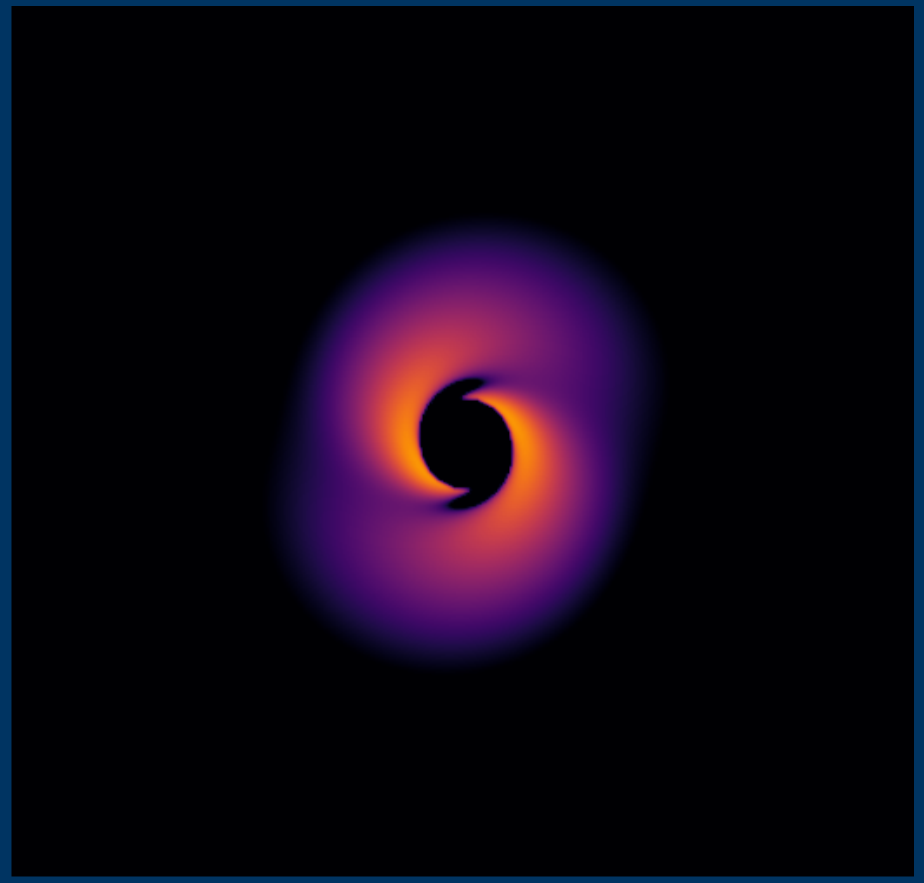


Image credit: Helfer / Clough

Exotic compact objects e.g. boson stars

SEE ALSO: Nature of Black Holes

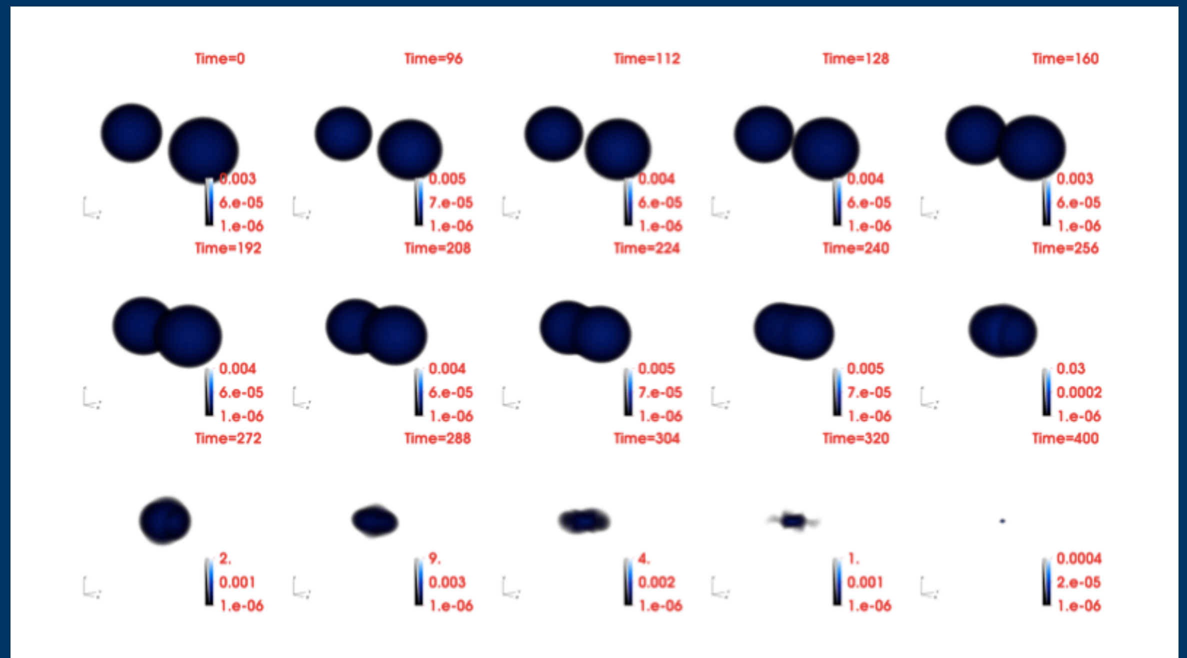


FIG. 5. **Snapshots of the time evolution of the energy density during the head-on collision of two PSs with $\omega/\mu_V = 0.8925$.** Time is given in code units.

Bustillo et. al. 2021
GW190521 as a merger of Proca stars: a potential new vector boson of 8.7 × 10−13 eV

Example 1: Superradiance with light bosons

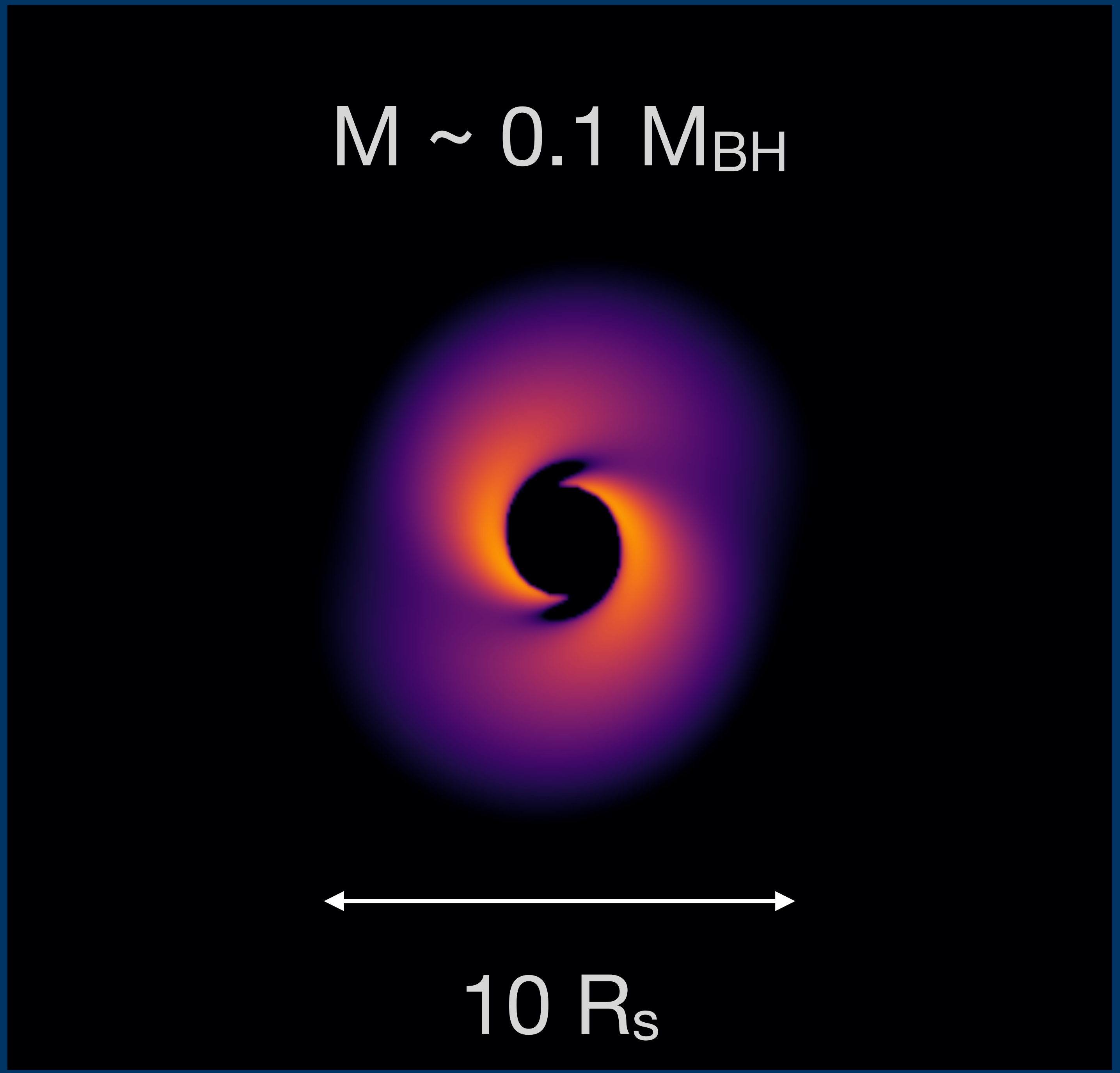


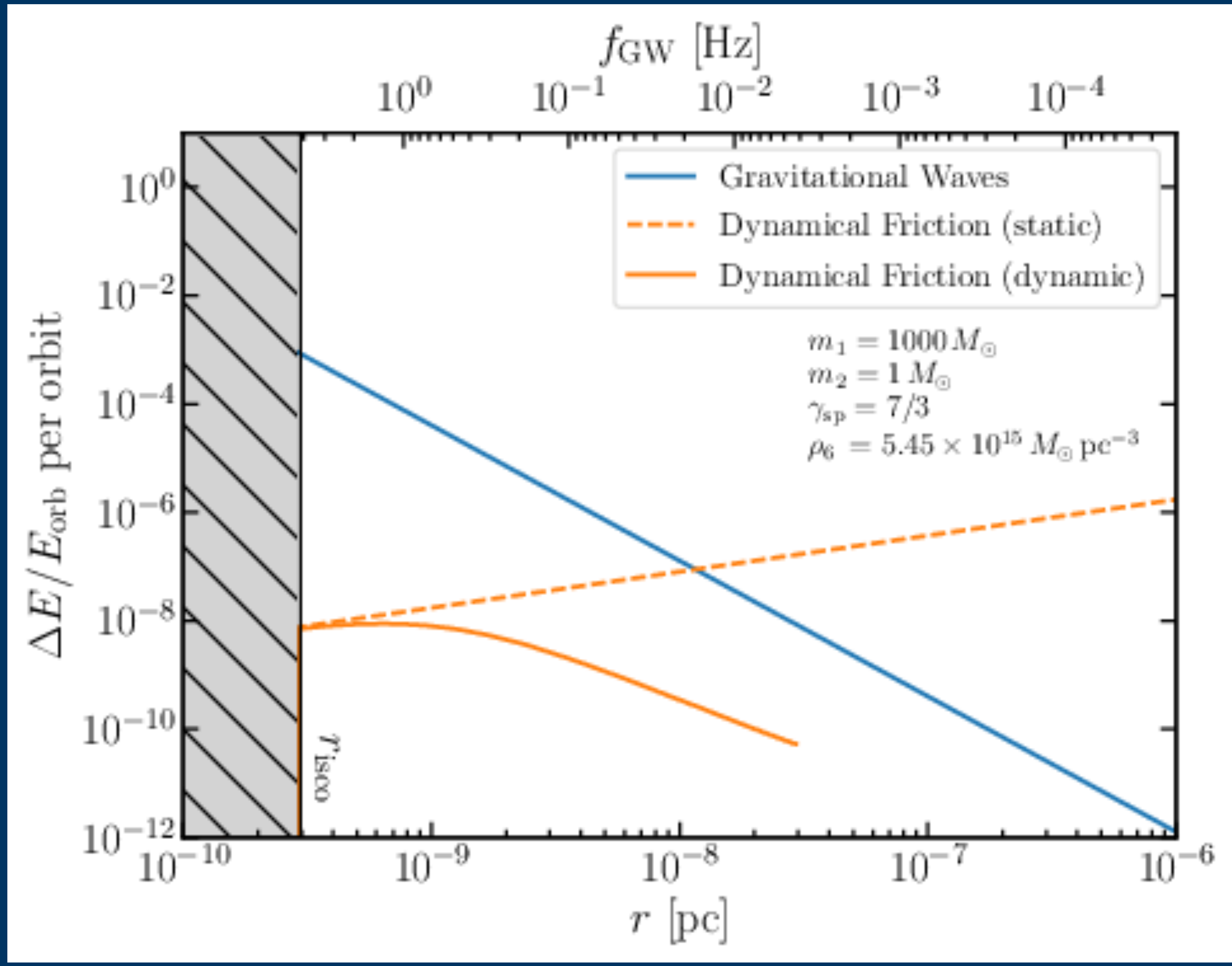
Image credit: Helfer / Clough

Superradiant boson densities (best case) $\rho / R_S^{-2} \sim 10^{-5}$

East et.al. 2017
Superradiant Instability and Backreaction of Massive Vector Fields around Kerr Black Holes

- Dephasing of GW signal due to:
  - impact of DM density on background metric - change of geodesic trajectories (neglect dynamical friction, accretion)
- In principle detectable in EMRIs with long inspiral times (10^5 orbits) in band
  Hannuksela et. al. 2019
  Probing the existence of ultralight bosons with a single gravitational-wave measurement
- Note also other potential observables from decay of the cloud, and resulting distribution of BH spins

Example 2: DM minispikes from particle DM



Kavanagh et. al. 2020, Coogan et. al. 2022
Detecting dark matter around black holes with gravitational waves: Effects of dark-matter dynamics on the gravitational waveform

DM overdensity described by power law $\rho \sim \rho_0 \left(\frac{r}{r_0}\right)^{-\gamma}$

- Dephasing of GW signal due to dynamical friction (neglect accretion, and impact of DM density on background metric)

- Phase space evolution of particles is important

- Impact on eccentricity of orbits during inspiral
  Becker et.al. 2021
  Circularization vs. Eccentrification in Intermediate Mass Ratio Inspirals inside Dark Matter Spikes

2. Can we measure that imprint *independently* of other factors?

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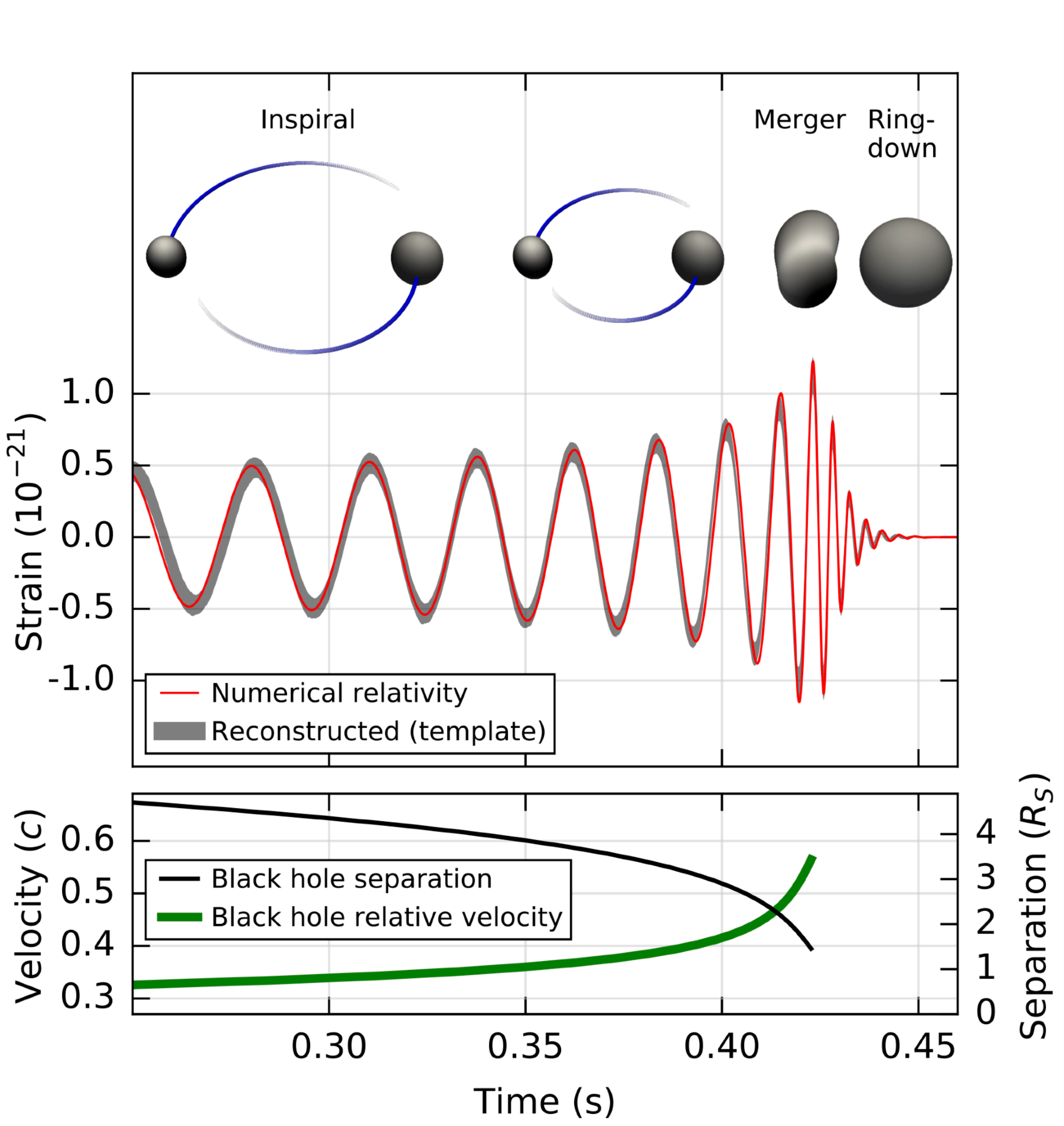
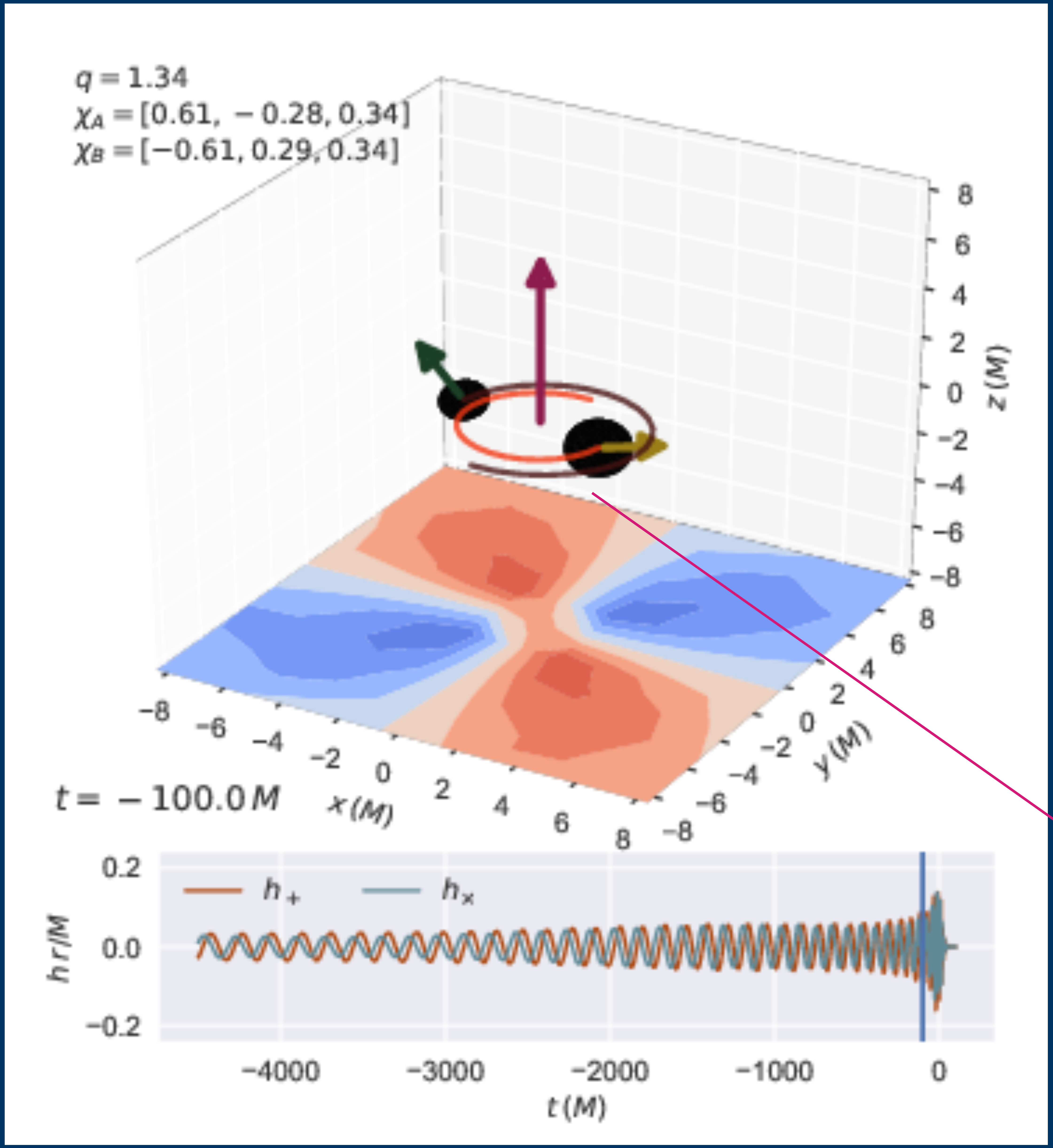
2. Is there a degeneracy between dark matter and other binary system parameters, and if so can it be broken?



Having additional matter around will change the different parts of the waveform in a distinctive way

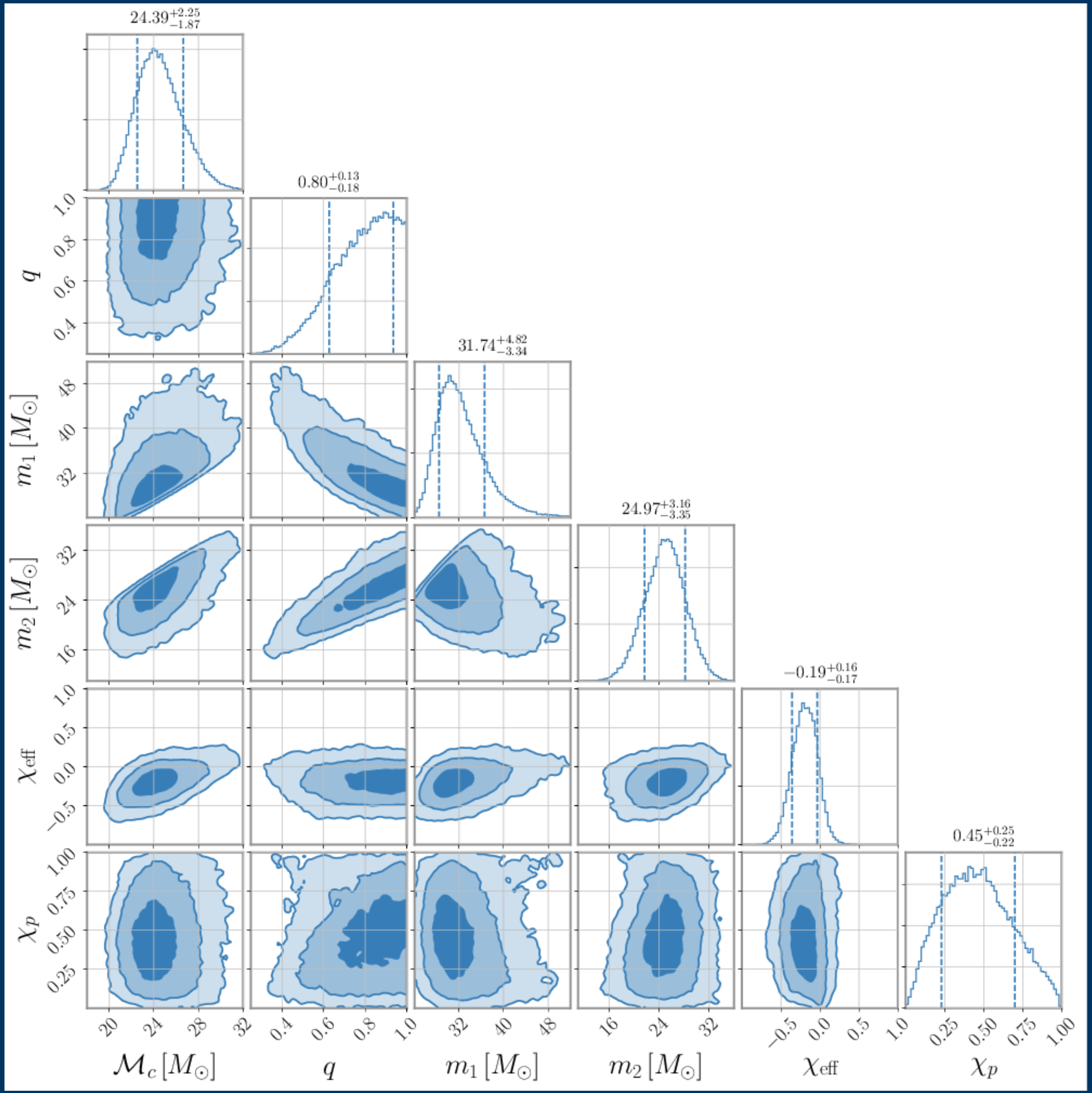


Varma et. al. 2021
The binary black hole explorer: on-the-fly visualizations of precessing binary black holes

Many intrinsic parameters to fit, plus observer effects

“the distance to the source; the time of merger; five angles specifying the position of the source on the sky, the plane of the orbit, and the orbital phase at some given time; and the masses and spin angular momenta of the two bodies—fifteen parameters in all, assuming that the eccentricity of the orbit is negligible”

Cutler et. al. 1994
Gravitational waves from merging compact binaries: How accurately can one extract the binary’s parameters from the inspiral waveform?

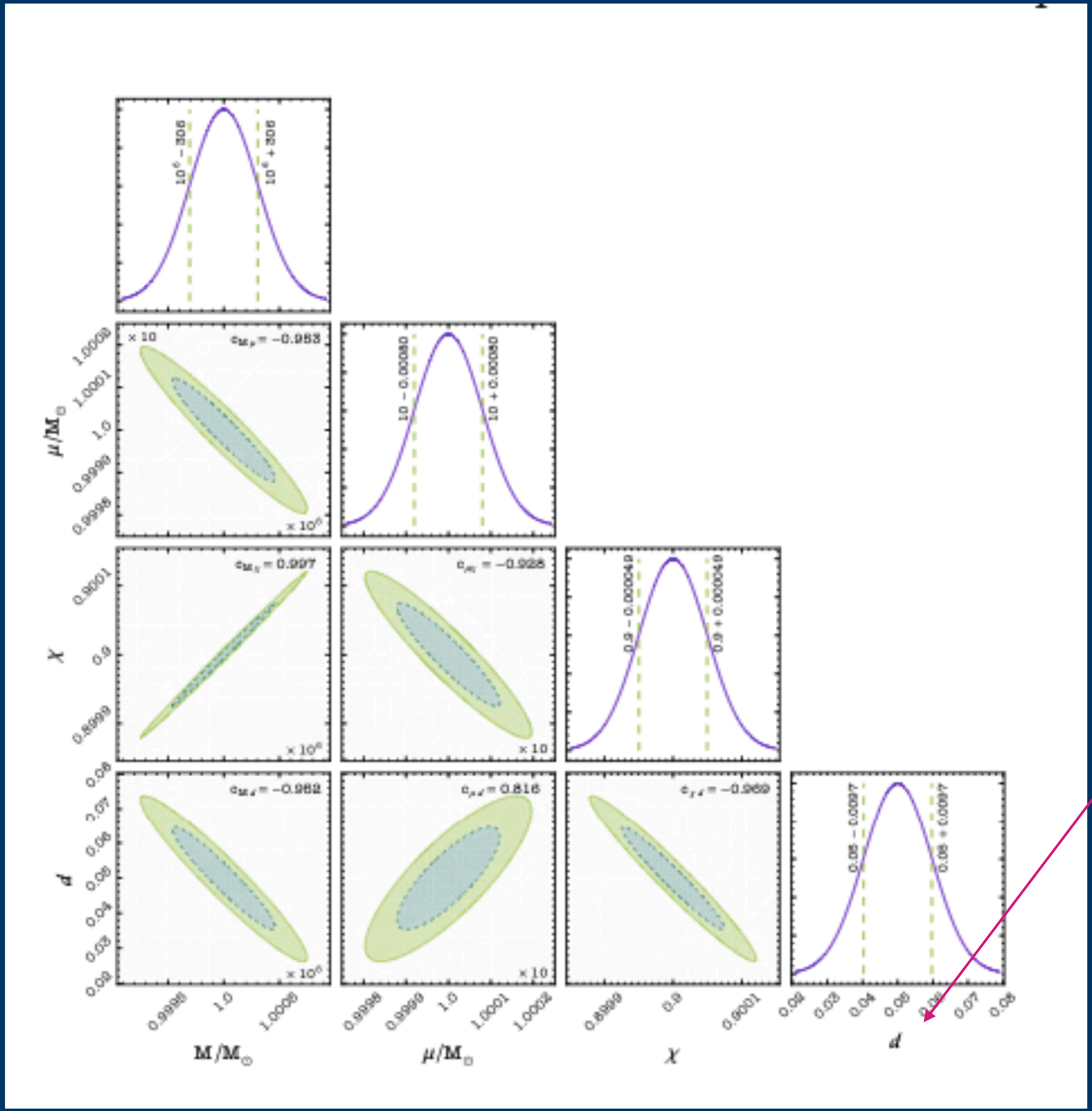


Pratten et. al. 2021
Assessing gravitational-wave binary black hole candidates with Bayesian odds

Even with a reduced set of the binary parameters, this is challenging

SEE ALSO: Astrophysics and Waveform systematics

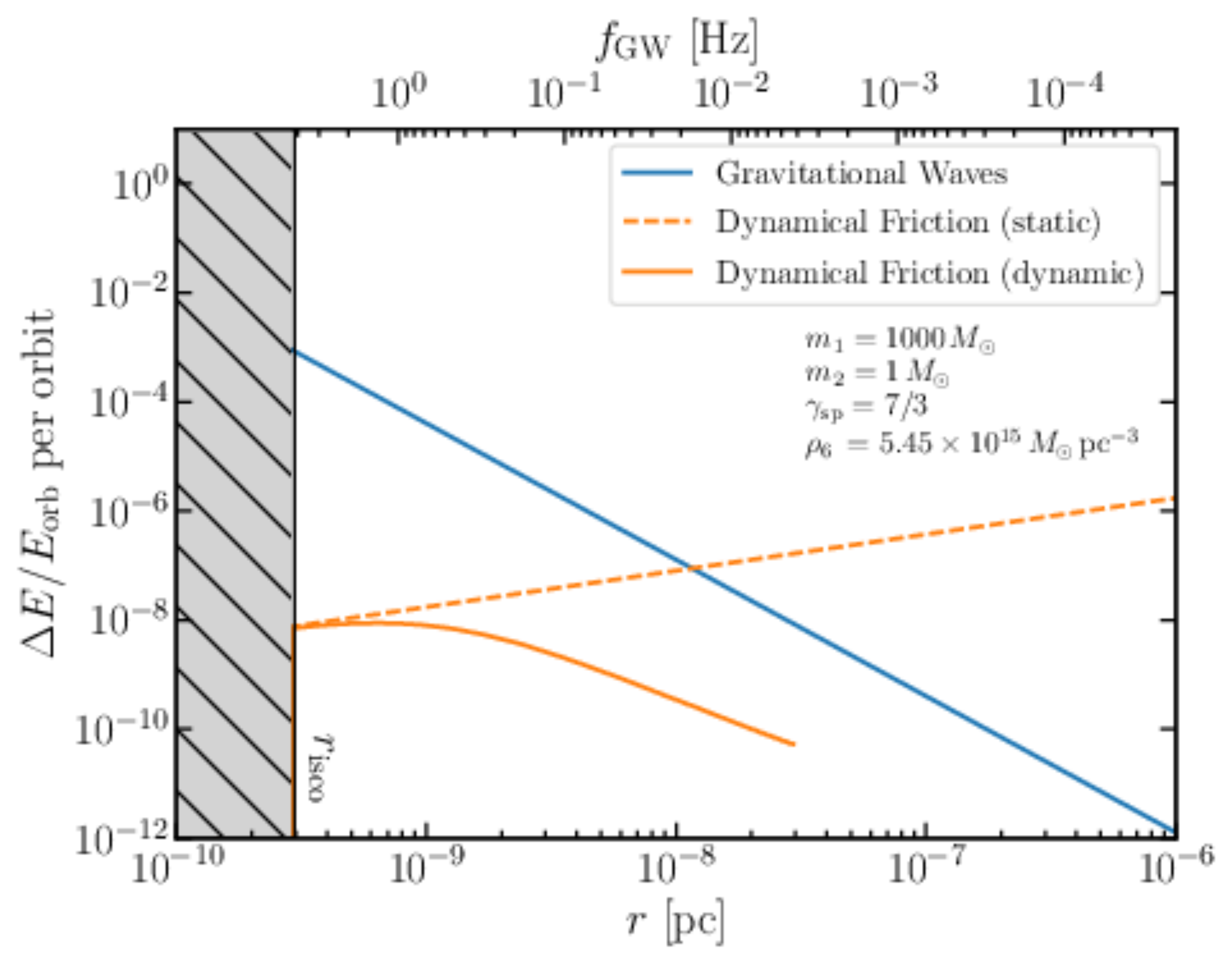
Will DM parameters be degenerate with others?



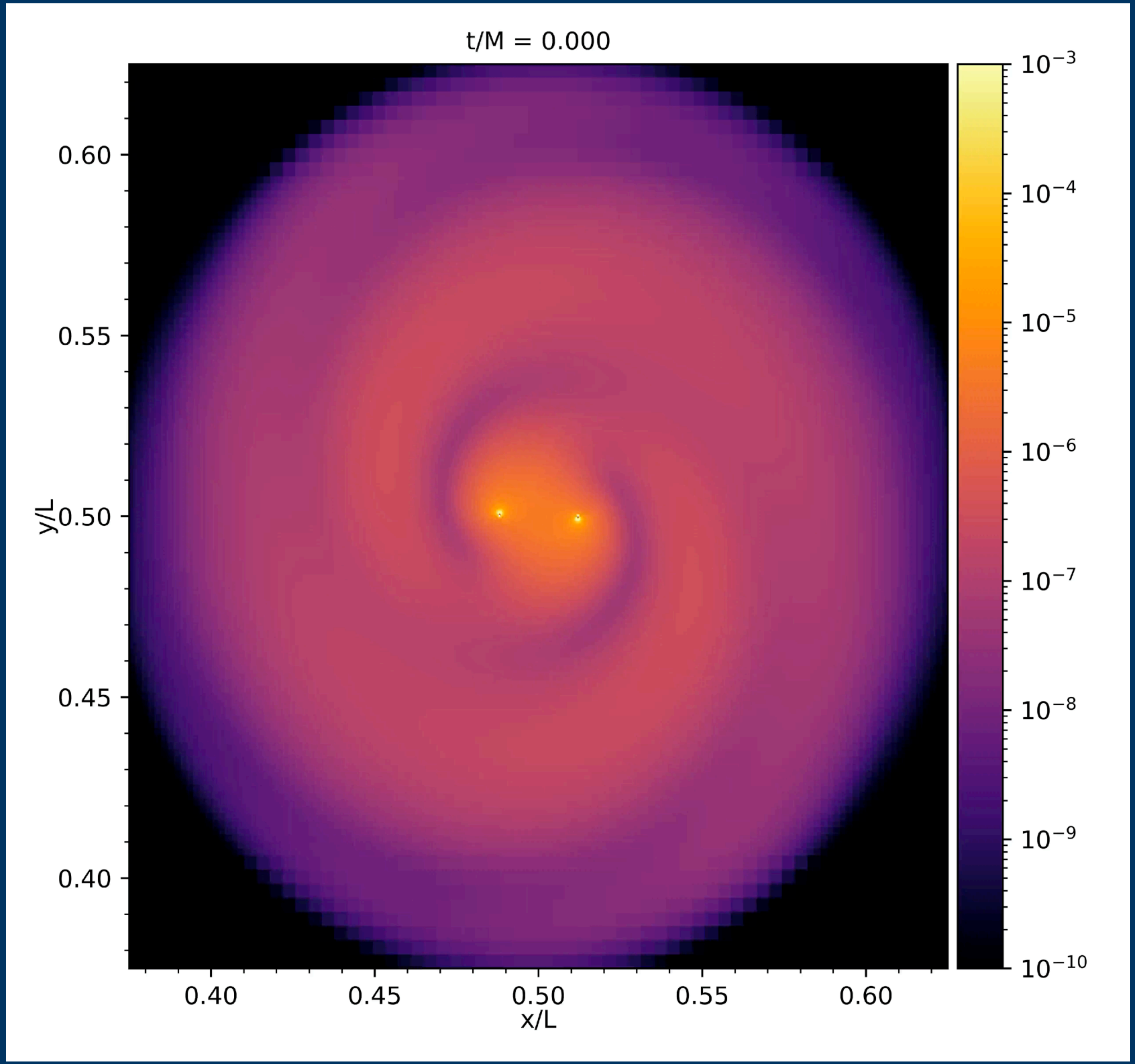
Scalar charge additionally constrained to be non zero

Maselli et. al. 2022
Detecting fundamental fields with LISA observations of gravitational waves from extreme mass-ratio inspirals

Will require accurate modelling of evolution, including that of the DM itself



What is the "right" DM profile on smaller scales around BHs?



Movie credit: Jamie Bamber, Oxford

3. Can we use LISA measurements to learn more about the *nature* of DM?

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3. Is the data sufficient to distinguish between different dark matter candidates (their mass, spin etc), and other effects (e.g. astrophysical accretion or modified gravity?)

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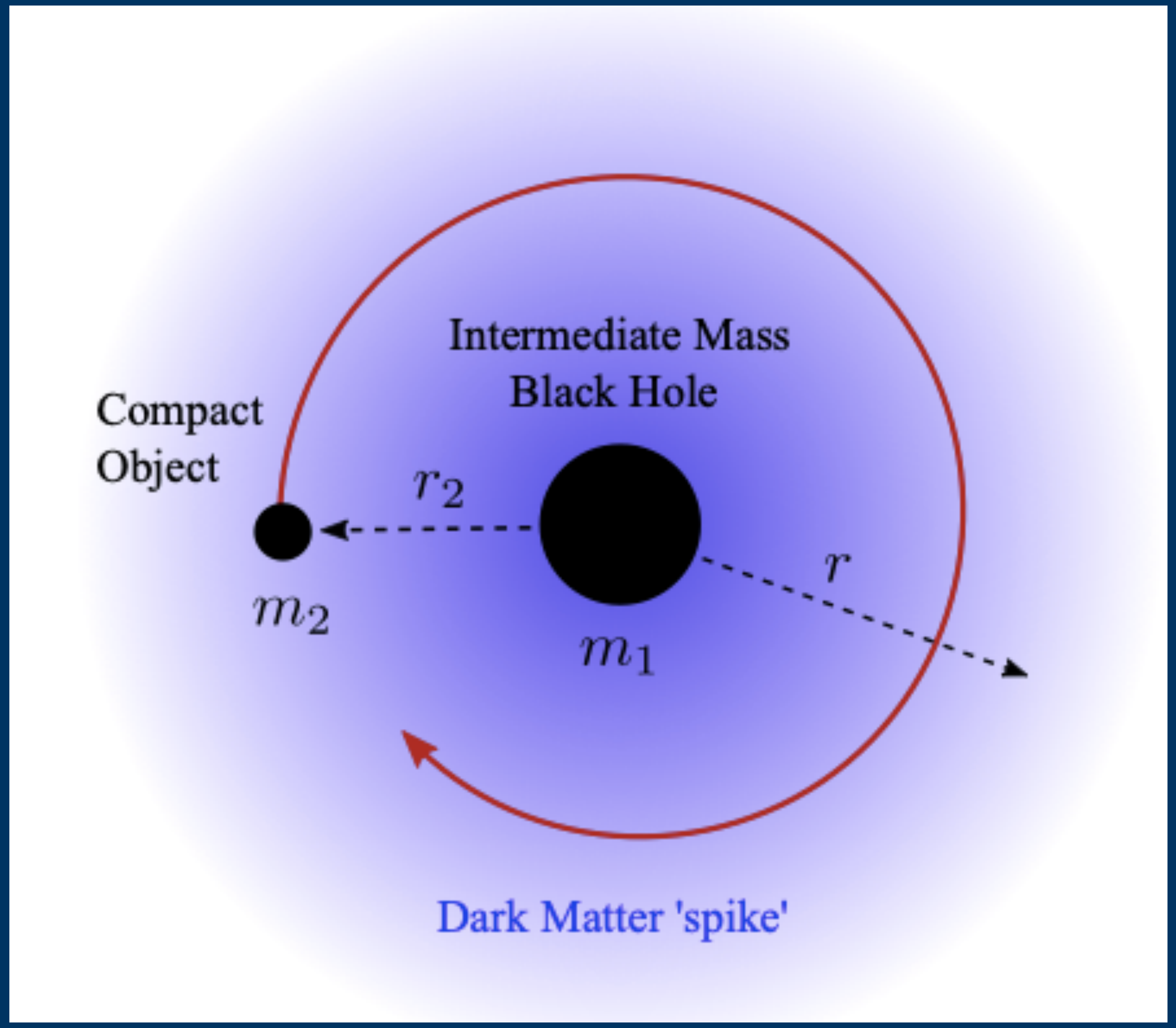
Traykova et. al. 2021
Dynamical friction from scalar dark matter in the relativistic regime



Kavanagh et. al. 2020, Coogan et. al. 2022
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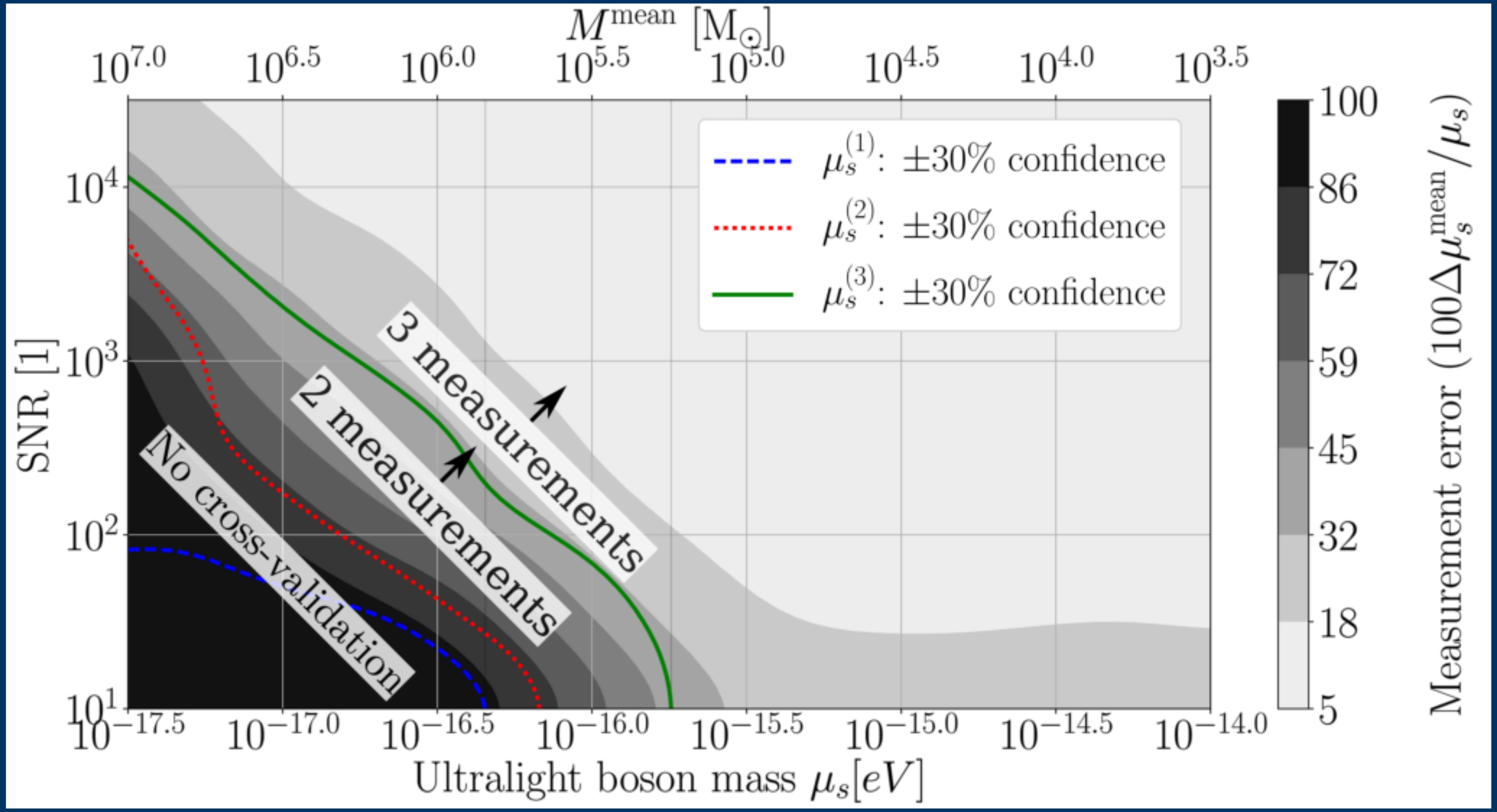

Hannuksela et. al. 2019
Probing the existence of ultralight bosons with a single gravitational-wave measurement

3. Is the data sufficient to distinguish between DM and other effects (e.g. accretion discs or modified gravity?)

Event Horizon Telescope

We will need to understand alternatives better too

SEE ALSO: Tests of General Relativity

SEE ALSO: Astrophysics and Waveform systematics

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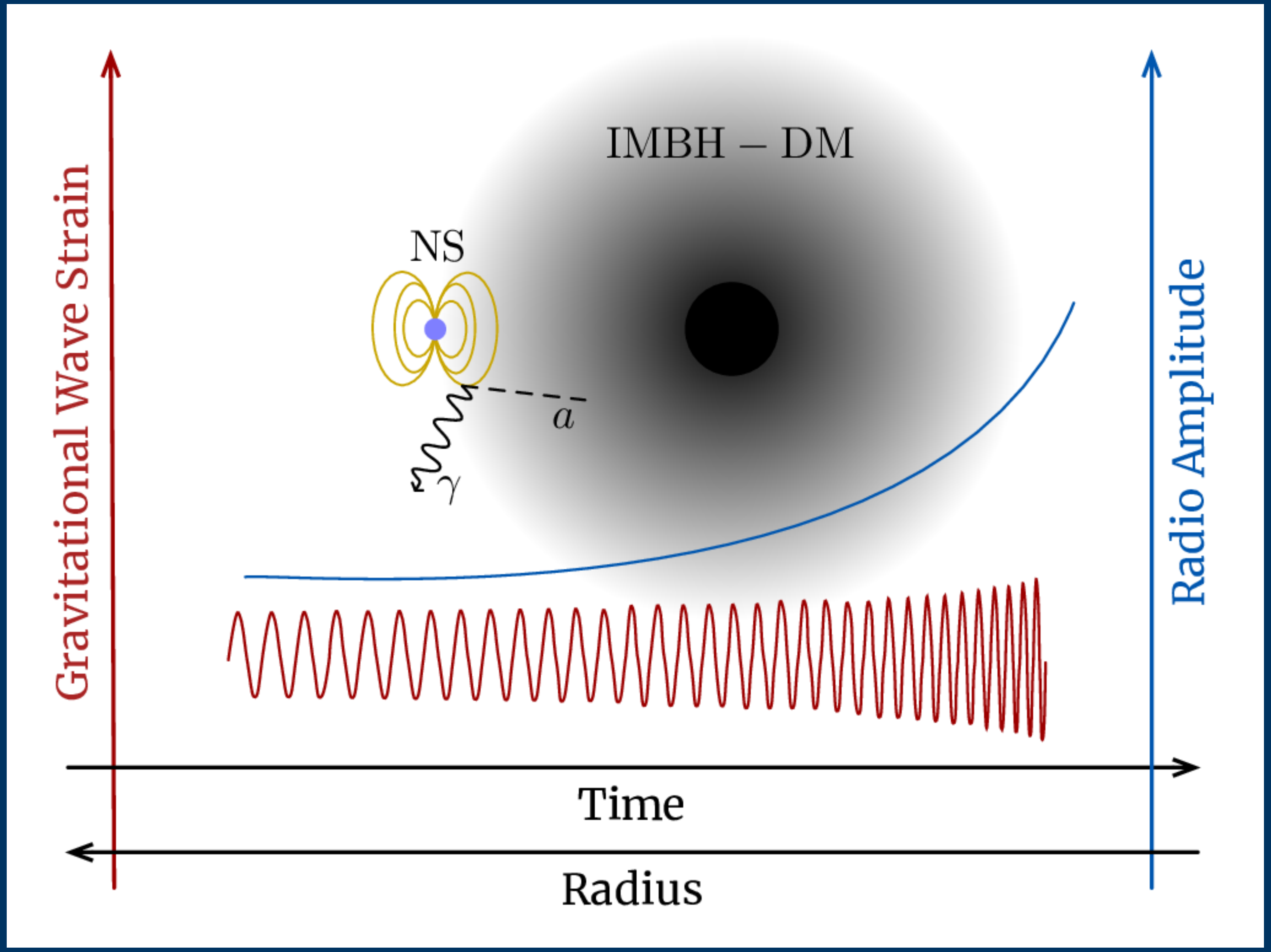

Edwards et. al. 2020
A Unique Multi-Messenger Signal of QCD Axion Dark Matter

Potential for the effect of standard model interactions to break degeneracies

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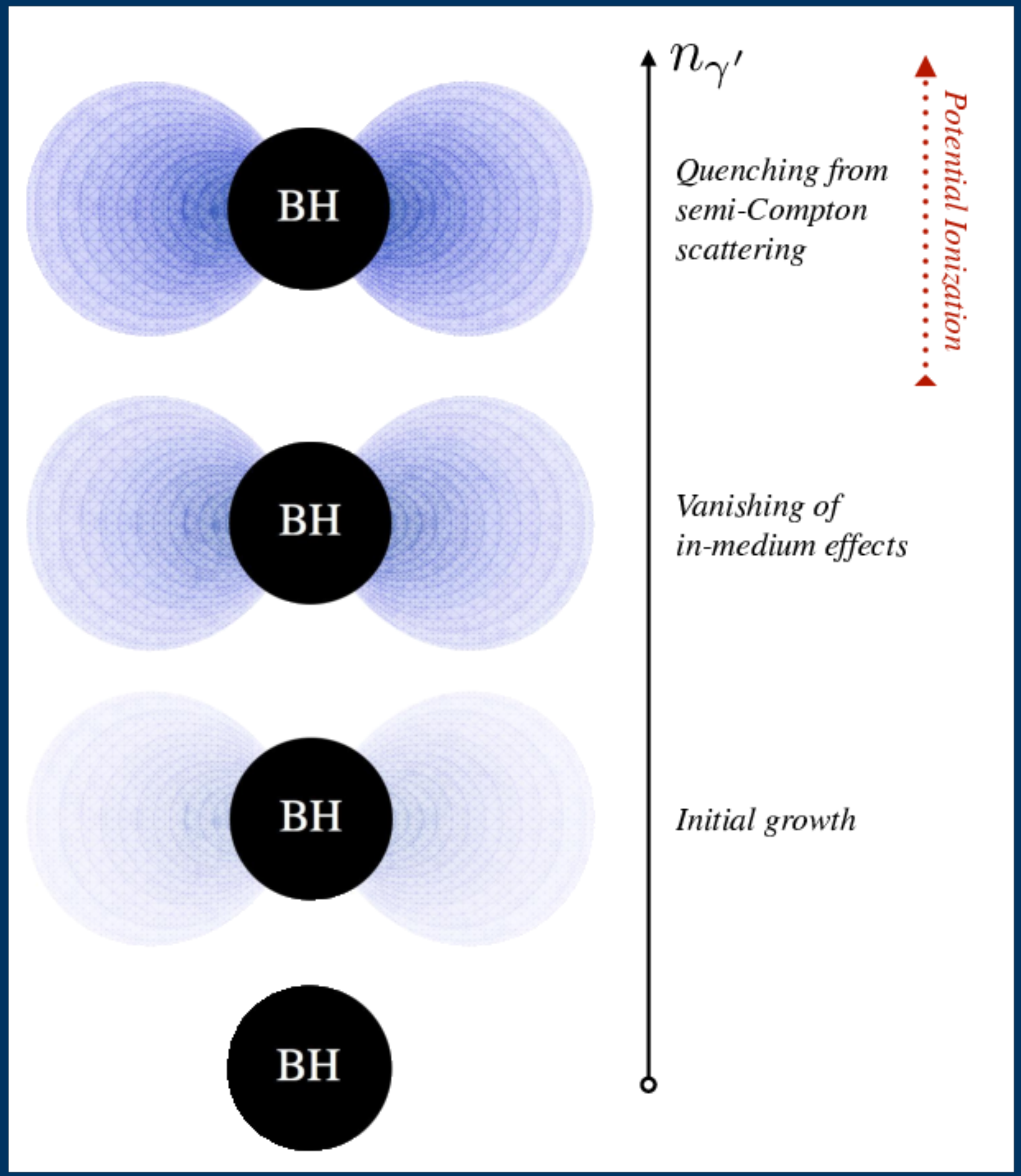

Caputo et. al.
Electromagnetic signatures of dark photon superradiance

Potential for the effect of self interactions to break degeneracies

Burning questions

H. Burning Questions

- The effects of dark matter on GW signals may often be degenerate with ‘environmental’ astrophysical effects (cf. Sect. VII). It will be absolutely crucial for the success of LISA to devote continual effort to disentangle these as much as possible.

- LISA has the potential to detect or constrain the presence of both ultralight and heavier dark matter fields in regions of parameter space that are complementary to those covered by ground-based GW observations. However, the waveform modelling for IMRIs and EMRIs embedded in DM halos is but in its infancy. More work is needed to build waveform models that incorporate the effects of DM fields in mergers, covering a significant parameter space, and that are sufficiently accurate for data analysis purposes.

- Beyond this, it will be important to study BBH dynamics with ultralight boson clouds with full NR simulations in order to understand how the presence, and the dynamics, of such boson clouds could be imprinted in the late stages of BBH mergers.