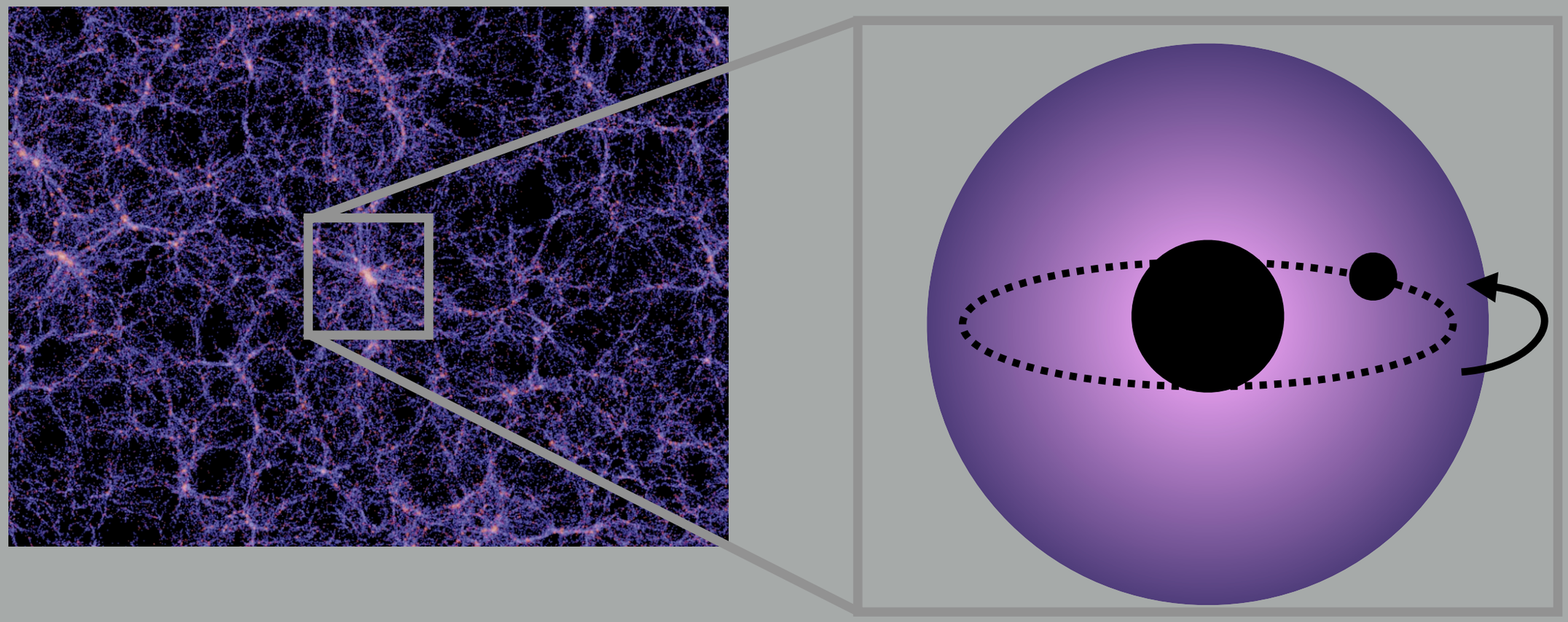
Dark matter and primordial black holes: Perspectives from the working group



David A. Nichols, University of Virginia, Dept. of Physics

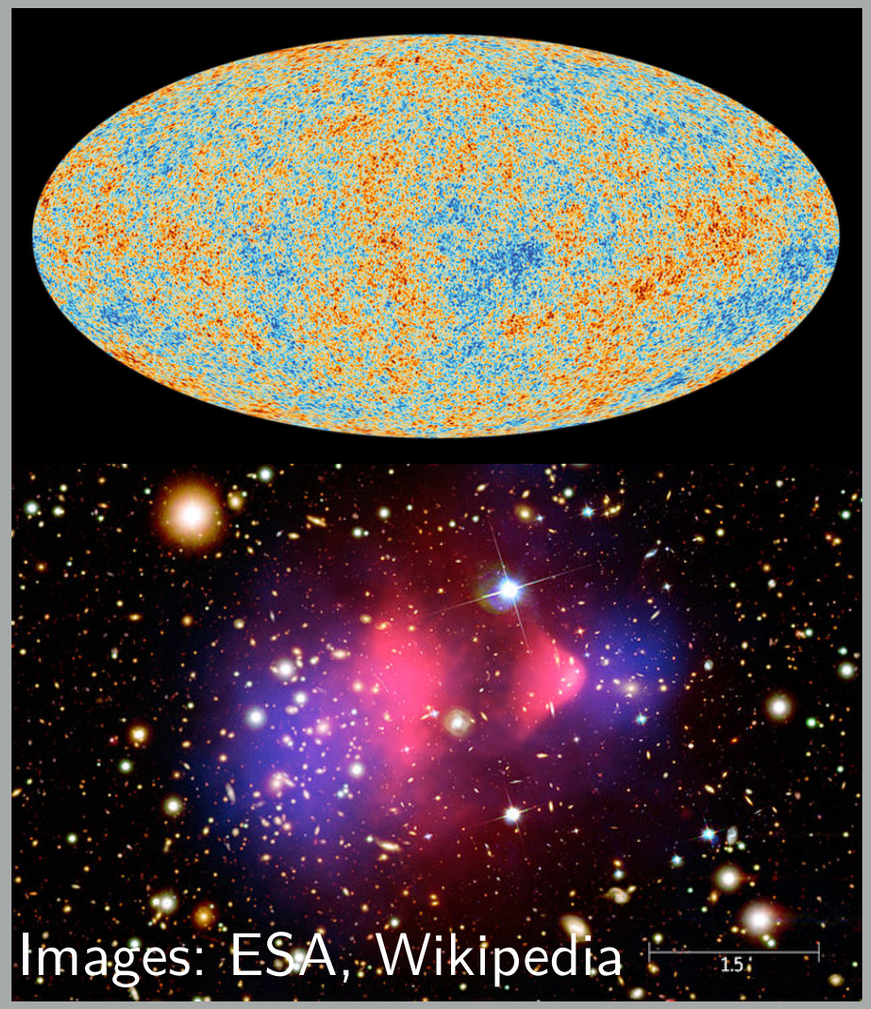
Fundamental Physics with LISA

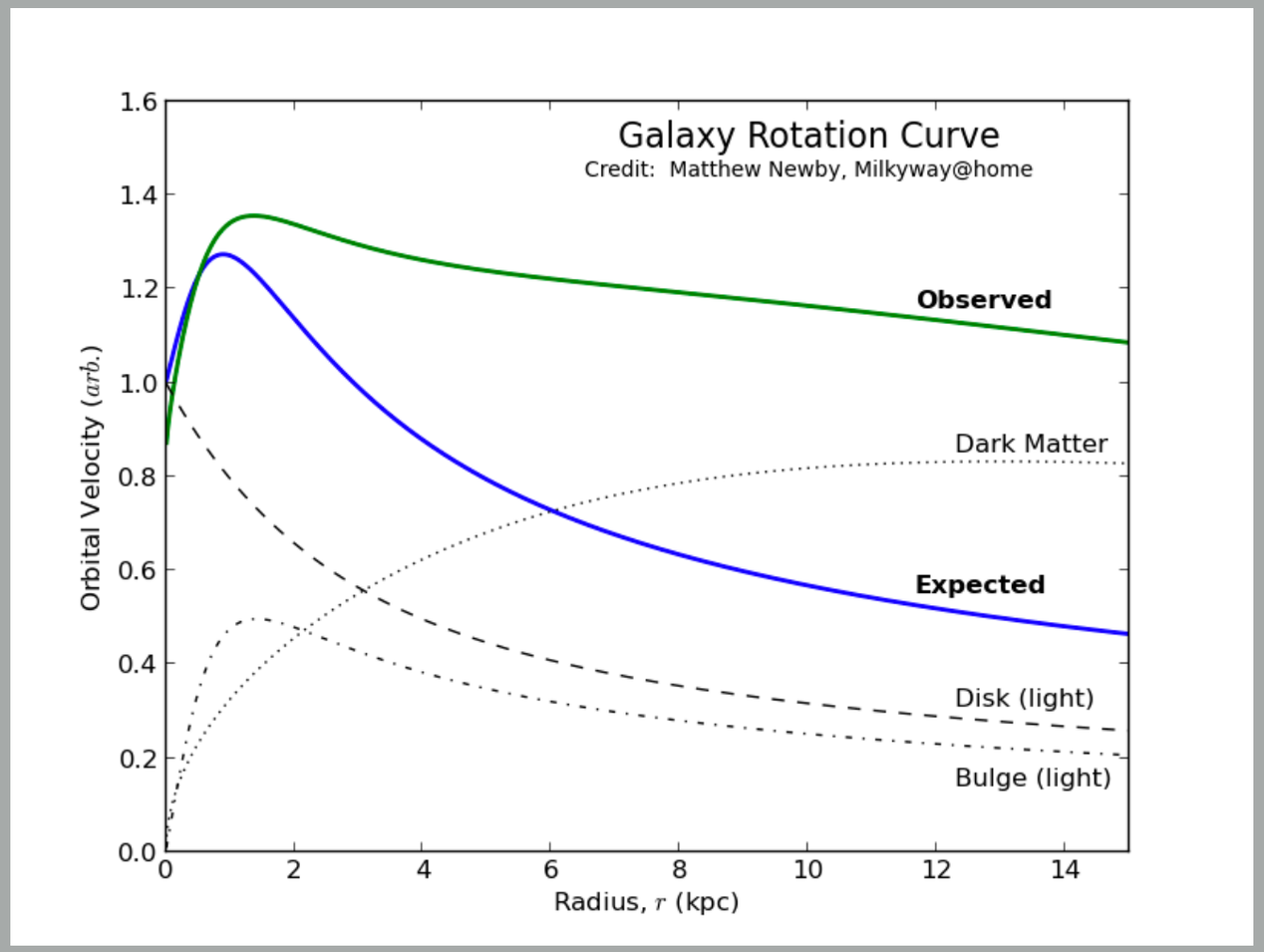
Niels Bohr Institute

10 August 2023

1. Astrophysical Evidence for Cold Dark Matter

- Strong evidence for cold dark matter (DM) on large scales (CMB, galaxy clusters, galaxy rotation curves)





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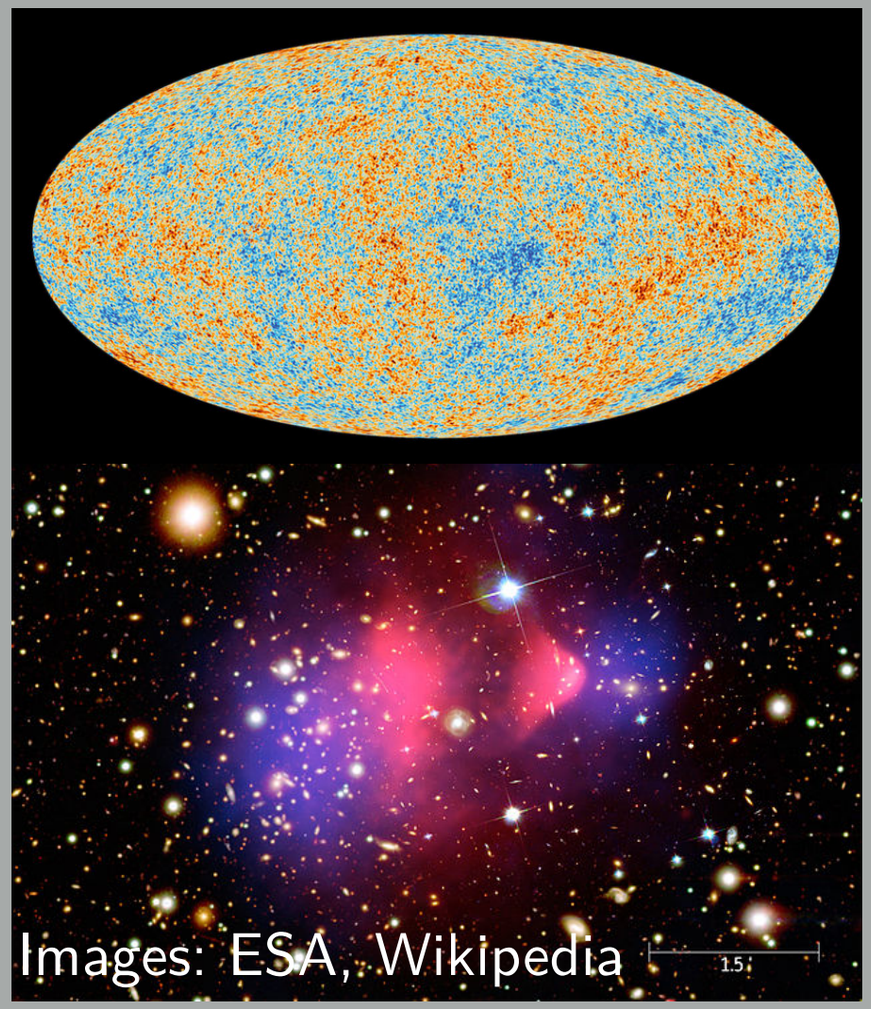

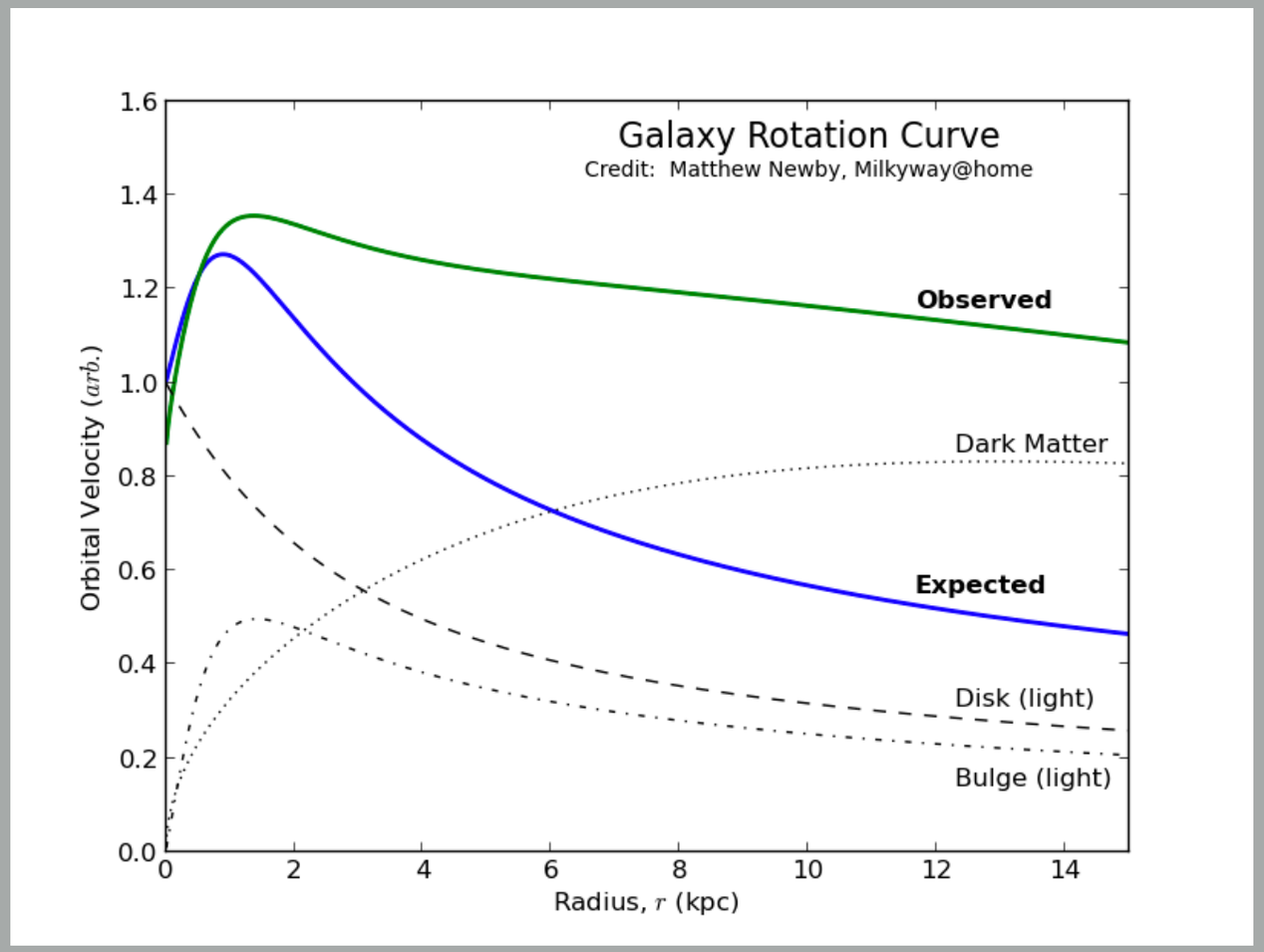

- DM on astrophysical sub-kpc scales less well measured
- Microscopic models of DM have different astrophysical predictions; underlying particle/field still unknown

Dark Matter Properties & Models

DM Properties

- DM should be: stable (seen today and in CMB), cold (not relativistic), & weakly interacting (e.g., no/minimal charge)
- Planck+BAO: DM is 26.8% of the "mass-energy budget"
- No standard model (SM) particle can explain DM
- Without further assumptions/models can't say much else

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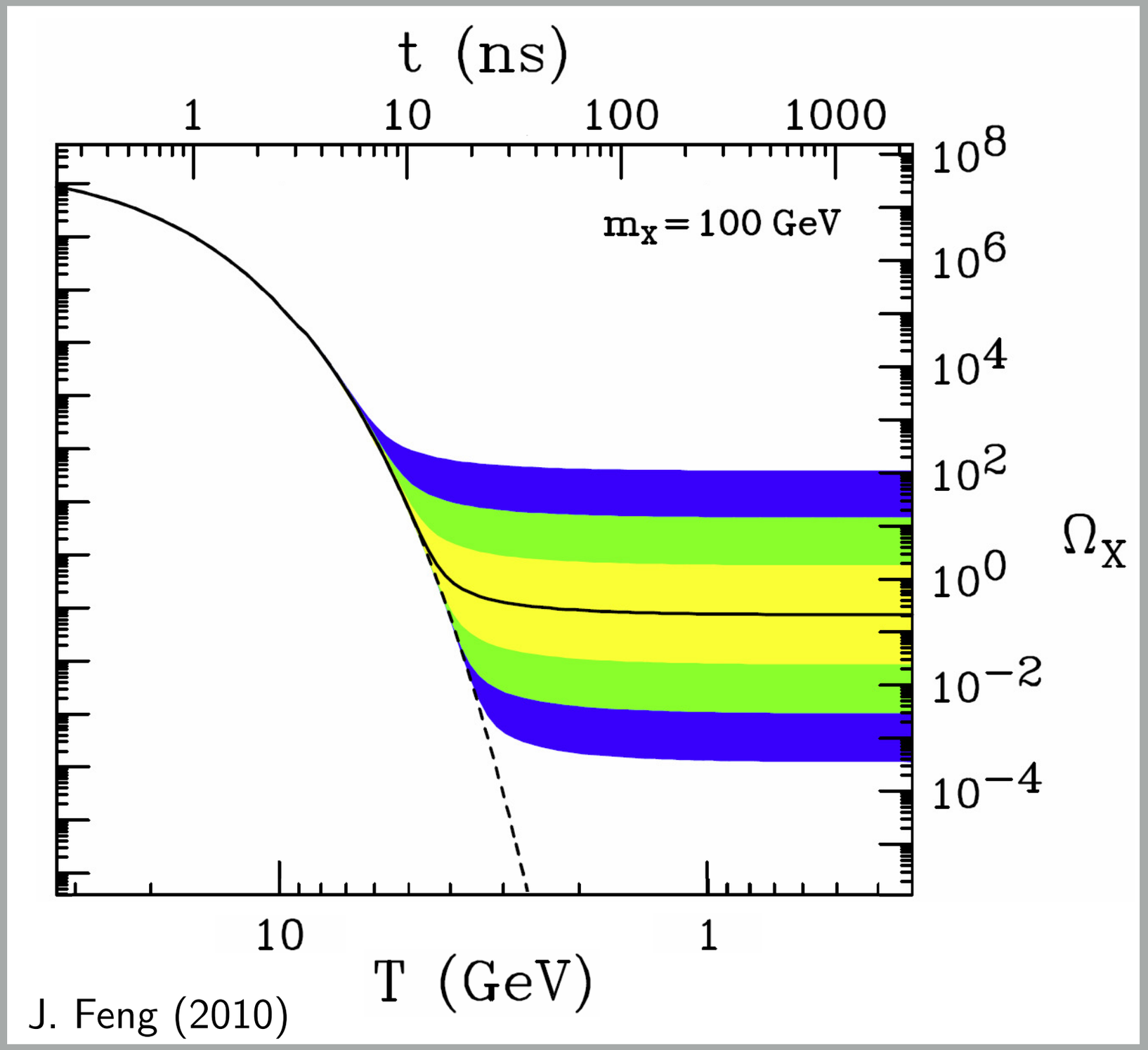
Thermal Freeze Out & WIMPs

- Assume DM had "thermal history" similar to SM particles in the early Universe: in equilibrium when $T > m_{DM}$
- Universe expands & cools, DM not produced, annihilates until too dilute to interact, and then "freezes out"
- What cross section needed to get 26.8% of energy budget?

WIMP "Miracle" (or Coincidence)



J. Feng (2010)

- Averaged cross section needed is

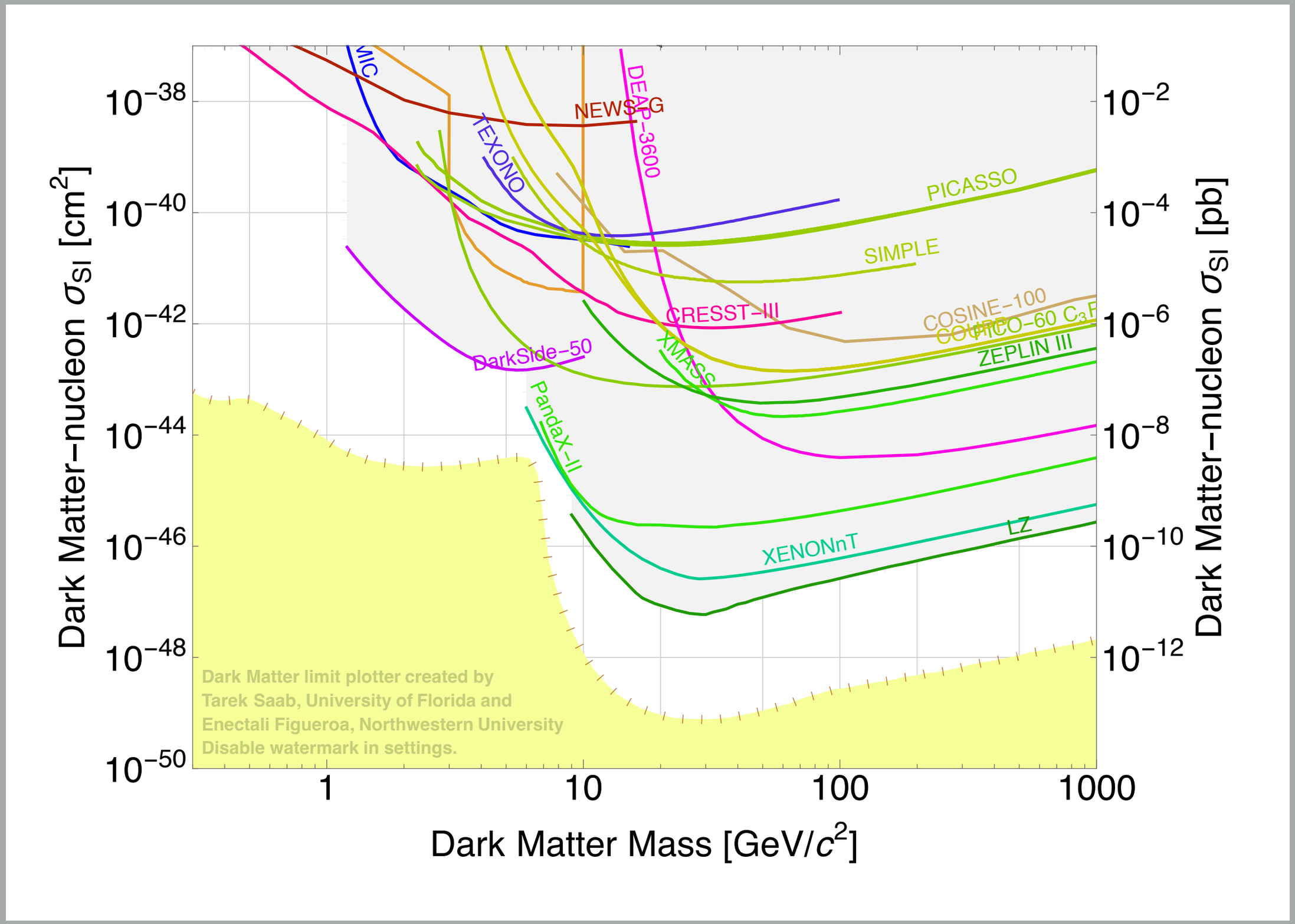
$$\langle \sigma v \rangle \sim 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$$

  - In terms of m_{DM} and coupling, g

$$\langle \sigma v \rangle \sim \frac{g^4}{m_{DM}^2}$$

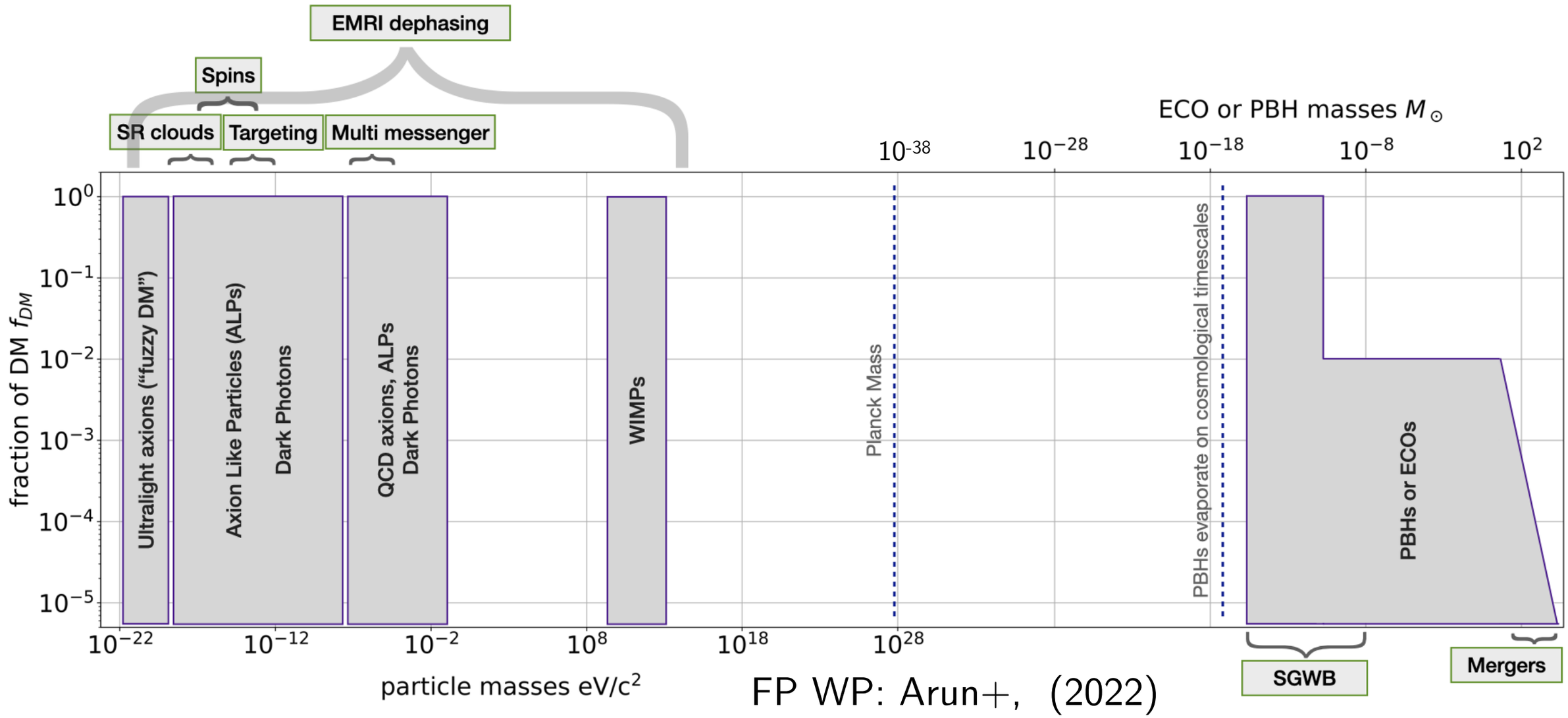
  - $g \sim g_{weak}$ and $m_{DM} \sim 100$ GeV gives right cross section!

WIMP Constrained Parameter Space



- WIMP not found and nearing neutrino floor

Renaissance/Opportunity for Other Models



FP WP: Arun+, (2022)

- Notes: *not* a comprehensive list of all DM models
- 50 orders of magnitude of fundamental particle masses
- 90 orders of magnitude of masses in total!

Outline/Plan for This Talk

Will cover

1. Introduction and background (✓)
2. "Heavy" particle dark matter (main focus)
3. Primordial black holes (PBHs) (briefly; see cosmo talks)

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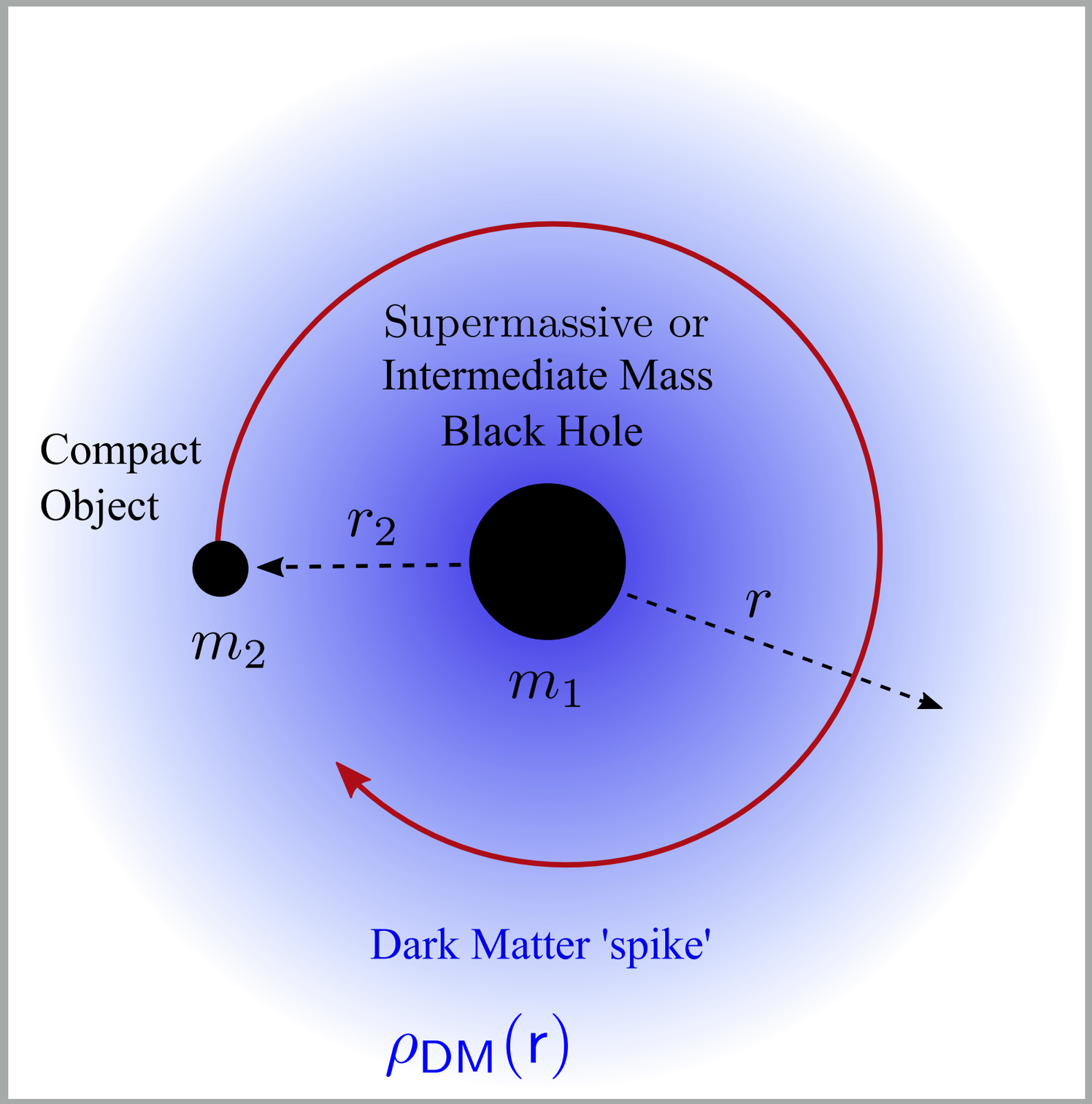
Will not cover

A. (Ultra-)light dark matter (see next talk)
B. Modified gravity (later today/tomorrow)
C. Exotic compact objects (yesterday)

2. Extreme/Intermediate Mass-Ratio Inspirals



- E/IMRIs+DM:

1. S/IMBH w/ mass m_1
2. Secondary compact object (BH or NS), w/ mass m_2
3. DM w/ density $\rho_{\rm DM}(r)$ and enclosed mass w/ in r_2: $m_{\rm enc}(r_2)$

- Mass ratio

  $q \equiv m_2/m_1$

  $q \in (10^{-2}, 10^{-7})$

E/IMRIs as a Spacetime Mapping Tool

- "Ryan's Theorem" (1994): SMBH metric can be mapped during an EMRI inspiral to test BH nature of primary
- Possible b/c of $\sim 10^4$ - 10^6 orbits in inspiral in LISA band allows for precise GW measurement of BH geometry
- Conversely, even "environmental" effects could disrupt this mapping and reveal info about environs + metric

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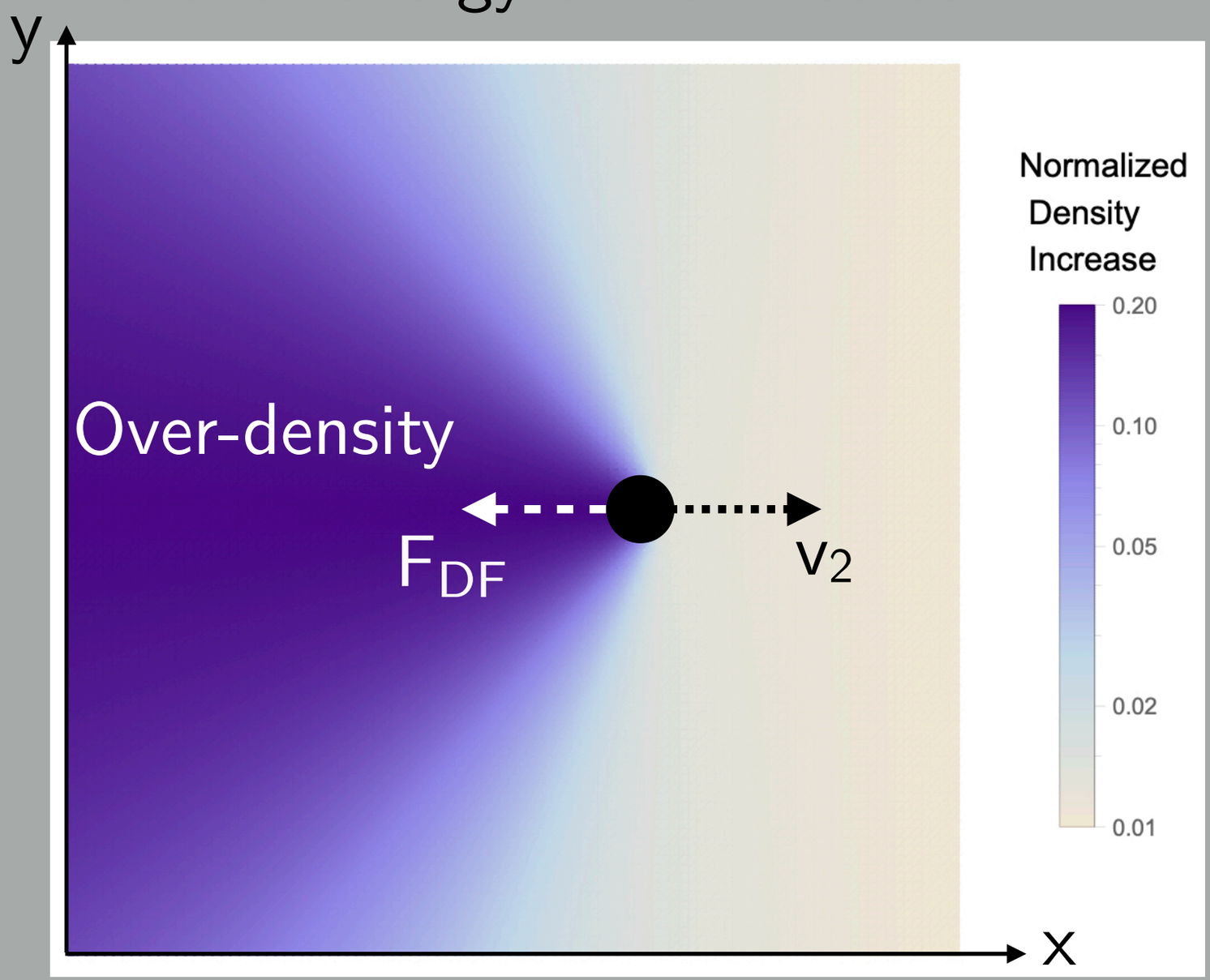
- With DM, 3 types of disruptions can occur:

1. Mass enclosed within orbit varies during inspiral
2. Mass accreted during inspiral makes mass time dependent
3. Dynamical friction transfers energy from orbit to dark matter distribution (more on this next)

Dynamical Friction (DF) in E/IMRIs

- DM speeds up inspiral from dynamical friction, b/c E/IMRI orbital energy transferred to DM binding energy



- Dynamical friction (DF)
  S. Chandrasekhar (1943)
  effective gravitational drag from an over-density in a wake formed as a body moves through DM
- Coulomb logarithm depends on

$$F_{DF} \sim \left(\frac{Gm_2}{v_2}\right)^2 \rho_{DM}(r_2; v < v_2) \log \Lambda \qquad \Lambda \sim \frac{b_{max}}{b_{min}}$$

DM GW Effects: Order of Magnitude

- Enclosed mass: frequency change via $M \to M + m_{enc}(r_2)$

$$\frac{m_{enc}(r_2)}{m_1} \sim 10^{-18} \left(\frac{m_1}{10^6 M_\odot}\right)^2 \left(\frac{r_2}{100 m_1}\right)^3 \left(\frac{\rho_{DM}}{10^3 M_\odot/pc^3}\right)$$

See Barausse, Cardoso, Pani (2014)

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- Largest effect from dynamical friction

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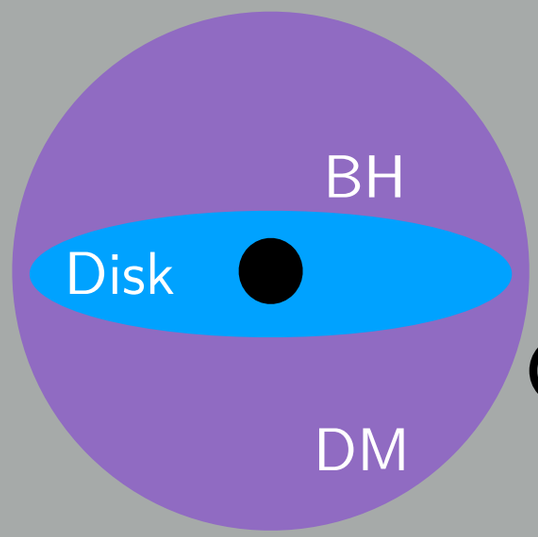
- Conclusion: We can't measure DM with I/EMRIs.

See Barausse, Cardoso, Pani (2014)

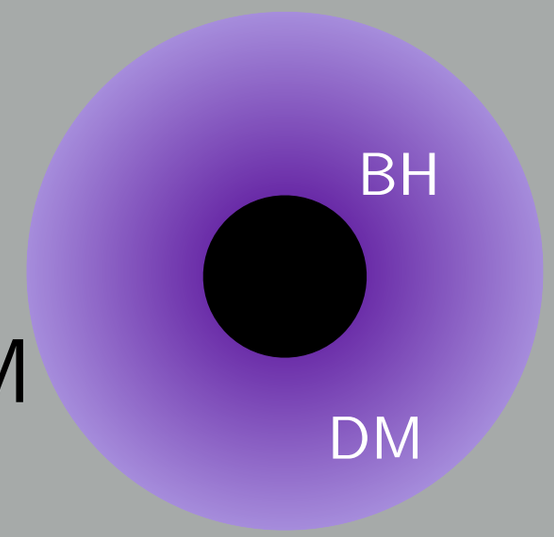
Formation of a DM "Spike"



BH slowly accretes matter

Changing potential redistributes DM

Gondalo & Silk (1999)



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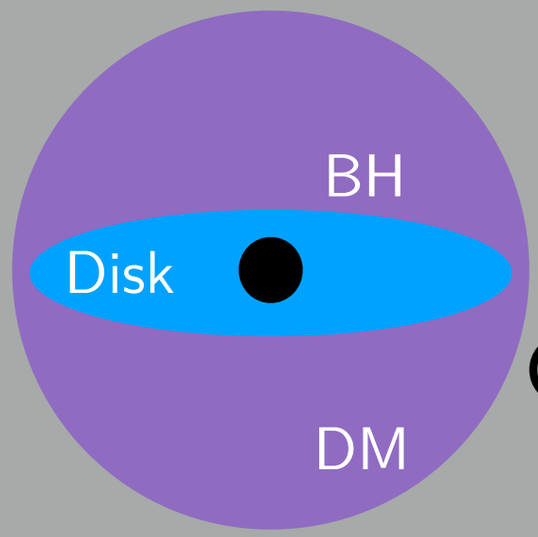

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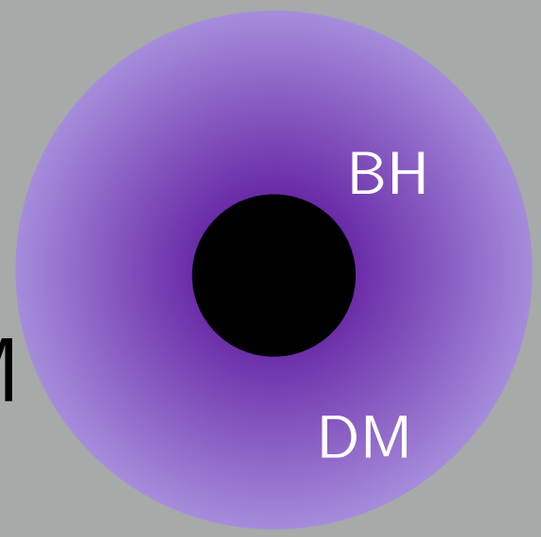

Initial density: $\alpha \in [0, 2]$

$$\rho_{\mathrm{DM}}(\mathrm{r}) = \rho_0 \left(\frac{\mathrm{r}_0}{\mathrm{r}}\right)^{\alpha}$$

Final density: $\gamma_{\mathrm{sp}} \in [9/4, 5/2]$

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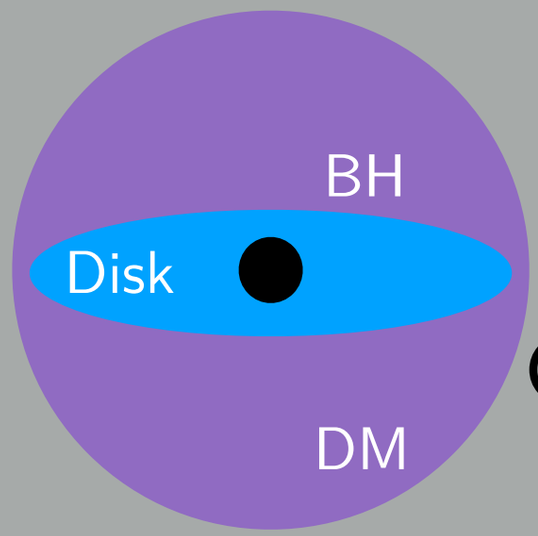

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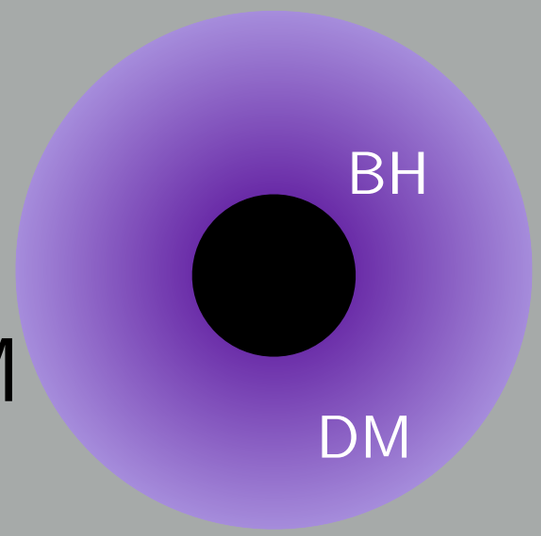

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- Galactic mergers
- Off-center growth
- Fast (non-adiabatic) growth
- & other processes... P. Ullio+ (2001)

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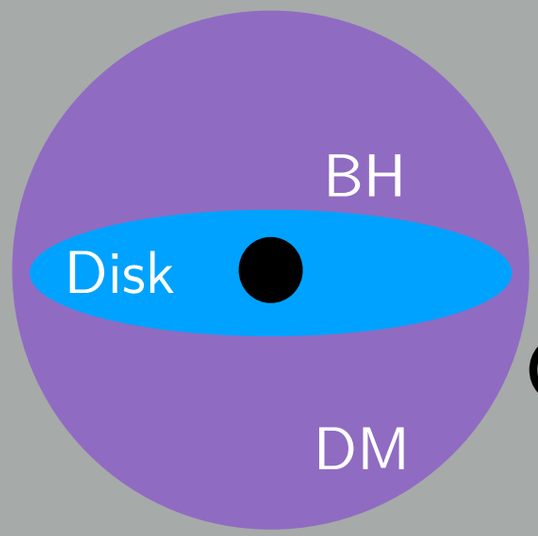

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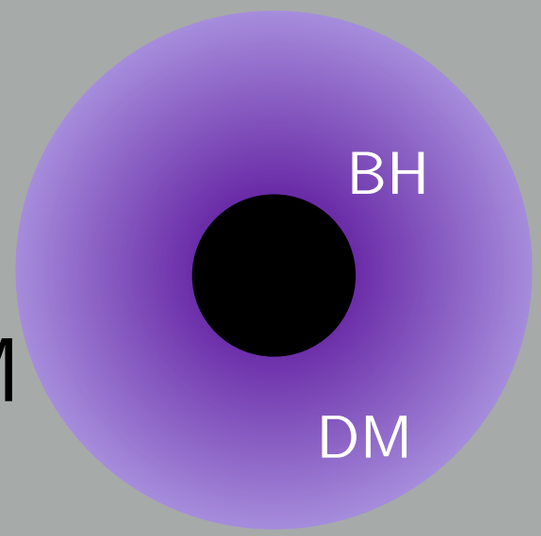

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- Galactic mergers
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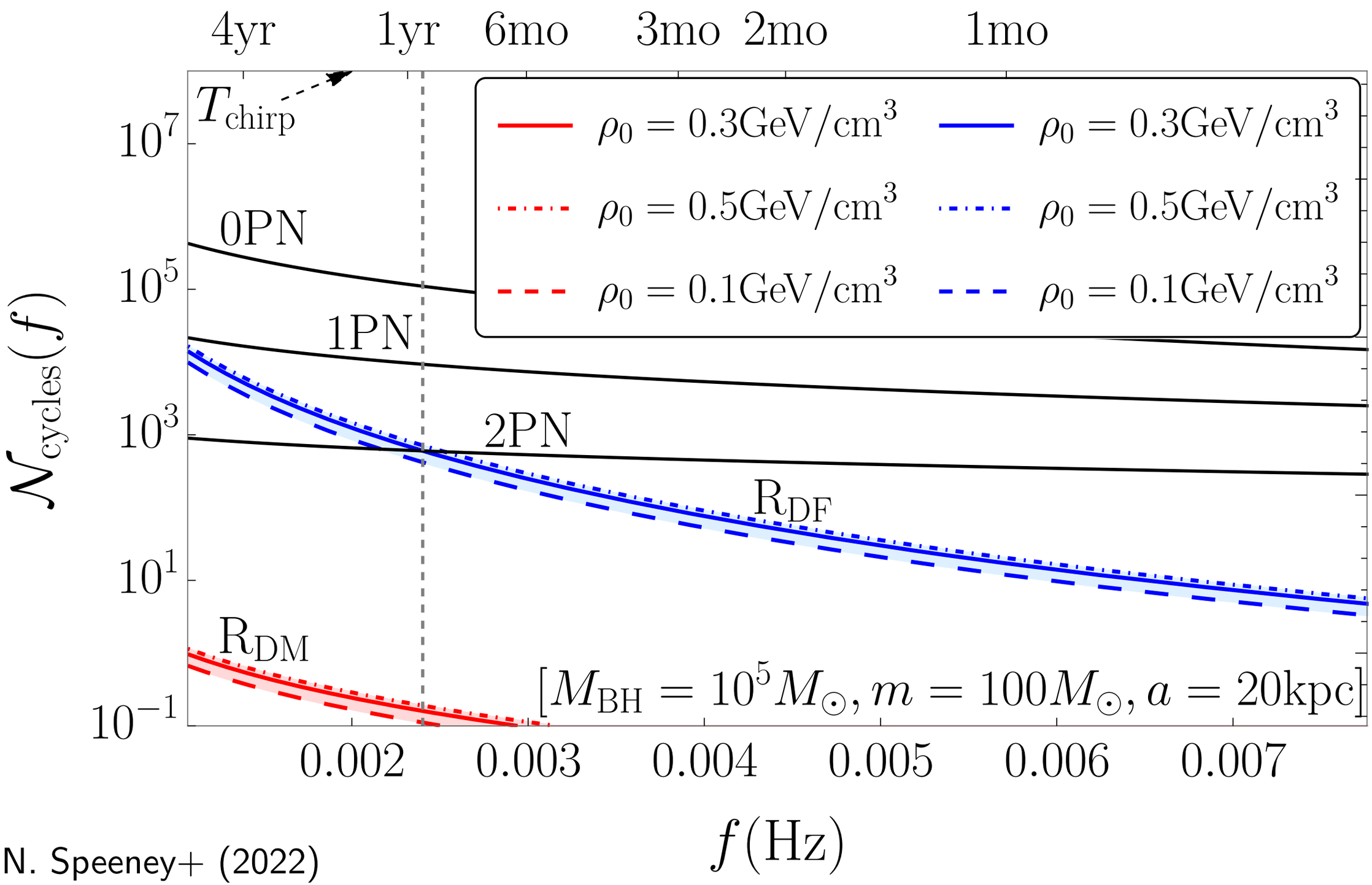
More likely to form for more isolated IMBHs (no major mergers)

$M_{\rm BH} \in [10^3, 10^5] M_\odot$ and primordial (PBHs), if not all of DM

Static DM Distributions around EMRIs

- Contributions of m_{enc} (red) and DF (blue) to N_{cycles}

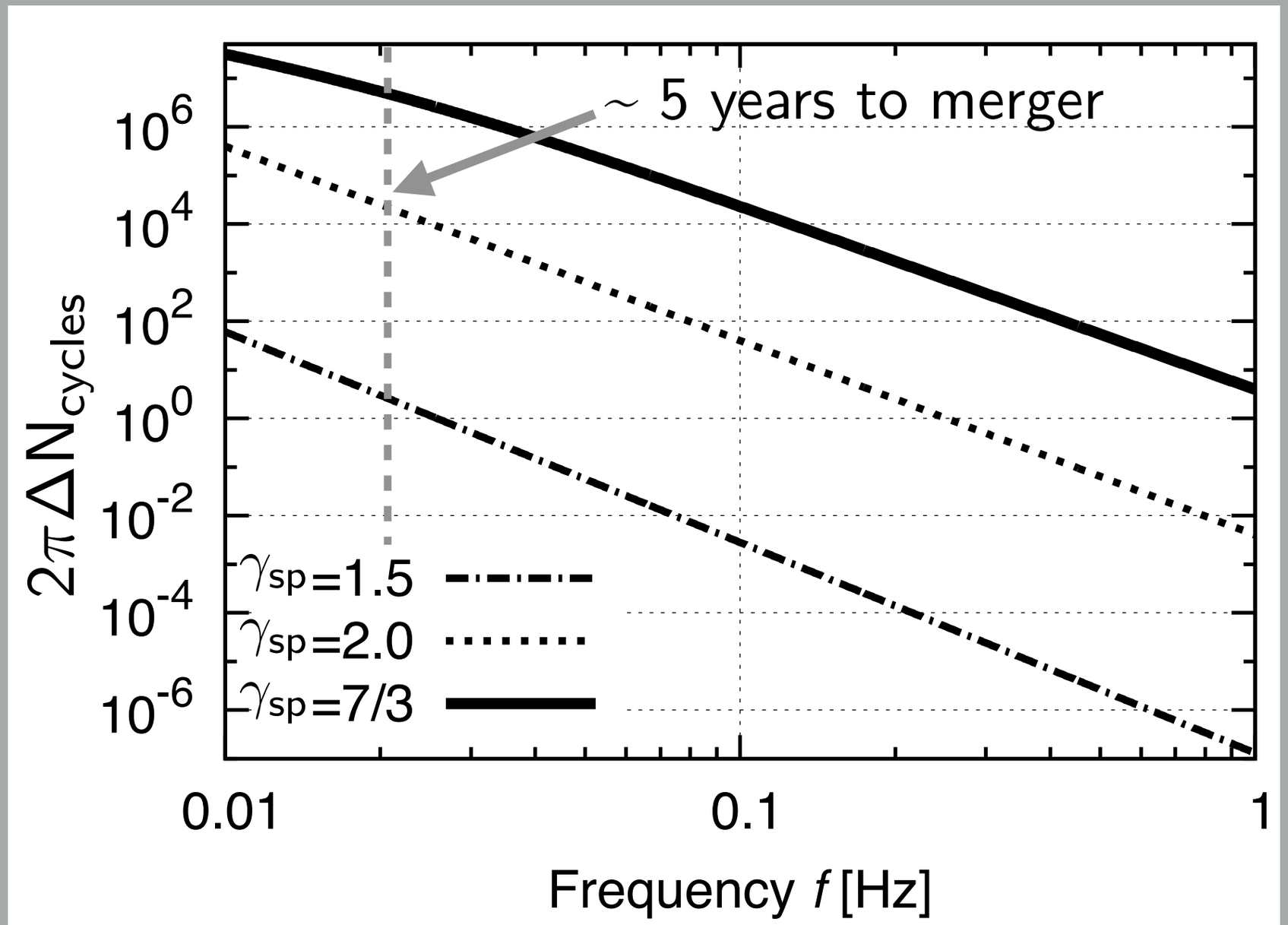


N. Speeney+ (2022)

Static DM Distributions around IMRIs

- "Dephasing" of binaries in vacuum vs. with DM

$$\Delta N_{cycles} = N_{cycles}^{(vac)} - N_{cycles}^{(DM)}$$



adapted from K. Eda+, (2014)

DM distribution

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

$$\rho_{sp} = 226 M_\odot/pc^3$$

$$r_{sp} \simeq 0.2\,pc$$

Binary properties

$$m_1 = 10^3 M_\odot$$

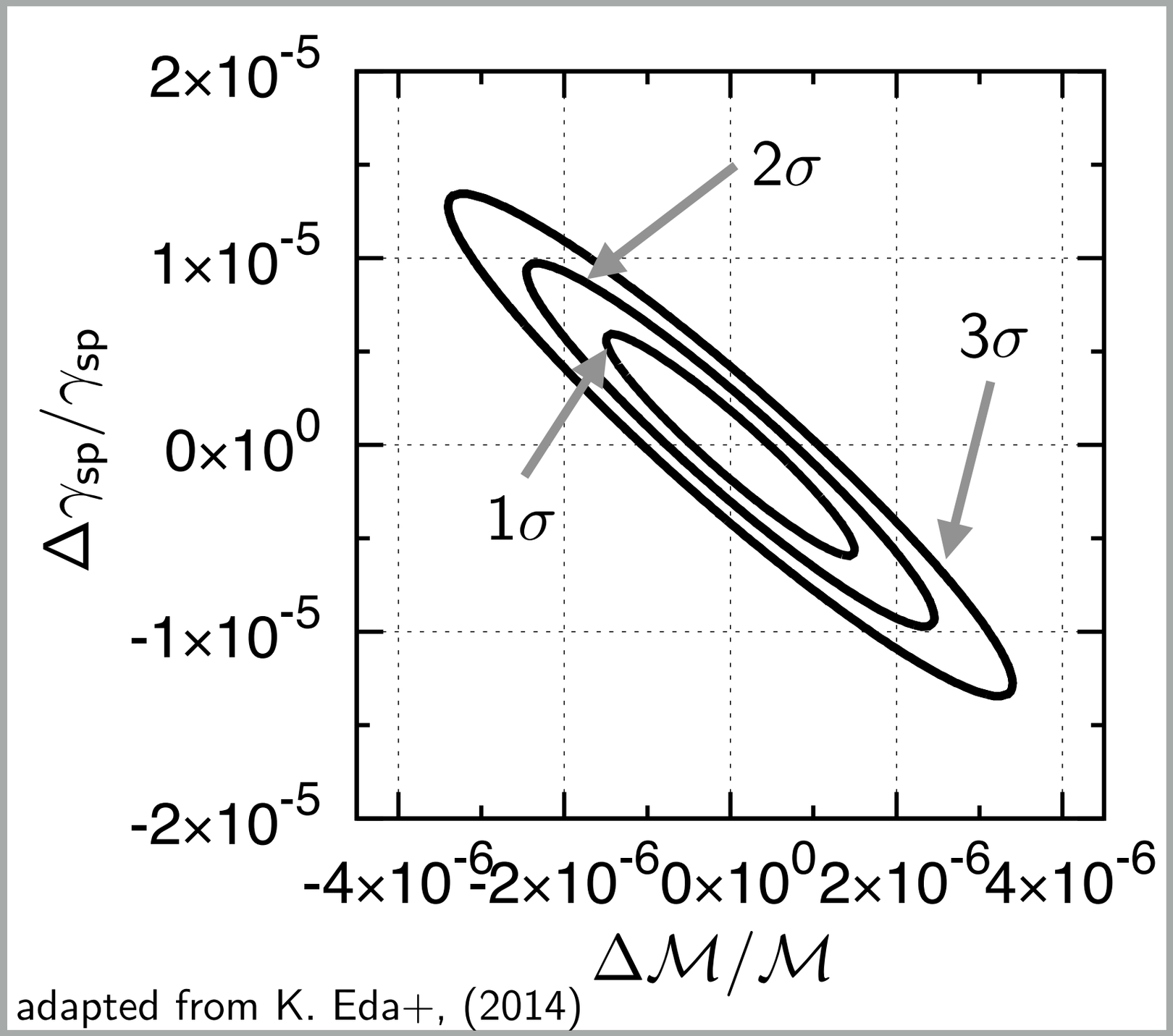
$$m_2 = 1 M_\odot$$

Circular orbit

- Large dephasing; LISA is sensitive to $\Delta N_{cycles} \sim \mathcal{O}(1)$

Static DM Distributions

- Fisher forecasting of measurement accuracy with LISA



adapted from K. Eda+, (2014)

Chirp mass

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

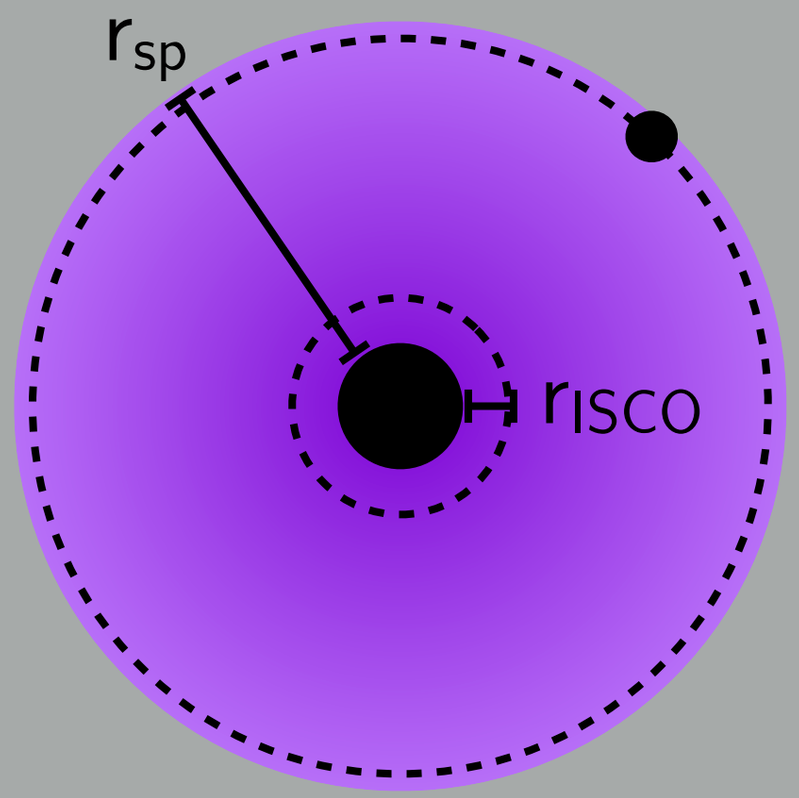
Statistical errors

$\Delta\mathcal{M}/\mathcal{M}$

$\Delta\gamma_{sp}/\gamma_{sp}$

- High-precision astrophysical DM measurement!

Energy Balance: Static DM Spike



- Total binding energy of spike: $\Delta U_{DM}(r_{sp})$
- Energy dissipated through DF as the m_2 inspirals from r_{sp} to r_{ISCO}: $\Delta E_{DF}(r_{sp})$

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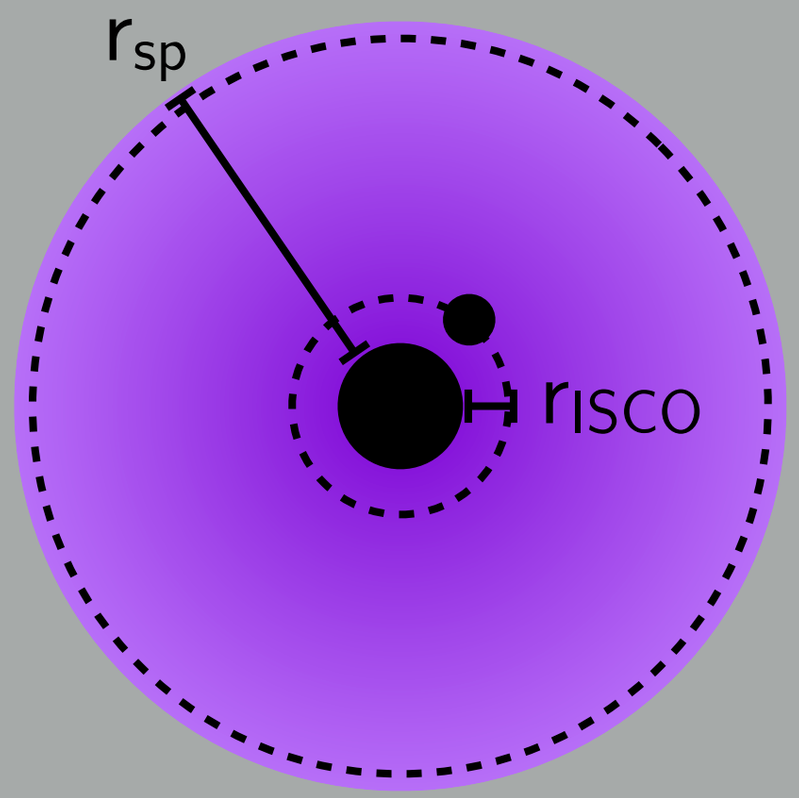

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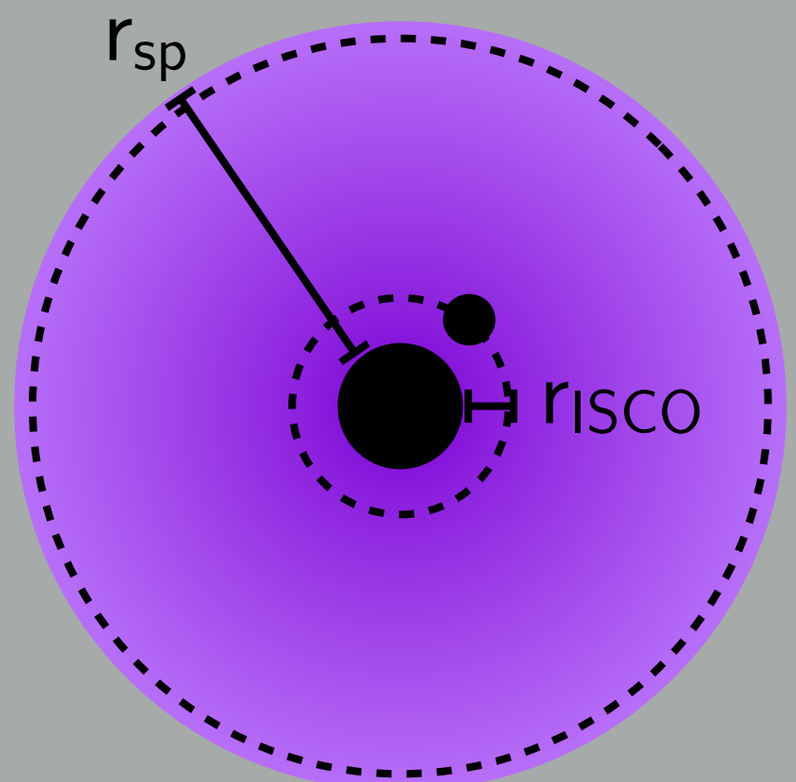
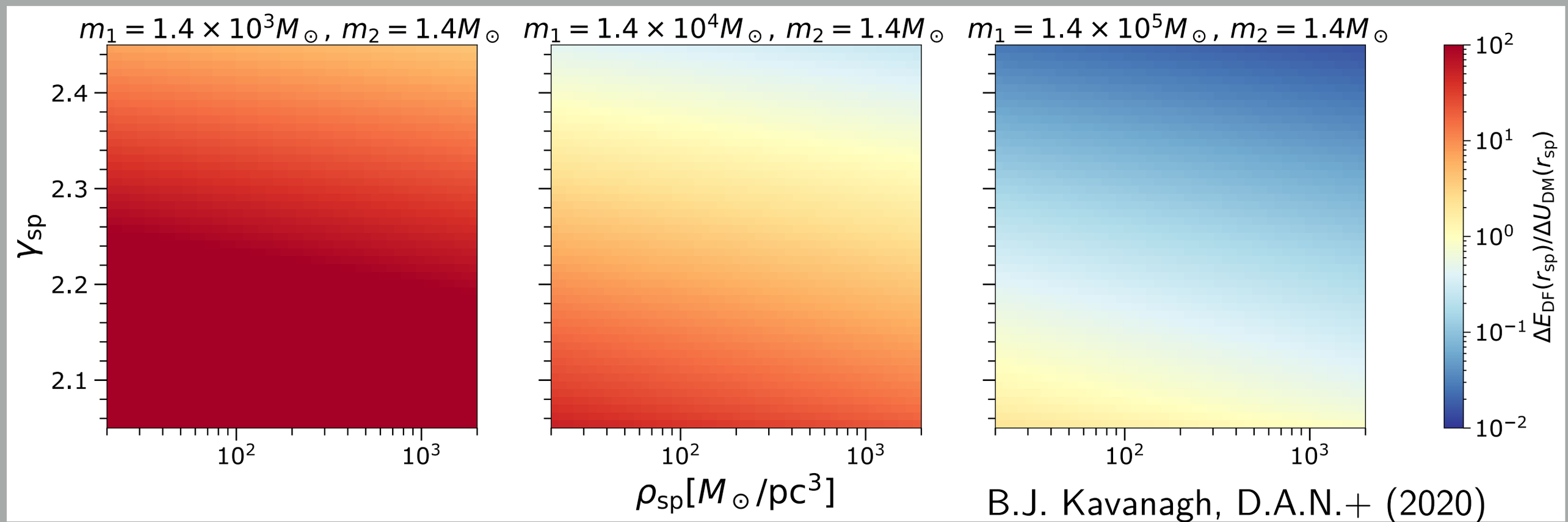


- Total binding energy of spike: $\Delta U_{DM}(r_{sp})$
- Energy dissipated through DF as the m_2 inspirals from r_{sp} to r_{ISCO}: $\Delta E_{DF}(r_{sp})$
- For a wide range of binaries and DM spikes, $\Delta E_{DF}(r_{sp}) \gg \Delta\gamma_{sp}/\gamma_{sp}$!



B.J. Kavanagh, D.A.N.+ (2020)

Must evolve the DM around the IMRI

- Evolve density via phase-space distribution of DM, $f(\mathcal{E})$

$$\rho_{\mathrm{DM}}(r) = \int d^3v\, f(\mathcal{E})$$

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$$\frac{\partial f(\mathcal{E})}{\partial t} = \int d\epsilon \{ -[\text{Rate-density of particles w}/\mathcal{E} \text{ scattering to } \mathcal{E}+\epsilon] + [\text{Rate-density of particles w}/\mathcal{E}+\epsilon \text{ scattering to } \mathcal{E}] \}$$

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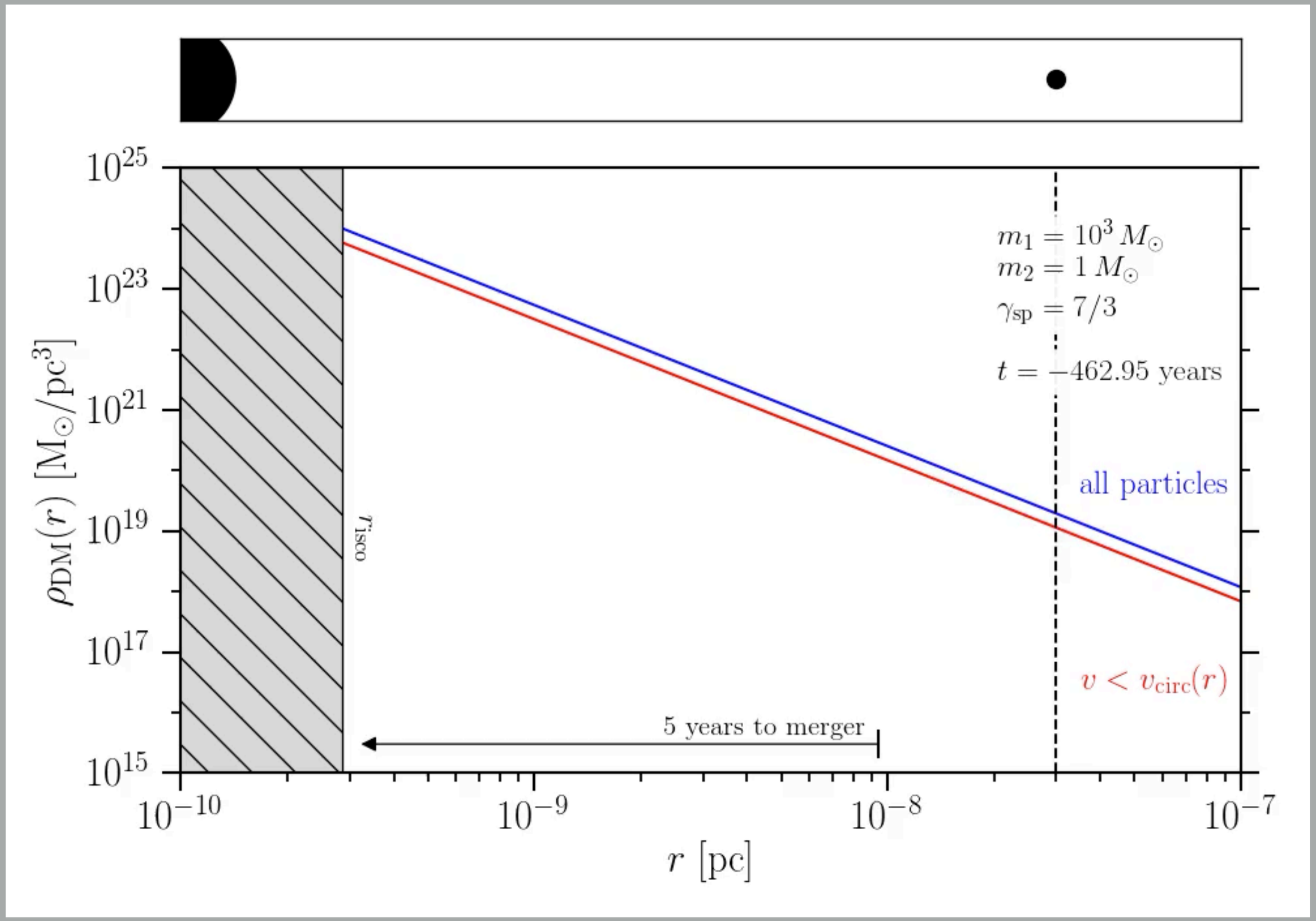
- Evolve simultaneously with the binary's orbital separation

$$\dot{r}_2 = \mathcal{F}_r \left[r_2, \int d^3v\, f(\mathcal{E}) \right] \qquad \frac{\partial f}{\partial t} = \mathcal{F}_f \left[r_2, f(\mathcal{E}), \int d\mathcal{E}\, f(\mathcal{E}) \right]$$

B.J. Kavanagh, D.A.N.+ (2020)

DM and binary co-evolution



B. J. Kavanagh, D.A.N.+ (2020)

Movie at http://tinyurl.com/GW4DM

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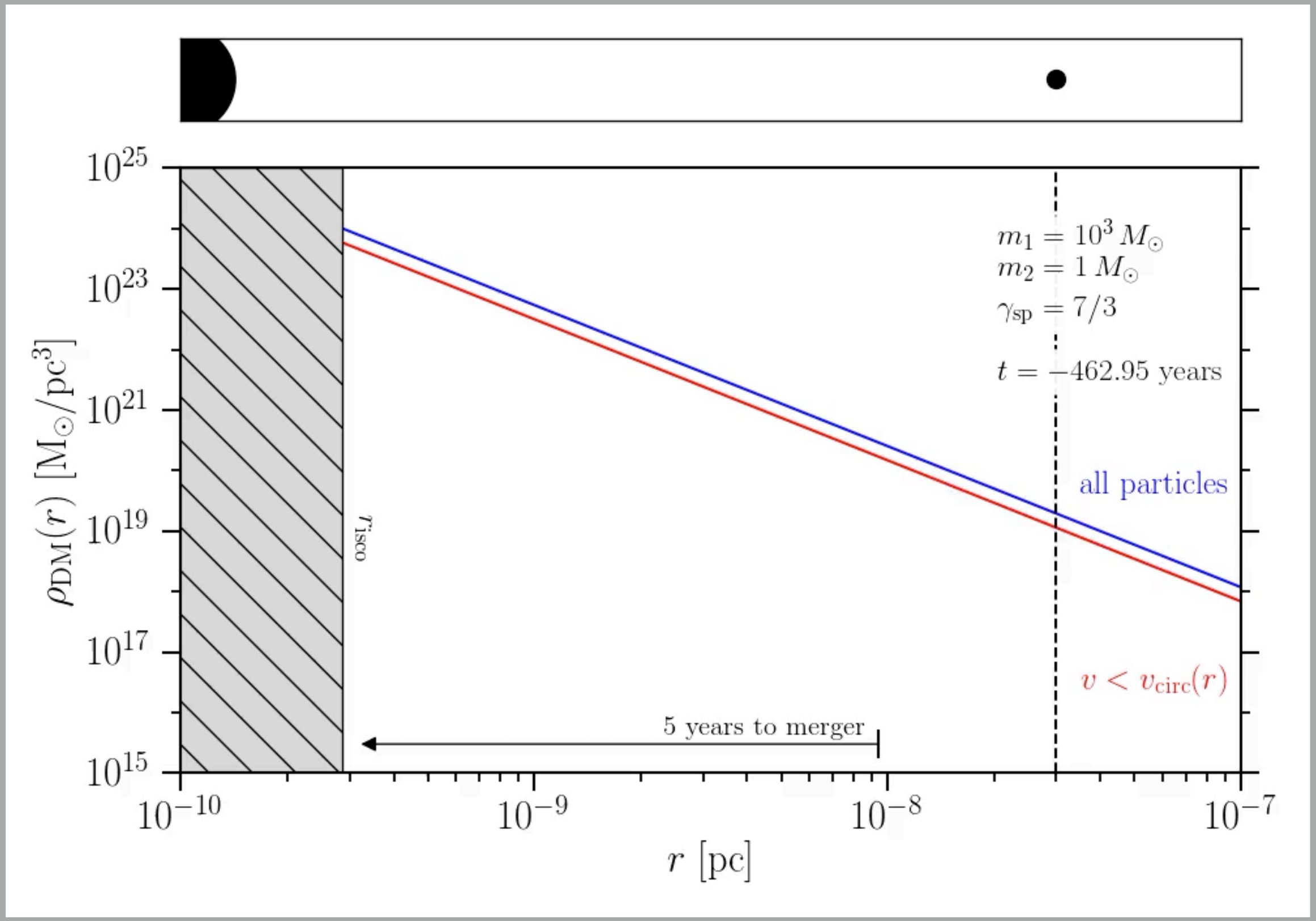

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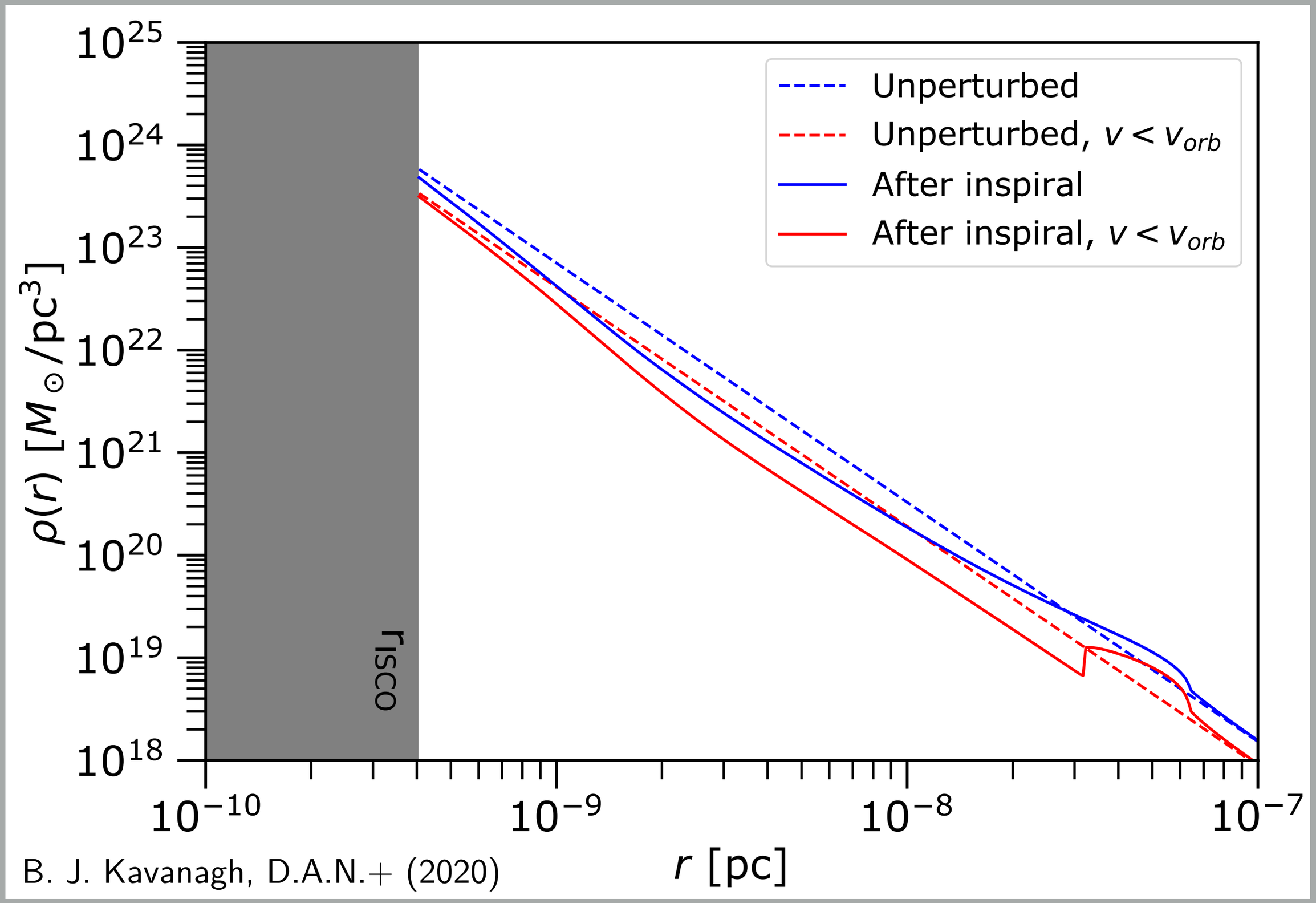
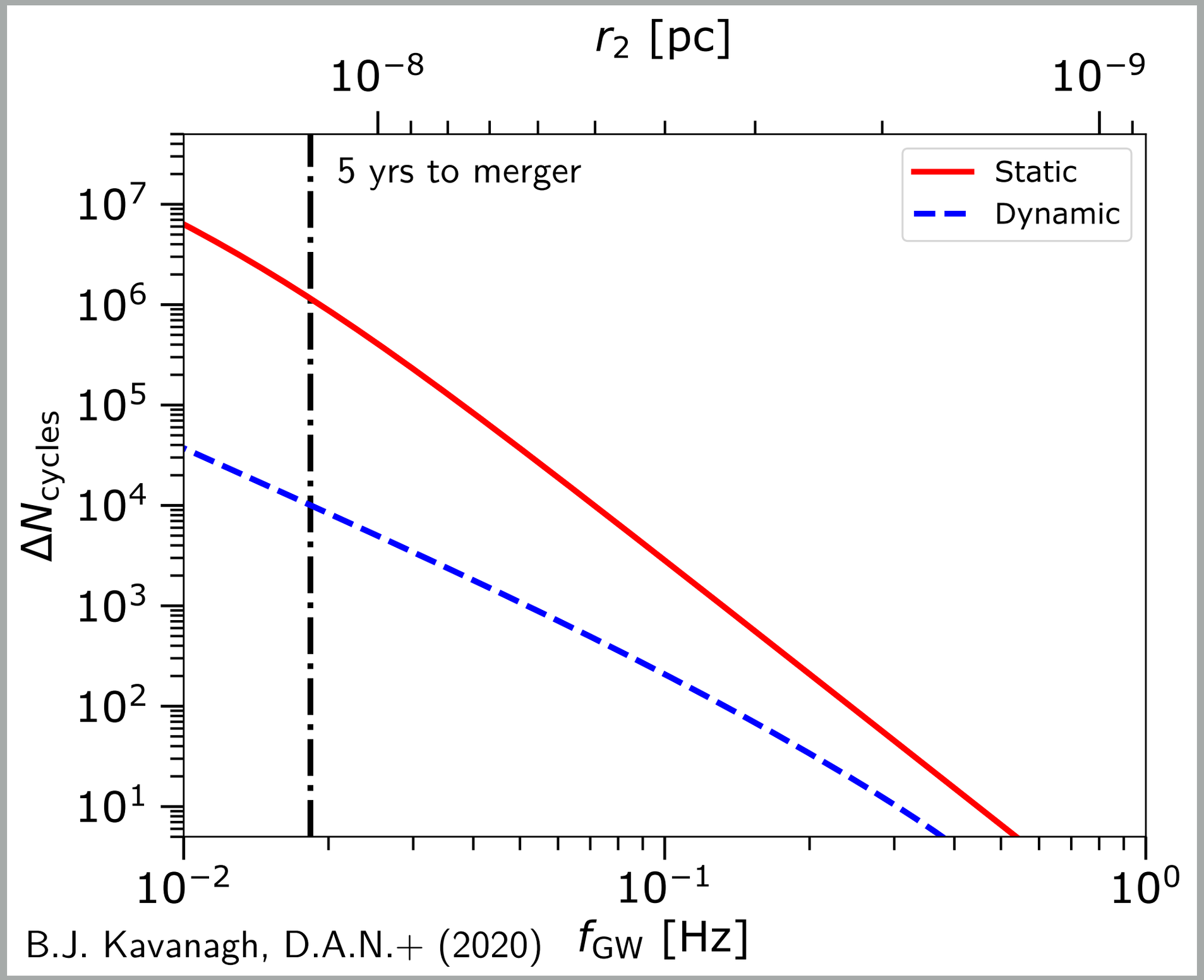
DM Initial and Final Density



B. J. Kavanagh, D.A.N.+ (2020)

Dynamic DM Distributions: Dephasing

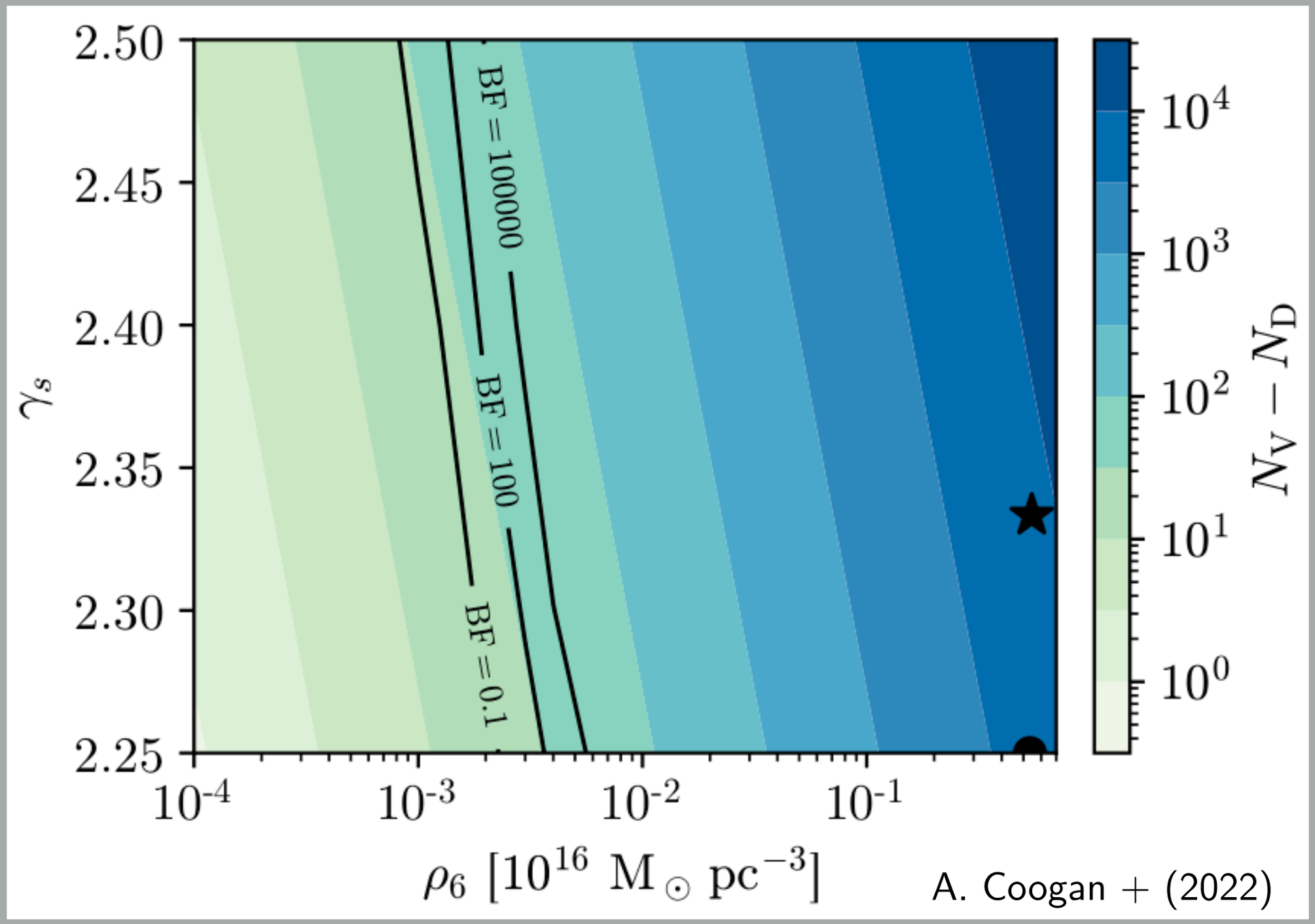


B.J. Kavanagh, D.A.N.+ (2020)

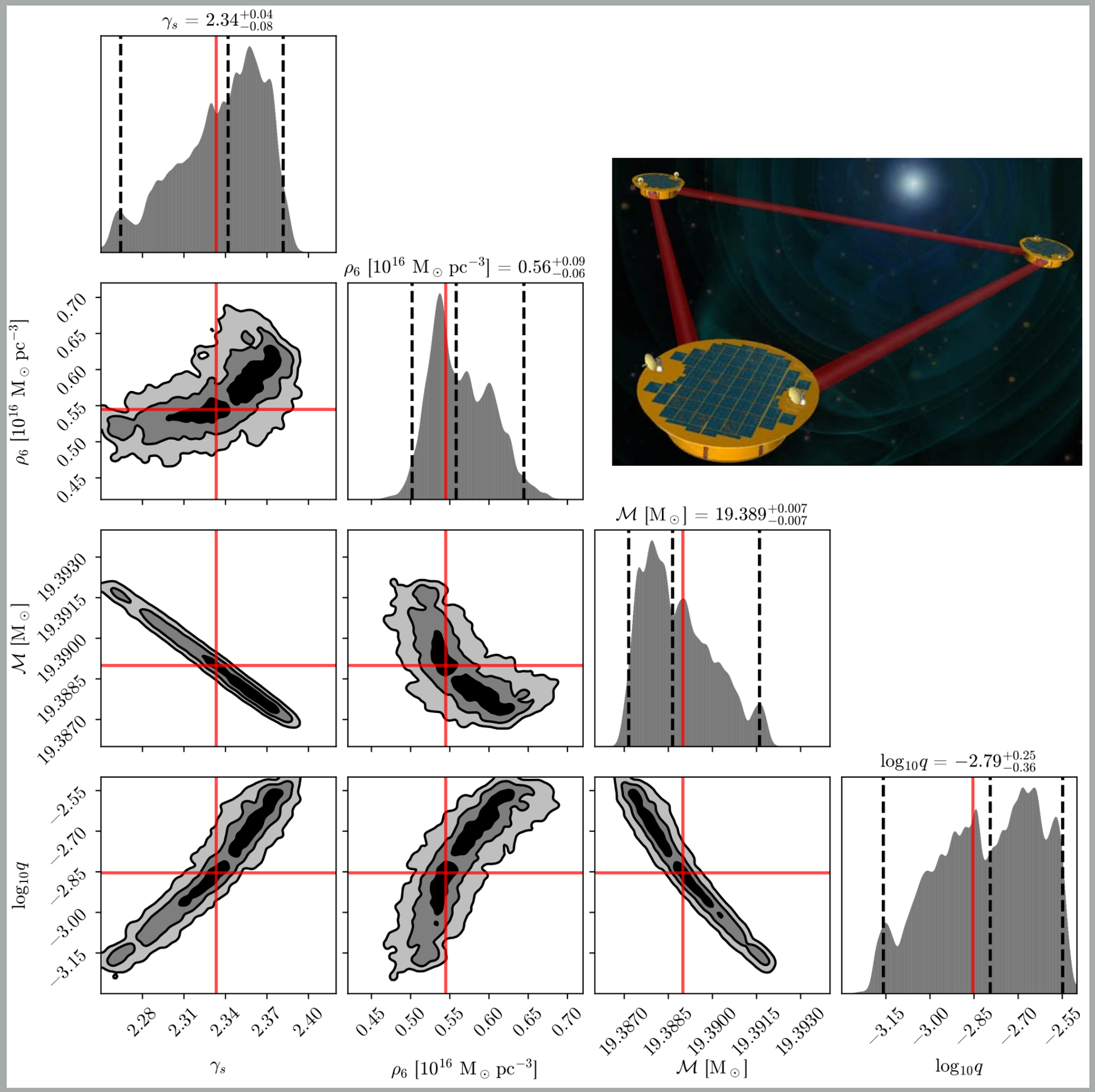
$m_1 = 1400 M_\odot\,,\ m_2 = 1.4 M_\odot\,,\ \rho_{\rm sp} = 226 M_\odot/{\rm pc}^3\,,\ \gamma_{\rm sp} = 7/3$

Dephasing with DM feedback

- Initial density: $\rho_{\rm DM} = \rho_6 (r_6/r)^{\gamma_{\rm sp}}$ w/ $\rho_6 \propto \rho_{\rm sp}/r_6^{\gamma_{\rm sp}}$ & $r_6 = 10^6$pc



Parameter Estimation with DM



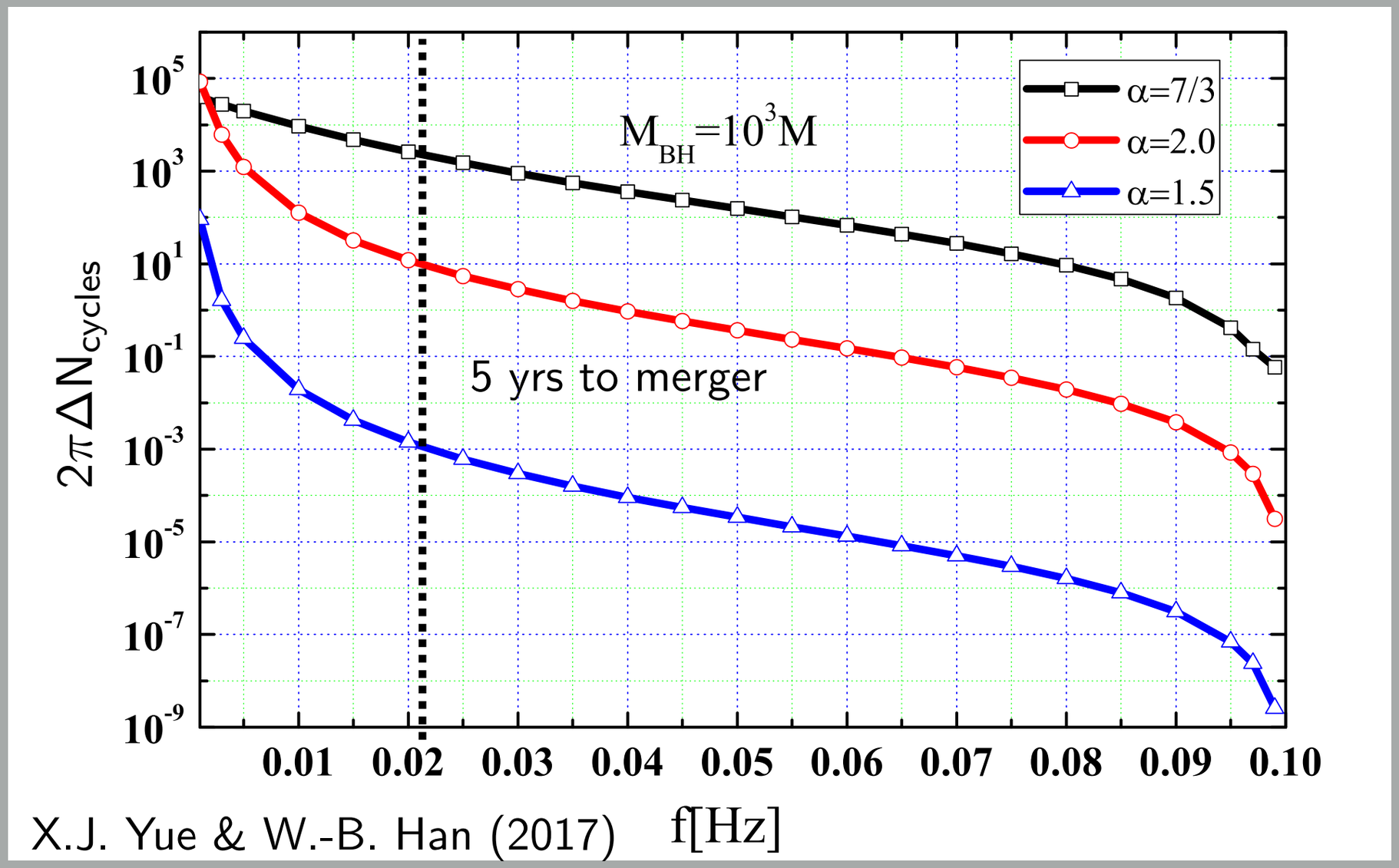
- Perform parameter estimation with ρ_6, γ_{sp}, $\log_{10}q$, and chirp mass
- Measure power law to a few percent and density to a few 10s of percent

A. Coogan + (2022)

DM Accretion: Formalism & Static Dephasing

- If m_2 a BH, captures DM with cross section $\sigma(v_2) \propto \left(\frac{Gm_2}{cv_2}\right)^2$
- Speeds up inspiral (m_2 increases); 1PN order weaker than DF

$$\dot{m}_2 = \sigma(v_2)\rho_{DM}(r_2)v_2\,, \quad \dot{r}_2^A = -2r_2\dot{m}_2/m_2$$



X.J. Yue & W.-B. Han (2017)

DM distribution

$r_{sp} \sim 1pc$

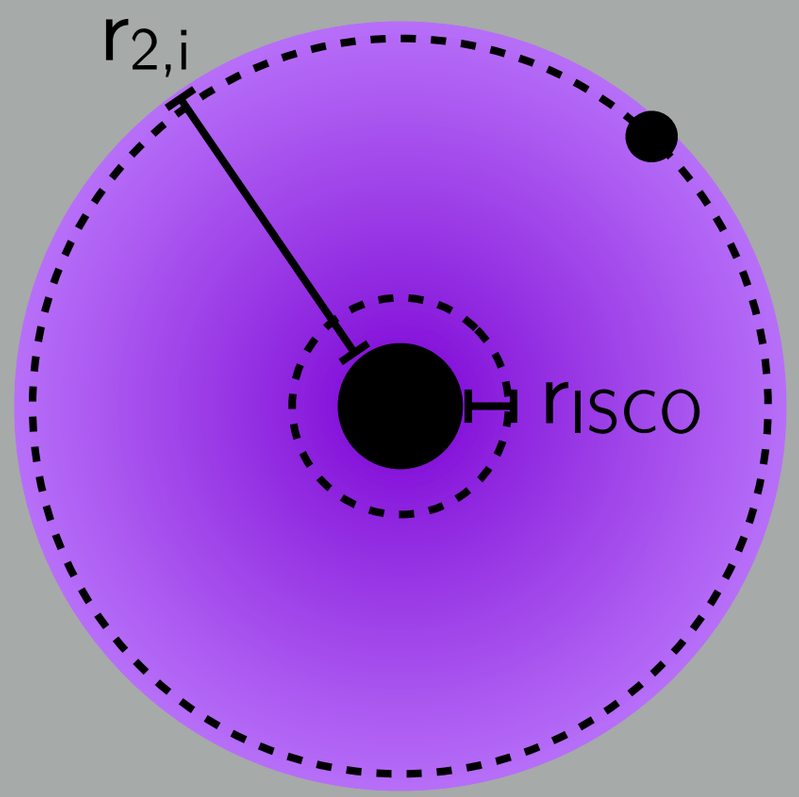
$\rho_{sp} = 226M_\odot/pc^3$

Initial m_2

$m_2 = 10M_\odot$

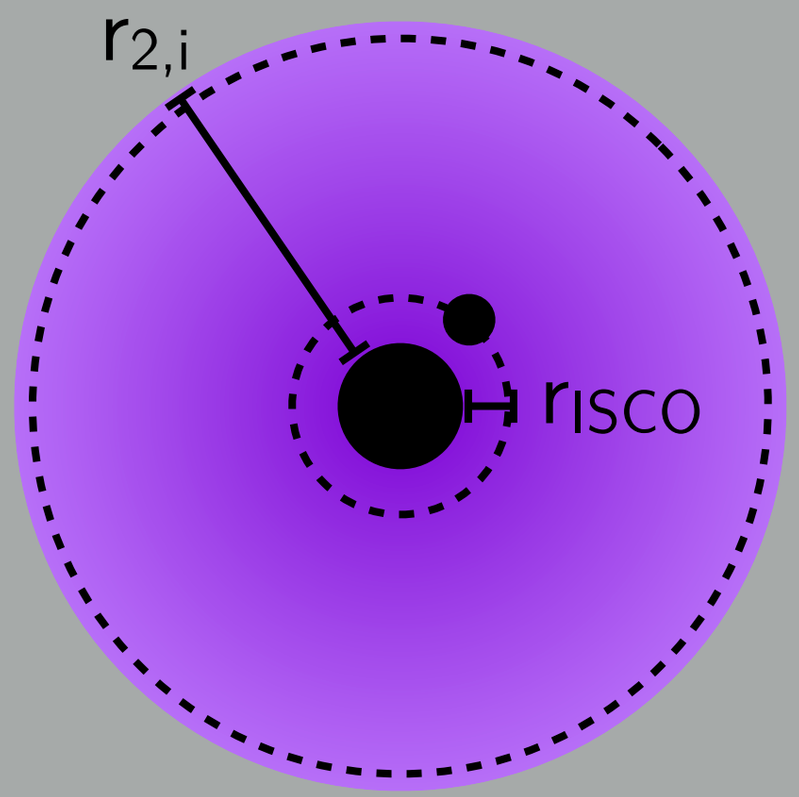
- Capture could produce very large dephasing

Excess Accreted Mass



- Mass captured by m_2 during inspiral:
  $m_{acc}(r_{2,i})$
- DM mass within $r_{2,i}$:
  $m_{enc}(r_{2,i})$
- If similar, should evolve DM density due to accretion

Excess Accreted Mass



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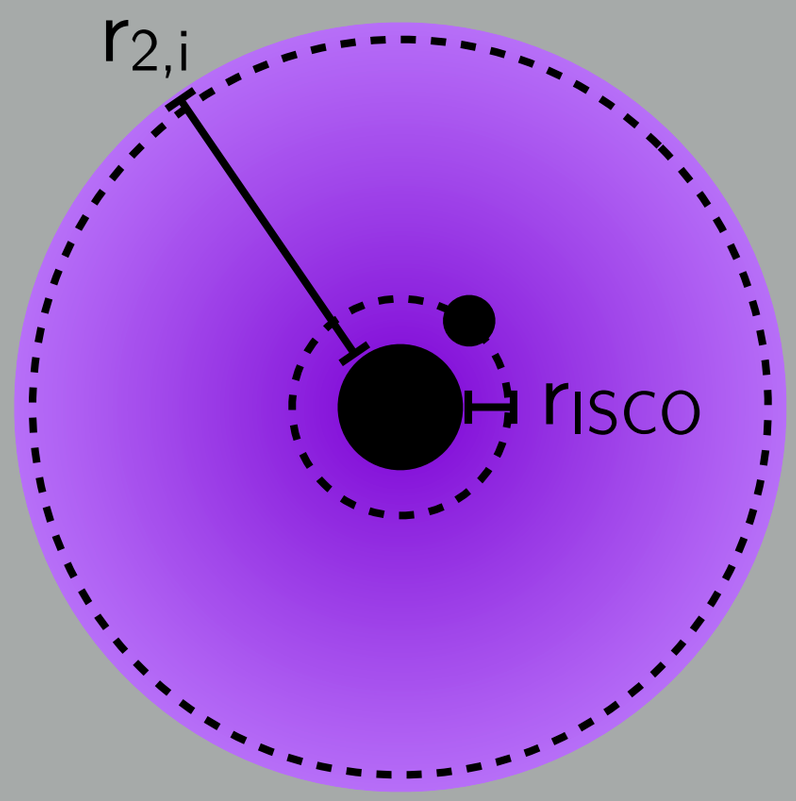
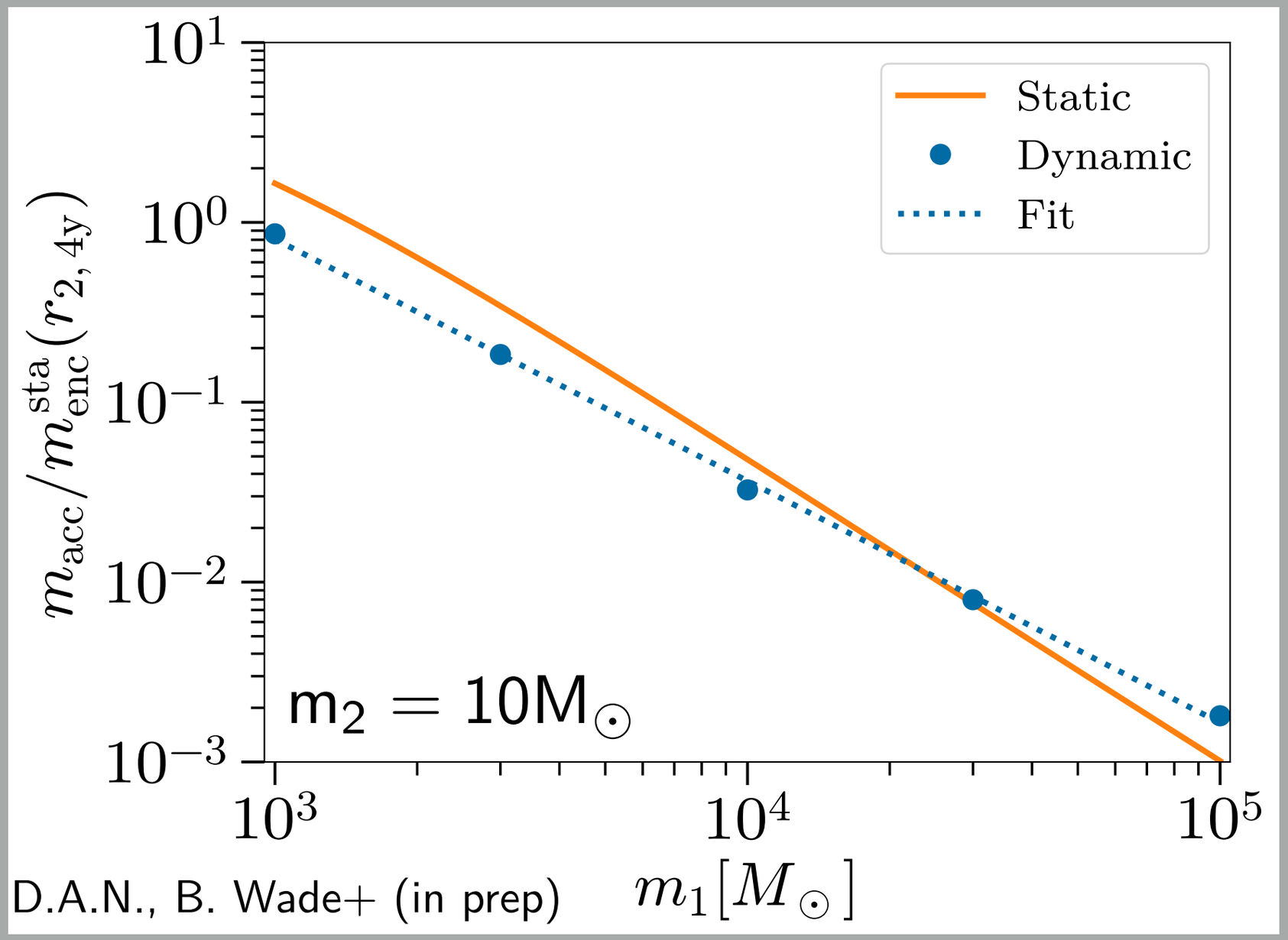




D.A.N., B. Wade+ (in prep)

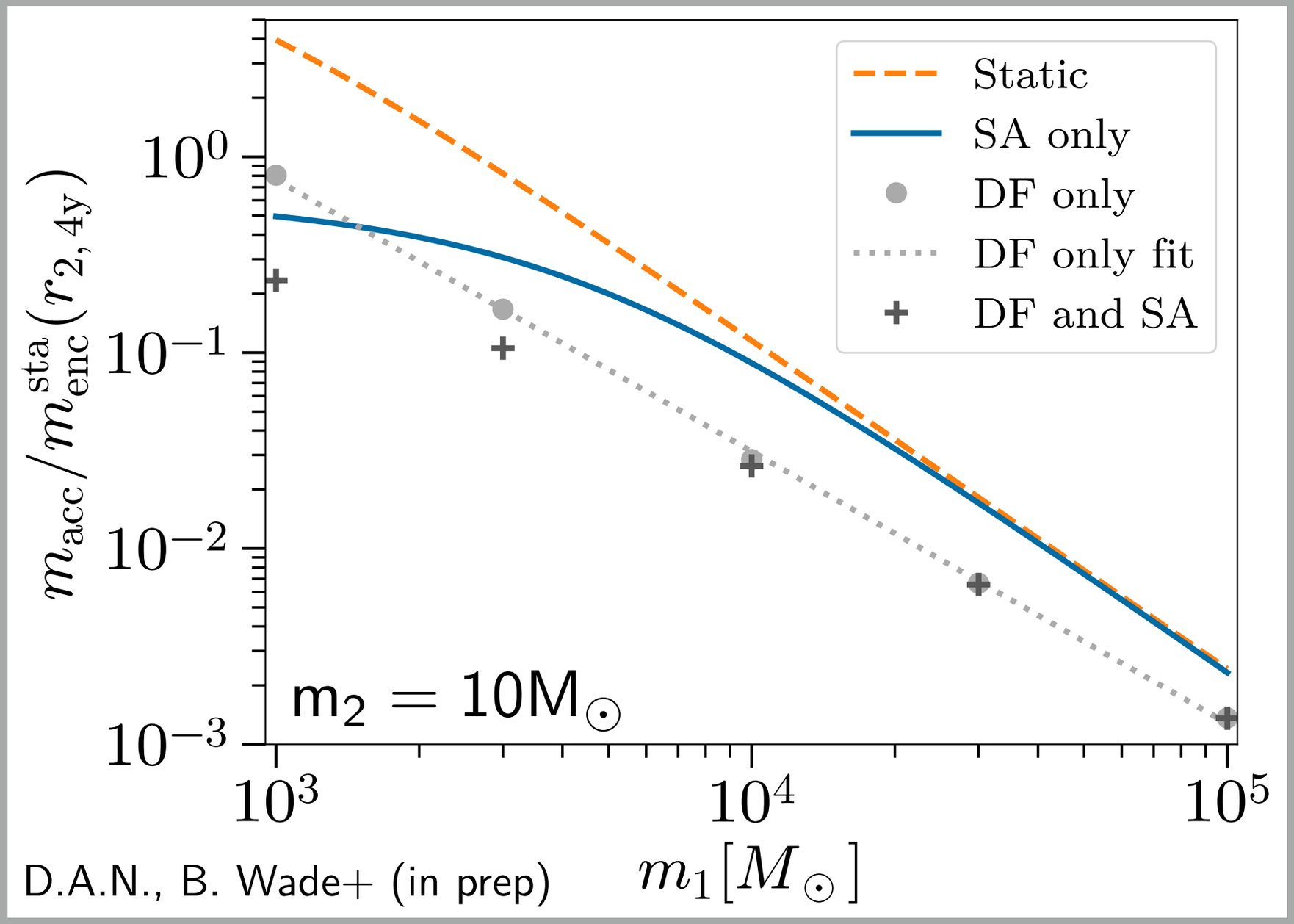
- Mass captured by m_2 during inspiral: $m_{acc}(r_{2,i})$
- DM mass within $r_{2,i}$: $m_{enc}(r_{2,i})$
- If similar, should evolve DM density due to accretion
- *Static*: DF, no feedback, accretion of only faster-moving particles
- *Dynamic*: w/ DF feedback and accretion but no accretion feedback

Accreted Mass and Accretion Feedback

- Developed formalism to remove DM particles from the halo s.t.

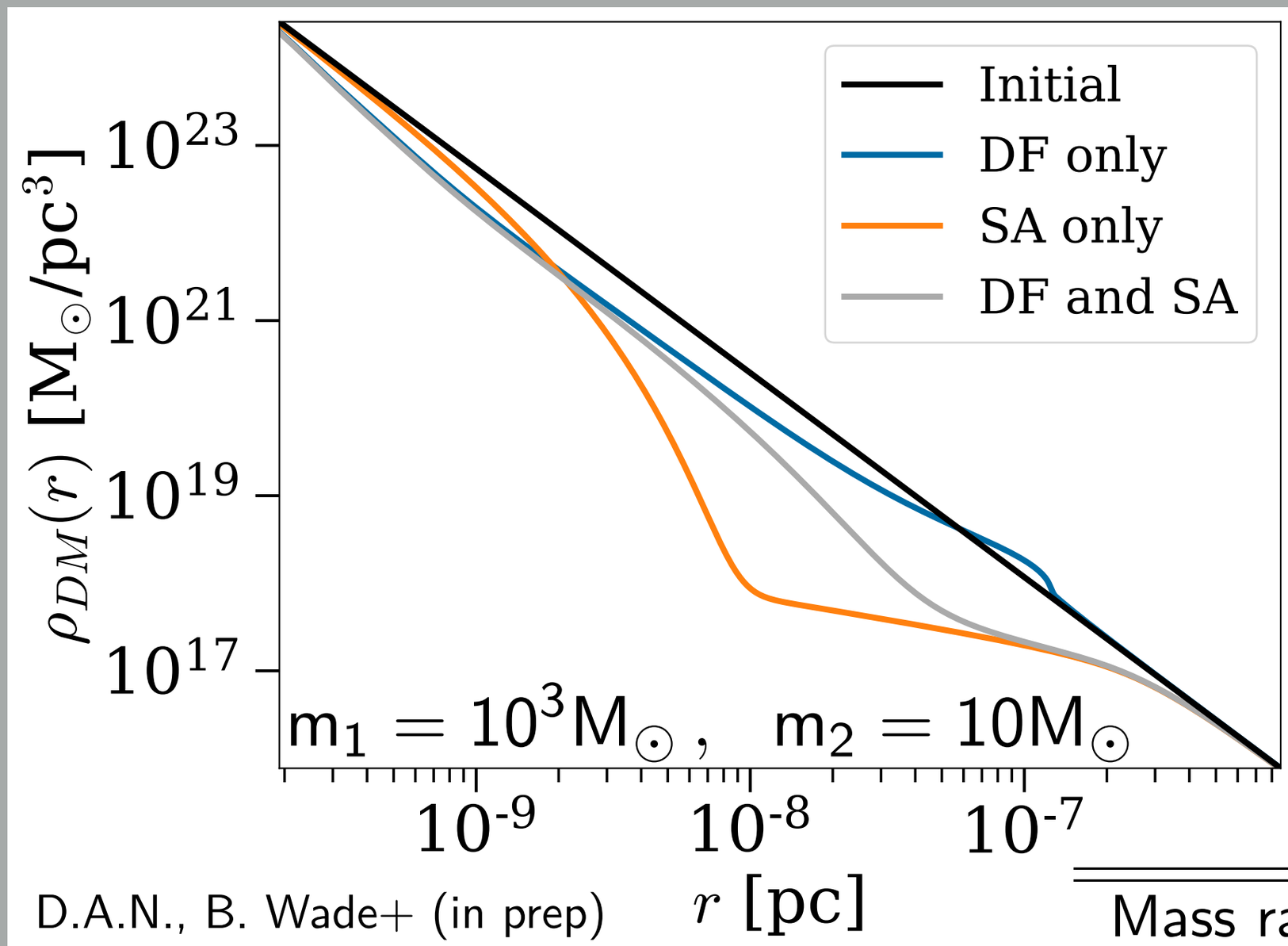
$$\dot{m}_2 = \frac{dm_{DM}}{dt}$$

- Makes similar assumptions of spherical sym. and evolution on orbital time scale only



- *SA*: "secondary" accretion w/ feedback
- *DF & SA*: Both kids of feedback

Impact of DM Accretion in E/IMRIs



D.A.N., B. Wade+ (in prep)

Additional dephasing

- Dephasing from SA w/ feedback still smaller than DF, but becomes more comparable

Density after inspiral

- Accretion can have a large impact on final density

Mass ratio (q)	$\Delta N_{\text{cycles}}^{\text{DF}-\text{DFSA}}$
10^{-2}	5×10^2
3×10^{-2}	8×10^2
10^{-3}	5×10^2
3×10^{-3}	2×10^2
10^{-4}	2×10^2

Primordial BHs (PHBs): Introduction

- Form in the early universe if curvature perturbations are O(1); form rapidly after modes re-enter the horizon
- *N.b.*: Slow-roll inflation produces perturbations of $O(10^{-4})$, as inferred from the CMB, on much larger scales
- PBH mass when forms: $m_{PBH} \sim 10^{15}\,\mathrm{g}\,(t_{form}/10^{-23}\,\mathrm{s})$

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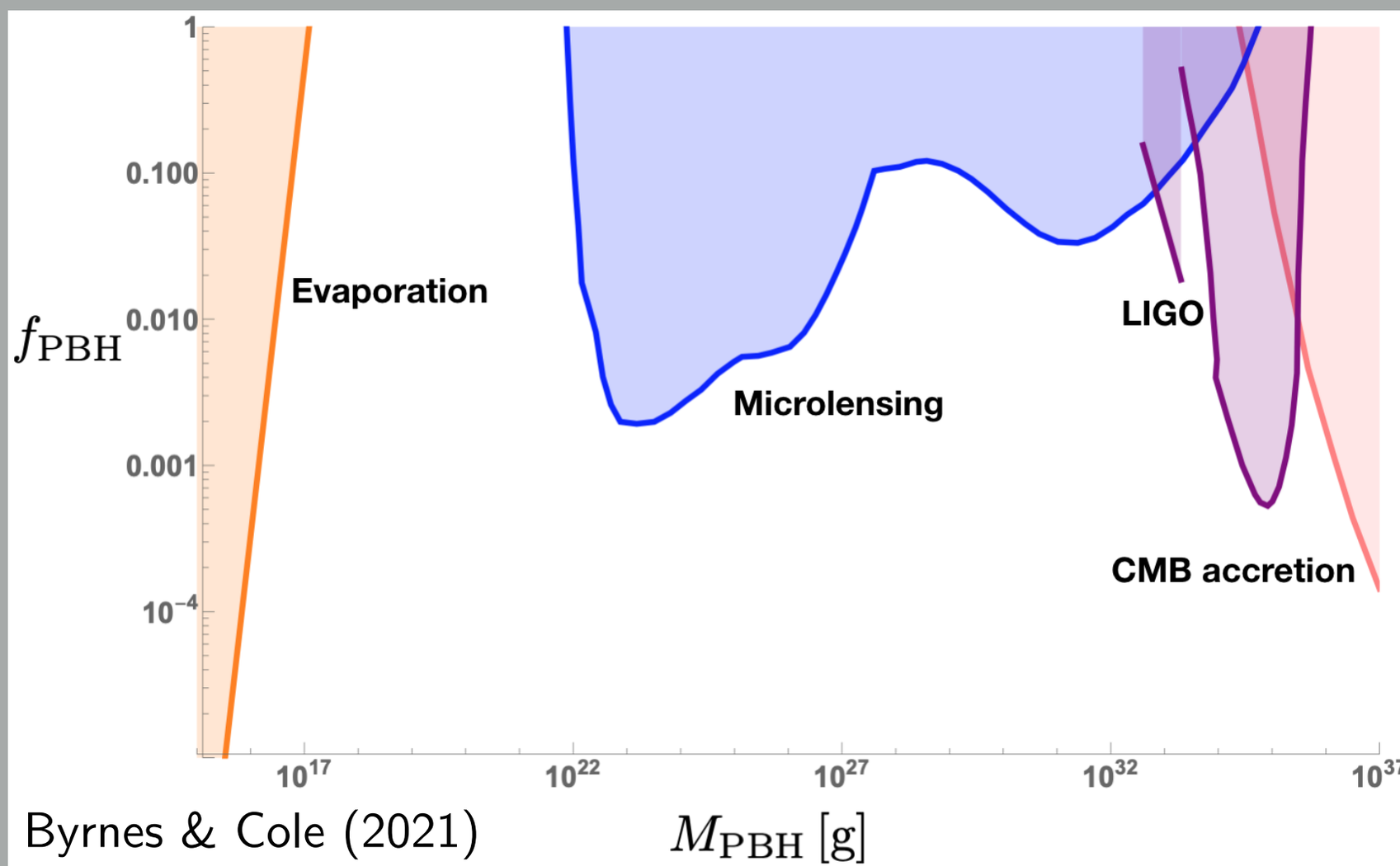

Byrnes & Cole (2021)

- f_{PBH}: fraction of DM that could be PBHs
- "Asteroid-mass window" no direct PBH constraints

PBHs and LISA GW Signals

- If large curvature perts to generate PBHs, then will also generate a nonlinear, "scalar-induced" GW background
- GW frequency is set by scale at horizon re-entry as w/ PBHs
- Astroid mass PBHs correspond to mHz GWs, where LISA most sensitive: $f_{peak} \sim 3\text{mHz}\ (m_{PBH}/10^{12}\ M_{sun})^{1/2}$
- Many predictions for SGWB spectra see G. Domènech (2021)

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- If LISA measures a merger at high z, also could be PBHs (hard to explain such a large BH early in cosmic history)
- BBH merger with mass(es) $M_{PBH} < M_{sun}$ compelling for PBH, but too low mass for LISA to measure

Conclusions and Future Directions

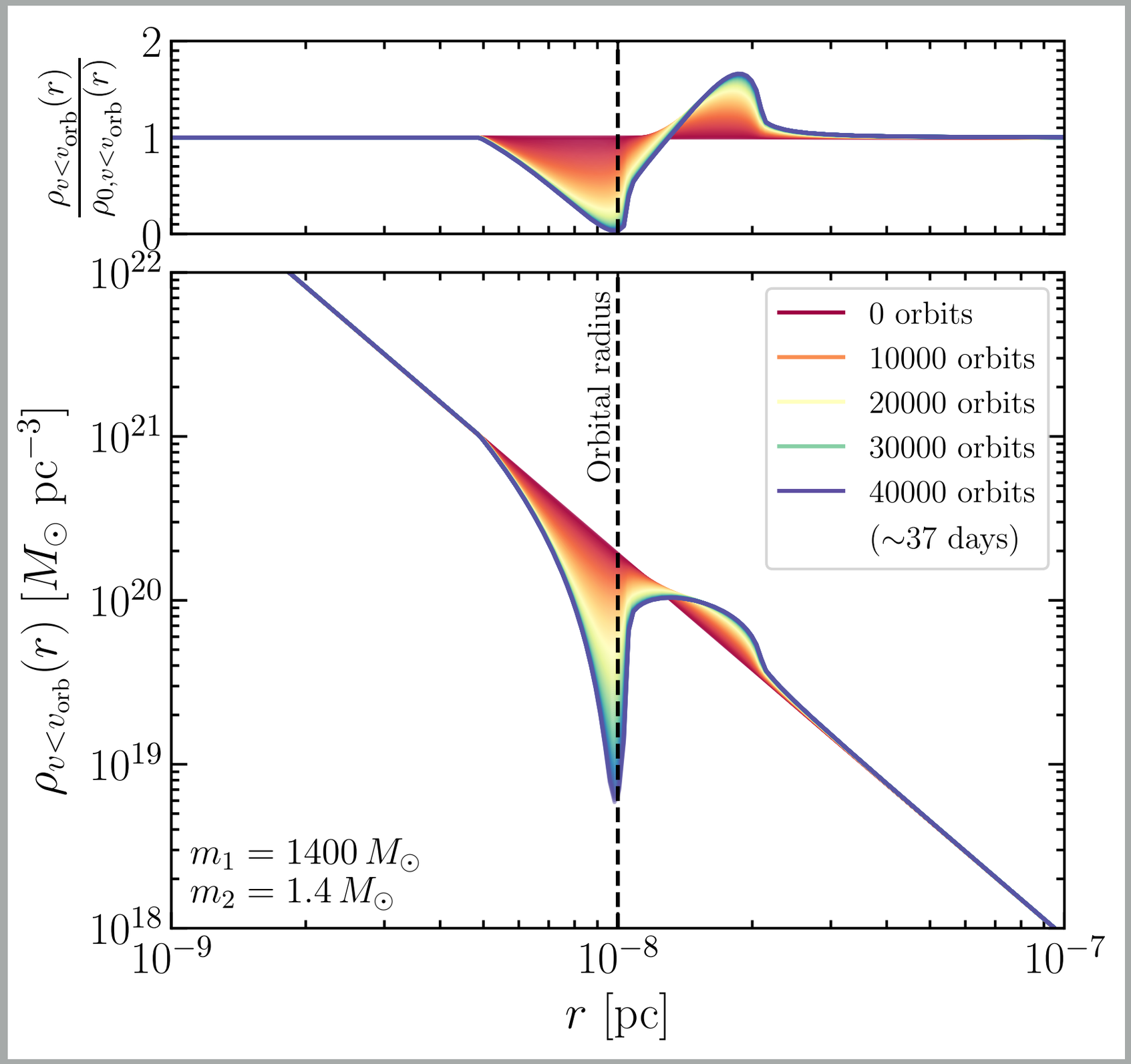
- LISA can be used to study the dark-matter environment of S/IMBHs if sufficiently high densities of dark matter are present
- E/IMRIs require careful relativistic modeling of binary and DM environment; IMRIs require evolving binary and DM as a coupled system

- Many open areas to be investigated: rates of E/IMRI mergers with dark matter spikes, improved and more rapid waveform modeling, developing search and parameter estimation pipelines, DM microphysics (and other points for discussion...)

- Thank you / mange tak!

Extras

DM evolution on short times



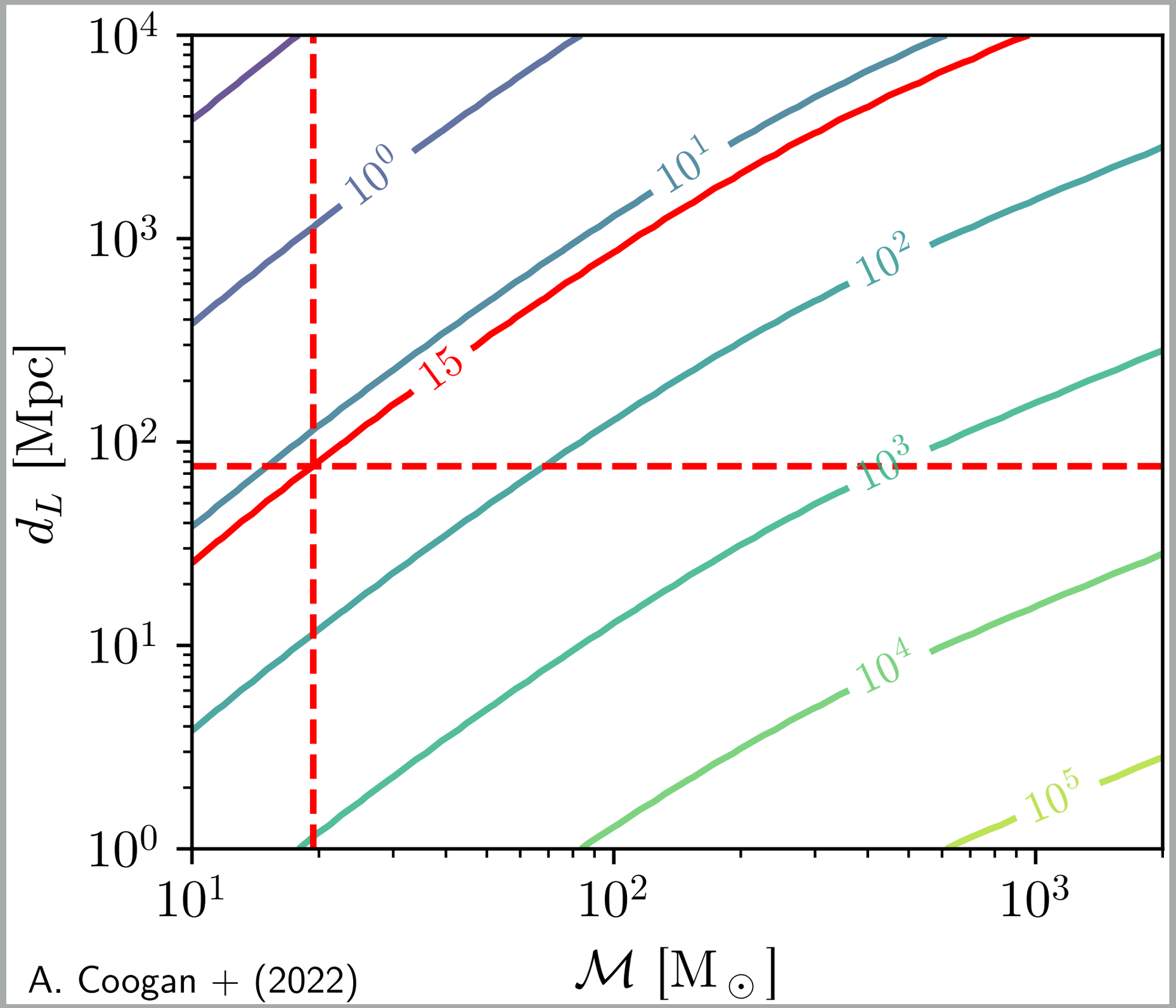
$F_{DF} \sim \rho_{DM}/v^2$

- More precisely ρ_{DM} in F_{DF} is density of particles moving more slowly than m_2, not the density of all particles

B.J. Kavanagh, D.A.N.+, (2020)

Signal-to-noise (S/N) and detection range

- Require S/N of 15 for detection to avoid look elsewhere effects



A. Coogan + (2022)