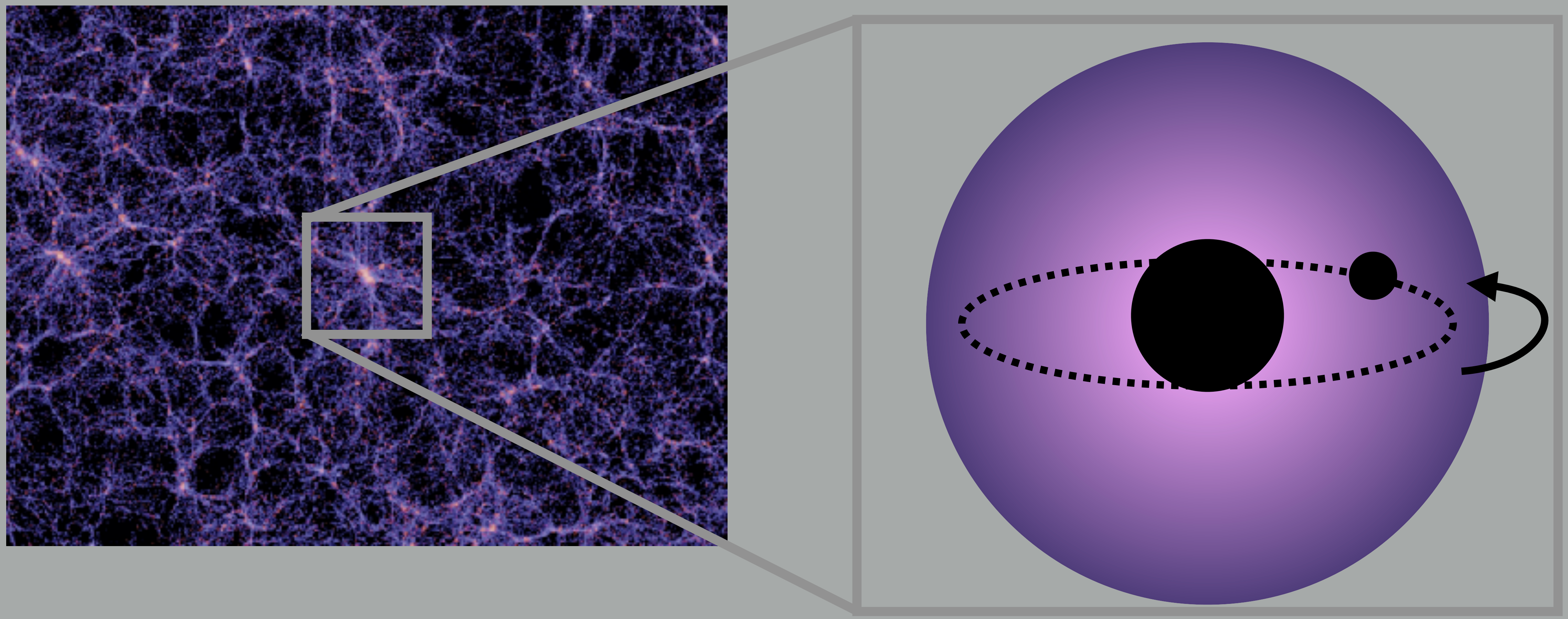
Gravitational-wave signatures of dark matter around black holes

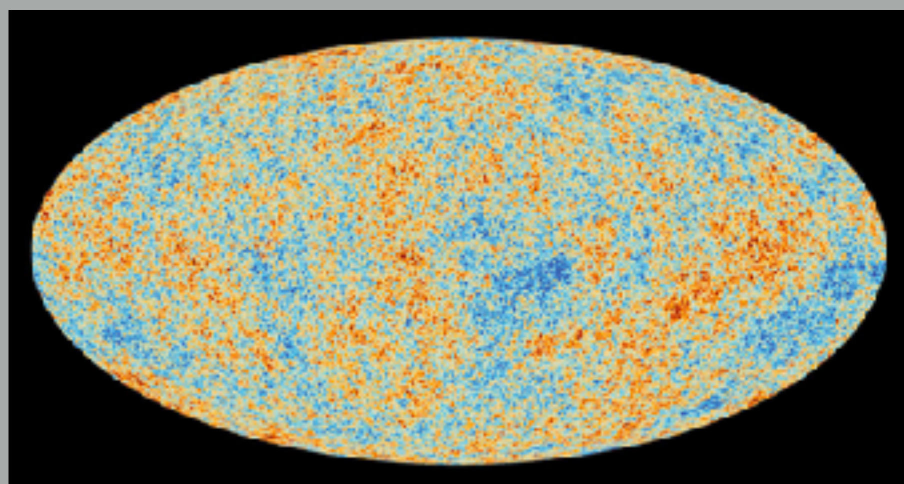


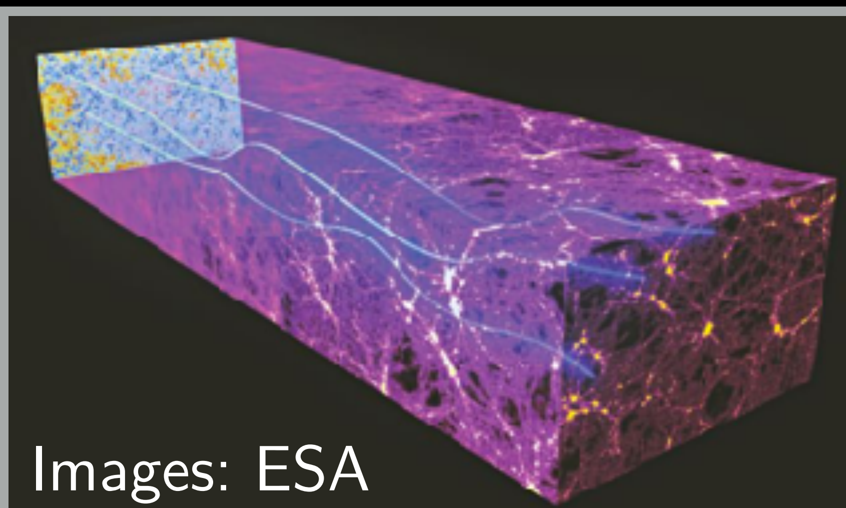
David A. Nichols, University of Virginia, Dept. of Physics

33rd Rencontre de Blois:
Exploring the Dark Universe
24 May 2022

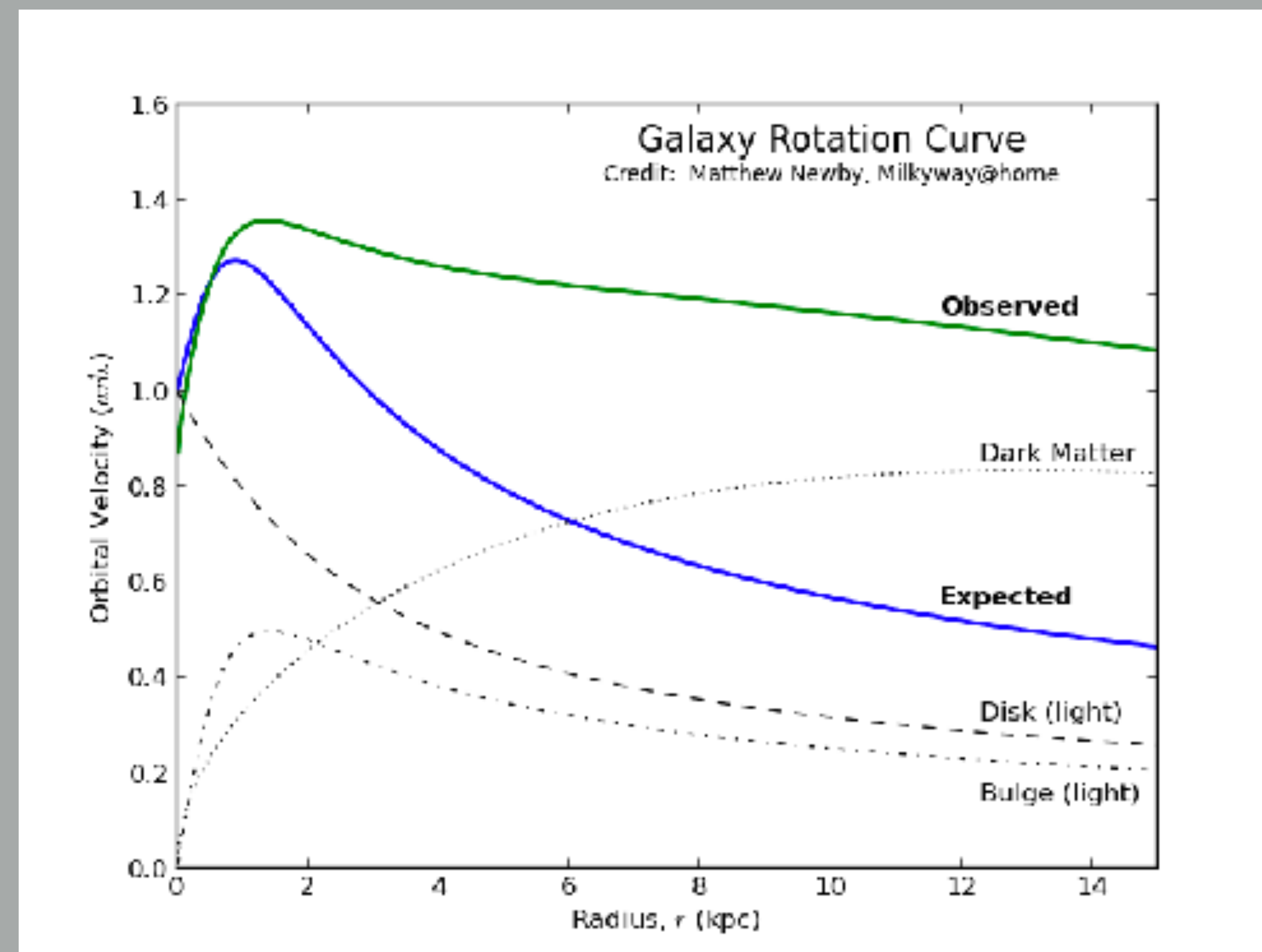
Astrophysical Evidence for Cold Dark Matter

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





Images: ESA

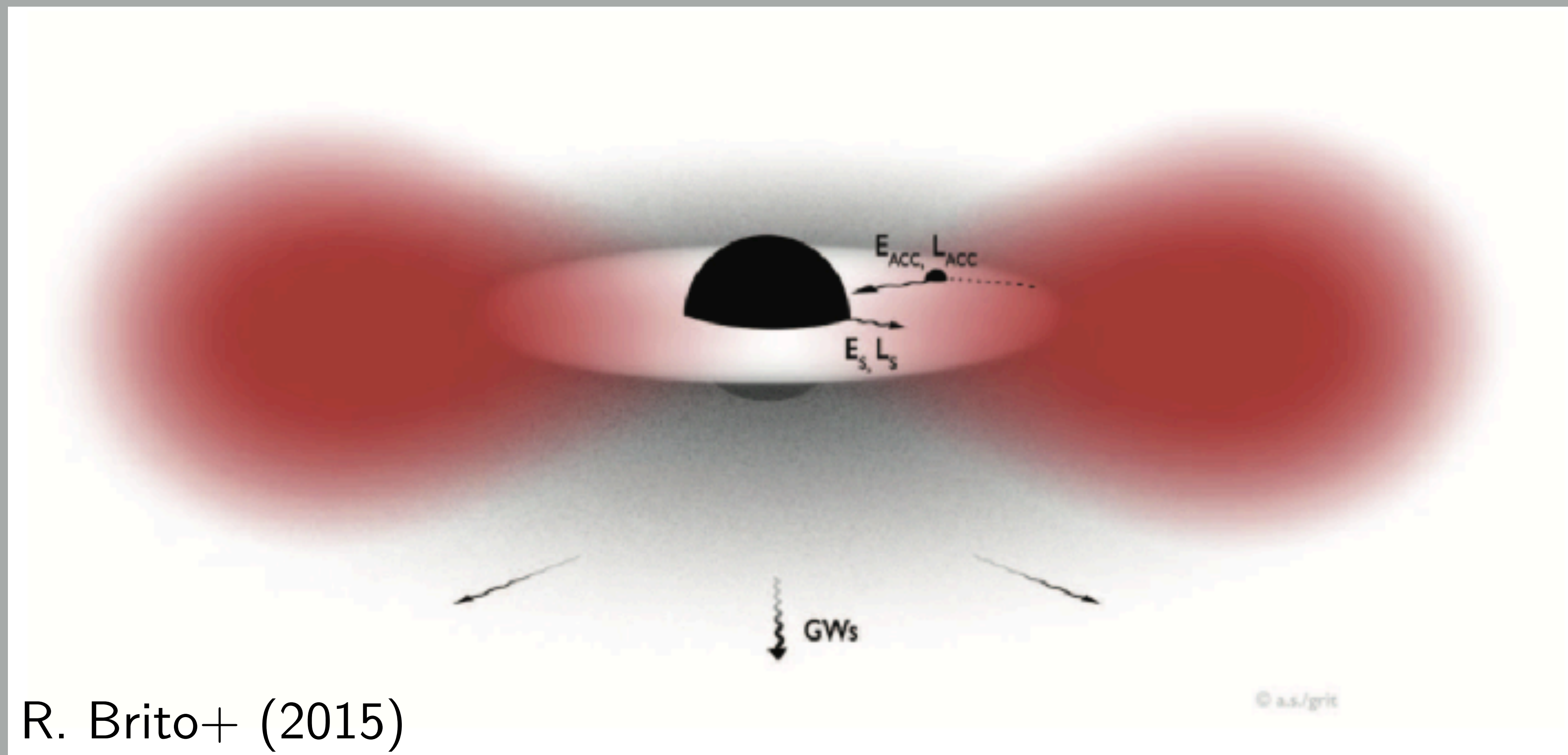


- DM on astrophysical sub-pc scales less constrained
- What is predicted on such scales, and how can these predictions be tested?

DM "Over-densities" around Black Holes (BHs)

Ultralight Dark Matter

[D. Blas, yesterday]



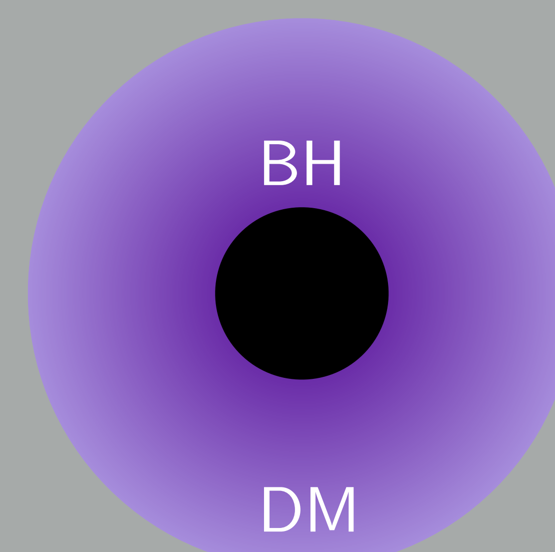
R. Brito+ (2015)

Cold, Particle Dark Matter

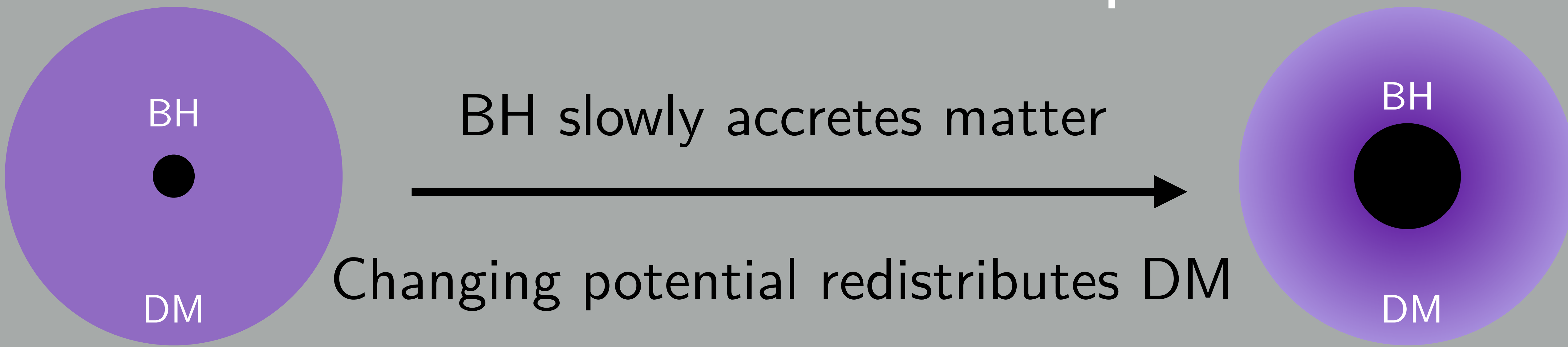
[this talk]

BH accretes mass adiabatically

Gondolo & Silk (1999)



Formation of a DM "Spike"



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

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

$$\rho_{DM}(r) = \rho_0 \left(\frac{r_0}{r}\right)^{\alpha} \longrightarrow \rho_{DM}(r) = \rho_{sp} \left(\frac{r_{sp}}{r}\right)^{\gamma_{sp}}$$

Spike power law can be decreased by several processes:

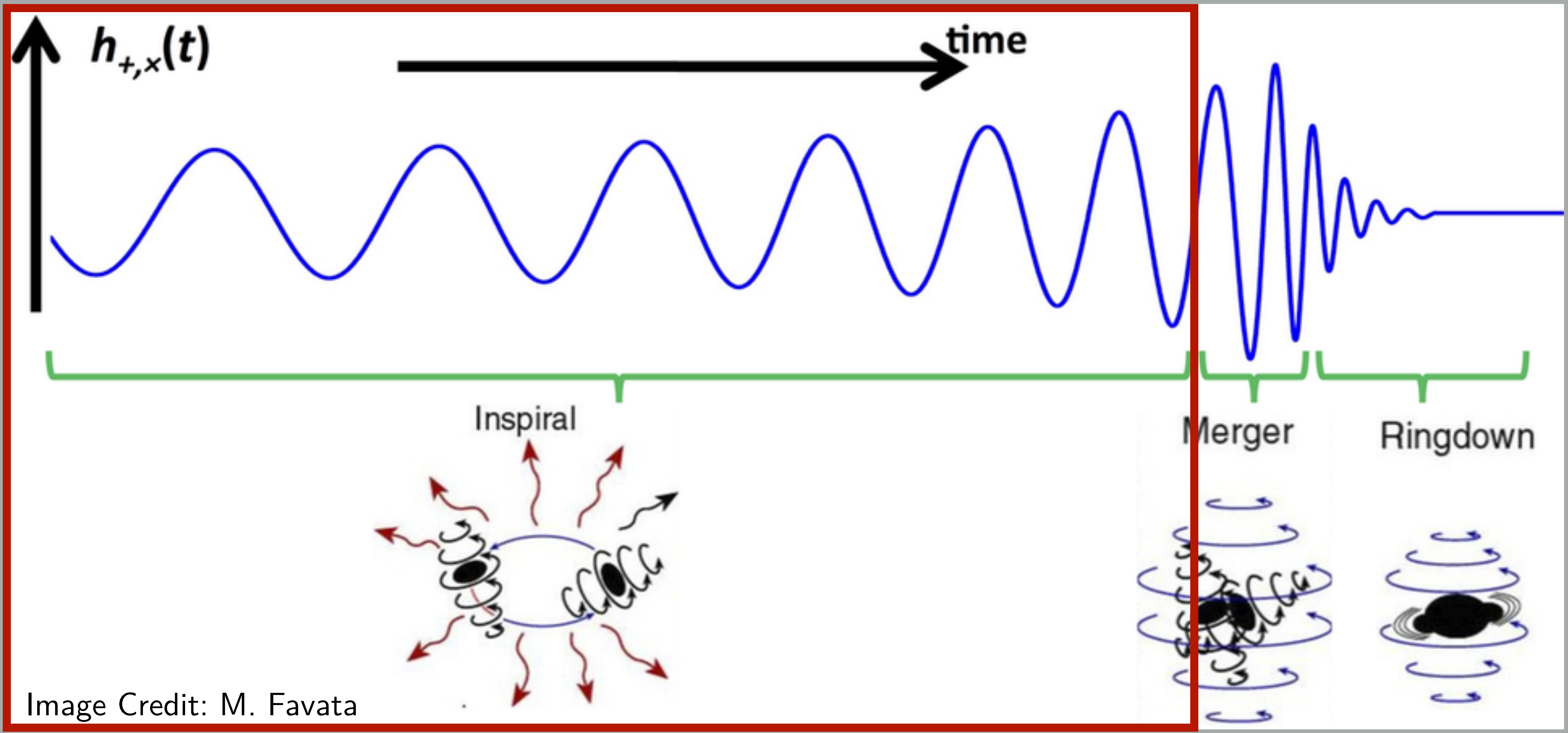
- Galactic mergers
- Off-center growth
- Fast (non-adiabatic) growth
- Baryonic processes

P. Ullio+ (2001)

Processes less likely to occur for intermediate-mass BHs (IMBHs) $M_{BH} \in [10^3, 10^5] M_\odot$ and primordial (PBHs)

Gravitational waves (GWs) from binaries

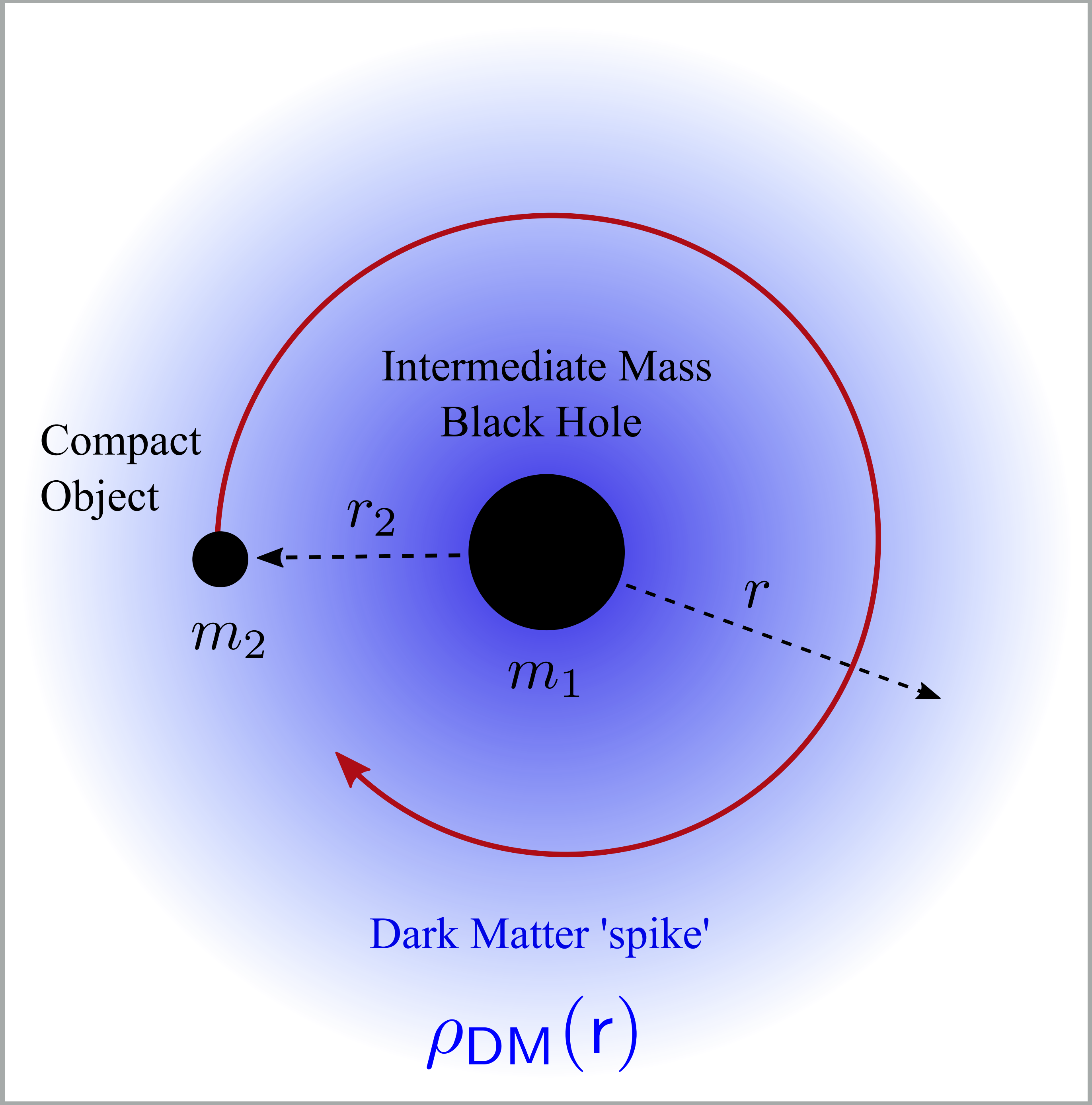
- IMBH+DM alone does not generate GWs; need a time-varying quadrupole moment from, e.g., a secondary.



- Need precise waveform templates to find GW signals in noise; need to evolve binary with effects of DM on orbit

Intermediate Mass-Ratio Inspirals (IMRIs)

- Consider an IMBH+DM that captured a secondary compact object (BH or NS), with mass m_2



Mass Ratio

$$m_2/m_1 \equiv q \in (10^{-2}, 10^{-5}) \ll 1$$

GW frequencies and cycles (years from merger)

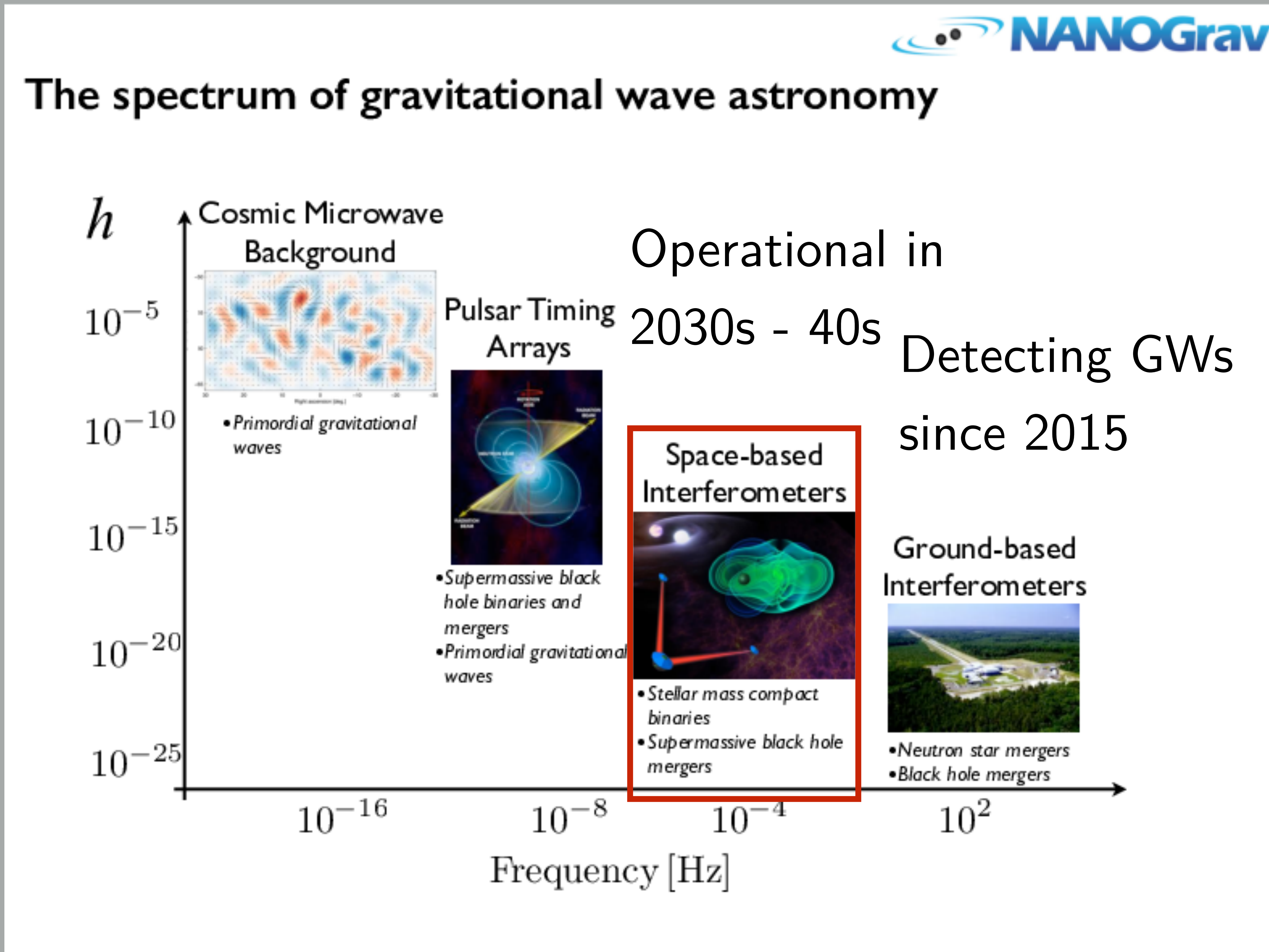
$$f_{GW} = 2f_{orb} \sim 10^{-2}\text{Hz}$$

$$N_{cycles} \sim 10^6$$

Initial orbital separation (years from merger)

$$r_2 \in (10^{-8}, 10^{-7})\text{pc}$$

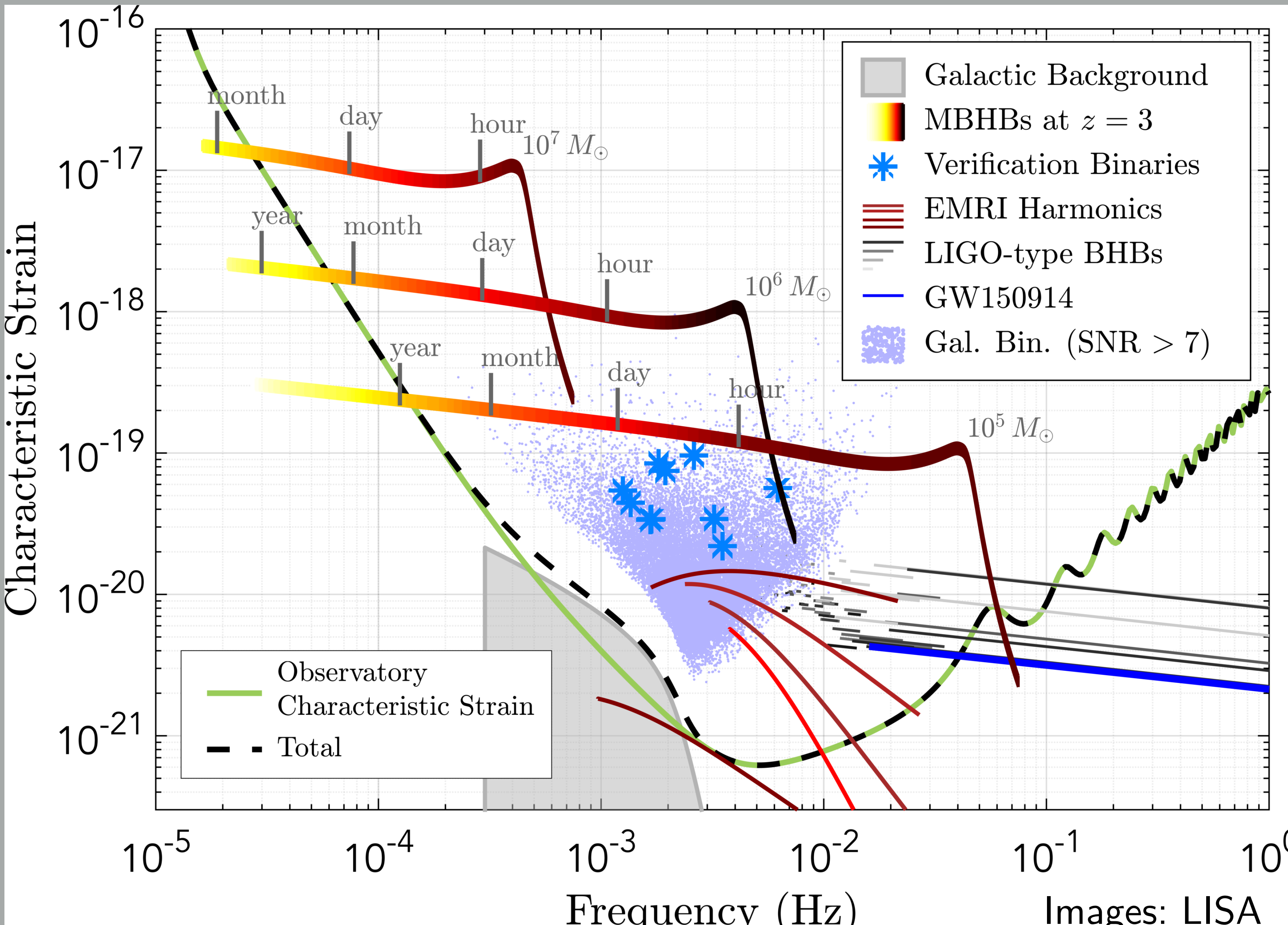
The gravitational-wave (GW) universe

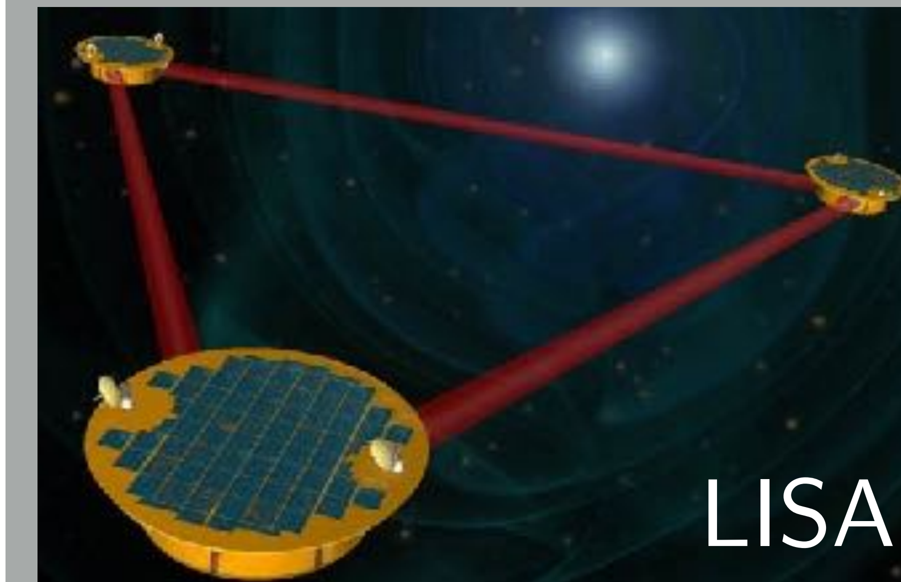


Operational in 2030s - 40s

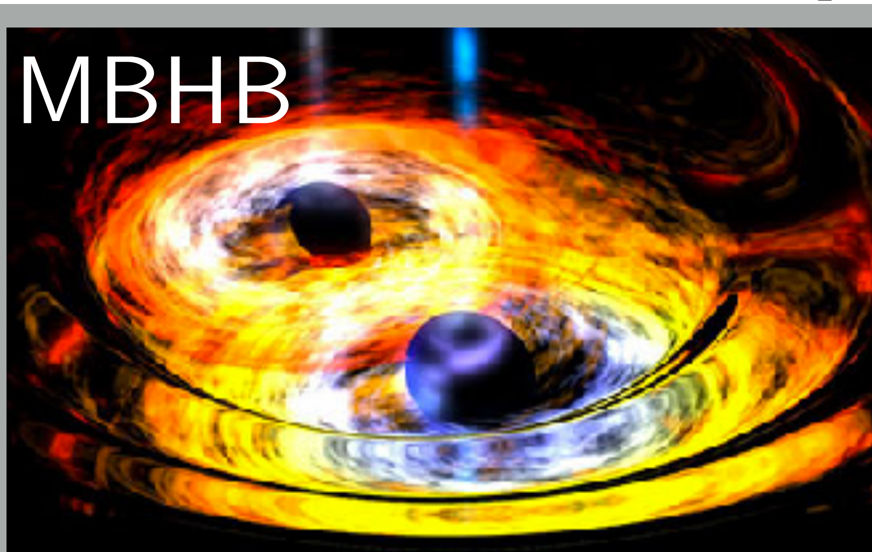
Detecting GWs since 2015

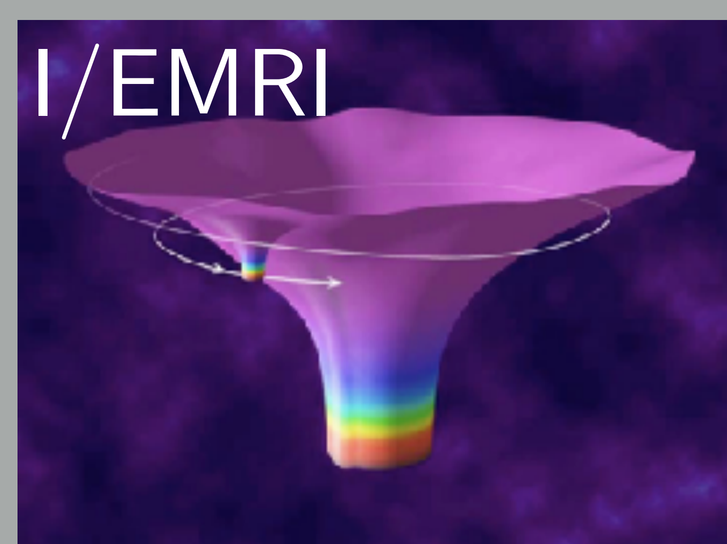
LISA Detector and Sources





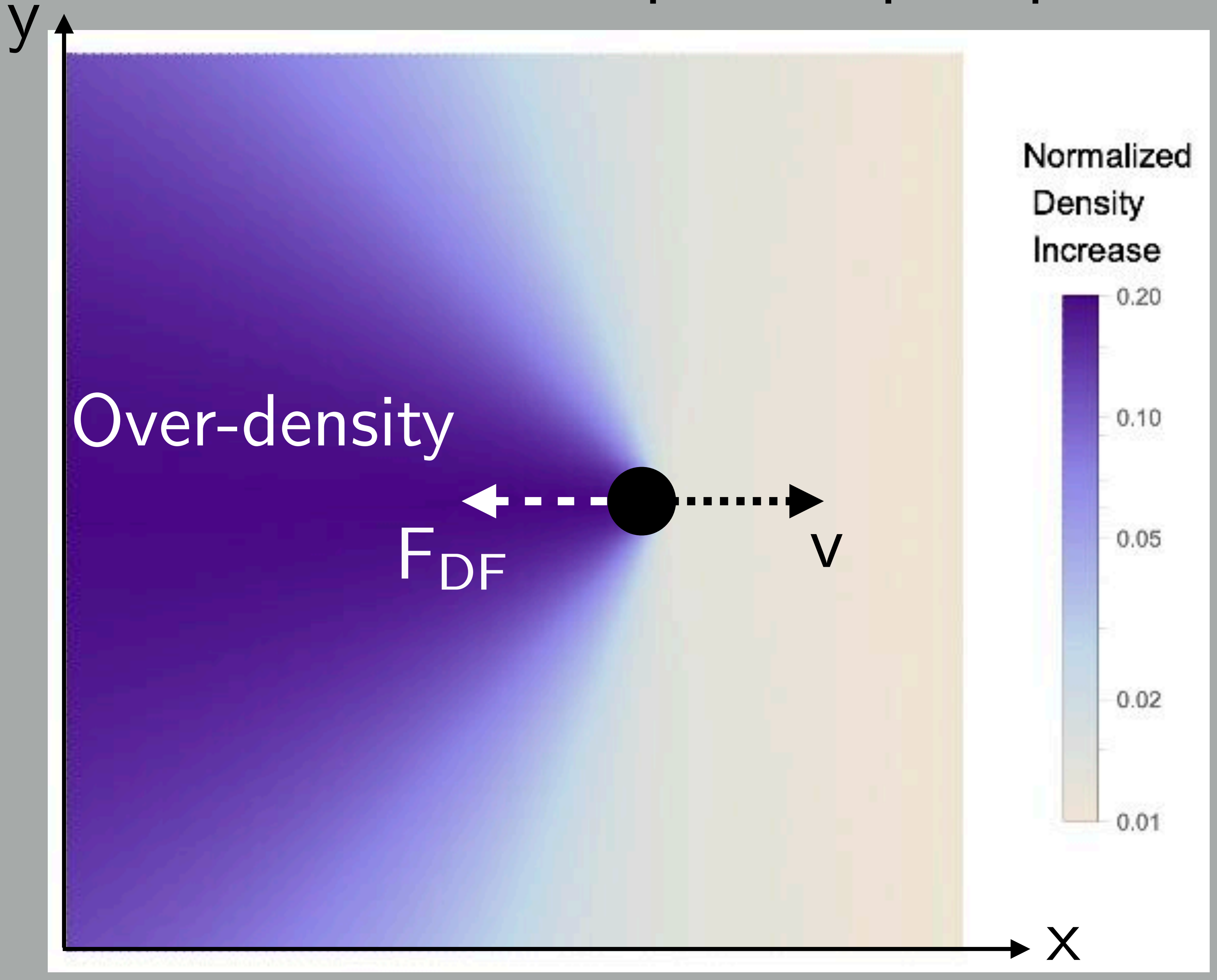
- 3 satellite constellation
- Earth-trailing orbit
- 10^6 km arms
- Operational: late 2030s
- 4 to 10 year mission lifetime





Effect of DM Distribution on IMRIs

- Without DM binary inspirals from GW emission only
- DM distribution speeds up inspiral from dynamical friction

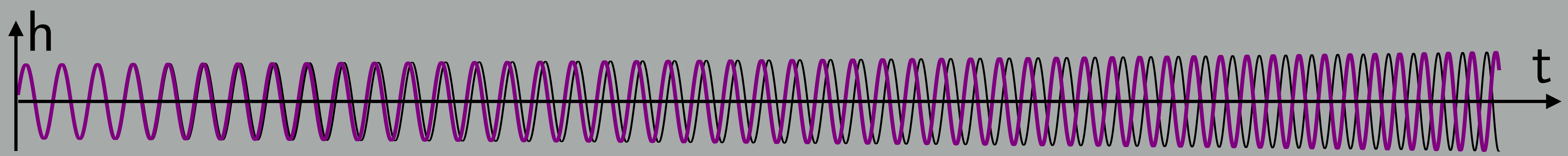


- Dynamical friction (DF)

  S. Chandrasekhar (1943)

  effective gravitational drag from an over-density in a wake formed as a body moves through DM

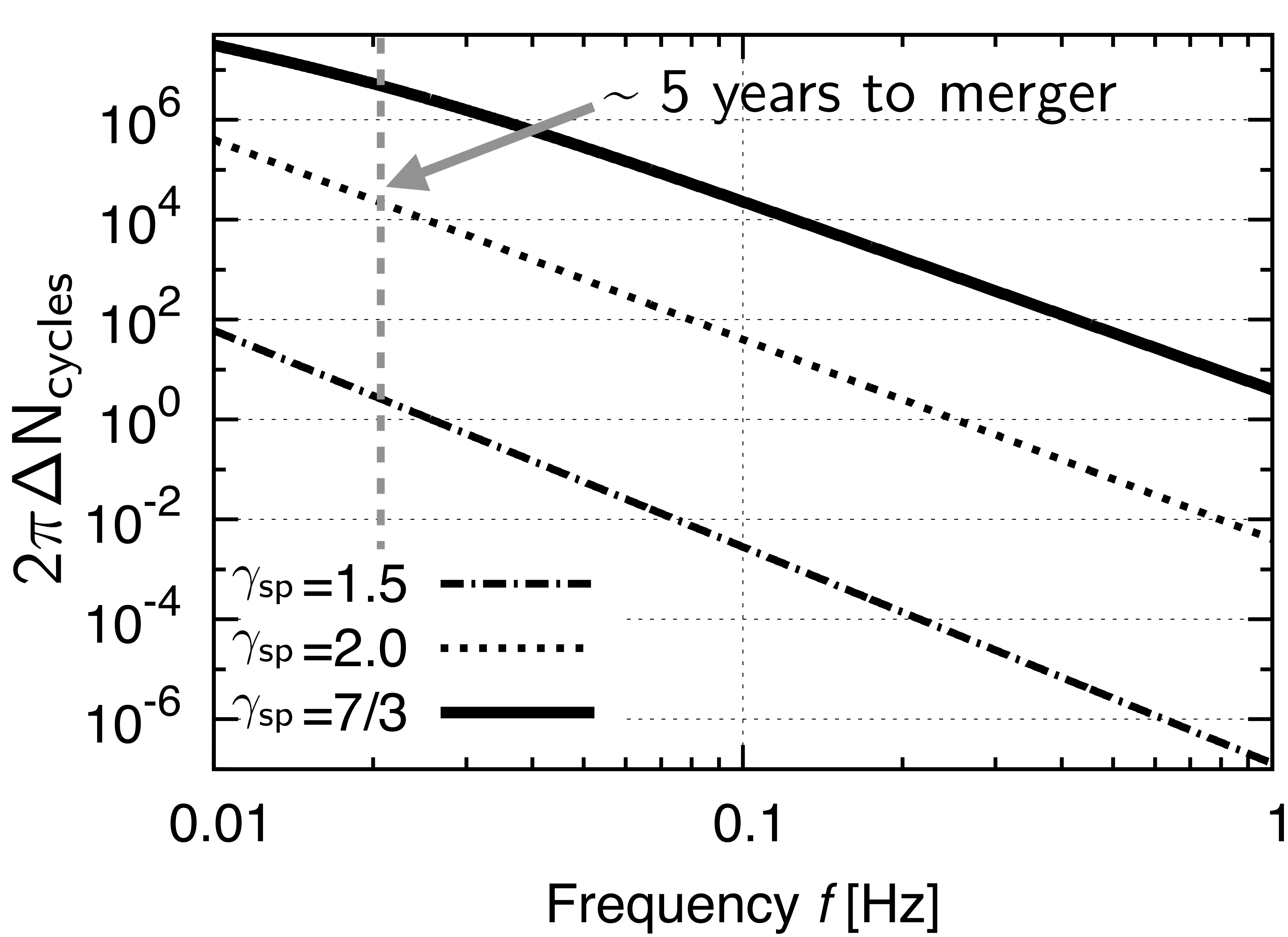
$$F_{DF} \sim \rho_{DM}/v^2$$



Static DM Distributions

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

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



K. Eda+, (2014)

DM distribution

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

$$\rho_{\rm sp} = 225 M_\odot/{\rm pc}^3 = 8500 {\rm Gev/cm}^3$$

$$r_{\rm sp} \sim 1{\rm pc}$$

Binary properties

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

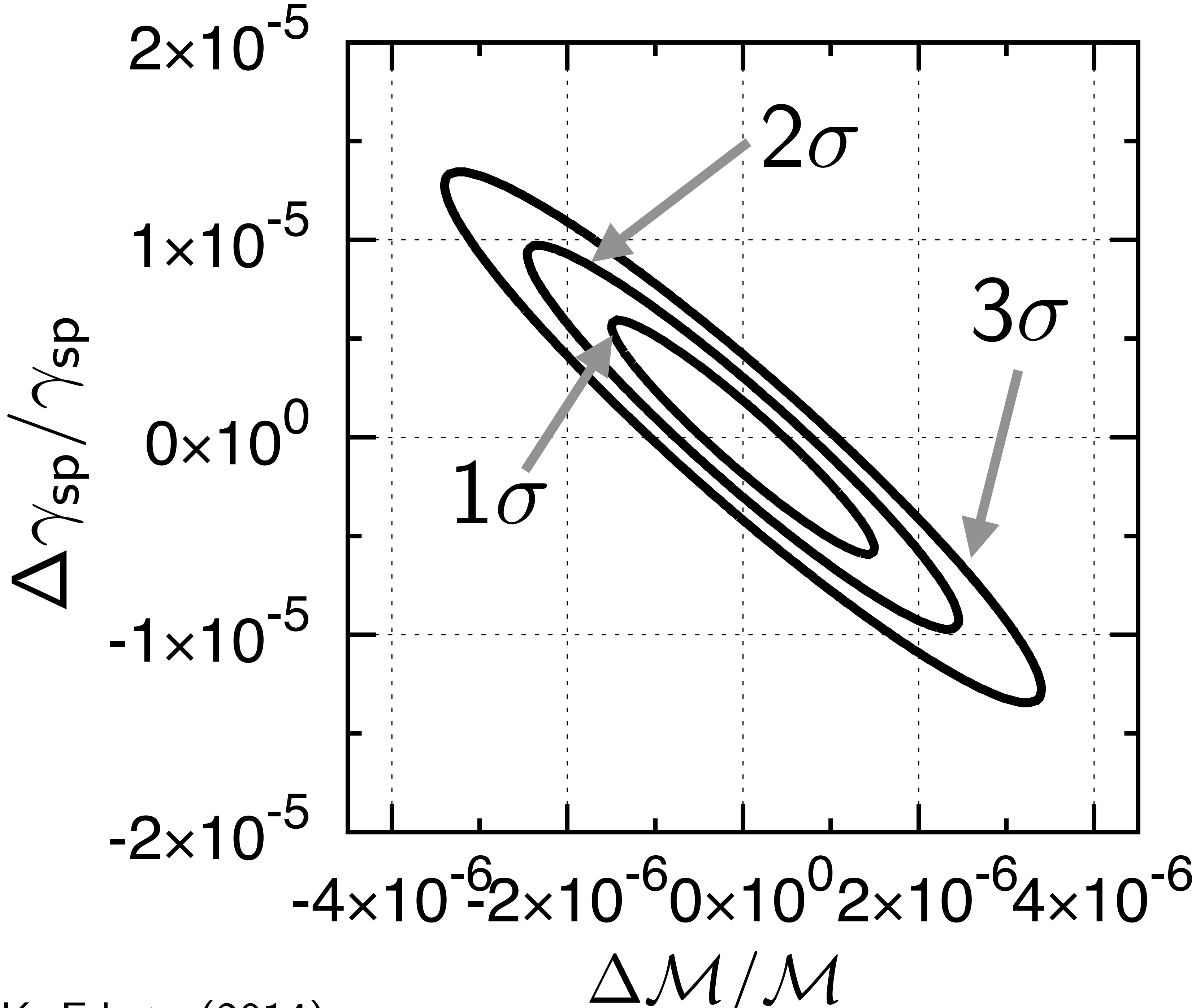
$$m_2 = M_\odot$$

Circular orbit

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

Static DM Distributions

- Fischer forecasting of measurement accuracy with LISA



K. Eda+, (2014)

Chirp mass

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

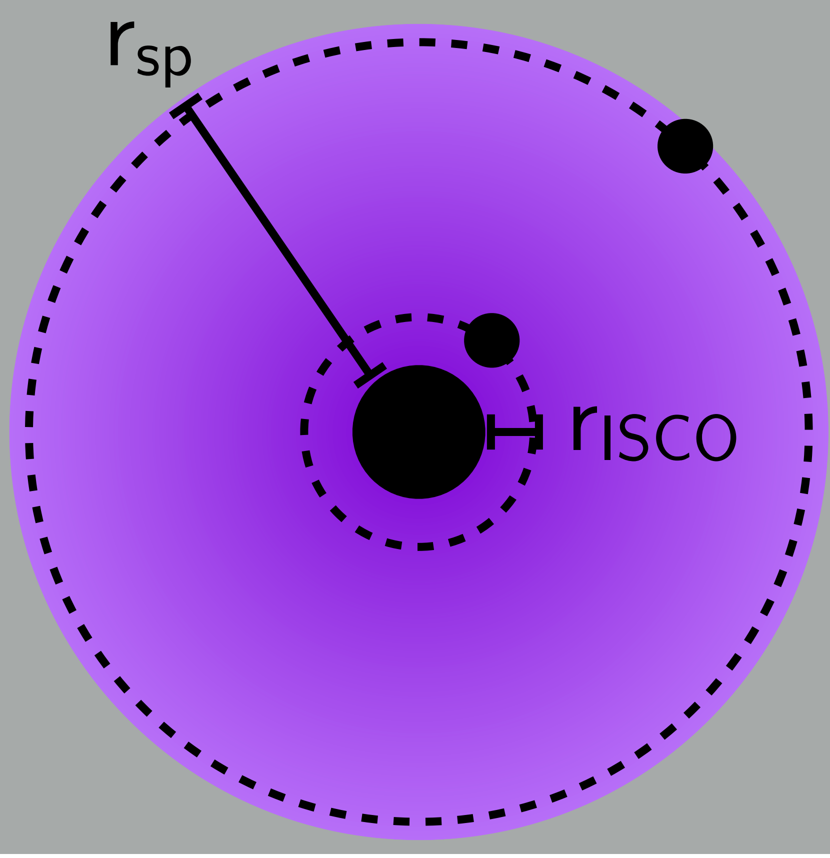
Statistical errors

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

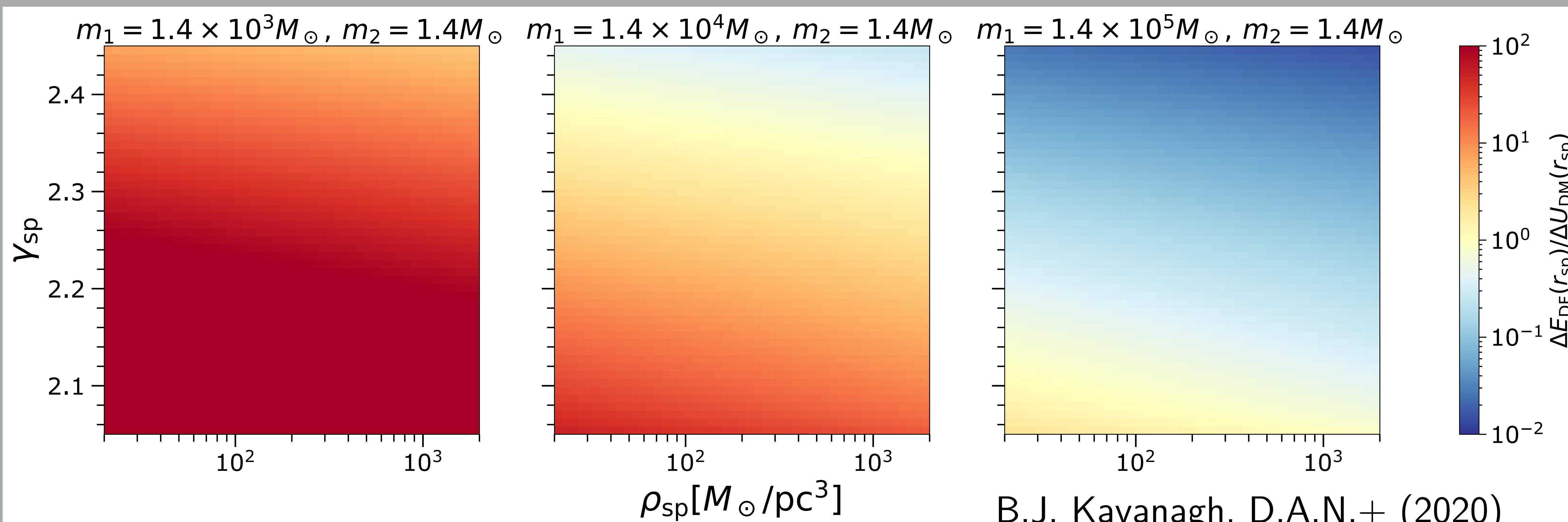
$$\Delta\gamma_{sp}/\gamma_{sp}$$

- 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}: $\Delta E_{DF}(r_{sp})$
- For a wide range of binaries and DM spikes, $\Delta E_{DF}(r_{sp}) \gg \Delta U_{DM}(r_{sp})$!



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

Must evolve the DM around the IMRI

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

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

- Assume spherical symmetry, and f evolves on timescales longer than orbital time T_{orb} via the prescription

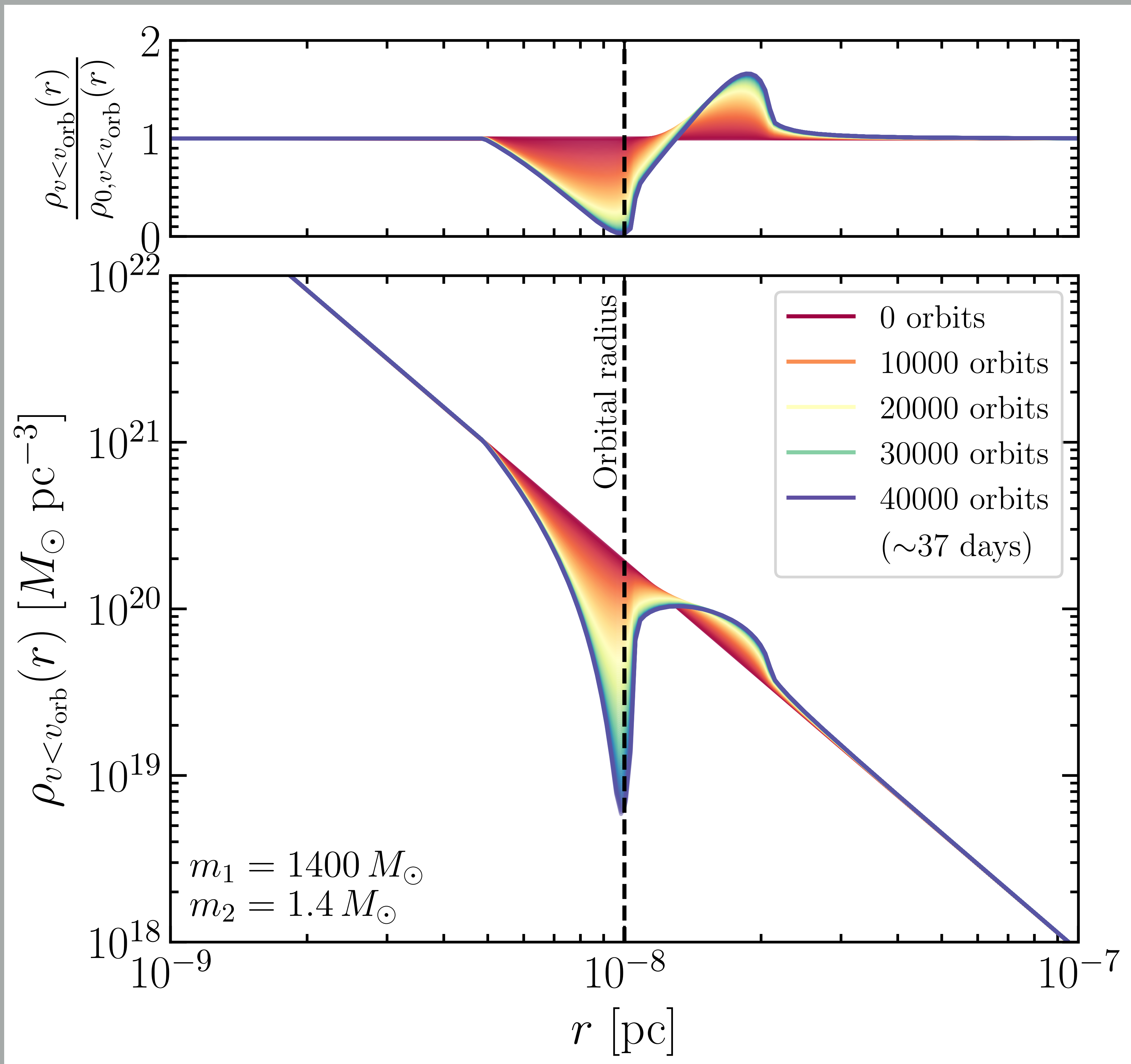
$$\frac{\partial f(\mathcal{E})}{\partial t} = \int d\delta\mathcal{E}\ \{\text{-[Density of particles w/}\ \mathcal{E}\ \text{scattering to}\ \mathcal{E}+\delta\mathcal{E}] + [\text{Density of particles w/}\ \mathcal{E}\ \text{scattering to}\ \mathcal{E}+\delta\mathcal{E}]\}/T_{orb}$$

- 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 evolution on short times

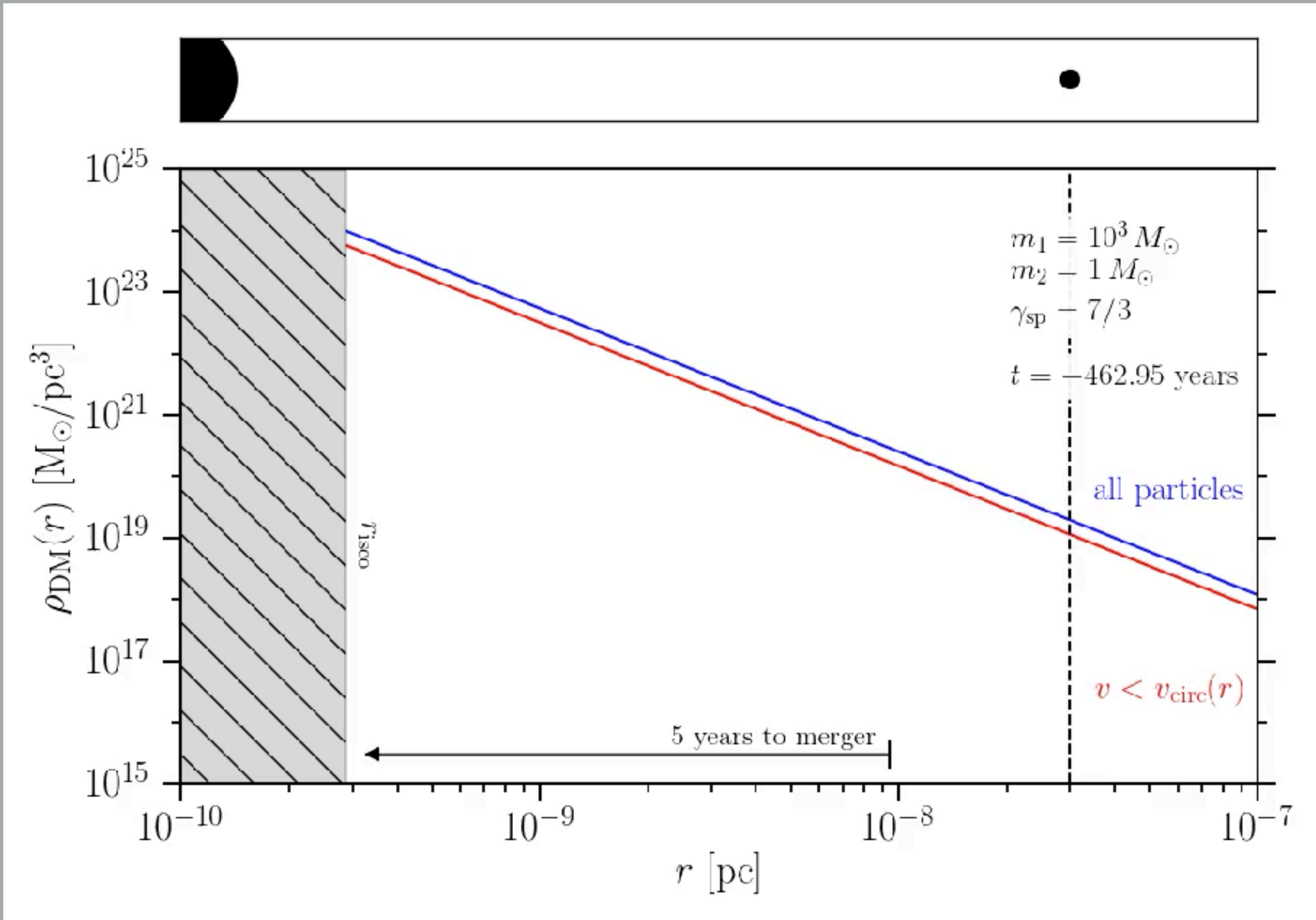


B.J. Kavanagh, D.A.N.+, (2020)

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

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

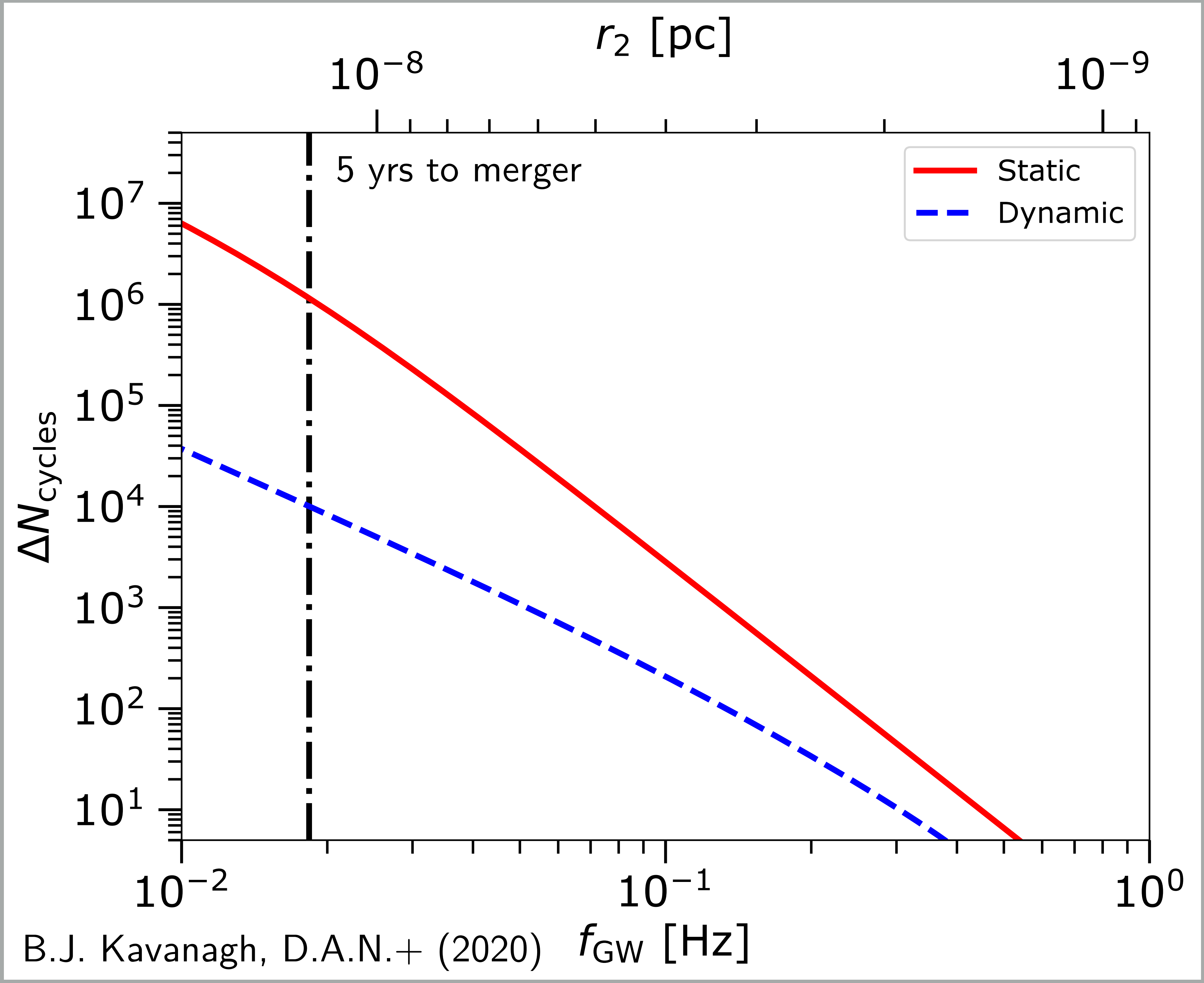
DM and binary co-evolution



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

Movie at http://tinyurl.com/GW4DM

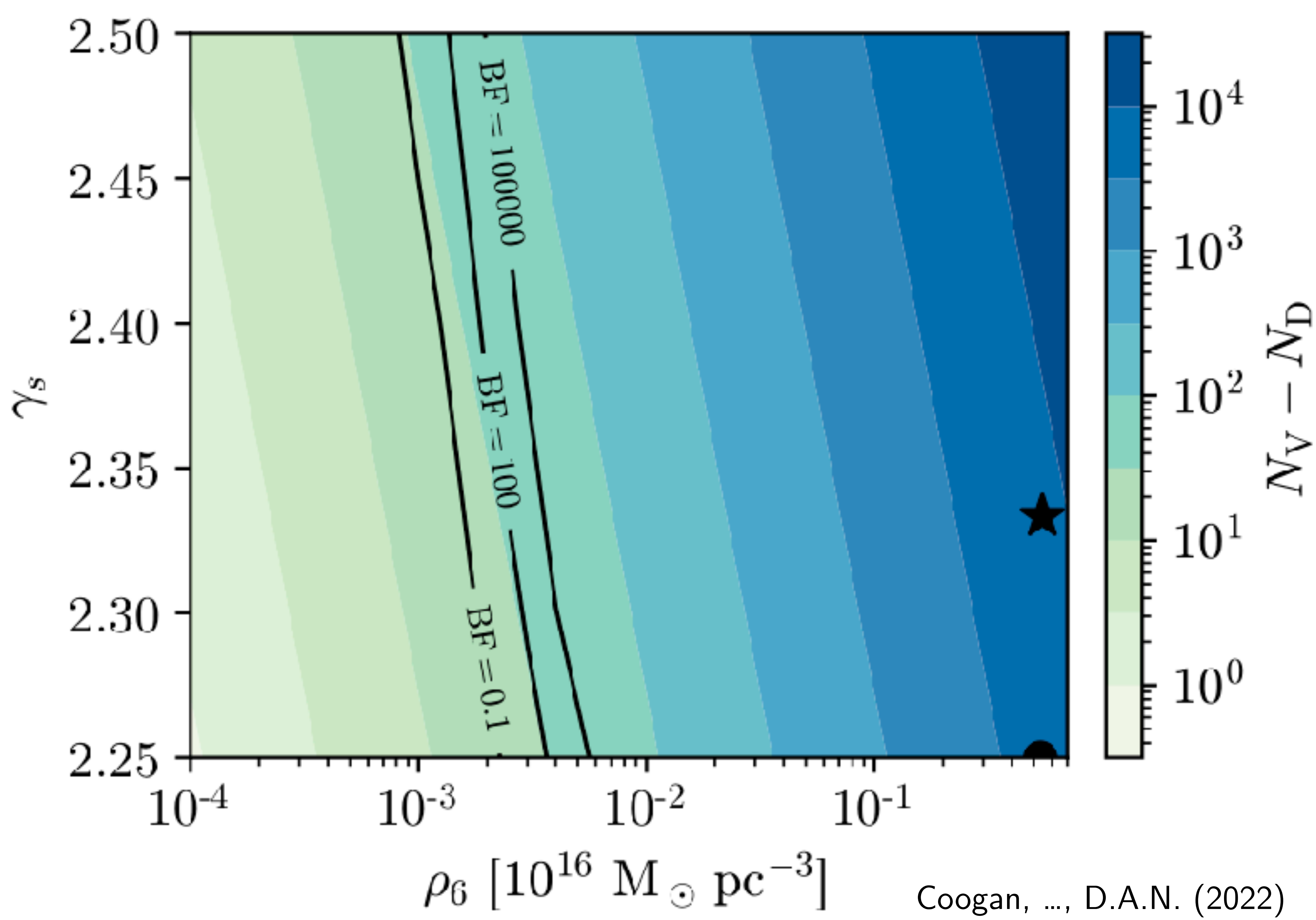
Dynamic DM Distributions: Dephasing



$$m_1 = 1400 M_\odot\,,\ m_2 = 1.4 M_\odot \quad \rho_{\rm sp} = 225 M_\odot/{\rm pc}^3\,,\ \gamma_{\rm sp} = 7/3$$

Dephasing with DM feedback

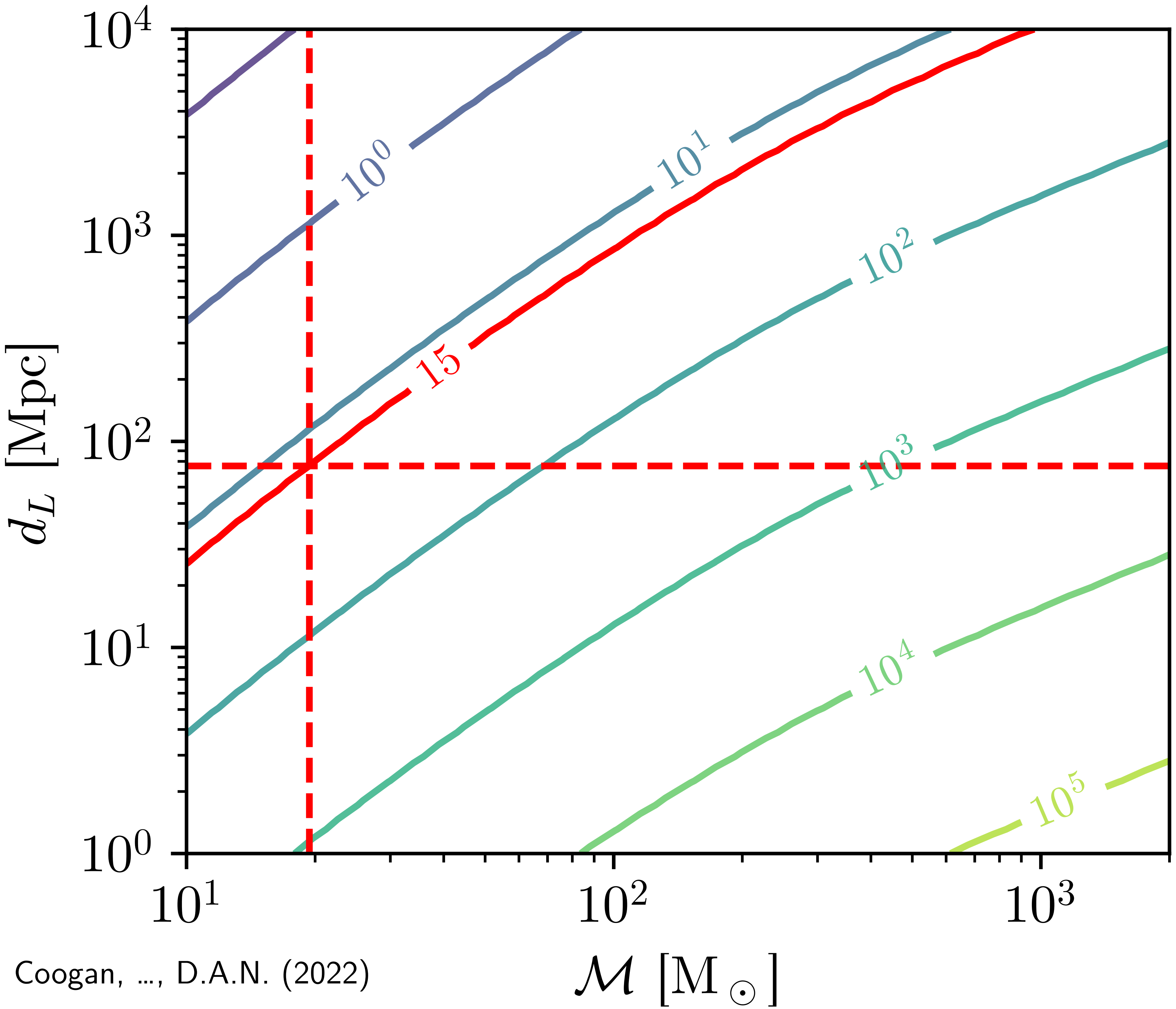
- Write density: $\rho_{\mathrm{DM}} = \rho_6 (r_6/r)^{\gamma_{\mathrm{sp}}}$ w/ $\rho_6 \propto \rho_{\mathrm{sp}}/r_6^{\gamma_{\mathrm{sp}}}$ & $r_6 = 10^6\mathrm{pc}$



Coogan, ..., D.A.N. (2022)

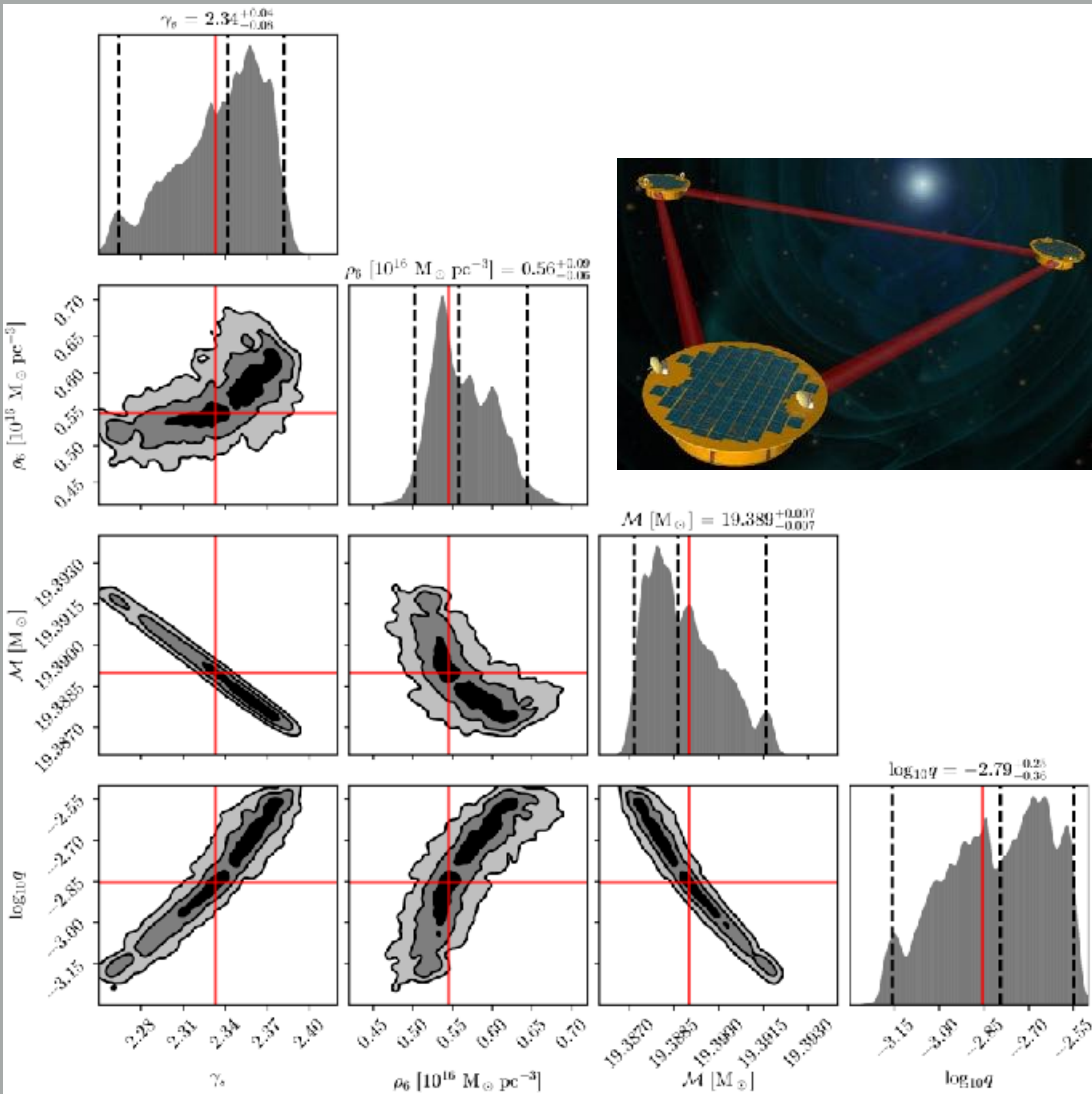
Signal-to-noise (S/N) and detection range

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



Coogan, ..., D.A.N. (2022)

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

Coogan, ..., D.A.N. (2022)

Conclusions and Future Directions

- LISA is a high-precision gravitational-wave observatory
- It can be used to study the dark-matter environment of massive black holes
- Studying these systems requires precise modeling of the binary's orbital dynamics coupled to the surrounding dark-matter distribution's dynamics

- Many open areas to be investigated: rates of IMRI mergers with dark matter spikes, improved waveform modeling, developing search and parameter estimation pipelines
- Translate density to microphysics of DM model?