Small-Scale Structure of the Universe and Self-Interacting Dark Matter
Valencia, 13 June 2025

SIGNATURES OF SELF-INTERACTING DARK SECTORS

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AKA: Do I have to care about the particle physics model?

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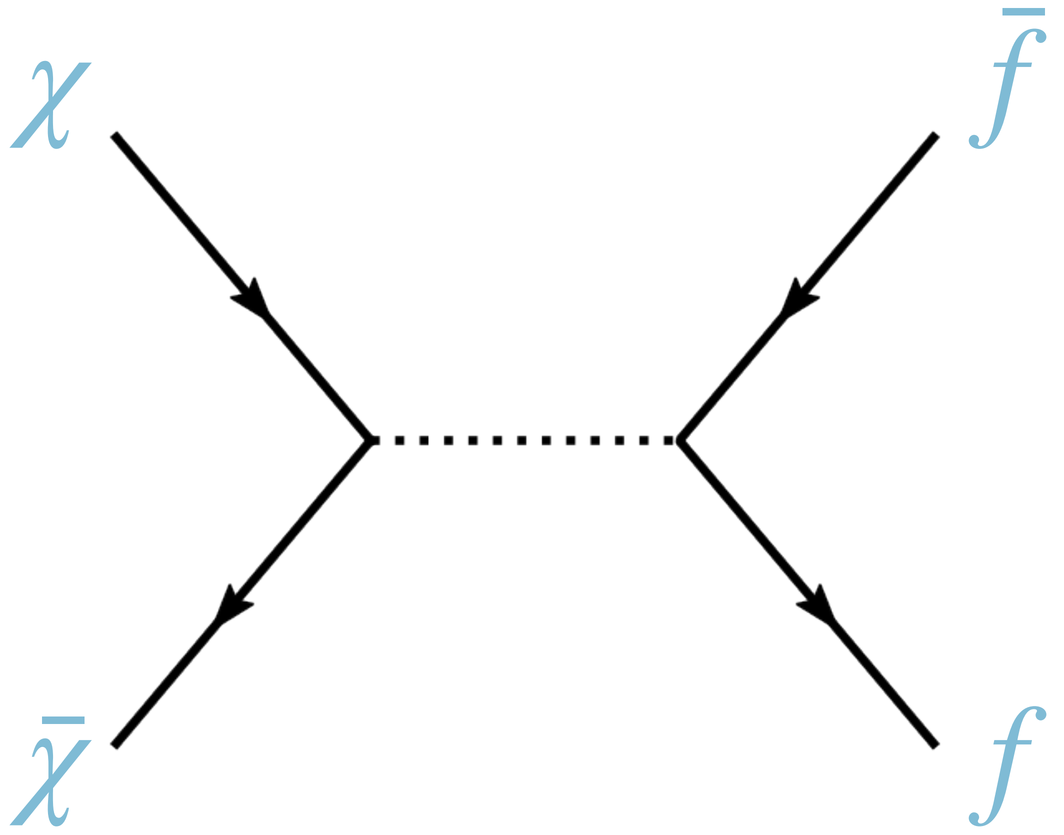
1 Particle models for SIDM

See Xiaoyong Chu's overview talk for more details and references

Thermal WIMP Freeze-Out



annihilation →

← creation

comoving number density

Hubble expansion
halts annihilations

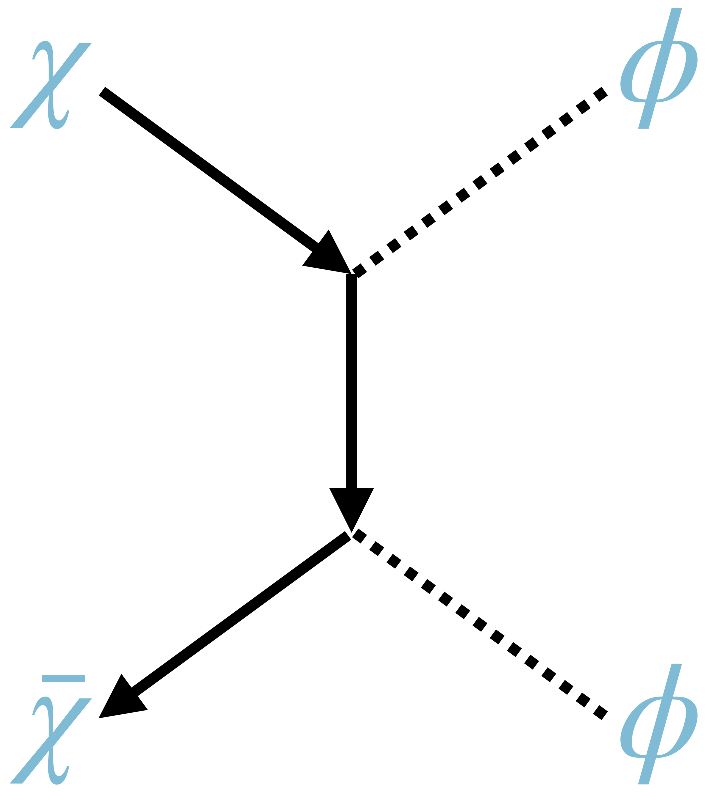
DM mass / temperature

assume $\langle \sigma v \rangle \sim \dfrac{\pi \alpha^2}{m^2}$

match observed abundance for weak-scale particles (WIMP miracle)

Dark Sector Freeze-Out

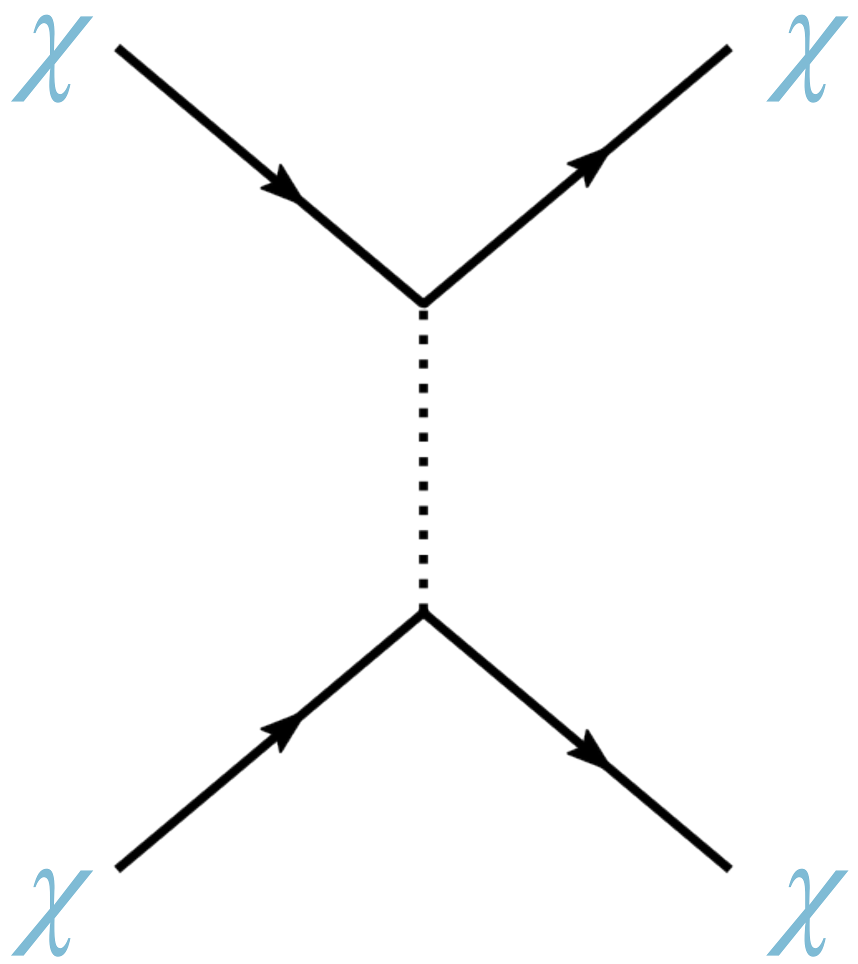
- Assume dark sector of dark matter particle χ and light mediator ϕ
- Set relic abundance of χ



- But ϕ itself contributes radiation energy density $\sim T^4_{\text{dark}}$, until it is nonrelativistic
- Can avoid very abundant ϕ by
  - allowing rapid decay, for example $\phi \to e^+e^-$
  - insisting ϕ mass is low enough for ϕ to redshift as radiation

Examples of Simplified Models for SIDM

- Heavy mediator: hard-sphere and velocity-independent scattering
- "Light" mediator: Yukawa interaction (velocity-dependent scattering)
- Very light or massless mediator: long-range, Coulomb-like interaction



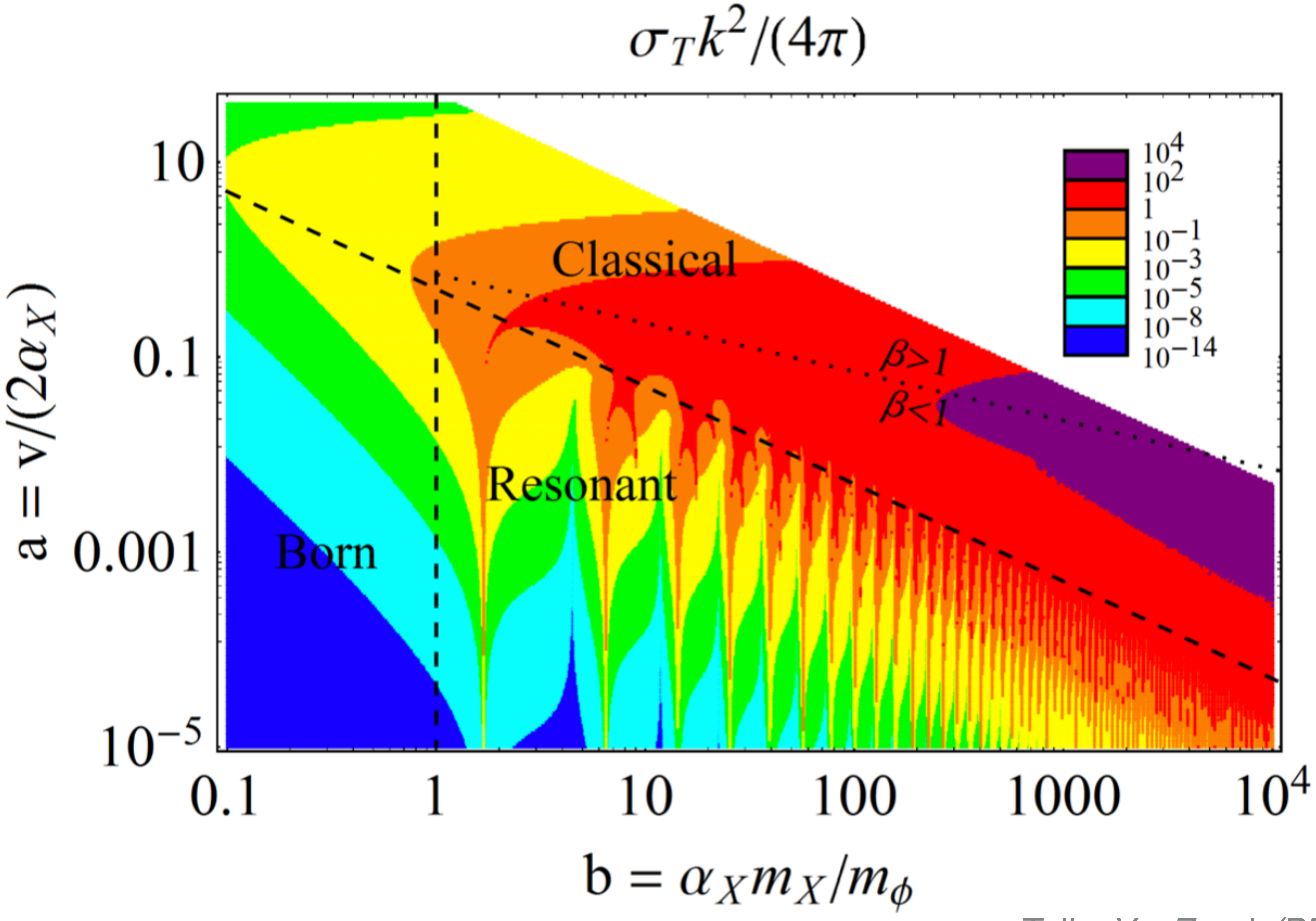
Model: Yukawa Scattering

- Vector and scalar mediators gives rise to Yukawa potential $V(r) = \pm \frac{\alpha_\chi}{r} e^{-m_\phi r}$
- Differential cross section (Born regime):

$$\frac{d\sigma}{d\Omega} = \frac{\sigma_0}{4\pi}\left(1 + \frac{v_{\rm rel}^2}{w^2}\sin^2\frac{\theta}{2}\right)^{-2}$$

where $w = m_\phi / m_\chi$

- Isotropic, hard-sphere scattering for $w \to \infty$



Tulin, Yu, Zurek (PRD 2013)

Examples of Simplified Models for SIDM

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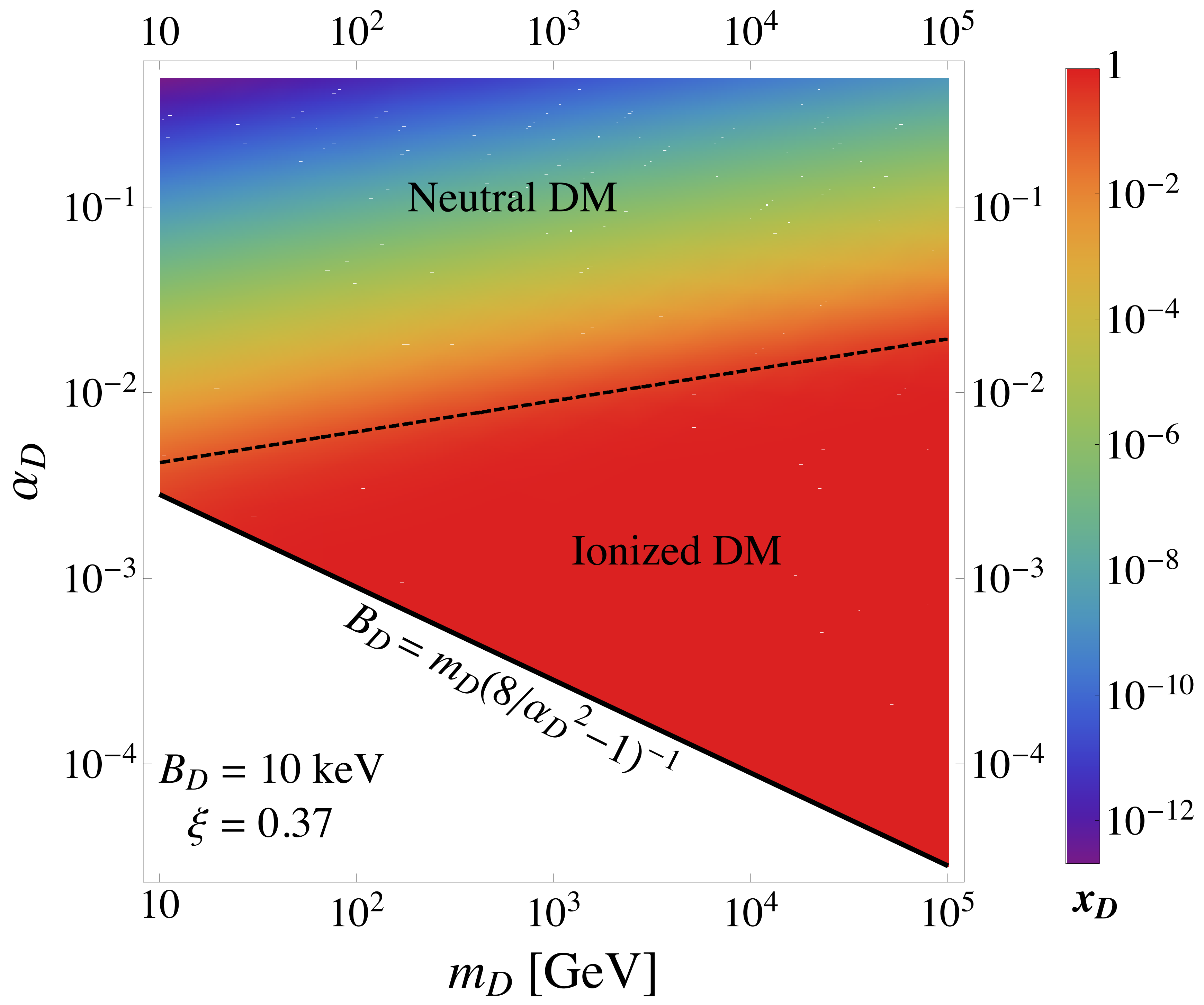
- Very light or massless mediator: long-range interaction

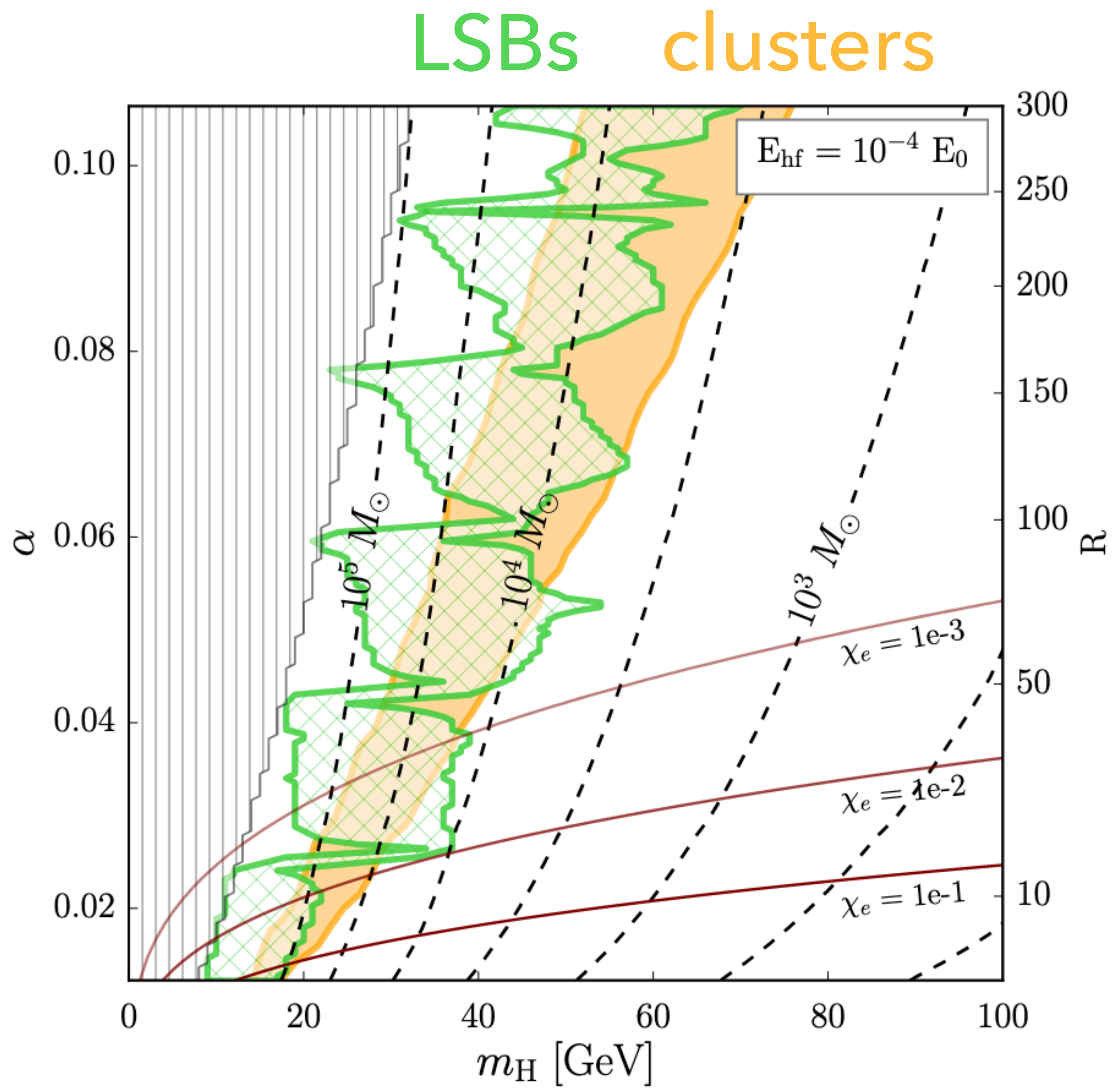
- Mediator is force carrier for dark U(1) – i.e., dark E&M
  - Dark electron interacts with dark photon (massive or massless)
  - Atomic dark matter: formation of dark hydrogen

Model: Atomic Dark Matter

- Dark electron and dark proton undergo dark recombination
- Composite dark hydrogen has atomic-scale self-interactions



Cyr-Racine, Sigurdson (PRD 2013)



KB, Kaplinghat, Kwa, Peter (PRD 2016)

Examples of Simplified Models for SIDM

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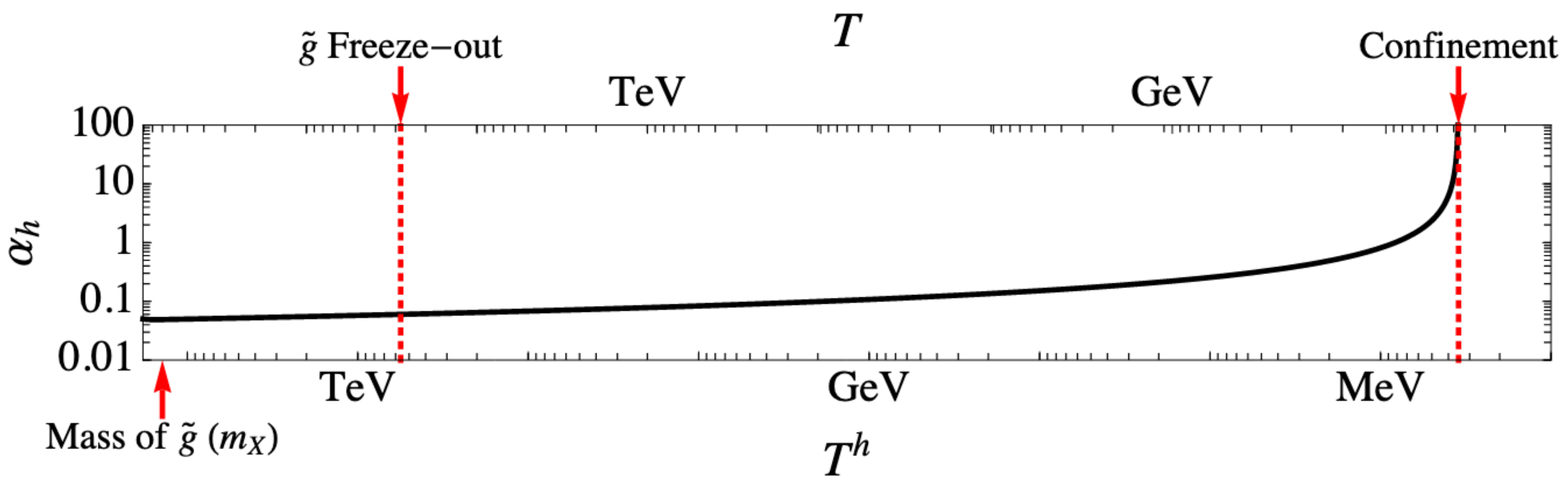
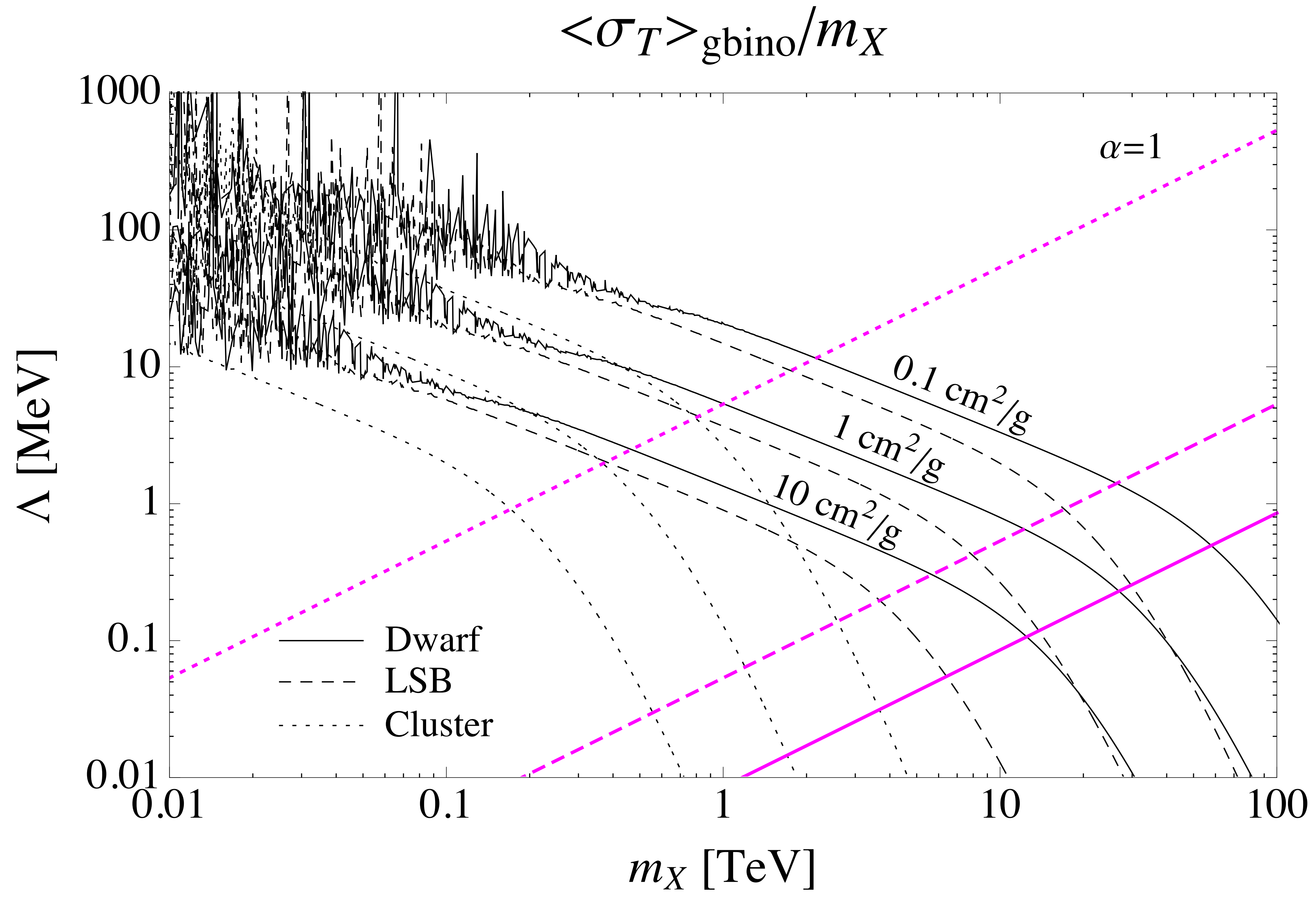
- Mediator is force carrier for dark SU(N) – i.e., dark strong force
  - Colored fermions interact with dark gluons
  - Below confinement scale: formation of dark nuclei, dark glueballs

Model: Strongly-Interacting Dark Matter

- Dark sector undergoes dark confinement
- Composite dark nuclei have nuclear-scale self-interactions





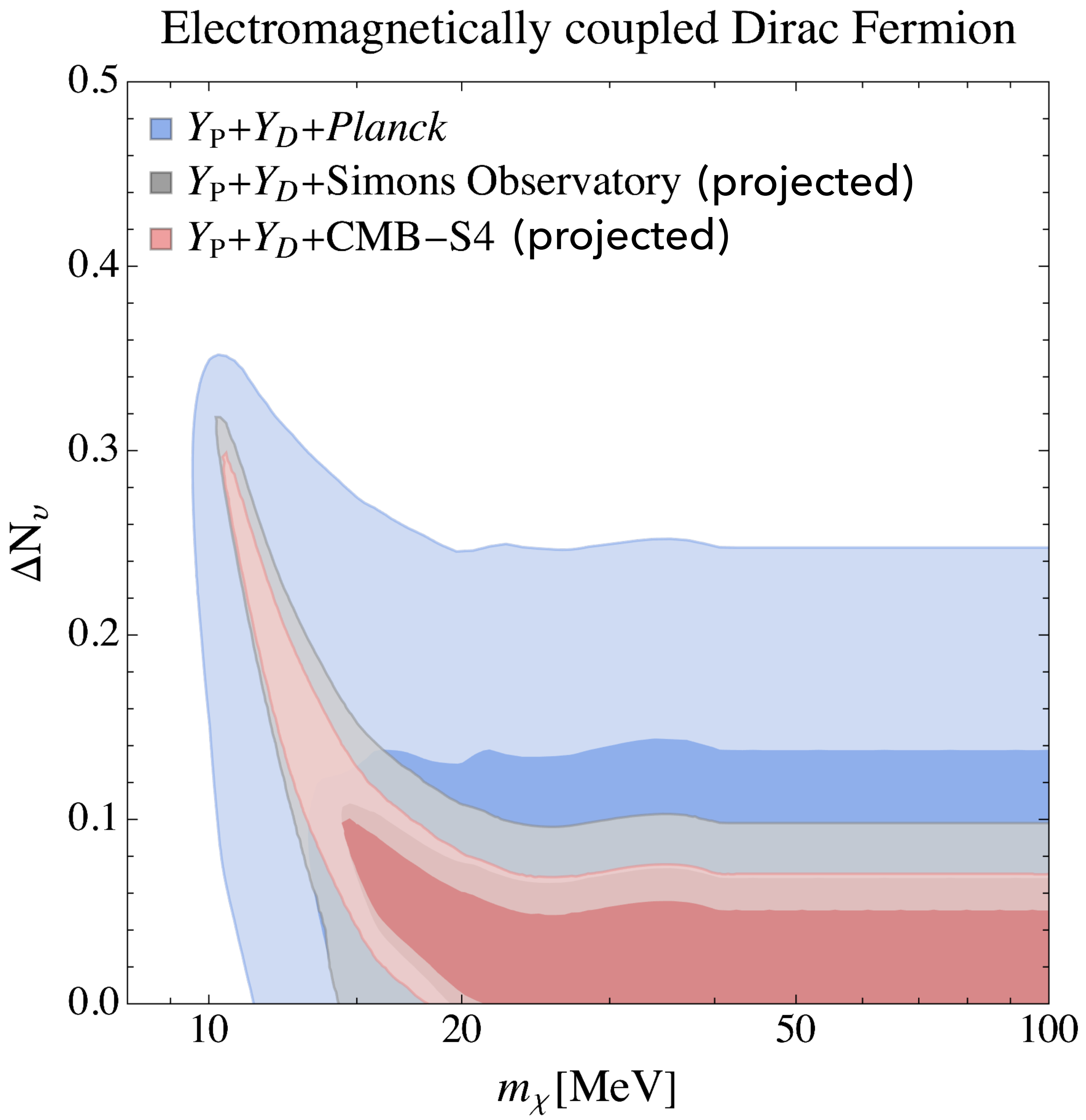
KB, Feng, Kaplinghat, Tait (PRD 2014)

2 Impact on cosmology

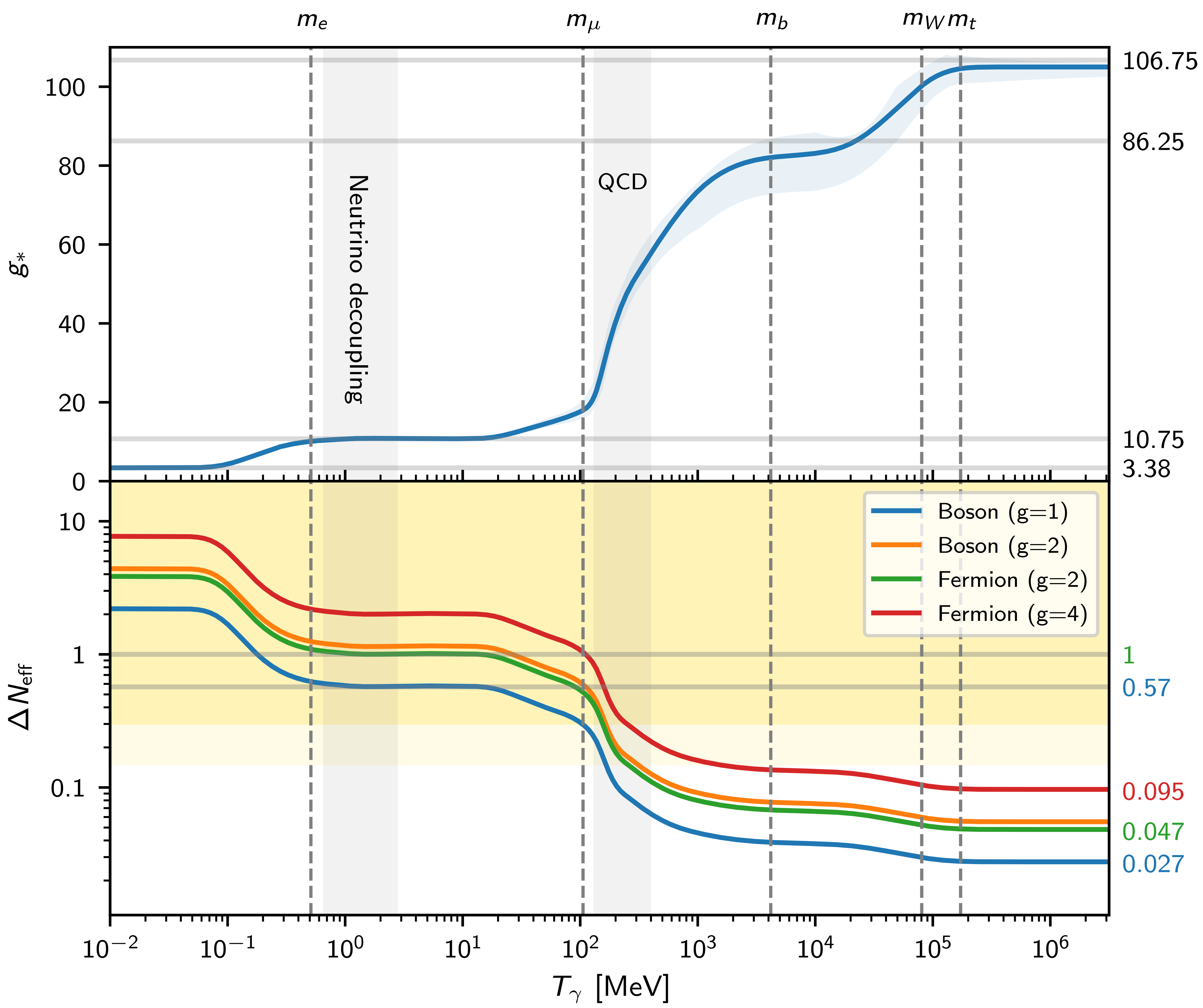
Early-Universe Cosmology: Expansion History

- Thermal dark particles contribute to $N_{\rm eff}$ (depends on decoupling temperature)

$$\rho_{\rm rad} = \rho_\gamma \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]$$



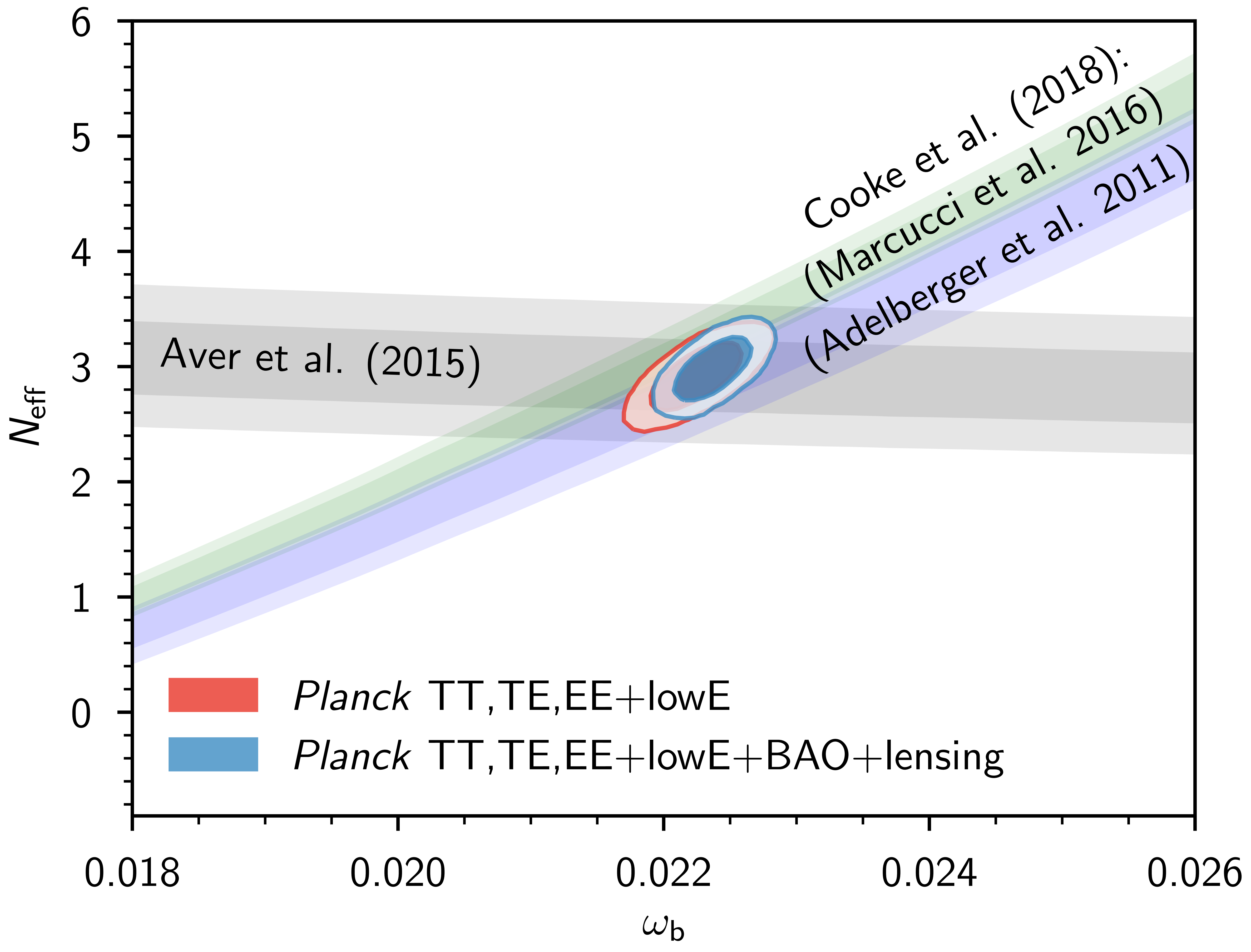
An, Gluscevic, Calabrese, Hill (JCAP 2022; 2202.03515)



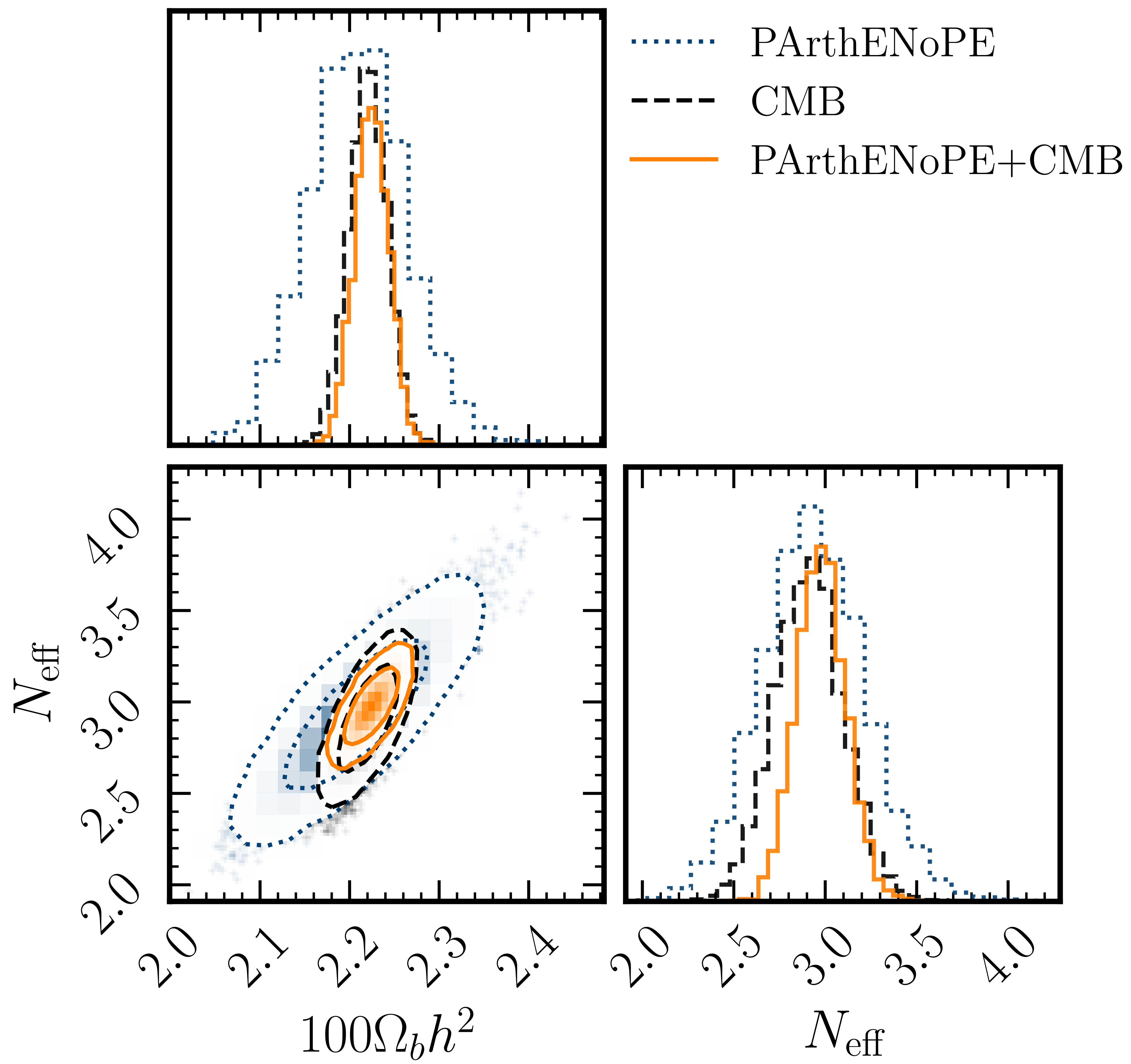
Planck 2018: Cosmological Parameters (1807.06209)

Early-Universe Cosmology: Expansion History

- Dark sector particles in general contribute to N_{eff} during BBN and CMB eras



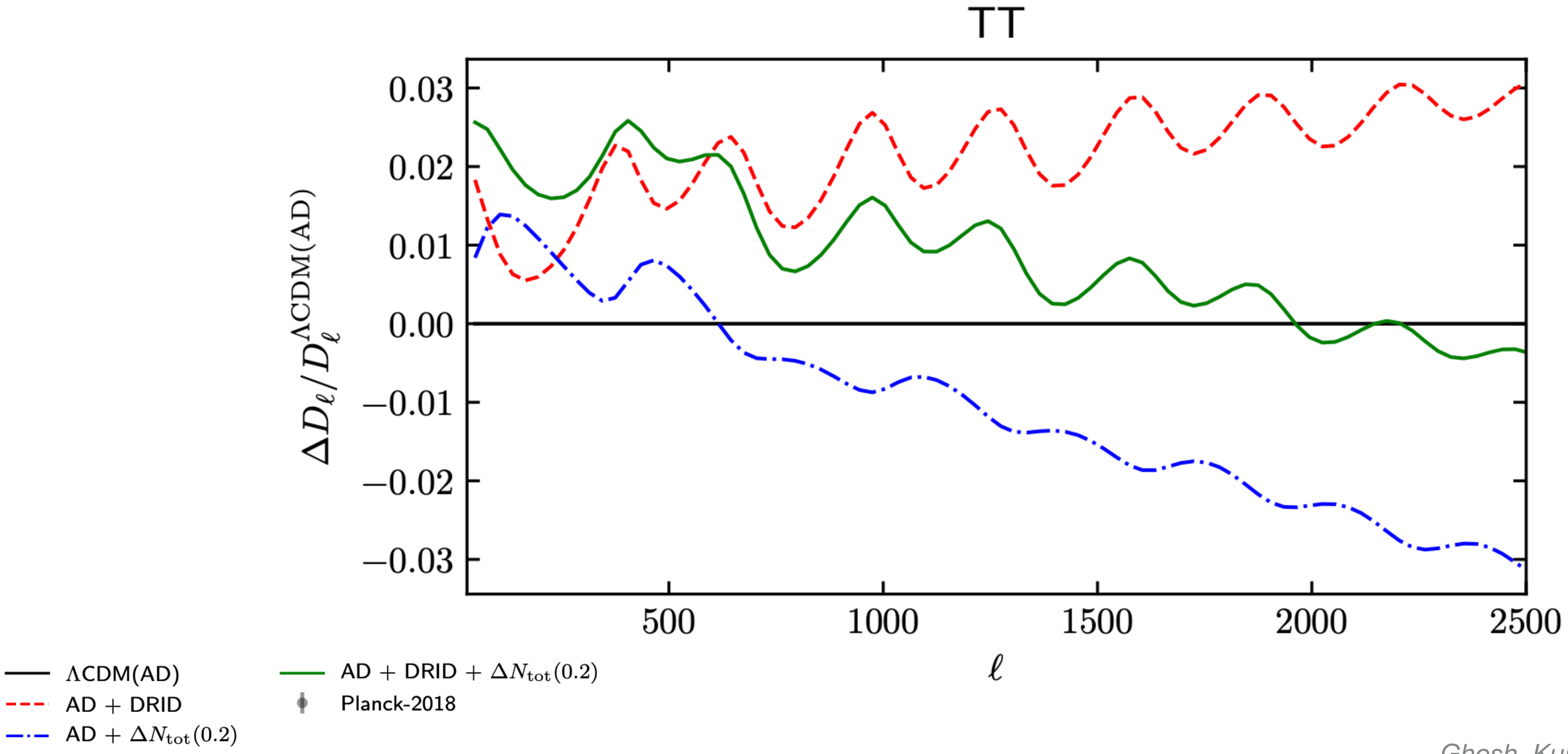
Planck 2018: Cosmological Parameters (1807.06209)



Giovanetti, Lisanti, Liu, Mishra-Sharma, Ruderman (2408.14531)

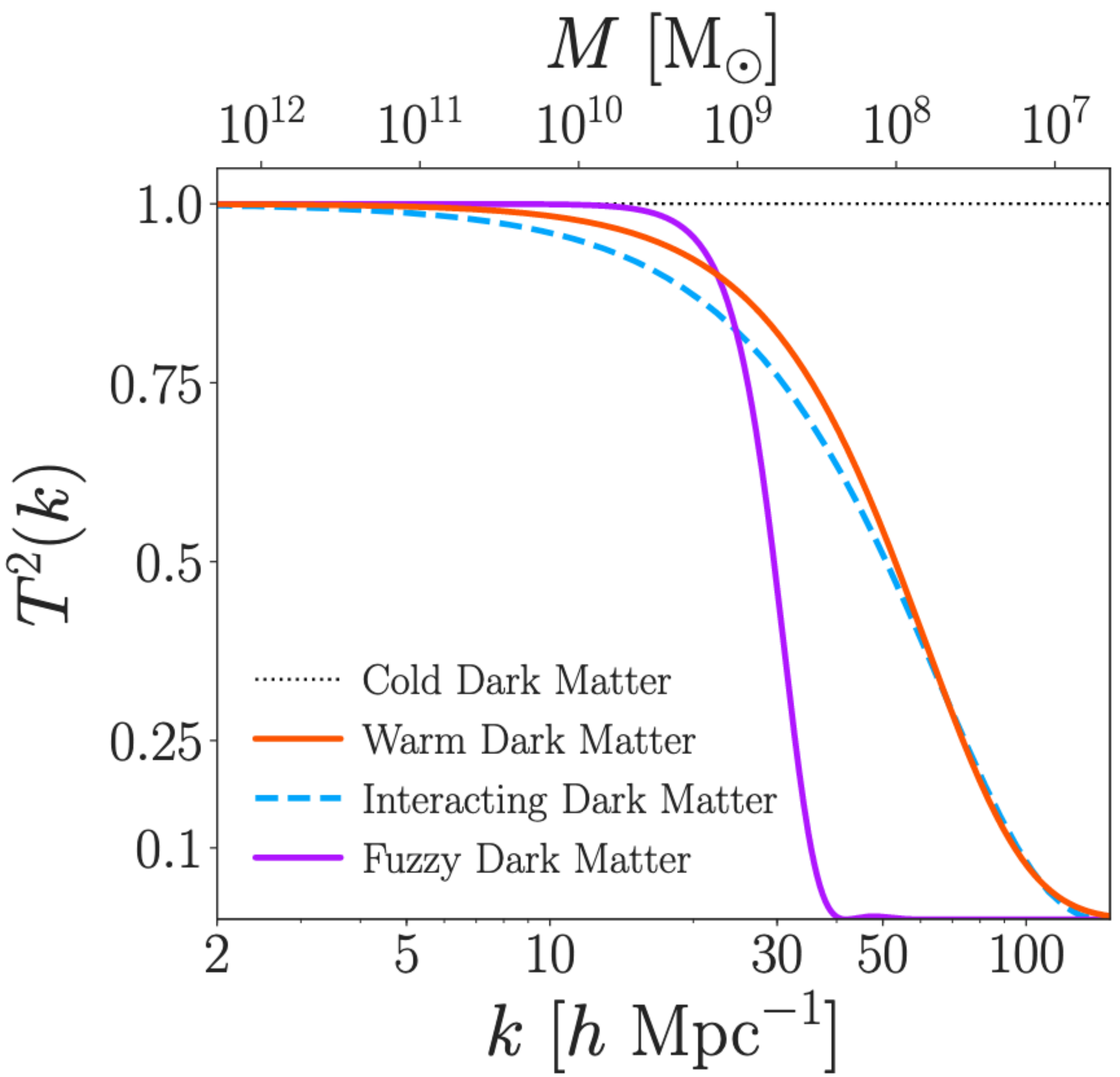
Early Universe Cosmology: Isocurvature

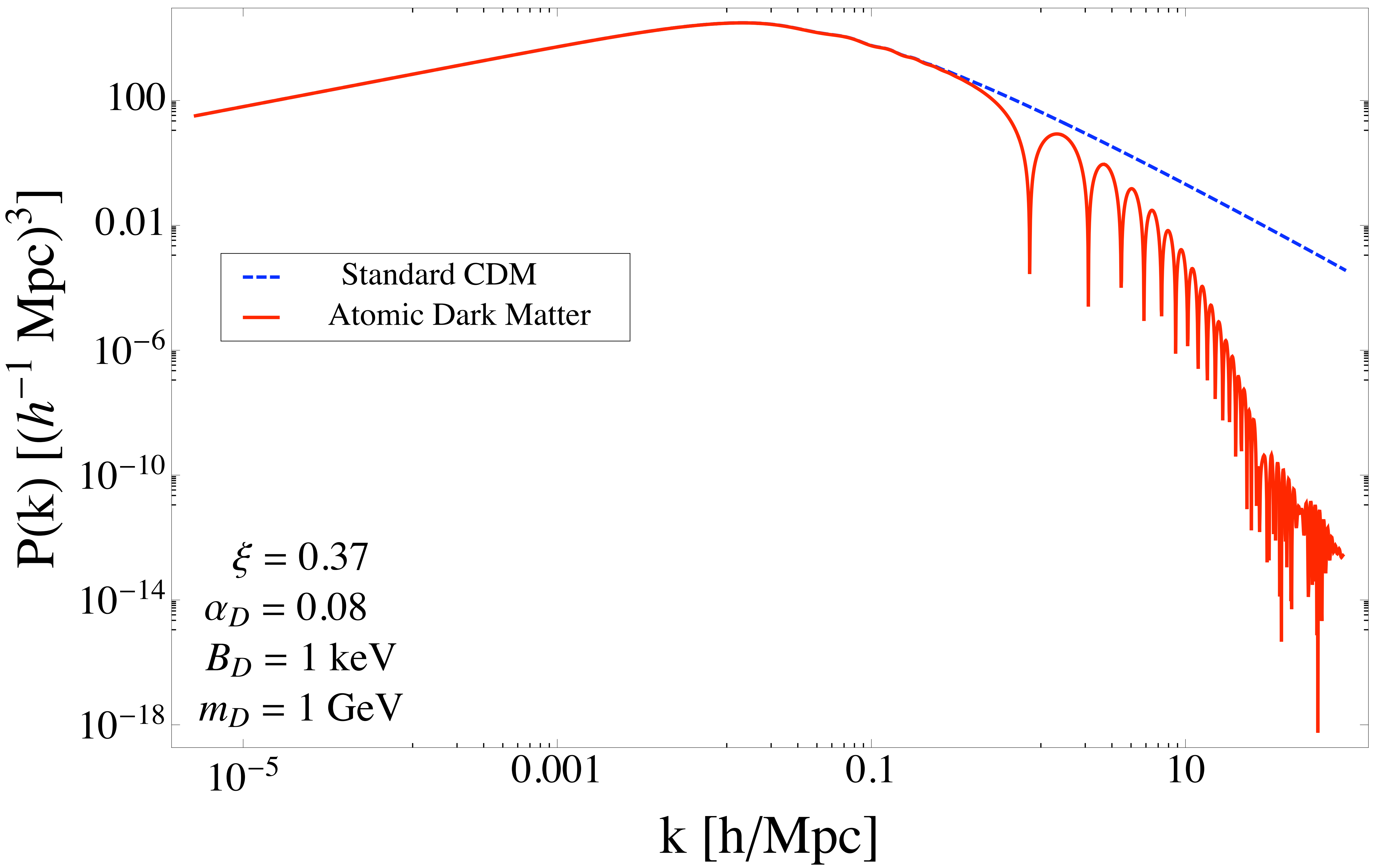
- Dark radiation could produce



Ghosh, Kumar, Tsai (JCAP 2022; 2107.09076)

Early-Universe Cosmology: Suppression of Structure





DES Collaboration, Nadler+ (PRL 2021; 2008.00022)

Cyr-Racine, Sigurdson (PRD 2013; 1209.5752)
see also ETHOS: Cyr-Racine+ (PRD 2016; 1512.05344) and Vogelsberger+ (MNRAS 2016; 1512.05349)

3 Impact on halos

Gravothermal Evolution

https://github.com/kboddy/GravothermalSIDM

Make equations dimensionless using G and 2 scales (e.g., r_s and ρ_s)

- Mass conservation

$$\frac{\partial M}{\partial r} = 4\pi r^2 \rho$$

- Hydrostatic equilibrium

$$\frac{\partial(\rho \nu^2)}{\partial r} = -G\frac{M\rho}{r^2}$$

where ν = 1d velocity dispersion

- Laws of thermodynamics

$$\frac{\partial L}{\partial r} = -4\pi r^2 \rho \nu^2 \left(\frac{\partial}{\partial t}\right)_M \ln\left(\frac{\nu^3}{\rho}\right)$$

where L = luminosity

- Heat conduction

$$\frac{L}{4\pi r^2} = -\kappa \frac{\partial T}{\partial r}$$

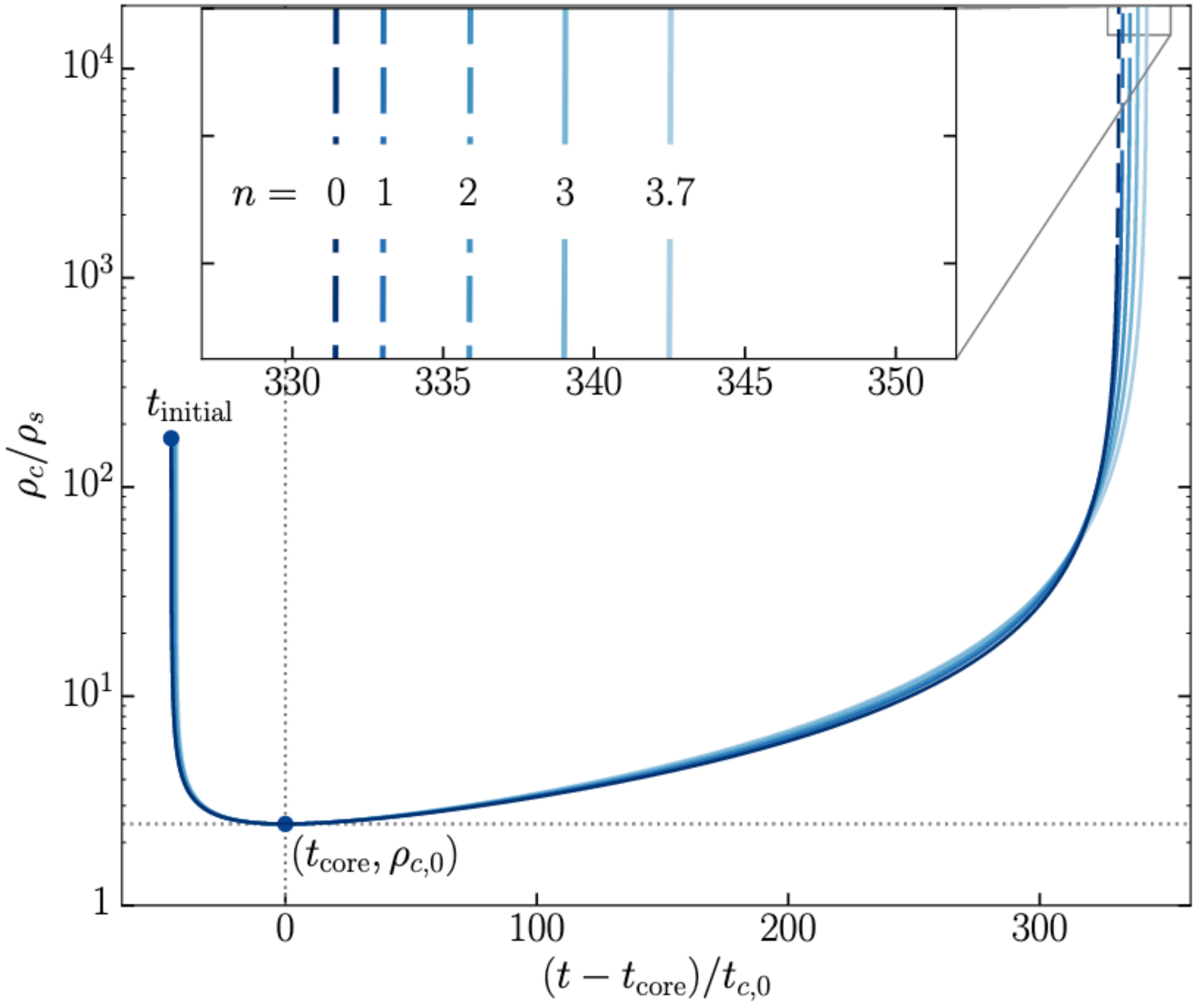
where κ = heat conductivity

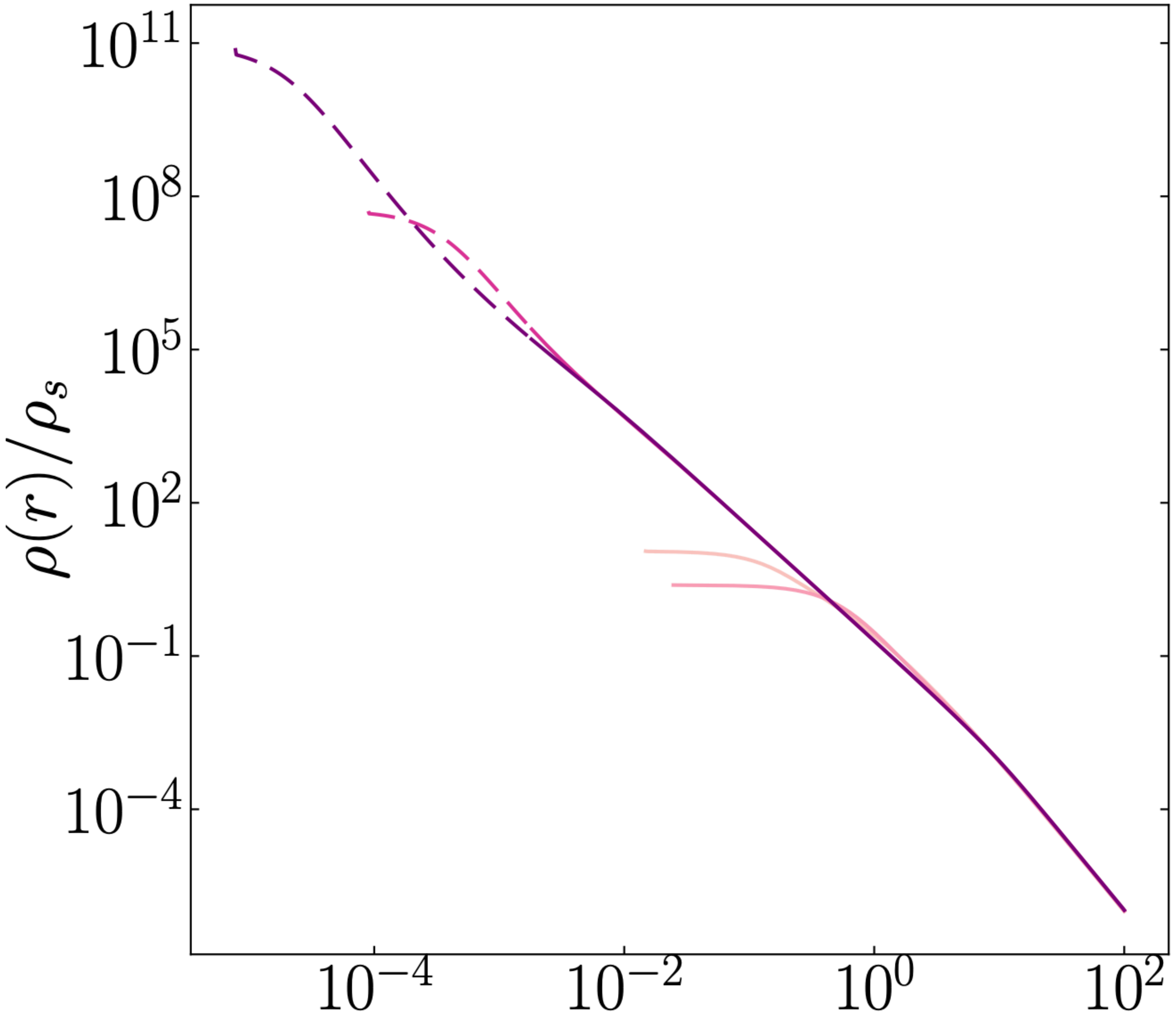
Self-gravitating systems have *negative* heat capacity

Unstable system → gravothermal catastrophe

Velocity-Dependent Scattering

$\kappa_{\mathrm{LMFP}} \sim \tilde{v}^{3-n}$





Obtain ~self-similar behavior in LMFP regime (dependence on n is mild)

Can still find some scaling relationships in the SMFP regime

Outmezguine, KB, Gad-Nasr, Kaplinghat, Sagunski (MNRAS 2023; 2204.06568)

Gad-Nasr, KB, Kaplinghat, Outmezguine, Sagunski (JCAP 2024; 2312.09296)

Implications for Black Hole Production

- Can extrapolate scaling relations from Gad-Nasr et al. to estimate mass of black hole that may form from collapse
- BUT what about the mediator!?!
- Inelastic processes that kick in during core collapse can change the story… stay tuned! (KB, Kaplinghat, Outmezguine, Ryan, Sagunski)

Broad Outlook

Generate Initial Conditions + Evolve Simulation (✓✓✓)

↓

Analyze Simulation Output (✓✓✓)

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Translate to Observable Parameter Space (✓✓✓)

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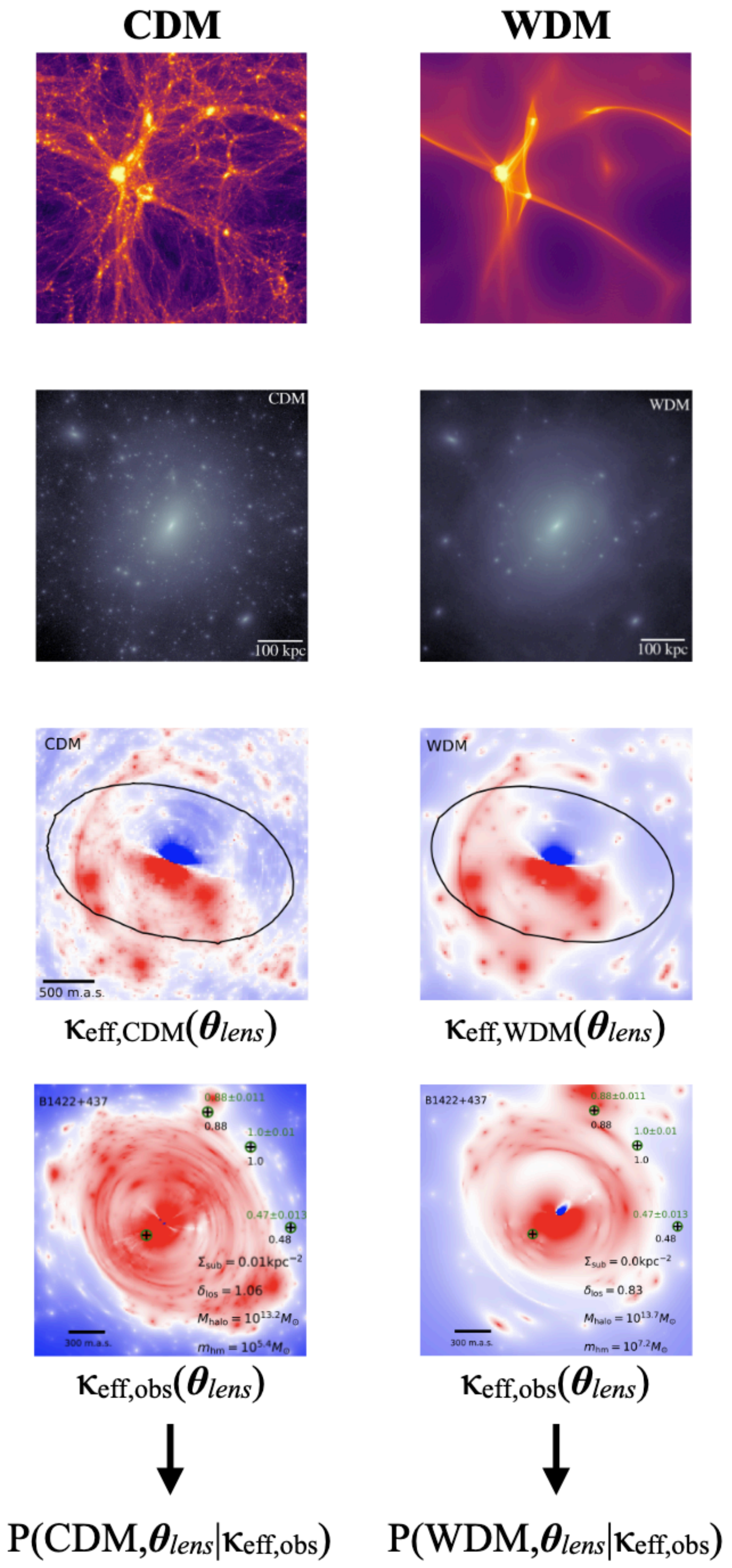
Efficiently Model Observables (✓✓✓)

↓

Compare to Data (✓✓✓)



Need #1: Collaboration between simulators and particle theorists
Need #2: Algorithm development and code comparison tests
Need #3: Hydrodynamic simulations for observational targets
Need #4: Compare simulations to data in observable parameter space
Need #5: Fast realizations of observed systems to constrain dark matter
Need #6: Provide guidance to observers about dark matter signatures

Challenges:

- Appropriate initial conditions from linear cosmology
- Degeneracies with cosmological and astrophysical parameters
- Incorporating dark sector physics into simulations

- What is needed from simulations that gives us the ability to say something robust about dark matter within the realm of reasonability?
- How can dark matter models be parameterized to get the most out of simulations?

Snowmass 2021 Cosmic Frontier White Paper: Cosmological Simulations for Dark Matter Physics (2203.07049)