Is gravity the only dark matter interaction that matters in the physics of galaxies?

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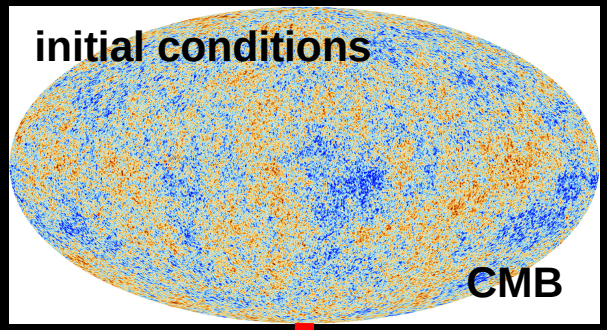
The Cold Dark Matter (CDM) hypothesis is the cornerstone of the current structure formation theory

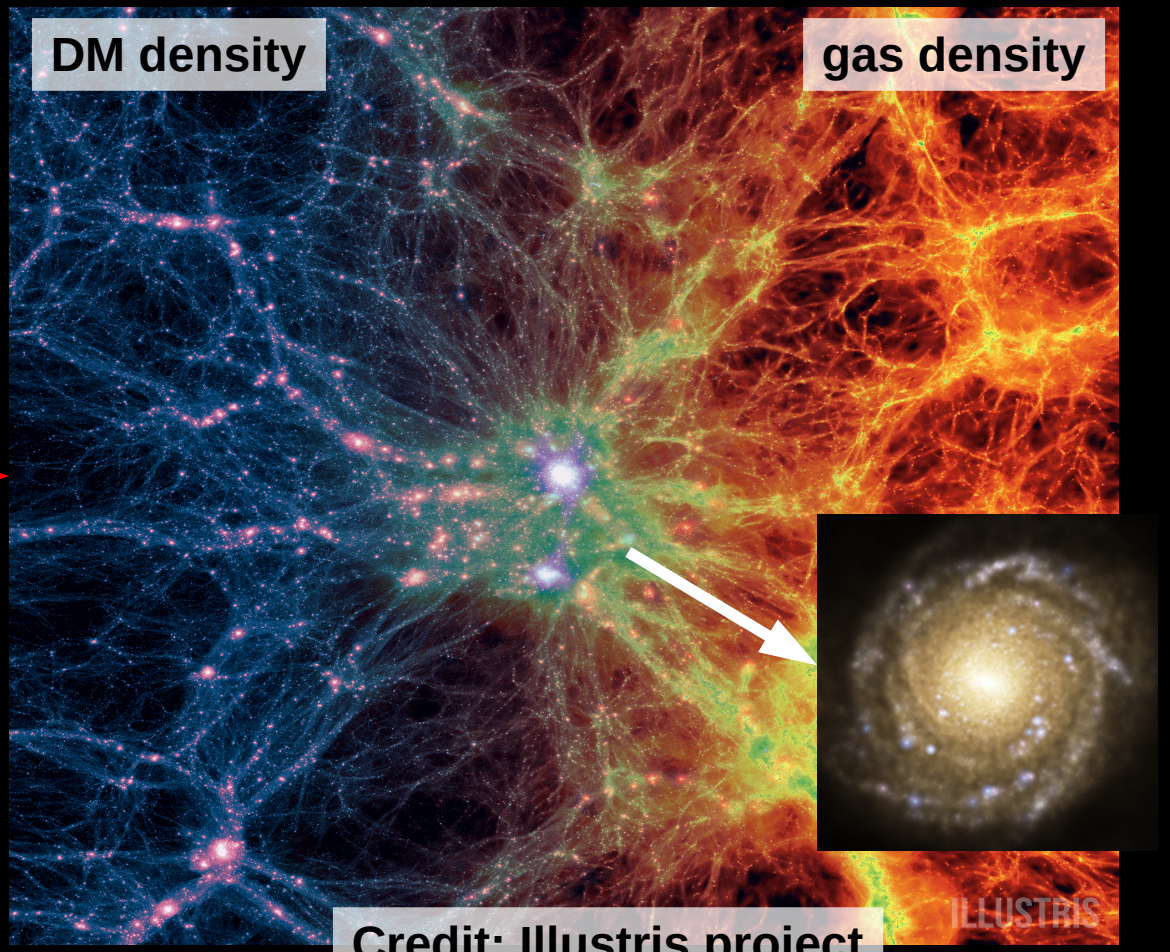


CDM assumes that the only DM interaction that matters is gravity!!

cosmological simulations

DM gravity only
+
"baryonic" physics
(radiative cooling, gas hydrodynamics, star formation, supernova and AGN feedback,...)

2000 CPU years!!

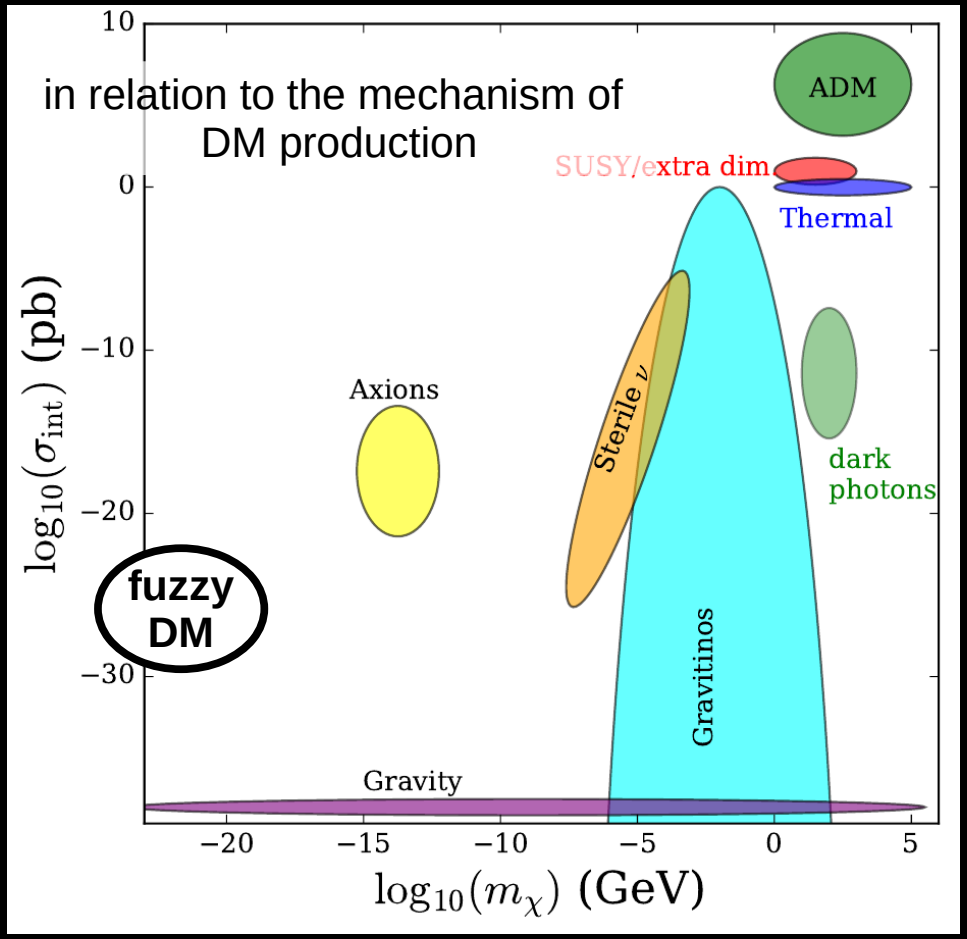


Credit: Illustris project

100 Mpc (comoving)

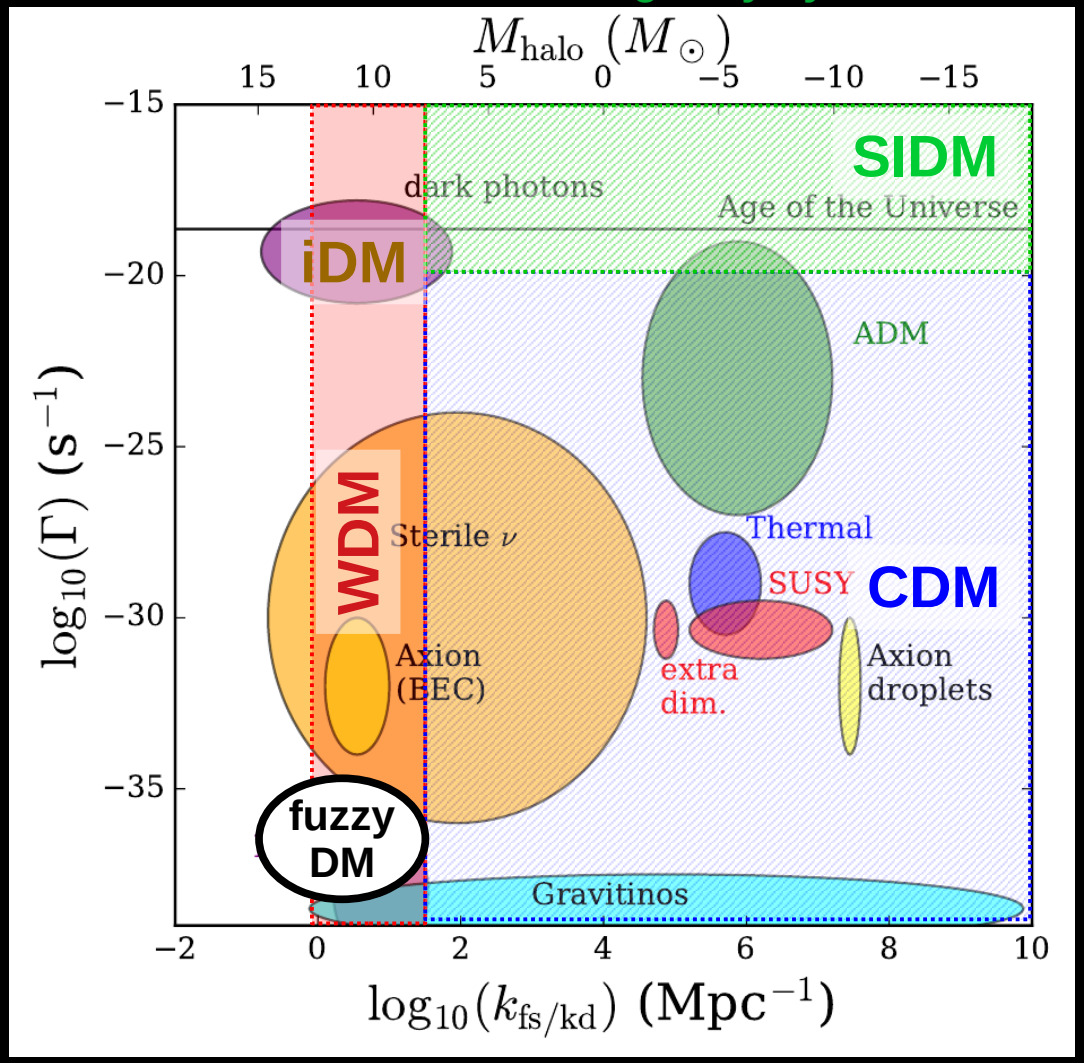
The (incomplete) particle DM landscape

Particle physics parameter space



Astrophysics parameter space

central galaxy dynamics

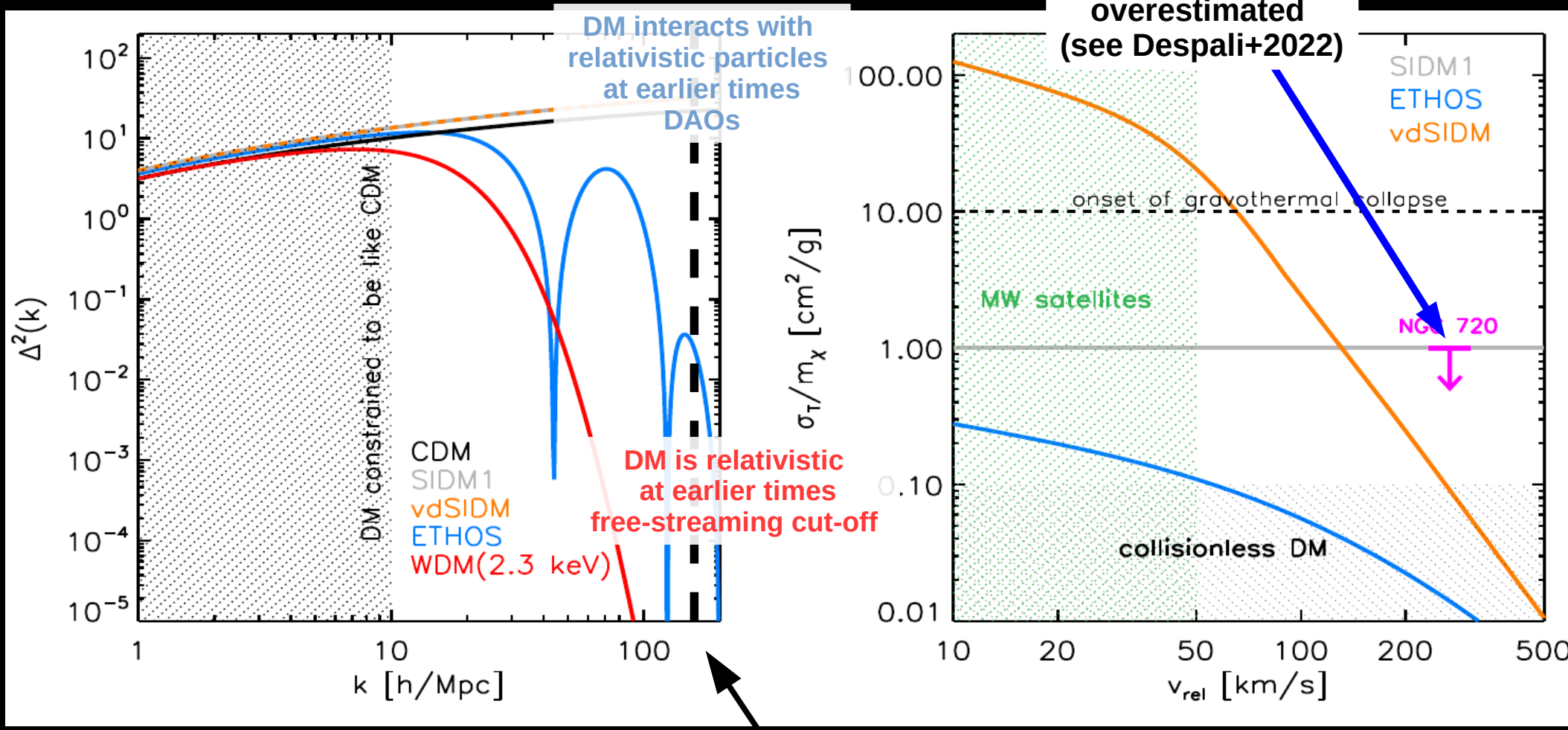


min. scale galaxy formation

Adapted from: Buckley & Peter 2018

An opportunity

- Additional free DM parameters might play a key role in the physics of galaxies. The window is relatively narrow:

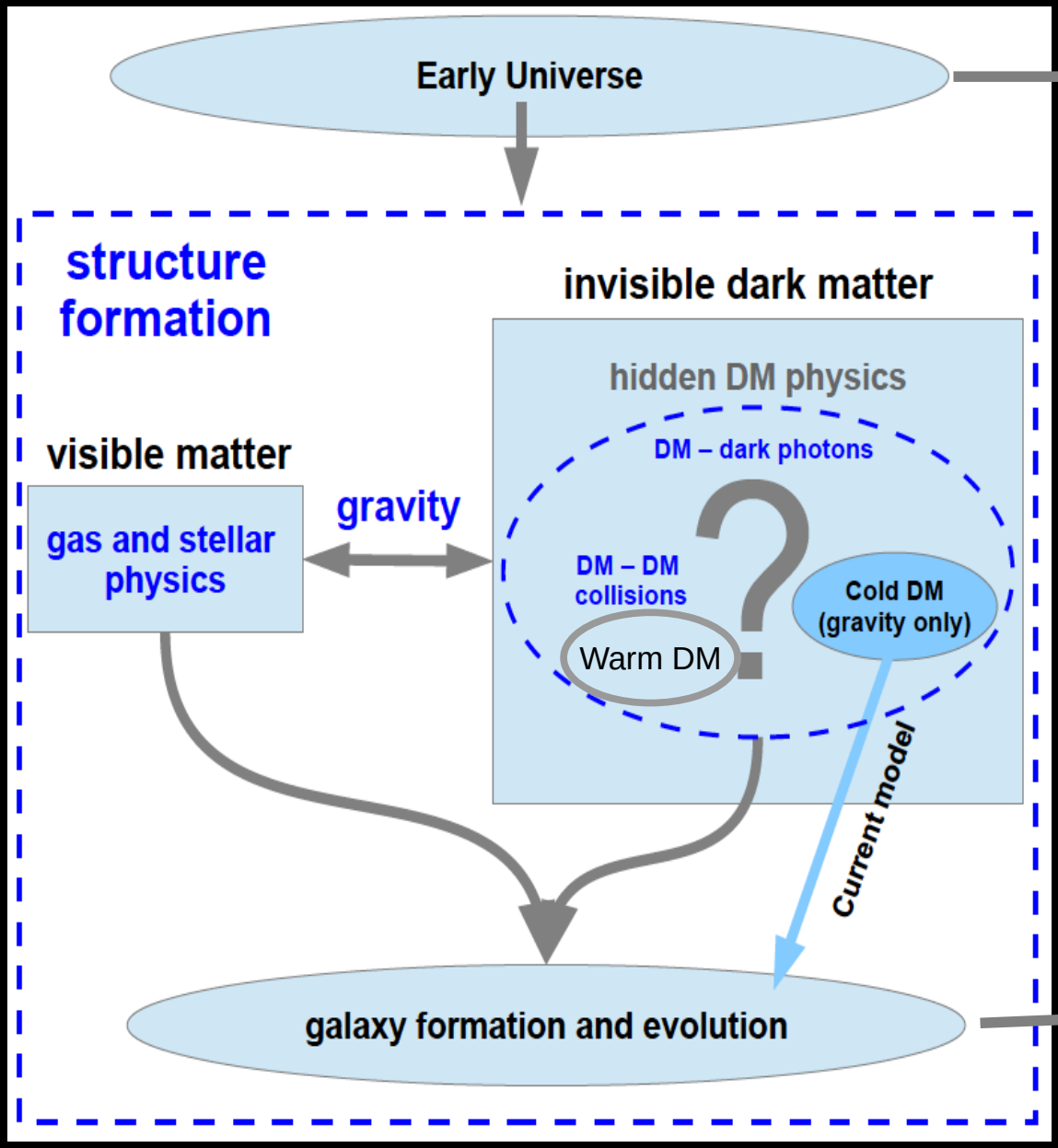


Zavala et al. 2019

below this value galaxy formation Is highly supressed (reionisation)

$$10^{9.5} M_{Sun} \quad at \quad z=0$$

An Effective THeory Of Structure formation (ETHOS)



DM production mechanism (verify consistency with global DM abundance)

Generalize the theory of structure formation (CDM) to include **a broader range of allowed DM phenomenology** coupled with our knowledge of galaxy formation/evolution

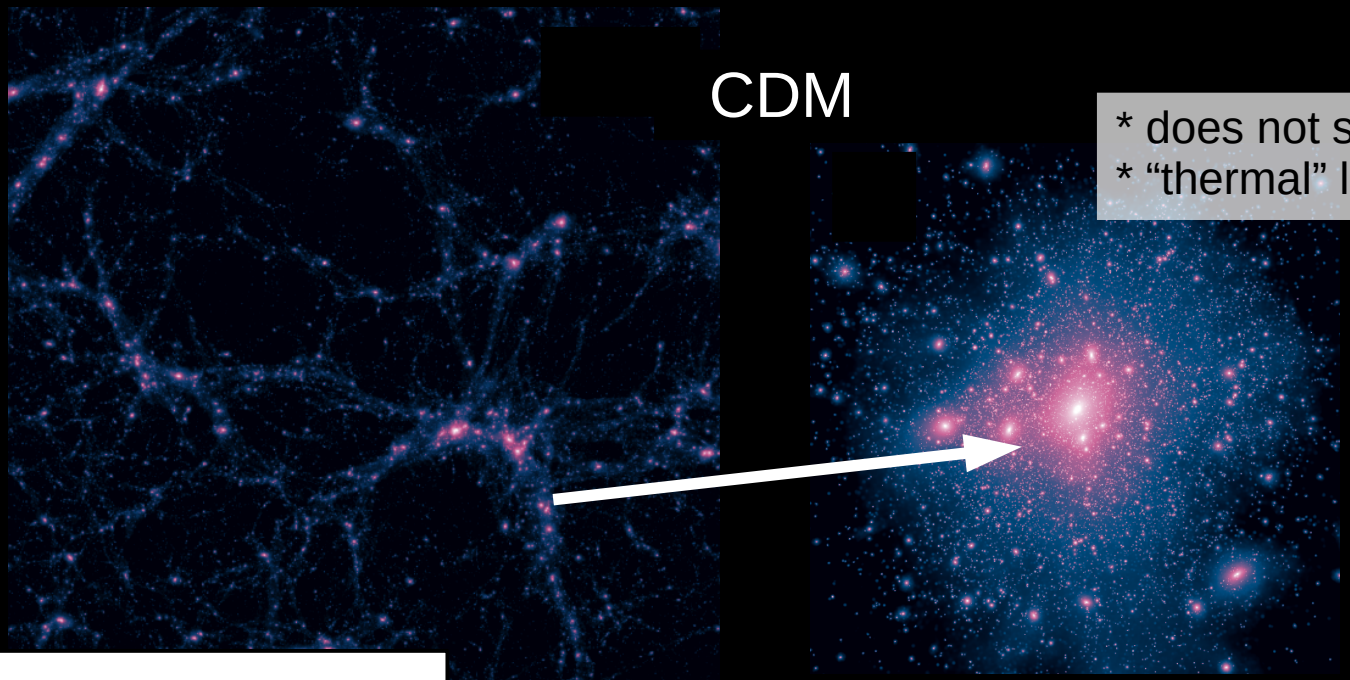
Signatures of non-gravitational DM interactions (dynamical, visible byproducts)

ETHOS~ΛWDM, ΛSIDM, ΛiDM (see Francis-Yan+2016, Vogelsberger+2016)

Impact on the minimum scale for galaxy formation (WDM/iDM/fuzzyDM)

Difference with the standard CDM model

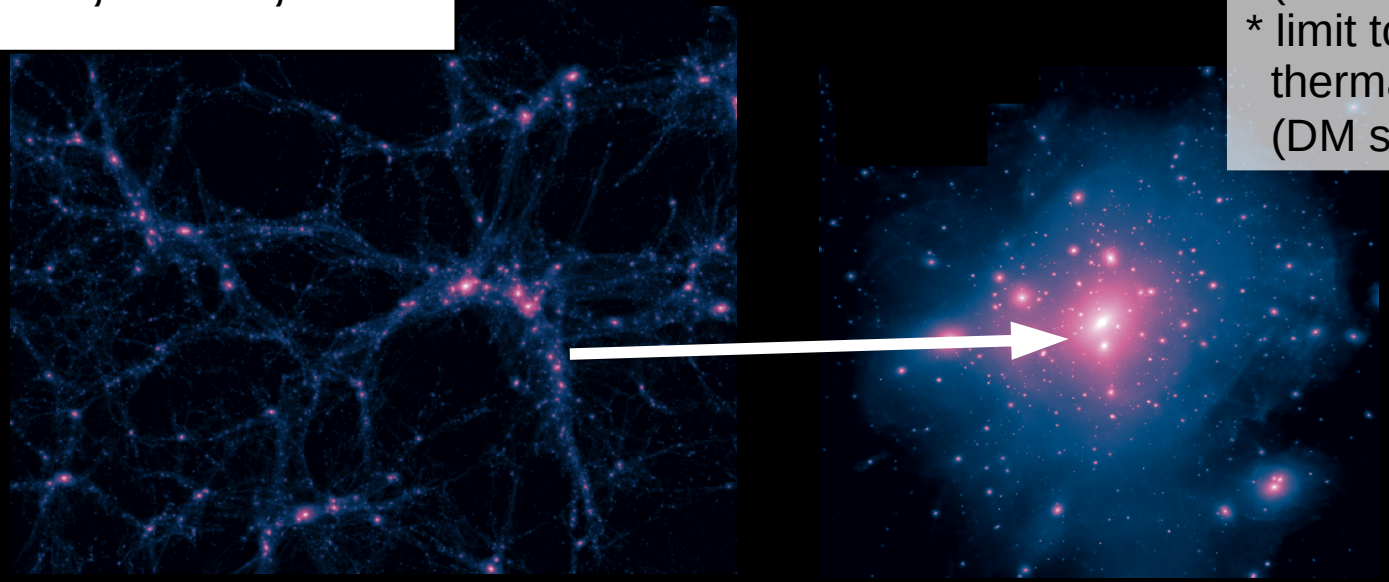
CDM



* does not set minimum galactic scale
* “thermal” limit to phase space density

The LSS success of ΛCDM is shared by ΛWDM, ΛSIDM, ΛiDM

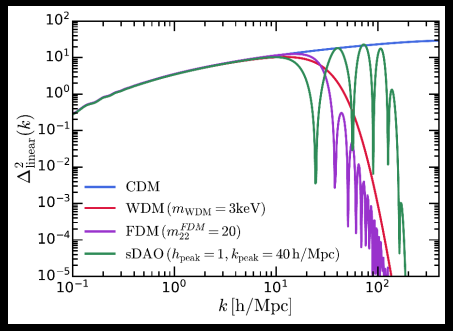
ETHOS



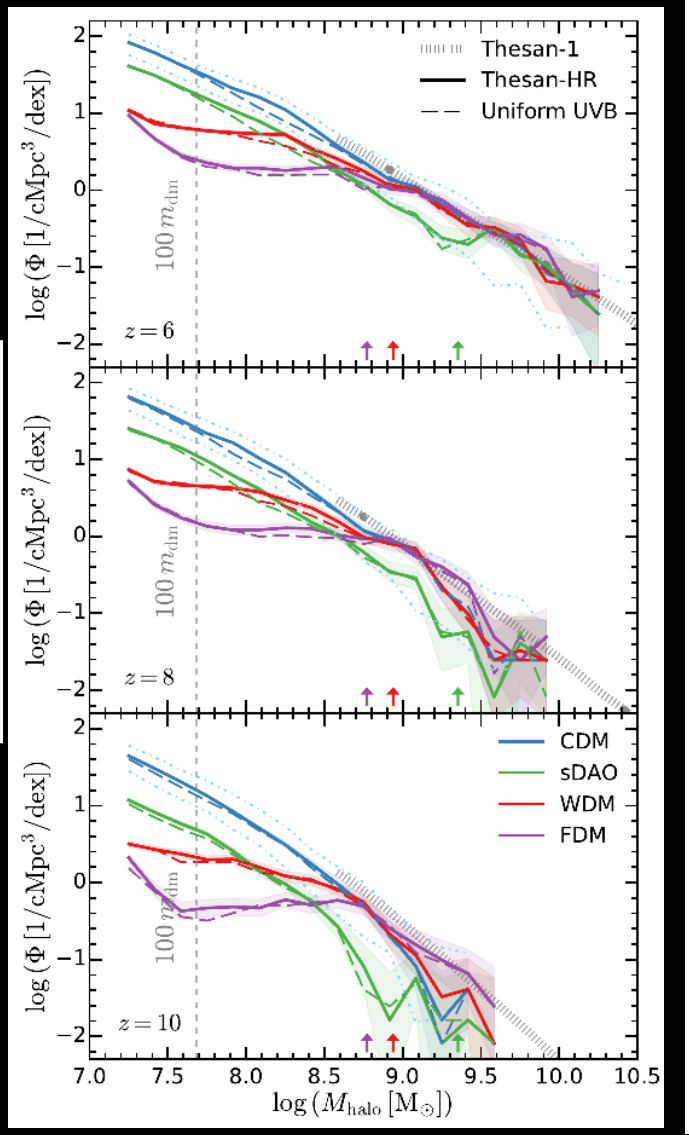
* sets minimum galactic scale (DM-DR Silk-like damping)
* limit to phase space density set by thermalization in the inner haloes (DM self-interactions)

Adding baryonic physics: the high-z Universe

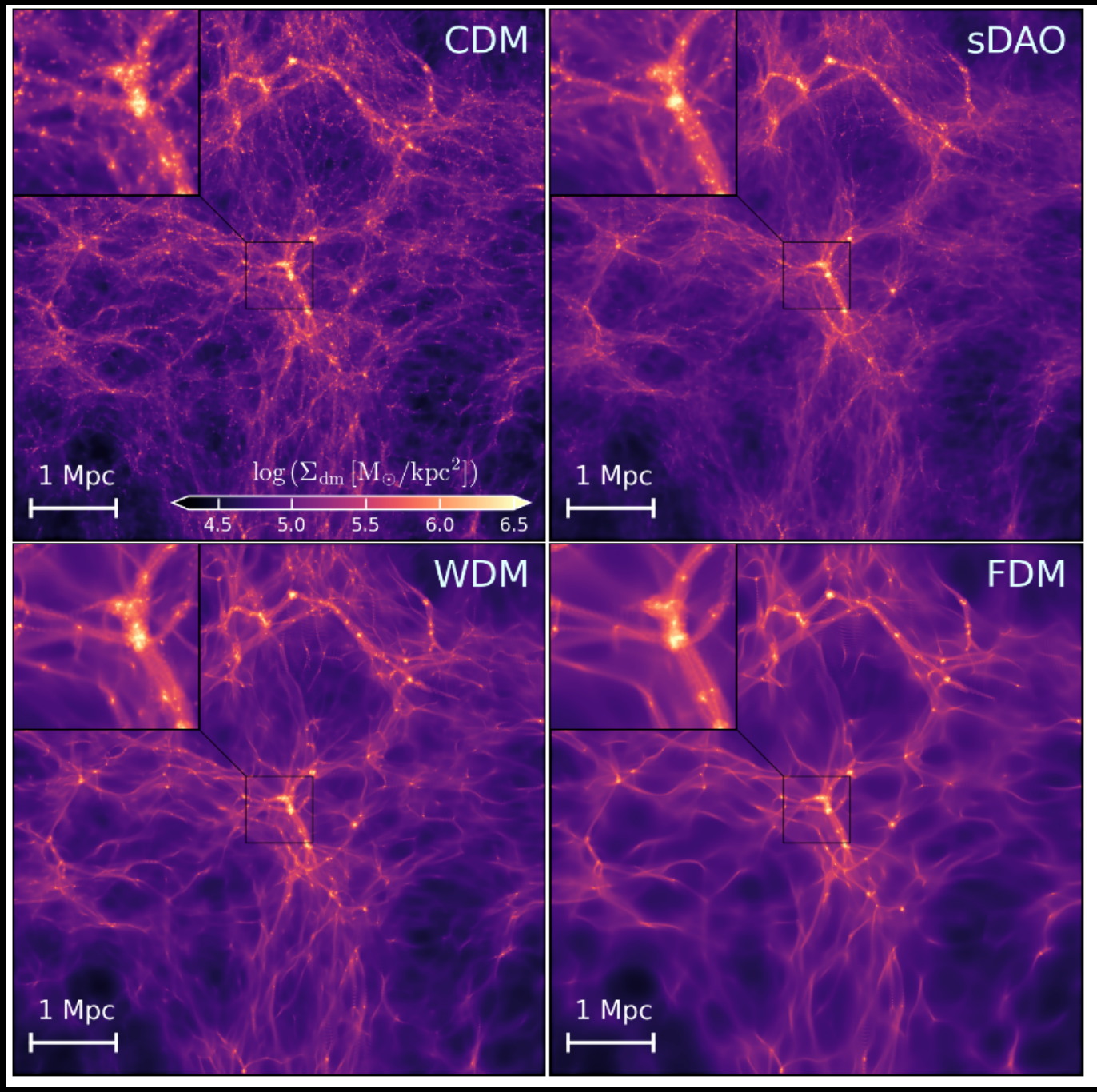
Shen et al. 2023



halo mass function



z=6

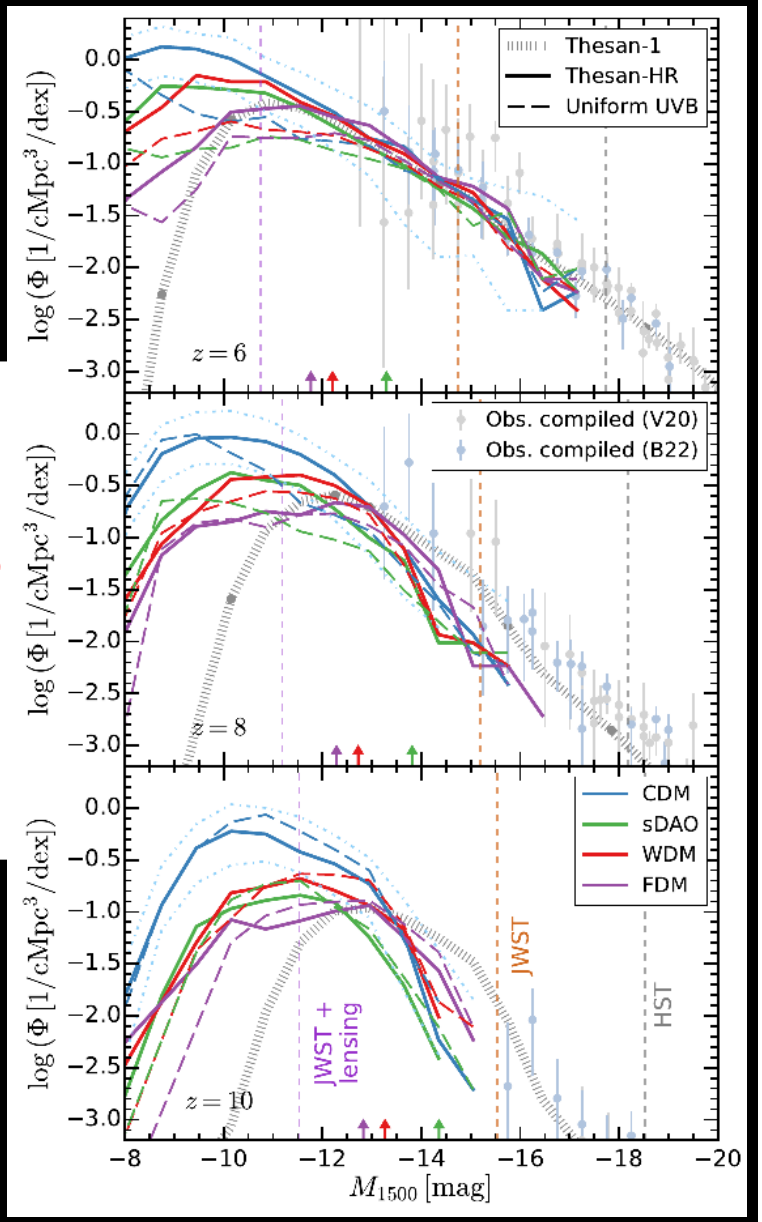


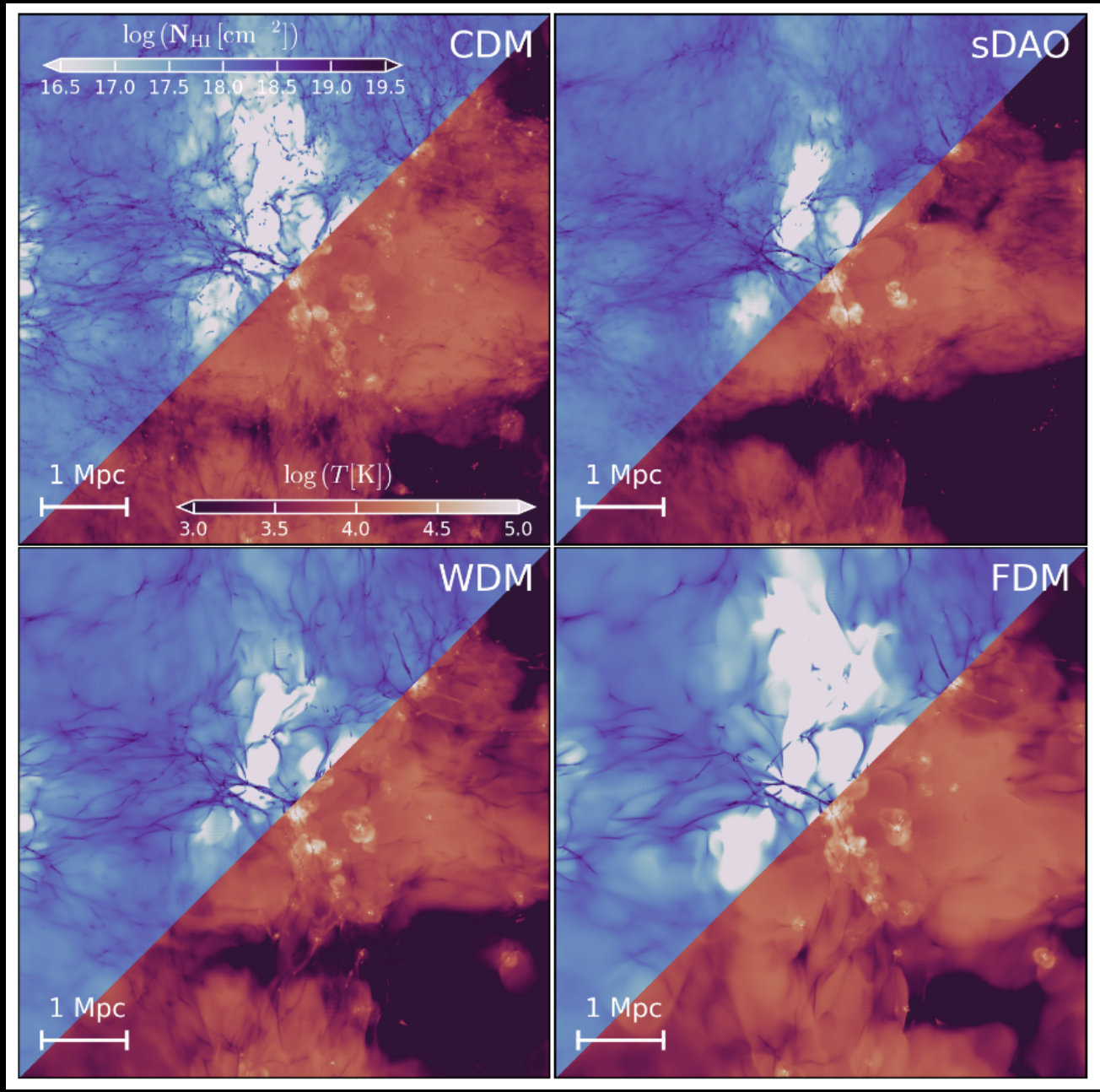
Adding baryonic physics: the high-z Universe

z=6

Shen et al. 2023

FUV luminosity function





see also: Lovell+2018, Lovell+2019 and Kurmus+2022

Impact on the inner dynamics of galaxies (SIDM)

SIDM (DM self-collisions) (gravothermal fluid approximation)

spherically symmetric ideal gas in hydrostatic equilibrium
Lynden-Bell & Eggleton 1980

$$\frac{\partial\left(\rho v^2\right)}{\partial r} = -\frac{GM\rho}{r^2}$$

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

$$\frac{\partial L}{\partial r} = -4\pi\rho r^2 v^2\left(\frac{\partial}{\partial t}\right)_M \ln\frac{v^3}{\rho},$$ 1st law

mass shell

$$\kappa \sim \left(3k/2m\right)\rho\lambda^2/\tau$$

$$\tau \equiv relaxation\ \ time$$

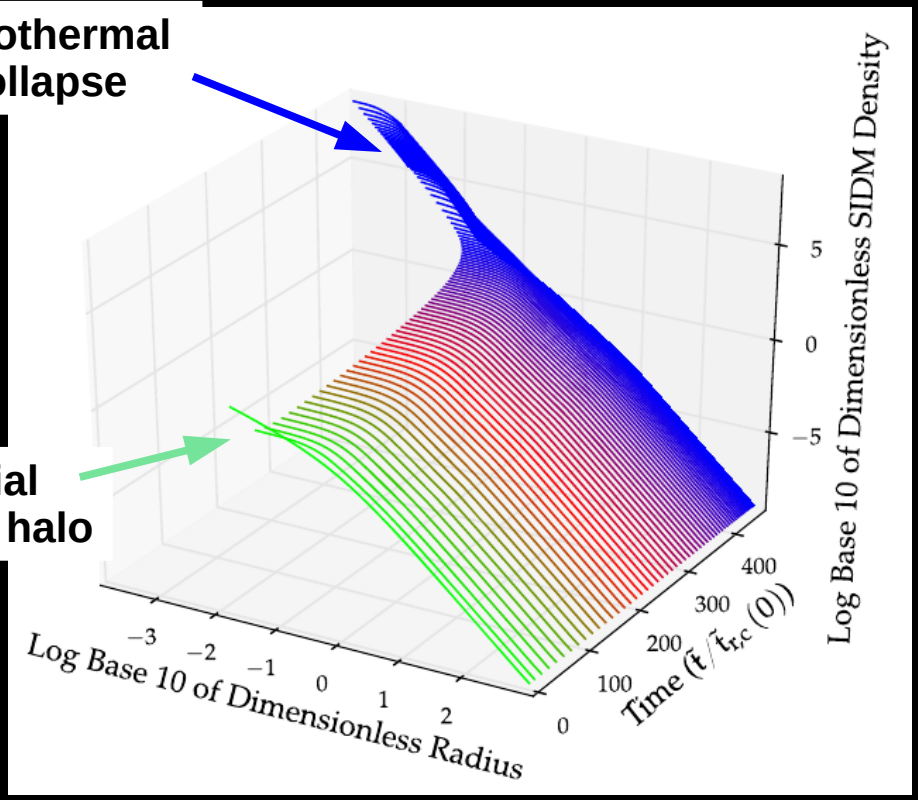
since Kn~1 conductivity is found as an empirical interpolation between fluid and collisionless regimes

$$\lambda \rightarrow l_{mean} = 1/\left(\rho\sigma\right) \qquad Kn \ll 1$$

$$\lambda \rightarrow \lambda_J^2 = v^2/\left(4\pi G\rho\right) \qquad Kn \gg 1 \ \ (LBE)$$

gravothermal collapse

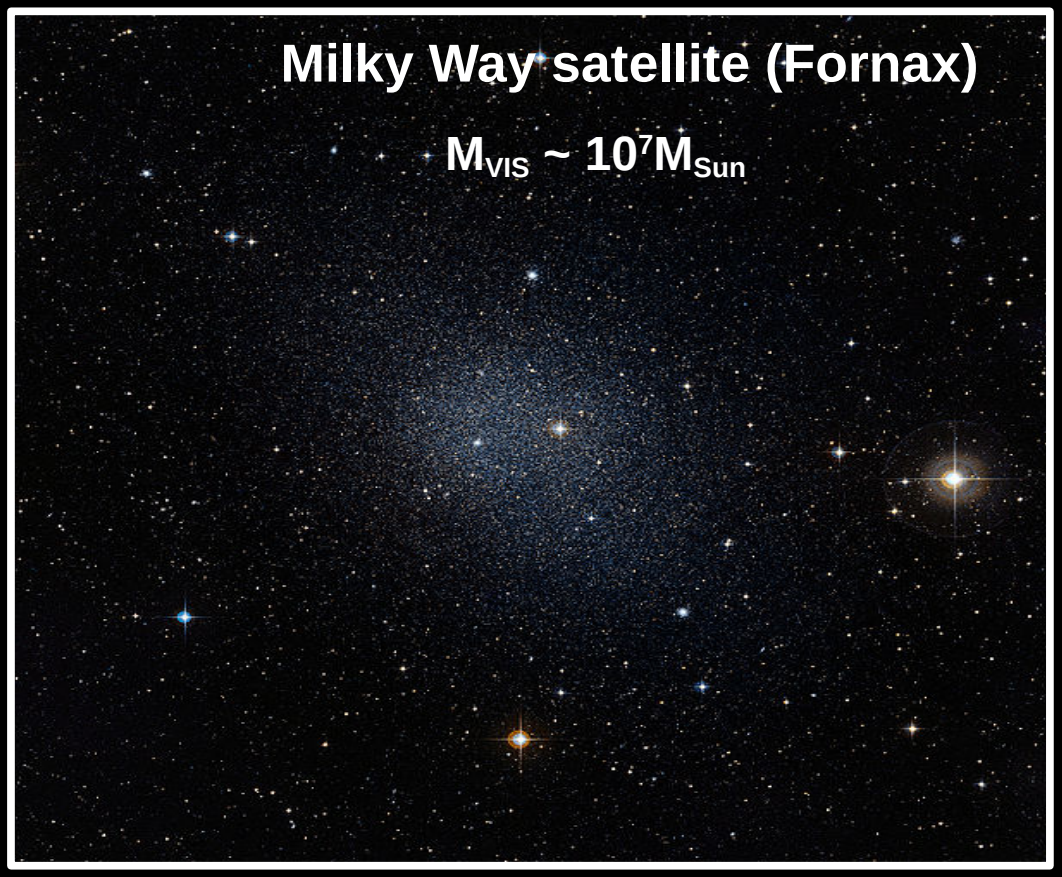
primordial CDM/NFW halo



e.g. Balberg, Shapiro & Inagaki 2002, Koda & Shapiro 2011, Pollack, Spergel & Steinhardt 2015

Clues from the properties of dwarf galaxies

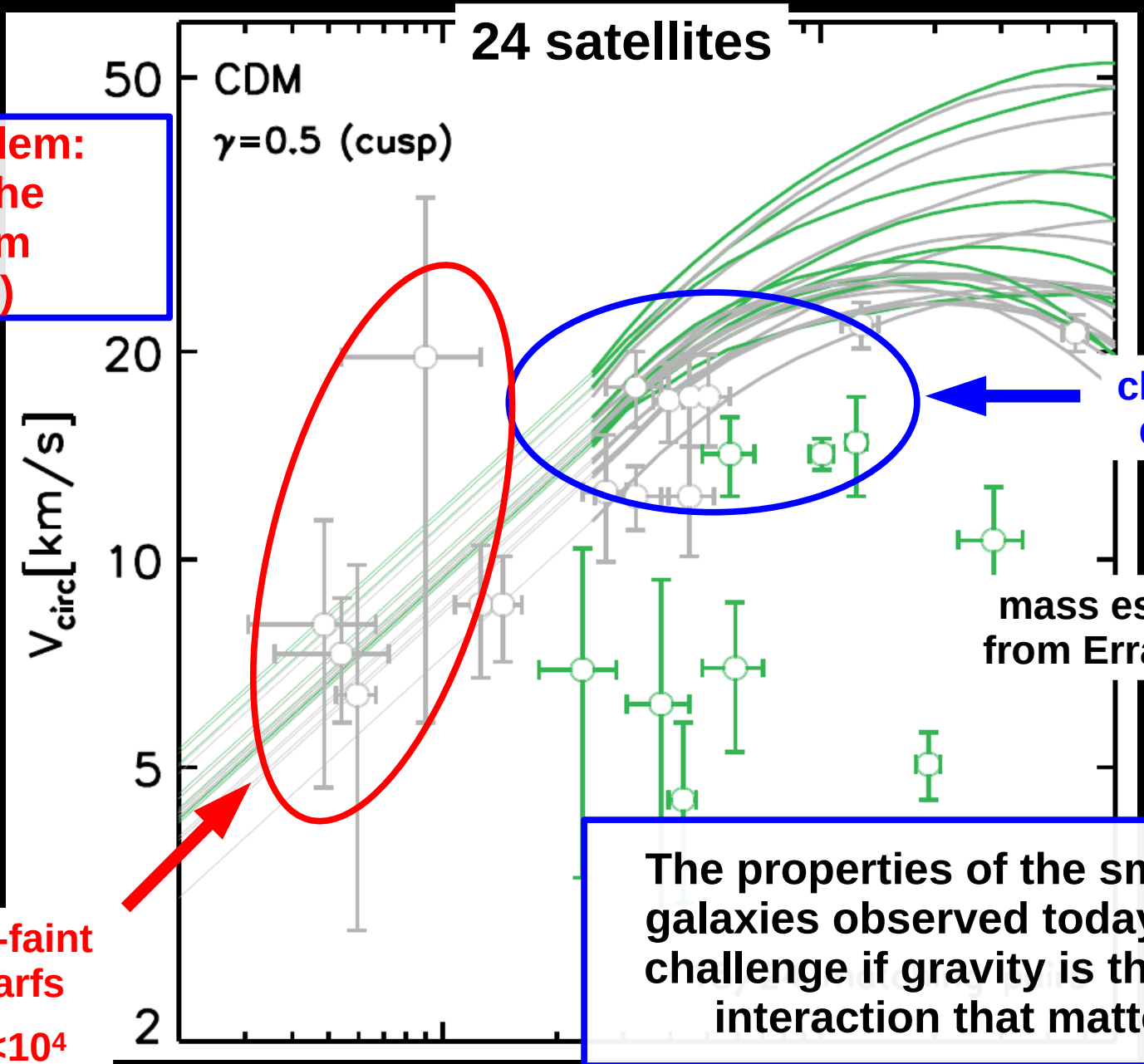
Dwarf galaxies:
most DM-dominated systems: $M_{DM} > 10\ M_{VIS}$
(ordinary matter is less dynamically relevant)



The stellar dynamics is simplified and the underlying DM distribution can be more easily constrained

“Optimal” dynamical detectors of new DM physics

Diverse sub-kpc DM densities in MW satellites



Structural problem: a revision of the TBTF problem (Zavala + 19)

classical dSphs

mass estimates from Errani+2018

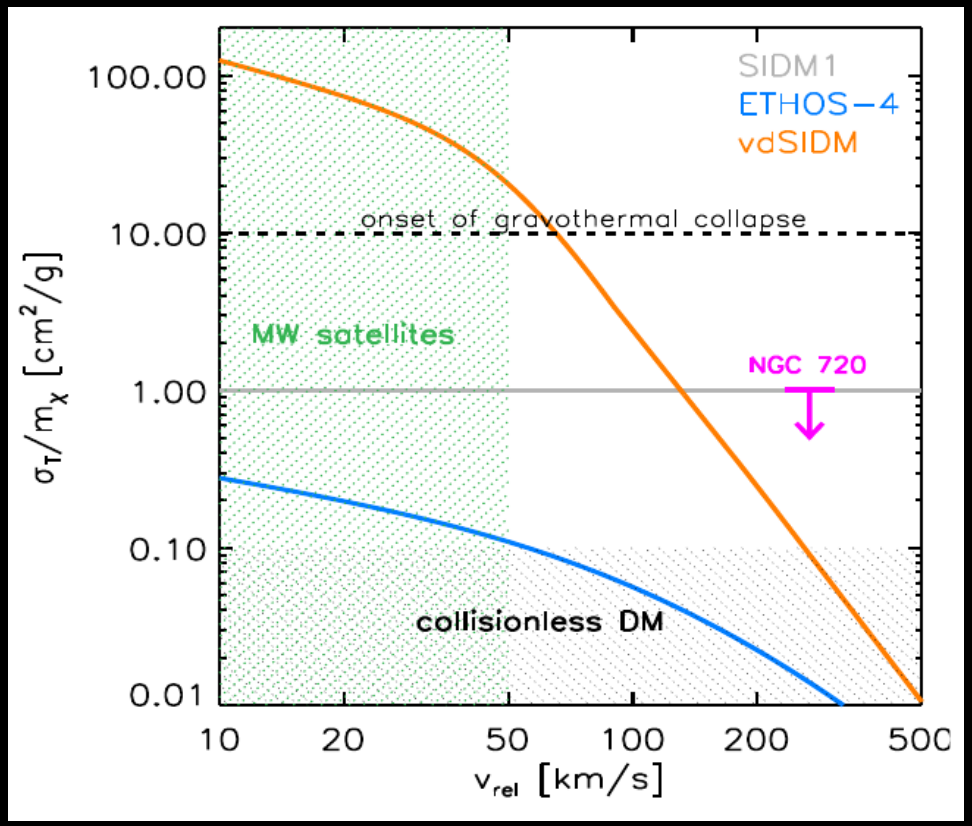
ultra-faint dwarfs

$M_* < 10^4$

The properties of the smallest galaxies observed today are a challenge if gravity is the only interaction that matters

Aquarius project
CDM-only (no baryonic physics)

Is this a strong constraint on SIDM?

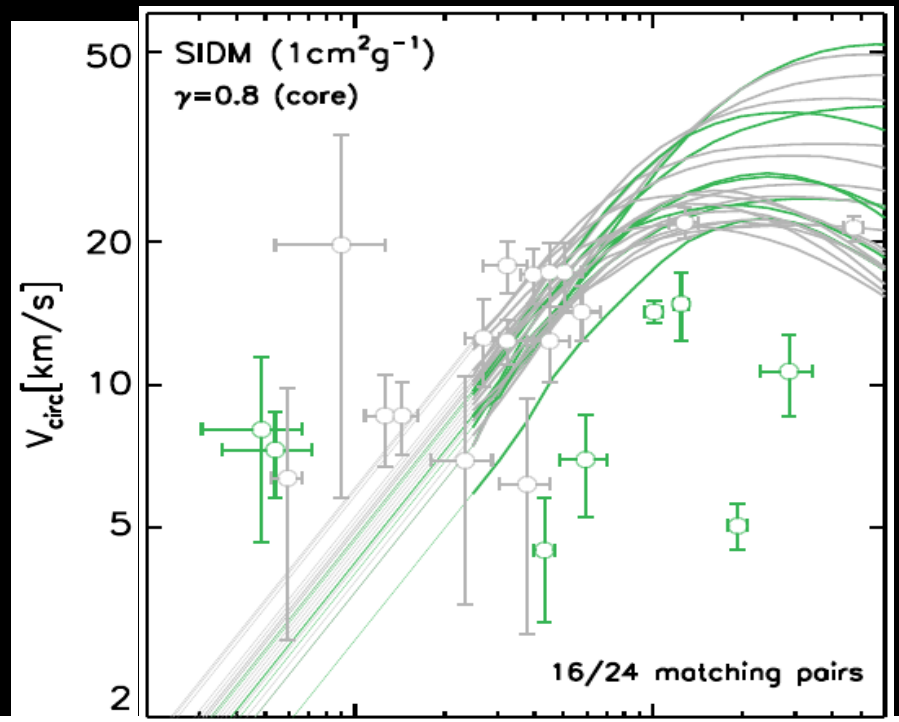


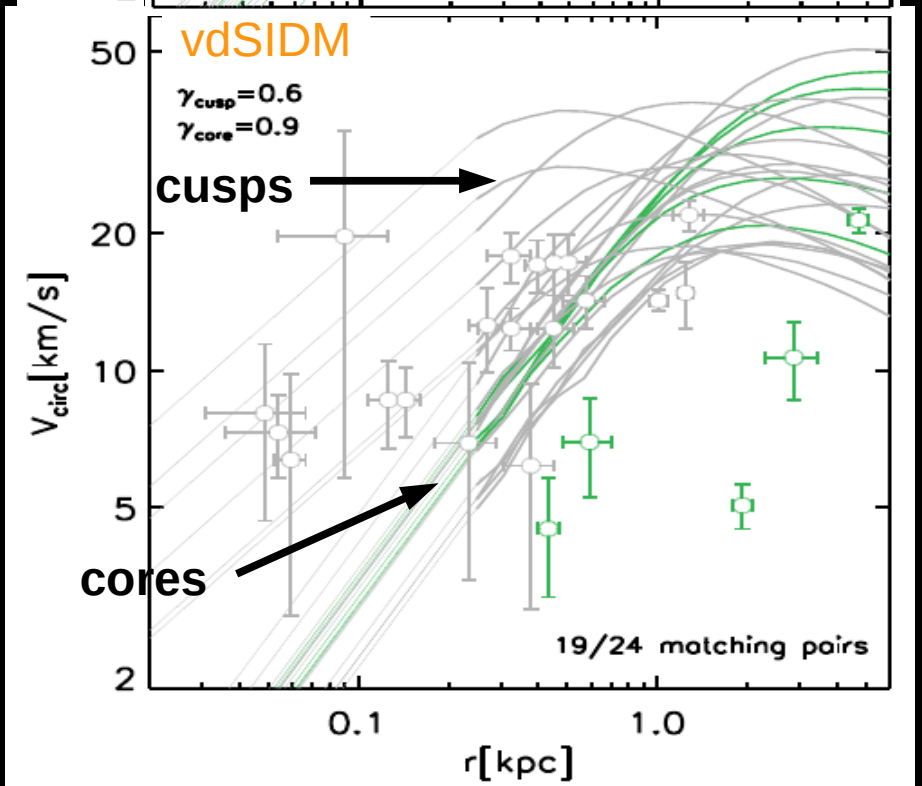
SIDM: fine if

$\sigma/m \prec 1\,cm^2/gr$ or $\sigma/m \gtrsim 20\,cm^2/gr$

(at dwarf scales)

Within SIDM, core collapse is needed to alleviate diversity problem (see also Correa 2020)





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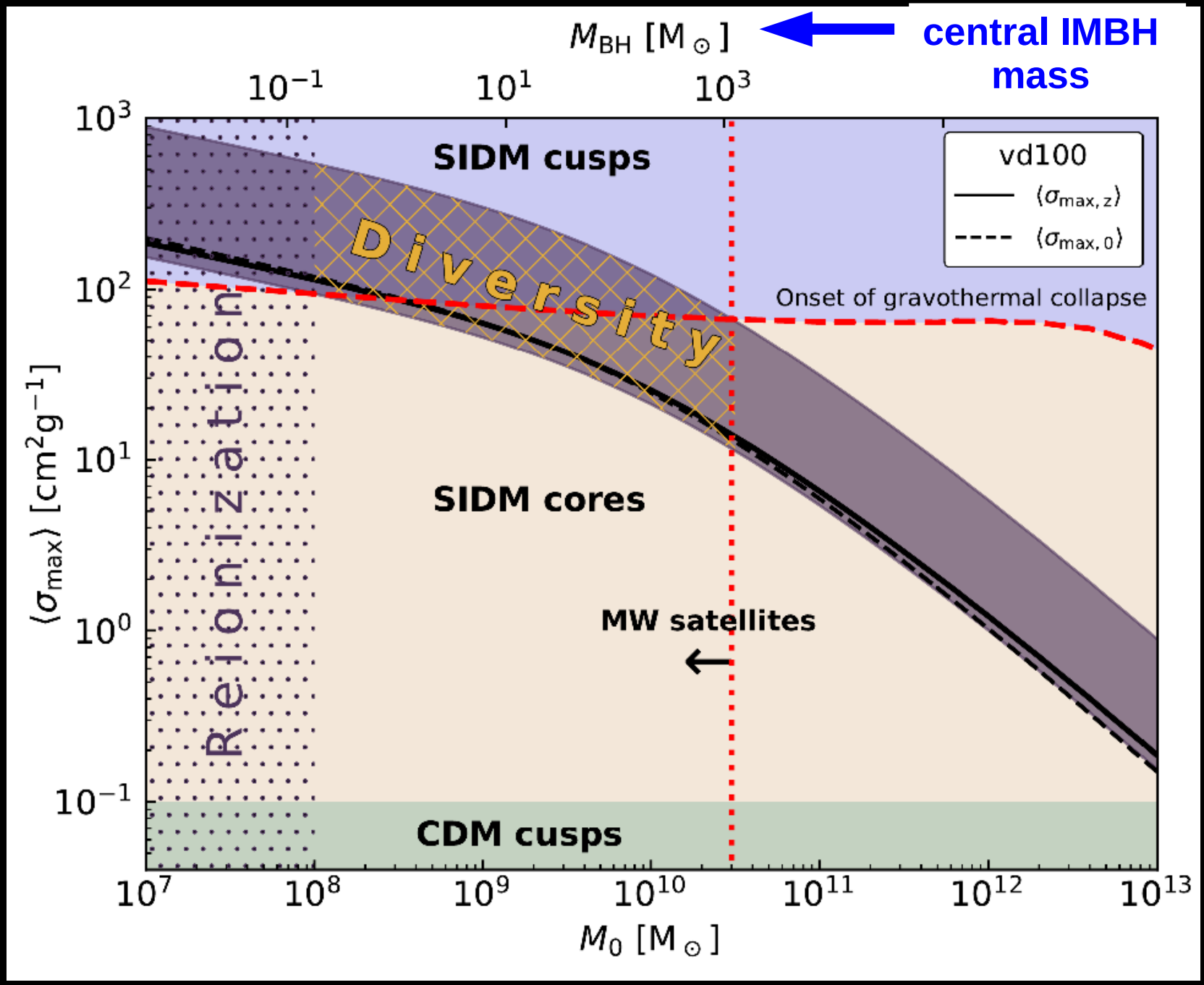

Meshveliani et al. 2023

SIDM with (relevant) core-collapse predicts IMBHs in the faintest dwarf galaxies

Concluding remarks

- **Whether or not gravity is the only relevant dark matter interactions in the physics of galaxies remains an open question**

- The minimum mass for galaxy formation could be set by a combination of baryonic physics (reionisation/feedback) and new dark physics (e.g. free streaming, dark matter – dark radiation interactions)

- The inner structure of DM haloes in dwarf galaxies could be set by a combination of baryonic physics (assembly of the galaxy + SNe feedback) and new dark physics (e.g. self-interacting dark matter)

- The DM/baryonic physics synergy remains largely unexplored: possible degeneracies in observational comparisons, albeit undesirable, reflect our current incomplete knowledge of the DM nature and galaxy formation/evolution

- The current challenge lies in finding distinct observables between these two possibilities