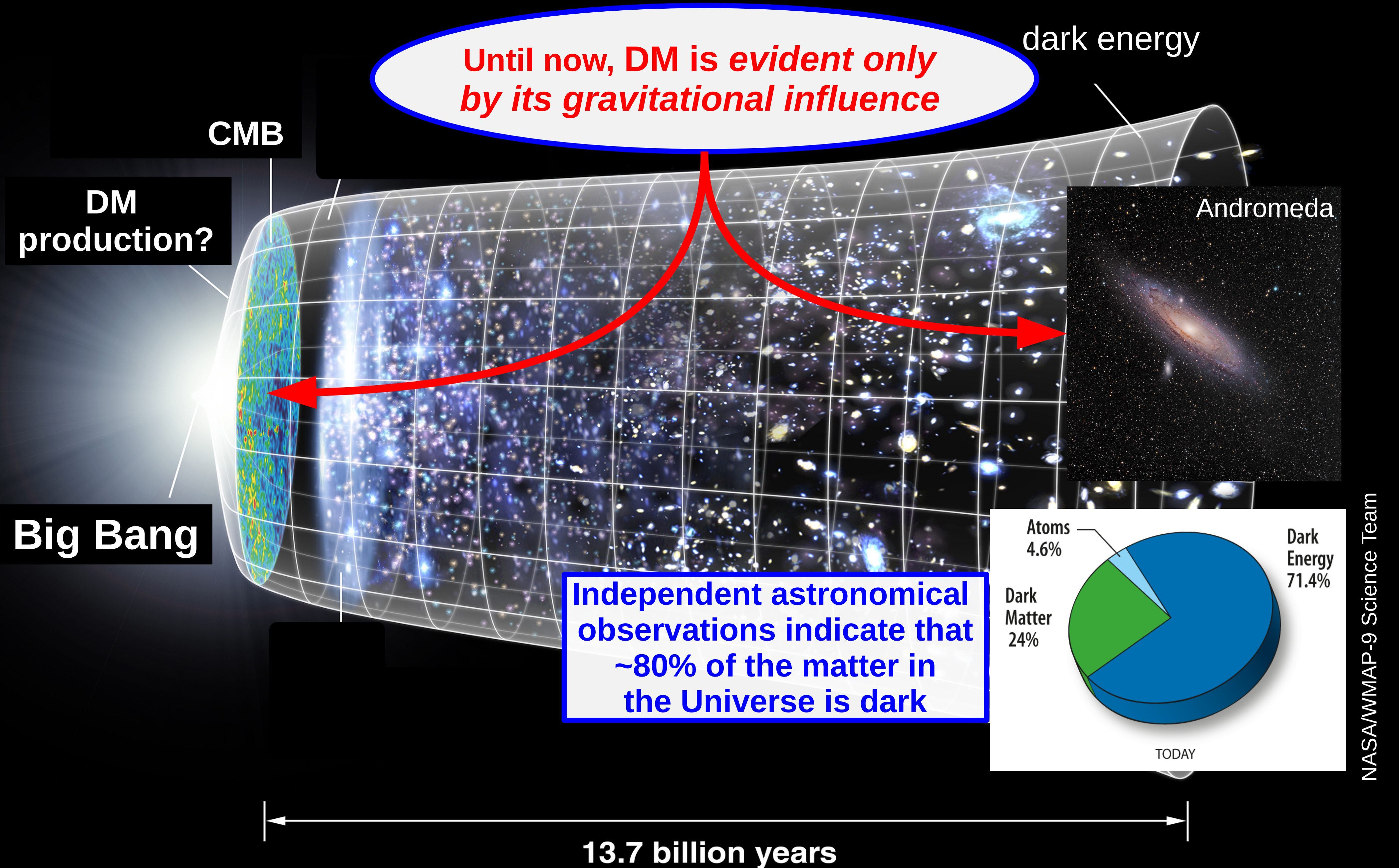
# Impact of non-gravitational dark matter interactions in the physics of galaxies


**Jesús Zavala Franco**
**Faculty of Physical Sciences, University of Iceland**


The Unbearable Lightness of the Universe
16-18 September 2021, Prague, Czech Republic

# The particle DM hypothesis:

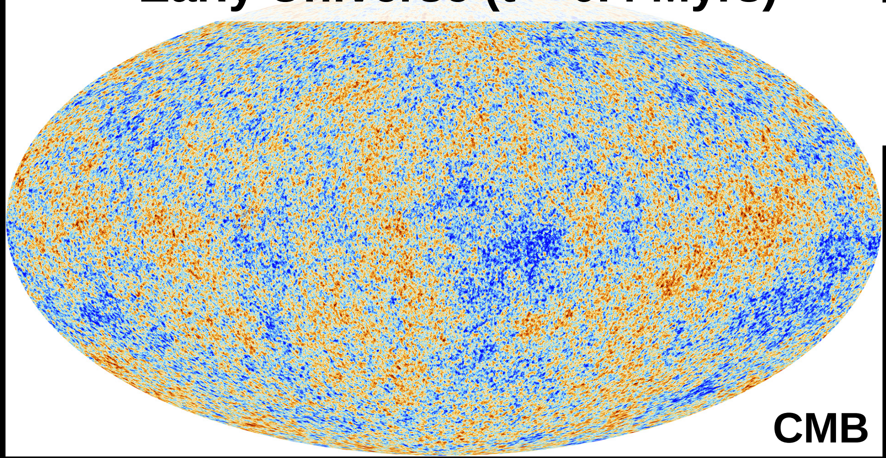
**DM is made of *new* particles that do not emit electromagnetic radiation at a significant level**



## The **particle DM hypothesis** is seemingly essential to explain the growth of perturbations into the structures we see today

Credit: ESA and the Planck Collaboration

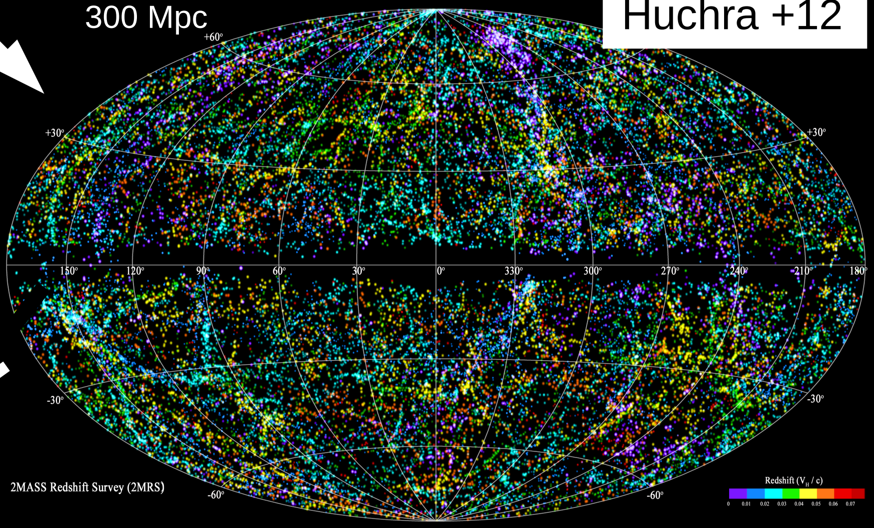
**Early Universe (t ~ 0.4 Myrs)**




$$\frac{\delta\rho_m}{\rho_m} \sim 10^{-3}$$

Universe today (t ~ 13.8 Gyrs)

Huchra +12



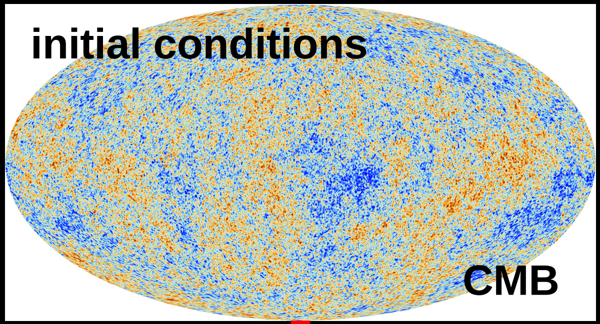

2MRS galaxy “map”, large-scale structure

$$\frac{\delta\rho_m}{\rho_m} \gtrsim 1$$


$$\frac{\delta\rho_m}{\rho_m} \gg 1$$

galactic scales

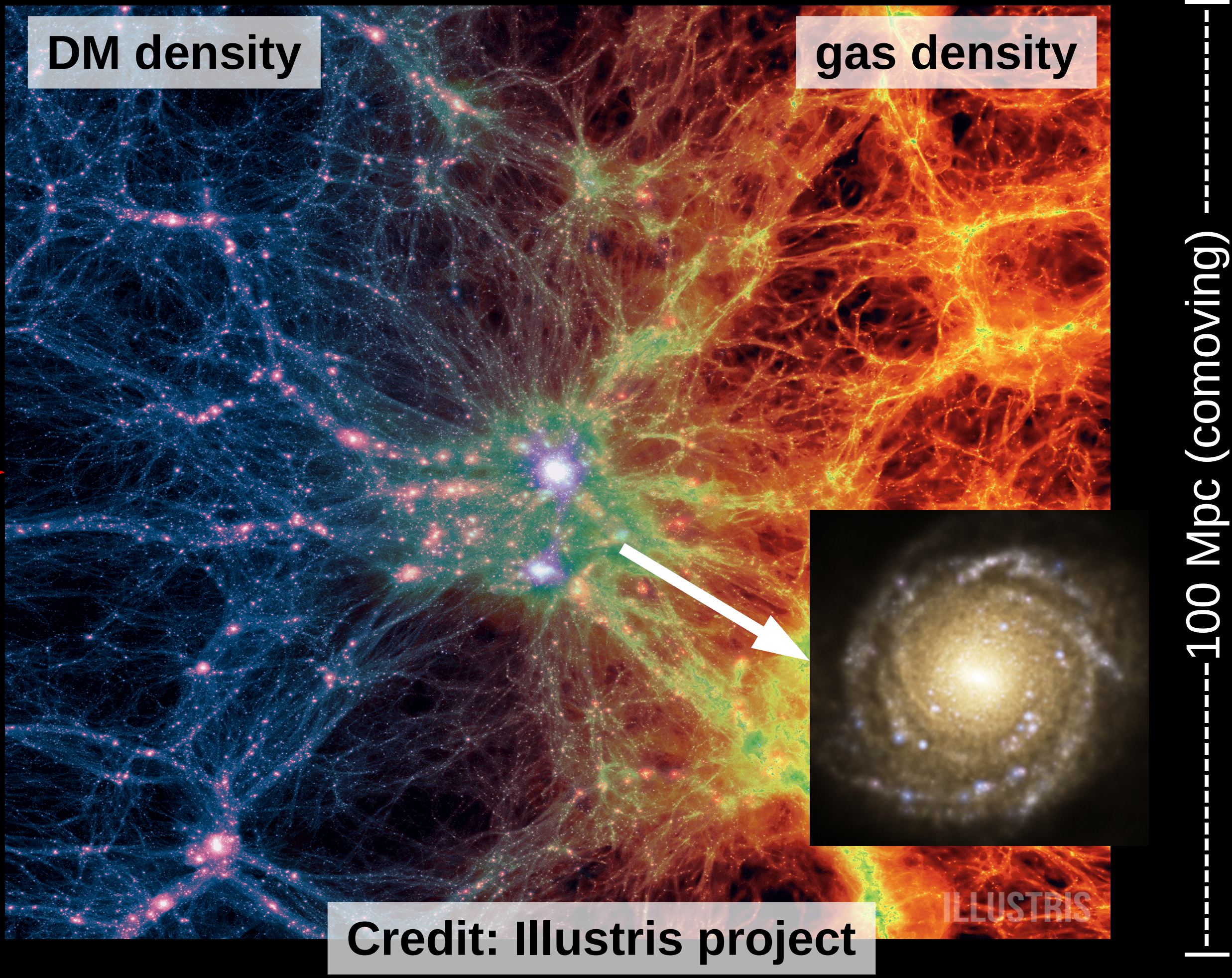
## The Cold Dark Matter (CDM) hypothesis is the cornerstone of the current structure formation theory




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

**cosmological simulations**

**<u>DM gravity only</u>**
**+**
**“baryonic” physics**
**(radiative cooling, gas hydrodynamics, star formation, supernova and AGN feedback,...)**




**<u>2000 CPU years!!</u>**

**despite the spectacular progress in developing a galaxy formation/evolution theory, it remains incomplete since we still don't know:**

**what is the nature of dark matter?**

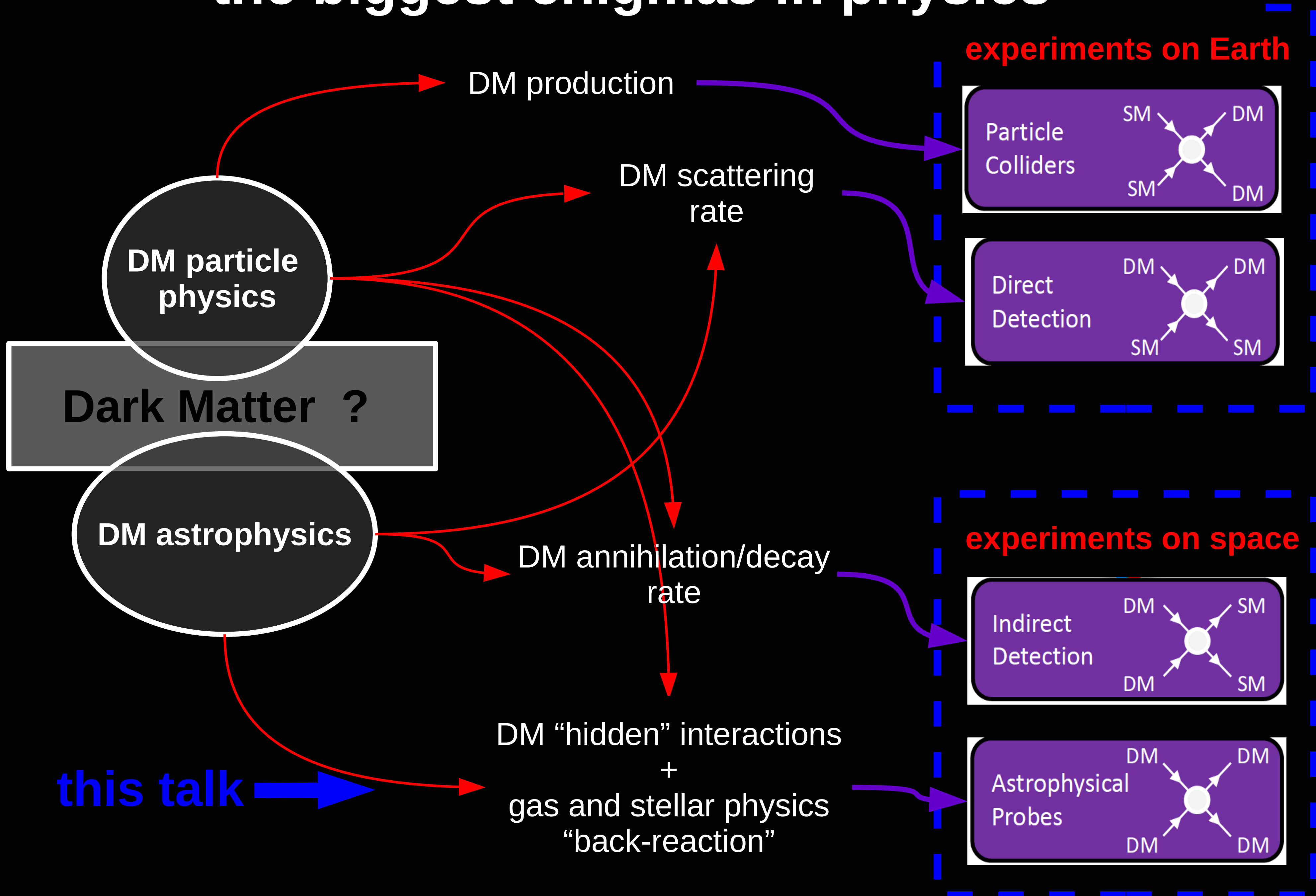
**What is the mass(es) of the DM particle(s) and through which forces does it interact?**

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

**this talk** →

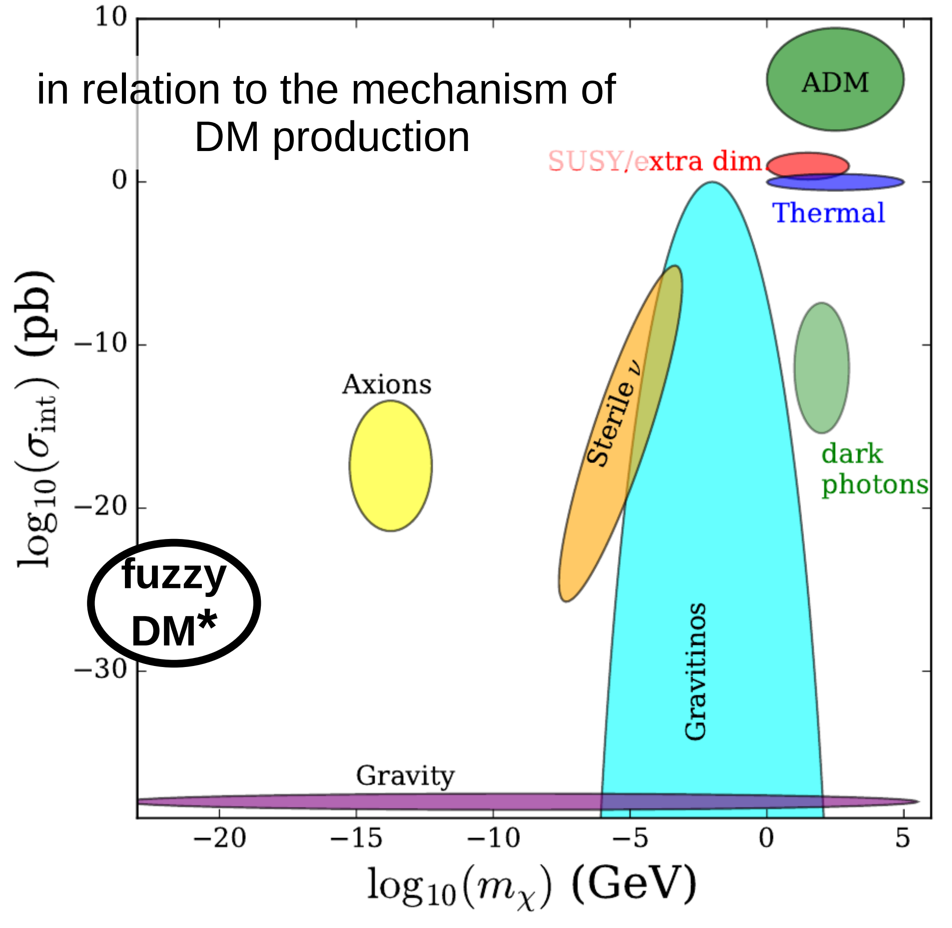
***Although there is no indisputable evidence that the CDM hypothesis is wrong, there are reasonable physical motivations to consider alternatives***

# The particle nature of dark matter is one of the biggest enigmas in physics



# The (incomplete) particle DM landscape

**Particle physics parameter space**

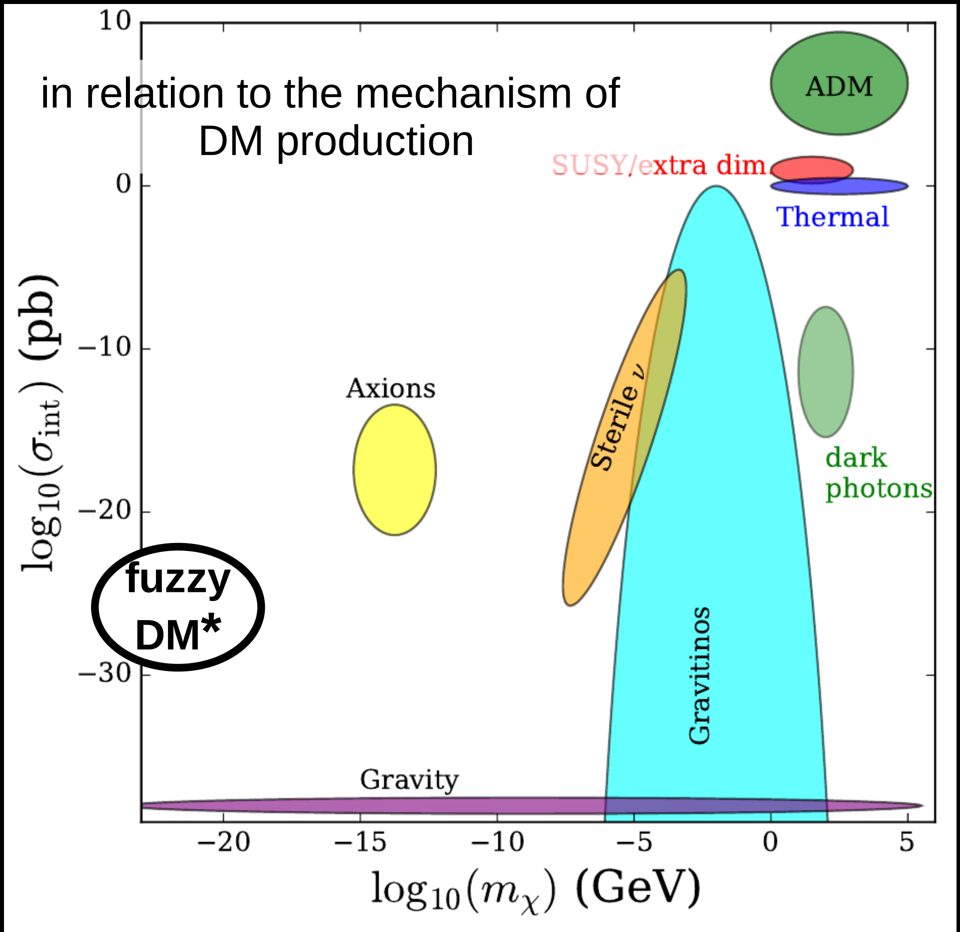



***for the reminder of this talk, I will leave aside "fuzzy" DM**

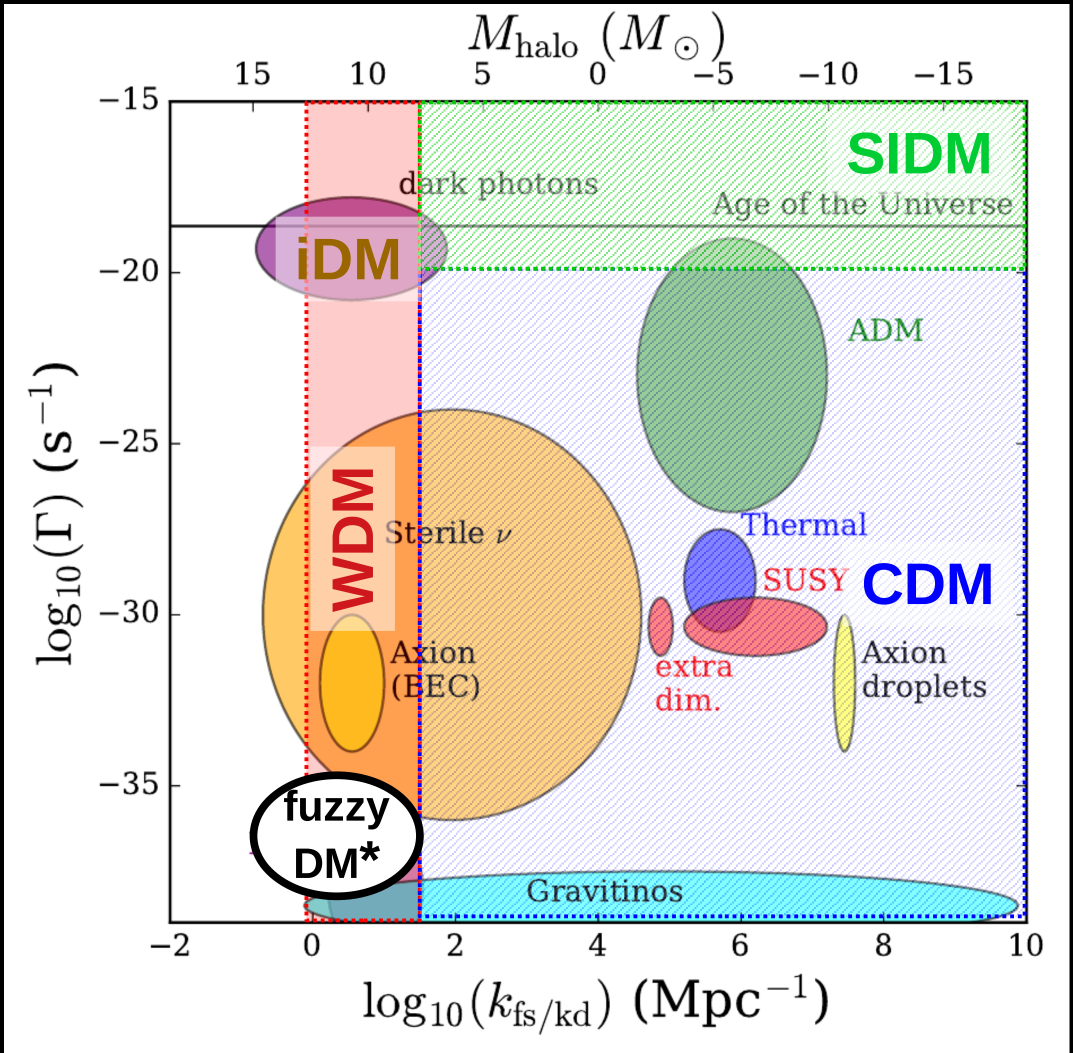
**Adapted from: Buckley & Peter 2018**

# The (incomplete) particle DM landscape

**Particle physics parameter space**




**Astrophysics parameter space**




*for the reminder of this talk, I will leave aside “fuzzy” DM

Adapted from: Buckley & Peter 2018

# two major unresolved questions in structure/galaxy formation theory

**What physical mechanisms set the minimum mass scale for galaxy formation?**

**What physical mechanisms set the (central) dynamics within the visible galaxy?**

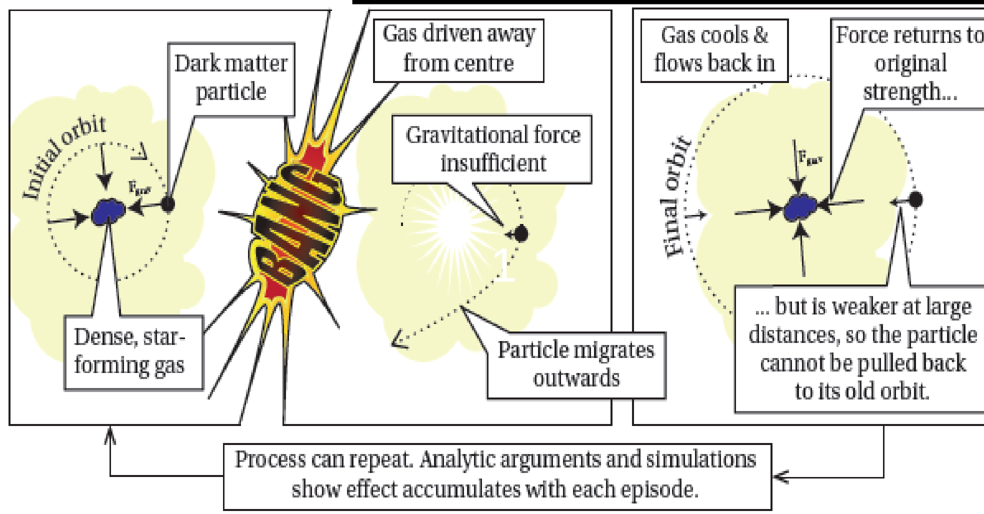
**Is it baryonic physics, is it new DM physics, or is it both?**

# Known but uncertain and complex "baryonic physics"

Gas and DM heating through supernovae

Jan's talk

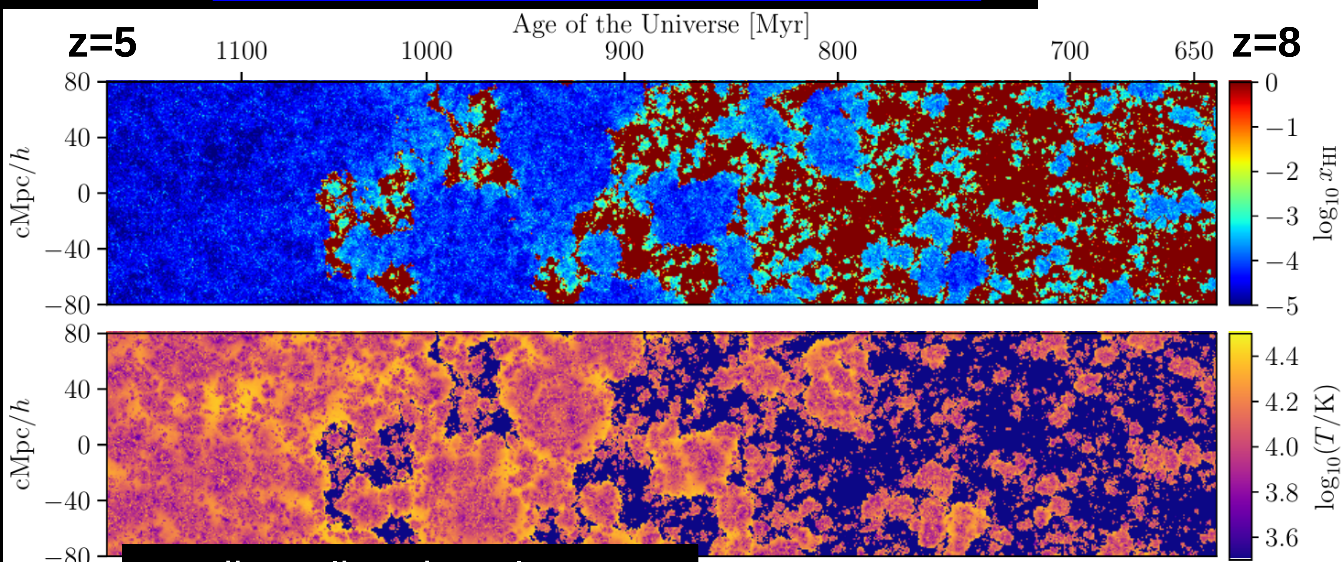
Credit: Pontzen & Governato 2014




these mechanisms are certainly there, but how efficient they are in nature for the smallest galaxies remains unclear

reduces the inner density of DM haloes

Gas heating (UV background from first generation of stars/galaxies)




Credit: Kulkarni et al 2019

sets a minimum halo scale for gas to cool

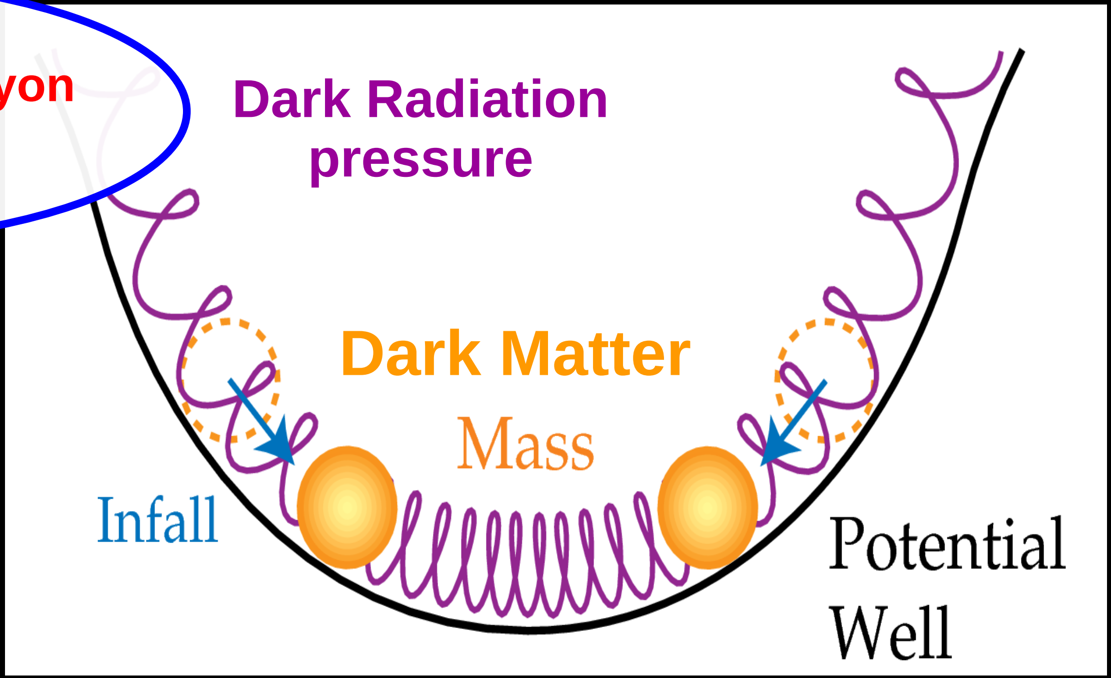
# Unknown but simple "dark physics"

can DM physics induce a galactic-scale primordial power spectrum cut-off?

Allowed interactions between DM and relativistic particles (e.g. "dark radiation") in the early Universe introduce pressure effects that impact the growth of DM structures

## Dark Acoustic Oscillations (DAOs)

analogous to the photon-electron-baryon plasma case: BAOs




Credit: Wayne Hu (U. Of Chicago)

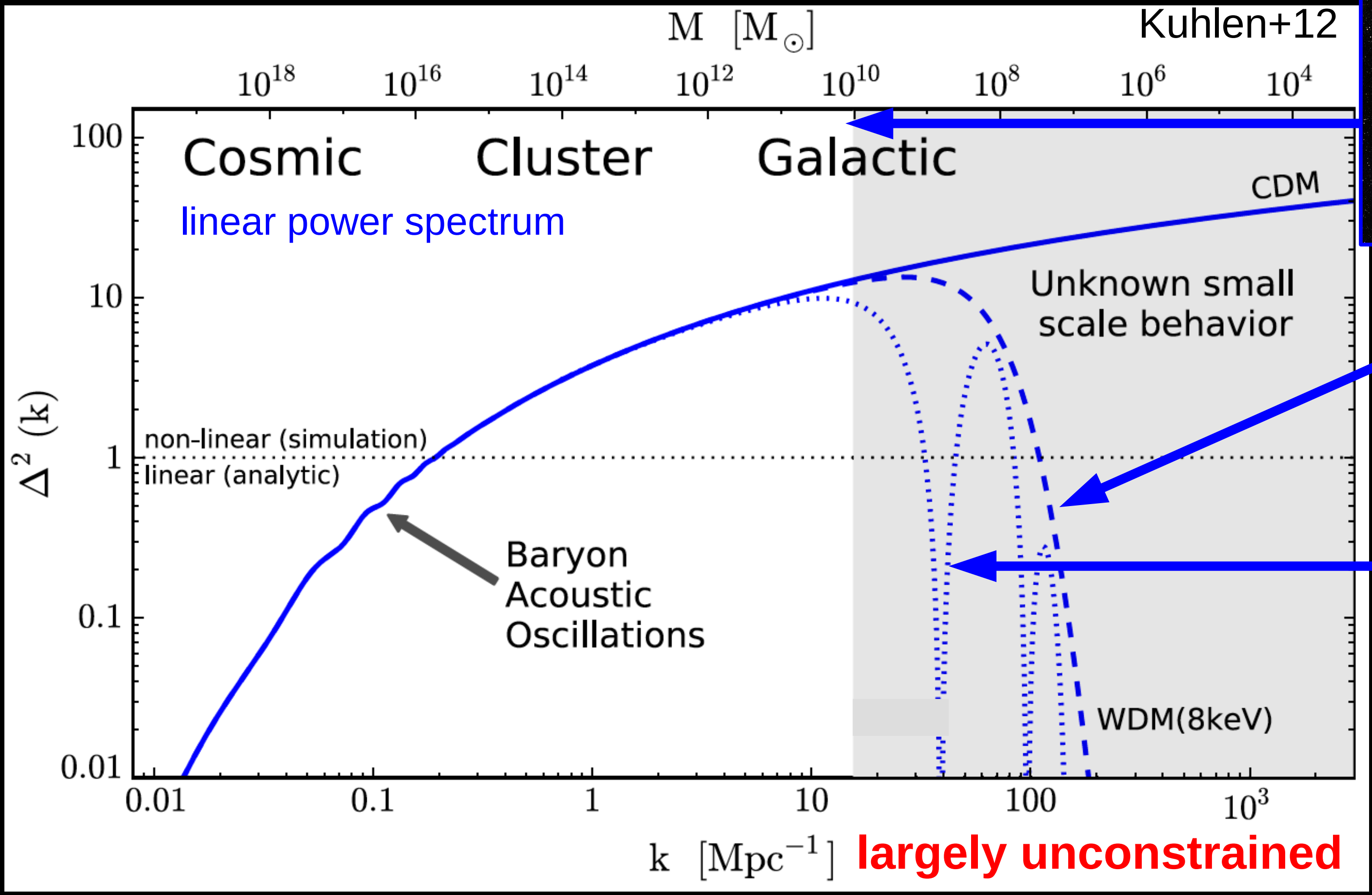
there is also the traditional collisionless (free streaming) damping (e.g. thermal WDM)

# Unknown but simple "dark physics"

**can DM physics induce a galactic-scale primordial power spectrum cut-off?**

**Observations have yet to measure the clustering of dark matter at the scale of the smallest galaxies**

**Dwarf galaxies**




**largely unconstrained**

**DM is relativistic at earlier times 'thermal' cut-off (WDM free-streaming)**

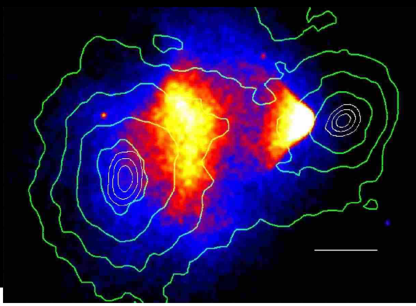
**DM interacts with relativistic particles at earlier times:**

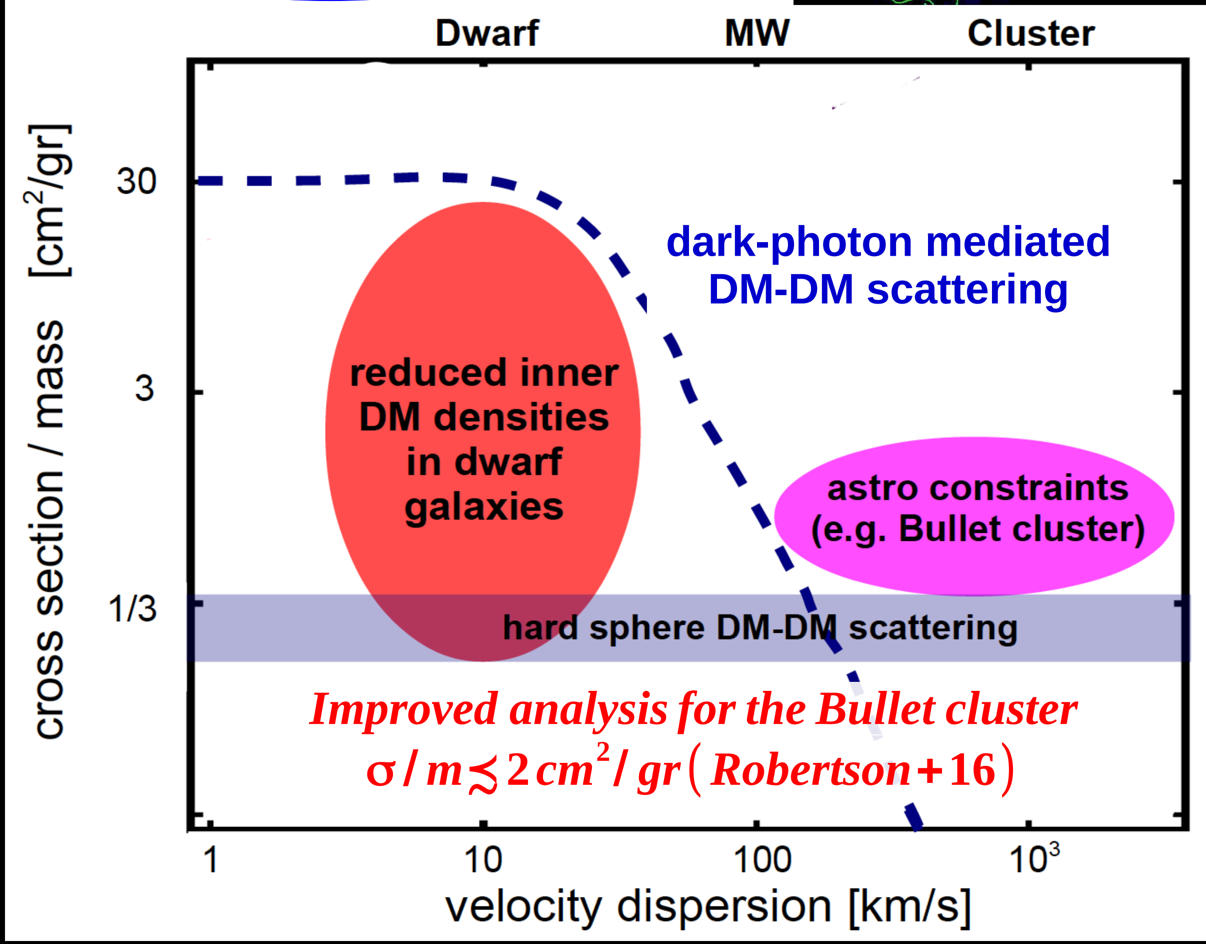
**DM-dark-photons DAOs and Silk damping**

# Unknown but simple "dark physics"

**can DM physics change the phase-space structure of DM haloes during their evolution?**

**constraints allow collisional DM that is astrophysically significant in the center of galaxies**






**average scattering rate per particle:**

$$\frac{\overline{R}_{sc}}{\Delta t} = \left(\frac{\sigma_{\rm sc}}{m_\chi}\right) \overline{\rho}_{\rm dm}\ \overline{v}_{\rm typ}$$

**~ 1 scatter / particle / Hubble time**

**Neither a fluid nor a collisionless system: ~ rarefied gas**

# A challenge

- The minimum scale for galaxy formation could be set by:
  - **physics of reionisation**: heating and photo-evaporation from the UV background produced by the first generation of stars/galaxies
  - **primordial ‘dark’ damping**: free streaming of DM particles (WDM) or collisional damping due to interactions between DM and relativistic particles
- The inner dynamics of dwarf galaxies could be driven by:
  - **supernovae energy/momentum deposition** in the ISM at ~kpc scales
  - thermalization of the inner DM halo due to **DM self-collisions**
- <u>Although dark and baryonic physics are to large extent degenerate, the situation is unavoidable given our current incomplete knowledge of the DM nature and gas an stellar physics</u>

# An opportunity

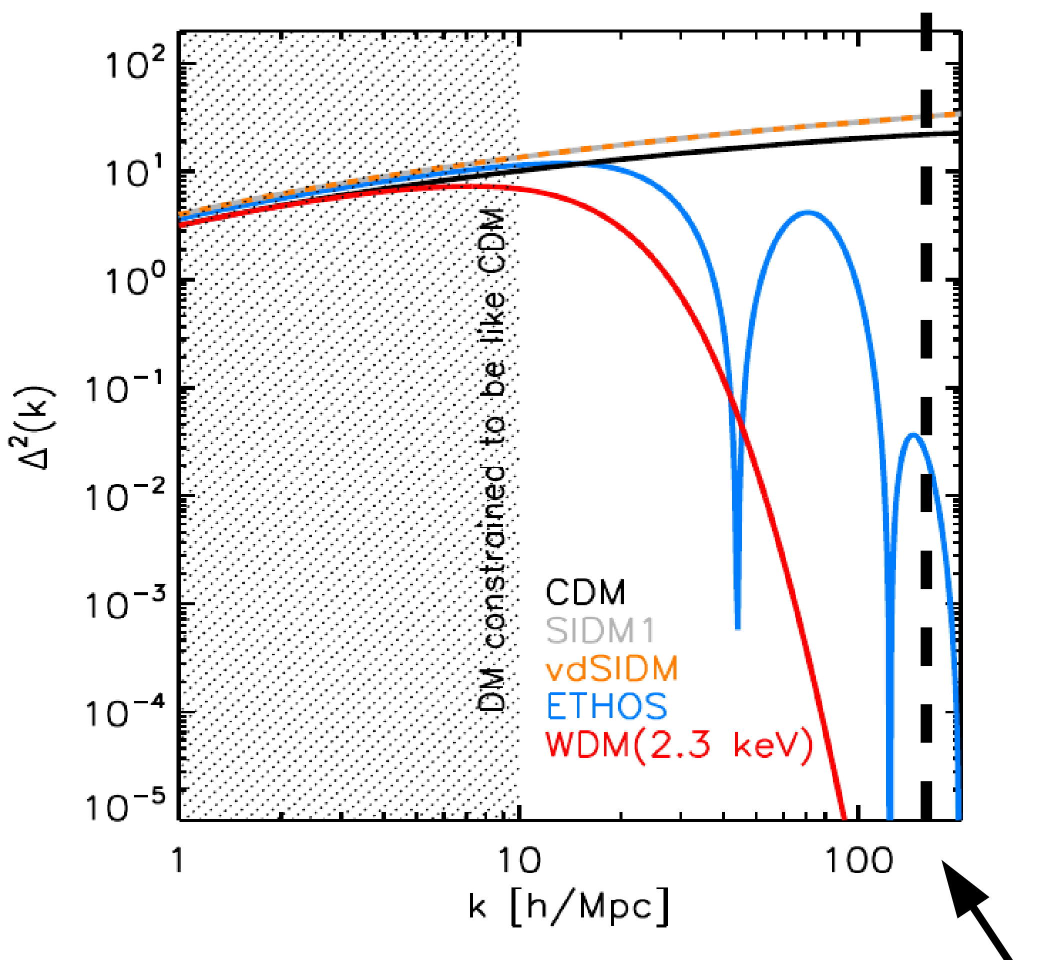
- Galaxies remain the best “dark matter detectors” we have

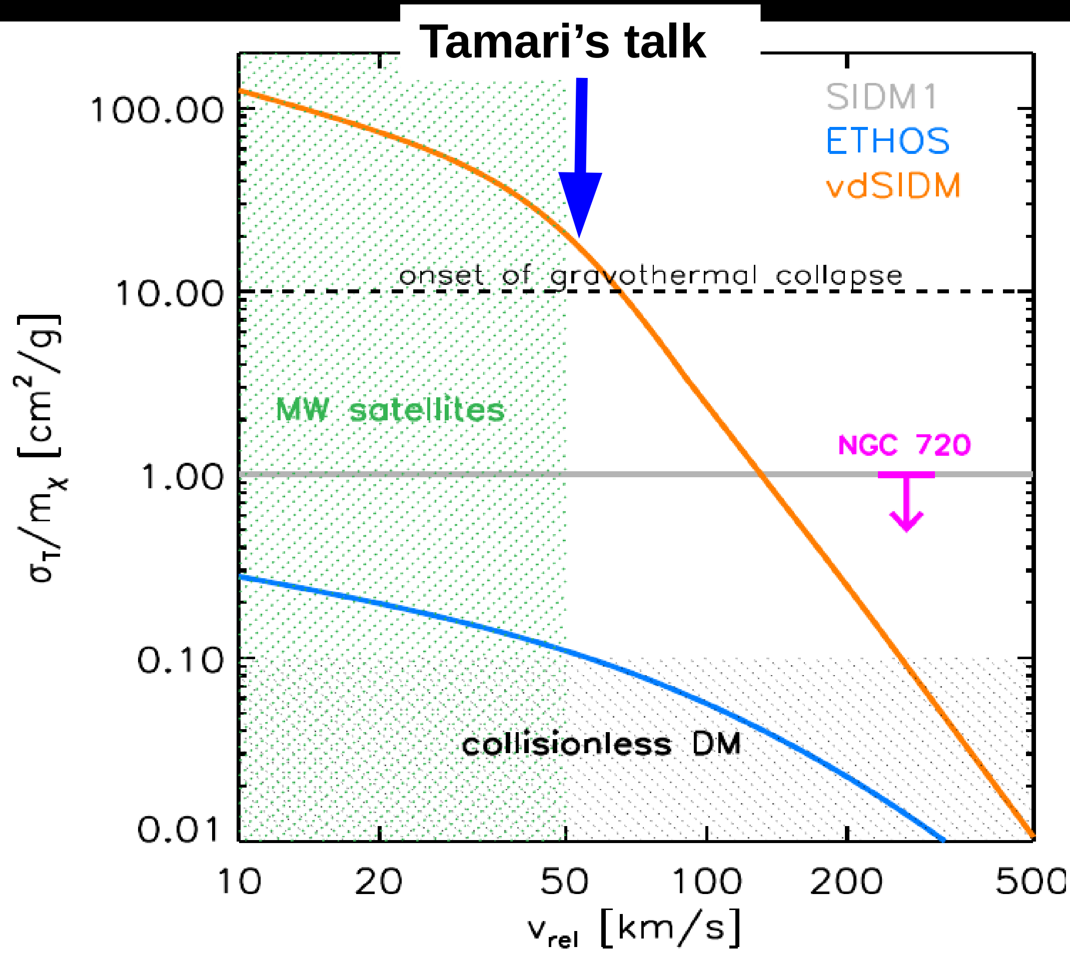
- Looking in detail at the properties of the galaxy population across time might give us a hint about the particle nature of dark matter

- Given the current situation (obs. constraints, complexity of baryonic physics), it is timely to consider additional free DM parameters, which might play a key role in the physics of galaxies. The window is relatively narrow:

# An opportunity

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



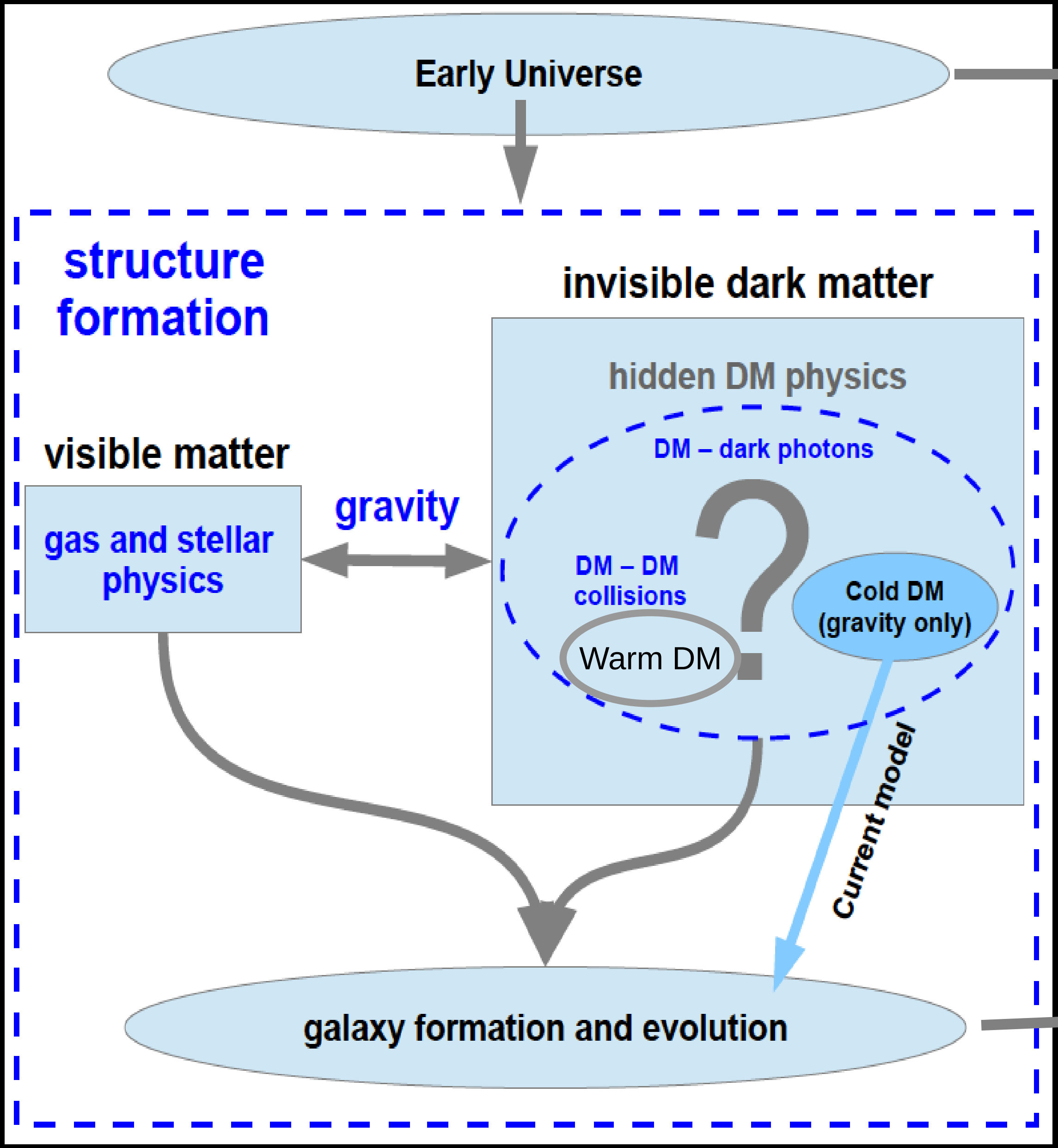




below this value galaxy formation Is highly supressed (reionisation)

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

Zavala et al. 2019

# 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)**

# An Effective THeory Of Structure formation (ETHOS)

stru
forn
visibl
gas an
ph

### In collaboration with:

**Sebastian Bohr (PhD, U. of Iceland)**
**Jan Burger (PhD, U. of Iceland)**
**Mark Lovell (Postdoc, U. of Iceland)**
**Tamari Meshveliani(PhD, U. of Iceland)**

Torsten Bringmann (UiO, Oslo)
Francis-Yan Cyr-Racine (UNM, New Mexico)
Christoph Pfrommer (AIP, Heidelberg)
Kris Sigurdson (UBC, Vancouver)
Mark Vogelsberger (MIT, Cambridge)

sm
obal

of

range
ology
dge
ution

onal

ucts)

# Ingredients

- ➔ DM-DR impact the linear regime
- ➔ DM-DM interactions impact the non-linear regime
- ➔ “effective” parameters for structure formation

# ETHOS: classify DM models according to their effective parameters for structure formation

**particle physics parameters (masses, couplings, ...)**

$$\left\{ m_\chi, \{g_i\}, \{h_i\}, \xi \right\}$$

**select a particle physics model**
**e.g. DM interacting with massless neutrino-like fermion via massive mediator**
**(e.g. van der Aarssen, Bringmann+12)**

DR to CMB temperature at z=0

**growth of structures (linear regime) with additional physics: DM-DR-induced DAOs and Silk damping**

# ETHOS: the linear regime

**collisional Boltzmann eqs.**

$$\frac{df_\chi}{d\lambda} = C_{\chi\tilde{\gamma}\leftrightarrow\chi\tilde{\gamma}}[f_\chi, f_{\rm DR}]$$

**in the linear regime:** $\delta_\chi(x,t) \ll 1$

**cosmological perturbation theory**

**eqs. for DM perturbations in Fourier space**

$$\dot{\delta}_\chi + \theta_\chi - 3\dot{\phi} = 0,$$

$$\dot{\theta}_\chi - c_\chi^2 k^2 \delta_\chi + \mathcal{H}\theta_\chi - k^2\psi = \dot{\kappa}_\chi[\theta_\chi - \theta_{\rm DR}]$$

$$\theta = \nabla \cdot \vec{v}$$

$$\mathcal{H} = \frac{\dot{a}}{a}$$

**related to DR opacity to DM scattering (collisional term of the Boltzmann eq.)**

$$C_{\chi\tilde{\gamma}\leftrightarrow\chi\tilde{\gamma}}[f_\chi, f_{\rm DR}]$$

# ETHOS: the linear regime

**collisional Boltzmann eqs.**

$$\frac{df_\chi}{d\lambda} = C_{\chi\tilde{\gamma}\leftrightarrow\chi\tilde{\gamma}}[f_\chi, f_{\mathrm{DR}}]$$

**in the linear regime:** $\delta_\chi(x,t) \ll 1$

**cosmological perturbation theory**

**eqs. for DM perturbations in Fourier space**

$$\boxed{\begin{aligned} &\dot{\delta}_\chi + \theta_\chi - 3\dot{\phi} = 0, \\ &\dot{\theta}_\chi - c_\chi^2 k^2 \delta_\chi + \mathcal{H}\theta_\chi - k^2\psi = \dot{\kappa}_\chi[\theta_\chi - \theta_{\mathrm{DR}}] \end{aligned}}$$

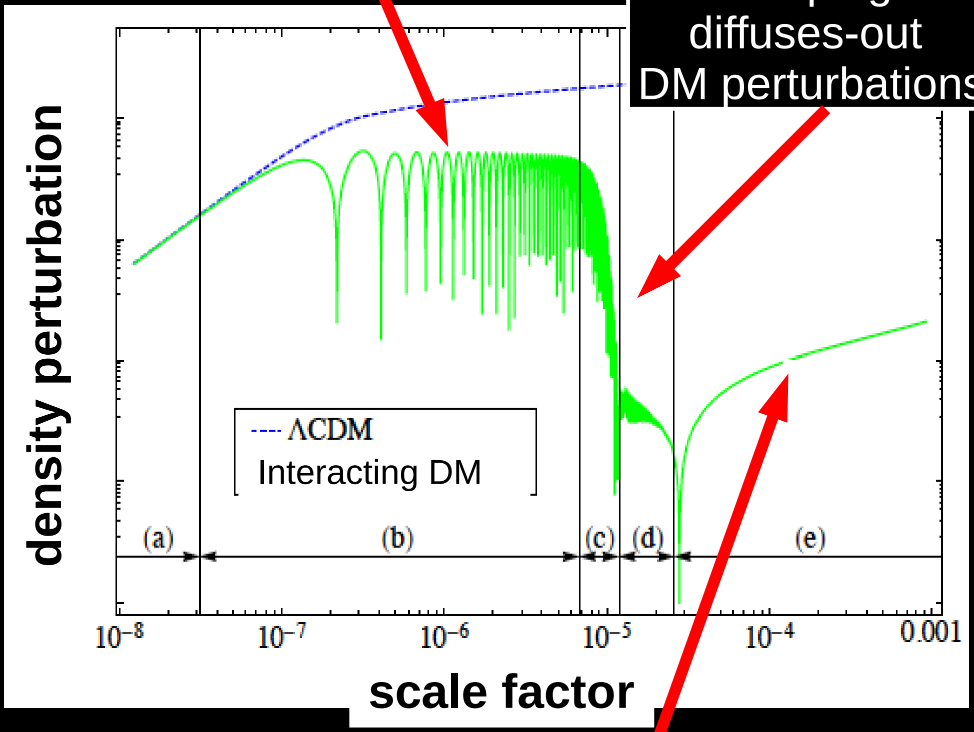
**related to DR opacity to DM scattering (collisional term of the Boltzmann eq.)**

$$C_{\chi\tilde{\gamma}\leftrightarrow\chi\tilde{\gamma}}[f_\chi, f_{\mathrm{DR}}]$$

DR pressure counteracts gravity creating “dark acoustic oscillations”

**Cyr-Racine+13**

collisional (Silk) damping diffuses-out DM perturbations




once kinetic decoupling (DM-DR) occurs DM behaviour is like CDM

**analogous to the photon-electron-baryon plasma case**

# ETHOS: classify DM models according to their effective parameters for structure formation

**particle physics parameters (masses, couplings, ...)**

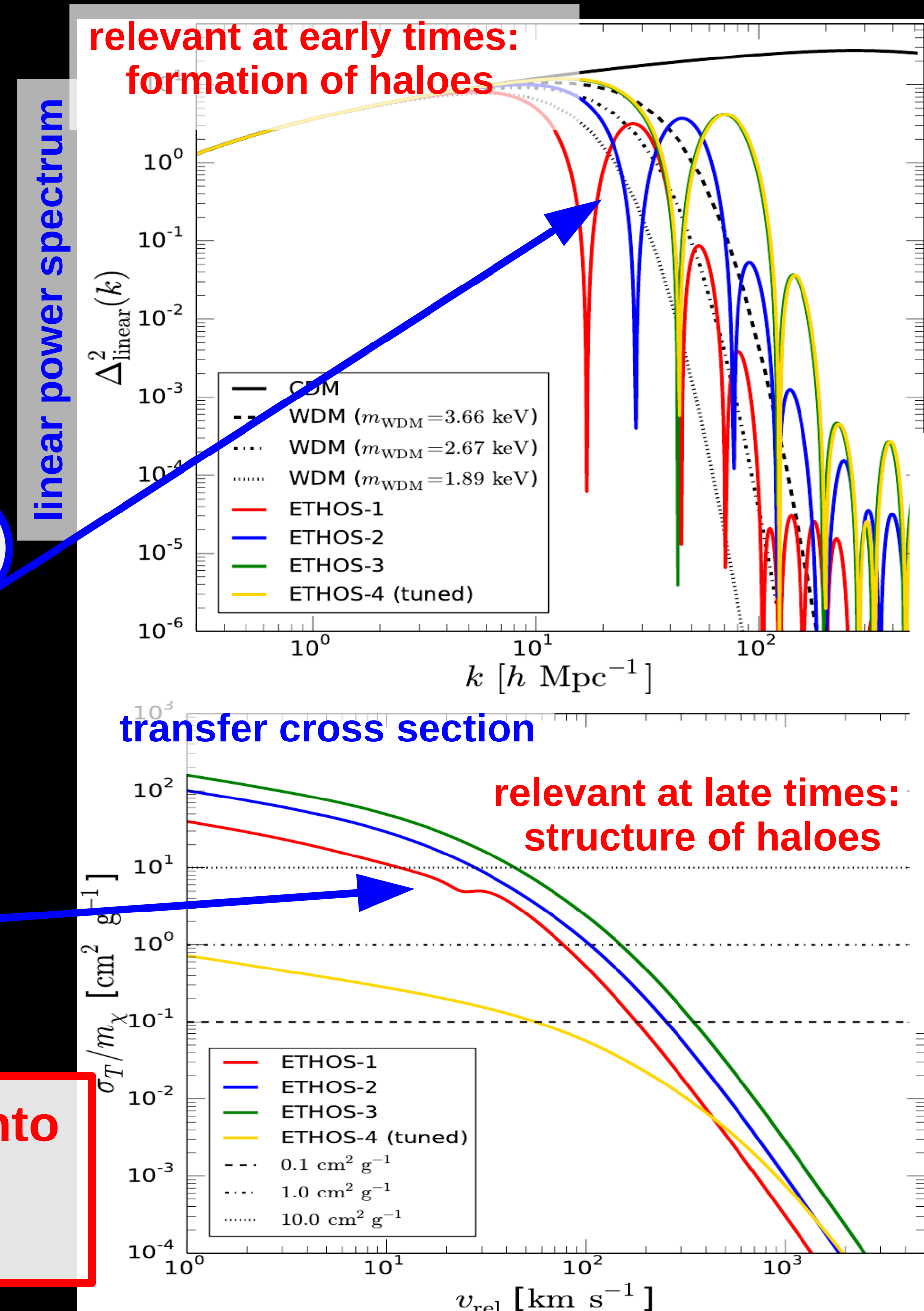
$$\left\{ m_\chi, \{g_i\}, \{h_i\}, \xi \right\}$$

**growth of structures: perturbation theory with additional physics: DM-DR-induced DAOs and collisional damping**

**effective parameters**

$$\Xi_{\rm ETHOS} = \left\{ \omega_{\rm DR}, \{a_n, \alpha_l\}, \left\{ \frac{\langle \sigma_T \rangle_{v_{M_i}}}{m_\chi} \right\} \right\}$$

**All DM particle physics models that map into the same ETHOS parameters can be studied (constrained) at the same time**




**ETHOS I: Cyr-Racine+16**

# ETHOS: the non-linear regime

$If\ \delta(x,t) \ll 1\ \ perturbation\ theory$

$If\ \delta(x,t) \gtrsim 1$

- DM-DR interactions no longer relevant (kinetic decoupling)
- DM-DM interactions increasingly relevant
- perturbation theory breaks down!!

**Far from the fluid and collisionless regimes (Knudsen number ~ 1)** → **full Collisional Boltzmann equation**

$$|\vec{v}_{\rm rel}| = |\vec{v}_1 - \vec{v}| = |\vec{v'}_1 - \vec{v'}|$$

$$\frac{Df(\mathbf{x},\mathbf{v},t)}{Dt} = \Gamma[f,\sigma]$$

**Rate of scattered particles into phase-space patch**

$$= \int d^3\mathbf{v}_1 \int d\Omega \frac{d\sigma}{d\Omega} |\mathbf{v} - \mathbf{v}_1| \left[ f(\mathbf{x},\mathbf{v}',t) f(\mathbf{x},\mathbf{v}_1',t) - f(\mathbf{x},\mathbf{v},t) f(\mathbf{x},\mathbf{v}_1,t) \right]$$

**Differential cross section**

**Rate of scattered particles out of phase-space patch**

**Discretization → N-body simulation**

# A selection of results
# (mostly dwarf-size haloes)

# ETHOS: classify DM models according to their effective parameters for structure formation

particle physics parameters
(masses, couplings, ...)

$$\left\{ m_\chi, \{g_i\}, \{h_i\}, \xi \right\}$$

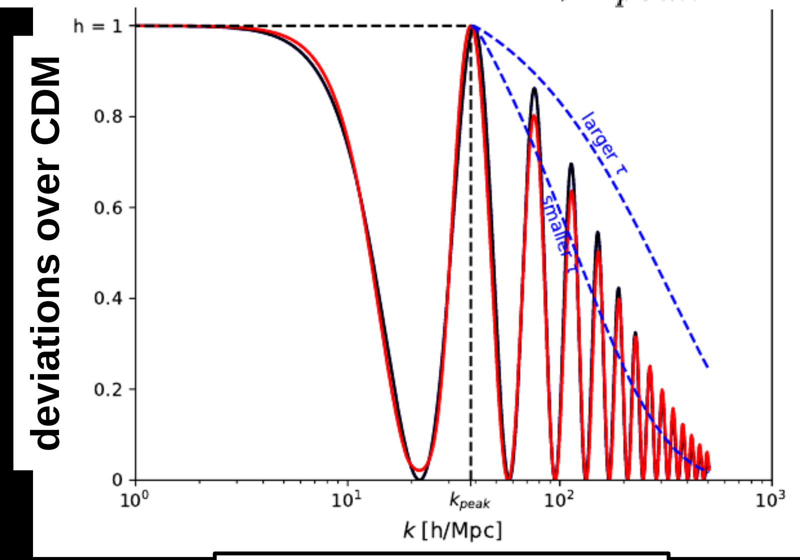
**growth of structures**
**(linear regime) with additional physics:**
**DM-DR-induced DAOs and Silk damping**

$$\Xi_{\rm ETHOS} = \left\{ \omega_{\rm DR}, \{a_n, \alpha_l\}, \left\{ \frac{\langle \sigma_T \rangle_{v_{M_i}}}{m_\chi} \right\} \right\}$$

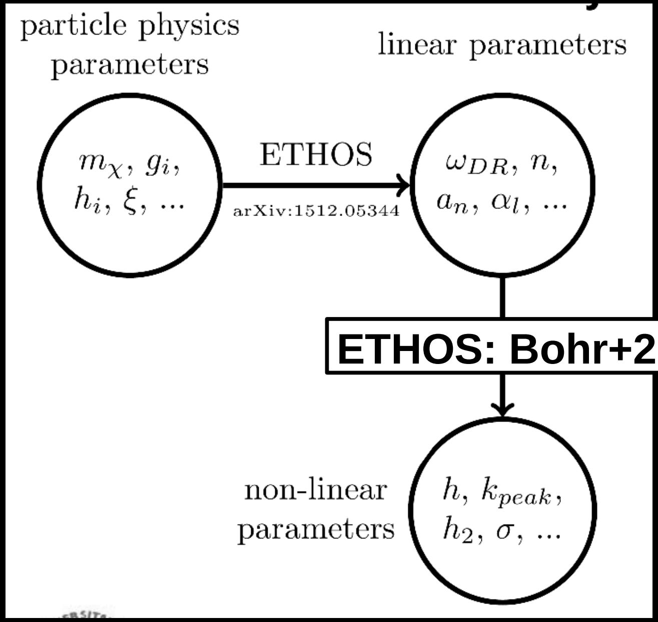
effective linear parameters

**All DM particle physics models that map into the same ETHOS parameters can be studied (constrained) at the same time**

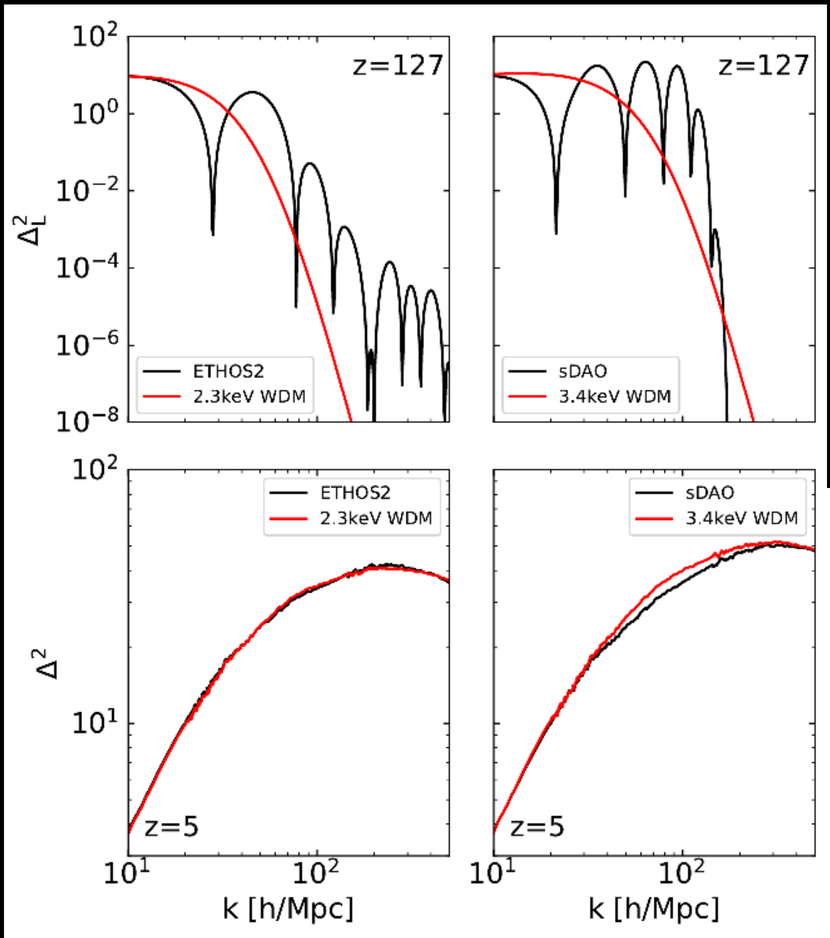
structure formation parameters h, $k_{peak}$ and $\tau$




ETHOS: Bohr+20

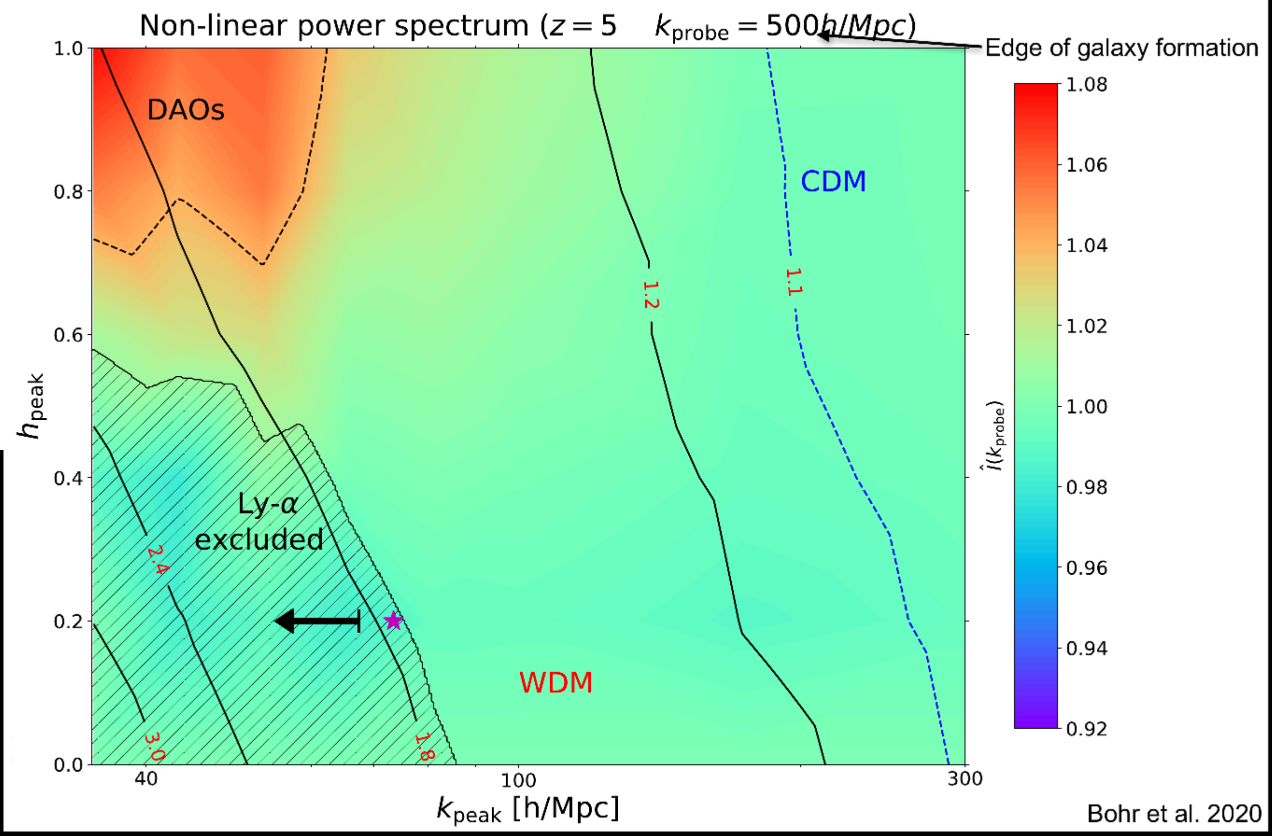


# ETHOS: classify DM models according to their effective parameters for structure formation




The differences in the linear P(k) between WDM and weak-DAOs are erased in the non-linear regime

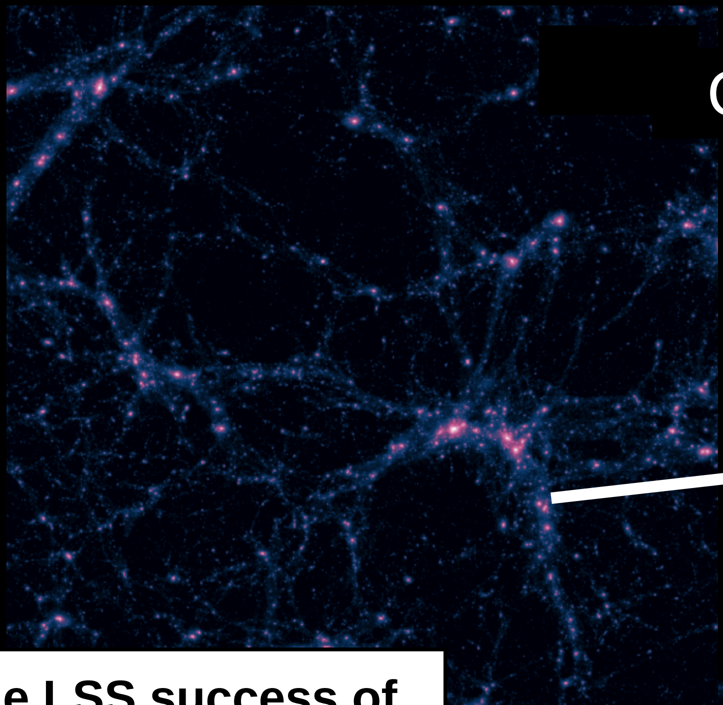
Strong-DAO models remain non-degenerate with WDM

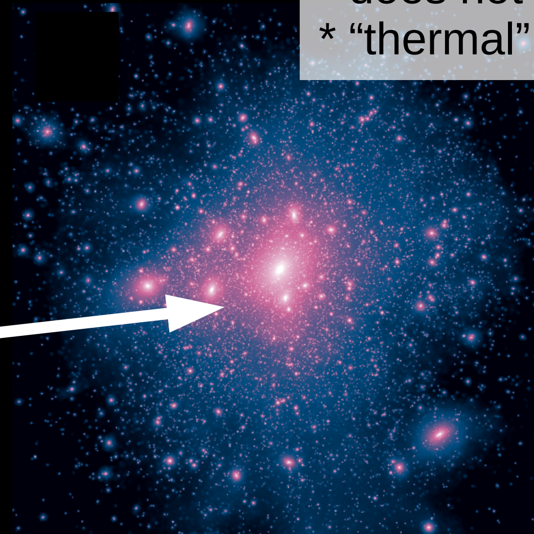



**ETHOS: Bohr+20**

# ETHOS: difference with the standard CDM model

CDM



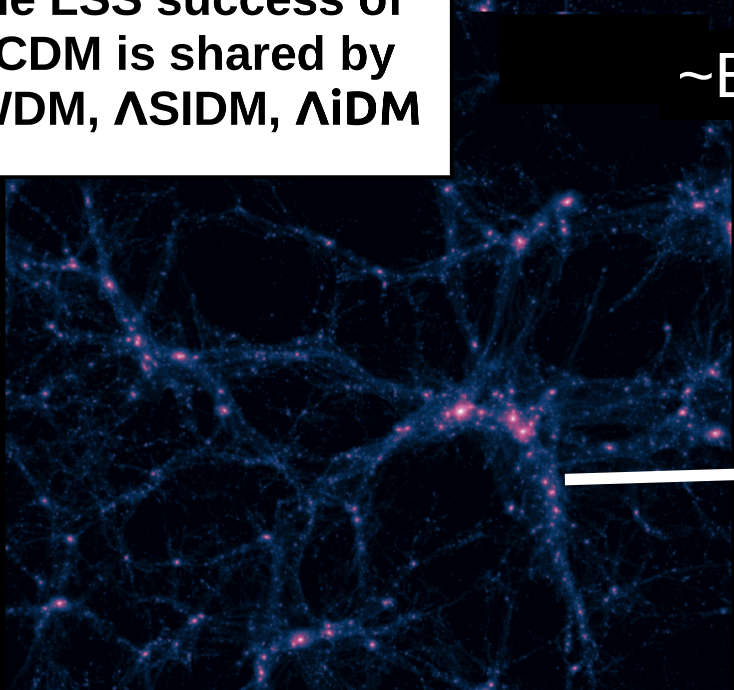


* does not set minimum galactic scale
* "thermal" limit to phase space density

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

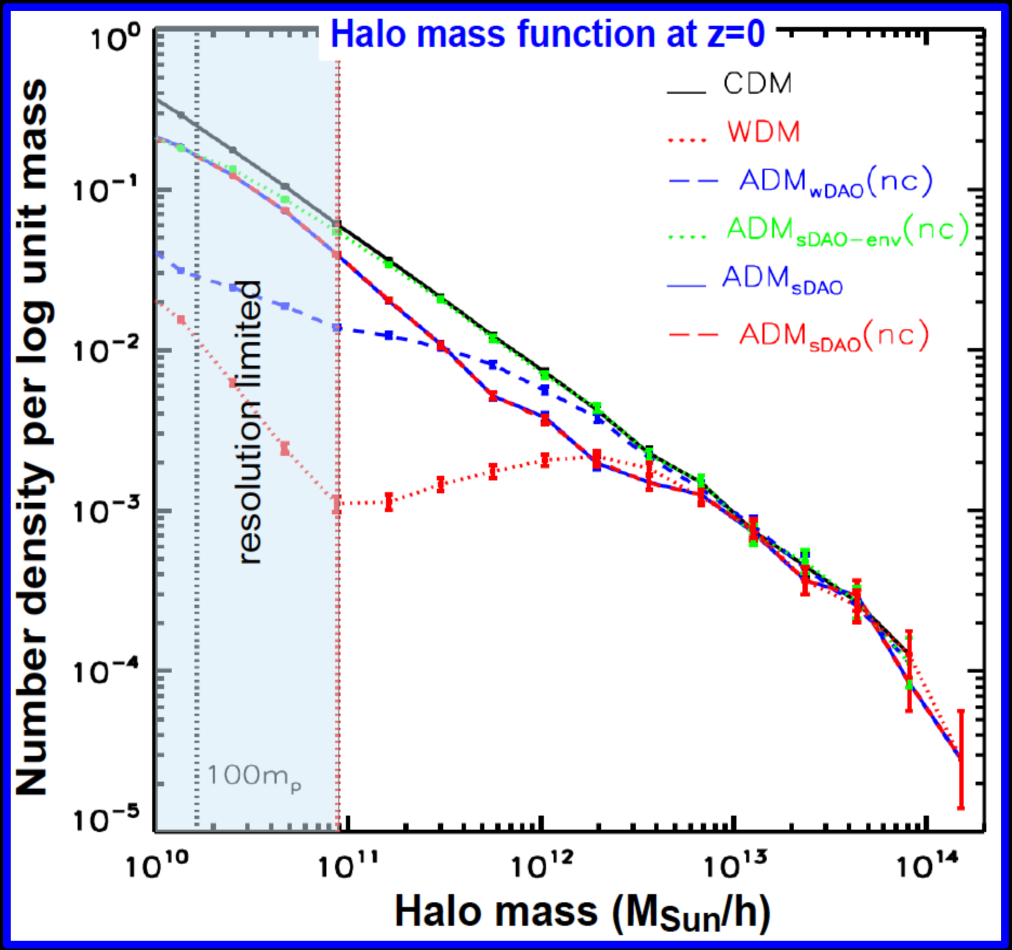
~ETHOS

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



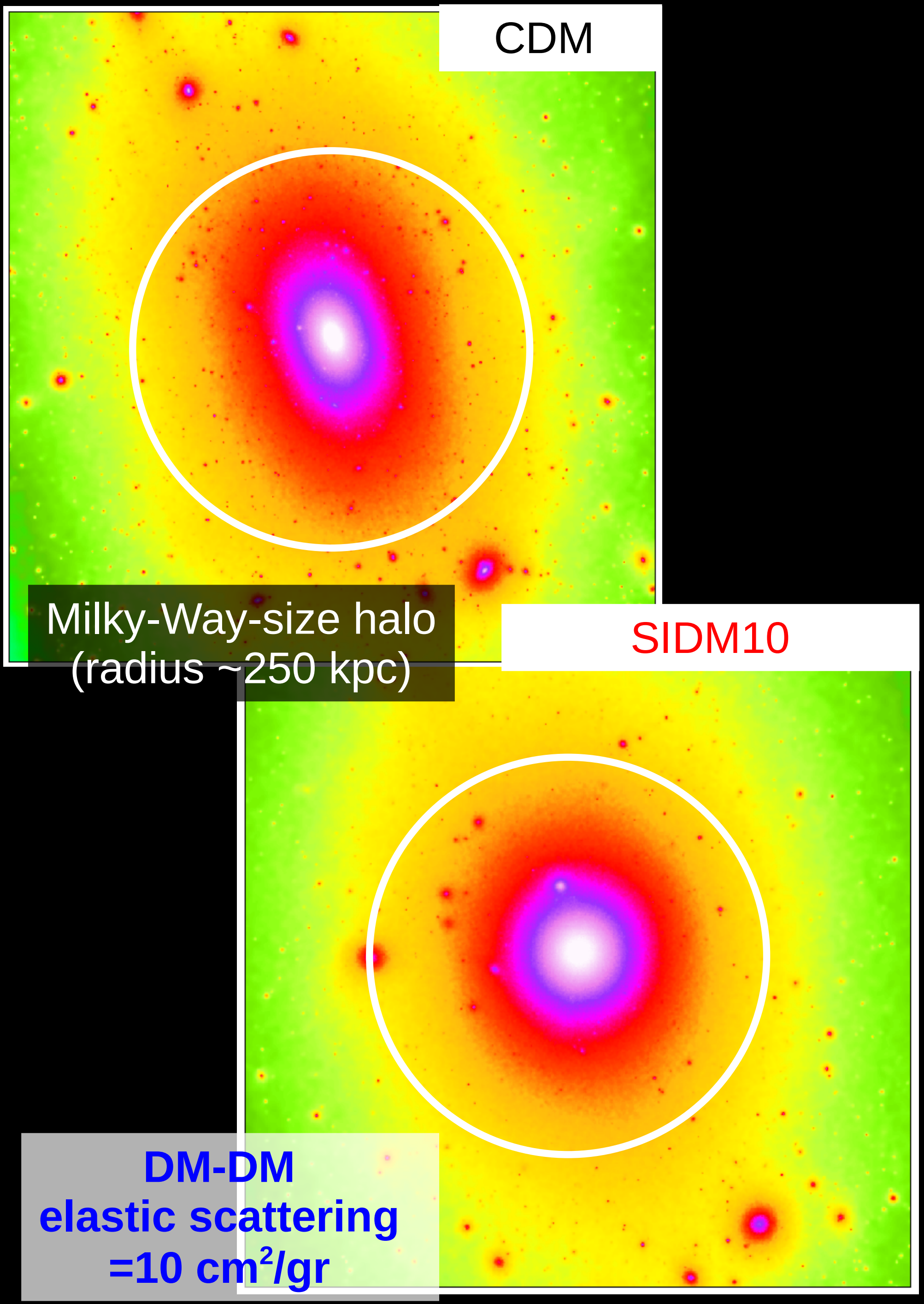
# The abundance and structure of ETHOS haloes

**Abundance of DM haloes (Buckley, Zavala+14)**



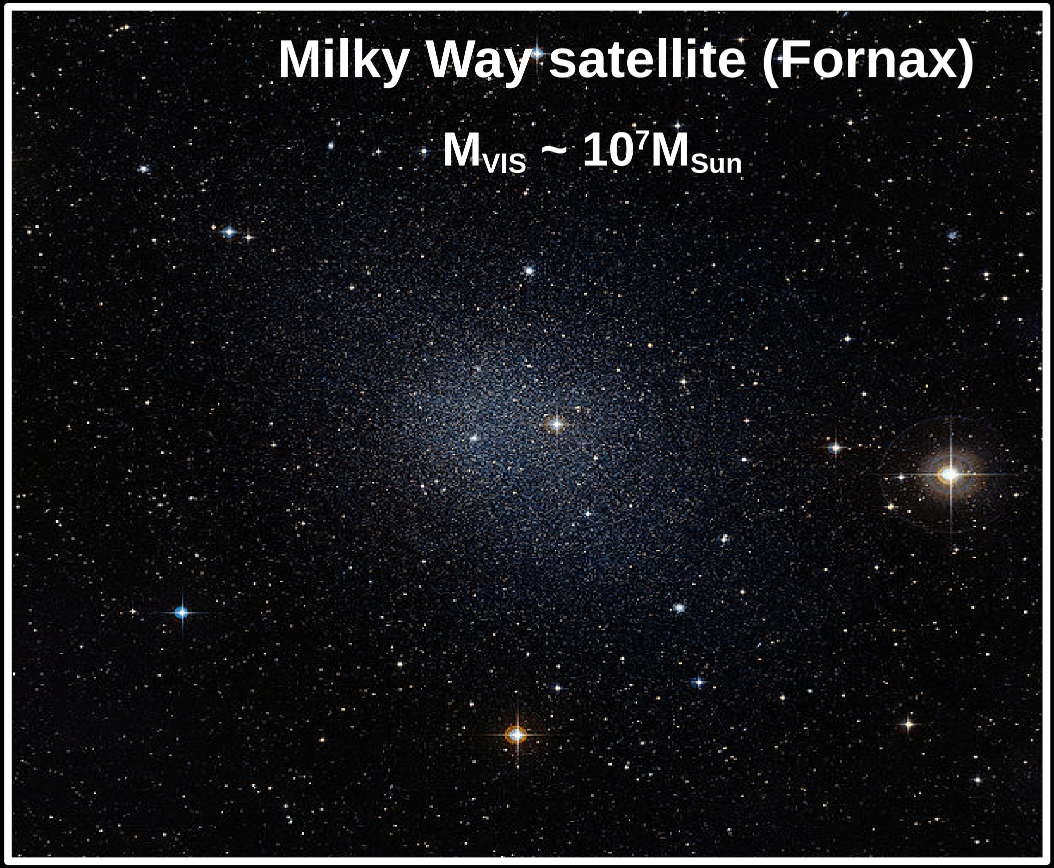

**interactions between DM and dark radiation**

**see also Boehm+14**



# Clues from the properties of dwarf galaxies

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



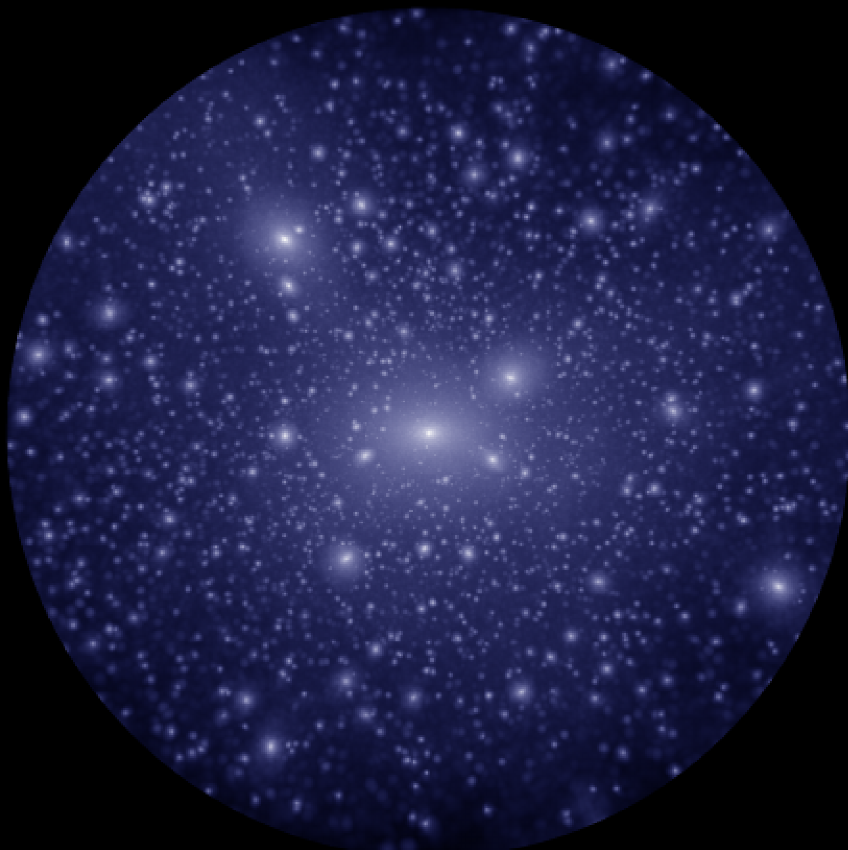

**The stellar dynamics is simplified and the underlying DM distribution can be more easily constrained**

**"Optimal" dynamical detectors of new DM physics**

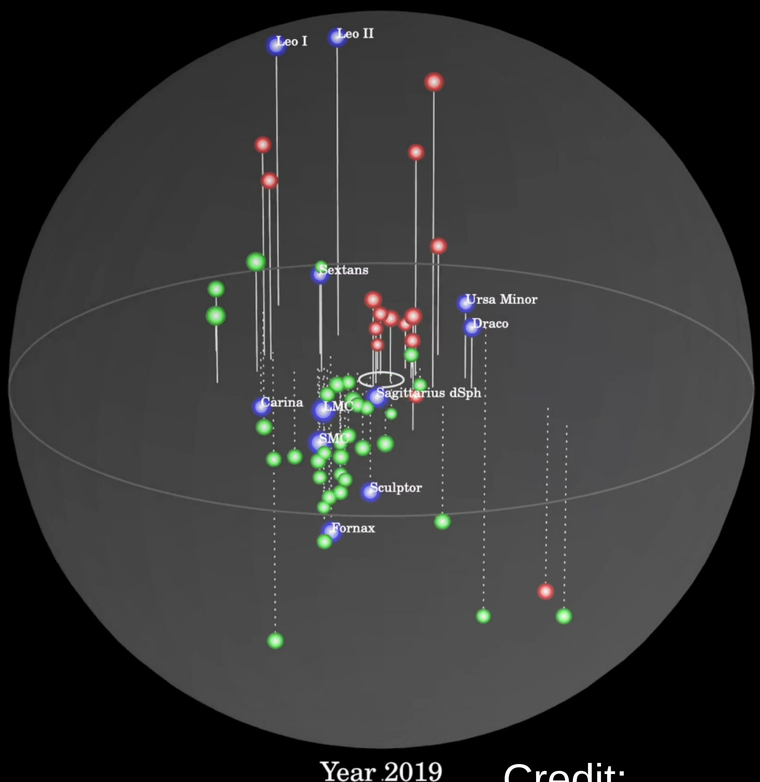
# Clues from the properties of dwarf galaxies

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

**Abundance challenge**
**(Klypin+ 99, MW satellites)**
**(Zavala+09, Klypin+15 field galaxies )**



Credit: Bullock and Boylan-Kolchin 2018



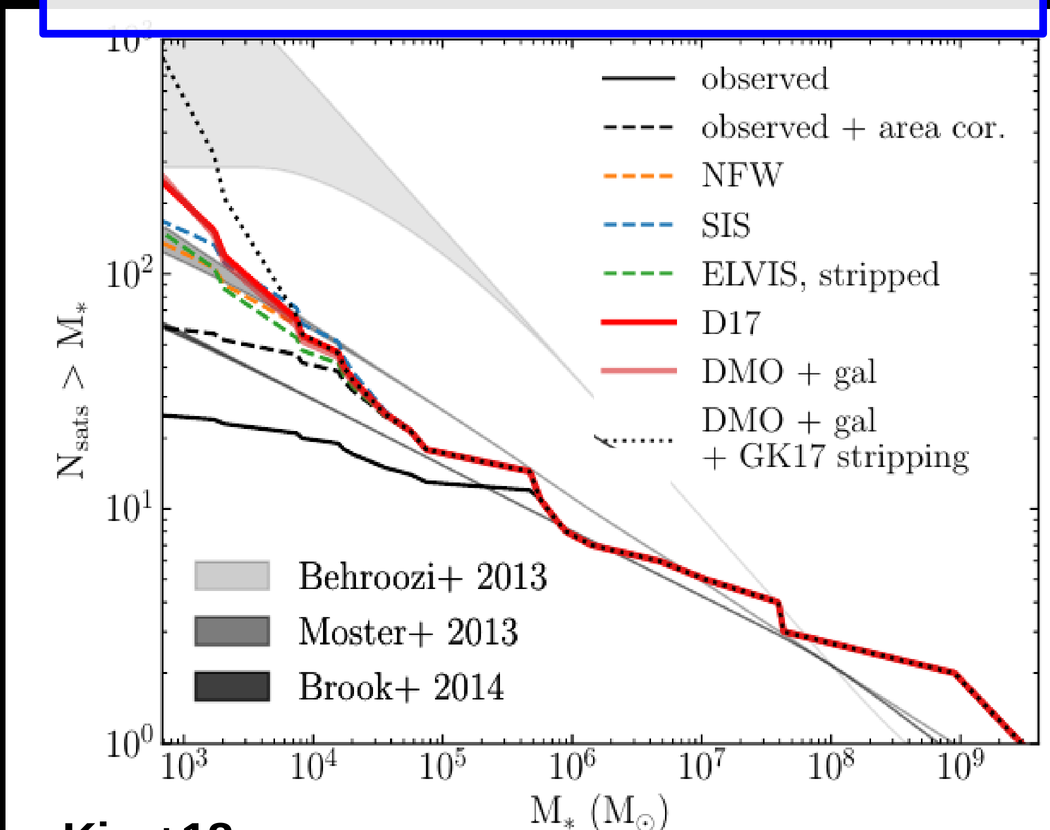

Credit:
M. Pawlowski 2019

# CDM with baryonic physics vs new DM physics

**Abundance challenge**

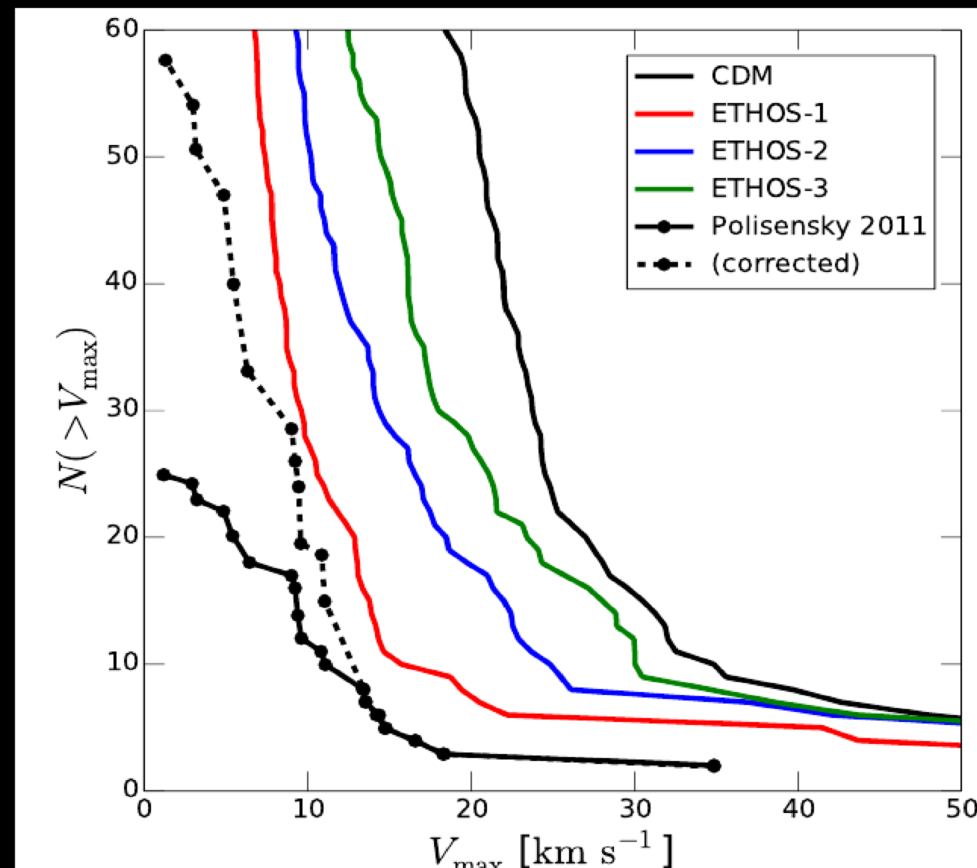
Gas heating (UV background and SN heating)
+
MW tidal effects
+
Observational effects

primordial power spectrum cutoff




**Kim+18**

full cosmological simulations
+ baryon modelling




**ETHOS II: Vogelsberger+16**

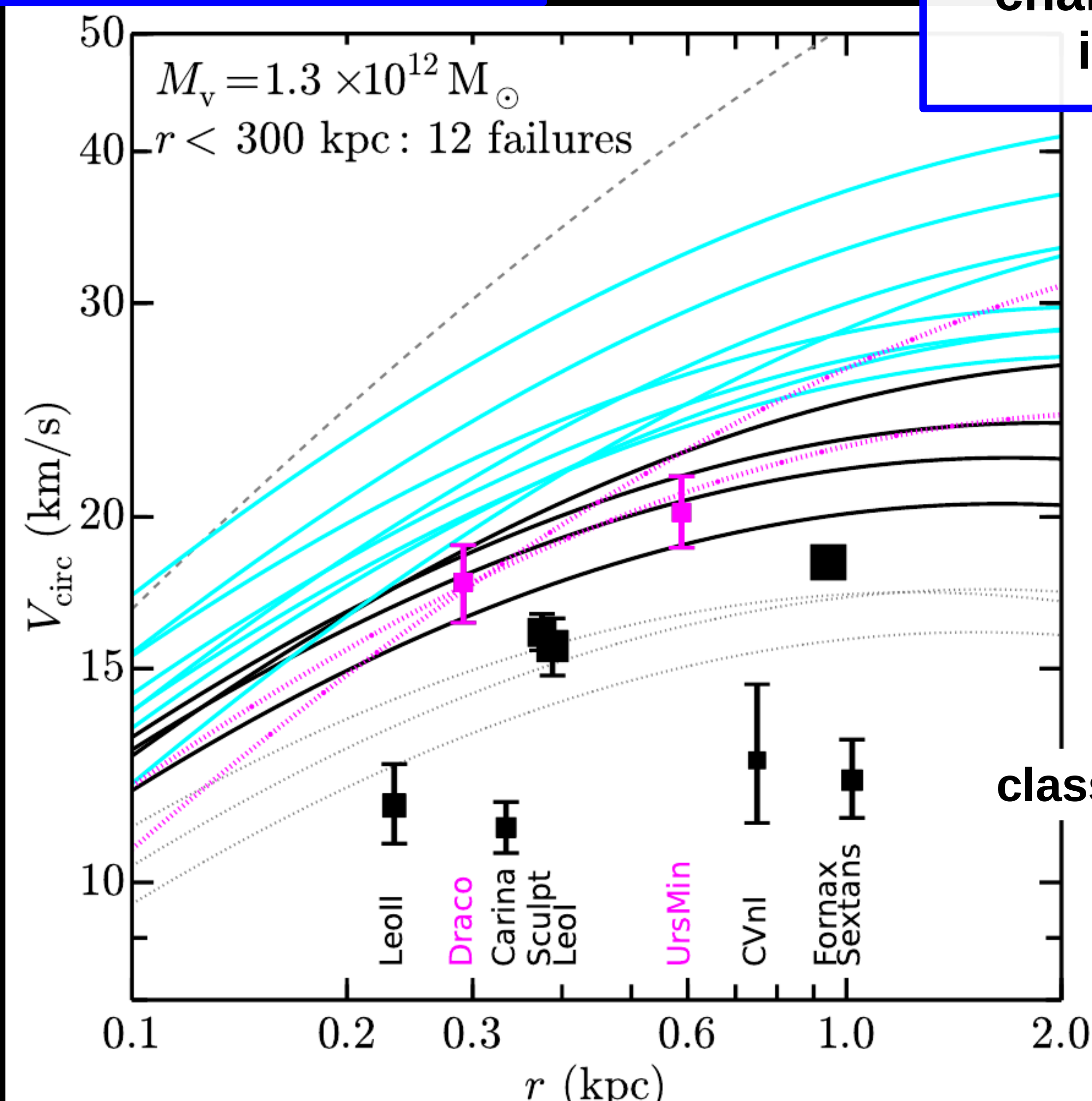
full cosmological simulations
<u>without</u> baryons

# Clues from the properties of dwarf galaxies

**CDM-only (structural) too-big-to-fail problem (Boylan-Kolchin+11)**

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

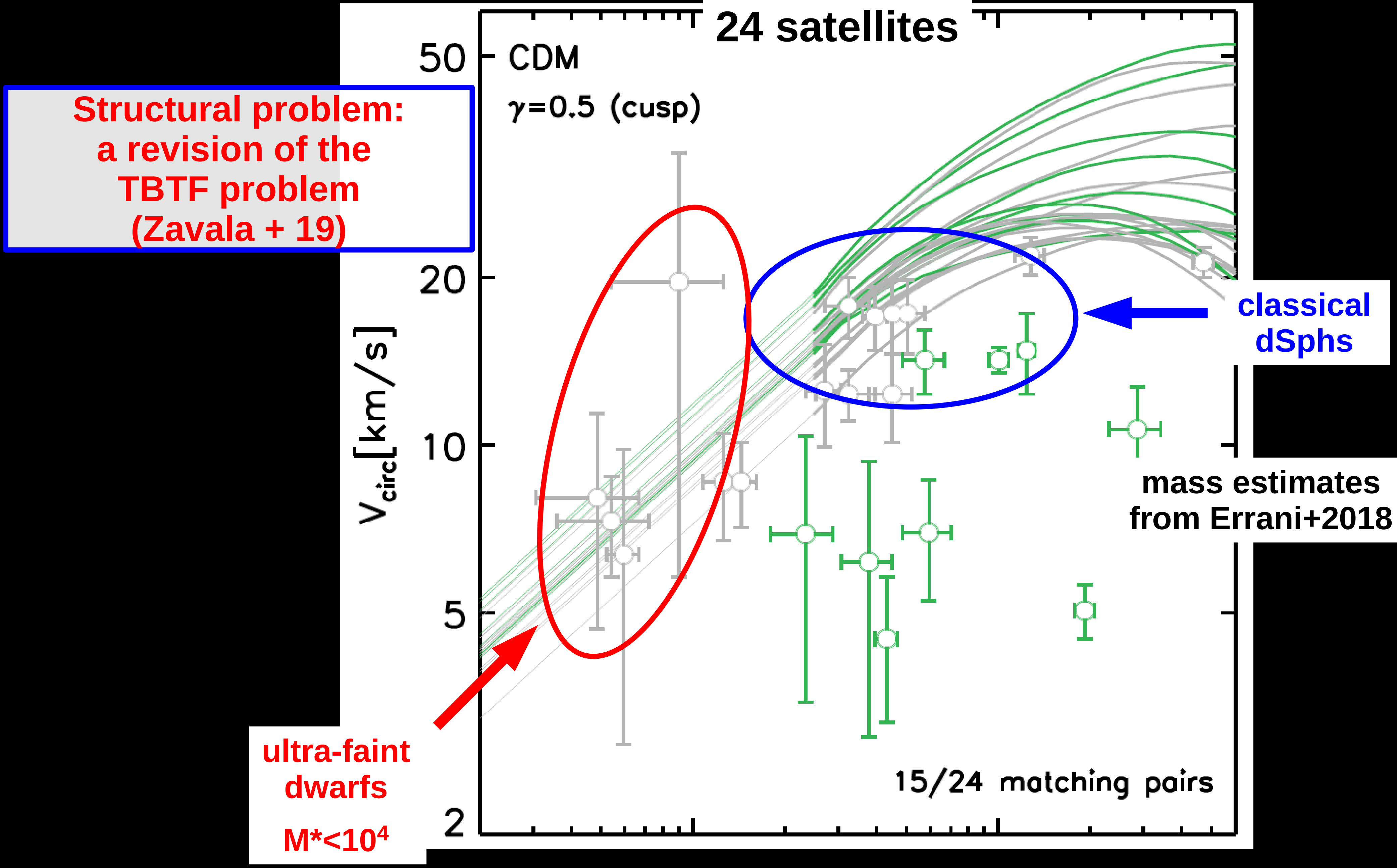
**Elvis project**
**CDM-only (no baryonic physics)**




**classical dSphs**

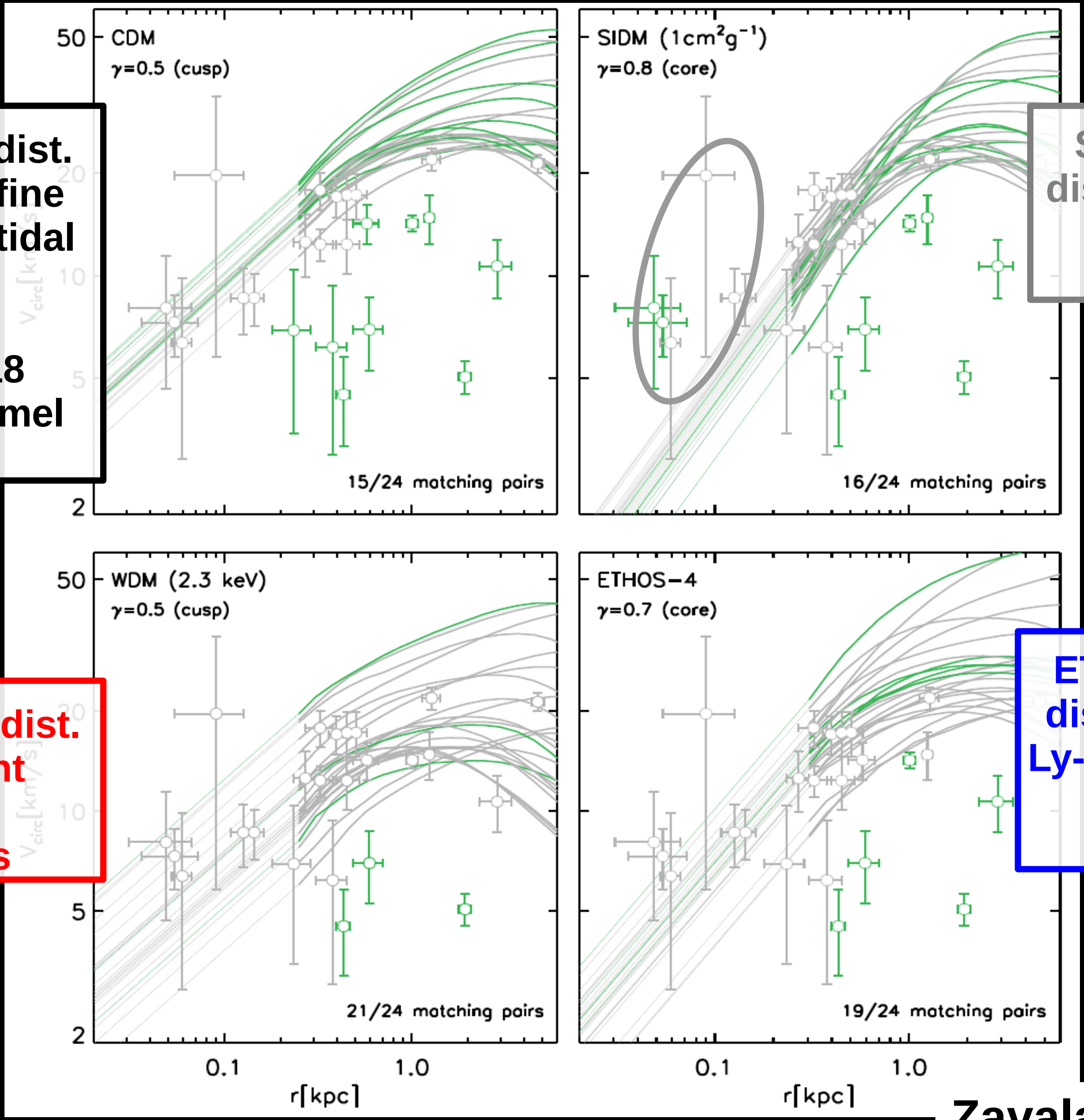
**Garrison-Kimmel+14**

# Diverse sub-kpc DM densities in MW satellites




Aquarius project
CDM-only (no baryonic physics)

# Diverse sub-kpc DM densities in MW satellites




CDM: narrow dist. but probably fine with MW disc tidal effects
e.g.
Fattahi+2018
Garrison-Kimmel 2018

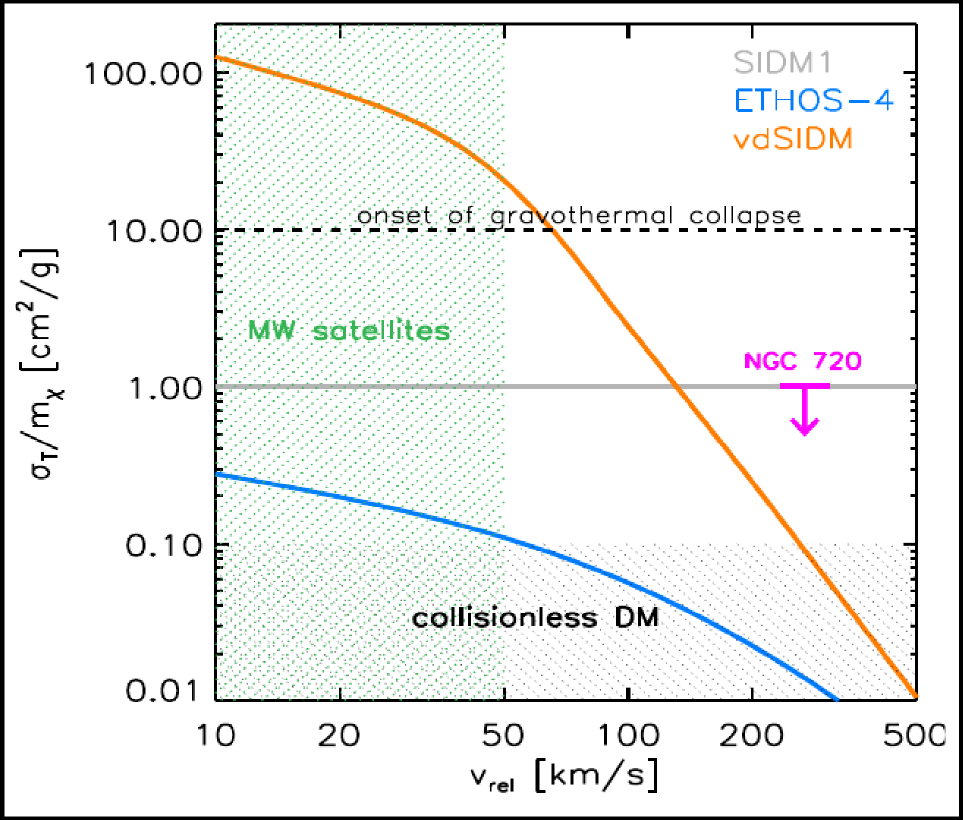
SIDM: as narrow dist. as CDM, but in tension with ultra-faints!

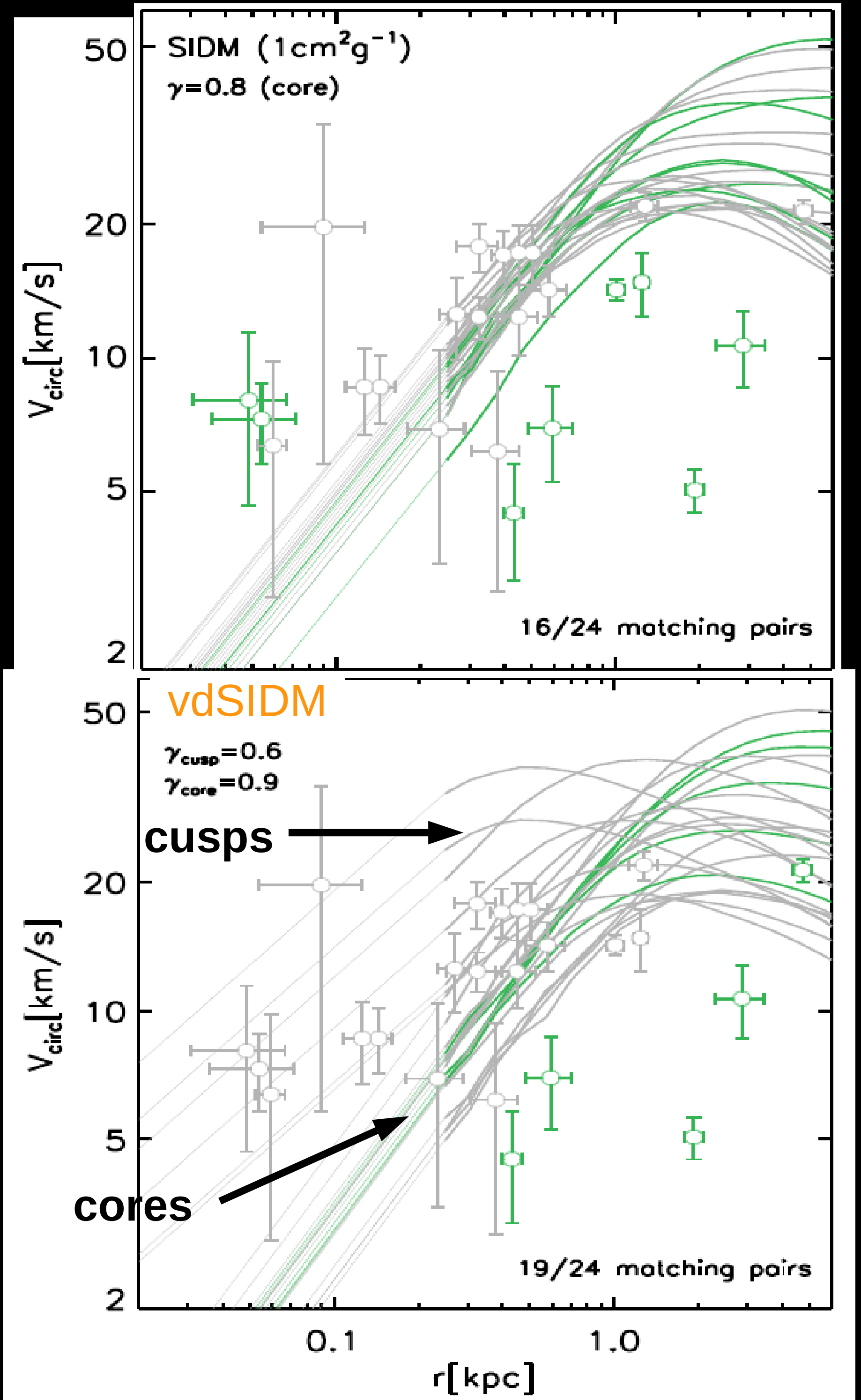
WDM: diverse dist. but stringent Ly-alpha constraints

ETHOS-4: diverse dist., likely ok with Ly-alpha constraints (needs to be confirmed)

Zavala et al. 2019

# Is this a strong constraint on SIDM?



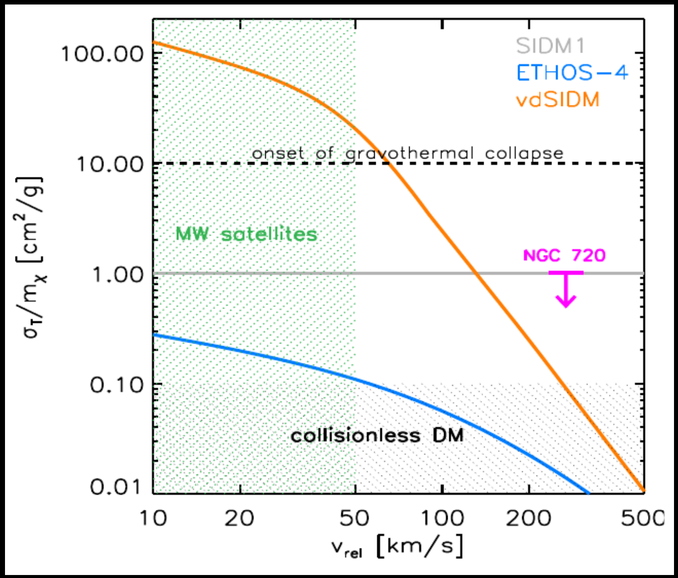




SIDM: fine if

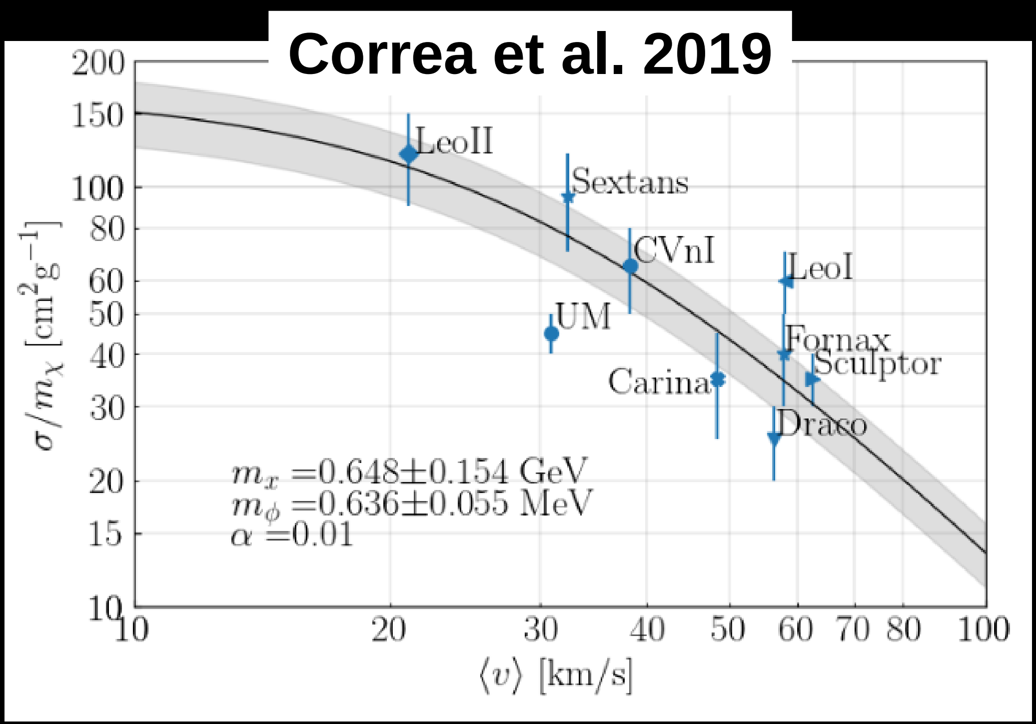
$\sigma/m < 1\,cm^2/gr$ or $\sigma/m \gtrsim 20\,cm^2/gr$

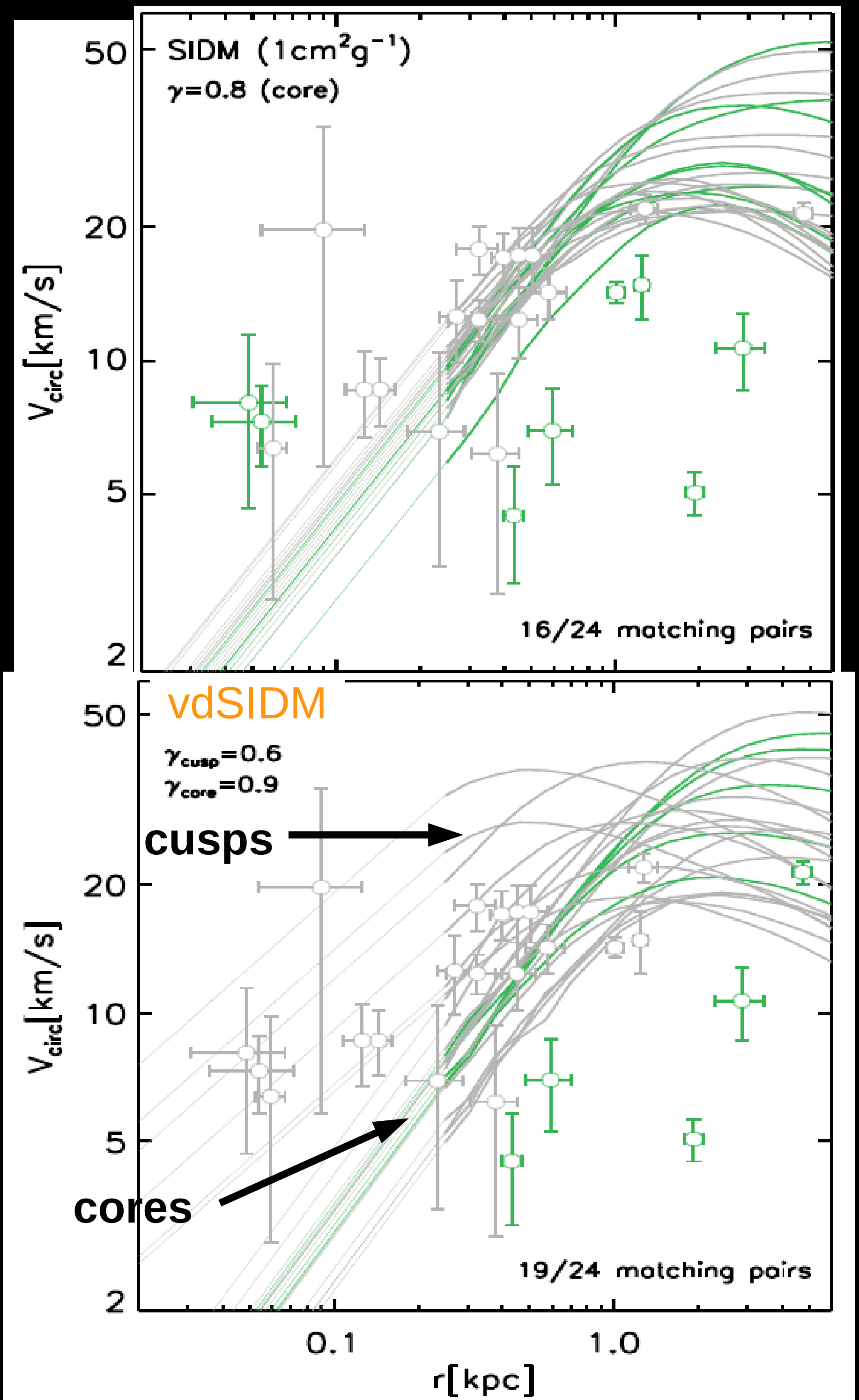
(at dwarf scales)

# Is this a strong constraint on SIDM?




Simulate orbital evolution of SIDM subhaloes constrained with GAIA proper motions



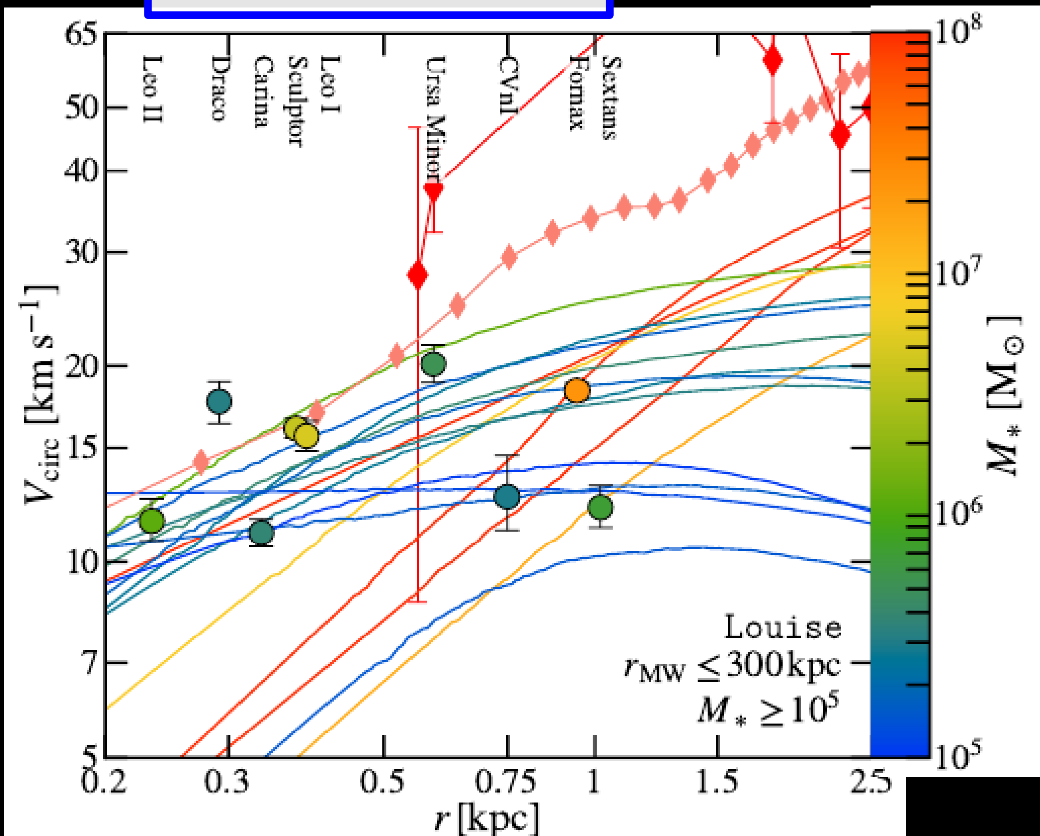



# CDM with baryonic physics vs new DM physics

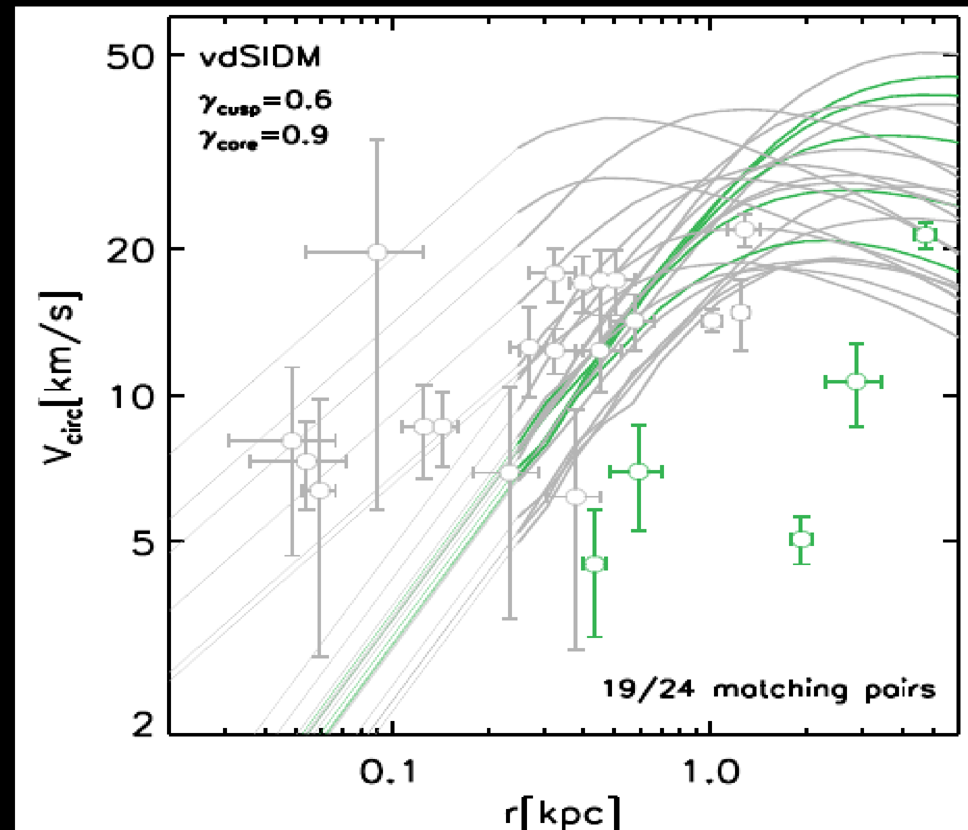
**too-big-to-fail problem**

MW disc tidal effects
+
DM heating
through supernovae

primordial power spectrum cutoff
or SIDM gravothermal collapse




**Garrison-Kimmel +2018**

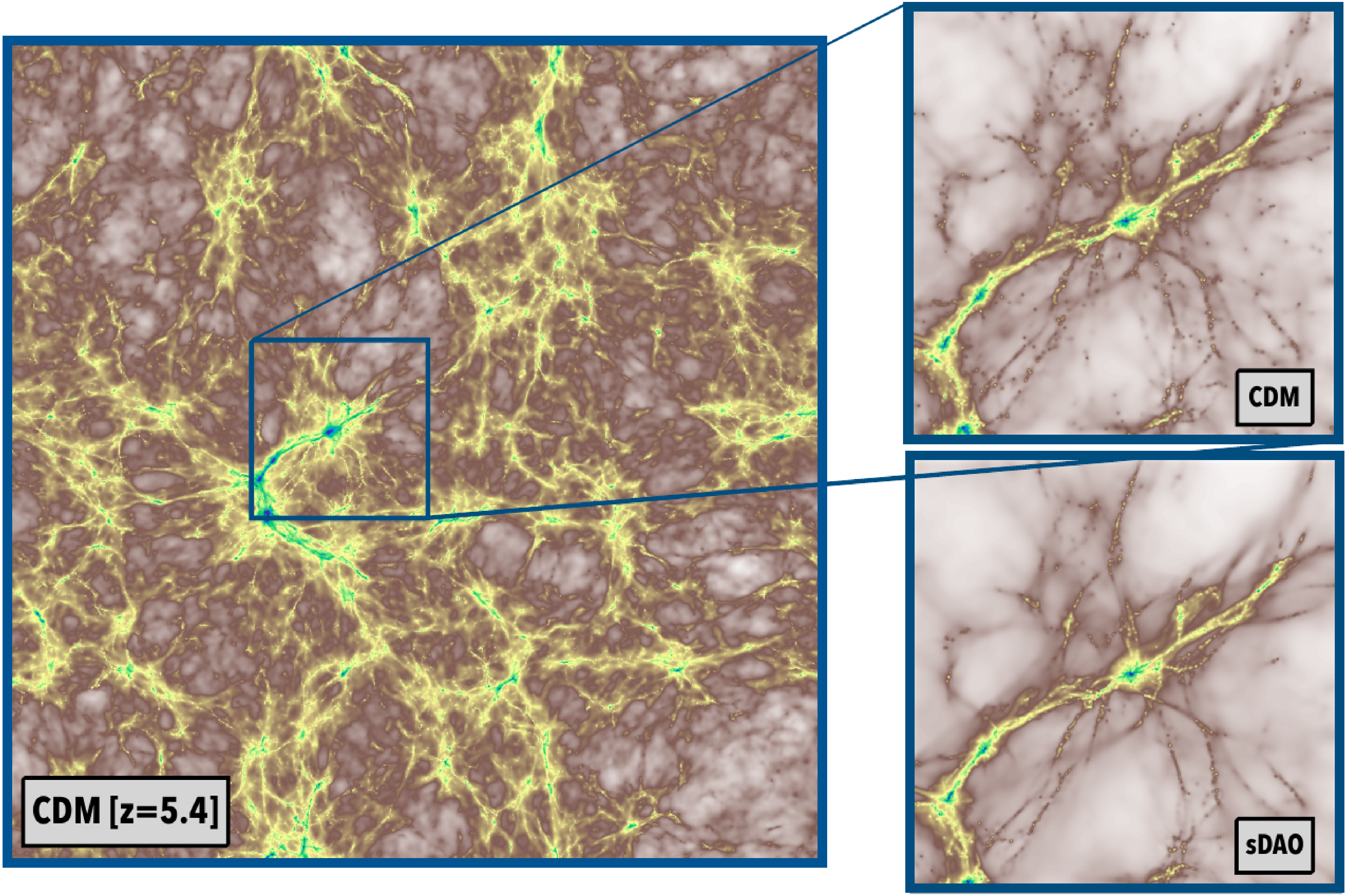



**Zavala et al. 2019**

full cosmological simulations with baryons

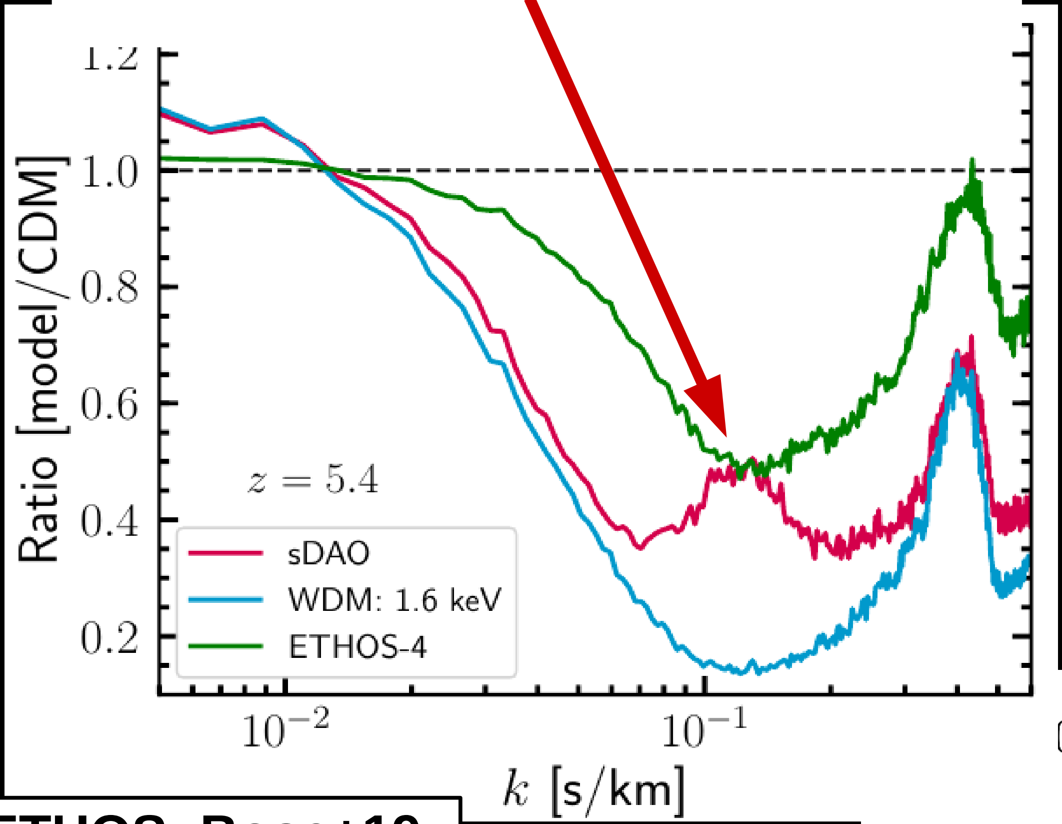
full cosmological simulations <u>without</u> baryons

# ETHOS with baryonic physics: the high-z Universe



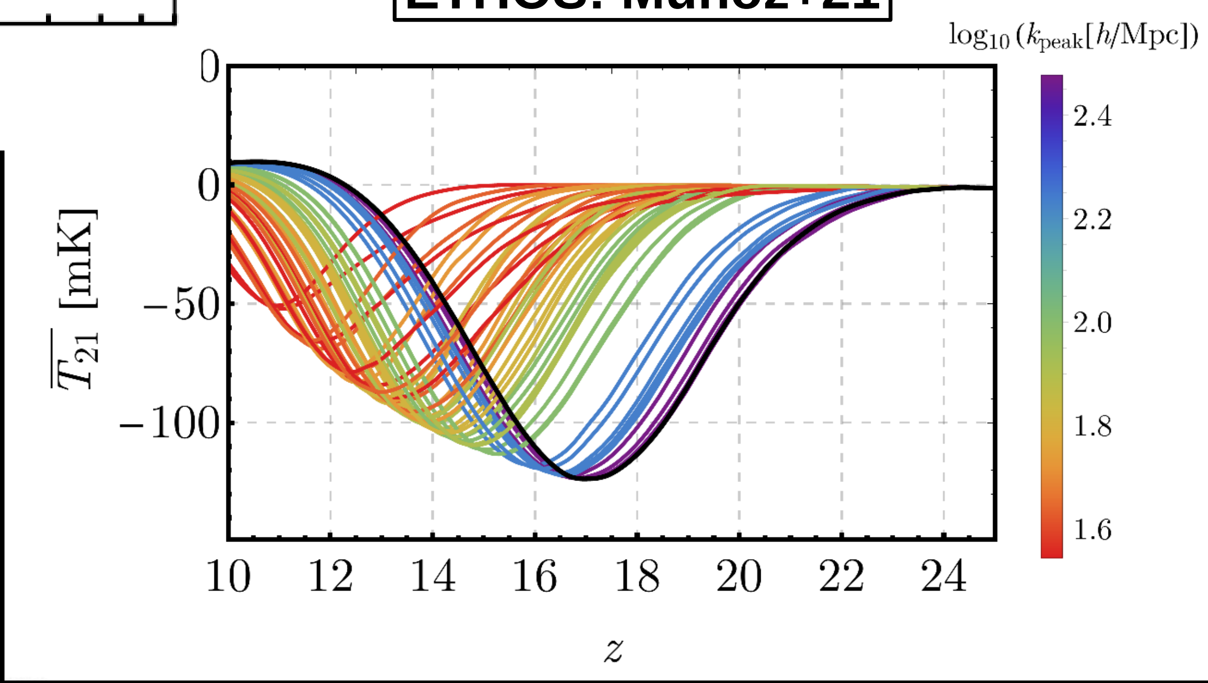
# Disentangling dark from baryonic physics: high-z

DAO signature in Ly-alpha 1D flux spectrum

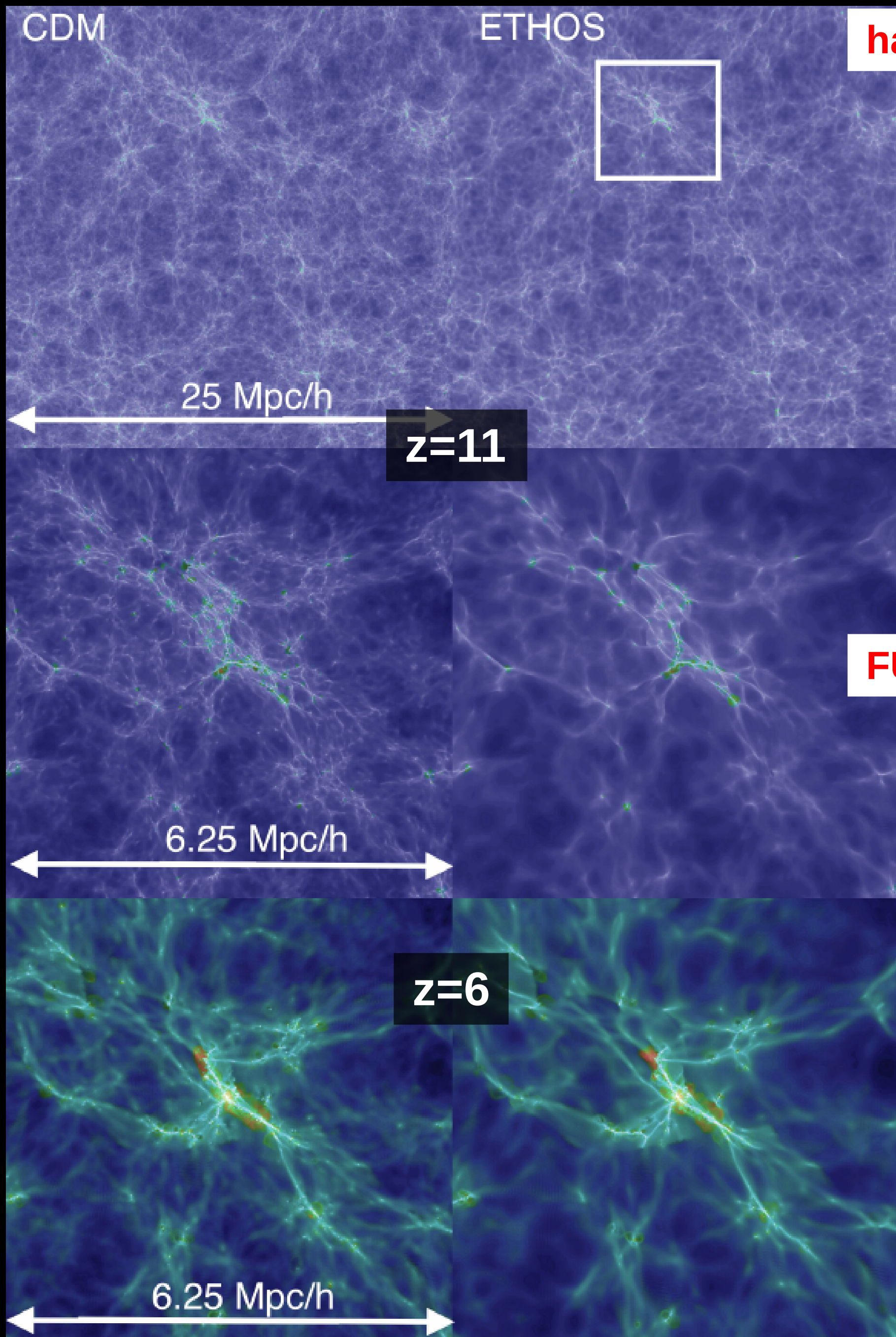


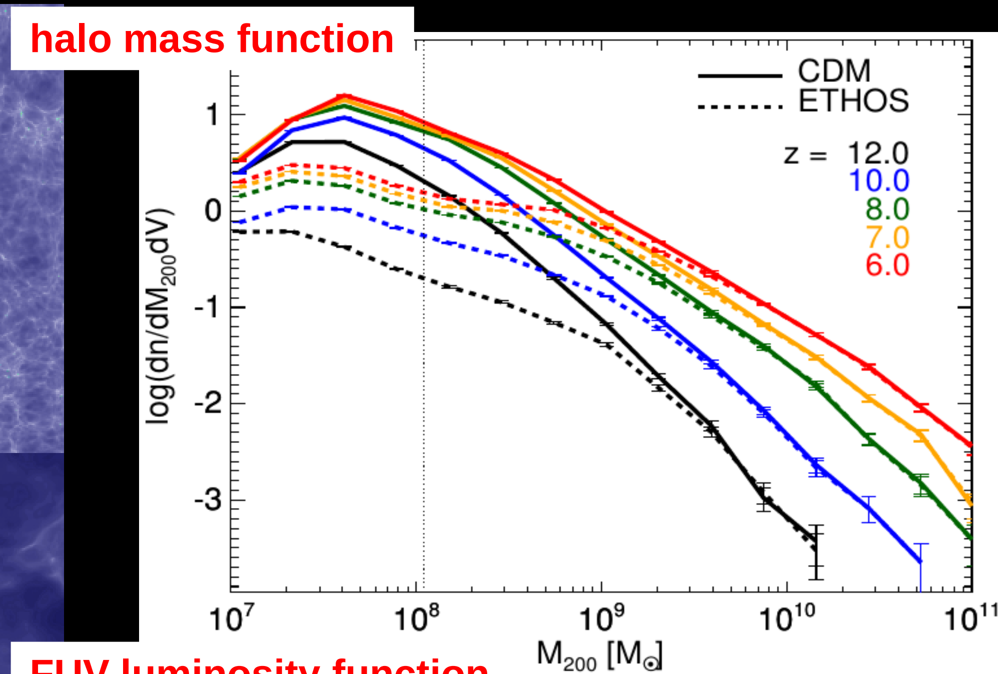

ETHOS: Bose+19

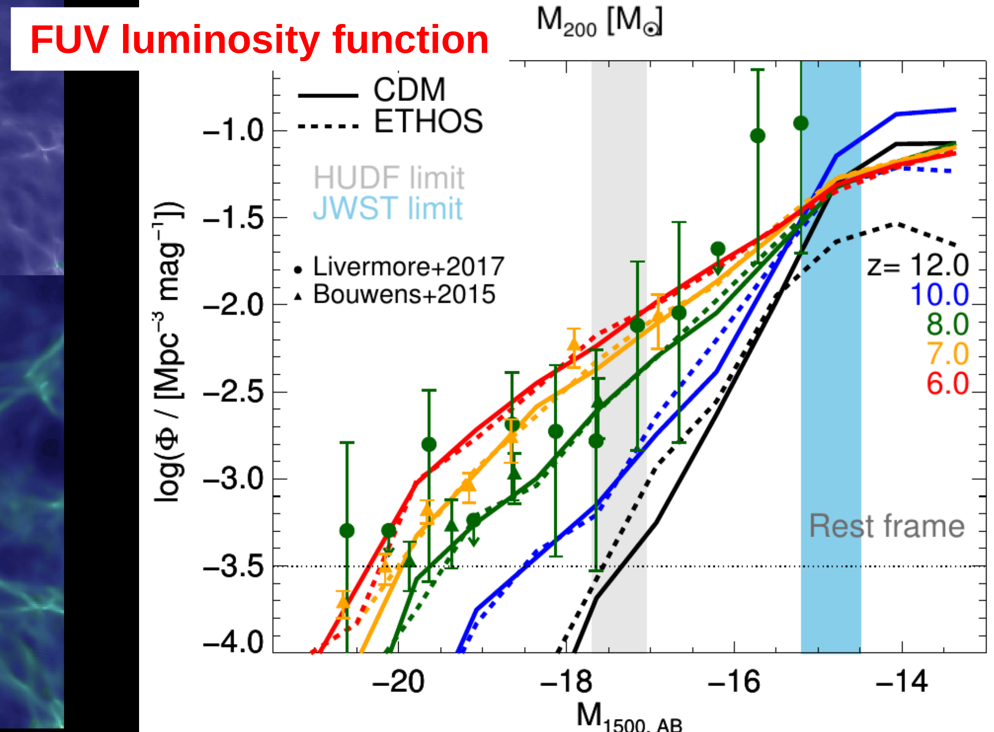
ETHOS: Muñoz+21



# ETHOS with baryonic physics: the high-z Universe




ETHOS: Lovell+2018 and Lovell+2019

# 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

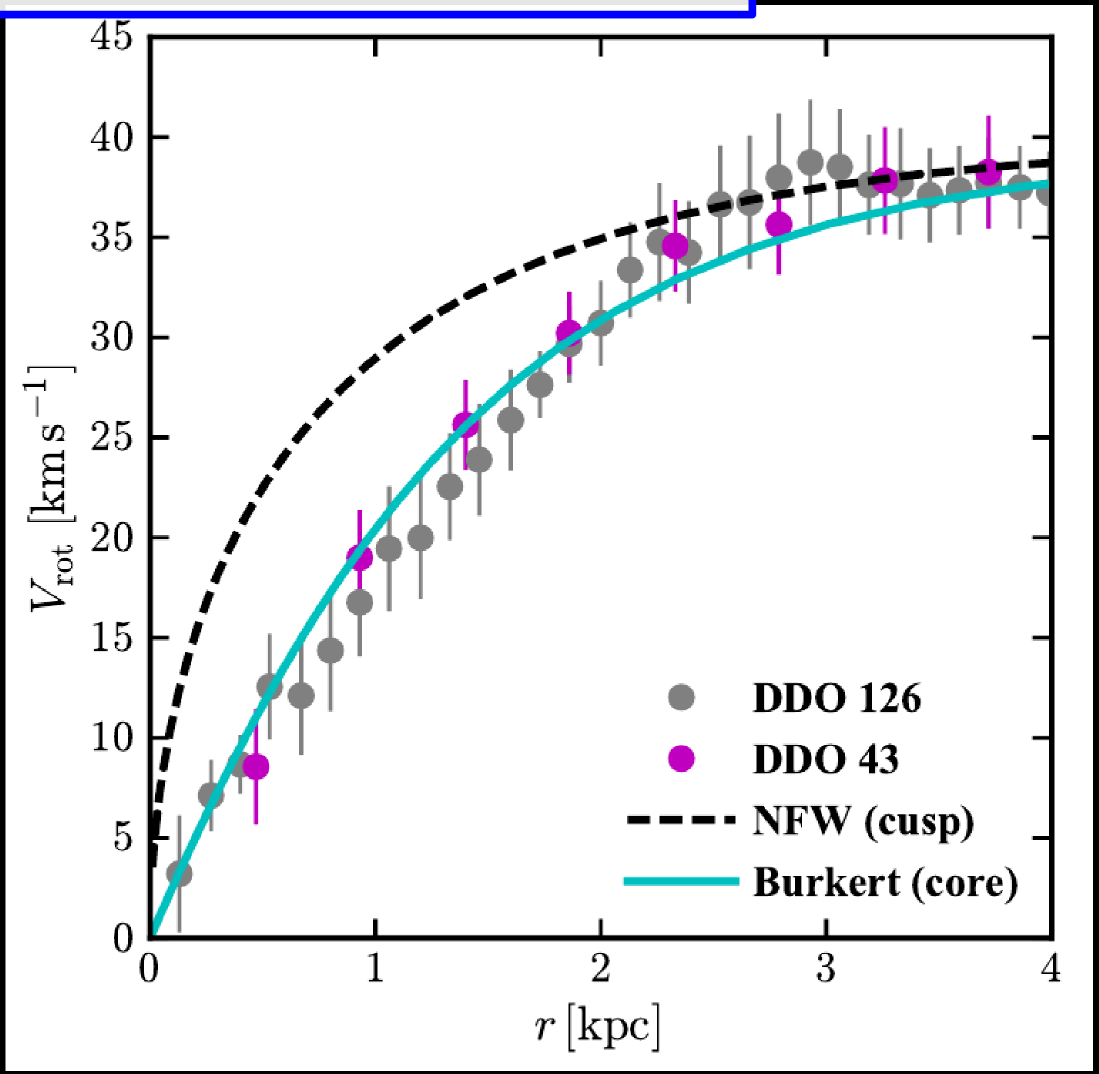
# EXTRA SLIDES

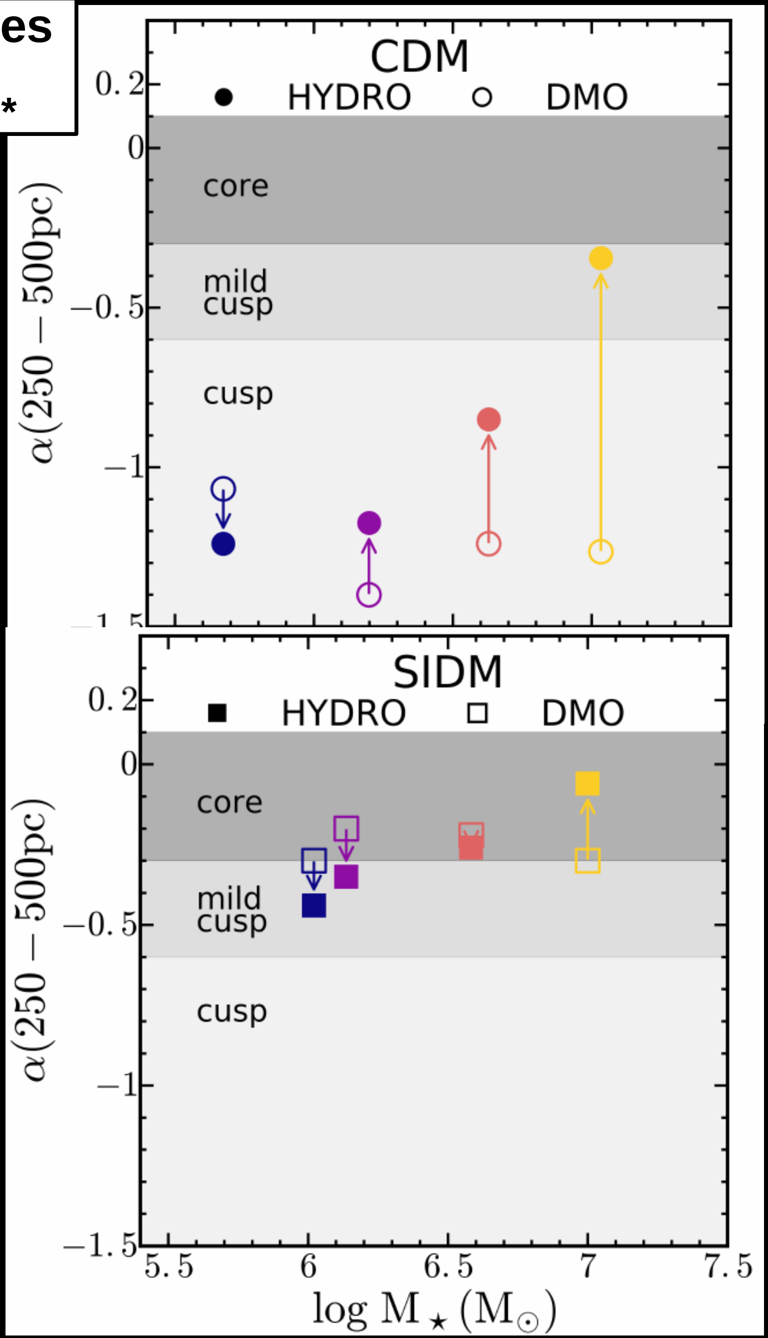
# Disentangling dark from baryonic physics

**SNe-driven DM cores inefficient at low M*∗***

**Inner DM deficit in dwarfs**

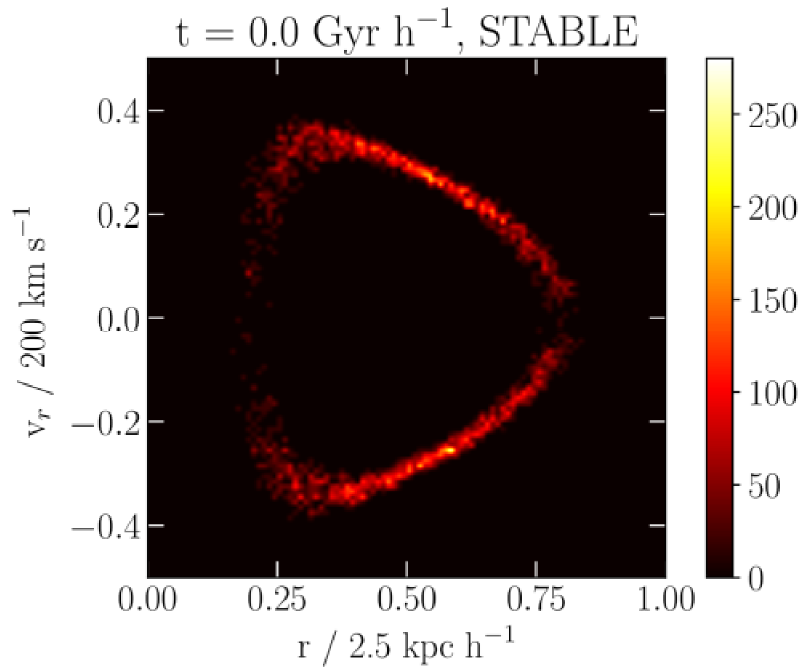
Bullock & Boylan-Kolchin 2018



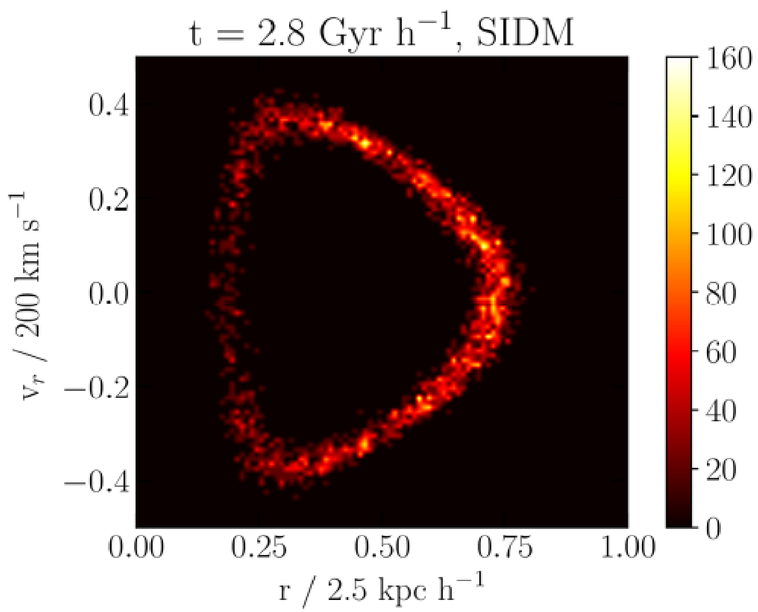
# Disentangling dark from baryonic physics

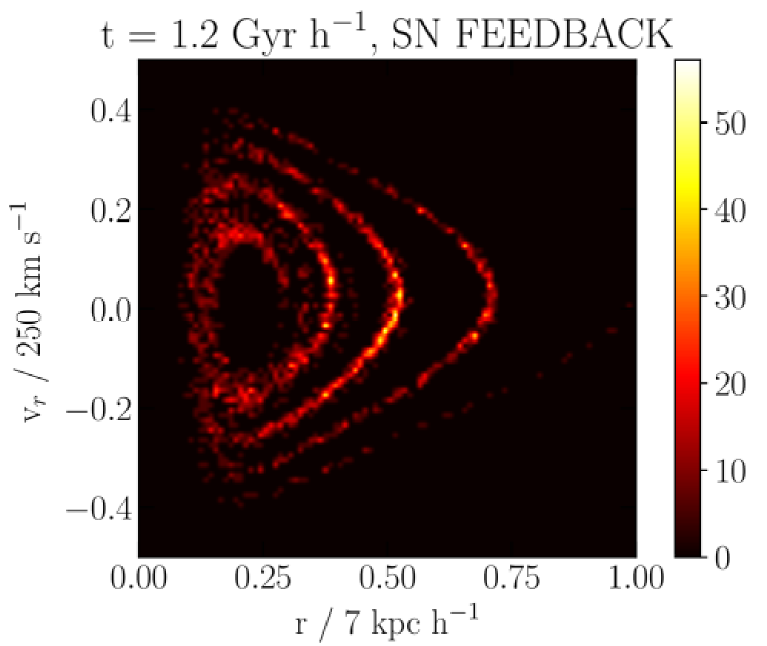
**Adiabatic (SIDM) vs impulsive (SNe) energy Injection into haloes**




**2000 star particles set in elliptical orbits with similar energy and angular momentum**

**ETHOS: Burger+19**



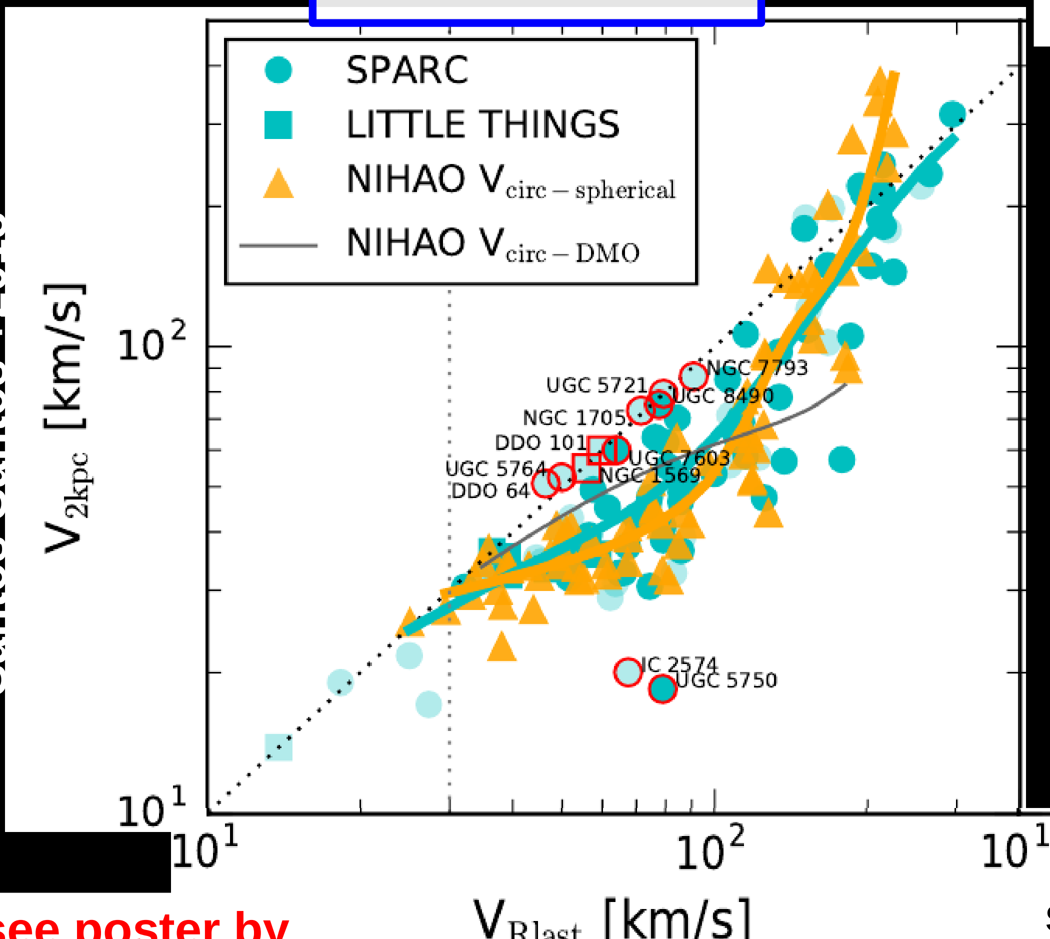
# CDM with baryonic physics vs new DM physics

**diversity of inner DM densities**

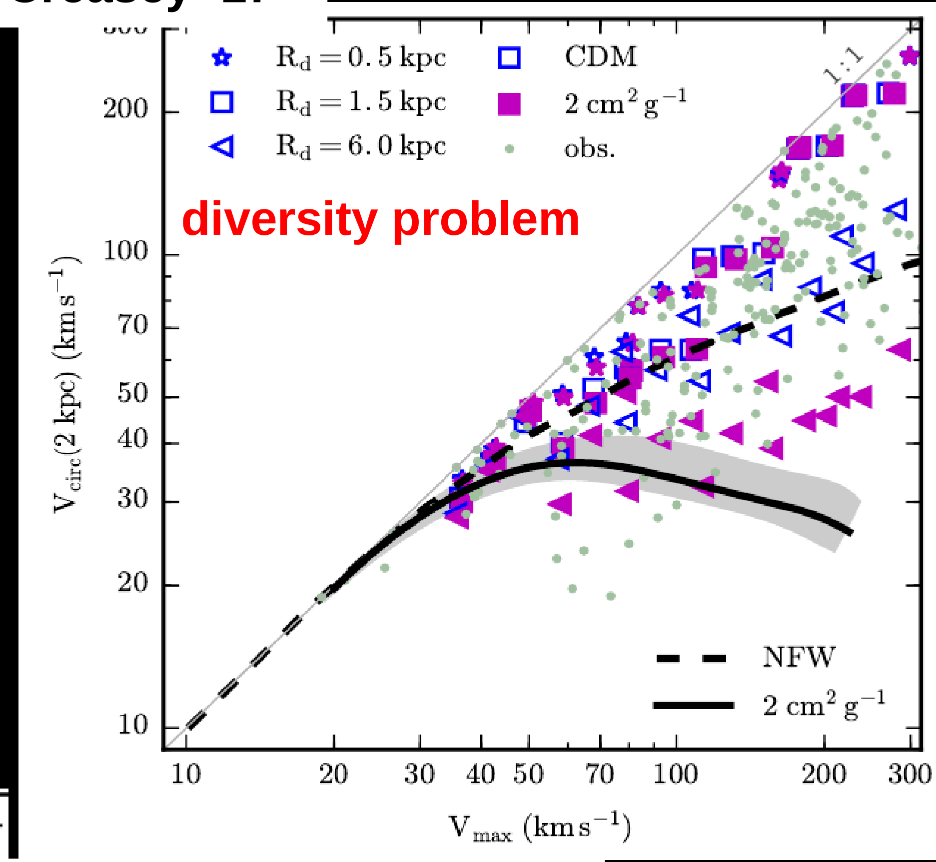
mass-dependent DM heating through supernovae

SIDM halo contraction due to baryonic disc (scale dependent)

Santos-Santos +2018




Creasey+17




**see poster by Santos-Santos**

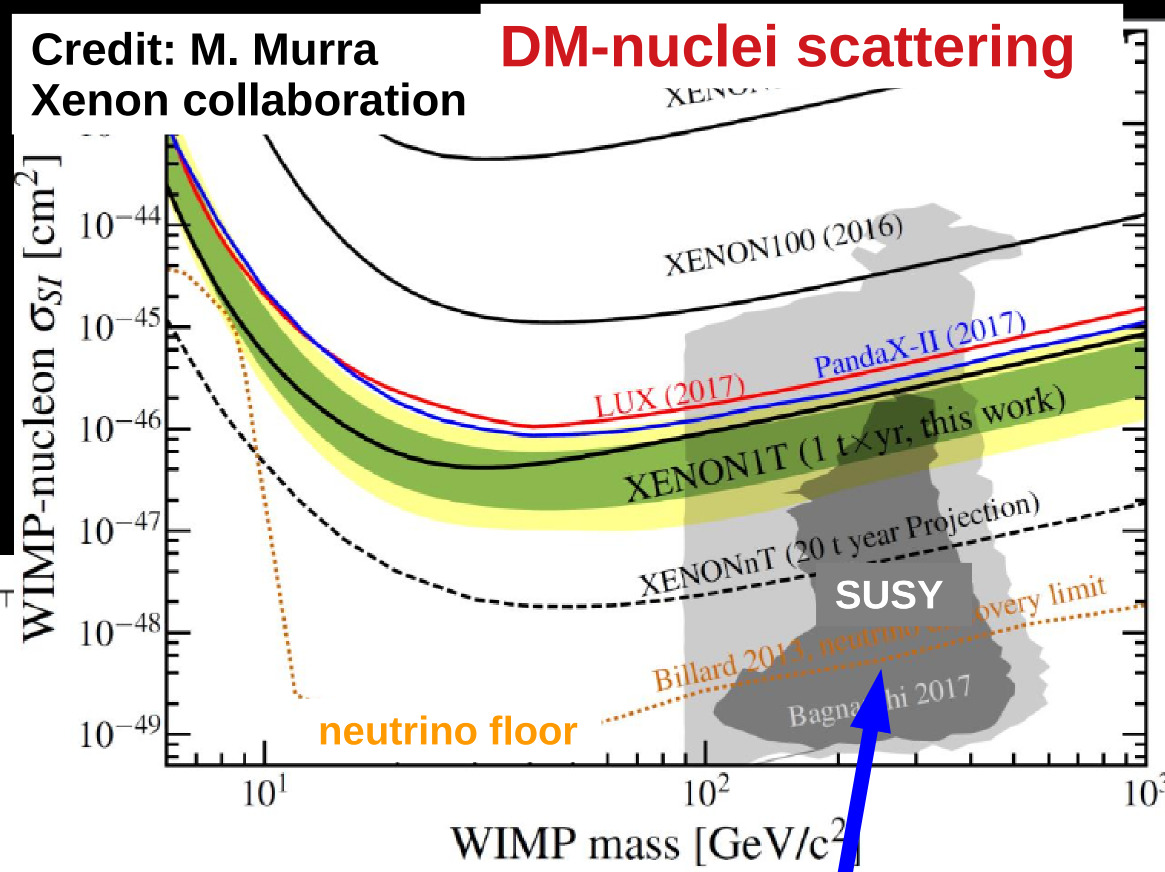
see also Kamada+2017

full cosmological simulations

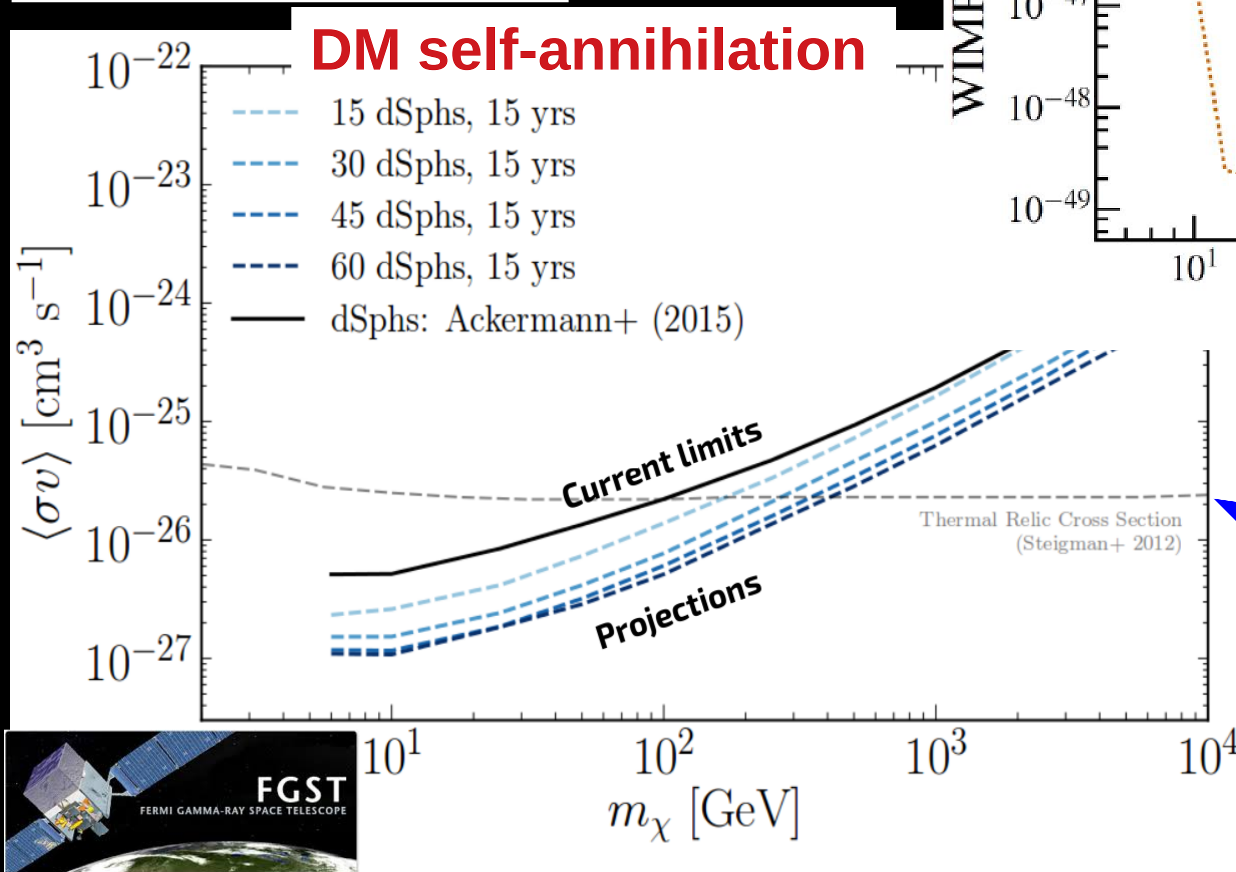
idealised modelling (not cosmological simulations)

# The argument for weak-scale DM is getting weaker

Credit: M. Murra
Xenon collaboration




Credit: C. Weniger
based on Charles+2106




“WIMP miracle” expectation

# ETHOS: the non-linear regime

The coarse-grained distribution is given by a discrete representation of N particles:

**macro-to-micro-particle mass ratio**

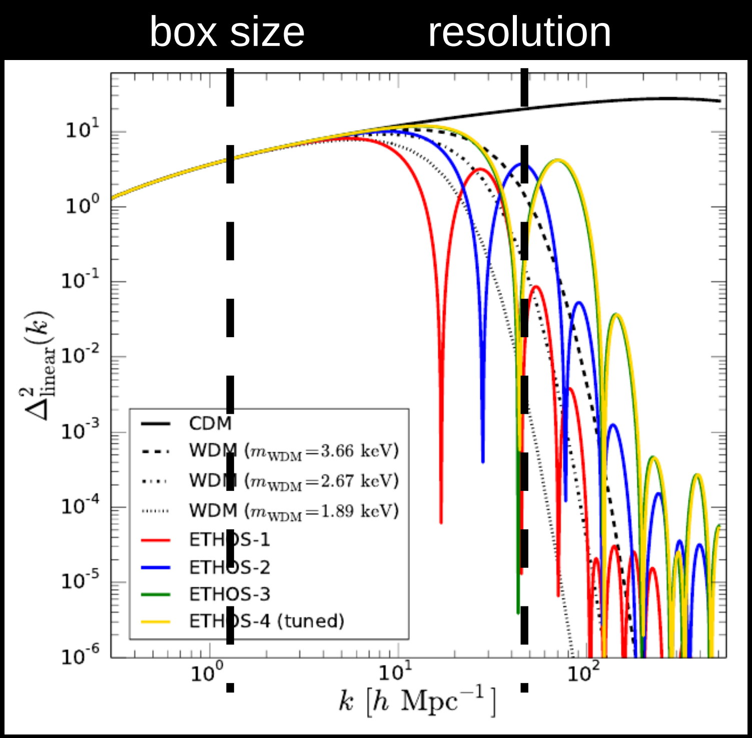
**each particle is smoothed in space to give a smooth local density**

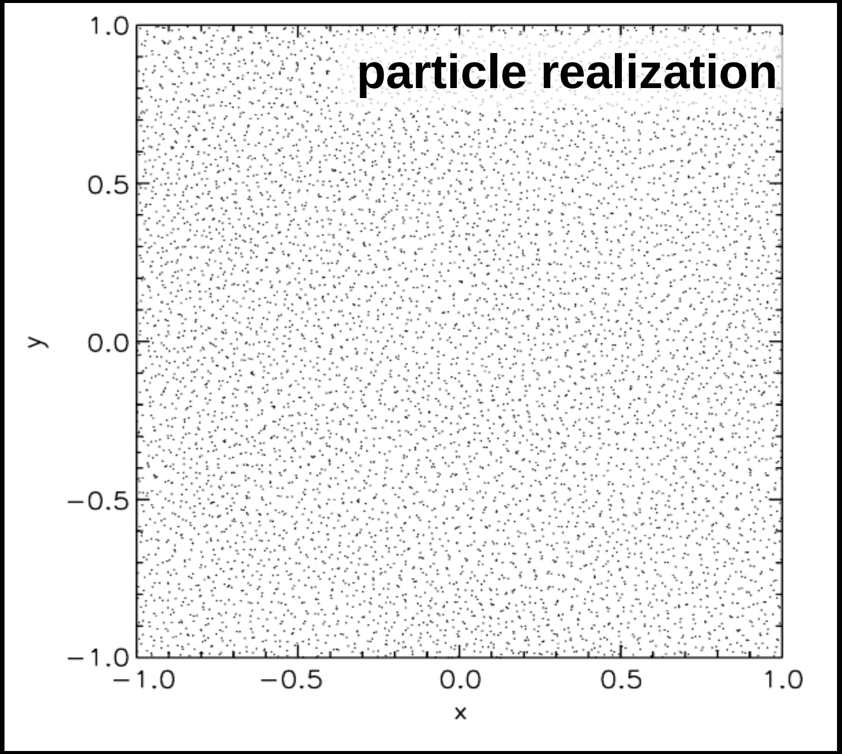
**each macro-particle travels at one speed**

$$\hat{f}(\mathbf{x},\mathbf{v},t) = \sum_i (M_i/m) W(|\mathbf{x}-\mathbf{x}_i|;h_i)\,\delta^3(\mathbf{v}-\mathbf{v}_i)$$

**Algorithm: Gravity + Probabilistic method for elastic scattering**

input power spectrum




Dolag+2008

# DM self-collisions in N-body simulations (probabilistic approach)

The coarse-grained distribution is given by a discrete representation of N particles:

$$\hat{f}(\mathbf{x}, \mathbf{v}, t) = \sum_i (M_i/m) W(|\mathbf{x} - \mathbf{x}_i|; h_i) \delta^3(\mathbf{v} - \mathbf{v}_i)$$

**Algorithm: Gravity + Probabilistic method for elastic scattering**

Consider a neighbourhood around each particle:

in pairs:

$$P_{ij} = \frac{m_i}{m_\chi} W(r_{ij}, h_i) \, \sigma_T(v_{ij}) v_{ij} \, \Delta t_i$$

total for a particle:

$$P_i = \sum_j P_{ij}/2$$

**discrete version of the collisional operator**

A collision happens if: $x \leqslant P_i$ , where x is a random number between 0 and 1

sort neighbours by distance and pick the one with: $x \leqslant \sum_i^l P_{ij}$

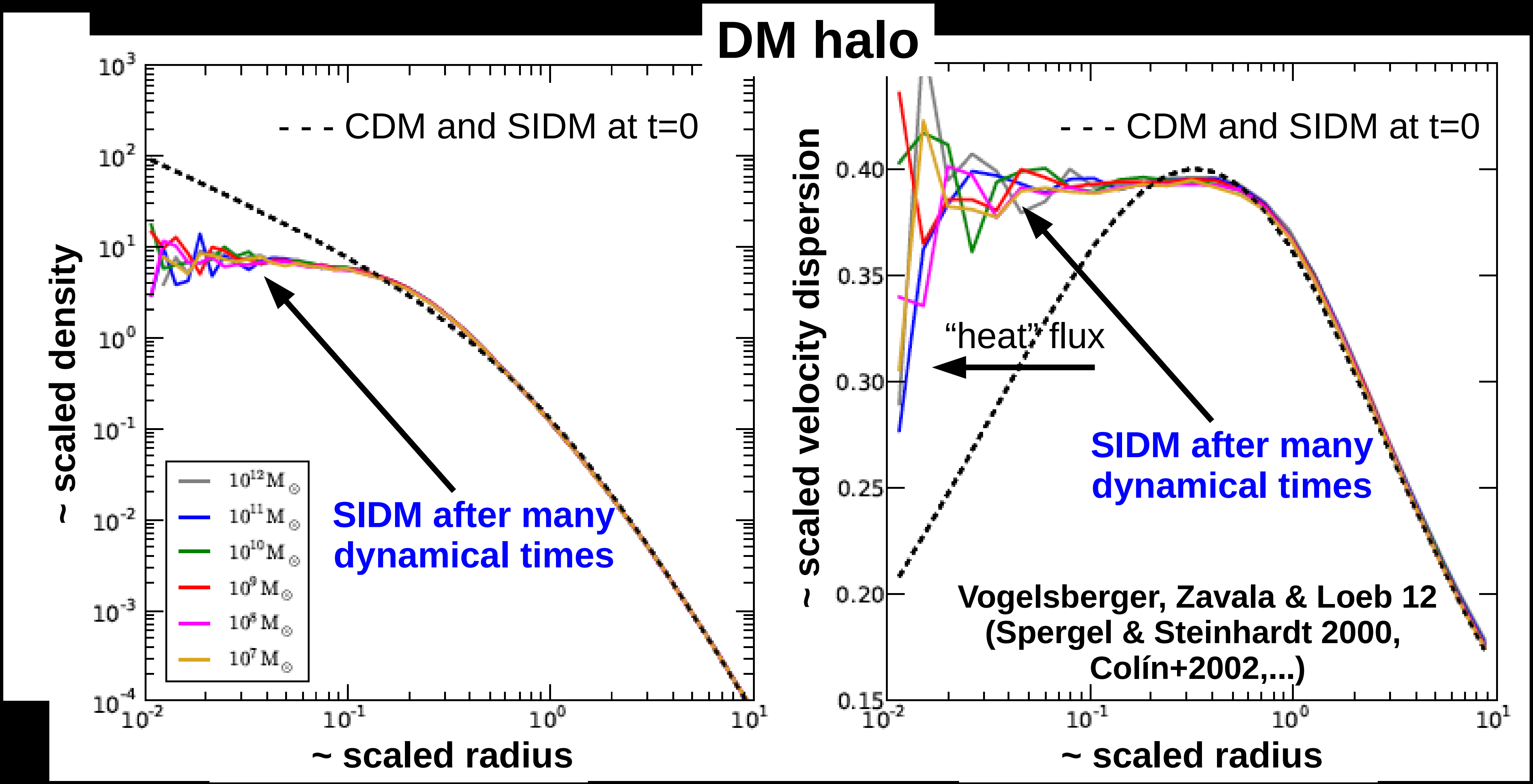
***Elastic collision***:

$$\vec{v}_i = \vec{v}_{cm} + (\vec{v}_{ij}/2)\,\hat{e}$$
$$\vec{v}_j = \vec{v}_{cm} - (\vec{v}_{ij}/2)\,\hat{e}$$

***randomly scattered***

Kochanek & White 2000, Yoshida+2000,...Vogelsberger, Zavala, Loeb 2012, Rocha+2013

# ETHOS: isothermal core formation with SIDM



# ETHOS: classify DM models according to their effective parameters for structure formation

**particle physics parameters (masses, couplings, ...)**

$$\left\{ m_\chi, \{g_i\}, \{h_i\}, \xi \right\}$$

**select a particle physics model**
**e.g. DM interacting with masless neutrino-like fermion via massive mediator**
**(e.g. van der Aarssen, Bringmann+12)**

**growth of structures (linear regime) with additional physics: DM-DR-induced DAOs and Silk damping**

$$\dot{\kappa}_\chi = -\frac{4}{3}(\Omega_{\rm DR}h^2)x_\chi(z)\sum_n a_n \frac{(1+z)^{n+1}}{(1+z_{\rm D})^n}$$

$$a_n \longrightarrow |\mathcal{M}|^2_{\chi\tilde{\gamma}\rightarrow\chi\tilde{\gamma}} \propto \left(\frac{p_{\rm DR}}{m_\chi}\right)^{n-2}$$

**opacity coefficients**

**effective parameters**

$$\Xi_{\rm ETHOS} = \left\{ \omega_{\rm DR}, \{a_n, \alpha_l\}, \left\{\frac{\langle\sigma_T\rangle_{v_{M_i}}}{m_\chi}\right\} \right\}$$

$$\omega_{\rm DR} \equiv \Omega_{\rm DR}h^2$$

**DM self-scattering (relevant for late-time evolution)**