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

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Opening remarks

Structure formation theory has become powerful enough to simulate a seemingly realistic Universe down to galactic scales.

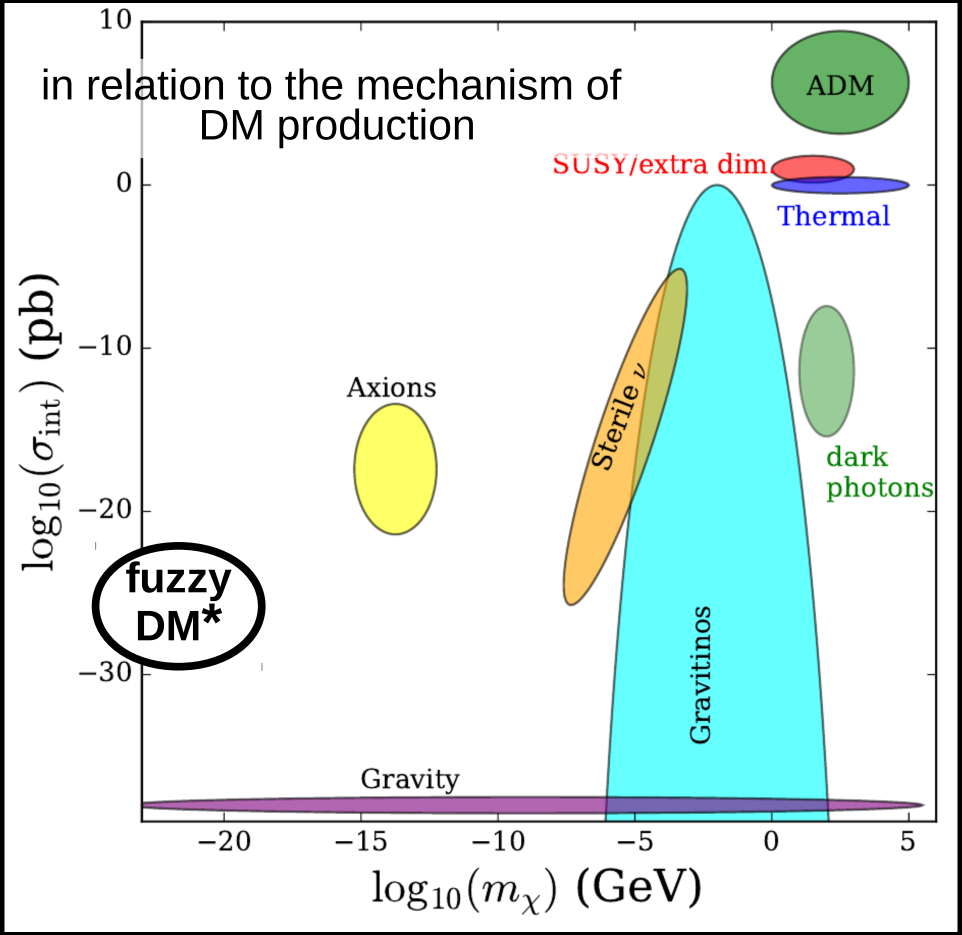
- The Cold Dark Matter (CDM) hypothesis has been the standard for nearly three decades and implies that DM gravity is the only relevant interaction (for galactic scales and above). It implies that structure formation within CDM has no free DM parameters. However:

CDM/WDM/SIDM are incomplete DM theories

They are "effective" structure formation theories that need completion from a particle physics model (all beyond SM: "exotic")

The (incomplete) particle DM landscape

Particle physics parameter space



in relation to the mechanism of DM production

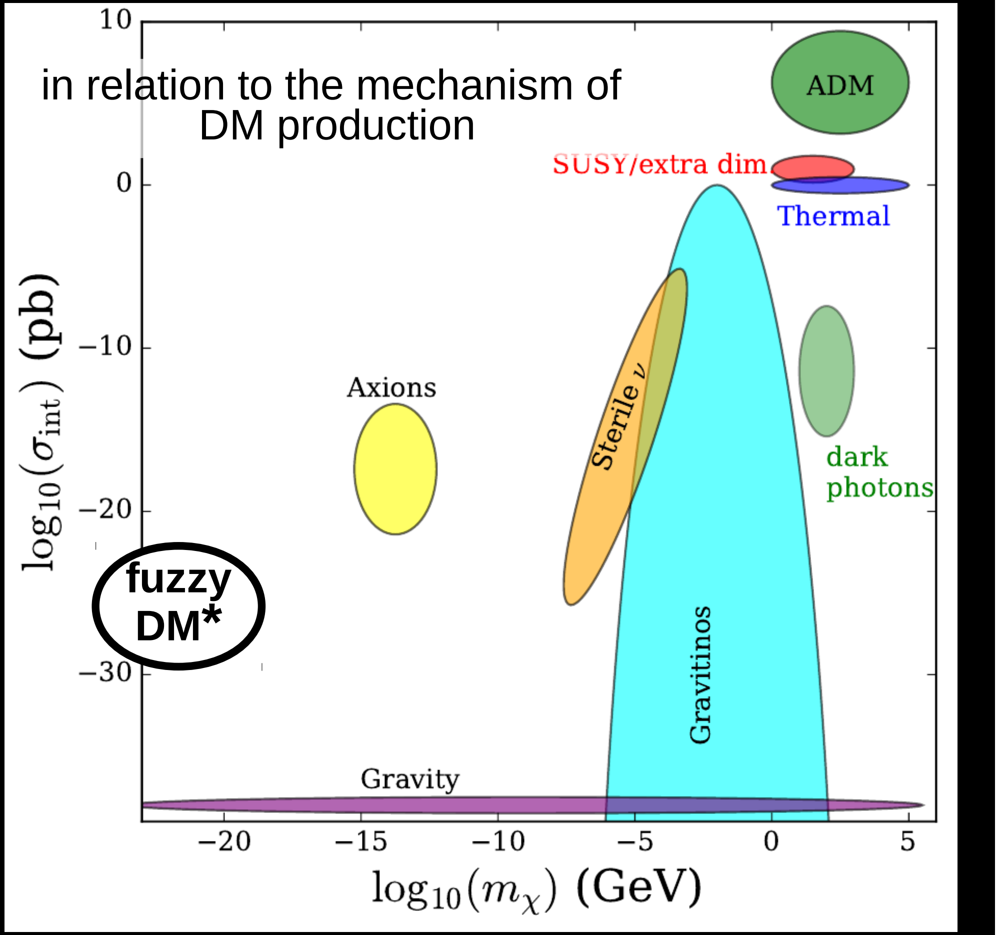
fuzzy DM*

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

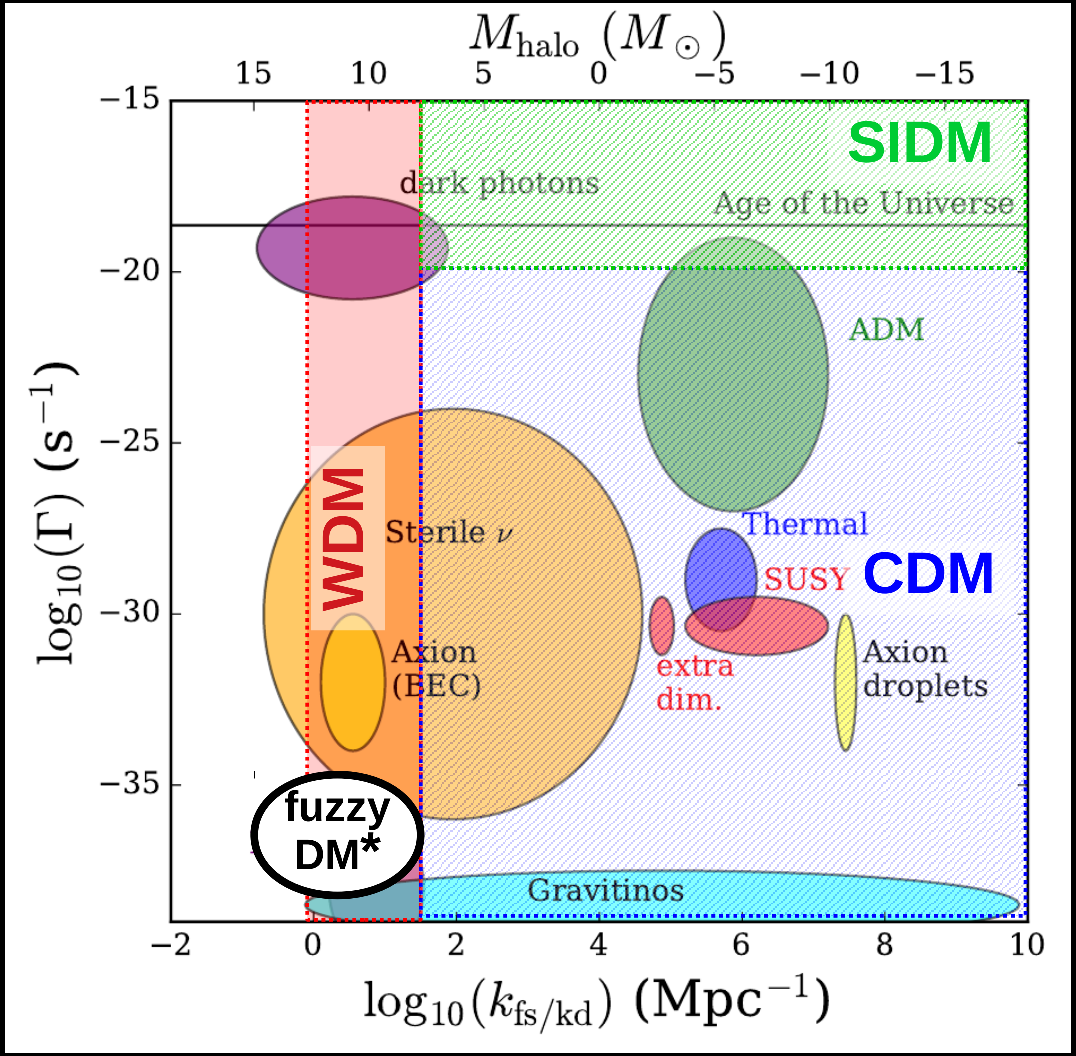
Adapted from: Buckley & Peter 2018

The (incomplete) particle DM landscape

Particle physics parameter space



Astrophysics parameter space



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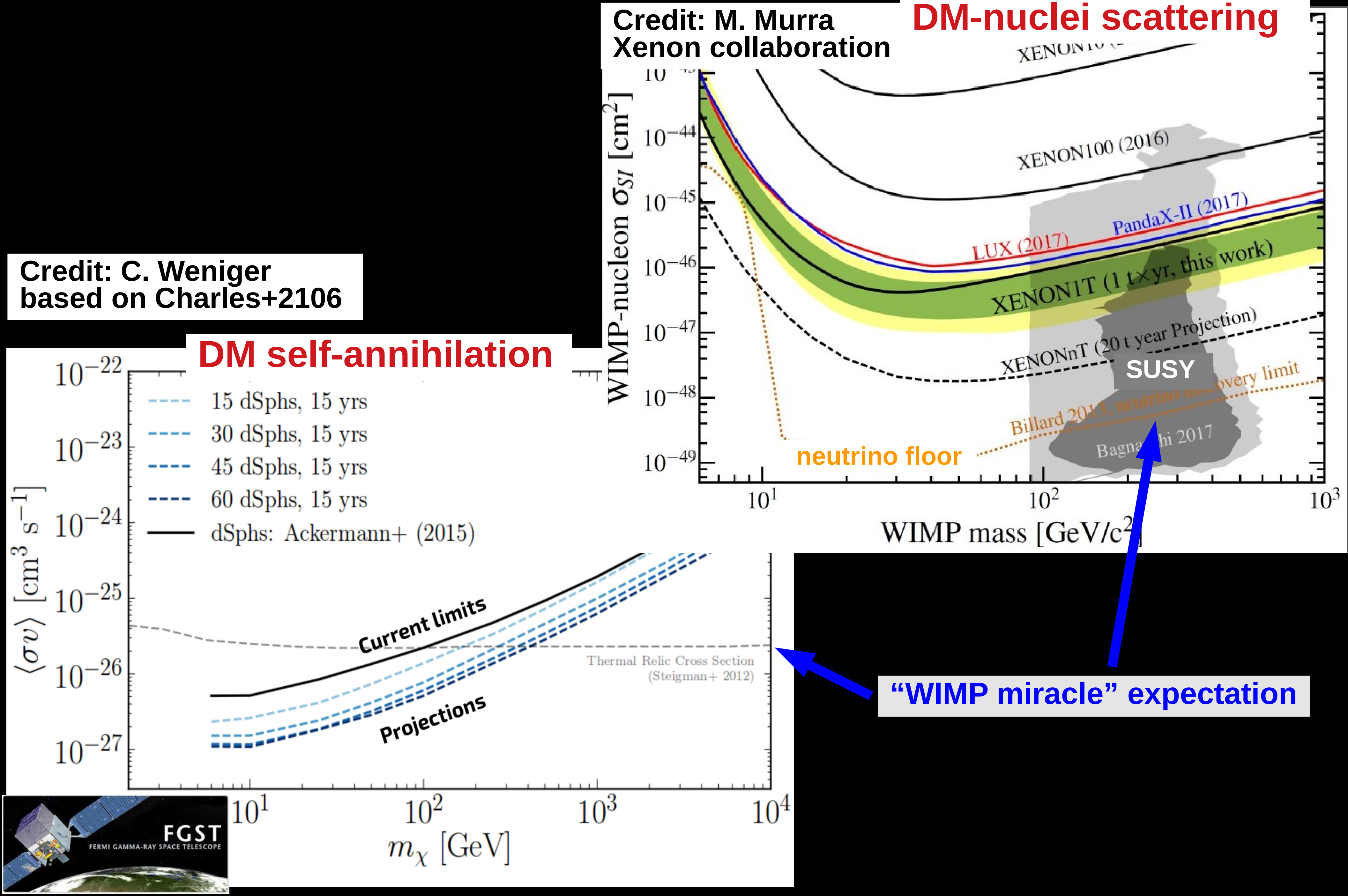
I will leave aside "fuzzy" DM

Adapted from: Buckley & Peter 2018

The argument for weak-scale DM is getting weaker



Credit: M. Murra
Xenon collaboration

DM-nuclei scattering

Credit: C. Weniger
based on Charles+2106

DM self-annihilation

"WIMP miracle" expectation

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?

this talk

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

In the physics of galaxies, is gravity the only dark matter interaction that matters?

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

two major unresolved questions in structure/galaxy formation theory

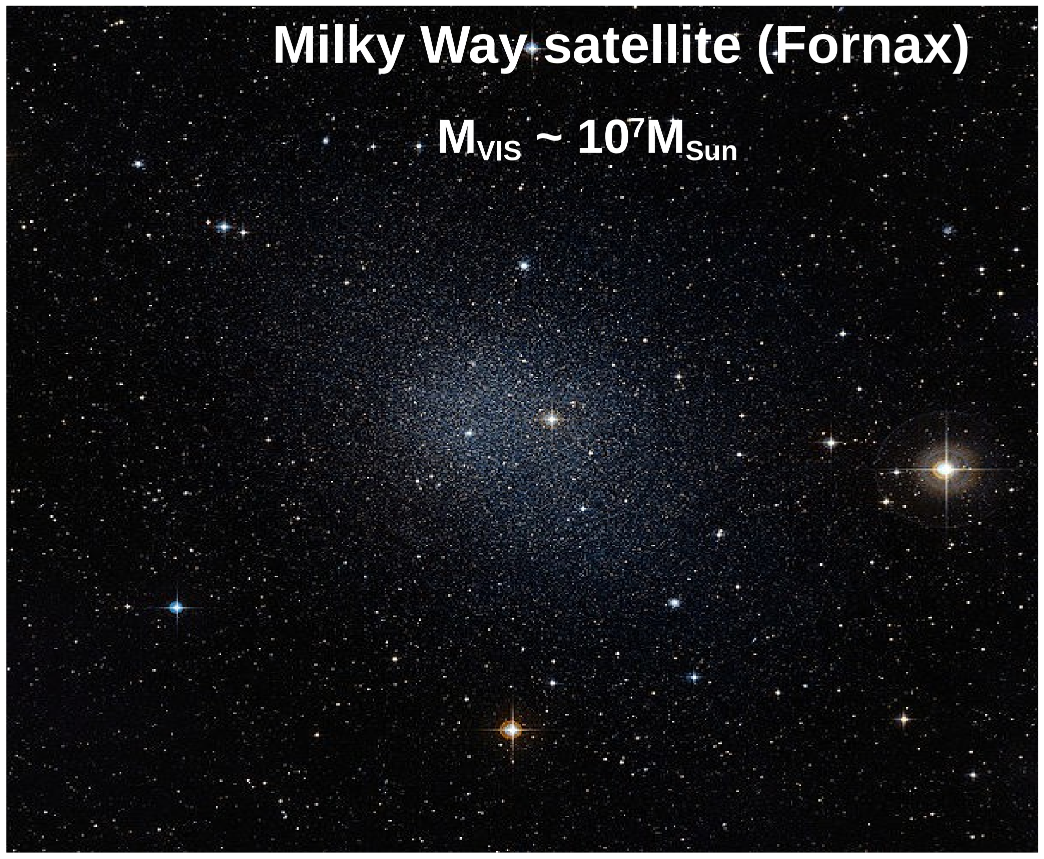
What physical mechanisms set the minimum mass scale for galaxy formation?

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

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

Clues from the properties of dwarf galaxies

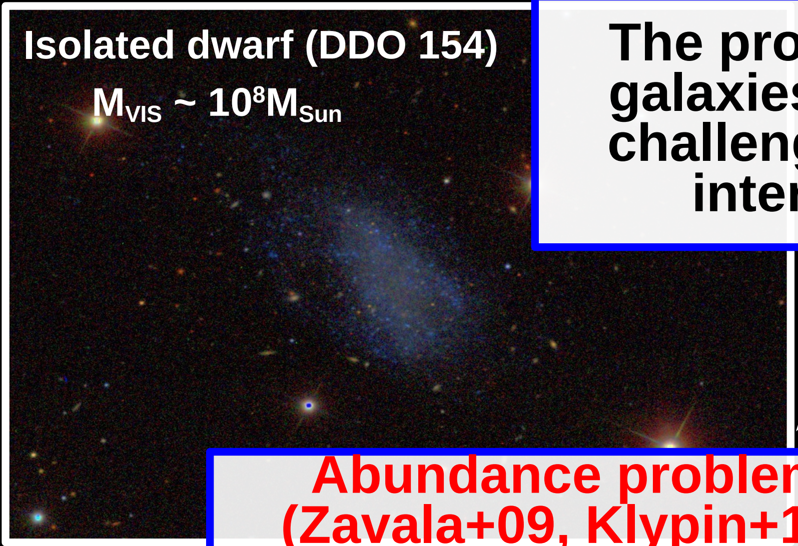
Dwarf galaxies:
most DM-dominated systems: $M_{DM} > 10\ M_{VIS}$
(ordinary matter is less dynamically relevant)



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

“Optimal” dynamical detectors of new DM physics

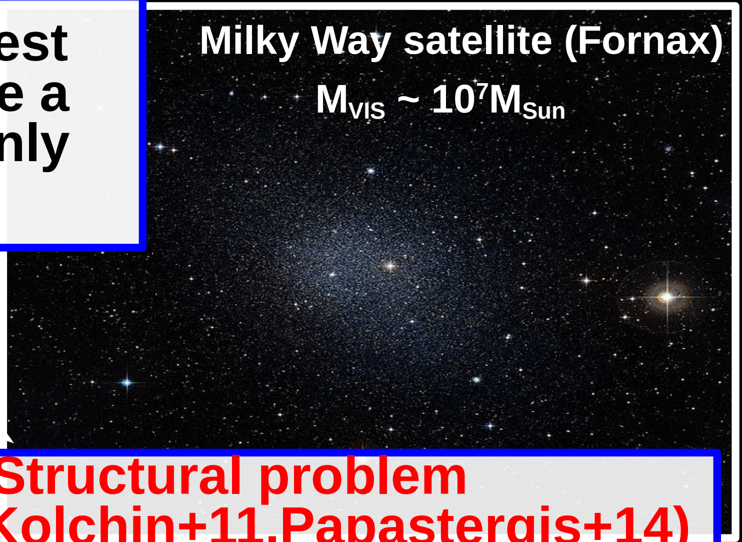
Clues from the properties of dwarf galaxies



Isolated dwarf (DDO 154)

$M_{VIS} \sim 10^8 M_{Sun}$

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

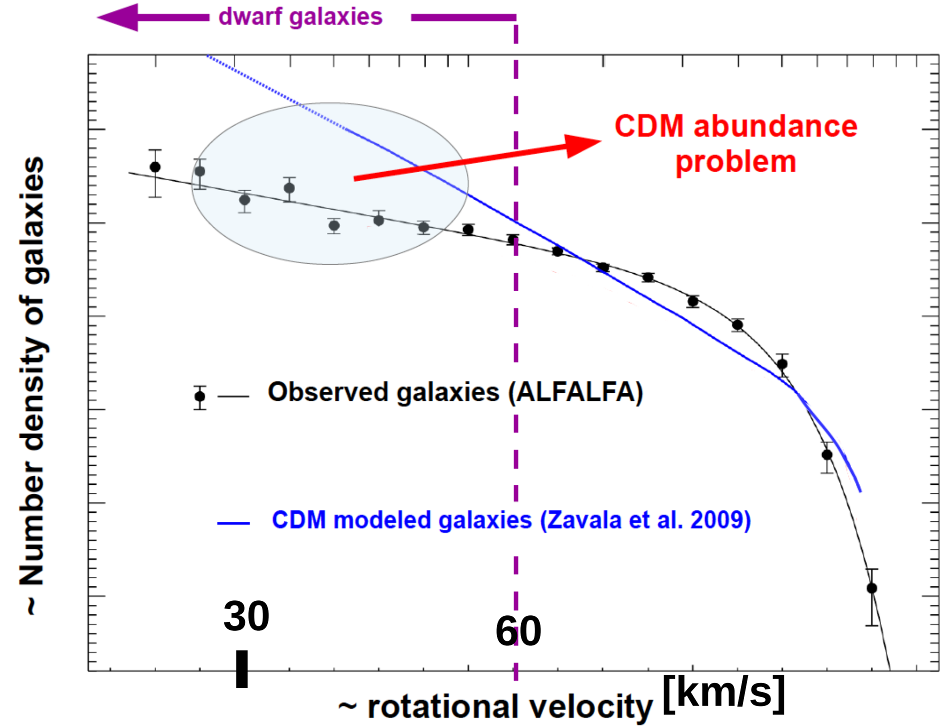


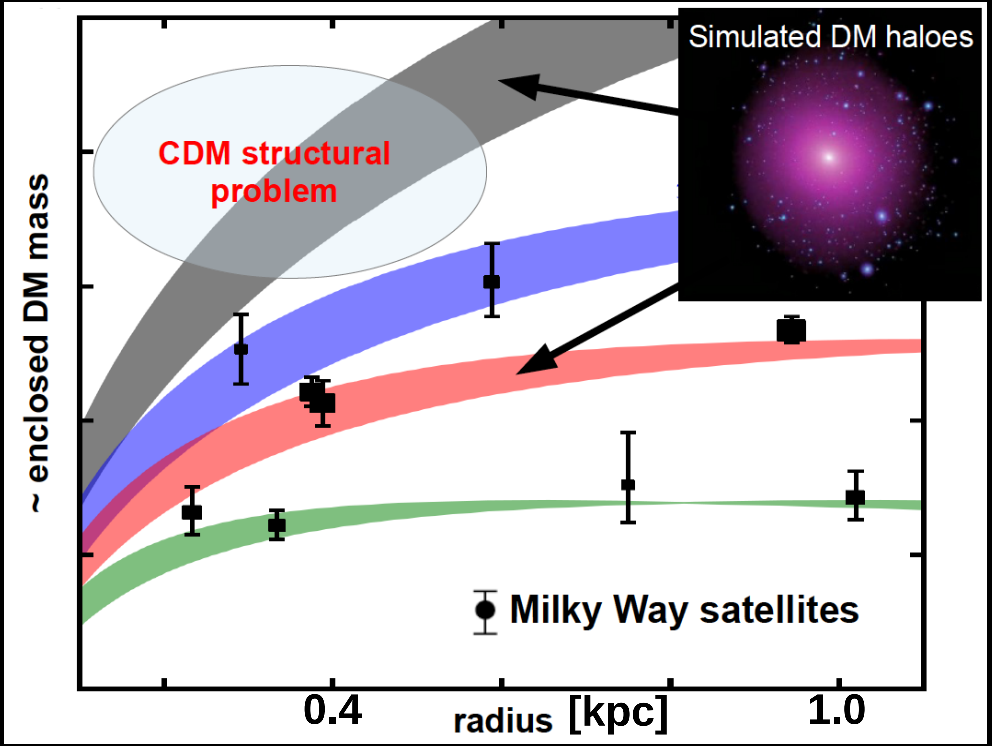
Milky Way satellite (Fornax)

$M_{VIS} \sim 10^7 M_{Sun}$

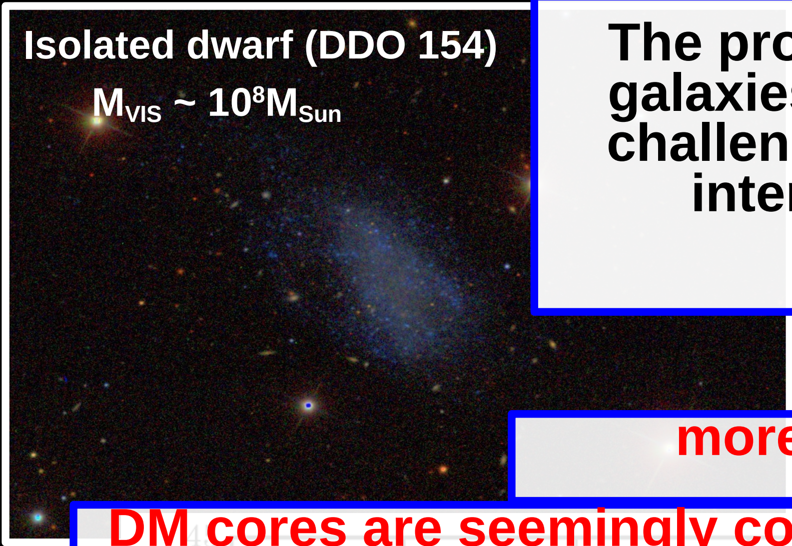
Abundance problem (Zavala+09, Klypin+15)

Structural problem (Boylan-Kolchin+11,Papastergis+14)





Clues from the properties of dwarf galaxies



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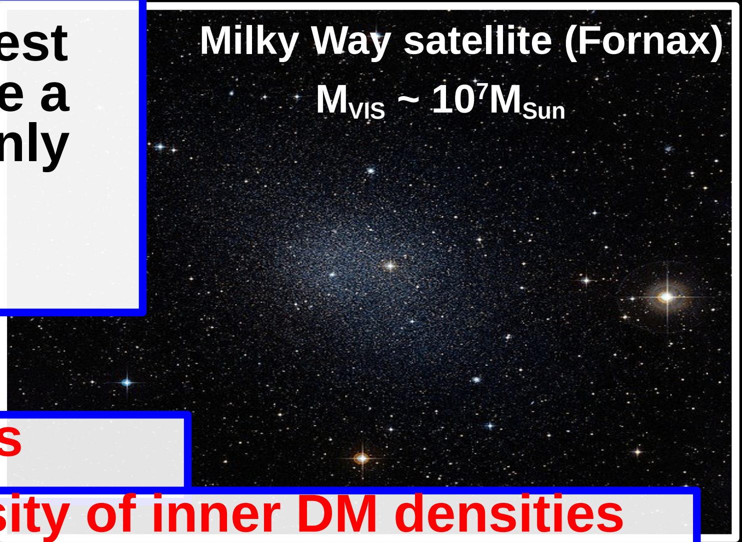


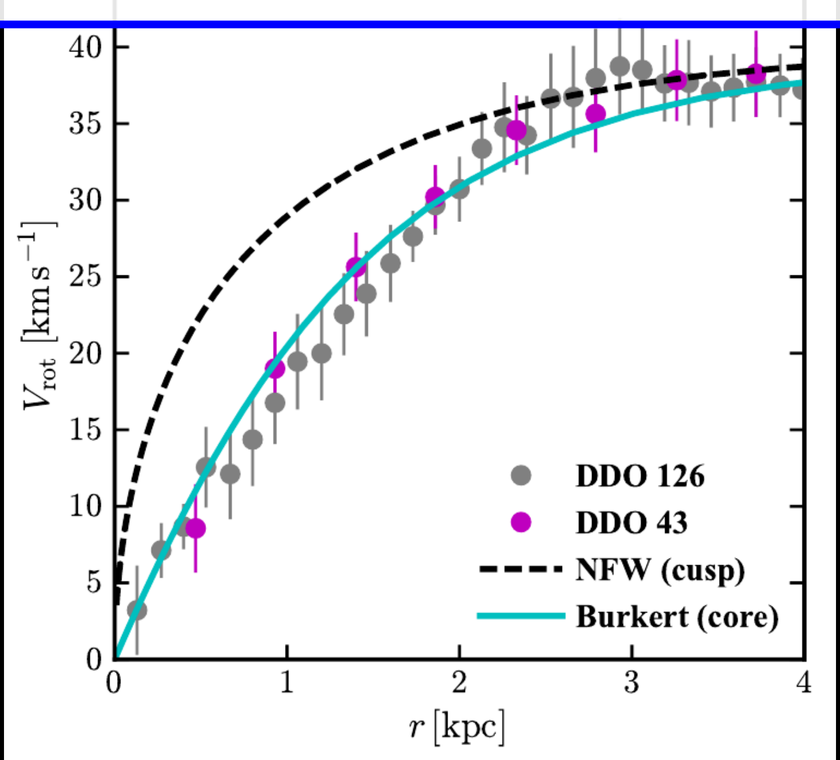
Milky Way satellite (Fornax)

$M_{VIS} \sim 10^7 M_{Sun}$

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

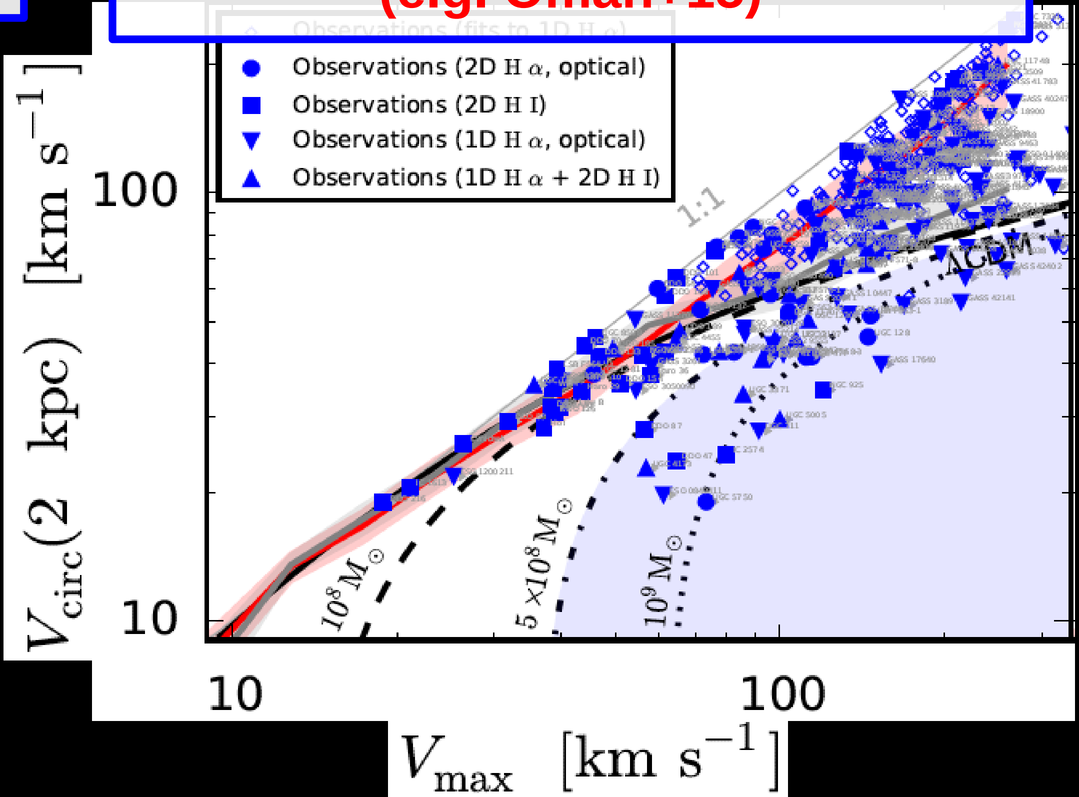
more structural problems

DM cores are seemingly common



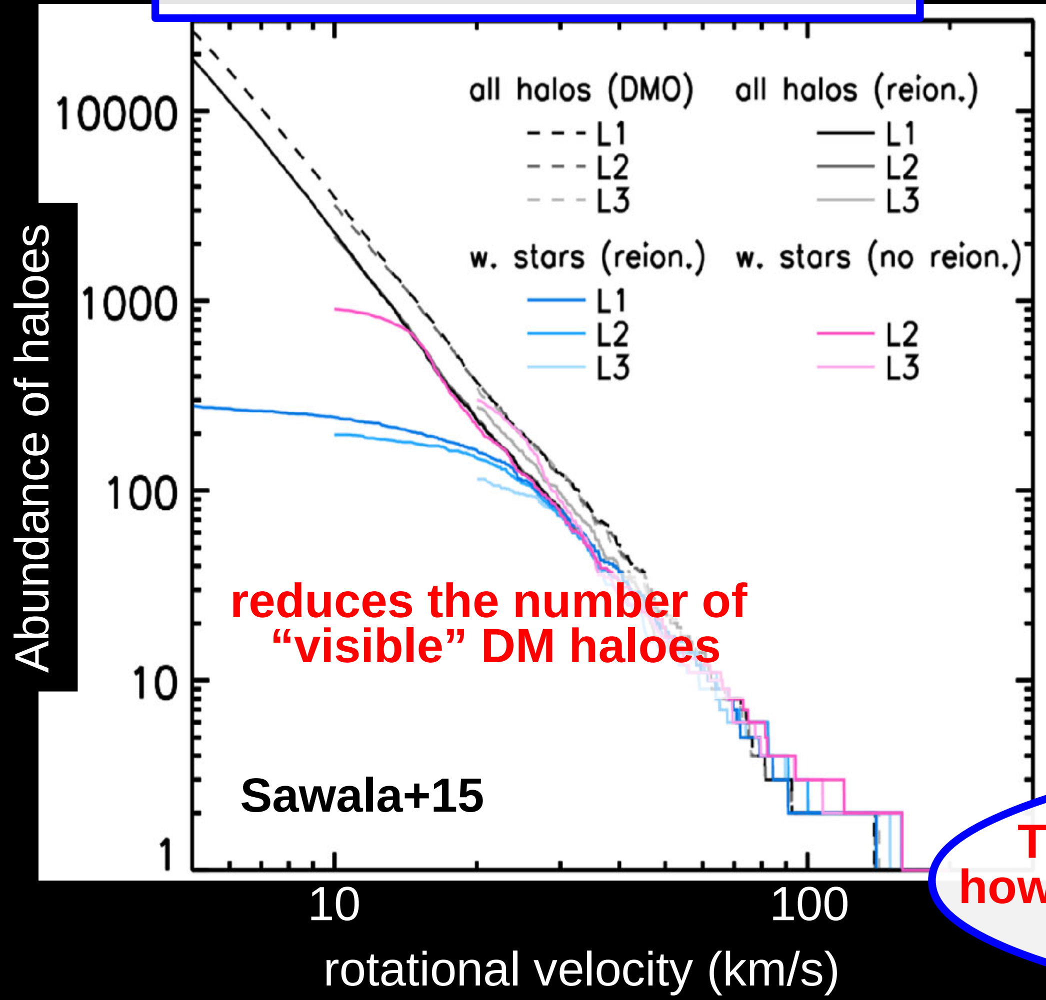
Bullock & Boylan-Kolchin 2017

diversity of inner DM densities (e.g. Oman+15)



Known but uncertain and complex “baryonic physics”

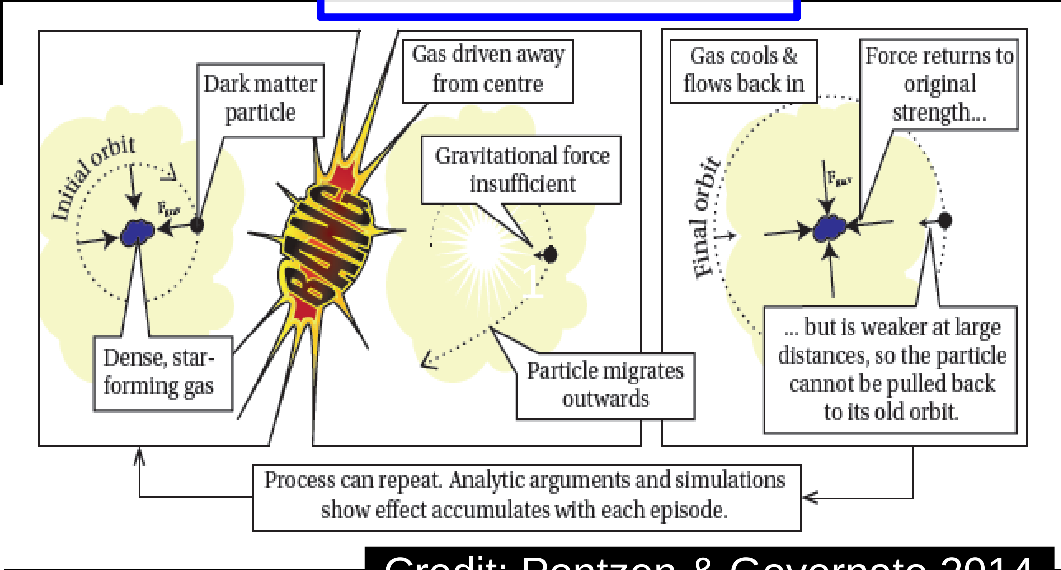
Gas heating (UV background from first generation of stars/galaxies)



reduces the number of “visible” DM haloes

Sawala+15

Gas and DM heating through supernovae



Credit: Pontzen & Governato 2014

reduces the inner density of DM haloes

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

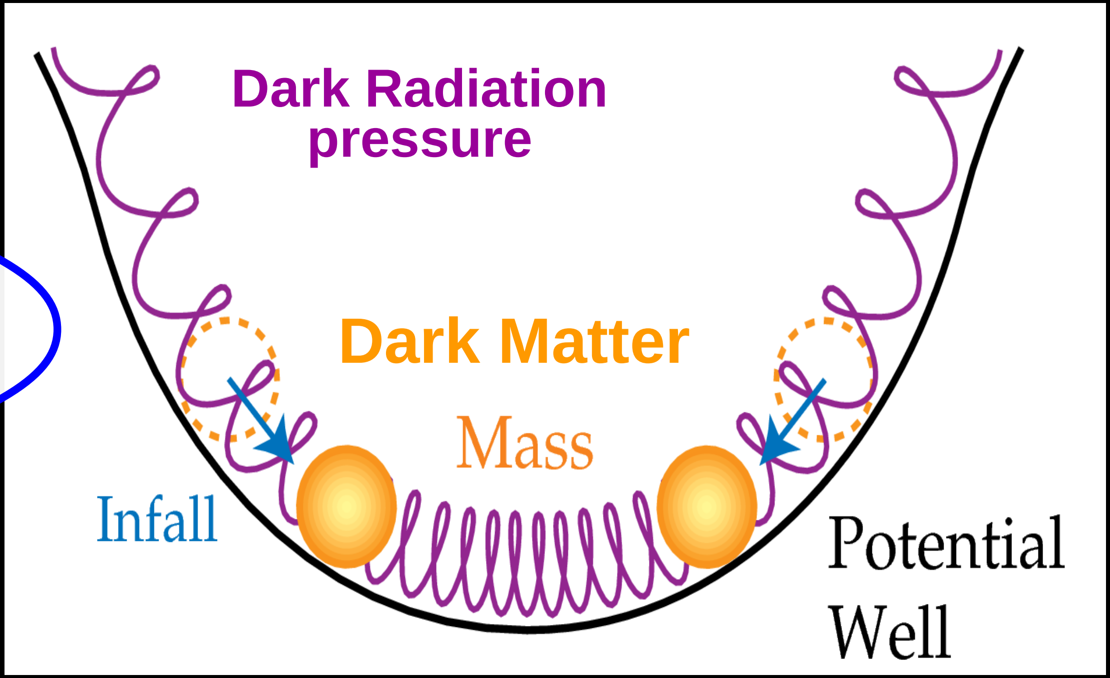
Unknown but simple “dark physics”

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 (phenomena analogous to that of the photon-baryon plasma)

Dark Acoustic Oscillations (DAOs)

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



Credit: Wayne Hu (U. Of Chicago)

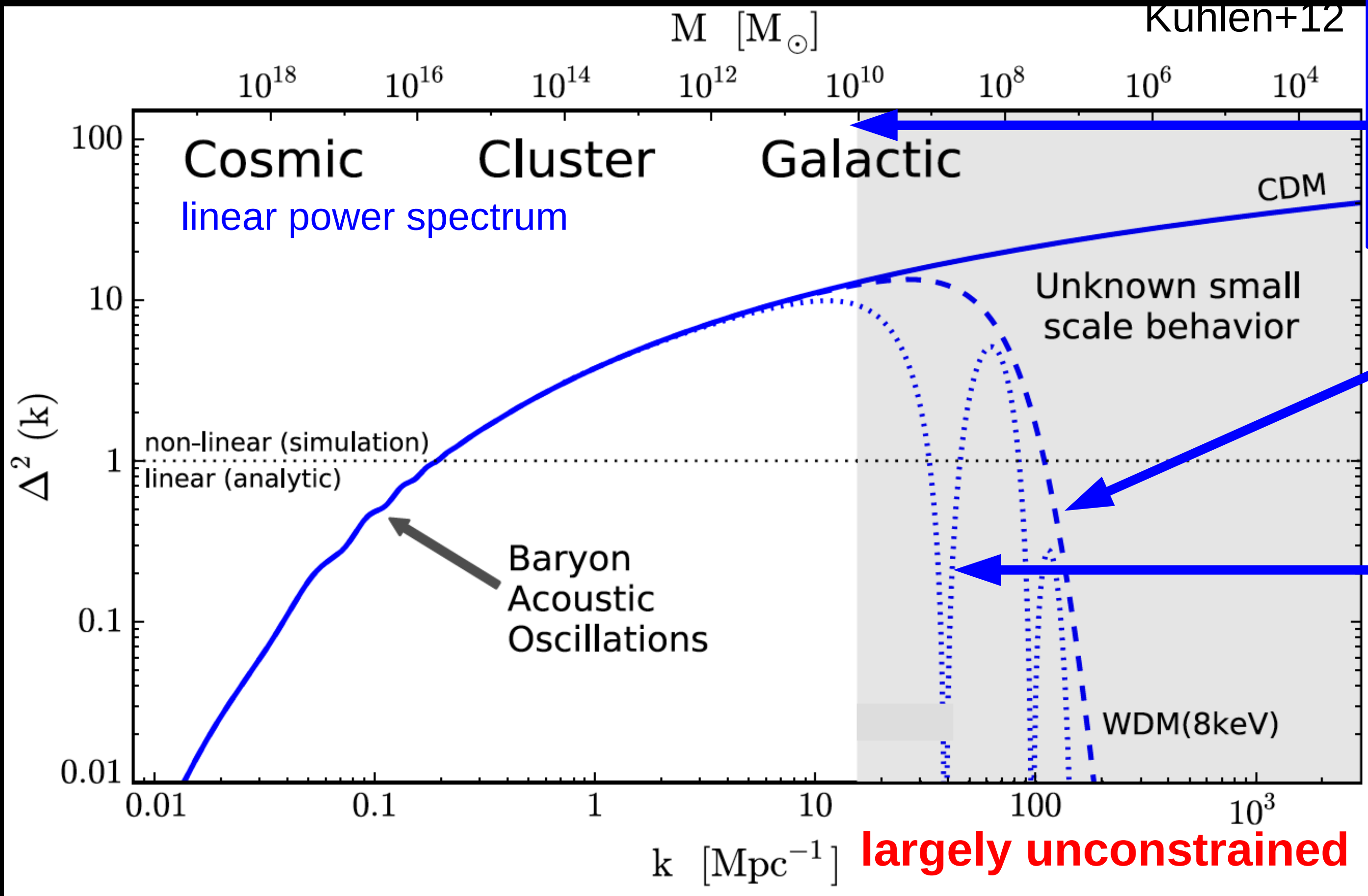
Unknown but simple “dark physics”

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

Kuhlen+12



largely unconstrained

DM is relativistic at earlier times
‘thermal’ cut-off
(WDM free-streaming)

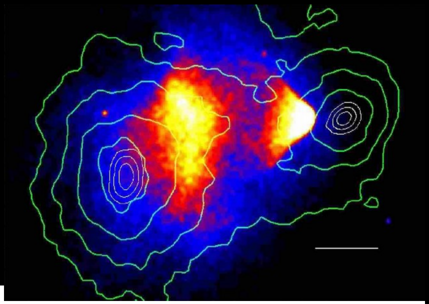
DM interacts with relativistic particles at earlier times:

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

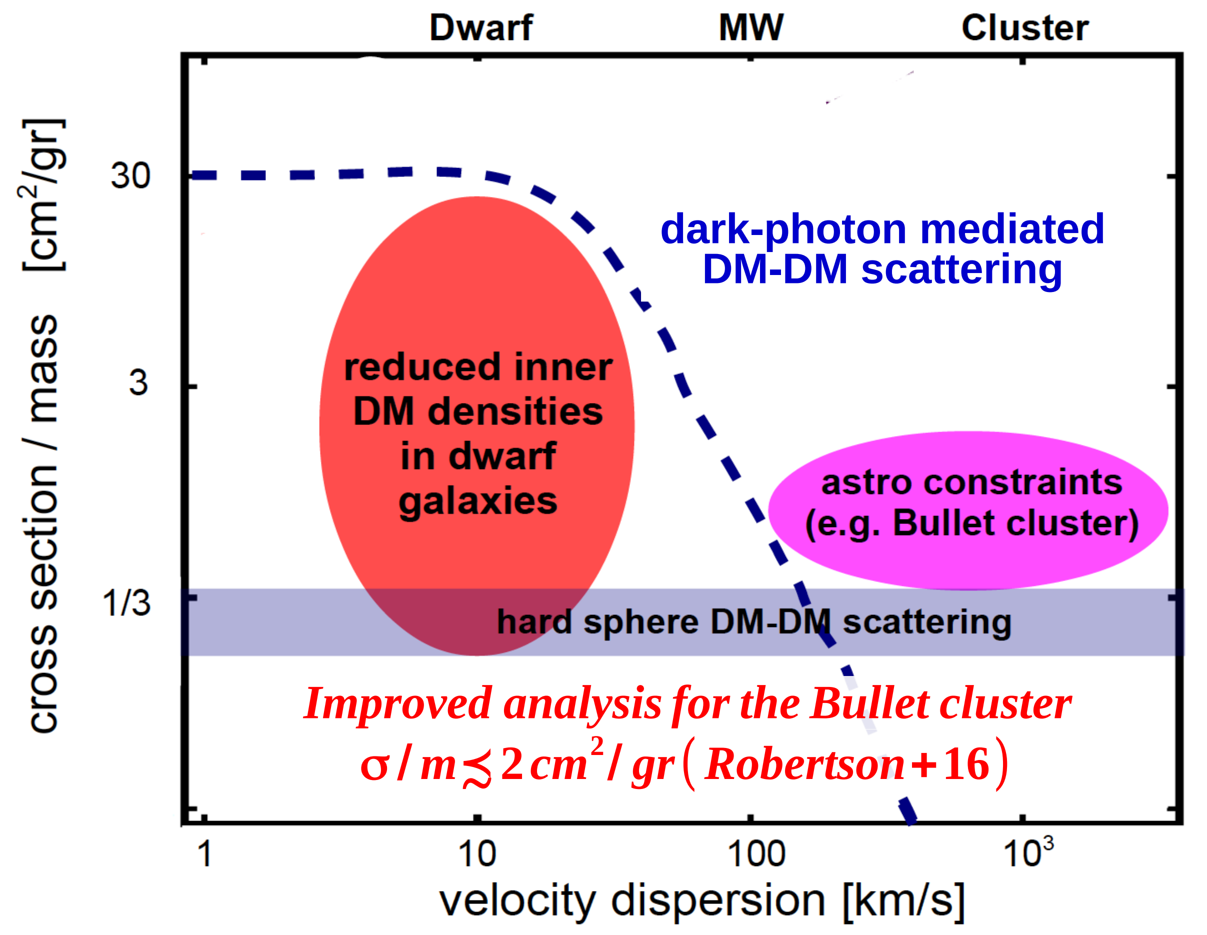


average scattering rate per particle:

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

~ 1 scatter / particle / Hubble time

Neither a fluid nor a collisionless system: ~ rarefied gas



Improved analysis for the Bullet cluster

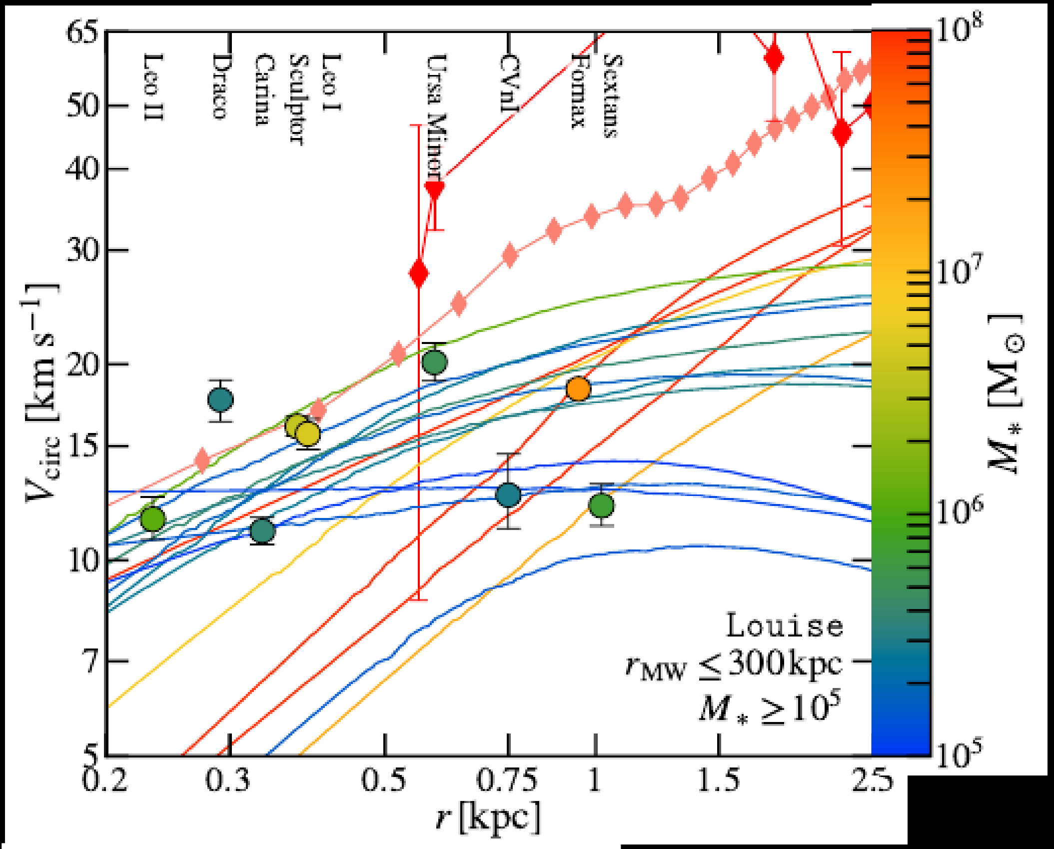
$\sigma/m \lesssim 2\,cm^2/gr$ (*Robertson+16*)

DM physics vs/with baryonic physics

too-big-to-fail problem

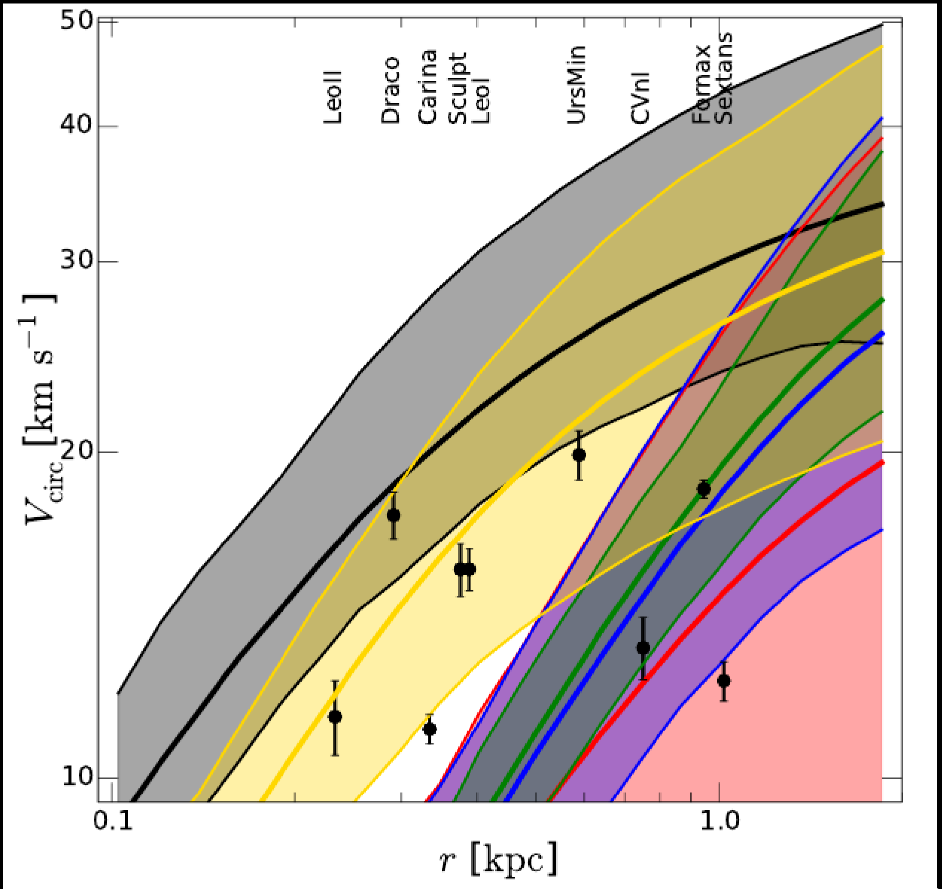
MW disc tidal effects
+
DM heating
through supernovae

primordial power spectrum cutoff
+
DM self-interactions



Garrison-Kimmel +2018

full cosmological simulations with baryons



ETHOS II: Vogelsberger+16

full cosmological simulations
without baryons

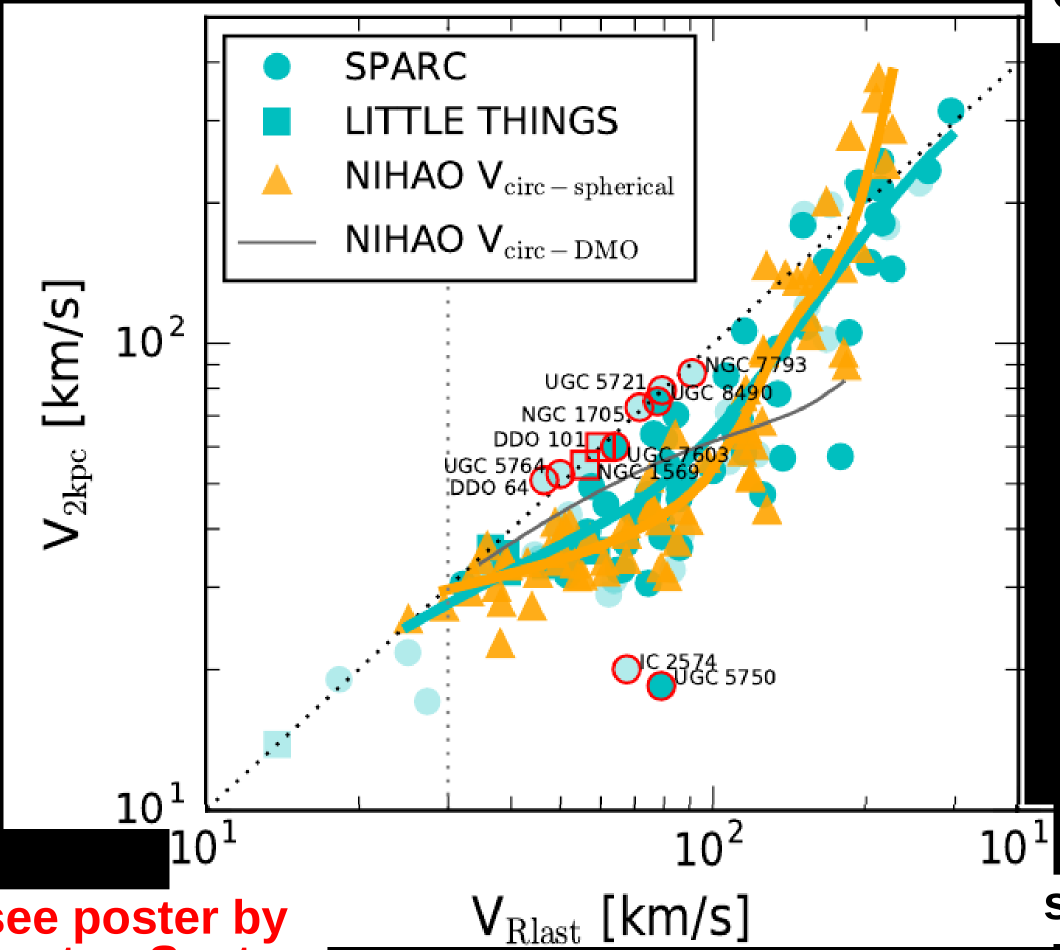
DM physics vs/with baryonic physics

diversity of inner DM densities

mass-dependent
DM heating
through supernovae

SIDM halo contraction
due to baryonic disc
(scale dependent)

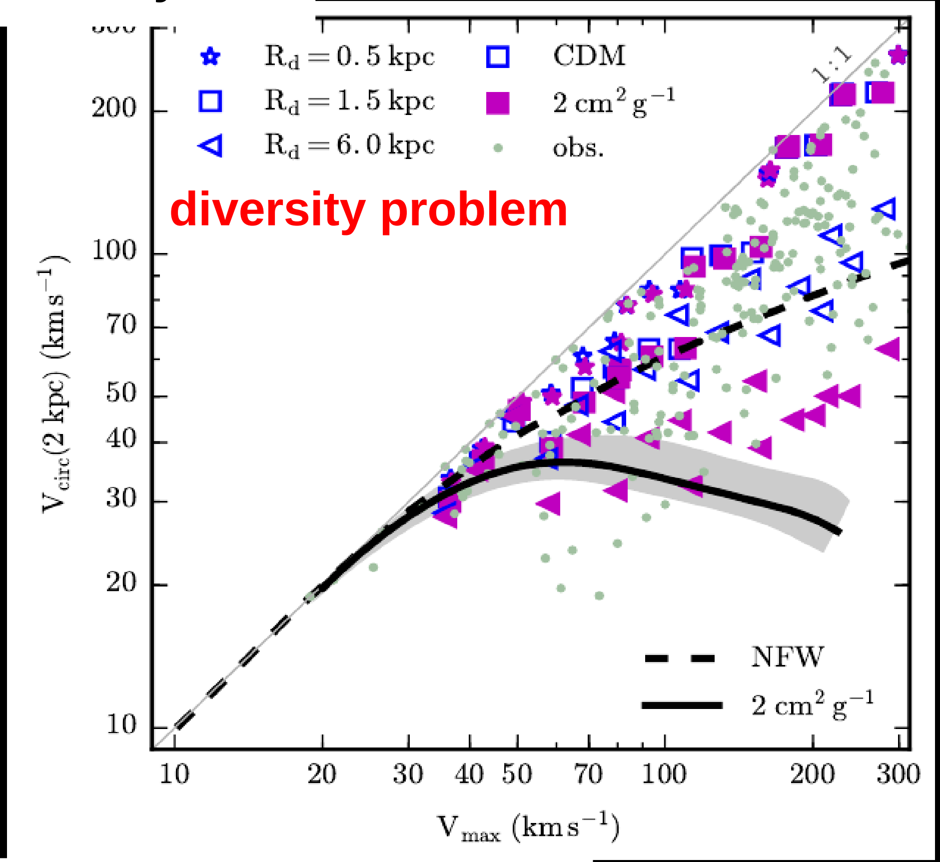
Santos-Santos +2018



see poster by Santos-Santos

full cosmological simulations

Creasey+17



see also Kamada+2017

idealised modelling
(not cosmological simulations)

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**
- 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

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 and within reach of upcoming observations:

SIDM transfer cross section

$$0.1\,cm^2/gr \lesssim \sigma/m \lesssim 2\,cm^2/gr$$

below this value, the
behaviour is
the same as CDM

above this value
constraints are strong
(at cluster scales)

‘cutoff’ halo mass at z=0

$$10^{9.5}\,M_{Sun} \lesssim M_{cut} \lesssim 10^{10.5}\,M_{Sun}$$

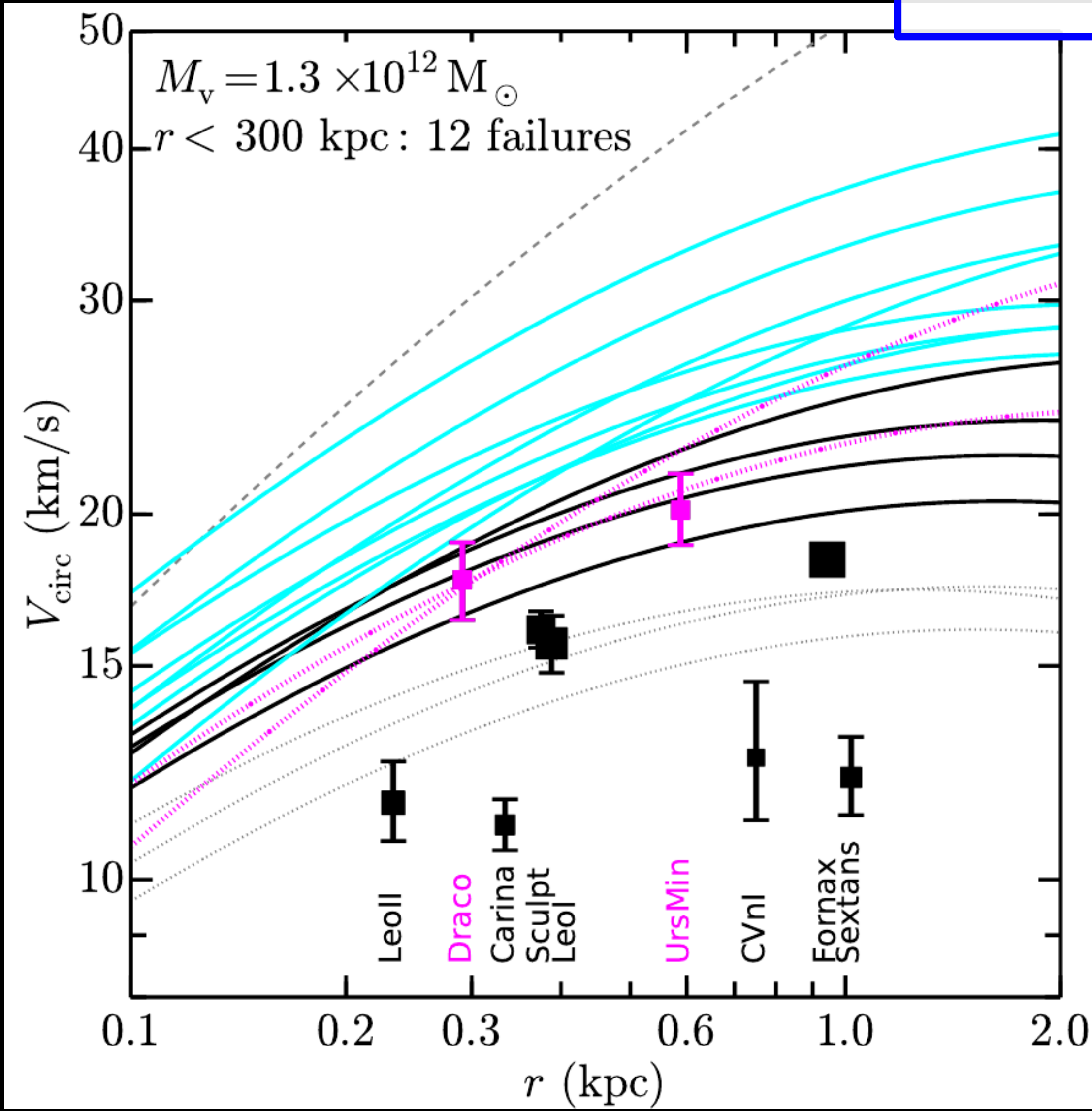
below this value
galaxy formation
Is highly supressed
(reionisation)

above this value
DM clustering
must be as in CDM

diverse sub-kpc DM densities in MW satellites

CDM-only
too-big-to-fail problem
circa 2014

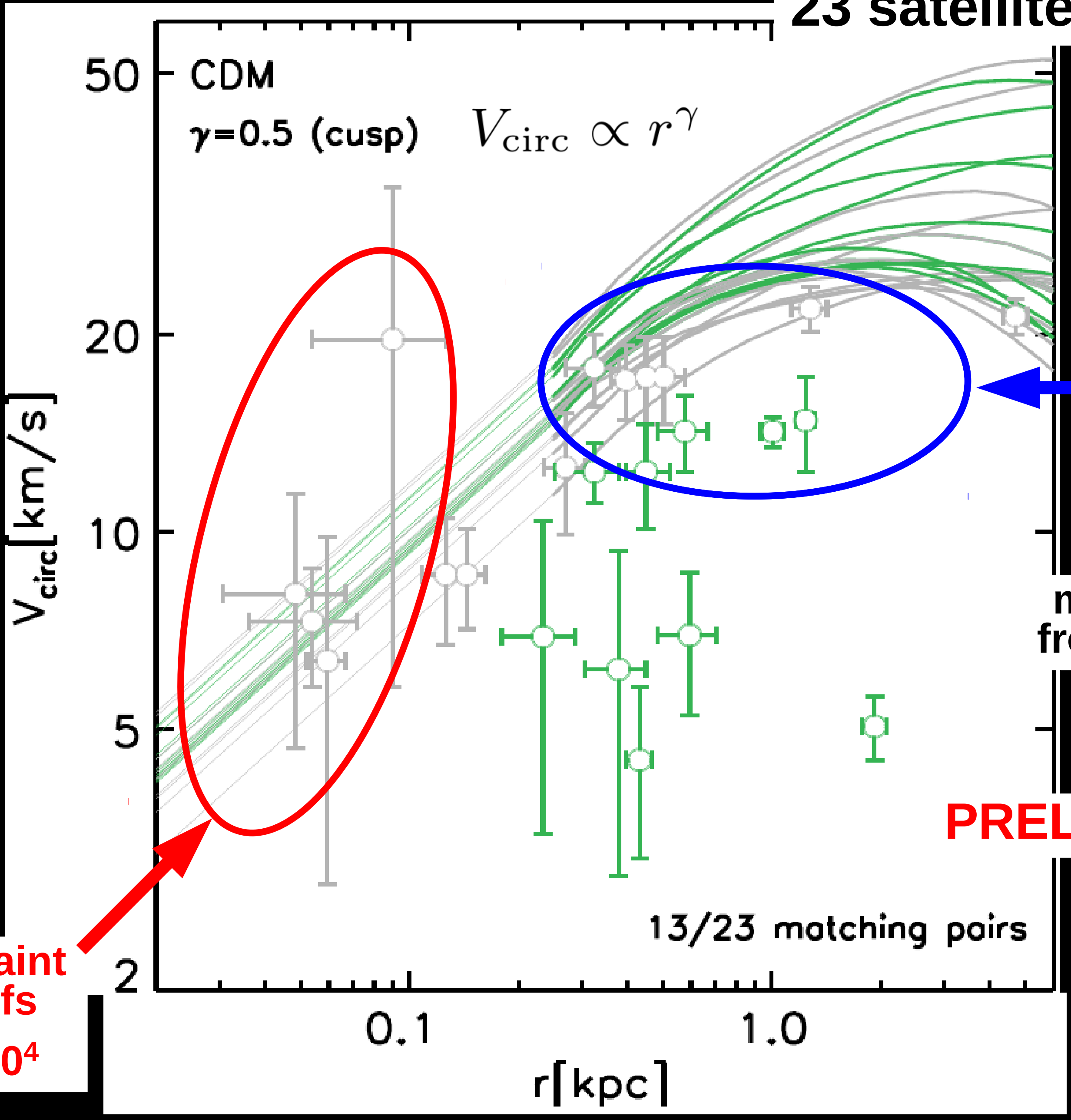
Elvis project
CDM-only (no baryonic physics)



classical dSphs

Garrison-Kimmel+2014

diverse sub-kpc DM densities in MW satellites



23 satellites

Aquarius project
CDM-only (no baryonic physics)

classical dSphs

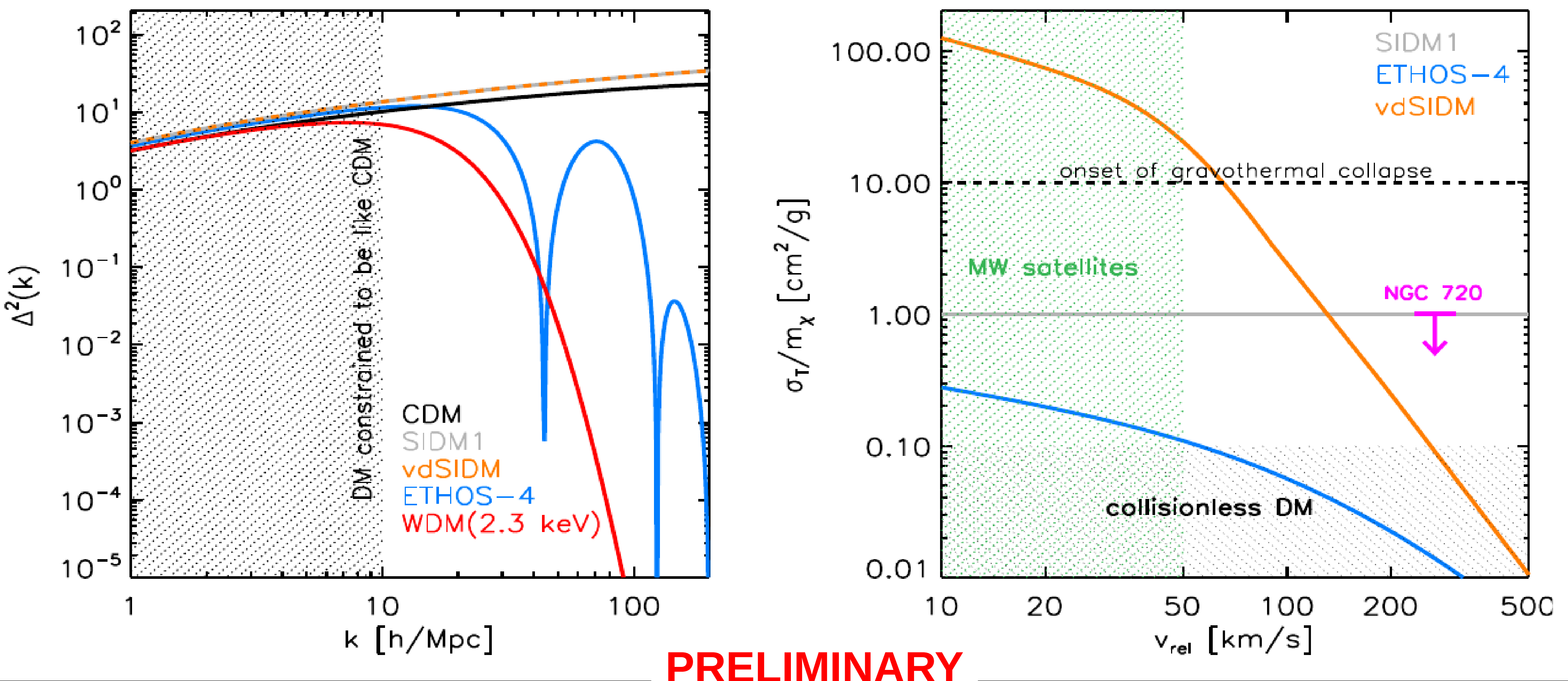
mass estimates
from Errani+2018

PRELIMINARY

ultra-faint dwarfs
$M^* < 10^4$

Zavala et al. 2018 in prep.

diverse sub-kpc DM densities in MW satellites: implications for the DM nature

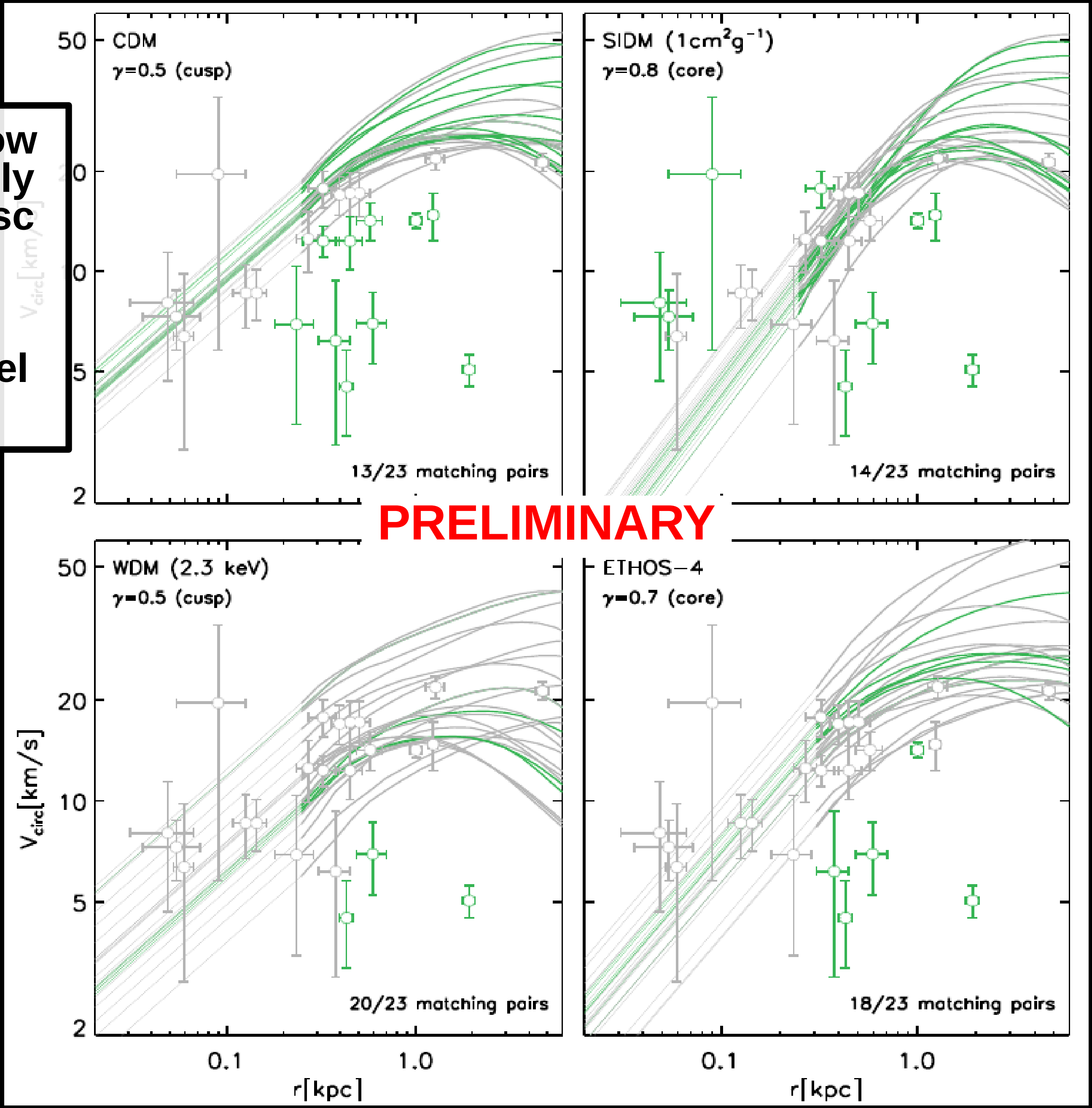


PRELIMINARY

Zavala et al. 2018 in prep.

diverse sub-kpc DM densities in MW satellites

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



PRELIMINARY

Zavala et al. 2018 in prep.

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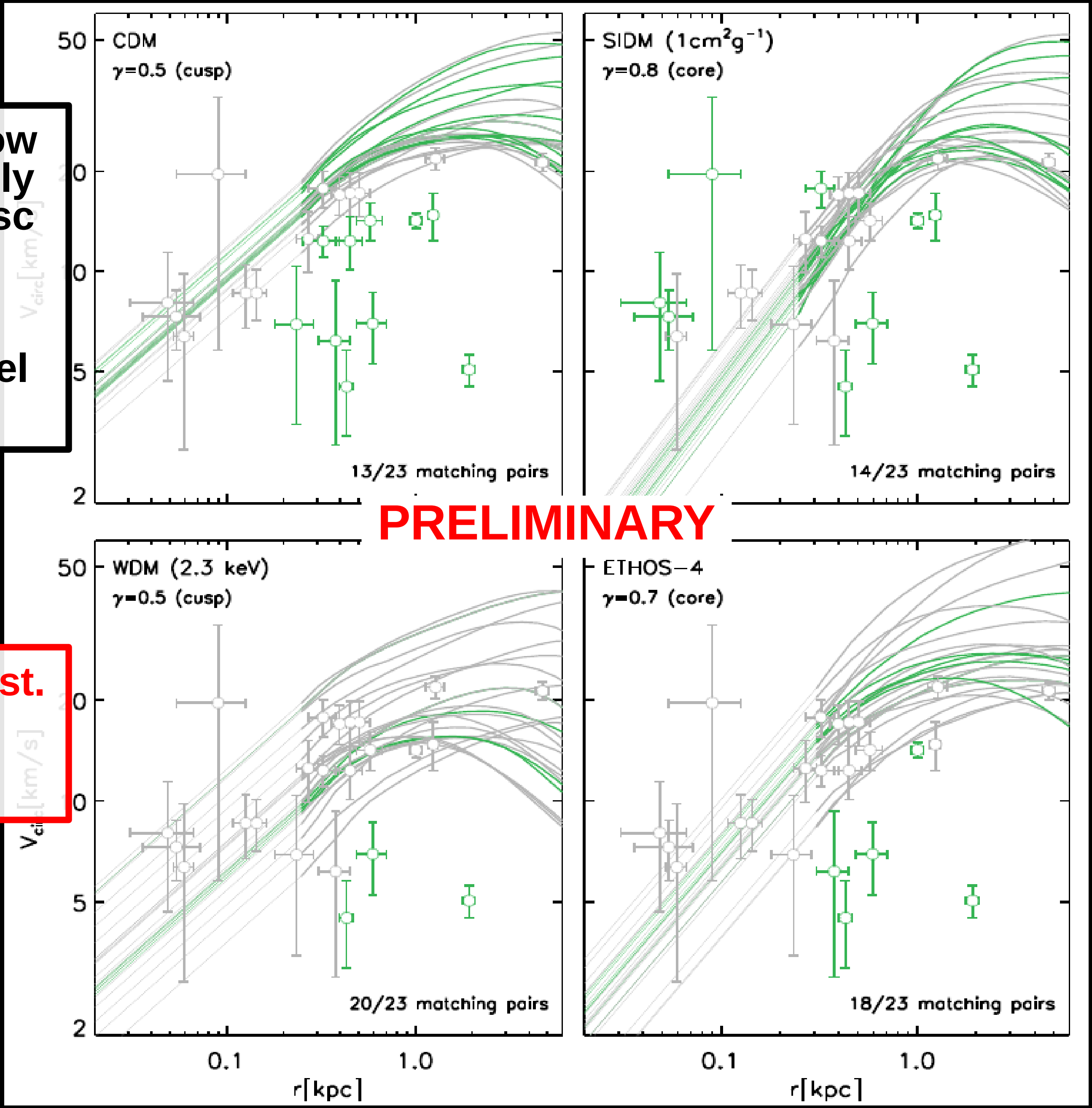

PRELIMINARY

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

WDM: diverse dist. but stringent Ly-alpha constraints

Zavala et al. 2018 in prep.

diverse sub-kpc DM densities in MW satellites

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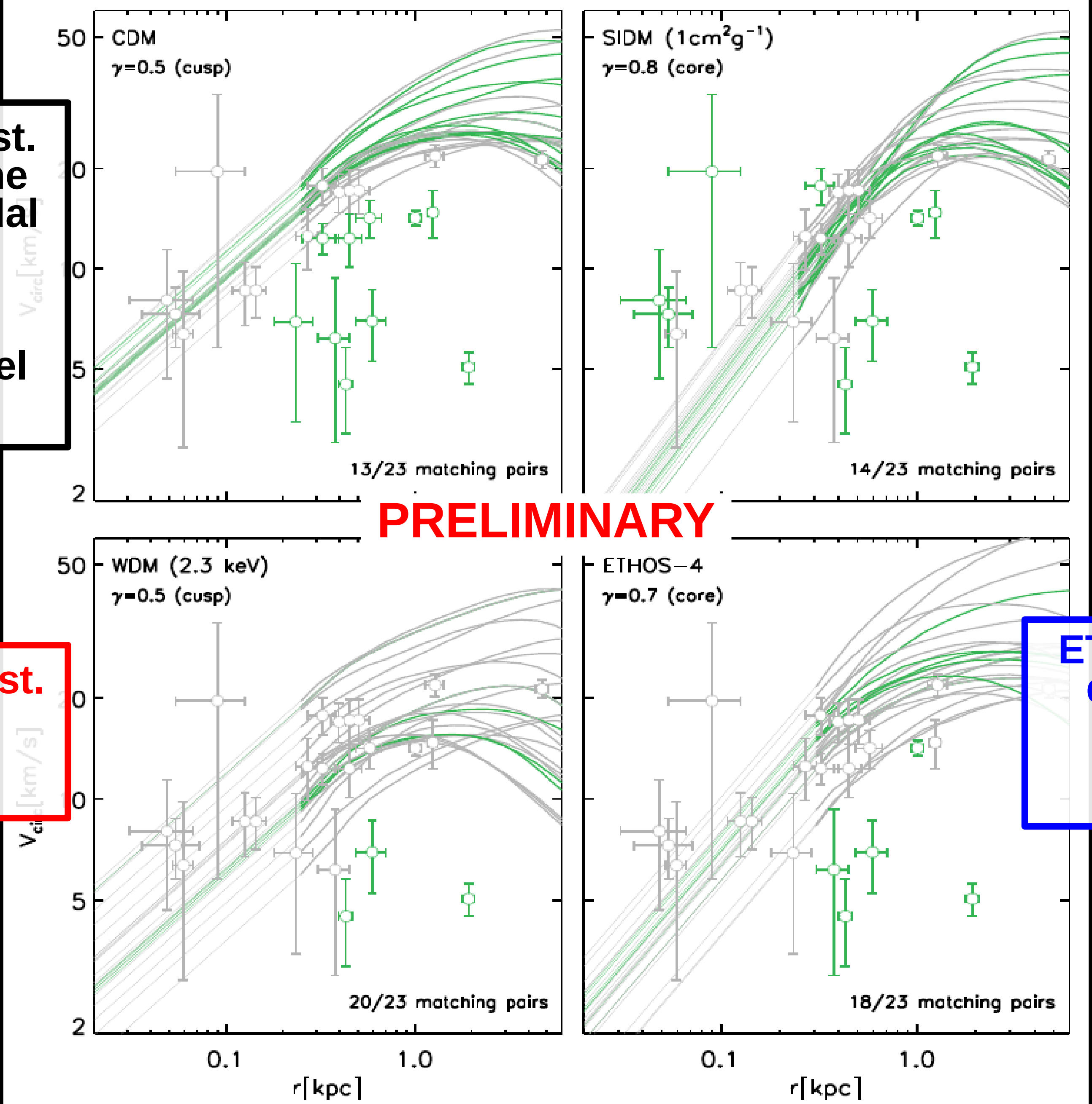


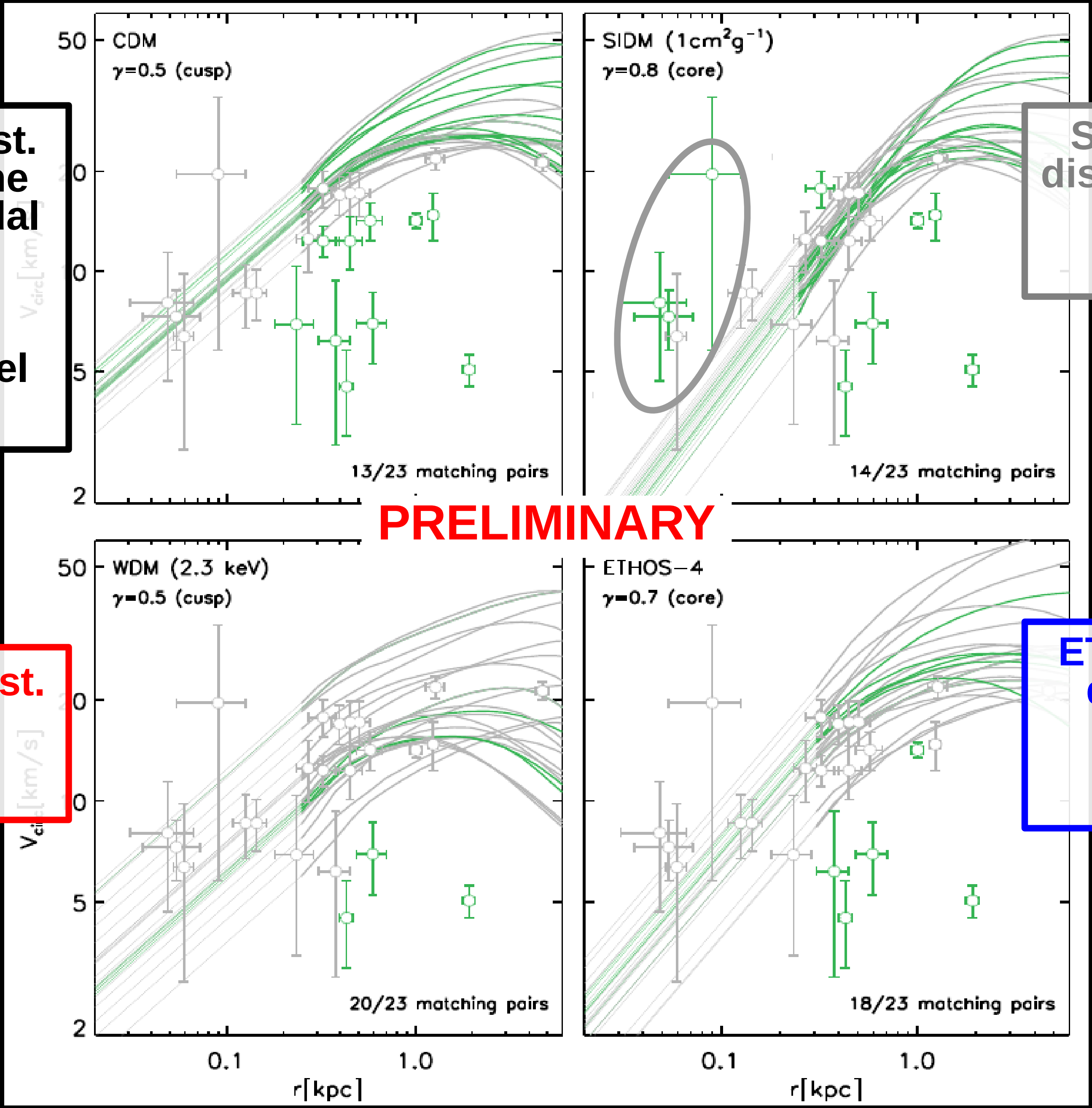
PRELIMINARY

WDM: diverse dist. but stringent Ly-alpha constraints

ETHOS-4: diverse dist., unclear if ok with Ly-alpha constraints

Zavala et al. 2018 in prep.

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., unclear if ok with Ly-alpha constraints

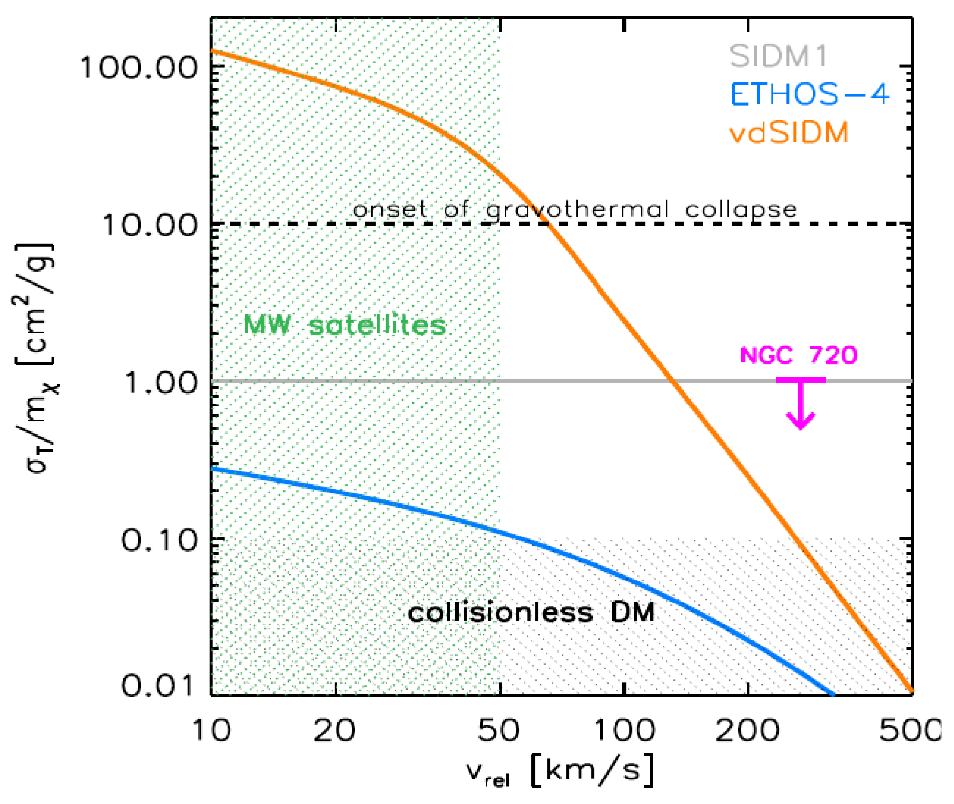
Zavala et al. 2018 in prep.

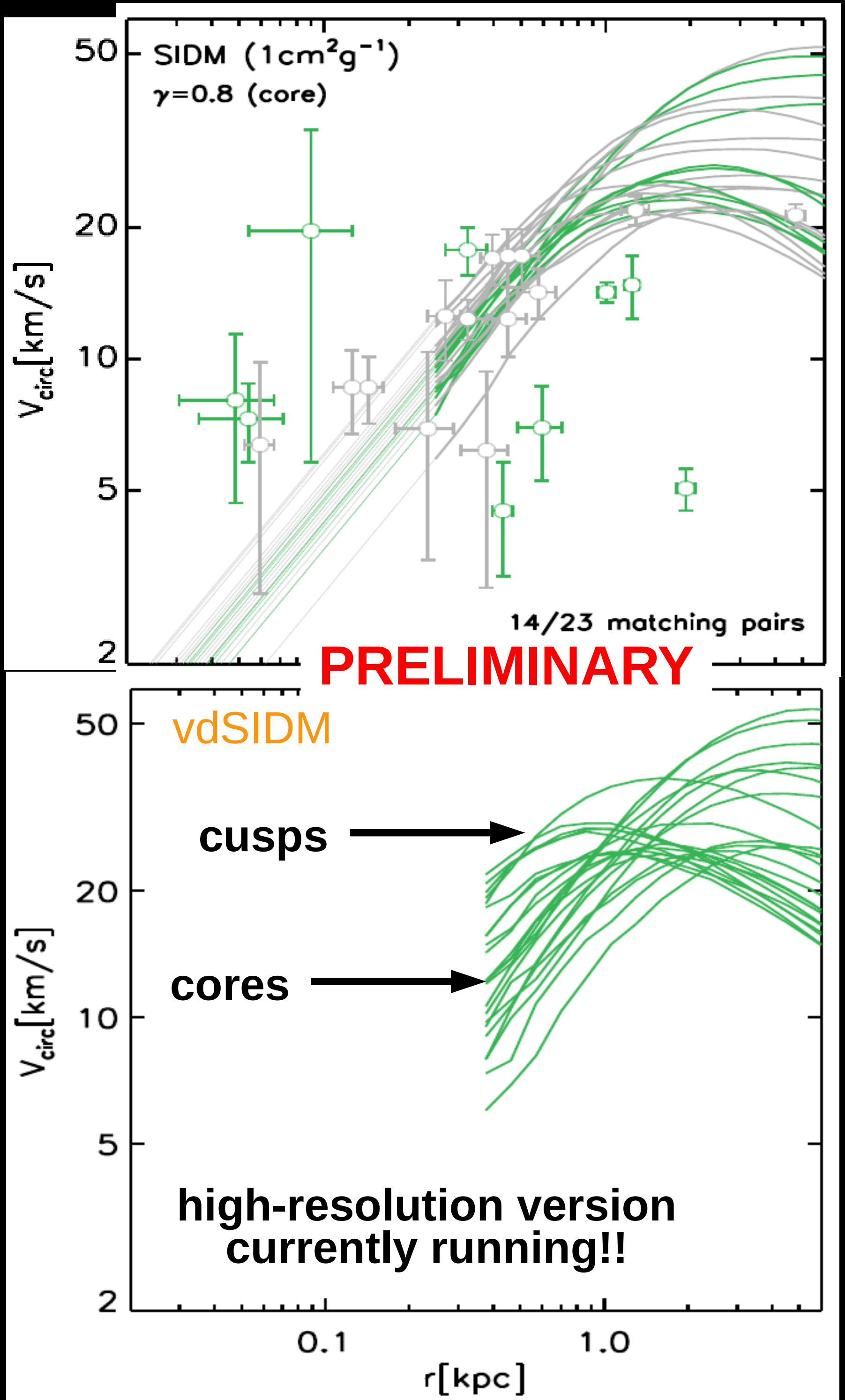
Is this a strong constraint on SIDM?

- Systematic uncertainties of mass estimators for ultra-faint galaxies (e.g. unambigous star membership for kinematic data, Segue I is probably the most reliable case)

- Surprisingly, even if ultra-faint data is confirmed, it is not an upper limit to the cross section...

Is this a strong constraint on SIDM?





PRELIMINARY

cusps

cores

high-resolution version currently running!!

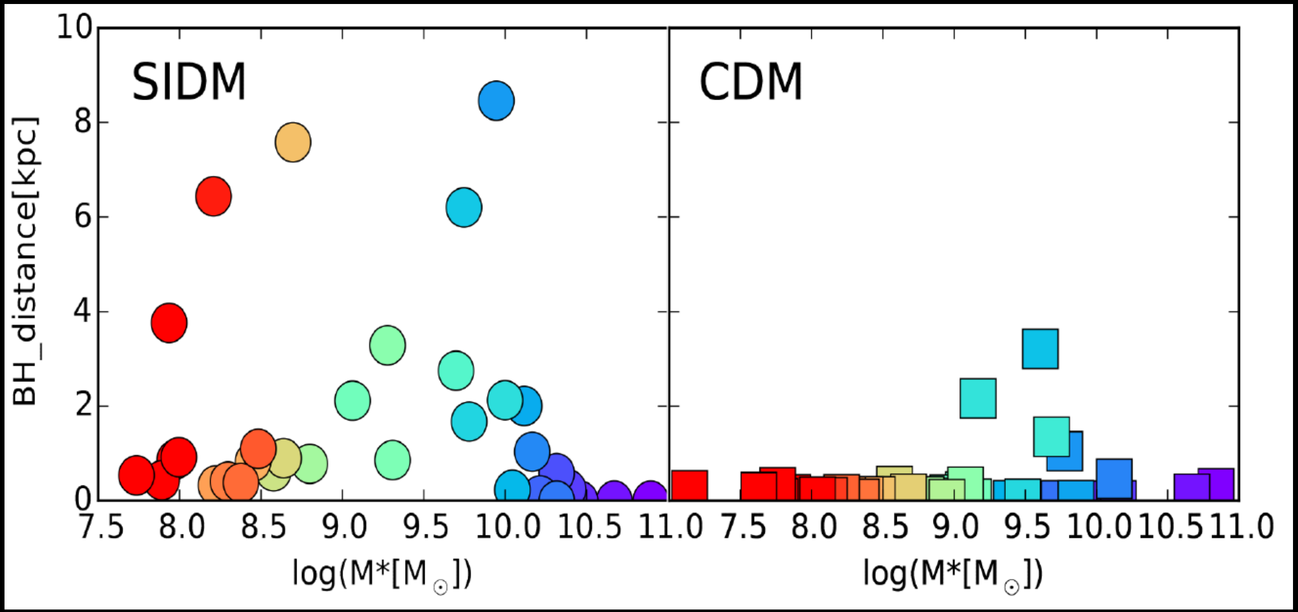
SIDM: fine if

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

(at dwarf scales)

Disentangling dark from baryonic physics

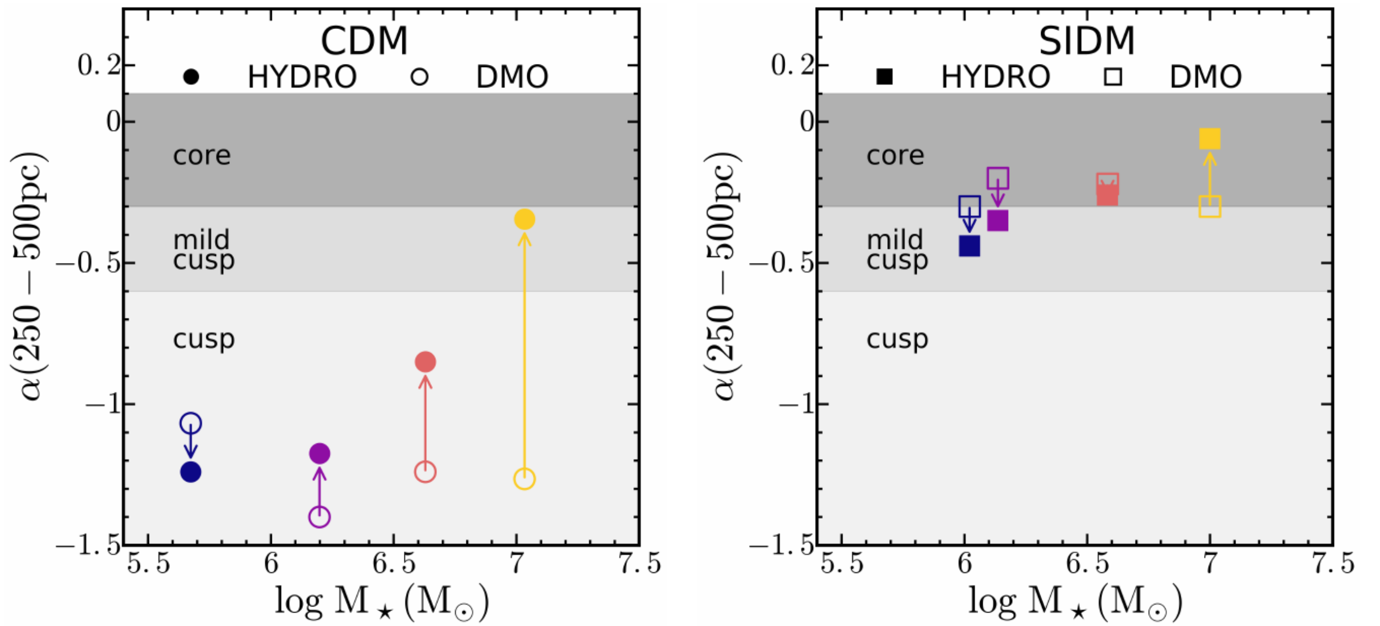
SMBH offsets



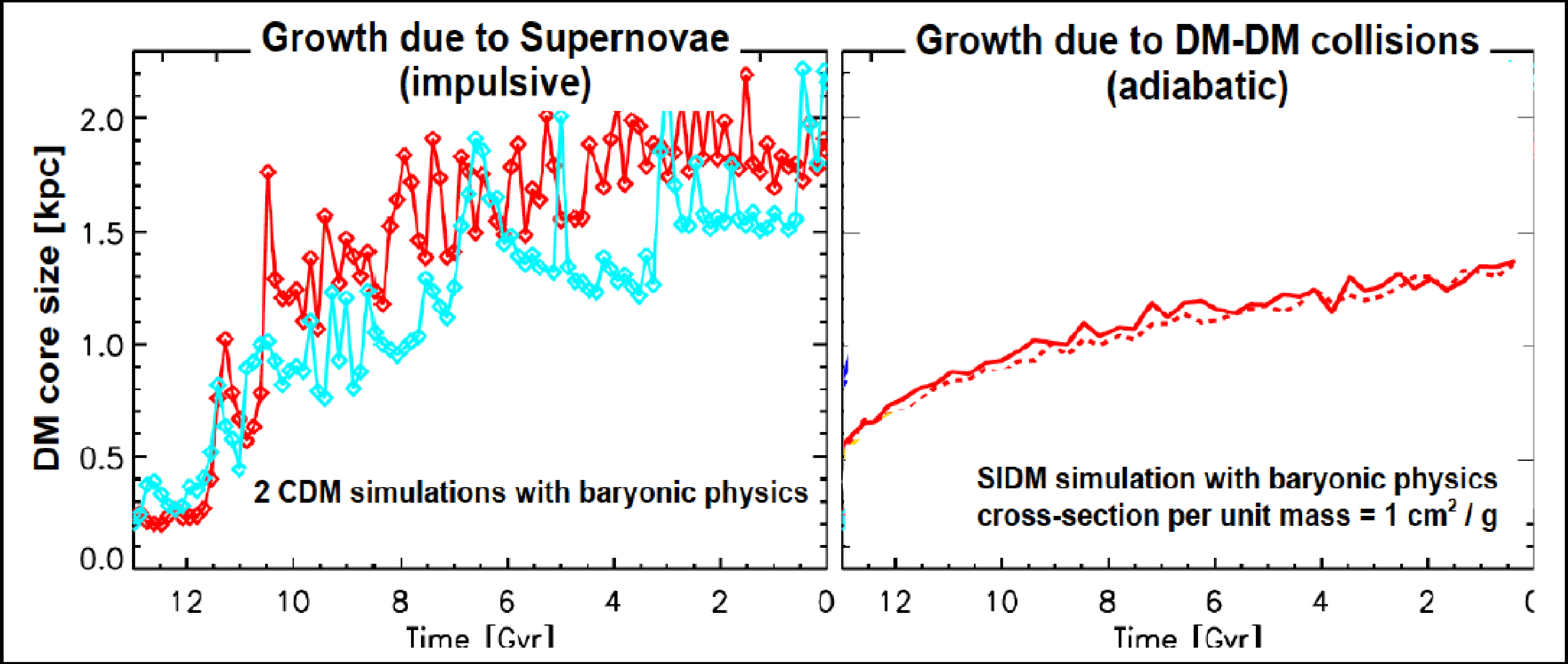
Di Cintio et al. 2017

SNe-driven DM cores inneficient at low M$_*$

Robles t al. 2017



Disentangling dark from baryonic physics



Growth due to Supernovae (impulsive)

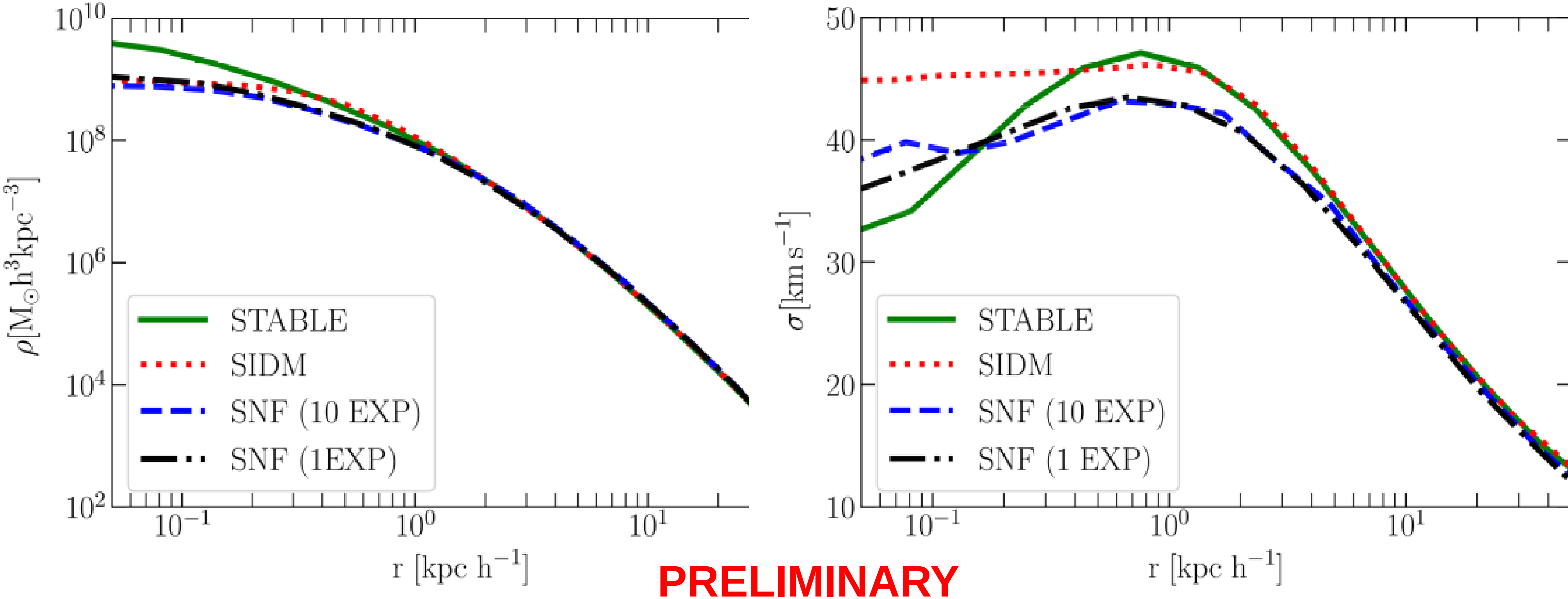
2 CDM simulations with baryonic physics

Growth due to DM-DM collisions (adiabatic)

SIDM simulation with baryonic physics
cross-section per unit mass = 1 cm^2 / g

Adiabatic (SIDM) vs Impulsive (SN feedback) DM core formation

isolated idealised spherical DM halo



PRELIMINARY

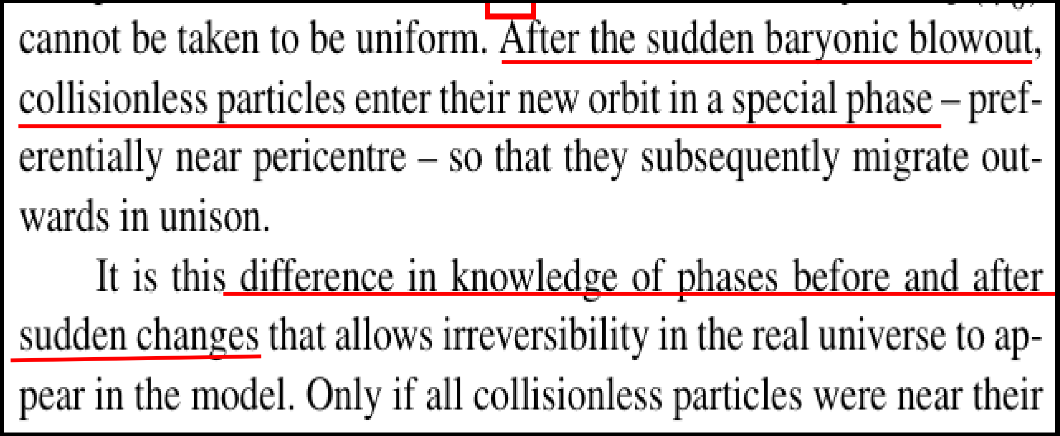
A “similar” DM core can be formed with these two mechanisms

Burger & Zavala 2018 in prep.

Adiabatic vs Impulsive DM core formation

What is the response of stars(tracers) to these two mechanisms of core formation?

from “how SN feedback turns DM cusps into cores”
Pontzen & Governato 2012

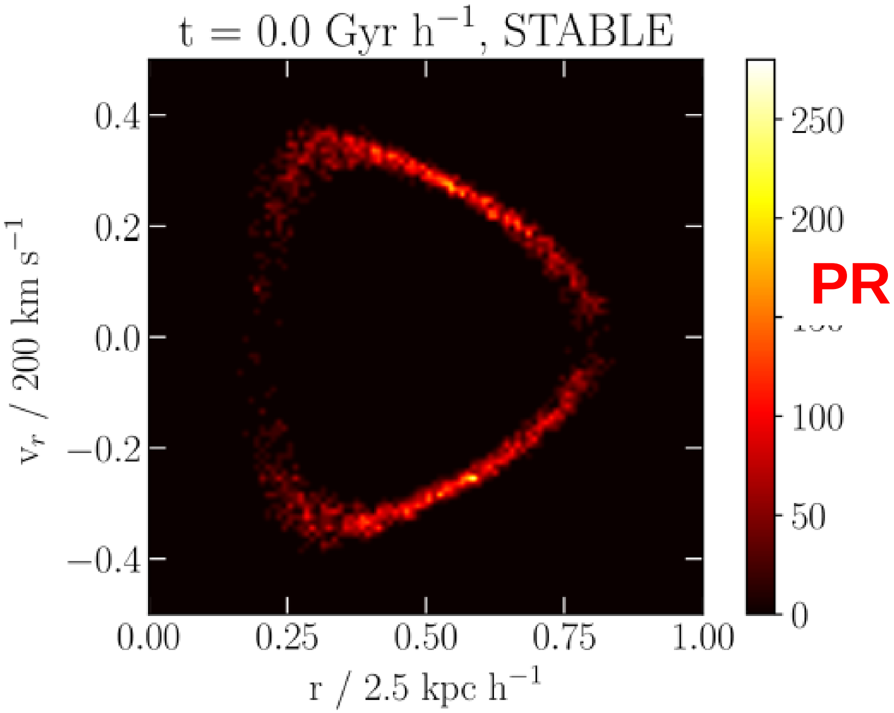


cannot be taken to be uniform. After the sudden baryonic blowout, collisionless particles enter their new orbit in a special phase – preferentially near pericentre – so that they subsequently migrate outwards in unison.

It is this difference in knowledge of phases before and after sudden changes that allows irreversibility in the real universe to appear in the model. Only if all collisionless particles were near their

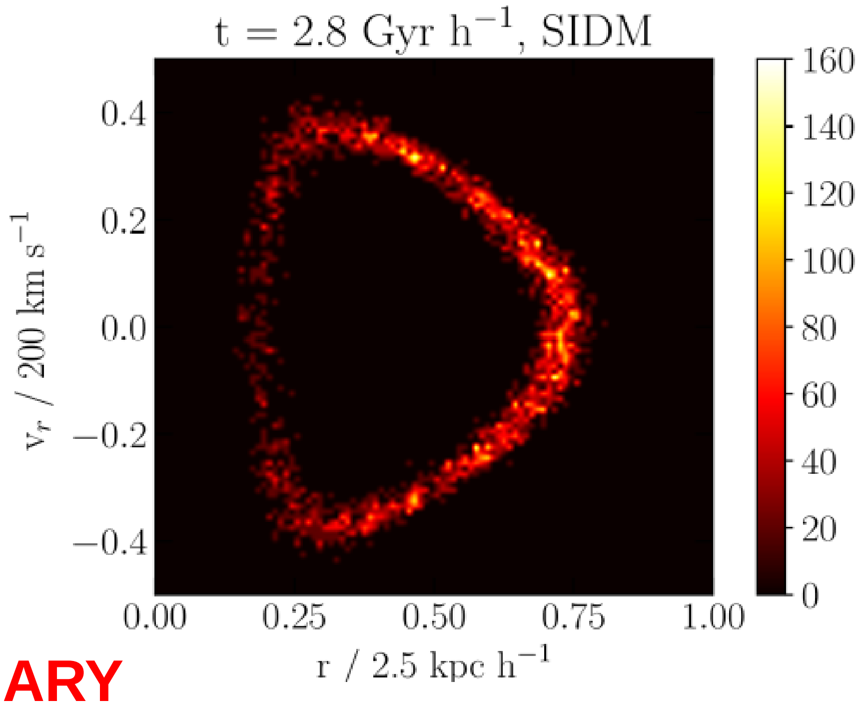
Adiabatic vs Impulsive DM core formation

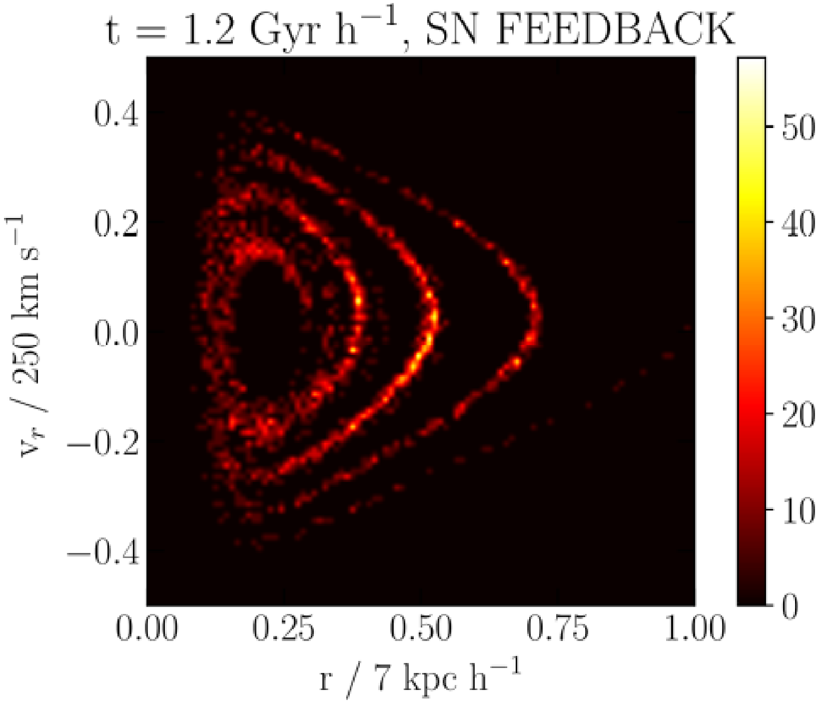
What is the response of stars(tracers) to these two mechanisms of core formation?



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

PRELIMINARY





Burger & Zavala 2018 in prep.

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 (free streaming, dark matter – dark radiation interactions)

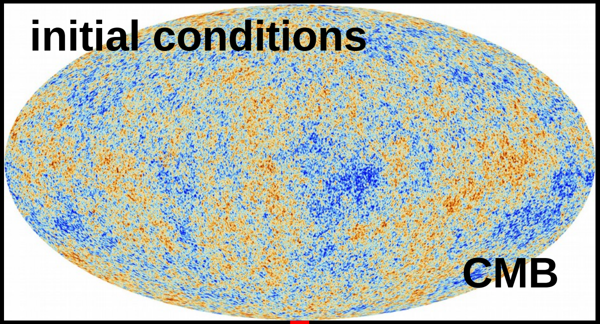
- The inner structure of DM haloes in dwarf galaxies could be set by a combination of baryonic physics (assembly of the galaxy + SNe feedback) and new dark physics (self-interacting dark matter)

- 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 the two

EXTRA SLIDES

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

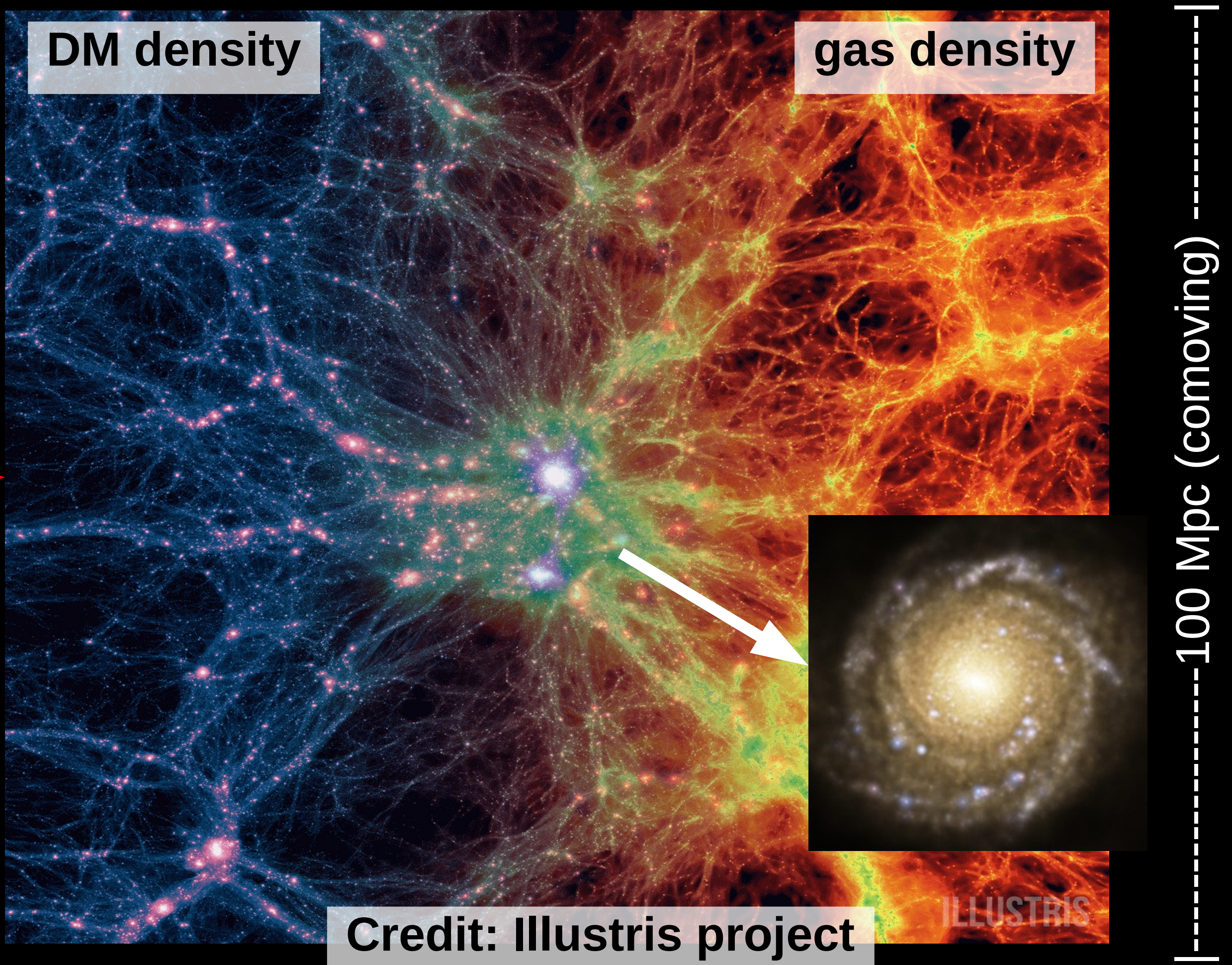


CDM assumes that the only DM interaction that matters is gravity!!

cosmological simulations

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

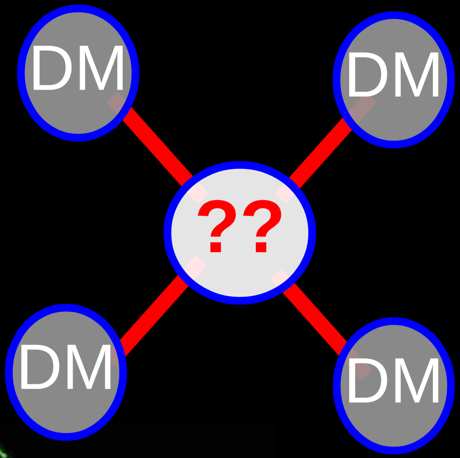
<u>**2000 CPU years!!**</u>

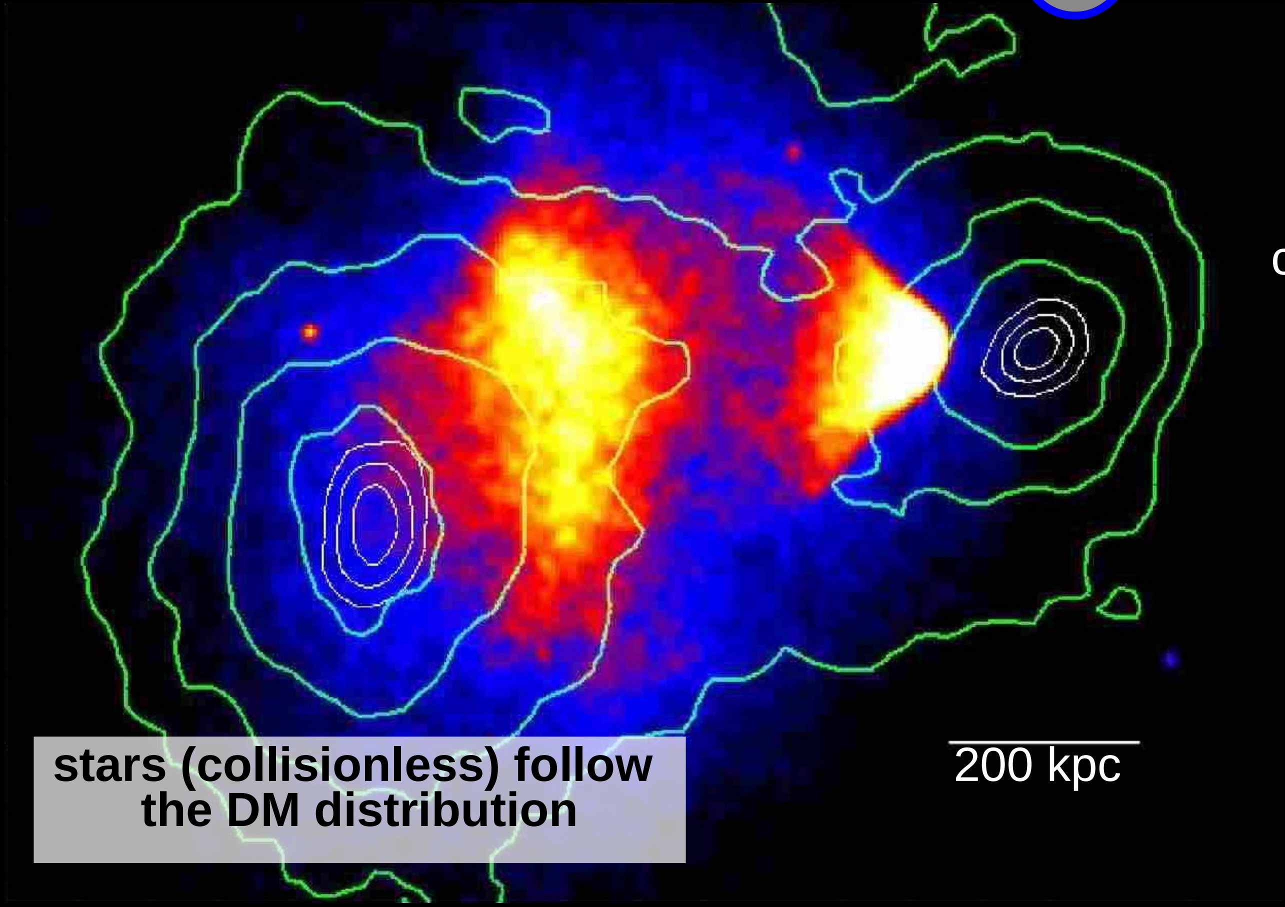


Credit: Illustris project

What types of DM interactions could impact structure formation?

Can DM particles collide with themselves?





Bullet Cluster (Clowe +06)

stars (collisionless) follow the DM distribution

constraint on DM self-collisions

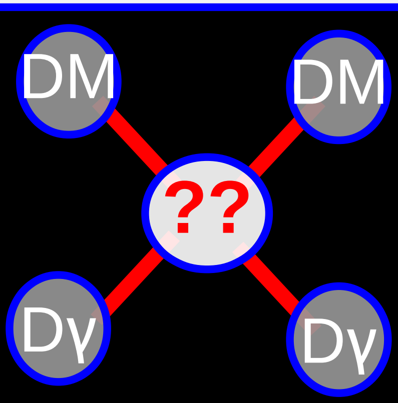
$$\sigma/m \lesssim 2\,cm^2/gr$$

Robertson+2016

nucleon-nucleon elastic scattering: ~10 cm^2/gr

Unknown and uncertain but simple “dark physics”

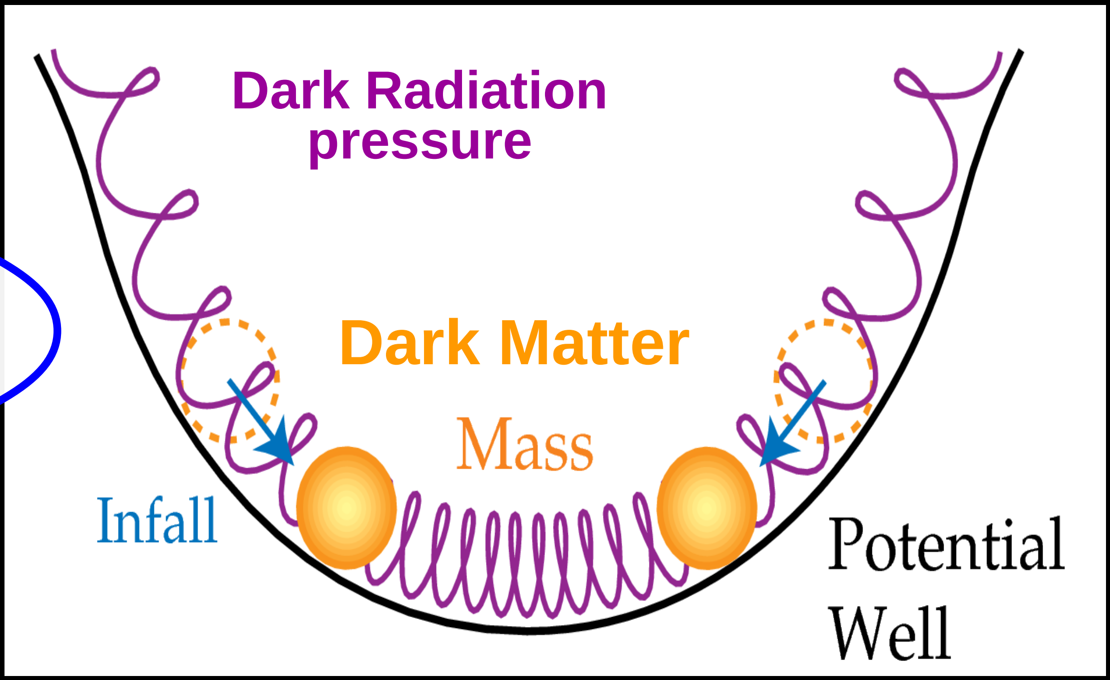
Can DM particles interact with other “dark” particles?



“dark photons”

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 (phenomena analogous to that of the photon-baryon plasma)

Dark Acoustic Oscillations (DAOs)



Credit: Wayne Hu (U. Of Chicago)

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

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

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

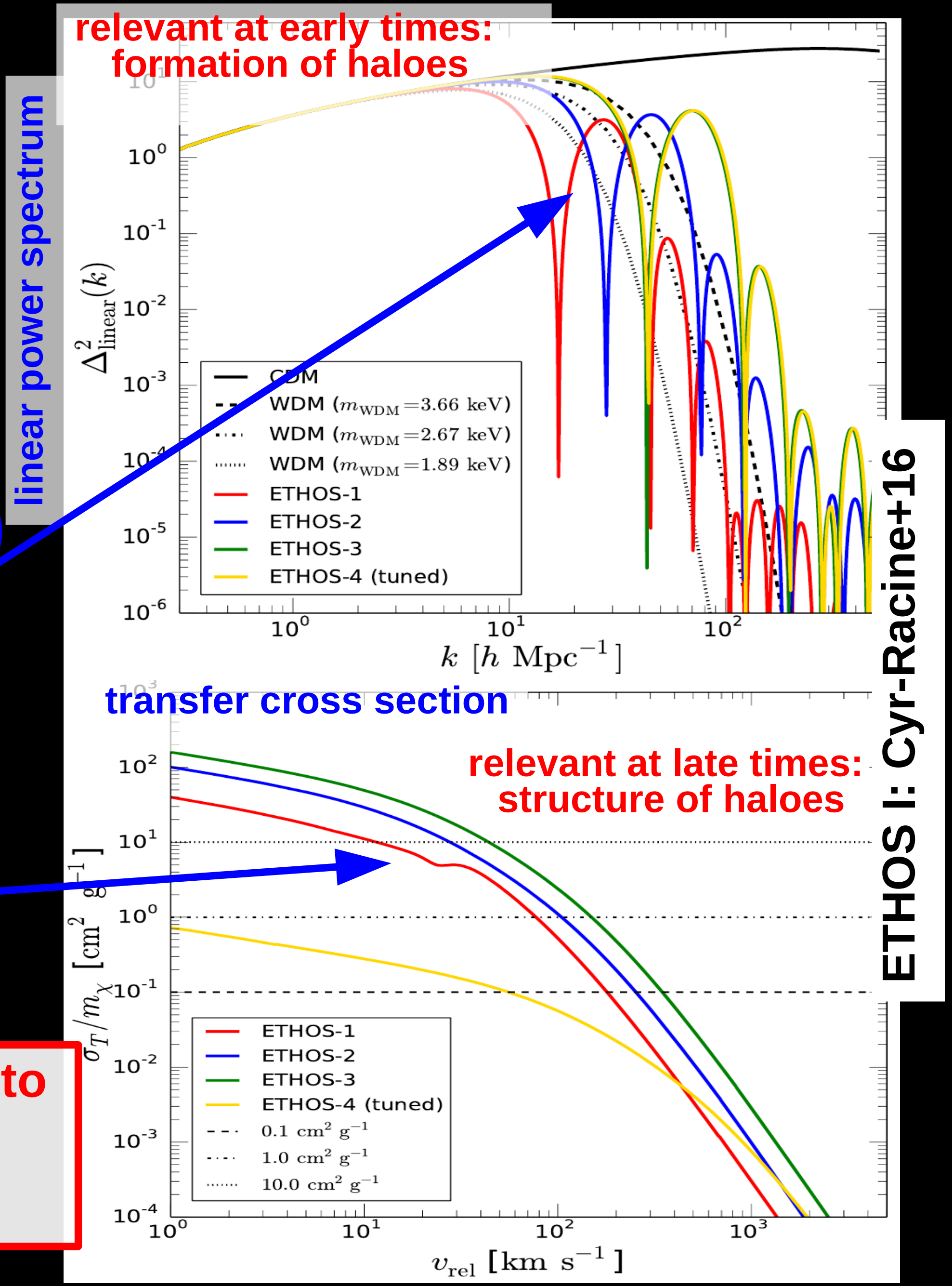
$$\left\{ m_\chi, \{g_i\}, \{h_i\}, \xi \right\}$$

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

ETHOS: the non-linear regime

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

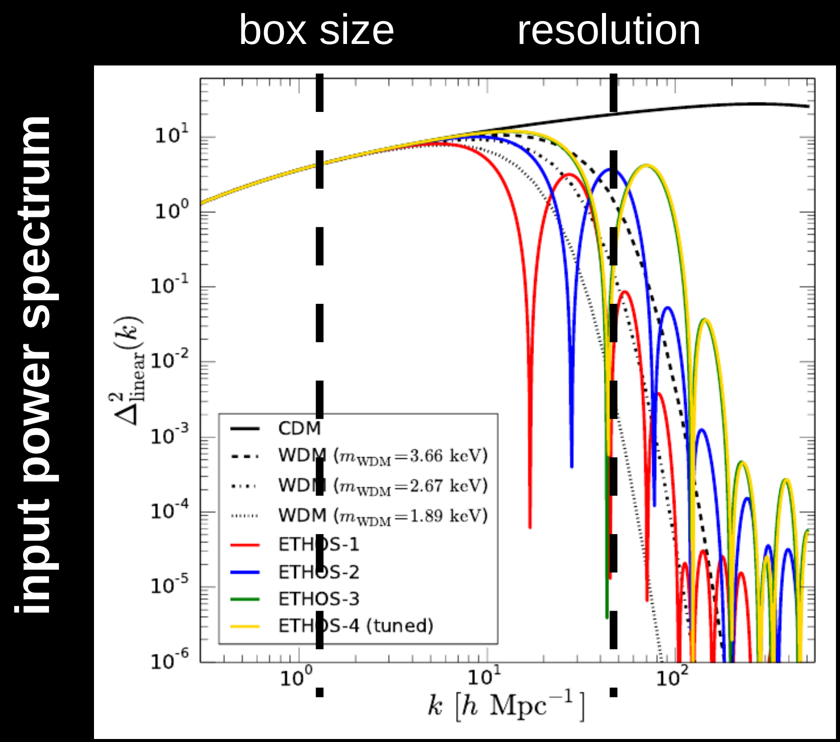
macro-to-micro-particle mass ratio

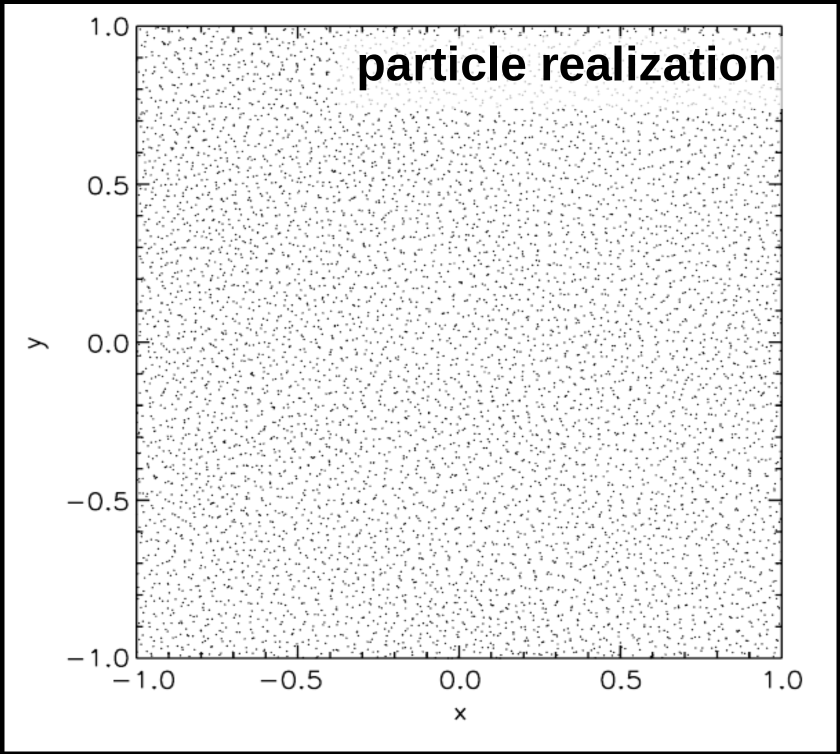
each particle is smoothed in space to give a smooth local density

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





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

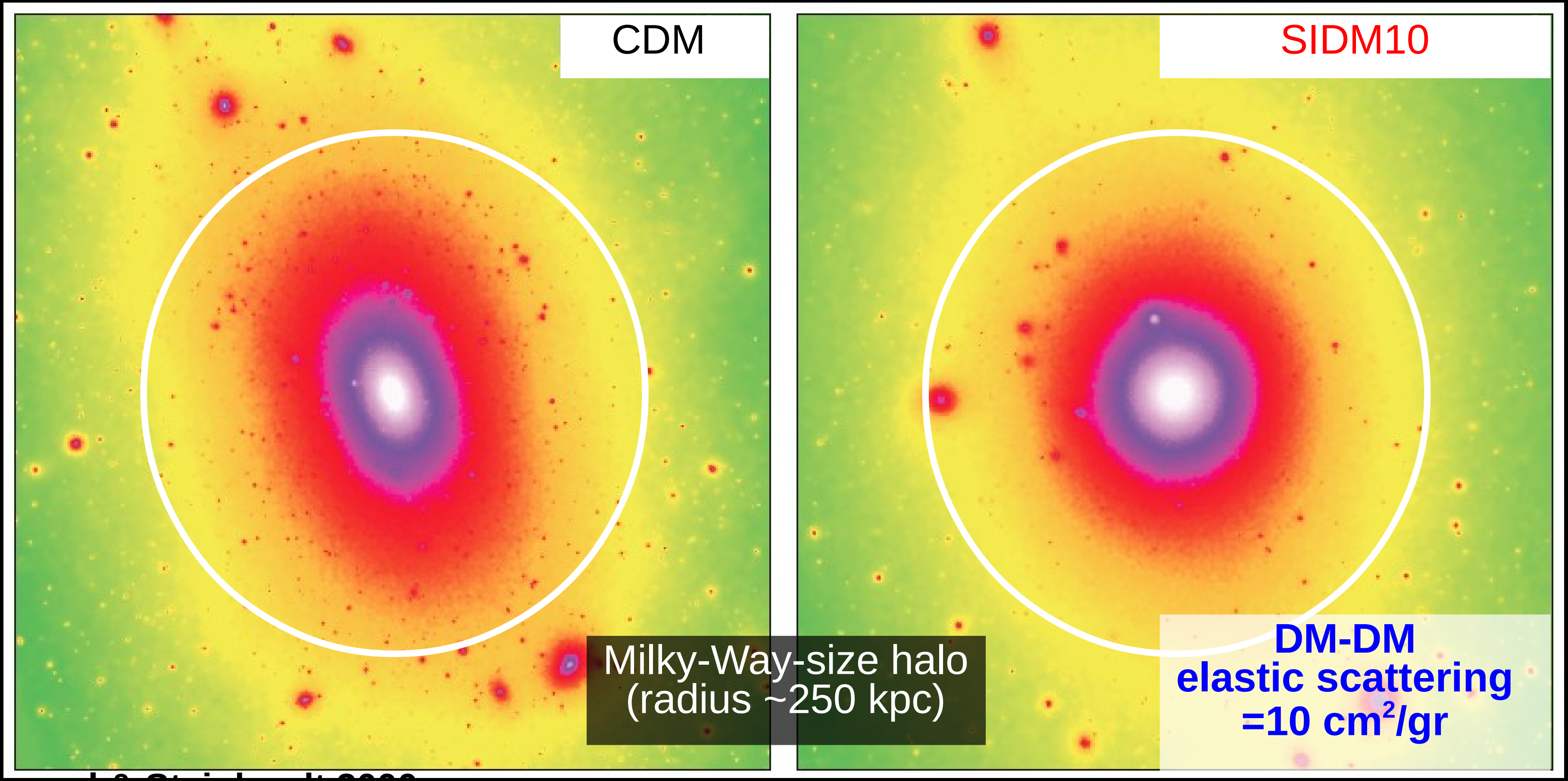
Kochanek & White 2000, Yoshida+2000,...Vogelsberger, Zavala, Loeb 2012, Rocha+2013

ETHOS: the structure of SIDM haloes

If gravity is the only relevant DM interaction, the central density of haloes is ever increasing

With strong self-interactions $\left(\sigma/m \gtrsim 0.5\,cm^2/gr\right)$ DM haloes develop nearly spherical“isothermal” cores

Vogelsberger, Zavala & Loeb 2012



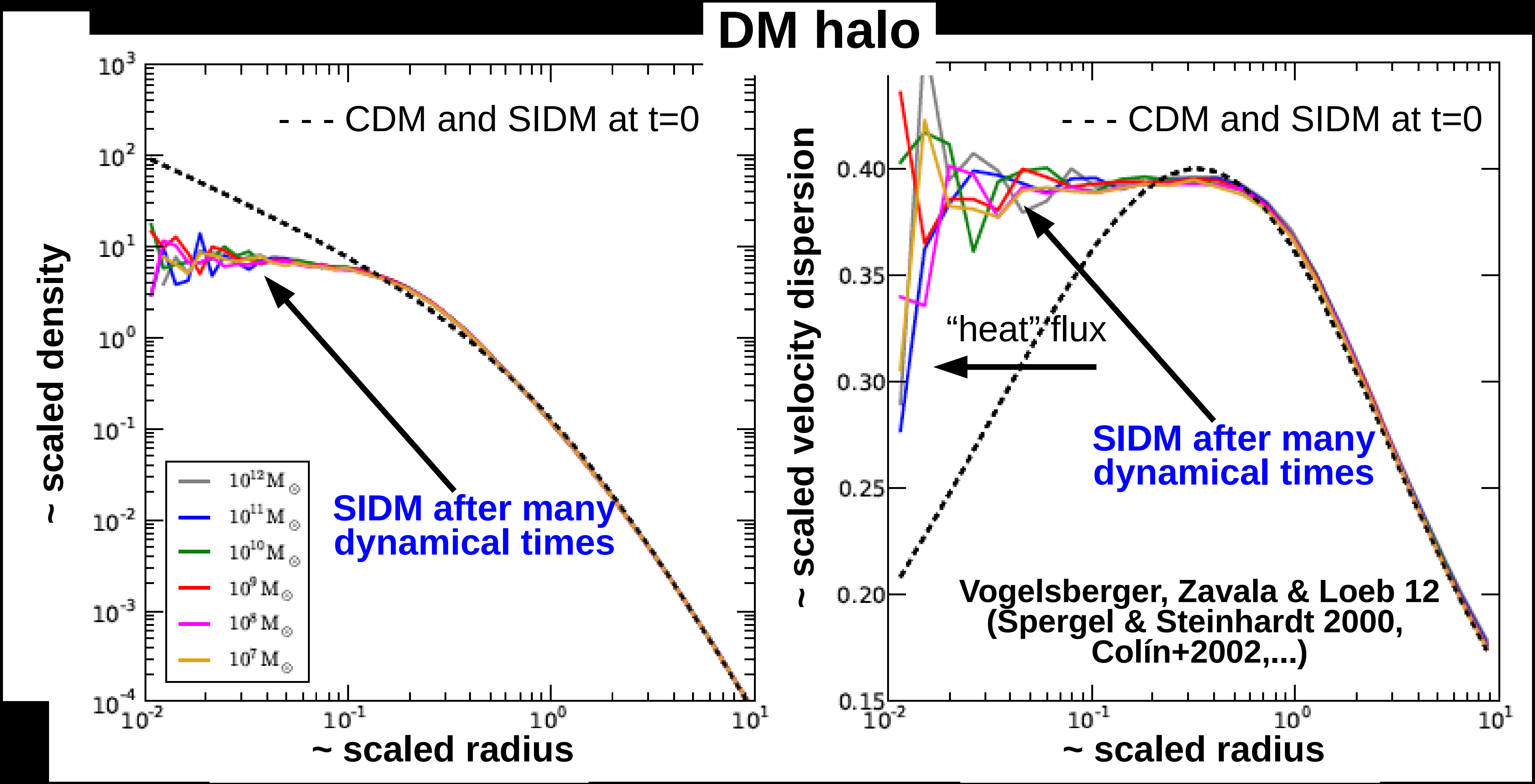
Milky-Way-size halo
(radius ~250 kpc)

DM-DM
elastic scattering
$=10\ cm^2/gr$

DM-only simulations

(Carlson+92, Spergel & Steinhardt 00, Yoshida+00, Davé+01, Colín+02, Rocha+13, Peter+13....)

ETHOS: isothermal core formation with SIDM



DM halo

- - - CDM and SIDM at t=0

SIDM after many dynamical times

- - - CDM and SIDM at t=0

“heat” flux

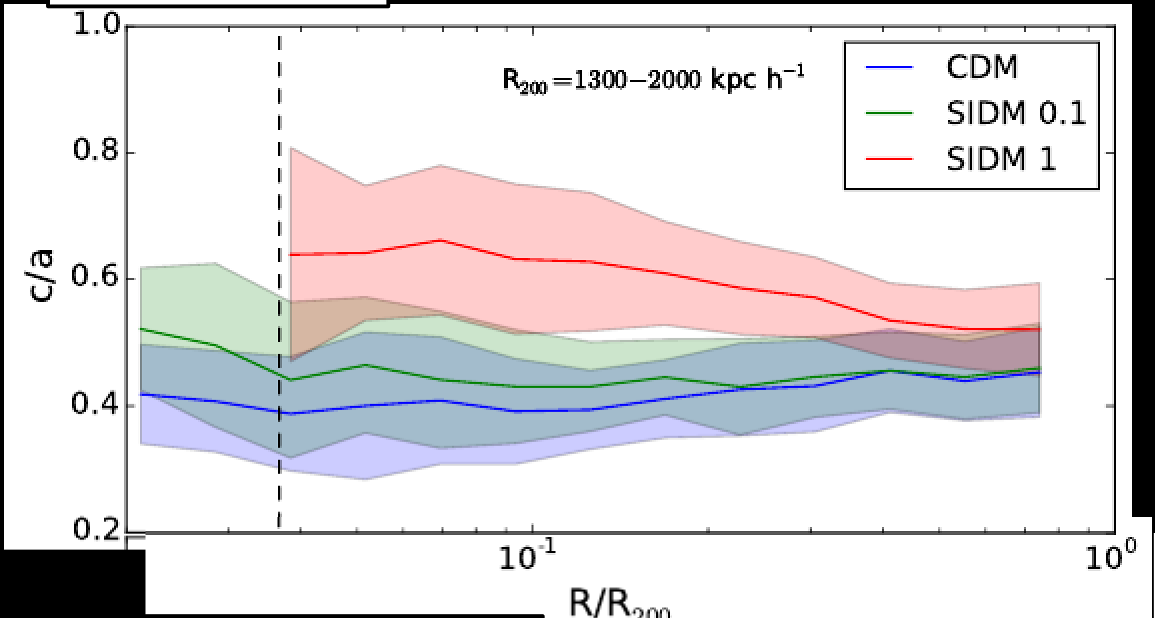
SIDM after many dynamical times

Vogelsberger, Zavala & Loeb 12
(Spergel & Steinhardt 2000,
Colín+2002,...)

ETHOS: the structure of SIDM haloes

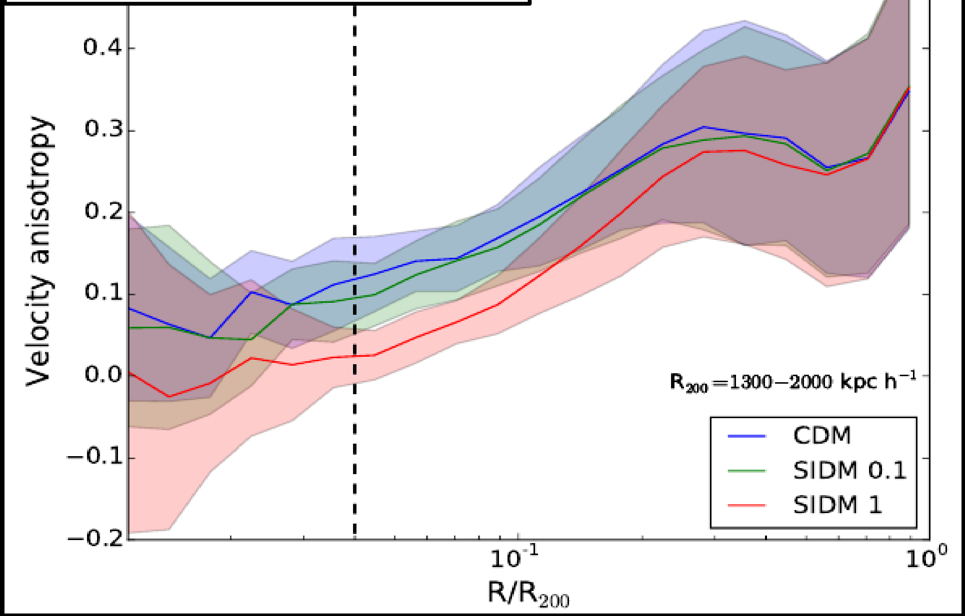
Brinckmann et al. 2017

Halo ellipticity

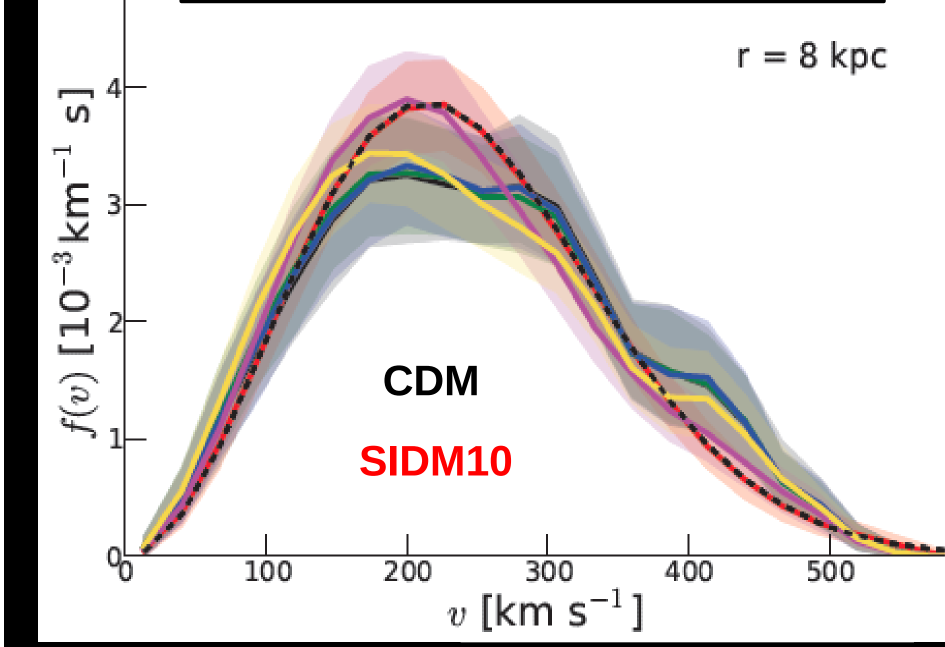


collisions erase the memory of assembly, haloes become more spherical, isotropic and Maxwellian

Halo velocity anisotropy



DM velocity distribution
at the Solar circle



Vogelsberger & Zavala 2013

The fate of all SIDM haloes (gravothermal fluid approximation)

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

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

isotropic
Jeans equation

heat flux

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

conductivity

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

1st law

mass shell

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

$$\tau \equiv \textit{relaxation}\quad \textit{time}$$

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

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

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

requires calibration from N-body sims

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

The fate of all SIDM haloes (gravothermal fluid approximation)

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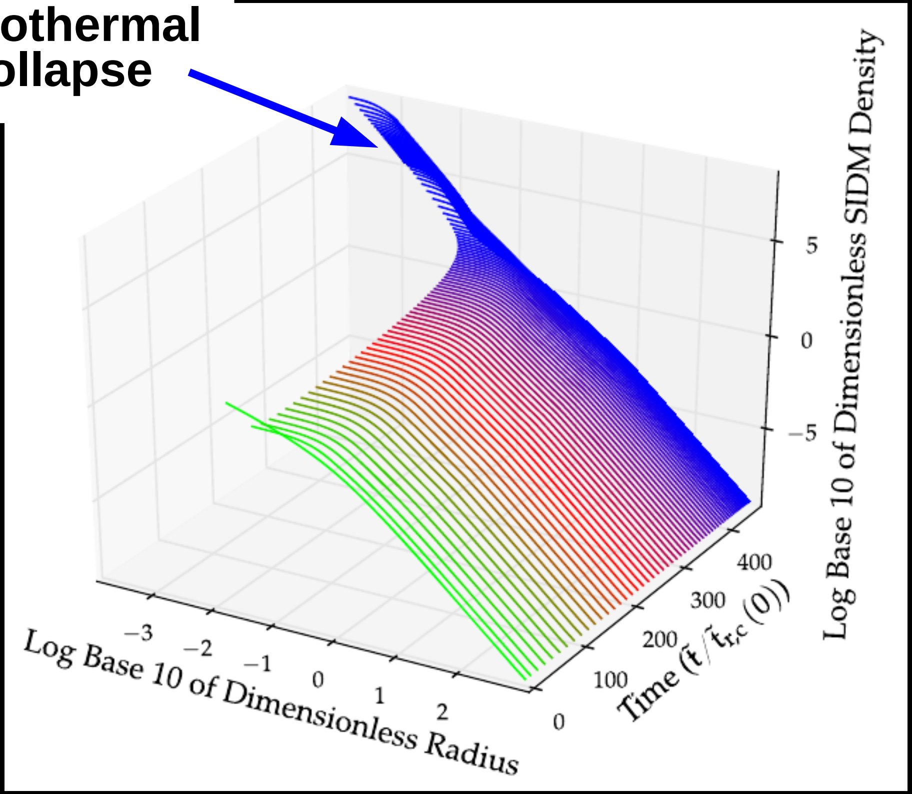
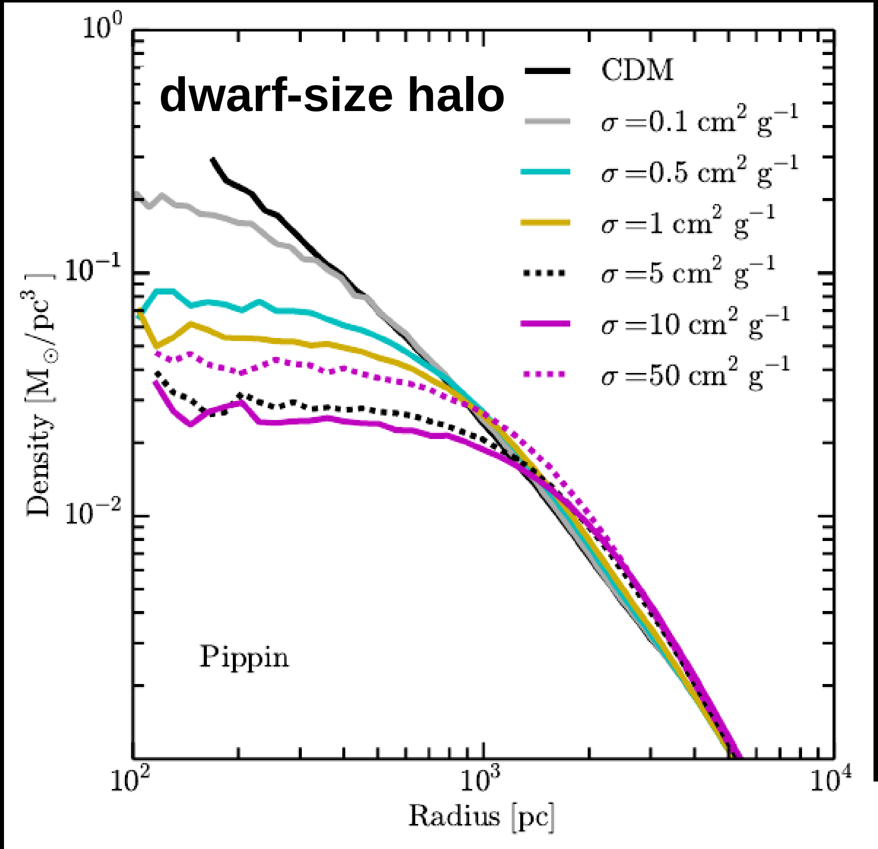

gravothermal collapse

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

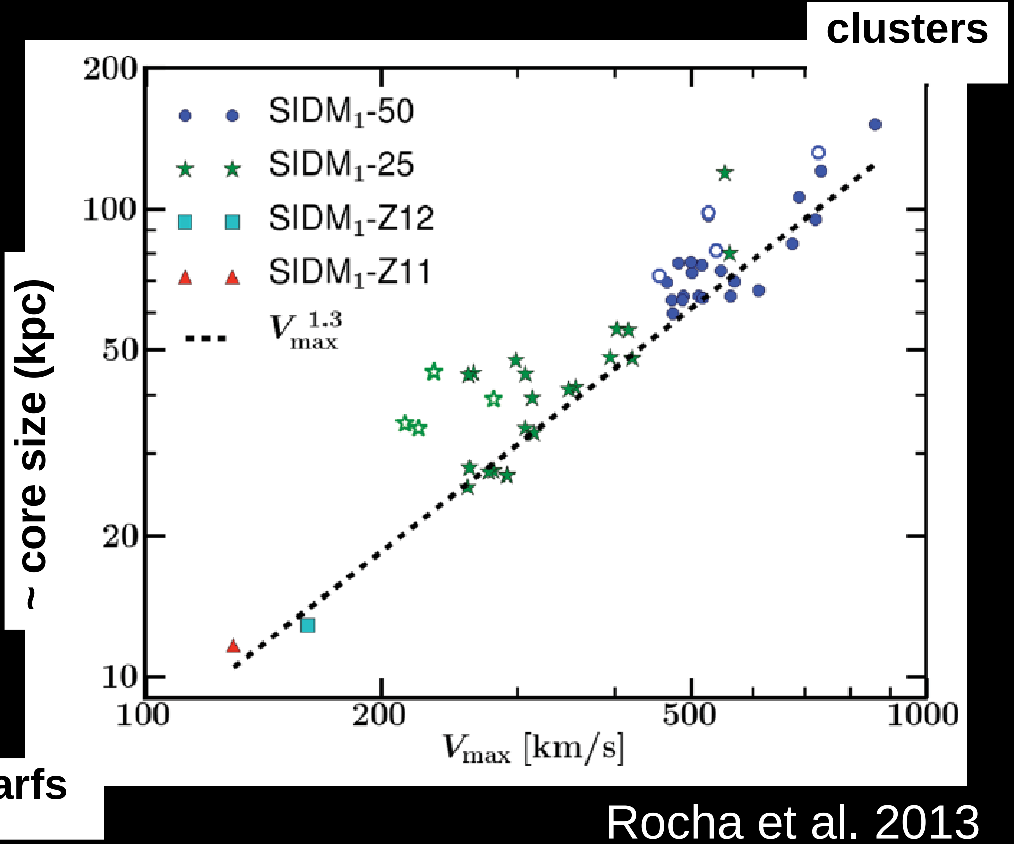
ETHOS: the structure of SIDM haloes

The size of the DM core scales with the amplitude of the cross section and the size of the DM halo (prior to the gravothermal collapse phase)

spherically averaged
DM distribution



Elbert et al. 2015



clusters

dwarfs

Rocha et al. 2013

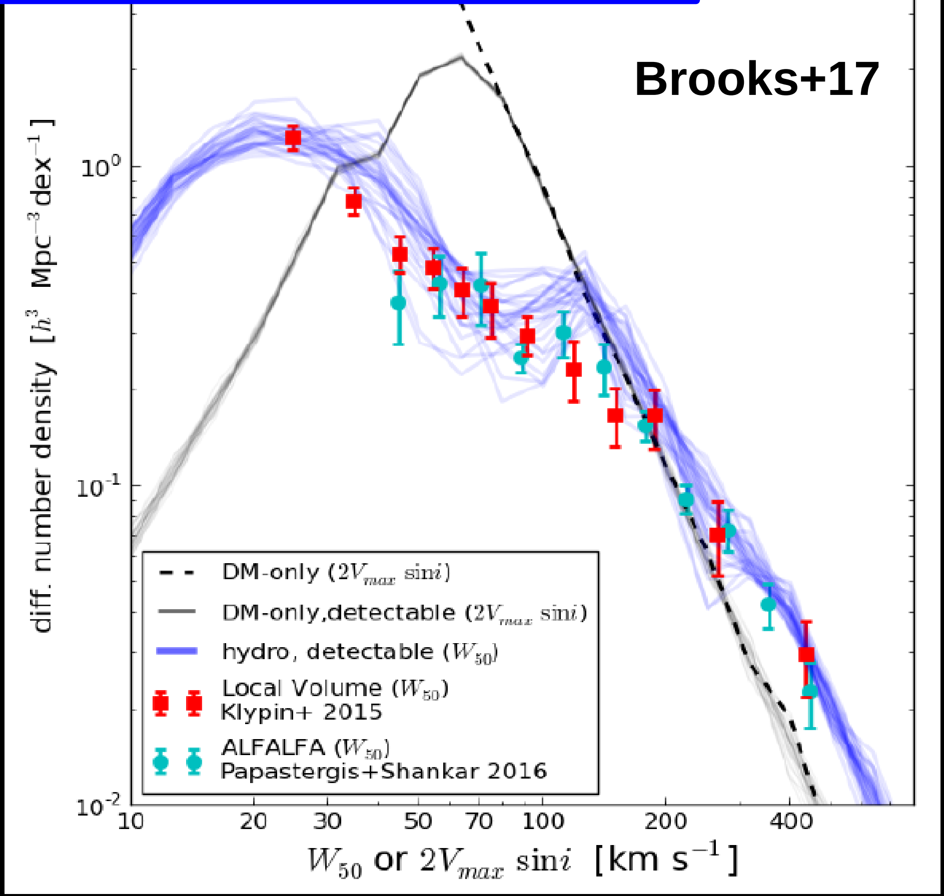
Known but uncertain and complex “baryonic physics”

Gas heating (UV background)
+
“strong” SN feedback
+
Observational effects

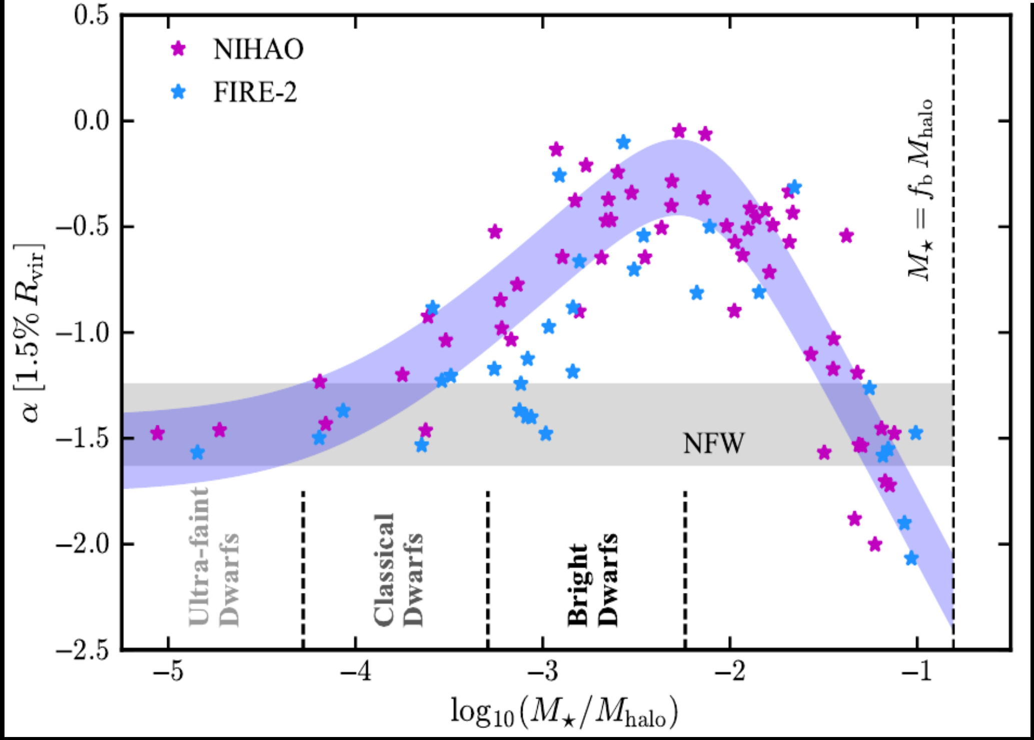
Gas and DM heating through supernovae

Core-cusp problem

Abundance problem

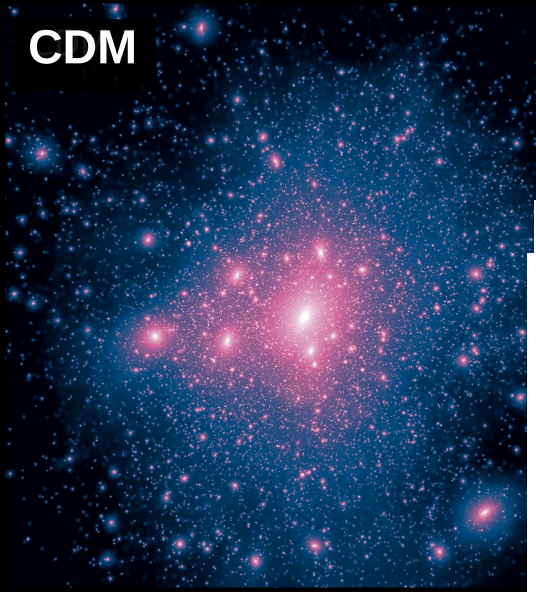


Bullock & Boylan-Kolchin 2017



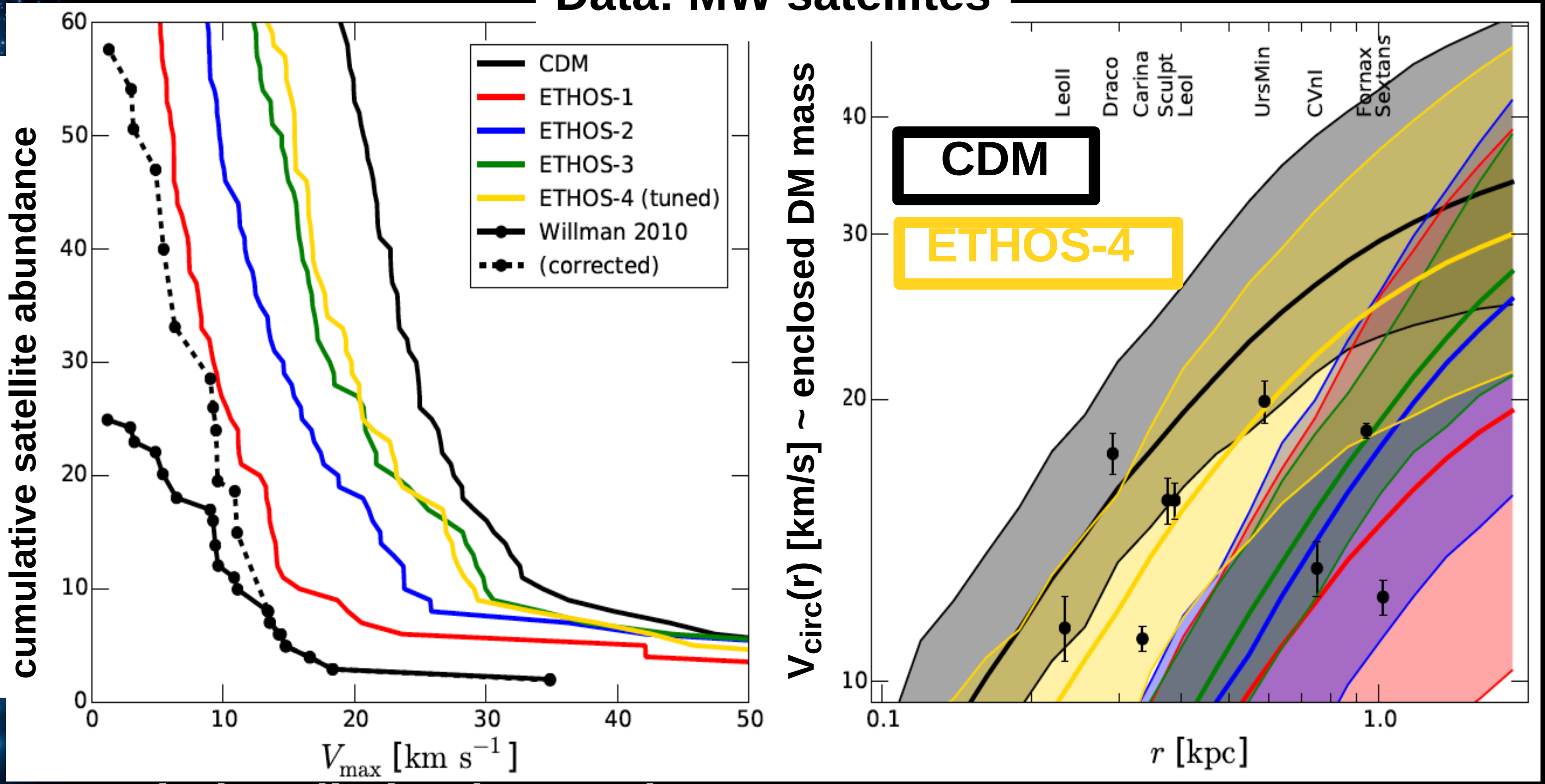
ETHOS: a couple of CDM challenges

Both CDM abundance and structural “problems” can be alleviated *simultaneously*



MW-size halo DM-only simulation

Data: MW satellites



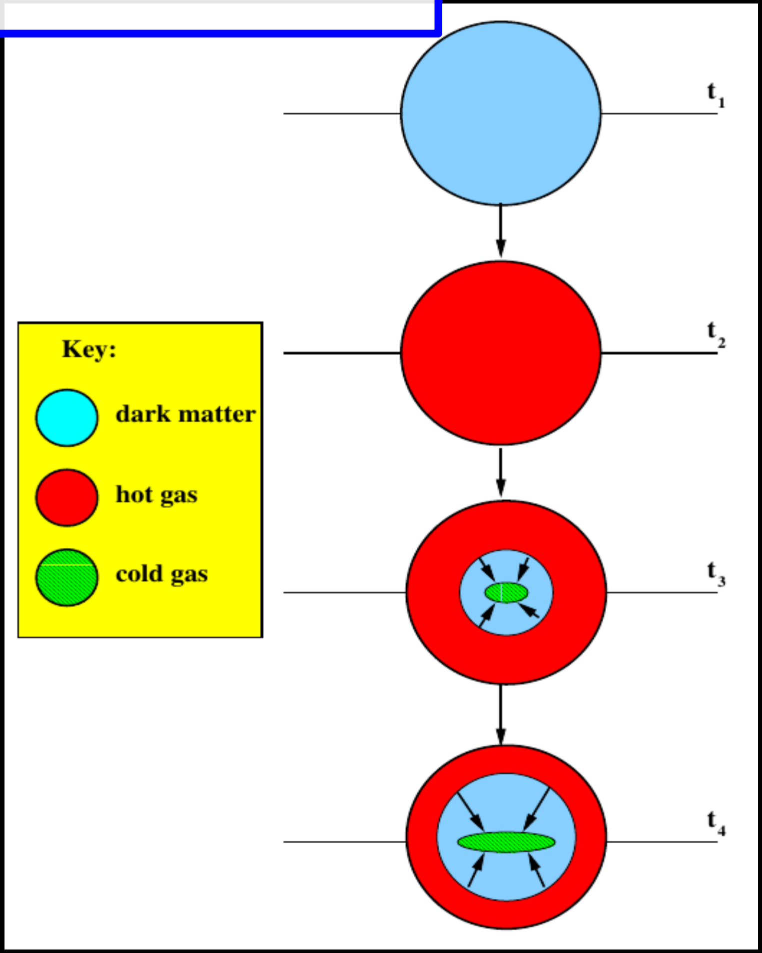
DM-dark radiation interactions suppress/delay the formation of small haloes (galaxies)

DM self-interactions reduce the central DM densities of haloes

ETHOS II: Vogelsberger+16

The challenging interplay between DM/baryonic physics

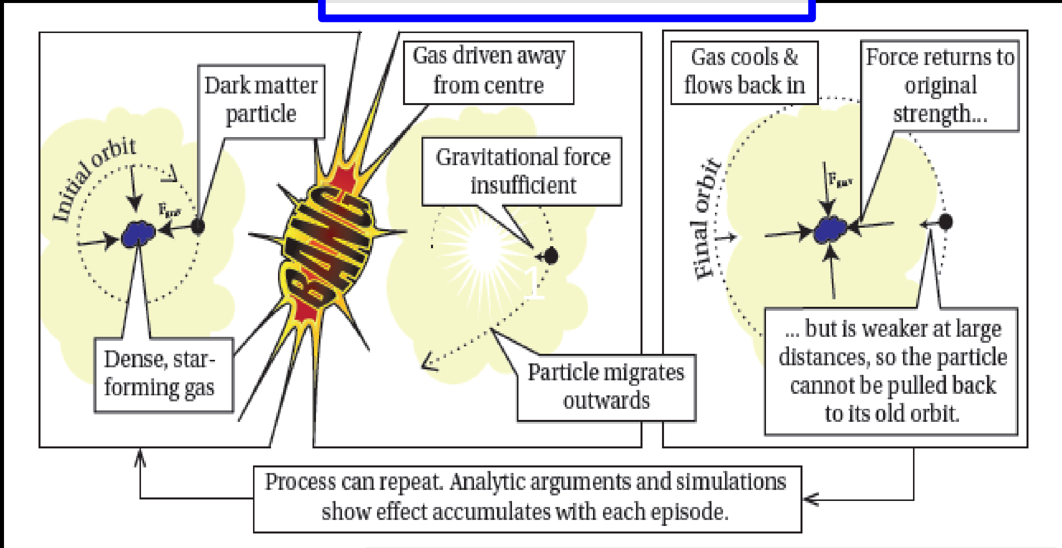
adiabatic contraction due to disk assembly



Baugh 2006

increases the inner density of DM haloes

gas and DM heating through supernovae



Dark matter particle

Dense, star-forming gas

Gas driven away from centre

Gravitational force insufficient

Particle migrates outwards

Gas cools & flows back in

Force returns to original strength...

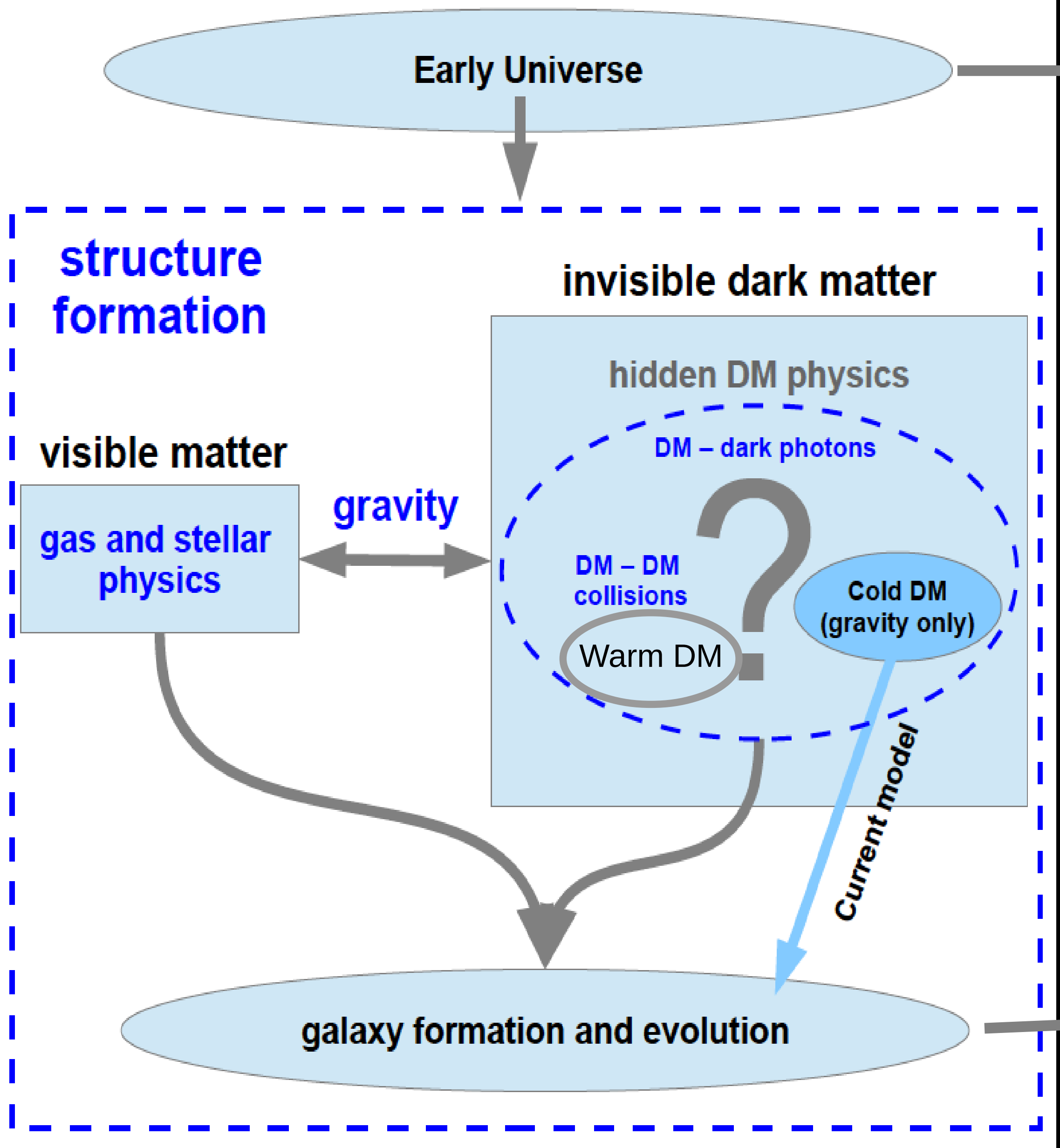
... but is weaker at large distances, so the particle cannot be pulled back to its old orbit.

Process can repeat. Analytic arguments and simulations show effect accumulates with each episode.

Credit: Pontzen & Governato 2014

reduces the inner density of DM haloes

Towards an Effective THeory Of Structure formation (ETHOS)



Early Universe

structure formation

invisible dark matter

hidden DM physics

visible matter

gas and stellar physics

gravity

DM – dark photons

DM – DM collisions

Warm DM

Cold DM (gravity only)

Current model

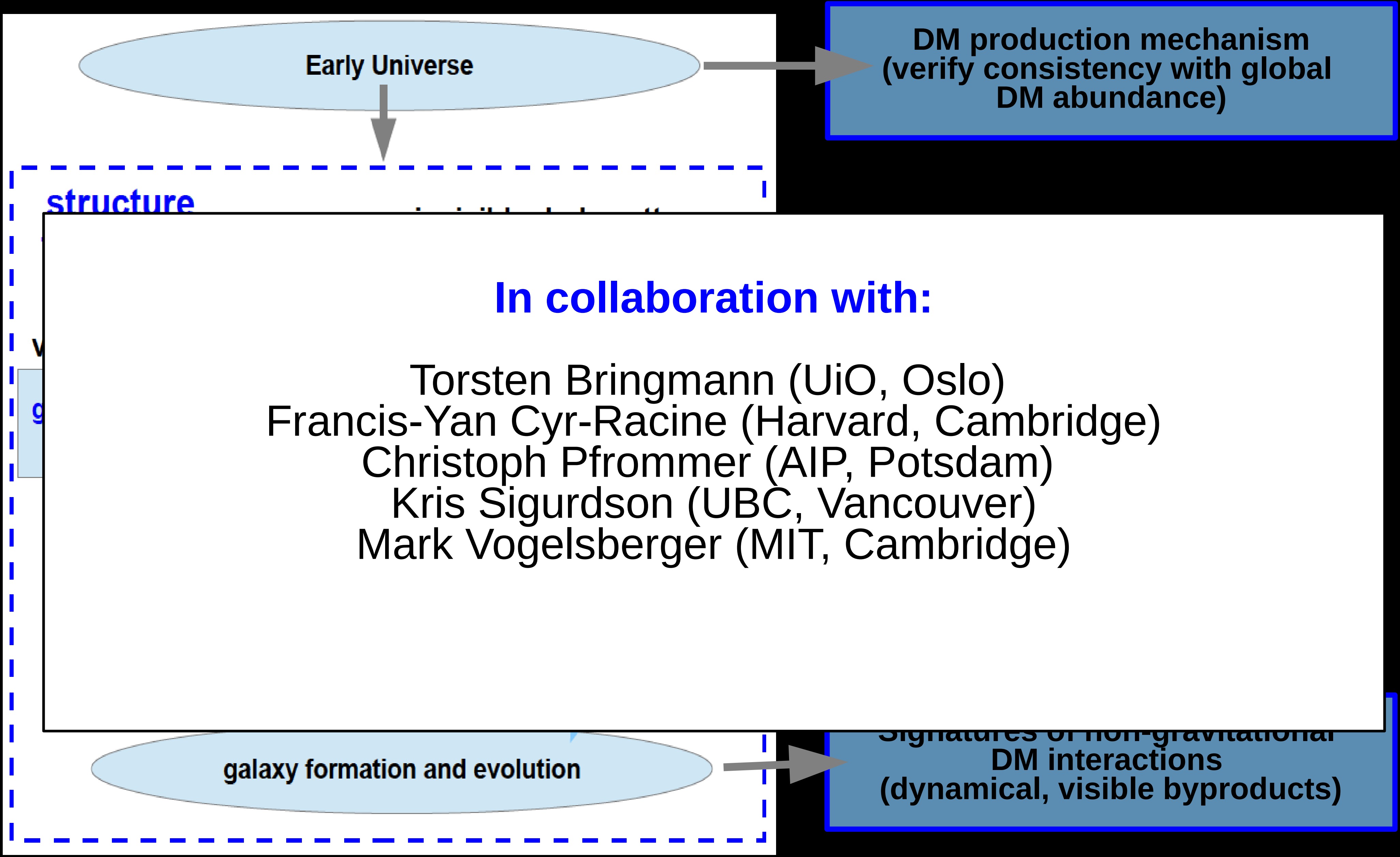
galaxy formation and evolution

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)

Towards an Effective THeory Of Structure formation (ETHOS)



Early Universe

DM production mechanism (verify consistency with global DM abundance)

structure

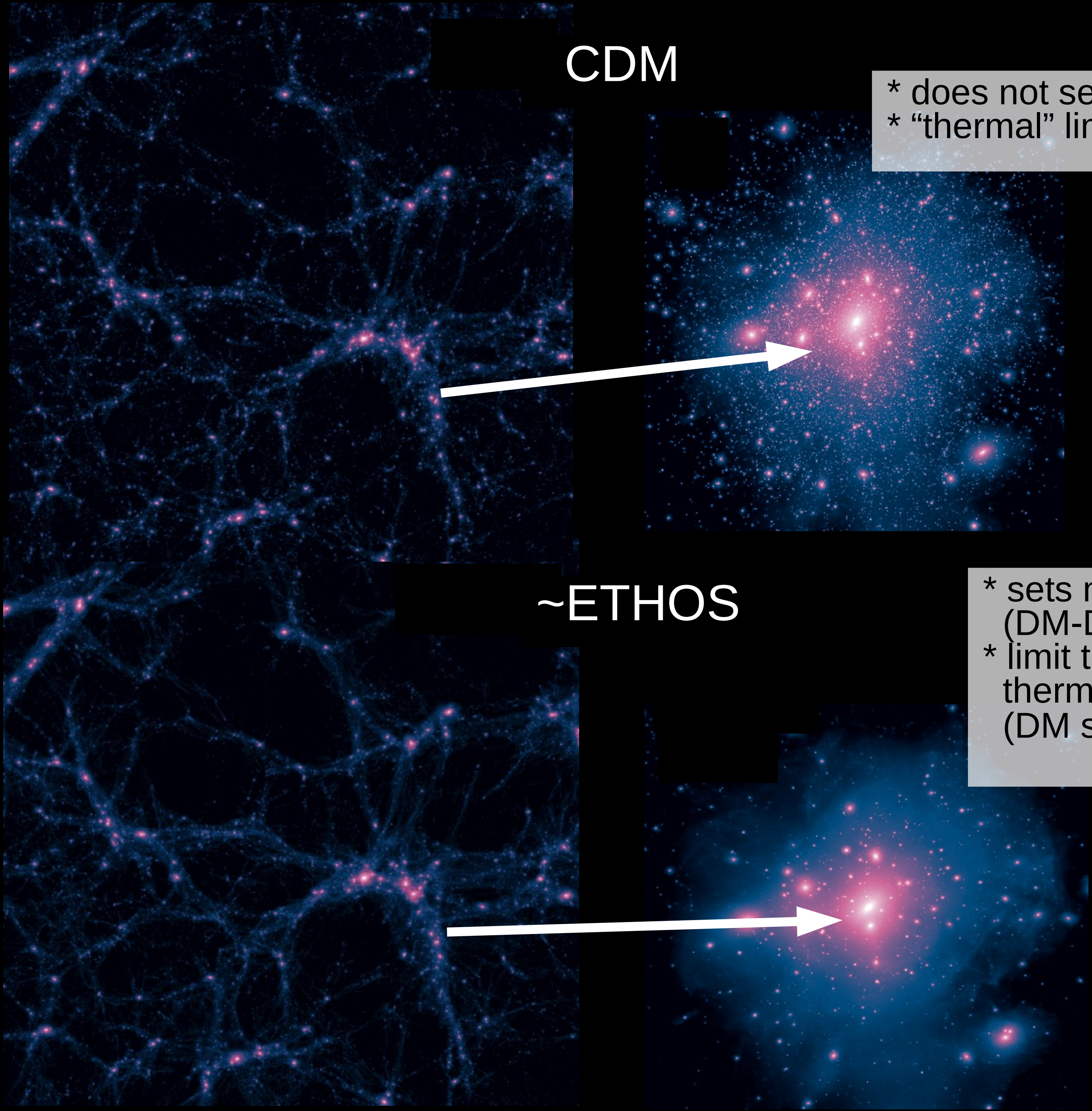
galaxy formation and evolution

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

In collaboration with:

Torsten Bringmann (UiO, Oslo)
Francis-Yan Cyr-Racine (Harvard, Cambridge)
Christoph Pfrommer (AIP, Potsdam)
Kris Sigurdson (UBC, Vancouver)
Mark Vogelsberger (MIT, Cambridge)

ETHOS: difference with the standard CDM model



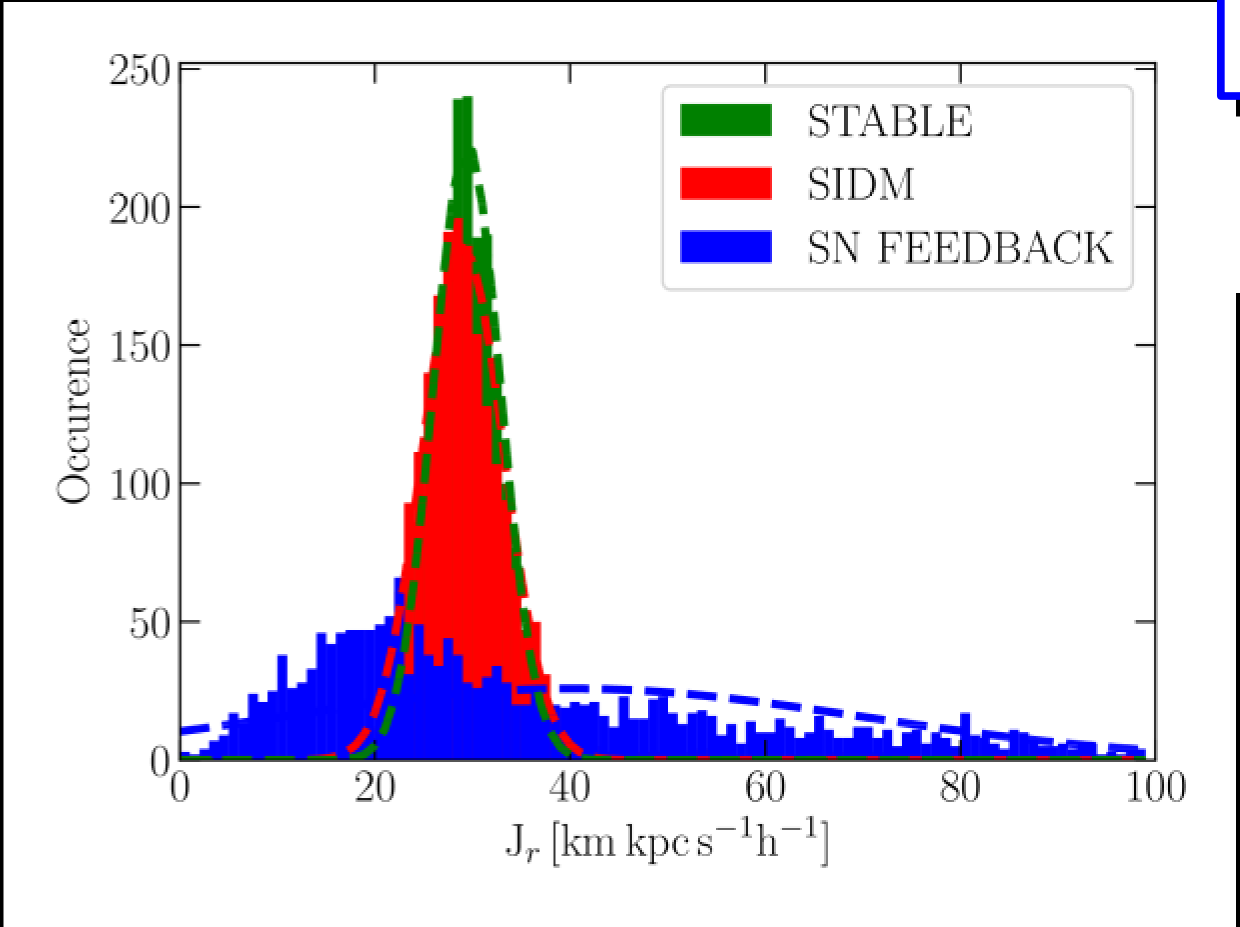
* does not set minimum galactic scale
* “thermal” limit to phase space density

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

Adiabatic (SIDM) vs Impulsive (SN feedback) DM core formation

What is the response of stars(tracers) to these two mechanisms of core formation?

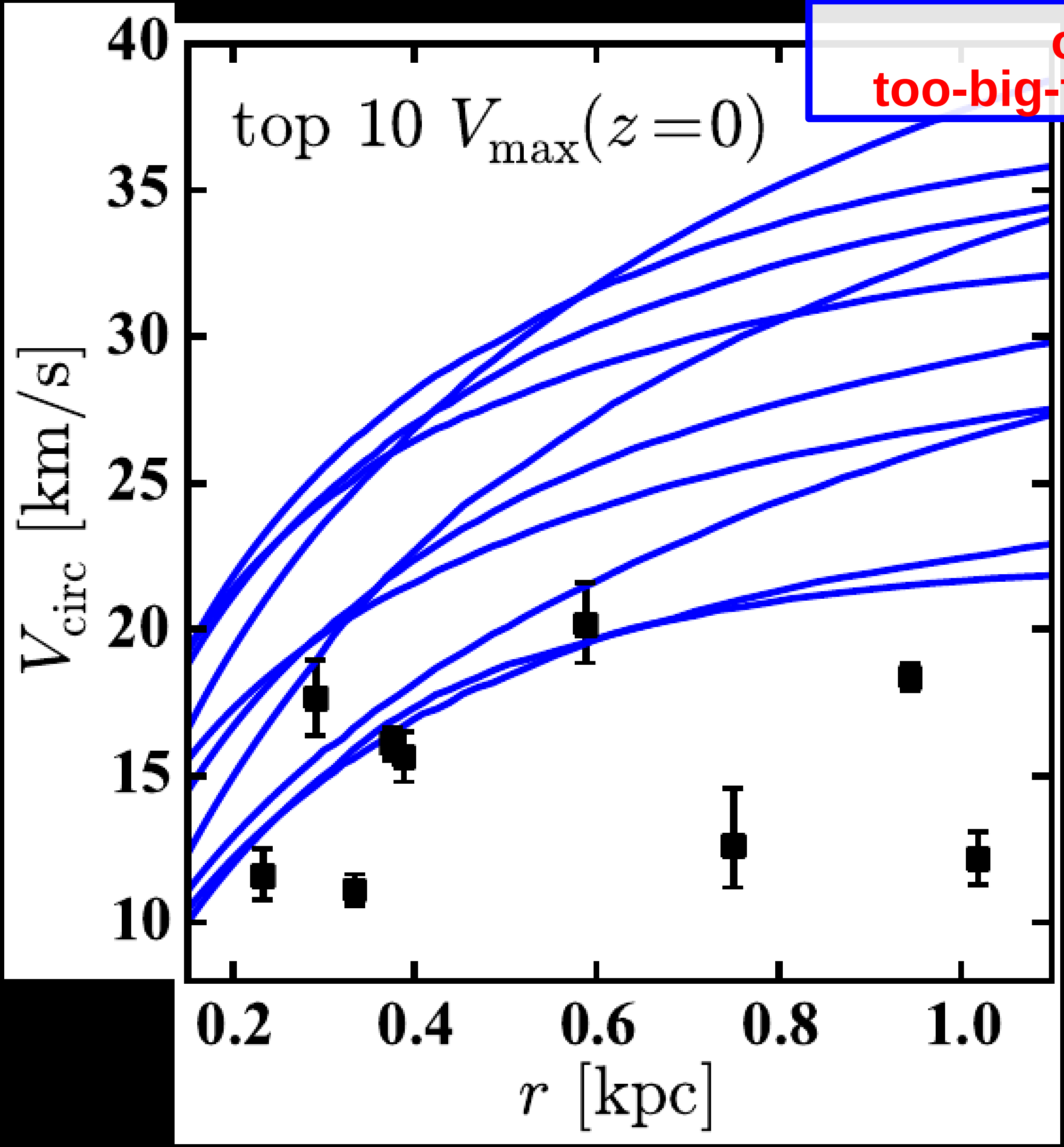
$$J_r = \frac{1}{\pi}\int_{r_{min}}^{r_{max}} dr\sqrt{2E - 2\Phi(r) - \frac{L^2}{r^2}}$$



Burger & Zavala 2018 in prep.

diverse sub-kpc DM densities in MW satellites

Aquarius project
CDM-only (no baryonic physics)



original
too-big-to-fail problem

Boylan-Kolchin+2012