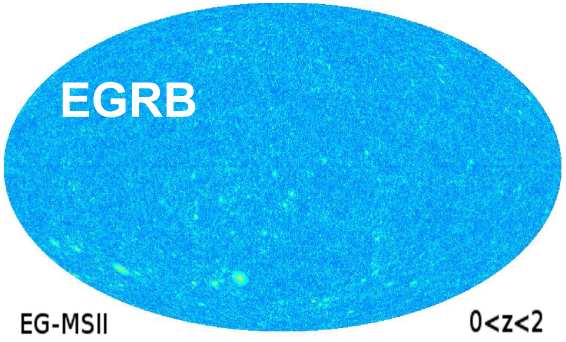
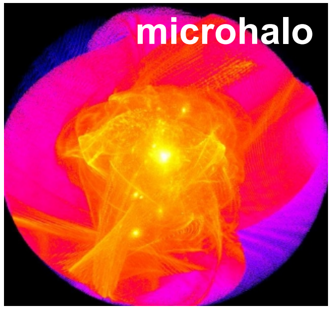
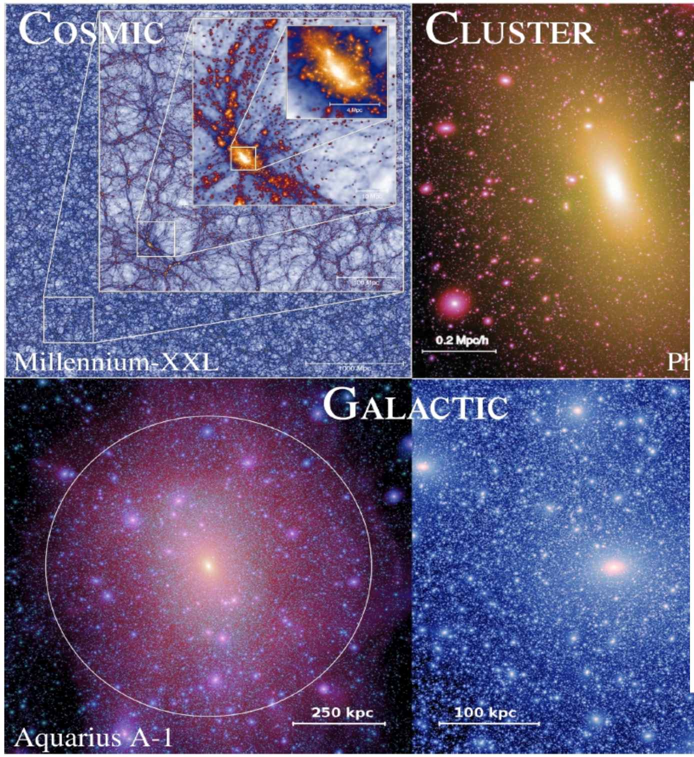
Investigating the nature of dark matter with numerical simulations of structure formation

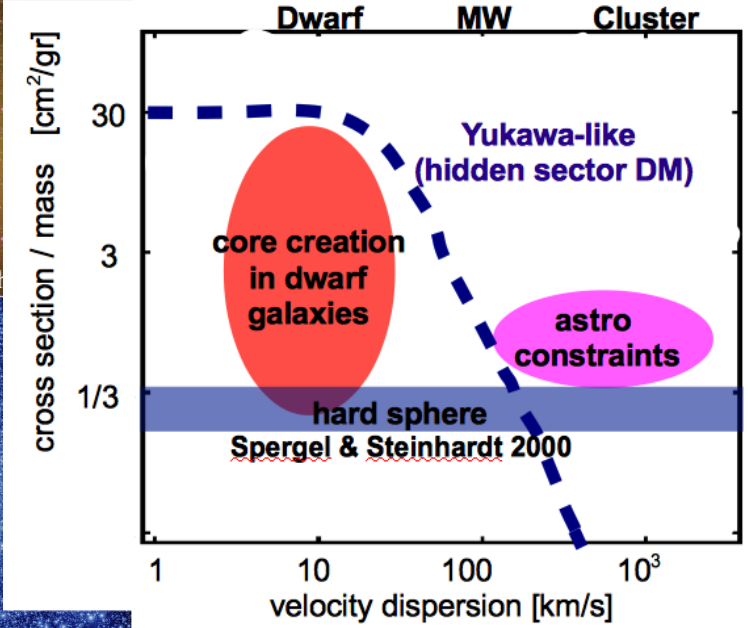
Jesús Zavala Franco

(Marie Curie Fellow)









Workshop: Dark Matter Numerical Simulations, Saclay, September 2014

Outline

- Towards an effective theory of structure formation

  - Motivation: DM interactions and structure formation
  - Implementation of new DM physics in N-body simulations (seminar tomorrow)
  - Consequences for galaxy formation/evolution (seminar tomorrow)

- Using N-body simulations to obtain predictions for non-gravitational DM signals

  - Resolved phase-space structure (what we know)
  - Unresolved phase-space structure (extrapolation)

The “standard model” of structure formation

The current model of structure formation
is the Cold Dark Matter (CDM) model

Hypothesis: DM is a new cold and collisionless particle

Galaxies form in a purely gravitational DM background, i.e., the nature of DM as a particle is irrelevant for galaxy formation and evolution

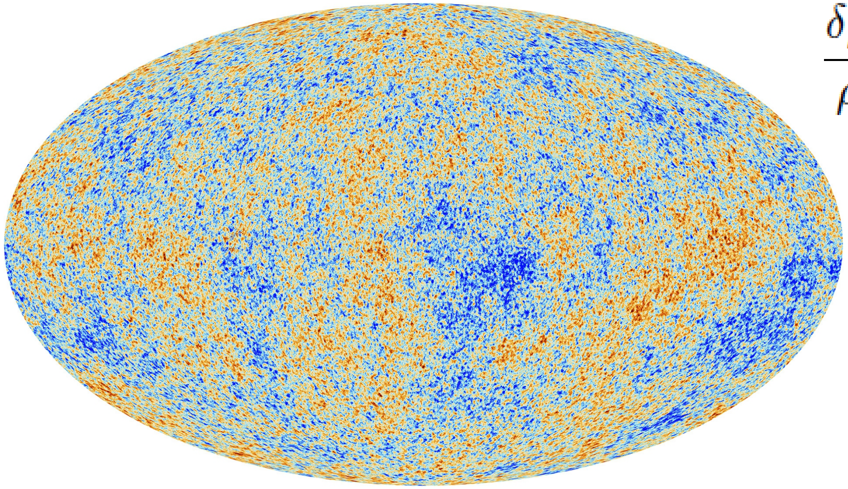
CDM is by itself an incomplete DM theory
that needs completion from a particle physics model
(all beyond SM: “exotic”)

Dark Matter astrophysics

The particle DM hypothesis is the cornerstone of the current theory of the formation and evolution of galaxies

Credit: ESA and the Planck Collaboration

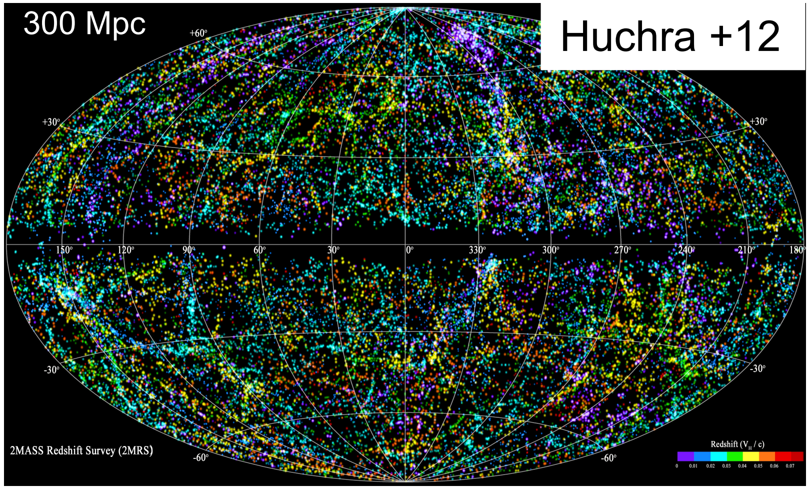
Early Universe (t ~ 0.4 Myrs)



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

Cosmic Microwave Background Radiation

Universe today (t ~ 13.8 Gyrs)



2MRS galaxy “map”, large-scale structure

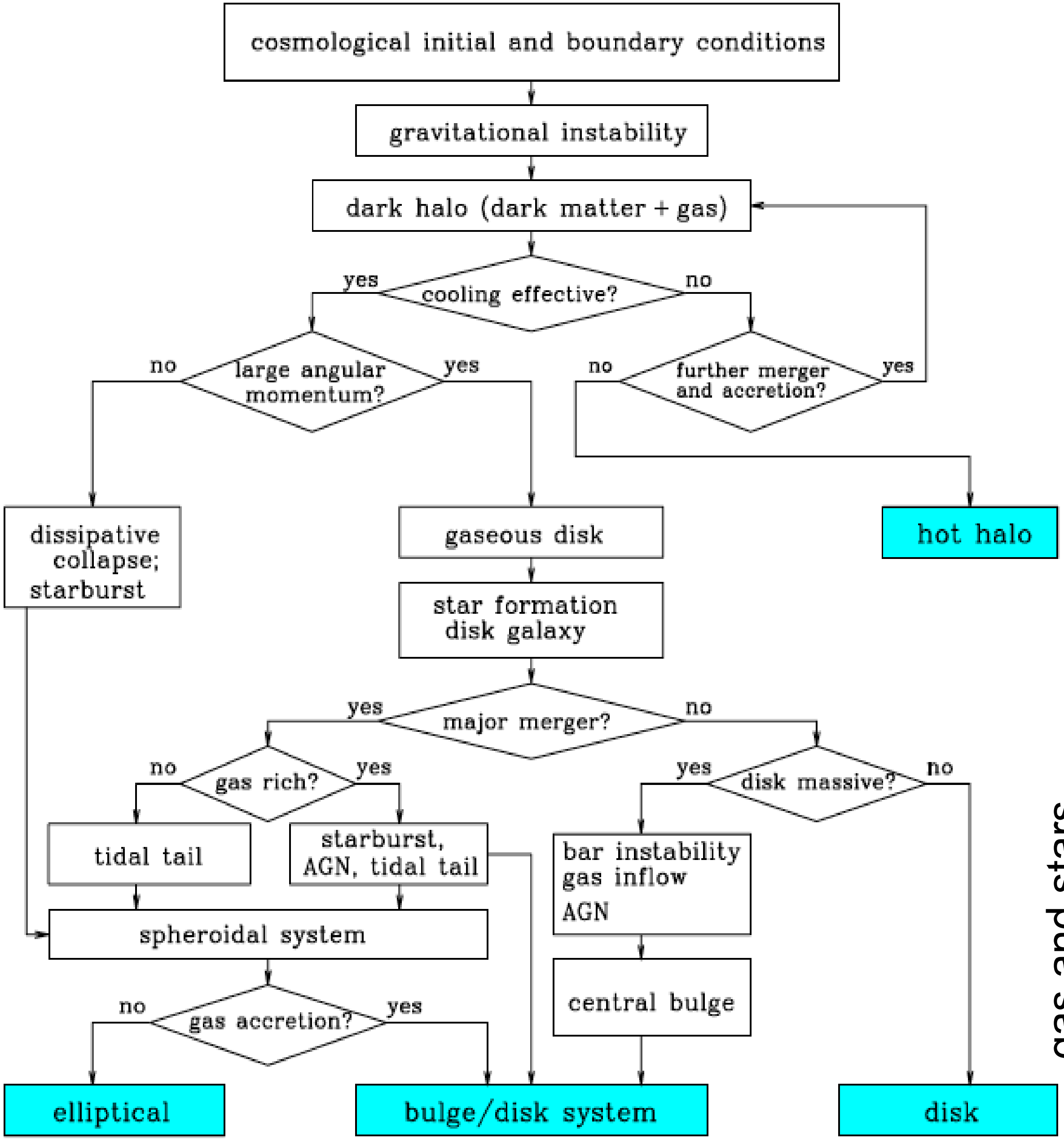
$$\frac{\delta\rho_m}{\rho_m} \gtrsim 1$$

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

galactic scales

Galaxy formation in a DM background

Fig. from Mo, Mao and White, 2010



cosmological initial and boundary conditions

gravitational instability

dark halo (dark matter + gas)

cooling effective?

yes

no

large angular momentum?

no

yes

further merger and accretion?

no

yes

dissipative collapse; starburst

gaseous disk

hot halo

star formation disk galaxy

major merger?

yes

no

gas rich?

no

yes

disk massive?

yes

no

tidal tail

starburst, AGN, tidal tail

bar instability gas inflow AGN

spheroidal system

central bulge

gas accretion?

no

yes

elliptical

bulge/disk system

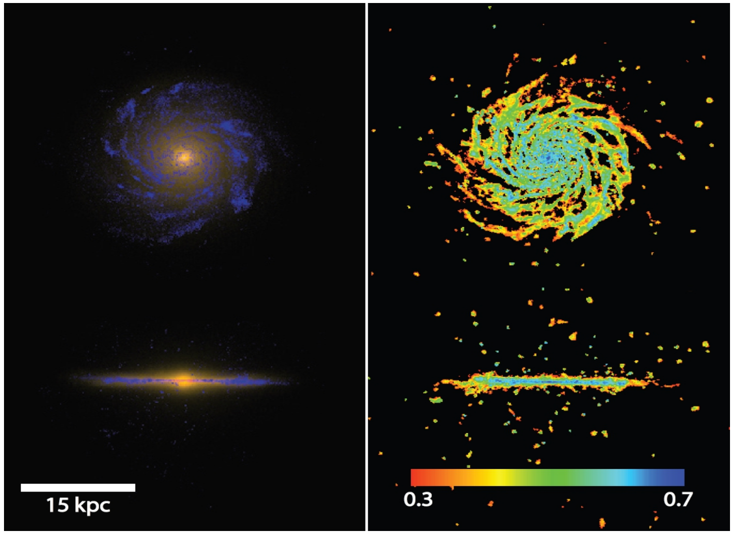
disk

DM gravity only

Aquarius project Springel+08

“Eris” simulation Guedes+11

gas and stars



Towards an effective theory of structure formation:

motivation for additional DM physics in structure formation

A few remarks

In CDM, galaxies form in a purely gravitational DM background, i.e., the nature of DM as a particle is irrelevant for galaxy formation and evolution

There is however, **no strong evidence** to support this **strong** hypothesis

A less stringent hypothesis preserves the success of CDM at large scales and predicts a distinct DM phase-space structure at smaller scales

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

DM nature and structure formation

Early Universe

DM nature (decoupling)

halo mass seed ?

Is the minimum scale for galaxy formation set by the DM nature or by gas physics (or by both)?

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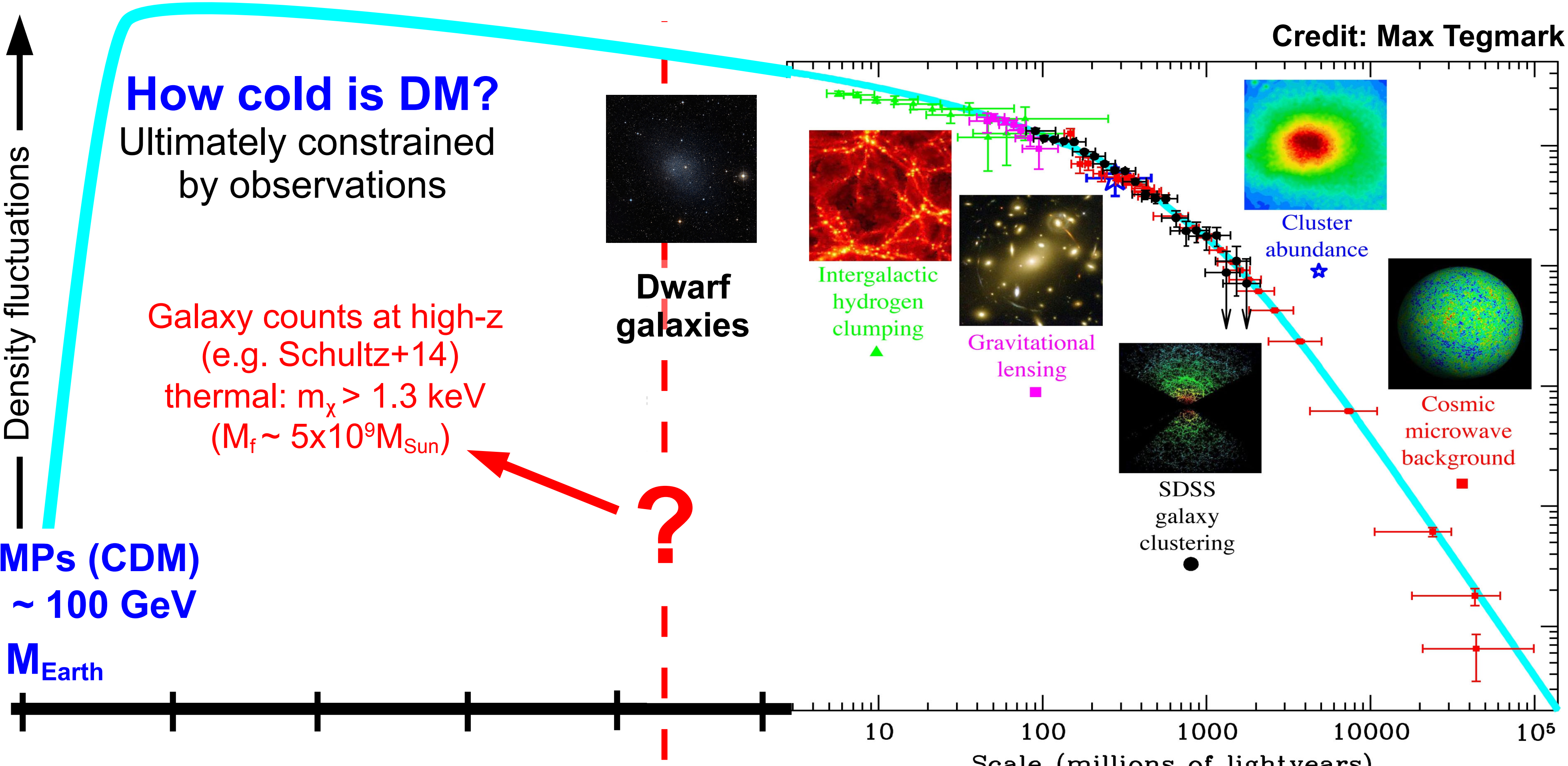


How cold is DM?

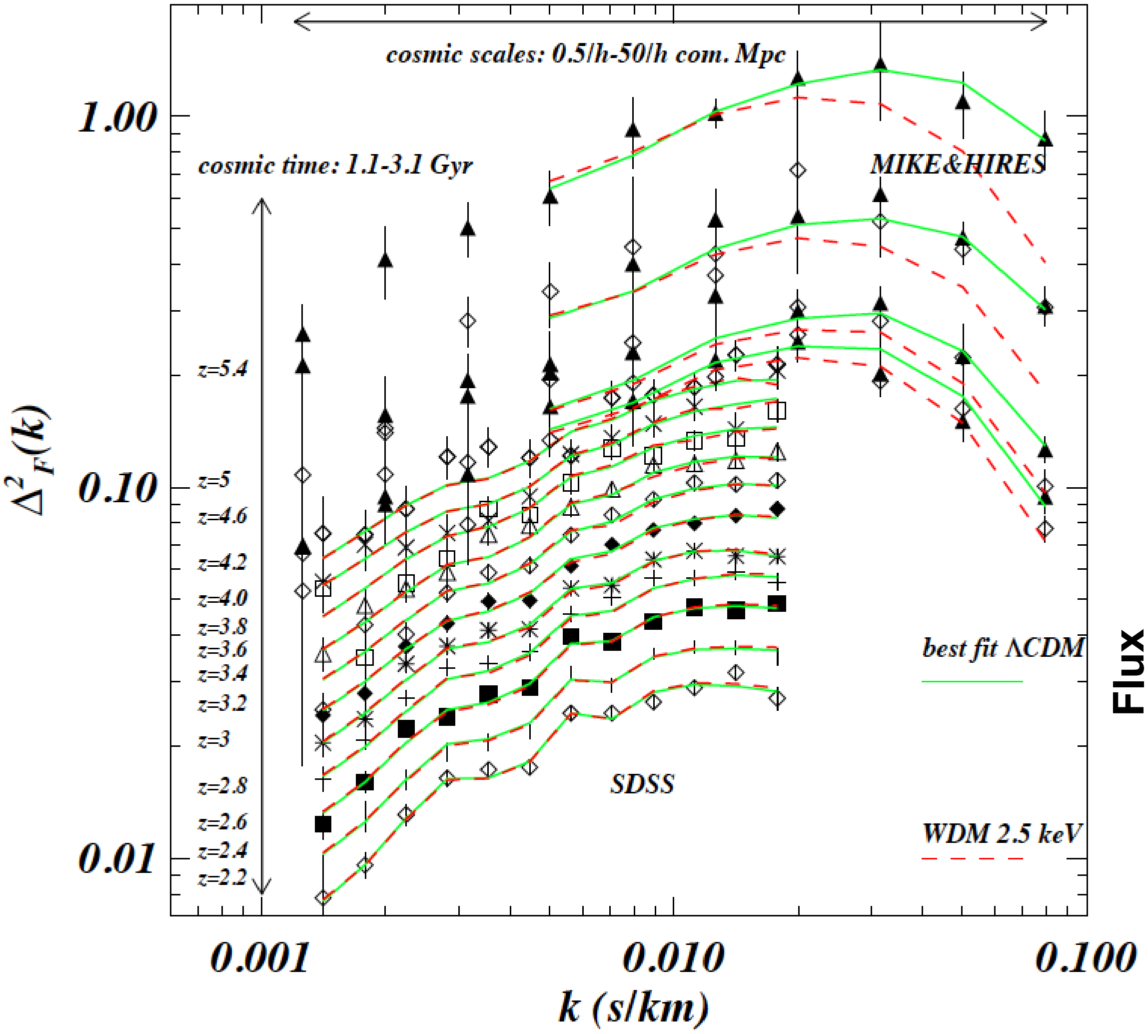
Ultimately constrained by observations

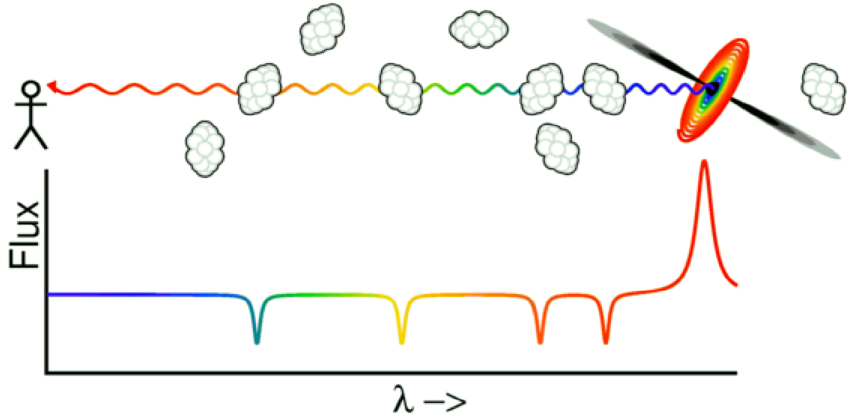
Galaxy counts at high-z (e.g. Schultz+14)
thermal: $m_\chi > 1.3$ keV
($M_f \sim 5\text{x}10^9 M_{Sun}$)

WIMPs (CDM)
$m_\chi \sim 100$ GeV
$1M_{Earth}$

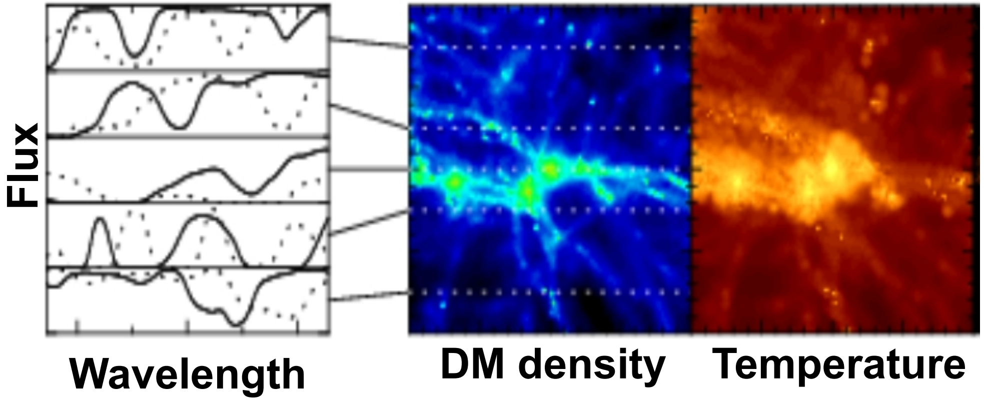
(e.g. Ly-α forest constraints)

Viel+13 thermal WDM (m_χ > 3.3 keV, $M_f(k_{1/2})$~$3x10^8 M_{Sun}$, 2σ C.L.)





DM power spectrum – IGM connection



Credit: Martin White

(e.g. Ly-α forest constraints)

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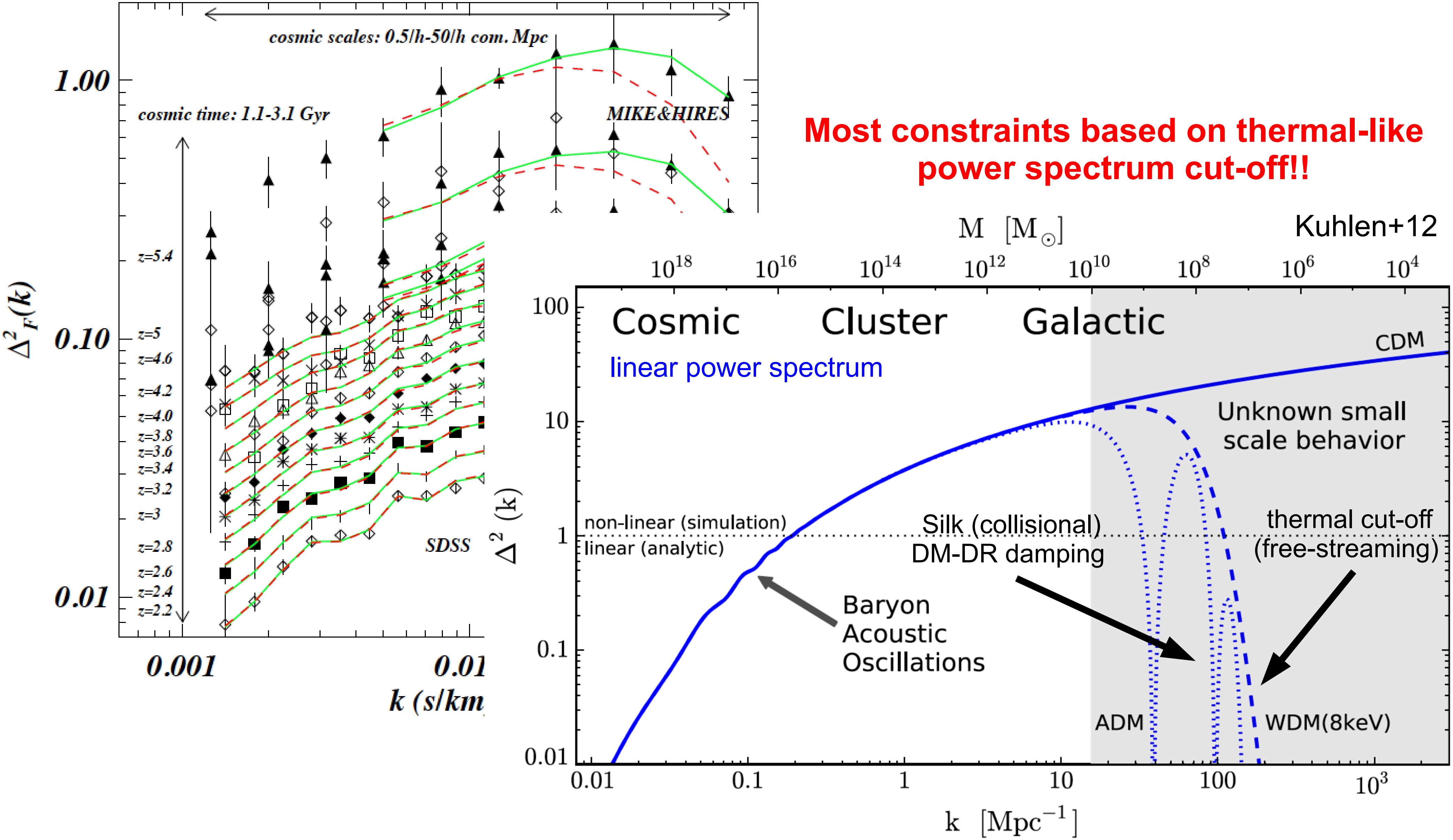
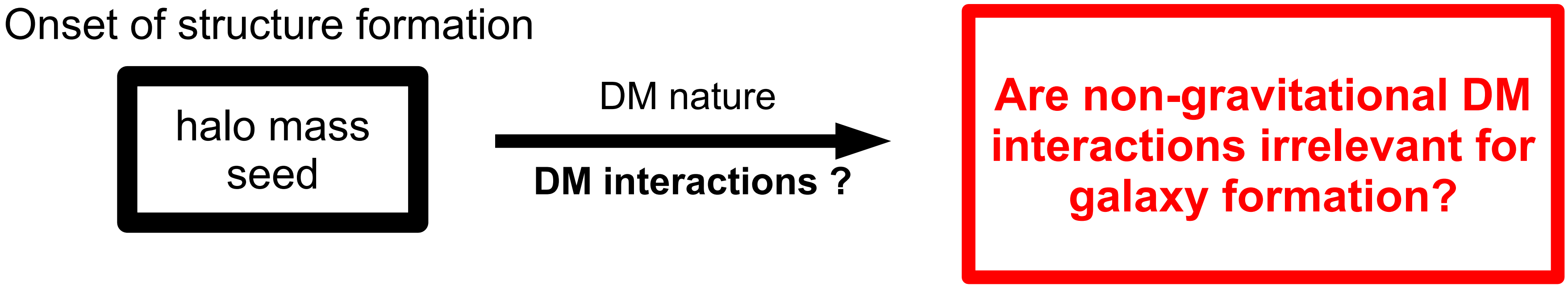


Most constraints based on thermal-like power spectrum cut-off!!

Kuhlen+12

Structure formation and DM interactions



Onset of structure formation

halo mass seed

DM nature

DM interactions ?

Are non-gravitational DM interactions irrelevant for galaxy formation?

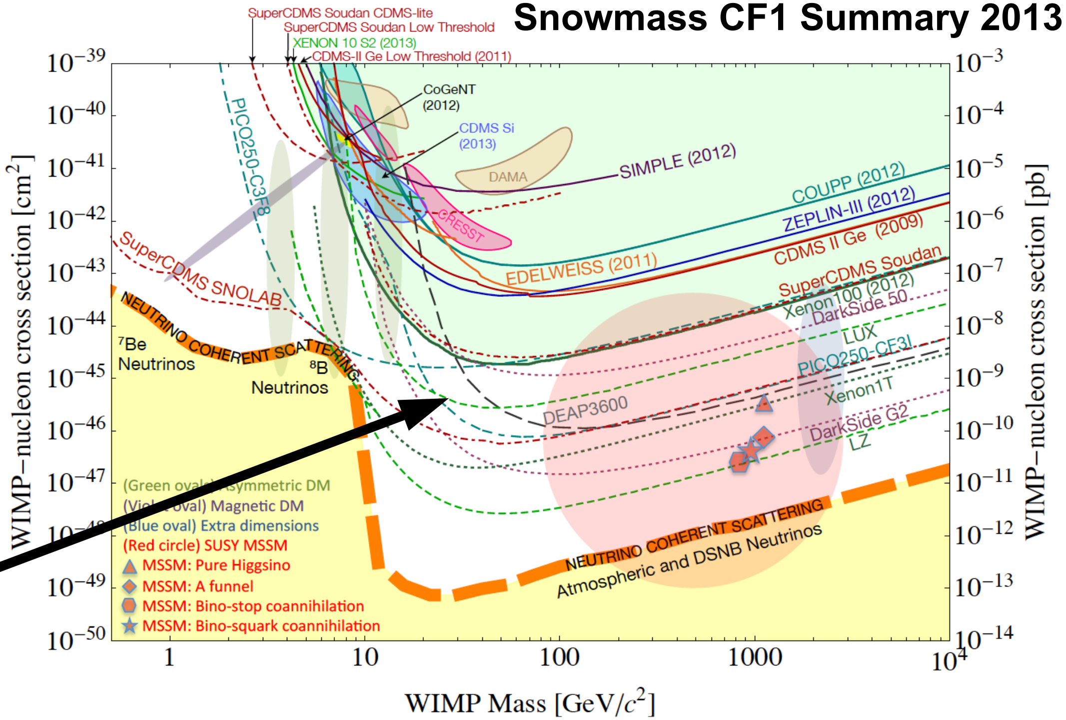
Structure formation and DM interactions

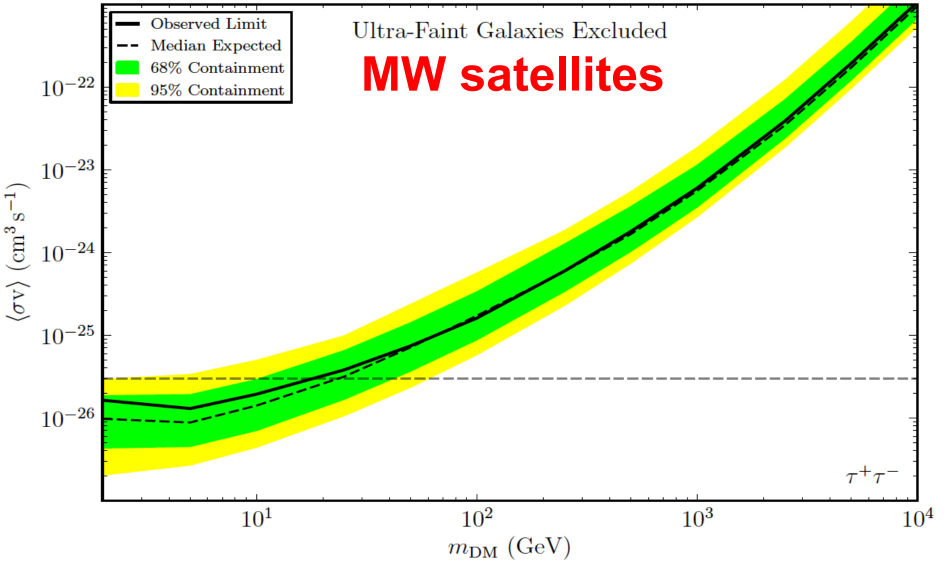
Are non-gravitational DM interactions irrelevant for galaxy formation?

DM particle interactions (weak scale)
hoped by most detection efforts!!

Cross section σ/m_χ [cm^2/gr]	Characteristic velocity $\tilde{v}$ [km/s]
SI $\chi-$nucleon $\lesssim 10^{-23}$	~ 200
$m_\chi \in (0.1-5)$ TeV	(local halo)
LUX	
$\chi\chi \rightarrow b\bar{b}$ $\lesssim 10^{-10}$	~ 10
$m_\chi \in (0.1-1)$ TeV	(dSphs)
Fermi-LAT	

1 cm^2/g ~ 2 barns/GeV


Snowmass CF1 Summary 2013


MW satellites

Fermi-LAT collaboration 14

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Fermi-LAT	

1 cm^2/g ~ 2 barns/GeV

Does it interact with ordinary matter?

χ-nucleus interactions extremely low to impact structure information

Does it interact with itself (annihilation)?

χ−χ self-annihilation extremely low to impact structure information

Structure formation and DM interactions

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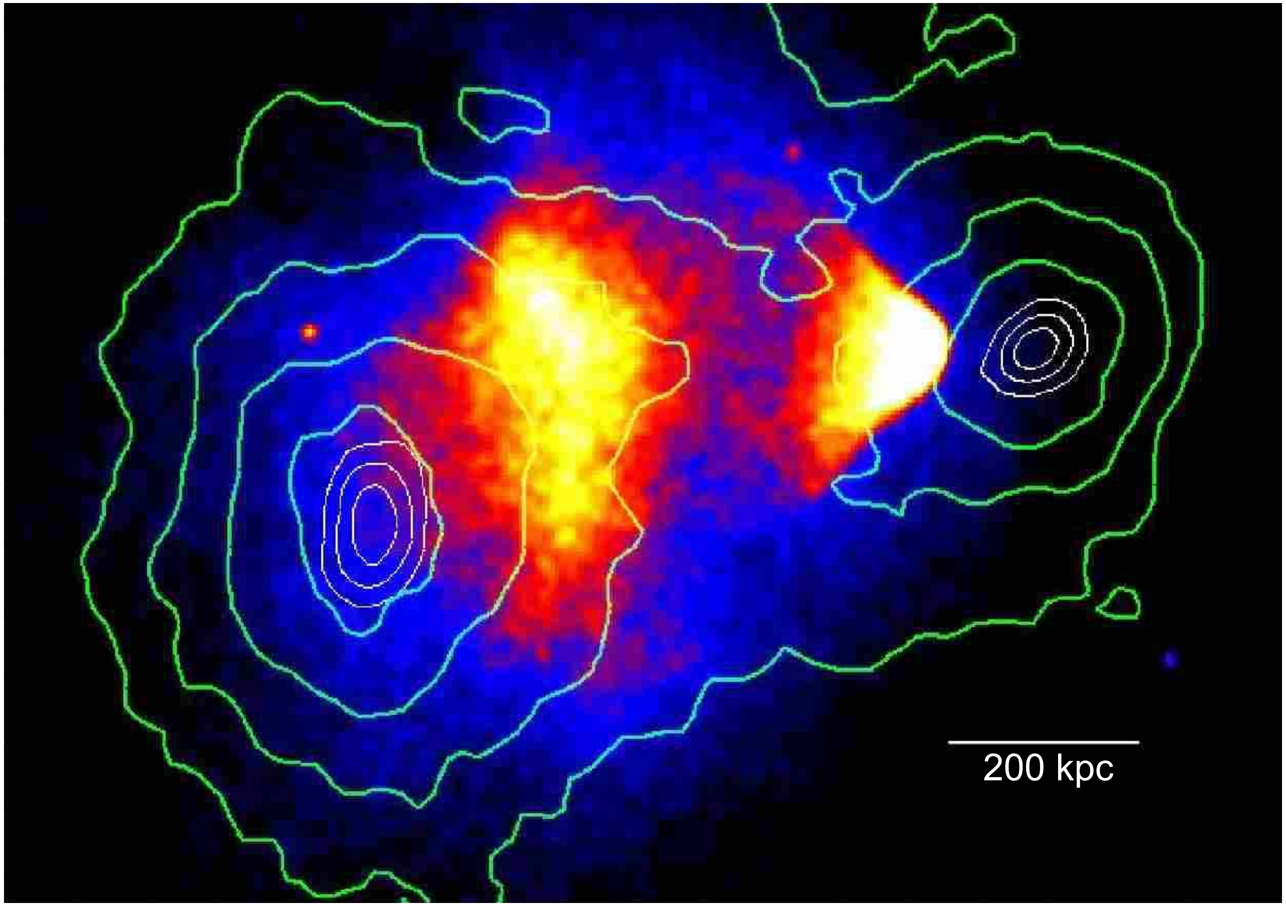
Are non-gravitational DM interactions irrelevant for galaxy formation?

Does it interact with itself (collisions)?



Bullet Cluster (Clowe +06)

(Randall+08)

$\sigma/m < 1.25\ cm^2/gr$

Credit: John Wise / KIPAC

Caveat: DM-only simulation gas and stars might weaken the constraint

Structure formation and DM interactions

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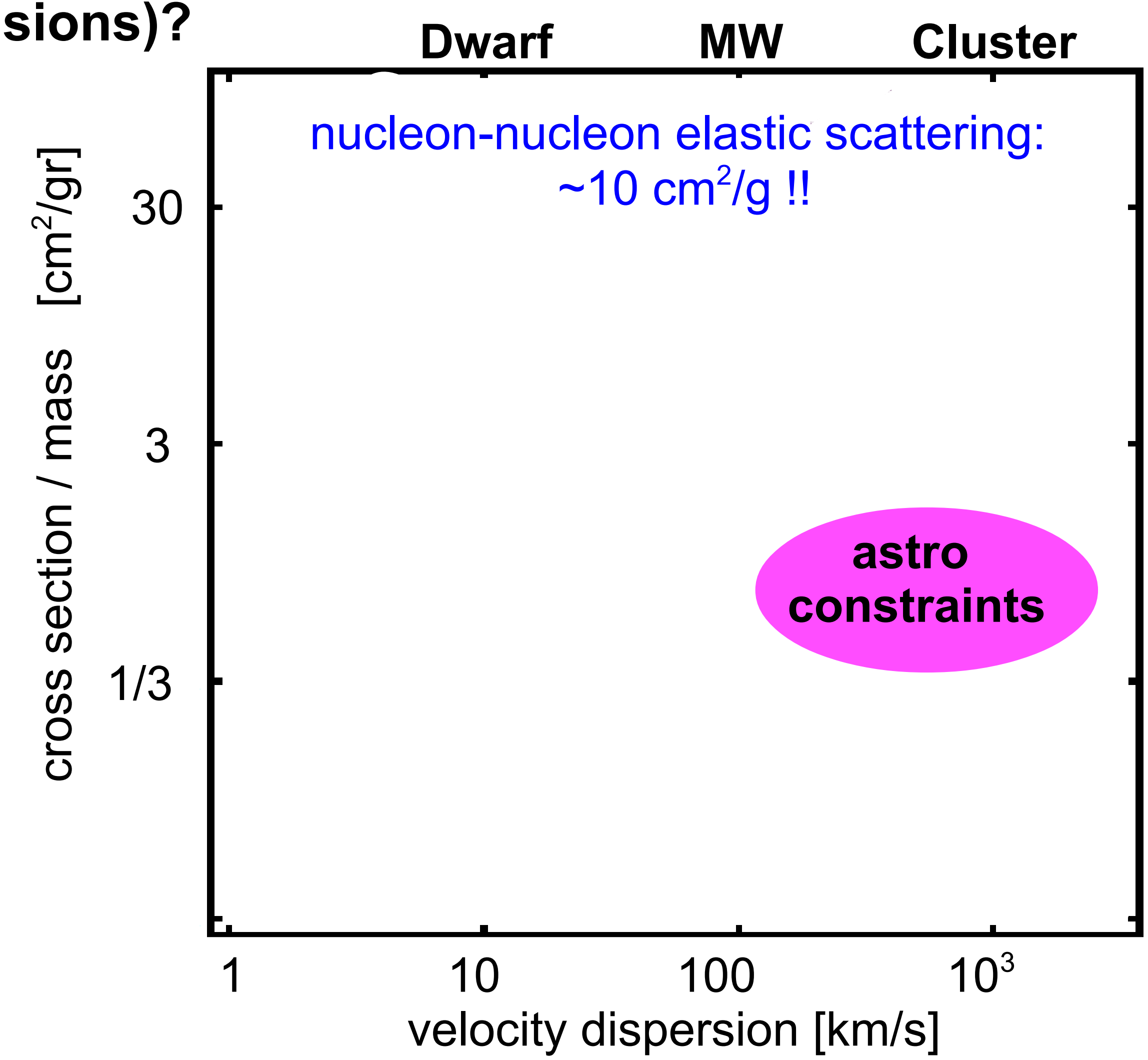
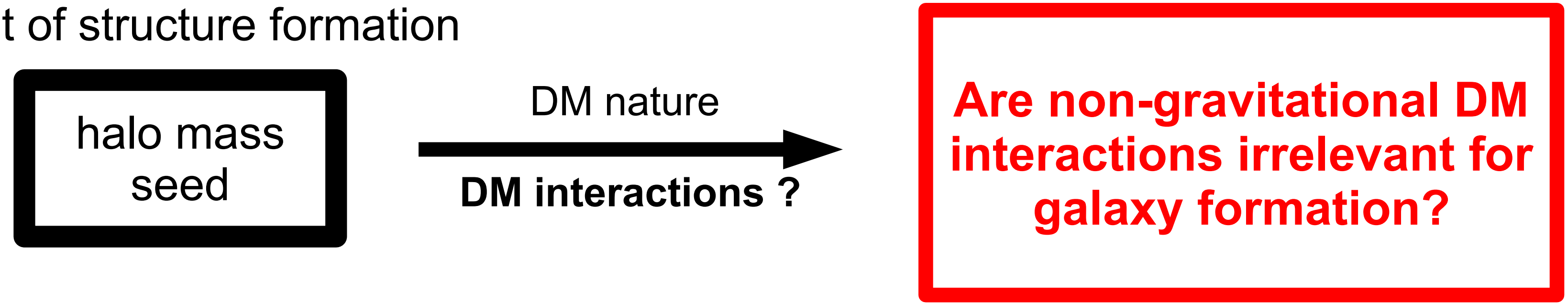


nucleon-nucleon elastic scattering:
~10 cm^2/g !!

Structure formation and DM interactions

Onset of structure formation



Are non-gravitational DM interactions irrelevant for galaxy formation?

Does it interact with itself (collisions)?

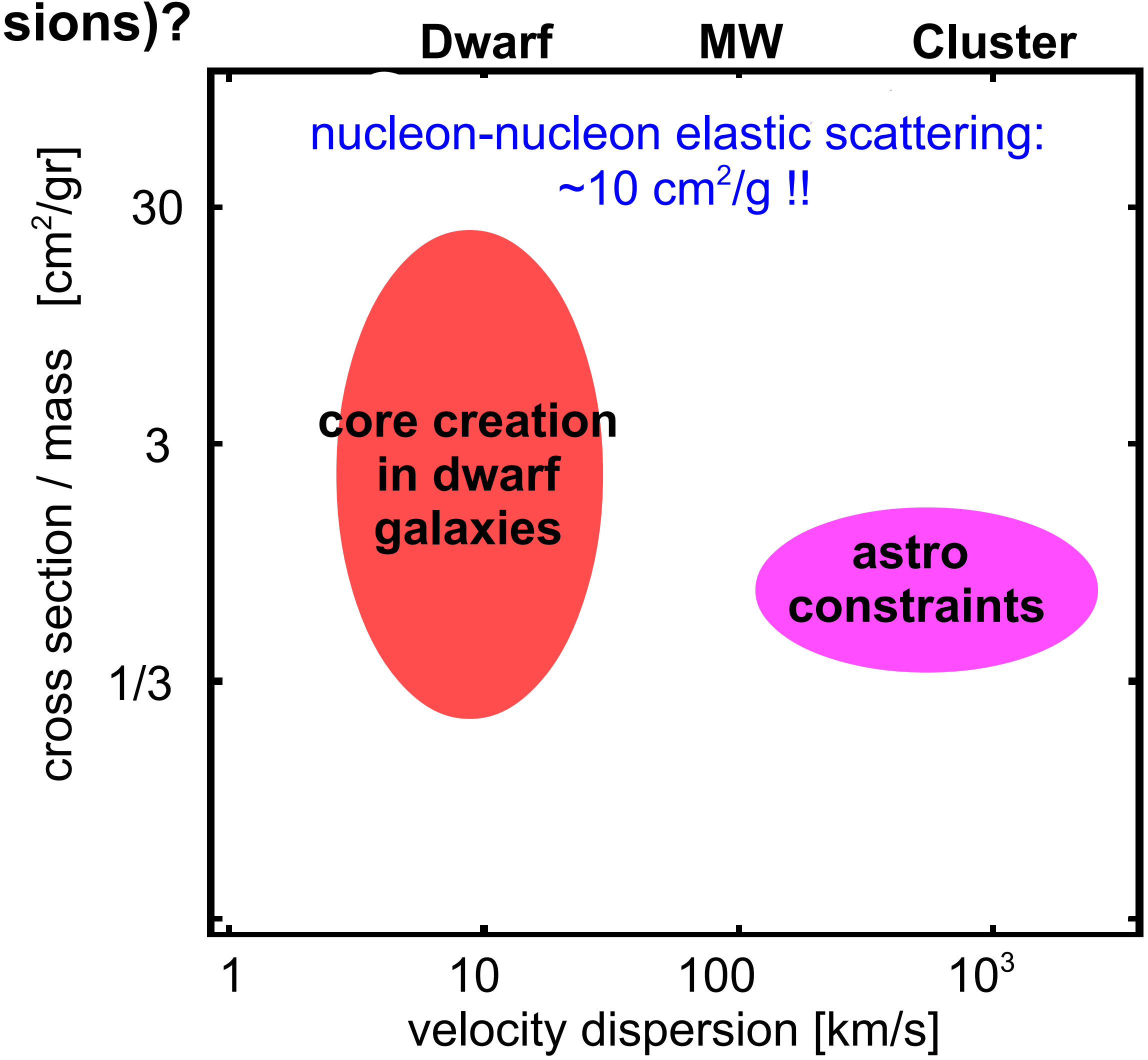
Constraints allow collisional DM that is astrophysically significant in the center of galaxies:

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/t_H>

Far from the fluid and collisionless regimes (Knudsen number = λ_{mean}/L >~ 1)



Structure formation and DM interactions

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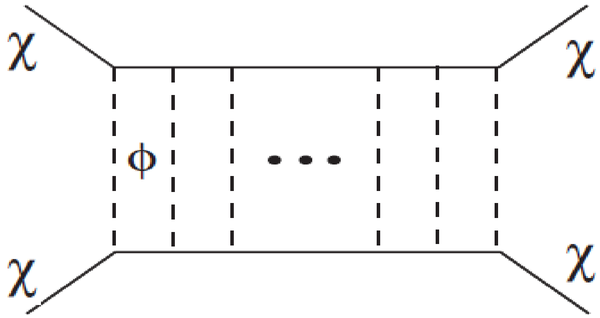
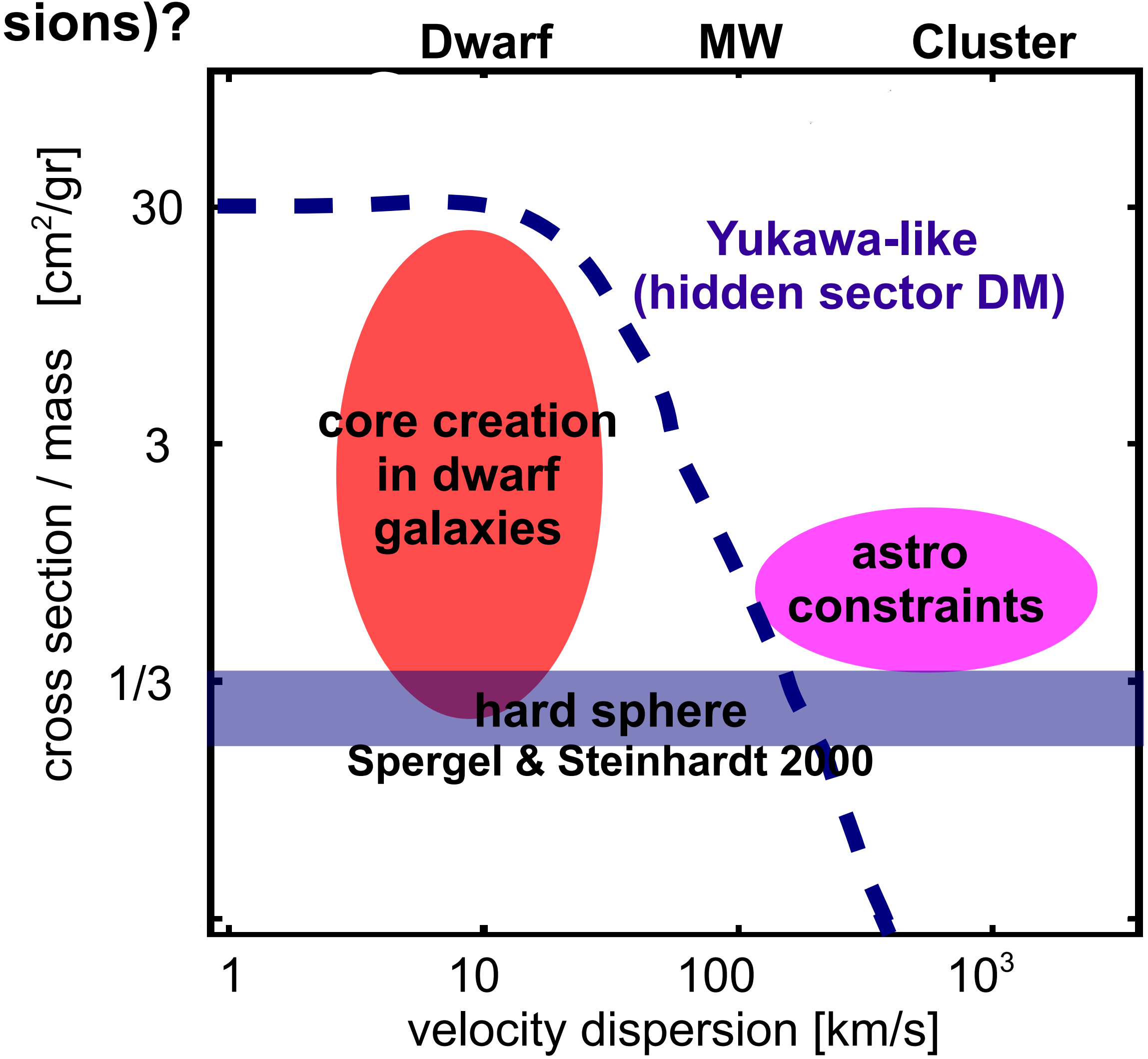
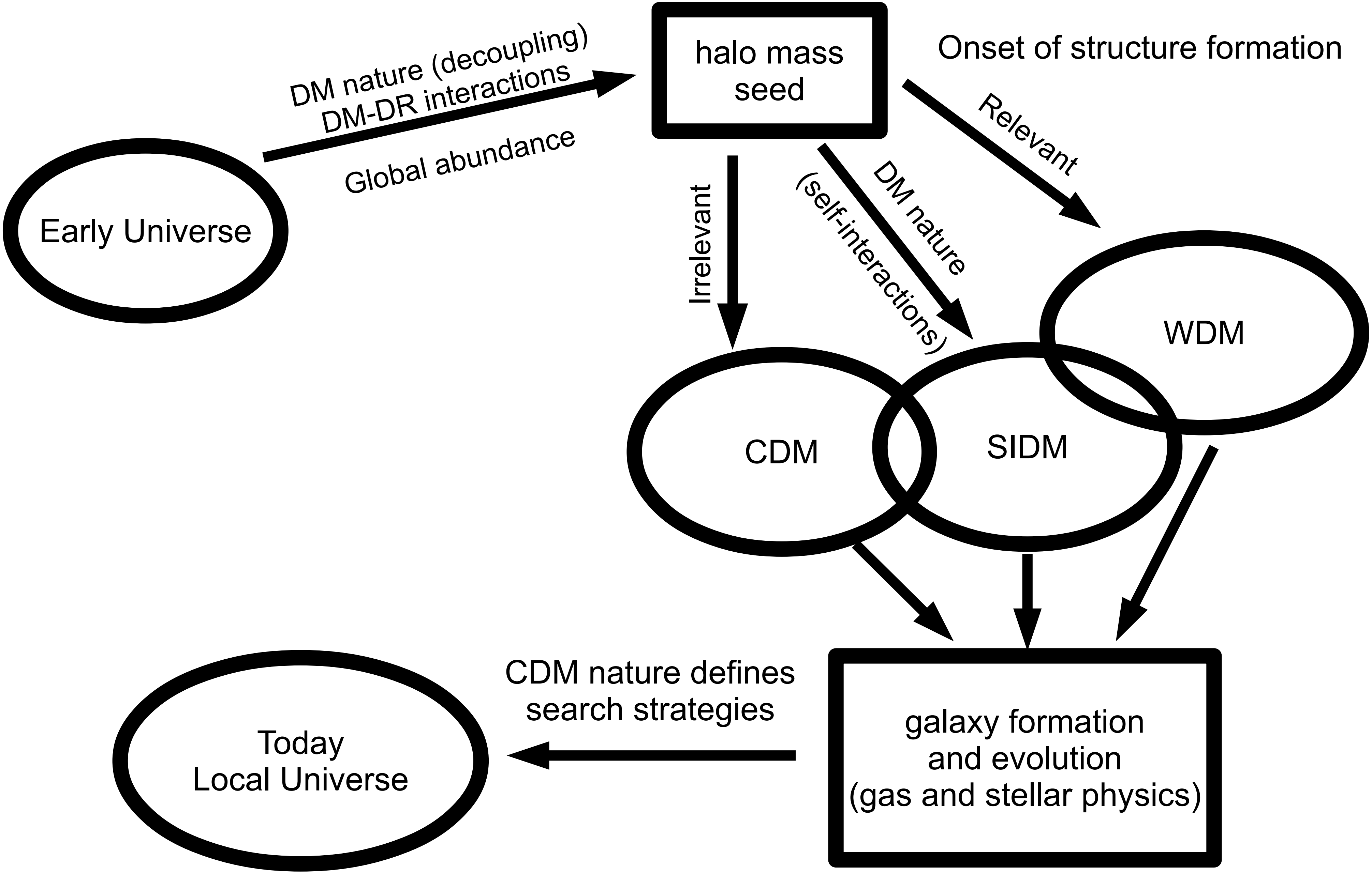
velocity-dependence motivated by a new force in the "dark sector" (analogous to Rutherford scattering)

e.g. Yukawa-like, Feng+09





Towards an effective theory of structure formation



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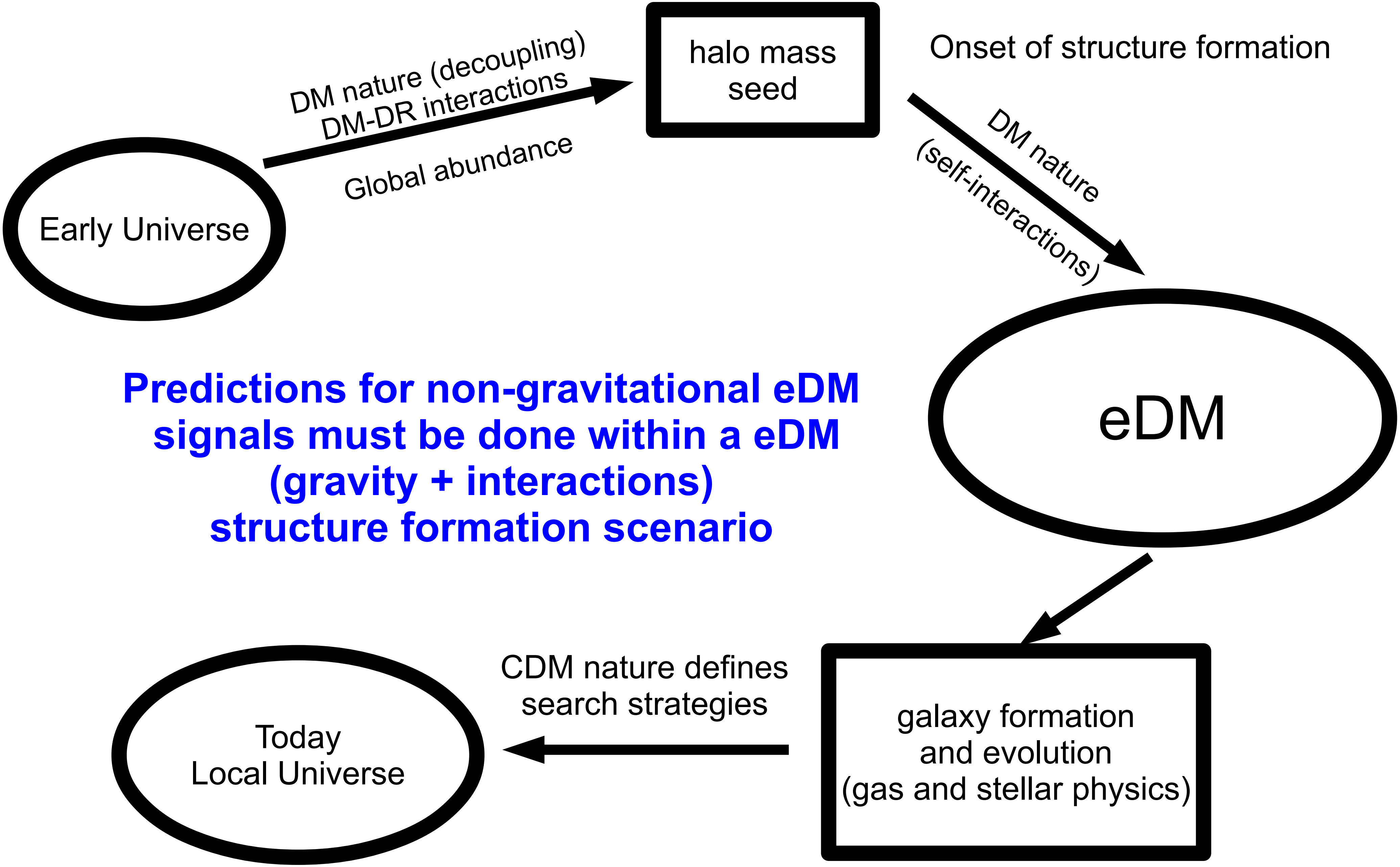


Early Universe

DM nature (decoupling)
DM-DR interactions

Global abundance

halo mass
seed

Onset of structure formation

DM nature
(self-interactions)

eDM

galaxy formation
and evolution
(gas and stellar physics)

CDM nature defines
search strategies

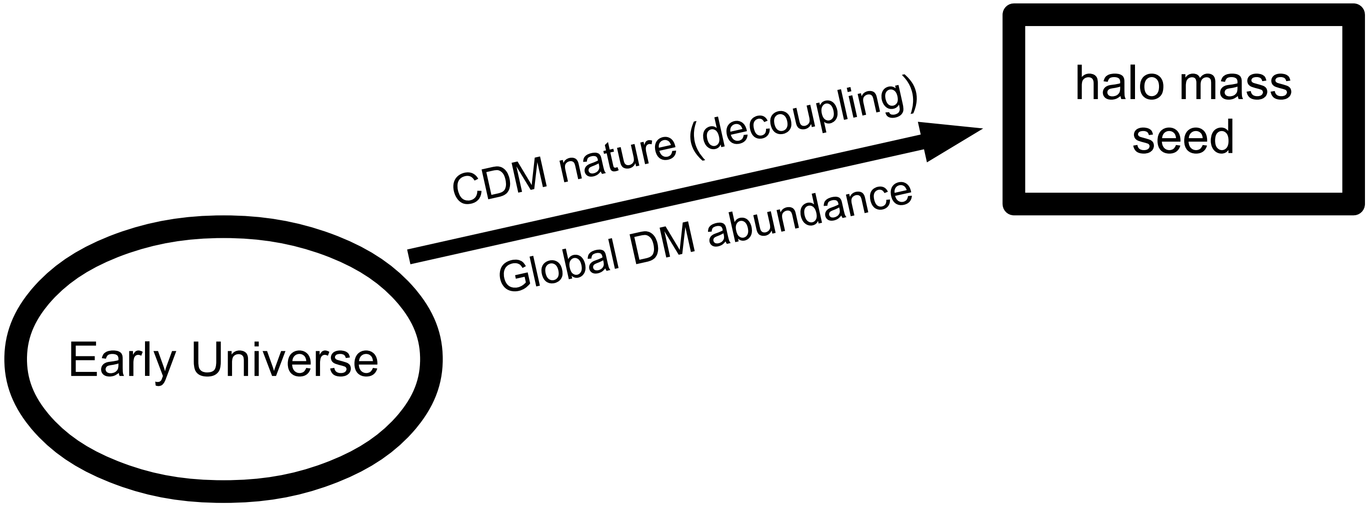
Today
Local Universe

Predictions for non-gravitational eDM signals must be done within a eDM (gravity + interactions) structure formation scenario

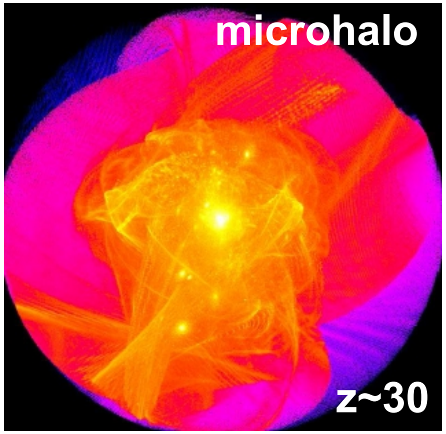
Using N-body simulations to obtain predictions for non-gravitational DM signals:

the CDM case

The relevance of the CDM nature across time



Onset of structure formation

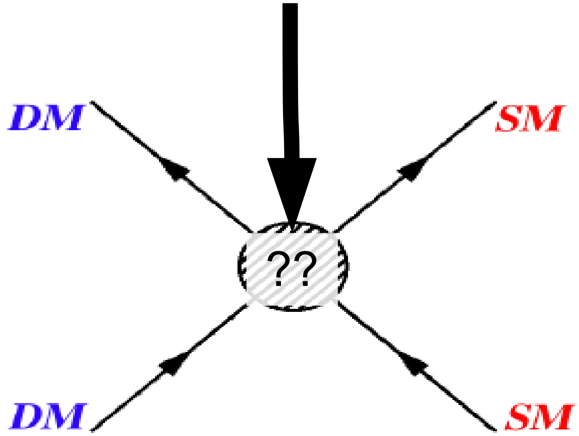


Anderhalden & Diemand 14

Minimum clustering scale
($\sim 10^{-6} M_\odot$ for "vanilla" WIMPs)

A guiding fundamental principle?
e.g. a new symmetry, SUSY

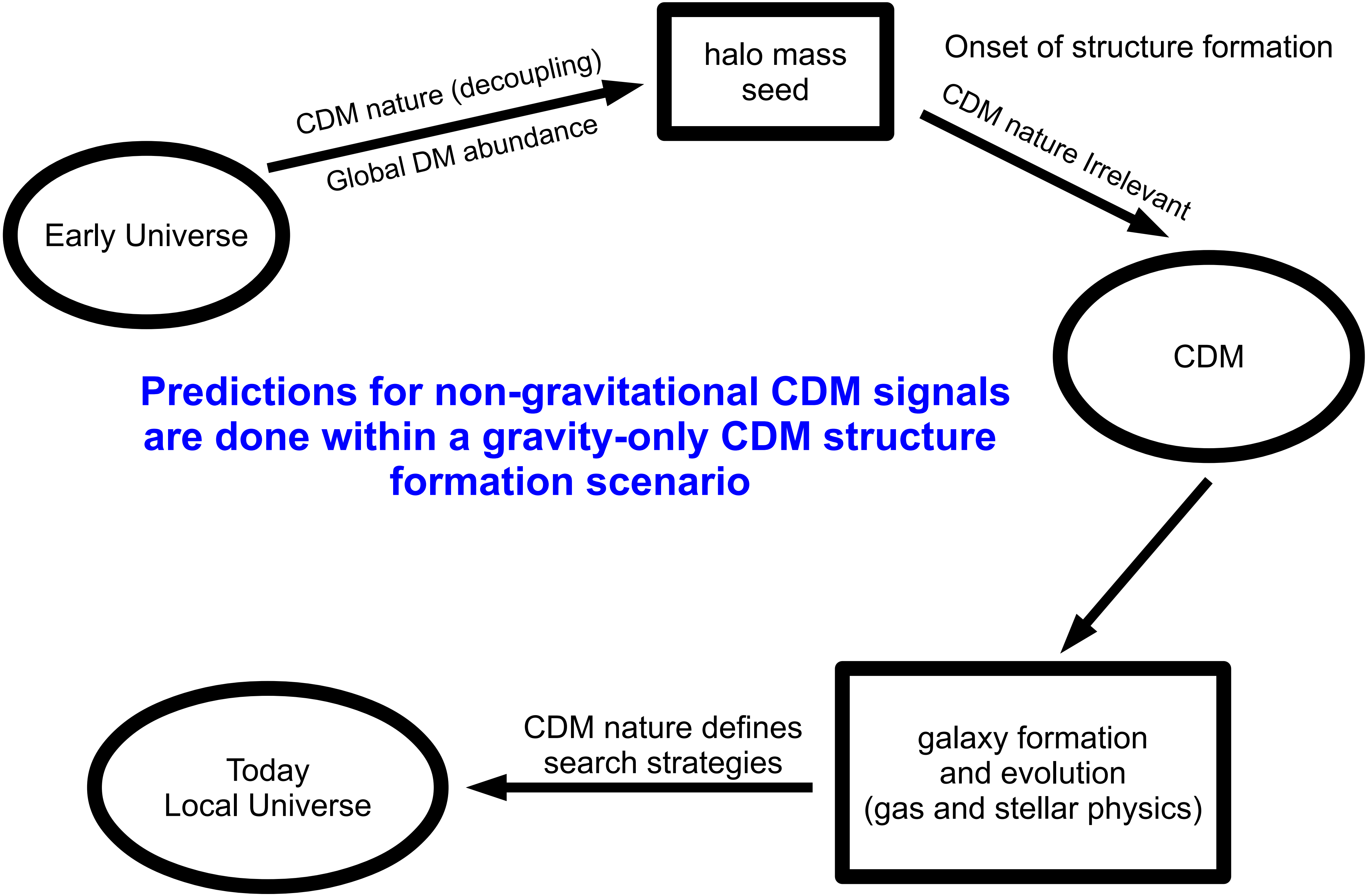
Multiple mechanisms of CDM production



messengers

Weak-scale (100 GeV) thermal dark particles (**WIMPs**) "naturally" give the right DM abundance

The relevance of the CDM nature across time



Early Universe

CDM nature (decoupling)

Global DM abundance

halo mass
seed

Onset of structure formation

CDM nature Irrelevant

CDM

Predictions for non-gravitational CDM signals are done within a gravity-only CDM structure formation scenario

galaxy formation
and evolution
(gas and stellar physics)

CDM nature defines
search strategies

Today
Local Universe

DM signals from CDM N-body simulations

Any DM signal could be predicted knowing the local DM distribution in phase space at all points and at all times:

$$f(\vec{x},\vec{v},t)\mathrm{d}^3\vec{x}\mathrm{d}^3\vec{v}$$

In practice however, we can only compute, measure, the DM distribution averaged over a certain macroscopic scale (coarse-grained distribution)

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In practice however, we can only compute, measure, the DM distribution averaged over a certain macroscopic scale (coarse-grained distribution)

In N-body simulations the coarse-grained distribution is given by a discrete representation of N particles:

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

macro-to-micro-particle mass ratio

each particle is smoothed in space to give a smooth local density (needed to compute potential)

each macro-particle travels at one speed

The system of N particles is advanced in time in a cosmological context (Andrea's talk)

$$n(x) = \int d^3\mathbf{v}\,\hat{f}$$

DM signals: standard approach

At a given time, split the phase space distribution in density and velocity distributions:

$$\hat{f}(\mathbf{x},\mathbf{v}) \propto \hat{\rho}(\mathbf{x})\hat{f}_v(\mathbf{v})$$

Example 1: Indirect detection (DM self-annihilation)

Annihilation rate (# of events per unit time in a region of volume V)

$$R_{\mathrm{ann}} = \frac{1}{2m_\chi^2}\int_V d^3\mathbf{x}\,\rho^2(\mathbf{x})\langle\sigma_{\mathrm{ann}}v\rangle$$

“thermal” average

$$\sim \int (\sigma v_{\mathrm{rel}}) f(v_{\mathrm{rel}}) d^3 v_{\mathrm{rel}}$$

particle physics model

Common method:

- **Assume Maxwell-Boltzmann speed distribution**
- **Local density estimated from simulation**

DM signals: standard approach

At a given time, split the phase space distribution in density and velocity distributions:

$$\hat{f}(\mathbf{x},\mathbf{v}) \propto \hat{\rho}(\mathbf{x})\hat{f}_v(\mathbf{v})$$

Example 2: Direct detection (DM-nuclei scattering)

Scattering rate (# of events per unit time per unit mass of detector):

$dN \sim n_X(\sigma_0 \langle v \rangle)/m_N$

particle physics

$$\frac{dN}{dE_r} = \frac{\sigma_0 \rho_\chi}{2\mu^2 m_\chi} F^2(q) \int_{v_{\rm min}}^{v_{\rm esc}} \frac{f(v)}{v} dv$$

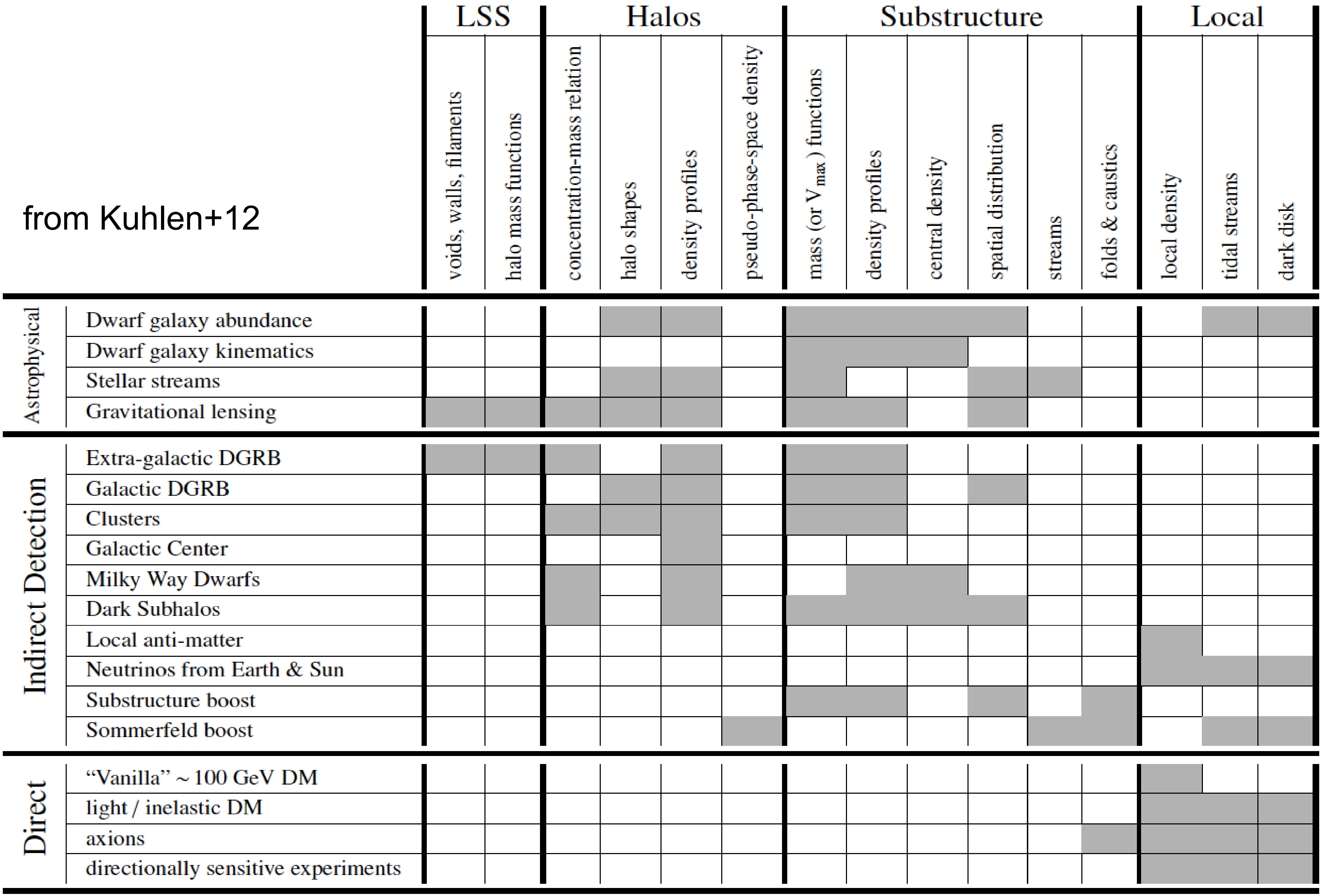
DM-nucleus reduced mass

threshold energy of the detector

Common method:

- **Assume Maxwell-Boltzmann speed distribution**
- **Local density estimate from observations**

N-body simulations and DM probes

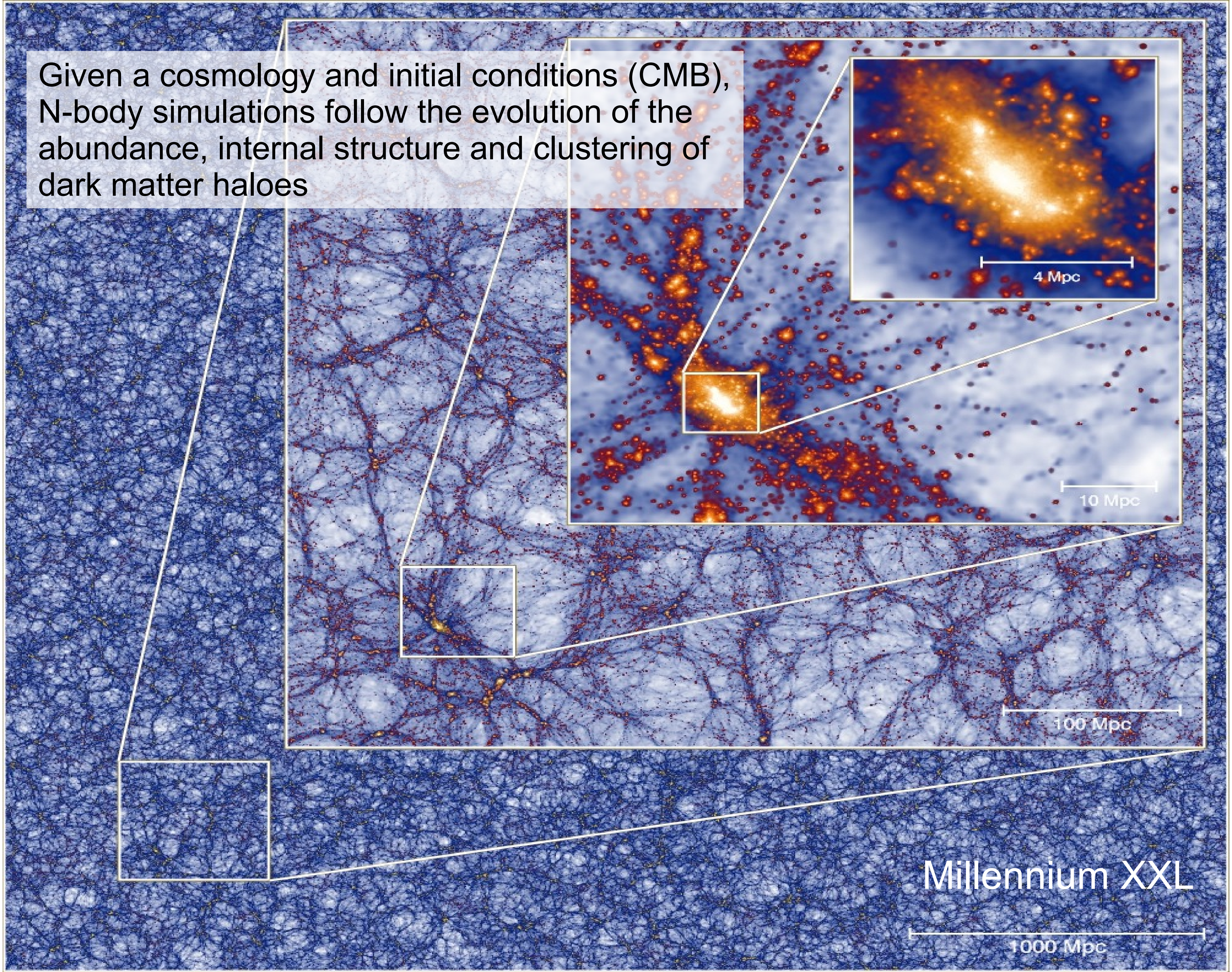


from Kuhlen+12

		LSS		Halos				Substructure						Local		
		voids, walls, filaments	halo mass functions	concentration-mass relation	halo shapes	density profiles	pseudo-phase-space density	mass (or V_{max}) functions	density profiles	central density	spatial distribution	streams	folds & caustics	local density	tidal streams	dark disk
Astrophysical	Dwarf galaxy abundance				▨	▨		▨	▨	▨	▨				▨	▨
	Dwarf galaxy kinematics							▨	▨	▨						
	Stellar streams				▨	▨		▨			▨	▨				
	Gravitational lensing	▨	▨	▨	▨	▨		▨	▨		▨					
Indirect Detection	Extra-galactic DGRB	▨	▨	▨		▨		▨	▨							
	Galactic DGRB				▨	▨		▨	▨		▨					
	Clusters			▨	▨	▨		▨	▨							
	Galactic Center					▨										
	Milky Way Dwarfs			▨		▨			▨	▨						
	Dark Subhalos			▨		▨		▨	▨	▨	▨					
	Local anti-matter													▨		
	Neutrinos from Earth & Sun													▨	▨	▨
	Substructure boost							▨	▨		▨		▨			
	Sommerfeld boost						▨					▨	▨		▨	▨
Direct	"Vanilla" ~ 100 GeV DM													▨		
	light / inelastic DM													▨	▨	▨
	axions												▨	▨	▨	▨
	directionally sensitive experiments													▨	▨	▨

What we know from N-body simulations:

the resolved regime



Given a cosmology and initial conditions (CMB), N-body simulations follow the evolution of the abundance, internal structure and clustering of dark matter haloes

Millennium XXL

A sample of state-of-the-art simulations

Precise prediction of CDM distribution from ~Gpc to ~100 pc scales

DM-only simulations

Cosmic

Name	Code	$L_{\rm box}$ [h^{-1}Mpc]	$N_{\rm p}$ [10^9]	$m_{\rm p}$ [h^{-1} $M_\odot$]	$\epsilon_{\rm soft}$ [h^{-1}kpc]
DEUS FUR	Ramses-Deus	21000	550	1.2×10^{12}	$40.0^\dagger$
Horizon Run 3	GotPM	10815	370	2.5×10^{11}	150.0
Millennium-XXL	Gadget-3	3000	300	6.2×10^{9}	10.0
Horizon-4Π	Ramses	2000	69	7.8×10^{9}	$7.6^\dagger$
Millennium-II	Gadget-3	100	10	6.9×10^{6}	1.0
MultiDark Run1	Art	1000	8.6	8.7×10^{9}	$7.6^\dagger$
Bolshoi	Art	250	8.6	1.4×10^{8}	$1.0^\dagger$

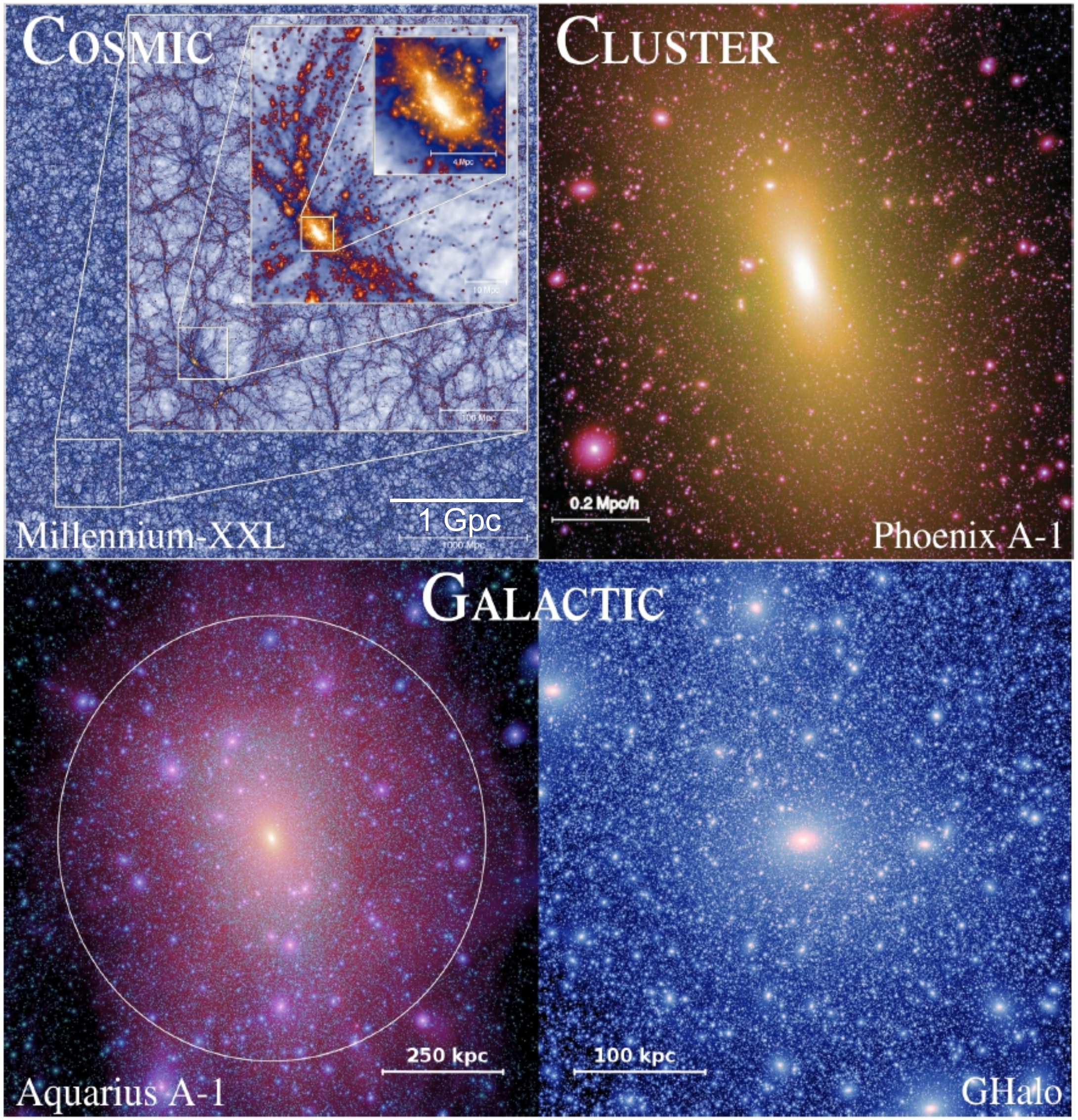
†For AMR simulations (Ramses, Art) $\epsilon_{\rm soft}$ refers to the highest resolution cell width.

Cluster

Name	Code	$L_{\rm hires}$ [h^{-1}Mpc]	$N_{\rm p,hires}$ [10^9]	$m_{\rm p,hires}$ [h^{-1} $M_\odot$]	$\epsilon_{\rm soft}$ [h^{-1}kpc]
Phoenix A-1	Gadget-3	41.2	4.1	6.4×10^{5}	0.15

Galactic

Name	Code	$L_{\rm hires}$ [Mpc]	$N_{\rm p,hires}$ [10^9]	$m_{\rm p,hires}$ [$M_\odot$]	$\epsilon_{\rm soft}$ [pc]
Aquarius A-1	Gadget-3	5.9	4.3×10^{9}	1.7×10^{3}	20.5
GHalo	Pkdgrav2	3.89	2.1×10^{9}	1.0×10^{3}	61.0
Via Lactea II	Pkdgrav2	4.86	1.0×10^{9}	4.1×10^{3}	40.0

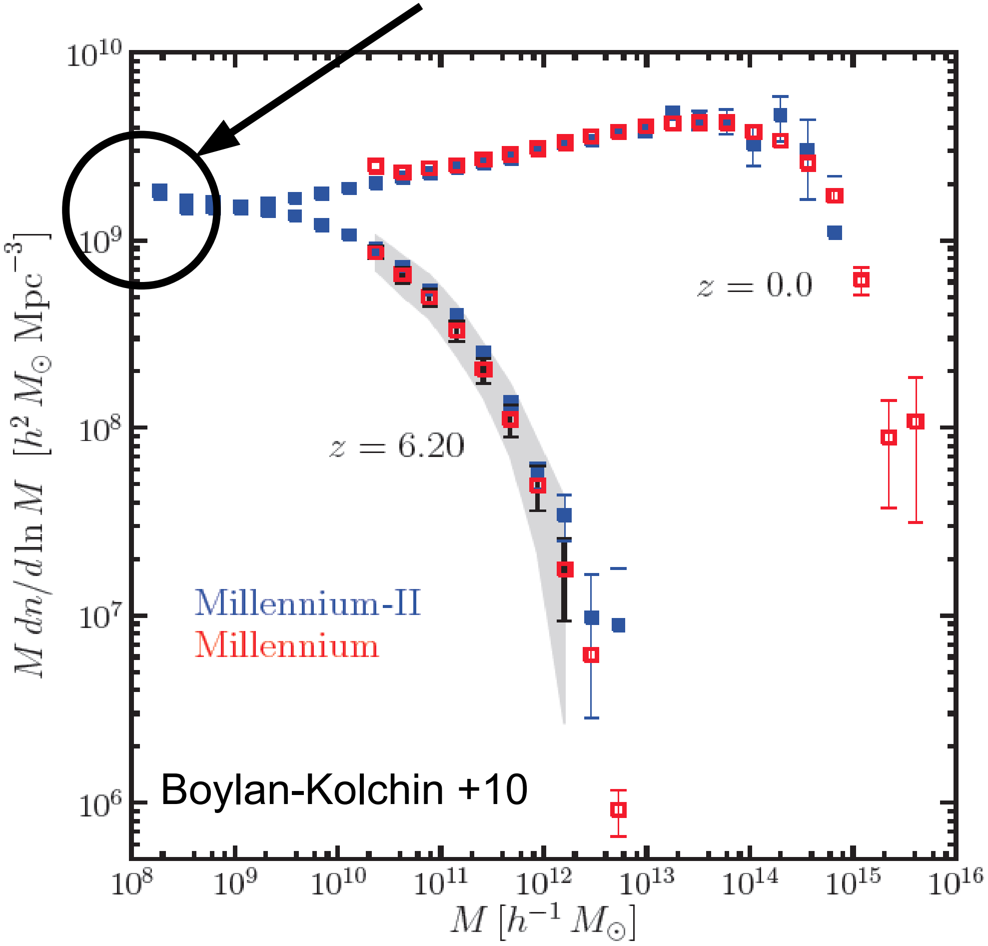


from Kuhlen+12

Abundance of CDM haloes

Mass function (dn/dM): number of haloes per comoving volume and per mass range.
It evolves with redshift according to the CDM hierarchical scenario.

dn/dM ~ $M^{-1.9}$ (at small masses)



Boylan-Kolchin +10

Minimum halo mass in CDM many orders
of magnitude below mass resolution
of current simulations!

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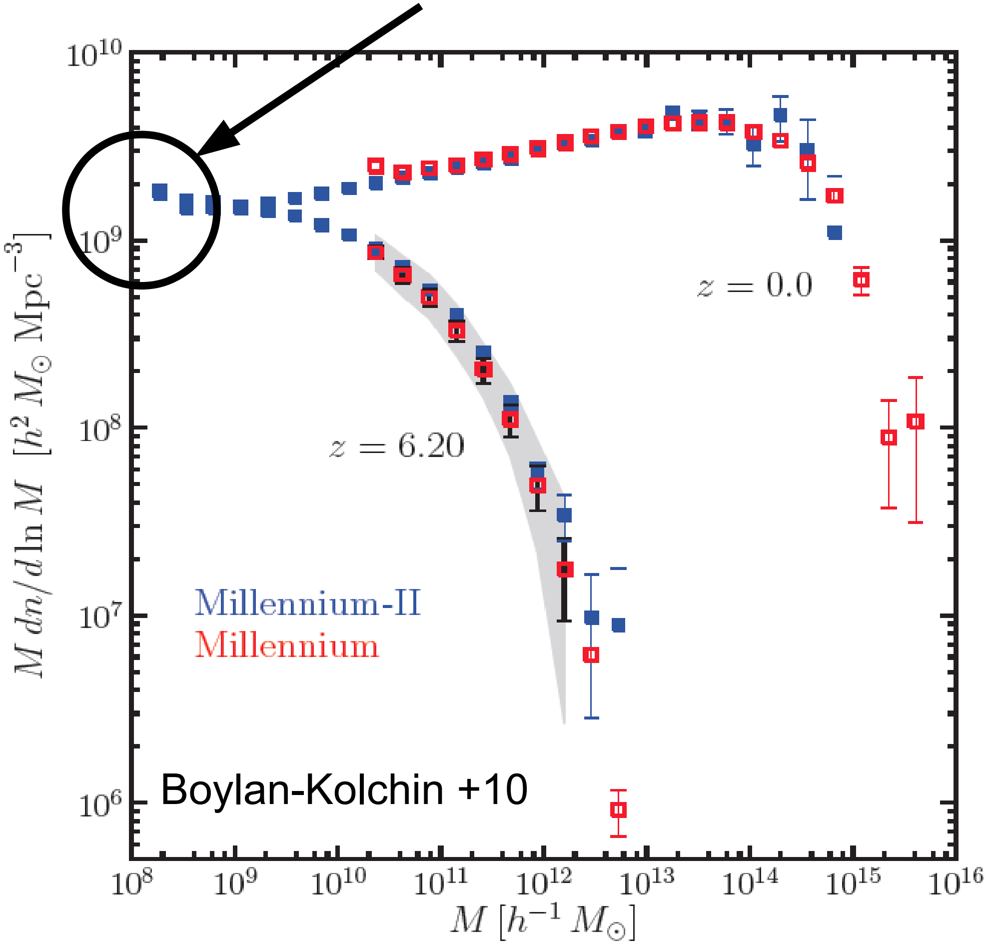
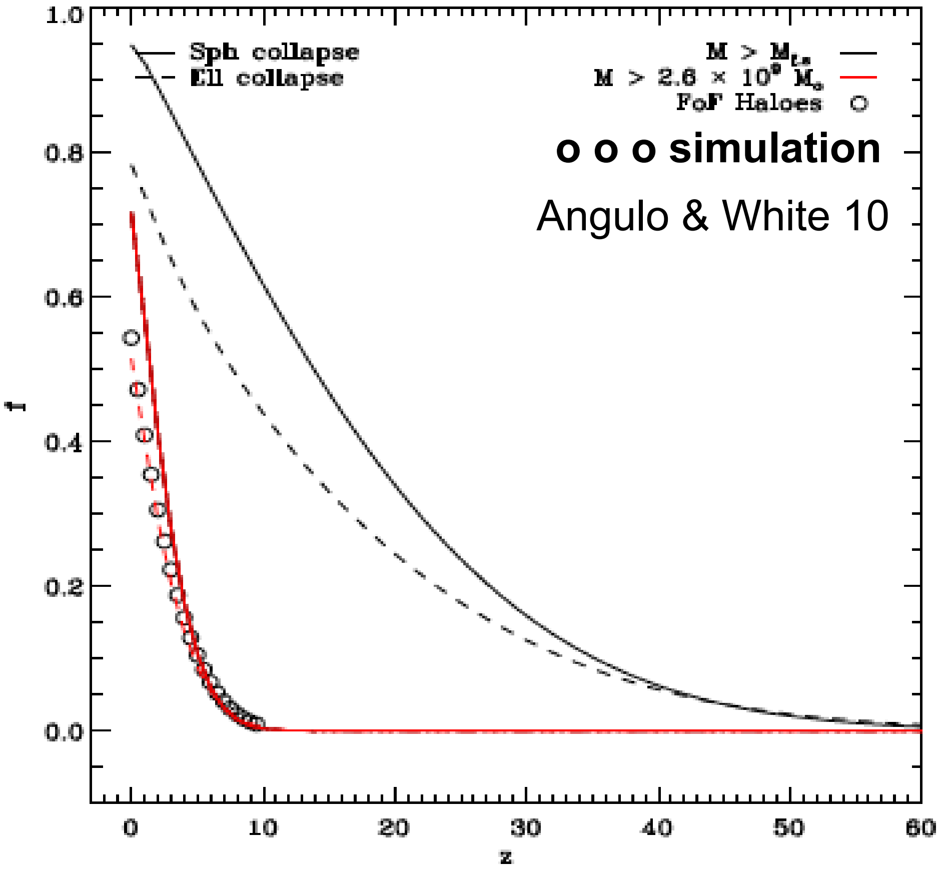


Boylan-Kolchin +10

Minimum halo mass in CDM many orders
of magnitude below mass resolution
of current simulations!

fraction of mass locked in haloes



o o o simulation

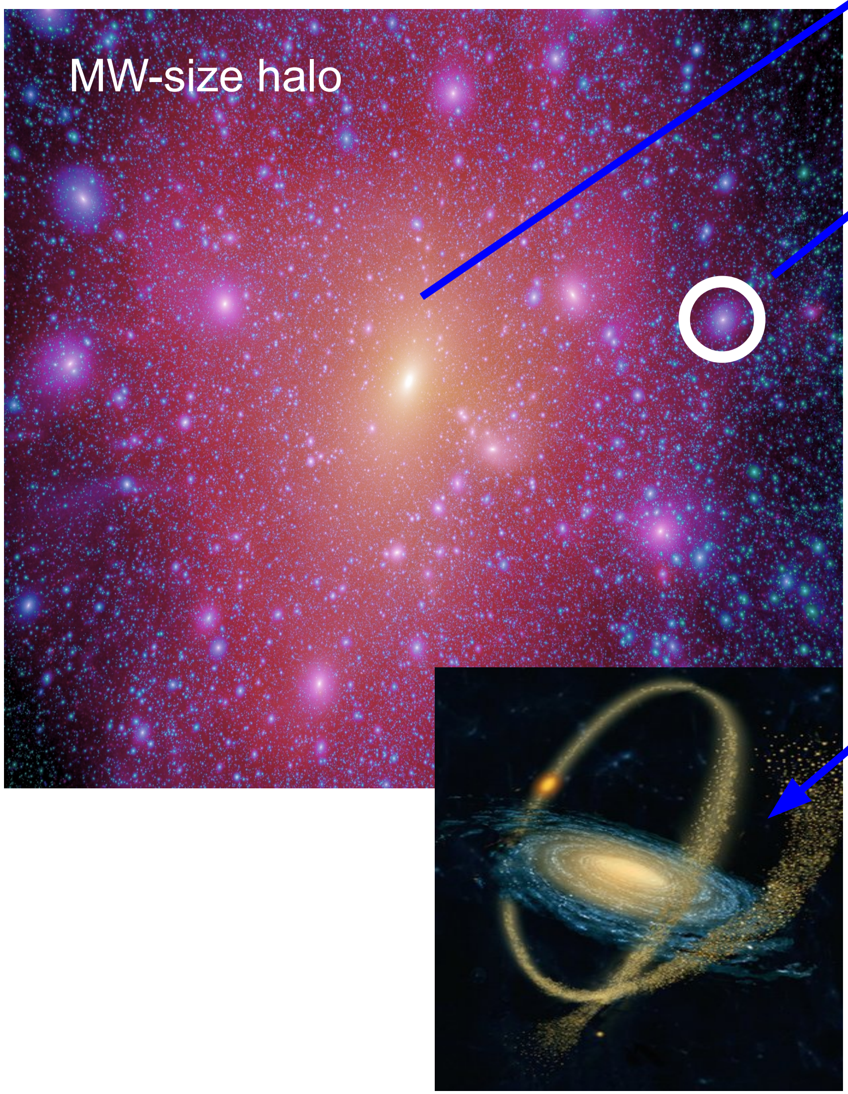
Angulo & White 10

Not all dark matter is in haloes!
but SM messengers from DM
interactions should be produced
more abundantly in haloes

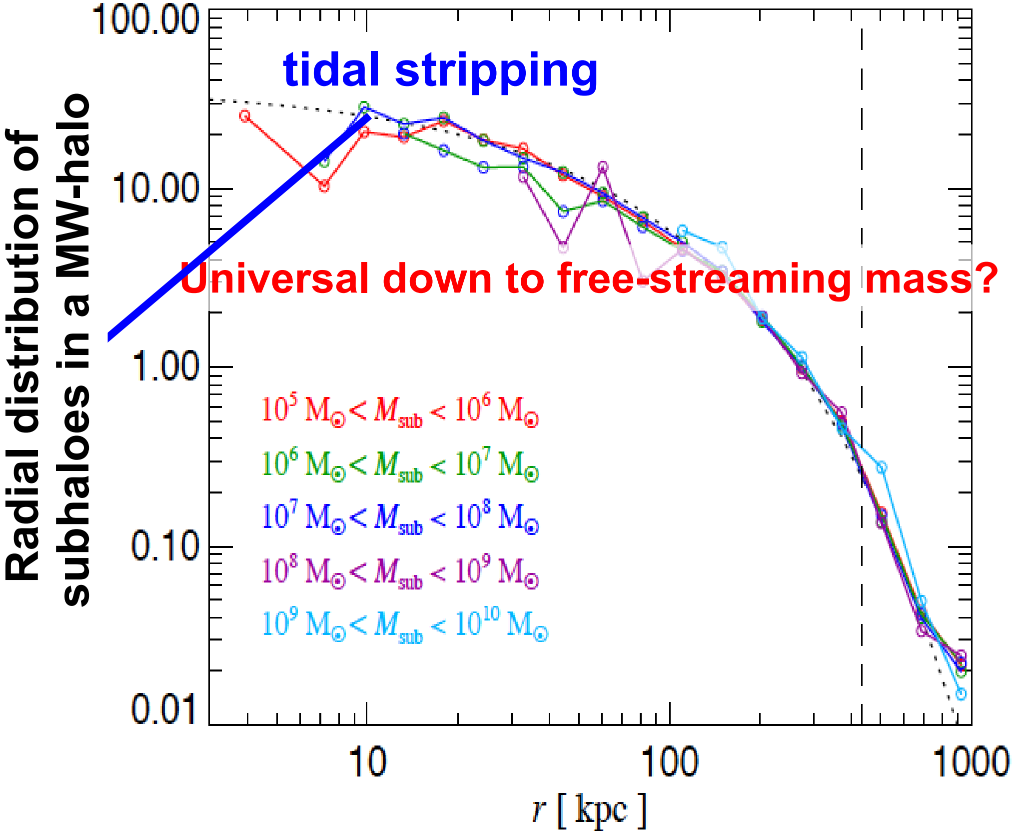
Inner structure of CDM haloes

smooth distribution + substructures

Aquarius project Springel+08



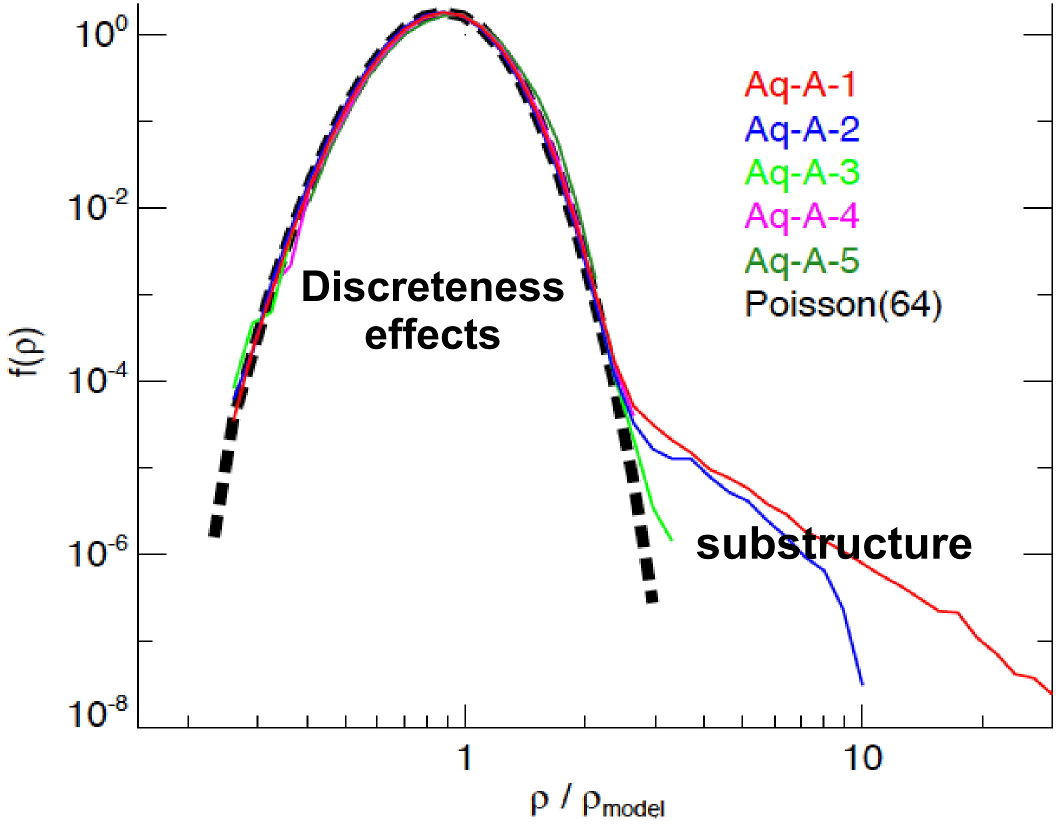
- Smooth spherical dist. (NFW or Einasto profile)
- Collection of subhaloes with a given:
  - Abundance (mass function)
  - Density profile (NFW or Einasto)
  - Radial distribution (“cored” Einasto)



CDM distribution at the solar circle

local (average) DM density distribution very smooth (chance of the Sun within a subhalo ~ 10^{-4})

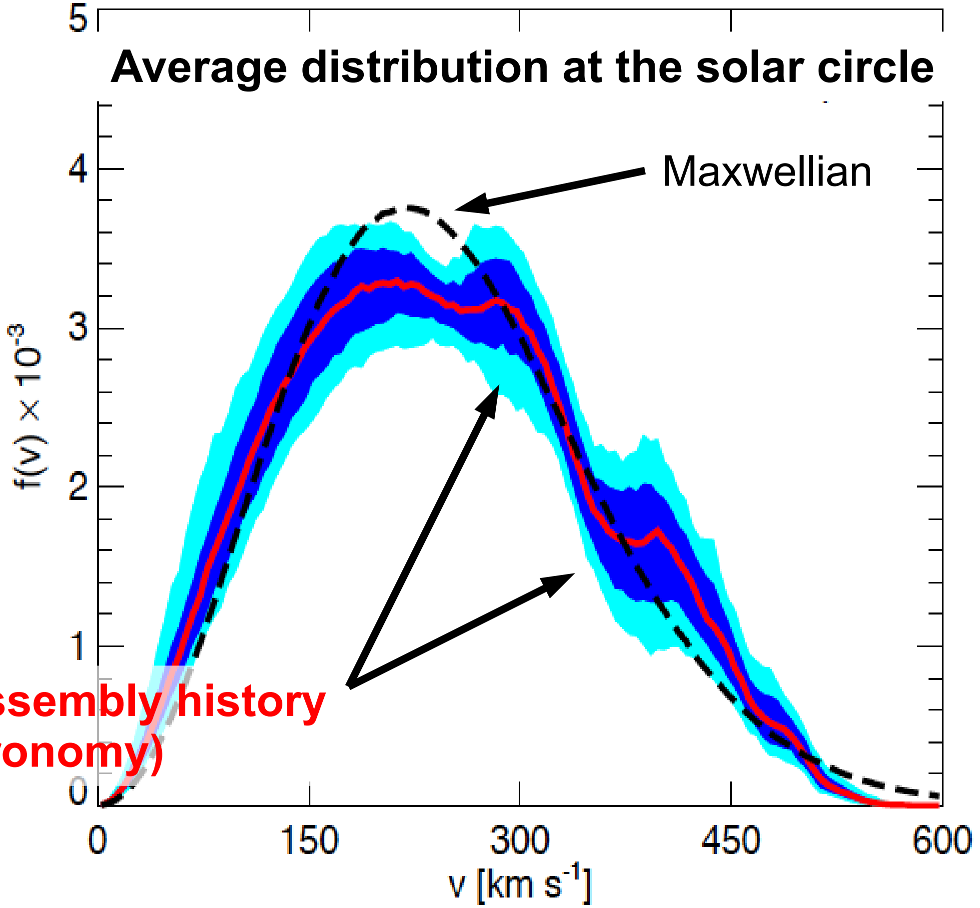
Density probability distribution at the solar circle



Discreteness effects

substructure

Velocity distribution is not fully Maxwellian (influence on direct detection rates)



Maxwellian

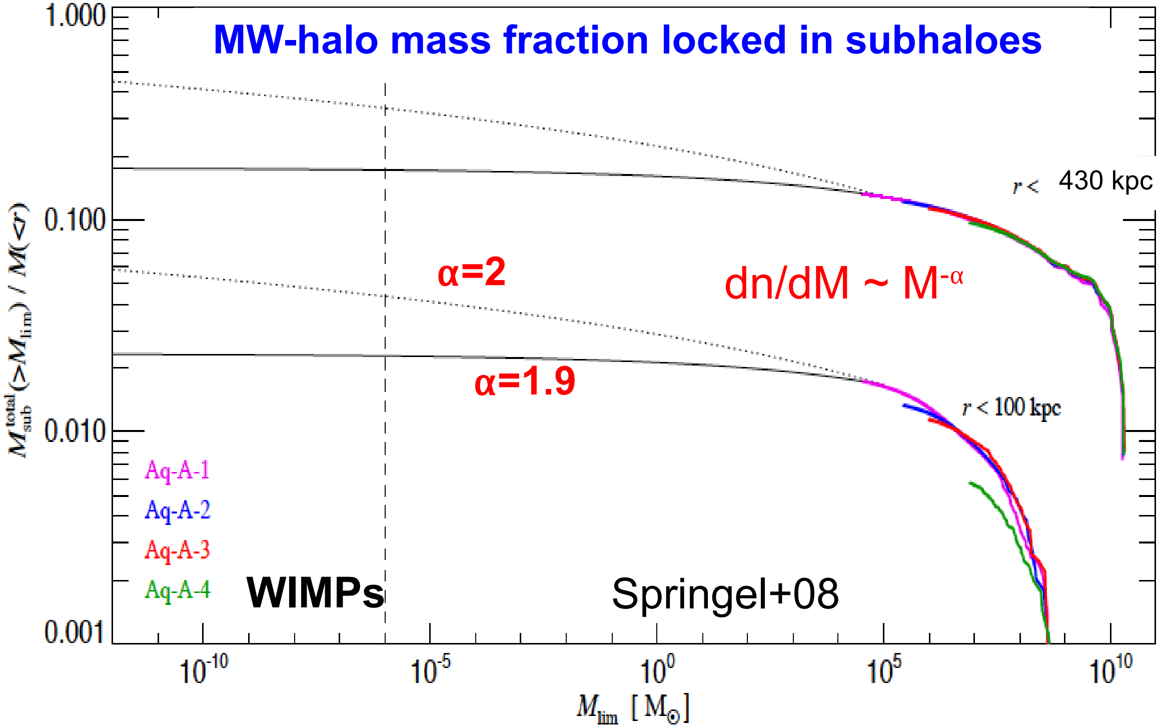
Related to individual assembly history (future: DM astronomy)

Vogelsberger+09

Going beyond numerical resolution:

Uncertainties for predictions of DM signals in a CDM background

Abundance and inner structure of unresolved haloes

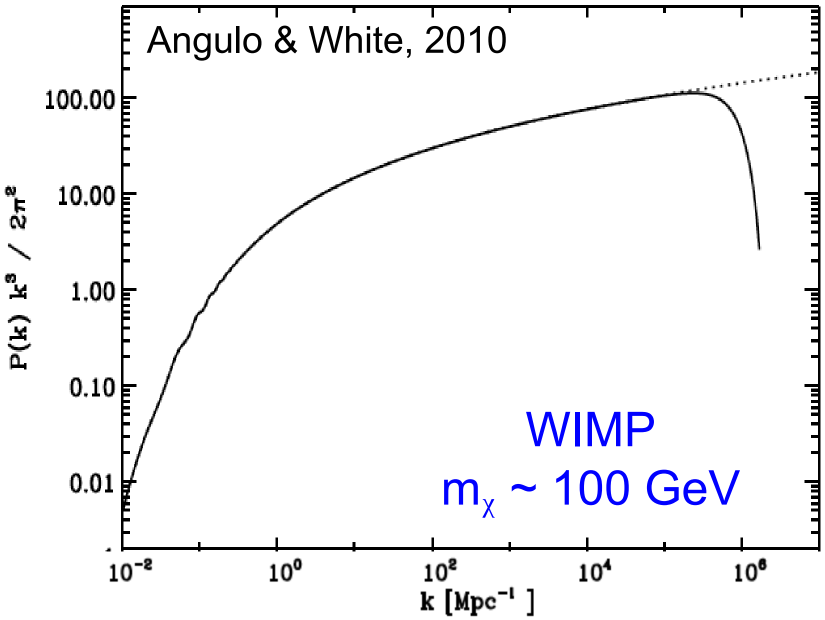


The minimum scale for
self-bound haloes is set by the DM nature
(**e.g. ~10^{-6} $M_\odot$ for “vanilla” WIMPs**)

Can we extrapolate simulation results to these scales?

The abundance of unresolved (sub)haloes is one of the main uncertainties in many predicted CDM signals

Abundance and inner structure of unresolved haloes



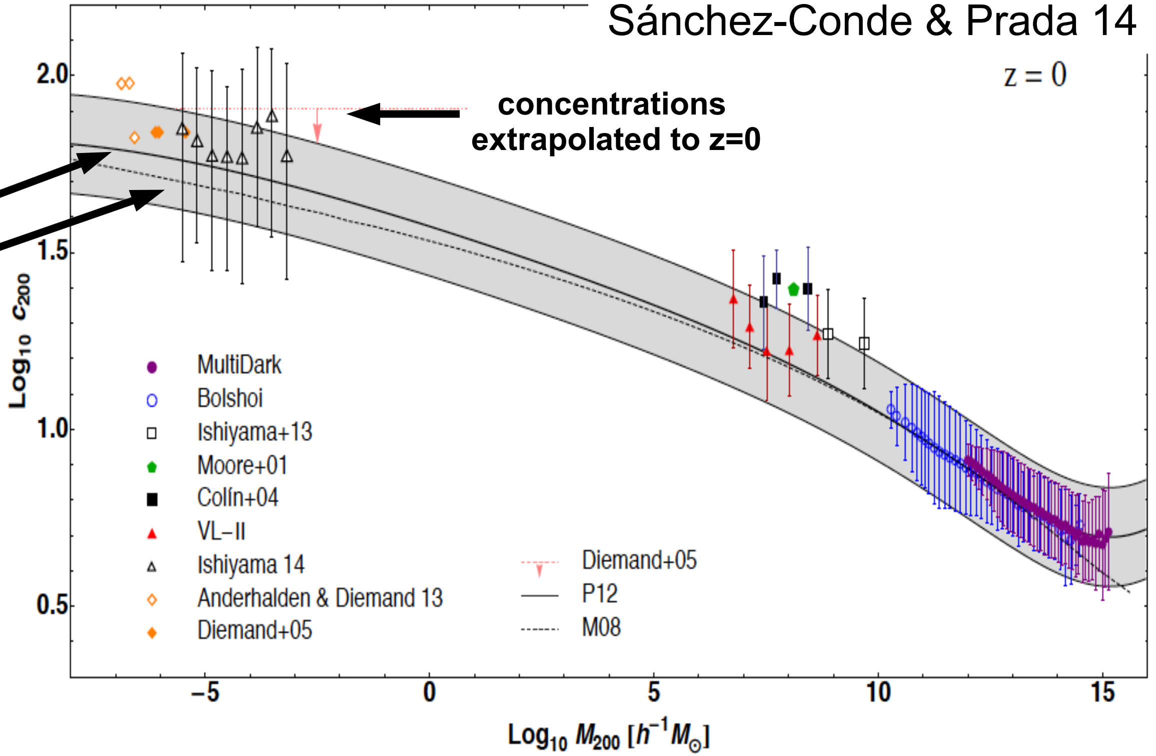
Angulo & White, 2010

WIMP
$m_\chi \sim 100$ GeV

The minimum scale for
self-bound haloes is set by the DM nature
(**e.g. ~10^{-6} M$_\odot$ for "vanilla" WIMPs**)

Can we extrapolate simulation results to
these scales?

Halo concentrations at low masses can
be predicted. Due to the flattening of
the CDM P(k), low-mass haloes form with
nearly the same concentration



Sánchez-Conde & Prada 14

concentrations extrapolated to z=0

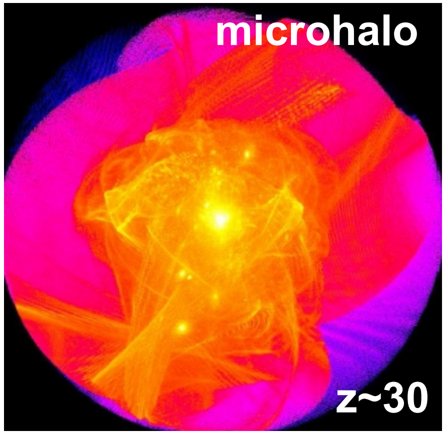
Models
Prada+12
Macciò+08

Assumption:
all haloes are nearly NFW, then, mass and concentration define the structure of any given halo

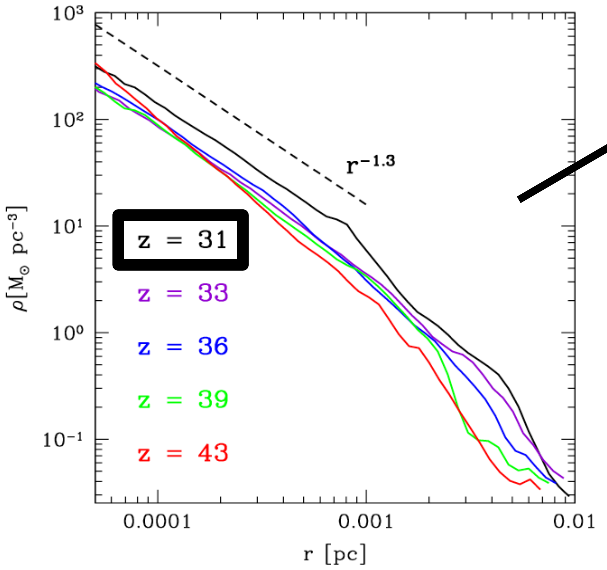
Abundance and inner structure of unresolved haloes

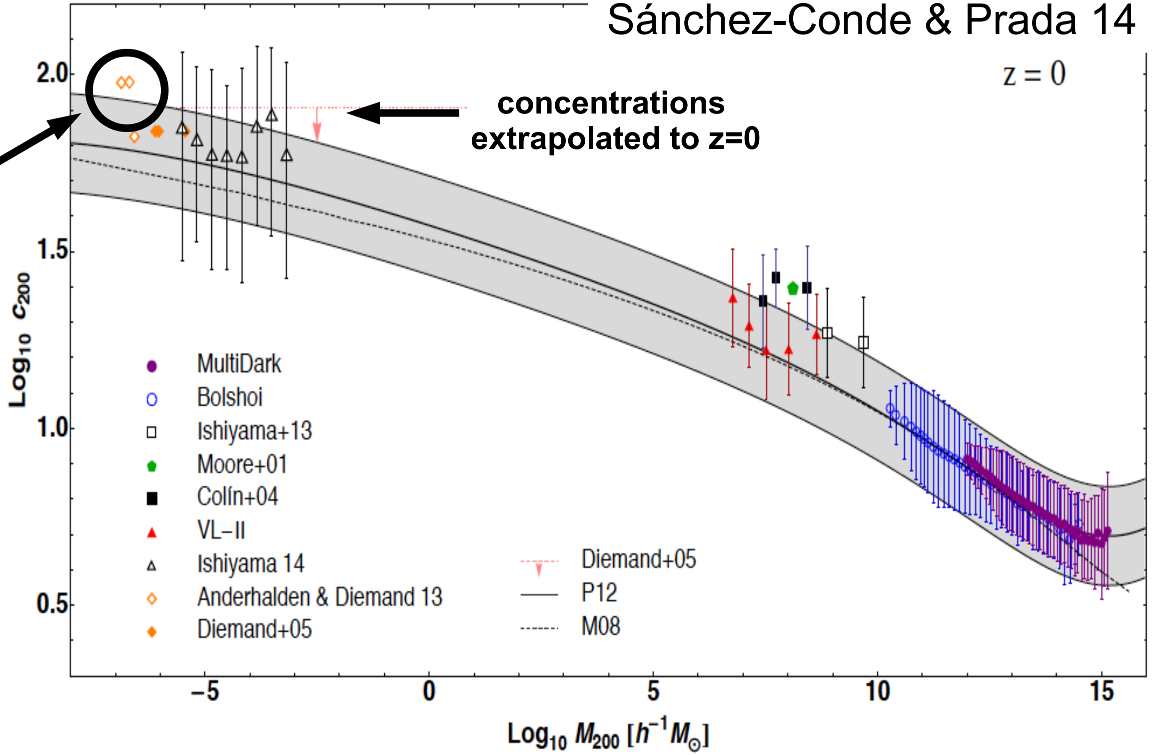
The minimum scale for
self-bound haloes is set by the DM nature
(**e.g. ~10^{-6} M⊙ for “vanilla” WIMPs**)

Can we extrapolate simulation results to
these scales?



mini-haloes have steeper density cusps (at least at high-z)





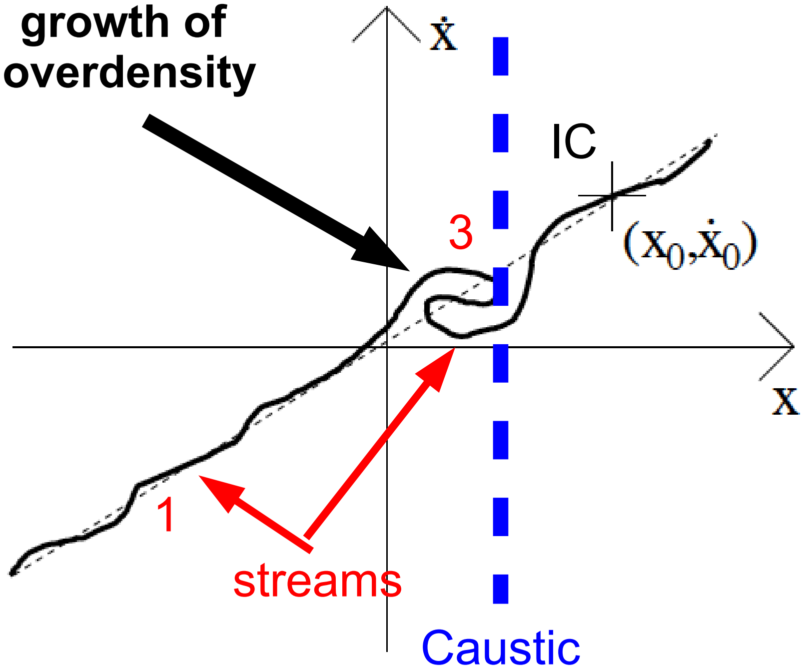
Sánchez-Conde & Prada 14

concentrations extrapolated to z=0

The fine-grained phase-space distribution of DM haloes

Since CDM is cold and and collisionless, it lies in a 3D hypersurface in the 6D phase space (most of which is empty)

1D fine-grained distribution



growth of overdensity

streams

Caustic
(local spatial density
very high)

Fig. from Vogelsberger+08

Thickness of line: primordial “thermal” velocity dispersion (width related to DM “coldness”)

The fine-grained phase-space distribution of DM haloes

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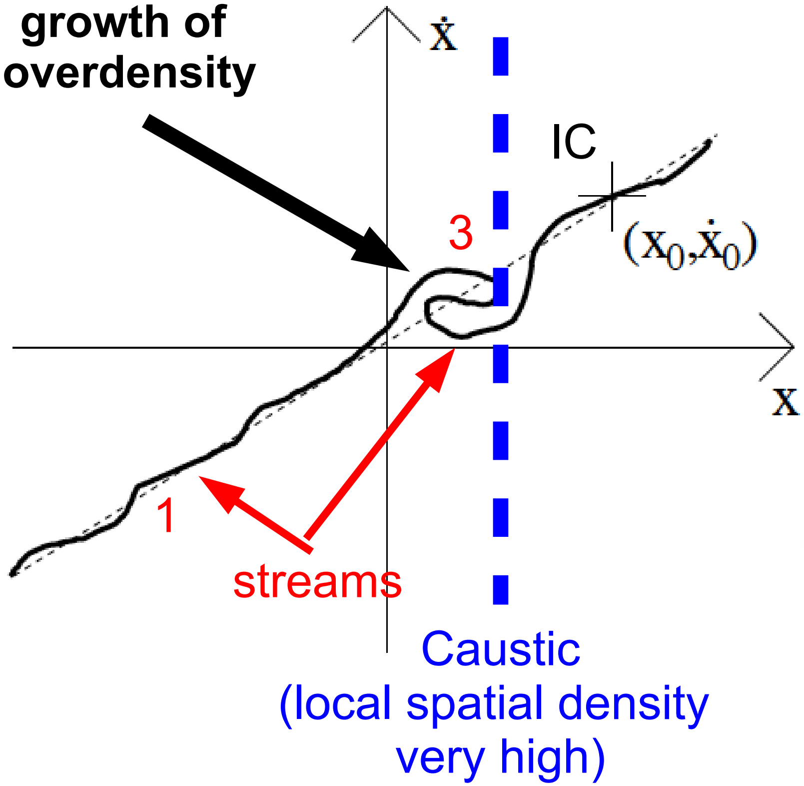
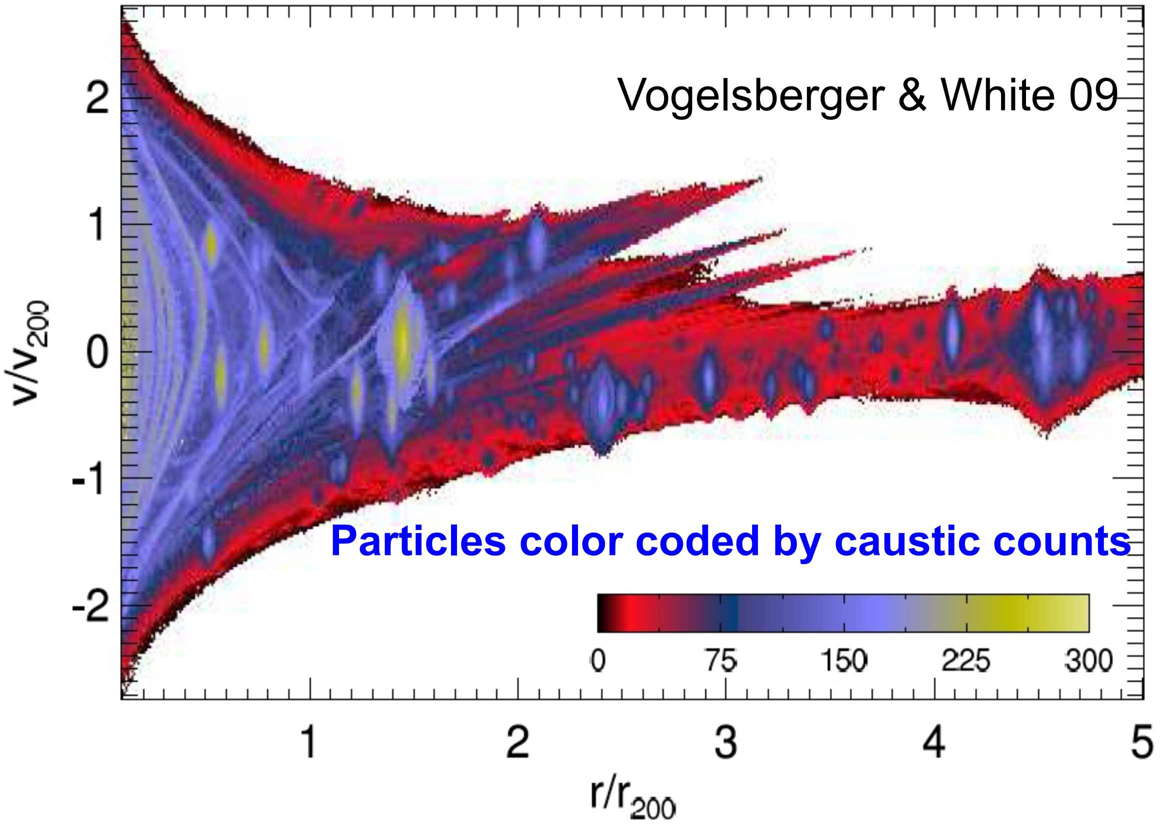


Fig. from Vogelsberger+08

Thickness of line: primordial "thermal" velocity dispersion (width related to DM "coldness")

Method developed to identify streams and caustics in N-Body simulations

Phase-space structure of a MW-size halo



DM Annihilation boosts

Since annihilation rates scale as ρ^2, any unresolved DM clumpiness should boost the annihilation rate

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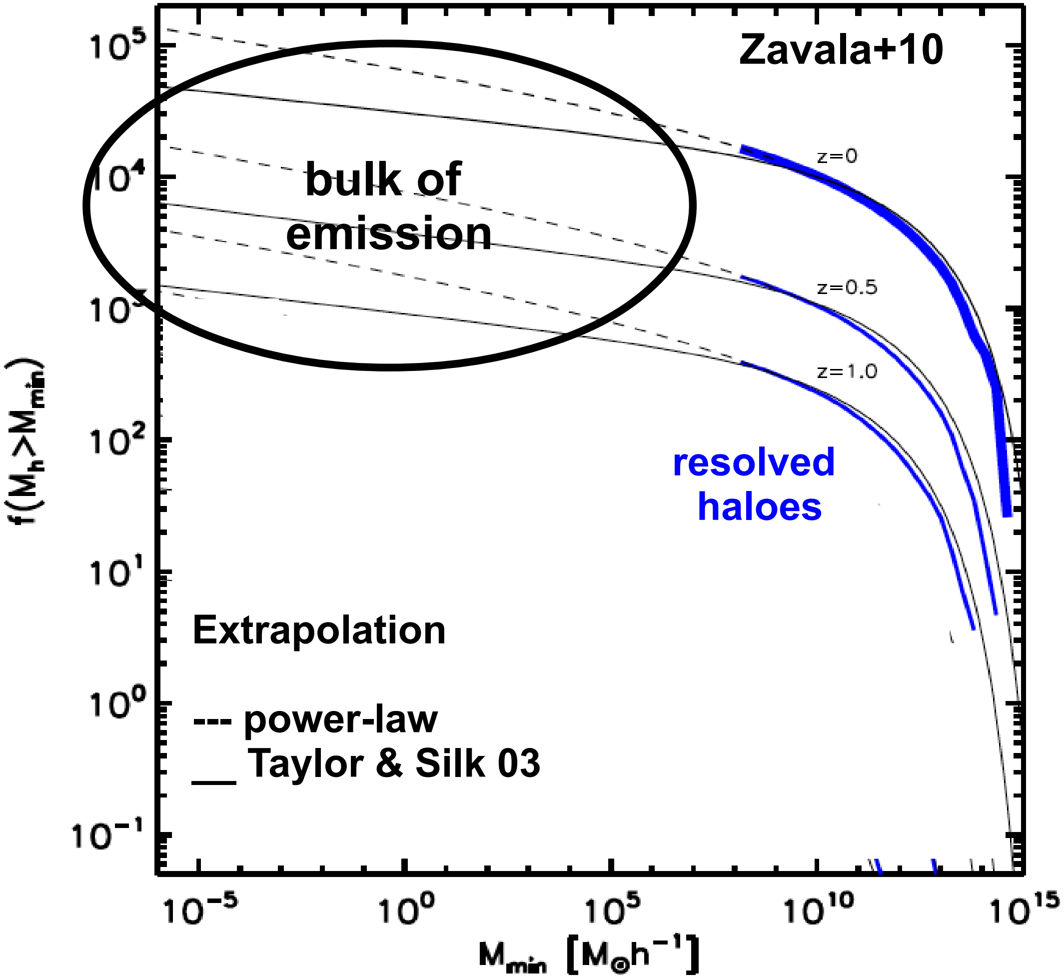
Cosmic halo boost: excess emission from haloes over homogeneous background

$$f(M > M_{\rm min}) = \frac{1}{\bar{\rho}_B^2}\int_{M_{\rm min}}^{\infty}\left(\frac{{\rm d}n(M)}{{\rm dlog}M}\right)\bar{\rho}_h^2 V(M) f_h(V(M)){\rm dlog}M$$

halo mass function

emission per halo

Cosmic signals dominated by unresolved haloes!!



DM Annihilation boosts

Since annihilation rates scale as ρ^2, any unresolved DM clumpiness should boost the annihilation rate

global subhalo boost: excess emission from subhaloes over that of a single halo

mass function

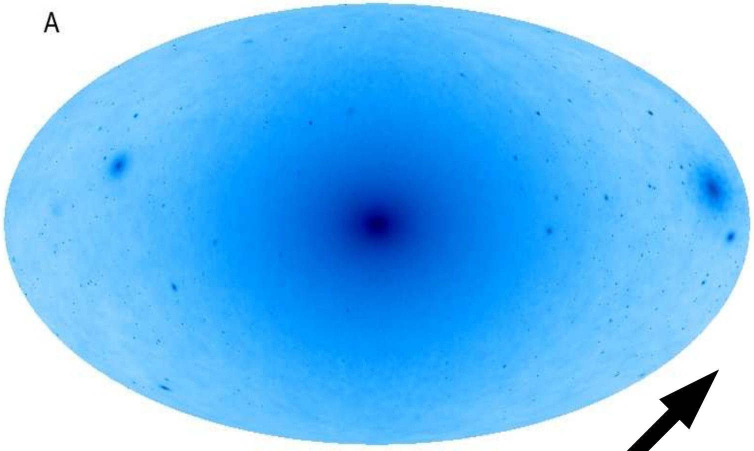
luminosity

$$B(M) = \frac{1}{L(M)} \int_{M_{min}}^{M} (dN/dm)\ [1 + B(m)]\ L(m)\ dm$$

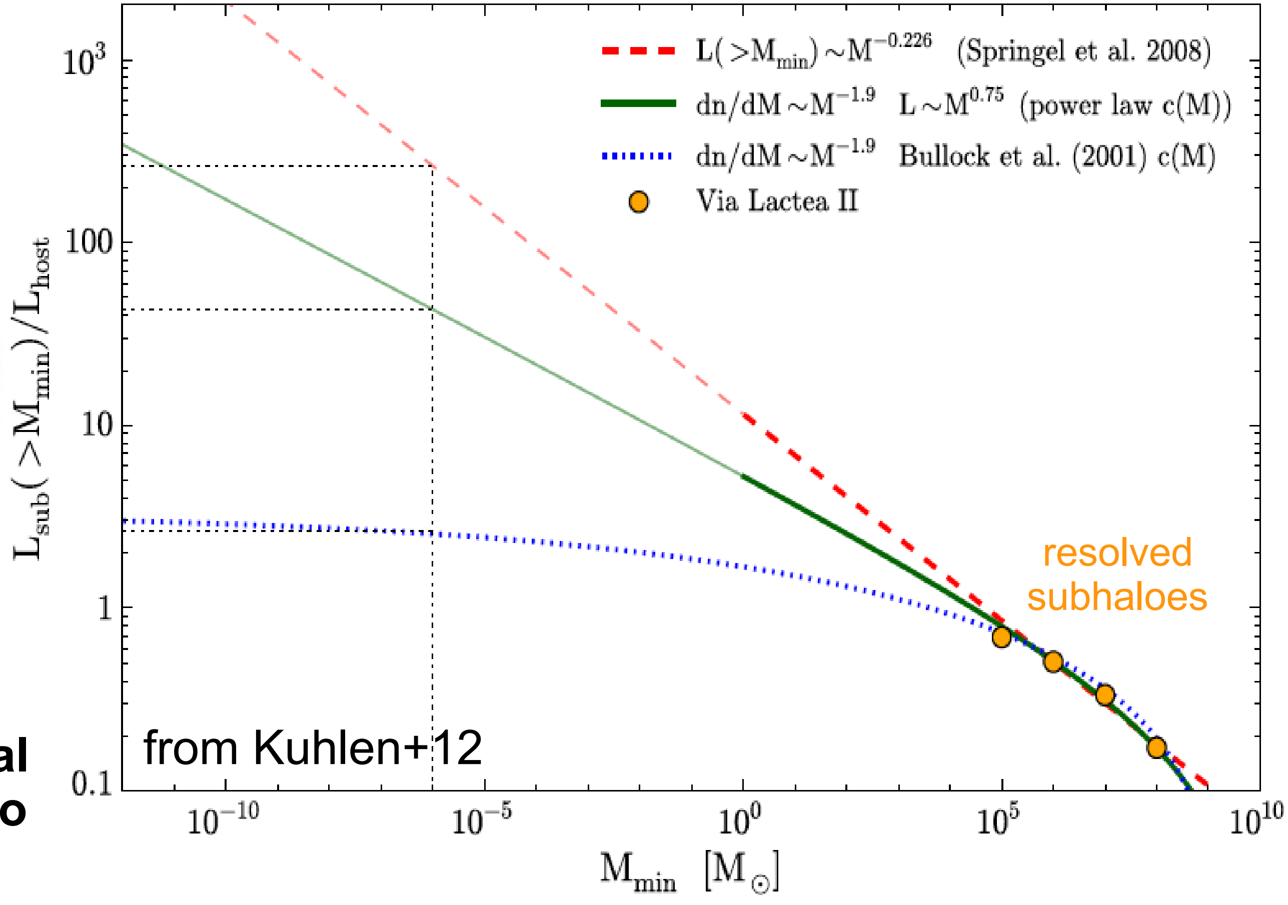
halo luminosity

sub-subhaloes (**subdominant**)

Sky-map of the annihilation signal from the Via Lactea II MW-halo simulation (Kuhlen, Madau & Silk 09)



Boost up to the virial radius for a MW-halo



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mass function

luminosity

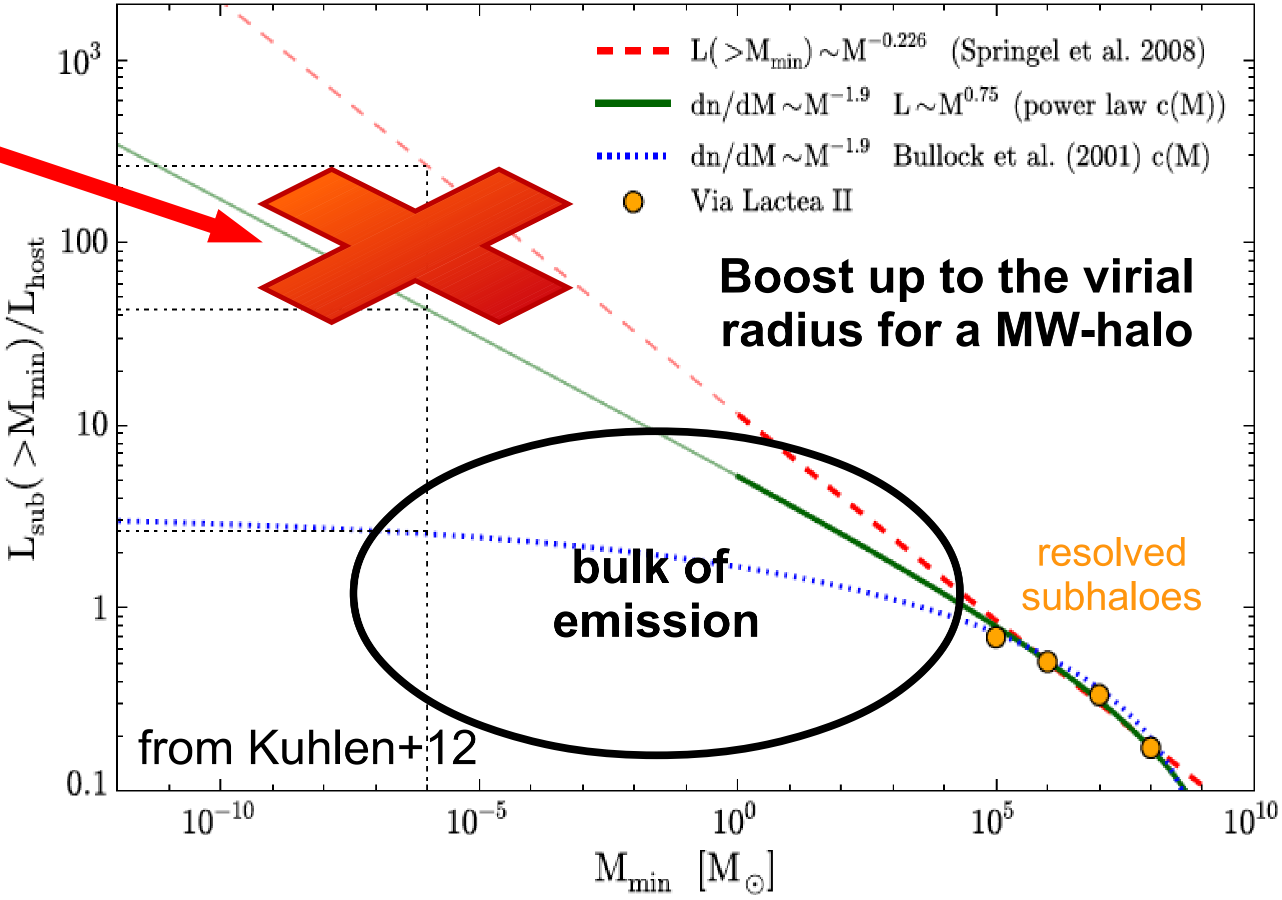
halo luminosity

sub-subhaloes (**subdominant**)

Models based on power-law extrapolations of c(M) are wrong!!

Important to consider the flattening of the power spectrum

Halo signals (integrated up to the virial radius) are dominated by unresolved subhaloes!!



DM Annihilation boosts

Since annihilation rates scale as ρ^2, any unresolved DM clumpiness should boost the annihilation rate

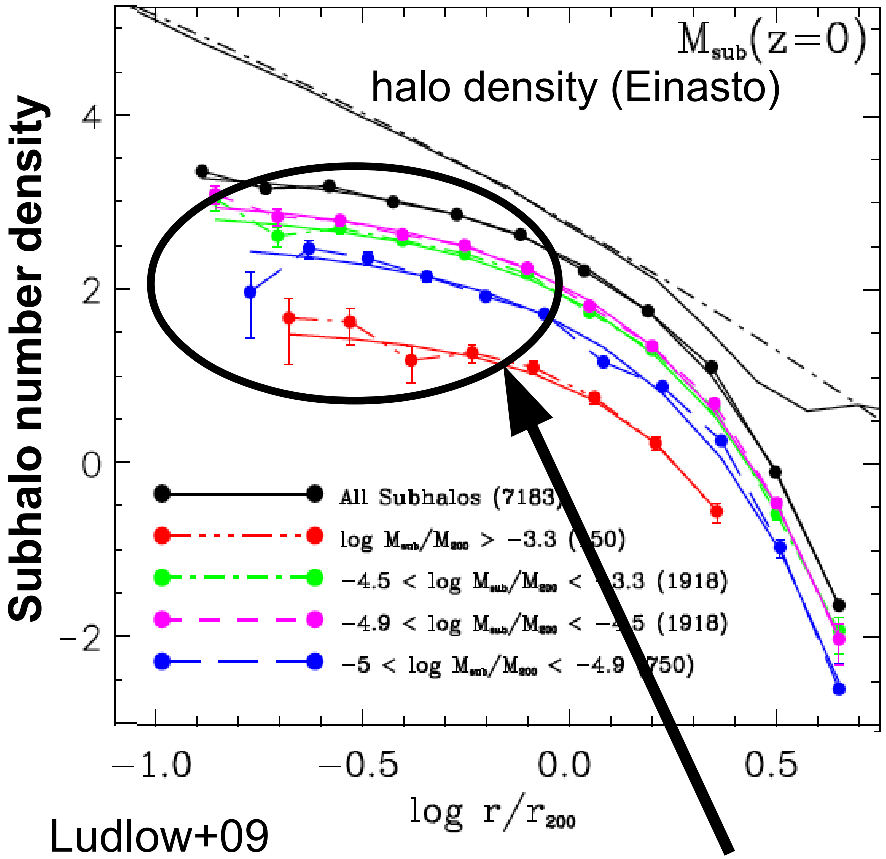
local (average) subhalo boost: local excess emission from subhaloes over that of the smooth halo emission

halo+subhaloes

$$B(r) = \frac{\int \rho^2 \, dV}{\int [\bar{\rho}(r)]^2 \, dV}$$

averaged over
a radial shell

halo



Ludlow+09

Tidal stripping disrupts subhaloes

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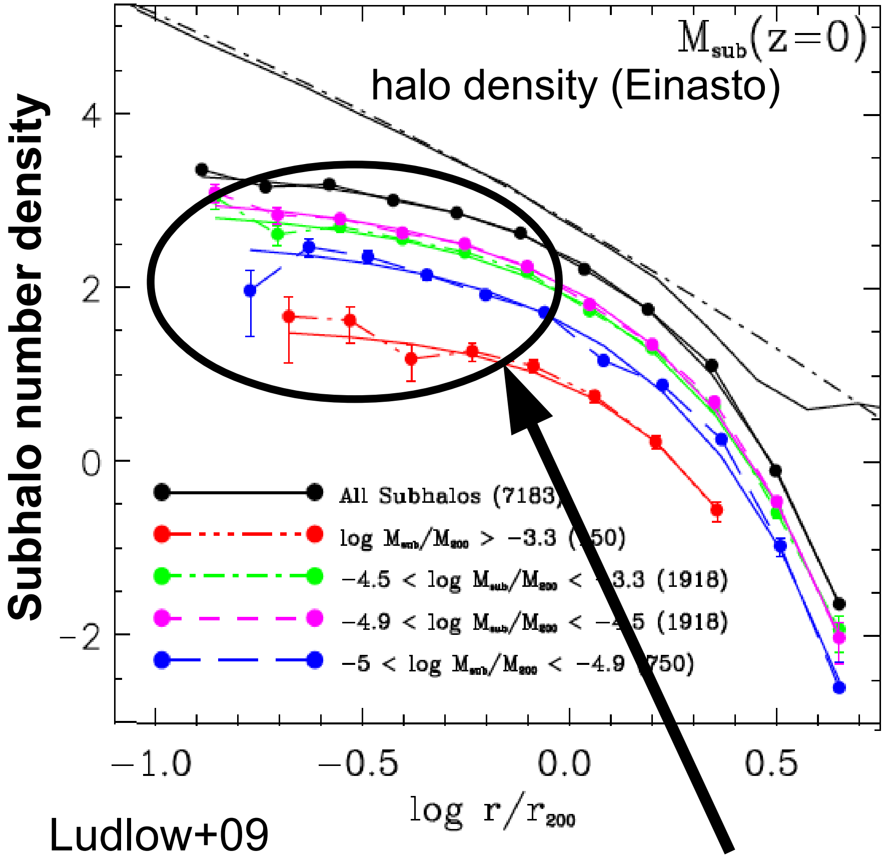
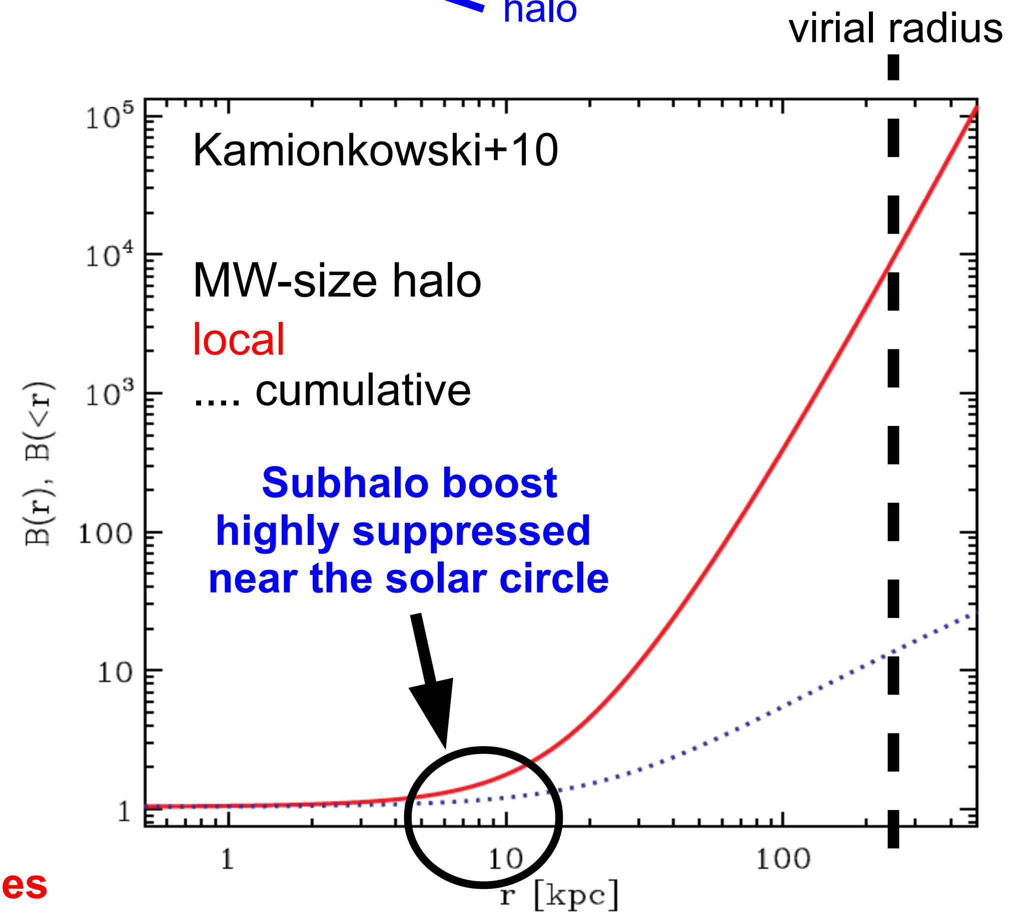


Ludlow+09

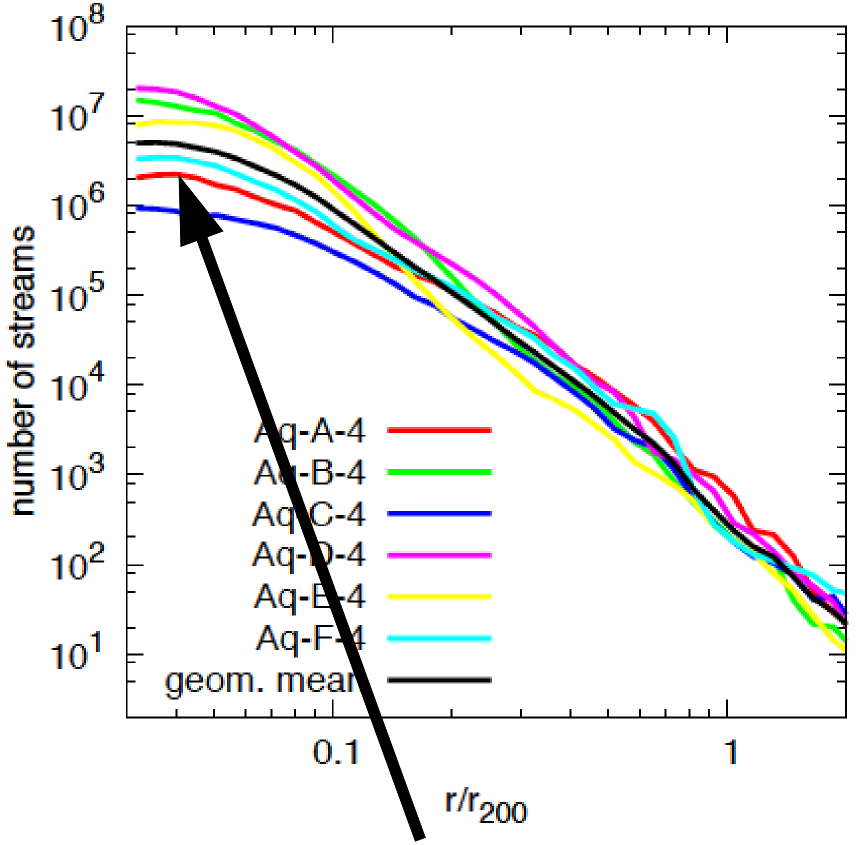
Tidal stripping disrupts subhaloes



Subhalo boost highly suppressed near the solar circle

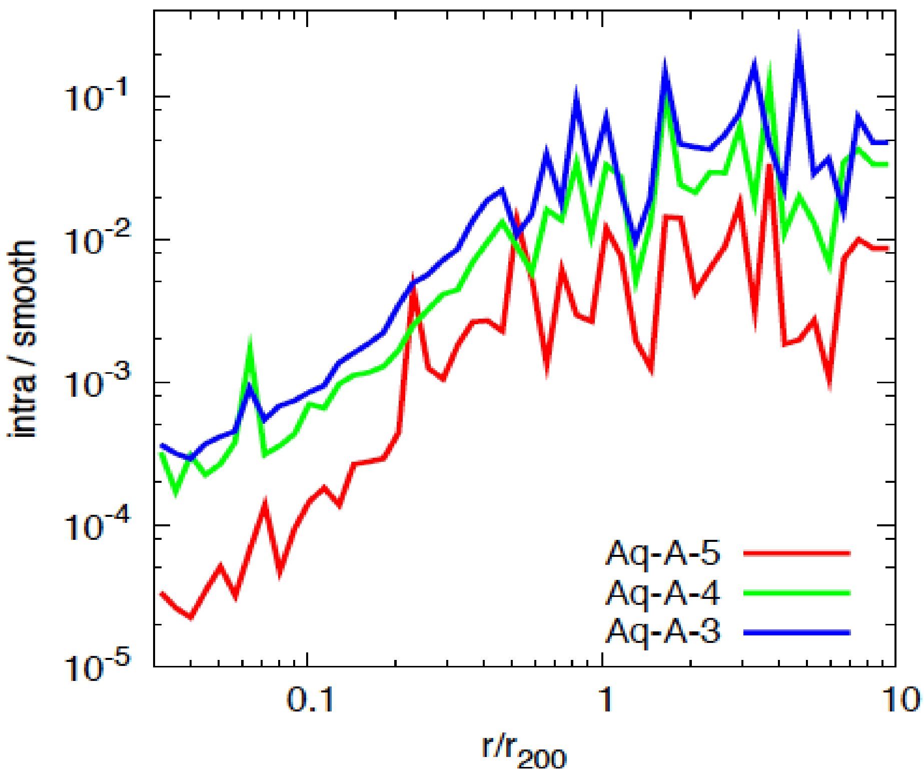
The role of streams and caustics?

Radial profile of the median number of streams in MW-size haloes



Very large number near the solar circle.
In most direct detection experiments,
it is "safe" to assume that the local velocity distribution is smooth

Radial profile of the boost to the annihilation rate from caustics



The annihilation boost by caustics is only important (but still subdominant) near the virial radius

Example: recipe to predict cosmic DM annihilation/decay signals

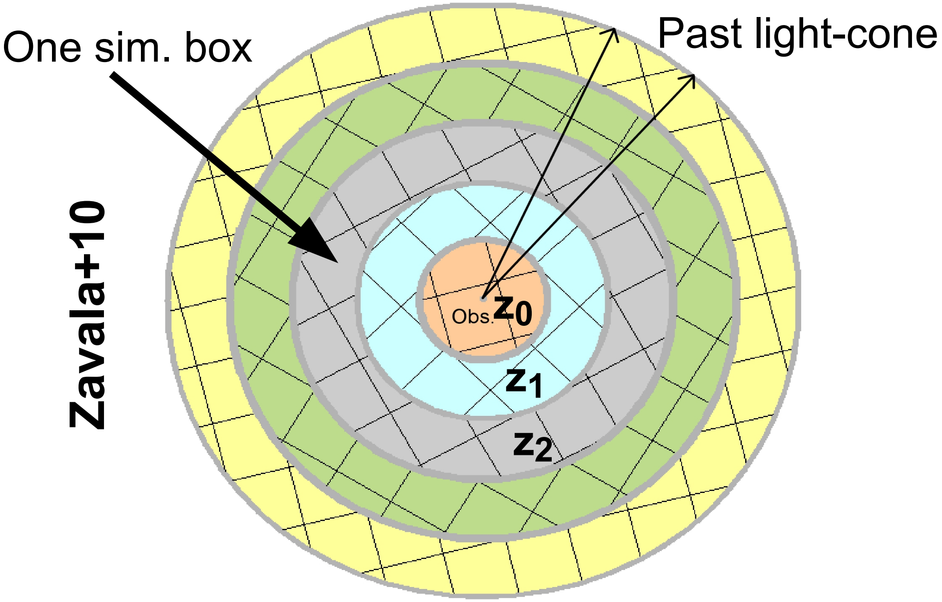
1) Take a large-scale simulation ~100Mpc (e.g. Millennium, Bolshoi)

2) Use resolved (sub)halo catalogues ~$M_h>10^8 M_\odot$ to get abundances and global properties (mass, concentration,..)

3) Assume a density profile for each (sub)halo (calibrated from higher resolution simulations)

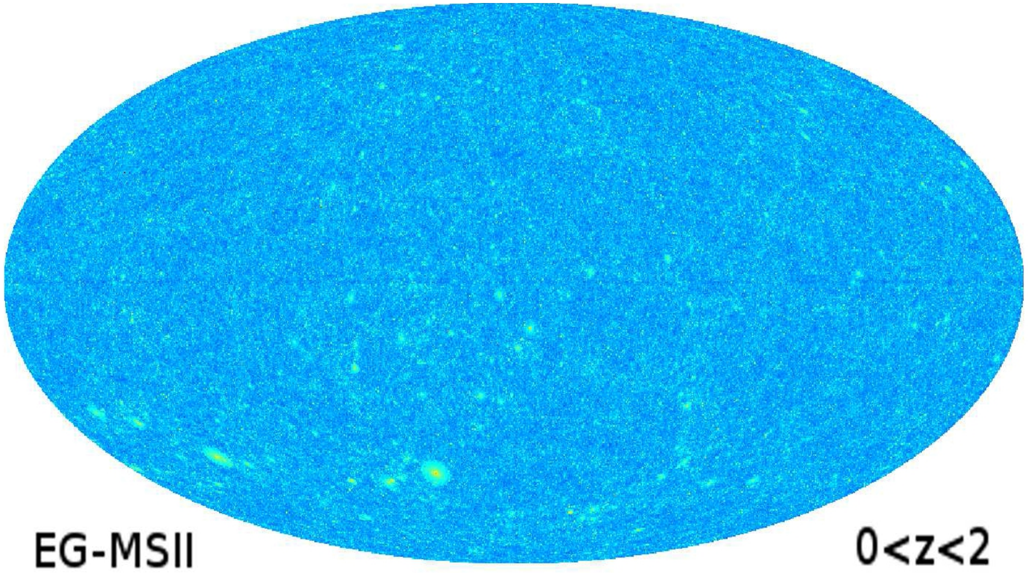
4) Extrapolate to unresolved masses (mass function, concentration-mass)

5) Produce a sky-map built on light-cones



Zavala+10

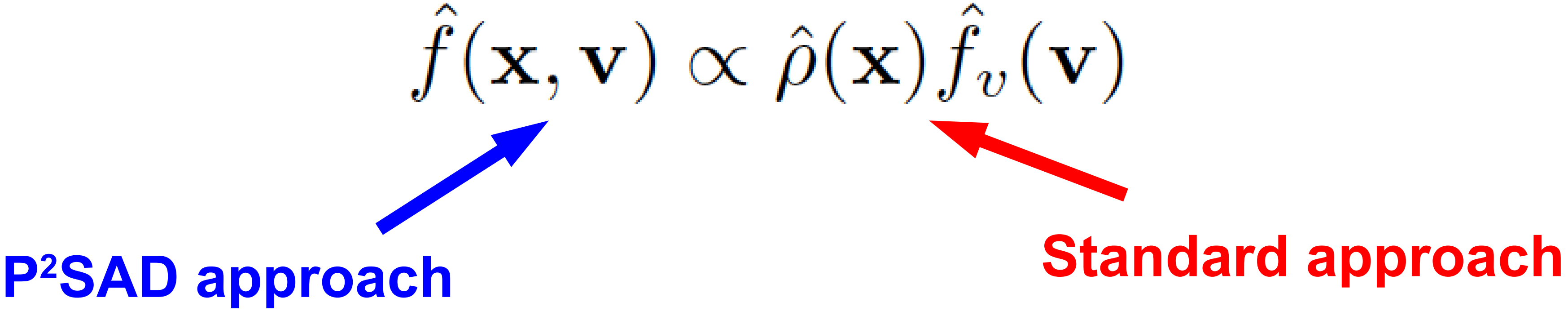
Gamma-ray map from DM decay



Fornasa+13

A new approach to predict non-gravitational DM signals: P^{2}SAD

Use the full phase-space distribution information



$$\hat{f}(\mathbf{x},\mathbf{v}) \propto \hat{\rho}(\mathbf{x})\hat{f}_v(\mathbf{v})$$

P^{2}SAD approach

Standard approach

Advantages:

a novel approach on DM clustering

built-in phase-space information is used to extrapolated to the unresolved regime (through a physically-motivated model)

naturally accounts for DM signals that have velocity-dependent cross sections (e.g. Sommerfeld-enhancement)

A new approach: P^{2}SAD

Example: Indirect detection (DM self-annihilation)

Annihilation rate (# of events per unit time in a region of volume V)

$$R_{\mathrm{ann}} = \lim_{\Delta x \to 0} \left[\frac{1}{2m_\chi^2} \int_V d^3\mathbf{x} \int d^3\mathbf{v}\, d^3\mathbf{\Delta v} (\sigma v)_{\mathrm{ann}} f(\mathbf{x}, \mathbf{v}) f(\mathbf{x} + \mathbf{\Delta x}, \mathbf{v} + \mathbf{\Delta v}) \right]$$

total DM mass within V

$$= \frac{1}{2m_\chi^2} \int d^3\mathbf{\Delta v} (\sigma v)_{\mathrm{ann}} M_V \lim_{\Delta x \to 0} \Xi(\Delta x, \Delta v)$$

Particle Phase Space Average Density (P^2SAD)

$\Xi(\Delta x, \Delta v) \propto$ 2D phase − space 2PCF

Zavala & Afshordi 14a, 14b

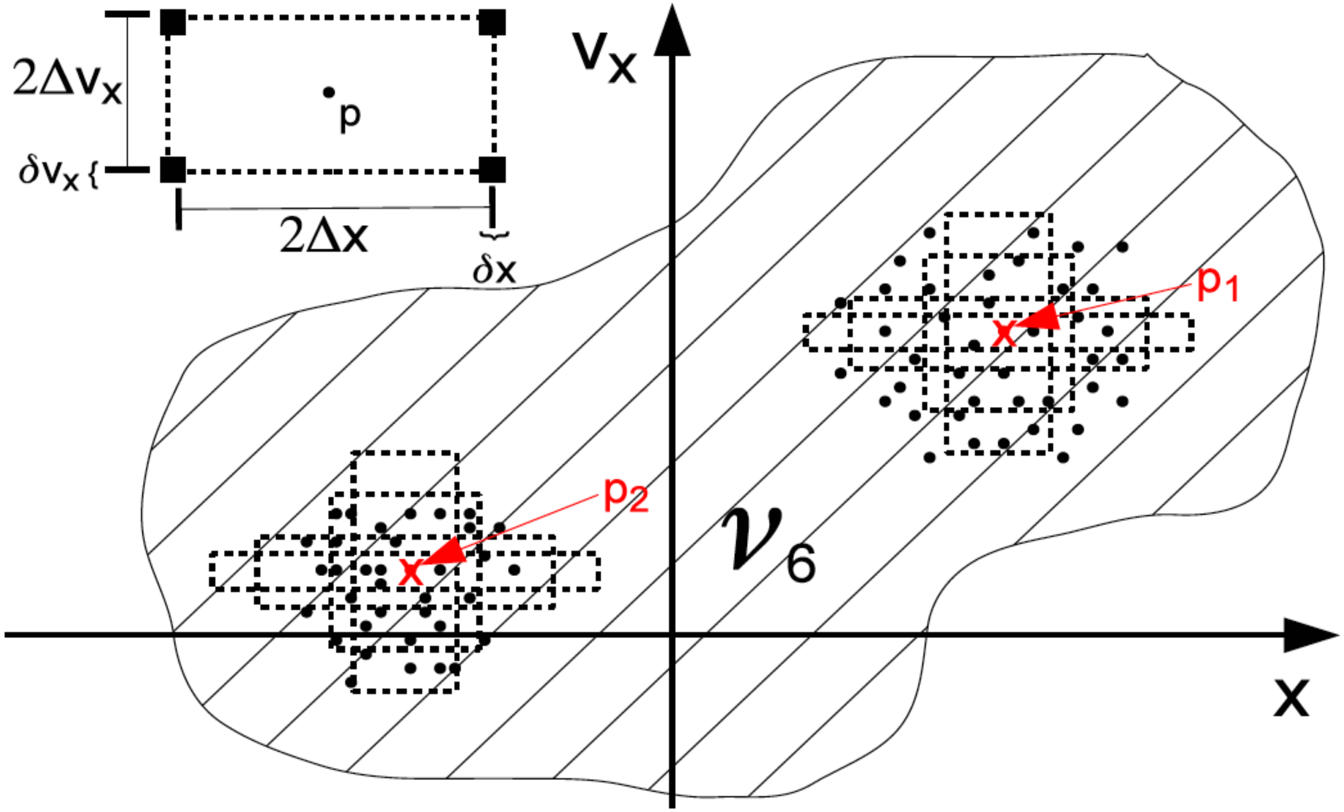
A new approach: P^2SAD

Particle Phase Space Average Density (P^2SAD)

$$\Xi(\Delta x, \Delta v) \propto \mathrm{2D\ phase-space\ 2PCF}$$

Estimator in an N-body simulation: $\Xi(\Delta x, \Delta v)_{\rm sim} = \dfrac{m_p \langle N_p(\Delta x, \Delta v)\rangle \nu_6}{\underset{\uparrow}{V_6(\Delta x, \Delta v)}}$

phase-space volume in the shell



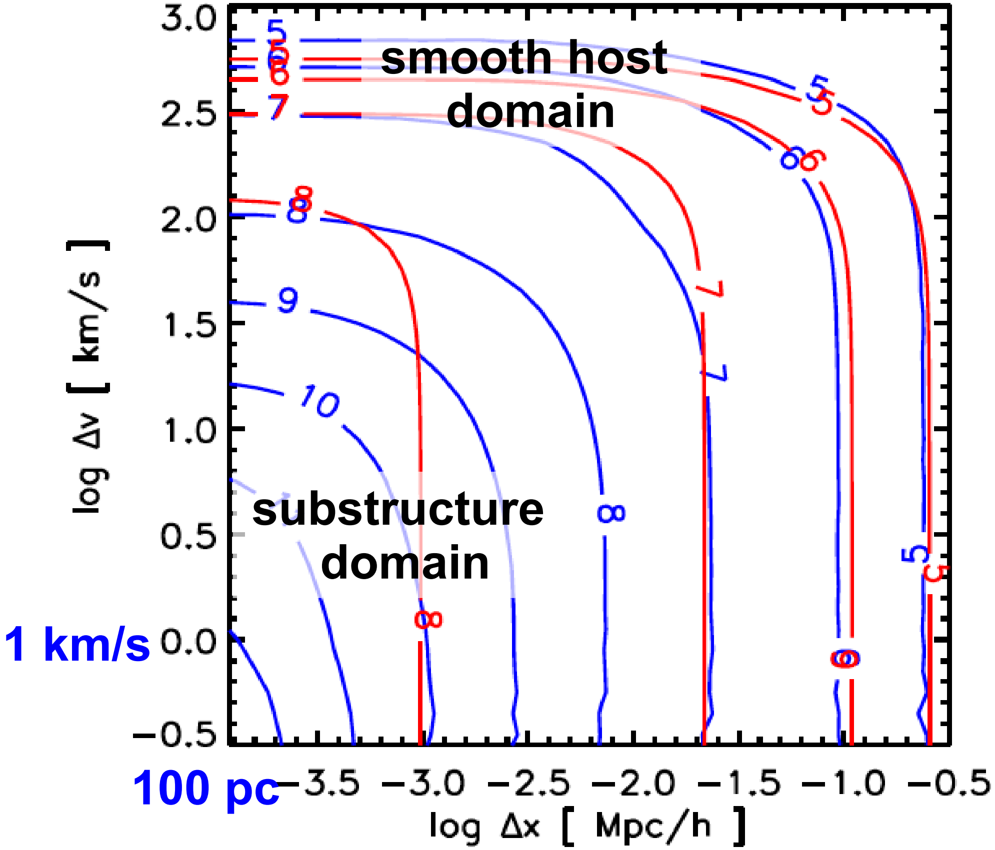
Zavala & Afshordi 14a, 14b

A new approach: P^2SAD

A novel way to look at DM clustering

Aquarius project Springel+08

Contours of constant log(P^2SAD)

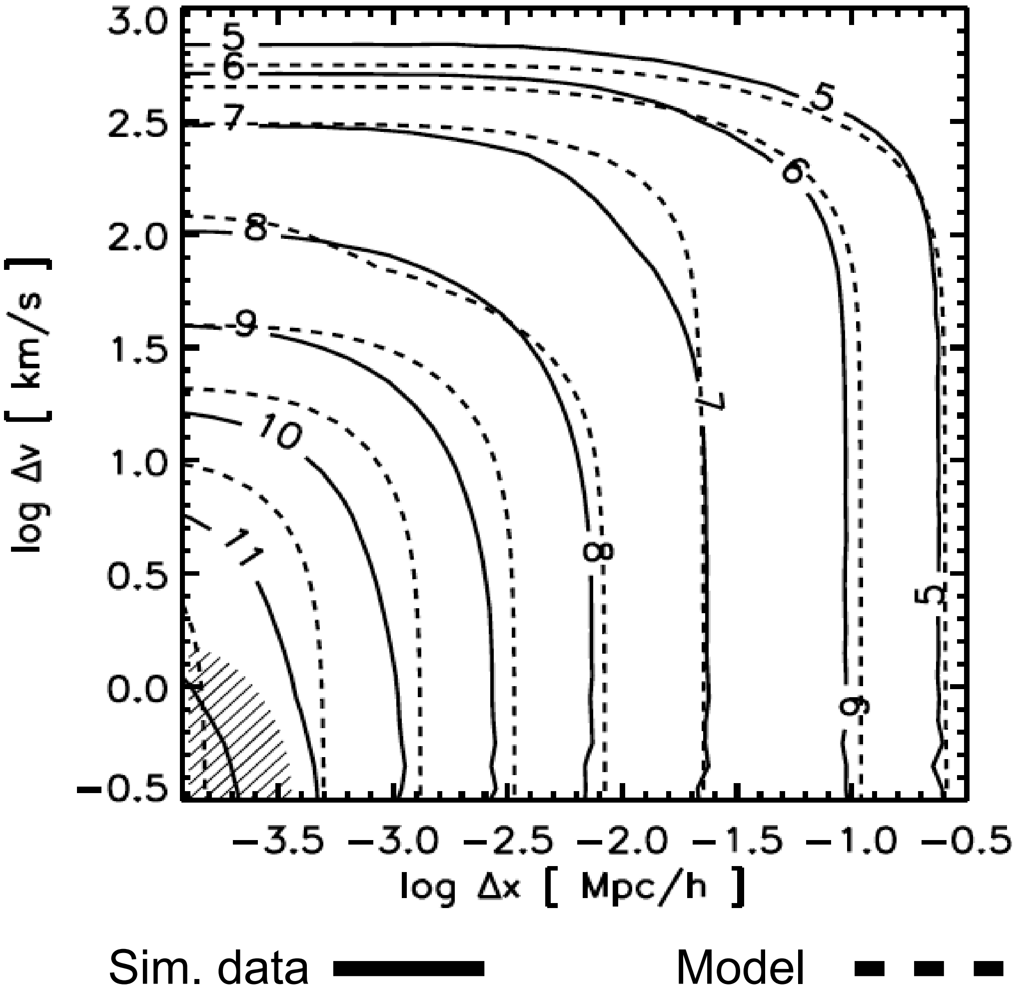


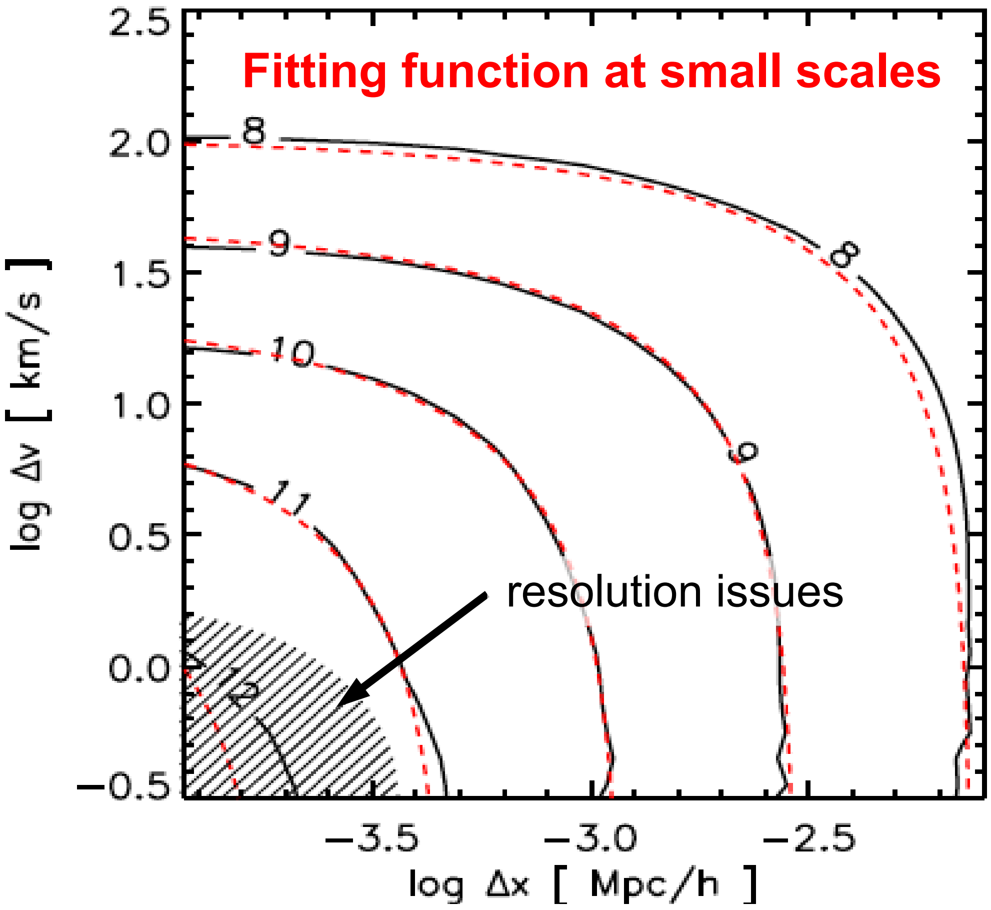
red: Einasto-fit to smooth Aquarius halo

blue: full DM distribution

Zavala & Afshordi 14a, 14b

Descriptive modelling of P^2SAD





$$\left(\frac{\Delta x}{\mathcal{X}(\Xi)}\right)^{\beta} + \left(\frac{\Delta v}{\mathcal{V}(\Xi)}\right)^{\beta} = 1$$

$$\mathcal{X}(\Xi) = q_X \Xi^{\alpha_X}$$

$$\mathcal{V}(\Xi) = q_V \Xi^{\alpha_V}$$

Parameters calibrated to Aquarius

(sub)halo model: smooth + substructures
(works at large separations, problems at small scales
-**specially if one wishes to extrapolate**-)

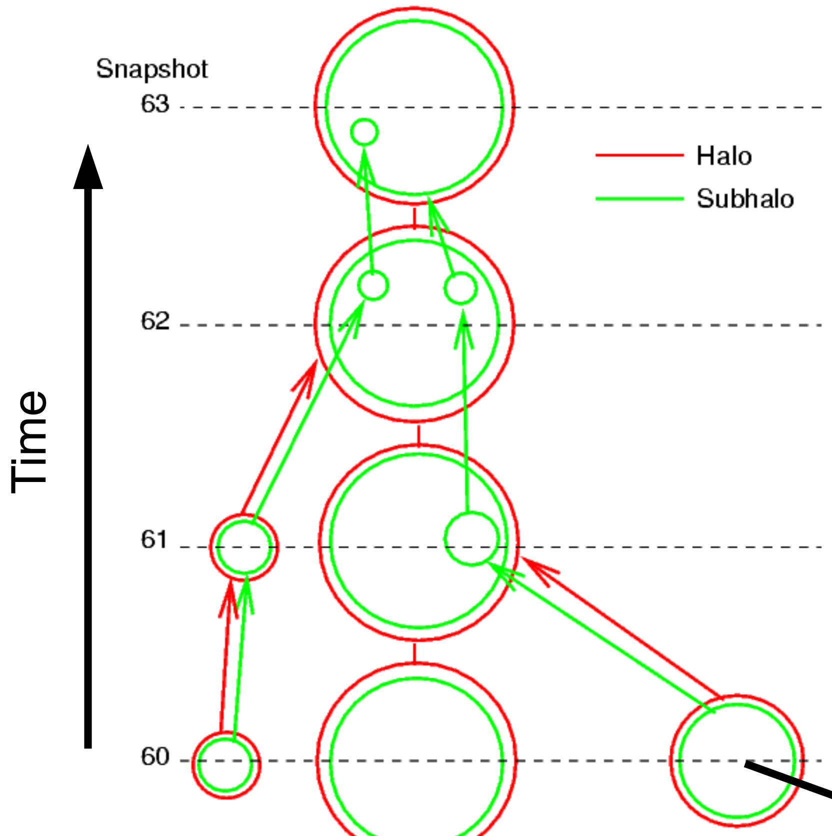
Zavala & Afshordi 14a, 14b

Physical model inspired by stable clustering

Hypothesis originally proposed by Davis & Peebles 1977. Extension to phase space: “the number of particles within the physical velocity Δv and physical distance Δx of a given particle does not change with time for small enough Δv and Δx”

Physical model inspired by stable clustering

Hierarchical assembly



m_{col}

spherical collapse

$$\boxed{\Xi(\Delta x, \Delta v) \equiv \xi_s = F\left((\mathbf{\Delta v})^2 + (4\pi/3)G\rho_{\rm char}(\mathbf{\Delta x})^2\right)}$$

stable clustering

+

collisionless Boltzmann eq.

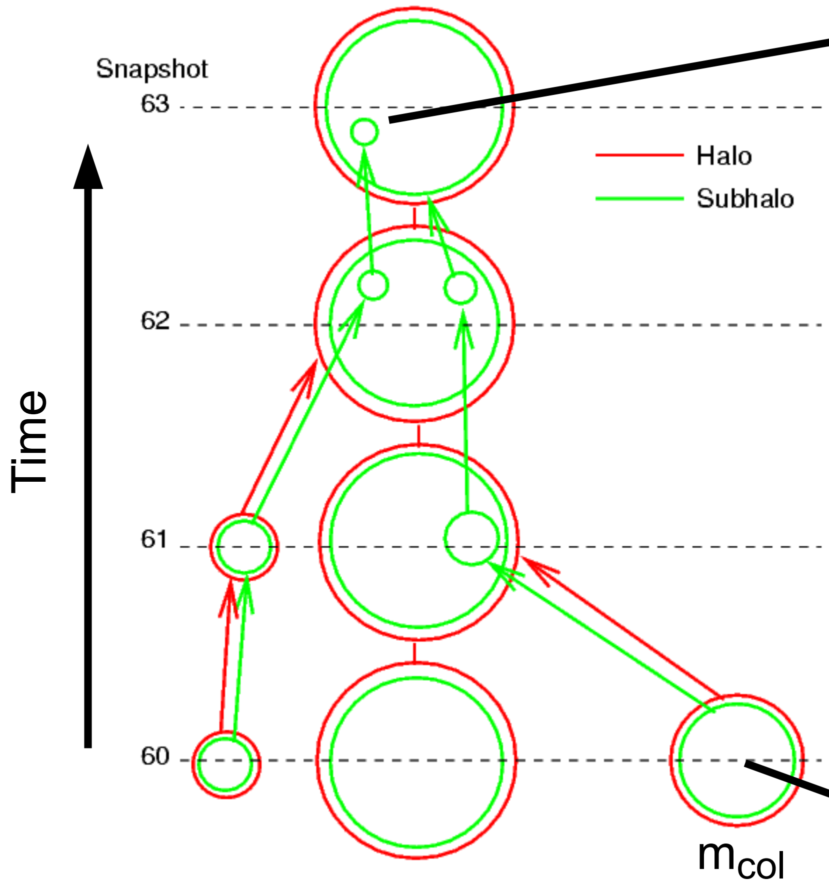
z_{col}

$$\xi_s = \frac{\rho_{\rm char}}{\sigma_{\rm vir}^3}$$

Afshordi, Mohayaee & Bertschinger 10

Physical model inspired by stable clustering

Hierarchical assembly



Tidal disruption

$$\boxed{\Xi(\Delta x, \Delta v) \equiv \mu\xi_s = F\left((\Delta \mathbf{v})^2 + (4\pi/3)G\rho_{\rm char}(\Delta \mathbf{x})^2\right)}$$

stable clustering

+

collisionless Boltzmann eq.

spherical collapse

$z_{\rm col}$

$$\xi_s = \frac{\rho_{\rm char}}{\sigma_{\rm vir}^3}$$

Afshordi, Mohayaee & Bertschinger 10

Physical model inspired by stable clustering

Deviations from stable clustering

$$\left(\frac{\Delta x}{a\lambda(m_{\rm col})}\right)^{\beta} + \left(\frac{\Delta v}{b\zeta(m_{\rm col})}\right)^{\beta} = 1$$

λ and ζ are given by spherical collapse

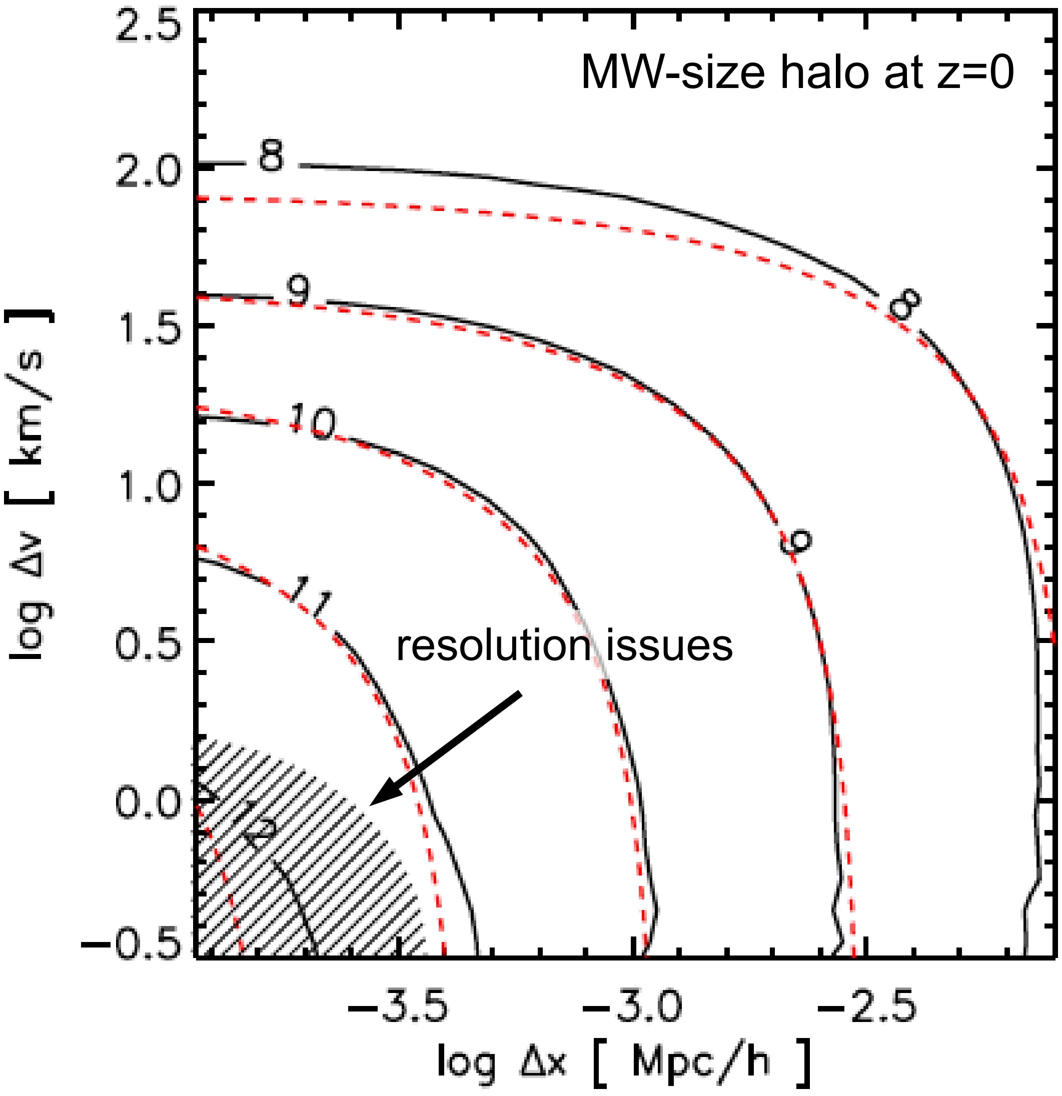
a, b and β slowly varying functions of redshift of order 1

We propose a tidal disruption model

$$\mu(m_{\rm col}; z)\xi_s = \Xi(\Delta x, \Delta v)$$

Parameters calibrated to Aquarius

Physically-motivated model to compute DM signals down to unresolved scales!!



Zavala & Afshordi 14a, 14b

(e.g. global substructure boost to annihilation: $(\sigma v)_{\rm ann}$ = cte)

$$R_{\rm ann} \propto \int d^3\boldsymbol{\Delta}\mathbf{v} \lim_{\Delta x \to 0} \Xi(\Delta x, \Delta v)$$

fitting function

$$R_{\rm ann} \propto q_v^3 \ln\left(\frac{\Xi_{\rm max}}{\Xi_{\rm min}}\right)$$

valid away from smooth component dominion

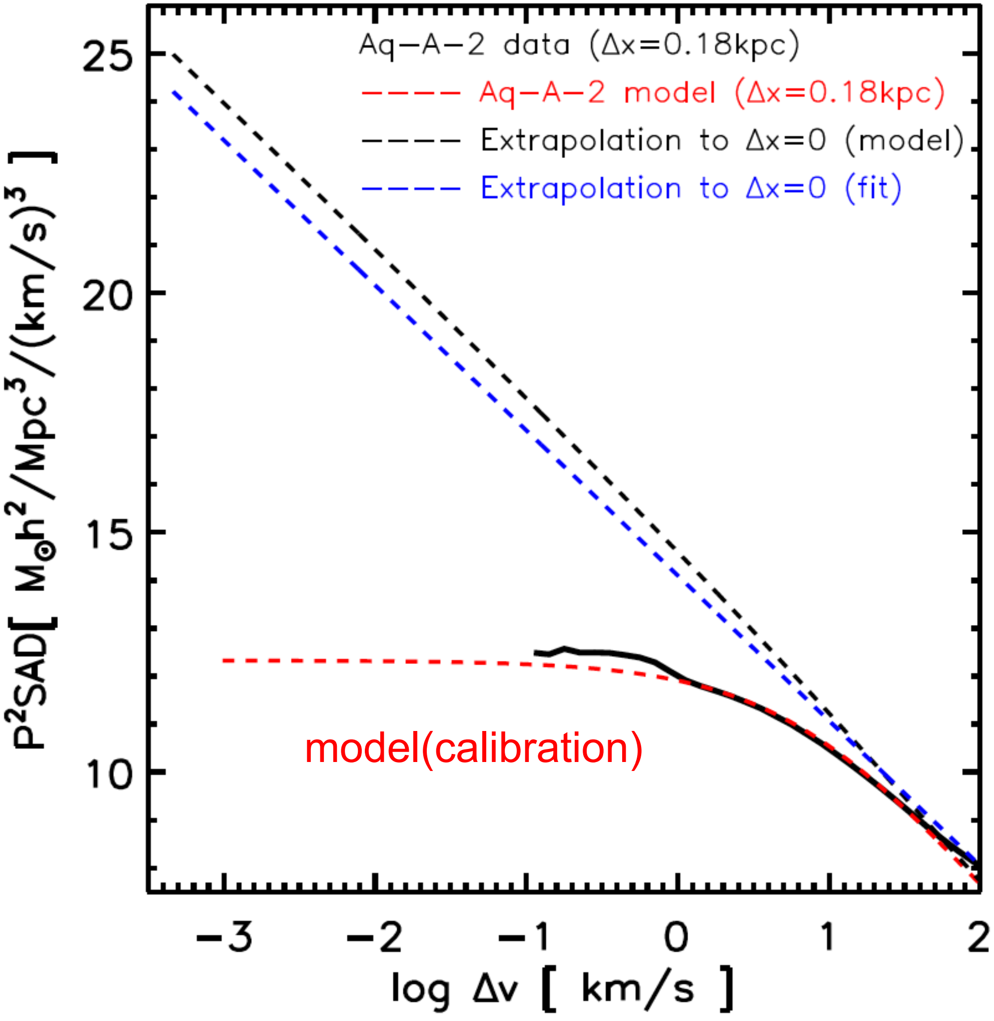
model

$$R_{\rm ann} \propto b^3 \int_{\rm M_{min}}^{\rm M_{max}} \mu(m_{\rm col}) d(m_{\rm col}\sigma^3(m_{\rm col}))$$

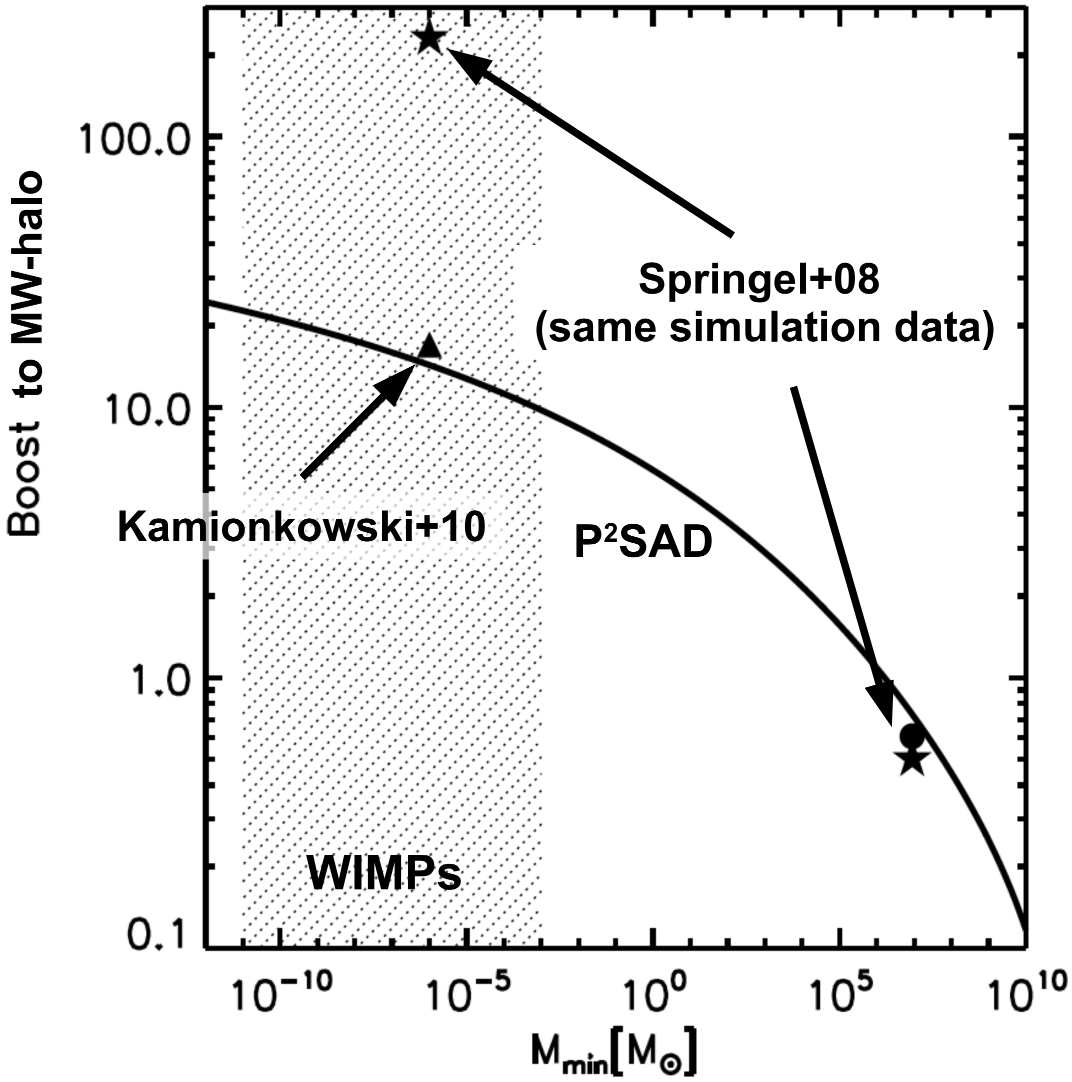
mass variance
(CDM power spectrum)

(e.g. global substructure boost to annihilation: $(\sigma v)_{\rm ann}$ = cte)

A “blind” extrapolation of P^2SAD reveals the advantage of using phase-space information



A “blind” extrapolation of the standard approach gives wrongly high boost values



Zavala & Afshordi 14a, 14b

Concluding remarks

- **CDM is by itself an incomplete DM theory**, it needs completion with a particle physics model (all beyond SM: “exotic”)

- Decisive decade for “standard” DM model (CDM + WIMPs): experiments reaching the “expected” WIMP cross sections (LHC, Fermi, LUX,...)

- An effective (more generic) theory of structure formation **must consider a broader range of allowed DM phenomenology** (DM interactions, different P(k)...) coupled with our developing knowledge of galaxy formation/evolution

Concluding remarks

- Current CDM simulations cover a vast dynamical range giving accurate predictions of the DM distribution (~100 pc to ~1Gpc, ~1km/s to ~1000 km/s). They are our most accurate method to predict non-gravitational DM signals in the resolved regime

- Still, many signals are sensitive to smaller scales, far from current resolutions. Extrapolations of several orders of magnitude are needed to predict these signals.

- Physically-motivated models calibrated to simulations must be used to extrapolate The challenge for future simulations lies in testing these models

- **The synergy between DM and baryons make many expected signals highly uncertain!!**

Remarks on future sims and DM signals

DM SIGNALS	**MAIN UNCERTAINTY**	**FUTURE SIMULATIONS**
Cosmic backgrounds	halo mass function and inner structure down to M_{min}	simulate microhaloes up to z=0 (in voids maybe?)
Extragalactic haloes (extended): e.g. clusters	subhalo mass function and radial distribution down to M_{min}	follow microhaloes as they orbit the host in highly clustered regions!
Galactic subhaloes	luminous: synergy with baryons dark: their abundance and radial distribution	full hydro sims of satellite galaxies (subgrid physics) *maybe future obs. (proper motions of stars) can constrain the DM distribution*
Galactic Centre	Synergy with baryons	As above
Local (direct detection)	DM phase-space clustering near Earth	physically motivated models calibrated with ~parsec scale simulations

M_{min} = minimum self-bound mass (set by DM free streaming, kinetic decoupling)