"CDM?" program — KITP — 4/13/18

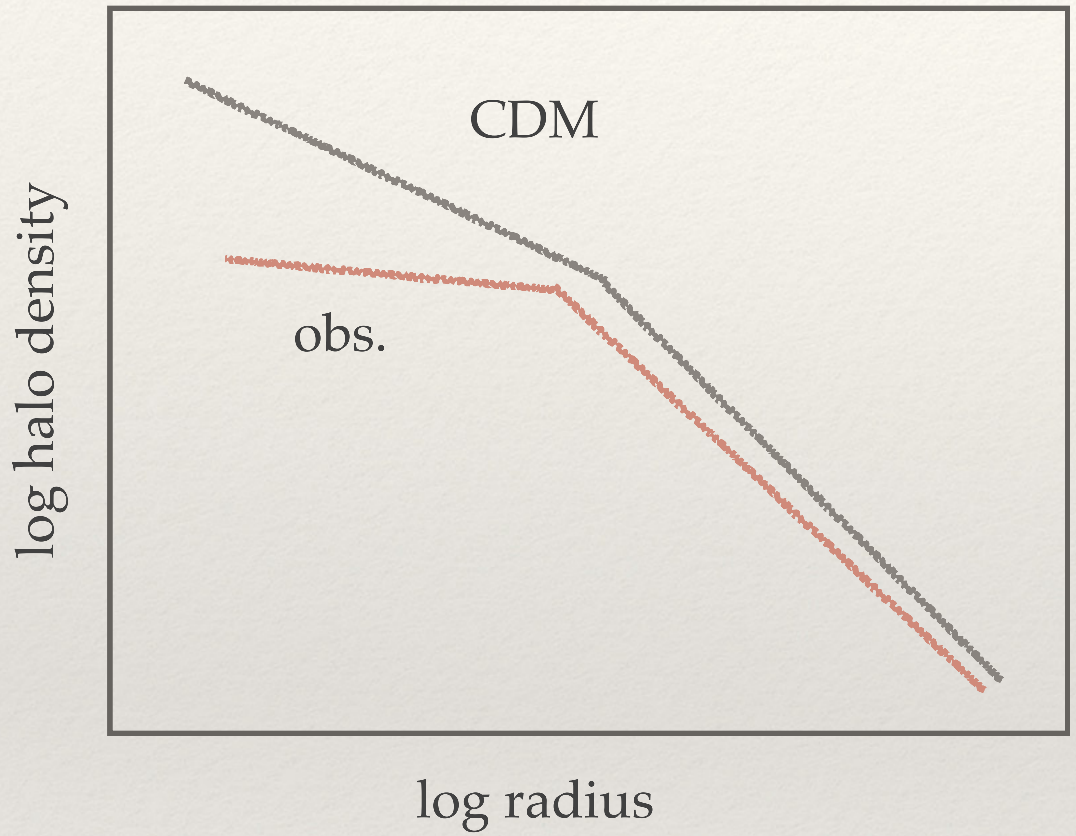
Cosmology of flavor-mixed dark matter

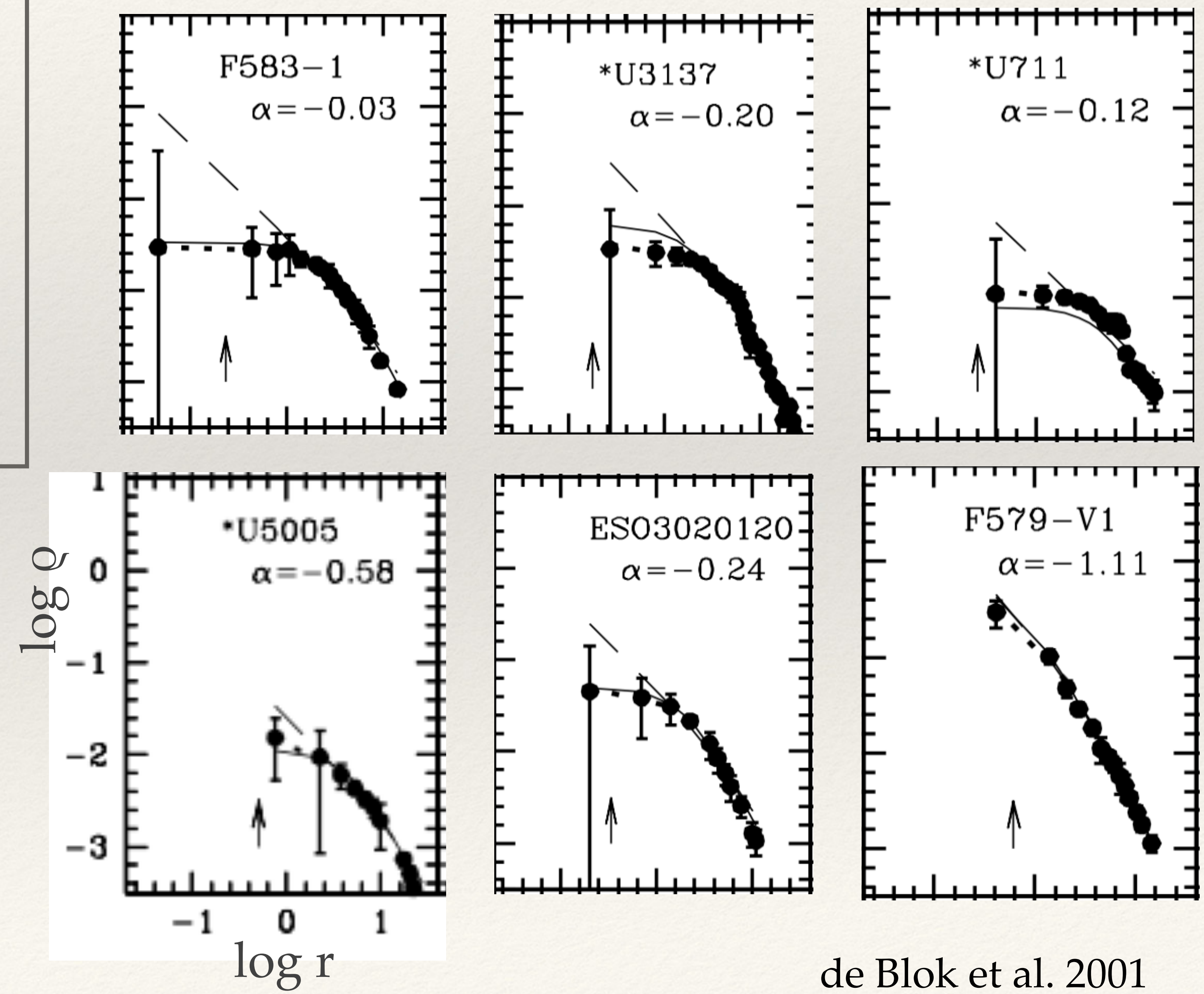
M. Medvedev, KU & MIT

supported by DOE via DE-SC0016368

ΛCDM at small scales

- core / cusp problem

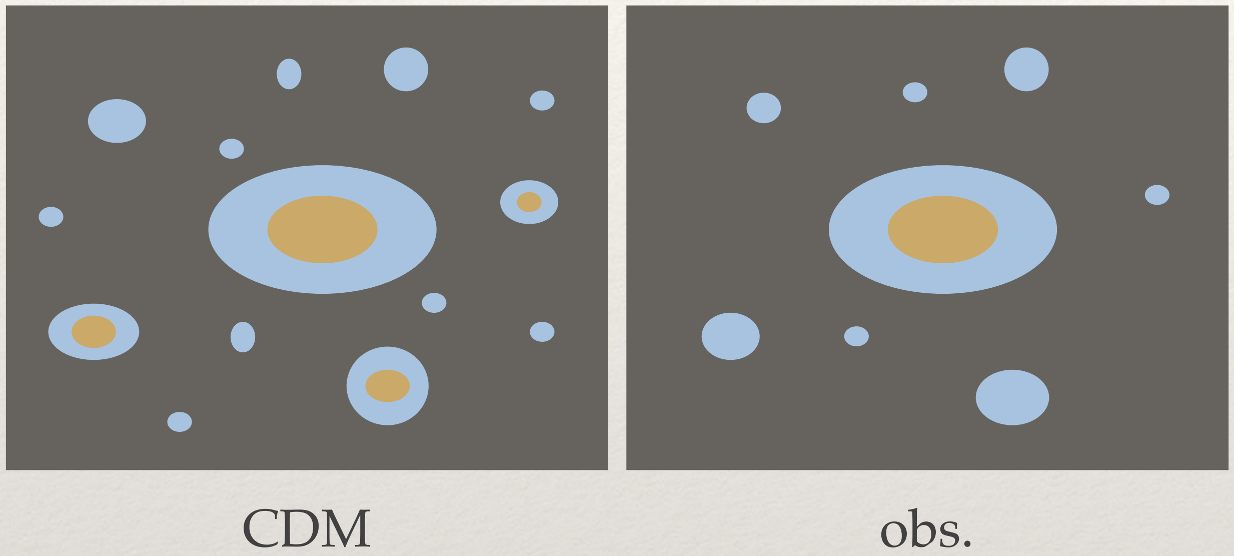


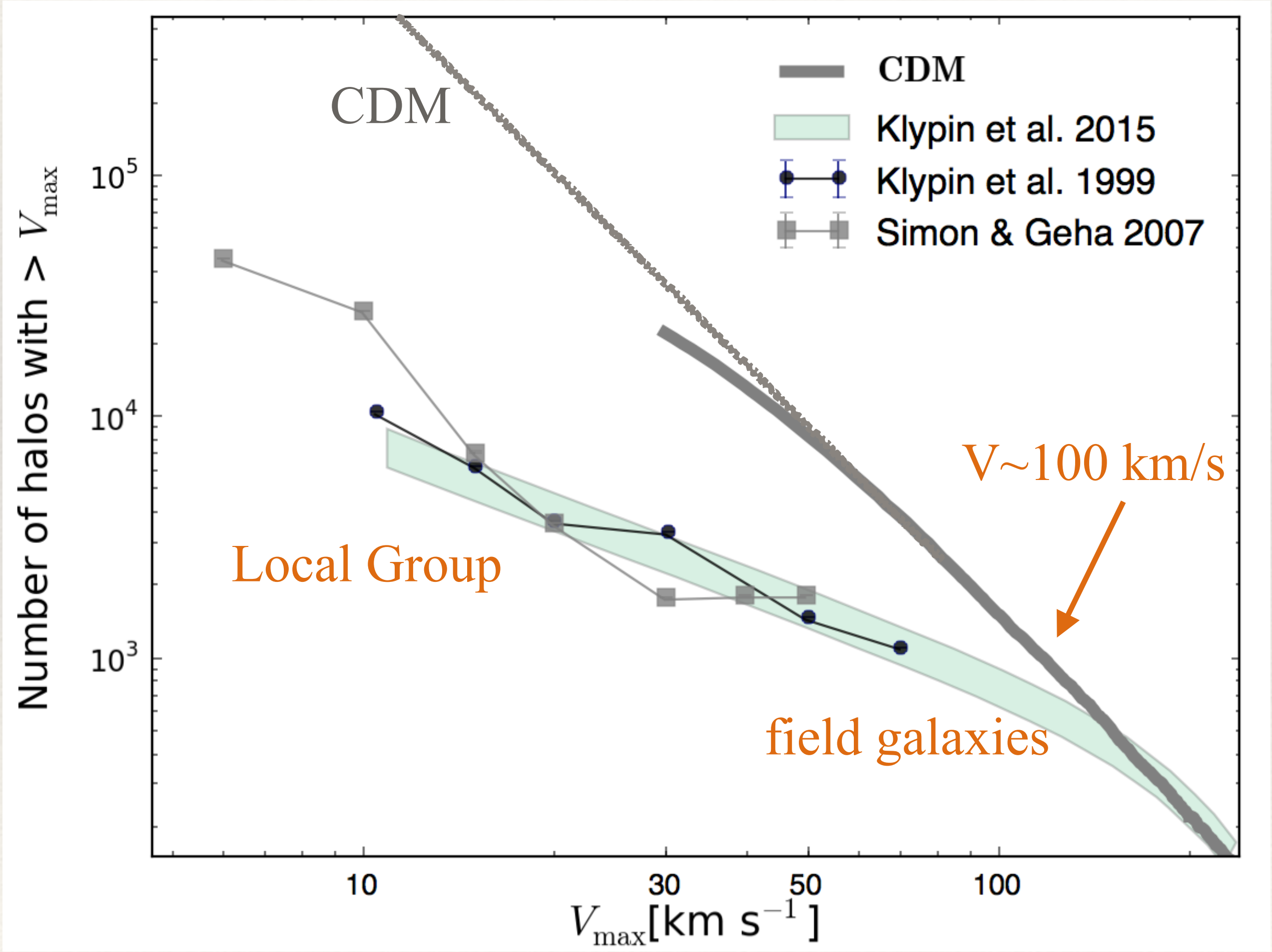


de Blok et al. 2001

ΛCDM at small scales

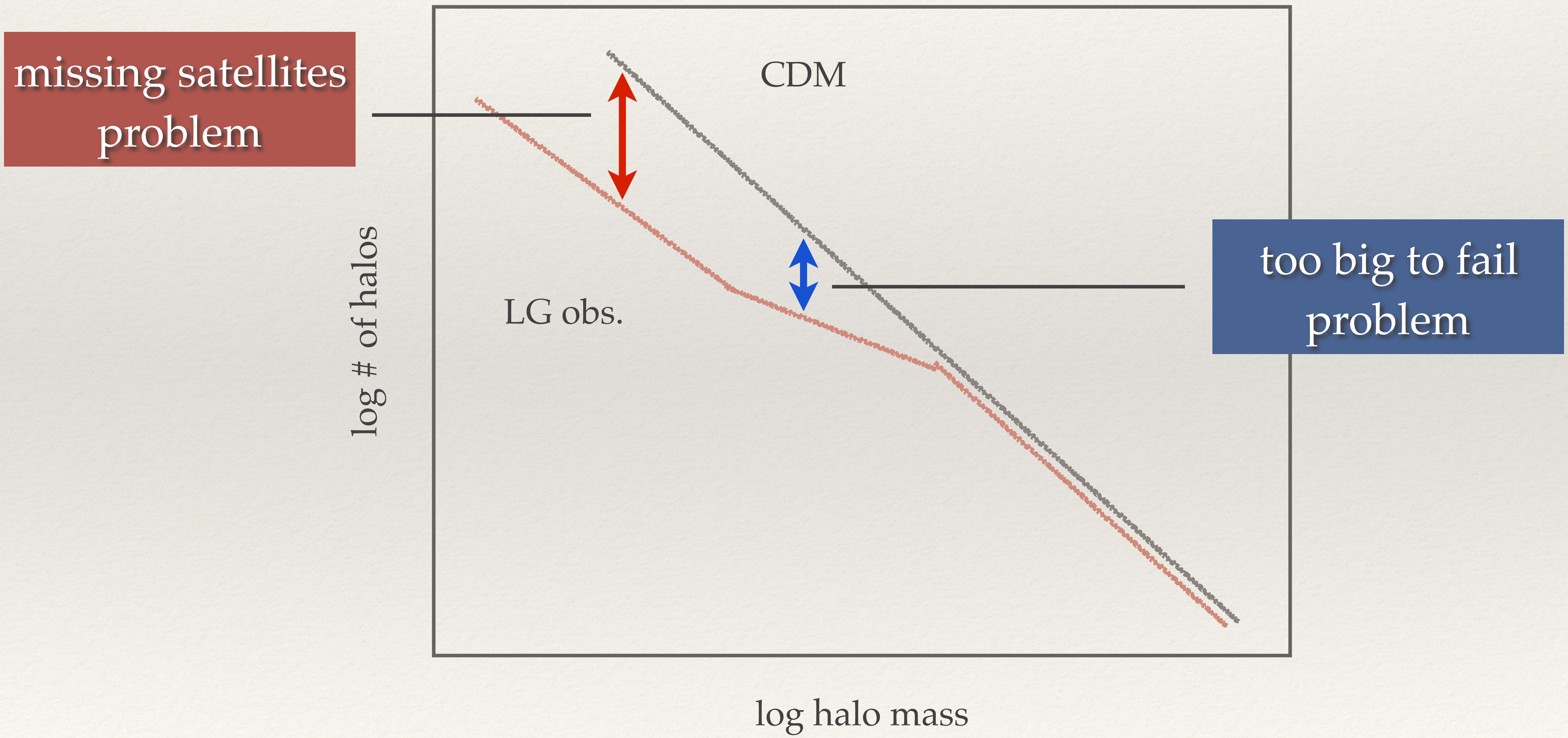
- substructure problem
  (missing satellites)





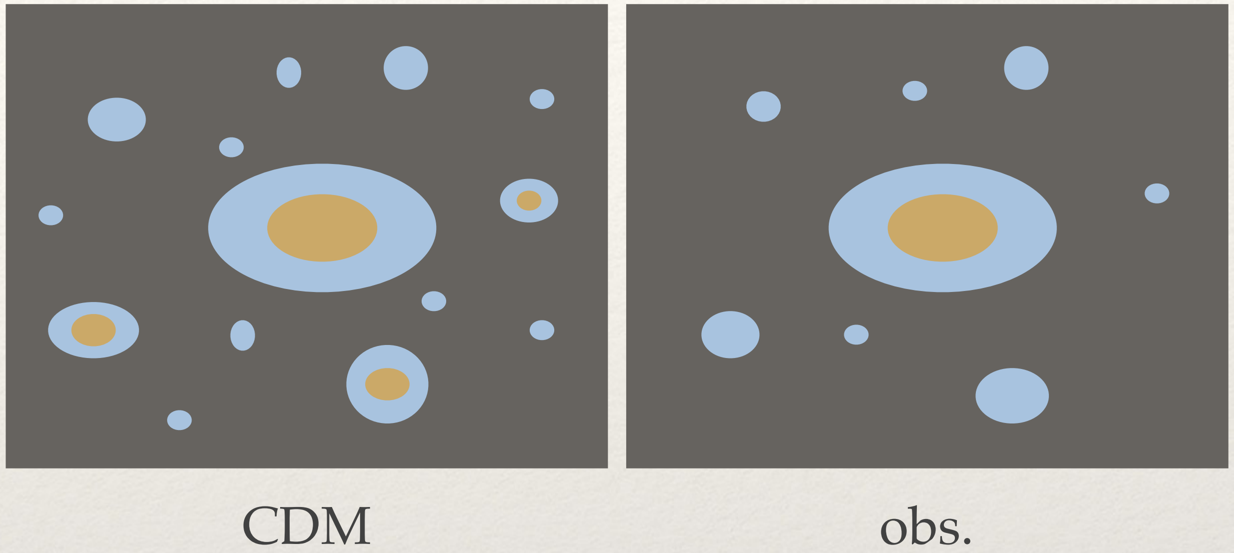
ΛCDM at small scales

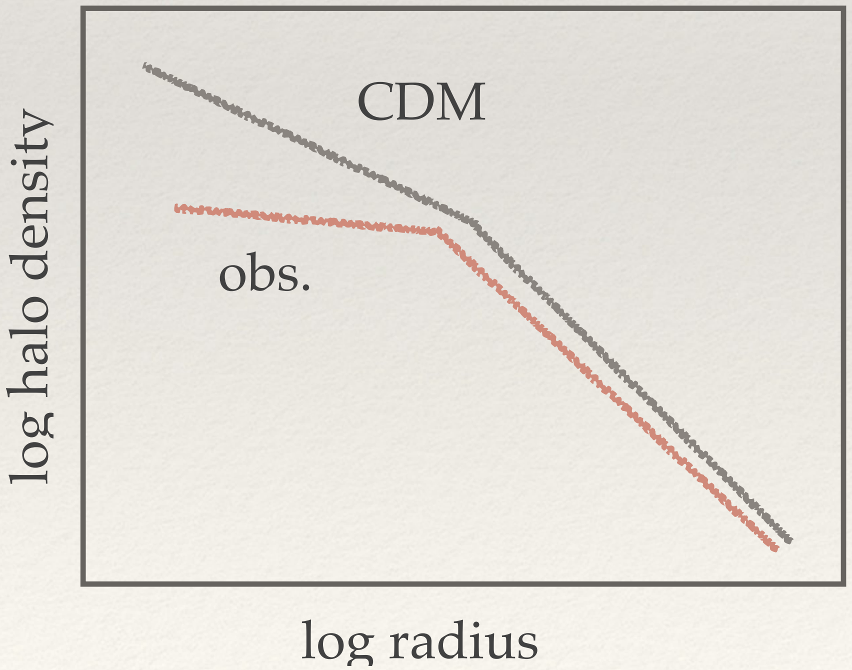
- too-big-to-fail problem

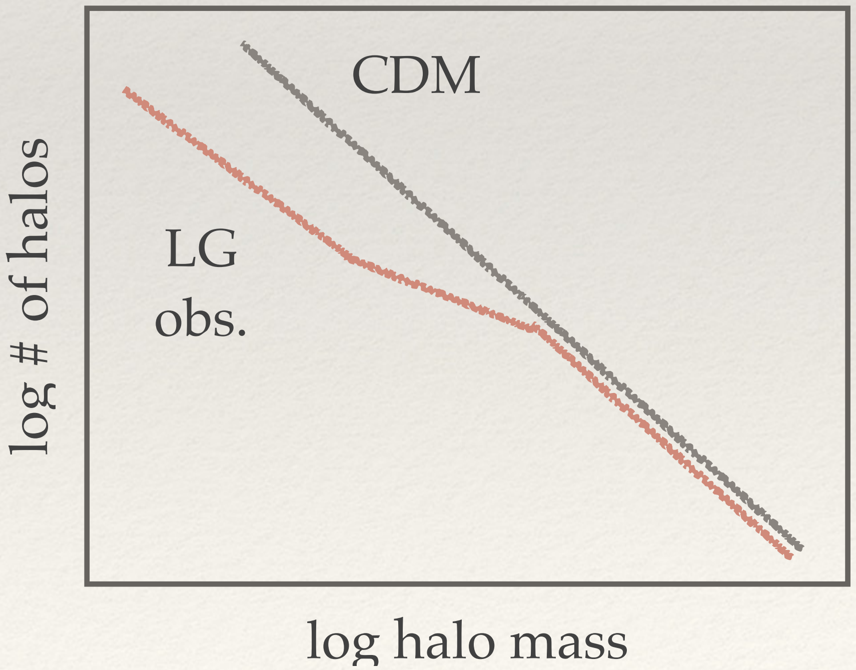


Cosmic Web: Small Scale Structure (SSS) - problems

- core/cusp problem
- substructure problem (missing satellites)
- too-big-to-fail problem







WIMP miracle

?

Traditional Cold Dark Matter paradigm

WIMP miracle
-- mass ~ hundreds GeV - few TeV
-- weak cross-section ~ 10^{-37} cm^2

$$\Omega \propto \frac{1}{\langle \sigma v \rangle} \propto \left(\frac{g_h^4}{m_h^2} \right)^{-1}$$

*seems to **fail***
or, at least, many scenarios ruled out
-- direct detection experiments push cross-section by orders of magnitude to < $10^{-44\text{-}45}$ cm^2

Possible solutions

- **Baryonic physics**
  - NS, BH feedback
  - outflows
  - star formation
  - CR, turbulence

- **Dark Matter physics**

Possible solutions

- **Baryonic physics**
  - NS, BH feedback
  - outflows
  - star formation
  - CR, turbulence

inconclusive
(or need too strong feedback)

- **Dark Matter physics**

- large σ in dark sector
- multi-flavor *

---

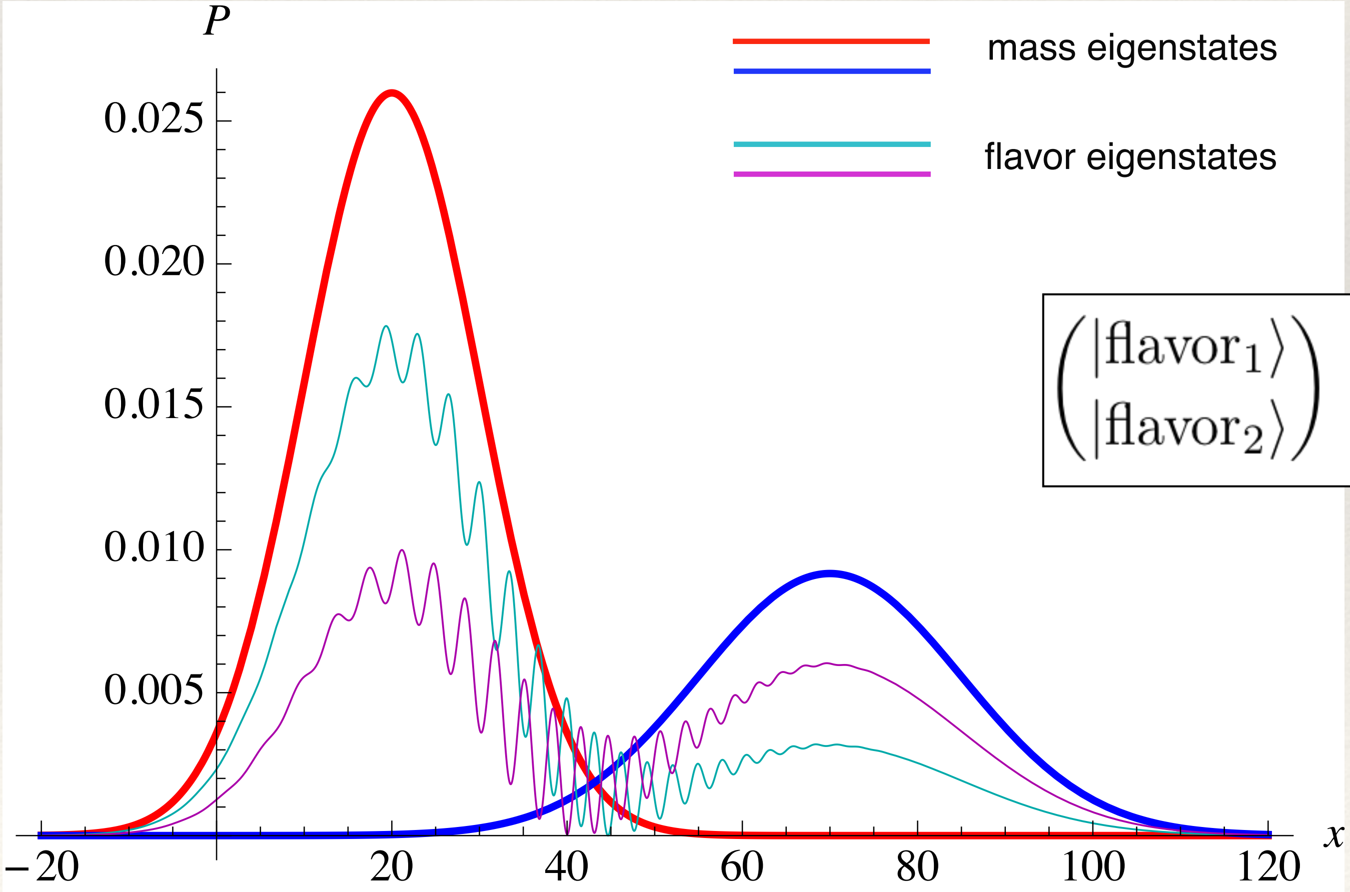
* naturally, *N*-component flavor-mixed DM (named *a la* Pontecorvo model of neutrinos)

2-component mixed particle

B. Pontecorvo (1957)

Interactions do not care about propagation (mass) eigenstates;

Propagation does not care about interaction (flavor) eigenstates.



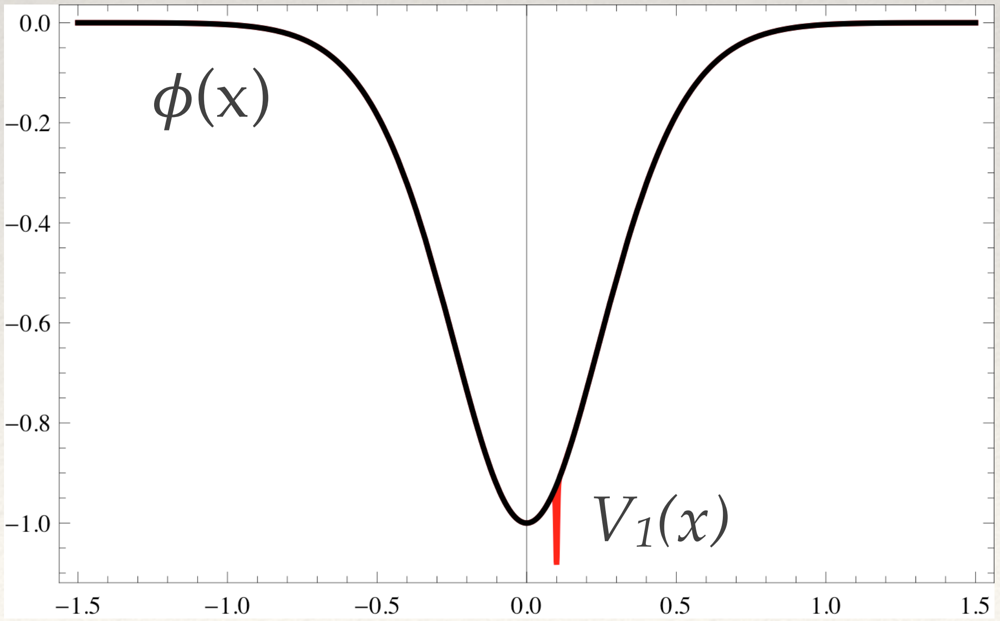
$$\begin{pmatrix} |\text{flavor}_1\rangle \\ |\text{flavor}_2\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |\text{mass}_{\text{heavy}}\rangle \\ |\text{mass}_{\text{light}}\rangle \end{pmatrix}$$

Illustrative model

Schrödinger equation

$$i\partial_t \begin{pmatrix} m_h(x,t) \\ m_l(x,t) \end{pmatrix} = \left[\begin{pmatrix} -\partial^2_{xx}/2m_h & 0 \\ 0 & -\partial^2_{xx}/2m_l - \Delta m \end{pmatrix} + \begin{pmatrix} m_h\phi(x) & 0 \\ 0 & m_l\phi(x) \end{pmatrix} + \begin{pmatrix} V_{hh} & V_{hl} \\ V_{lh} & V_{ll} \end{pmatrix} \right] \begin{pmatrix} m_h(x,t) \\ m_l(x,t) \end{pmatrix}$$

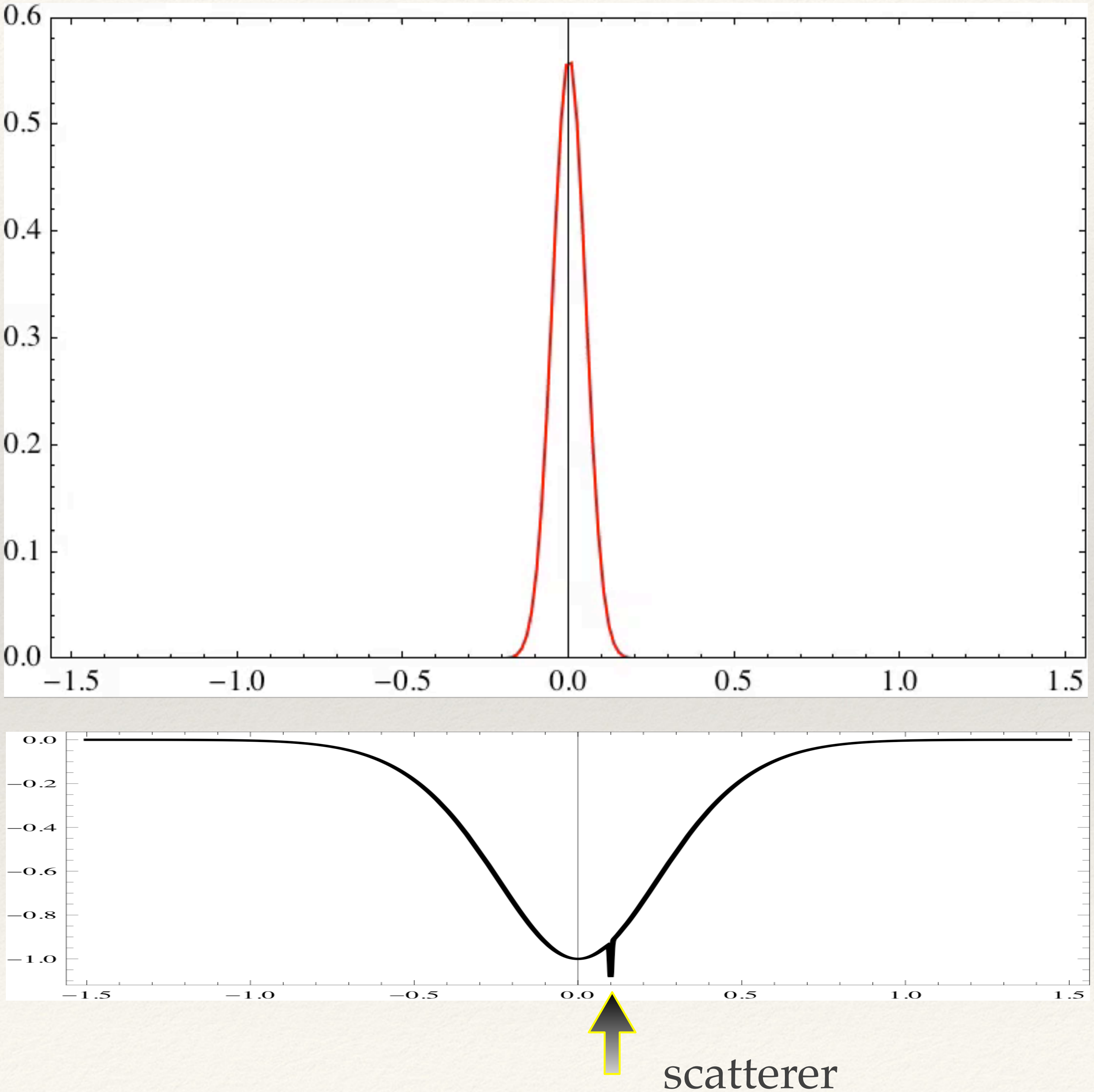
H_{free} H_{grav} V



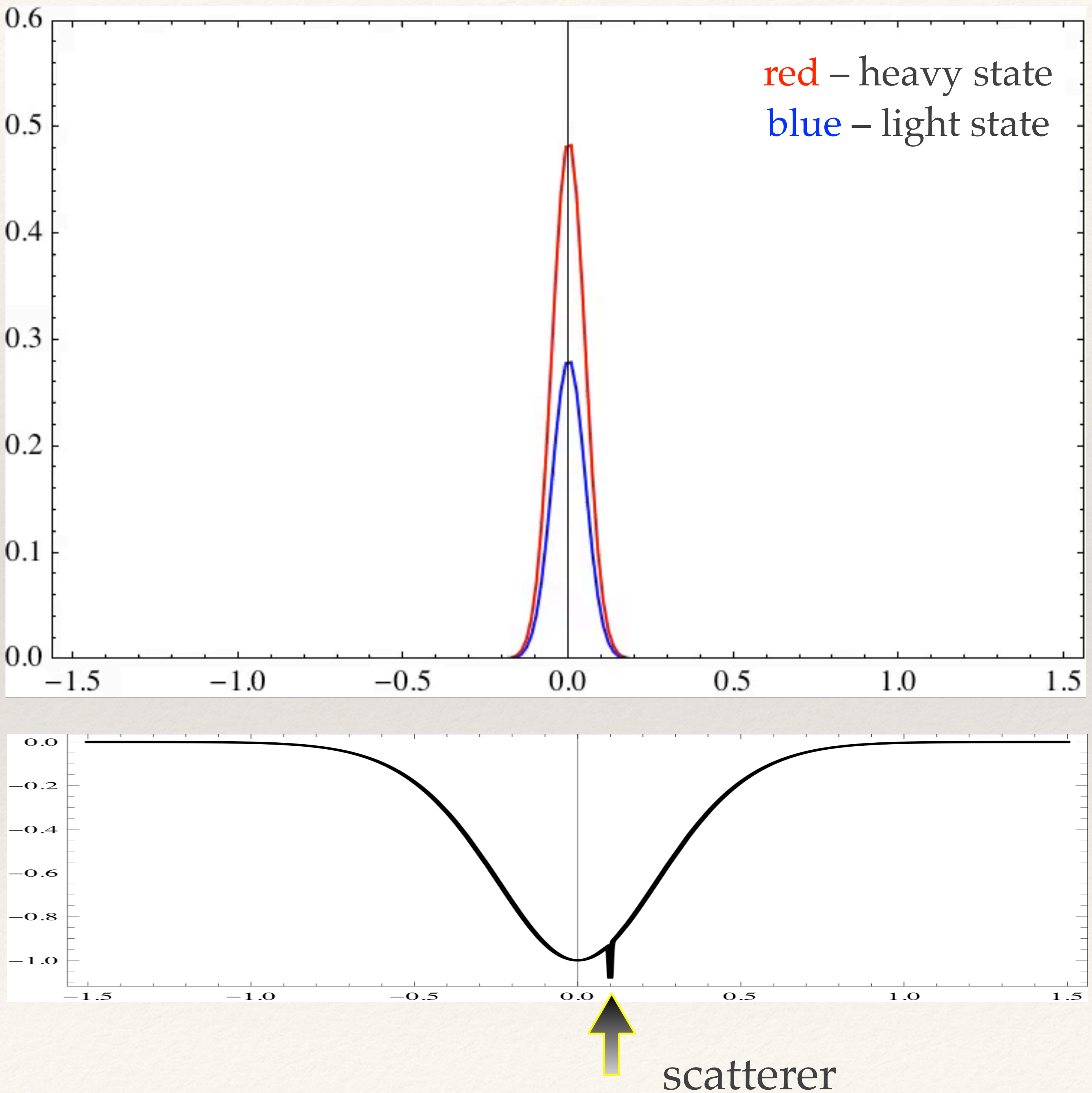
$$\begin{pmatrix} V_{hh} & V_{hl} \\ V_{lh} & V_{ll} \end{pmatrix} = U \begin{pmatrix} V_1 & 0 \\ 0 & 0 \end{pmatrix} U^\dagger$$

(MM, J Phys A 2010)

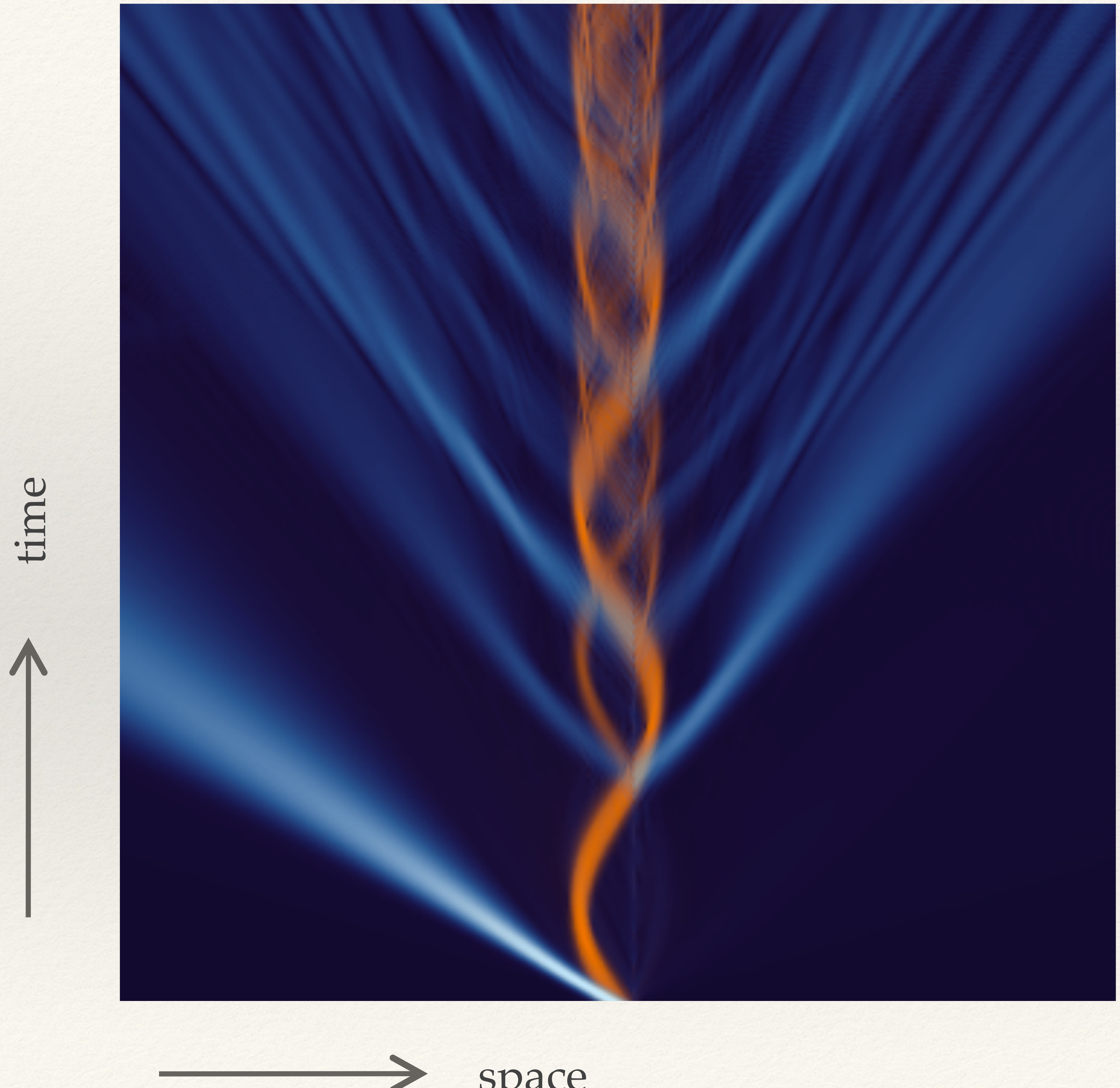
No flavor mixing case



With flavor mixing

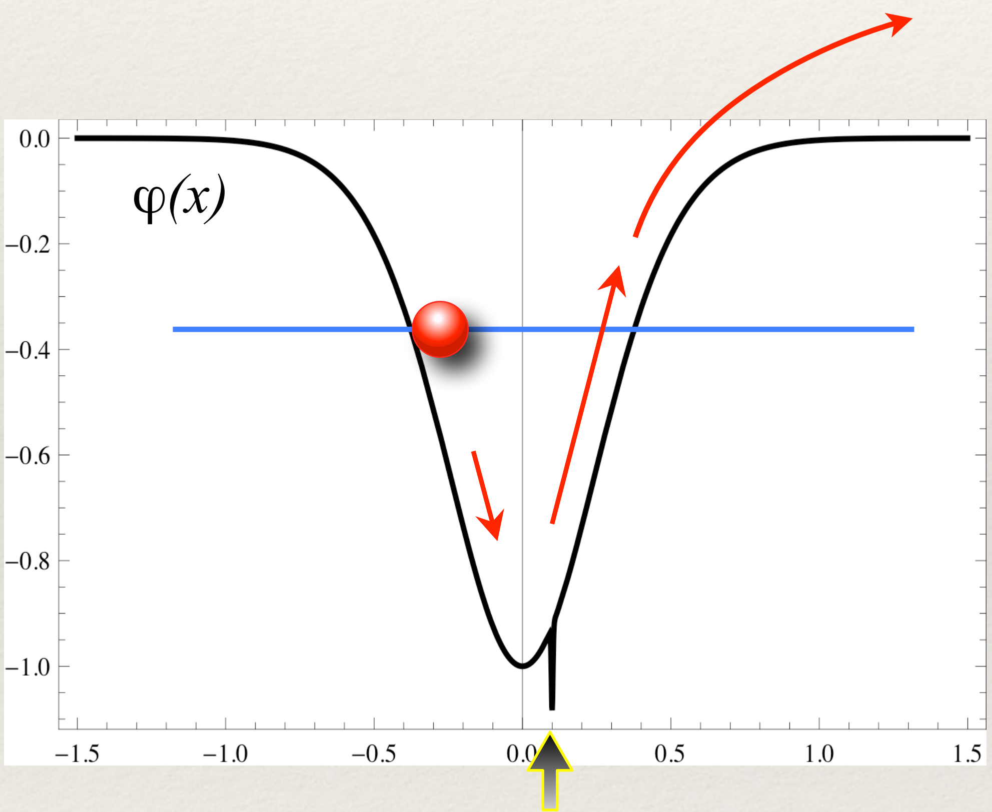


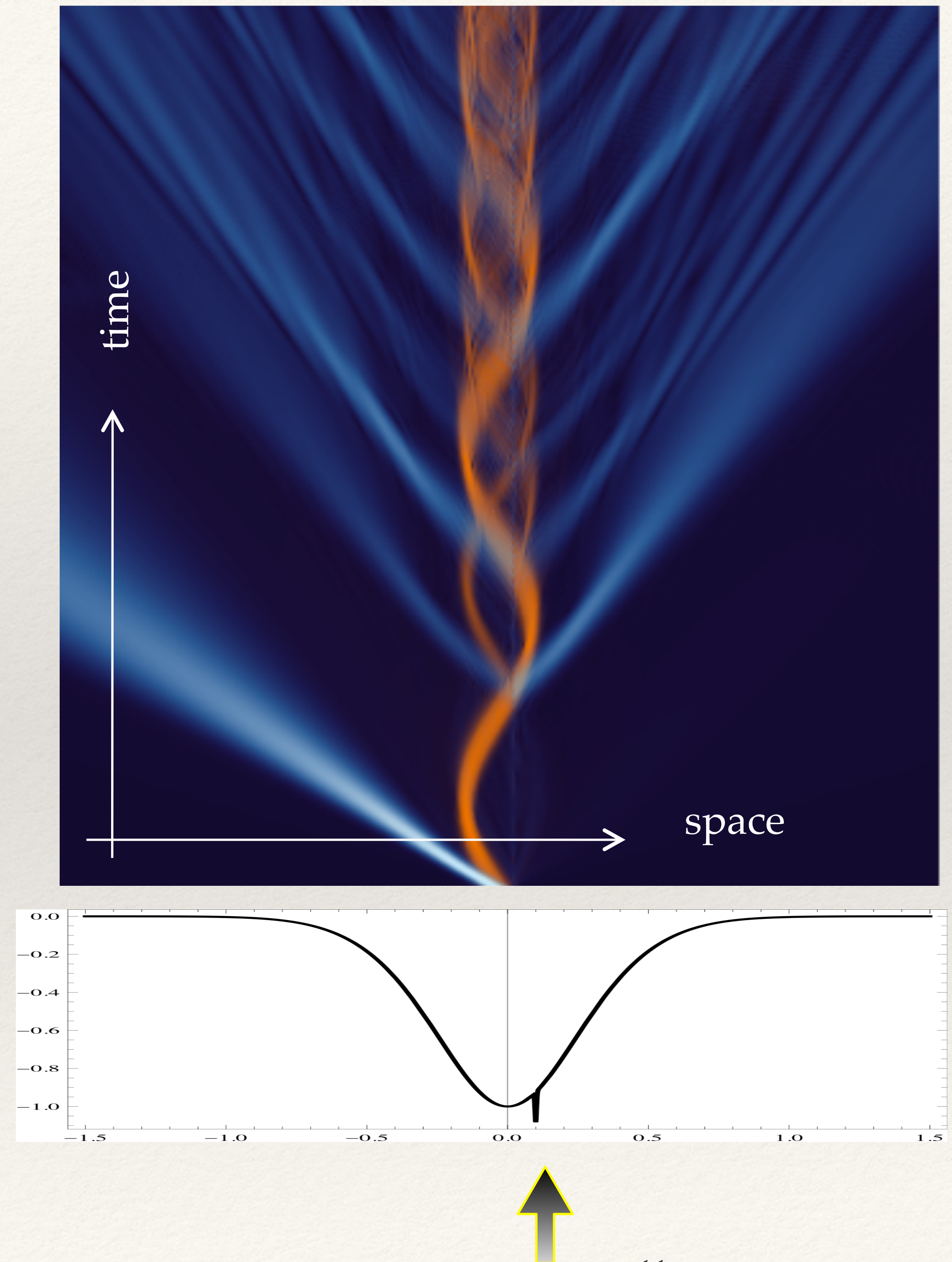
Space-Time diagram



Quantum evaporation - the “Münchhausen effect”

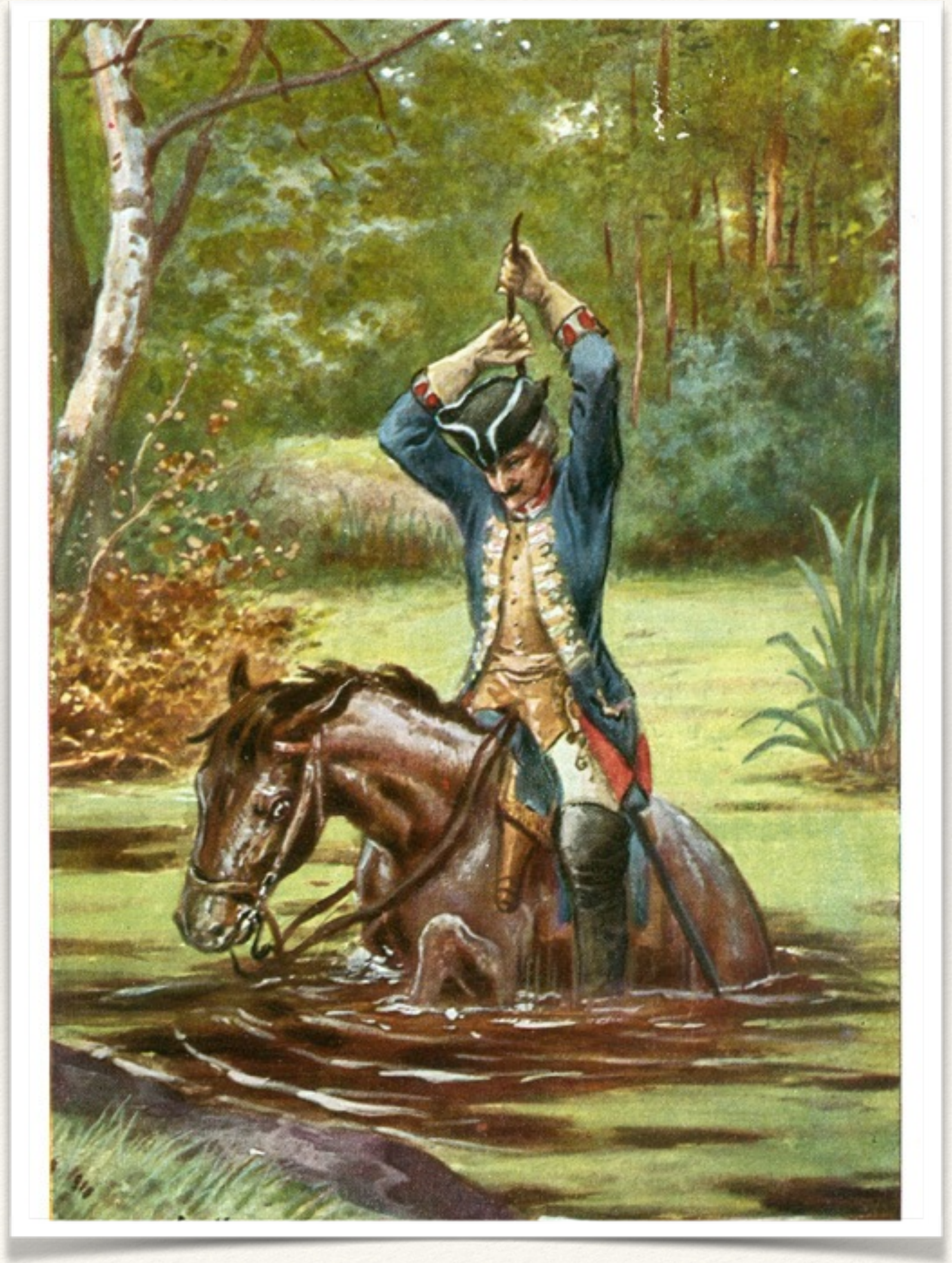
Particle gradual escape from a gravitational potential (in "elastic" collisions) without changing particle's identity





MM, J Phys A 2010; JCAP 2014

“Münchhausen effect”



Baron von Münchhausen lifted himself (and his horse) out of the mud by pulling on his own pigtail.

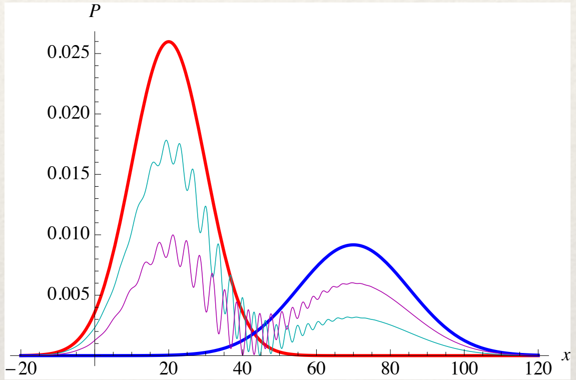
It is one of the “true” stories from *“The Surprising Adventures of Baron Munchhausen”* by R.E. Raspe

Flavor-mixed *N*cDM model (2cDM)

/*N*-component flavor-mixed DM with *N*=2 (2cDM) - simplest/

Postulates

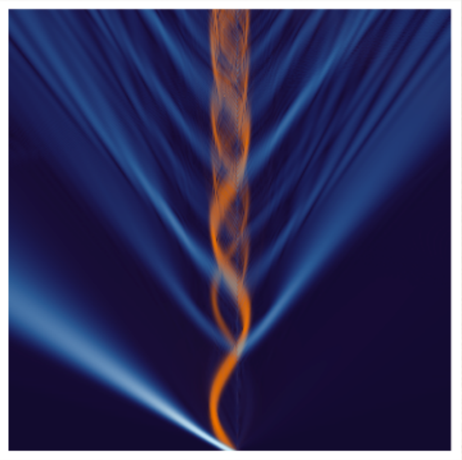
(i) Dark Matter — stable *N*-component mixed particles



Neutralinos
Sterile neutrinos
Axion+photon
...

(ii) DM halos — self-gravitating ensembles of mass eigenstates $|h\rangle, |l\rangle$

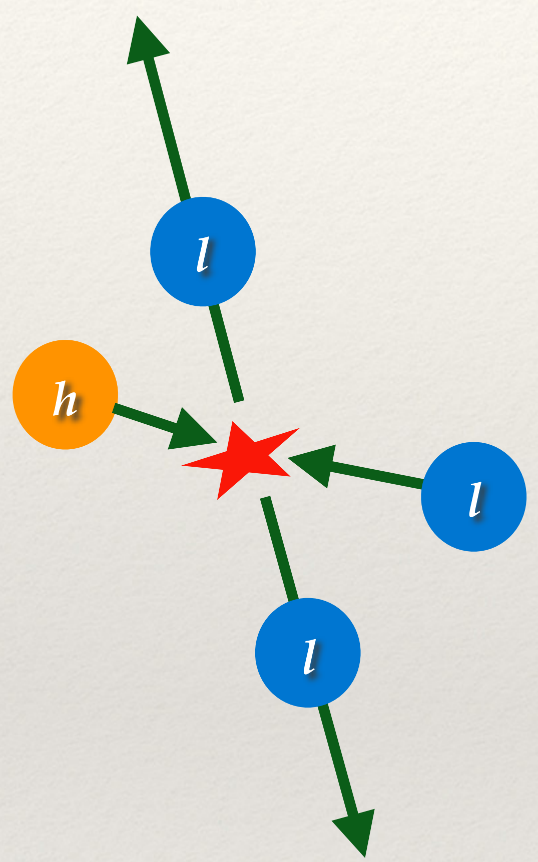
(iii) Quantum evaporation of DM mass eigenstates



$$|h\rangle + |l\rangle \rightarrow |l\rangle + |l\rangle$$

2cDM kinematics

example: $|h\rangle + |l\rangle \rightarrow |l\rangle + |l\rangle$



$$p_h + p_l = 0 = p_l' + p_l'$$

$$(m_h^2 c^4 + p_l^2 c^2)^{1/2} + (m_l^2 c^4 + p_l^2 c^2)^{1/2} = 2(m_l^2 c^4 + p_l'^2 c^2)^{1/2}$$

$$\Delta m/m \ll 1$$

$$\Delta v = v' - v \simeq \left[(\Delta m/m)c^2 + v^2\right]^{1/2} - v$$

$$\simeq \begin{cases} v_k, & \text{if } v \ll v_k, \\ \frac{1}{2}v_k^2/v, & \text{if } v \gg v_k, \end{cases}$$

"kick" velocity: $v_k = c\,(\Delta m/m_l)^{1/2}$

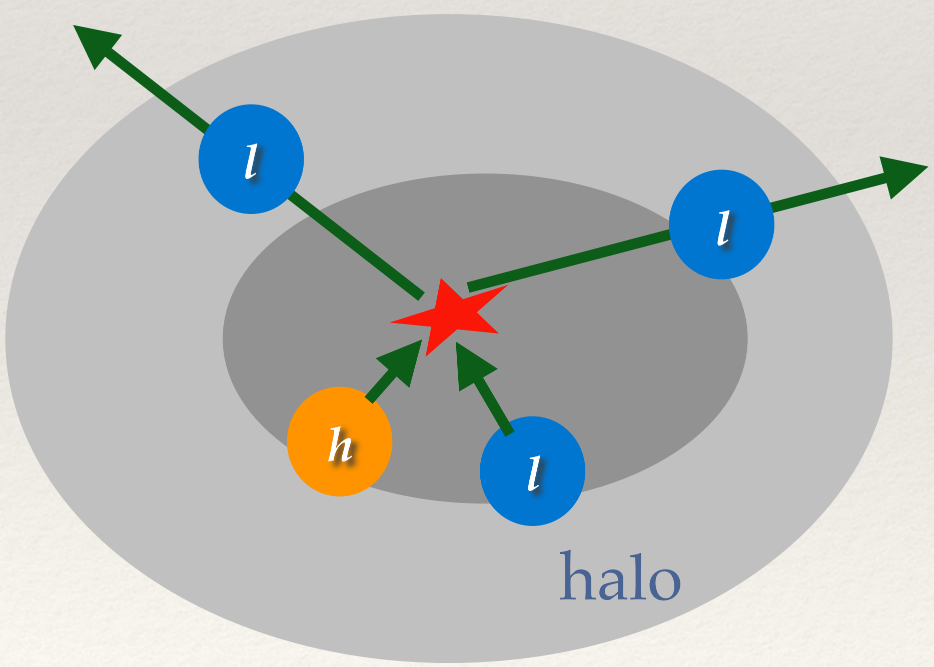
MM, J Phys A 2010; JCAP 2014

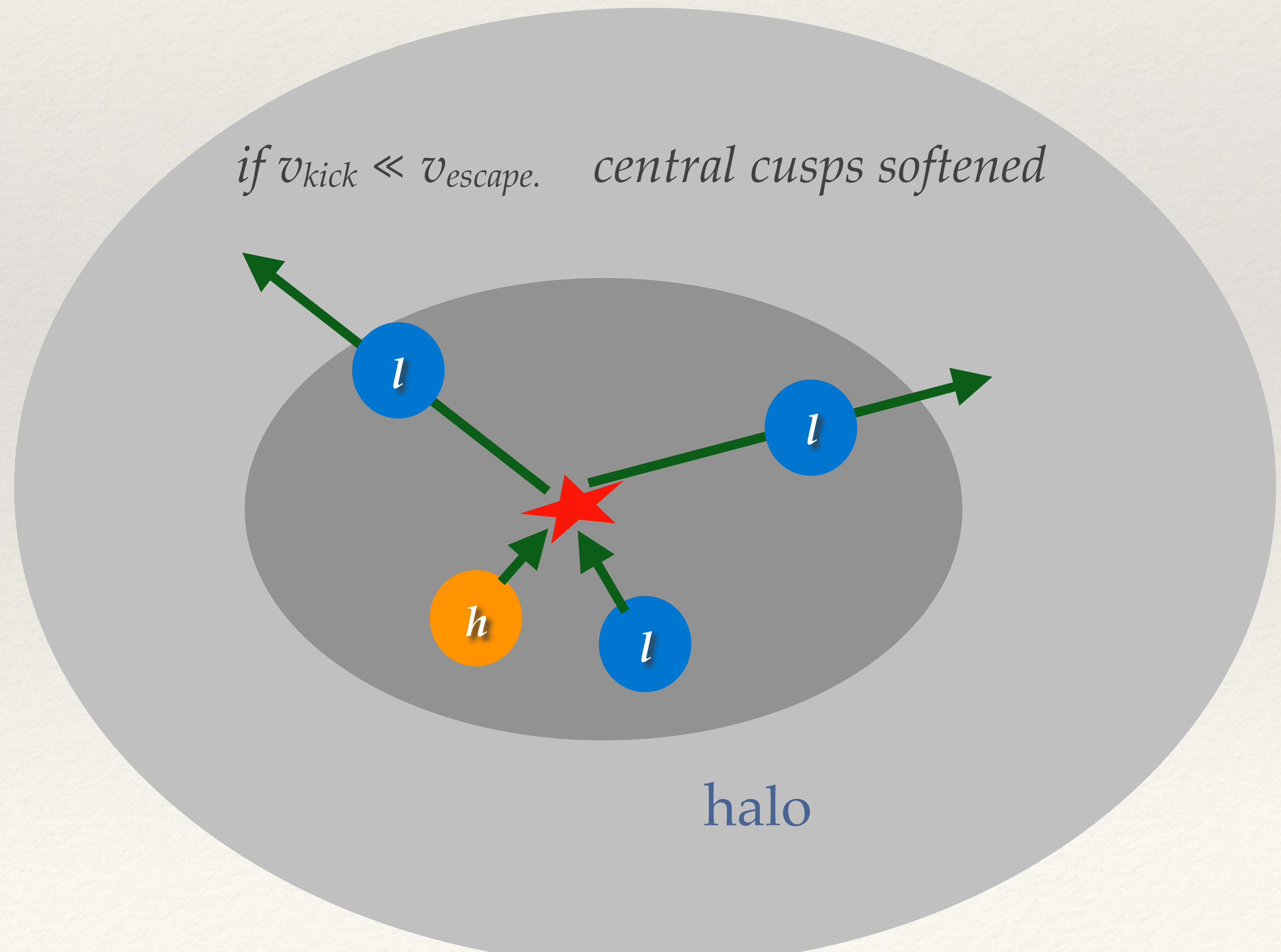
2cDM kinematics

example: $|h\rangle + |l\rangle \rightarrow |l\rangle + |l\rangle$

"kick" velocity: $v_k = c\,(\Delta m/m_l)^{1/2}$

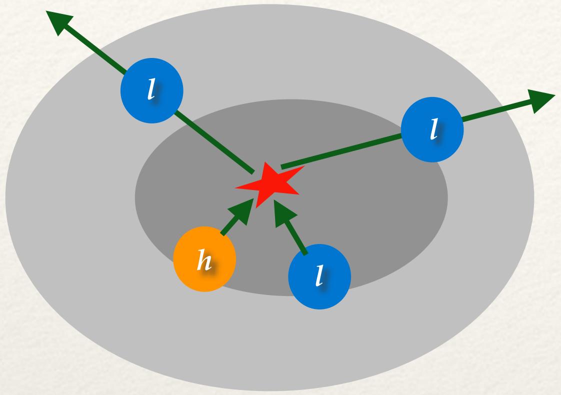
if $v_{kick} \gg v_{escape.}$ *dwarf halos destroyed*





MM, J Phys A 2010; JCAP 2014

Do halos evaporate completely?



abundance evolution eqns.
$$\dot n_h = -(\sigma_{hh} v)\, n_h^2 - (\sigma_{hl} v)\, n_h n_l,$$
$$\dot n_l = -(\sigma_{hl} v)\, n_h n_l,$$

then $$\frac{d\,n_h}{d\,n_l} = \frac{\sigma_{hh}\, n_h}{\sigma_{hl}\, n_l} + 1$$

solution $$\frac{n_h(t)}{n_{h,0}} = \left(\frac{n_{l,0}/n_{h,0}}{1-R}\right)\left(\frac{n_l(t)}{n_{l,0}}\right) + \left(1 - \frac{n_{l,0}/n_{h,0}}{1-R}\right)\left(\frac{n_l(t)}{n_{l,0}}\right)^R$$

$$R = \sigma_{hh}/\sigma_{hl}$$

asymptotically $n_h(\infty) \to 0,\ n_l(\infty) \to n_{l,\infty}$

$$\frac{n_{l,\infty}}{n_{l,0}} = \left[1 - \frac{n_{h,0}}{n_{l,0}}(1-R)\right]^{\frac{1}{1-R}}$$

complete evaporation is possible when

$$\frac{n_{l,0}}{n_{h,0}} \leq 1 - \frac{\sigma_{hh}}{\sigma_{hl}}$$

MM, J Phys A 2010; JCAP 2014

N-body simulations

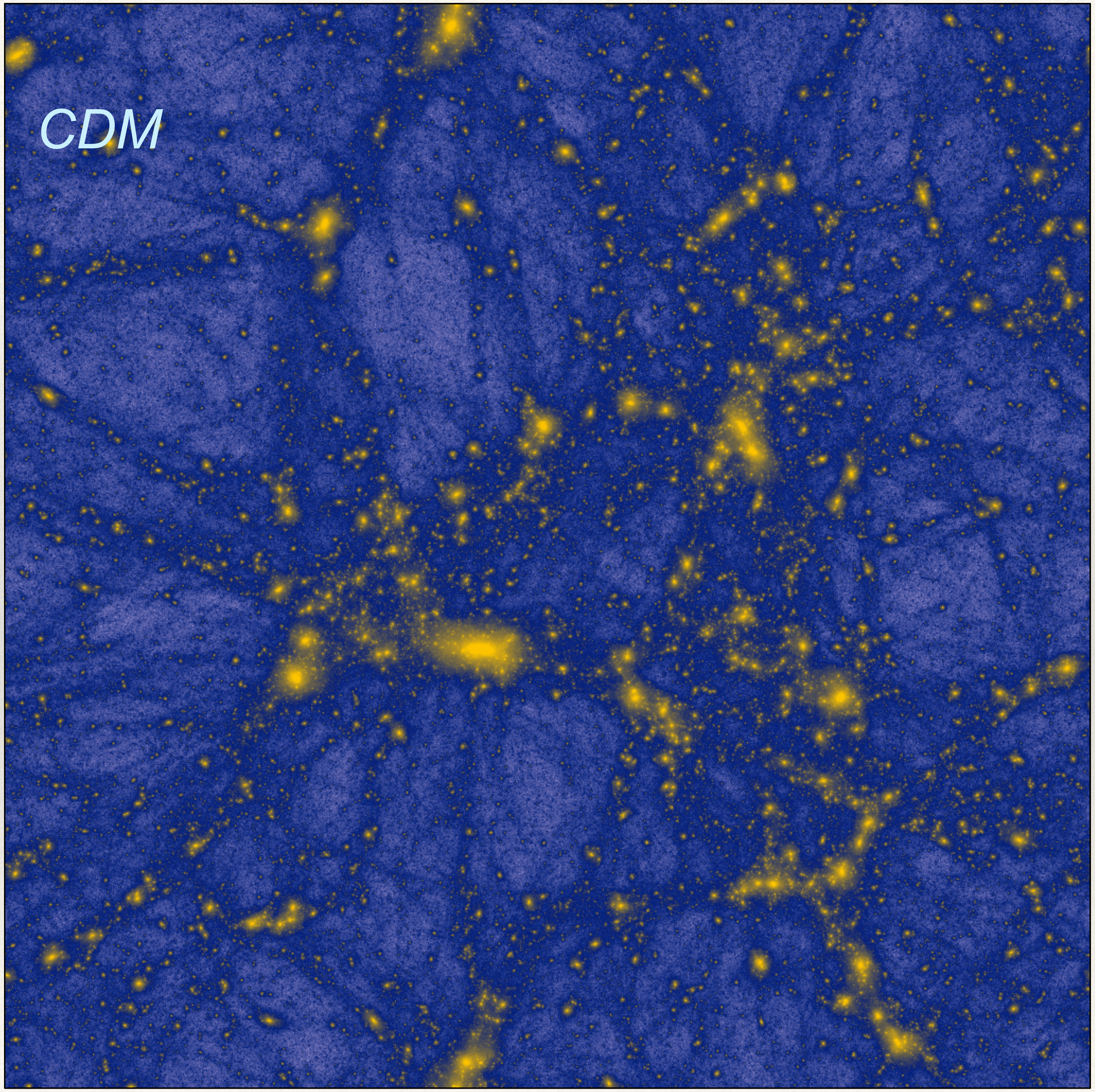
- GADGET, 50 Mpc/h box, standard ΛCDM cosmology
- At each step:
  - Pairs of nearest neighbors are identified
  - Densities of each species are found at each particle location
  - Conversion probabilities are calculated
  - Monte-Carlo module is used for conversions
  - Energy-momentum is manifestly conserved in every interaction
- 2 free parameters: $\sigma(v)/m$ [with $\sigma \propto (v/v_k)^{-1}$] and $\Delta m/m$ [or $v_k = c(2\Delta m/m)^{1/2}$]

$$P_{s_i t_i \to s_f t_f} = (\rho_{t_i}/m_{t_i})\, \sigma_{s_i t_i \to s_f t_f} |\mathbf{v}_{t_i} - \mathbf{v}_{s_i}| \Delta t\, \Theta(E_{s_f t_f})$$

$$\sigma_{s_i t_i \to s_f t_f} = \sigma_{\rm si}(v) = \sigma\,(v/v_0)^{-a}$$

$$a = 1$$

No change on large scales



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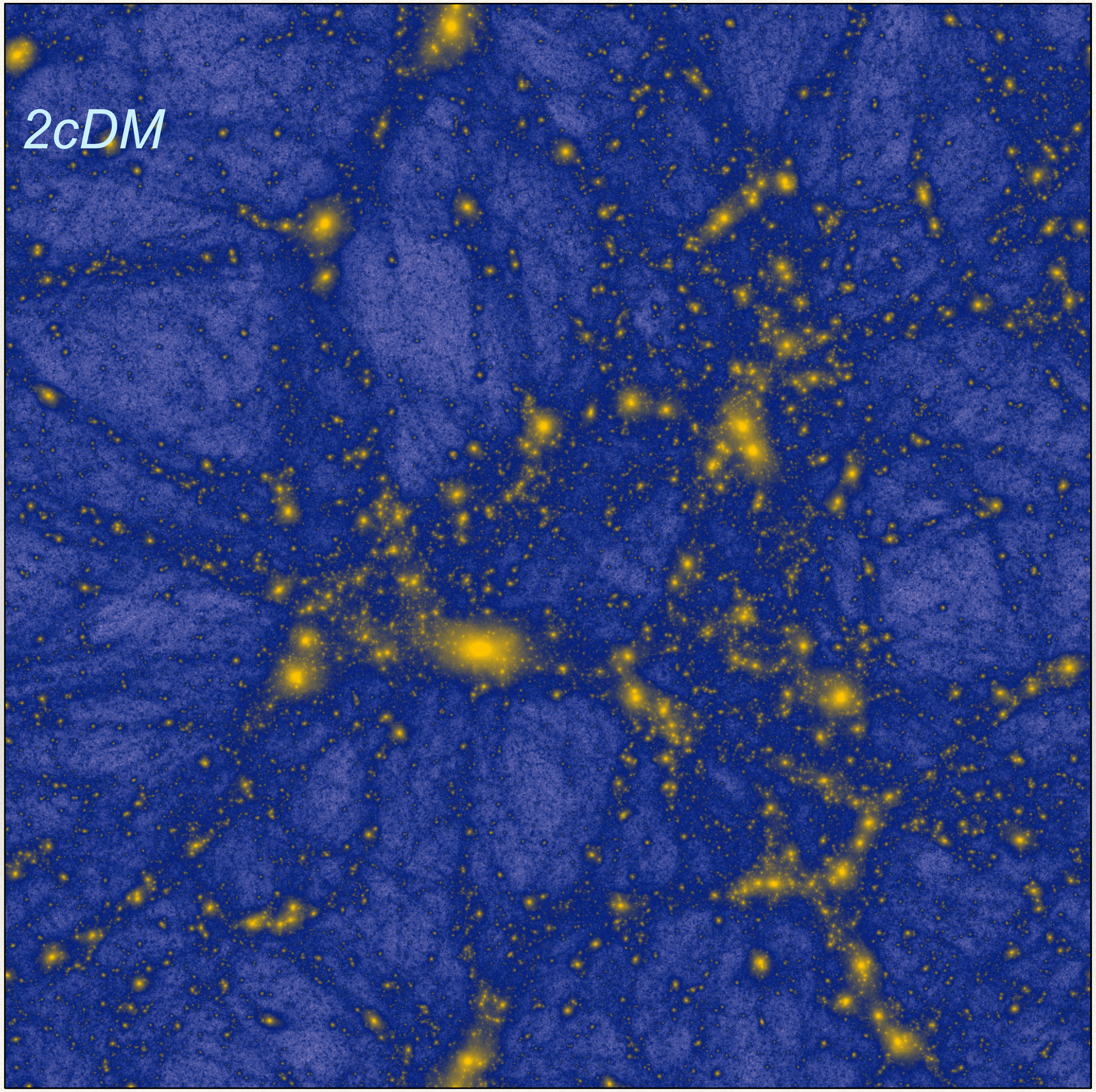

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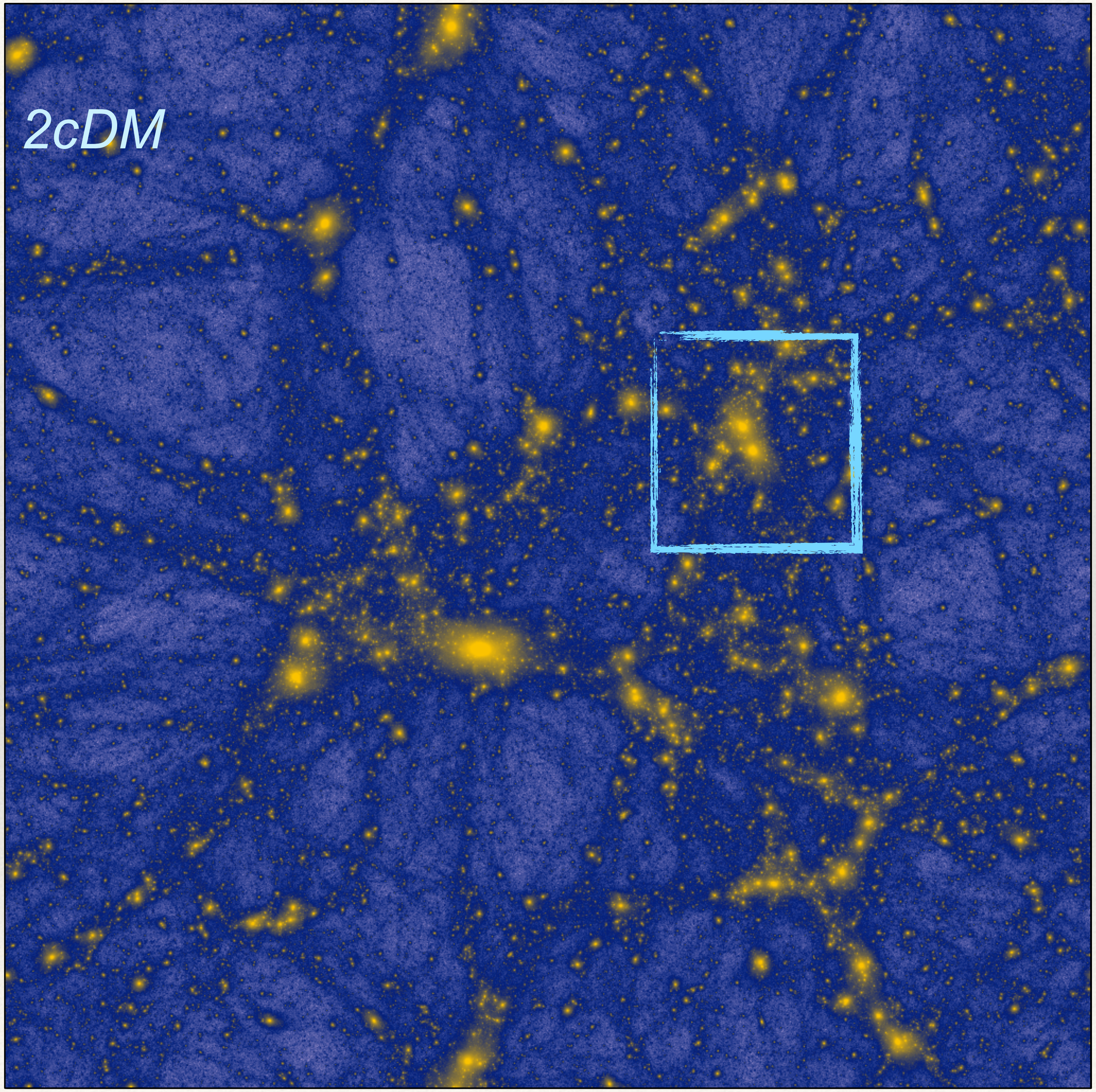
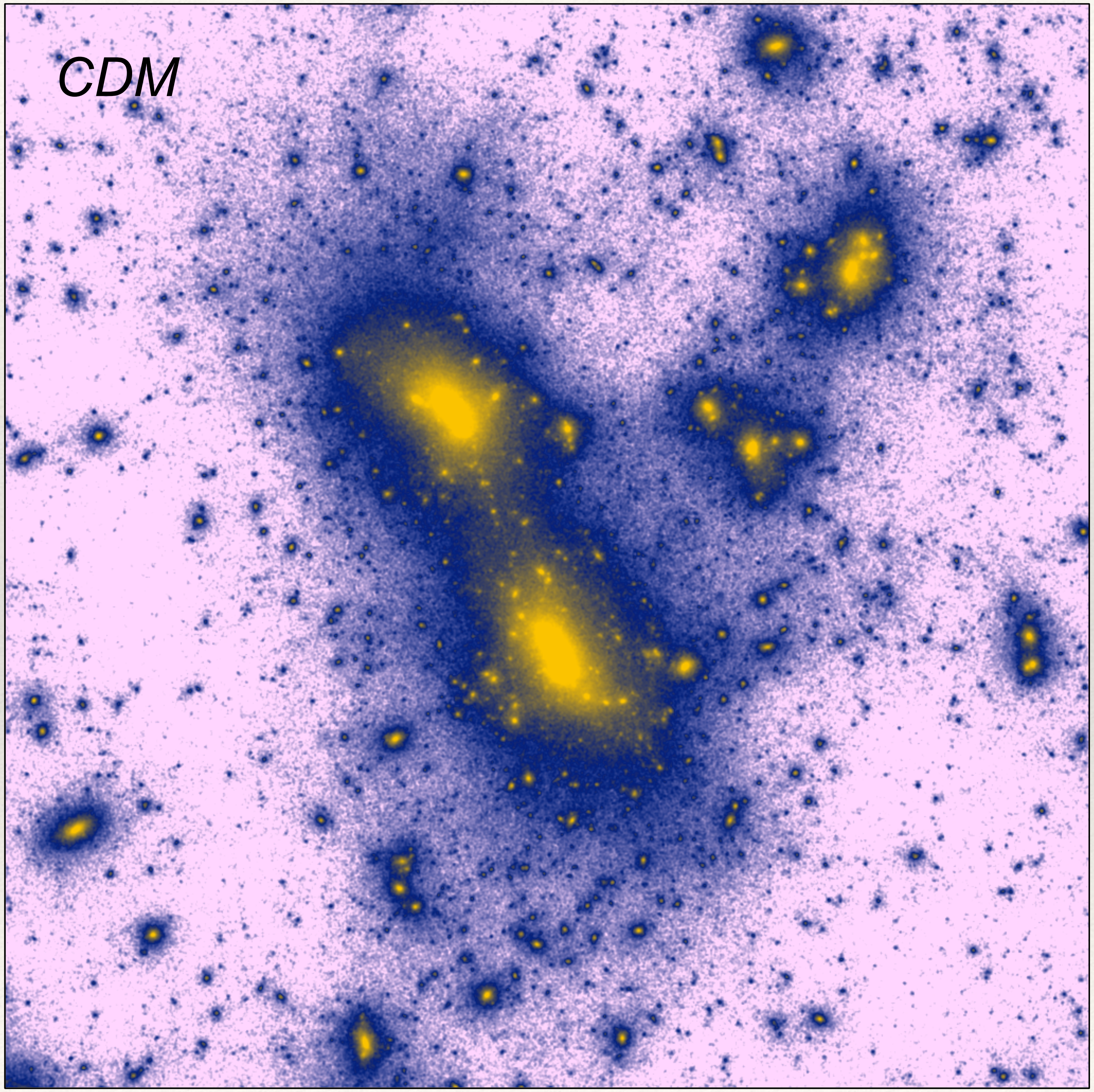


Less substructure on small scales



(MM, PRL 2014)

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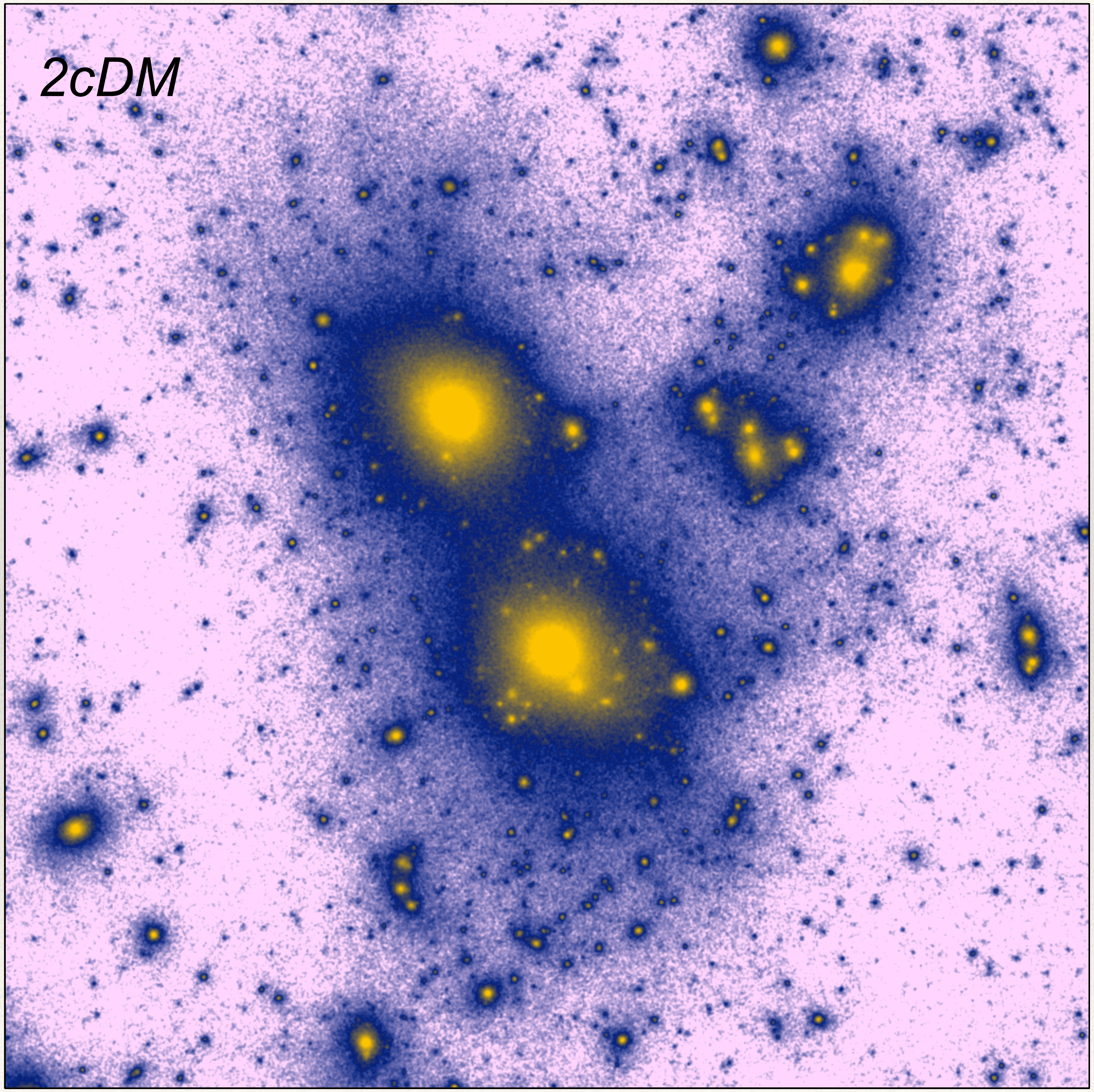
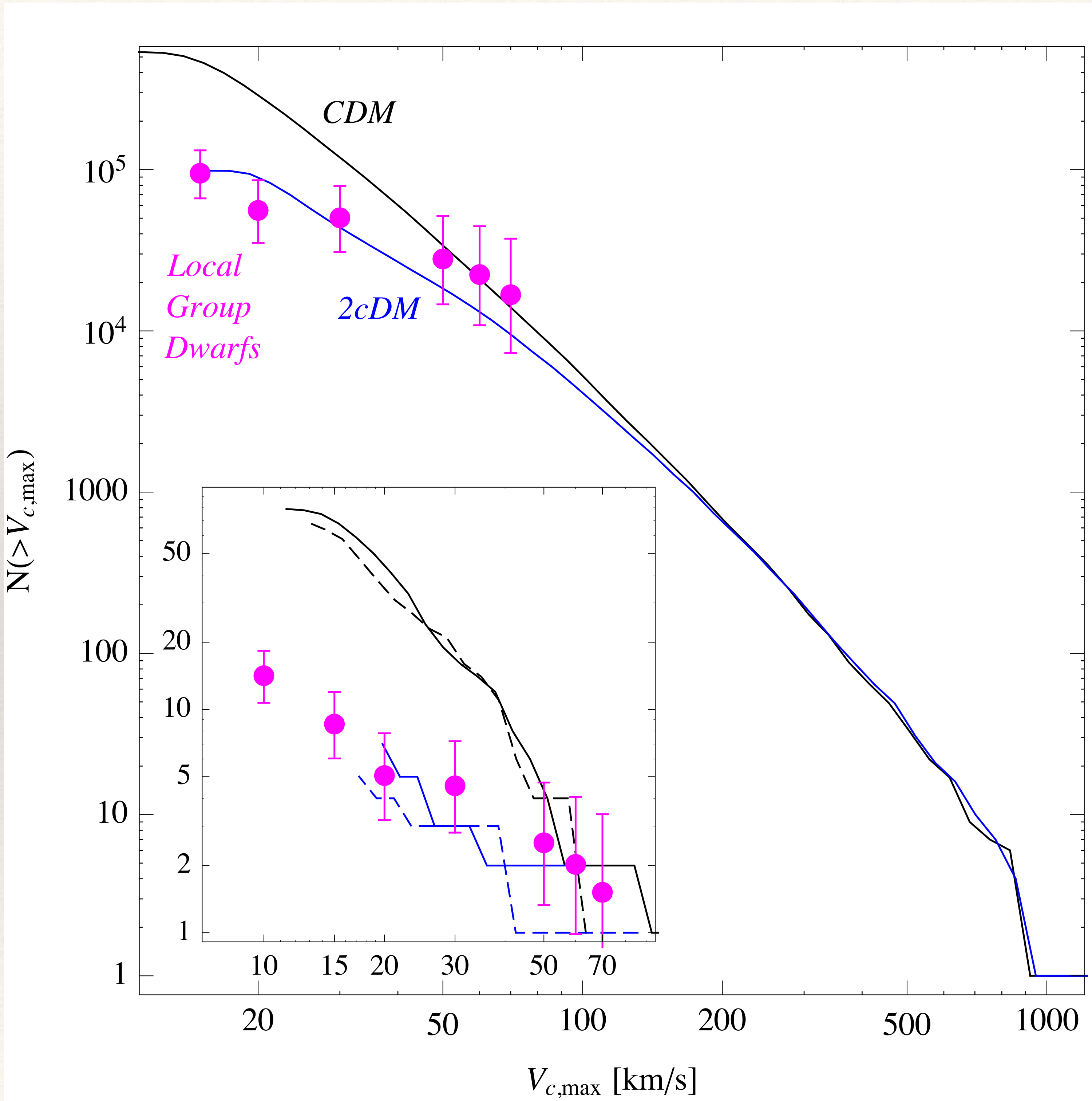


(MM, PRL 2014)

Velocity function

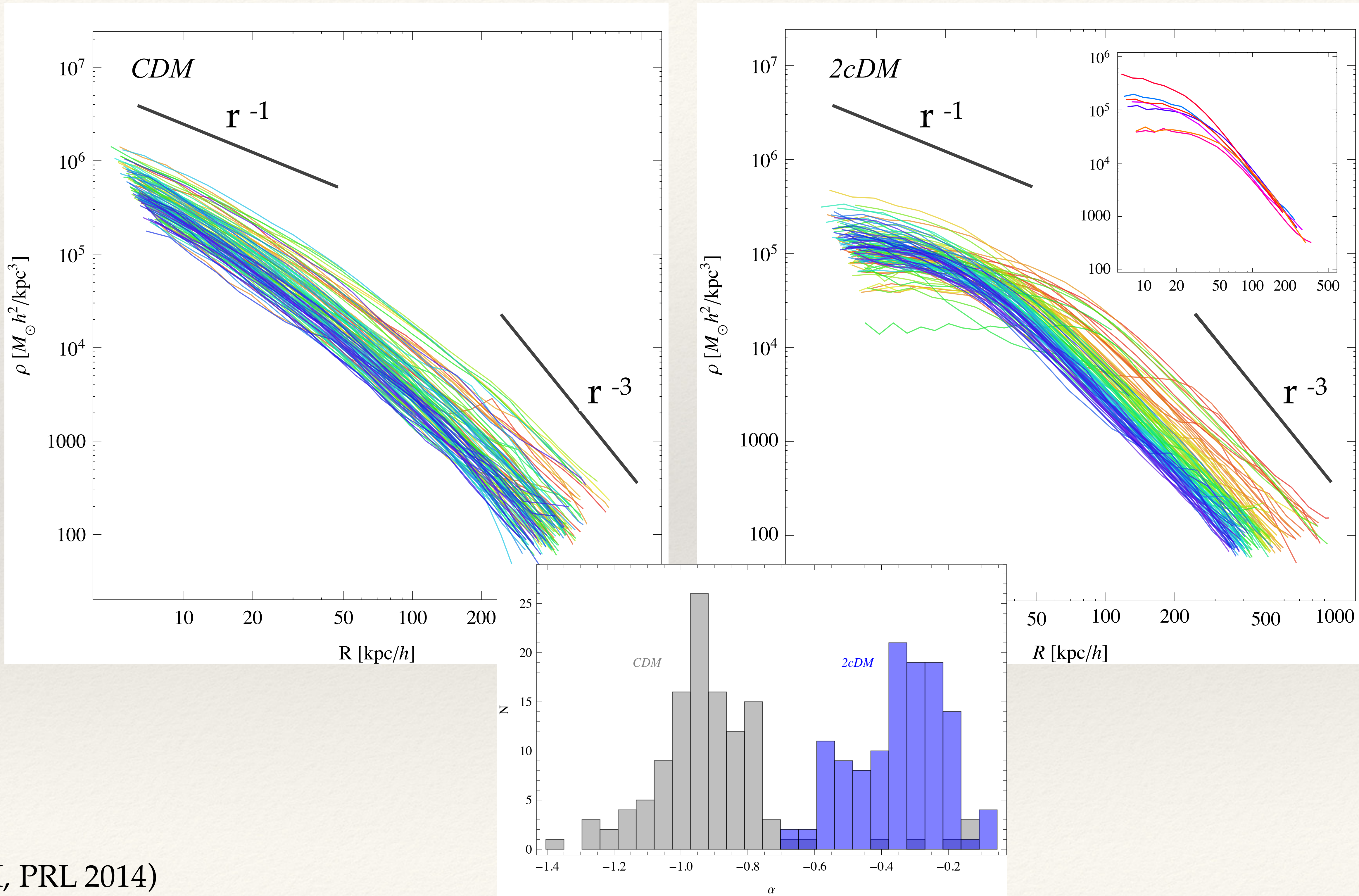


σ_{*}=0.75 cm²/g
v_k=50 km/s

$\Delta m/m = 10^{-8}$

(MM, PRL 2014)

Density profiles



(MM, PRL 2014)

Key: cross-sections

cross-sections

$$\sigma_{(s_it_i)\to(s_it_i)} = \frac{\pi}{k_i^2}\sum_{l=0}^{\infty}(2l+1)\left|1-S^{(l)}_{(s_it_i)(s_it_i)}\right|^2,$$

$$\sigma_{(s_it_i)\to(s_ft_f)} = \frac{\pi}{k_i^2}\sum_{l=0}^{\infty}(2l+1)\left|S^{(l)}_{(s_it_i)(s_ft_f)}\right|^2,$$

parameterize

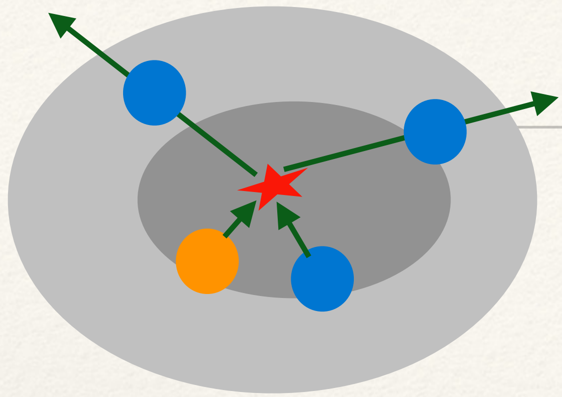
$$\sigma_{i\to f}(v) = \begin{cases} \sigma_0(v/v_0)^{a_s} & \text{for scattering,} \\ \sigma_0(p_f/p_i)(v/v_0)^{a_c} & \text{for conversion} \end{cases}$$

natural: $a_s = a_c$

examples:

$a_s = a_c = 0$	"hard spheres" (*s*-wave scattering)
$a_s = a_c = -1$	annihilation-like
$a_s = a_c = -2$	maximum conversion probability
$a_s = -4$	Rutherford-like

Substructure evaporation



assume profile

$$\rho(r) = \rho_0 \left(\frac{r}{R}\right)^{-\beta}$$

hydrostatic balance yields

$$v_{th}^2 = \frac{4\pi G \rho_0 R^\beta}{\beta(3-\beta)} r^{2-\beta}$$

mass-loss per radius

$$\frac{d\dot{M}}{dr} = 4\pi r^2 \dot{\rho} = 4\pi r^2 \dot{\rho}_0 \left(\frac{r}{R}\right)^{\lambda = 1 - \frac{5}{2}\beta + a(1-\frac{\beta}{2})}$$

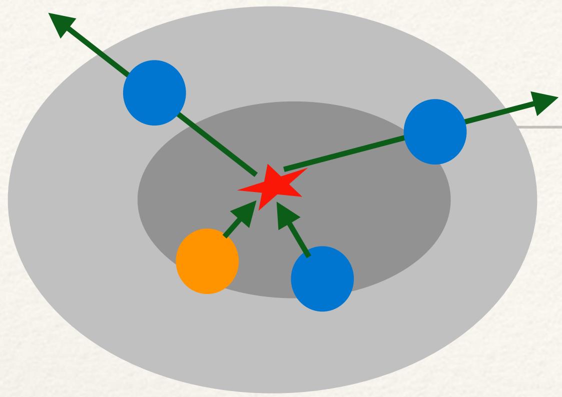
$$\dot{\rho} = -(n\sigma v)\rho = -\rho^2 \left(\frac{\sigma}{m}\right) v = \rho_0 \left(\frac{r}{R}\right)^{-2\beta} \frac{\sigma_0}{m} \left(\frac{v}{v_0}\right)^a v$$

integrate to yield the total halo mass-loss

$$\dot{M} = \frac{3-\beta}{\lambda+3} \frac{\sigma_0 v_0}{m} \left[\frac{G}{v_0 \beta} \left(\frac{4\pi\rho_0}{3-\beta}\right)^{1/3}\right]^{a+1} \left(\frac{r_c}{R}\right)^{\lambda+3} M^{1+\frac{2}{3}(a+1)}$$

just a constant *approximately constant*

Substructure evaporation



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just a constant

approximately constant

$$\dot{M} = -|A| M^\xi$$

indep. of halo shape (beta)

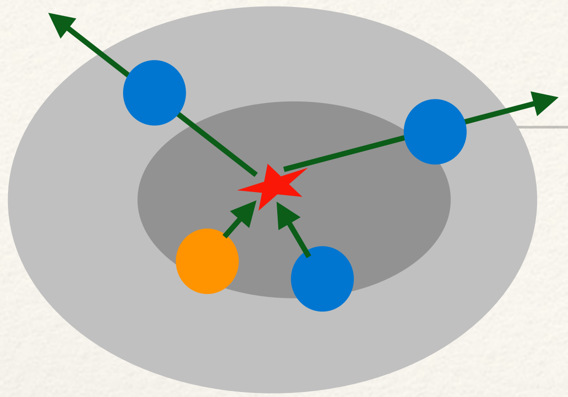
solution

$$M_0 = \left[(1-\xi)At + M^{1-\xi}\right]^{1/(1-\xi)}$$

initial halo mass

final halo mass

Substructure evaporation

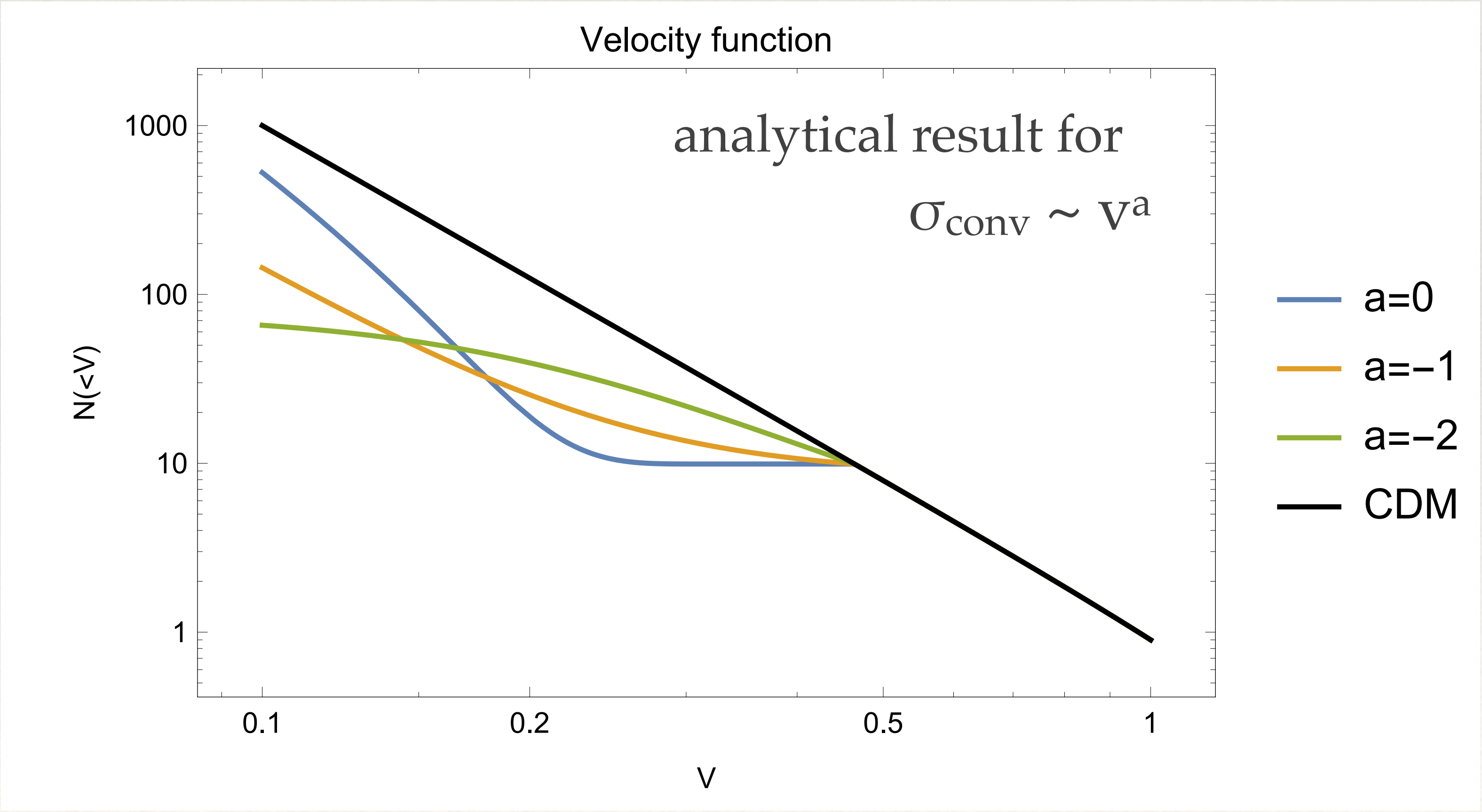


mapping of old to new

$$M_0 = \begin{cases} \left(M^{-2/3} - \frac{2}{3}At\right)^{-3/2}, & a = 0 \\ Me^{At}, & a = -1 \\ \left(M^{2/3} + \frac{2}{3}At\right)^{3/2}, & a = -2 \end{cases}$$

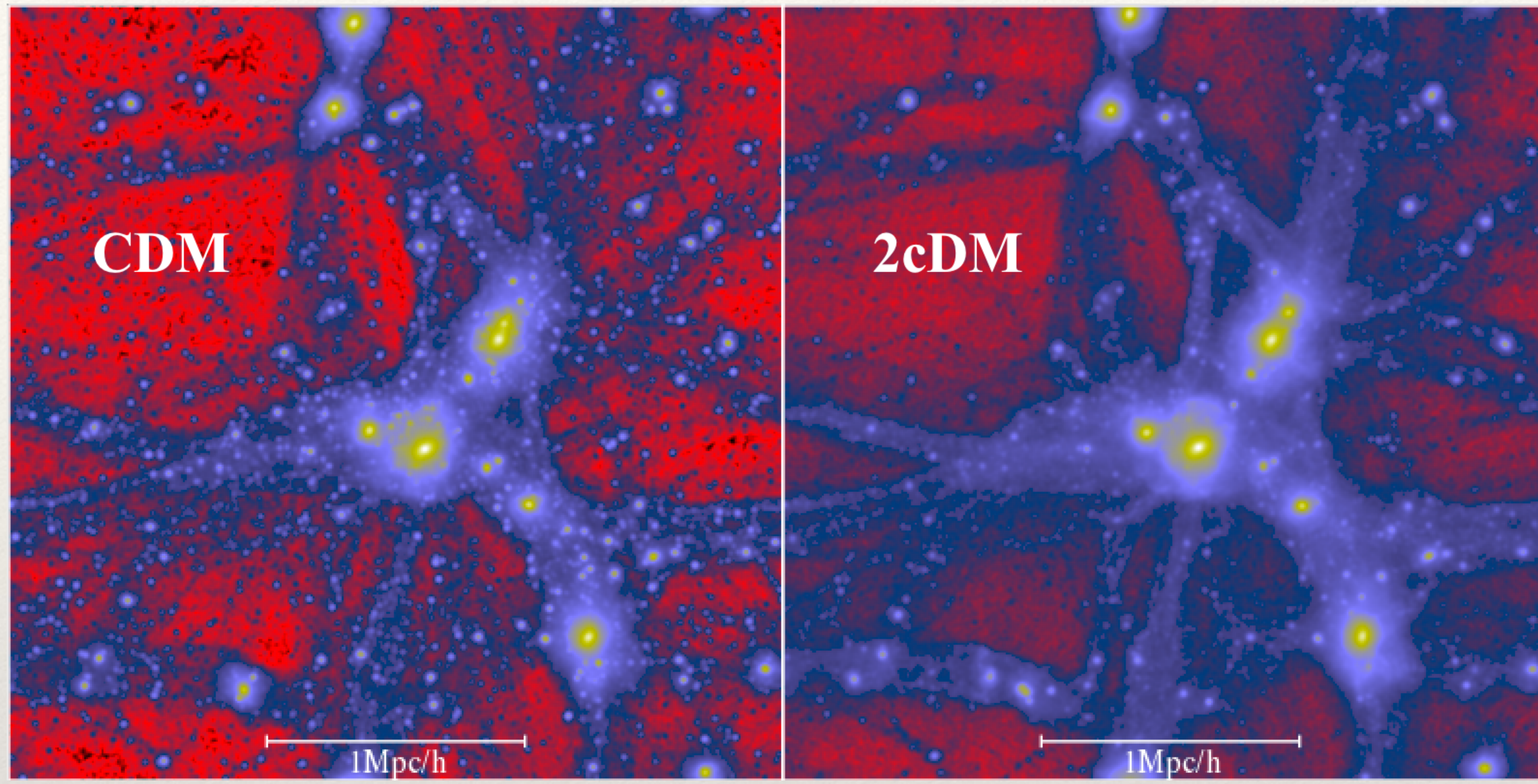
New mass function given the old one $f(M_0)$ is $f(M_0) = f(M_0(M,t)) \equiv f(M,t)$

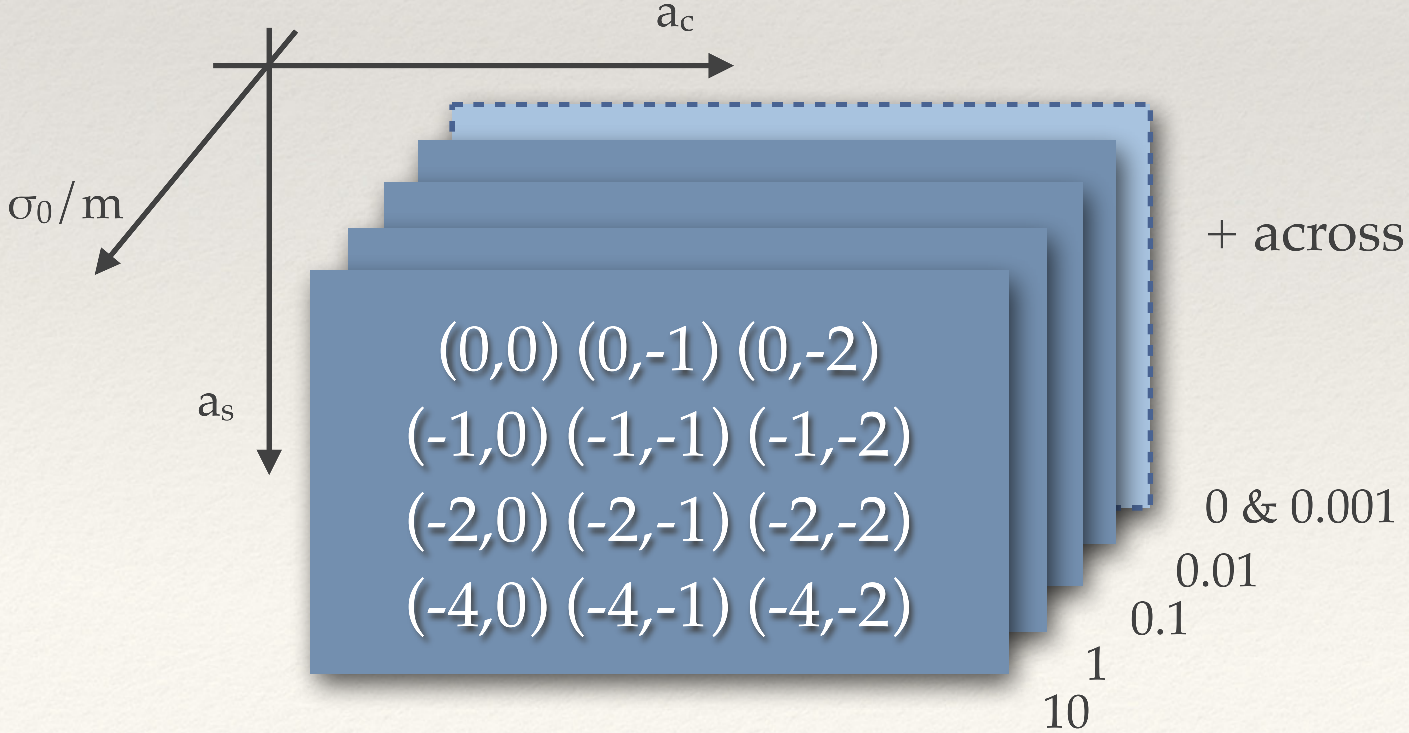
and similarly for the velocity function



Evaporation resolves substructure & TBTF problems
Shape of mass function tells:
index a_c (conversion)
and σ_0/m

2cDM σ(v)-simulations





+ across halo mass scales: dwarfs -- clusters

10^7 10^{15}

over 120 different simulations

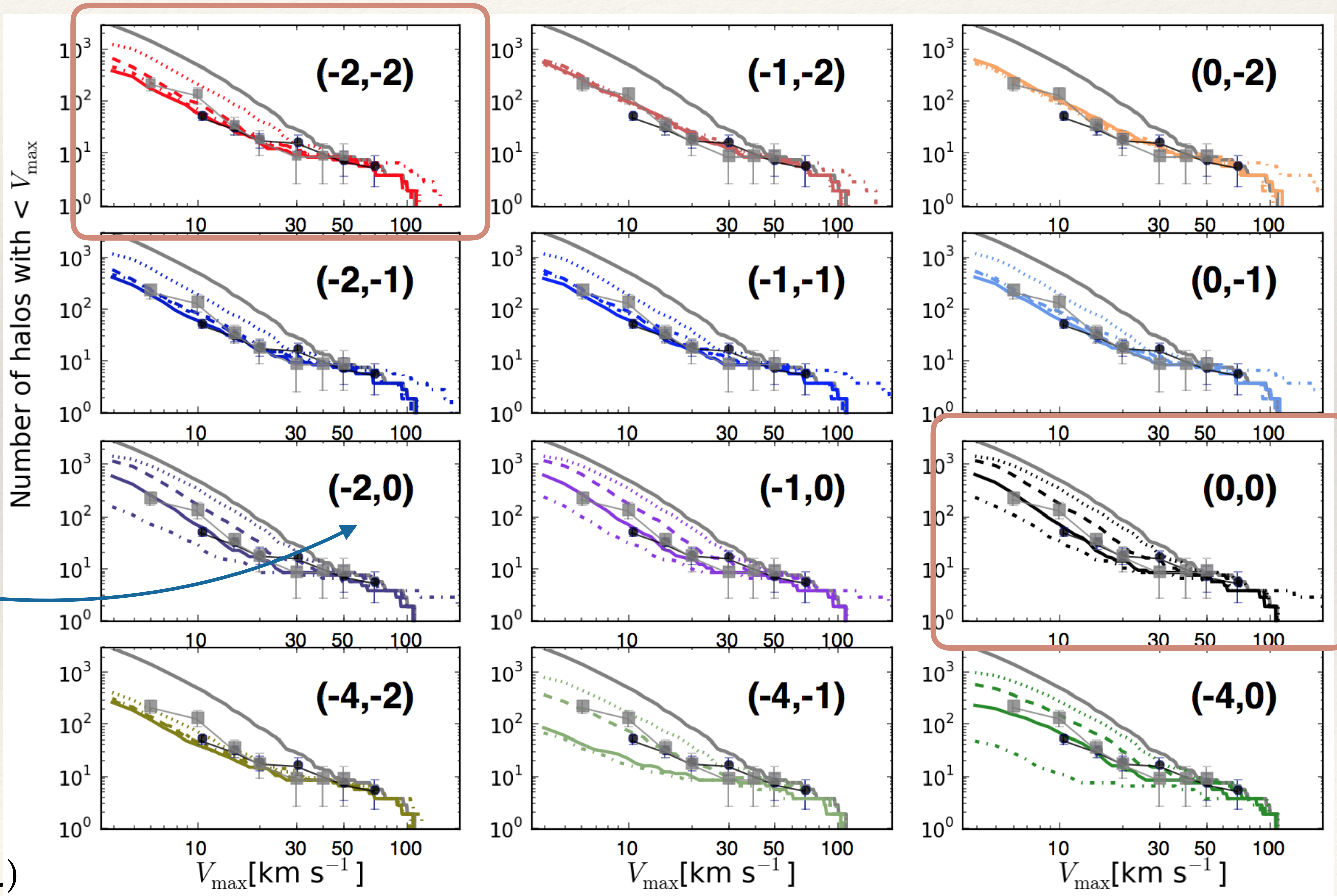
2cDM-σ(v) -- Substructure

$$\sigma(v) = \begin{cases} \sigma(v/v_0)^{a_s} & \text{for} \quad \text{scattering} \\ \sigma(v/v_0)^{a_c} & \text{for} \quad \text{conversion} \end{cases}$$

$\sigma = 0.01, 0.1, 1$ and 10,

consistent with observations

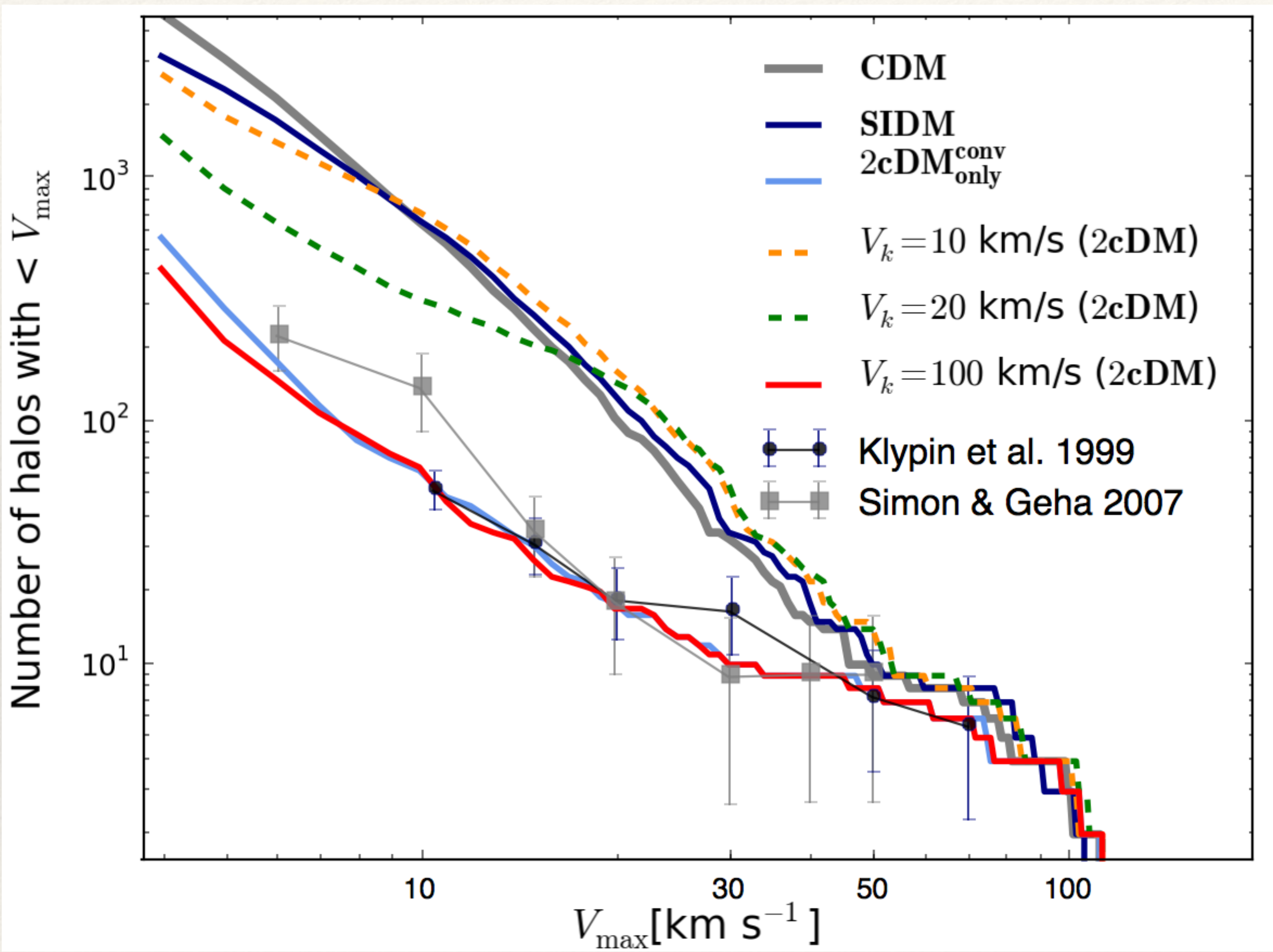
(a_s, a_c)



(Todoroki & MM, in prep.)

Message 1

SUBSTRUCTURE



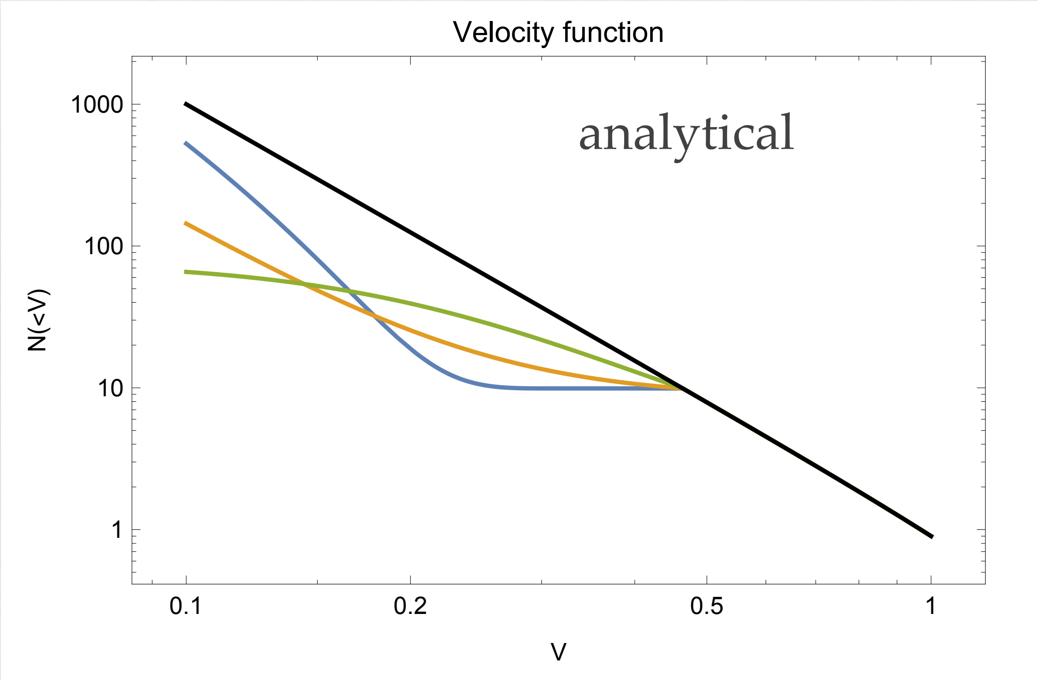
2cDM: Resolves substructure & TBTF problems.

Position of break tells:

$\Delta m/m \Leftrightarrow v_k$

Shape of mass function tells:

index a_c (conversion) and σ_0/m

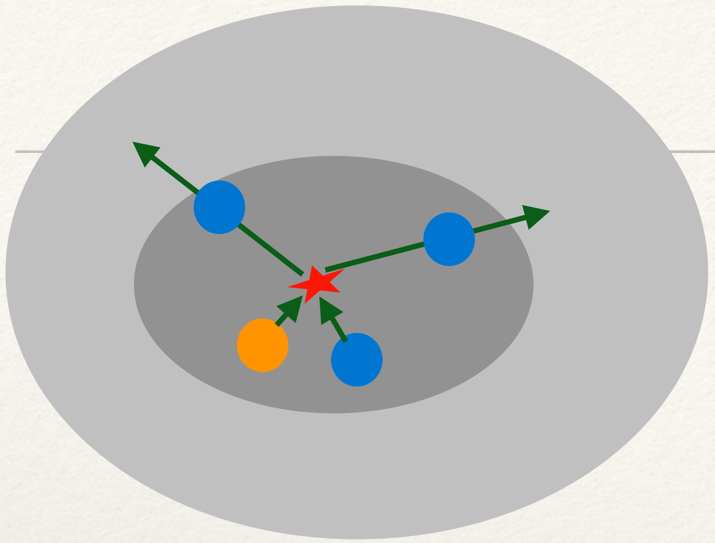


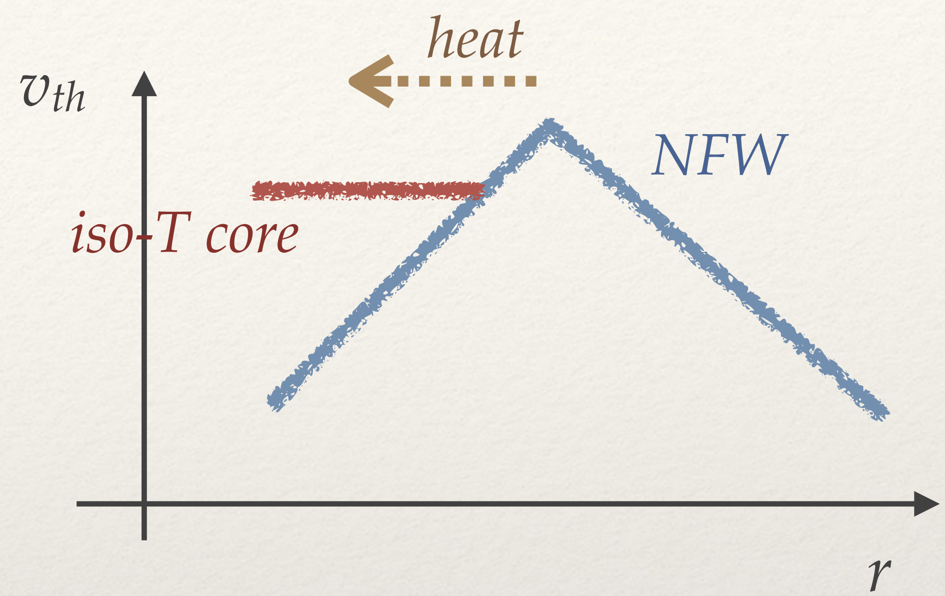
Wide parameter region allowed:

$\sigma(v) \sim 1...0.1...0.01$ – consistent with all constraints

$\Delta m/m \sim 10^{-8} \Leftrightarrow v_k \sim$ 50-100 km/s

Cusp softening





number of interactions per particle

$$N_{int} = n\sigma v t_H = \rho_{\rm vir}\frac{\sigma_0}{m}t_{\rm H}v_0\left(\frac{V_{\rm vir}}{v_0}\right)^{a+1}\left(\frac{r_c}{R_{\rm vir}}\right)^{a+1-\frac{\beta}{2}(a+3)}$$

$$\rho_{\rm vir} = \frac{(3-\beta)M_{\rm vir}}{4\pi R_{\rm vir}^3}$$

$$V_{\rm vir}^2 = GM_{\rm vir}/R_{\rm vir}$$

$$N_{\rm vir} \equiv \rho_{\rm vir}\frac{\sigma_0}{m}V_{\rm vir}t_{\rm H}$$

core radius

$$\frac{r_c}{R_{\rm vir}} \simeq \left[\left(\frac{\text{a few}}{N_{\rm vir}}\right)\left(\frac{V_{\rm vir}}{v_0}\right)^{-a}\right]^{-\xi} \propto \sigma_0^{\xi}$$

$$\xi = \frac{2}{\beta(a+3)-2(a+1)}$$

Scattering resolves core-cusp problem
Core size tells:
σ_0/m and index a_s (scattering)

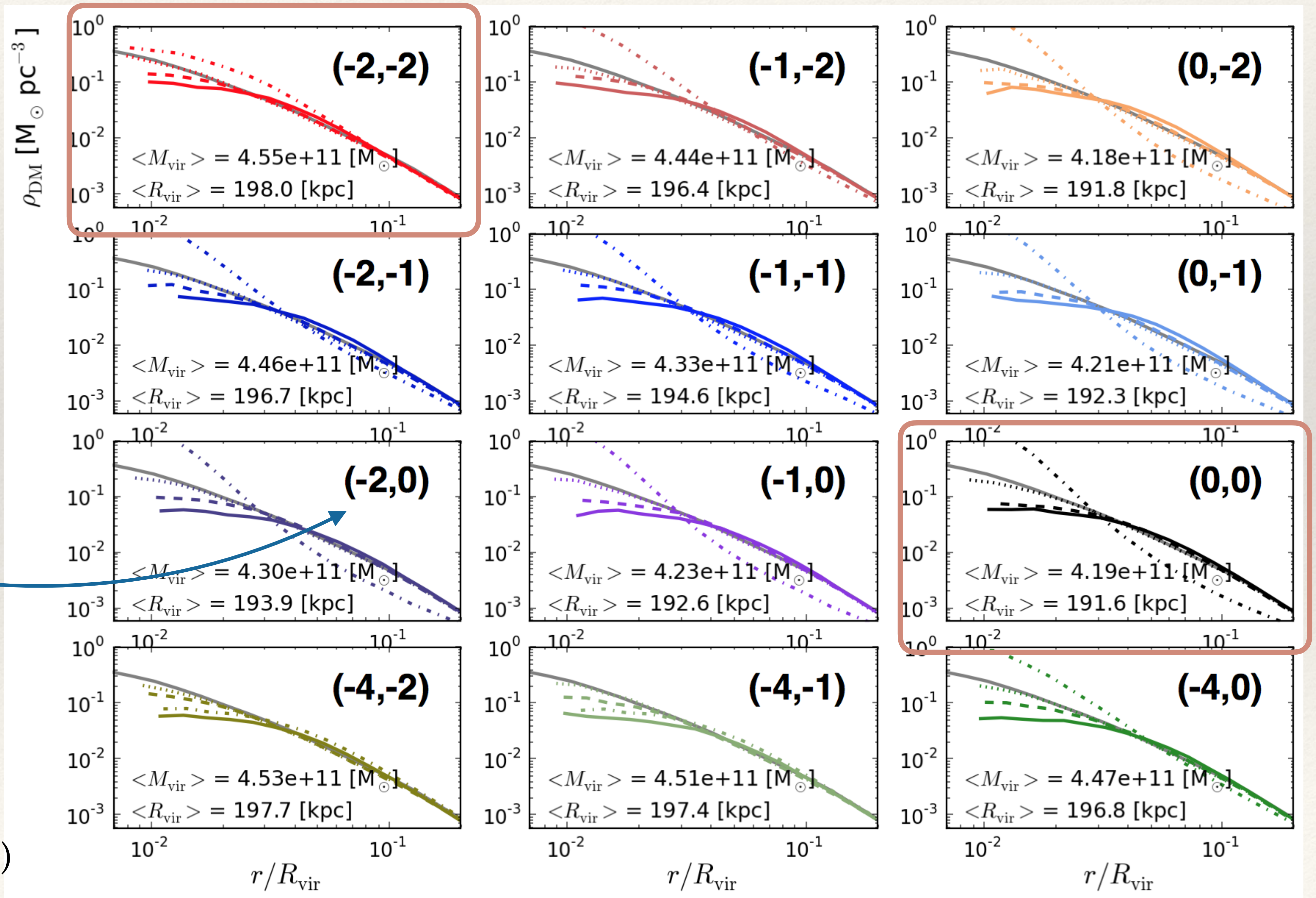
2cDM-σ(v) -- Profiles (MW-like)

$$\sigma(v) = \begin{cases} \sigma(v/v_0)^{a_s} & \text{for} \quad \text{scattering} \\ \sigma(v/v_0)^{a_c} & \text{for} \quad \text{conversion} \end{cases}$$

$\sigma = 0.01, 0.1, 1$ and 10,

consistent with observations

(a_s, a_c)



(Todoroki & MM, in prep.)

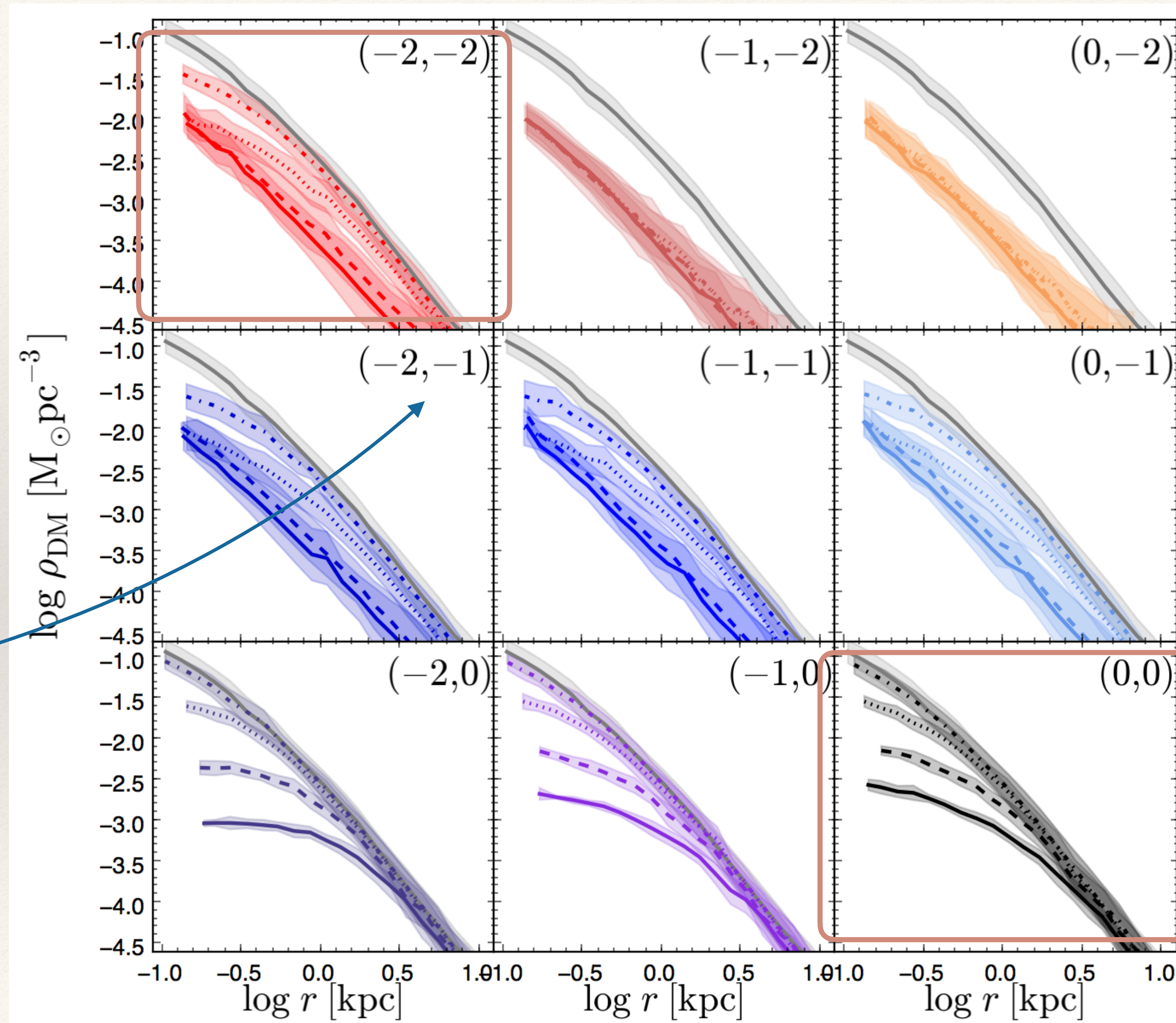
2cDM-σ(v) -- Profiles (Dwarfs)

$$\sigma(v) = \begin{cases} \sigma(v/v_0)^{a_s} \\ \sigma(v/v_0)^{a_c} \end{cases}$$

$\sigma = 0.01, 0.1, 1$

consistent with observations

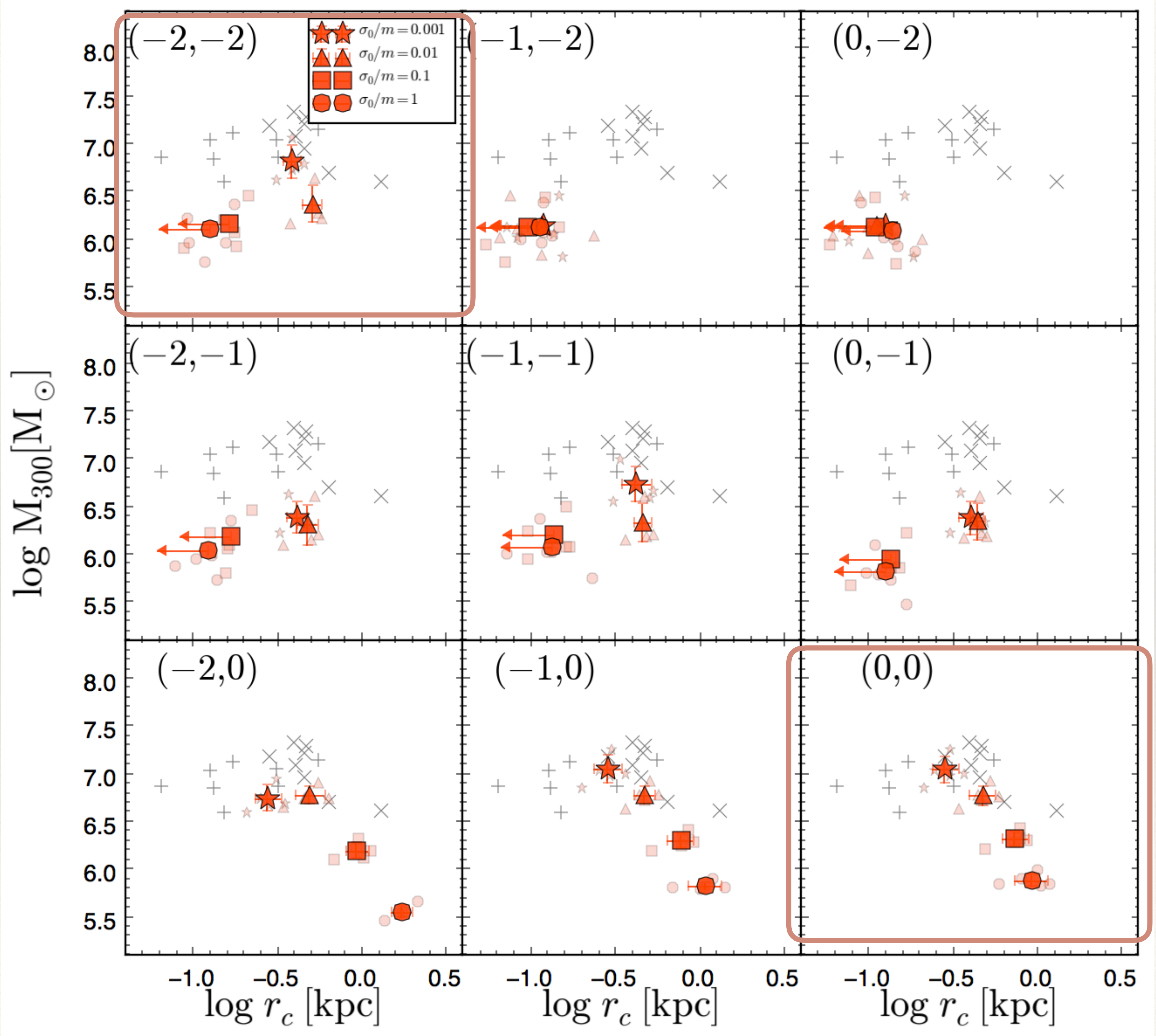
(a_s, a_c)



(Todoroki & MM, in prep.)

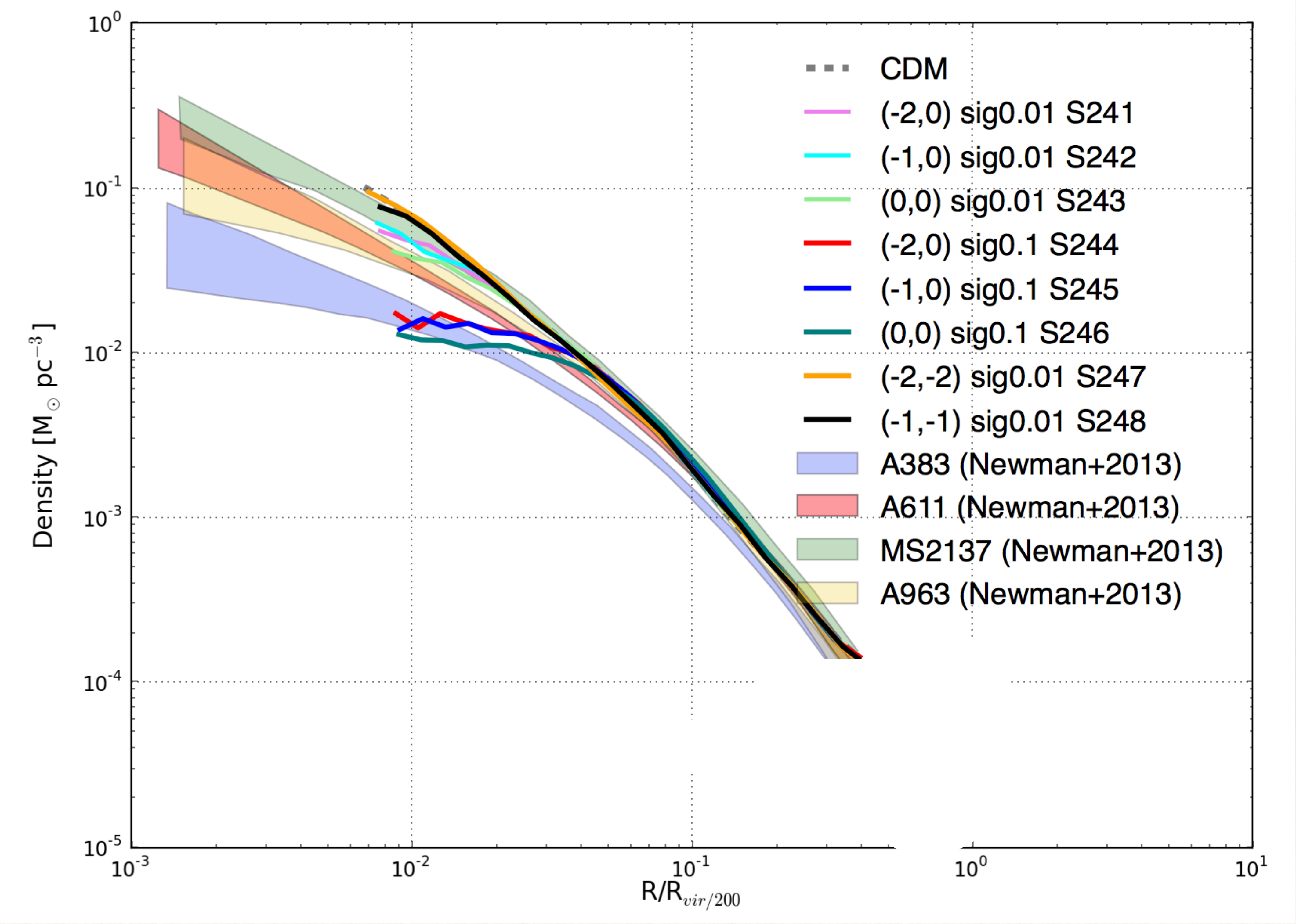
2cDM-σ(v) -- Core relations (obs vs sim)

Red symbols - simulations
Gray crosses - MW sSph



(Data:
Strigari et al. 2008;
Burkert 2015)

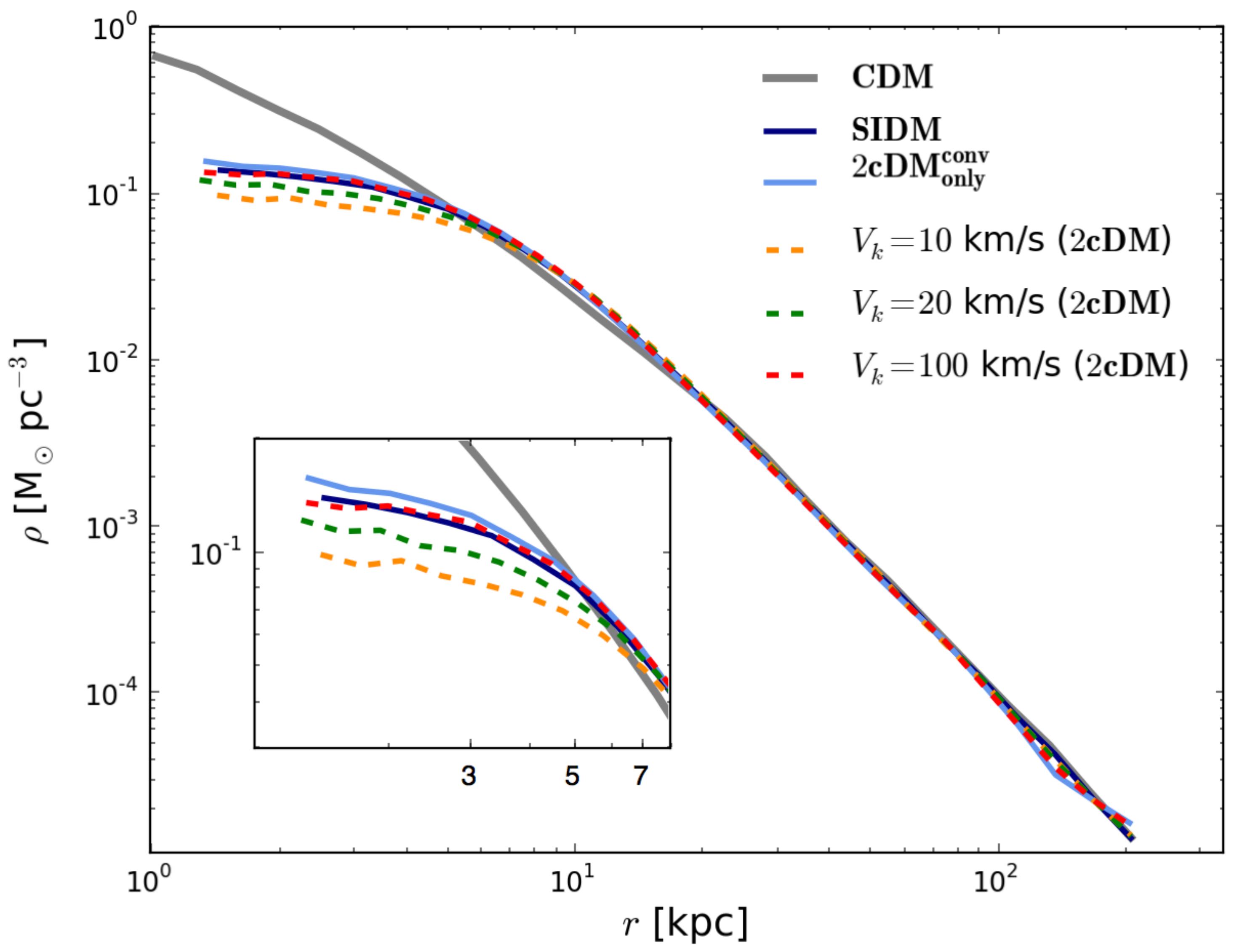
2cDM-σ(v) -- Profiles (Clusters)



(Todoroki & MM, in prep.)

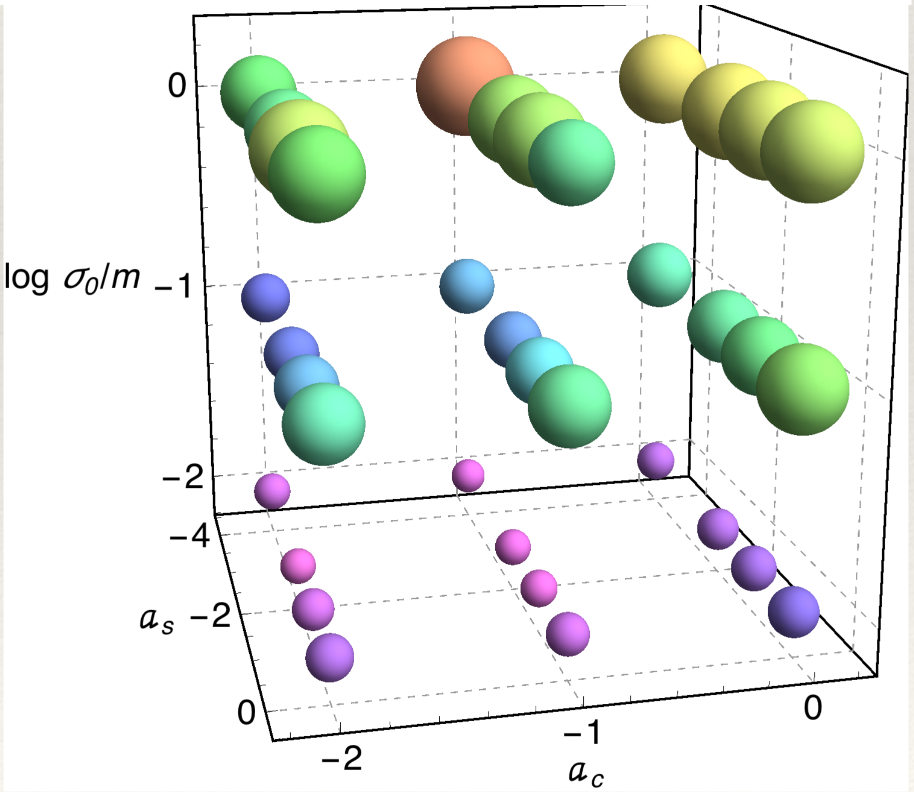
Message 2

PROFILES



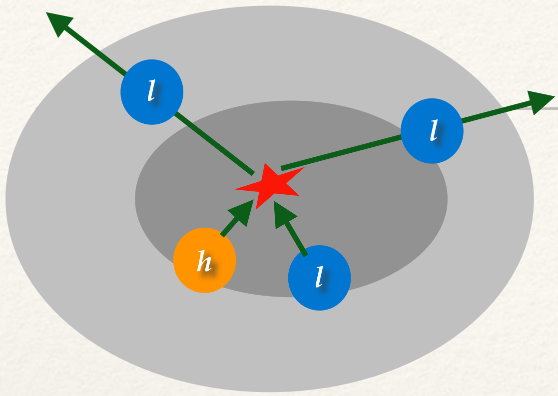
2cDM: Resolves core-cusp problem.
Core size tells:
σ_0/m and index a_s (scattering)

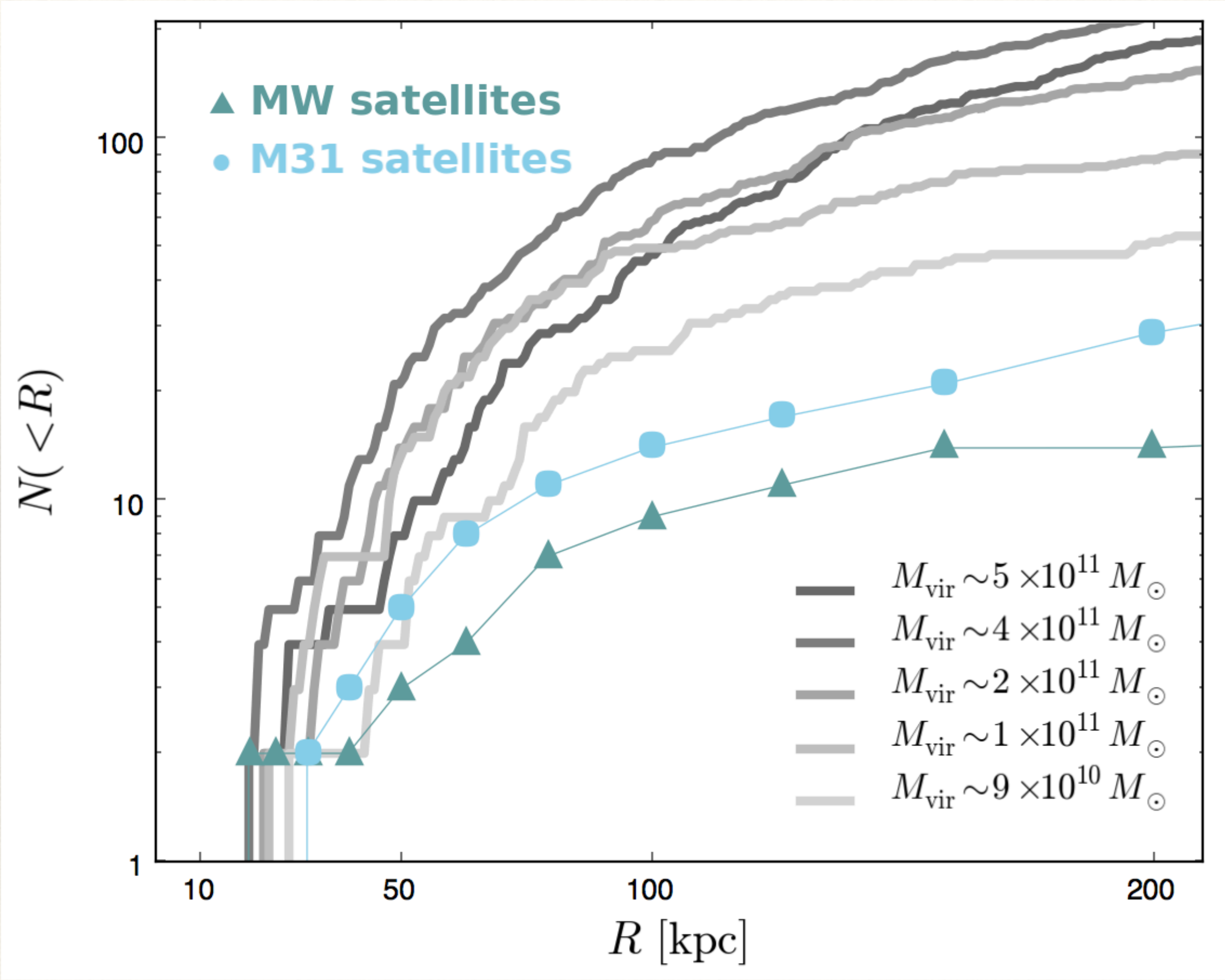
core sizes from fits to simulated halos



Wide parameter region allowed:
$\sigma(v) \sim 1...0.1...0.01$ – consistent with all constraints
$\Delta m/m \sim 10^{-8}$ $\Leftrightarrow$ $v_k \sim 50\text{-}100$ km/s

Radial distribution of satellites (CDM)





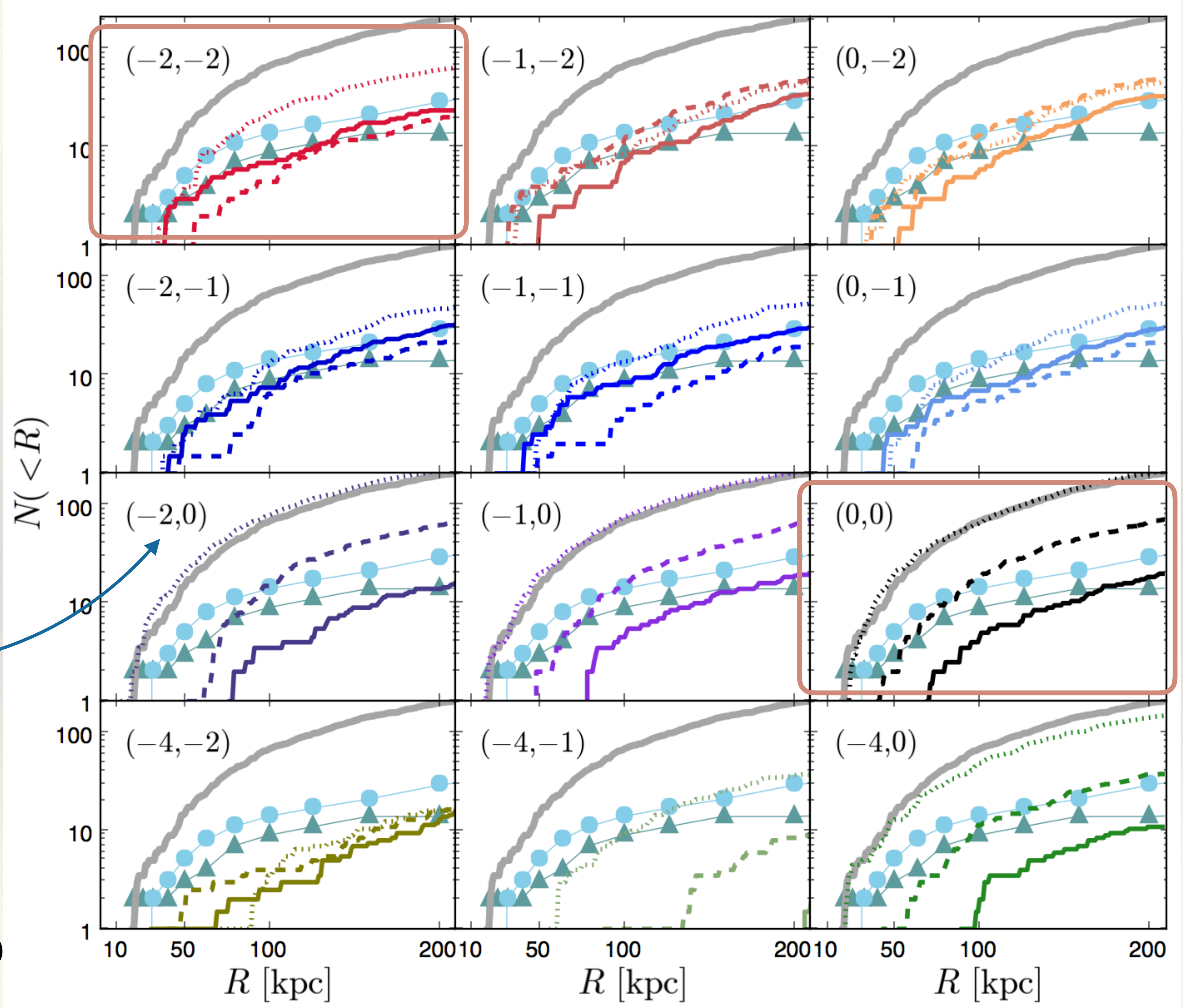
2cDM-σ(v) -- dwarf distribution

$$\sigma(v) = \begin{cases} \sigma(v/v_0)^{a_s} \\ \sigma(v/v_0)^{a_c} \end{cases}$$

$\sigma = 0.01, 0.1, 1$

consistent with observations

(a_s, a_c)

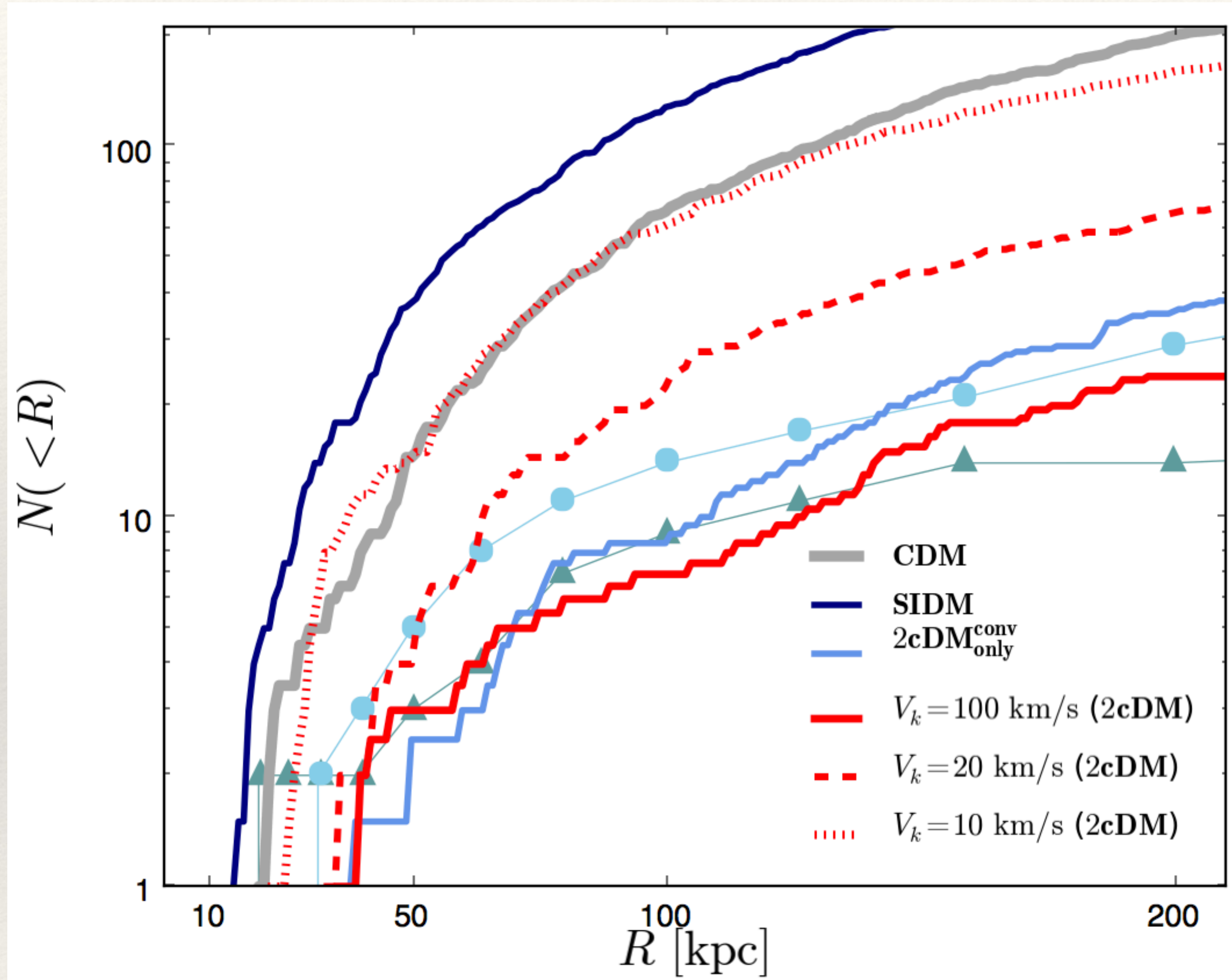


(Todoroki & MM, in prep.)

Message 3

DISTRIBUTION of SATELLITES

2cDM: Resolves substructure radial distribution.
Shape of function depends on all parameters



Wide parameter region allowed:
$\sigma(v) \sim 1...0.1...0.01$ – consistent with all constraints
$\Delta m/m \sim 10^{-8}$ ⇔ $v_k \sim 50\text{-}100$ km/s

2cDM model summary

Some 2cDM models*
simultaneously resolve:

- Substructure Problem
- TBTF problem
- Core/cusp problem across halo mass scales from dwarfs to clusters
- Radial distribution of dwarfs (problem?)

$\sigma(v) \sim 1(?)...0.1...0.01$

$(a_s, a_c) = (0,0), (-2,-2)$ -- natural

$\Delta m/m \sim 10^{-8}$ $\Leftrightarrow$ $v_k \sim$ 50-100 km/s

Model	σ_0/m	MW Density profile	VF	RHDF	Dwarf Density Profile	GC Density Profile	β-r_s	c-M relation	Theoretical preference
$(-2,-2)$	0.001	NO	YES	YES	NO	–	–	–	YES
	0.01	Baryon	Baryon	YES	YES	YES	YES	YES	YES
	0.1	YES	YES	YES	NO	–	–	–	YES
	1	YES	YES	YES	NO	–	–	–	YES
	10	NO	YES	YES	NO	–	–	–	YES
$(-1,-2)$	0.001	NO	YES	YES	NO	–	–	–	
	0.01	Baryon	YES	YES	NO	–	–	–	
	0.1	YES	YES	YES	NO	–	–	–	
	1	YES	YES	YES	NO	–	–	–	
	10	NO	YES	YES	NO	–	–	–	
$(0,-2)$	0.001	NO	YES	YES	NO	–	–	–	
	0.01	Baryon	YES	YES	NO	–	–	–	
	0.1	YES	YES	YES	NO	–	–	–	
	1	YES	YES	YES	NO	–	–	–	
	10	NO	YES	YES	NO	–	–	–	
$(-2,-1)$	0.001	NO	YES	YES	NO	–	–	–	
	0.01	Baryon	Baryon	YES	YES	–	–	–	
	0.1	YES	YES	YES	NO	–	–	–	
	1	YES	YES	YES	NO	–	–	–	
	10	NO	YES	YES	NO	–	–	–	
$(-1,-1)$	0.001	NO	YES	YES	NO	–	–	–	YES
	0.01	Baryon	Baryon	YES	YES	YES	YES	YES	YES
	0.1	YES	YES	YES	NO	–	–	–	YES
	1	YES	YES	YES	NO	–	–	–	YES
	10	NO	YES	YES	NO	–	–	–	YES
$(0,-1)$	0.001	NO	YES	YES	NO	–	–	–	
	0.01	Baryon	Baryon	YES	YES	–	–	–	
	0.1	YES	YES	YES	NO	–	–	–	
	1	YES	YES	YES	NO	–	–	–	
	10	NO	YES	YES	NO	–	–	–	
$(-2,0)$	0.001	NO	NO	YES	NO	–	–	–	
	0.01	Baryon	NO	NO	YES	YES	YES	YES	
	0.1	YES	Baryon	YES	YES	?	YES	YES	
	1	YES	YES	NO	NO	–	–	–	
	10	NO	NO	YES	NO	–	–	–	
$(-1,0)$	0.001	NO	NO	YES	NO	–	–	–	
	0.01	Baryon	NO	NO	YES	YES	YES	YES	
	0.1	YES	Baryon	YES	YES	?	YES	YES	
	1	YES	YES	NO	NO	–	–	–	
	10	YES	NO	YES	NO	–	–	–	
$(0,0)$	0.001	NO	NO	YES	NO	–	–	–	YES
	0.01	YES	NO	NO	YES	YES	YES	YES	YES
	0.1	YES	Baryon	YES	YES	?	YES	YES	YES
	1	YES	YES	NO	NO	–	–	–	YES
	10	NO	NO	YES	NO	–	–	–	YES
SIDM	0.001	YES	NO	–	–	–	–	–	
	0.01	YES	NO	–	–	–	–	–	
	0.1	YES	NO	–	–	–	–	–	
	1	YES	NO	–	–	–	–	–	
	10	–	–	–	–	–	–	–	
CDM	–	NO	NO	NO	NO	?	YES	?	

Typical constraints

"Bullet cluster" $\sigma/m < 1\ cm^2/g$ 2cDM cross-sections $\sigma/m \sim 1...0.1$, even...0.01

Stability to decay "mass-eigenstates must decay to leave the lightest only"

$\Delta m/m \sim 10^{-8}$ -- enough room to avoid: no secondaries to decay into (cf 100keV/1TeV)

(MM, JCAP 2014)

Typical constraints

"Bullet cluster" $\sigma/m < 1\ \mathrm{cm}^2/\mathrm{g}$ 2cDM cross-sections $\sigma/m \sim 1...0.1$, even...0.01

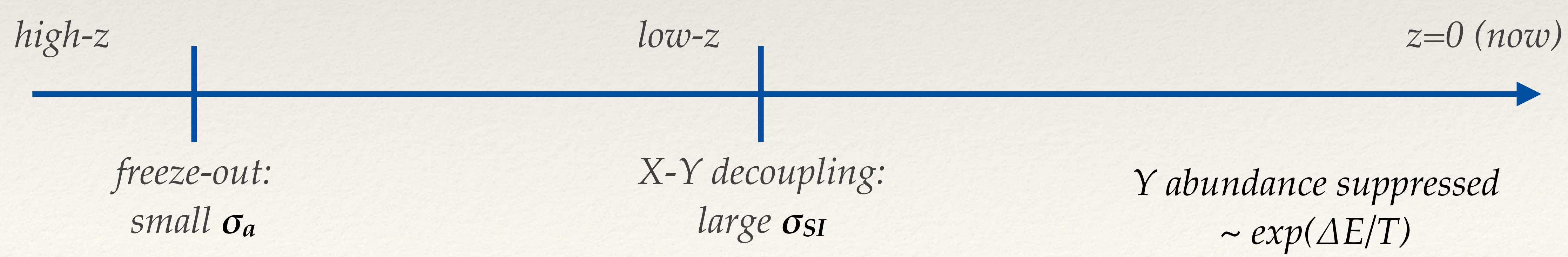
Stability to decay "mass-eigenstates must decay to leave the lightest only"

$\Delta m/m \sim 10^{-8}$ -- enough room to avoid: no secondaries to decay into (cf 100keV/1TeV)

Early universe "catastrophe"

2cDM looks like any multi-species/composite DM -- allows rapid "reactions" $Y \rightarrow X$
$\Rightarrow$ abundance of heavy states must be exponentially suppressed

excited,
inelastic,
exothermal DM,...



(MM, JCAP 2014)

Typical constraints

if wave packets overlap, particles interact coherently (as flavor states) - *no conversions*

time-dependent wave packet of a mass eigenstate

$$\psi_j(x,t) = \left[2\pi\left(\Delta_0 + \frac{i\hbar t}{2m_j\Delta_0}\right)^2\right]^{-1/4} \exp\left[-\frac{(x-x_0-v_j t)^2}{4\Delta_0^2 + 2i\hbar t/m_j} + \frac{i}{\hbar}\left(m_j v_j x - \frac{m_j v_j^2}{2}t\right)\right]$$

wave packet width $\Delta_j^2(t) = \Delta_0^2 + \left(\frac{\hbar}{2m_j\Delta_0}\right)^2 t^2$

packet spreads as fast as it propagates

interaction amplitude ~ overlap of two mass states

$$I(t) = \int_{-\infty}^{\infty} A_h(x,t)A_l(x,t)\,dx \qquad I(\infty) \simeq 1 - \left(\frac{\Delta m}{m}\right)^2 \xi + \mathcal{O}\left(\frac{\Delta m^3}{m^3}\right)$$

$$\xi = \frac{1}{4} + \frac{p^2\Delta_0^2}{2\hbar^2} \sim \frac{1}{4} + \frac{p^2}{2(\Delta p)^2} \sim \mathcal{O}(1)$$

Catastrophe isn't a problem for 2cDM: conversions do not occur before structure formation starts (needed to separate mass states)

$$\sigma_{\rm conv}^{\rm fst} \sim (\Delta m/m)^4 \sigma_{\rm conv}$$

before structure formation

after structure formation

(MM, JCAP 2014)

Caveats

some fine tuning of σ to Hubble time

$0.001 < \sigma/m < 1\ \mathrm{cm}^2/\mathrm{g}$

too few collisions
- uninteresting

too many collisions
- collapse

large $\sigma \sim 1\ \mathrm{cm}^2/\mathrm{g} \sim 1\ \mathrm{barn}/\mathrm{GeV}$

not very natural in particle physics

high degeneracy $\Delta m/m \sim 10^{-8}$

not very natural in particle physics - possibly needs light mediator

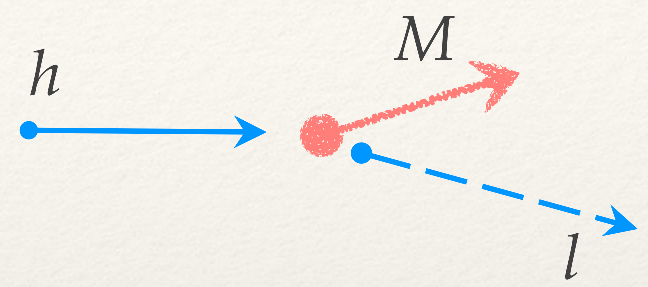
small mass splitting:

Y. Zhang, Phys. Dark Univ. 15 (2017)
K. Schutz, T.R. Slatyer, JCAP 01 (2015) 021
J. Kopp et al. JHEP 12 (2016) 033
M. Baumgart et al. JHEP 0904:014,2009
....

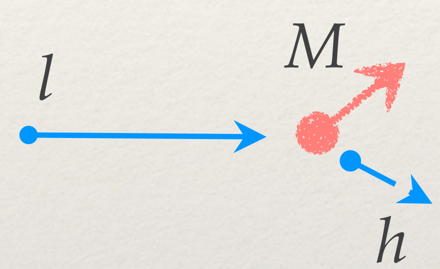
2cDM predictions

direct detection

“inelastic recoil”



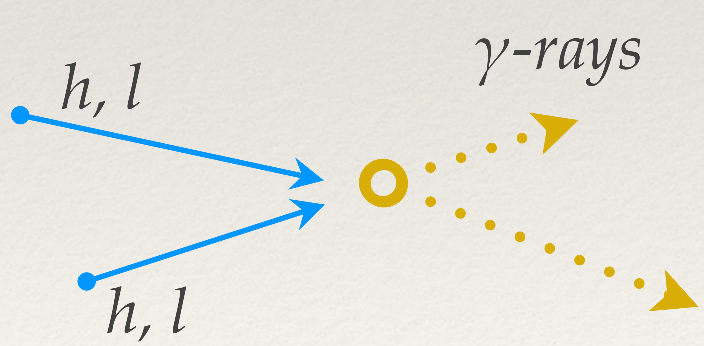
$+ \Delta mc^2$



$- \Delta mc^2$

indirect detection

“γ-ray annihilation line triplet”



$E_\gamma = mc^2 \pm \frac{1}{2} \Delta mc^2$

example, 100 GeV ± ~ keV

(MM, PRL 2014)

Conclusions

flavor-mixed DM – just works

- resolves small-scale problems simultaneously across many scales
- cosmologically interesting (v ~ 100 km/s)
- $\sigma(v)/m \sim 1...0.1...0.01$ – consistent with all obs. constraints
- $\Delta m/m \sim 10^{-8}$ – can be naturally stable
- passes the "early universe catastrophe" challenge
- makes predictions for DM detection experiments: inelastic recoil, gamma triplet

further study – "realistic" simulations with star formation, baryons, feedback,...

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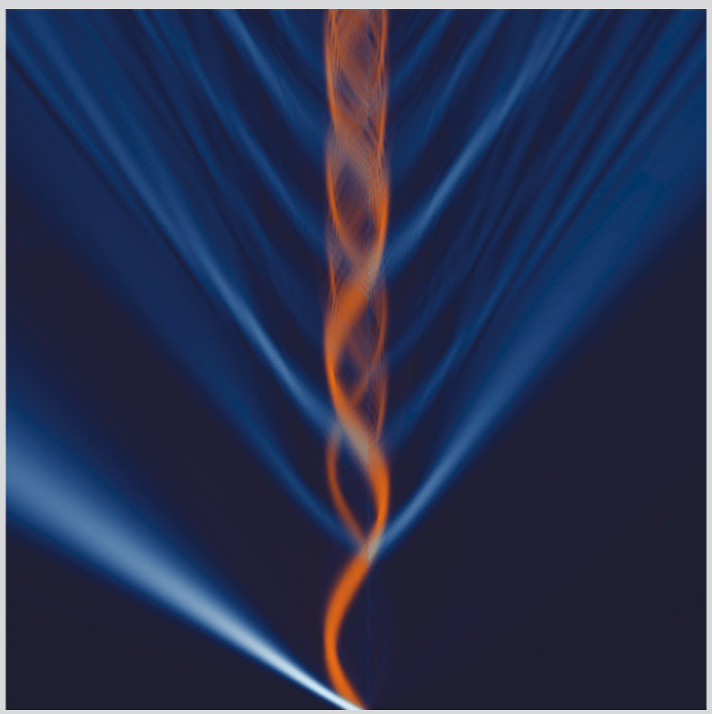

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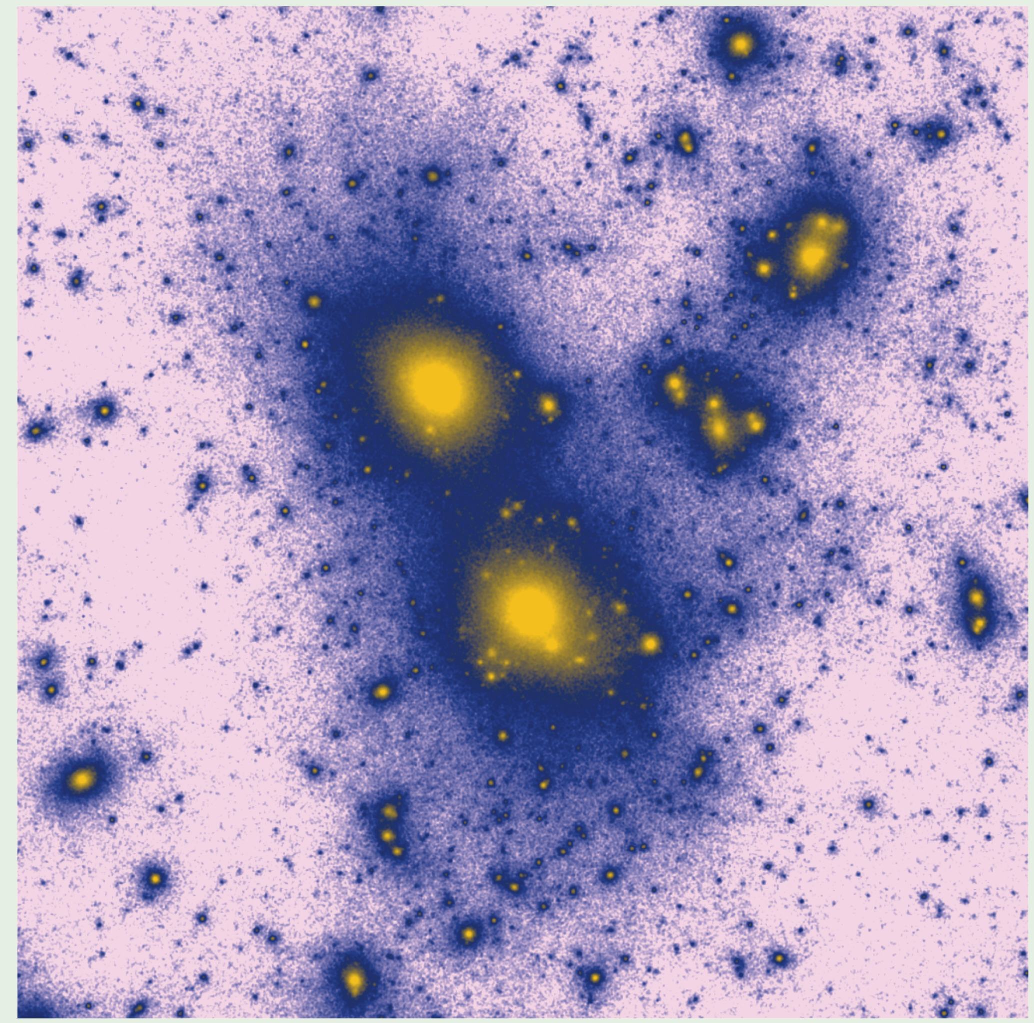

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