Workshop on Non-Standard Dark Matter — Warsaw, Poland — 5 June 2016

Flavor-Mixed DM in Cosmology

M. Medvedev, University of Kansas

Outline

Cosmology

– small-scale problems in CDM

Quantum physics

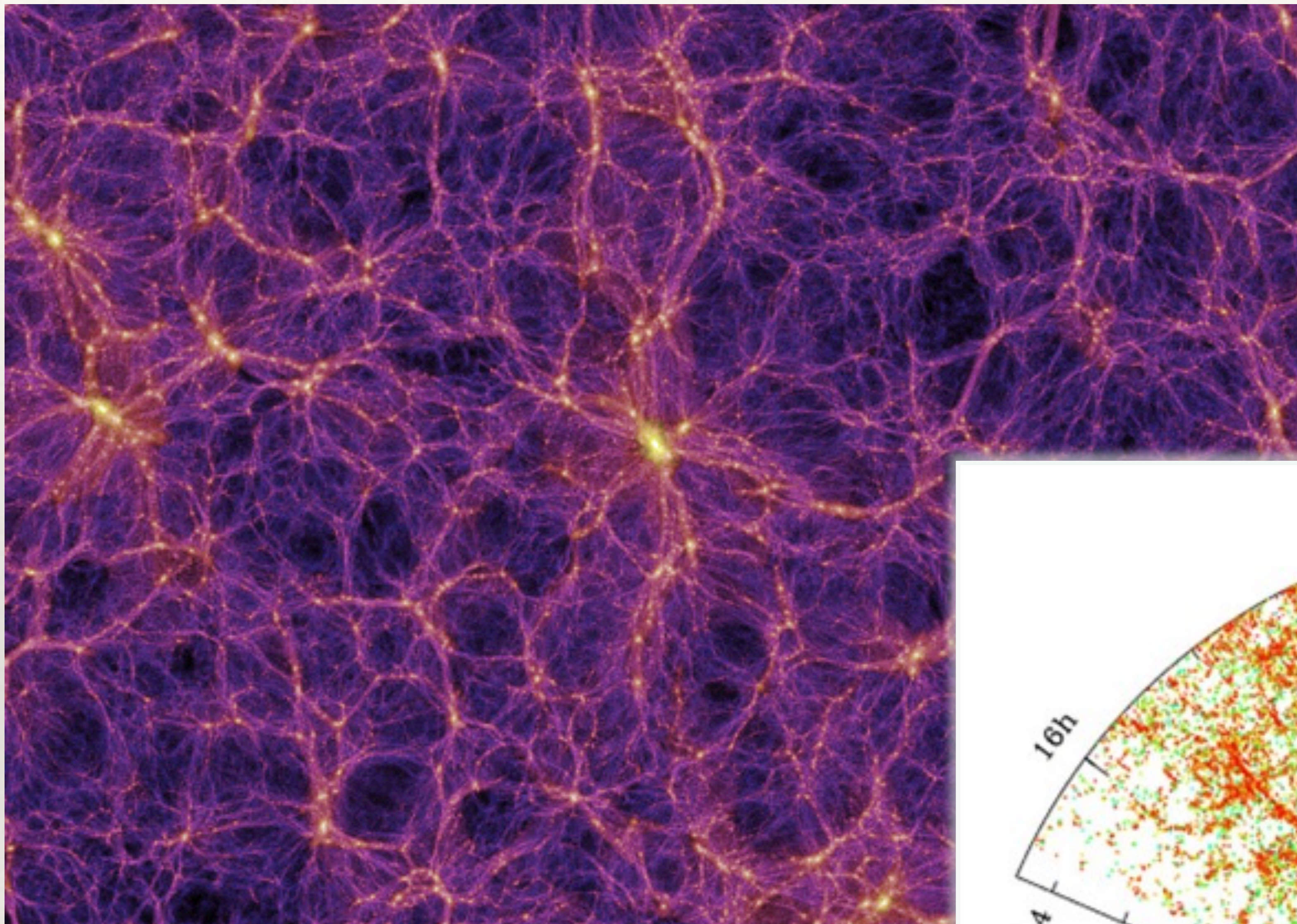
– quantum evaporation

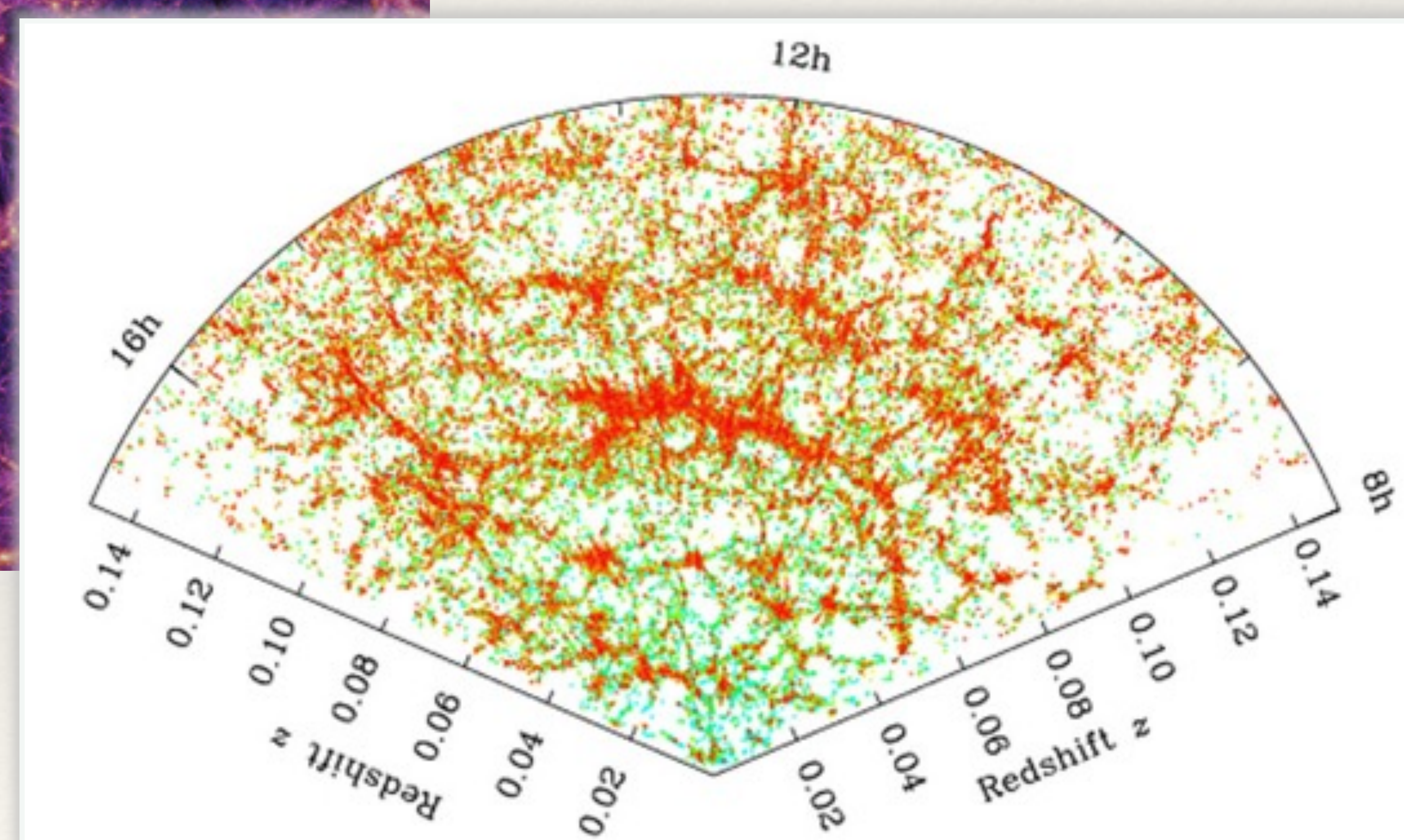
Cosmology again

– 2-component dark matter (2cDM)

Triumph on large scales

ΛCDM reproduces Large-Scale Structure of the universe



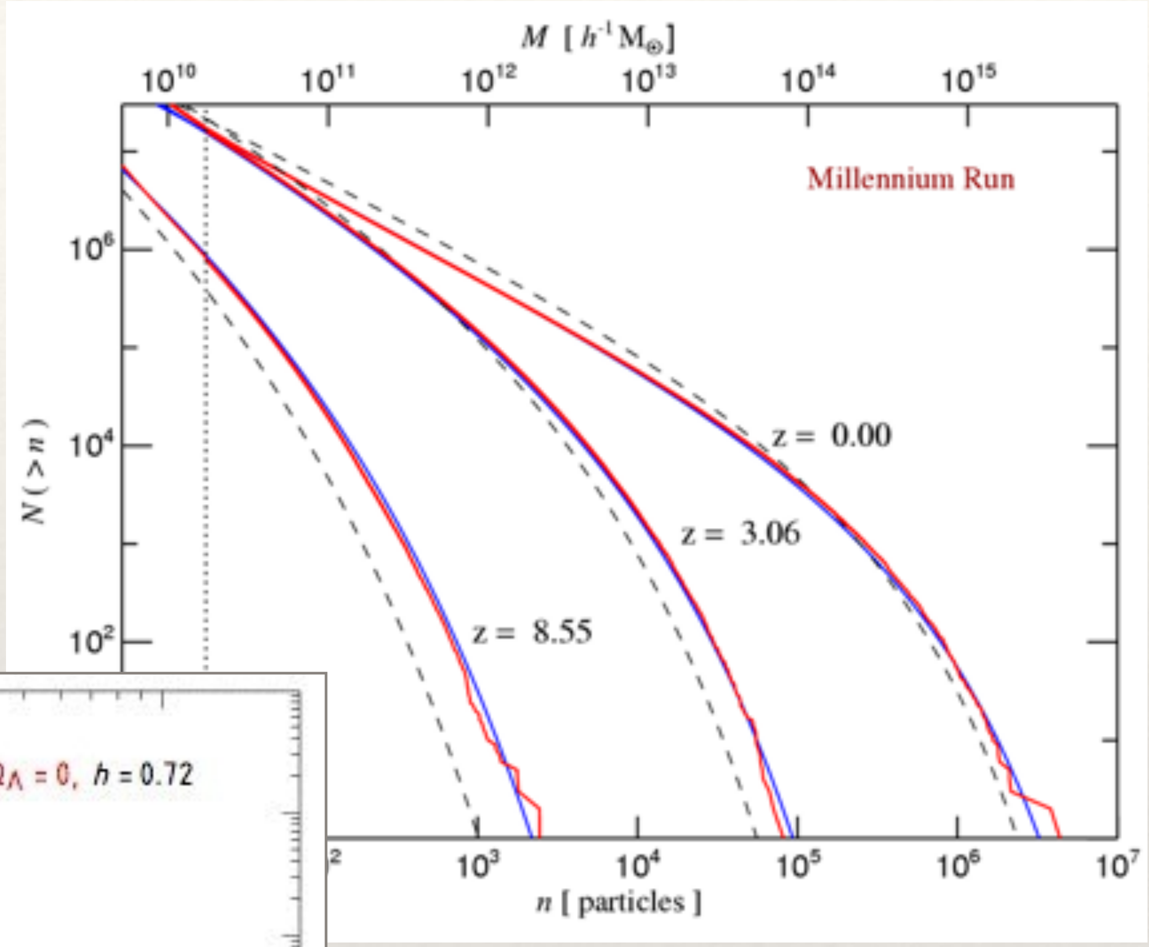


Millenium simulation

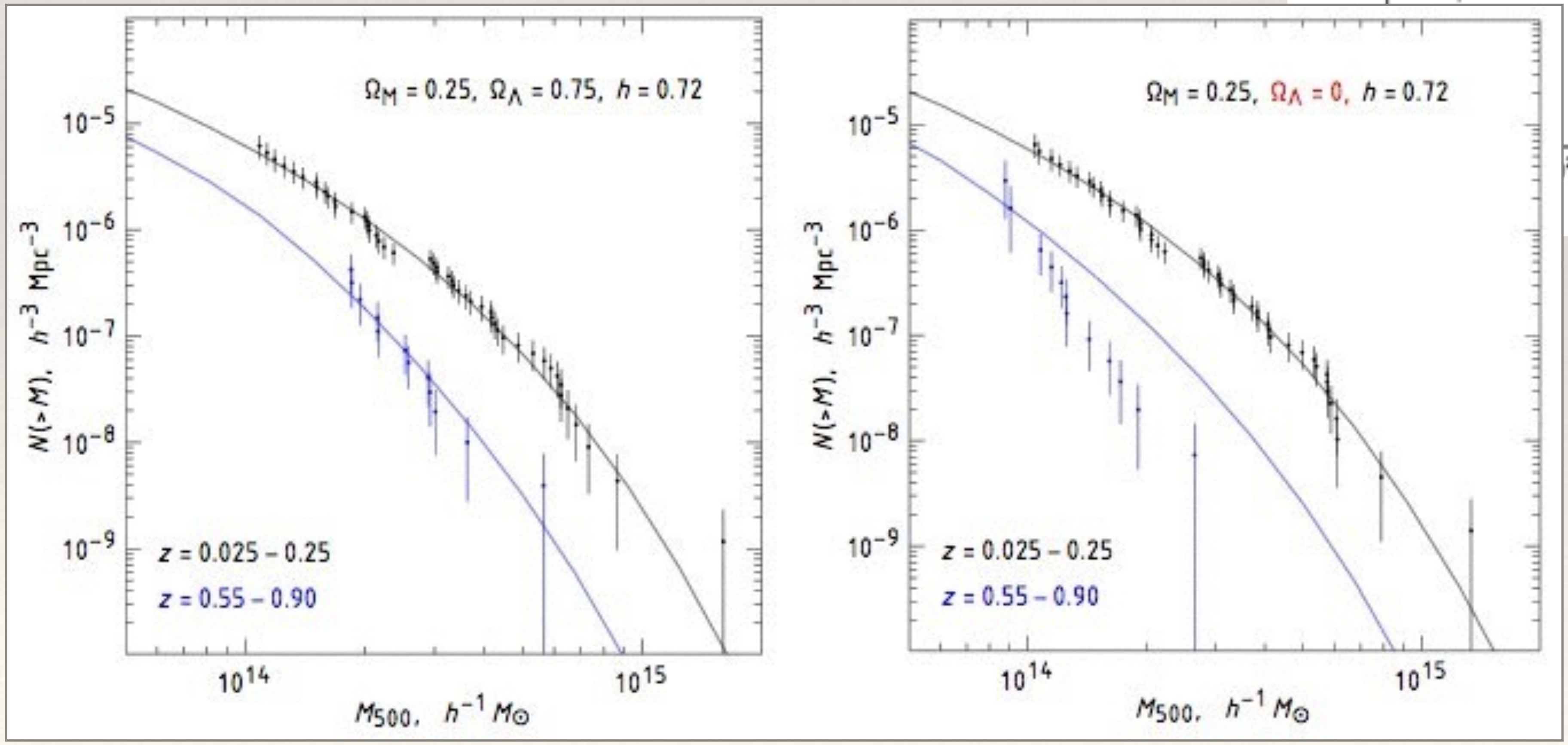
SDSS survey

ΛCDM on large scales - halo counts

- Cumulative distribution of Dark Matter halos by mass fits cluster data

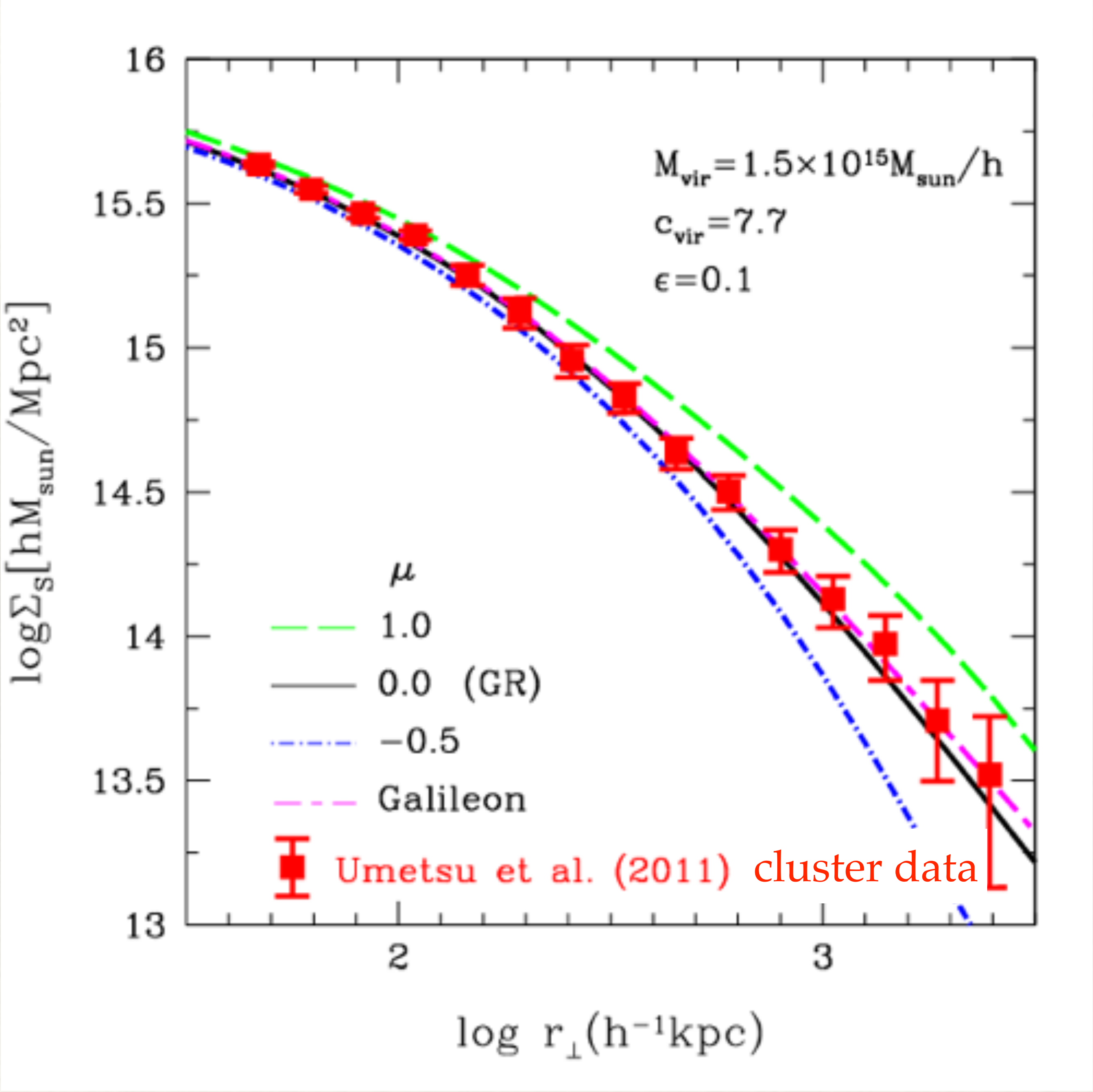


- Halo counts yields cosmological parameters



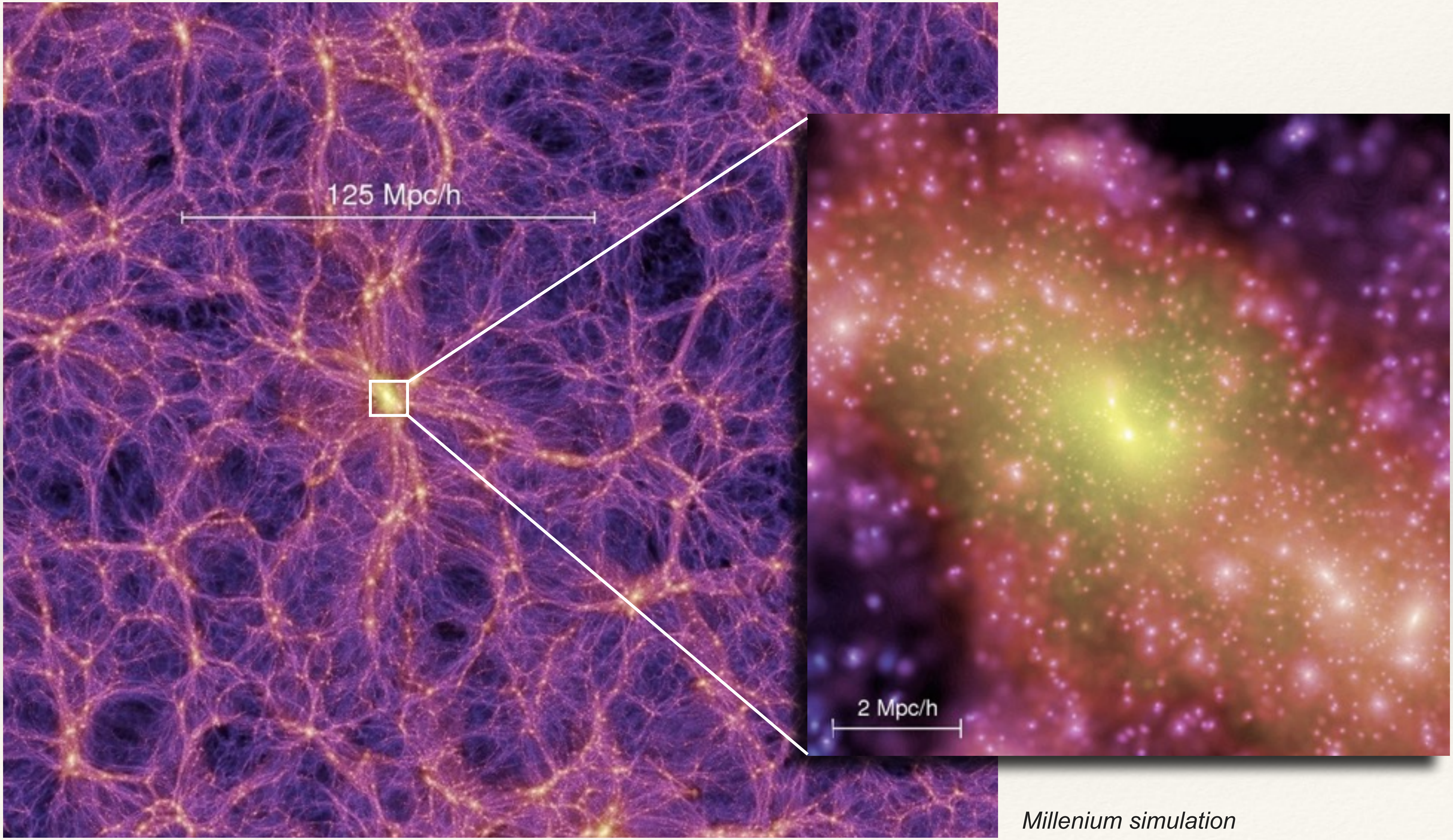
Vikhlinin et al

ΛCDM on large scales - density profiles



- Dark Matter density profiles in halos described by Navarro-Frenk-White (NFW) profile fit galaxy cluster data

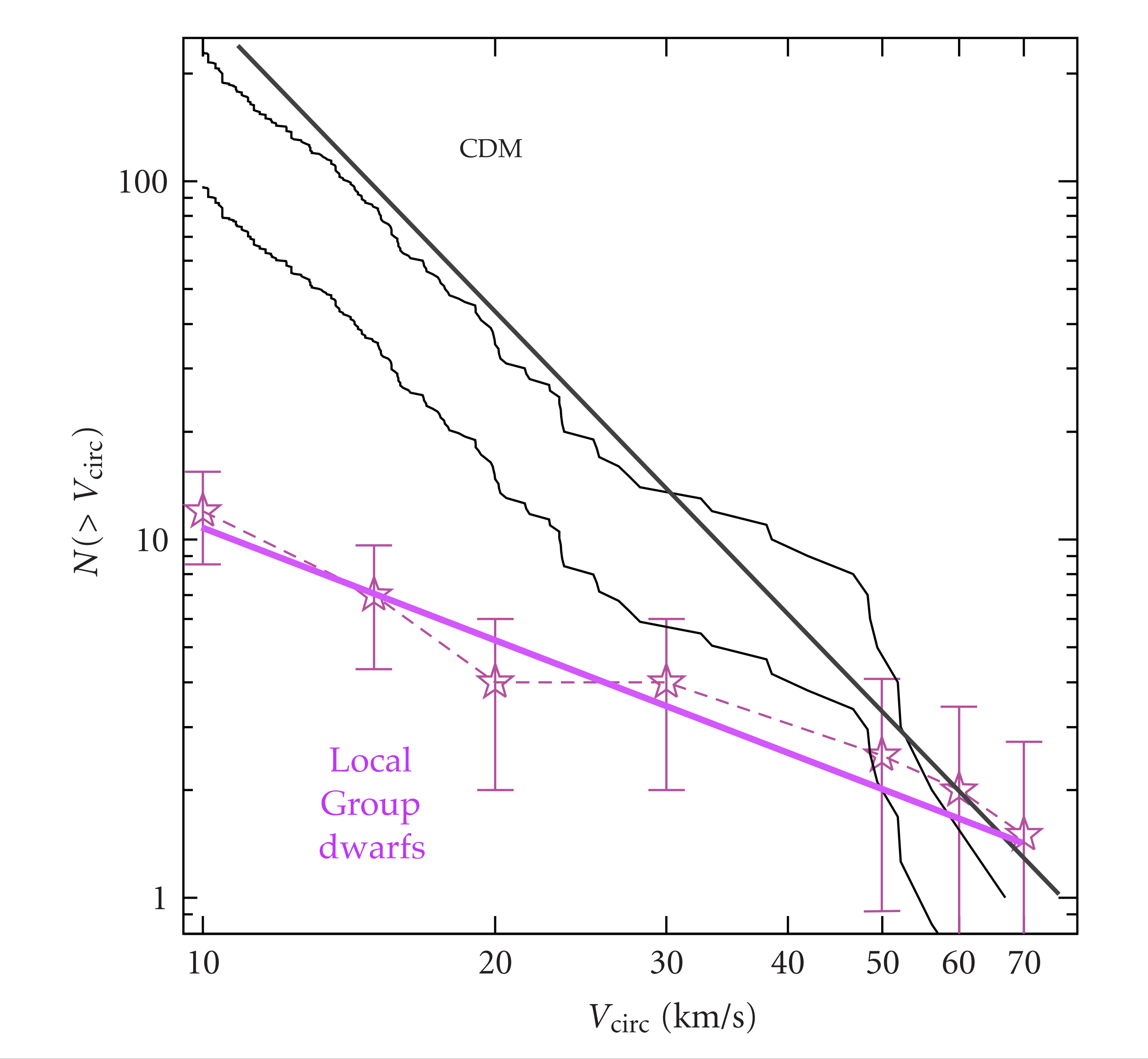
…but too much small-scale stuff



Millenium simulation

ΛCDM problems – small scales

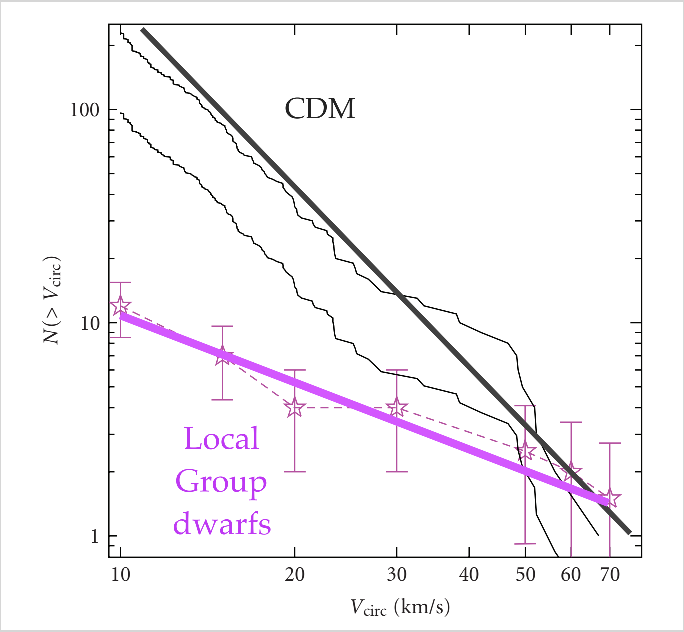
- **substructure problem (missing satellites)**



Klypin+ 1999
Kravtsov 2010

ΛCDM problems – small scales

- substructure problem (missing satellites)

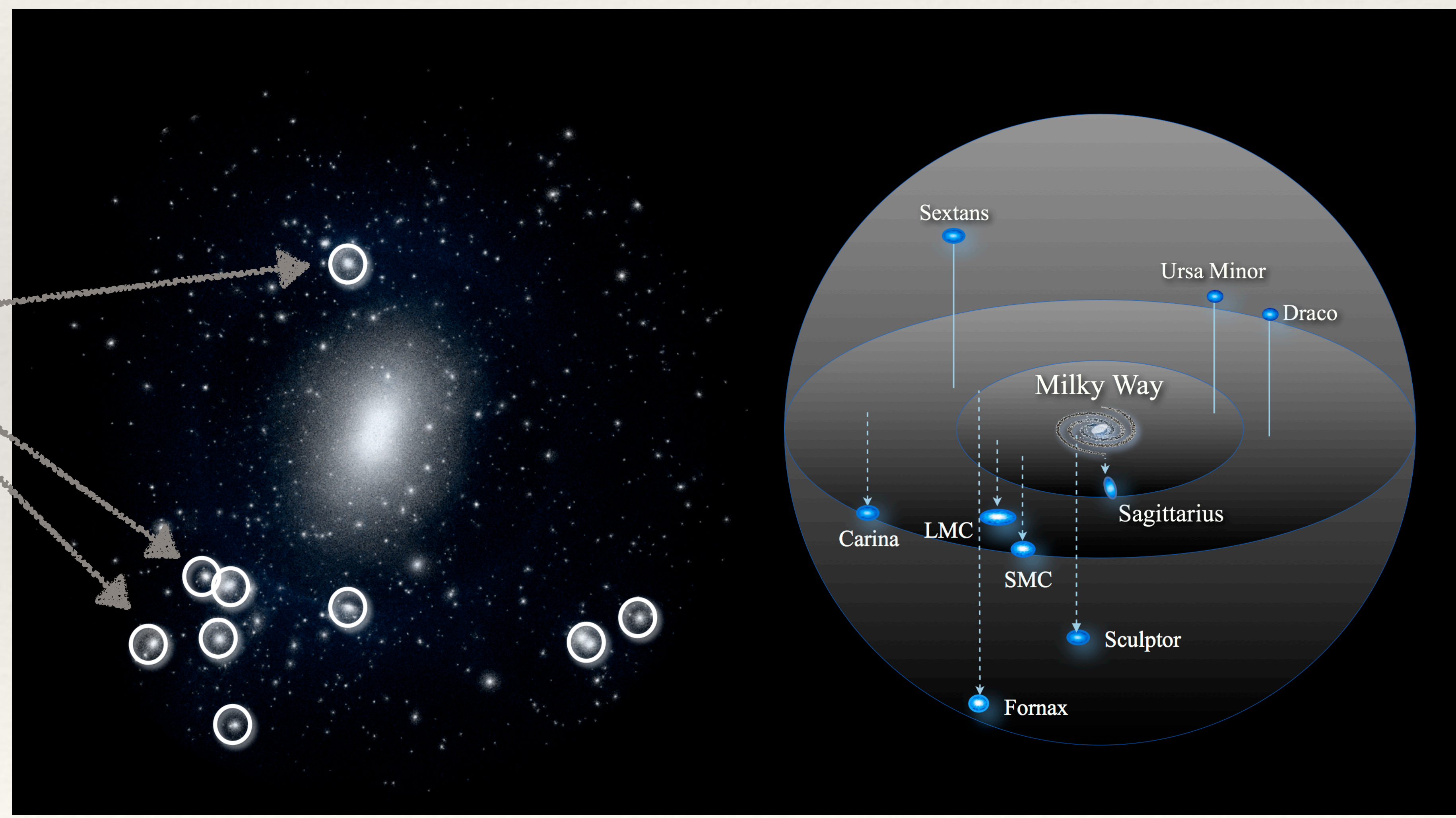


ΛCDM problems – small scales

- substructure problem
  (missing satellites)

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

None of these
most massive
are observed

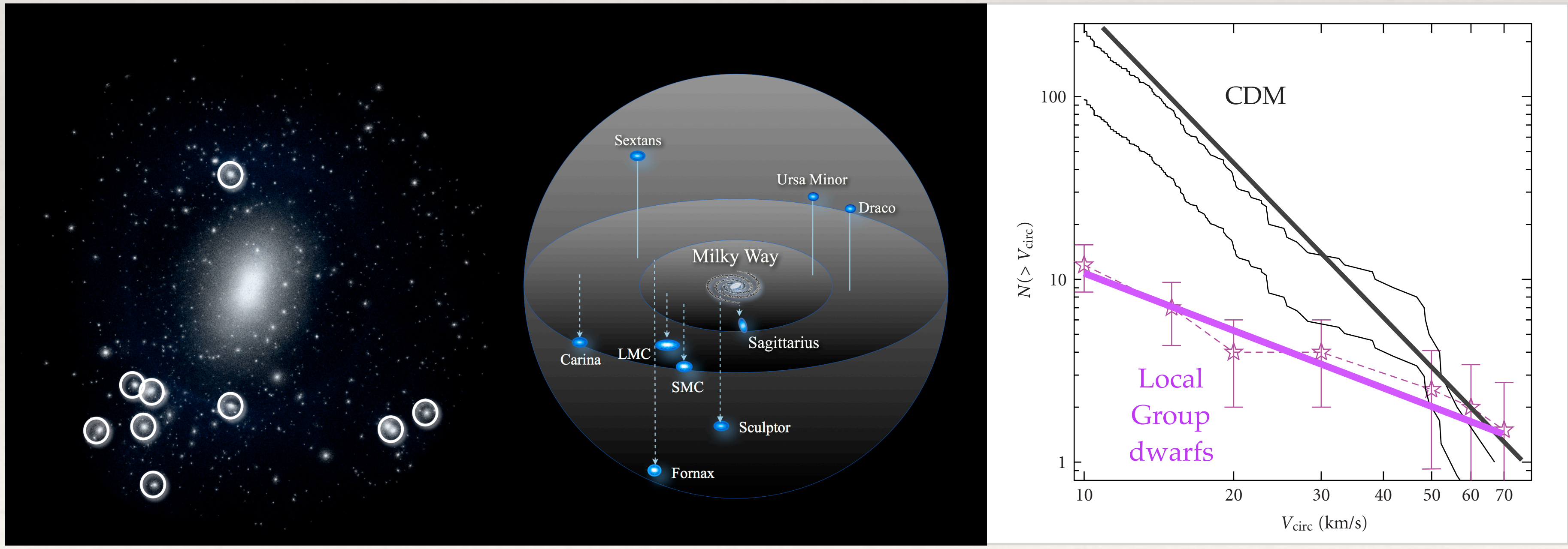


from Weinberg et al 2013
by Garrison-Kimmel, Boylan-Kolchin & Bullock

Yniguez et al. 2013

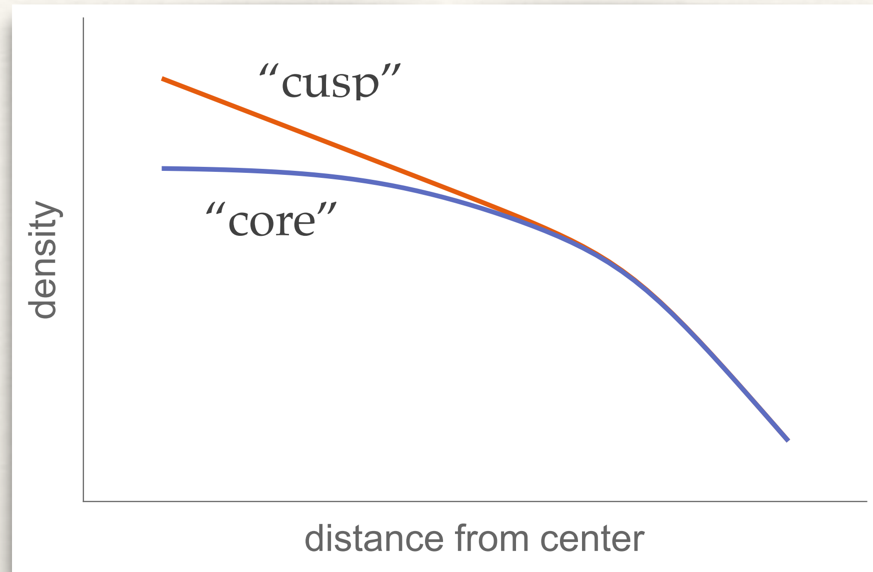
ΛCDM problems – small scales

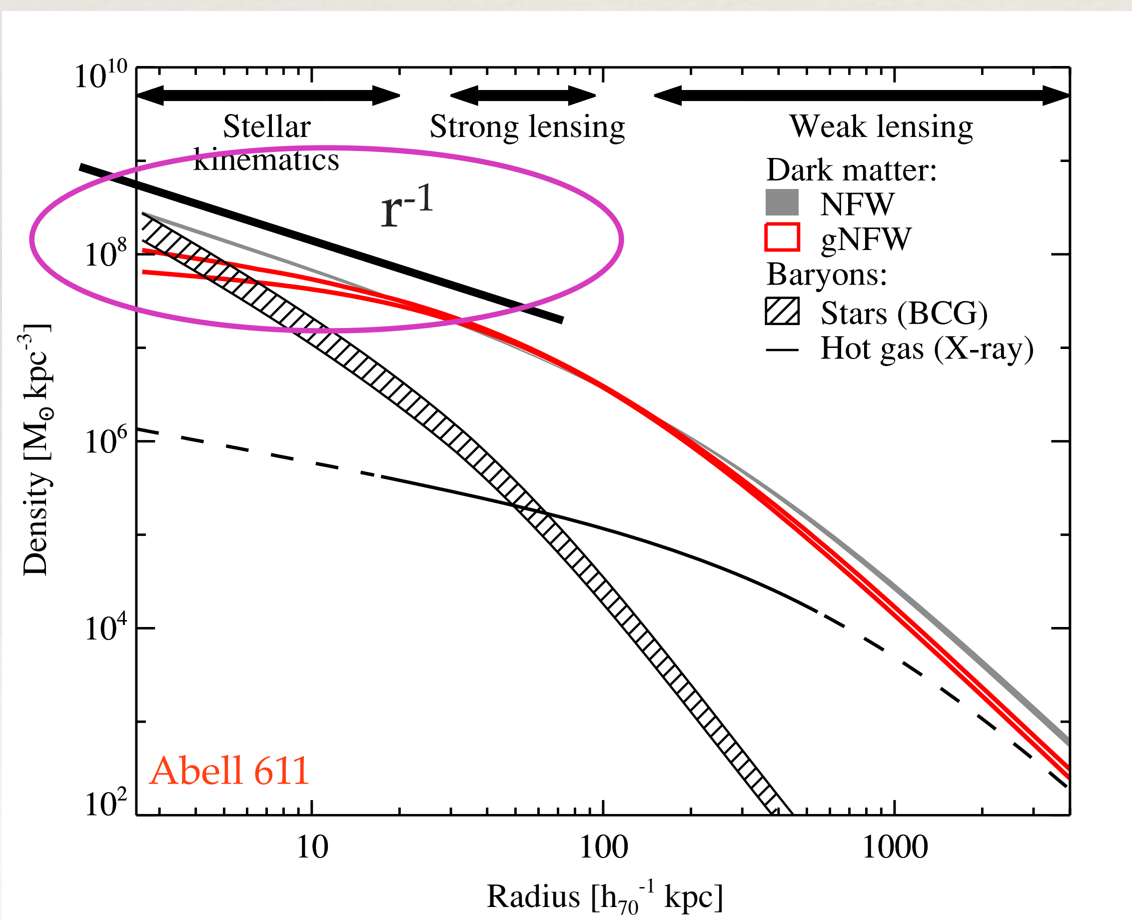
- substructure problem (missing satellites)
- too-big-to-fail problem



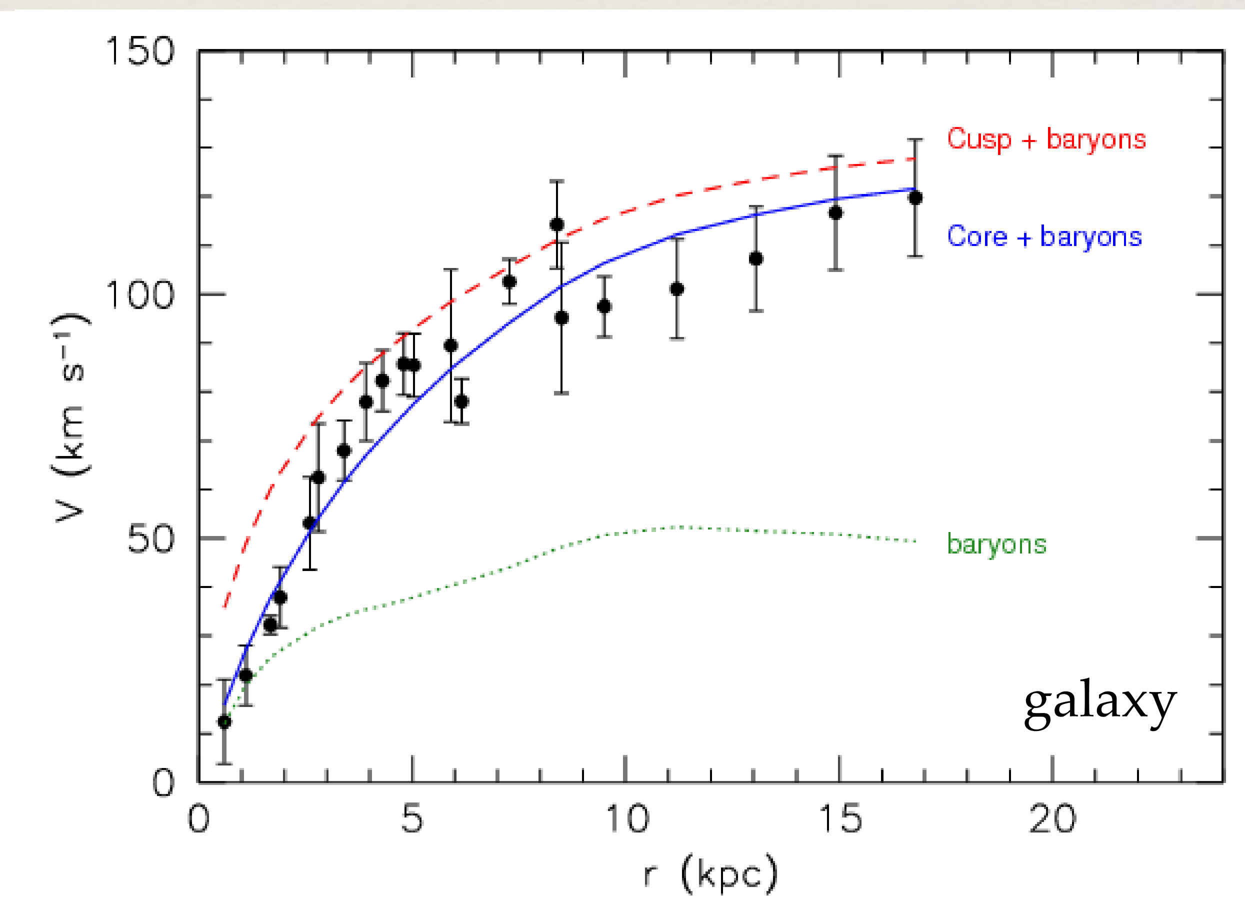
ΛCDM problems – small scales

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



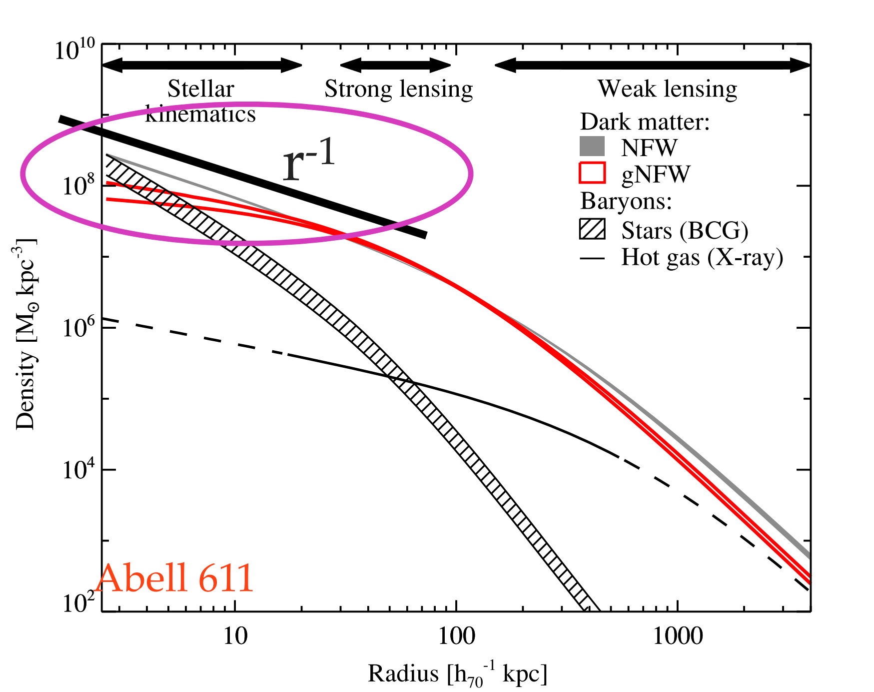


Newman+ 2009

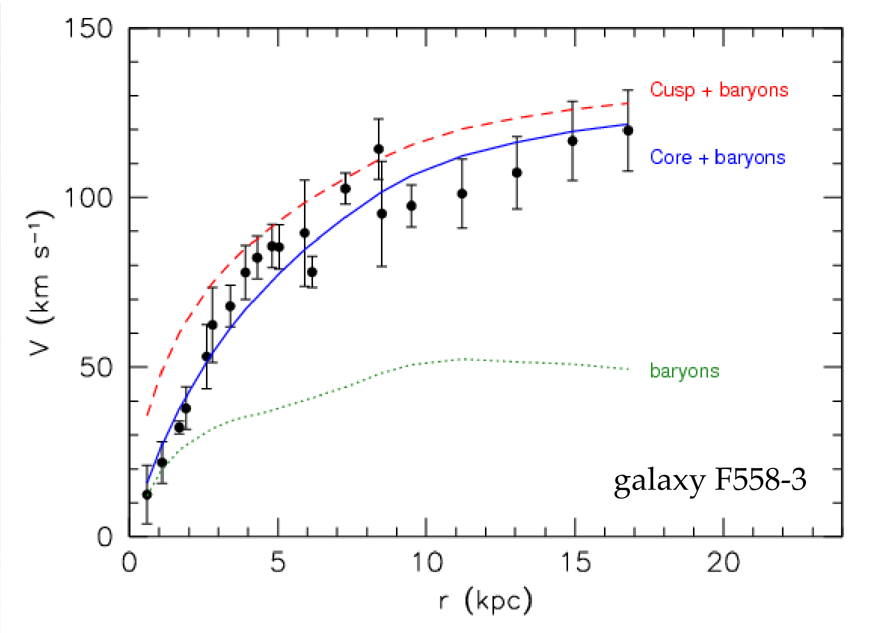


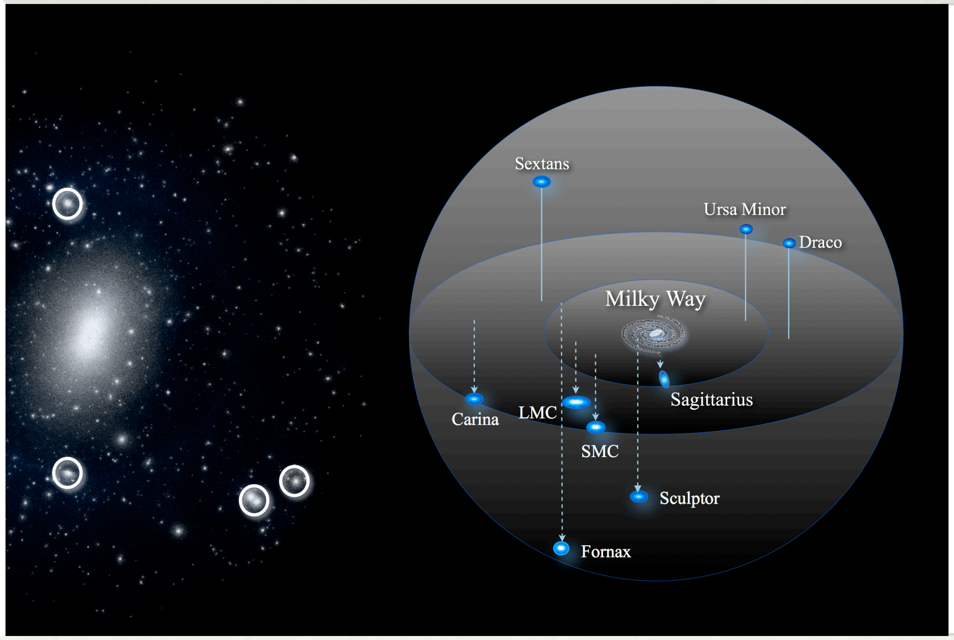
Kuzio de Naray et al. 2008

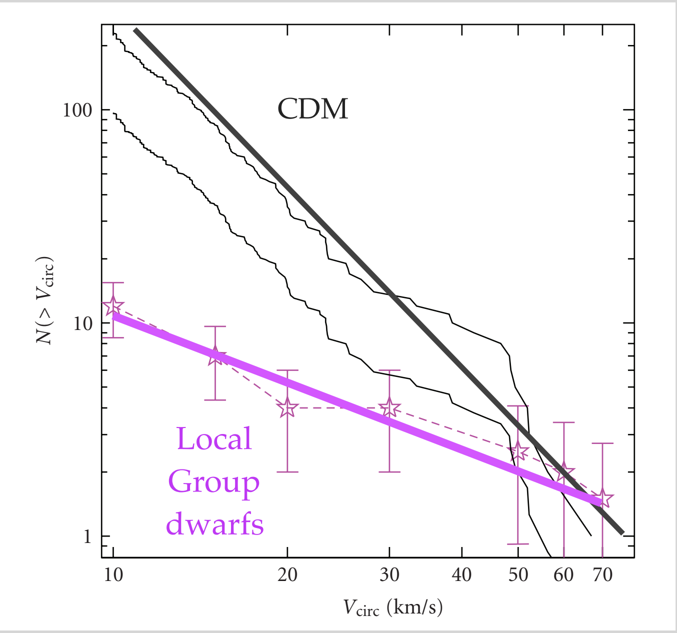
ΛCDM problems – small scales



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







Possible solutions

- **Baryonic physics**
  - NS feedback
  - outflows
  - modified star formation

- **Dark Matter physics**

Possible solutions

- **Baryonic physics**
  - NS feedback
  - outflows
  - modified star formation

) Inconclusive

- **Dark Matter physics**

Dark Matter

Dark Matter m "just" a parameter

Dark Matter

m

"just" a parameter

T

WDM - cannot solve satellites and cusp problem simultaneously: different scales

Dark Matter

m

"just" a parameter

T

WDM - cannot solve satellites and cusp problem simultaneously: different scales

σ

SIDM - solves cusp problem only; cannot affect satellite counts

Dark Matter

m

T

σ

Dark Matter

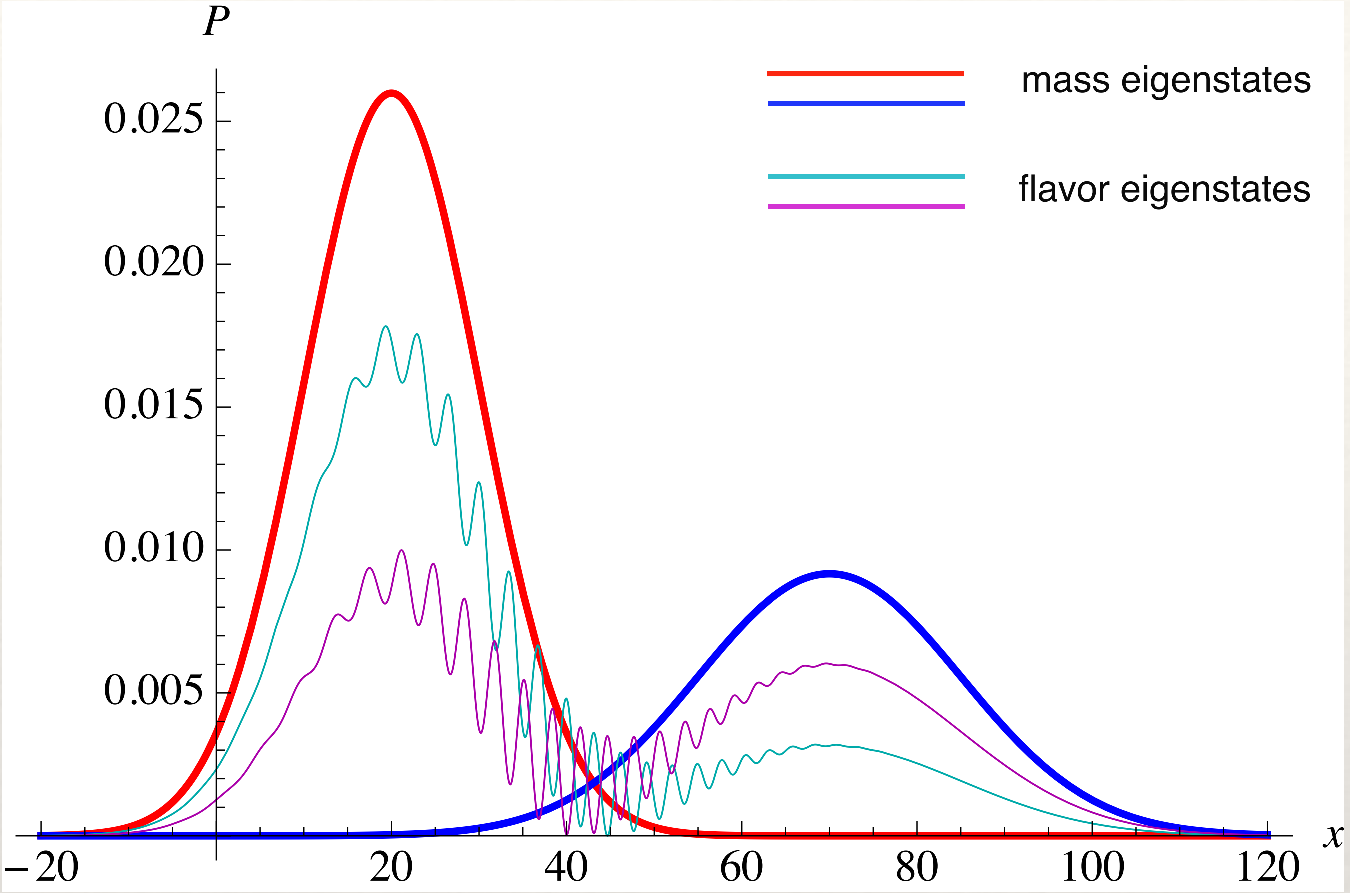
m

T

σ

flavor

2-component particle



B. Pontekorvo
Zh. Teor. Exp Fiz (1957); Soviet JETP (1958)

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

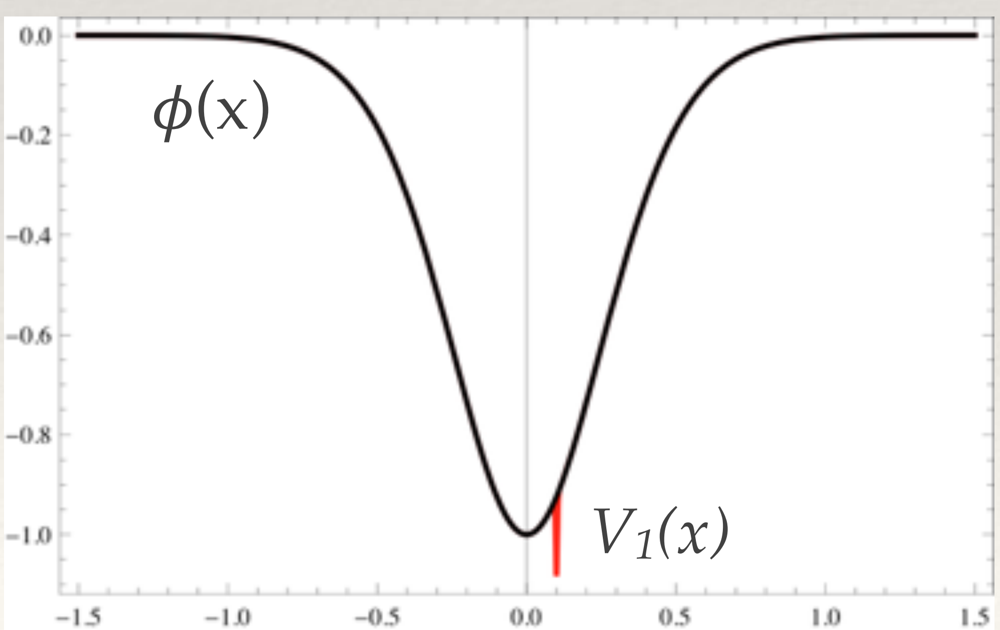
Flavor is a quantum property that allows a particle to have several masses altogether, at the same time and vice versa

Illustrative model

Schrödinger equation

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

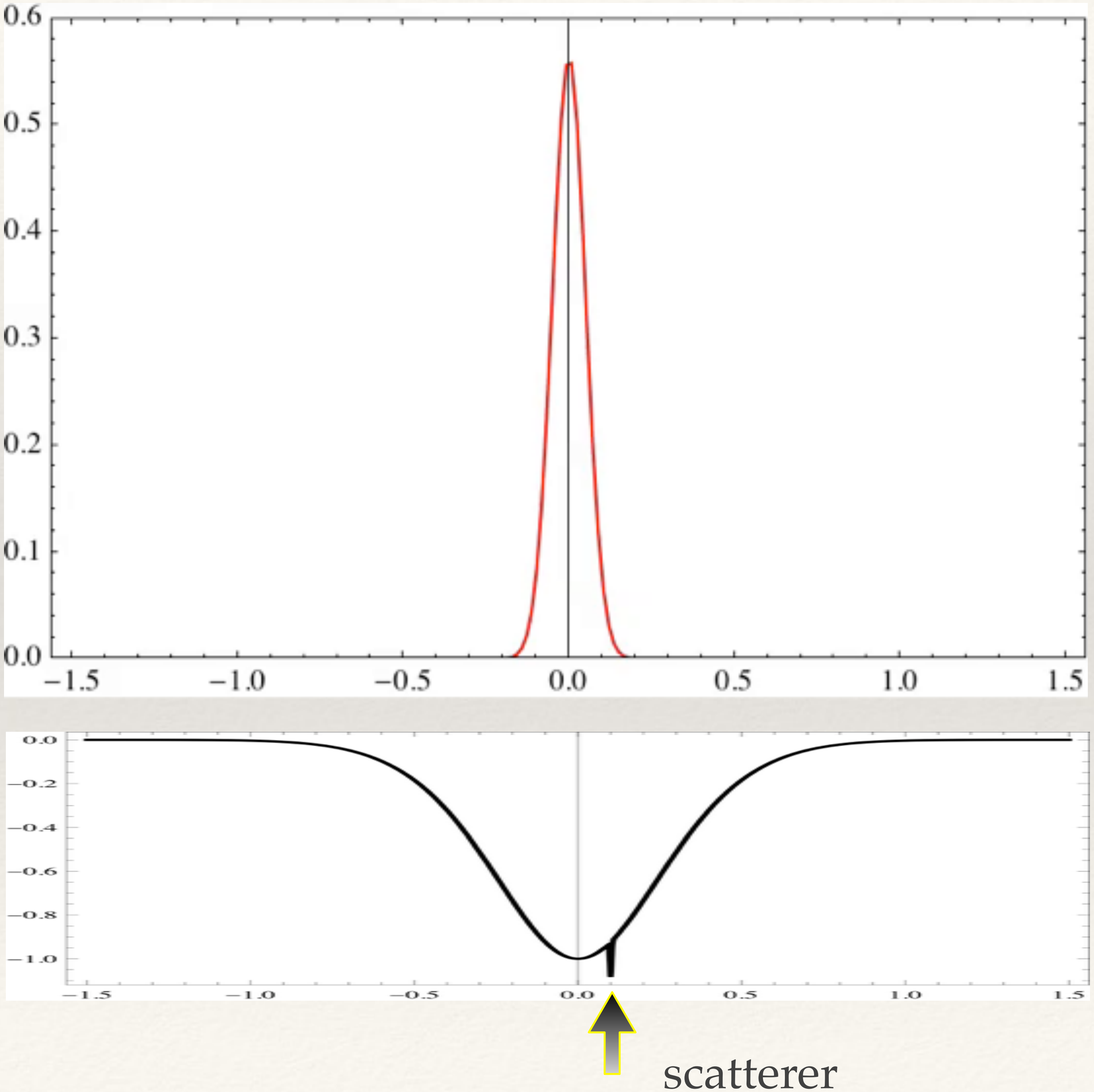
H_{free} H_{grav} V



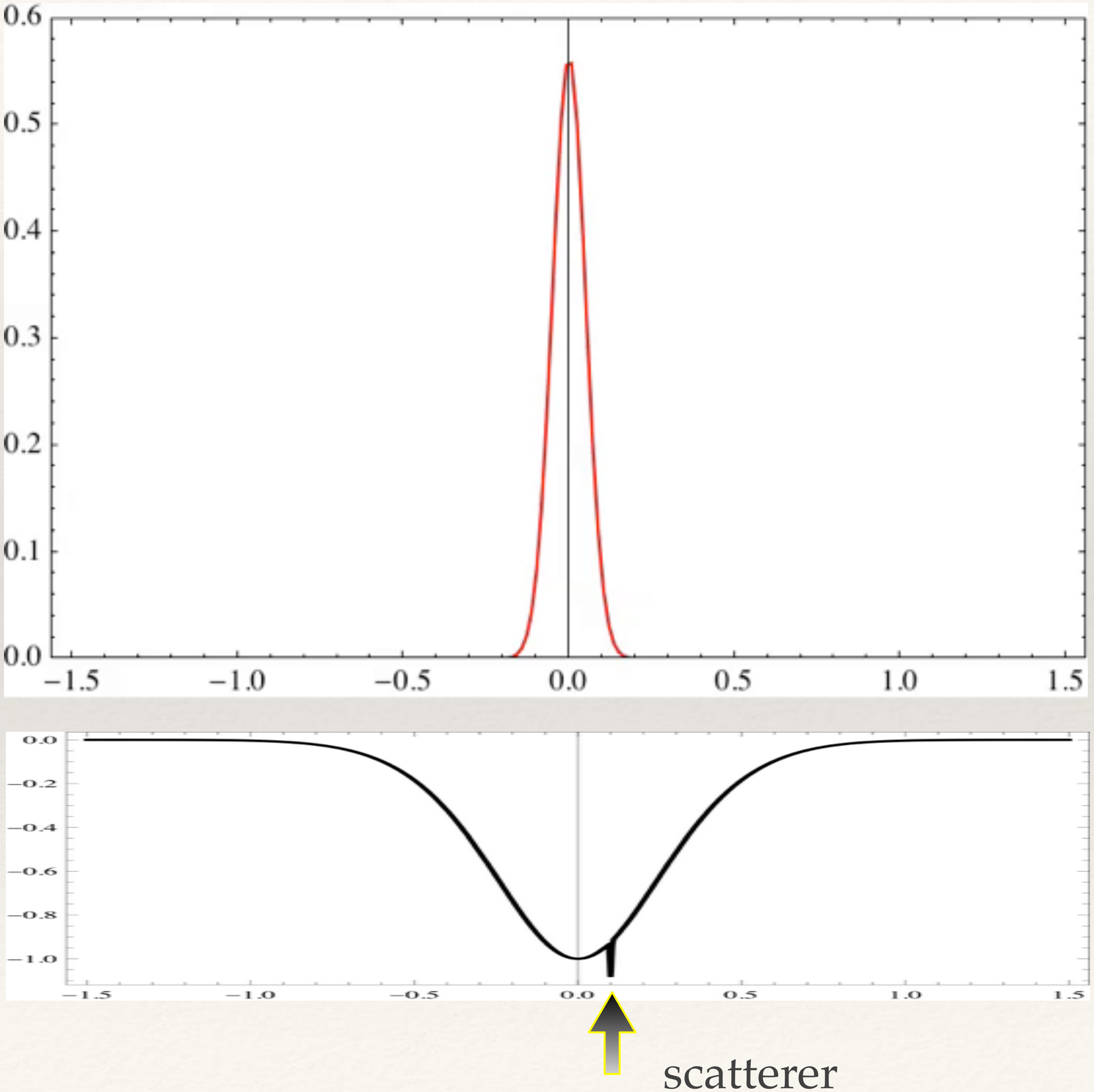
$$\begin{pmatrix} V_{hh} & V_{hl} \\ V_{lh} & V_{ll} \end{pmatrix} = U \begin{pmatrix} V_1 & 0 \\ 0 & 0 \end{pmatrix} U^\dagger$$

(MM, J Phys A 2010)

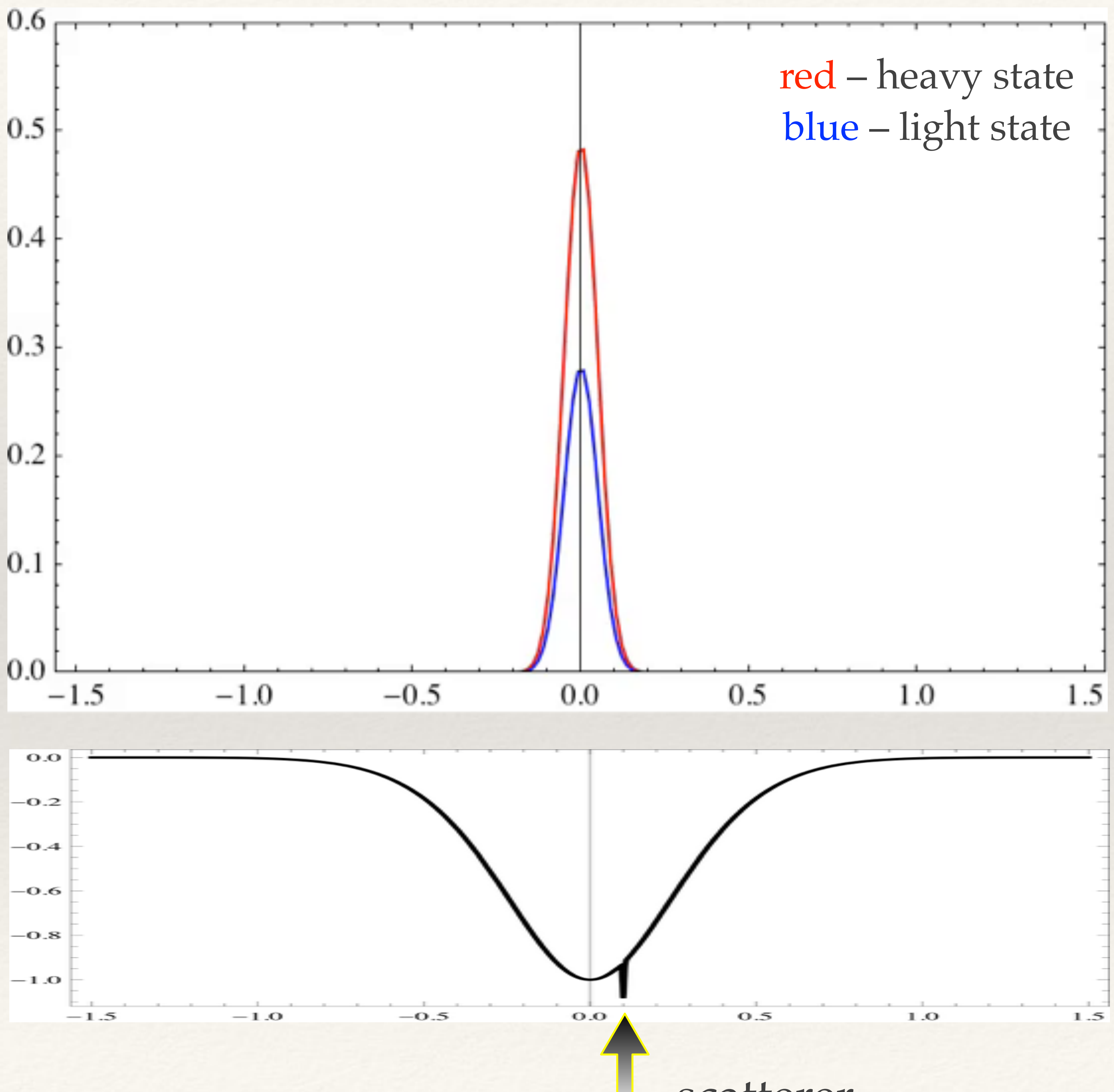
No flavor mixing case



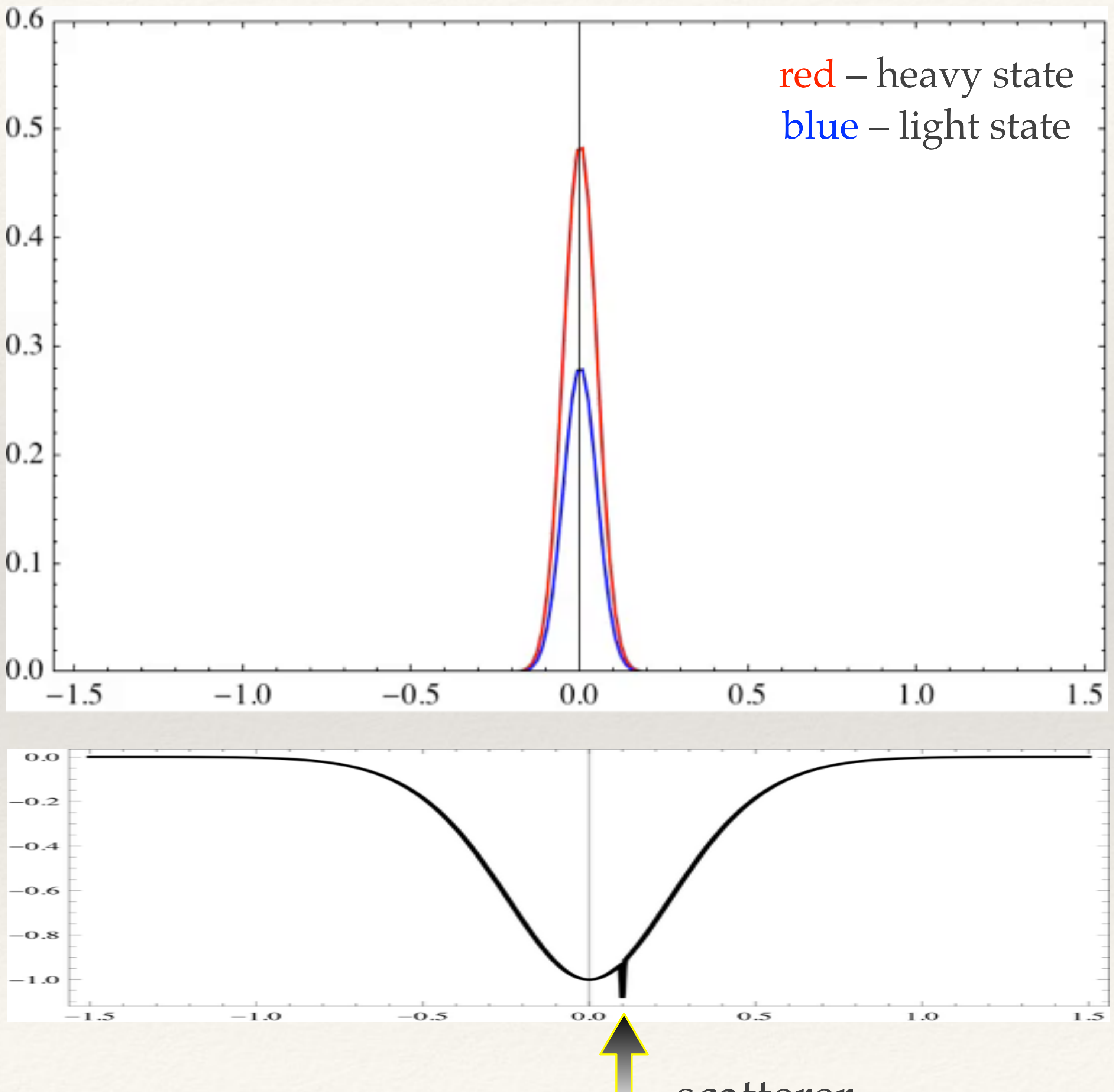
No flavor mixing case



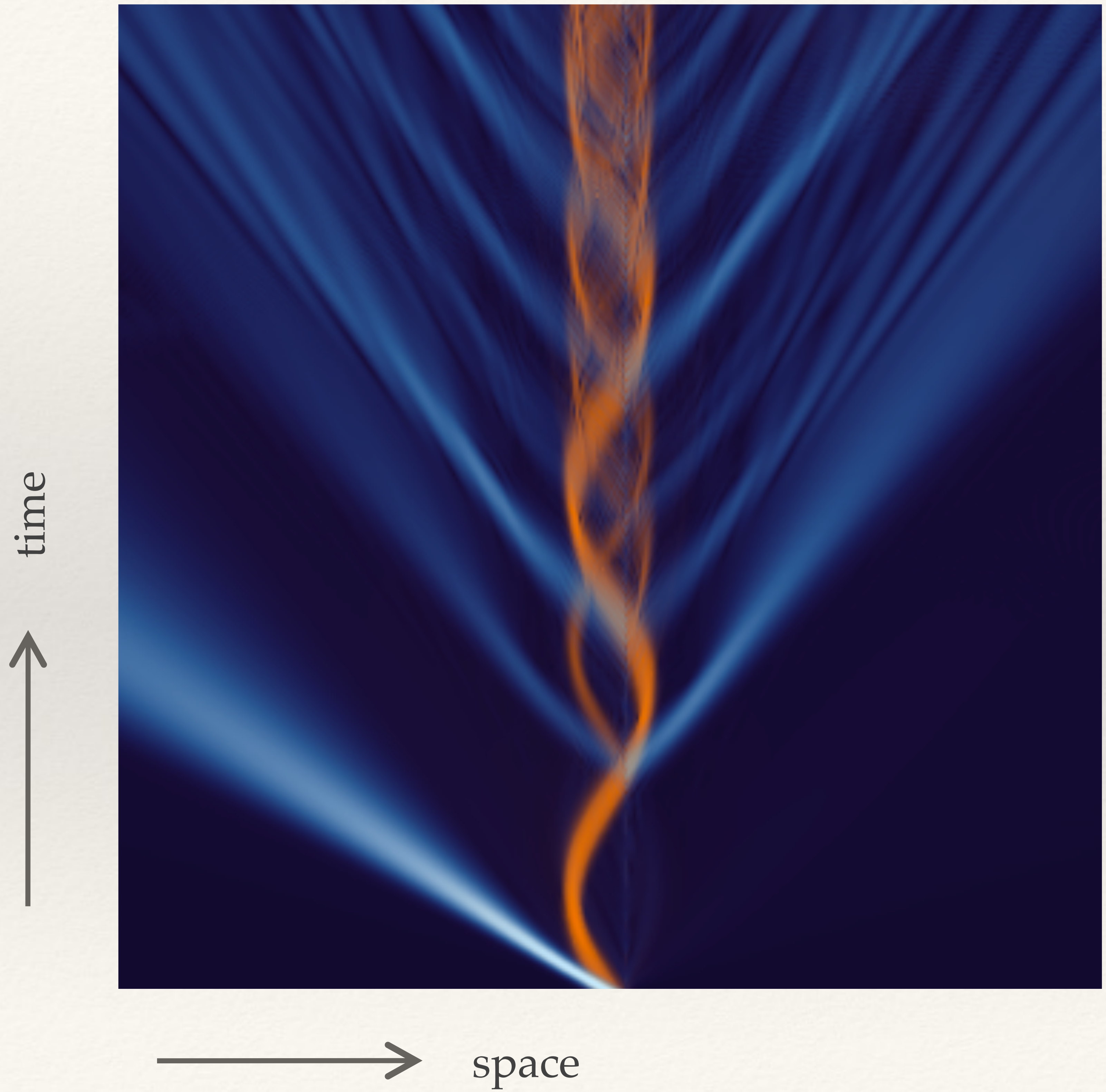
With flavor mixing



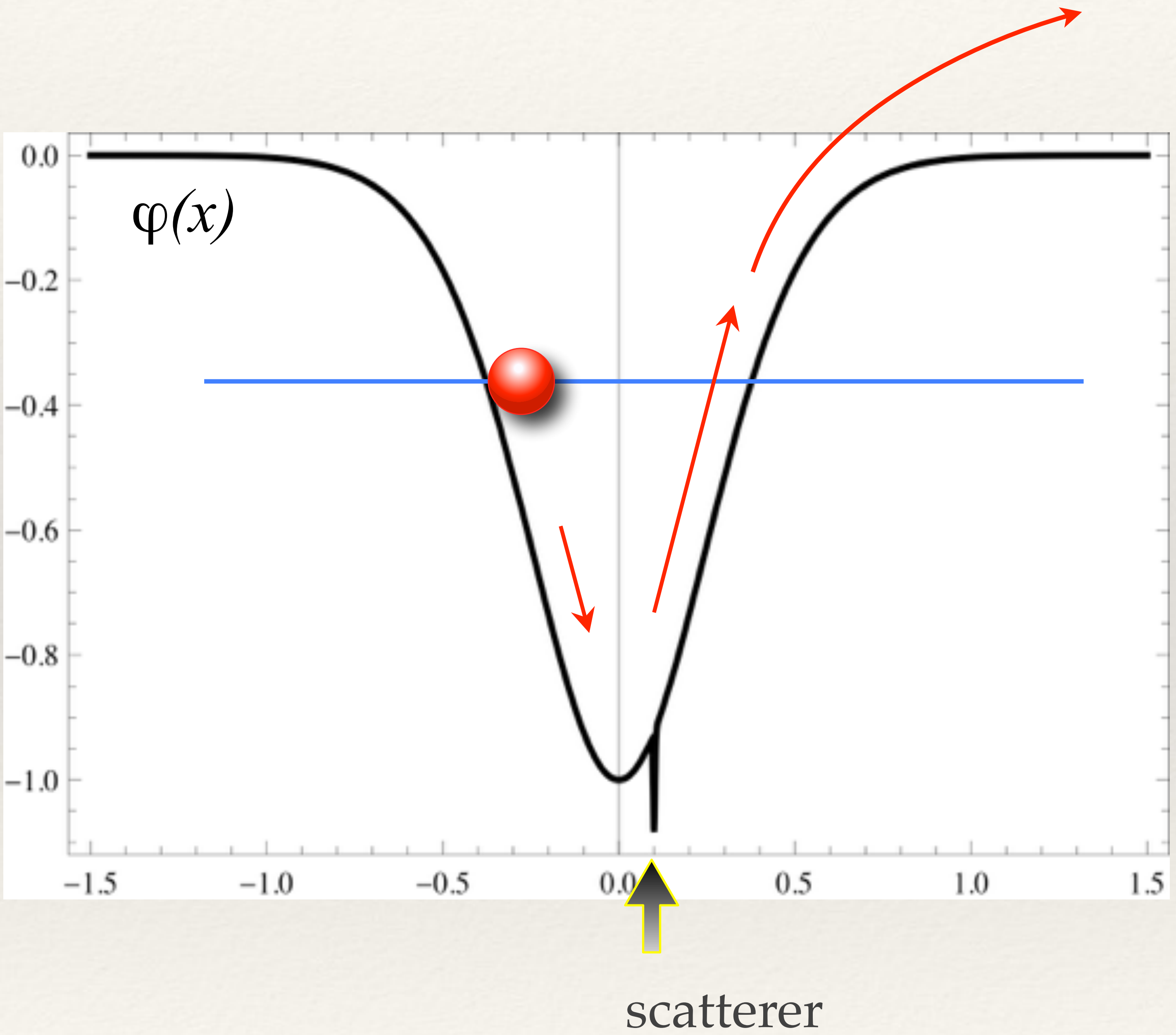
With flavor mixing



Space-Time diagram



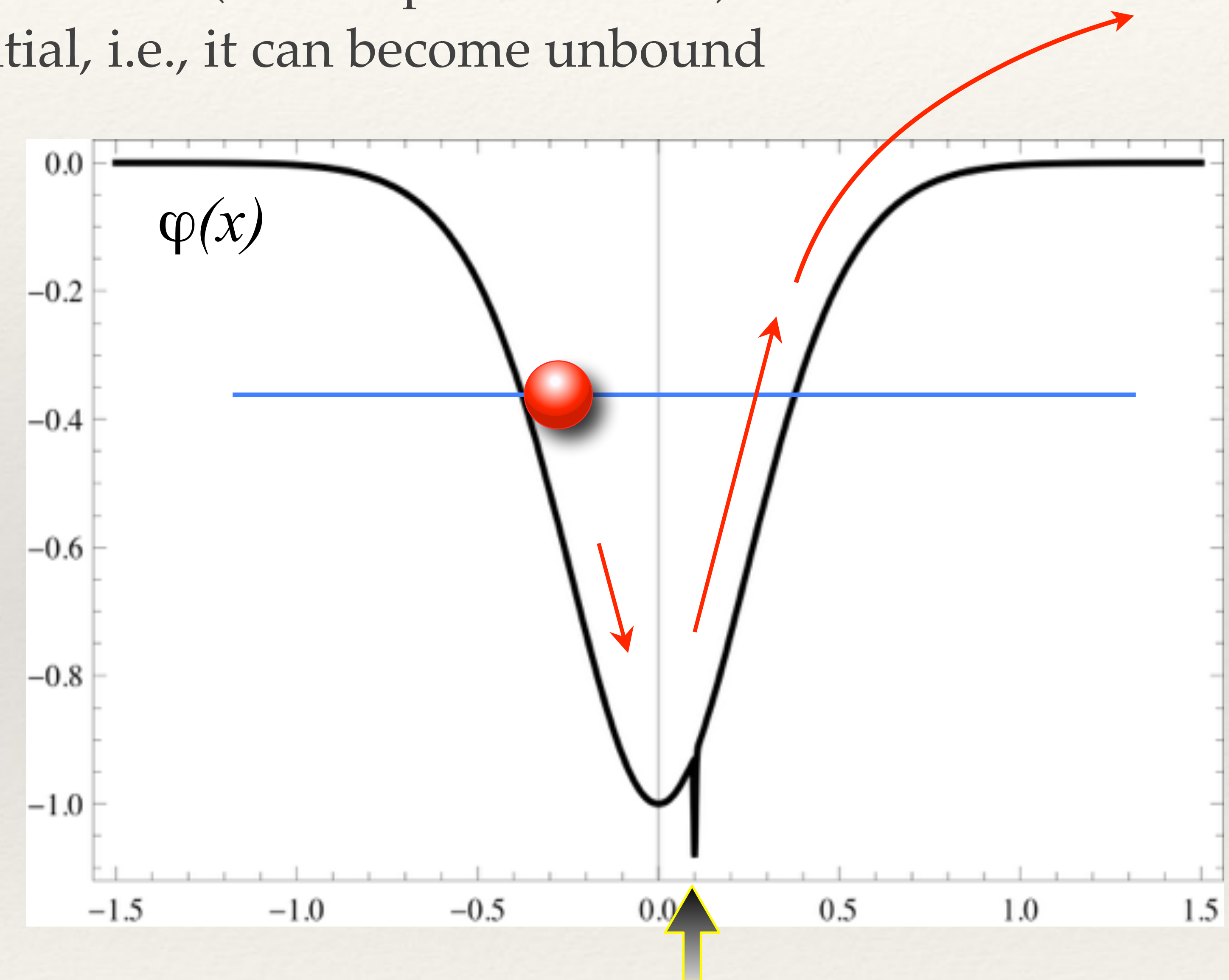
A trapped particle + scattering + flavor mixing



(MM, J Phys A 2010)

A trapped particle + scattering + flavor mixing

The particle can leak out of (or “evaporate” from) the gravitational potential, i.e., it can become unbound



scatterer

(MM, J Phys A 2010)

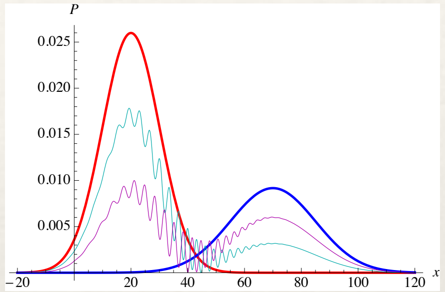
“Münchhausen effect”

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

2-component flavor-mixed DM (2cDM)

Dark Matter — stable 2-component mixed particle



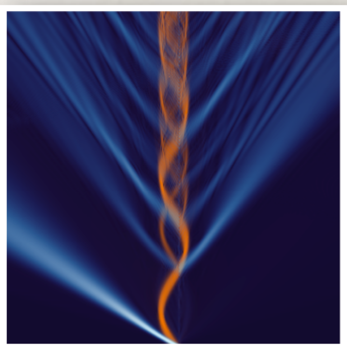
Neutralinos
Sterile neutrinos
Axion+photon
...

DM halos — self-gravitating ensembles of mass eigenstates

$|h\rangle$, $|l\rangle$

Mass-conversions and quantum evaporation

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

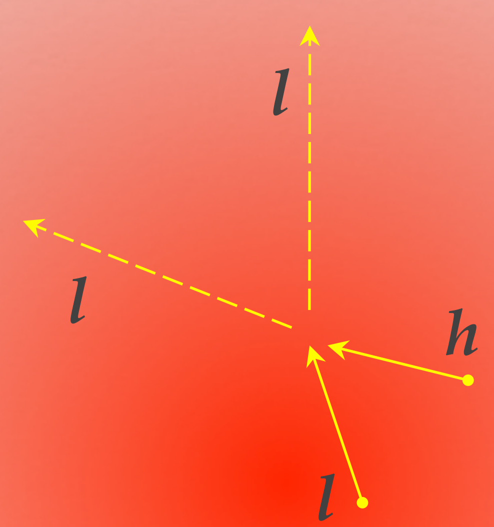


DM halos

Energy conservation:

$$2\ \tfrac{1}{2}(m_l\, v_l^{\,2}) = (m_h - m_l)\, c^2$$

$$v \sim v_{kick} = c\, (\Delta m/m_l)^{1/2}$$



if $v_{kick} \gg v_{escape}$

dwarf halos destroyed

if $v_{kick} \ll v_{escape}$

central cusps softened

(MM, J Phys A, 2010; JCAP 2014)

Technical: Interaction of 2-comp particles

Wave-functions

$$|ff\rangle \equiv \begin{pmatrix} \alpha\alpha \\ \alpha\beta \\ \beta\alpha \\ \beta\beta \end{pmatrix} \equiv \begin{pmatrix} \alpha_1\alpha_2(\mathbf{x}_1,\mathbf{x}_2,t) \\ \alpha_1\beta_2(\mathbf{x}_1,\mathbf{x}_2,t) \\ \beta_1\alpha_2(\mathbf{x}_1,\mathbf{x}_2,t) \\ \beta_1\beta_2(\mathbf{x}_1,\mathbf{x}_2,t) \end{pmatrix} \qquad |mm\rangle \equiv \begin{pmatrix} hh \\ hl \\ lh \\ ll \end{pmatrix} \equiv \begin{pmatrix} h_1h_2(\mathbf{x}_1,\mathbf{x}_2,t) \\ h_1l_2(\mathbf{x}_1,\mathbf{x}_2,t) \\ l_1h_2(\mathbf{x}_1,\mathbf{x}_2,t) \\ l_1l_2(\mathbf{x}_1,\mathbf{x}_2,t) \end{pmatrix}$$

Mixing

$$|ff\rangle = U_2\,|mm\rangle$$

$$U_2 \equiv U\otimes U = \begin{pmatrix} \cos^2\theta & -\cos\theta\,\sin\theta & -\cos\theta\,\sin\theta & \sin^2\theta \\ \cos\theta\,\sin\theta & \cos^2\theta & -\sin^2\theta & -\cos\theta\,\sin\theta \\ \cos\theta\,\sin\theta & -\sin^2\theta & \cos^2\theta & -\cos\theta\,\sin\theta \\ \sin^2\theta & \cos\theta\,\sin\theta & \cos\theta\,\sin\theta & \cos^2\theta \end{pmatrix}$$

Interaction

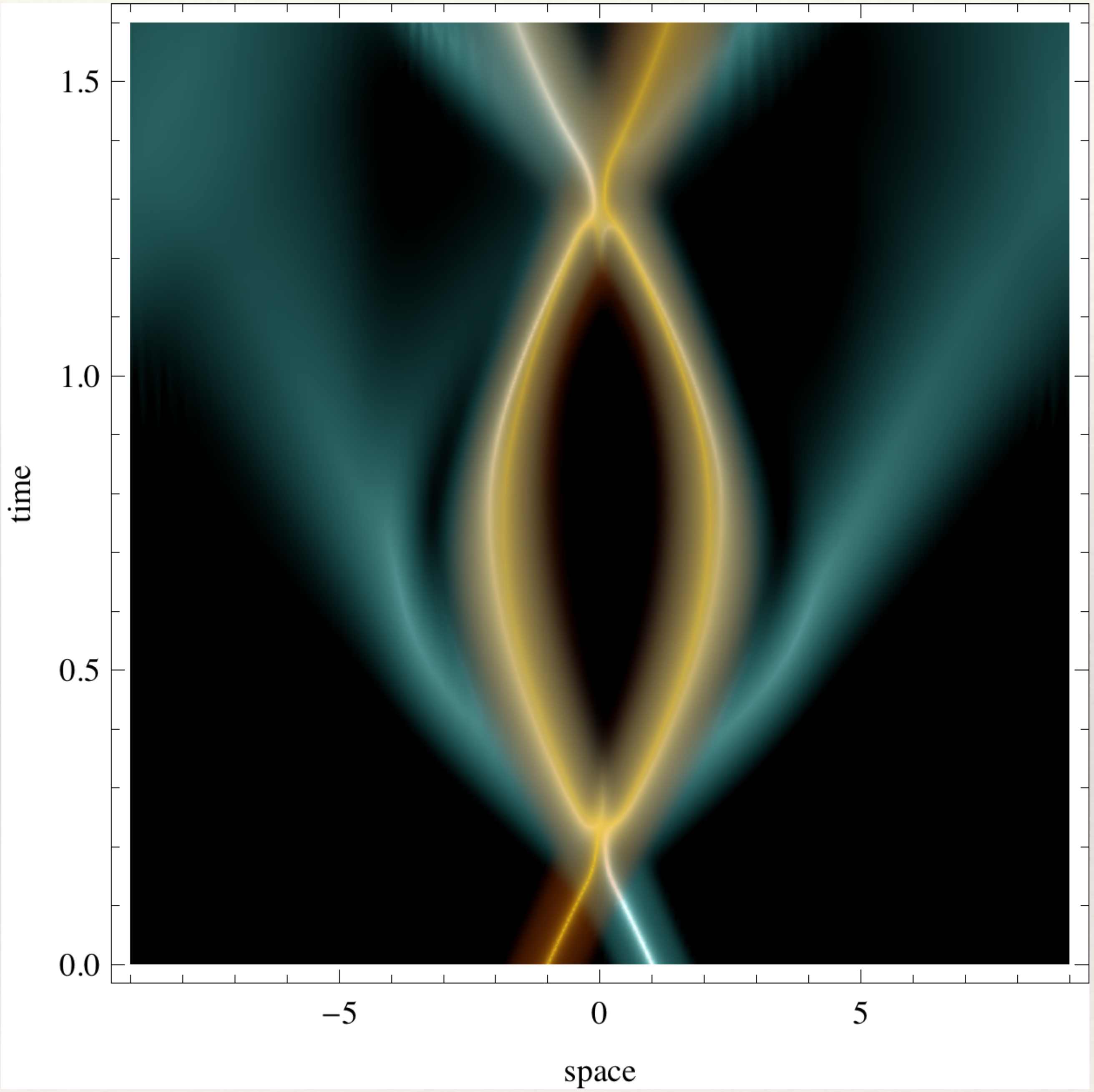
$$\tilde{V} = \begin{pmatrix} V_{\alpha\alpha} & 0 & 0 & 0 \\ 0 & V_{\alpha\beta} & 0 & 0 \\ 0 & 0 & V_{\beta\alpha} & 0 \\ 0 & 0 & 0 & V_{\beta\beta} \end{pmatrix}$$

$$V = U_2^\dagger \tilde{V} U_2 = \begin{pmatrix} A & E & E & D \\ E & C & D & F \\ E & D & C & F \\ D & F & F & B \end{pmatrix}$$

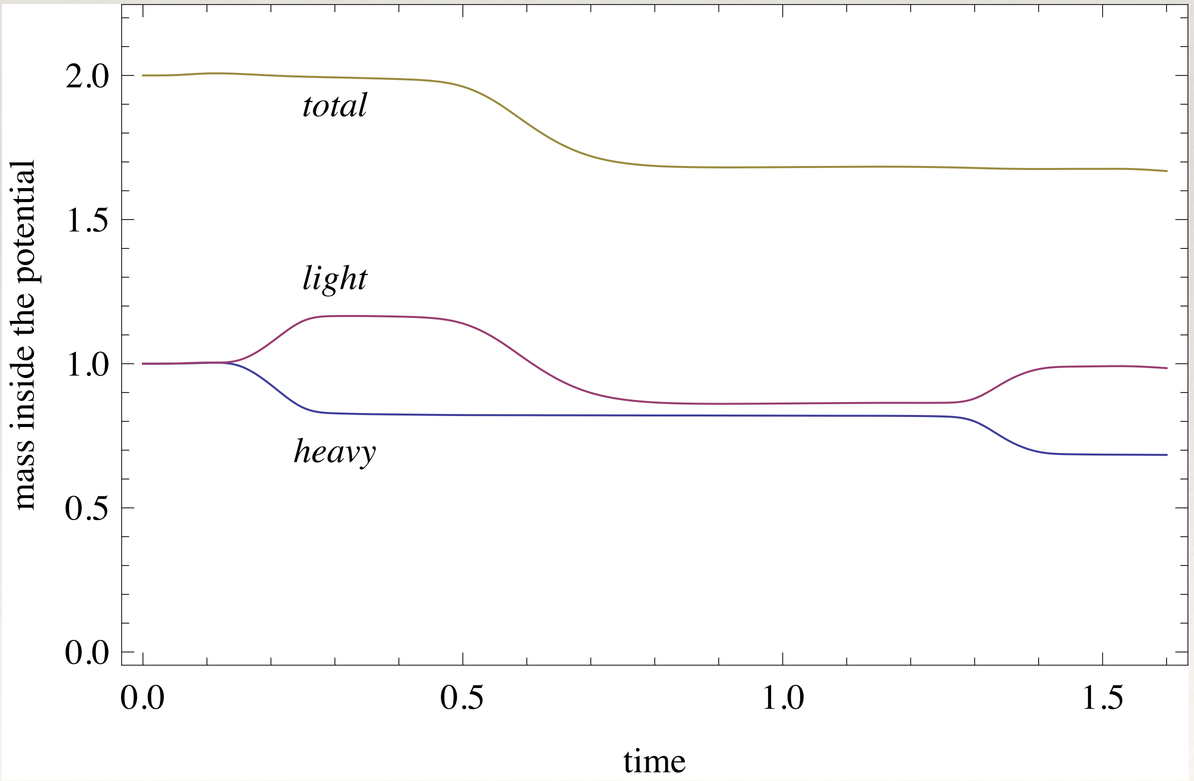
$$\begin{aligned}
A &= \tfrac{1}{8}\left[3V_{\alpha\alpha} + 2V_{\alpha\beta} + 3V_{\beta\beta} + 4(V_{\alpha\alpha} - V_{\beta\beta})\cos 2\theta + (V_{\alpha\alpha} - 2V_{\alpha\beta} + V_{\beta\beta})\cos 4\theta\right], \\
B &= \tfrac{1}{8}\left[3V_{\alpha\alpha} + 2V_{\alpha\beta} + 3V_{\beta\beta} - 4(V_{\alpha\alpha} - V_{\beta\beta})\cos 2\theta + (V_{\alpha\alpha} - 2V_{\alpha\beta} + V_{\beta\beta})\cos 4\theta\right], \\
C &= \tfrac{1}{8}\left[V_{\alpha\alpha} + 6V_{\alpha\beta} + V_{\beta\beta} - (V_{\alpha\alpha} - 2V_{\alpha\beta} + V_{\beta\beta})\cos 4\theta\right], \\
D &= \tfrac{1}{4}\left[V_{\alpha\alpha} - 2V_{\alpha\beta} + V_{\beta\beta}\right]\sin^2 2\theta, \\
E &= -\tfrac{1}{4}\left[V_{\alpha\alpha} - V_{\beta\beta} + (V_{\alpha\alpha} - 2V_{\alpha\beta} + V_{\beta\beta})\cos 2\theta\right]\sin 2\theta, \\
F &= -\tfrac{1}{4}\left[V_{\alpha\alpha} - V_{\beta\beta} - (V_{\alpha\alpha} - 2V_{\alpha\beta} + V_{\beta\beta})\cos 2\theta\right]\sin 2\theta,
\end{aligned}$$

(MM, JCAP 2014)

Complete evaporation of 2-comp. particles



$|h\rangle + |l\rangle \longrightarrow |l\rangle + |l\rangle$



(MM, JCAP 2014)

Implementation

- 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 $v_k = c(2\Delta m/m)^{1/2}$]

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

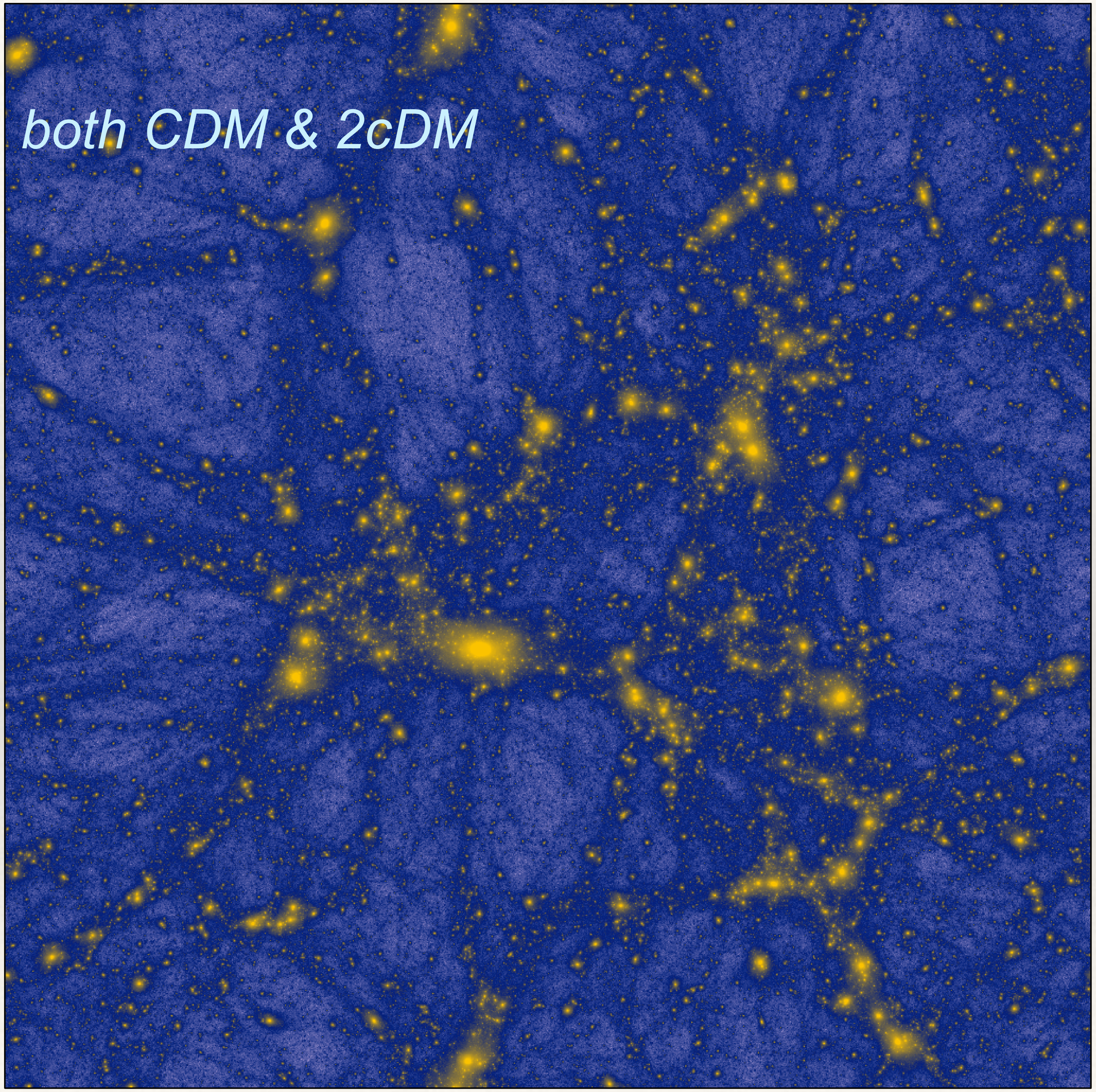
$$\sigma_{s_i t_i \to s_f t_f} = \sigma_{\rm si}(v) = \sigma\,(v/v_0)^{-a}$$

$$a = 1$$

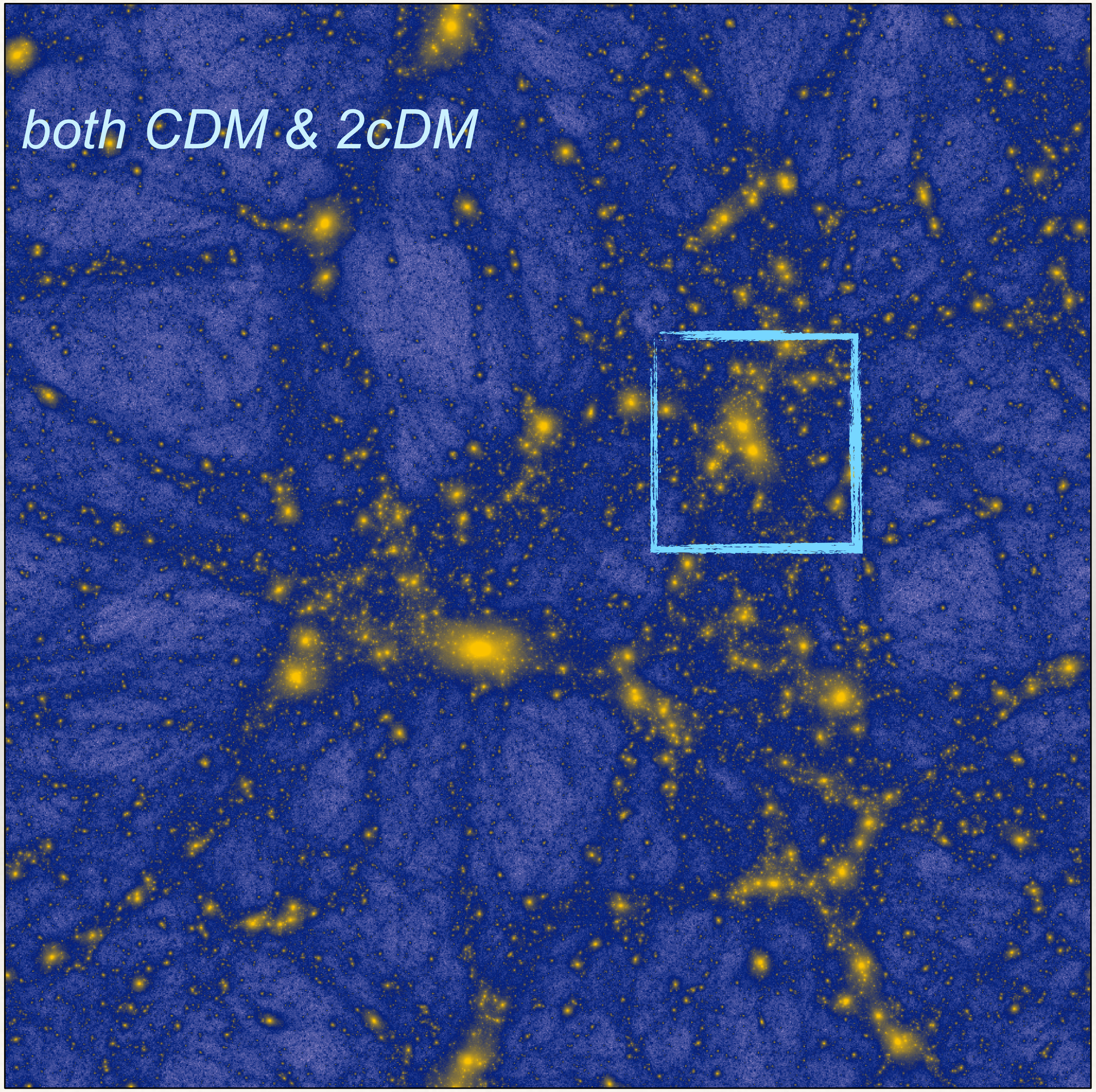
No change on large scales

CDM

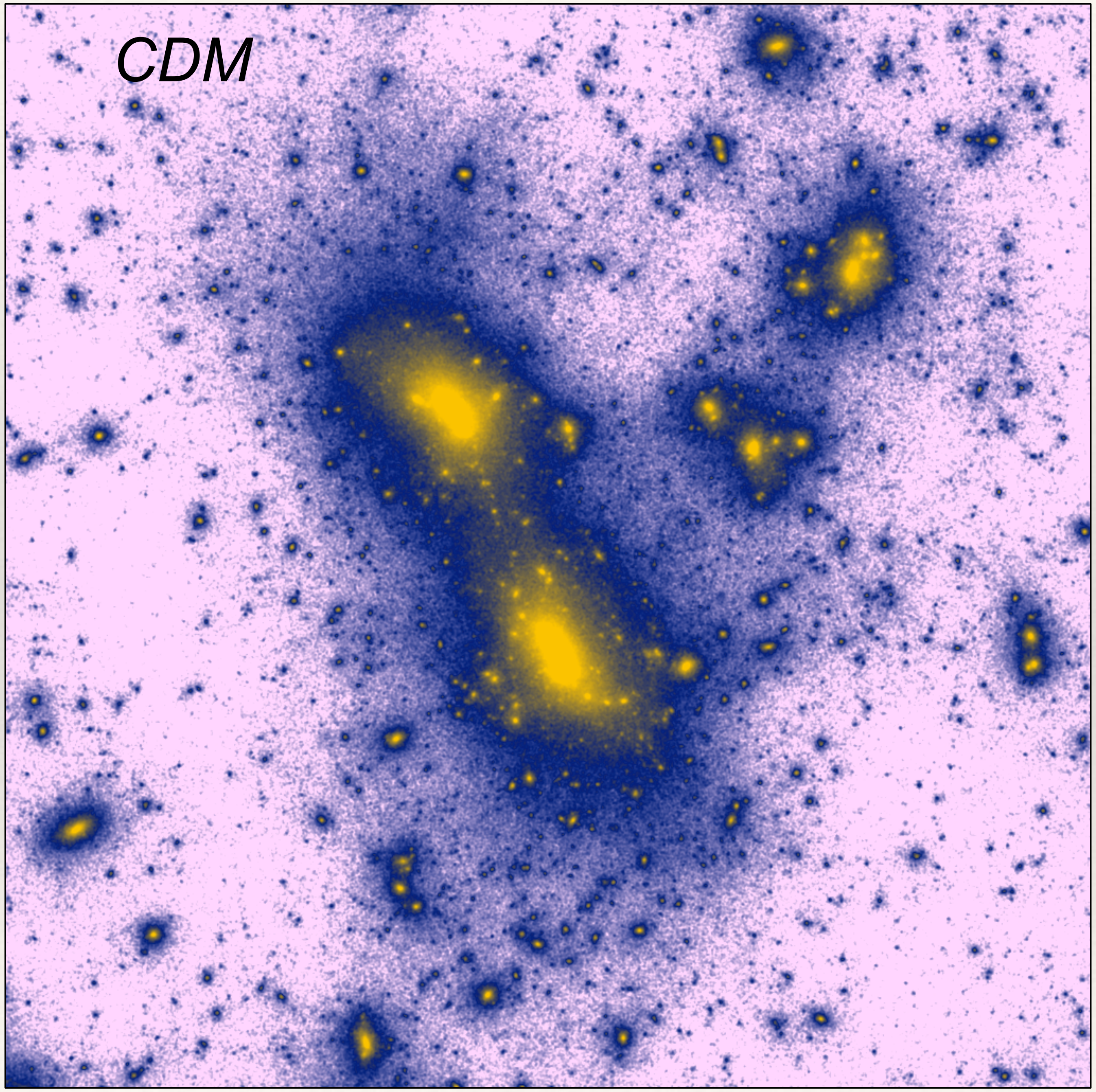
No change on large scales



No change on large scales

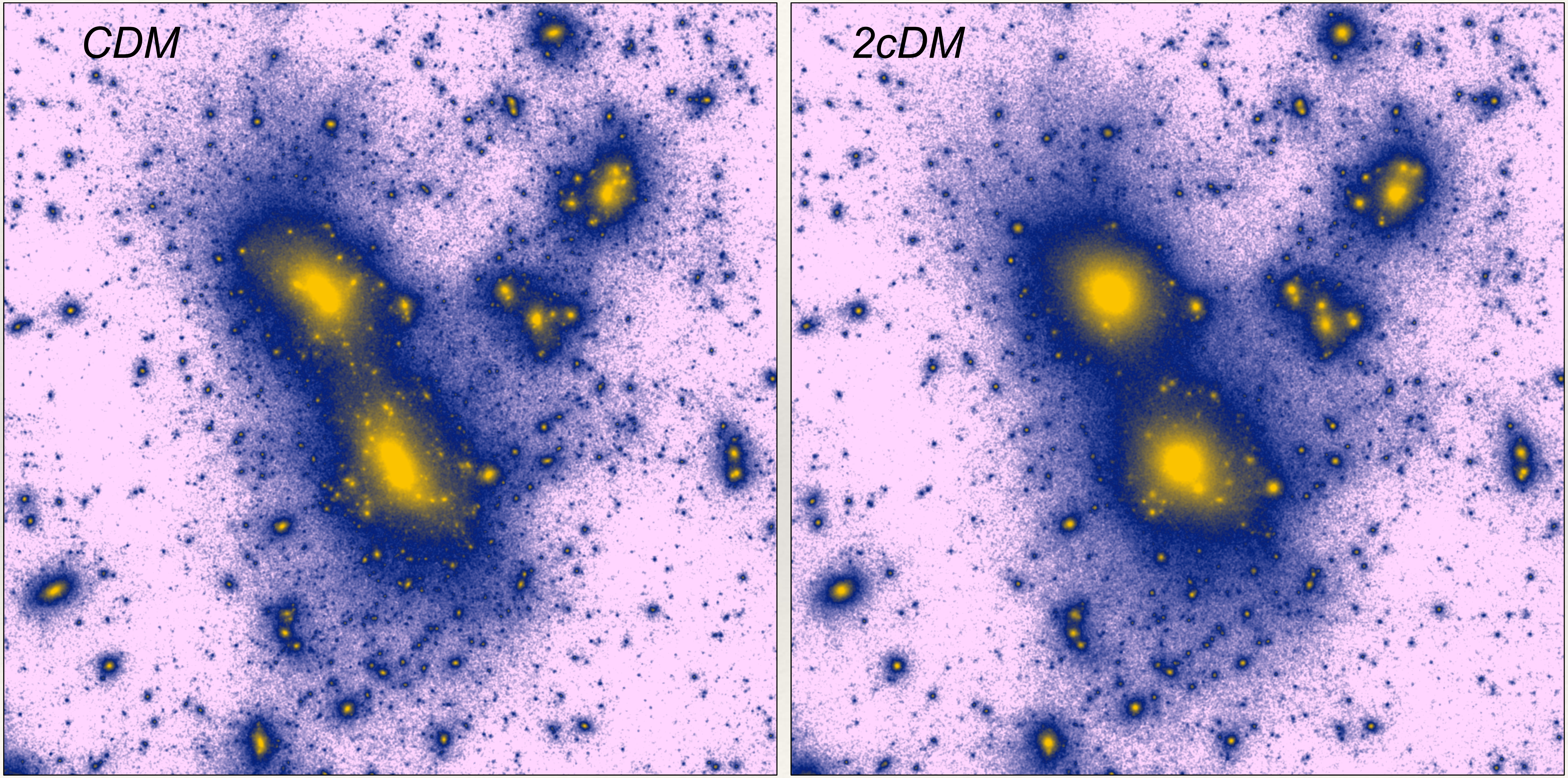


Less substructure on small scales



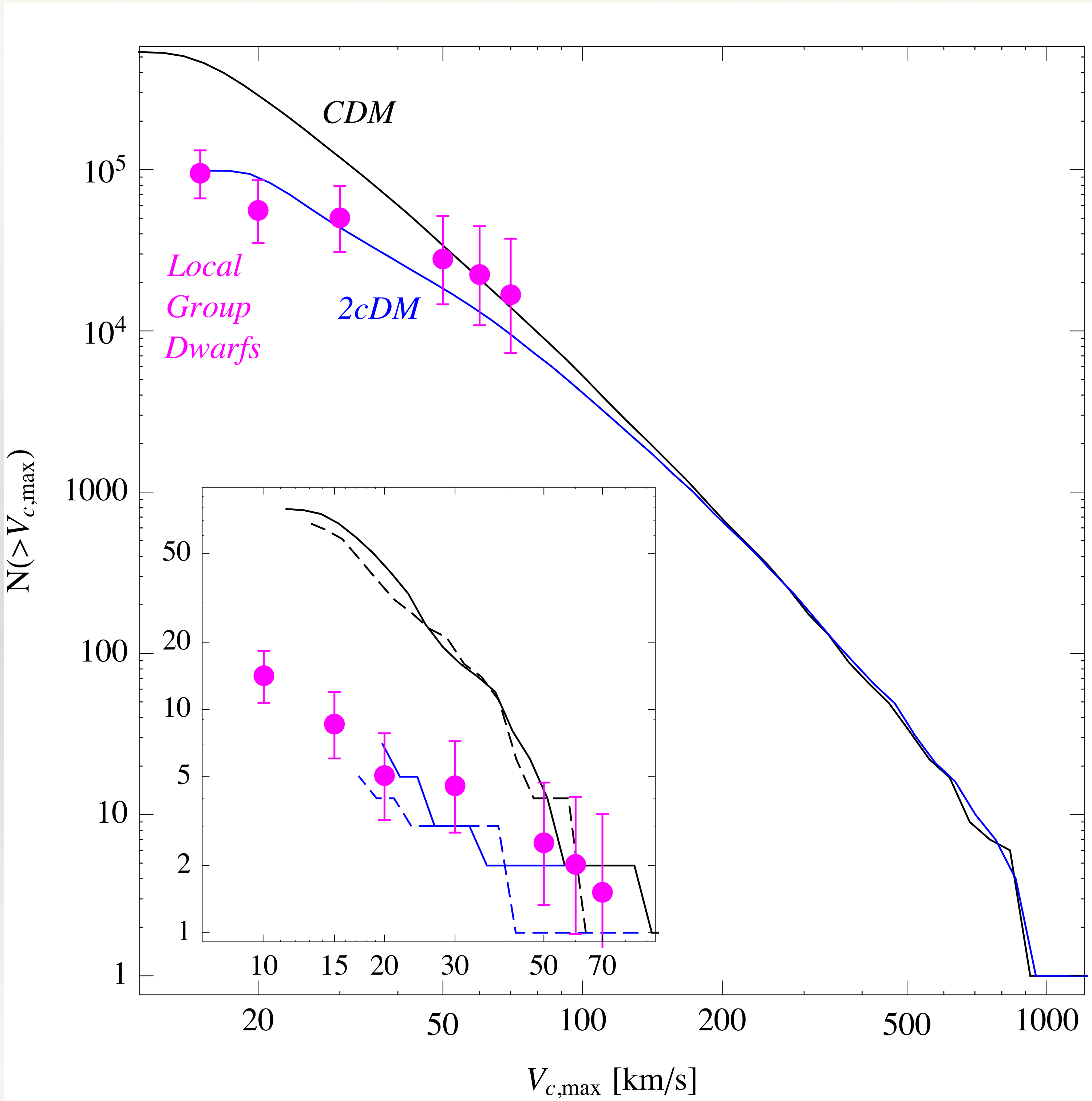
(MM, PRL 2014)

Less substructure on small scales



(MM, PRL 2014)

Velocity function

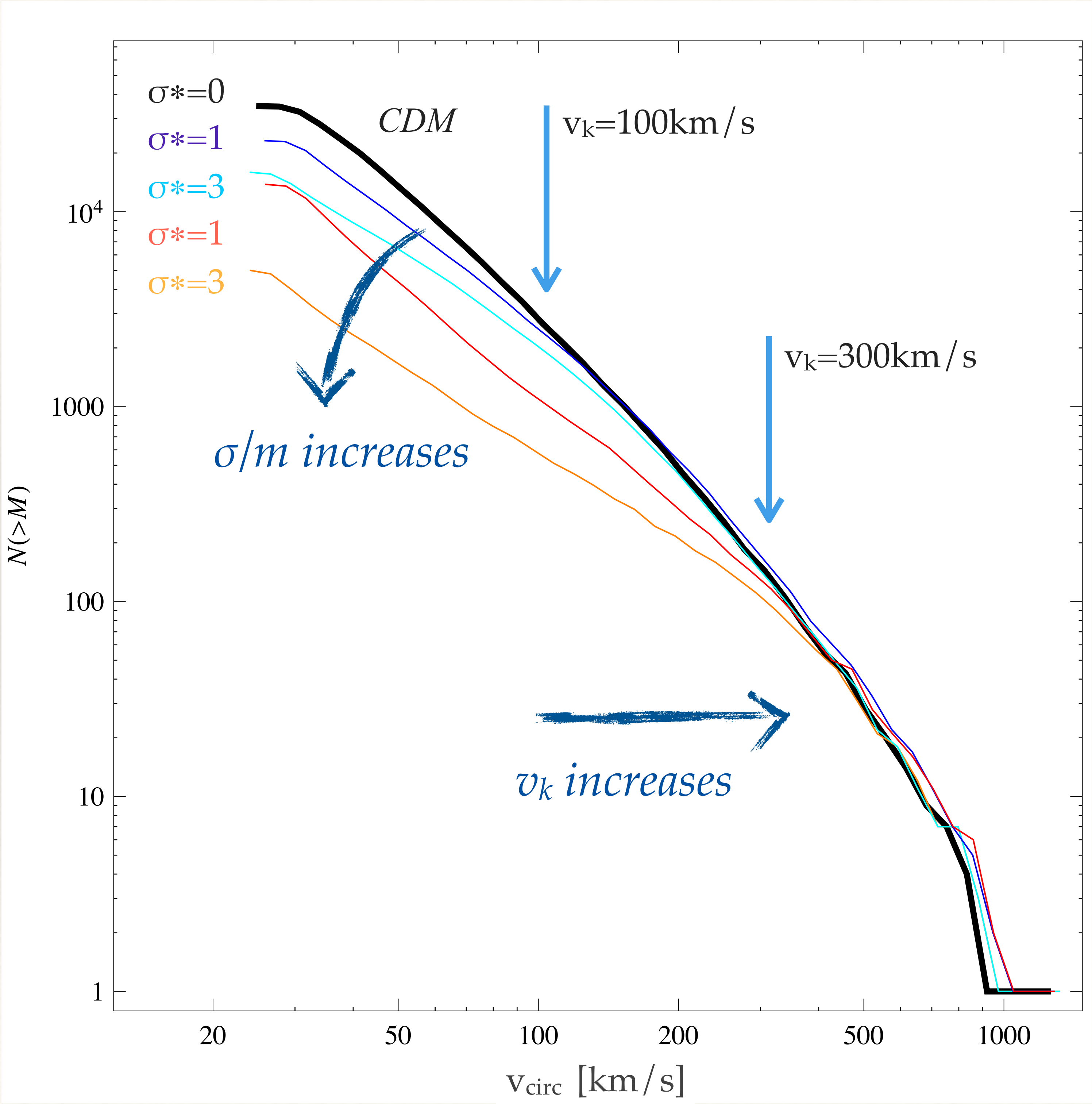


σ_*=0.75 cm²/g
v_k=50 km/s

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

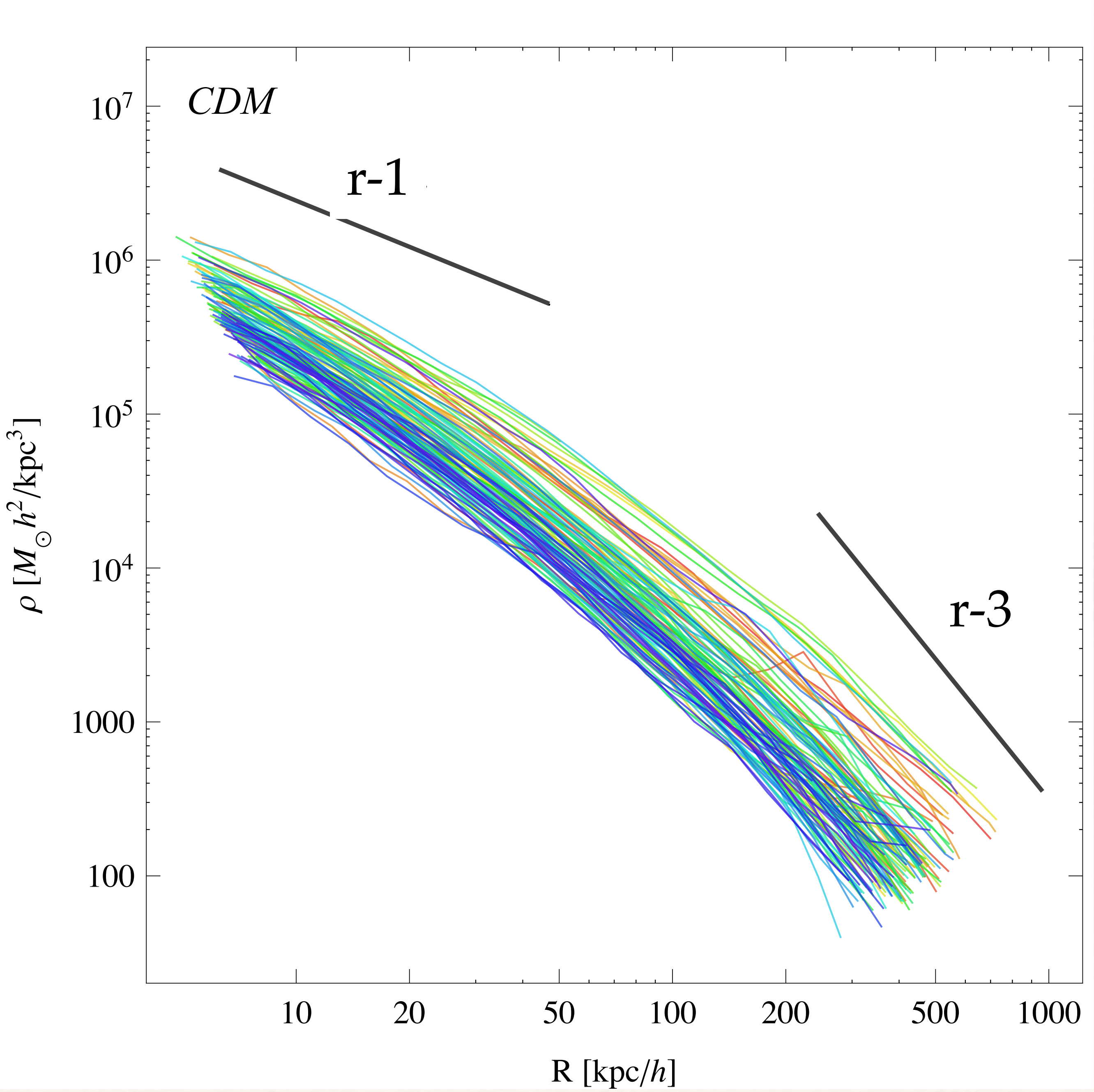
(MM, PRL 2014)

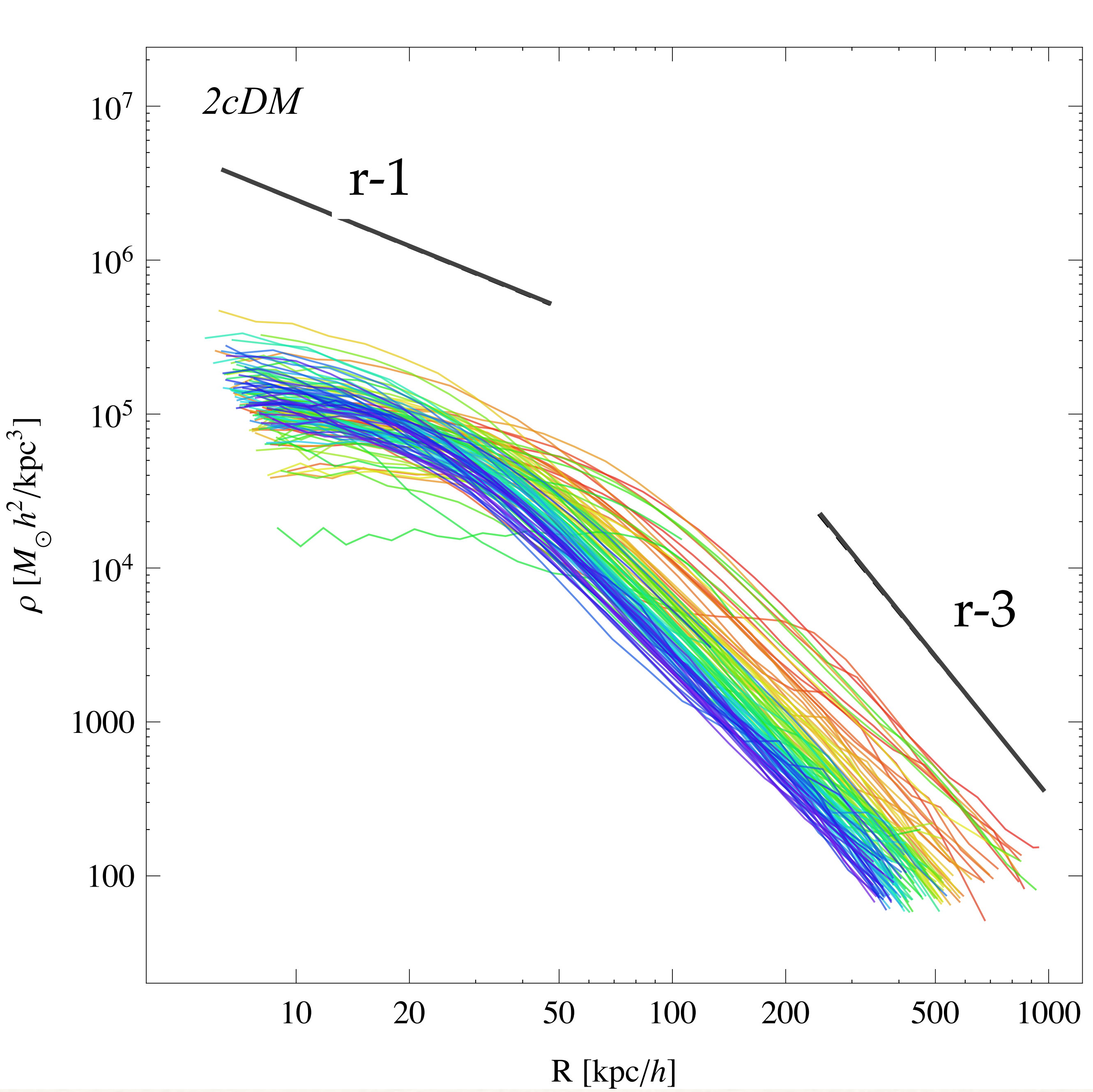
Key parameters



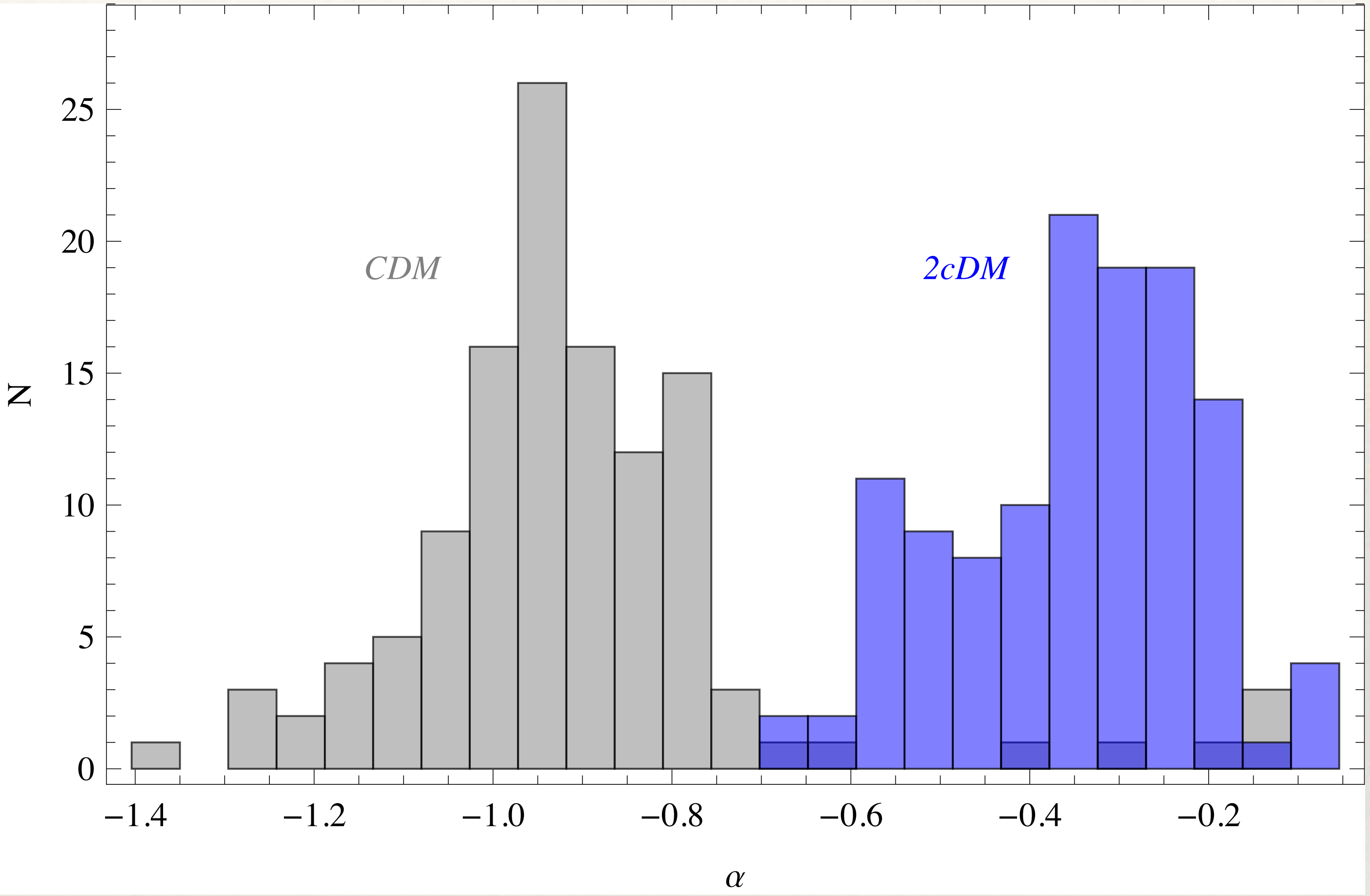
$v_k = c(2\Delta m/m)^{1/2}$
$\sigma_* = \sigma/m$

Density profiles





Slopes of density profiles



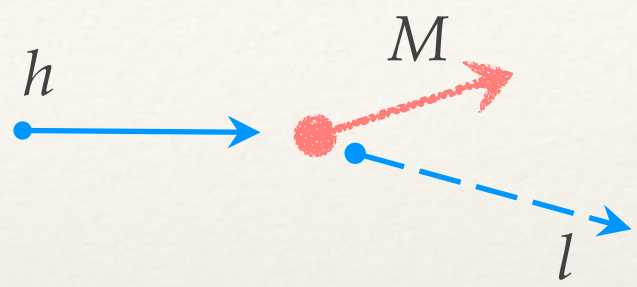
We fit density profiles with function
$\rho = r^{\alpha}/(1+r^{\beta})$ and evaluating α at $r = 7$ kpc/h

(MM, PRL 2014)

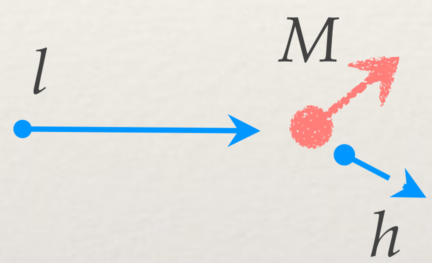
2cDM predictions

direct detection

“inelastic recoil”



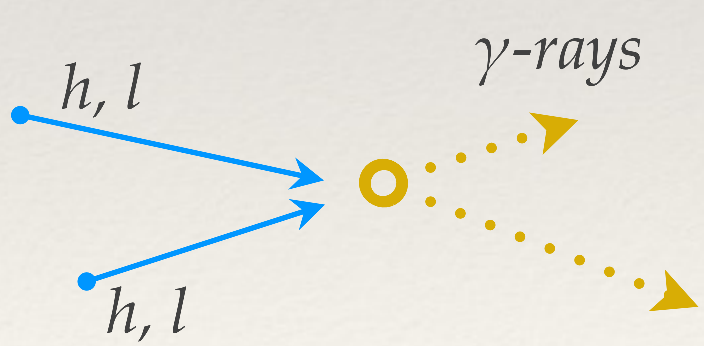
$+ \Delta mc^2$



$- \Delta mc^2$

indirect detection

“γ-ray annihilation
line triplet”



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

100 GeV ± ~ keV

(MM, PRL 2014)

2cDM vs SIDM

$\sigma_{conv}(v)$ — determines slope
$\sigma_{scatt}(v)$ — determines core
$\Delta m/m$ (or v_k) — determines break

$\sigma(v)$ — determines cores
-- nothing can reduce substructure

-- gravi-thermal collapse
- stronger cusps r^{-2} unless fine tune $\sigma(v)$ - H_0

How robust is the model?

How robust is the 2cDM model?

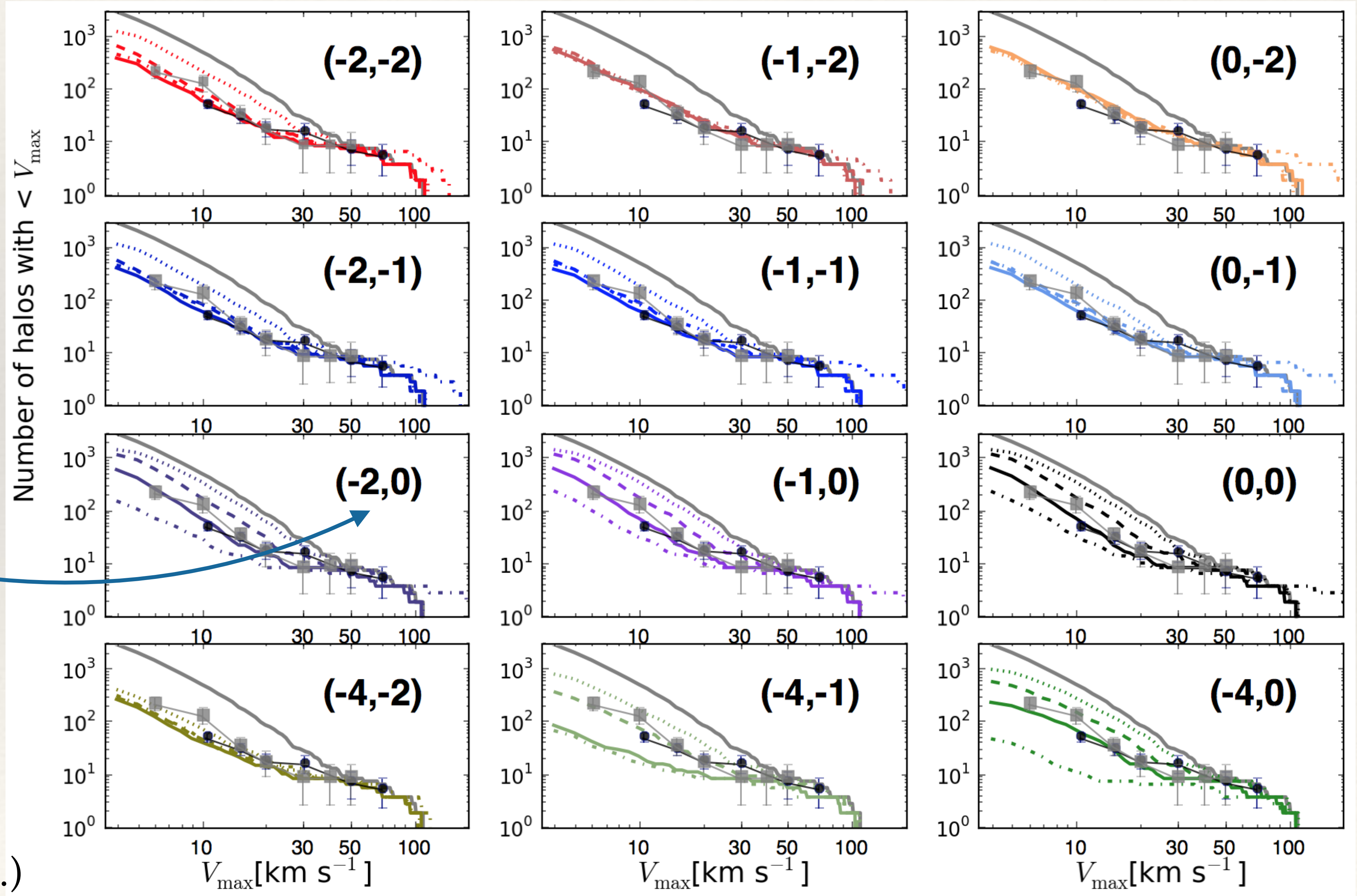
$$\sigma(v) = \begin{cases} \sigma(v/v_0)^{a_s} & \text{for scattering} \\ \sigma(v/v_0)^{a_c} & \text{for conversion} \end{cases}$$

SUBSTRUCTURE

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

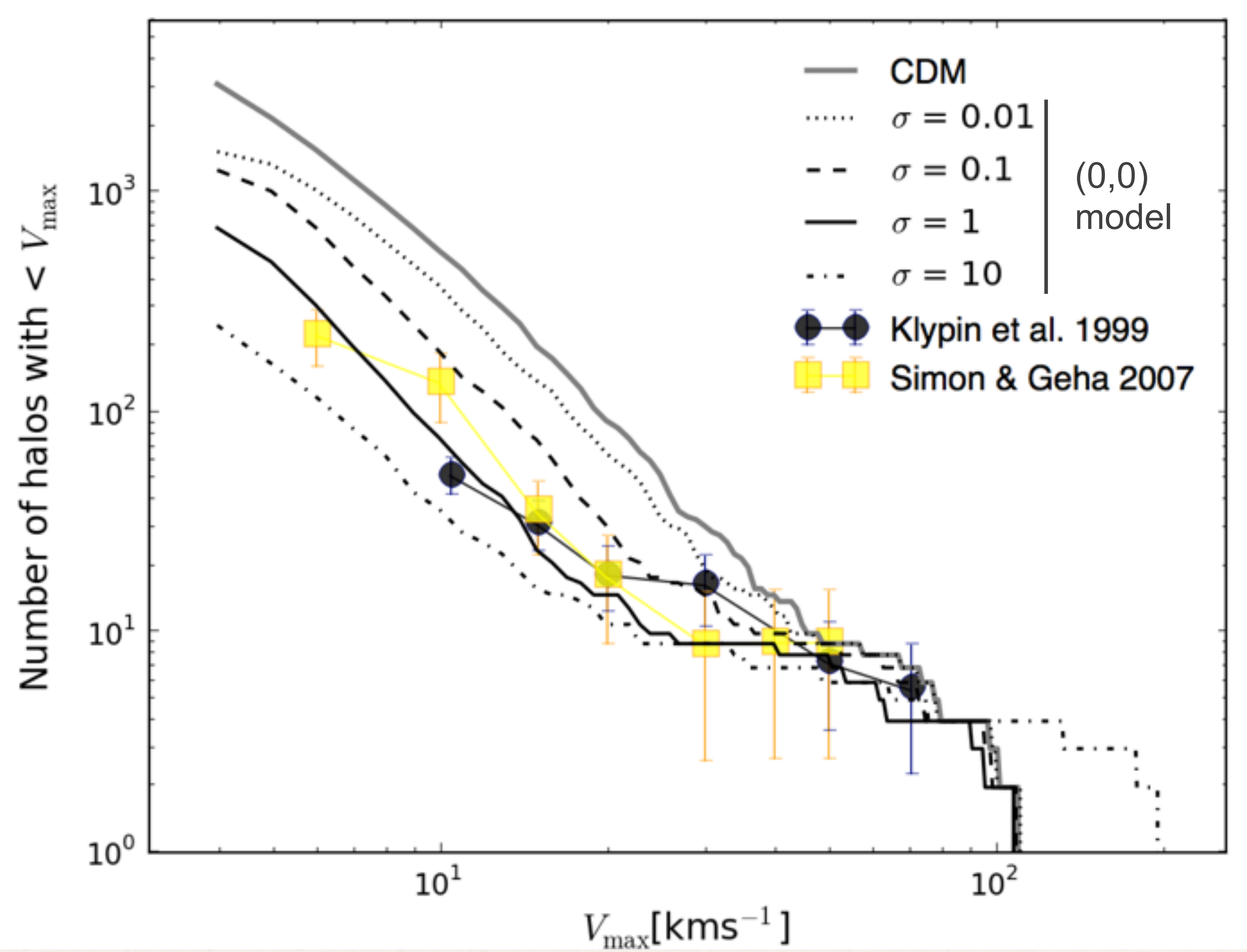
consistent with observations

(a_s, a_c)



(Todoroki & MM, in prep.)

Just one example



$M_{vir} \sim 10^8\, M_\odot$ $M_{vir} \sim 10^{11}\, M_\odot$

(Todoroki & MM, in prep.)

How robust is the 2cDM model?

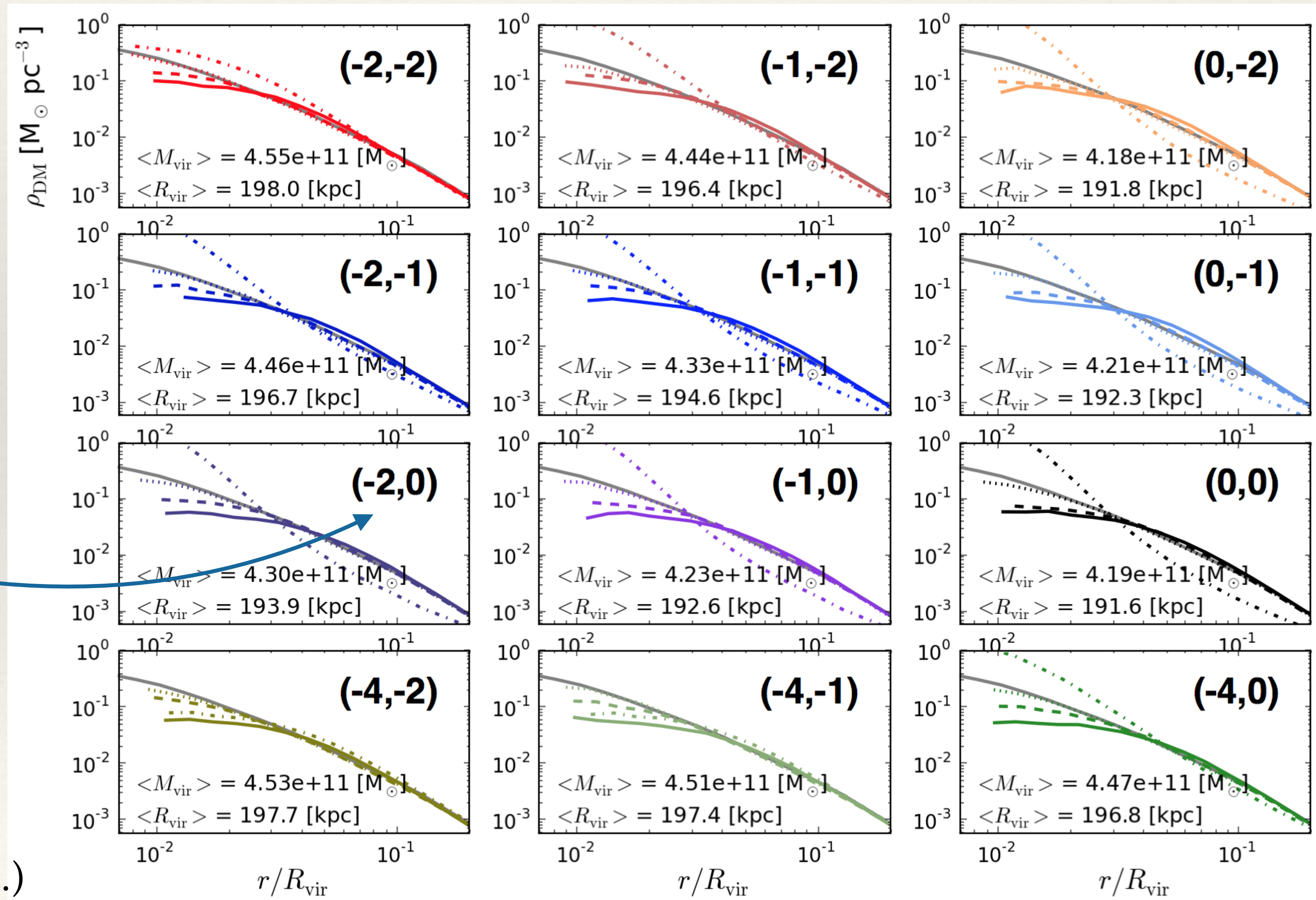
$$\sigma(v) = \begin{cases} \sigma(v/v_0)^{a_s} & \text{for} \quad \text{scattering} \\ \sigma(v/v_0)^{a_c} & \text{for} \quad \text{conversion} \end{cases}$$

PROFILES

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

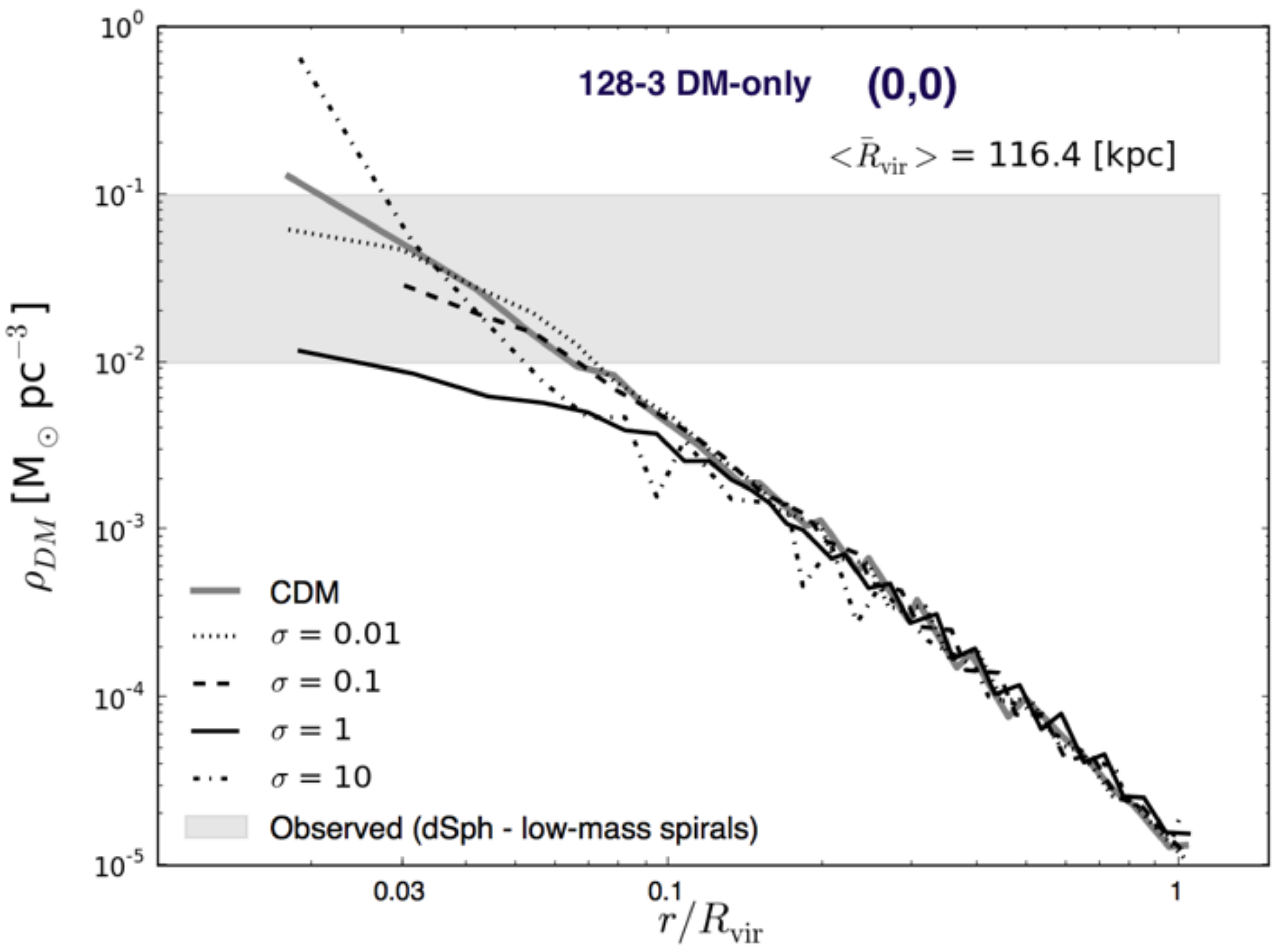
consistent with observations

(a_s, a_c)



(Todoroki & MM, in prep.)

Just one example



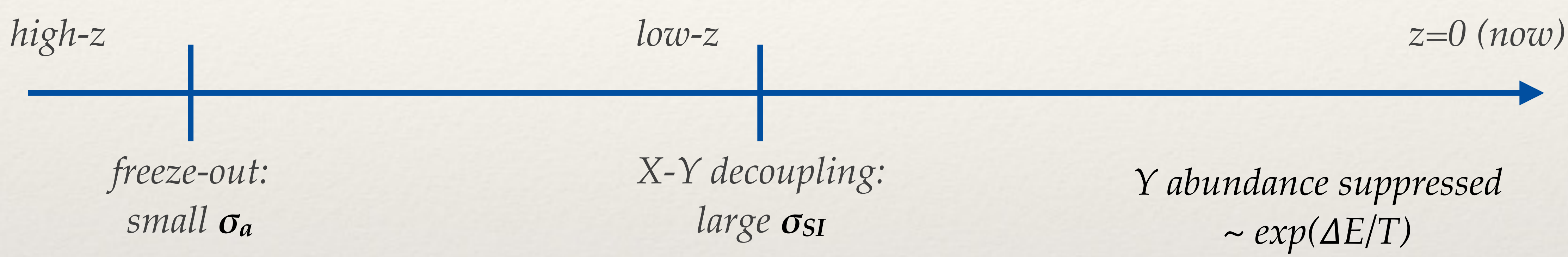
(Todoroki & MM, in prep.)

2cDM vs others

2cDM looks like any multi-species/composite DM -- allows "reactions" Y→X

excited, inelastic, exothermal DM,...

early universe "catastrophe"



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

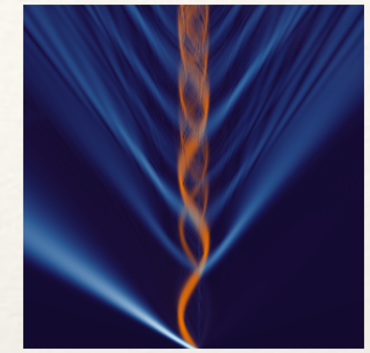
$$\sigma_{\rm conv}^{\rm fst} \sim (\Delta m/m)^4 \sigma_{\rm conv}$$

before structure formation

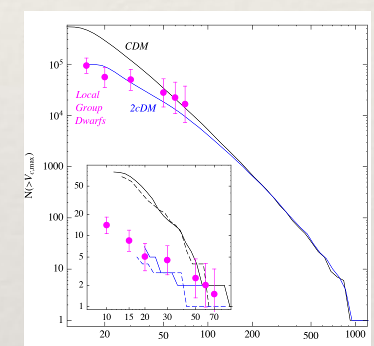
after structure formation

(MM, JCAP 2014)

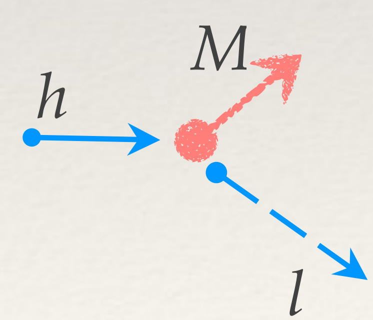
Conclusions



- **“quantum evaporation”** – a new effect (MVM 2010)
- **2cDM:**
  - can solve all small-scale problems simultaneously
  - $\sigma(v) \sim 0.1...0.01$ – consistent with all constraints
  - $\Delta m/m \sim 10^{-8}$ ⇔ $v_k \sim$ 50-100 km/s



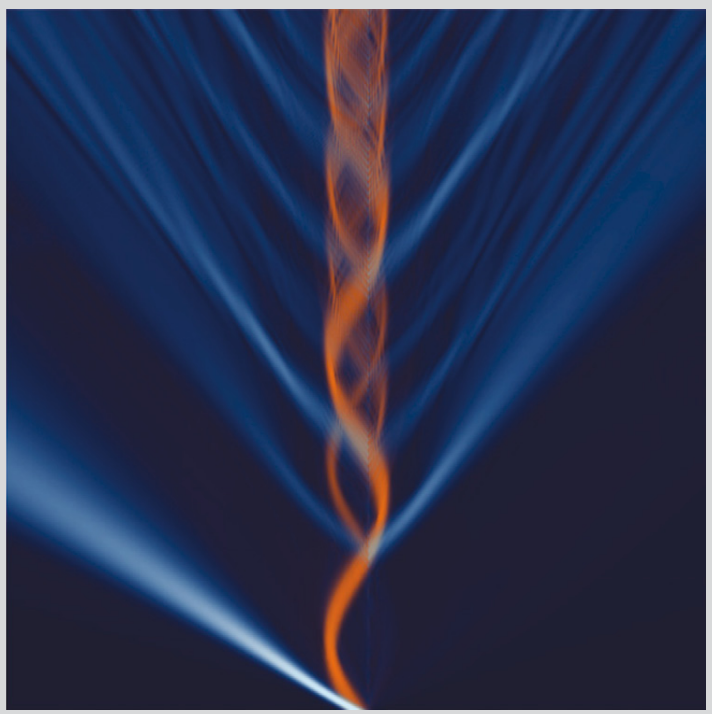
- **2cDM predicts**
  - break in mass function: suppression at $M_{vir} \leq 10^{10} M_\odot$
  - *inelastic* recoils with $\Delta E \sim \Delta mc^2$ in direct detection DM
  - γ-ray annihilation line *triplet* with $\Delta E_\gamma = ½\, \Delta mc^2$,
    (if $m_\chi \sim$ 100 GeV, then $\Delta E_\gamma \sim \Delta m \sim$ keV)
  - direct detection DM recoil may depend on target species



ISSN 1751-8113

Journal of Physics A
Mathematical and Theoretical

Volume 43 Number 37 17 September 2010



iopscience.org/jphysa

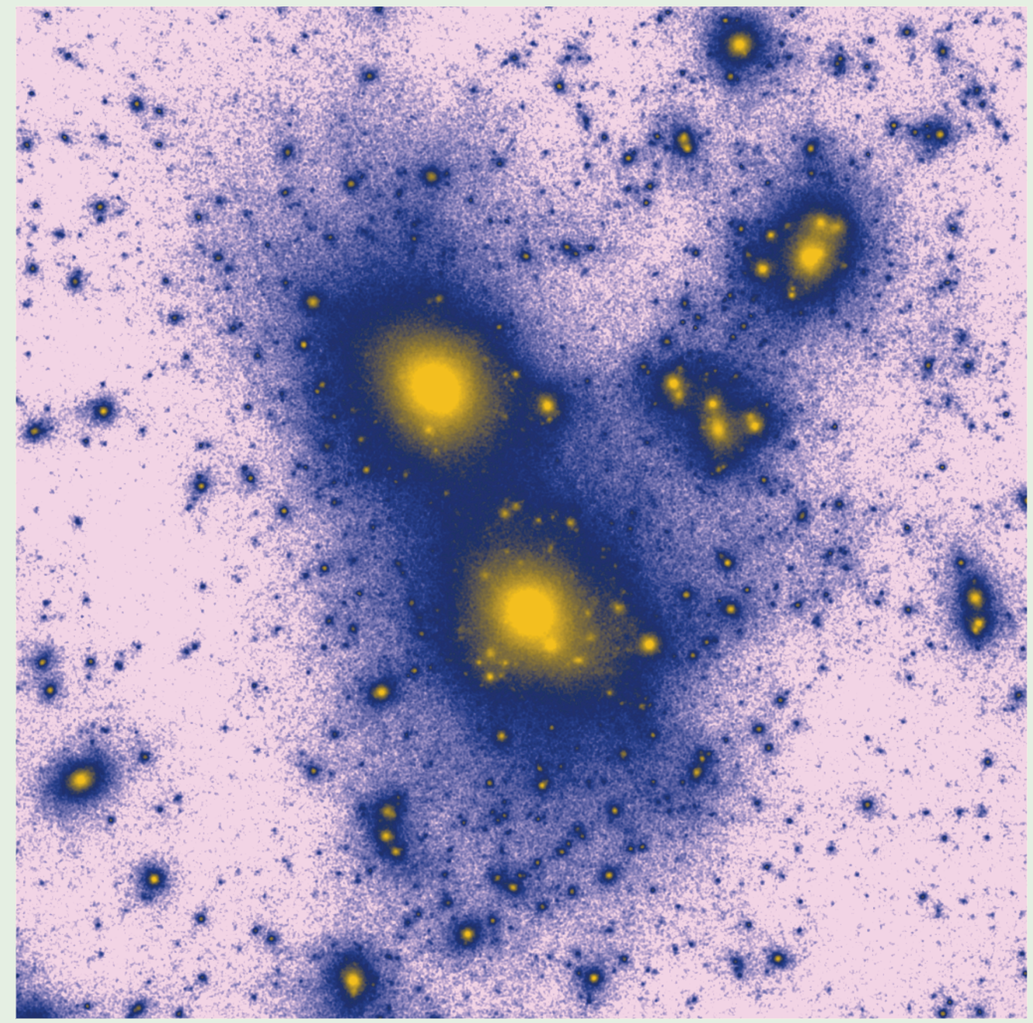
IOP Publishing

113

Physical Review Letters™

Articles published week ending 15 August 2014

PRL 113 (7), 070201–079901, 15 August 2014 (256 total pages)



7

Published by
American Physical Society™

APS physics

Volume 113, Number 7