Cosmological Simulations with 2-component CDM

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Ripples in the Cosmos, Durham University, UK 22/7/13

Dark Matter

m

T

σ

flavor

Flavor

$$i\hbar\,\partial_t \Psi = (H+V)\Psi$$

propagation (H) — interaction (V)

- Flavor is a quantum number relevant for particle interactions
- Mass is a property which determines particle propagation

Superposition

Any wave function satisfying the Schrödinger equation

$$i\hbar\, \partial_t\, \Psi = (H+V)\Psi$$

can be written as a superposition of a full set of basis functions

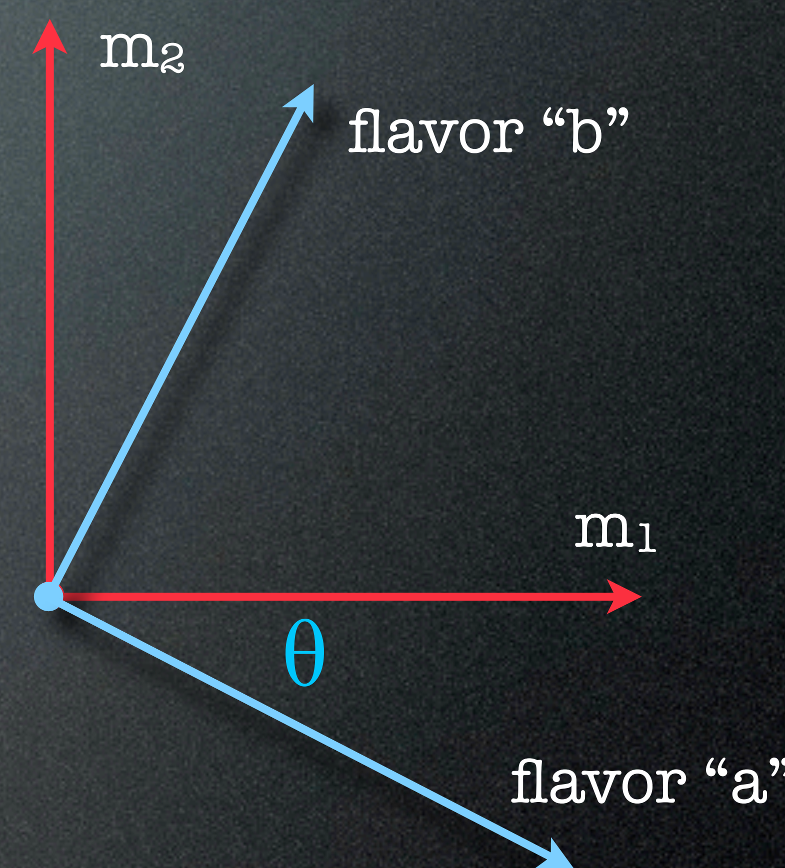
$$\Psi = c_1\psi_1 + c_2\psi_2 + c_3\psi_3 + \ldots$$

Basis; for example, eigenfunctions of a Hamiltonian

Flavor mixing

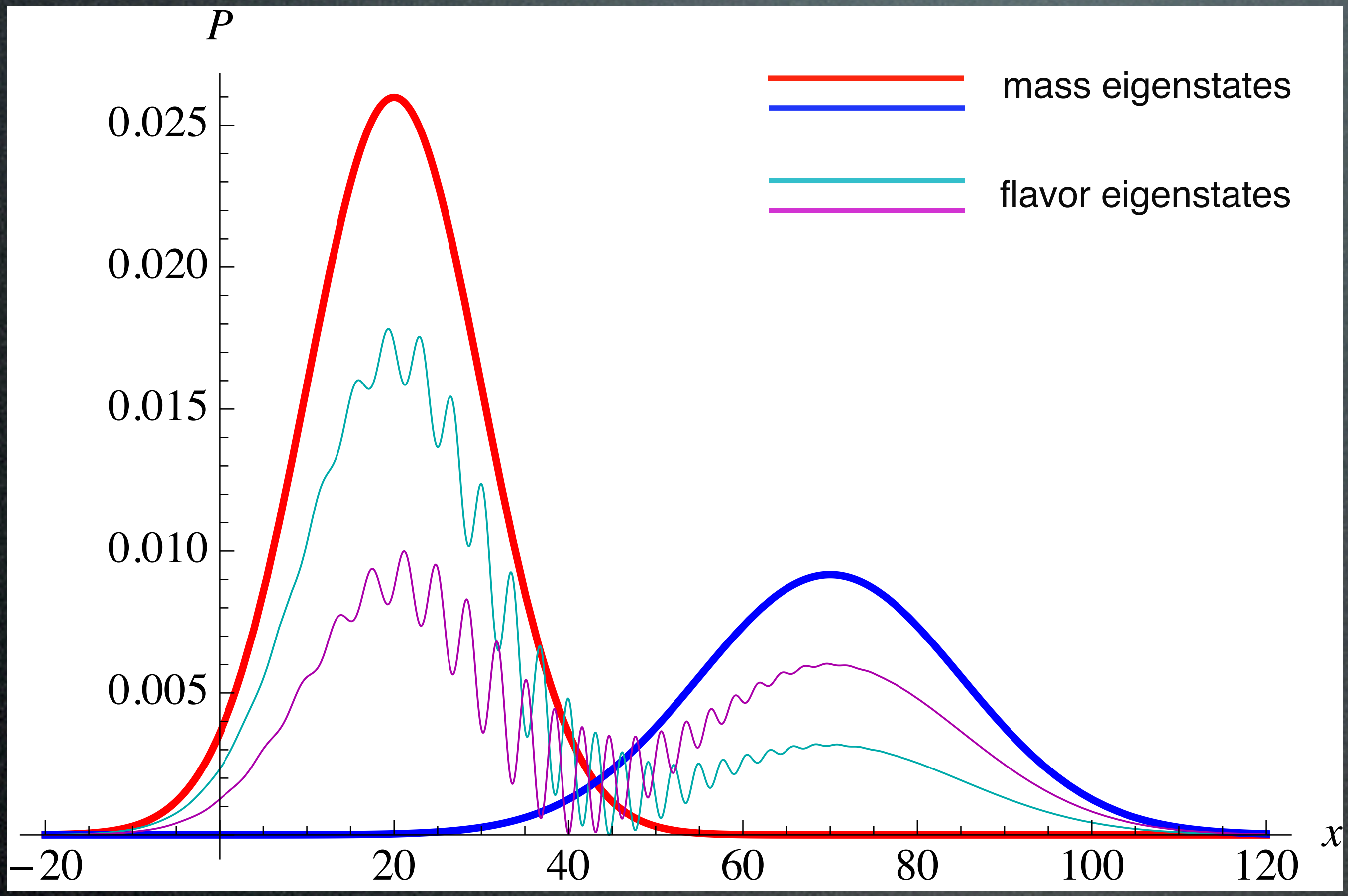
$$\Psi_a = \cos\theta\ \psi_1 - \sin\theta\ \psi_2$$

flavor “a” m1 m2



Interactions do not care about propagation (mass) eigenstates;
Propagation does not care about interaction (flavor) eigenstates.

2-component particle



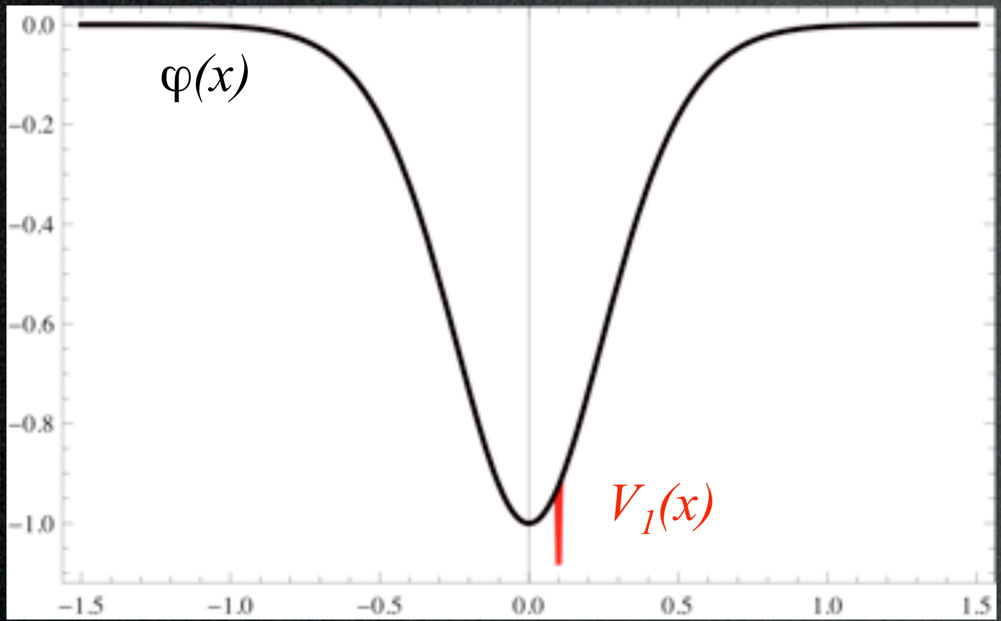
$$\begin{pmatrix} |\text{flavor}_1\rangle \\ |\text{flavor}_2\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |\text{mass}_{\text{heavy}}\rangle \\ |\text{mass}_{\text{light}}\rangle \end{pmatrix}$$

Illustrative model

Schrödinger equation

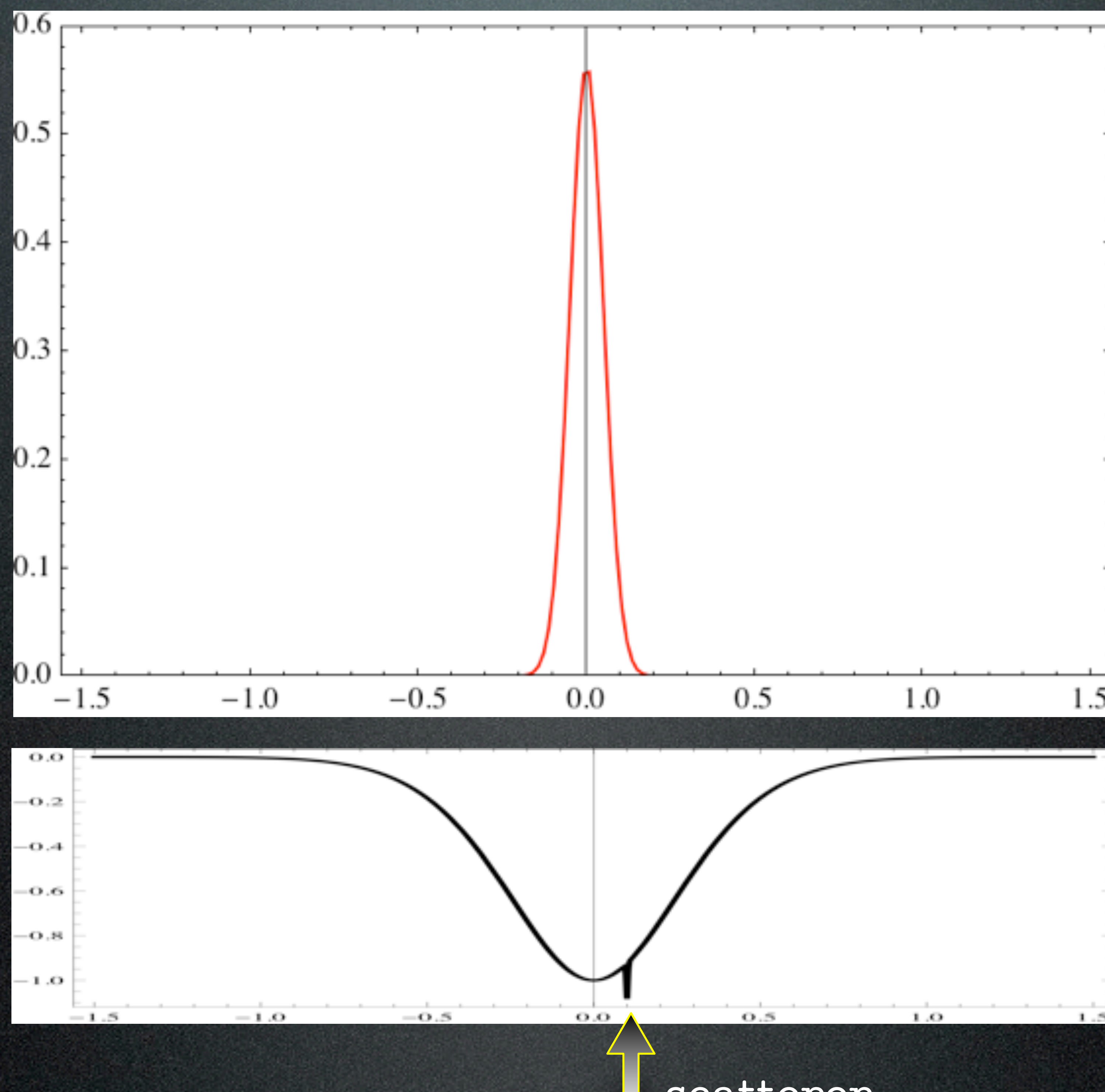
$$i\partial_t \begin{pmatrix} m_h(x,t) \\ m_l(x,t) \end{pmatrix} = \left[\begin{pmatrix} -\partial_{xx}^2/2m_h & 0 \\ 0 & -\partial_{xx}^2/2m_l - \Delta m \end{pmatrix} + \begin{pmatrix} m_h\phi(x) & 0 \\ 0 & m_l\phi(x) \end{pmatrix} + \begin{pmatrix} V_{hh} & V_{hl} \\ V_{lh} & V_{ll} \end{pmatrix}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

H^{free} $\quad H^{grav}$ $\quad V$

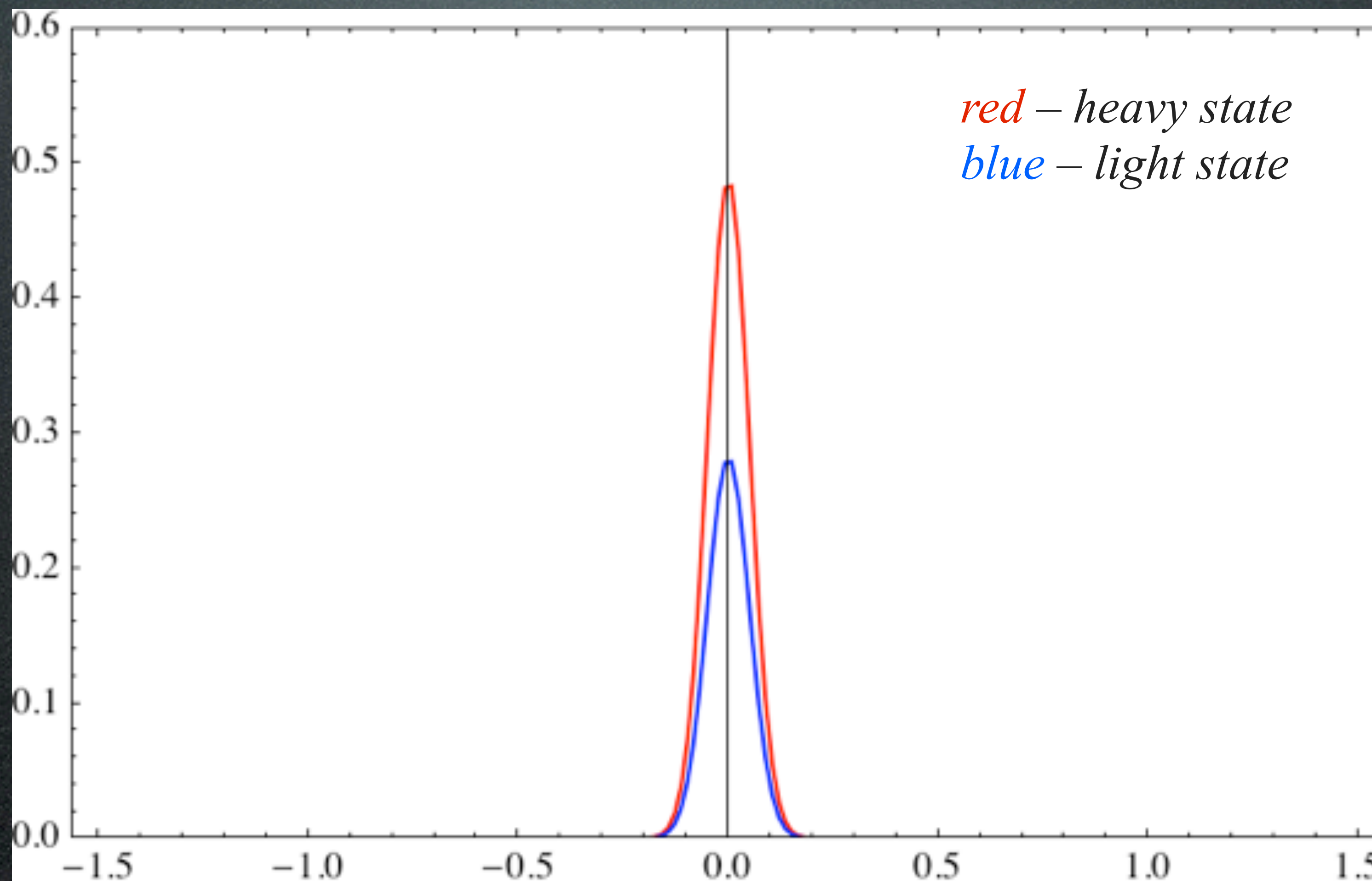


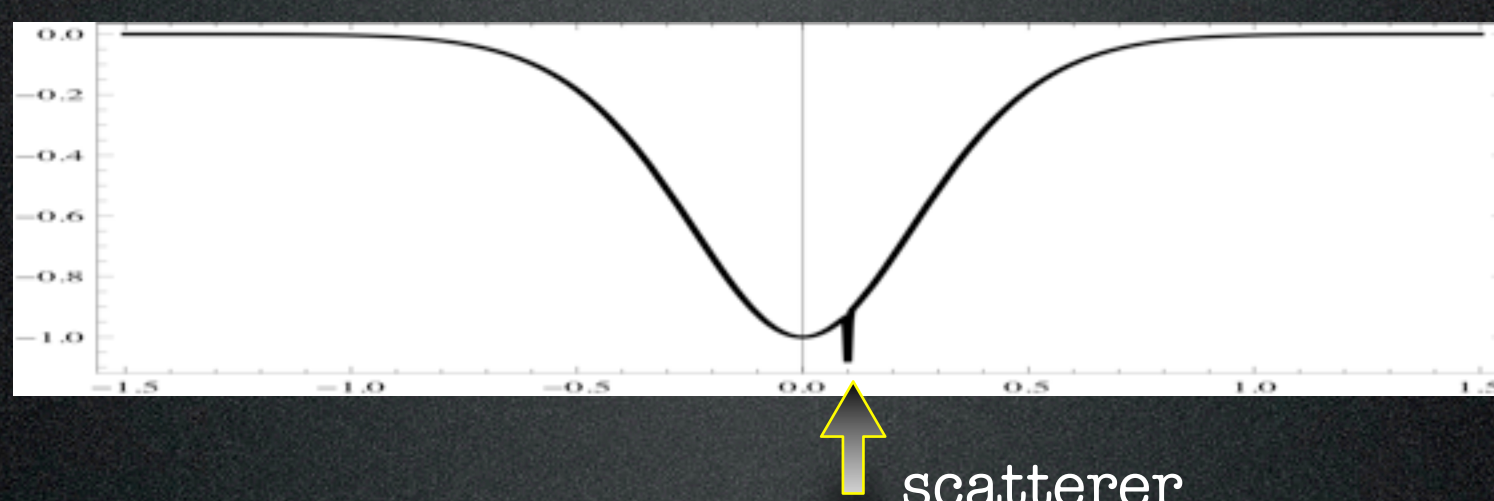
$$\begin{pmatrix} V_{hh} & V_{hl} \\ V_{lh} & V_{ll} \end{pmatrix} = U \begin{pmatrix} V_1 & 0 \\ 0 & 0 \end{pmatrix} U^\dagger$$

No flavor mixing case

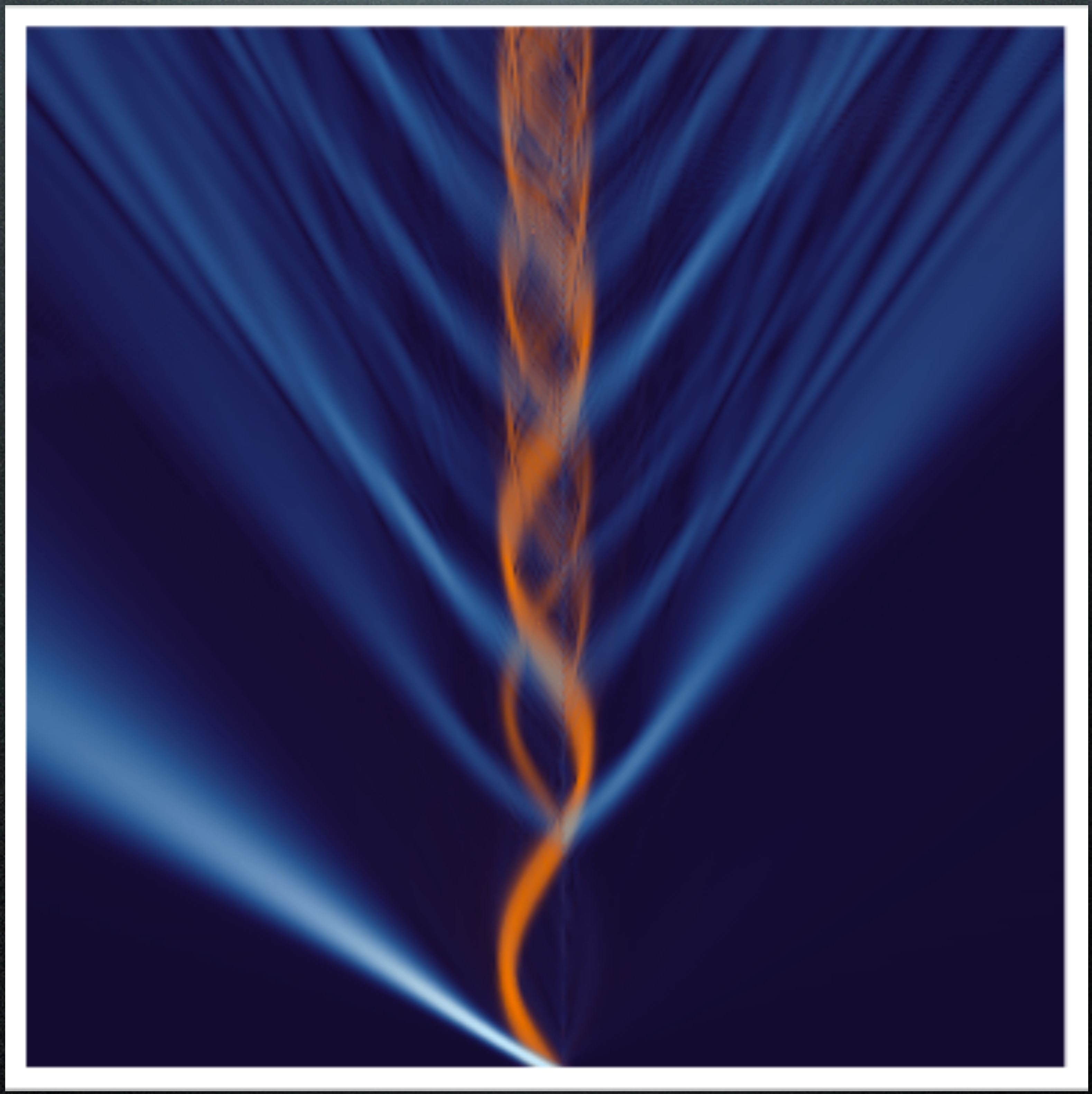


With flavor mixing





Space-Time diagram

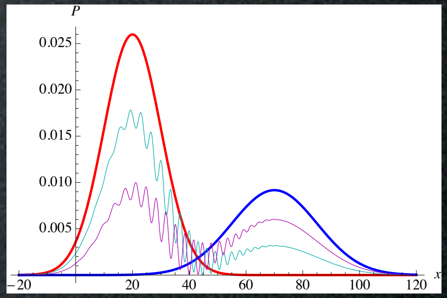


time

space

2-component dark matter

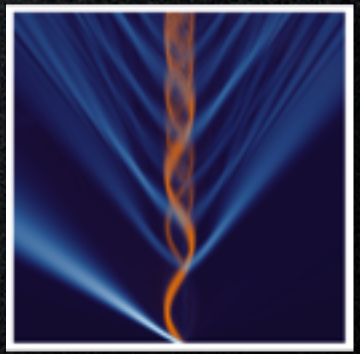
Dark Matter -- stable 2-component mixed particle



Neutralinos
Sterile neutrinos
Axion+photon
...

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

Mass-conversions and quantum evaporation



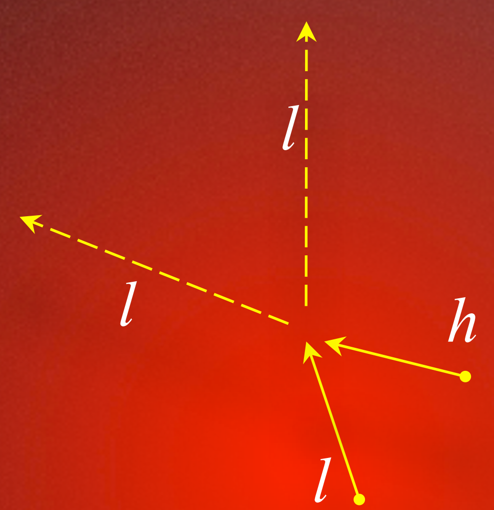
$$|h\rangle + |l\rangle \rightarrow |l\rangle + |l\rangle$$

DM halos

Energy conservation:

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

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



if $v_{kick} >> v_{escape}$

dwarf halos destroyed

if $v_{kick} << v_{escape}$

central cusps softened

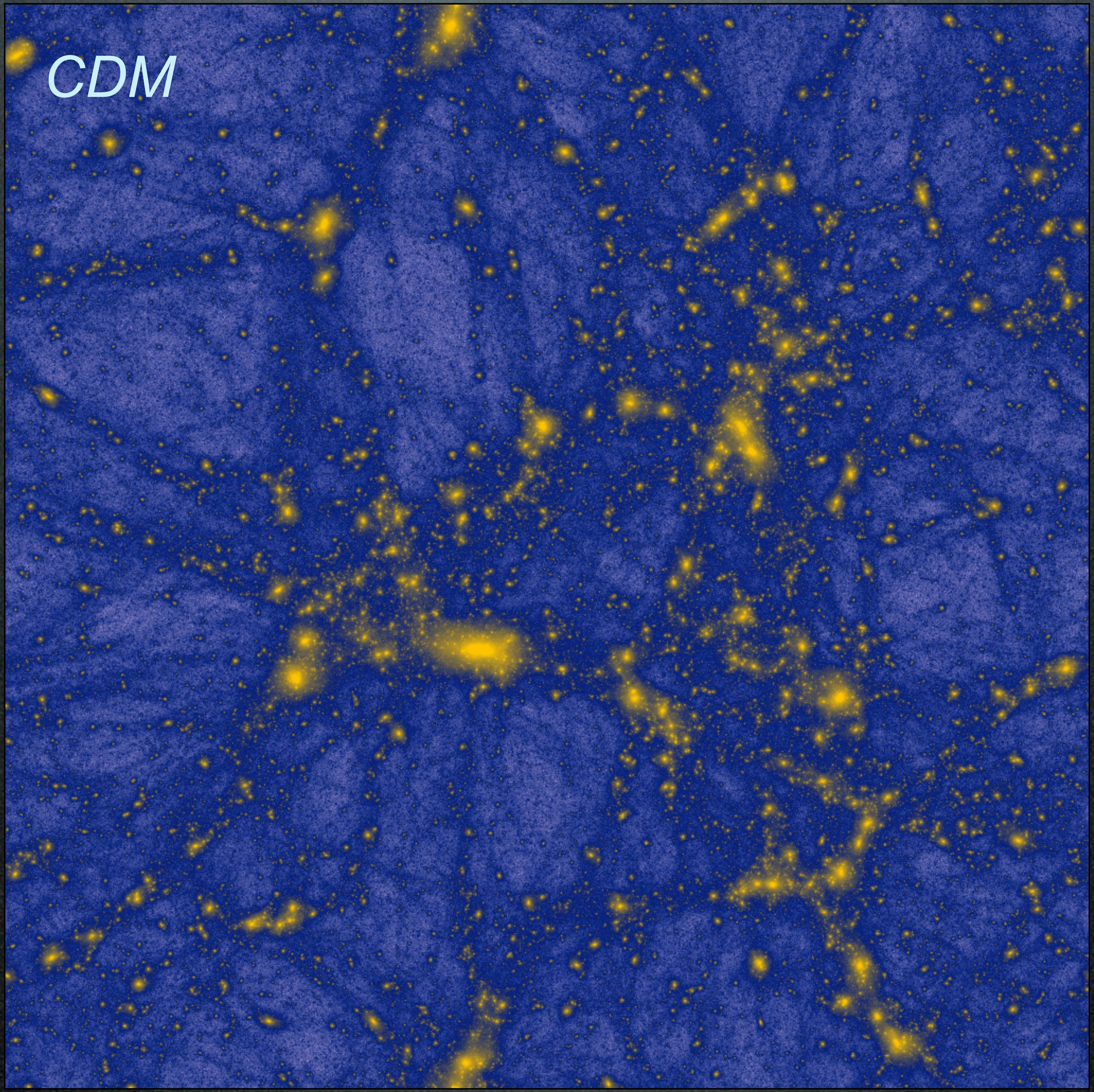
Implementation

- Gadget; 50 Mpc/h box; 3.5 kpc/h, 8×10^7 $M_\odot$ resolution; standard ΛCDM cosmol.
- 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 $v_k = c(2\Delta m/m)^{1/2}$]

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

$$\sigma_{s_i t_i \to s_f t_f} = \sigma\, \frac{p_{s_f}}{p_{s_i}}\, \Theta(E_{s_f t_f})\, B_{(s_i t_i)(s_f t_f)} \qquad B \equiv (B_{ij}) = \begin{pmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \end{pmatrix}$$

No modification on large scales



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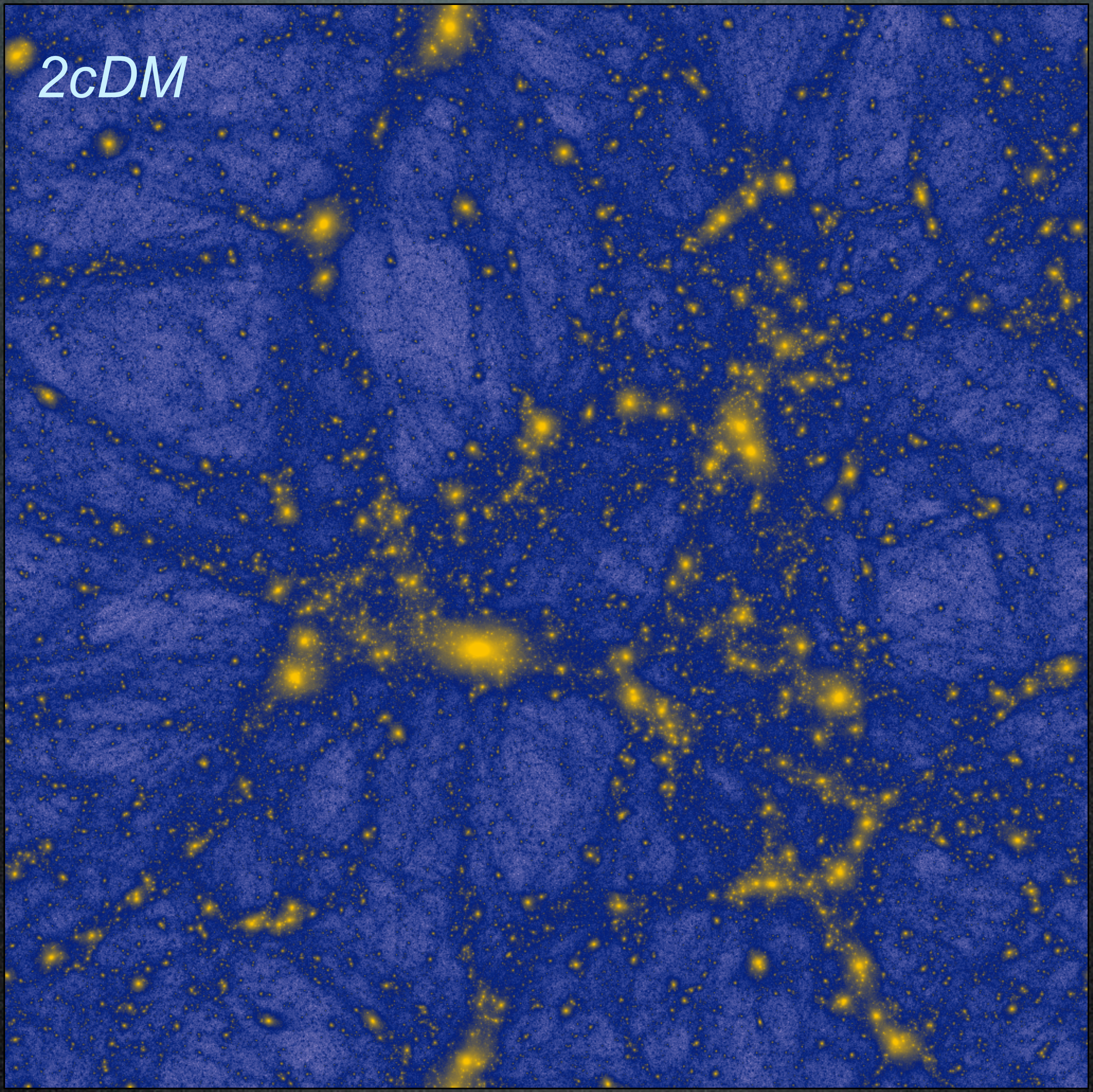

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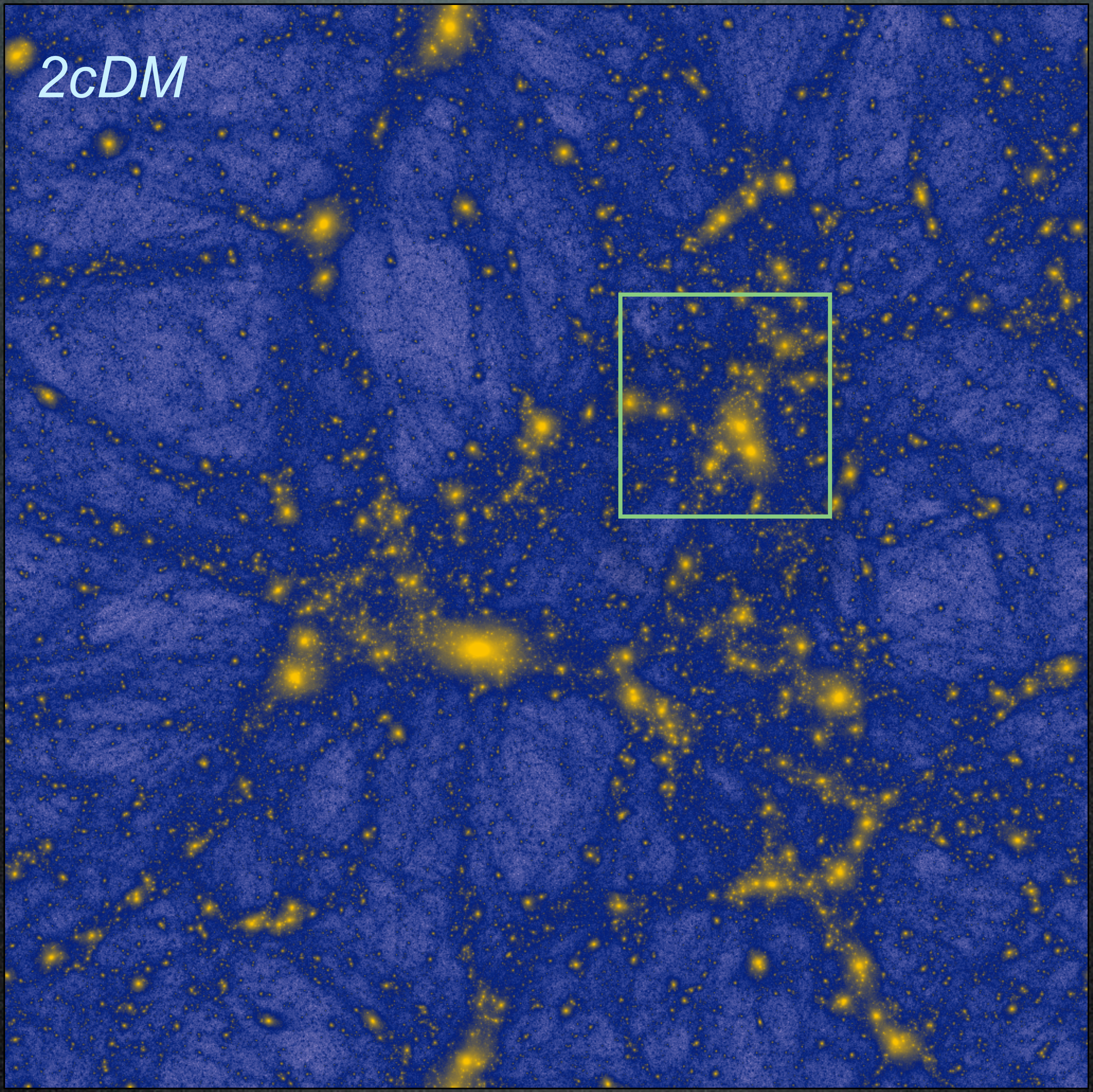
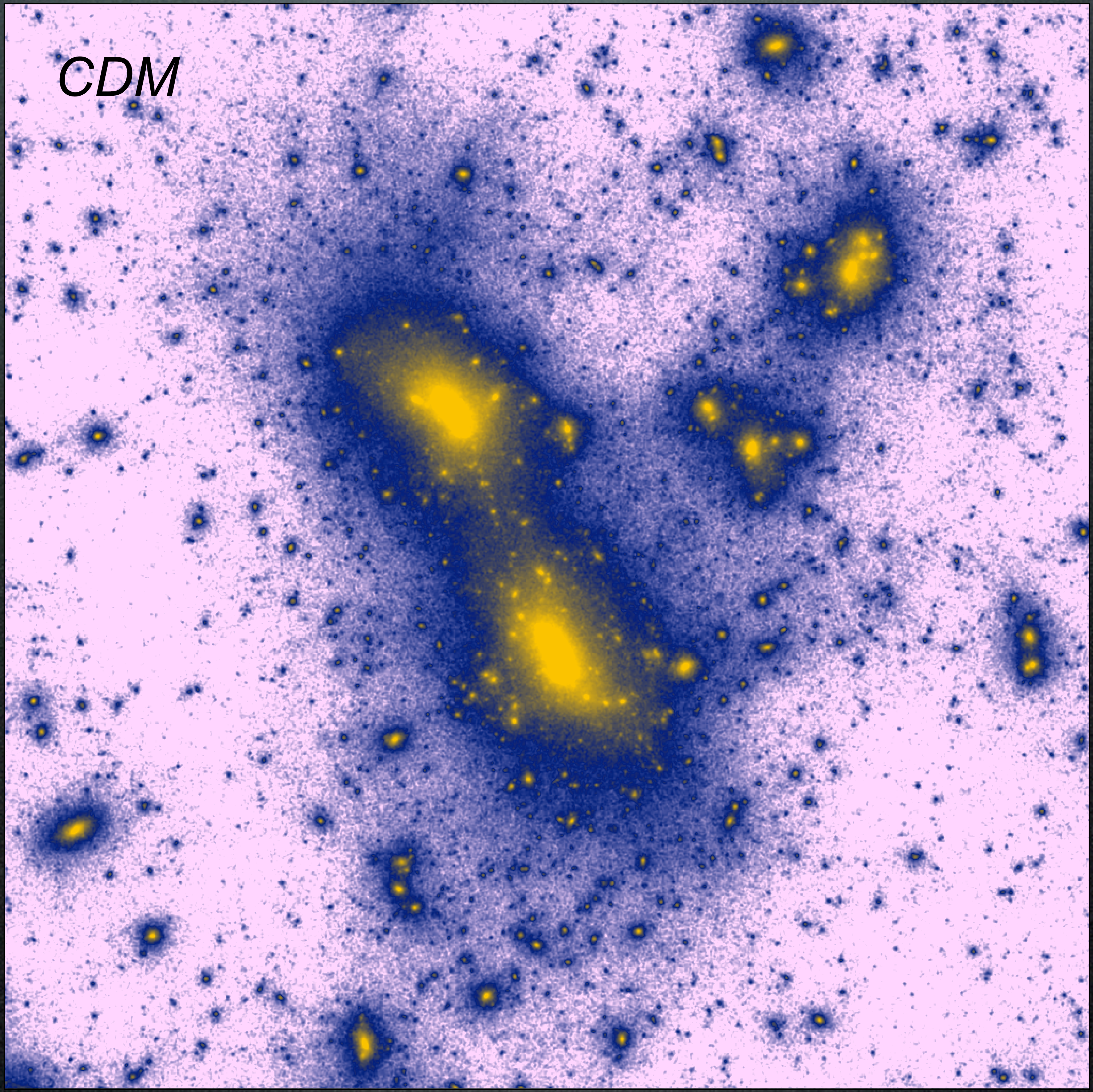


Less substructure on small scales



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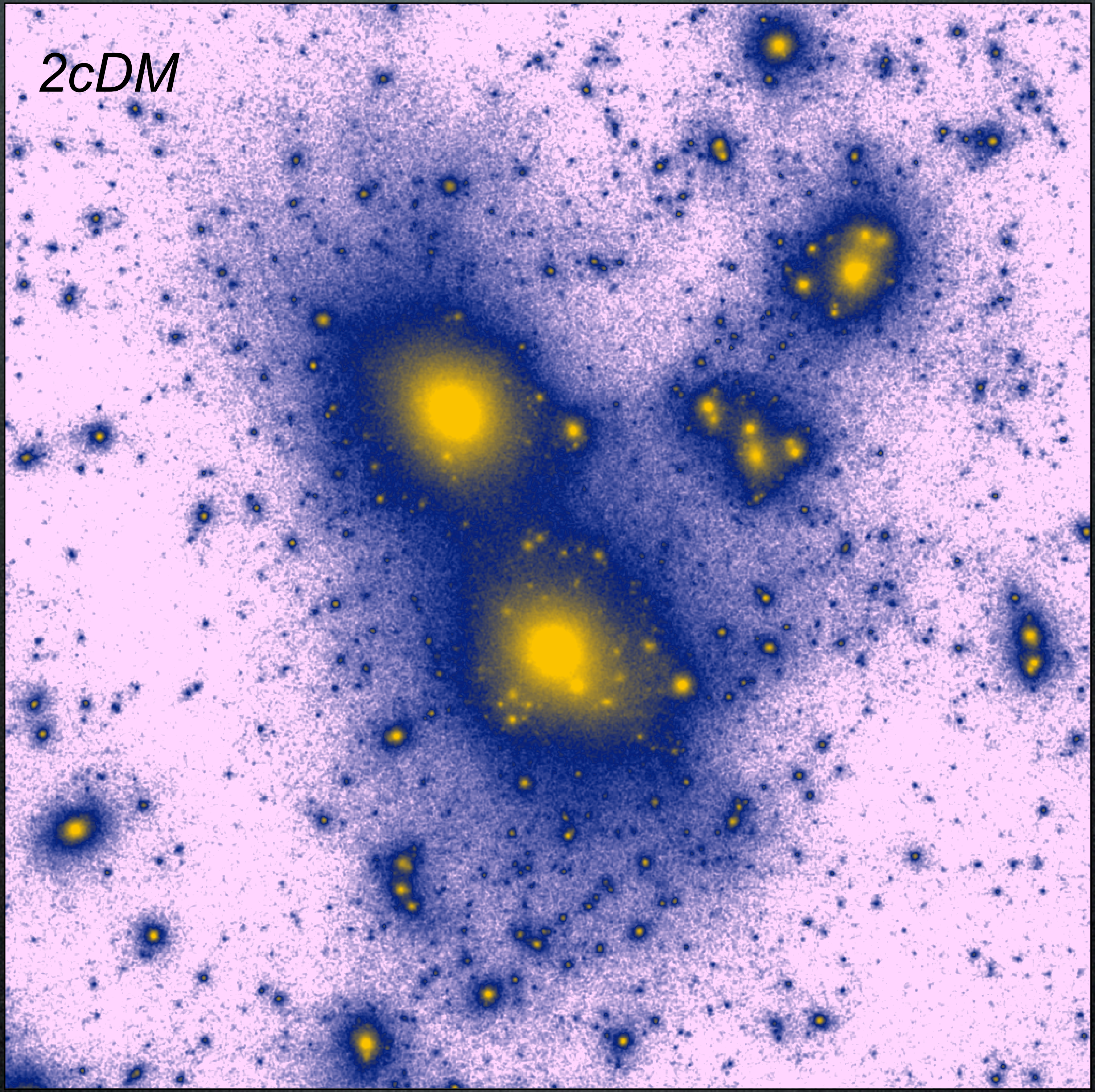
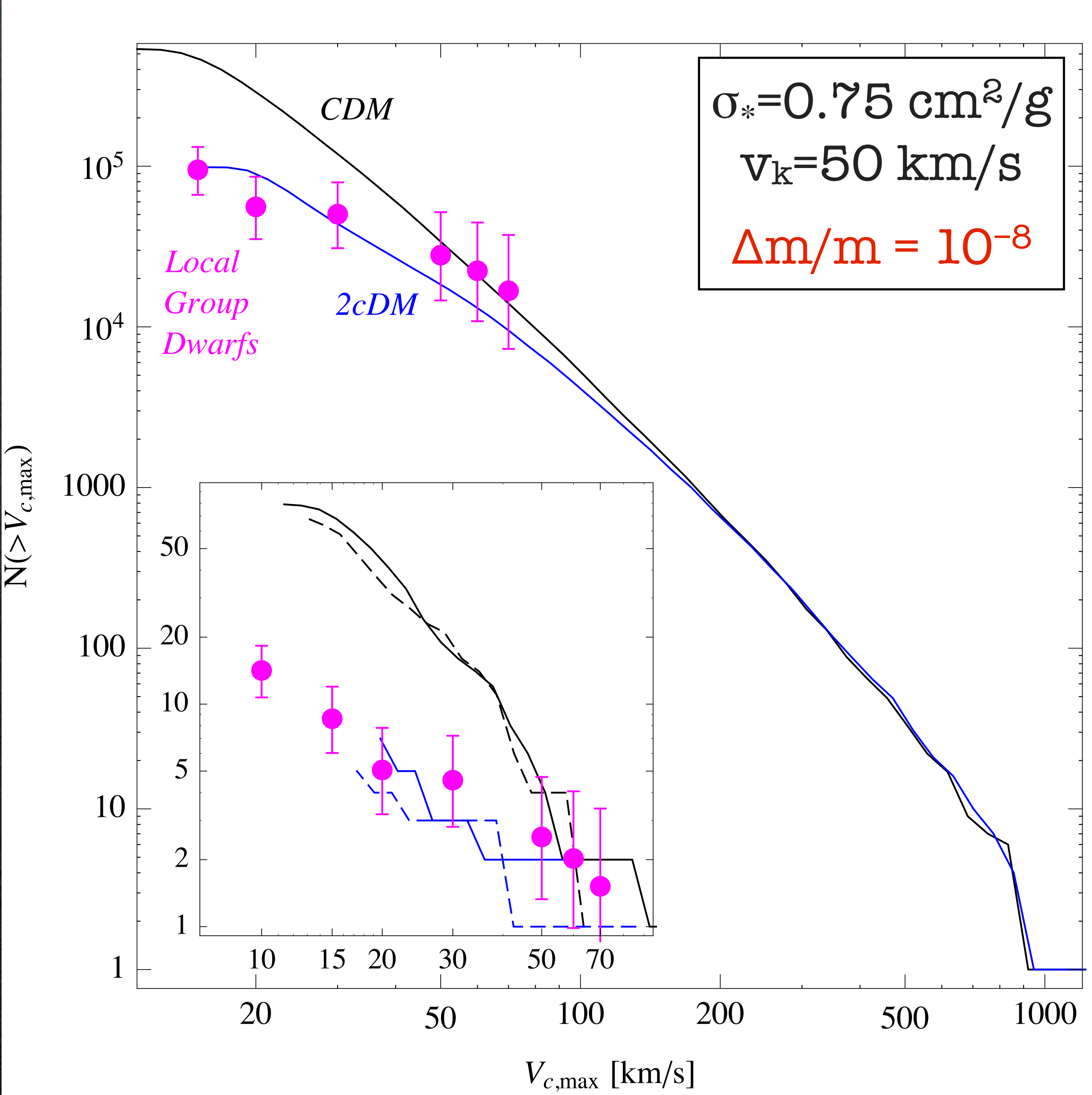
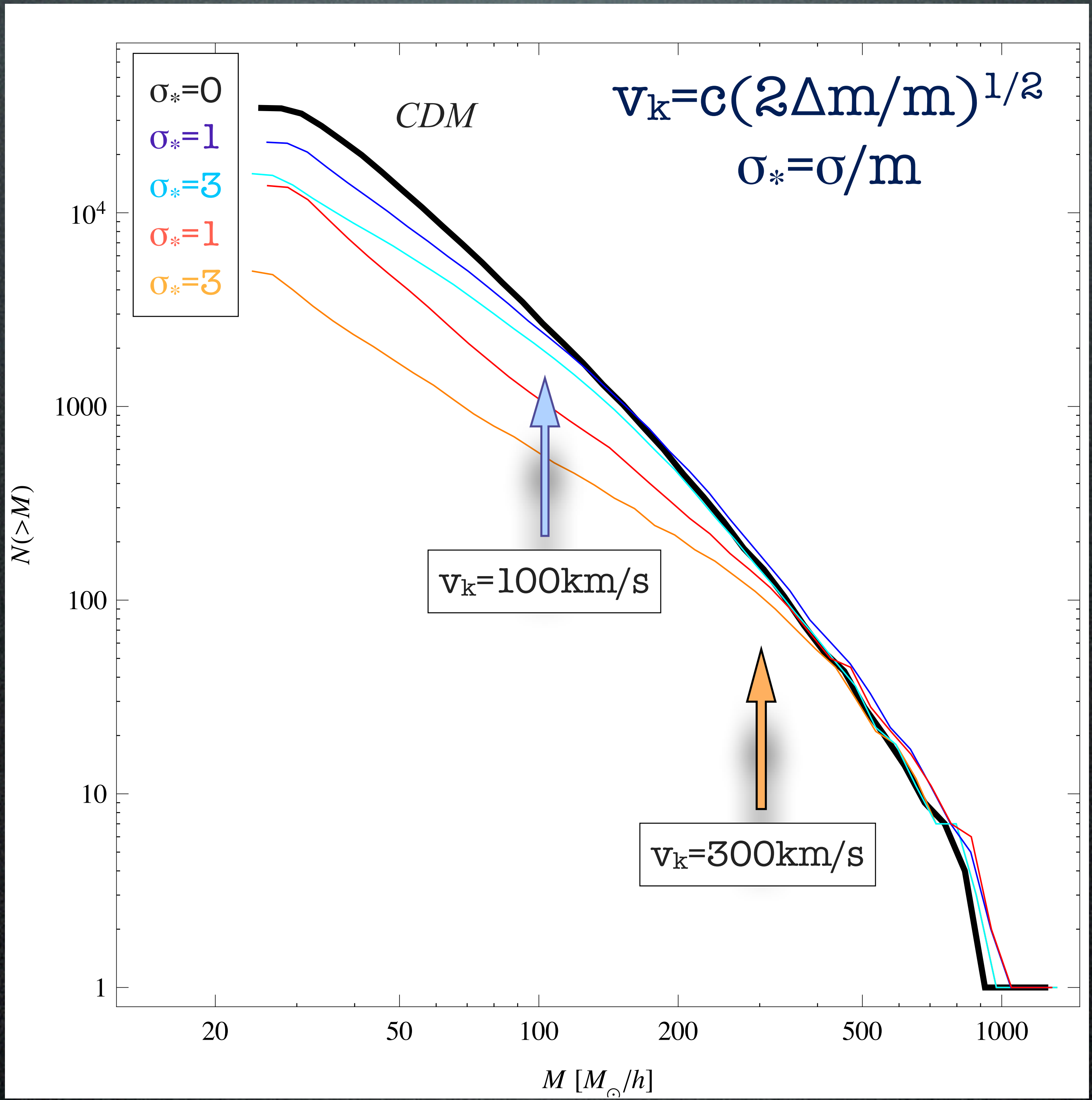


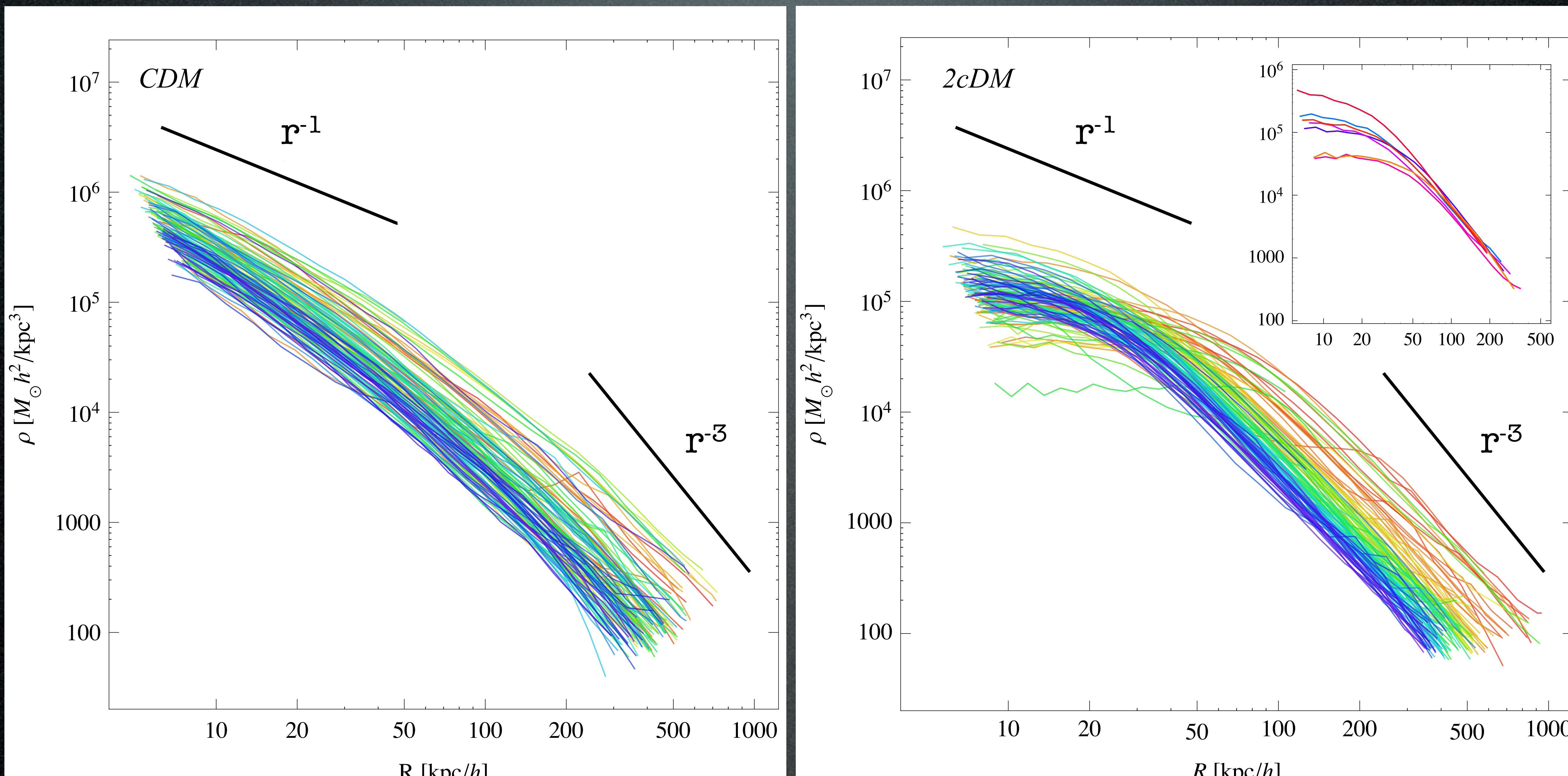
Velocity function



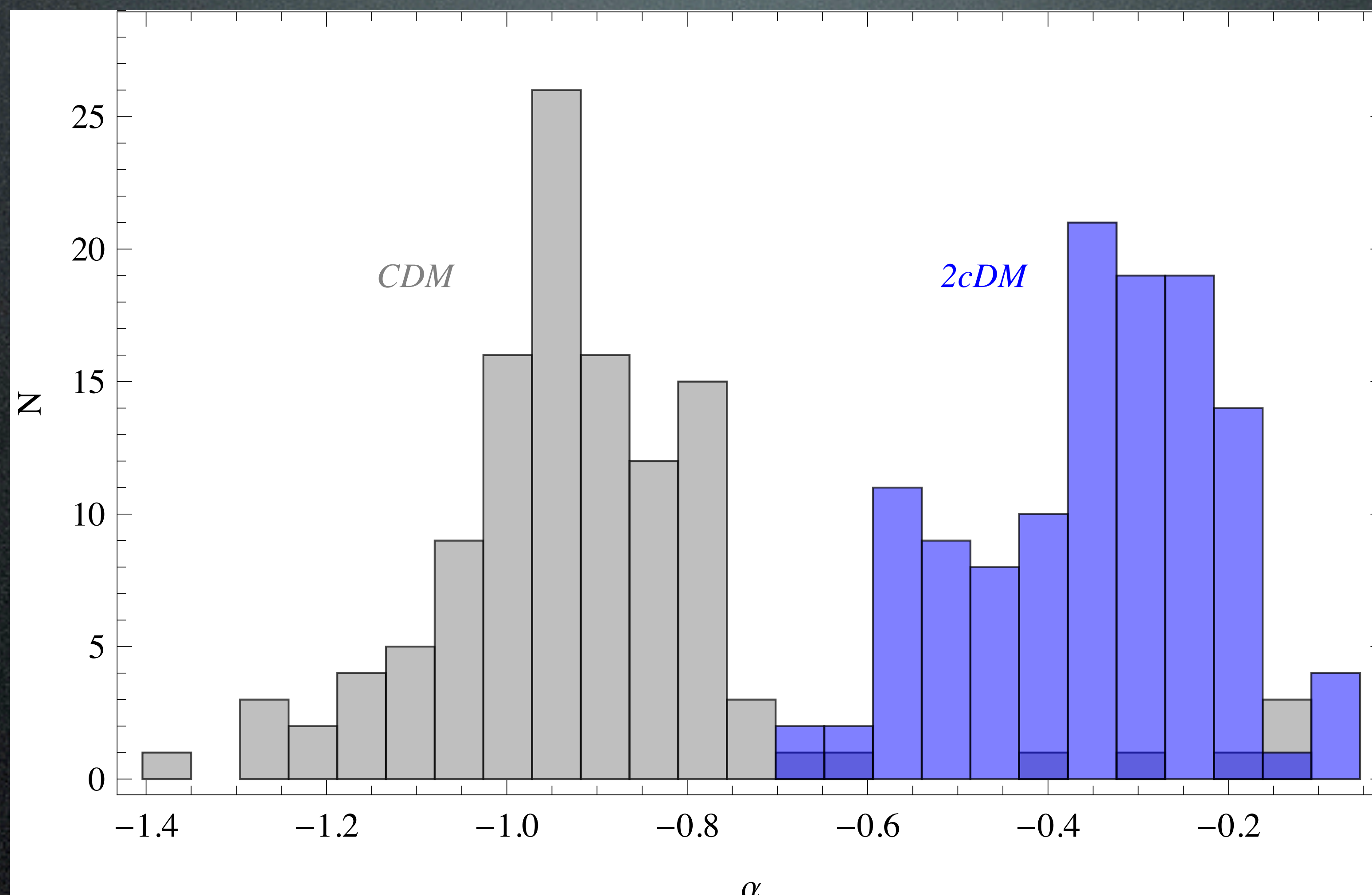
Key parameters



Density profiles



Slopes of density profiles



We fit density profiles with function

$\rho = r^{\alpha}/(1+r^{\beta})$ and evaluating α at $r = 7\ kpc/h$

2cDM vs SIDM

$\sigma(v)$ -- determines slopes:

density profile (core/cusp)

mass/vel function (amount of substructure)

$\Delta m/m$ (or v_k) -- determines break:

mass/vel function (where deviates from CDM)

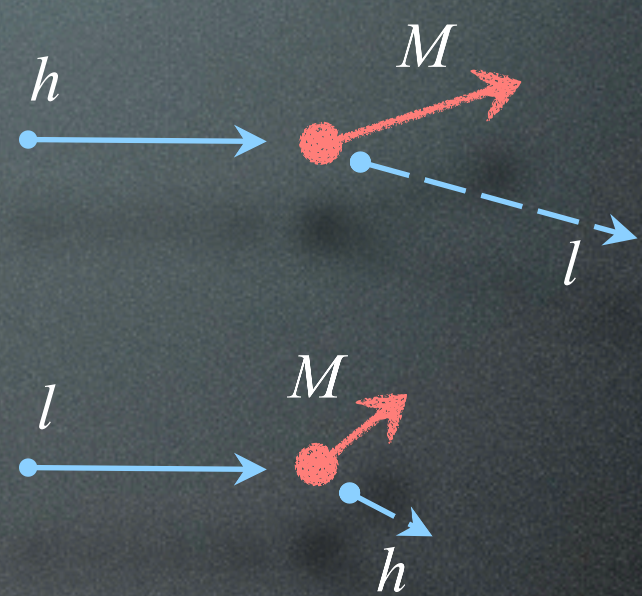
SIDM -- one species, collisional -- $\sigma(v)$
2cDM -- 2 species, same constraint on $\sigma(v)$

Caveat: fine tuning:
"why now?"

Predictions

direct detection

"inelastic recoil"

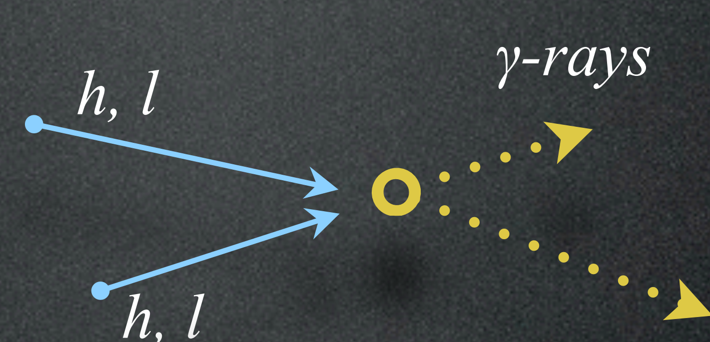


$+ \Delta mc^2$

$- \Delta mc^2$

indirect detection

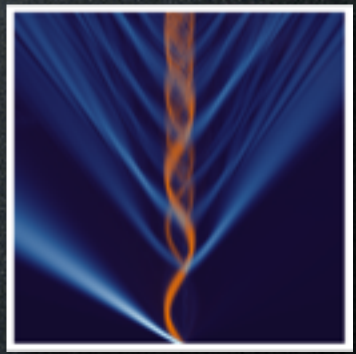
"γ-ray annihilation line triplet"



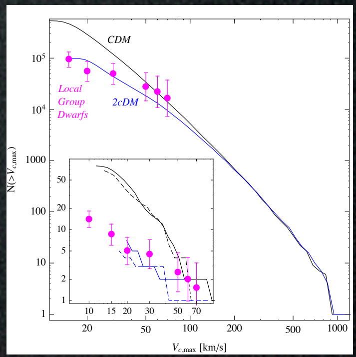
$E_\gamma = mc^2 \pm \frac{1}{2} \Delta mc^2$

130 GeV $\pm \sim$ keV

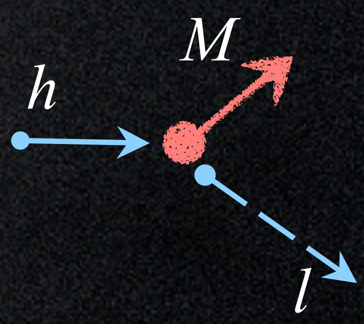
Summary



- "quantum evaporation" is a new effect (MVM 2010)



- 2cDM:
  - can solve small-scale problems simultaneously
  - $\sigma(v)$ consistent with all constraints
  - $\Delta m/m \sim 10^{-8}$ <==> $v_k \sim 50$ *km/s*



- 2cDM predicts
  - if $m_\chi \sim 100\ GeV$, then $\Delta m_\chi \sim\ keV$
  - inelastic recoils with $\Delta E \sim \Delta mc^2$ in direct detection DM
  - γ-ray annihilation line triplet with $\Delta E_\gamma = ½\, \Delta mc^2 \sim keV$