Cosmological Simulations Evidence in Favor of Two-Component Flavor-Mixed Cold Dark Matter

M.V. Medvedev (KU)

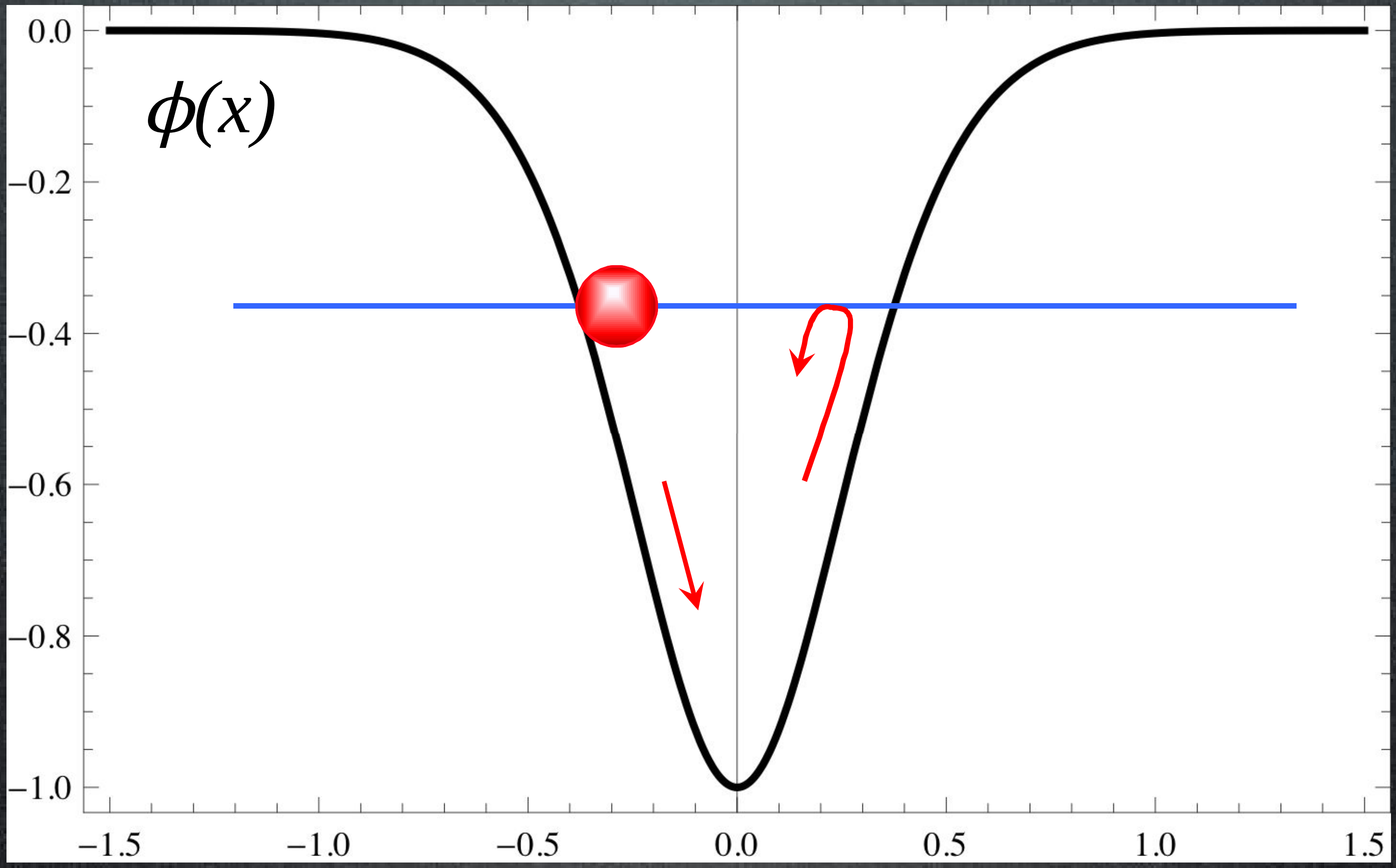
Ginzburg Conference, Lebedev Institute (FIAN), Moscow, 31/5/12

Plan

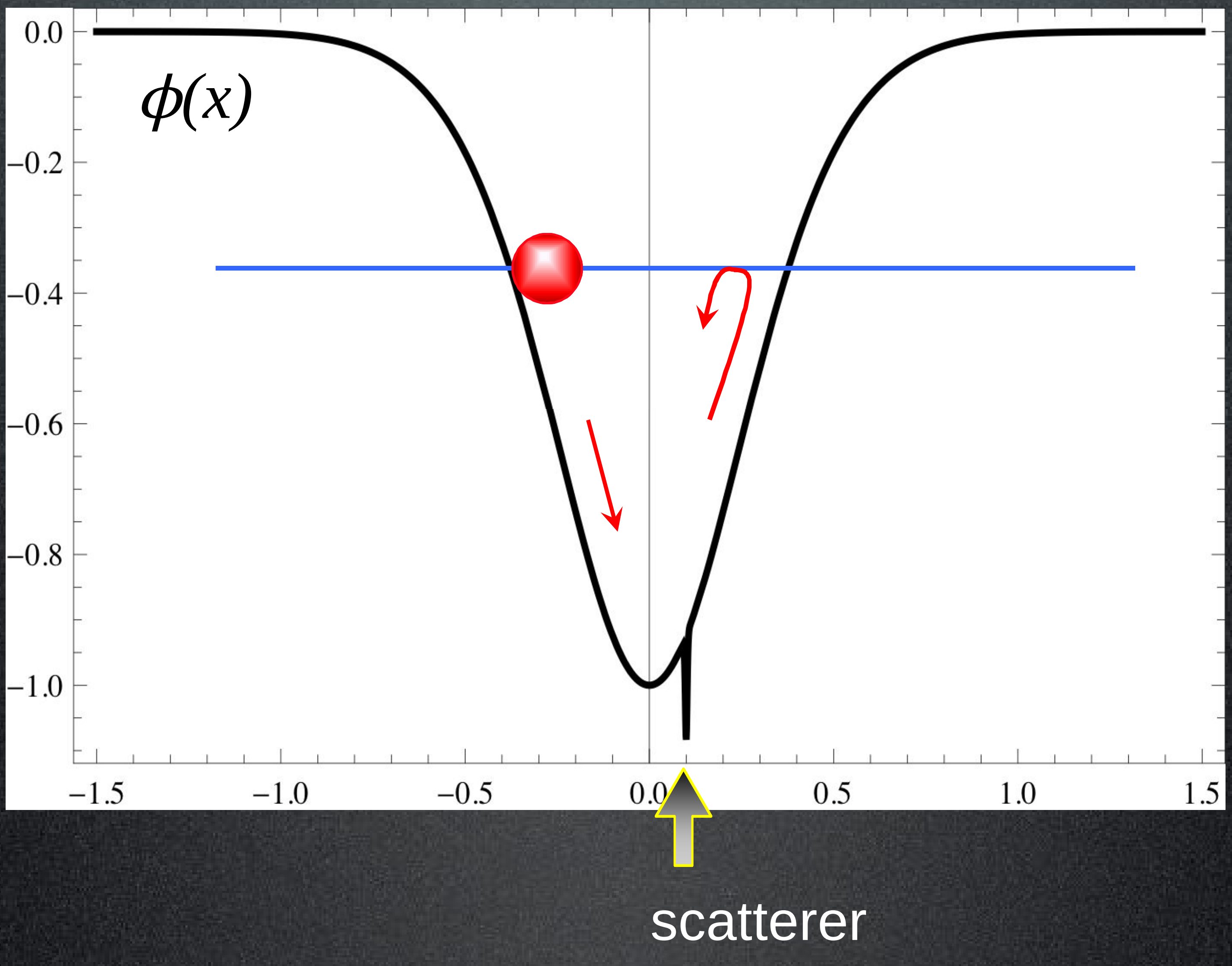
- Flavor mixing
- Mass eigenstate conversion and quantum evaporation
- CDM cosmology
- Cosmology with 2-component CDM (with mixing)

Preface

A particle trapped in a potential



A particle trapped in a potential
+
scattering



A particle trapped in a potential

+

scattering

+

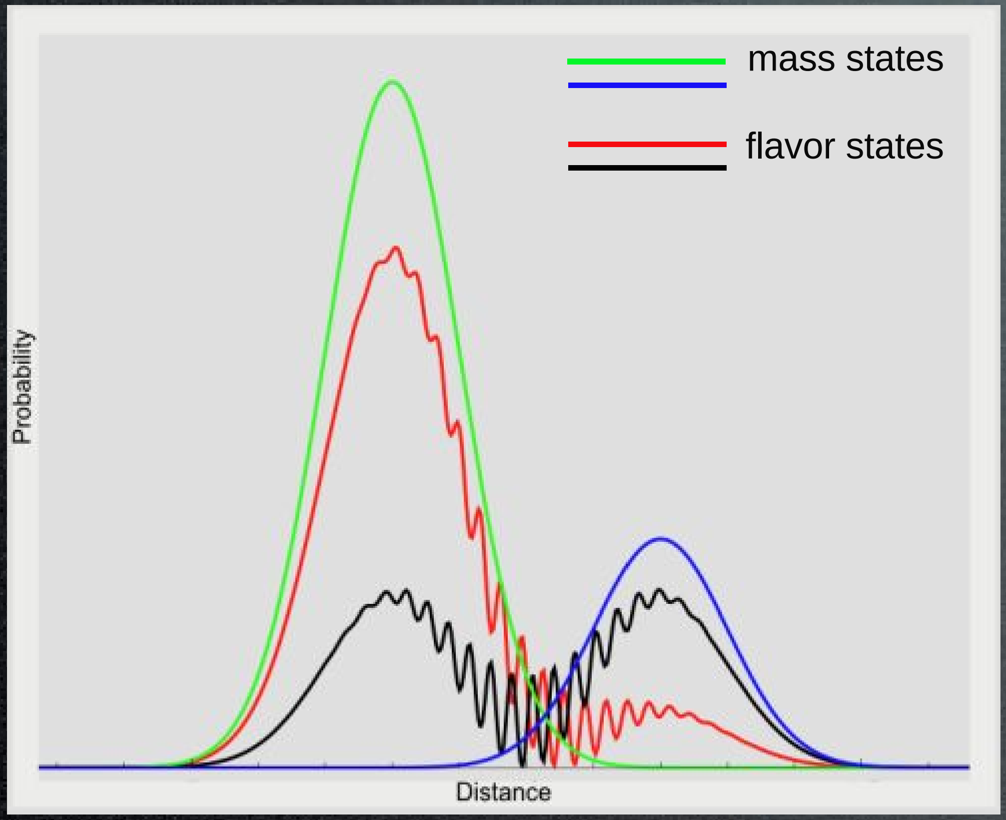
flavor mixing

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

Flavor mixing

Flavor-mixed particles

Quantum mixed particles were proposed by Bruno Pontecorvo
Zh. Teor. Exp Fiz (1957); Soviet JETP (1958)



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

Interactions do not care about propagation (mass) eigenstates;

Propagation does not care about interaction (flavor) eigenstates.

In general, a flavor state can be a linear combination (superposition) of several different mass states and vice versa

$$|f_i\rangle = \sum_j U_{ij} |m_j\rangle$$

Flavor-mixed particles

Mixed particles: neutrinos, quarks, Kaons,… , axions, neutralinos, …

Cosmic Neutrino Background
(non-relativistic at present)

Cold Dark Matter candidates
|
|
...will be discussed in this talk...

Flavor mixing is the cause of neutrino oscillations (Nobel Prize 2002):
simple time-dependent interference of mass eigenstates moving with (slightly) different velocities

– directly observed for relativistic neutrinos (solar, atmospheric, collider), Kaons, B-mesons

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Flavor mixing is the cause of neutrino oscillations:
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Quantum evaporation

Illustrative model

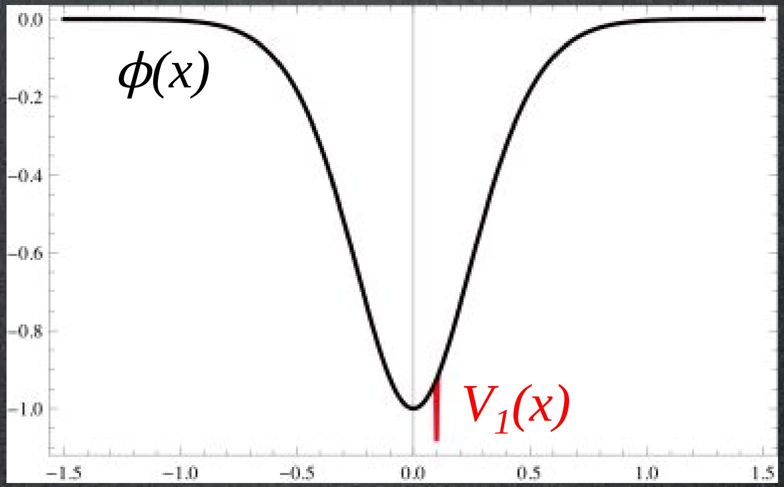
2-component particle

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

Schrödinger equation

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

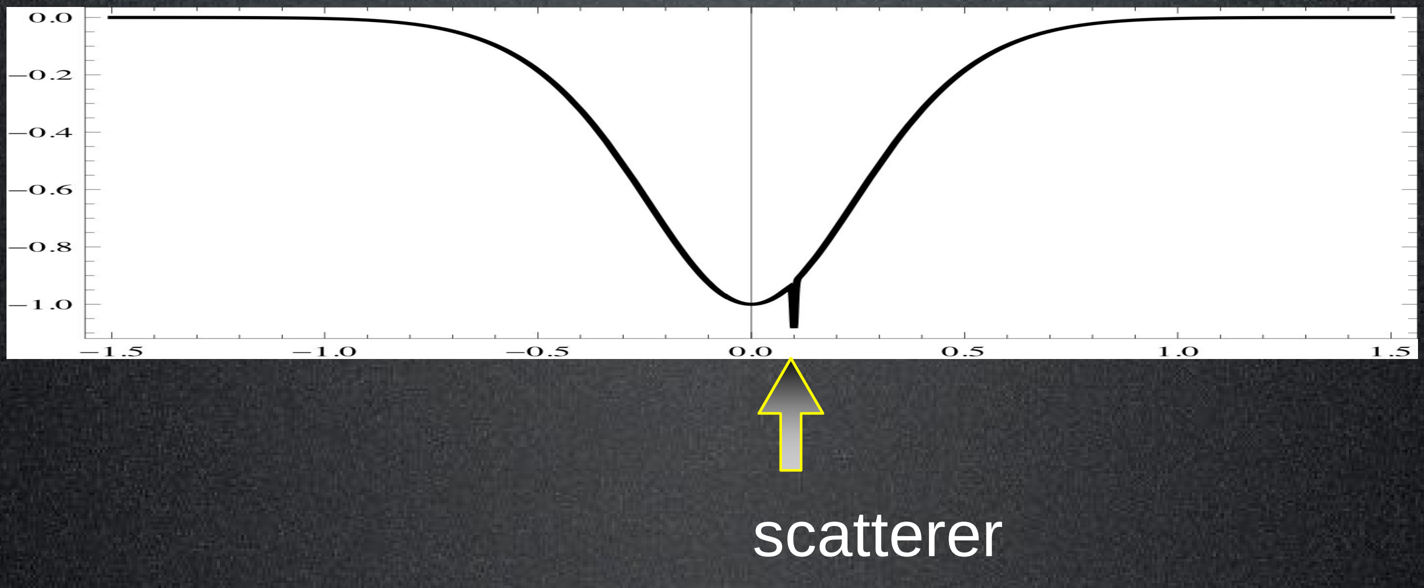
H^{free} $\quad$ H^{grav} $\quad$ V



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

No flavor mixing case

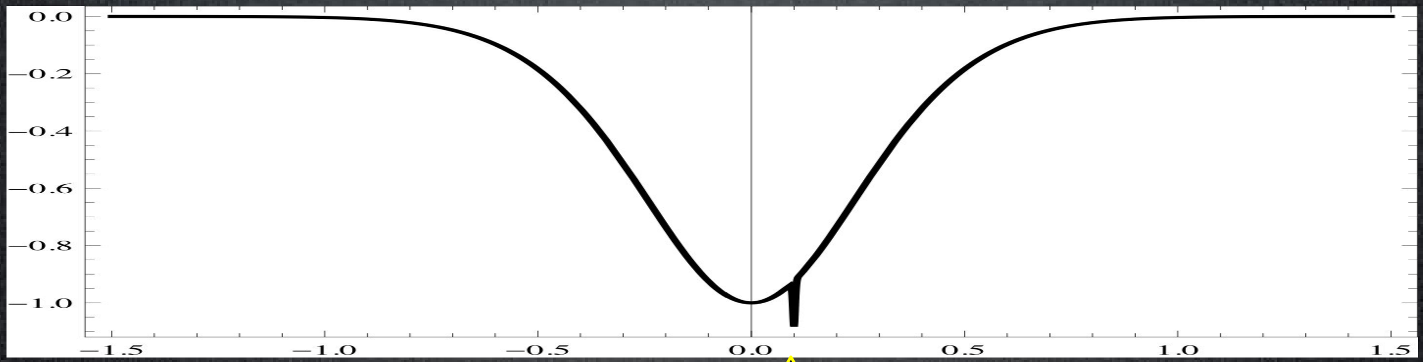
QuickTime™ and a
GIF decompressor
are needed to see this picture.



With flavor mixing

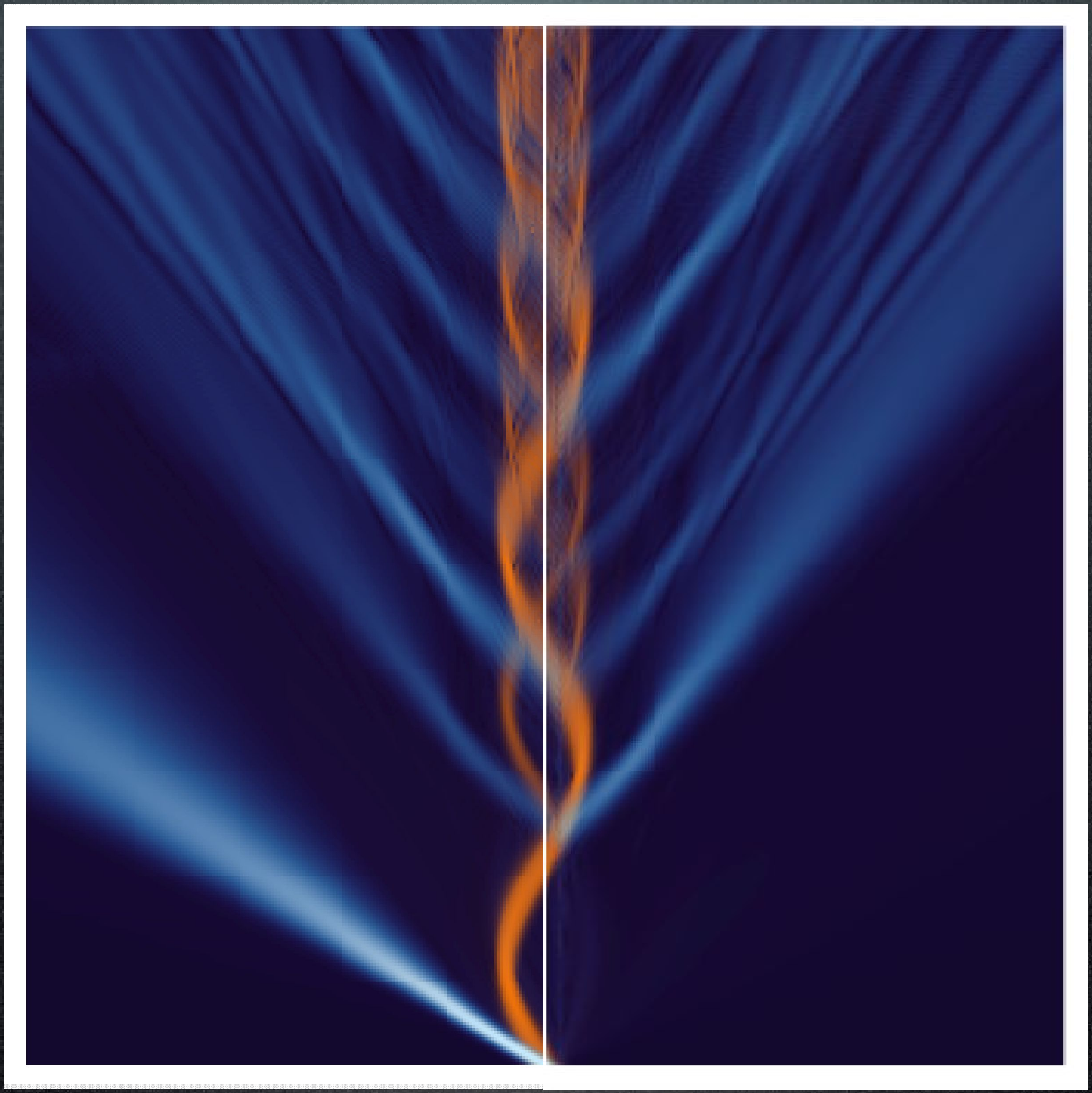
red – *heavy state*
blue – *light state*

QuickTime™ and a
GIF decompressor
are needed to see this picture.



scatterer

Space-Time diagram

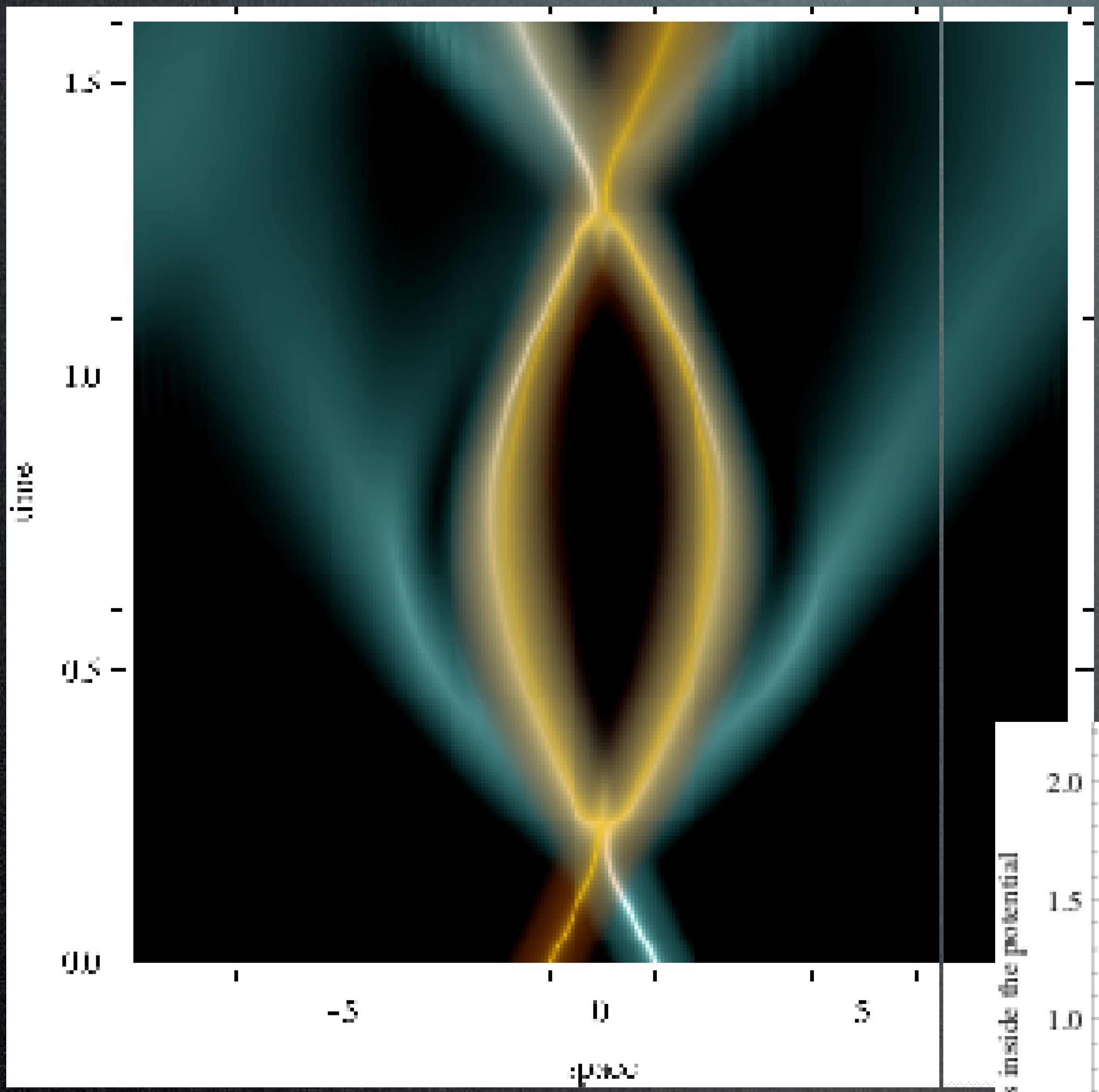


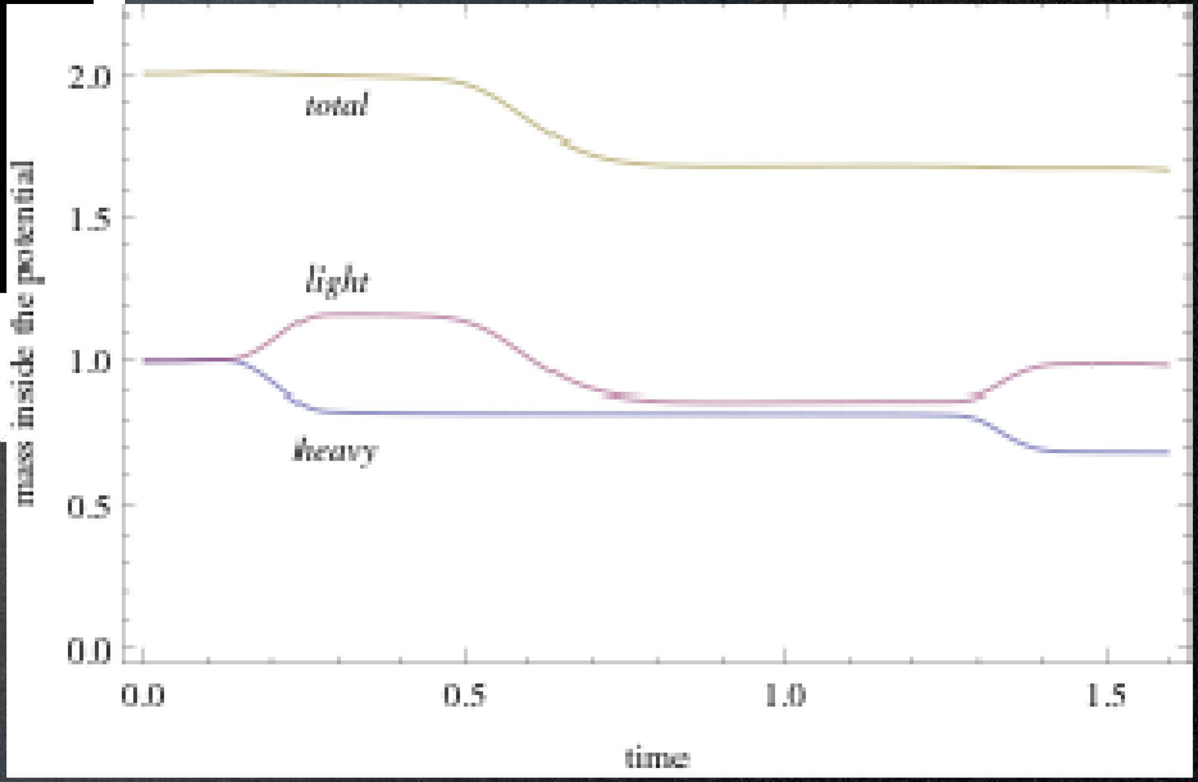
time

space

Complete evaporation of 2-comp particles

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





Implications

The effects of evaporation and mass-conversion are applicable to all known and unknown mixed particles (neutrinos, quarks, Kaons, B-mesons, neutralinos, axions,...)

Wide field for further investigation.
Particularly interesting:

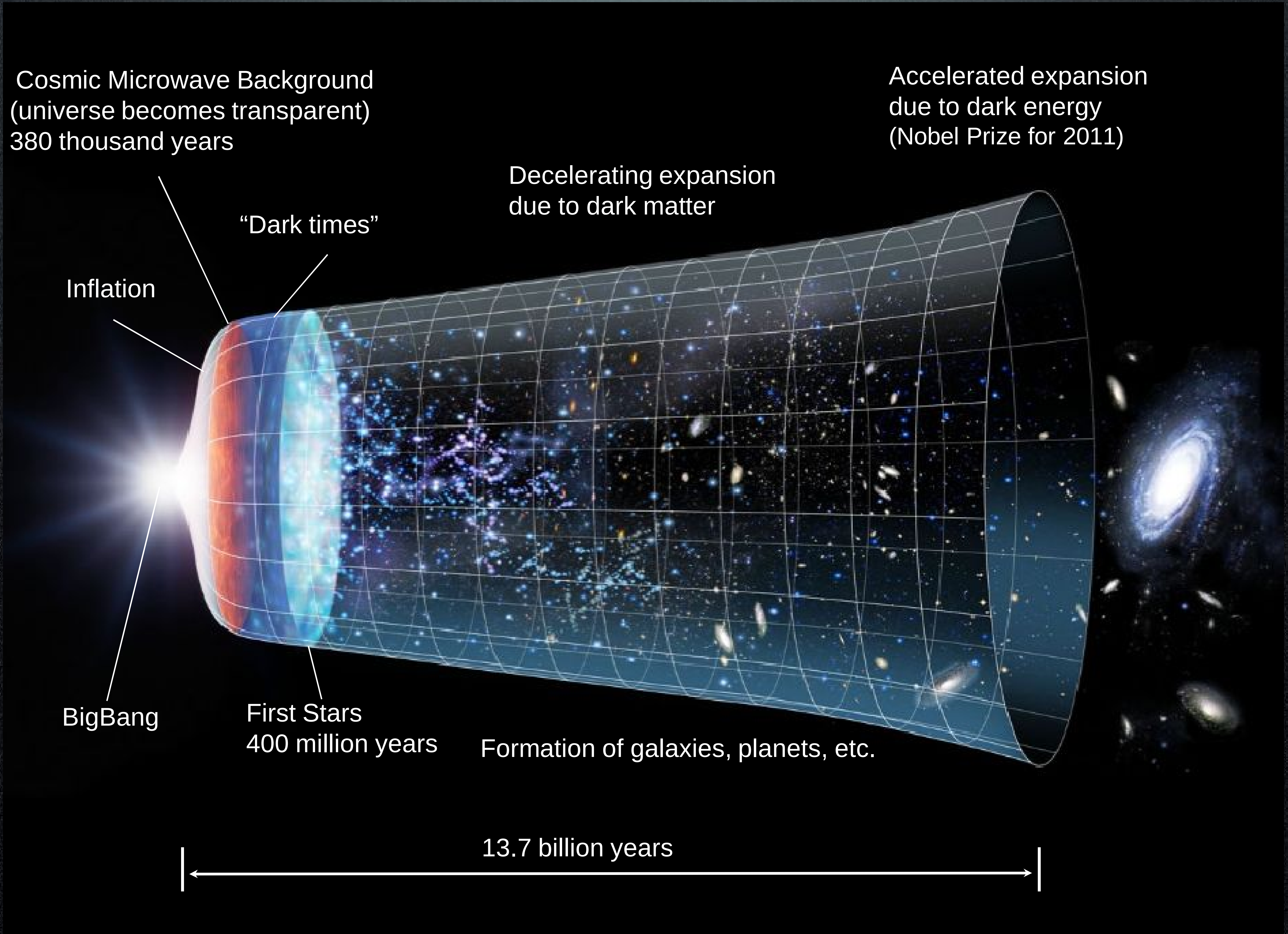
- Composition change of cosmic neutrino background (and production of its anisotropy if measured on Earth)

- Change the CDM predictions (mostly at small scales, if CDM is a multi–component and stable)

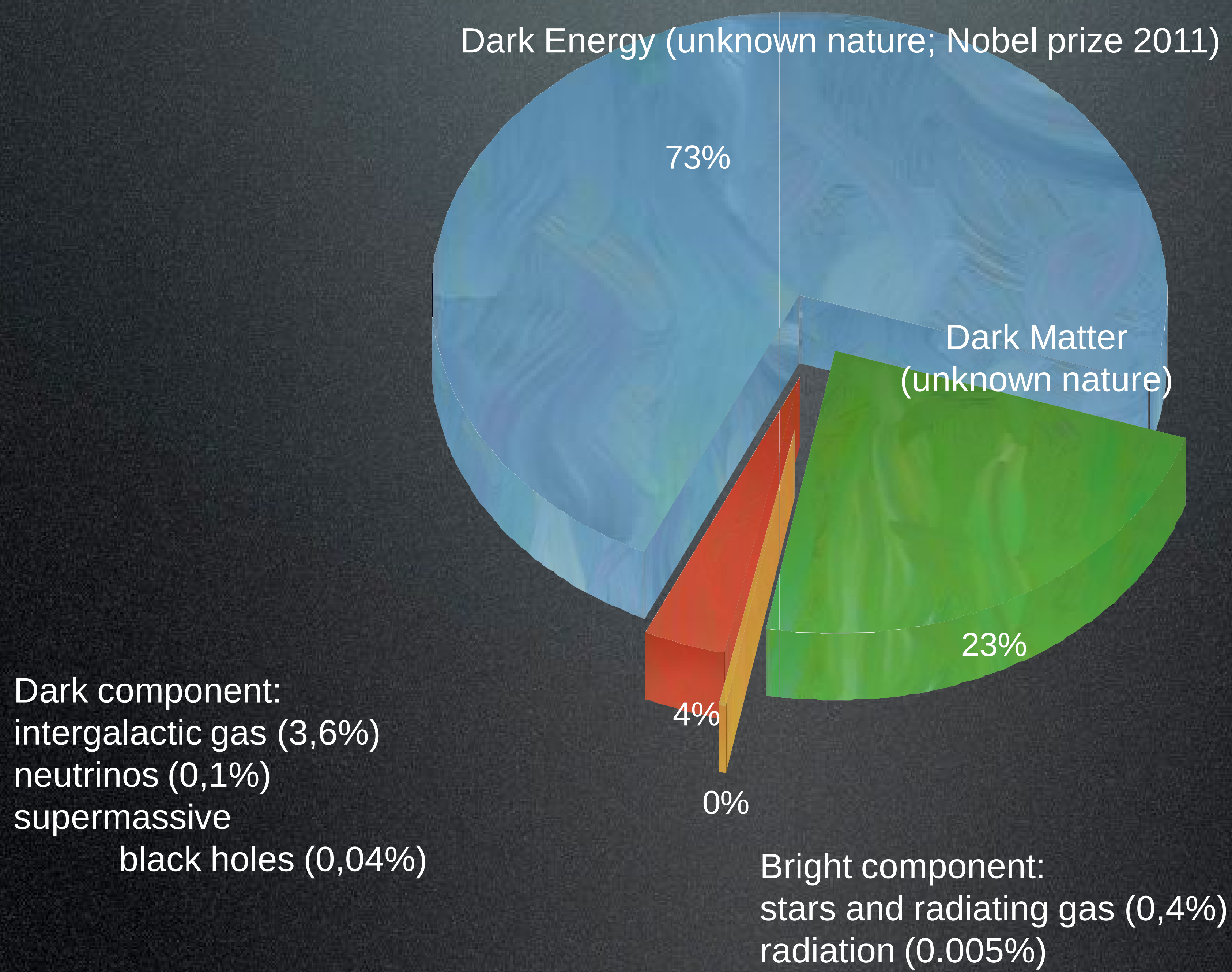
–

CDM cosmology

Brief history of the Universe



Composition of the universe



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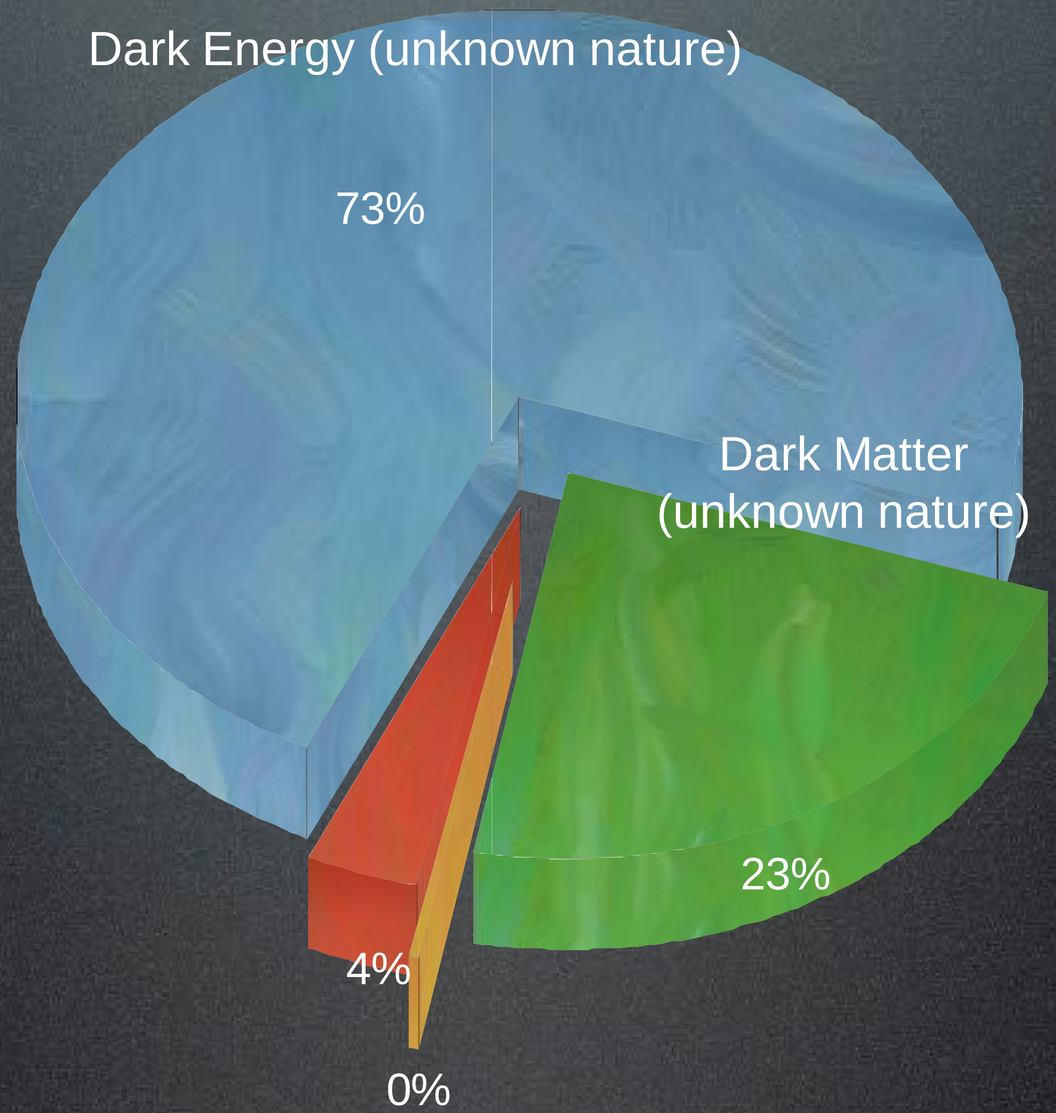


Dark component:
intergalactic gas (3,6%)
neutrinos (0,1%)
supermassive
black holes (0,04%)

Bright component:
stars and radiating gas (0,4%)
radiation (0.005%)

Dark Matter

Weakly-interacting, massive, neutral, stable particles beyond the Standard Model.
WIMPs = Weakly Interacting Massive Particles

- Neutralino
- Axion
- Sterile neutrino
- Gravitino
- Sneutrino
- Axino
- Heavy photon
- Inert Higgs
- Wimpzilla
- ???

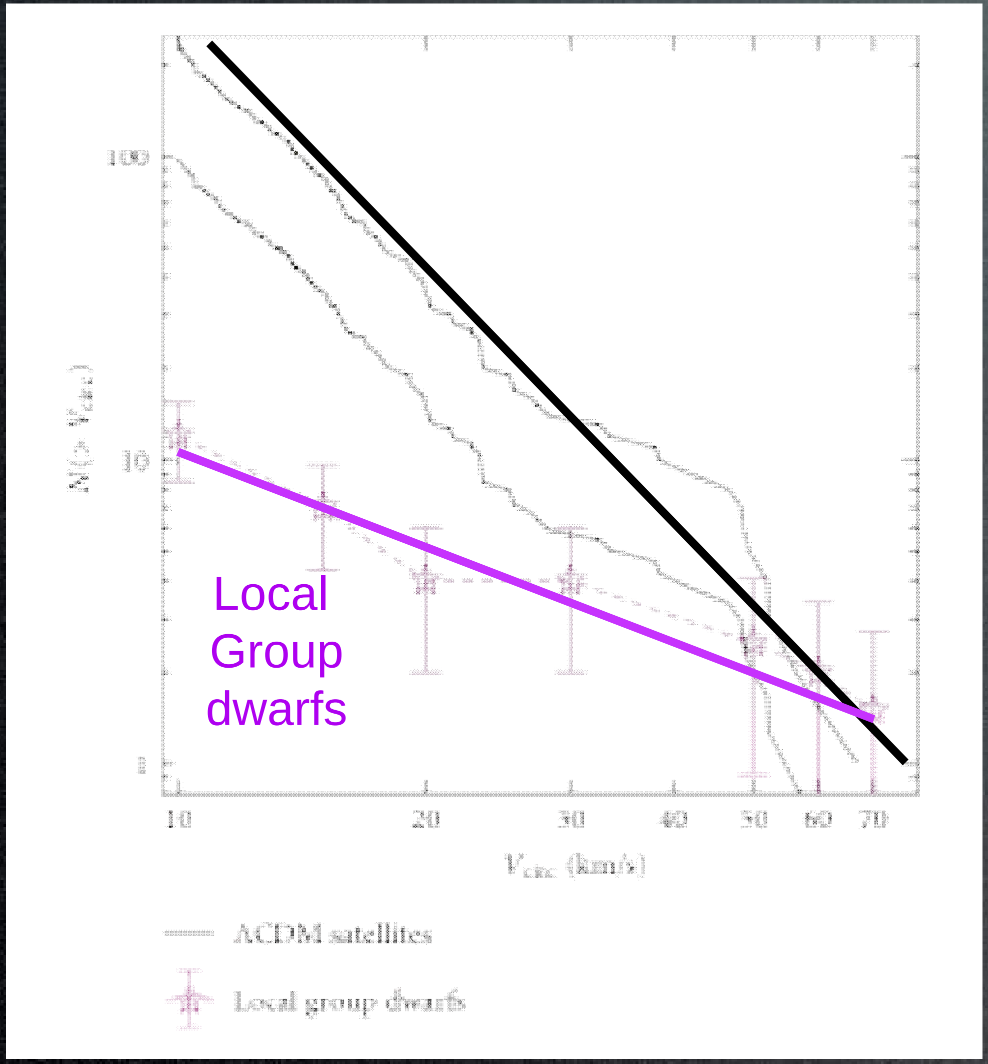
Large and small scales in ΛCDM

CDM - hypothetic massive particles with very small thermal velocity dispersion -- “cold” -- at the beginning of structure formation, which interact with normal matter via gravity only

Millenium simulation

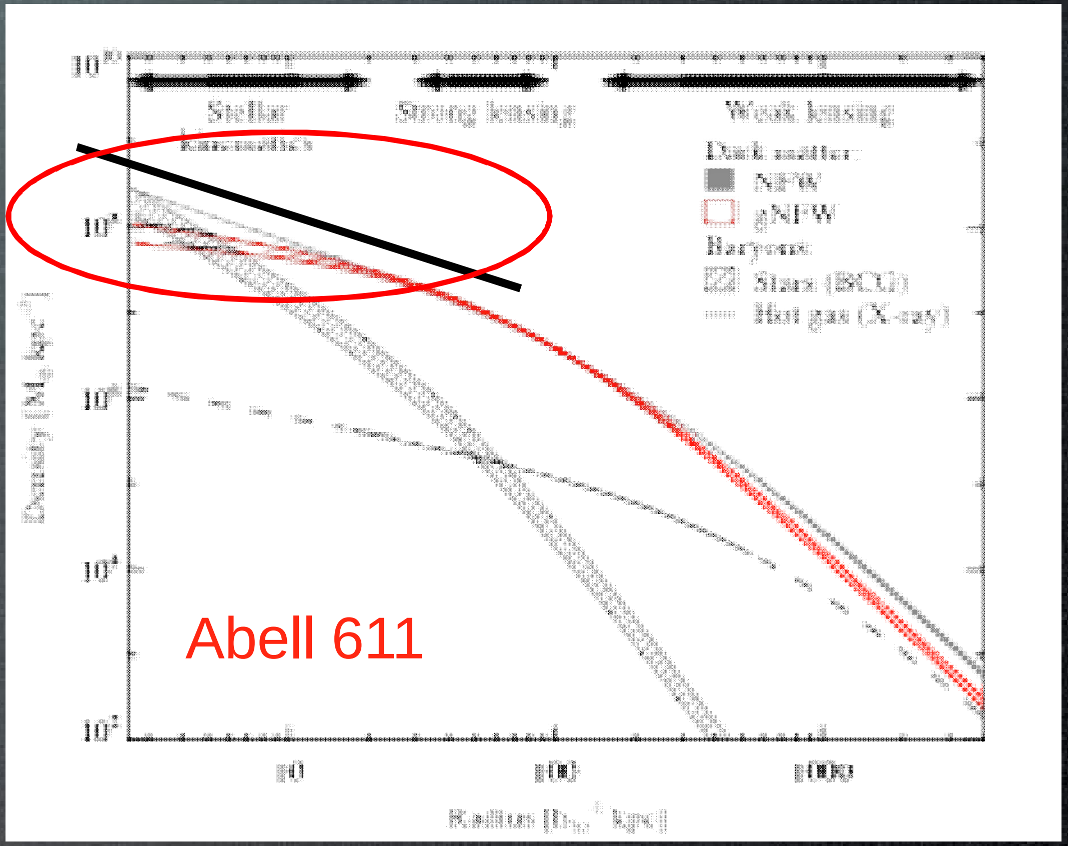
Problems of standard CDM

Sub-structure problem
("missing satellites")



Kravtsov 2010

Core/cusp problem (central density profile)



Newman, et al 2009

Density in the inner halo is flatter than R^{-1}, though other studies indicate the opposite

2-component CDM

Dark Matter

WIMP – ~~lightest~~ neutralino – mixed particle of bino, wino and higgsinos

$$\tilde{\chi}_1^0 = N_{11}\,\tilde{B}^0 + N_{12}\,\tilde{W}_3^0 + N_{13}\,\tilde{H}_d^0 + N_{14}\,\tilde{H}_u^0$$

if masses are degenerate, decays can be kinematically forbidden and more than one can be stable

Axion

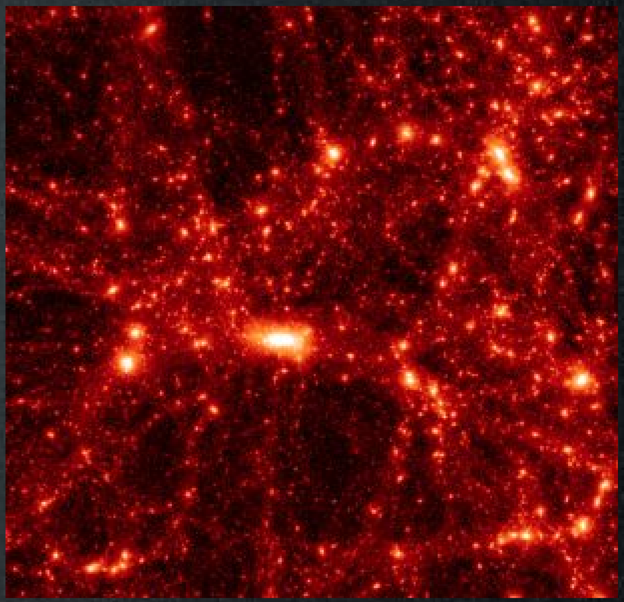
can be mixed with photons

A multi-component flavor-mixed CDM (2cDM) emerges

a 2-component toy model

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

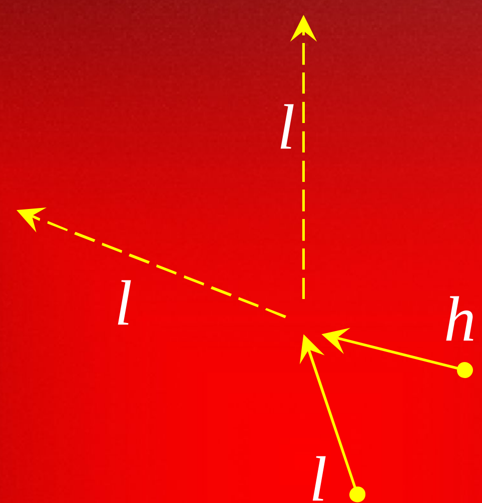
2cDM halos



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

a 2-component DM toy model

$v_{kick} \equiv (\Delta m / m)^{1/2}$



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

small-mass (dwarf) halos destroyed

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

central density cusps softened

$\rho = r^{-a}\,(a<1)$

Technical: Interaction of 2-comp particles

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

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

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

Technical: 2-comp 2-particle dynamics

$$H^{\text{free}} = \begin{pmatrix} H^{\text{free}}_{hh} & 0 & 0 & 0 \\ 0 & H^{\text{free}}_{hl} & 0 & 0 \\ 0 & 0 & H^{\text{free}}_{lh} & 0 \\ 0 & 0 & 0 & H^{\text{free}}_{ll} \end{pmatrix}$$

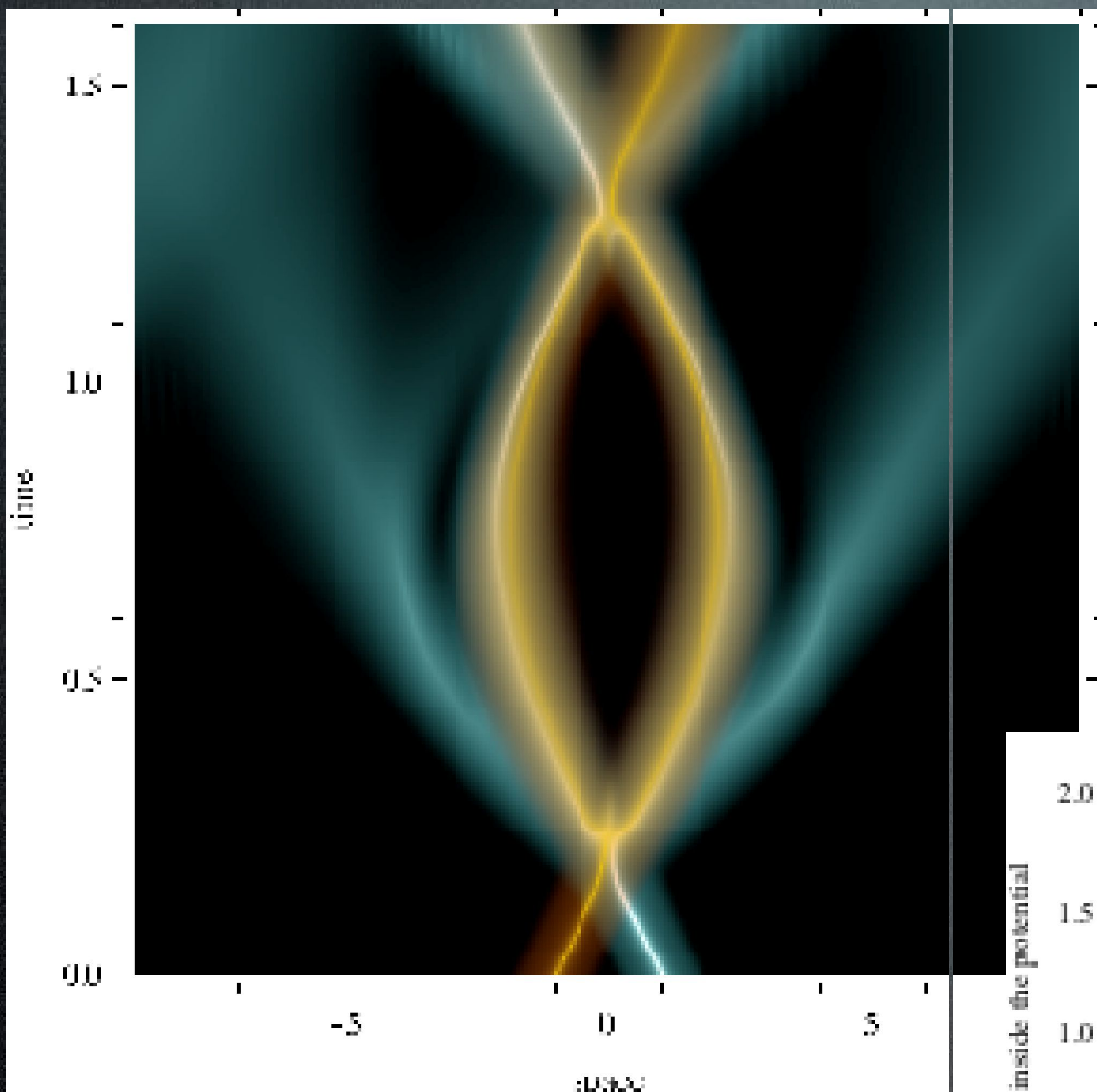
$$\begin{aligned} H^{\text{free}}_{hh} &= -\partial^2_{x_1x_1}/2m_h - \partial^2_{x_2x_2}/2m_h, \\ H^{\text{free}}_{hl} &= -\partial^2_{x_1x_1}/2m_h - \partial^2_{x_2x_2}/2m_l - \Delta m, \\ H^{\text{free}}_{lh} &= -\partial^2_{x_1x_1}/2m_l - \partial^2_{x_2x_2}/2m_h - \Delta m, \\ H^{\text{free}}_{ll} &= -\partial^2_{x_1x_1}/2m_l - \partial^2_{x_2x_2}/2m_l - 2\Delta m. \end{aligned}$$

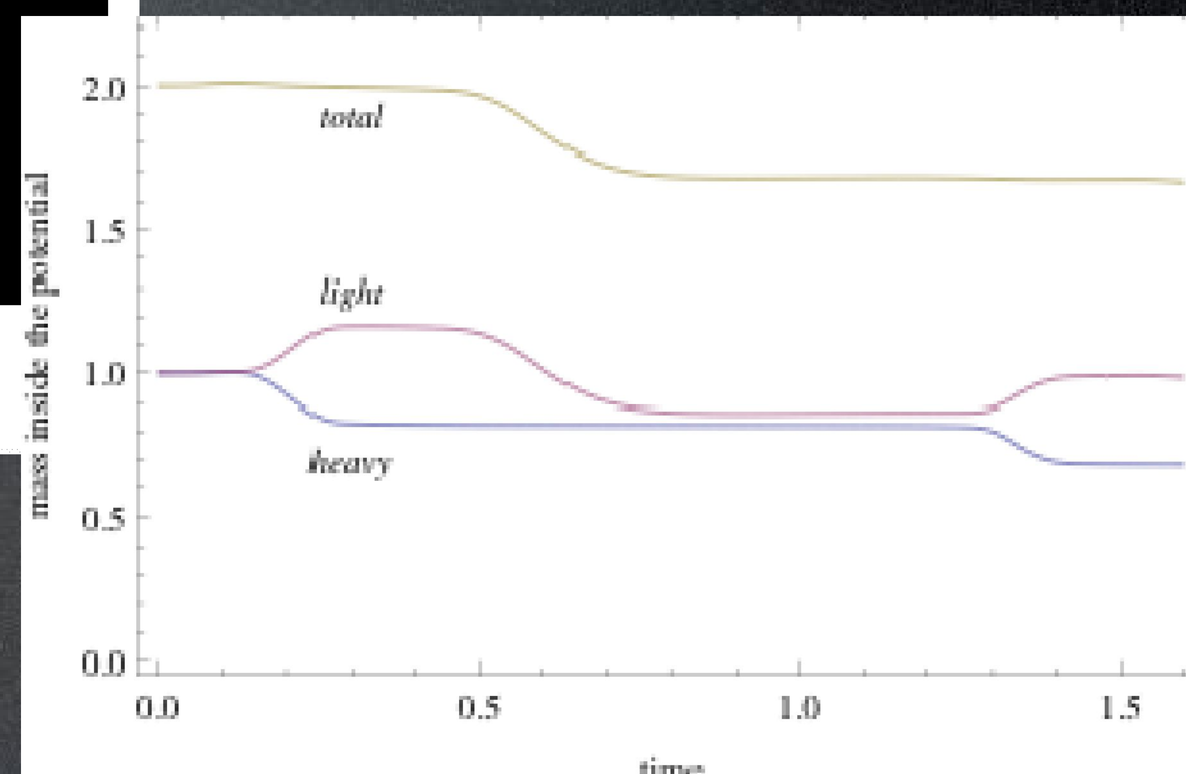
$$H^{\text{grav}} = \begin{pmatrix} H^{\text{grav}}_{hh} & 0 & 0 & 0 \\ 0 & H^{\text{grav}}_{hl} & 0 & 0 \\ 0 & 0 & H^{\text{grav}}_{lh} & 0 \\ 0 & 0 & 0 & H^{\text{grav}}_{ll} \end{pmatrix}$$

$$\begin{aligned} H^{\text{grav}}_{hh} &= m_h\phi(x_1) + m_h\phi(x_2), \\ H^{\text{grav}}_{hl} &= m_h\phi(x_1) + m_l\phi(x_2), \\ H^{\text{grav}}_{lh} &= m_l\phi(x_1) + m_h\phi(x_2), \\ H^{\text{grav}}_{ll} &= m_l\phi(x_1) + m_l\phi(x_2). \end{aligned}$$

Technical: 2-comp 2-particle evaporation

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





2cDM simulations - setup

- Code: open source Gadget-2 (V.Springel, 2005) modified to include DM particle interactions (conversions)
- ΛCDM cosmology: σ_8=0.9, Λ=0.7, Ω_{DM}=0.3, Ω_{tot}=1, h=0.7, n=1
- Box (50 Mpc/h)^3 comoving
- Large runs: 128M (=504^3) SPH-DM (2cDM) particles and
524M (=806^3) pure DM particles (reference run)
- Smallest resolution: 3.5 kpc/h (2cDM) & 2.2 kpc/h (CDM)
- Resource: XSEDE (former TeraGrid)
Kraken (NICS), Trestles (SDSC), Lonestar & Ranger (TACC)
- SU usage: 150 kSU (SU=CPU-hour) for largest SPH 2cDM runs

Implementation

- DM particles are treated as SPH (smooth particle hydro)
- Pairs if 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 conserved

$$V = (U \otimes U)^\dagger \begin{pmatrix} V_{\alpha\alpha} & 0 & 0 & 0 \\ 0 & V_{\alpha\beta} & 0 & 0 \\ 0 & 0 & V_{\beta\alpha} & 0 \\ 0 & 0 & 0 & V_{\beta\beta} \end{pmatrix} U \otimes U,$$

$$A_{(s_i t_i)(s_f t_f)} = \langle m_{s_f} m_{t_f} | V_{(s_f t_f)(s_i t_i)} | m_{s_i} m_{t_i} \rangle$$

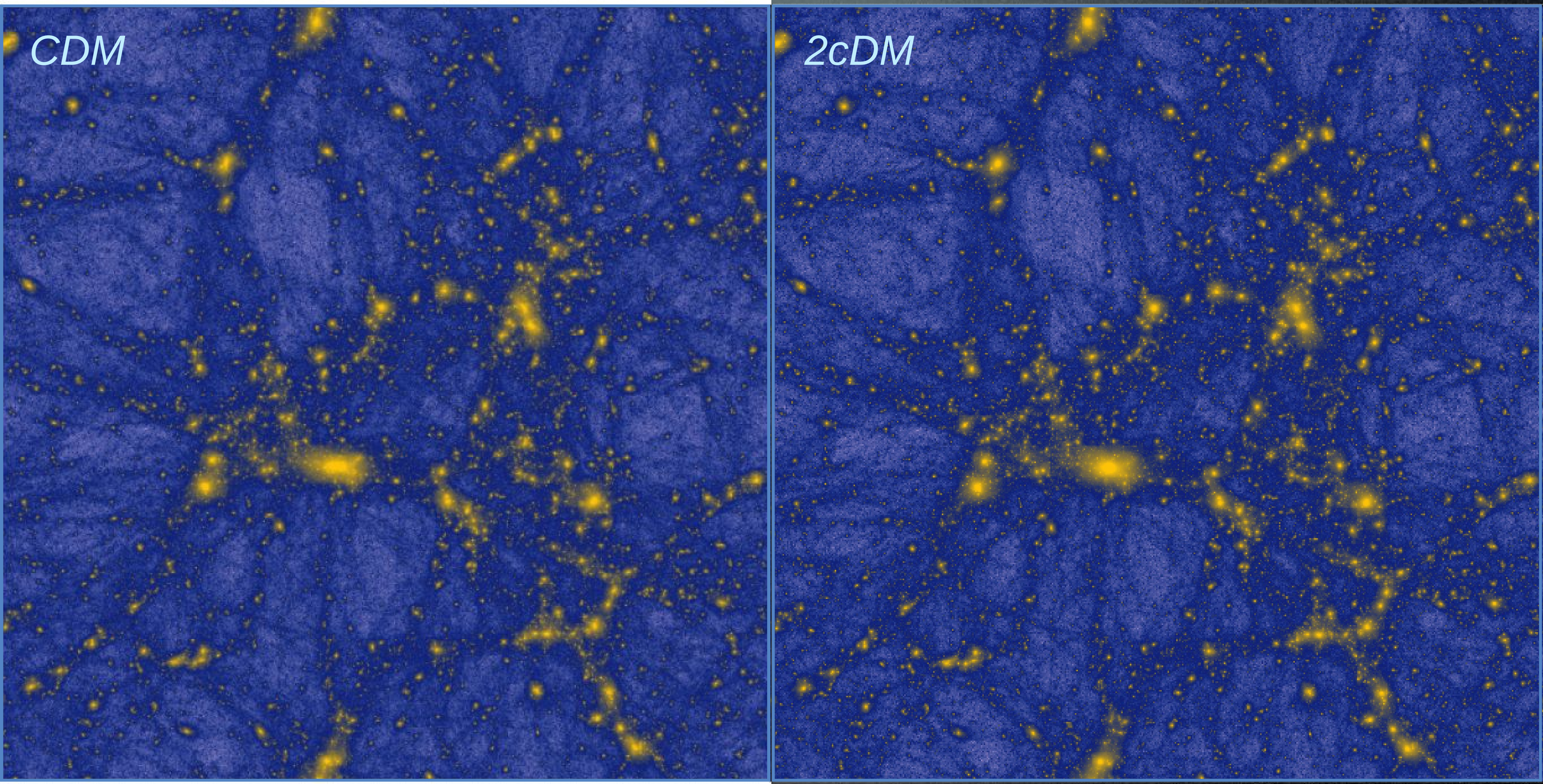
$$\sigma_{s_i t_i \to s_f t_f} \simeq (p_{s_f}/p_{s_i}) \left| A_{(s_i t_i)(s_f t_f)} \right|^2$$

$$\sigma_{s_i t_i \to s_f t_f} = \sigma \, \frac{p_{s_f}}{p_{s_i}} \, \Theta(E_{s_f t_f}) \, B_{(s_i t_i)(s_f t_f)}$$

$$B = (B_{ij}) = \begin{pmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \end{pmatrix}$$

2cDM simulations

--- No modifications on large scales ---



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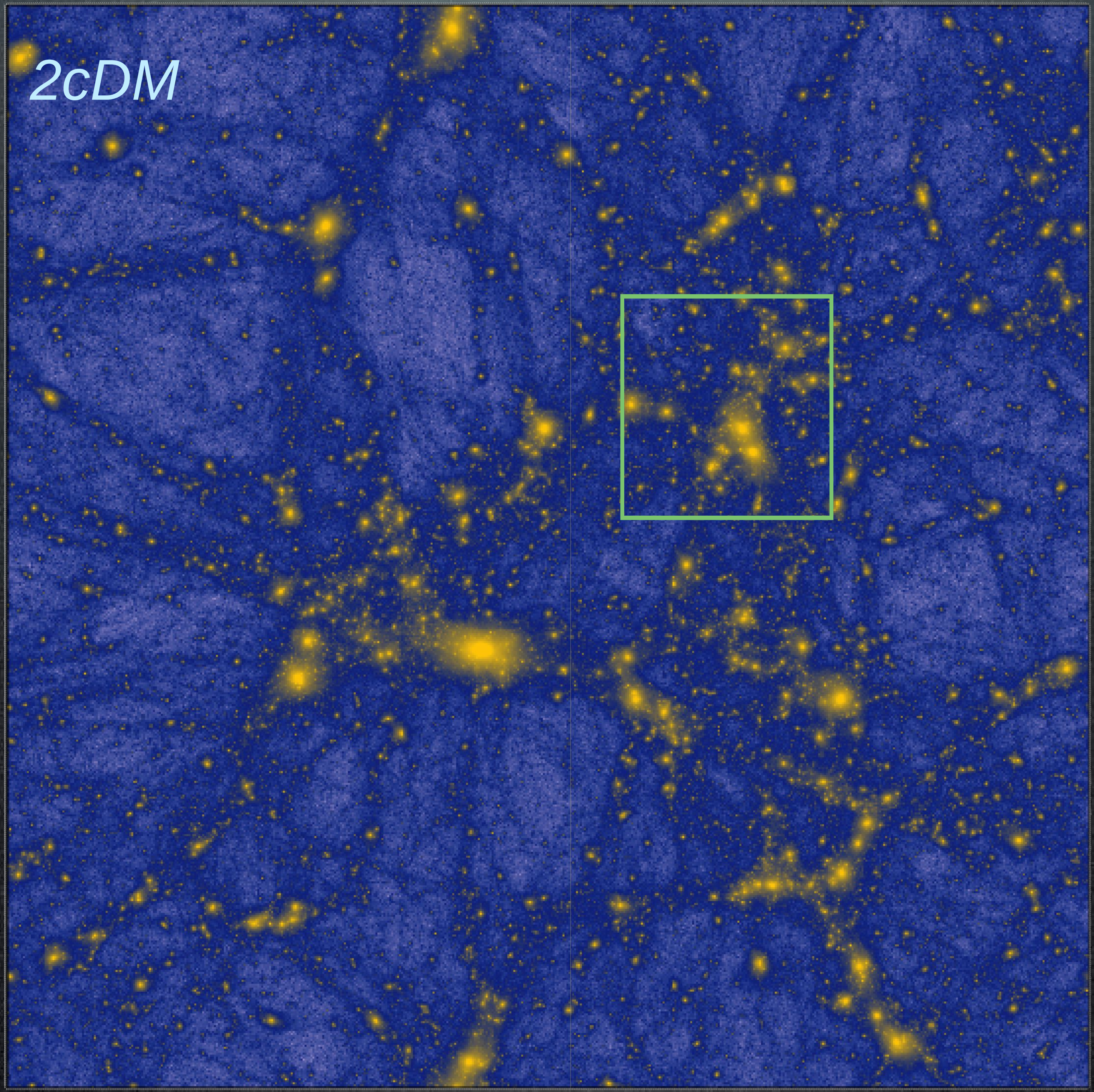
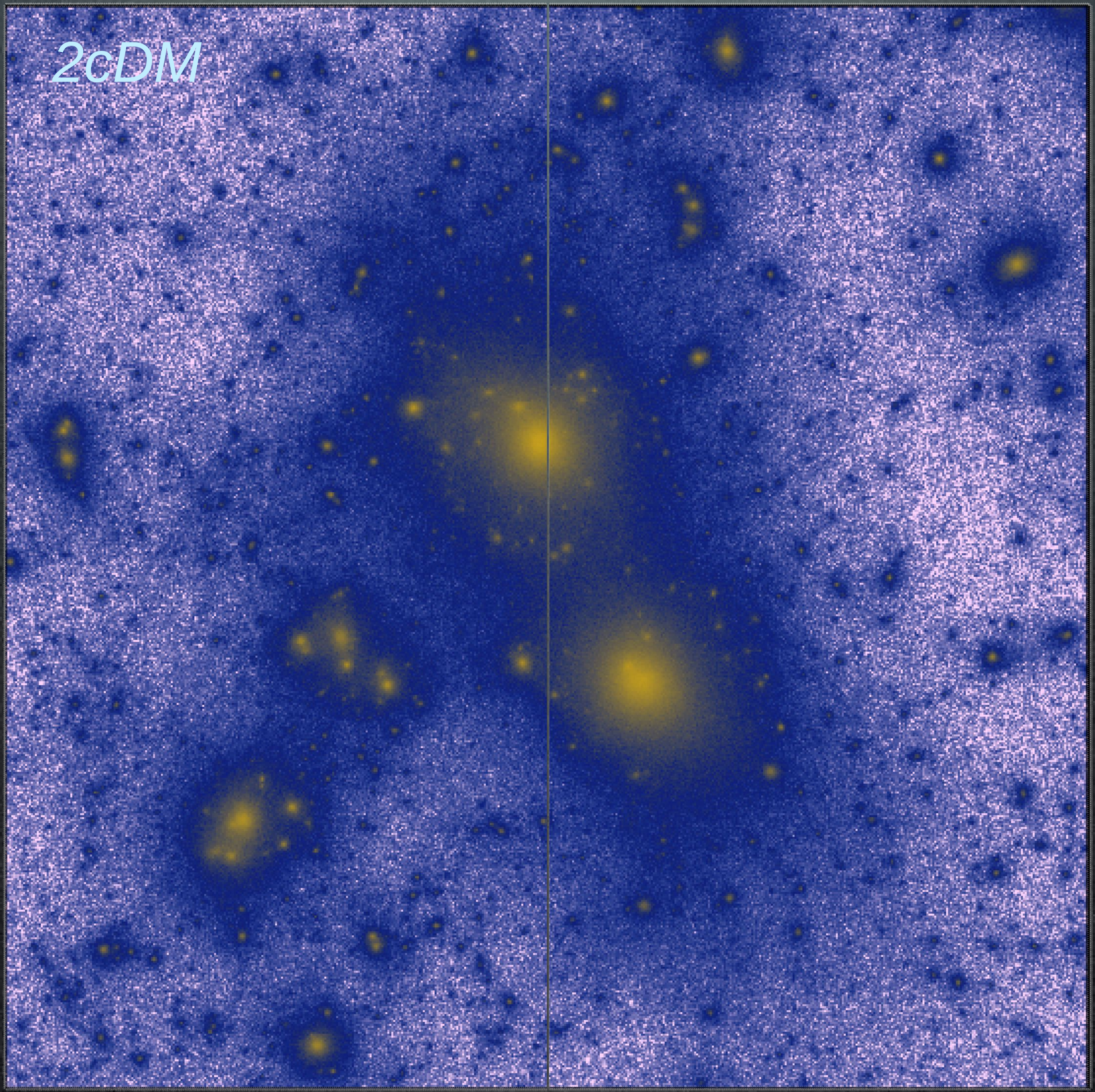


2cDM simulations

--- Less substructure on large scales ---



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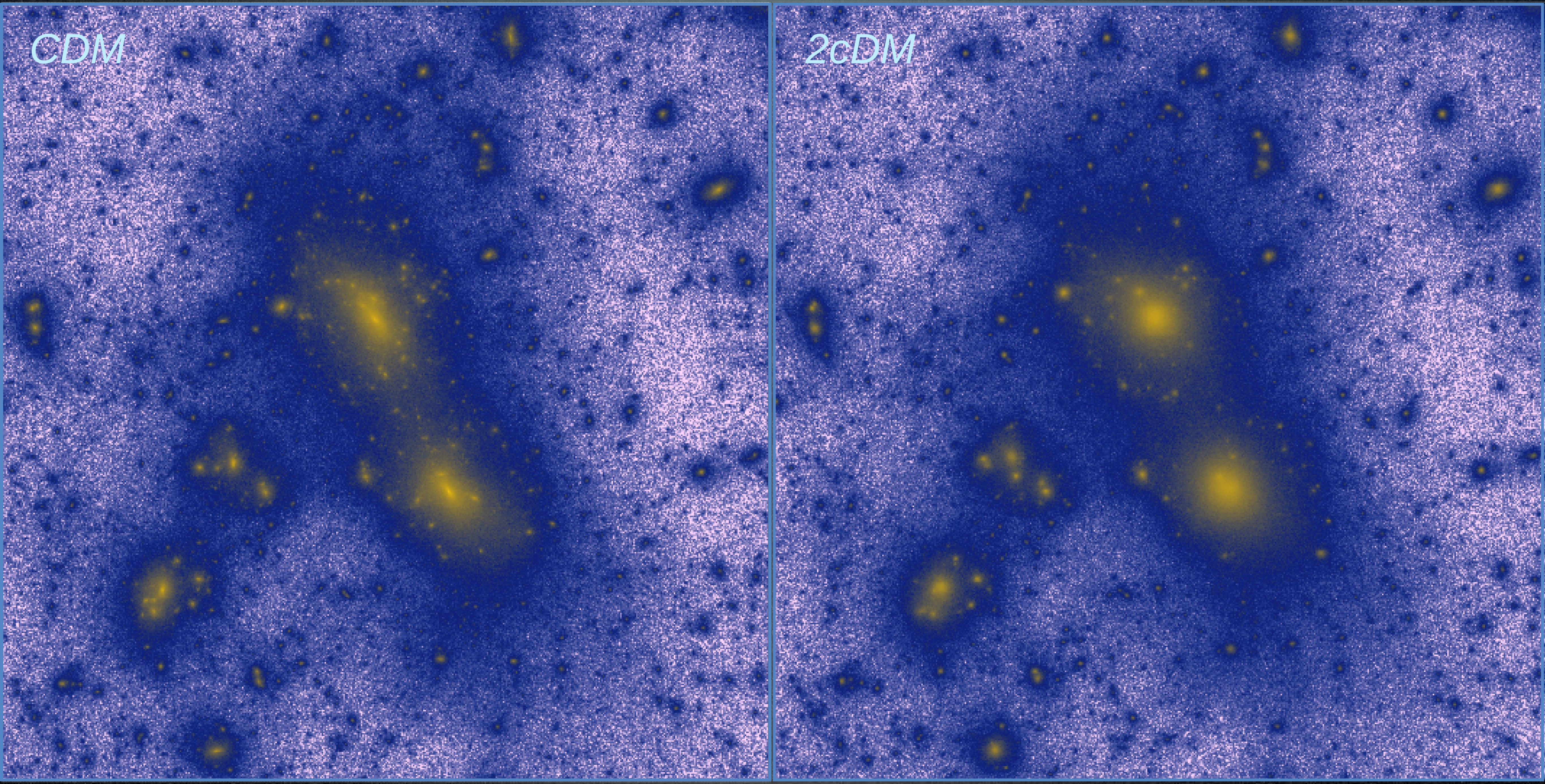
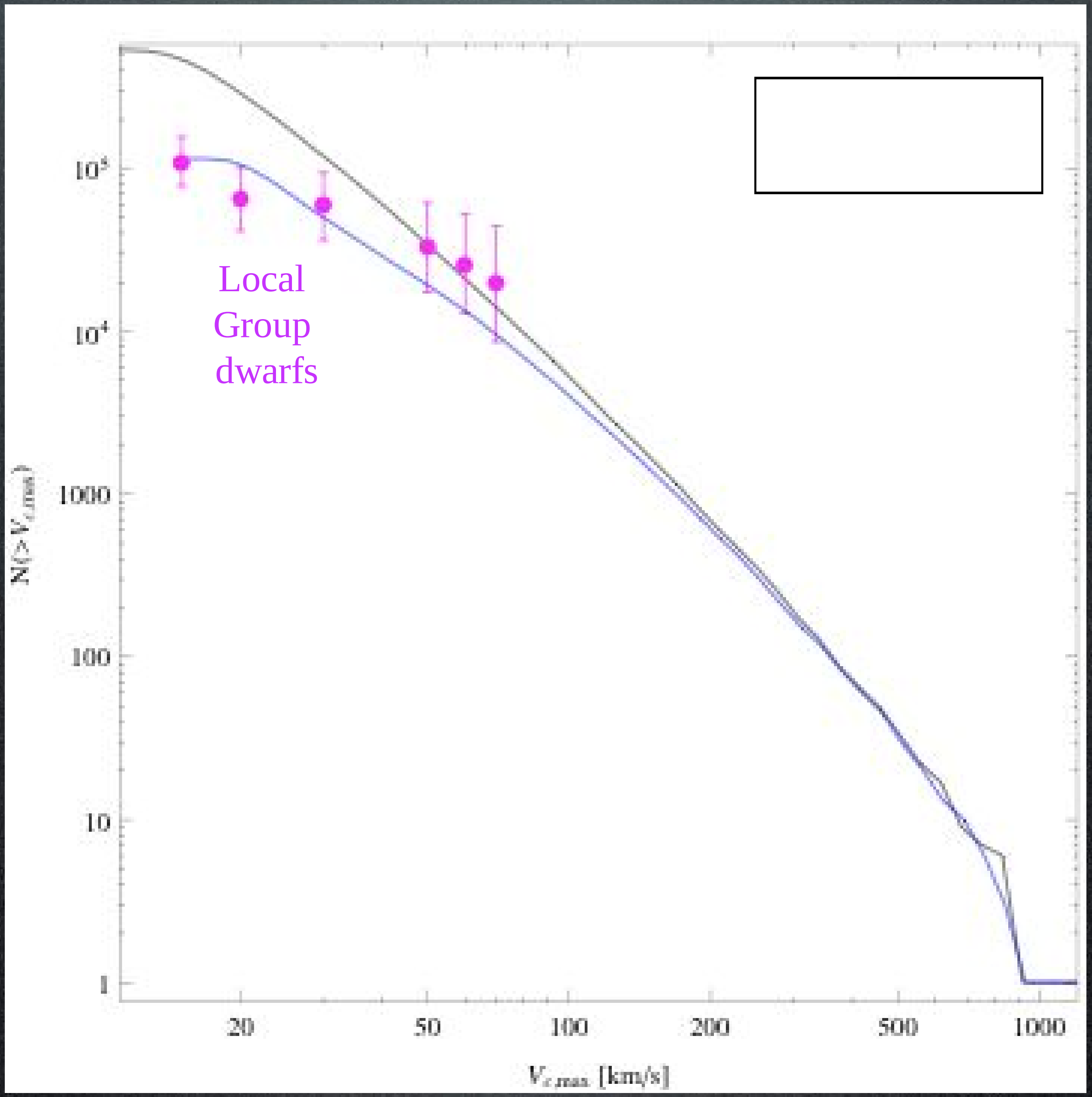


2cDM vs CDM & observations

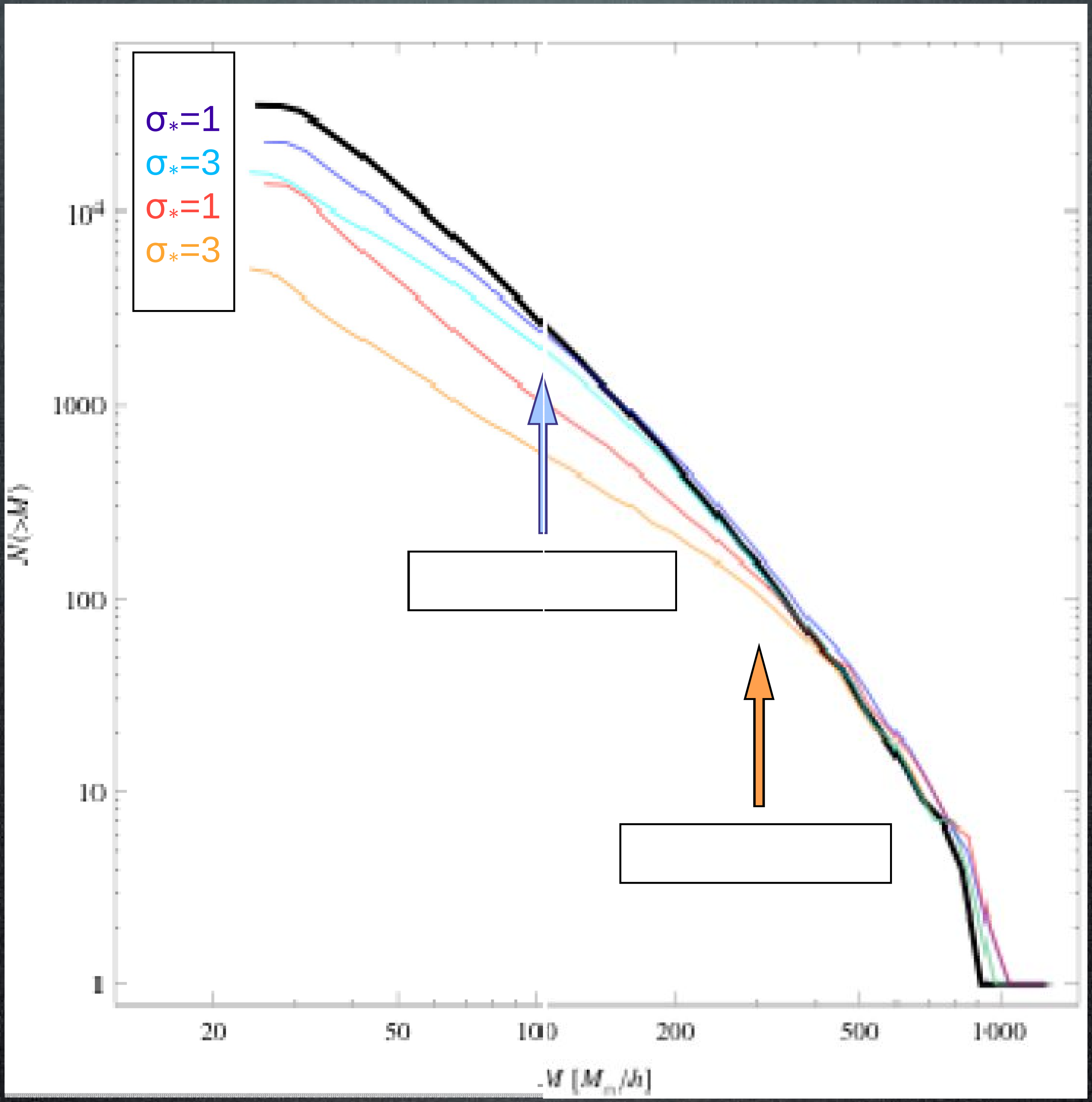
maximum circular velocity function
(# of halos with $V_{circ,max}$ greater than a given value)



Key parameters

$V_{kick}=(\Delta m/2m)^{1/2}$

$\sigma_*=\sigma/m$



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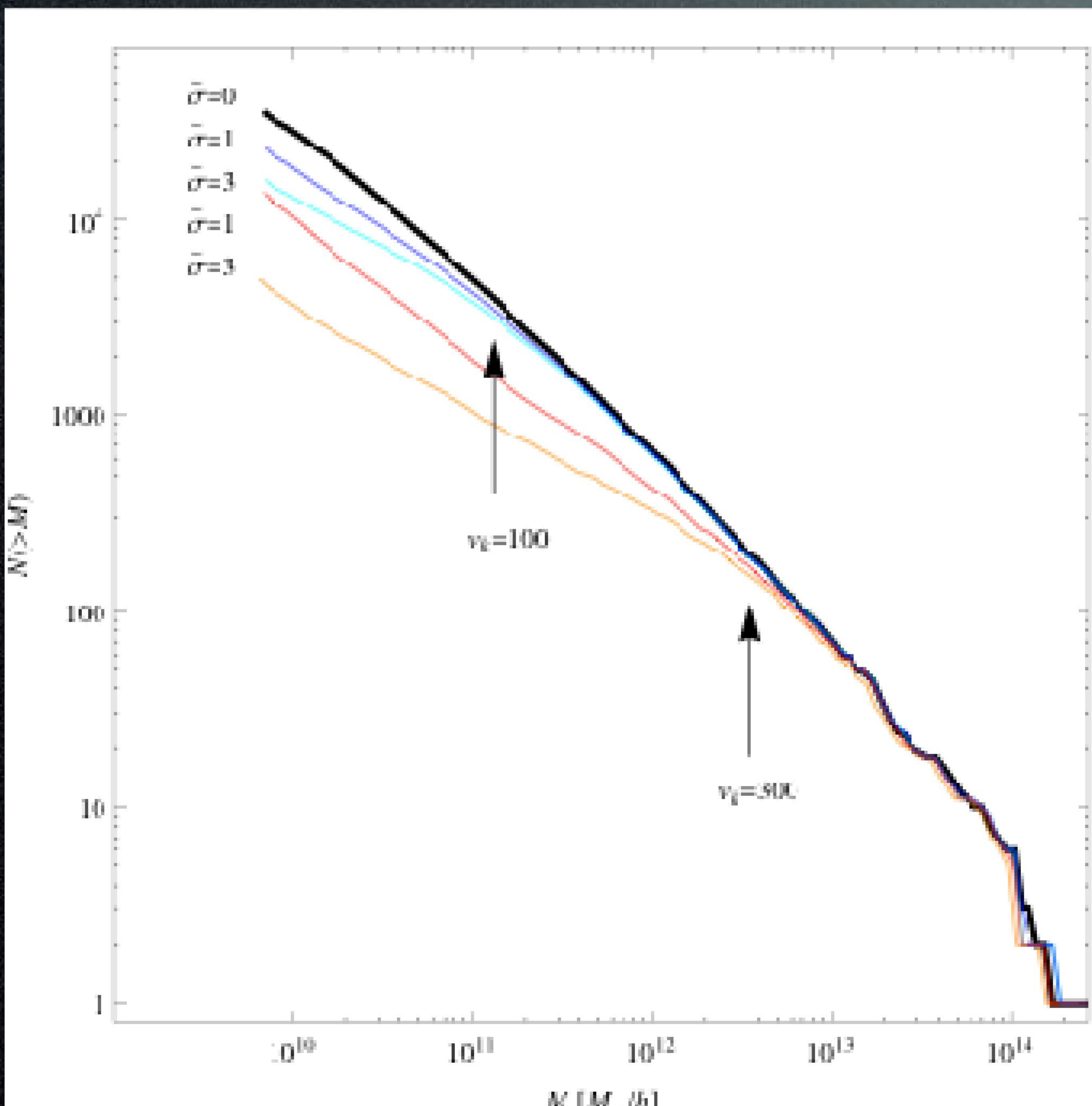
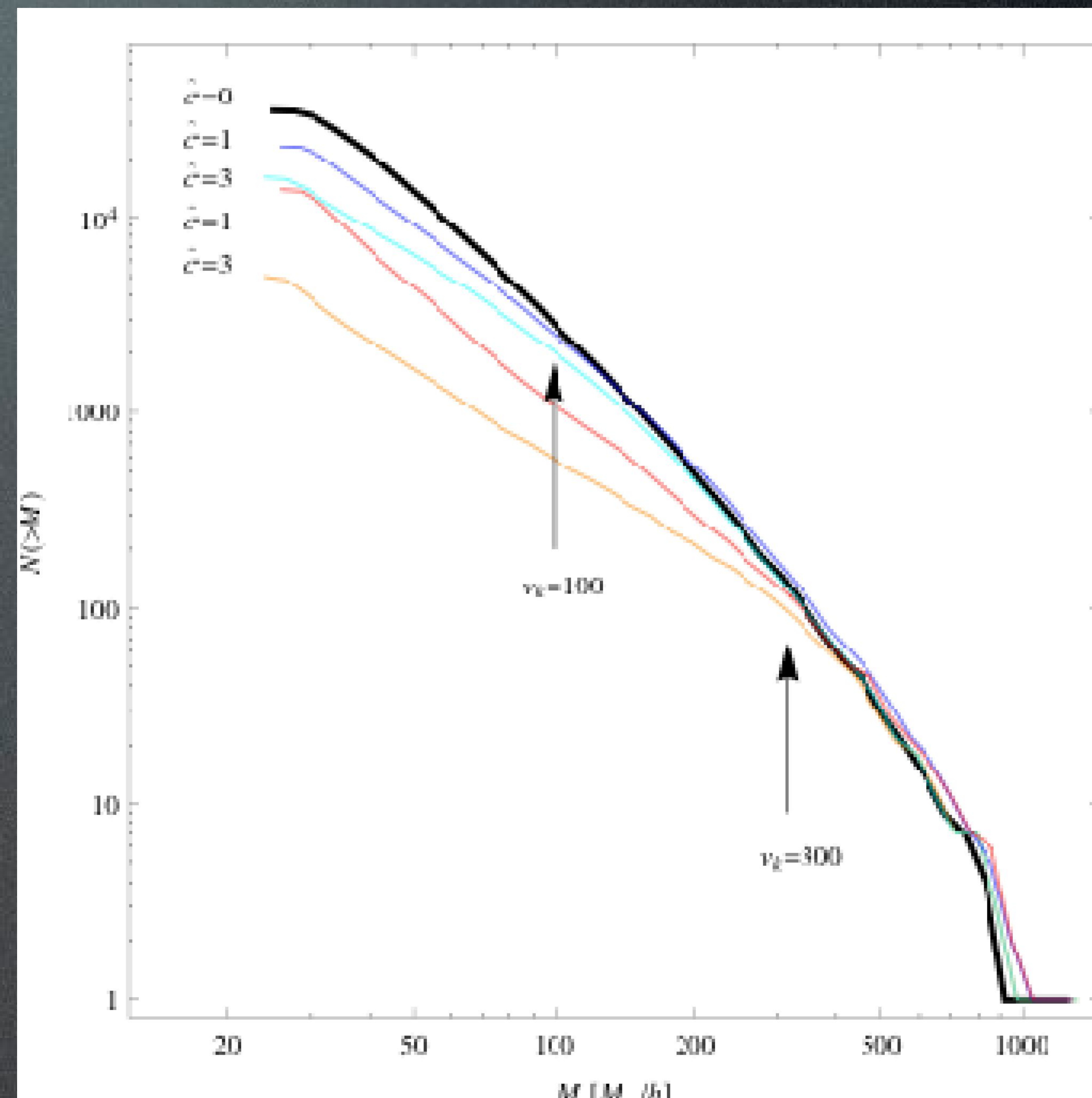
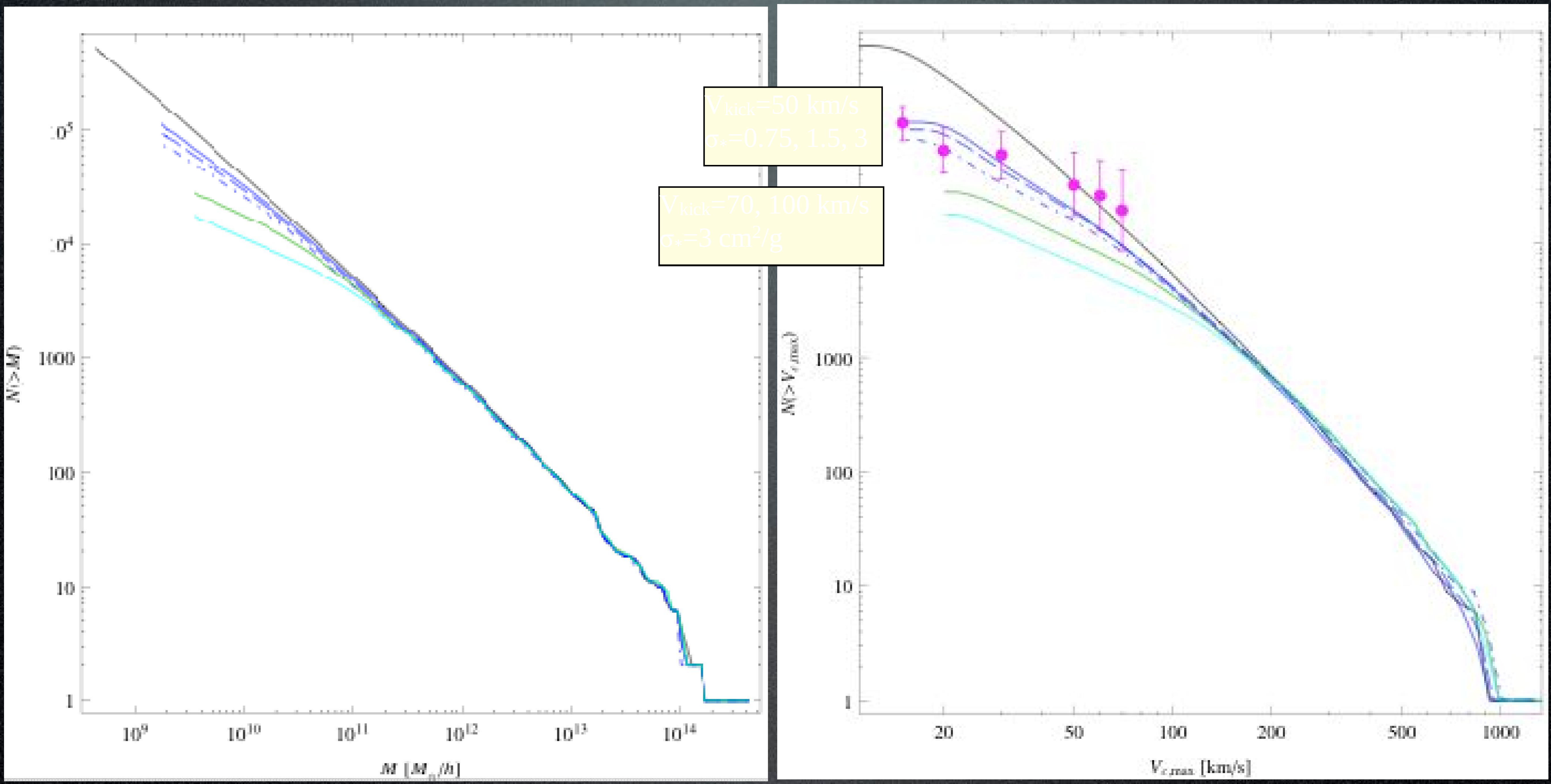




2cDM vs CDM & observations

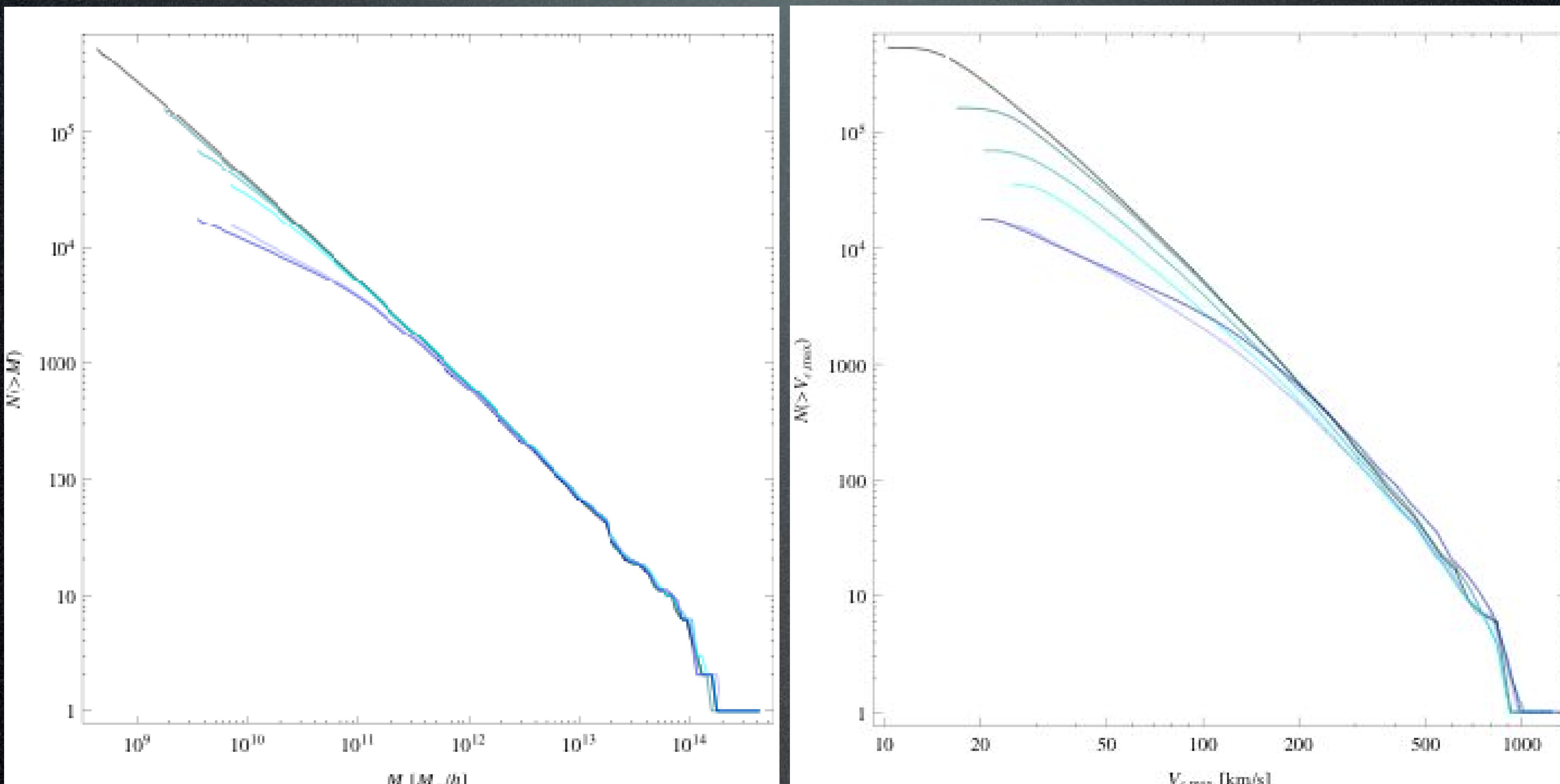
mass and velocity functions

(# of halos with M or $V_{circ,max}$ greater than a given value)



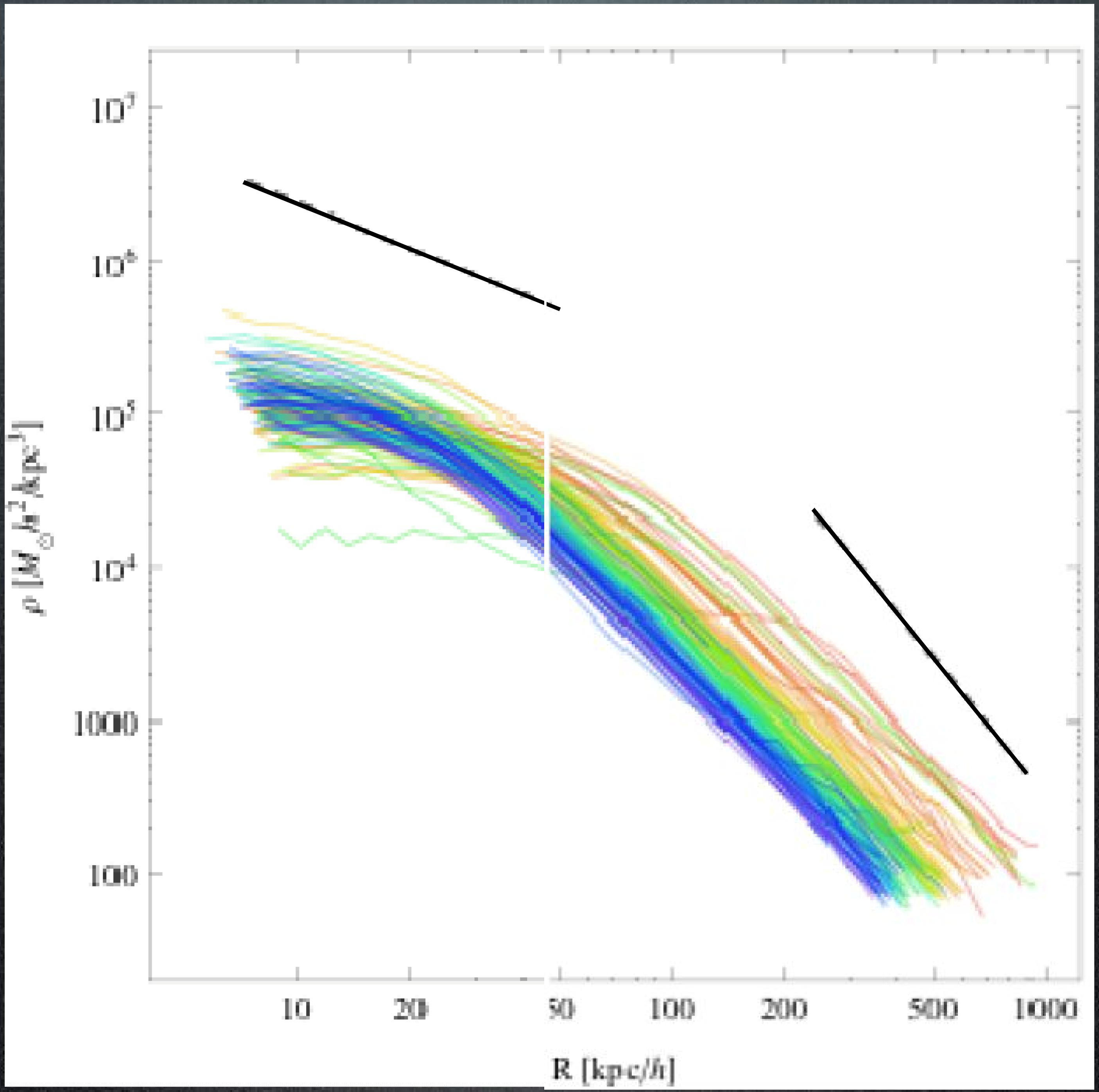
Numerical convergence

mass and velocity functions from simulations
with different particle number (V_{kick}=100km/s, σ_*=3 cm^2/g)



2cDM vs CDM

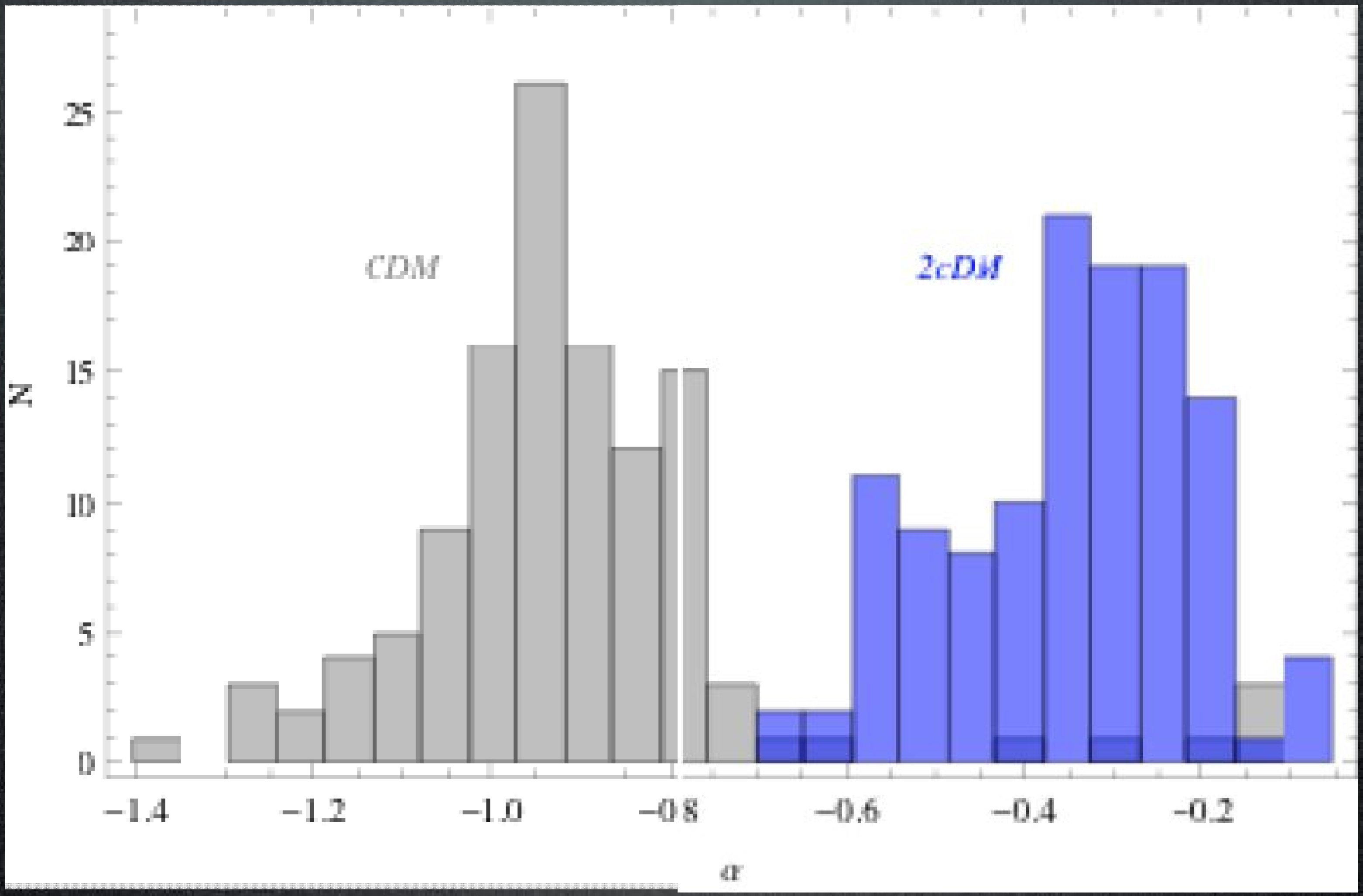
density profiles



2cDM vs CDM

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 CDM

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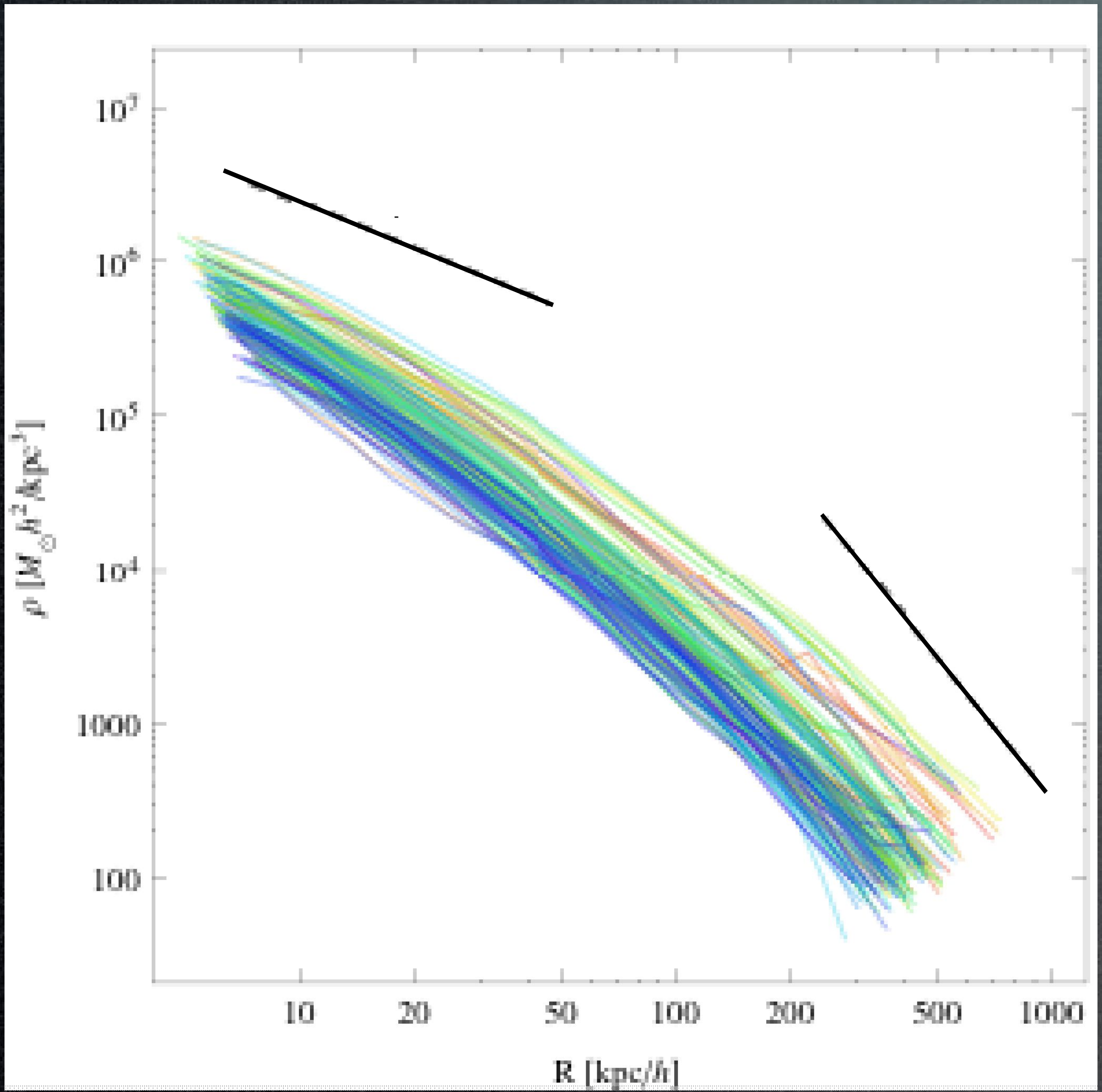
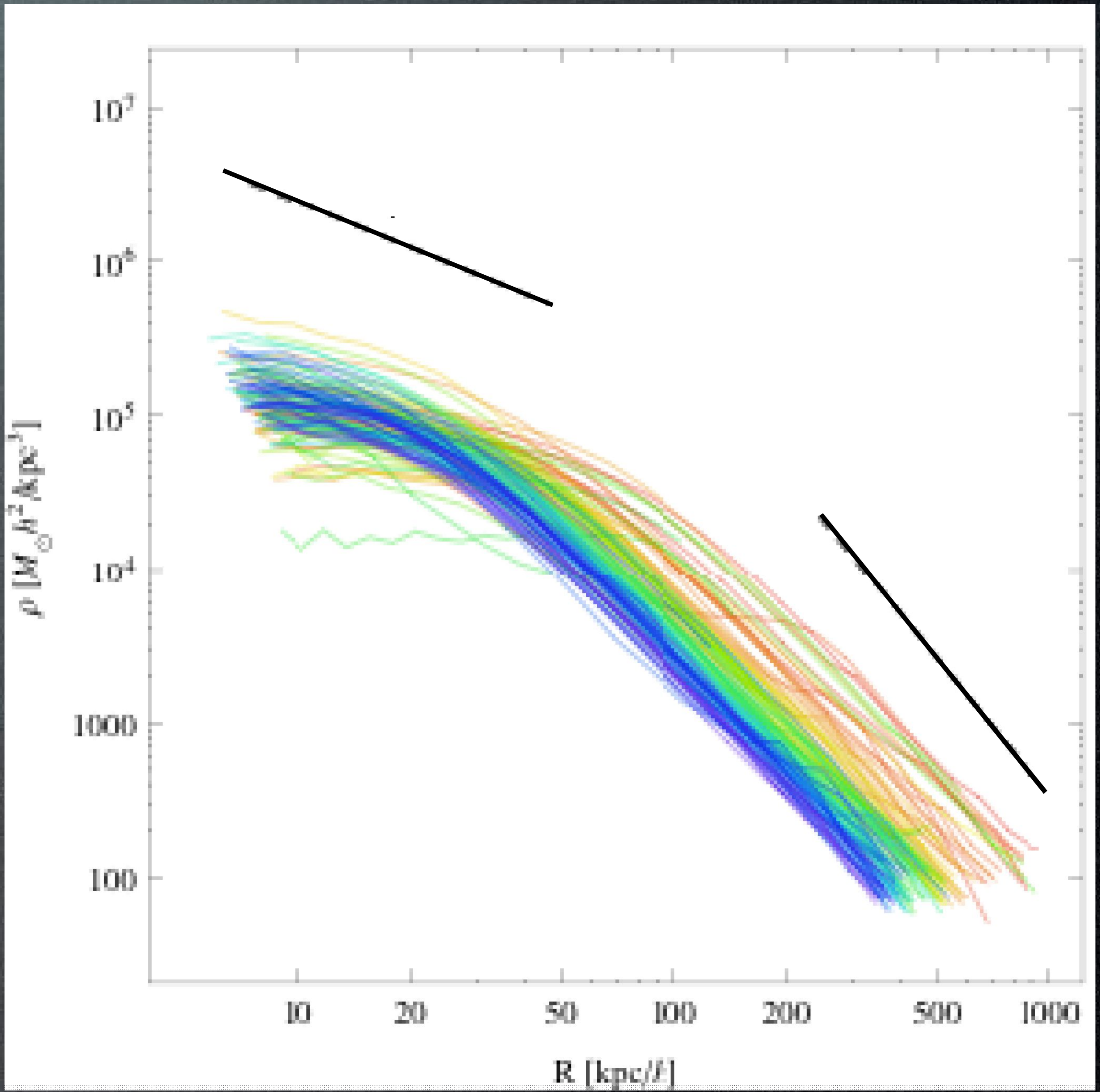
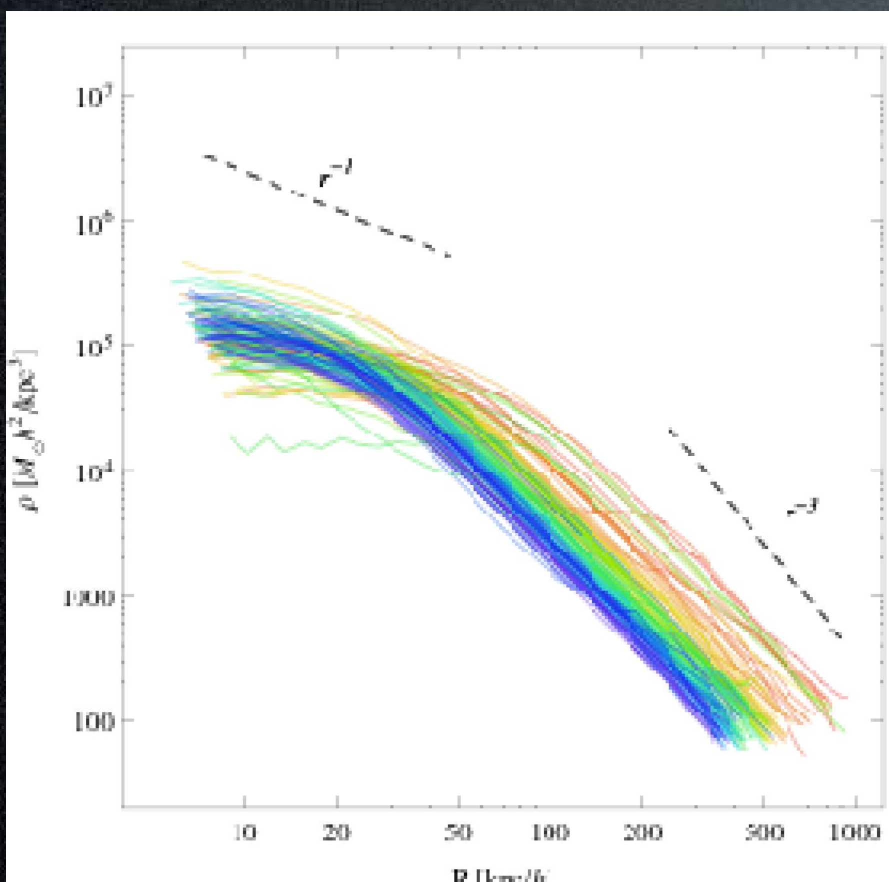




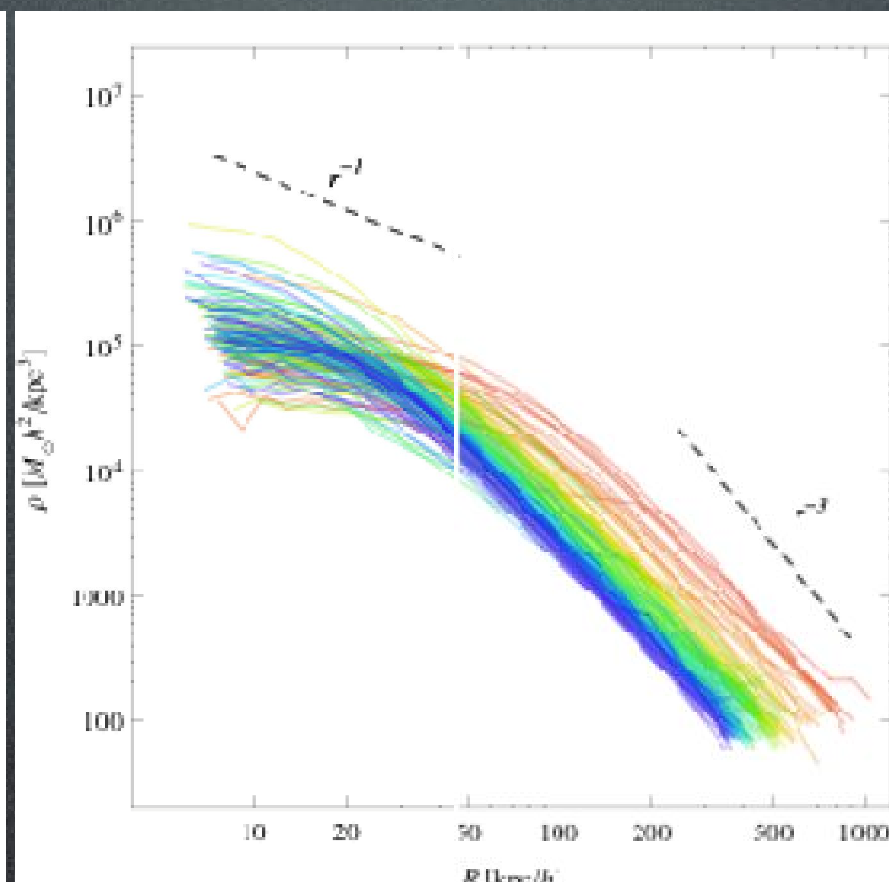
2cDM

density profiles

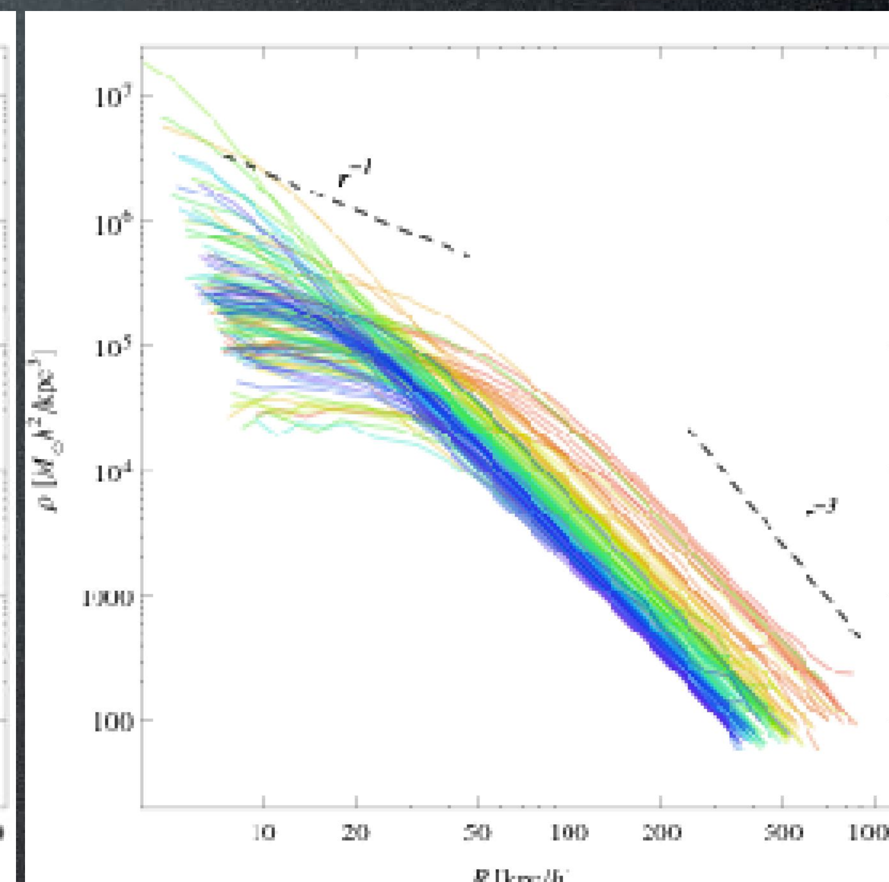
V_{kick} = 50 km/s
σ_* = 0.75 cm^2/g



V_{kick} = 50 km/s
σ_* = 1.5 cm^2/g

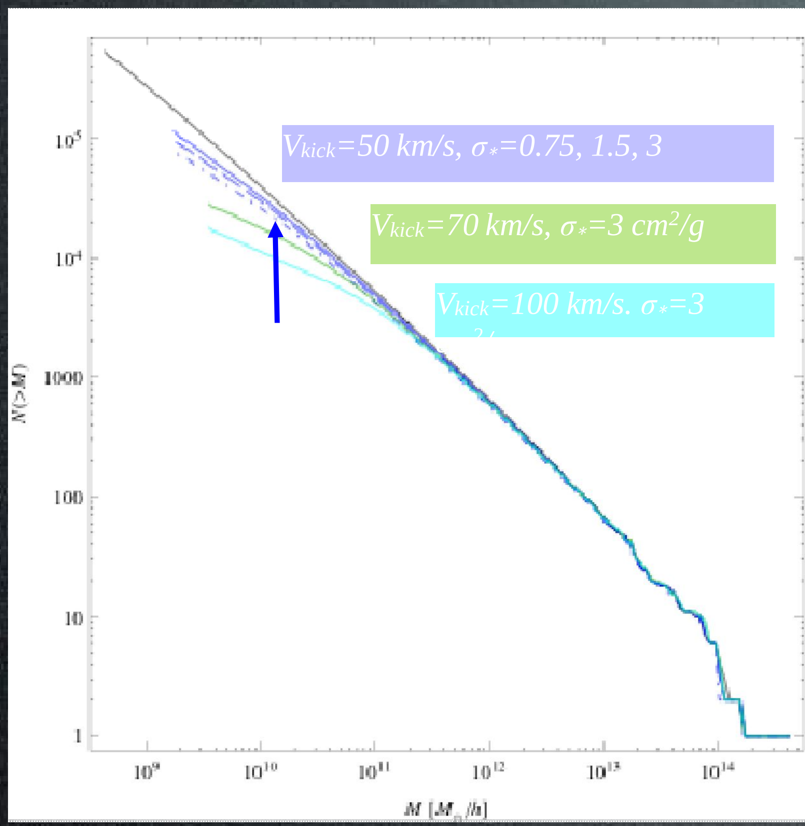


V_{kick} = 50 km/s
σ_* = 3 cm^2/g

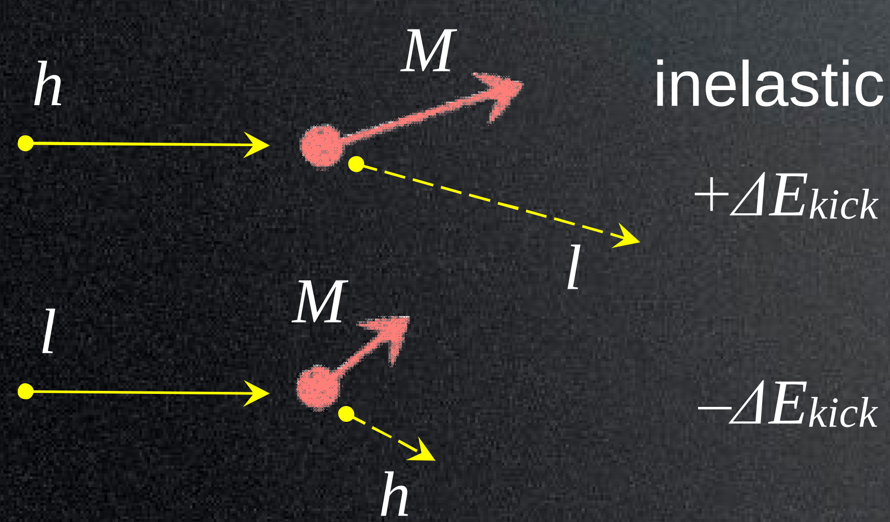


Predictions/Conclusions

Astro observations



Direct detection experiments



- DM with at least two components is preferred
- break in mass function of dark matter halos at $M \sim 10^{10} M_\odot$
- $v_{kick} \sim (\Delta m / m)^{1/2} \sim 50\ km/s$, hence: $\Delta m/m \sim 10^{-8}$
- axion-photon DM disfavored (and other non-degenerate models)
- neutralino-like (or other massive, mixed) DM favored
- such $\Delta m/m \sim 10^{-8}$ means: if $m_\chi \sim few \times 100\ GeV$, then $\Delta m_\chi \sim few\ keV$
- inelastic events with $\Delta E \sim few\ keV$ in direct detection DM

Conclusions

- flavor mixing and oscillations were proposed back in 1957 by B. Pontecorvo
- mass eigenstate conversions have not so far been discussed (see: Medvedev, J Phys A: Math Theor 43 (2010) 372002)
- “evaporation” is a new effect not related to tunneling, nuclear reactions, etc
- in “evaporation” just the particle’s probability is re-distributed in space, particle identity is not changed
- full-scale cosmological simulations of the 2-component Dark Matter model were performed
- 2-component Dark Matter model can resolve :
  - cusp/core problem (too steep density profiles in centers of dark halos)
  - substructure problem (overabundance of dwarf satellites in CDM)
- predictions:
  - break in mass function of dark matter halos at $M{\sim}10^{10}M_\odot$
  - axion-photon DM disfavored
  - neutralino (or other massive mixed) DM favored
  - $\Delta m/m \sim 10^{-8}$ which means: if $m_\chi \sim few \times 100\ GeV$, then $\Delta m_\chi \sim few\ keV$
  - inelastic events with $\Delta E \sim few\ keV$ in direct detection DM (CoGeNT ?, DAMA ?)