Dark Matter: Galaxy Formation, Small Scale Crisis, and WDM

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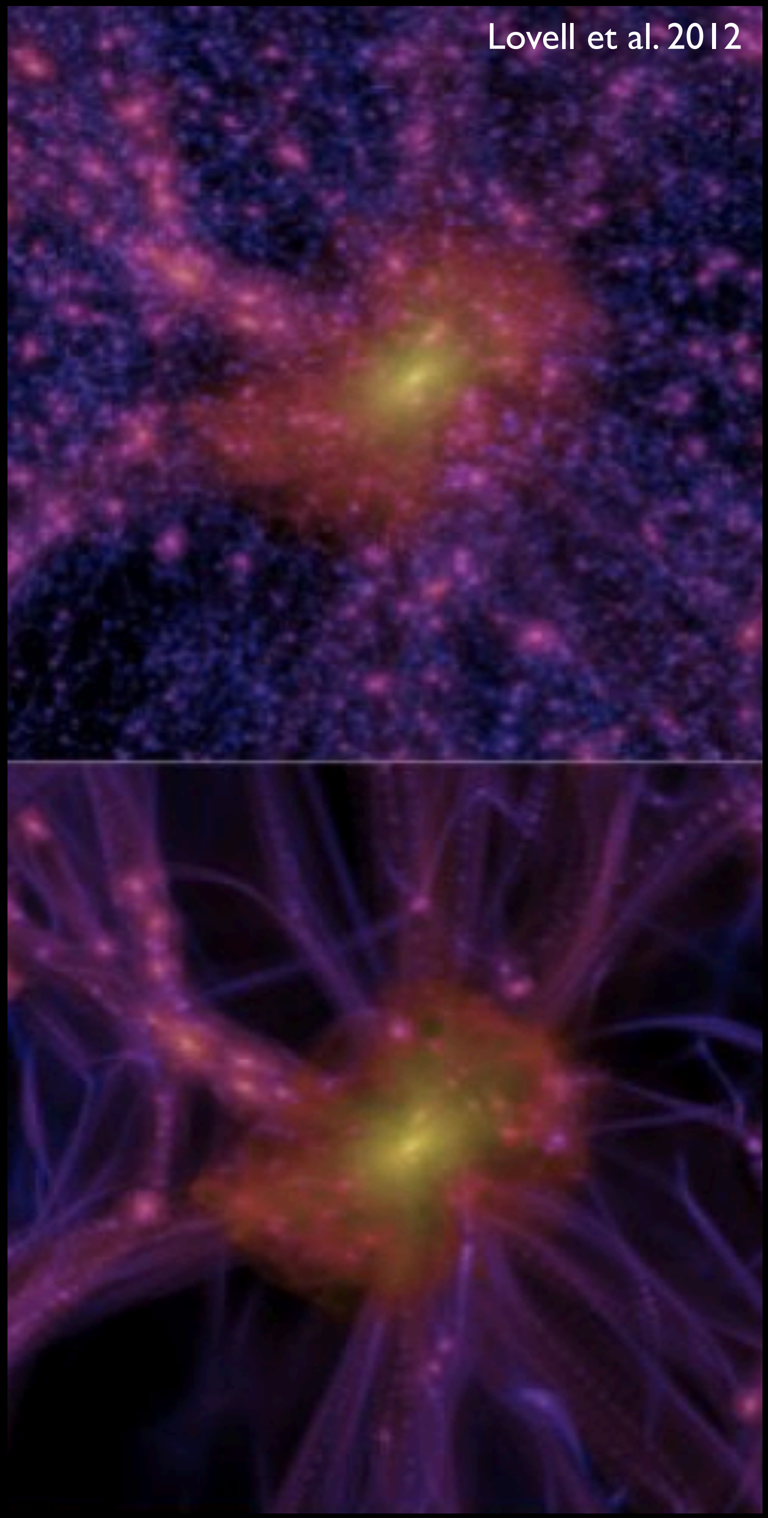


Outline

Evidences for DM
- rotation curves
- galaxy clusters
- growth of perturbatios from CMB
- concordance cosmology

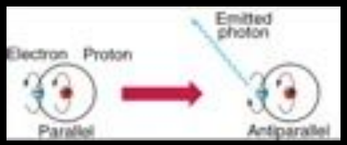
The Impact of the mass DM particles on the formation of cosmic structues

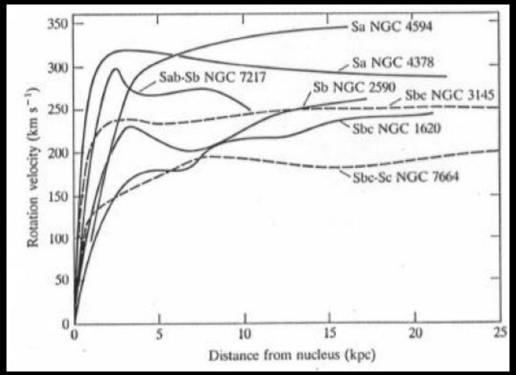
Galaxy Formation in Cold Dark Matter:
The small-scale crisis

Galaxy Formation in Warm Dark Matter scenarios

Galaxy rotation curves

$\boxed{M/L \approx 10\text{-}50}$

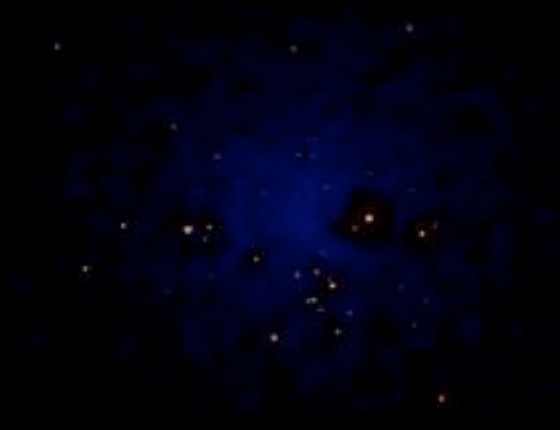


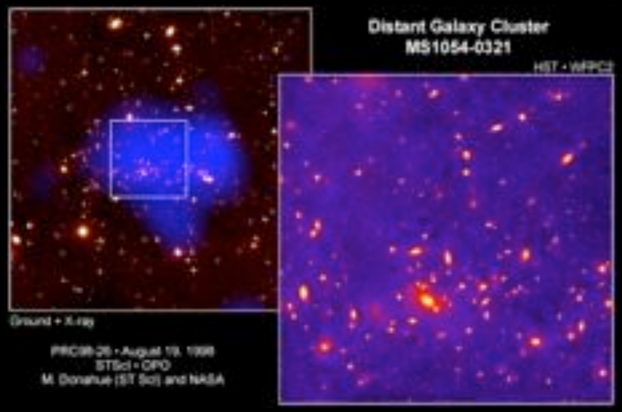


Galaxy clusters:

velocity dispersions
X-ray temperature
Gravitational lensing

$\boxed{M/L \sim 100}$





$$\langle v^2 \rangle = \frac{GM}{R}$$

$$KT = \frac{GM}{R} / \mu m_p$$

Cosmology

Ordinary matter (baryons) can only grow after ricombination (z~1000).
Since $\delta \sim (1+z)^{-1}$, they can grow at most a factor 1000.

$\delta \simeq 10^{-5}$ observed at recombination implies that they cannot grow non-linear ($\delta \simeq 1$) at the present time

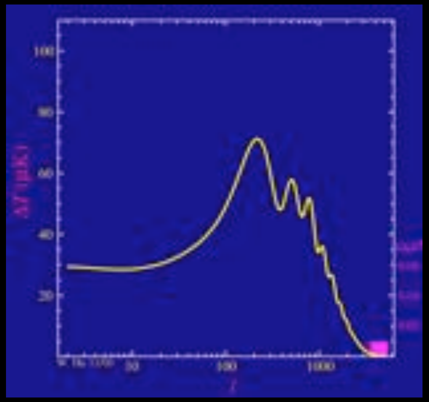
Dark Matter: starts to grow earlier. At recombination baryons fall into potential wells which are already in place

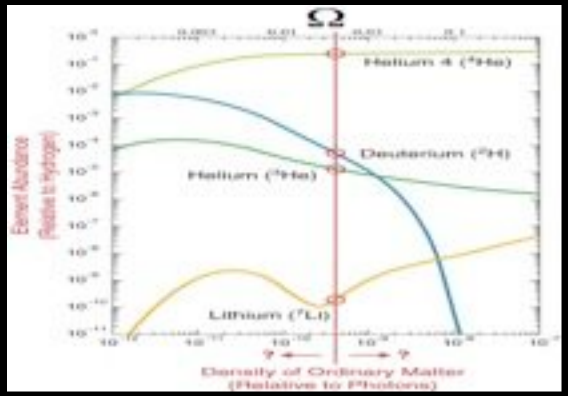
$$\delta(t_{rec}) \sim 10^{-5}$$

$$\delta(t) \sim t^{2/3} \sim (1+z)$$

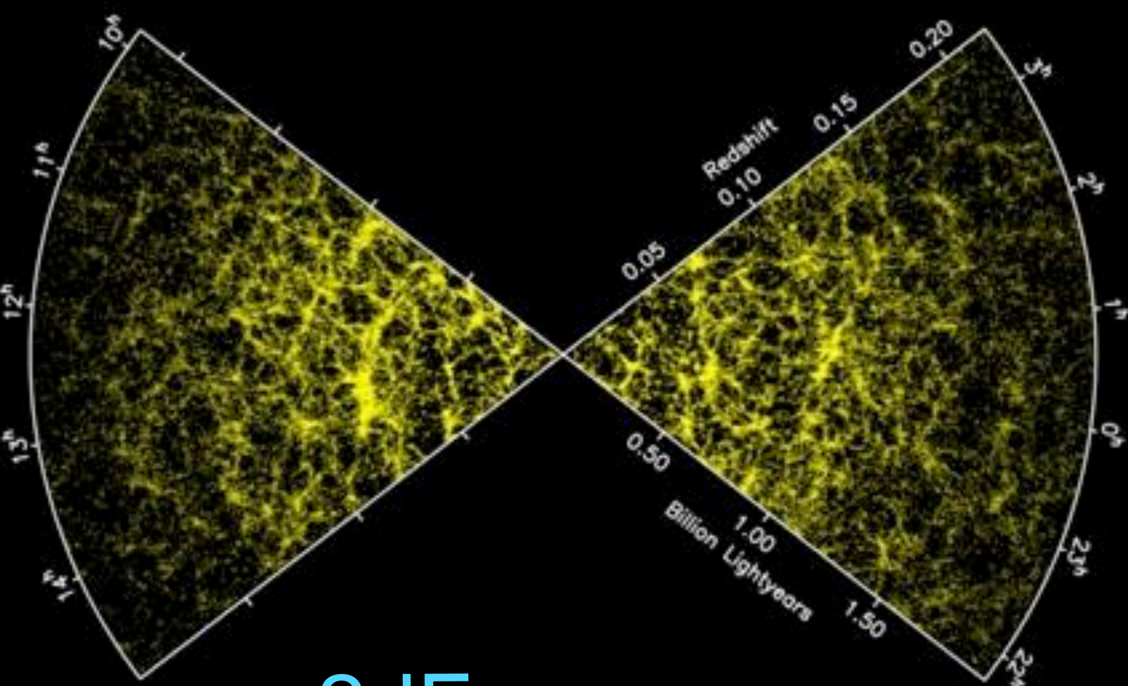
CMB+Baryon Nucleosynthesis

$\boxed{\Omega_b \approx 0.04}$ $\boxed{\Omega_M \approx 0.25}$

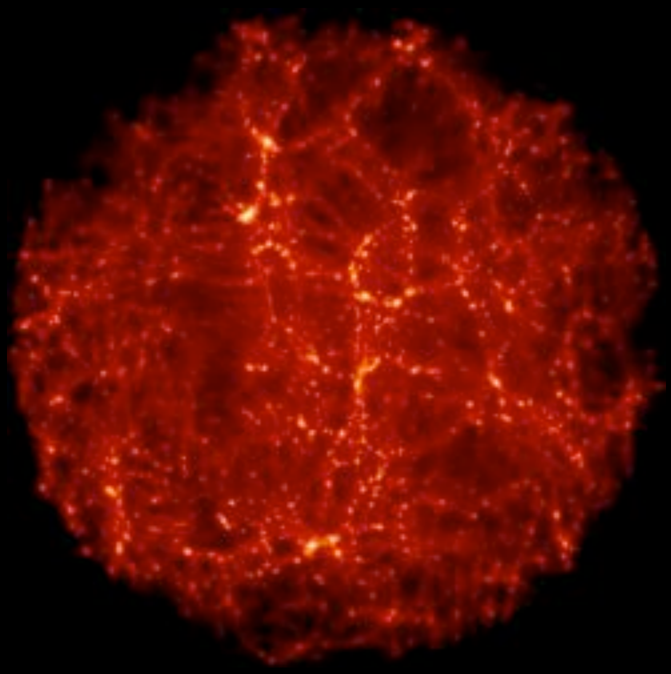


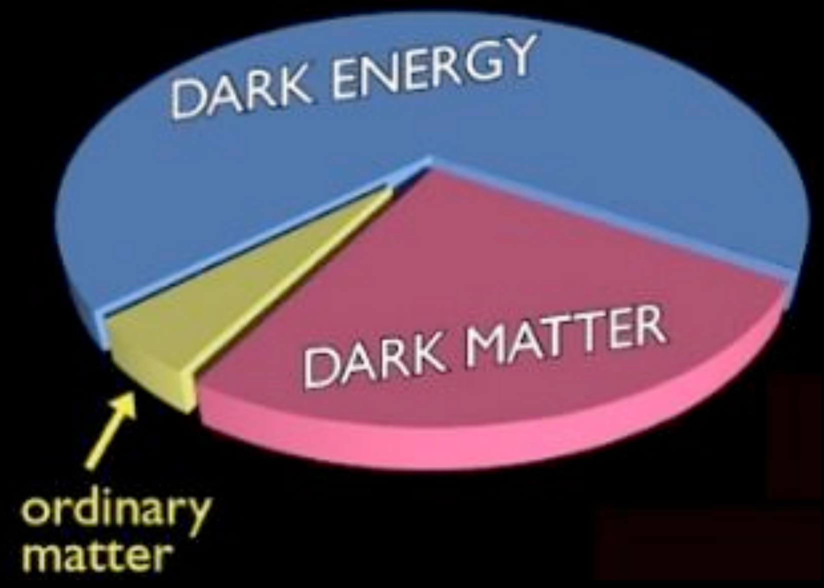


Galaxies are the tip of the iceberg (underlying DM distribution)



2dF survey



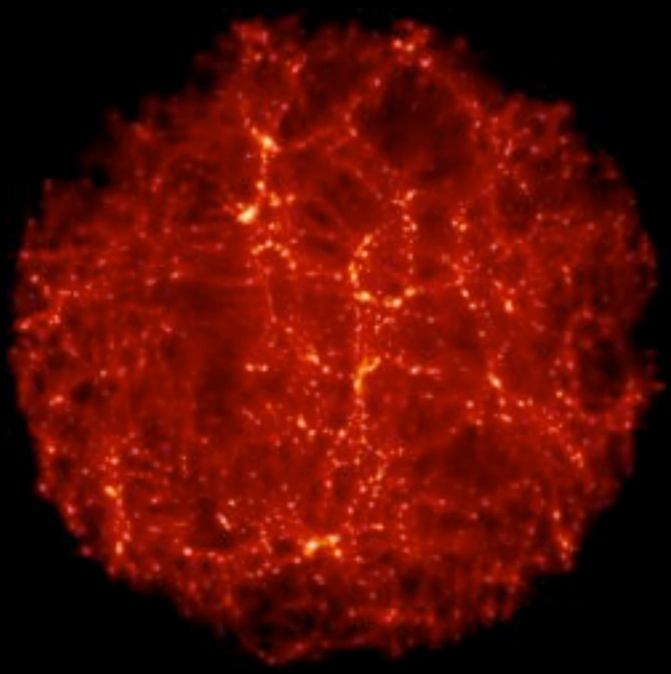


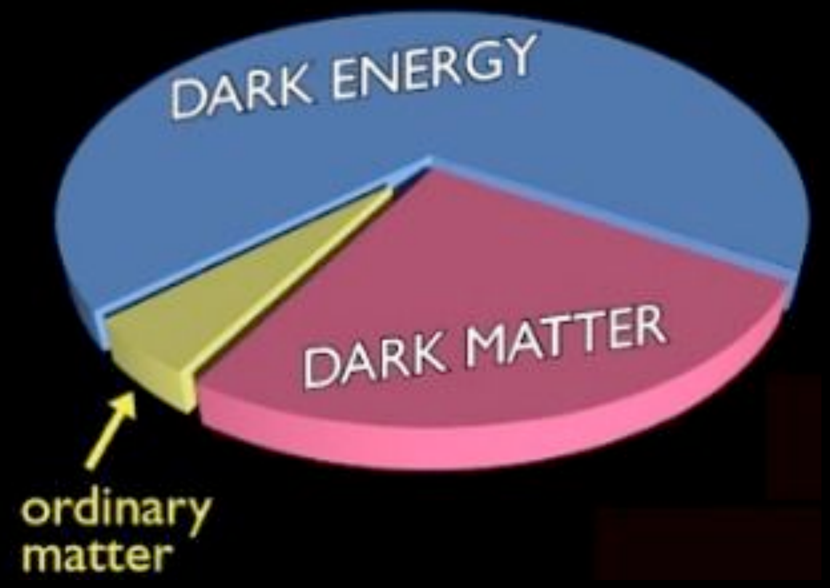
Galaxies are the tip of the iceberg (underlying DM distribution)

Galaxy Formation Theory

Describe the collapse and evolution of the DM clumps dominating the gravitational dynamics

Connect properties of ordinary matter (gas physics, star formation,astrophysical processes) to the potential wells of DM condensations





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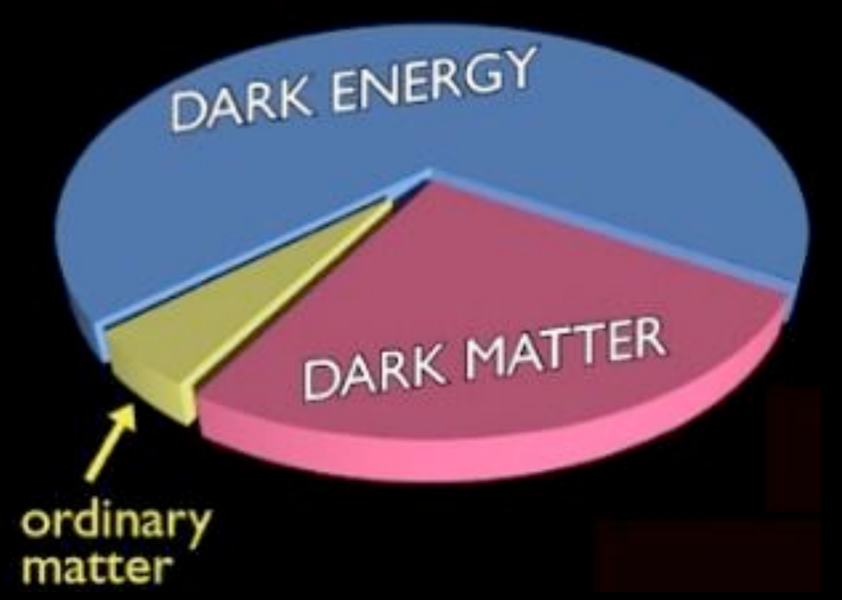

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Diemand et al. 2008

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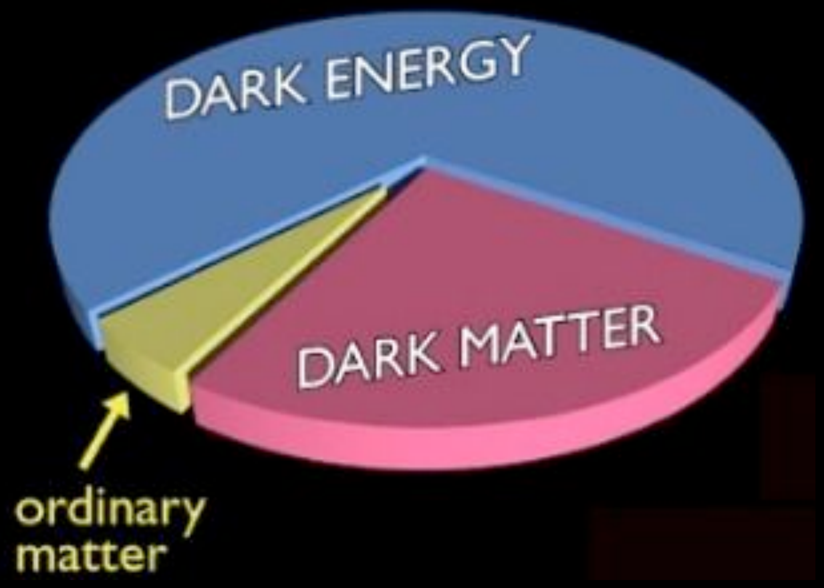
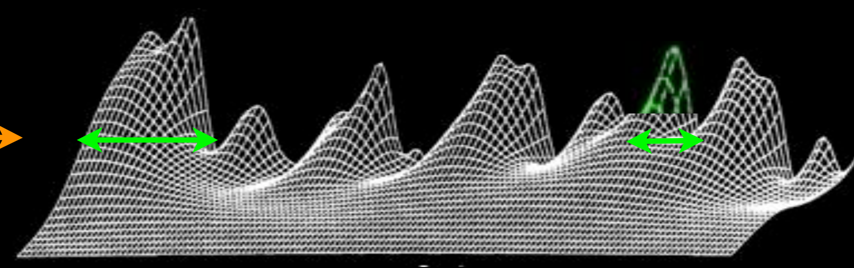
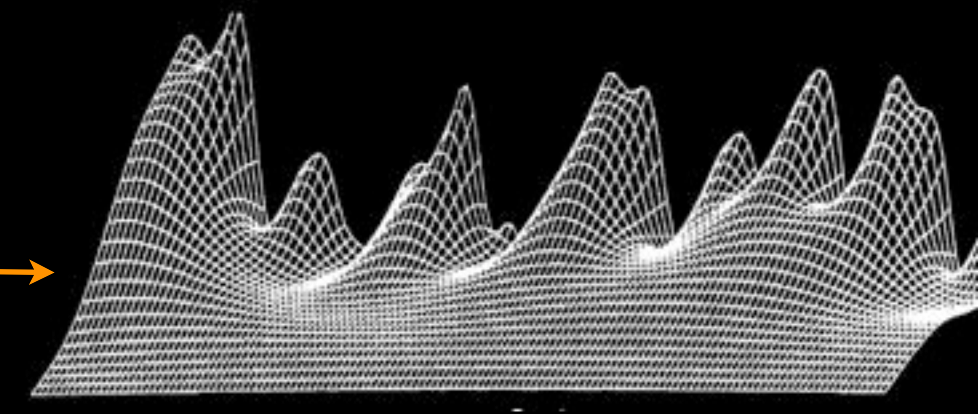


Cosmic Structures form from the collapse of overdense regions in the DM primordial density field, and grow by gravitational instability





R=2π/k

$$M = \frac{4\,\pi}{3}\,\rho\,R^3$$

$$\langle \delta_M^2 \rangle = \sigma^2(M)\,g(t)$$

Gaussian Random field

$$\delta = \frac{\delta\rho}{\rho}$$

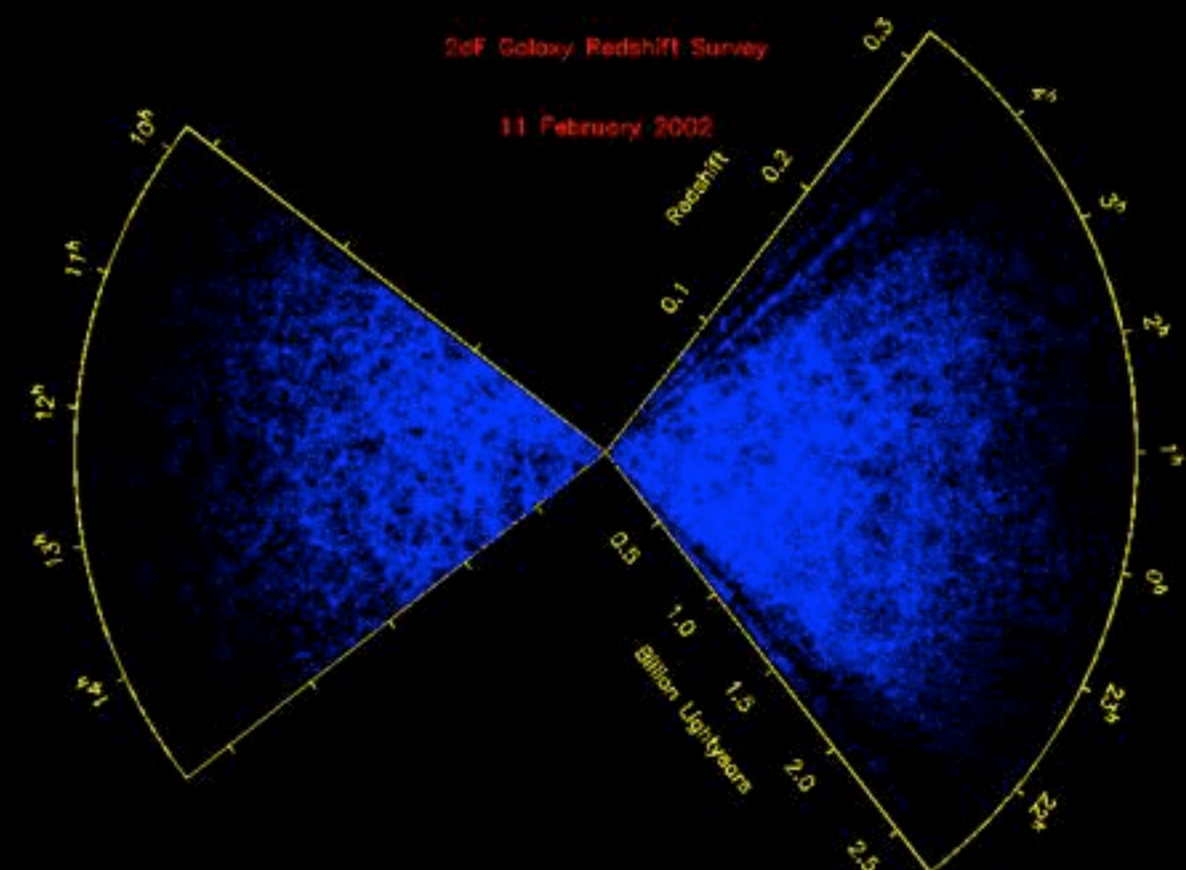
$$p(\delta_k) = \frac{1}{\sqrt{2\pi}\,\sigma_k}\,e^{\frac{\delta_k^2}{2\,\sigma_k^2}}$$

Mean (square) value of perturbations of size R(~1/k) enclosing a mass M

$$P(k) = \frac{1}{V}\,\langle |\delta_k|^2 \rangle$$

$$\sigma_M^2 = \frac{1}{(2\pi)^3\,V}\int^{M\leftrightarrow k} dk\,k^2\,P(k)$$

$$\sigma_M^2 \leftrightarrow P(k)$$



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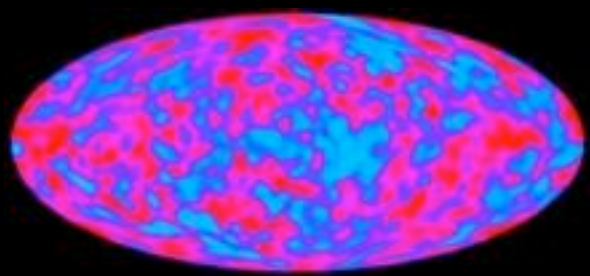

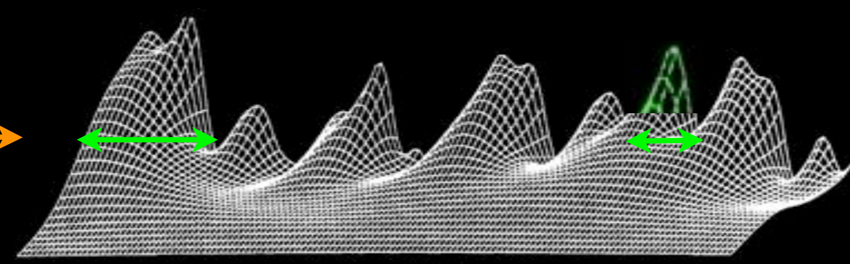

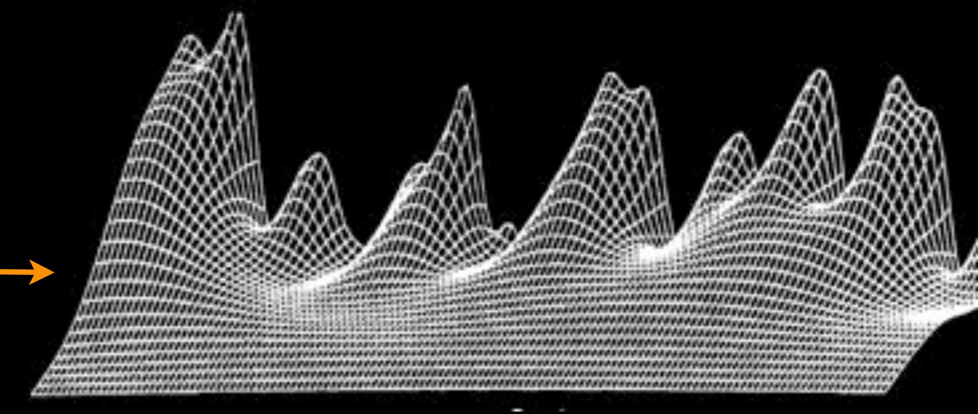

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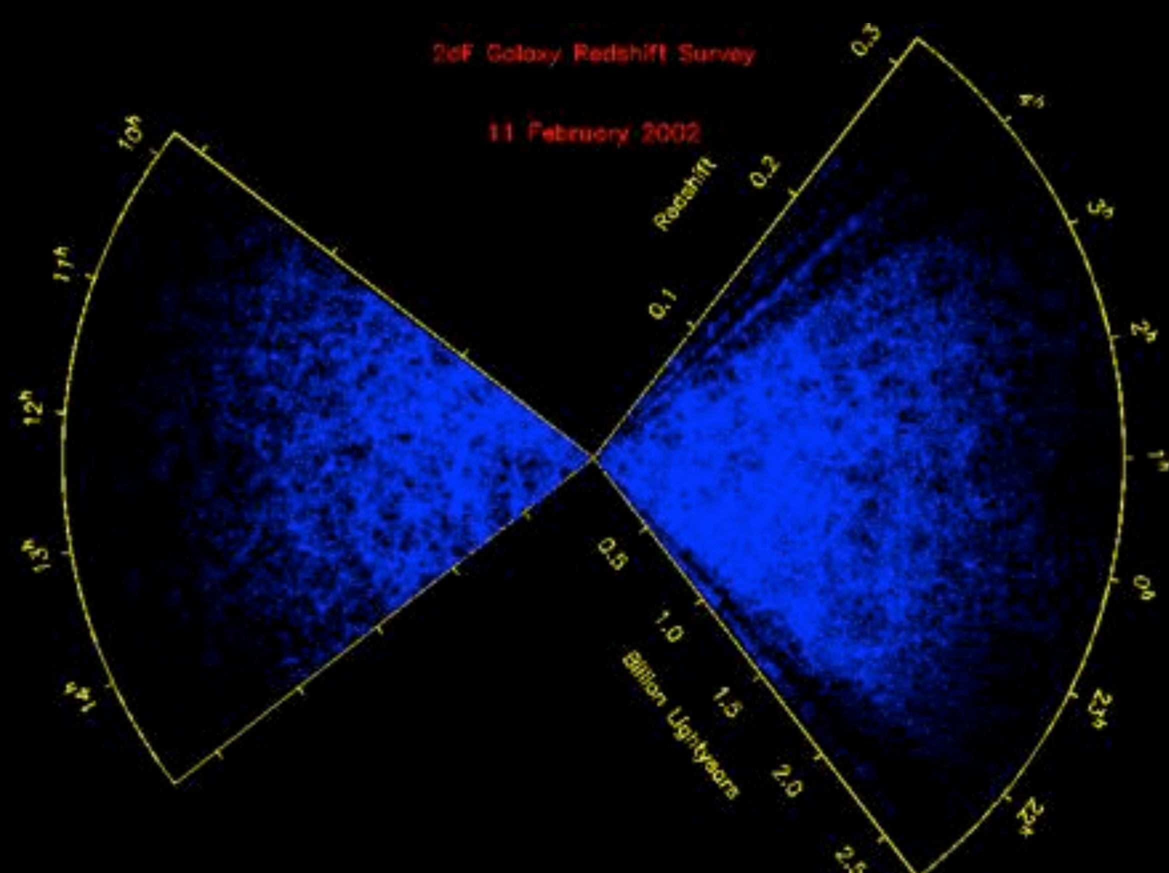
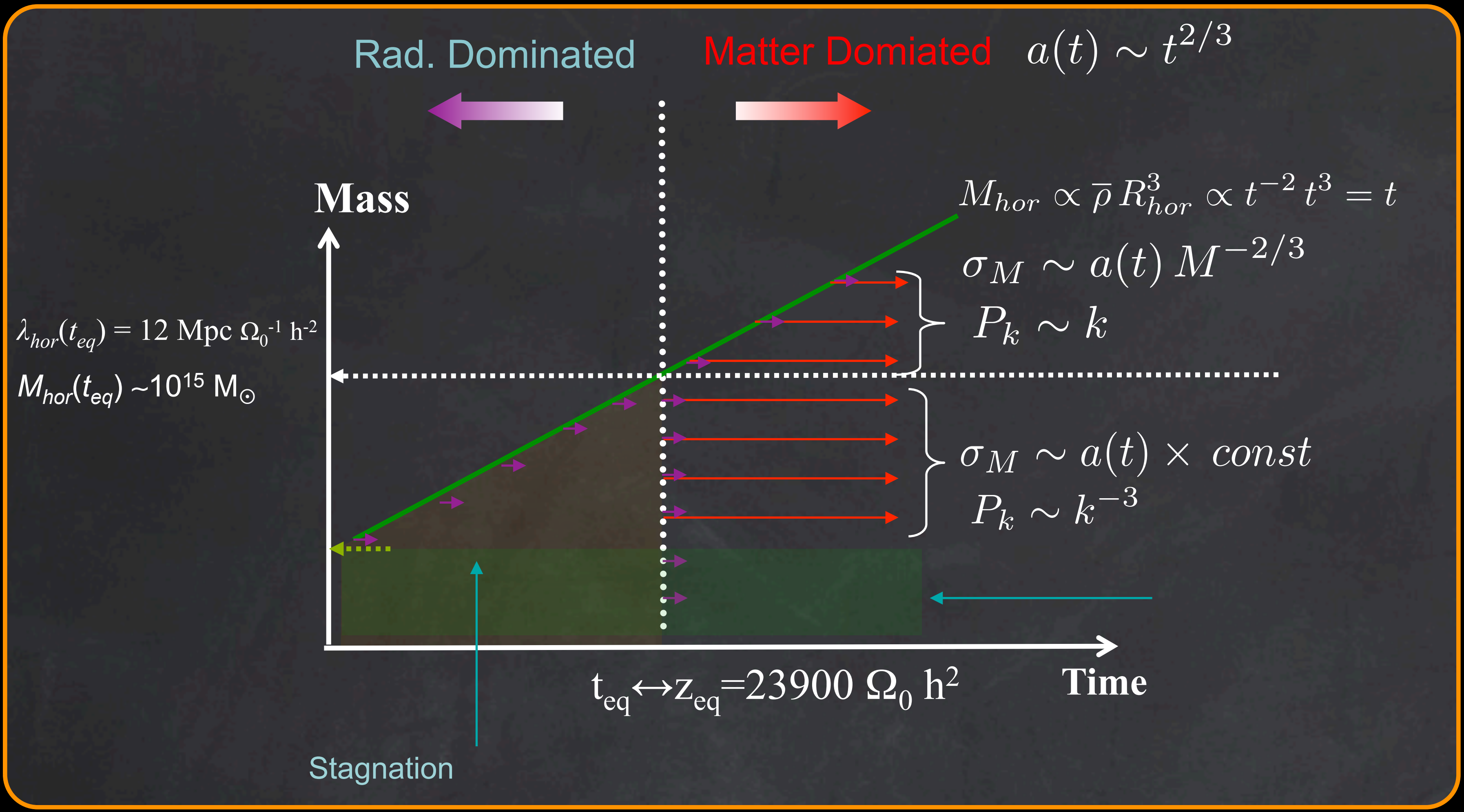
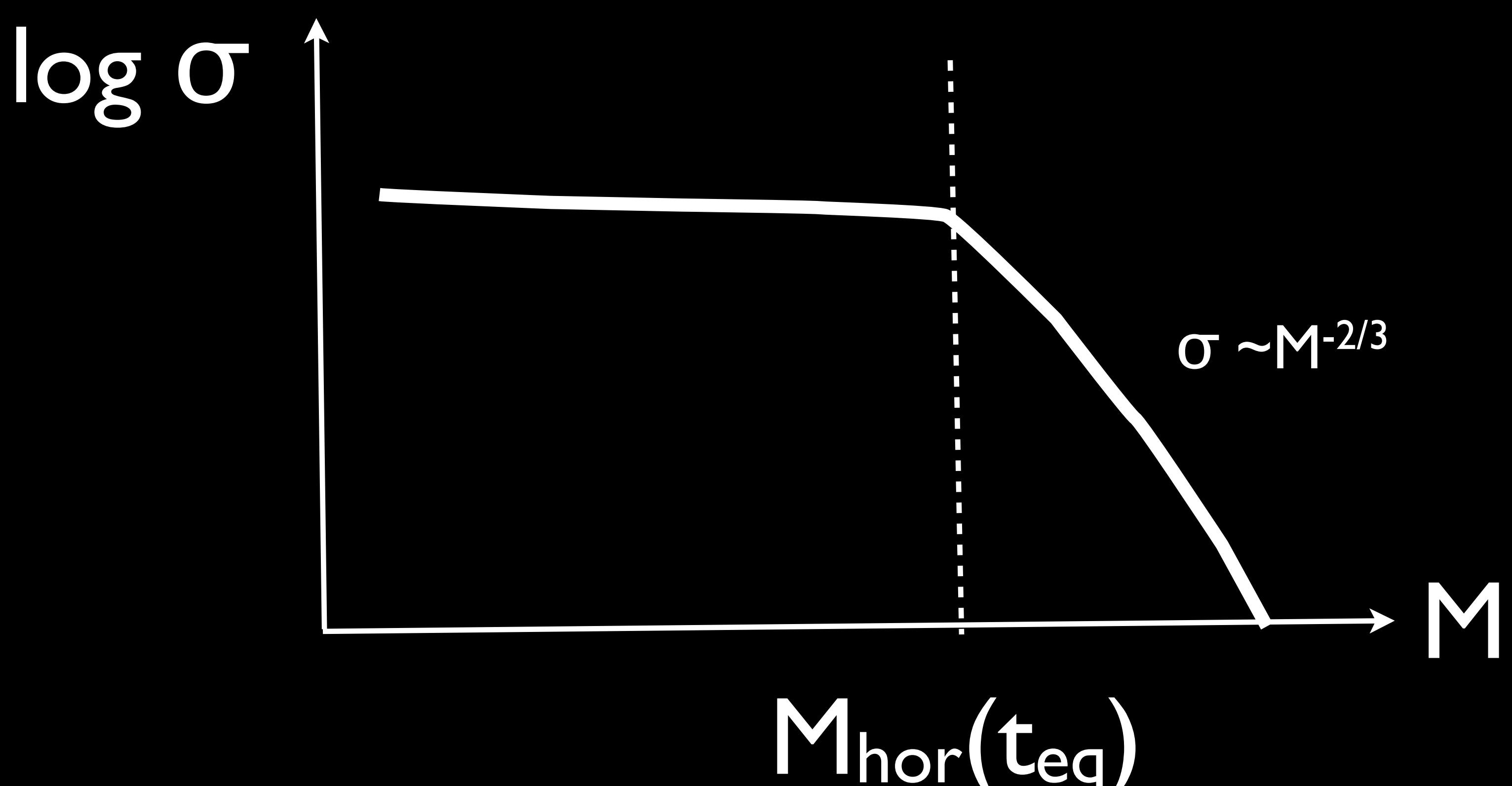


The Variance of the perturbation field



Perturbations
involving scales
larger than that of
the
horizon at the
equivalence
start to grow later

$R_{hor} = 2c\, t_{hor} = 13\, h^{-2}\, Mpc$
=110 Mpc for σ_0=0.3 h=0.7



The Variance of the perturbation field

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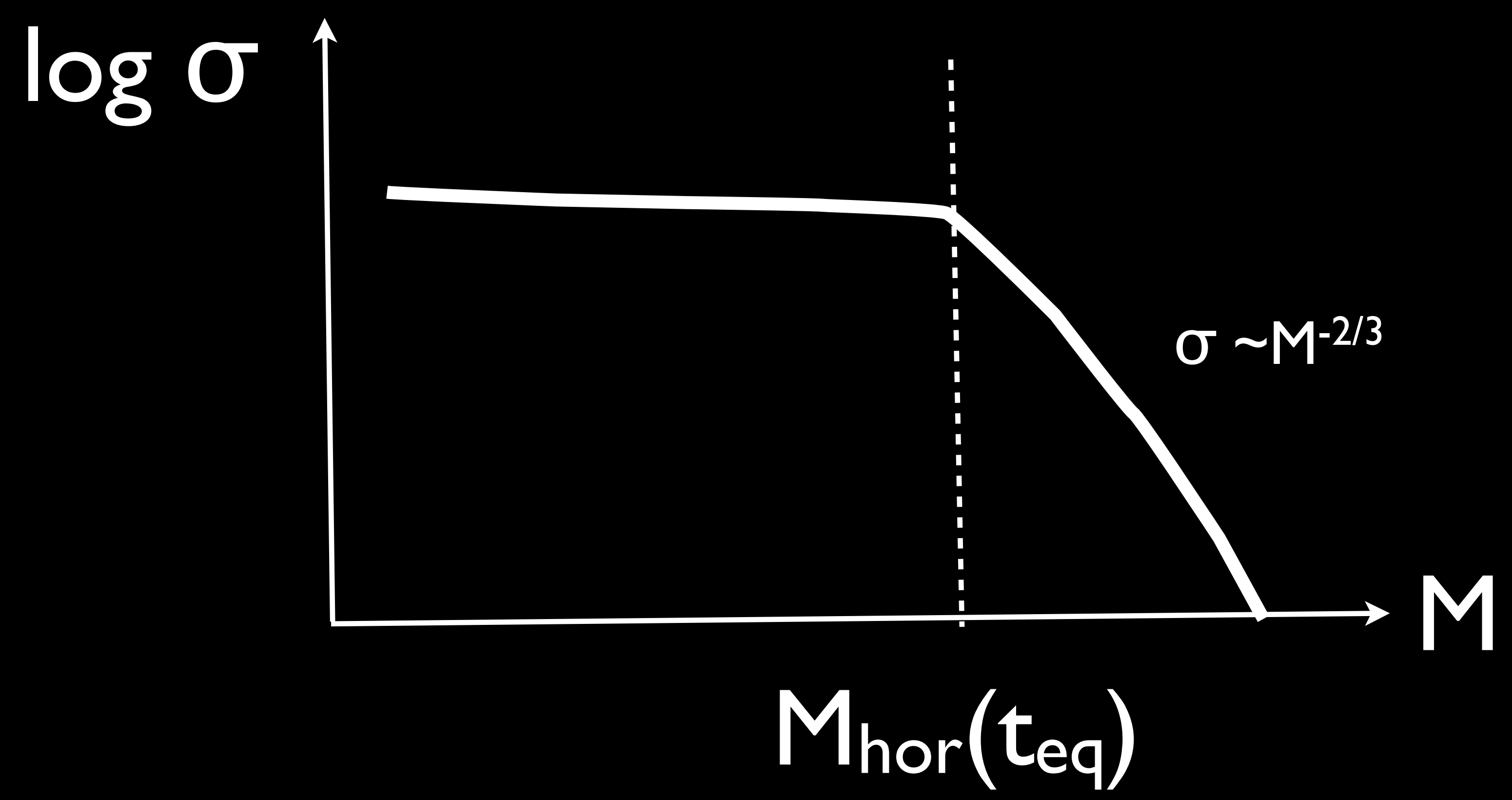
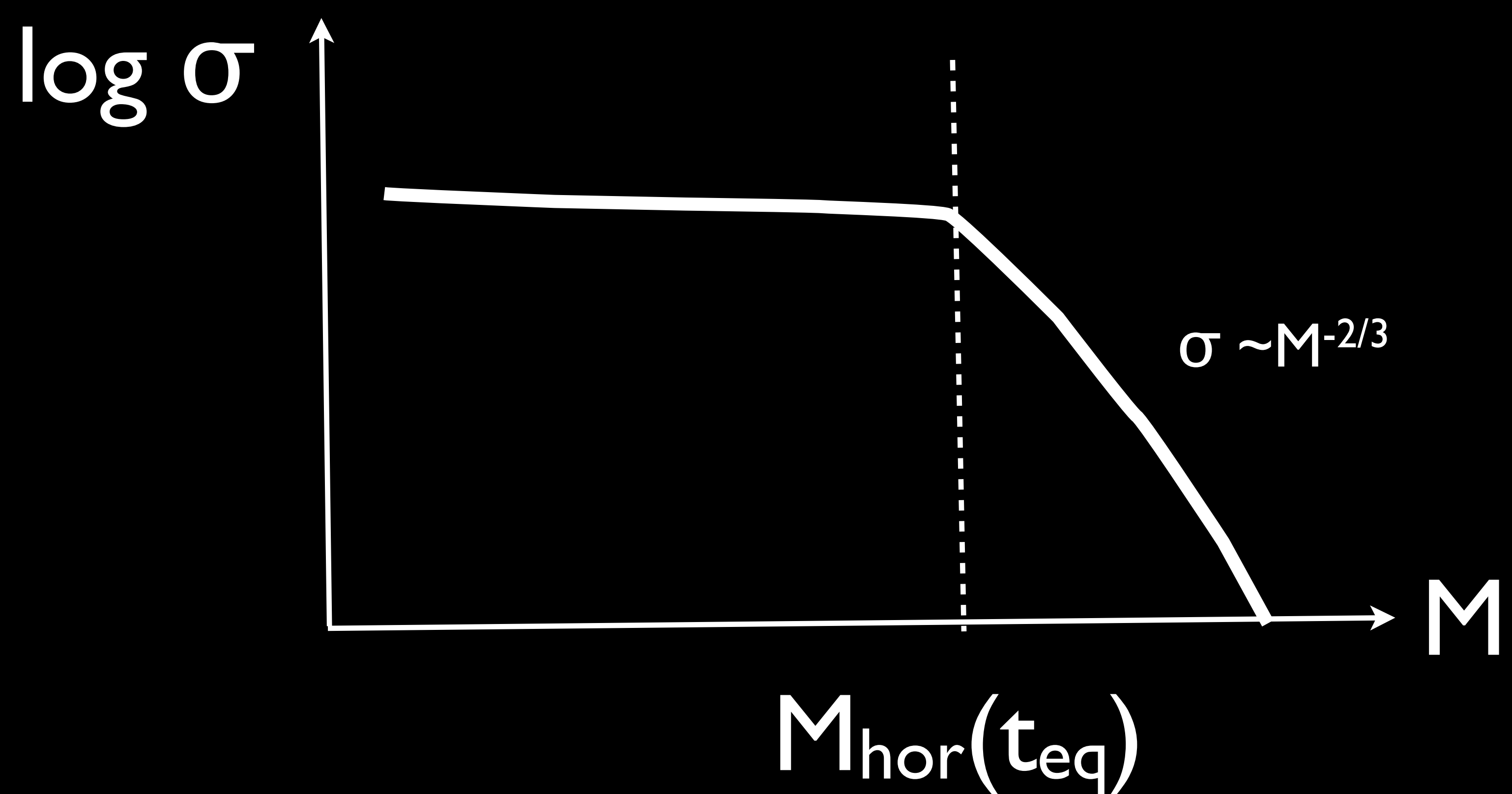


The Variance of the perturbation field

On average, perturbations on large scales (large masses) have a lower amplitude

$\sigma \sim$ const for $M < M_{hot}(t_{eq})$
$\sigma \sim M^{-2/3}$ for $M > M_{hot}(t_{eq})$



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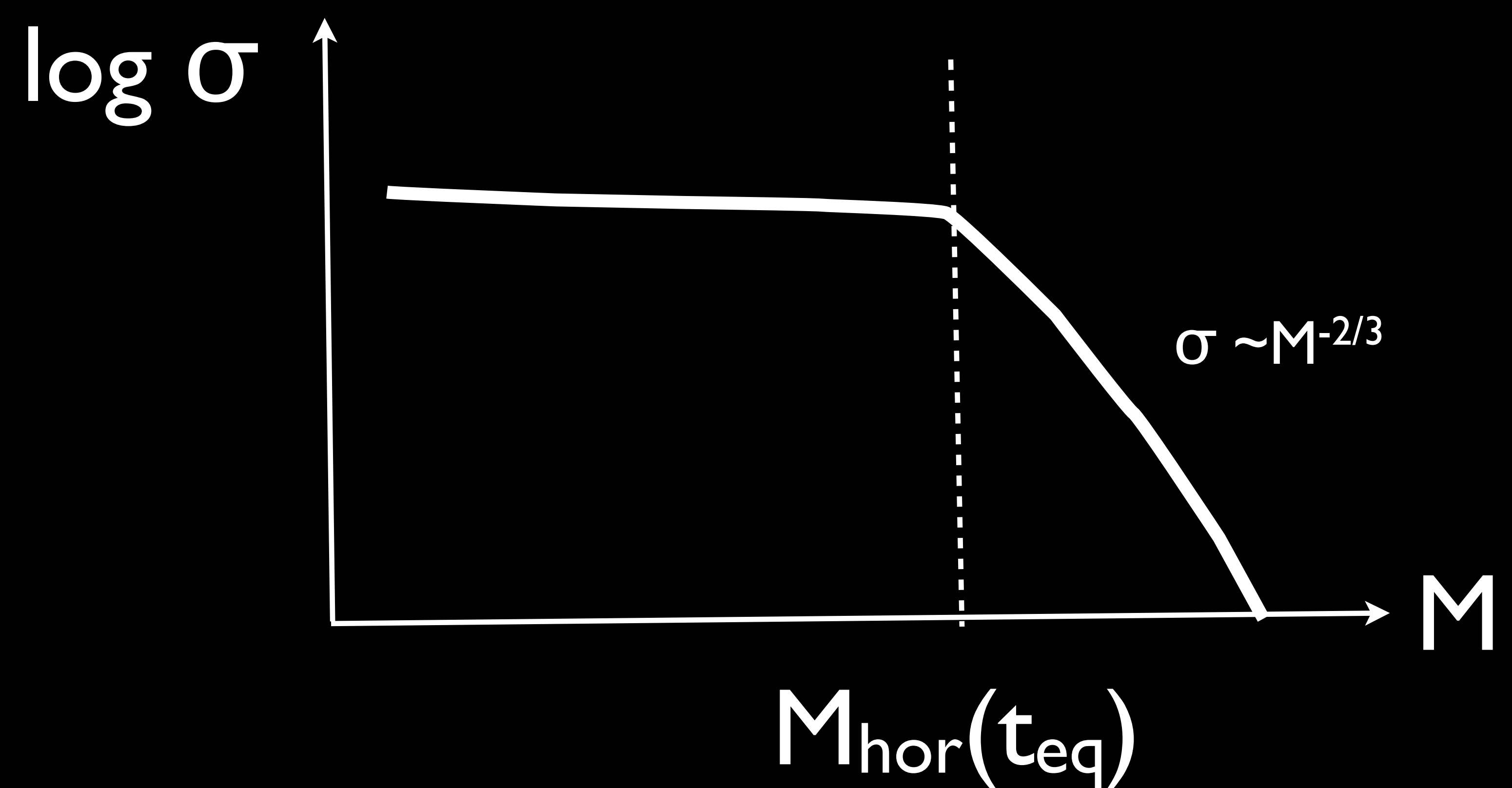
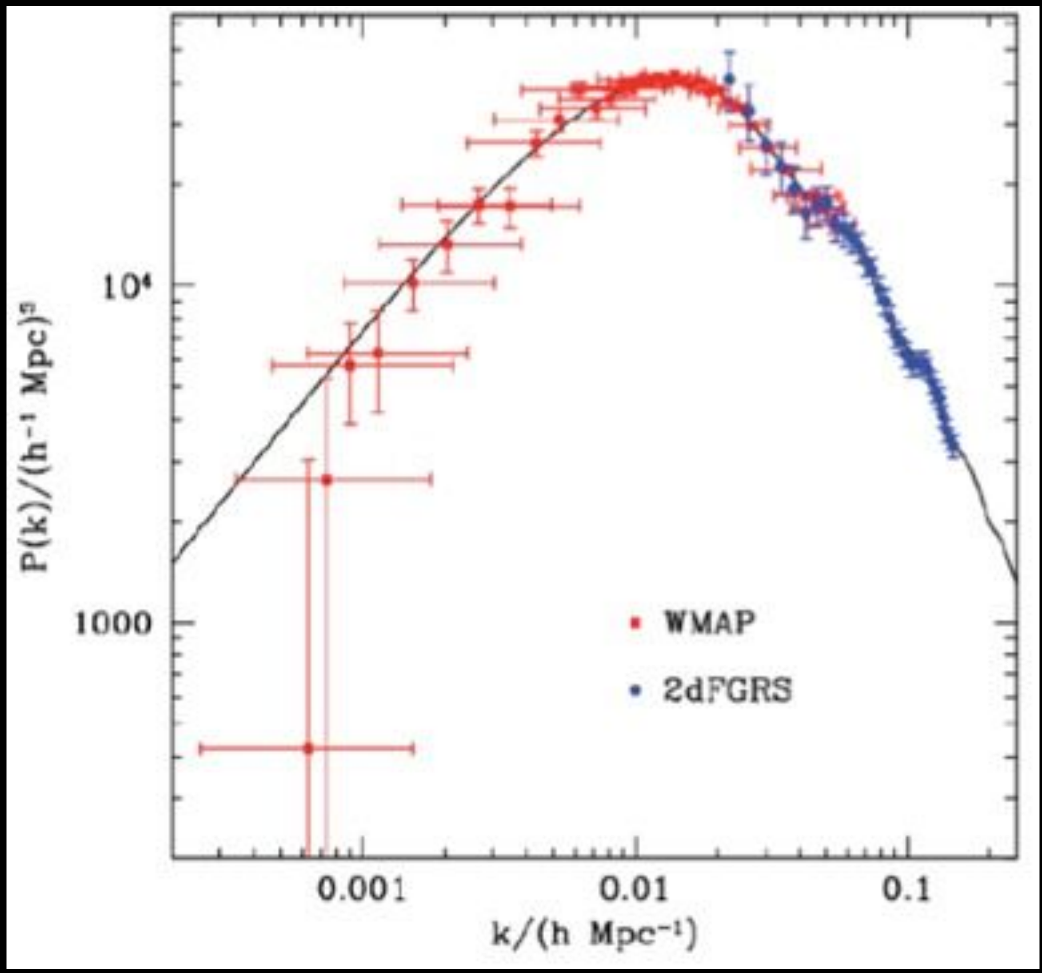


In terms of wavenumber k→Power Spectrum

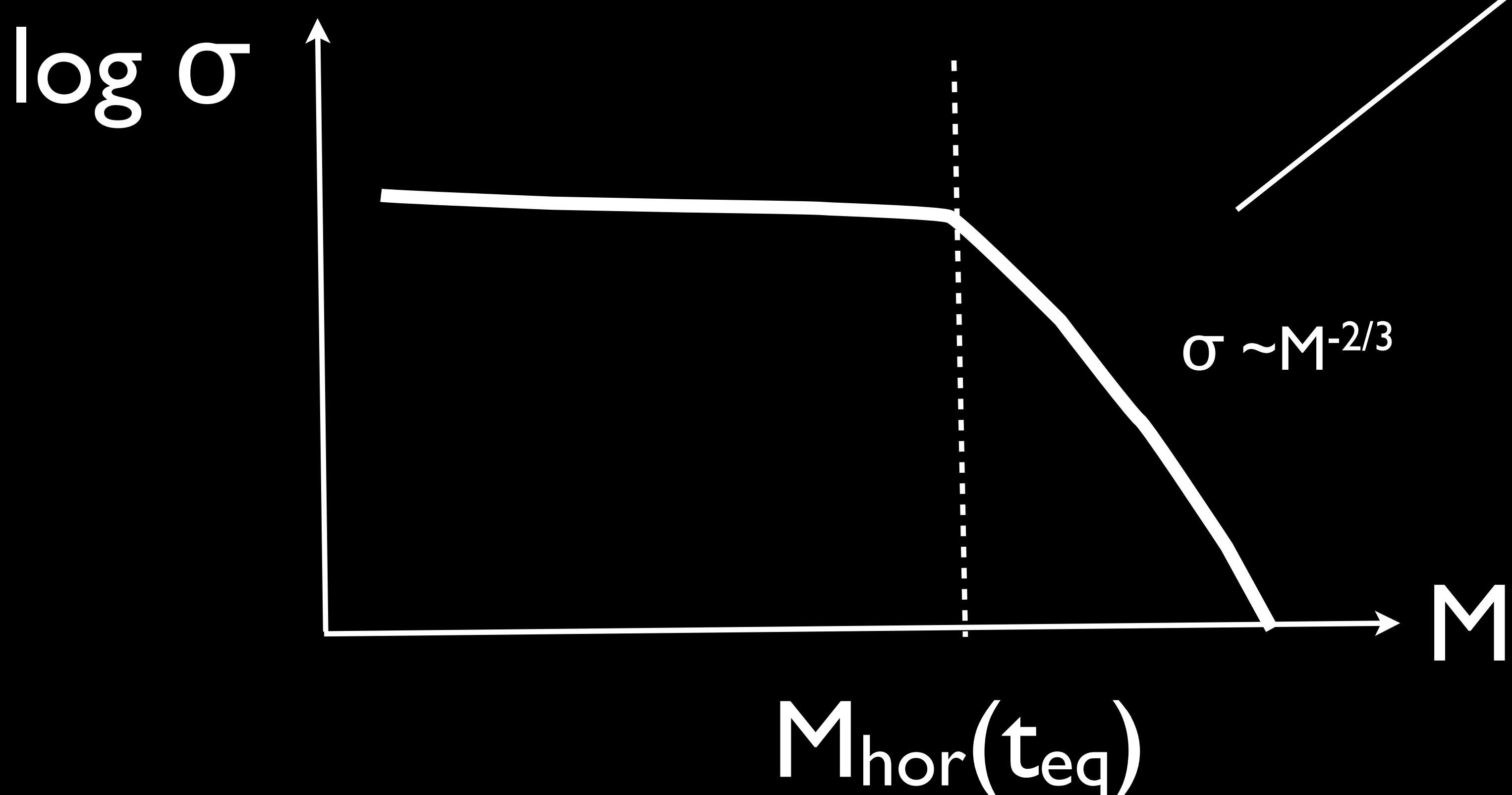
$$\sigma_M^2 = \frac{1}{(2\pi)^3 V} \int^{M \leftrightarrow k} dk\, k^2\, P(k)$$



$$\langle|\delta_k^2\rangle = P(k) \propto k^2$$

$$\sigma_M \propto M^{-2/3} \qquad P(k) \propto k$$

$$\sigma_M = const \qquad P(k) \propto k^-3$$



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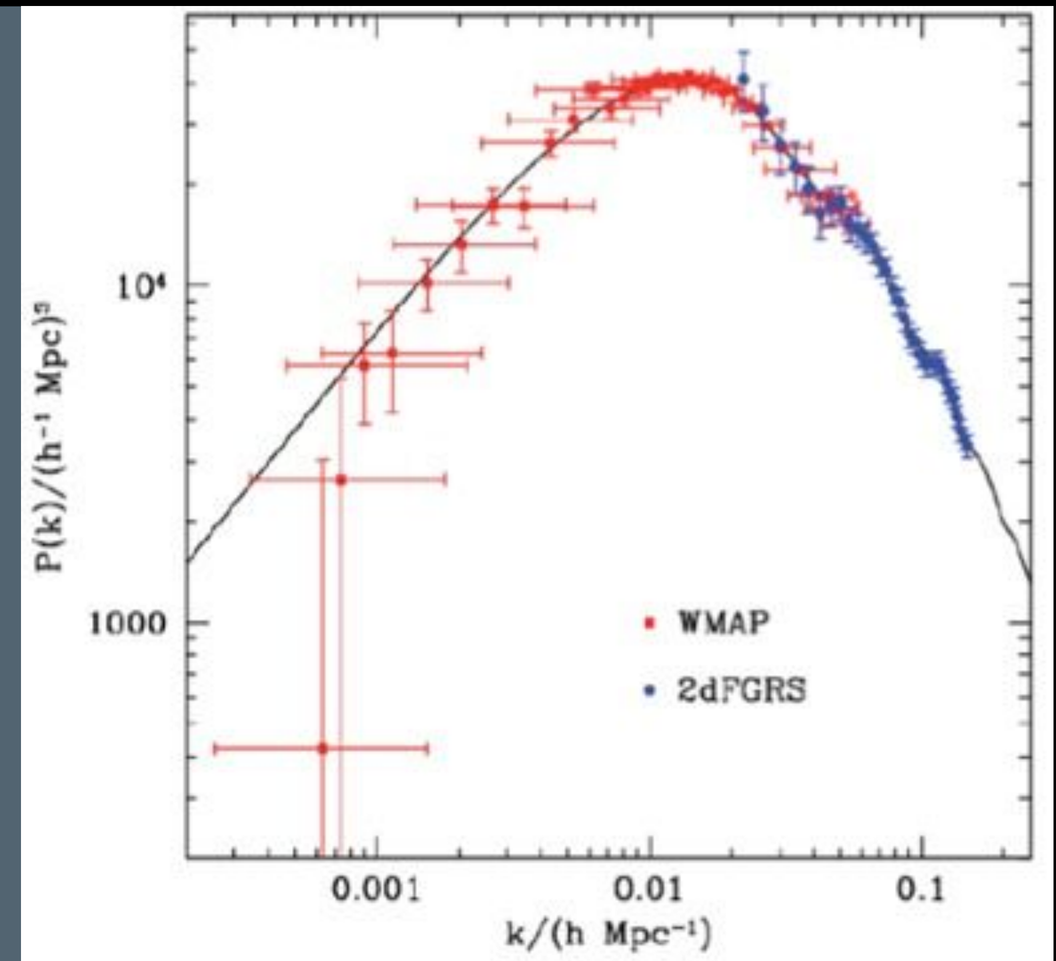
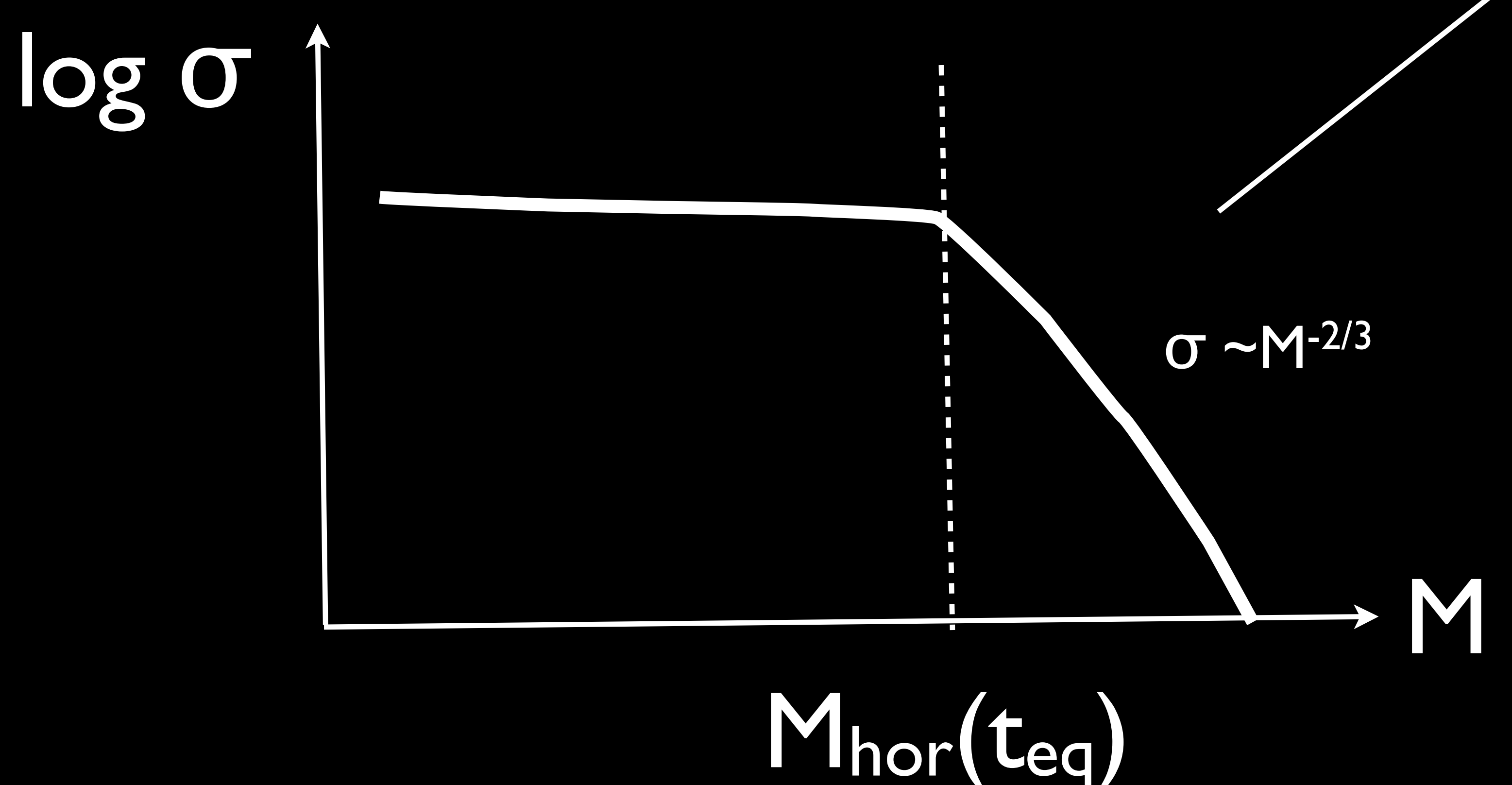


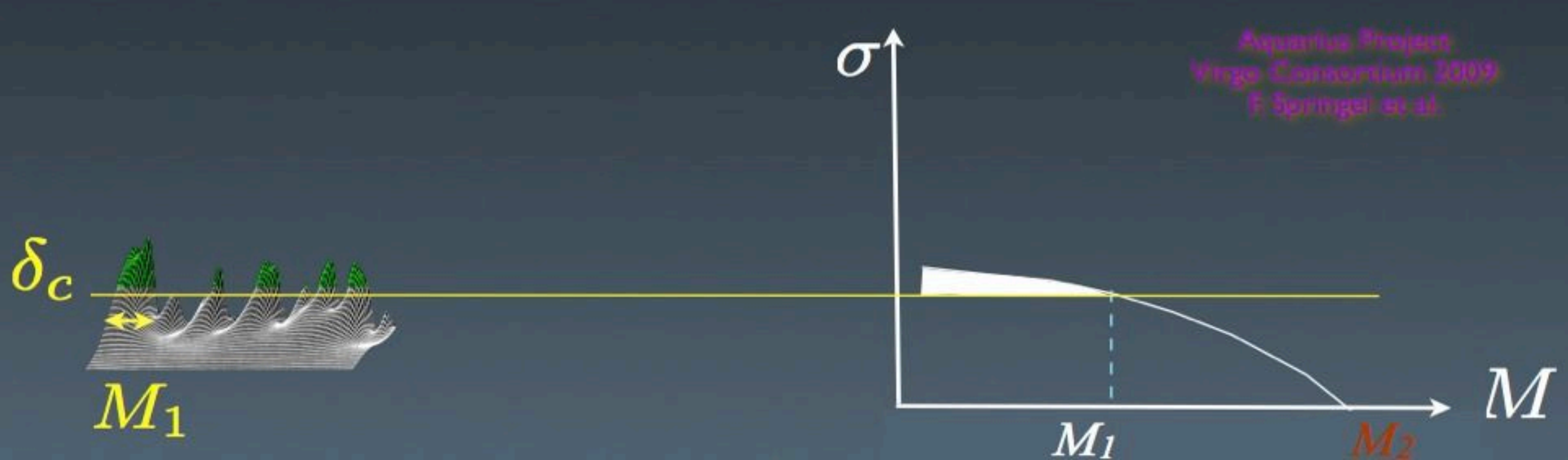


The evolution of DM perturbation

Initial density perturbations constitute a random Gaussian field.

Measurements of the CMB show that its variance is inversely related to their mass scale.

This implies that small scales collapse - on average - at earlier times



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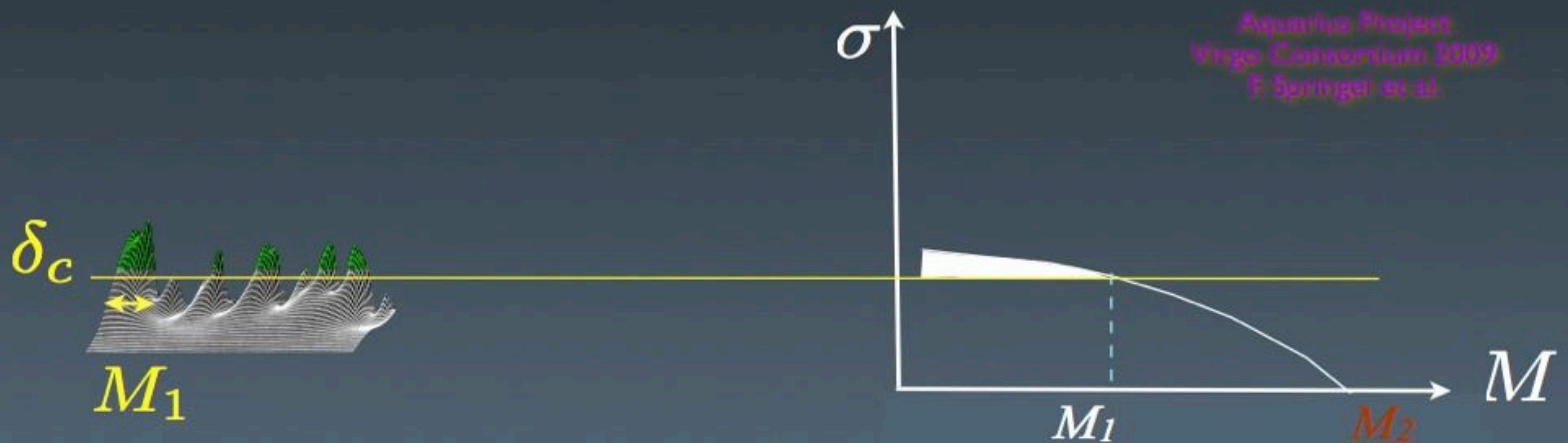

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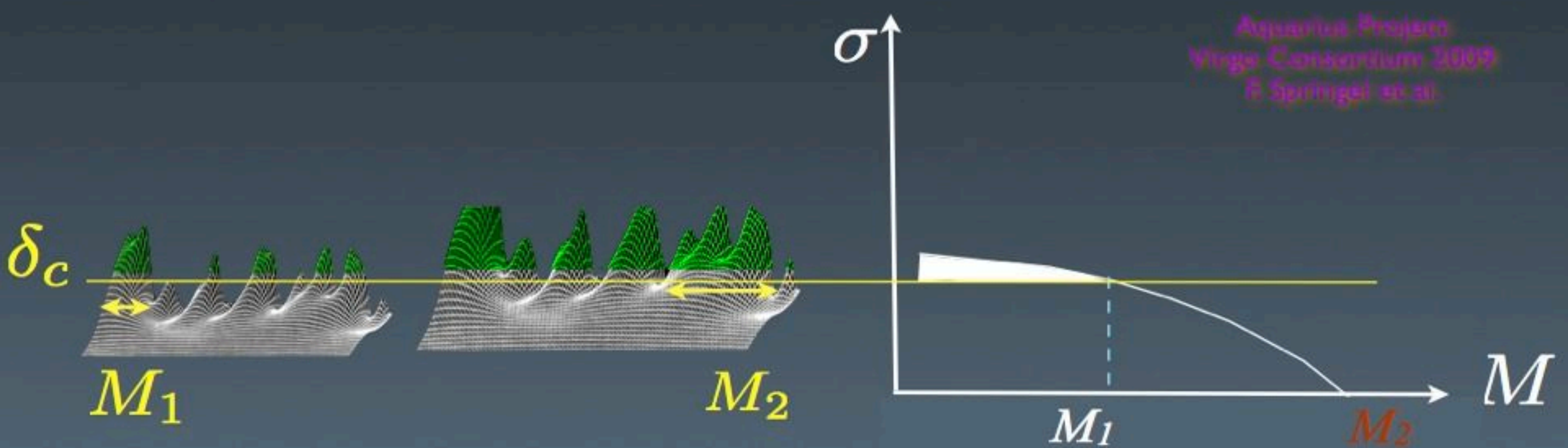

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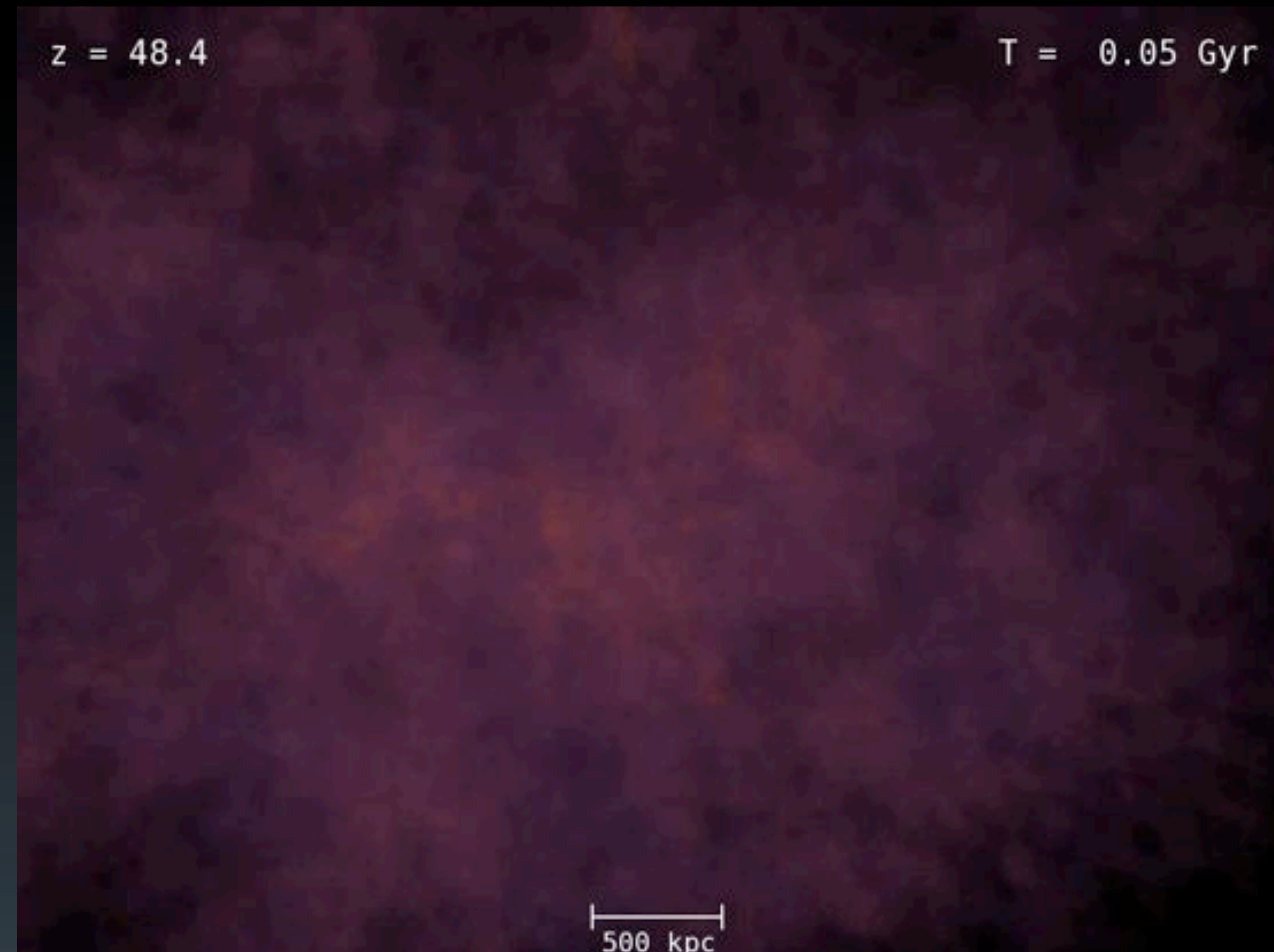
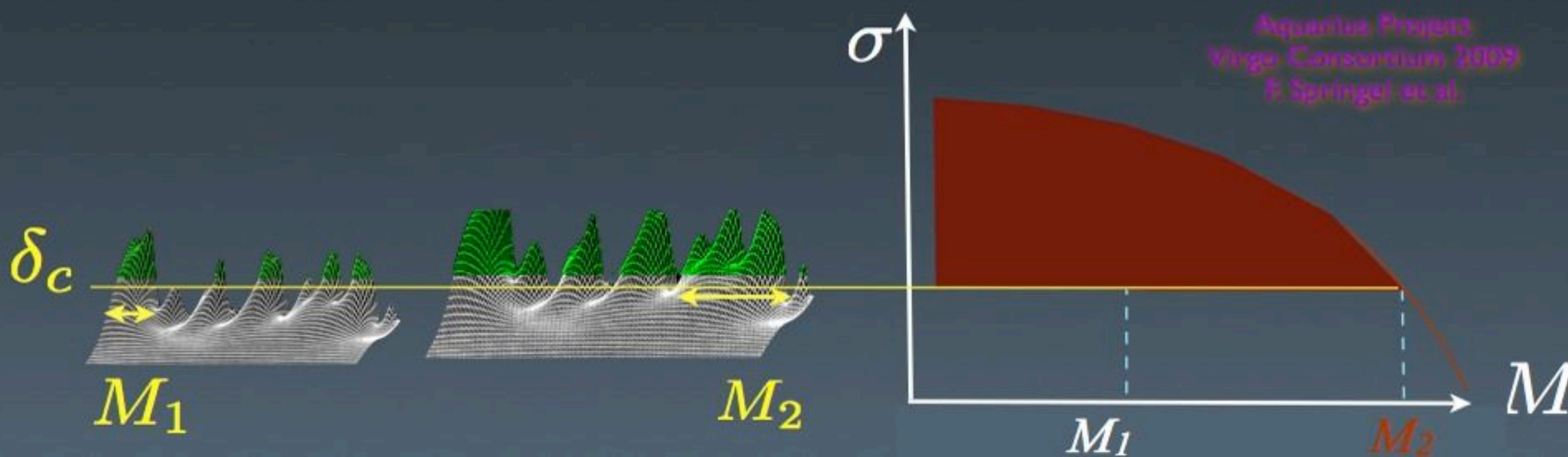
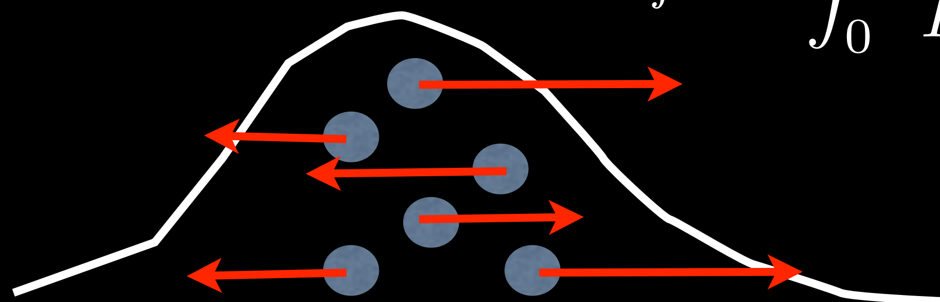
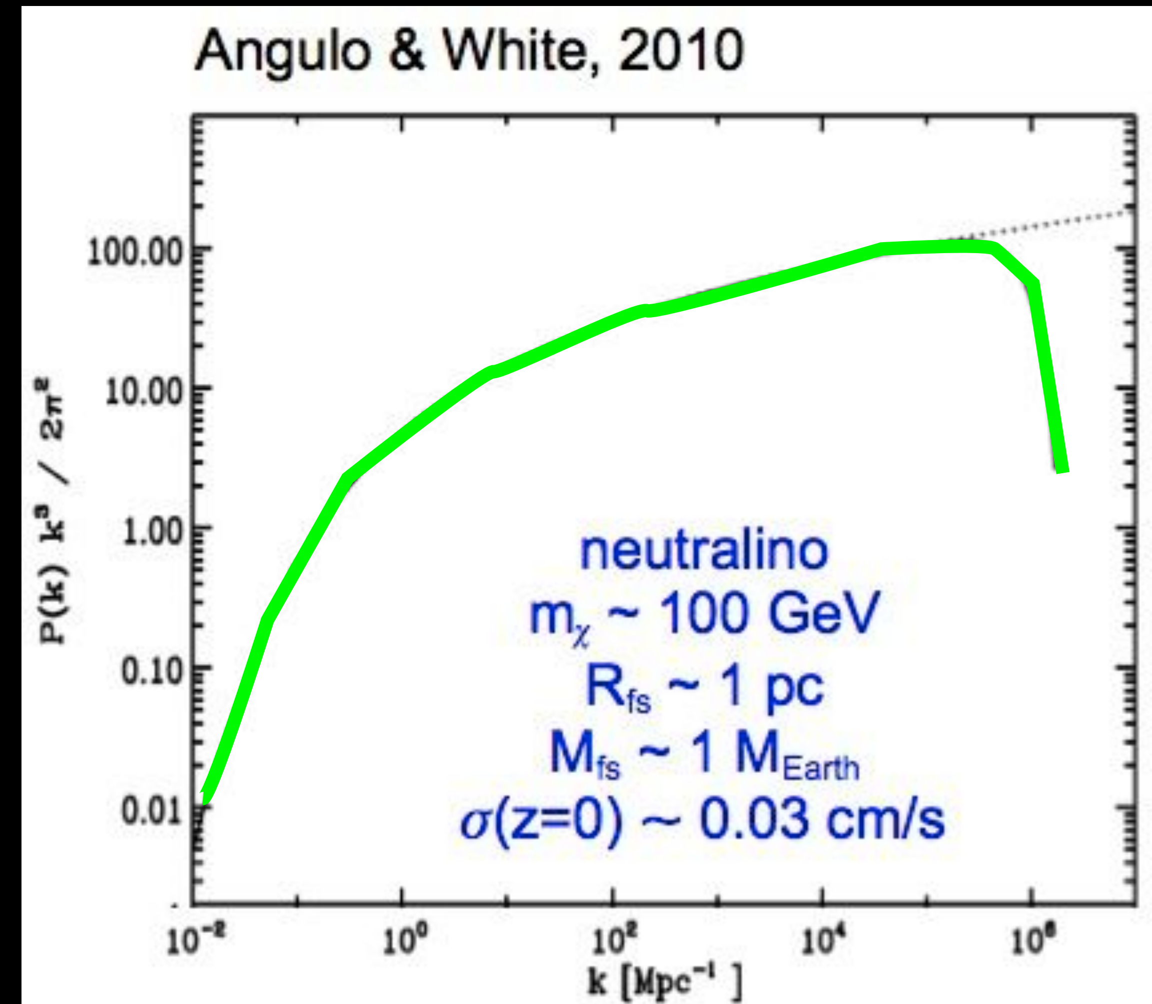




Dissipation, free-streaming scale

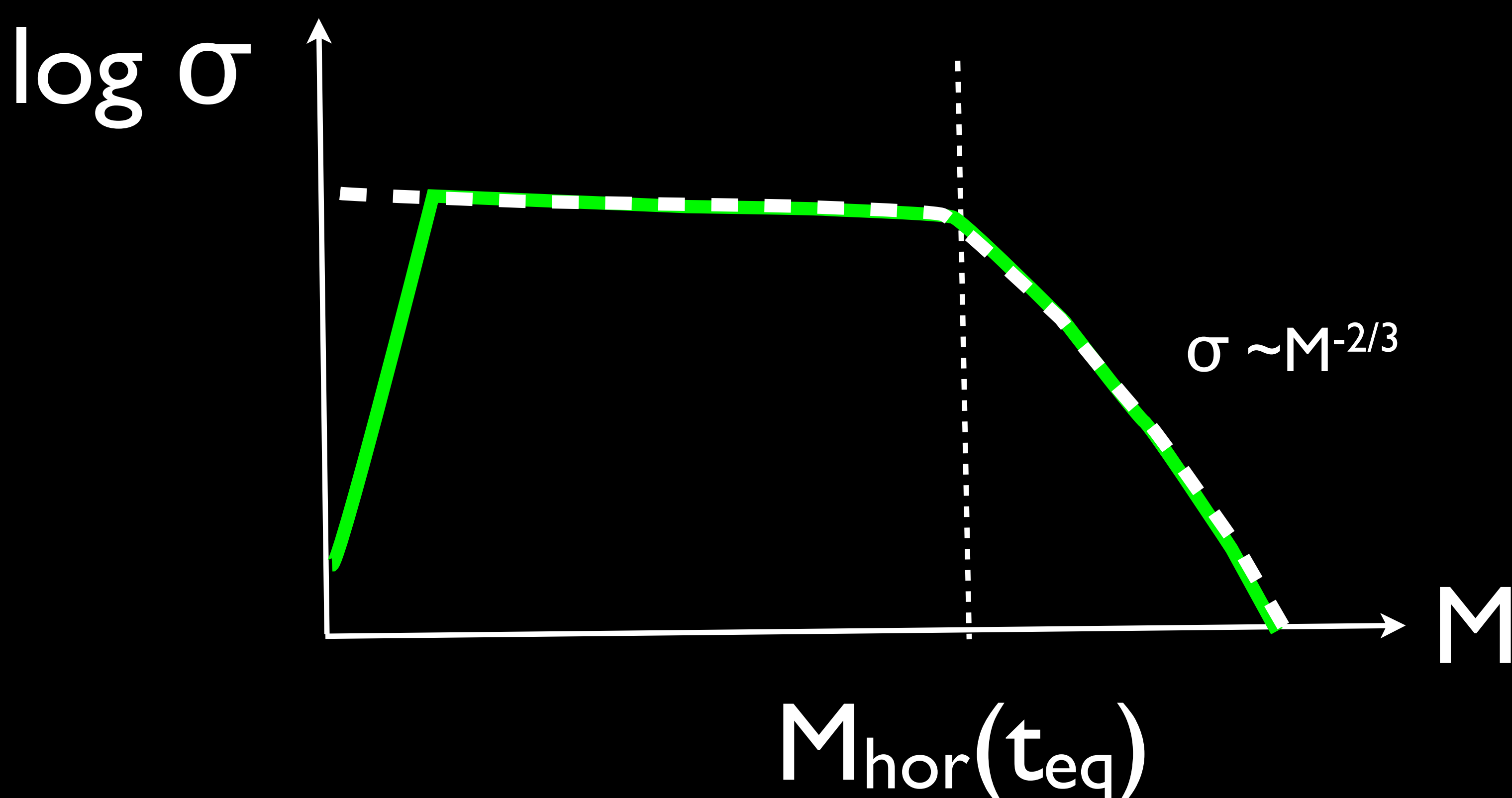
$$r_{fs} = \int_0^t \frac{v(t)}{R(t)}$$





$$\sigma_\chi \propto a^{-1} m_\chi^{-1/2}$$

$$M_{fs} = 4 \times 10^{15} \left(\frac{m_\nu}{30 \text{ eV}}\right)^{-2} M_\odot$$



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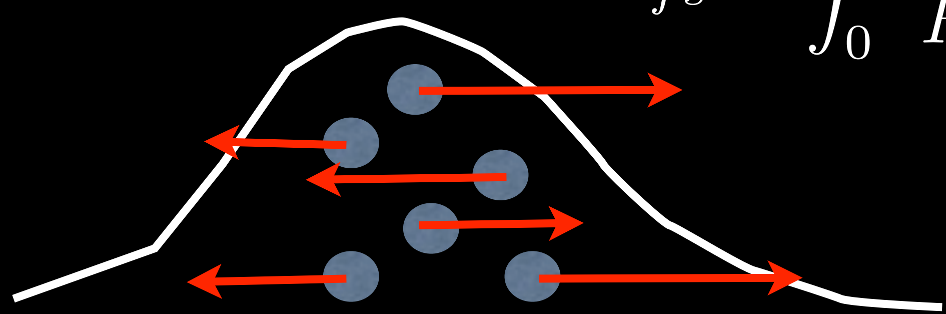

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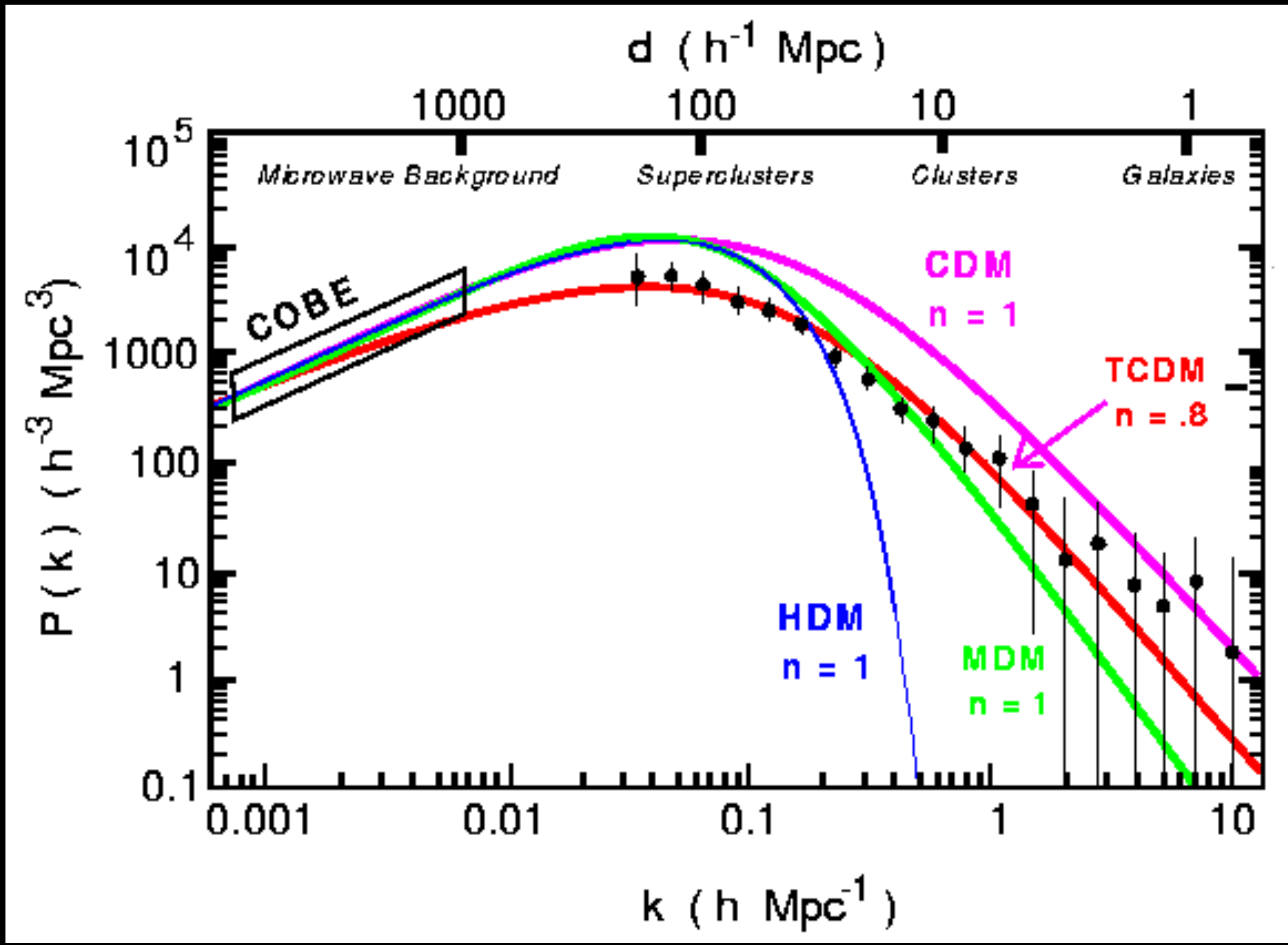
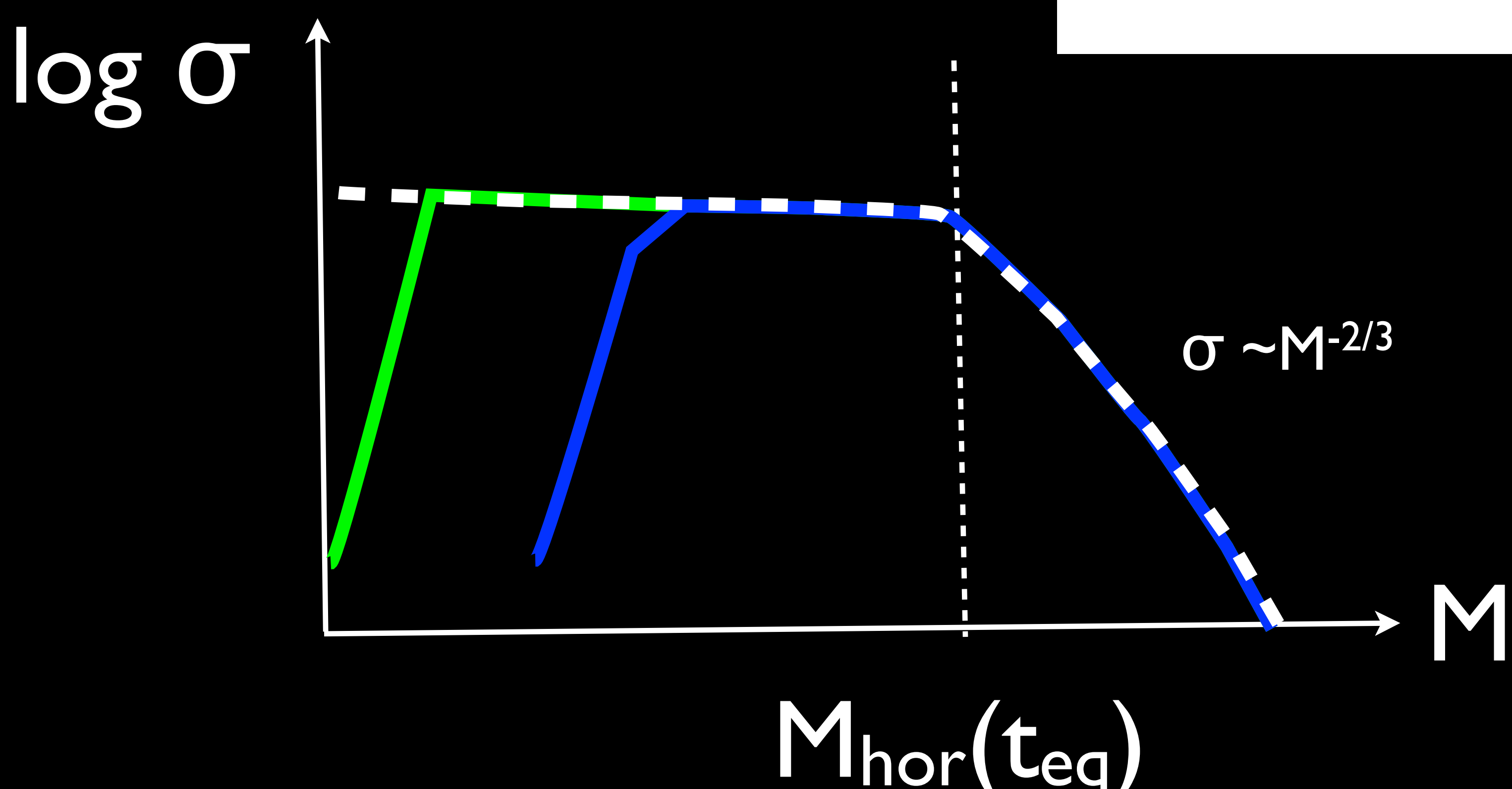
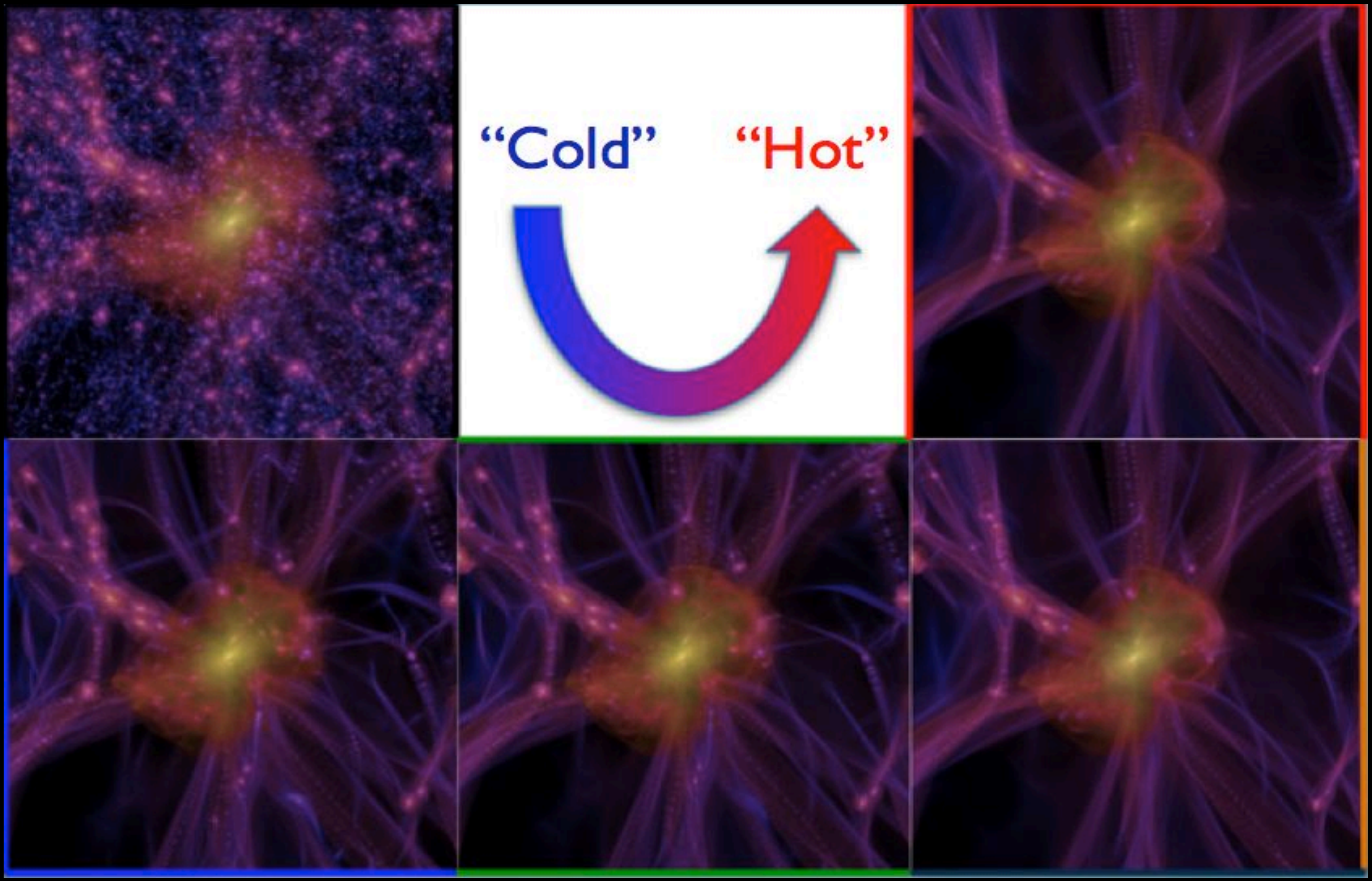




Varying the particle mass



Lovell et al. 2012

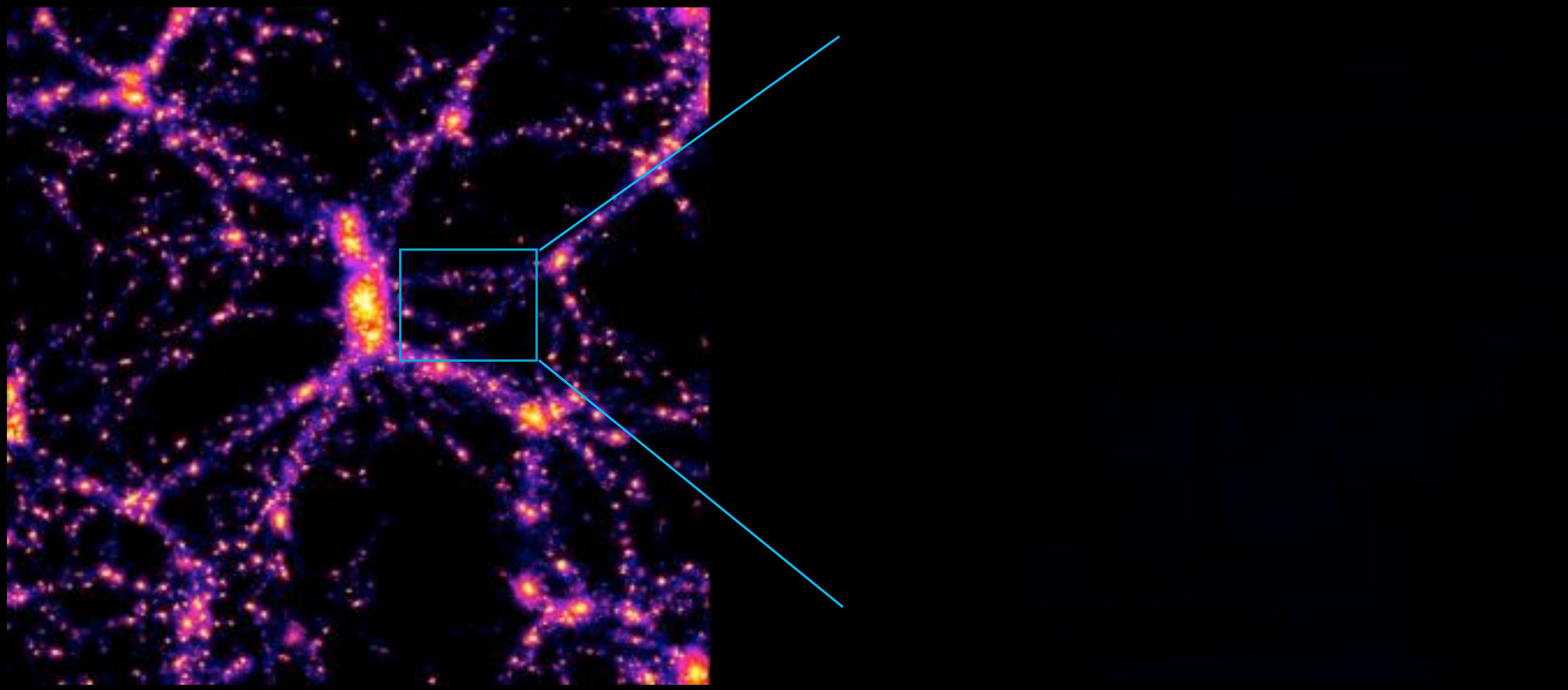
What’ so cold about CDM

For “thermal relics” such as neutrinos, it is relatively straightforward to compute their present day abundance.
Neutrinos relativistic at decoupling → large velocity dispersion.

Candidates for “Hot Dark Matter” -- ruled out by observation.

CDM: Velocity dispersion assumed to be vanishingly small

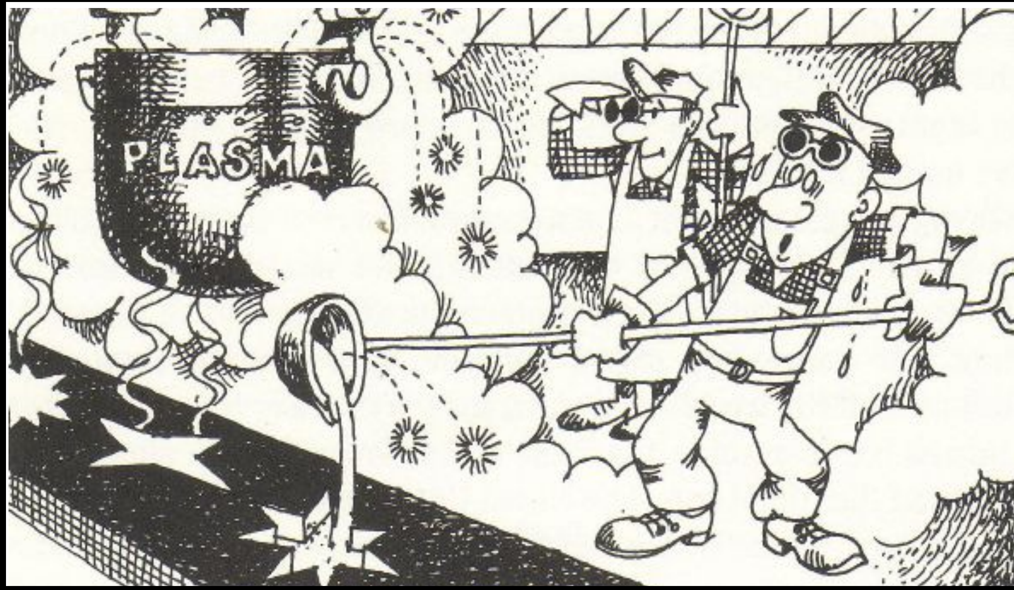
limit M_{fs} << Masses of Cosmological Relevance

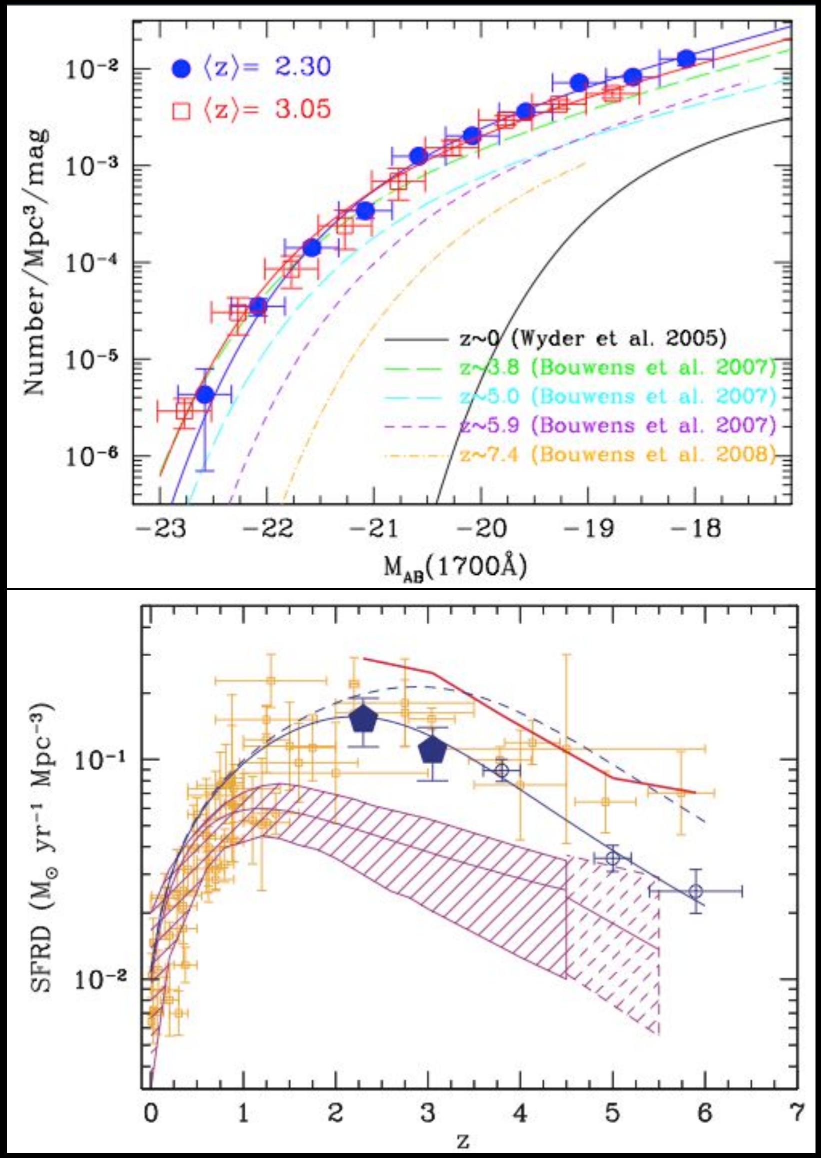


Testing the COLD DARK MATTER scenario against observations: the evolution of galaxies

Requires modelling of baryon physics inside evolving DM potential wells

- gas physis (cooling, heating)
- disk formation
- star formation
-evolution of the stellar population
- injection of energy into the gas
  from SNae





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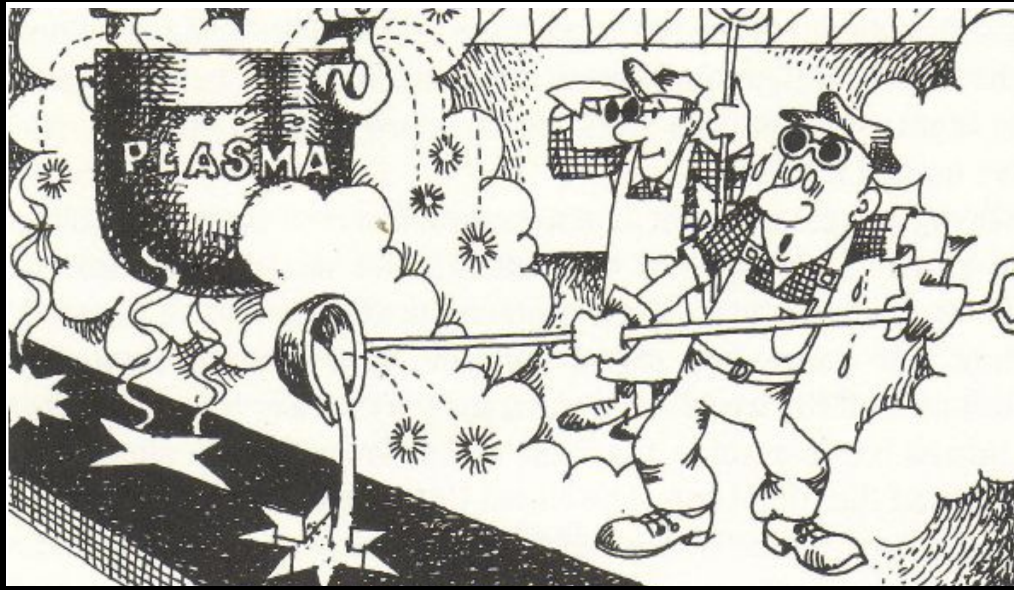

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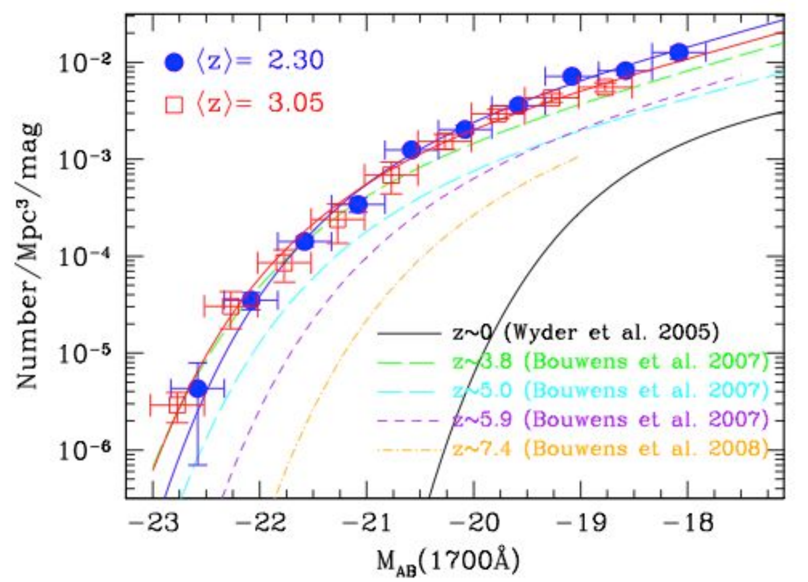
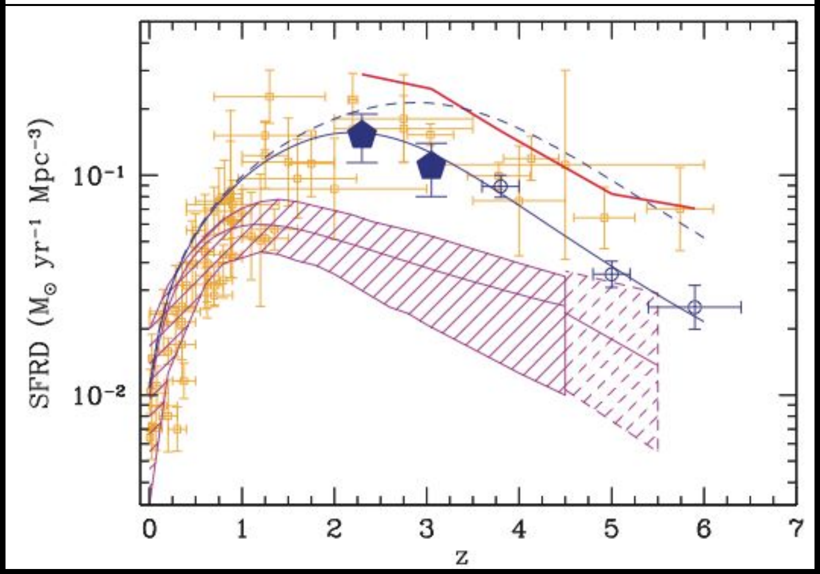
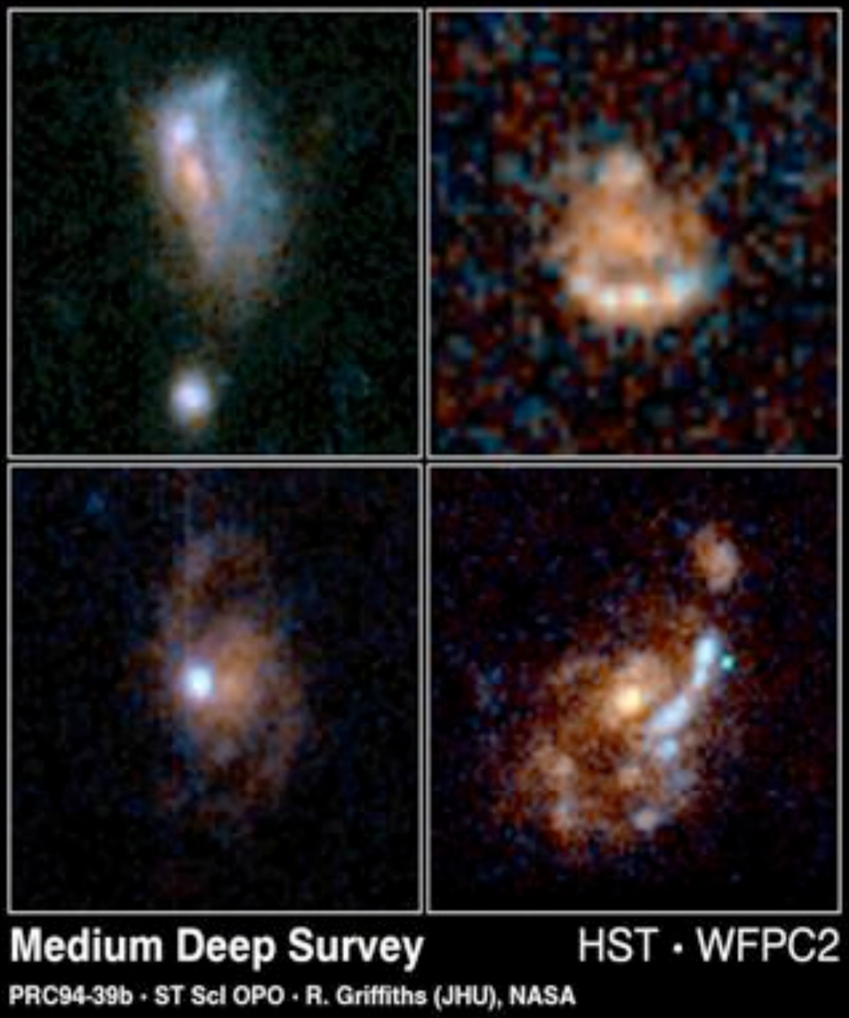






Galaxy Formation in a Cosmological Context

Hydrodynamcal
N-body simulations

Pros

include hydrodynamics of gas
contain spatial information

Cons

numerically expensive
(limited exploration of parameter space)
requires sub-grid physics

Semi-Analytic Models
Monte-Carlo realization of collapse and merging histories

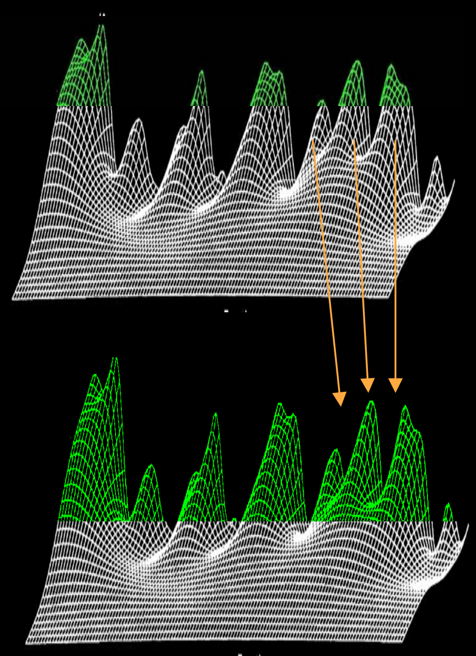
Pros

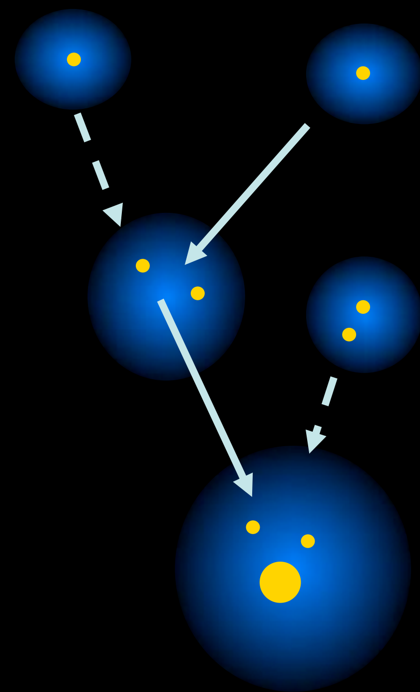
Physics of baryons linked to DM halos through scaling laws, allows a fast spanning of parameter space

Cons

Simplified description of gas physics
Do not contain spatial informations

Galaxy Formation in a Cosmological Context





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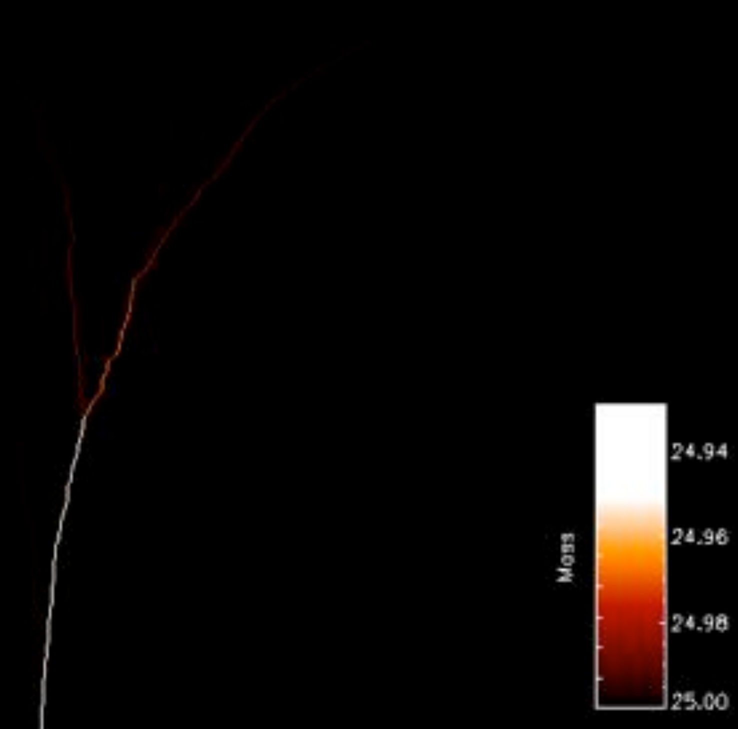


Sub-Halo dymanics:
dynamical friction, binary aggregation

Halo Properties
Density Profiles
Virial Temperature

Gas Properties
Profiles
Cooling - Heating Processes
Collapse, disk formation

Star Formation Rate

Gas Heating (feedback)
SNae
UV background

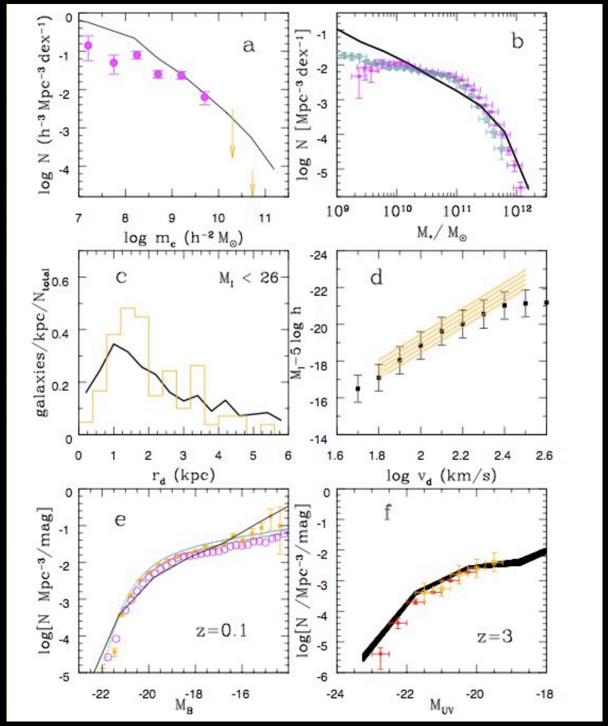
Evolution of stellar populations

Growth of Supermassive BHs
Evolution of AGNs

Galaxy Formation models in CDM scenario

Local properties:

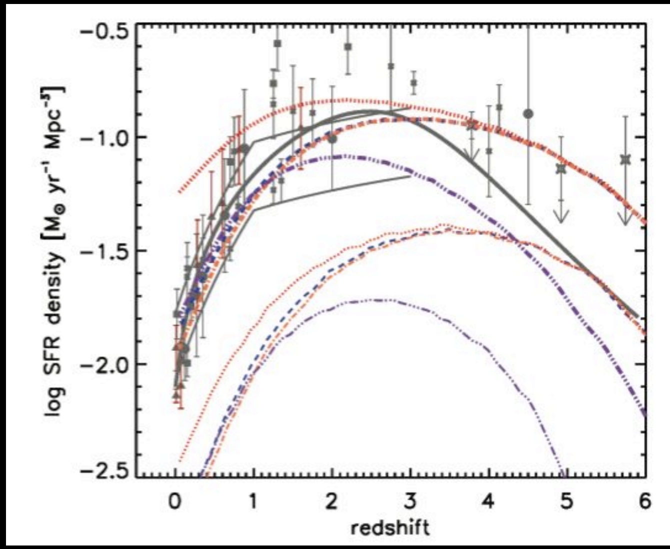
gas content
luminosity distribution
disk sizes
distribution of the stellar mass content



NM et al. 2006

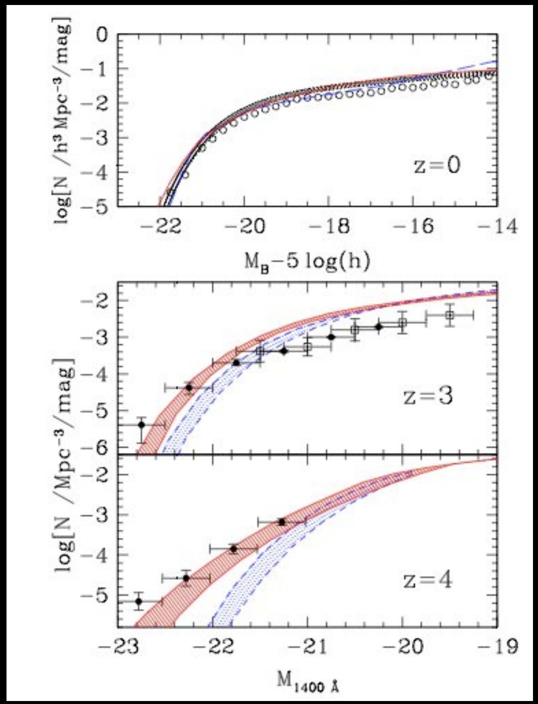
properties of distant galaxies:

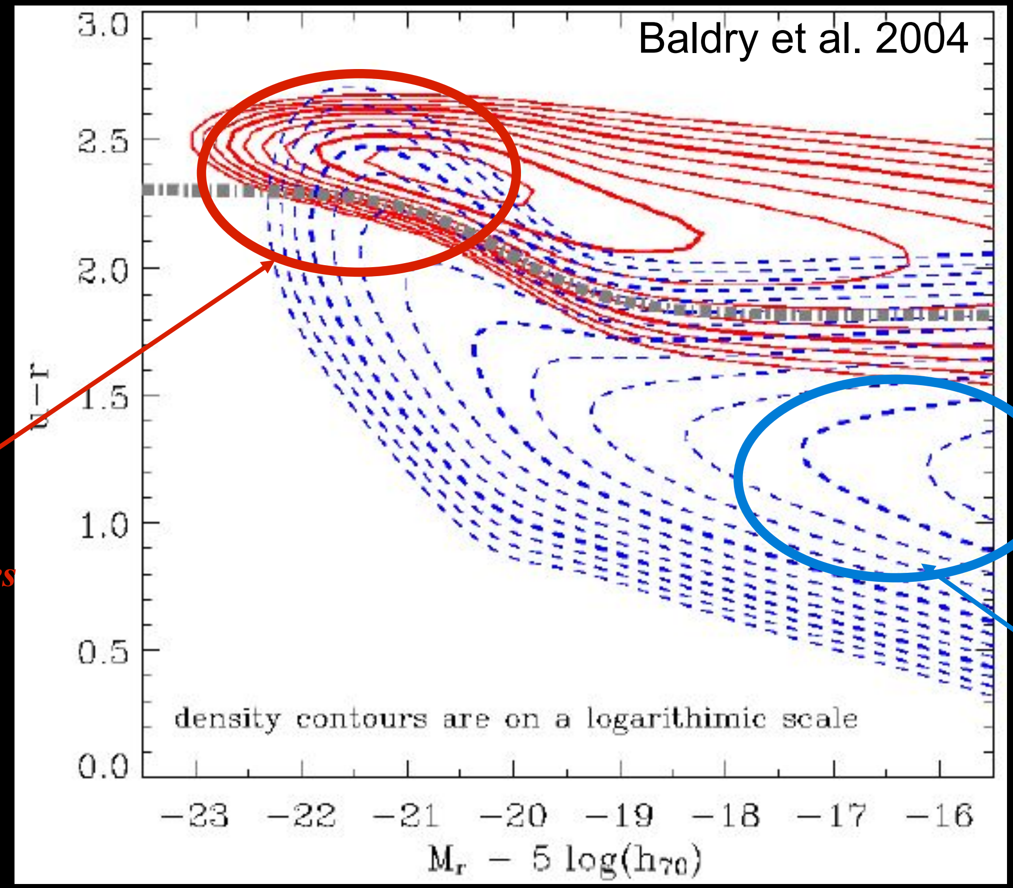
luminosity distribution
evolution of the star formation rate



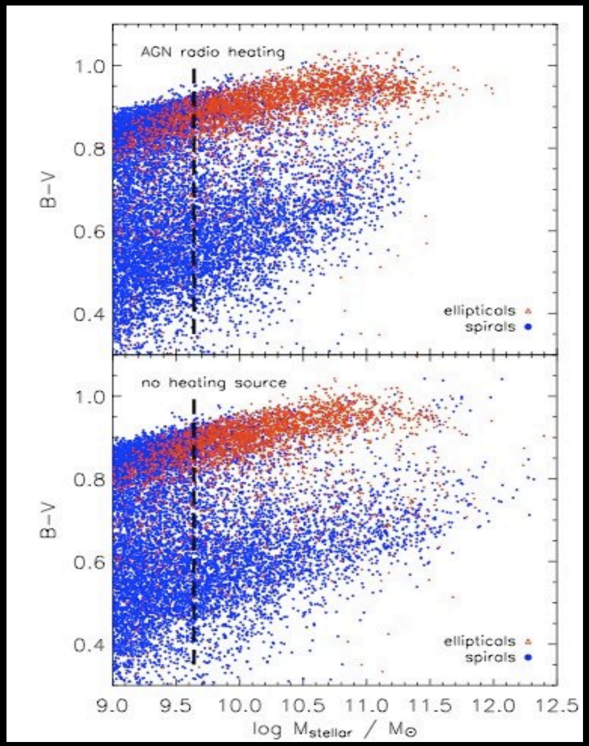
Somerville et al. 2010

NM et al. 2006

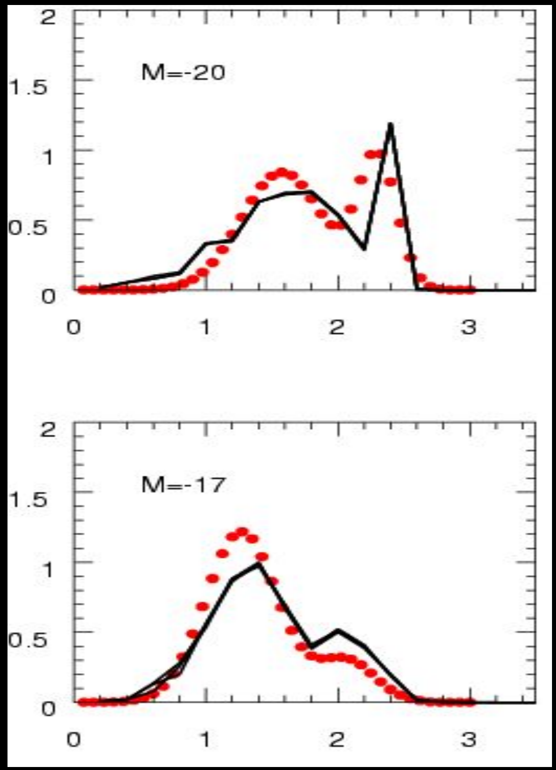




Color Distributions: bimodal distribution (early type vs late type)



Croton et al. 2006



NM et al. 2008

Critical Issues

Overabundance of low-mass objects

i) satellite DM haloes

ii) density profiles

iii) abundance of faint galaxies

iv) abundance of faint AGN

Critical Issues

i) satellite DM haloes

CDM Substructure in simulated cluster and galaxy haloes look similar.

Expected number of satellites in Milky Way- like galaxies in CDM largely exceeds the observed abundance.

Via Lactea simulation of a Milky Way - like galaxy
Diemand et al. 2008

Critical Issues

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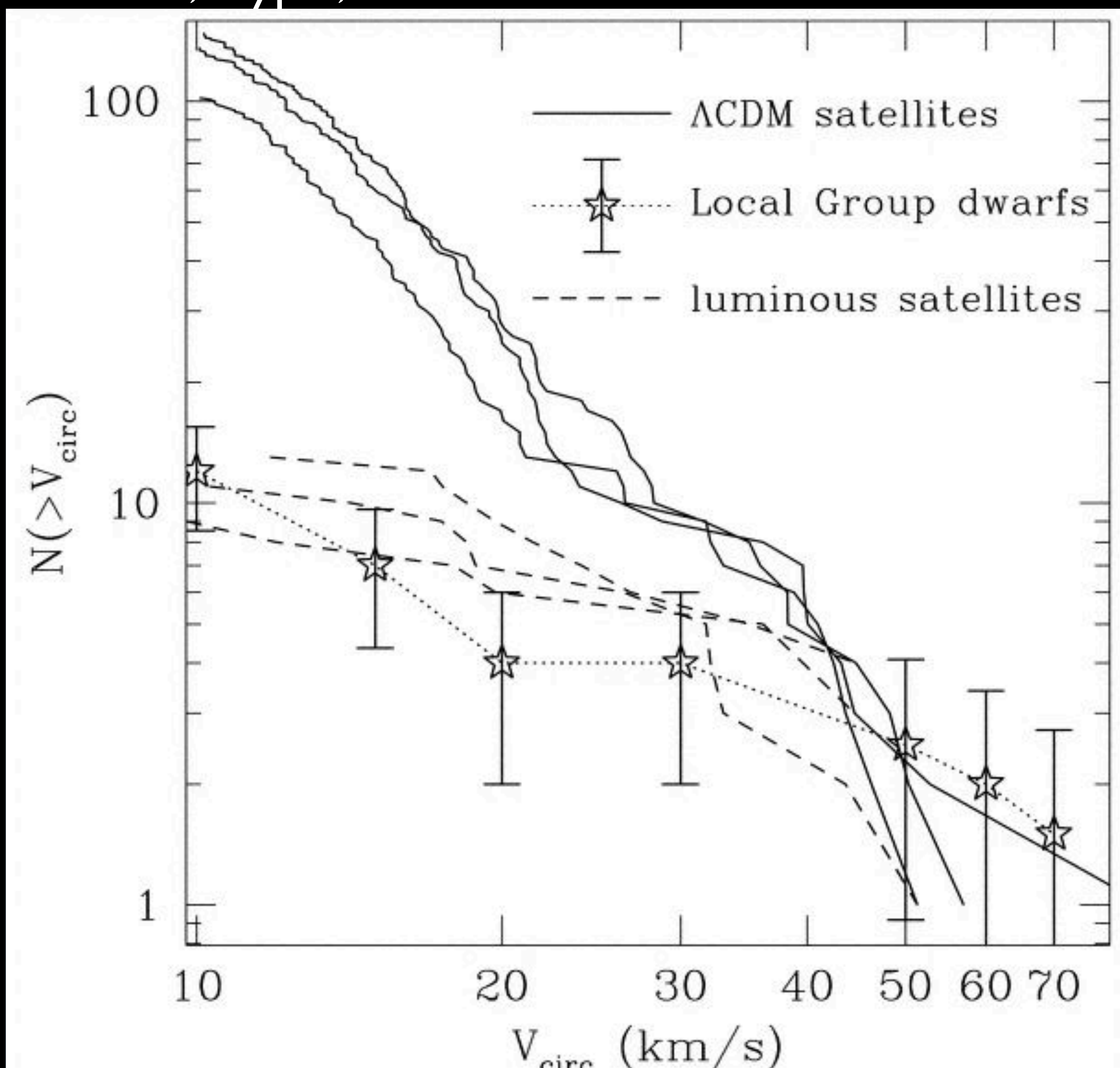
Kravtsov, Klypin, Gnedin 2004

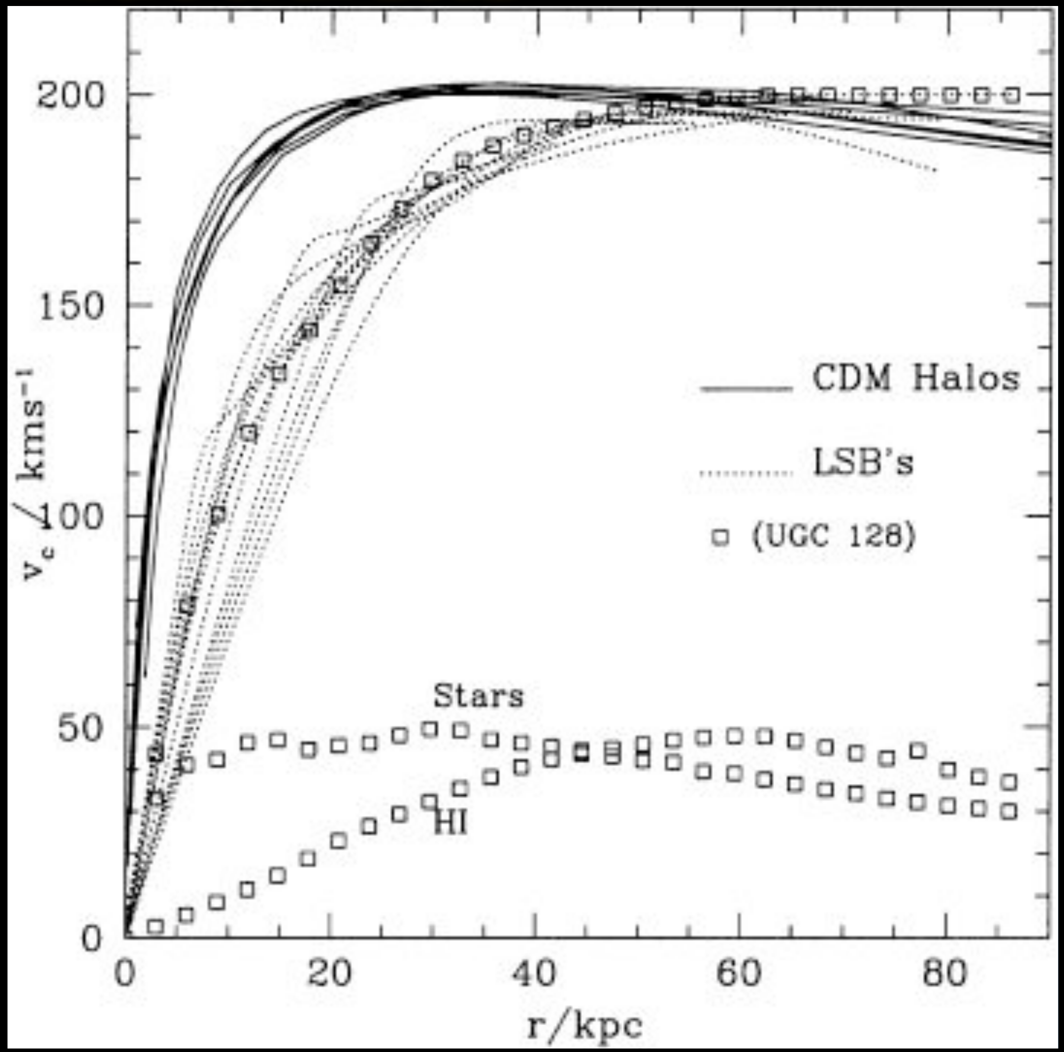


Critical Issues

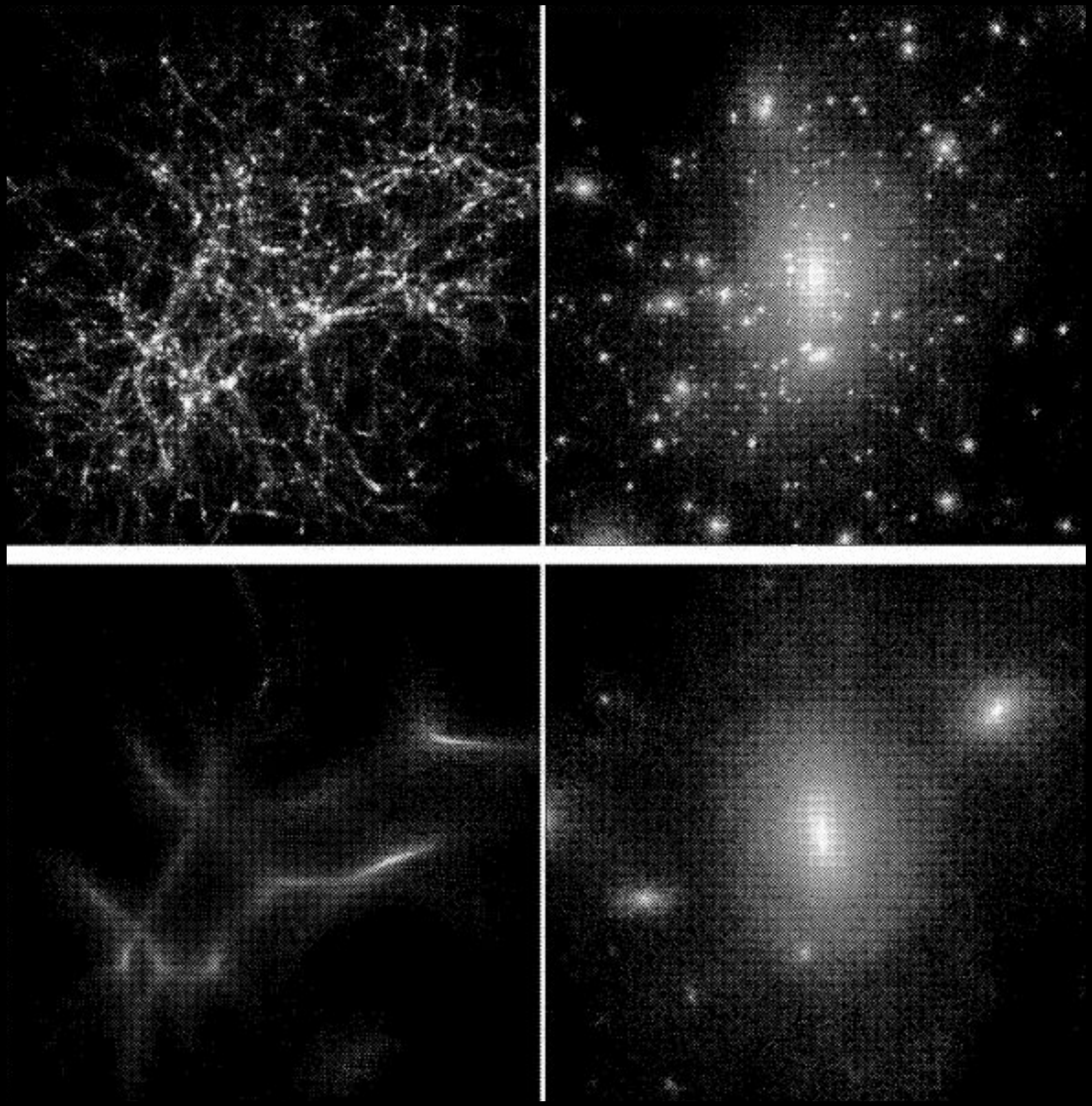
ii) density profiles

Most observed dwarf galaxies consist of a rotating stellar disk embedded in a massive dark-matter halo with a near-constant-density core. Models based on the dominance of CDM, however, invariably form galaxies with dense spheroidal stellar bulges and steep central dark-matter profiles, because low-angular- momentum baryons and dark matter sink to the centres of galaxies through accretion and repeated mergers.

Moore et al. 2002



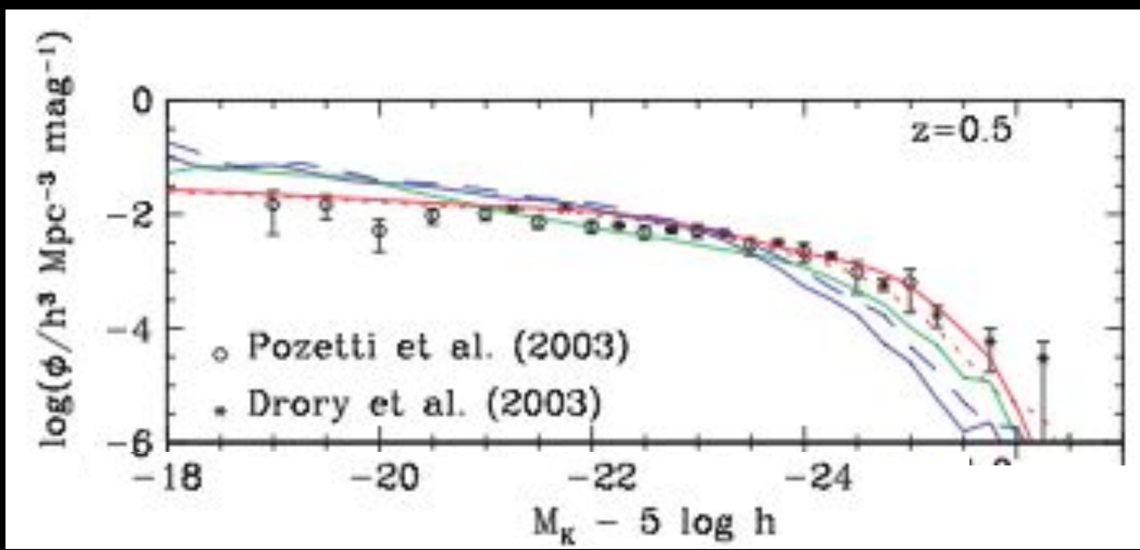
The effect of adopting a cutoff
in the power spectrum for r<8 Mpc



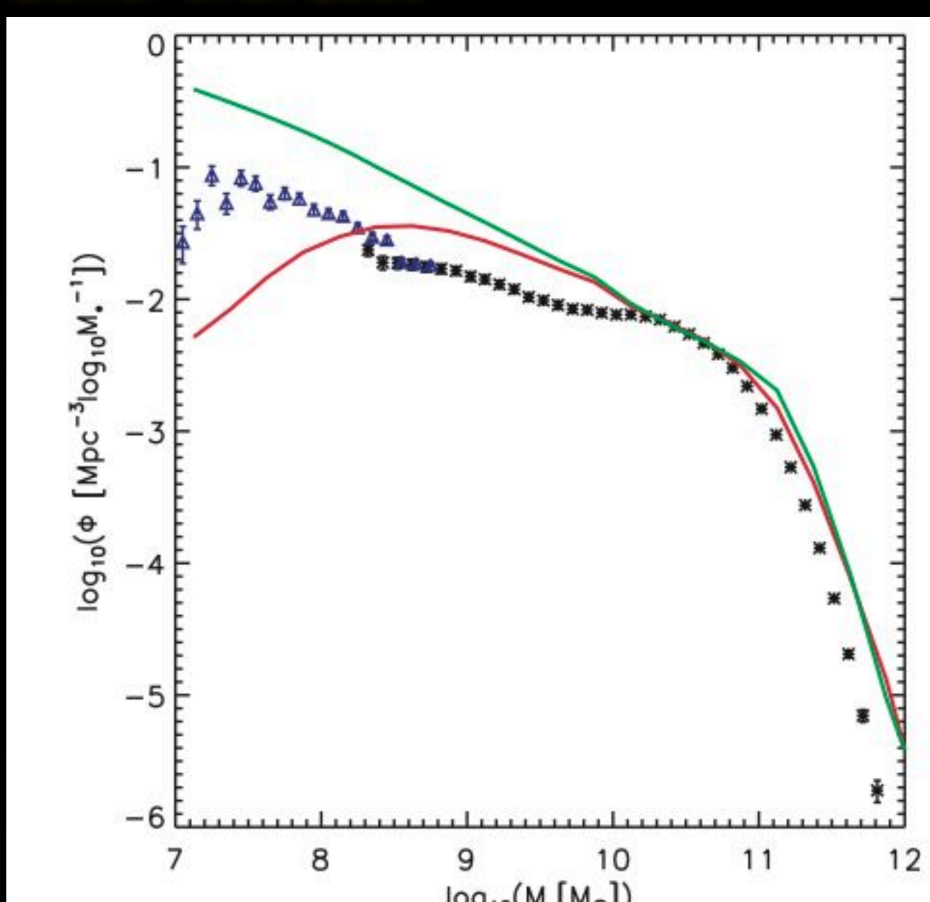
Critical Issues

iii)over-prediction of faint galaxies

In all first-generation SAM the number density of faint (low-mass) galaxies was over-predicted

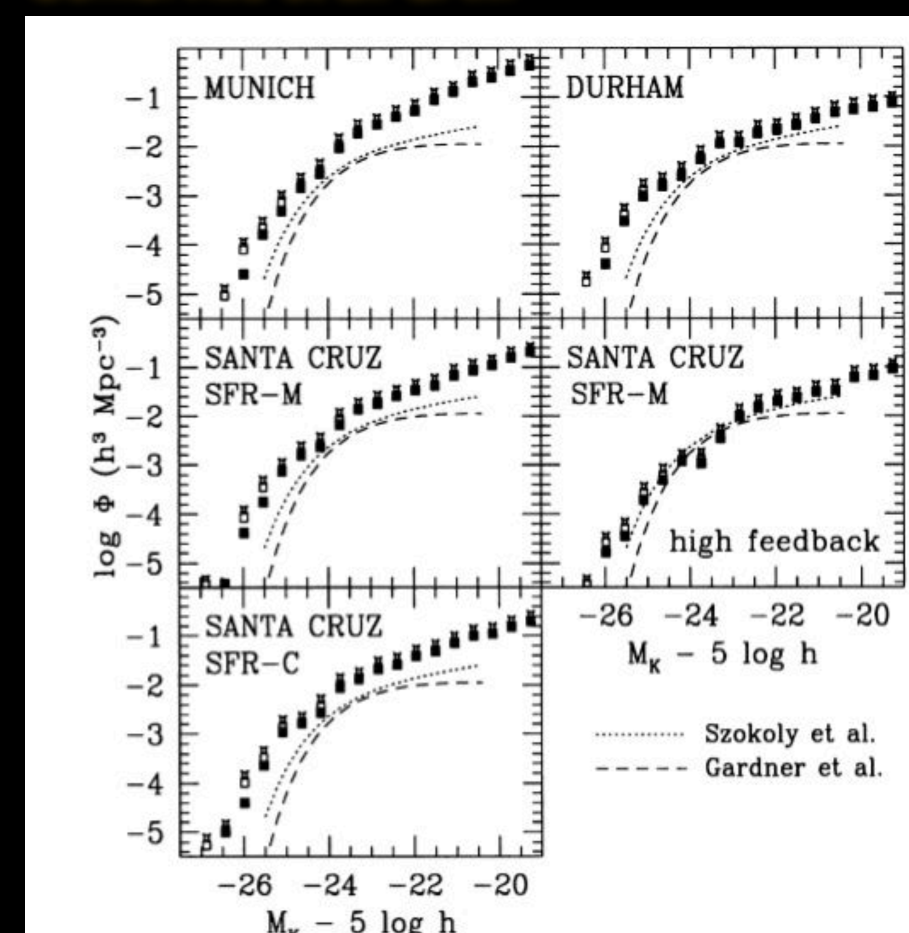


Bower et al. 2006

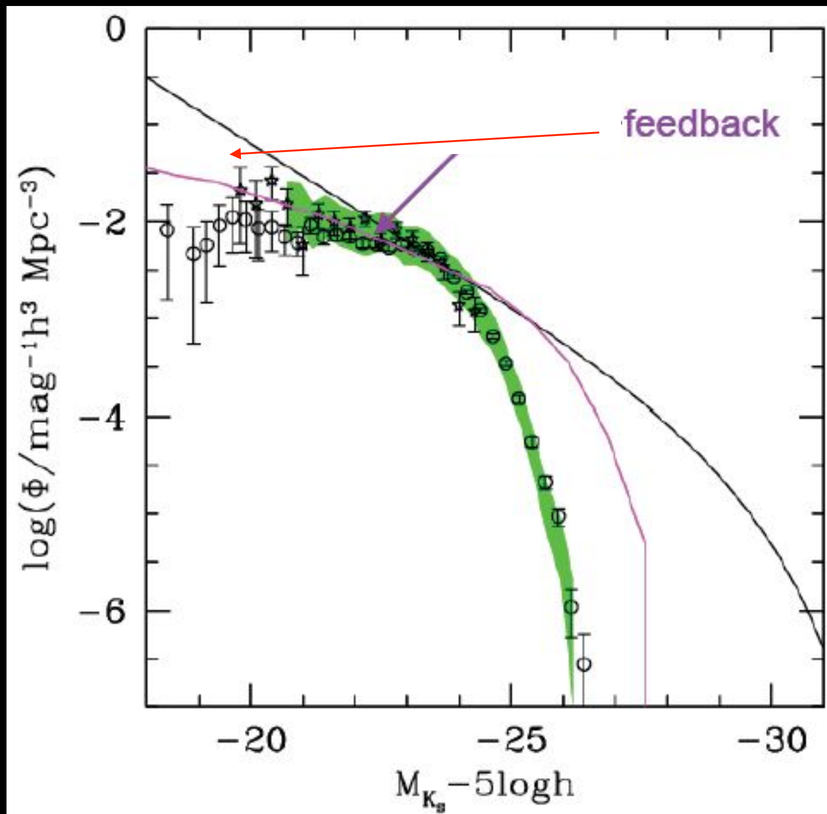


The Stellar Mass Function in the De Lucia et al. SAM based on Millenium merger trees

The K-Band Luminosity Function in the Somerville et al. SAM



A first-order solution: feedback and UV background



The origin of the problem:
The DM halo Mass function has a steep log slope $N{\sim}M^{-1.8}$
While the Observed Galaxy Luminosity Function
has a much flattter slope $N{\sim}L^{-1.2}$

A Possible Solution:
Suppress luminosity (star formation) in low-mass haloes
Heat - Expell Gas from shallow potential wells
- Enhanced SN feedback
- UV background

$$E_{SN} \approx 10^{51}\,\eta_0\eta_{IMF}\,\Delta M_* erg/s$$

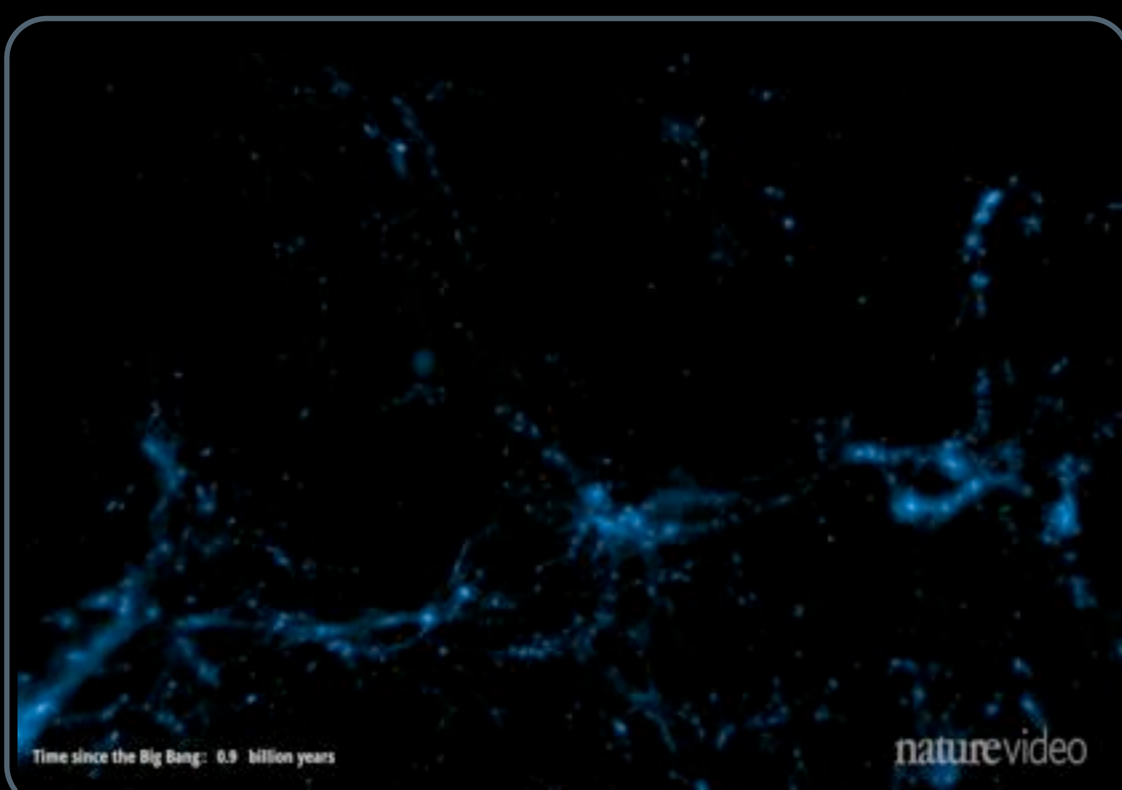
$$v_{esc} = \sqrt{E_{SN}/M_{gas}} \approx 100\ km/s$$

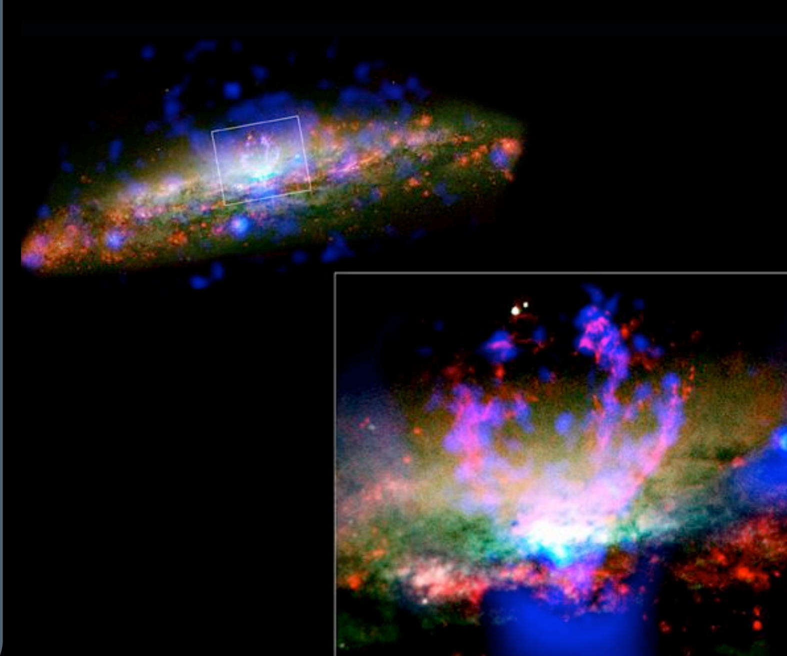
Mass scale at which
SN can effectively espell gas from
DM potential wells

$$M_{SN} \sim 10^{10}\ M_\odot$$

at low z, att higher redshift the
density is higher an M_{SN} increases

Vogelsberger et al. 2014





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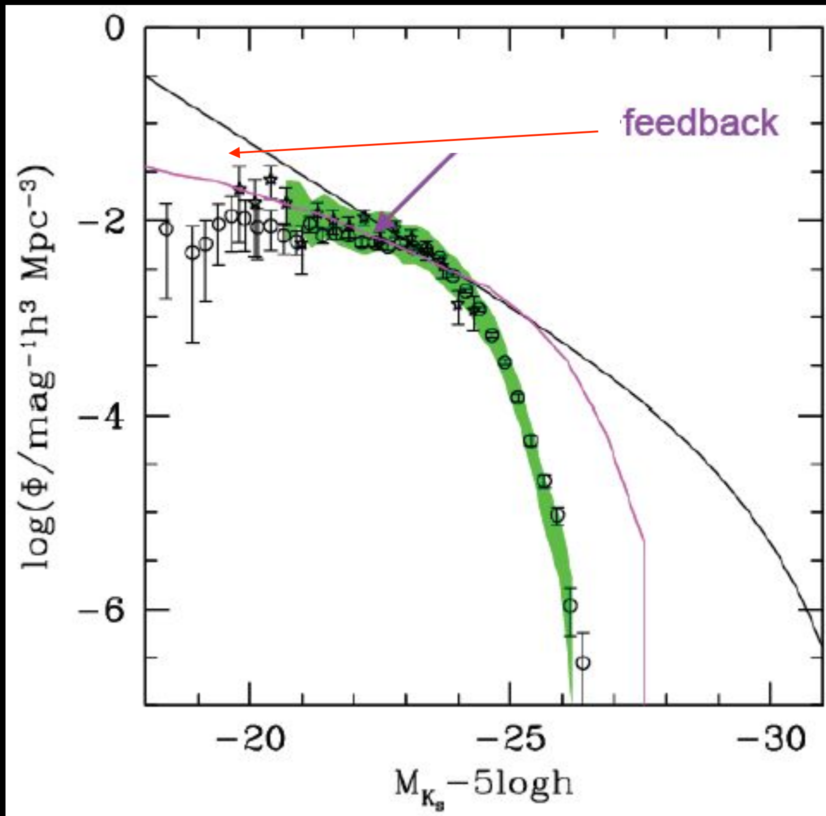

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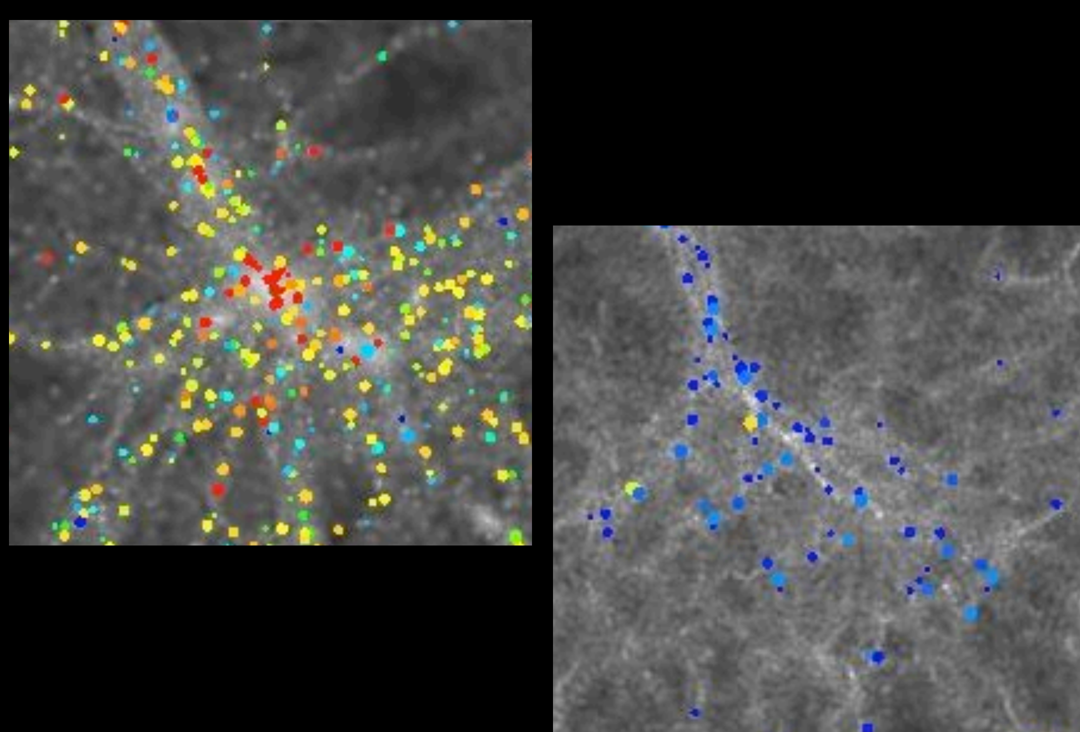
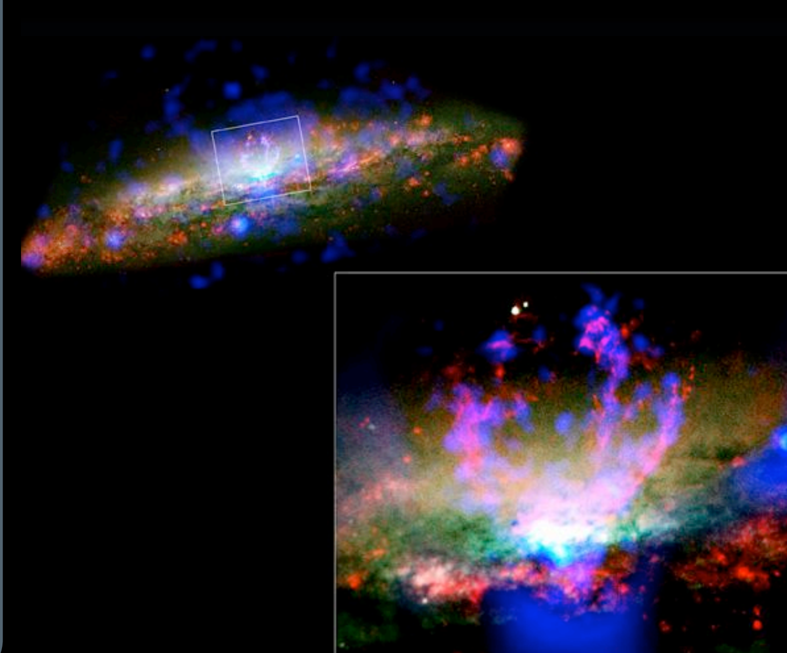
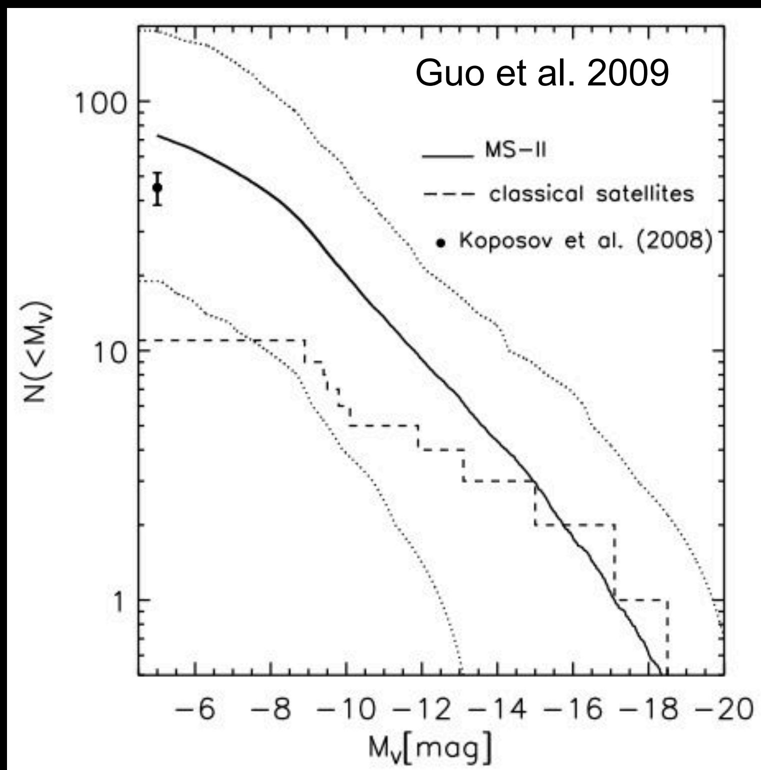
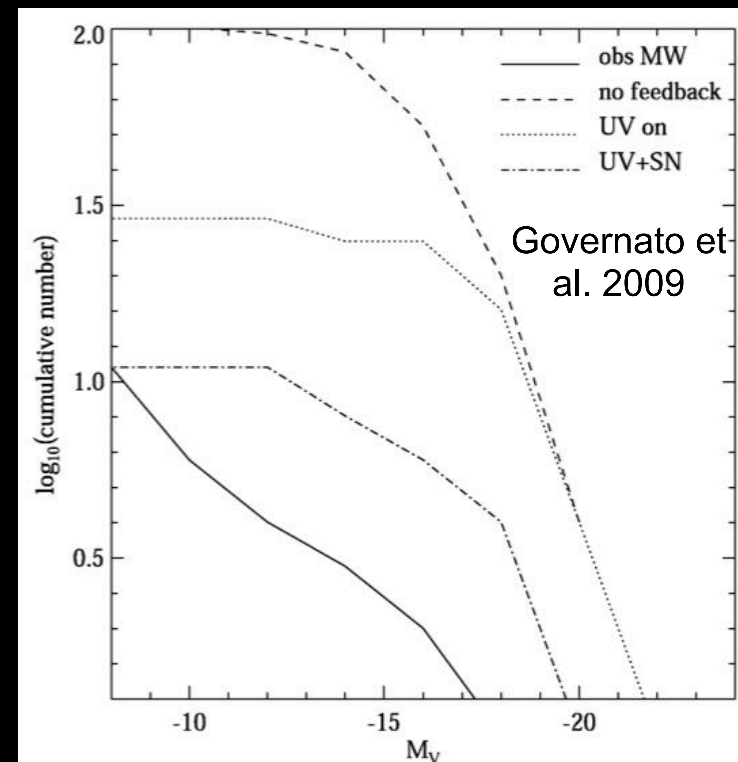




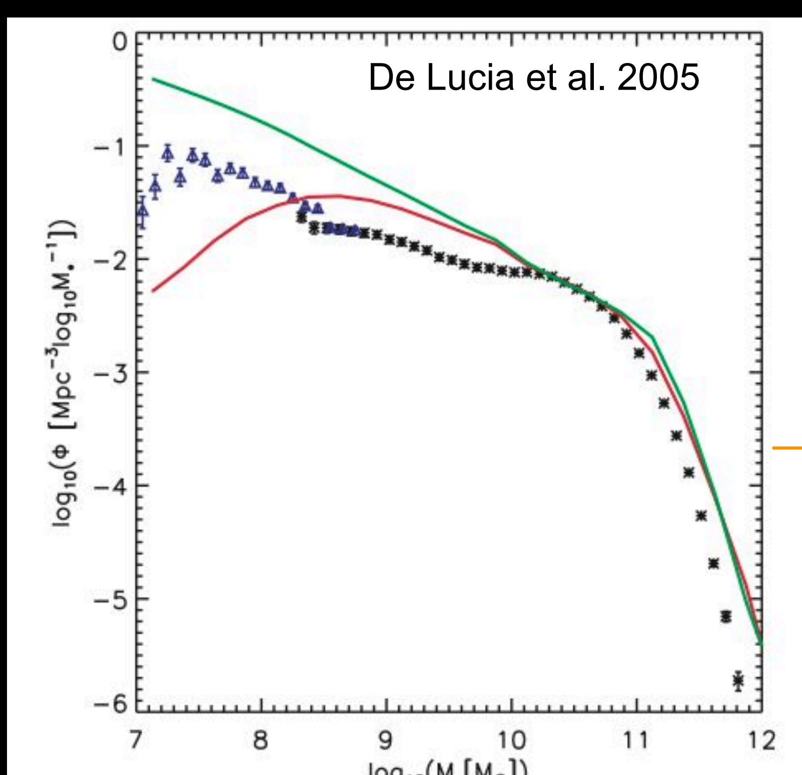
The effect of feedback

i) the abundance of satellites



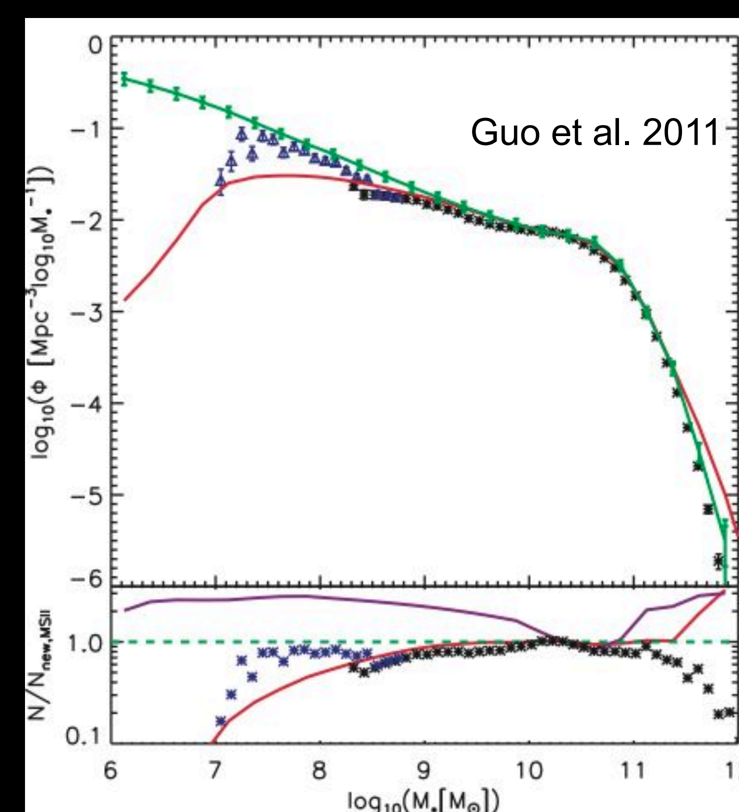


ii) the abundance of faint galaxies

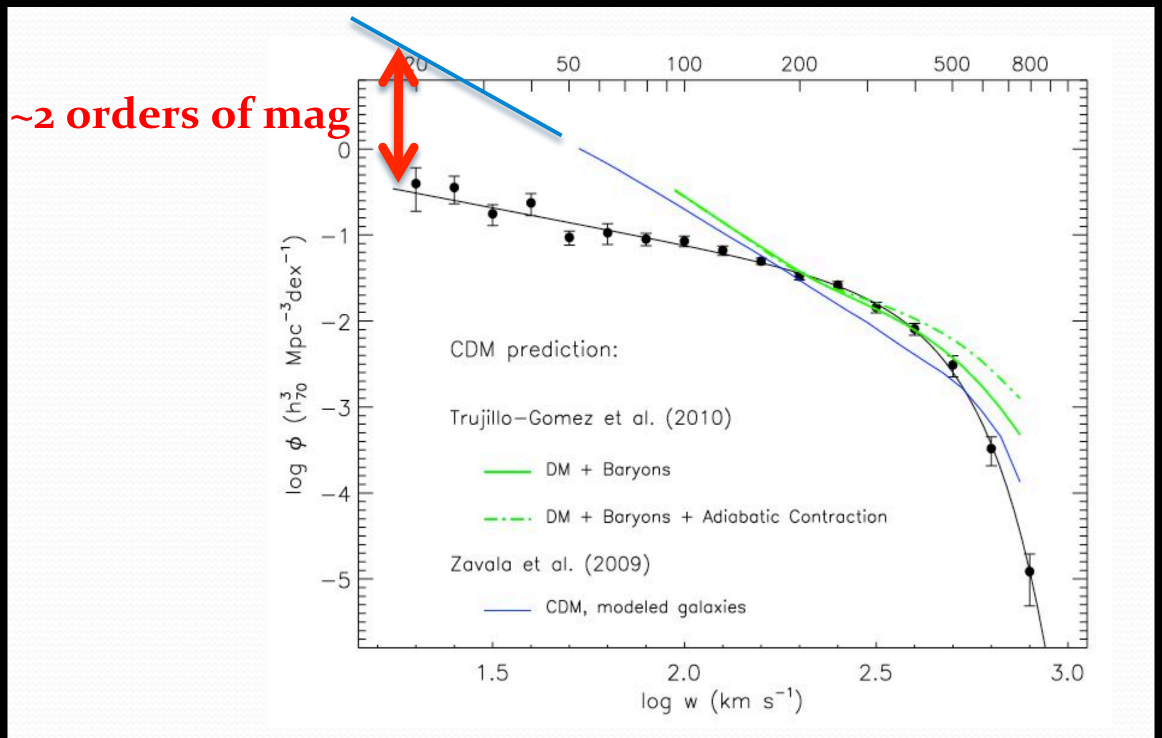


Refined treatment of Gas and Stellar Stripping

Enhanced (tuned) feedback dependence on the circular velocity of the DM halo



Abundance of galaxies as a function of their velocity width (gas rotation velocity)

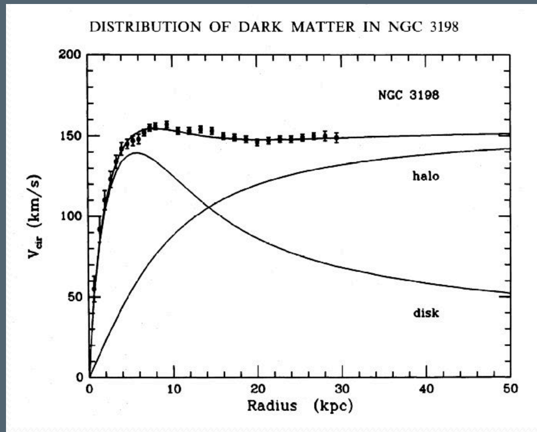


Papastergis+ (2011)

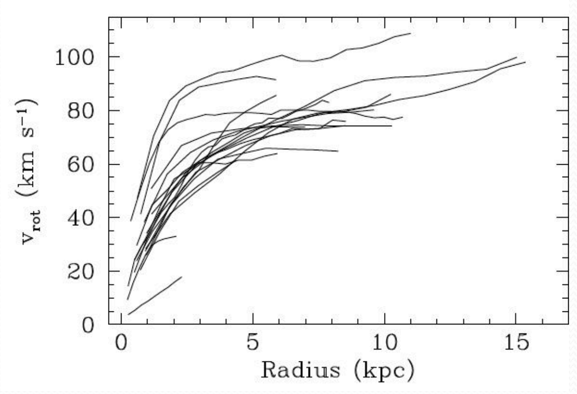
21-cm survey done with Arecibo Telescope: 3000 deg^2; 11000 detections
measures: redshift, velocity width, integrated flux
No spatial resolution (size, inclination, shape)

Directly measures
the depth of the potential well:
less prone to physics of gas (feedback)

Solutions within CDM scenario ?
- large fraction of galaxies with low gas content (below the sensitivity)
-large fraction of galaxies with rising rotation curve



'flat' rotation curve



'rising' rotation curves

Swaters+ (2009)

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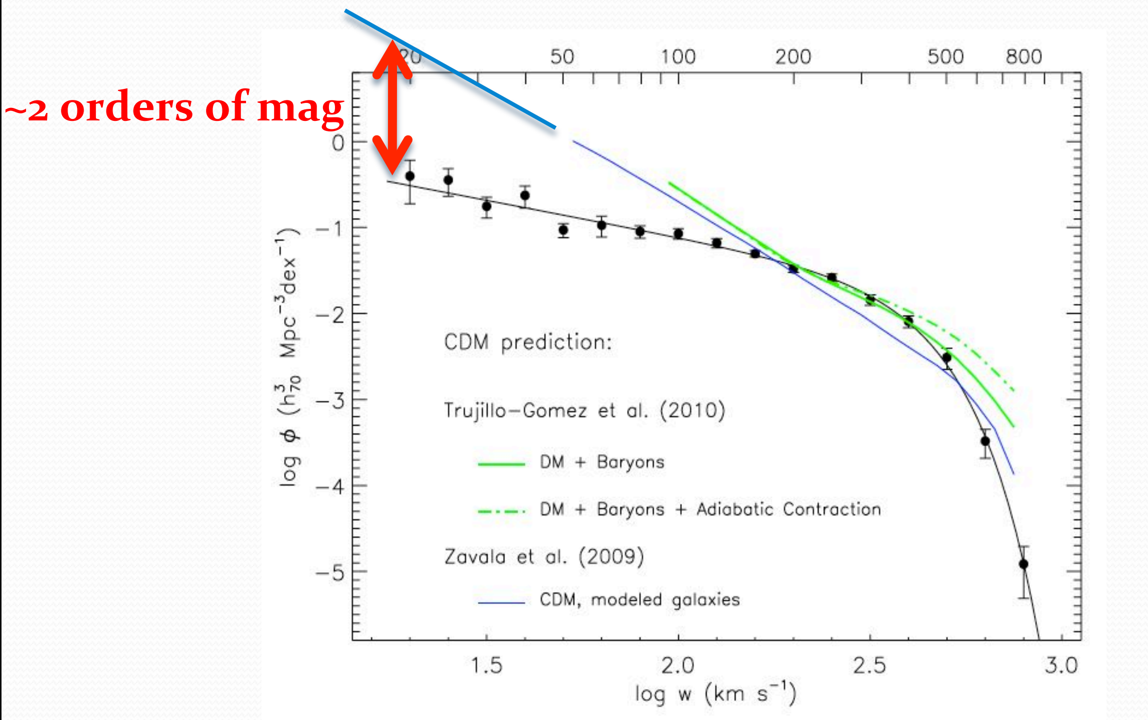

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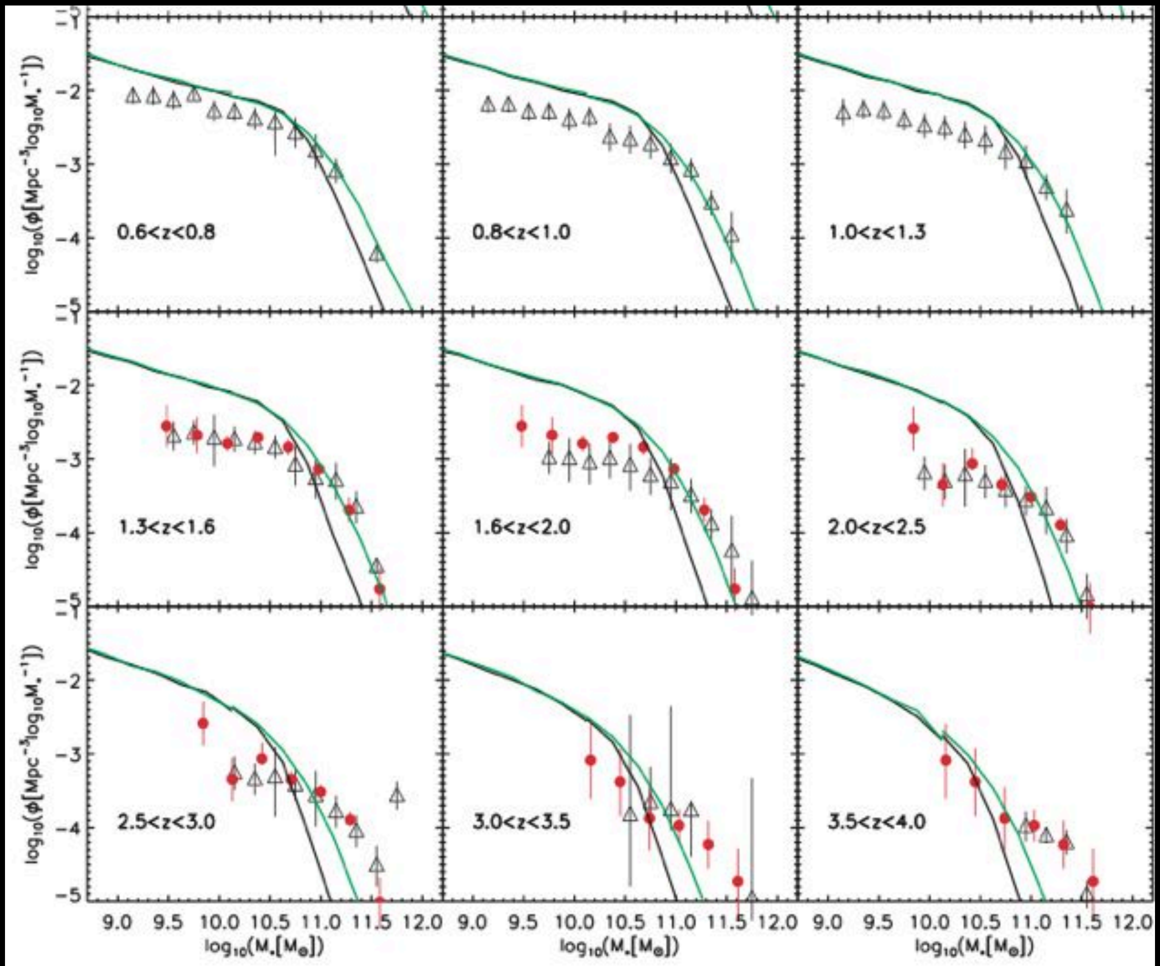


At high redshift, galaxies are denser

Difficult to expel gas from such compact objects

Even with maximized feedback, current models still over estimate the number of small mass galaxies

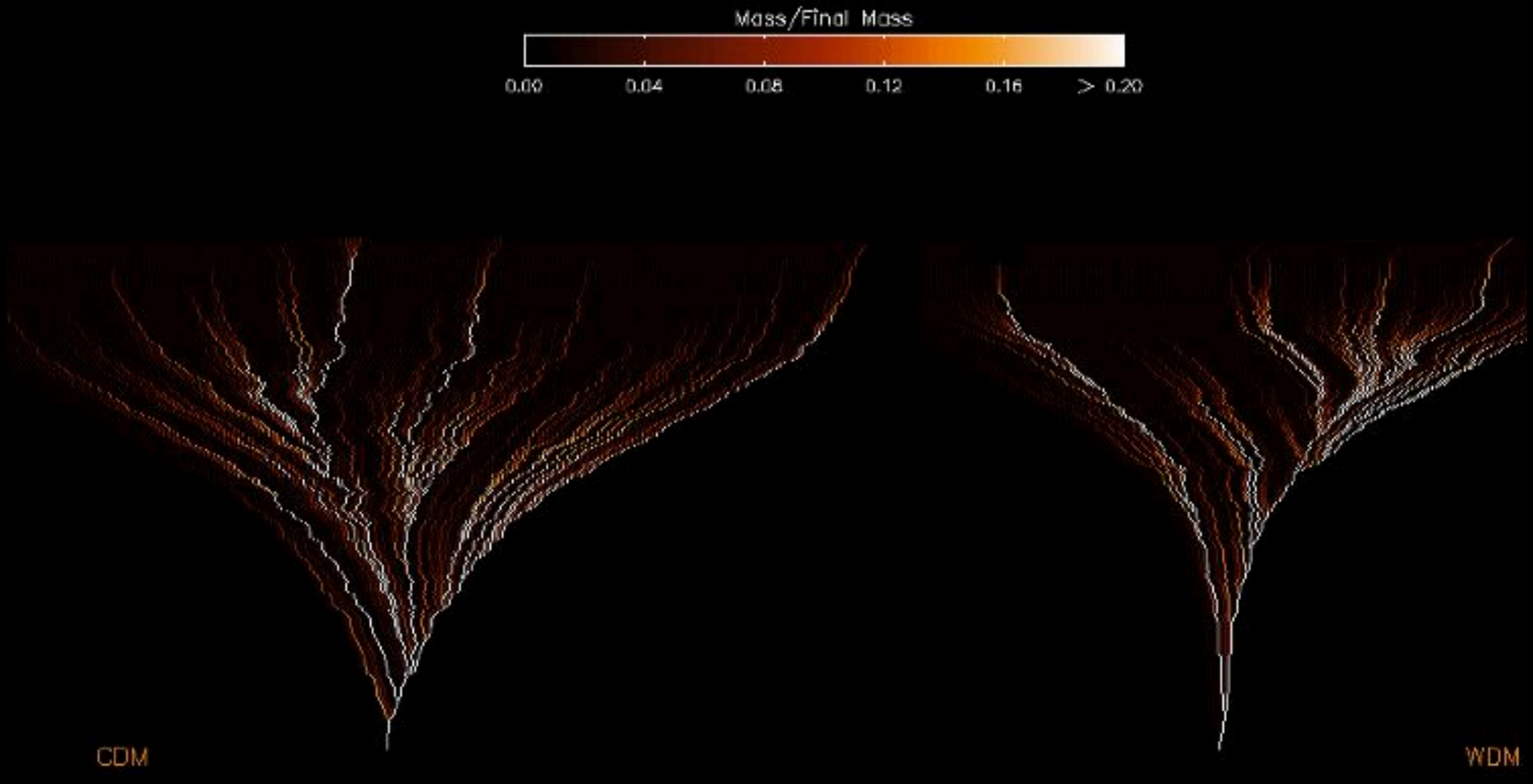
Galaxy formation in WDM Cosmology

Problem Persists at high redshifts

Too many low-mass structures

Need to suppress Power Spectrum at small scales ?

can WDM solve all problems simultaneously ?



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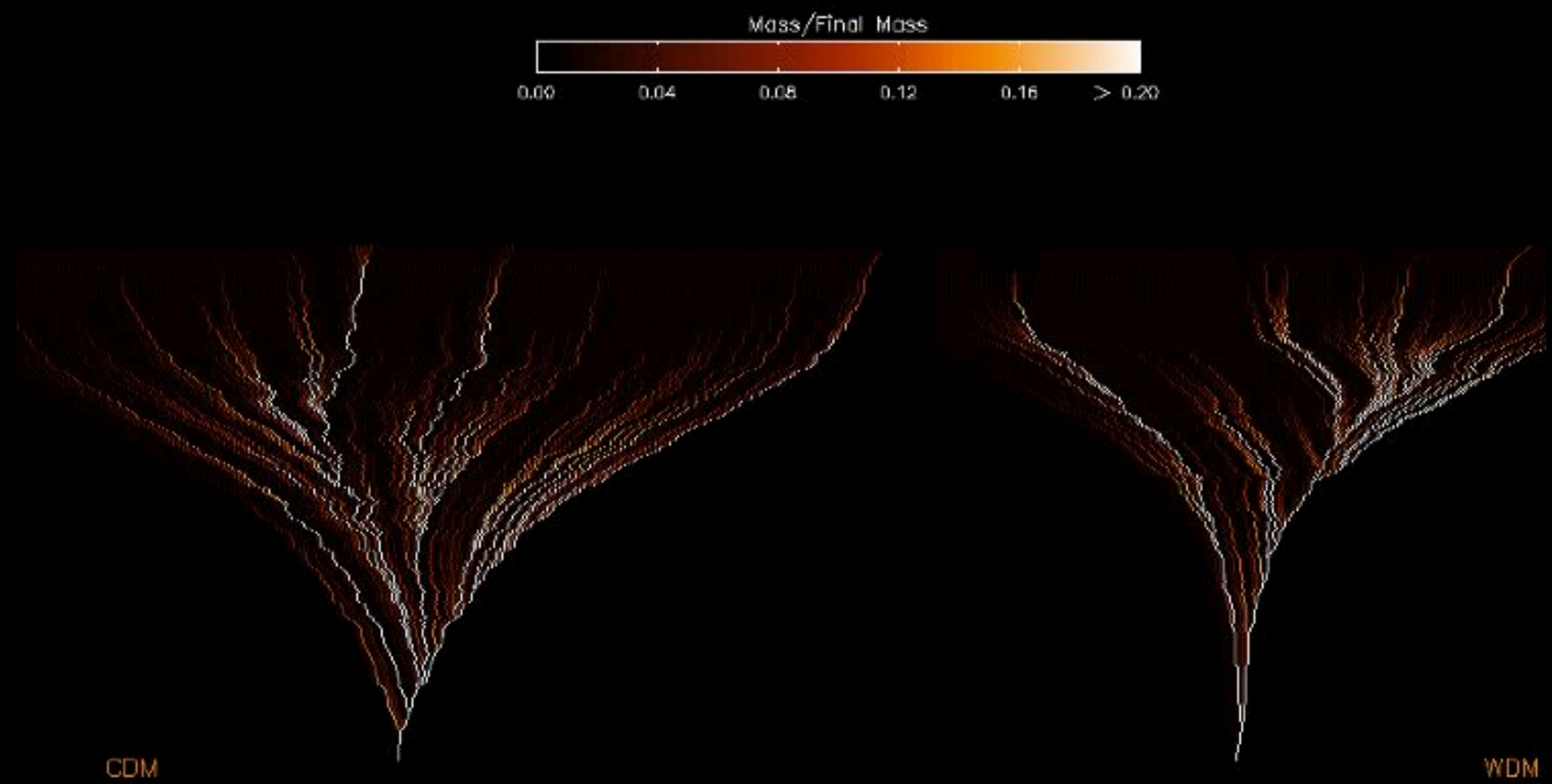
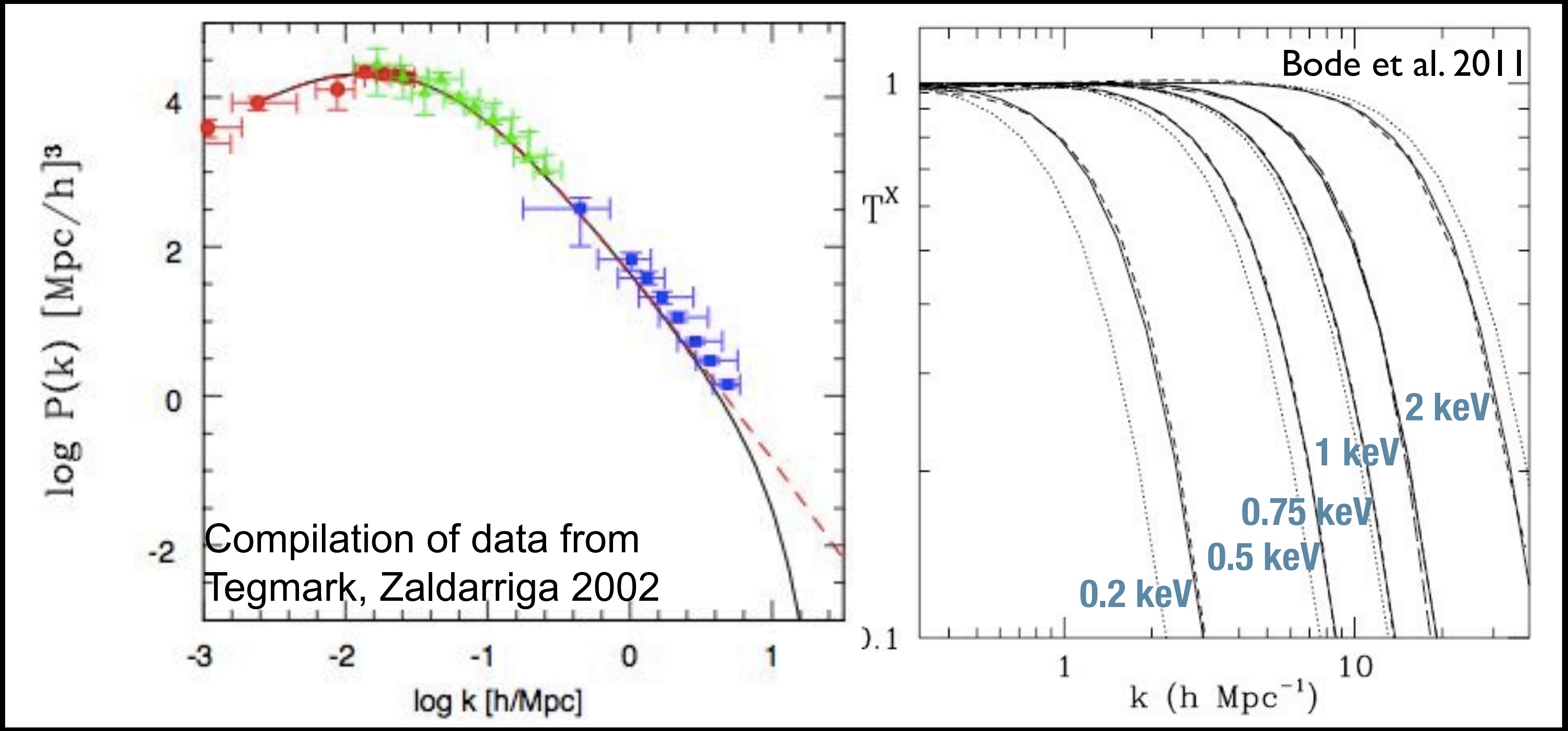


Rome PANDA model

NM, A. Lamstra

Implementing WDM power spectrum in the galaxy formation model



To explore the maximal effect of a power-spectrum cutoff on galaxy formation, we consider a cutoff at scales just below 0.2 Mpc, where data from Lyman-α systems (compared to N-body simulations) yields stringer upper limits on power suppression. This corresponds to mass scales $M_{fs} \sim 5\ 10^8\ M_\odot$

$$r_{fs} \approx 0.2 \left[\frac{\Omega_X h^2}{0.15}\right]^{1/3} \left[\frac{m_X}{rmkeV}\right]^{-4/3} \mathrm{Mpc} \qquad \frac{P_{WDM}(k)}{P_{CDM}(k)} = \left[1 + (\alpha\, k)^{2\,\mu}\right]^{-5\,\mu}$$

$$\alpha = 0.049 \left[\frac{\Omega_X}{0.25}\right]^{0.11} \left[\frac{m_X}{\mathrm{keV}}\right]^{-1.11} \left[\frac{h}{0.7}\right]^{1.22} h^{-1}\ \mathrm{Mpc}$$

WDM
particle mass
1 kev

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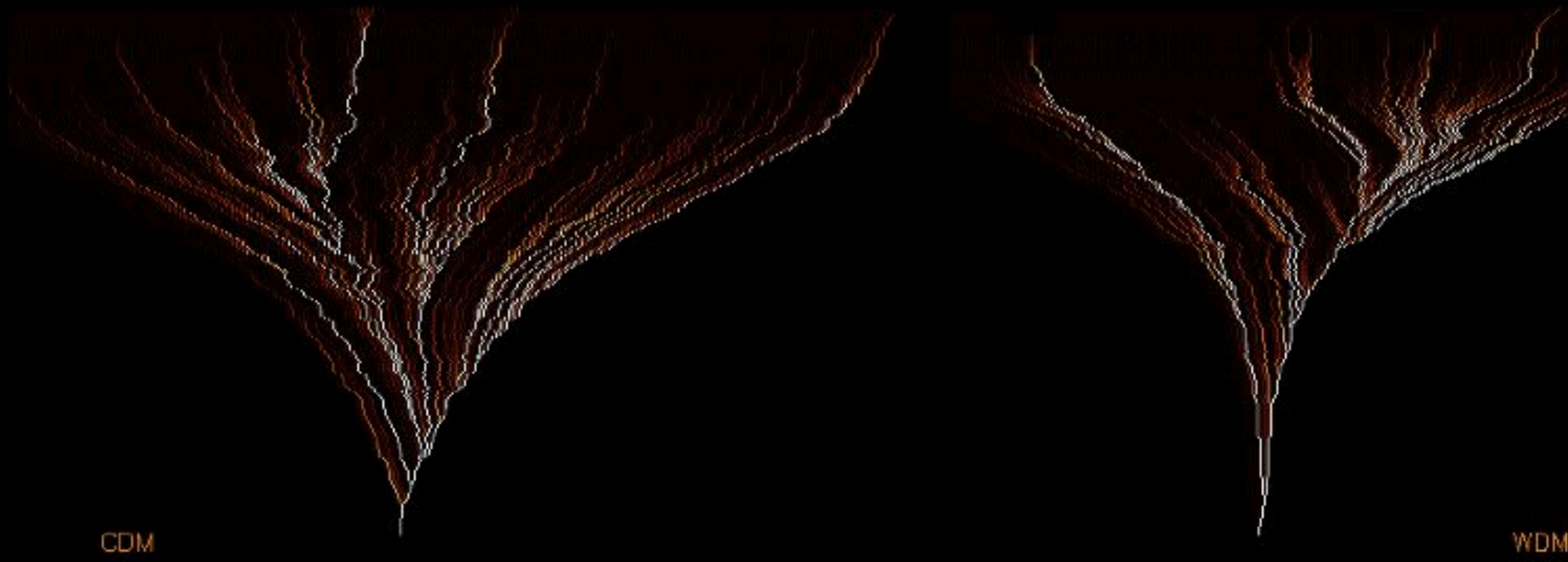

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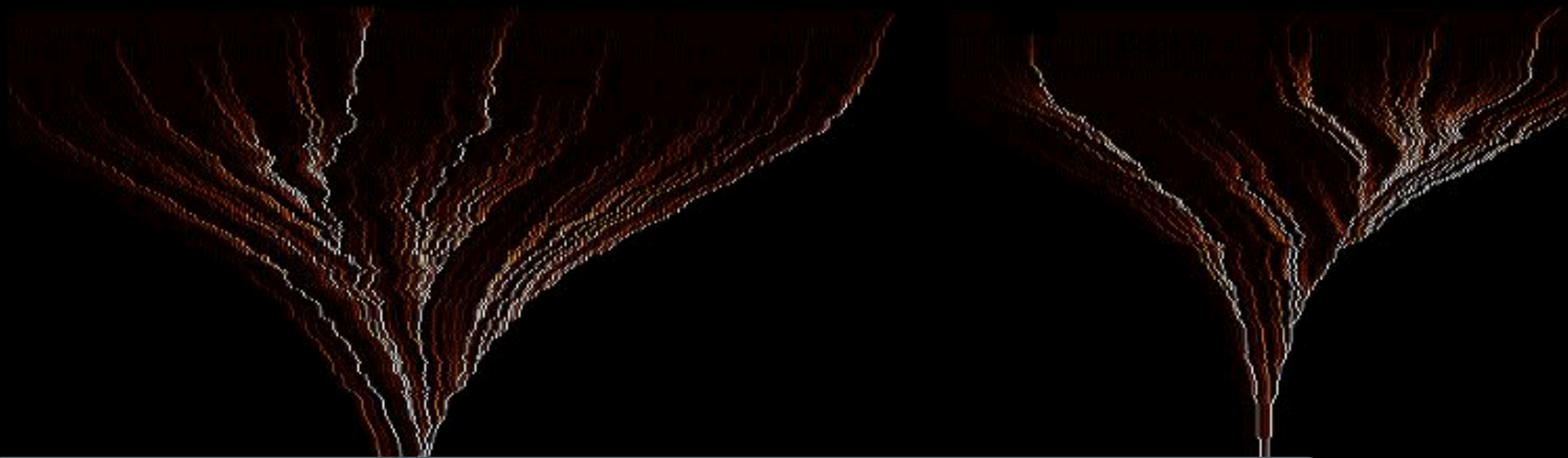

Halo Properties
Density Profiles
Virial Temperature

Gas Properties
Profiles
Cooling - Heating
Collapse
Disk formation

Star Formation

Gas Heating (feedback)
SNae
UV background

Evolution of stellar populations

WDM

Galaxy formation in WDM implies computing how modifications of the power spectrum propagate to the above processes

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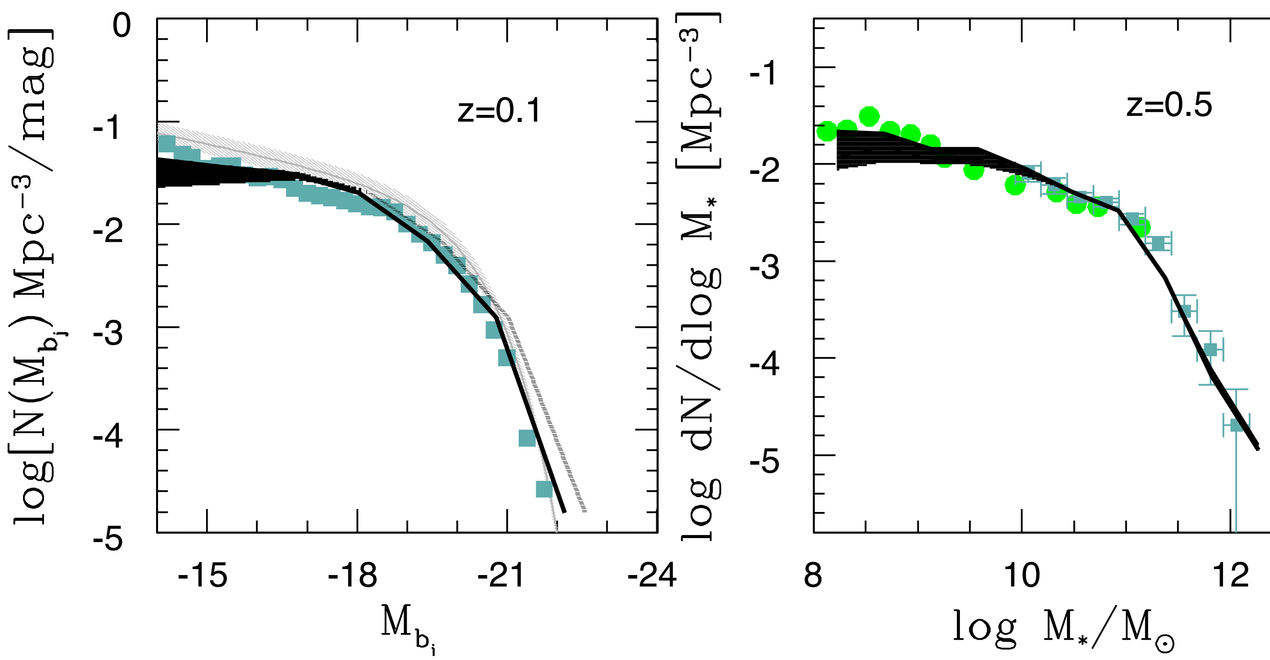
WDM
particle mass
1 kev

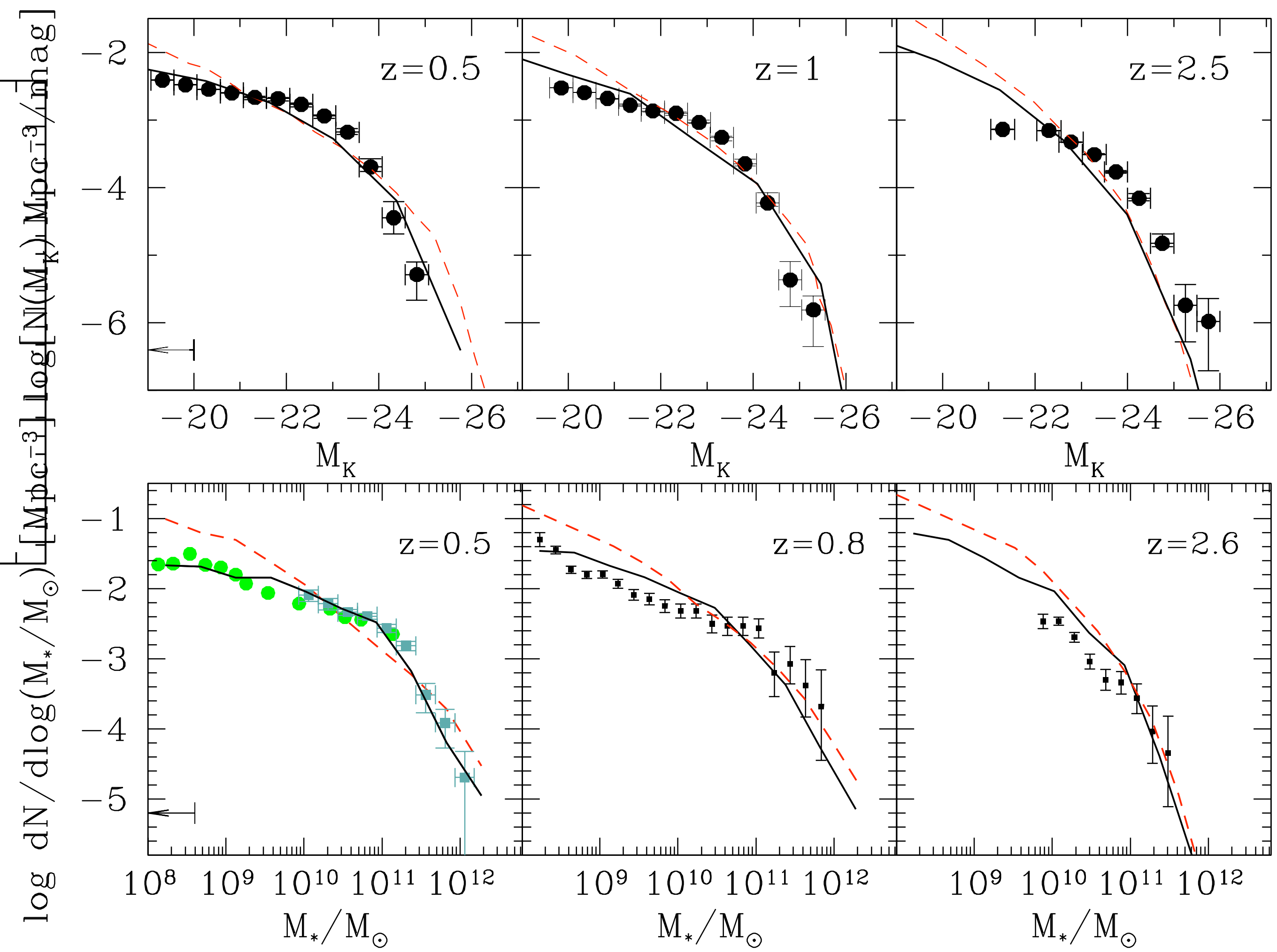
Galaxy Formation in WDM cosmology (m_{WDM}=1 keV)

NM et al. 2012-2013

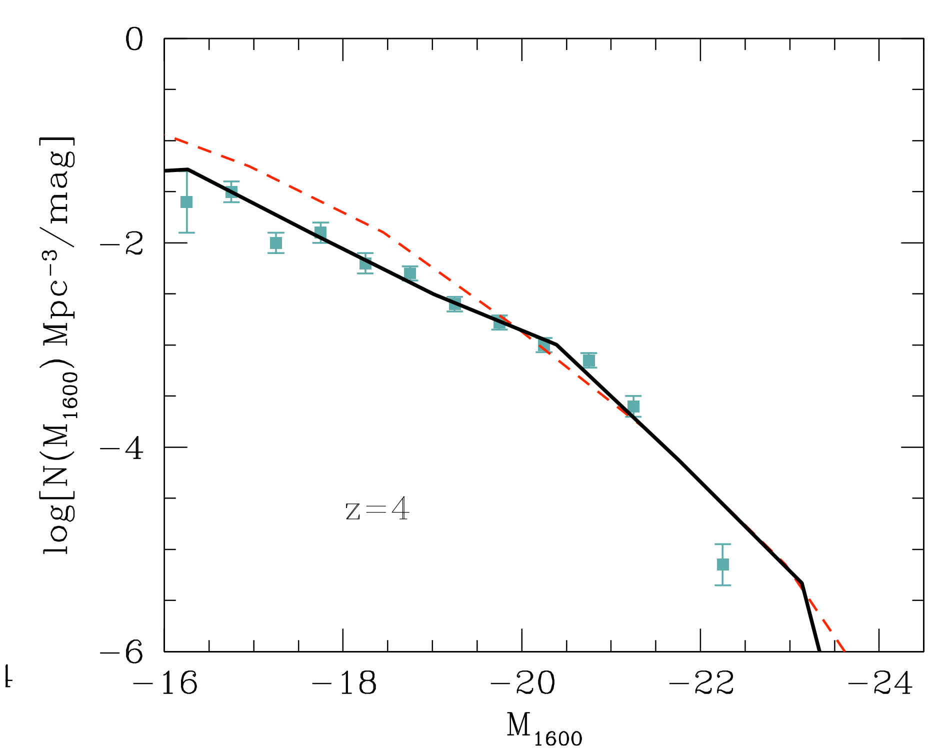
local lum. and stell. mass distributions



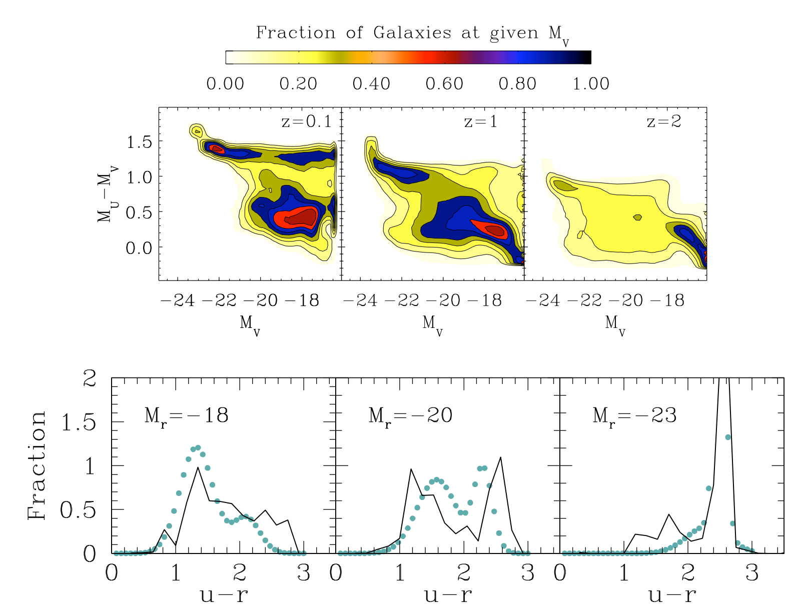
Evolution



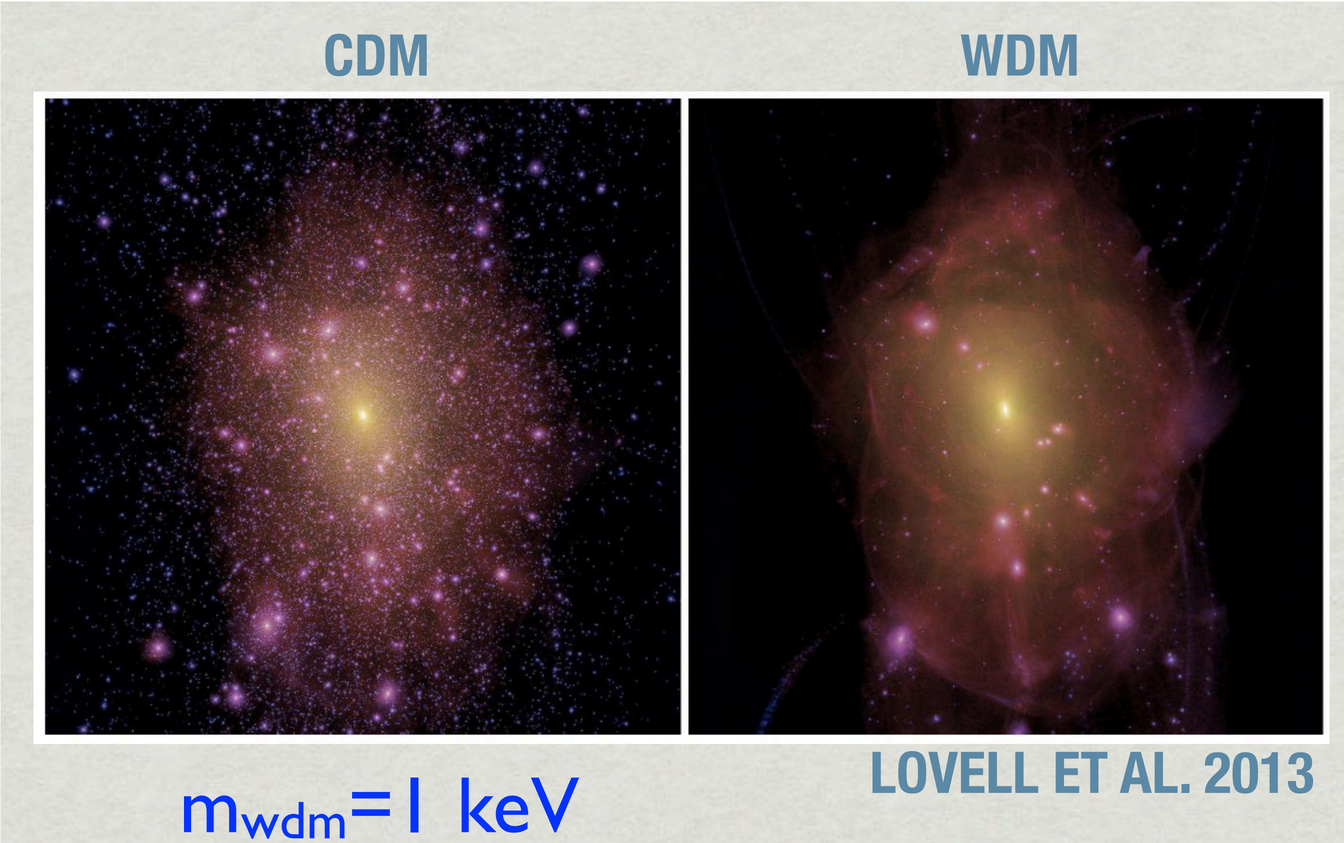
High-z (z=4) lum. distributions



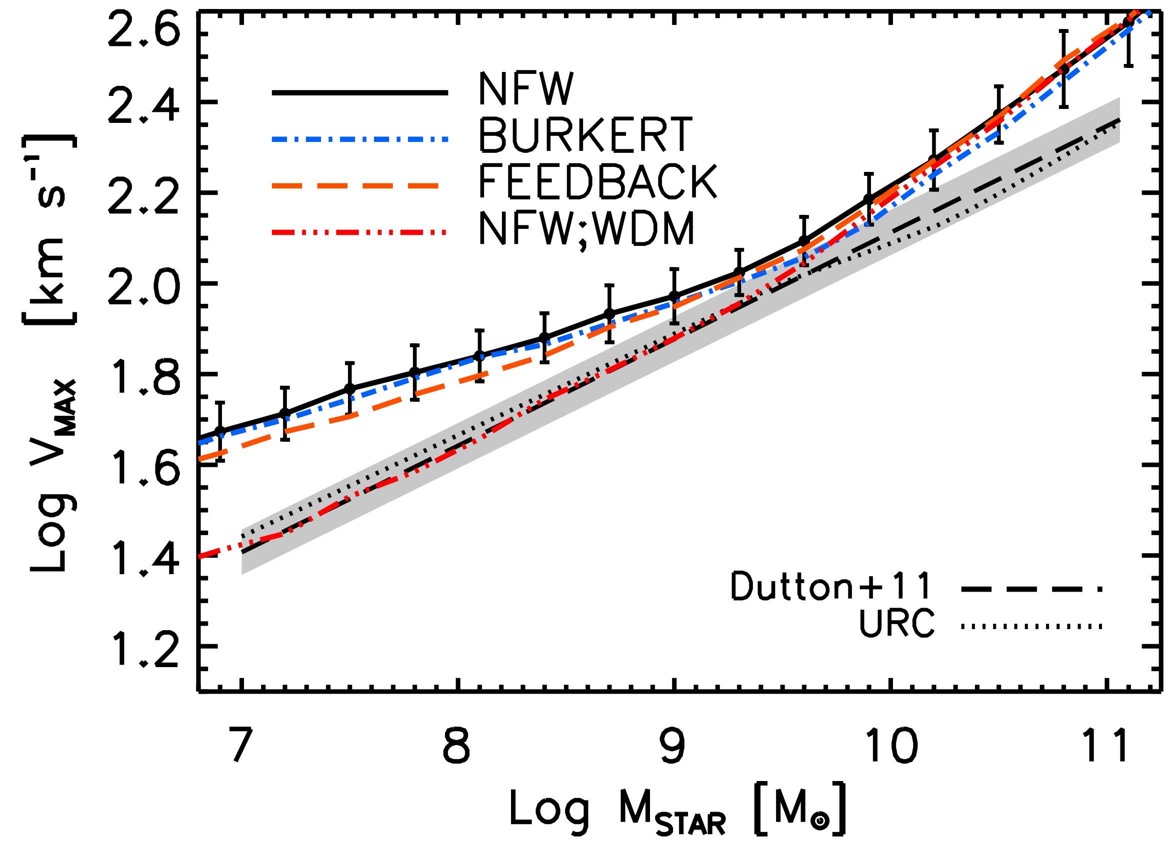
color distributions

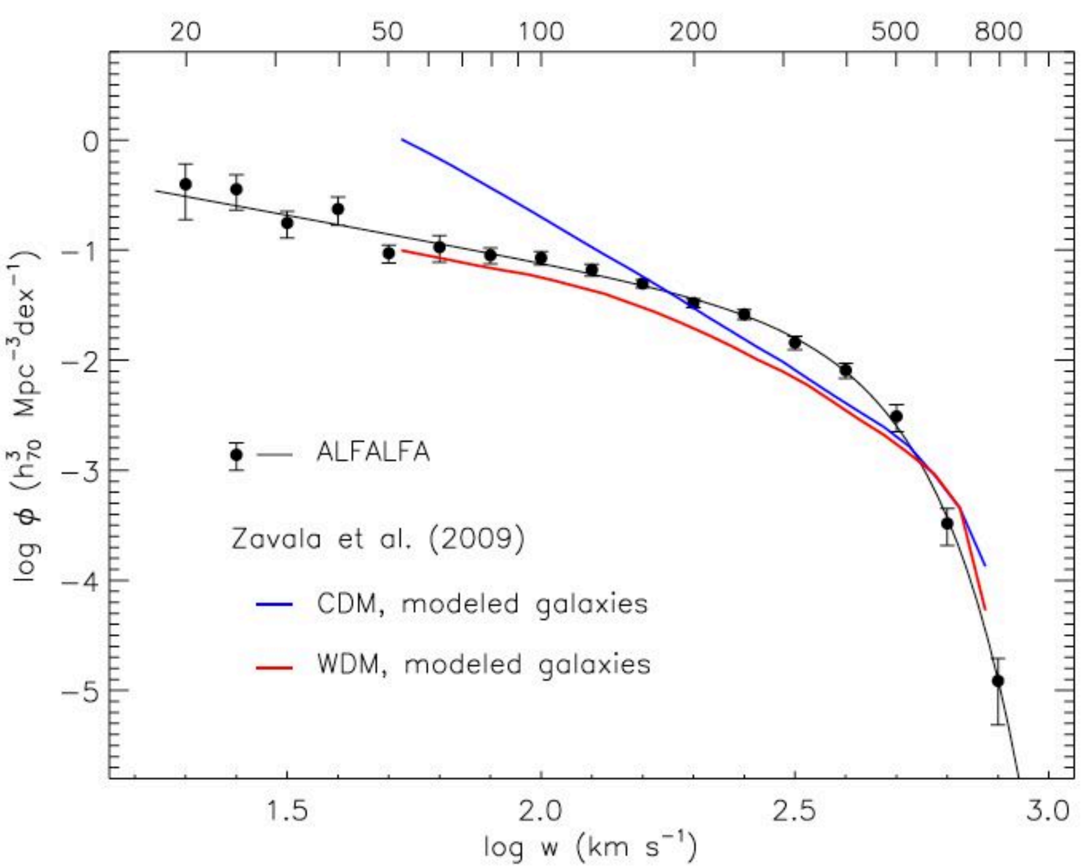


Substructure Predictions



Shankar et al. 2014

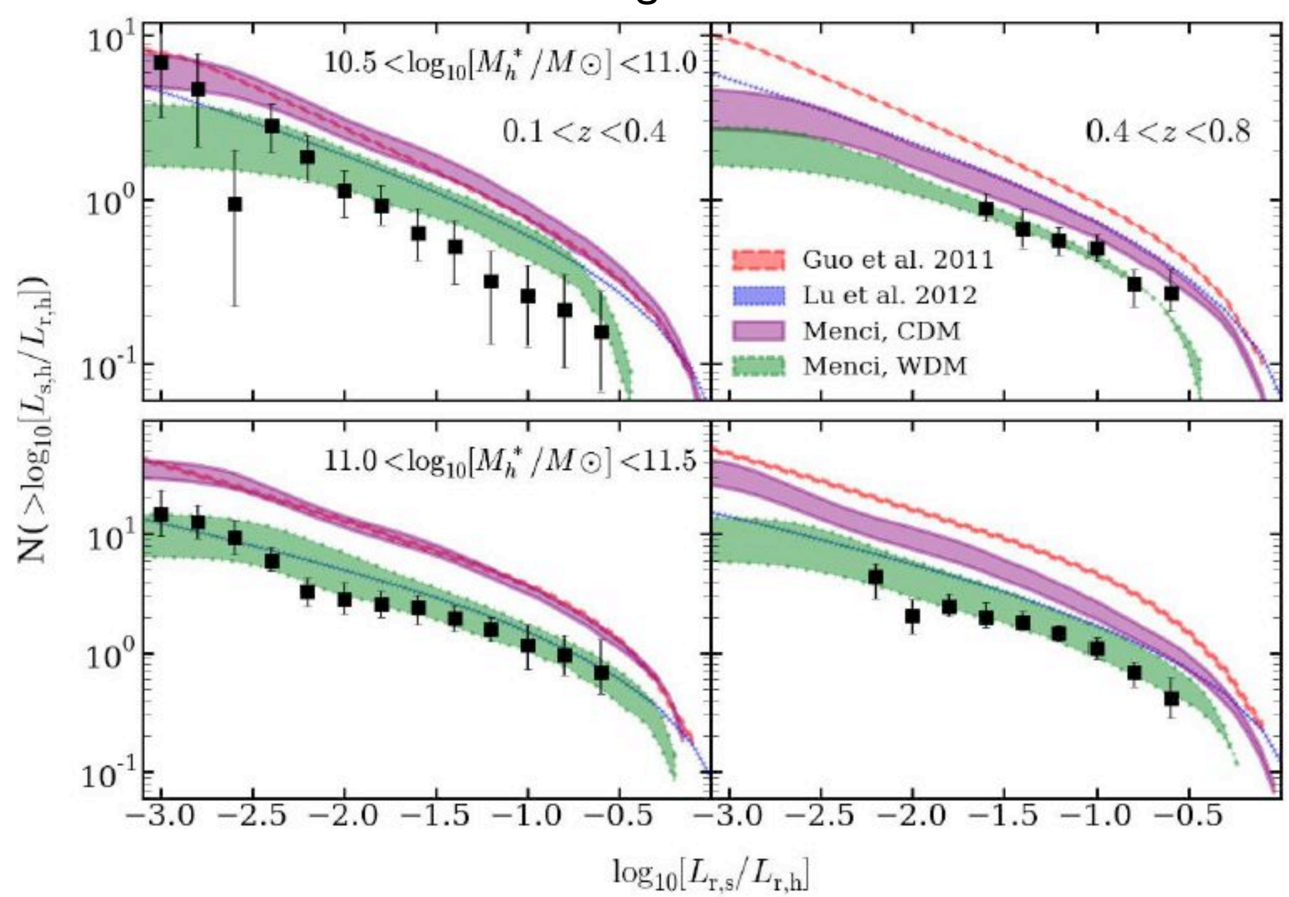




Papastergis+ (2011)

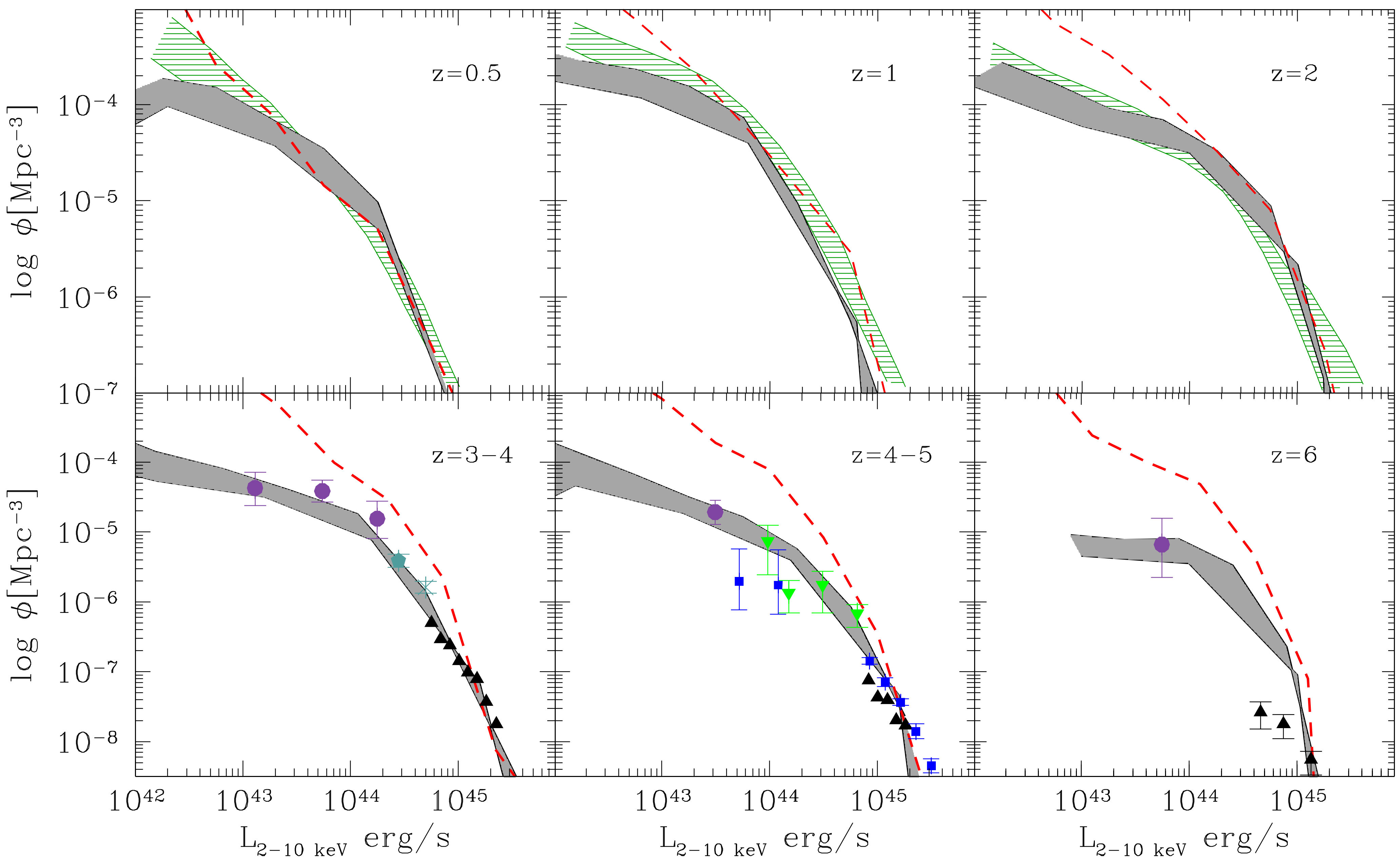
modeling: Zavala+ (2009)

The luminosity distribution of Satellite Galaxies
Nierenberg, Treu, NM 2013



observations of satellites between 0.1 < z < 0.8 based on Hubble Space Telescope images

The AGN luminosity Functions



WDM particle mass: limits from the Ly-α forest

Viel et al. 2005-2013

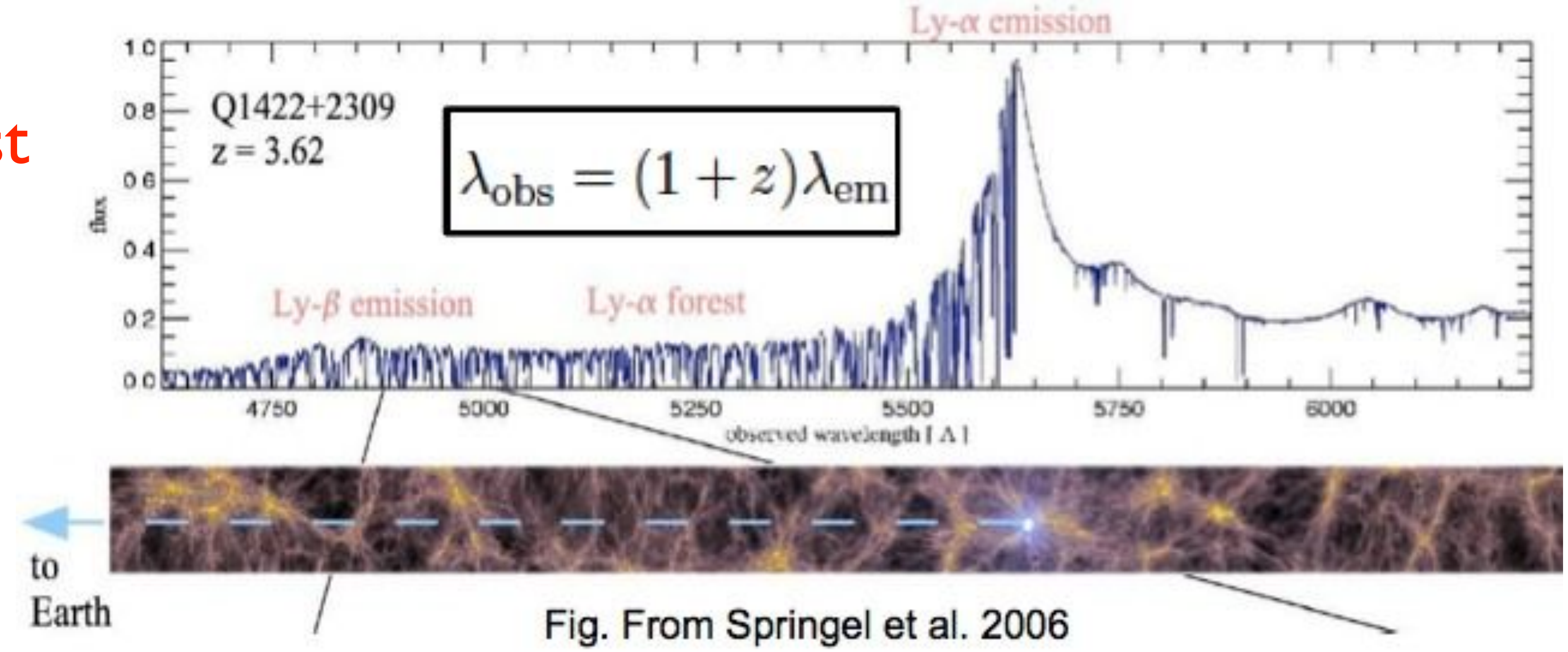
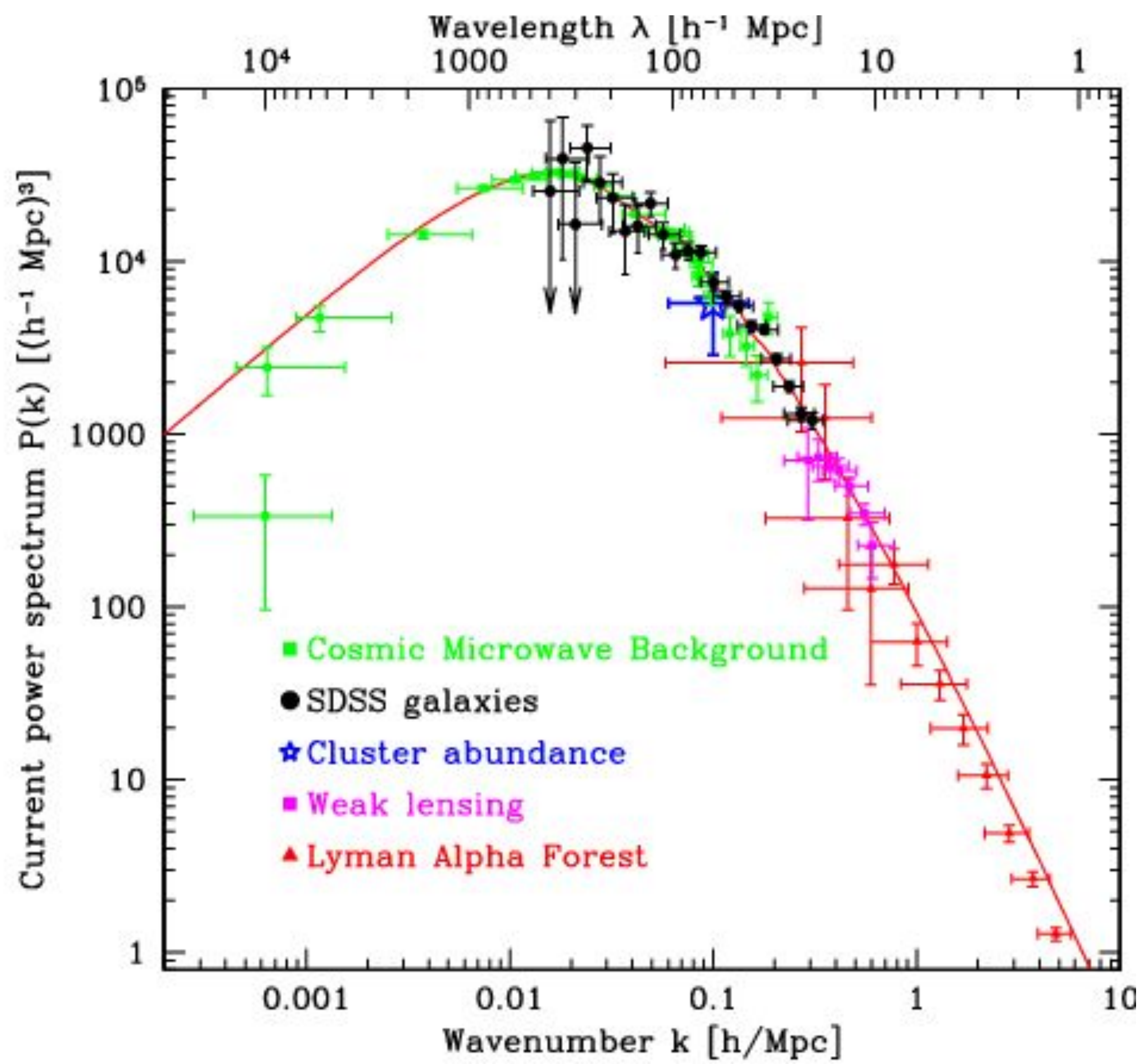


Fig. From Springel et al. 2006

m_{WDM}>1 keV	Thermal relics WDM
m_ν>4 keV	Sterile ν WDM (DW) **Dodelson-Widrow**

m_{WDM}>4 keV	Thermal relics WDM
m_ν>12 keV	Sterile ν WDM (DW) **Dodelson-Widrow**



Constraints from X-ray emission from clusters and galaxies

if $m_s > m_\alpha$ the radiative decay $\nu_s \rightarrow \nu_\alpha + \gamma$ becomes allowed

$$E_\gamma = \frac{1}{2} m_s \left(1 - \frac{m_\alpha^2}{m_s^2}\right) .$$

Emission lines in X-rays from DM concentrations:
- clusters (large signal but also large background)
- galaxies

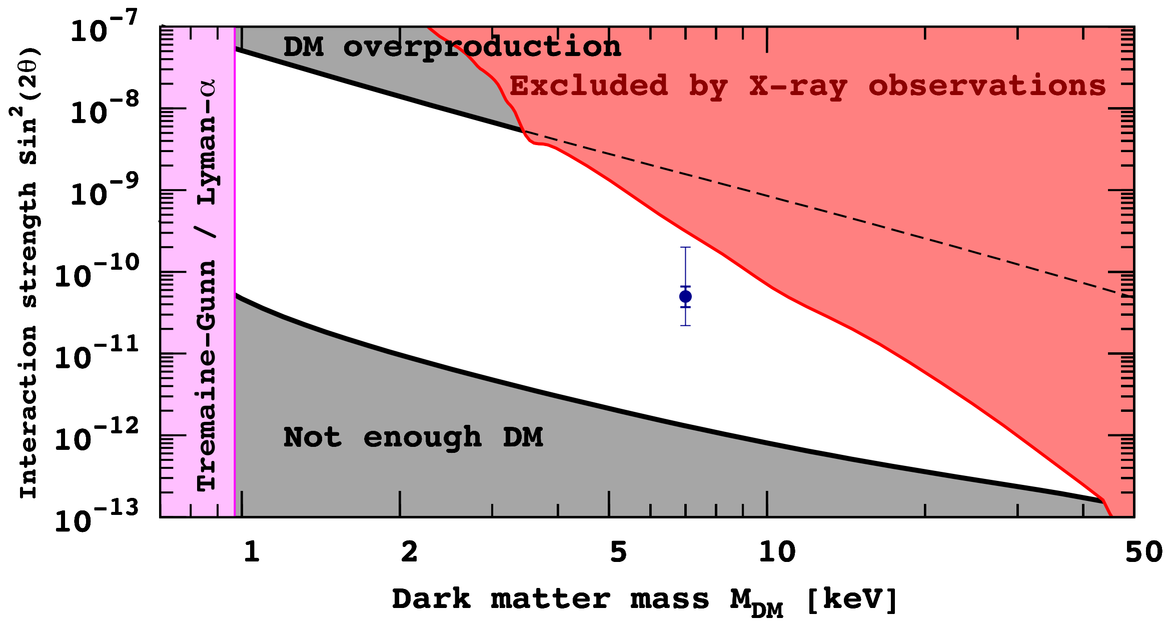
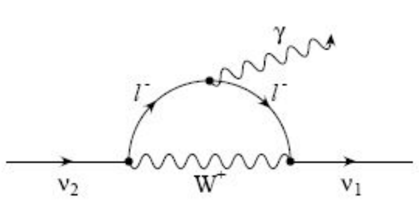
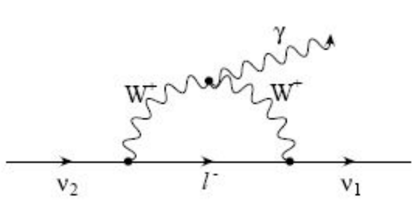


FIG. 4: Constraints on sterile neutrino DM within νMSM [4]. The blue point would corresponds to the best-fit value from M31 if the line comes from DM decay. Thick errorbars are $\pm 1\sigma$ limits on the flux. Thin errorbars correspond to the uncertainty in the DM distribution in the center of M31.

Boyarsky et al. 2014





Abazajian et al. 2001-2005

Summary

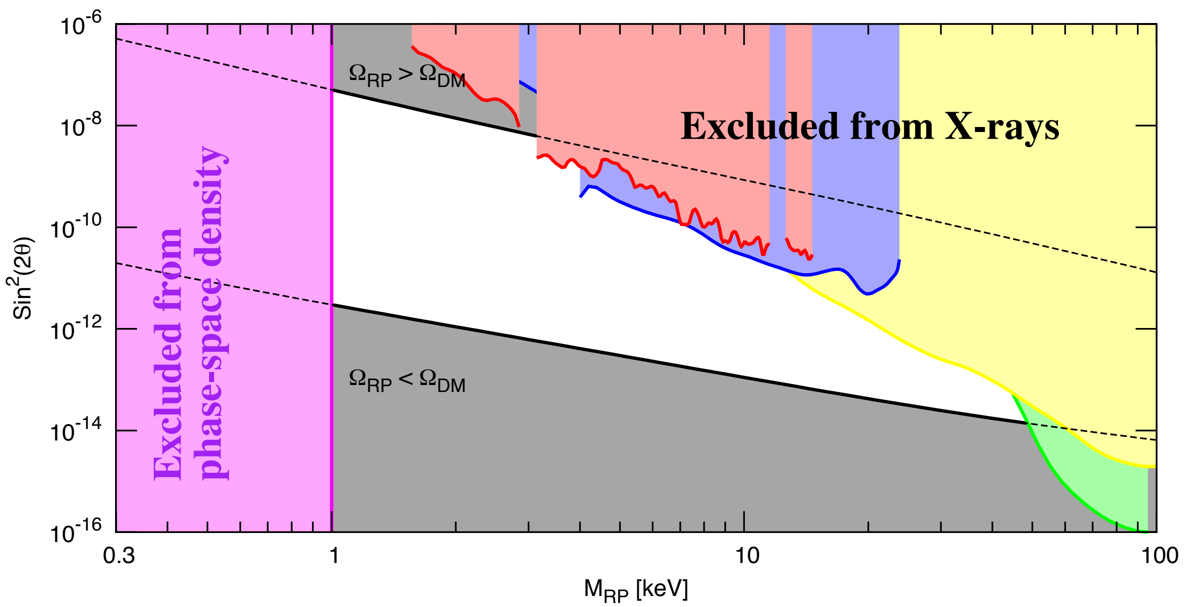
The mass of DM particles has a major impact on structure formation (suppression of small-scale perturbations due to free-streaming)
CDM is the limit of $M_{fs} <<$ masses of cosmological interest

CDM problems on small scales:
- cusps
- number of satellite galaxies
- abundance of low-mass (faint) galaxies at low and high redhsifts

Baryonic physics can hardly solve the problems

Galaxy formation in WDM cosmology is a viable solution

There is a tension:
current limits from high-z structure (Lyman-a forest)
suggest $m>10$ keV, but to solve the galactic small-scale crisis $m<2$ keV is needed



Window corresponds to resonant production

Upper boundary - zero lepton asymmetry

Lower boundary - maximal lepton asymmetry

Boyarsky et al 2009

6 – Sterile neutrino resonant production

In presence of a large lepton asymmetry, $\mathcal{L} \equiv (n_\nu - n_{\bar\nu})/n_\gamma$, matter effects become important and the mixing angle can be resonantly enhanced. [Shi, Fuller, 1998; Abazajian et al., 2001

$$\boxed{\sin^2 2\theta_m = \frac{\Delta^2(p)\sin^2 2\theta}{\Delta^2(p)\sin^2 2\theta + D^2 + (\Delta(p)\cos 2\theta - \frac{2\sqrt{2}\zeta(3)}{\pi^2} G_F T^3 \mathcal{L} + |V_T|)^2}}$$

The mixing angle is maximal $\sin^2 2\theta_m = 1$ when the resonant condition is satisfied (with $\Delta(p) \equiv m_4^2/(2p)$)

$$\boxed{\Delta(p)\cos 2\theta - \frac{2\sqrt{2}\zeta(3)}{\pi^2} G_F T^3 \mathcal{L} + |V_T| = 0}$$

$$\boxed{\left(\frac{m_4}{1\mathrm{keV}}\right)^2 \simeq 0.08 \frac{p}{T} \frac{\mathcal{L}}{10^{-4}} \left(\frac{T}{100\,\mathrm{MeV}}\right)^4 + 2\left(\frac{p}{T}\right)^2 \frac{B}{\mathrm{keV}} \left(\frac{T}{100\,\mathrm{MeV}}\right)^6}$$

Sterile neutrinos are produced in primordial plasma through

• off-resonance oscillations. [Dodelson, Widrow; Abazajian, Fuller; Dolgov, Hansen; Asaka, Laine, Shaposhnikov et al.]

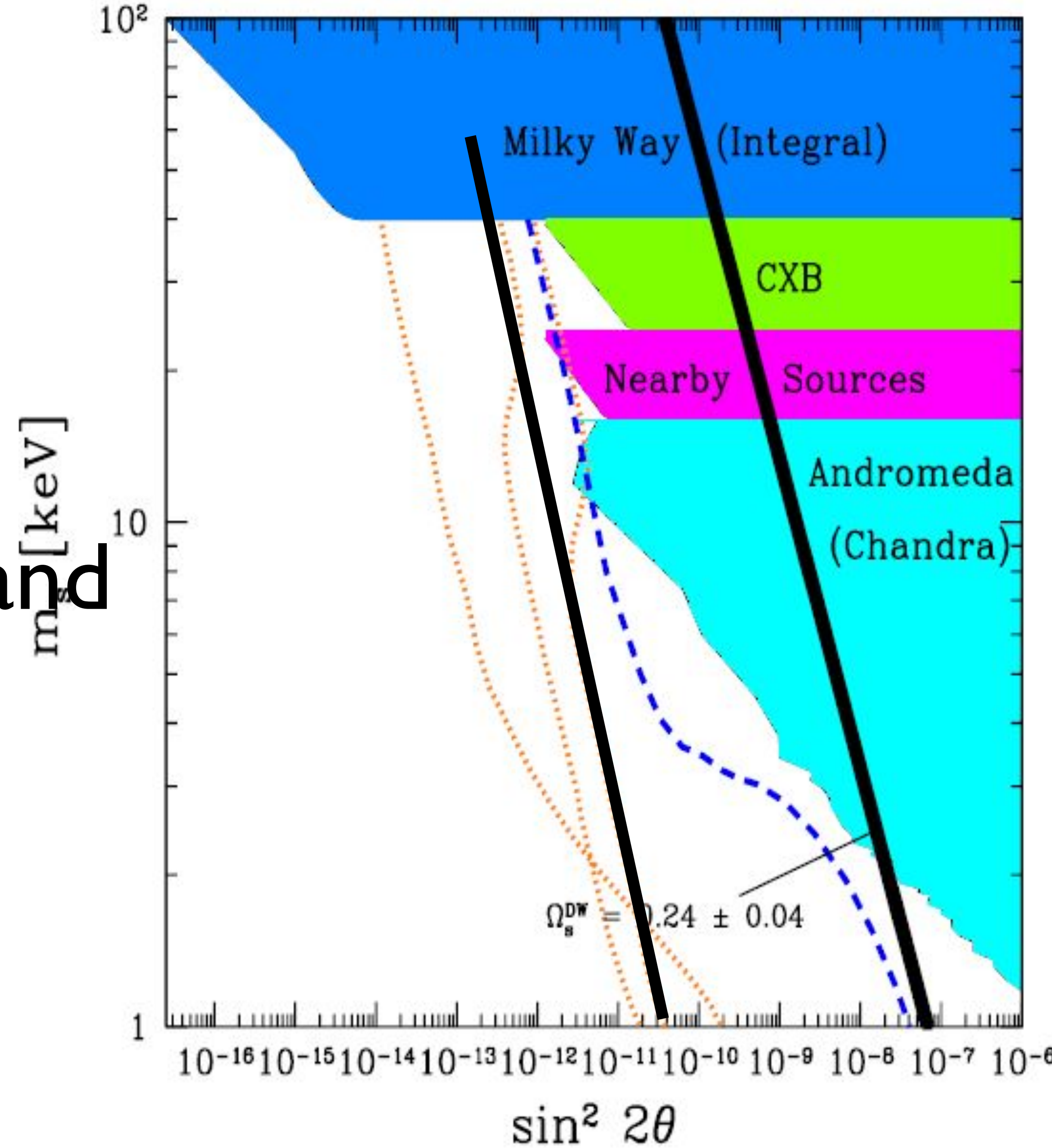
• oscillations on resonance, if the lepton asymmetry is non-negligible [Fuller, Shi]

• production mechanisms which do not involve oscillations

– inflaton decays directly into sterile neutrinos [Shaposhnikov, Tkachev] – Higgs physics: both mass and production [AK, Petraki]

Watson et al. 2012

Limits from the
X-ray emission from clusters and
galaxies



Very small mixing ($\sin^2 2\theta \lesssim 10^{-7}$) between

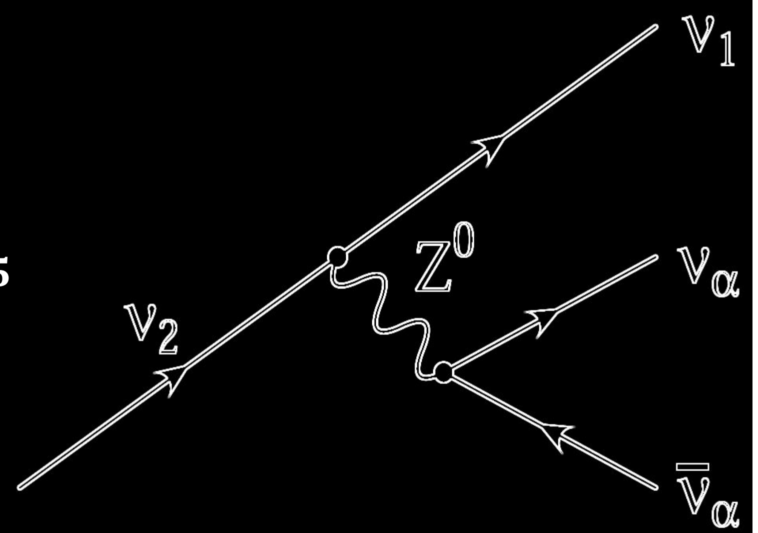
mass $|\nu_{1,2}>$ & flavor $|\nu_{\alpha,s}>$ states:

$$|\nu_\alpha\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$
$$|\nu_s\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

For $m_s < m_e$,

3ν Decay Mode Dominates:

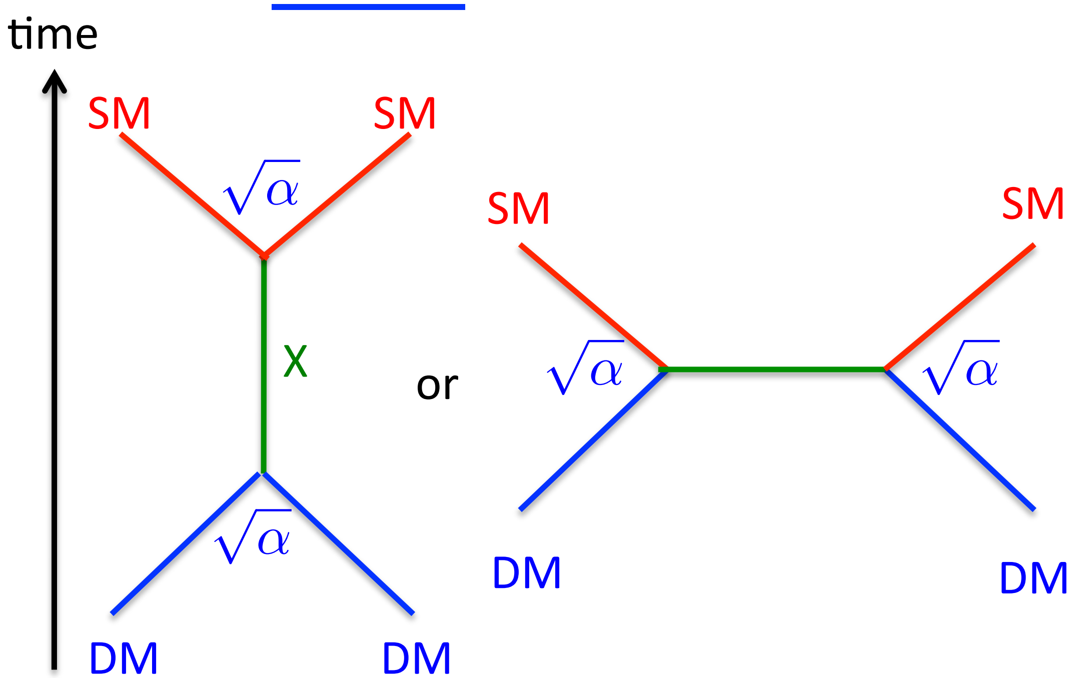
$$\Gamma_{3\nu} \backsimeq 1.74\times 10^{-30} s^{-1}\left(\frac{\sin^2 2\theta}{10^{-10}}\right)\left(\frac{m_s}{\mathrm{keV}}\right)^5$$



Radiative Decay Rate is:

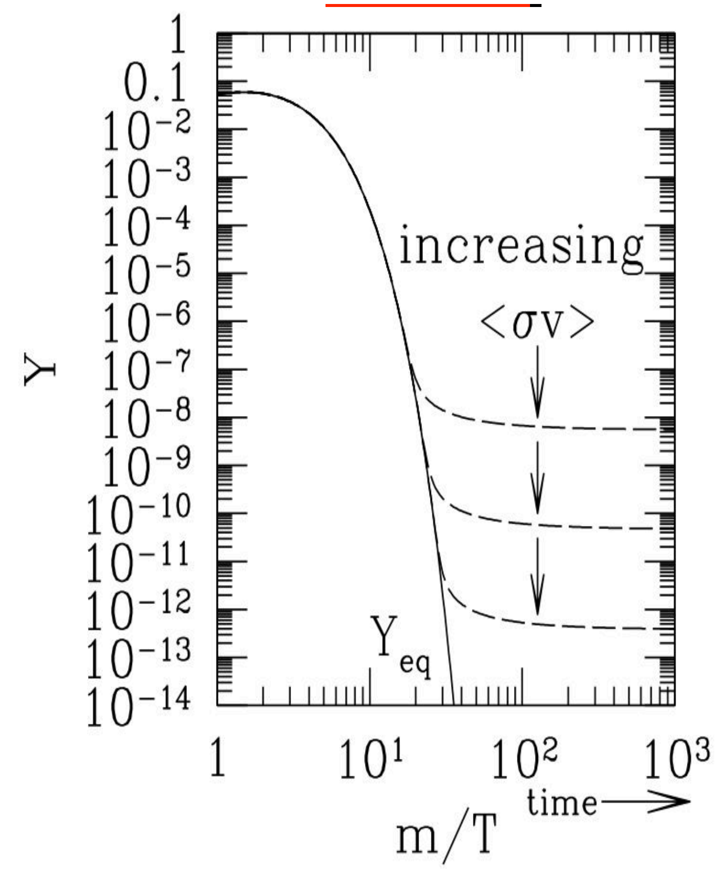
$$\Gamma_s \backsimeq 1.36\times 10^{-32} s^{-1}\left(\frac{\sin^2 2\theta}{10^{-10}}\right)\left(\frac{m_s}{\mathrm{keV}}\right)^5 \quad \nu_s \to \nu_\alpha + \gamma$$

WIMP



self-annihilation

freeze out



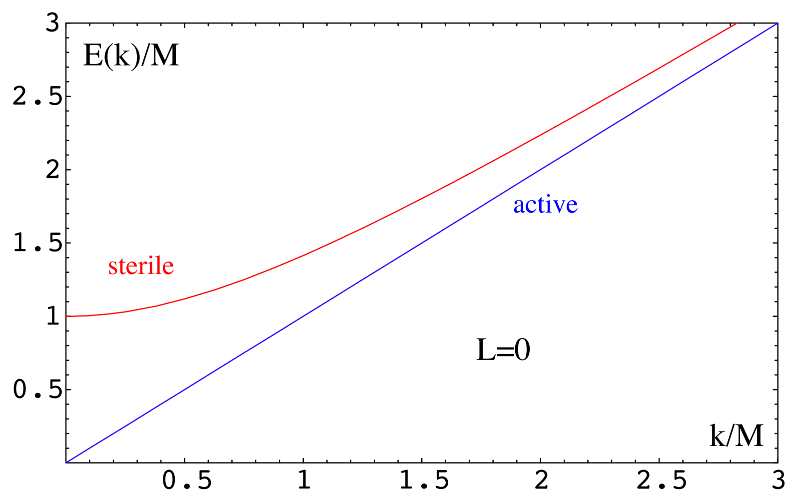
$$\Omega h^2 \approx \frac{3 \times 10^{-27}\ \mathrm{cm}^3/\mathrm{s}}{\langle \sigma_{\mathrm{ann}} v \rangle}.$$

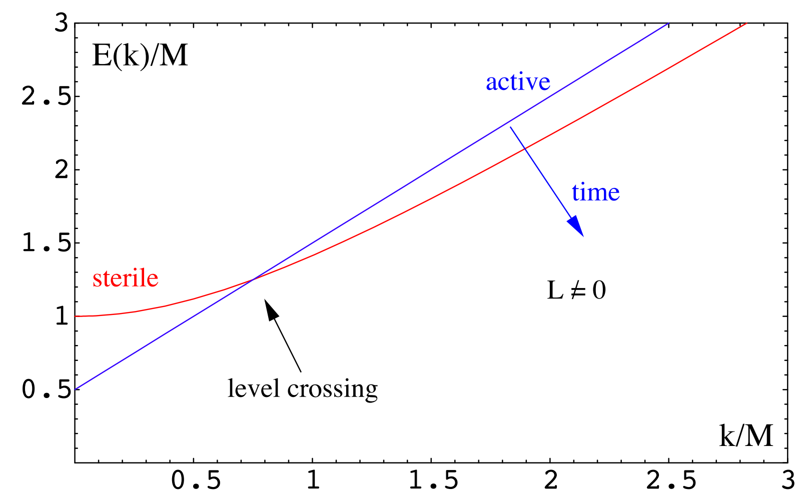
$$\langle \sigma_{\mathbf{ann}} \mathbf{v} \rangle \sim \mathbf{10^{-25}} \mathrm{cm}^3 \mathrm{s}^{-1} \left(\frac{\alpha}{\mathbf{10^{-2}}} \right)^{\mathbf{2}} \left(\frac{\mathbf{100GeV}}{\mathbf{m_X}} \right)^{\mathbf{2}}$$

➡ Electro Weak Scale(∼100GeV) WIMP naturally explains the relic abundance.

TeV scale SUSY & neutralino dark matter

Dispersional relations for active and sterile neutrinos (from real part)





Transitions $\nu \to N_1$

Dodelson-Widrow

Zero lepton asymmetry

Resonant transitions

Shi-Fuller

Lepton asymmetry

created in $N_{2,3}$ decays

Dark matter and the Lyman-α forest.

The bounds depend on the production mechanism.

$$\lambda_{FS} \approx 1\,\mathrm{Mpc}\left(\frac{\mathrm{keV}}{m_s}\right)\left(\frac{\langle p_s\rangle}{3.15\,T}\right)_{T\approx 1\,\mathrm{keV}}$$

The ratio

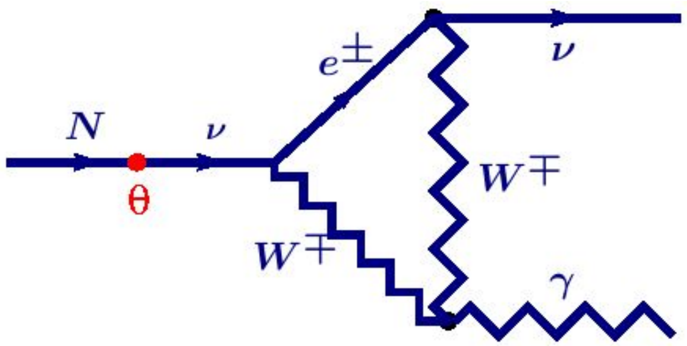
$$\left(\frac{\langle p_s\rangle}{3.15\,T}\right)_{T\approx 1\,\mathrm{keV}} = \begin{cases} 0.9 & \text{for production off} - \text{resonance} \\ 0.6 & \text{for MSW resonance (depends on L)} \\ 0.2 & \text{for production at T} > 100\ \text{GeV} \end{cases}$$

- Photon energy:

$$E_\gamma = \frac{M_1}{2}$$

- Radiative decay width

$$\Gamma = \frac{9\alpha_{\mathrm{EM}} G_F^2}{256\pi^4}\,\theta^2\,M_1^5$$



Dark matter made of sterile neutrino is not completely dark

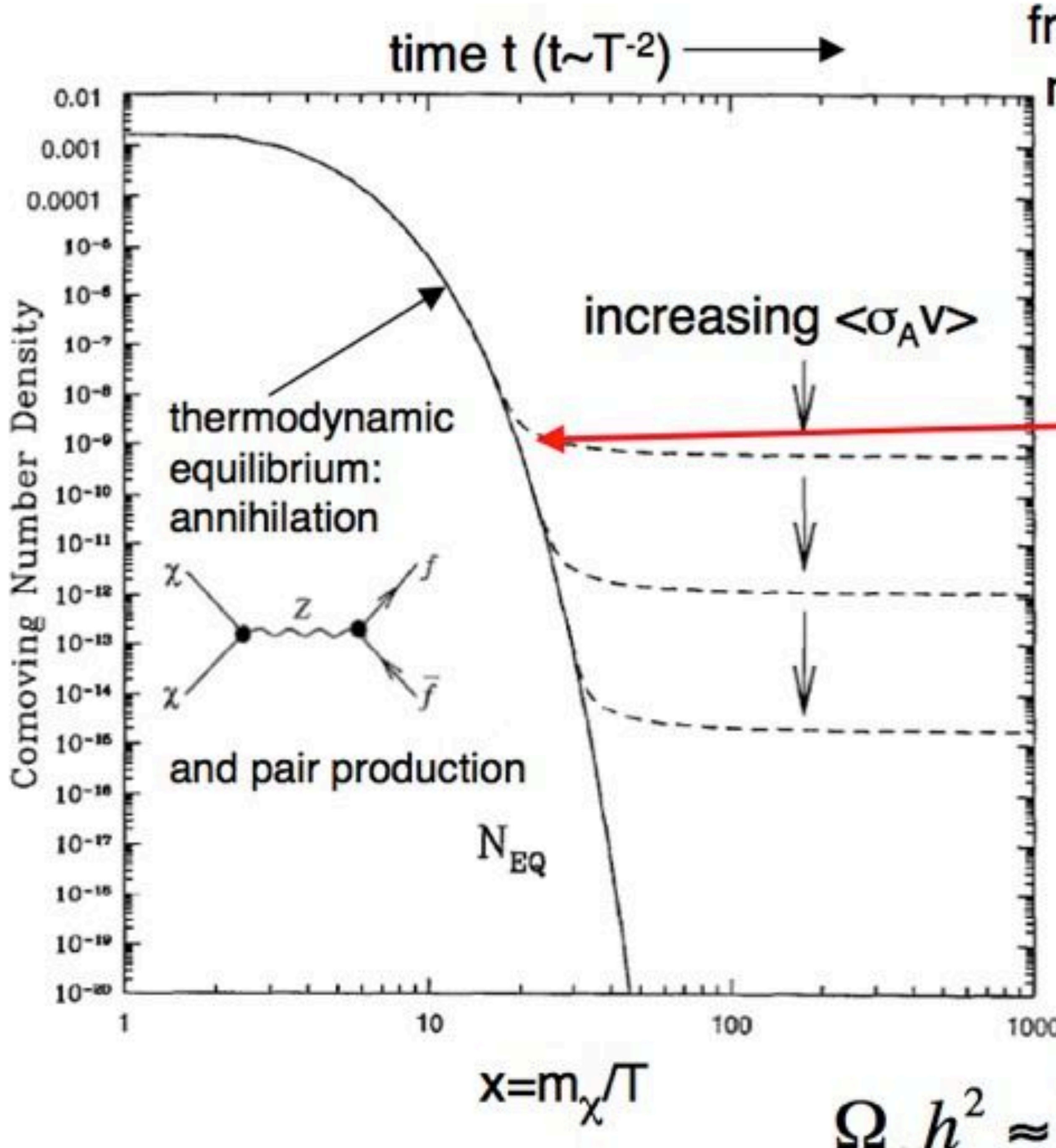
Dolgov & Hansen (2000)

Where to look for DM decay line?

Extragalactic diffuse X-ray background (XRB)	Dolgov & Hansen, 2000; Abazajian et al., 2001 Mapelli & Ferrara, 2005; **Boyarsky et al. 2005**
Clusters of galaxies	Abazajian et al., 2001 **Boyarsky et al. astro-ph/0603368**
DM halo of the Milky Way. Signal increases as we increase FoV!	**Boyarsky et al. astro-ph/0603660** Riemer-Sørense et al. astro-ph/0603661 **Boyarsky, Nevalainen, O.R.** (in preparation)
Local Group galaxies	**Boyarsky et al. astro-ph/0603660** Watson et al. astro-ph/0605424
"Bullet" cluster 1E 0657-56	**Boyarsky, Markevitch, O.R.** (in preparation)
Cold nearby clusters	**Boyarsky, Vikhlinin, O.R.** (in preparation)
Soft XRB	**Boyarsky, Neronov, O.R.** (in preparation)

Need to find the best ratio between the DM decay *signal* and object's X-ray emission

CDM as particle Dark Matter



freeze-out of a weakly interacting massive particle (WIMP χ) when reaction rate drops below expansion rate

$T_{freeze\text{-}out}$~ 1/20 x m(WIMP)

Cold Dark Matter:

- non-relativistic

"survival of the weakest"

At or below the weak scale

$$\Omega_\chi h^2 \approx \frac{m_\chi n_\chi}{\rho_c} \approx \frac{3\times10^{-27}\,\mathrm{cm}^3/\mathrm{sec}}{\langle\sigma_A v\rangle}$$