Decaying Majoron DM

and

Structure Formation

kingman Cheung June 28, 2019 IPMU

References

Majoron DM: Berezinsky and Valle, PLB318 (1993), 360

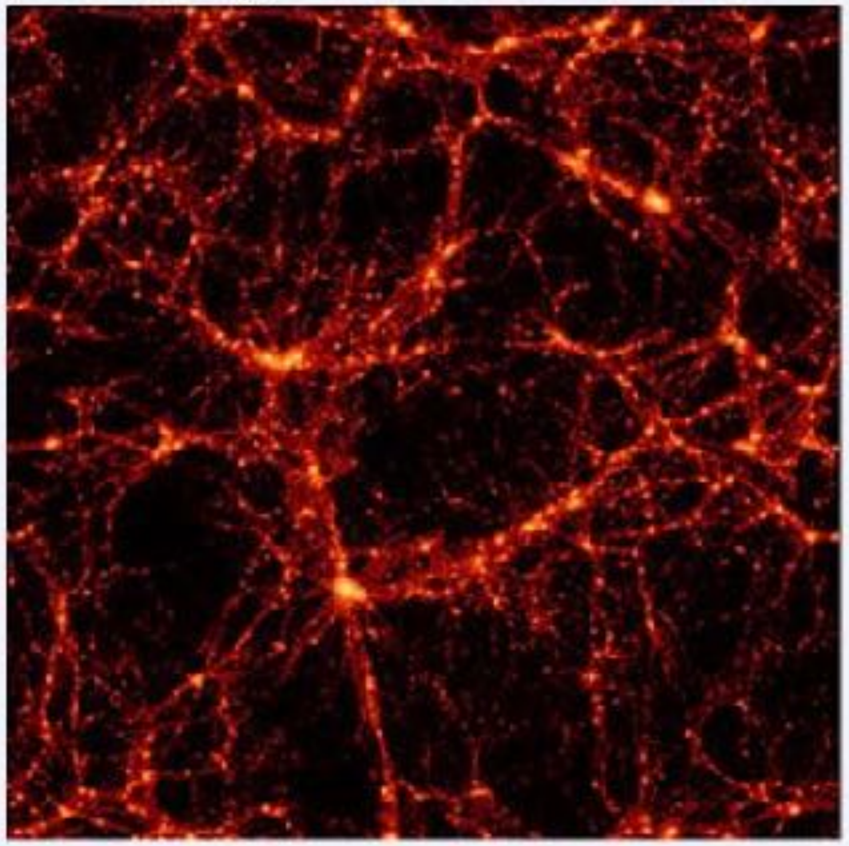
CMB constraint: Lattanzi, Riemer-Sørensen, Tortola, Valle, PRD 88 (2013) 063528

Structure Formation: Kuo, Lattanzi, KC, Valle, JCAP 1812 (2018) 12

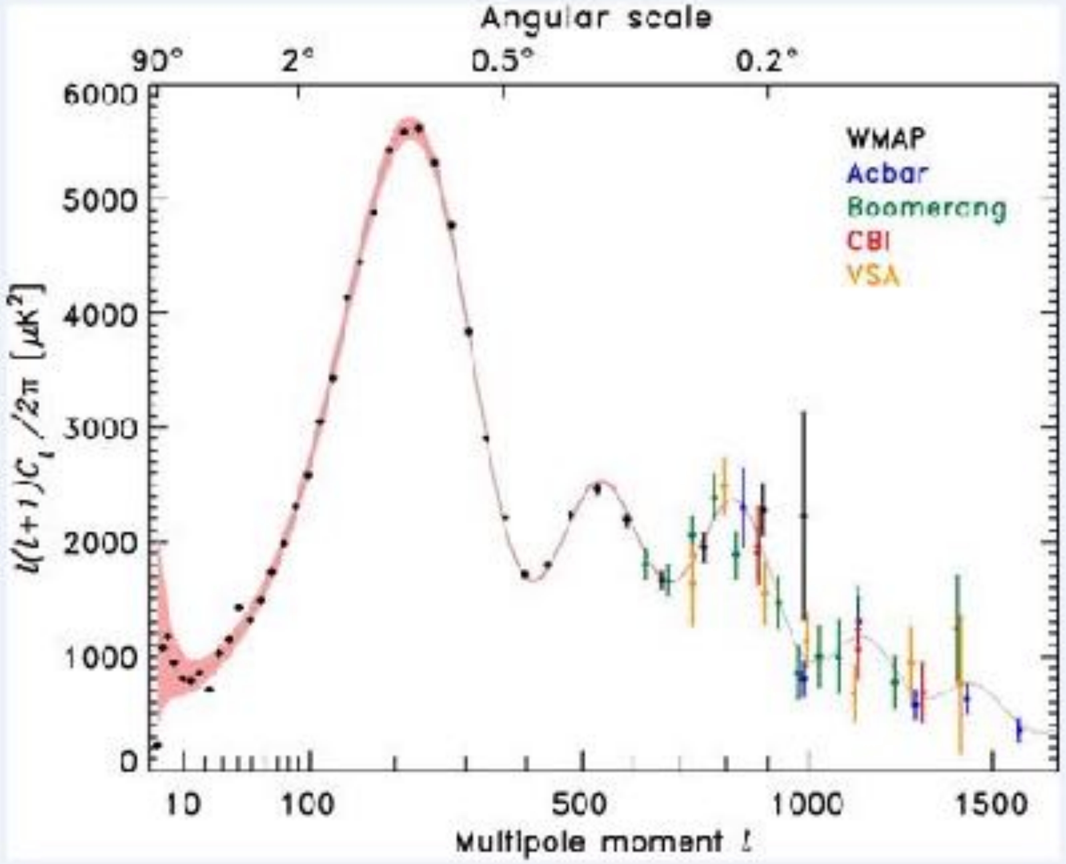
Evidence for Dark Matter

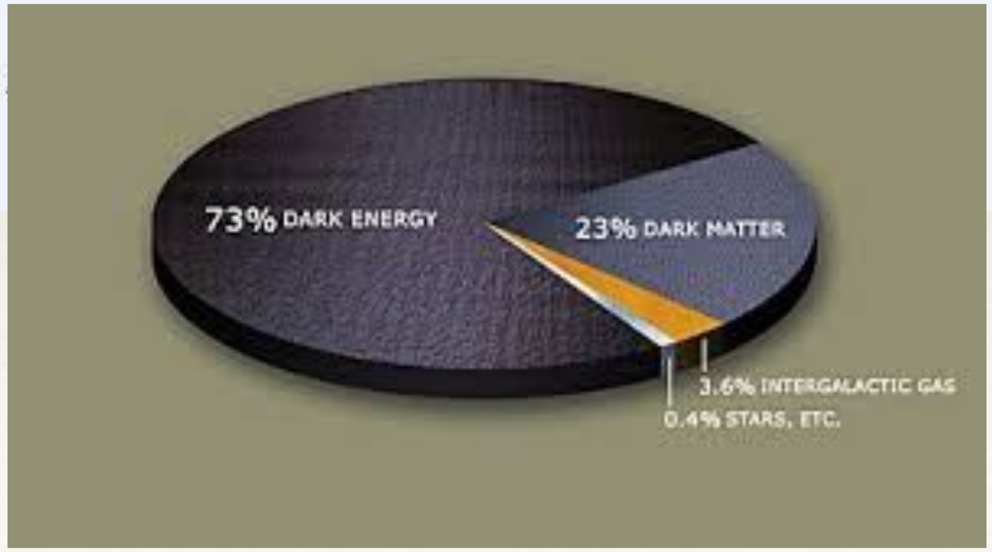
clustering of galaxies (LSS)
sensitive to amount of DM

Virgo Consortium

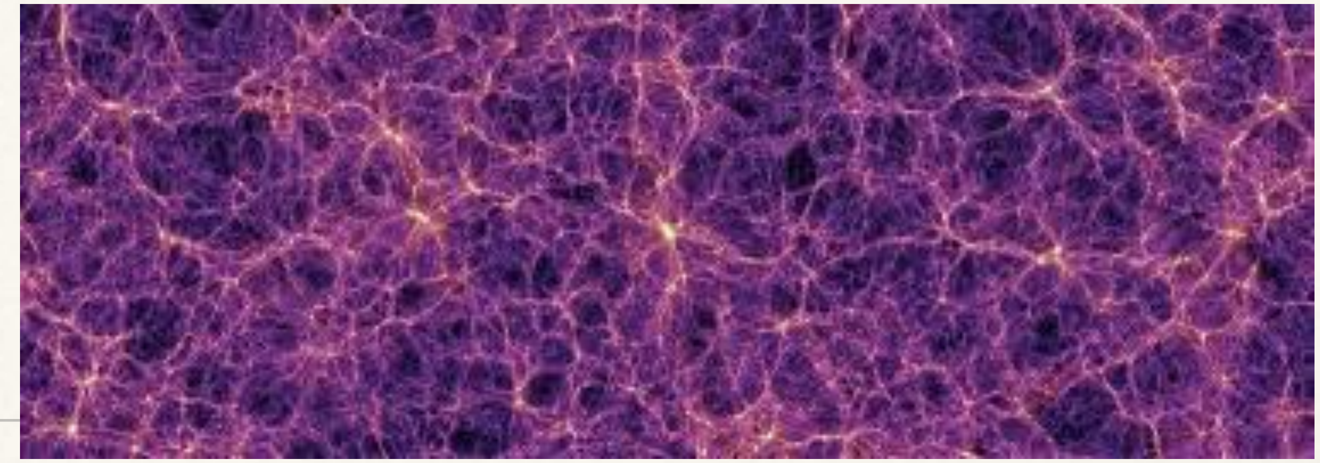


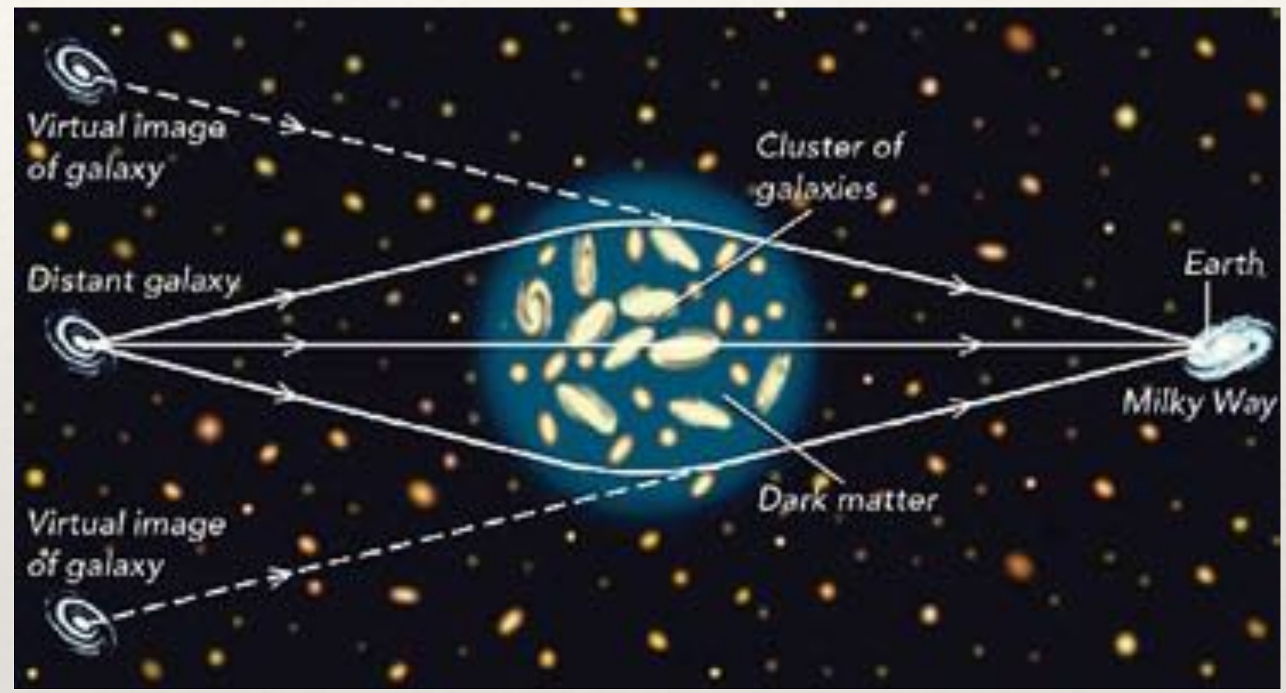
angular power spectrum of CMB
sensitive to baryonic, DM, DE

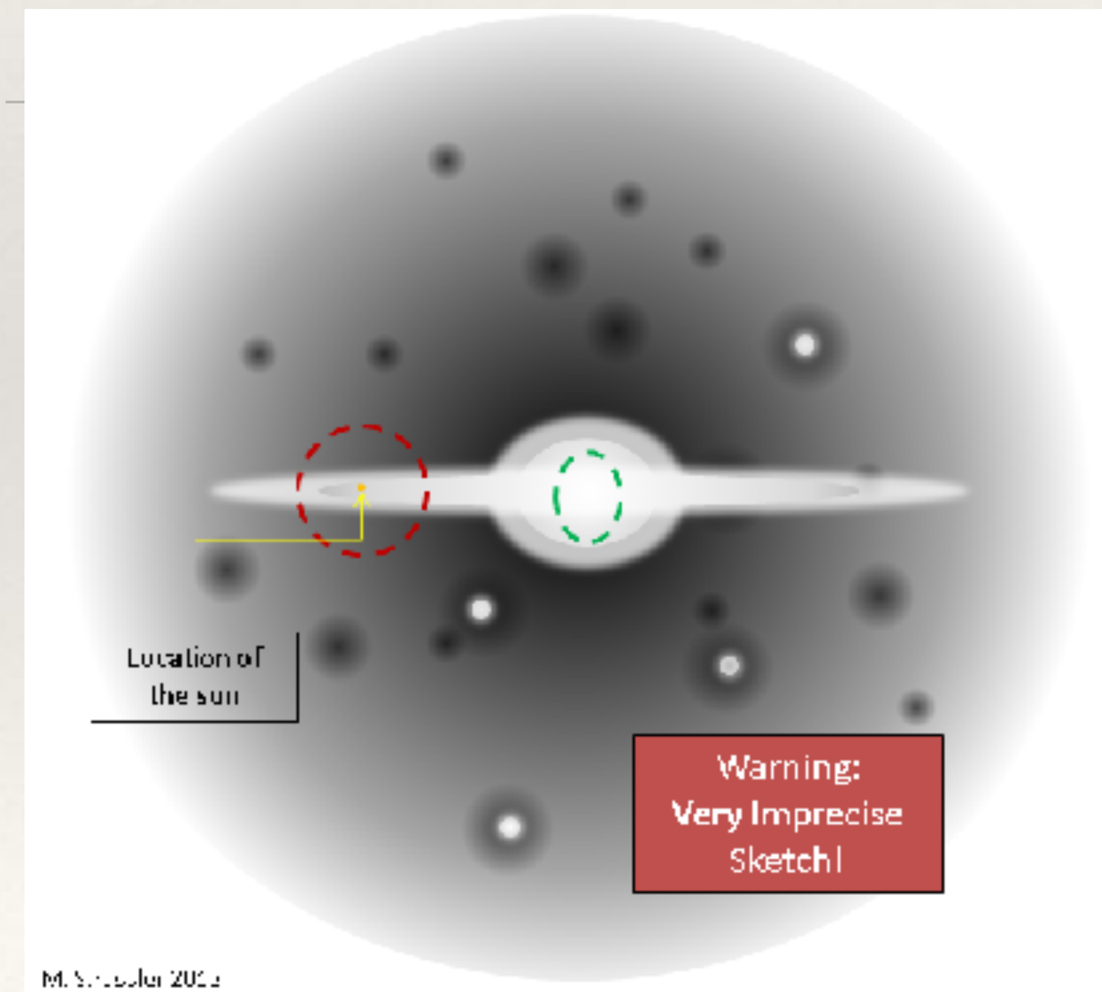




Yet the identity of Dark Matter is unknown







We only know it exists throughout the Universe

Dark Matter Candidates

- WIMP — weakly interacting massive particles, e.g., LSP in SUSY, LTP in little Higgs models,LKP in UED model, hidden-sector fermions, …
- Ultra-weak — axion, axino, gravitino, RH neutrinos, …
- Decaying dark matter

A lot of experiments are designed to detect WIMPs, but so far … …

Lambda Cold Dark Matter Model

- **Standard model of Cosmology.**

Dark matter consists of unknown elementary particle(s), produced in early universe, that is "cold" — velocity dispersion on structure formation is negligible.

- **Explains structure formation for large scales:**

  with small density fluctuations normalised to the observed CMB and allowed to grow via gravitational instability, can account for many properties of structures a t most well- observed scales and epochs. On scales larger than about 10 kpc, the predictions of ΛCDM have been successful.

- **Yet, for scale smaller than 10 kpc, inconsistent with observations.**

  Missing satellite problem, the too-big-to-fail problem, the cusp-core problem.

CDM Has a Missing Satellite Problem

Springel et al. 2001

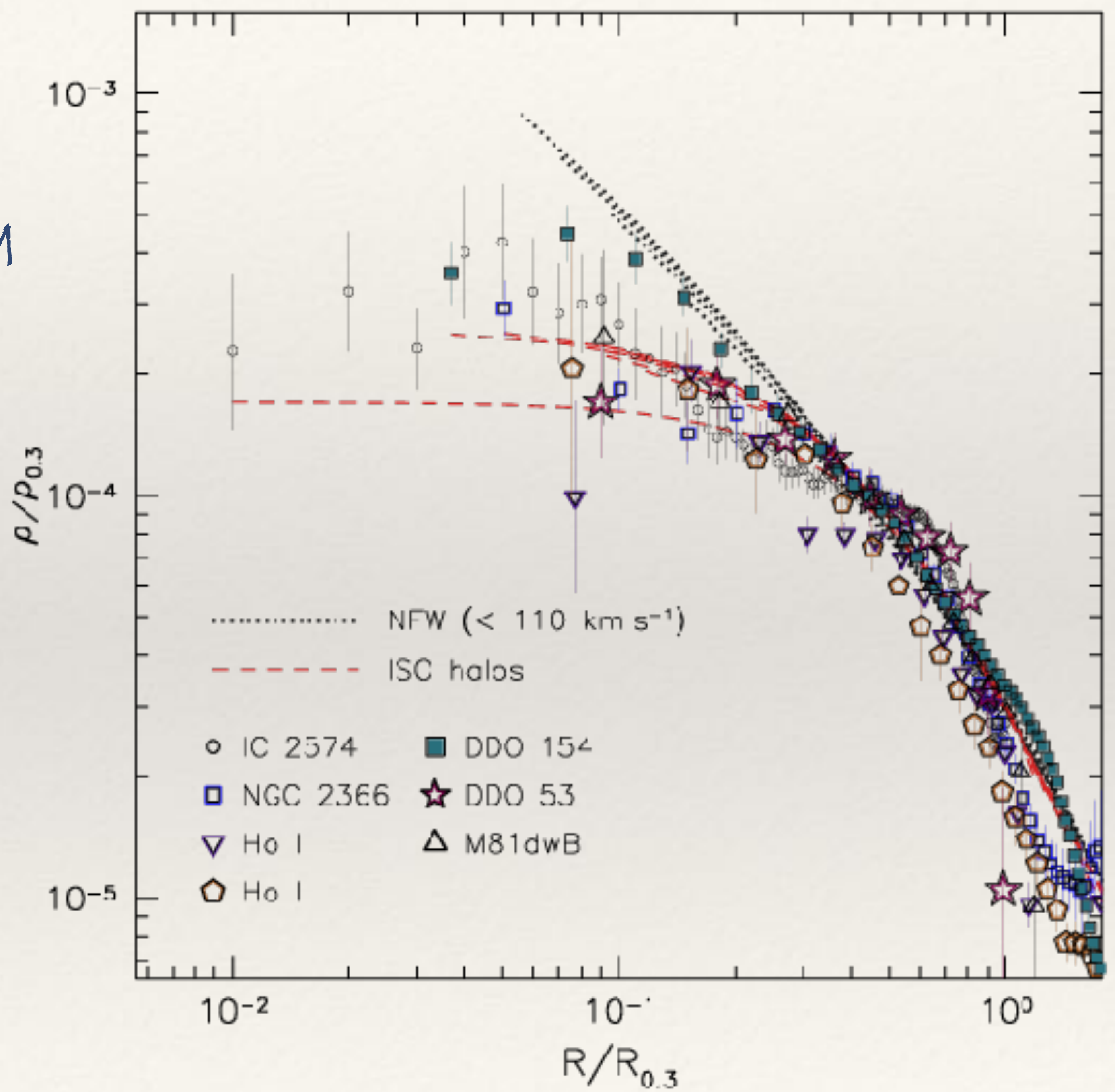
CDM predicts large numbers of subhalos (~100-1000 for a Milky Way-sized galaxy)

Milky Way only has 23 known satellites

What happened to the rest of them?

Cusp-Core Problem

- LCDM simulations predict DM density cusp in center of galaxies, but inconsistent with observations.
- Especially low-mass galaxies.



A Few Possible Solutions

- Baryon physics: efficiency of transforming baryons into stars to be lower in lower-mass systems.
- Some warm DM: its thermal velocity dispersion provides free streaming that suppresses low-mass halos or sub-halos, and also reduce the density cusp at the center.
- DM has self-interactions, reducing the density cusp, form less sub-halos.
- Fuzzy dark matter: large de Broglie wavelength suppresses small-scale structures (Hu et al.).

Outline

1. Warm DM with relativistic properties can alleviate the small-scale crisis. Majoron DM is warm.

2. In addition, majoron DM can decay into neutrinos:
$$J \to \nu\nu$$
with a life-time of order of the age of the Universe.

3. CMB provides a strong constraint on majoron DM life-time, in order to avoid producing too much fluctuation power on the largest CMB scales.

4. We investigate the WARM and DECAY nature of majoron DM on structure formation.

Majoron Physics

The seesaw mechanism involves spontaneously broken lepton number symmetry, involves a singlet scalar coupling to singlet neutrino:

$$\lambda \sigma \nu_L^{cT} \tau_2 \nu_L^c, \qquad \langle \sigma \rangle \equiv v_1$$

v_1 can be large to give a large majorana mass. So the mass matrix for left- and right-handed neutrino is

$$\mathcal{M}_\nu = \begin{bmatrix} Y_3 v_3 & Y_\nu v_2 \\ {Y_\nu}^T v_2 & Y_1 v_1 \end{bmatrix}$$

$$m_\nu = Y_3 v_3 - Y_\nu Y_1^{-1} Y_\nu^T \frac{v_2^2}{v_1}$$

v_3 (v_2) is the VEV of the Higgs triplet (doublet).

Since the lepton-number symmetry is spontaneously broken, there is Nambu-Goldstone boson:

$$J \propto v_3 v_2^2 \Im(\Delta^0) - 2 v_2 v_3^2 \Im(\Phi^0) + v_1 (v_2^2 + 4 v_3^2) \Im(\sigma)$$

In principle, J is massless but acquires a mass via non-perturbative gravitational effect.

$$m_J \simeq O(\mathrm{keV})$$

J mainly decays into light neutrinos via

$$\mathscr{L}_Y = \frac{i}{2} J \sum_{ij} \nu_i^T g_{ij} \tau_2 \nu_j + h.c. \qquad g_{ij} = -\frac{m_{\nu_i}}{v_1}\delta_{ij}$$

Decay width into neutrinos is

$$\Gamma_{J\to\nu\nu} = \frac{m_J}{32\pi} \frac{\sum_i m_{\nu_i}^2}{2v_1^2}$$

Subleading decay into a pair of photons:

$$\Gamma_{J\to\gamma\gamma} = \frac{\alpha^2 m_J^3}{64\pi^3} \left| \sum_f N_f Q_f^2 \frac{2v_3^2}{v_2^2 v_1}(-2T_3^f)\frac{m_J^2}{12m_f^2} \right|^2$$

CMB Constraint

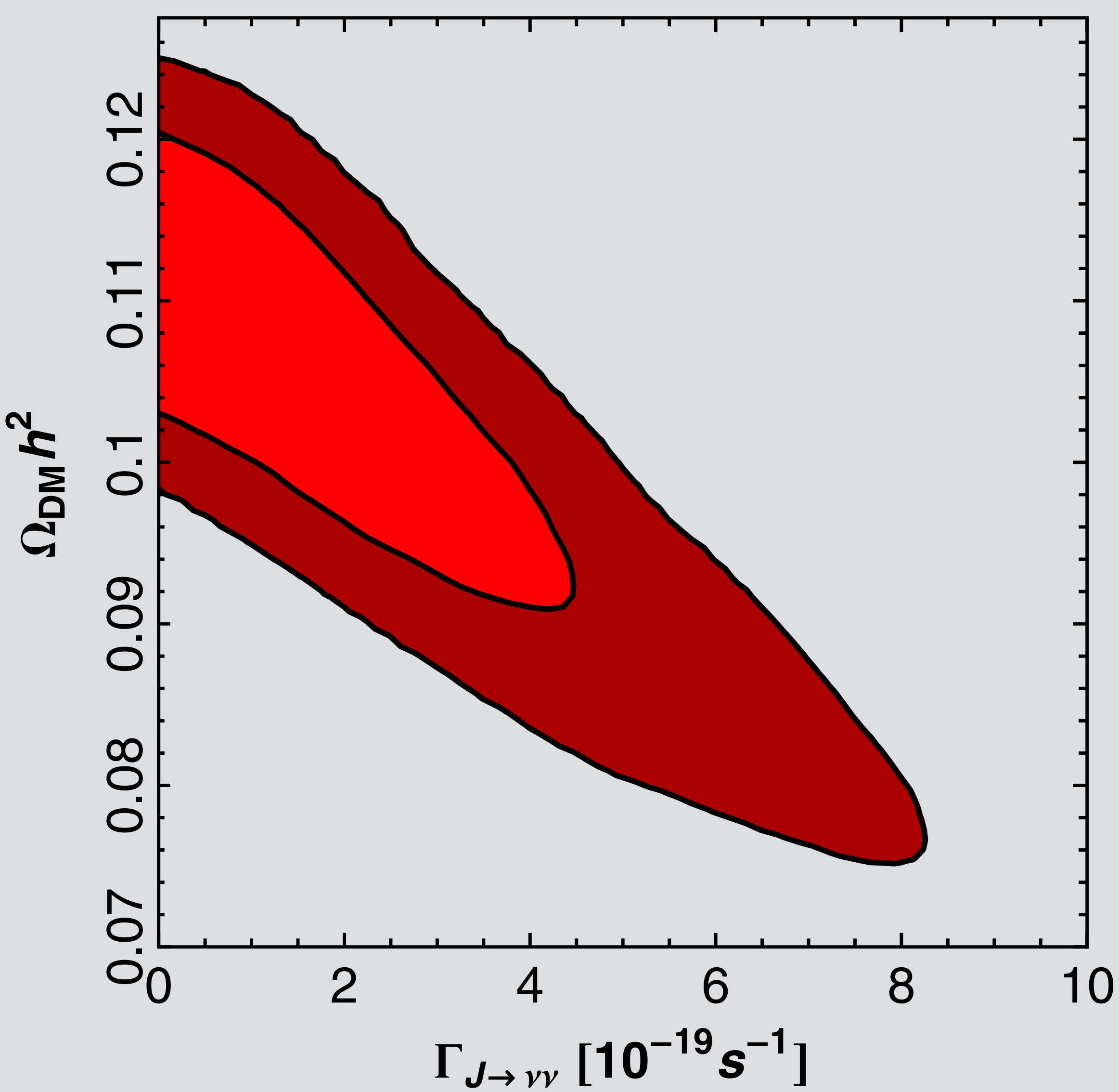
$$J \to \nu\nu$$

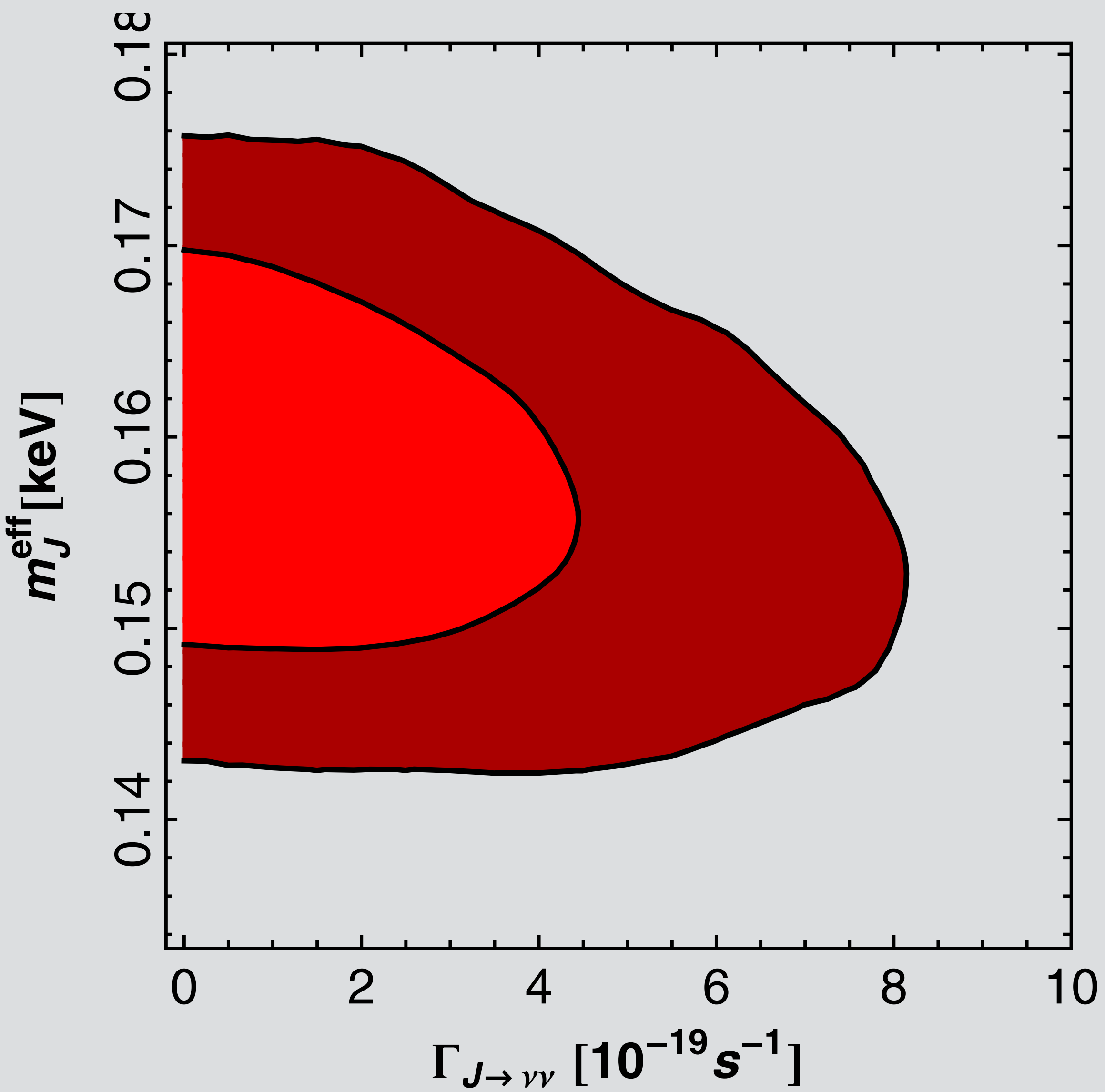
Lattanzi, Riemer-Sorense, Tortola, Valle 2013

Late DM decay to invisible relativistic particles:

- gives extra radiation at small redshifts
- too much power to CMB at the large angular scale.

Thus, CMB can constrain the decay rate or lifetime of J.





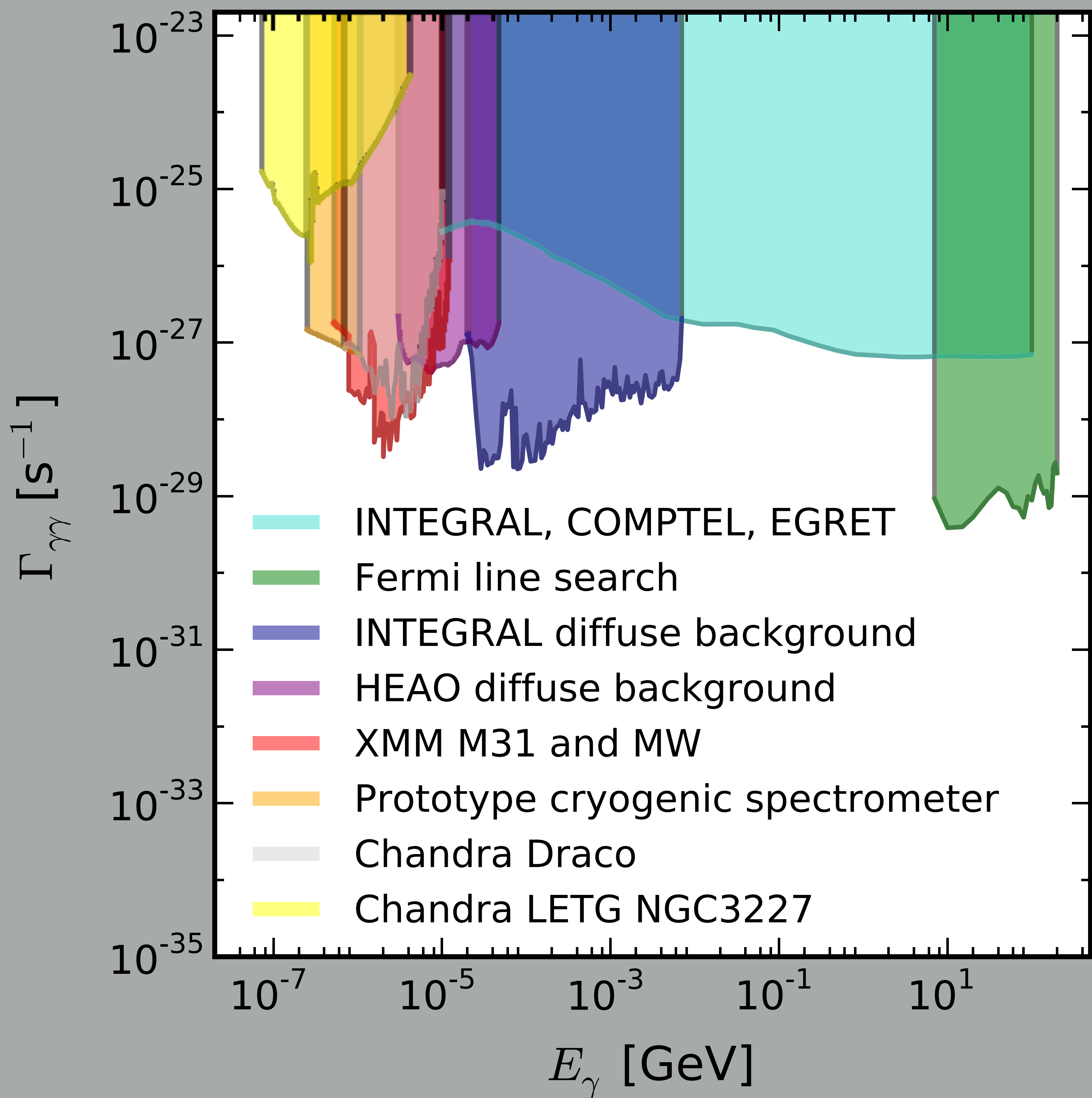
$\Gamma_{J\to\nu\nu} \leq 6.4\times 10^{-19}\,\mathrm{s}^{-1}$ at 95 % CL

$m_J^{\mathrm{eff}} = 0.158 \pm 0.007$ keV

X-ray, Gamma-ray Constraint

$$J \to \gamma\gamma$$

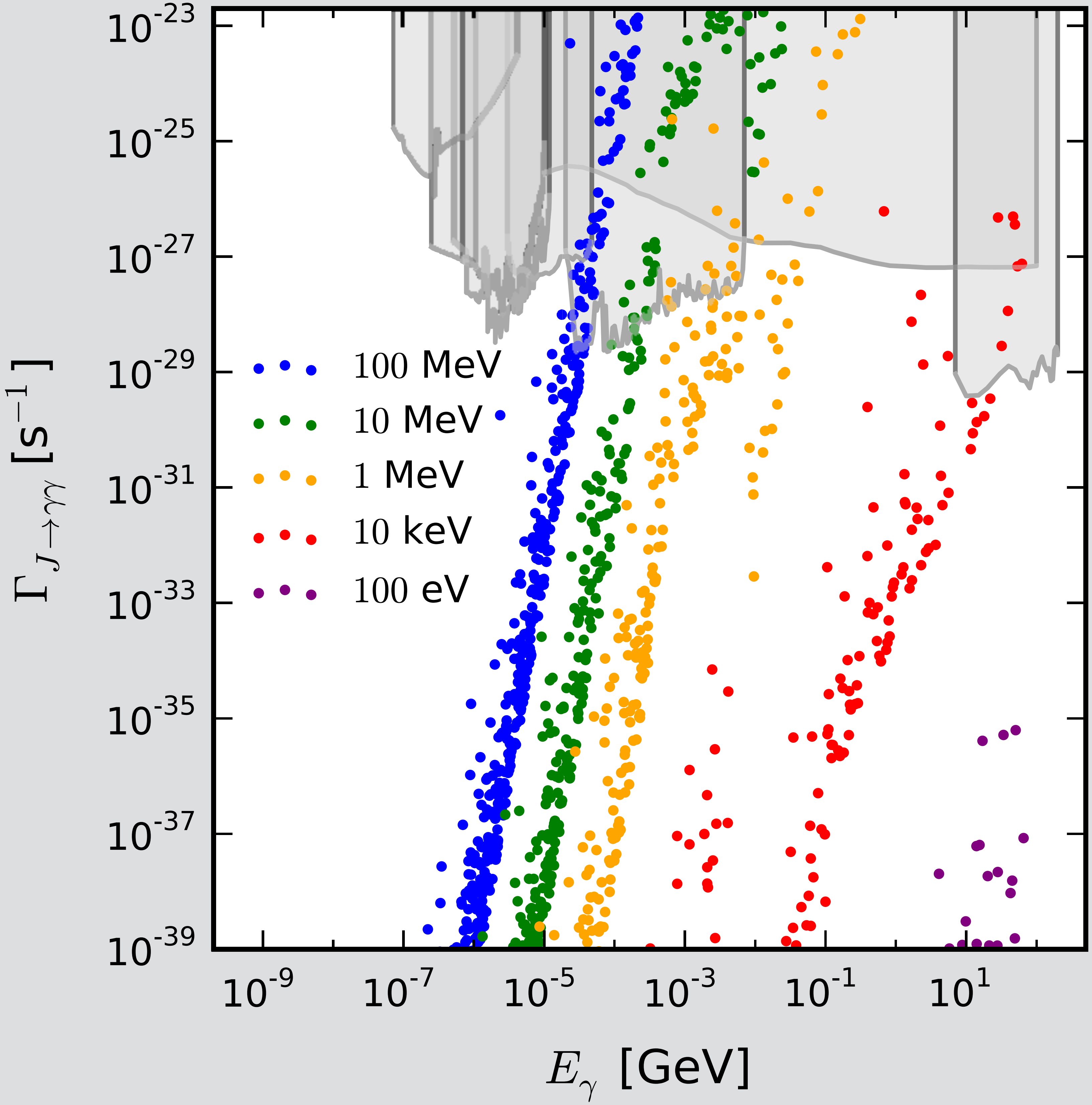
Lattanzi, Riemer-Sorense, Tortola, Valle 2013



3-sigma line emission
constraint on
DM -> 2 photons

The most relevant
range for majoron by:
Chandra LETG
XMM M31 and MW

Model predictions with various v_3



Lattanzi, Riemer-Sorensen, Tortola, Valle 2013

Structure Formation

Goal of this study

We examine the effect of decaying warm dark matter on non-linear structure formation, due to two effects

(1) Warm nature (free streaming) of the majoron DM

(2) Decay of majoron DM

Abbreviations	Initial Conditions	Lifetime	WDM mass
SCDM	CDM	∞	N/A
DCDM	CDM	$50\,\mathrm{Gyr}$	N/A
SWDM-M	WDM	∞	$1.5\,\mathrm{keV}$
DWDM-M	WDM	$50\,\mathrm{Gyr}$	$1.5\,\mathrm{keV}$
SWDM-m	WDM	∞	$0.158\,\mathrm{keV}$
DWDM-m	WDM	$50\,\mathrm{Gyr}$	$0.158\,\mathrm{keV}$

Table 1. The abbreviations and features of the simulations we have performed in this article. To avoid word cluttering in the following we will use these abbreviations.

We use two values for

$$m_J = 0.158 \text{ eV and } 1.5 \text{ eV}$$

and lifetime

$$\tau = 50\,\mathrm{Gyr} \quad \mathrm{or} \quad \infty$$

- The lighter one is for thermal DM production
- the heavier one is for non-thermal history or based on thermal production but later diluted by additional entropy after decoupling.
- The lifetime from CMB is 50 Gyr. We also study the stable DM case.

Remarks:

- The lighter mass 0.158 keV gives the correct relic density as a scalar particle that decouples in early Universe.

- Both values are in tension with the lower limit from Lyman-alpha, $m_J > 3.5$ keV. Nevertheless, the limit is model dependent, e.g., IGM thermal history.

- If $m_J = 5.3$ keV is chosen, it is almost no different from CDM.

- The lighter value is chosen so as to maximize the free streaming effects. And it mainly decays into neutrinos.

- Here we only investigate the effects of free streaming and decays, not the exact mass limit from structure formation.

Simulation of Decaying particle

- We concern with decay of DM into relativistic neutrinos
- The mass of "simulation particles" is reduced by a small amount at each time step due to decay of DM:

$$M(t) = M(1 - R + R\,e^{-t(z)/\tau_J}),$$

where $R \equiv (\Omega_M - \Omega_b)/\Omega_M$ is the DM fraction

- In addition to reducing simulation particle mass, the expansion rate of the Universe also modified according to the energy content at each z

The evolution of DM and decay product is described by

$$\dot{\rho}_{dm} + 3\mathcal{H}\rho_{dm} = -\frac{a}{\tau_J}\rho_{dm},$$

$$\dot{\rho}_{dp} + 4\mathcal{H}\rho_{dp} = \frac{a}{\tau_J}\rho_{dm},$$

H and a are the conformal Hubble parameter and scale factor.

The Hubble parameter at each red-shift is

$$\mathcal{H}^2(z) = \frac{8\pi G}{3}a^2(\rho_{dm}(z) + \rho_b(z) + \rho_{dp}(z) + \rho_\Lambda(z)),$$

- ρ_b, ρ_Λ are unaffected by energy exchange between DM and dp, so they evolve in standard way:

$$\rho_b \propto a^{-3}, \quad \rho_\Lambda \propto \mathrm{const}$$

- Further assumption: contribution of decay product dp to energy density is very small, due to long lifetime of majoron.

- The decay product, neutrinos, are free streaming and do not cluster.

- The decay is to reduce the amount of matter that is able to cluster. But we expect this assumption to break down on the largest scale above the free-streaming length, which is the size of horizon scale much larger than our simulation size.

- Given initial conditions for ρ_{dm}, ρ_{dp} we solve for the evolution equations and calculate the Hubble parameter at each time-step

Initial Conditions

- Use linear theory to evolve the primordial perturbation in k space to some initial redshift z = 99, which is well before the DM decays, so decaying DM and stable DM have the same initial condition.

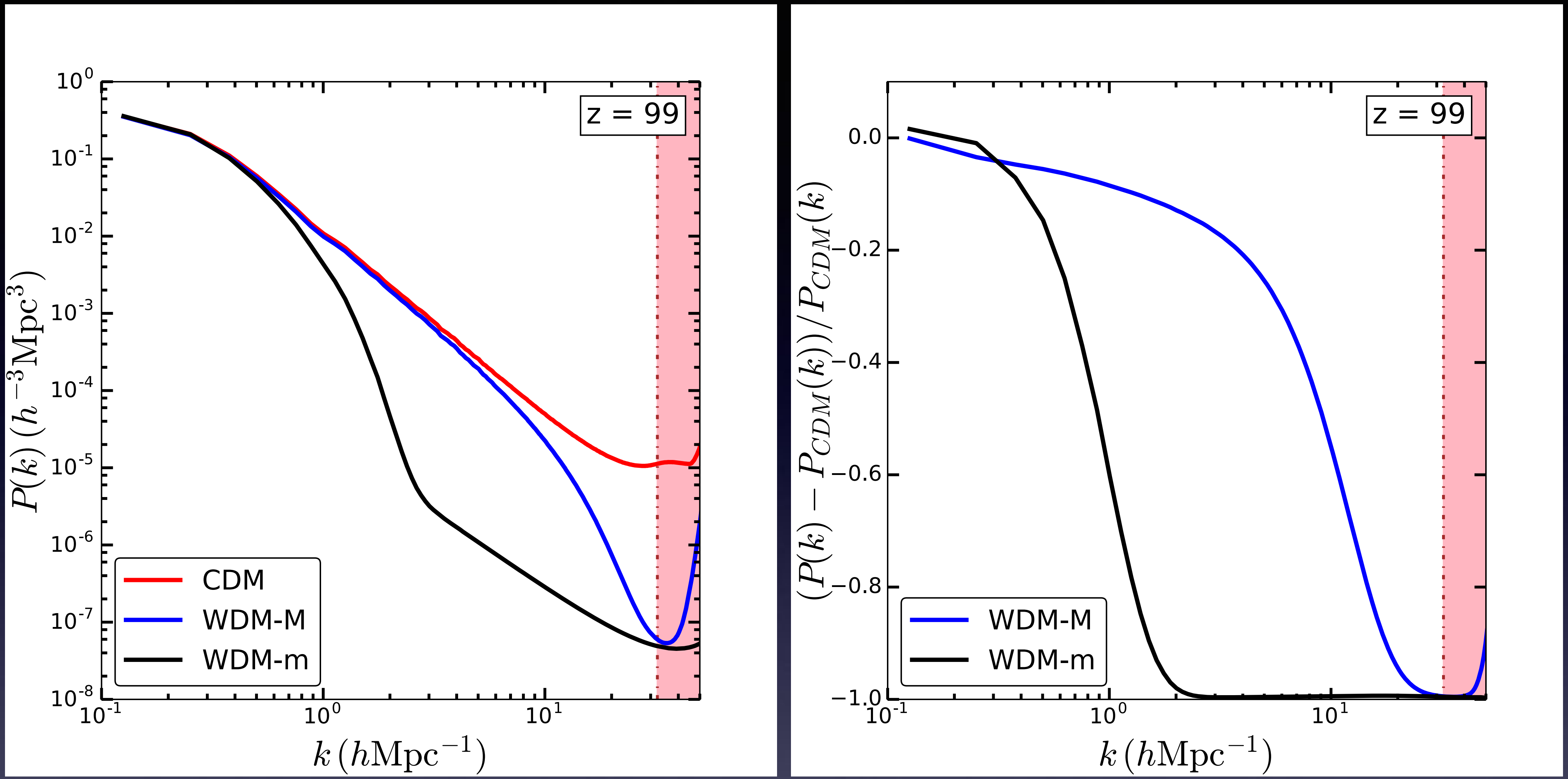
- In WDM, we estimate the initial power spectrum as

$$P_{\rm WDM}(k) = T^2_{\rm WDM}(k) \times P_{\rm CDM}(k)\,,$$

where transfer function $T_{WDM}(k)$

$$T_{\rm WDM}(k) = \left(1 + (\alpha k)^{2\nu}\right)^{-5/\nu}\,,$$

where $\alpha = 0.048(\Omega_{DM}/0.4)^{0.15}(h/0.65)^{1.3}({\rm keV}/m_{\rm DM})^{1.15}(1.5/g)^{0.29}$ Mpc and $\nu = 1.2$.



Initial matter power spectra for CDM and WDM using 2LTPic code. Power spectrum drops to 1/e of CDM at k≈1 (0.158 keV) and 17h (1.5 keV). These are roughly the free-streaming wave numbers.

Simulation Details

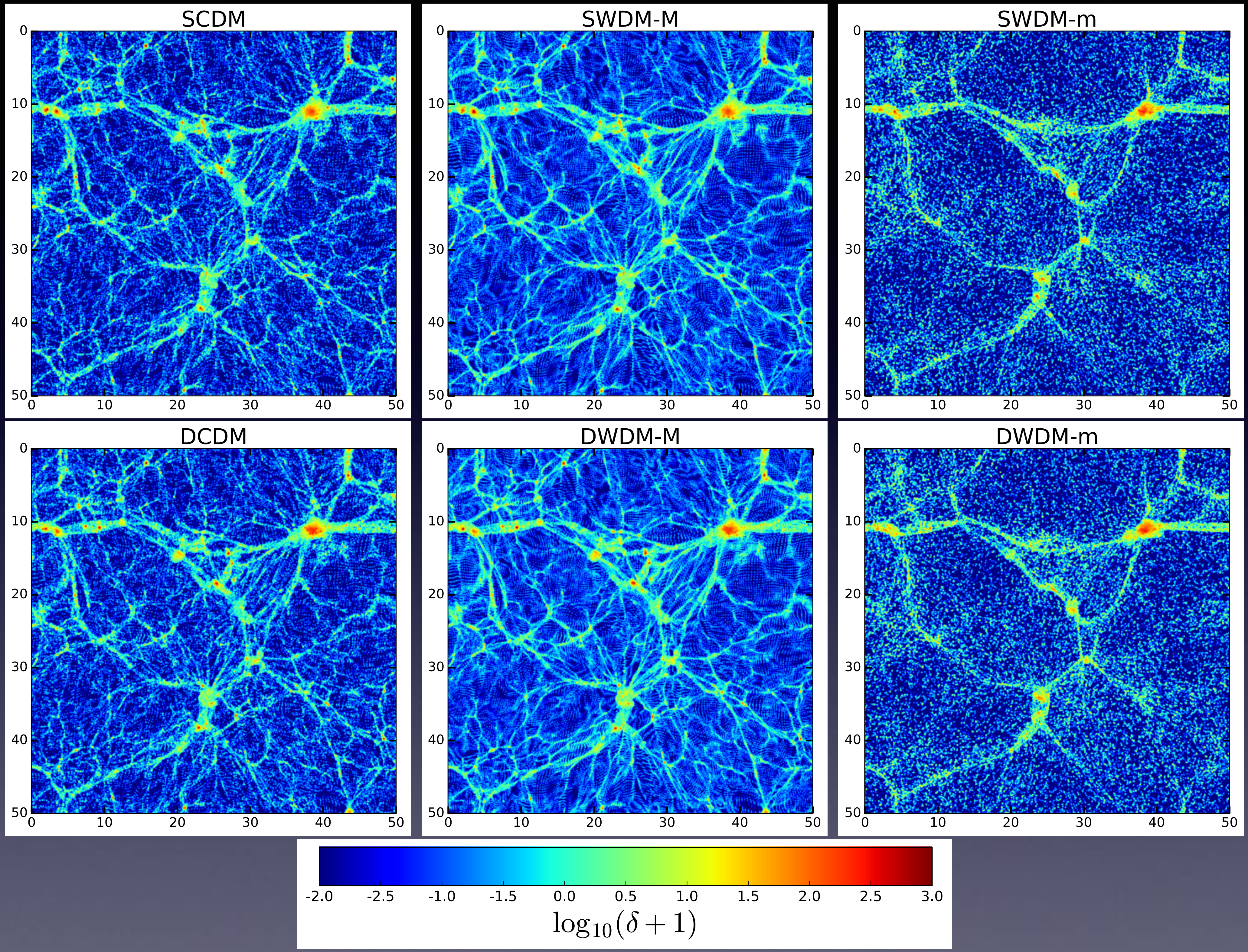
- starts at z = 99
- both stable and decaying DM exact same initial conditions and same random seed.
- For WDM simulations, thermal velocity at z=99 was input to simulation particles consistent with initial spectrum.
- Other cosmological parameters:

$$\Omega_m = 0.3, \Omega_\Lambda = 0.7, \Omega_b = 0.04; \quad h = 0.7, n_s = 0.96, \sigma_8 = 0.8$$

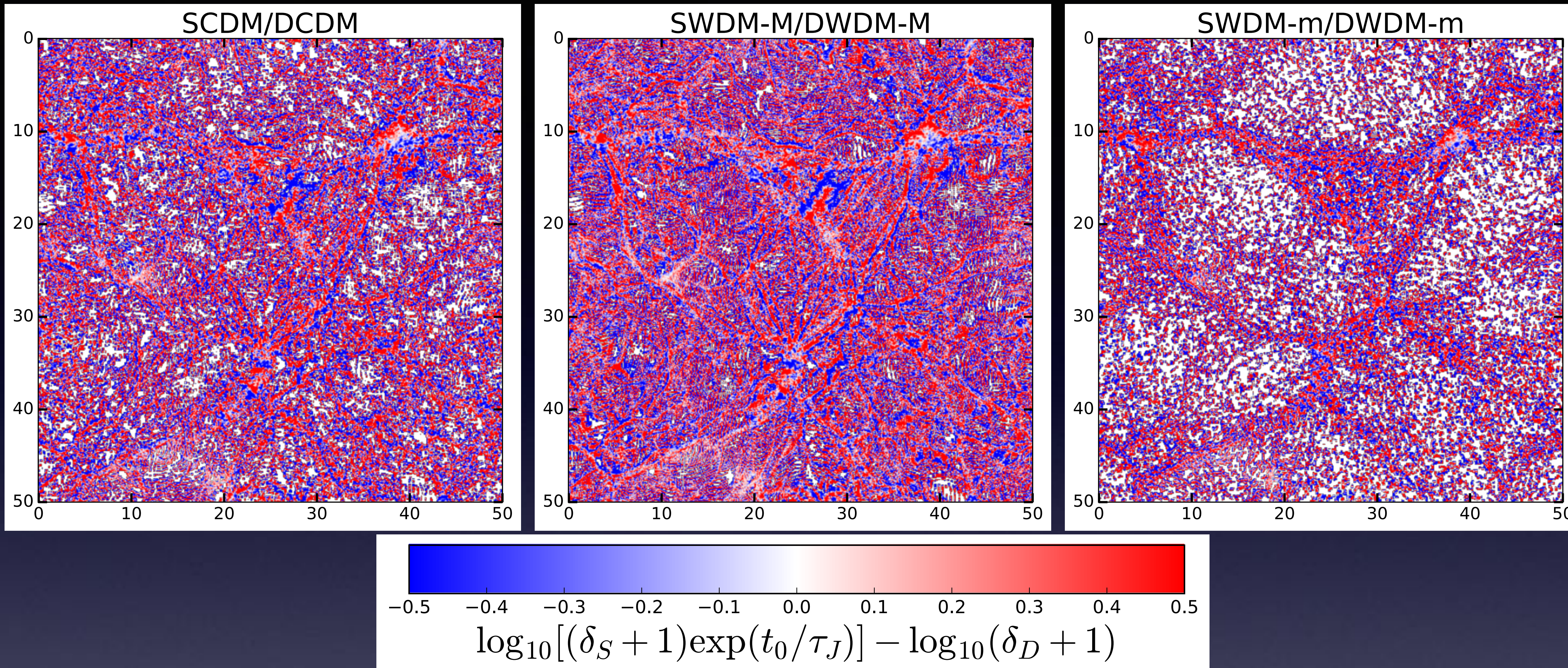
- Use 512^3 simulation particles in a cube with side 50 h^{-1} Mpc
- $M_{sim} \approx 7.8 \; 10^7 \; h^{-1} \; M_{sun}$.
- Periodic boundary condition.

Simulation Results

Density Fields



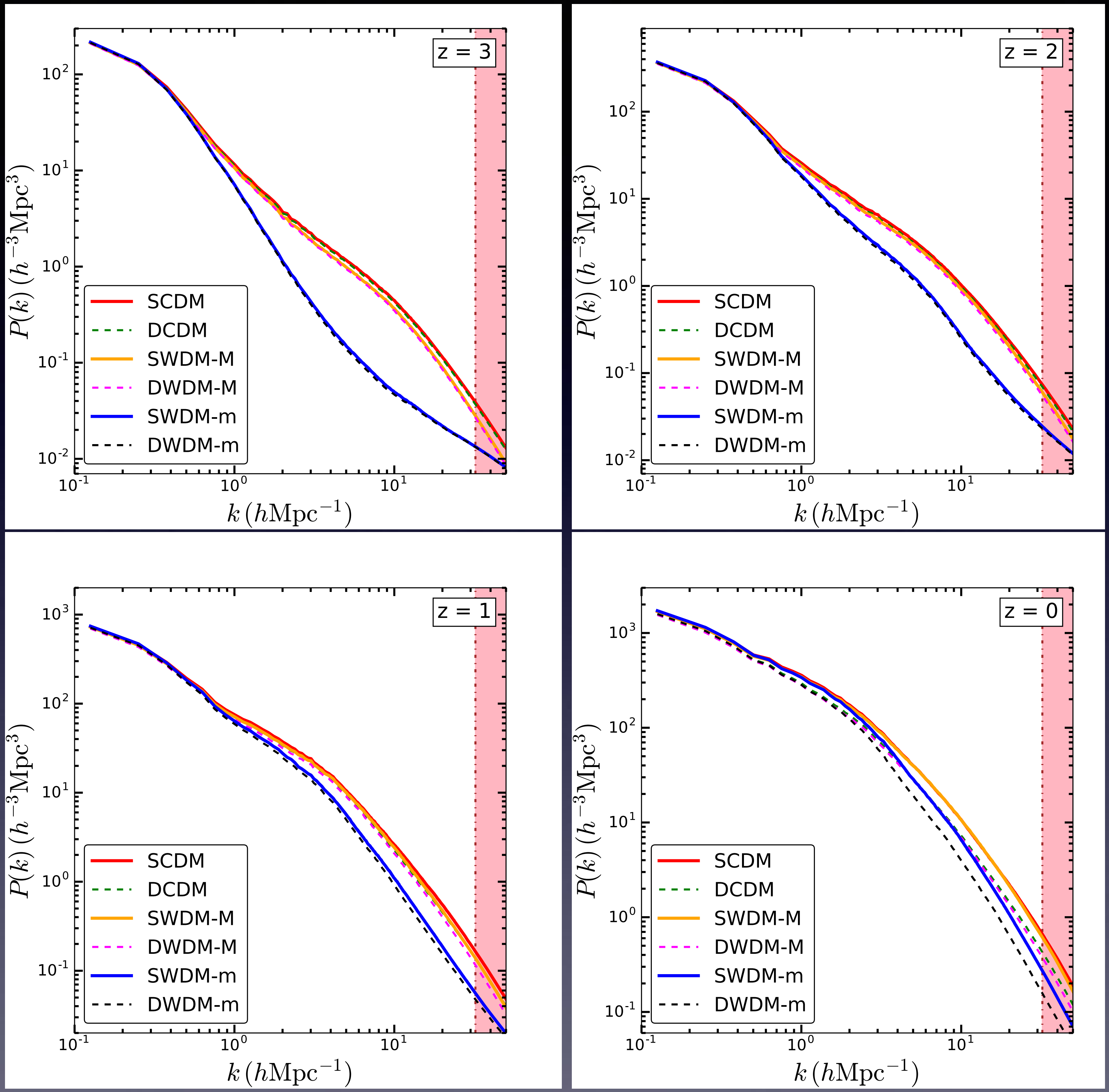
Density field: $1+\delta=\rho/\bar{\rho}$ M: 1.5 keV, m: 0.158 keV



Stable / Decay

$$\log_{10}(\rho_S/\rho_D) = \log_{10}[(\delta_S+1)\exp(t_0/\tau_J)] - \log_{10}(\delta_D+1)$$

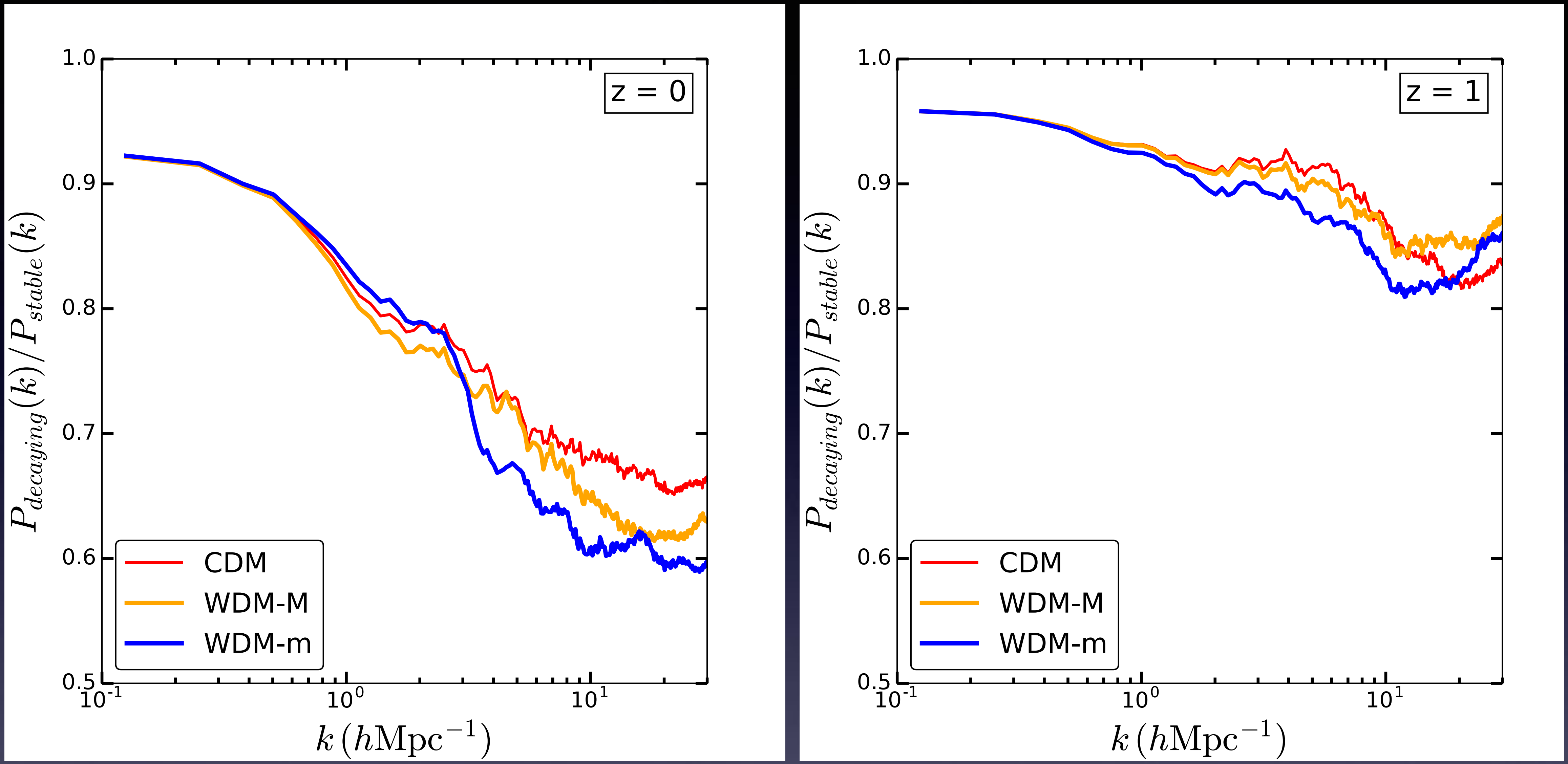
Matter Power Spectrum



Matter Power Spectrum comparison

Interpretations

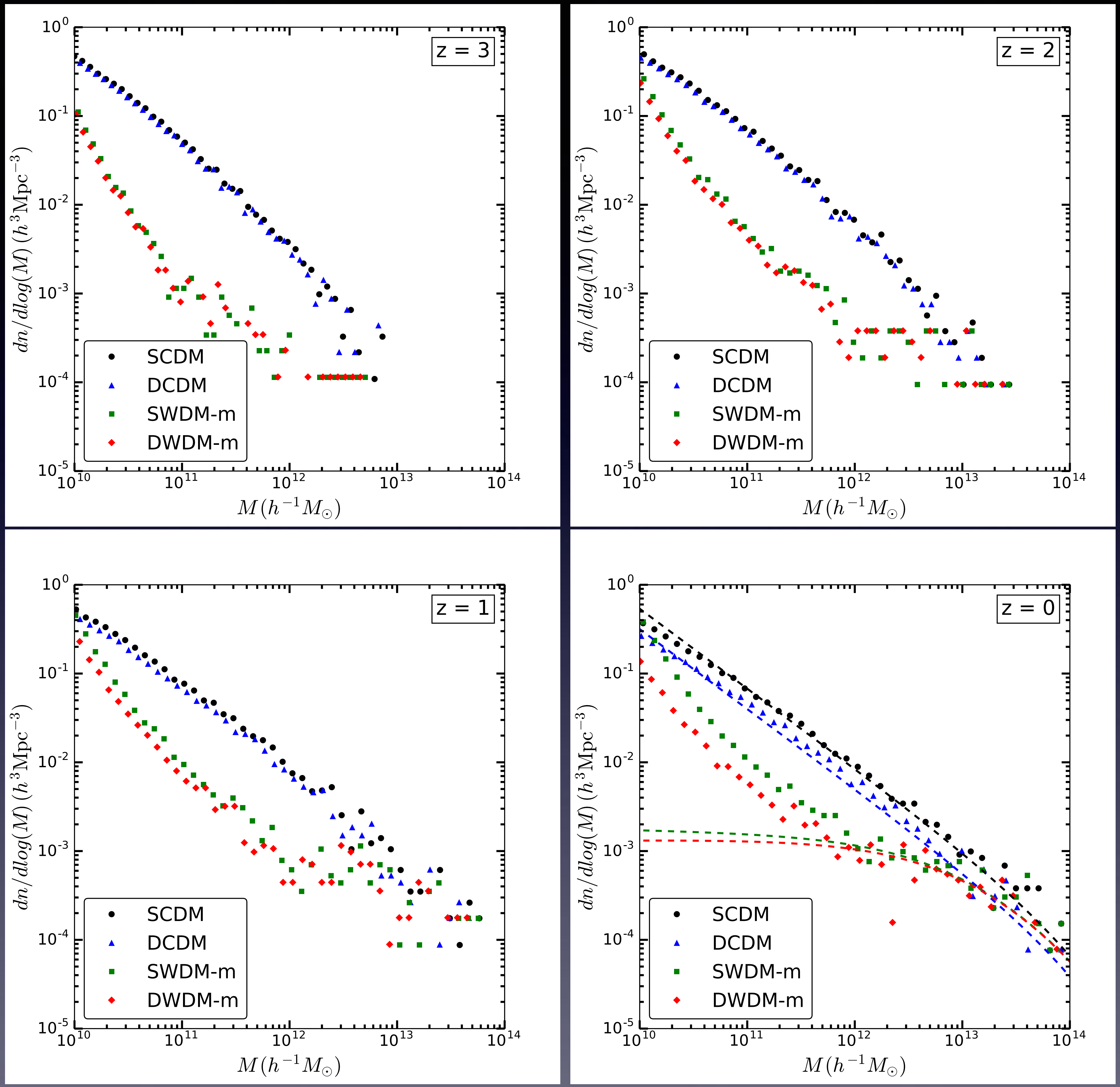
- Effects of decay is more obvious at low z
- Compare SCDM with SWDM-(M,m), at large scale (small k) are very close, but differ at small scale (large k), due to free-streaming of WDM.
- Free-streaming of m_J=1.5 keV is really small.
- Compare DWDM-M and DWDM-m, free-streaming effect still there for small scale suppression.
- Further suppression at all scales due to decay, which do not show strong dependence on scales. In contrast to free-streaming effect of WDM.



Ratio of matter power spectrum

- The decay suppresses the matter power at all scales.
- The suppression due to decay is more obvious at small scale.
- The suppression due to decay gradually decreases toward large scale. All curves converge to the same value as beyond free-streaming length CDM and WDM behave the same.
- Nonlinear enhancement of the effect of decay on small scales is stronger for lighter WDM. There is a sharp drop for m_J=0.158 keV near the free-streaming length scale.

Halo Mass Function


z = 3
z = 2
z = 1
z = 0
SCDM
DCDM
SWDM-m
DWDM-m
$dn/dlog(M)\,(h^3\mathrm{Mpc}^{-3})$
$M\,(h^{-1}M_{\odot})$

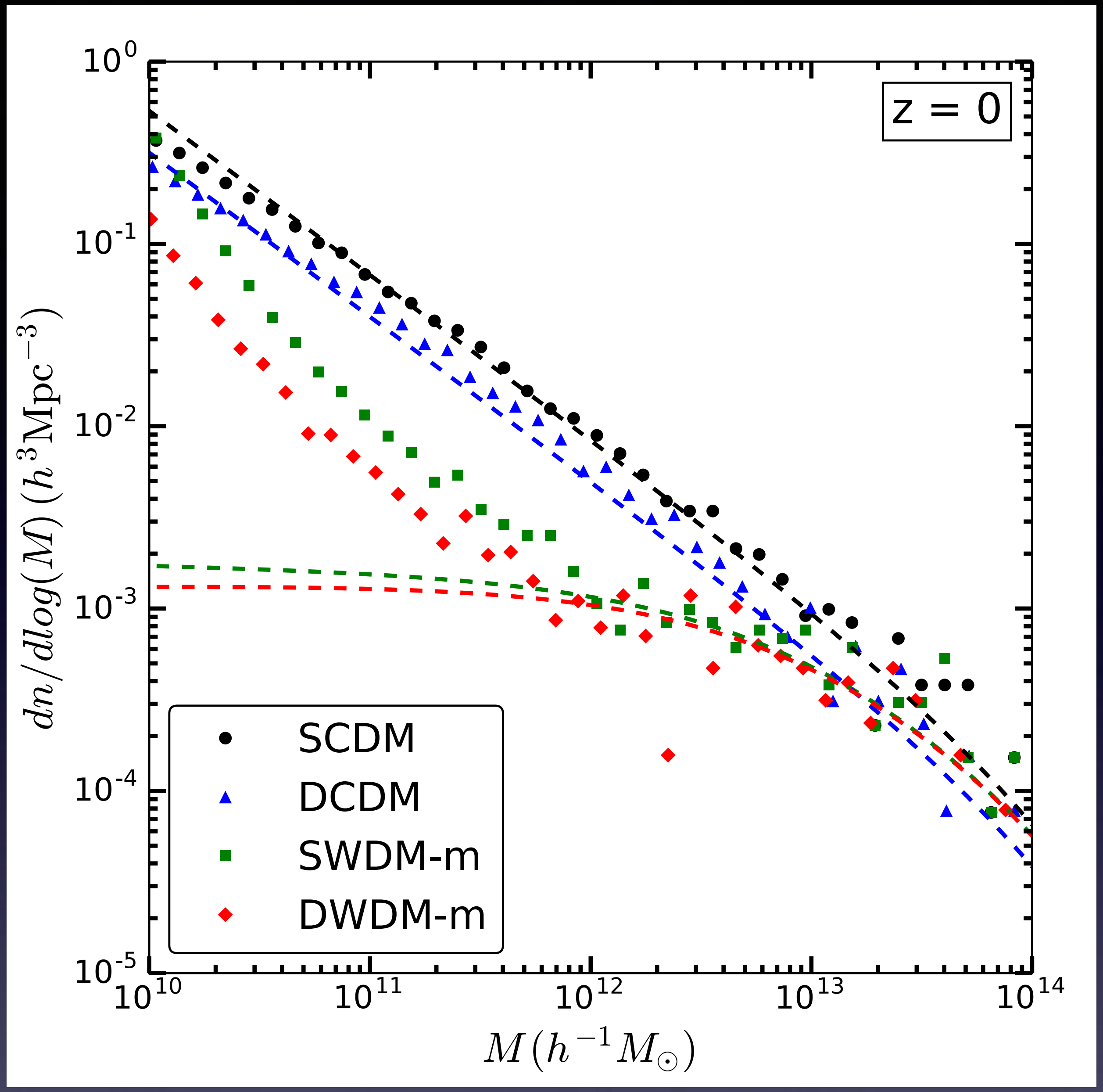
Remarks from Halo mass functions

- Compare stable and decaying DM, the decay reduced the number density of halos at all mass scales.

- Free-streaming effect of WDM is to set a cutoff halo mass, where the WDM halo mass function starts to deviate from CDM halo mass function.

- At large halo masses, the difference among various cosmologies are difficult due to few halos with large mass.

- Number density of small-mass halos is much higher in CDM than WDM



Deviations in WDM due to many spurious halos (numerical artifacts) due to strong cutoff in WDM transfer fuction

Halo mass function fit:

$$n(M) = (1 + M_{hm}/M)^{-\gamma} \times n_{Tinker}(M)$$

$\gamma \approx 0.309$ (SWDM-m) $\gamma \approx 0.345$ (DWDM-m)

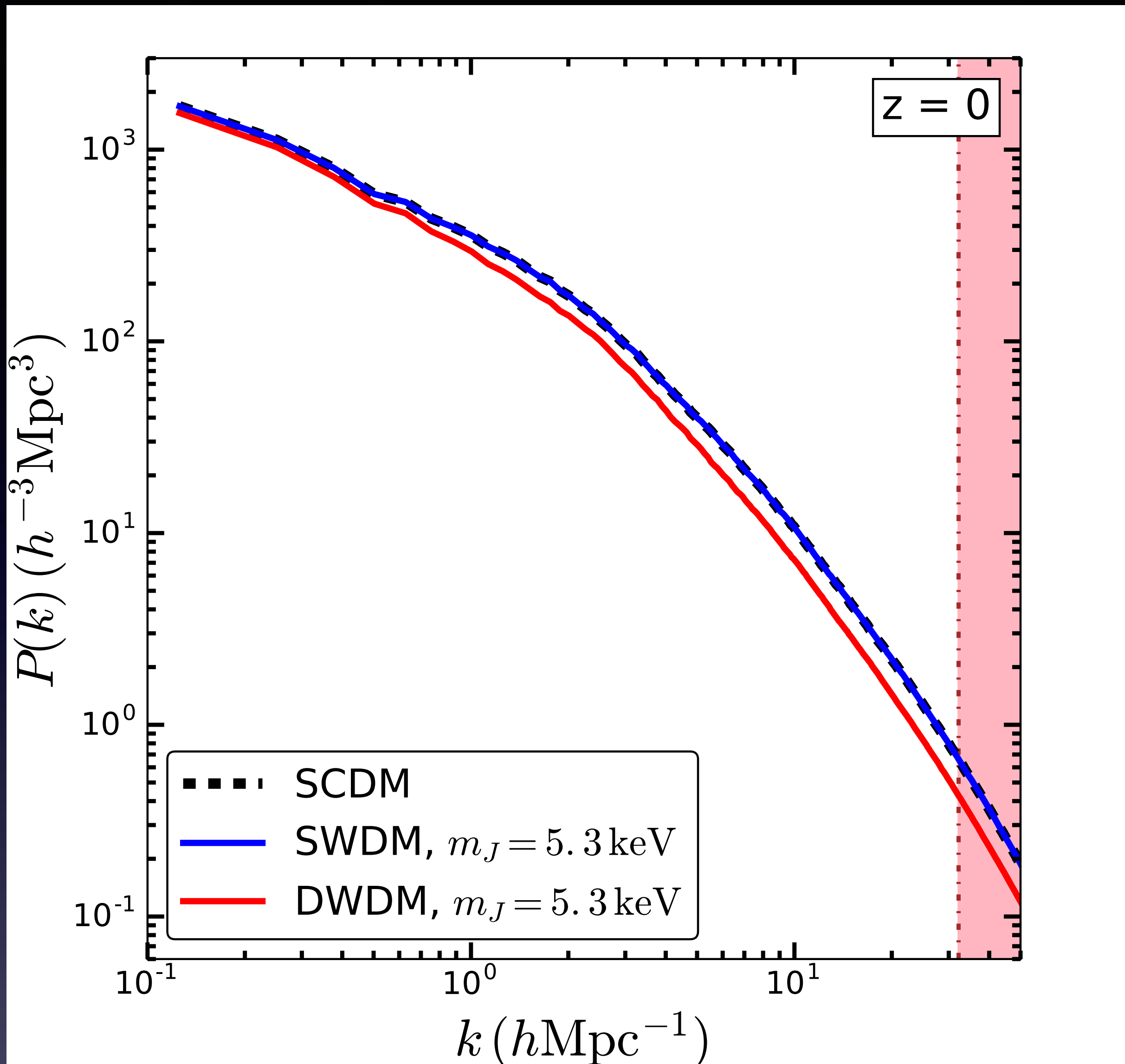
Outlooks and Further Improvements

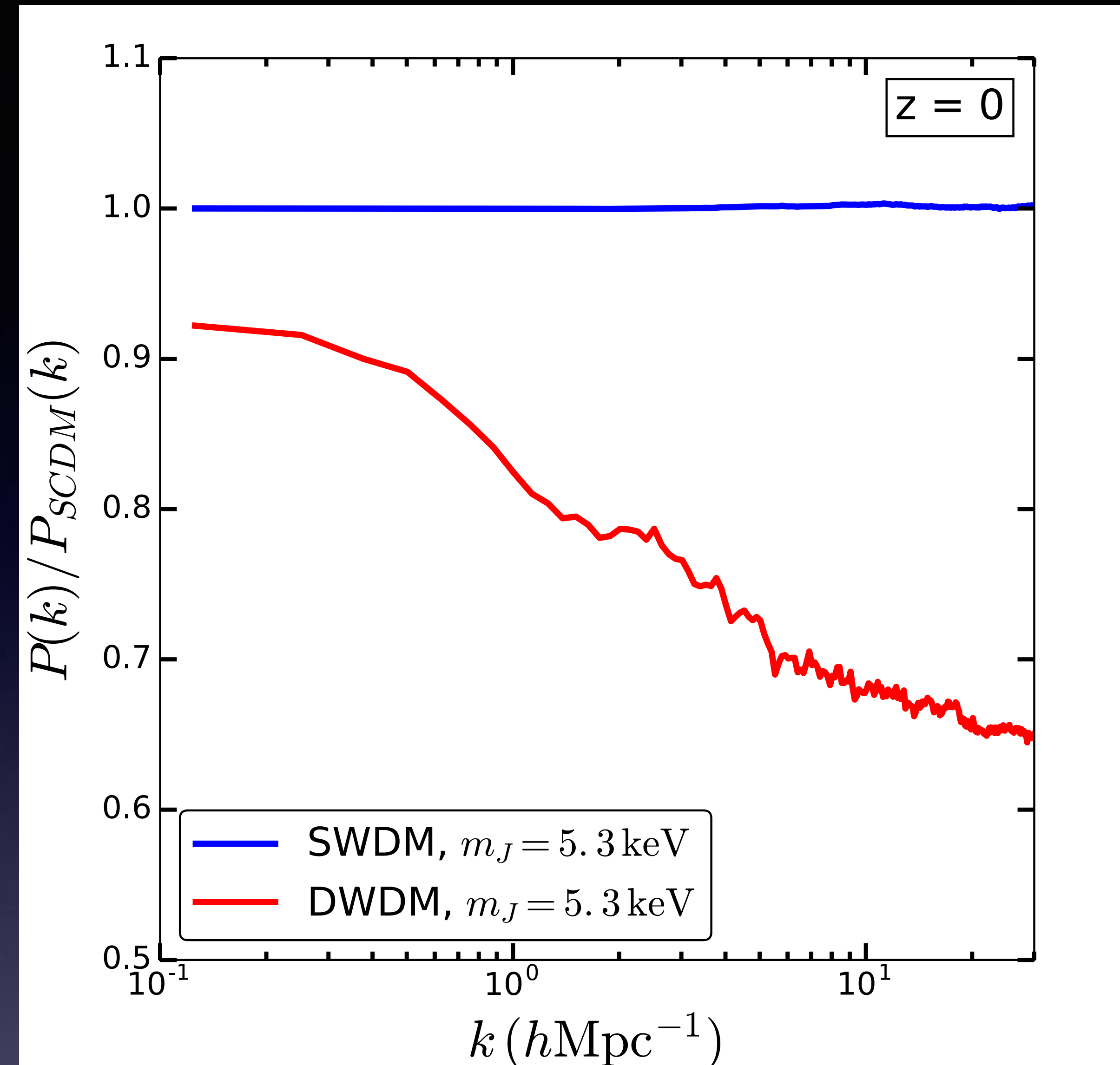
- Include baryons in simulations — ability to cool down by radiative processes, gravitational heated, affects the halo density profile, star formation, other compact massive objects.

- Here we ignore the free-streaming effects of the neutrinos. If the decay time is much shorter (but much later than CMB), relativistic effect is important in large scales.

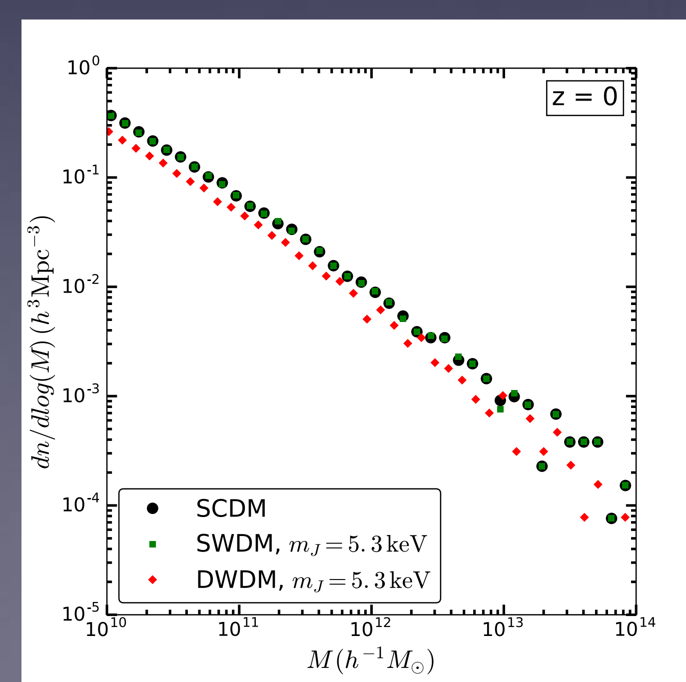
- Other scenarios:
  * CDM decays into relativistic neutrinos,
  * CDM decays into another CDM, velocity boost,
  * CDM interacts non-trivially with baryons, non-minimal heat exchange between CDM and baryons.

Back up Slides





Check for m_J=5.3 keV



Numerical Convergence tests

There are two numerical limitations:

- cosmic variance — finite volume of simulations, preventing predictions at very large scale. Box size:

  50 h^{-1} Mpc, corresponding to $k \approx 0.13$ h Mpc^{-1}.

- Discreteness of simulation particles

- Resolution limited by box size and the number of particles, described by Nyquist wavenumber

$$K_{N_{yq}} = \pi (N/V)^{1/3} \simeq 32\, h\, \mathrm{Mpc}^{-1}$$

Beyond that the accuracy strongly degraded.

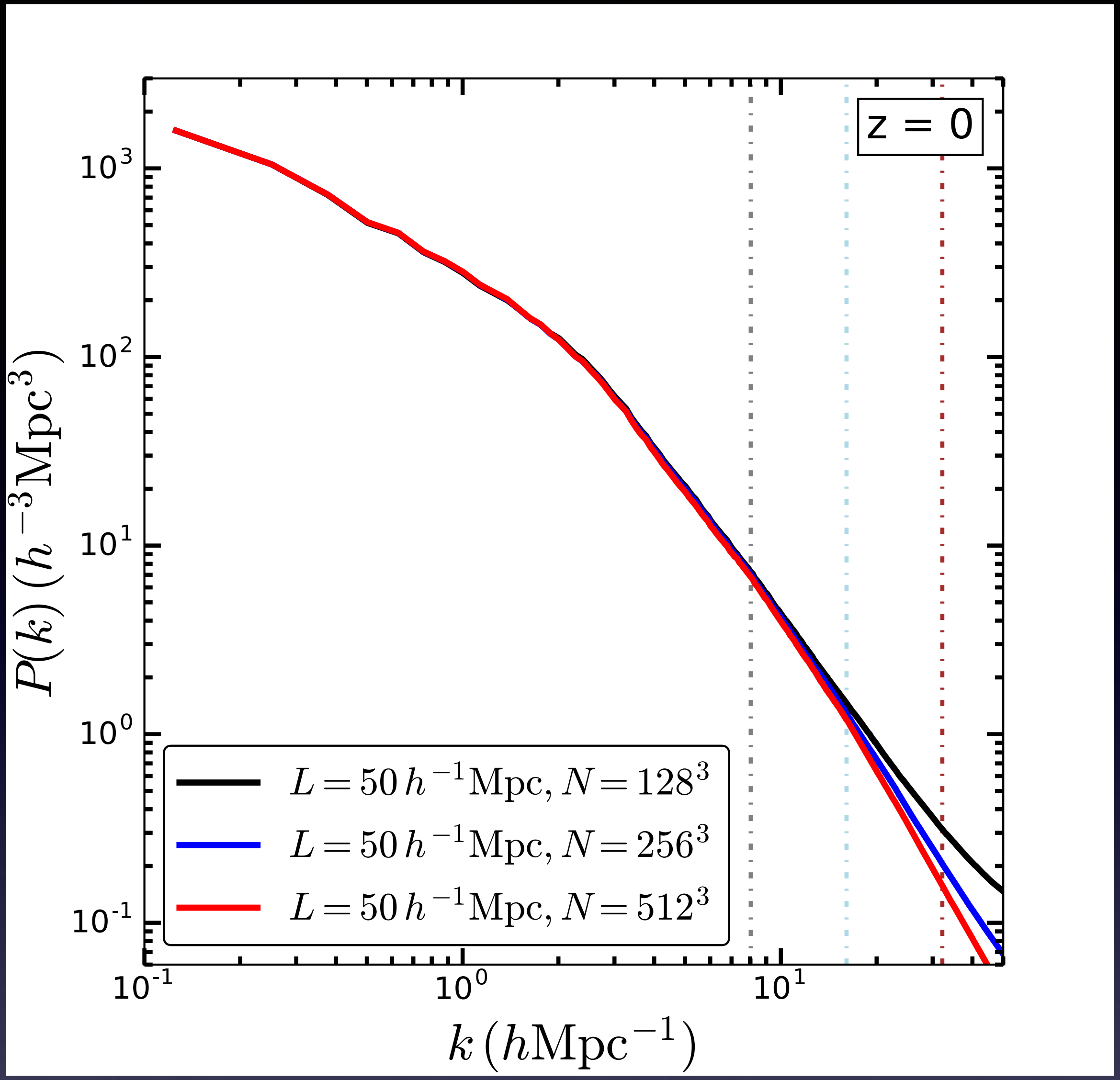
Consequences of finite resolution

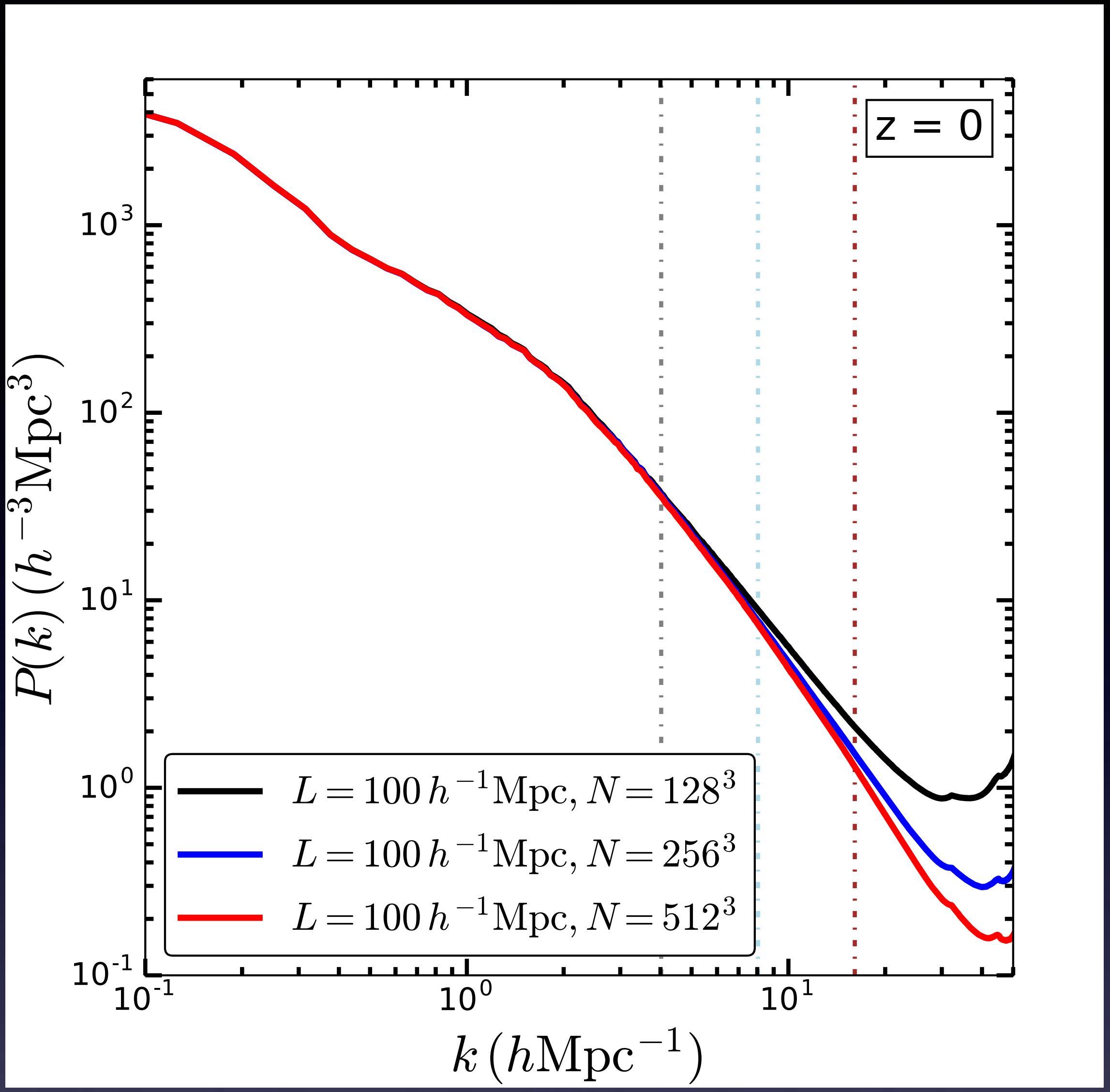
- Non-zero power exists on all scales — shot noise. Independent of k, but depend on the number of simulation particles.
- A discrete peak in power spectrum at 2 x Nyquist limit.

The excess power is of more problem to WDM because of much small power at small scales — well known spurious halo issue in WDM simulations

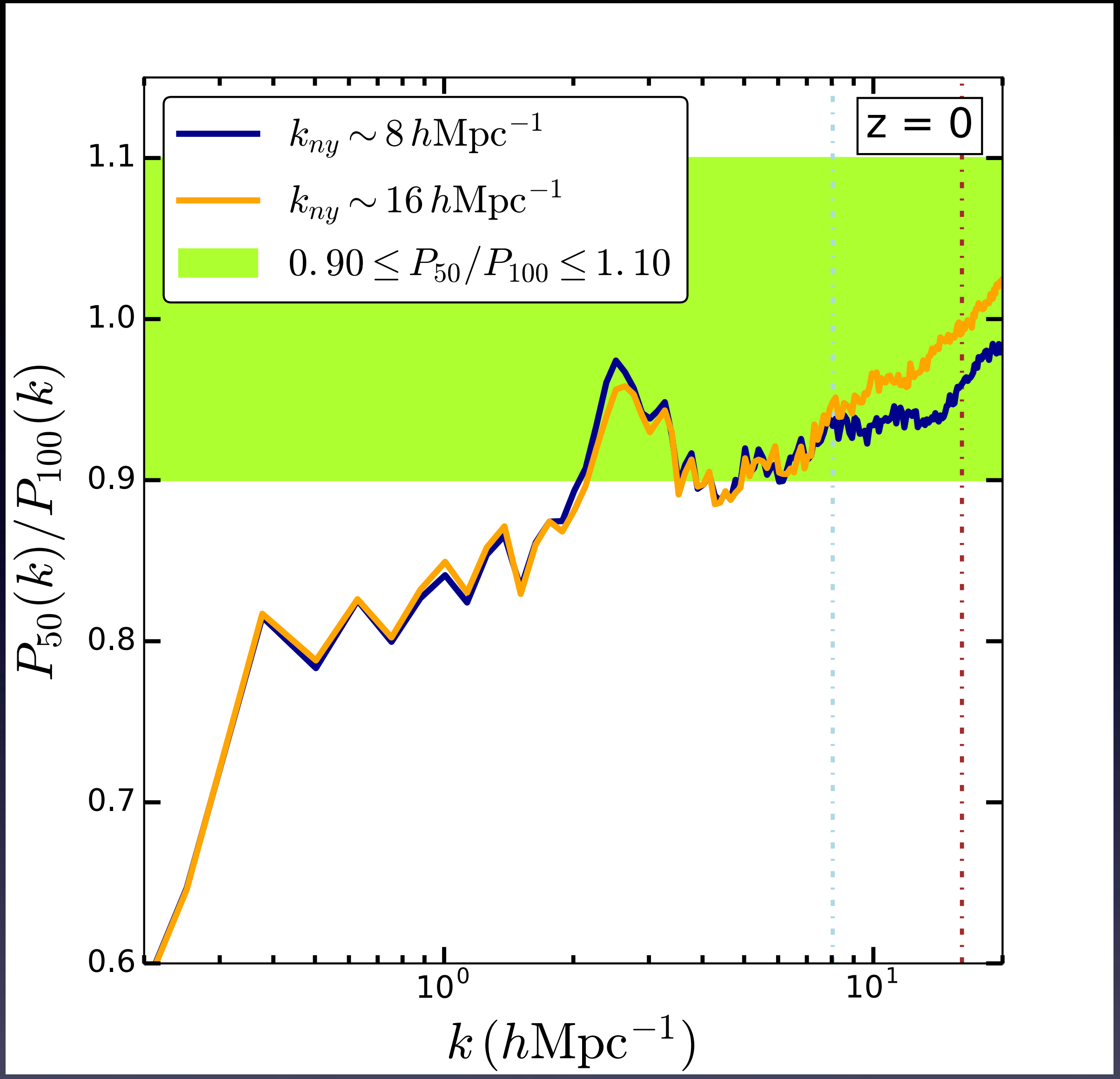
We compare simulations at z=0 with different N and V

$$N = 128^3, 256^3, 512^3; \quad L = V^{1/3} = 50,100\, h^{-1}\,\mathrm{Mpc}$$

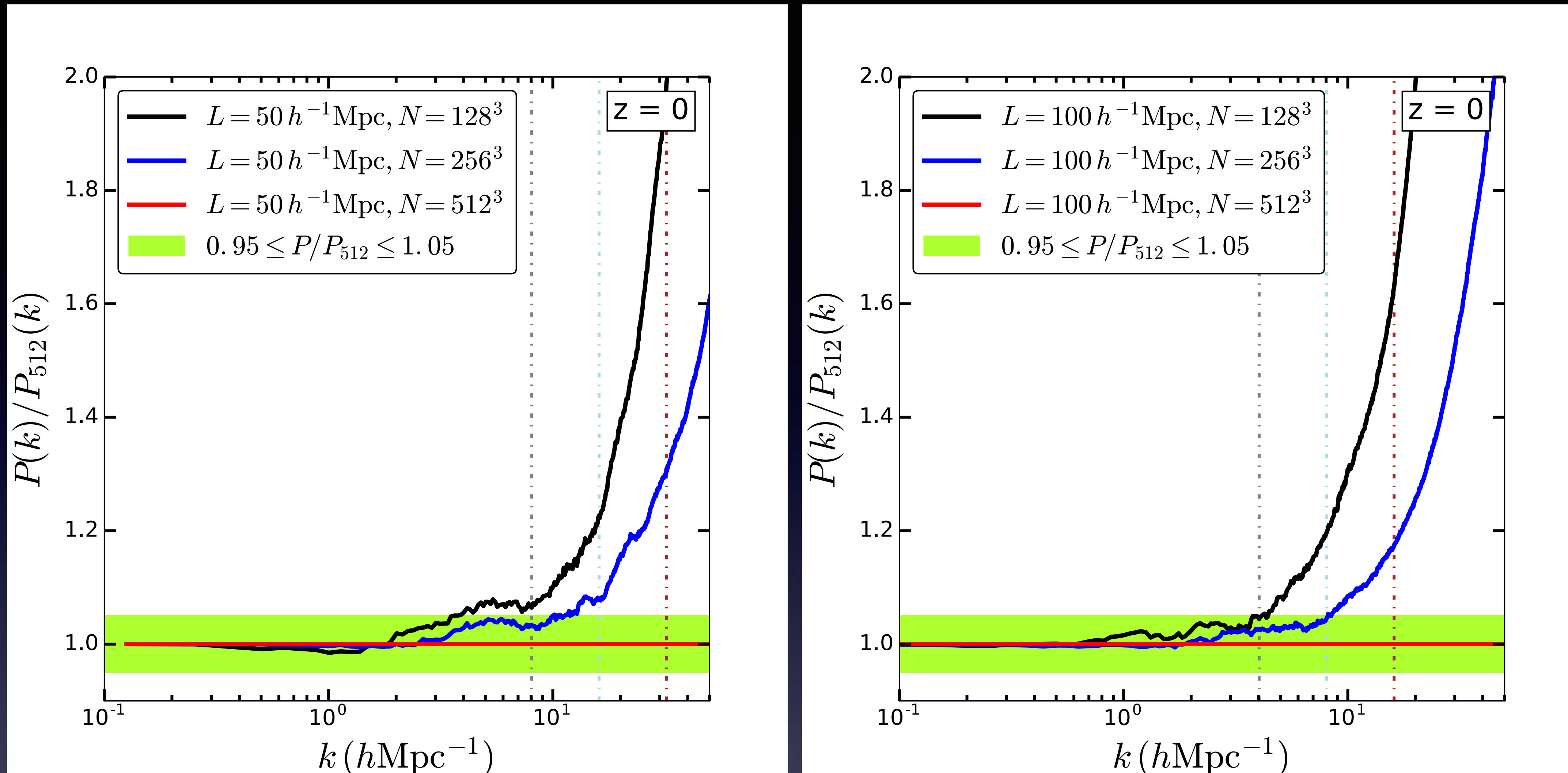




In almost entire range of scales the matter power spectrum at different resolution converge all the way up to Nyquist limit.



Ratio of power spectrum for L = 50 and 100 h^{-1} Mpc.
The green band is 10% deviation.



Ratio of matter power spectrum at z = 0