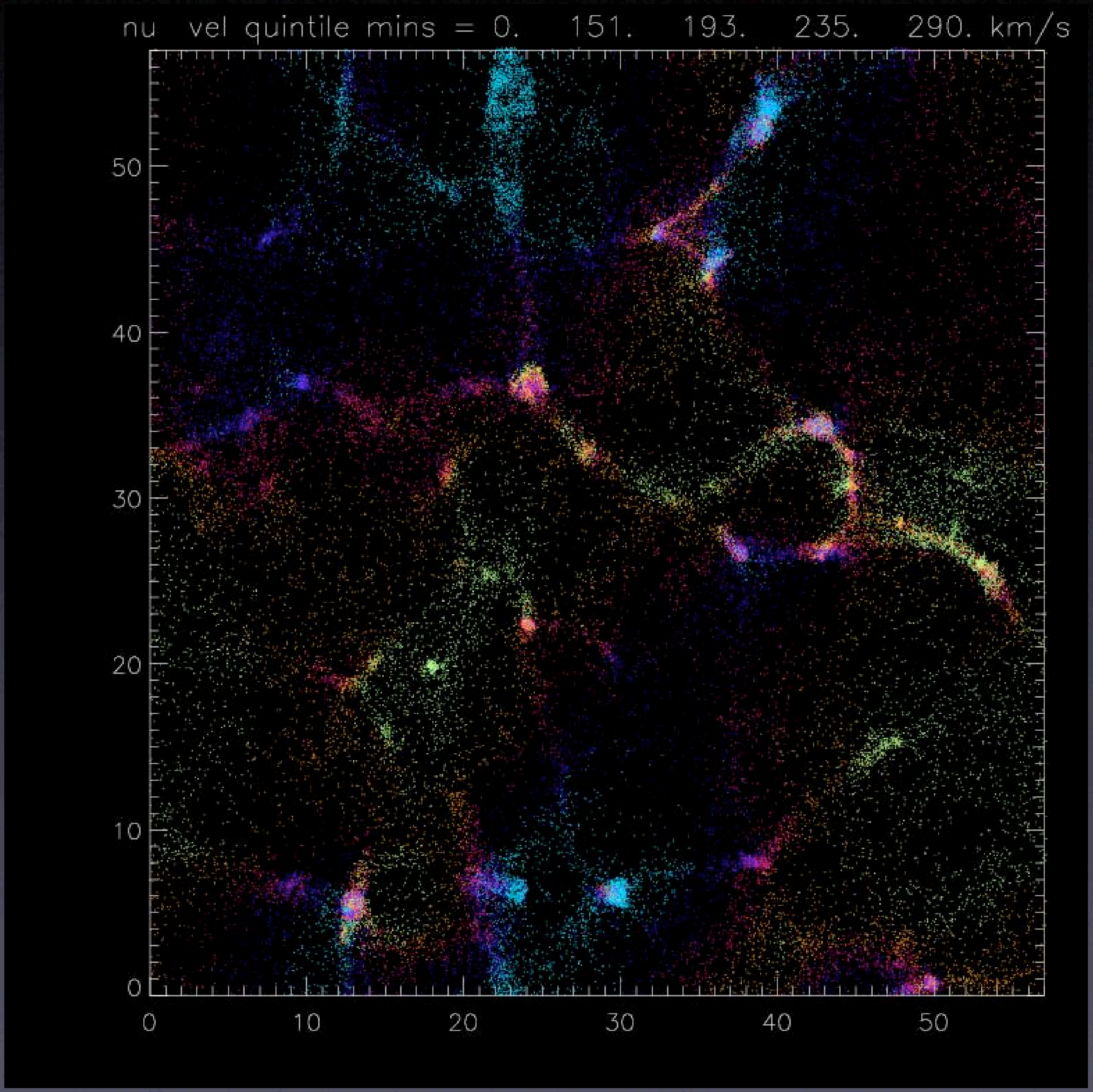
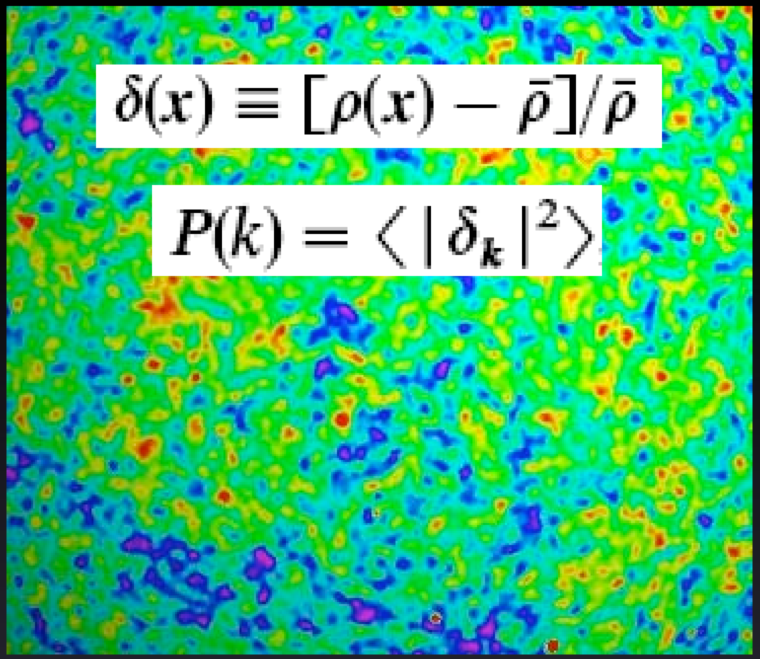
Neutrinos and Cosmological Large Scale Structure



Kevork Abazajian

Los Alamos National Laboratory

The cosmological density perturbation spectrum

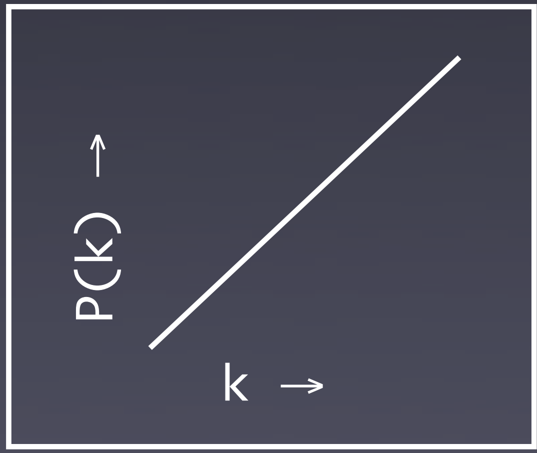


- Power spectrum of cosmological density fluctuations

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

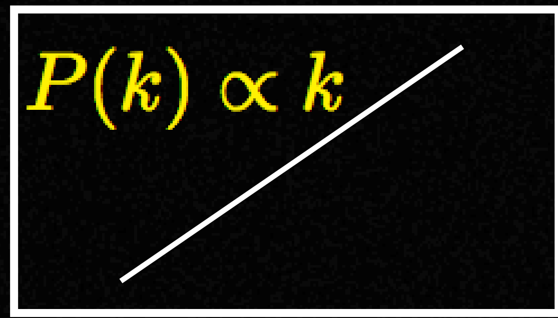
- Primordial Harrison-Zeldovich: from scale invariance

$$P(k) \propto k^n \quad n \approx 1$$

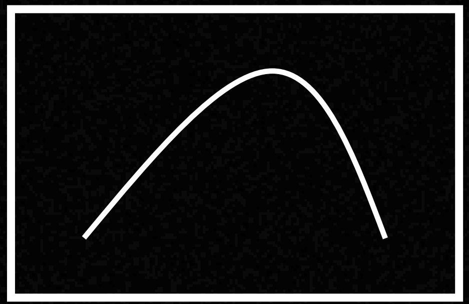


  – Natural solution to perturbation spectrum: self-similar evolution

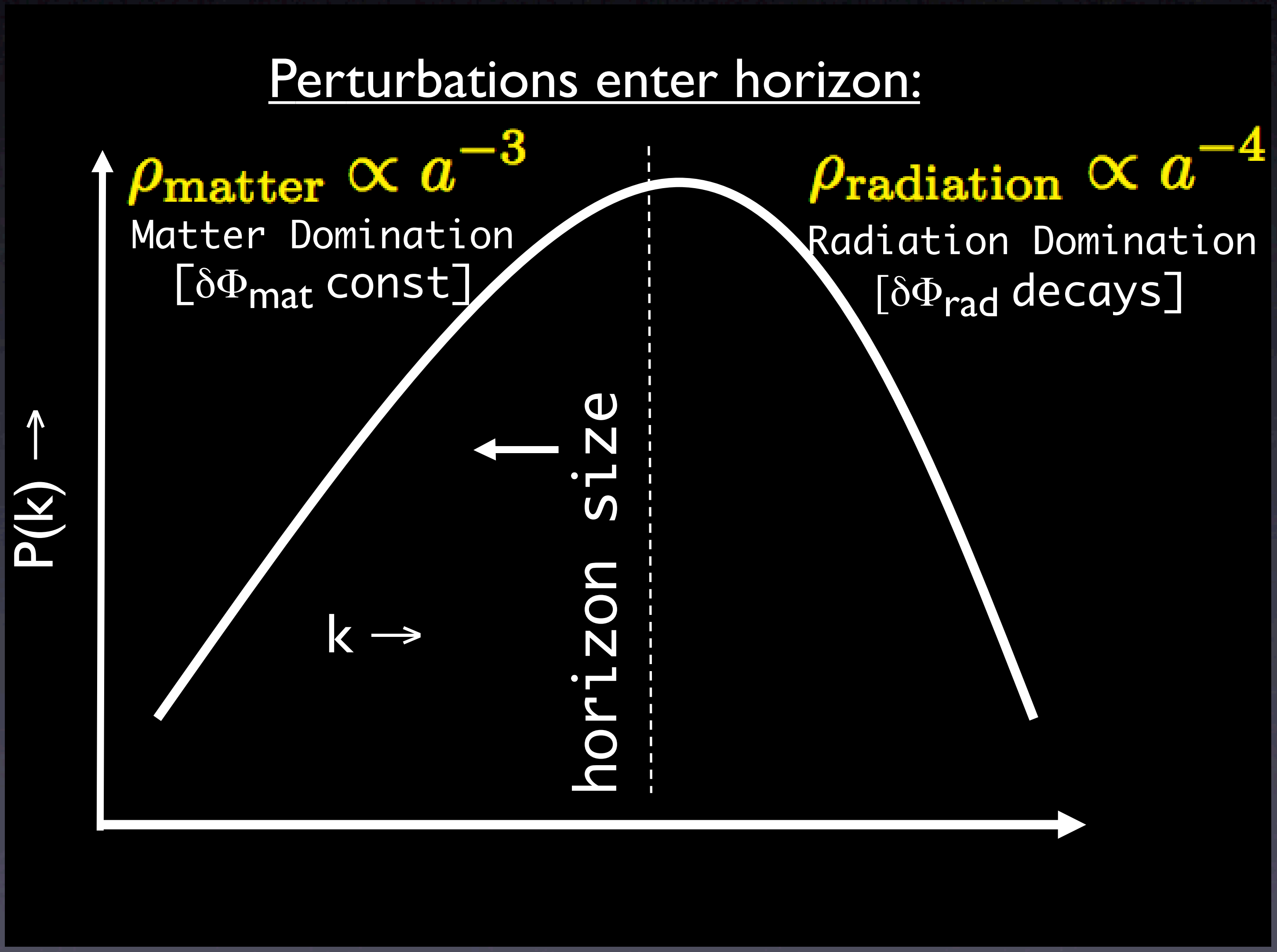
- Predicted by inflation

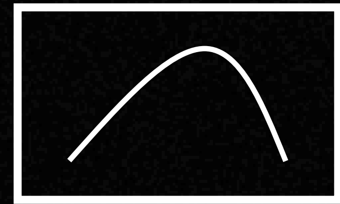

$P(k) \propto k$

→



?


Perturbations enter horizon:
$\rho_{\mathrm{matter}} \propto a^{-3}$
Matter Domination
[$\delta\Phi_{\mathrm{mat}}$ const]
$\rho_{\mathrm{radiation}} \propto a^{-4}$
Radiation Domination
[$\delta\Phi_{\mathrm{rad}}$ decays]
P(k) →
k →
horizon size

How does  probe neutrinos?

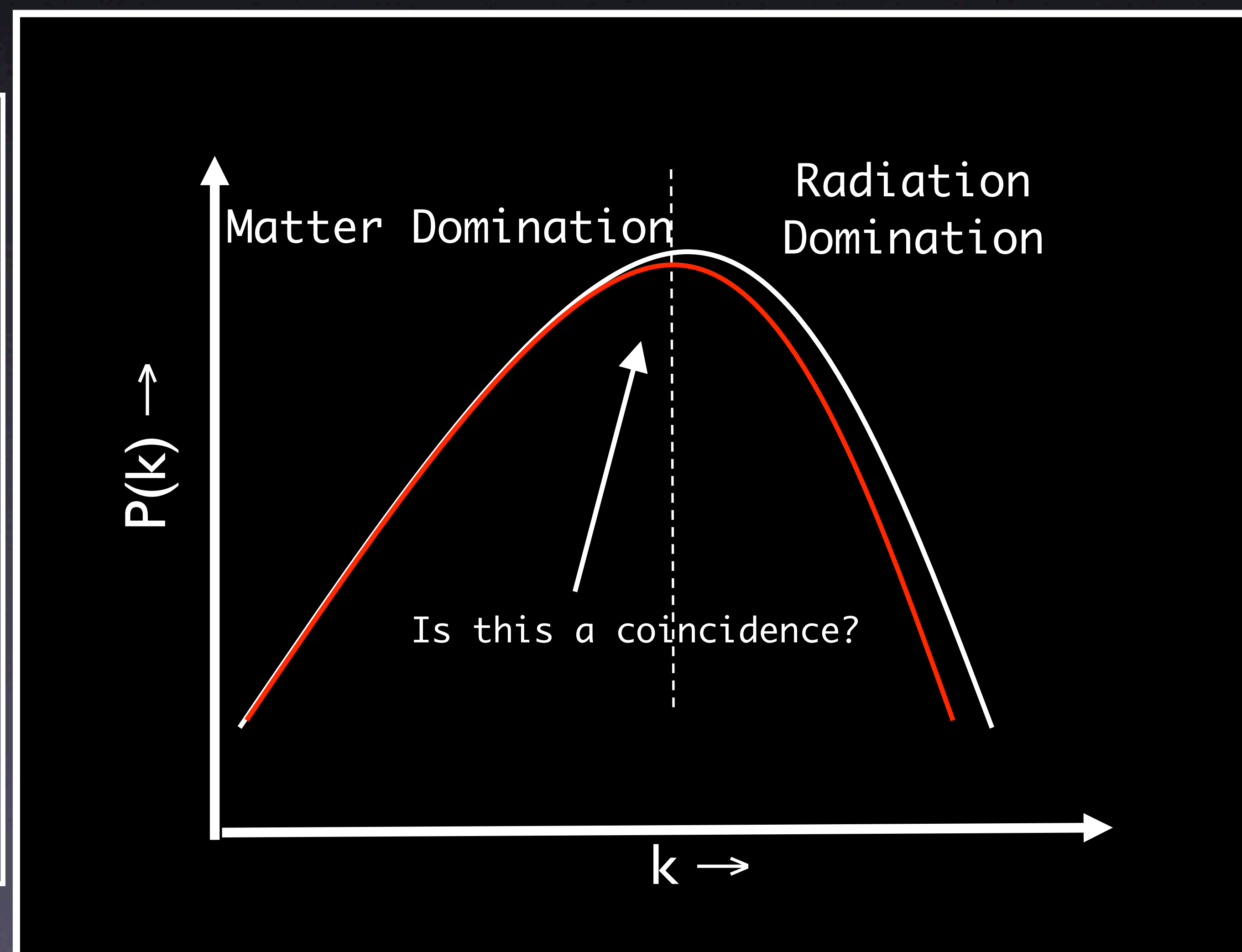
$$n_\nu = N_\nu \times \left(\frac{3}{11}\right) n_\gamma \approx 340 \text{ cm}^{-3}$$

(Assuming thermal equilibrium)

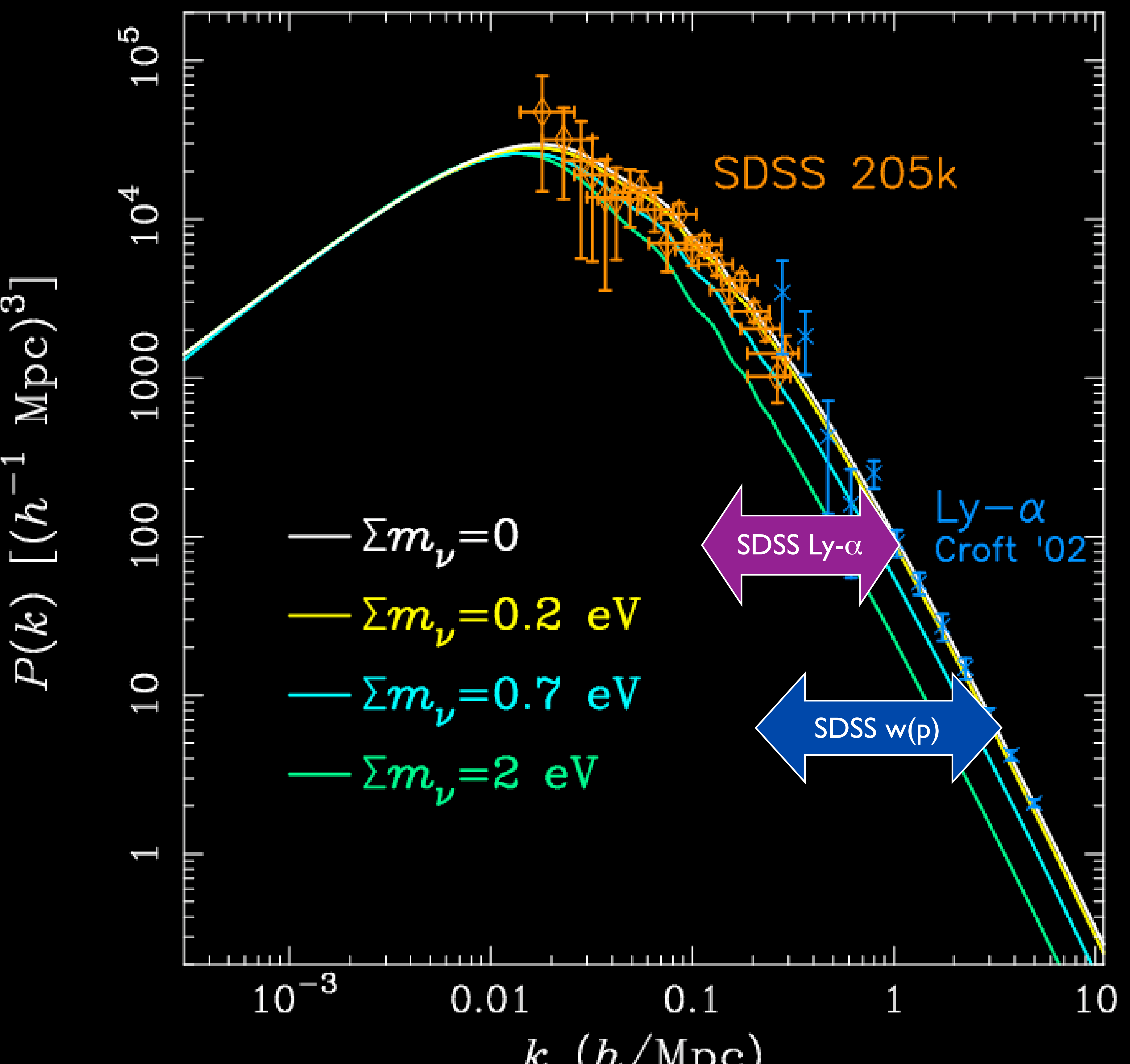
$$\rho_\nu = \sum m_i n_{\nu_i}$$

$$\Omega_\nu = \frac{\sum m_i n_{\nu_i}}{\rho_{\text{crit}}} = \frac{\sum m_i}{94 h^2 \text{ eV}}$$

$$E^2 = p^2 + m^2$$



Measuring P(k)



Current CMB+LSS Limits on Standard Massive Neutrinos

WMAPext +

SDSS 3D $P_g(k)$:

$$\sum m_{\nu_i} \leq 1.4 \text{ eV (95\%CL)}$$

[Tegmark et al 2004]

SDSS $w_p(r_p)$:

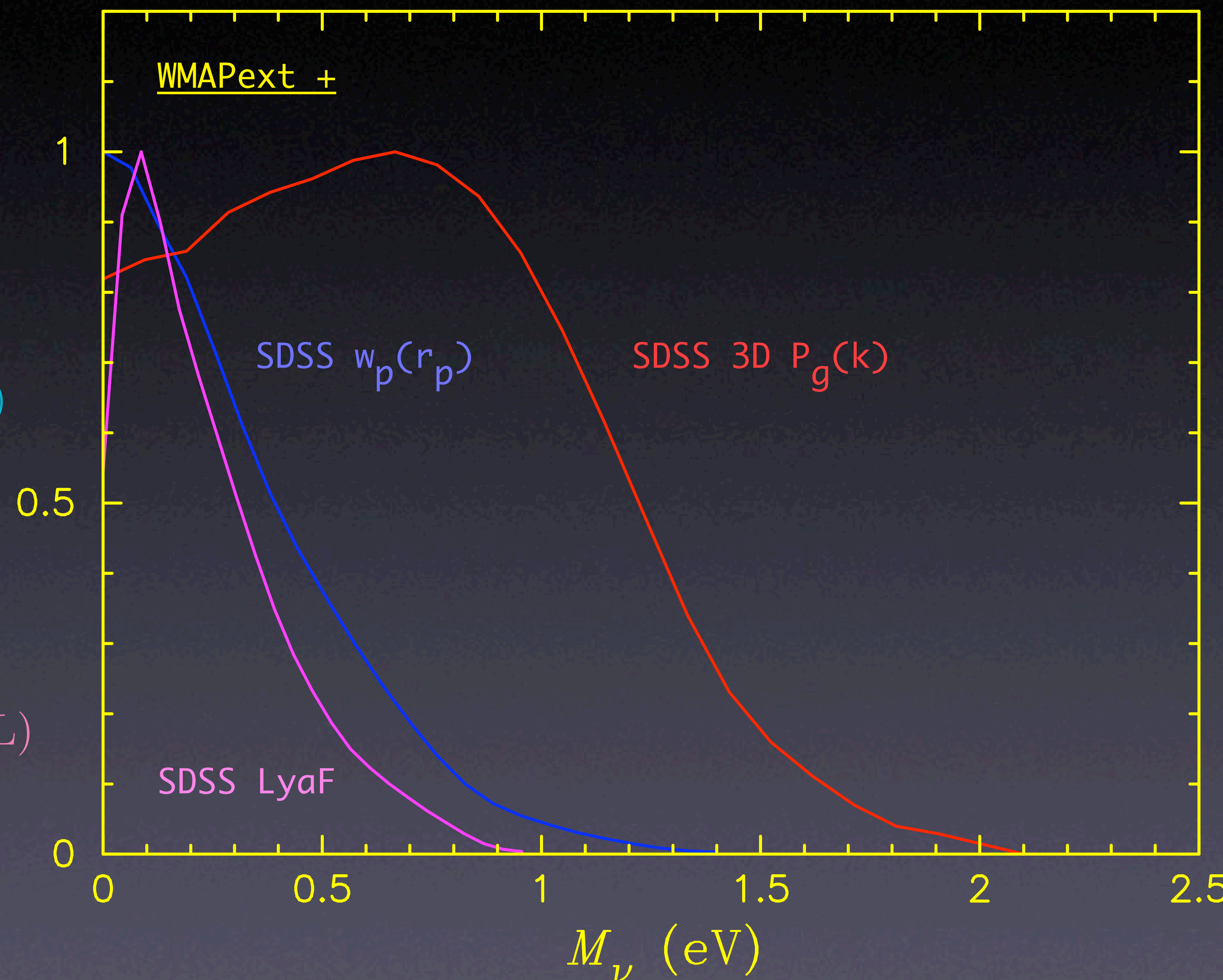
$$\sum m_{\nu_i} \leq 0.80 \text{ eV (95\%CL)}$$

[Abazajian et al 2005]

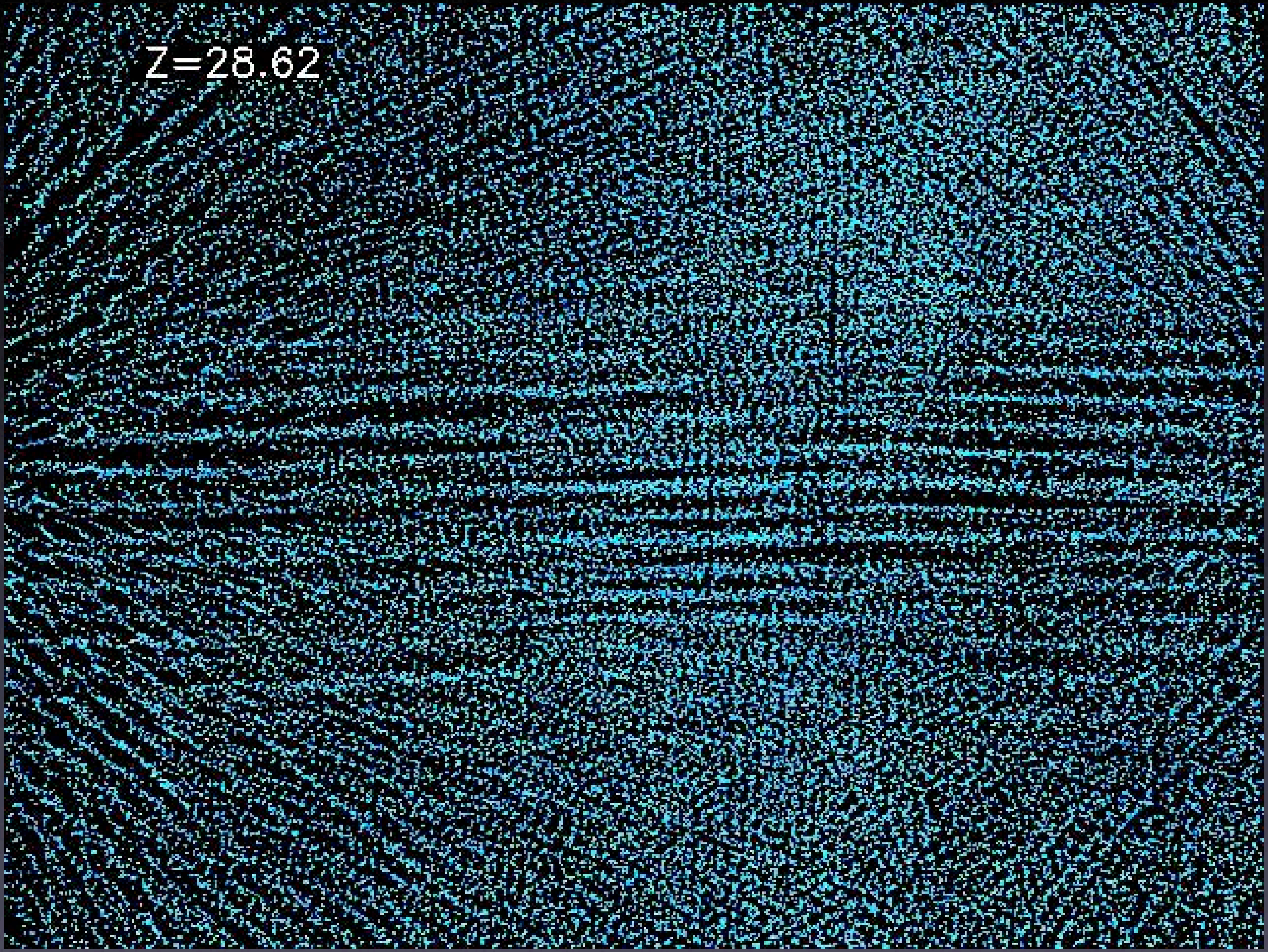
SDSS LyaF:

$$\sum m_{\nu_i} \leq 0.70 \text{ eV (95\%CL)}$$

[McDonald et al 2004]

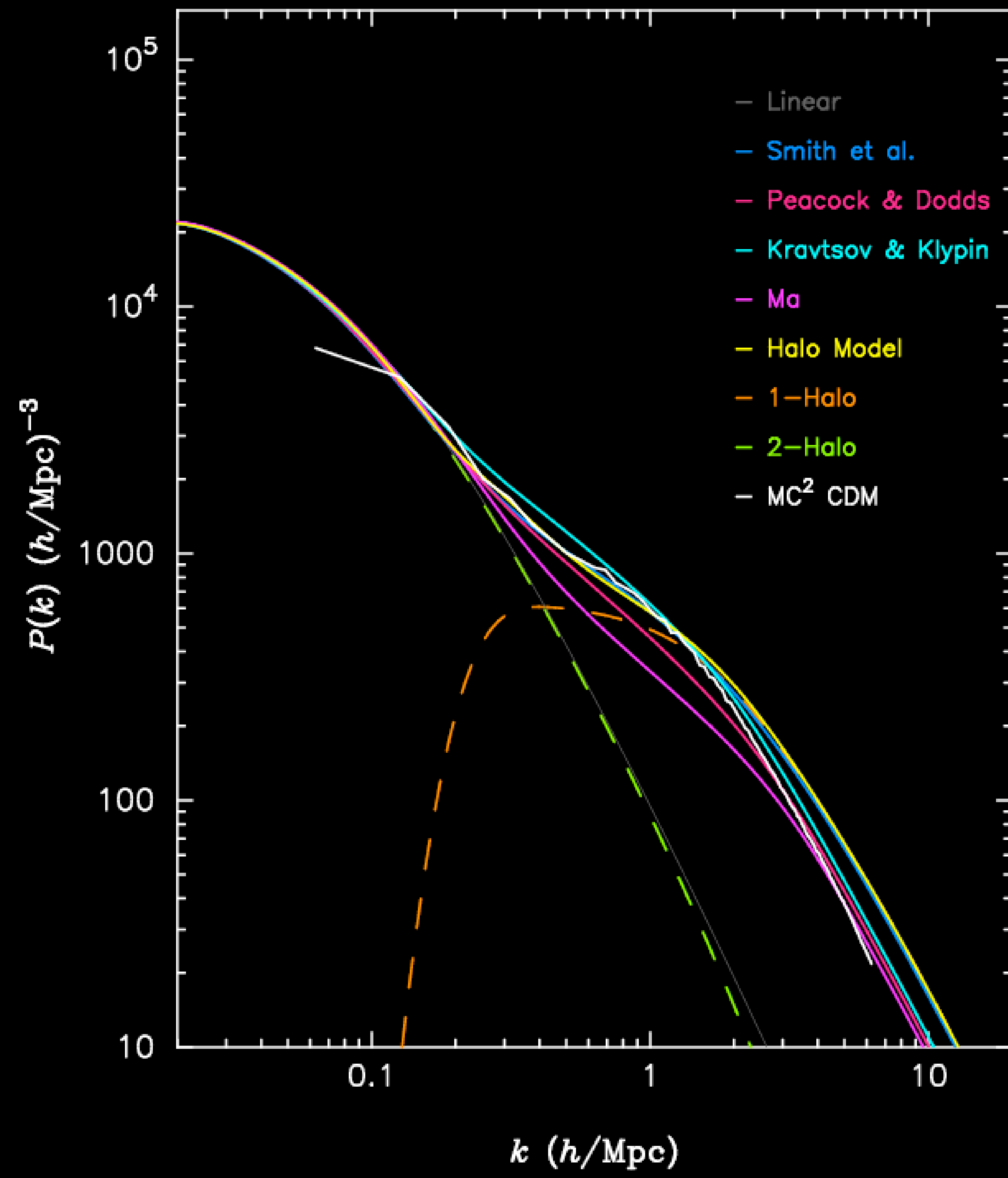


Formation of a Group of Galaxies

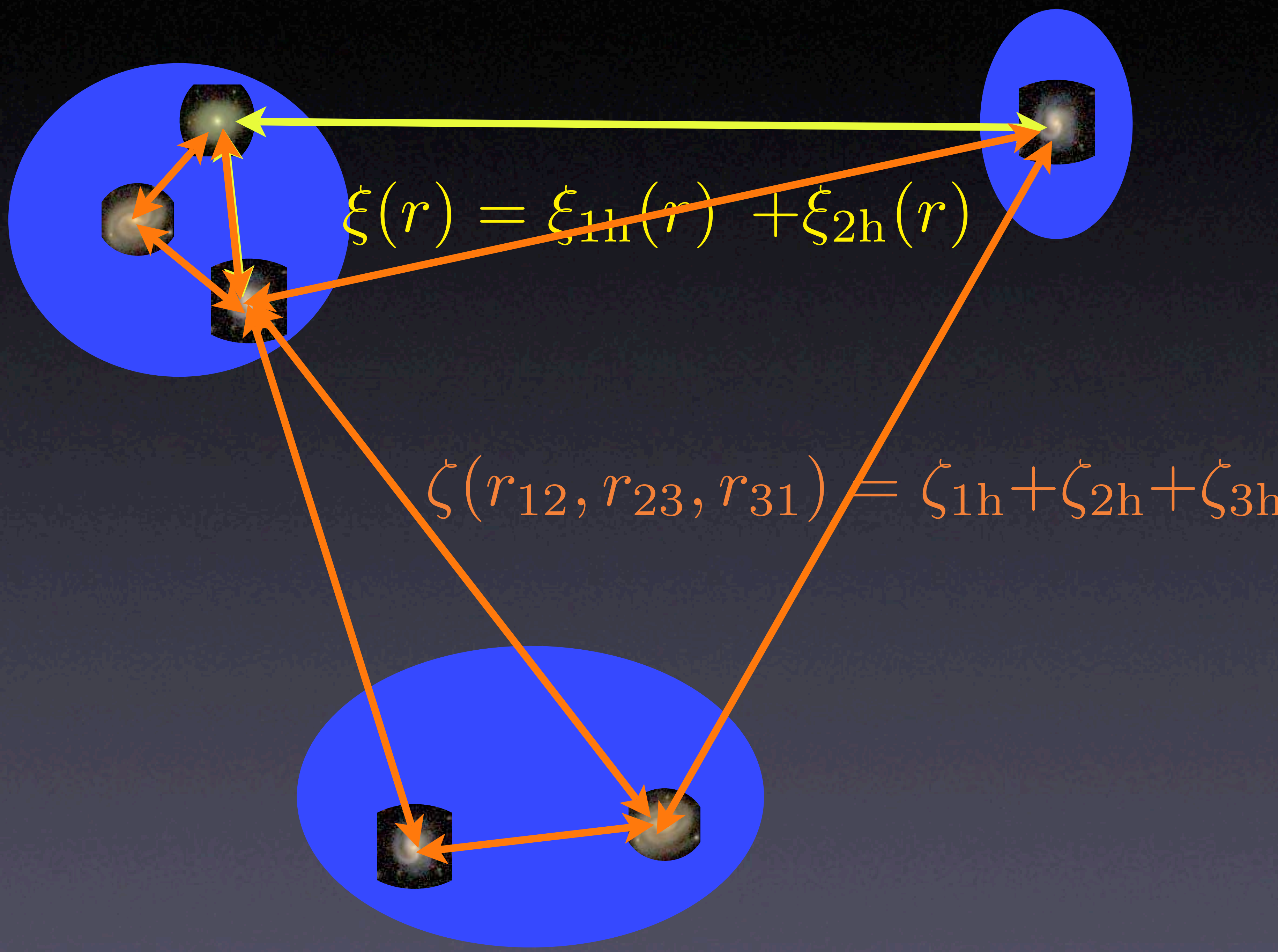


Courtesy Andrey Kravtsov

Nonlinear Structure Formation



The Halo Model in its Simplest Form



Components of the Halo Model

- The halo model will give statistics of the dark matter halo and mass distribution, given
  - The number density of halos of a given mass n(m), i.e., the mass function
    - Warren, Abazajian, Holz & Teodoro, astro-ph/0506395
    - Jenkins, et al 2001 with correction for cosmological variation of Δ_{vir} (Evrard et al, 2002; appendix of Hu & Kravtsov 2002)
  - The density distribution within the halos $\rho(m)$: typically an NFW profile
    - Halo concentration dependence on cosmology (Huffenberger & Seljak 2003)
  - The bias of halos of given mass, b(m): analytically from n(m), plus any scale dependence
    - from high-resolution HOT-code simulations (LANL) (Warren & Seljak 2004)

Simulating Structure Formation:

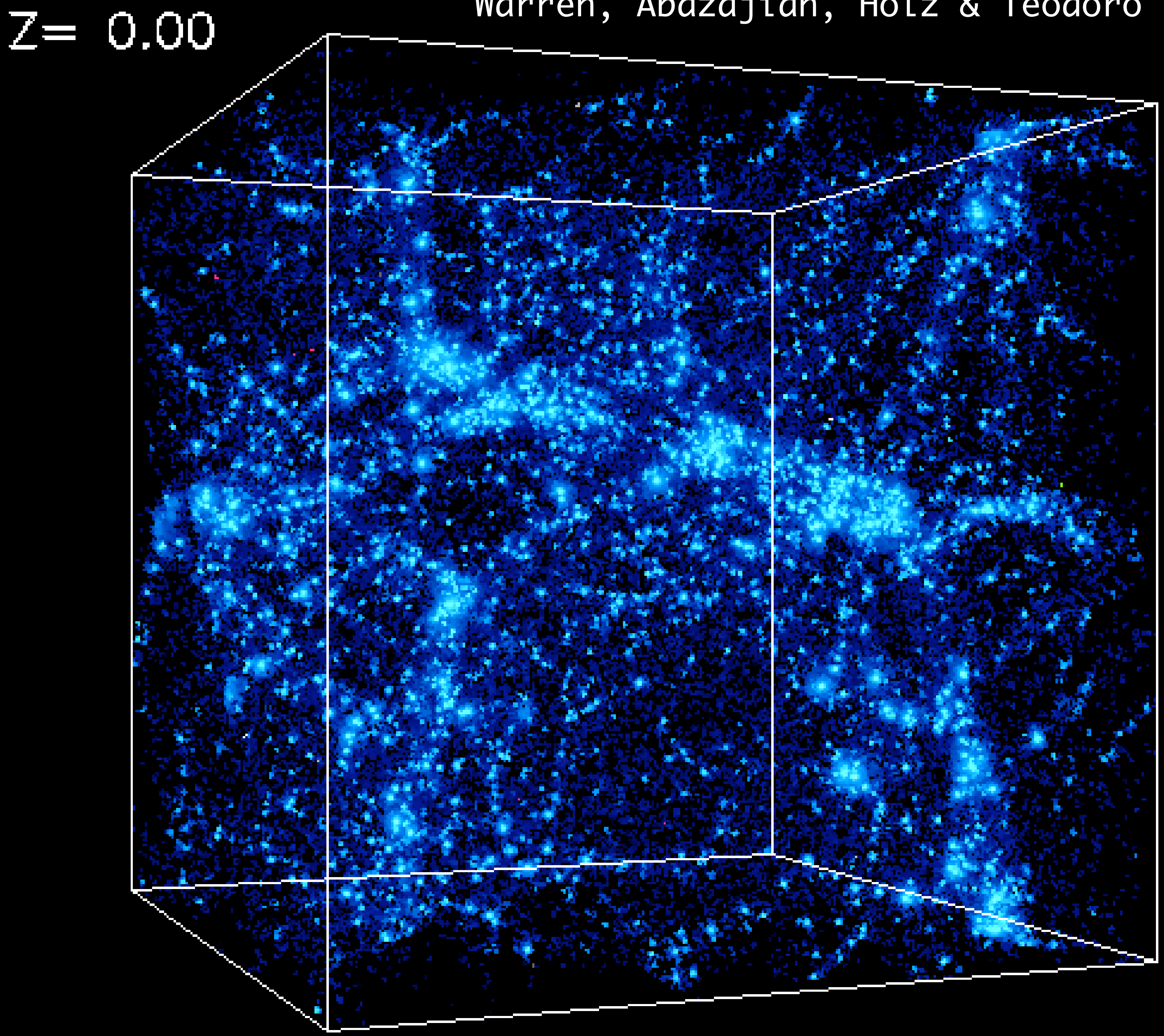
Gravitational N-body Solvers of the DM Vlasov-Poisson Equation

Los Alamos HOT Simulations:

4 Exaflops (4 x 10^{18} flops) of Computation

$$3072\ h^{-1}\mathrm{Mpc}/2.1\ h^{-1}\mathrm{kpc} = 1.5 \times 10^6$$

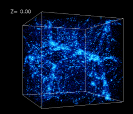
Warren, Abazajian, Holz & Teodoro 2005



Virgo Consortium Millennium Run

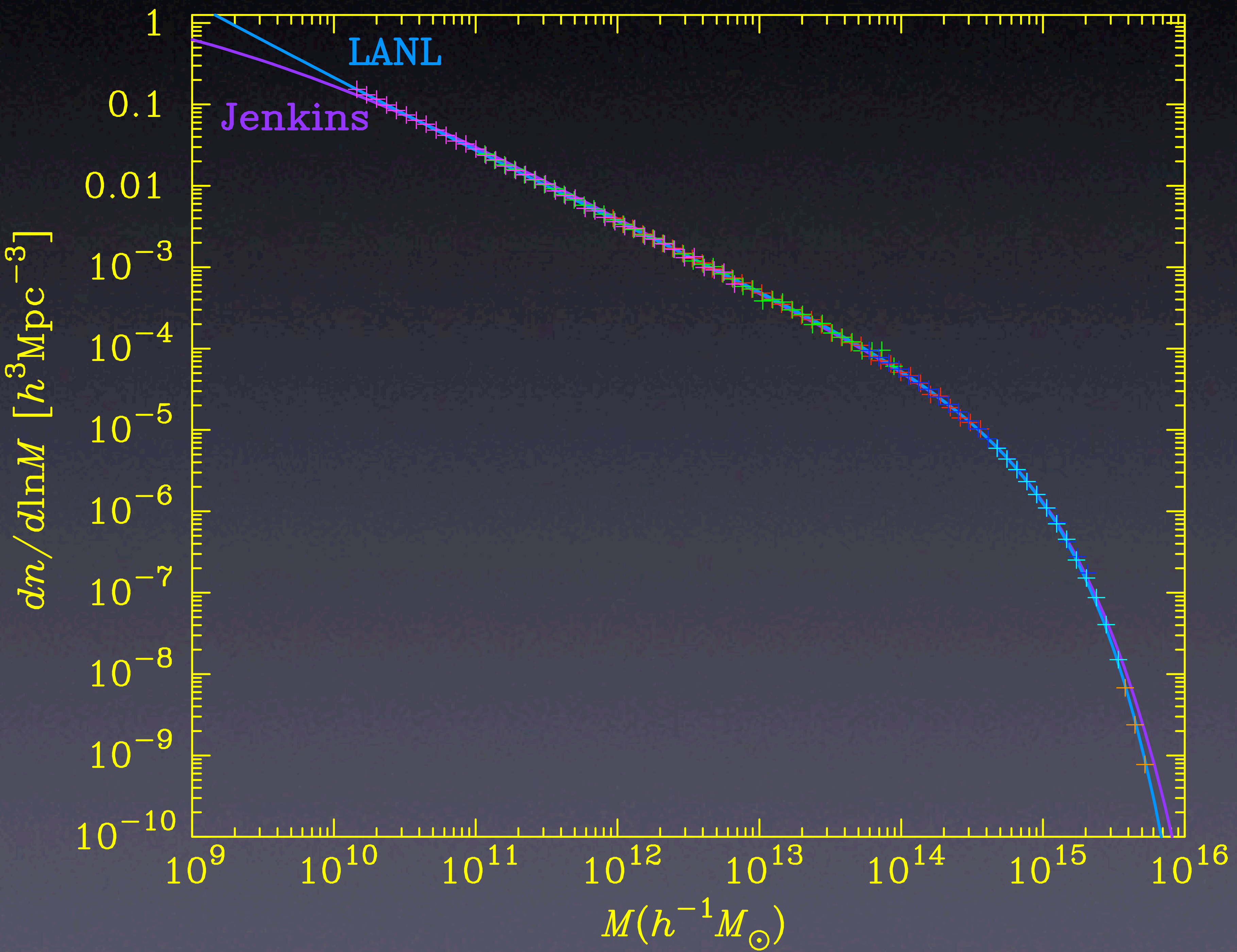
$$500\ h^{-1}\mathrm{Mpc}/5\ h^{-1}\mathrm{kpc} = 10^5$$

Springel et al. 2005

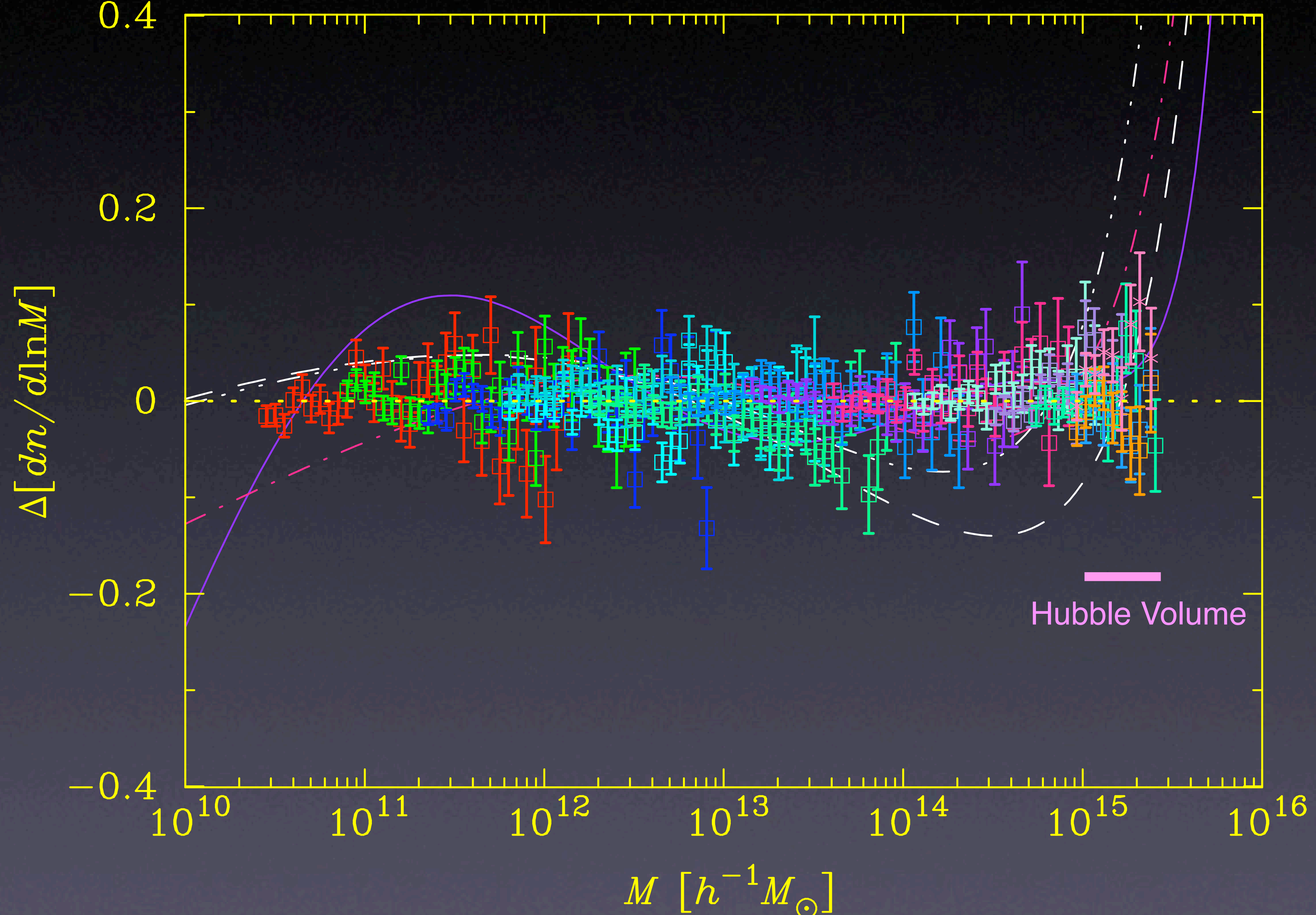


Predictive Mass Function & Uncertainty

Sixteen Nested Simulations:
96, 135, 192, 272, 384, 543, 768, 1086, 1536, 2172, 2583 and 3072 Mpc/h

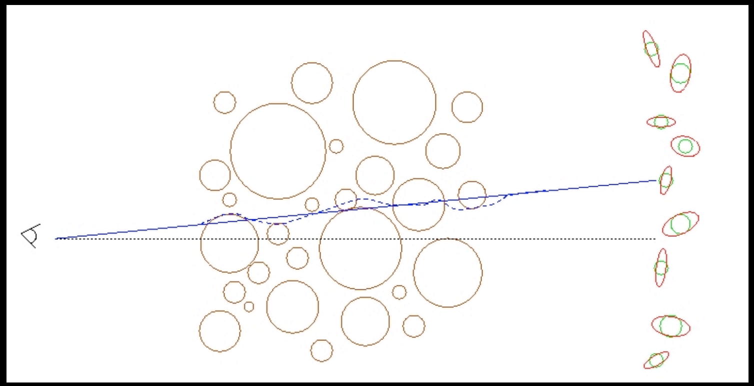


Mass Function Residuals

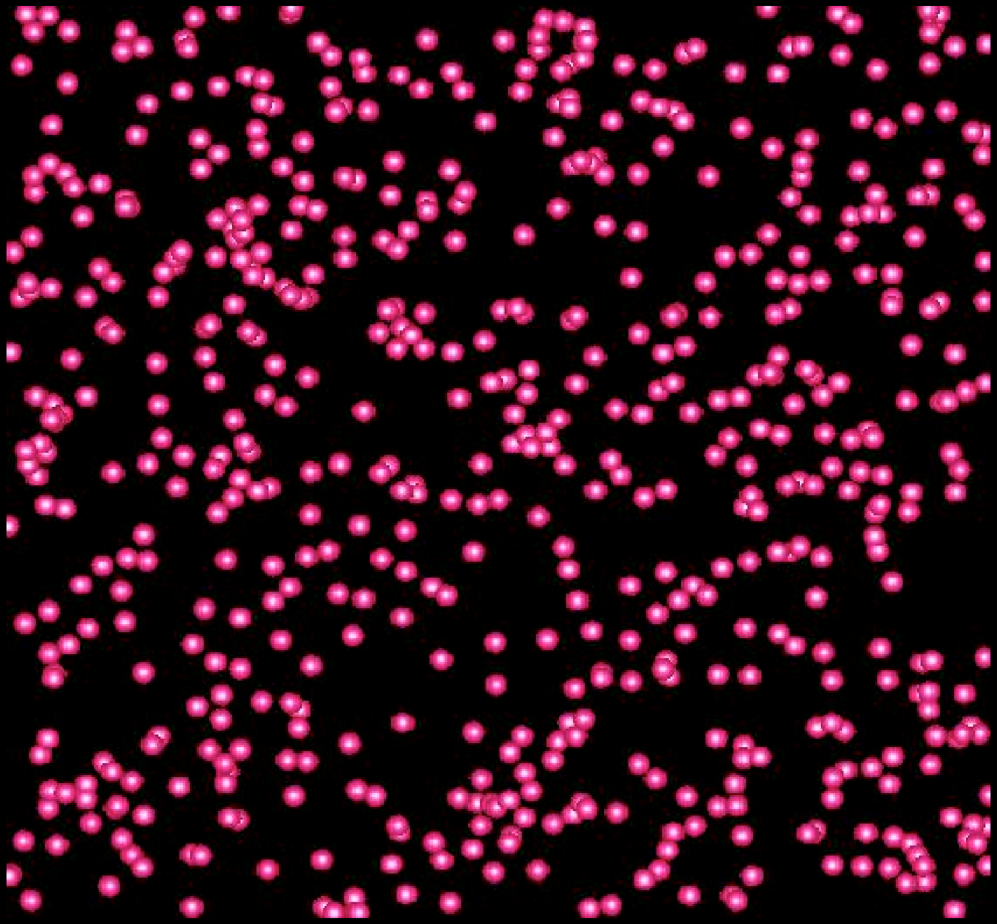


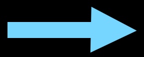
Warren, Abazajian, Holz & Teodoro 2005

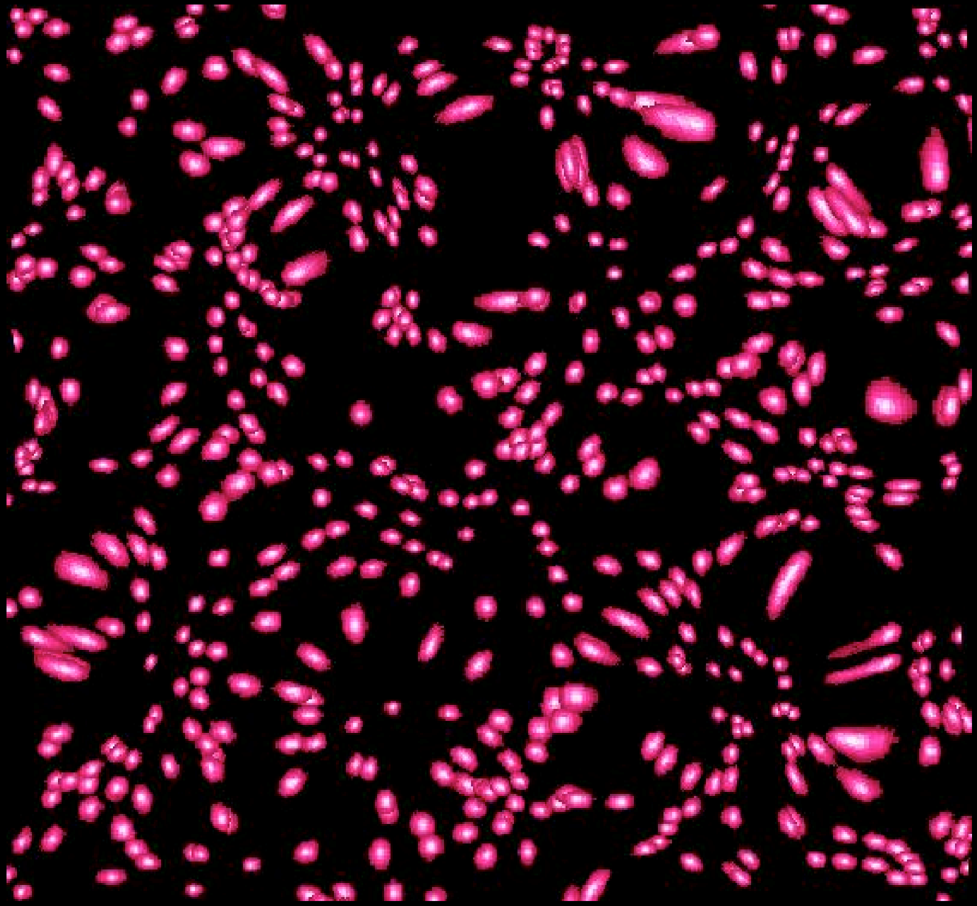
Gravitational Lensing



Distortion of background images by foreground matter





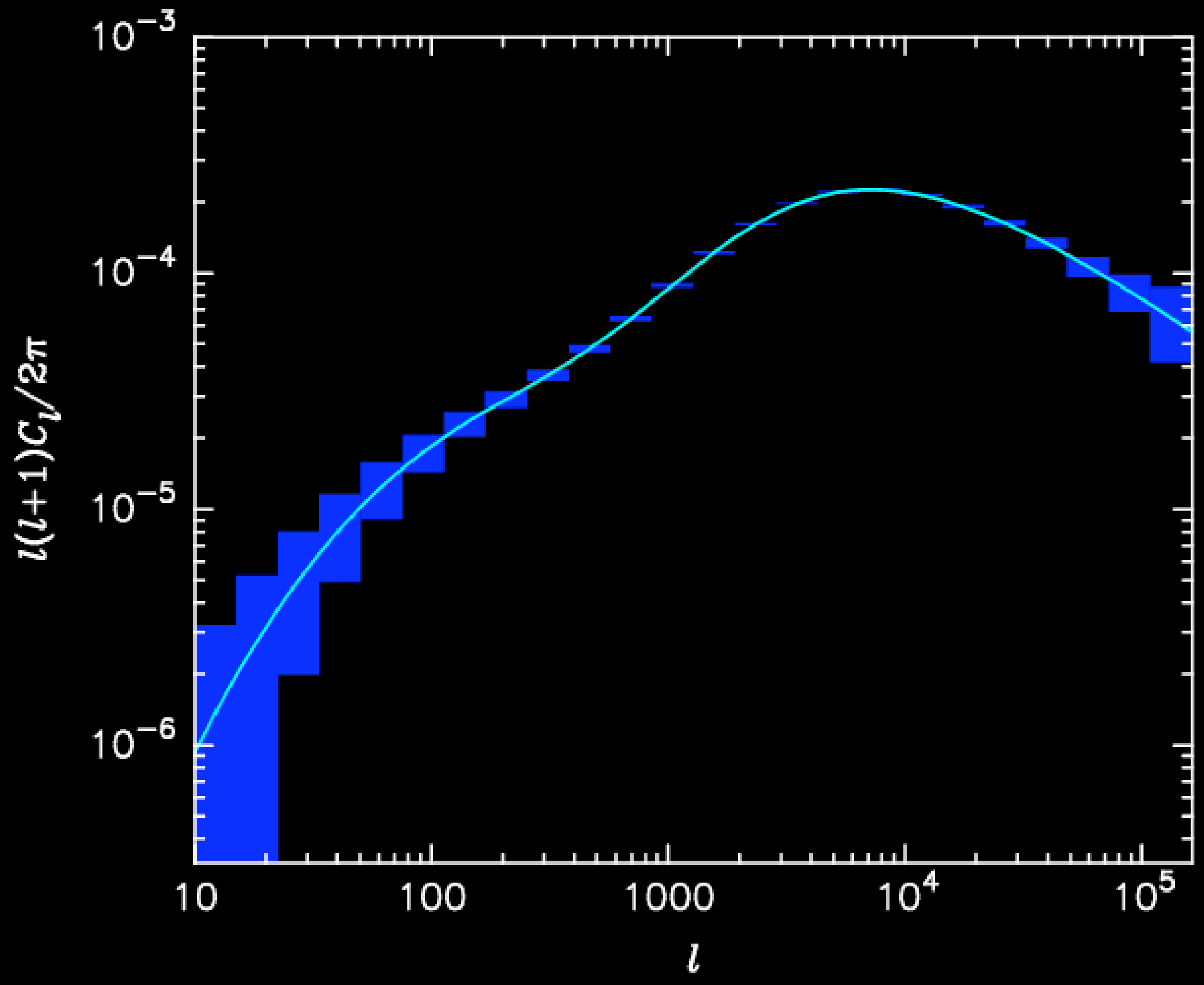


Unlensed **Lensed**

Cosmic Shear

$$C_l = \frac{9}{16}\left(\frac{H_0}{c}\right)^4 \Omega_m^2 \int_0^{\chi_h} d\chi \left[\frac{g(\chi)}{ar(\chi)}\right]^2 P\left(\frac{l}{r}, \chi\right)$$

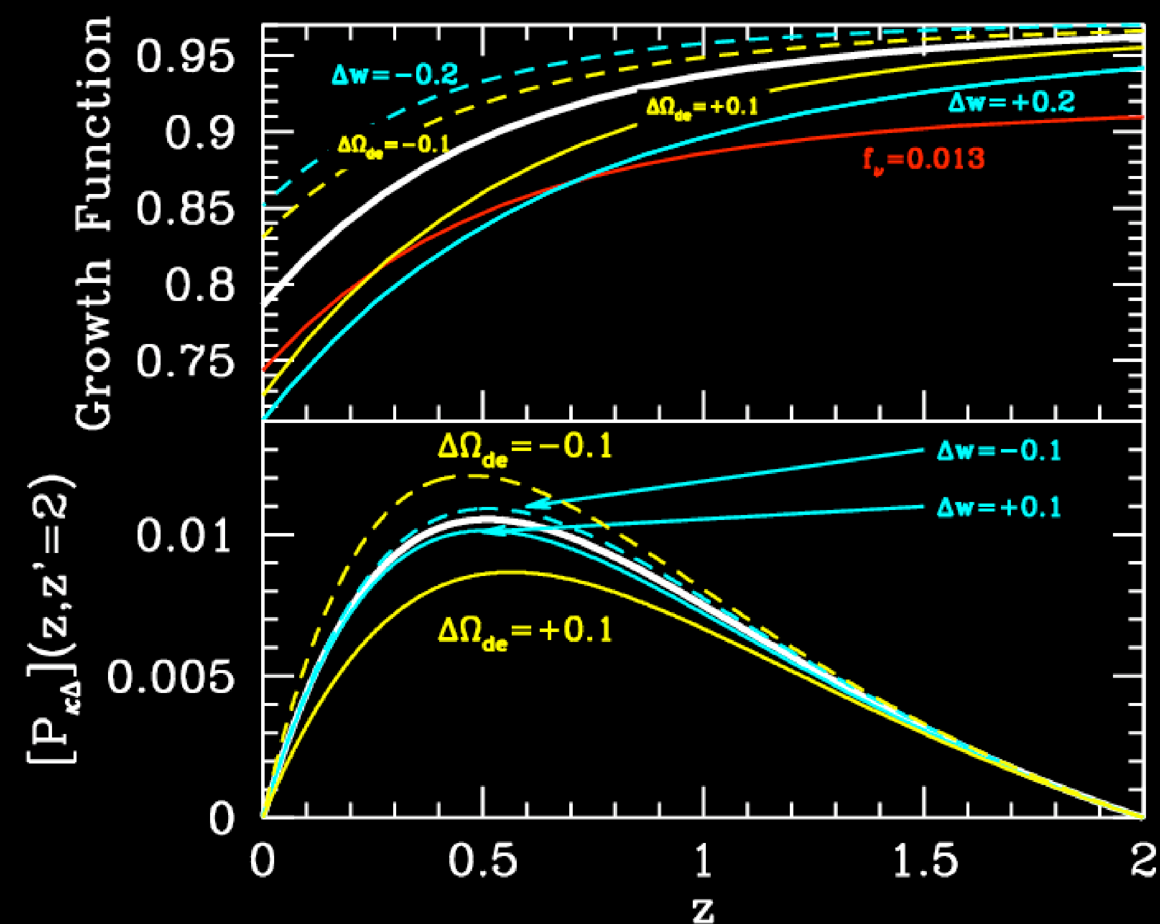
$$P(k, z)$$

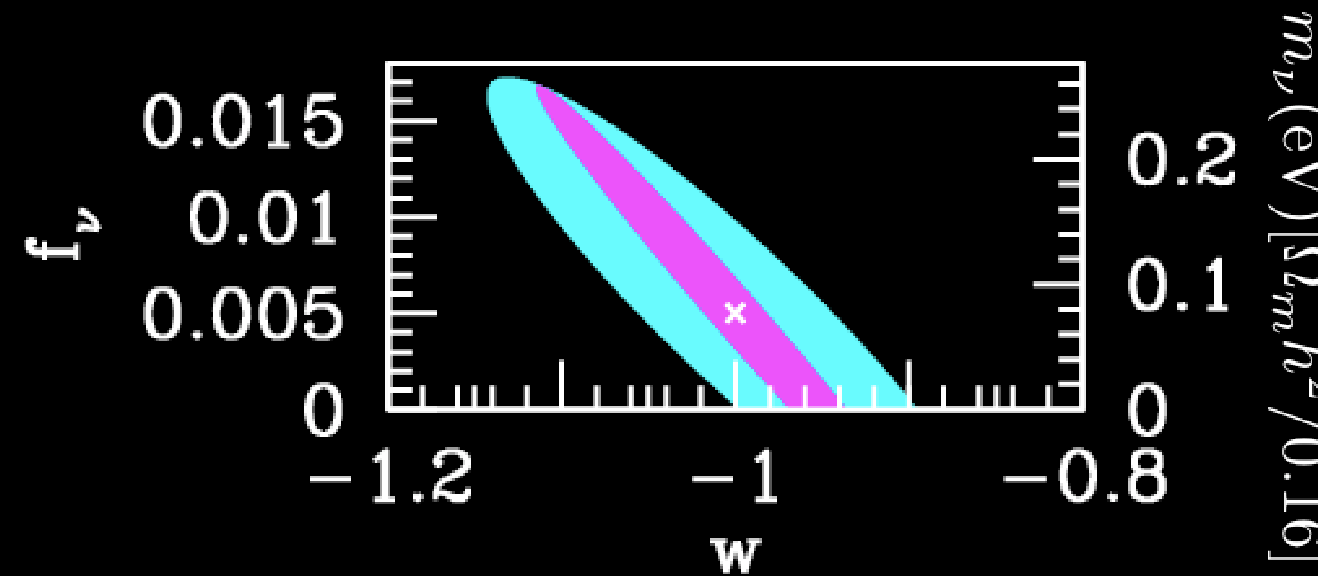


[SNAP Projected],
Refregier et al 2003

$$g(\chi) = \chi \int_\chi^\infty d\chi'\, n(\chi') \frac{\chi' - \chi}{\chi'},$$

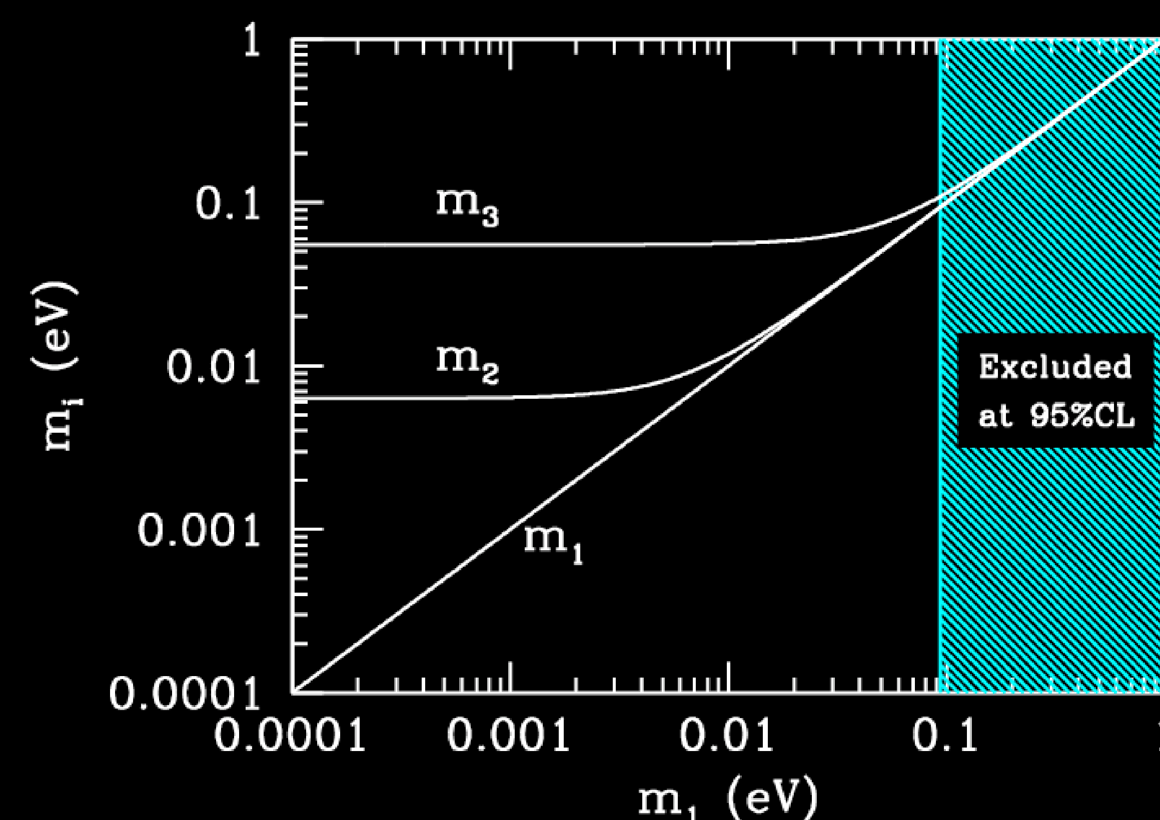
Projected errors for Weak Lensing (Linear Regime)





- Using tomographic information in the radial for a 4000 deg^2 survey with 100 gal/arcmin^2 LSST-like galaxy densities
- Dependence on linear power spectrum only

(Abazajian & Dodelson 2003)



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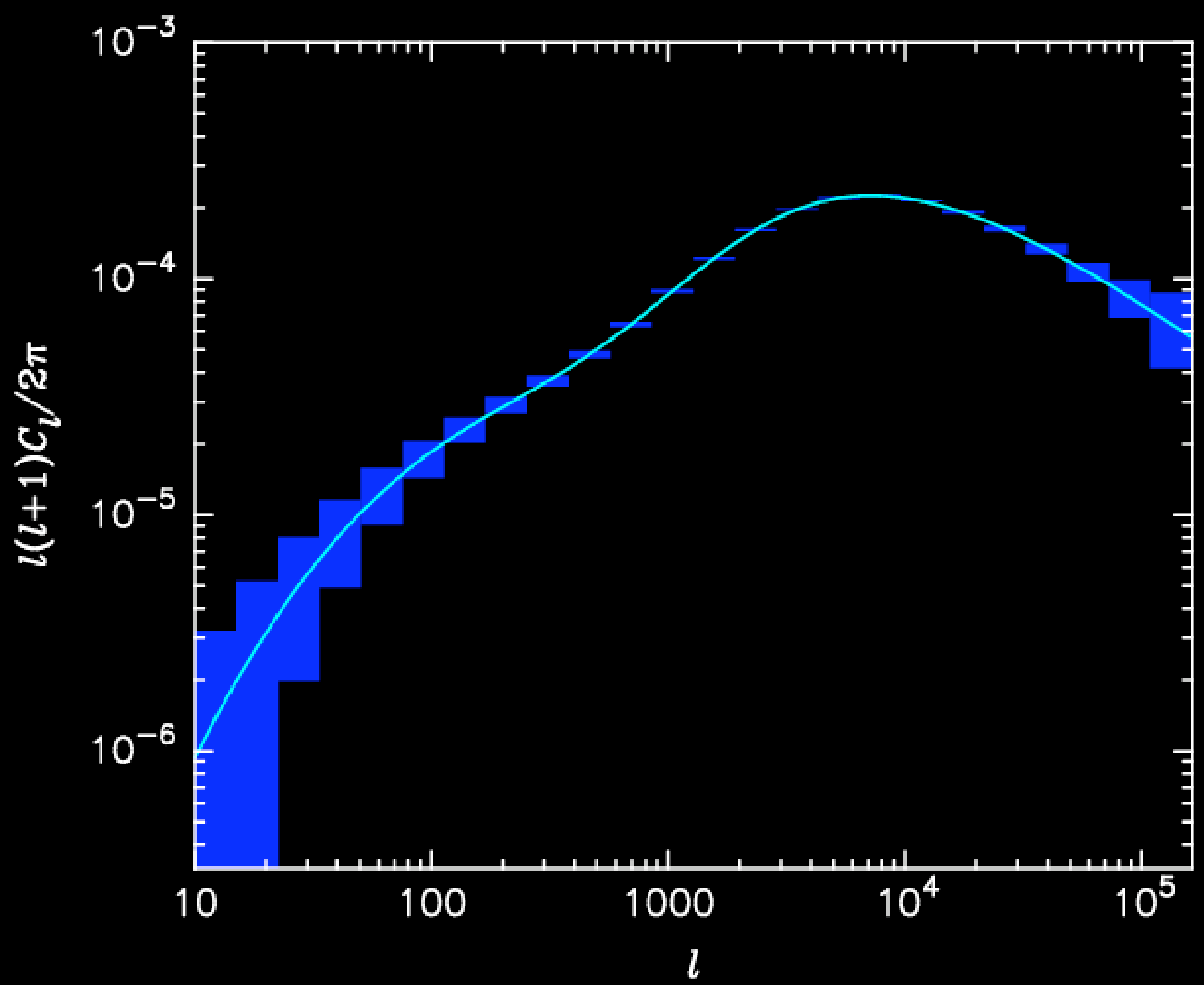

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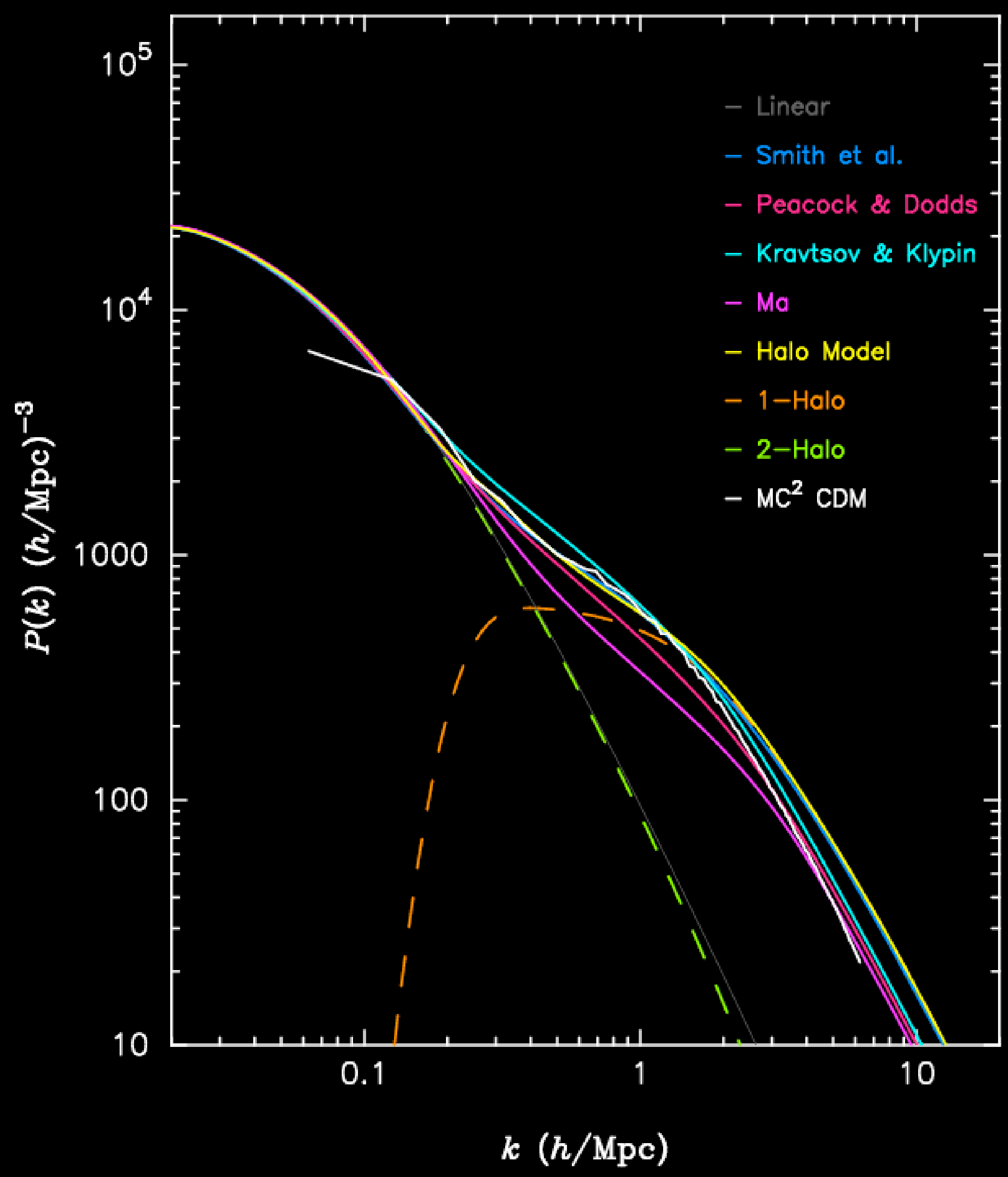
Nonlinear P(k)



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    - from high-resolution HOT-code simulations (LANL) (Warren & Seljak 2004)

2-point statistics in the halo model

- The correlation function

$$\xi(r) = 1 + \xi^{1h}(r) + \xi^{2h}(r)$$

$$1 + \xi^{1h}(r) = \frac{1}{2}\bar{\rho}^{-2} \int dm\, n(m)\, \lambda(r|m)$$

$$\xi^{2h}(r) = \xi^{lin}(r)\bar{\rho}^{-2} \int dm_1\, n(m_1)\, b(m_1) \int dm_2\, n(m_2)\, b(m_2)\lambda(r|m_1, m_2)$$

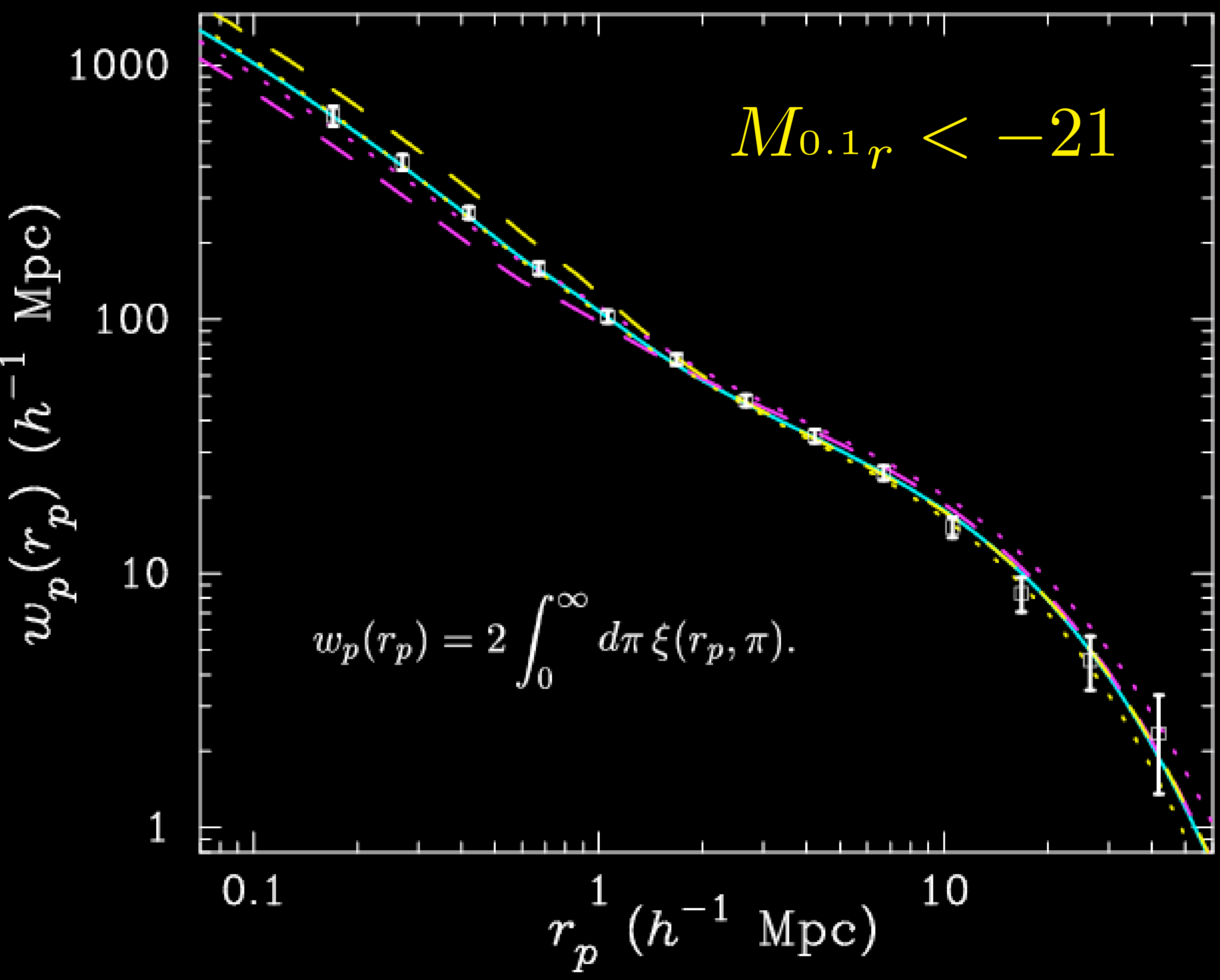
- The power spectrum

$$P(k) = P^{1h}(k) + P^{2h}(k)$$

$$P^{1h}(k) = \int dm\; n(m) \left(\frac{m}{\bar{\rho}}\right)^2 |u(k|m)|^2$$

$$P^{2h}(k) = P_{lin}(k) \left[\int dm\, n(m)\, b(m) \left(\frac{m}{\bar{\rho}}\right) u(k|m)\right]^2$$

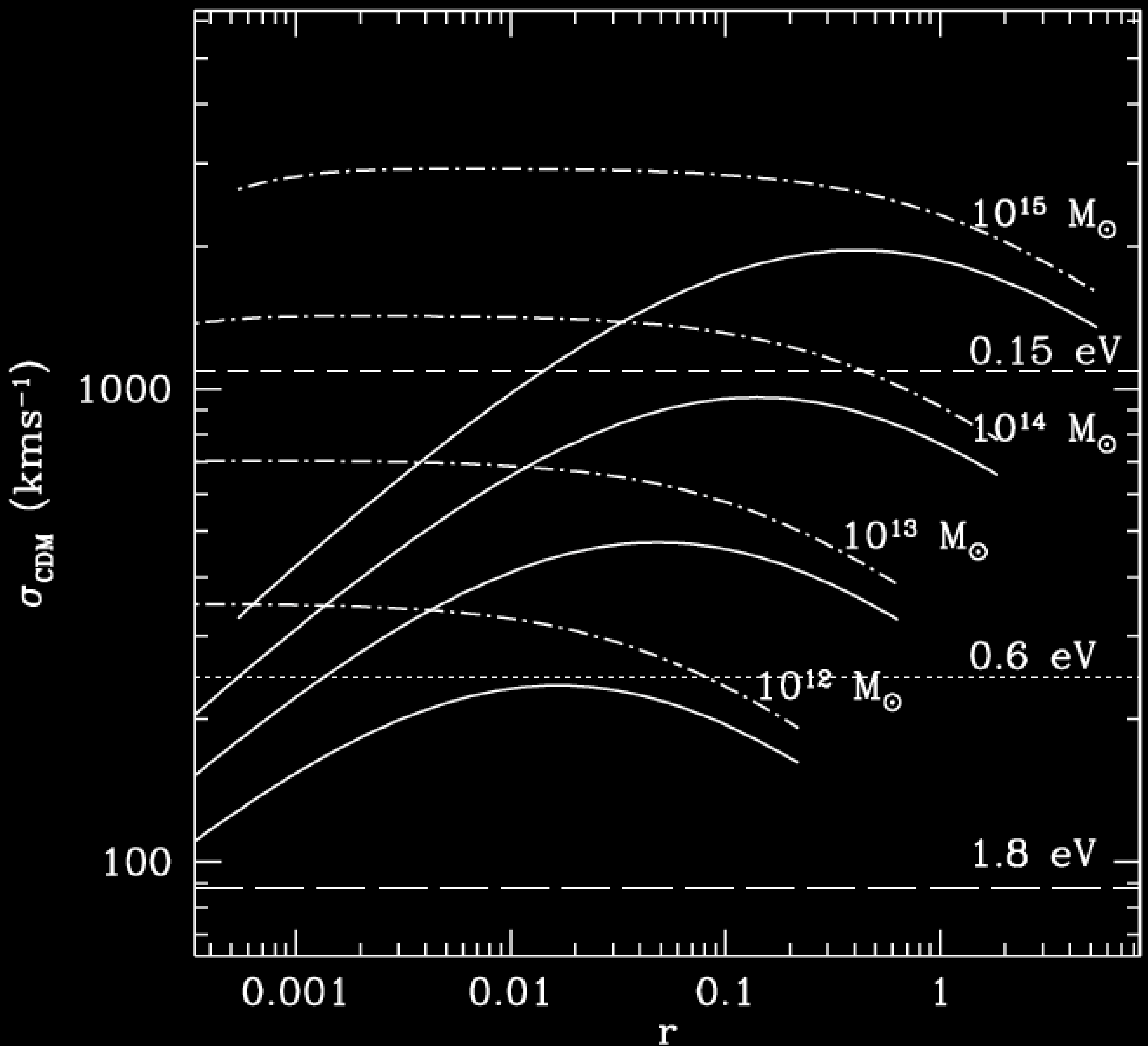
The Measured Galaxy Two-point correlation function - 2005



Measurement:
Zehavi et al., 2005

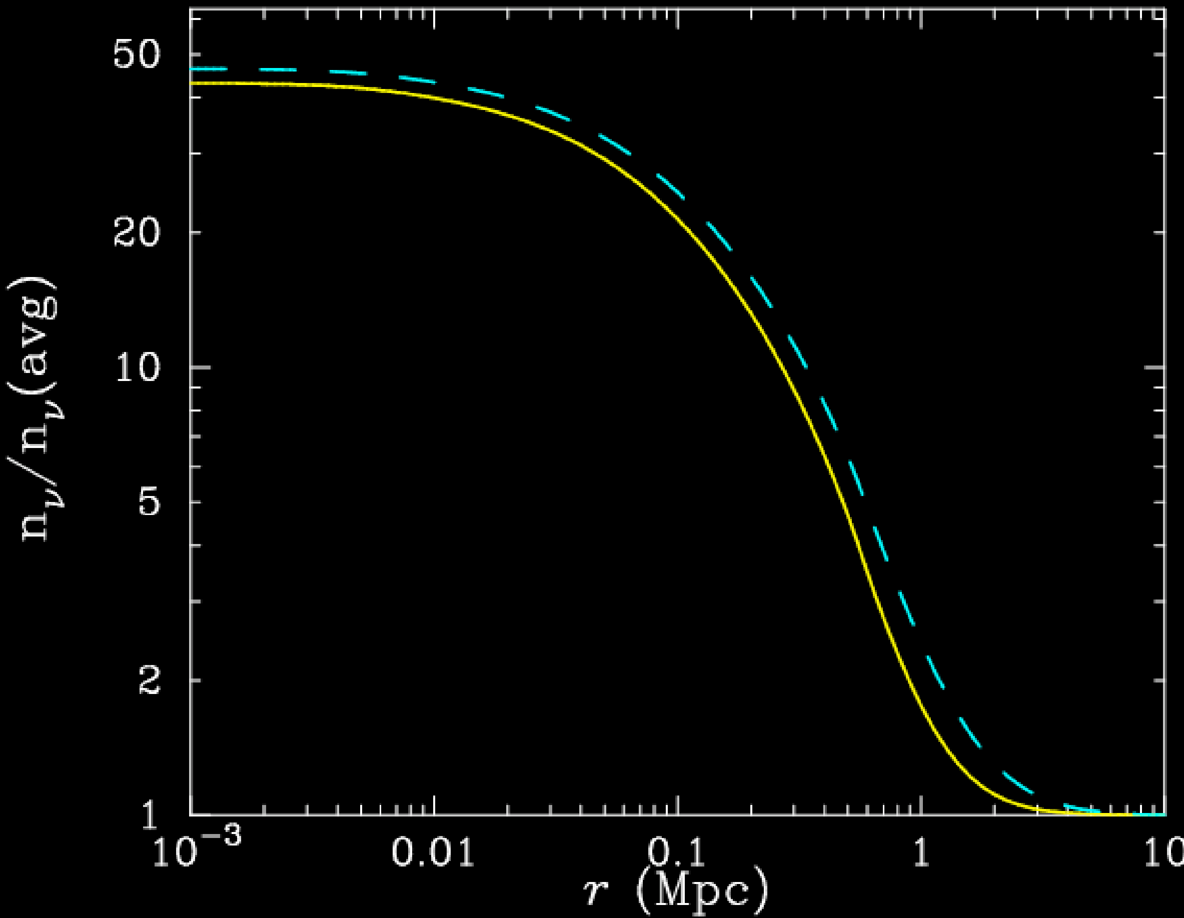
Cosmology:
Abazajian et al 2005

Neutrino Infall into CDM Halos



Singh & Ma 2003

Neutrino Infall into CDM Halos - Boltzmann Solution



$$\frac{\partial f}{\partial t} + \dot{\boldsymbol{r}} \cdot \nabla_r f + \dot{\boldsymbol{p}} \cdot \nabla_p f = 0.$$

$$f(\boldsymbol{x}, \boldsymbol{q}, \tau) = f_0(q) + f_1(\boldsymbol{x}, \boldsymbol{q}, \tau)$$

[Neutrino clustering around cosmic strings]
Brandenburger, Kaiser & Turok (1987)

[CDM Halos for UHECR]
Singh & Ma 2003

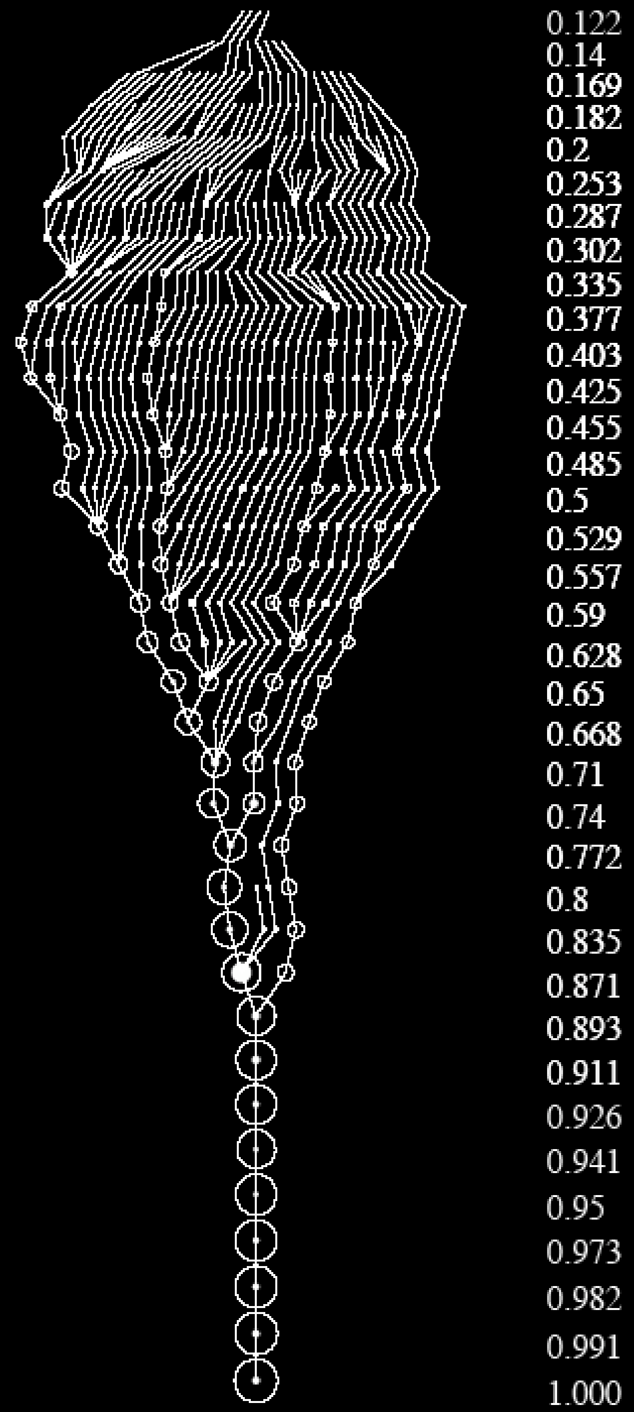
$$\frac{\partial \tilde{f}_1}{\partial \eta} + \frac{i\boldsymbol{k}\cdot\boldsymbol{q}}{m_\nu}\tilde{f}_1 + \frac{i m_\nu}{k^2} 4\pi G a^4 \tilde{\rho}\, \boldsymbol{k}\cdot\nabla_q f_0 = 0\,,$$

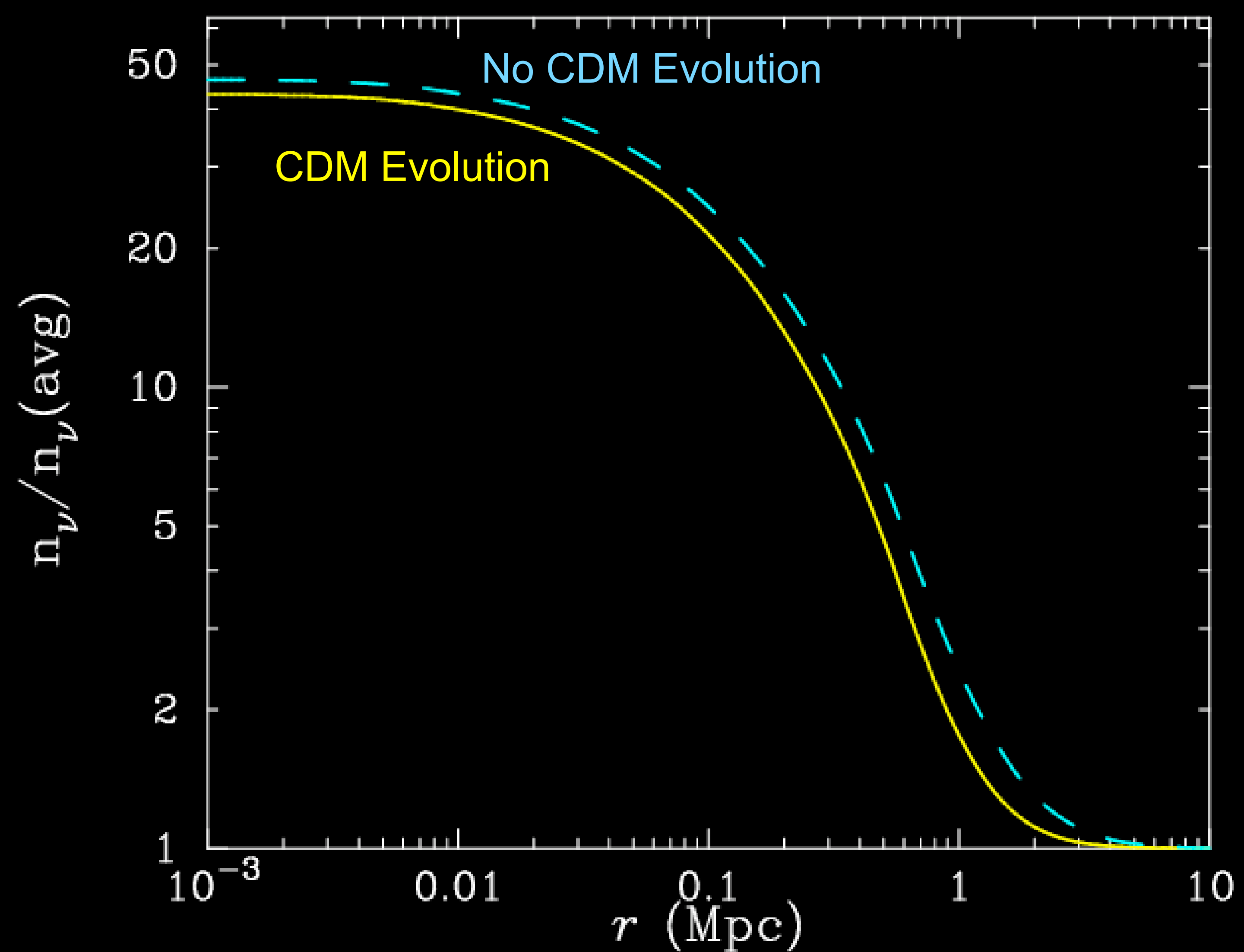
Volterra Equation of the second kind

$$\tilde{\rho}_\nu(k,\vartheta) = \frac{4G m_\nu^2 T_{\nu,0}^2}{\pi k a^3(\vartheta)} \int_{\vartheta(z=3)}^{\vartheta} d\vartheta' a^4(\vartheta')(\tilde{\rho}_{CDM}(k,\vartheta') + \tilde{\rho}_\nu(k,\vartheta')) I\left(\frac{k(\vartheta-\vartheta')T_{\nu,0}}{m_\nu}\right)$$

Abazajian, Switzer, Heitmann & Habib, 2005

CDM Halo Assembly History



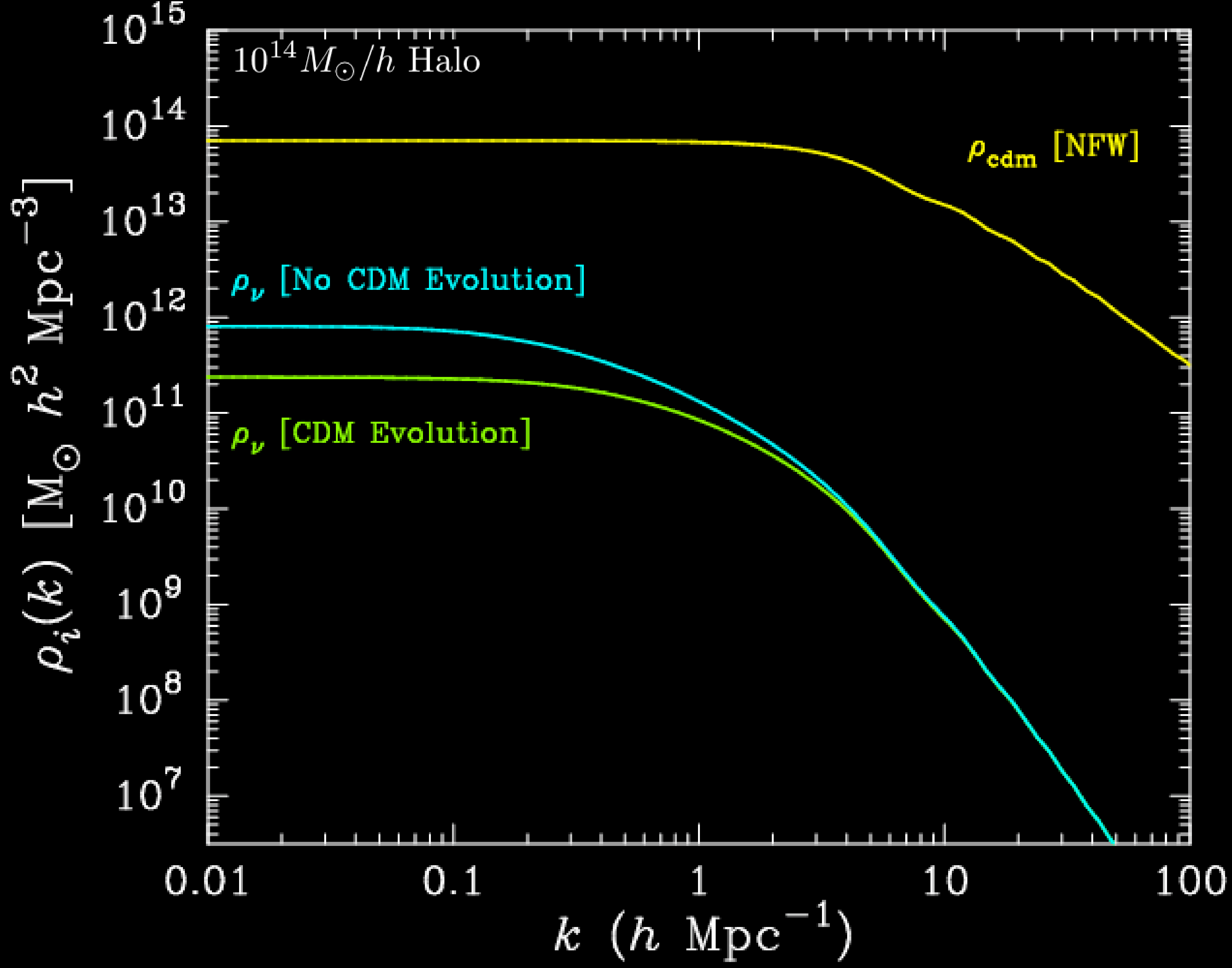


$$M(a_c) = M_0 e^{-2a_c z}$$

$$M_*(a_c) \approx 0.018M$$

Wechsler et al 2002

Moving to Fourier Space $\rho_\nu(k)$



Abazajian, Switzer, Heitmann & Habib, 2005

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$$\xi^{2\mathrm{h}}(r) = \xi^{\mathrm{lin}}(r)\bar{\rho}^{-2} \int dm_1\, n(m_1)\, b(m_1) \int dm_2\, n(m_2)\, b(m_2)\lambda(r|m_1, m_2)$$

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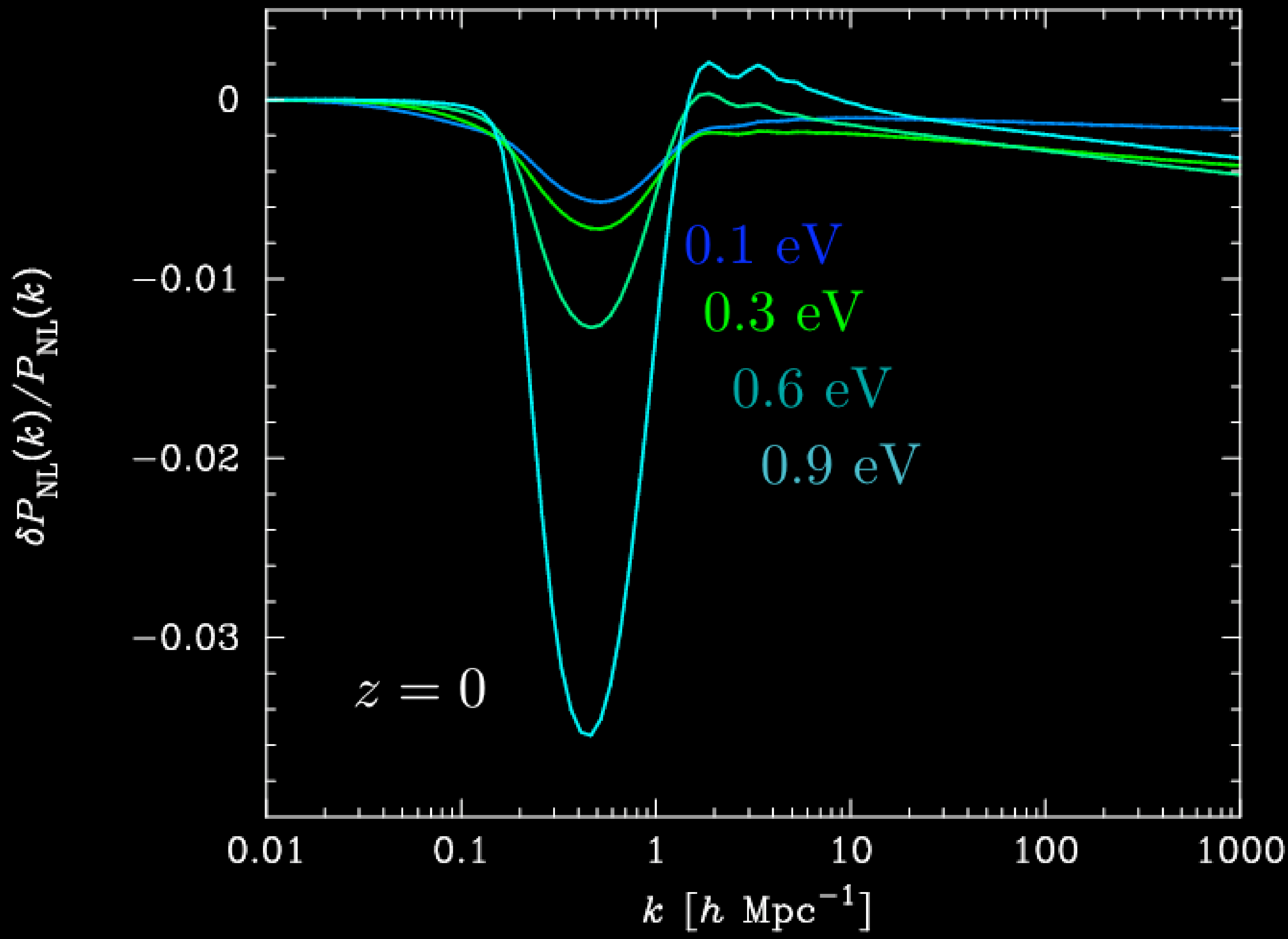
$$P^{2\mathrm{h}}(k) = P_{\mathrm{lin}}(k) \left[\int dm\, n(m)\, b(m) \left(\frac{m}{\bar{\rho}}\right) u(k|m)\right]^2$$

Halo Model Modification with Neutrinos

$$P_{1h}^{\mathrm{CDM}+\nu}(k) = \int d\mu \frac{f(\mu)}{\bar{\rho}(M_{\mathrm{CDM}}(\mu) + M_\nu(\mu))} \left[\tilde{\rho}_{\mathrm{CDM}}(k,\mu) + \tilde{\rho}_\nu(k,\mu)\right]^2$$

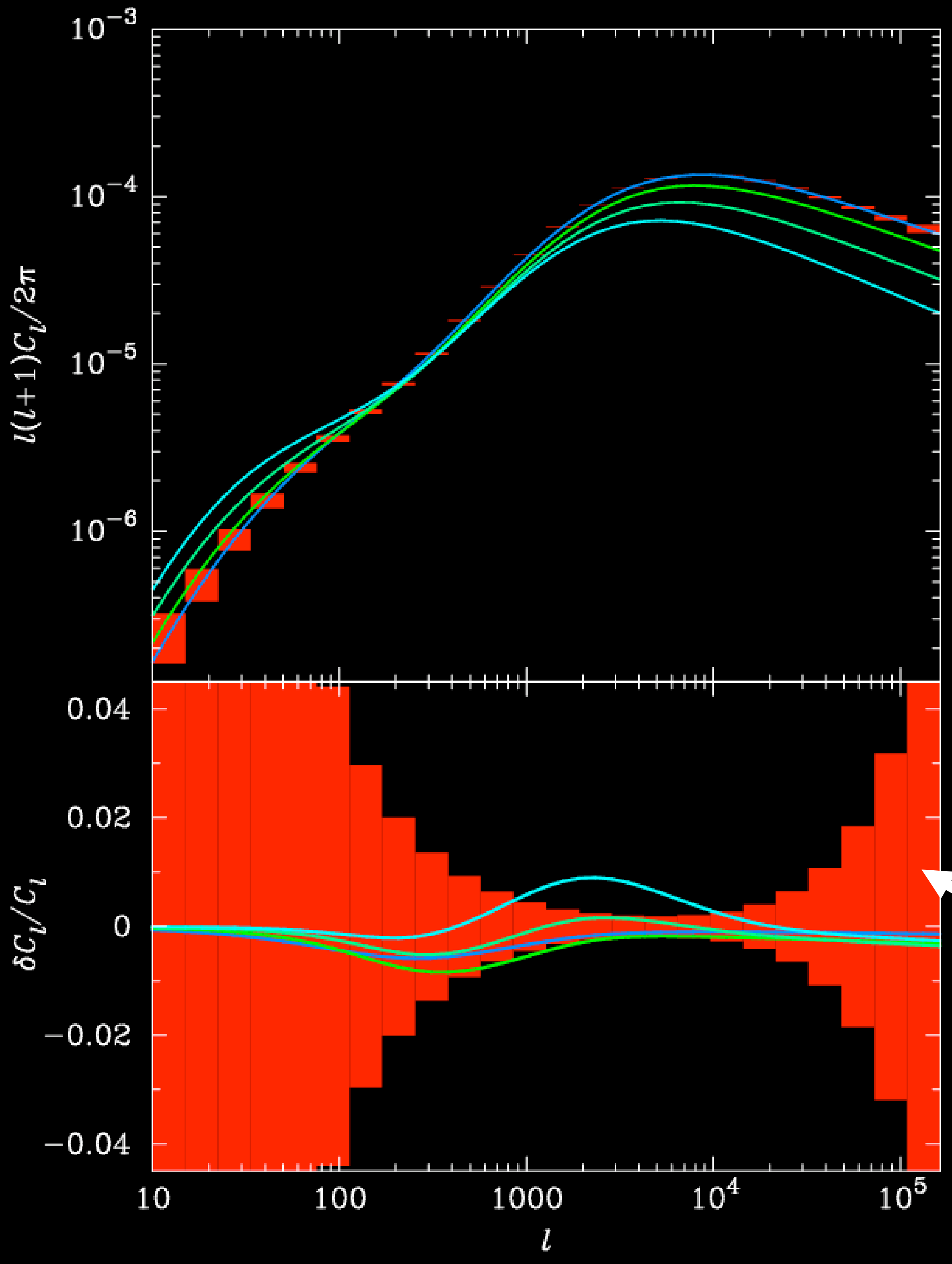
$$P_{2h}^{\mathrm{CDM}+\nu}(k) = P_{\mathrm{lin}}^{\mathrm{CDM}+\nu}(k) \left[\int d\mu \frac{f(\mu)b(\mu)}{\bar{\rho}(M_{\mathrm{CDM}}(\mu) + M_\nu(\mu))} \left[\tilde{\rho}_{\mathrm{CDM}}(k,\mu) + \tilde{\rho}_\nu(k,\mu)\right]\right]^2$$

Deviation of Power Spectrum from the Halo Profile



Abazajian, Switzer, Heitmann & Habib, 2005

Alteration of the Weak Lensing Signal



0.1 eV
0.3 eV
0.6 eV
0.9 eV

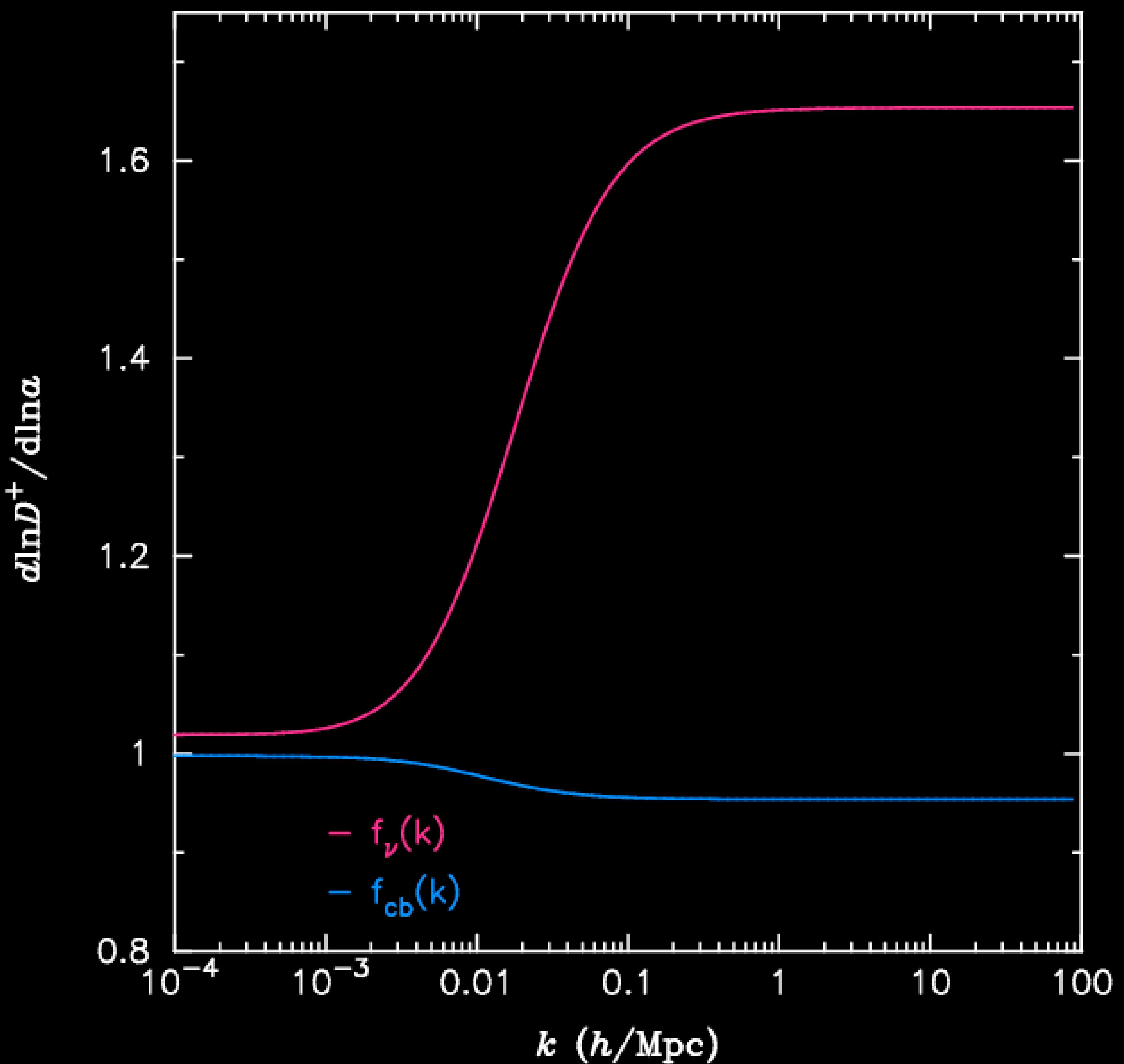
$$\Delta C_\ell = \sqrt{\frac{2}{(2\ell+1)f_{\rm sky}}}\left(C_\ell + \frac{\gamma_{\rm rms}^2}{\bar{n}_{\rm gal}}\right)$$

Errors for LSST-like survey

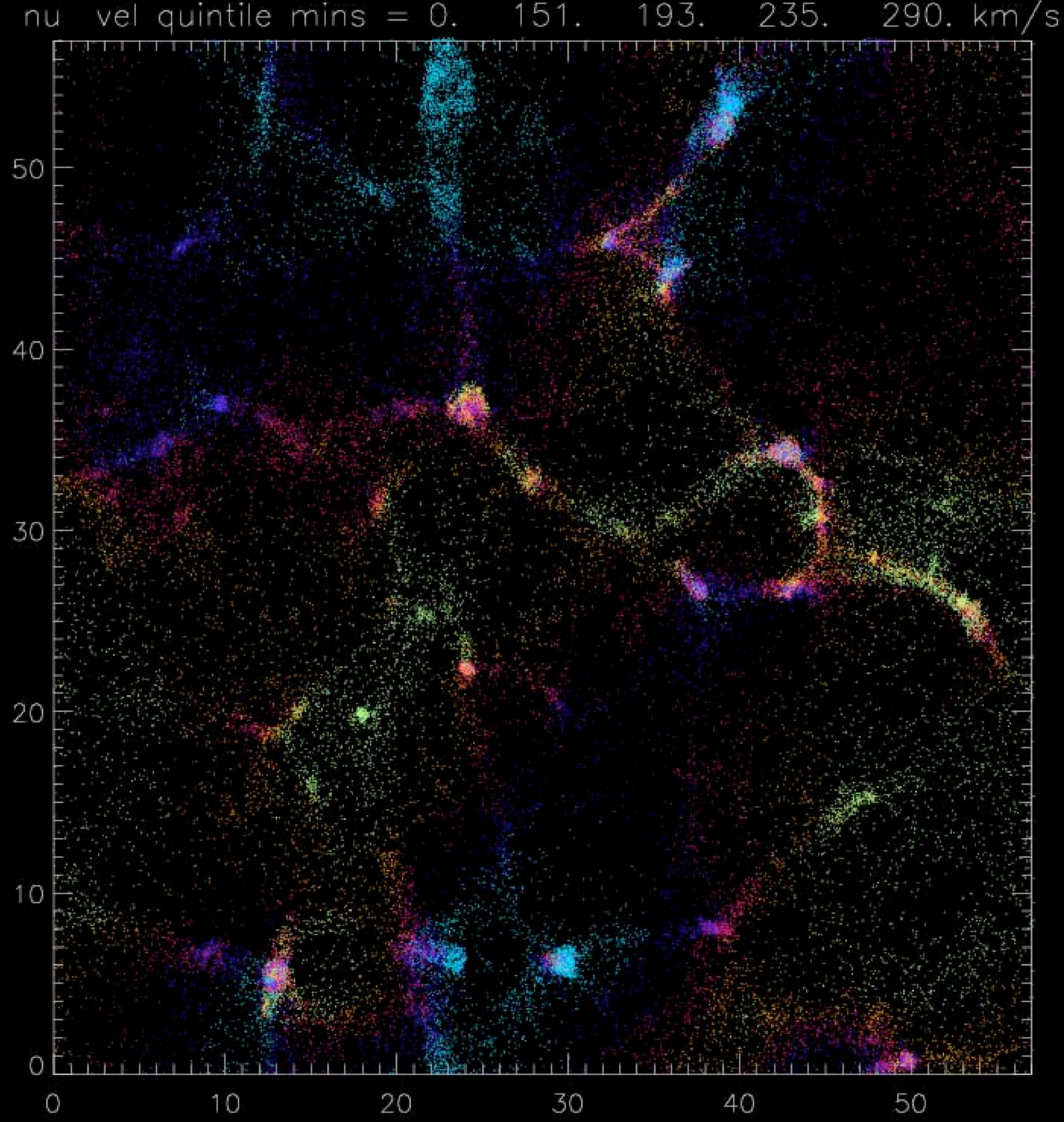
Abazajian, Switzer, Heitmann & Habib, 2005

Numerical Simulations

- Initial conditions for neutrino dark matter with Fermi-Dirac distribution of velocities
- Scale dependent growth function for CDM and neutrinos for initial Zeldovich step
- Pair-wise positioning neutrino velocities to avoid large scale accidental flows



Abazajian, Switzer, Heitmann & Habib, 2005


nu vel quintile mins = 0. 151. 193. 235. 290. km/s
0
10
20
30
40
50
0
10
20
30
40
50

Conclusions

- Cosmological Large Scale Structure is, and will remain to be (in the foreseeable future), the best probe of absolute neutrino mass
- Weak lensing promises to measure the shape of the linear & nonlinear power spectrum to high precision
- Theoretical understanding of CDM clustering & clustering of massive neutrinos is crucial in confidently limiting or detecting the presence of the massive relic neutrinos
- We study neutrino clustering using analytic and numerical methods as cross-reference