Neutrino and Cosmology

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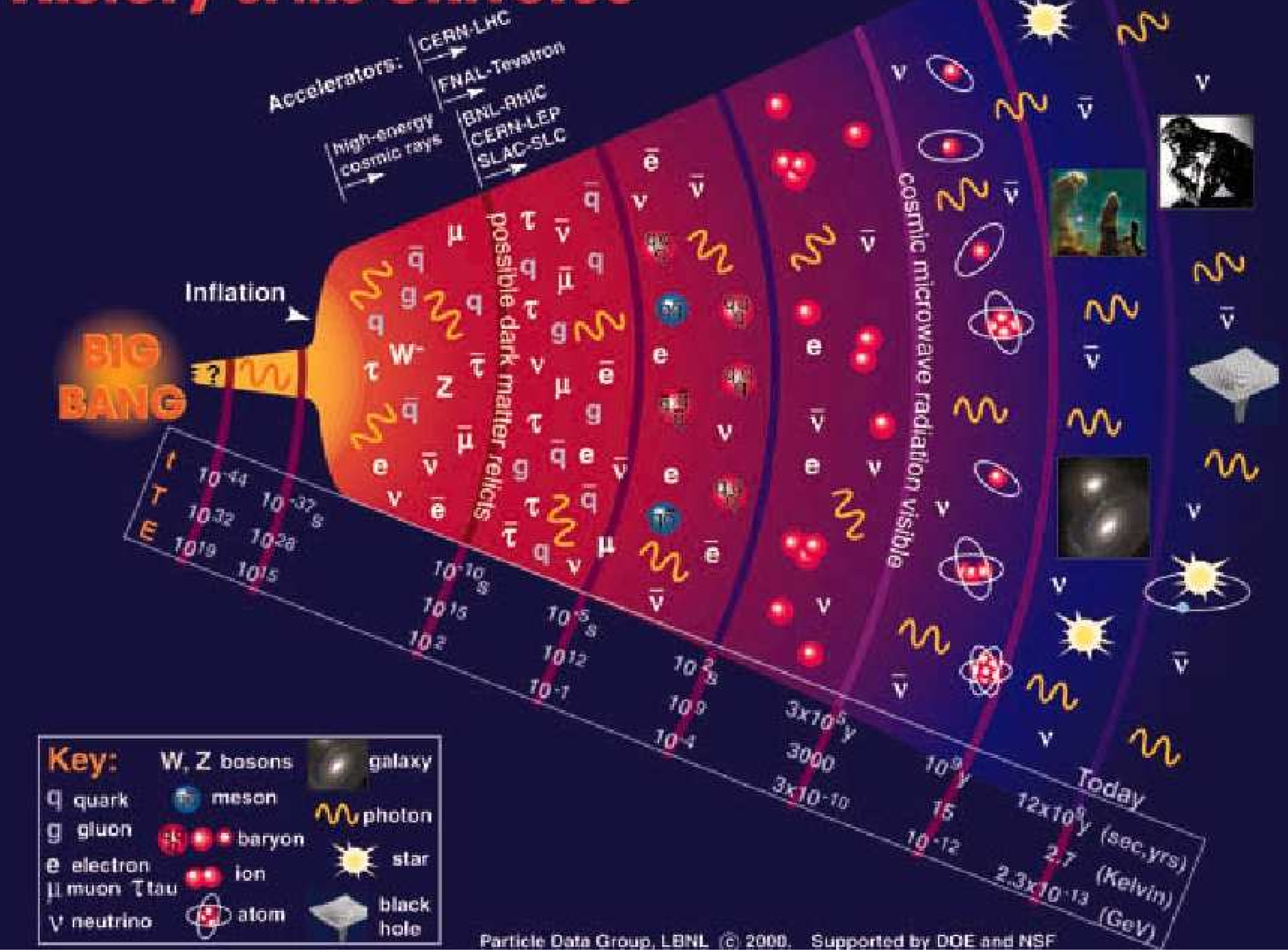
Brief brief review of thermal history of the Universe

- Useful Conversion
  - Temperature 1eV ~ 10^4K

    Present epoch 2.725K~10^{-4}eV

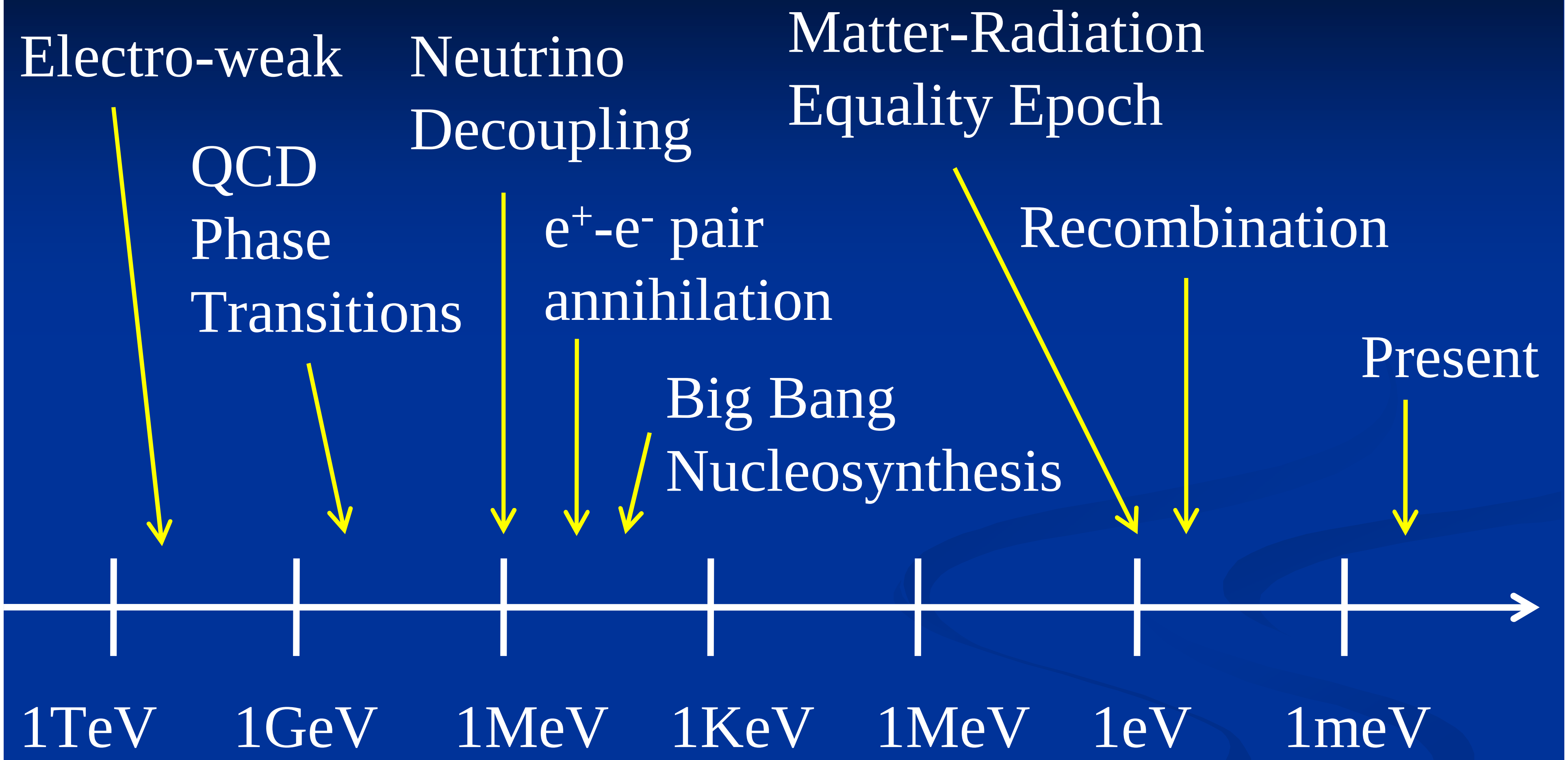
    Recombination 3000K~0.1eV
  - Redshift $1+z=T/2.725$K

History of the Universe



Particle Data Group, LBNL © 2000. Supported by DOE and NSF

Thermal History of the Universe



Electro-weak

QCD Phase Transitions

Neutrino Decoupling

e$^+$-e$^-$ pair annihilation

Big Bang Nucleosynthesis

Matter-Radiation Equality Epoch

Recombination

Present

- After Inflation, the Universe is dominated by Radiation (Massless Components)
- At T=1MeV, neutrinos are decupled from thermal bath
- At T=500keV, positrons and electrons are pair-annihilated.
  - Photons are produced, and photon temperature increases: Tphoton > Tneutrinos
- At 1MeV~100keV, Primordial Nucleosynthesis
- At 1eV($z=24000\Omega_M h^2$), radiation and matter densities become equal: equality epoch. Since then, the Universe is dominated by Matter.
- Recombination takes place at 0.1eV ($z=1089$)

1. What is the role of Neutrios on Observational Cosmology?

- Neutrinos were mostly massless through history
  - Until T ~m_ν, massless
  - e.g., 0.1eV roughly corresponds to 1000K , which is after (yet close) to the recombination epoch, 3000K.

Neutrinos are Radiation Component

- On top of photons, neutrinos consist of radiation component
- Modify (if change the number of family)
  - Expansion Rate of the Universe=Hubble Parameter
    - Primordial Nucleosynthesis
  - Matter Radiation Equality Epoch
    - Temperature Anisotropies of Cosmic Microwave Background (CMB)

Evolution of the Universe

Friedmann Equation:

Einstein Equation with homogeneity & isotropy

Energy-Momentum Conservation

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2} + \frac{\Lambda}{3}$$

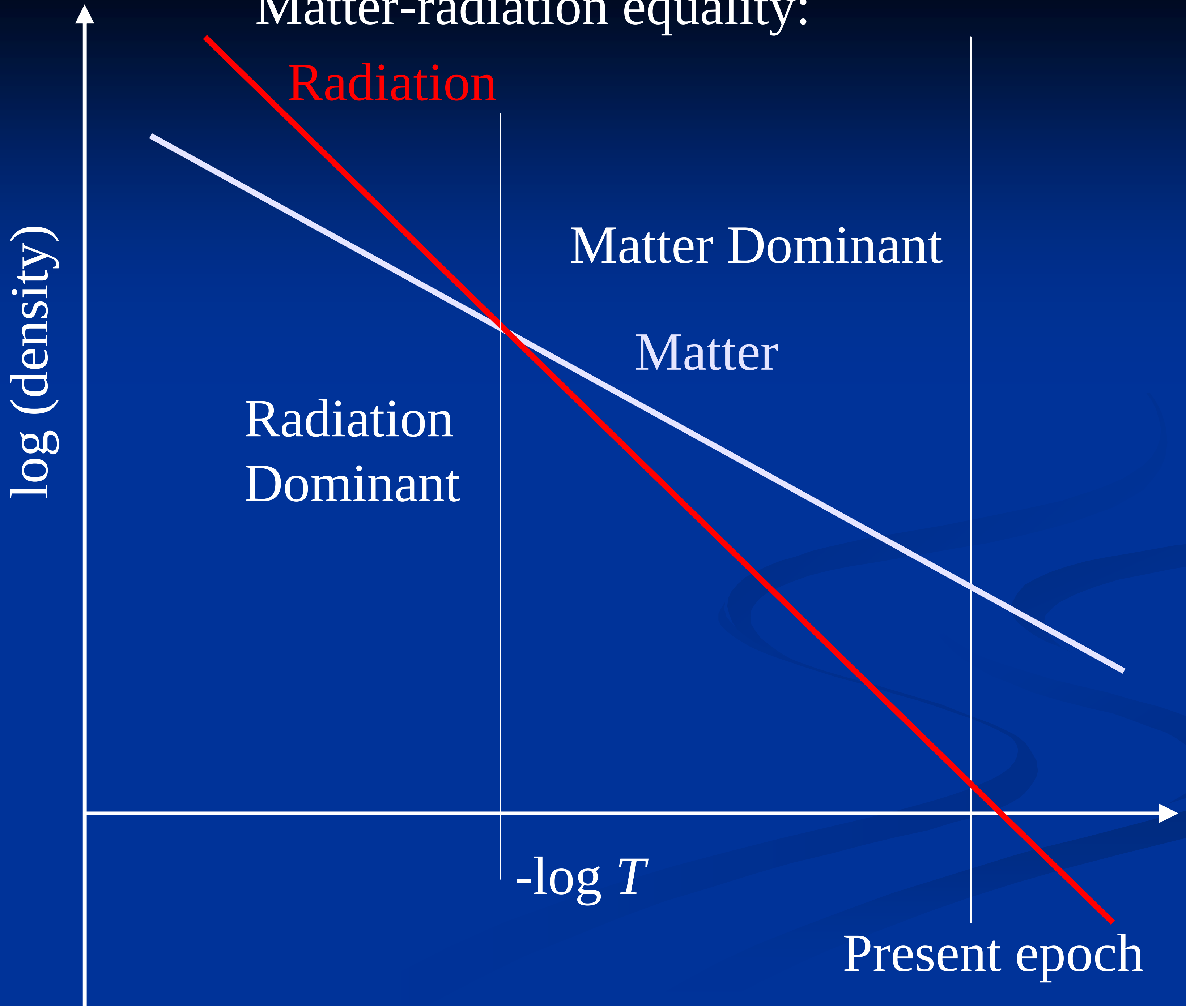
$$\rho = \rho_{Radiation} + \rho_{Matter} \qquad \rho_{Radiation} \equiv \rho_\gamma + \rho_\nu$$

$$\rho \propto a^{-3(1+w)} : w \equiv p/\rho\,(w = 0 \text{ for matter}, 1/3 \text{ radiation})$$

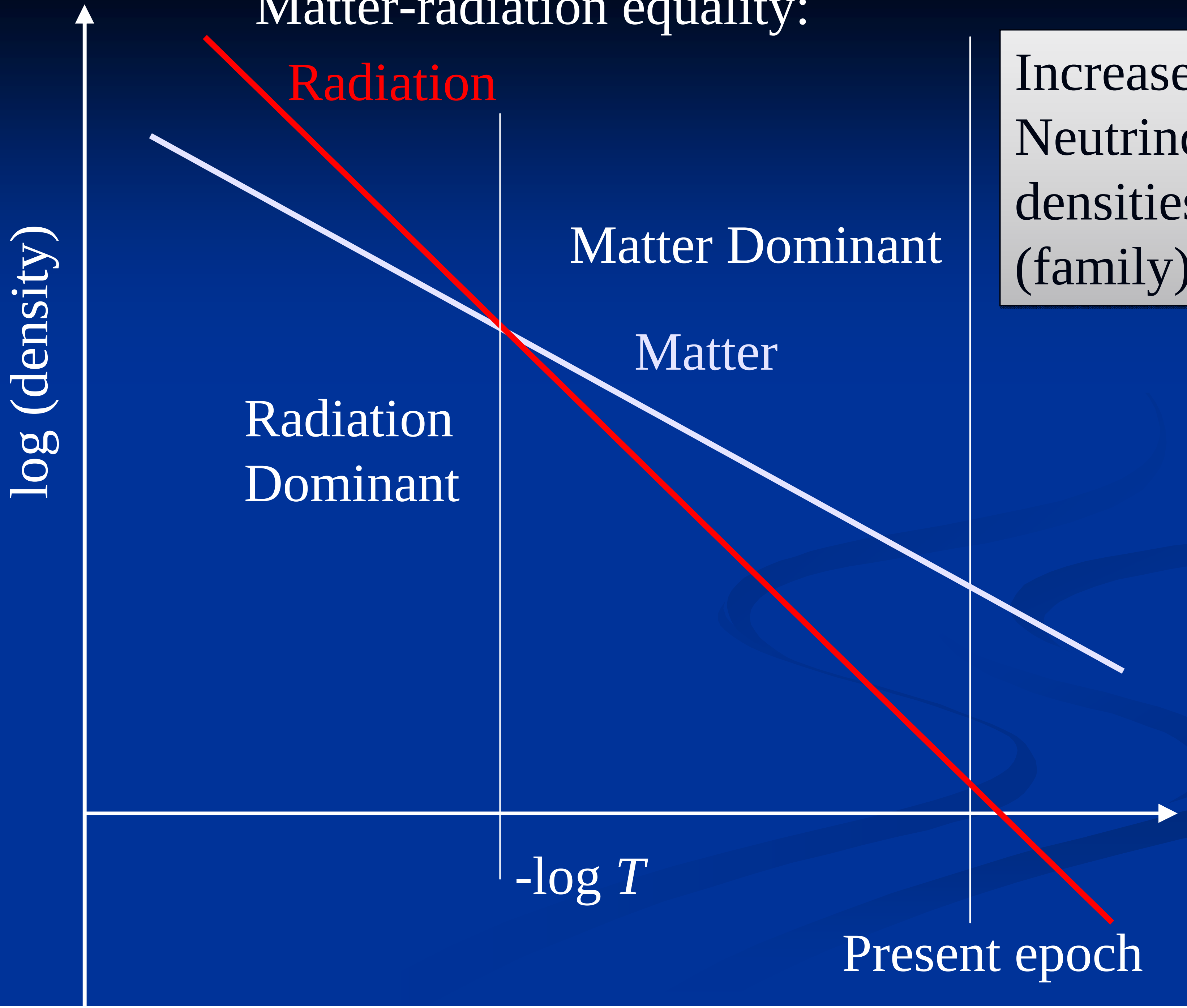
$$\rho_c = 3H_0^2/8\pi G, H_0 : \text{Hubble Const.}$$

$$\Omega \equiv \rho/\rho_c, \Omega_K = -K/H_0^2, \Omega_\Lambda \equiv \Lambda/3H_0^2$$

Matter-radiation equality:



Matter-radiation equality:



Increase
Neutrino
densities
(family)

Constraints from Big Bang Nucleosysnthesis

$$\rho_\nu = \mathrm{N}_{\mathrm{eff}}\,\frac{7}{8}\left(\frac{T_\nu}{T}\right)^4\rho_\gamma$$

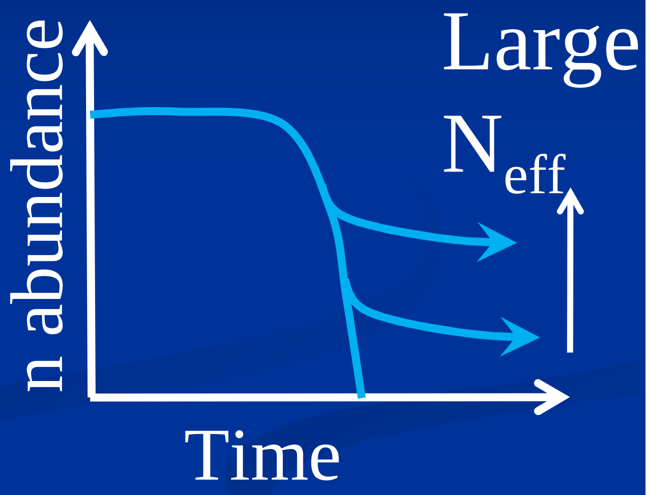
Expansion Rate (Hubble Parameter) depends on Effective Neutrino Number, $\mathrm{N}_{\mathrm{eff}}$

Change the predicted abundances of light elements

Larger Neff → Higher Expansion → Neutrons were decoupled from Chemical Equilibrium Early

$$n \leftrightarrow p + e^{-} + \bar{\nu}$$

$$n + \nu \leftrightarrow p + e^{-}$$

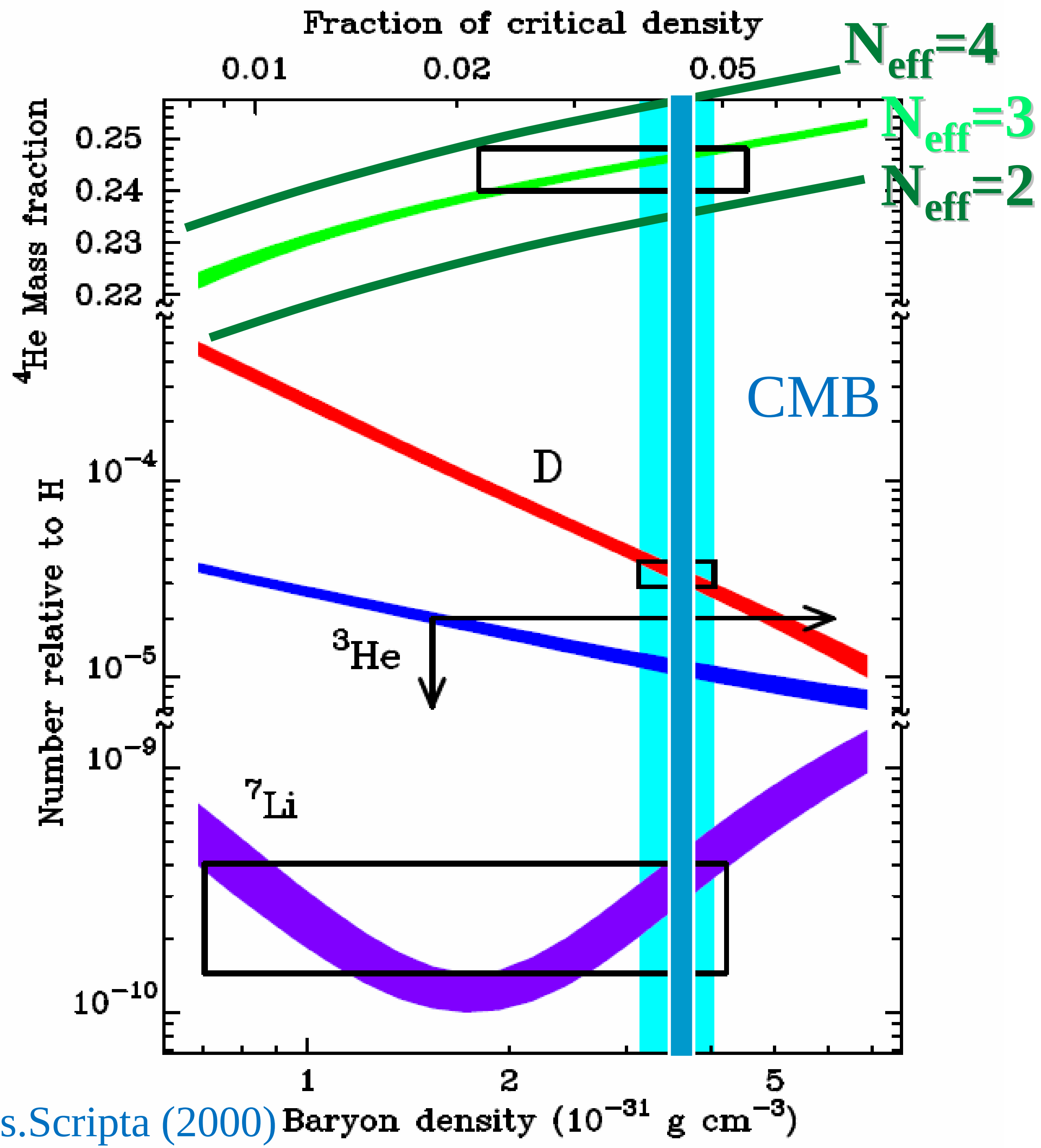


Larger number of Neutrons were left

Larger amount of Helium were left

Compare Theoretical Prediction with

- Observational Abundances of ^{4}He, D, ^{3}He, ^{7}Li
- Determination of $\Omega_B h^2 = 0.023 \pm 0.001$ from Cosmic Microwave Background Anisotropies



Tytler et al. Phys.Scripta (2000)

Life is not so Simple:
Some Caveats

- Observations were not consistent with each other
  - Treatments of Systematics are Complicated (Effect of stellar absorptions etc.)

    Cheating?
  - Neutron Life Time:

    Used to be 885.7 ± 0.8, but new measurement:

    878.5±0.7(stat) ±0.3(sys) (Serebrov, et al., (2005))

    Shorter Life time -> Neutron Decoupling from Chemical equaillibrium becomes later -> Less Neutrons are left -> Less Hellium Abundance

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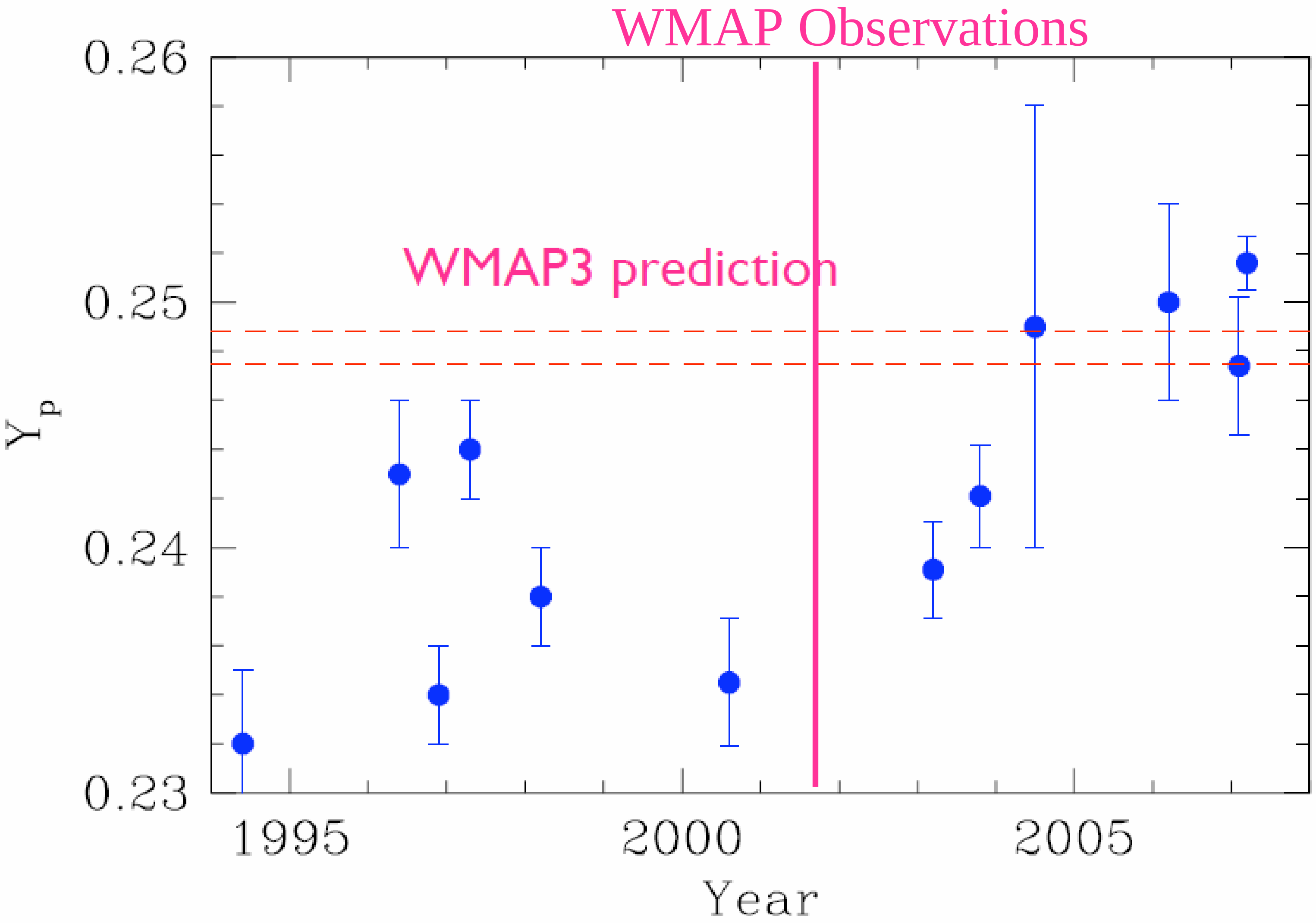
Helium Abundance History



Courtesy from M. Kawasaki

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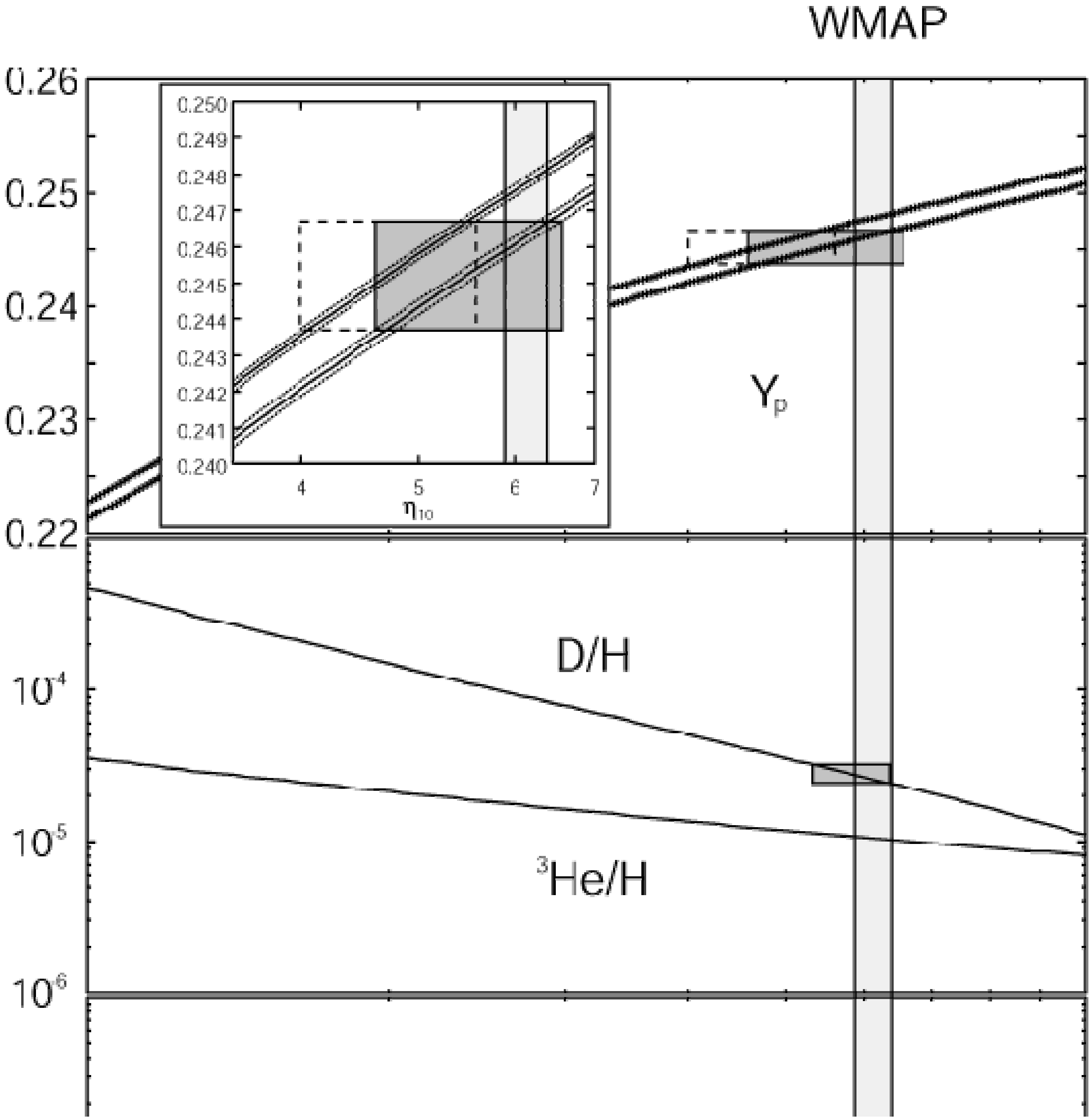
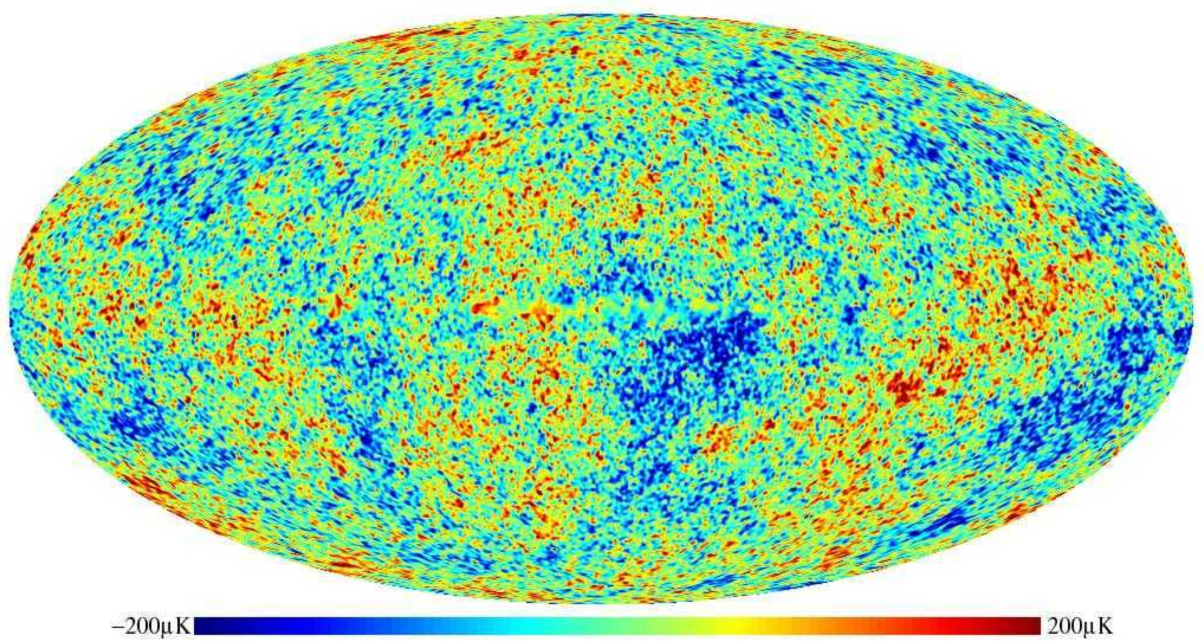
0.4% Neutron Life Time Dependence

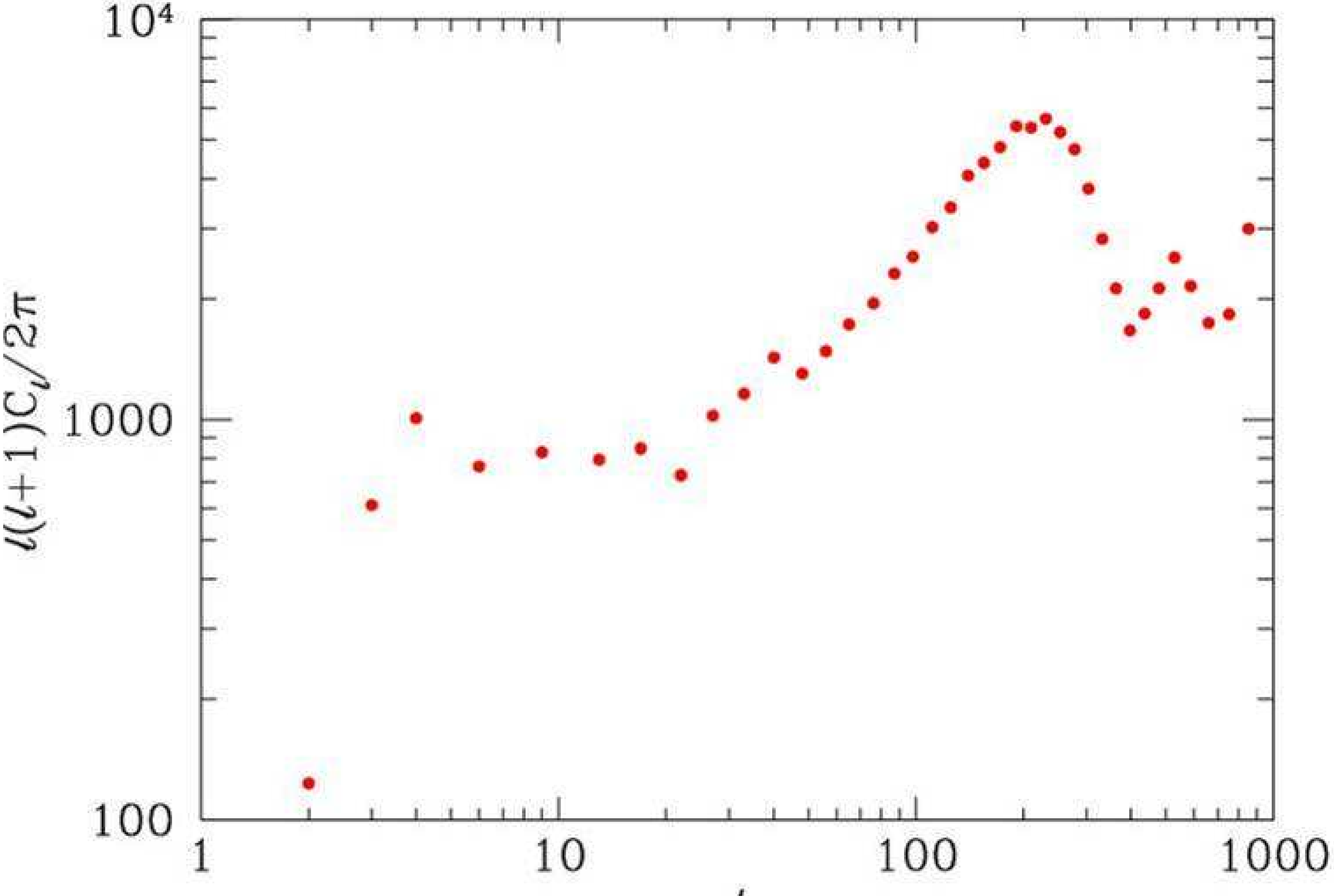


Mathews et al (2005)

Constraints from Cosmic Microwave Background Anisotropies

- Increase N_{eff}, pushes matter-radiation equality at the later epoch, which modifies the peak heights and locations of CMB spectrum.
- Additional neutrino species alters the damping tail on high *l*'s.

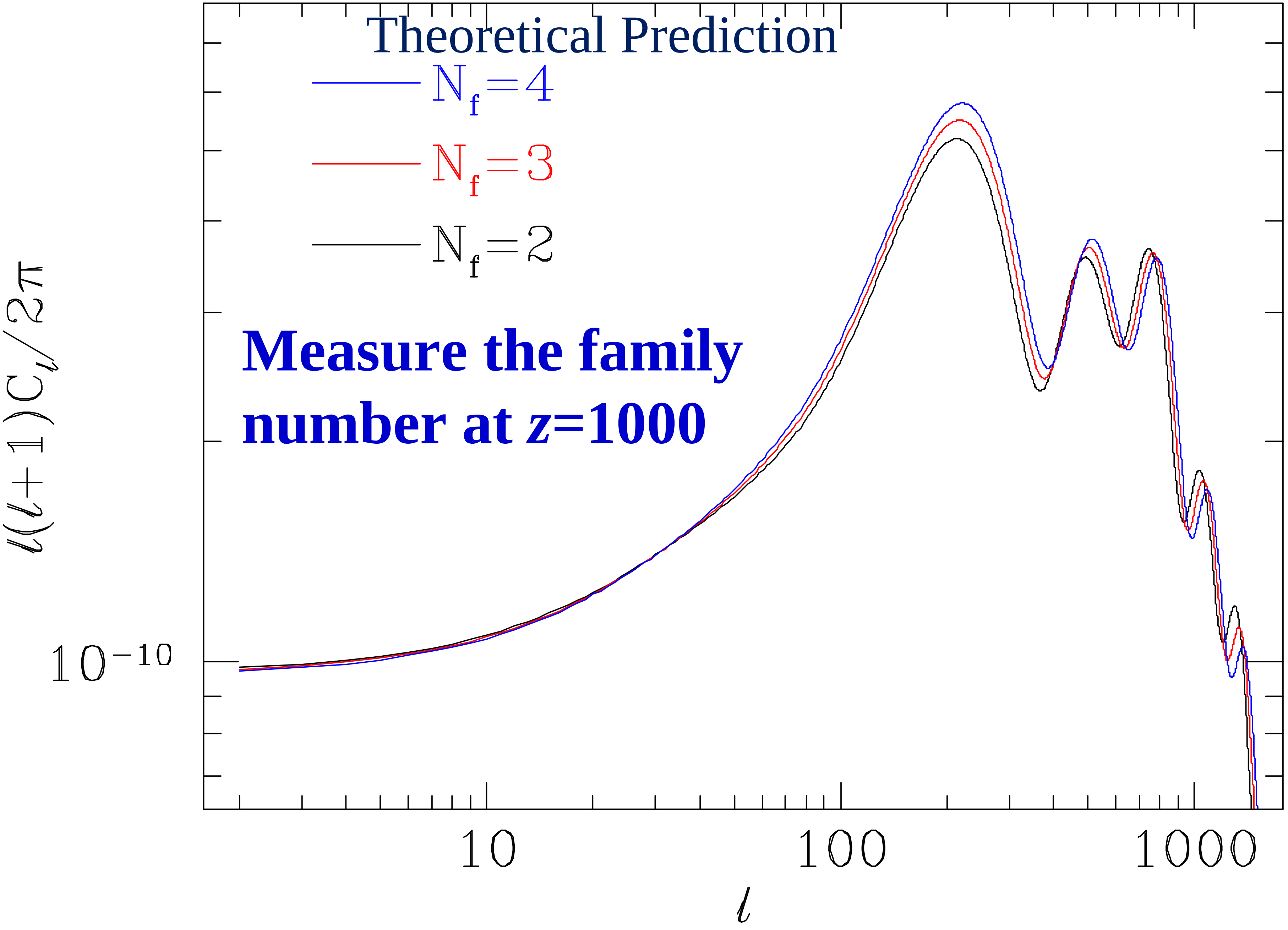




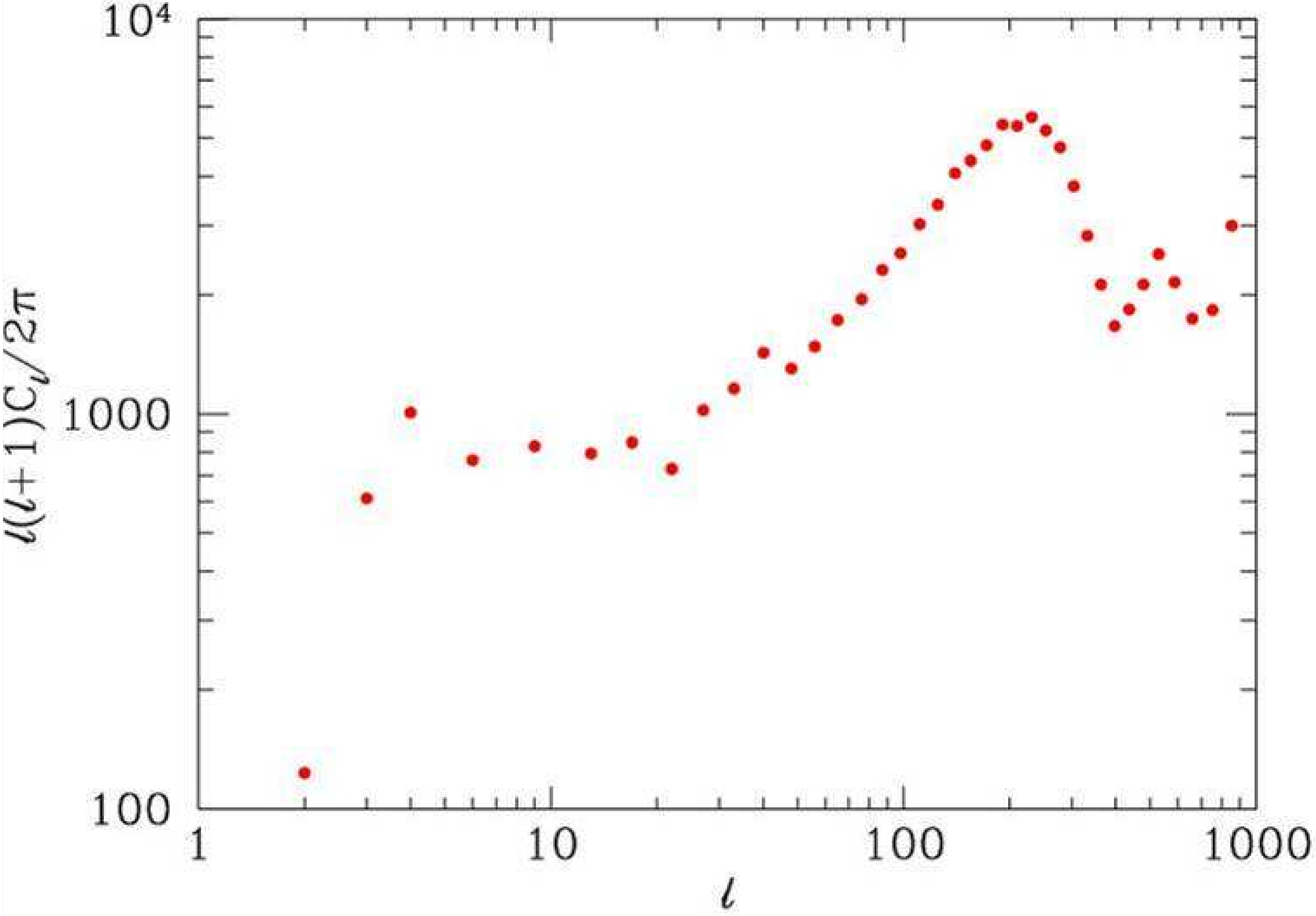
多重極モーメント

CMB Angular Power Spectrum

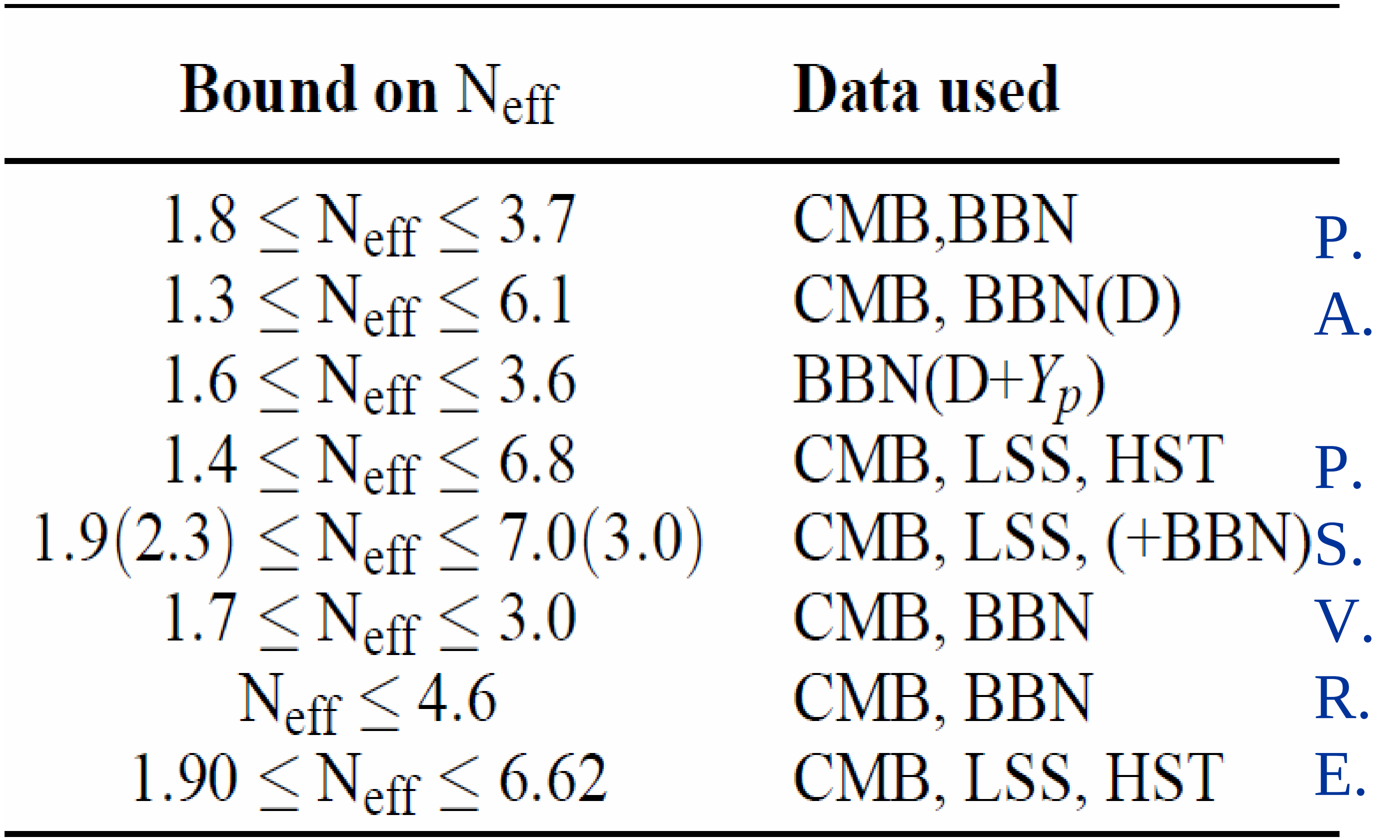
Theoretical Prediction



Measure the family number at *z*=1000



10^4
1000
100
1
10
100
1000
$\ell(\ell+1)C_\ell/2\pi$
ℓ



Bound on N_{eff}	Data used	
$1.8 \leq N_{eff} \leq 3.7$	CMB,BBN	P. Serpico *et al.*, ***(2004)***
$1.3 \leq N_{eff} \leq 6.1$	CMB, BBN(D)	A. Cuoco *et al.*, ***(2004)***
$1.6 \leq N_{eff} \leq 3.6$	BBN(D+Y_p)	
$1.4 \leq N_{eff} \leq 6.8$	CMB, LSS, HST	P. Crotty *et al.*, ***(2003)***
$1.9(2.3) \leq N_{eff} \leq 7.0(3.0)$	CMB, LSS, (+BBN)	S. Hannestad, ***(2003)***
$1.7 \leq N_{eff} \leq 3.0$	CMB, BBN	V. Barger *et al.*, ***(2003)***
$N_{eff} \leq 4.6$	CMB, BBN	R. Cyburt *et al.* ***(2005)***
$1.90 \leq N_{eff} \leq 6.62$	CMB, LSS, HST	E. Pierpaoli ***(2003)***

2. How Neutrino Mass Affect?

- Present Density Parameter

$$\Omega_\nu = [3m_\nu/(93.84\ \mathrm{eV})]h^{-2}$$

- Neutrino Components prevent galaxy scale structure to be formed due to their kinetic energy
  - Constraints from Large Scale Structure
- Change the matter-radiation ratio near the recombination epoch, if m ~ a few eV
  - Constraints from Cosmic Microwave Background (Ihikawa’s Talk)

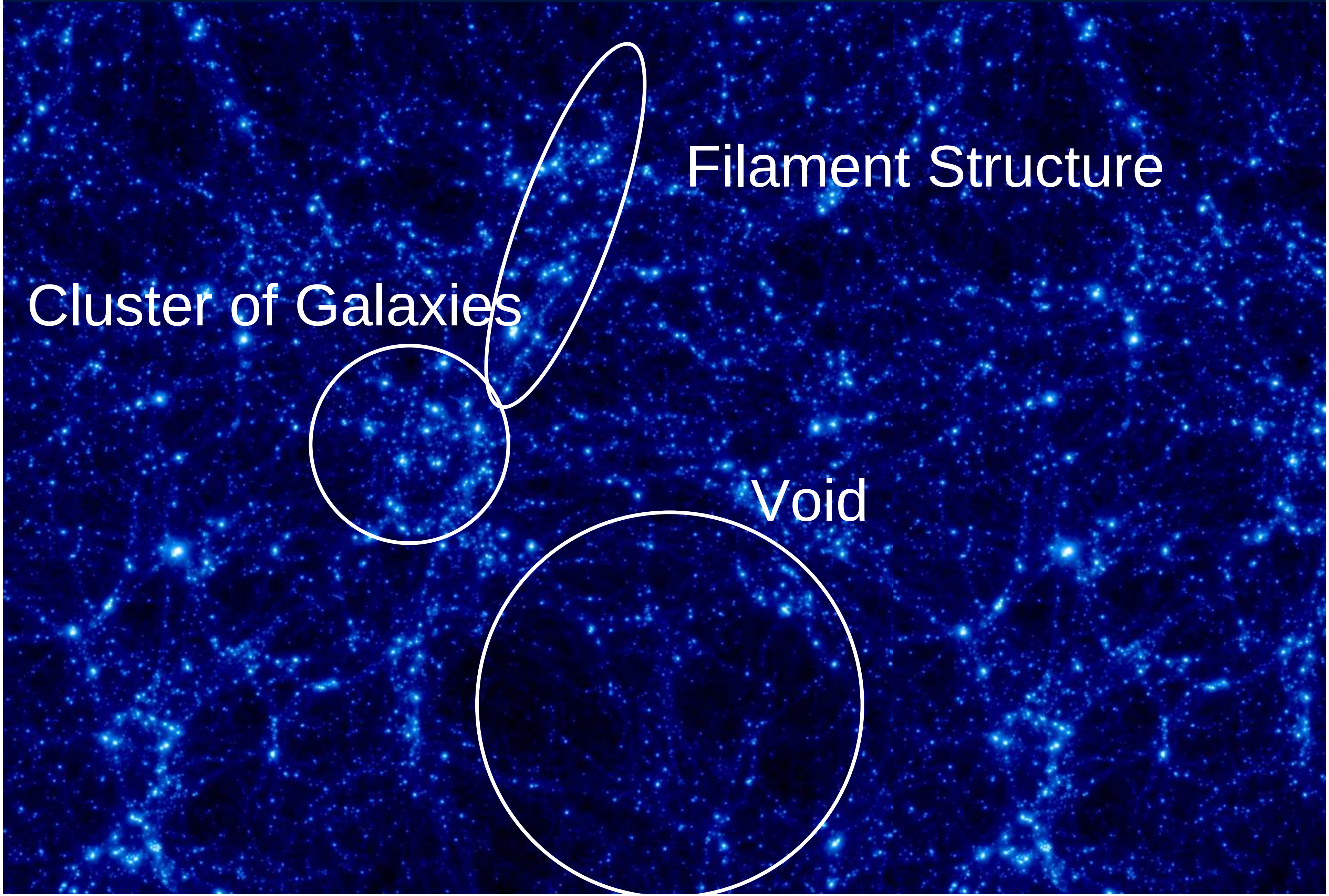
Large Structure Formation

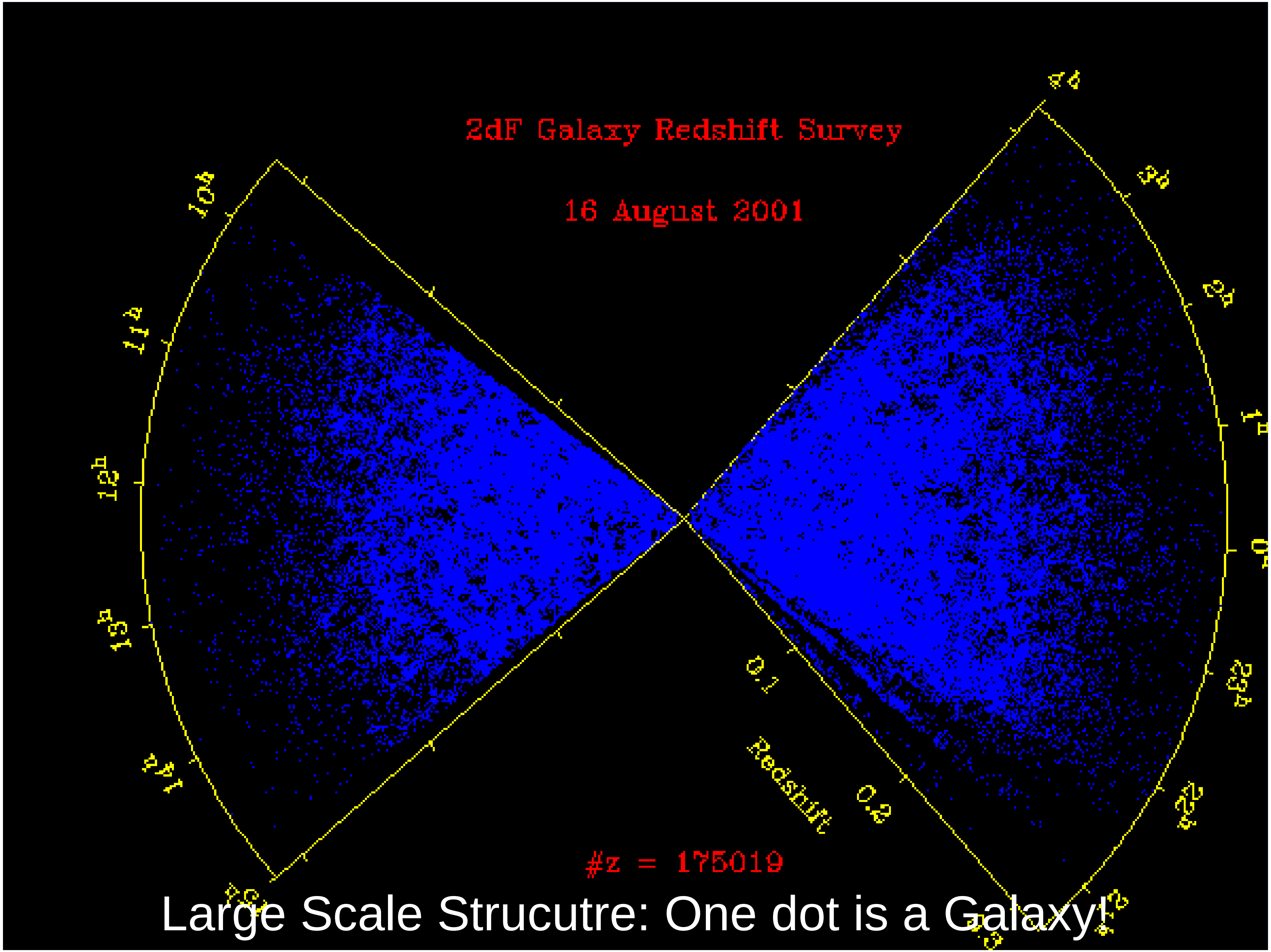
- Self Gravity of Cold Dark Matter forms the structure
- Comparison between Numerical Simulation and Observations are Superb
  - Power Spectrum (matter distribution in k-space) obtained by Cold Dark Matter fluctuations fits very well to the data

Numerical Simulation of Large Scale Structure

Courtesy by Naoki Yoshid

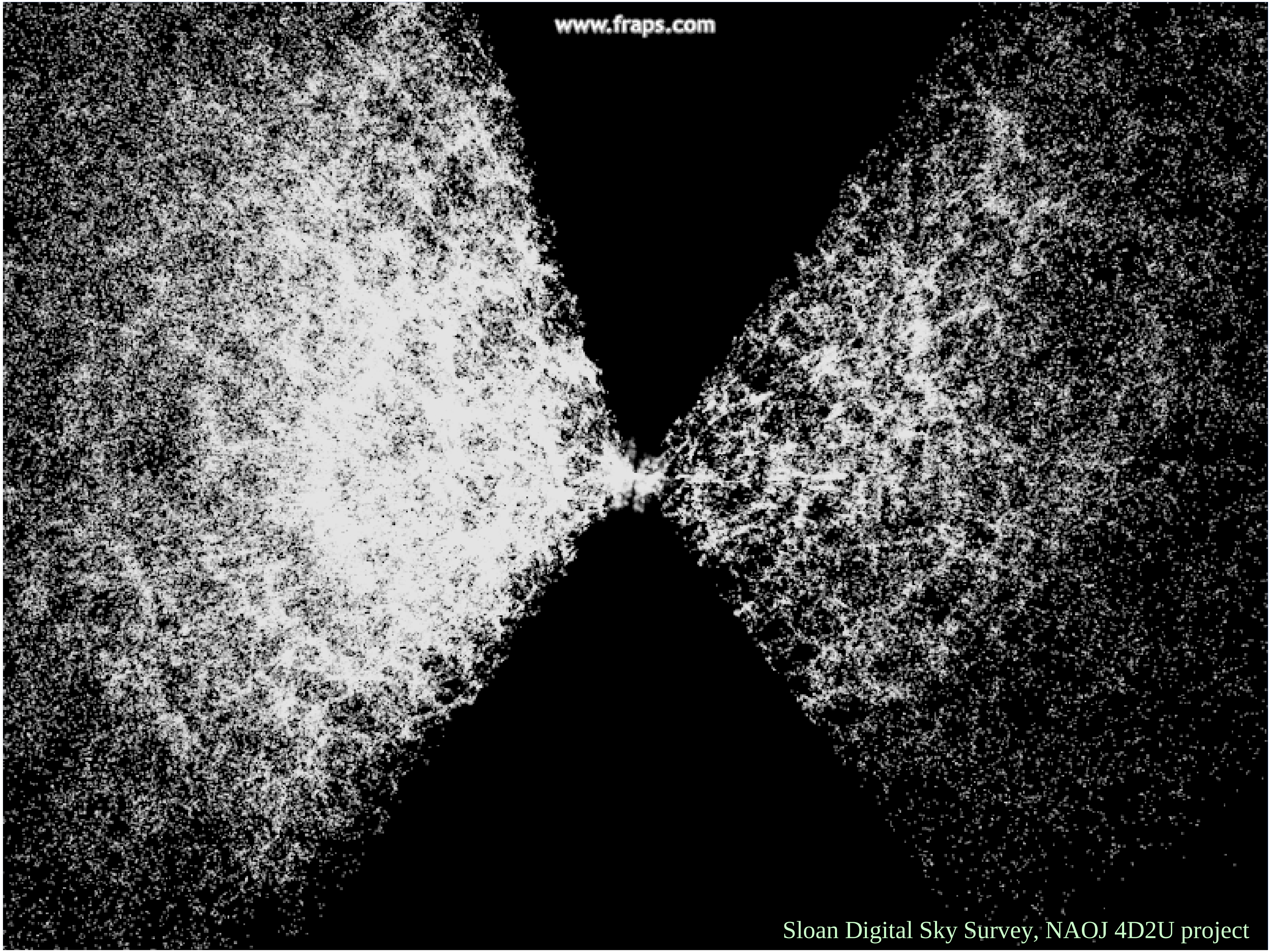
Large Scale Structure of the Universe



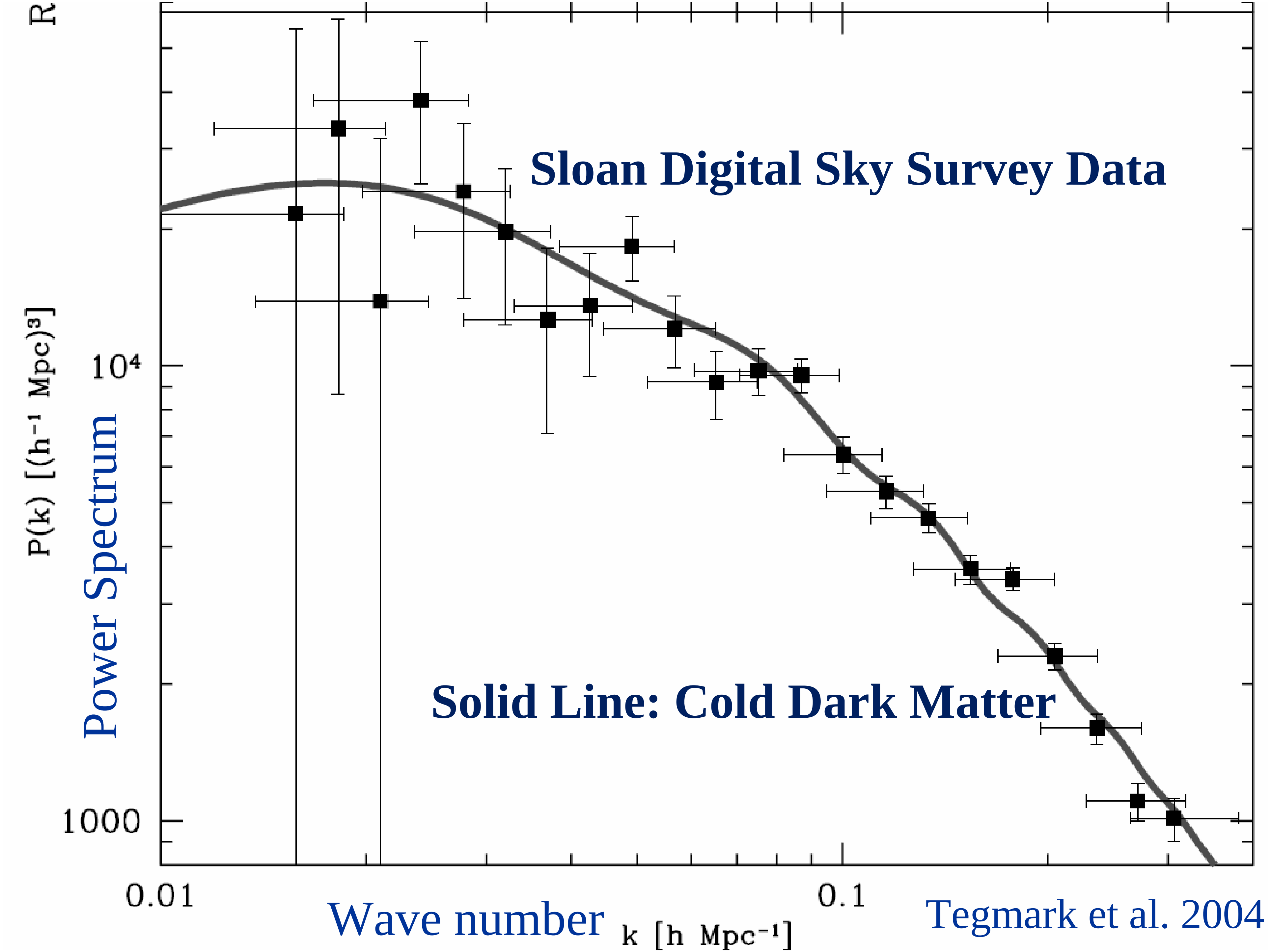


Large Scale Strucutre: One dot is a Galaxy!


2dFGRS



Sloan Digital Sky Survey, NAOJ 4D2U project



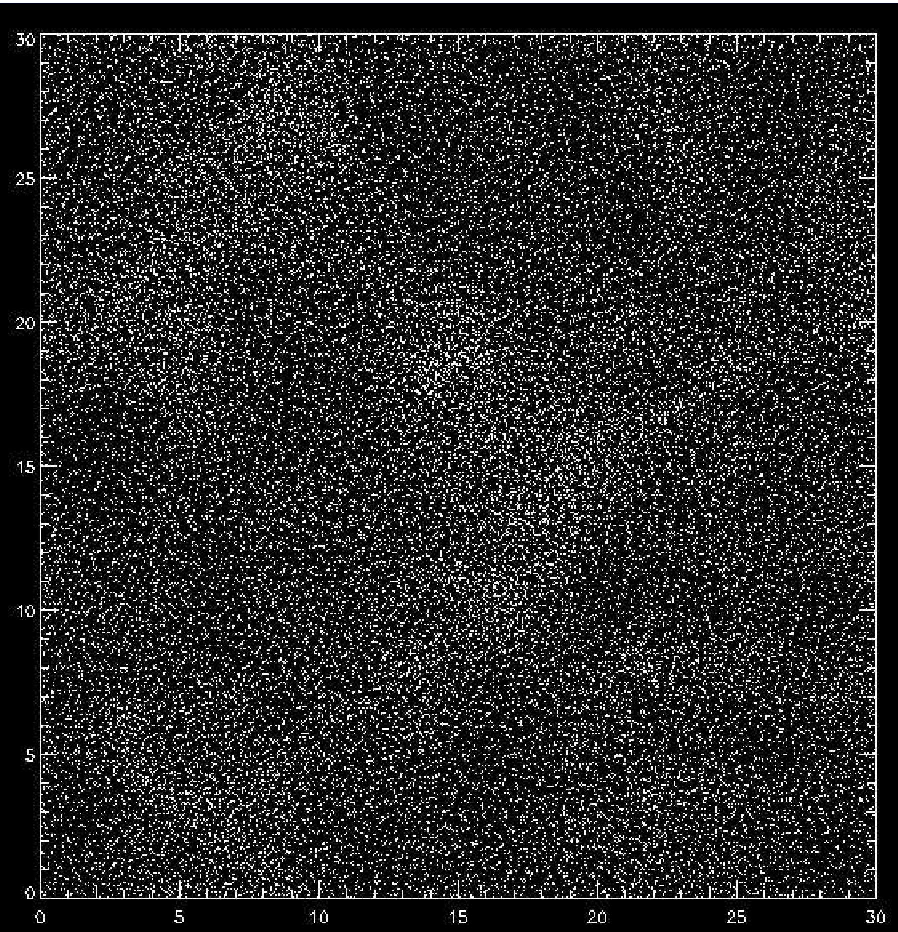
Sloan Digital Sky Survey Data

Solid Line: Cold Dark Matter

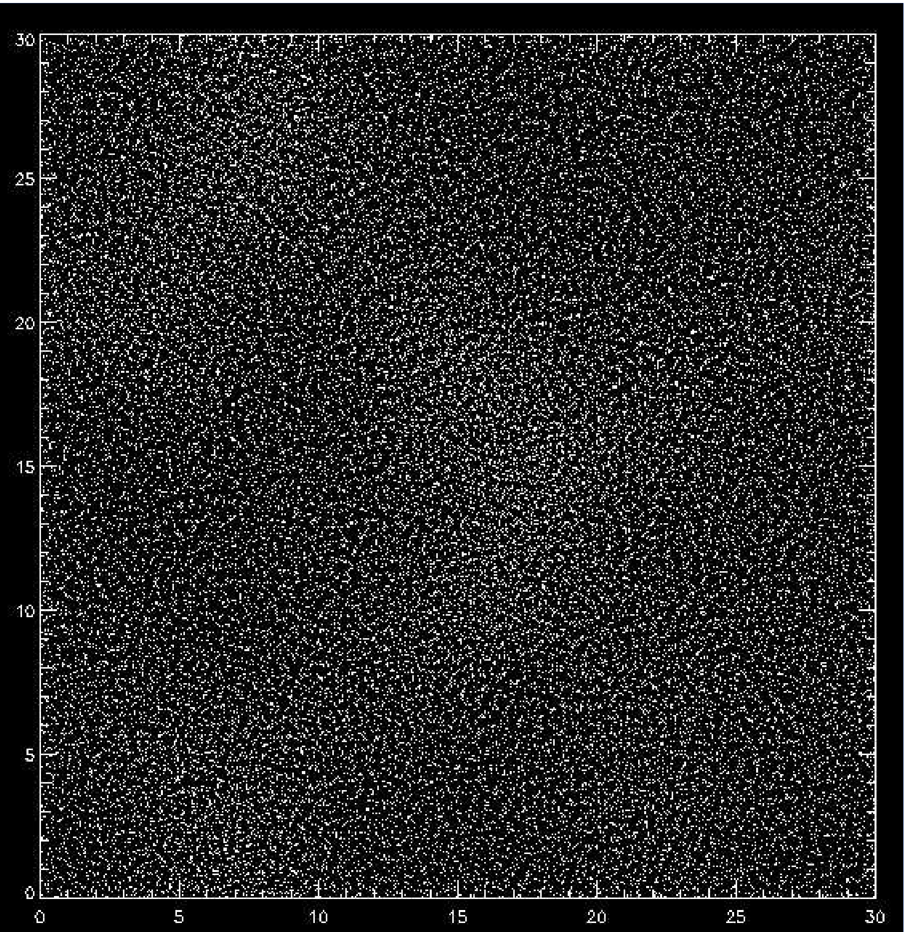
Power Spectrum

Wave number

Tegmark et al. 2004

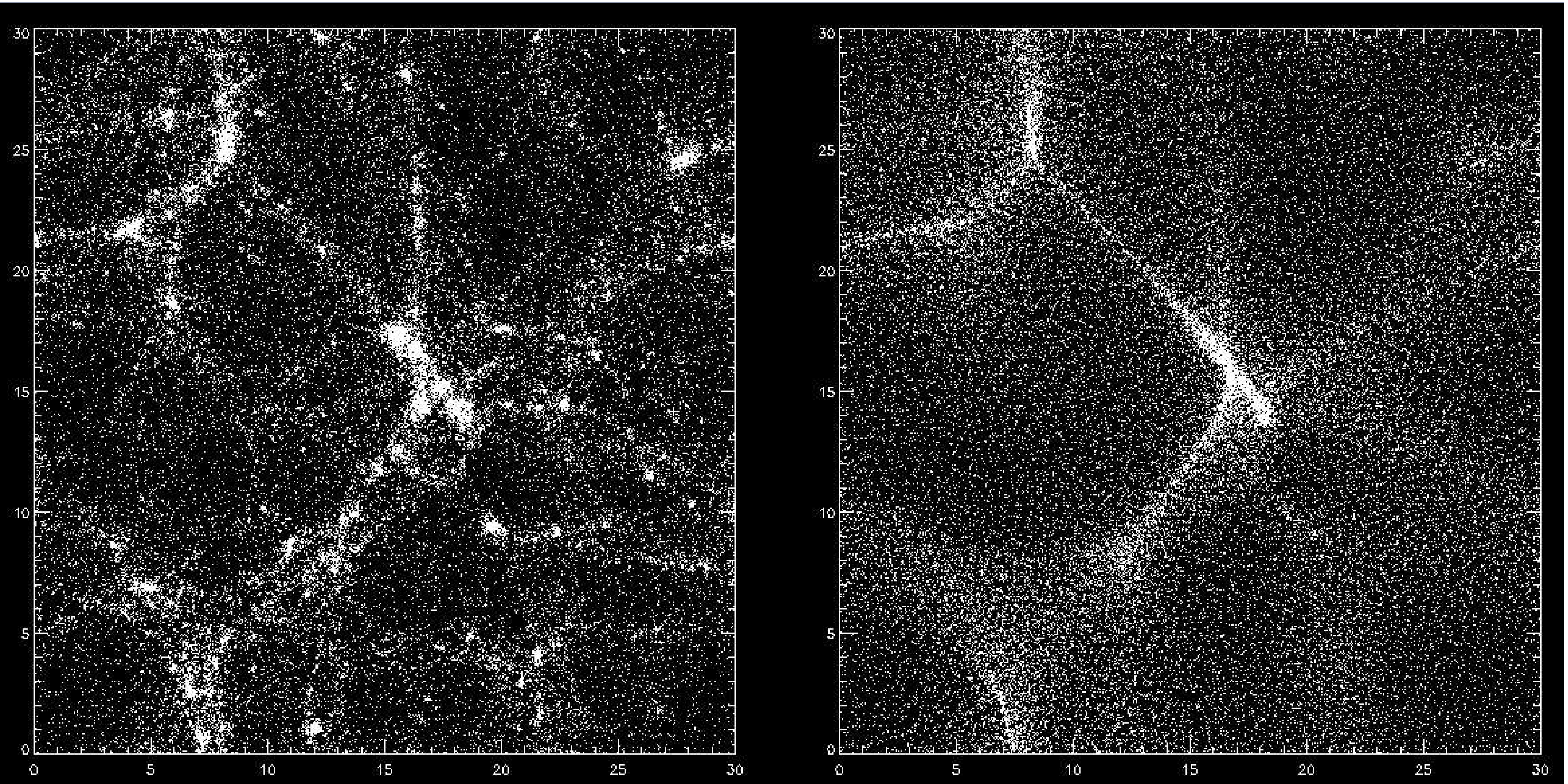


Cold Dark Matter



Neutrino as Dark Matter
(Hot Dark Matter)

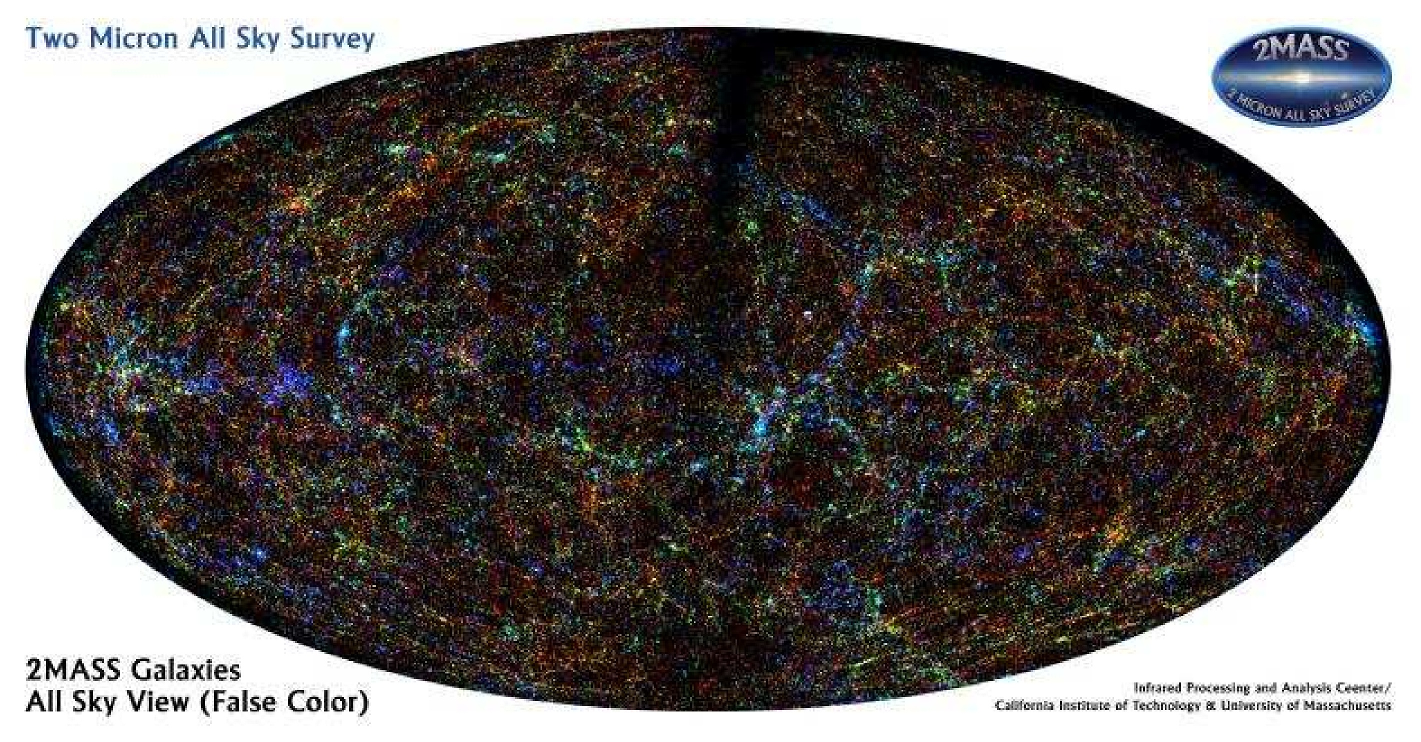
Numerical Simulation, at $z=10$



Cold Dark Matter

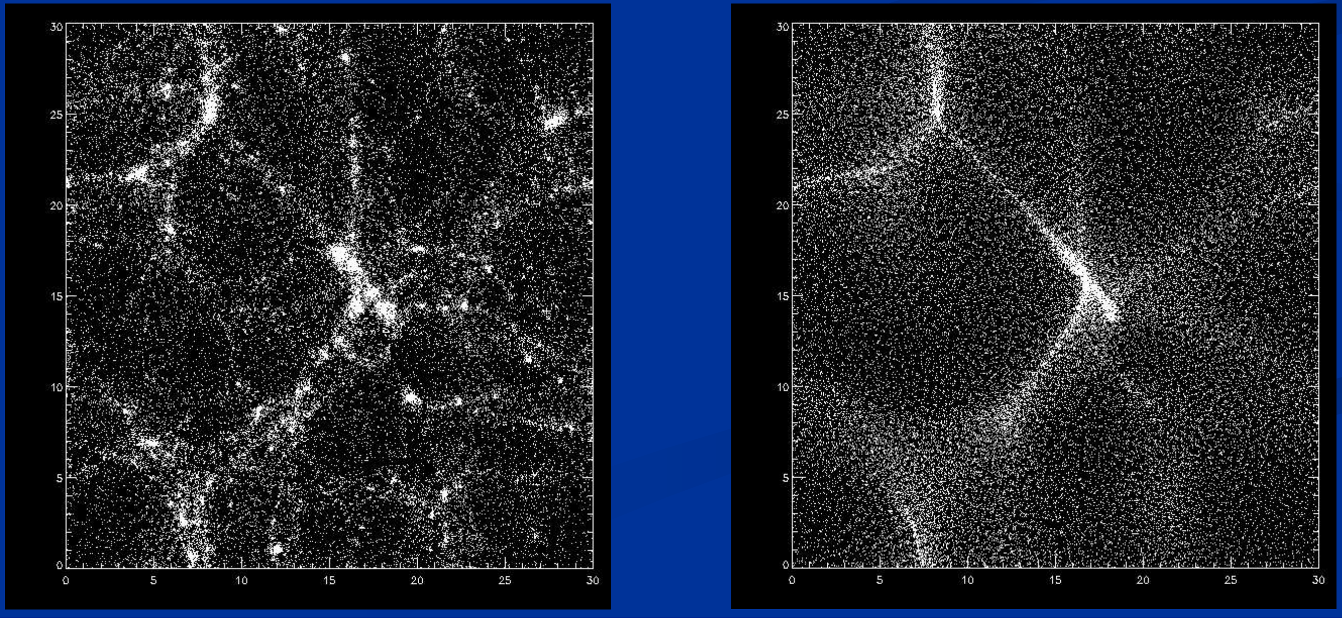
Neutrino as Dark Matter
(Hot Dark Matter)

Numerical Simulation, at present

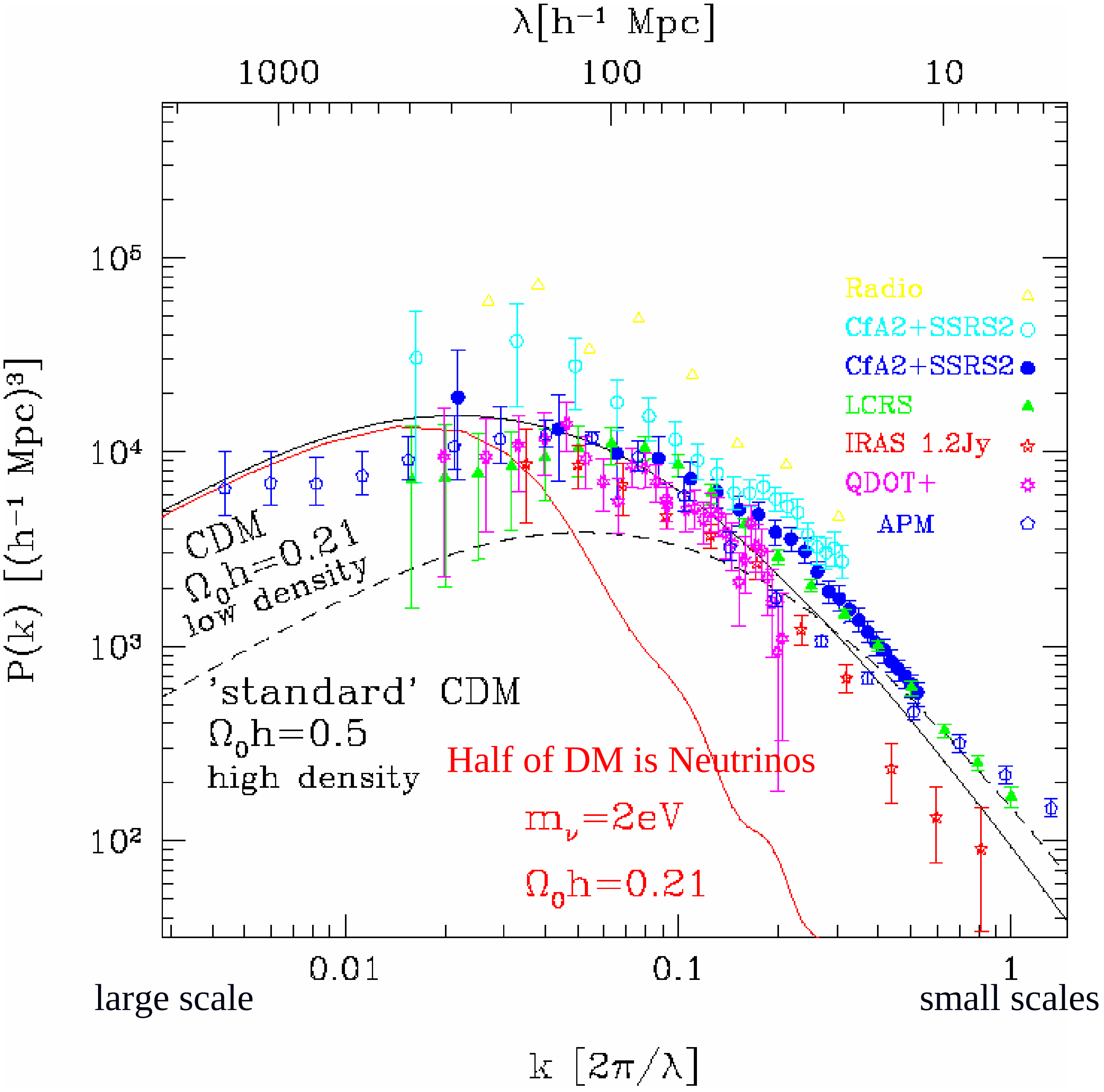

Two Micron All Sky Survey

2MASS Galaxies
All Sky View (False Color)

Infrared Processing and Analysis Ceenter/
California Institute of Technology & University of Massachusetts

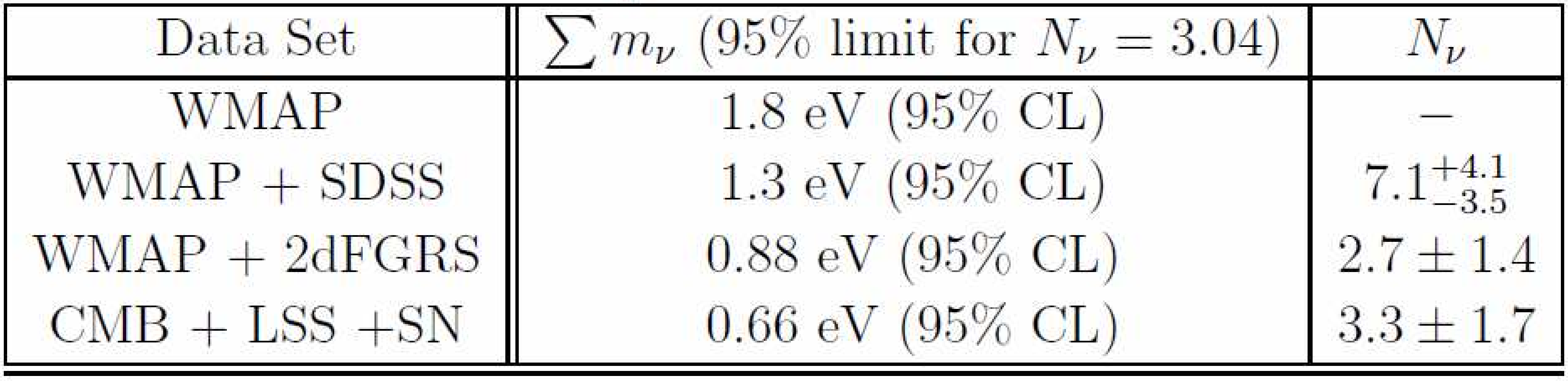


- Neutrinos cannot be Dark Matter (Hot Dark Matter) since Galaxy scale structure cannot be formed!
- Even small fraction of Neutrino component with Cold Dark Matter causes Problem


λ[h⁻¹ Mpc]
1000
100
10
P(k) [(h⁻¹ Mpc)³]
10⁵
10⁴
10³
10²
Radio △
CfA2+SSRS2 ○
CfA2+SSRS2 ●
LCRS ▲
IRAS 1.2Jy ☆
QDOT+ ✡
APM ⬠
CDM
Ω₀h=0.21
low density
'standard' CDM
Ω₀h=0.5
high density
Half of DM is Neutrinos
m_ν=2eV
Ω₀h=0.21
0.01
0.1
1
large scale
small scales
k [2π/λ]

Set Constraints on Neutrino Mass and Neff

WMAP 3yr Data paper by Spergel et al.



Data Set	$\sum m_\nu$ (95% limit for $N_\nu = 3.04$)	N_ν
WMAP	1.8 eV (95% CL)	–
WMAP + SDSS	1.3 eV (95% CL)	$7.1^{+4.1}_{-3.5}$
WMAP + 2dFGRS	0.88 eV (95% CL)	2.7 ± 1.4
CMB + LSS +SN	0.66 eV (95% CL)	3.3 ± 1.7

Summary

- Cosmology can set the most stringent constraints on the properties of Neutrinos: # of Species, and Masses
- Still we have some room for improvement, for example Polarization of CMB Anisotropies
  - PLANCK (2008) or Future Satellite