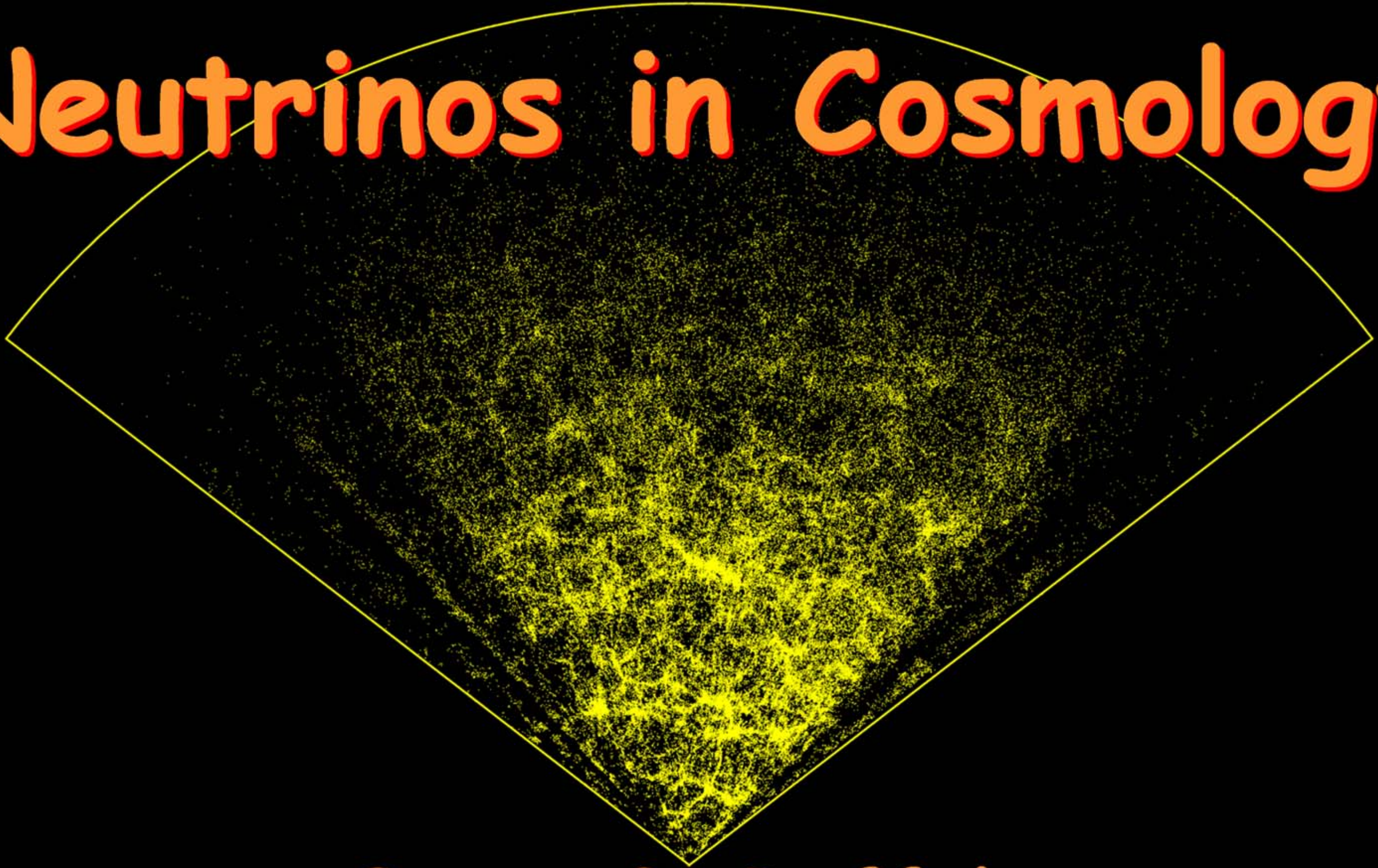
NuFact 03: 5th International Workshop on Neutrino Factories & Superbeams
Columbia University, New York, 5-11 June 2003

Neutrinos in Cosmology



Georg G. Raffelt
Max-Planck-Institut für Physik, München, Germany

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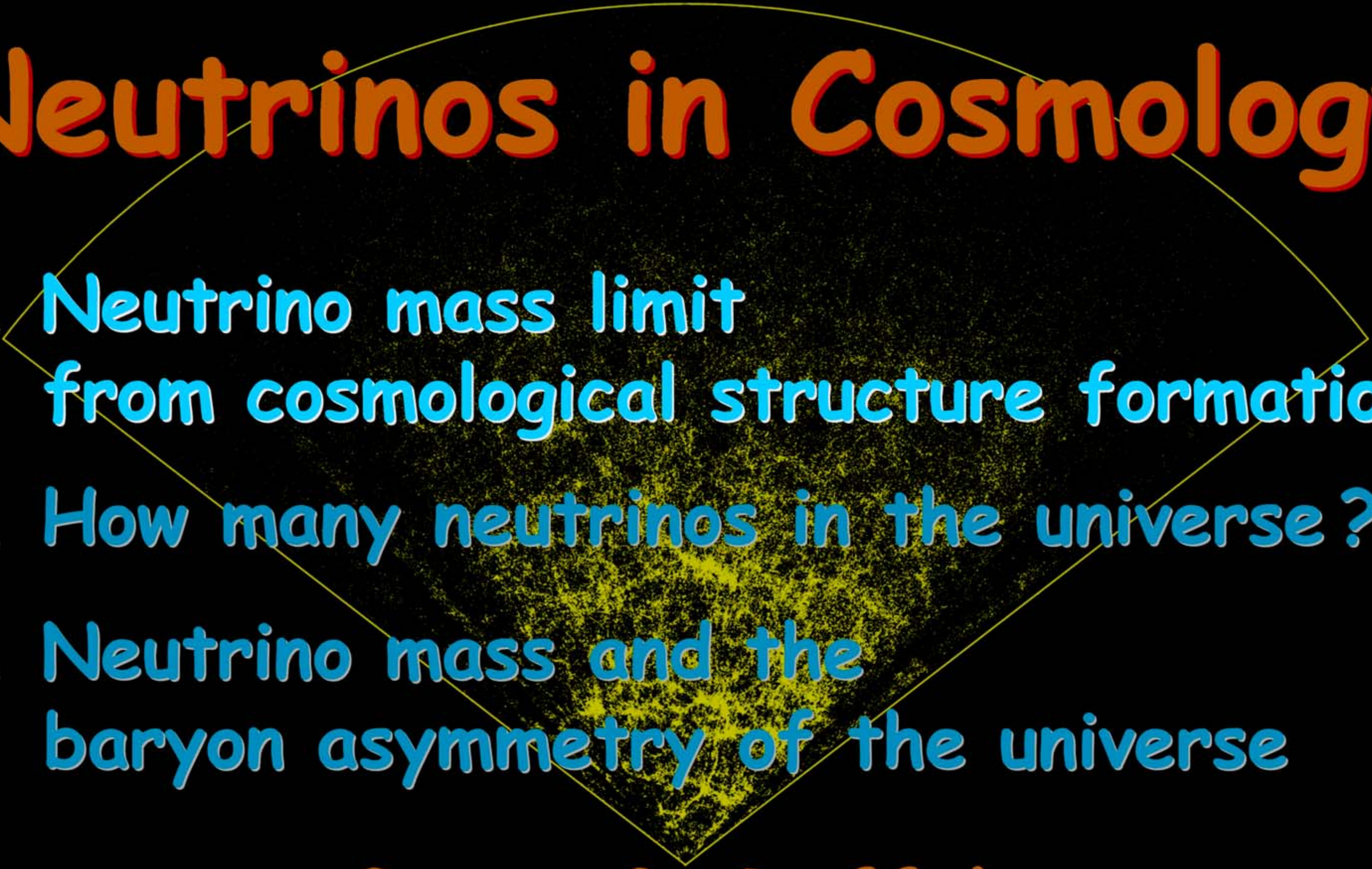

1. Neutrino mass limit
   from cosmological structure formation
2. How many neutrinos in the universe?
3. Neutrino mass and the
   baryon asymmetry of the universe

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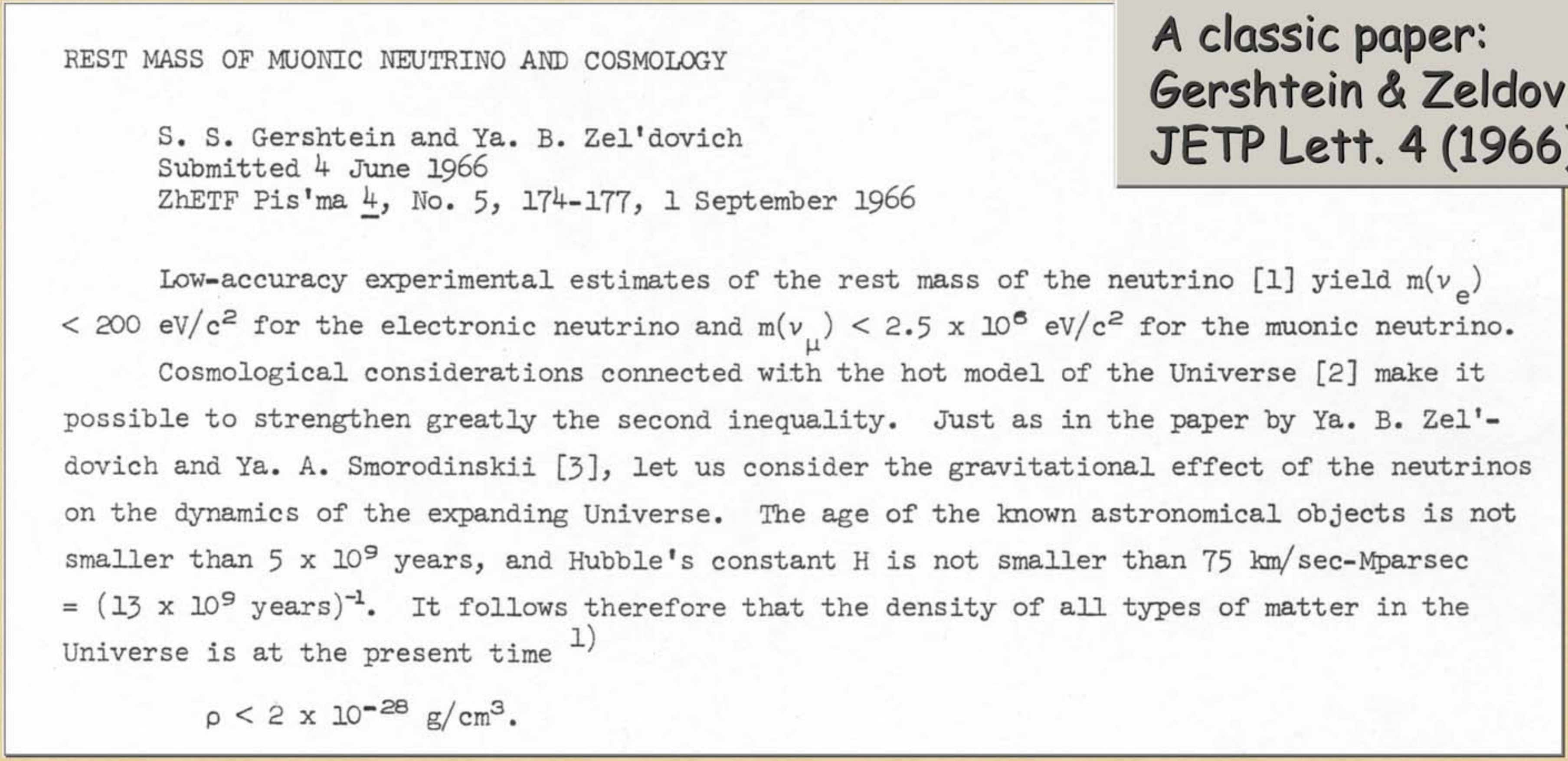
Cosmological Limit on Neutrino Masses

Cosmic neutrino "sea" ~ 112 cm^{-3} neutrinos + anti-neutrinos per flavor

$$\Omega_\nu h^2 = \sum \frac{m_\nu}{94\,\mathrm{eV}} < 0.4$$

$m_\nu < 40$ eV For all stable flavors

A classic paper:
Gershtein & Zeldovich
JETP Lett. 4 (1966) 120



REST MASS OF MUONIC NEUTRINO AND COSMOLOGY

S. S. Gershtein and Ya. B. Zel'dovich
Submitted 4 June 1966
ZhETF Pis'ma 4, No. 5, 174-177, 1 September 1966

Low-accuracy experimental estimates of the rest mass of the neutrino [1] yield $m(\nu_e) < 200\ \mathrm{eV}/c^2$ for the electronic neutrino and $m(\nu_\mu) < 2.5 \times 10^6\ \mathrm{eV}/c^2$ for the muonic neutrino.

Cosmological considerations connected with the hot model of the Universe [2] make it possible to strengthen greatly the second inequality. Just as in the paper by Ya. B. Zel'dovich and Ya. A. Smorodinskii [3], let us consider the gravitational effect of the neutrinos on the dynamics of the expanding Universe. The age of the known astronomical objects is not smaller than 5×10^9 years, and Hubble's constant H is not smaller than 75 km/sec-Mparsec $= (13 \times 10^9\ \text{years})^{-1}$. It follows therefore that the density of all types of matter in the Universe is at the present time 1)

$$\rho < 2 \times 10^{-28}\ \mathrm{g/cm^3}.$$

What is wrong with neutrino dark matter?

Galactic Phase Space ("Tremaine-Gunn-Limit")

Maximum mass density of a Fermi gas

$$\rho_{max} = m_\nu\, n_{max} = m_\nu\, p_{max}^3/3\pi^2 = m_\nu\, (m_\nu v_{escape})^3/3\pi^2$$

$m_\nu > 20 - 40$ eV

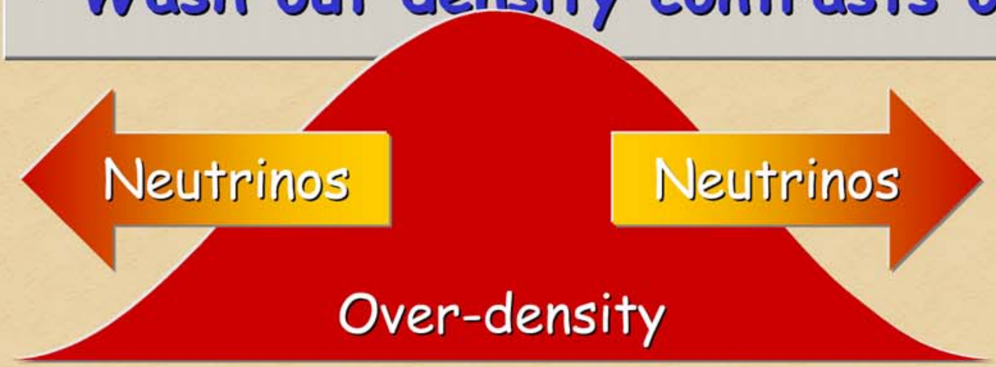
Spiral galaxies

More restrictive from dwarf galaxies

$m_\nu > 100 - 200$ eV

Neutrino Free Streaming (Collisionless Phase Mixing)

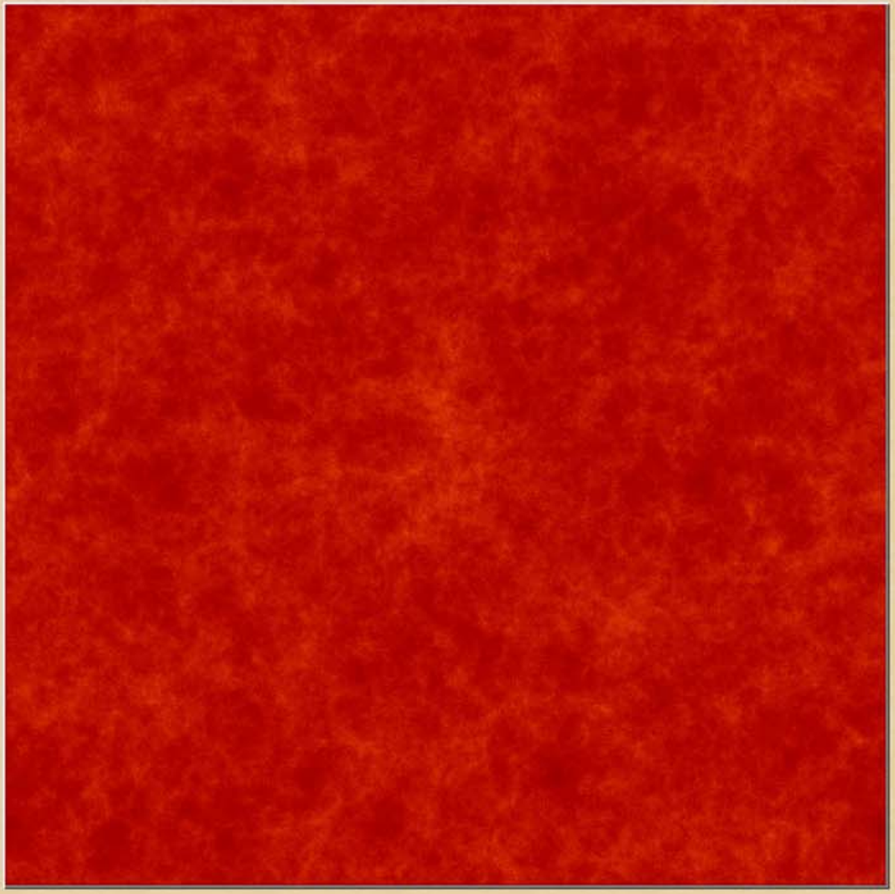
- At $T < 1$ MeV neutrino scattering in early universe ineffective
- Stream freely until nonrelativistic
- Wash out density contrasts on small scales

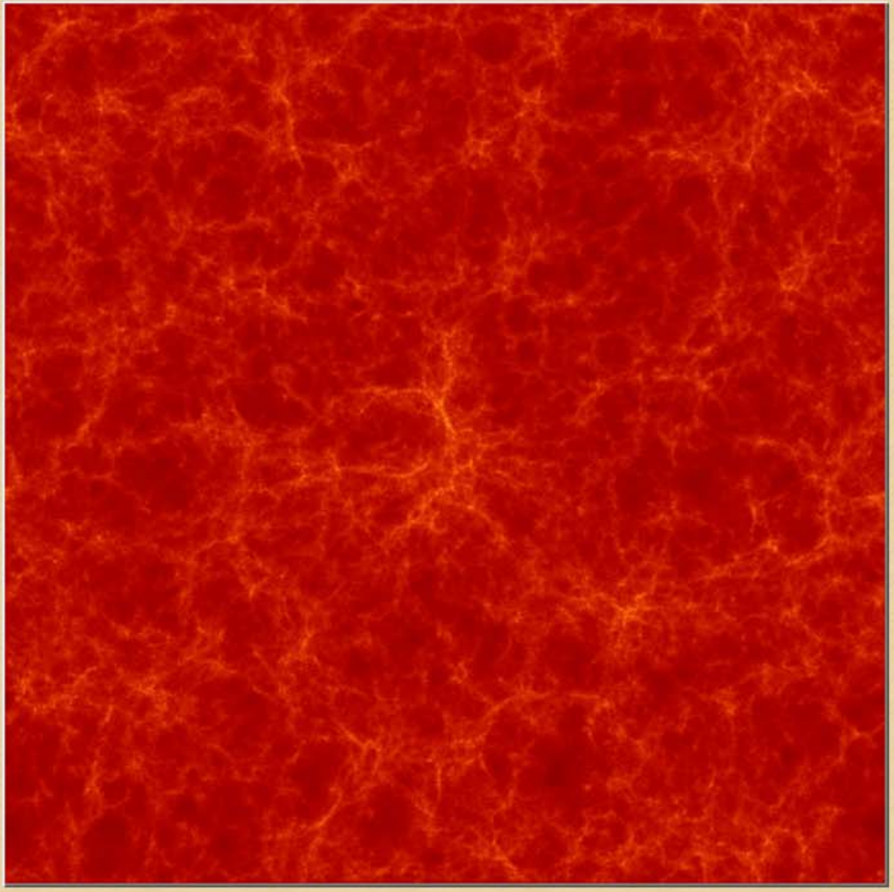


- Nus are "Hot Dark Matter"
- Ruled out
  by structure formation

Formation of Structure

Smooth → **Structured**





Formation of Structure

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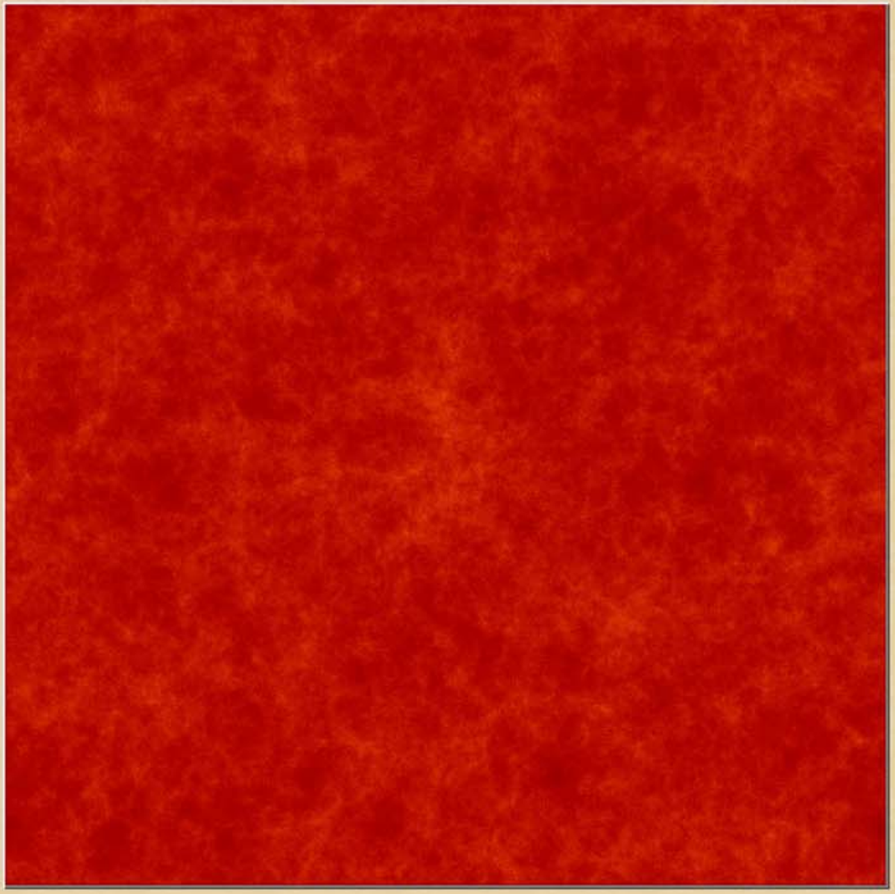
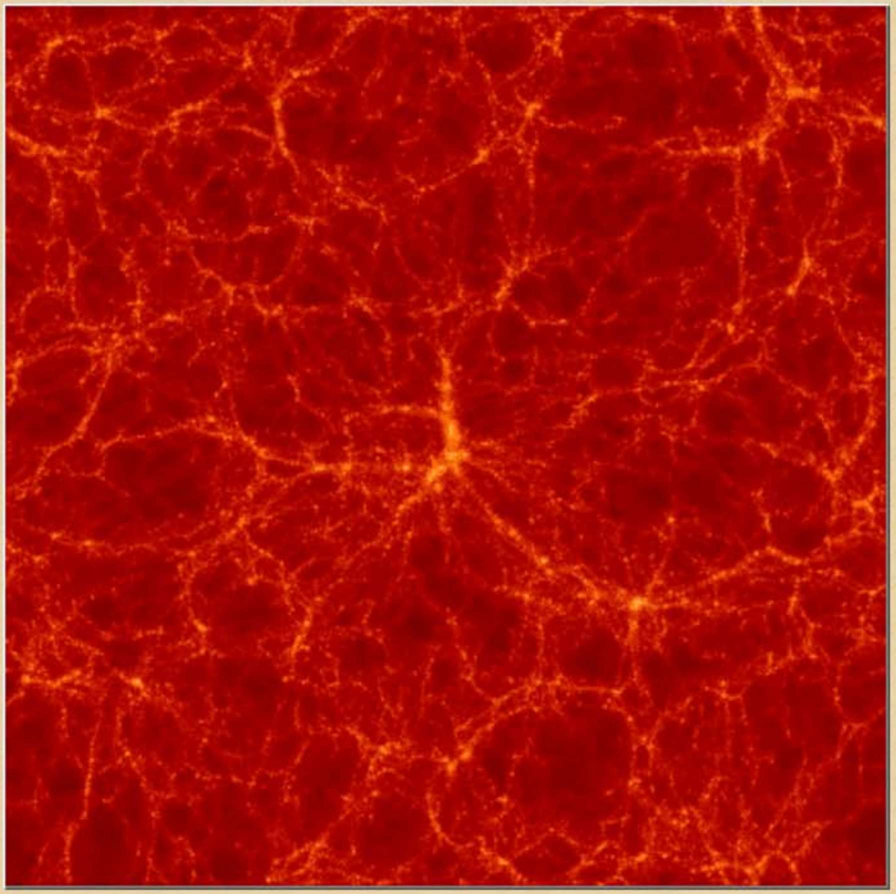
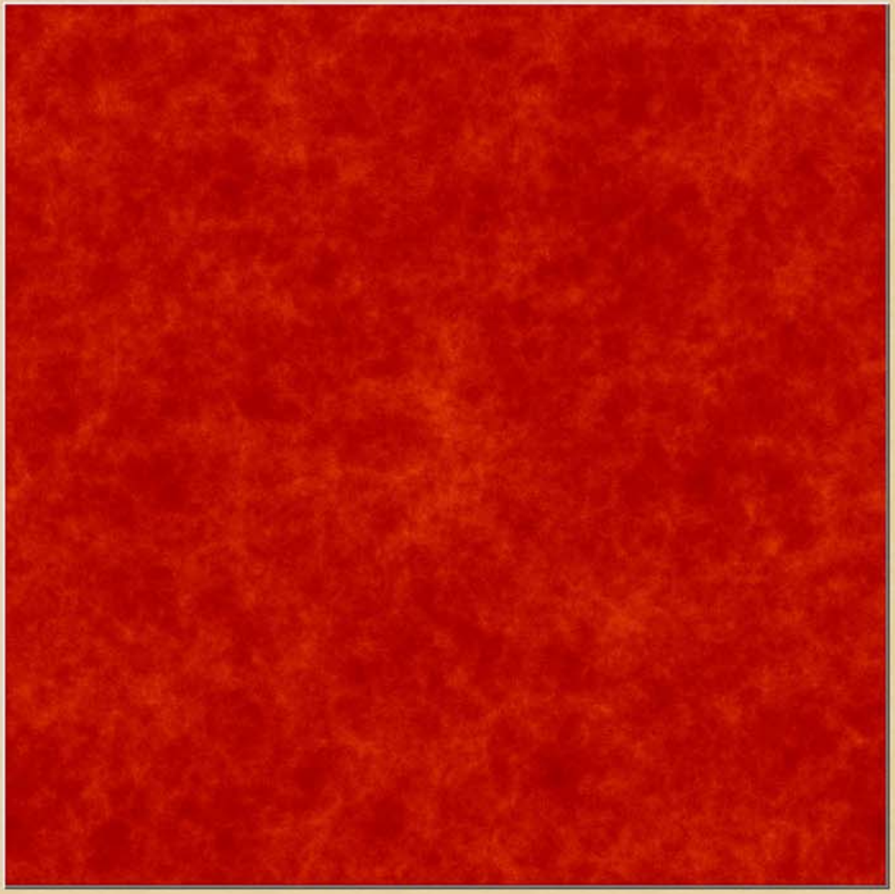


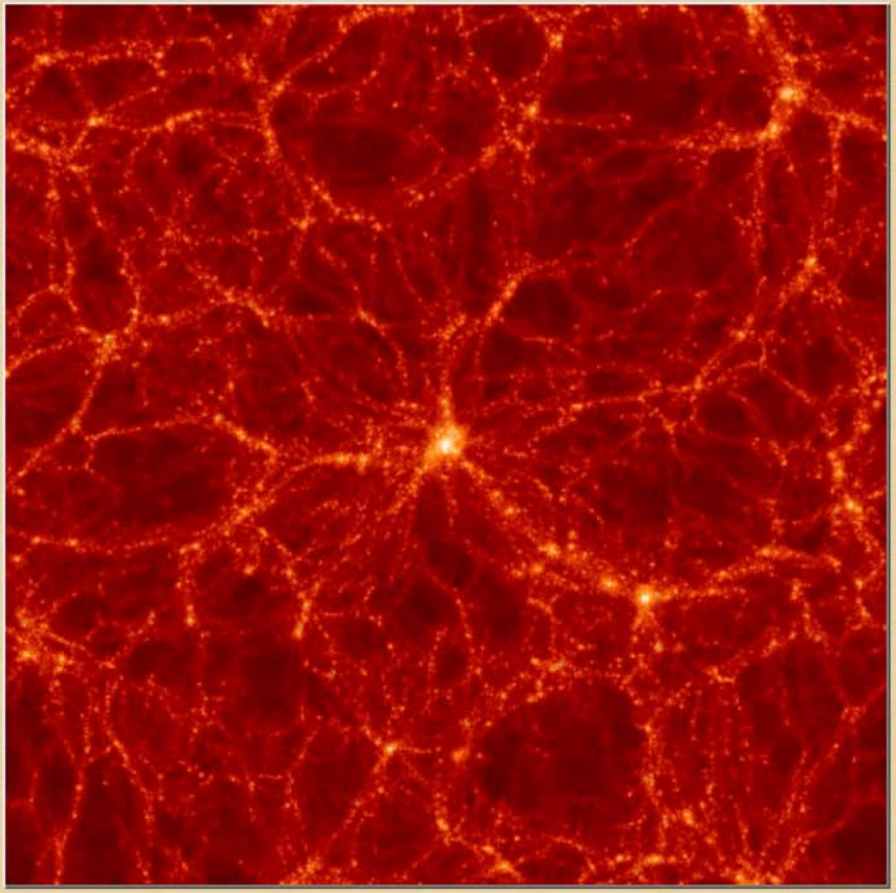


Formation of Structure

Smooth



Structured



Formation of Structure

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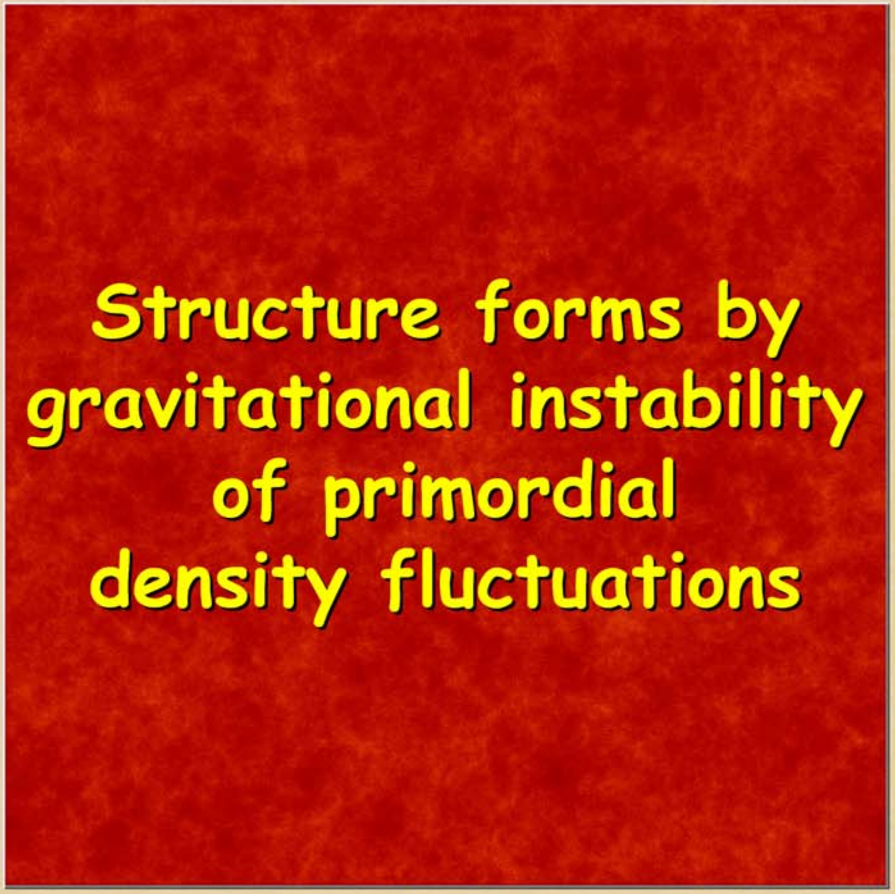
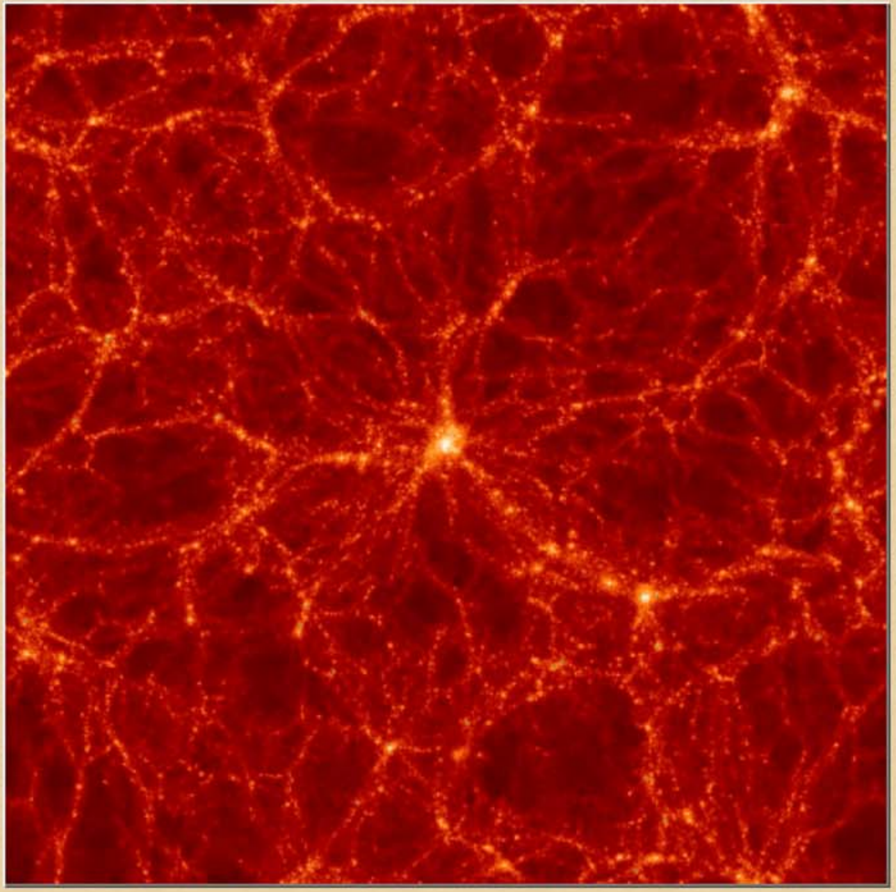


Structure forms by gravitational instability of primordial density fluctuations



Formation of Structure

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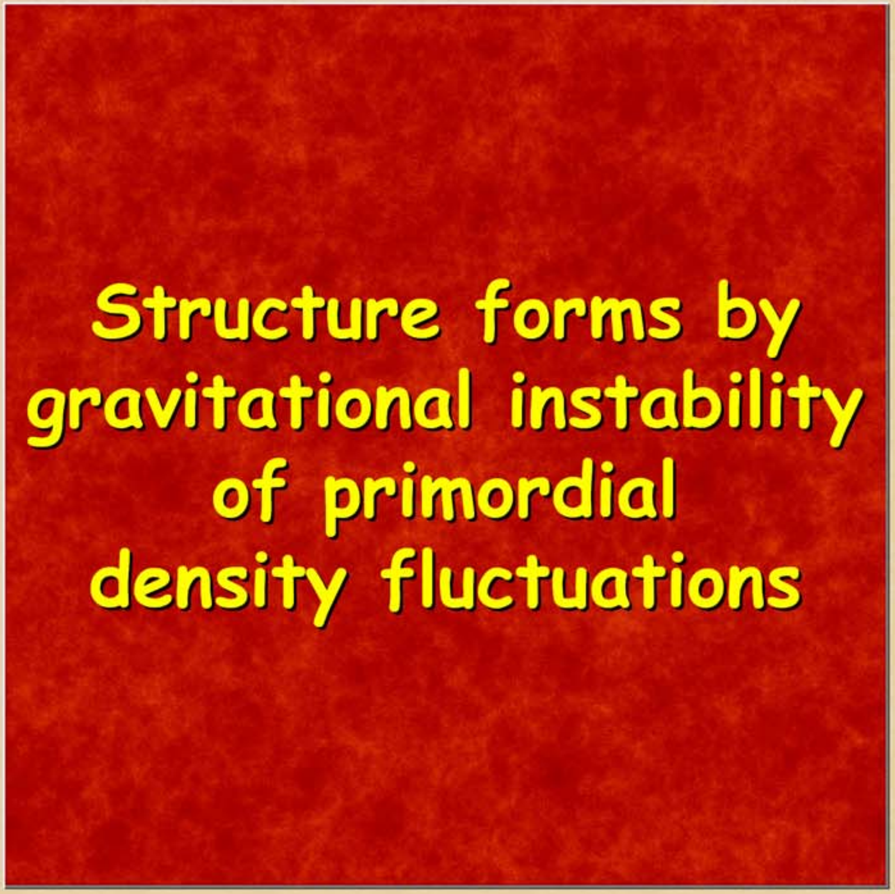

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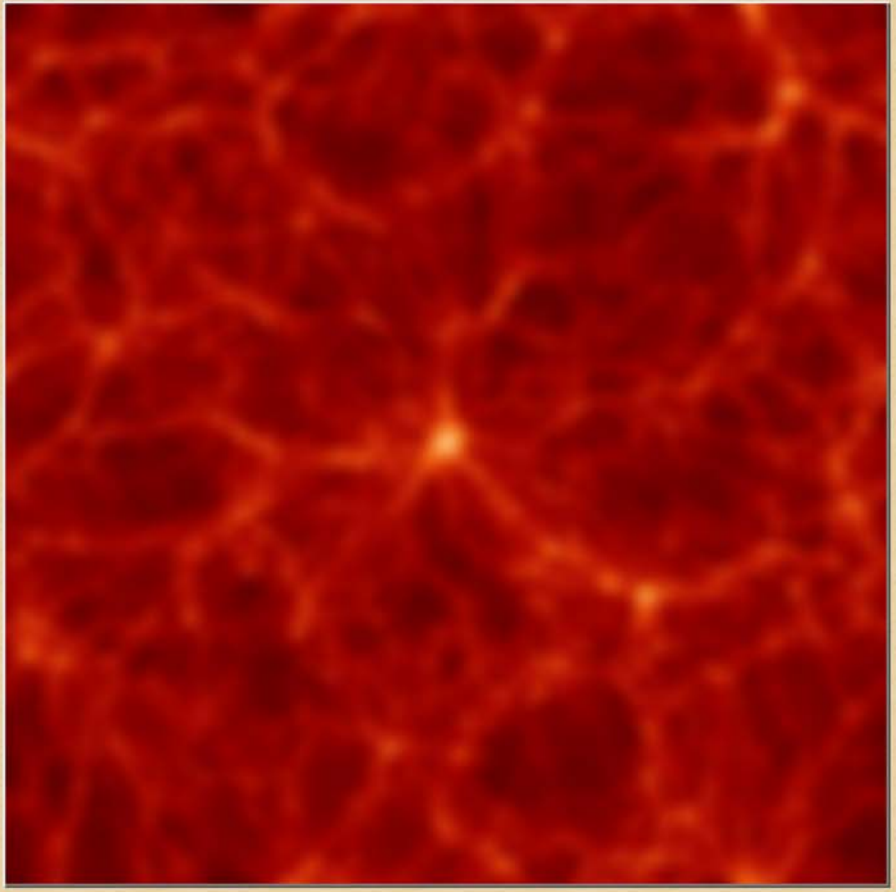
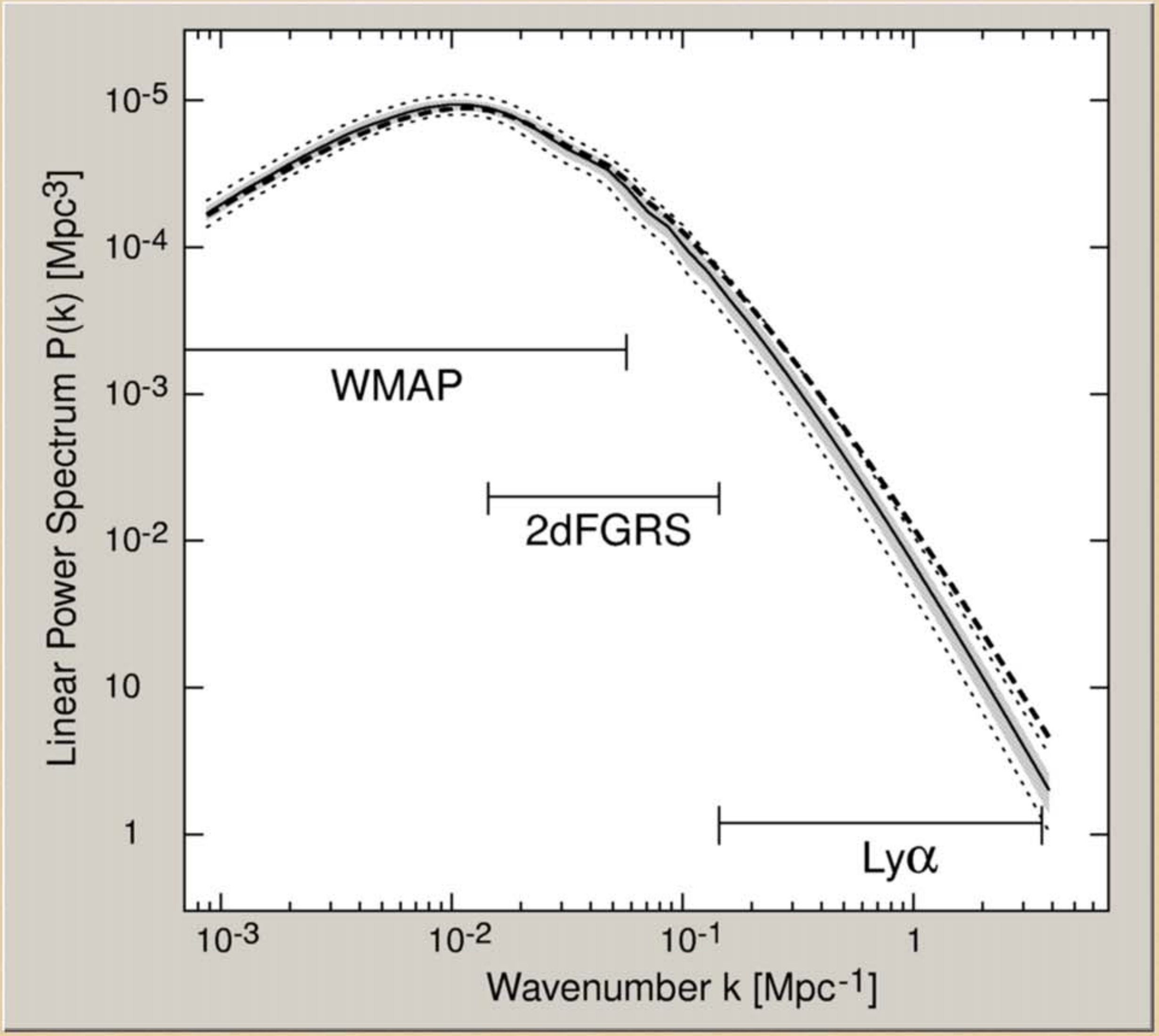


A fraction of hot dark matter suppresses small-scale structure

Probes of Cosmic Structure

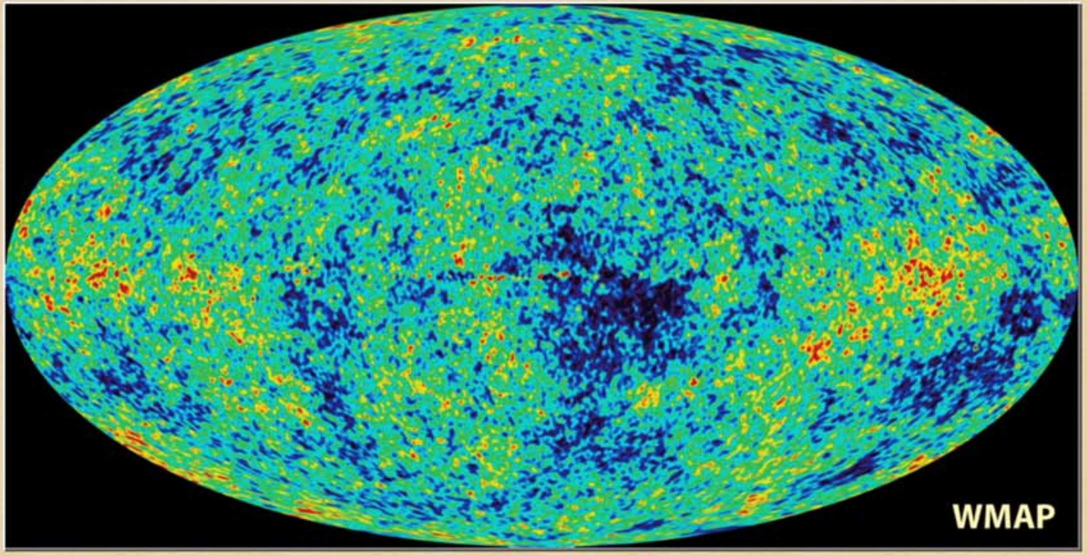


WMAP Collaboration:
First Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations:
Determination of Cosmological Parameters [astro-ph/0302209]

Power Spectrum of CMBR Temperature Fluctuations

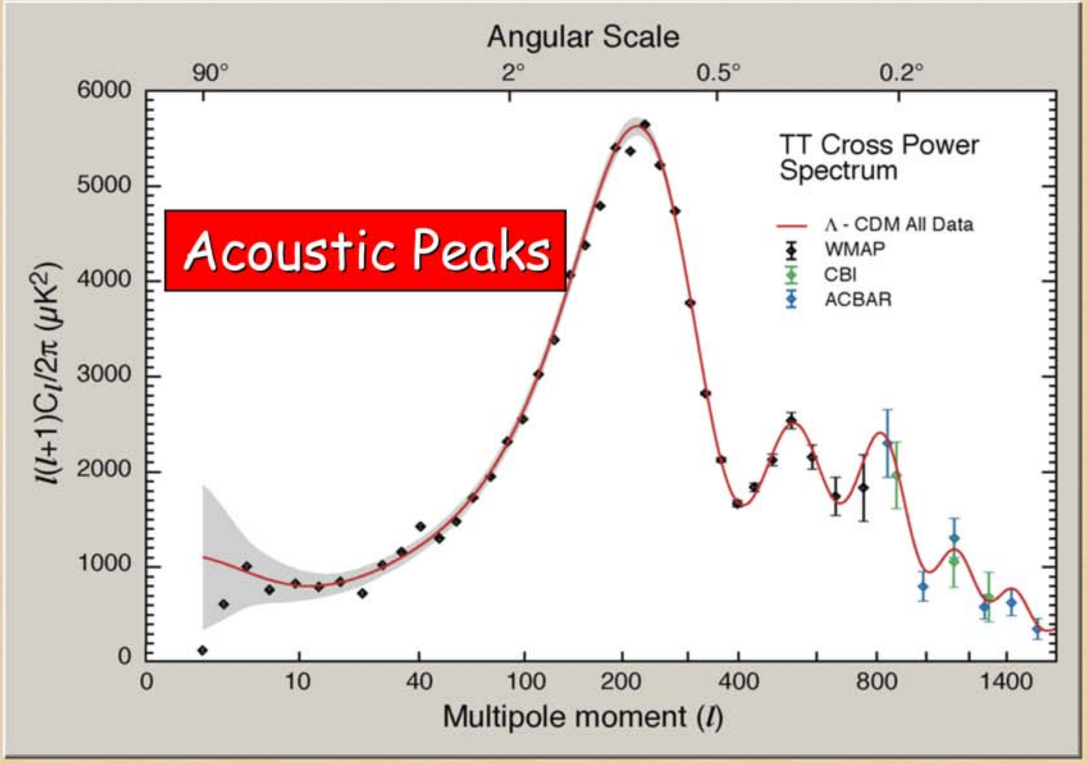
Sky map of CMBR temperature fluctuations

$$\Delta(\theta,\varphi) = \frac{T(\theta,\varphi) - \langle T \rangle}{\langle T \rangle}$$



Multipole expansion

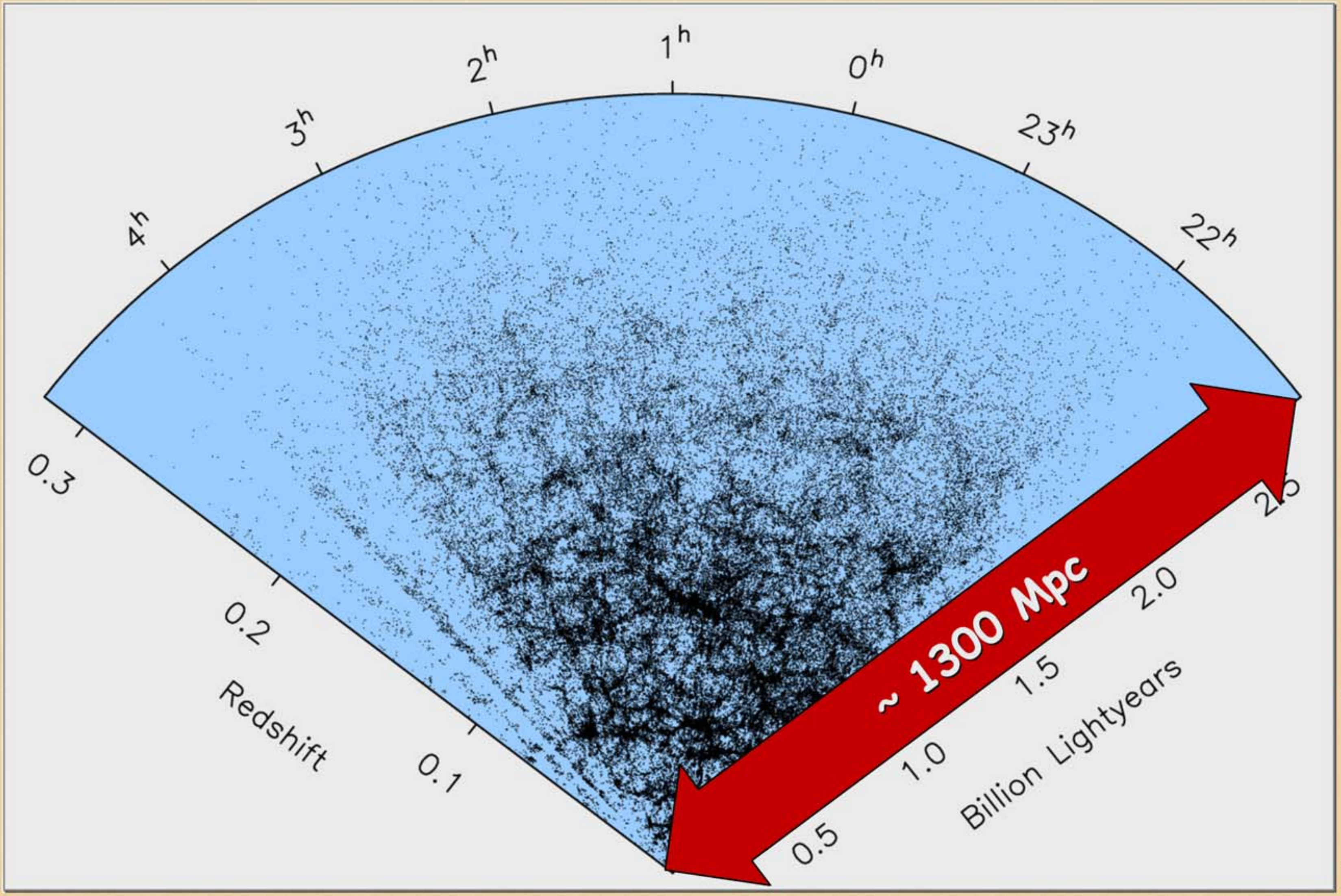
$$\Delta(\theta,\varphi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta,\varphi)$$



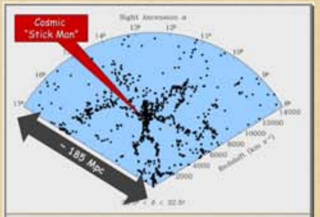
Angular power spectrum

$$C_\ell = \left\langle a^*_{\ell m} a_{\ell m} \right\rangle = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} a^*_{\ell m} a_{\ell m}$$

Galaxy Redshift Surveys



2dF Galaxy Redshift Survey (May 2002), Northern Slice
http://www.mso.anu.edu.au/2dFGRS/

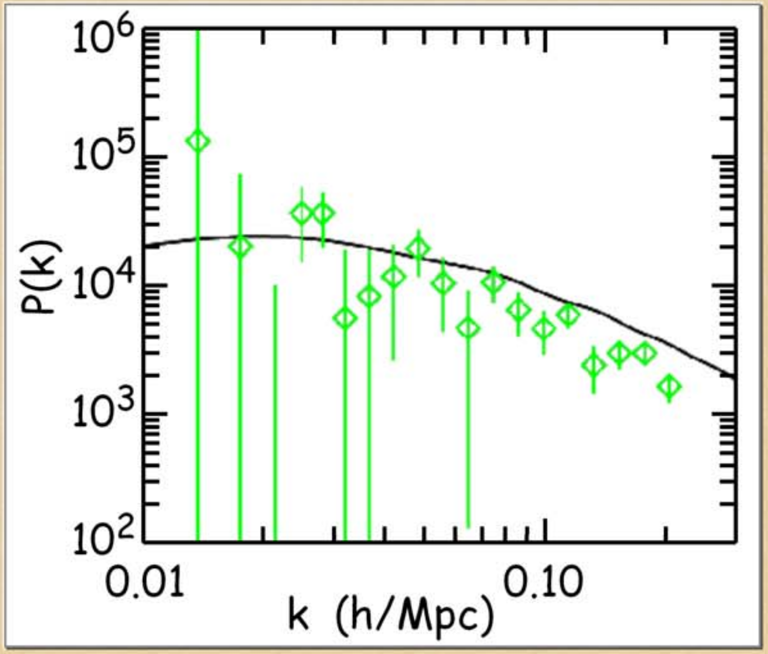


Galaxy distribution from the CfA redshift survey
[ApJ 302 (1986) L1]

Cosmic Structure Modified by Hot Dark Matter

Galaxy Distribution (2dF, PSCz)

Scales 1–200 Mpc



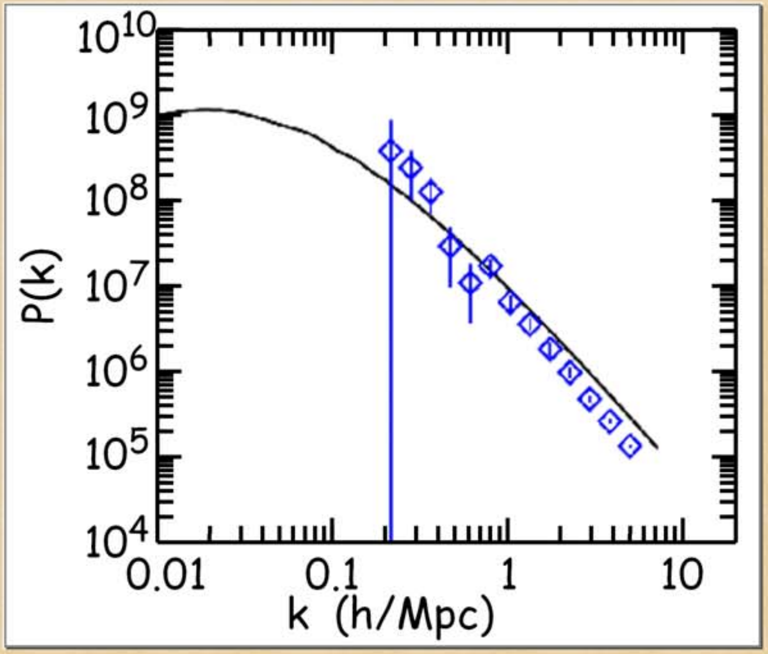
$\Omega_0 = 1$
$\Omega_\Lambda = 0.66$
$\Omega_B = 0.04$
$H_0 = 72$
$n_s = 0.94$

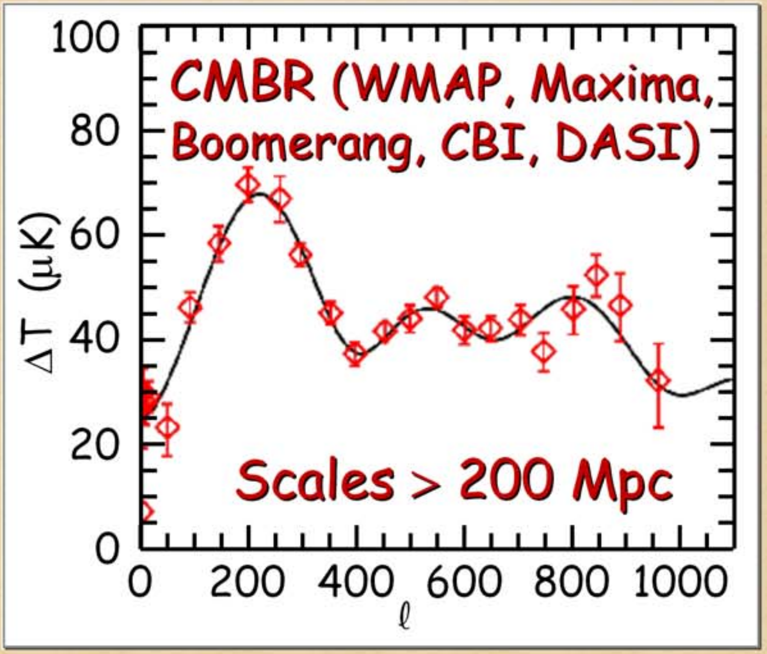
Adapted from S.Hannestad

$\Omega_\nu = 0.00$

Lyman-α forest at large redshift $\langle z \rangle = 2.72$

Scales 0.1–10 Mpc




CMBR (WMAP, Maxima, Boomerang, CBI, DASI)

Scales > 200 Mpc

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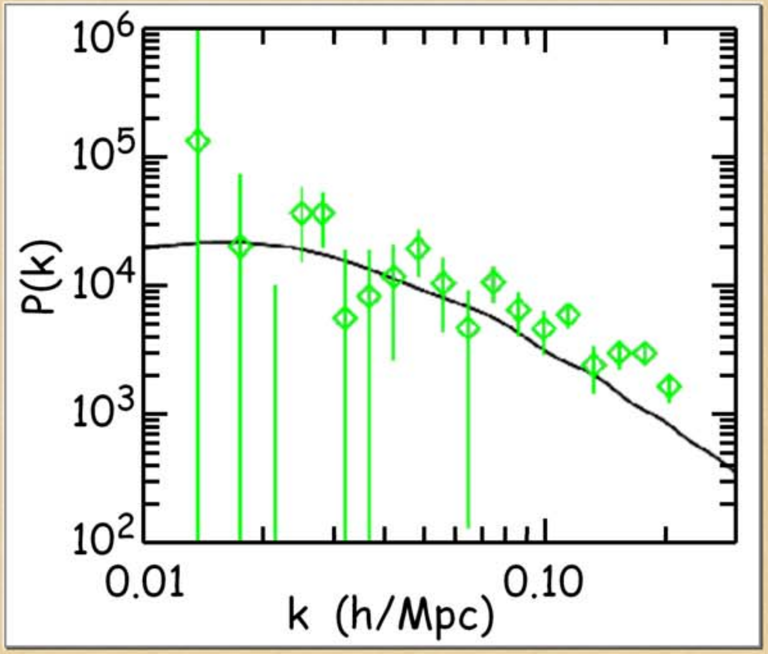
Galaxy Distribution (2dF, PSCz)

Scales 1–200 Mpc



$\Omega_0 = 1$
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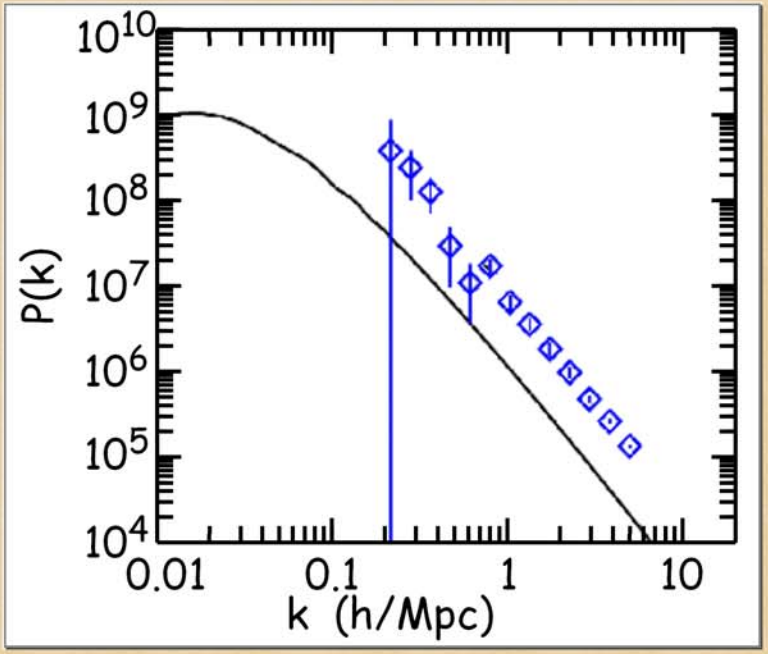
$\Omega_B = 0.04$
$H_0 = 72$
$n_s = 0.94$

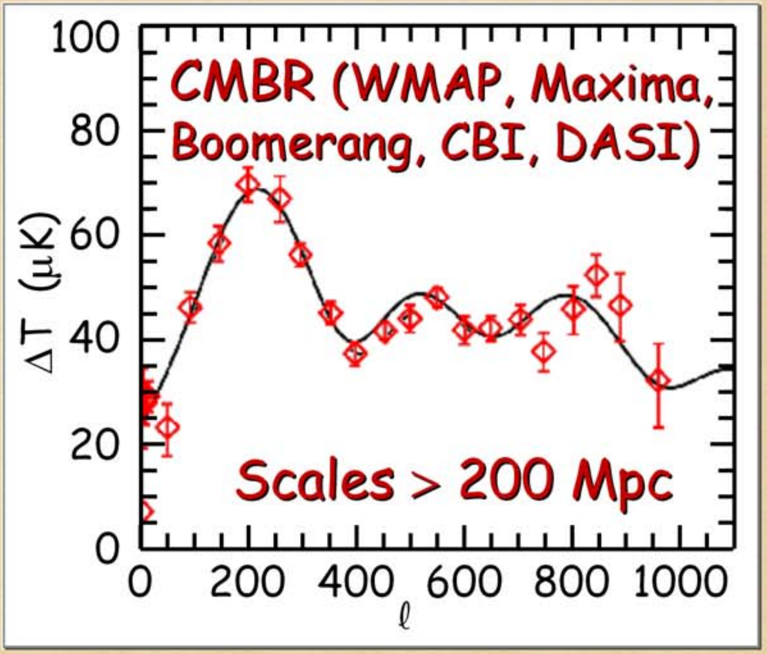
Adapted from S.Hannestad

$\Omega_\nu = 0.05$

Lyman-α forest at large redshift $\langle z \rangle = 2.72$

Scales 0.1–10 Mpc





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Scales > 200 Mpc

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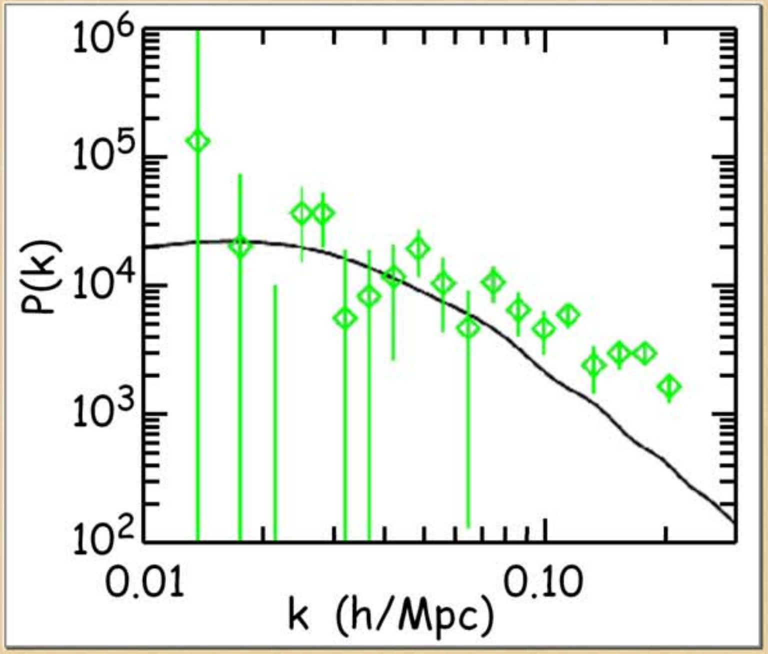
Galaxy
Distribution
(2dF, PSCz)

Scales
1–200 Mpc



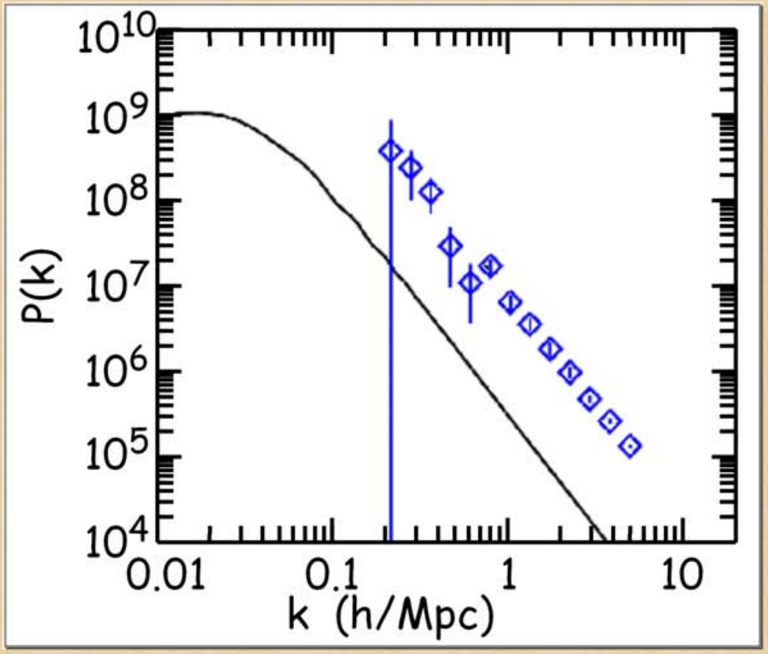
$\Omega_0 = 1$
$\Omega_\Lambda = 0.66$
$\Omega_B = 0.04$
$H_0 = 72$
$n_s = 0.94$

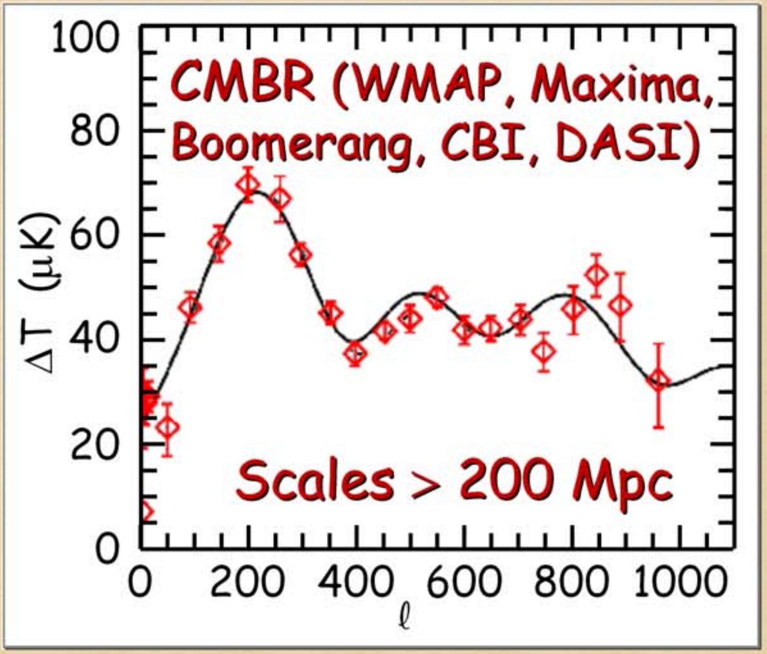
$\Omega_\nu = 0.10$

Adapted
from
S.Hannestad

Lyman-α
forest
at large
redshift
$\langle z \rangle = 2.72$

Scales
0.1–10 Mpc





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Galaxy
Distribution
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Scales
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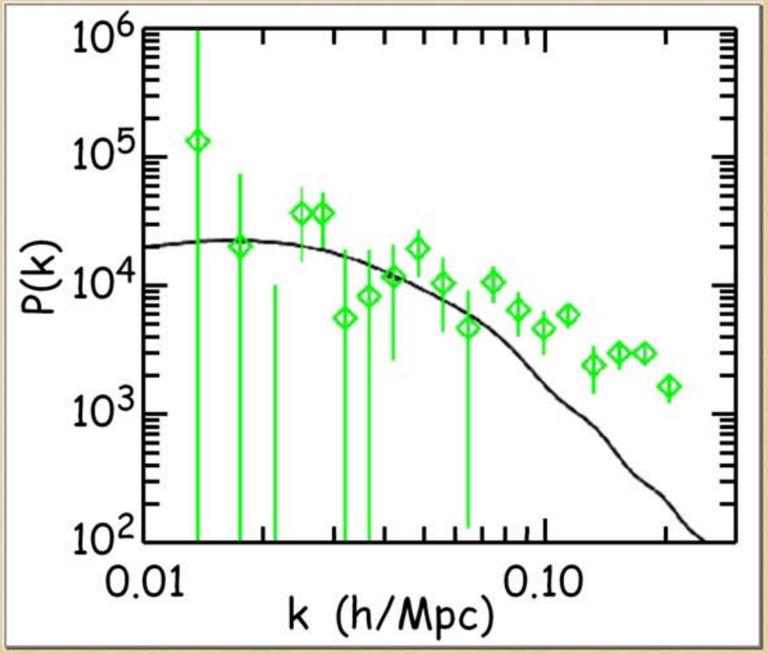

$\Omega_0 = 1$
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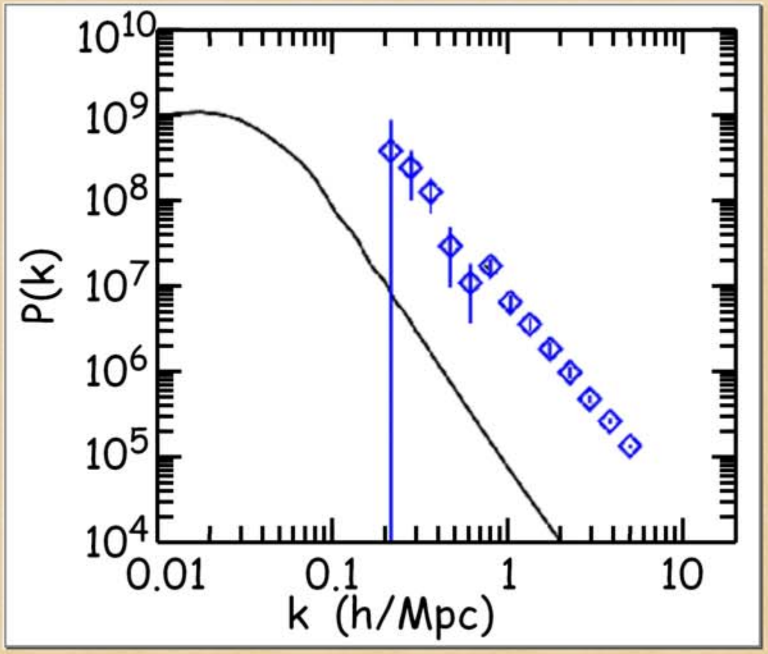
$\Omega_B = 0.04$
$H_0 = 72$
$n_s = 0.94$

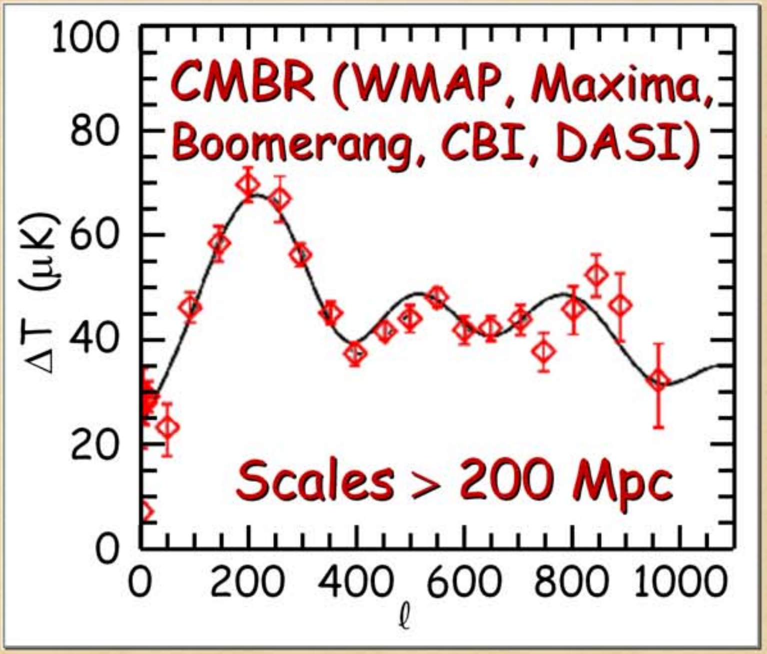
Adapted
from
S.Hannestad

$\Omega_\nu = 0.15$

Lyman-α
forest
at large
redshift
$\langle z \rangle = 2.72$

Scales
0.1–10 Mpc





CMBR (WMAP, Maxima, Boomerang, CBI, DASI)

Scales > 200 Mpc

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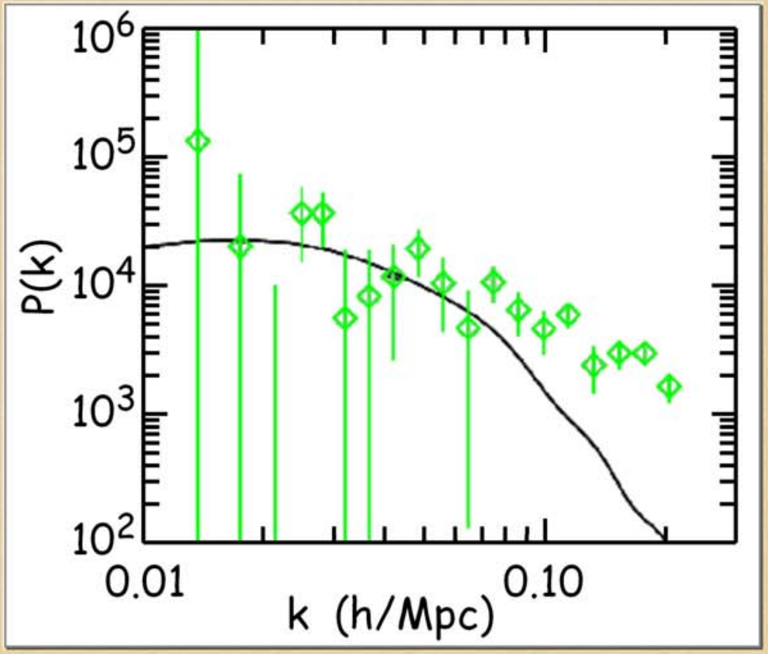
Galaxy
Distribution
(2dF, PSCz)

Scales
1–200 Mpc



$\Omega_0 = 1$
$\Omega_\Lambda = 0.66$
$\Omega_B = 0.04$
$H_0 = 72$
$n_s = 0.94$

$\Omega_\nu = 0.20$

Adapted
from
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Lyman-α
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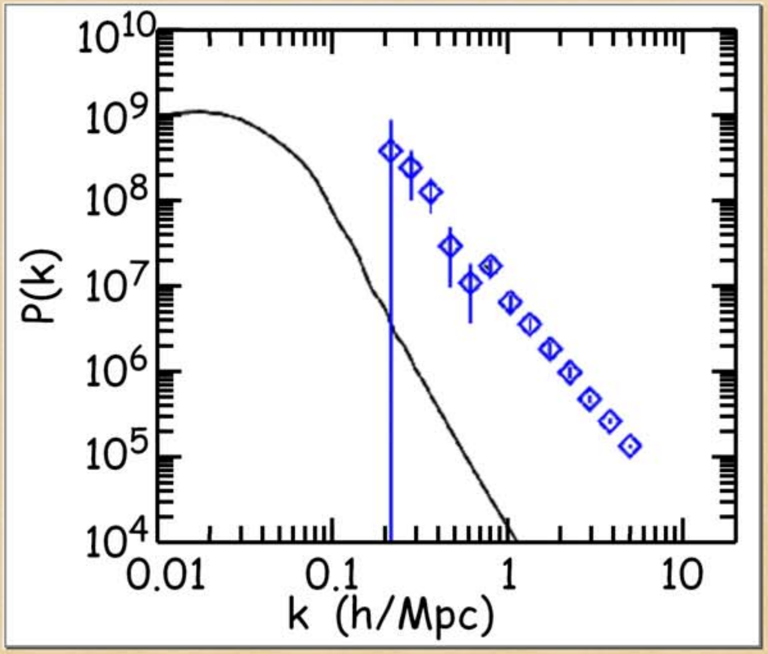
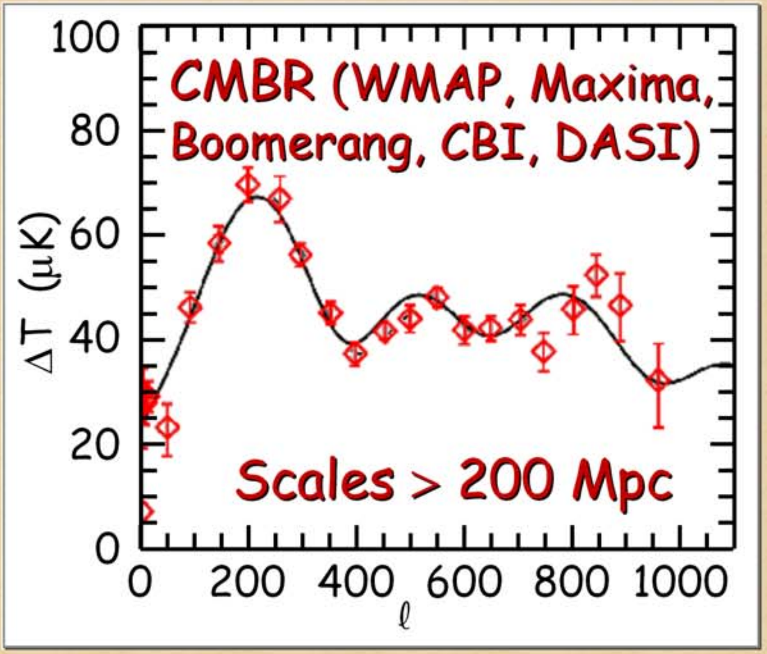
Scales
0.1–10 Mpc





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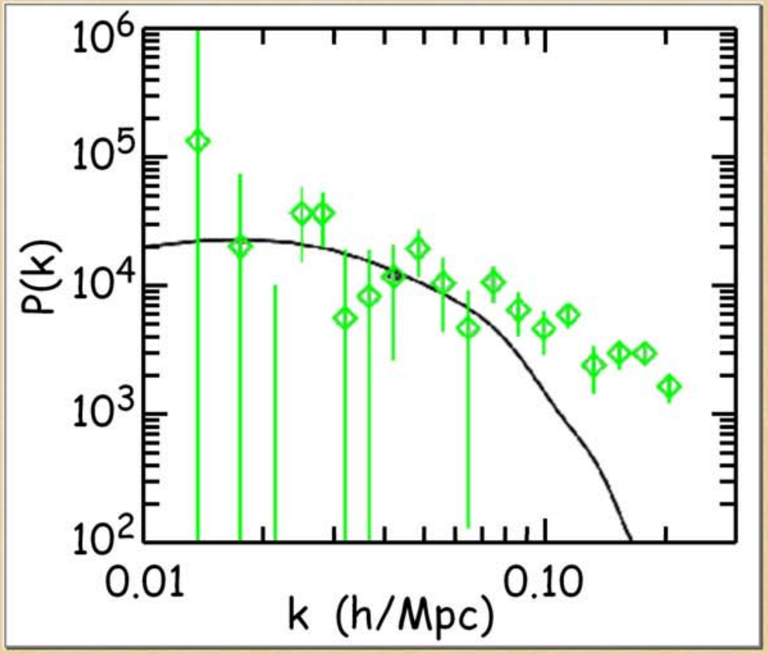


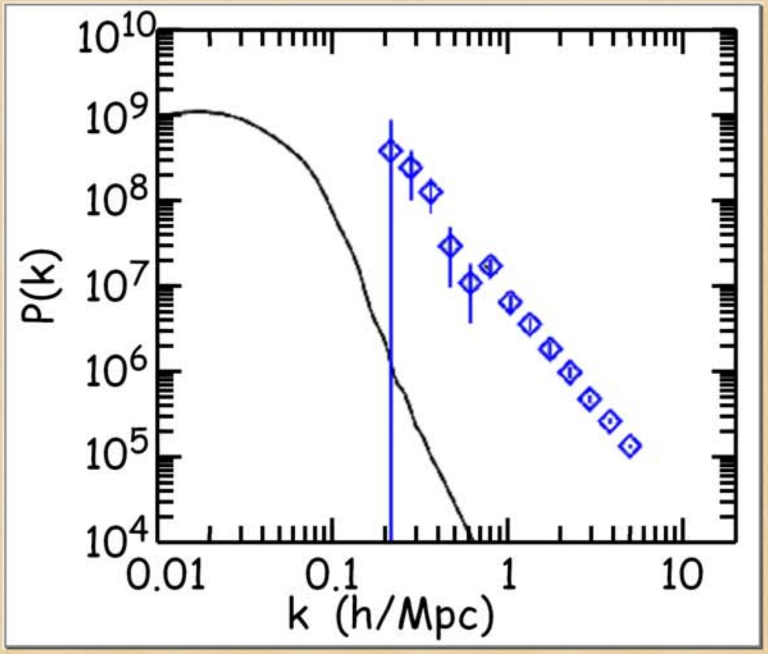
$\Omega_0 = 1$
$\Omega_\Lambda = 0.66$
$\Omega_B = 0.04$
$H_0 = 72$
$n_s = 0.94$

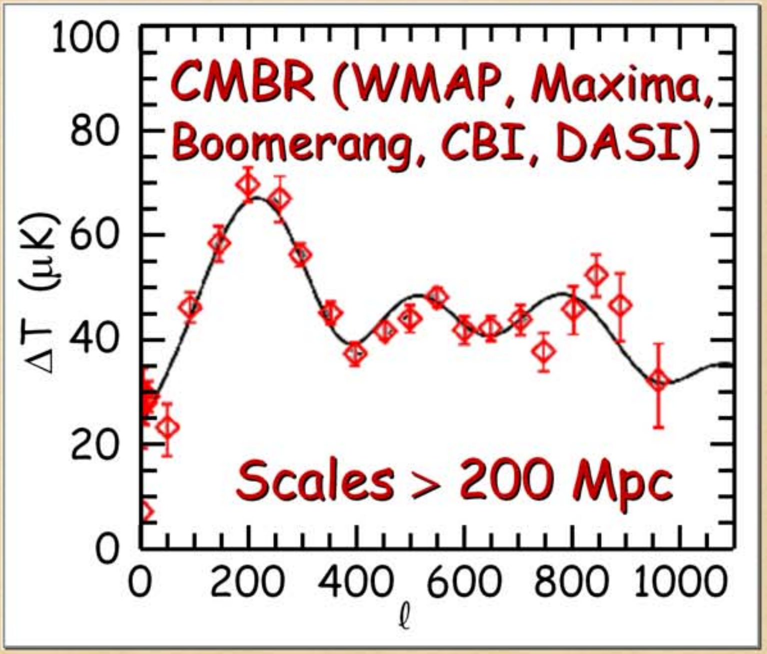
$\Omega_\nu = 0.25$

Adapted from S.Hannestad

Lyman-α forest at large redshift $\langle z \rangle = 2.72$

Scales 0.1–10 Mpc





CMBR (WMAP, Maxima, Boomerang, CBI, DASI)

Scales > 200 Mpc

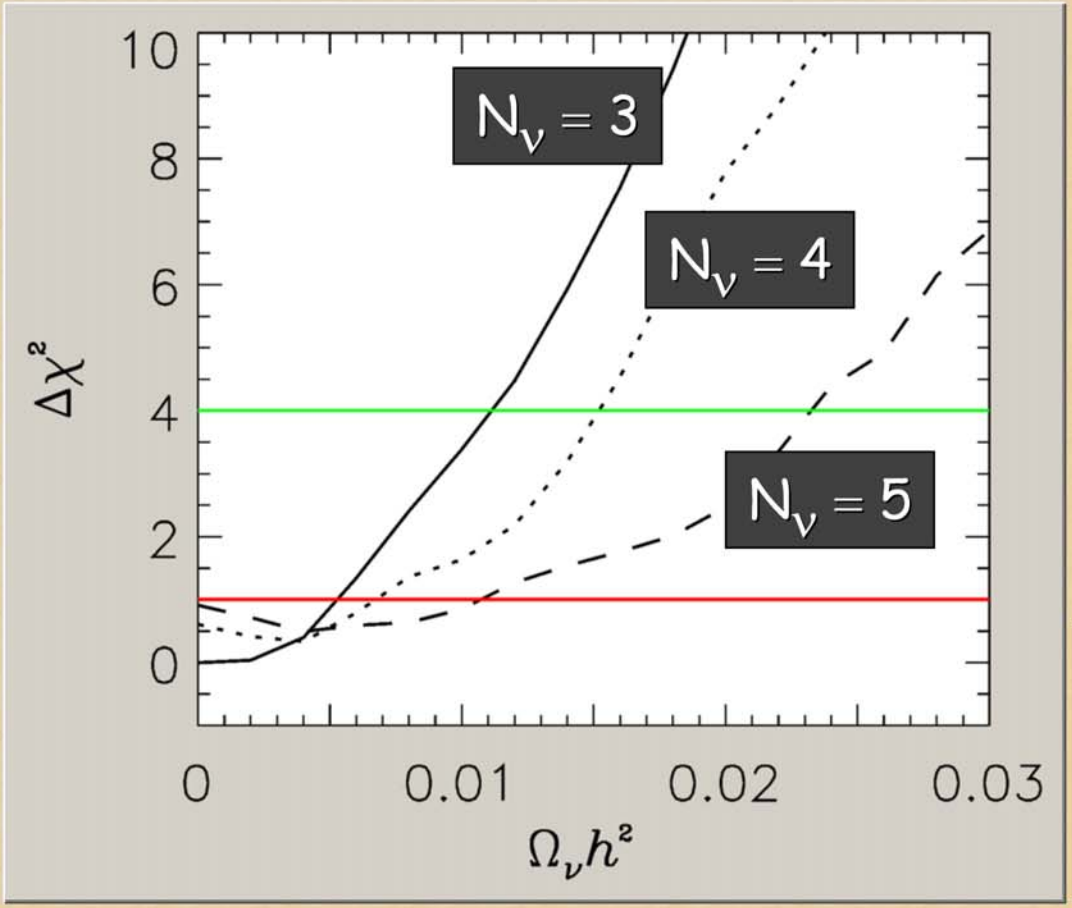
Neutrino Mass Limits from Large-Scale Structure

Statistical 95% C.L. limits depend on used data and on priors for other parameters. For detailed analyses see

- Hannestad, astro-ph/0303076
- Elgaroy & Lahav, astro-ph/0303089

$\Sigma m_\nu < 2.1$ eV	WMAP (Cosmic microwaves) 2dF (Galaxy-galaxy correlation)
$\Sigma m_\nu < 1.2$ eV	+ Small-scale CMBR (breaks degeneracy with bias)
$\Sigma m_\nu < 1.0$ eV	+ Priors (1σ) $h = 0.72 \pm 0.08$ $\Omega_M = 0.28 \pm 0.14$
$\Sigma m_\nu < 0.7$ eV	+ Lyman-α forest data

Cosmological Mass Limit vs. Neutrino Density



$\sum m_\nu \leq 1.0$ eV (95% C.L.) for $N_\nu = 3$

$\sum m_\nu \leq 1.4$ eV (95% C.L.) for $N_\nu = 4$

$\sum m_\nu \leq 2.1$ eV (95% C.L.) for $N_\nu = 5$

S. Hannestad, "Neutrino masses and the number of neutrino species from WMAP and 2dFGRS", JCAP 05 (2003) 004 [astro-ph/0303076]

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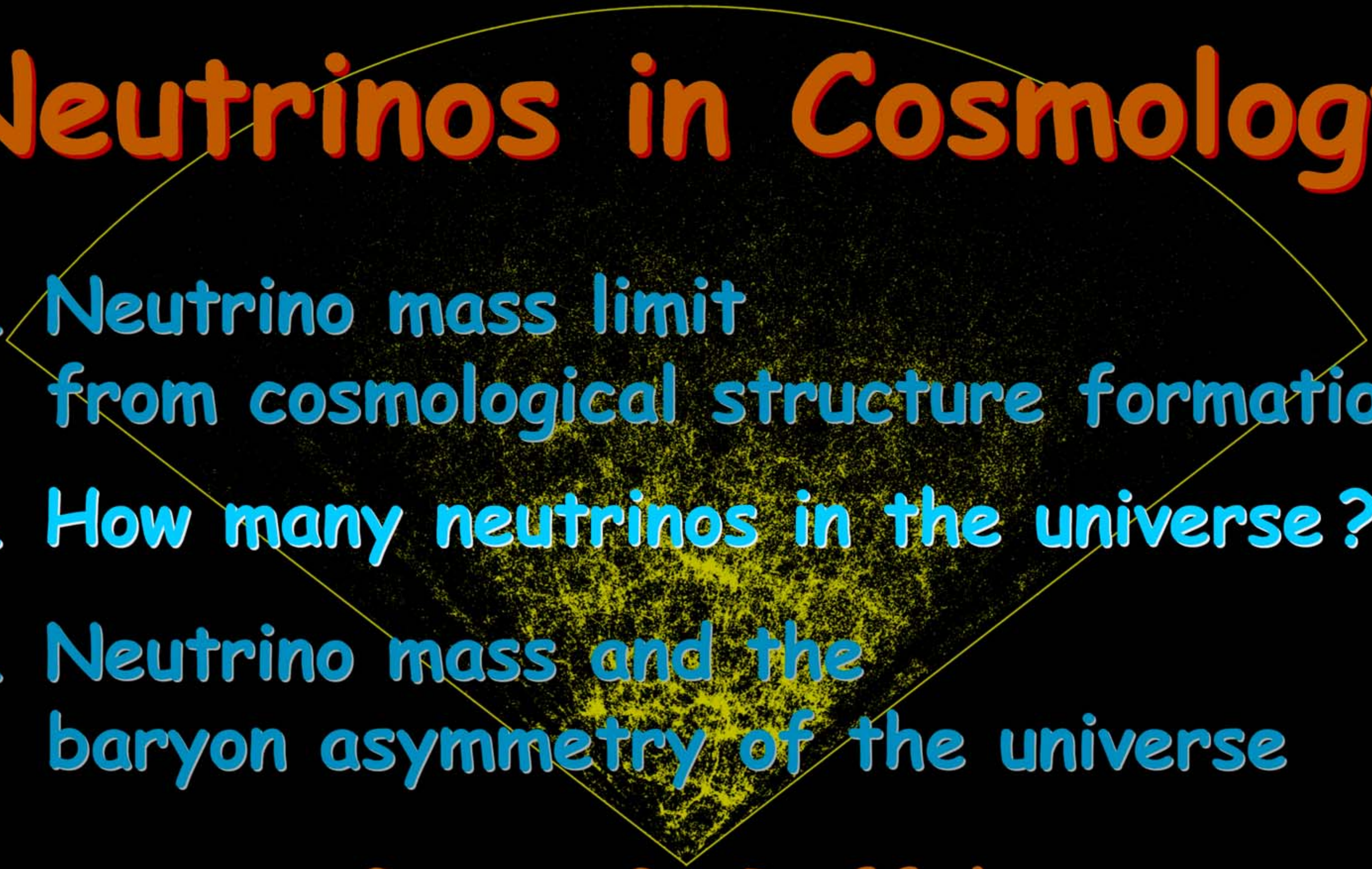

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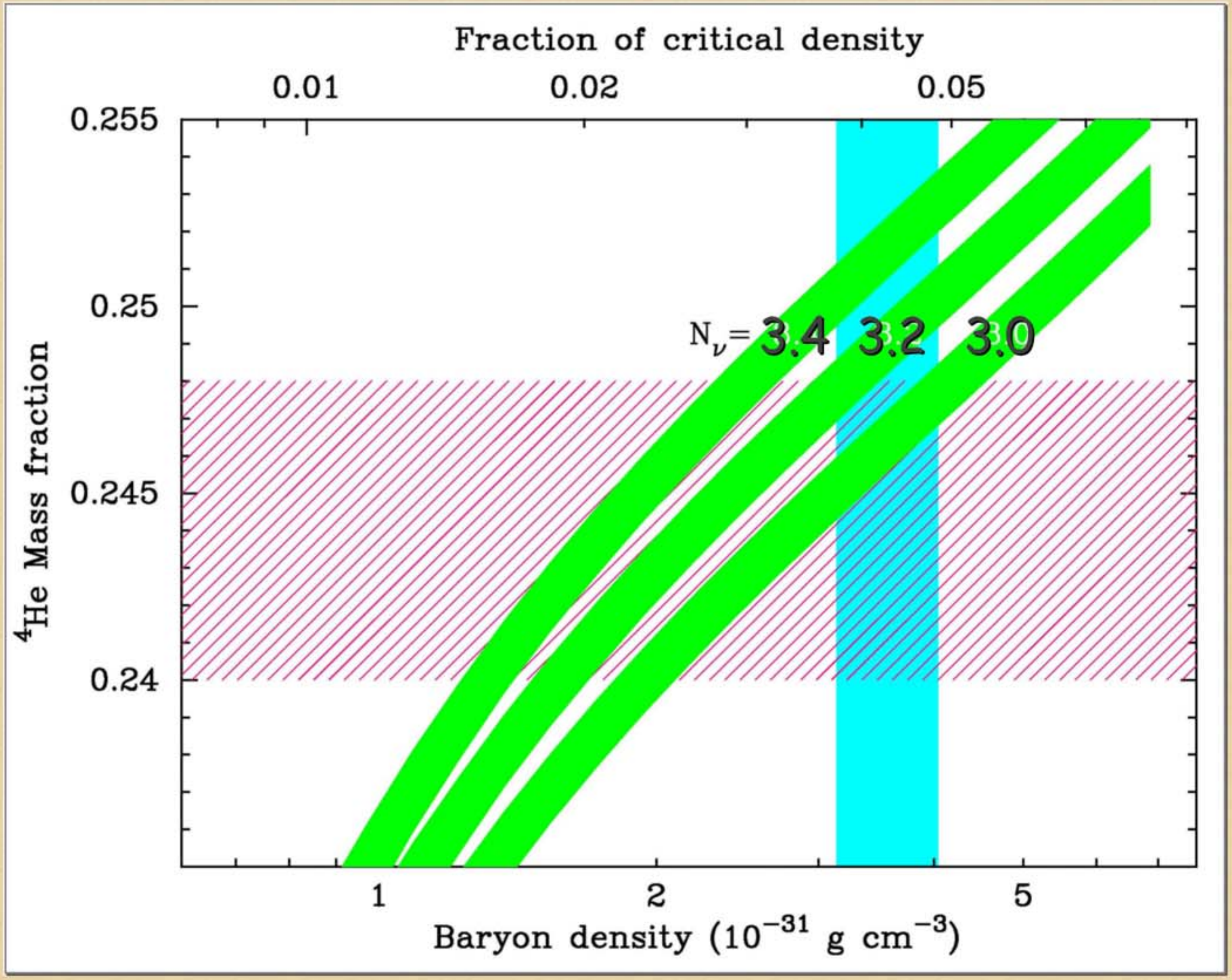
Max-Planck-Institut für Physik, München, Germany

How Many Relic Neutrinos?

Standard thermal population in one flavor $n_{\nu\overline{\nu}} = \frac{3}{11} n_\gamma \approx 112\,\mathrm{cm}^{-3}$

Additional active neutrinos beyond standard population of ν_e, ν_μ, ν_τ	Additional families	Excluded by Z^0 width ($N_\nu = 3$)
	Chemical potentials for ν_e, ν_μ, ν_τ	Possible
Sterile (right-handed) states Populated by $\nu_L \to \nu_R$ transitions	Dirac mass	Not effective in sub-eV range
	Right-handed currents	Excluded by energy loss of SN 1987A
	Electromagnetic dipole moments	Excluded by energy loss of globular cluster stars
	Oscillations/collisions	Hot/warm/cold DM possible

BBN Limits on Neutrino Flavors



- At BBN one flavor contributes about 16% to cosmic mass-energy density
- Extra flavors modify expansion parameter accordingly

Conservative limit

$|\Delta N_{\rm eff}| < 1$

Burles, Nollett & Turner, astro-ph/9903300

BBN and Neutrino Chemical Potentials

Expansion Rate Effect (all flavors)

Energy density in one neutrino flavor with degeneracy parameter $\xi = \eta/T$

$$\rho_{\nu\bar{\nu}} = \frac{7\pi^2}{120} T_\nu^4 \left[1 + \underbrace{\frac{30}{7}\left(\frac{\xi}{\pi}\right)^2 + \frac{15}{7}\left(\frac{\xi}{\pi}\right)^4}_{\Delta N_{\mathrm{eff}}}\right]$$

Beta equilibrium effect for electron flavor

$$n + \nu_e \leftrightarrow p + e^-$$

Helium abundance essentially fixed by n/p ratio at beta freeze-out

$$\frac{n}{p} = e^{-(m_n - m_p)/T - \xi_{\nu_e}}$$

Effect on helium equivalent to $\Delta N_{\mathrm{eff}} \sim -18\,\xi_{\nu e}$

$|\Delta N_{\mathrm{eff}}| < 1$ → $|\xi_{\nu e}| < 0.06$

- ν_e beta effect can compensate expansion-rate effect of $\nu_{\mu,\tau}$
- No significant BBN limit on neutrino number density

Chemical Potentials and Flavor Oscillations

Flavor mixing (neutrino oscillations)

Flavor lepton numbers not conserved

Only one common nu chemical potential

Stringent ξ_{ν_e} limit applies to all flavors

$|\xi_{\nu_{e,\mu,\tau}}| < 0.07$

Extra neutrino density

$\Delta N_{\rm eff} < 0.0064$

Cosmic neutrino density close to standard value

Flavor equilibrium before n/p freeze out?

yes	Solar LMA solution
maybe	LOW (depends on Θ_{13})
no	SMA or VAC

- Our knowledge of the cosmic nu density depends on the solution of the solar neutrino problem
- KamLAND most relevant experiment

- Lunardini & Smirnov, hep-ph/0012056
- Dolgov, Hansen, Pastor, Petcov, Raffelt & Semikoz, hep-ph/0201287
- Abazajian, Beacom & Bell, astro-ph/0203442
- Wong, hep-ph/0203180

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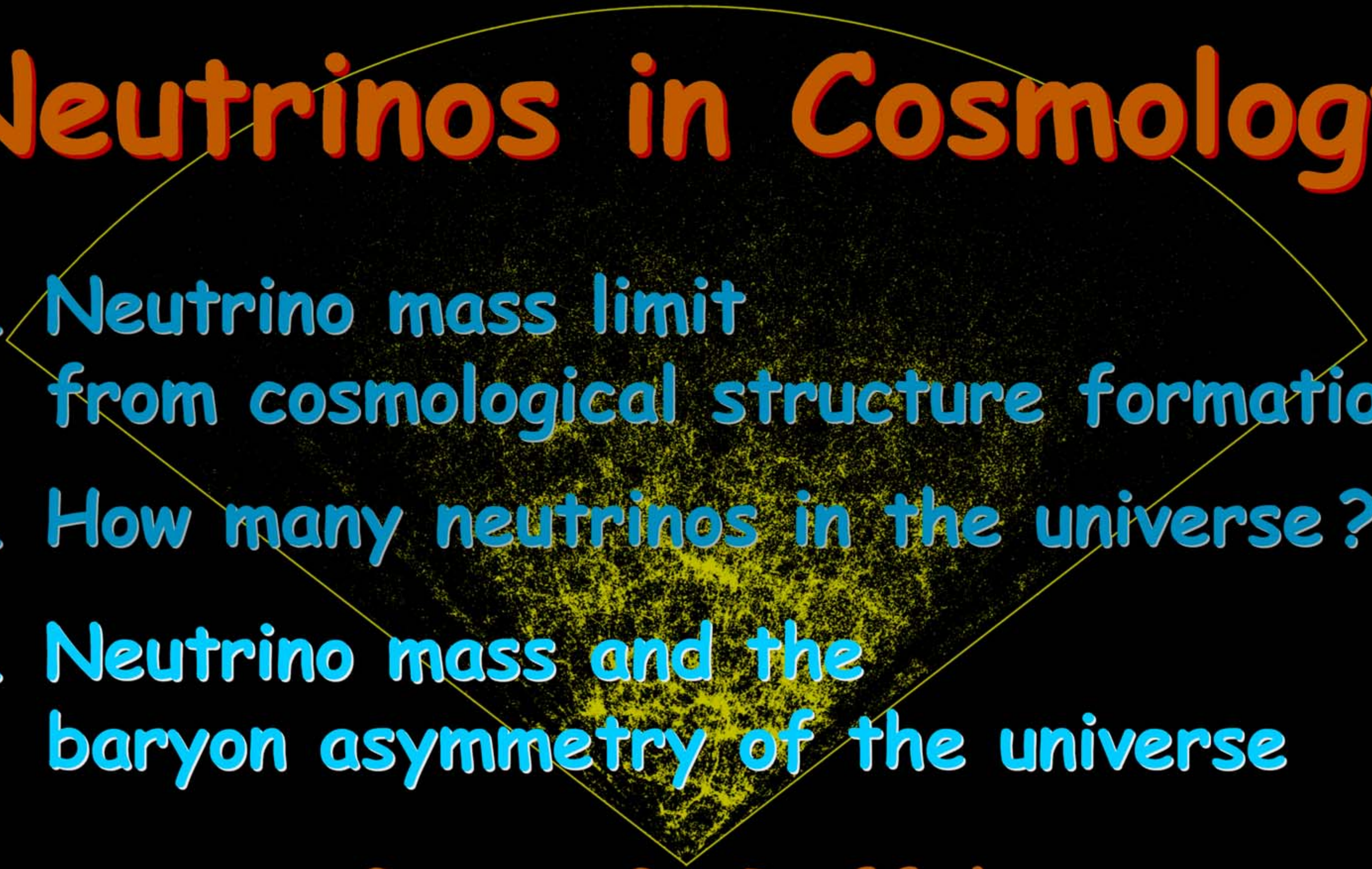

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Baryogenesis in the Early Universe

Andrei Sakharov
1921 - 1989

Sakharov conditions for creating the Baryon Asymmetry of the Universe (BAU)

- C and CP violation
- Baryon number violation
- Deviation from thermal equilibrium

Particle-physics standard model

- Violates C and CP
- Violates B and L by EW instanton effects (B – L conserved)

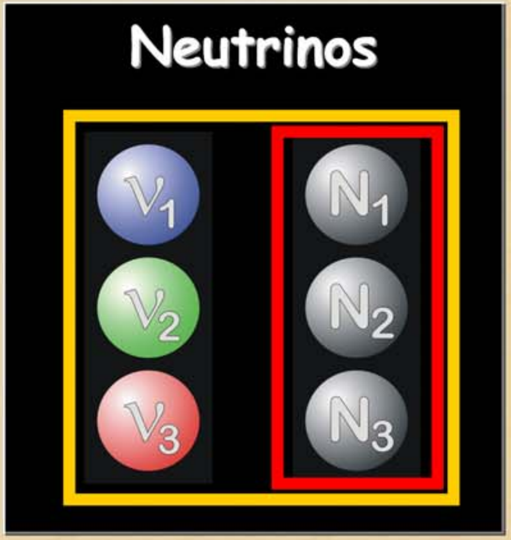
- However, electroweak baryogenesis not quantitatively possible within particle-physics standard model
- Works in SUSY models for small range of parameters

A.Riotto & M.Trodden: Recent progress in baryogenesis
Ann. Rev. Nucl. Part. Sci. 49 (1999) 35

See-Saw Model for Neutrino Masses

Dirac masses from coupling to standard Higgs field ϕ


Charged Leptons


Neutrinos

Heavy Majorana masses $M_j > 10^{10}$ GeV

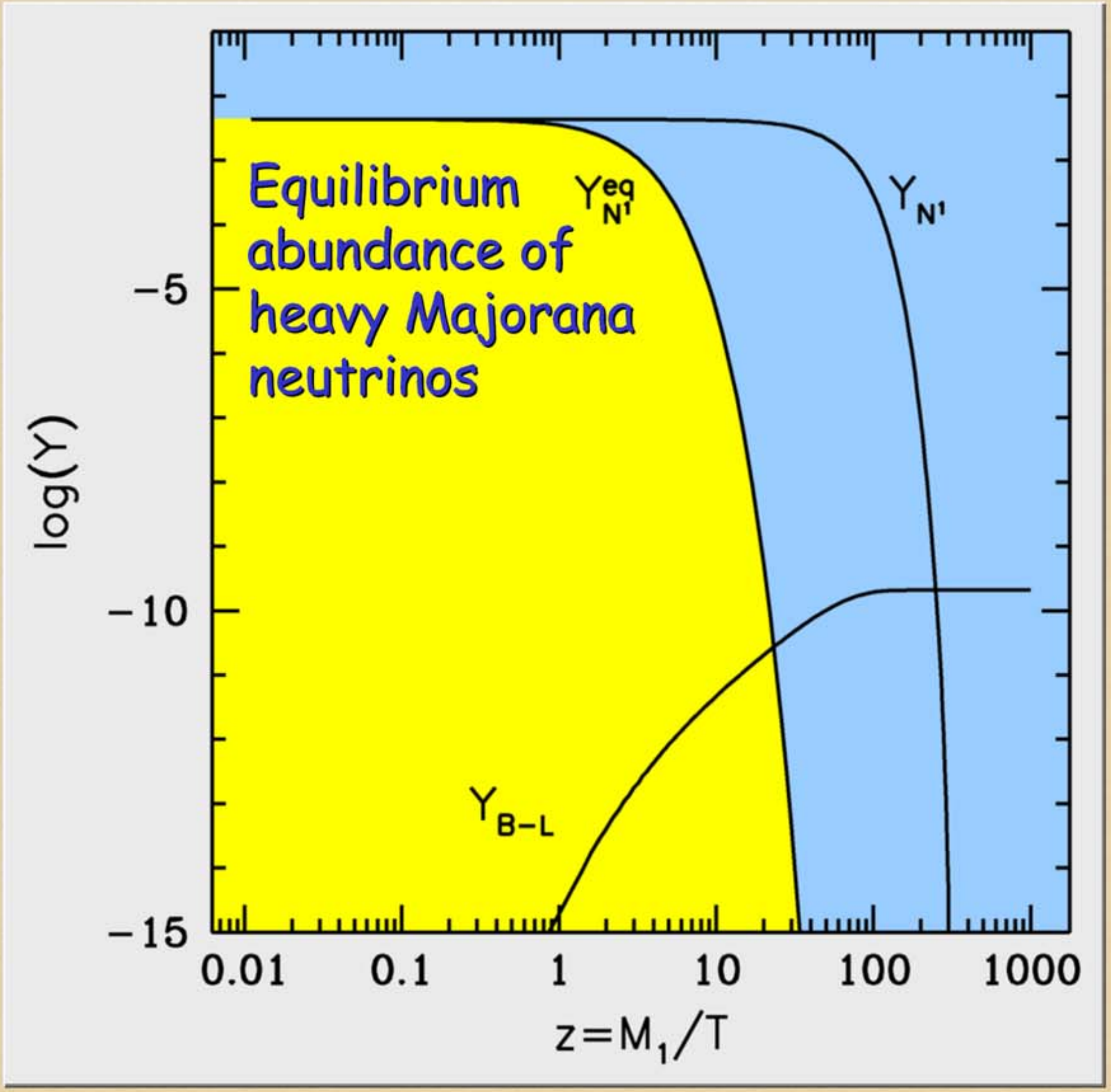
Lagrangian for particle masses

$$\mathcal{L}_{\rm mass} = -\bar{\ell}_L \phi\, g_\ell\, e_R - \bar{\ell}_L \phi\, g_\nu N_R - \frac{1}{2}\overline{N_R^c} M N_R + \text{h.c.}$$

Light Majorana mass

$$\begin{pmatrix}\bar{\nu}_L & \bar{N}_R\end{pmatrix}\begin{pmatrix}0 & g_\nu\langle\phi\rangle \\ g_\nu\langle\phi\rangle & M\end{pmatrix}\begin{pmatrix}\nu_L \\ N_R\end{pmatrix} \xrightarrow{\text{Diagonalize}} \begin{pmatrix}\bar{\nu}_L & \bar{N}_R\end{pmatrix}\begin{pmatrix}\frac{g_\nu^2\langle\phi\rangle^2}{M} & 0 \\ 0 & M\end{pmatrix}\begin{pmatrix}\nu_L \\ N_R\end{pmatrix}$$

Leptogenesis by Out-of-Equilibrium Decay



M. Fukugita & T. Yanagida:
Baryogenesis without Grand Unification
Phys. Lett. B 174 (1986) 45

W. Buchmüller & M. Plümacher: Neutrino masses and the baryon asymmetry
Int. J. Mod. Phys. A15 (2000) 5047-5086

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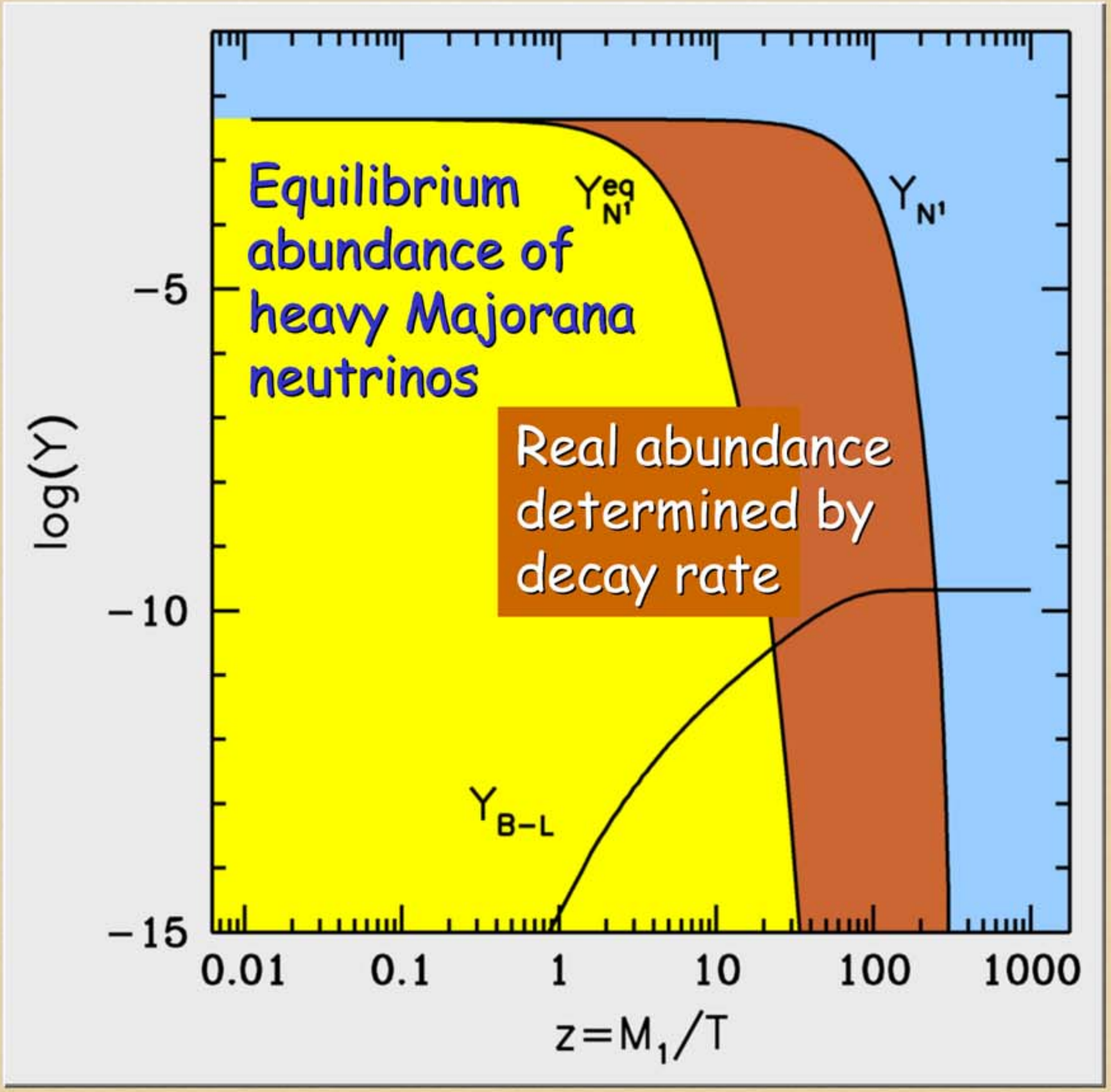

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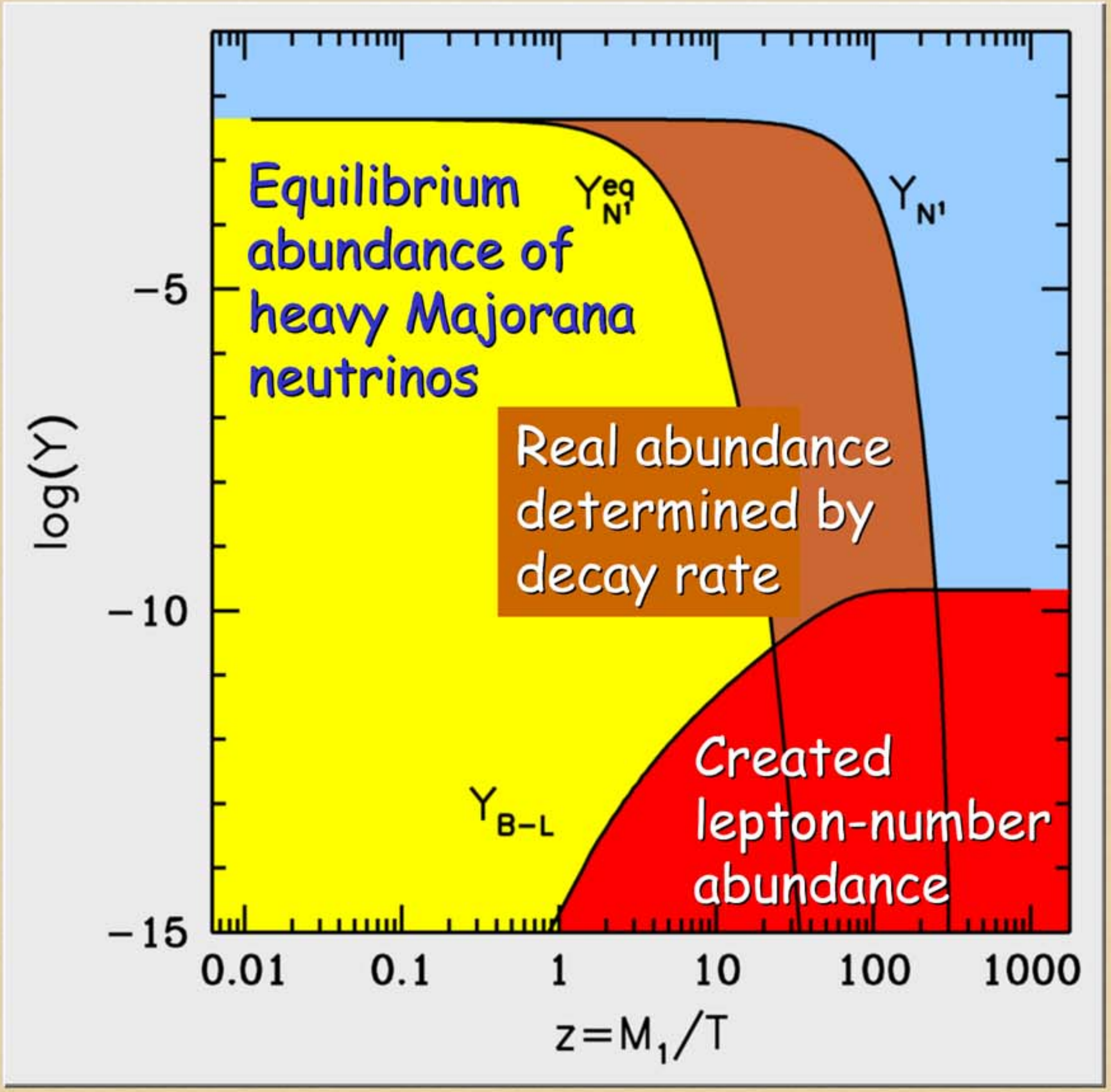

Equilibrium abundance of heavy Majorana neutrinos

Real abundance determined by decay rate

Created lepton-number abundance

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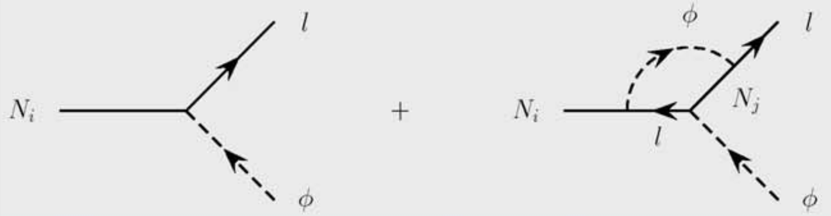
CP-violating decays by interference of tree-level with one-loop diagram



$$\Gamma_{\text{Decay}} = g_\nu^2 \frac{M}{8\pi}$$

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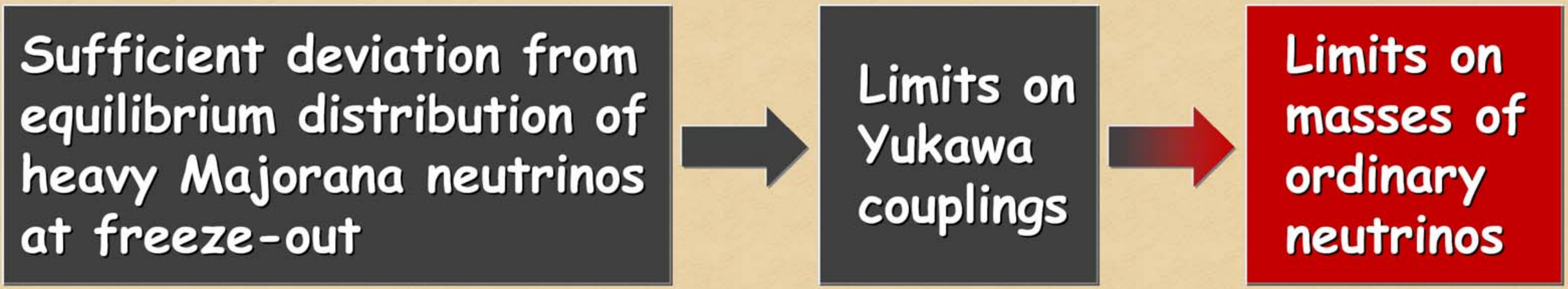
Leptogenesis by Majorana Neutrino Decays

In see-saw models for neutrino masses, out-of-equilibrium decay of right-handed heavy Majorana neutrinos provides source for CP- and L-violation

Cosmological evolution:

- B = L = 0 early on
- Thermal freeze-out of heavy Majorana neutrinos
- Out-of-equilibrium CP-violating decay creates net L
- Shift L excess into B by sphaleron effects



Sufficient deviation from equilibrium distribution of heavy Majorana neutrinos at freeze-out

Limits on Yukawa couplings

Limits on masses of ordinary neutrinos

Requires Majorana neutrino masses below 0.1 eV

Buchmüller, Di Bari & Plümacher, hep-ph/0209301 & hep-ph/0302092

Summary

Cosmological structure: $\Sigma m_\nu < 0.7-2.1$ eV, depending on data sets and priors
Assumes cosmological concordance model to be correct

Limit gets worse with neutrino density larger than standard

After KamLAND, neutrino chemical equilibrium before BBN assured
No large neutrino-antineutrino asymmetry possible

Majorana neutrino masses below 0.1 eV can nicely account for baryonic matter in leptogenesis scenario

Apparently massive neutrinos irrelevant as dark matter
but
maybe crucial for ordinary matter
(leptogenesis mechanism for baryon asymmetry)