Neutrino Physics

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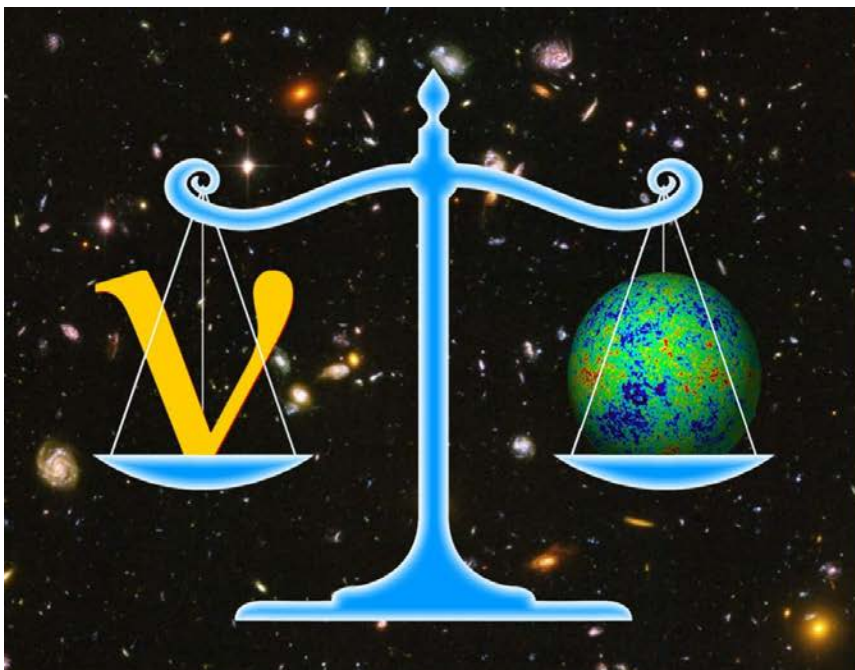
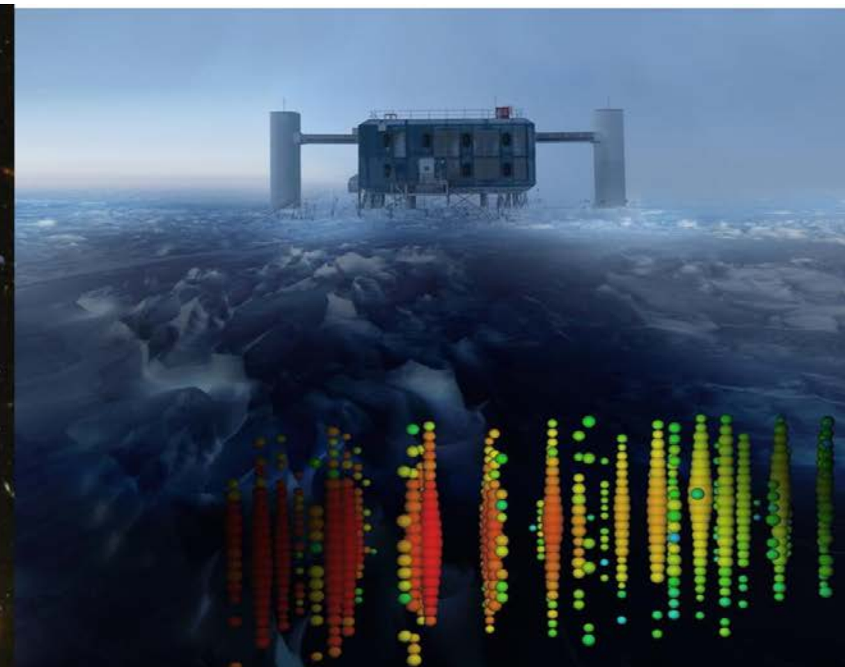
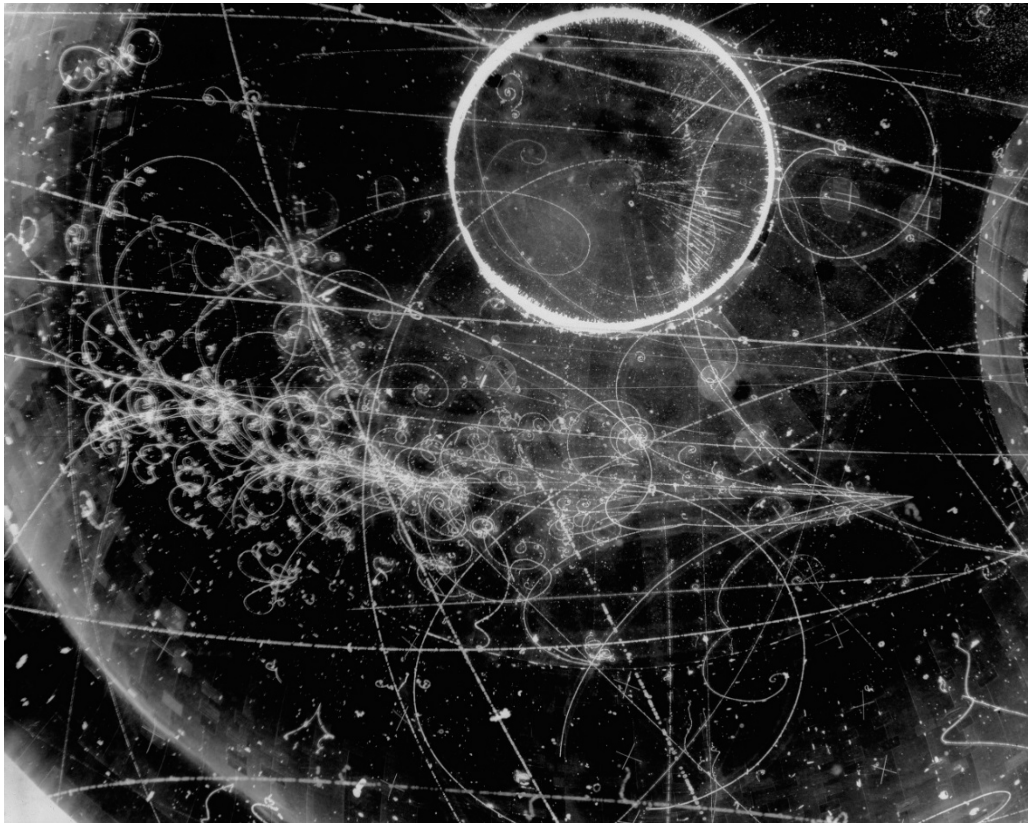
The Invisible Universe 2019





Detecting neutrinos

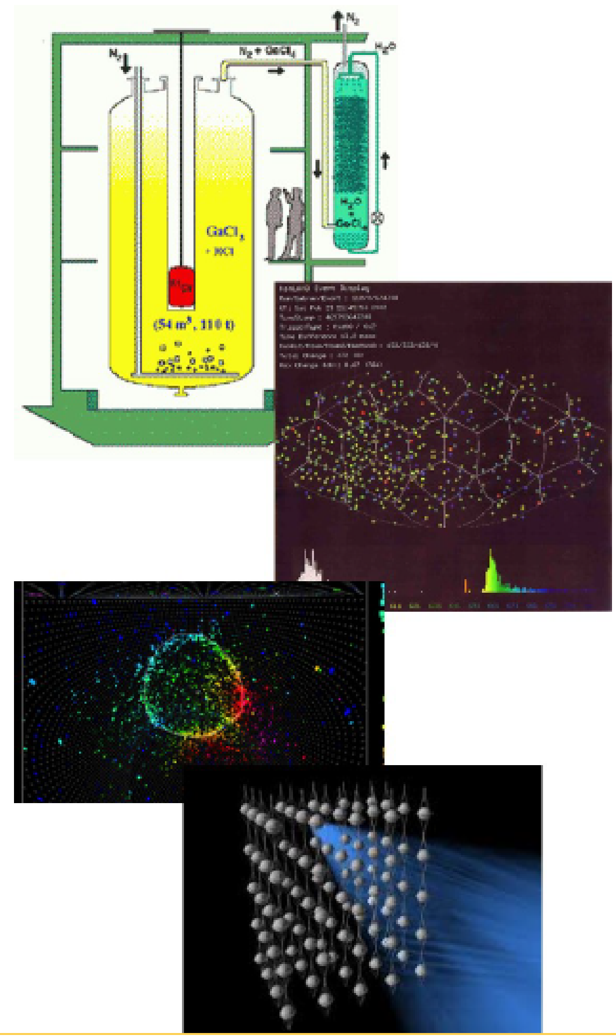
No neutrino tracks…



Basic principle is to look for evidence that neutrinos have interacted, by detecting products of the interaction

Detecting neutrinos

- Large volumes needed to combat weak interaction
- Shielding required to reduce backgrounds $\Longrightarrow$ underground
- Three main detection techniques

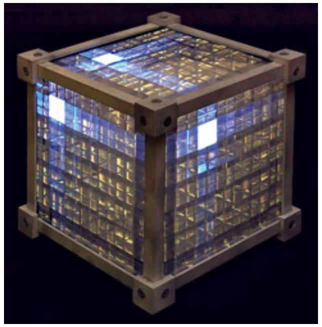


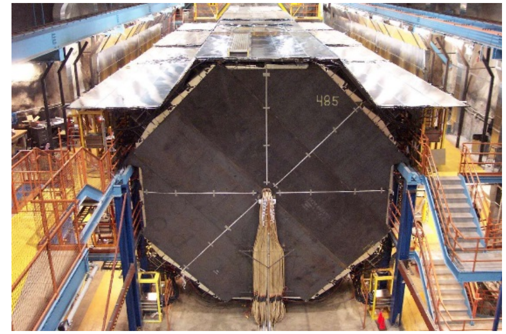
- Radio-chemical: Radioactive atoms formed by capture of neutrinos in target Eg Ray Davis's solar neutrino experiment, used the isotope ^{37}Cl, neutrino capture produces radioactive ^{37}Ar, a gas, which was removed from the target, purified, and counted.

- Scintillation Use liquid scintillator, organic liquid that gives off light, when charged particles pass through it. The scintillator is monitored by optical detectors.

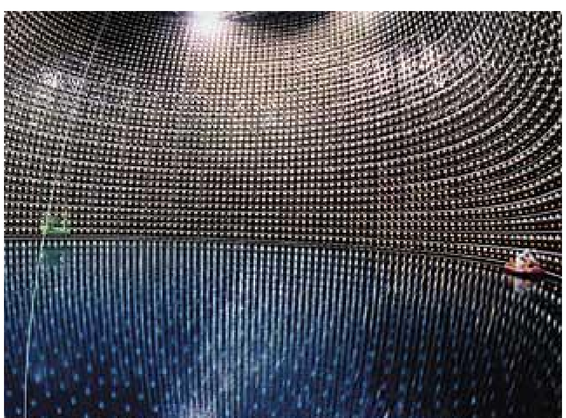
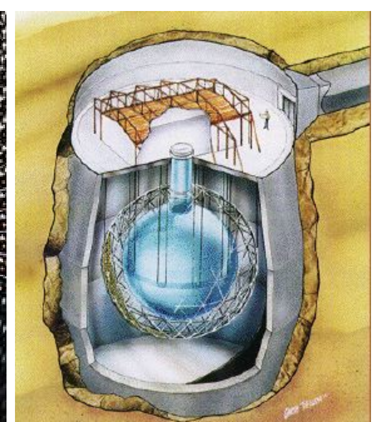
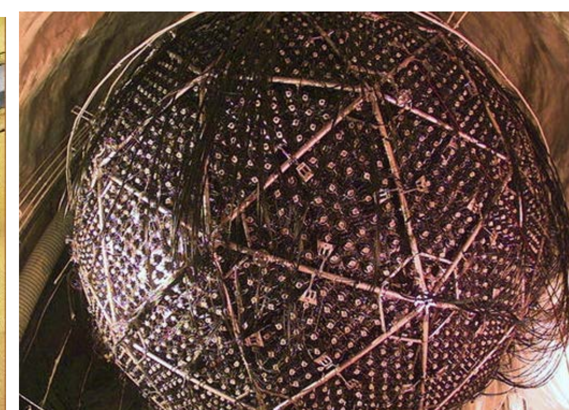
- Cherenkov light detectors Cherenkov light is produced by particles moving faster than the speed of light in the medium. Optical detectors detect the Cherenkov light.

Neutrino dectectors



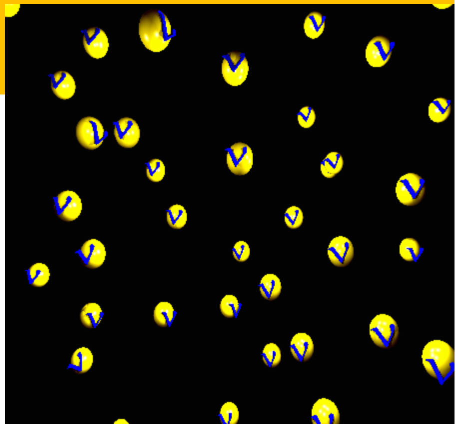



ANITA ANNIE ANTARES ARIANNA BDUNT (NT-200+) BOREXINO CLEAN COBRA Daya Bay Double Chooz EXO-200 GALLEX GERDA GNO HALO HERON HOMESTAKE ICARUS IceCube INO JUNO Kamiokande KamLAND KM3NeT LAGUNA LBNE/DUNE LENS MAJORANA DEMONSTRATOR MicroBooNE MINERvA MiniBooNE MINOS MINOS+ NEMO Experiment MOON NEMO Telescope NEVOD NOvA OPERA RENO SAGE SciBooNE SNO SNO+ Super-K T2K UNO

Cosmic Neutrino Background

Neutrino Cosmology



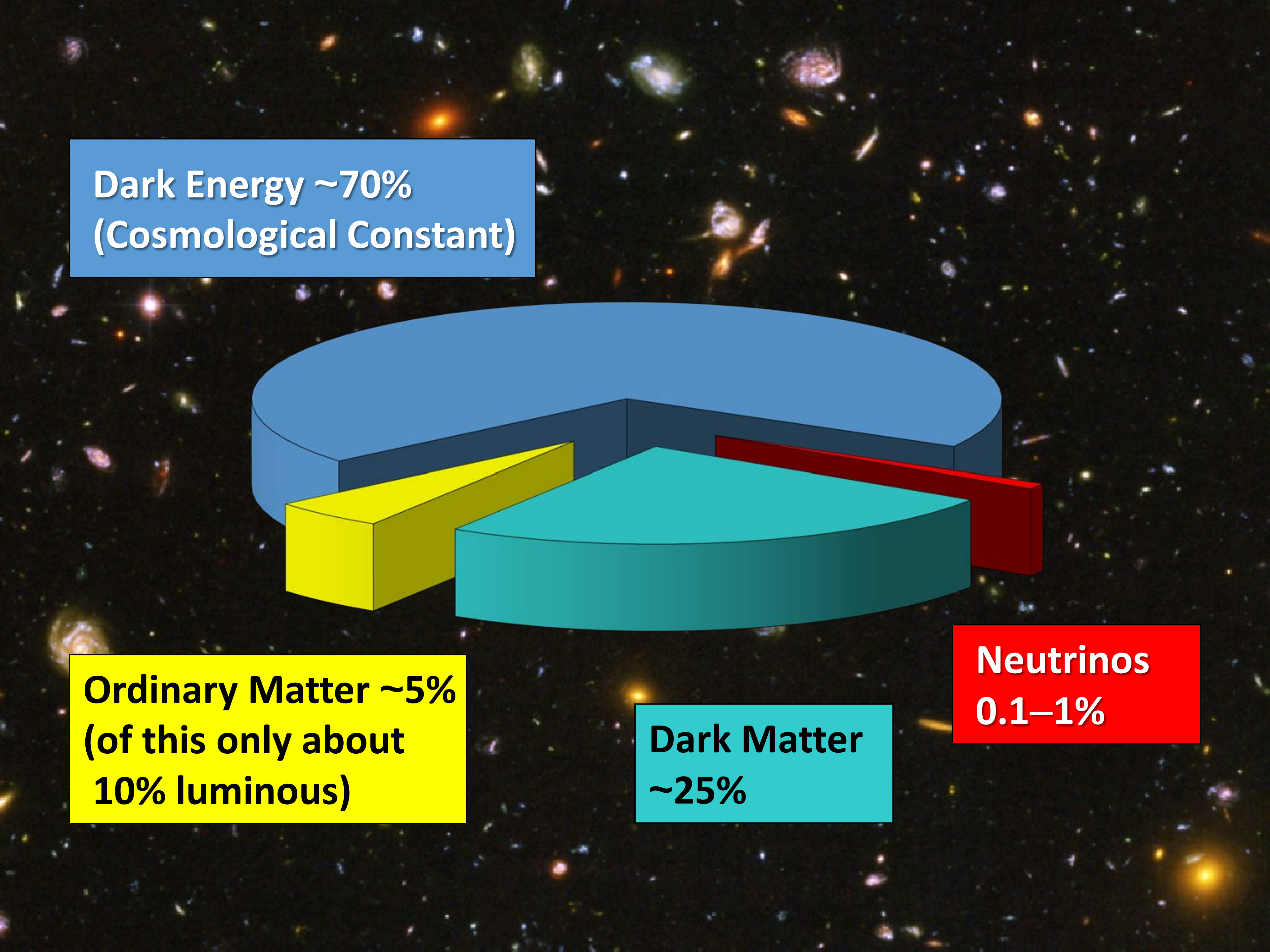
- There is a cosmic background neutrino population which is a relic from the early universe
- The neutrino background affects cosmological processes
  - Primordial nucleosynthesis
  - Cosmic microwave background
  - Large structure formation
- Observations probing these processes give us information about neutrinos
- It is important to include the neutrino background effects to be able to interpret observations and learn about other constituents of the universe

Generic Solutions of Friedman Equation

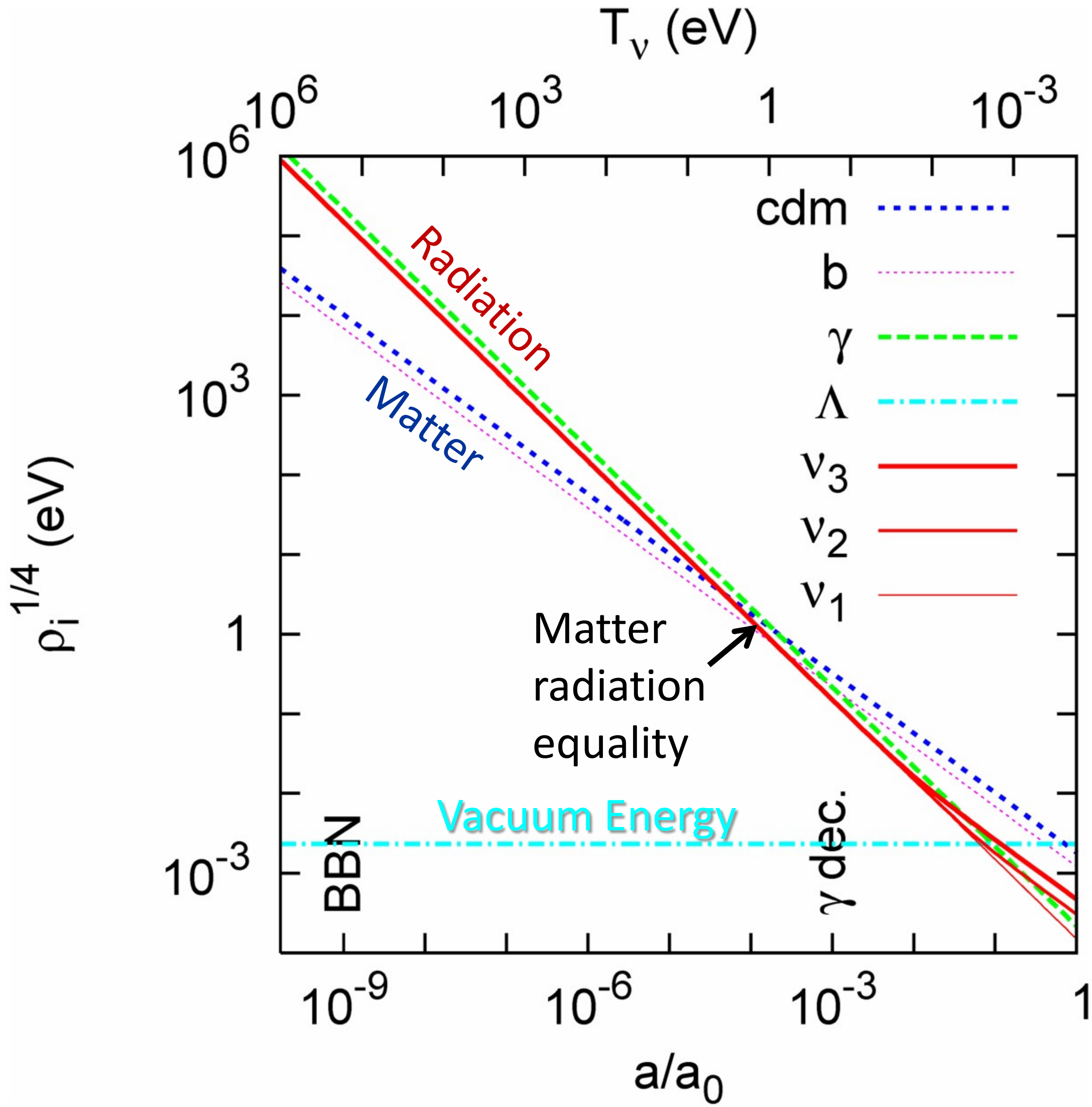
	Equation of state	Behavior of energy-density under cosmic expansion		Evolution of cosmic scale factor
Radiation	$p = \frac{\rho}{3}$	$\rho \propto a^{-4}$	Dilution of radiation and redshift of energy	$a(t) \propto t^{1/2}$
Matter	$p = 0$	$\rho \propto a^{-3}$	Dilution of matter	$a(t) \propto t^{2/3}$
Vacuum energy	$p = -\rho$	$\rho = \text{const}$	Vacuum energy not diluted by expansion	$a(t) \propto e^{\sqrt{\Lambda/3}\,t}$ $\Lambda = 8\pi G_\mathrm{N}\rho_\mathrm{vac}$

Energy-momentum tensor of a perfect fluid with density ρ and pressure p

$$T^{\mu\nu} = \begin{pmatrix} \rho & & & \\ & p & & \\ & & p & \\ & & & p \end{pmatrix} \qquad T^{\mu\nu}_{\mathrm{vac}} = \rho\, g^{\mu\nu} \begin{pmatrix} \rho & & & \\ & -\rho & & \\ & & -\rho & \\ & & & -\rho \end{pmatrix}$$


Dark Energy ~70%
(Cosmological Constant)
Ordinary Matter ~5%
(of this only about
10% luminous)
Dark Matter
~25%
Neutrinos
0.1–1%

Evolution of Cosmic Density Components



Assumed neutrino masses

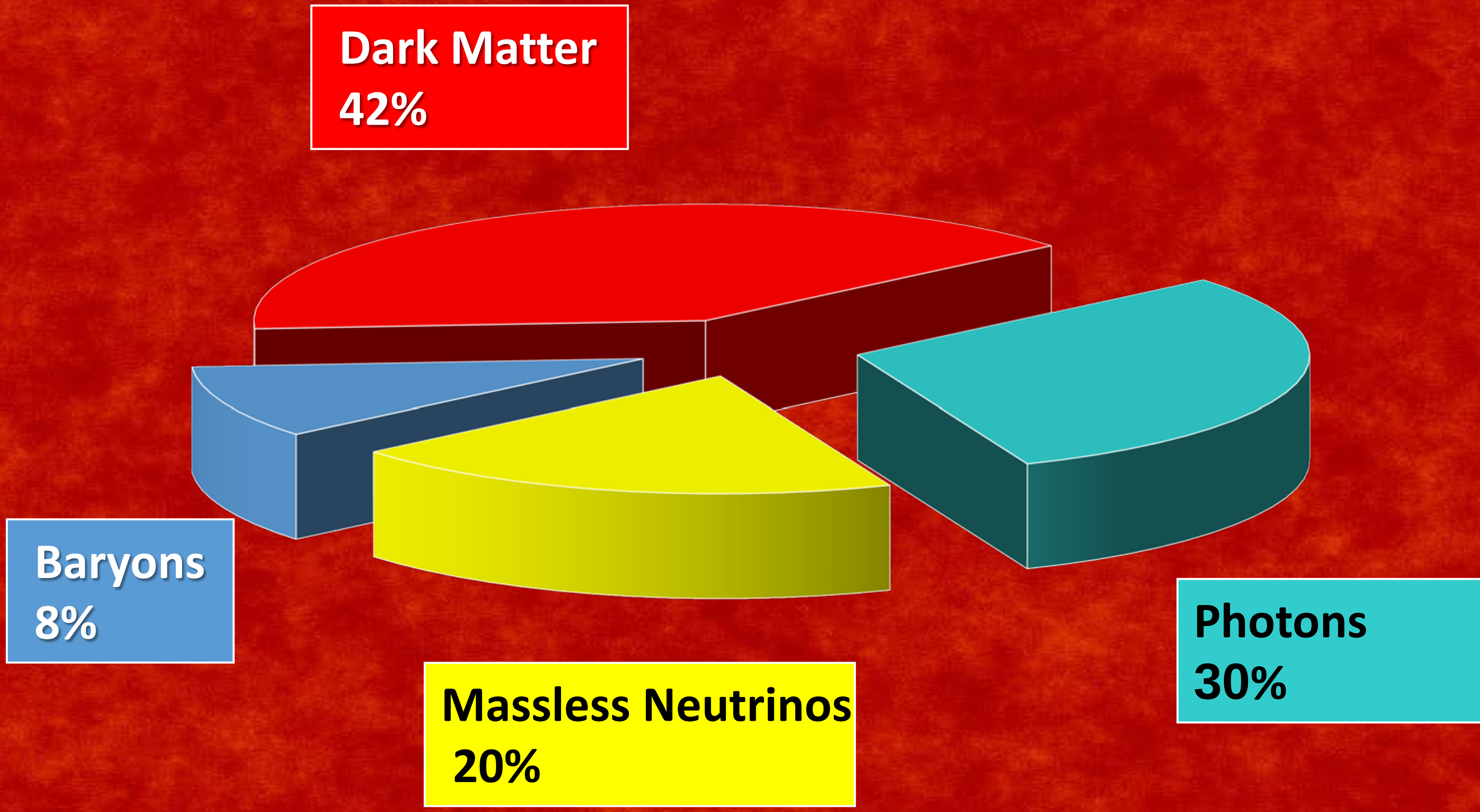
m_3 = 50 meV

m_2 = 9 meV

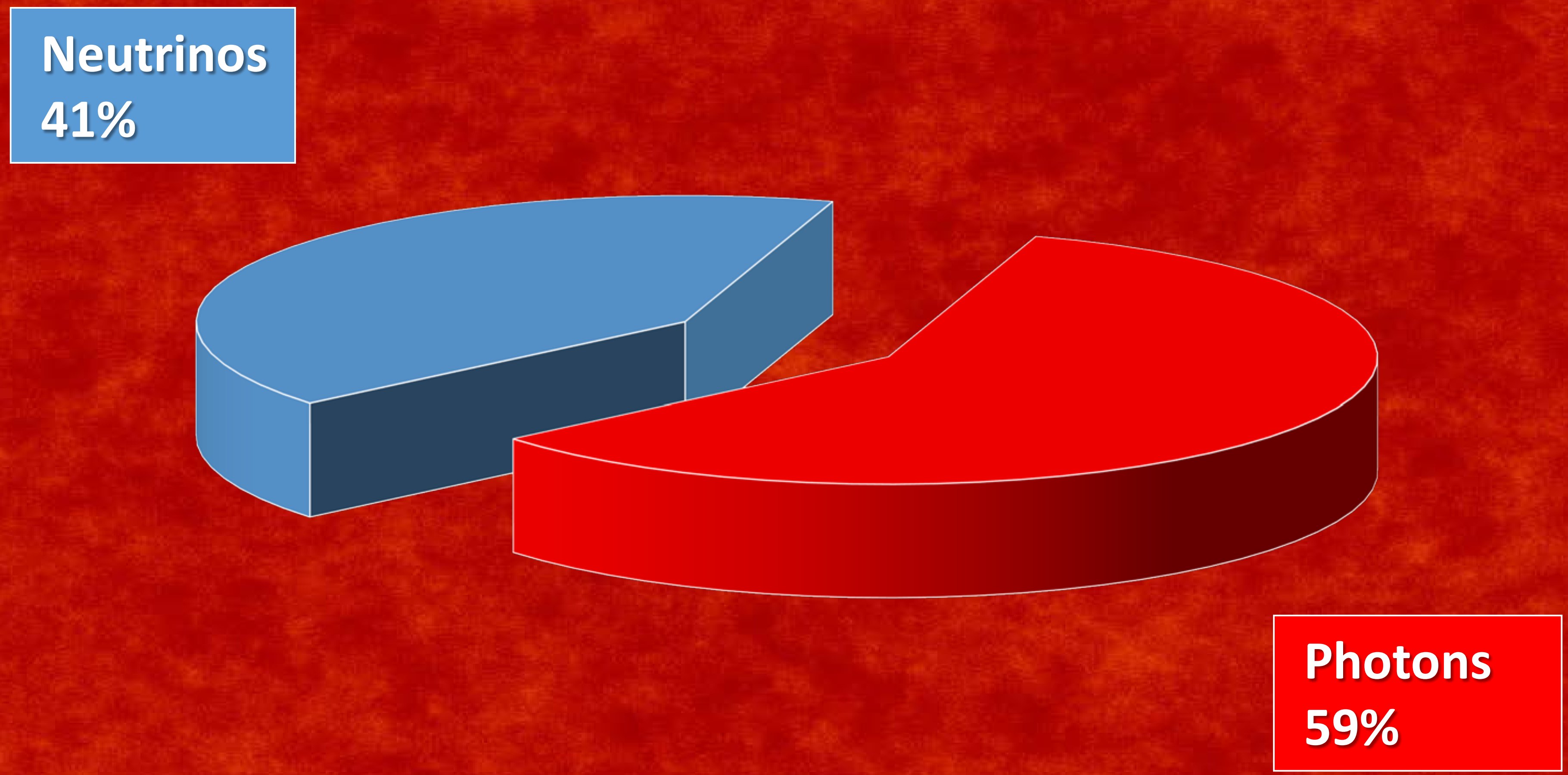
m_1 = 0

Lesgourgues & Pastor
astro-ph/0603494

Matter-Radiation Equality (Redshift 3400)

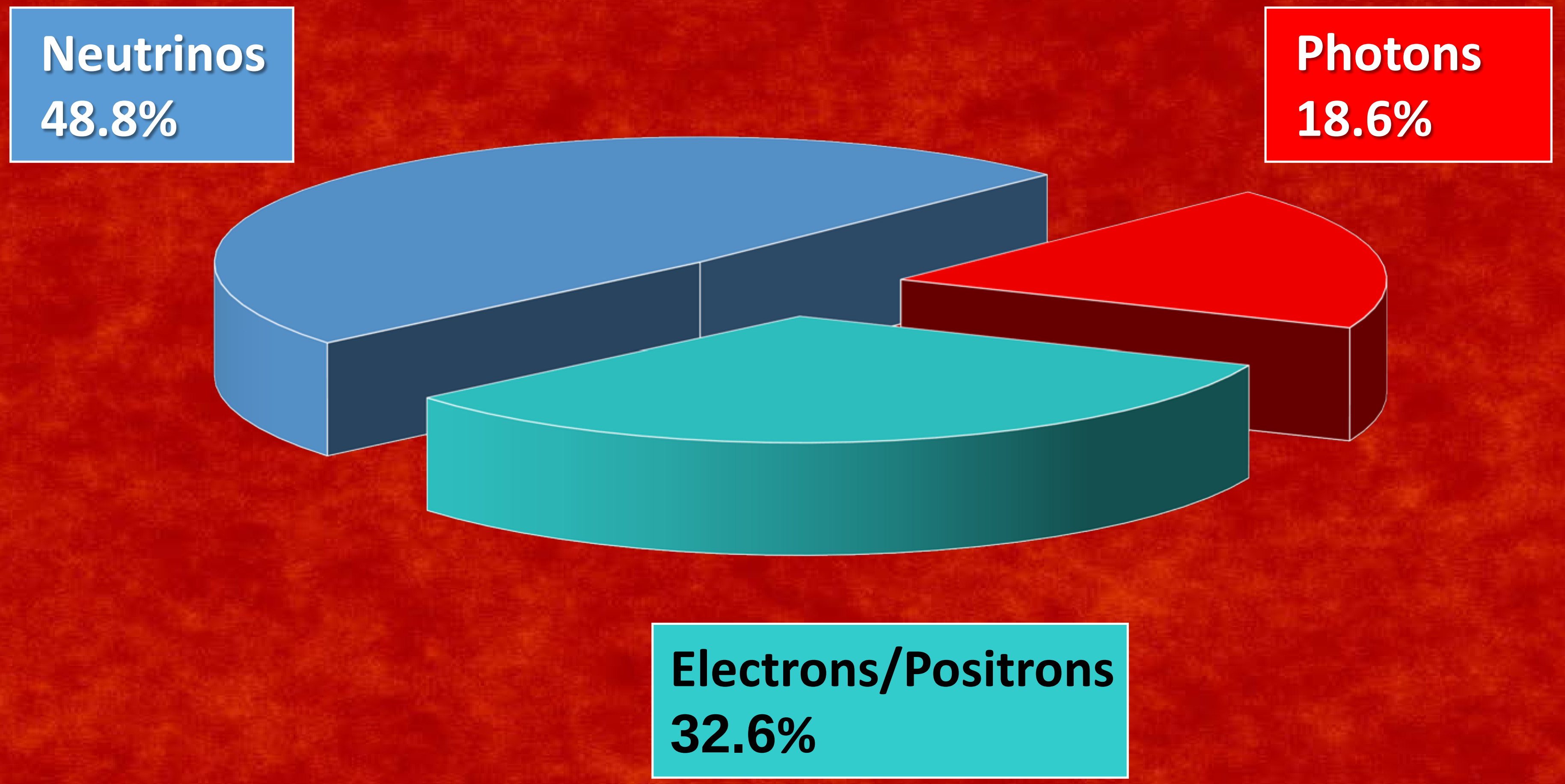


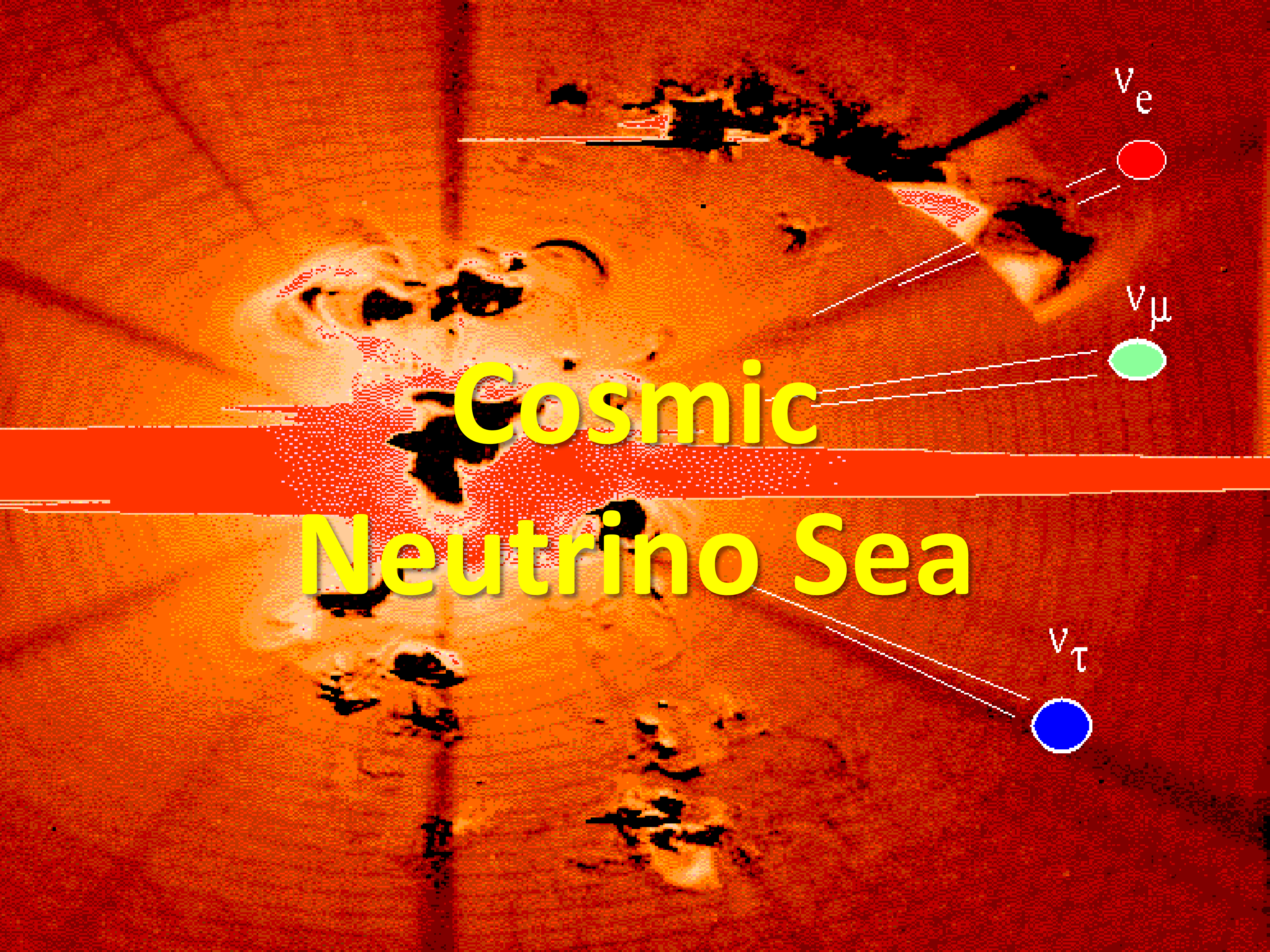
After Electron-Positron Annihilation (T = 100 keV)



Relevant for Big Bang Nucleosynthesis (BBN)

Before Electron-Positron Annihilation (T = 1 MeV)



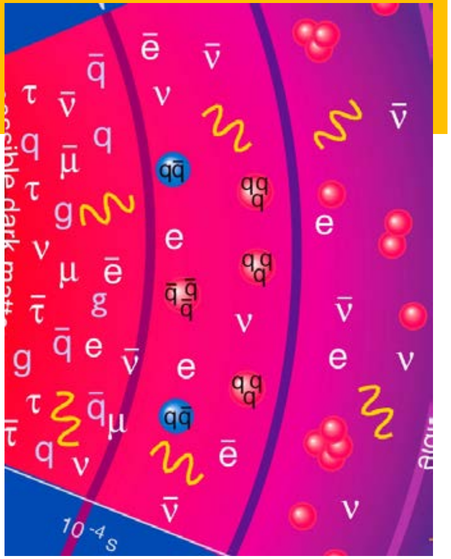

Cosmic
Neutrino Sea
ν_e
ν_μ
ν_τ

Neutrino Background

$$n_{\nu\bar{\nu}}(1 \text{ flavour}) \approx 112 \text{ cm}^{-3}$$

$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \approx 1.95 \text{ K}$ for massless neutrinos

Equilibrium Particle Interactions



- Boltzmann equation governs distributions

$$\frac{\mathrm{d}f_X}{\mathrm{d}t} + 3\frac{\dot{a}}{a}f_X + \langle\sigma_A v\rangle\left({f_X}^2 - {f_{Xeq}}^2\right) = 0$$

- Two regimes:

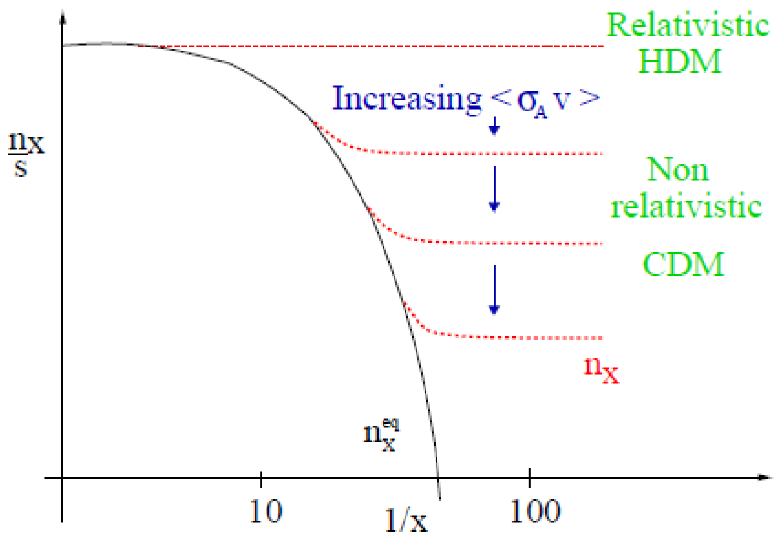
$\Gamma = \langle\sigma_A v\rangle n_X > H$ Thermal equilibrium

Interaction rate > Expansion rate

$$f_{eq}(\boldsymbol{p}) = \frac{1}{e^{E\boldsymbol{p}/T} \pm 1}$$ + Fermions, - Bosons

$\Gamma \ll H$ Freezeout

Distribution constant at freezeout level, only redshifted



Thermal Radiation

	General	Bosons	Fermions
Number density n	$g\int \frac{d^3\boldsymbol{p}}{(2\pi)^3}\frac{1}{e^{E_{\boldsymbol{p}}/T}\pm 1}$	$g_B\frac{\zeta_3}{\pi^2}T^3$	$\frac{3}{4}\,g_F\frac{\zeta_3}{\pi^2}T^3$
Energy density ρ	$g\int \frac{d^3\boldsymbol{p}}{(2\pi)^3}\frac{E_{\boldsymbol{p}}}{e^{E_{\boldsymbol{p}}/T}\pm 1}$	$g_B\frac{\pi^2}{30}T^4$	$\frac{7}{8}\,g_F\frac{\pi^2}{30}T^4$
Pressure P	$g\int \frac{d^3\boldsymbol{p}}{(2\pi)^3}\frac{\lvert\boldsymbol{p}^2\rvert}{E_p}\frac{1}{e^{E_{\boldsymbol{p}}/T}\pm 1}$	$\frac{\rho}{3}$	
Entropy density s	$\frac{\rho+P}{T}=\frac{4}{3}\frac{\rho}{T}$	$g_B\frac{2\pi^2}{45}T^3$	$\frac{7}{8}\,g_F\frac{2\pi^2}{45}T^3$

$$\mathrm{d}E = T\mathrm{d}S - P\mathrm{d}V$$
$$T\mathrm{d}S = (\rho + P)dV$$

using integrals

$$\int_0^\infty \frac{x^2dx}{\exp(x)-1} = 2\zeta(3),$$
$$\int_0^\infty \frac{x^2dx}{\exp(x)+1} = \frac{6}{8}\zeta(3),$$
$$\int_0^\infty \frac{x^3dx}{\exp(x)-1} = 6\zeta(4) = \frac{\pi^4}{15},$$
$$\int_0^\infty \frac{x^3dx}{\exp(x)+1} = \frac{7}{48}\zeta(4) = \frac{7}{8}\frac{\pi^4}{15}$$

Riemann Zeta Function
$\zeta = 1.2020569\ldots$

Thermal Degrees of Freedom

$$g_* = g_B + \frac{7}{8} g_F$$

Mass threshold		Particles	g_B	g_F	g_*
	low	γ, 3ν	2	6	(7.25)
m_e	0.5 MeV	$e^\pm$	2	10	10.75
m_μ	105 MeV	$\mu^\pm$	2	14	14.25
m_π	135 MeV	π^0, $\pi^\pm$	5	14	17.25
Λ_{QCD}	~170 MeV	u, d, s, gluons	18	50	61.75
$m_{c,\tau}$	2 GeV	c, τ	18	66	75.75
m_b	6 GeV	$b^\pm$	18	78	86.25
$m_{W,Z}$	90 GeV	Z^0, $W^\pm$	27	78	92.25
m_H	126 GeV	Higgs	28	78	93.25
m_t	170 GeV	t	28	90	106.75
Λ_{SUSY}	~ 1 TeV ?	SUSY particles	118	118	213.50

Neutrino Thermal Equilibrium

Neutrino reaction rate

Examples of neutrino processes

$$e^+ + e^- \leftrightarrow \overline{\nu} + \nu$$
$$\overline{\nu} + \nu \leftrightarrow \overline{\nu} + \nu$$
$$\nu + e^\pm \leftrightarrow \nu + e^\pm$$

Reaction rate in a thermal medium

for $T \ll m_{W,Z}$

$$\Gamma \sim G_F^2 T^5$$

Cosmic expansion rate

Friedmann equation (flat universe)

$$H^2 = \frac{8\pi}{3}\frac{\rho}{m_{Pl}^2} \qquad \left(G_N = \frac{1}{m_{Pl}^2}\right)$$

Radiation dominates

$$\rho \sim T^4$$

Expansion rate

$$H \sim \frac{T^2}{m_{Pl}}$$

Condition for thermal equilibrium: $\Gamma > H$

$$T > \left(m_{Pl} G_F^2\right)^{-1/3} \sim [10^{19}\text{GeV}\,(10^{-5}\text{GeV}^{-2})^2]^{-1/3} = 1\ \text{MeV}$$

Neutrinos are in thermal equilibrium for $T \gtrsim 1$ MeV
corresponding to $t \lesssim 1$ sec

Present-Day Neutrino Density

Neutrino decoupling (freeze out)	$H \sim \Gamma$ $T \approx 2.4\ \text{MeV}$ (electron flavour) $T \approx 3.7\ \text{MeV}$ (other flavours)
Redshift of Fermi-Dirac distribution ("nothing changes at freeze-out")	$\frac{dn_{\nu\bar{\nu}}}{dE} = \frac{1}{\pi^2} \frac{E^2}{e^{E/T}+1}$ Temperature scales with redshift $T_\nu = T_\gamma \propto (z+1)$
Electron-positron annihilation beginning at T ≈ m_e = 0.511 MeV	• Entropy of e^+e^- transfered to photons $g_* T_\gamma^3 \big\vert_{\text{before}} = g_* T_\gamma^3 \big\vert_{\text{after}}$ $\overbrace{2 + \frac{7}{8}4 = \frac{11}{2}}$ $\overbrace{2}$ $\Big\} T_\gamma^3 \big\vert_{\text{before}} = \frac{\mathbf{4}}{\mathbf{11}} T_\gamma^3 \big\vert_{\text{after}}$
Redshift of neutrino and photon thermal distributions so that today we have	$n_{\nu\bar{\nu}}(1\ \text{flavour}) = \frac{4}{11} \times \frac{3}{4} \times n_\gamma = \frac{3}{11} n_\gamma \approx 112\ \text{cm}^{-3}$ $T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \approx 1.95\ \text{K}$ for massless neutrinos

Cosmic radiation density after e^+e^- annihilation

Radiation density for $N_\nu = 3$ standard neutrino flavors

$$\rho_{\rm rad} = \rho_\gamma + \rho_\nu = \frac{\pi^2}{15}\left(T_\gamma^4 + N_\nu \frac{7}{8}\, T_\nu^4\right) = \left[1 + \mathrm{N}_\nu \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\right]\rho_\gamma$$

Cosmic radiation density is expressed in terms of "effective number of thermally excited neutrino species" $N_{\rm eff}$

$$\rho_{\rm rad} = \left[1 + \mathrm{N}_{\rm eff}\, \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\right]\rho_\gamma = [1 + \mathrm{N}_{\rm eff}\, 0.2271]\rho_\gamma$$

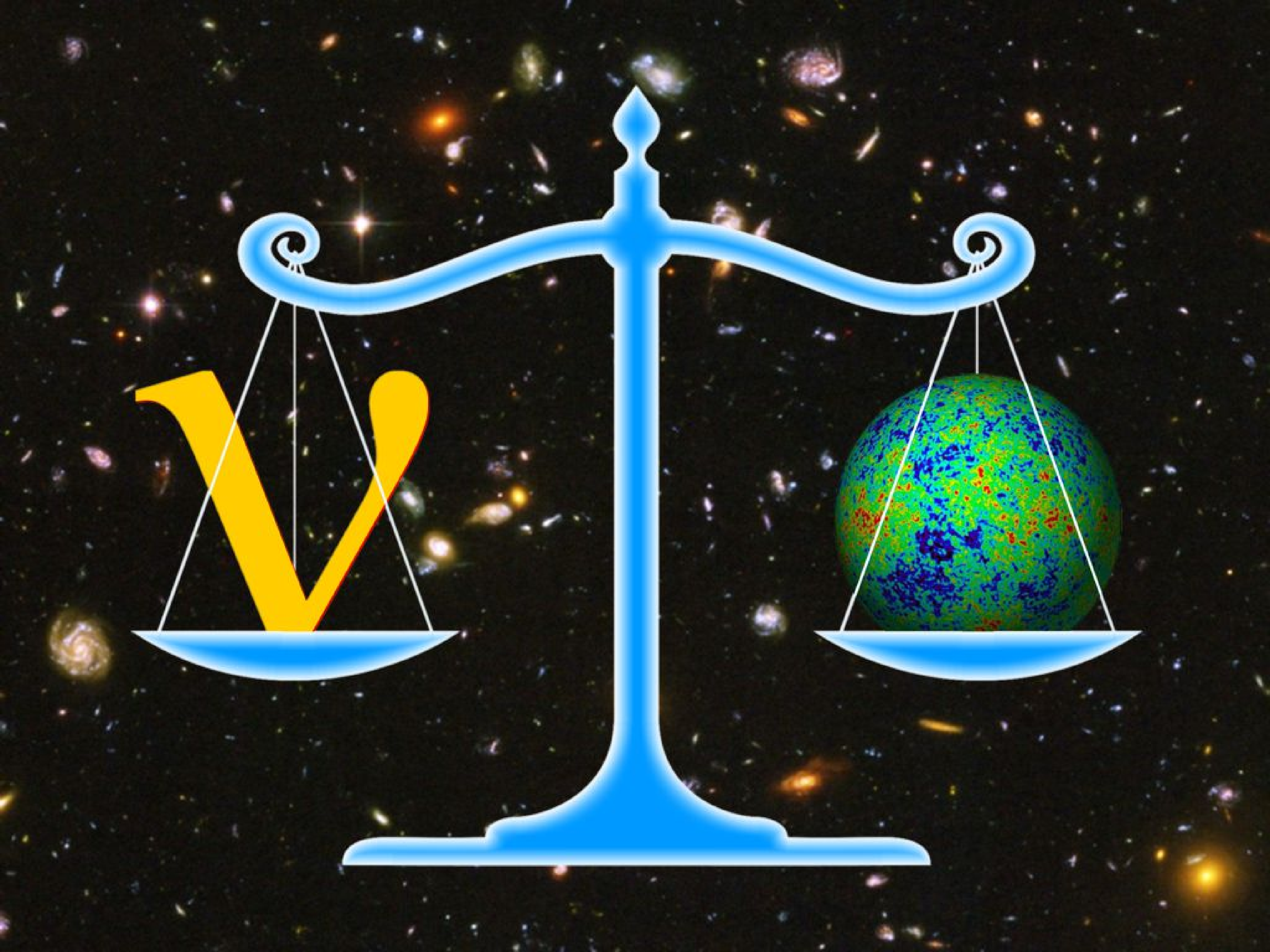
$N_{\rm eff}$ is a measure for the radiation density, not necessarily related to neutrinos

Residual neutrino heating by e^+e^- annihilation and corrections for finite temperature QED effects and neutrino flavor oscillations means T_ν *not exactly* $\left(\frac{4}{11}\right)^{1/3} T_\gamma$

$N_{\rm eff} = 3.046$ Standard value

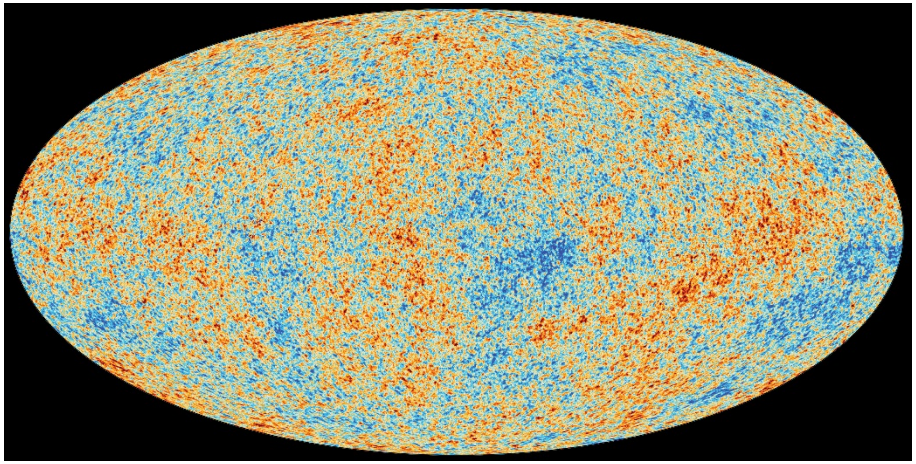
$$\rho_{\rm rad} = (1 + 0.6918 + 0.2271\, \Delta\mathrm{N}_{\rm eff})\, \rho_\gamma$$

Of course, the number of known neutrino species ν_e, ν_μ, ν_τ is exactly 3

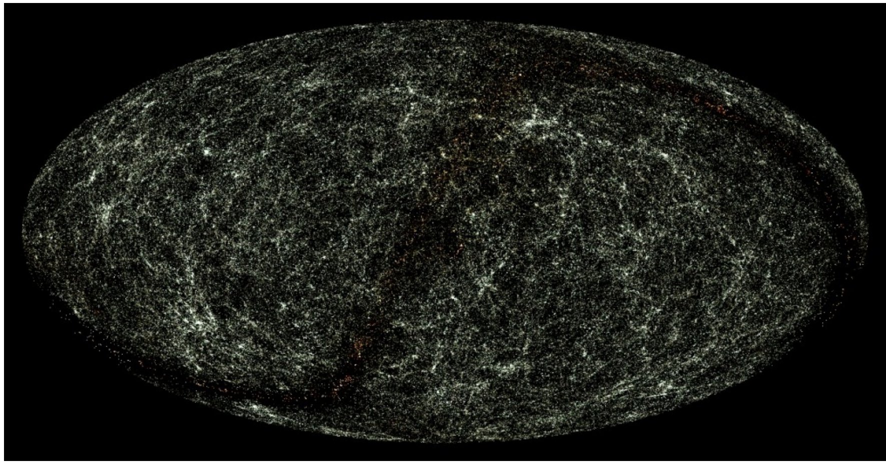

ν

Basic Idea

Comparison of theoretical predictions with observations of the anisotropy
(temperature (and polarisation) differences from isotropy)
of the cosmic microwave background and correlations in the large scale structure

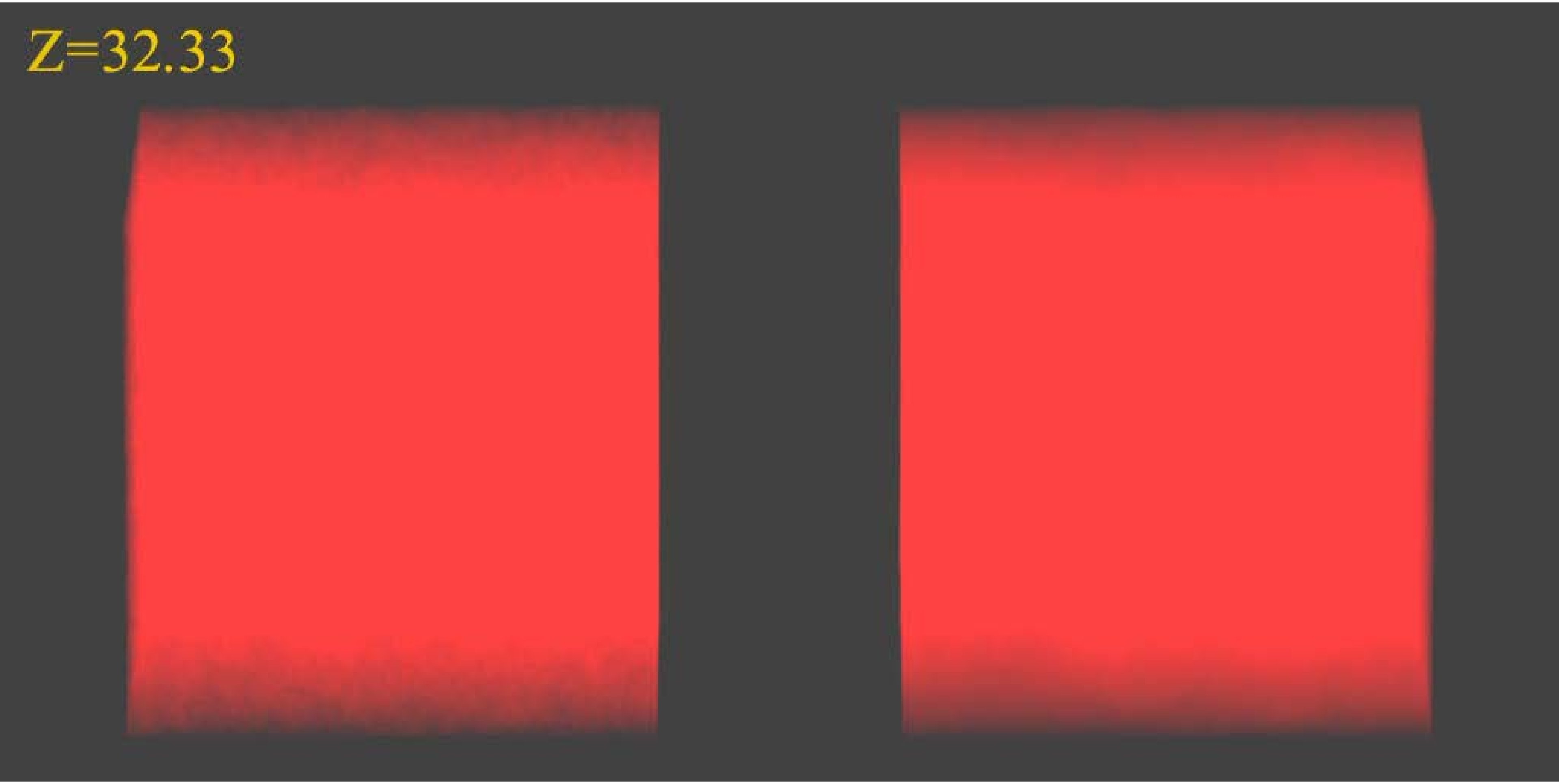


Planck(2018)
https://www.esa.int/spaceinimages/Images/2018/07/Planck_s_view_of_the_cosmic_microwave_background



Sky Map of Galaxies (2MASS XSC)
http://spider.ipac.caltech.edu/staff/jarrett/2mass/XSC/jarrett_allsky.html

Neutrino effect on large scale structure growth

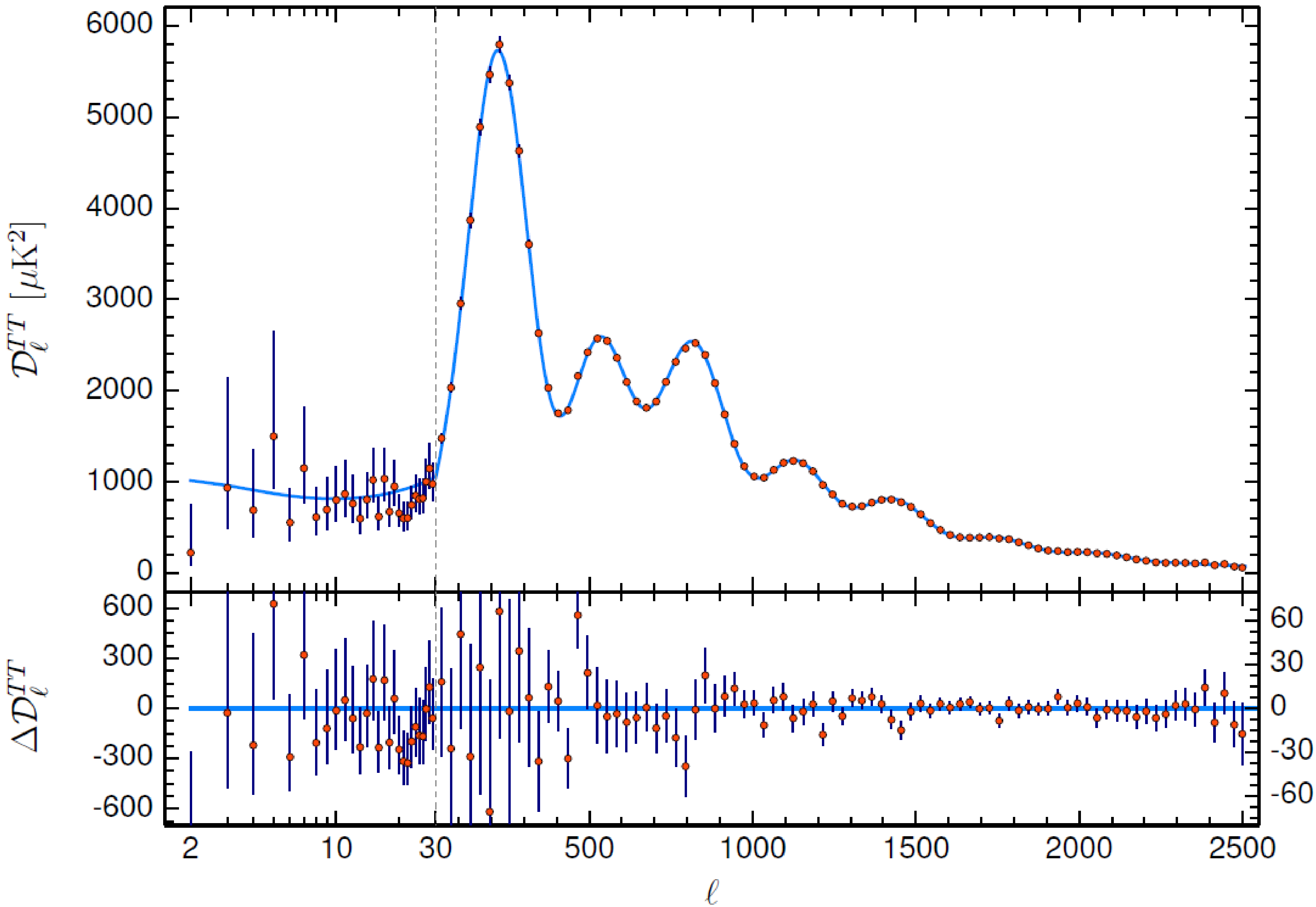


Standard ΛCDM Model

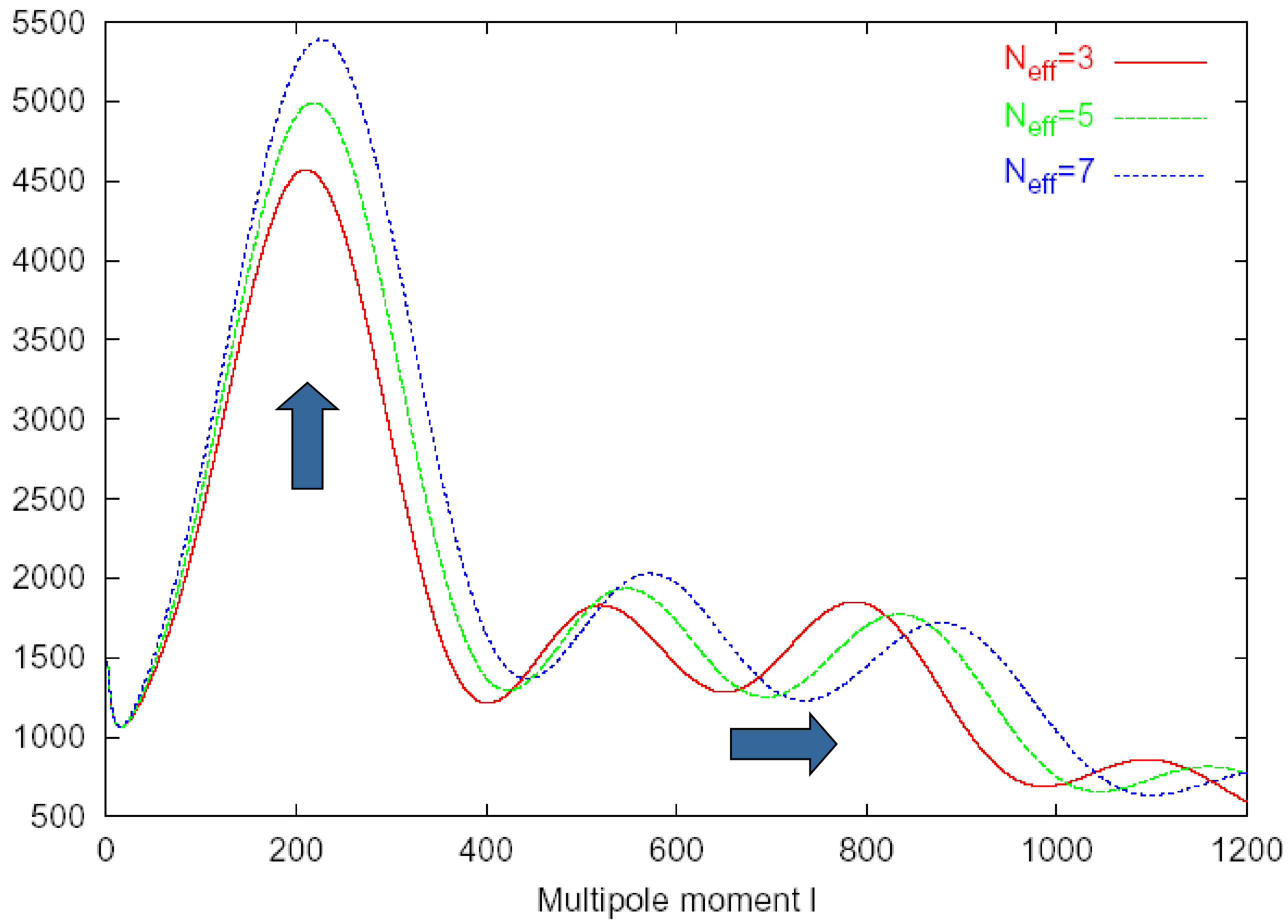
Neutrinos with $\Sigma m_\nu = 6.9$ eV

Troels Haugbølle, http://users-phys.au.dk/haugboel

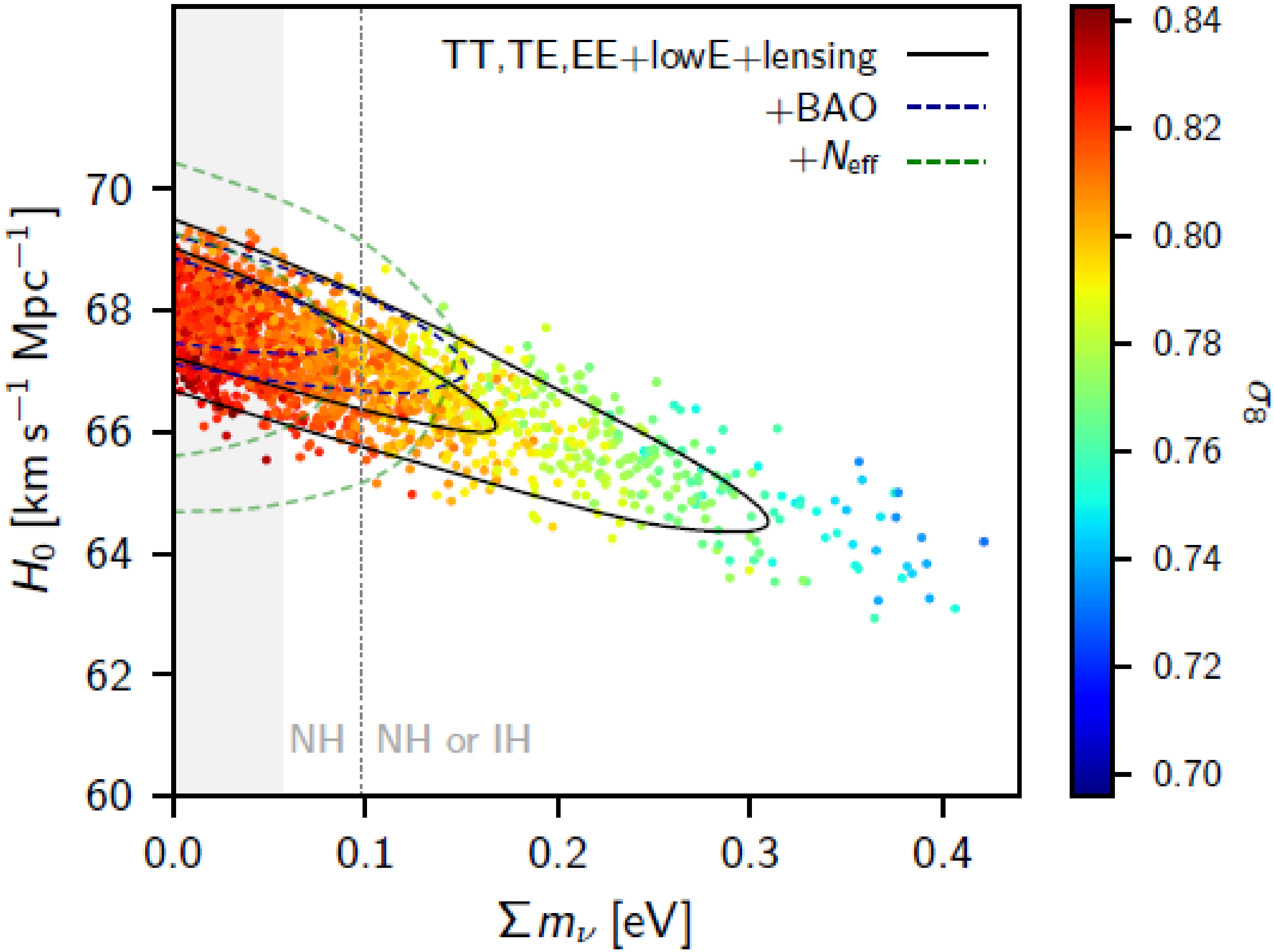
CMB Planck (2018)



Impact of extra radiation on CMB power spectrum



Planck constraints on neutrino masses



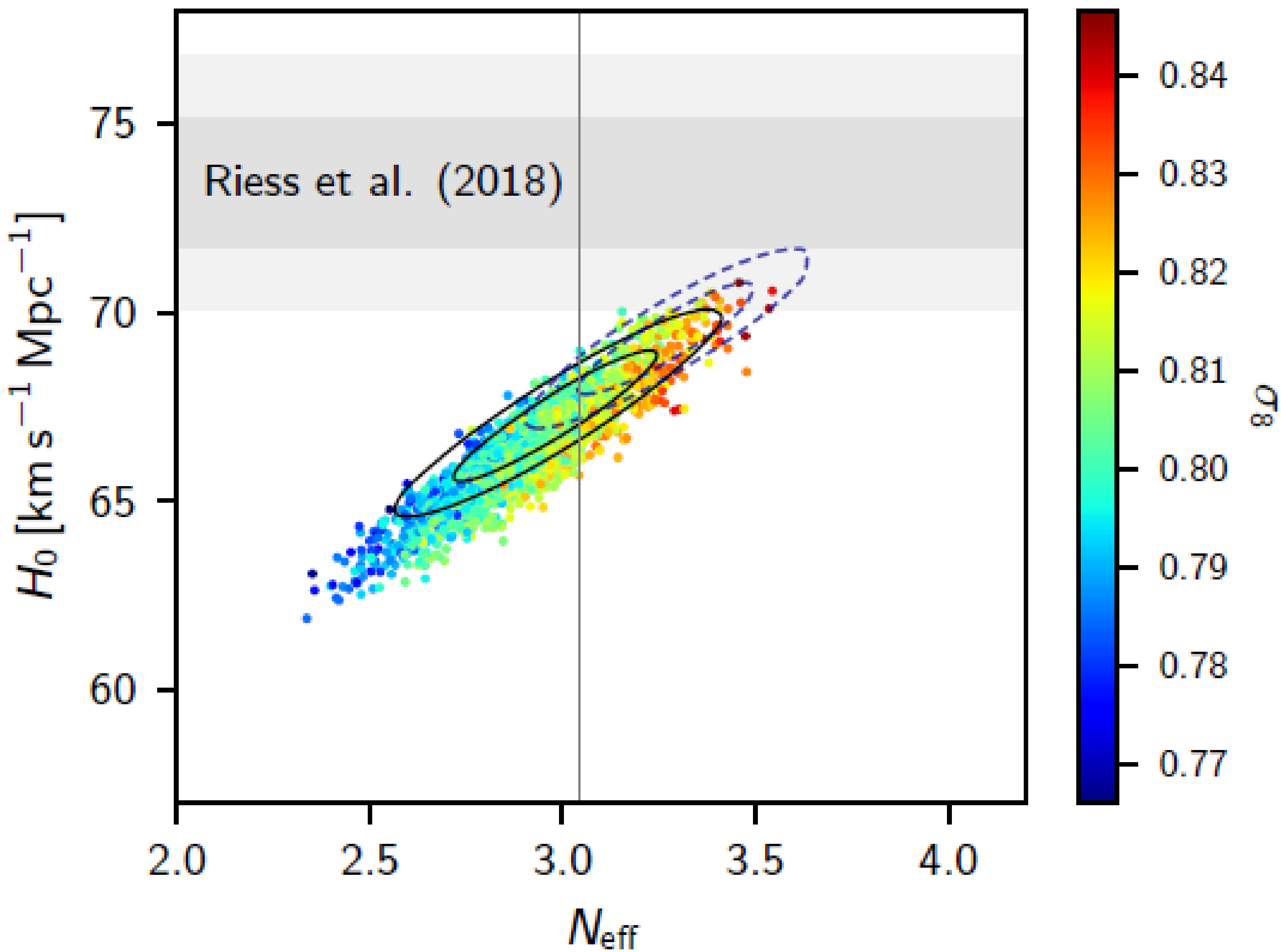
Planck (2018) Number of relativistic degrees of freedom

New light particles appear in many extensions of the Standard Model of particle physics. Additional dark relativistic degrees of freedom are usually parameterized by N_{eff}, defined so that the total relativistic energy density well after electron-positron annihilation is given by

$$\rho_{\mathrm{rad}} = N_{\mathrm{eff}} \, \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} \rho_{\gamma}. \tag{64}$$

The standard cosmological model has $N_{\mathrm{eff}} \approx 3.046$, slightly larger than 3 since the three standard model neutrinos were not completely decoupled at electron-positron annihilation

Planck N_{eff}


Riess et al. (2018)
75
70
65
60
H_0 [km s^{-1} Mpc^{-1}]
2.0
2.5
3.0
3.5
4.0
N_{eff}
0.84
0.83
0.82
0.81
0.80
0.79
0.78
0.77
σ_8

Neutrino Cosmology Summary

- There is a cosmic background neutrino population which is a relic from the early universe
- The neutrino background affects cosmological processes
  - Primordial nucleosynthesis
  - Cosmic microwave background
  - Large structure formation
- Observations probing these processes give us information about neutrinos
- It is important to include the neutrino background effects to be able to interpret observations and learn about other constituents of the universe