

Neutrinos in Cosmology



Sergio Pastor
(IFIC Valencia)

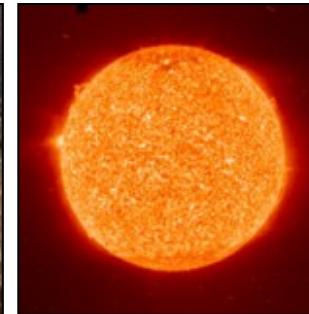
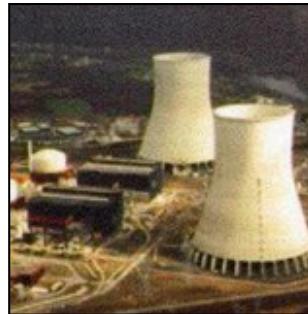
ISAPP 2017
Arenzano, 22-23 June



Where do neutrinos come from?



Nuclear reactors



Sun



Particle accelerators

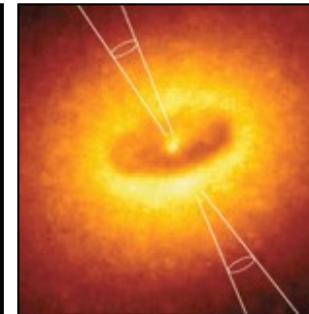
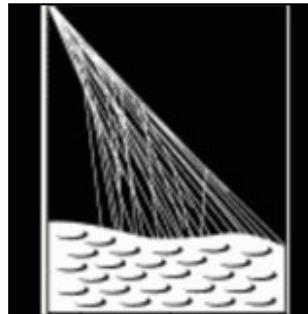


Supernovae

SN 1987A ✓



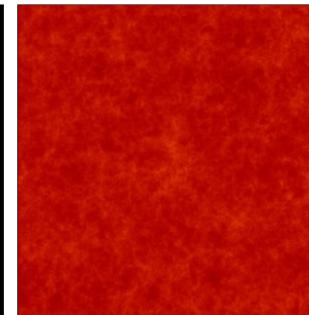
Earth Atmosphere
(Cosmic rays)



Accelerators in
astrophysical sources ?✓



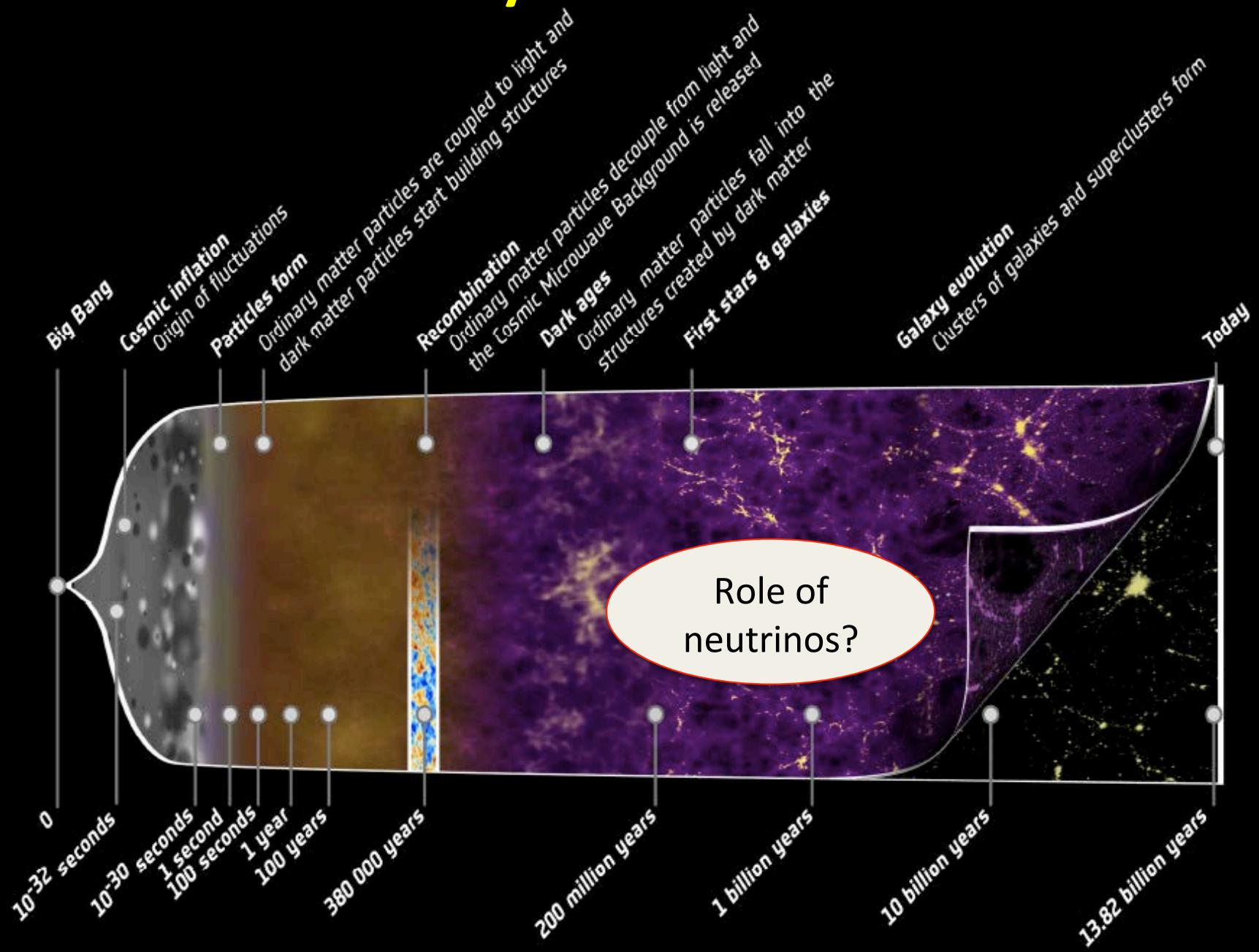
Earth interior
(Natural Radioactivity)

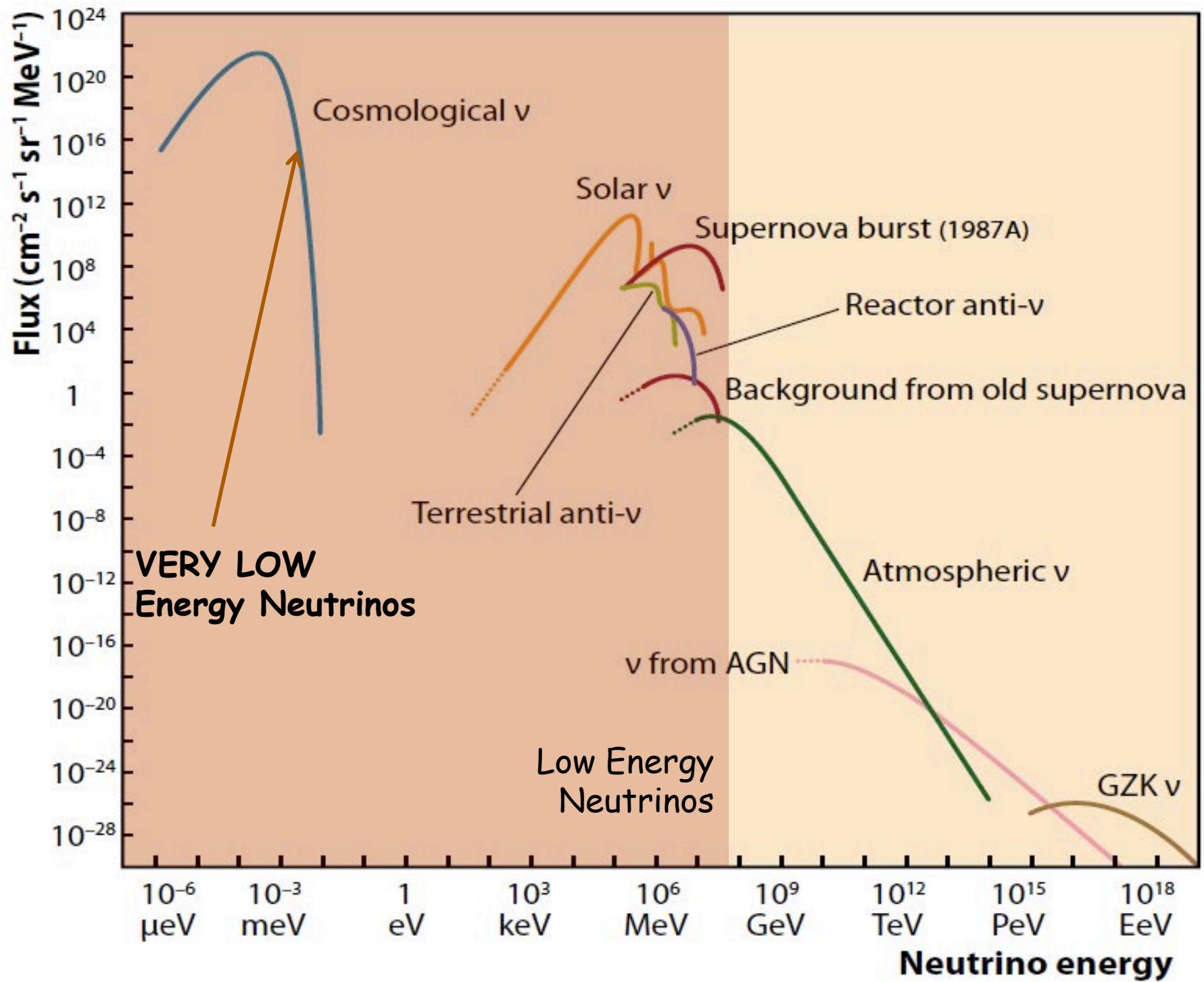


Early Universe
(today 336 v/cm^3)

Indirect evidence

History of the Universe

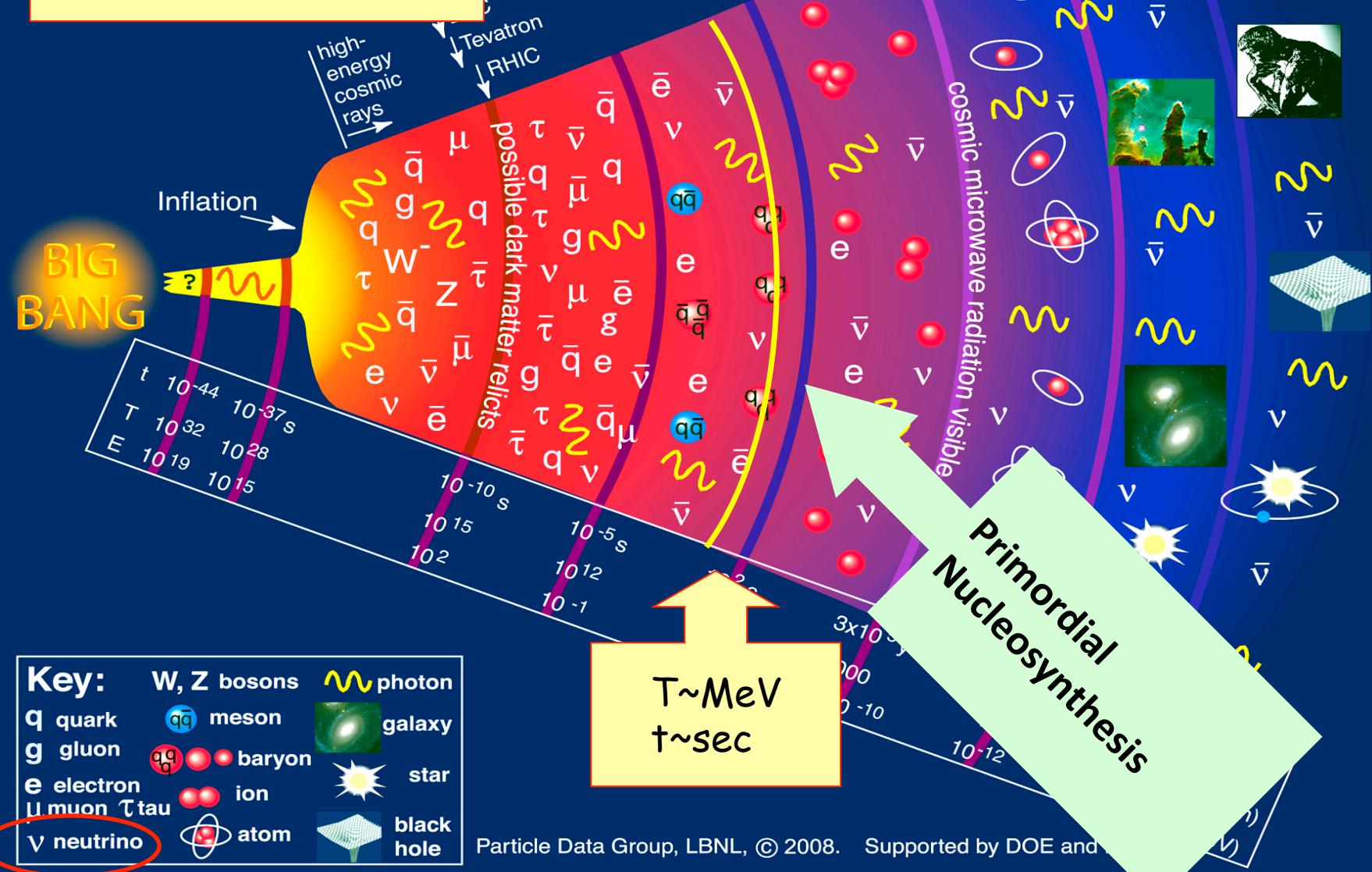




Introduction: neutrinos and the history of the Universe

History of the Universe

Neutrinos coupled by weak interactions

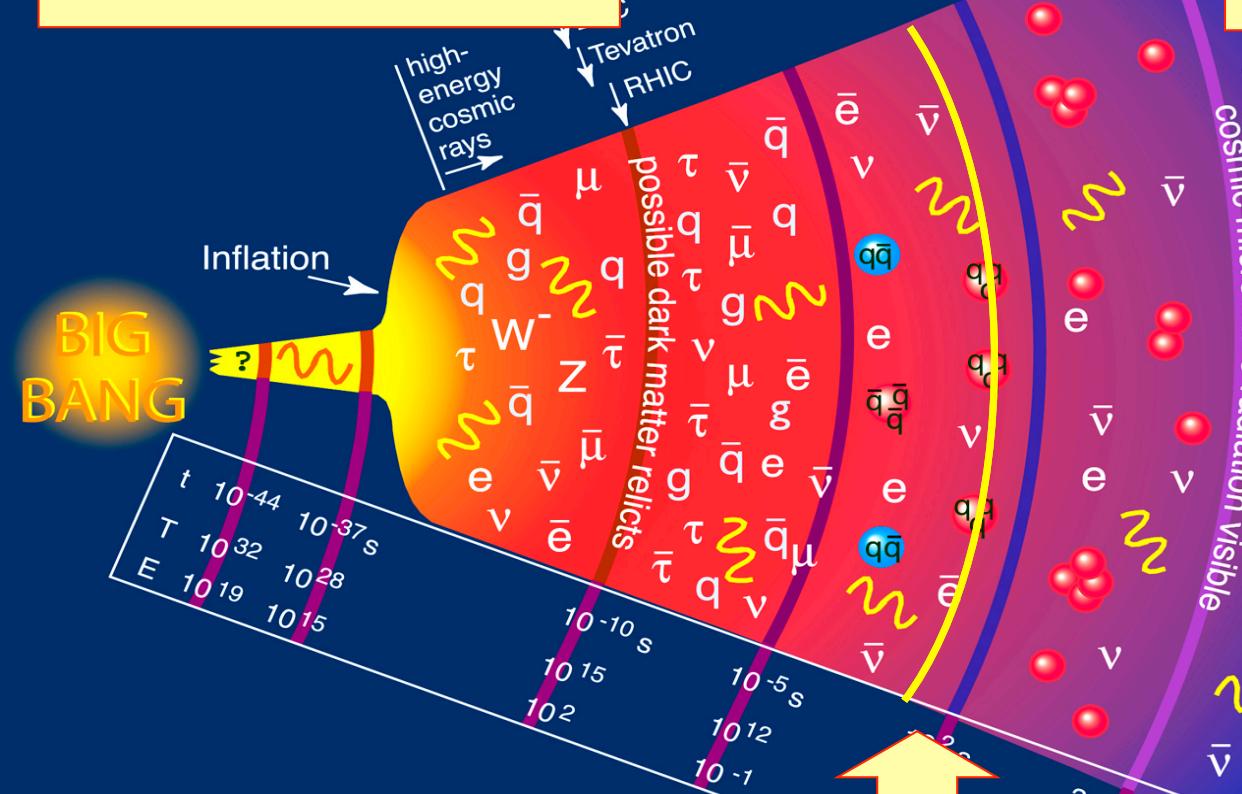


Particle Data Group, LBNL, © 2008. Supported by DOE and

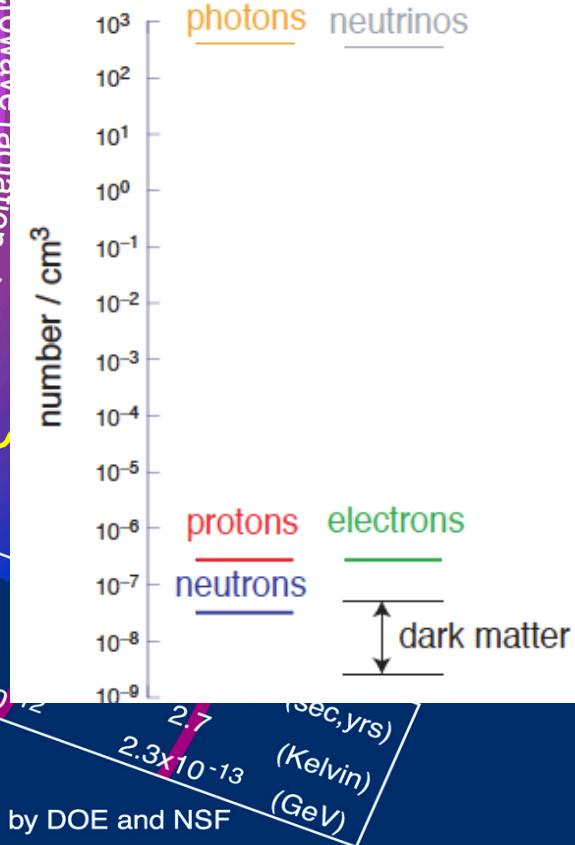
History of the Universe

Neutrinos coupled by weak interactions

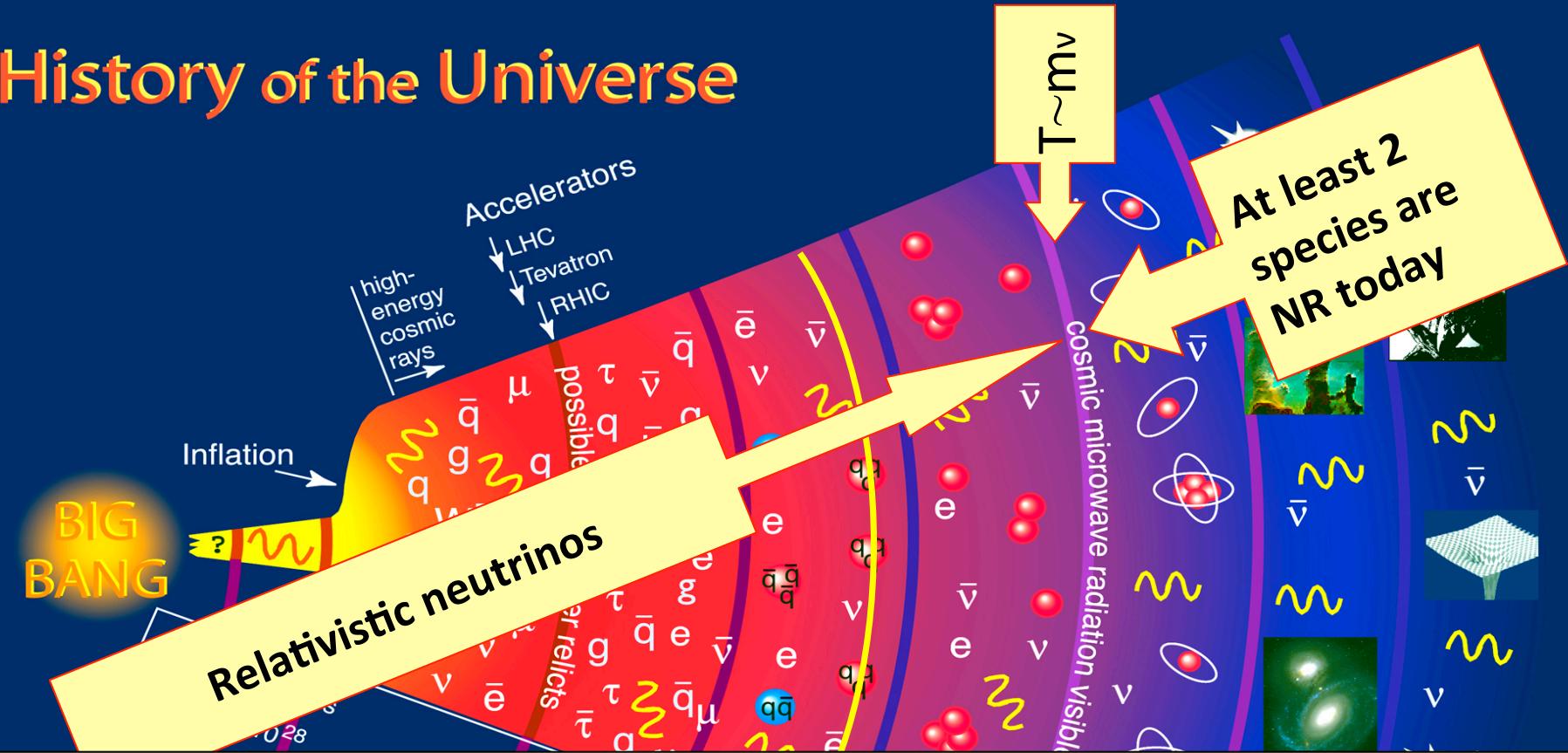
Decoupled neutrinos
(Cosmic Neutrino
Background or CNB)



The Particle Universe



History of the Universe

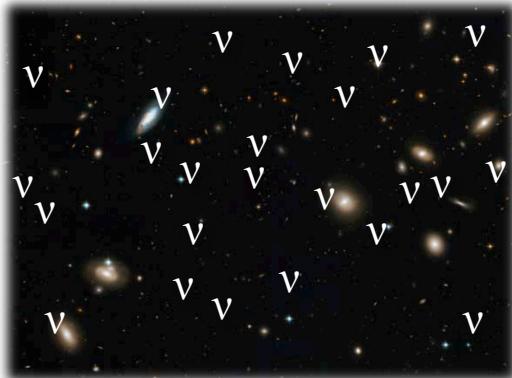


Neutrino cosmology is interesting because Relic neutrinos are very abundant:

- The CNB contributes to **radiation at early times** and to matter at late times (info on the number of neutrinos and their masses)
- Cosmological observables can be used to **test standard or non-standard neutrino properties**



Outline

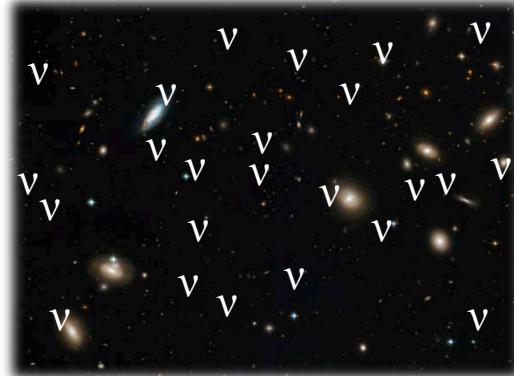


Introduction: neutrinos and the history of the Universe

Basics of Cosmology

Production and decoupling of relic neutrinos

Outline

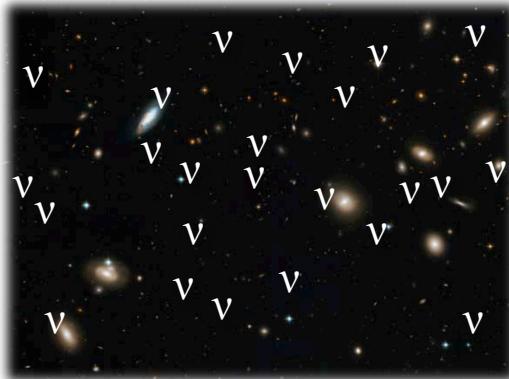


**The radiation content
of the Universe (N_{eff})**

**Neutrinos and Primordial
Nucleosynthesis**

**Neutrino oscillations
in the Early Universe**

Outline



Massive neutrinos as Dark Matter

**Effects of neutrino masses
on cosmological observables**

**Present bounds on neutrino
properties from cosmology**

**Future sensitivities on neutrino
physics from cosmology**

Basics of Cosmology

Eqs in the SM of Cosmology

The FLRW Model describes the evolution of the isotropic and homogeneous expanding Universe

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu = dt^2 - a(t)^2 \left(\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2 \theta d\phi^2 \right)$$

$a(t)$ is the scale factor and $k=-1,0,+1$ the curvature

Einstein eqs



$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = 8\pi G T_{\mu\nu} - \Lambda g_{\mu\nu}$$

Energy-momentum
tensor of a perfect
fluid



$$T_{\mu\nu} = (p + \rho)u_\mu u_\nu - p g_{\mu\nu}$$

Eqs in the SM of Cosmology

00 component
(Friedmann eq)



$$H(t)^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2}$$

$$\rho = \rho_M + \rho_R + \rho_\Lambda$$

$H(t)$ is the Hubble parameter

$$\frac{k}{H(t)^2 a^2} = \Omega - 1 \quad \Omega = \rho / \rho_{\text{crit}}$$

$$\dot{\rho} = \frac{d\rho}{dt} = -3H(\rho + p)$$

$\rho_{\text{crit}} = 3H^2/8\pi G$ is the critical density

Eq of state $p = \alpha \rho$



$$\rho = \text{const } a^{-3(1+\alpha)}$$

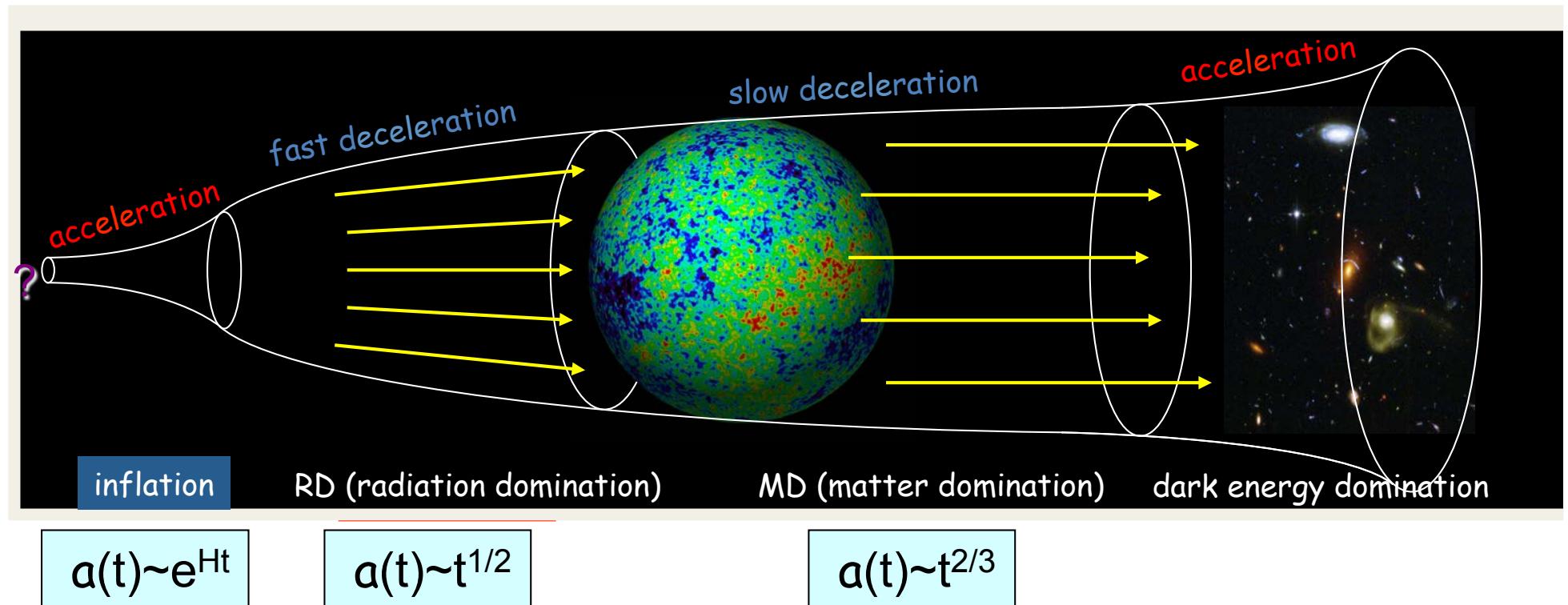
Radiation $\alpha = 1/3$
 $\rho_R \sim 1/a^4$

Matter $\alpha = 0$
 $\rho_M \sim 1/a^3$

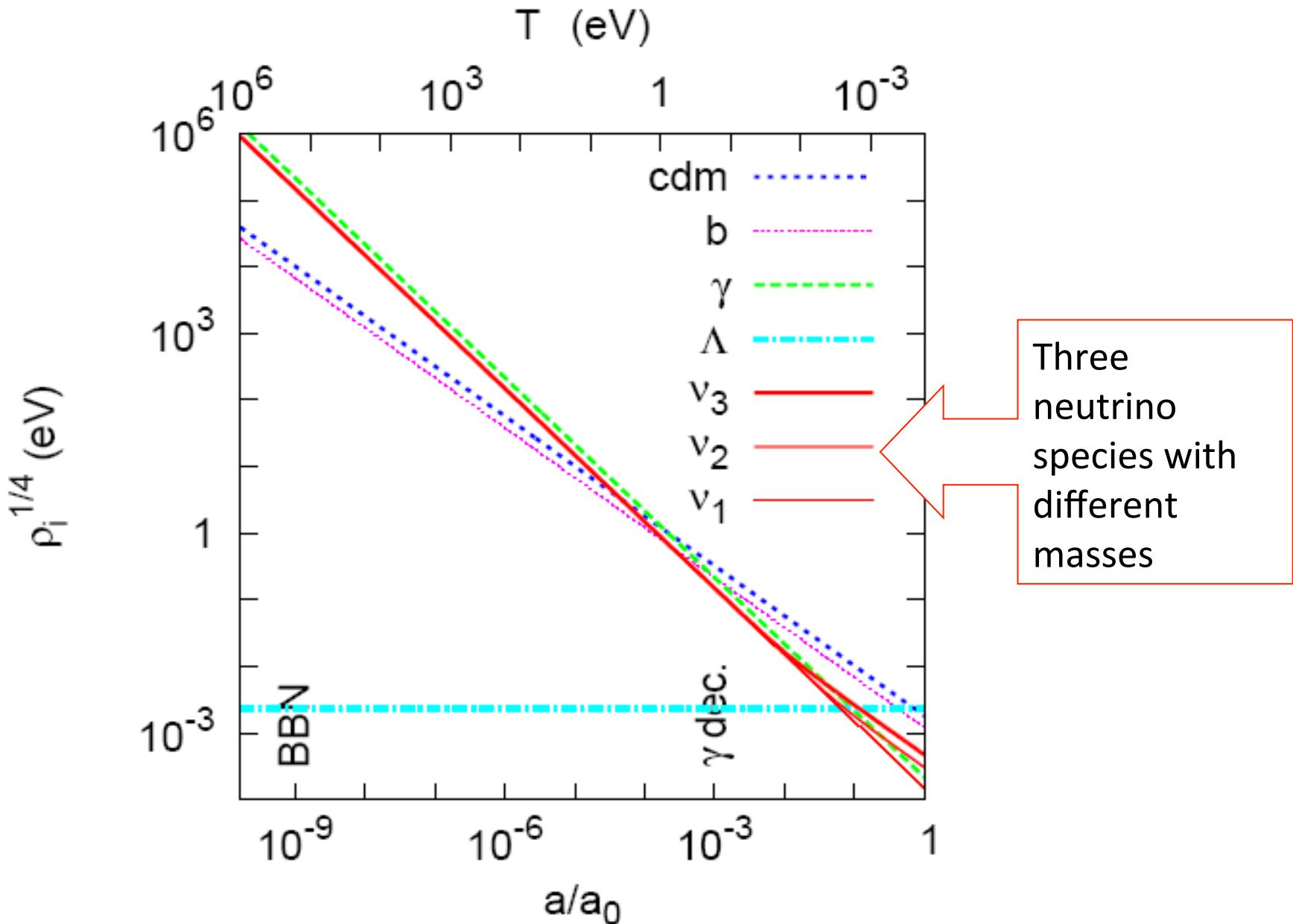
Cosmological constant $\alpha = -1$
 $\rho_\Lambda \sim \text{const}$

Evolution of the Universe

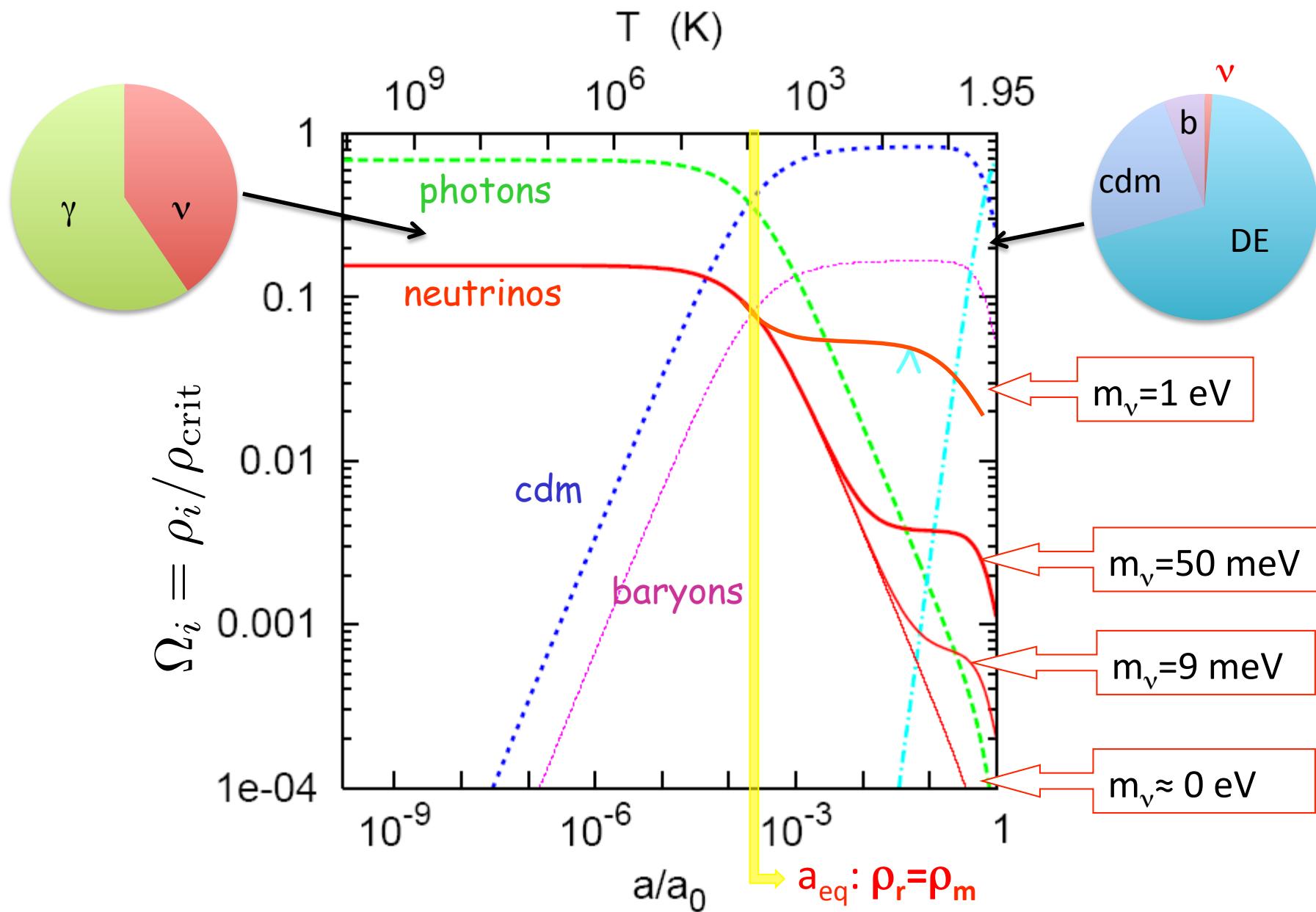
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) + \frac{\Lambda}{3}$$



Evolution of the background densities: 1 MeV → now



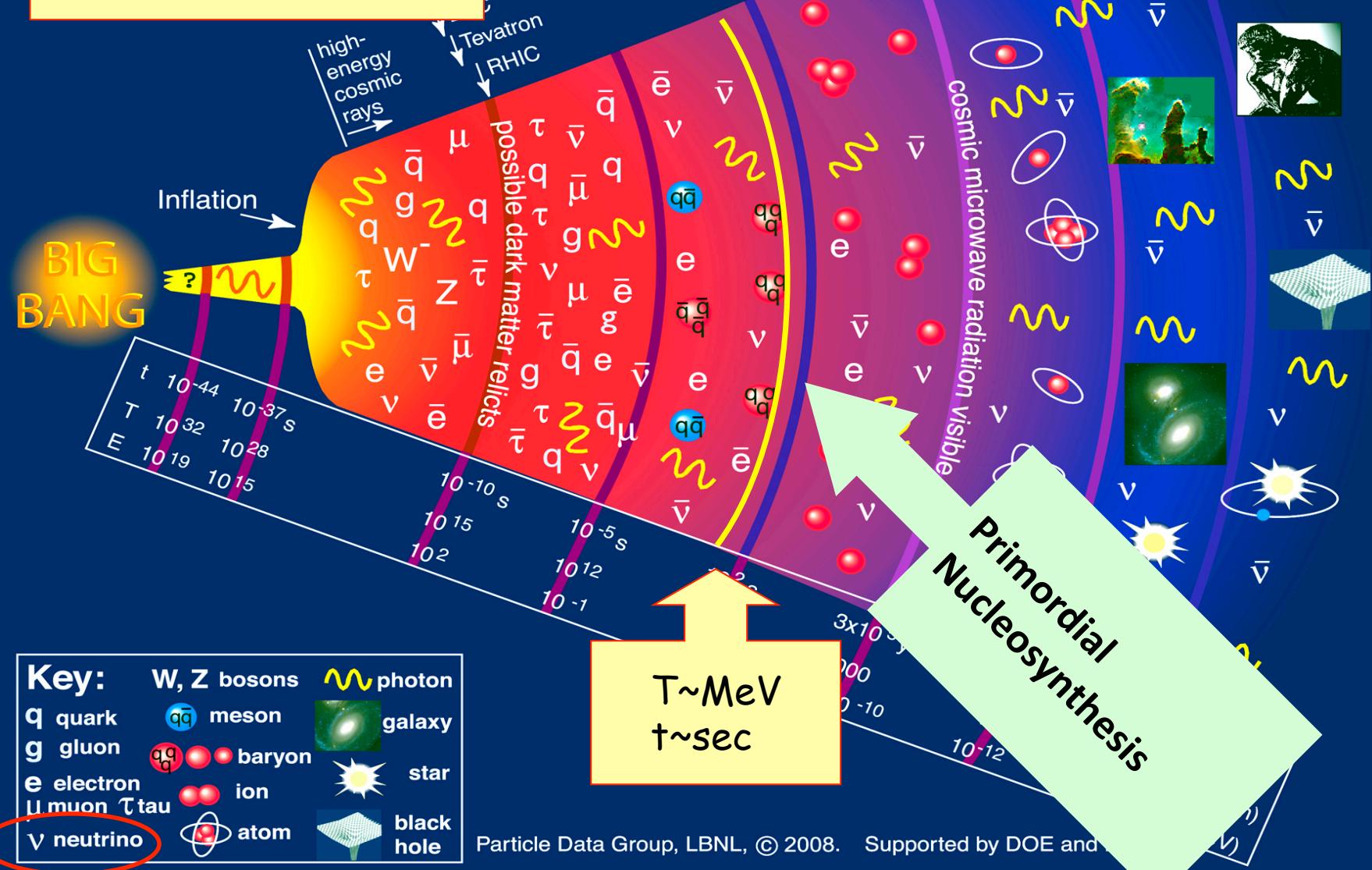
Background densities: 1 MeV → now



Production and decoupling of relic neutrinos

History of the Universe

Neutrinos coupled by weak interactions



Equilibrium thermodynamics

Particles in equilibrium when T are high and interactions effective

$$T \sim 1/a(t)$$

Distribution function of particle momenta in equilibrium

$$f_i^{eq}(p, T) = \left[\exp \left(\frac{E_i - \mu_i}{T} \right) \mp 1 \right]^{-1}$$

Thermodynamical variables

VARIABLE	RELATIVISTIC		NON REL.
	BOSE	FERMI	
n	$\frac{\zeta(3)}{\pi^2} g T^3$	$\frac{3\zeta(3)}{4\pi^2} g T^3$	$g \left(\frac{mT}{2\pi} \right)^{3/2} e^{-m/T}$
ρ	$\frac{\pi^2}{30} g T^4$	$\frac{7\pi^2}{8 \cdot 30} g T^4$	mn
p		$\frac{\rho}{3}$	$nT \ll \rho$
$\langle E \rangle$	$2,701T$	$3,151T$	$m + \frac{3}{2}T$

$$n = g_i \int \frac{d^2 \vec{p}}{(2\pi)^3} f_i(p, T) \quad \rho = g_i \int \frac{d^2 \vec{p}}{(2\pi)^3} E_i f_i(p, T)$$

$$p = g_i \int \frac{d^2 \vec{p}}{(2\pi)^3} \frac{p^2}{3E_i} f_i(p, T) \quad \langle E \rangle = \rho/n$$

Neutrinos in Equilibrium

$$1 \text{ MeV} \lesssim T \lesssim m_\mu$$

$$T_\nu = T_{e^\pm} = T_\gamma$$

$$\begin{aligned}\nu_\alpha \nu_\beta &\leftrightarrow \nu_\alpha \nu_\beta \\ \nu_\alpha \bar{\nu}_\beta &\leftrightarrow \nu_\alpha \bar{\nu}_\beta \\ \nu_\alpha e^\pm &\leftrightarrow \nu_\alpha e^\pm \\ \nu_\alpha \bar{\nu}_\alpha &\leftrightarrow e^+ e^-\end{aligned}$$

$$\mathcal{L}_{\text{SM}} = -2\sqrt{2}G_F \left\{ (\bar{\nu}_e \gamma^\mu L \nu_e)(\bar{e} \gamma_\mu L e) + \sum_{P,\alpha} g_P (\bar{\nu}_\alpha \gamma^\mu L \nu_\alpha)(\bar{e} \gamma_\mu P e) \right\}$$

$$P = L, R = (1 \mp \gamma_5)/2 \quad g_L = -\tfrac{1}{2} + \sin^2 \theta_W \text{ and } g_R = \sin^2 \theta_W$$

Neutrino decoupling

As the Universe expands, particle densities are diluted and temperatures fall. Weak interactions become **ineffective** to keep neutrinos in good thermal contact with the e.m. plasma

Rough, but quite accurate estimate of the decoupling temperature

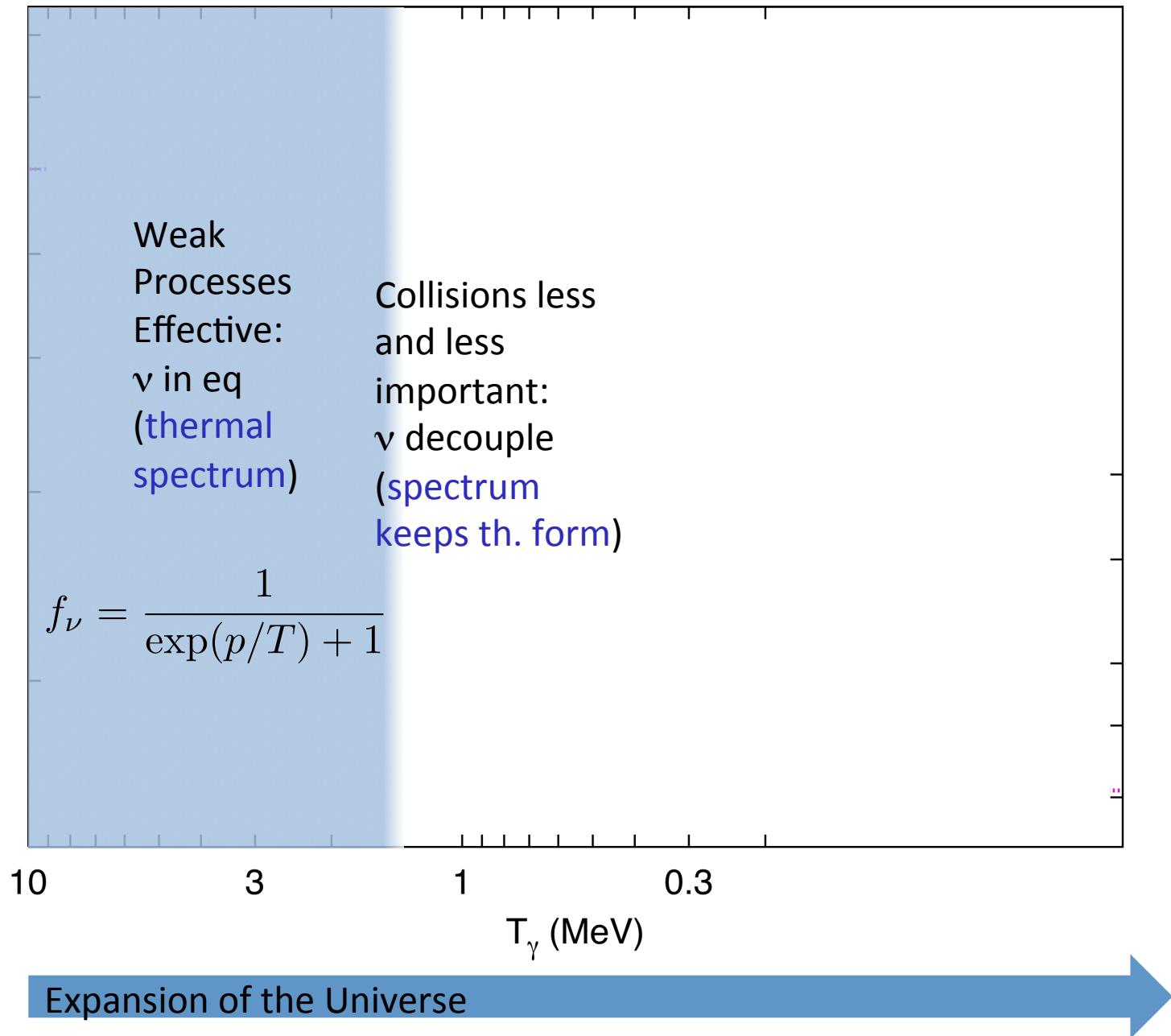
Rate of weak processes \sim Hubble expansion rate

$$\Gamma_W \approx \sigma_W |v| n, \quad H^2 = \frac{8\pi\rho_{\text{rad}}}{3M_P^2} \rightarrow G_F^2 T^5 \approx \sqrt{\frac{8\pi\rho_{\text{rad}}}{3M_P^2}} \rightarrow T_{\text{dec}}(\nu) \approx 1 \text{ MeV}$$

Since ν_e have both CC and NC interactions with e^\pm

$$T_{\text{dec}}(\nu_e) \simeq 2 \text{ MeV} \quad T_{\text{dec}}(\nu_{\mu,\tau}) \simeq 3 \text{ MeV}$$

Neutrino decoupling



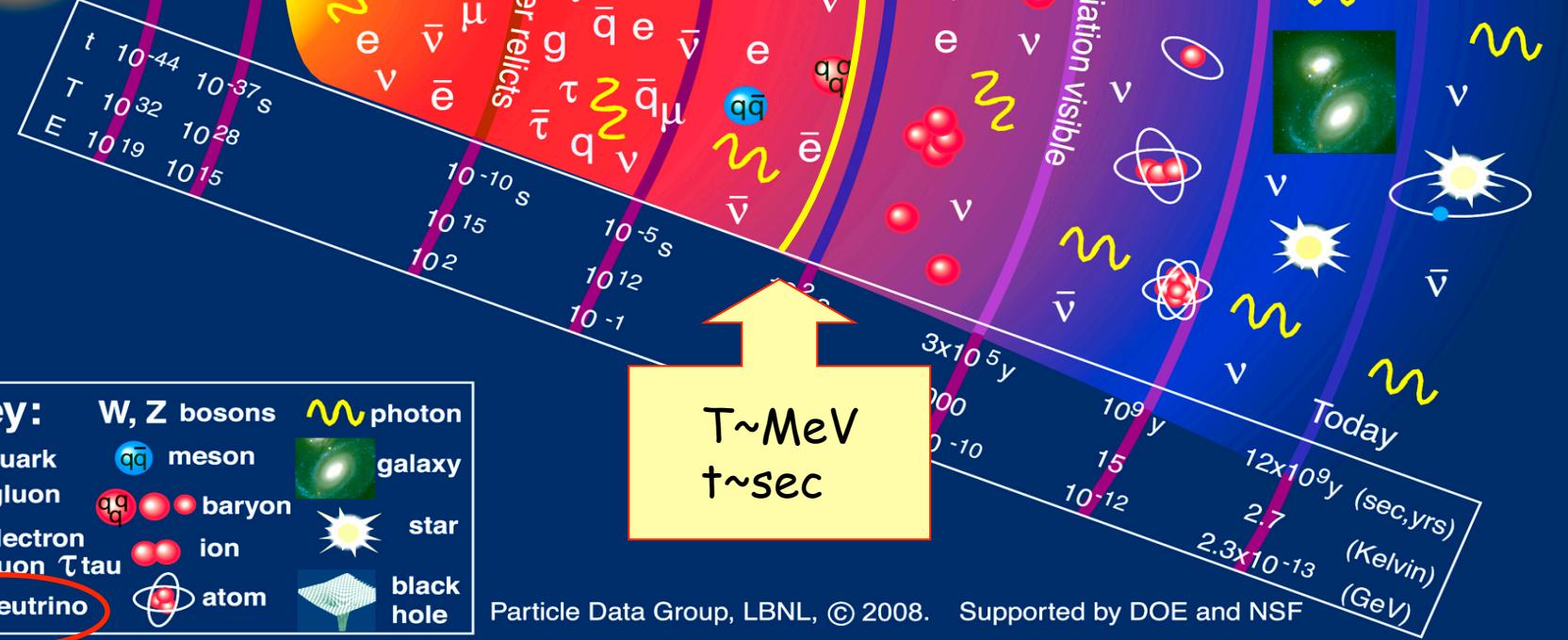
History of the Universe

Neutrinos coupled by weak interactions

$$f_\nu(p, T) = \frac{1}{\exp(p/T) + 1}$$

BIG BANG

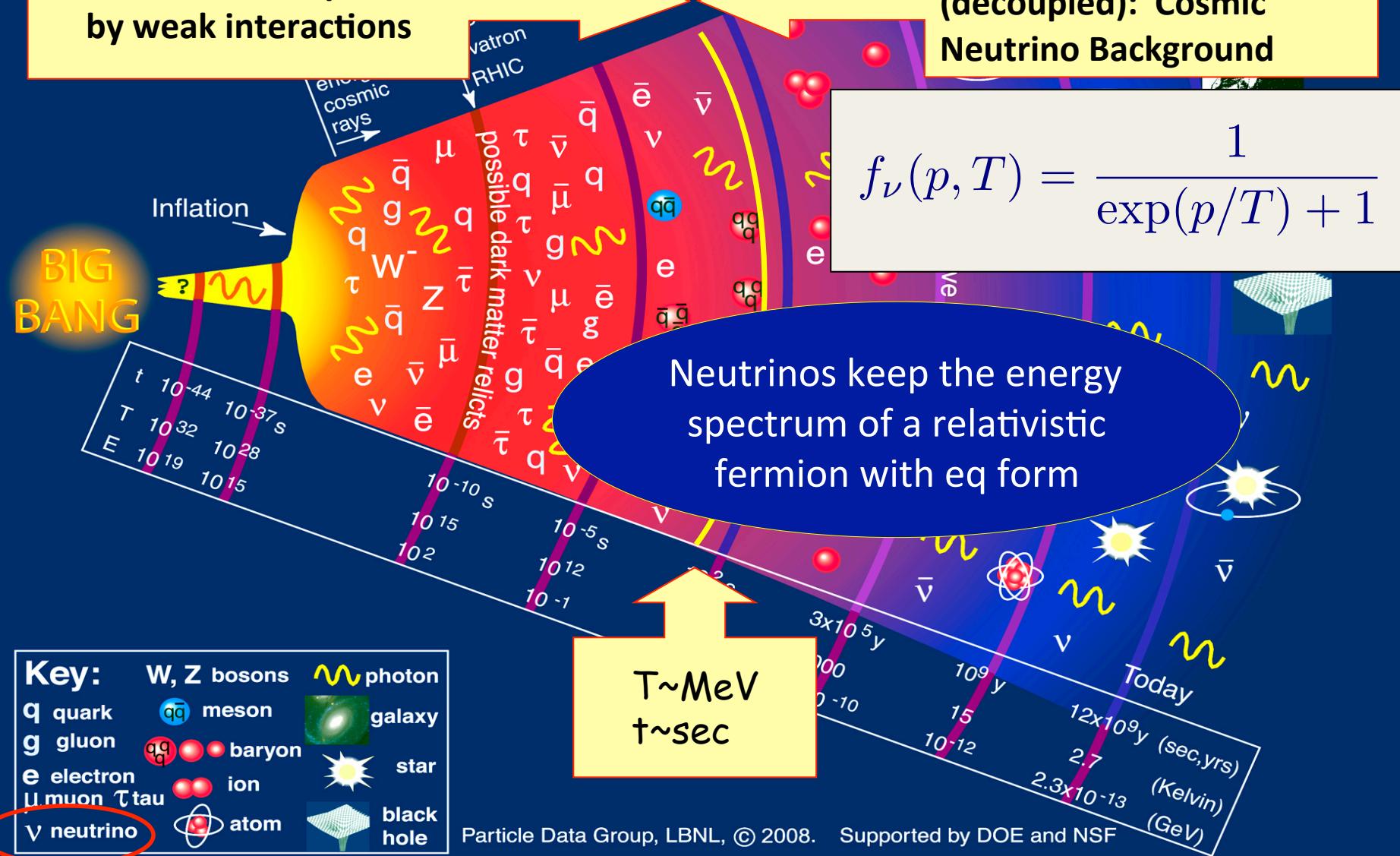
Key:	W, Z bosons	Photon
q quark	qq meson	W
g gluon	qq baryon	Z
e electron	ion	gamma
μ muon	atom	galaxy
τ tau	black hole	star
ν neutrino		



History of the Universe

Neutrinos coupled by weak interactions

Free-streaming neutrinos (decoupled): Cosmic Neutrino Background



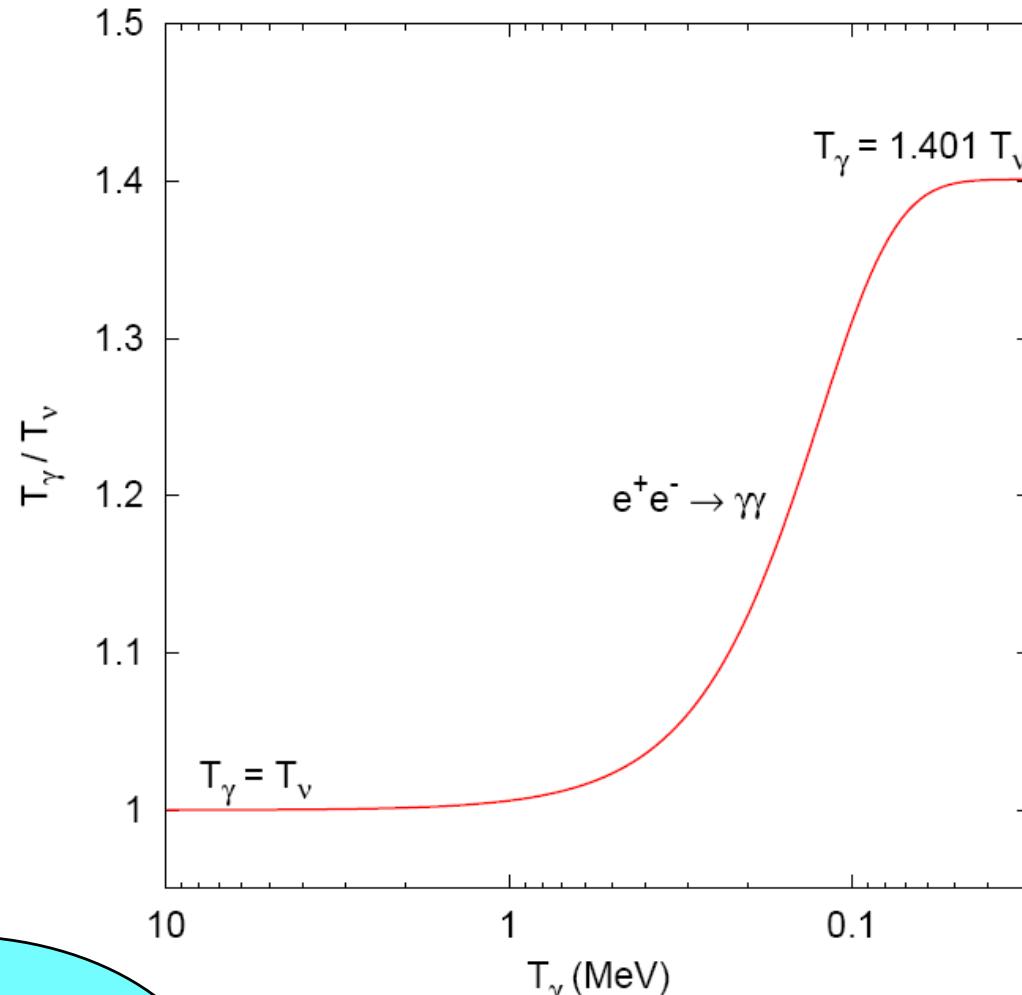
Neutrino and photon (CMB) temperatures

At $T \sim m_e$,
electron-
positron pairs
annihilate



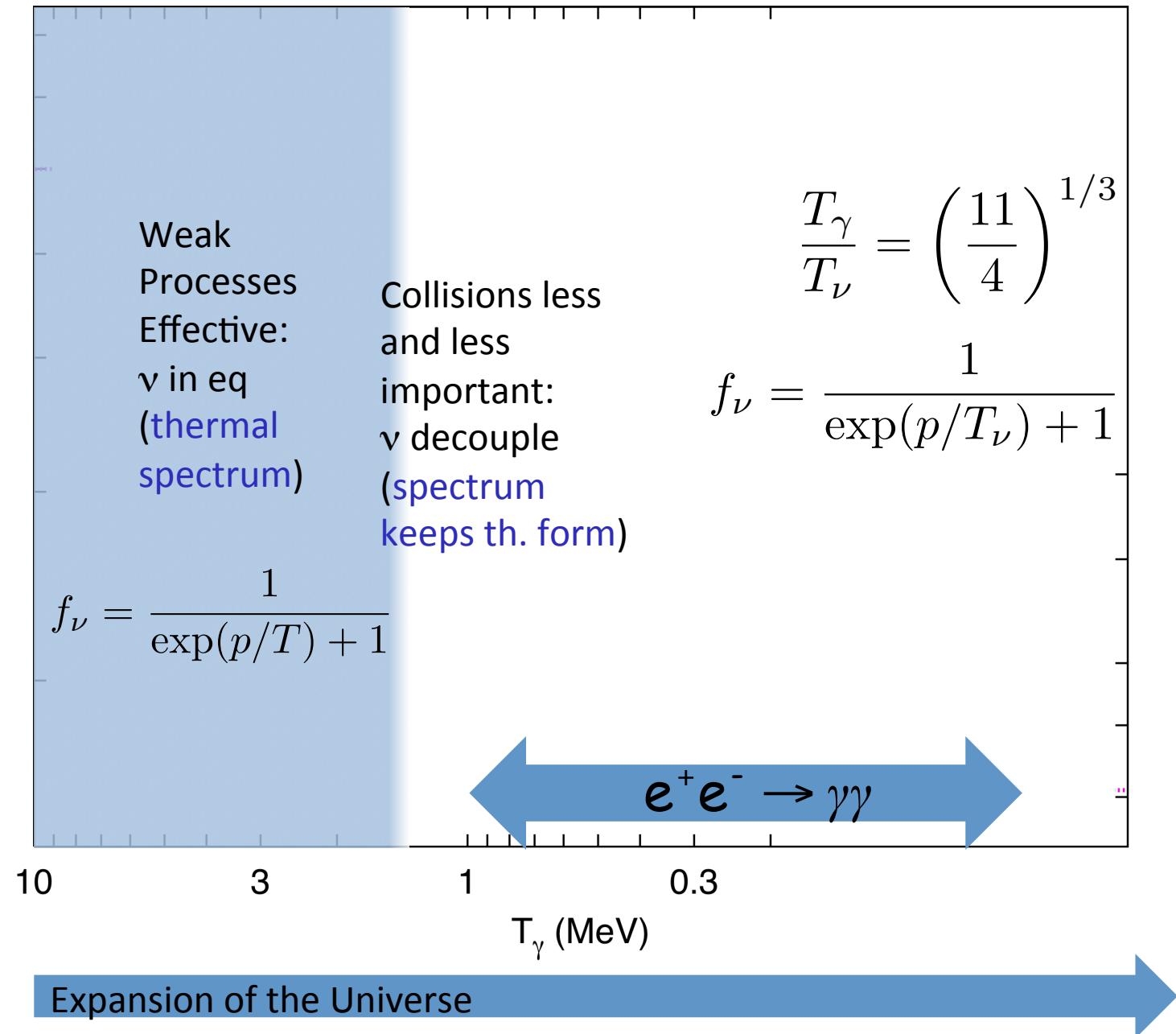
heating photons
but not the
decoupled
neutrinos

$$\frac{T_\gamma}{T_\nu} = \left(\frac{11}{4}\right)^{1/3}$$



$$f_\nu(p, T) = \frac{1}{\exp(p/T_\nu) + 1}$$

Neutrino decoupling and e^\pm annihilations



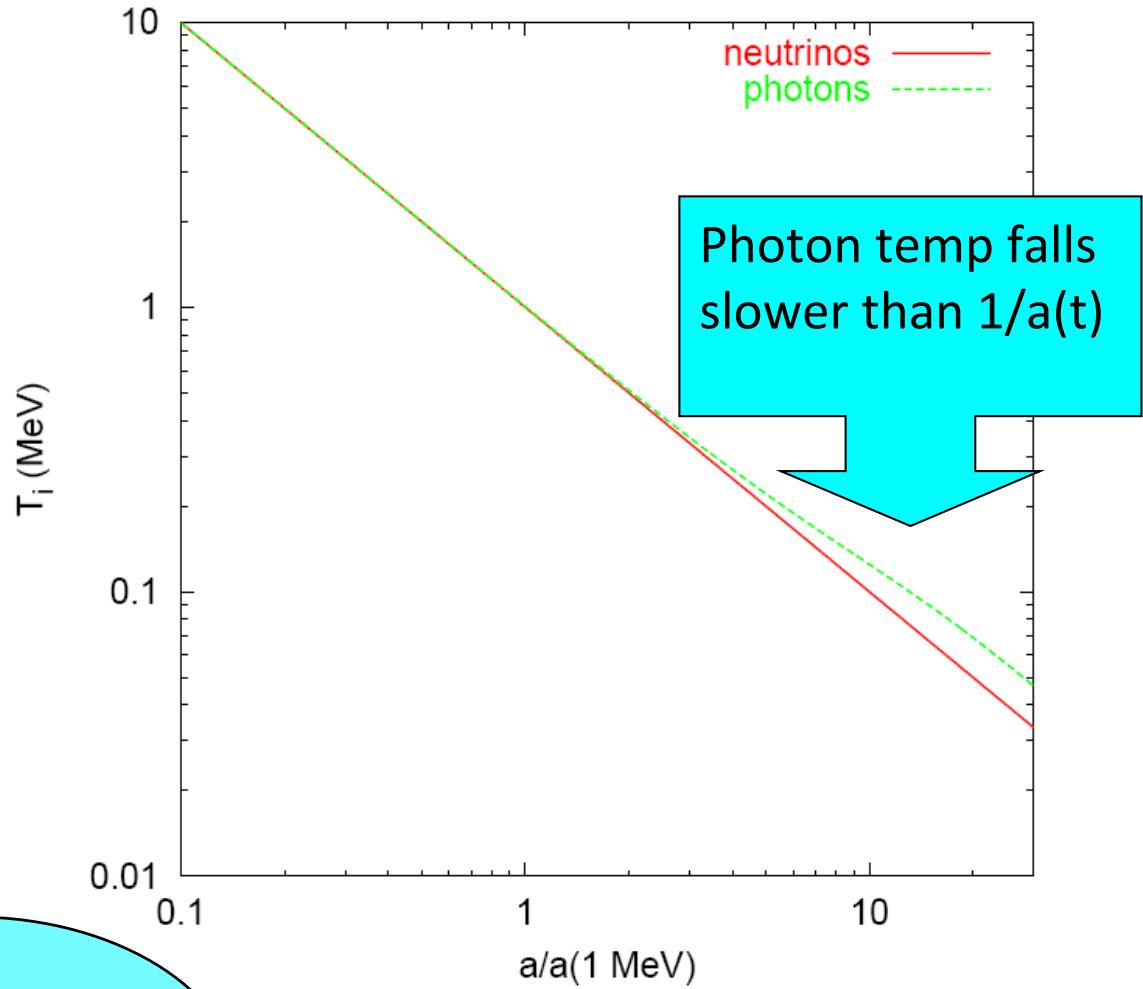
Neutrino and Photon (CMB) temperatures

At $T \sim m_e$,
electron-
positron pairs
annihilate



heating photons
but not the
decoupled
neutrinos

$$\frac{T_\gamma}{T_\nu} = \left(\frac{11}{4}\right)^{1/3}$$



$$f_\nu(p, T) = \frac{1}{\exp(p/T_\nu) + 1}$$

The Cosmic Neutrino Background

Neutrinos decoupled at $T \sim \text{MeV}$, keeping a spectrum as that of a relativistic species

$$f_\nu(p, T) = \frac{1}{\exp(p/T_\nu) + 1}$$

- Number density

$$n_\nu = \int \frac{d^3 p}{(2\pi)^3} f_\nu(p, T_\nu) = \frac{3}{11} n_\gamma = \frac{6\zeta(3)}{11\pi^2} T_{\text{CMB}}^3$$

- Energy density

$$\rho_{\nu_i} = \int \sqrt{p^2 + m_{\nu_i}^2} \frac{d^3 p}{(2\pi)^3} f_\nu(p, T_\nu) \rightarrow \begin{cases} \frac{7\pi^2}{120} \left(\frac{4}{11}\right)^{4/3} T_{\text{CMB}}^4 & \text{Massless} \\ m_{\nu_i} n_\nu & \text{Massive } m_\nu \gg T \end{cases}$$

The Cosmic Neutrino Background

Neutrinos decoupled at $T \sim \text{MeV}$, keeping a spectrum as that of a relativistic species

$$f_\nu(p, T) = \frac{1}{\exp(p/T_\nu) + 1}$$

- Number density

At present $112 (\nu + \bar{\nu}) \text{ cm}^{-3}$ per flavour

- Energy density

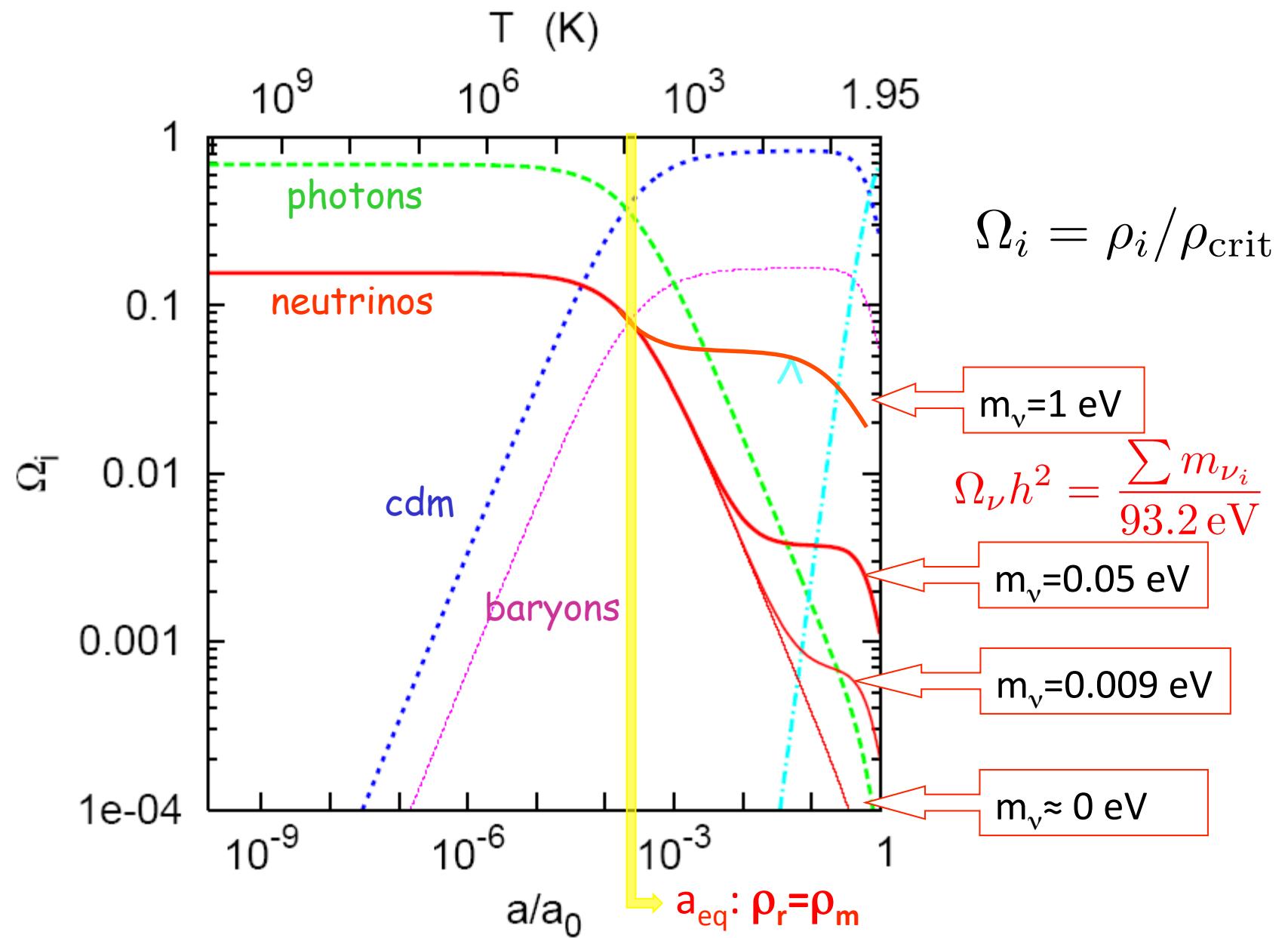
$$\Omega_\nu h^2 \simeq 1.7 \times 10^{-5} \quad \text{Massless}$$

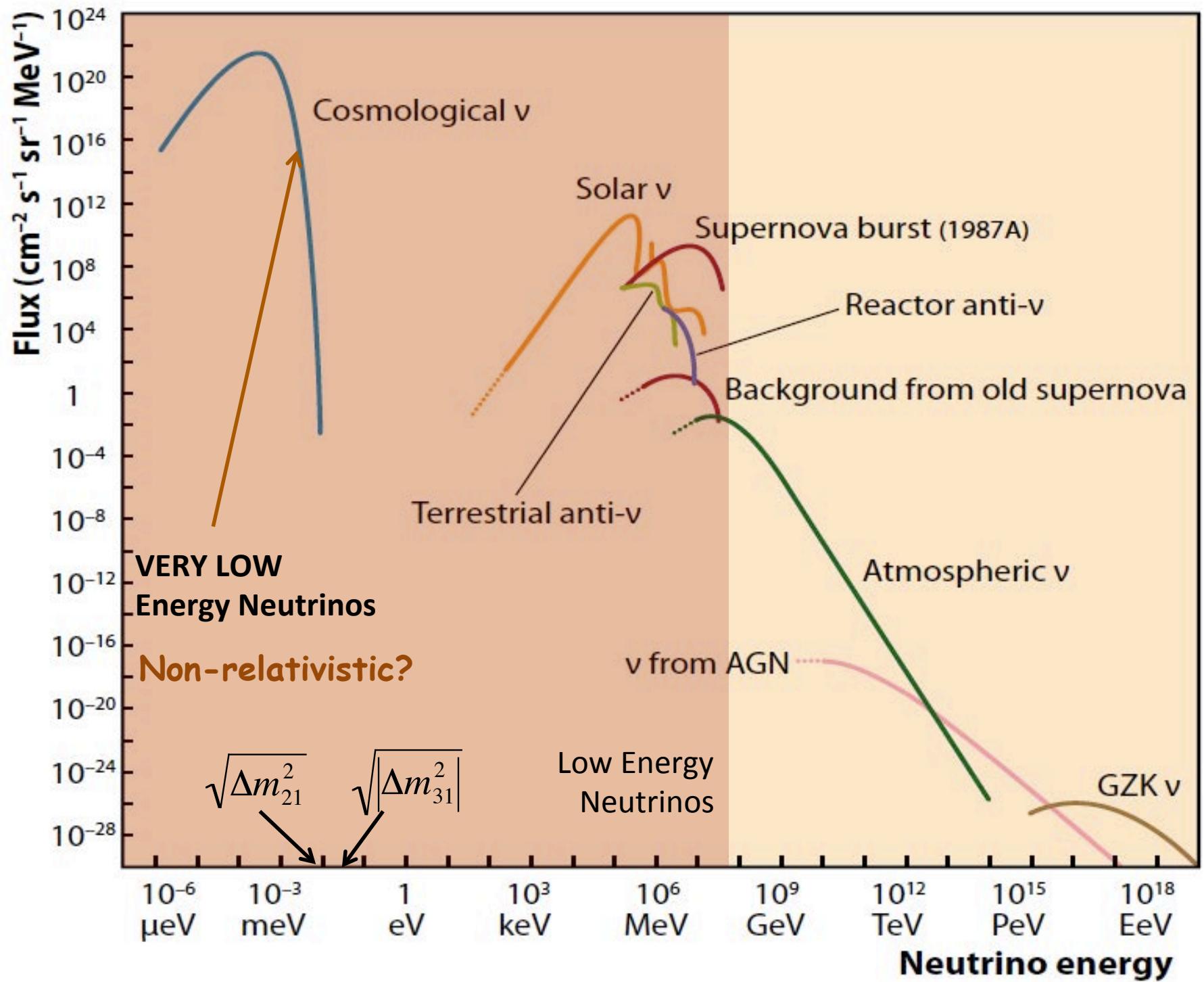
Contribution to the energy density of the Universe

$$\Omega_\nu h^2 = \frac{\sum_i m_{\nu_i}}{94.1 \text{ eV}}$$

Massive
 $m_\nu \gg T$

Evolution of the background densities: 1 MeV → now





The radiation content of the Universe (N_{eff})

Relativistic particles in the Universe

At $T >> m_e$, the radiation content of the Universe is

$$\rho_r = \rho_\gamma + \rho_\nu = \frac{\pi^2}{15} T^4 + 3 \times \frac{7}{8} \times \frac{\pi^2}{15} T^4 = \left[1 + \frac{7}{8} \times 3 \right] \rho_\gamma$$

At $T < m_e$, the radiation content of the Universe is

$$\rho_r = \rho_\gamma + \rho_\nu = \frac{\pi^2}{15} T_\gamma^4 + 3 \times \frac{7}{8} \times \frac{\pi^2}{15} T_\nu^4 = \left[1 + \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} 3 \right] \rho_\gamma$$

$$\rho_r = \rho_\gamma + \rho_\nu = \left[1 + \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} N_{\text{eff}} \right] \rho_\gamma \quad \frac{T_\nu^4}{T_\gamma^4}$$

of flavour neutrinos: $N_\nu = 2.984 \pm 0.008$ (LEP data)

Relativistic particles in the Universe

At $T < m_e$, the radiation content of the Universe is

$$\rho_r = \rho_\gamma + \rho_\nu + \rho_x = \left[1 + \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} N_{\text{eff}} \right] \rho_\gamma$$

Effective number of relativistic neutrino species

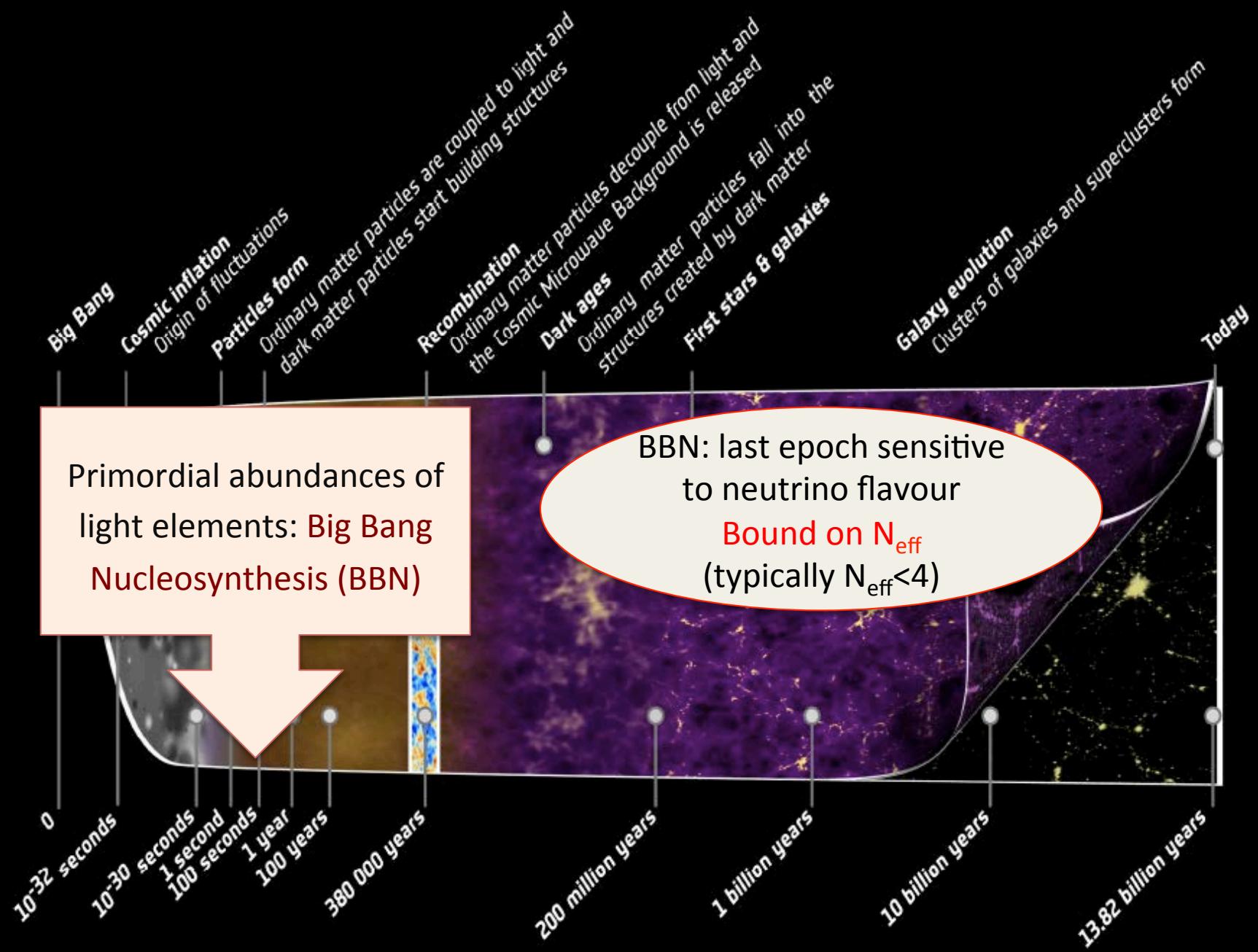
Traditional parametrization of ρ stored in relativistic particles

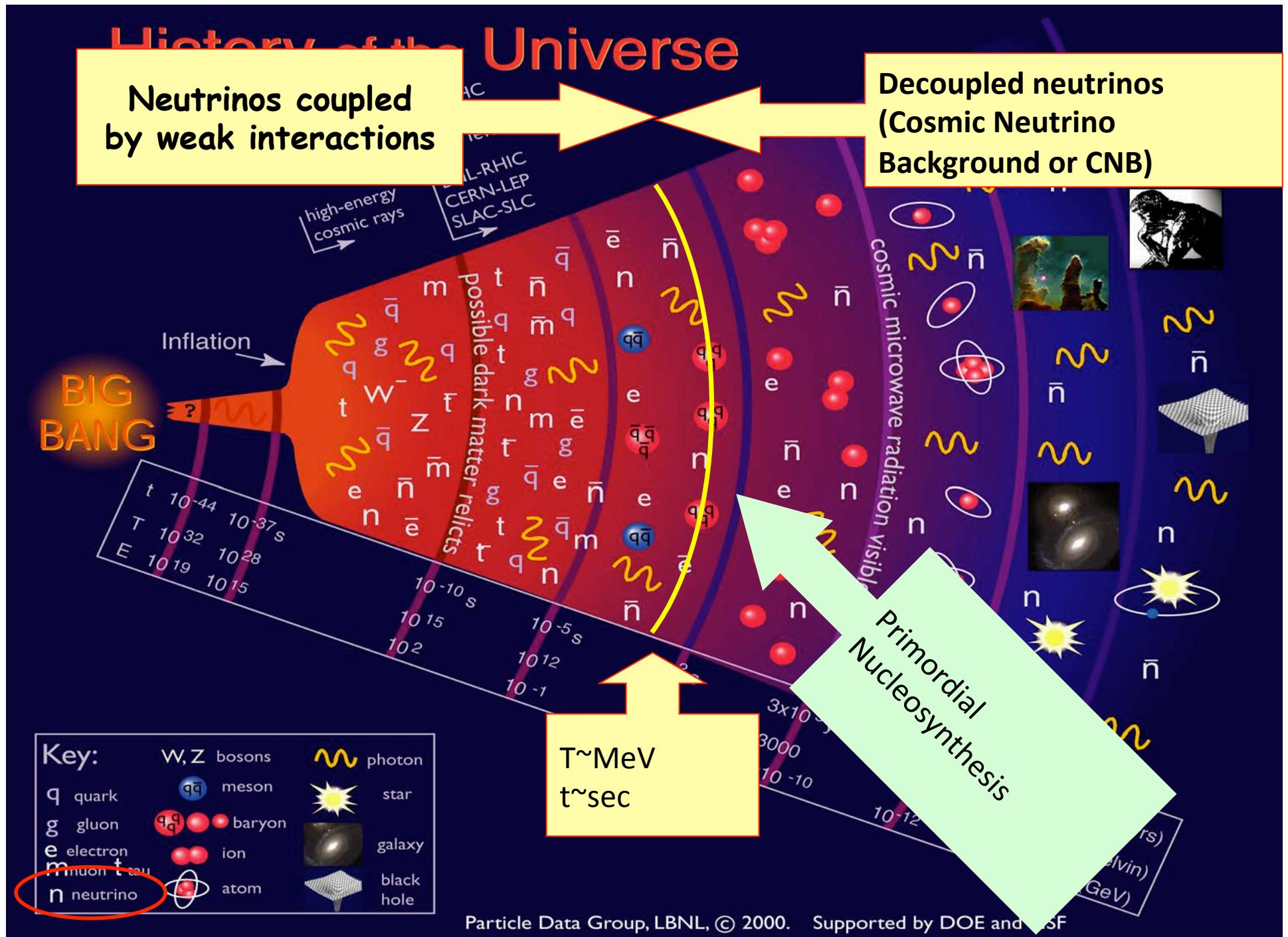
N_{eff} is a way to measure the ratio $\frac{\rho_\nu + \rho_x}{\rho_\gamma}$

- standard neutrinos only: $N_{\text{eff}} \simeq 3$ (3.045)
- $N_{\text{eff}} > 3$ (delays equality time) from **additional relativistic particles** (scalars, pseudoscalars, decay products of heavy particles,...) or **non-standard neutrino physics** (primordial neutrino asymmetries, totally or partially thermalized light sterile neutrinos, non-standard interactions with electrons,...)

Bounds on N_{eff} from
Primordial Nucleosynthesis
and other cosmological
observables (CMB+LSS)

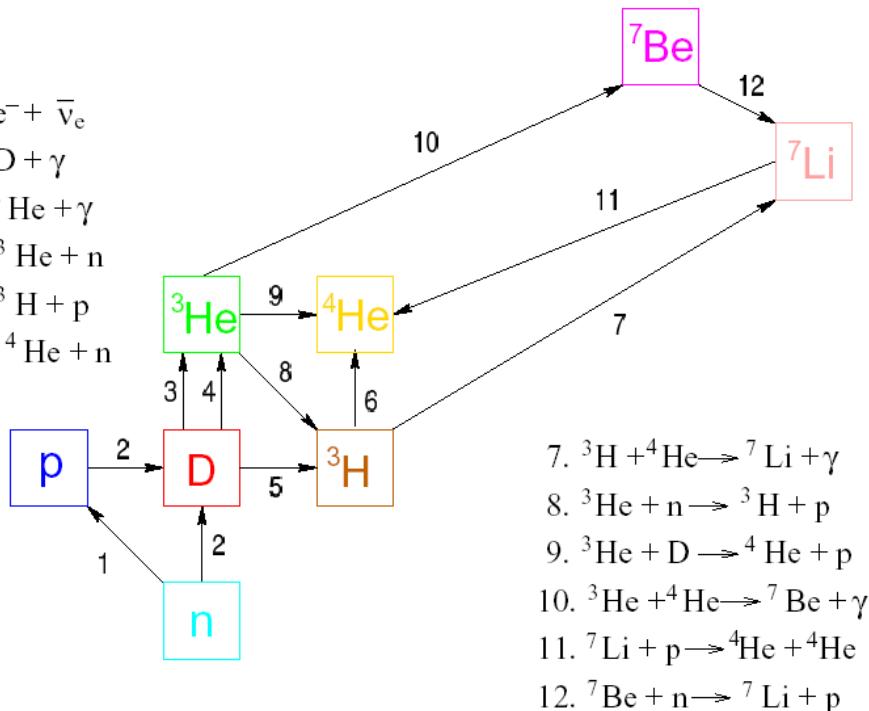
Neutrinos and Primordial Nucleosynthesis





BBN: Creation of light elements

1. $n \rightarrow p + e^- + \bar{\nu}_e$
2. $p + n \rightarrow D + \gamma$
3. $D + p \rightarrow {}^3\text{He} + \gamma$
4. $D + D \rightarrow {}^3\text{He} + n$
5. $D + D \rightarrow {}^3\text{H} + p$
6. ${}^3\text{H} + D \rightarrow {}^4\text{He} + n$



Theoretical inputs:

- τ_n , the neutron lifetime;
- G_N , the Newton gravitational constant;
- η , the baryon to photon number density ratio;
- the nuclear rates.

Produced elements: D, ${}^3\text{He}$, ${}^4\text{He}$, ${}^7\text{Li}$ and small abundances of others

BBN: Creation of light elements

Range of temperatures: from 0.8 to 0.01 MeV

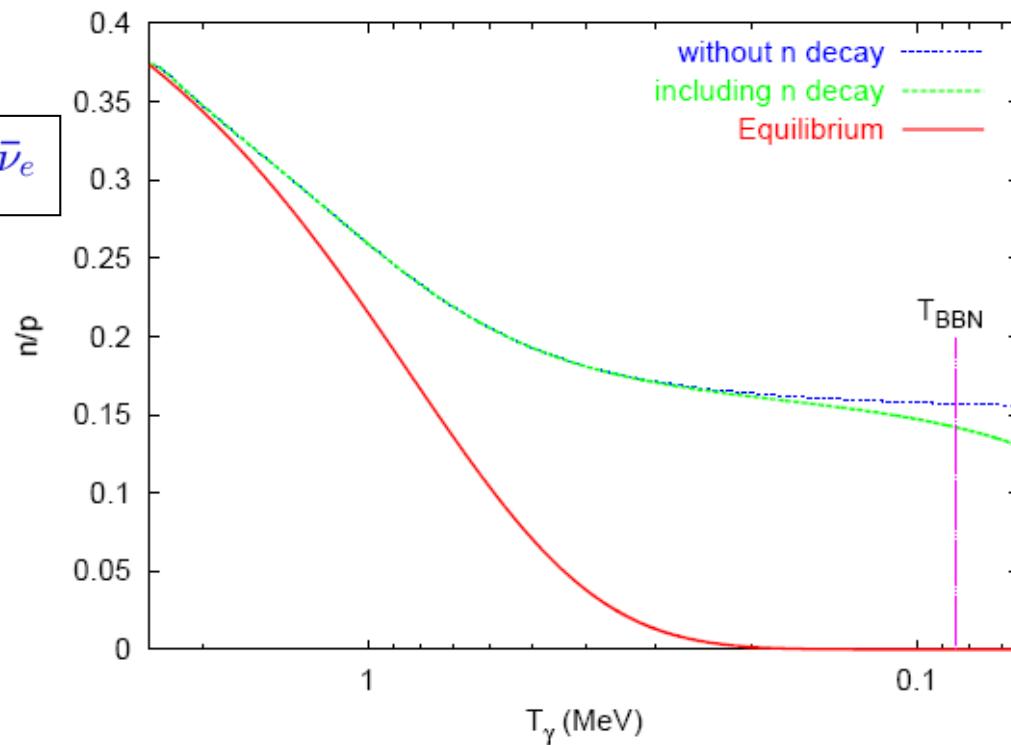
$$t \simeq 0,74 \left(\frac{\text{MeV}}{T} \right)^2 \text{ sec}$$

Phase I: 0.8-0.1 MeV

n-p reactions



n/p freezing and
neutron decay



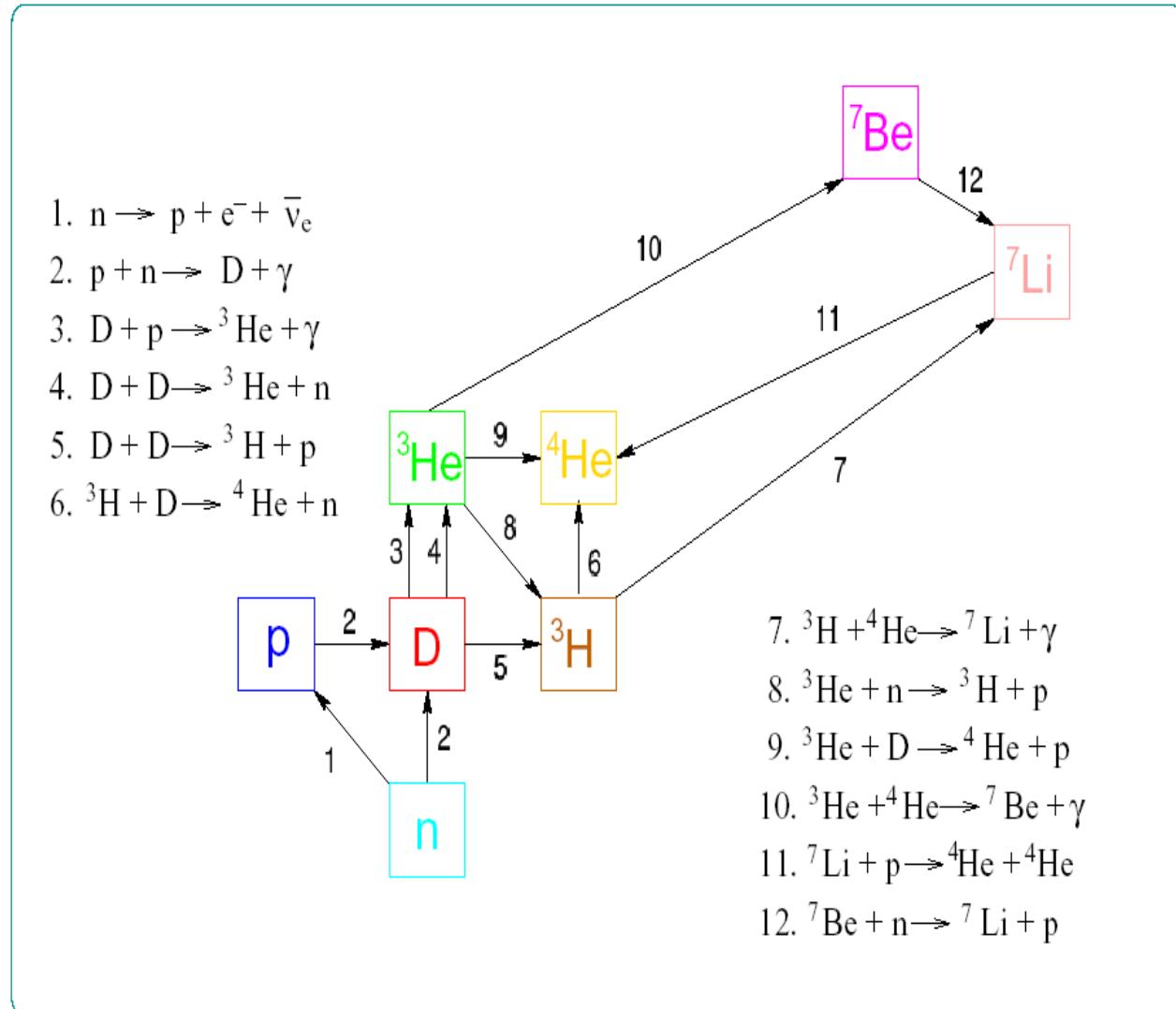
$$\left(\frac{n}{p} \right)_{eq} \simeq \exp \left(-\frac{m_n - m_p}{T_\gamma} \right) = \exp \left(-\frac{1,293 \text{ MeV}}{T_\gamma} \right)$$

BBN: Creation of light elements

Phase II: 0.1-0.01 MeV

Formation of light nuclei
starting from D

Photodesintegration
prevents earlier formation
for temperatures closer
to nuclear binding energies



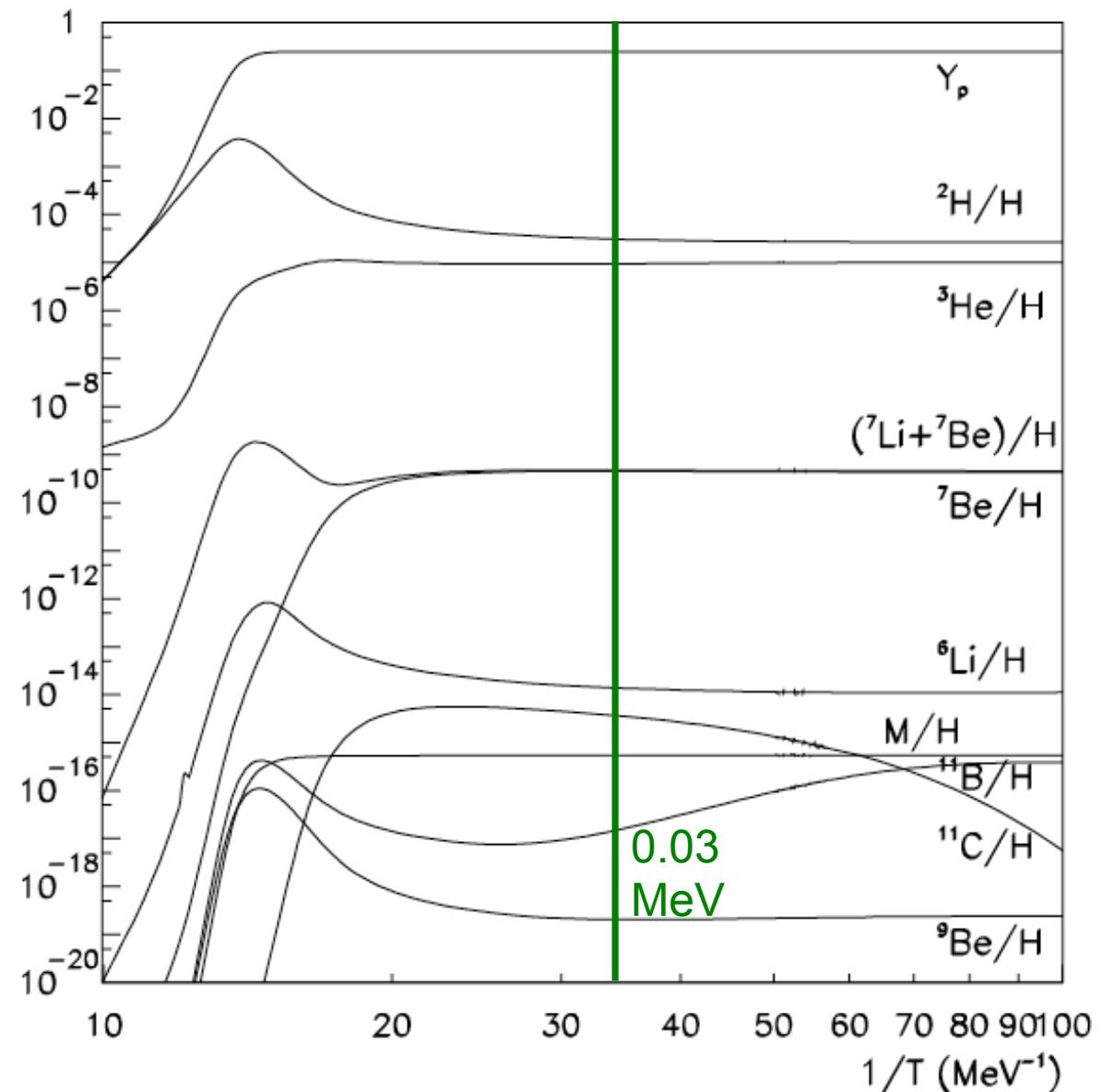
BBN: Creation of light elements

Phase II: 0.1-0.01 MeV

Formation of light nuclei
starting from D

Photodesintegration

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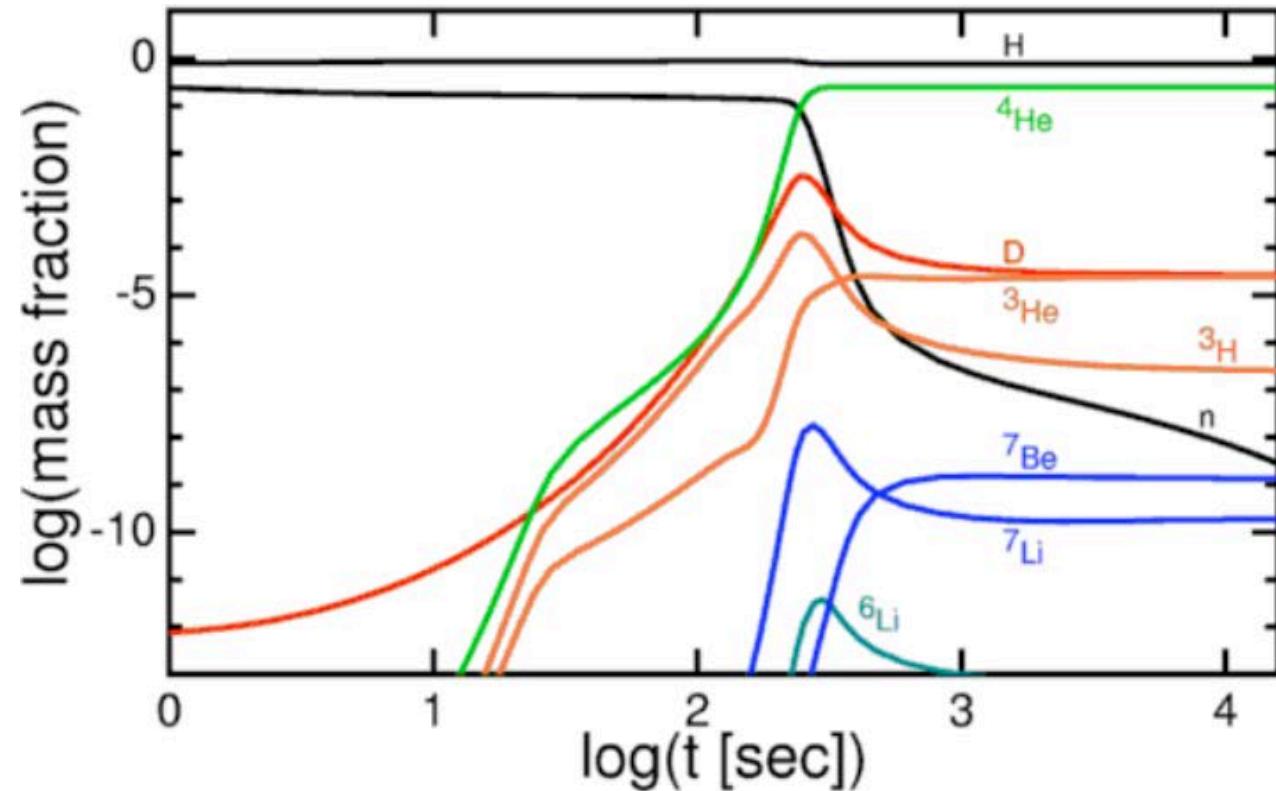


BBN: Creation of light elements

Phase II: 0.1-0.01 MeV

Formation of light nuclei
starting from D

Photodesintegration
prevents earlier formation
for temperatures closer
to nuclear binding energies



BBN: Measurement of Primordial abundances

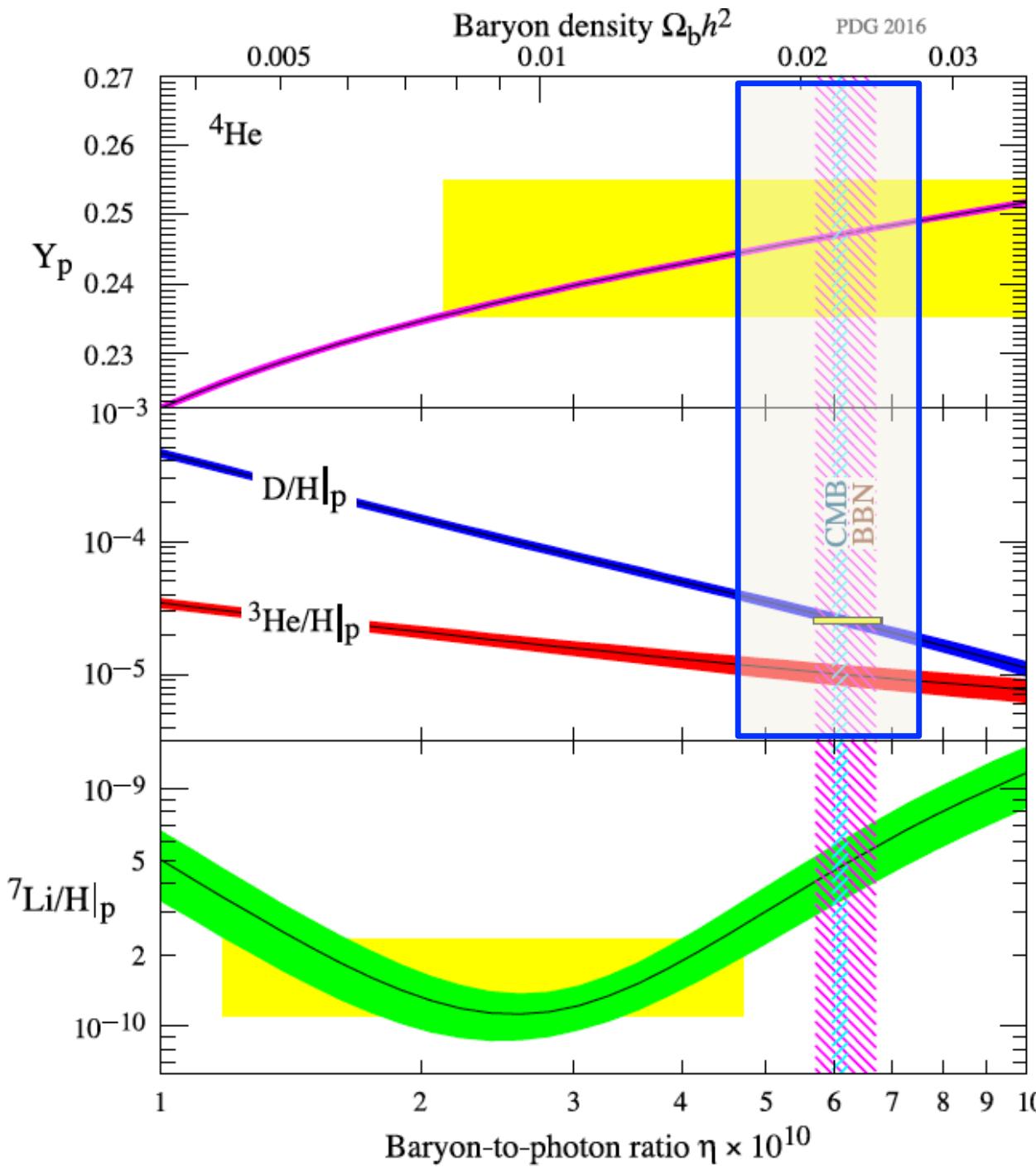
Difficult task: search in astrophysical systems with chemical evolution as small as possible

Deuterium: destroyed in stars. Any observed abundance of D is a *lower limit* to the primordial abundance. Data from high-z, low metallicity QSO absorption line systems

Helium-3: produced and destroyed in stars (complicated evolution)
Data from solar system and galaxies but not used in BBN analysis

Helium-4: primordial abundance increased by H burning in stars.
Data from low metallicity, extragalactic HII regions

Lithium-7: destroyed in stars, produced in cosmic ray reactions.
Data from oldest, most metal-poor stars in the Galaxy

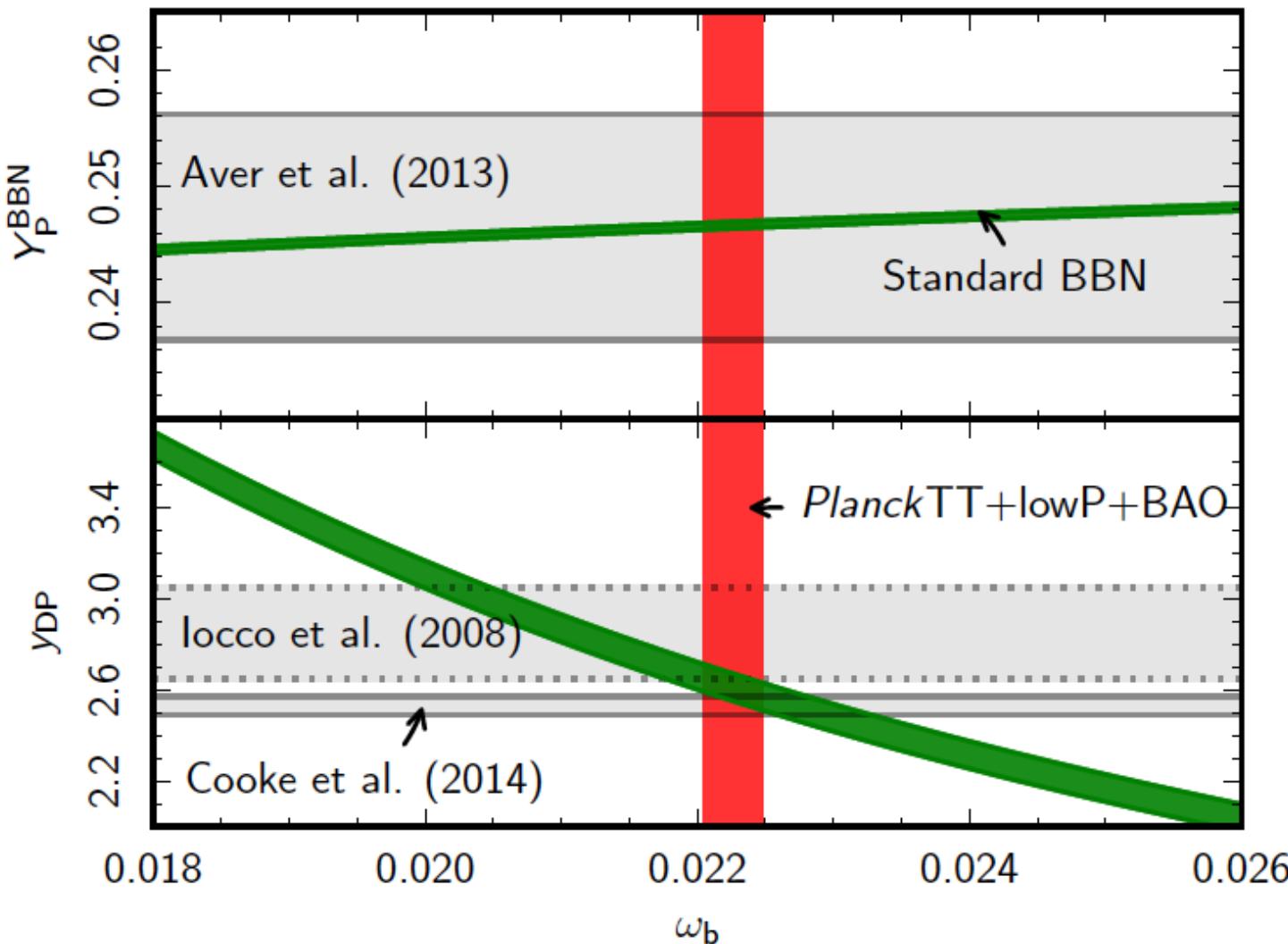


BBN: Predictions vs Observations

$$\eta_{10} = \frac{n_B/n_\gamma}{10^{-10}} \simeq 274 \Omega_B h^2$$

Fields, Molaro & Sarkar,
PDG 2016

BBN: Predictions vs Observations



Planck 2015, arXiv:1502.01589

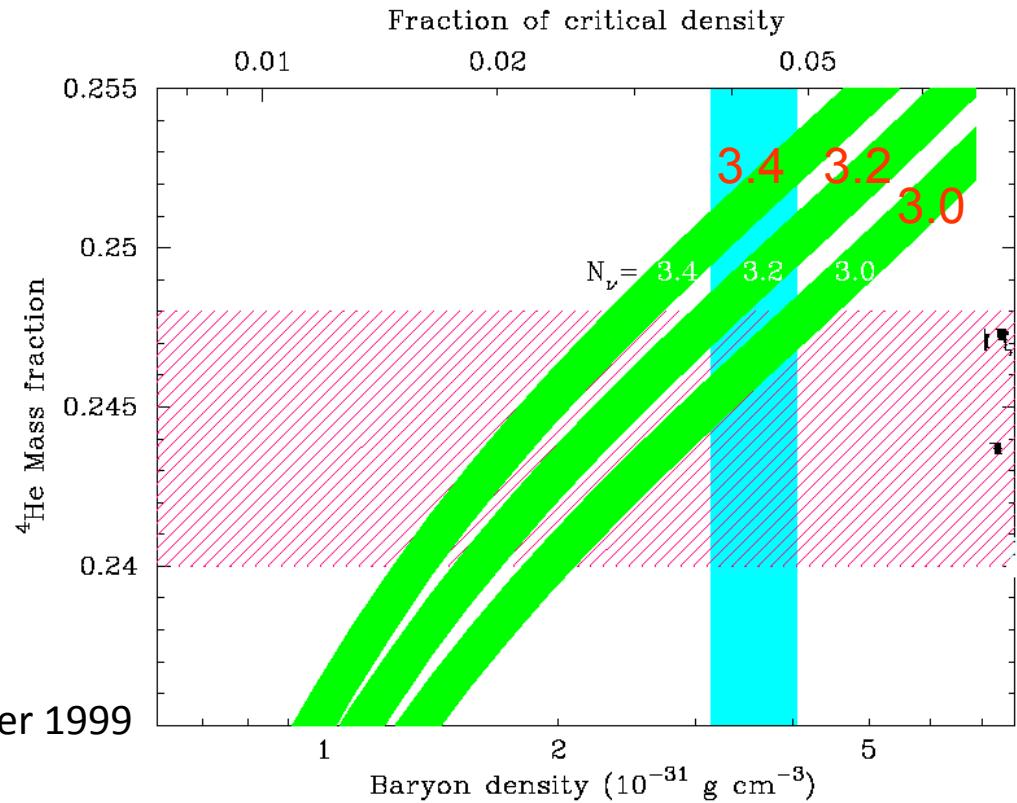
Effect of neutrinos on BBN

1. N_{eff} fixes the expansion rate during BBN

$$H = \sqrt{\frac{8\pi\rho}{3M_p^2}}$$



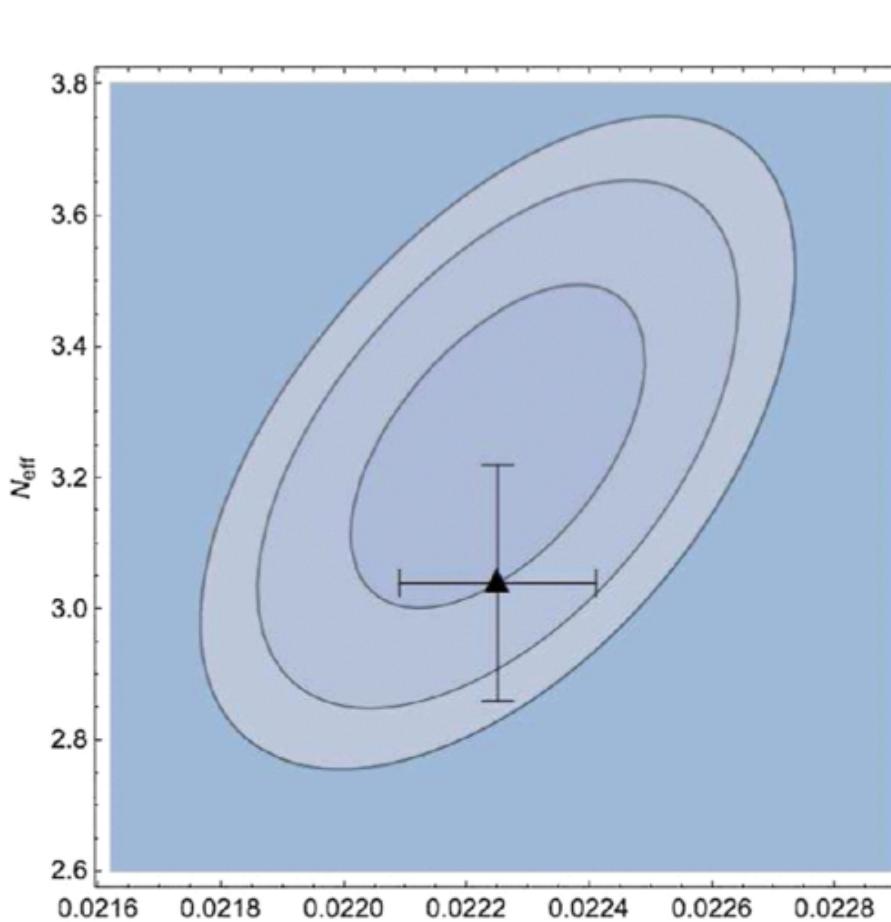
Burles, Nollett & Turner 1999



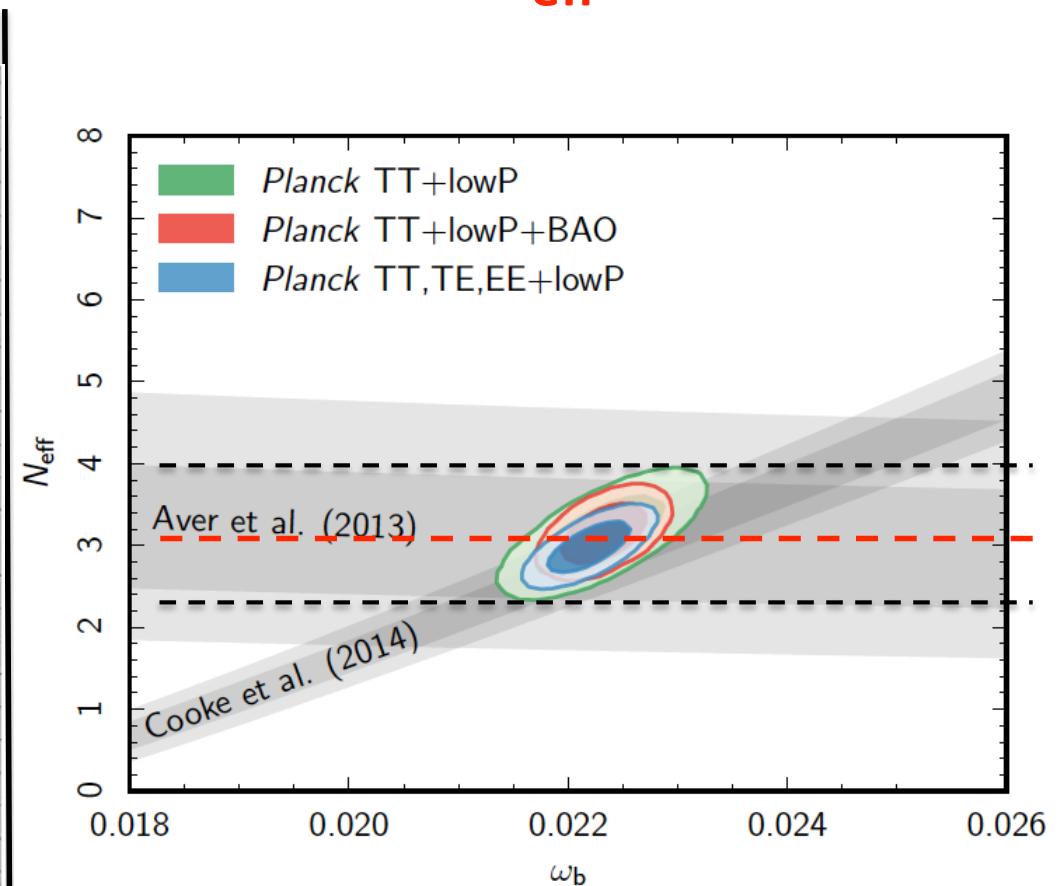
2. Direct effect of electron neutrinos and antineutrinos on the n-p reactions



BBN: allowed ranges for N_{eff}



Deuterium-only bounds
Marcucci et al, PRL 116 (2016) 102501
[arXiv:1510.07877]

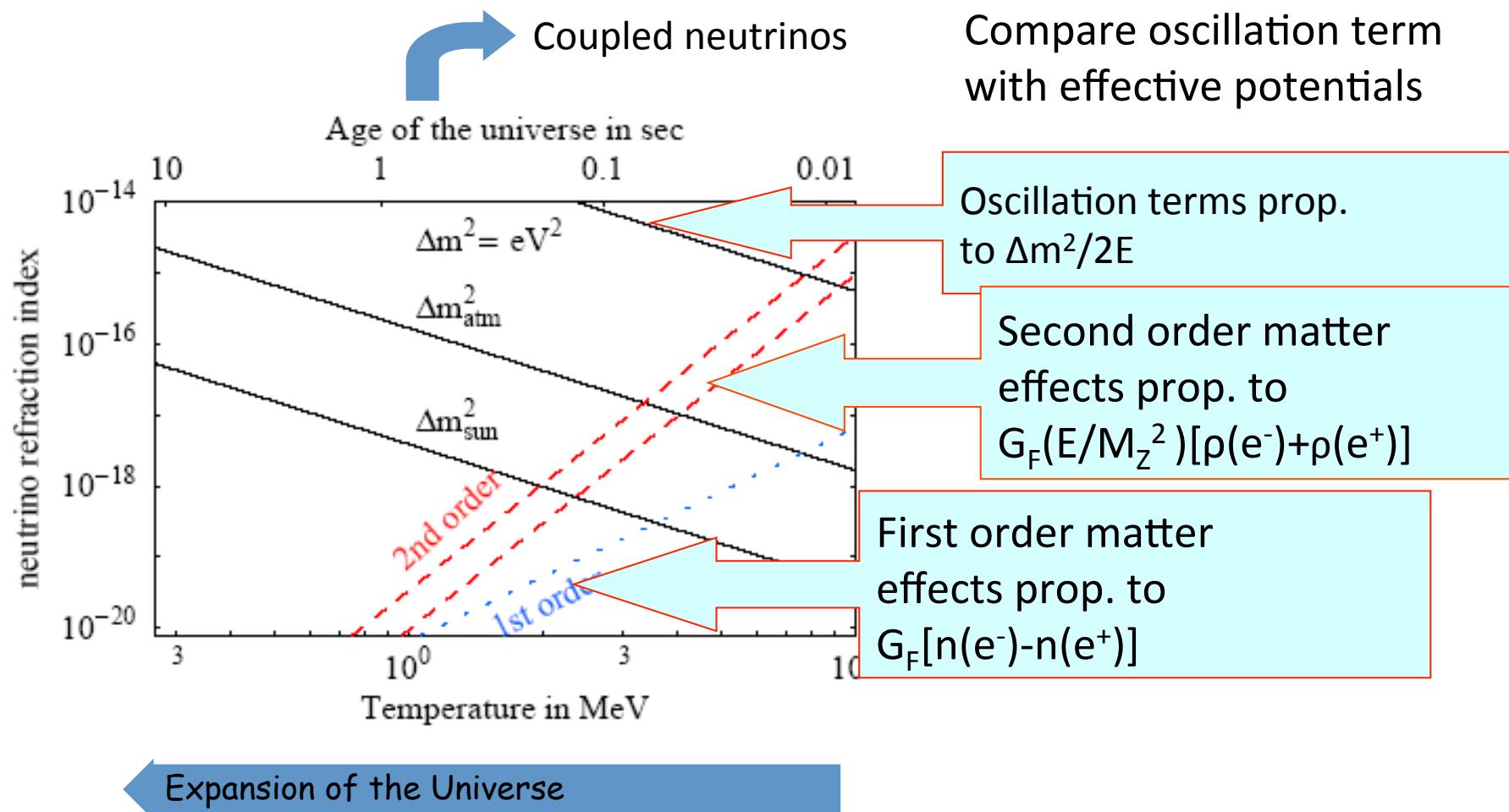


Planck 2015, arXiv:1502.01589

Neutrino oscillations in the Early Universe

Neutrino oscillations in the Early Universe

Neutrino oscillations are **effective** when medium effects get small enough



Flavour neutrino oscillations in the Early Universe

Standard case: all neutrino flavours equally populated

→ oscillations are effective below a few MeV, but have no effect (except for mixing the small distortions δf_ν)

Cosmology is insensitive to neutrino flavour after decoupling!

Non-zero neutrino asymmetries: flavour oscillations lead to (approximate) global flavour equilibrium



the restrictive BBN bound on the $\nu_e \bar{\nu}_e$ asymmetry applies to all flavors, but fine-tuned initial asymmetries always allow for a large surviving neutrino excess radiation that may show up in precision cosmological data (value depends on θ_{13})

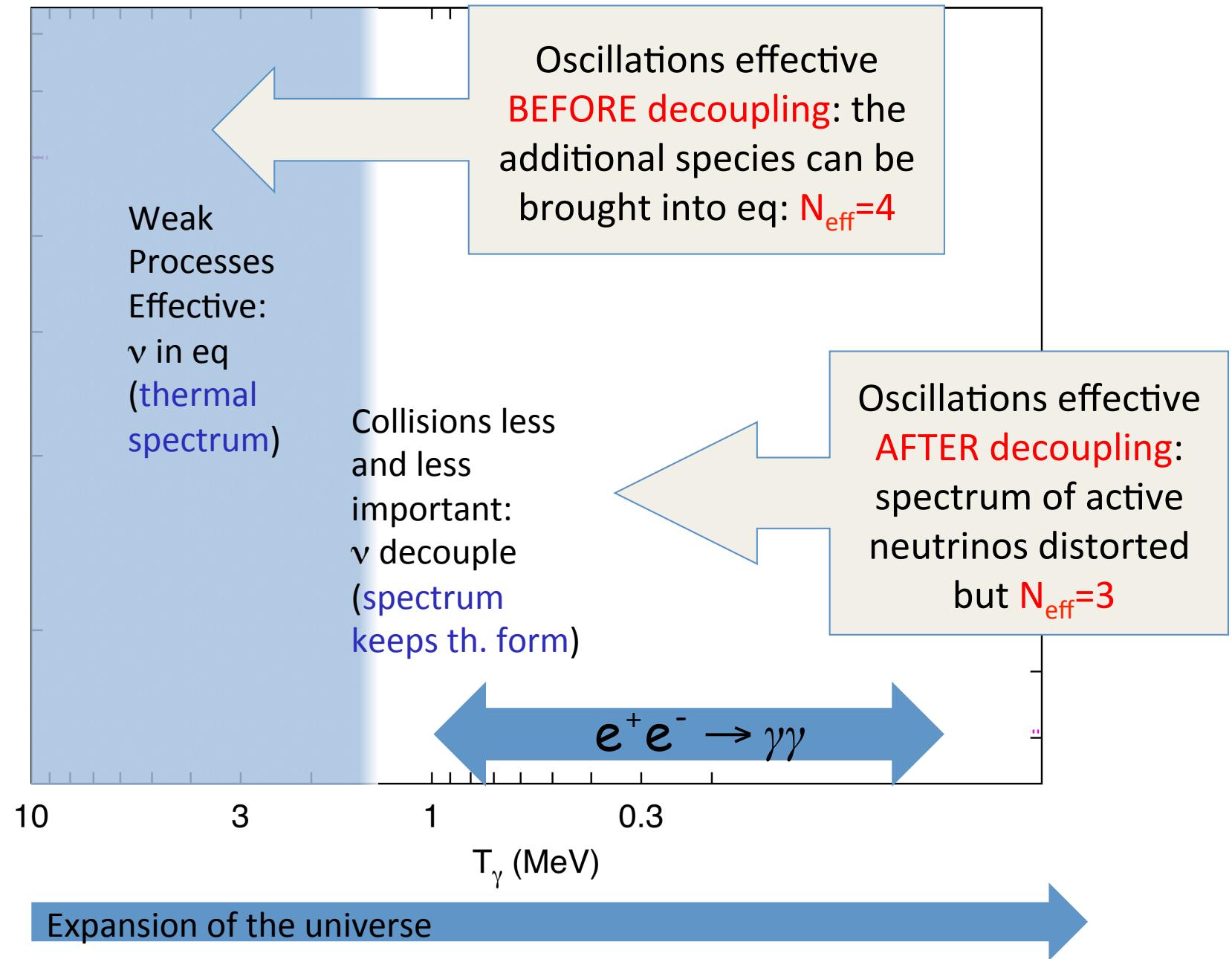
Active-sterile neutrino oscillations

What if additional, light *sterile* neutrino species are mixed with the flavour neutrinos?

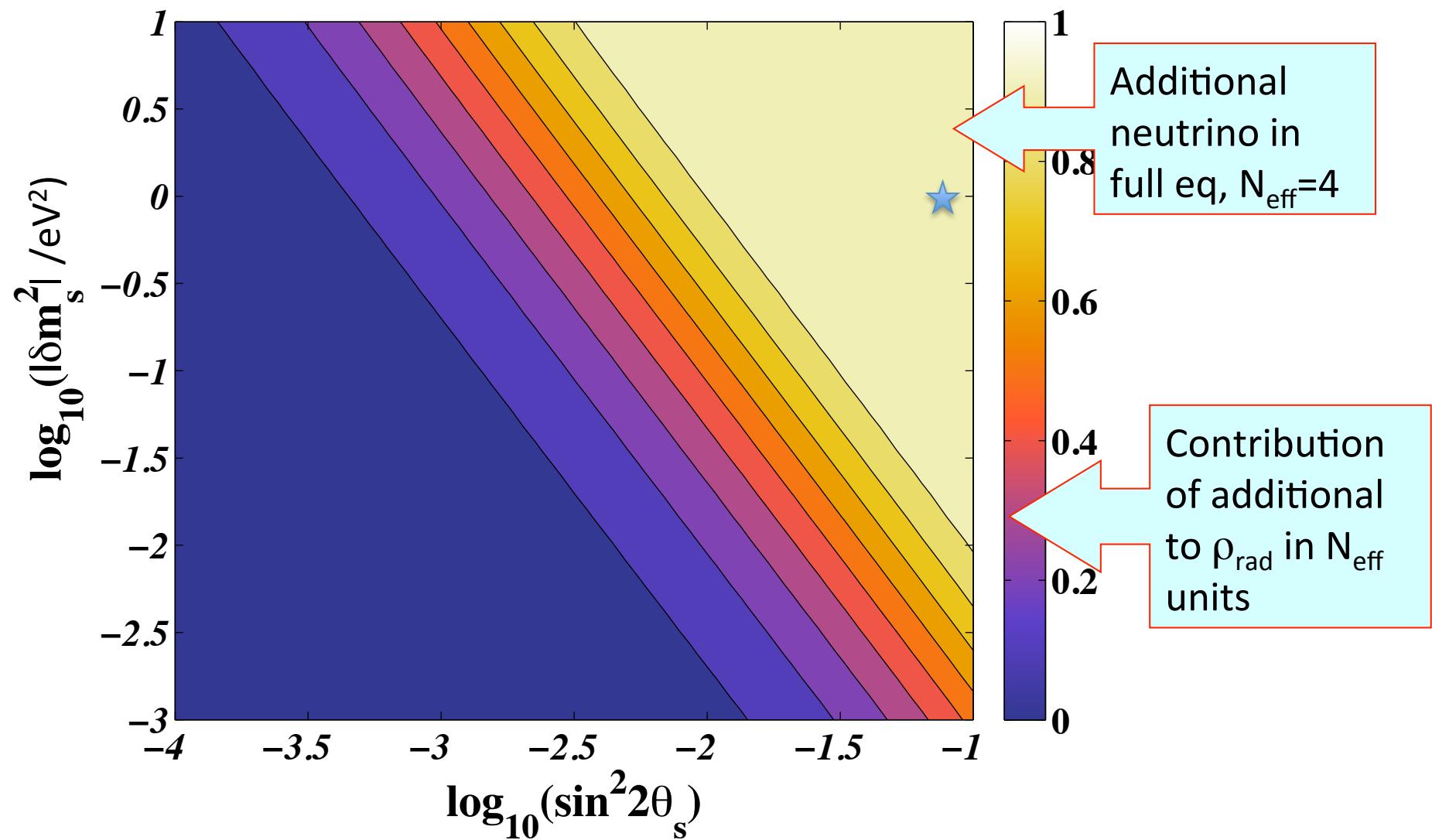
- ♣ If oscillations are effective before decoupling: the additional species can be brought into equilibrium: $N_{\text{eff}}=4$
- ♣ If oscillations are effective after decoupling: $N_{\text{eff}}=3$ but the spectrum of active neutrinos is distorted (direct effect of ν_e and anti- ν_e on BBN)

Results depend on the sign of Δm^2
(resonant vs non-resonant case)

N_{eff} & Active-sterile neutrino oscillations



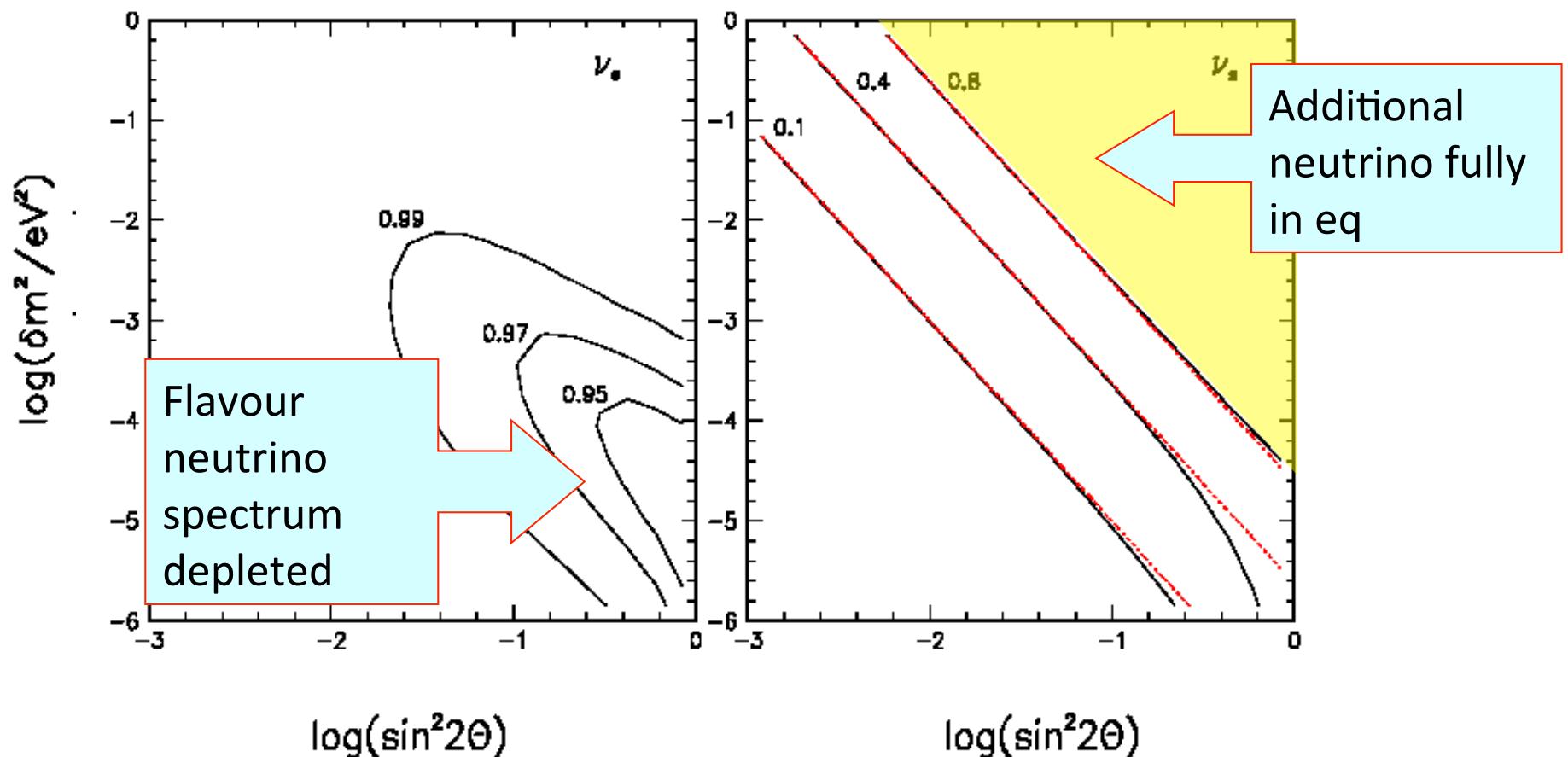
N_{eff} & Active-sterile neutrino oscillations

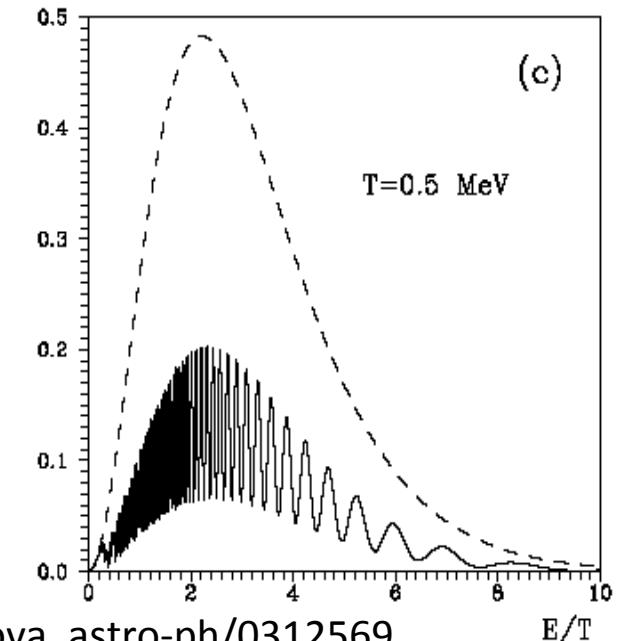
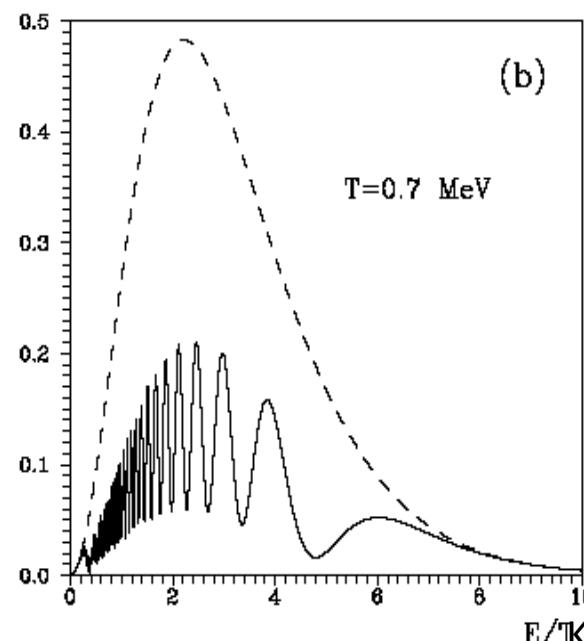
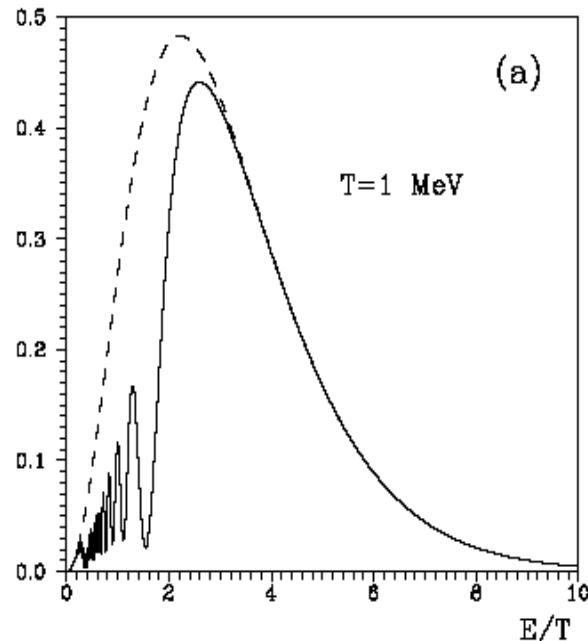


Hannestad, Tamborra & Tram, JCAP 07 (2012) 025

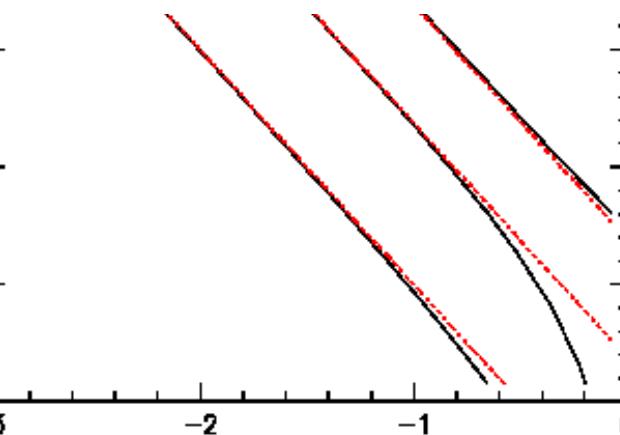
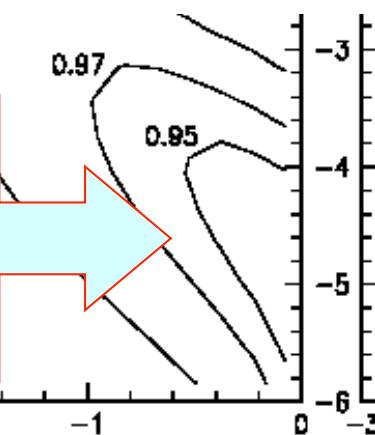
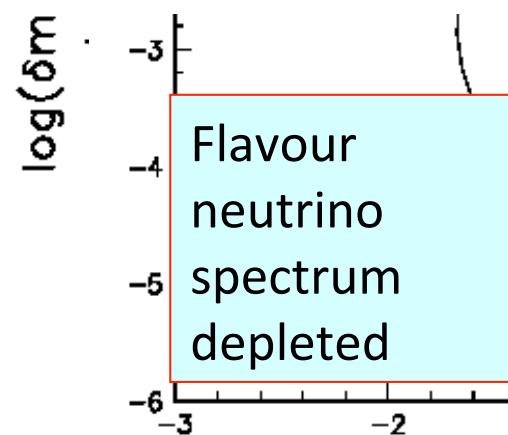
N_{eff} & Active-sterile neutrino oscillations

$\nu_\mu - \nu_s$ mixing – Non resonance case





Kirilova, astro-ph/0312569



log($\sin^2 2\theta$)

log($\sin^2 2\theta$)

Exercises: try to calculate...

- The present number density of massive/massless neutrinos n_ν^0 in cm^{-3}
 - The present energy density of massive/massless neutrinos Ω_ν^0 and find the limits on the total neutrino mass from $\Omega_\nu^0 < 1$ and $\Omega_\nu^0 < \Omega_m^0$
 - The final ratio T_γ/T_ν using the conservation of entropy density before/after e^\pm annihilations
 - The decoupling temperature of relic neutrinos using $\Gamma_w \approx H$
-
- The photon temperature / redshift of the matter radiation equality for $m_\nu = 1 \text{ eV}$

End of 1st lecture