Light neutrinos in Cosmology

Picture from Hubble ST

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AHEP Astroparticle and High Energy Physics Group

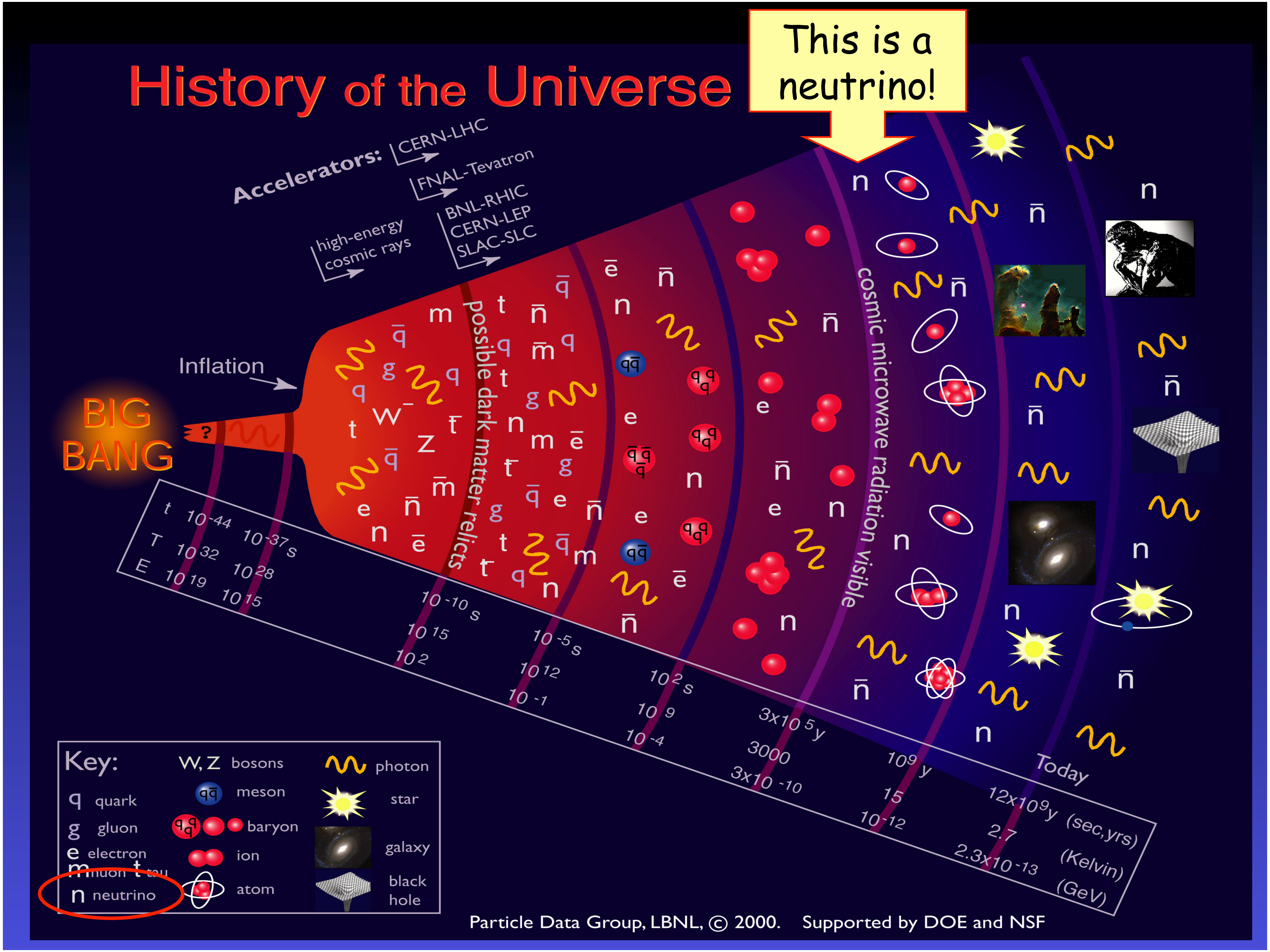
CSIC Consejo Superior de Investigaciones Científicas

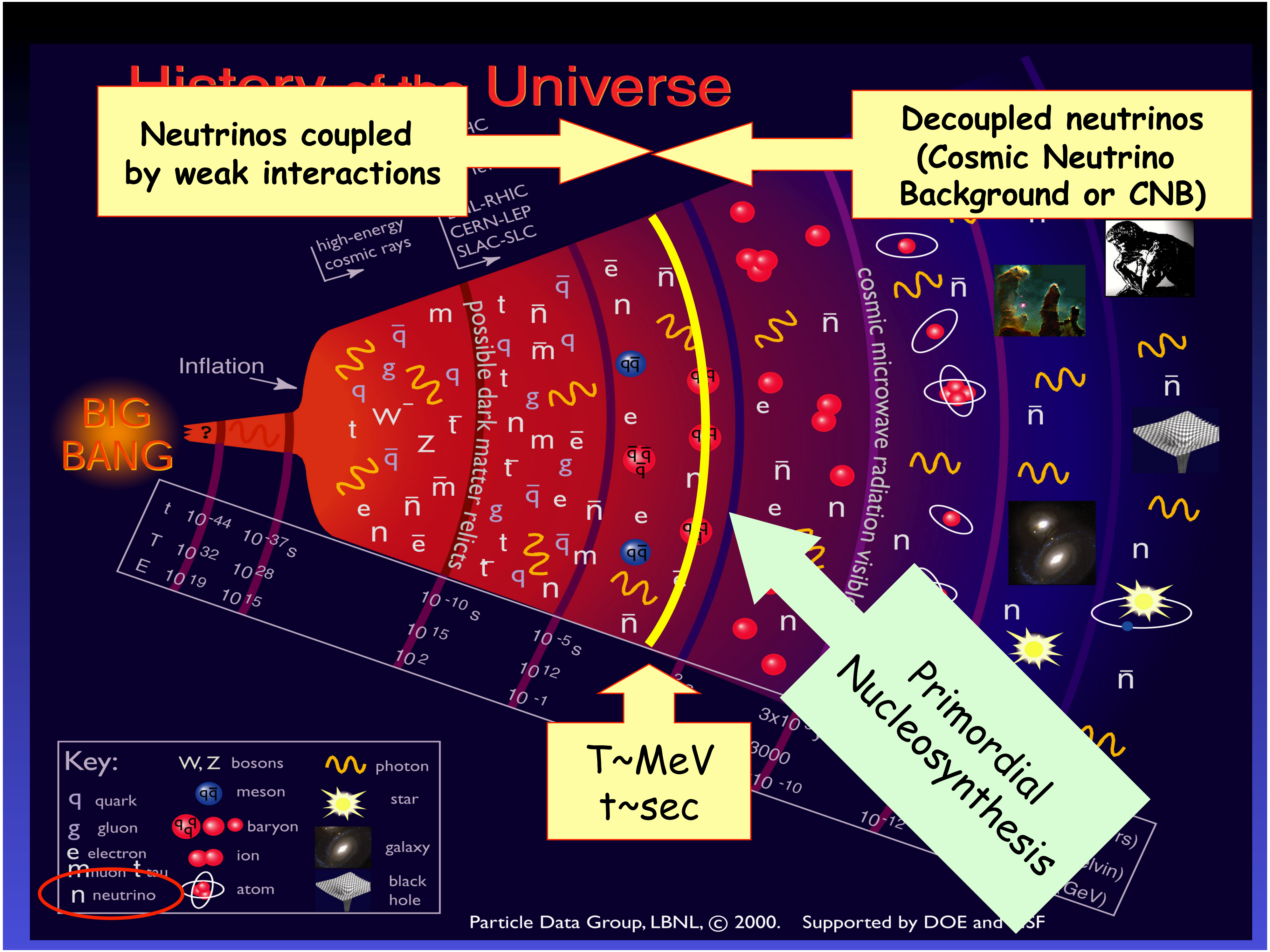
Vniversitat de València

Light neutrinos in Cosmology

1st lecture

Introduction: neutrinos and the History of the Universe


History of the Universe
This is a neutrino!
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s 10^-10 s 10^-5 s 10^2 s 3x10^5 y 10^9 y 12x10^9 y (sec,yrs)
T 10^32 10^28 10^15 10^12 10^9 3000 15 2.7 (Kelvin)
E 10^19 10^15 10^2 10^-1 10^-4 3x10^-10 10^-12 2.3x10^-13 (GeV)
Today
Key:
q quark
g gluon
e electron
m muon
t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF



Universe
Neutrinos coupled by weak interactions
Decoupled neutrinos (Cosmic Neutrino Background or CNB)
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation
T~MeV
t~sec
Primordial Nucleosynthesis
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
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Key:
W, Z bosons
photon
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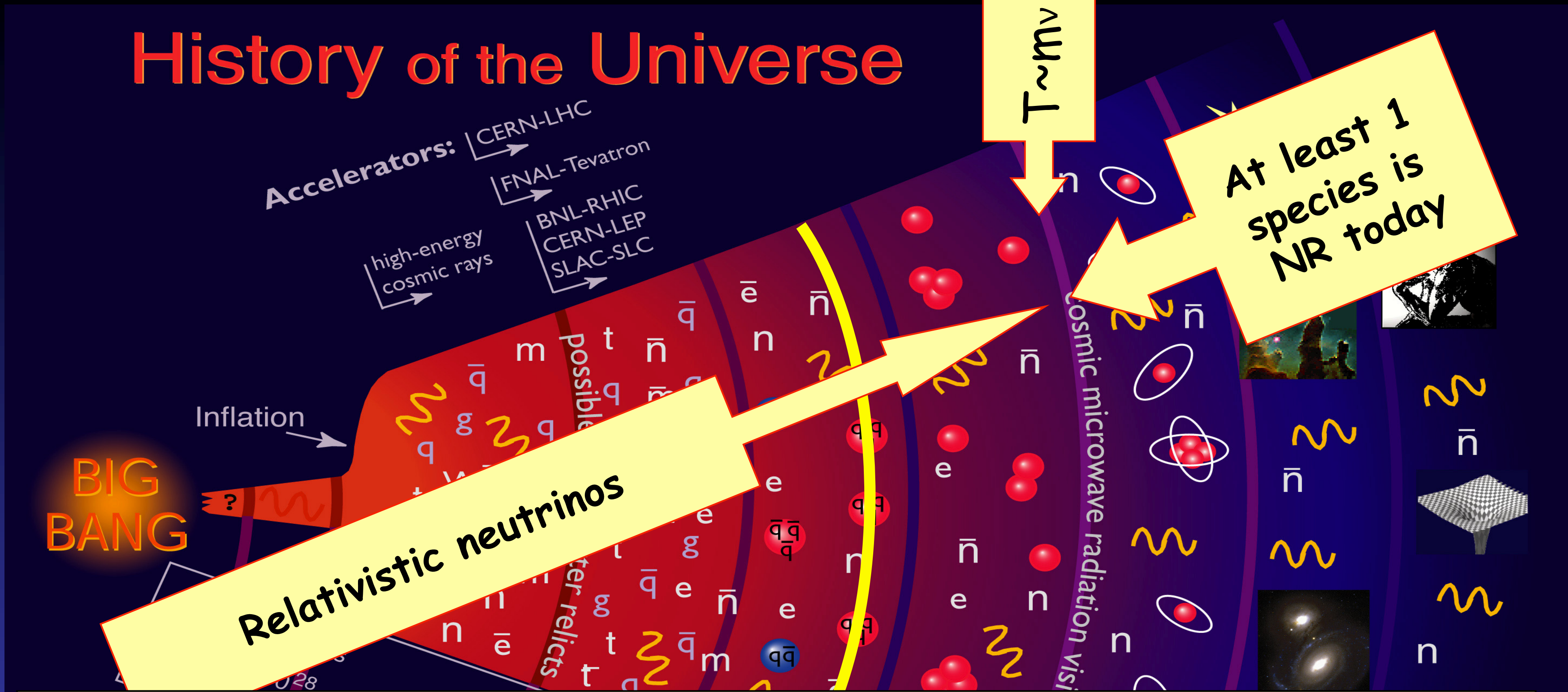

Neutrino cosmology is interesting because Relic neutrinos are very abundant:

• 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

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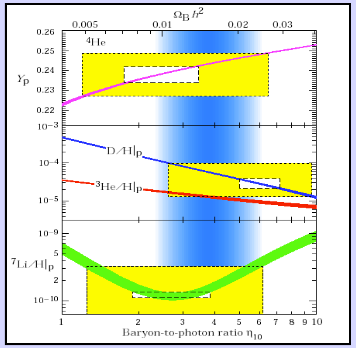
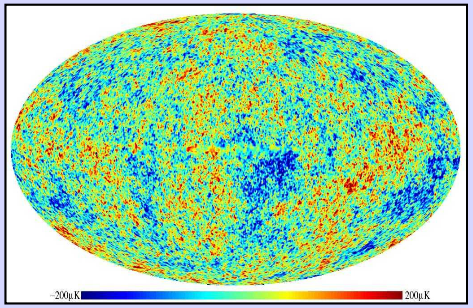
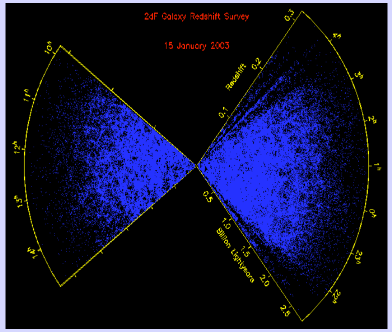
Relic neutrinos influence several cosmological epochs

		
Primordial Nucleosynthesis BBN	Cosmic Microwave Background CMB	Formation of Large Scale Structures LSS
$T \sim$ MeV	$T <$ eV	
ν_e vs $\nu_{\mu,\tau}$ N_{eff}	No flavour sensitivity N_{eff} & m_ν	

Light neutrinos in Cosmology

1st lecture

Introduction: neutrinos and the History of the Universe

Basics of cosmology: background evolution

Relic neutrino production and decoupling

Neutrinos and Primordial Nucleosynthesis

Neutrino oscillations in the Early Universe

Light neutrinos in Cosmology

2nd lecture

Massive neutrinos as Dark Matter

Effects of neutrino masses on cosmological observables

Bounds on m_ν from CMB, LSS and other data

Future sensitivities on m_ν and N_ν from cosmology

Suggested References

Books

Modern Cosmology, S. Dodelson (Academic Press, 2003)

The Early Universe, E. Kolb & M. Turner (Addison-Wesley, 1990)

Kinetic theory in the expanding Universe, Bernstein (Cambridge U., 1988)

Recent reviews

Neutrino Cosmology, A.D. Dolgov,
Phys. Rep. 370 (2002) 333-535 [hep-ph/0202122]

Massive neutrinos and cosmology, J. Lesgourgues & SP,
Phys. Rep. 429 (2006) 307-379 [astro-ph/0603494]

Neutrino physics from precision cosmology, S. Hannestad
arXiv:1007.0658

Primordial Nucleosynthesis: from precision cosmology to fundamental physics,
F. Iocco, G. Mangano, G. Miele, O. Pisanti & P.D. Serpico
Phys. Rep. 472 (2009) 1-76 [arXiv:0809.0631]

Background evolution

Eqs in the SM of Cosmology

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

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

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 ➡

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

Pressure (p) **Energy density** (ρ)

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**

$$\frac{k}{H(t)^2 a^2} = \Omega - 1$$

$\Omega = \rho/\rho_{crit}$

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

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

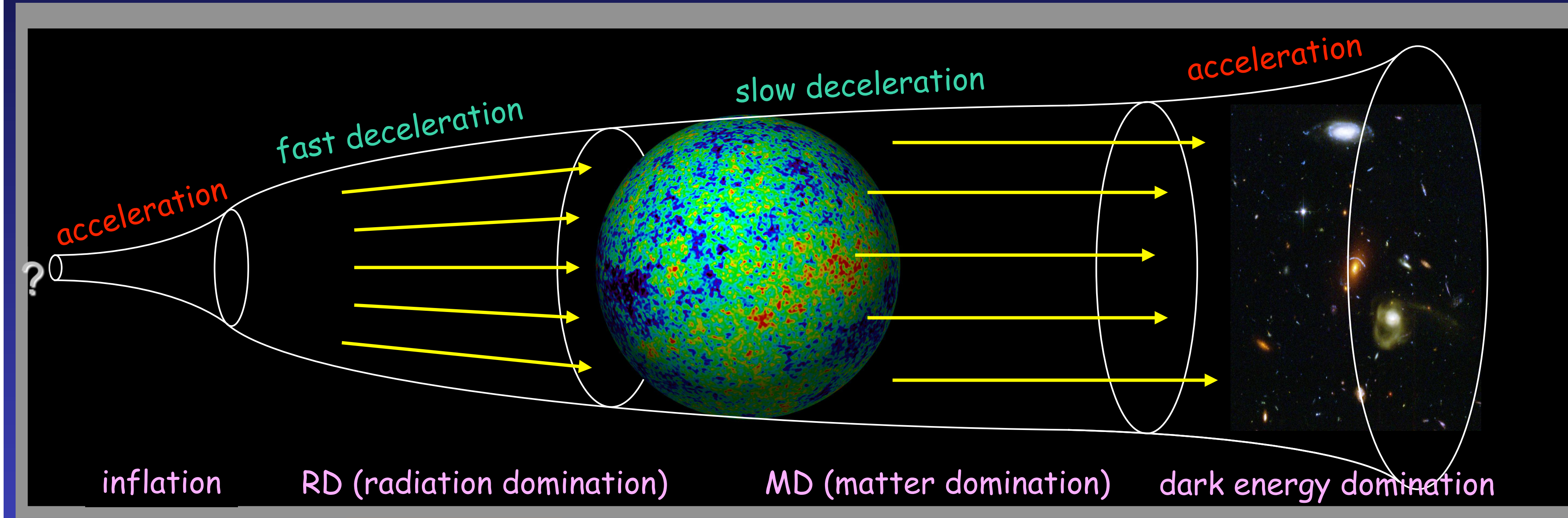
Eq of state $p=\alpha\rho$

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

Radiation $\alpha=1/3$	Matter $\alpha=0$	Cosmological constant $\alpha=-1$
$\rho_R \sim 1/a^4$	$\rho_M \sim 1/a^3$	$\rho_\Lambda \sim \text{const}$

Evolution of the Universe

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

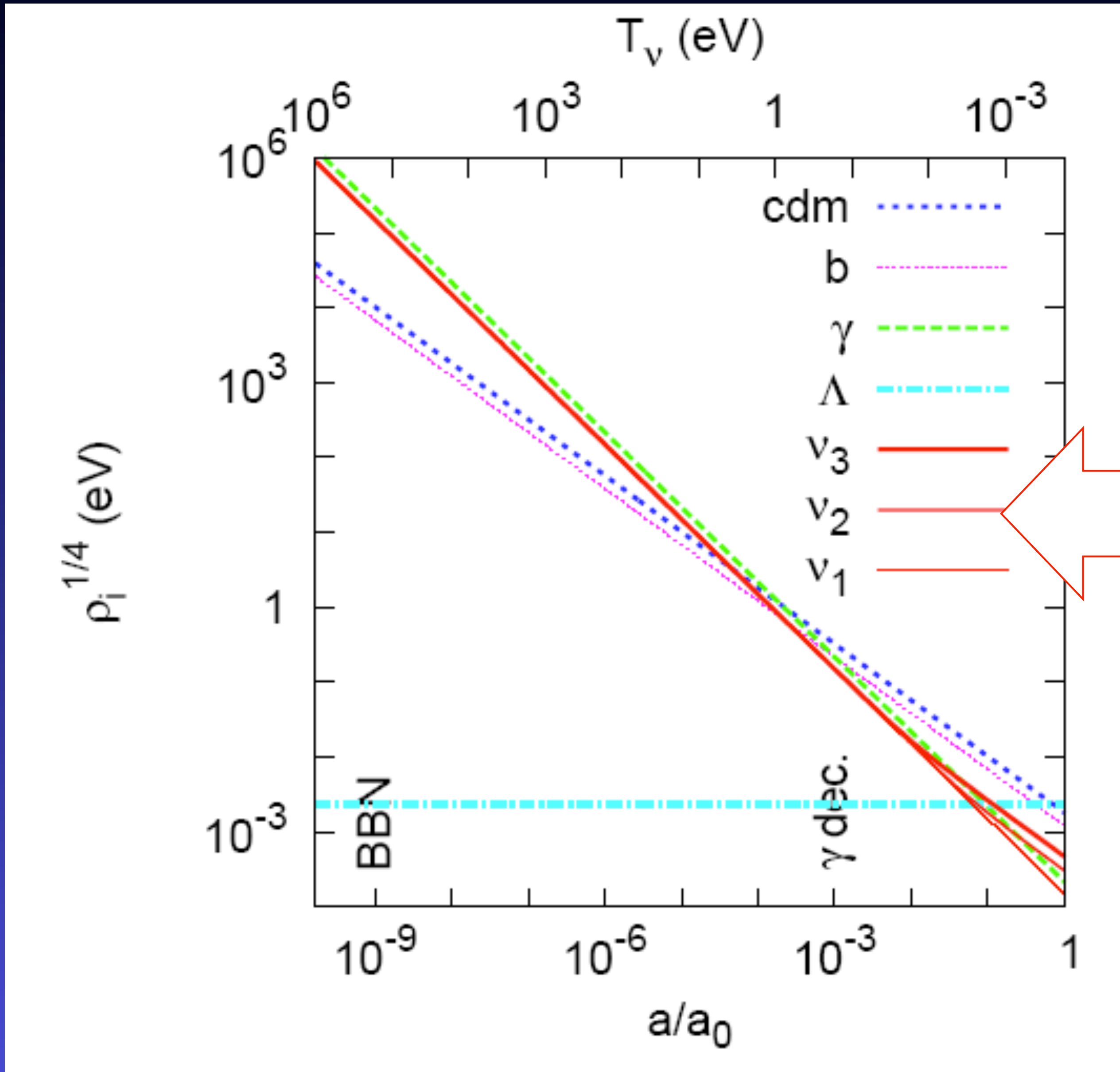


$a(t) \sim e^{Ht}$

$a(t) \sim t^{1/2}$

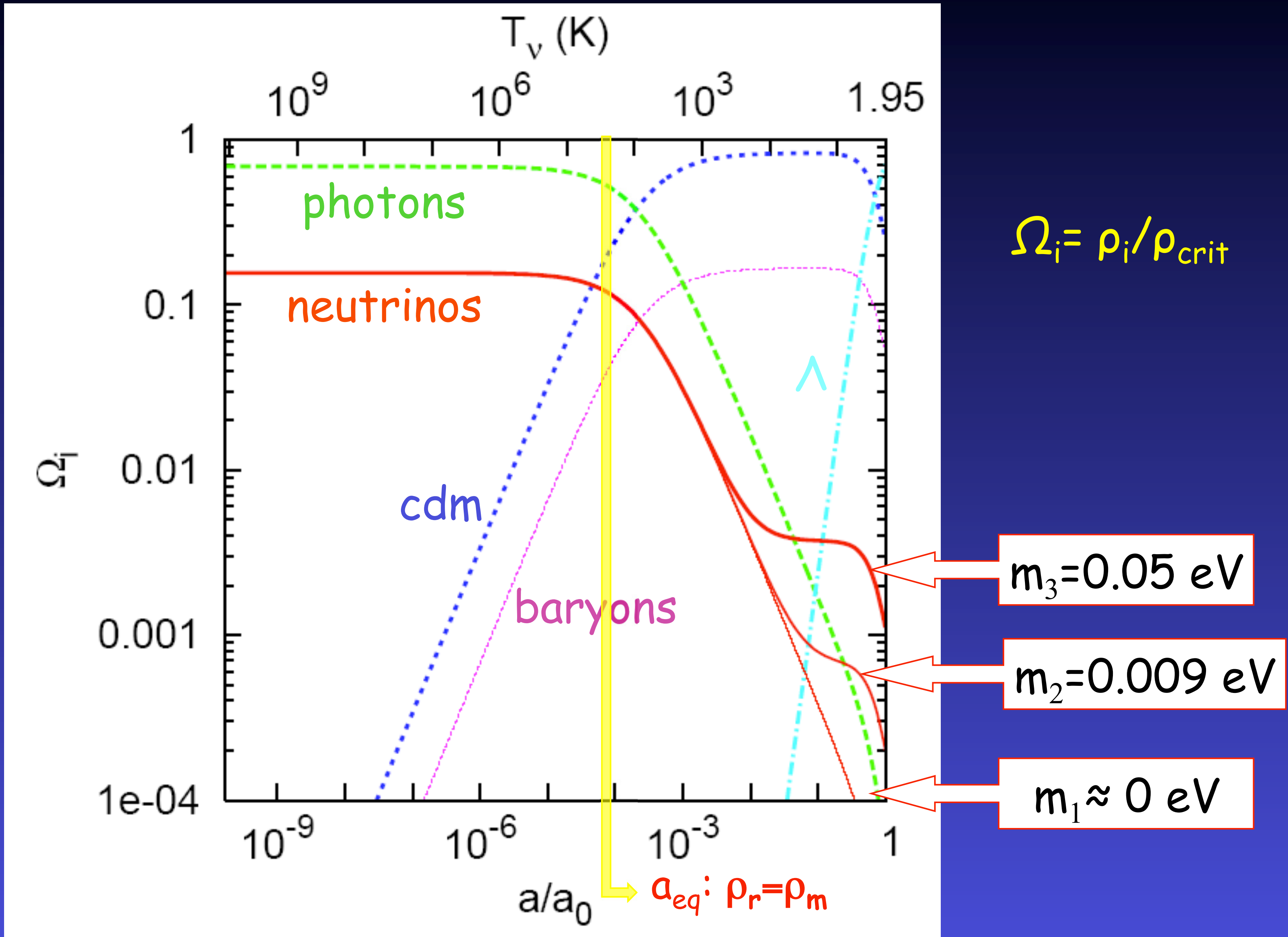
$a(t) \sim t^{2/3}$

Evolution of the background densities: 1 MeV → now



3 neutrino species with different masses

Evolution of the background densities: 1 MeV → now



Relic neutrino production and decoupling

Equilibrium thermodynamics

Particles in equilibrium when T are high and interactions effective

T~1/a(t)

Distribution function of particle momenta in equilibrium

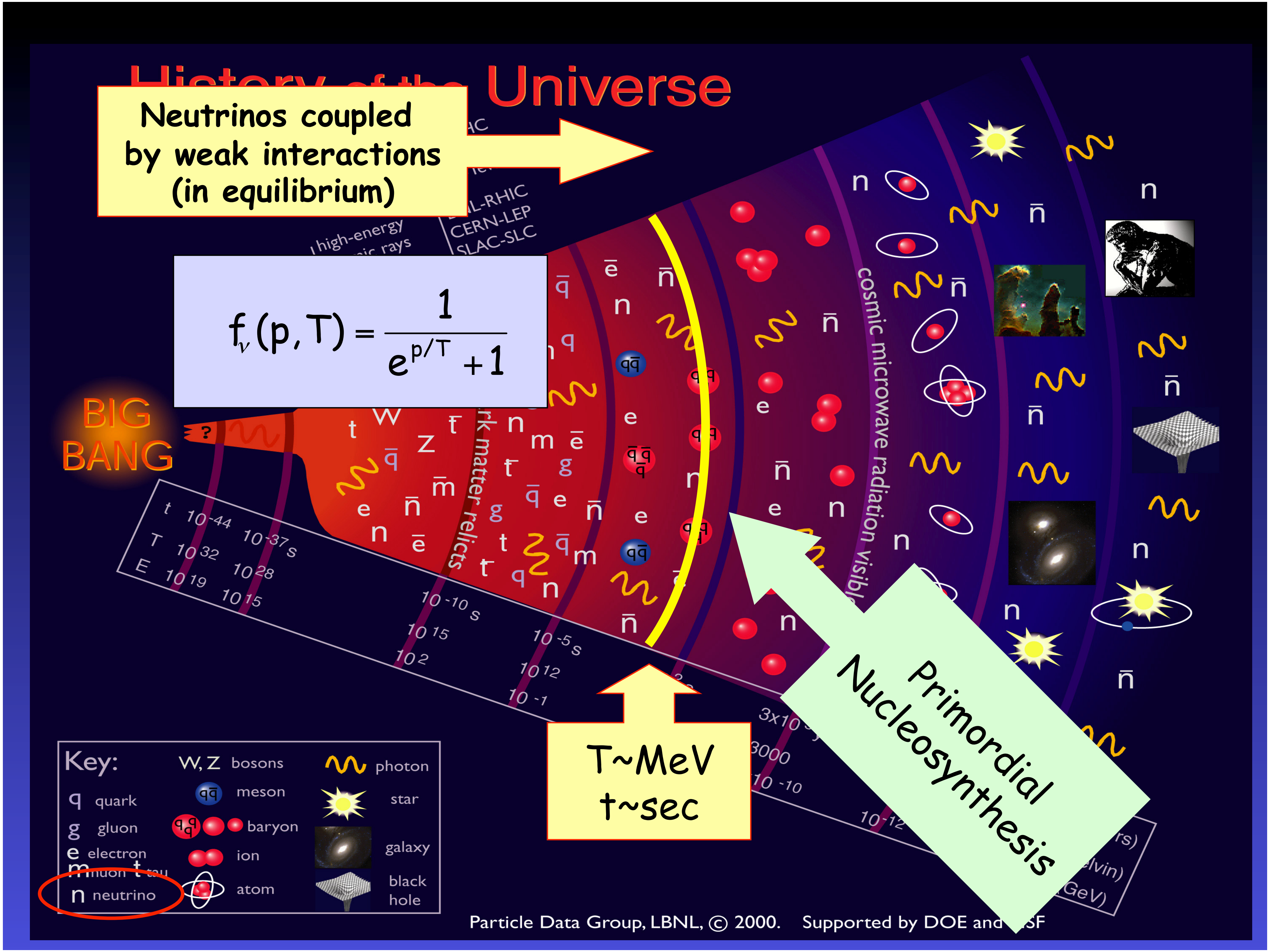
$$f_i^{eq}(p,T) = \left[\exp\left(\frac{E_i - \mu_i}{T}\right) \mp 1\right]^{-1}$$

Thermodynamical variables

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

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

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



History of the Universe
Neutrinos coupled by weak interactions (in equilibrium)
$$f_\nu(p,T) = \frac{1}{e^{p/T}+1}$$
BIG BANG
high-energy cosmic rays
CERN-LEP
SLAC-SLC
cosmic microwave radiation
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
3000
10^-10
10^-12
T~MeV
t~sec
Primordial Nucleosynthesis
Key:
W, Z bosons
photon
q quark
meson
star
g gluon
baryon
e electron
ion
galaxy
n neutrino
atom
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Neutrinos in Equilibrium

$1\ \mathrm{MeV} \leq T \leq m_\mu$

$T_\nu = T_e = T_\gamma$

$\nu_\alpha \nu_\beta \leftrightarrow \nu_\alpha \nu_\beta$

$\nu_\alpha \bar{\nu}_\beta \leftrightarrow \nu_\alpha \bar{\nu}_\beta$

$\nu_\alpha e^- \leftrightarrow \nu_\alpha e^-$

$\nu_\alpha \bar{\nu}_\alpha \leftrightarrow e^+ e^-$

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

$P = L, R = (1 \mp \gamma_5)/2$

$g_L = -\frac{1}{2} + \sin^2\theta_W$ 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 ~ Hubble expansion rate

$$\Gamma_w \approx \sigma_w |\mathrm{v}| n \,,\; H^2 = \frac{8\pi\rho_R}{3M_p^2} \rightarrow G_F^2 T^5 \approx \sqrt{\frac{8\pi\rho_R}{3M_p^2}} \rightarrow T_{dec}^{\nu} \approx 1\; MeV$$

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

$T_{dec}(\nu_e)$ ~ 2 MeV

$T_{dec}(\nu_{\mu,\tau})$ ~ 3 MeV

History of the Universe

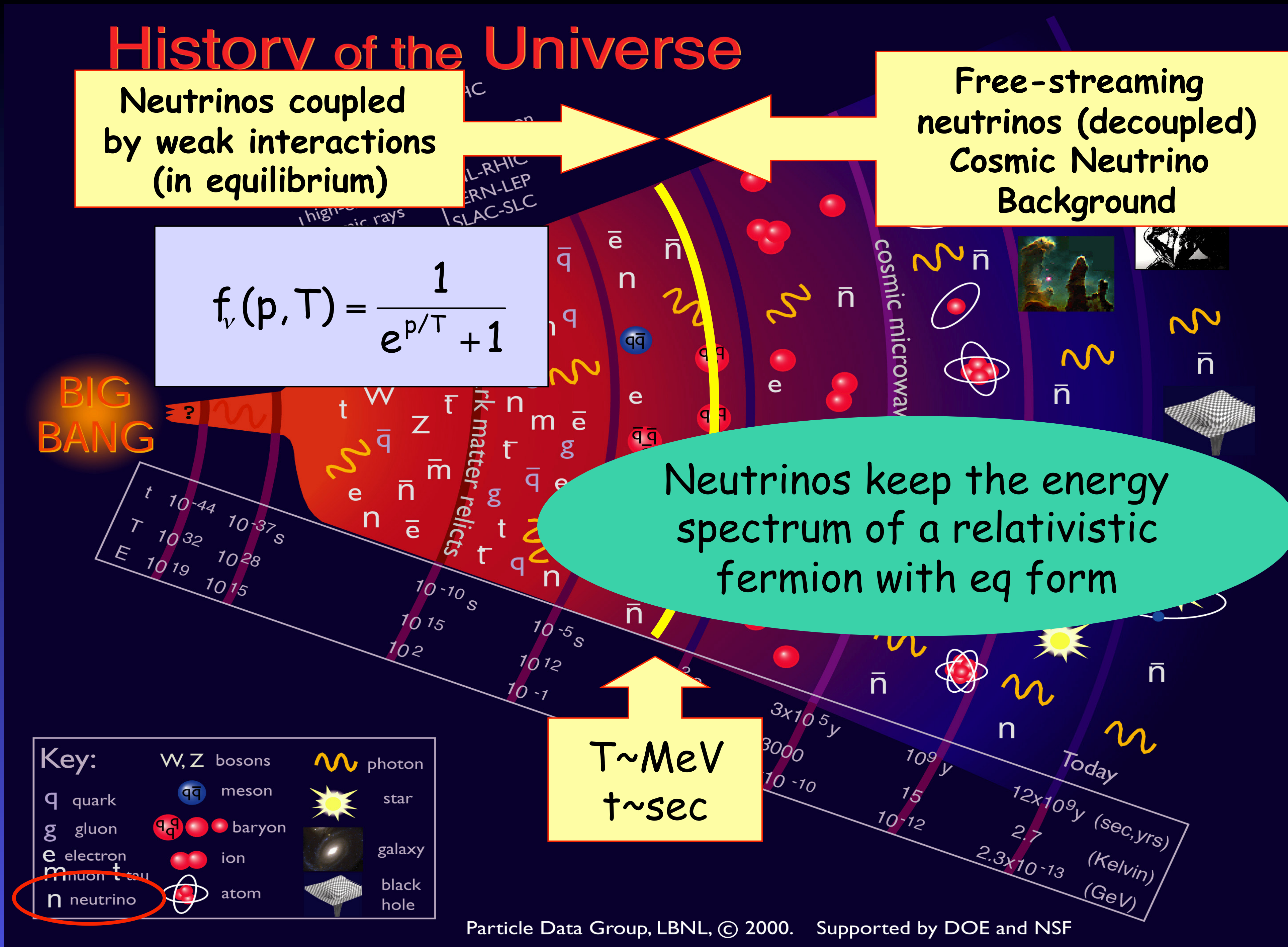
Neutrinos coupled by weak interactions (in equilibrium)

Free-streaming neutrinos (decoupled) Cosmic Neutrino Background

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

Neutrinos keep the energy spectrum of a relativistic fermion with eq form

T~MeV
t~sec

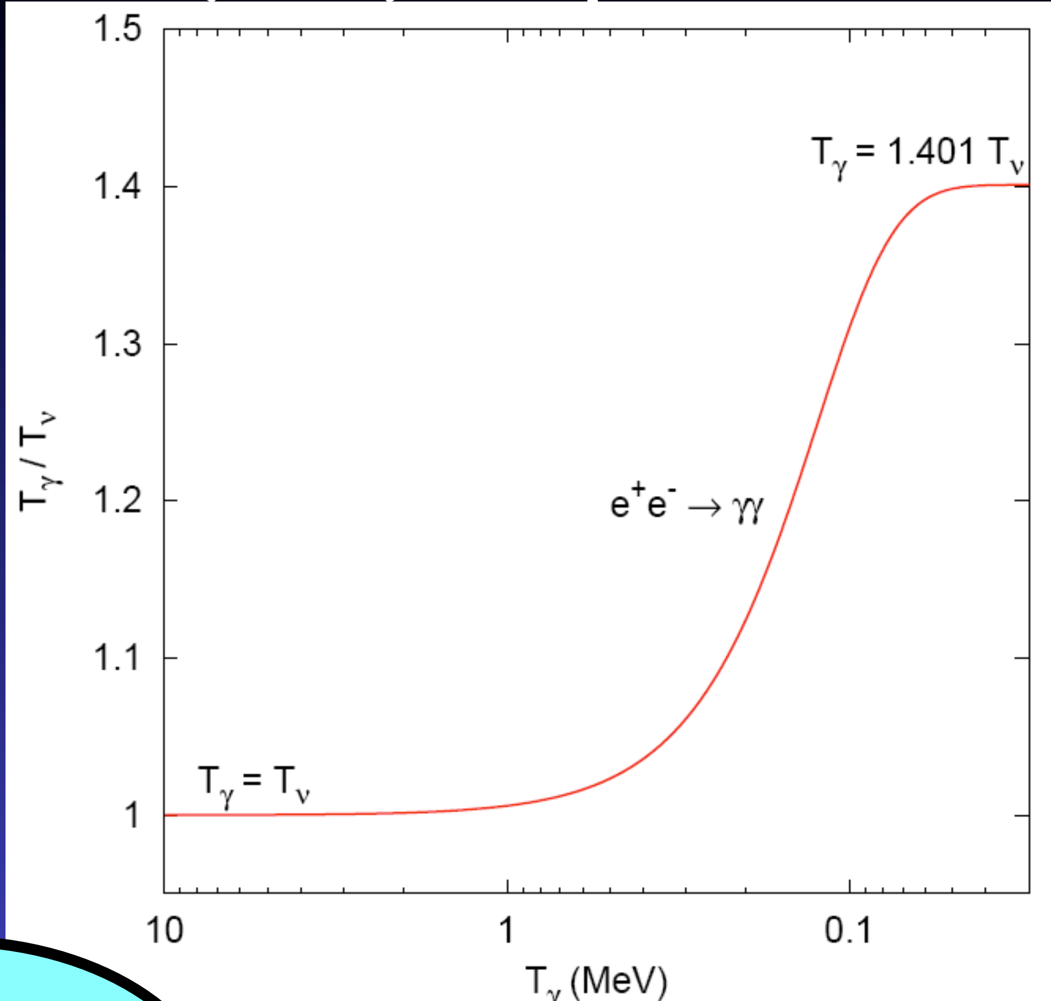


Neutrino and Photon (CMB) temperatures

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

$$e^+ e^- \to \gamma\gamma$$

heating photons but not the decoupled neutrinos



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

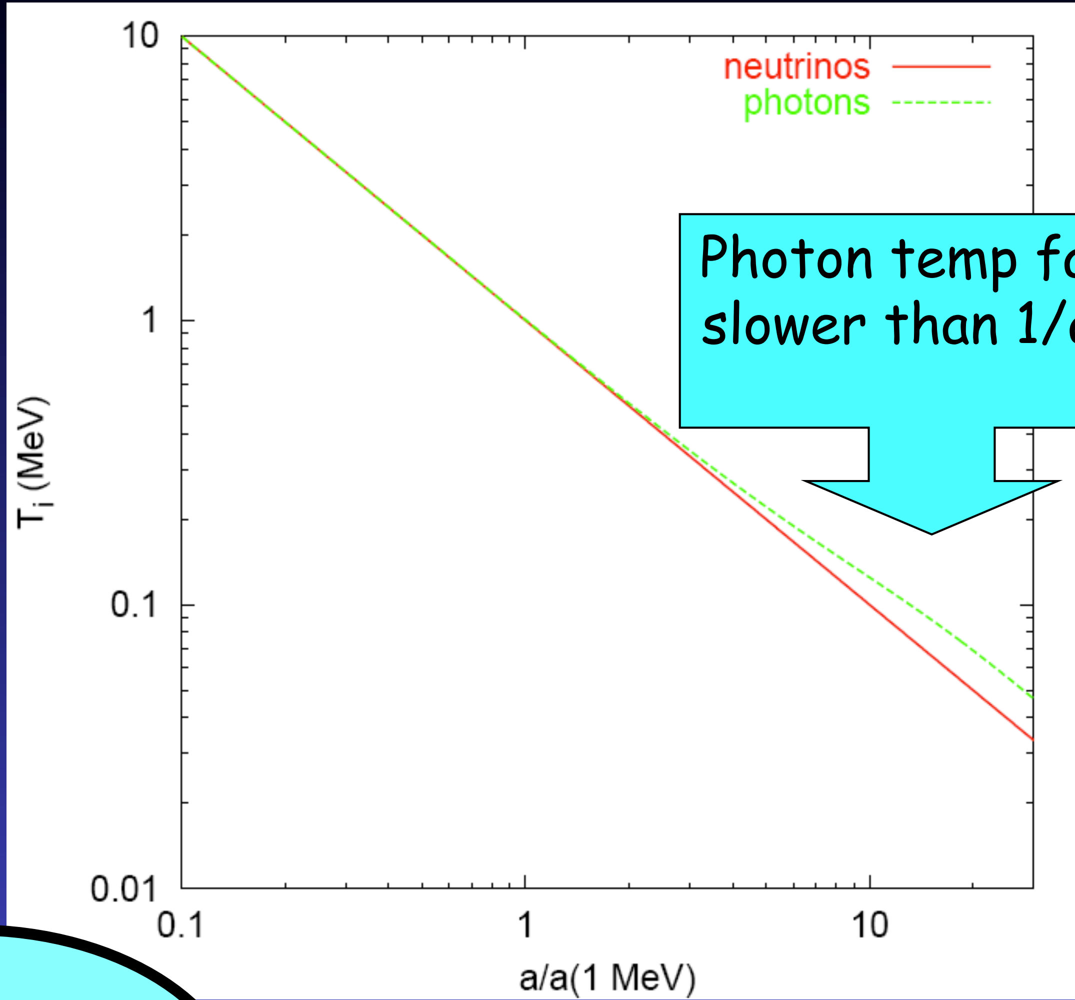
$$f_\nu(p,T) = \frac{1}{e^{p/T_\nu} + 1}$$

Neutrino and Photon (CMB) temperatures

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

$$e^+e^- \rightarrow \gamma\gamma$$

heating photons but not the decoupled neutrinos



Photon temp falls slower than 1/a(t)

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

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

The Cosmic Neutrino Background

Neutrinos decoupled at T~MeV, keeping a spectrum as that of a relativistic species

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

- Number density

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

- Energy density

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

The Cosmic Neutrino Background

Neutrinos decoupled at T~MeV, keeping a spectrum as that of a relativistic species

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

- Number density

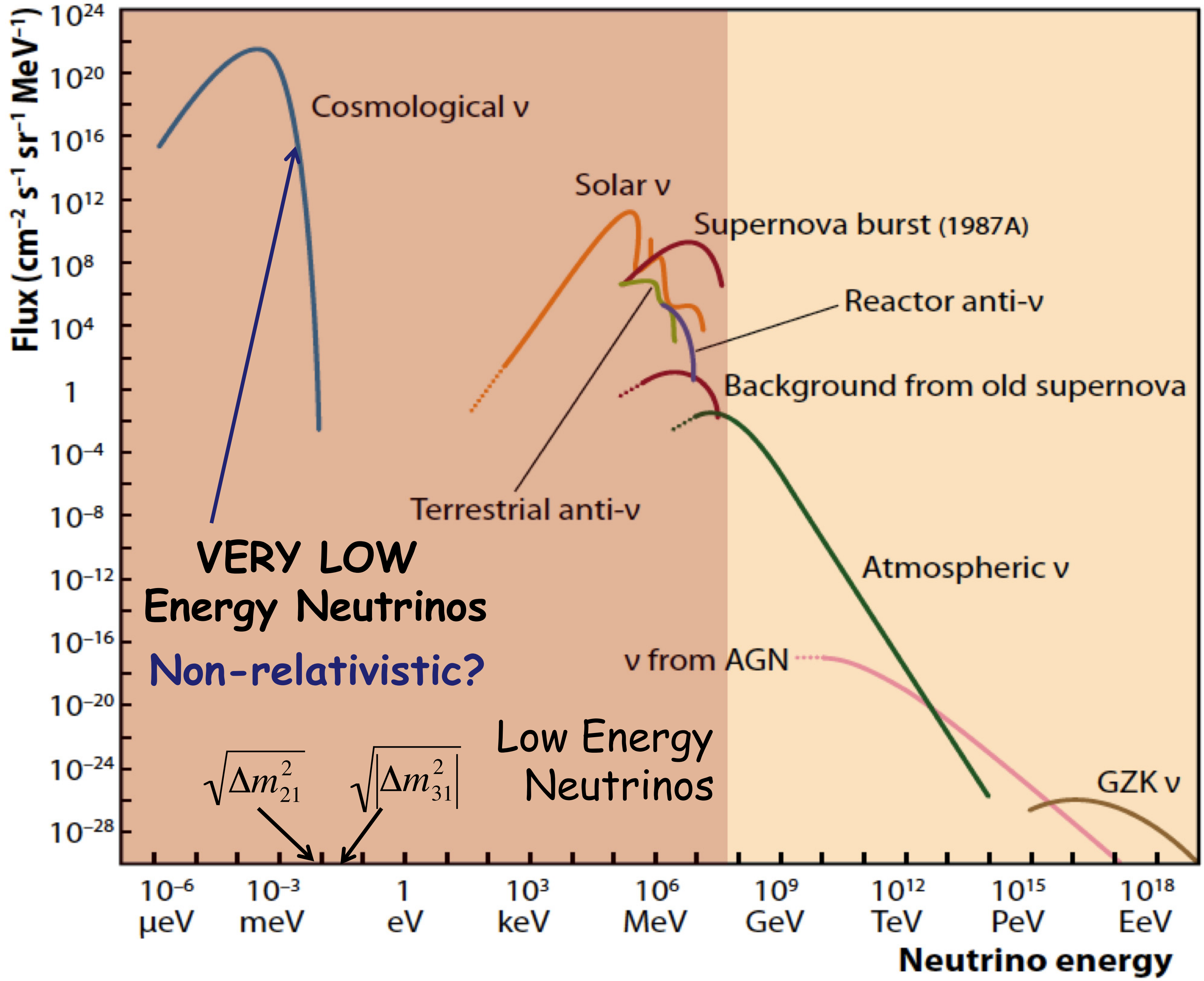
At present $112\,(\nu+\bar{\nu})\,\mathrm{cm}^{-3}$ per flavour

- Energy density

Contribution to the energy density of the Universe

$$\Omega_\nu h^2 \simeq 1.7\times10^{-5}$$ Massless

$$\Omega_\nu h^2 = \frac{\sum_i m_{\nu_i}}{94.1\ \mathrm{eV}}$$ Massive $m_\nu \gg T$



Flux (cm^{-2} s^{-1} sr^{-1} MeV^{-1})
10^{24}
10^{20}
10^{16}
10^{12}
10^{8}
10^{4}
1
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-24}
10^{-28}
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernova
Terrestrial anti-ν
Atmospheric ν
ν from AGN
GZK ν
VERY LOW
Energy Neutrinos
Non-relativistic?
Low Energy
Neutrinos
$\sqrt{\Delta m^2_{21}}$
$\sqrt{|\Delta m^2_{31}|}$
10^{-6} μeV
10^{-3} meV
1 eV
10^{3} keV
10^{6} MeV
10^{9} GeV
10^{12} TeV
10^{15} PeV
10^{18} EeV
Neutrino energy

The Cosmic Neutrino Background

Neutrinos decoupled at T~MeV, keeping a spectrum as that of a relativistic species

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

•

• Number density

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

• Direct detection?

Very difficult, if not impossible in the near future…

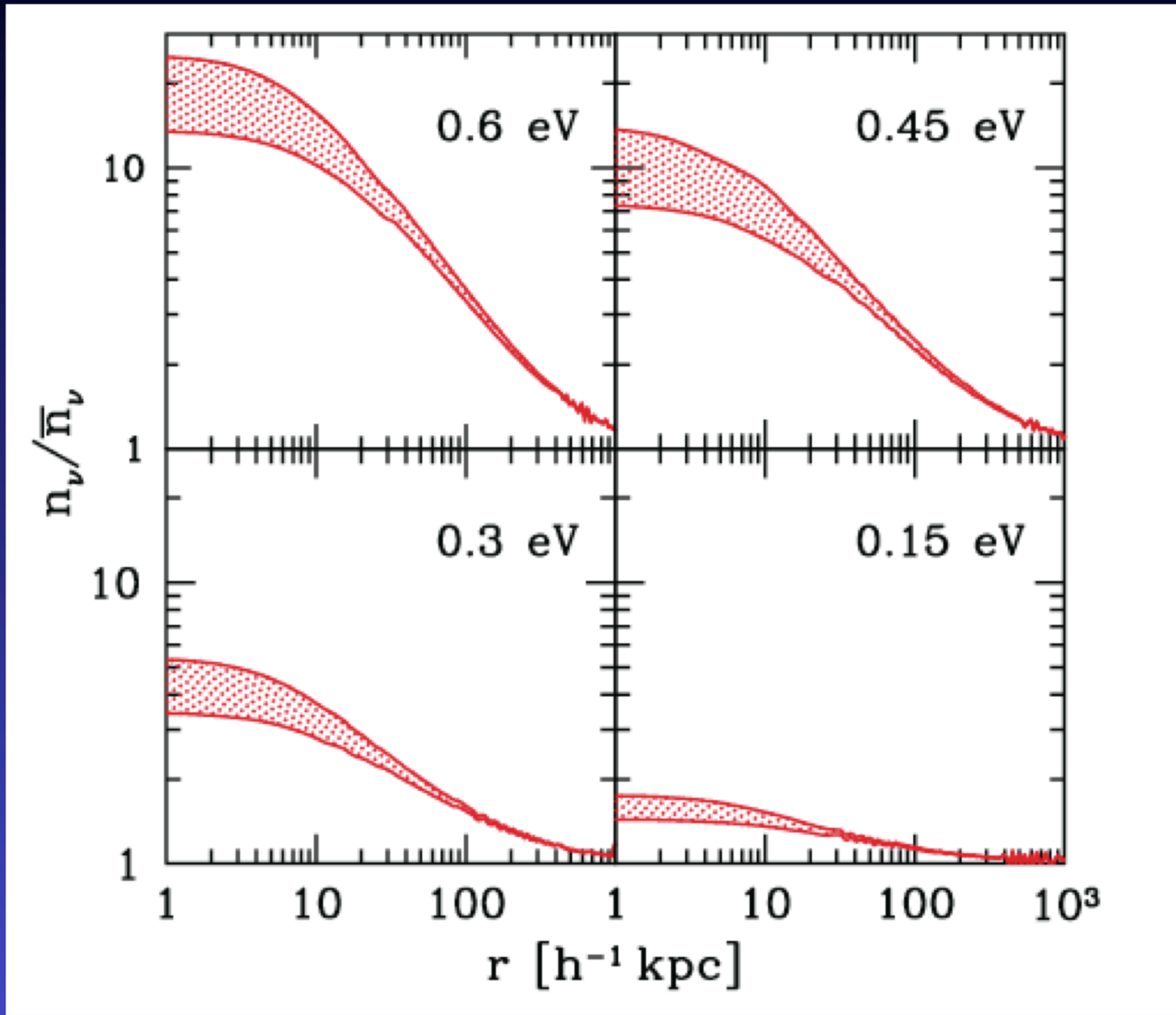
Most promising technique:

peak in β−decay spectra related to neutrino absorption from the CNB

Problem: would need a **huge** local overdensity of n_ν

Cocco et al, JCAP 06 (2007) 015; Blennow, PRD 77 (2008) 113014; Kaboth et al, arXiv:1006.1886

Overdensity of the CNB in the Milky Way



Ringwald & Wong, JCAP 12 (2004) 005
Brandbyge et al, JCAP 09 (2010) 014

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

Relativistic particles in the Universe

At $T \gg m_e$, 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

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

$$\frac{T_\nu^4}{T_\gamma^4}$$

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

Relativistic particles in the Universe

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

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

Effective number of relativistic neutrino species

Traditional parametrization of the energy density stored in relativistic particles

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

Extra relativistic particles

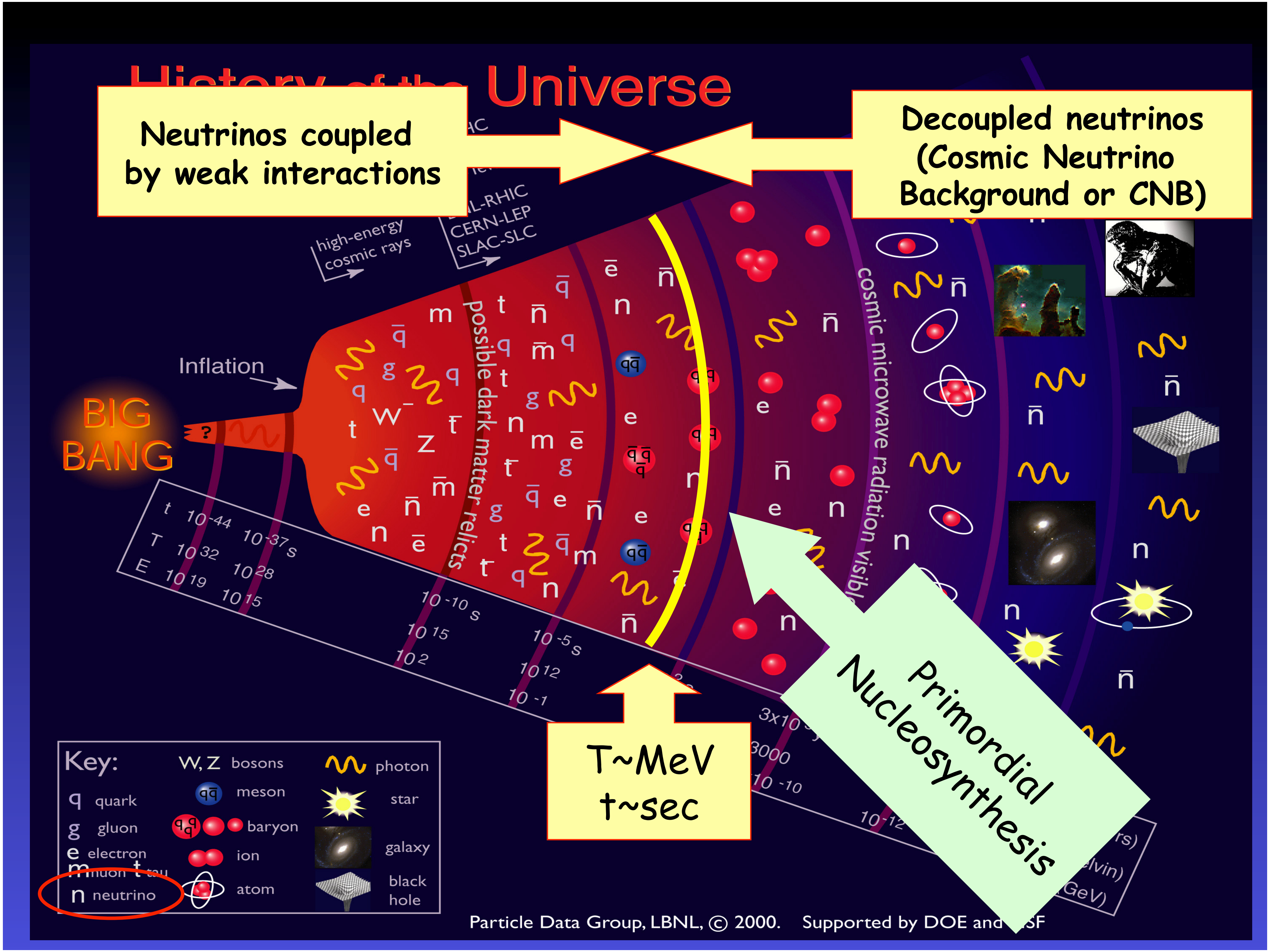
- Extra radiation: How to get $N_{eff} > 3$?

Neutrinos in non-standard scenarios: NS Interactions, sterile neutrinos (totally or partially thermalized), relic neutrino asymmetries

Other relativistic particles: scalars, pseudoscalars, relativistic decay products of heavy particles…

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

Neutrinos and Primordial Nucleosynthesis



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1012
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Primordial Nucleosynthesis
Key:
W, Z bosons
photon
q quark
meson
star
g gluon
baryon
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atom
black hole
Particle Data Group, LBNL, © 2000.
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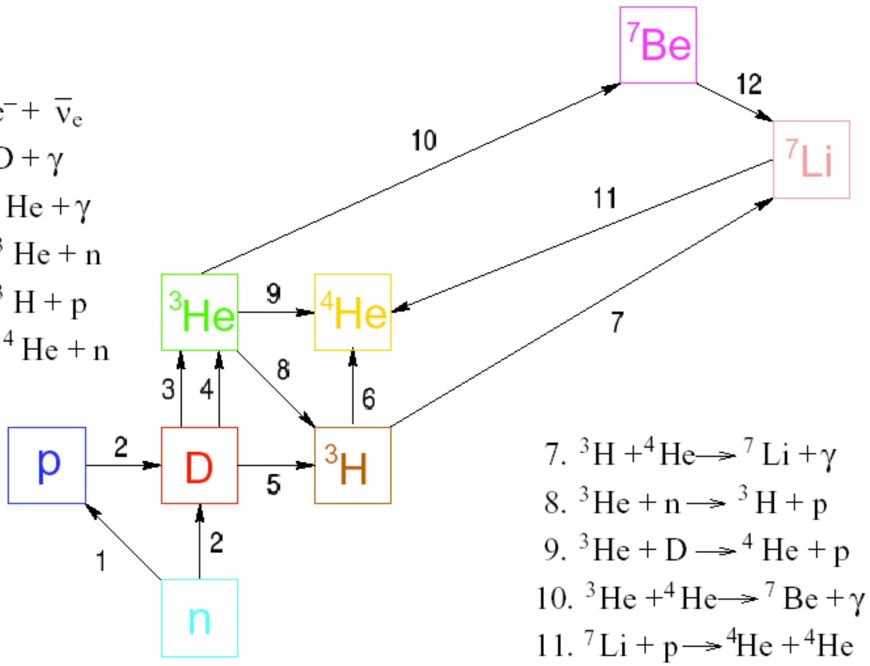
BBN: Creation of light elements



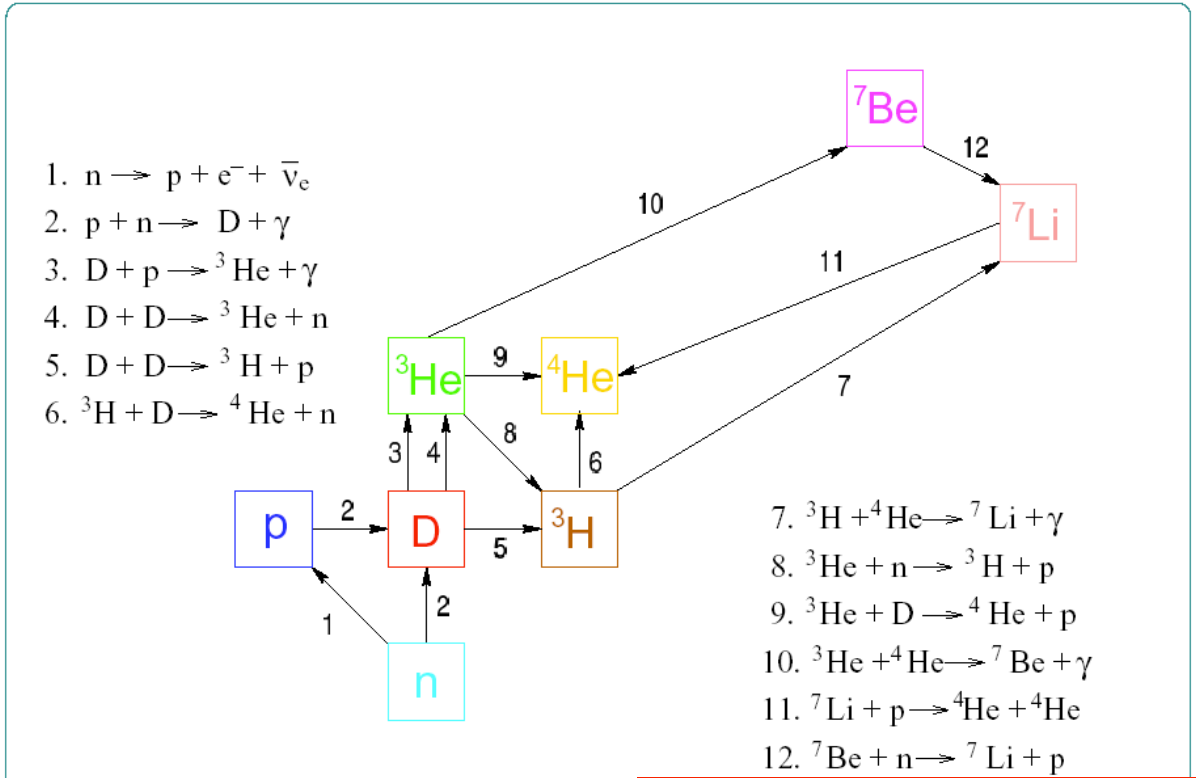
1. $n \rightarrow p + e^- + \bar{\nu}_e$
2. $p + n \rightarrow D + \gamma$
3. $D + p \rightarrow {}^3He + \gamma$
4. $D + D \rightarrow {}^3He + n$
5. $D + D \rightarrow {}^3H + p$
6. ${}^3H + D \rightarrow {}^4He + n$
7. ${}^3H + {}^4He \rightarrow {}^7Li + \gamma$
8. ${}^3He + n \rightarrow {}^3H + p$
9. ${}^3He + D \rightarrow {}^4He + p$
10. ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$
11. ${}^7Li + p \rightarrow {}^4He + {}^4He$
12. ${}^7Be + n \rightarrow {}^7Li + p$

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

Theoretical inputs:

1)	n	7)	^{6}Li	13)	^{10}B	19)	^{13}C	25)	^{15}O
2)	p	8)	^{7}Li	14)	^{11}B	20)	^{13}N	26)	^{16}O
3)	^{2}H	9)	^{7}Be	15)	^{11}C	21)	^{14}C		
4)	^{3}H	10)	^{8}Li	16)	^{12}B	22)	^{14}N		
5)	^{3}He	11)	^{8}B	17)	^{12}C	23)	^{14}O		
6)	^{4}He	12)	^{9}Be	18)	^{12}N	24)	^{15}N		

BBN: Creation of light elements



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

Theoretical inputs:

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

The first two parameters are now known with a satisfactory accuracy

$$\tau_n = 885.7 \pm 0.8\, s \quad ,$$
$$G_N = 6.7087 \pm 0.0010 \cdot 10^{-39}\, GeV^{-2} \quad .$$

BBN: Creation of light elements

Range of temperatures: from 0.8 to 0.01 MeV

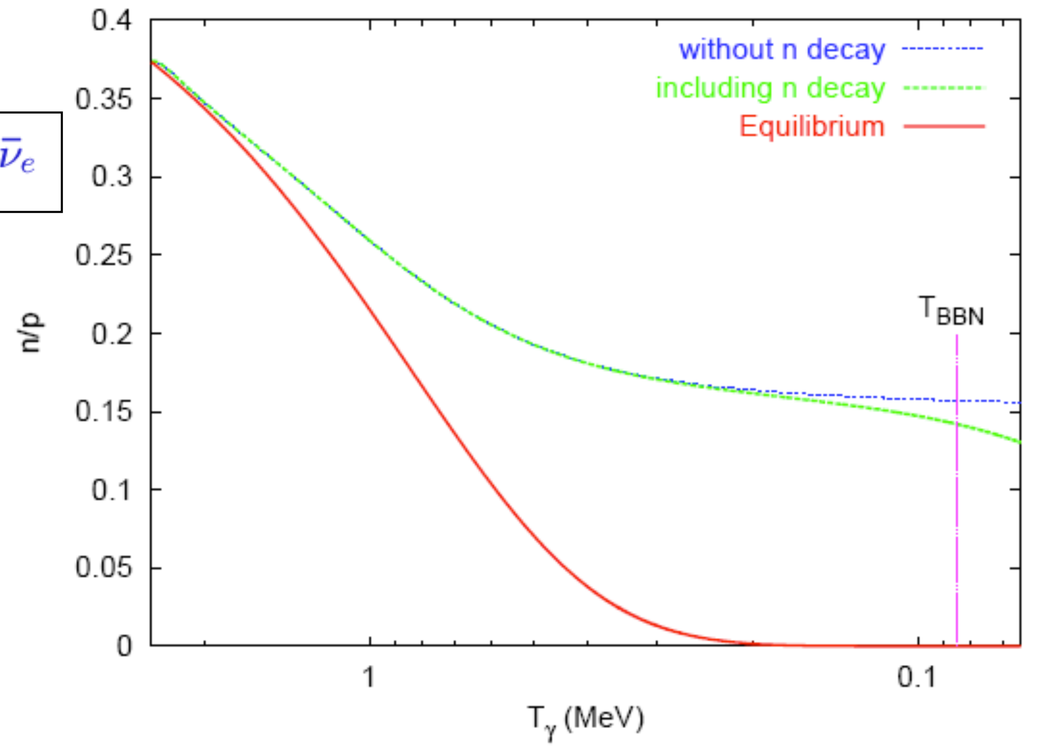
$$t \simeq 0{,}74 \left(\frac{\text{MeV}}{T}\right)^2 \text{ sec}$$

Phase I: 0.8-0.1 MeV
n-p reactions

$$\nu_e + n \longleftrightarrow p + e^- \qquad e^+ + n \longleftrightarrow p + \bar{\nu}_e$$

n/p freezing and
neutron decay

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

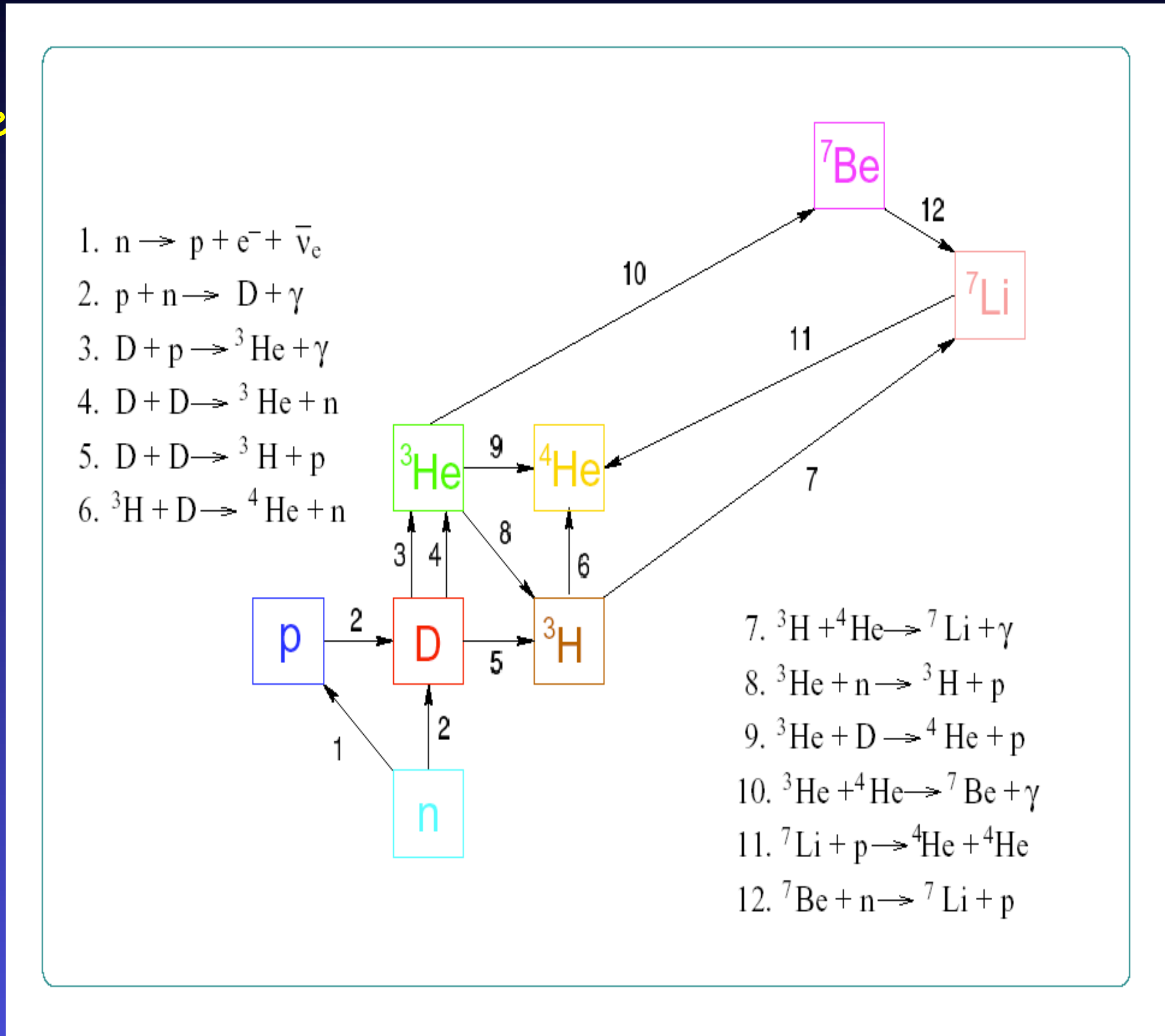


$$\left(\frac{n}{p}\right)_{eq} \simeq \exp\left(-\frac{m_n - m_p}{T_\gamma}\right) = \exp\left(-\frac{1{,}293 \text{ MeV}}{T_\gamma}\right)$$

BBN: Creation of light elements

Phase II: 0.1-0.01 MeV
Formation of light nucle
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

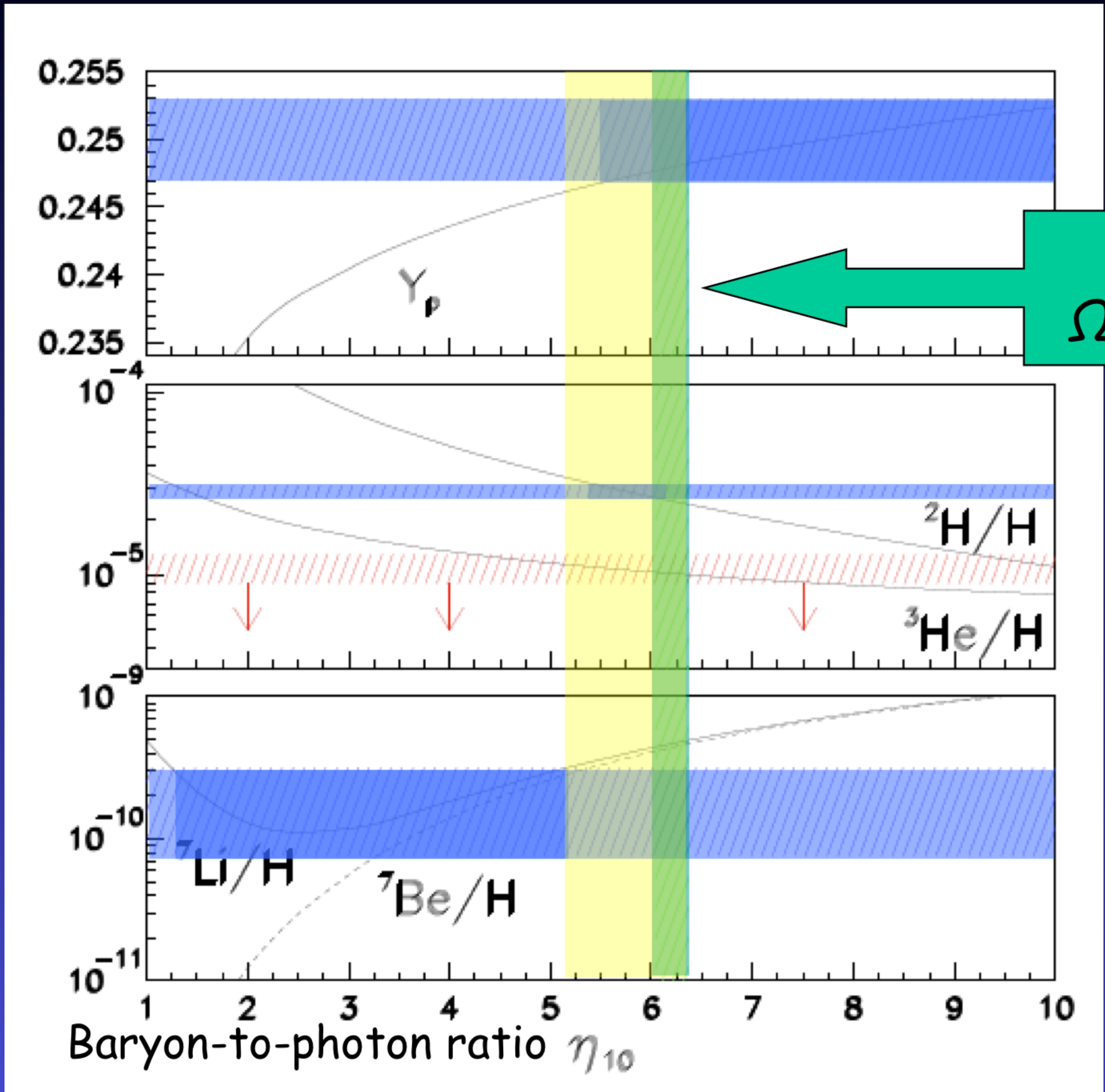
Deuterium: destroyed in stars. Any observed abundance of D is a *lower* limit to the primordial abundance. Data from high-z, low metallicity QSO absorption line systems

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, extragalatic 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



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

after WMAP
$\Omega_B h^2 = 0.02273 \pm 0.00062$

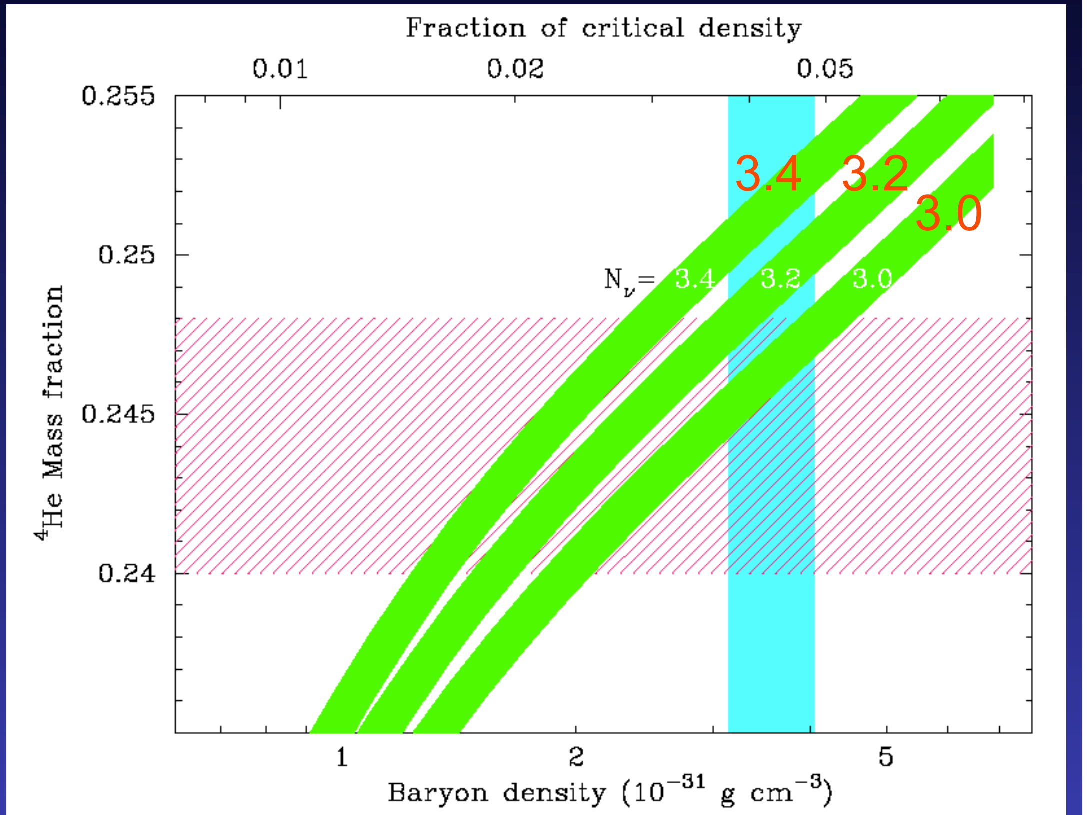
F. Iocco et al,
Phys. Rep. 472 (2009) 1

Effect of neutrinos on BBN

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

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

$\rho(N_{eff}) > \rho_0 \rightarrow \uparrow {}^4He$

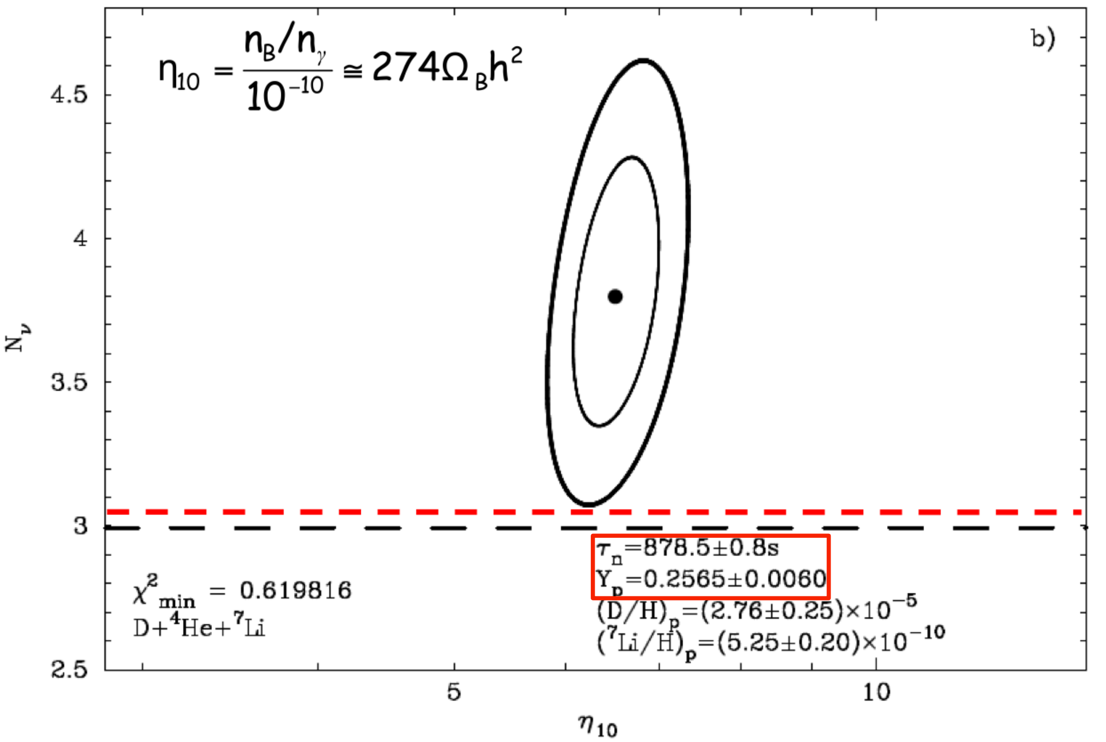


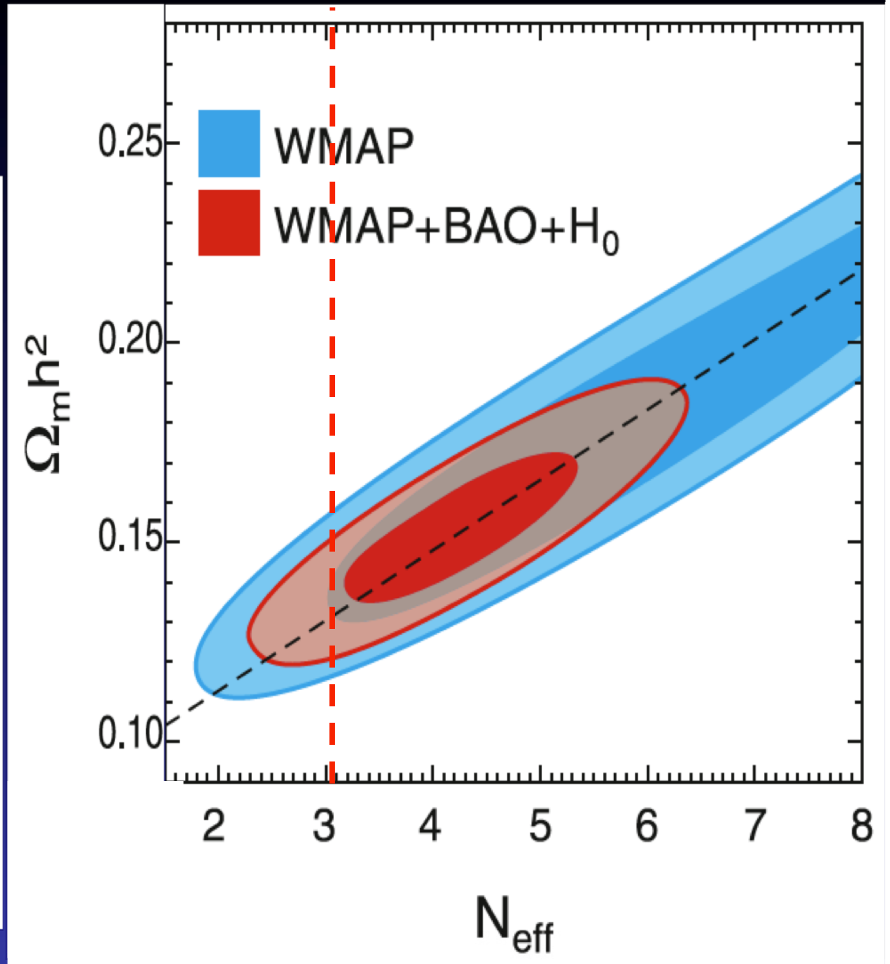
Burles, Nollett & Turner 1999

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

$$\nu_e + n \longleftrightarrow p + e^- \qquad e^+ + n \longleftrightarrow p + \bar{\nu}_e$$

allowed ranges for N_{eff}





Recent ^{4}He data

Izotov & Thuan, ApJ 710 (2010) L67

$$N_{eff} = 3.80^{+0.80}_{-0.70}$$
(95% CL)

from non-BBN data

WMAP [7-year], arXiv:1001.4538

$$2.7 < N_{eff} < 6.2 \text{ (WMAP+BAO+}H_0\text{)}$$

Larger errors: Aver et al, JCAP 05 (2010) 003

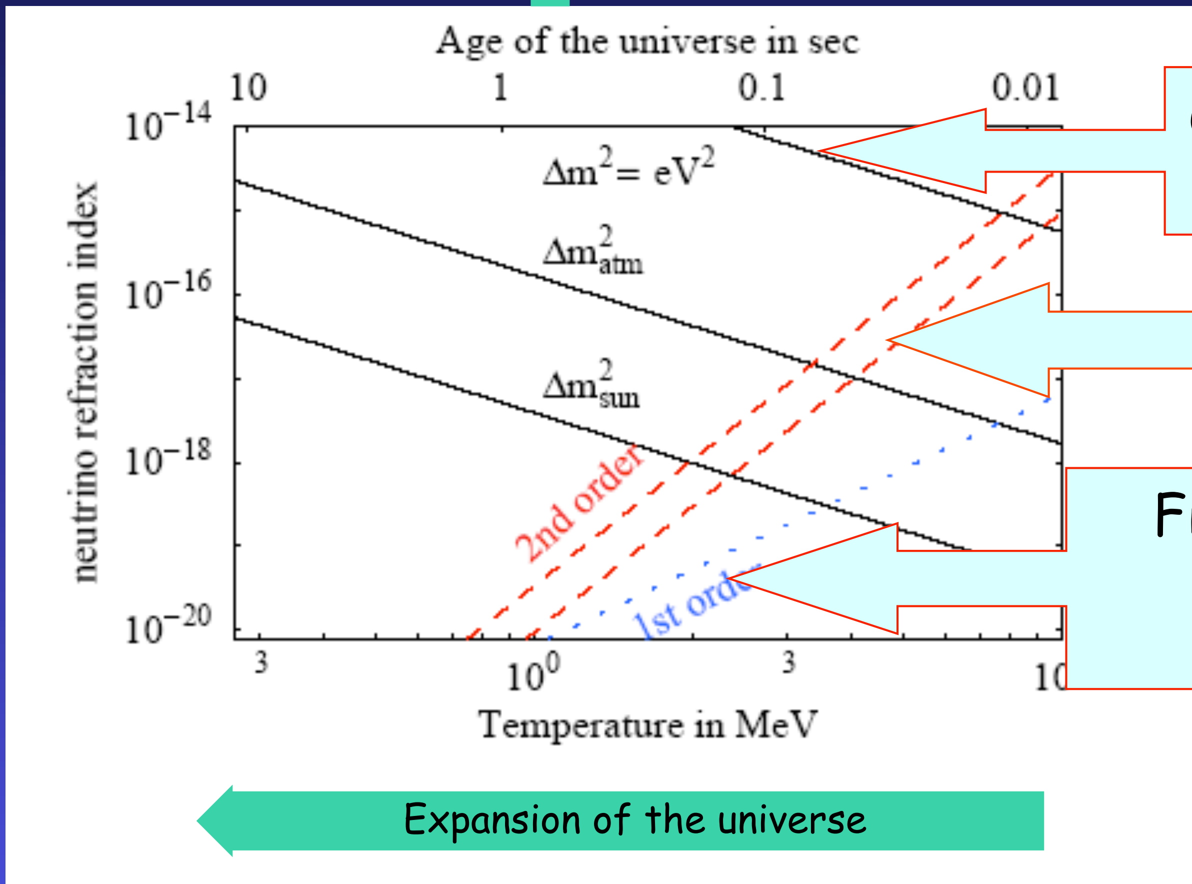
Neutrino oscillations in the Early Universe

Neutrino oscillations in the Early Universe

Neutrino oscillations are effective when medium effects get small enough

Coupled neutrinos

Compare oscillation term with effective potentials



Oscillation terms prop. to $\Delta m^2/2E$

Second order matter effects prop. to $G_F(E/M_Z^2)[\rho(e^-)+\rho(e^+)]$

First order matter effects prop. to $G_F[n(e^-)-n(e^+)]$

Strumia & Vissani, hep-ph/0606054

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}**)

SP, Pinto & Raffelt, PRL 102 (2009) 241302

Active-sterile neutrino oscillations

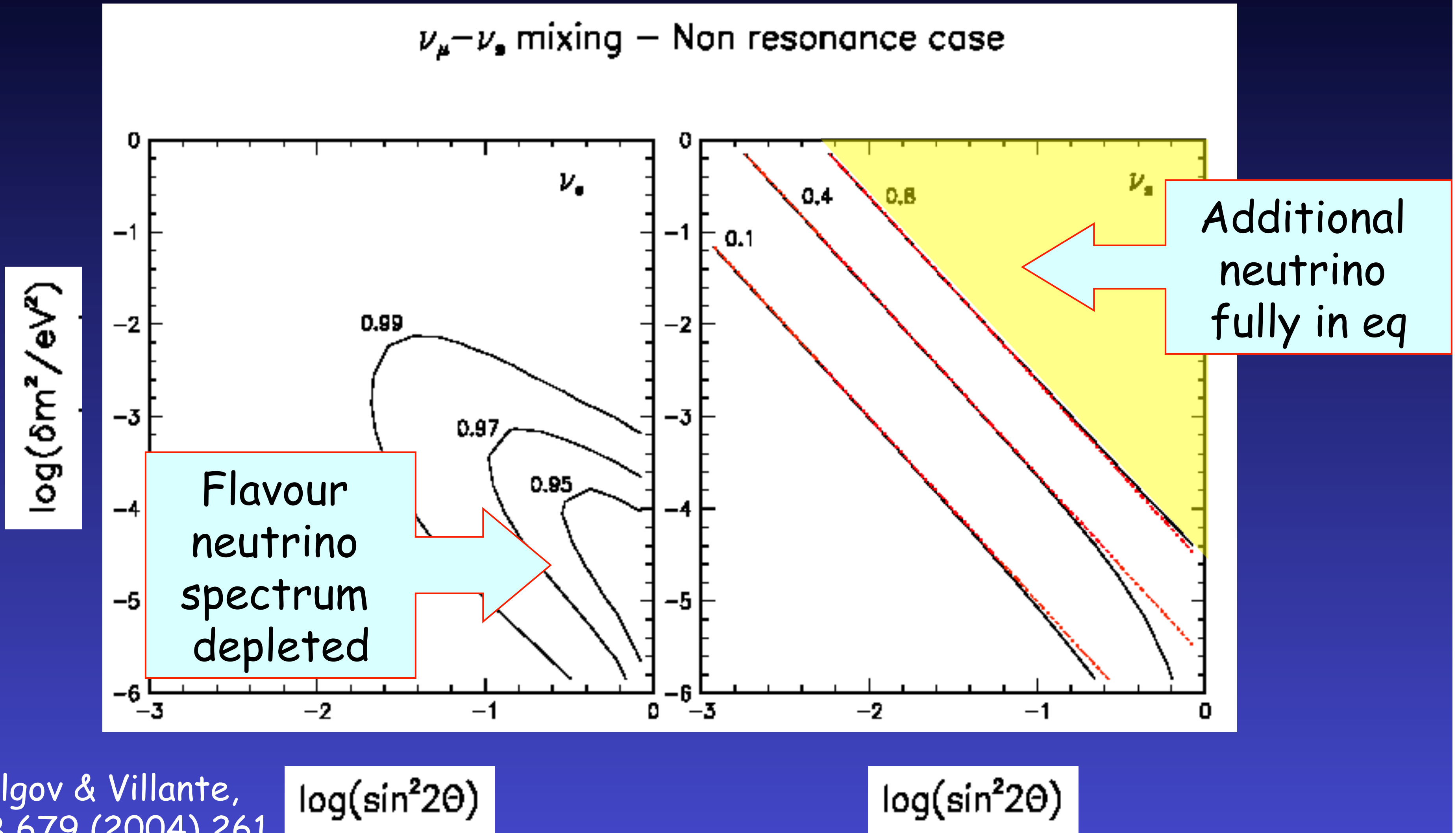
What if additional, light *sterile* neutrino species are mixed with the flavour neutrinos?

♣ If oscillations are effective <u>before decoupling</u>: the additional species can be brought into equilibrium: $N_{eff}=4$

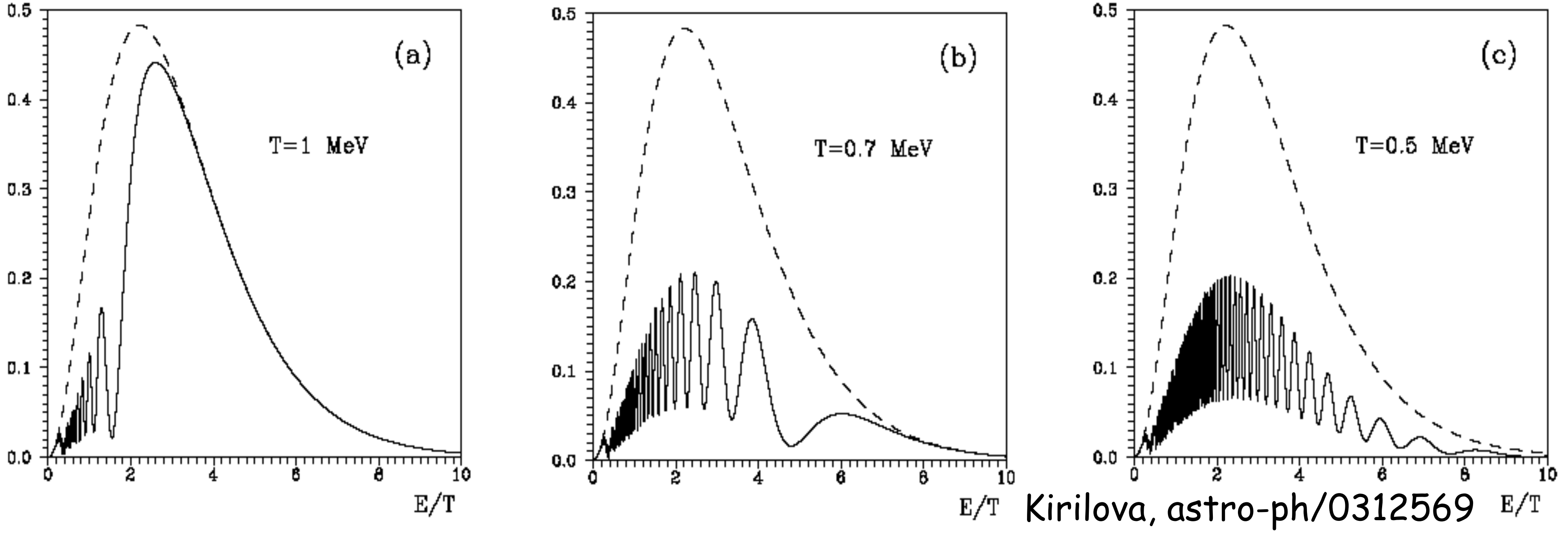
♣ If oscillations are effective <u>after decoupling</u>: $N_{eff}=3$ but the spectrum of active neutrinos is distorted (direct effect of ν_e and anti-ν_e on BBN)

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

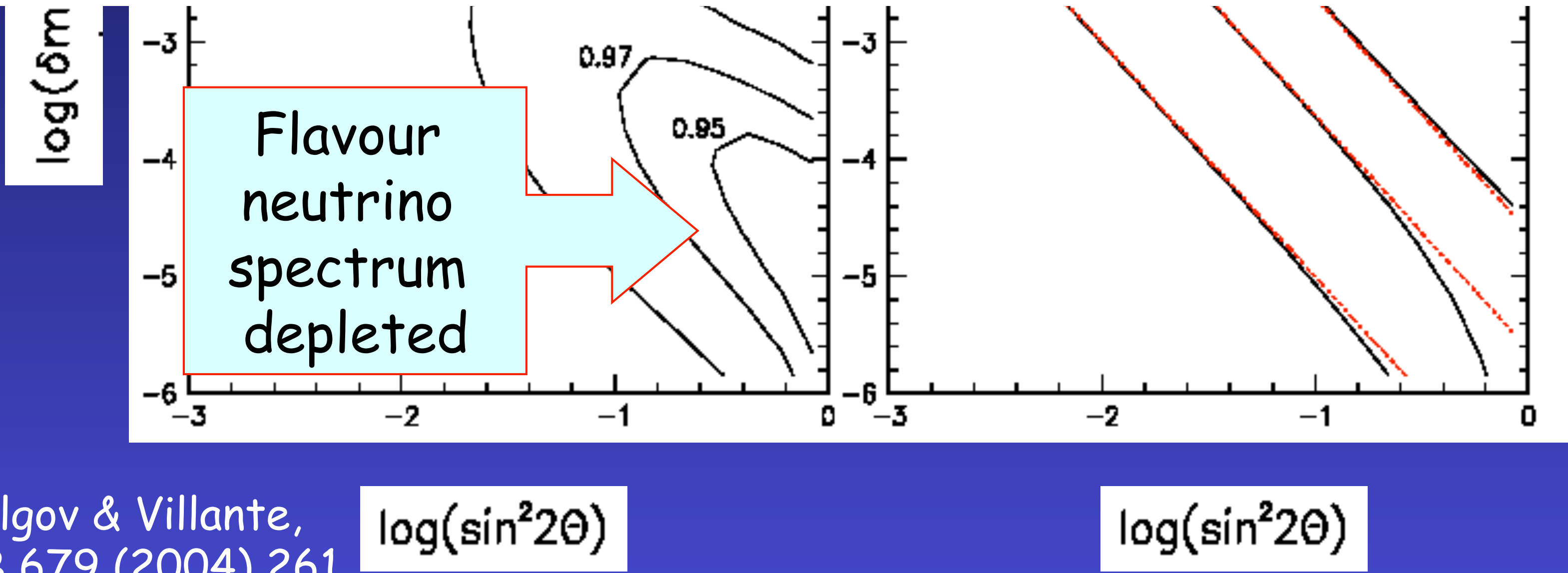
Active-sterile neutrino oscillations



Dolgov & Villante,
NPB 679 (2004) 261

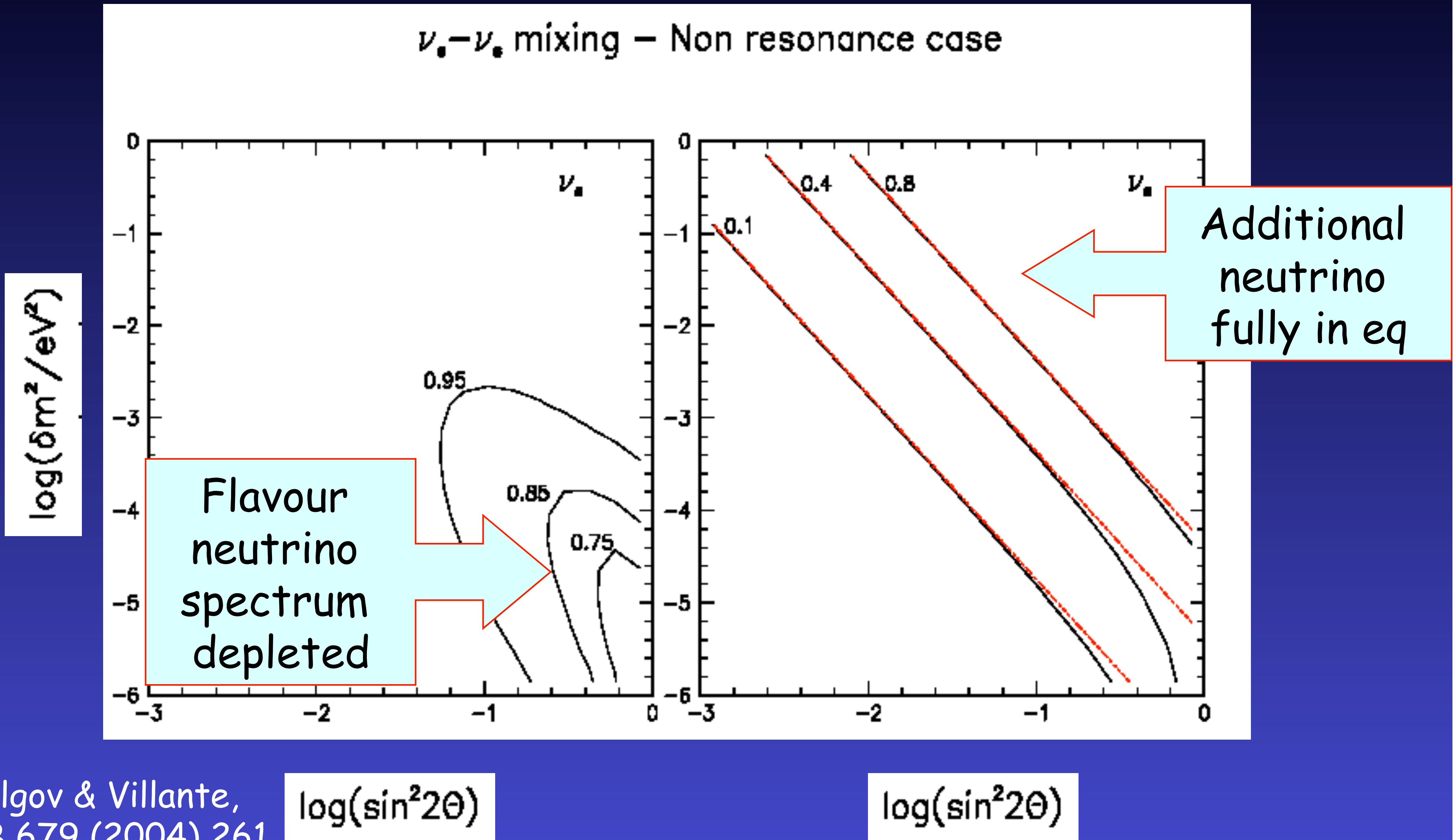


Kirilova, astro-ph/0312569



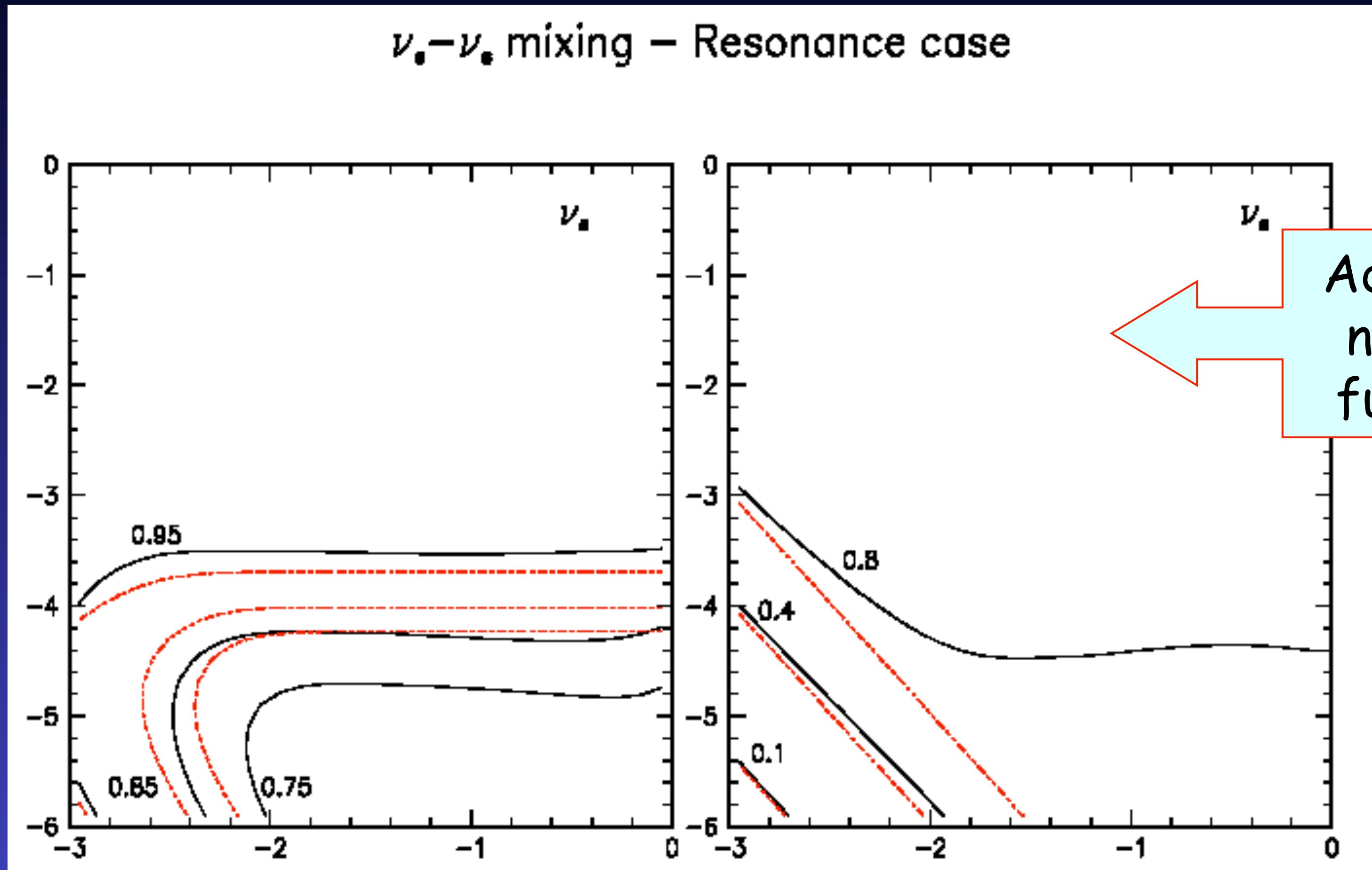
Dolgov & Villante,
NPB 679 (2004) 261

Active-sterile neutrino oscillations



Dolgov & Villante,
NPB 679 (2004) 261

Active-sterile neutrino oscillations



log(δm²/eV²)

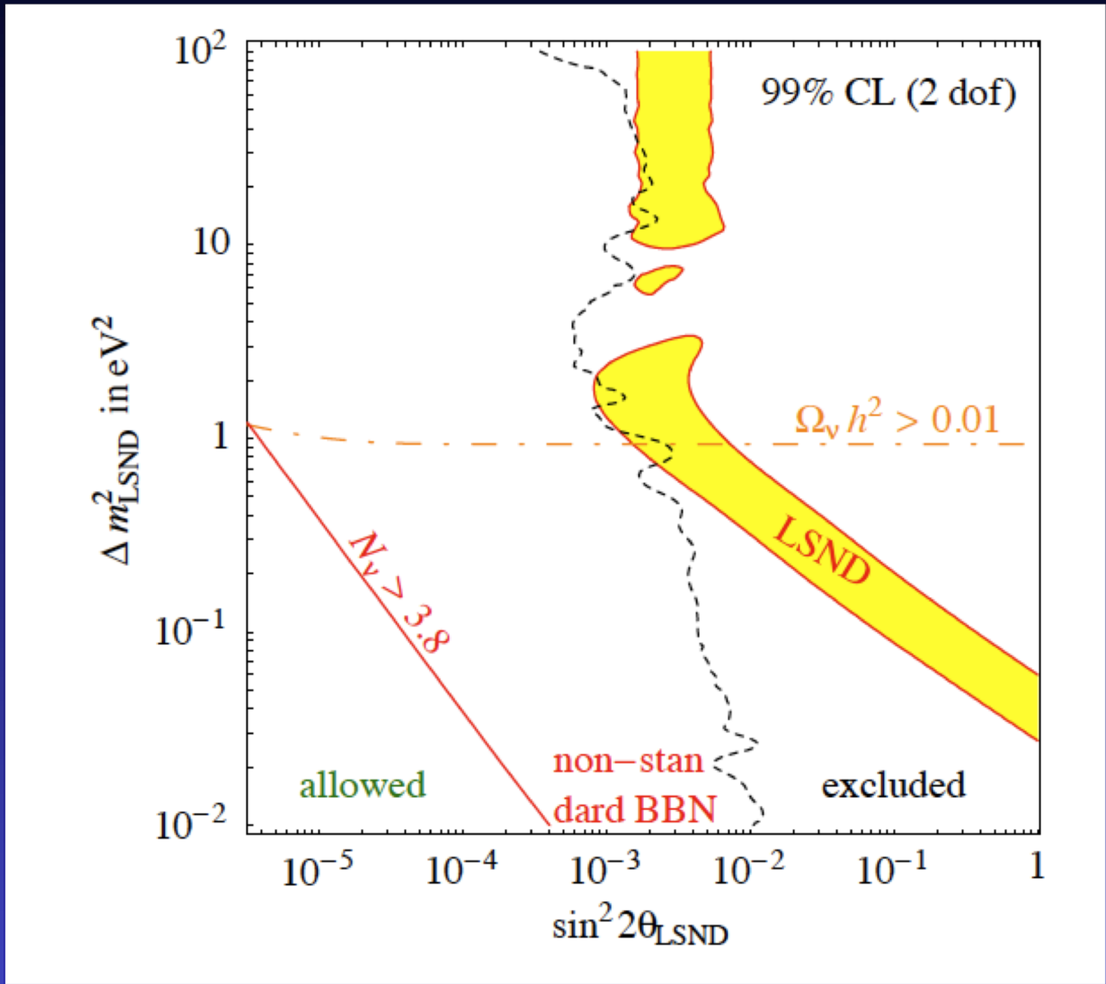
log(sin²2Θ)

log(sin²2Θ)

Additional neutrino fully in eq

Dolgov & Villante, NPB 679 (2004) 261

Active-sterile neutrino oscillations



Cirelli et al,
NPB 708 (2005) 215

But not always thermalized if multiple sterile states (3+2 schemes), see Melchiorri et al, JCAP 01 (2009) 036

End of 1st lecture

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 $\Gamma \approx H$

- The evolution of $\Omega(\nu,\gamma,b,cdm)$ with the expansion for (3,0,0), (1,1,1) and (0.05,0.009,0) [masses in eV]
- The value of N_{eff} if neutrinos decouple at T_{dec} in [5,0.2] MeV