Neutrinos in Cosmology

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IFIC INSTITUT DE FÍSICA CORPUSCULAR

ASTROPARTICLES Astroparticles and High Energy Physics Group

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VNIVERSITAT DE VALÈNCIA

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Suggested References

Books

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

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Reviews

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Phys. Rep. 429 (2006) 307-379 [astro-ph/0603494]

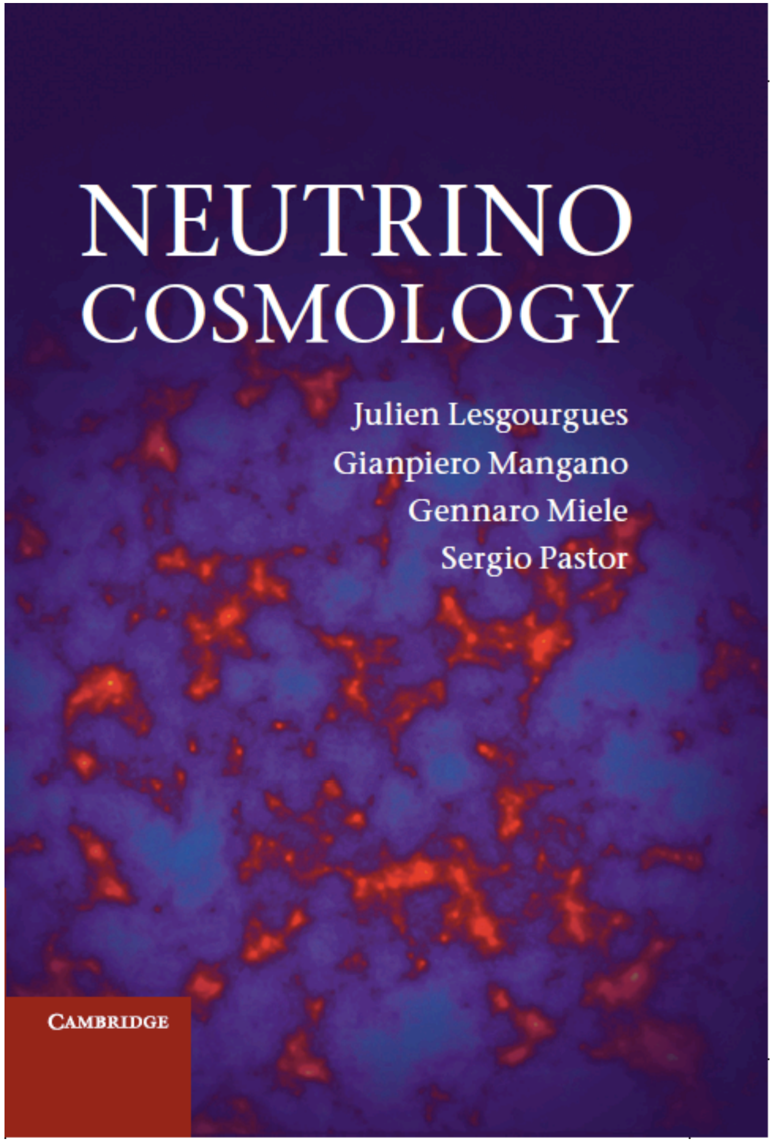
Primordial Nucleosynthesis: from precision cosmology to fundamental physics,
F. Iocco, G. Mangano, G. Miele, O. Pisanti & P.D. Serpico
Phys. Rep. 472 (2009) 1-76 [arXiv:0809.0631]

Neutrino mass in cosmology: status and prospects, Y.Y.Y. Wong
Ann. Rev. Nucl. Part. Sci. 61 (2011) 69-98 [arXiv:1111.1436]

Neutrino Physics from the CMB and LSS, K.N. Abazajian, M. Kaplinghat
Ann. Rev. Nucl. Part. Sci. 66 (2016) 401-420

Cosmological and astrophysical constraints on neutrino properties, M. Lattanzi &
M. Gerbino, *Frontiers in Physics 5 (2018) 70 [arXiv:1712.07109]*

For more details…



Ed. Cambridge Univ. Press, 2013

Where do neutrinos come from?

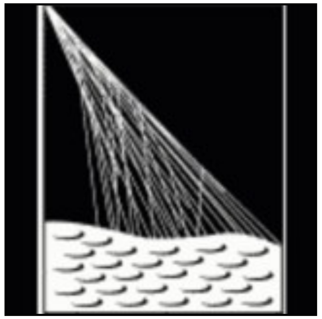
✓ Nuclear reactors

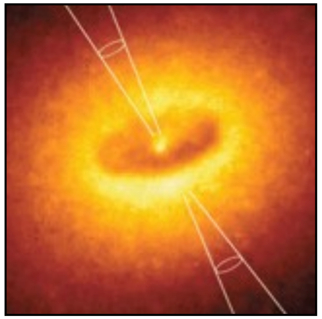
Sun ✓

✓ Particle accelerators

Supernovae
SN 1987A ✓

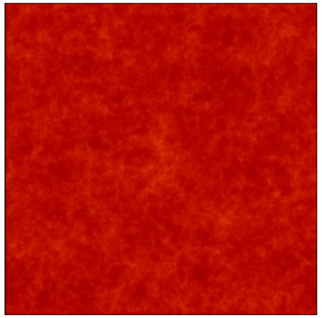
✓ Earth Atmosphere
(Cosmic rays)



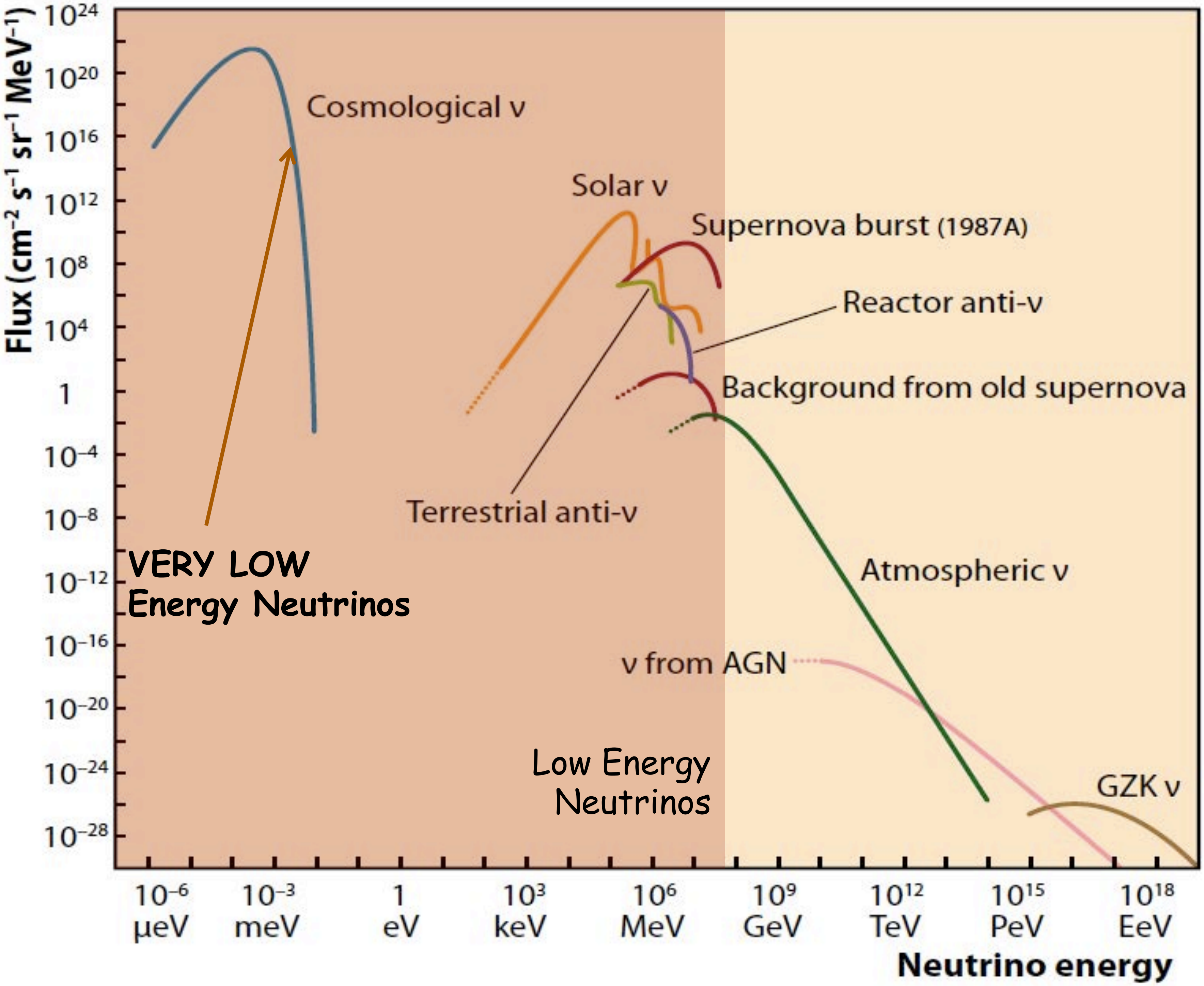


Accelerators in
astrophysical sources ?✓

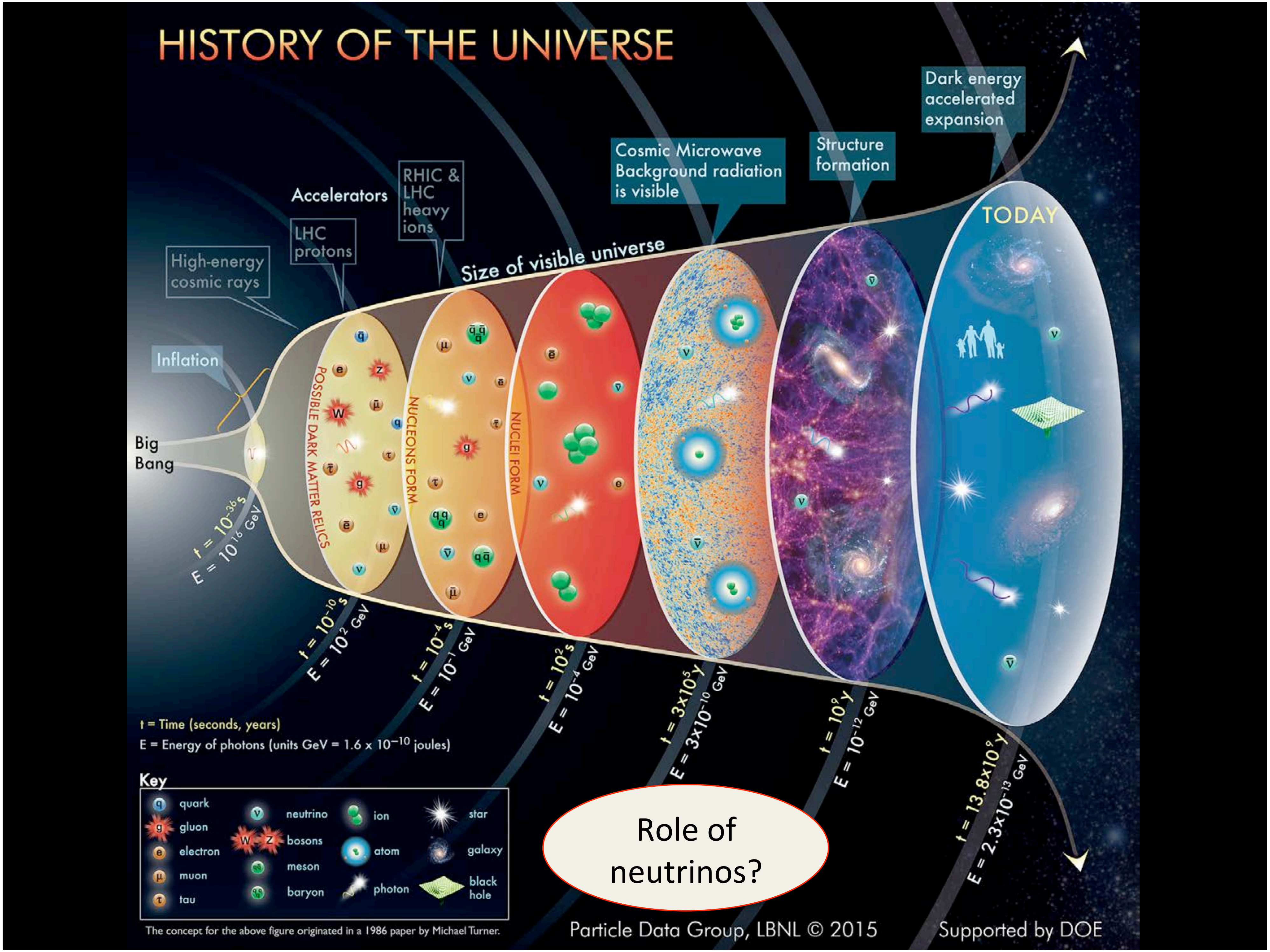
✓ Earth interior
(Natural Radioactivity)



Early Universe
(today 336 ν/cm^3)
Indirect evidence

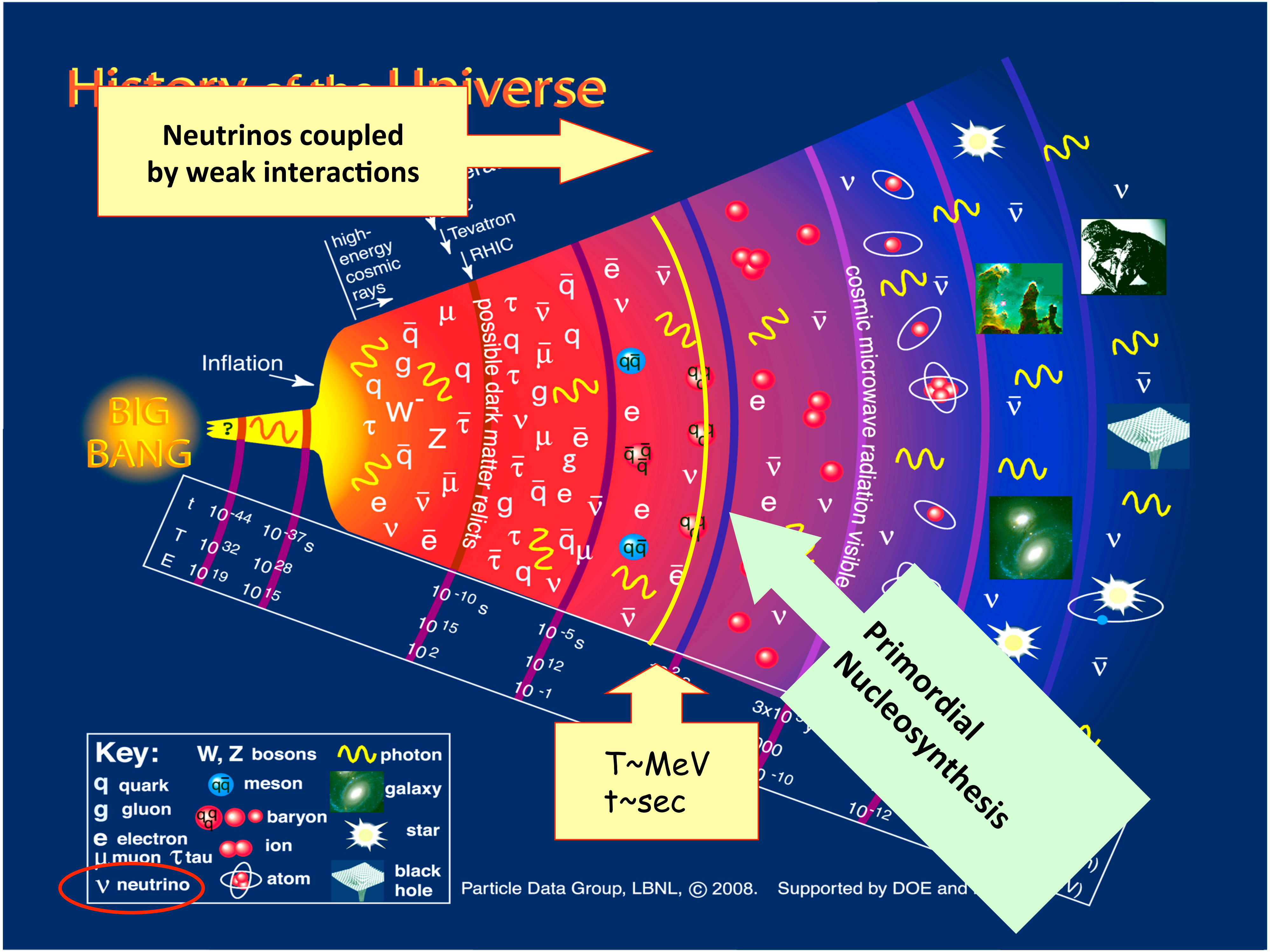


Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
10^24
10^20
10^16
10^12
10^8
10^4
1
10^-4
10^-8
10^-12
10^-16
10^-20
10^-24
10^-28
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernova
Terrestrial anti-ν
Atmospheric ν
ν from AGN
GZK ν
VERY LOW
Energy Neutrinos
Low Energy
Neutrinos
10^-6 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



Role of neutrinos?

Introduction: neutrinos and the history of the Universe


History of the Universe
Neutrinos coupled
by weak interactions
high-energy cosmic rays
Tevatron
RHIC
Inflation
BIG BANG
possible dark matter relics
cosmic microwave radiation visible
T~MeV
t~sec
Primordial Nucleosynthesis
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
star
e electron
ion
μ muon τ tau
ν neutrino
atom
black hole
Particle Data Group, LBNL, © 2008.
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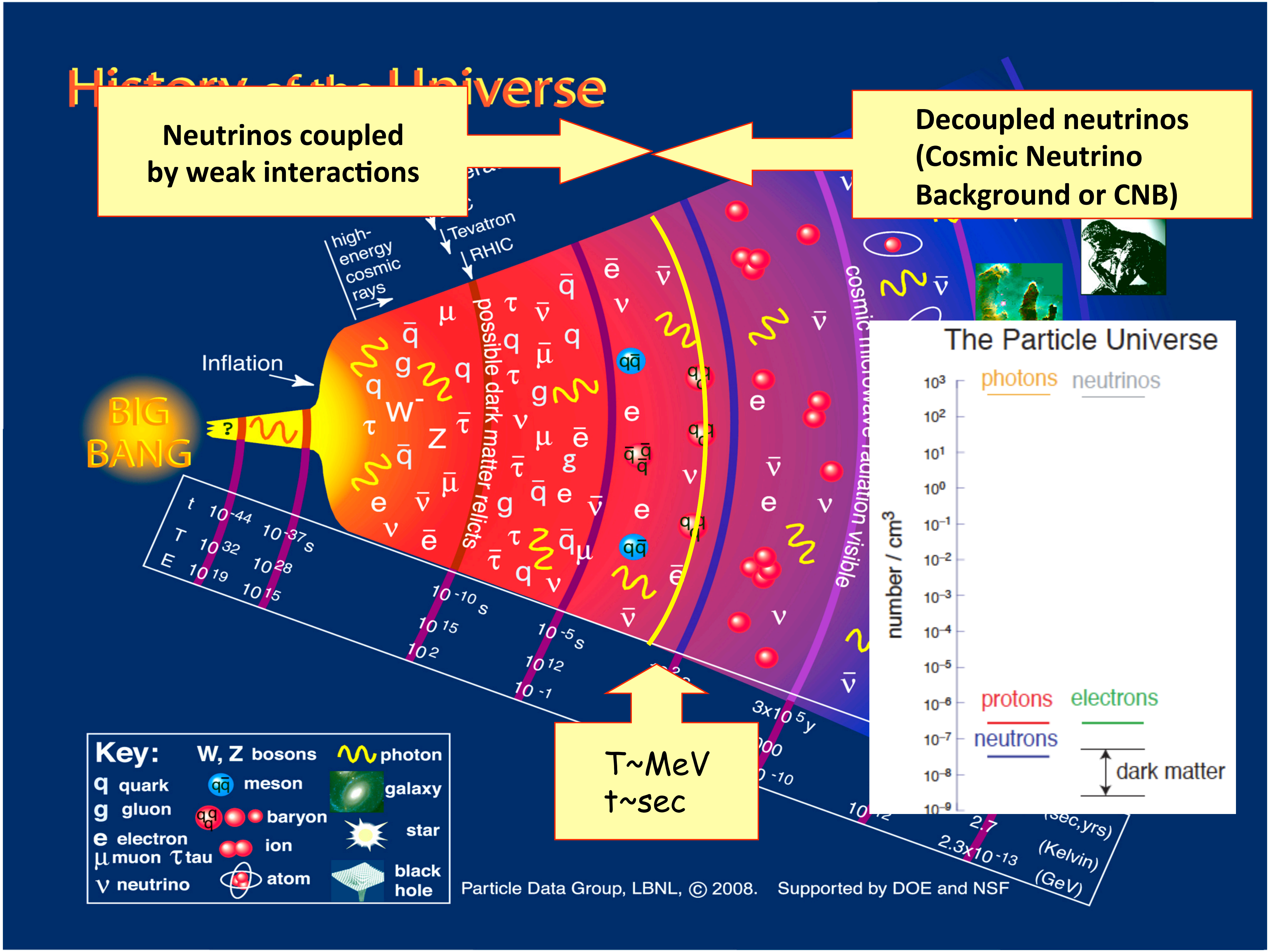
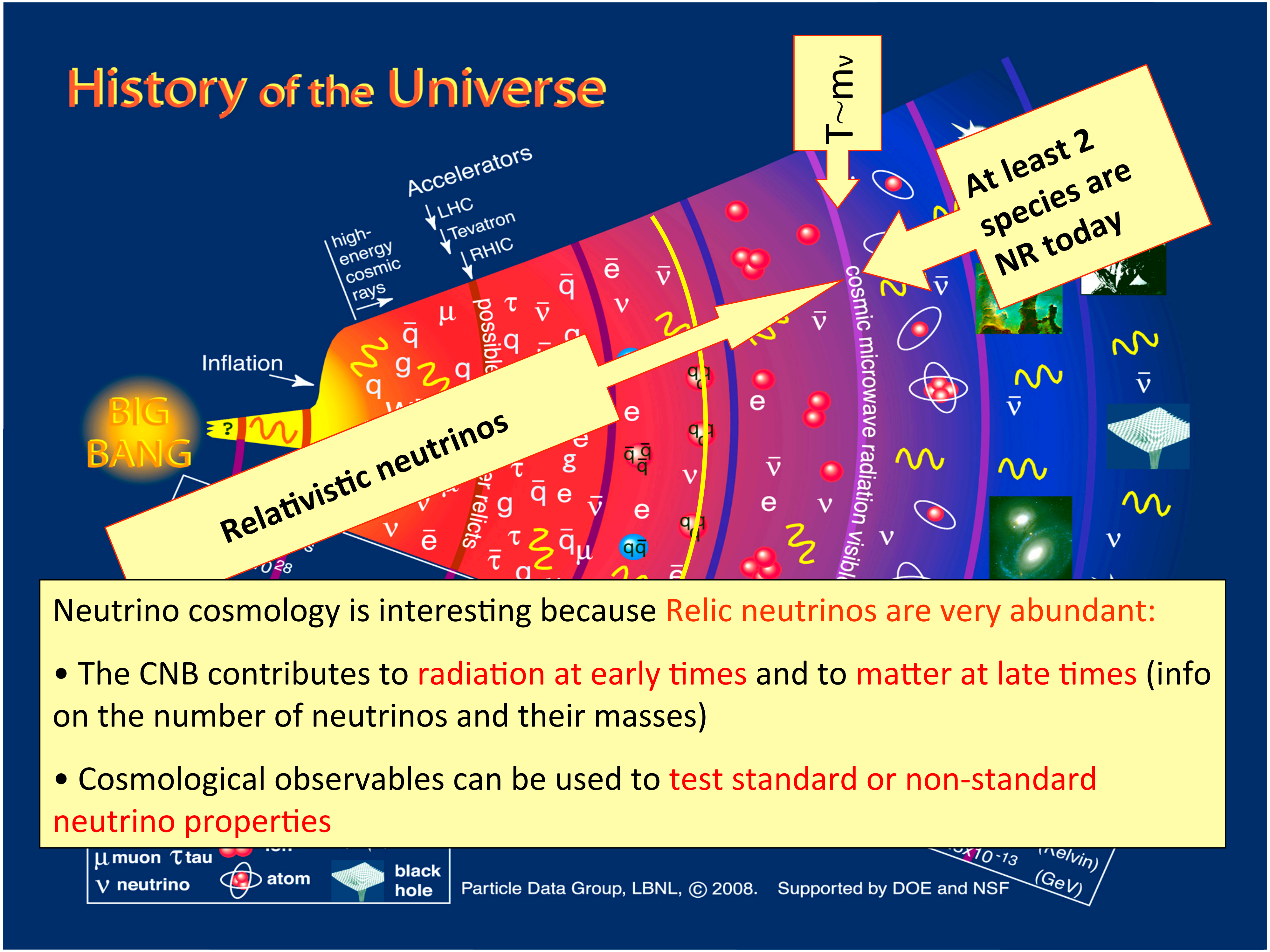
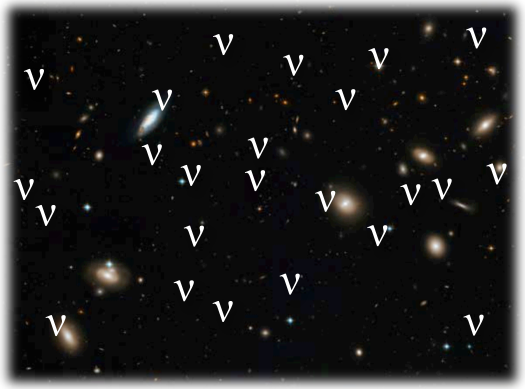

History of the Universe
Neutrinos coupled by weak interactions
Decoupled neutrinos (Cosmic Neutrino Background or CNB)
T~MeV
t~sec
high-energy cosmic rays
Tevatron
RHIC
Inflation
BIG BANG
possible dark matter relics
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
3x10 5 y
The Particle Universe
photons
neutrinos
protons
electrons
neutrons
dark matter
number / cm³
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF



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

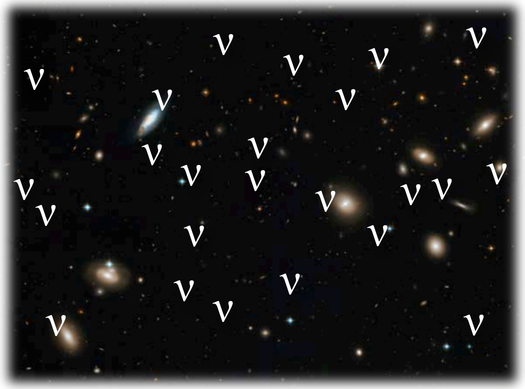


Introduction: neutrinos and the history of the Universe

Basics of Cosmology

Production and decoupling of relic neutrinos

Outline

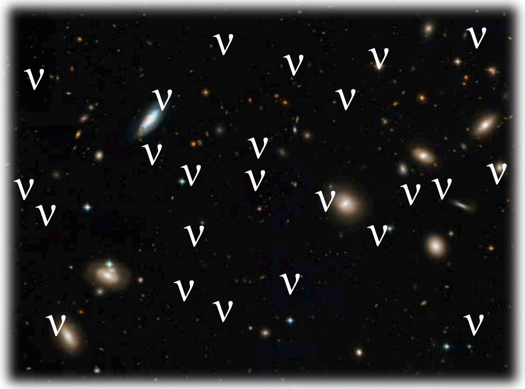


The radiation content of the Universe (N_{eff})

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

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

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 ➡

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

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**

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

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

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

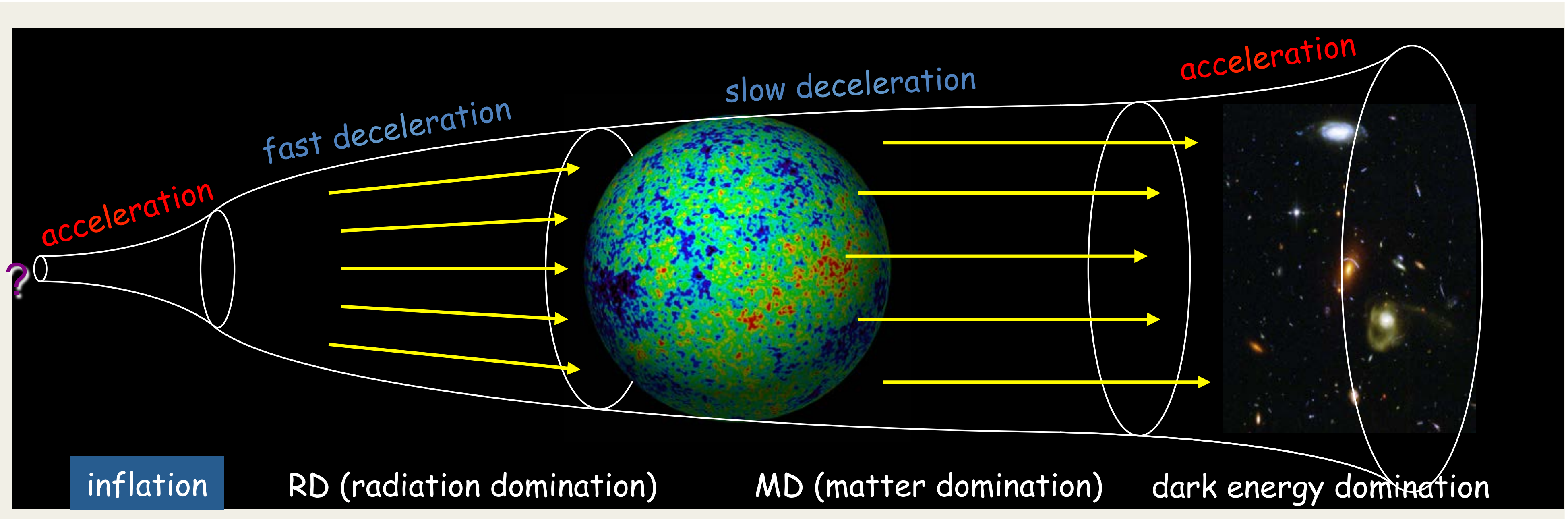
$\rho_{crit} = 3H^2/8\pi G$ **is the critical density**

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

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

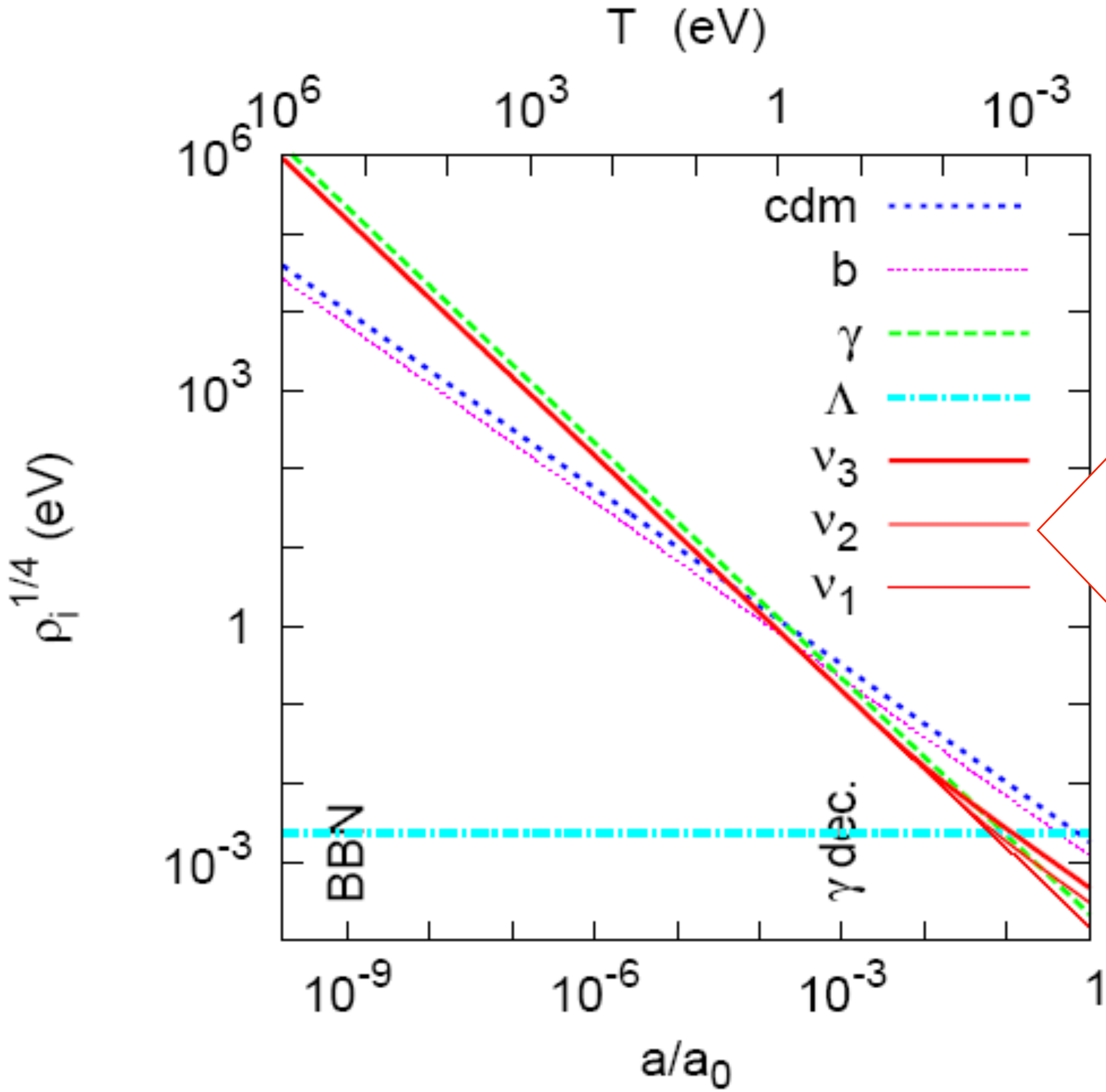


$a(t) \sim e^{Ht}$

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

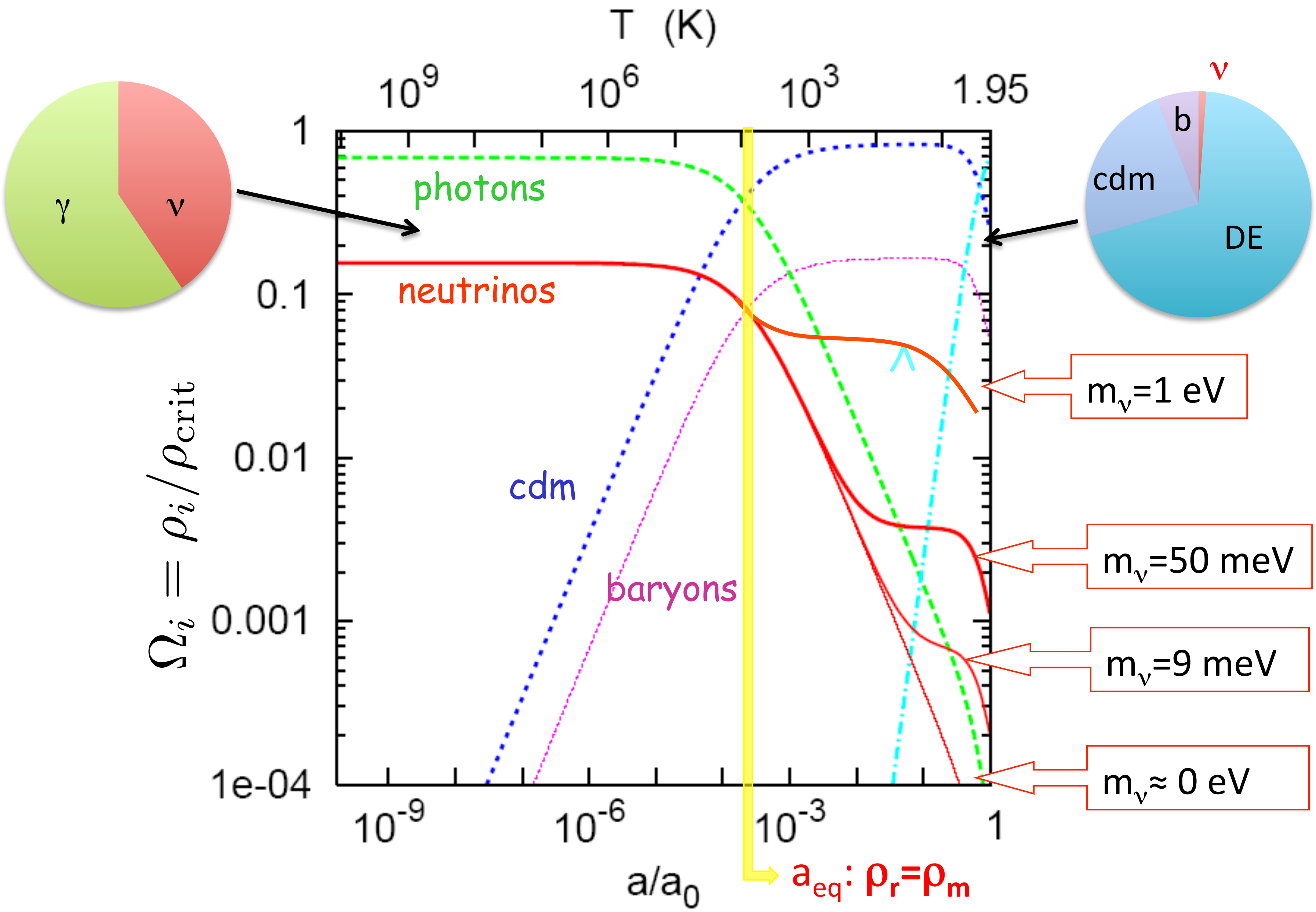
$a(t) \sim t^{2/3}$

Evolution of the background densities: 1 MeV → now

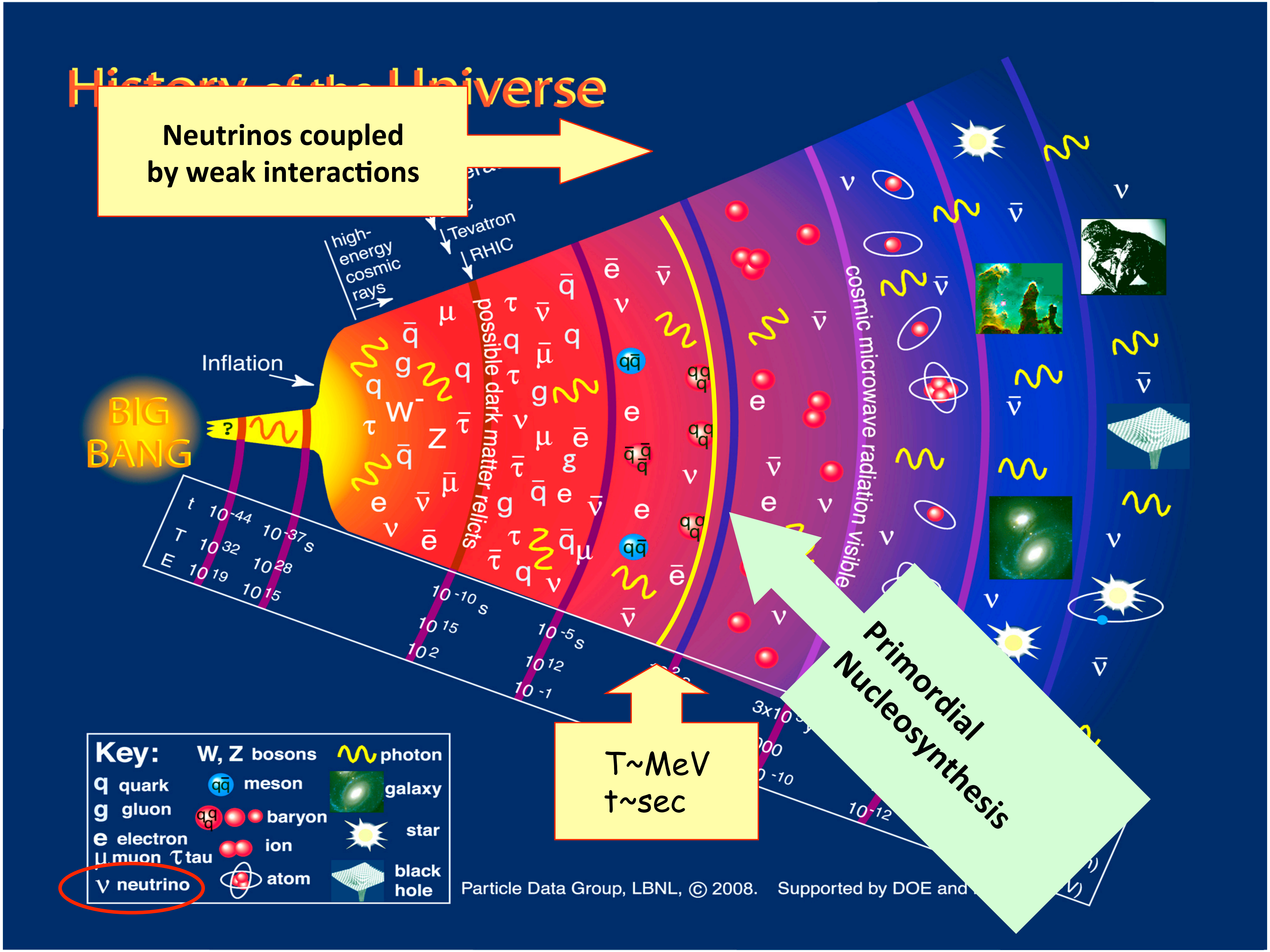


Three neutrino species with different masses

Background densities: 1 MeV → now



Production and decoupling of relic neutrinos



History of the Universe
Neutrinos coupled
by weak interactions
Inflation
BIG BANG
high-energy cosmic rays
Tevatron
RHIC
possible dark matter relics
cosmic microwave radiation visible
T~MeV
t~sec
Primordial Nucleosynthesis
Key:
q quark
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ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and

Equilibrium thermodynamics

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	$\frac{\rho}{3}$		$nT \ll \rho$
$\langle E \rangle$	$2{,}701T$	$3{,}151T$	$m + \frac{3}{2}T$

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

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

Particles in equilibrium when T are high and interactions effective

T~1/a(t)

Neutrinos in Equilibrium

$$1\ \mathrm{MeV} \lesssim \mathrm{T} \lesssim \mathrm{m}_\mu$$

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

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

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

$$\nu_\alpha e^\pm \leftrightarrow \nu_\alpha e^\pm$$

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

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

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

$$g_L = -\frac{1}{2} + \sin^2\theta_W \text{ and } g_R = \sin^2\theta_W$$

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

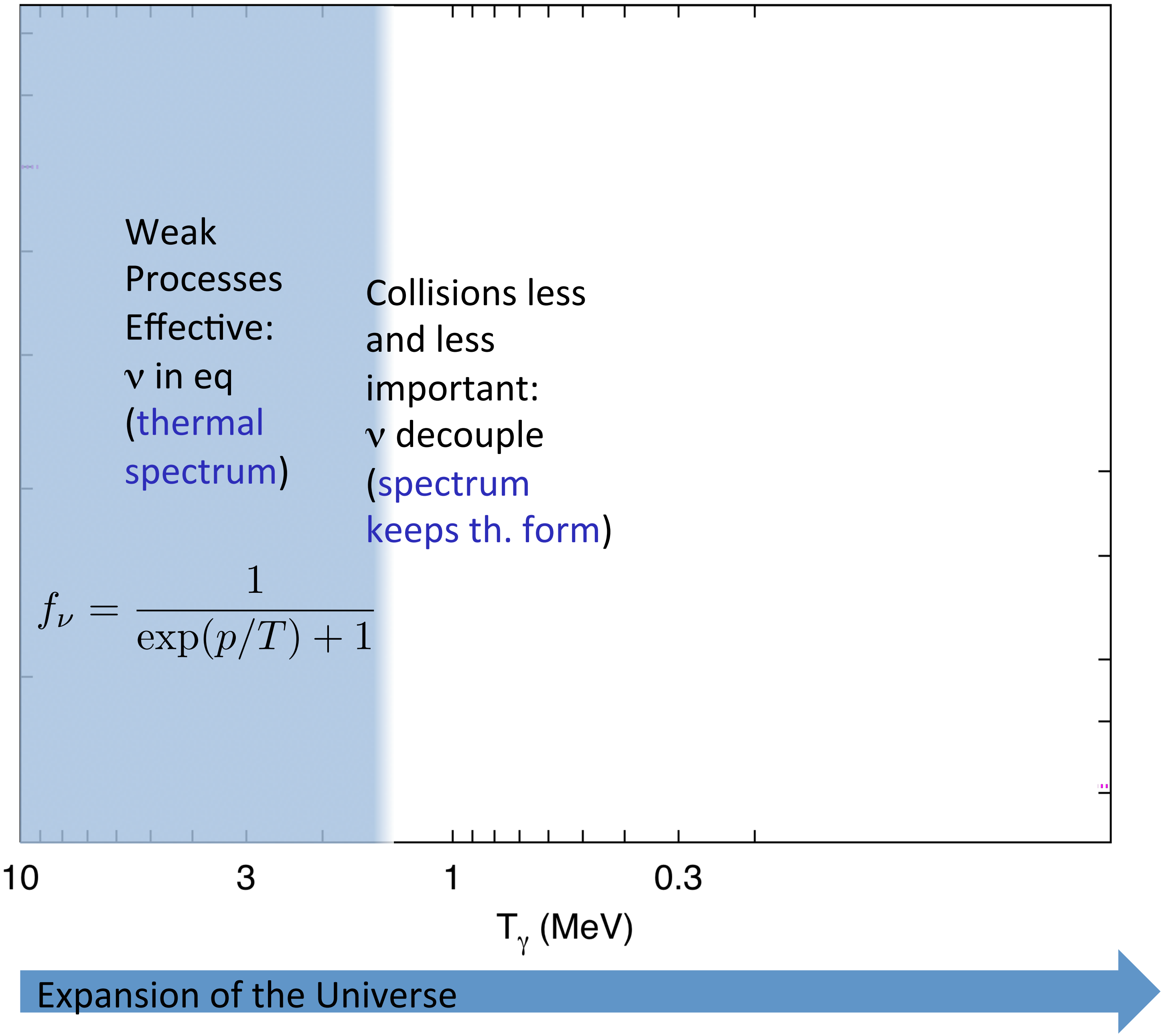
Rate of weak processes ~ Hubble expansion rate

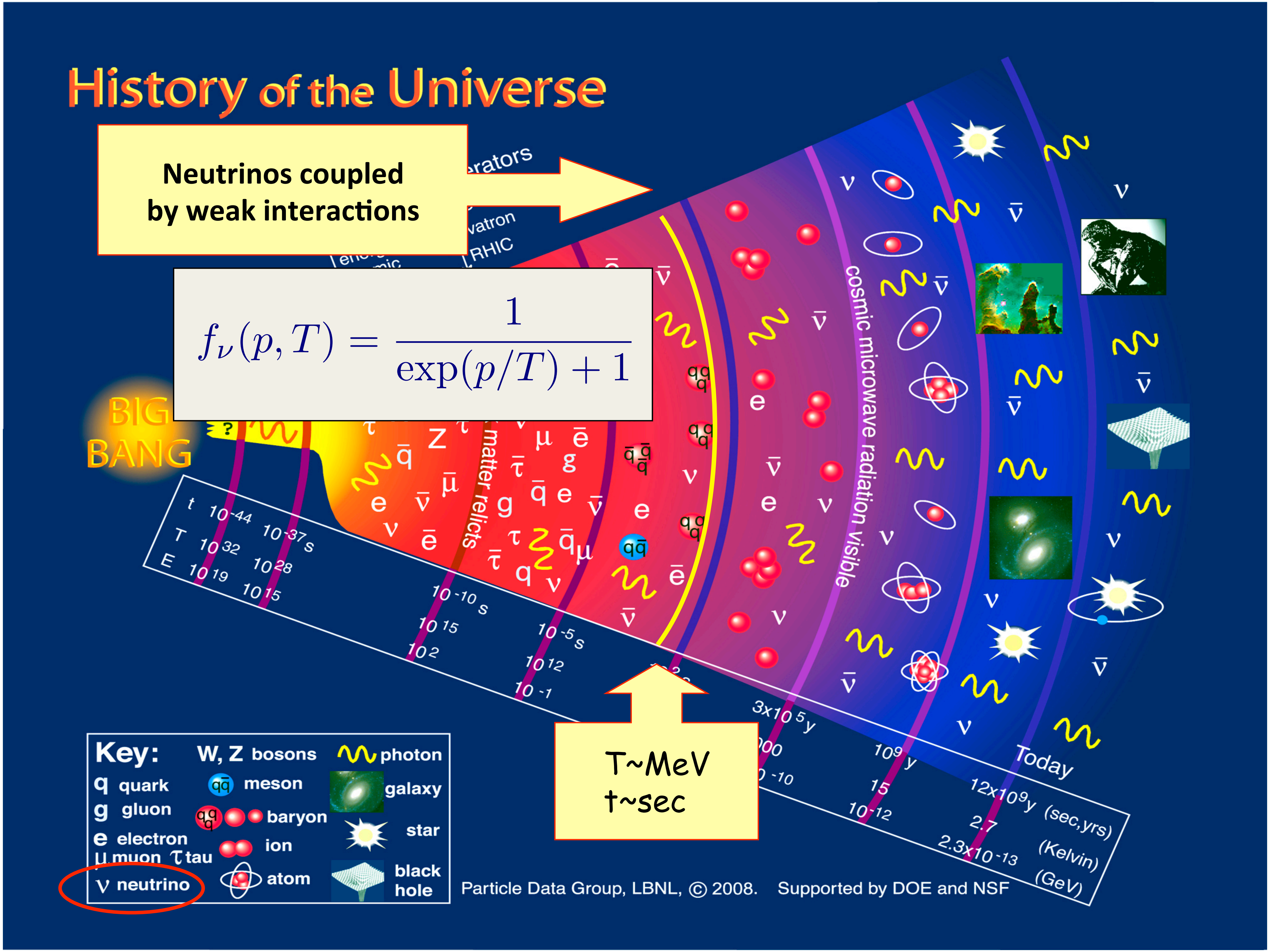
$$\Gamma_W \approx \sigma_W |v| n,\ \ H^2 = \frac{8\pi\rho_{\rm rad}}{3M_P^2} \ \ \to \ \ G_F^2 T^5 \approx \sqrt{\frac{8\pi\rho_{\rm rad}}{3M_P^2}} \ \ \to \ \ T_{\rm dec}(\nu) \approx 1\ {\rm MeV}$$

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

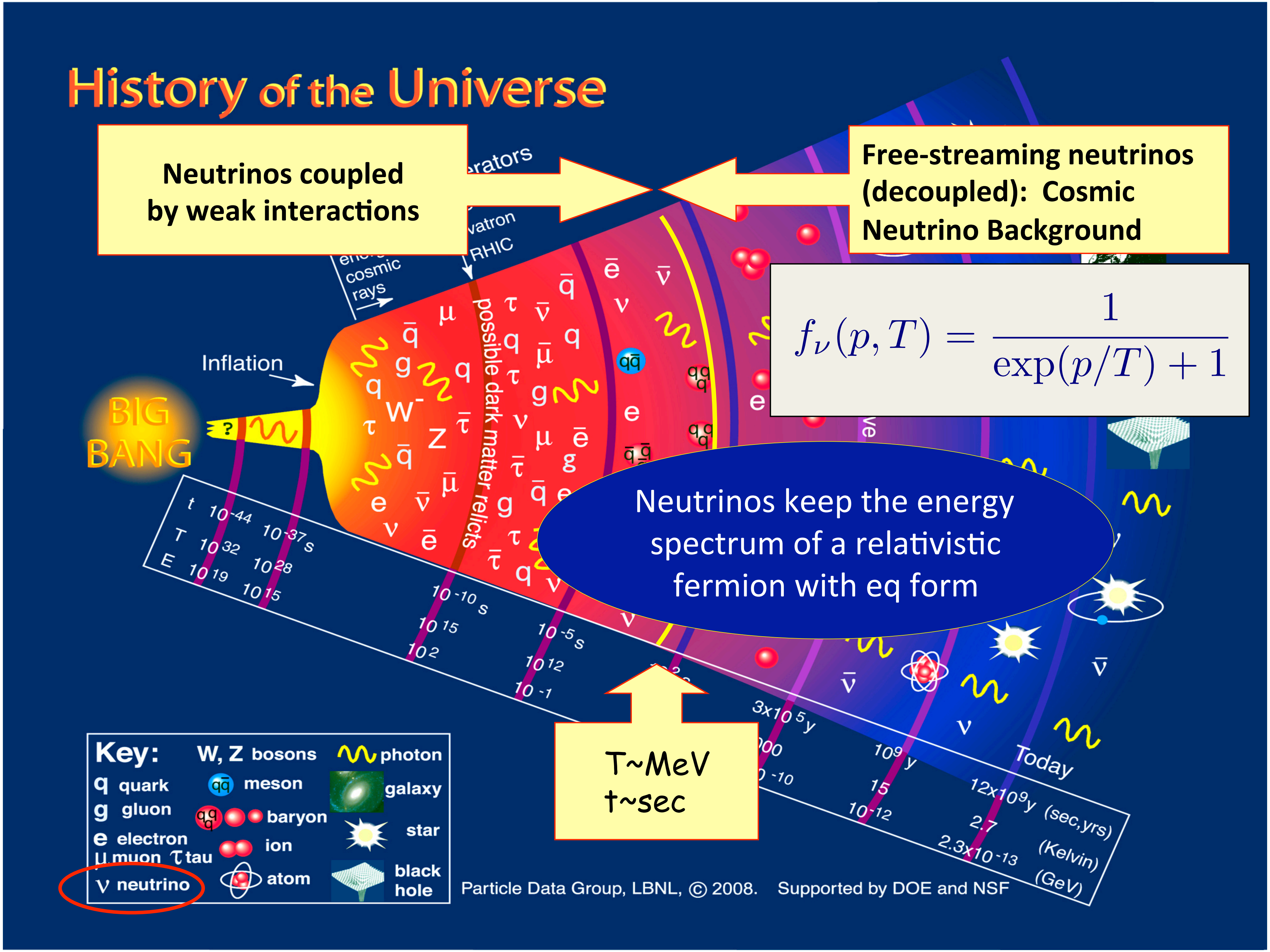
$$T_{\rm dec}(\nu_e) \simeq 2\ {\rm MeV} \qquad T_{\rm dec}(\nu_{\mu,\tau}) \simeq 3\ {\rm MeV}$$

Neutrino decoupling





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



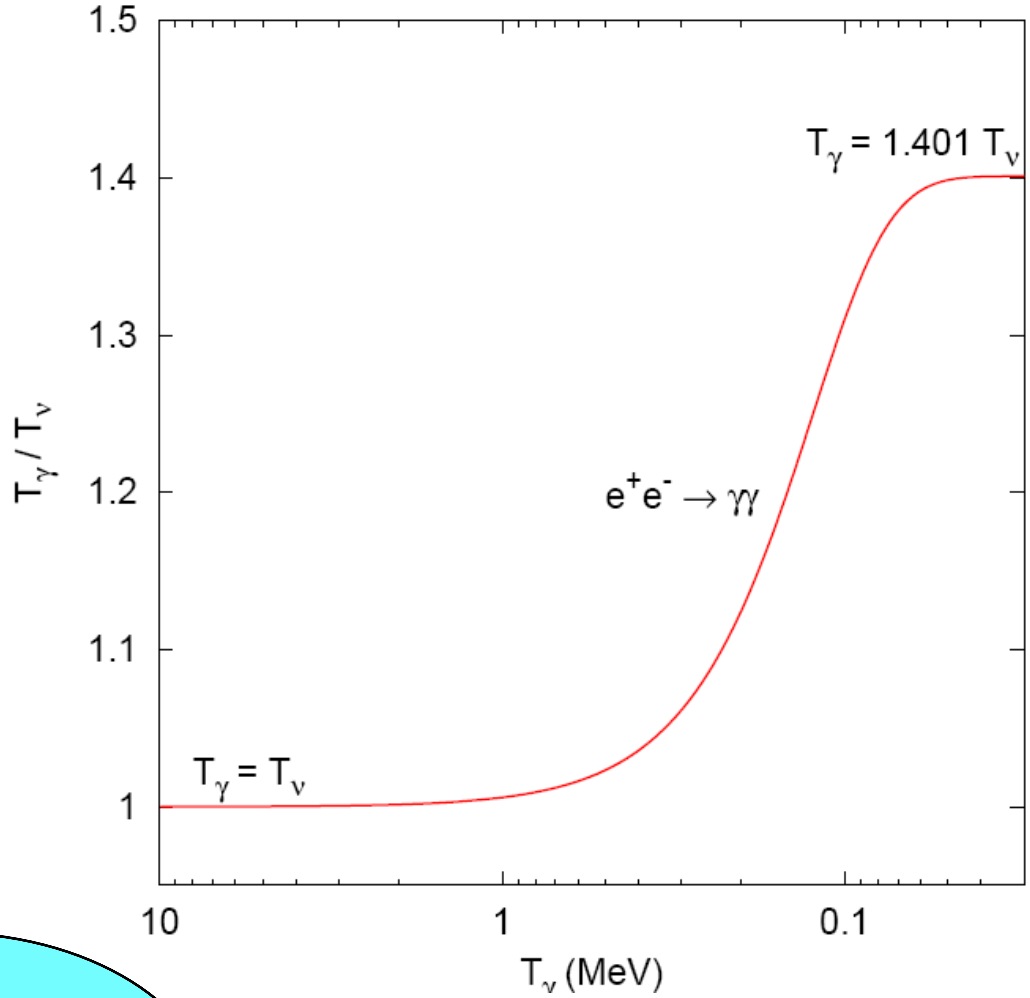
History of the Universe
Neutrinos coupled by weak interactions
Free-streaming neutrinos (decoupled): Cosmic Neutrino Background
$$f_\nu(p,T) = \frac{1}{\exp(p/T)+1}$$
Neutrinos keep the energy spectrum of a relativistic fermion with eq form
T~MeV
t~sec
BIG BANG
Inflation
cosmic rays
RHIC
possible dark matter relics
t 10^-44 10^-37 s 10^-10 s 10^-5 s 3x10^5 y 10^9 y 12x10^9 y (sec,yrs)
T 10^32 10^28 10^15 10^12 15 2.7 (Kelvin)
E 10^19 10^15 10^2 10^-1 10^-12 2.3x10^-13 (GeV)
Today
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
star
e electron
ion
μ muon τ tau
ν neutrino
atom
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

Neutrino and photon (CMB) temperatures

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

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

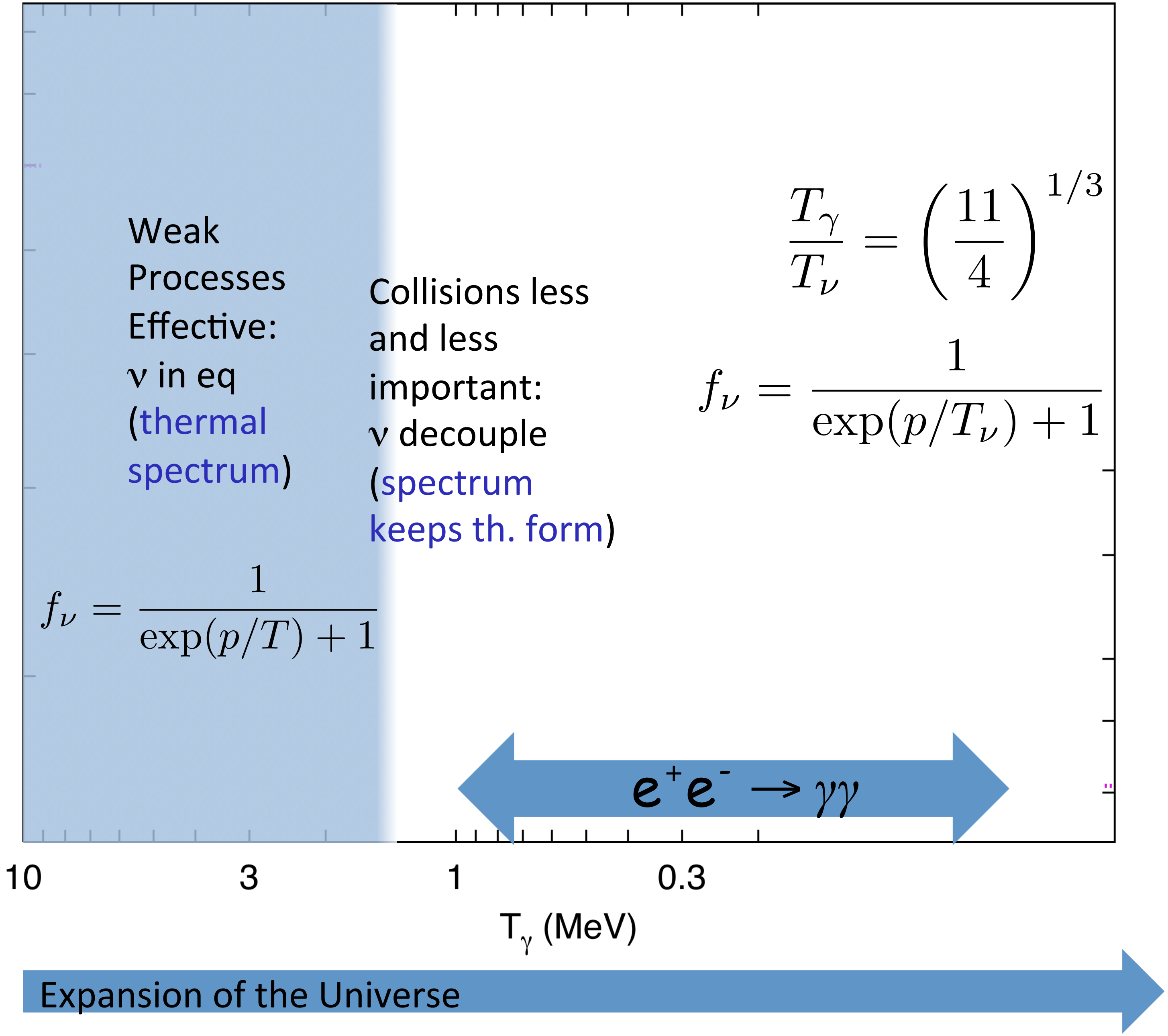
heating photons but not the decoupled neutrinos



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

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

Neutrino decoupling and e$^{\pm}$ annihilations



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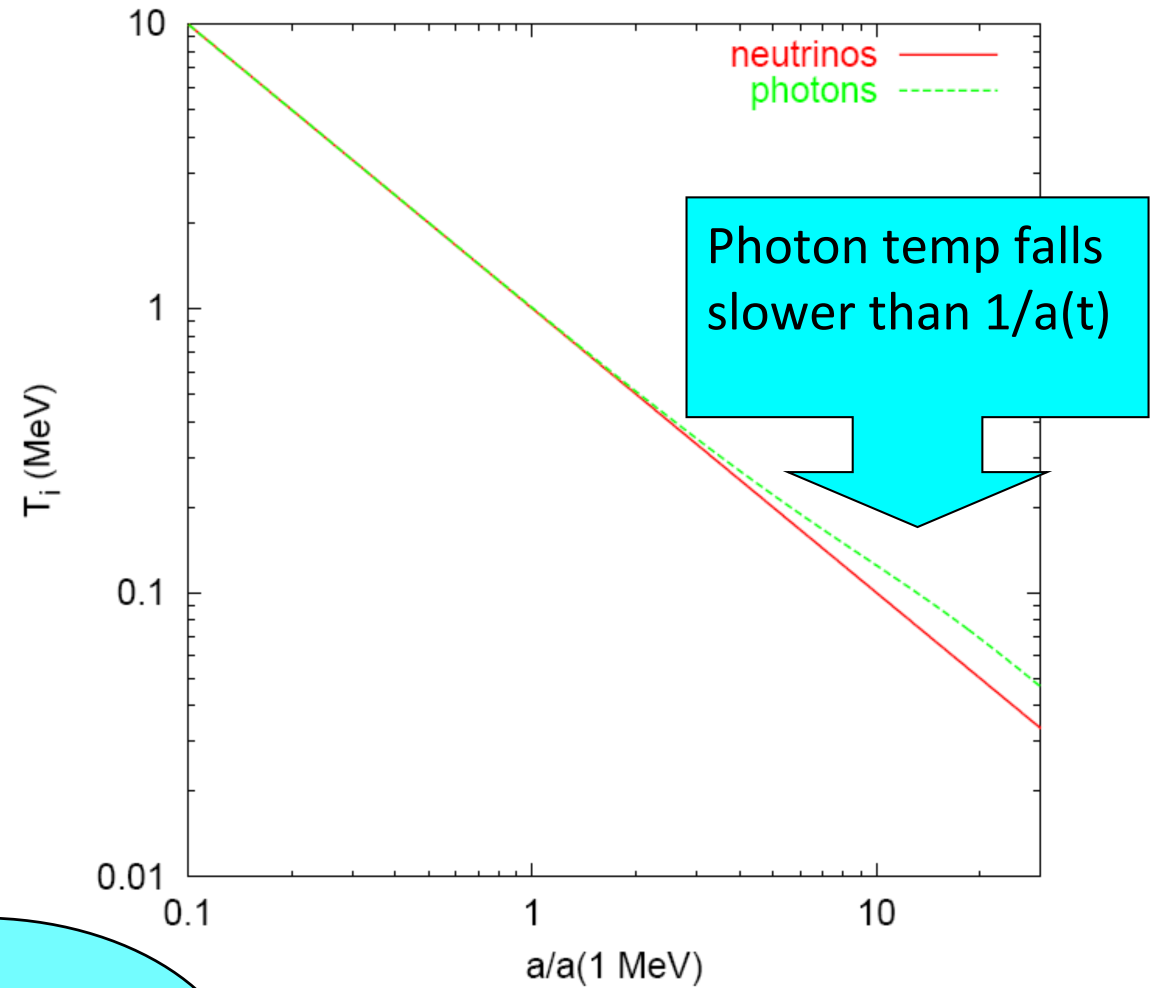


$$\frac{T_\gamma}{T_\nu} = \left(\frac{11}{4}\right)^{1/3}$$

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

The Cosmic Neutrino Background

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

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

- Number density

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

- Energy density

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

The Cosmic Neutrino Background

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

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

- Number density

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

- Energy density

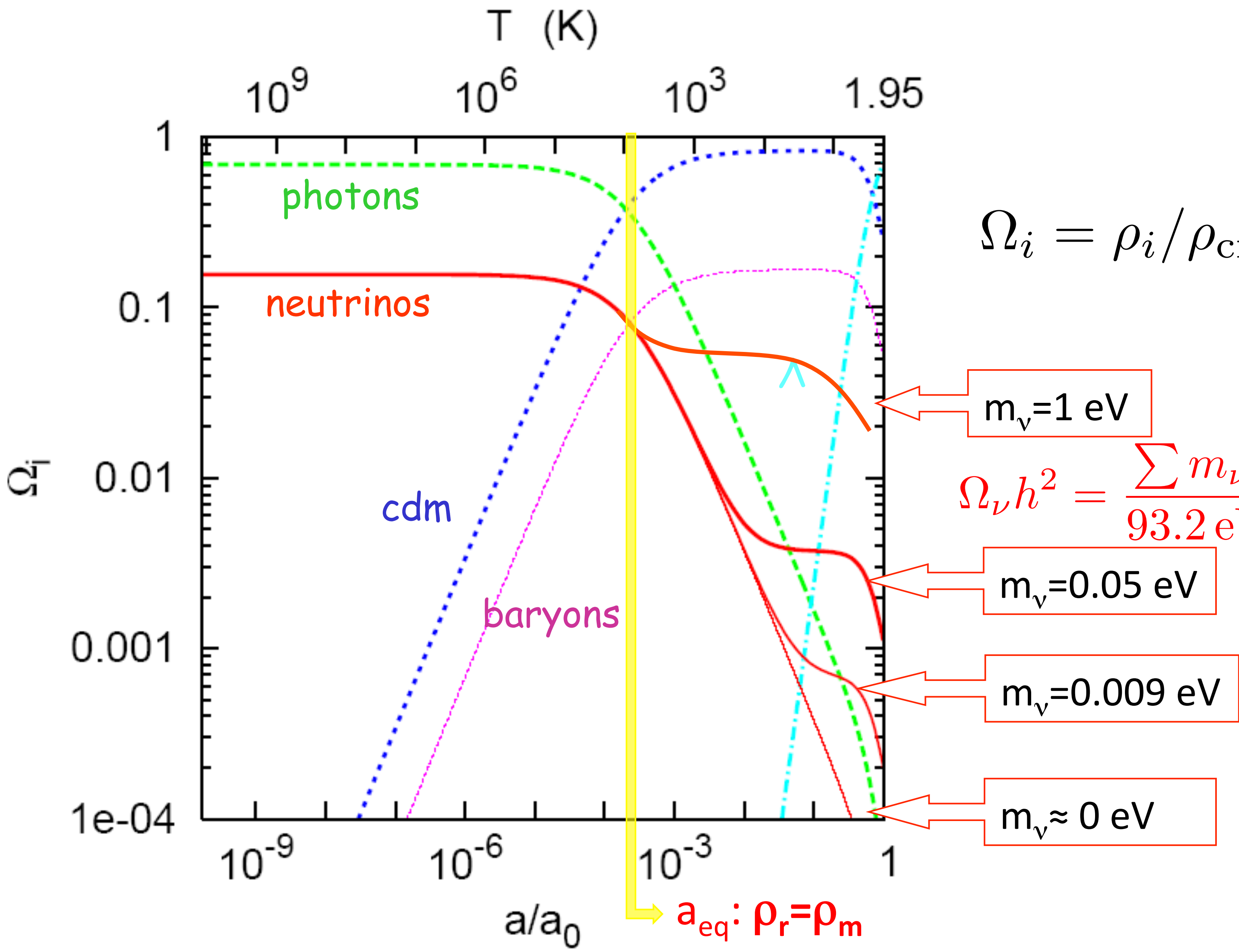
Contribution to the energy density of the Universe

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

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

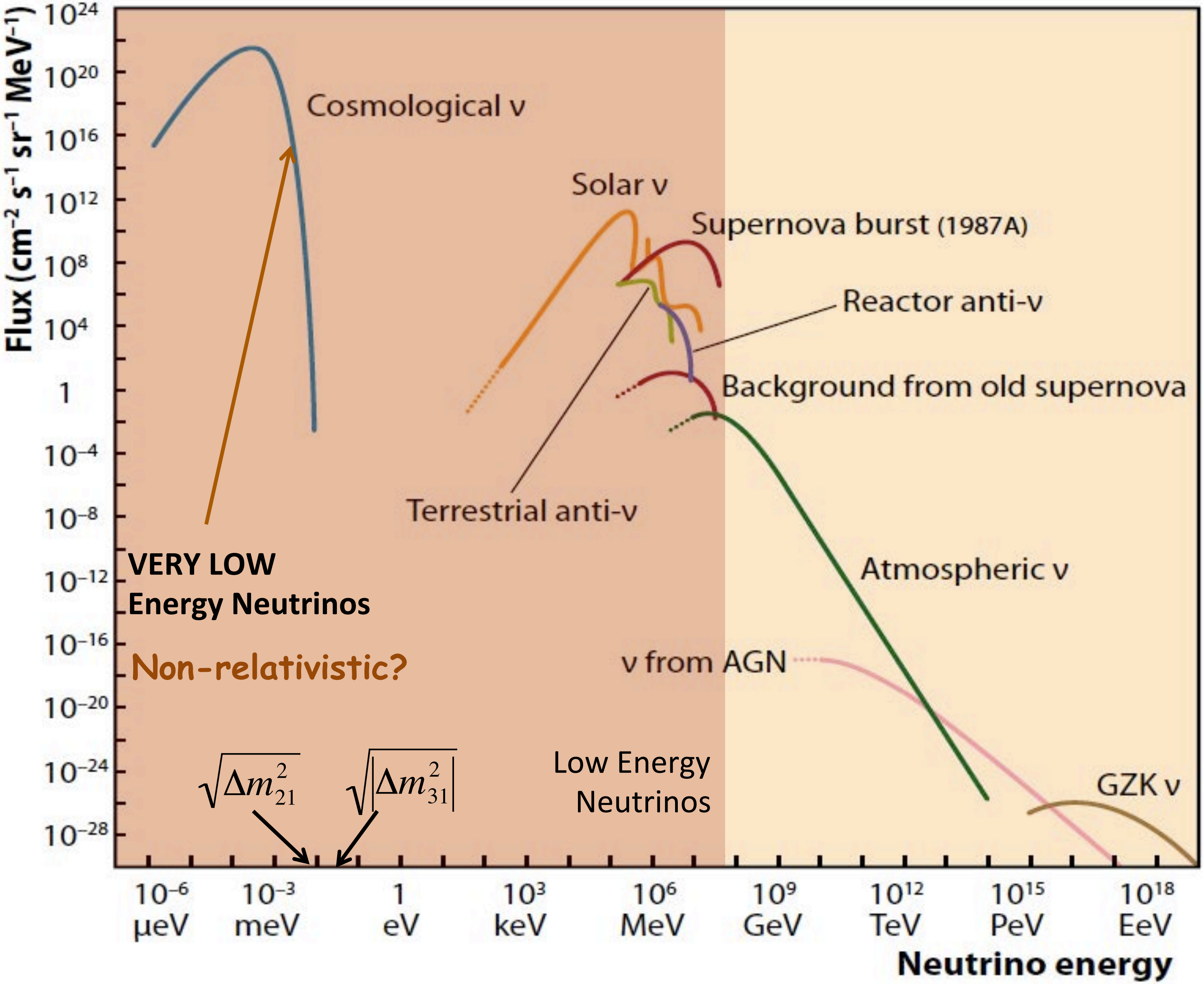
$m_\nu \gg T$

Evolution of the background densities: 1 MeV → now



$$\Omega_i = \rho_i / \rho_{\rm crit}$$

$$\Omega_\nu h^2 = \frac{\sum m_{\nu_i}}{93.2\,\mathrm{eV}}$$



Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
10^{24}
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1
10^{-4}
10^{-8}
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10^{-20}
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10^{-28}
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
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VERY LOW
Energy Neutrinos
Non-relativistic?
$\sqrt{\Delta m^2_{21}}$
$\sqrt{|\Delta m^2_{31}|}$
Low Energy
Neutrinos
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 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

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

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

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

# 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

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

Effective number of relativistic neutrino species

Traditional parametrization of ρ stored in relativistic particles

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

- standard neutrinos only: $N_{\rm eff} \simeq 3$ (3.045)

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

- $N_{\rm eff} > 3$ (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,…)

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 $m_\nu = 1$ eV

End of 1st lecture