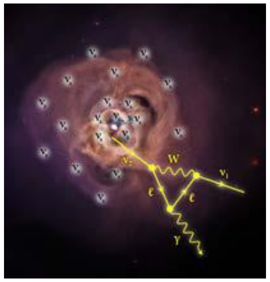
Neutrino Astrophysics I

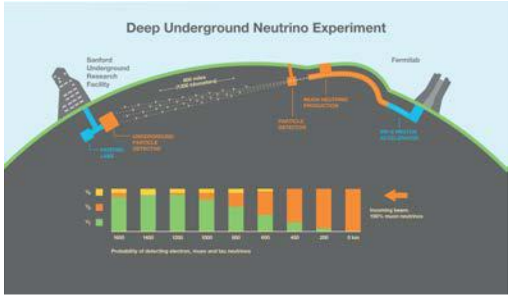
Neutrino Physics, Entropy, Gravitation: The early universe, nucleosynthesis, the CνB

CMB: e.g., Simons Observatory

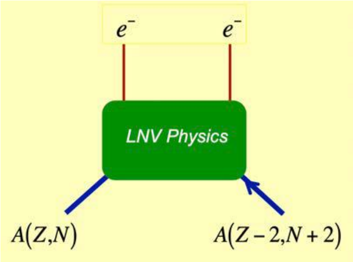
30m telescope/ NAOJ



X-Ray Astronomy
Image credit: Science/Abazajian



Long Baseline Oscillation experiments, e.g., DUNE, https://www.dunescience.org/



Lepton Number Violation:
$0\nu\beta\beta$
Lepton degeneracy in compact objects

N3AS Summer School in Multi-Messenger Astrophysics
July 22 and 23, 2023

George M. Fuller
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University of California, San Diego

Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

Weak Nuclear Force

Much about this aspect of nature remains mysterious. Consequently, it is the subject of frontier research in elementary particle physics, nuclear physics, and astrophysics.

Despite its well deserved moniker, “weak”, this force is the origin of all of humanity’s energy sources (fossil fuels, solar, nuclear fission & fusion), save one (tidal).

An insidious conspiracy of this weak nuclear force and an even weaker force, gravitation,
sets the conditions in the early universe,
murders massive stars by causing their collapse and explosion,
but brings about the creation of the elements in both of these venues!

Astrophysical Neutrino *"Laboratories"*

Early Universe, Weak Decoupling/BBN

Gravitation dictates a **slow expansion**, allowing very weakly interacting particles to affect the physics. **Large entropy-per-baryon**, $S/k_{\mathrm{b}} \sim 10^{10}$, simplifying the nuclear physics. **Low lepton numbers**, implying very small $\nu - \bar{\nu}$ asymmetry.
n/p, deuterium (D), helium, N_{eff} sensitive to any BSM physics that alters the time/temperature/scale factor relationship.

very tightly constrained
by CMB (soon Stage-4) observables and 30m-class telescope-determined D/H.

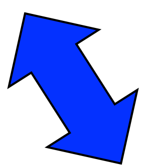
Stellar Collapse, supernovae, binary compact object mergers

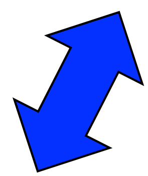
Weak interaction dictates all aspects of evolution. Very **large** electron lepton number, so evolution is **exquisitely sensitive to lepton number violation**.

Low-to-high entropy, $S/k_{\mathrm{b}} \sim 1$ to ~ 100; primary site for intermediate and heavy nucleus nucleosynthesis; many aspects can be sensitive to neutrino flavor transformation and BSM physics.

Manufactures neutron stars and black holes.

Not well constrained





$$\nu_e + \mathrm{n} \rightleftharpoons \mathrm{p} + e^-$$

$$\bar{\nu}_e + \mathrm{p} \rightleftharpoons \mathrm{n} + e^+$$

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

Gravitation is really, really feeble compared to the strong, electromagnetic, and even the weak interaction

$$\Gamma = (n\,v) \cdot \sigma$$

$$\text{scattering rate } (\mathrm{s}^{-1}) = \text{flux } (\mathrm{cm}^{-2}\,\mathrm{s}^{-1}) \cdot \text{cross section } (\mathrm{cm}^2)$$

$$\sigma_{\text{strong}} = \text{geometric area of particle}$$

$$\sigma_{\text{elec}} \approx \sigma_{\mathrm{T}} \approx 6.65246 \times 10^{-25}\,\mathrm{cm}^2 \approx 10^{-24}\,\mathrm{cm}^2 = 1\,\mathrm{barn}$$

$$\sigma_{\text{weak}} \sim G_{\mathrm{F}}^2\,E_\nu^2 \approx 10^{-44}\,\mathrm{cm}^2 = 10^{-20}\,\mathrm{barn}$$

$$\sigma_{\text{grav}} \sim G^2\,m_{\text{nuc}}^2 \sim 10^{-80}\,\mathrm{barn}$$

Dimensionless comparison of the forces

$$\alpha_{\text{strong}} = 1$$

$$\alpha_{\text{weak}} = G_{\mathrm{F}}\,m_{\mathrm{e}}^2 \approx 3.045 \times 10^{-12}$$

$$\alpha_{\text{elec}} = \frac{1}{4\pi\,\epsilon_0} \cdot \frac{e^2}{\hbar c} \approx \frac{1}{137.036} \approx 7.297 \times 10^{-3}$$

$$\alpha_{\text{grav}} = G\,m_{\mathrm{e}}^2 = \left(\frac{m_{\mathrm{e}}}{m_{\mathrm{pl}}}\right)^2 \approx 1.751 \times 10^{-45}$$

The elementary particles:

These particles are
the building blocks
of the ***Standard Model***.

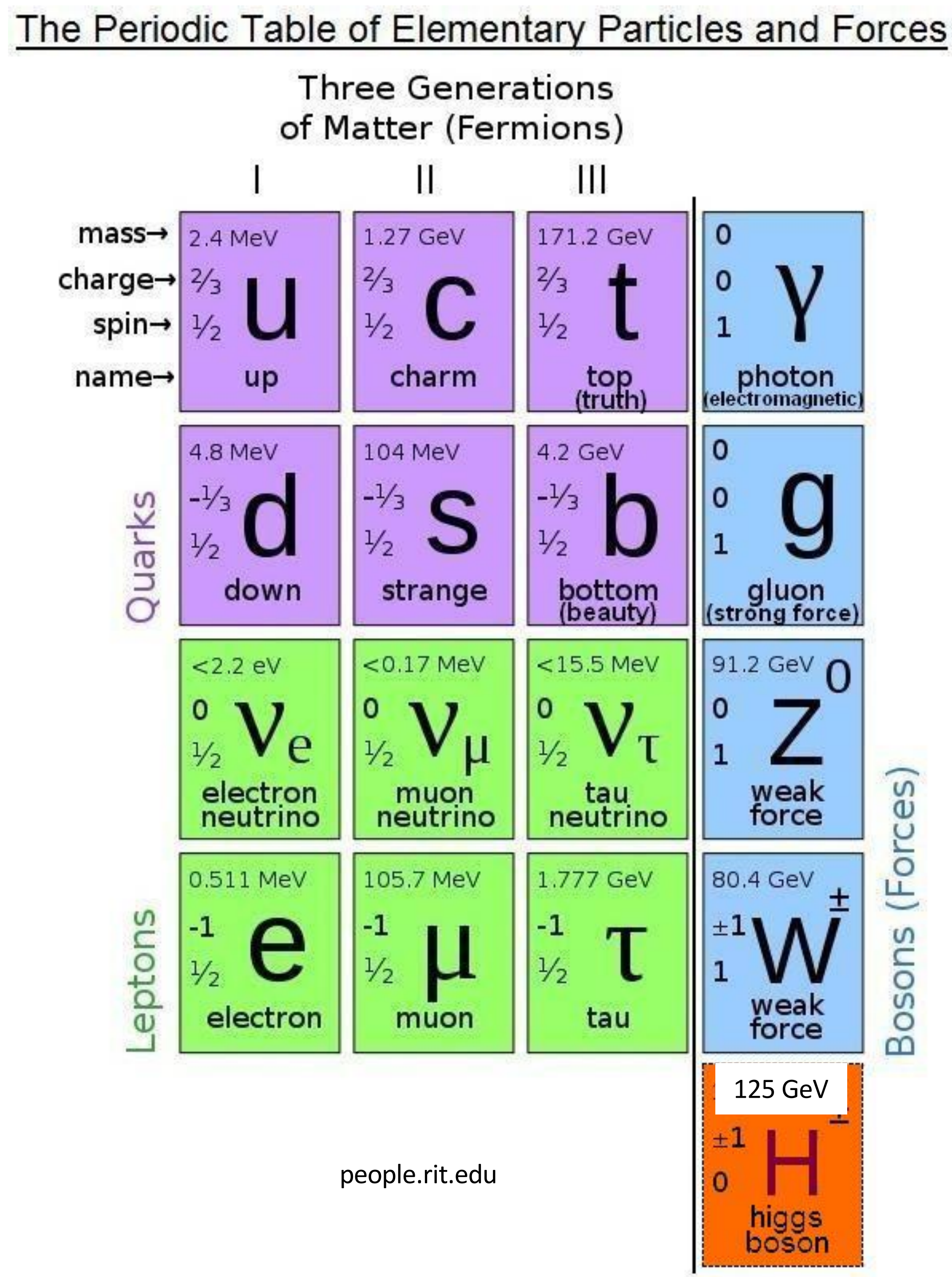
Neutrinos, like the charged leptons and quarks, are spin-1/2 but, unlike those particles, neutrinos have no electric charge.

Each particle has an antiparticle,
so there are six *known* neutrinos:

$$\underbrace{\nu_e, \bar{\nu}_e}_{\text{electron flavor}}, \underbrace{\nu_\mu, \bar{\nu}_\mu}_{\text{muon flavor}}, \underbrace{\nu_\tau, \bar{\nu}_\tau}_{\text{tau flavor}}$$

electron flavor **muon flavor** **tau flavor**

Fermions: *half-integral spin*
Bosons: *integral spin*



people.rit.edu

much remains mysterious about neutrinos and the weak interaction

- origin of neutrino mass (another Higgs? See-Saw? Heavy sterile states?)

- Majorana or Dirac?

- baryon/lepton numbers (related to neutrino mass physics, e.g., νMSM ?)

- Dark Matter/Dark Sector (Non-standard ν interactions? ν dark sector?)

- ν & other BSM physics may affect relic neutrinos/cosmology
  as well as compact object physics and nucleosynthesis

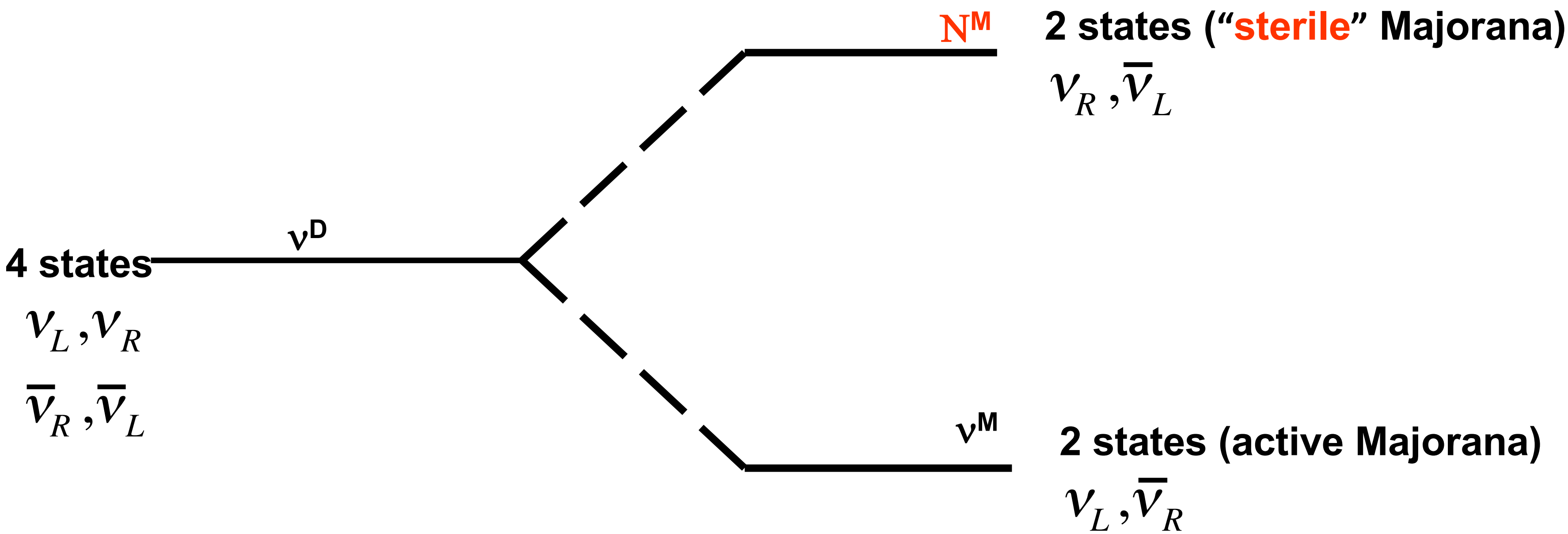
We have: mass-squared differences/mixing angles.

We need: absolute masses; mass-hierarchy (normal?); Majorana/Dirac; CP-violating phase(s); unknown unknowns!

Why Are Neutrinos so light? – See-Saw?

Dirac Neutrinos $\nu \neq \overline{\nu}$ $\nu + \overline{\nu} = 4$ states

Majorana Neutrinos $\nu = \overline{\nu}$ $\nu + \overline{\nu} = 2$ states



See-Saw Relation for the Product of Neutrino Masses: $(m_N)(m_\nu) \sim (\text{Really Big Mass Scale})^2$

↑ Unification Scale?

Gell-Mann, Ramond, Slansky; Yanagida; Mohapatra & Senjanovic

(after a slide by Boris Kayser)

Neutrino Properties

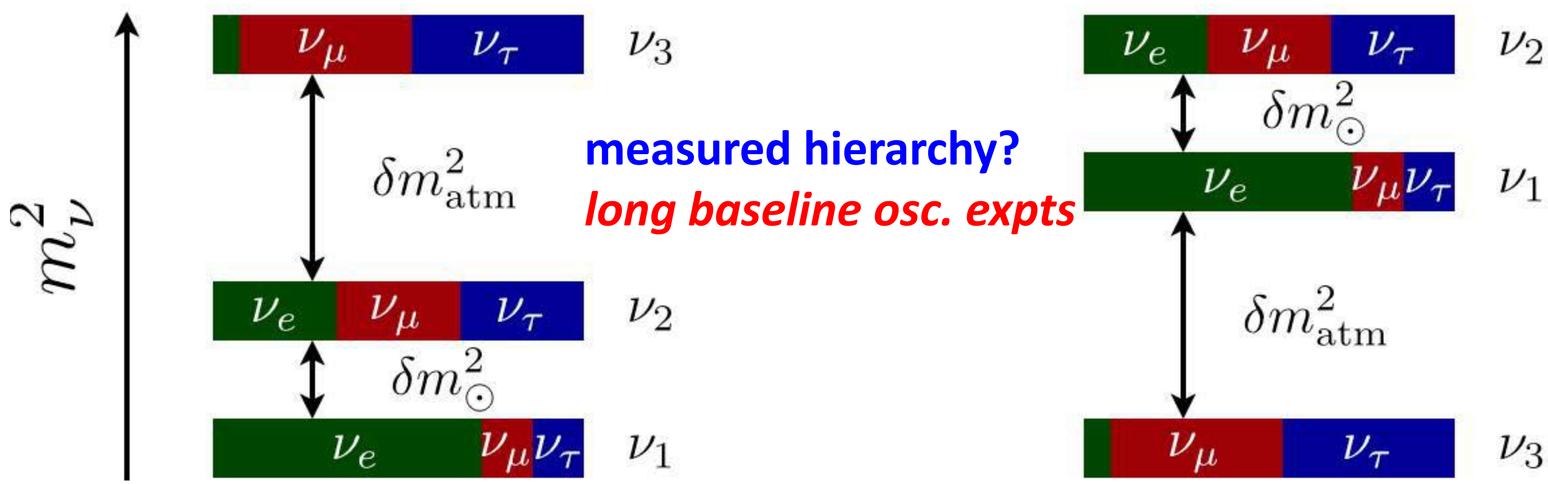
we know the ***mass-squared*** differences:

$$\begin{cases} \delta m_\odot^2 \approx 7.6 \times 10^{-5}\,\mathrm{eV}^2 \\ \delta m_{\mathrm{atm}}^2 \approx 2.4 \times 10^{-3}\,\mathrm{eV}^2 \end{cases}$$

$$e.g., \quad \delta m_{21}^2 \equiv m_2^2 - m_1^2$$

we ***do not*** know the ***absolute masses***,
but likely we soon will know the ***mass hierarchy***:

normal mass hierarchy | inverted mass hierarchy



measured hierarchy?
long baseline osc. expts

A key development that will ***increase*** the discovery potential of the CMB-Neutrino connection and
and compact object/nucleosynthesis/neutrino signal physics:

DUNE/long baseline experiments:

Will pin down the neutrino mass hierarchy at $5\,\sigma$ within 6 years
Good hints within a few years(?)

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = U_m \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

Pontecorvo-Maki-Nakagawa-Sakata matrix

$$U_m = U_{23}\, U_{13}\, U_{12}$$

If Neutrinos are Majorana . . .

$$M = \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_1/2} & 0 \\ 0 & 0 & e^{-i\alpha_2/2} \end{bmatrix}$$

unknown:
Majorana phases α_1, α_2

Hints in $0\nu\beta\beta$ or supernovae?

$$U_{23} \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

$$U_{13} \equiv \begin{pmatrix} \cos\theta_{13} & 0 & e^{i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}$$

$$U_{12} \equiv \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

4 parameters

$$\theta_{12}, \theta_{23}, \theta_{13}, \delta$$

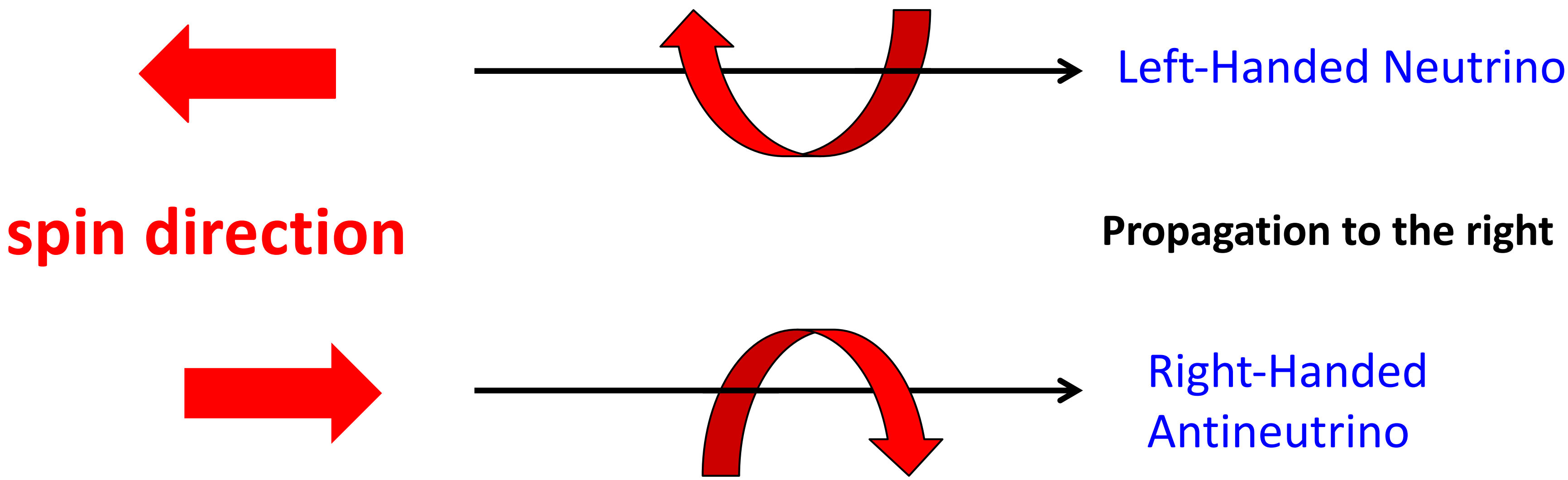
$$\theta_{12} \approx 0.59^{+0.02}_{-0.015}$$

$$\theta_{23} \approx 0.785^{+0.124}_{-0.124} \approx \frac{\pi}{4}$$

$$\theta_{13} \approx 0.154^{+0.065}_{-0.065}$$

$$\delta = CP \text{ violating phase } = ?$$

neutrino “spin”

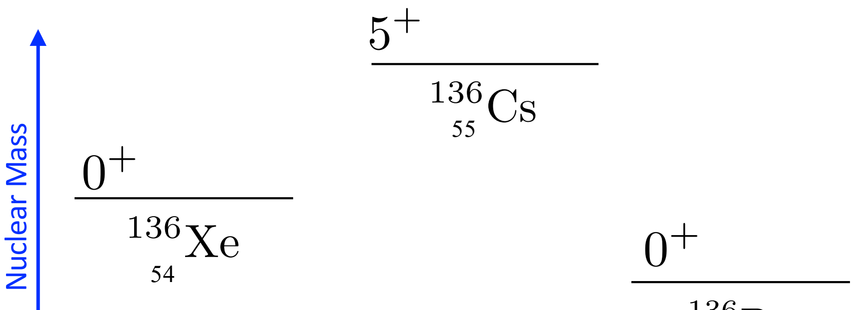


neutrino spin flip, *i.e.*, converting a left-handed neutrino to a right-handed antineutrino is always $\propto m_\nu/E_\nu$

The surprise is that it can be done coherently and possibly collectively in environments with anisotropic neutrino distributions

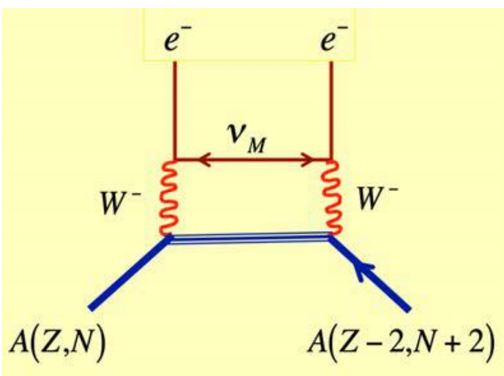
neutrinoless double beta decay (0νββ)

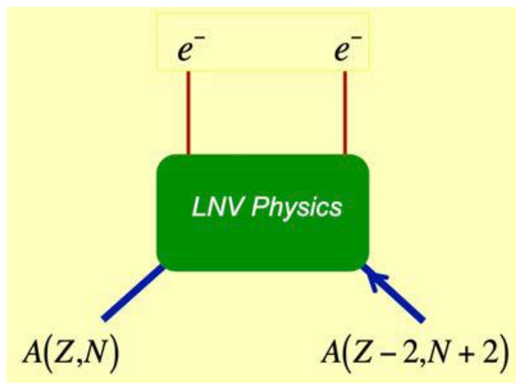
an observation of 0νββ implies *that* ***neutrinos are Majorana*** and ***lepton number is violated***



Two neutrons decay to two protons.
Example: $^{136}\mathrm{Xe} \rightarrow ^{136}\mathrm{Ba}$

Discovery of **Lepton Number Violation** (LNV)
would have profound implications
for particle physics and astrophysics





Neutrino mass-mediated spin flip

$0\nu\beta\beta$ decay rate:

$$\lambda = G^0(E,Z)\ |m_{\beta\beta}|^2 \cdot |M_{\mathrm{NUC}}|^2$$

with half-life $\tau_{1/2} = \ln 2/\lambda$

$$|m_{\beta\beta}| = \left| m_1\, c_{12}^2\, c_{13}^2 \;+\; m_2\, s_{12}^2\, c_{13}^2\, e^{2i\alpha} \;+\; m_3\, s_{13}^2\, e^{2i\beta} \right|$$

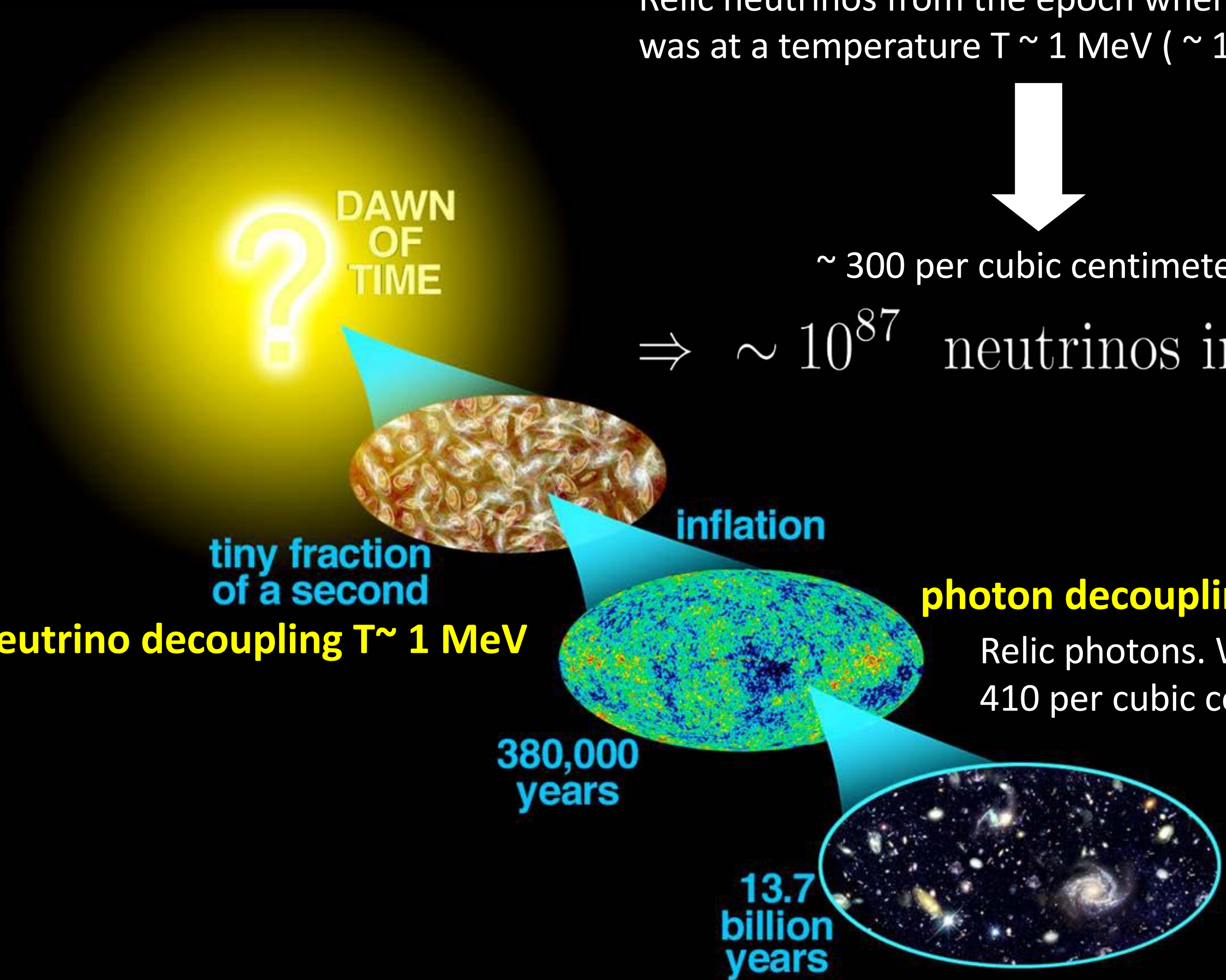
In addition to the conventional neutrino mass-mediated spin flip channel, **many BSM physics possibilities could also enable 0νββ.**
The alternative BSM scenarios include right-handed currents, heavy neutrino states, R-parity-violating incarnations of supersymmetry, etc.
But even if facilitated by these BSM channels, an observation of 0νββ implies that neutrinos are Majorana and lepton number is violated.
Observing 0νββ in different nuclei could help ferret out what standard or BSM channel is involved, and this is why the US DOE is backing several different detector ideas.

The Early Universe

Relic neutrinos from the epoch when the universe was at a temperature T ~ 1 MeV (~ 10^{10} K)

~ 300 per cubic centimeter

$$\Rightarrow \ \sim 10^{87} \ \text{neutrinos in universe}$$



neutrino decoupling T~ 1 MeV

photon decoupling T~ 0. 2 eV

Relic photons. We measure 410 per cubic centimeter

vacuum+matter dominated at current epoch

Gravitation is weak

Gravitation drives the expansion of the universe

Consequently, the expansion rate is *SLOW*, and this allows *very weakly interacting particles* to affect the physics of the early universe

The ***infinite raisin bread*** model of the universe . . .

Image: Pleasant Hill Grain

. . . as it bakes it expands uniformly everywhere

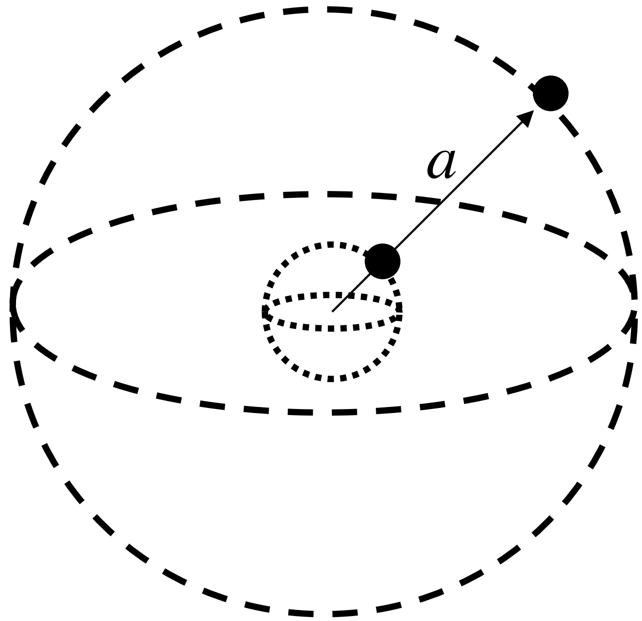
the expansion is slow because it is driven by gravitation, which is very weak, and it is uniform everywhere -- there is no center. This is not “an explosion into vacuum”.

Homogeneity and isotropy of the universe:
implies that *total energy* inside a co-moving spherical surface is constant with time.

total energy **= (kinetic energy of expansion) + (gravitational potential energy)**

mass-energy density = ρ

test mass = m



$$\approx \tfrac{1}{2} m \dot{a}^2$$

$$\approx -\frac{G\left[\frac{4}{3}\pi a^3 \rho\right] m}{a}$$

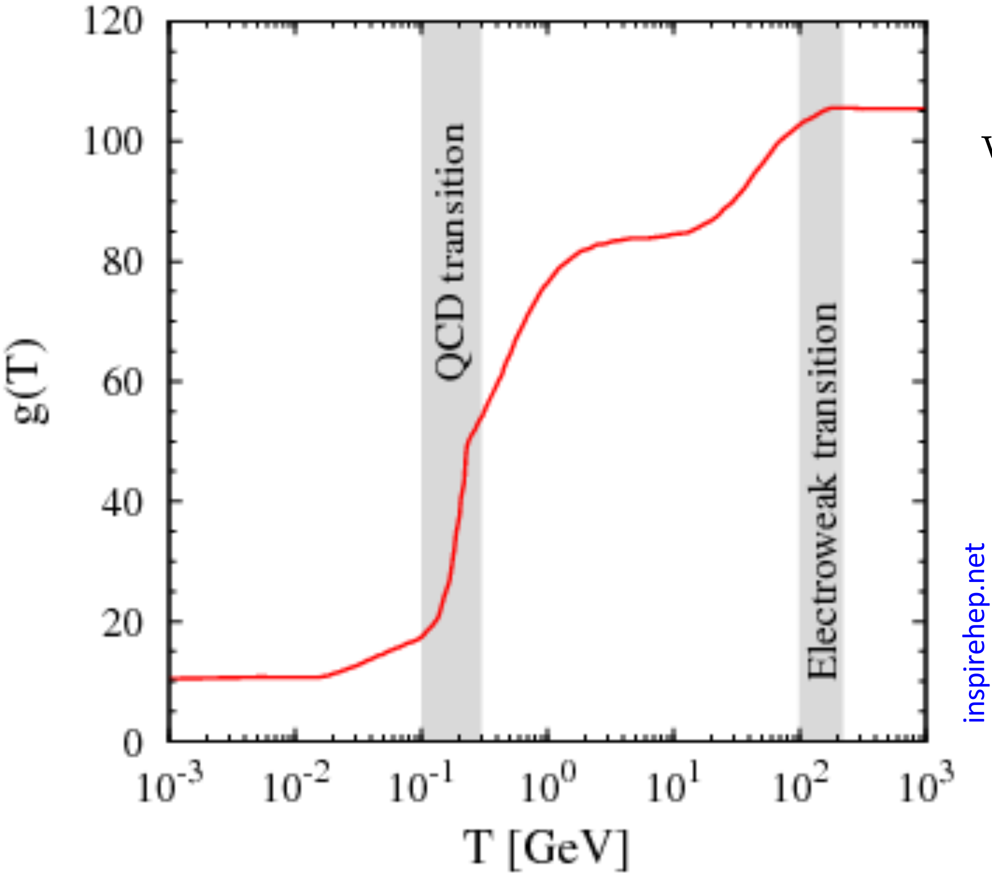
$$\dot{a}^2 + k = \frac{8}{3}\pi G \rho\, a^2$$

total energy > 0	**expand forever**	**k = -1**
total energy $= 0$ **for** $\rho = \rho_{crit}$		**k = 0**
total energy < 0	**re-collapse**	**k = +1**

$$\Omega = \rho/\rho_{crit} = \Omega_\gamma + \Omega_\nu + \underbrace{\Omega_{\text{baryon}} + \Omega_{\text{dark matter}}}_{\approx 0.27} + \Omega_{\text{vacuum}} \approx 1 \quad \textbf{(k=0)}$$

Depending on temperature, particles could be in thermal equilibrium in the "*soup*" of the early universe.

Scienceblogs http://www.mbio.ncsu.edu/jwb/soup.html cartoon by James Bullock particle i, j, contribution to energy density $\rho_{i,j} = \frac{g}{2\,\pi^2} \cdot \int_{m_{i,j}}^{\infty} \frac{E^2\left(E^2 - m_{i,j}^2\right)^{1/2} dE}{\exp\left[E/T - \eta_{i,j}\right] \pm 1}$



where degeneracy parameter is $\eta_{i,j} \equiv \frac{\mu_{i,j}}{T}$

where $g = \sum_i g_i^{\mathrm{b}} \left(\frac{T_i}{T}\right)^4 + \frac{7}{8} \sum_j g_j^{\mathrm{f}} \left(\frac{T_j}{T}\right)^4$

in the ultra relativistic limit, $\mu_{i,j} \to 0$ and $m_{i,j}/T \to 0$, we have $\rho = g\,\frac{\pi^2}{30}\,T^4$

With expansion, temperature T falls below rest mass $m_{i,j}$, and particle i, j will no longer contribute significantly to the statistical weight g.

Equation of state and entropy for particles with relativistic kinematics

energy density $$\rho = g\,\frac{\pi^2}{30}\,T^4 \qquad \text{where} \quad g = \sum_i g_i^{\mathrm{b}} \left(\frac{T_i}{T}\right)^4 + \frac{7}{8} \sum_j g_j^{\mathrm{f}} \left(\frac{T_j}{T}\right)^4$$

$$\text{example}: T = 1\,\mathrm{MeV} \;\Rightarrow\; g = 2_\gamma + \frac{7}{8}\left(2_{e^-} + 2_{e^+} + [2+2+2]_{6\ \text{neutrinos}}\right) = 10.75$$

$$\text{entropy per unit proper volume} \quad S = \frac{4}{3}\cdot\frac{\pi^2}{30}\,g_s\,T^3 = \frac{2\,\pi^2}{45}\,g_s\,T^3$$

$$\text{where} \quad g = \sum_i g_{\mathrm{s}\,i}^{\mathrm{b}} \left(\frac{T_i}{T}\right)^3 + \frac{7}{8} \sum_j g_{\mathrm{s}\,j}^{\mathrm{f}} \left(\frac{T_j}{T}\right)^3$$

$$\text{entropy} - \text{per} - \text{baryon} \quad s = \frac{S}{n_{\mathrm{b}}}$$

$$\text{baryon} - \text{to} - \text{photon ratio} \quad \eta \equiv \frac{n_{\mathrm{b}}}{n_\gamma} \approx 6.11 \times 10^{-10}$$

relation between entropy-per-baryon, a co-moving invariant at low T, and the baryon-to-photon ratio (not invariant)

$$s = \frac{\pi^4}{45\,\zeta(3)} \cdot g_s \cdot \frac{1}{\eta} \approx \left[5.89 \times 10^9\ k_{\mathrm{b}}\ \text{per baryon}\right] \left(\frac{g_s}{2}\right) \left(\frac{6.11 \times 10^{-11}}{\eta}\right)$$

The temperature in the weak decoupling/BBN epoch is

$$T \sim 1\,\mathrm{MeV}$$

The time-temperature relationship there is roughly

$$t \sim \frac{1\ \mathrm{second}}{\left(T/\mathrm{MeV}\right)^2}$$

baryon number of universe → $$\eta \equiv \frac{n_{\mathrm{b}} - n_{\bar{\mathrm{b}}}}{n_\gamma}$$

From CMB acoustic peaks, and/or observationally-inferred primordial D/H:

$$\eta = 6.11 \times 10^{-10}$$

three lepton numbers →

$$\begin{cases} L_{\nu_e} \approx \dfrac{n_{\nu_e} - n_{\bar{\nu}_e}}{n_\gamma} \\[2ex] L_{\nu_\mu} = \dfrac{n_{\nu_\mu} - n_{\bar{\nu}_\mu}}{n_\gamma} \\[2ex] L_{\nu_\tau} = \dfrac{n_{\nu_\tau} - n_{\bar{\nu}_\tau}}{n_\gamma} \end{cases}$$

From observationally-inferred ^{4}He and large scale structure and using *collective (synchronized) active-active neutrino oscillations* (Abazajian, Beacom, Bell 03; Dolgov et al. 03):

$$|L_{\nu_{\mu,\tau}}| \sim L_{\nu_e} < 0.15$$

Conditions in the universe when it is $\sim 1\,\mathrm{s}$ in age

Temperature $T \sim 1\,\mathrm{MeV}$, a thousand times the temperature at the center of the sun.

We will discuss a temperature range $10\,\mathrm{MeV} > T > 10\,\mathrm{keV}$, a range which subsumes the weak decoupling/BBN epoch.

Baryon rest mass density $\rho_b \sim 10^{-3}\,\mathrm{g\,cm^{-3}}$, roughly the density of air.

But, effective inertia of the intense radiation field at this epoch
$\Rightarrow \quad \rho_{\mathrm{rad}} \sim 10^4\,\mathrm{g\,cm^{-3}}$

Dynamic viscosity of this fluid ranges from $\sim 10^{21}\,\mathrm{MeV}^3$, roughly the same as the earth's mantle rock (!!!), to near zero later as neutrinos decouple.

Why does this time in the early history of the universe hold promise to be a laboratory for probing *Beyond-Standard-Model* (BSM) physics?

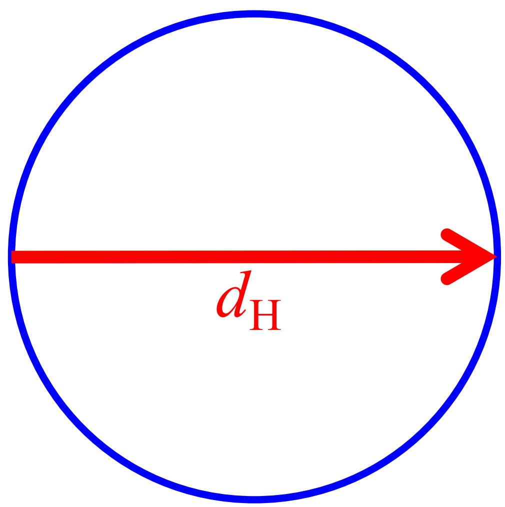
Mass-energy inside horizon: $M_\mathrm{H} = \frac{4}{3}\,\pi\left(\frac{d_\mathrm{H}}{2}\right)^3 \rho$

radiation-dominated case: $M_\mathrm{H} = \frac{4}{3}\,\pi\,(t^3)\left[g\,\frac{\pi^2}{30}\,T^4\right]$;

with $t \approx \frac{1}{2}\left(\frac{90}{8\,\pi^3}\right)^{\frac{1}{2}}\, g^{-\frac{1}{2}}\,\frac{m_\mathrm{pl}}{T^2}$, implying

$\Rightarrow\;\; M_\mathrm{H} \approx \left(\frac{45}{2^{10}\,\pi^3}\right)^{\frac{1}{2}} g^{-\frac{1}{2}}\,\frac{m_\mathrm{pl}^3}{T^2} \;\approx 2\times 10^4\,\mathrm{M}_\odot \left[\frac{10.75}{g}\right]^{\frac{1}{2}} \left[\frac{\mathrm{MeV}}{T}\right]^2.$

radiation-dominated horizon length: $d_\mathrm{H} \approx \left(\frac{90}{8\,\pi^3}\right)^{\frac{1}{2}}\, g^{-\frac{1}{2}}\,\frac{m_\mathrm{pl}}{T^2} \approx 4.43\times 10^{10}\,\mathrm{cm}\left[\frac{10.75}{g}\right]^{\frac{1}{2}} \left[\frac{\mathrm{MeV}}{T}\right]^2$



some significant events/epochs in the early universe

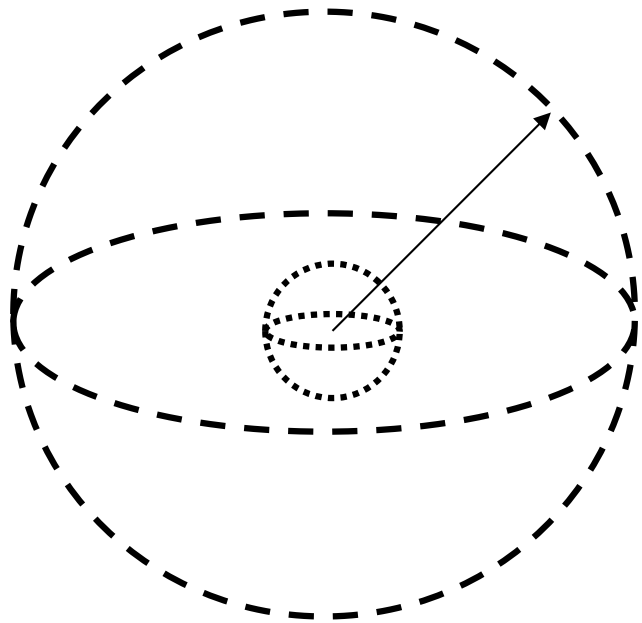
Epoch	T	g_{eff}	Horizon Length	Mass-Energy (solar masses)	Baryon Mass (solar masses)
Electroweak phase transition	100 GeV	~100	~ 1 cm	~ 10^{-6} (~ earth mass)	~ 10^{-18}
QCD	100 MeV	51 - 62	20 km	~ 1	~ 10^{-9}
weak decoupling	2 MeV	10.75	~ 10^{10} cm	~ 10^{4}	~ 10^{-3}
weak freeze out	0.7 MeV	10.75	~ 10^{11} cm	~ 10^{5}	~ 10^{-2}
BBN	100 keV	10.75	~ 10^{13} cm (~ 1 A.U.)	~ 10^{6}	~ 1
e^-/e^+ annihilation	~ 20 keV	3.36	~ 10^{14} cm	~ 10^{8}	~ 100
photon decoupling	0. 2 eV	-	~ 350 kpc	~ 10^{18} dark matter	~ 10^{17}

$$1 \text{ solar mass } \approx 2\times10^{33} \text{ g } \approx 10^{60} \text{ MeV}$$

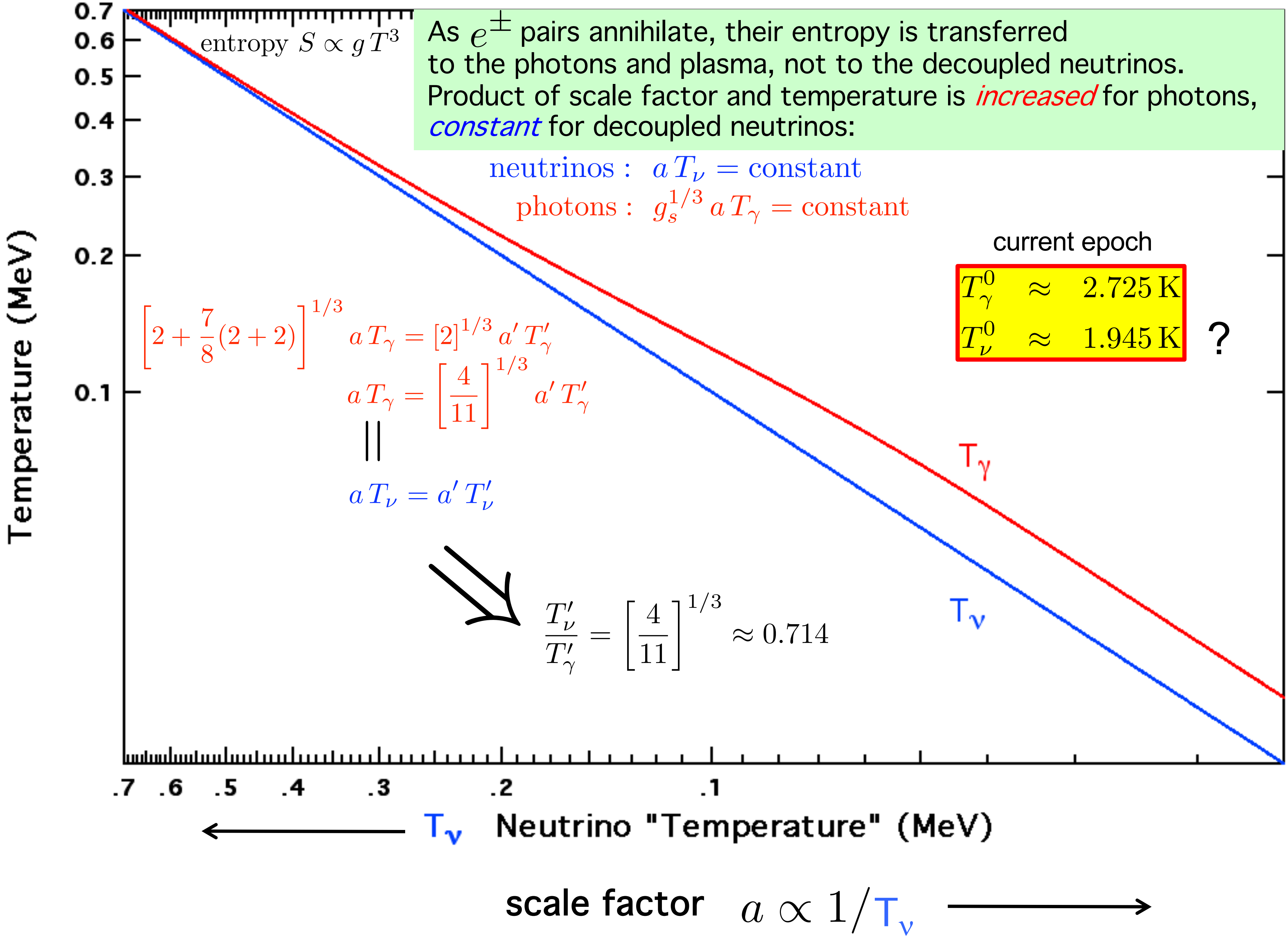
Symmetry is (nearly) everything in General Relativity

homogeneity and *isotropy* of this FLRW spacetime dictates that there be ***no spacelike heat flow*** or non-uniform heat sources: evolution is ***adiabatic***

entropy in a co-moving volume is conserved*



***Symmetry does not preclude *timelike* heat flows, e.g., from decaying particles *or* from non-equilibrium processes like decoupling ν's scattering on e^-/e^+**



As $e^{\pm}$ pairs annihilate, their entropy is transferred to the photons and plasma, not to the decoupled neutrinos. Product of scale factor and temperature is *increased* for photons, *constant* for decoupled neutrinos:
entropy $S \propto g\,T^3$
neutrinos : $a\,T_\nu = \text{constant}$
photons : $g_s^{1/3}\,a\,T_\gamma = \text{constant}$
$\left[2+\frac{7}{8}(2+2)\right]^{1/3} a\,T_\gamma = [2]^{1/3}\,a'\,T'_\gamma$
$a\,T_\gamma = \left[\frac{4}{11}\right]^{1/3} a'\,T'_\gamma$
$||$
$a\,T_\nu = a'\,T'_\nu$
$\frac{T'_\nu}{T'_\gamma} = \left[\frac{4}{11}\right]^{1/3} \approx 0.714$
current epoch
$T^0_\gamma \approx 2.725\,\mathrm{K}$
$T^0_\nu \approx 1.945\,\mathrm{K}$
?
T_γ
T_ν
Temperature (MeV)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
.7
.6
.5
.4
.3
.2
.1
T_ν Neutrino "Temperature" (MeV)
scale factor $a \propto 1/T_\nu$

Is Co-Moving Entropy *always* constant?

What happens when particles have dropped out of equilibrium, and then decay into particles *that are coupled, that do interact*?

This results in entropy generation.

If these decoupled particles are distributed homogeneously and isotropically, then the decay-generated entropy represents a *timelike* heat flow. This is allowed by symmetry!

There could be (*timelike*) *sources* of entropy:

These must be uniform, homogeneous and isotropic

Example-1: out-of-equilibrium processes

e.g., neutrino decoupling

Example-2: particle decay where the particles are (reasonably) homogenously distributed on a spacelike hypersurface t=constant

e.g., inflaton decay

Weak Decoupling, where neutrinos cease to scatter frequently enough to maintain thermal equilibrium with the electron/positron/photon plasma, and **Weak Freeze Out**, where weak interactions with nucleons are not fast enough to maintain chemical equilibrium,
occur ***concurrently*** over a protracted time duration,
~ 100 Hubble times!

This is in stark contrast with photon (CMB) decoupling which occurs abruptly, in a small fraction of a Hubble time, Driven by the (exponential) process of the formation of atomic bound states for the electrons at temperature scale T ~ 0.2 eV

HIGH ENTROPY

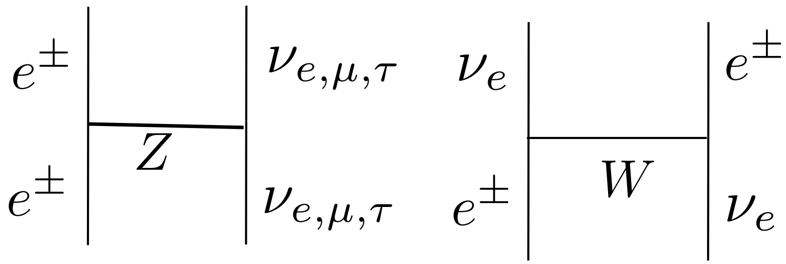
Radiation Dominated!

The entropy is high, $s \sim 10^{10}$ units of Boltzmann's constant per baryon, and that means $\sim 10^{10}$ photons per baryon, and $\sim 10^{10}$ neutrinos per baryon!

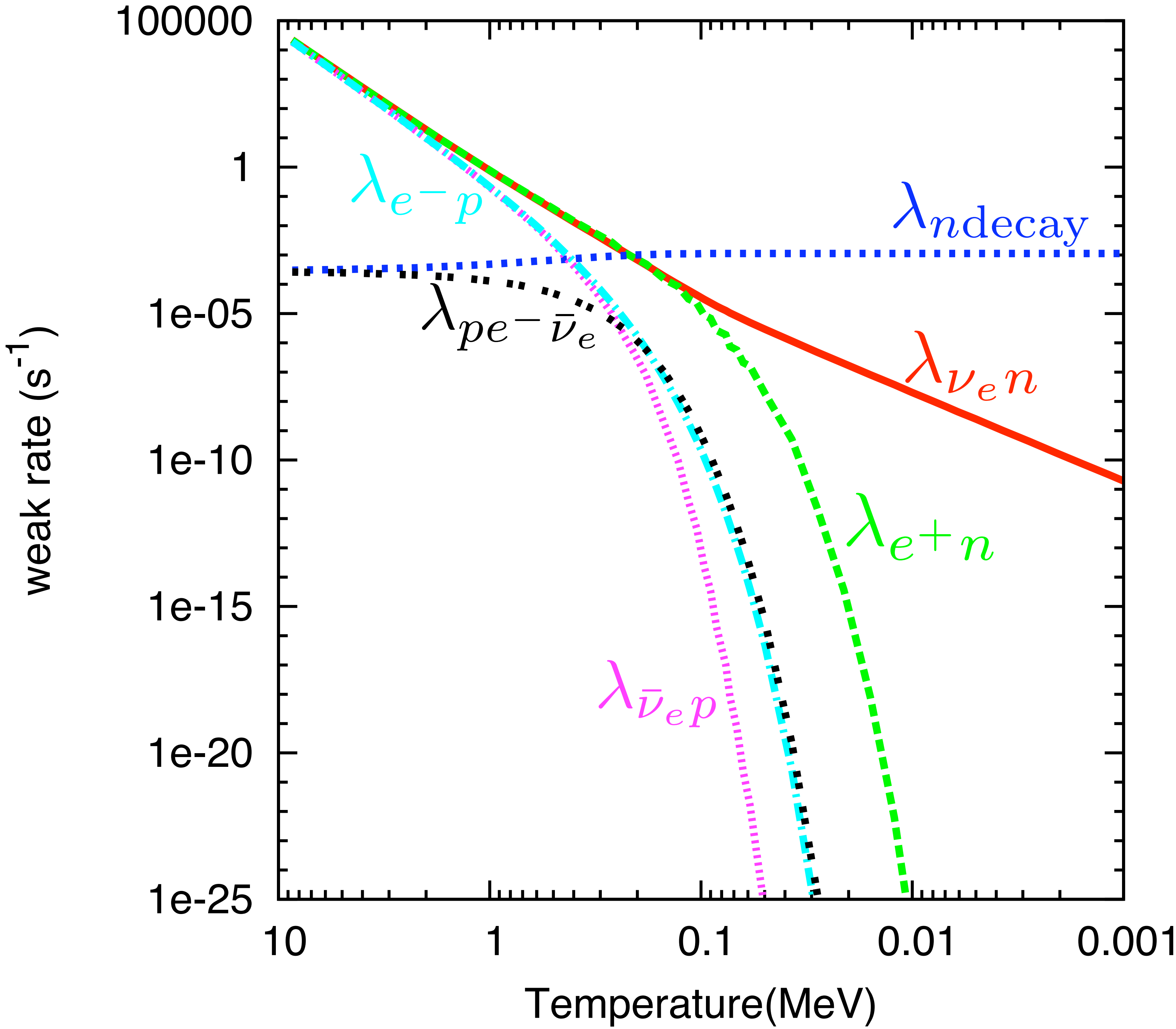
Even down to temperatures $\sim 10\,\mathrm{keV}$ there will be plenty of photons on the tail of the Planck distribution with enough energy to make $e^{\pm}$-pairs. We have a pair-dominated plasma all the way through weak decoupling/freeze-out and BBN!

. . . and lots of neutrinos per baryon, so even when the neutrinos have decoupled thermally, they still "have purchase" on neutron-to-proton inter-conversion!

neutral- and (*and for electron flavor*) **charged-current** neutrino scattering on electrons and positrons couples the neutrinos to the electron/positron/photon plasma



+ neutral current **neutrino-neutrino scattering**



100000
1
1e-05
1e-10
1e-15
1e-20
1e-25
weak rate (s^{-1})
10
1
0.1
0.01
0.001
Temperature(MeV)
λ_{e^-p}
$\lambda_{n\mathrm{decay}}$
$\lambda_{pe^-\bar{\nu}_e}$
$\lambda_{\nu_e n}$
λ_{e^+n}
$\lambda_{\bar{\nu}_e p}$

Follow the Boltzmann evolution of the (binned) energy distribution functions *f* of the of the active neutrinos

$$\frac{df(p,t)}{dt} = C[f(p,t)] \quad \Rightarrow \quad \left(\frac{\partial}{\partial t} - H\,p\,\frac{\partial}{\partial p}\right) f\,(p,t) = C\,(f)$$

$f\,(p,t)$ = occupation probabilities for a neutrino with momentum p at FLRW time coordinate t.

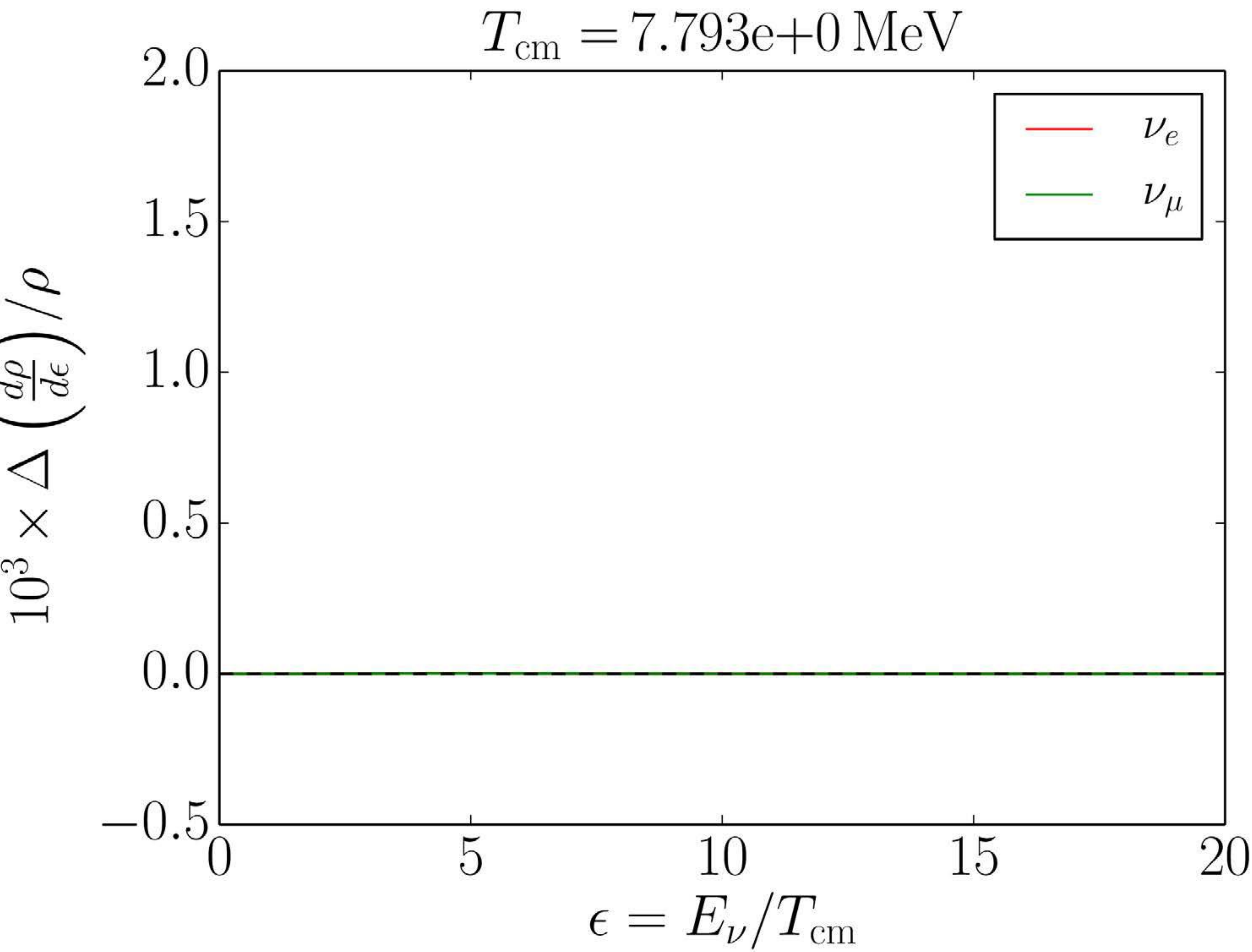
If all neutrino/antineutrino scattering rates fast compared to the expansion rate of the universe H, then we attain thermal, chemical equilibrium $\Rightarrow f\,(p,t) = \frac{1}{e^{p/T-\eta}+1}$

A. Dolgov, S. Hansen, D. V. Semikoz, NP B 503, 426 (1997) arXiv:9712199
S. Esposito et al. NP 590, 539 (2000), arXiv:0005973

"Neutrino energy transport in weak decoupling and big bang nucleosynthesis"
E. Grohs, G. M. Fuller, C. T. Kishimoto, M. W. Paris, A. Vlasenko arXiv:1512.02205

Plasma/QED corrections critical:

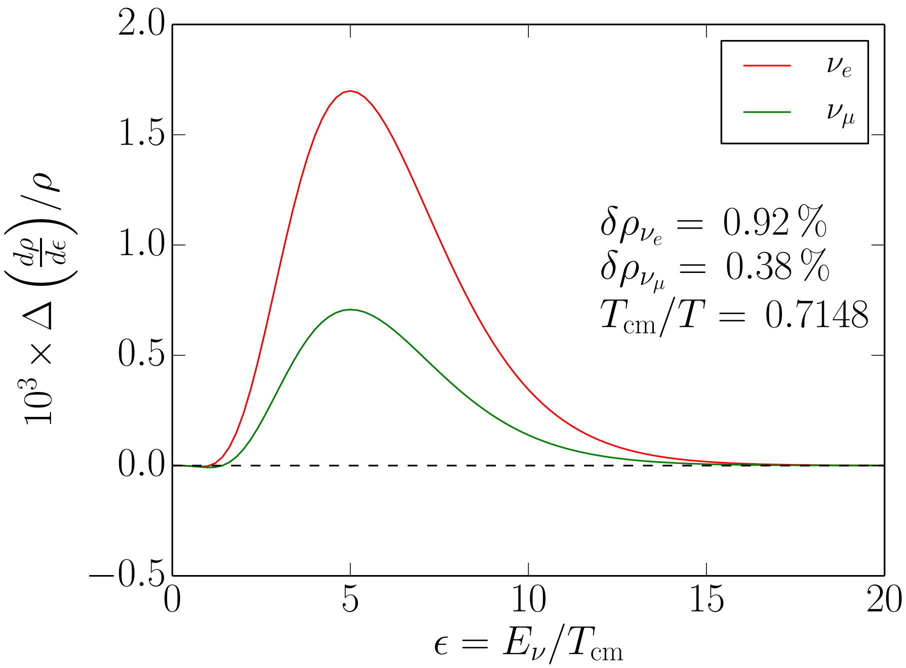
D. Dicus, E. W. Kolb et al, PRD 26, 2649 (1982)
S. Dodelson & M. S. Turner PRD 46, 3372 (1992)
R. Lopez & M. S. Turner, PRD 59, 103502 (1999)

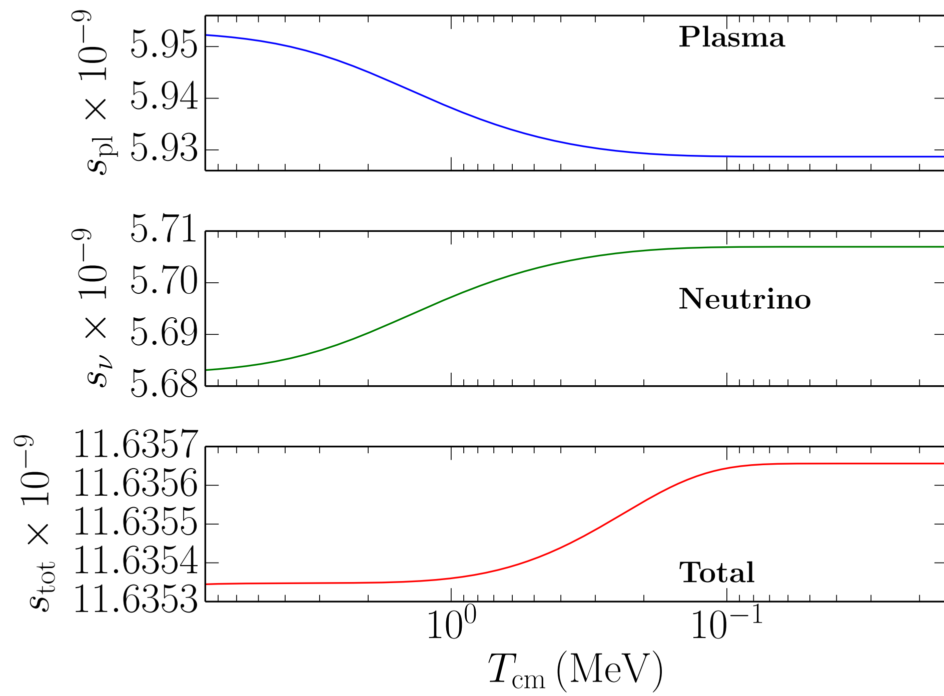


E. Grohs, G. M. Fuller, C. T. Kishimoto, M. W. Paris, A. Vlasenko arXiv:1512.02205

out-of-equilibrium neutrino scattering leads to ***neutrino spectral distortions*** and timelike ***entropy flow/generation***

$$\nu - \nu/e^{\pm} \text{ scattering}$$





"Neutrino energy transport in weak decoupling and big bang nucleosynthesis". **E.Grohs**, G. M. Fuller, C. T. Kishimoto, M. W. Paris, A. Vlasenko Phys. Rev. D **93**, 083522 (2016)

$N_{\rm eff}$

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

integrated history of the rates of these charged current processes and ***entropy flow*** determine n/p which is key to nucleosynthesis

$$Z\,p + N\,n \rightleftharpoons A\,(Z, N) + \gamma$$

D, ^{4}He