Neutrino Physics

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Lecture A:
Neutrino's history and lepton family

Lecture B:
Neutrino masses and flavor mixing

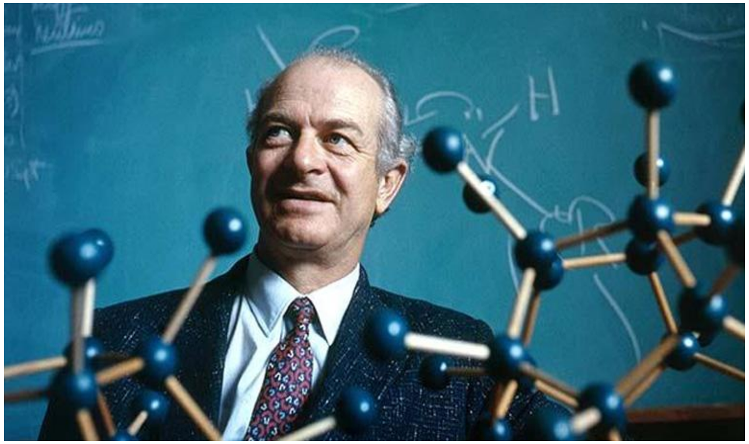
Lecture C:
Neutrino oscillation phenomenology

Lecture D:
Selected topics on cosmic neutrinos

@ Weihai High Energy Physics School, 2—10/8/2015

Lecture D

- ★ **Matter-antimatter asymmetry**
- ★ **Cosmic neutrino background**
- ★ **UHE cosmic neutrinos**



Linus Pauling:

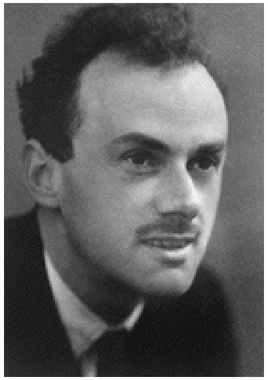
The best way to have a good idea is to have a lot of ideas.

Dirac's expectation

PAUL A. M. DIRAC

Theory of electrons and positrons

Nobel Lecture, December 12, 1933



If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods.

The puzzle

Why there isn't an anti-Universe as expected by Dirac?

$t = 10^{16}$ sec

$r = 10^{29}$ cm

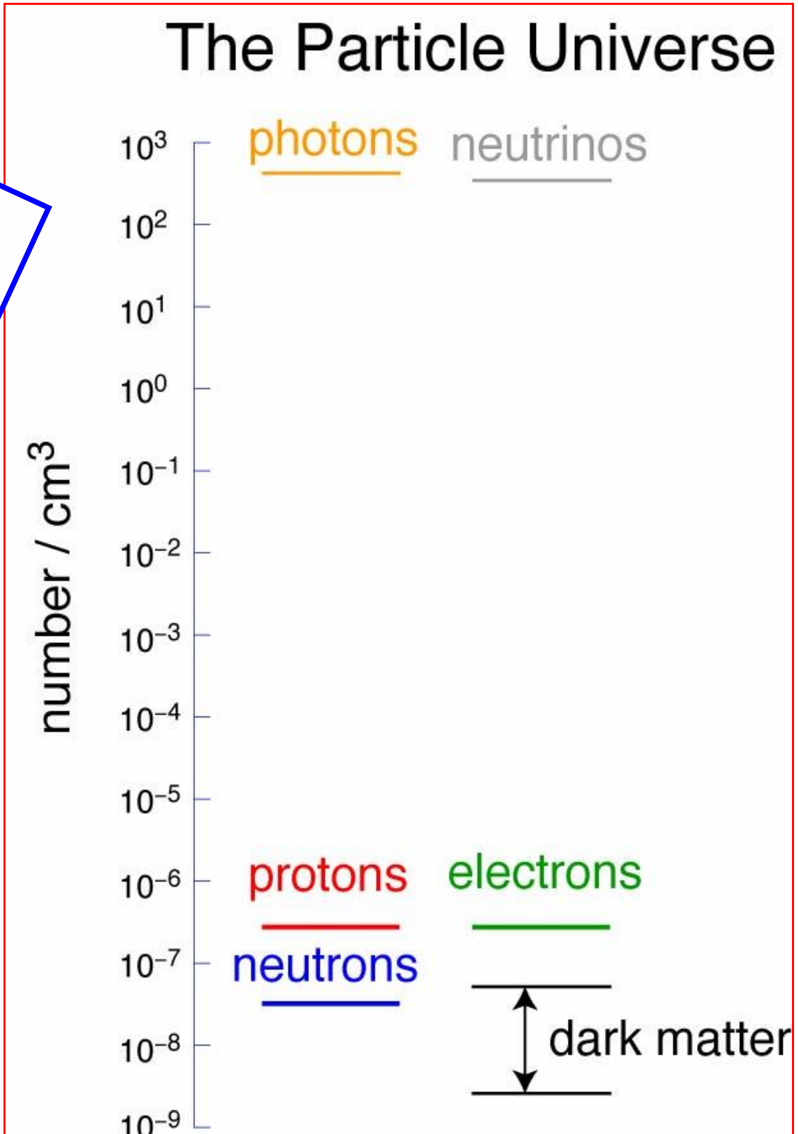
$T = 2.7$ K

$400\gamma / \text{cm}^3$

10^{80} p, n

0 $\bar{p}, \bar{n}$

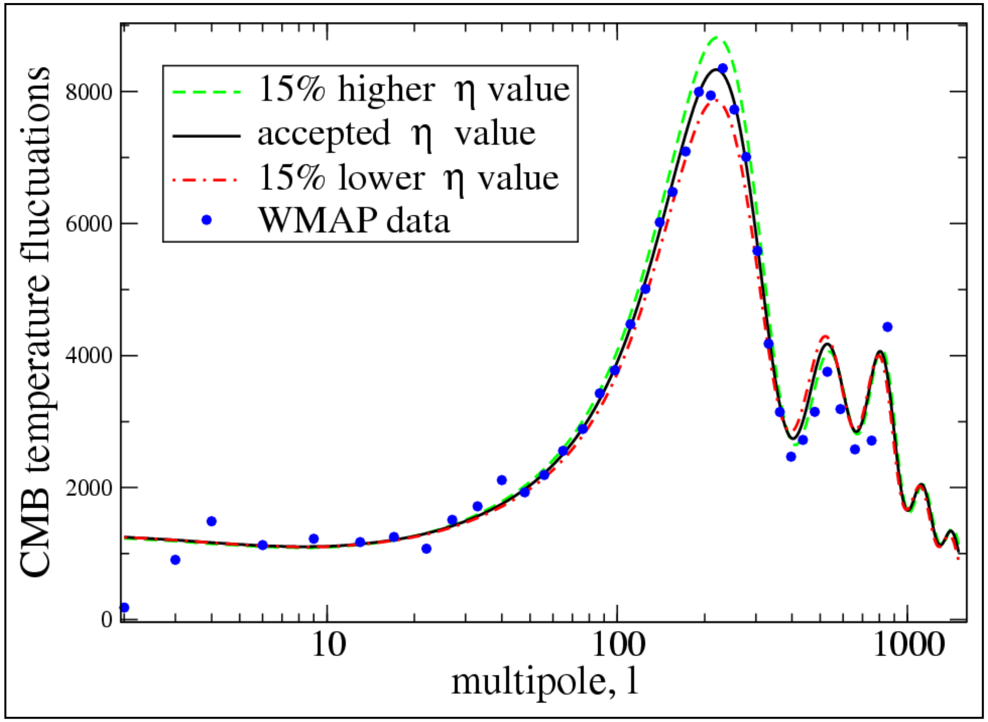
$\eta_B \equiv n_B/n_\gamma = (6.1 \pm 0.2) \times 10^{-10}$

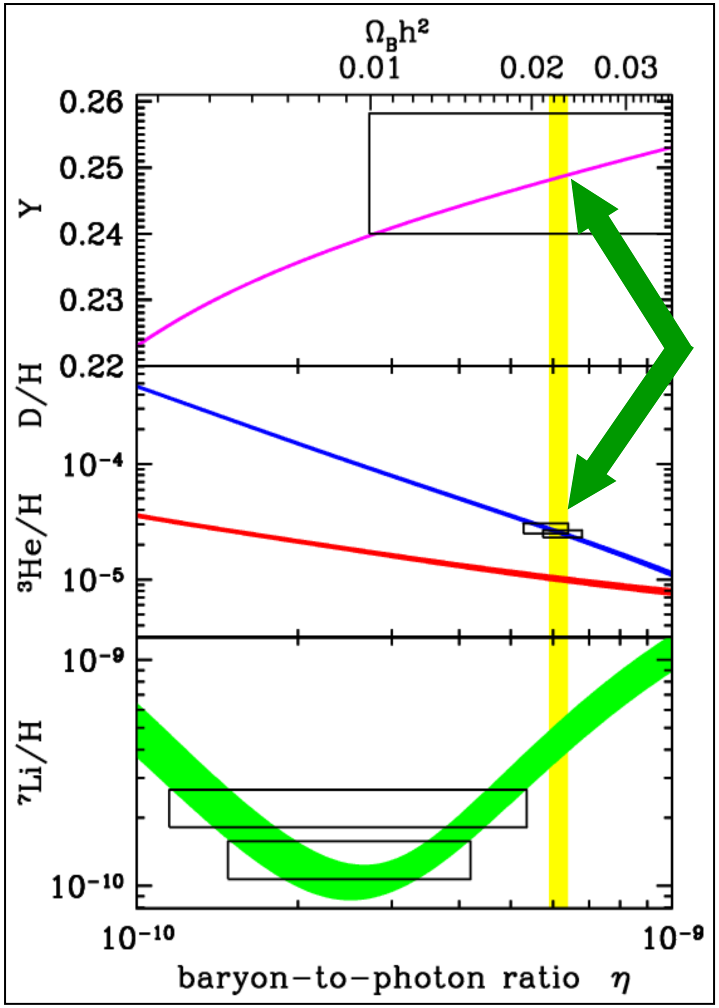


Evidence

η_B was historically determined from the **Big Bang Nucleosynthesis**: Primordial abundances of BBN light elements are sensitive to it.

η_B can now be measured from **Cosmic Microwave Background**: Relative sizes of those Doppler peaks of CMB temperature anisotropy are sensitive to it.





Sakharov conditions

Baryogenesis: ★ Just-So: $B > 0$ from the very beginning up to now;
★ ★ Dynamical picture: $B > 0$ evolved from $B = 0$ after inflation.

Condition 1: baryon number (B) violation.
[GUT, SUSY & even SM allow it, but no direct experimental evidence]

Condition 2: breaking of C and CP symmetries.
[C & CP asymmetries are both needed to keep B violation survivable]

Condition 3: departure from thermal equilibrium.
[Thermal equilibrium might erase B asymmetry due to CPT symmetry]


(Sakharov, 67)

Baryogenesis Mechanisms

- Planck/GUT Baryogenesis;
- Electroweak Baryogenesis;
- Leptogenesis; ⟵ Neutrino Physics
- Affleck-Dine Mechanism; ...

Sakharov's paper: almost no citation during 1967-1979

Now >1300 times

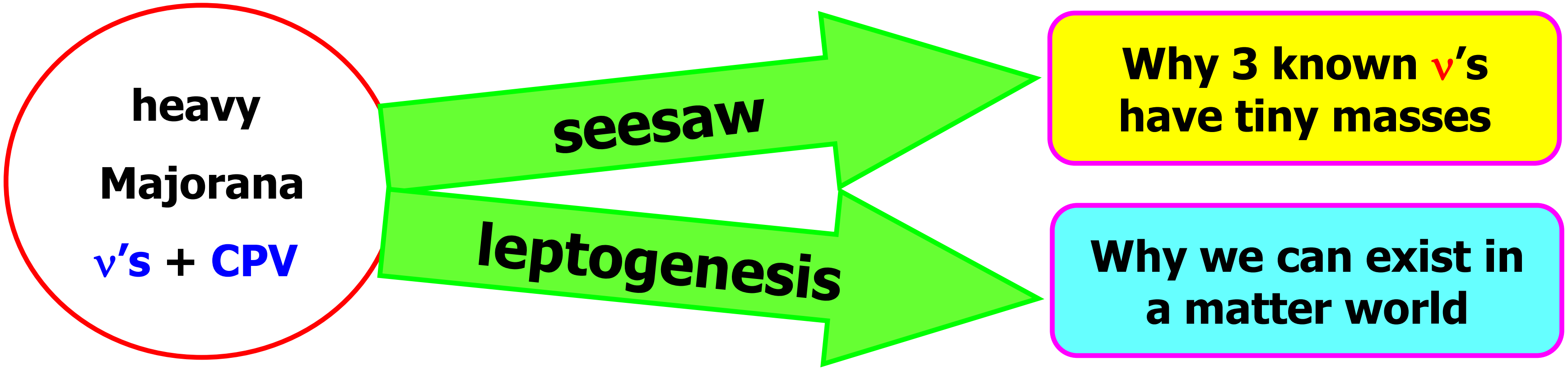
Remarks on CP violation

CP violation from the *CKM* quark mixing matrix is not the whole story to explain the matter-antimatter asymmetry of the visible Universe.

Two reasons for this in the SM:

- CP violation from the SM's quark sector is highly suppressed;
- The electroweak phase transition is not strongly first order.

New sources of CP violation are necessarily required.



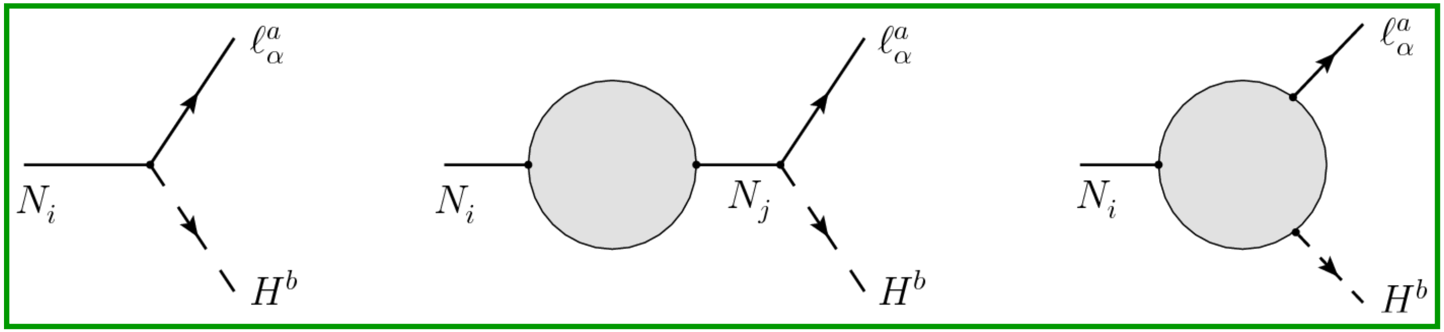
Thermal leptogenesis (1)

◆ add 3 heavy right-handed Majorana neutrinos into SM & keep its SU(2)×U(1) gauge symmetry:

$$-\mathcal{L}_{\rm lepton} = \overline{\ell_{\rm L}} Y_l H E_{\rm R} + \overline{\ell_{\rm L}} Y_\nu \tilde{H} N_{\rm R} + \frac{1}{2}\overline{N^{\rm c}_{\rm R}} M_{\rm R} N_{\rm R} + {\rm h.c.}$$

Fukugita, Yanagida 86

◆ lepton-number-violating & CP-violating decays of heavy neutrinos:



$$\varepsilon_i \equiv \frac{\sum\limits_\alpha \left[\Gamma(N_i \to \ell_\alpha + H) - \Gamma(N_i \to \overline{\ell}_\alpha + \overline{H})\right]}{\sum\limits_\alpha \left[\Gamma(N_i \to \ell_\alpha + H) + \Gamma(N_i \to \overline{\ell}_\alpha + \overline{H})\right]}$$

$$\approx \frac{1}{8\pi (Y^\dagger_\nu Y_\nu)_{ii}} \sum_j {\rm Im}\left[(Y^\dagger_\nu Y_\nu)_{ij}\right]^2 \left[f_{\rm V}\left(\frac{M_j^2}{M_i^2}\right) + f_{\rm S}\left(\frac{M_j^2}{M_i^2}\right)\right]$$

$$f_{\rm V}(x) = \begin{cases} \sqrt{x}\left[1 - (1+x)\ln\dfrac{1+x}{x}\right] & ({\rm SM}) \,, \\ -\sqrt{x}\ln\dfrac{1+x}{x} & ({\rm SUSY}) \,; \end{cases}$$

$$f_{\rm S}(x) = \begin{cases} \dfrac{\sqrt{x}}{1-x} & ({\rm SM}) \,, \\ \dfrac{2\sqrt{x}}{1-x} & ({\rm SUSY}) \,. \end{cases}$$

Thermal leptogenesis (2)

◆ to prevent **CP** asymmetries from being washed out by the inverse decays and scattering processes, the decays of heavy neutrinos must be **out of thermal equilibrium** (their decay rates must be smaller than the expansion rate of the Universe.

$$\Gamma(N_i \to \ell_\alpha + H) < H(T = M_i)$$

The **net** lepton number asymmetry:

$$Y_\mathrm{L} \equiv \frac{n_\mathrm{L} - n_{\overline{\mathrm{L}}}}{s} = \frac{1}{g_*} \sum_i \kappa_i \varepsilon_i$$

κ_i : efficiency factors

g_* : number of relativistic d.o.f

s : entropy density

(Boltzmann equations for time evolution of particle number densities)

◆ non-perturbative but (***B*–*L***)-**conserving** weak **sphaleron** reactions convert a lepton number asymmetry to a baryon number asymmetry.

$$\partial_\mu J^\mu_\mathrm{B} = \partial_\mu J^\mu_\mathrm{L} = \frac{N_f}{32\pi^2}\left(-g^2 W^i_{\mu\nu}\tilde{W}^{i\mu\nu} + g'^2 B_{\mu\nu}\tilde{B}^{\mu\nu}\right)$$

at the quantum level via triangle anomaly.

$$B - L = \int \mathrm{d}^3x \left(J^0_\mathrm{B} - J^0_\mathrm{L}\right) = 0$$

(***B*–*L***) is conserved in the SM (**'t Hooft**, **76**)

$$\Delta B = \Delta L = N_f \Delta N_\mathrm{CS}$$

Chern-Simons (CS) numbers = ±1, ±2, ...

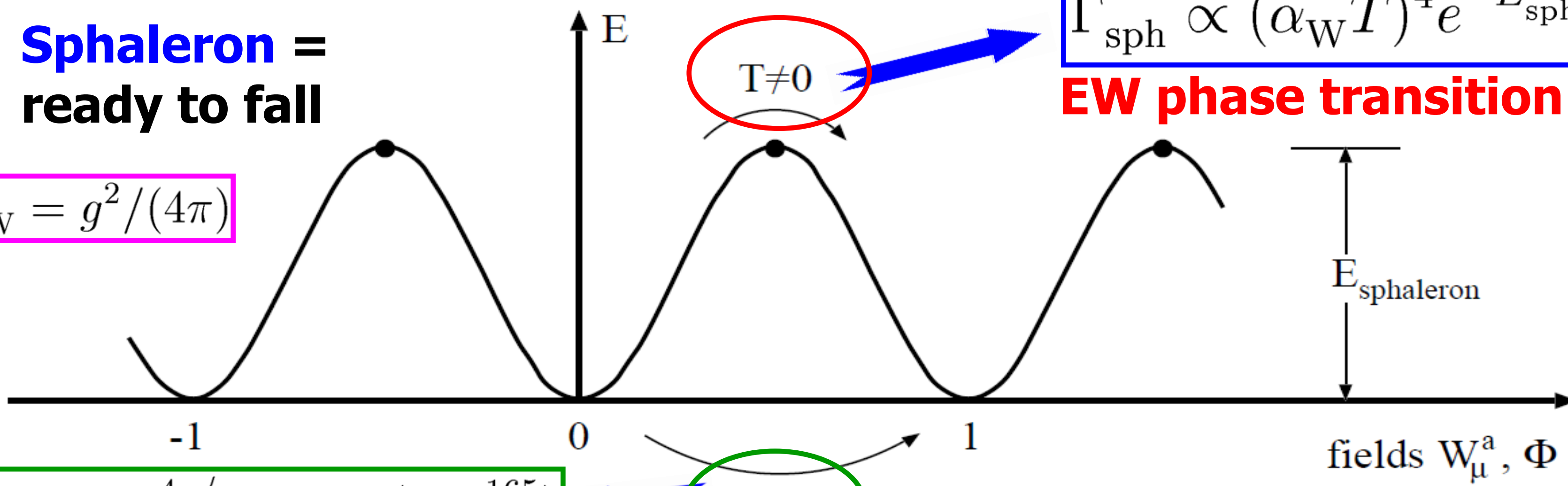
Thermal leptogenesis (3)

Sphaleron = ready to fall

$$\Gamma_{\rm sph} \propto (\alpha_{\rm W} T)^4 e^{-E_{\rm sph}/T}$$

EW phase transition

$$\alpha_{\rm W} = g^2/(4\pi)$$



$$\Gamma_{\rm sph} \propto e^{-4\pi/\alpha_{\rm W}} \sim \mathcal{O}(10^{-165})$$

Sphaleron-induced (*B*+*L*)-violating process is in thermal equilibrium when the temperature:

$$10^2\,\text{GeV} < T < 10^{12}\,\text{GeV}$$

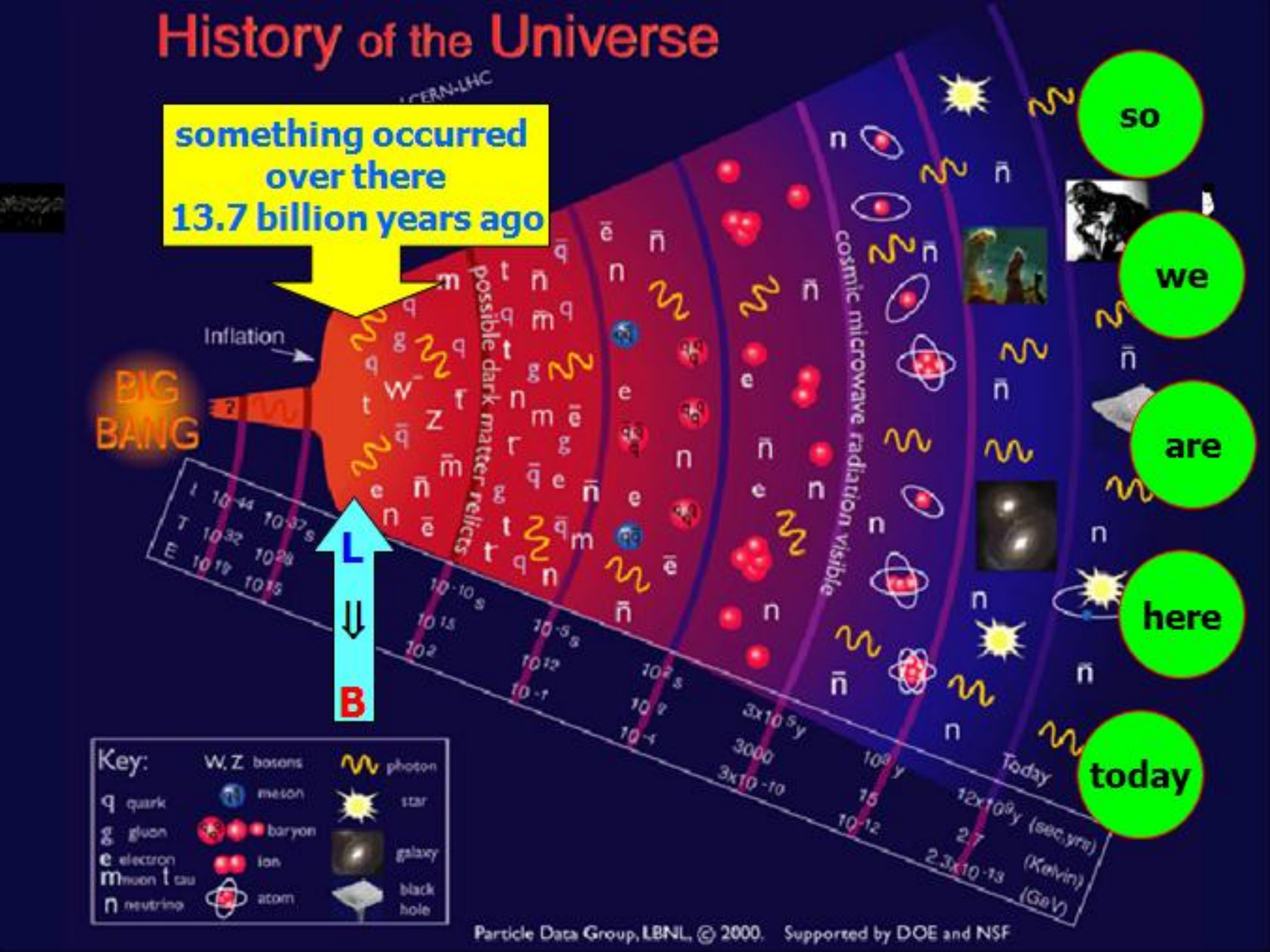
Baryogenesis via leptogenesis is realized:

$$Y_{\rm B} \equiv \frac{n_{\rm B} - n_{\overline{\rm B}}}{s} = -C Y_{\rm L}$$

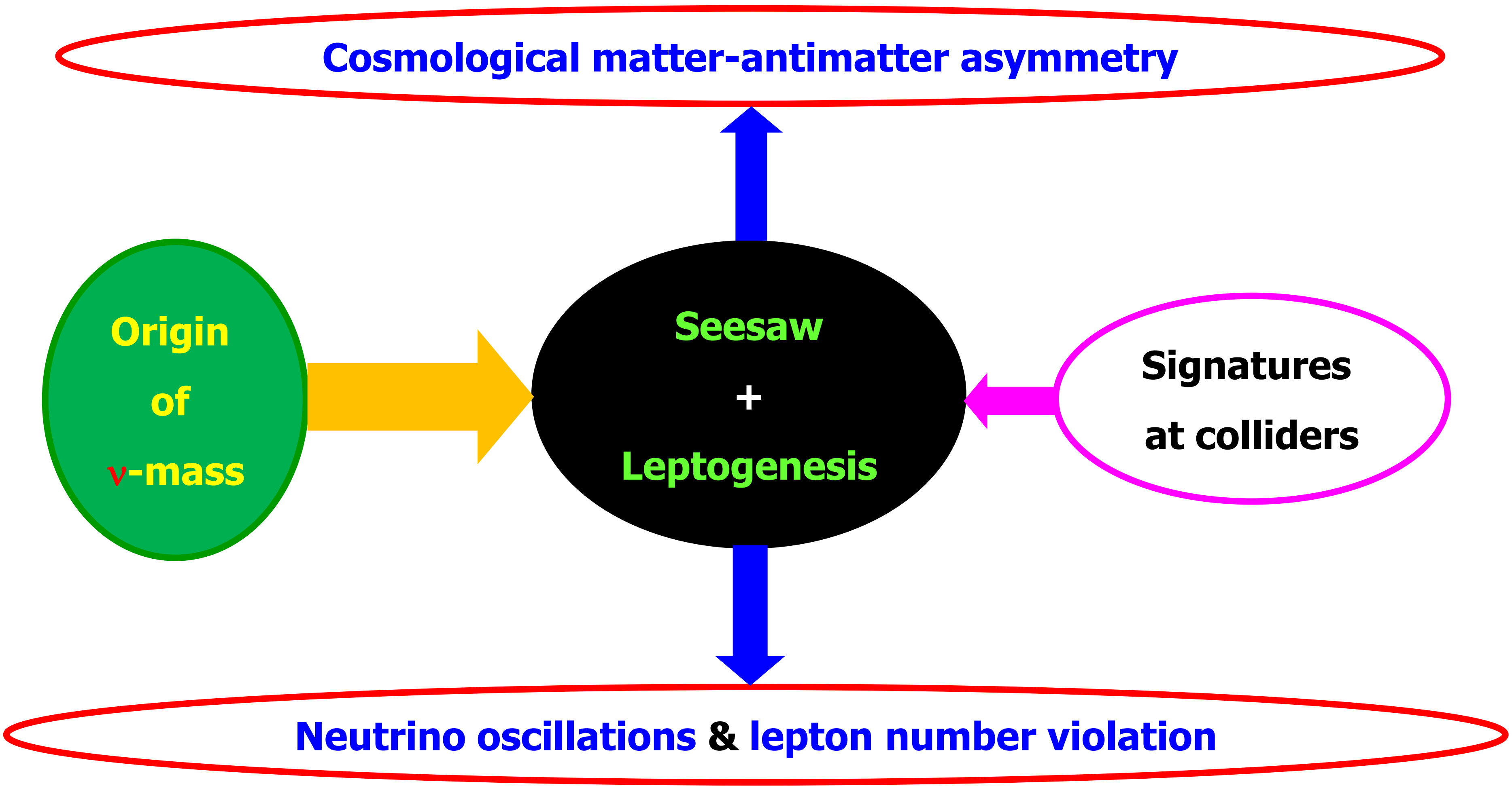
$$\left.\frac{n_{\rm B}}{s}\right|_{\rm equilibrium} = C \left.\frac{n_{\rm B} - n_{\rm L}}{s}\right|_{\rm equilibrium} = -C \left.\frac{n_{\rm L}}{s}\right|_{\rm initial}$$

$$\left.\frac{n_{\overline{\rm B}}}{s}\right|_{\rm equilibrium} = C \left.\frac{n_{\overline{\rm B}} - n_{\overline{\rm L}}}{s}\right|_{\rm equilibrium} = -C \left.\frac{n_{\overline{\rm L}}}{s}\right|_{\rm initial}$$

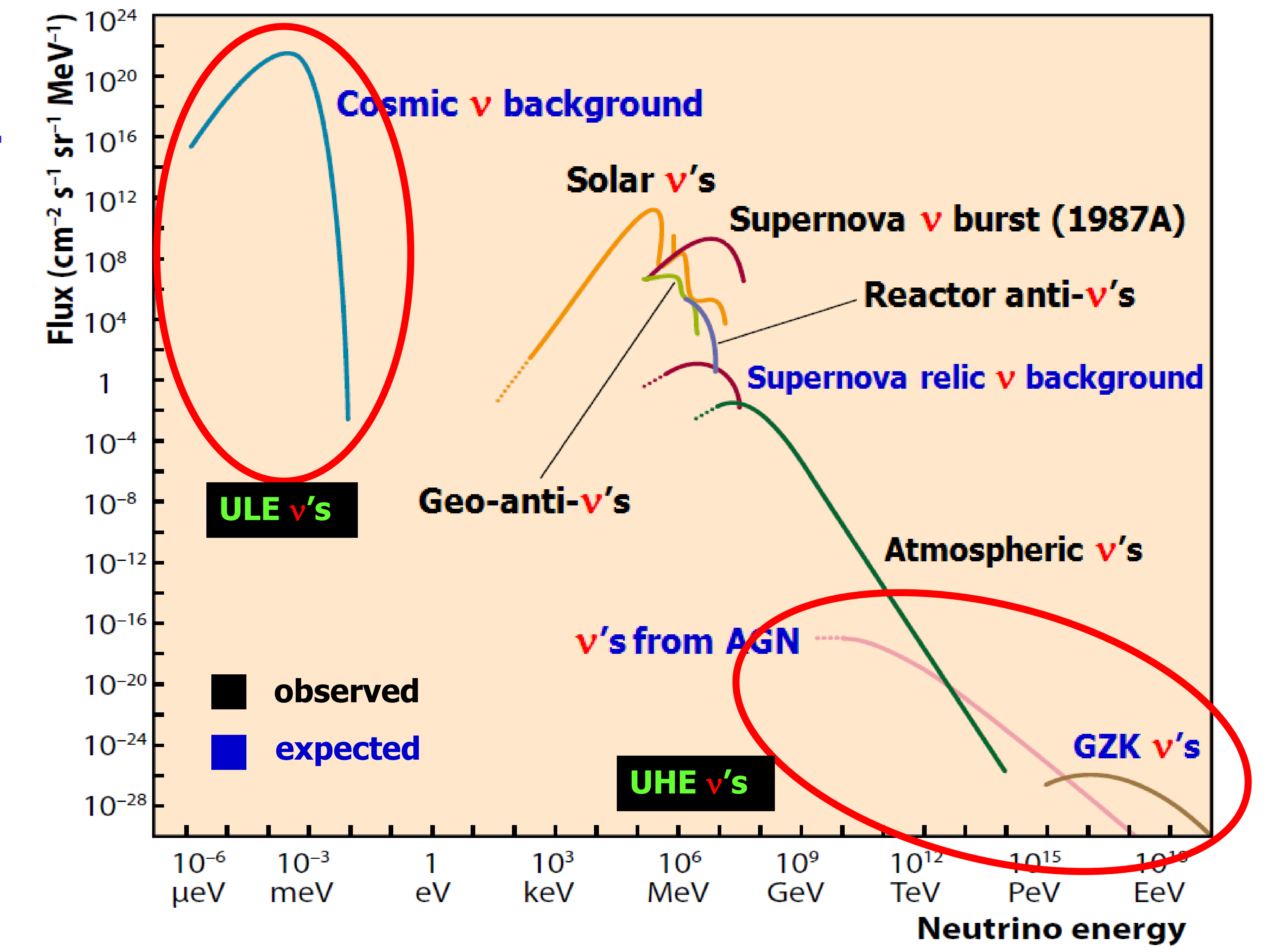
$$C = \frac{8N_f + 4N_\Phi}{22N_f + 13N_\Phi} = \begin{cases} 28/79 & \text{(SM)} \\ 8/23 & \text{(MSSM)} \end{cases}$$


History of the Universe
CERN-LHC
something occurred
over there
13.7 billion years ago
so
we
are
here
today
Inflation
BIG
BANG
L
⇓
B
possible dark matter relics
cosmic microwave radiation visible
10-10 s
10-5 s
3000
Today
(sec,yrs)
(Kelvin)
(GeV)
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

A grand picture?



Cosmic messenger: neutrino astronomy and neutrino cosmology.
Surprise maker: history of neutrino physics was full of surprises.



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}
Cosmic ν background
Solar ν's
Supernova ν burst (1987A)
Reactor anti-ν's
Supernova relic ν background
Geo-anti-ν's
Atmospheric ν's
ULE ν's
ν's from AGN
GZK ν's
UHE ν's
observed
expected
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

Formation of CνB

As $T \sim$ a few MeV in the Universe, the survival relativistic particles were photons, electrons, positrons, neutrinos and antineutrinos.

Electroweak reactions:

$$\gamma + \gamma \rightleftharpoons e^+ + e^- \rightleftharpoons \nu_\alpha + \overline{\nu}_\alpha \quad (\text{for } \alpha = e, \mu, \tau)$$

$$\nu_e + n \rightleftharpoons e^- + p, \overline{\nu}_e + p \rightleftharpoons e^+ + n \qquad \overline{\nu}_e + e^- + p \rightleftharpoons n$$

Neutrinos decoupled from matter:

Weak interactions: $\Gamma \sim G_F^2 T^5$

Hubble expansion: $H \sim \dfrac{\sqrt{g_*} T^2}{M_{Pl}}$

Number density of 6 relic ν's:

$$n_\nu = \frac{9}{11} n_\gamma \approx 336 \left(\frac{T_\gamma}{2.725\ \text{K}}\right)^3 \text{cm}^{-3}$$

$\Gamma > H$ — ν's in thermal contact with cosmic plasma

$\Gamma \sim H$ — neutrino decoupling

$\Gamma < H$ — ν's not in thermal contact with matter

arrow of time

$T < m_e$ $\quad e^+ + e^- \to \gamma + \gamma$

neutrino and photon temperatures (blue)

$$T_\nu = T_\gamma$$

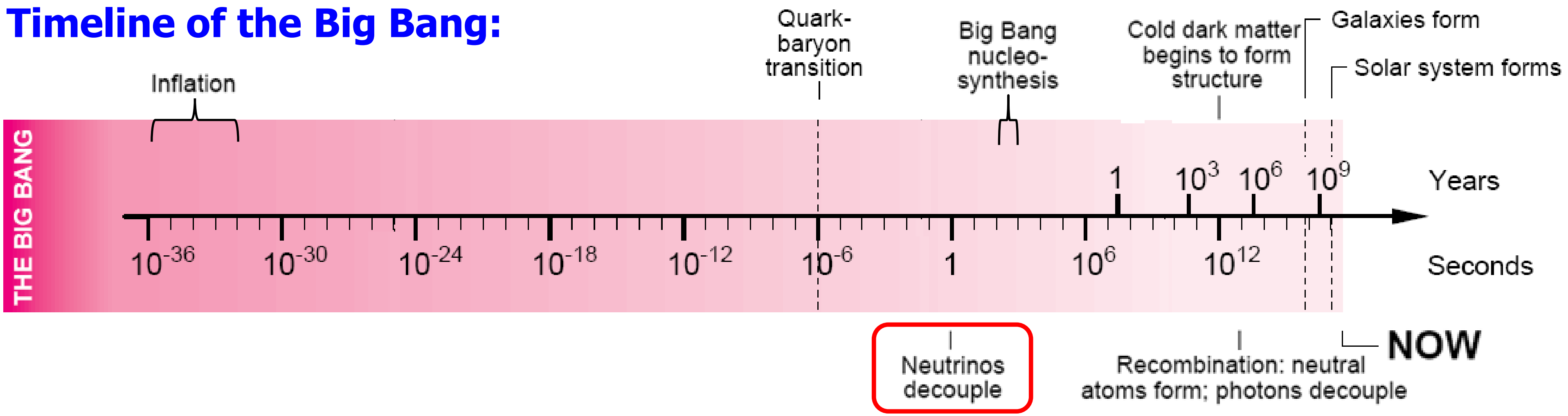
$$T_{fr} \sim \left(\frac{\sqrt{g_*}}{G_F^2 M_{Pl}}\right)^{1/3} \sim 1\ \text{MeV}$$

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

Witness / Participant

CMB and LSS: the existence of relic neutrinos had an impact on the epoch of matter-radiation equality, their species and masses could affect the CMB anisotropies and large scale structures.

Timeline of the Big Bang:



At the time of recombination (t ~ 380 000 yrs):

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

The CνB contribution to the total energy density of the Universe today

relativistic

$$\Omega_\nu = \frac{21}{8} \left(\frac{4}{11} \right)^{4/3} \Omega_\gamma \approx 1.68 \times 10^{-5} h^{-2}$$

non-relativistic

$$\Omega_\nu = \frac{8\pi G_{\rm N}}{3H^2} \sum_i m_i \left(n_{\nu_i} + n_{\overline{\nu}_i} \right) \approx \frac{1}{94\ h^2\ {\rm eV}} \sum_i m_i$$

Is CνB detectable?

Today's matter & energy densities in the Universe (Dunkley et al 09; Komatsu et al 09; Nakamura et al 10): 5-year WMAP + ΛCDM model

Parameter	Value
Hubble parameter h	0.72 ± 0.03
Total matter density $\Omega_{\rm m}$	$\Omega_{\rm m} h^2 = 0.133 \pm 0.006$
Baryon density $\Omega_{\rm B}$	$\Omega_{\rm B} h^2 = 0.0227 \pm 0.0006$
Vacuum energy density $\Omega_{\rm v}$	$\Omega_{\rm v} = 0.74 \pm 0.03$
Radiation density $\Omega_{\rm r}$ ⟵	$\Omega_{\rm r} h^2 = 2.47 \times 10^{-5}$
Neutrino density Ω_ν ⟵	$\Omega_\nu h^2 = \sum m_i / (94\ {\rm eV})$
Cold dark matter density $\Omega_{\rm CDM}$	$\Omega_{\rm CDM} h^2 = 0.110 \pm 0.006$

The CMB (t ~ 380 000 years) is already measured today

Is it likely to detect the CνB (t ~ 1 s) in the foreseeable future? ---- Here we'll look at a Gedankenexperiment.

Detection of CνB

Way 1: CνB-induced **mechanical effects** on Cavendish-type torsion balance;

Way 2: **Capture** of relic ν's on radioactive β-decaying nuclei (Weinberg 62);

Way 3: *Z*-resonance **annihilation** of UHE cosmic ν's and relic ν's (Weiler 82).

Temperature today

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \simeq 1.945\ \mathrm{K}$$

Mean momentum today

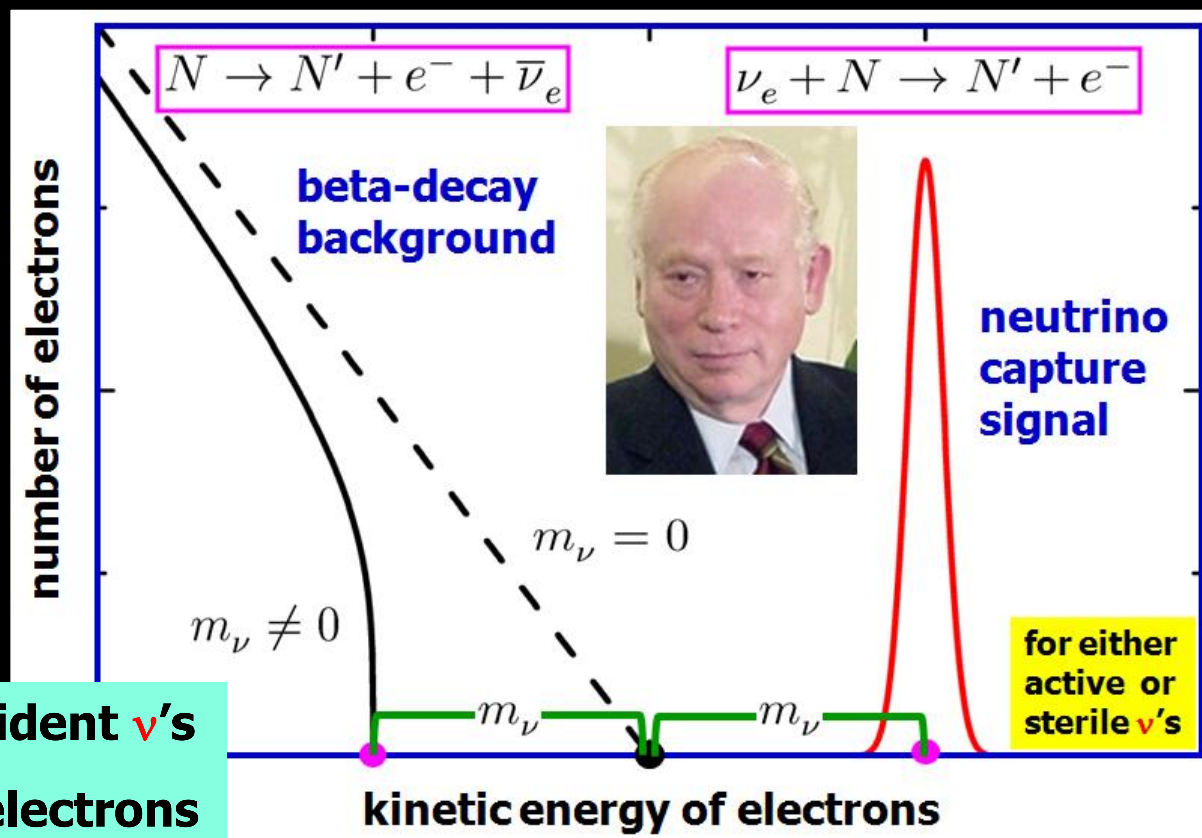
$$\langle p_\nu \rangle \simeq 3.151 T_\nu \simeq 5.281 \times 10^{-4}\ \mathrm{eV}$$

At least 2 ν's cold today

How to detect ULE ν's ?

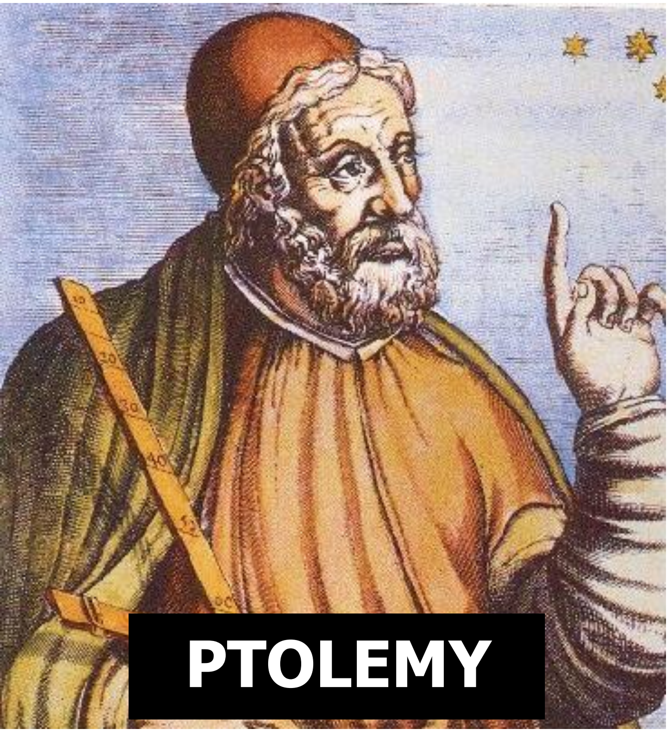
(Irvine & Humphreys, 83)

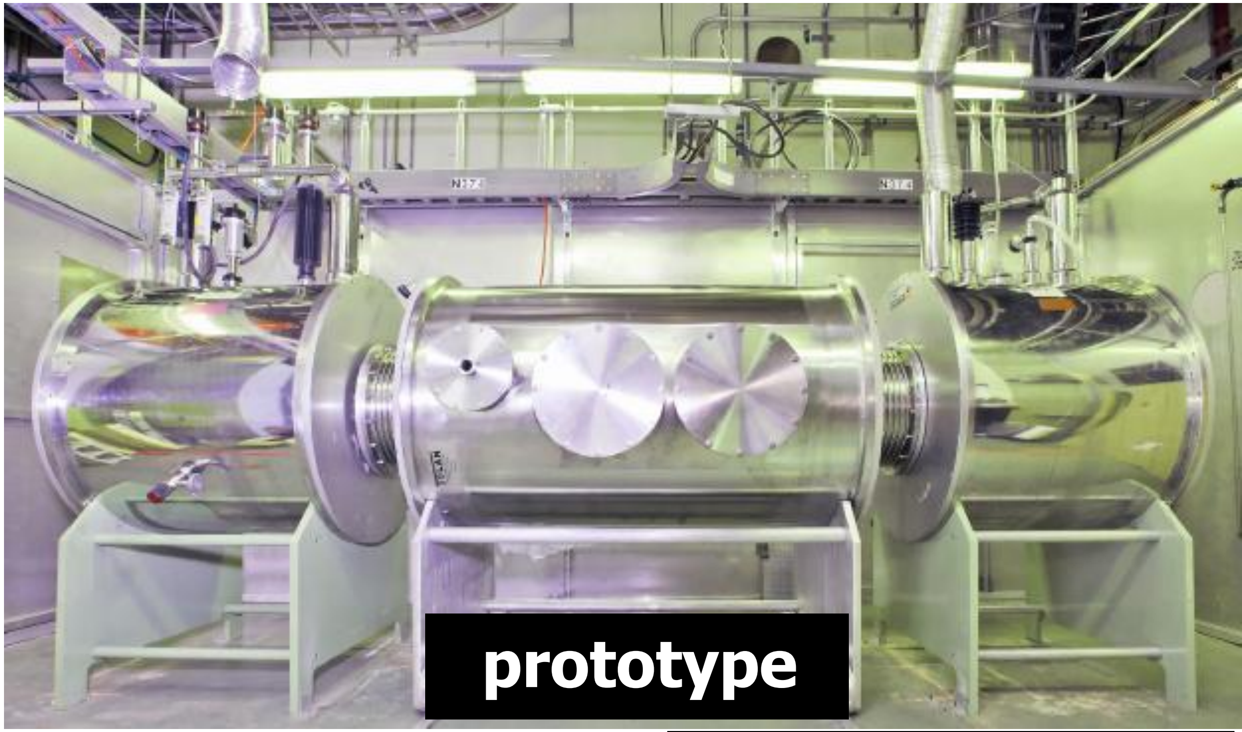
Relic neutrino capture on β-decaying nuclei



- no energy threshold on incident ν's
- **mono**-energetic outgoing electrons

Towards a real experiment?


PTOLEMY


prototype

★ **first experiment**

★ **100 g of tritium**

★ **graphene target**

★ **planned energy resolution 0.15 eV**

★ **CνB capture rate**

$$\Gamma^{\rm D}_{{\rm C}\nu{\rm B}} \sim 4\ {\rm yr}^{-1}$$

$$\Gamma^{\rm M}_{{\rm C}\nu{\rm B}} \sim 8\ {\rm yr}^{-1}$$

D = Dirac

M = Majorana

PTOLEMY
Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield (Betts et al, arXiv:1307.4738)

Example

Salient feature: the cross section of a capture reaction scales with $\frac{c}{v_\nu}$ so that the number of events converges to a constant for $v_\nu \to 0$:

$$\sigma(\nu_e N) \cdot \left.\frac{v_\nu}{c}\right|_{v_\nu \to 0} = \text{const.}$$

e.g. $$\sigma(\nu_e {}^3\text{H}) \cdot \left.\frac{v_\nu}{c}\right|_{v_\nu \to 0} \simeq (7.84 \pm 0.03) \times 10^{-45} \text{cm}^2$$

(Cocco et al 07, Lazauskas et al 08).

$$\nu_e + {}^3\text{H} \to {}^3\text{He} + e^-$$

Capture rate: (1 MCi = 100 g = $N_\text{T} \approx 2.1 \times 10^{25}$ tritium atoms)

$$\frac{\mathrm{d}\mathcal{N}_{\text{C}\nu\text{B}}}{\mathrm{d}T_e} \approx 6.5 \sum_i |V_{ei}|^2 \frac{n_{\nu_i}}{\langle n_{\nu_i} \rangle} \cdot \frac{1}{\sqrt{2\pi}\,\sigma} \exp\left[-\frac{(T_e - T_e^i)^2}{2\sigma^2}\right] \text{yr}^{-1}\,\text{MCi}^{-1}$$

$$T_e^i = Q_\beta + E_{\nu_i}$$

Background: (the tritium β-decay)

$$E_e = T_e' + m_e \qquad \langle n_{\nu_i} \rangle \approx \langle n_{\bar{\nu}_i} \rangle \approx 56 \text{ cm}^{-3}$$

$$\frac{\mathrm{d}\mathcal{N}_\beta}{\mathrm{d}T_e} \approx 5.55 \int_0^{Q_\beta - \min(m_i)} \mathrm{d}T_e' \left\{ N_\text{T} \frac{G_\text{F}^2 \cos^2\theta_\text{C}}{2\pi^3} F(Z, E_e) \sqrt{E_e^2 - m_e^2}\, E_e (Q_\beta - T_e') \right.$$
$$\left. \times \sum_i \left[|V_{ei}|^2 \sqrt{\left(Q_\beta - T_e'\right)^2 - m_i^2}\; \Theta(Q_\beta - T_e' - m_i) \right] \frac{1}{\sqrt{2\pi}\,\sigma} \exp\left[-\frac{(T_e - T_e')^2}{2\sigma^2}\right] \right\}$$

Energy resolution (Gaussian function) :

$$\Delta = 2\sqrt{2 \ln 2}\,\sigma \approx 2.35482\,\sigma$$

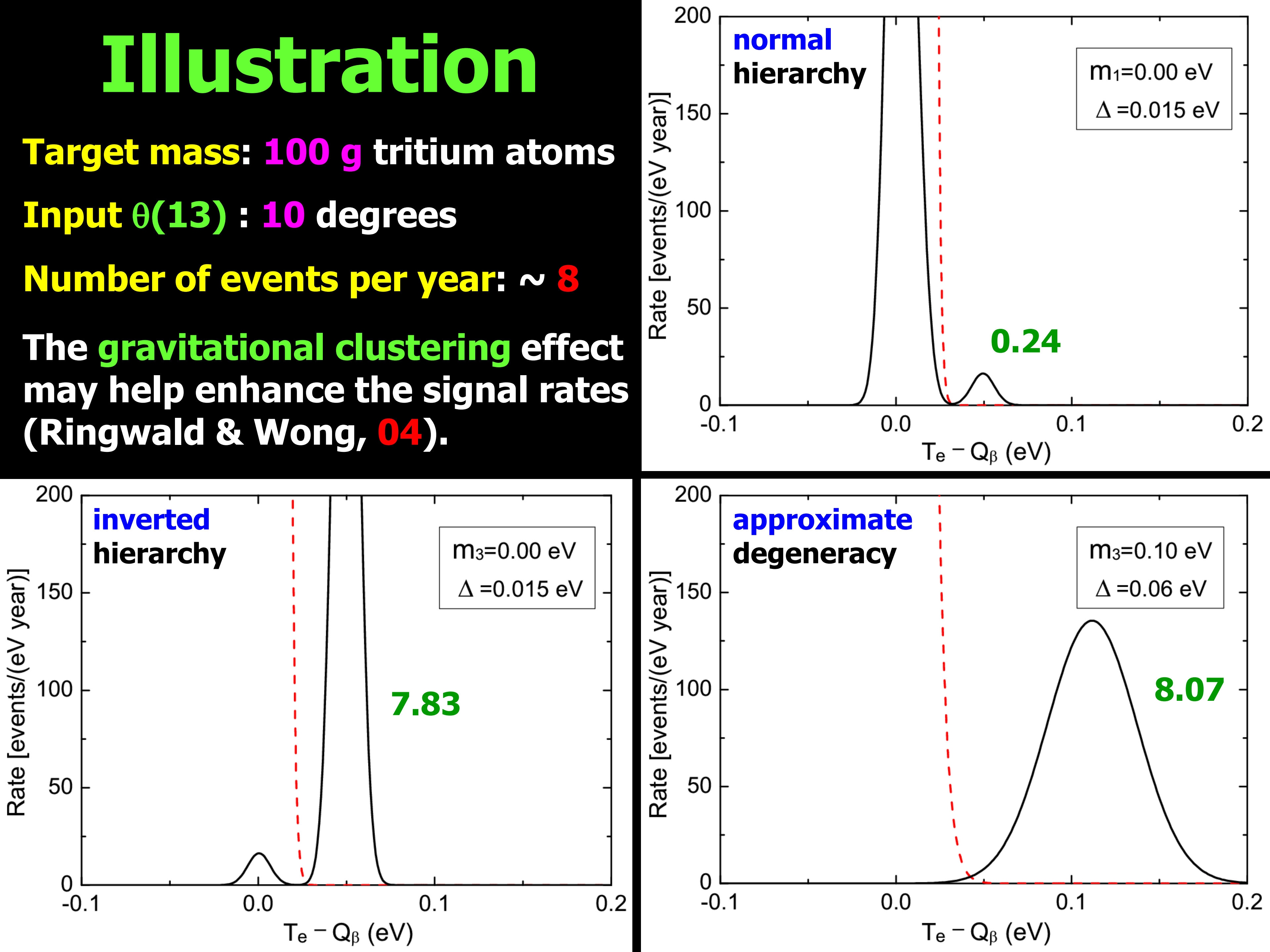
Illustration

Target mass: 100 g tritium atoms

Input θ(13) : 10 degrees

Number of events per year: ~ 8

The gravitational clustering effect may help enhance the signal rates (Ringwald & Wong, 04).

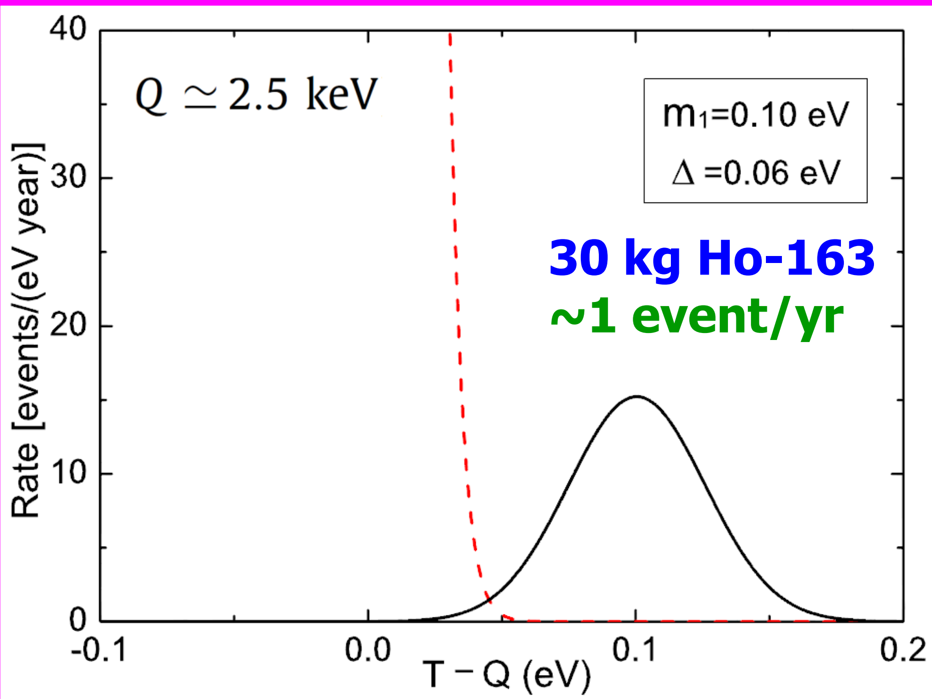


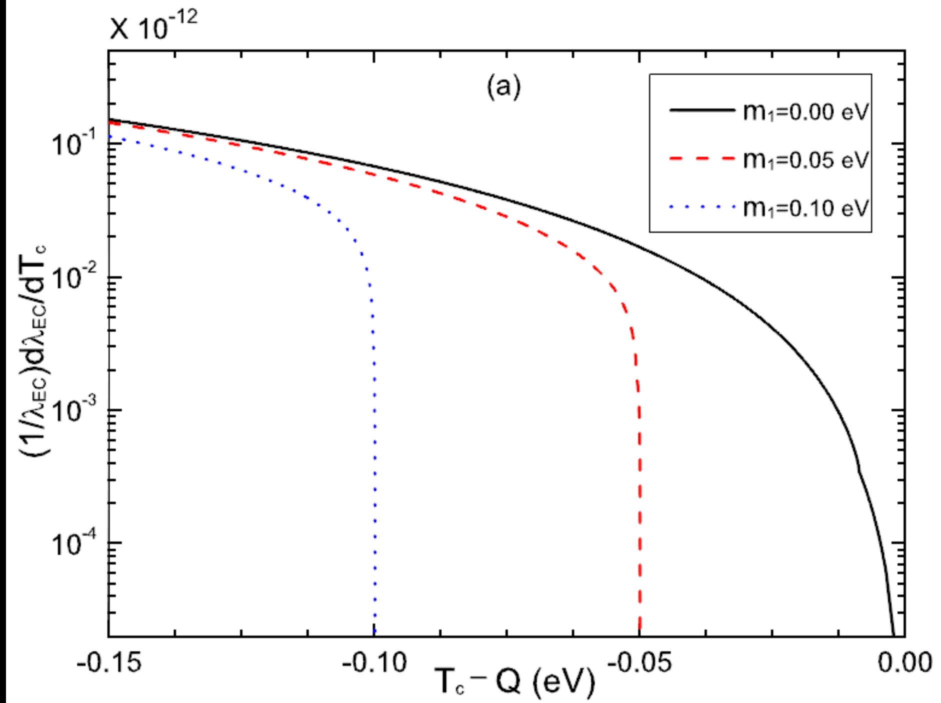
Cosmic anti-ν Background?

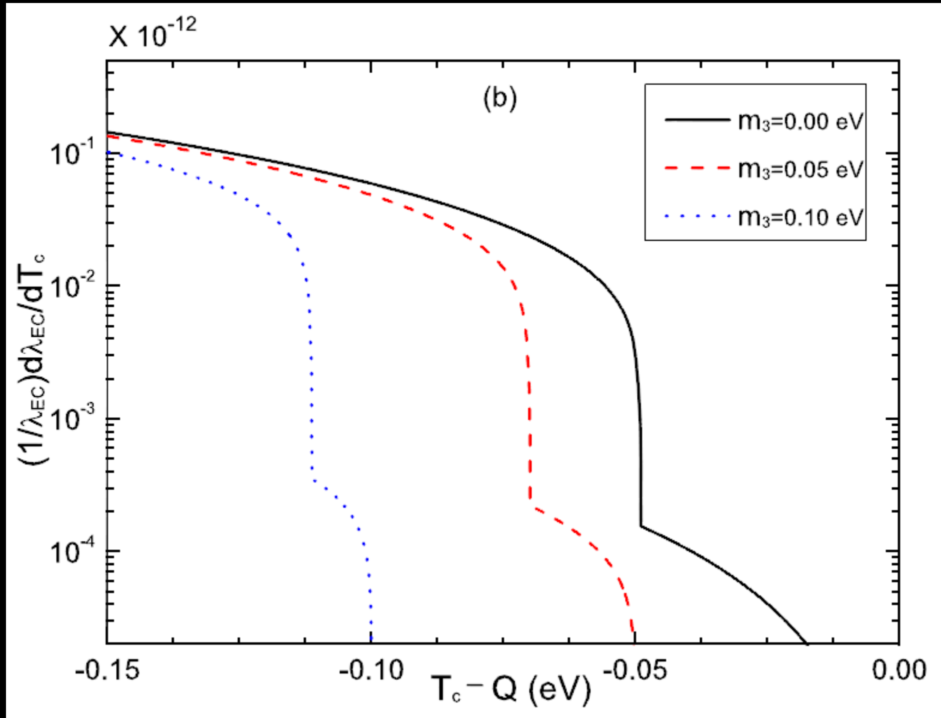
Relic antineutrino capture on EC-decaying Ho-163 nuclei.

$$\overline{\nu}_e + {}^{163}\mathrm{Ho} + e^-_{i(\mathrm{shell})} \rightarrow {}^{163}\mathrm{Dy}^*_i \rightarrow {}^{163}\mathrm{Dy} + E_i$$

(Lusignoli, Vignati, 11; Li, Xing, 11)







A naïve (why not) picture

Hot dark matter: CνB is guaranteed but not significant.

Cold dark matter: most likely? At present most popular.

Warm dark matter: suppress the small-scale structures.

If you think so,

Do not put all your eggs in one basket

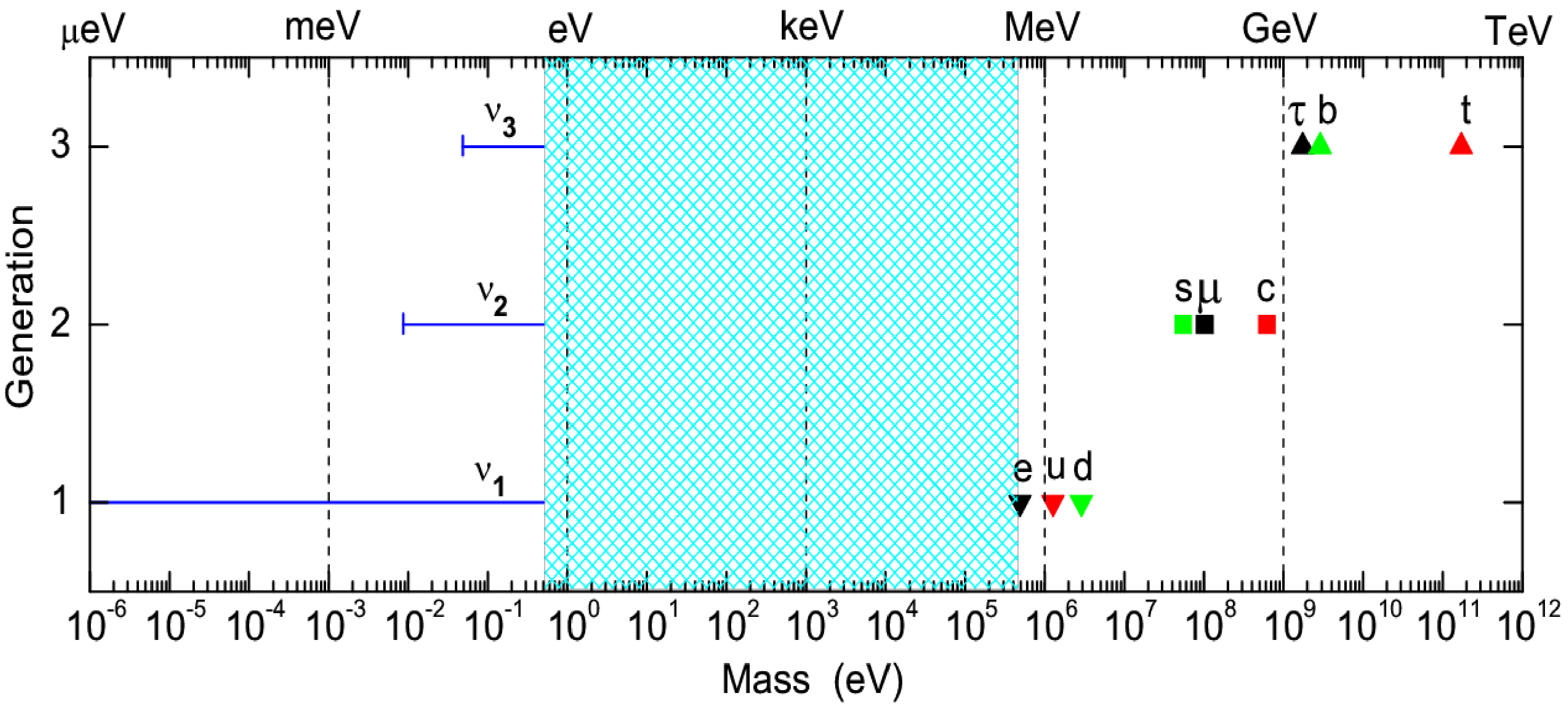
hot dark matter

warm dark matter

keV sterile ν dark matter

NO strong prior theoretical motivation for the existence of keV sterile ν's. Typical models: Asaka et al, 05; Kusenko et al, 10; Lindner et al, 11….

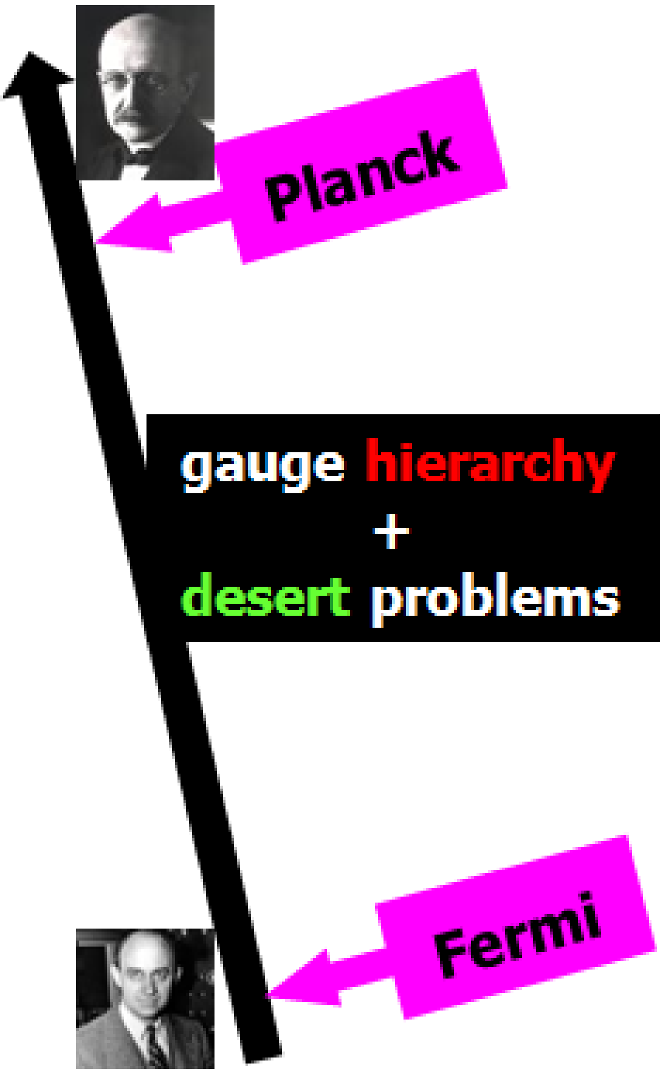
A purely phenomenological argument to support keV sterile ν's in the FLAVOR DESERT of the standard model (Xing, 09).

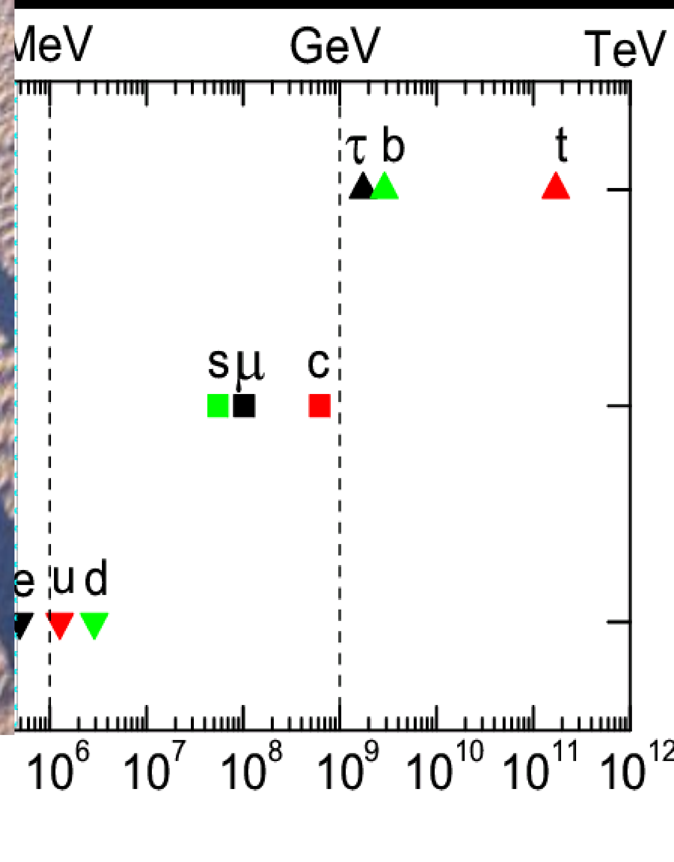


keV sterile ν dark matter

NO strong prior theoreti … existence of **keV** sterile ν's. **Typical models**: Asa … t al, **10**; Lindner et al, **11**....

… ort **keV** sterile ν's in the

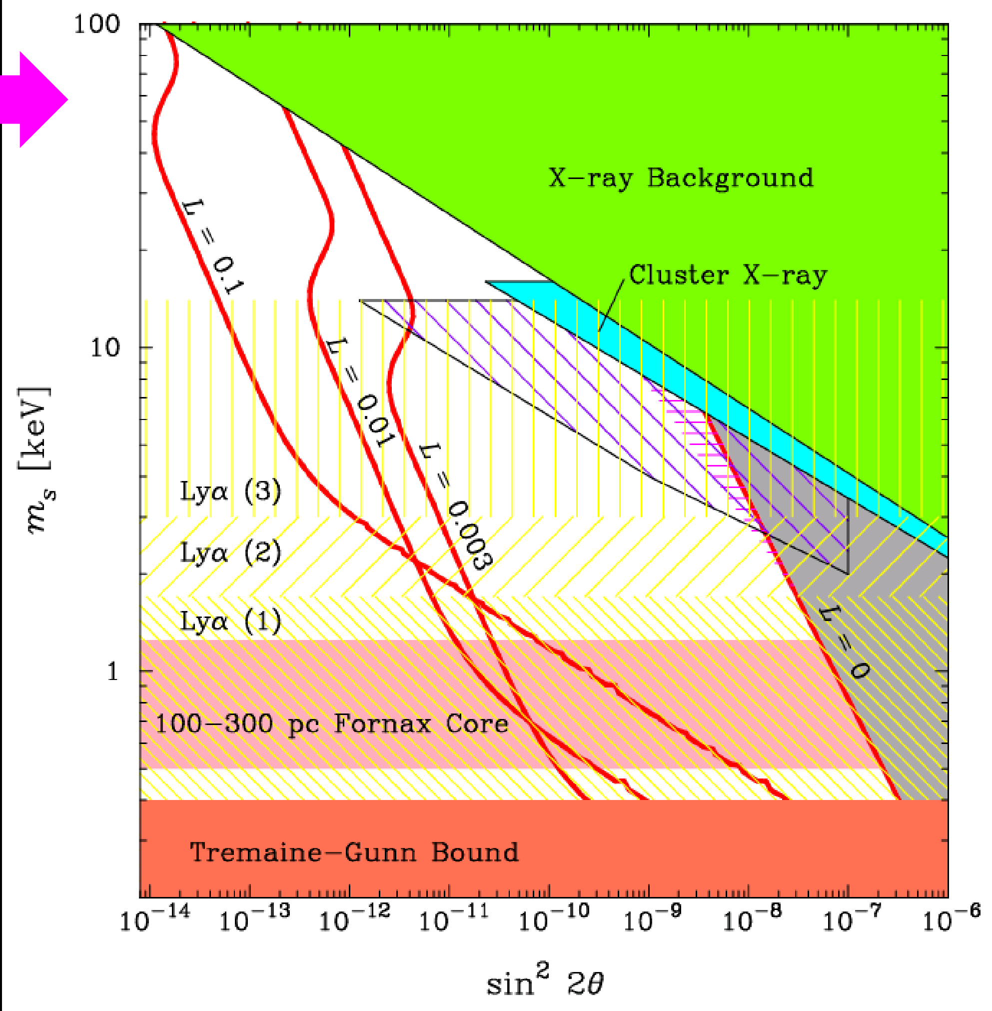




keV sterile ν dark matter

Production: via active-sterile ν oscillations in the early Universe, etc;
Salient feature: warm DM in the form of keV sterile ν's can suppress the formation of dwarf galaxies and other small-scale structures.

Bounds on 2-flavor parameters:
(Abazajian, Koushiappas, 2006)



For simplicity, we assume only one type of keV sterile neutrinos:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} & V_{e4} \\ V_{\mu1} & V_{\mu2} & V_{\mu3} & V_{\mu4} \\ V_{\tau1} & V_{\tau2} & V_{\tau3} & V_{\tau4} \\ V_{s1} & V_{s2} & V_{s3} & V_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

Standard parameterization of V:
6 mixing angles & 3 (Dirac) or 6 (Majorana) CP-violating phases.

$$V_{s1} \simeq s_{14}\, e^{-i\delta_{14}}\,, \qquad V_{s2} \simeq s_{24}\, e^{-i\delta_{24}}$$
$$V_{s3} \simeq s_{34}\, e^{-i\delta_{34}}\,, \qquad V_{s4} \simeq 1$$

$$V_{e4} \simeq -c_{12}c_{13}s_{14}e^{i\delta_{14}} - s_{12}c_{13}s_{24}e^{i(\delta_{24}-\delta_{12})}$$

Decay rates

Dominant decay mode [C_ν = 1 (Dirac) or 2 (Majorana)]:

$$\sum_{\alpha=e}^{\tau}\sum_{\beta=e}^{\tau}\Gamma(\nu_4 \to \nu_\alpha + \nu_\beta + \overline{\nu}_\beta) = \frac{C_\nu G_F^2 m_4^5}{192\pi^3}\sum_{\alpha=e}^{\tau}|V_{\alpha 4}|^2 = \frac{C_\nu G_F^2 m_4^5}{192\pi^3}\sum_{i=1}^{3}|V_{si}|^2$$

Lifetime (the Universe's age ~ 10^17 s):

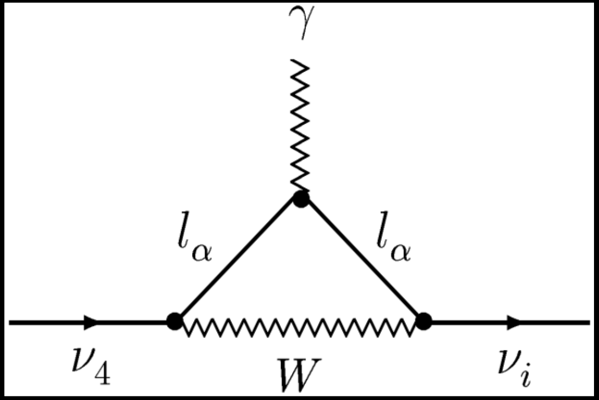
$$\tau_{\nu_4} \simeq \frac{2.88\times 10^{27}}{C_\nu}\left(\frac{m_4}{1\ \mathrm{keV}}\right)^{-5}\left(\frac{s_{14}^2+s_{24}^2+s_{34}^2}{10^{-8}}\right)^{-1}\ \mathrm{s}$$

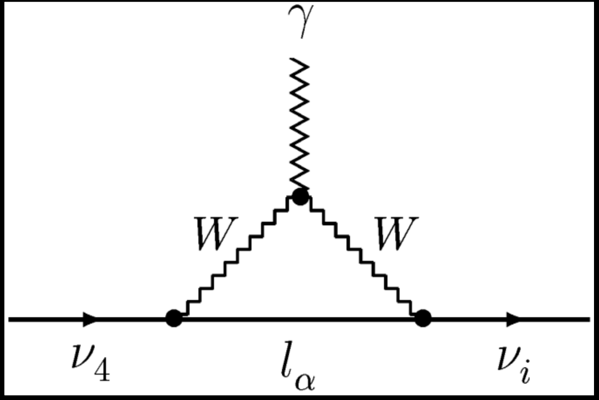
Radiative decay: X-ray and Lyman-alpha forest observations.

$$\sum_{i=1}^{3}\Gamma(\nu_4 \to \nu_i + \gamma) \simeq \frac{9\alpha_{\mathrm{em}} C_\nu G_F^2 m_4^5}{512\pi^4}\sum_{i=1}^{3}\left|\sum_{\alpha=e}^{\tau} V_{\alpha 4}V_{\alpha i}^*\right|^2$$

$$= \frac{9\alpha_{\mathrm{em}} C_\nu G_F^2 m_4^5}{512\pi^4}\sum_{i=1}^{3}|V_{s4}V_{si}^*|^2$$

$$\simeq \frac{9\alpha_{\mathrm{em}} C_\nu G_F^2 m_4^5}{512\pi^4}\left(s_{14}^2+s_{24}^2+s_{34}^2\right)$$





Detection in the Lab

The same method as the detection of the CνB in the lab.

$$\nu_e + N \to N' + e^-$$

$$Q_\beta = m_N - m_{N'} - m_e$$

$$N \to N' + e^- + \overline{\nu}_e$$

Capture rate with a Gaussian energy resolution:

$$\frac{\mathrm{d}\mathcal{N}_\nu}{\mathrm{d}T_e} = \sum_{i=1}^{4} N_\mathrm{T} |V_{ei}|^2 \sigma_{\nu_i} v_{\nu_i} n_{\nu_i} \frac{1}{\sqrt{2\pi}\,\sigma} \exp\left[-\frac{(T_e - T_e^i)^2}{2\sigma^2}\right]$$

Assumption: the number density of sterile ν's is equivalent to the total amount of DM in our galactic neighborhood.

$$\rho_\mathrm{DM}^\mathrm{local} \simeq 0.3\ \mathrm{GeV\ cm^{-3}}$$

$$n_{\nu_4} \simeq 10^5\ (3\ \mathrm{keV}/m_4)\ \mathrm{cm}^{-3}$$

Half-life effect of target nuclei (Li, Xing, 11)

$$N_\mathrm{T} = \frac{N(0)}{\lambda t}\left(1 - e^{-\lambda t}\right) , \quad \lambda = \frac{\ln 2}{t_{1/2}}$$

Two sources (Liao, 10; Li, Xing, 11):

$$^3\mathrm{H} \ :\ Q_\beta = 18.6\ \mathrm{keV}\ ,\quad t_{1/2} = 3.888\times 10^8\ \mathrm{s}\ ,\quad \sigma_{\nu_i} v_{\nu_i}/c = 7.84\times 10^{-45}\ \mathrm{cm}^2$$

$$^{106}\mathrm{Ru} \ :\ Q_\beta = 39.4\ \mathrm{keV}\ ,\quad t_{1/2} = 3.228\times 10^7\ \mathrm{s}\ ,\quad \sigma_{\nu_i} v_{\nu_i}/c = 5.88\times 10^{-45}\ \mathrm{cm}^2$$

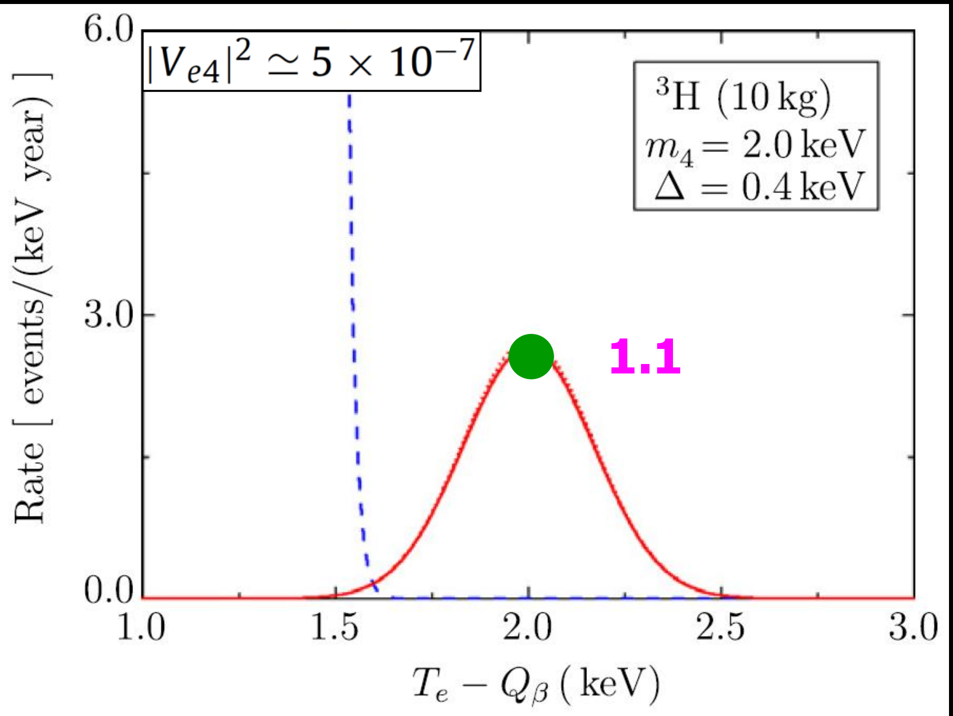
This method & the X-ray detection probe different parameter space.

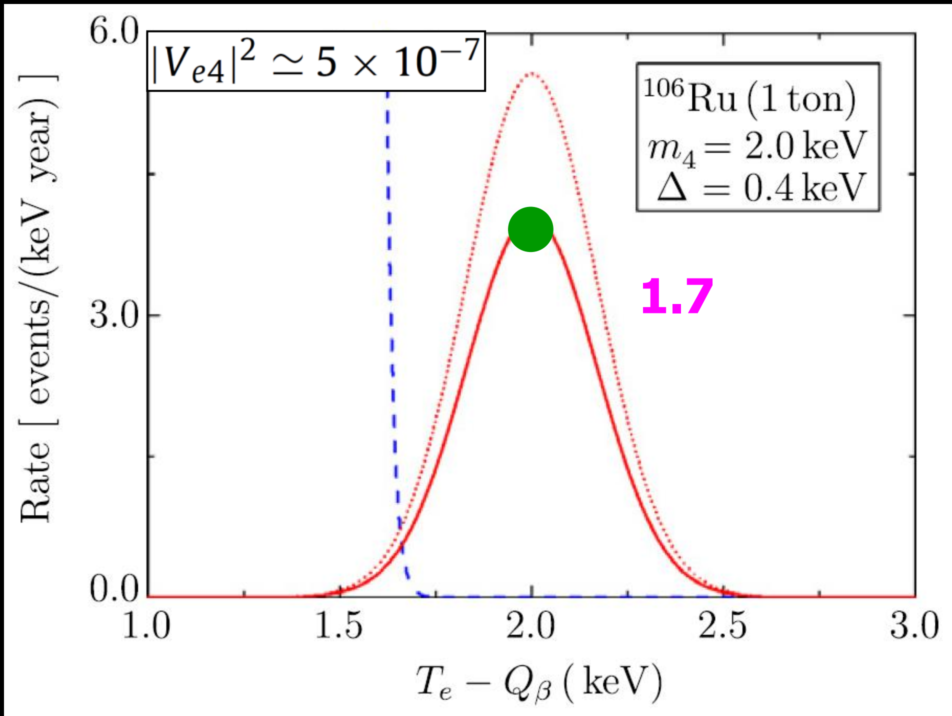
$$|V_{e4}|^2 \simeq c_{12}^2 s_{14}^2 + s_{12}^2 s_{24}^2 + 2 c_{12} s_{12} s_{14} s_{24} \cos\left(\delta_{24} - \delta_{12} - \delta_{14}\right)$$

Illustration

For illustration: solid (dotted) curves with (without) half-life effects.

Number of events per year: pink



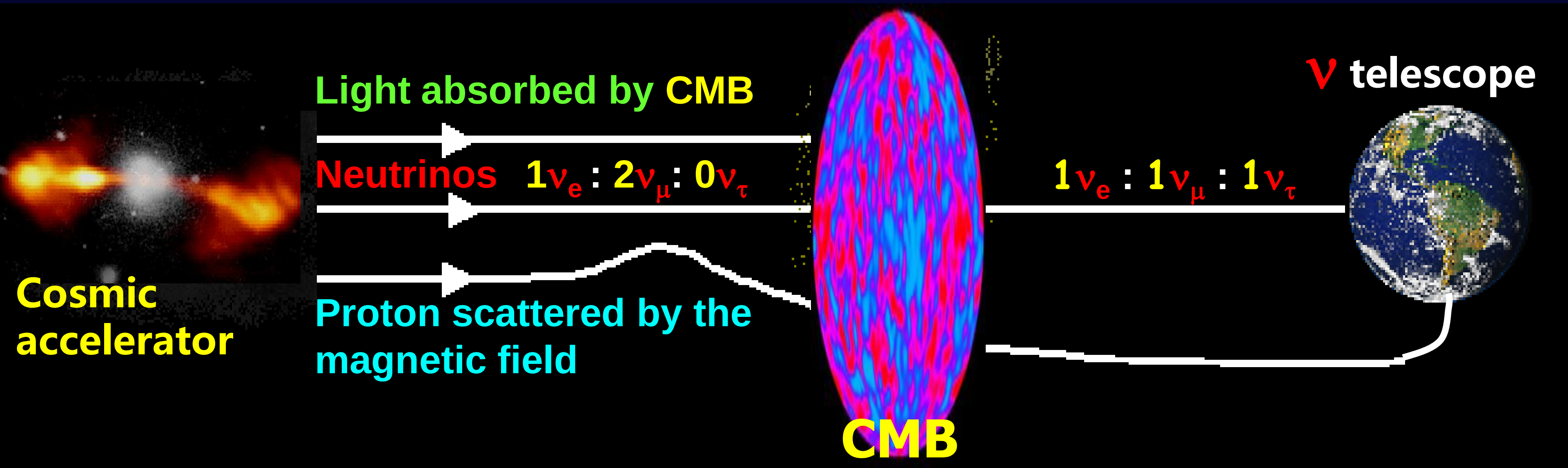


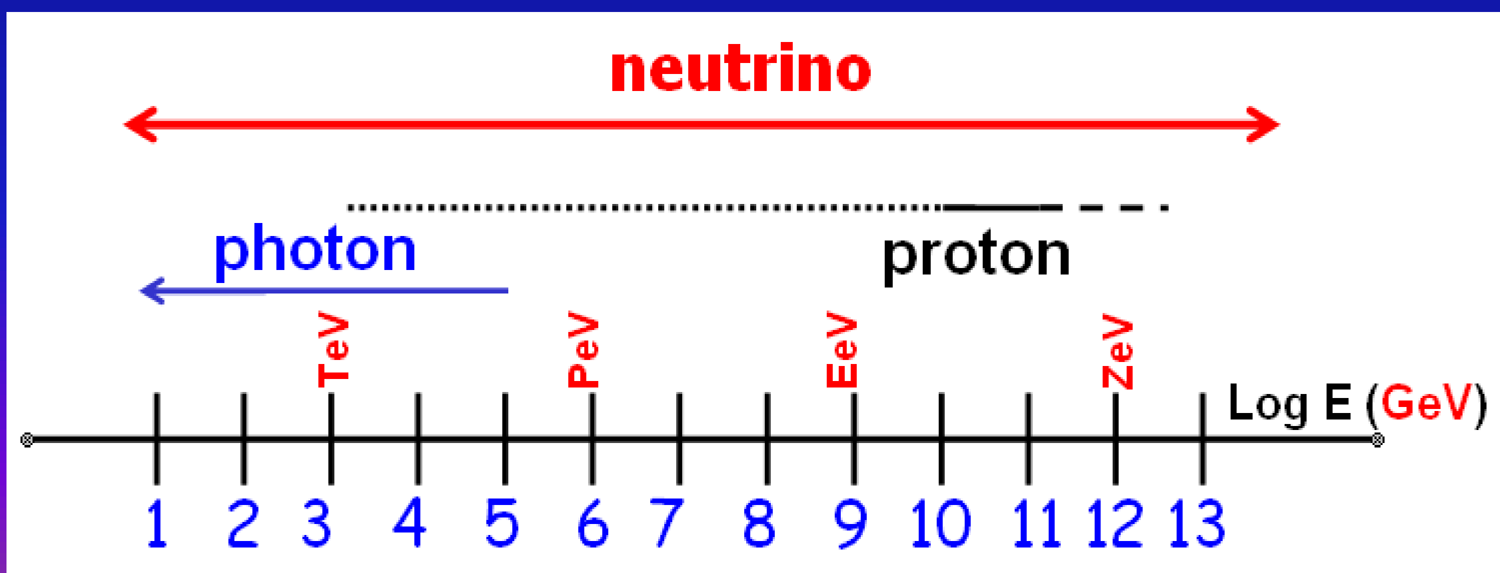
Dim and remote observability of keV sterile neutrino DM in this way:

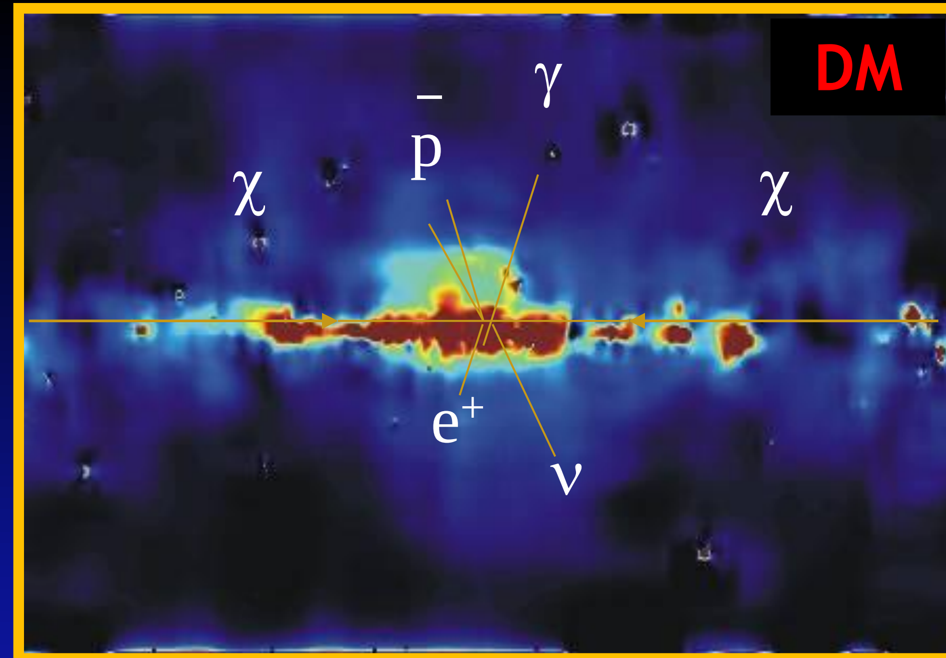
--- tiny active-sterile neutrino mixing angles (main problem)

--- background: keV solar neutrinos or $\nu_4 + e^- \rightarrow \nu_i + e^-$ scattering.

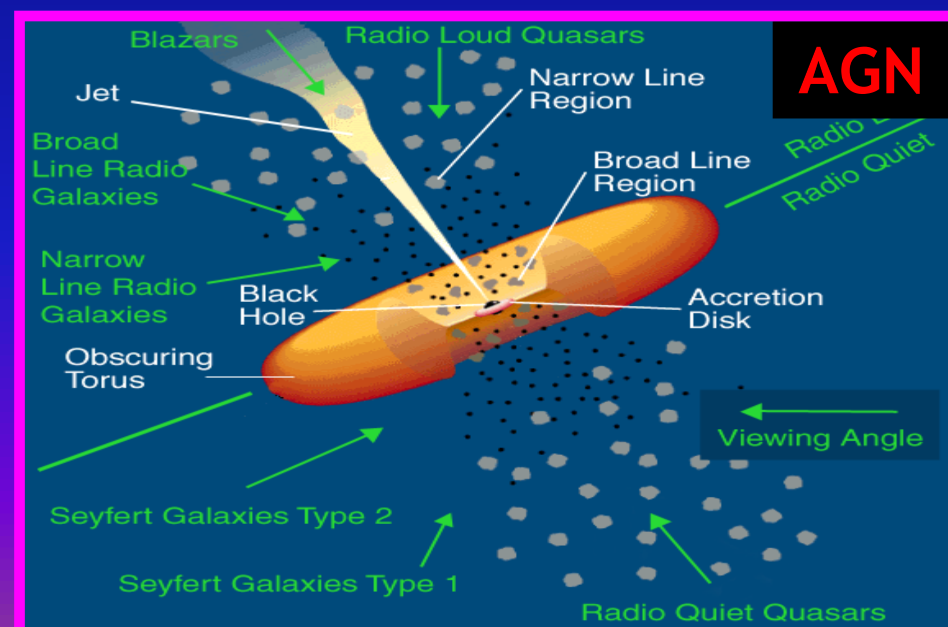
UHE cosmic messenger







Possible astrophysical sources of UHE cosmic neutrinos ...



Optical Cherencov NTs

ANTARES
La-Seyne-sur-Mer, France

NEMO
Catania, Italy

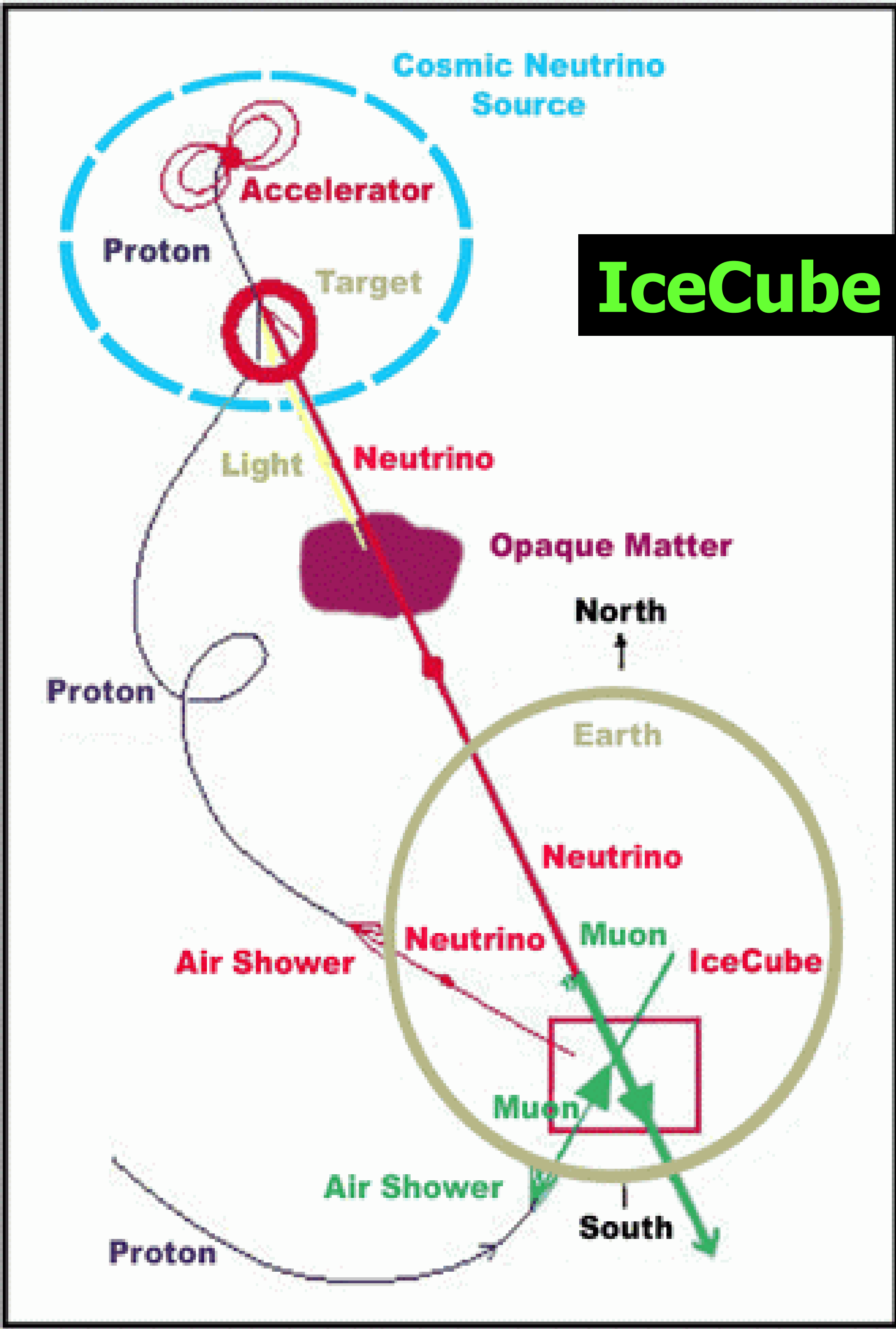
NESTOR
Pylos, Greece

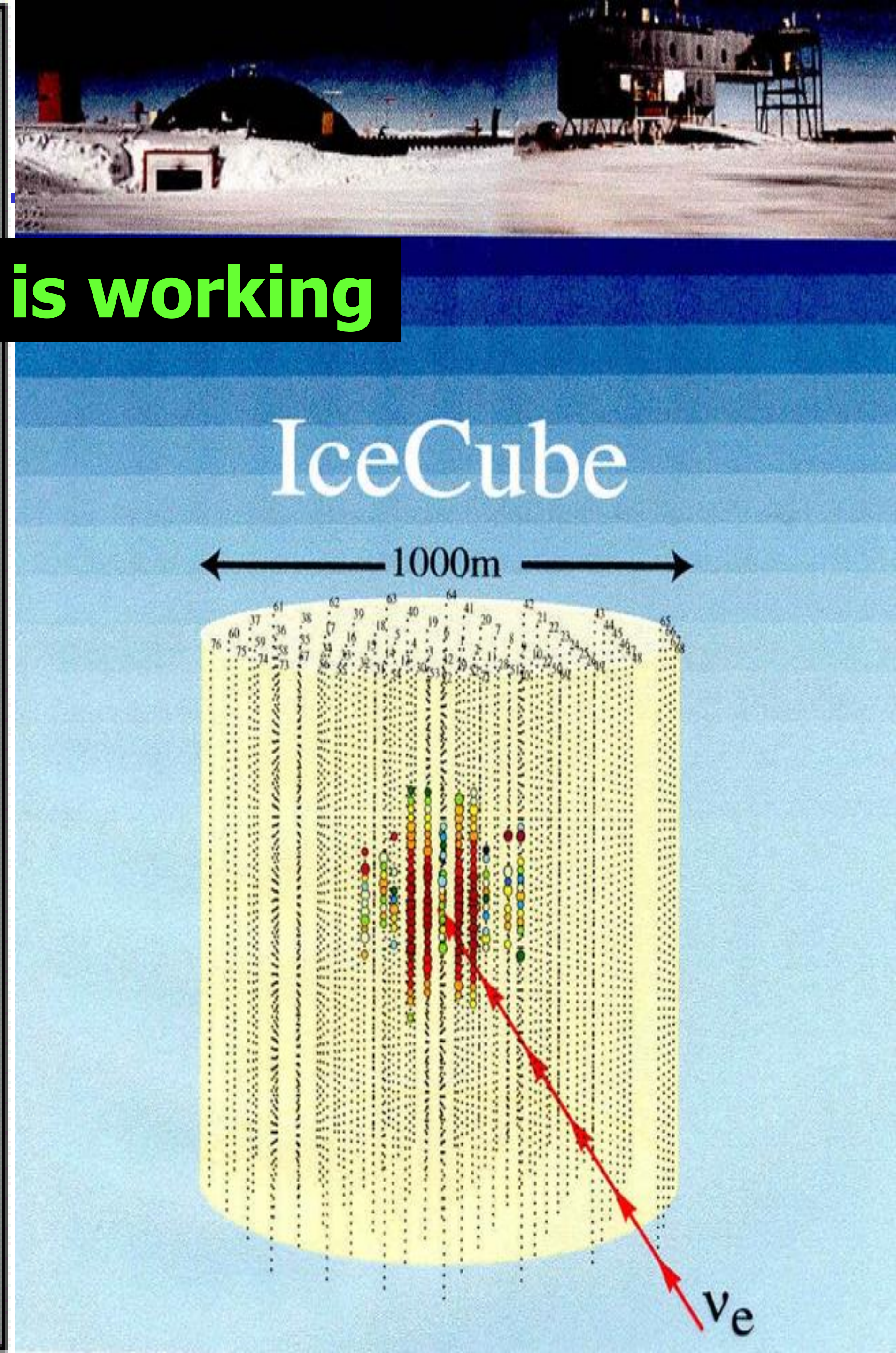
BAIKAL
Russia

AMANDA and IceCube

South Pole, Antarctica

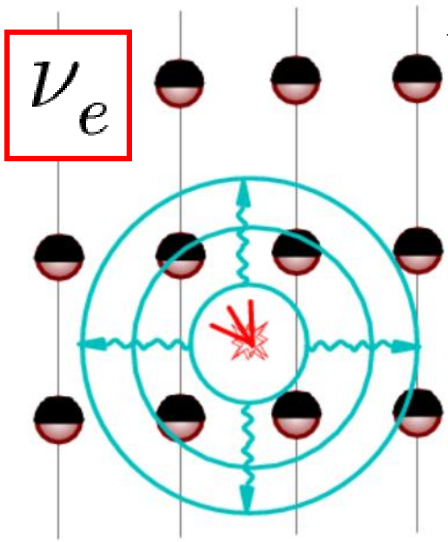
IceCube is working

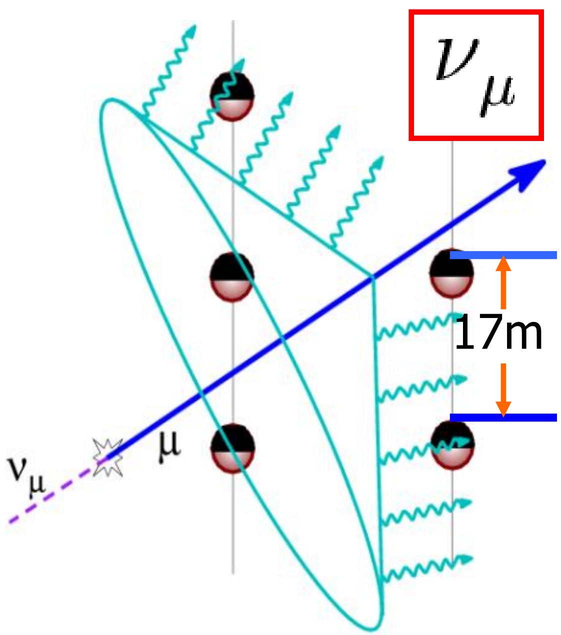




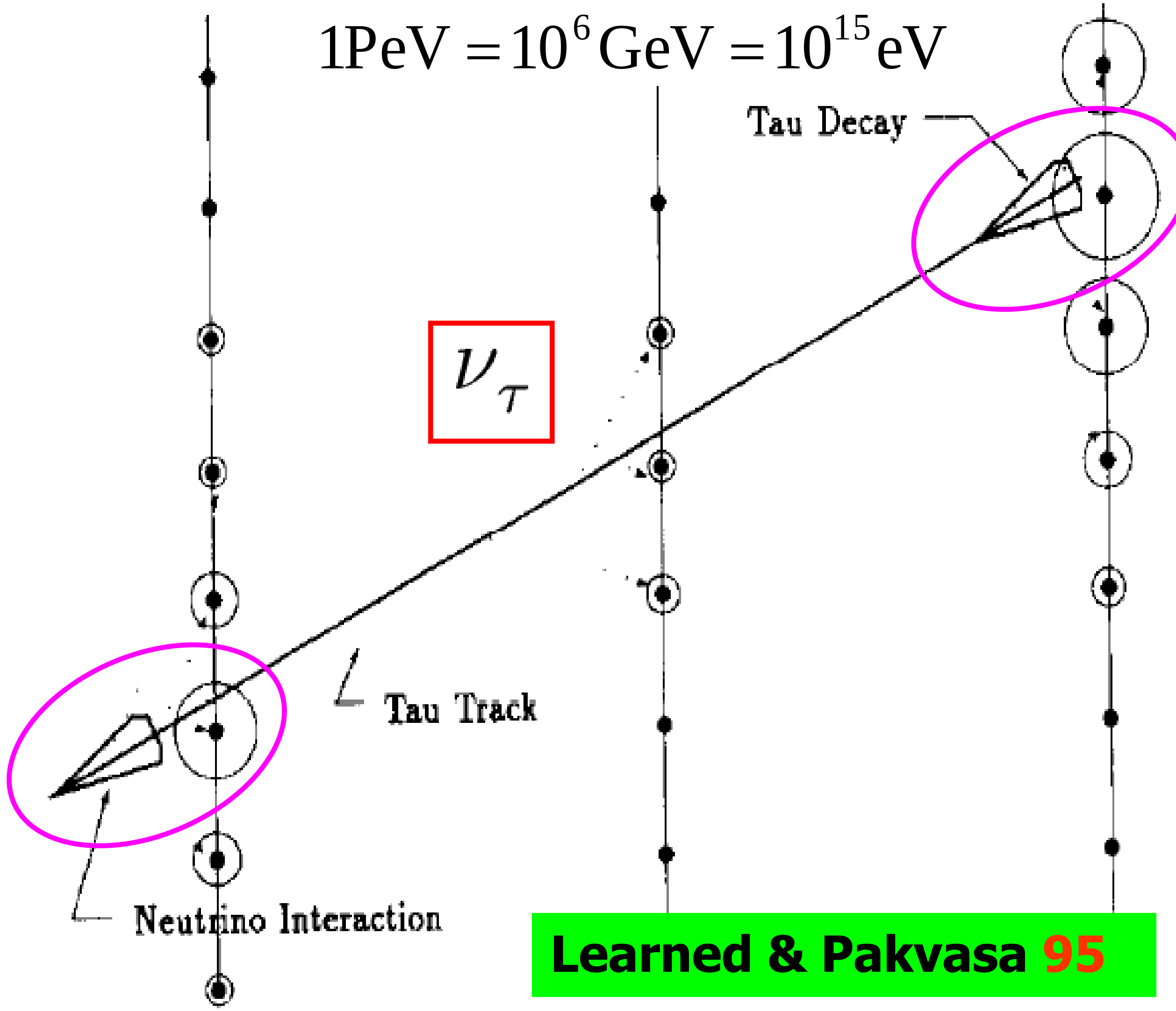
Flavor identification

Halzen, astro-ph/0602132





$$1\text{PeV} = 10^6\,\text{GeV} = 10^{15}\,\text{eV}$$



Learned & Pakvasa 95

2 PeV Events

IceCube:

arXiv:1304.5356 (PRL)

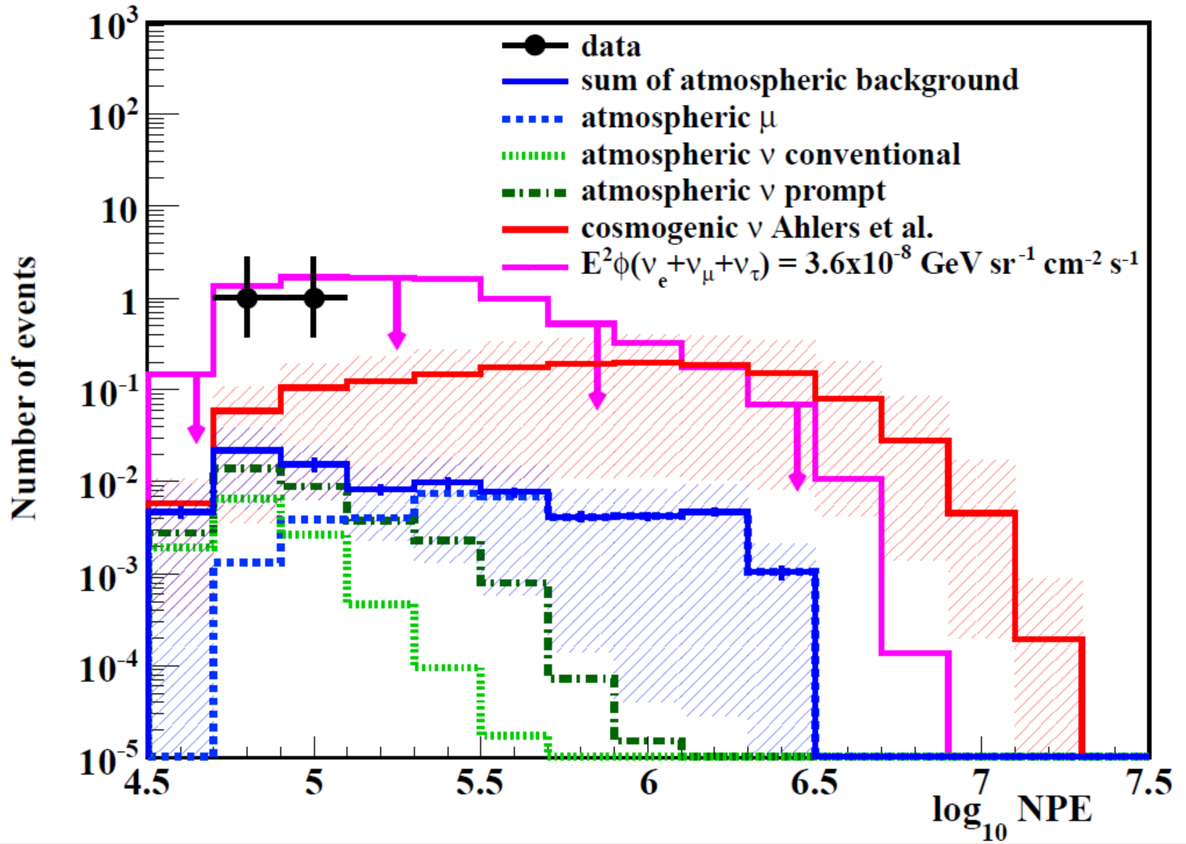
Event 1: 1.04 ± 0.16 PeV

Event 2: 1.14 ± 0.17 PeV

Very unlikely

--- ATM conventional ν's

--- Cosmogenic ν's



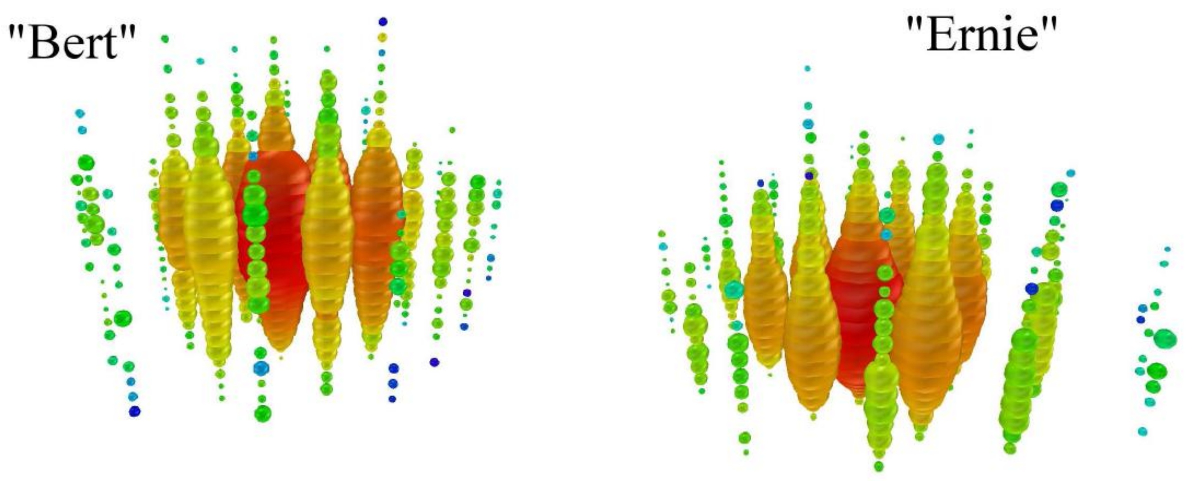
neutral-current $\nu_{e,\mu,\tau}$ $(\bar{\nu}_{e,\mu,\tau})$ or charged-current ν_e $(\bar{\nu}_e)$ interactions

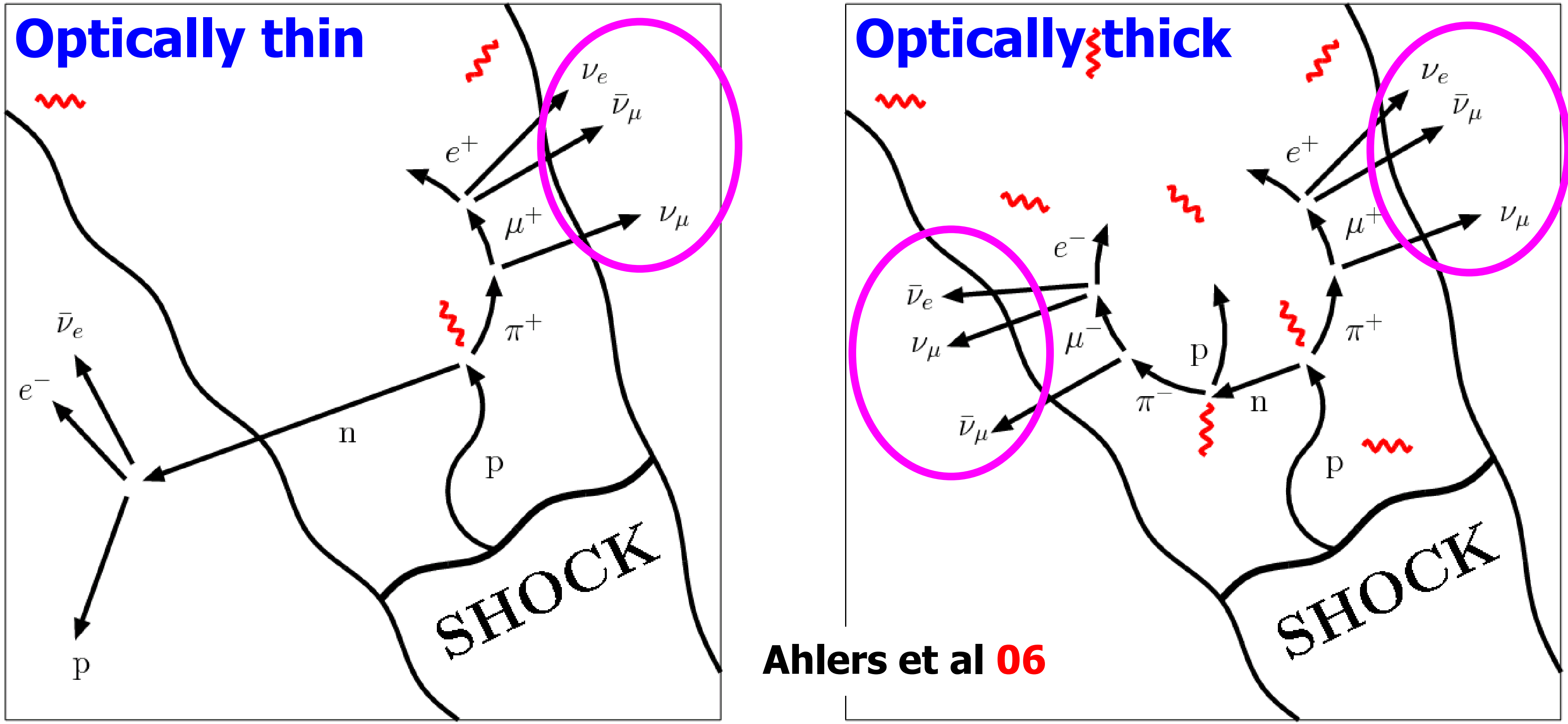
Disfavored

--- ATM prompt ν's

Plausible (2.8σ)

--- Astrophysical ν's





Ahlers et al 06

Conventional mechanism:

$$p + \gamma \to \Delta^+ \to \pi^+ + n$$

$$p + p \to \pi^\pm + X$$

$$\Phi_e^S : \Phi_\mu^S : \Phi_\tau^S = 1 : 2 : 0$$

$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^- \to \mu^- + \bar{\nu}_\mu$$
$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

Oscillations

The transition probability: $\alpha, \beta = e, \mu, \tau$ $\quad j, k = 1, 2, 3$

$$P(\nu_\alpha \to \nu_\beta) = \sum_{j=1}^{3} |V_{\alpha j}|^2 |V_{\beta j}|^2 + 2\mathrm{Re} \sum_{j<k} V_{\alpha j} V_{\beta k} V^*_{\alpha k} V^*_{\beta j} \exp\left\{ -\mathrm{i} \frac{\Delta m^2_{kj}}{2E} L \right\}$$

Expected sources (AGN) at a typical distance: ~100 Mpc.

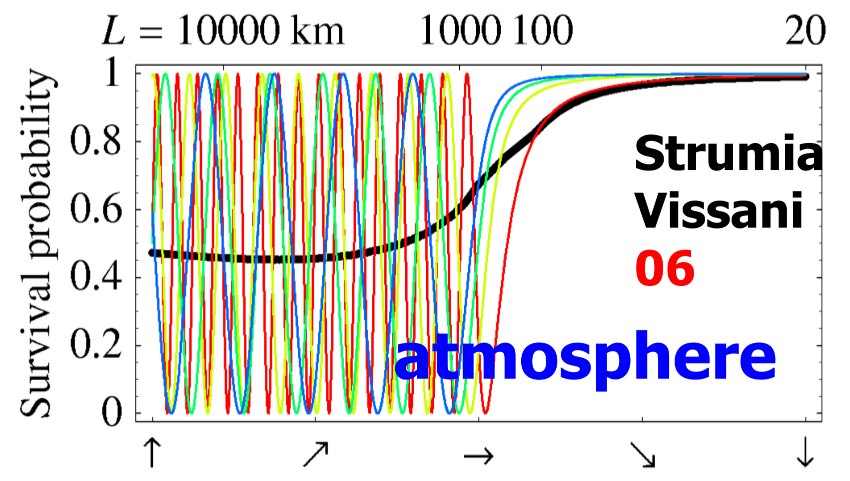
For $|\Delta m^2| \sim 10^{-4}\ \mathrm{eV}^2$ **, the oscillation length in vacuum:**

$$L_{\mathrm{OSC}} \equiv \frac{4\pi E_\nu}{|\Delta m^2|} \sim 8 \times 10^{-25} \mathrm{Mpc} \left(\frac{E_\nu}{1\ \mathrm{eV}} \right)$$

$$1\ \mathrm{Mpc} \approx 3.1 \times 10^{22}\ \mathrm{m}.$$

After many oscillations, the averaged probability of UHE cosmic neutrinos is

$$P(\nu_\alpha \to \nu_\beta) = \sum_{j=1}^{3} |V_{\alpha j}|^2 |V_{\beta j}|^2$$



Flavor democracy

At an astrophysical source: $\Phi_e^{\rm S} : \Phi_\mu^{\rm S} : \Phi_\tau^{\rm S} = 1 : 2 : 0$

At a ν-telescope: $\Phi_\beta^{\rm T} = \sum_\alpha \Phi_\alpha^{\rm S} P(\nu_\alpha \to \nu_\beta) = \sum_\alpha \sum_{i=1}^{3} \Phi_\alpha^{\rm S} |V_{\alpha i}|^2 |V_{\beta i}|^2$

If there is a μ-τ symmetry for *V*: $|V_{\mu i}| = |V_{\tau i}|$ $(i = 1, 2, 3)$

Then the unitarity of *V* leads to: $\Phi_e^{\rm T} : \Phi_\mu^{\rm T} : \Phi_\tau^{\rm T} = 1 : 1 : 1$

In the PDG parametrization (Xing, Zhou, 08):

$$V = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & +c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & c_{13}s_{23} \\ +s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

→

CPC: $\begin{cases} \theta_{13} = 0 \\ \theta_{23} = \pi/4 \end{cases}$

or

CPV: $\begin{cases} \delta = \pm\pi/2 \\ \theta_{23} = \pi/4 \end{cases}$

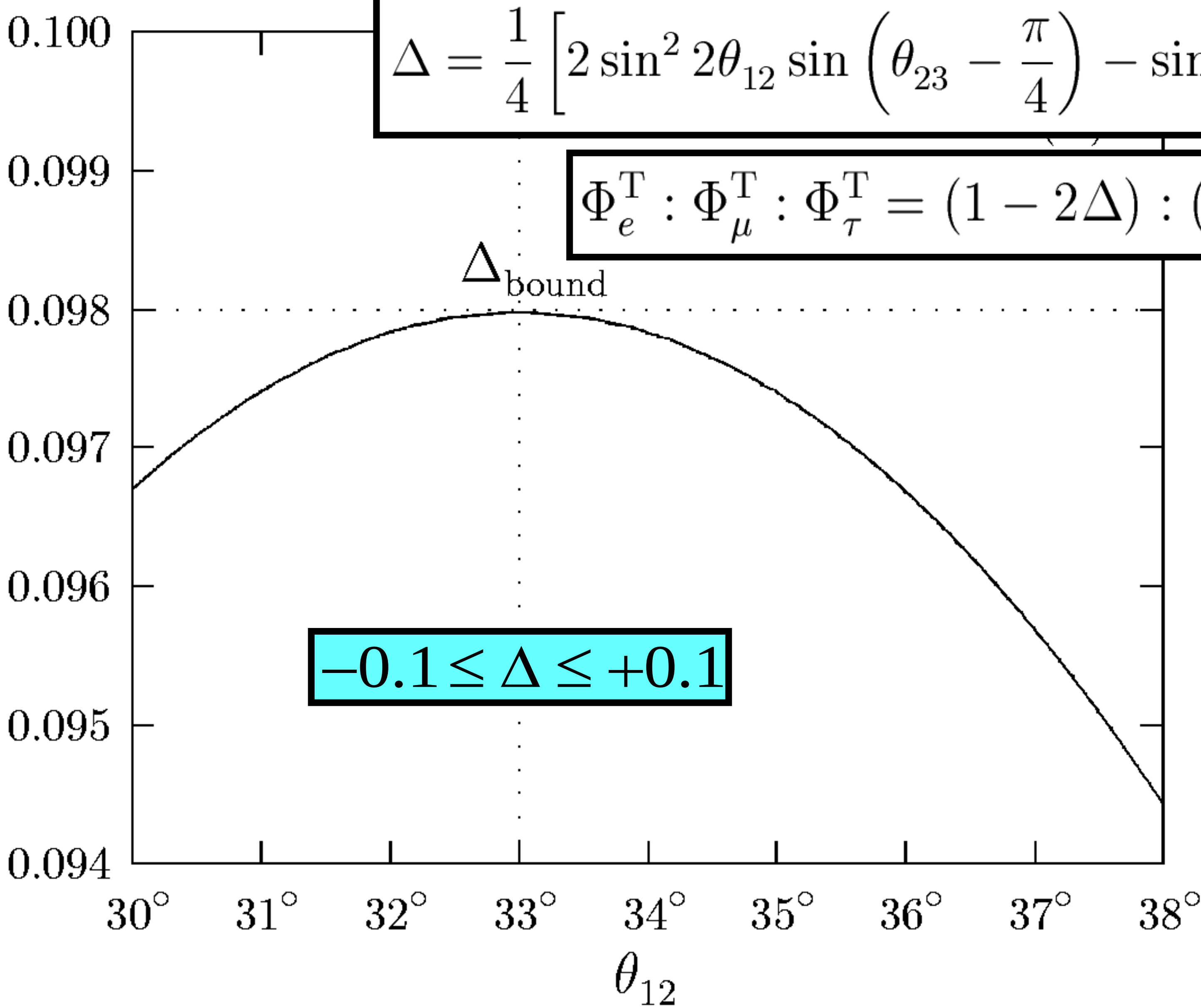
Near flavor democracy (Learned, Pakvasa, 95)

μ-τ symmetry breaking (Xing, 06, 12) $\Phi_e^{\rm T} : \Phi_\mu^{\rm T} : \Phi_\tau^{\rm T} = (1 - 2\Delta) : (1 + \Delta) : (1 + \Delta)$

μ-τ symmetry breaking

$$\Delta = \frac{1}{4}\left[2\sin^2 2\theta_{12}\sin\left(\theta_{23} - \frac{\pi}{4}\right) - \sin 4\theta_{12}\sin\theta_{13}\cos\delta\right]$$

$$\Phi_e^{\rm T} : \Phi_\mu^{\rm T} : \Phi_\tau^{\rm T} = (1 - 2\Delta) : (1 + \Delta) : (1 + \Delta)$$



A Question:

Even if such a nice flavor distribution is detected, we still do not know if UHE cosmic ν's originate from pγ or pp collisions

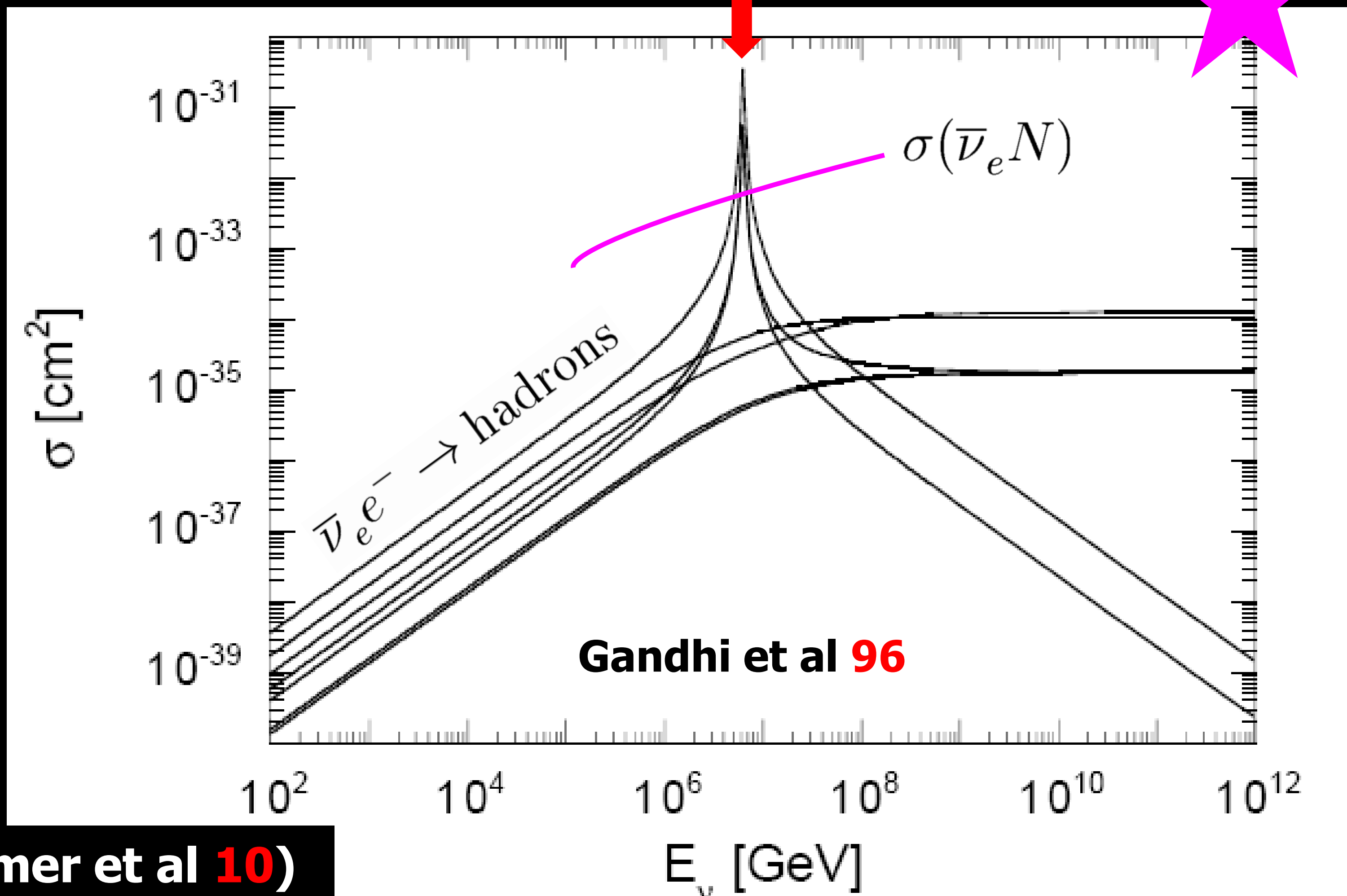
The Glashow resonance

$$\overline{\nu}_e + e^- \to W^- \to \text{anything}$$

Unique for electron anti-ν's!

(Glashow 60)

$$E_{\overline{\nu}_e} \simeq M_W^2/(2m_e) \simeq 6.3 \text{ PeV}$$



An interesting discriminator between pγ & pp collisions at an optically thin source of cosmic rays. (Anchordoqui et al 05, Hummer et al 10)

Cosmic Flavor Physics

CνB

Hot DM

keV ν's

Warm DM

Baryogenesis

Leptogenesis

Energetic ν's

from cold DM

UHE

Cosmic ν's

Supernova ν's

(relic background)

......

A New Road Ahead?