Physics of Massive Neutrinos

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(IHEP, Beijing)

A: Neutrino history and lepton family

B: Neutrino masses and flavor mixing

C: Description of neutrino oscillations

D: Implication of neutrino oscillations

E: θ_{13} hint and sterile neutrino puzzle

F: On TeV neutrino physics at the LHC

G: Extreme corners in the neutrino sky

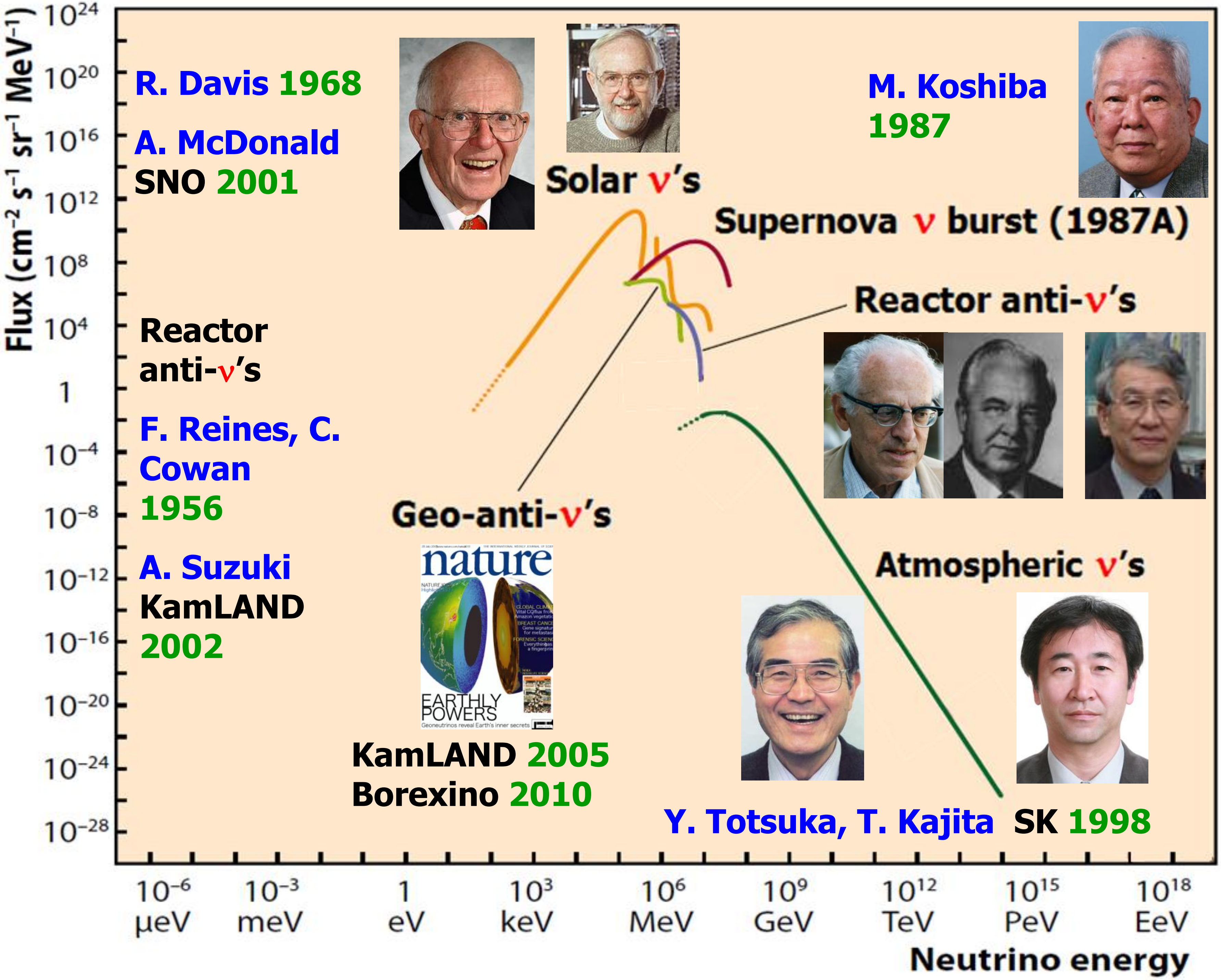
H: Cosmic baryon number asymmetry

ν ν ν

@Lectures at CP3, UCL, Louvain-la-Neuve, Belgium, Jan 2012

Lecture G

- ★ **Two Extremes in the Neutrino Sky**
- ★ **UHE Cosmic Neutrino Telescopes**
- ★ **ULE Cosmic Neutrino Background**



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}
R. Davis 1968
A. McDonald
SNO 2001
Reactor anti-ν's
F. Reines, C. Cowan 1956
A. Suzuki KamLAND 2002
Solar ν's
M. Koshiba 1987
Supernova ν burst (1987A)
Reactor anti-ν's
Geo-anti-ν's
nature
EARTHLY POWERS
Atmospheric ν's
KamLAND 2005
Borexino 2010
Y. Totsuka, T. Kajita
SK 1998
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

Lesson: ν Oscillations + MSW













arXiv:1103.0734
T. Schwetz, et al.

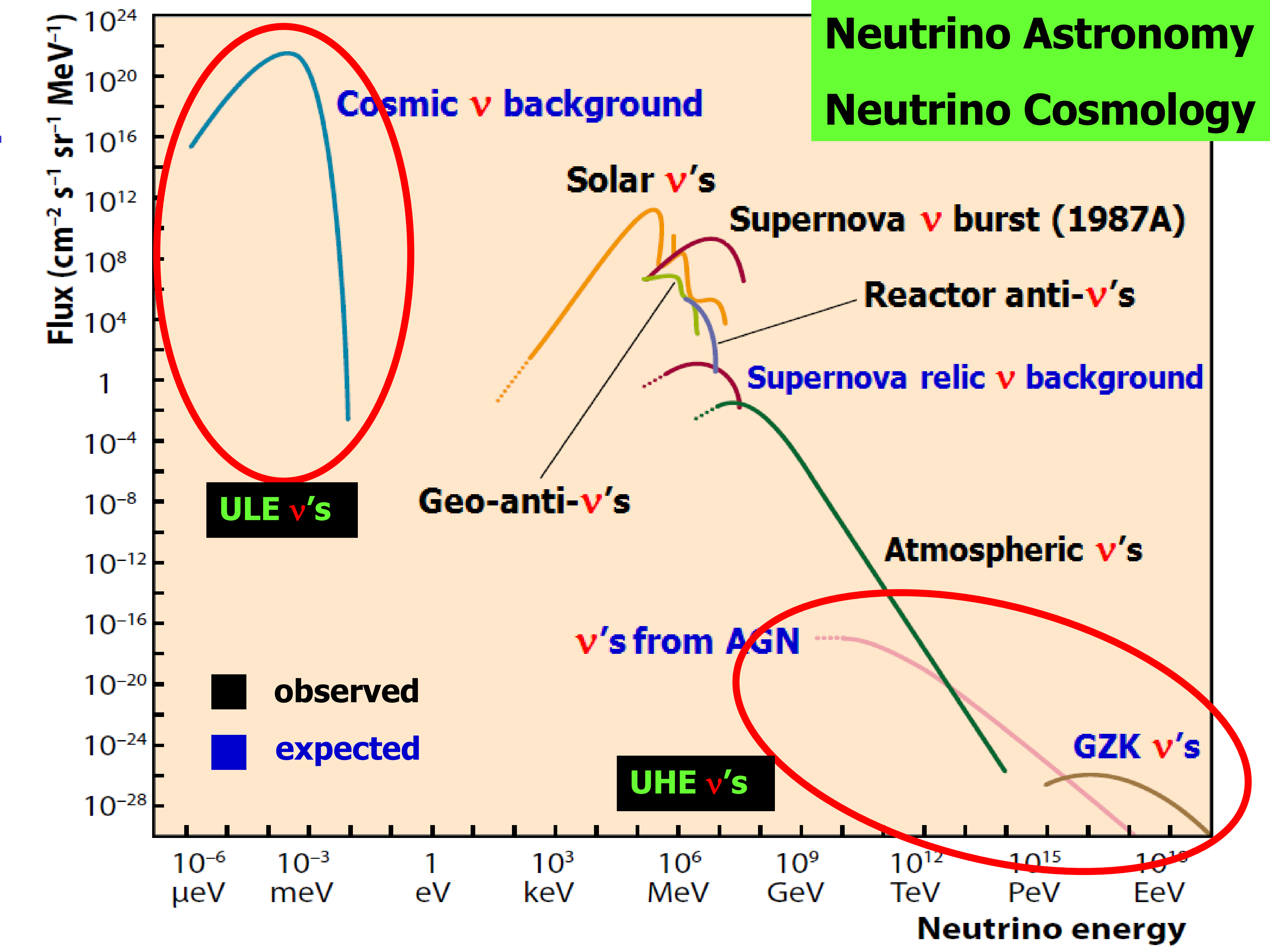
Current Data

parameter	best fit $\pm 1\sigma$		3σ
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.59^{+0.20}_{-0.18}$	7.2	7.09–8.19
Δm^2_{31} $[10^{-3}\mathrm{eV}^2]$	2.45 ± 0.09 $-(2.34^{+0.10}_{-0.09})$	$2.28 - 2.64$ $-(2.17 - 2.54)$	$2.18 - 2.73$ $-(2.08 - 2.64)$
$\sin^2\theta_{12}$	$0.312^{+0.017}_{-0.015}$	0.28–0.35	0.27–0.36
$\sin^2\theta_{23}$	0.51 ± 0.06 0.52 ± 0.06	0.41–0.61 0.4	[illegible]
$\sin^2\theta_{13}$	$0.010^{+0.009}_{-0.006}$ $0.013^{+0.009}_{-0.007}$	$\leq$ $\leq$	

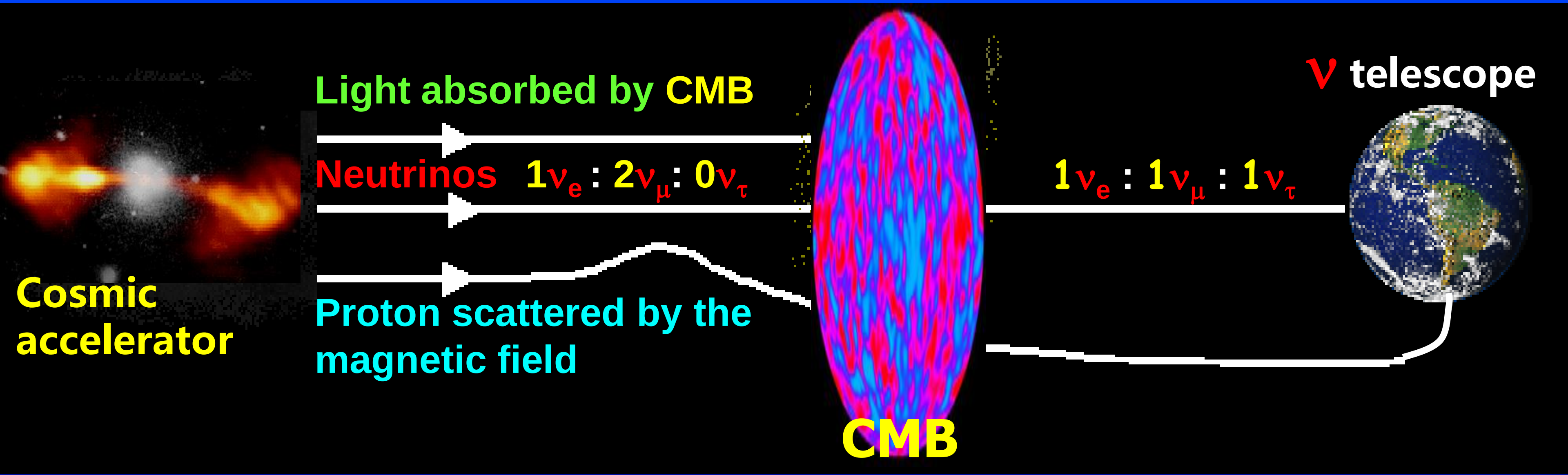
Much larger theta(13)

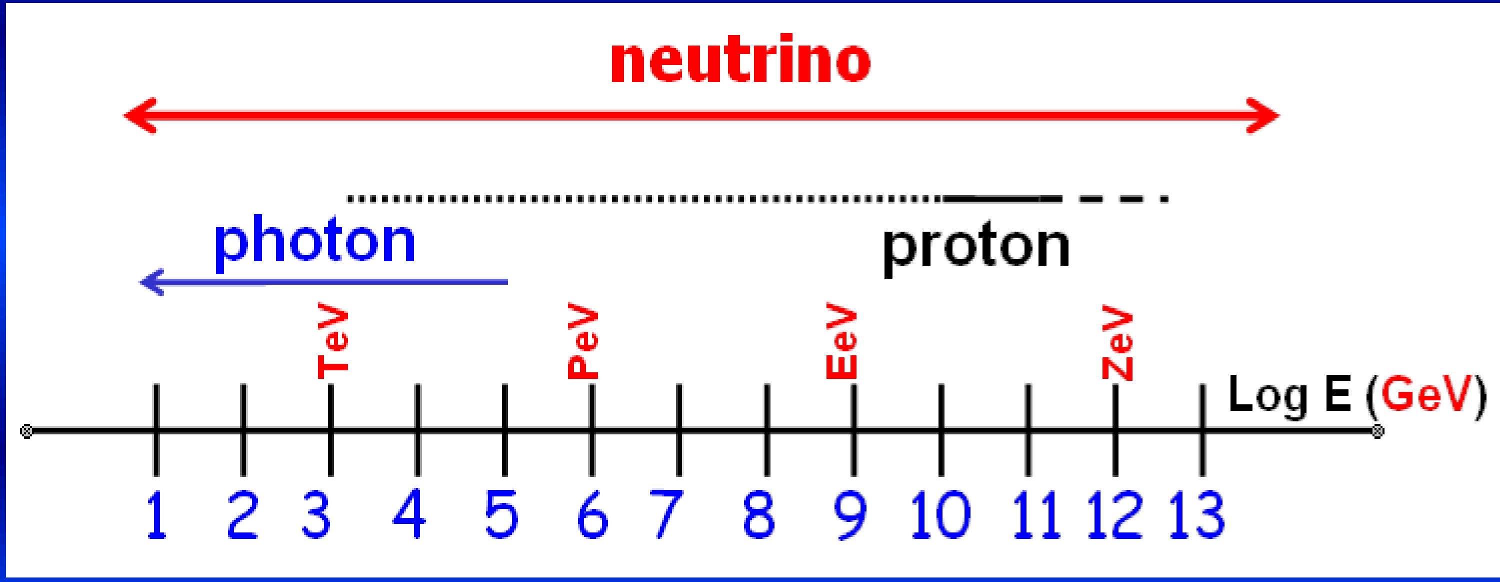
T2K/MINOS/Double Chooz

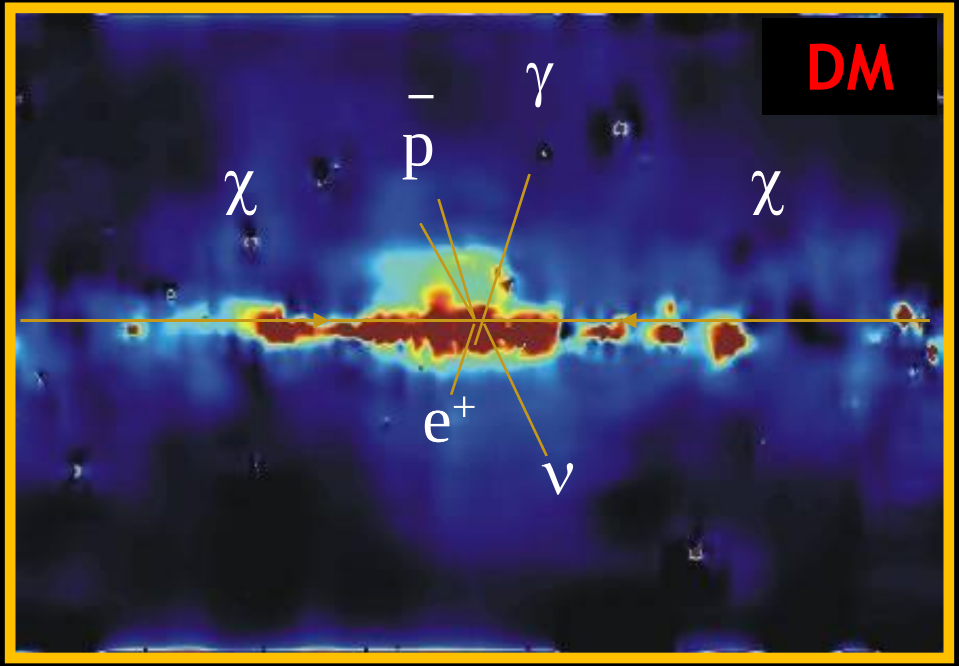
~ 8 degrees (3.5 σ ?)


Neutrino Astronomy
Neutrino Cosmology
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
ULE ν's
Atmospheric 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
EeV
Neutrino energy

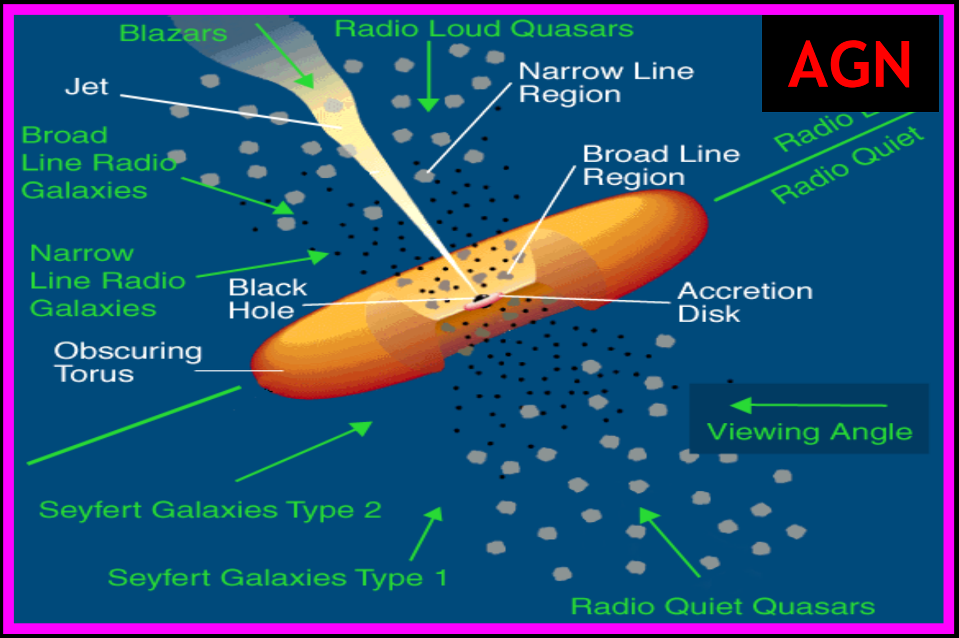
UHE Cosmic Messenger







Possible astrophysical sources of UHE cosmic neutrinos ...



Optical Cherencov NTs

ANTARES
La-Seyne-sur-Mer, France

BAIKAL
Russia

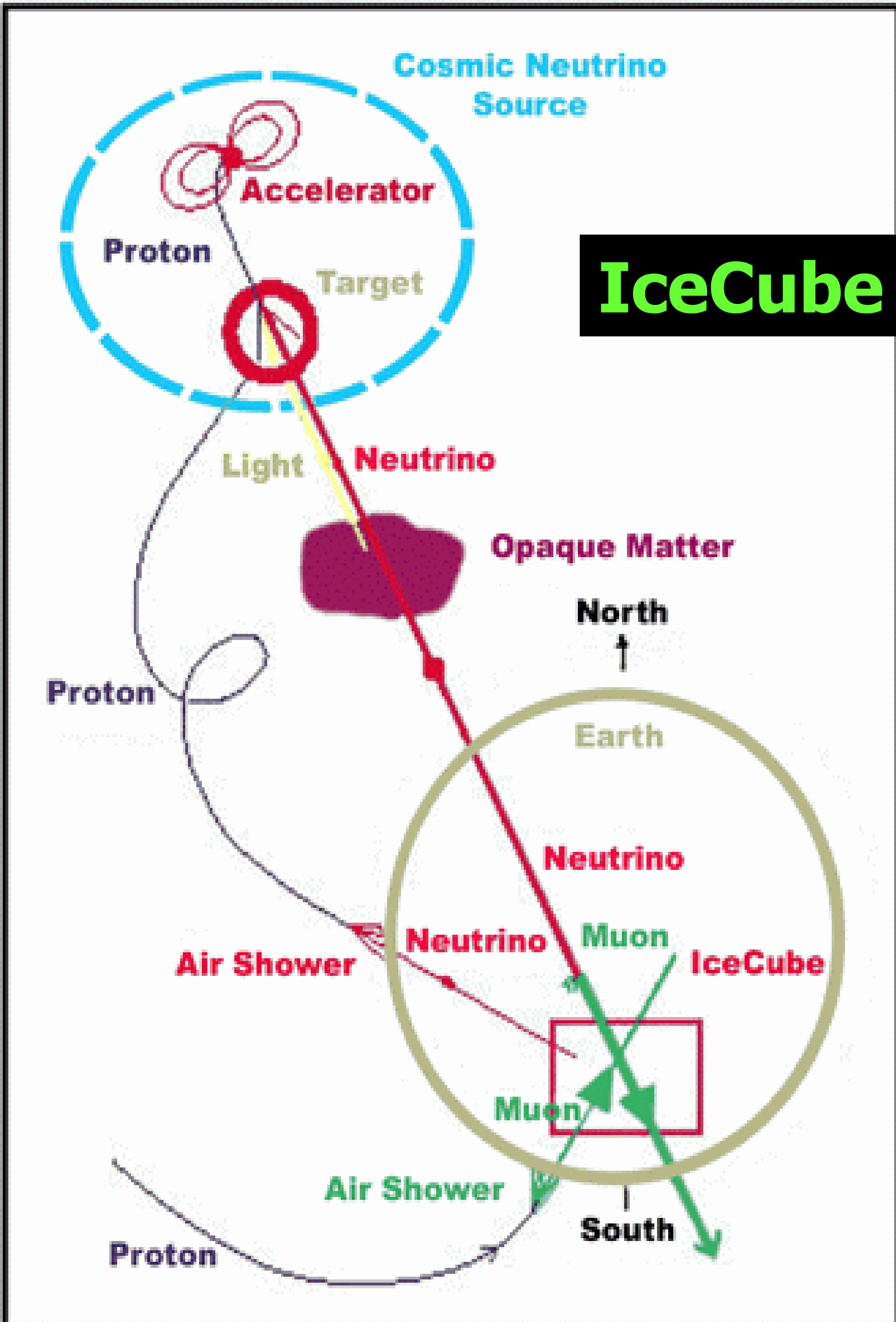
NEMO
Catania, Italy

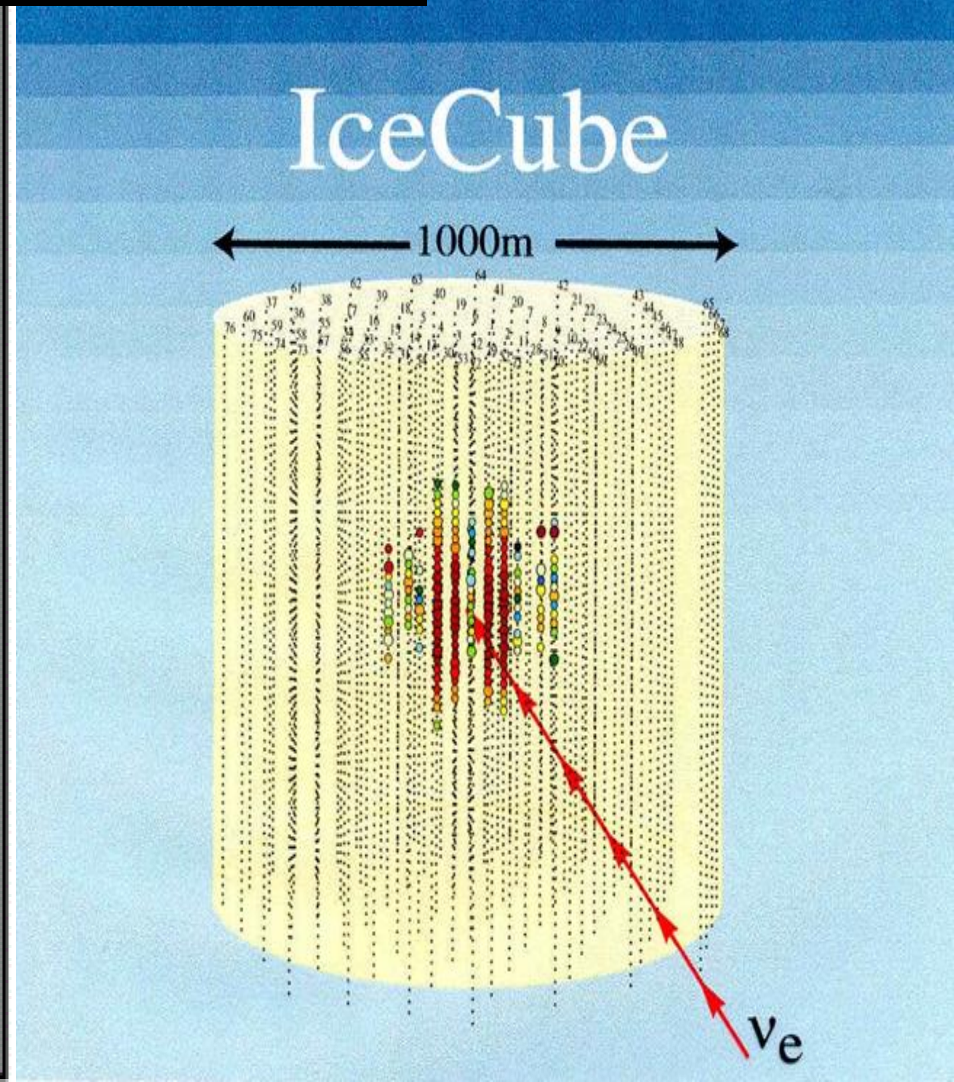
NESTOR
Pylos, Greece

AMANDA and IceCube

South Pole, Antarctica

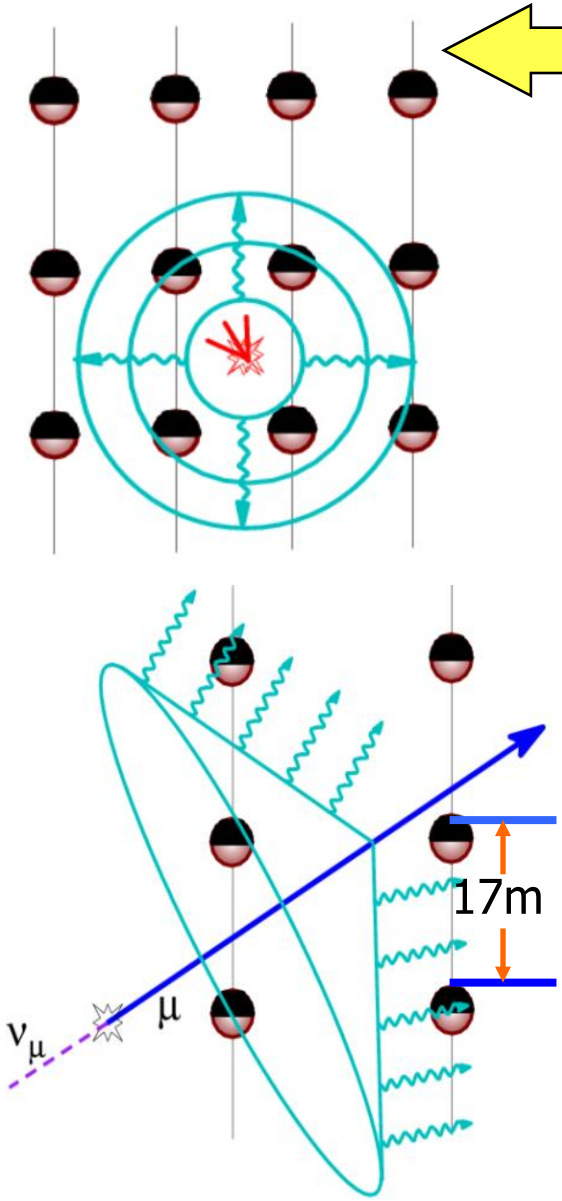
IceCube is working



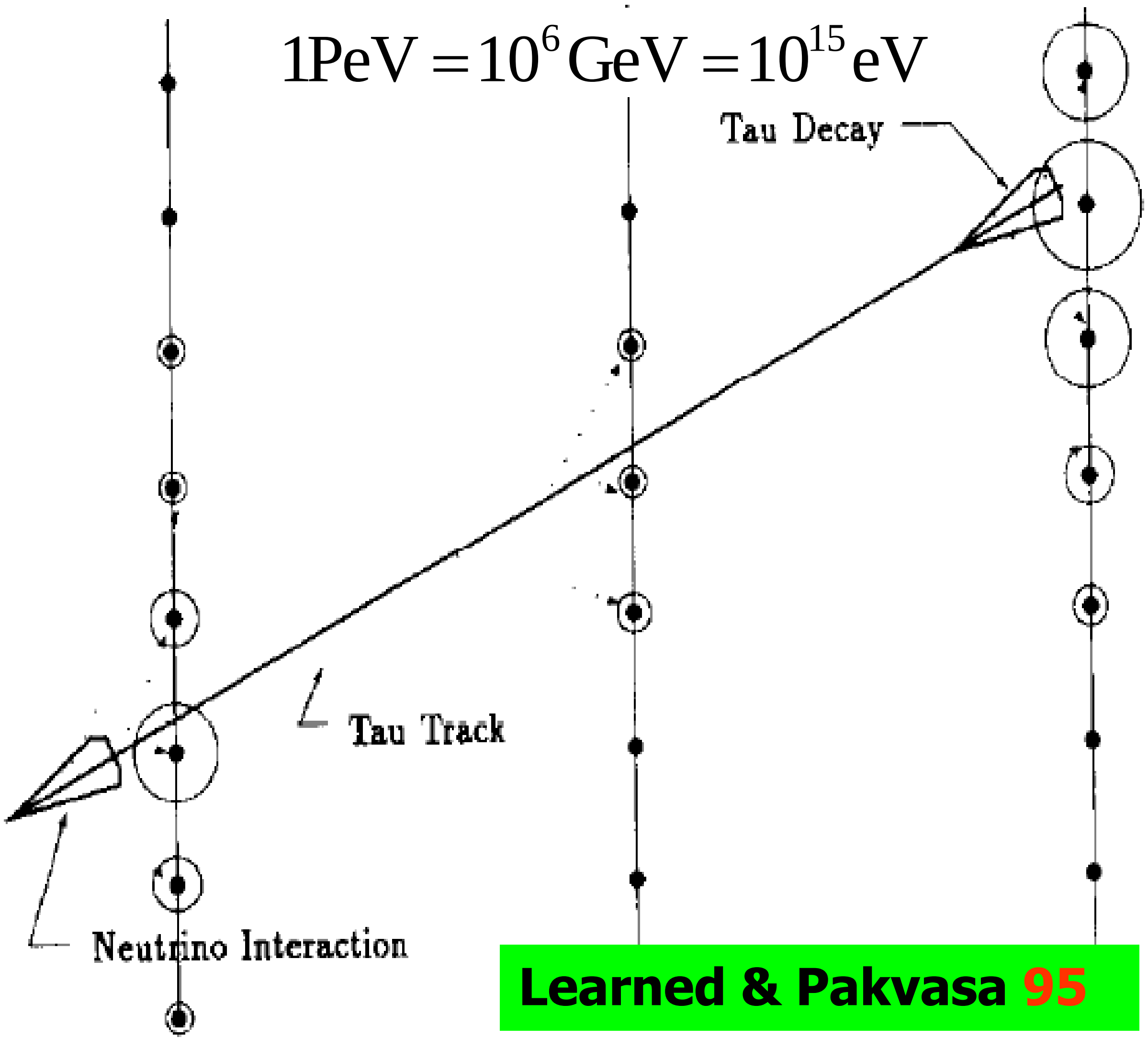


Flavor Identification

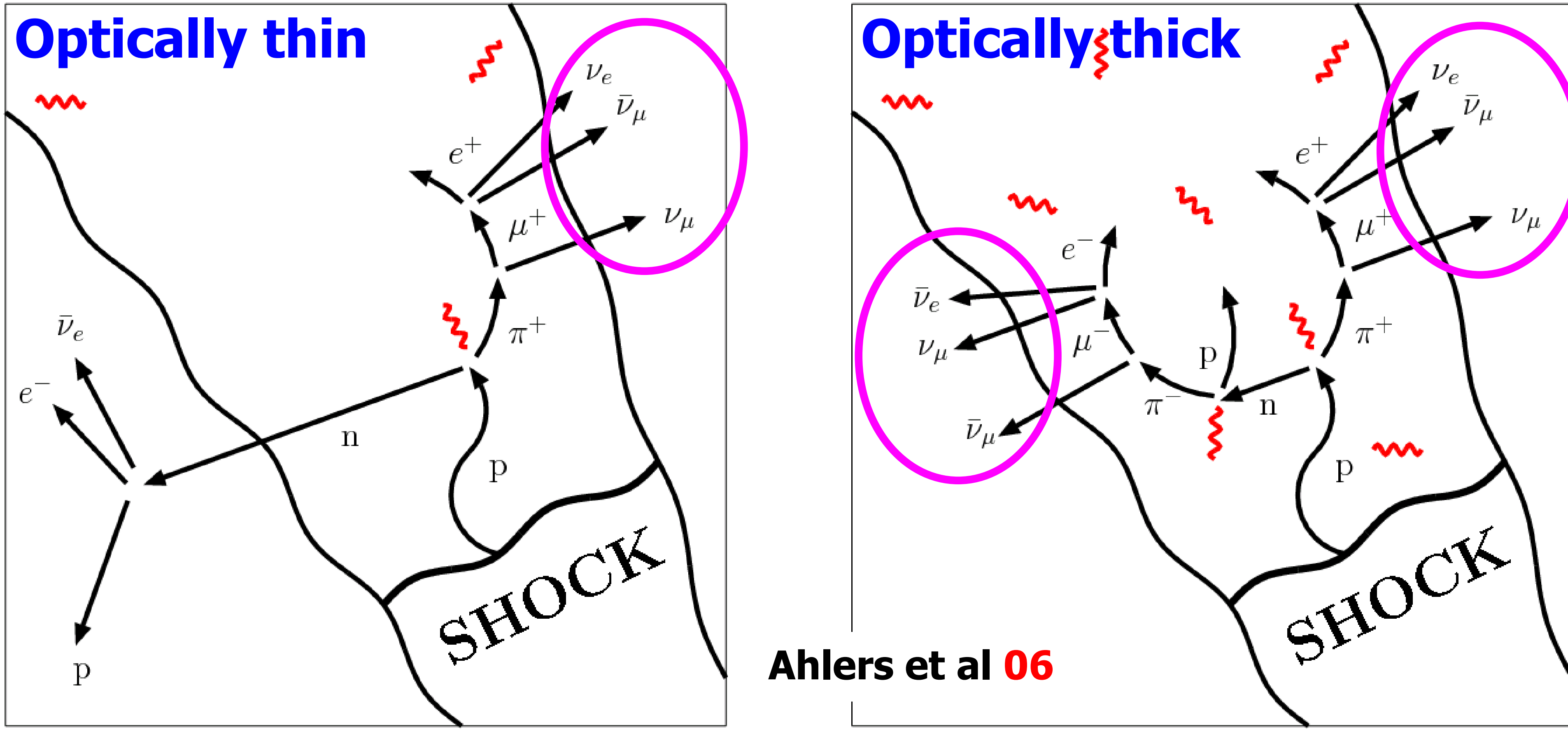
Halzen, astro-ph/0602132



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



Learned & Pakvasa 95



Ahlers et al 06

Conventional mechanism:

$$p + \gamma \rightarrow \Delta^{+} \rightarrow \pi^{+} + n$$

$$p + p \rightarrow \pi^{\pm} + X$$

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

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

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

Oscillations

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

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

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

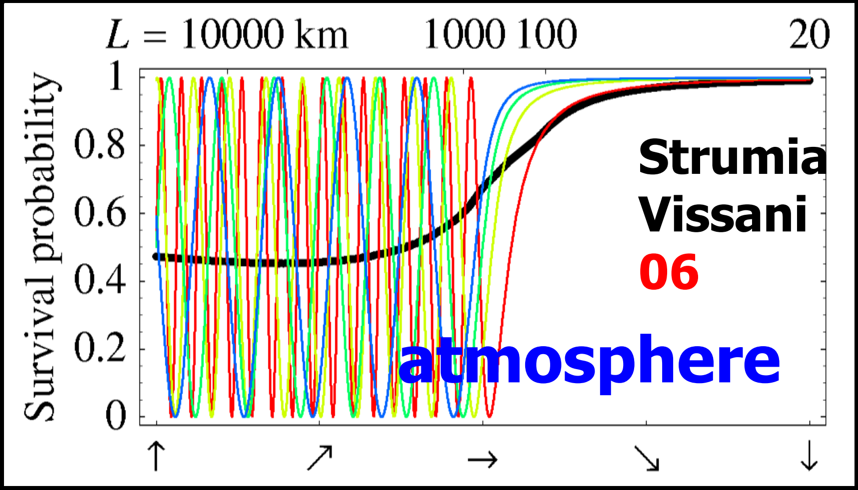
For $|\Delta m^2| \sim 10^{-4}\ \mathrm{eV}^2$, the oscillation length in vacuum:

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

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

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

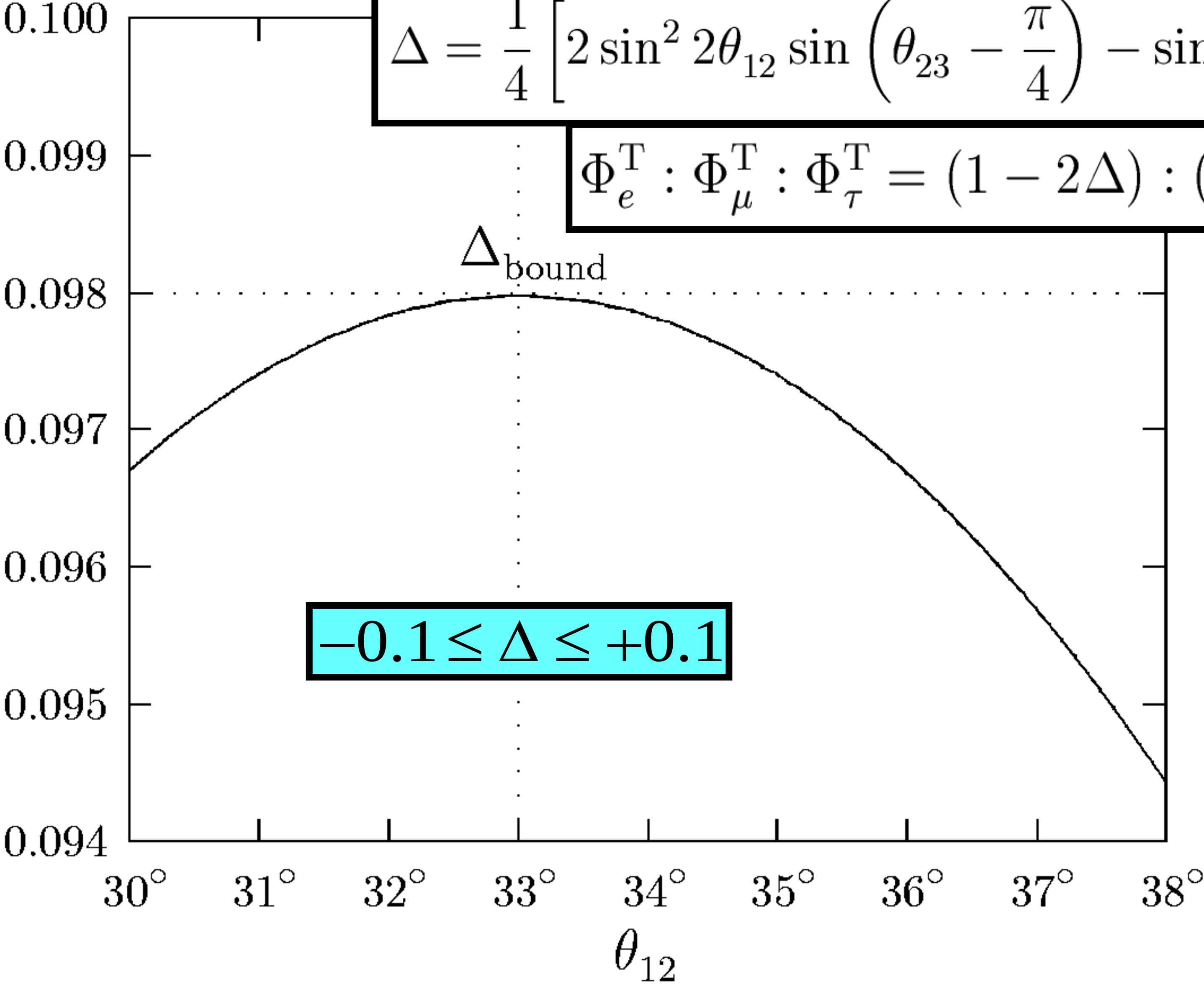
Near flavor democracy (Learned, Pakvasa, 95)

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

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

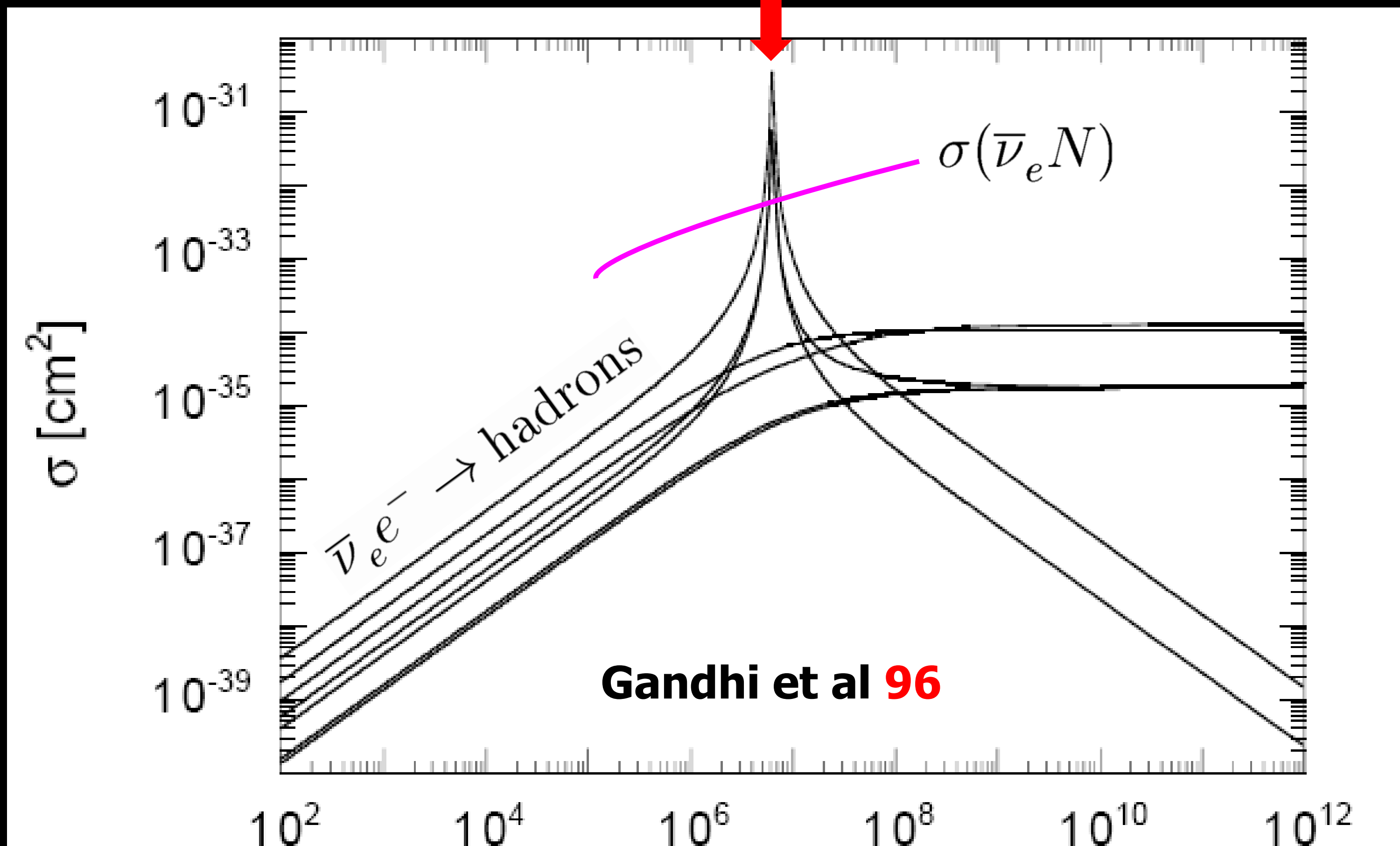
The Glashow Resonance

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

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)

A Parametrization

Assume a cosmic accelerator with both **p**γ & **pp** collisions.

$$\delta_{p\gamma} \equiv \frac{\Phi^{p\gamma}_{\pi^-}}{\Phi^{p\gamma}_{\pi^+}} \qquad \delta_{pp} \equiv \frac{\Phi^{pp}_{\pi^-}}{\Phi^{pp}_{\pi^+}} - 1$$

$$\kappa \equiv \frac{\Phi^{p\gamma}_{\pi^+} + \Phi^{p\gamma}_{\pi^-}}{\Phi^{pp}_{\pi^+} + \Phi^{pp}_{\pi^-} + \Phi^{p\gamma}_{\pi^+} + \Phi^{p\gamma}_{\pi^-}}$$

- ★ Pure pγ collisions: κ = 1
- ★ Pure pp collisions: κ = 0

They describe departures from the conventional cases (Xing, Zhou, 11)

At the source: (note that $\Phi^{\rm S}_e : \Phi^{\rm S}_\mu : \Phi^{\rm S}_\tau = 1:2:0$ doesn't change)

$$\left\{\Phi^{\rm S}_{\nu_e} : \Phi^{\rm S}_{\overline{\nu}_e} : \Phi^{\rm S}_{\nu_\mu} : \Phi^{\rm S}_{\overline{\nu}_\mu} : \Phi^{\rm S}_{\nu_\tau} : \Phi^{\rm S}_{\overline{\nu}_\tau}\right\}$$

$$= \left(\Phi^{p\gamma}_{\pi^+} + \Phi^{pp}_{\pi^+}\right)\left\{\frac{1}{3} : 0 : \frac{1}{3} : \frac{1}{3} : 0 : 0\right\} + \left(\Phi^{p\gamma}_{\pi^-} + \Phi^{pp}_{\pi^-}\right)\left\{0 : \frac{1}{3} : \frac{1}{3} : \frac{1}{3} : 0 : 0\right\}$$

$$= \left\{\frac{1}{3}\left[\frac{1}{2+\delta_{pp}} + \frac{1+\delta_{pp}-\delta_{p\gamma}}{(2+\delta_{pp})(1+\delta_{p\gamma})}\kappa\right] : \frac{1}{3}\left[\frac{1+\delta_{pp}}{2+\delta_{pp}} - \frac{1+\delta_{pp}-\delta_{p\gamma}}{(2+\delta_{pp})(1+\delta_{p\gamma})}\kappa\right] : \frac{1}{3} : \frac{1}{3} : 0 : 0\right\}$$

At the ν-telescope: (the Glashow resonance working observable)

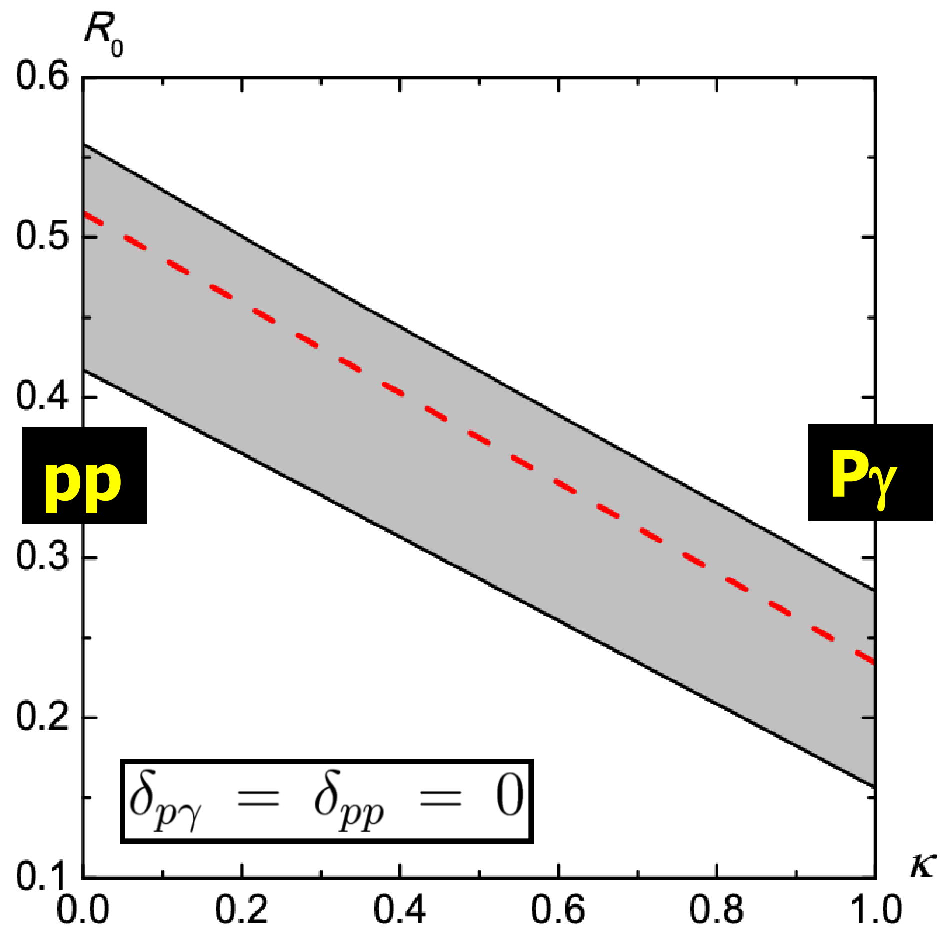
$$R_0 \equiv \frac{\Phi^{\rm T}_{\overline{\nu}_e}}{\Phi^{\rm T}_{\nu_\mu} + \Phi^{\rm T}_{\overline{\nu}_\mu}} = \left[\frac{1+\delta_{pp}}{2+\delta_{pp}} - \frac{1+\delta_{pp}-\delta_{p\gamma}}{(2+\delta_{pp})(1+\delta_{p\gamma})}\kappa\right]\frac{P_{ee}}{P_{e\mu}+2P_{\mu\mu}} + \frac{P_{e\mu}}{P_{e\mu}+2P_{\mu\mu}}$$

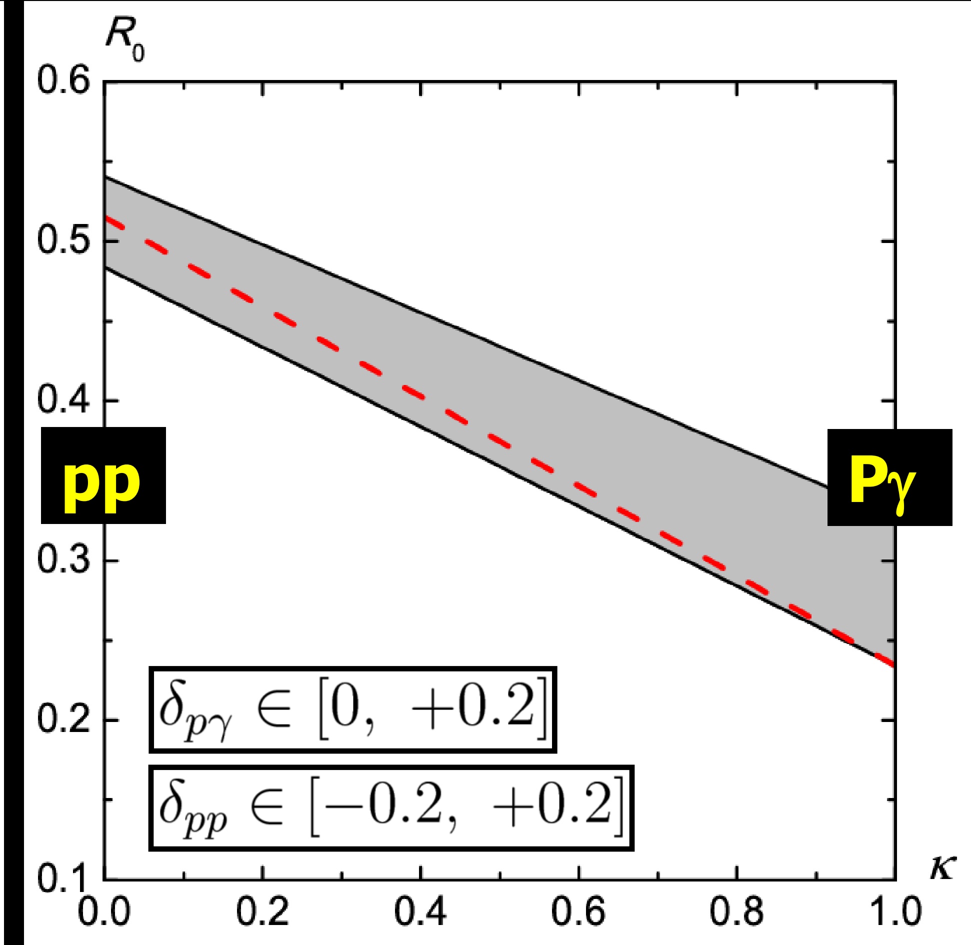
Numerical Illustration

Input the best-fit values + 1σ error bars of 3 neutrino mixing angles (Schwetz et al 11)

$$\sin^2\theta_{12} = 0.312^{+0.017}_{-0.015}$$
$$\sin^2\theta_{23} = 0.51 \pm 0.06$$
$$\sin^2\theta_{13} = 0.010^{+0.009}_{-0.006}$$

---- : best-fit + δ = 0 + $\delta_{p\gamma} = \delta_{pp} = 0$





IceCube

WB $E_\nu^2 \Phi_{\nu+\overline{\nu}} = 2 \times 10^{-8}\ \epsilon_\pi\ \xi_z\ \text{GeV cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$

$\Phi_0 \equiv 6 \times 10^{-8}\ \text{GeV}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}\ (1\ \text{GeV}/E_\nu)^2$

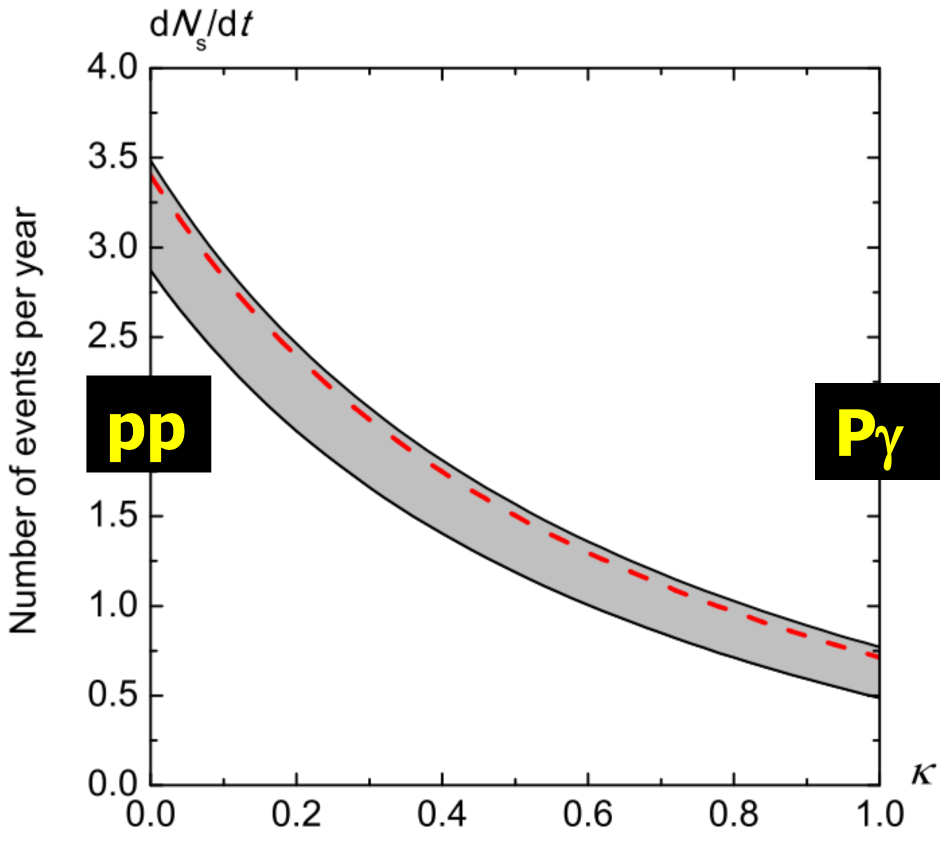
$$\Phi^{\mathrm{T}}_{\nu_\alpha} = \Phi_0 \frac{\epsilon_\pi^{pp}\ \epsilon_\pi^{p\gamma}}{(1-\kappa)\,\epsilon_\pi^{p\gamma} + \kappa\ \epsilon_\pi^{pp}} \times \left\{ \frac{1}{3}\left[\frac{1}{2+\delta_{pp}} + \frac{1+\delta_{pp}-\delta_{p\gamma}}{(2+\delta_{pp})(1+\delta_{p\gamma})}\kappa\right] P_{e\alpha} + \frac{1}{3} P_{\mu\alpha} \right\}$$

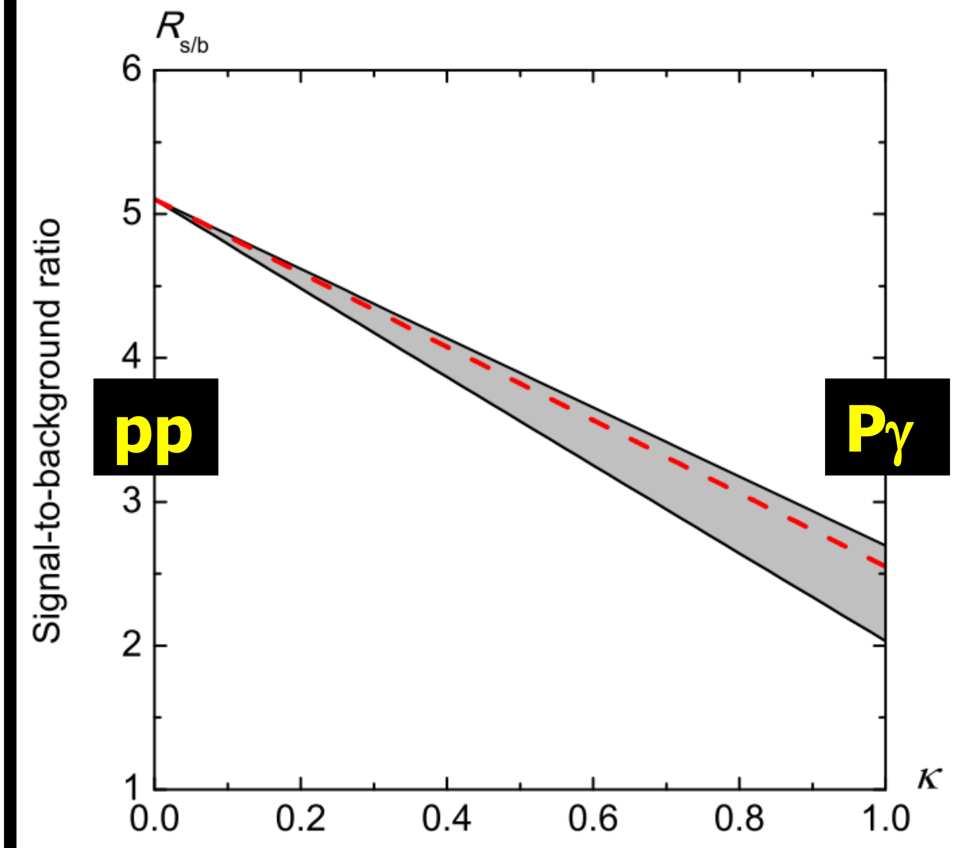
$$\Phi^{\mathrm{T}}_{\overline{\nu}_\alpha} = \Phi_0 \frac{\epsilon_\pi^{pp}\ \epsilon_\pi^{p\gamma}}{(1-\kappa)\,\epsilon_\pi^{p\gamma} + \kappa\ \epsilon_\pi^{pp}} \times \left\{ \frac{1}{3}\left[\frac{1+\delta_{pp}}{2+\delta_{pp}} - \frac{1+\delta_{pp}-\delta_{p\gamma}}{(2+\delta_{pp})(1+\delta_{p\gamma})}\kappa\right] P_{e\alpha} + \frac{1}{3} P_{\mu\alpha} \right\}$$

$\epsilon_\pi^{p\gamma} \approx 0.25$

$\epsilon_\pi^{pp} \approx 0.6$

$\delta_{p\gamma} = \delta_{pp} = 0$

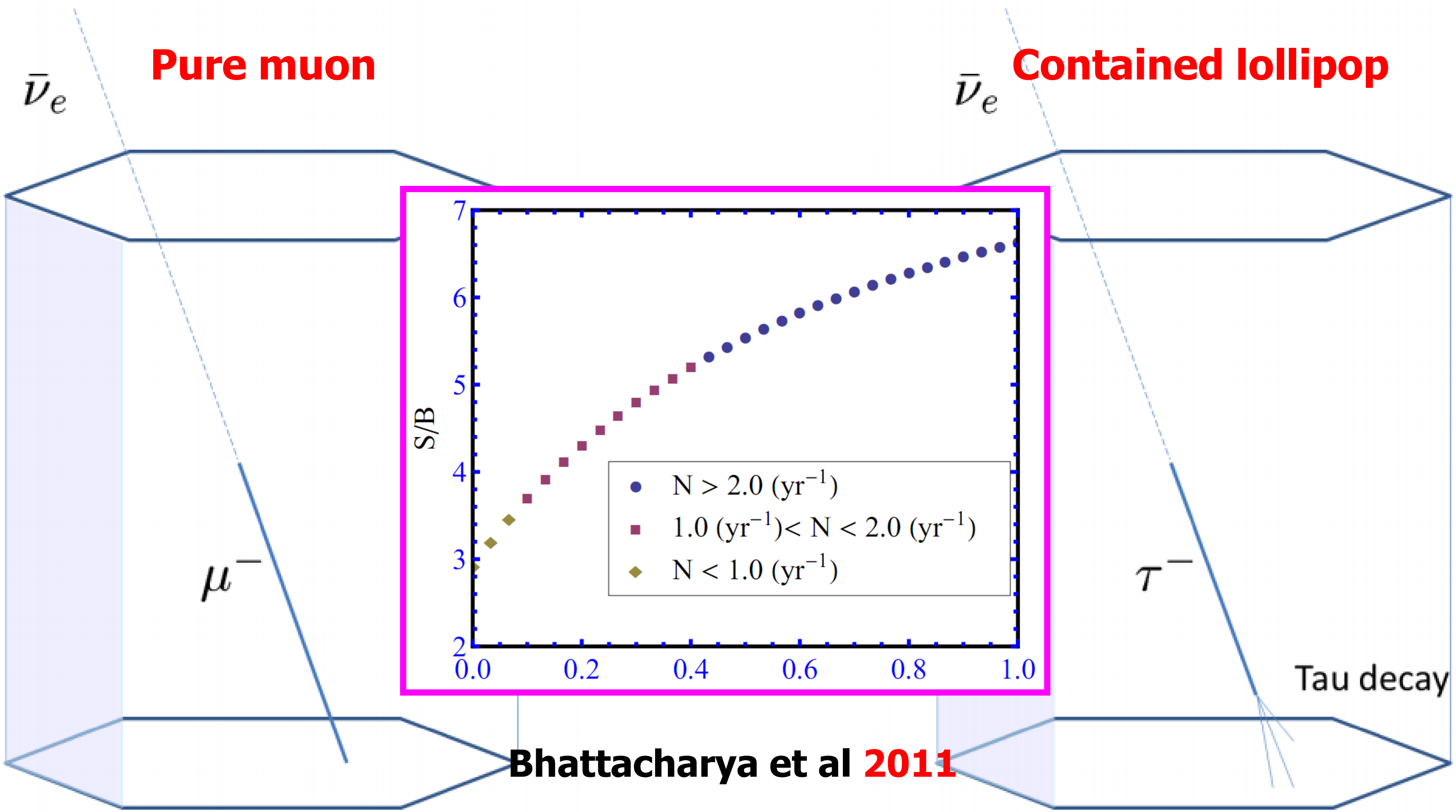




$\mu + \tau$ modes

Interaction	σ [cm^2]
$\bar{\nu}_e e \to \bar{\nu}_e e$	5.38×10^{-32}
$\bar{\nu}_e e \to \bar{\nu}_\mu \mu$	5.38×10^{-32}
$\bar{\nu}_e e \to \bar{\nu}_\tau \tau$	5.38×10^{-32}
$\bar{\nu}_e e \to$ hadrons	3.41×10^{-31}
$\bar{\nu}_e e \to$ anything	5.02×10^{-31}

Interaction	σ [cm^2]
$\nu_\mu N \to \mu +$ anything	1.43×10^{-33}
$\nu_\mu N \to \nu_\mu +$ anything	6.04×10^{-34}
$\nu_\mu e \to \nu_e \mu$	5.42×10^{-35}



Bhattacharya et al 2011

Generic Flavor Distribution

Parametrization [Xing, Zhou 06]:

$$\{\phi_e, \phi_\mu, \phi_\tau\} = \{\sin^2\xi \cos^2\zeta, \cos^2\xi \cos^2\zeta, \sin^2\zeta\}\phi_0$$

where ζ characterizes the small amount of tau ν's at the source [e.g., from Ds- or B-meson decays (Learned, Pakvasa 95)].

Lipari et al 07; Pakvasa et al 08: 1 : 2 : 0 → 1 : 1.852 : 0.001

- **Conventional (or standard) source:**

$$\phi_e : \phi_\mu : \phi_\tau = 1:2:0 \longleftrightarrow (\xi, \zeta) = (35.3^\circ, 0^\circ)$$

- **Postulated neutron source:**

$$\phi_e : \phi_\mu : \phi_\tau = 1:0:0 \longleftrightarrow (\xi, \zeta) = (90^\circ, 0^\circ)$$

- **Possible muon-damped source:**

$$\phi_e : \phi_\mu : \phi_\tau = 0:1:0 \longleftrightarrow (\xi, \zeta) = (0^\circ, 0^\circ)$$

Working Observables

We define the following observables:

$$\{R_e, R_\mu, R_\tau\} \equiv \left\{ \frac{\phi_e^{\mathrm{T}}}{\phi_\mu^{\mathrm{T}} + \phi_\tau^{\mathrm{T}}}, \frac{\phi_\mu^{\mathrm{T}}}{\phi_\tau^{\mathrm{T}} + \phi_e^{\mathrm{T}}}, \frac{\phi_\tau^{\mathrm{T}}}{\phi_e^{\mathrm{T}} + \phi_\mu^{\mathrm{T}}} \right\}$$

Only two of them are independent, because

$$\hat{R}_e + \hat{R}_\mu + \hat{R}_\tau = 1$$

with

$$\hat{R}_\alpha \equiv \frac{R_\alpha}{1 + R_\alpha}$$

Another observable is the total neutrino flux of all flavors:

$$\phi_0 = \phi_e + \phi_\mu + \phi_\tau = \phi_e^{\mathrm{T}} + \phi_\mu^{\mathrm{T}} + \phi_\tau^{\mathrm{T}}$$

Question: **can all of the three observables be well measured?**

Point: **by using any two observables, we may determine the initial flavor composition of UHE neutrino fluxes (i.e., ξ and ζ)**

Formula

Definition:

$$\{R_e, R_\mu, R_\tau\} \equiv \left\{ \frac{\phi_e^{\mathrm{T}}}{\phi_\mu^{\mathrm{T}} + \phi_\tau^{\mathrm{T}}}, \frac{\phi_\mu^{\mathrm{T}}}{\phi_\tau^{\mathrm{T}} + \phi_e^{\mathrm{T}}}, \frac{\phi_\tau^{\mathrm{T}}}{\phi_e^{\mathrm{T}} + \phi_\mu^{\mathrm{T}}} \right\}$$

Parametrization:

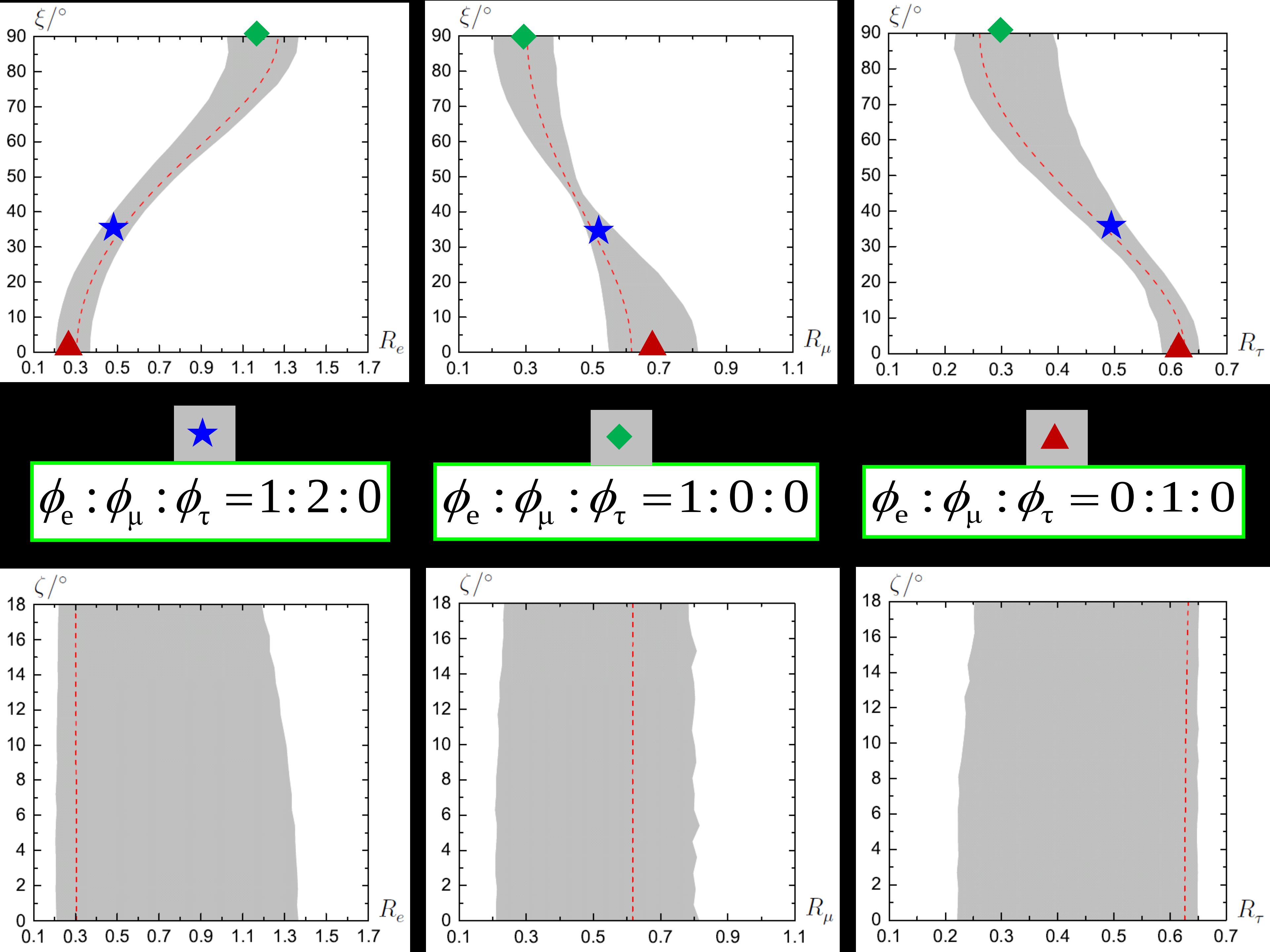
$$\{\phi_{\mathrm{e}}, \phi_{\mu}, \phi_{\tau}\} = \{\sin^2\xi \cos^2\zeta, \cos^2\xi \cos^2\zeta, \sin^2\zeta\}\phi_0$$

$$\phi_\beta^{\mathrm{T}} = \sum (\phi_\alpha P_{\alpha\beta}) \quad \Rightarrow \quad R_\alpha = \frac{P_{e\alpha}\sin^2\xi + P_{\mu\alpha}\cos^2\xi + P_{\tau\alpha}\tan^2\zeta}{\sec^2\zeta - (P_{e\alpha}\sin^2\xi + P_{\mu\alpha}\cos^2\xi + P_{\tau\alpha}\tan^2\zeta)}$$

Determination of the source parameters

$$\sin^2\xi = \frac{\hat{R}_\alpha (P_{\tau\beta} - P_{\mu\beta}) - \hat{R}_\beta (P_{\tau\alpha} - P_{\mu\alpha}) + (P_{\mu\beta}P_{\tau\alpha} - P_{\mu\alpha}P_{\tau\beta})}{(\hat{R}_\alpha - P_{\tau\alpha})(P_{e\beta} - P_{\mu\beta}) - (\hat{R}_\beta - P_{\tau\beta})(P_{e\alpha} - P_{\mu\alpha})}$$

$$\tan^2\zeta = \frac{\hat{R}_\alpha (P_{\mu\beta} - P_{e\beta}) - \hat{R}_\beta (P_{\mu\alpha} - P_{e\alpha}) + (P_{e\beta}P_{\mu\alpha} - P_{e\alpha}P_{\mu\beta})}{(\hat{R}_\alpha - P_{\tau\alpha})(P_{e\beta} - P_{\mu\beta}) - (\hat{R}_\beta - P_{\tau\beta})(P_{e\alpha} - P_{\mu\alpha})}$$


ξ/°
ζ/°
R_e
R_μ
R_τ
$\phi_e : \phi_\mu : \phi_\tau = 1:2:0$
$\phi_e : \phi_\mu : \phi_\tau = 1:0:0$
$\phi_e : \phi_\mu : \phi_\tau = 0:1:0$

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.

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:

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

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

Neutrinos decoupled from matter:

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

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

Number density of 6 relic ν's:

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

$\Gamma > H$ | $\Gamma \sim H$ | $\Gamma < H$

ν's in thermal contact with cosmic plasma | ν's not in thermal contact with matter

arrow of time

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

neutrino and photon temperatures (blue)

neutrino decoupling

$$T_\nu = T_\gamma$$

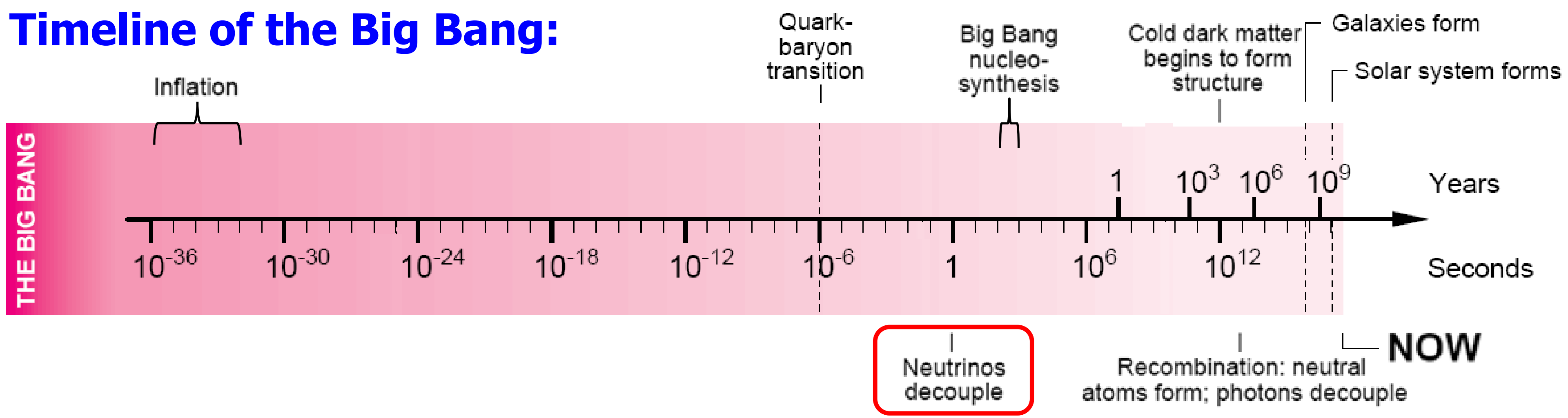
$$T_{\rm fr} \sim \left(\frac{\sqrt{g_*}}{G_F^2 M_{\rm Pl}}\right)^{1/3} \sim 1\ \rm MeV$$

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

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

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

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

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

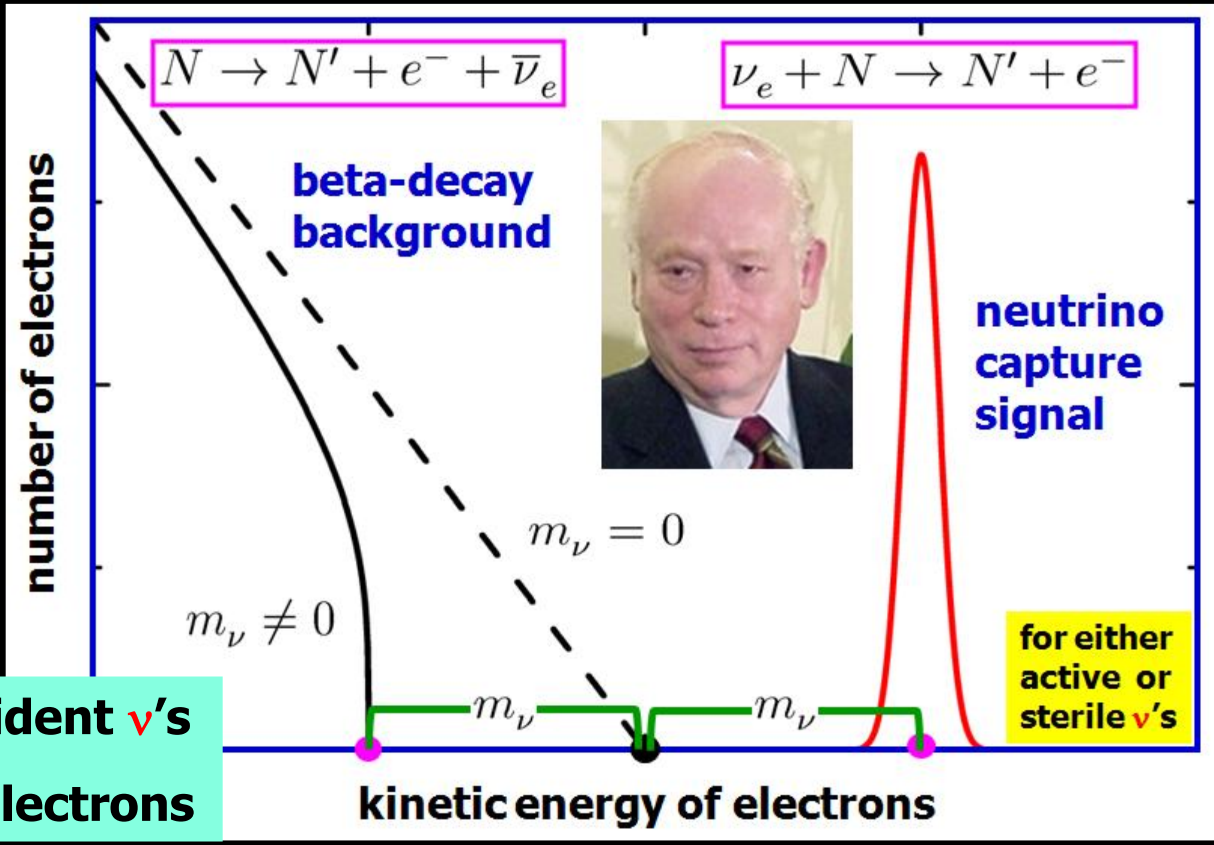
At least 2 ν's cold today

How to detect ULE ν's ?

(Irvine & Humphreys, 83)

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

Relic neutrino capture on β-decaying nuclei



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

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

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

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

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

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

Background: (the tritium β-decay)

$$E_e = T_e' + m_e$$

$$\langle n_{\nu_i} \rangle \approx \langle n_{\overline{\nu}_i} \rangle \approx 56\ \mathrm{cm}^{-3}$$

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

Energy resolution (Gaussian function) :

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

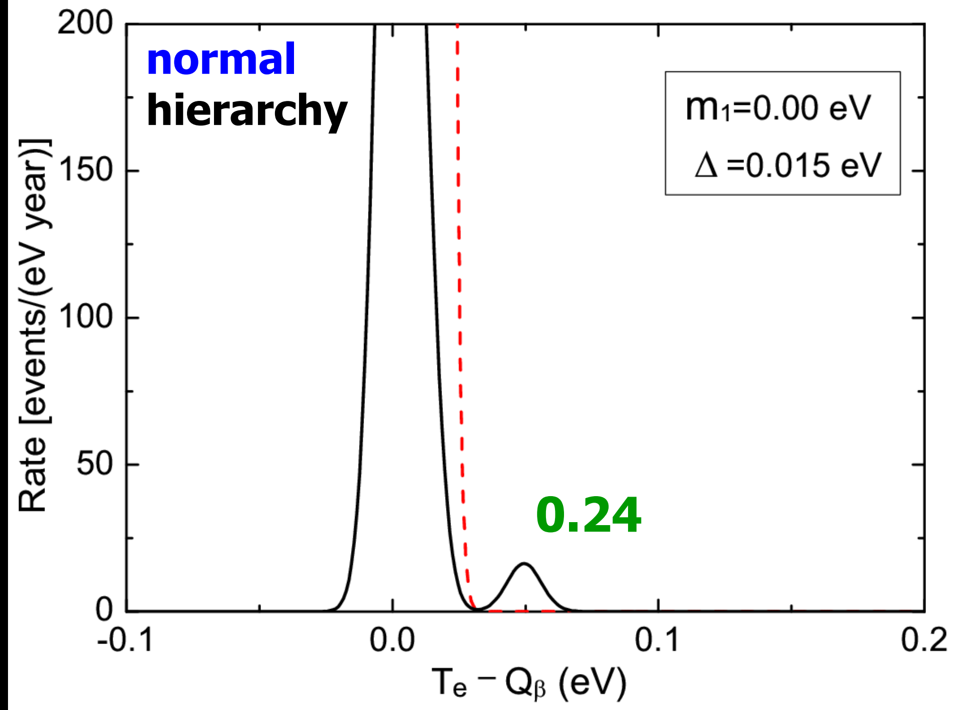
Illustration

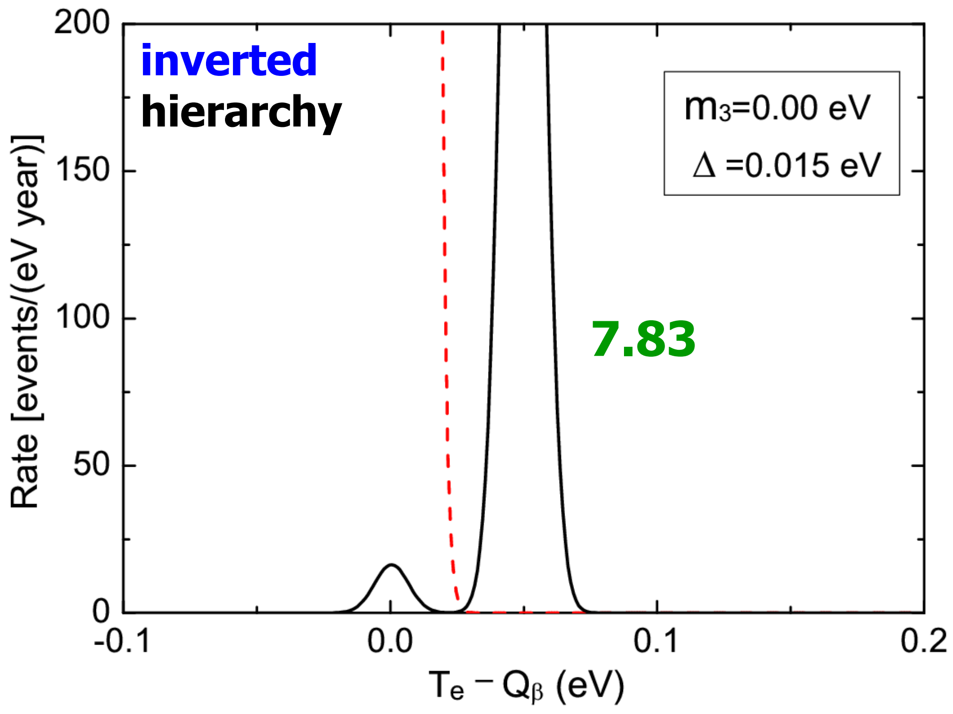
Target mass: 100 g tritium atoms

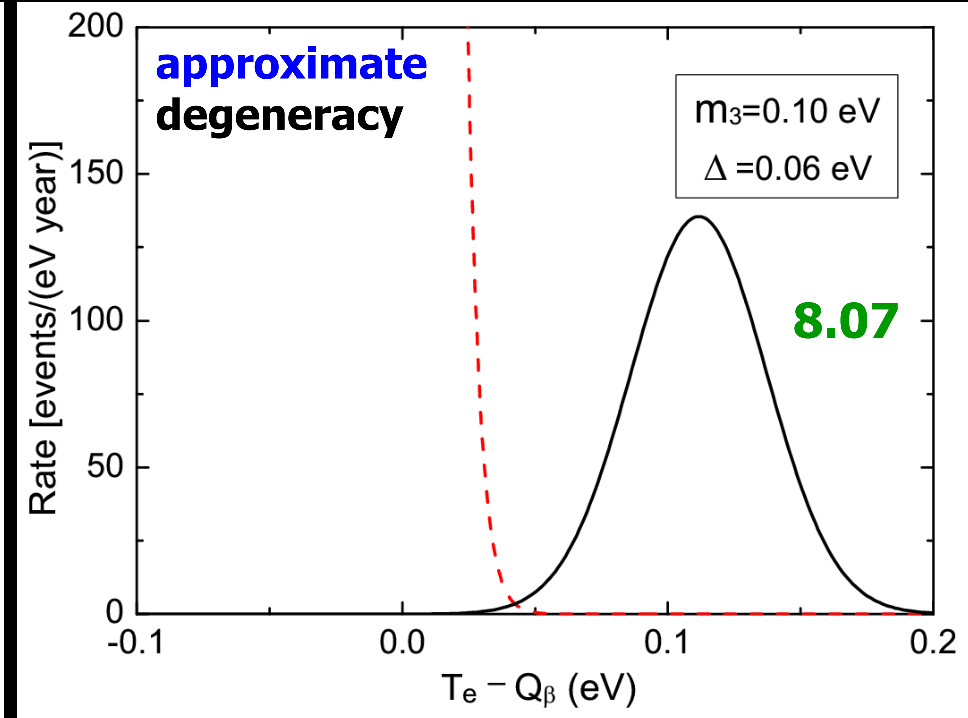
Input θ(13) : 10 degrees

Number of events per year: ~ 8

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



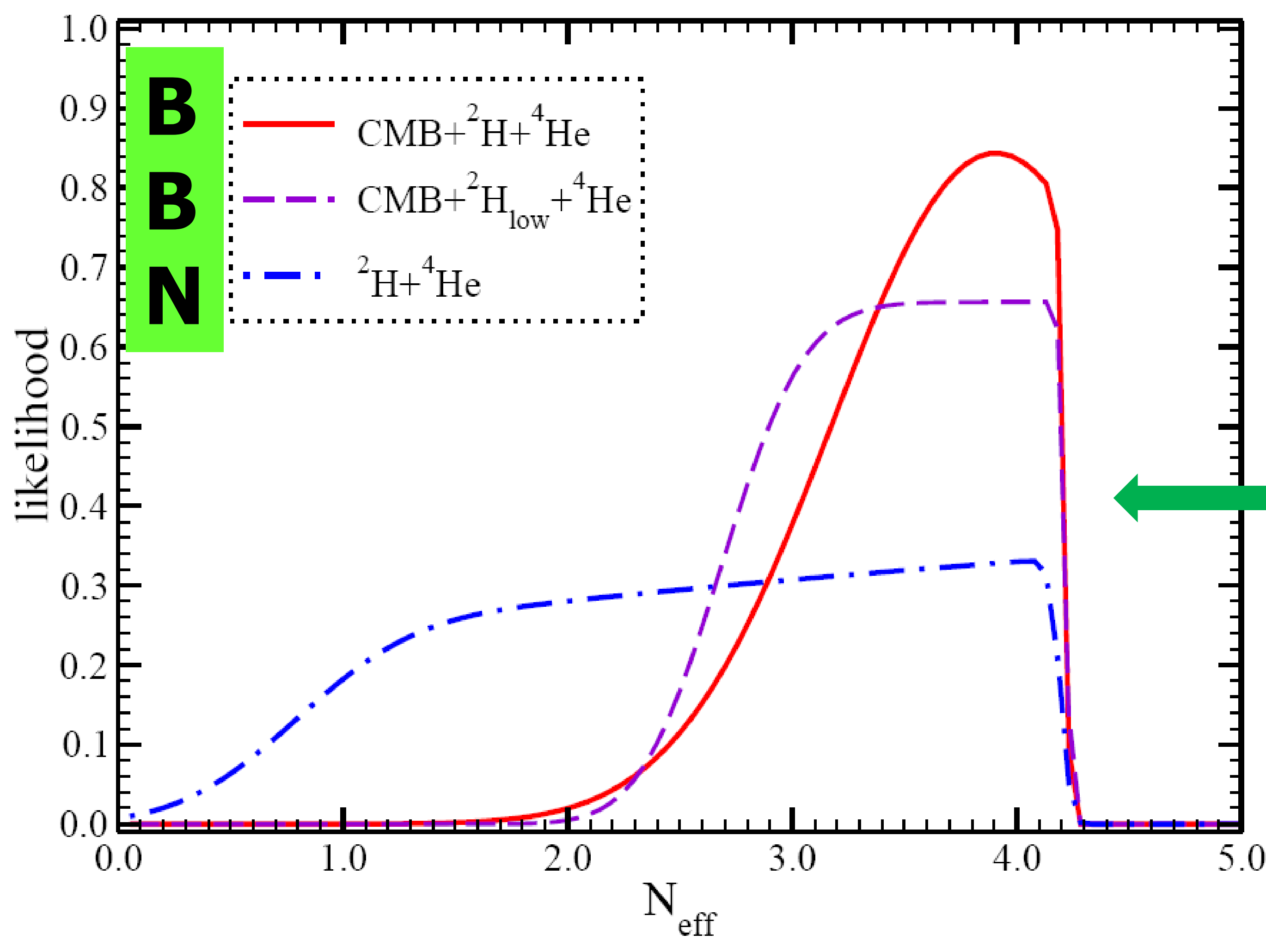




Sub-eV Sterile ν's?

BBN: current data only allow one sub-eV sterile neutrino;

CMB: current data can allow two sub-eV sterile neutrinos.



G. Mangano,
P. Serpico,
arXiv:1103.1261

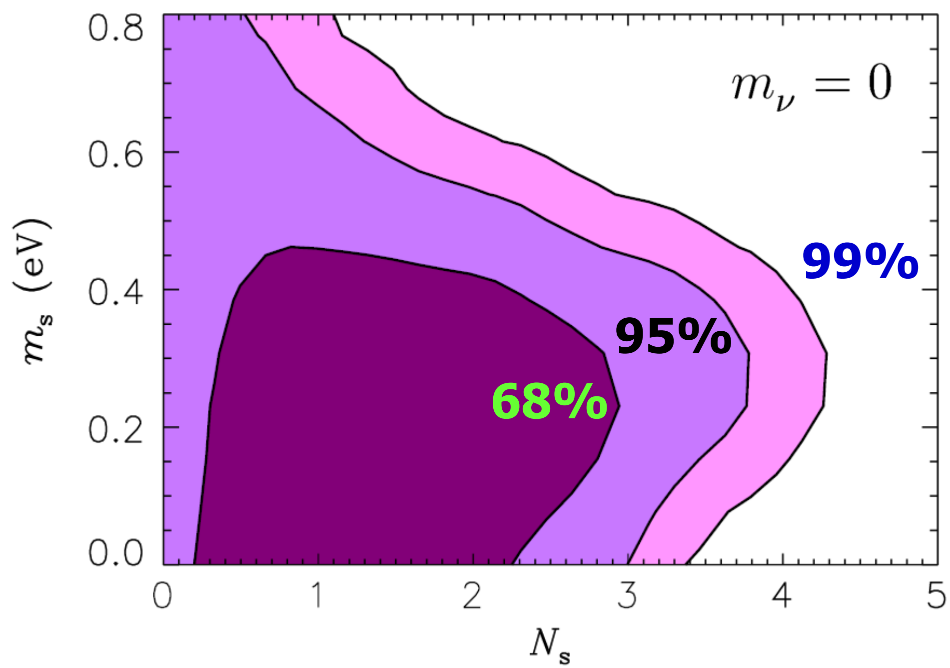
$$N_{\rm eff} < 4.2$$

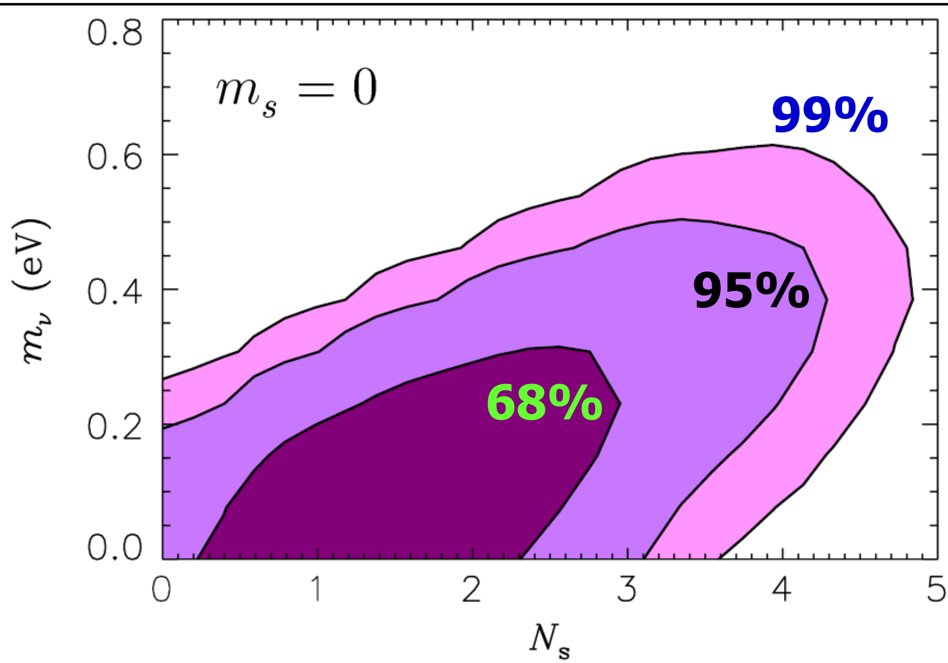
(95% C.L.)

The sharp cut-off is due to a He-4 abundance upper bound (<0.2631).

$$N_{\rm eff}^{\rm SM} = 3.046$$

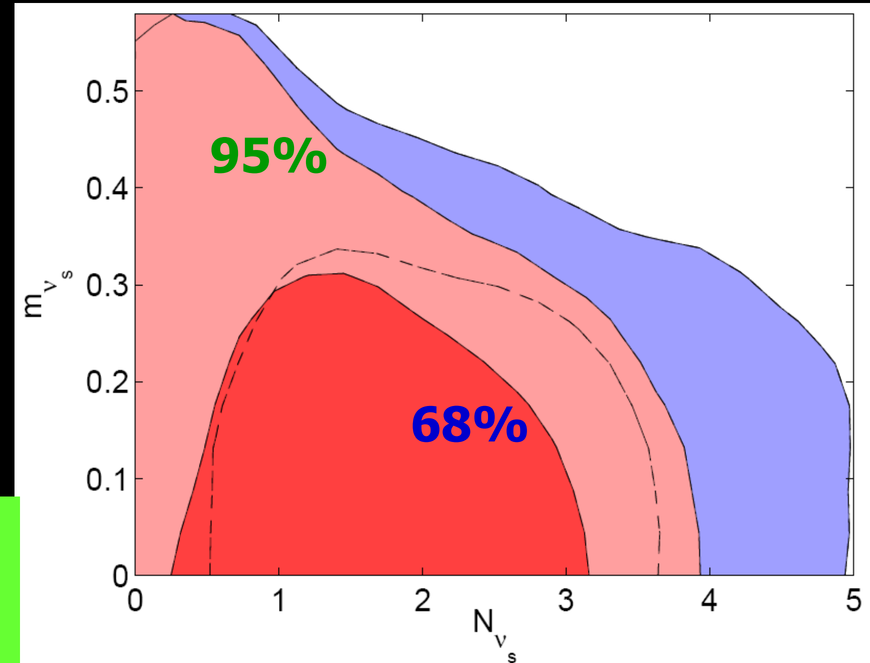
J. Hamann et al, arXiv:1006.5276

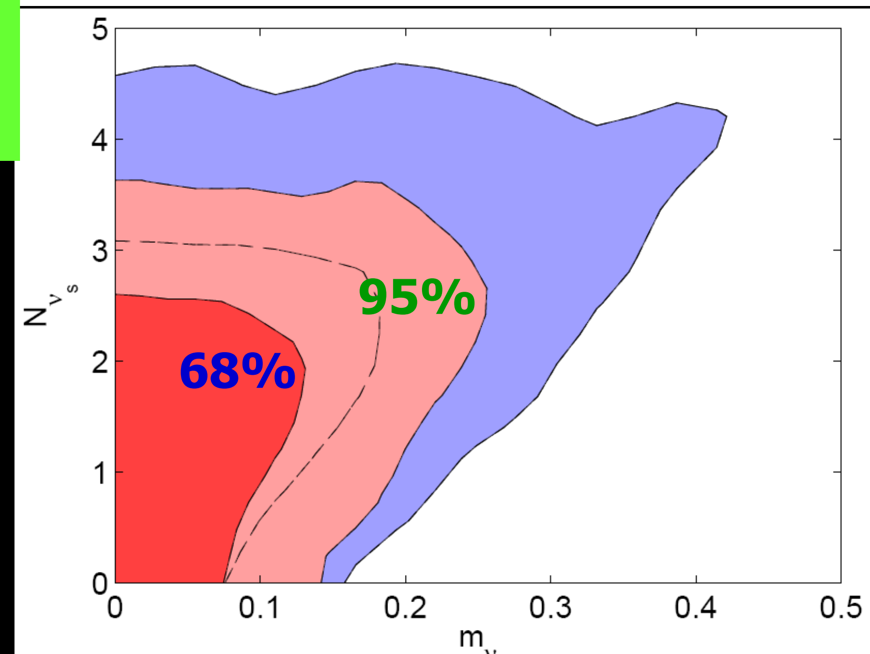




C M B

E. Giusarma, arXiv:1102.4774



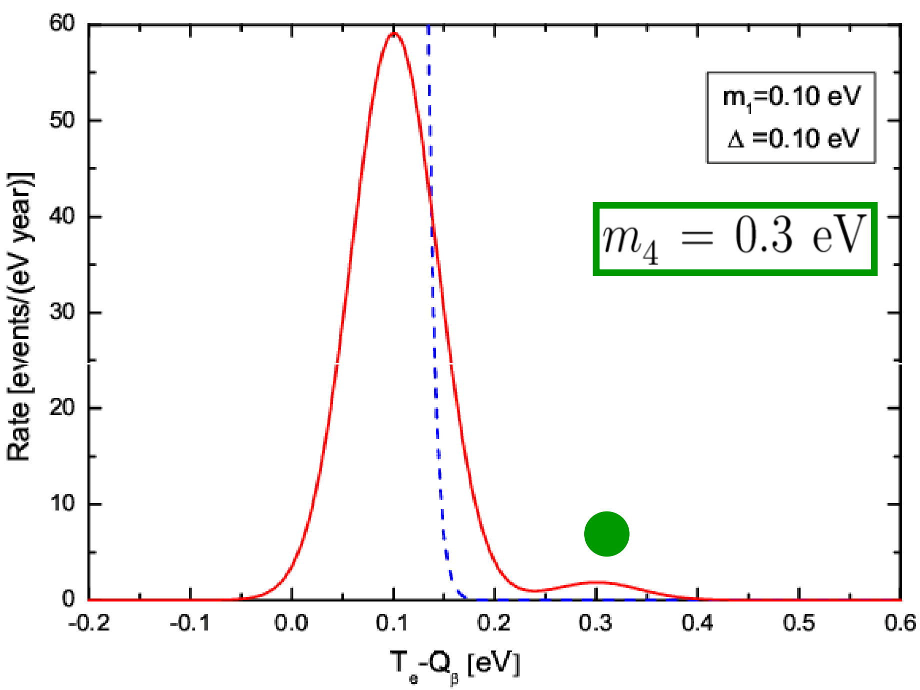


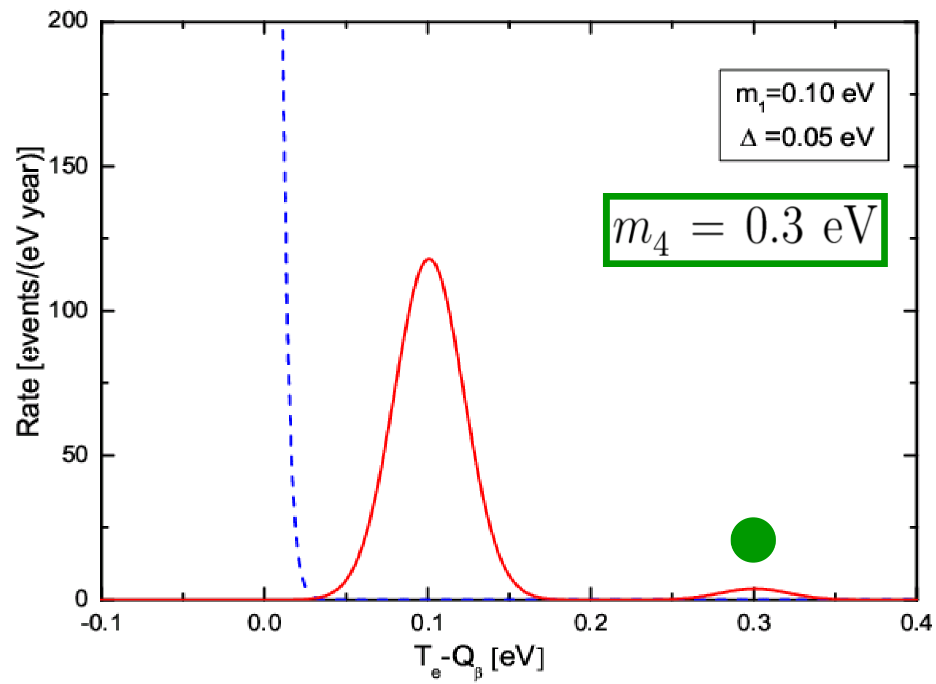
(3+1) Scheme

Besides the **CMB** + **BBN** hints, the **LSND** + **MiniBOONE** anomalies and the **reactor antineutrino anomaly** also hint at **1** or **2** **sub-eV sterile** ν's.

They could be thermally excited in the early Universe via oscillations or collisions with active ν's; they are now non-relativistic; and their number density per species is expected to equal that of active ν's.

Input: $|V_{e1}| \approx 0.804\ , \ |V_{e2}| \approx 0.542\ , |V_{e3}| \approx 0.171\ , |V_{e4}| \approx 0.174$ (Li, Xing, Luo, 10)





Overdensity

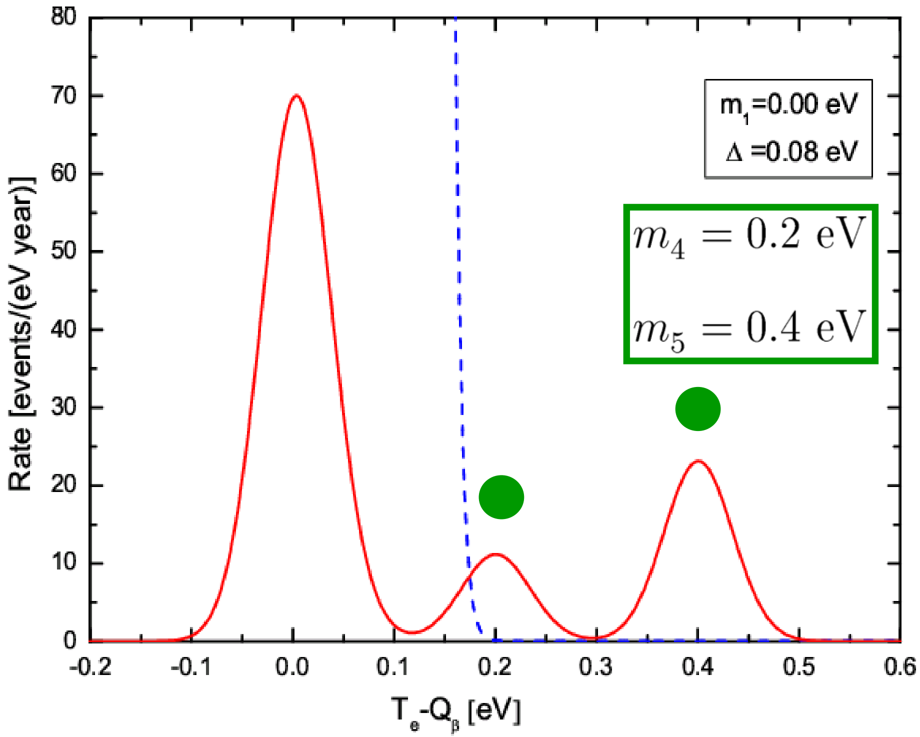
Gravitational clustering: only those cosmic ν's with velocities smaller than the escape velocity of a given structure can be bound to it. Let's assume a larger GC effect for a heavier ν around the Earth.

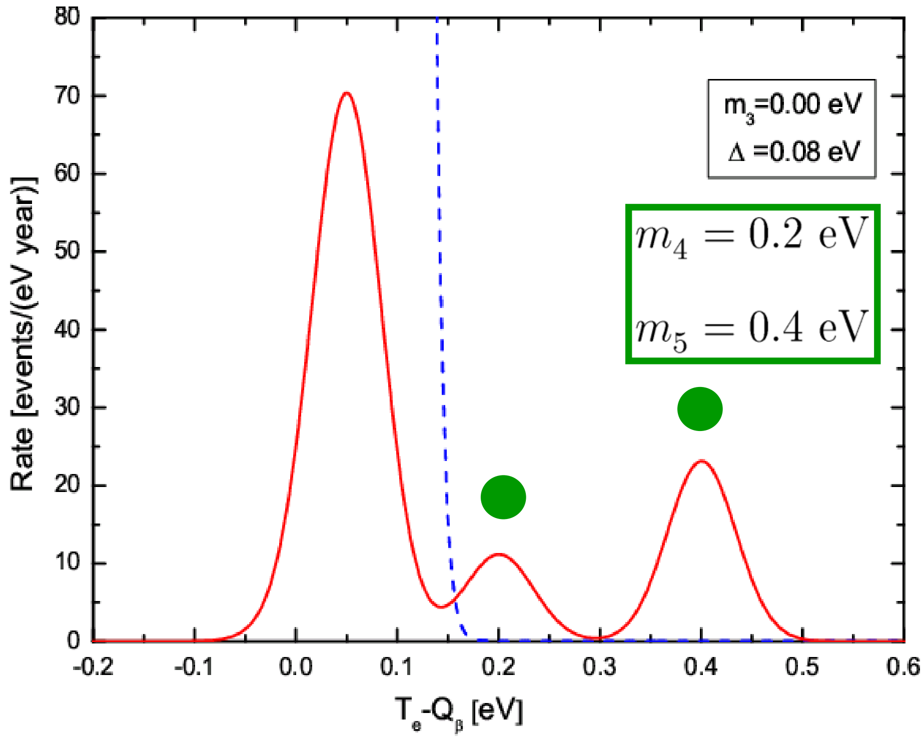
The (3+2) scheme:

$$\frac{n_{\nu_1}}{\langle n_{\nu_i}\rangle} \approx \frac{n_{\nu_2}}{\langle n_{\nu_i}\rangle} \approx \frac{n_{\nu_3}}{\langle n_{\nu_i}\rangle} \approx 1 \, , \qquad \frac{n_{\nu_5}}{\langle n_{\nu_i}\rangle} \approx 2\frac{n_{\nu_4}}{\langle n_{\nu_i}\rangle} \approx 10$$

Input:

$$|V_{e1}| \approx 0.792 \, , \; |V_{e2}| \approx 0.534 \, , |V_{e3}| \approx 0.168 \, , |V_{e4}| \approx 0.171 \, , |V_{e5}| \approx 0.174$$



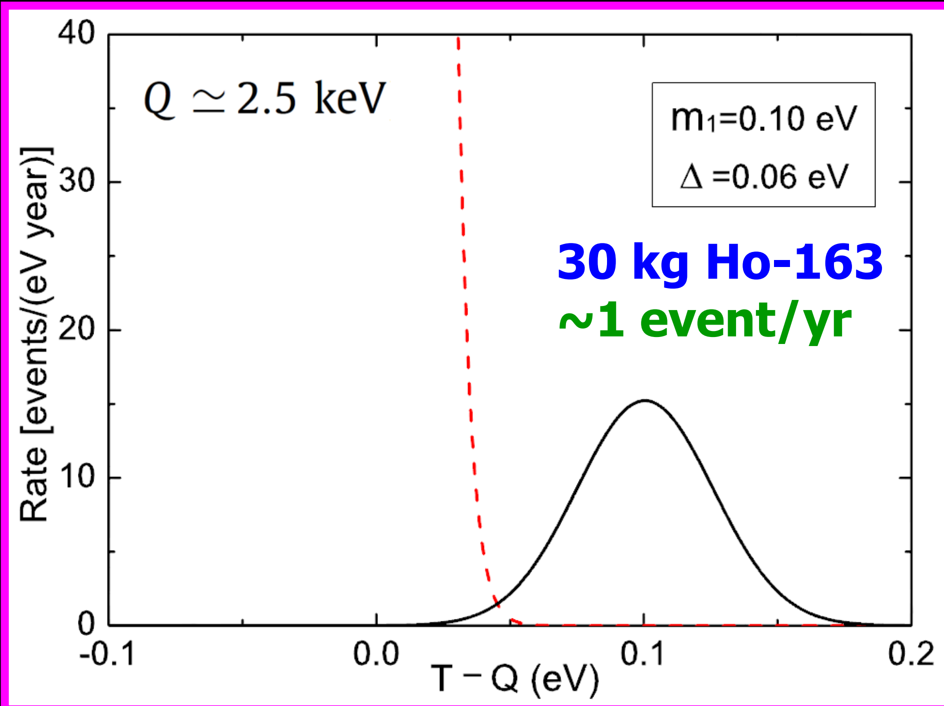


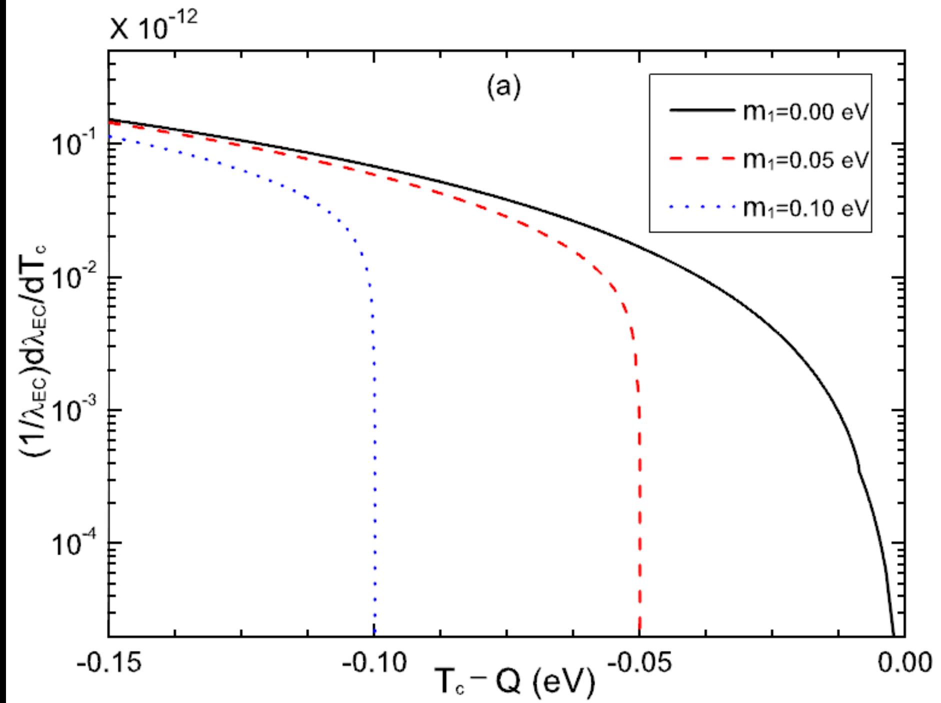
Cosmic anti-ν Background?

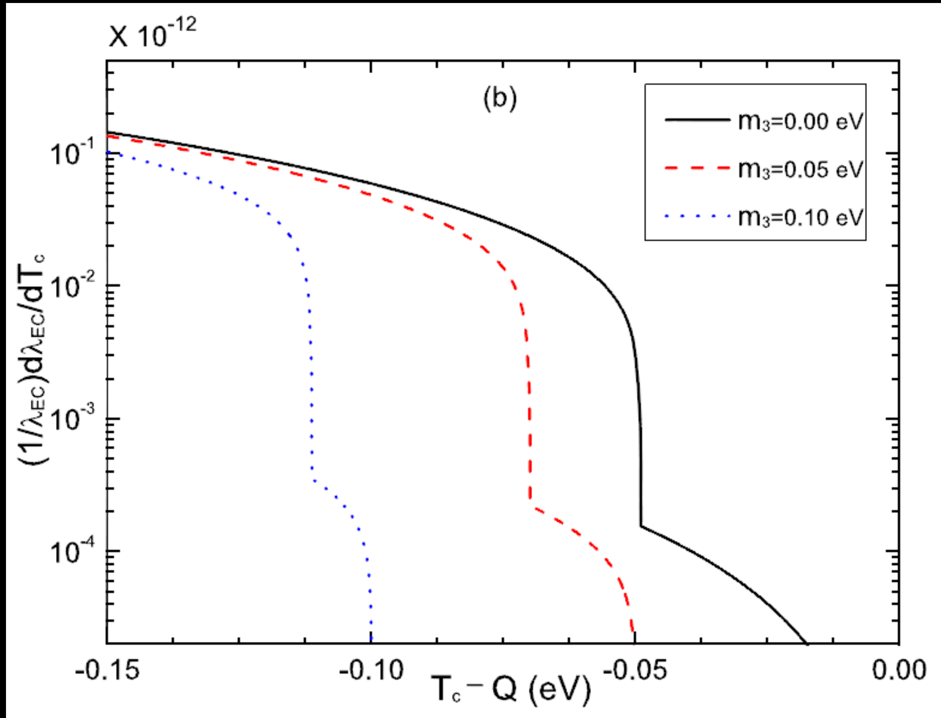
Relic antineutrino capture on EC-decaying Ho-163 nuclei.

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

(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.

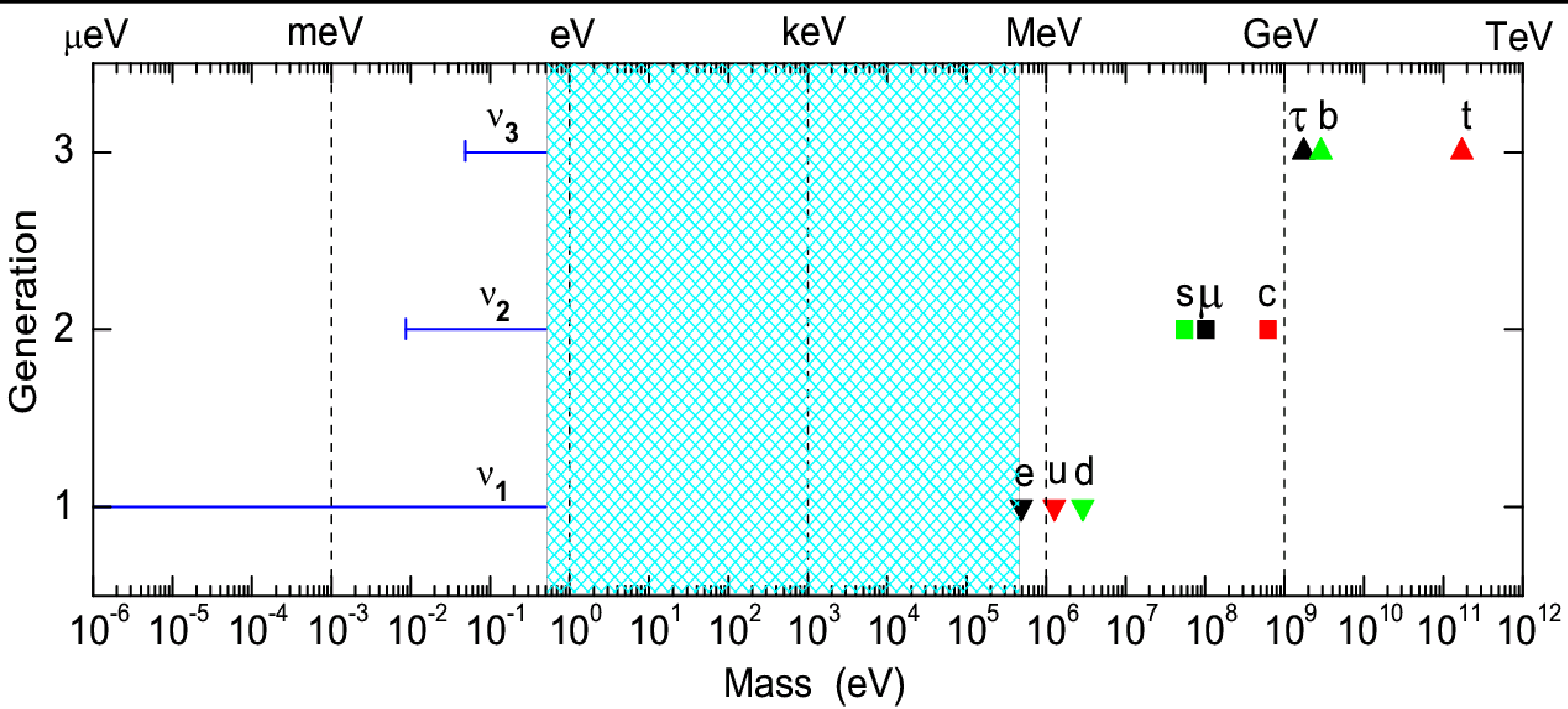
If you think so,

Do not put all your eggs in one basket

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

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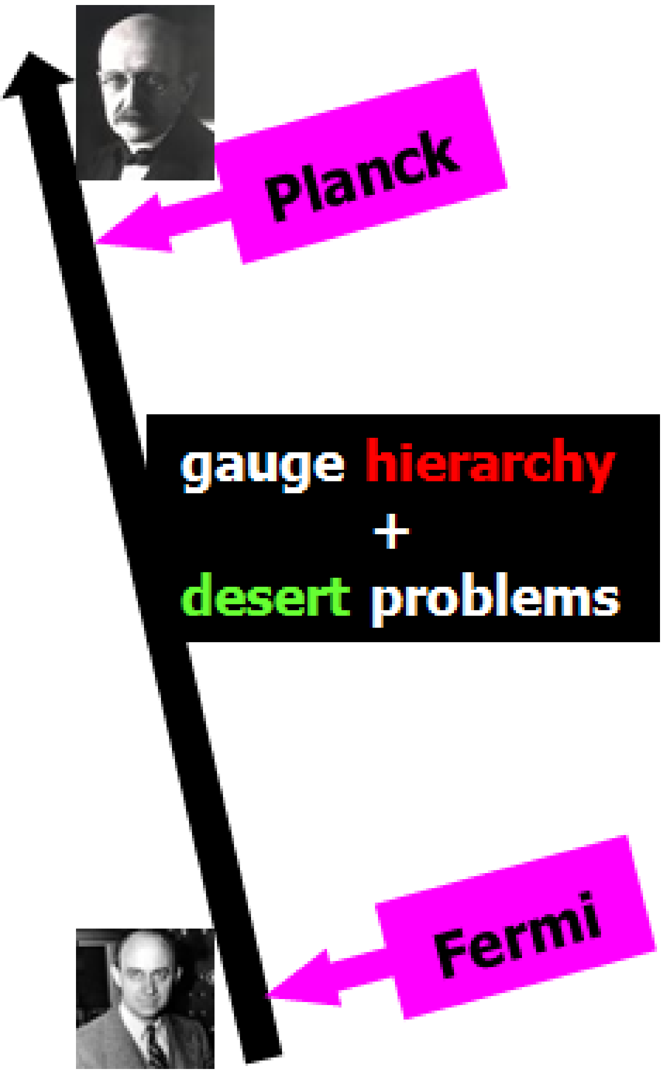
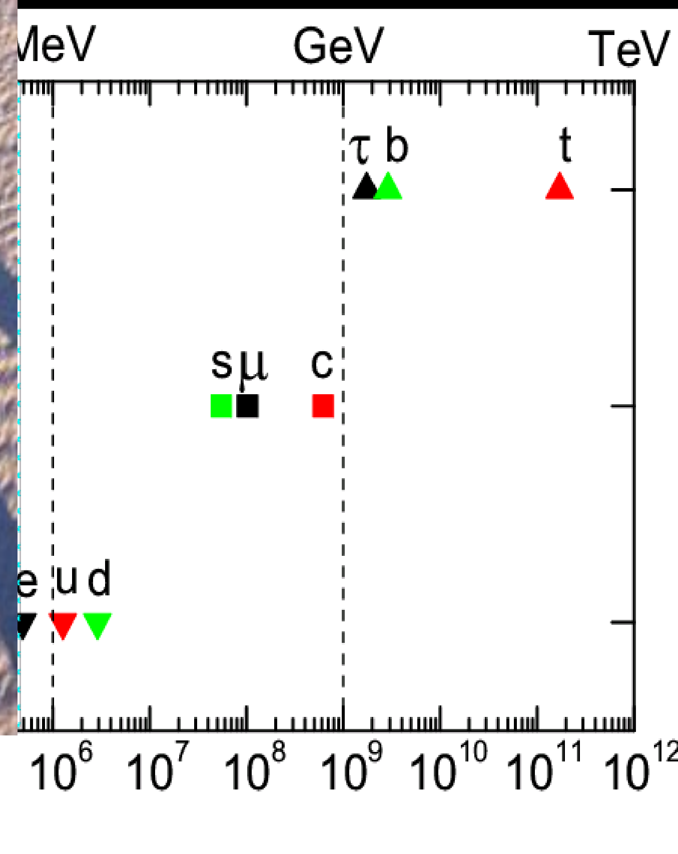
ort keV sterile ν's in the

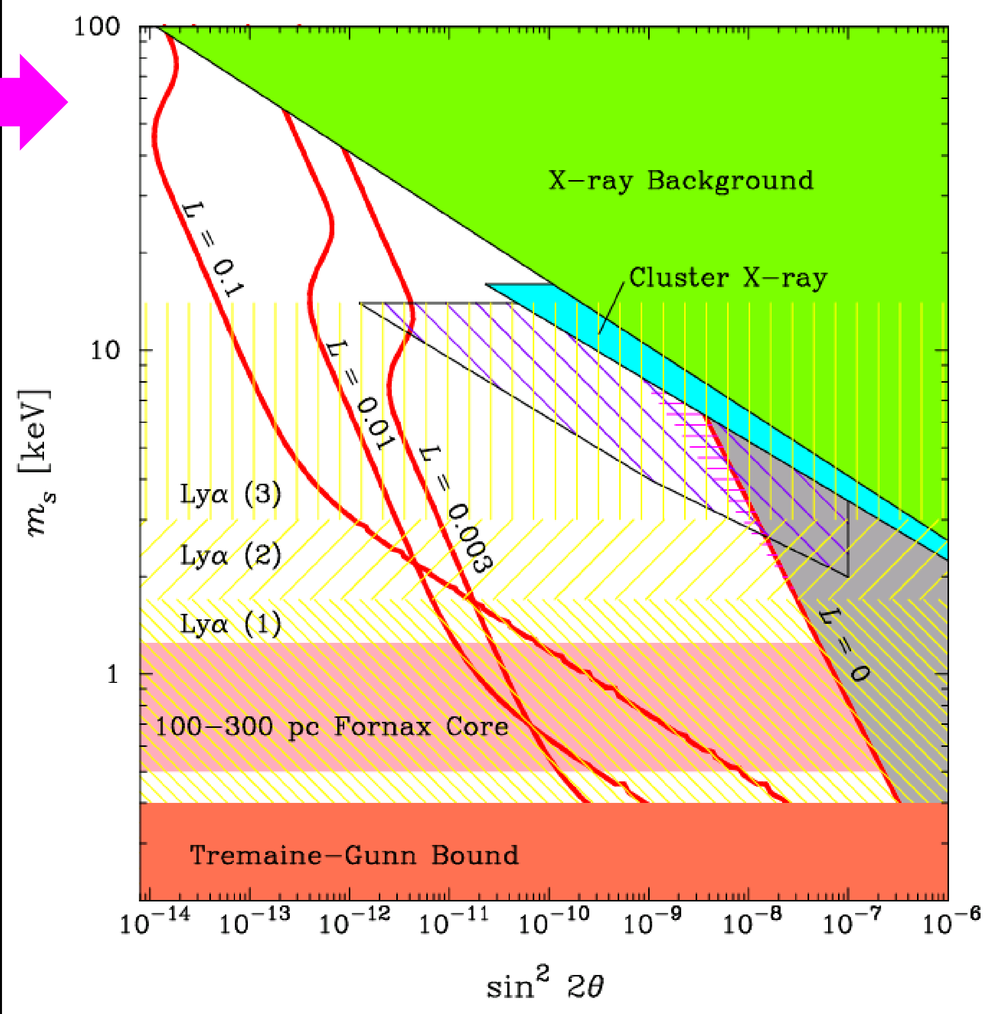




keV sterile ν Dark Matter

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.

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

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

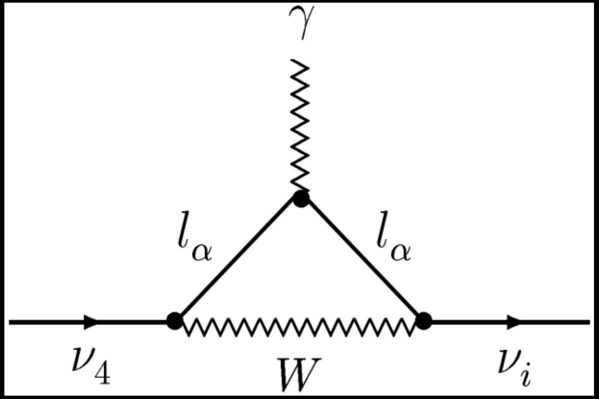
Decay Rates

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

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

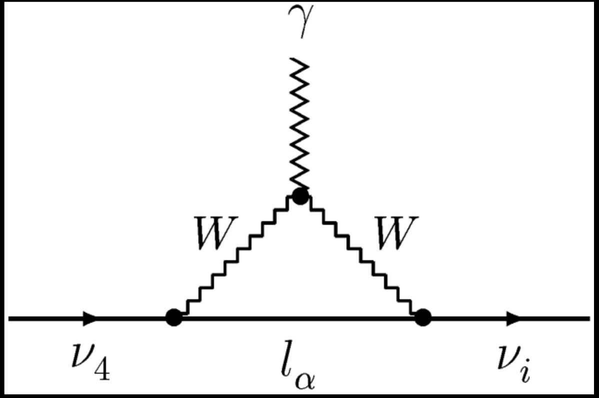
Lifetime (the Universe's age ~ 10^17 s):

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



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

$$\sum_{i=1}^{3}\Gamma(\nu_4\to\nu_i+\gamma) \simeq \frac{9\alpha_{\rm em}C_\nu G_{\rm F}^2 m_4^5}{512\pi^4}\sum_{i=1}^{3}\left|\sum_{\alpha=e}^{\tau}V_{\alpha 4}V_{\alpha i}^*\right|^2$$
$$= \frac{9\alpha_{\rm em}C_\nu G_{\rm F}^2 m_4^5}{512\pi^4}\sum_{i=1}^{3}|V_{s4}V_{si}^*|^2$$
$$\simeq \frac{9\alpha_{\rm em}C_\nu G_{\rm F}^2 m_4^5}{512\pi^4}\left(s_{14}^2+s_{24}^2+s_{34}^2\right)$$



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):

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

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

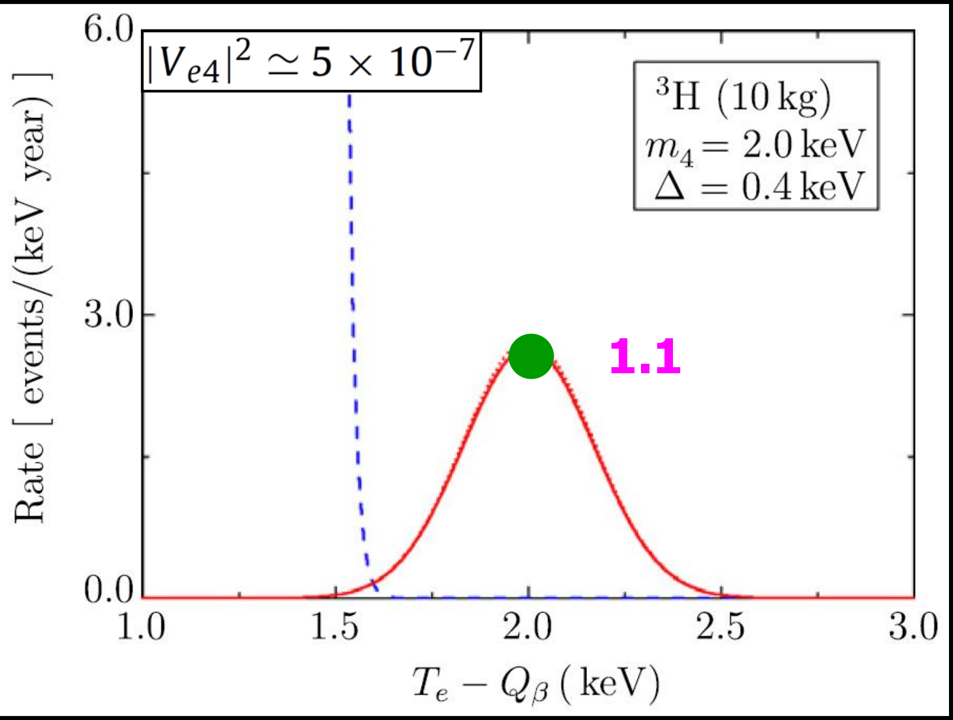
This method & the X-ray detection probe different parameter space.

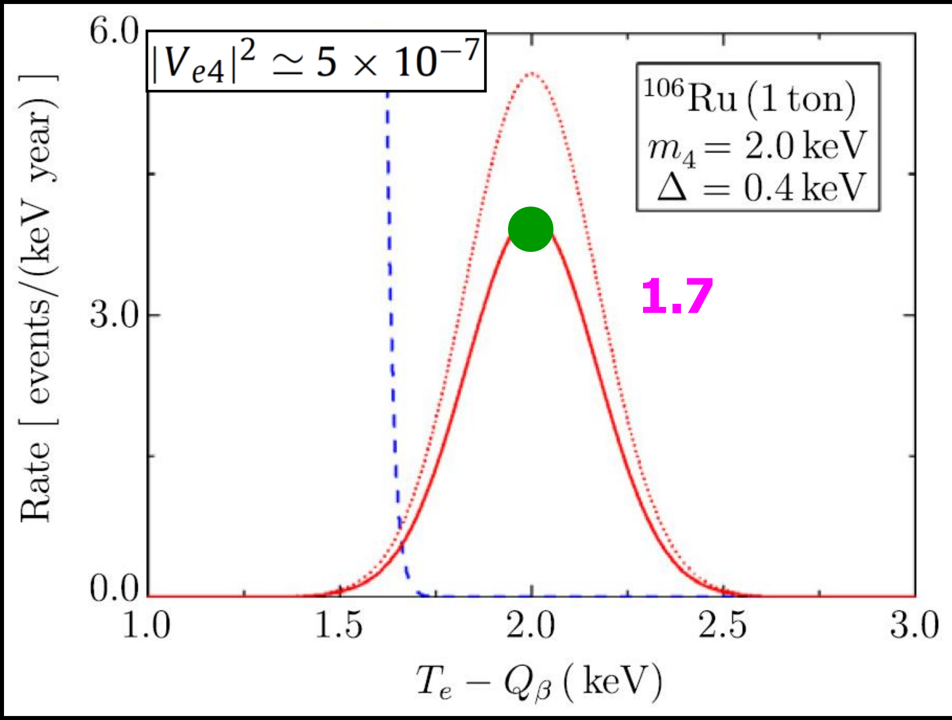
$$|V_{e4}|^2 \simeq c_{12}^2 s_{14}^2 + s_{12}^2 s_{24}^2 + 2 c_{12} s_{12} s_{14} s_{24} \cos\left(\delta_{24} - \delta_{12} - \delta_{14}\right)$$

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 $\nu_4 + e^- \to \nu_i + e^-$ scattering.

Summary

There remain some big unknowns in the ν sky:

---- CνB: a test of cosmology as early as $t \sim 1$ s after the Big Bang, but a direct measurement is extremely difficult

The Weinberg trap?

---- UHE cosmic ν's: a probe to the origin of UHE cosmic rays, but a direct measurement is extremely challenging

ν telescopes? The Glashow resonance?

---- Sterile ν's as either hot DM (eV) or warm DM (keV), but this seems hopeless

The Weinberg trap?

These dreams are so remote that better ideas are needed.

Lecture H

- ★ **Where is Primordial Antimatter?**
- ★ **Sakharov Conditions**
- ★ **Baryogenesis via Leptogenesis**

Dirac's Expectation

PAUL A. M. DIRAC

Theory of electrons and positrons

Nobel Lecture, December 12, 1933

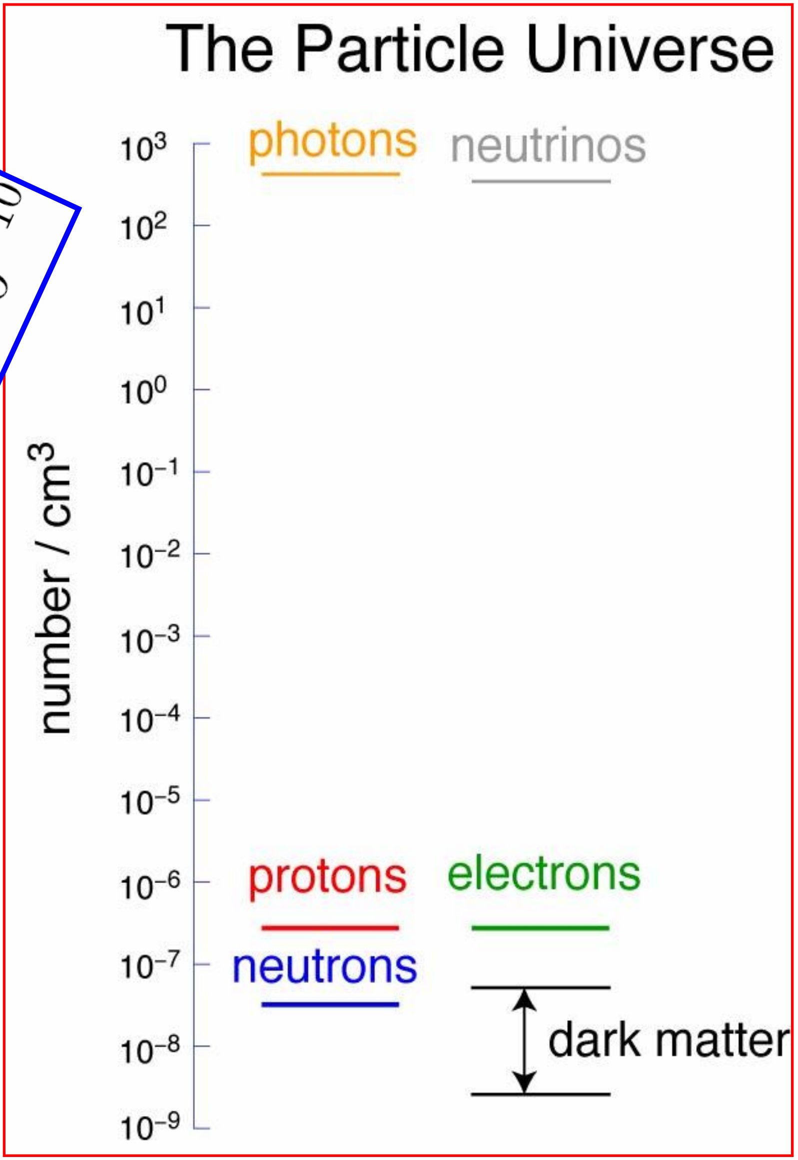
If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. 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 **is there** **not** **an anti-Universe as expected by Dirac?**

$$t = 10^{16} sec$$
$$r = 10^{29} cm$$
$$T = 2.7\ K$$
$$400\gamma / cm^3$$
$$10^{80}\ p, n$$
$$0\quad \bar{p}, \bar{n}$$

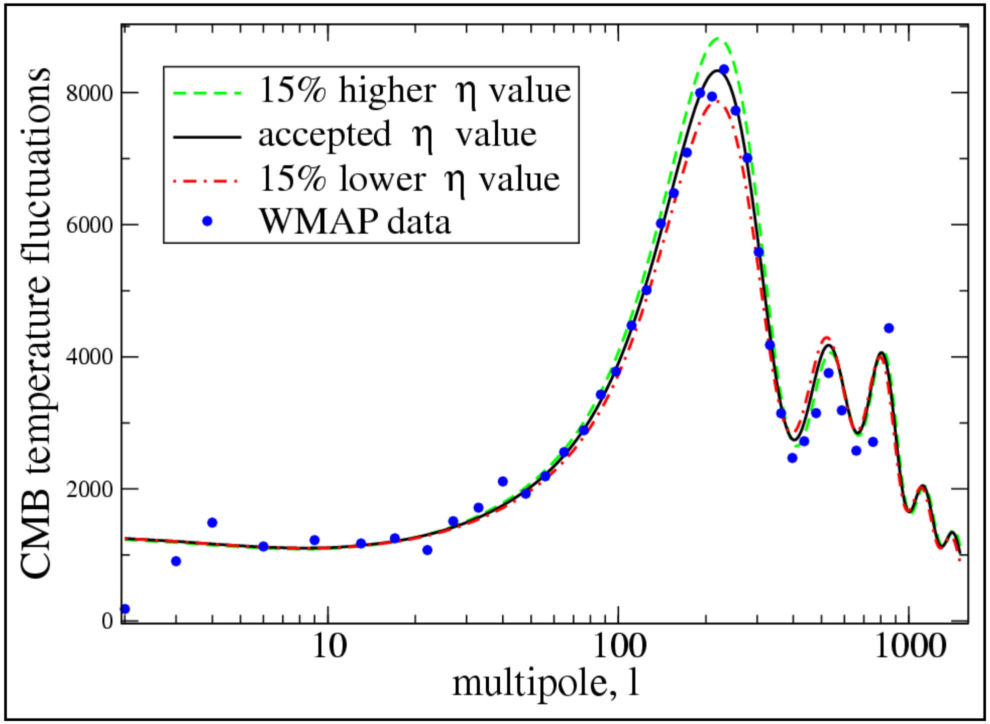
$$\eta_B \equiv n_B / n_\gamma = (6.1 \pm 0.2) \times 10{-}10$$

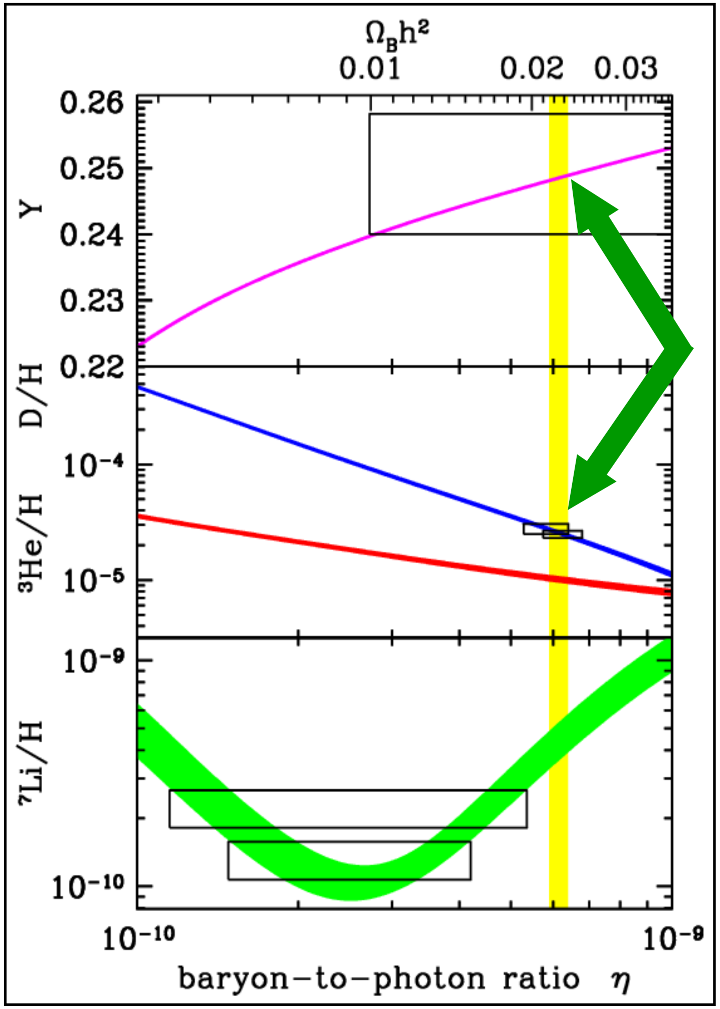


Evidence

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]

Baryogenesis Mechanisms

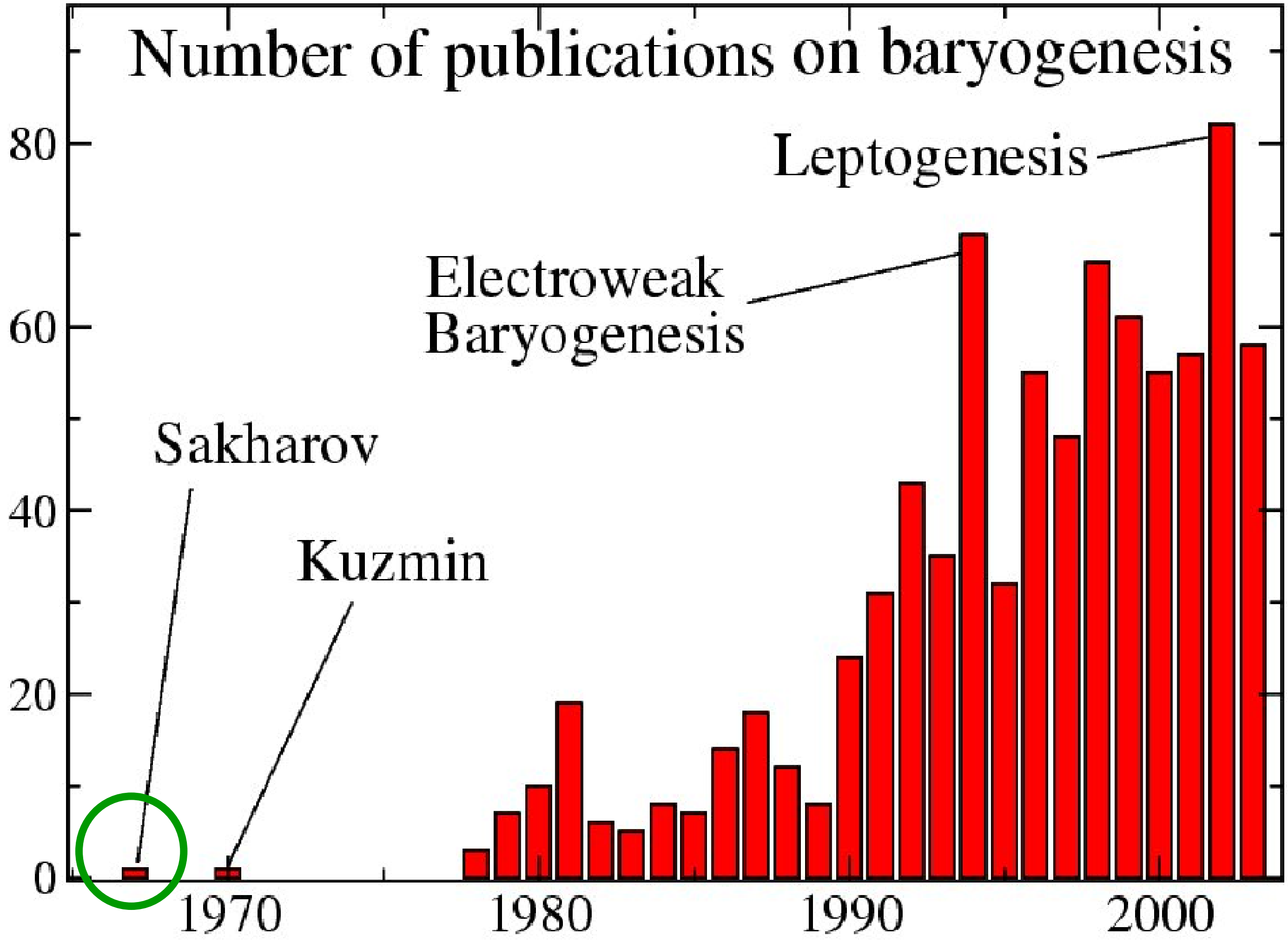
- Planck/GUT Baryogenesis;
- Electroweak Baryogenesis;
- Leptogenesis;
- Affleck-Dine Mechanism; ...

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

Now >1300 times

Neutrino Physics

From Cold to Hot



Lesson: if you publish a paper that noboday cares today, don't worry, as it might actually be a seminal work and become popular tomorrow.

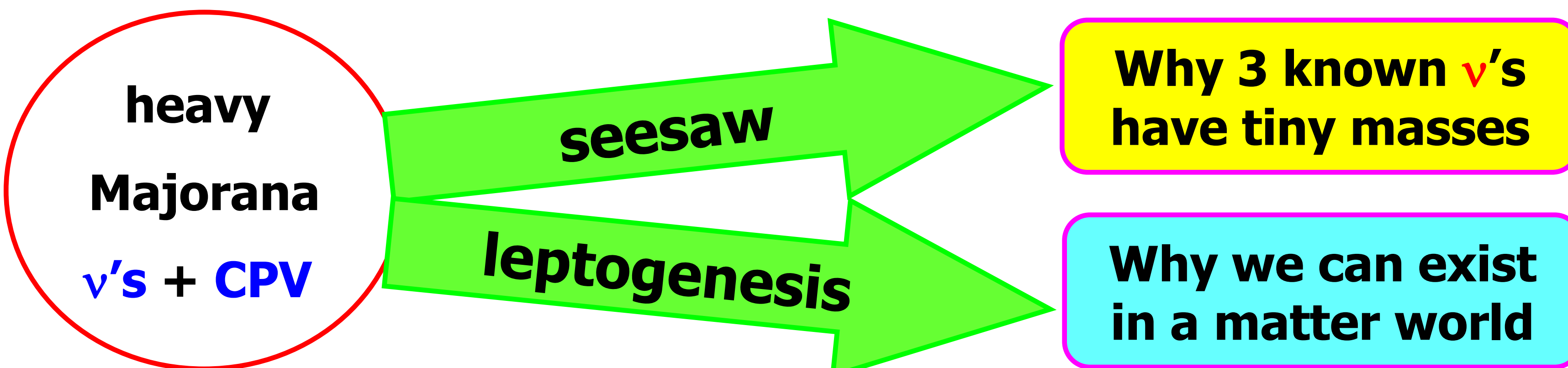
Remarks on CP Violation

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.



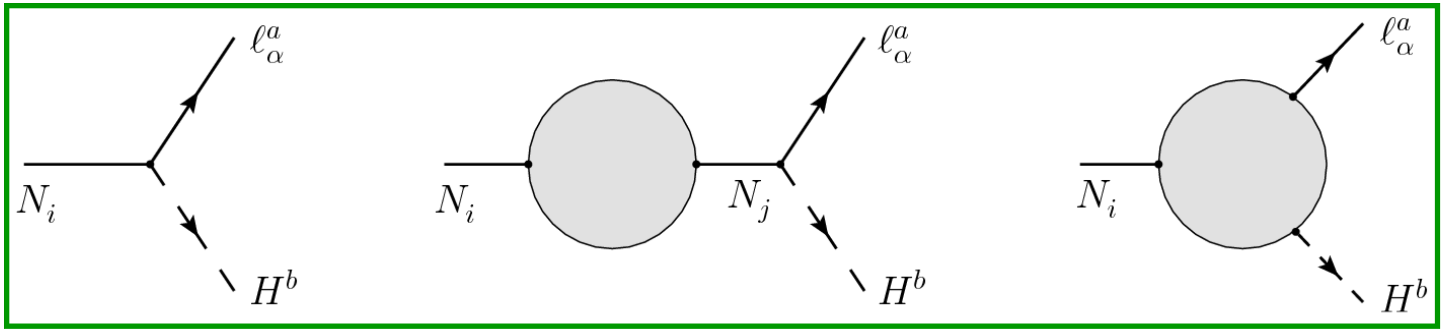
Thermal Leptogenesis (1)

◆ 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:



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

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

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

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

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:

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

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.

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

at the quantum level via triangle anomaly.

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

(*B*–*L*) is conserved in the SM (‘t Hooft, 76)

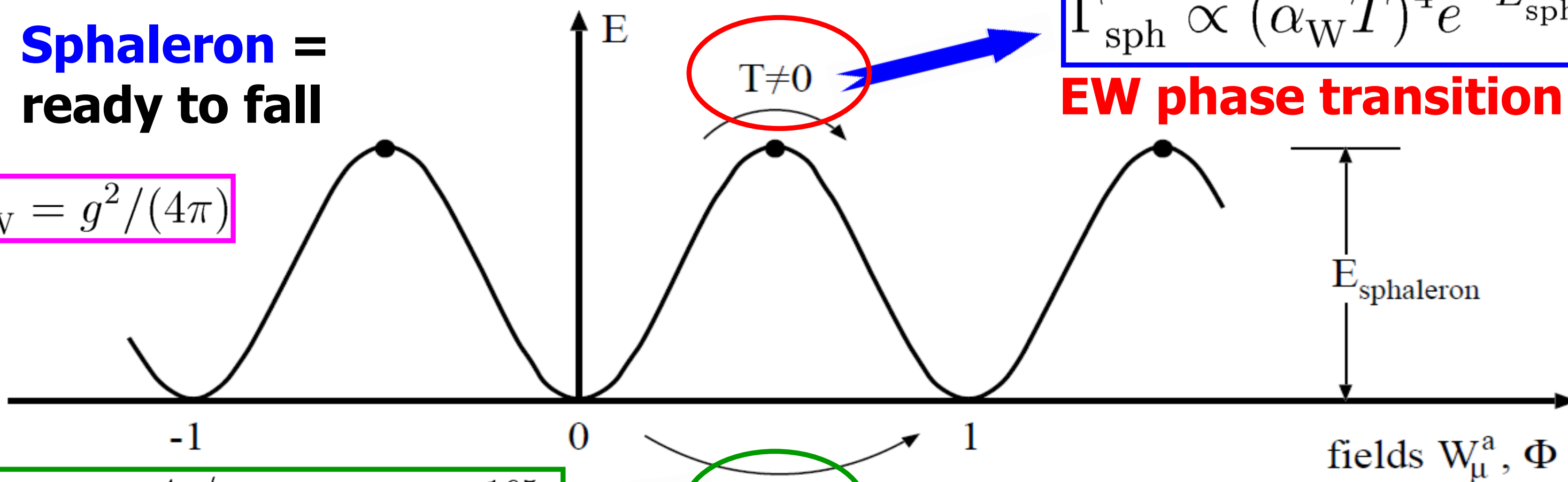
Chern-Simons (CS) numbers = ±1, ±2, ...

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

Thermal Leptogenesis (3)

Sphaleron =
ready to fall

$\alpha_W = g^2/(4\pi)$



$\Gamma_{\text{sph}} \propto (\alpha_W T)^4 e^{-E_{\text{sph}}/T}$

EW phase transition

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

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

10^2 GeV < T < 10^{12} GeV

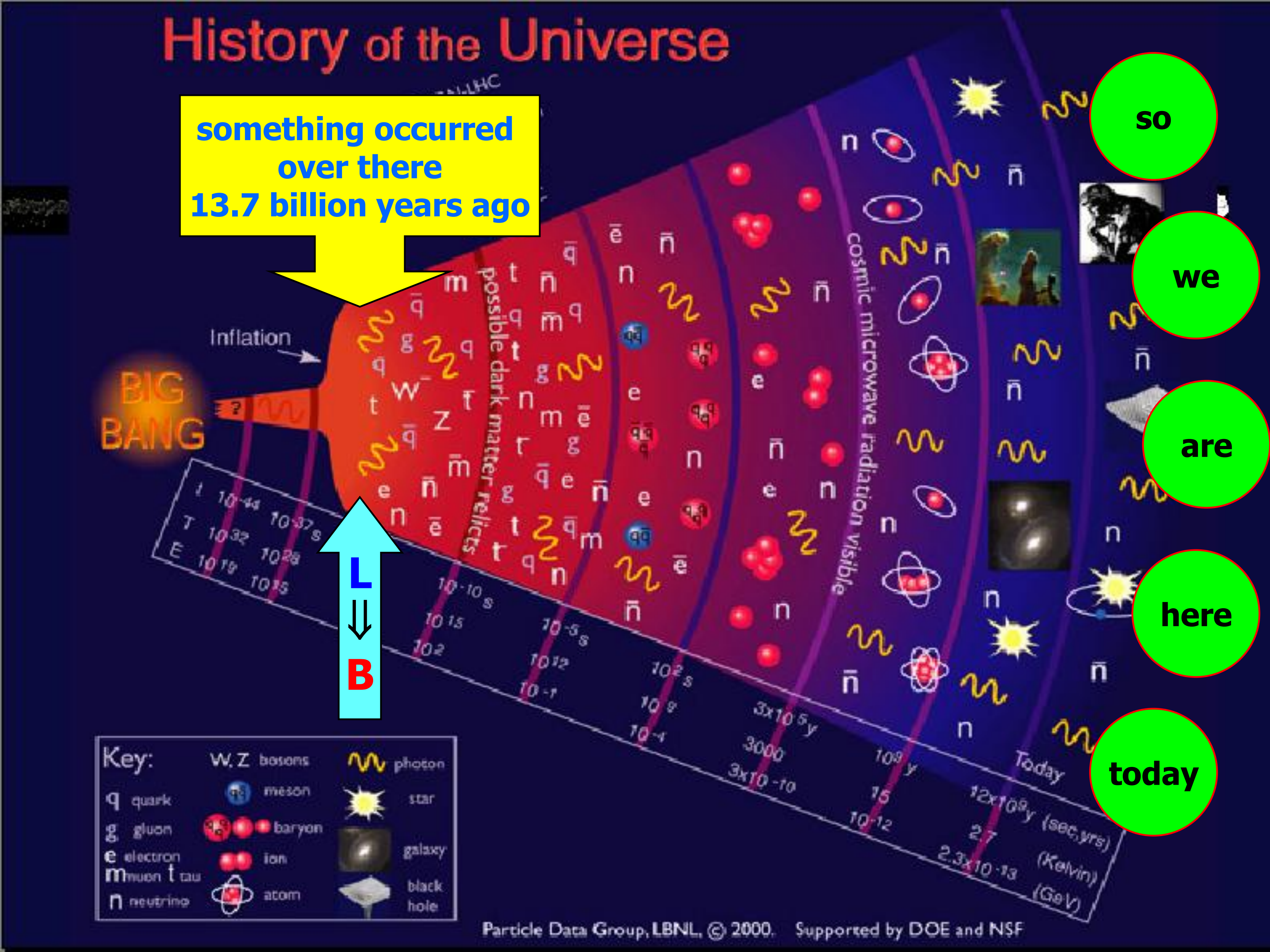
Baryogenesis via leptogenesis is realized:

$$Y_B \equiv \frac{n_B - n_{\overline{B}}}{s} = -C Y_L$$

$$\left.\frac{n_B}{s}\right|_{\text{equilibrium}} = C \left.\frac{n_B - n_L}{s}\right|_{\text{equilibrium}} = -C \left.\frac{n_L}{s}\right|_{\text{initial}}$$

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

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


History of the Universe
something occurred
over there
13.7 billion years ago
L
⇓
B
so
we
are
here
today
BIG BANG
Inflation
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 Today 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)
Key:
W, Z bosons
photon
q quark
meson
star
g gluon
baryon
galaxy
e electron
ion
m muon
t tau
black hole
n neutrino
atom
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

1 Stone Kills 2 Birds

(A) It is not difficult to build a canonical "seesaw + leptogenesis" model which simultaneously account for current data on neutrino oscillations and baryon number asymmetry.

(B) It is also possible to realize baryogenesis via leptogenesis in other seesaw mechanisms at a super-high energy scale.

(C) Lower-scale leptogenesis is not impossible, but suffers from fine-tuning (resonant leptogenesis) and very difficult to produce observable signatures at the LHC.

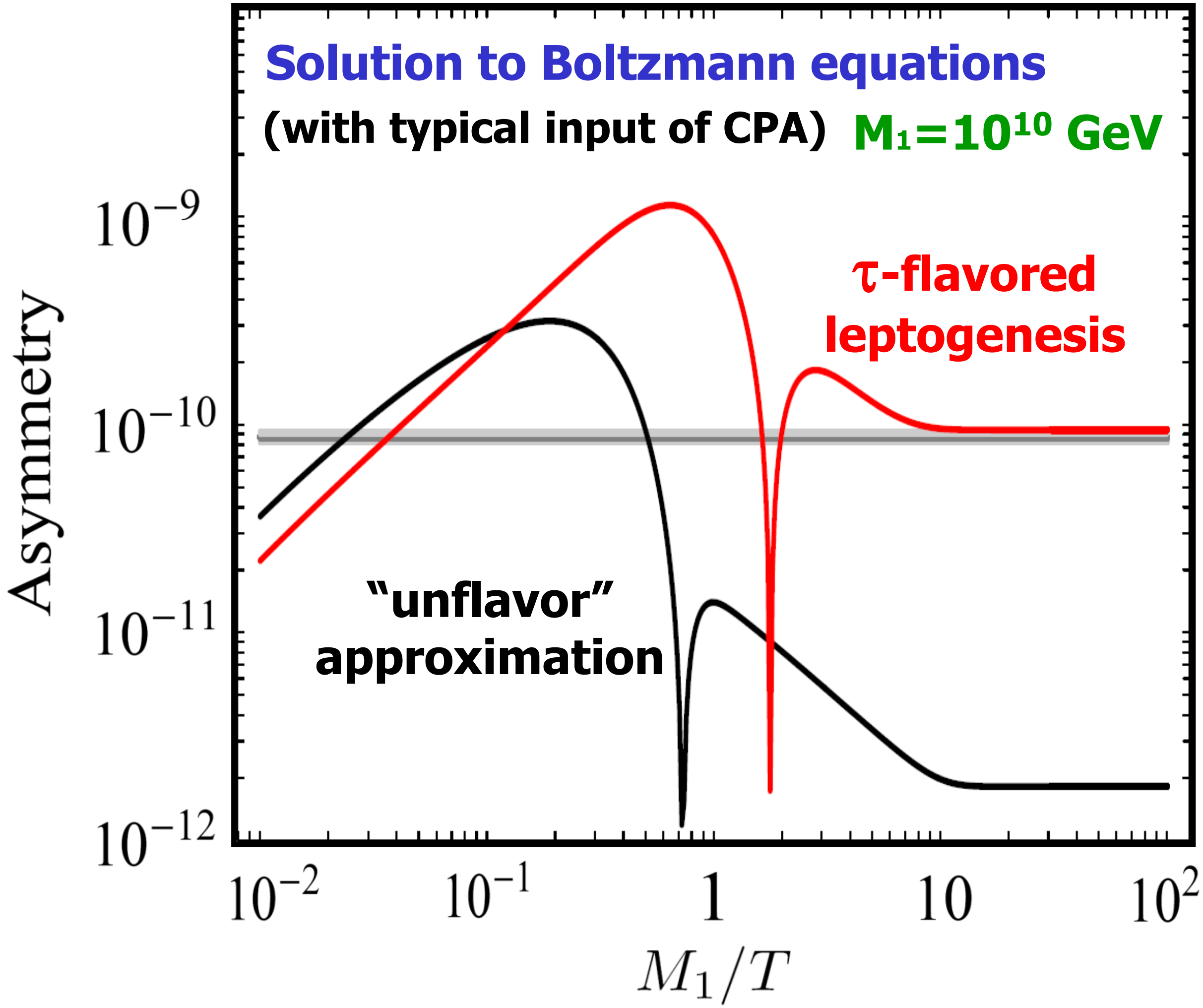
(D) How to test baryogenesis via leptogenesis remains an open question: indirect test? (Majorana ν's, leptonic CP violation, ...).

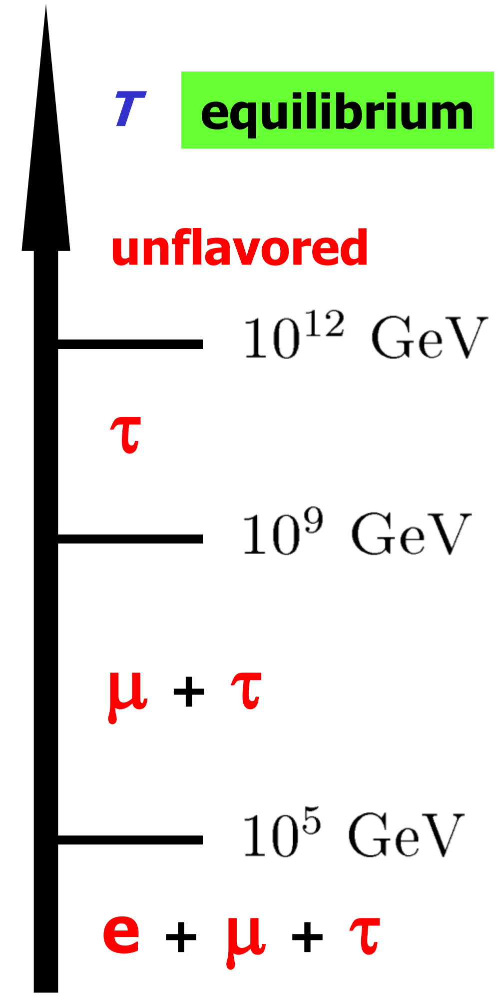
Developments and variations (Davidson, Nardi, Nir, Phys. Rept. 08):

- **Recent developments:** spectator processes; finite temperature effects; flavor effects; *N*_2 leptogenesis; resonant (TeV) leptogenesis; ......
- **Some variations:** soft (SUSY) leptogenesis; type-II leptogenesis; Dirac leptogenesis; type-III leptogenesis; electromagnetic leptogenesis; ....

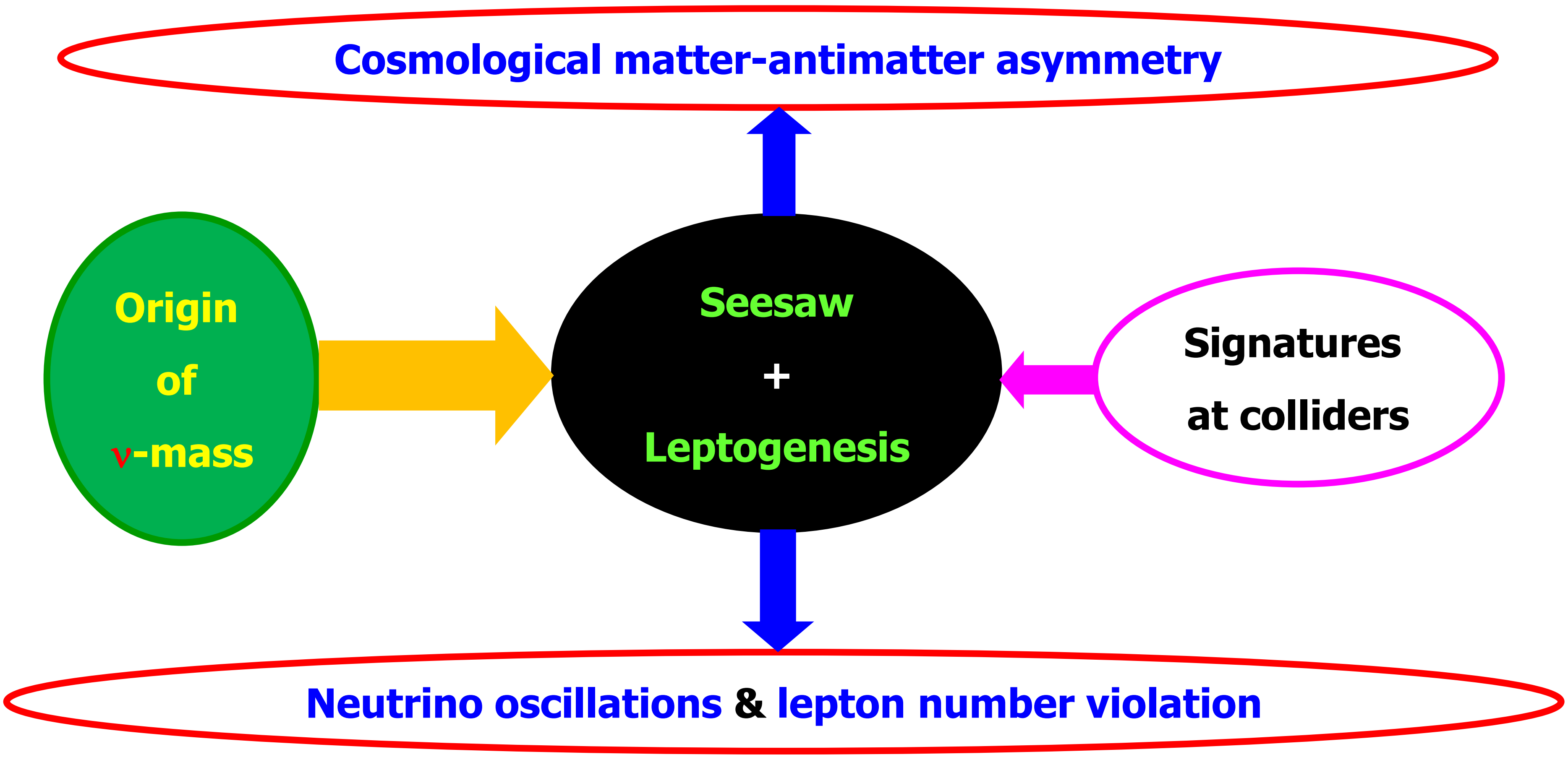
Flavored Leptogenesis

Flavor effect: Barbieri et al 00; Endoh et al 04; Pilaftsis 05; Abada et al 06; Nardi et al 06; … (Review: Davidson, Nardi, Nir, Phys. Rept. 08).





A Grand Picture?



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

Cosmic Flavor Physics

CνB
Hot DM

keV ν's
Warm DM

Baryogenesis
Leptogenesis

Energetic ν's
from cold DM

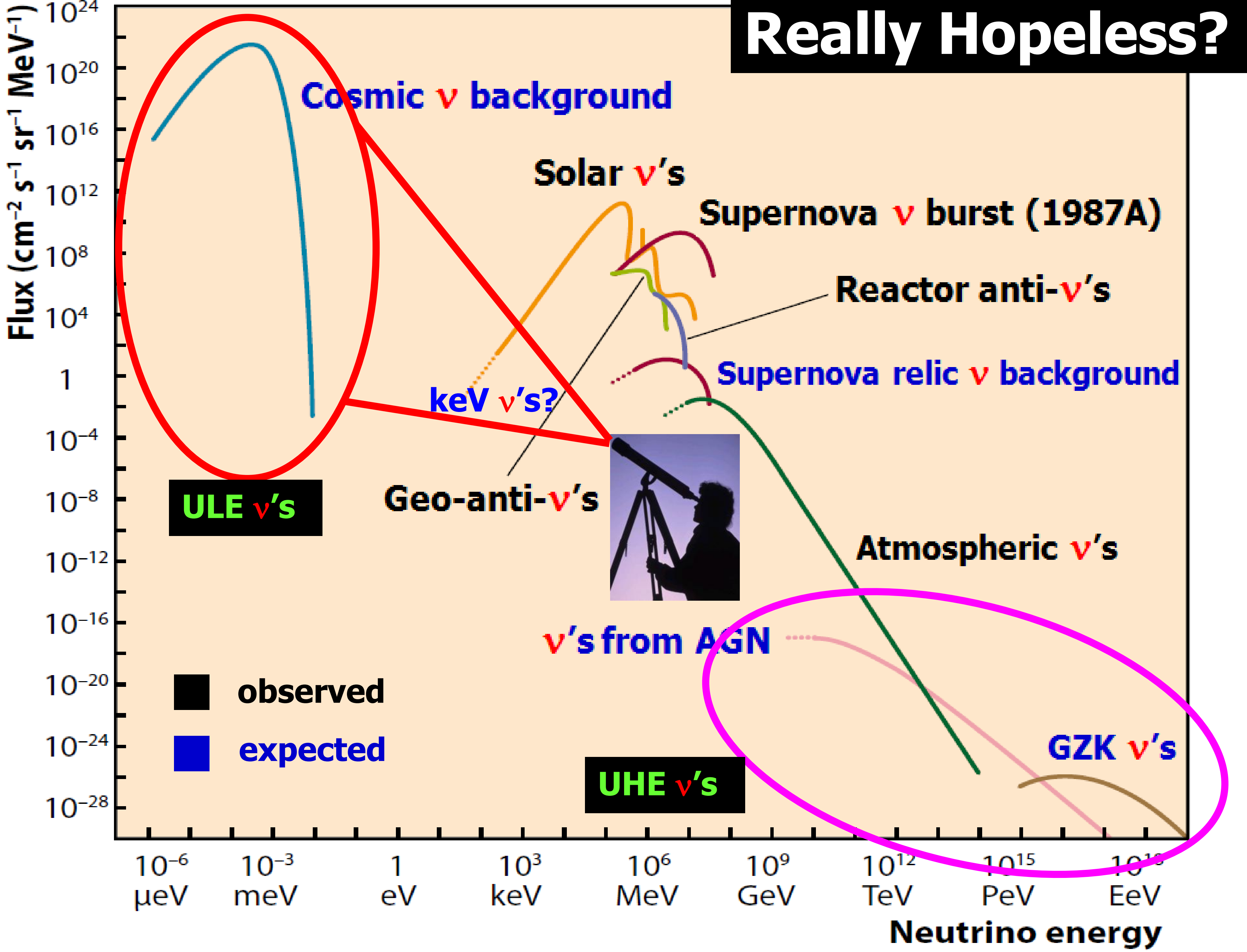
UHE
Cosmic ν's

Supernova ν's
(relic background)

……

A New Road Ahead?

Really Hopeless?




L. Pauling
good idea?
Thank you for your attention!