The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
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IAEA
International Atomic Energy Agency

2246-31

Workshop on Cosmic Rays and Cosmic Neutrinos: Looking at the Neutrino Sky

20 - 24 June 2011

UHE cosmic neutrinos and ULE neutrino dark matter

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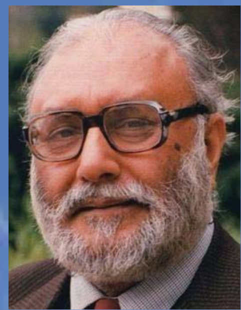
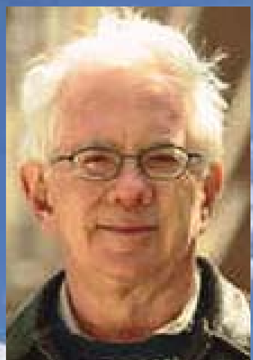
UHE cosmic ν's & ULE ν dark matter

Zhi-zhong Xing (IHEP, Beijing)

Why not much cloudier?



Salam's center



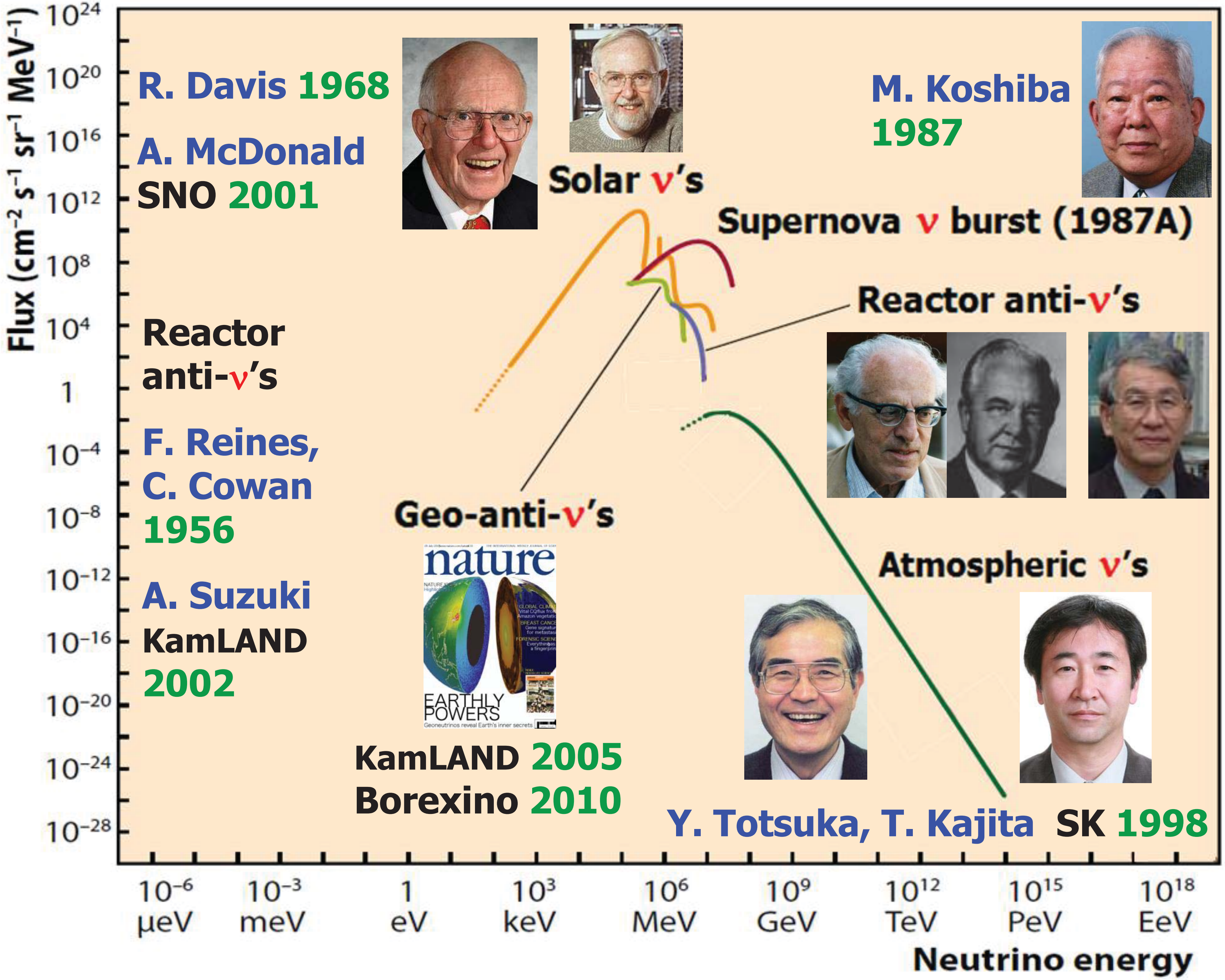
Glashow's resonance

Weinberg's trap

NUSKY: Looking at the Neutrino Sky, Trieste, June 2011

THE MENU

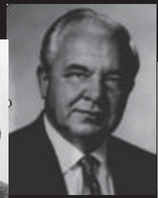
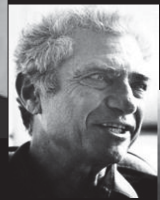
- ♣ Extremes in the ν sky
- ♣ UHE cosmic ν flavors
- ♣ Cosmic ν background
- ♣ Warm ν dark matter?


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





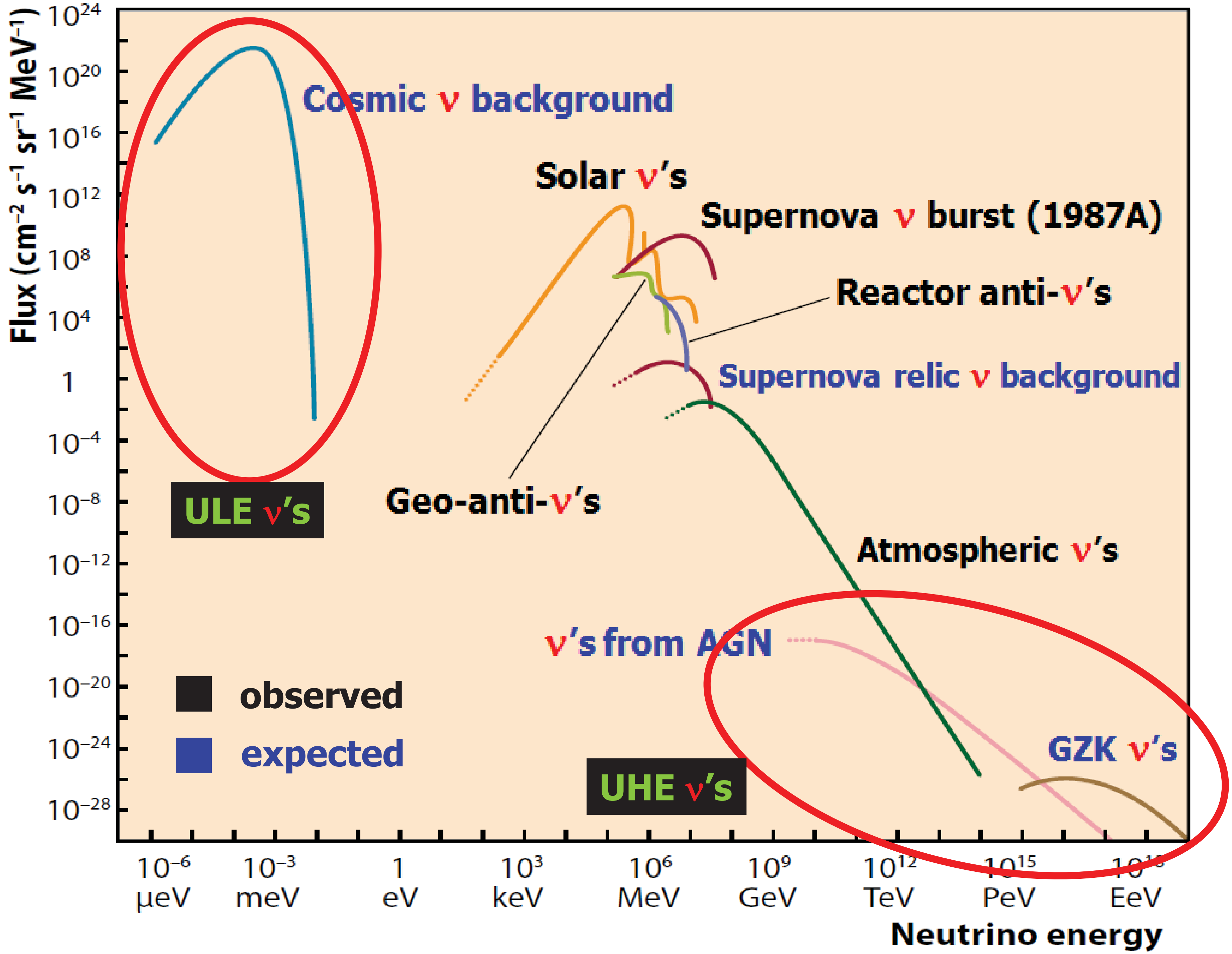

Current Data

parameter	best fit $\pm 1\sigma$		3σ
$\Delta m^2_{21}\ [10^{-5}\mathrm{eV}^2]$	$7.59^{+0.20}_{-0.18}$	7.2	7.09–8.19
$\Delta m^2_{31}\ [10^{-3}\mathrm{eV}^2]$	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		
$\sin^2\theta_{13}$	$0.010^{+0.009}_{-0.006}$ $0.013^{+0.009}_{-0.007}$		

Much larger theta(13)?

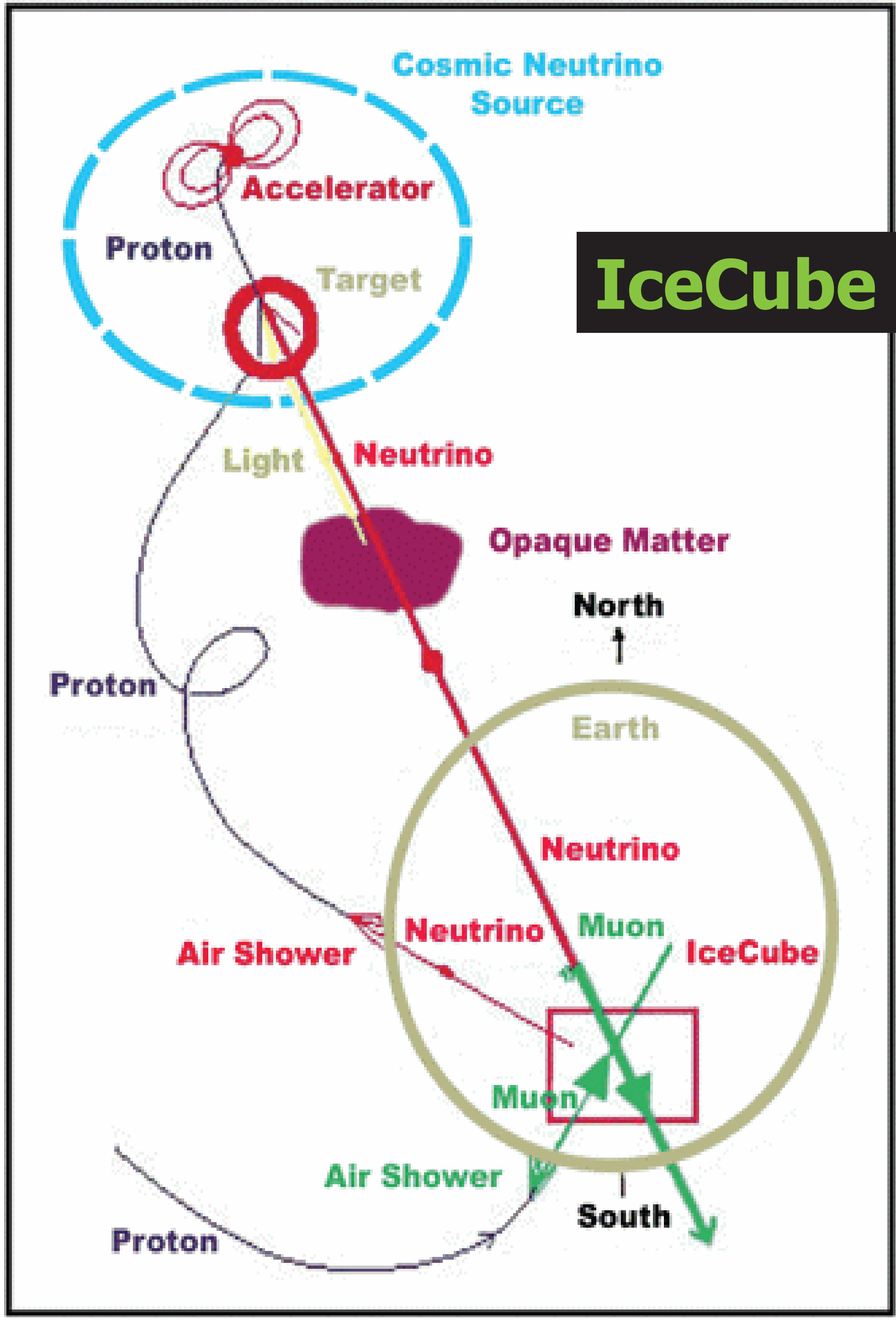
T2K's latest indication:

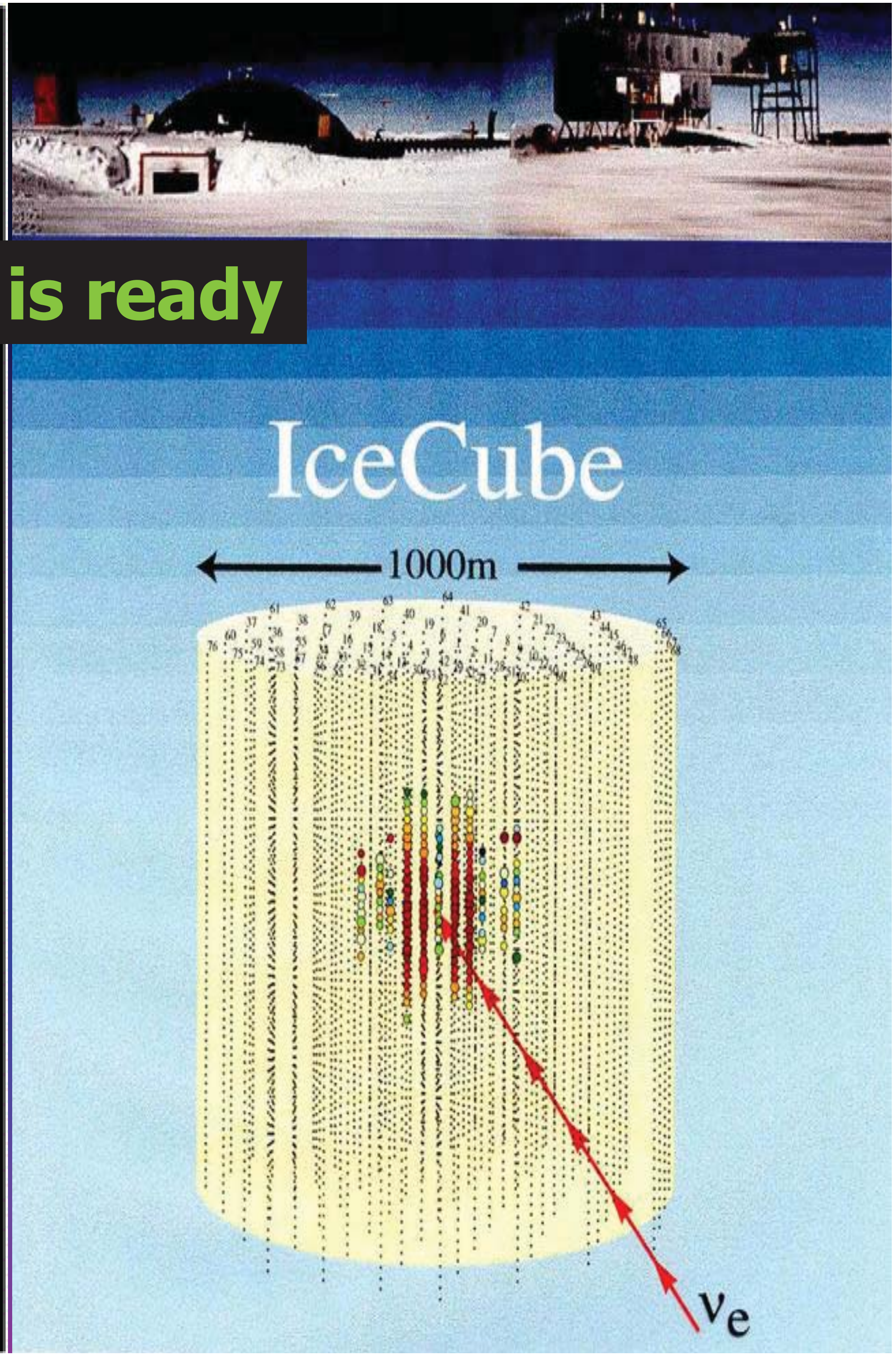
~ 9 degrees 1106.2822



Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
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
ν's from AGN
GZK ν's
ULE ν's
UHE ν's
observed
expected
μeV
meV
eV
keV
MeV
GeV
TeV
PeV
EeV
Neutrino energy

IceCube is ready





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.

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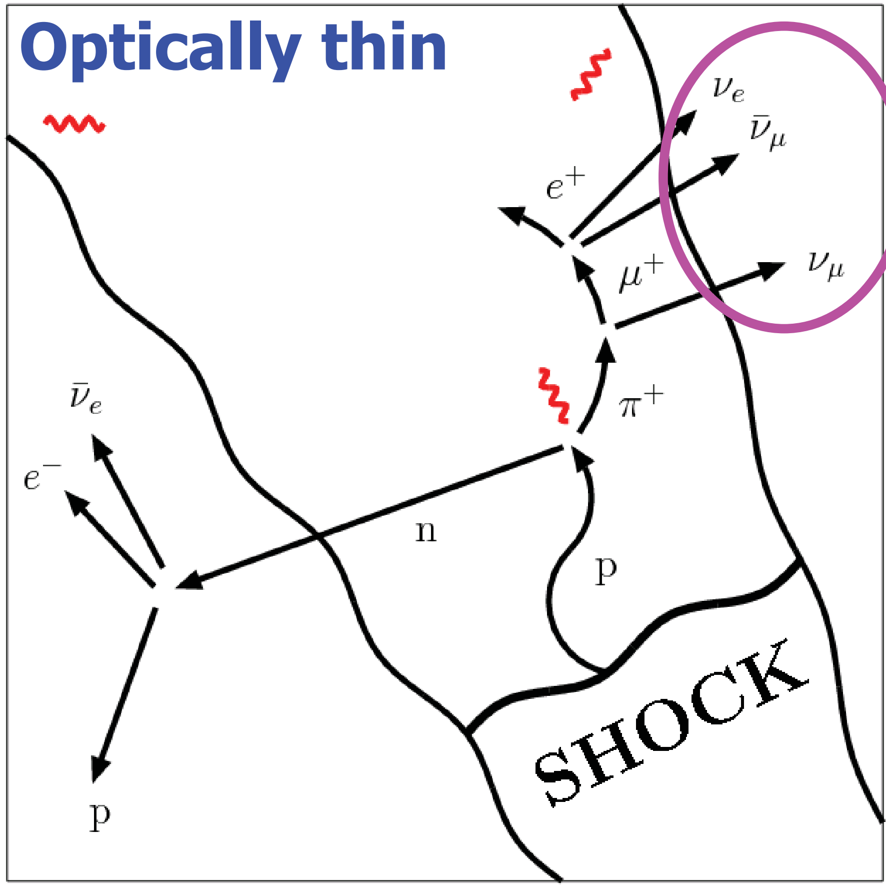
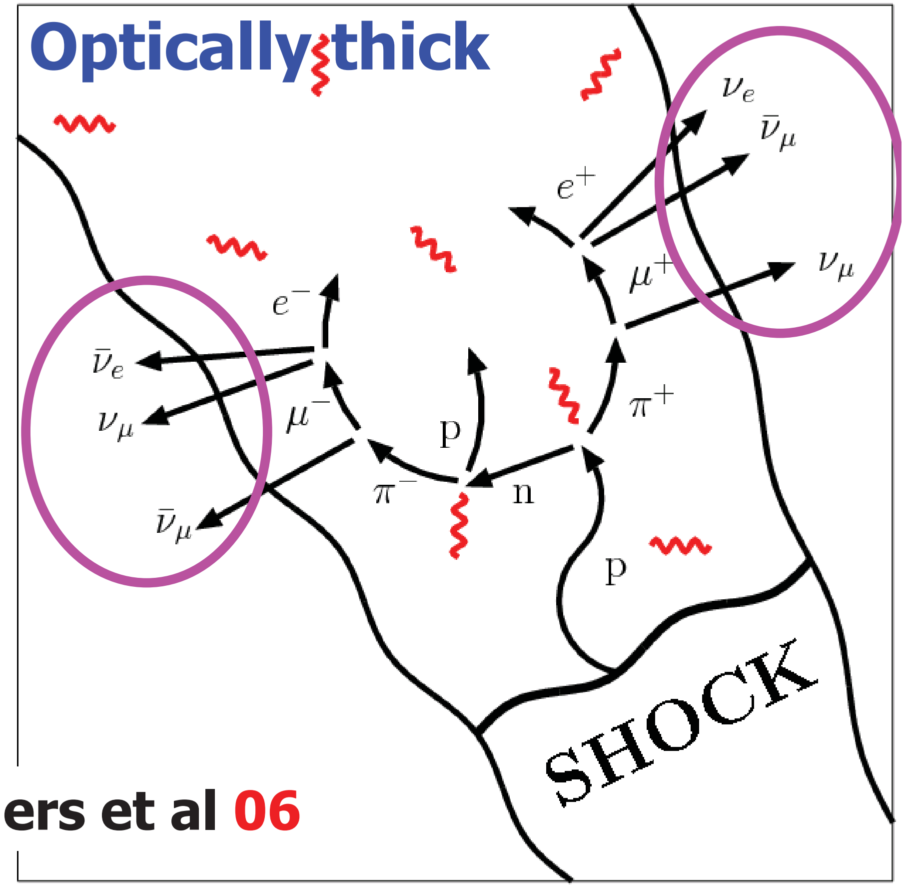




Ahlers et al 06

Conventional mechanism:

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

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

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

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

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

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.

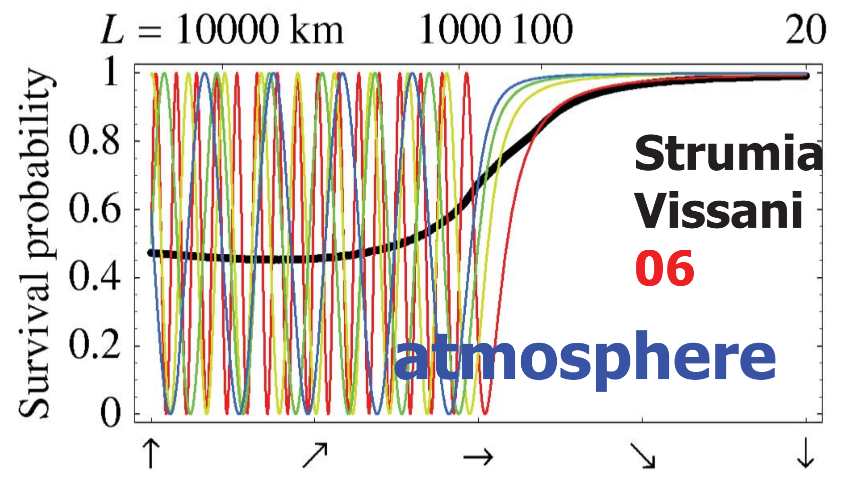
For $|\Delta m^2| \sim 10^{-4}\ \mathrm{eV}^2$ **, the oscillation length in vacuum:**

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

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

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*: $\boxed{|V_{\mu i}| = |V_{\tau i}|}$ $(i = 1, 2, 3)$

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):

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

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)

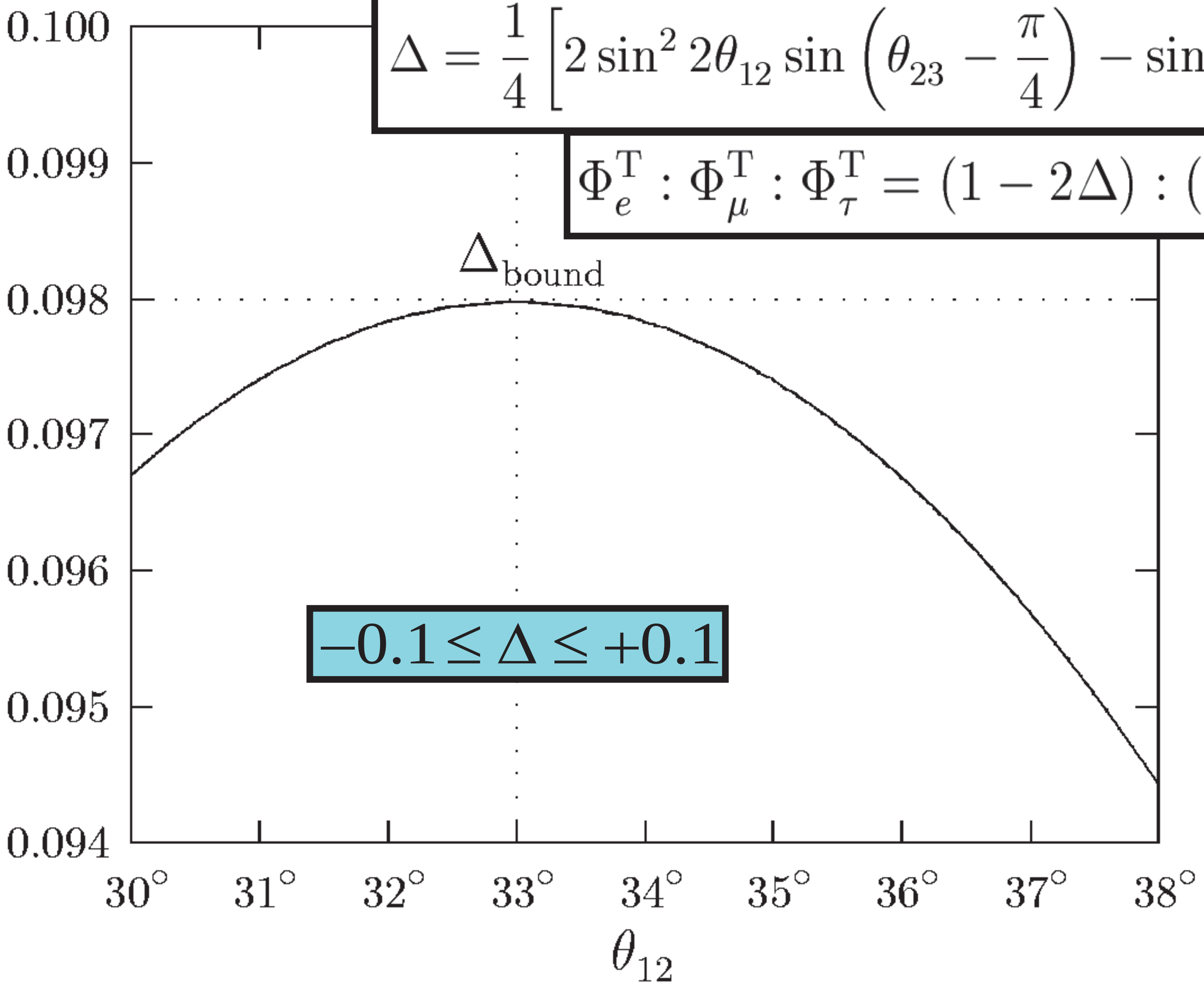
μ-τ symmetry breaking (Xing, 06)

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

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 $p\gamma$ or pp collisions

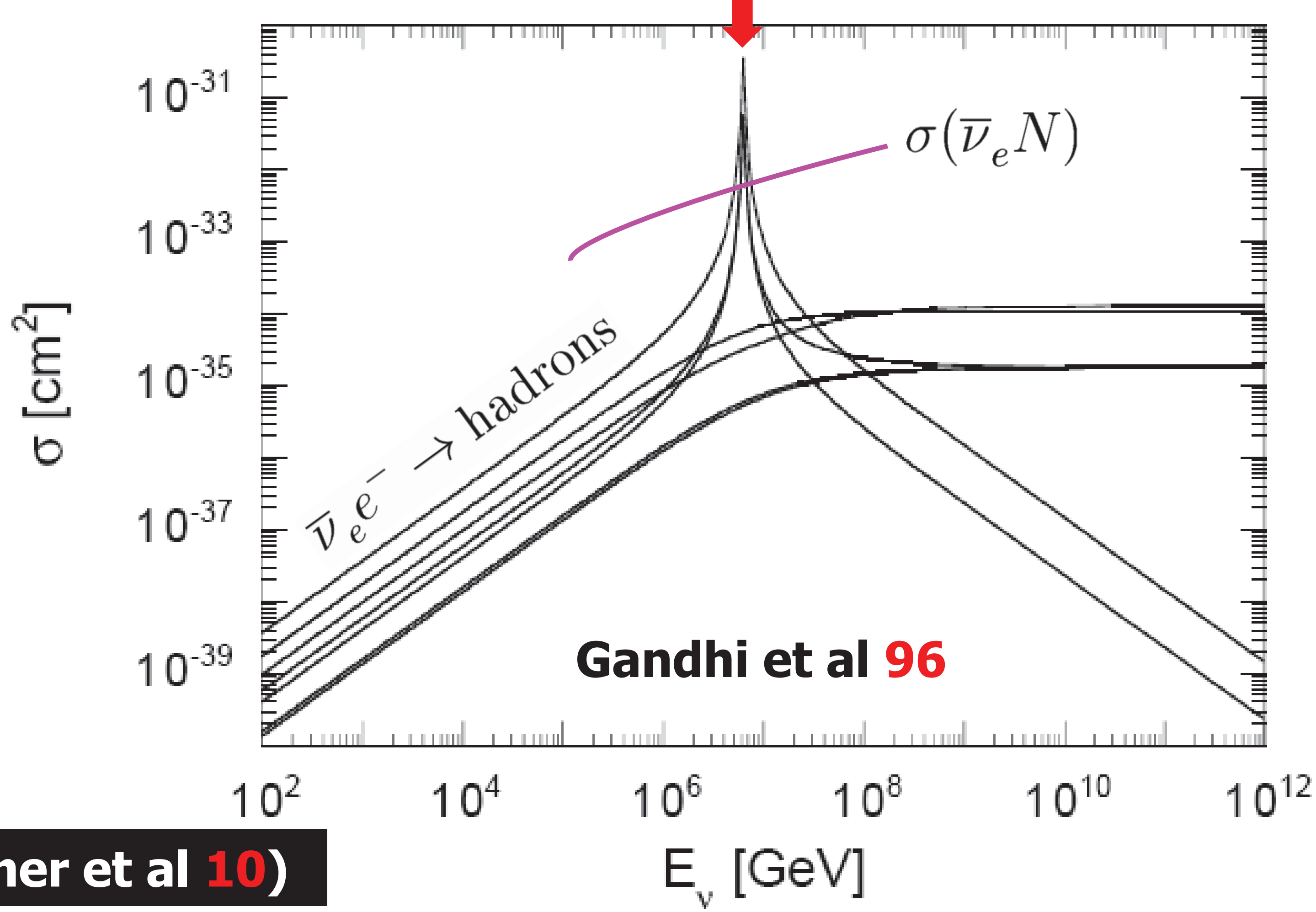
The Glashow Resonance

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

Unique for electron anti-ν's!

(Glashow 60)

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



Gandhi et al 96

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

A New Parametrization

Assume a cosmic accelerator with both pγ & pp collisions.

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

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

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

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

At the source:

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

$$\begin{aligned} &\left\{\Phi^{\rm S}_{\nu_e} : \Phi^{\rm S}_{\overline{\nu}_e} : \Phi^{\rm S}_{\nu_\mu} : \Phi^{\rm S}_{\overline{\nu}_\mu} : \Phi^{\rm S}_{\nu_\tau} : \Phi^{\rm S}_{\overline{\nu}_\tau}\right\} \\ &= \left(\Phi^{p\gamma}_{\pi^+} + \Phi^{pp}_{\pi^+}\right)\left\{\frac{1}{3} : 0 : \frac{1}{3} : \frac{1}{3} : 0 : 0\right\} + \left(\Phi^{p\gamma}_{\pi^-} + \Phi^{pp}_{\pi^-}\right)\left\{0 : \frac{1}{3} : \frac{1}{3} : \frac{1}{3} : 0 : 0\right\} \\ &= \left\{\frac{1}{3}\left[\frac{1}{2+\delta_{pp}} + \frac{1+\delta_{pp}-\delta_{p\gamma}}{(2+\delta_{pp})(1+\delta_{p\gamma})}\kappa\right] : \frac{1}{3}\left[\frac{1+\delta_{pp}}{2+\delta_{pp}} - \frac{1+\delta_{pp}-\delta_{p\gamma}}{(2+\delta_{pp})(1+\delta_{p\gamma})}\kappa\right] : \frac{1}{3} : \frac{1}{3} : 0 : 0\right\} \end{aligned}$$

At the ν-telescope:

(the Glashow resonance working observable)

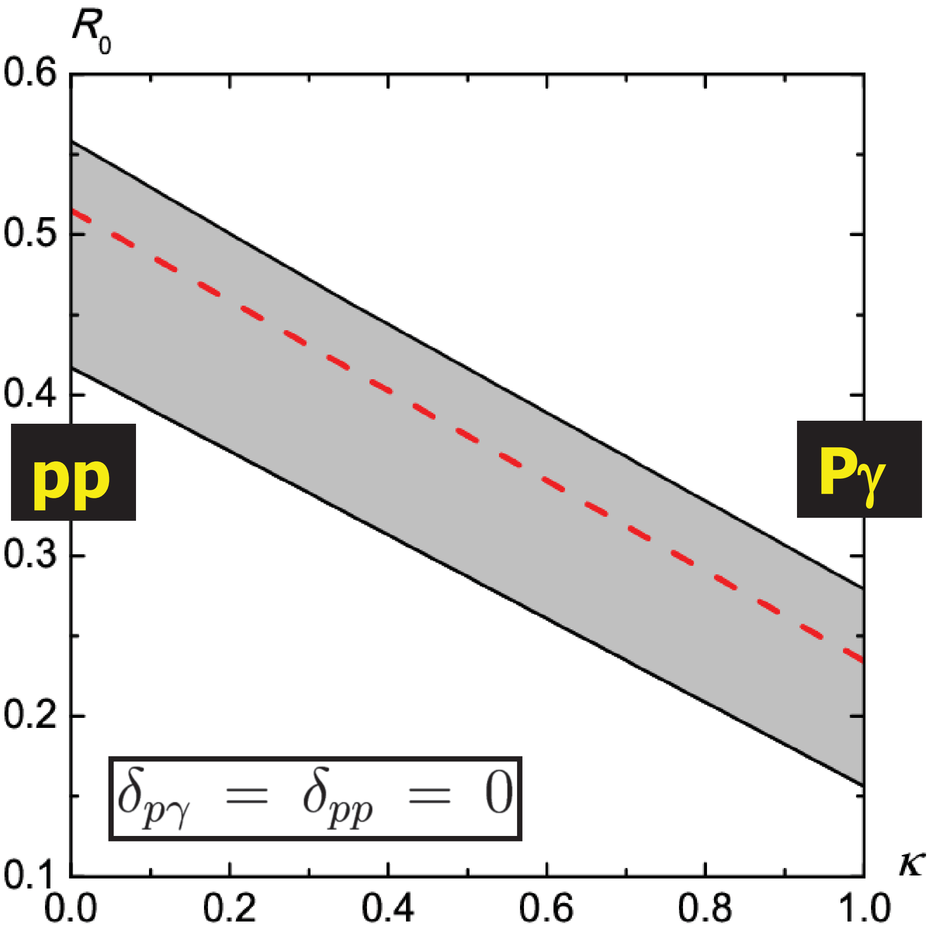
$$R_0 \equiv \frac{\Phi^{\rm T}_{\overline{\nu}_e}}{\Phi^{\rm T}_{\nu_\mu} + \Phi^{\rm T}_{\overline{\nu}_\mu}} = \left[\frac{1+\delta_{pp}}{2+\delta_{pp}} - \frac{1+\delta_{pp}-\delta_{p\gamma}}{(2+\delta_{pp})(1+\delta_{p\gamma})}\kappa\right]\frac{P_{ee}}{P_{e\mu}+2P_{\mu\mu}} + \frac{P_{e\mu}}{P_{e\mu}+2P_{\mu\mu}}$$

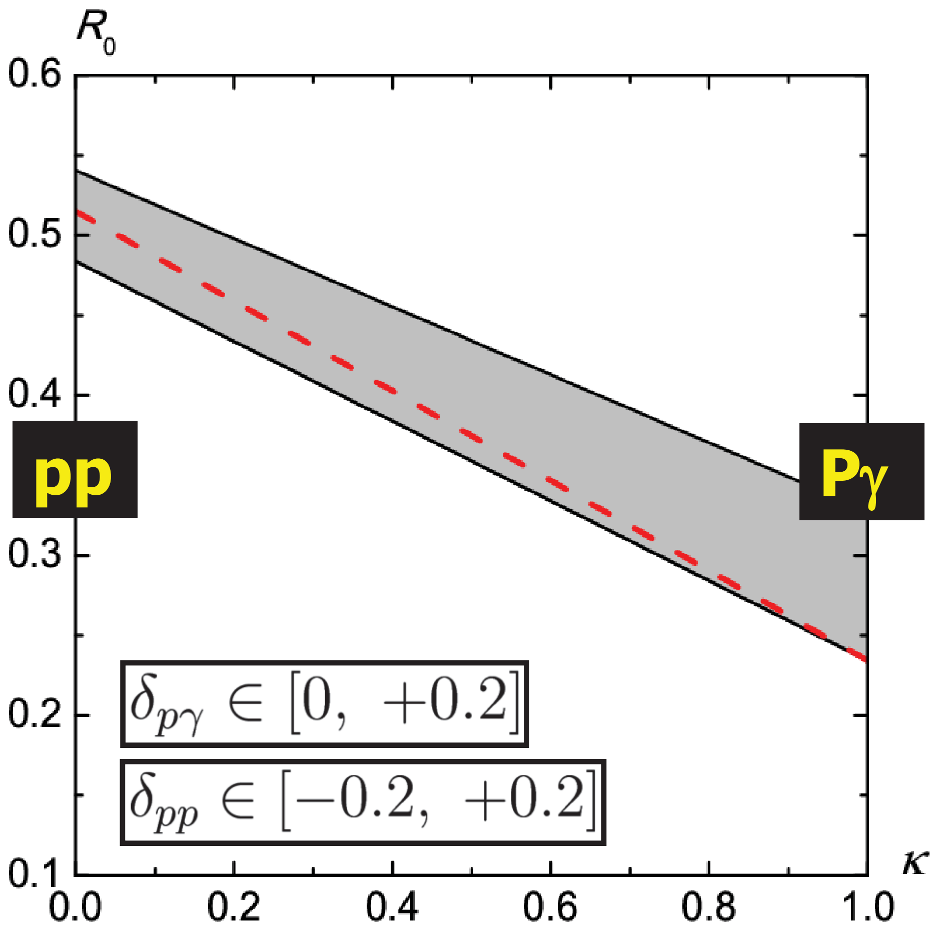
Numerical Illustration

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





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:

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

- Postulated neutron source:

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

- Possible muon-damped source:

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

Working Observables

We define the following observables:

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

Only two of them are independent, because

$$\hat{R}_e + \hat{R}_\mu + \hat{R}_\tau = 1 \qquad \text{with} \qquad \hat{R}_\alpha \equiv \frac{R_\alpha}{1+R_\alpha}$$

Another observable is the total neutrino flux of all flavors:

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

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:

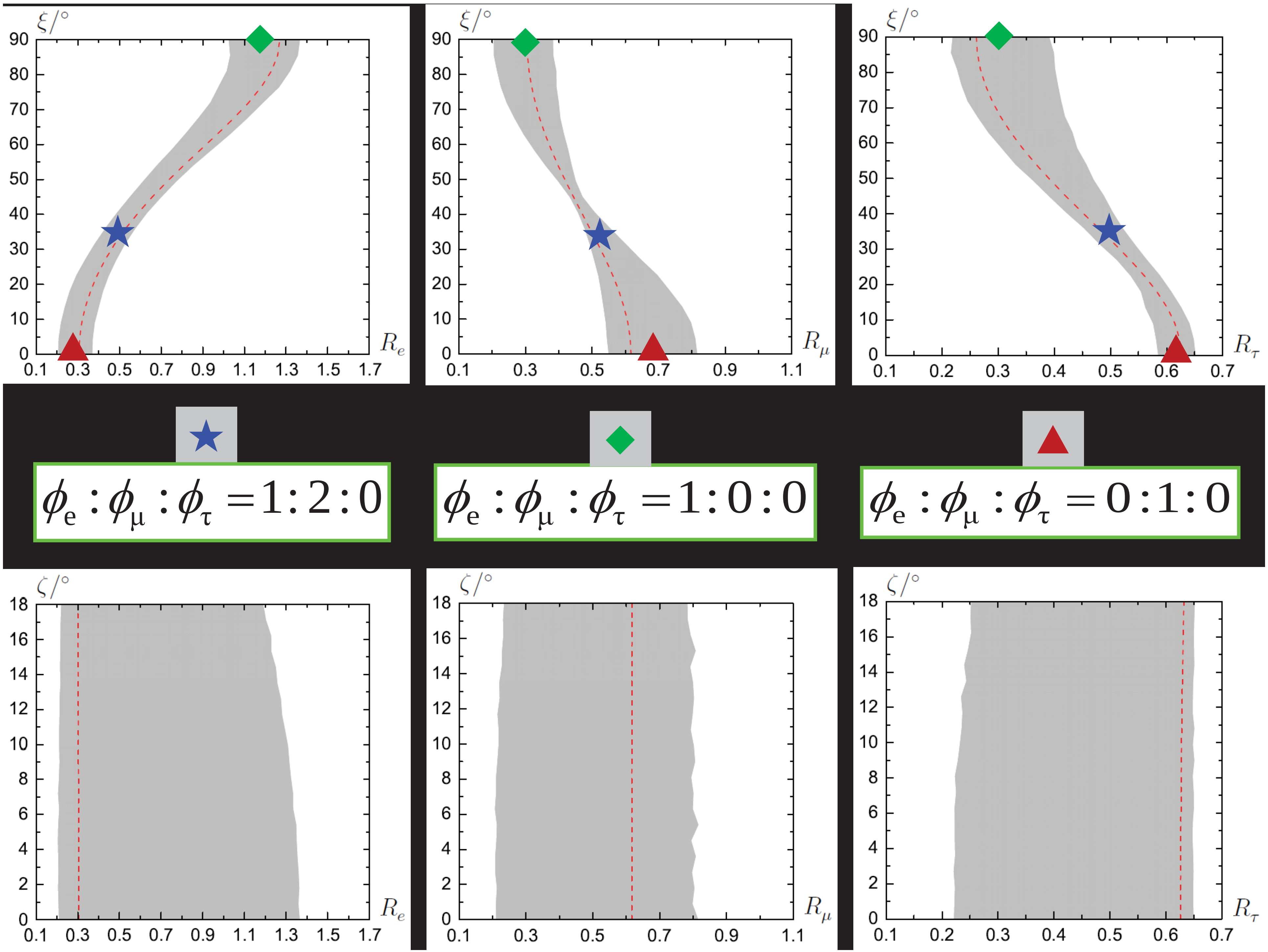
$$\{\phi_e, \phi_\mu, \phi_\tau\} = \{\sin^2\xi \cos^2\zeta, \cos^2\xi \cos^2\zeta, \sin^2\zeta\}\phi_0$$

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

Determination of the source parameters

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

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


$\xi/^\circ$
R_e
R_μ
R_τ
$\phi_e : \phi_\mu : \phi_\tau = 1:2:0$
$\phi_e : \phi_\mu : \phi_\tau = 1:0:0$
$\phi_e : \phi_\mu : \phi_\tau = 0:1:0$
$\zeta/^\circ$
R_e
R_μ
R_τ

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

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

Neutrinos decoupled from matter:

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

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

Number density of 6 relic ν's:

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

$\Gamma > H$ $\quad$ $\Gamma \sim H$ $\quad$ $\Gamma < H$

ν's in thermal contact with cosmic plasma | 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)

$T_\nu = T_\gamma$

neutrino decoupling

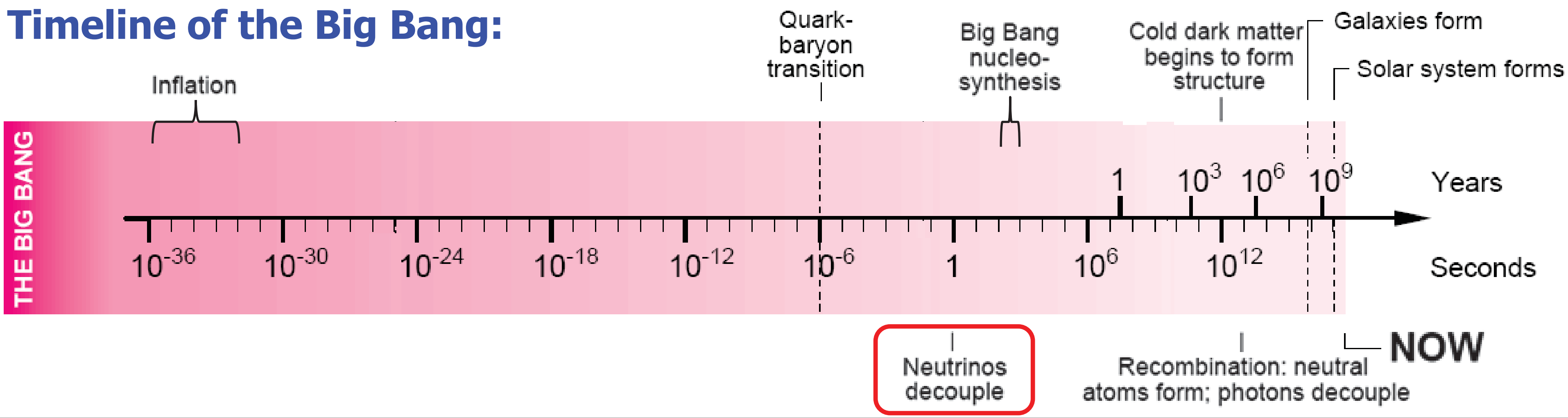
$$T_{fr} \sim \left(\frac{\sqrt{g_*}}{G_F^2 M_{Pl}}\right)^{1/3} \sim 1\ \mathrm{MeV}$$

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

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

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

Mean momentum today

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

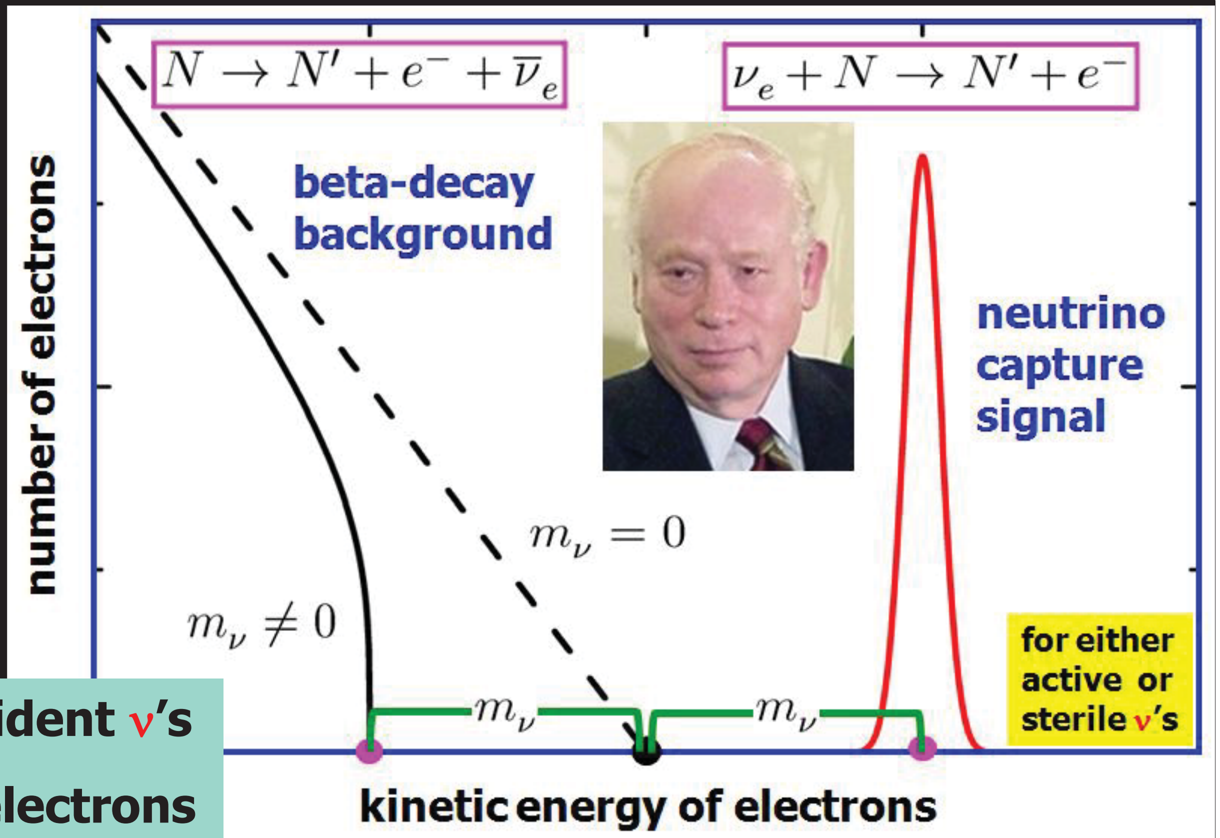
At least 2 ν's cold today

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 $\boxed{\dfrac{c}{v_\nu}}$ so that the number of events converges to a constant for $\boxed{v_\nu \to 0}$:

$$\sigma(\nu_e N) \cdot \frac{v_\nu}{c}\bigg|_{v_\nu \to 0} = \text{const.} \qquad \text{e.g.} \quad \sigma(\nu_e {}^3\text{H}) \cdot \frac{v_\nu}{c}\bigg|_{v_\nu \to 0} \simeq (7.84 \pm 0.03) \times 10^{-45}\,\text{cm}^2$$

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

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

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

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

Background: (the tritium β-decay) $\quad E_e = T_e' + m_e \qquad \langle n_{\nu_i} \rangle \approx \langle n_{\bar{\nu}_i} \rangle \approx 56\ \text{cm}^{-3}$

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

Energy resolution (Gaussian function) : $\quad \Delta = 2\sqrt{2\ln 2}\,\sigma \approx 2.35482\,\sigma$

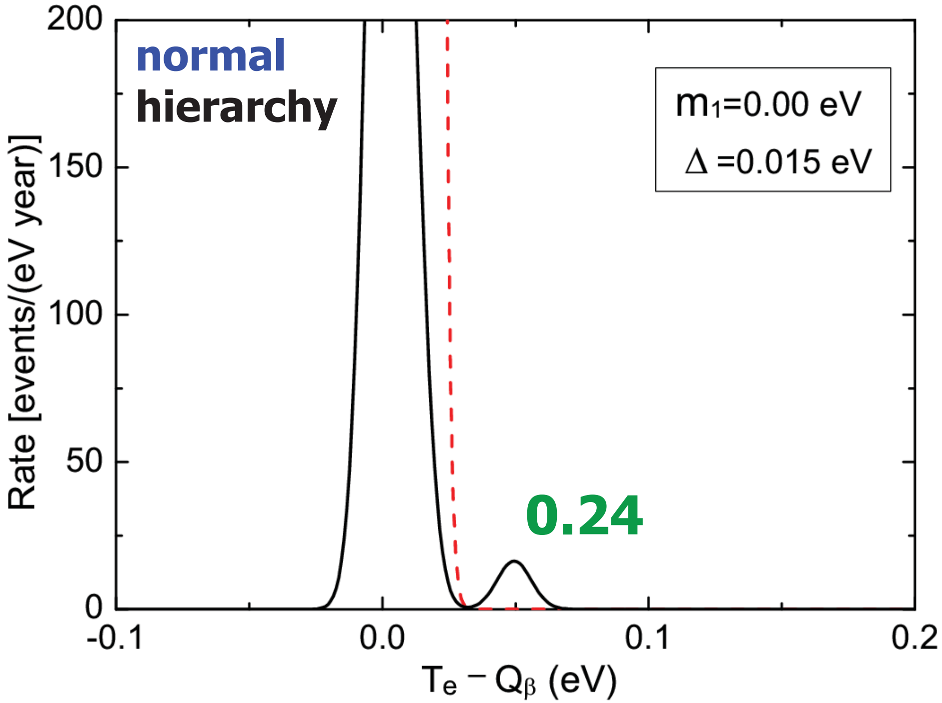
Illustration

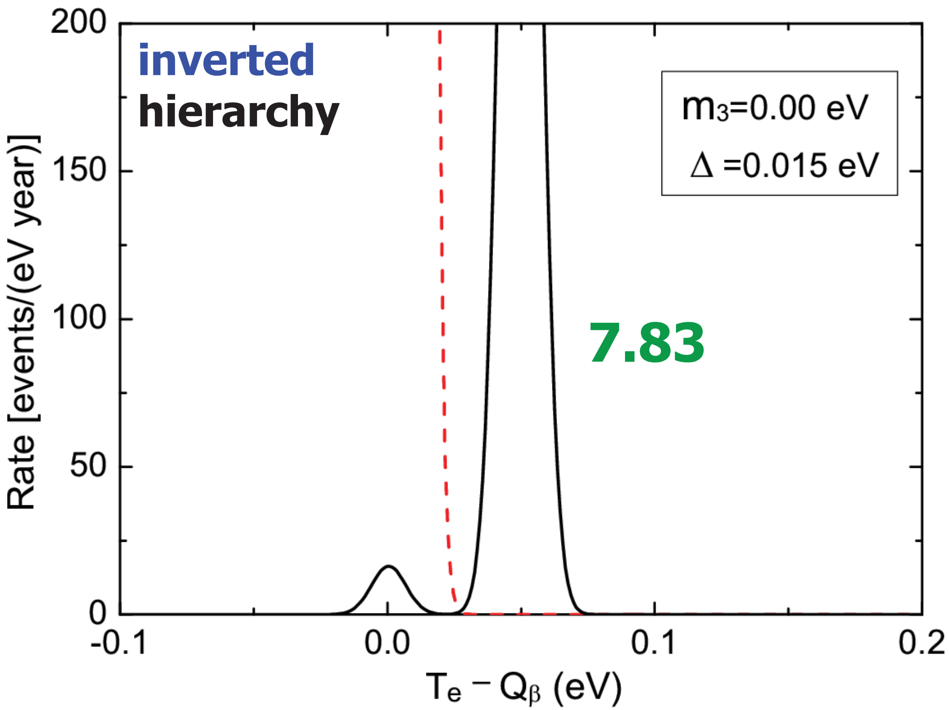
Target mass: 100 g tritium atoms

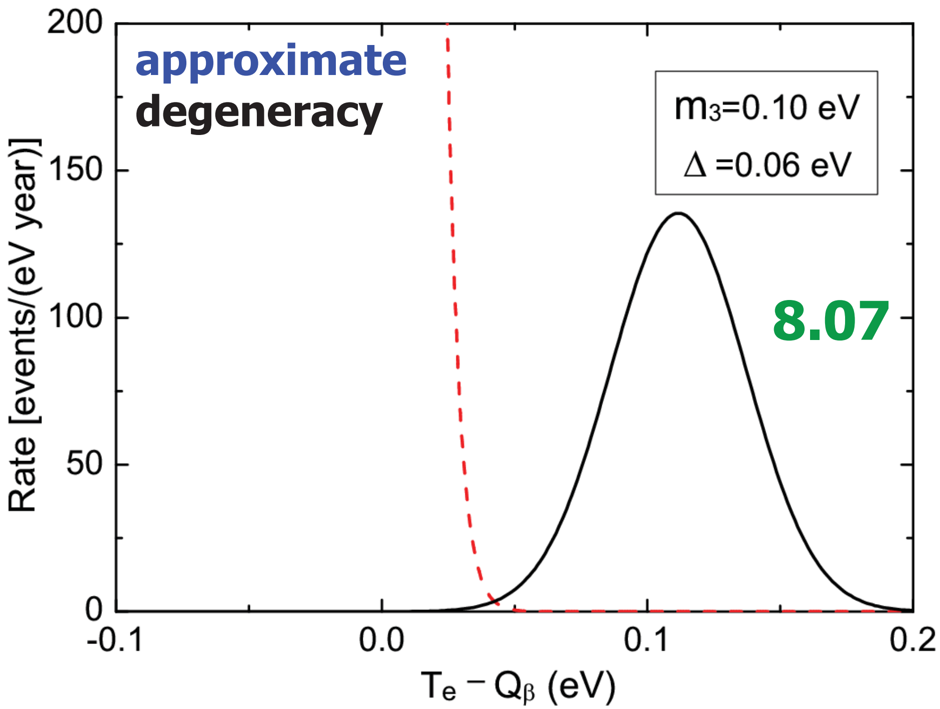
Input θ(13) : 10 degrees

Number of events per year: ~ 8

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



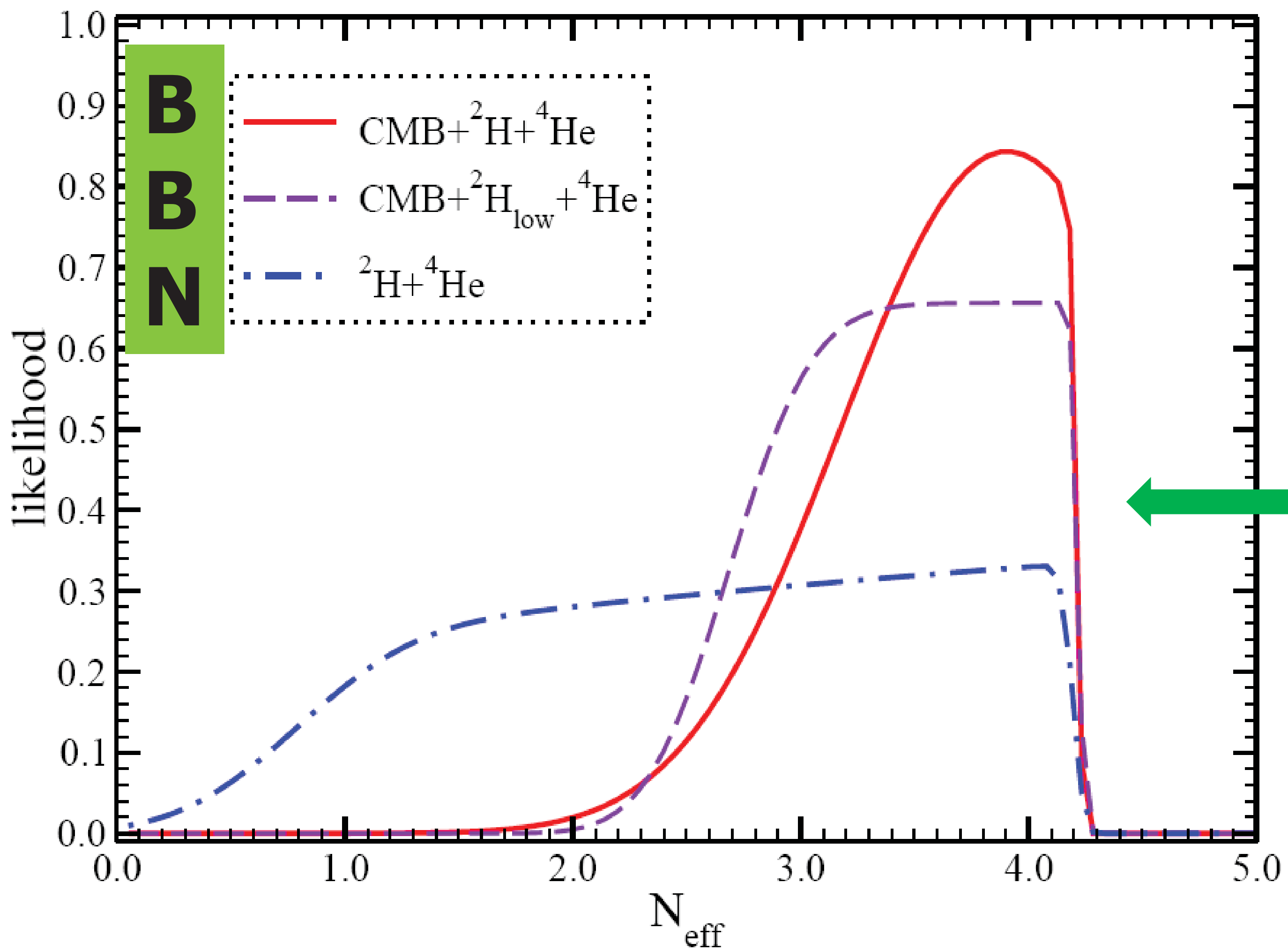




Sub-eV Sterile ν's?

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

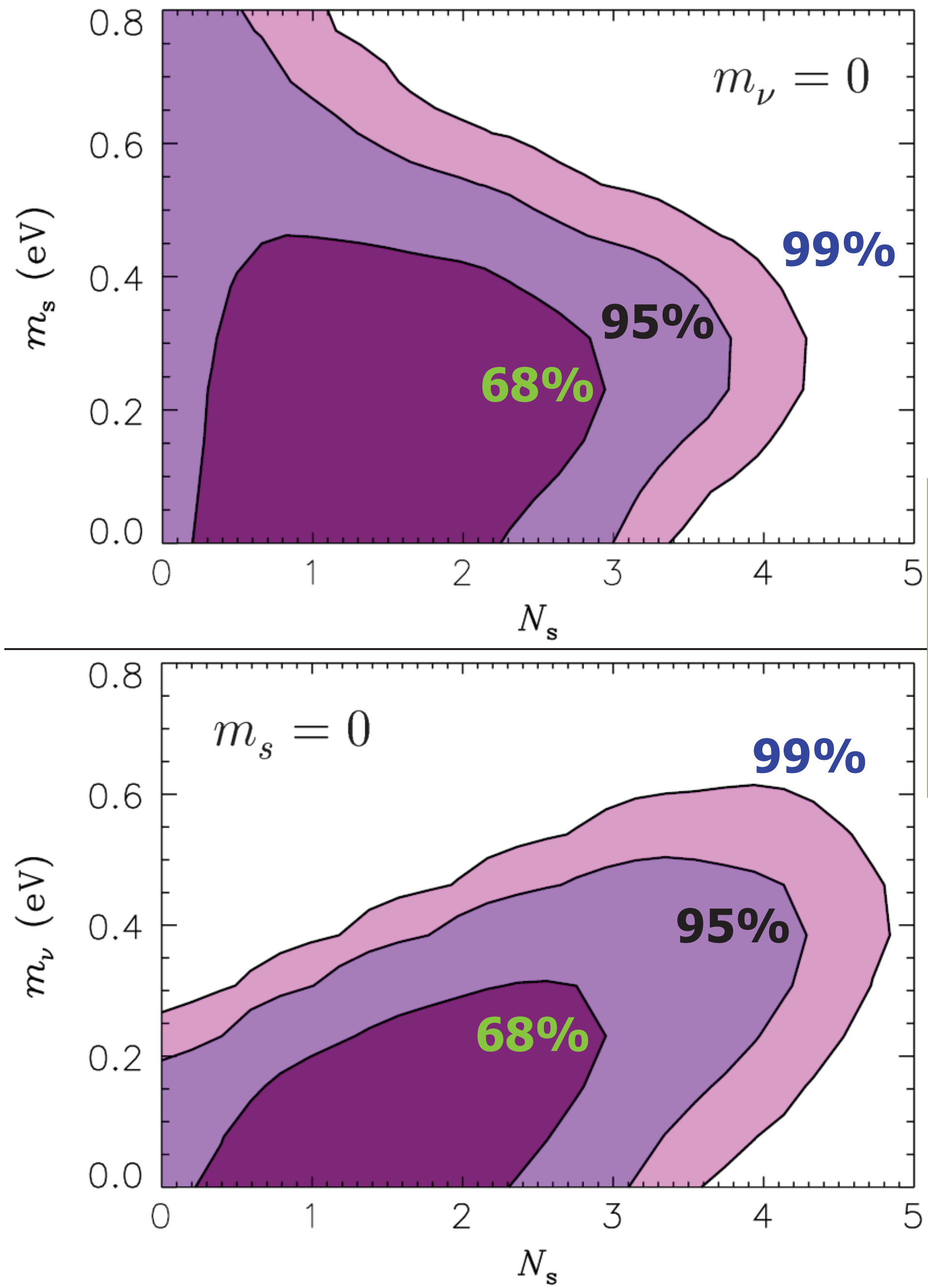
$N_{\rm eff} < 4.2$

(95% C.L.)

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

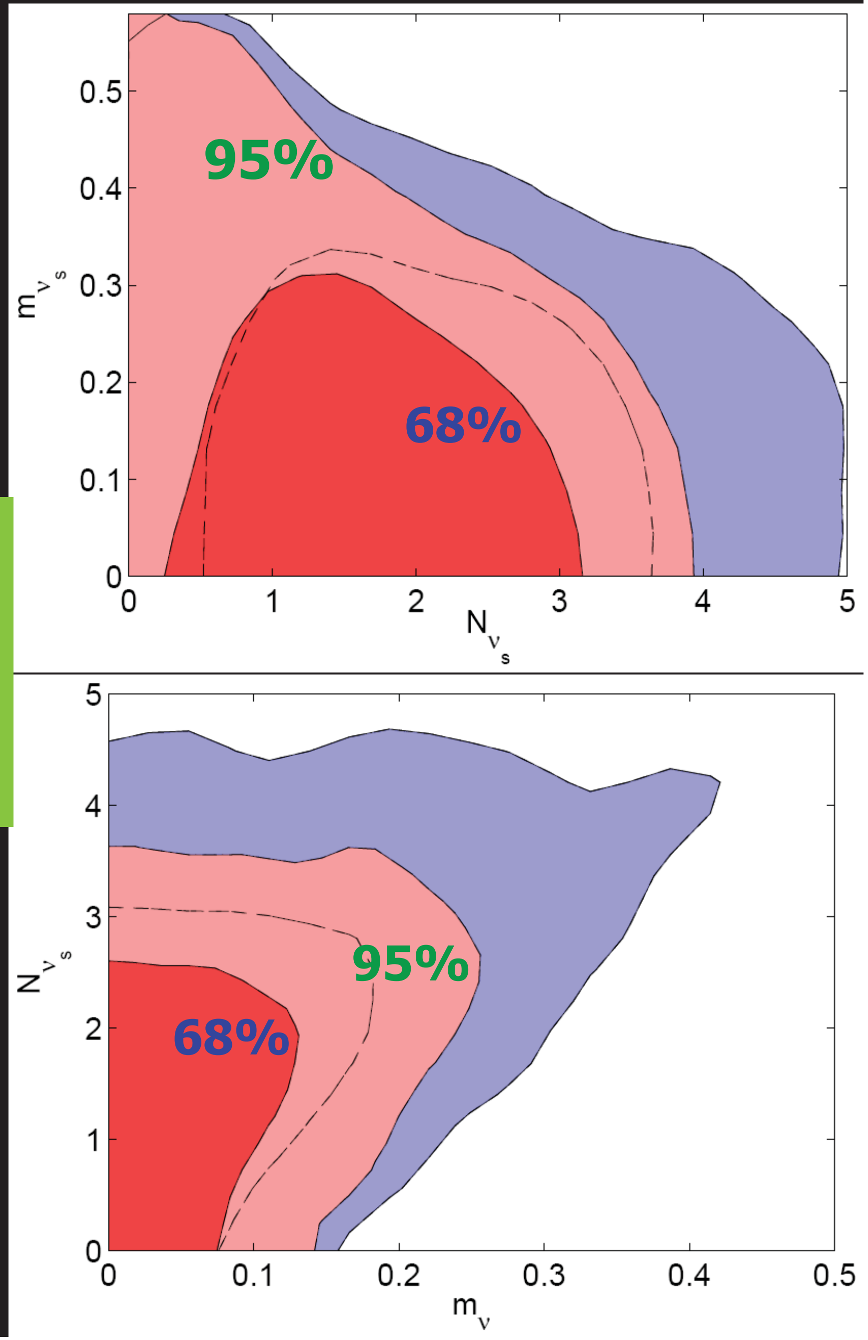
$N_{\rm eff}^{\rm SM} = 3.046$

J. Hamann et al, arXiv:1006.5276



CMB

E. Giusarma, arXiv:1102.4774

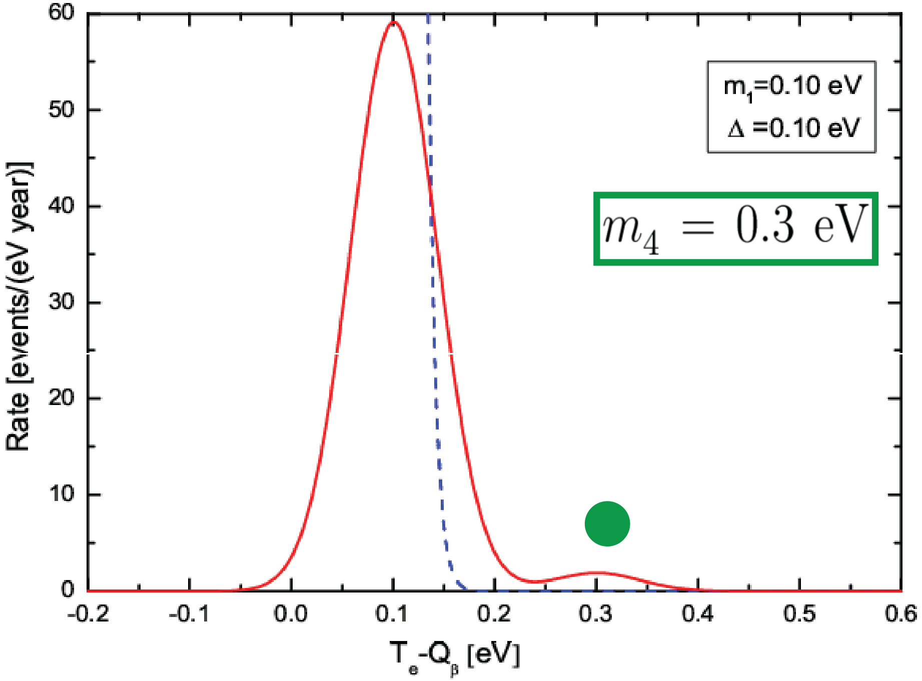


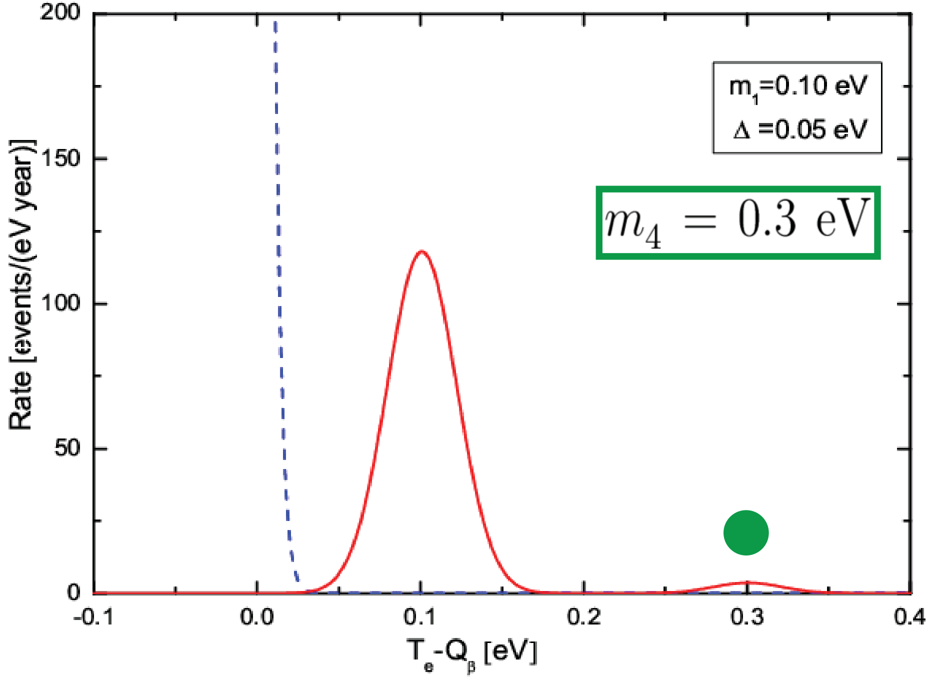
(3+1) Scheme

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

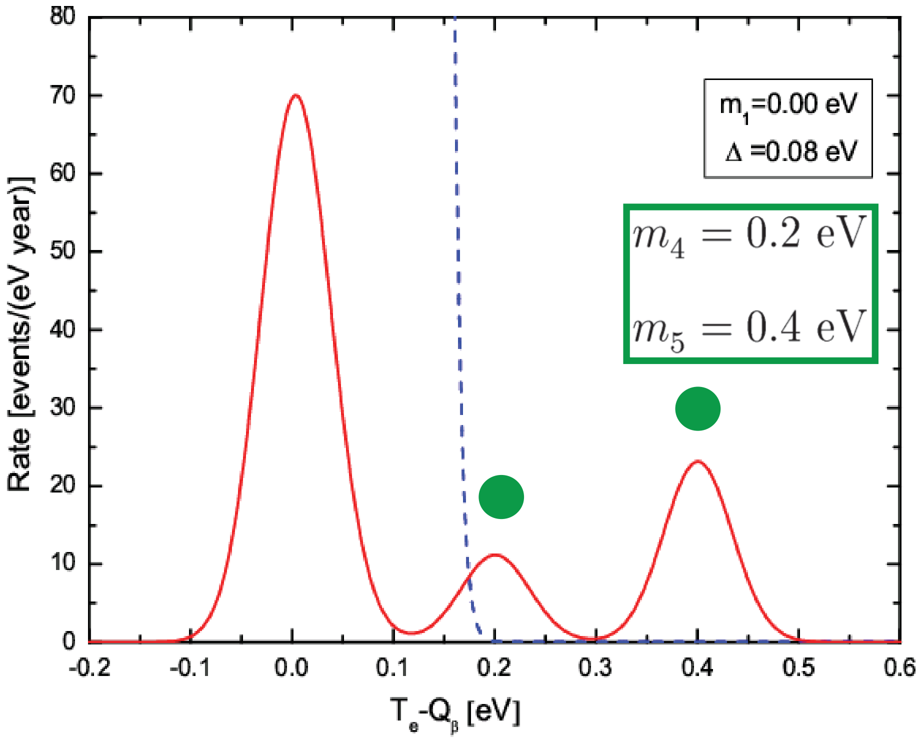
Gravitational clustering: only those cosmic ν's with velocities smaller than the escape velocity of a given structure can be bound to it. Let's assume a larger GC effect for a heavier ν around the Earth.

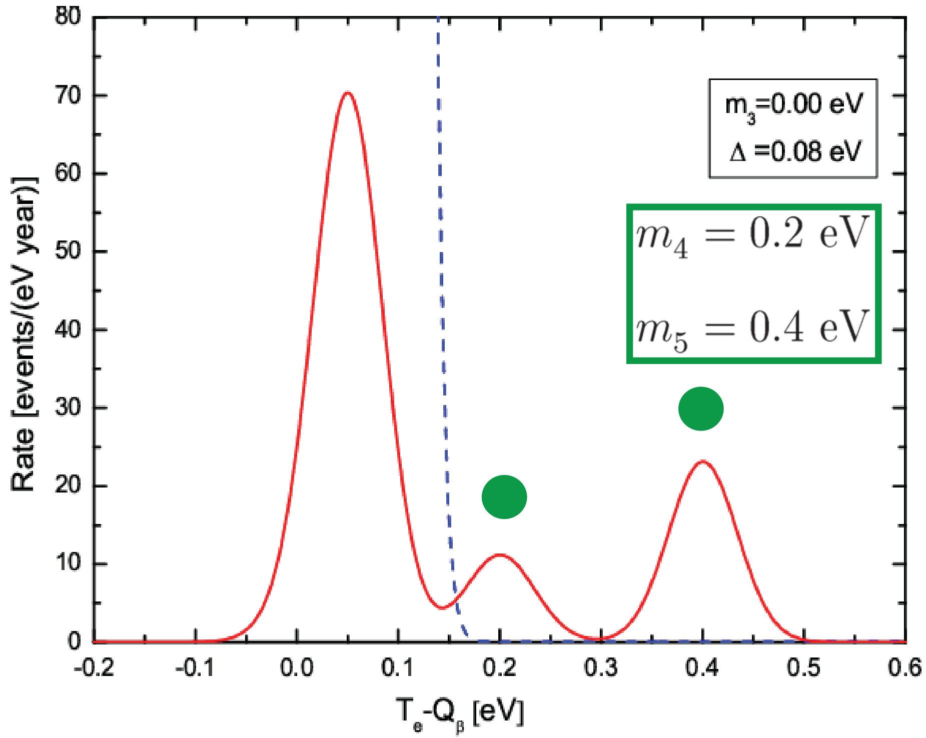
The (3+2) scheme:

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

Input:

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



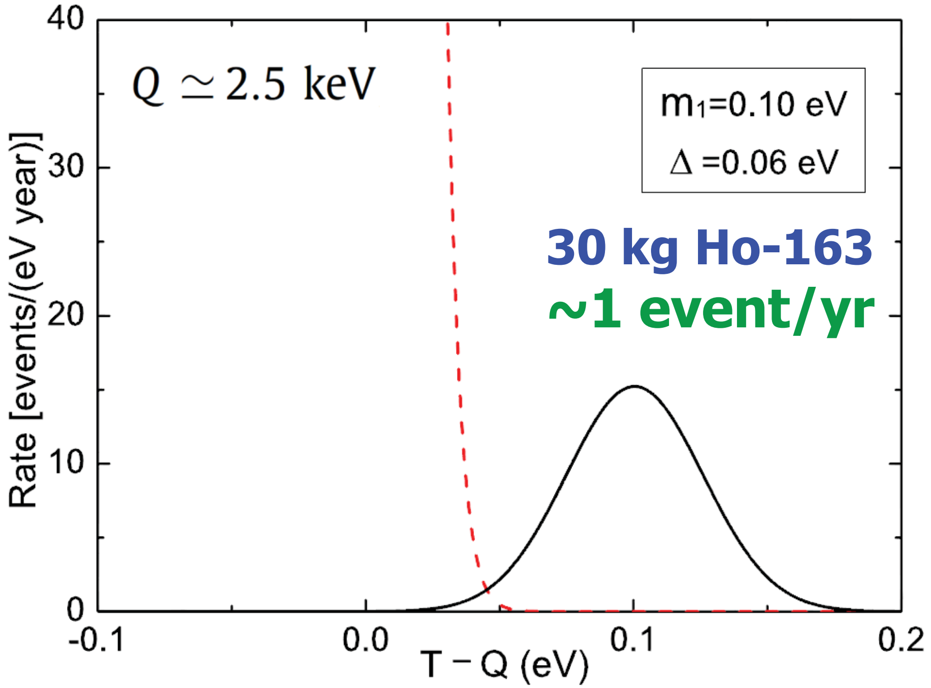


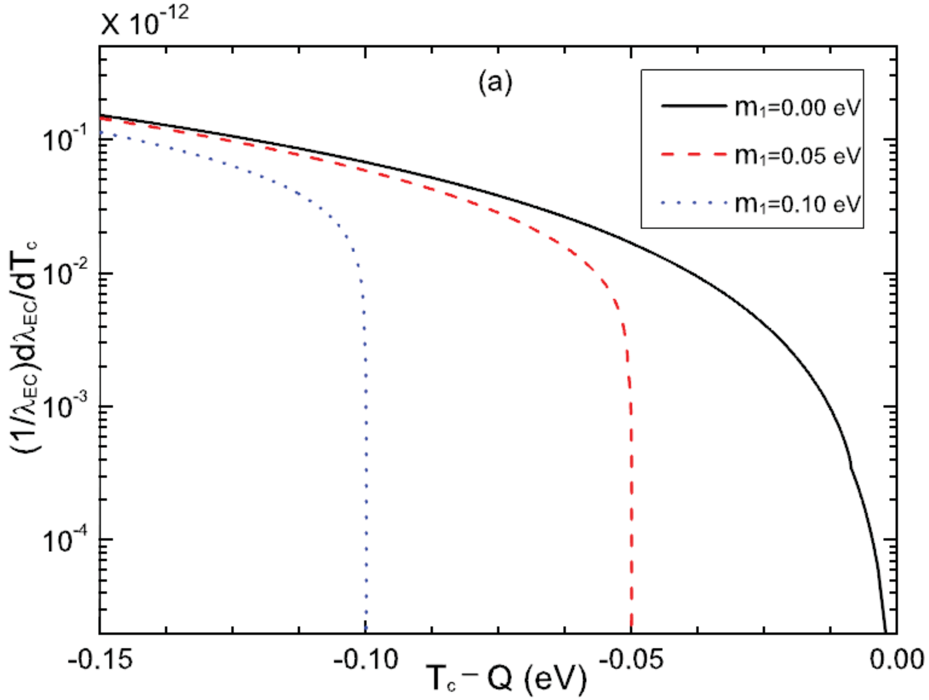
Cosmic anti-ν Background?

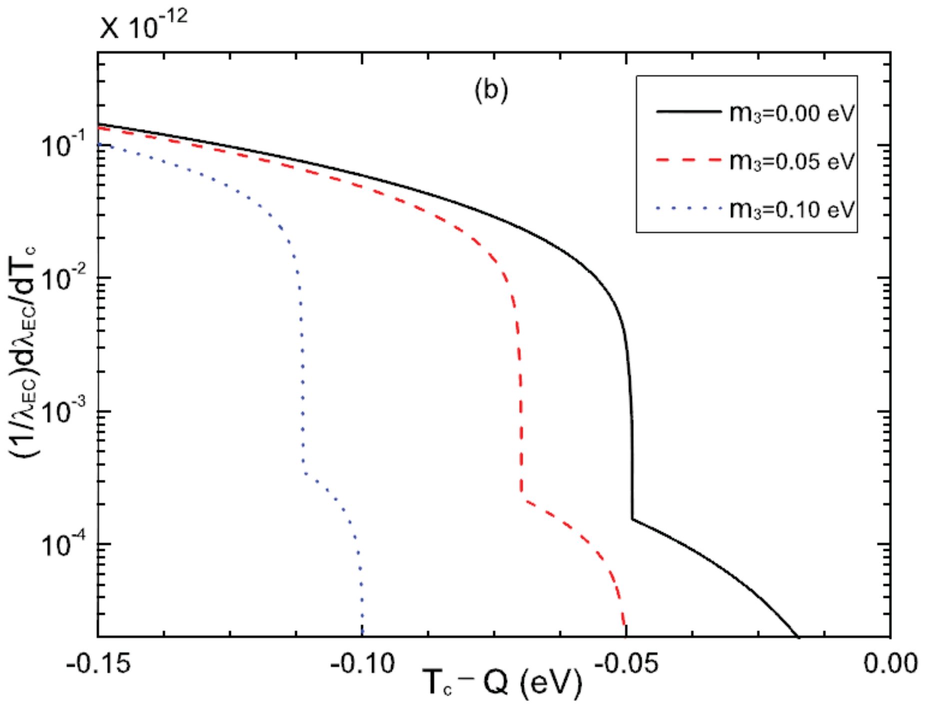
Relic antineutrino capture on EC-decaying Ho-163 nuclei.

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

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







THE MENU

- ♣ Extremes in the ν sky
- ♣ UHE cosmic ν flavors
- ♣ Cosmic ν background
- ♣ Warm ν dark matter?

If it isn't Dark, it doesn't Matter

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	$\Omega_\nu h^2 = \sum m_i / (94 \text{ eV})$
Cold dark matter density $\Omega_{\rm CDM}$	$\Omega_{\rm CDM} h^2 = 0.110 \pm 0.006$

$\boxed{\Omega_{\rm CDM}/\Omega_{\rm m} \approx 83\%}$

$\boxed{\Omega_{\rm B}/\Omega_{\rm m} \approx 17\%}$

Hot dark matter: CνB is guaranteed but not significant.

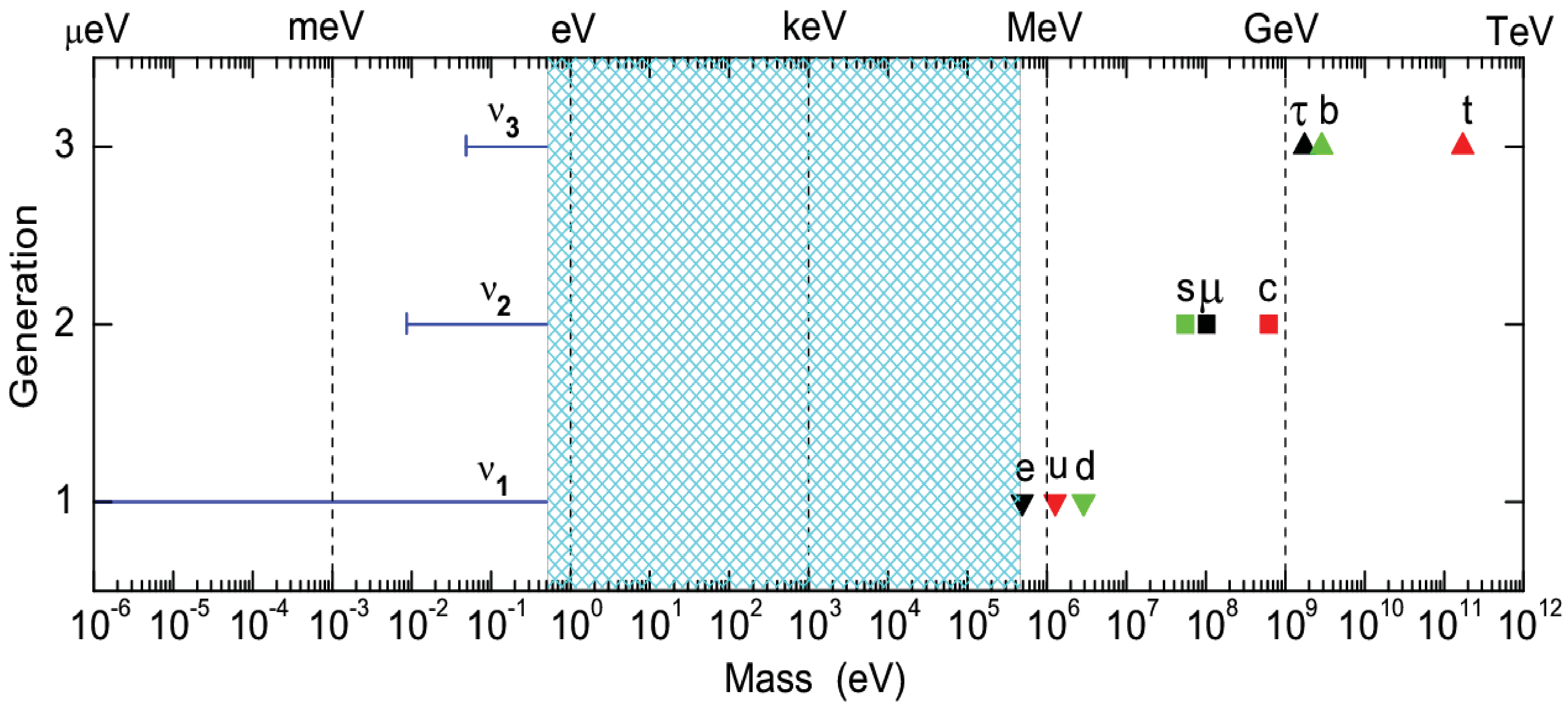
Cold dark matter: most likely? At present most popular.

Warm dark matter: suppress the small-scale structures.

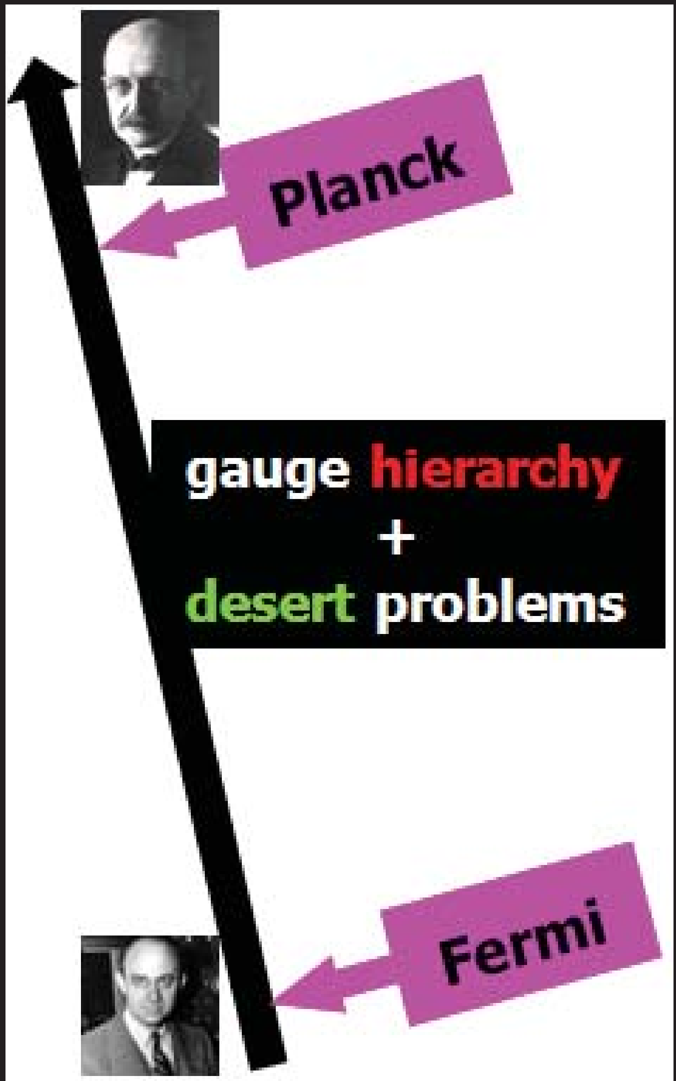
keV sterile ν Dark Matter

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).



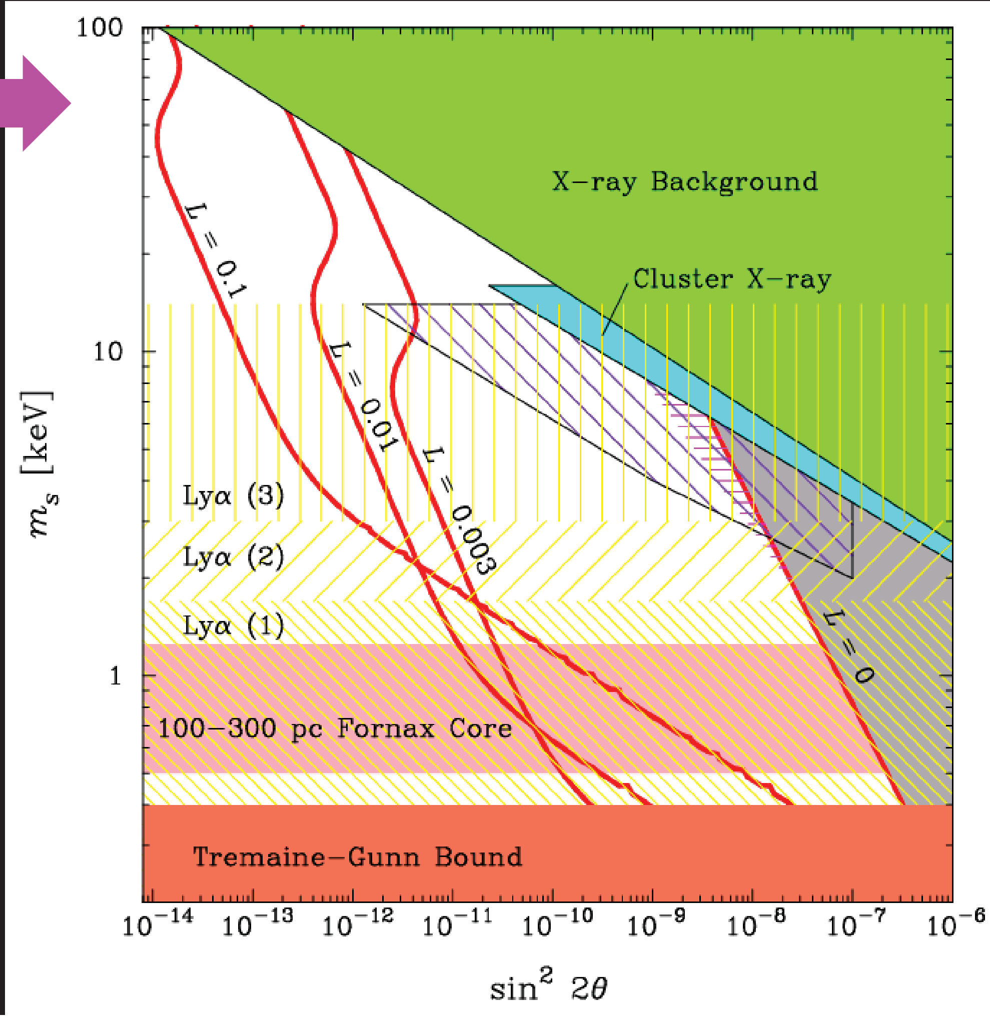
keV sterile ν Dark Matter



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:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} & V_{e4} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} & V_{\mu 4} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} & V_{\tau 4} \\ V_{s1} & V_{s2} & V_{s3} & V_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

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

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

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

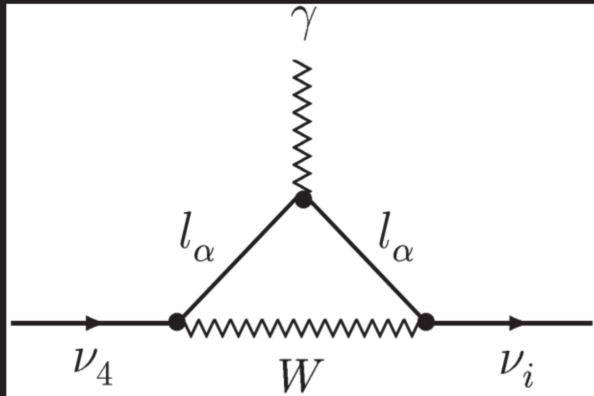
Decay Rates

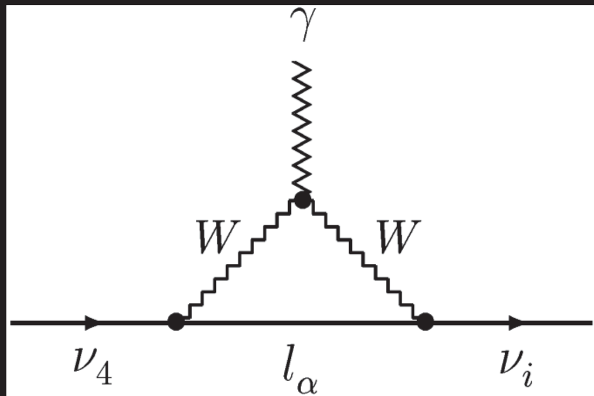
Dominant decay mode [C_ν = 1 (Dirac) or 2 (Majorana)]:

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

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)

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

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

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

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

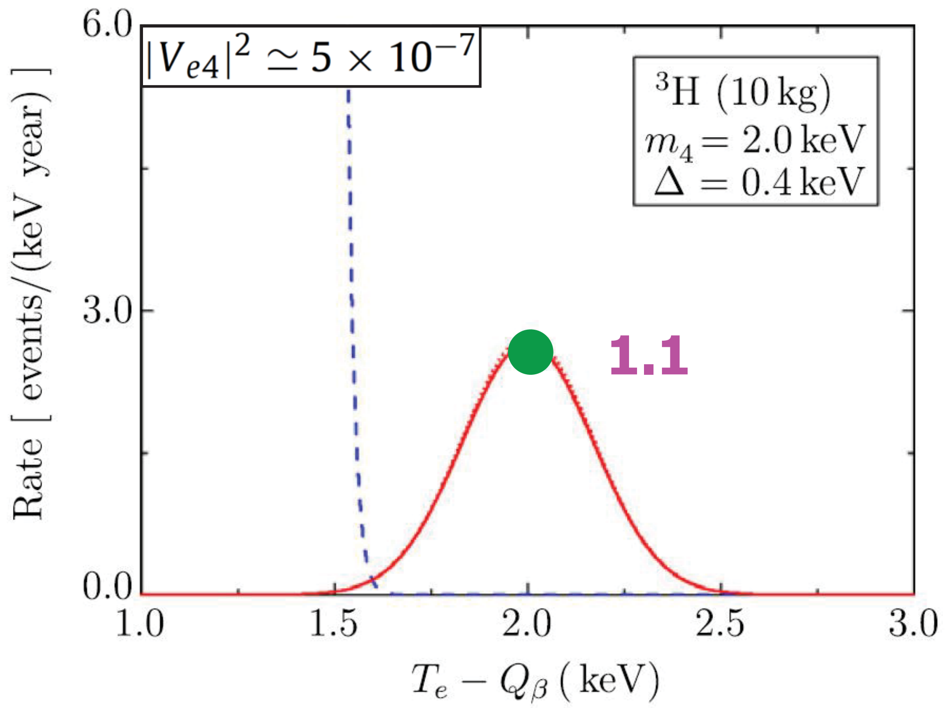
This method & the X-ray detection probe different parameter space.

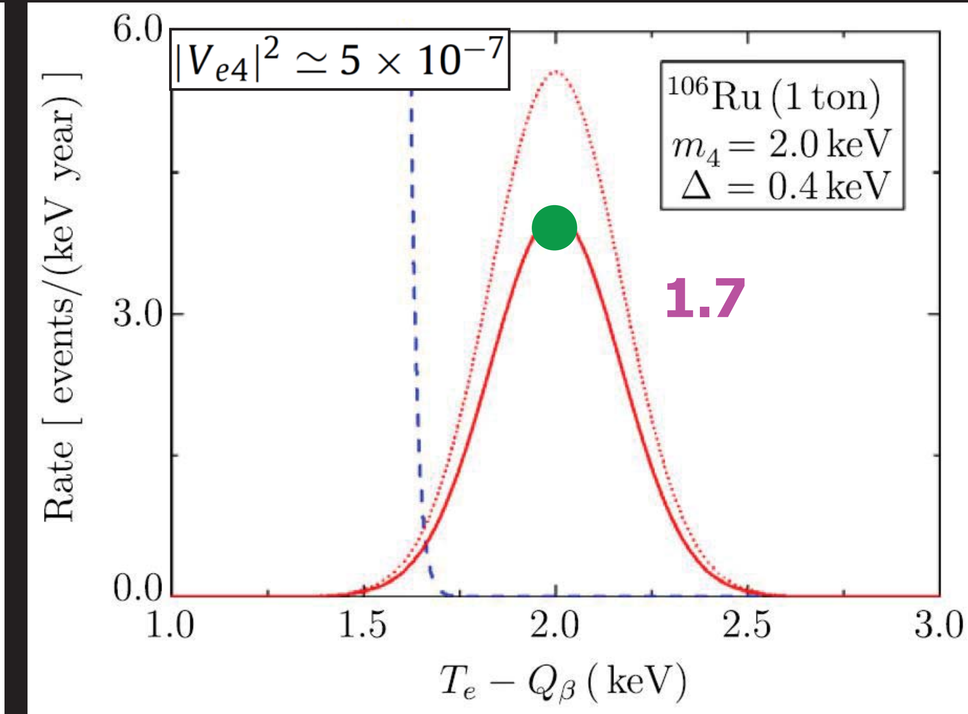
$$|V_{e4}|^2 \simeq c_{12}^2 s_{14}^2 + s_{12}^2 s_{24}^2 + 2 c_{12} s_{12} s_{14} s_{24} \cos\left(\delta_{24} - \delta_{12} - \delta_{14}\right)$$

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