Neutrino Mixing & Cosmic Flavor Problems

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- ♣ Flavor puzzles in particle physics
- ♣ Current knowledge on 3 ν flavors
- ♣ Cosmic ν background & sterile ν's
- ♣ DM in the form of keV sterile ν's

@COSMO/CosPA, September 27 – October 1, 2010

Part A

The Birth of "Flavor"

The term Flavor was coined by Harald Fritzsch & Murray Gell-Mann at a Baskin-Robbins ice-cream store in Pasadena in 1971.

LEPTONS

QUARKS

Stop by and add a little "Yay" to your day with our classic ice cream
the neighborhood.

Vanilla

Mint Chocolate Chip

Chocolate

Chocolate Chip

Pralines 'n Cream

Very Berry Strawberry

Color & Flavor

Discoveries of Flavors

1897 electron (Thomson)

1919: proton (up & down) (Rutherford)

1932: neutron (up & down) (Chadwick)

1933: positron (Anderson)

1936 muon (Neddermeyer & Anderson)

1947: strange (Rochester & Butler)

1956: electron antineutrino (Cowan *et al*)

1962: muon neutrino (Danby *et al*)

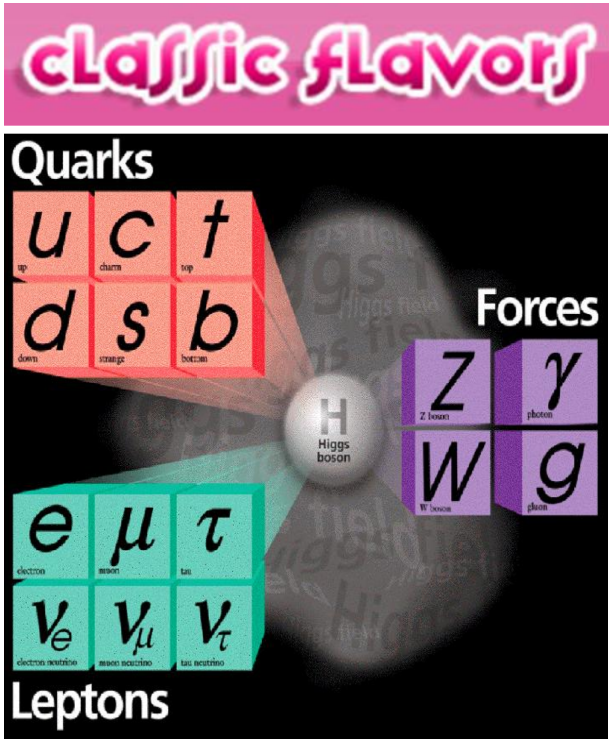
1974: charm (Aubert *et al* / Abrams *et al*)

1975 tau (Perl *et al*)

1977: bottom (Herb *et al*)

1995: top (Abe *et al* / Abachi *et al*)

2000: tau neutrino (Kodama *et al*)



Lesson one: Charged leptons cropped up with a 39-year gap: 1936 – 1897 = 1975 – 1936 = 39, so the 4th would show up in 2014 (Sarma-Xing 1995)

Lesson two: All the bosons were discovered in Europe; and almost all the fermions were discovered in America.

If this is true, the Higgs boson can only be discovered at the LHC.

Part A

Family Puzzle

What distinguishes 3 different families of leptons or quarks?

----- they have the same gauge quantum numbers,

but they are quite different from one another.


Isidor Isaac Rabi

Who ordered that?

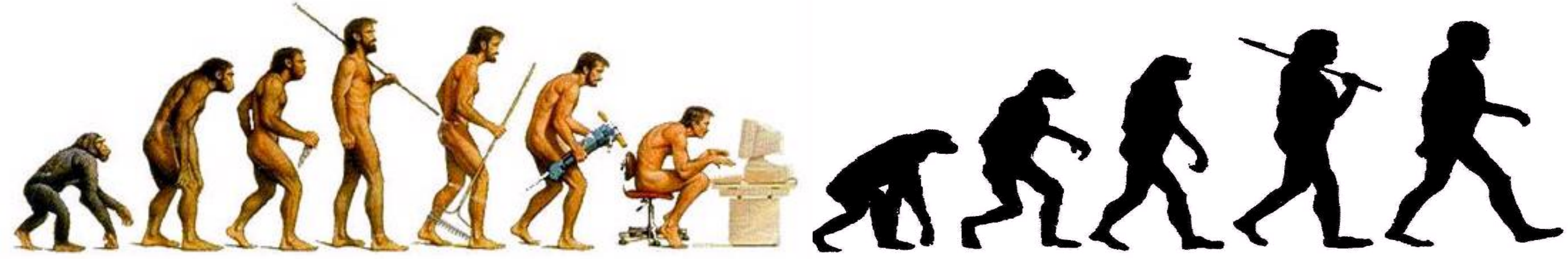
Conjecture:

Hidden flavor quantum number or flavor symmetry behind them

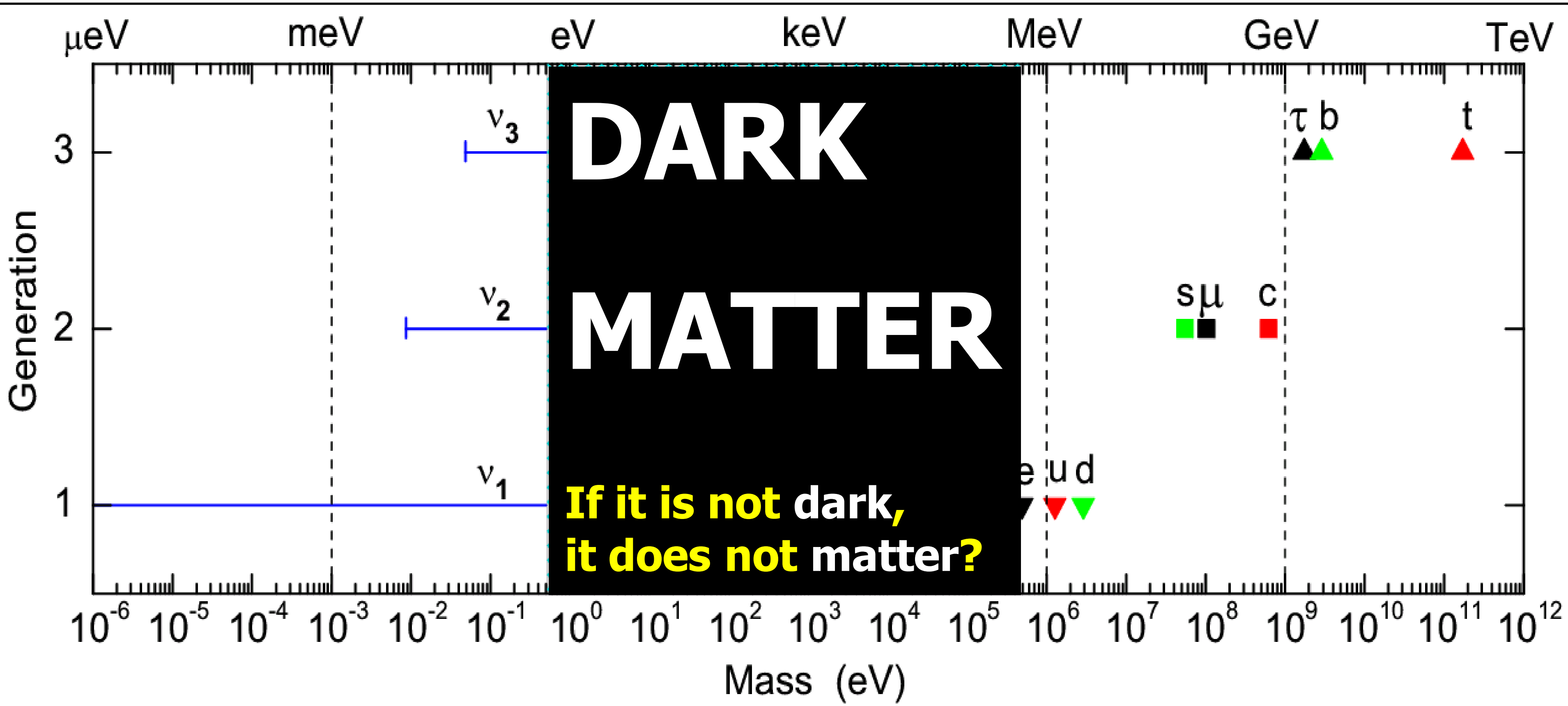
Open questions:

--- is there the 4th (sequential) family of leptons or quarks? 5th? …

--- are there (non-sequential) new fermions? heavy? sterile? dark?



Mass Puzzle



DARK

MATTER

If it is not dark,
it does not matter?

The flavor hierarchy problem: the mass spectrum has a big hierarchy!

Tiny neutrino masses must have a different origin: a seesaw picture?

The flavor desert problem: why is there nothing between eV & MeV?

Flavor Mixing

CKM quark mixing:

$$\mathbf{V} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Exp. steps:	θ_{12} →	θ_{23} →	θ_{13} →	δ	new physics ?
	$\sim 13^\circ$	$\sim 2^\circ$	$\sim 0.2^\circ$	$\sim 65^\circ$	unitarity ?

MNSP lepton mixing:

A hint at: $\theta_{13} \sim 7^\circ$ (KamLAND on Monday)

$$\mathbf{V} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

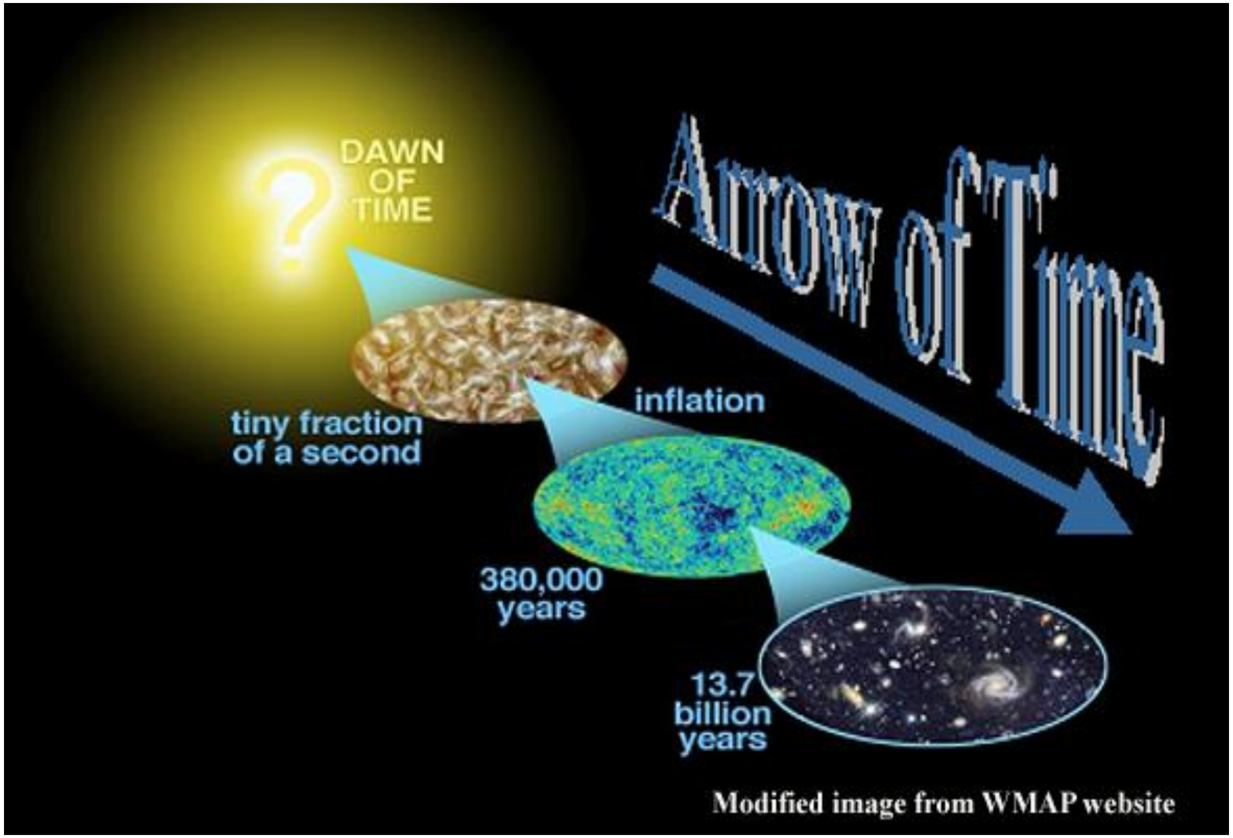
Exp. steps:	θ_{23} →	θ_{12} →	θ_{13} →	$\delta/\rho/\sigma$	new physics ?
	$\sim 45^\circ$	$\sim 34^\circ$	$< 10^\circ$	$\sim$? ? ?	unitarity ?

known theta_13: a turning point to the era of precision measurements

The hierarchy of three quark mixing angles might arise from that of quark masses. But how to understand two large lepton mixing angles?

Part A

CP Violation



Modified image from WMAP website

Today's Universe

$t \sim 10^{17}\,\mathrm{sec}$

$r \sim 10^{28}\,\mathrm{cm}$

$T \sim 2.725\ \mathrm{K}$

$411\ \gamma\ \mathrm{cm}^{-3}$

$336\ \nu\ \mathrm{cm}^{-3}$

$10^{80}\quad p, n$

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

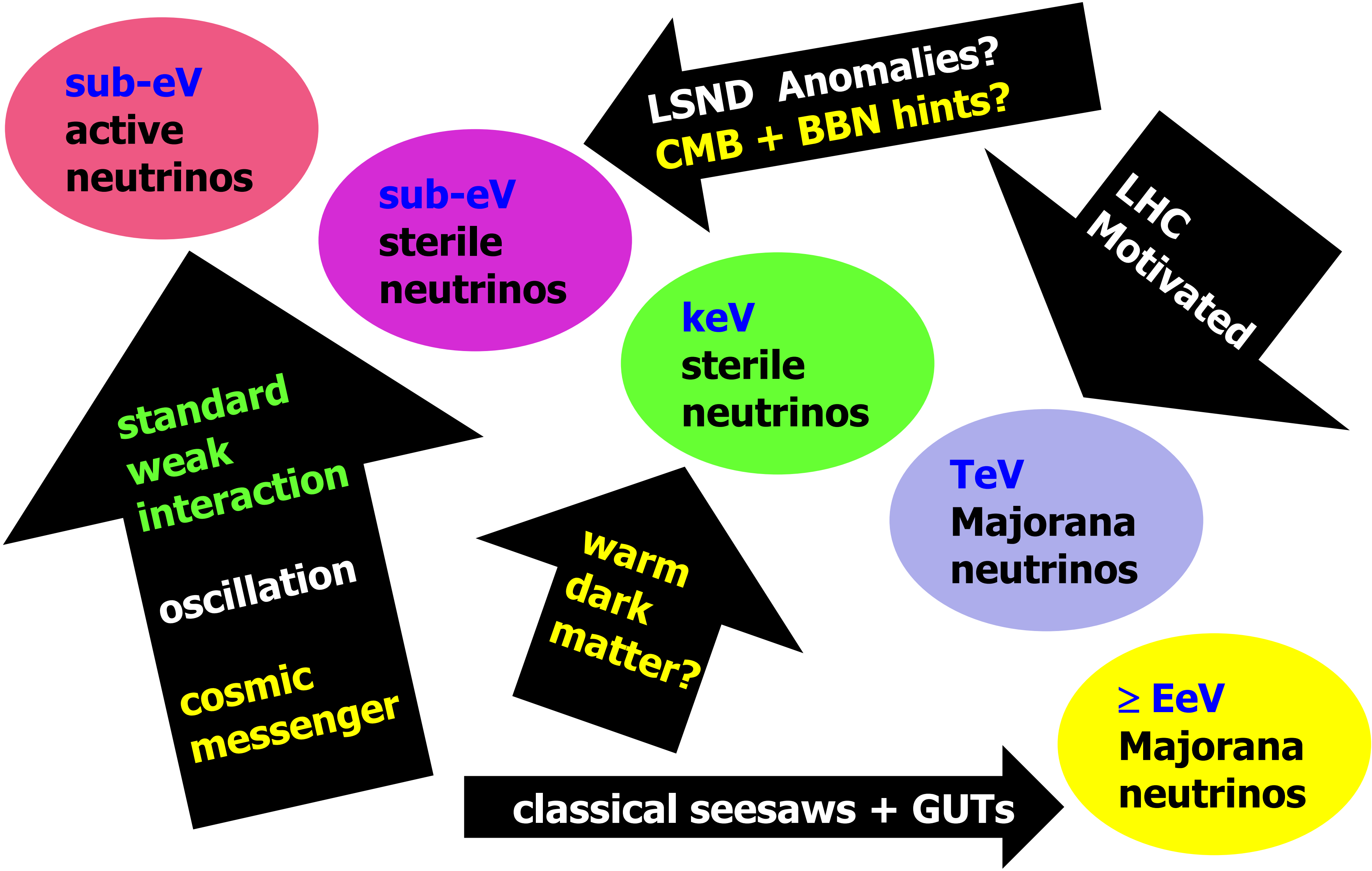
Why is there not an anti-Universe as expected by Dirac?

The Kobayashi-Maskawa mechanism of CP violation is successful in the quark sector, but it cannot account for the cosmological matter antimatter asymmetry!

Baryogenesis with new flavor physics?

Part A

Neutrinos



sub-eV active neutrinos

sub-eV sterile neutrinos

keV sterile neutrinos

TeV Majorana neutrinos

≥ EeV Majorana neutrinos

standard weak interaction

oscillation

cosmic messenger

LSND Anomalies?
CMB + BBN hints?

LHC Motivated

warm dark matter?

classical seesaws + GUTs

Part B

Origin of ν Masses

ν oscillations: a slight change of values of two ν mass-squared differences;
In cosmology, a more stringent constraint on the absolute scale of ν mass.

$$\Delta m^2_{21} = 7.59 \pm 0.20 \left(^{+0.61}_{-0.69}\right) \times 10^{-5}\ \mathrm{eV}^2$$

$$\Delta m^2_{31} = \begin{cases} -2.36 \pm 0.07\ (\pm 0.36) \times 10^{-3}\ \mathrm{eV}^2 \\ +2.47 \pm 0.12\ (\pm 0.37) \times 10^{-3}\ \mathrm{eV}^2 \end{cases}$$

1 σ (3 σ) (Gonzalez-Garcia et al, 2010)

$$\sum m_i \lesssim 0.28\ \mathrm{eV}$$

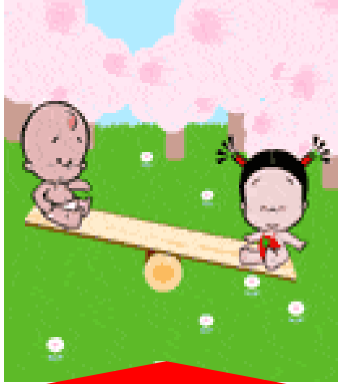
SDSS + photometric redshift + WMAP data in the ΛCDM model

(Thomas et al, 2010) 95% CL

Model building attempts: the seesaw ideas remain most popular, but they are suffering from trivialization.

SEESAW

- SU(2)_L singlet fermions (Type-1)
- SU(2)_L triplet scalars (Type-2)
- SU(2)_L triplet fermions (Type-3)



Linear trivialization:

tiny ν masses
large ν mixing
leptogenesis
LHC signature

Type i + Type j

?

Multiple trivialization:

Inverse seesaw, etc.

$$m \sim (\lambda \Lambda_{\rm EW})^{n+1} / \Lambda^n_{\rm SS}$$

Fermi scale

Seesaw Scales

TeV scale is a geometric mean of the Planck mass and CνB temperature.

$$M_{PL} \approx 1.22 \times 10^{19}\,\mathrm{GeV}$$

$$T_\nu \approx 1.9\ \mathrm{K} \approx 1.6 \times 10^{-13}\,\mathrm{GeV}$$

$$\sqrt{M_{PL} T_\nu} \approx 1.4\ \mathrm{TeV}$$

Planck

GUT to unify strong, weak & electromagnetic forces?

Conventional Seesaws: heavy degrees of freedom near Λ_GUT.

Hierarchy problem

either SUSY or TeV seesaw

TeV Seesaw Idea: driven by testability at LHC.

TeV to solve the unnatural gauge hierarchy problem?

Fermi

Naturalness? ⟷ **Testability?**

Part B

Neutrino Mixing

A global analysis (Gonzalez-Garcia et al, **2010**):

$$\theta_{12} = 34.4 \pm 1.0 \ \left({}^{+3.2}_{-2.9}\right)^\circ$$

$$\theta_{23} = 42.9\,{}^{+4.1}_{-2.8} \ \left({}^{+11.1}_{-7.2}\right)^\circ$$

$$\theta_{13} = 7.3\,{}^{+2.1}_{-3.2} \ (\leq 13.3)^\circ$$

Hint 1: the **(2,3)** mixing might not be maximal;

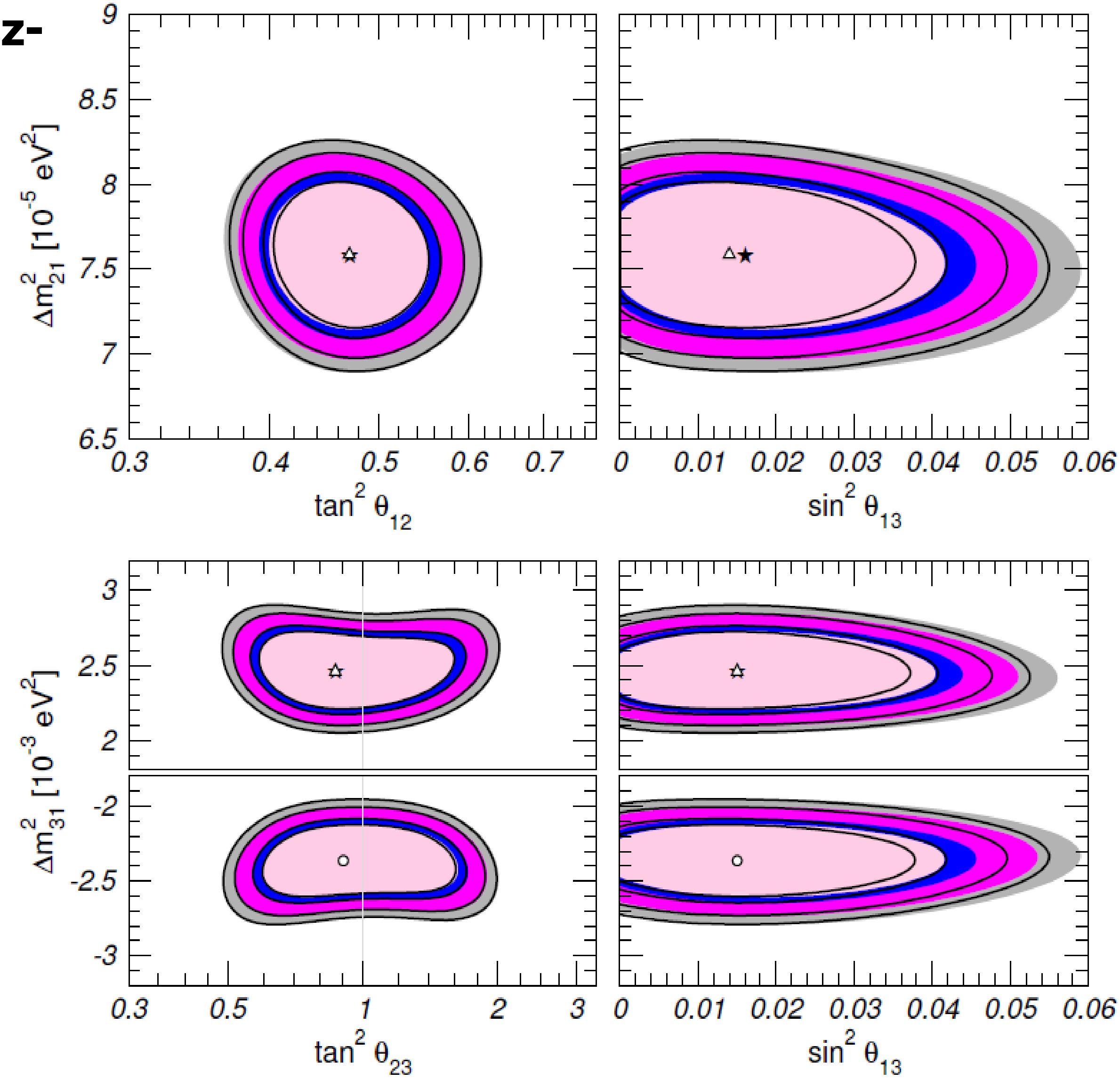
Hint 2: the **(1,3)** mixing might not be very small.

Quark flavor mixing!

$$V_{\rm CKM} = I + \mathcal{O}(\theta_{\rm C})$$

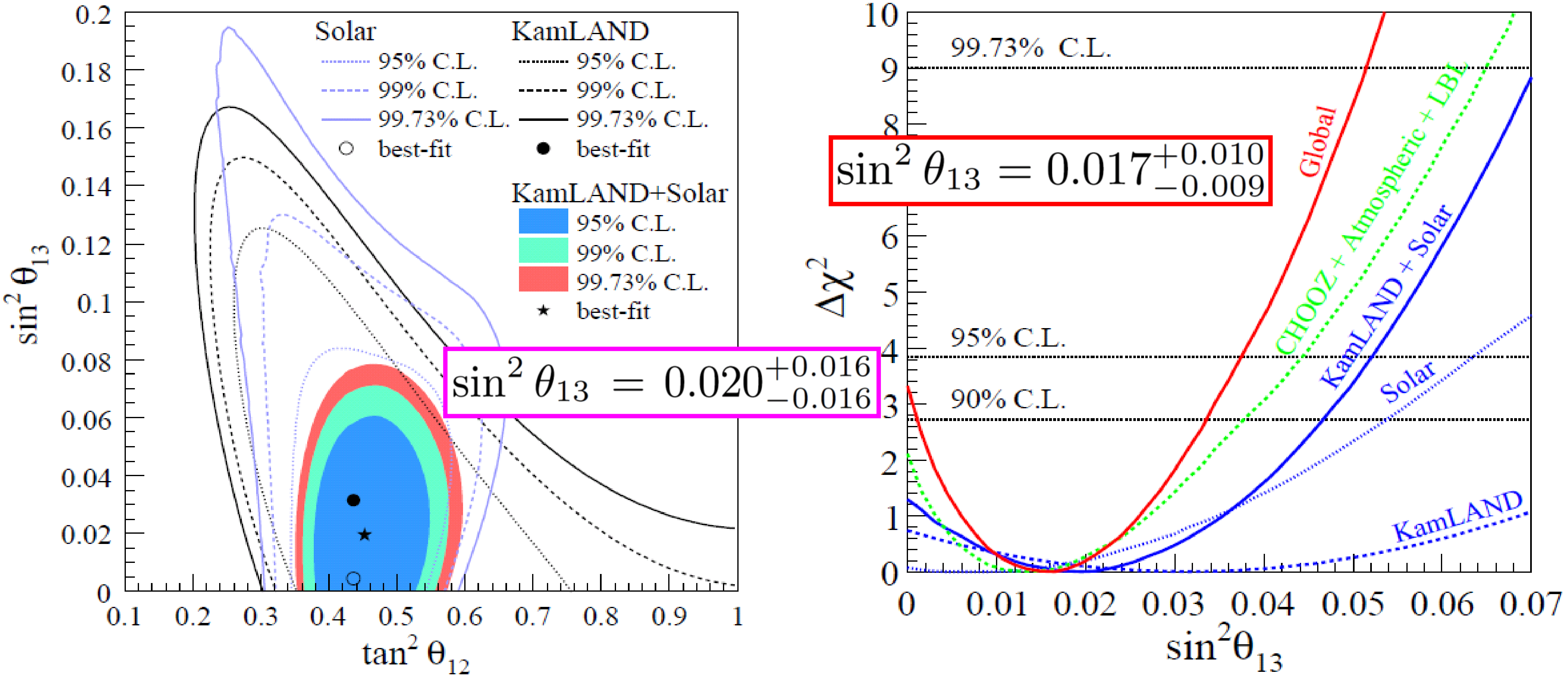
Lepton flavor mixing?

$$V_{\rm MNSP} = V_0 + \Delta V$$



Part B

KamLAND Hint



$$\sin^2\theta_{13} = 0.020^{+0.016}_{-0.016}$$

$$\sin^2\theta_{13} = 0.017^{+0.010}_{-0.009}$$

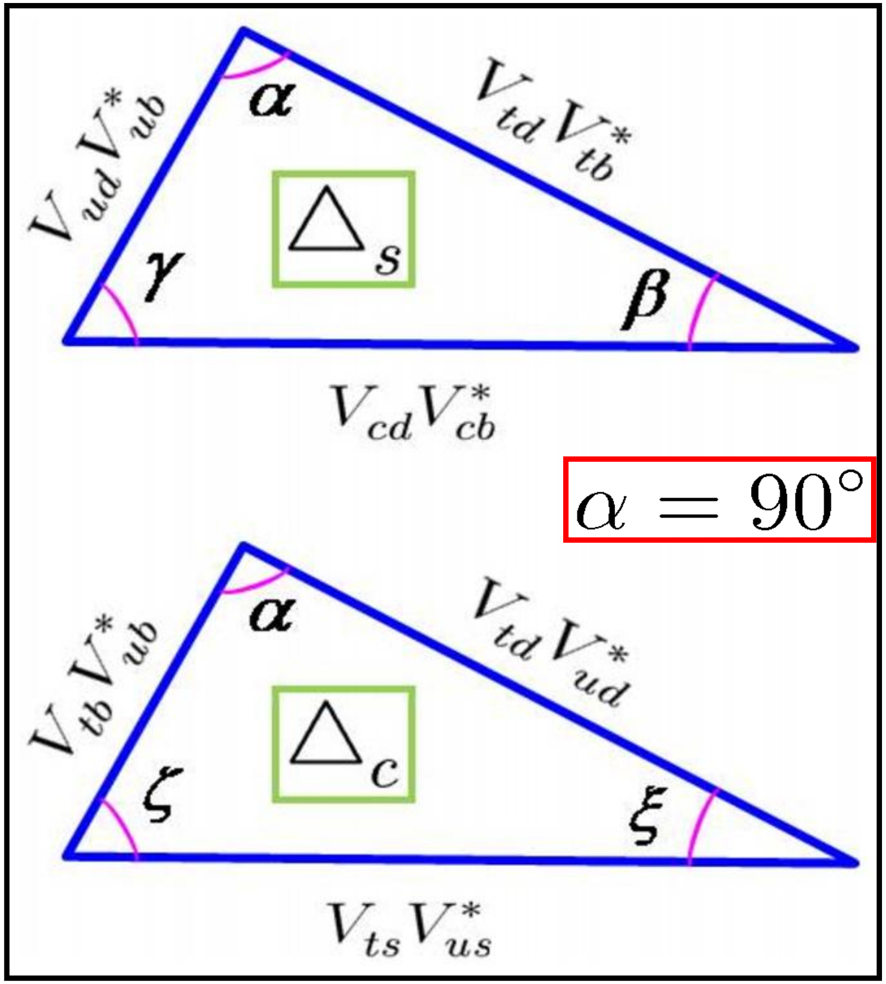
If θ_{13} is really of this size, then the tri-bimaximal ν mixing pattern would not be a good starting point for model building.

$$V_0 = \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ \frac{-1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & \frac{-1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

Reason: Perturbations to V_0 would look rather unnatural in this case.

CP Violation

No information on CP or T violation in the lepton sector. No reason for its absence. It might be small, but how small is small?



A lesson from the quark sector: CP violation is small but not very small.

KM


小林诚


益川敏英

Leptonic CP or T violation, why not?
Right leptonic unitarity triangles?
Non-unitary CP or T violation?

Baryogenesis via leptogenesis
(Fukugita, Yanagida 1986)
Talk by W. Buchmueller

Part C

Cosmic ν Background

When *T* ~ a few MeV in the Universe, the only survival relativistic particles were photons, electrons, positrons, neutrinos and antineutrinos.

Electroweak reactions:

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

Neutrinos decoupled from matter:

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

Weak interactions

$$\Gamma \sim G_F^2 T^5$$

Hubble expansion

$$H \sim \frac{\sqrt{g_*} T^2}{M_{\rm Pl}}$$

Number density of 6 relic active ν's:

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

$$\boxed{\Gamma > H} \qquad \boxed{\Gamma \sim H} \qquad \boxed{\Gamma < H}$$

ν's in thermal contact with cosmic plasma

ν's not in thermal contact with matter

arrow of time

neutrino decoupling

$$\boxed{T < m_e} \quad \boxed{e^+ + e^- \rightarrow \gamma + \gamma}$$

neutrino and photon temperatures (blue)

$$\boxed{T_\nu = T_\gamma}$$

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

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

BBN

BBN: soon after **neutrino decoupling**, synthesis of the light elements began in the Universe (*t* ≥ 160 s).

Helium-4

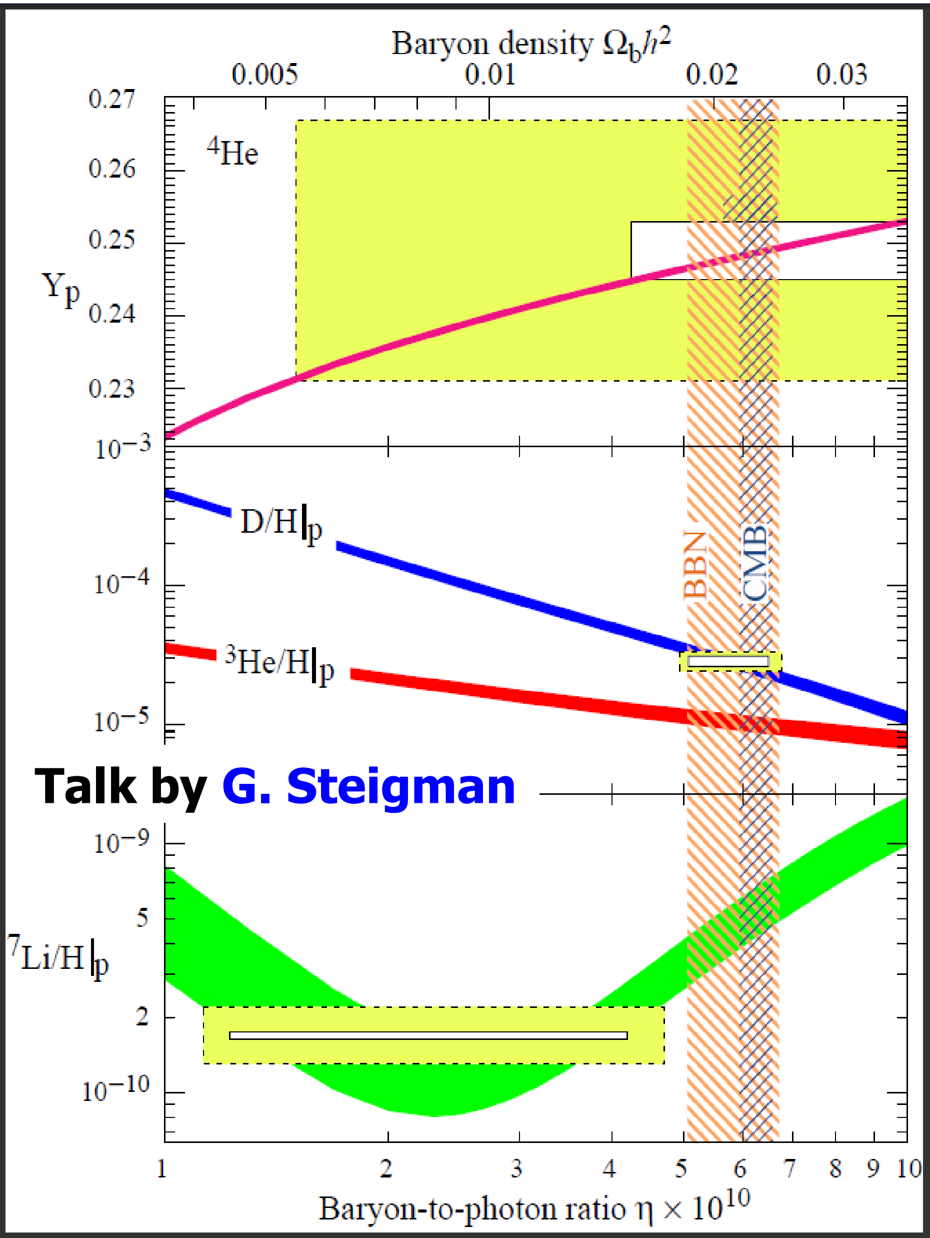
$$Y_{\rm p} \approx 0.248 + 0.0096 \times \ln\left(\frac{\eta}{6.15 \times 10^{-10}}\right) + 0.013 \times \left(N_\nu^{^4{\rm He}} - 3\right)$$

Deuterium (Cirelli et al 2005)

$$\left.\frac{\rm D}{\rm H}\right|_{\rm p} \approx (2.75 \pm 0.13) \times 10^{-5} \left(\frac{6.15 \times 10^{-10}}{\eta}\right)^{1.6} \times \left[1 + 0.11\left(N_\nu^{\rm D} - 3\right)\right]$$

The standard case: $N_\nu = 3$.

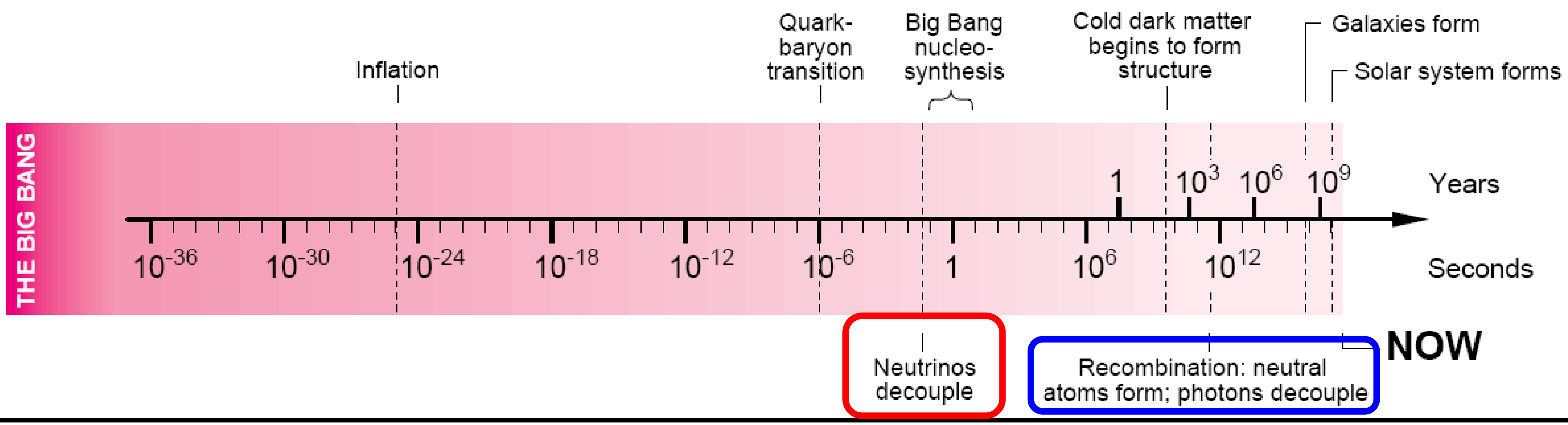
A slightly larger Y_p with $N_\nu > 3$ is not impossible (Izotov, Thuan 2010; Aver et al 2010; Krauss et al 2010).



Talk by G. Steigman

CMB and LSS

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



At the time of recombination (*t*_rec ~ 35000 yr): $\rho_\gamma + \rho_\nu = \rho_\gamma \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_\nu^{\mathrm{CMB}}\right]$

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

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

Part C

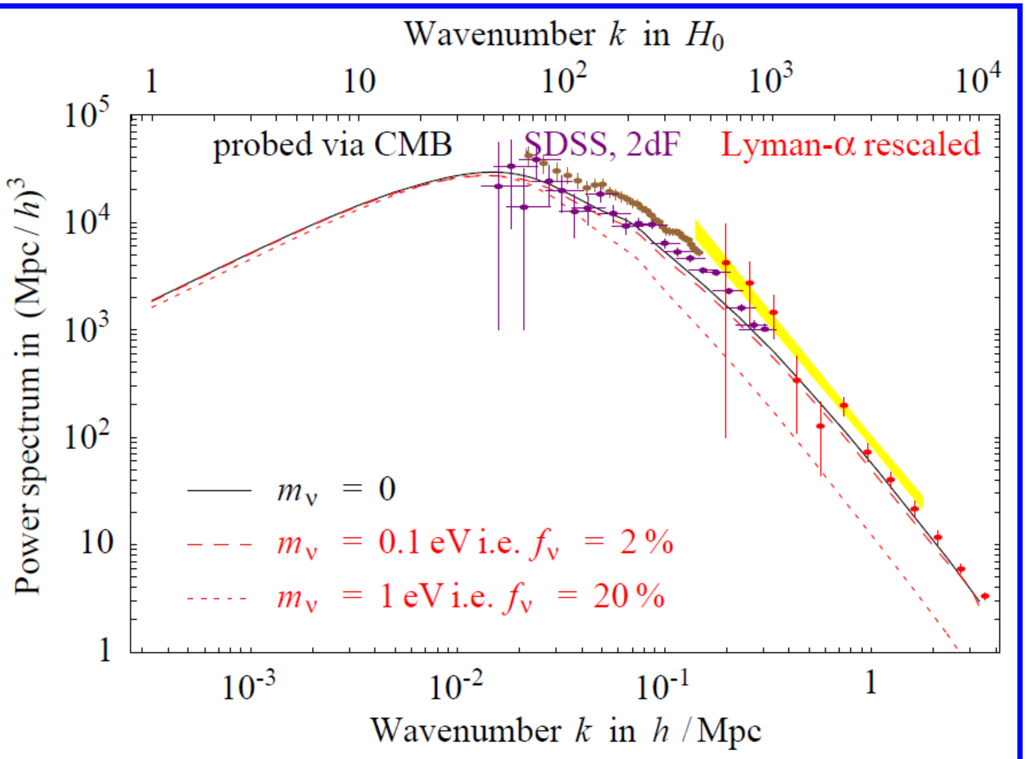
CMB + LSS Constraints

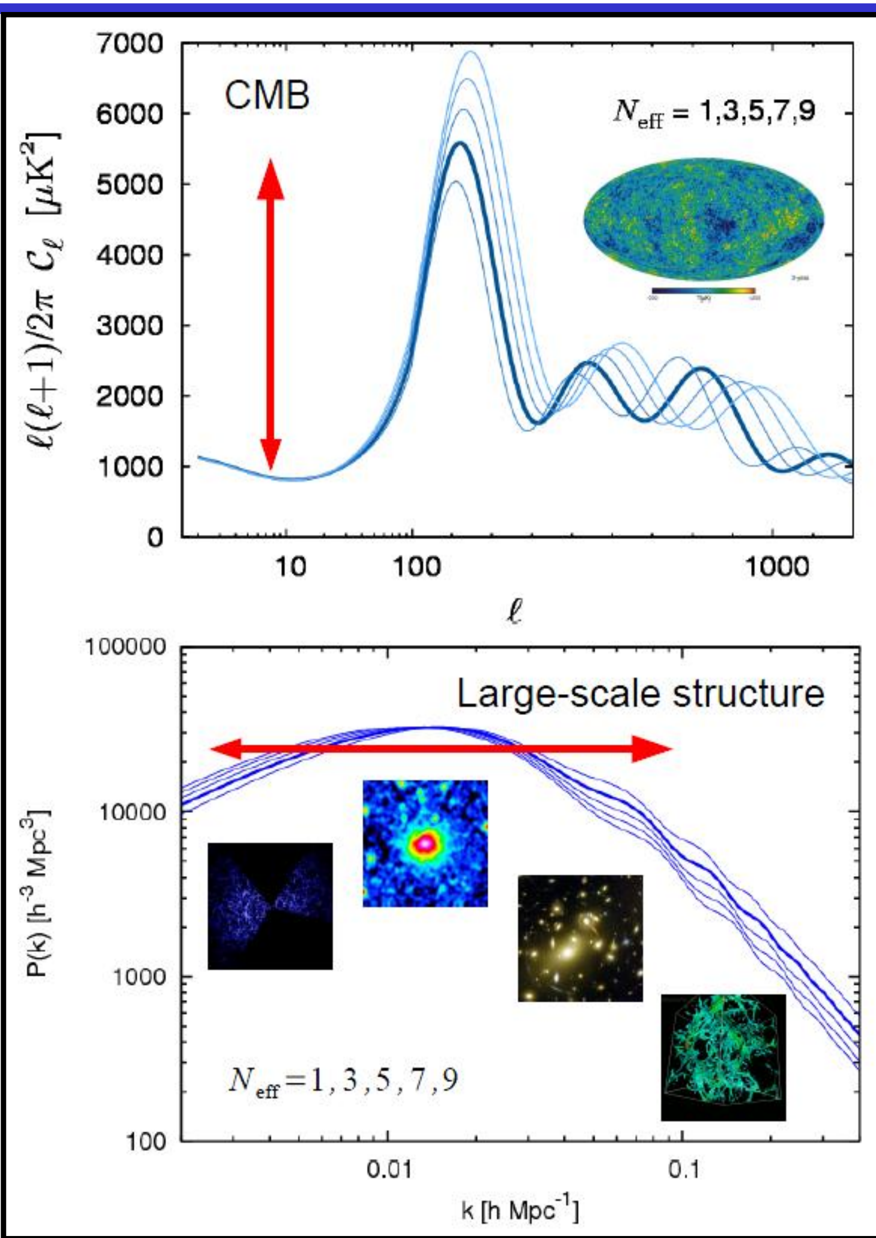
If there were no relic neutrinos:

---- CMB: suppression of the first peak;

---- LSS: a shift in the turning point to larger values of k (Wong 2008).

The matter power spectrum predicted by the ΛCDM model (Strumia, Vissani 2006):





Part C

Detection of CνB

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

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

Way 3: **Annihilation** of the EHE cosmic ν's with relic ν's on the *Z* resonance.

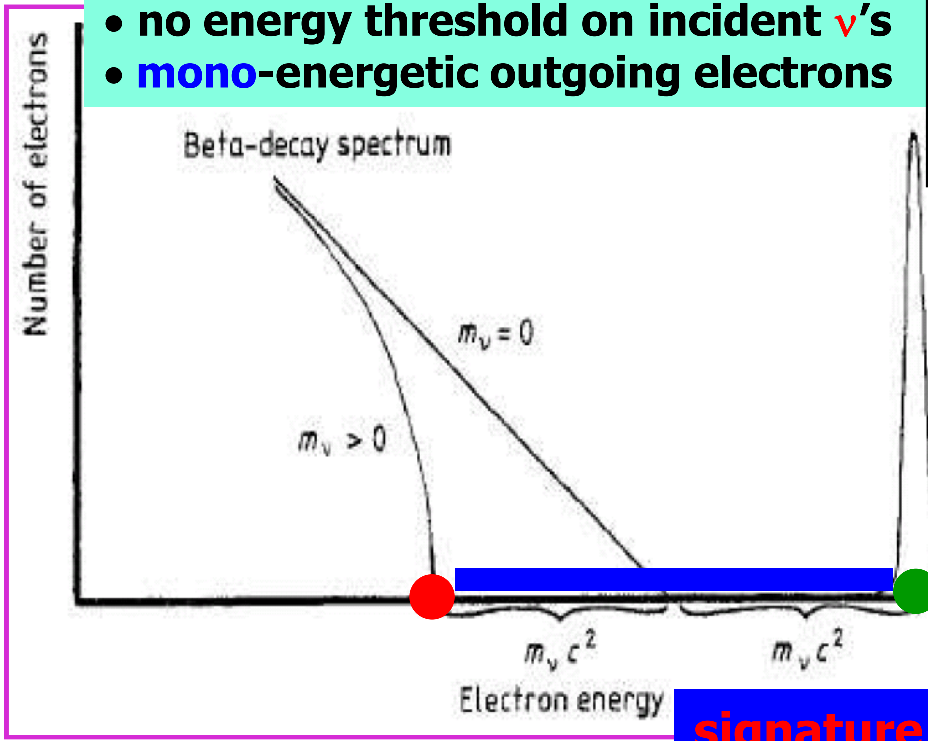
Relic neutrino capture on β-decaying nuclei

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

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

$$\boxed{\nu_e + N \rightarrow N' + e^-}$$

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



Signature = the **gap** between 🔴 and 🟢 measured by ν mass

Active and **sterile** CνB;
Energy resolution;
Gravitational clustering

Sub-eV Sterile ν's

Conjecture: there might exist one or more cosmologically friendly **sub-eV** sterile ν's (*N*_ν > 3 from some recent analyses of **CMB** or **BBN** data, and a hint from **LSND** & **MiniBOONE** data after *Neutrino 2010*. See, Komatsu et al 2010; Hamann et al 2010; Izotov, Thuan 2010; Aver et al 2010; Karagiorgi 2010).

(3+1) scheme: $|V_{e1}| \approx 0.804\;,\;\; |V_{e2}| \approx 0.542\;, |V_{e3}| \approx 0.171\;, |V_{e4}| \approx 0.174$

(3+2) scheme: $|V_{e1}| \approx 0.792\;,\;\; |V_{e2}| \approx 0.534\;, |V_{e3}| \approx 0.168\;, |V_{e4}| \approx 0.171\;, |V_{e5}| \approx 0.174$

(these values are **just for illustration**, to show possible signatures of CνB).

Comments: (1) such **sub-eV** sterile ν's could be **thermally excited** through oscillations and collisions with active ν's; (2) they are now **non-relativistic** as at least two active ν's; (3) their **number density** per species is expected to be equal to that of active ν's.

Example: relic neutrino capture on tritium (background: tritium β-decay).

$$\boxed{{}^3\mathrm{H} \to \;\; {}^3\mathrm{He} + e^- + \overline{\nu}_e} \qquad \boxed{\nu_e + \;{}^3\mathrm{H} \to \;\; {}^3\mathrm{He} + e^-} \qquad \boxed{\langle p_\nu \rangle \; = \; 3 T_\nu \; \approx \; 5 \times 10^{-4} \;\; \mathrm{eV}}$$

$$\boxed{Q_\beta = M_{^3\mathrm{H}} - M_{^3\mathrm{He}} - m_e \approx 18.6 \;\mathrm{keV}} \qquad \boxed{\langle n_{\nu_i} \rangle \;\; \approx \;\; \langle n_{\overline{\nu}_i} \rangle \;\; \approx \;\; 56 \;\; \mathrm{cm}^{-3}}$$

(**Active**: Cocco et al 2007; Lazauskas et al 2008; Blennow 2008; Kaboth et al 2010)

Signal vs Background

ACTIVE + STERILE: Y.F. Li, Z.Z. Xing, S. Luo, arXiv:1007.0914 (PLB 2010).

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

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

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

Background: (the tritium β-decay)

$$\boxed{E_e = T_e' + m_e}$$

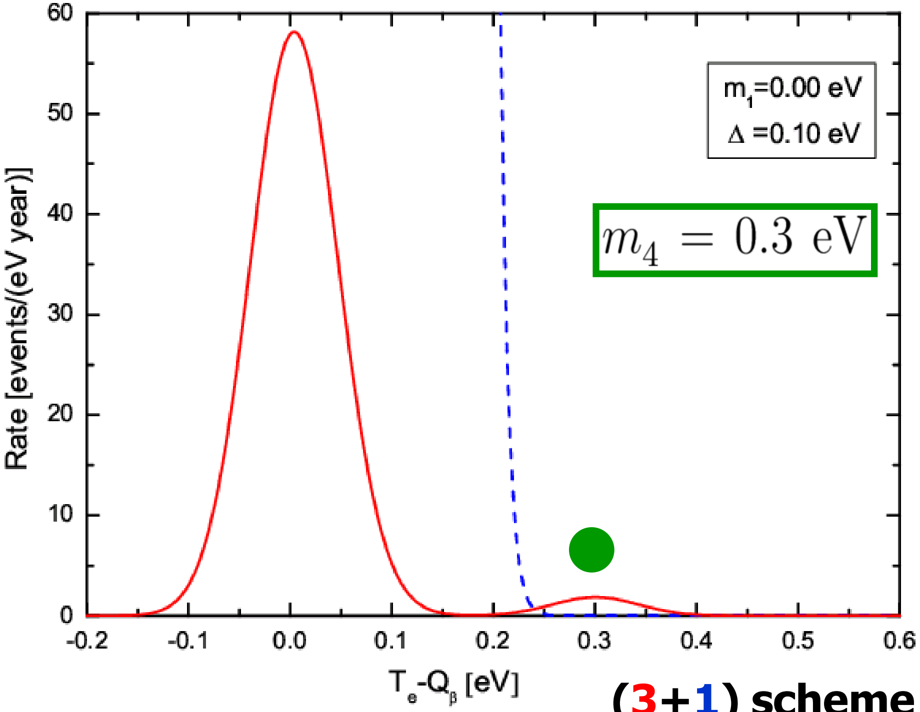
$$\boxed{\langle n_{\nu_i}\rangle \approx \langle n_{\overline{\nu}_i}\rangle \approx 56~{\rm cm}^{-3}}$$

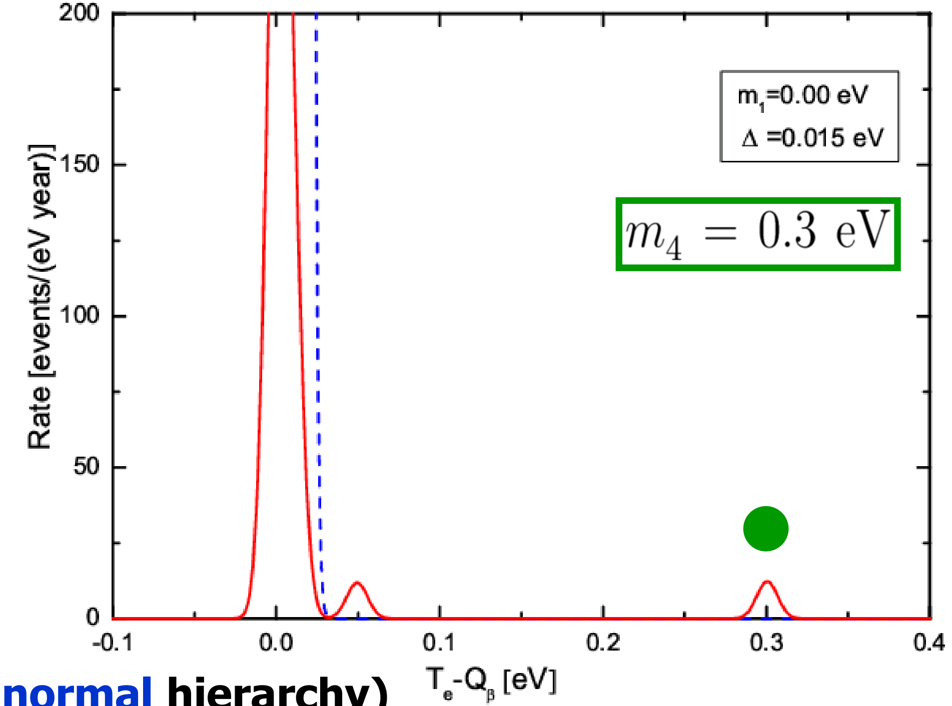
$$\boxed{\begin{aligned} \frac{{\rm d}\mathcal{N}_\beta}{{\rm d}T_e} \approx 5.55 \int_0^{Q_\beta - {\rm min}(m_i)} {\rm d}T_e' \Bigg\{ N_{\rm T} \frac{G_{\rm F}^2 \cos^2\theta_{\rm C}}{2\pi^3} F(Z,\, E_e) \sqrt{E_e^2 - m_e^2}\, E_e (Q_\beta - T_e') \\ \times \sum_i \left[|V_{ei}|^2 \sqrt{\left(Q_\beta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

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

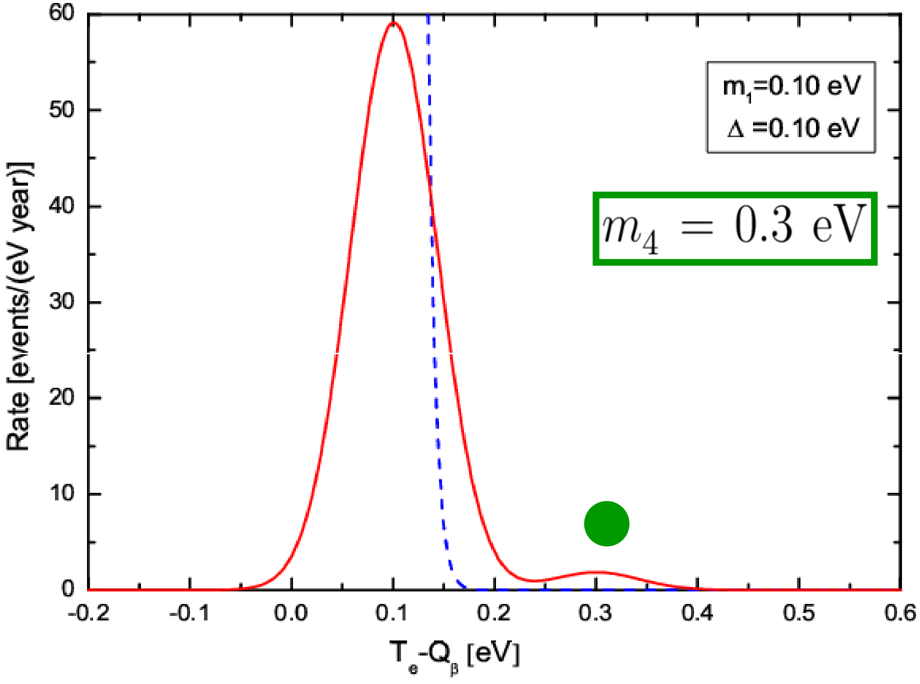
Assumption: sterile ν masses are sub-eV and larger than active ν masses.

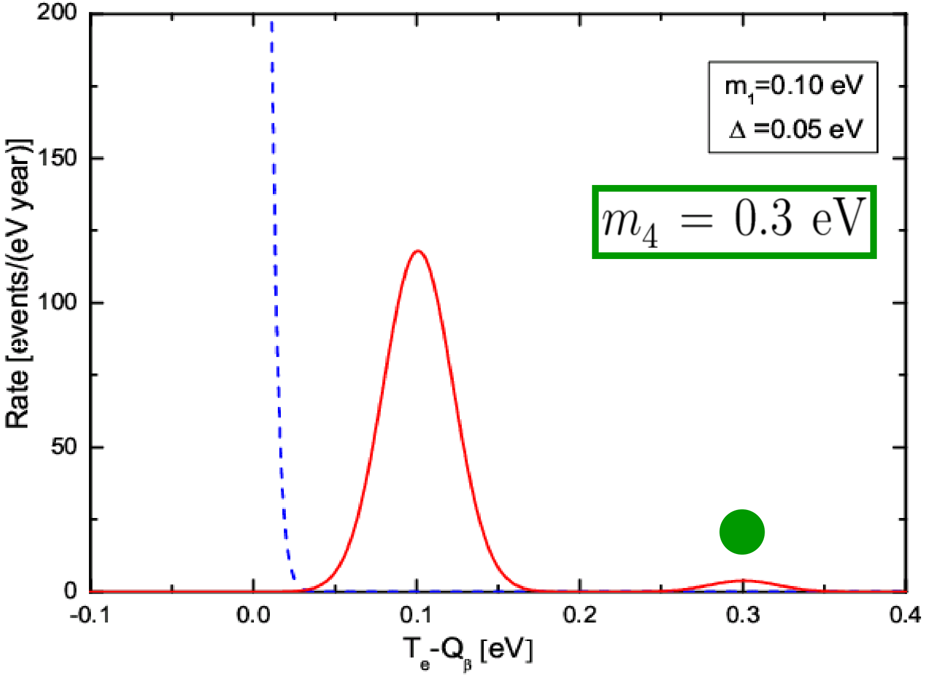
Expectation: a signal of the sterile component of the CνB is on the right-hand side of the eletron *T_e* spectrum; a resolution $\boxed{\Delta \leq m_i/2}$ is required.



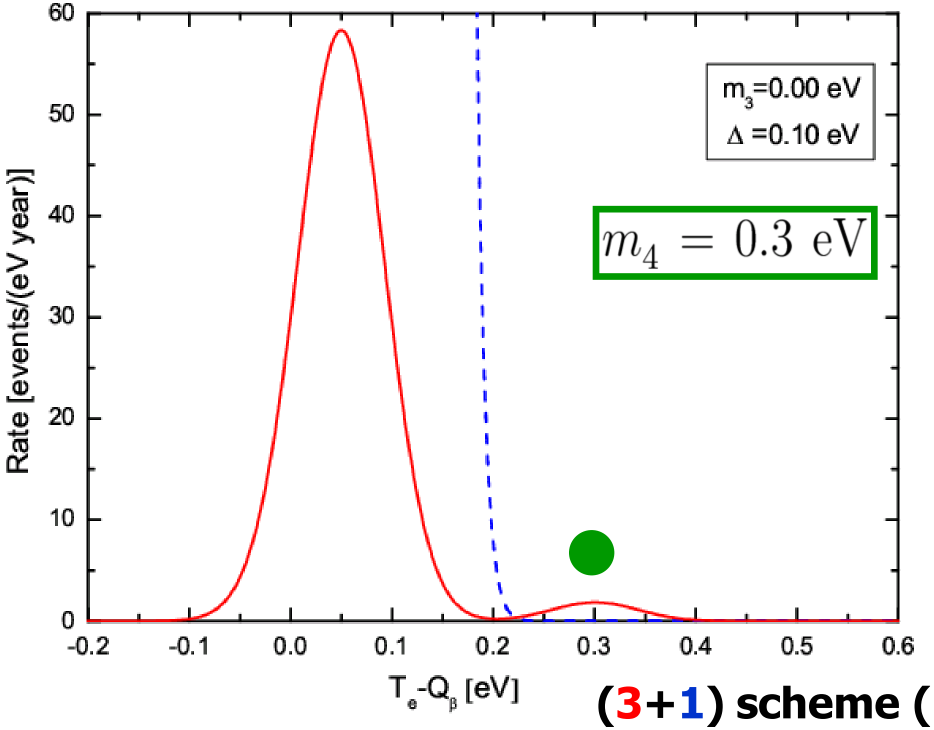


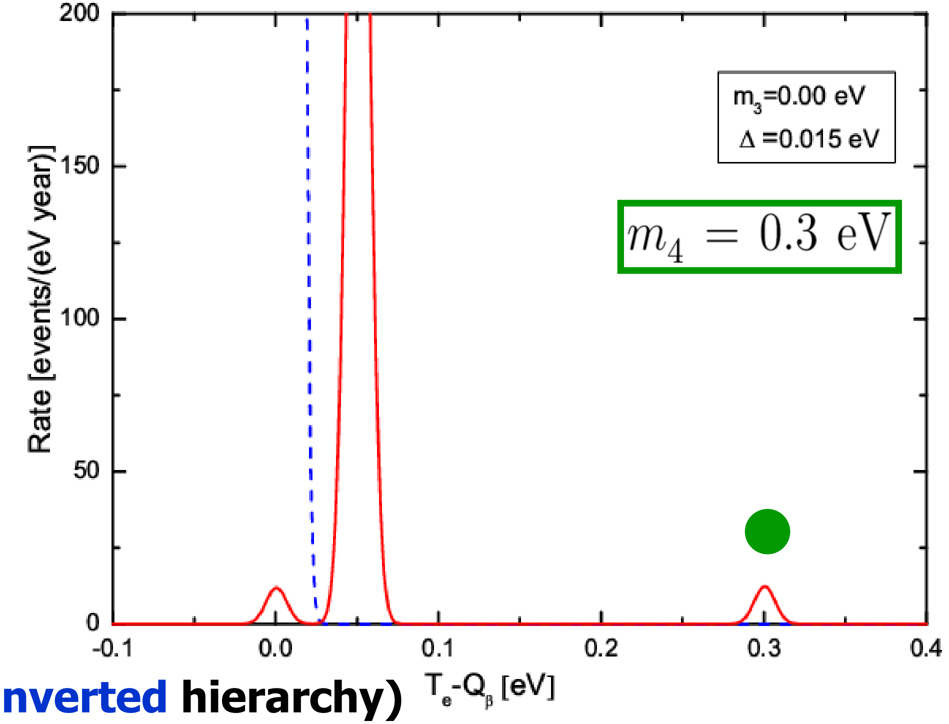
(3+1) scheme (normal hierarchy)

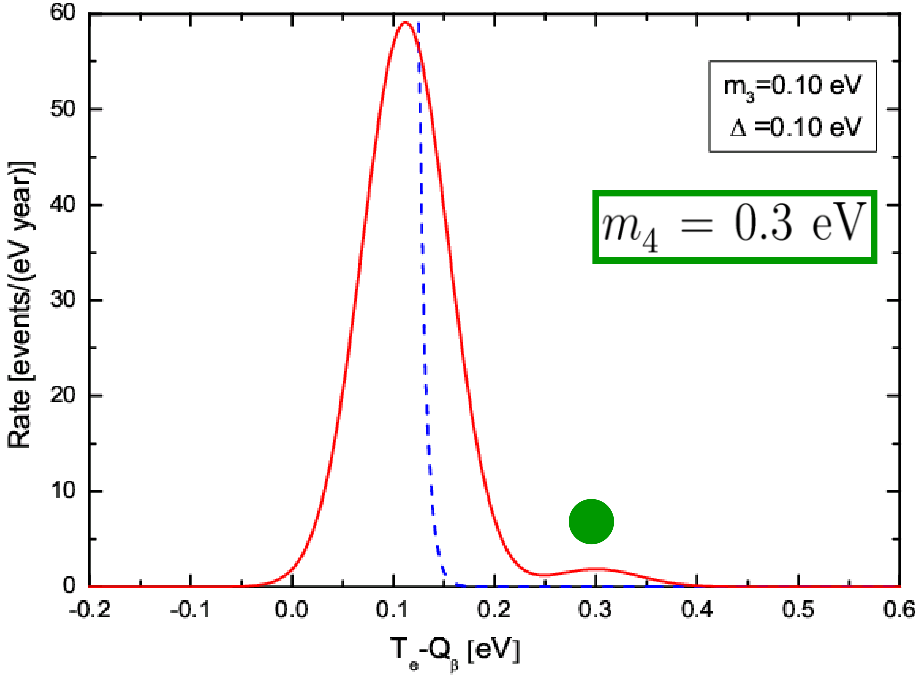


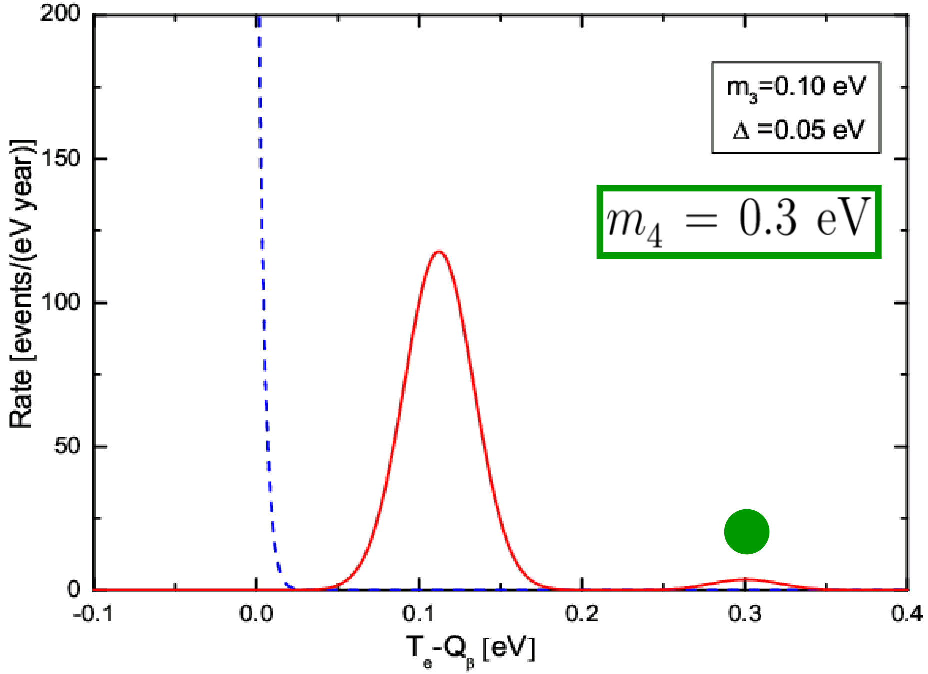


(3+1) scheme (inverted hierarchy)

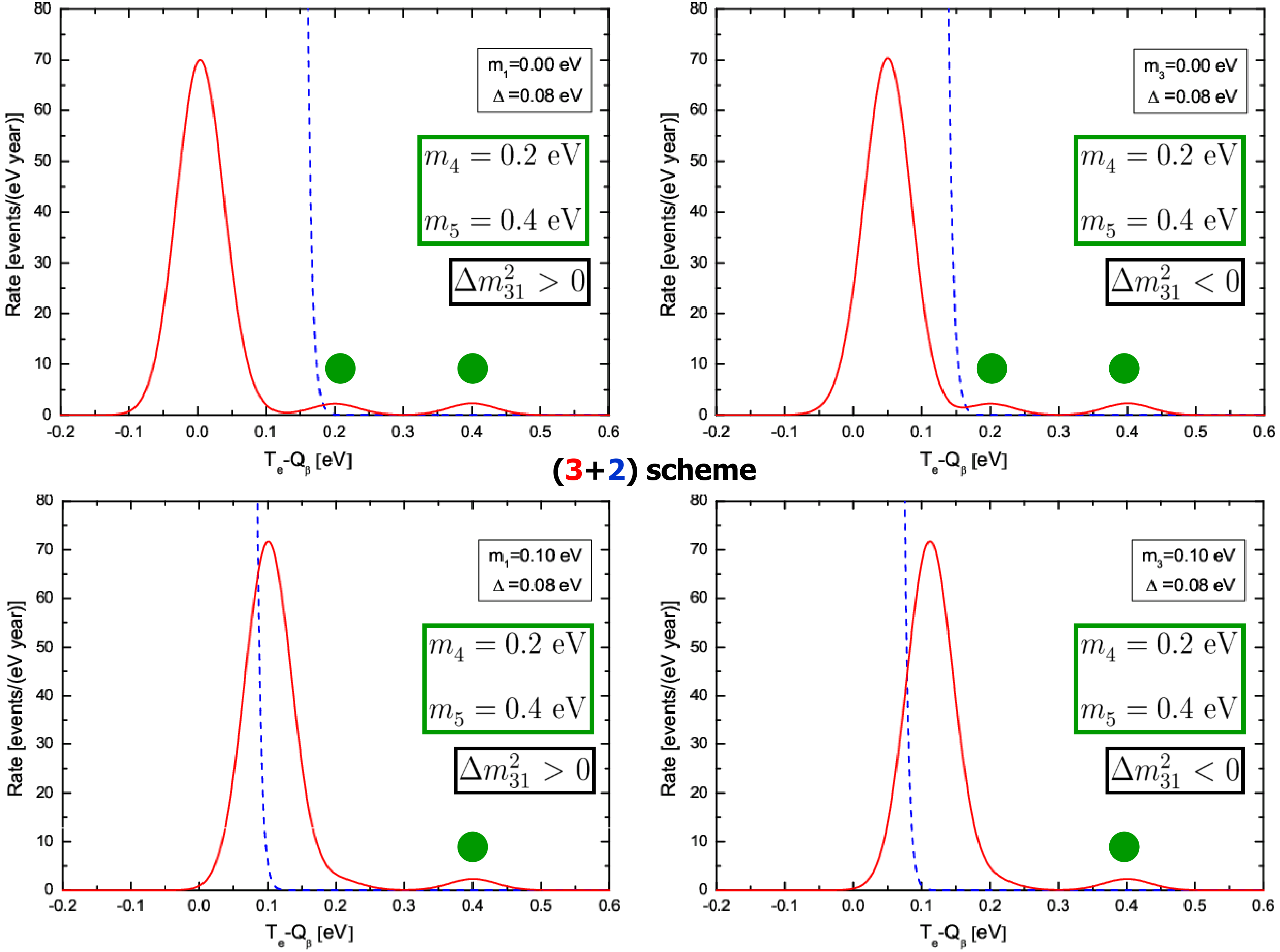








(3+2) scheme



Rate [events/(eV year)]
T$_e$-Q$_\beta$ [eV]
m_1=0.00 eV
Δ =0.08 eV
$m_4 = 0.2$ eV
$m_5 = 0.4$ eV
$\Delta m^2_{31} > 0$
m_3=0.00 eV
Δ =0.08 eV
$m_4 = 0.2$ eV
$m_5 = 0.4$ eV
$\Delta m^2_{31} < 0$
m_1=0.10 eV
Δ =0.08 eV
$m_4 = 0.2$ eV
$m_5 = 0.4$ eV
$\Delta m^2_{31} > 0$
m_3=0.10 eV
Δ =0.08 eV
$m_4 = 0.2$ eV
$m_5 = 0.4$ eV
$\Delta m^2_{31} < 0$
0
10
20
30
40
50
60
70
80
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5
0.6

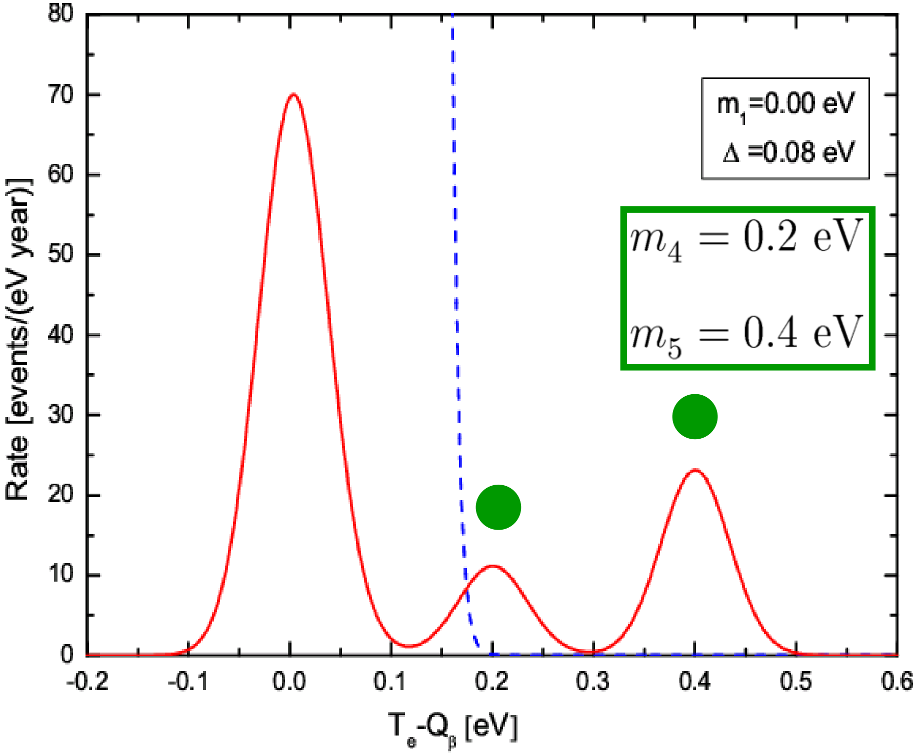
Overdensities

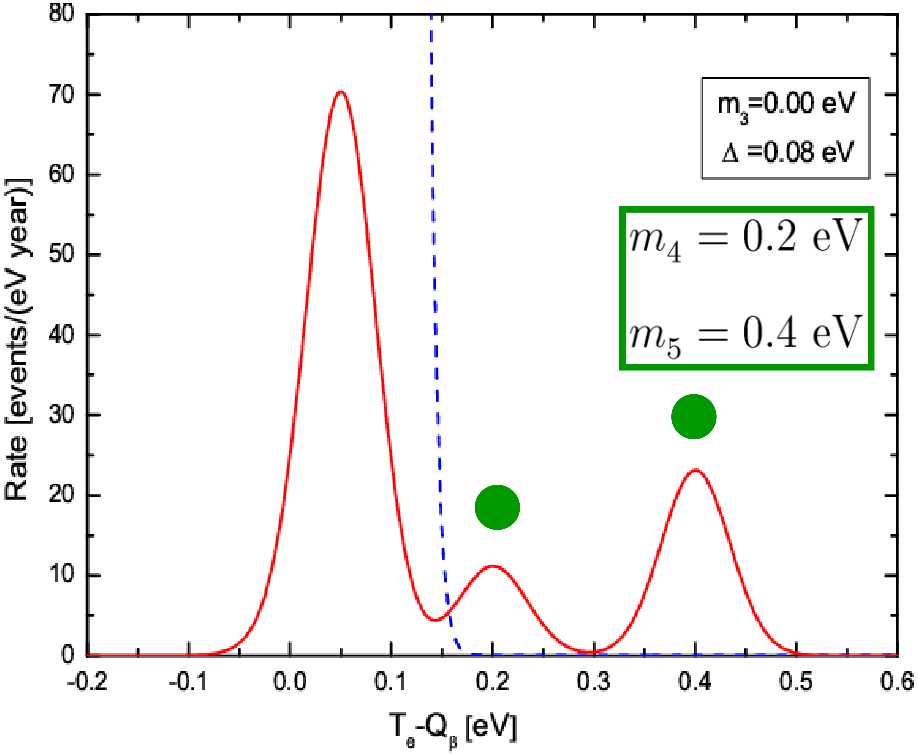
Gravitational clustering: only those cosmic ν's with velocities smaller than the escape velocity of a given structure can be bound to it. Let's assume a **larger GC** effect for a **heavier ν** around the Earth (Ringwald, Wong, **2004**).

For illustration:

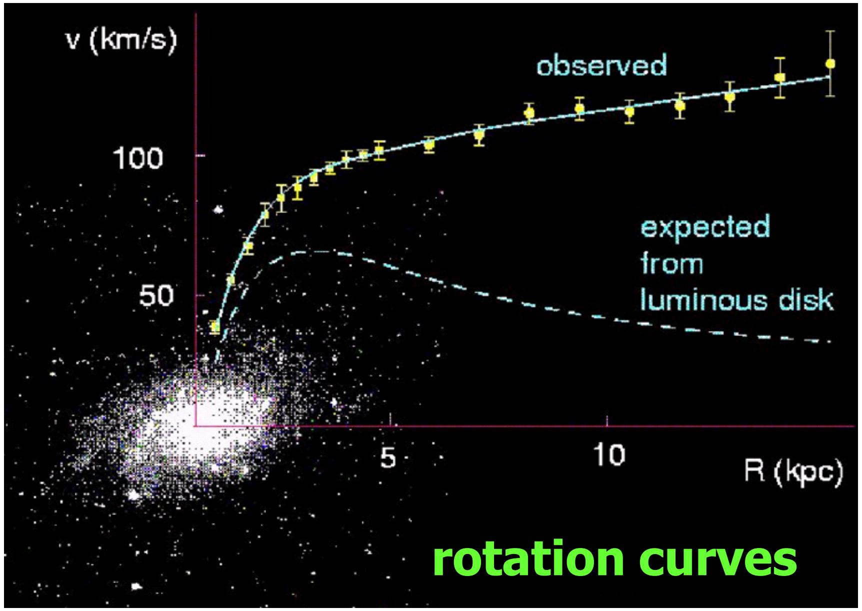
(**3**+**2**) scheme with the **normal** mass hierarchy

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



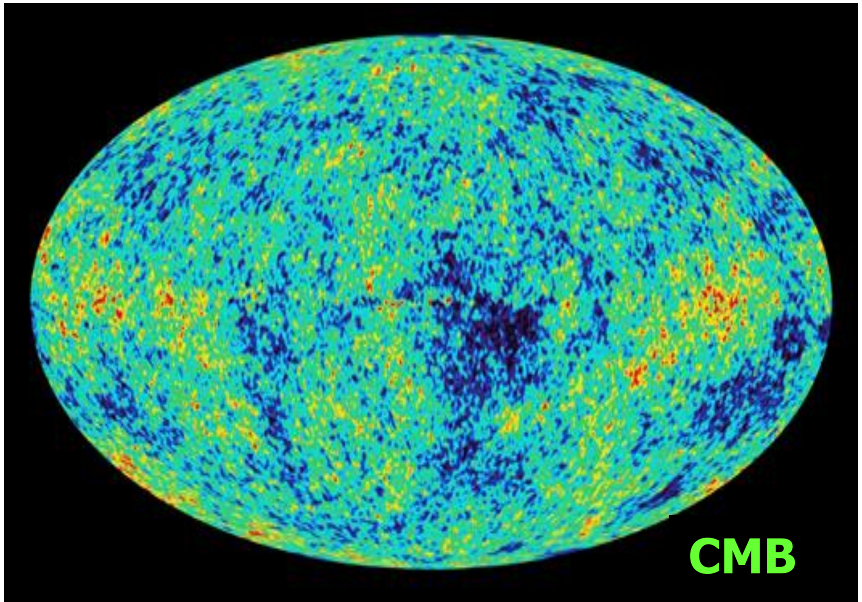


Evidence for Dark Matter

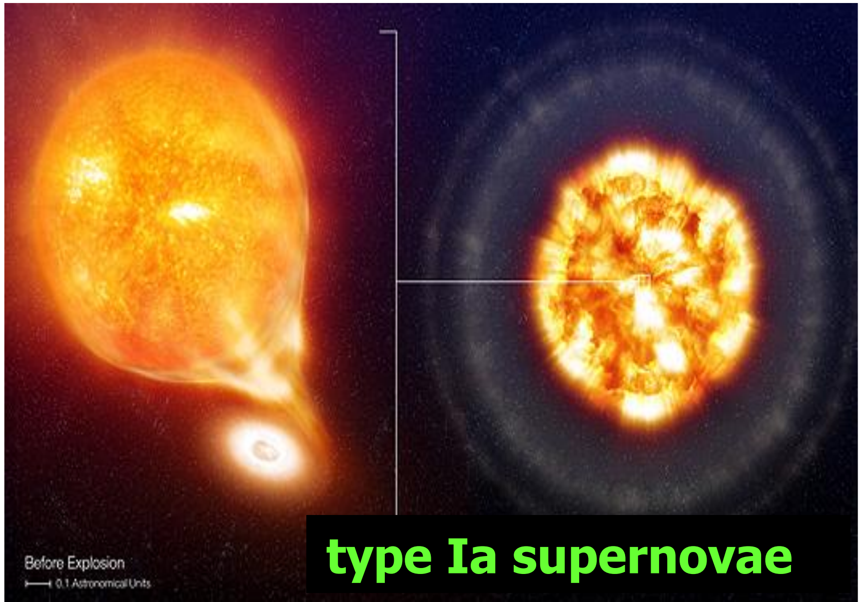


rotation curves

clusters of galaxies



CMB



type Ia supernovae

Candidates for DM

Today's matter and energy densities in the Universe (Dunkley et al 2009; Komatsu et al 2009; Nakamura et al 2010): 5-year WMAP + ΛCDM model.

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

$\Omega_\mathrm{CDM}/\Omega_\mathrm{m} \approx 83\%$

$\Omega_\mathrm{B}/\Omega_\mathrm{m} \approx 17\%$

L. Pauling: the best way to have a good idea is to have a lot of ideas

WIMPS

Axions

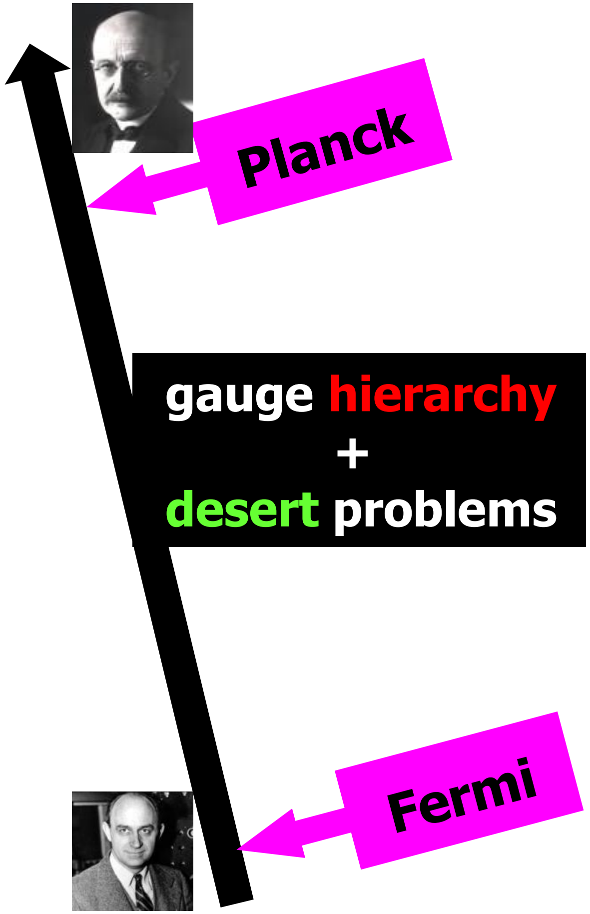
Sterile neutrinos

Part D

keV Sterile ν DM

NO strong prior theoretical motivation for the existence of keV sterile ν's.
A typical model: νMSM (Asaka, Blanchet, Shaposhnikov 2005).

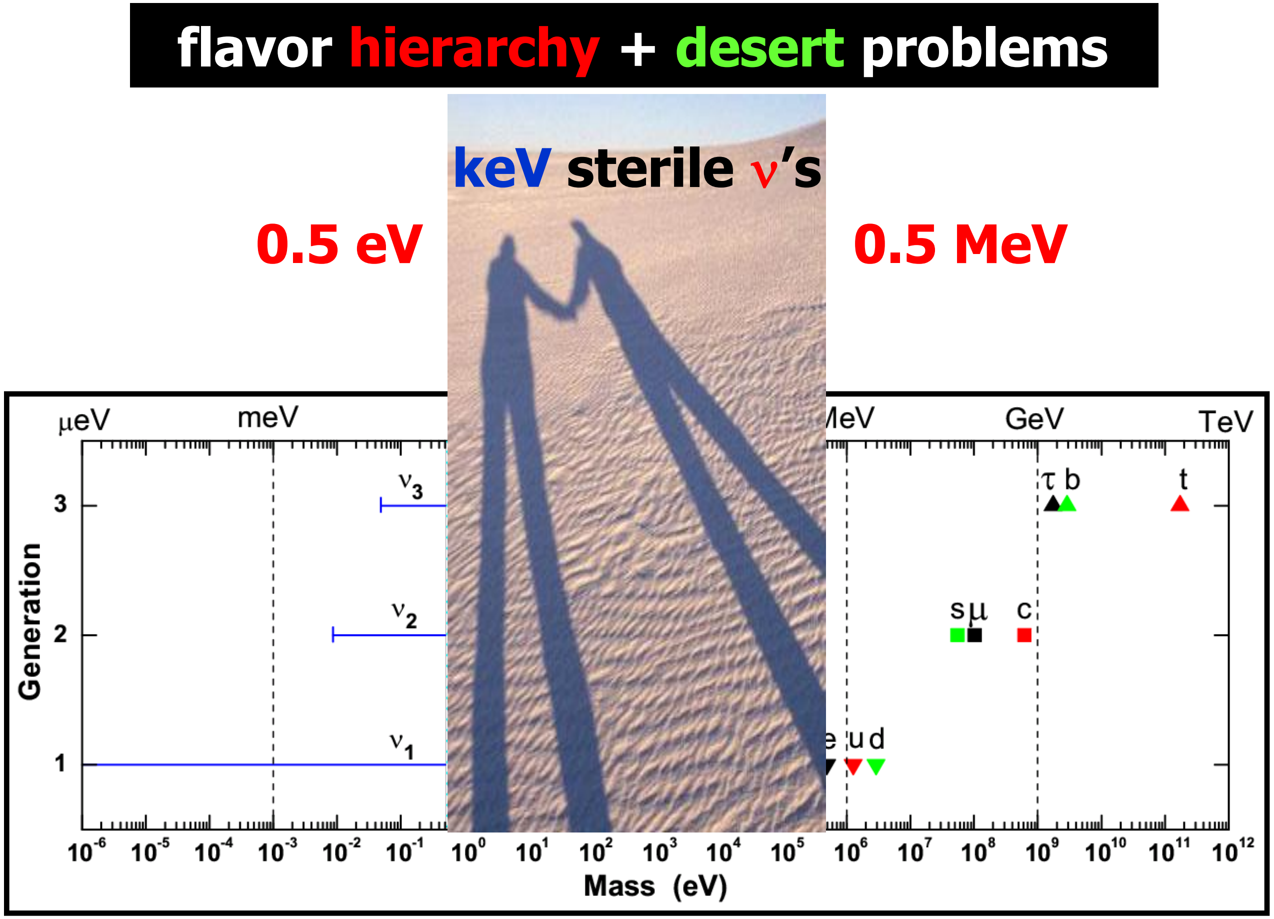
A purely phenomenological argument to support keV sterile ν's in DESERT.



Planck

gauge hierarchy
+
desert problems

Fermi



flavor hierarchy + desert problems

keV sterile ν's

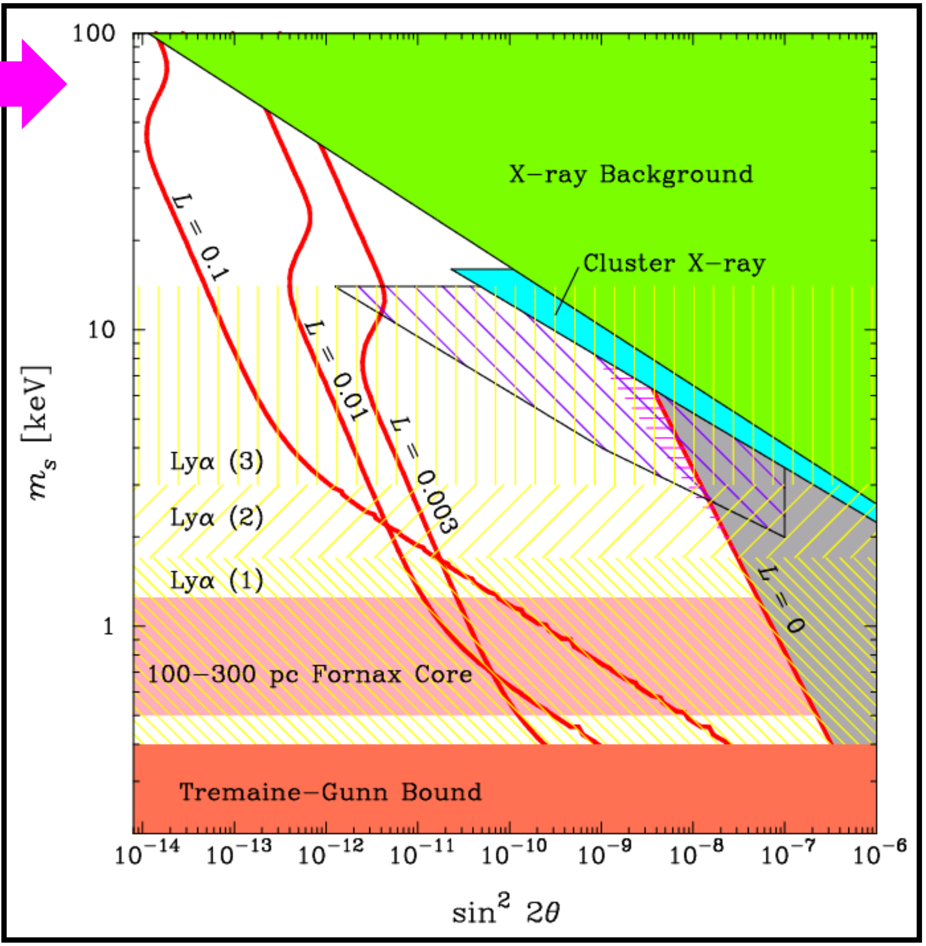
0.5 eV

0.5 MeV

Warm DM

Production: through active-sterile ν oscillations in the early Universe, etc; **Salient feature**: **warm** DM in the form of **keV** sterile ν's may 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 neutrino:

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

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 [Cν = 1 (Dirac) or 2 (Majorana)]:

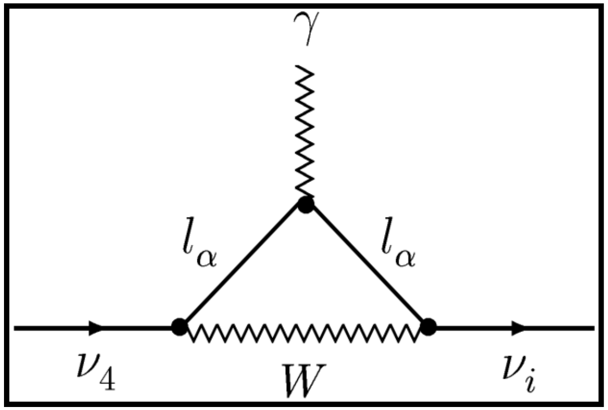
$$\boxed{\sum_{\alpha=e}^{\tau}\sum_{\beta=e}^{\tau}\Gamma(\nu_4 \to \nu_\alpha + \nu_\beta + \overline{\nu}_\beta) = \frac{C_\nu G_{\rm F}^2 m_4^5}{192\pi^3}\sum_{\alpha=e}^{\tau}|V_{\alpha 4}|^2 = \frac{C_\nu G_{\rm F}^2 m_4^5}{192\pi^3}\sum_{i=1}^{3}|V_{si}|^2}$$

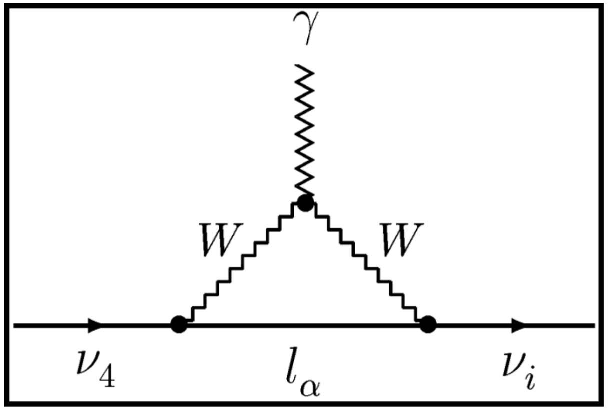
Lifetime (the Universe's age ~ 10^17 s):

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

Radiative decay: the X-ray measurement and the Lyman-alpha forest observation.

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





Part D

Detection in the Laboratory

The method is rather similar to the detection of the **CνB** in the laboratory.

$$\boxed{\nu_e + N \to N' + e^-}$$

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

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

The capture rate with a Gaussian energy resolution:

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

Assumption: the **number density** of sterile **ν**'s could account for the total amount of DM. In our galactic neighborhood, we have

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

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

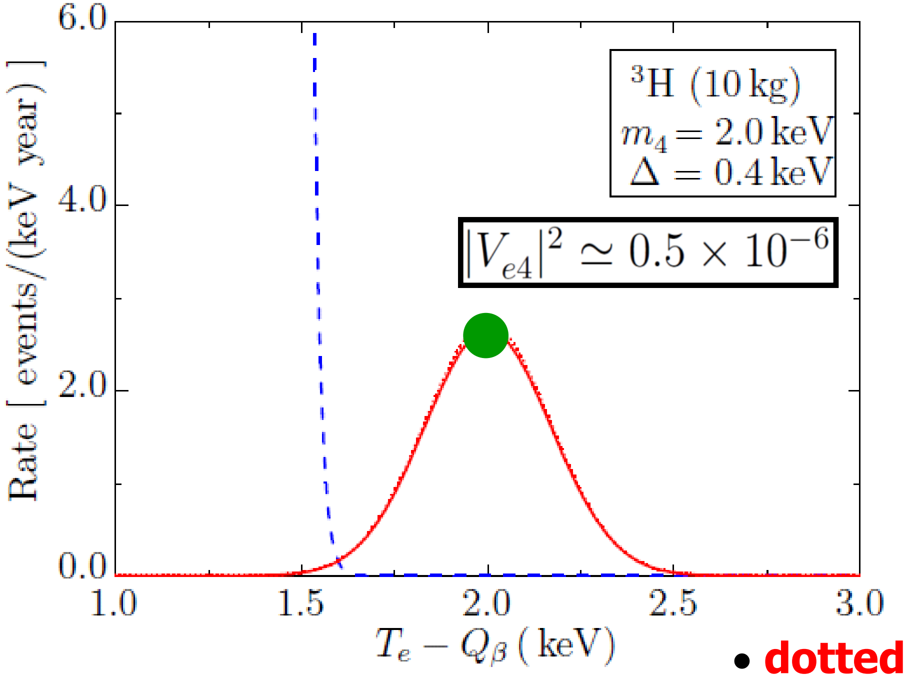
Half-life effects of target nuclei. We study two sources (Liao, **2010**, Cocco et al **2007**):

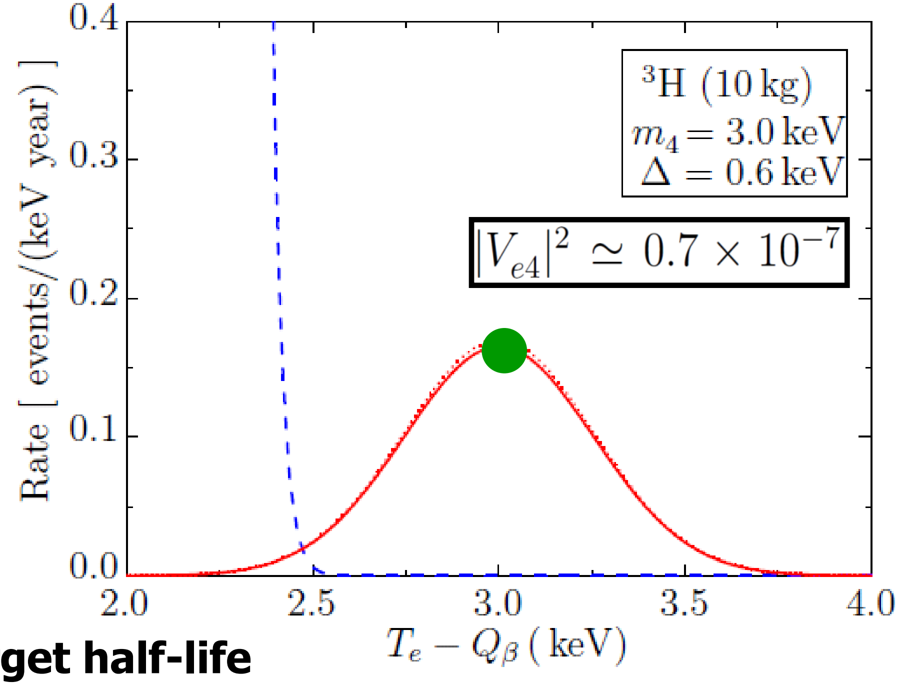
$$N_{\rm T} = \frac{N(0)}{\lambda t}\left(1 - e^{-\lambda t}\right) , \qquad \lambda = \frac{\ln 2}{t_{1/2}}$$

$$\begin{array}{rl} {}^3{\rm H} : & Q_\beta = 18.6~{\rm keV}~, \quad t_{1/2} = 3.888 \times 10^8~{\rm s}~, \quad \sigma_{\nu_i} v_{\nu_i}/c = 7.84 \times 10^{-45}~{\rm cm}^2 \\ {}^{106}{\rm Ru} : & Q_\beta = 39.4~{\rm keV}~, \quad t_{1/2} = 3.228 \times 10^7~{\rm s}~, \quad \sigma_{\nu_i} v_{\nu_i}/c = 5.88 \times 10^{-45}~{\rm cm}^2 \end{array}$$

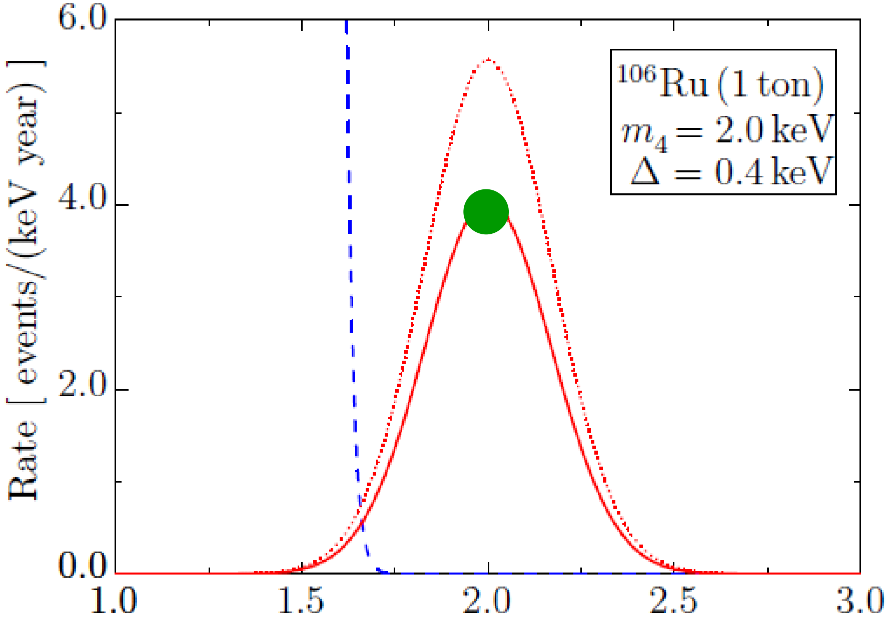
This method & the X-ray measurement probe **different** parameter spaces.

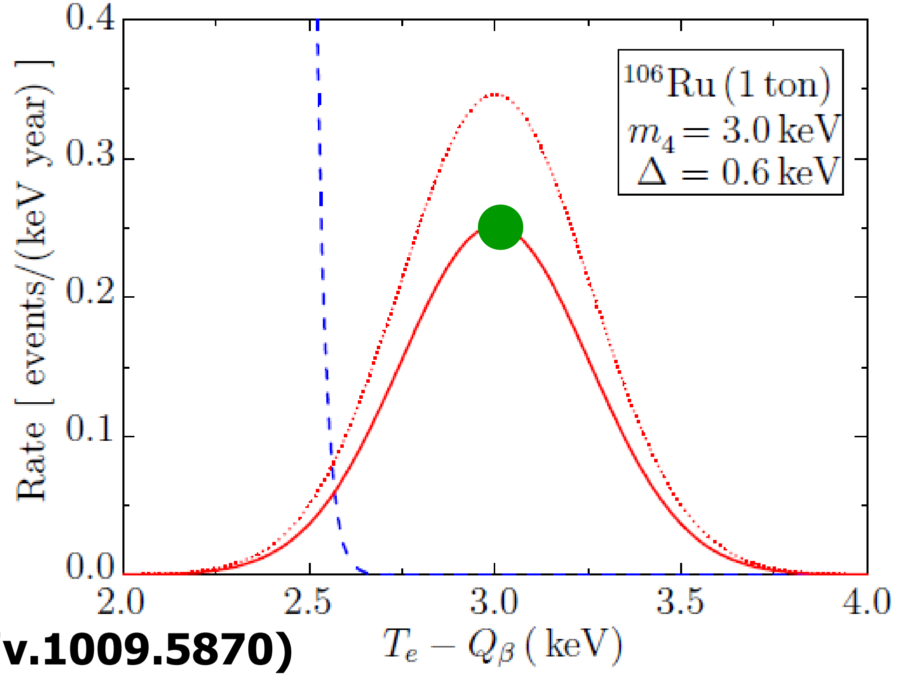
$$\boxed{|V_{e4}|^2 \simeq c_{12}^2 s_{14}^2 + s_{12}^2 s_{24}^2 + 2 c_{12} s_{12} s_{14} s_{24} \cos\left(\delta_{24} - \delta_{12} - \delta_{14}\right)}$$





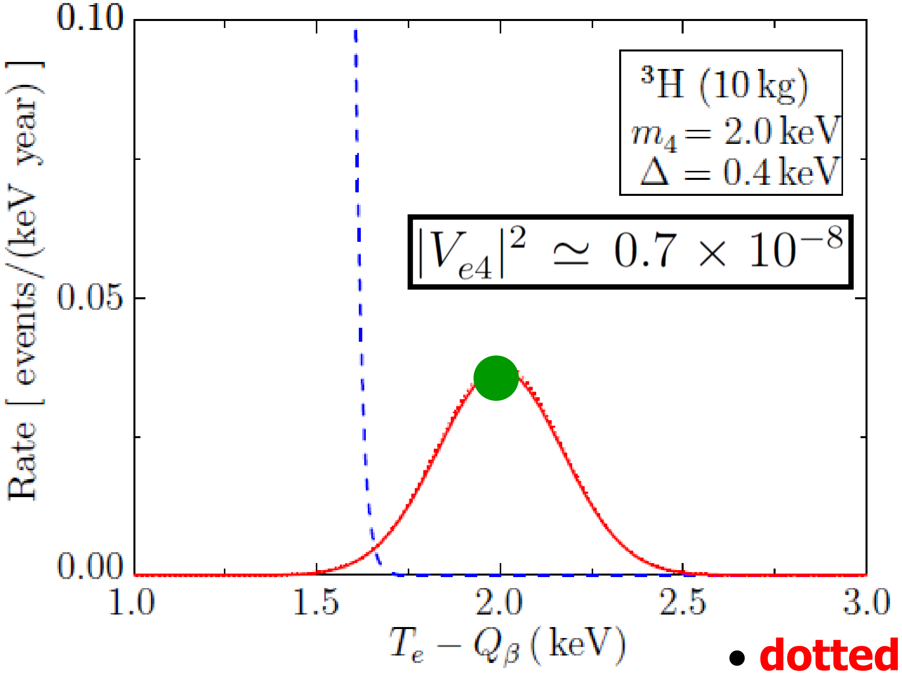
- **dotted: forget half-life**
- **solid: include half-life**

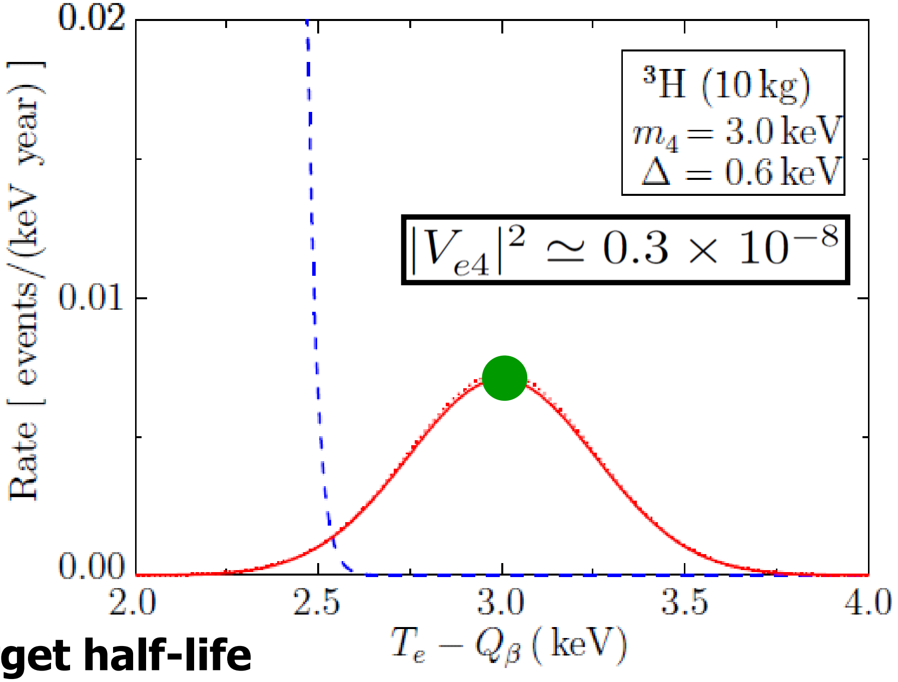




$T_e - Q_\beta$ (keV)

(Li, Xing, arXiv.1009.5870)





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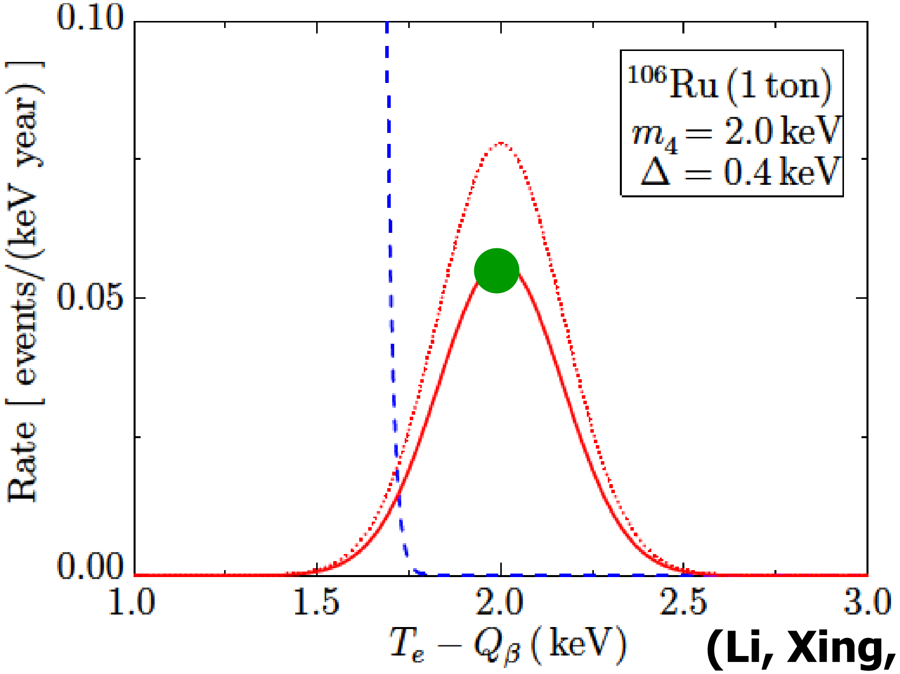

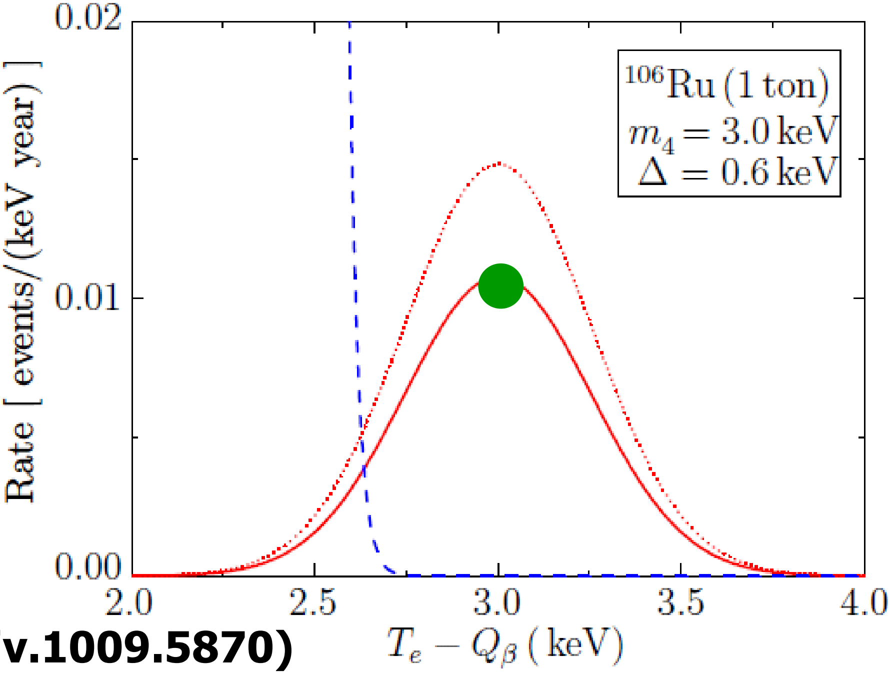

(Li, Xing, arXiv.1009.5870)

Summary

- **Cosmic Flavor Physics is becoming an exciting field in the epoch of LHC, precision cosmology and astrophysics:**

---- cosmic ν background

---- BBN

---- DM

---- matter-antimatter asymmetry

---- UHE cosmic ν's

---- stellar and supernova ν's

---- super(symmetric) flavors ……

- **The desert in the SM fermion mass spectrum might be a refuge of keV sterile ν's as a natural candidate for warm DM**

- **A capture of CνB or keV sterile ν DM on radioactive β-decaying nuclei would become a promising detection way in the laboratory**