Neutrino Physics

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A1: Neutrino's history & lepton families

A2: Dirac & Majorana neutrino masses

B1: Lepton flavor mixing & CP violation

B2: Neutrino oscillation phenomenology

C1: Seesaw & leptogenesis mechanisms

C2: Extreme corners in the neutrino sky

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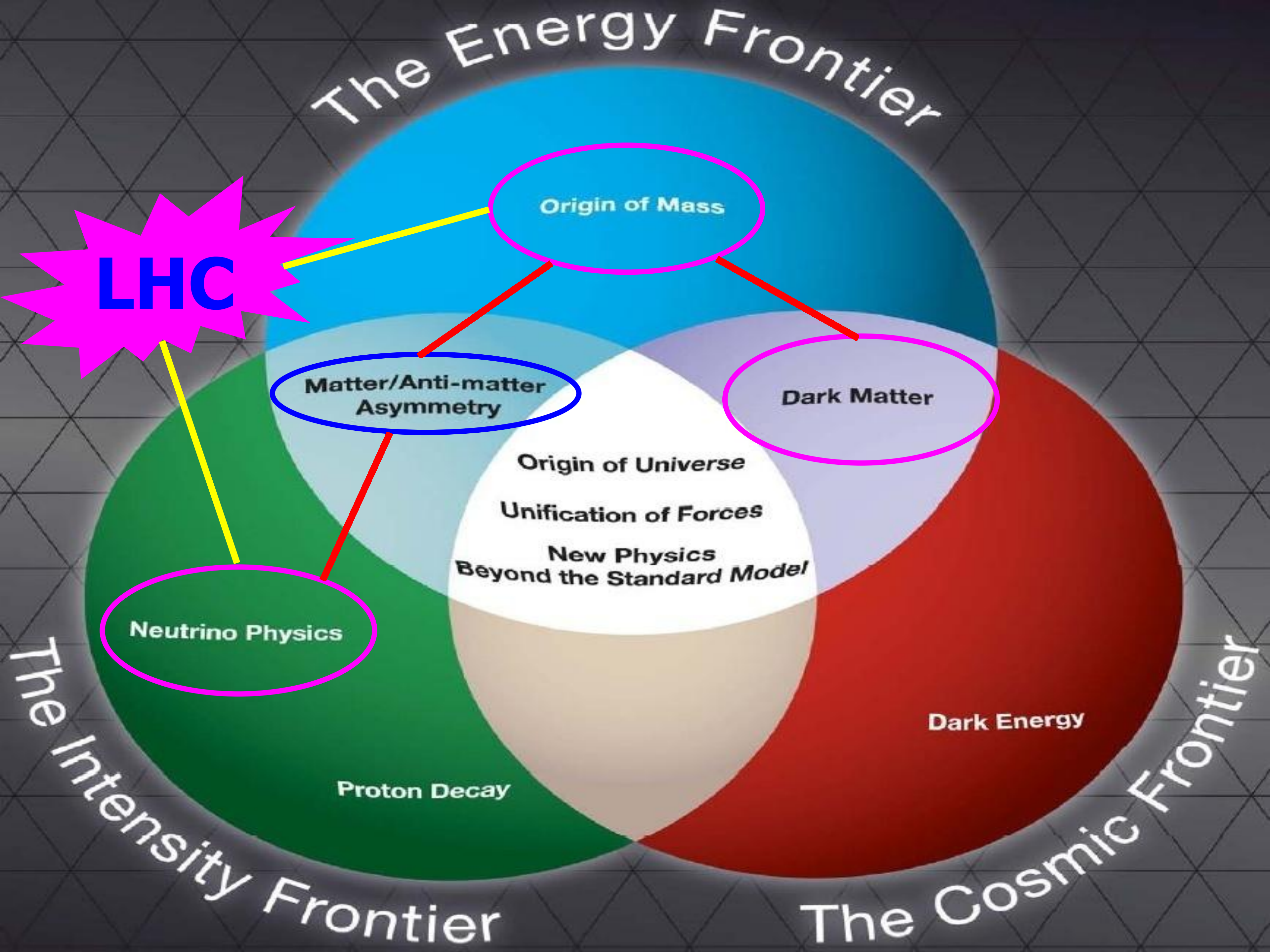
Lecture C1

★ **Ways to Generate Neutrino Mass**

★ **TeV Seesaws: Natural/Testable?**

★ **Collider Signals of TeV Seesaws?**


The Energy Frontier
LHC
Origin of Mass
Matter/Anti-matter
Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics
Beyond the Standard Model
Neutrino Physics
Dark Energy
Proton Decay
The Intensity Frontier
The Cosmic Frontier

Within the SM

All ν's are massless in the SM, a result of the model's simple structure:

---- SU(2)_L×U(1)_Y gauge symmetry and Lorentz invariance;

Fundamentals of the model, mandatory for consistency of a QFT.

---- Economical particle content:

No right-handed neutrinos --- a Dirac mass term is not allowed.

Only one Higgs doublet --- a Majorana mass term is not allowed.

---- Mandatory renormalizability:

No dimension ≥ 5 operators: a Majorana mass term is forbidden.

To generate ν-masses, one or more of the constraints must be relaxed.

--- The gauge symmetry and Lorentz invariance cannot be abandoned;

--- The particle content can be modified;

--- The renormalizability can be abandoned.

How many ways?

Beyond the SM (1)

Way 1: to relax the requirement of **renormalizability** (S. Weinberg 79)

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{\mathcal{L}_{\rm d=5}}{\Lambda} + \frac{\mathcal{L}_{\rm d=6}}{\Lambda^2} + \cdots$$

In the SM, the **lowest-dimension operator** that violates **lepton**/**baryon** number is

$$\frac{1}{M} HHLL$$

neutrino mass

Seesaw: $m_{1,2,3} \sim \langle H \rangle^2 / M$

$$m_{1,2,3} < 1\,\mathrm{eV} \;\Rightarrow\; M > 10^{13}\ \mathrm{GeV}$$

$$\frac{1}{M^2} QQQL$$

proton decay

Example : $p \to \pi^0 + e^+$

$$\tau_p > 10^{33}\ \text{years} \;\Rightarrow\; M > 10^{15}\ \mathrm{GeV}$$

Neutrino masses/**proton decays**: windows onto physics at high scales

Beyond the SM (2)

Way 2: to add 3 right-handed neutrinos & demand a (B - L) symmetry

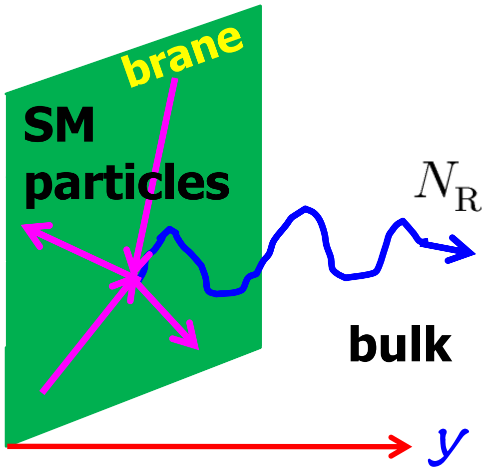
A pure Dirac mass term

$$-\mathcal{L}_{\rm lepton} = \overline{l_{\rm L}} Y_l H E_{\rm R} + \overline{l_{\rm L}} Y_\nu \tilde{H} N_{\rm R} + {\rm h.c.}$$

$$M_l = \frac{v}{\sqrt{2}} Y_l \qquad M_\nu = \frac{v}{\sqrt{2}} Y_\nu$$

The hierarchy problem: $y_i/y_e = m_i/m_e \lesssim 0.5~{\rm eV}/0.5~{\rm MeV} \sim 10^{-6}$

A very speculative way out: the smallness of Dirac masses is ascribed to the assumption that *N*_R have access to an extra spatial dimension (Dienes, Dudas, Gherghetta 98; Arkani-Hamed, Dimopoulos, Dvali, March-Russell 98) :



The wavefunction of *N*_R spreads out over the extra dimension *y*, giving rise to a suppressed Yukawa interaction at *y* = 0.

$$\left[\overline{l_{\rm L}} Y_\nu \tilde{H} N_{\rm R}\right]_{y=0} \sim \boxed{\frac{1}{\sqrt{L}}} \left[\overline{l_{\rm L}} Y_\nu \tilde{H} N_{\rm R}\right]_{y=L}$$

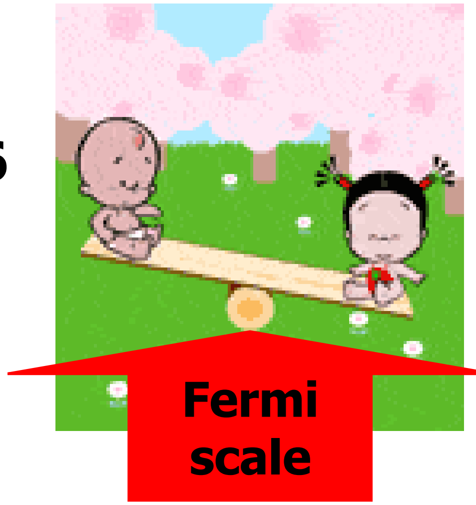
(e.g., King 08)

$$\Lambda_{\rm String}/\Lambda_{\rm Planck} \sim 10^{-12}$$

Beyond the SM (3)

Seesaw: add **new heavy degrees of freedom** and allow (**B**-**L**) violation:

Seesaw—A Footnote Idea:
H. Fritzsch, M. Gell-Mann,
P. Minkowski, PLB 59 (1975) 256



T-1: SM + 3 right-handed neutrinos (Minkowski 77; Yanagida 79; Glashow 79; Gell-Mann, Ramond, Slanski 79; Mohapatra, Senjanovic 79)

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

T-2: SM + 1 Higgs triplet (Konetschny, Kummer 77; Magg, Wetterich 80; Schechter, Valle 80; Cheng, Li 80; Lazarides et al 80; Mohapatra, Senjanovic 80)

$$-\mathcal{L}_{\rm lepton} = \overline{l_{\rm L}} Y_l H E_{\rm R} + \frac{1}{2} \overline{l_{\rm L}} Y_\Delta \Delta i\sigma_2 l^c_{\rm L} - \lambda_\Delta M_\Delta H^T i\sigma_2 \Delta H + {\rm h.c.}$$

variations

T-3: SM + 3 triplet fermions (Foot, Lew, He, Joshi 89)

$$-\mathcal{L}_{\rm lepton} = \overline{l_{\rm L}} Y_l H E_{\rm R} + \overline{l_{\rm L}} \sqrt{2} Y_\Sigma \Sigma^c \tilde{H} + \frac{1}{2} {\rm Tr}\left(\overline{\Sigma} M_\Sigma \Sigma^c\right) + {\rm h.c.}$$

combinations

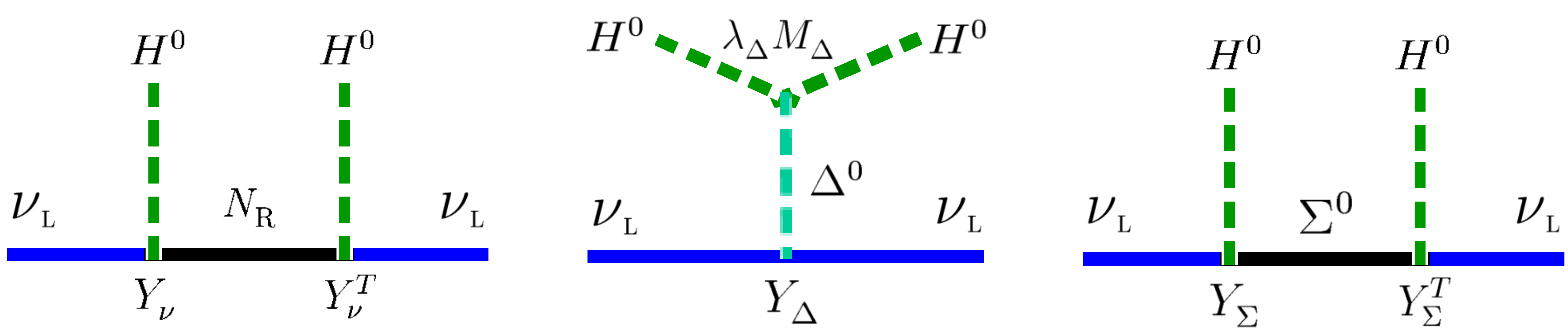
Seesaws

Weinberg operator: the unique **dimension-five** operator of ν-masses after integrating out the heavy degrees of freedom.

$$\frac{\mathcal{L}_{\rm d=5}}{\Lambda} = \begin{cases} \frac{1}{2}\left(Y_\nu M_{\rm R}^{-1} Y_\nu^T\right)_{\alpha\beta} \overline{l_{\alpha \rm L}}\tilde{H}\tilde{H}^T l^c_{\beta \rm L} + {\rm h.c.} \\ -\frac{\lambda_\Delta}{M_\Delta}\left(Y_\Delta\right)_{\alpha\beta} \overline{l_{\alpha \rm L}}\tilde{H}\tilde{H}^T l^c_{\beta \rm L} + {\rm h.c.} \\ \frac{1}{2}\left(Y_\Sigma M_\Sigma^{-1} Y_\Sigma^T\right)_{\alpha\beta} \overline{l_{\alpha \rm L}}\tilde{H}\tilde{H}^T l^c_{\beta \rm L} + {\rm h.c.} \end{cases}$$

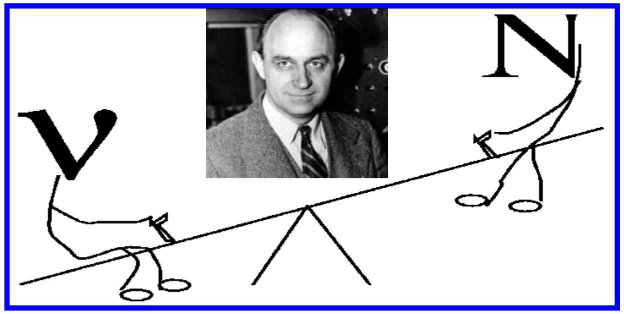
$$M_\nu = \begin{cases} -\frac{1}{2} Y_\nu \frac{v^2}{M_{\rm R}} Y_\nu^T & \text{(Type 1)} \\ \lambda_\Delta Y_\Delta \frac{v^2}{M_\Delta} & \text{(Type 2)} \\ -\frac{1}{2} Y_\Sigma \frac{v^2}{M_\Sigma} Y_\Sigma^T & \text{(Type 3)} \end{cases}$$

After SSB, a Majorana mass term is $-\mathcal{L}_{\rm mass} = \frac{1}{2}\overline{\nu_{\rm L}} M_\nu \nu^c_{\rm L} + {\rm h.c.}$ $\quad \langle \tilde{H} \rangle = v/\sqrt{2}$



Seesaw Scale?

What is the energy scale at which the seesaw mechanism works?



Planck

GUT to unify strong, weak & electromagnetic forces

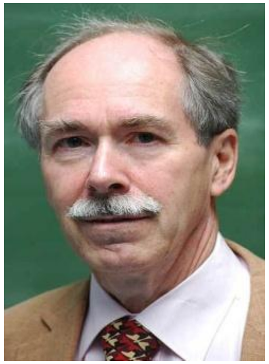
Conventional Seesaws: heavy degrees of freedom near GUT

This appears to be rather reasonable, since one often expects new physics to appear around a fundamental scale

Fermi

Naturalness √	Testability ✕
Uniqueness ✕	Hierarchy ✕

Lower Scale?



There is no direct evidence for a large or extremely large seesaw scale. So eV-, keV-, MeV- or GeV-scale seesaws are all possible, at least in principle; they are technically natural according to 't Hooft's naturalness criterion.

't Hooft's naturalness criterion (80):

At any energy scale μ, a set of parameters, $\alpha_i(\mu)$ describing a system can be small, if and only if, in the limit $\alpha_i(\mu) \rightarrow 0$ for each of these parameters, the system exhibits an enhanced symmetery.

Potential problems of low-scale seesaws:

---- No obvious connection to a theoretically well-justified fundamental scale (for example, Fermi scale, TeV scale, GUT or Planck scale).

---- The neutrino Yukawa couplings are simply tiny, no actual explanation of why the masses of three known neutrinos are so small.

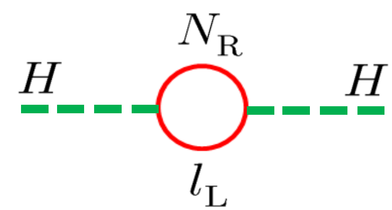
---- A very low seesaw scale doesn't allow canonical thermal leptogenesis to work, though there might be a very *contrived* way out.

Hierarchy Problem

Seesaw-induced fine-tuning problem: the Higgs mass is very sensitive to quantum corrections from the heavy degrees of freedom in seesaw (Vissani 98; Casas et al 04; Abada et al 07)

Type 1:

$$\boxed{\delta m_H^2 = -\frac{y_i^2}{8\pi^2}\left(\Lambda^2 + M_i^2 \ln\frac{M_i^2}{\Lambda^2}\right)}$$

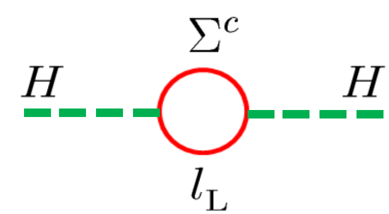


Type 2:

$$\boxed{\delta m_H^2 = \frac{3}{16\pi^2}\left[\lambda_3\left(\Lambda^2 + M_\Delta^2 \ln\frac{M_\Delta^2}{\Lambda^2}\right) + 4\lambda_\Delta^2 M_\Delta^2 \ln\frac{M_\Delta^2}{\Lambda^2}\right]}$$

Type 3:

$$\boxed{\delta m_H^2 = -\frac{3y_i^2}{8\pi^2}\left(\Lambda^2 + M_i^2 \ln\frac{M_i^2}{\Lambda^2}\right)}$$



here y_i & M_i are eigenvalues of Y_ν (or Y_Σ) & M_R (or M_Σ), respectively.

An illustration of fine-tuning

$$\boxed{M_i \sim \left[\frac{(2\pi v)^2|\delta m_H^2|}{m_i}\right]^{1/3} \sim \underline{10^7\mathrm{GeV}}\left[\frac{0.2\ \mathrm{eV}}{m_i}\right]^{1/3}\left[\frac{|\delta m_H^2|}{0.1\ \mathrm{TeV}^2}\right]^{1/3}}$$

Possible way out: (1) Supersymmetric seesaw? (2) TeV-scale seesaw?

The Seesaw Scale?

Planck scale $\Lambda \sim 10^{19}\,\mathrm{GeV}$

GUT scale? $\Lambda \sim 10^{16}\,\mathrm{GeV}$

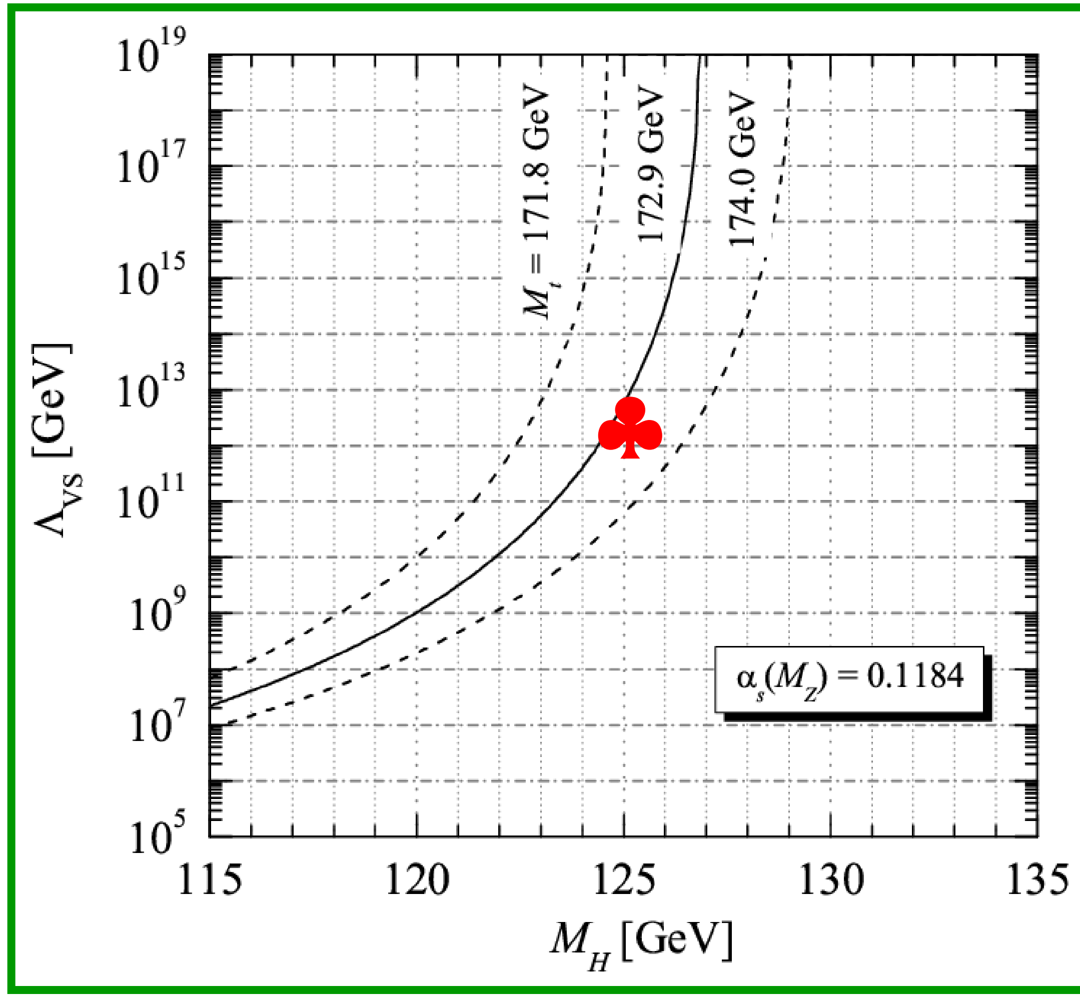
Seesaw scale? $\Lambda \sim 10^{12}\,\mathrm{GeV}$

TeV / SUSY? $\Lambda \sim 10^{3}\,\mathrm{GeV}$

Fermi scale $\Lambda \sim 10^{2}\,\mathrm{GeV}$

QCD scale $\Lambda \sim 10^{2}\,\mathrm{MeV}$

The SM vacuum stability for a light Higgs



Elias-Miro et al., arXiv:1112.3022;
Xing, Zhang, Zhou, arXiv:1112.3112; ...

TeV Neutrino Physics?

to discover the SM Higgs boson

Why

to verify Yukawa interactions

to pin down heavy seesaw particles

to test seesaw mechanism(s)

Not

to measure low-energy effects

Try

Type-1 Seesaw

Type-1 Seesaw: add 3 *right-handed* Majorana neutrinos into the SM.

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

or

$$-\mathcal{L}_{\rm mass} = \overline{e_{\rm L}} M_l E_{\rm R} + \frac{1}{2}\overline{(\nu_{\rm L} \quad N^{\rm c}_{\rm R})} \begin{pmatrix} \mathbf{0} & M_{\rm D} \\ M_{\rm D}^T & M_{\rm R} \end{pmatrix} \begin{pmatrix} \nu^{\rm c}_{\rm L} \\ N_{\rm R} \end{pmatrix} + {\rm h.c.}$$

Diagonalization (flavor basis ⇒ mass basis):

$$\begin{pmatrix} V & R \\ S & U \end{pmatrix}^\dagger \begin{pmatrix} \mathbf{0} & M_{\rm D} \\ M_{\rm D}^T & M_{\rm R} \end{pmatrix} \begin{pmatrix} V & R \\ S & U \end{pmatrix}^* = \begin{pmatrix} \widehat{M}_\nu & \mathbf{0} \\ \mathbf{0} & \widehat{M}_N \end{pmatrix}$$

$$V^\dagger V + \underline{S^\dagger S} = V V^\dagger + \underline{R R^\dagger} = 1$$

Hence *V* is not unitary

Seesaw: $$M_\nu \equiv V \widehat{M}_\nu V^T \approx -M_{\rm D} M_{\rm R}^{-1} M_{\rm D}^T$$

$$R \sim S \sim M_{\rm D} / M_{\rm R}$$

Strength of Unitarity Violation

$$V \approx \left(1 - \frac{1}{2} R R^\dagger\right) V_{\rm unitary}$$

Natural or Unnatural?

Natural case: no large cancellation in the leading seesaw term.

$$M_\nu \approx M_\mathrm{D} M_\mathrm{R}^{-1} M_\mathrm{D}^T$$

0.01 eV

10^{15} GeV

100 GeV

$$R \sim S \sim M_\mathrm{D} / M_\mathrm{R} \sim 10^{-13}$$

$$\text{Unitarity Violation} \sim 10^{-26}$$

Unnatural case: large cancellation in the leading seesaw term.

$$M_\nu \approx M_\mathrm{D} M_\mathrm{R}^{-1} M_\mathrm{D}^T$$

0.01 eV

1 TeV

100 GeV

$$R \sim S \sim M_\mathrm{D} / M_\mathrm{R} \sim 10^{-1}$$

$$\text{Unitarity Violation} \sim 10^{-2}$$

TeV-scale (right-handed) Majorana neutrinos: small masses of 3 light Majorana neutrinos come from sub-leading perturbations.

Structural Cancellation

Given diagonal *M_R* with 3 mass igenvalues *M_1*, *M_2* and *M_3*, the leading (i.e., type-I seesaw) term of the active neutrino mass matrix vanishes, if and only if *M_D* has rank 1,

$$\boldsymbol{M}_{\mathbf{D}} = m \begin{pmatrix} y_1 & y_2 & y_3 \\ \alpha y_1 & \alpha y_2 & \alpha y_3 \\ \beta y_1 & \beta y_2 & \beta y_3 \end{pmatrix}$$

and if

$$\frac{y_1^2}{M_1} + \frac{y_2^2}{M_2} + \frac{y_3^2}{M_3} = 0$$

$$\boldsymbol{M}_{\nu} \approx \boldsymbol{M}_{\mathbf{D}} \boldsymbol{M}_{\mathbf{R}}^{-1} \boldsymbol{M}_{\mathbf{D}}^{T} = 0$$

(Buchmueller, Greub 91; Ingelman, Rathsman 93; Heusch, Minkowski 94; ……; Kersten, Smirnov 07).

Tiny ν-masses can be generated from tiny corrections to this complete "structural cancellation", by deforming *M_D* or *M_R* .

Simple example:

$$M'_{\mathrm{D}} = M_{\mathrm{D}} + \epsilon X_{\mathrm{D}}$$

$$\begin{aligned} M'_{\nu} &= M'_{\mathrm{D}} M_{\mathrm{R}}^{-1} M_{\mathrm{D}}'^{T} \\ &\approx \epsilon \left(M_{\mathrm{D}} M_{\mathrm{R}}^{-1} X_{\mathrm{D}}^{T} + X_{\mathrm{D}} M_{\mathrm{R}}^{-1} M_{\mathrm{D}}^{T} \right) + \mathcal{O}(\epsilon^2) \end{aligned}$$

Fast Lessons

Lesson 1: two necessary conditions to test a seesaw model with heavy right-handed Majorana neutrinos at the **LHC**:

---Masses of heavy Majorana neutrinos must be of $O(1)$ TeV or below

---Light-heavy neutrino mixing (i.e. *M*_D/*M*_R) must be large enough

Lesson 2: A collider signature of the heavy Majorana ν's is essentially decoupled from masses and mixing parameters of light ν's.

Lesson 3: non-unitarity of the light ν flavor mixing matrix might lead to observable effects in ν oscillations and rare processes.

Lesson 4: nontrivial limits on heavy Majorana ν's could be derived at the **LHC**, if the SM backgrounds are small for a specific final state.

$\Delta L = 2$ like-sign dilepton events

$$\boxed{pp \to W^{\pm}W^{\pm} \to \mu^{\pm}\mu^{\pm}jj \text{ and } pp \to W^{\pm} \to \mu^{\pm}N \to \mu^{\pm}\mu^{\pm}jj}$$

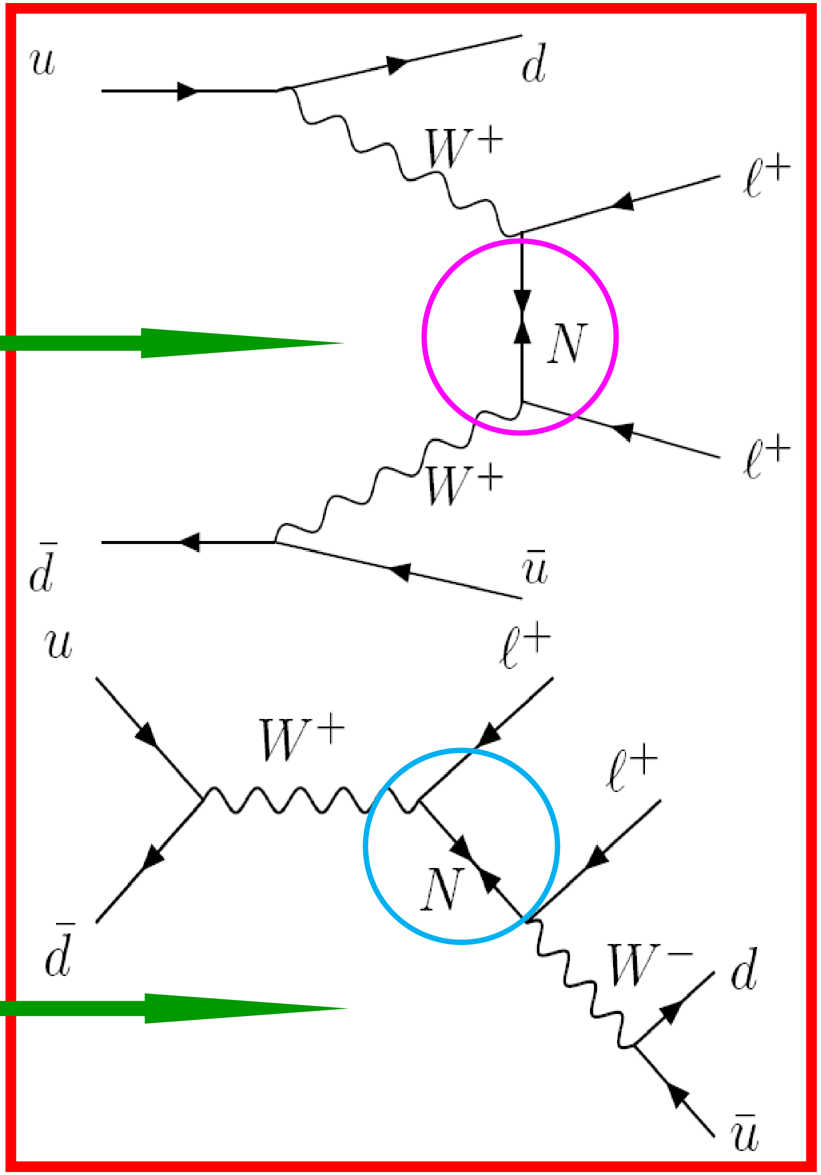
Collider Signature

Lepton number violation: **like-sign dilepton events at hadron colliders, such as Tevatron (~2 TeV) and LHC (~14 TeV).**

collider analogue to 0νββ decay

dominant channel

N **can be produced on resonance**



Testability at the LHC

2 recent comprehensive works:

Distinguishing seesaw models at LHC with multi-lepton signals

F. del Aguila, J. A. Aguilar–Saavedra

arXiv:0808.2468v2 [hep-ph] 12 Sep 2008

The Search for Heavy Majorana Neutrinos

arXiv:0901.3589v1 [hep-ph] 23 Jan 2009

Anupama Atre[1,2], Tao Han[2,3,4], Silvia Pascoli[5], Bin Zhang[4*]

We also extend the search to hadron collider experiments. We find that, at the Tevatron with 8 fb^{-1} integrated luminosity, there could be 2σ (5σ) sensitivity for resonant production of a Majorana neutrino in the $\mu^\pm\mu^\pm$ modes in the mass range of $\sim 10-180$ GeV ($10-120$ GeV). This reach can be extended to $\sim 10-375$ GeV ($10-250$ GeV) at the LHC of 14 TeV with 100 fb^{-1}. The production cross section at the LHC of 10 TeV is also presented for comparison. We study the $\mu^\pm e^\pm$ modes as well and find that the signal could be large enough even taking into account the current bound from neutrinoless double-beta decay. The signal from the gauge boson fusion channel $W^+W^+ \to \ell_1^+\ell_2^+$ at the LHC is found to be very weak given the rather small mixing parameters. We comment on the search strategy when a τ lepton is involved in the final state.

Non-unitarity

Type-1 seesaw: a typical signature would be the **unitarity violation** of the 3×3 neutrino mixing matrix ***V*** in the charged-current interactions

Current experimental constraints at the 90% C.L. (Antusch *et al* 07):

$$|VV^\dagger| \approx \begin{pmatrix} 0.994 \pm 0.005 & < 7.0 \cdot 10^{-5} & < 1.6 \cdot 10^{-2} \\ < 7.0 \cdot 10^{-5} & 0.995 \pm 0.005 & < 1.0 \cdot 10^{-2} \\ < 1.6 \cdot 10^{-2} & < 1.0 \cdot 10^{-2} & 0.995 \pm 0.005 \end{pmatrix}$$

$\mu \rightarrow e + \gamma$ etc, *W* / *Z* decays, *universality*, ν-oscillation.

$$|V^\dagger V| \approx \begin{pmatrix} 1.00 \pm 0.032 & < 0.032 & < 0.032 \\ < 0.032 & 1.00 \pm 0.032 & < 0.032 \\ < 0.032 & < 0.032 & 1.00 \pm 0.032 \end{pmatrix}$$

accuracy of a few **percent**!

Extra CP-violating phases exist in a non-unitary ν mixing matrix may lead to observable *CP-violating effects* in short- or medium-baseline ν oscillations (Fernandez-Martinez *et al* 07; Xing 08).

Typical example: non-unitary CP violation in the $\nu_\mu \rightarrow \nu_\tau$ oscillation, an effect probably **at the percent level**.

Type-2 Seesaw

Type-2 (Triplet) Seesaw: add one SU(2)_L Higgs triplet into the SM.

$$-\mathcal{L}_{\rm lepton} = \overline{l_{\rm L}} Y_l H E_{\rm R} + \frac{1}{2}\overline{l_{\rm L}} Y_\Delta \Delta i\sigma_2 l^c_{\rm L} + {\rm h.c.}$$

$$\Delta \equiv \begin{pmatrix} H^- & -\sqrt{2}\ H^0 \\ \sqrt{2}\ H^{--} & -H^- \end{pmatrix}$$

or

$$-\mathcal{L}_{\rm mass} = \overline{e_{\rm L}} M_l E_{\rm R} + \frac{1}{2}\overline{\nu_{\rm L}} M_{\rm L} \nu^c_{\rm L} + {\rm h.c.}$$

$$M_{\rm L} \approx \lambda_\Delta Y_\Delta \frac{v^2}{M_\Delta}$$

Potential:

$$V(H,\Delta) = -\mu^2 H^\dagger H + \lambda\left(H^\dagger H\right)^2 + \frac{1}{2}M_\Delta^2 {\rm Tr}\left(\Delta^\dagger \Delta\right) - \underline{\left[\lambda_\Delta M_\Delta H^T i\sigma_2 \Delta H + {\rm h.c.}\right]}$$

L **and** ***B–L*** **violation**

Naturalness? (t' Hooft 79, …, Giudice 08)

(1) *M_Δ* is O(1) TeV or close to the scale of gauge symmetry breaking.
(2) *λ_Δ* must be tiny, and *λ_Δ* =0 enhances the symmetry of the model.

$$M_{\rm L} \approx \lambda_\Delta Y_\Delta \frac{{\rm v}^2}{M_\Delta}$$

0.01 eV

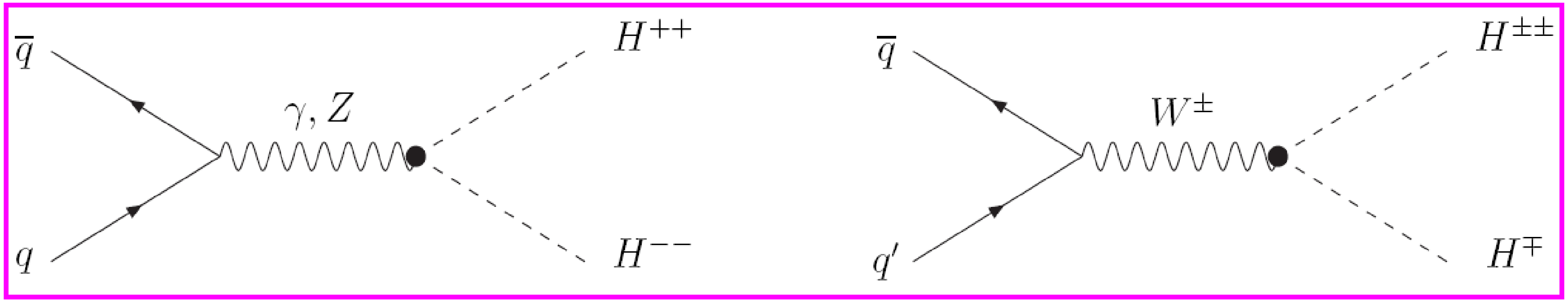
1 TeV

$$\lambda_\Delta Y_\Delta \sim 10^{-12} \Rightarrow \begin{cases} Y_\Delta \sim 1, \lambda_\Delta \sim 10^{-12} \\ \lambda_\Delta \sim Y_\Delta \sim 10^{-6} \\ \ldots\ldots \end{cases}$$

Collider Signature

From a viewpoint of direct tests, the triplet seesaw has an advantage:

The SU(2)_L Higgs triplet contains a doubly-charged scalar which can be produced at colliders: it is dependent on its mass but independent of the (small) Yukawa coupling.



Typical LNV signatures: $\boxed{H^{\pm\pm} \longrightarrow l^{\pm}_{\alpha} l^{\pm}_{\beta}}$ $\boxed{H^{+} \longrightarrow l^{+}_{\alpha} \bar{\nu}_{\beta}}$ $\boxed{H^{-} \longrightarrow l^{-}_{\alpha} \nu}$

$$\mathcal{B}(H^{\pm\pm} \to l^{\pm}_{\alpha} l^{\pm}_{\beta}) = \frac{(2-\delta_{\alpha\beta})|(M_{\rm L})_{\alpha\beta}|^2}{\sum\limits_{\rho,\sigma} |(M_{\rm L})_{\rho\sigma}|^2} \; , \qquad \mathcal{B}(H^{+} \to l^{+}_{\alpha} \overline{\nu}) = \frac{\sum\limits_{\beta} |(M_{\rm L})_{\alpha\beta}|^2}{\sum\limits_{\rho,\sigma} |(M_{\rm L})_{\rho\sigma}|^2}$$

Testability at the LHC

Lesson one: the above branching ratios **purely** depend on 3 neutrino masses, 3 flavor mixing angles and the CP-violating phases.

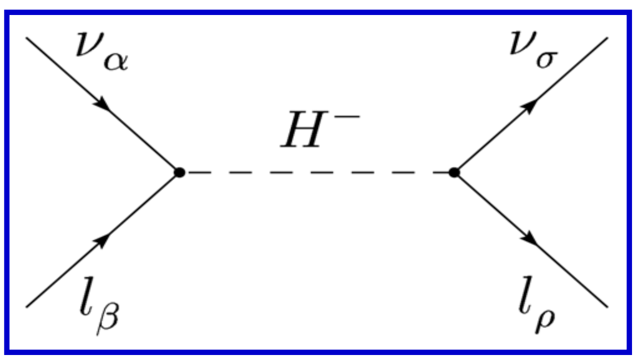
Lesson two: the **Majorana phases** may affect LNV $H^{\pm\pm} \longrightarrow l^{\pm}_{\alpha} l^{\pm}_{\beta}$ decay modes, but they do not enter $H^{+} \longrightarrow l^{+}_{\alpha} \bar{\nu}_{\beta}$ and $H^{-} \longrightarrow l^{-}_{\alpha} \nu$ processes.

$$\boxed{\left|\left(M_{\rm L}\right)_{\alpha\beta}\right|^2 = \left|\sum_{i=1}^{3}\left(m_i V_{\alpha i} V_{\beta i}\right)\right|^2 , \qquad \sum_{\beta}\left|\left(M_{\rm L}\right)_{\alpha\beta}\right|^2 = \sum_{i=1}^{3}\left(m_i^2 \left|V_{\alpha i}\right|^2\right)}$$

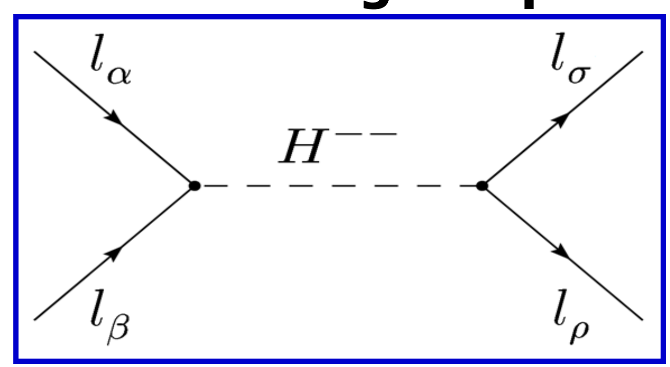
Dimension-6 operator:
(2 low-energy effects)

$$\boxed{\frac{\mathcal{L}_{\rm d=6}}{\Lambda^2} = -\frac{\left(Y_\Delta\right)_{\alpha\beta}\left(Y_\Delta\right)^{\dagger}_{\rho\sigma}}{4M^2_\Delta}\left(\overline{l_{\alpha\rm L}}\gamma^\mu l_{\sigma\rm L}\right)\left(\overline{l_{\beta\rm L}}\gamma_\mu l_{\rho\rm L}\right)}$$

1) NSIs of 3 neutrinos



2) LFV of 4 charged leptons



Type-3 Seesaw

Type-3 Seesaw: add 3 SU(2)_L triplet fermions (Y = 0) into the SM.

$$-\mathcal{L}_{\rm lepton} = \overline{l_{\rm L}} Y_l H E_{\rm R} + \overline{l_{\rm L}} \sqrt{2} Y_\Sigma \Sigma^c \tilde{H} + \frac{1}{2} {\rm Tr}\left(\overline{\Sigma} M_\Sigma \Sigma^c\right) + {\rm h.c.}$$

$$\Sigma = \begin{pmatrix} \Sigma^0/\sqrt{2} & \Sigma^+ \\ \Sigma^- & -\Sigma^0/\sqrt{2} \end{pmatrix}$$

or

$$-\mathcal{L}_{\rm mass} = \overline{\begin{pmatrix} e_{\rm L} & \Psi_{\rm L} \end{pmatrix}} \begin{pmatrix} M_l & \sqrt{2} M_{\rm D} \\ \mathbf{0} & M_\Sigma \end{pmatrix} \begin{pmatrix} E_{\rm R} \\ \Psi_{\rm R} \end{pmatrix} + \frac{1}{2} \overline{\begin{pmatrix} \nu_{\rm L} & \Sigma^0 \end{pmatrix}} \begin{pmatrix} \mathbf{0} & M_{\rm D} \\ M_{\rm D}^T & M_\Sigma \end{pmatrix} \begin{pmatrix} \nu_{\rm L}^c \\ \Sigma^{0c} \end{pmatrix} + {\rm h.c.}$$

$$M_l = Y_l v/\sqrt{2}\,, \quad M_{\rm D} = Y_\Sigma v/\sqrt{2}\,, \quad \Psi = \Sigma^- + \Sigma^{+c}$$

Diagonalization of the neutrino mass matrix:

$$\begin{pmatrix} V & R \\ S & U \end{pmatrix}^\dagger \begin{pmatrix} \mathbf{0} & M_{\rm D} \\ M_{\rm D}^T & M_\Sigma \end{pmatrix} \begin{pmatrix} V & R \\ S & U \end{pmatrix}^* = \begin{pmatrix} \widehat{M}_\nu & \mathbf{0} \\ \mathbf{0} & \widehat{M}_\Sigma \end{pmatrix}$$

Seesaw formula:

$$M_\nu \equiv V \widehat{M}_\nu V^T \approx -M_{\rm D} M_\Sigma^{-1} M_{\rm D}^T$$

Comparison between type-1 and type-3 seesaws (Abada et al 07):

a) The 3×3 flavor mixing matrix *V* is non-unitary in both cases (CC);

b) The modified couplings between *Z* & neutrinos are different (NC);

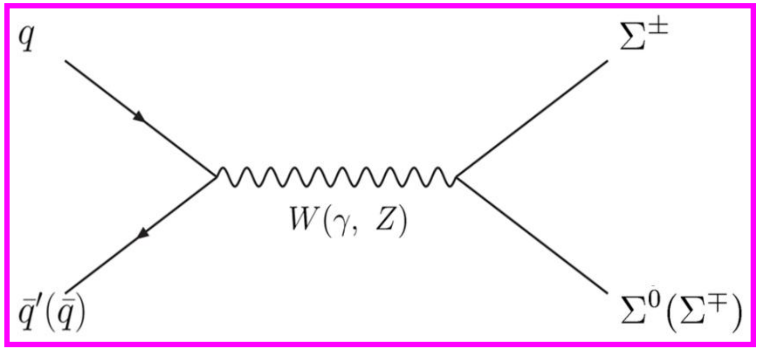
c) Non-unitary flavor mixing is also present in the coupling between *Z* and charged leptons in the type-3 seesaw (NC).

Testability at the LHC

LNV signatures at the LHC:

$$pp \to \Sigma^+\Sigma^0 \to l_\alpha^+ l_\beta^+ + Z^0 W^-(\to 4j)$$

$$pp \to \Sigma^-\Sigma^0 \to l_\alpha^- l_\beta^- + Z^0 W^+(\to 4j)$$



PHYSICAL REVIEW D **78,** 033002 (2008)

Type-III seesaw mechanism at CERN LHC

Roberto Franceschini,[1] Thomas Hambye,[2] and Alessandro Strumia[3]

Neutrino masses can be generated by fermion triplets with TeV-scale mass, that would manifest at LHC as production of two leptons together with two heavy standard model (SM) vectors or Higgs, giving rise to final states such as $2\ell + 4j$ (that can violate lepton number and/or lepton flavor) or $\ell + 4j + \not{E}_T$. We devise cuts to suppress the SM backgrounds to these signatures. Furthermore, for most of the mass range suggested by neutrino data, triplet decays are detectably displaced from the production point, allowing to infer the neutrino mass parameters. We compare with LHC signals of type-I and type-II seesaw.

Distinguishing seesaw models at LHC with multi-lepton signals

F. del Aguila, J. A. Aguilar–Saavedra

2 latest comprehensive works.

arXiv:0808.2468v2 [hep-ph] 12 Sep 2008

Low-energy Tests

Type-3 seesaw: a typical signature would be the **non-unitary effects** of the 3×3 lepton flavor mixing matrix ***N*** in both **CC** and **NC** interactions.

Current experimental constraints at the 90% C.L. (Abada *et al* 07):

$$|NN^\dagger| \approx \begin{pmatrix} 1.001 \pm 0.002 & < 1.1\cdot 10^{-6} & < 1.2\cdot 10^{-3} \\ < 1.1\cdot 10^{-6} & 1.002 \pm 0.002 & < 1.2\cdot 10^{-3} \\ < 1.2\cdot 10^{-3} & < 1.2\cdot 10^{-3} & 1.002 \pm 0.002 \end{pmatrix}$$

accuracy at 0.1%.

These bounds are stronger than those obtained in the type-1 seesaw, as the flavor-changing processes with charged leptons are allowed at the tree level in the type-3 seesaw.

Two types of LFV processes:

Radiative decays of charged leptons: $\mu \to e + \gamma$, $\tau \to e + \gamma$, $\tau \to \mu + \gamma$.

Tree-level rare decays of charged leptons: $\mu \to 3e$, $\tau \to 3e$, $\tau \to 3\mu$, $\tau \to e + 2\mu$, $\tau \to 2e + \mu$ **(Abada et al 07, 08; He, Oh 09)**

TeV leptogenesis or muon g-2 problems? (Strumia 08, Blanchet, Chacko, Mohapatra 08, Fischler, Flauger 08; Chao 08, Biggio 08; ......)

Seesaw Trivialization

Linear trivialization: **use three types of seesaws to make a family tree.**

Type 1 + Type 2

Type 1 + Type 3

Type 2 + Type 3

Type 1 + Type 2 + Type 3

Weinberg's ***3rd law of progress in theoretical physics*** **(83):**

You may use any degrees of freedom you like to describe a physical system, but if you use the wrong ones, you will be sorry ……………………………………. What could be better?

Linearly trivialized seesaws usually work at super-high energies.

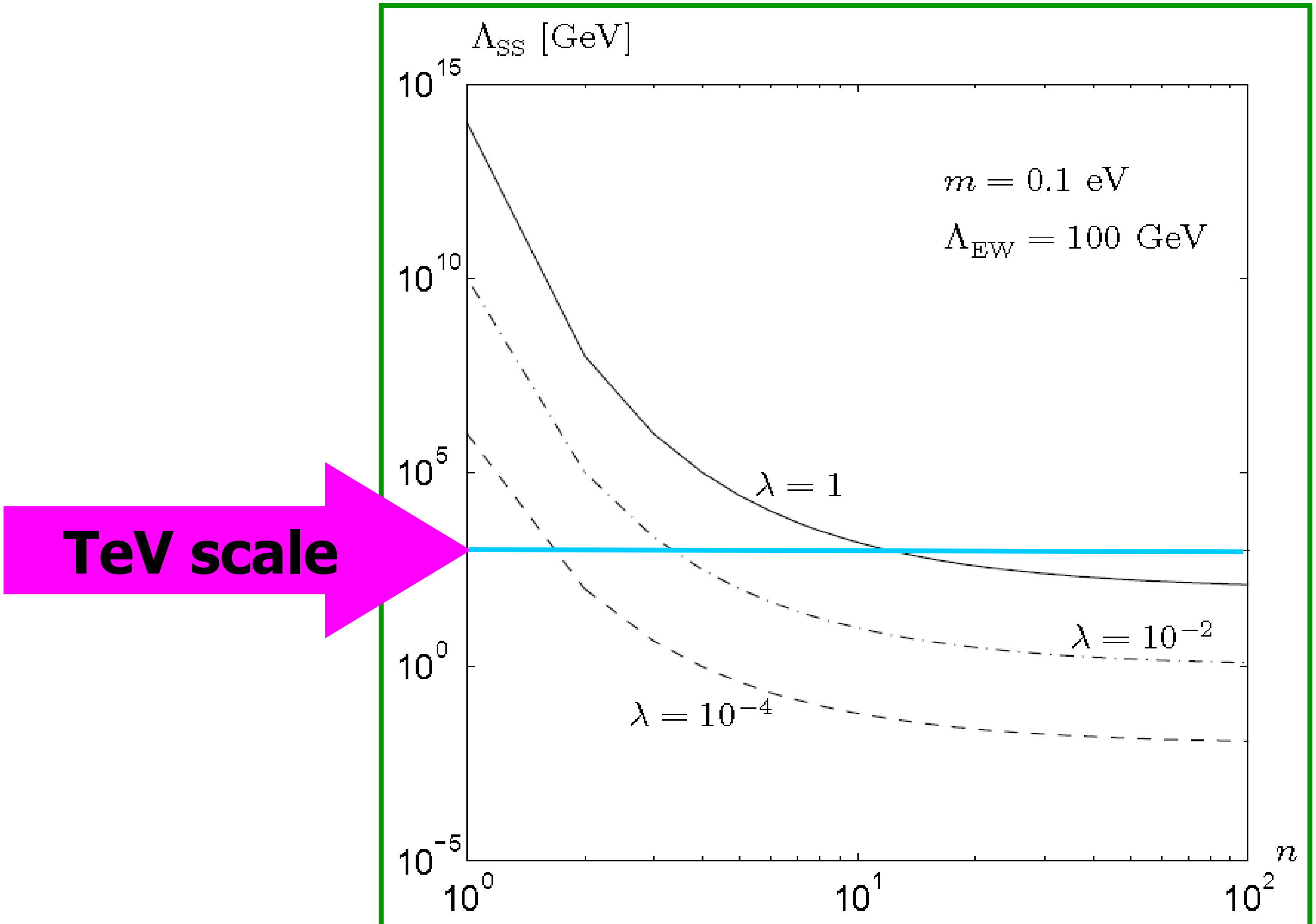
Multiple trivialization: **well motivated to lower the seesaw scale.**

Illustration

Neutrino mass:

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

$$\boxed{\Lambda_{\rm SS} \sim \lambda^{\frac{n+1}{n}}\left[\frac{\Lambda_{\rm EW}}{100\ \rm GeV}\right]^{\frac{n+1}{n}}\left[\frac{0.1\ \rm eV}{m}\right]^{\frac{1}{n}} 10^{\frac{2(n+6)}{n}}\ \rm GeV}$$



Example: Inverse Seesaw

The Inverse Seesaw: SM + 3 heavy right-handed neutrinos + 3 gauge singlet neutrinos + one Higgs singlet (Wyler, Wolfenstein 83; Mohapatra, Valle 86; Ma 87).

$$-\mathcal{L}_{\rm lepton} = \overline{l_{\rm L}} Y_l H E_{\rm R} + \overline{l_{\rm L}} Y_\nu \tilde{H} N_{\rm R} + \overline{N^{\rm c}_{\rm R}} Y_S \Phi S_{\rm R} + \frac{1}{2}\overline{S^{\rm c}_{\rm R}} \mu S_{\rm R} + {\rm h.c.}$$

LNV: tiny

ν-mass matrix:

$$\overline{\begin{pmatrix}\nu_{\rm L} & N^{\rm c}_{\rm R} & S^{\rm c}_{\rm R}\end{pmatrix}} \begin{pmatrix} \mathbf{0} & M_{\rm D} & \mathbf{0} \\ M_{\rm D}^T & \mathbf{0} & M_S \\ \mathbf{0} & M_S^T & \mu \end{pmatrix} \begin{pmatrix} \nu^{\rm c}_{\rm L} \\ N_{\rm R} \\ S_{\rm R} \end{pmatrix}$$

$$\begin{aligned} M_{\rm D} &= Y_\nu \langle H \rangle \\ M_S &= Y_S \langle \Phi \rangle \end{aligned}$$

Effective light ν-mass matrix

$$M_\nu \approx M_{\rm D} \frac{1}{M_S^T} \mu \frac{1}{M_S} M_{\rm D}^T \quad \Longleftrightarrow \quad -\mathcal{L}_{\rm mass} = \frac{1}{2} \overline{\nu_{\rm L}} M_\nu \nu^c_{\rm L} + {\rm h.c.}$$

Merit: more natural tiny ν-masses and appreciable collider signatures;
Fault: some new degrees of freedom. **Is Weinberg's 3rd law applicable?**

Multiple seesaw mechanisms: to *naturally* lower seesaw scales to TeV (Babu et al 09; Xing, Zhou 09; Bonnet et al 09, etc).

Appendix

Misguiding principles for a theorist to go beyond the SM

(Schellekens 08: “The Emperor’s Last Clothes?”)

- Agreement with observation
- Consistency
- Uniqueness
- Naturalness
- Simplicity
- Elegance
- Beauty
- ……

?

Lecture C2

- ★ **Baryogenesis via Leptogenesis**
- ★ **The Cosmic Neutrino Background**
- ★ **UHE Cosmic Neutrino Telescopes**

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?

$t = 10^{16}\,sec$

$r = 10^{29}\,cm$

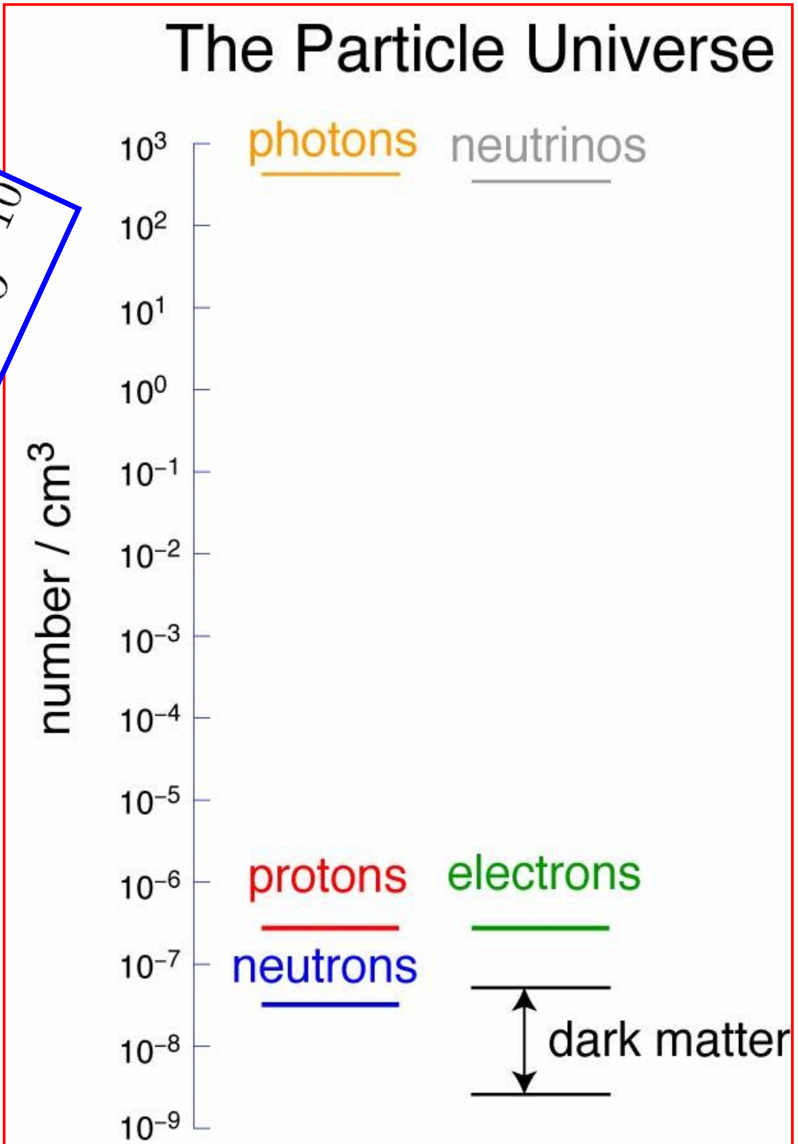
$T = 2.7\ K$

$400\gamma\ /\ cm^3$

$10^{80}\ p, n$

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

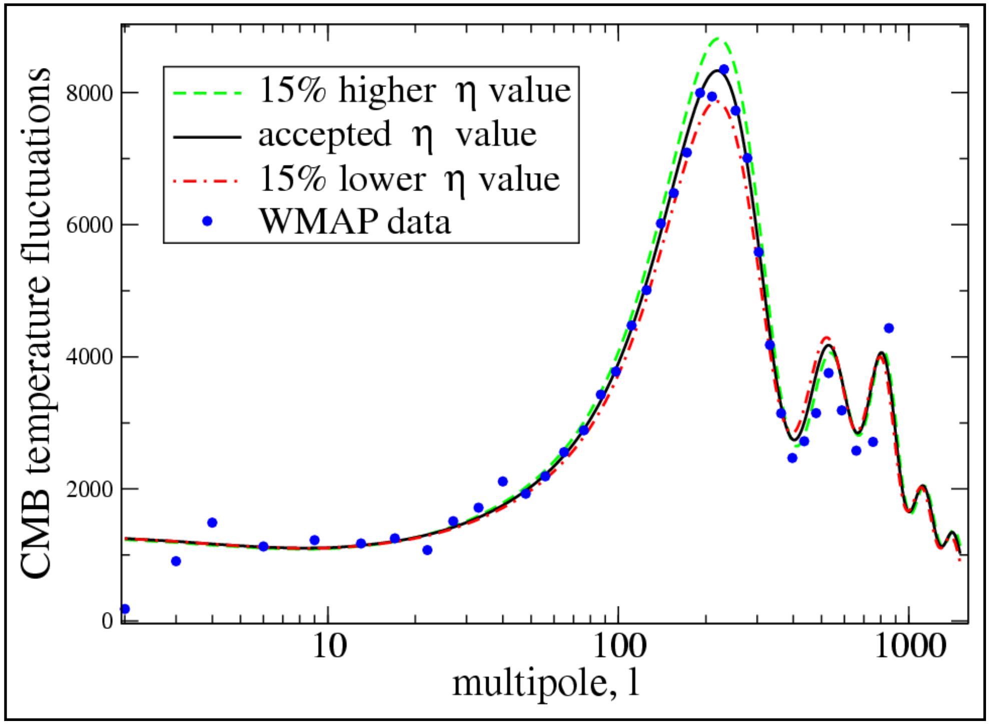
$$\eta_B \equiv n_B/n_\gamma = (6.1 \pm 0.2) \times 10{-}10$$

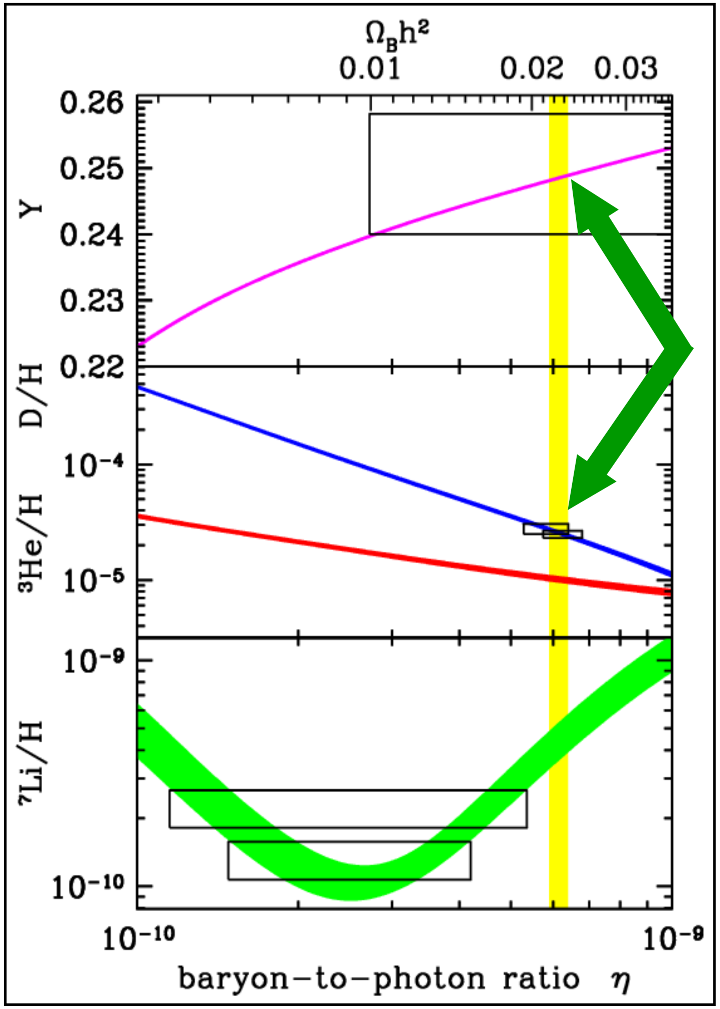


Evidence

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

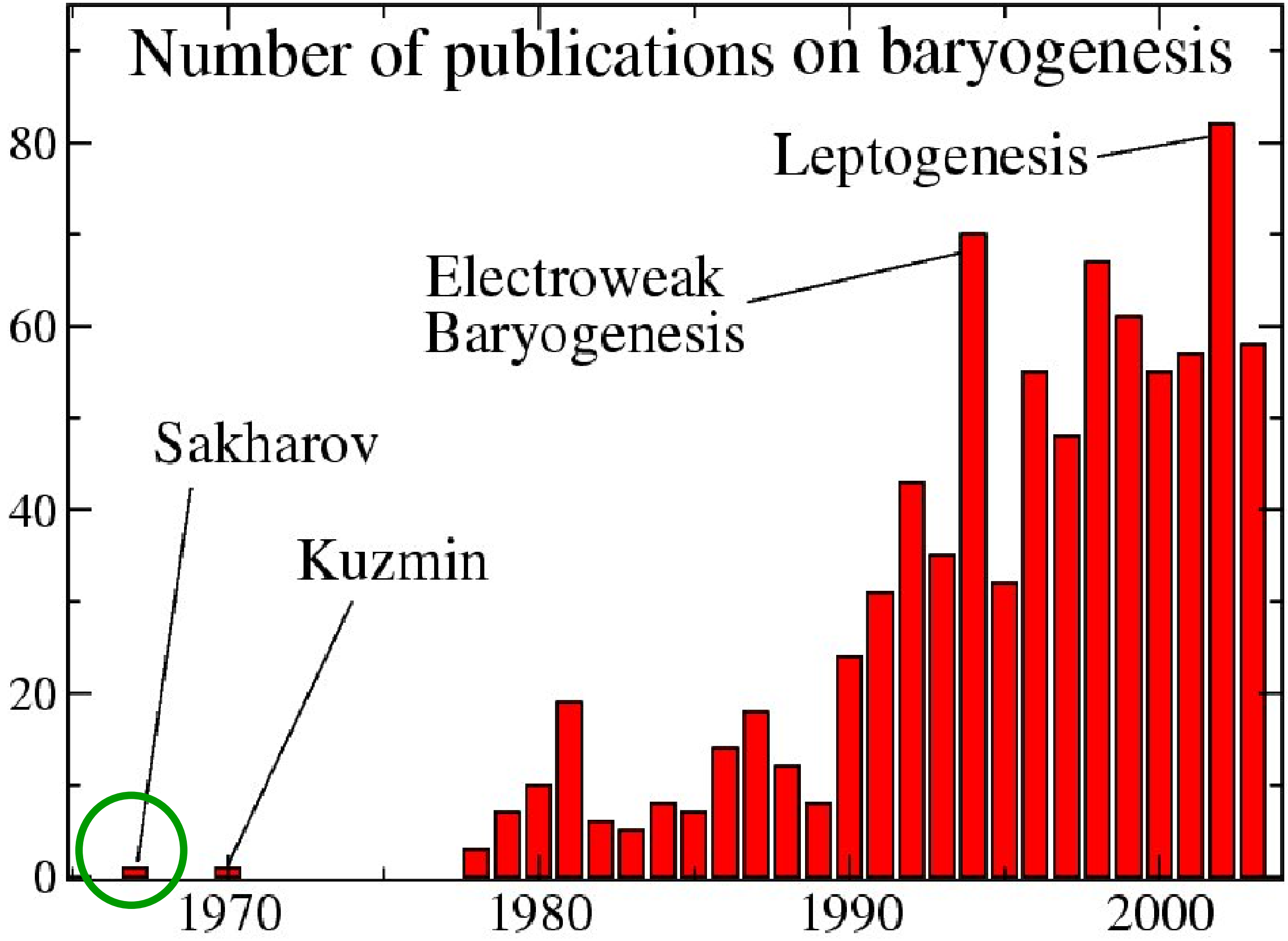
- Planck/GUT Baryogenesis;
- Electroweak Baryogenesis;
- Leptogenesis;
- Affleck-Dine Mechanism; ...

Neutrino Physics

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

Now >1300 times

Hot Topic



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.**

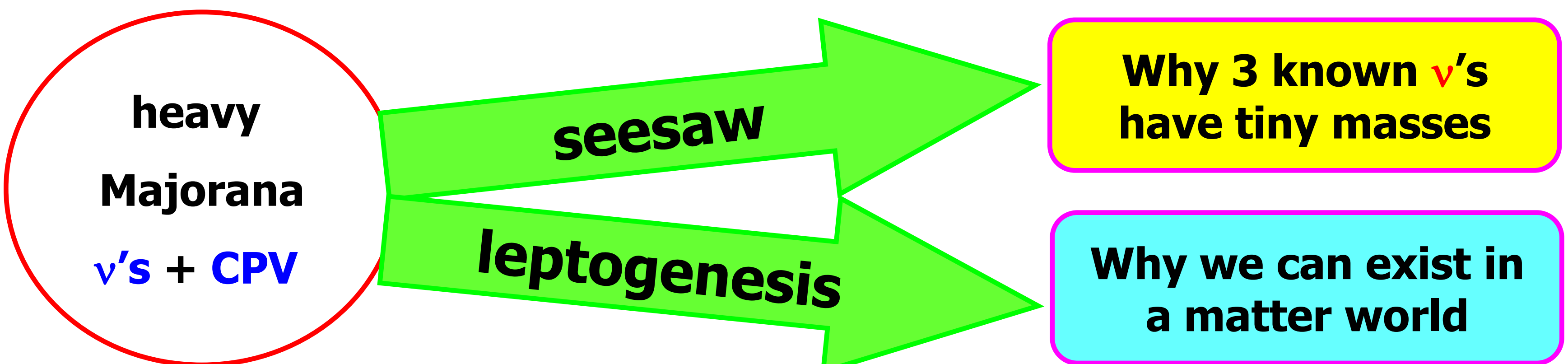
Remarks on CP Violation

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.



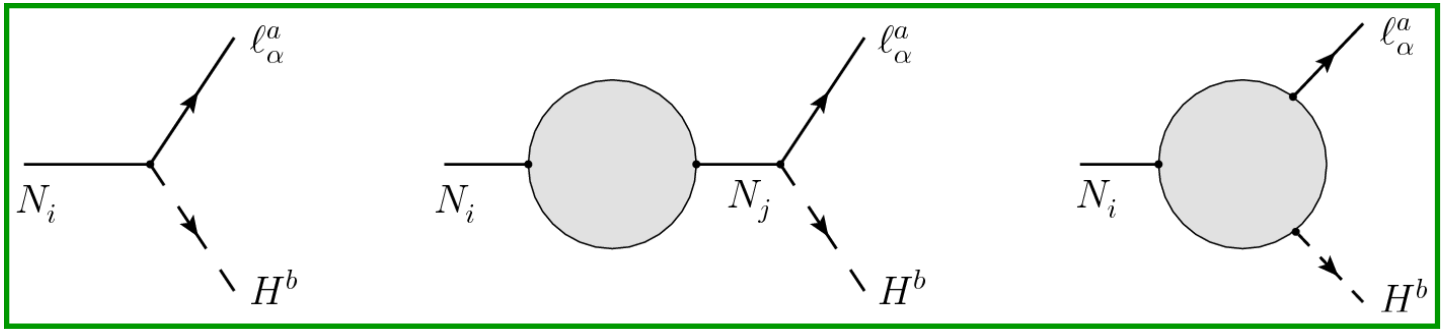
Thermal Leptogenesis

◆ 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:



$$\begin{aligned}\varepsilon_i &\equiv \frac{\sum\limits_\alpha \left[\Gamma(N_i \to \ell_\alpha + H) - \Gamma(N_i \to \overline{\ell}_\alpha + \overline{H})\right]}{\sum\limits_\alpha \left[\Gamma(N_i \to \ell_\alpha + H) + \Gamma(N_i \to \overline{\ell}_\alpha + \overline{H})\right]} \\ &\approx \frac{1}{8\pi (Y^\dagger_\nu Y_\nu)_{ii}} \sum_j {\rm Im}\left[(Y^\dagger_\nu Y_\nu)_{ij}\right]^2 \left[f_{\rm V}\left(\frac{M^2_j}{M^2_i}\right) + f_{\rm S}\left(\frac{M^2_j}{M^2_i}\right)\right]\end{aligned}$$

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

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

Thermal Leptogenesis

◆ 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.

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

The **net** lepton number asymmetry:

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

κ_i : efficiency factors

g_* : number of relativistic d.o.f

s : entropy density

(Boltzmann equations for time evolution of particle number densities)

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

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

at the quantum level via triangle anomaly.

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

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

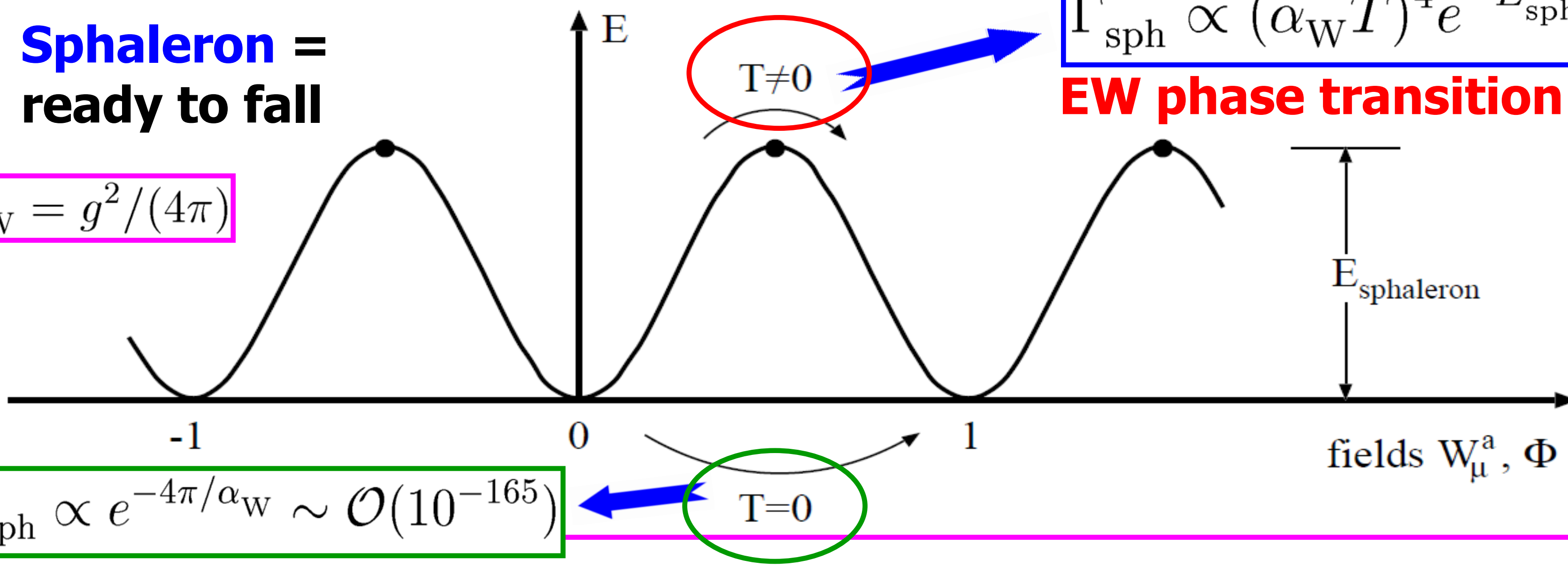
Chern-Simons (CS) numbers = ±1, ±2, ...

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

Thermal Leptogenesis

Sphaleron =
ready to fall

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



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

EW phase transition

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

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

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

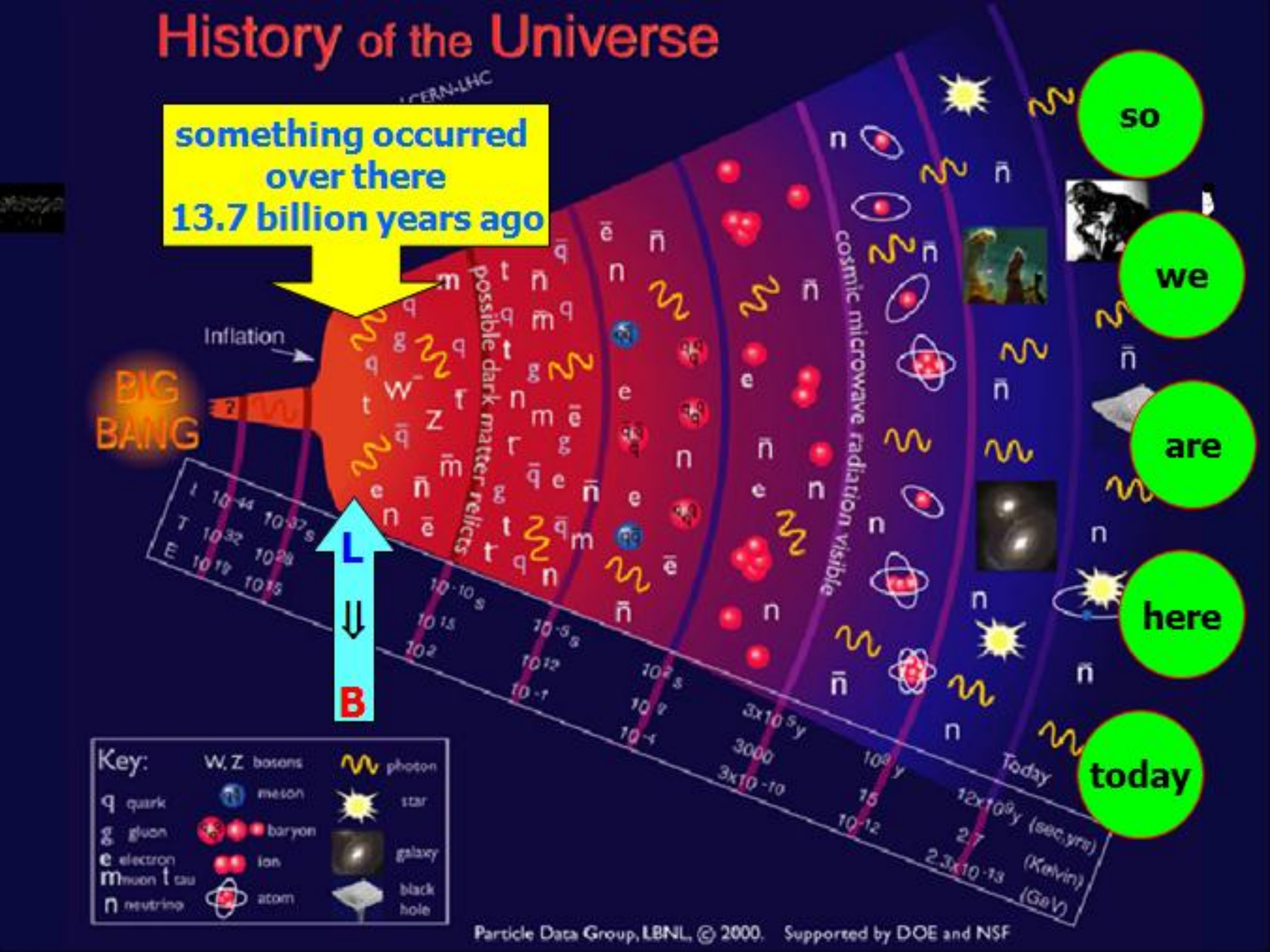
Baryogenesis via leptogenesis is realized:

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

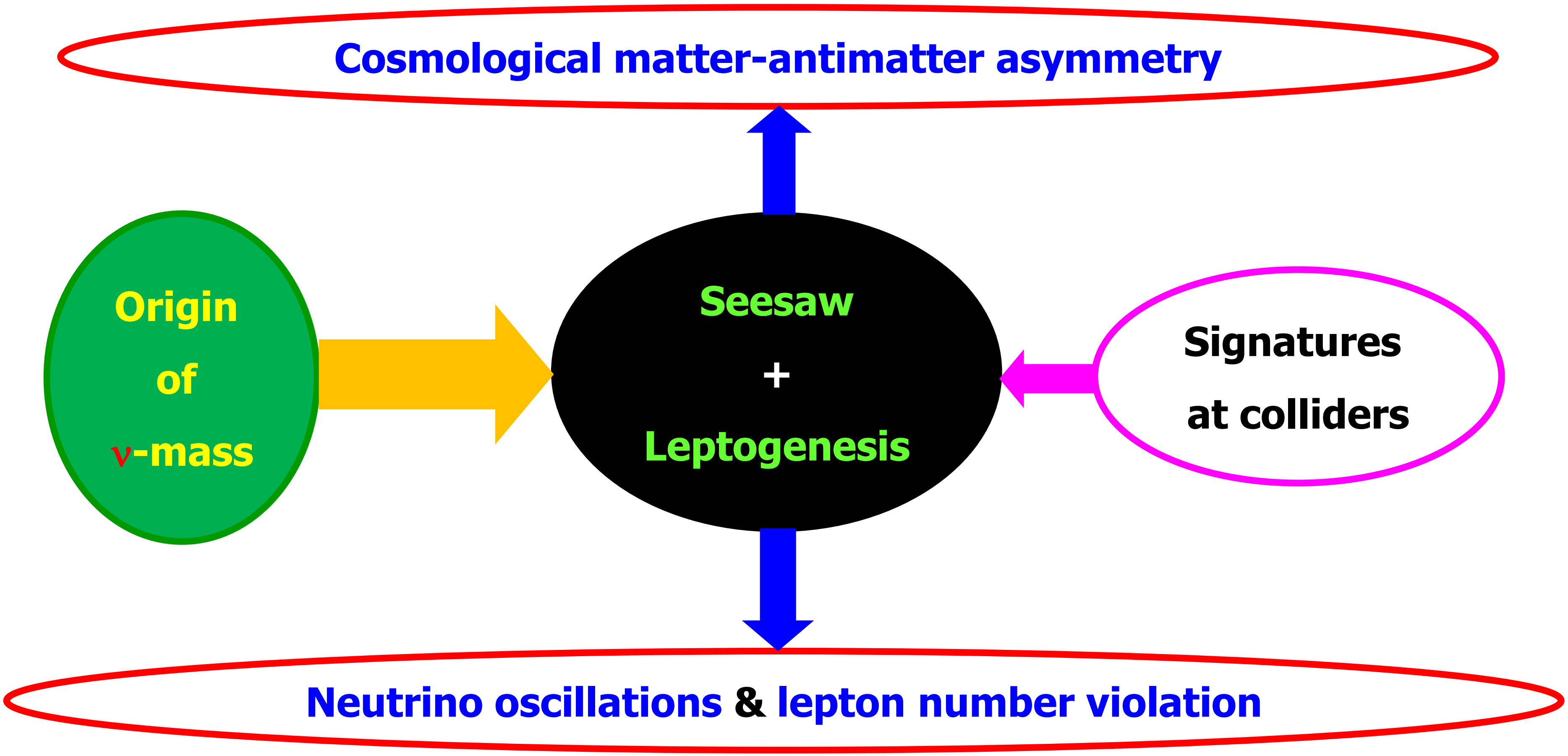
$$\left.\frac{n_{\mathrm{B}}}{s}\right|_{\mathrm{equilibrium}} = C \left.\frac{n_{\mathrm{B}} - n_{\mathrm{L}}}{s}\right|_{\mathrm{equilibrium}} = -C \left.\frac{n_{\mathrm{L}}}{s}\right|_{\mathrm{initial}}$$

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

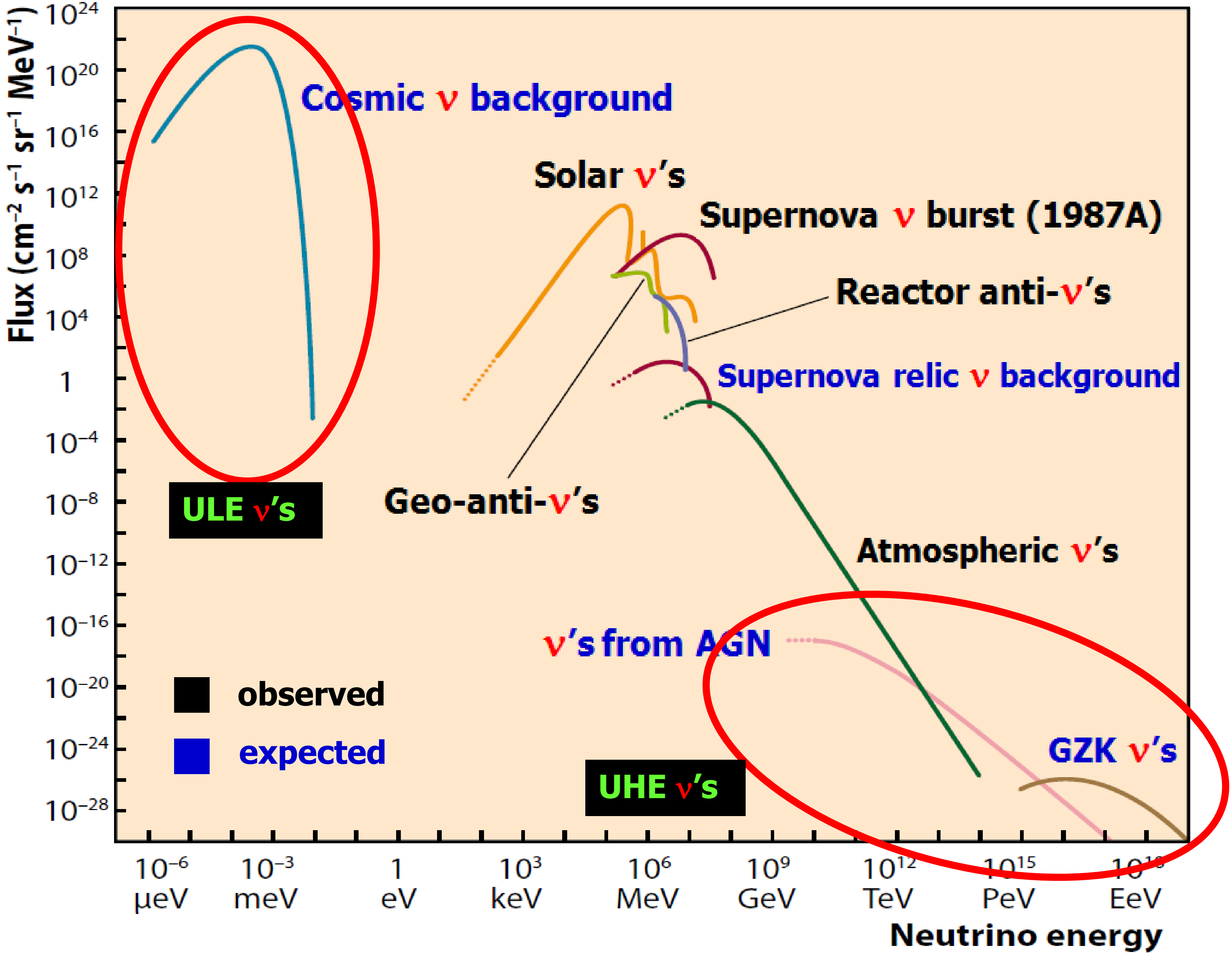
$$\begin{aligned} C &= \frac{8N_f + 4N_\Phi}{22N_f + 13N_\Phi} \\ &= \begin{cases} 28/79 & (\mathrm{SM}) \\ 8/23 & (\mathrm{MSSM}) \end{cases} \end{aligned}$$


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

A Grand Picture?



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


Flux (cm^{-2} s^{-1} sr^{-1} MeV^{-1})
10^{24}
10^{20}
10^{16}
10^{12}
10^{8}
10^{4}
1
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-24}
10^{-28}
Cosmic ν background
Solar ν's
Supernova ν burst (1987A)
Reactor anti-ν's
Supernova relic ν background
Geo-anti-ν's
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
10^{18} EeV
Neutrino energy

Formation of CνB

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

Electroweak reactions:

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

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

Neutrinos decoupled from matter:

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

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

Number density of 6 relic ν's:

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

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

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

arrow of time

neutrino and photon temperatures (blue)

neutrino decoupling

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

$$T_\nu = T_\gamma$$

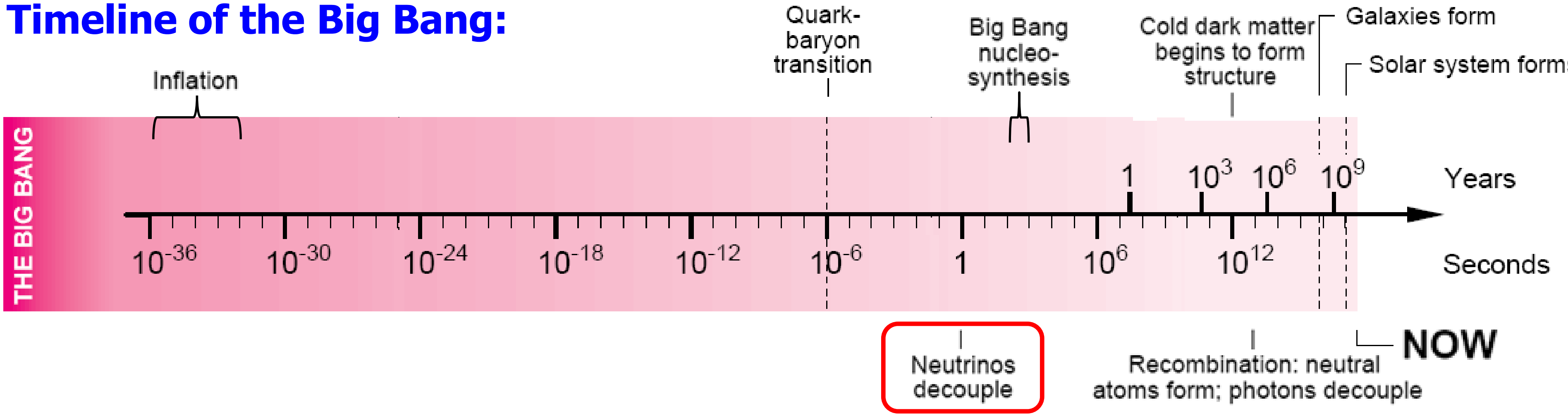
$$T_{\rm fr} \sim \left(\frac{\sqrt{g_*}}{G_F^2 M_{\rm Pl}}\right)^{1/3} \sim 1\ \text{MeV}$$

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

Witness / Participant

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

Timeline of the Big Bang:



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

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

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

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

Is CνB Detectable?

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

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

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

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

Detection of CνB

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

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

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

Temperature today

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

Mean momentum today

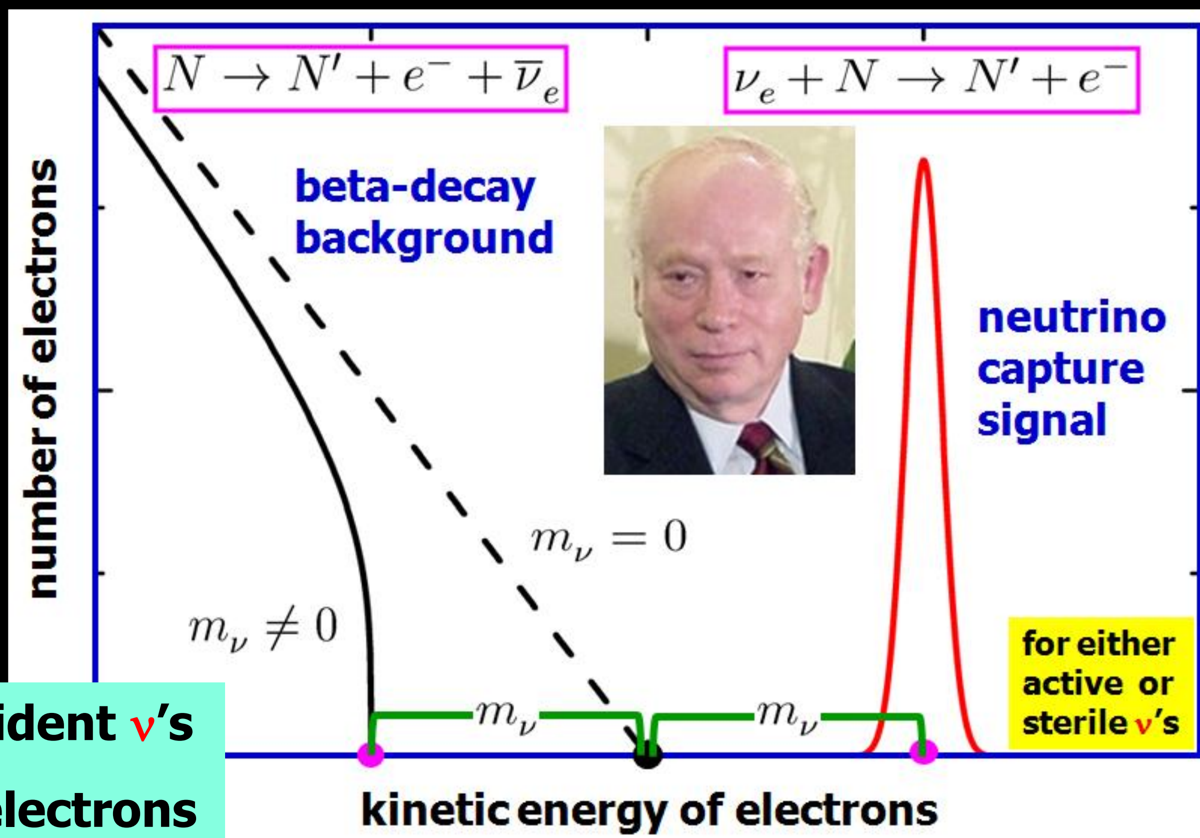
$$\langle p_\nu \rangle \simeq 3.151 T_\nu \simeq 5.281 \times 10^{-4} \text{ eV}$$

At least 2 ν's cold today

How to detect ULE ν's ?

(Irvine & Humphreys, 83)

Relic neutrino capture on β-decaying nuclei



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

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)

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

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

Energy resolution (Gaussian function) :

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

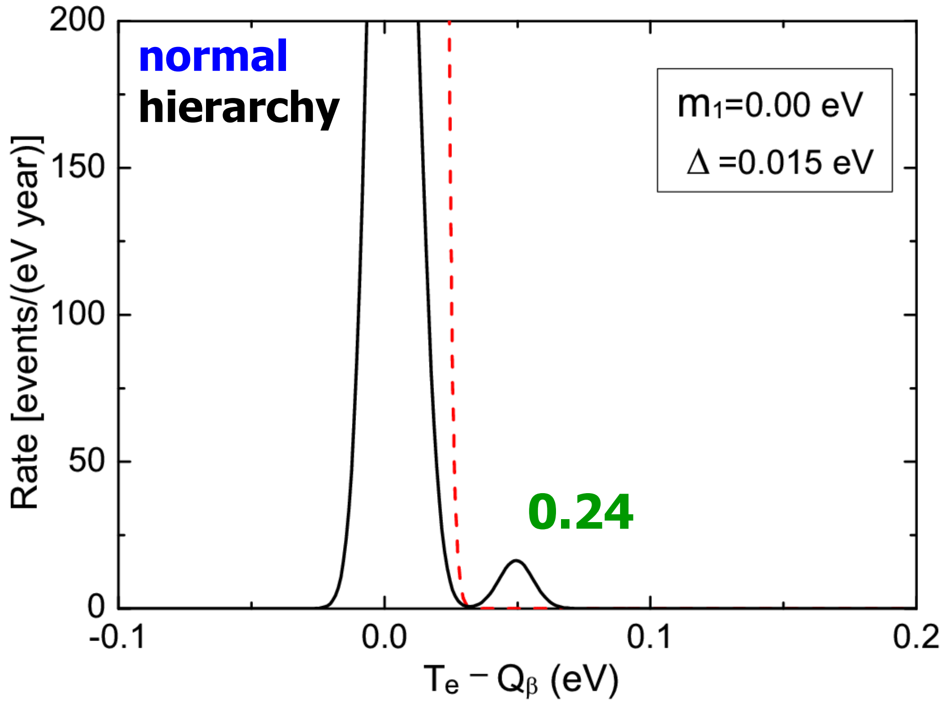
Illustration

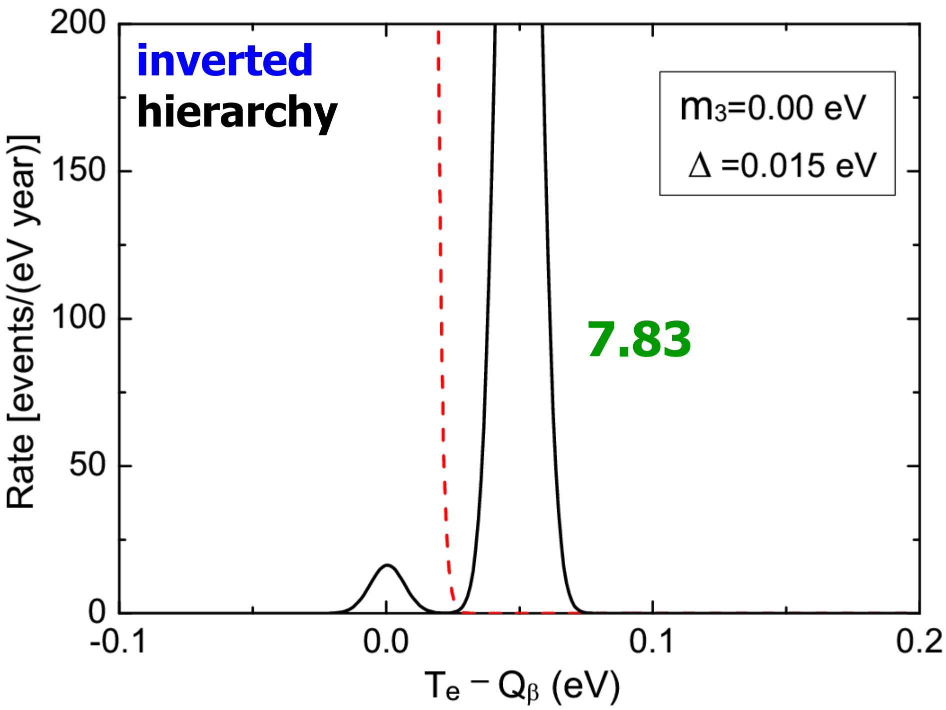
Target mass: 100 g tritium atoms

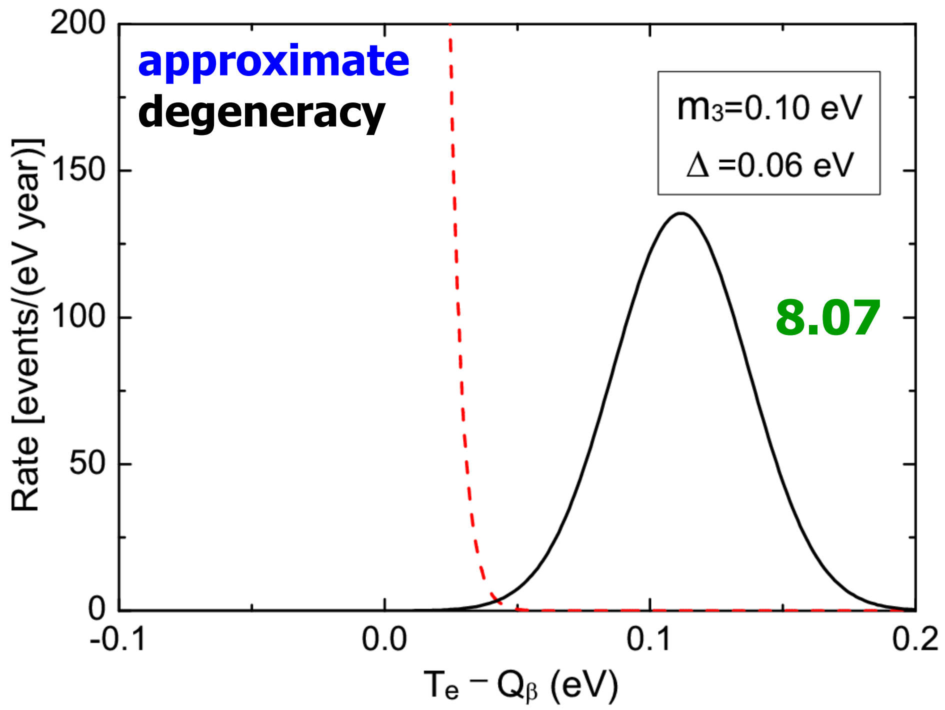
Input $\theta(13)$: 10 degrees

Number of events per year: ~ 8

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





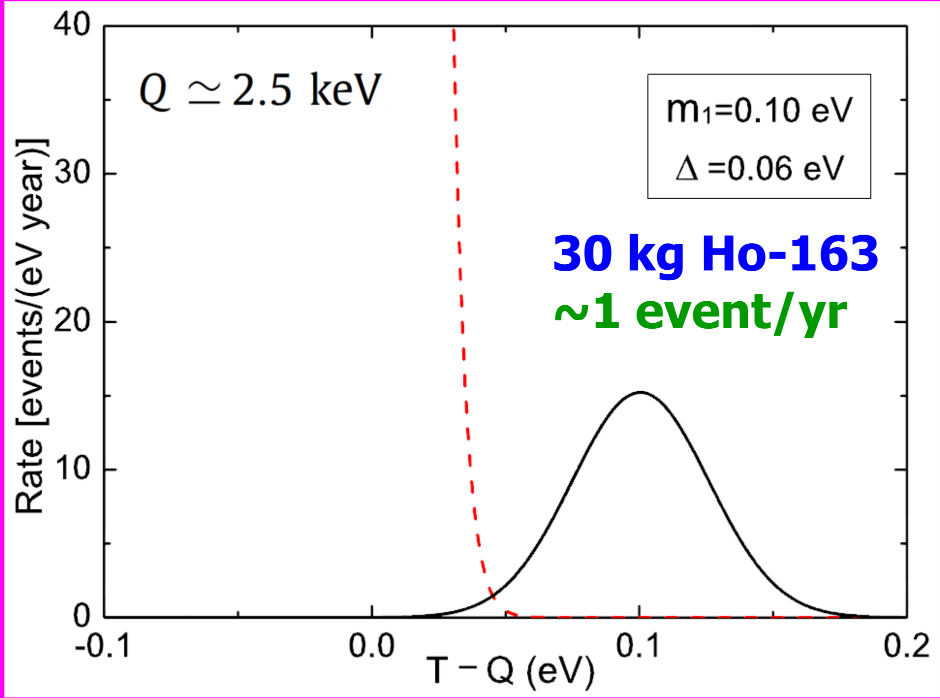


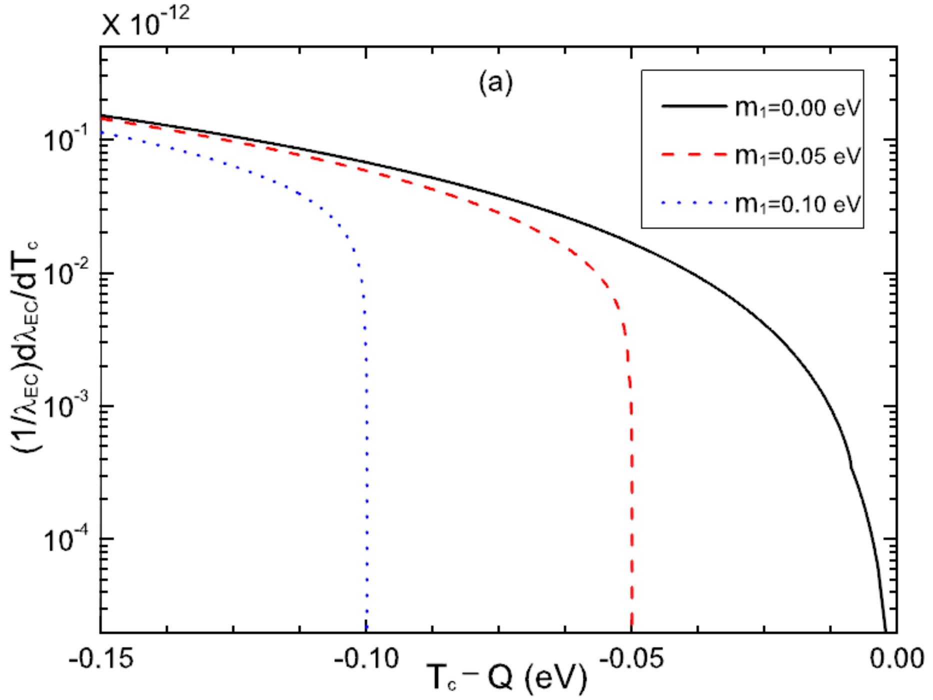
Cosmic anti-ν Background?

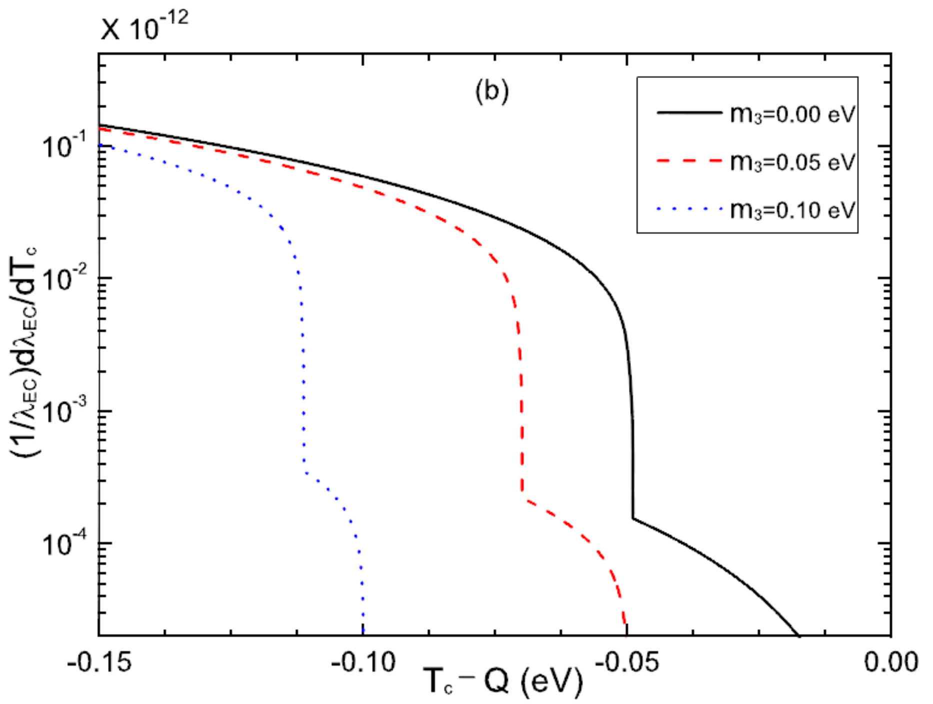
Relic antineutrino capture on EC-decaying Ho-163 nuclei.

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

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







A Naïve (Why Not) Picture

Hot dark matter: **CνB is guaranteed but not significant.**

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

Warm dark matter: **suppress the small-scale structures.**

If you think so,

Do not put all your eggs in one basket

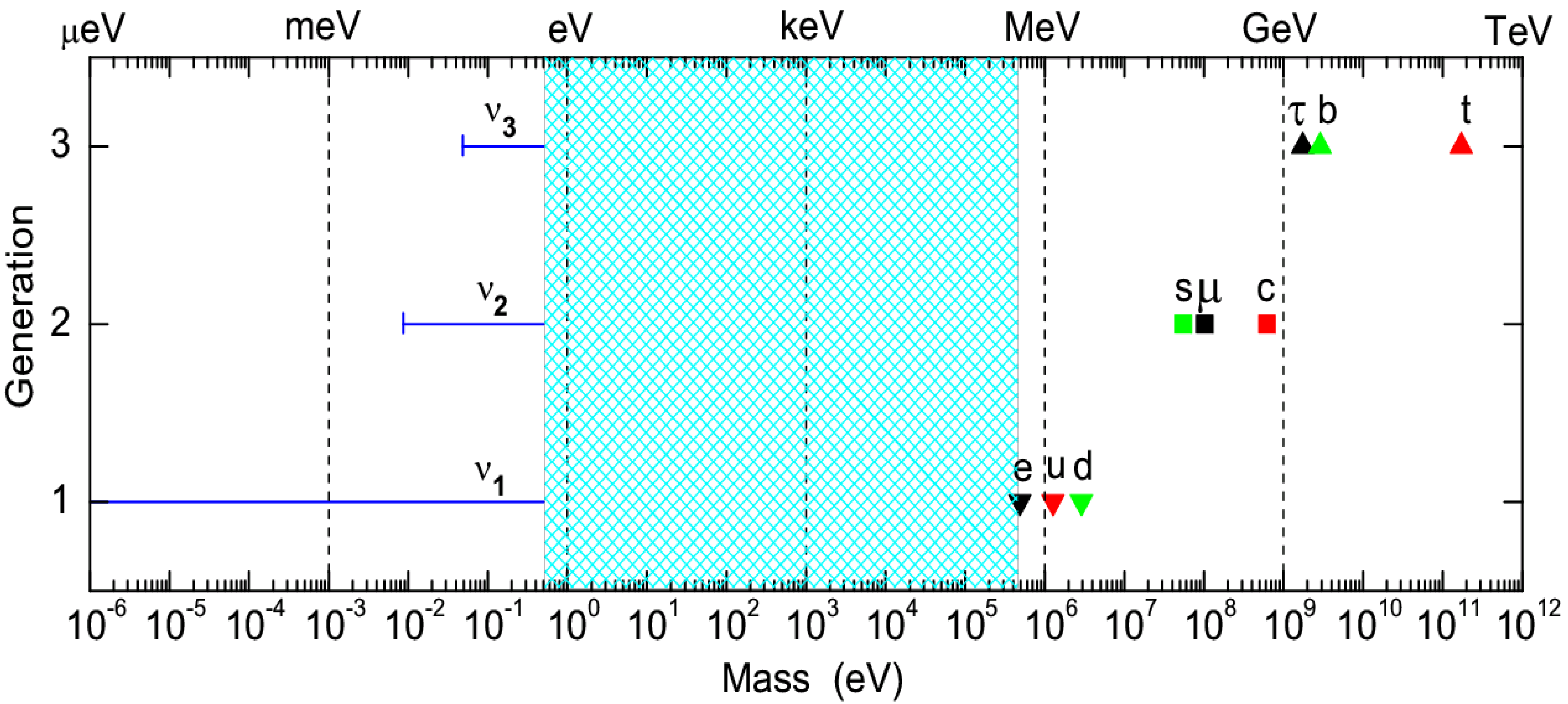
hot dark matter

warm dark matter

keV sterile ν Dark Matter

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

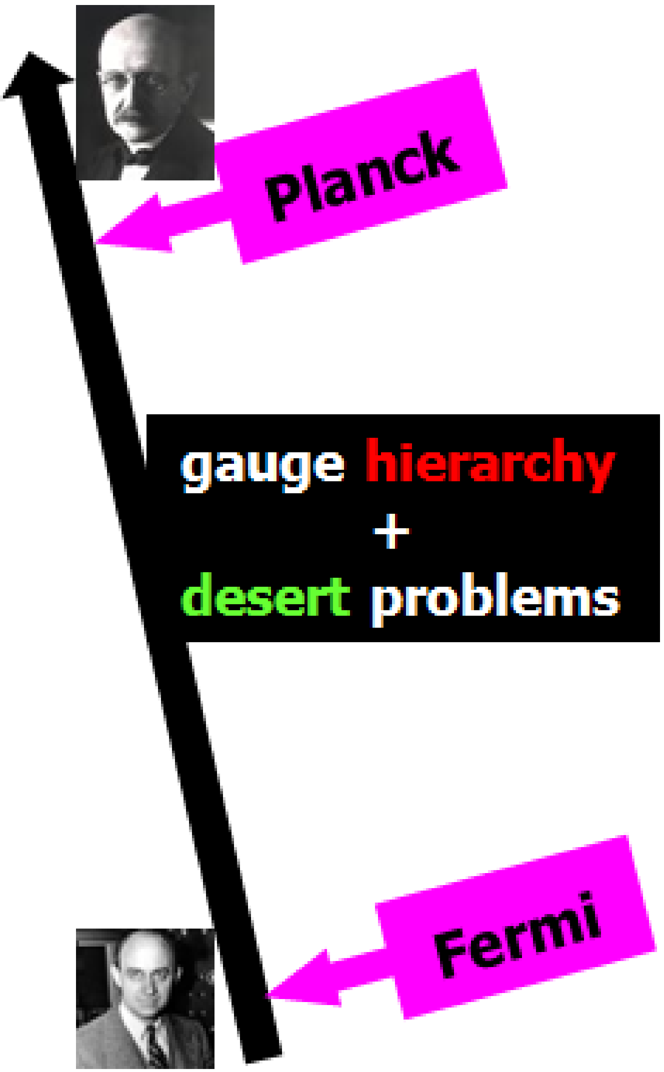
A purely phenomenological argument to support **keV** sterile ν's in the **FLAVOR DESERT** of the standard model (Xing, 09).

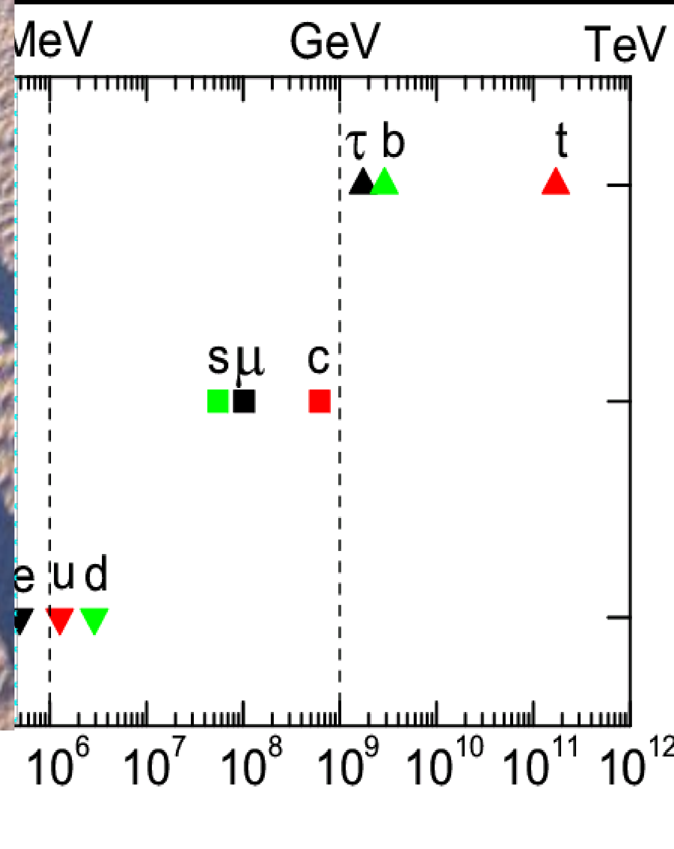


keV sterile ν Dark Matter

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

... ort **keV** sterile ν's in the

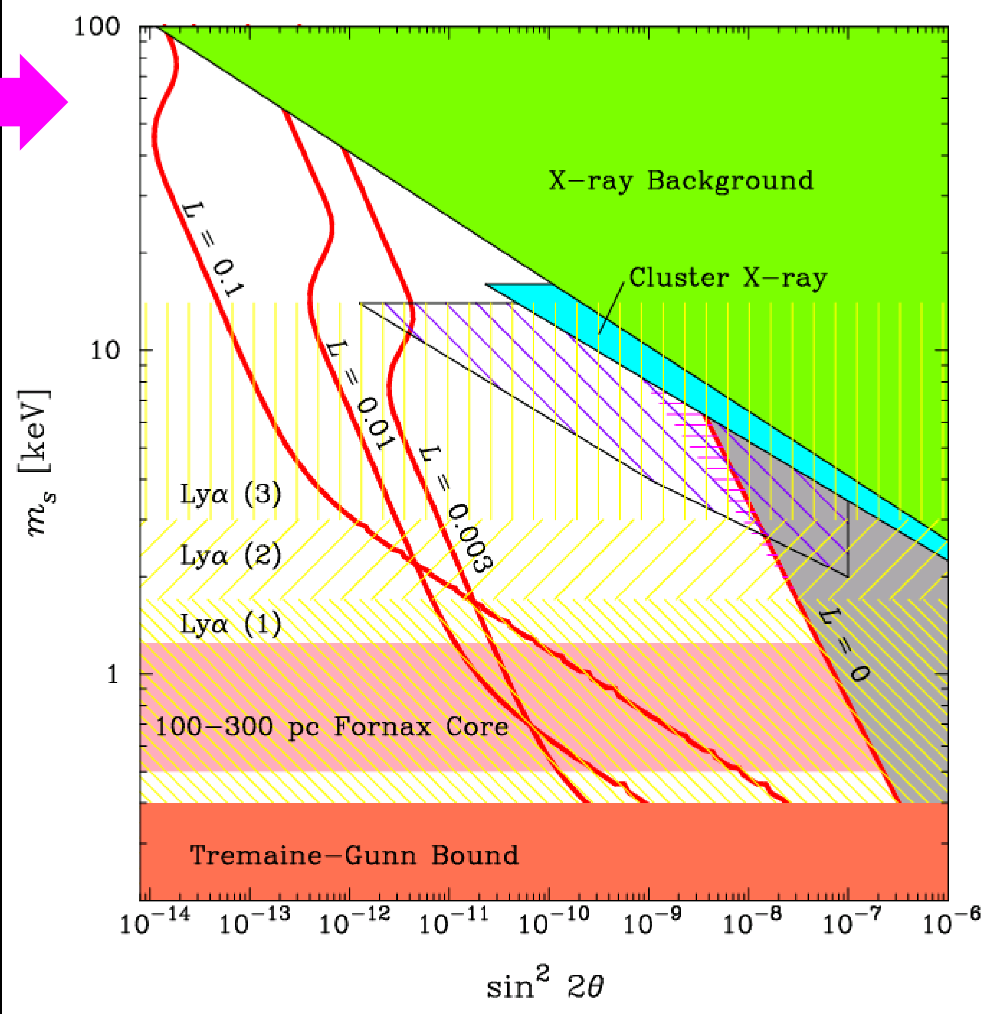




keV sterile ν Dark Matter

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

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



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

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

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

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

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

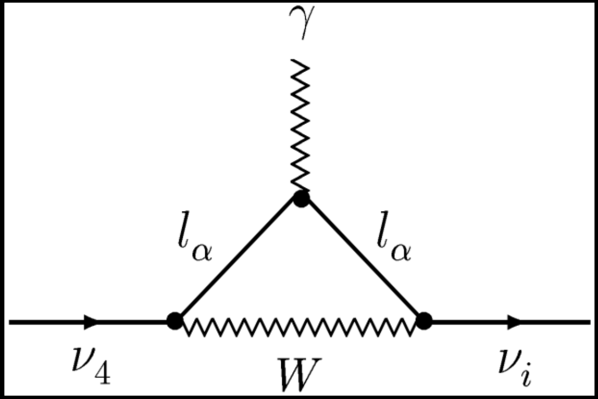
Decay Rates

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):

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

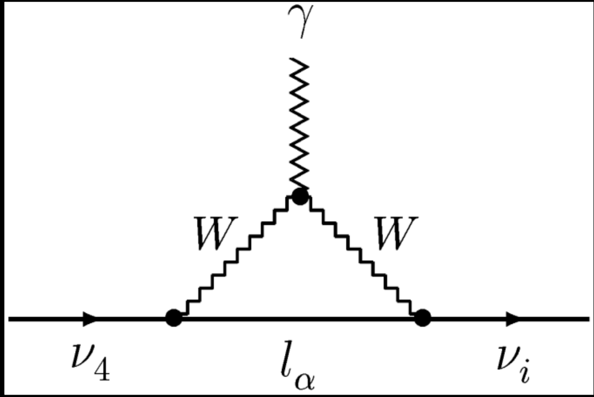


Radiative decay: X-ray and Lyman-alpha forest observations.

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

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

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



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.

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

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

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

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

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

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

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

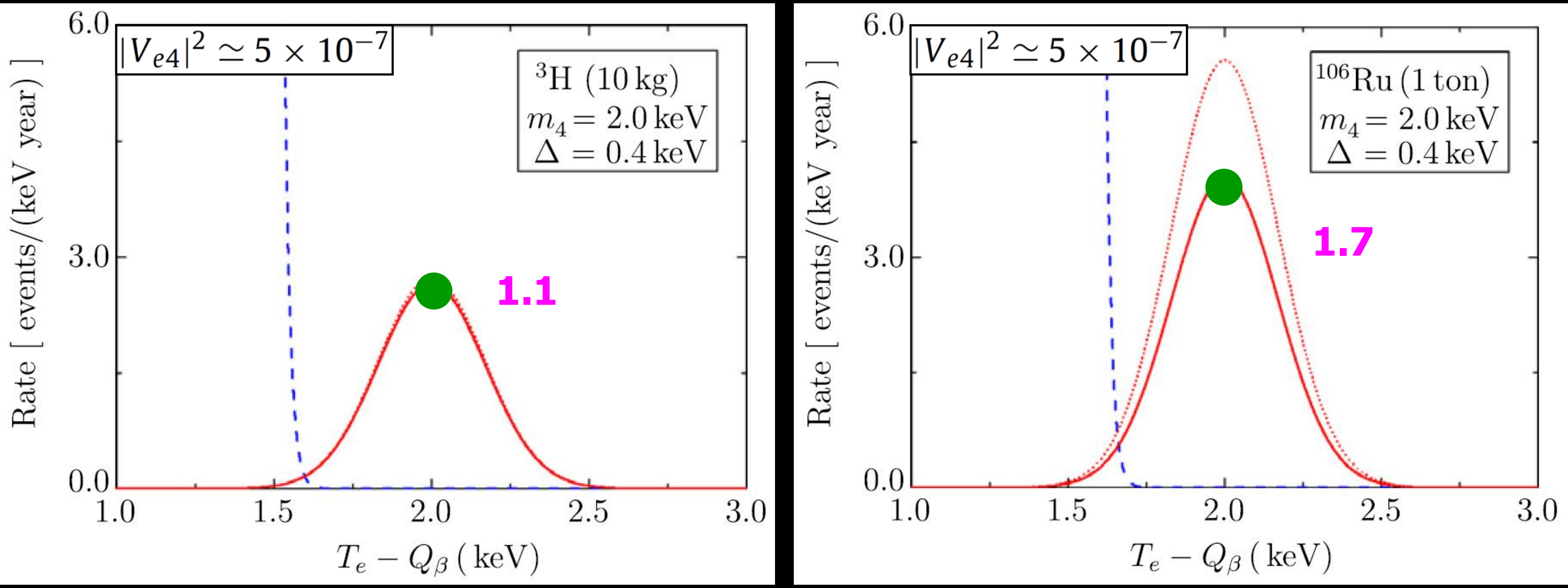
This method & the X-ray detection probe different parameter space.

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

Illustration

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

Number of events per year: pink

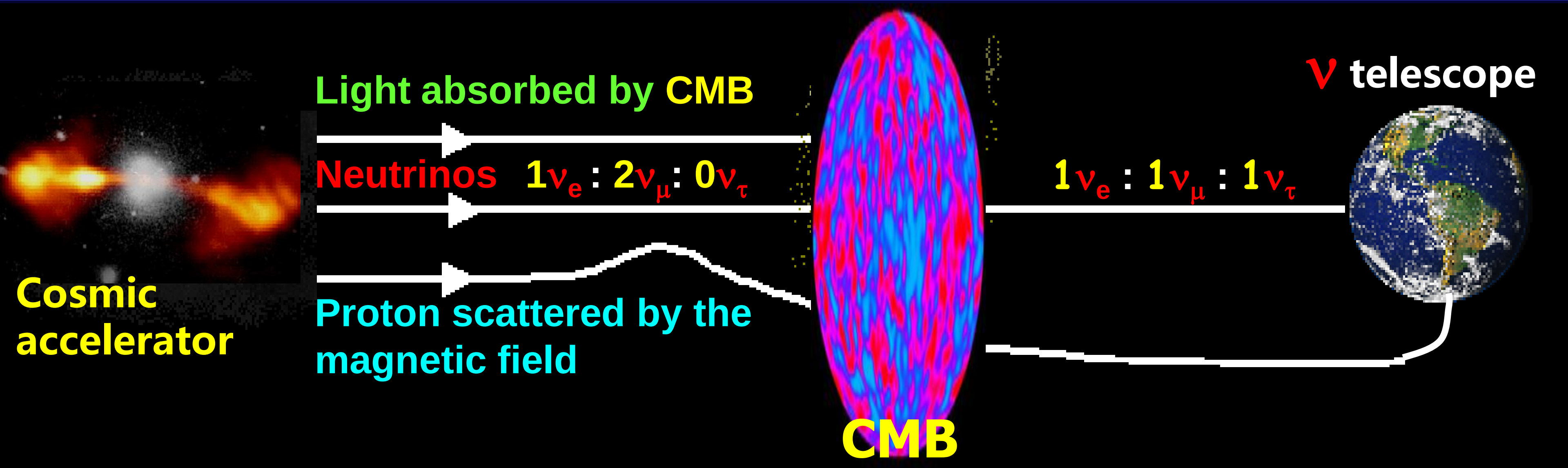


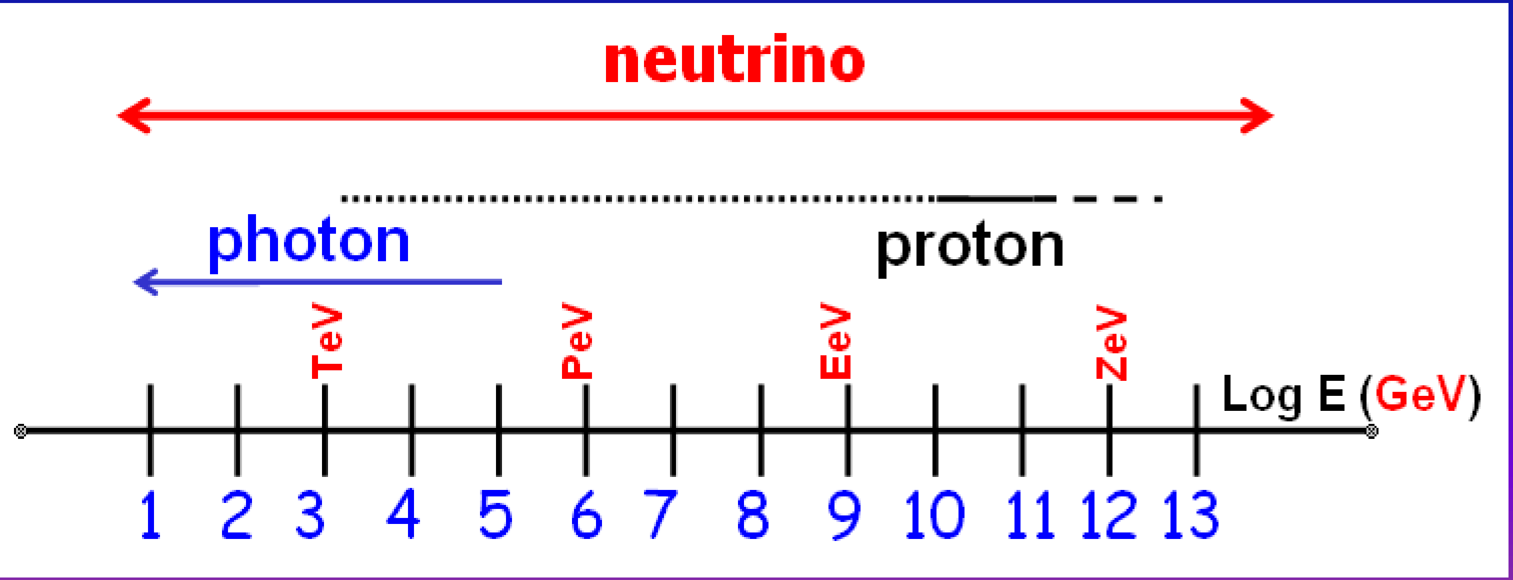
Dim and remote observability of keV sterile neutrino DM in this way:

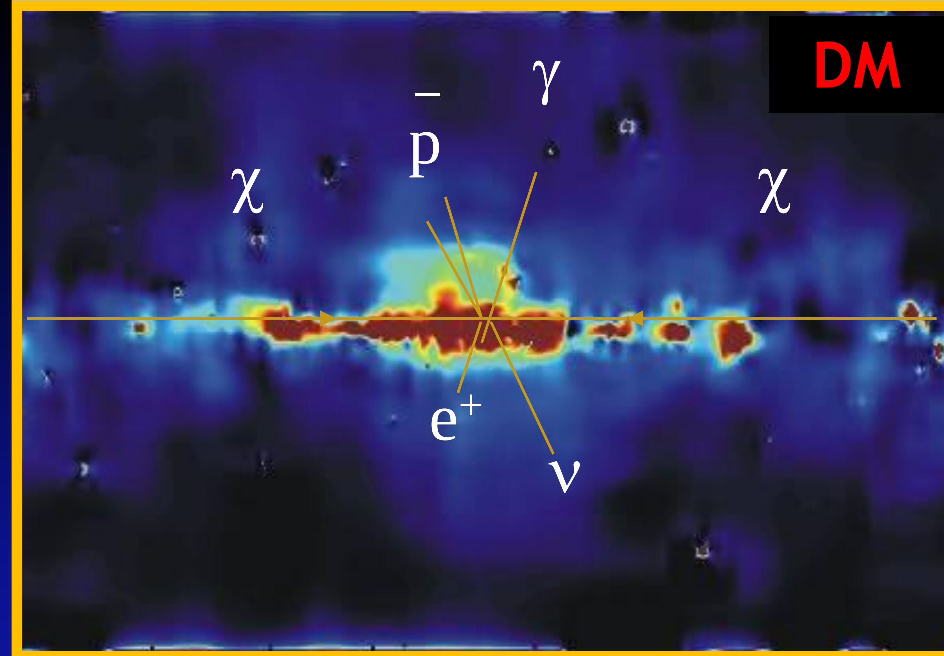
--- tiny active-sterile neutrino mixing angles (main problem)

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

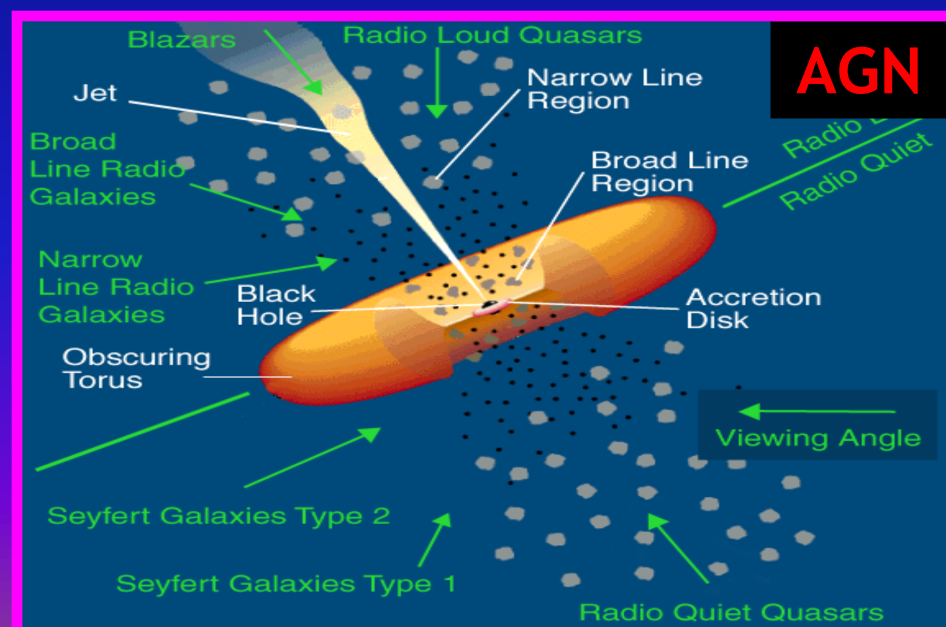
UHE Cosmic Messenger







Possible astrophysical sources of UHE cosmic neutrinos ...



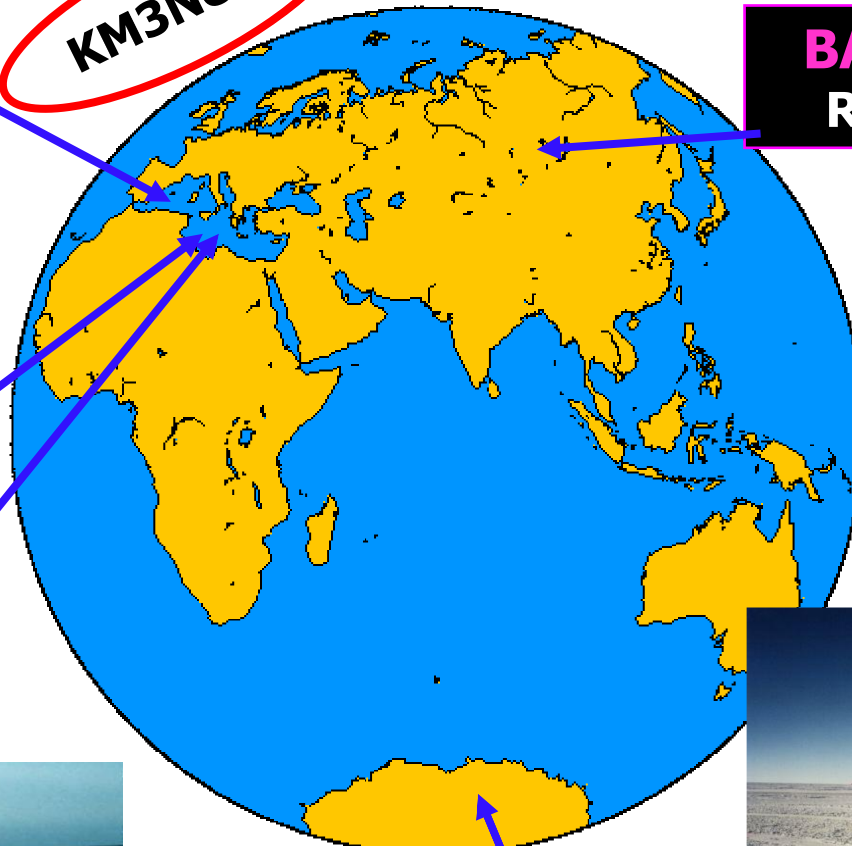
Optical Cherencov NTs

ANTARES
La-Seyne-sur-Mer, France

NEMO
Catania, Italy

NESTOR
Pylos, Greece

KM3NeT

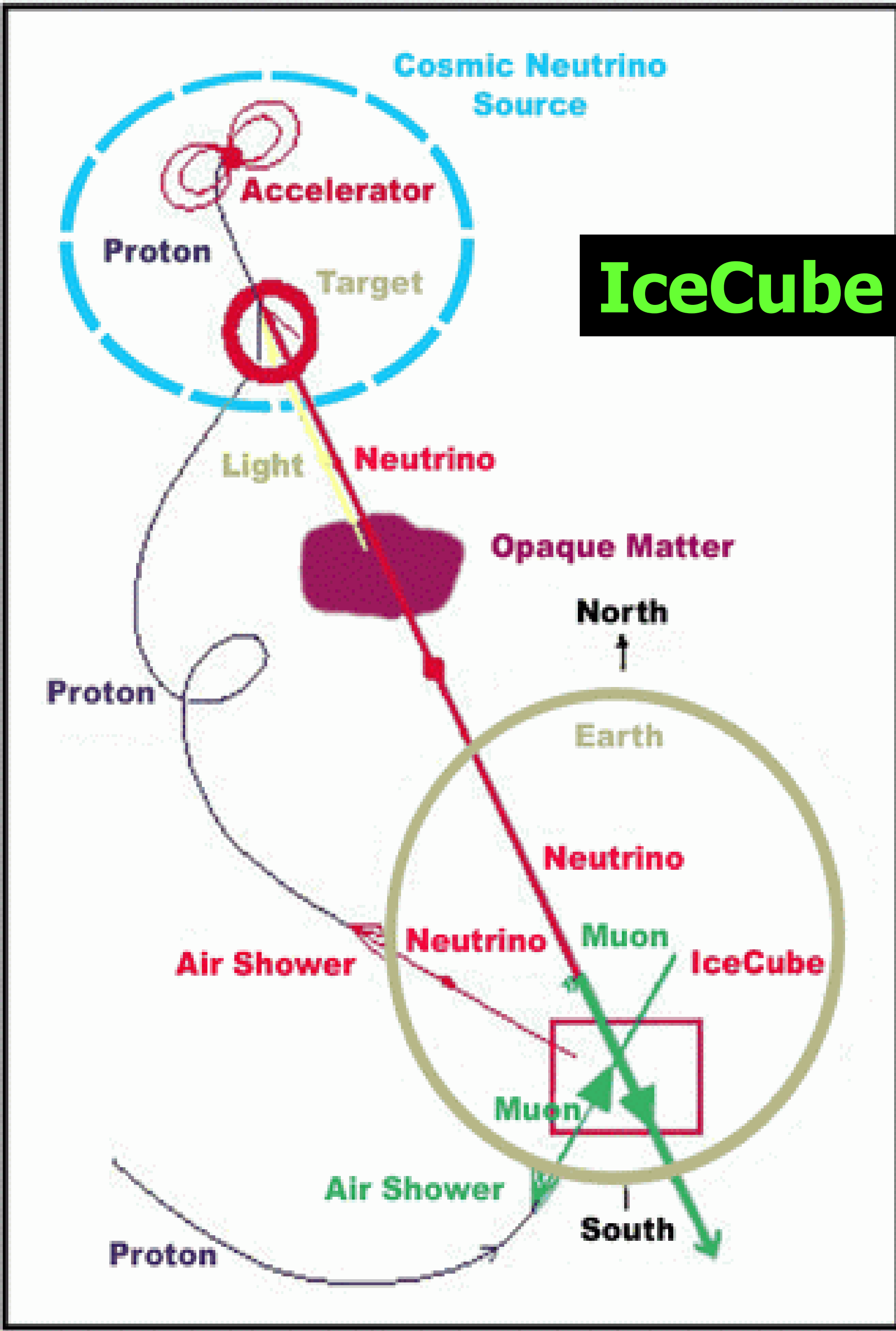


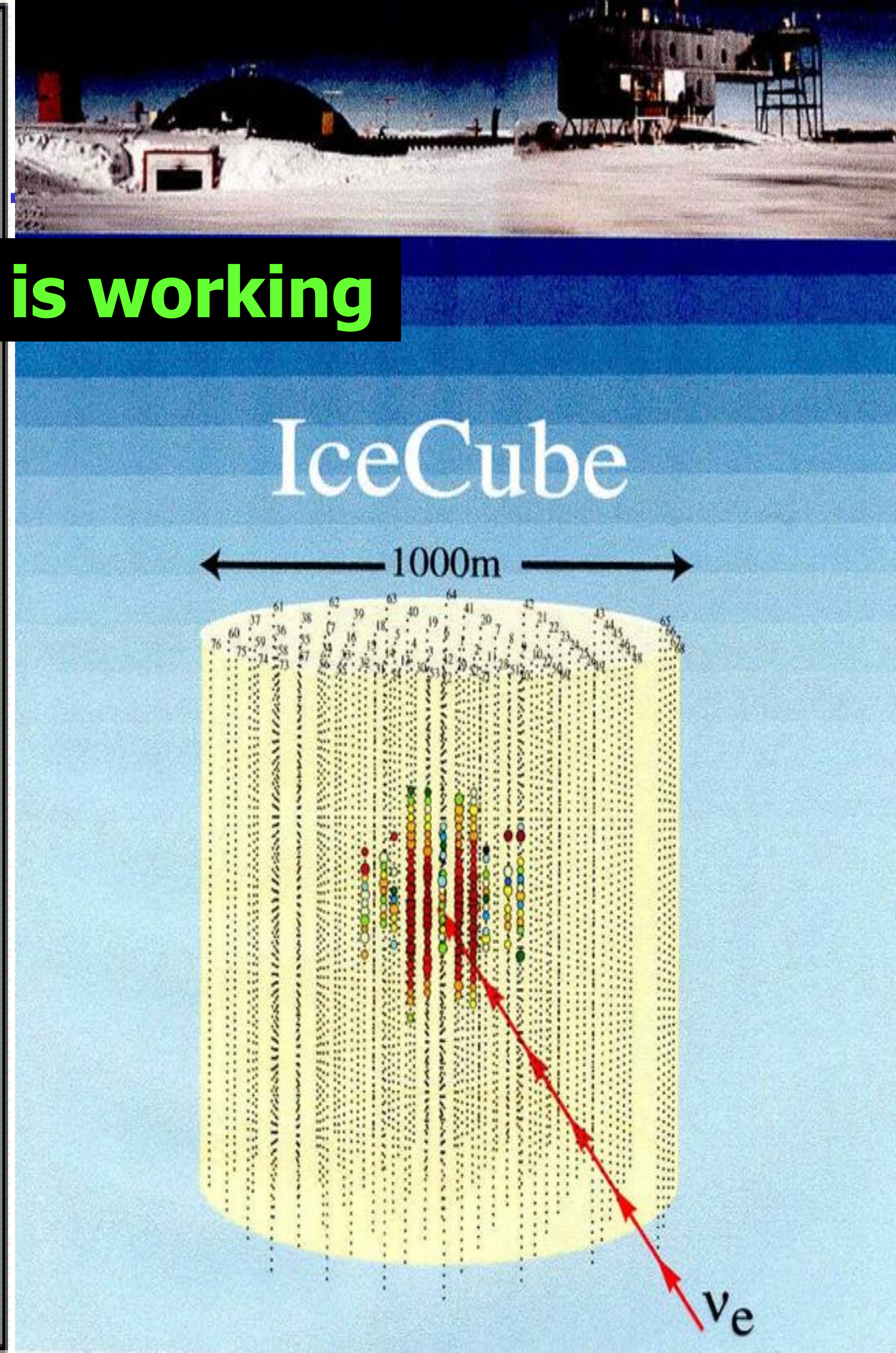
BAIKAL
Russia

AMANDA and IceCube

South Pole, Antarctica

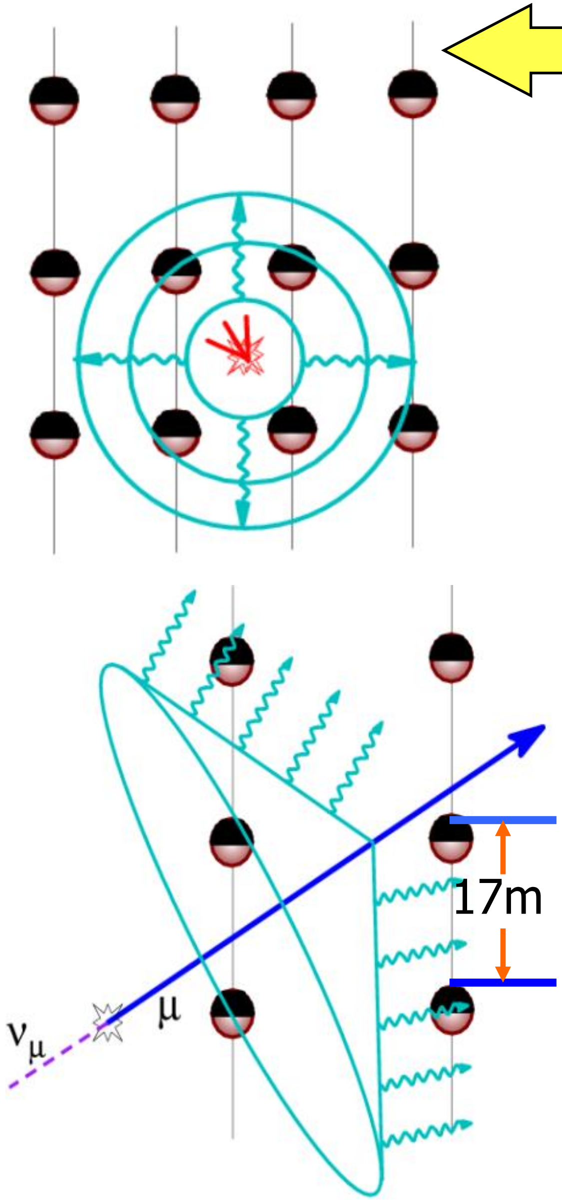
IceCube is working



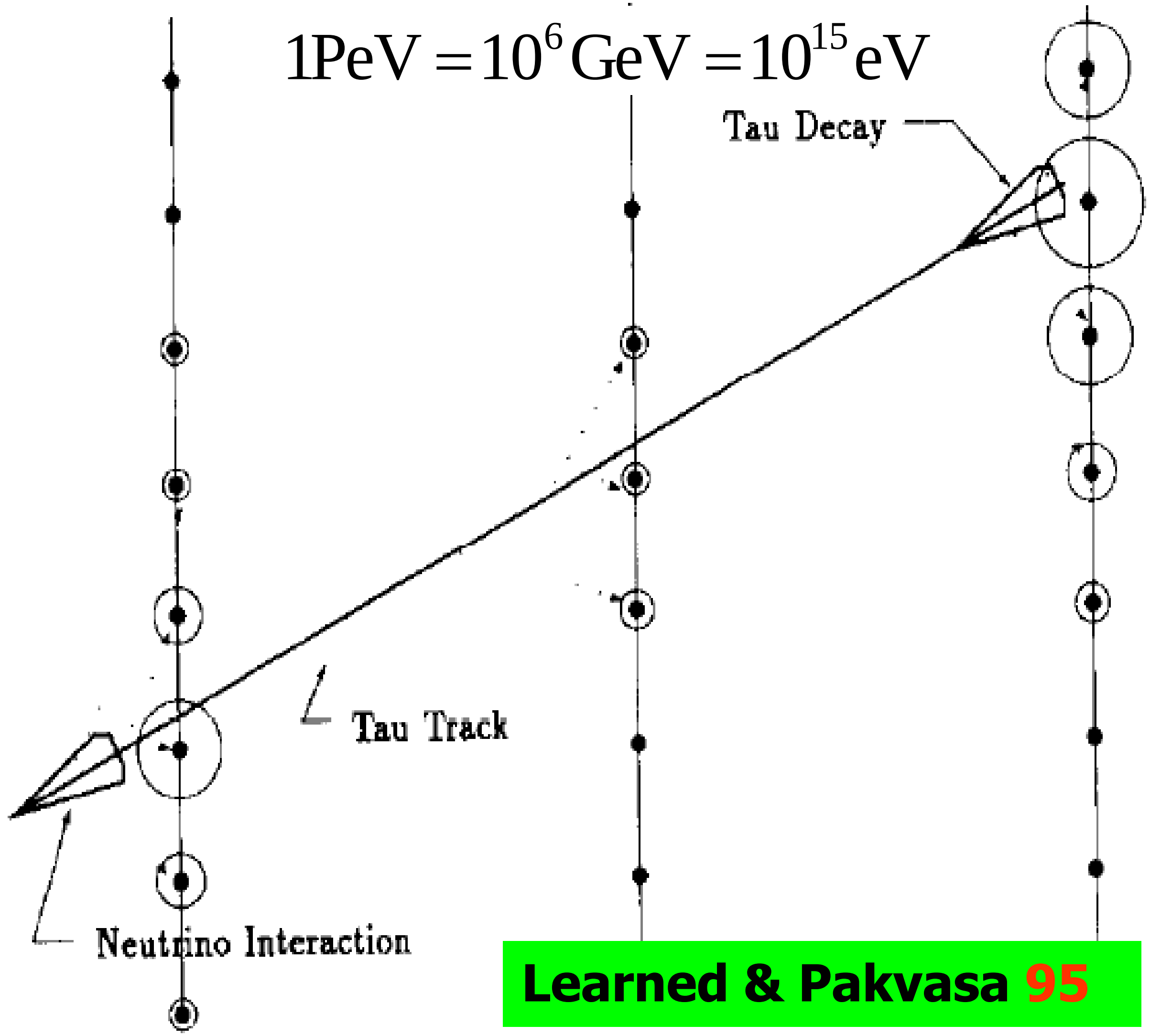


Flavor Identification

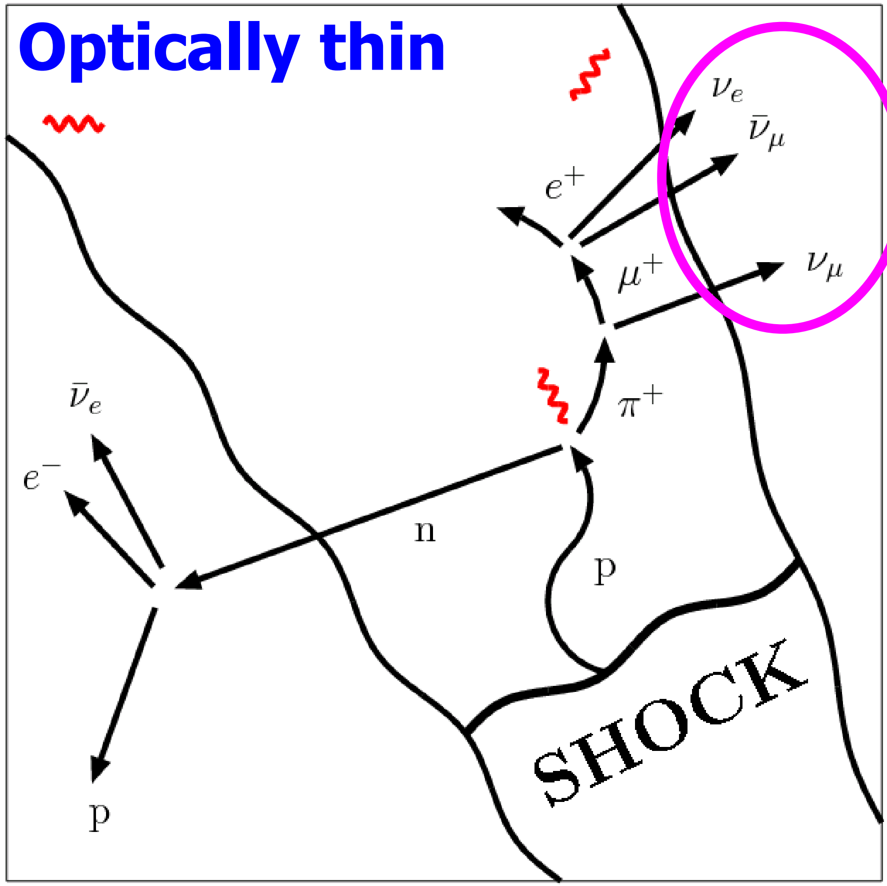
Halzen, astro-ph/0602132

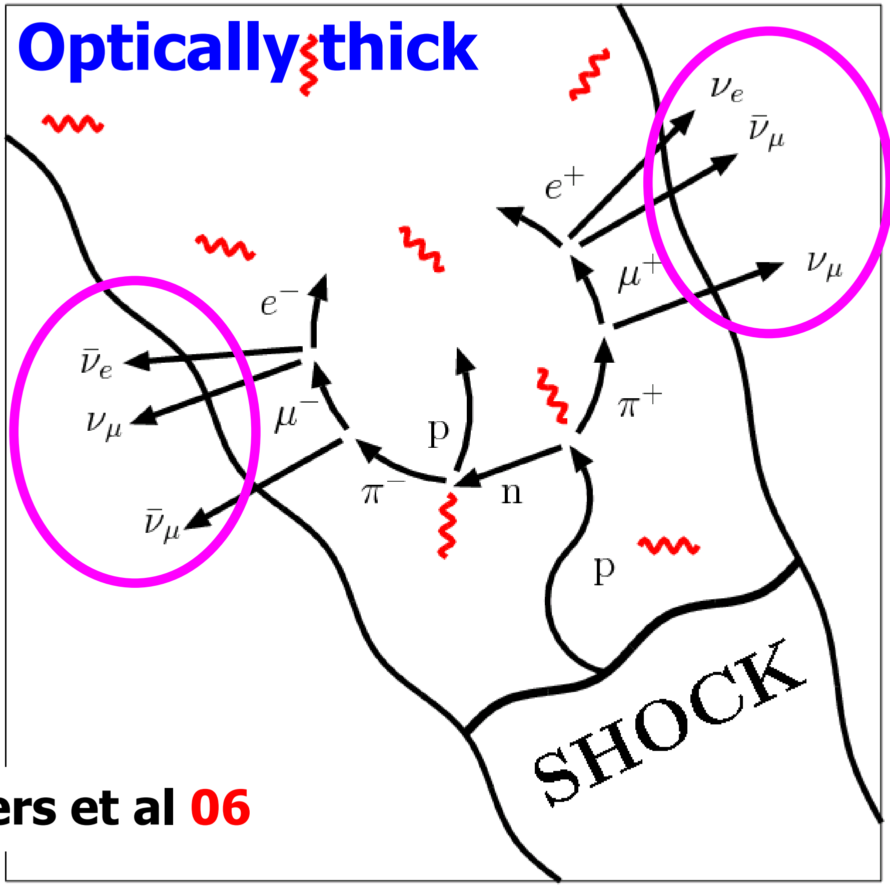


$$1\text{PeV} = 10^{6}\,\text{GeV} = 10^{15}\,\text{eV}$$



Learned & Pakvasa 95





Ahlers et al 06

Conventional mechanism:

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

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

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

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

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

Oscillations

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

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

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

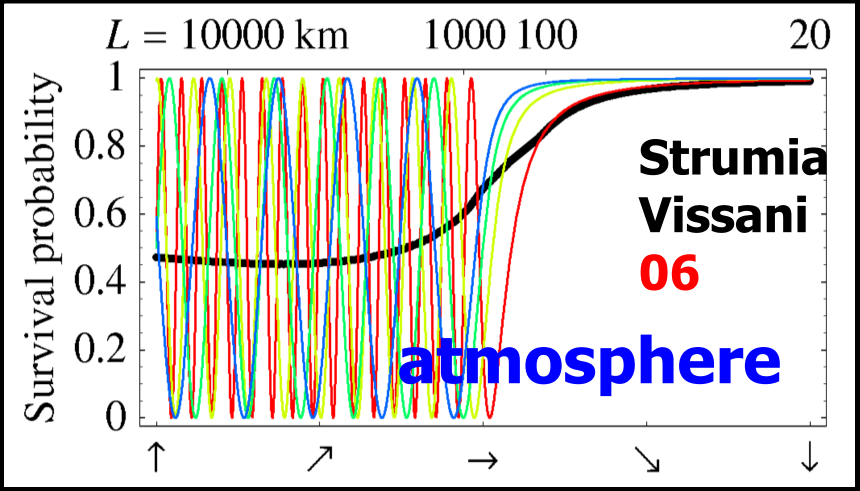
For $|\Delta m^2| \sim 10^{-4}\ \mathrm{eV}^2$ **, the oscillation length in vacuum:**

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

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

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

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



Flavor Democracy

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

At a ν-telescope:

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

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

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)

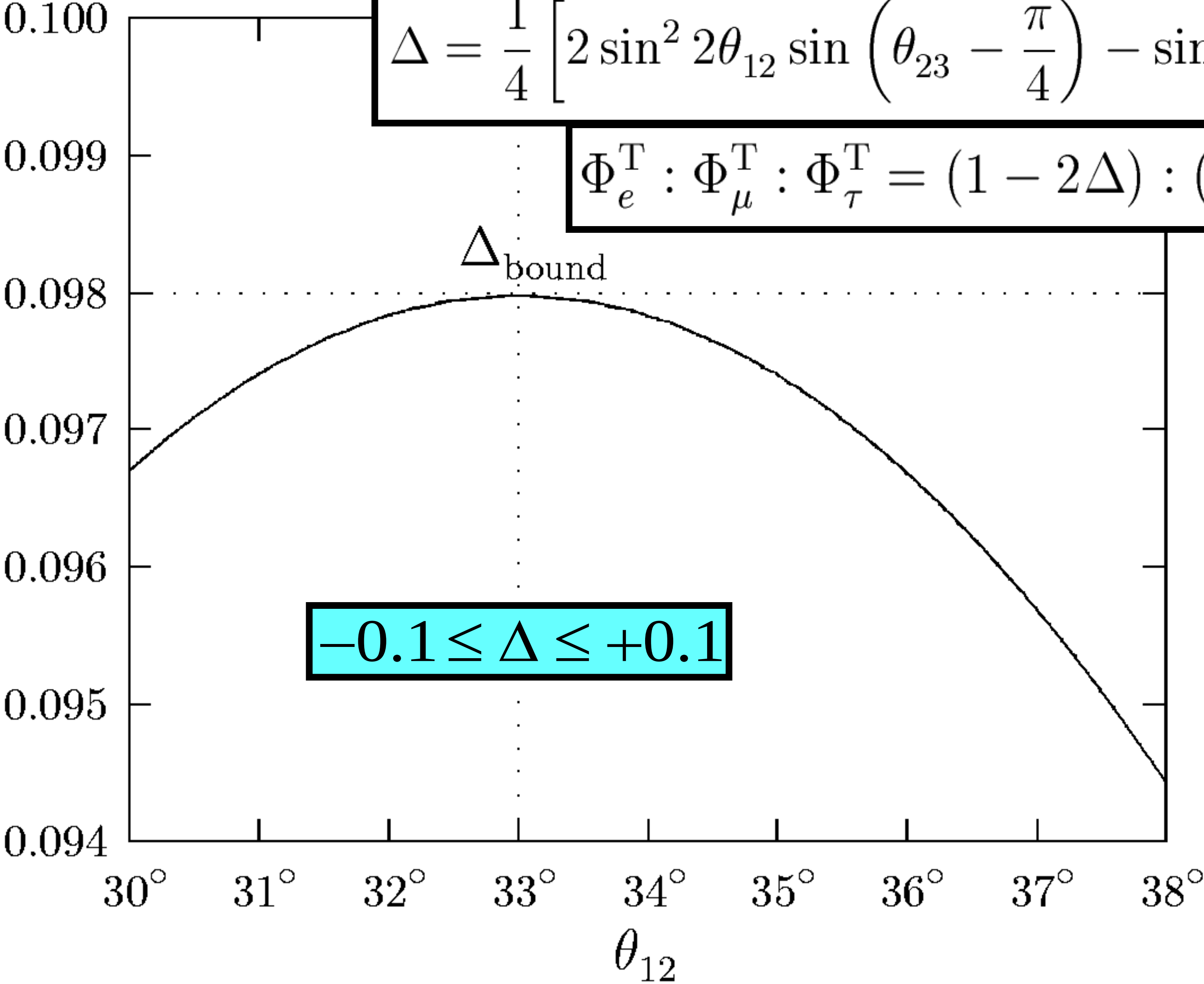
μ-τ symmetry breaking (Xing, 06, 12)

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

μ-τ Symmetry Breaking

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

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



A Question:

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

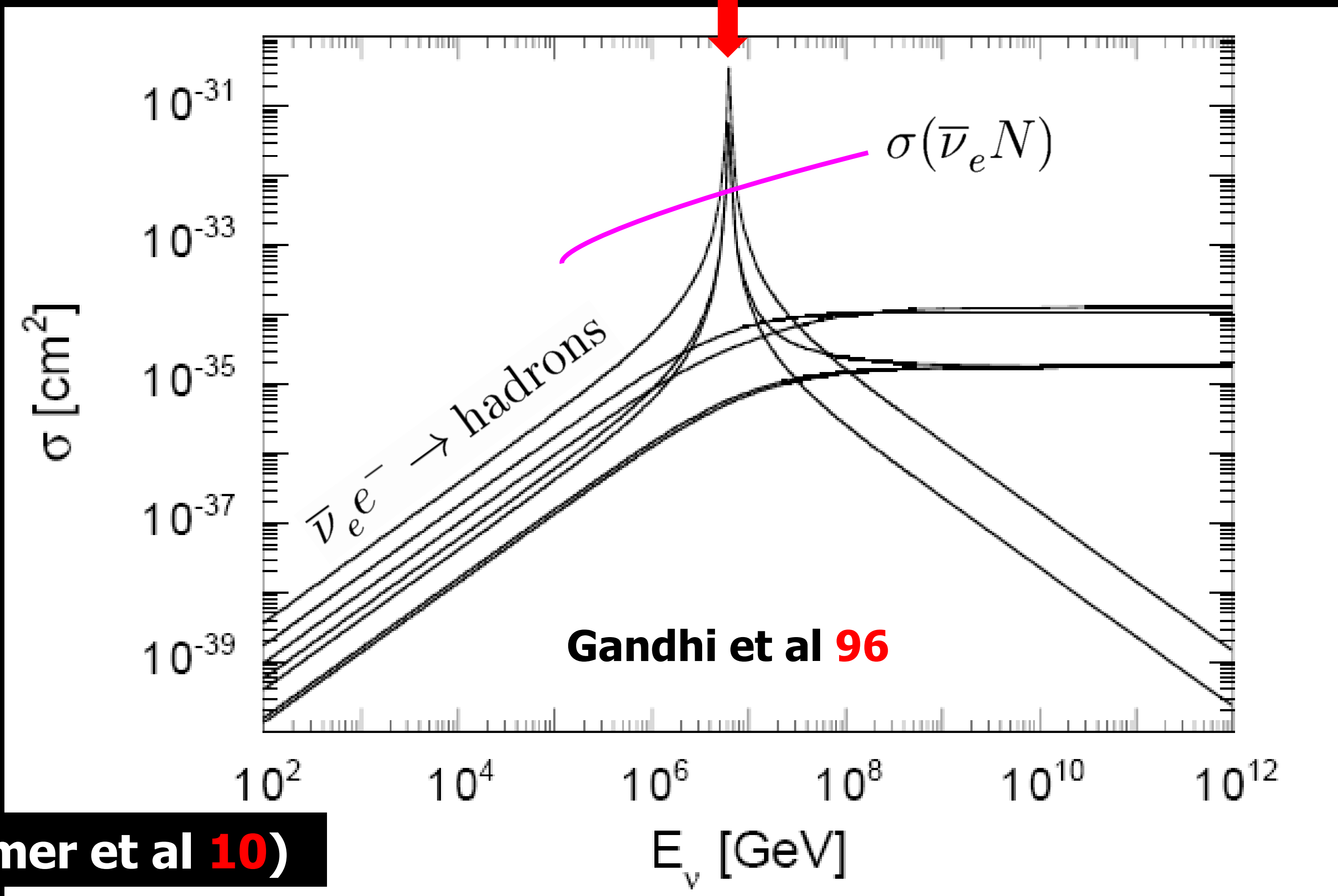
The Glashow Resonance

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

Unique for electron anti-ν's!

(Glashow 60)

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



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

Cosmic Flavor Physics

CνB
Hot DM

keV ν's
Warm DM

Baryogenesis
Leptogenesis

Energetic ν's
from cold DM

UHE
Cosmic ν's

Supernova ν's
(relic background)

......

A New Road Ahead?