Non-standard Physics probed by Neutrinos

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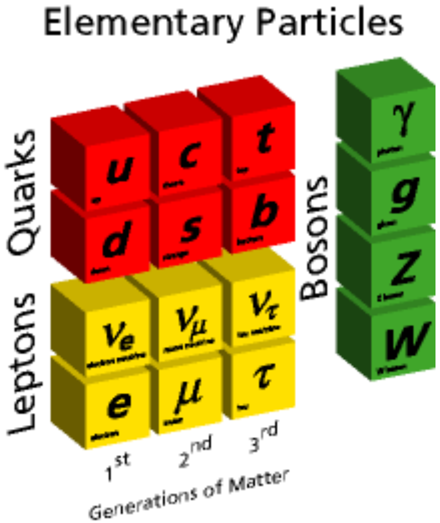
Physics Beyond the Standard Model

QED ➔QCD ➔SM
$U(1)_{em}$ $SU(3)_C$ $SU(3)_C \times SU(2)_L \times U(1)_Y$

Success story of d=4 renormalizable QFTs



TOE solving all problems does not (yet) exist ➔ solve some problems ➔ increasing levels of speculation:

1) new fields
2) extend gauge group
3) new concepts (SUSY, ...)
4) wild speculations

Theoretical reasons for BSM:

SM does not exist without cutoff (triviality)
Higgs-doublett = only simplest extension
Gauge hierarchy problem
Gauge unification, charge quantization
Strong CP problem
Unification with gravity
Why: 3 generations , which representations
Many parameters (9+? masses, 4+? mixings)

Experimental BSM facts:

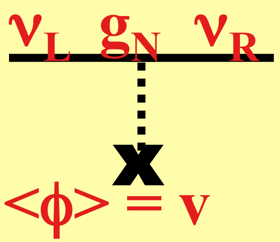
- Electro weak scale << Planck scale
- Gauge couplings almost unify
- Neutrinos have masses & large mixings
- Baryon asymetry of the Universe
- Dark Matter, Dark Energy, few $\geq 2\sigma$ hints?

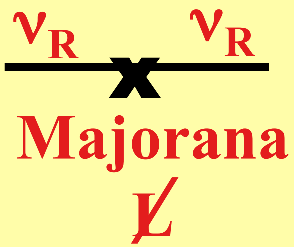
➔ **BSM from a neutrino perspective**

New Physics: Neutrino Mass Terms

1) **Simplest possibility: add 3 right handed neutrino fields**

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$L_Q = \begin{pmatrix} l_u \\ l_d \end{pmatrix}$	3	2	1/3
r_u	3	1	4/3
r_d	3	1	-2/3
$L_L = \begin{pmatrix} l_\nu \\ l_e \end{pmatrix}$	1	2	-1
r_ν ???	1	1	0
r_e	1	1	-2





$$\begin{pmatrix} \bar{\nu}_L & \bar{\nu}_R^c \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

like quarks and charged leptons ➔ Dirac mass terms (including NMS mixing)

New ingredients:
1) Majorana mass (explicit)
2) lepton number violation

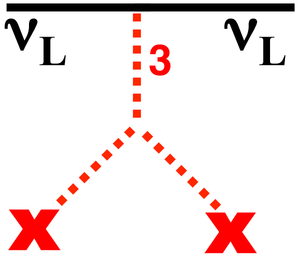
6x6 block mass matrix
block diagonalization
M_R heavy ➔ 3 light ν's

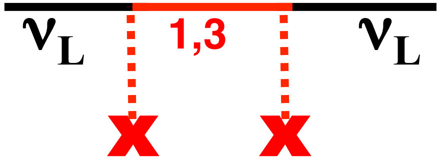
NEW ingredients, 9 parameters ➔ SM+

2) Maybe 3+N right handed neutrino fields

➔ (6+N) x (6+N) mass matrix
➔ how many of the 6+N eigenvalues are light (also for N=0)

3) new: scalar tripelts (3_L) or fermionic 1_L ro 3_L





➔left-handed Majorana mass term:

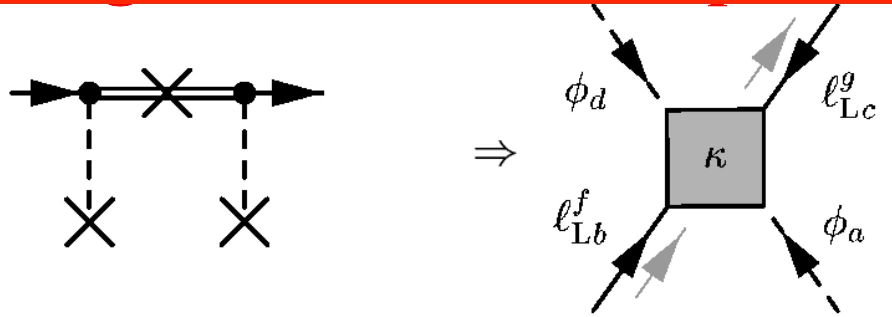
➔ $M_L \bar{L} L^c$

4) Both ν_R and new singlets / triplets:

➔ see-saw type II, III

$$m_\nu = M_L - m_D M_R^{-1} m_D^T$$

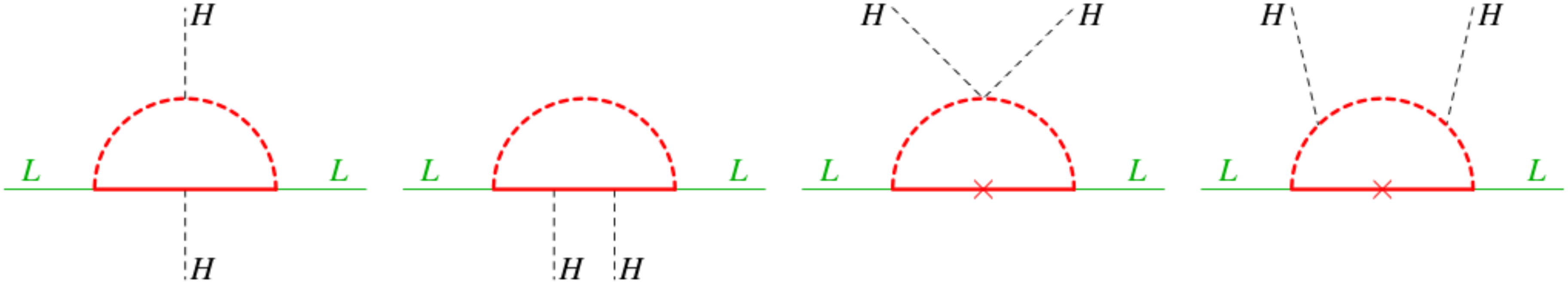
5) Higher dimensional operators: d=5, …



⇔ $\mathcal{L}_{mass} = \kappa \cdot \overline{\nu}^C_L \nu_L \Phi^T \Phi$

➔ $M_L \overline{L} L^c$

6) Radiative neutrino mass generation



7-N) SUSY, extra dimensions, …

Other effective Operators Beyond the SM

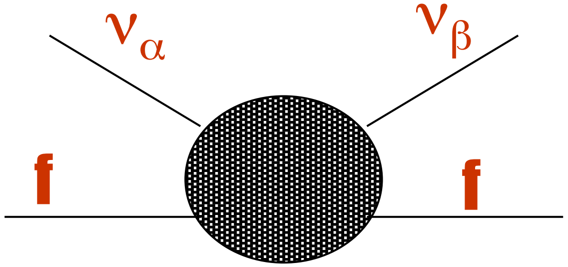
➔ **effects beyond 3 flavours**

➔ **Non Standard Interactions = NSIs ➔ effective 4f opersators**

$$\mathcal{L}_{NSI} \simeq \epsilon_{\alpha\beta} 2\sqrt{2} G_F (\bar{\nu}_{L\beta}\ \gamma^\rho\ \nu_{L\alpha})(\bar{f}_L \gamma_\rho f_L)$$

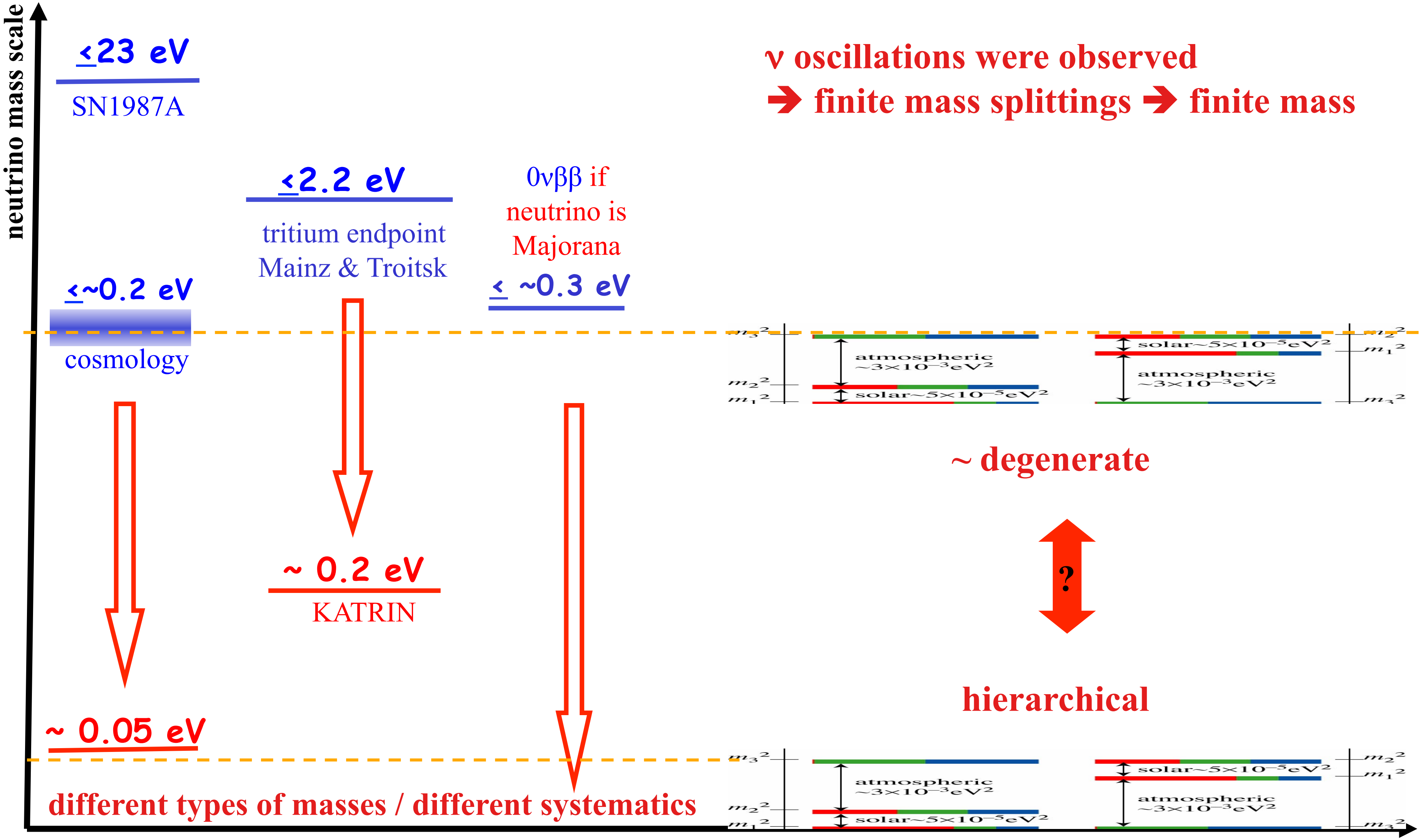
- **integrating out heavy physics (c.f. G_F ⇔ M_W)**

$$|\epsilon| \simeq \frac{M_W^2}{M_{NSI}^2}$$



Grossman, Bergmann+Grossman, Ota+Sato, Honda et al., Friedland+Lunardini, Blennlow +Ohlsson+Skrotzki, Huber+Valle, Huber+Schwetz+Valle, Campanelli+Romanino, Bueno et al., Barranco+Miranda+Rashba, Kopp+ML+Ota, …

Overview of Neutrino Mass Knowledge



$\leq$23 eV
SN1987A

$\leq$2.2 eV
tritium endpoint
Mainz & Troitsk

0νββ if
neutrino is
Majorana
$\leq$ ~0.3 eV

$\leq$~0.2 eV
cosmology

~ 0.2 eV
KATRIN

~ 0.05 eV

different types of masses / different systematics

ν oscillations were observed
➔ finite mass splittings ➔ finite mass

~ degenerate

hierarchical

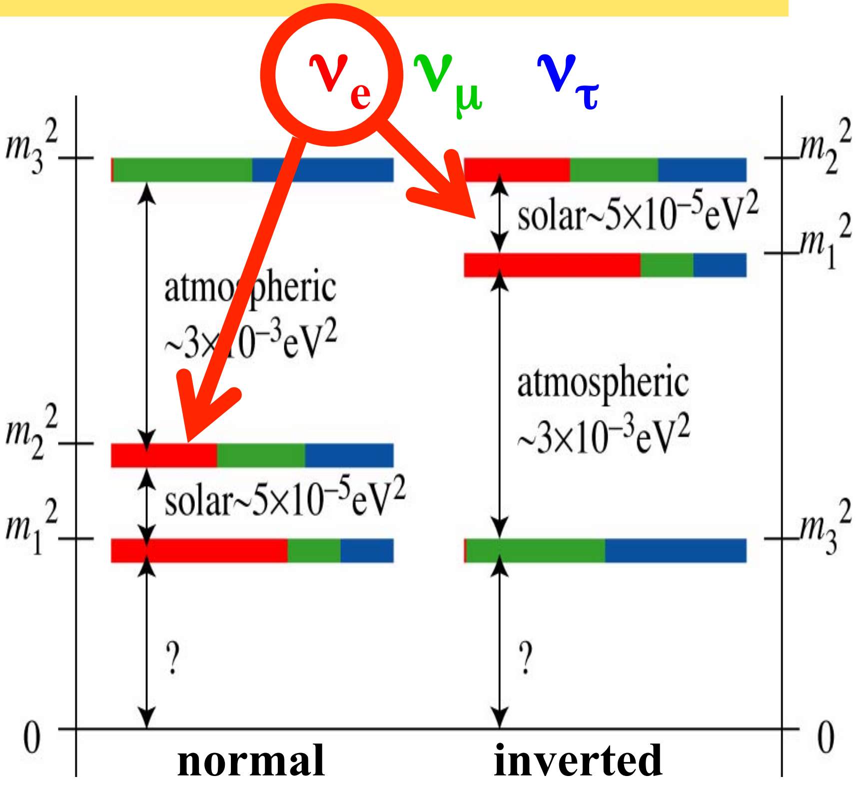
3 Light Neutrinos (...assumed)

Mass & mixing parameters: m_1 , Δm^2_{21}, $|\Delta m^2_{31}|$, sign(Δm^2_{31})

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \; \mathrm{diag}(e^{i\alpha}, e^{i\beta}, 1)$$

questions:

- ➔ Dirac / Majorana
- ➔ mass scale: m_1
- ➔ mass ordering: sgn(Δm^2_{31})
- ➔ how small is θ_{13}, θ_{23} maximal?
- ➔ leptonic CP violation
- ➔ 3 flavour unitarity?
- ➔ why 3 generations, why d=4, …



hierarchical or degenerate

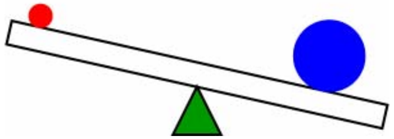
Suggestive Seesaw Features

QFT: natural value of mass operators ⇔ scale of symmetry

$m_D \sim$ electro-weak scale

$M_R \sim$ L violation scale ⇐?⇒ embedding (GUTs, …)

See-saw mechanism (type I)



$$\overset{\downarrow}{m_\nu}=\overset{\downarrow}{m_D}\underset{\downarrow}{M_R^{-1}}\overset{\downarrow}{m_D^T}$$

$$m_h=M_R$$

Numerical hints:

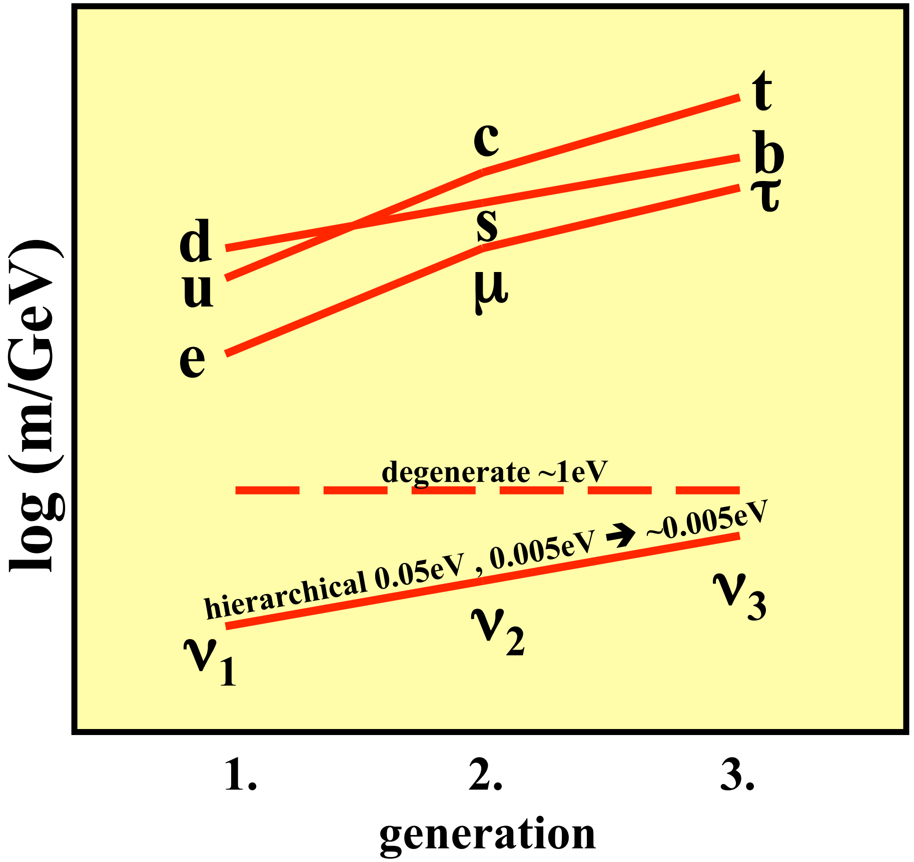
For $m_3 \sim (\Delta m^2_{atm})^{1/2}$, $m_D \sim$ leptons ⇒ $M_R \sim 10^{11} - 10^{16}\,\mathrm{GeV}$

⇒ν's are Majorana particles , m_ν probes ~ GUT scale physics!

⇒smallness of m_ν ⇔ high scale of $\not{L}$, symmetries of m_D ,M_R

2nd Look Questions

Quarks & charged leptons → hierarchical masses → neutrinos?



Quarks and charged leptons:

$m_D \sim H^n$; $n = 0,1,2$ → $H \geq 20...200$

Neutrinos: $m_\nu \sim H^n$ → $H \leq \sim 10$

See-saw:

$$m_\nu = -m_D^T \, M_R^{-1} \, m_D$$

↕ ↕ ↕ ↕

H $\sim$**10** $\geq$**20** **?** $\geq$**20**

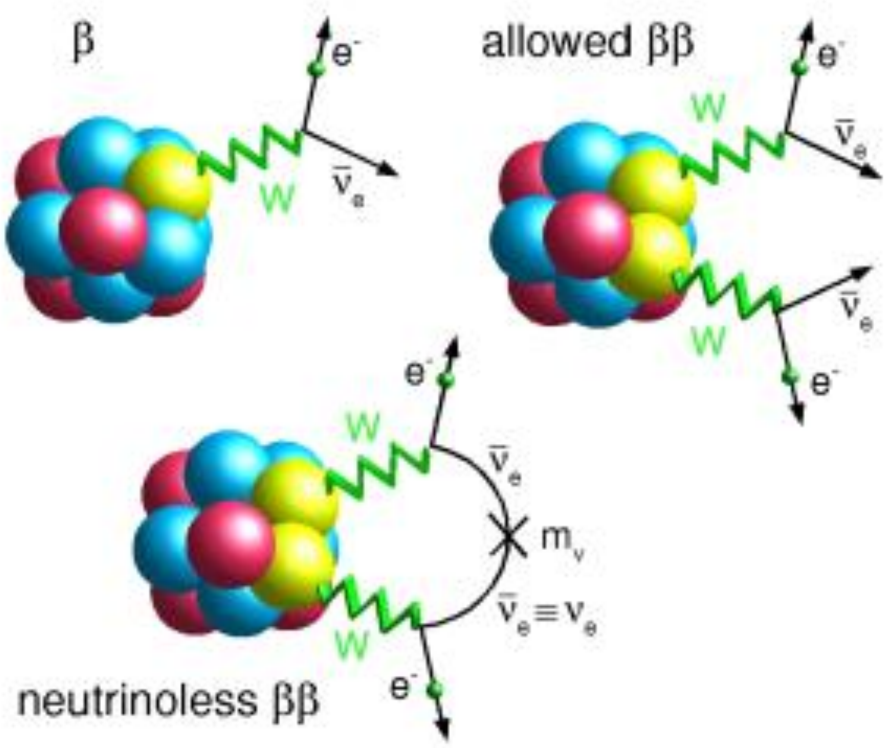
» **less hierarchy in m_D or corr. hierarchy in M_R? →theoretically not connected!**

» **other version of see-saw? → type II, III, …?**

» **Dirac masses?**

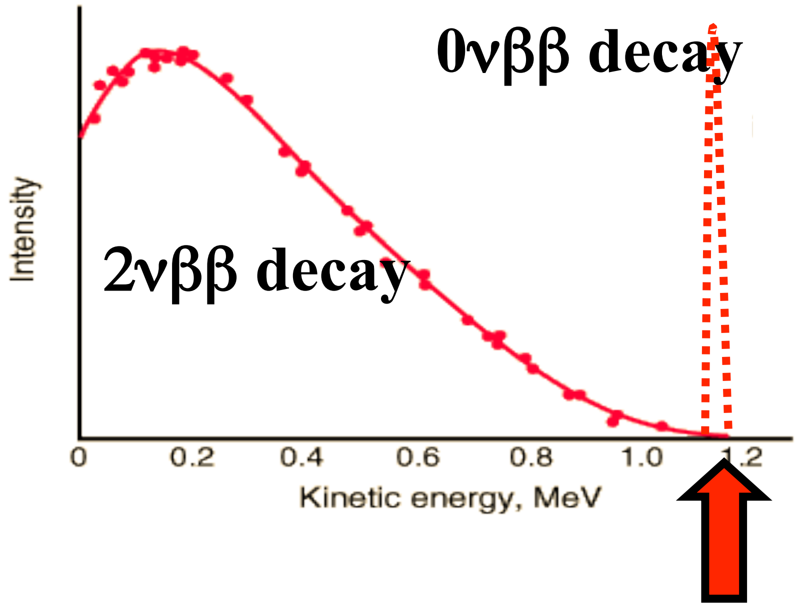
What do we actually measure?

Neutrino-less Double Beta Decay



2νββ decay of ^{76}Ge observed:

$\tau = 1.5 \times 10^{21}$ y

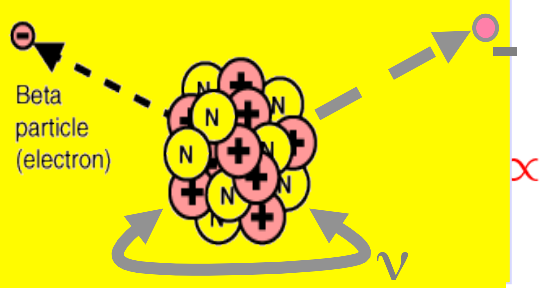


Majorana ν ➔ 0νββ decay

warning: other lepton number violating processes may exist…

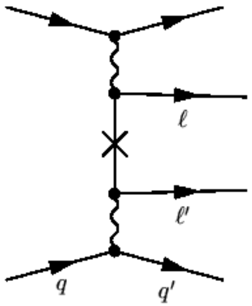
- **signal at known Q-value**
- **2νββ background (resulution)**
- **nuclear backgrounds**
  ➔ **use different nuclei**

Neutrino Masses from Double β-Decay



Majorana ν ➔ 0ν2β decay

$\propto$

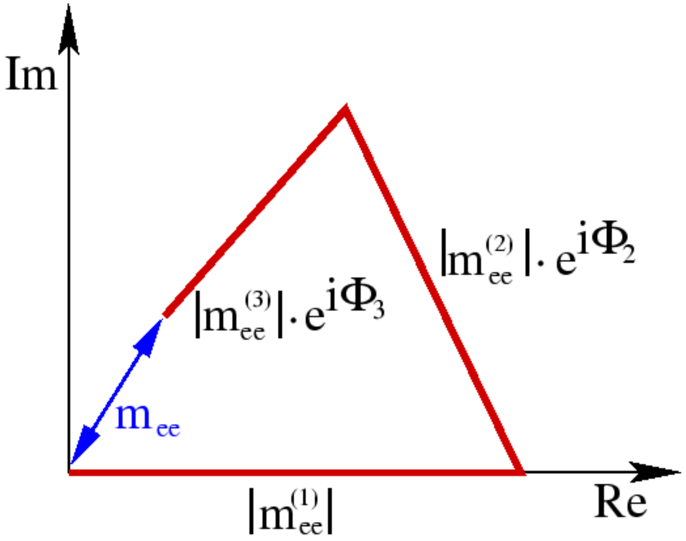


$$\propto |\langle m_{ee} \rangle| = |\sum m_i U_{ei}^2| \underline{<} 0.35 \text{ eV ?}$$

Heidelberg-Moscow experiment

$$m_{ee} = |m_{ee}^{(1)}| + |m_{ee}^{(2)}| \cdot e^{i\Phi_2} + |m_{ee}^{(3)}| \cdot e^{i\Phi_3}$$

$$\begin{aligned} |m_{ee}^{(1)}| &= |U_{e1}|^2 m_1 \\ |m_{ee}^{(2)}| &= |U_{e2}|^2 \sqrt{m_1^2 + \Delta m_{21}^2} \\ |m_{ee}^{(3)}| &= |U_{e3}|^2 \sqrt{m_1^2 + \Delta m_{31}^2} \end{aligned}$$



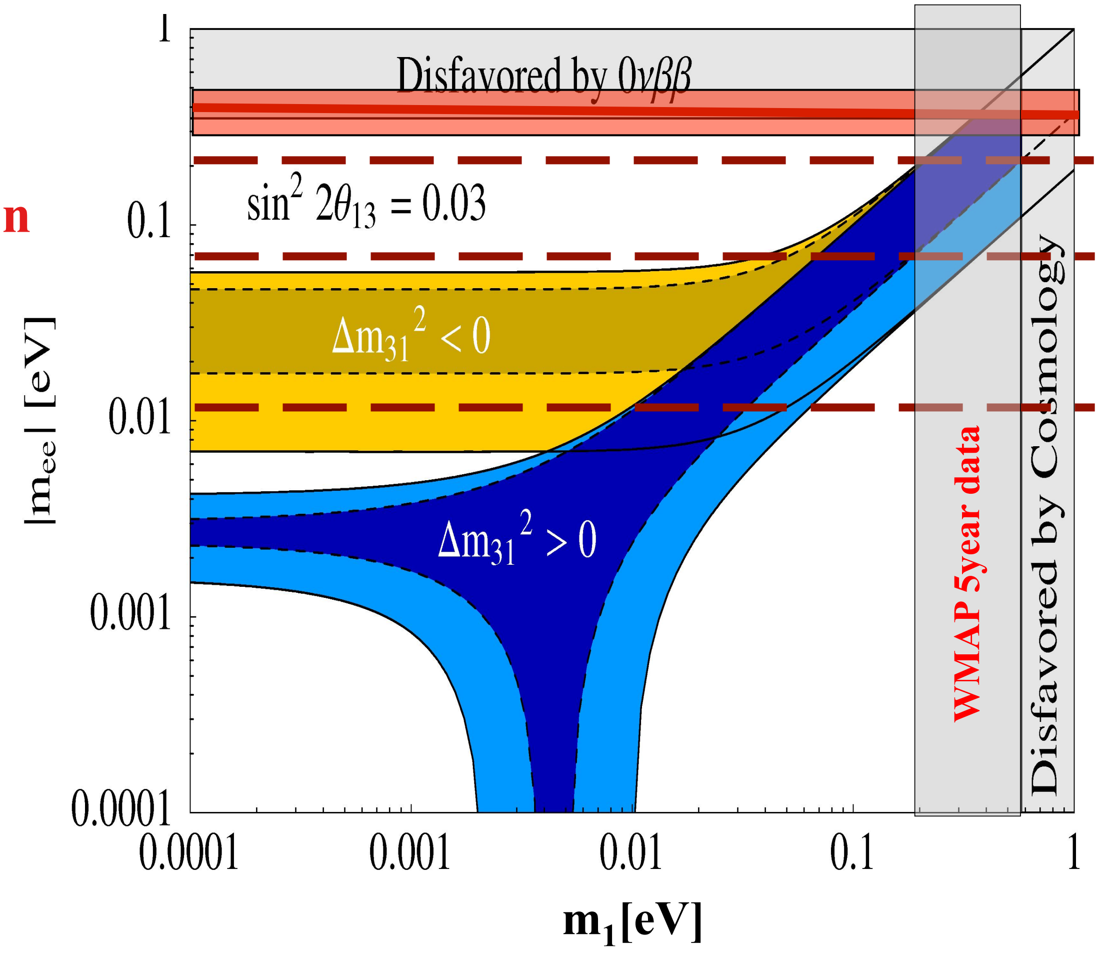
solar $\Rightarrow$ $|U_{e1}|^2, |U_{e2}|^2, \Delta m_{21}^2$ atmosph. $\Rightarrow$ $|\Delta m_{31}^2|$ CHOOZ $\Rightarrow$ $|U_{e3}|^2 < 0.05$

➔ **free parameters: m_1 , sign(Δm^2_{31}) , CP-phases Φ_2, Φ_3**

Claim of part of the original Heidelberg-Moscow collaboration ←➔ cosmology ➔ ‚tension‘

aims of new experiments:

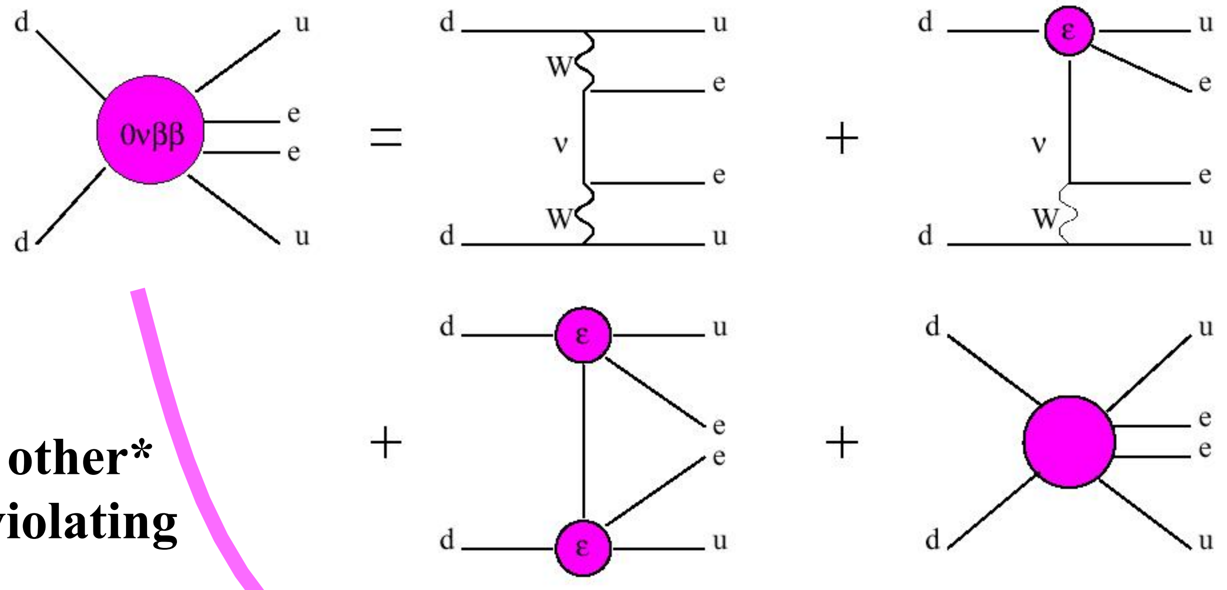
- **test HM claim**
- **$(\Delta m_{31}^2)^{1/2} \simeq 0.05$eV ± errors**
  - **➔ reach 0.01eV**
  - **➔ CUORE**
  - **➔ GERDA phases I, II, (III)**



Comments:

- **cosmology: limitation by systematical errors ➔ ~another factor 5?**
- **$0\nu\beta\beta$ nuclear matrix elements ~factor 1.3-2 theoretical uncertainty in m_{ee}**
- **$\Delta m^2 > 0$ allows complete cancellation**
  - **➔ $0\nu\beta\beta$ signal not guaranteed, but cancelation appears unlikely**

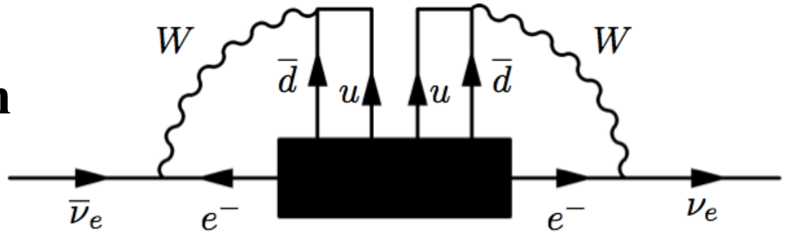
0νββ from Alternative ΔL=2 Operators



Various possibilities:
- LR symmetry
- SUSY (RPV)
- …

➔0νββ signal from *some other* new BSM lepton number violating operator

➔ very promising interplay of neutrino mass determinations, cosmology, LHC, LVF experiments and theory



Schechter + Valle: **Any ΔL=2 violating operator**

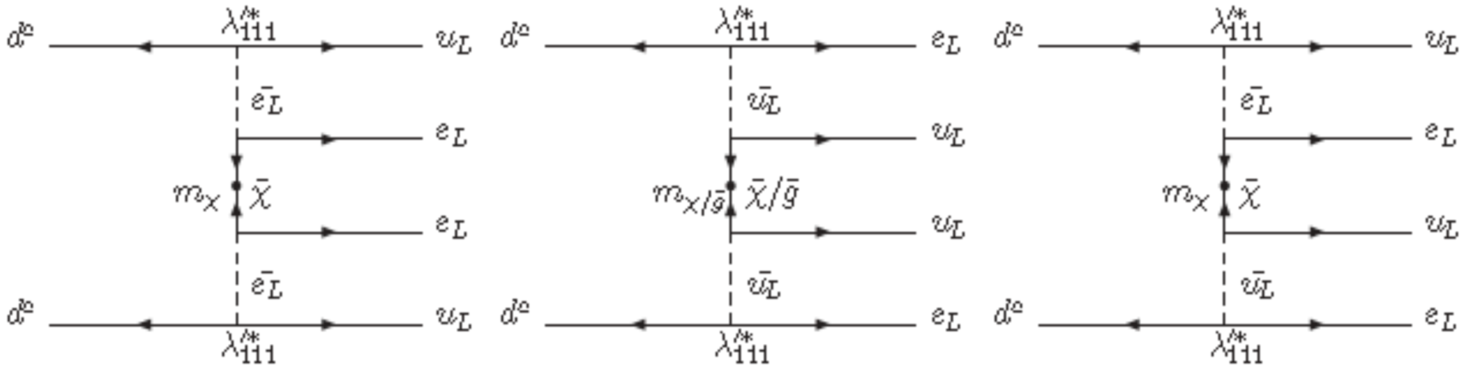
➔ radiative generation of Majorana mass term

➔ Majorana nature of ν's guaranteed

➔ but how big is the mass?

SUSY Example

Direct, TeV scale short range mediation w/o intermediate light ν, e.g.



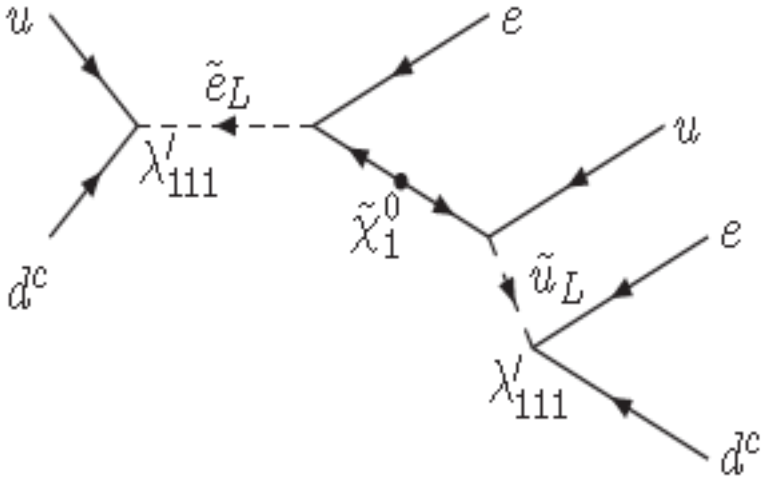
$$\mathcal{L}^{eff,\,\Delta L_e=2}_{\lambda'_{111}\lambda'_{111}}(x) \quad = \quad \frac{G_F^2}{2} m_p^{-1}[\bar{e}(1+\gamma_5)e^c]$$

$$\times\left[(\epsilon_{\tilde{g}}+\epsilon_\chi)(J_{PS}J_{PS}-\frac{1}{4}J_T^{\mu\nu}J_{T\mu\nu})+(\epsilon_{\chi\tilde{e}}+\epsilon'_{\tilde{g}}+\epsilon_{\chi\tilde{f}})J_{PS}J_{PS}\right]$$

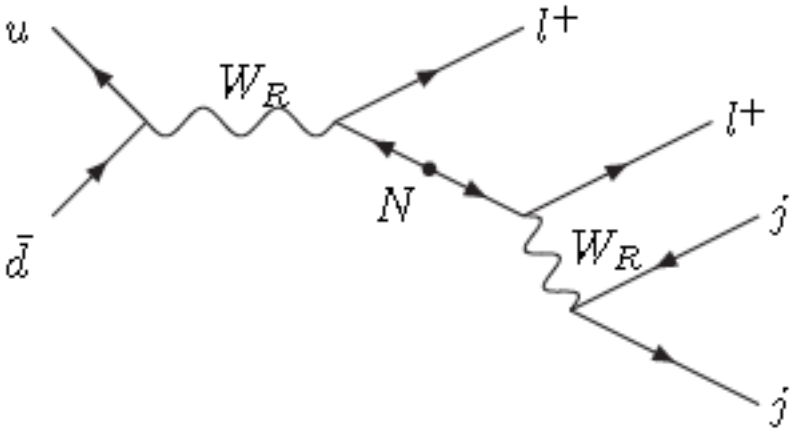
$$\epsilon_i \quad \sim \quad \pi\alpha_{(\mathrm{Strong,EW})}\frac{\lambda'^2_{111}}{G_F^2}\frac{m_P}{m_{(\tilde{g},\tilde{\chi})}}\frac{1}{m^4_{(\tilde{u},\tilde{d},\tilde{e})}}.$$

$\Delta L=2$ Operators and TeV Scale Physics

SUSY: direct test of λ'_{111}

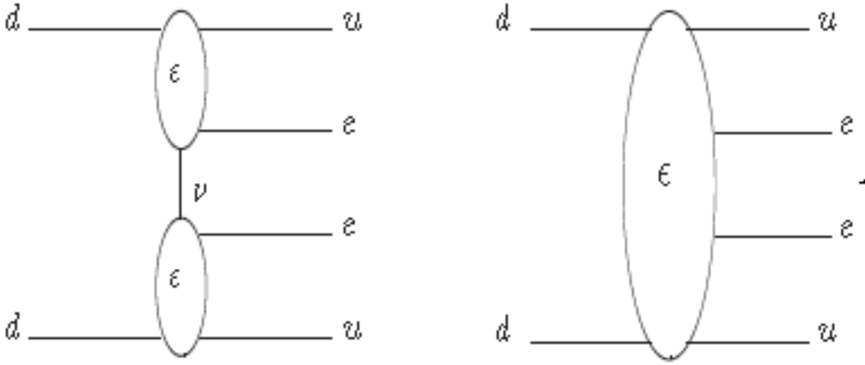


L-R symmetry: heavy N's



Relative strength of 'light' and 'heavy' $0\nu\beta\beta$ amplitudes:

$$M_{\text{light}} \sim G_F^2 \frac{m_{\beta\beta}}{\langle k^2 \rangle}$$



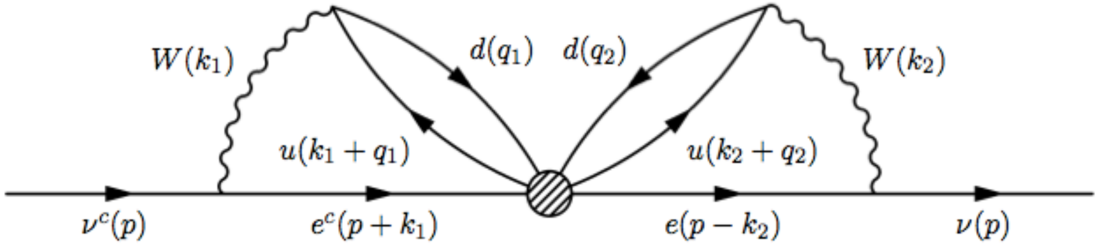
$$M_{\text{heavy}} \sim G_F^2 \left(\frac{\lambda}{g_2}\right)^4 \frac{M_W^4}{\Lambda^5}$$

SV-induced Neutrino Masses

General Lorentz-invariant Lagrangian for 0νββ (point operator)

$$\mathcal{L} = \frac{G_F^2}{2} m_p^{-1} \left(\epsilon_1 J J j + \epsilon_2 J^{\mu\nu} J_{\mu\nu} j + \epsilon_3 J^{\mu} J_{\mu} j + \epsilon_4 J^{\mu} J_{\mu\nu} j^{\nu} + \epsilon_5 J^{\mu} J j_{\mu} \right)$$

$$J = \overline{u}\,(1 \pm \gamma_5)\,d,\ \ J^{\mu} = \overline{u}\gamma^{\mu}\,(1 \pm \gamma_5)\,d \text{ etc.}$$



Outcome: M. Dürr, ML, A. Merle, arXiv:1105.0901

If other ΔL=2 physics drives 0νββ ➔ SV gives $\delta m_\nu = 10^{-24}$ eV

➔ mass correction too small to explain observed masses and splittings

➔ explicit neutrino mass operators required

Dirac: 0νββ essentially unrelated to neutrino masses ←➔ other BSM

Majorana: dominates over SV contribution

0νββ may be a mixture of Majorana mass and other ΔL=2 physics

➔ mimics higher Majorana neutrino mass

Neutrinos Oscillation Surprises

… many untested assumptions: Majorana, 3 ν's, mass mechanism

➔ example: How NSI's can fool us in precision experiments:

Source ⊗	Oscillation ⊗	Detector
- neutrino energy E	- oscillation channels	- effective mass, material
- flux and spectrum	- realistic baselines	- threshold, resolution
- flavour composition	- MSW matter profile	- particle ID (flavour, charge, event reconstruction, ...)
- contamination	- degeneracies	- backgrounds
- symmetric $\nu/\overline{\nu}$ operation	- correlations	- x-sections (at low E)

precision experiments migh see new effects beyond oscillations!

NSI Operators

- Good reasons for physics beyond the SM+ (with ν's)
  ➔ expect effects beyond 3 flavours in many models
  ➔ effective 4f interactions

$$\mathcal{L}_{NSI} \simeq \epsilon_{\alpha\beta} 2\sqrt{2} G_F (\bar{\nu}_{L\beta}\, \gamma^\rho\, \nu_{L\alpha})(\bar{f}_L \gamma_\rho f_L)$$

- integrating out heavy physics (c.f. G_F ⇔ M_W)

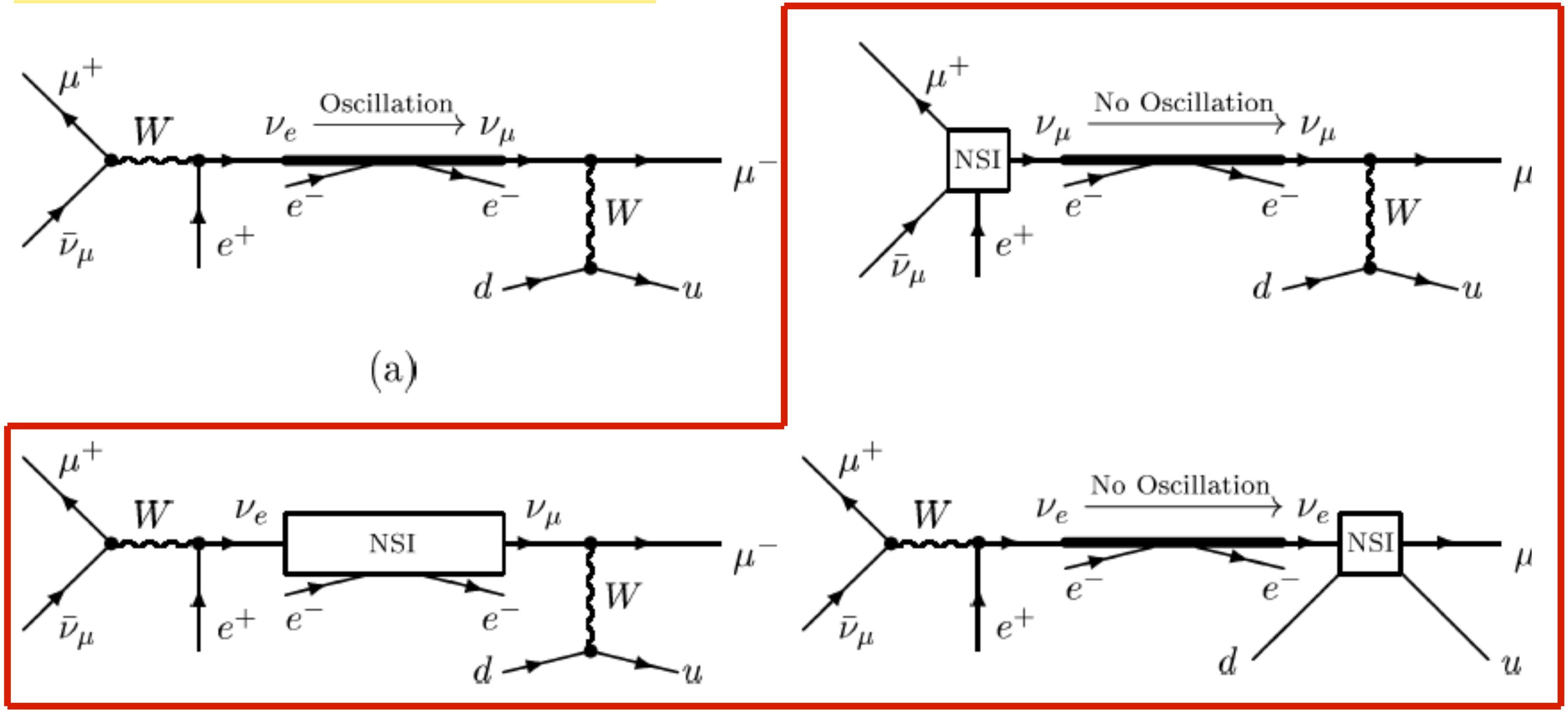
$$|\epsilon| \simeq \frac{M_W^2}{M_{NSI}^2}$$

Grossman, Bergmann+Grossman, Ota+Sato, Honda et al., Friedland+Lunardini, Blennlow+Ohlsson+Skrotzki, Huber+Valle, Huber+Schwetz+Valle, Campanelli +Romanino, Bueno et al., Kopp+ML+Ota, …

NSIs interfere with Oscillations

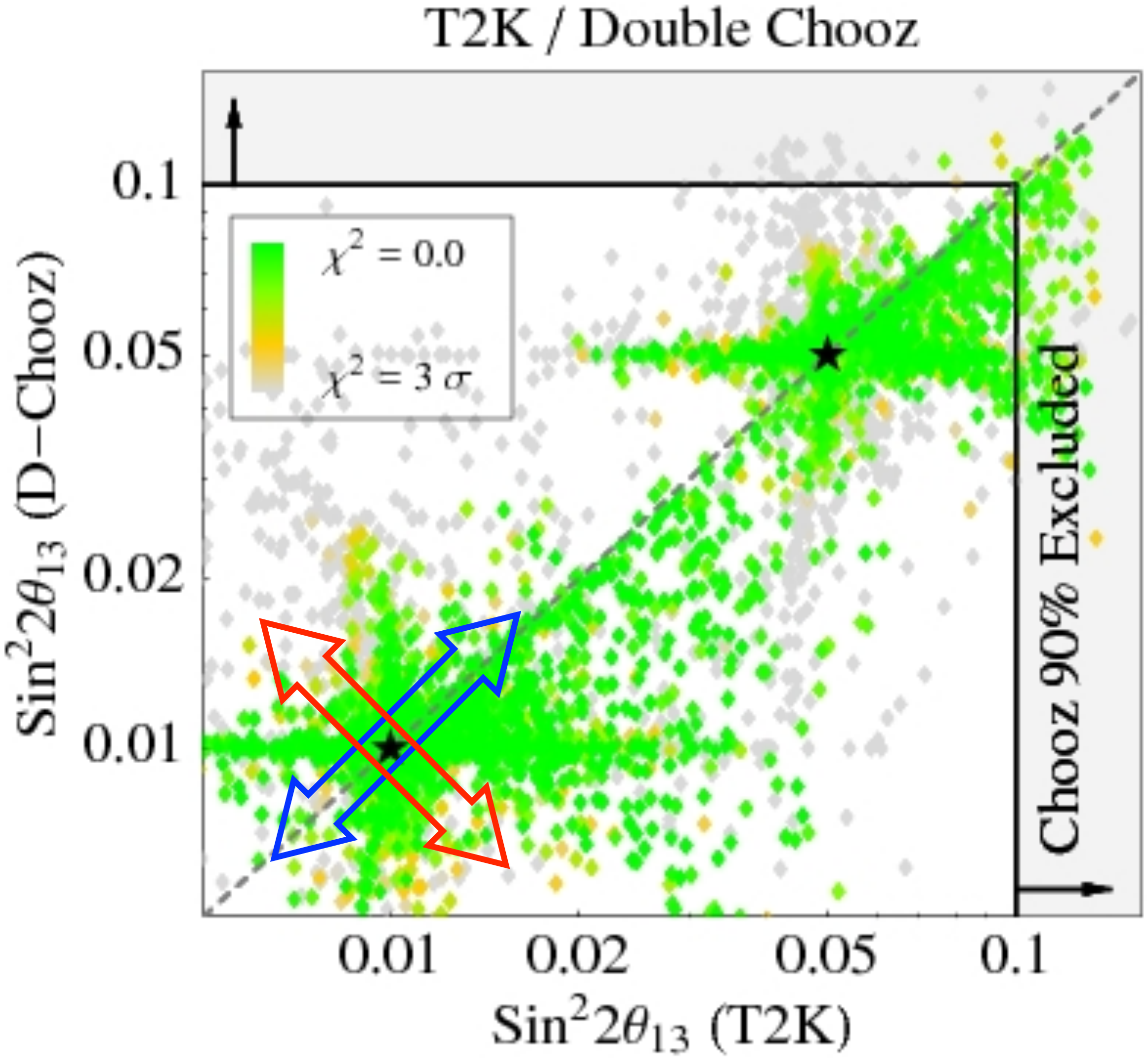
the “golden” oscillation channel

NSI contributions to the “golden” channel



note: interference in oscillations $\sim\varepsilon$ ⇔ FCNC effects $\sim\varepsilon^2$

NSI: Offset and Mismatch in θ_{13}



Redundant measurements:

Double Chooz + T2K

***=assumed 'true' values of θ_{13}**

scatter-plot: ε values random

- **below existing bounds**
- **random phases**

NSIs can lead to:

- **offset**
- **mismatch**

➔ **redundancy**

➔ **interesting potential**

'natural magnitude' …more natural for NuFact ➔ **see talk by S. Pascoli**

Evidence(s) for Sterile Neutrinos

LSND - MiniBooNE - MINOS – Gallex - … ➔ evidence for sterile ν's?

➔ see talk by E. Lisi

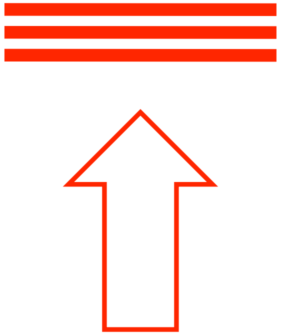
➔ New and better data / experiments are needed to clarify the situation

➔ maybe something exciting around the corner?

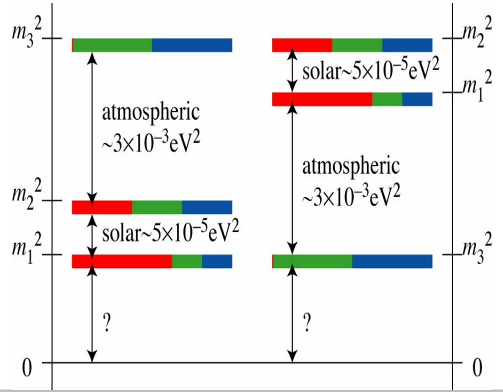
The standard picture:

3 heavy sterile neutrinos typ. $\geq 10^{13}$ GeV

➔ leptogenesis, role in GUTs, …



3 light active neutrinos



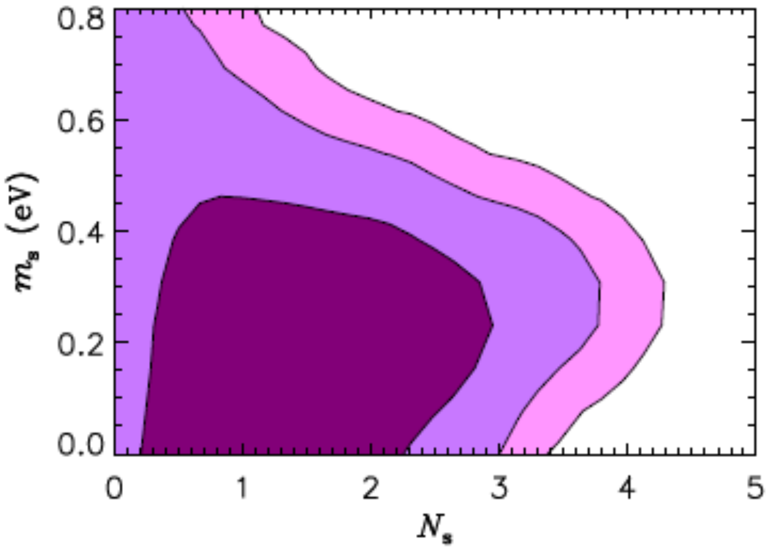
➔ this cold easily be wrong

- more than 3 N_R states, …

- M_R may have special eigenvalues, …

➔ light sterile neutrinos ?!

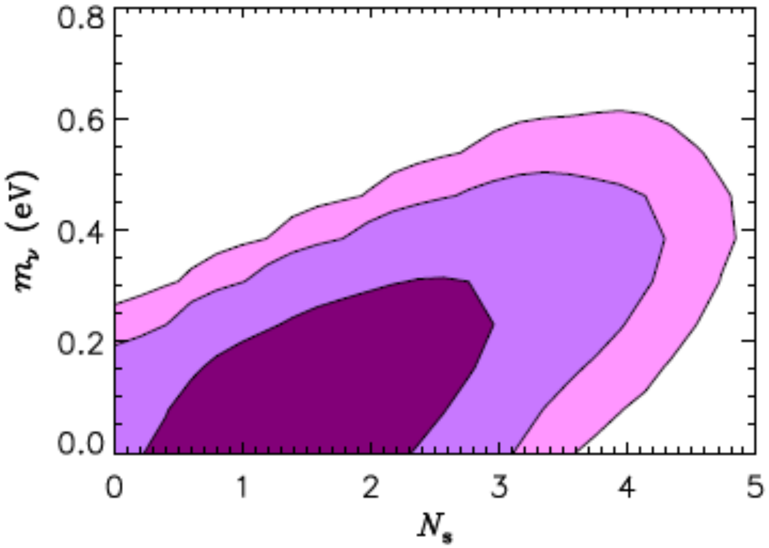
Extra Sterile Neutrinos & CMB



3 active massless neutrinos

+

N_s massive neutrinos



3 active massive neutrinos

+

N_s massless neutrinos

J. Hamann et al

More Indications for light sterile Neutrinos

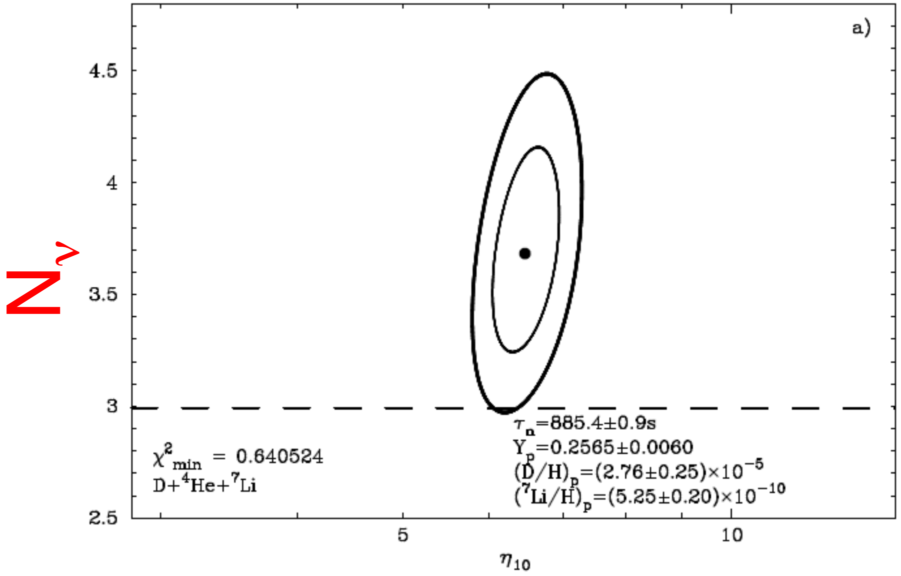
Astrophysics:

- Effects of keV-ish sterile neutrinos on pulsar kicks

Kusenko, Segre, Fuller, Mocioiu, Pascoli

- …

Cosmology: BBN – ‘feels’ extra light particles:



$N_\nu \simeq 3.7 \pm 1$

E. Aver, K. Olive, E. Skillman (2010)
Y. Izotov, T. Thuan(2010)

Could Neutrinos be Dark Matter?

- **Active neutrinos = perfect Hot Dark Matter** ➔ **ruled out:**
  - destroys small scale structures in cosmological evolution
  - required neutrino masses much too small → useful HDM component

- **keV sterile neutrinos: Warm Dark Matter** ➔ workes very well:
  - ➔ relativistic at decoupling
  - ➔ non-relativistic at radiation to matter dominance transition
  - OK for $M_X \simeq$ few keV
  - reduced small scale structure ➔ smoother profile, less dwarf satellites
  - ➔ scenario where one sterile neutrino is keV-ish, the others heavy

  - ➔ right handed neutrinos probably exist
  - ➔ only a mechanism to make one state light required
  - ➔ observational hints from astronomy
  - hints that a keV sterile particle may exist ➔ right-handed neutrino?

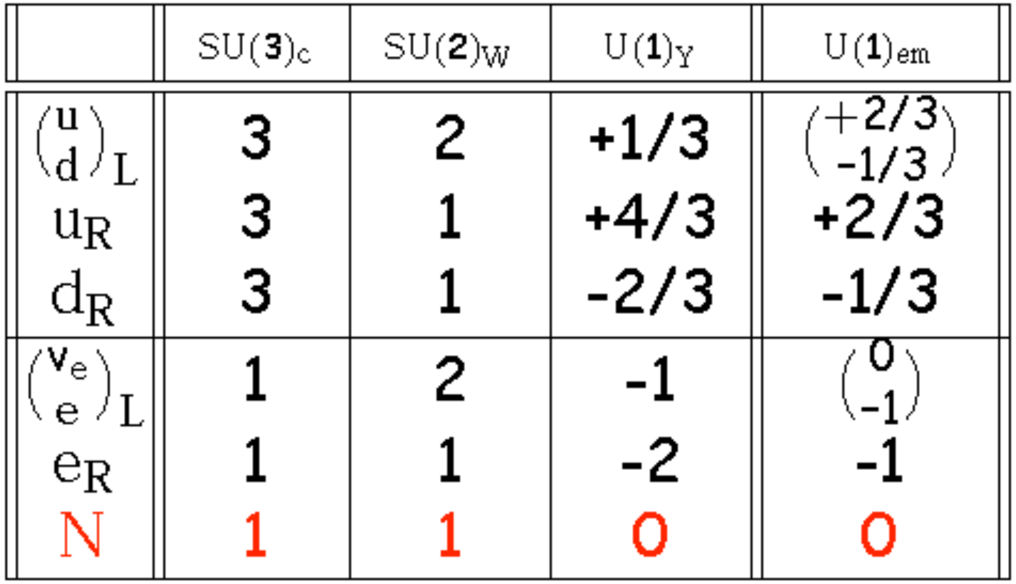
  Biermann, Kusenko & Segre, Fuller et al., Biermann & Kusenko, Stasielak et al., Loewenstein et al., Dodelson, Widrow, Dolgov, …

The νMSM

Asaka, Blanchet, Shaposhnikov, 2005 Asaka, Shaposhnikov, 2005

Particle content:

- Gauge fields of $SU(3)_c$ x $SU(2)_W$ x $U(1)_Y$: g, $W_\pm$, Z, g
- Higgs doublet: F=(1,2,1)
- Matter



	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	$U(1)_{em}$
$\begin{pmatrix}u\\d\end{pmatrix}_L$	3	2	+1/3	$\begin{pmatrix}+2/3\\-1/3\end{pmatrix}$
u_R	3	1	+4/3	+2/3
d_R	3	1	-2/3	-1/3
$\begin{pmatrix}\nu_e\\e\end{pmatrix}_L$	1	2	-1	$\begin{pmatrix}0\\-1\end{pmatrix}$
e_R	1	1	-2	-1
N	1	1	0	0

x3 generations

➔ lepton sector more symmetric to the quark sector

➔ Majorana masses for N

➔ choose for one sterile n ~keV mass ➔ exceeds lifetime of Universe

Abundance in the νMSM and in Alternatives

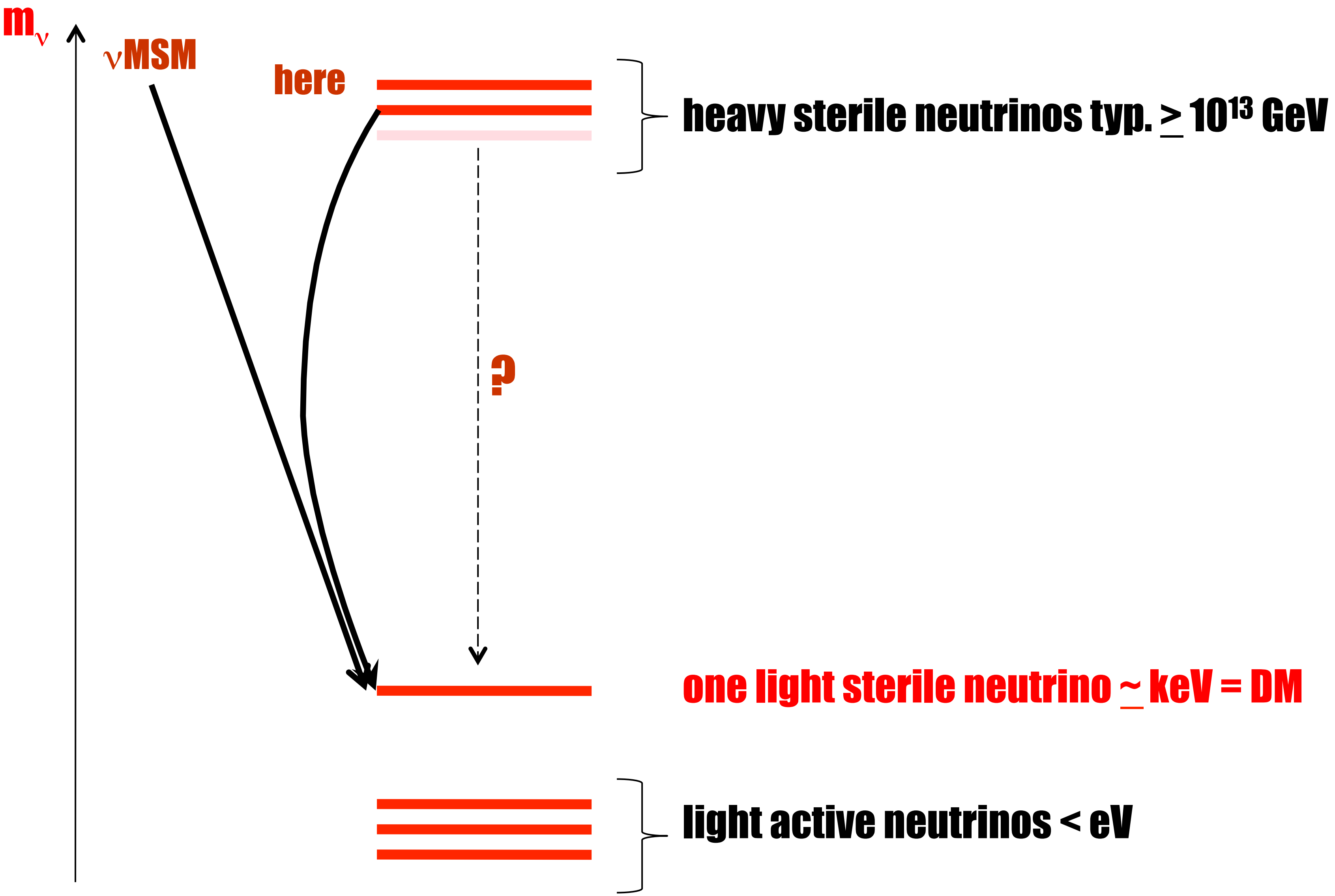
- **Virtue and problem of νMSM:**
  - scenario with sterile ν and tiny mixing ➔ never enters thermal equilibrium
  ➔ requires non-thermal production from other particles (avoid over-closure)
  ➔ new physics before the beginning of the thermal evolution sets abundance

- **An alternative scenario:** **Bezrukov, Hettmannsperger, ML**

  - Three right-handed neutrinos N_1 , N_2 , N_3
  - Dirac and Majorana mass terms
  - N Charged under some (BSM) gauge group ➔ scale M
  - Specific LR example: $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

- **everything follows nicely from sterile neutrinos**

The Scenario



m_ν

νMSM

here

heavy sterile neutrinos typ. $\geq 10^{13}$ GeV

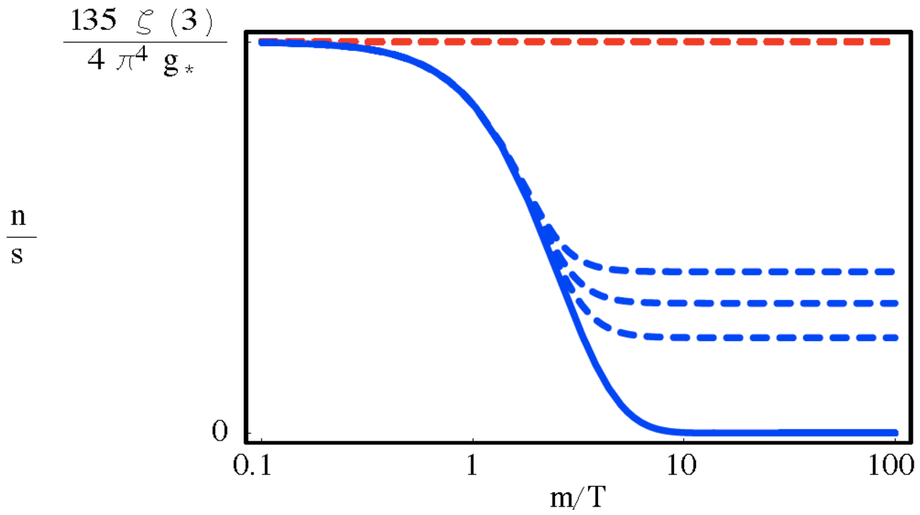
?

one light sterile neutrino $\simeq$ keV = DM

light active neutrinos < eV

Obtaining the right Abundance

Usual thermal case:



HDM:

$$\frac{\Omega}{\Omega_{DM}} \simeq \left(\frac{10}{g_{*f}}\right)\left(\frac{M}{10\,eV}\right)$$

Decoupled relativistic

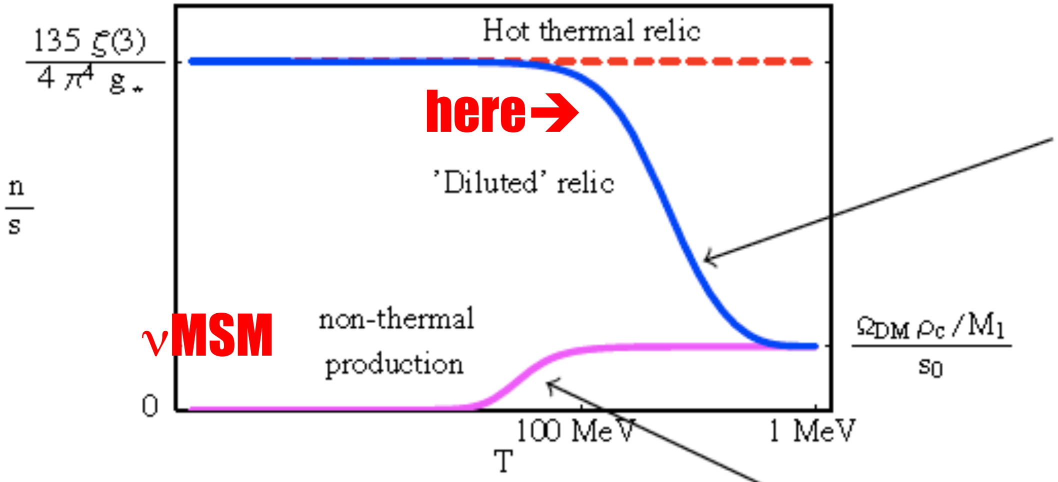
CDM:
(M>>MeV)

$$\Omega \sim \Omega_{DM}$$

Decoupled

nonrelativistic

keV sterile neutrinos:



Diluted after decoupling
(entropy generated by other
particle decay)

$$\Omega \sim \Omega_{DM}$$

Never entered thermal equilibrium

Observing keV-ish Neutrino DM

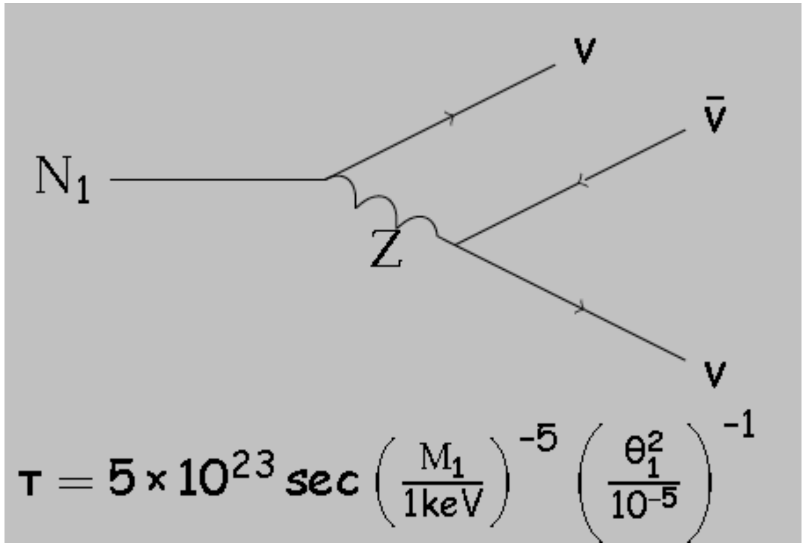
- LHC
  - sterile neutrino DM is not observable
  - WIMP-like particles still possible – but not DM
- direct searches
  - sterile neutrino DM is not observable
- astrophysics/cosmology ➔ at some level: keV X-rays

  ➔ sterile neutrino DM is decaying into active neutrinos

  - decay $N_1 \rightarrow \bar{\nu}\nu\nu$, $N_1 \rightarrow \bar{\nu}\bar{\nu}\nu$

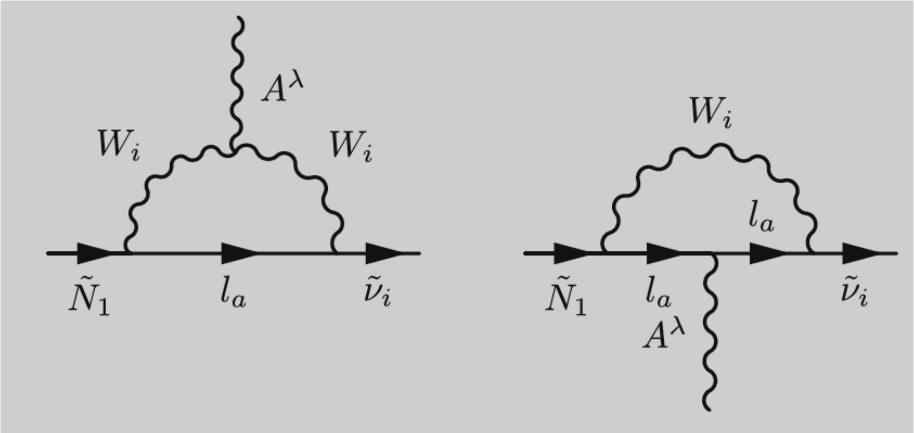
  - not very constraining since

    $\tau >> \tau_{\text{Universe}}$



$$\tau = 5 \times 10^{23}\,\text{sec} \left(\frac{M_1}{1\text{keV}}\right)^{-5} \left(\frac{\theta_1^2}{10^{-5}}\right)^{-1}$$

- - radiative decays $N_1 \rightarrow \nu\gamma$



- so far: observations limit active-sterile mixing angle

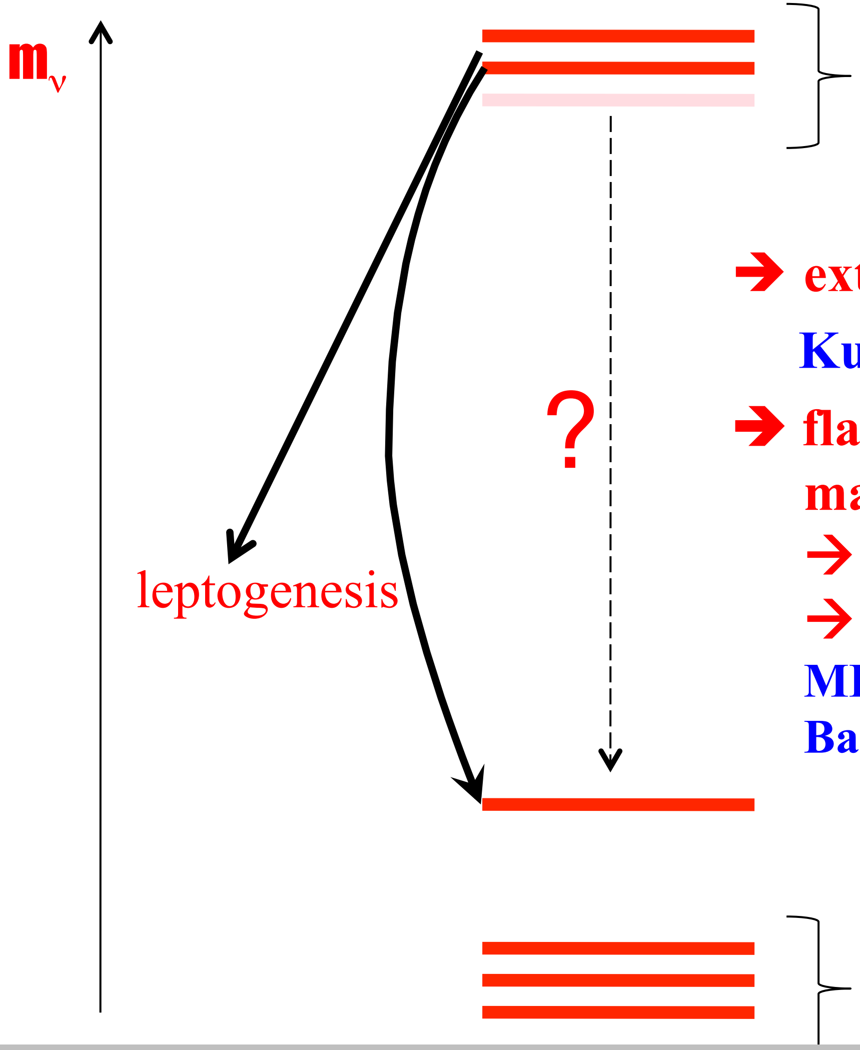
$$\Gamma_{N_1 \to \nu\gamma} \simeq 5.5 \times 10^{-22} \theta_1^2 \left(\frac{M_1}{1\ \mathrm{keV}} \right)^5 \mathrm{s}^{-1}$$

$$\theta_1^2 \lesssim 1.8 \times 10^{-5} \left(\frac{1\ \mathrm{keV}}{M_1} \right)^5$$

- mixing tiny, but naturally expected to be tiny: O(scale ratio)

Generating keV-ish Sterile Neutrinos

Possible scenario: See-saw + a reason why 1 sterile ν is light



heavy sterile neutrinos typ. ≥ 10^{13} GeV

- ➔ **extra dimensional physics ➔ ‘split see-saw’**
  Kusenko, Takahashi, Yanagida,
- ➔ **flavour symmetries explaining active neutrino masses + charged leptons + quarks**
  → consequences for heavy mass matrix
  → L_e-L_μ-L_τ DM←→ flavour problem
  ML, Merle, Niro ; Merle, Niro,
  Barry, Rodejohann, Zhang

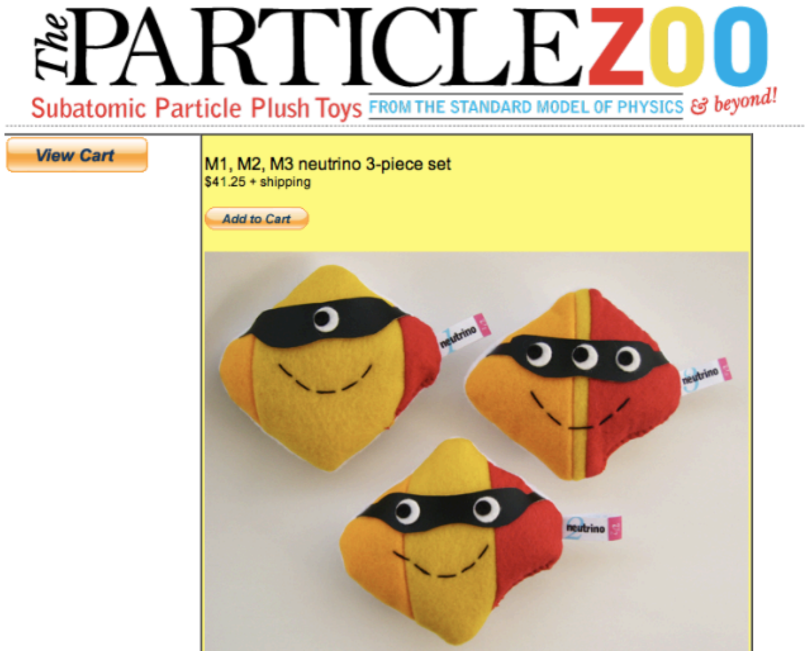
one light sterile neutrino ≃ keV = DM

light active neutrinos < eV

Conclusions

- There are very good reasons to go beyond the SM
- Neutrino masses are still the only solid direct evidence for BSM
- Many non-standard neutrino options & connections exist
  - the three neutrino picture may be incomplete
  - connections to EW-SB, DM, LFV, …

➔ neutrinos may easily surprise us again!



M1, M2, M3 neutrino 3-piece set

$41.25 + shipping