Neutrinos as Probes of New Physics

Manfred Lindner

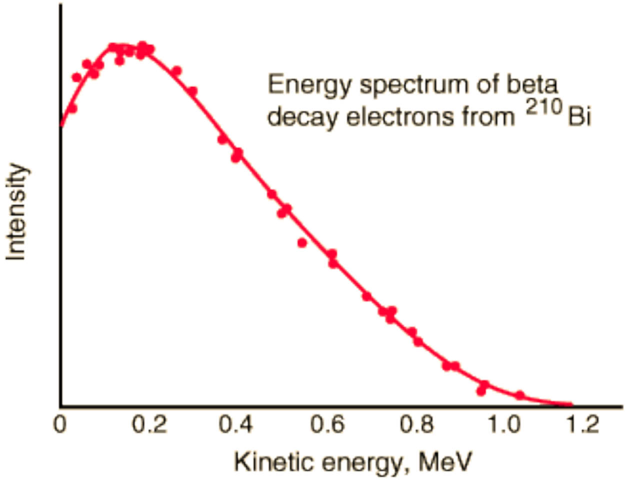
MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK
HEIDELBERG

The Birth of the Neutrino

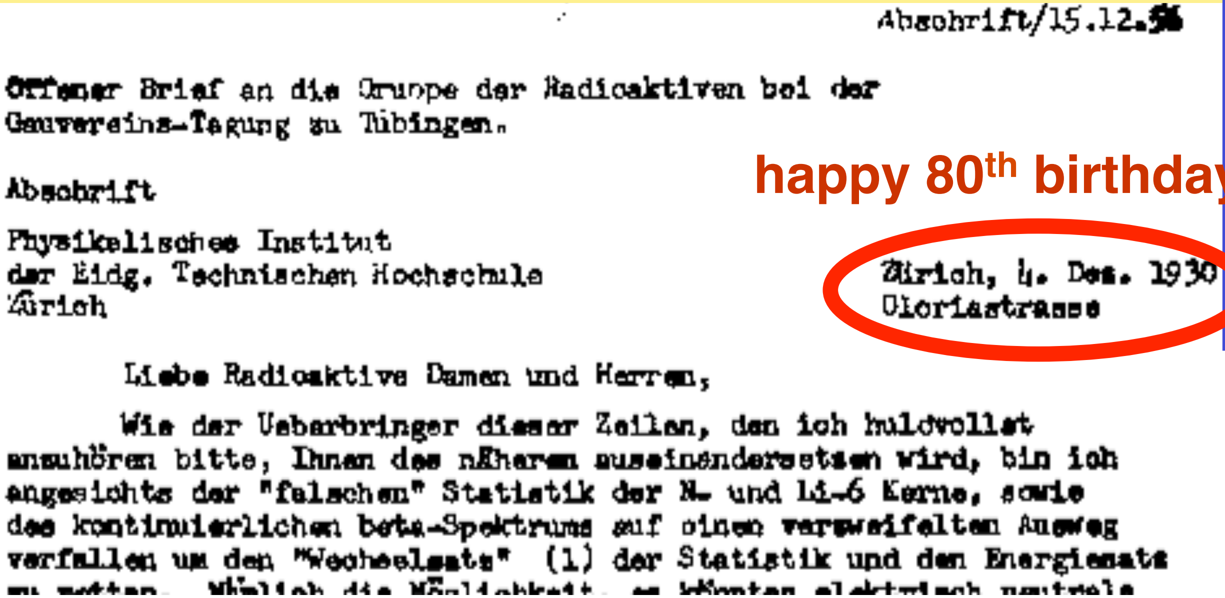
ν

energy-momentum conservation:

→ postulate new particle
→ invisible, since Q=0
→ spin ½, ...



W. Pauli: Letter to DPG meeting in Tübingen



Abschrift/15.12.56

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

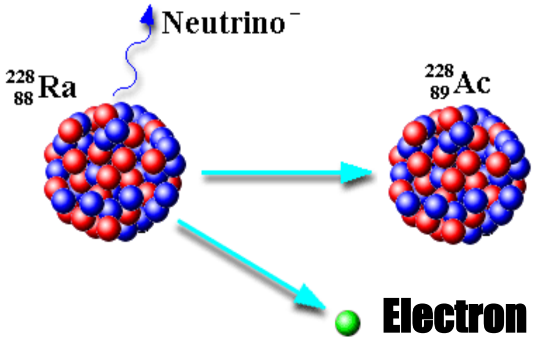
Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

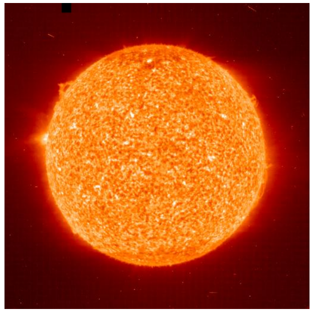
Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale

happy 80th birthday

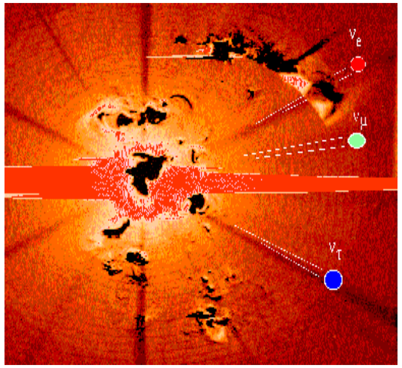


… never detectable!

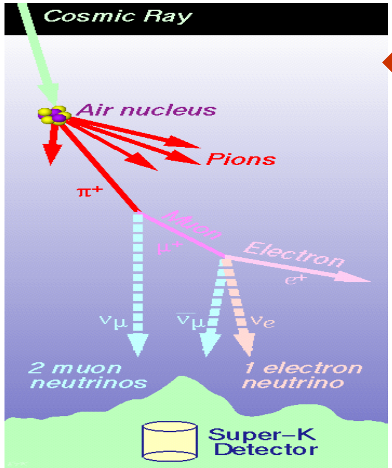
New Physics: Neutrino Sources



←Sun



←Cosmology



←Atmosphere

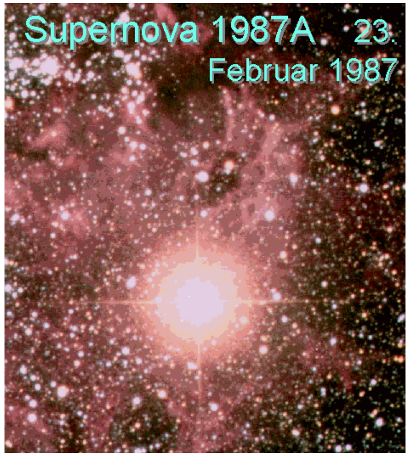
←Earth

Astronomy: →

Supernovae

GRBs

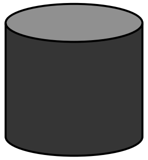
UHE ν‘s



Reactors→

Accelerators→

β-Sources→



Fermion Mass Terms in SM

SM: Fermion masses via Yukawa Couplings

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

← ???

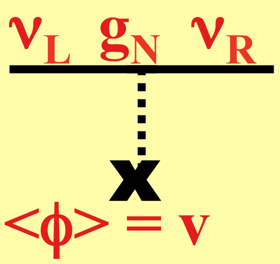
Mass terms: $m\bar{\Psi}\Psi = m\,(\bar{L}\,r + \bar{r}\,L)$

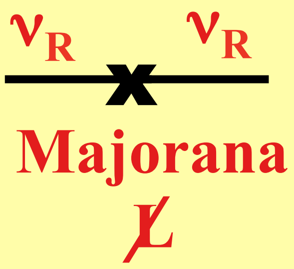
L=2, r=1 ➔ no singlet mass terms

Φ=2 ➔ $m\,(\bar{L}\,\Phi\,r + \bar{r}\,\Phi\,L)$ ➔ singlet mass via $\langle\Phi\rangle = v$

New Physics: Neutrino Mass Terms

1) Simplest possibility: add 3 right handed neutrino fields





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

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

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

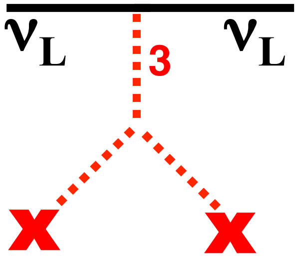
6x6 block mass matrix
block diagonalization
M_R heavy → 3 light ν's

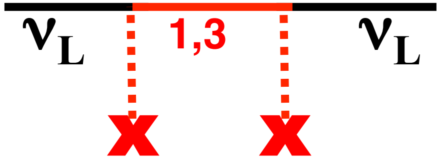
NEW ingredients, 9 parameters → SM+

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:

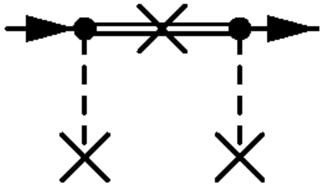
$\rightarrow M_L \overline{L} L^c$

4) Both ν_R and new singlets / triplets:

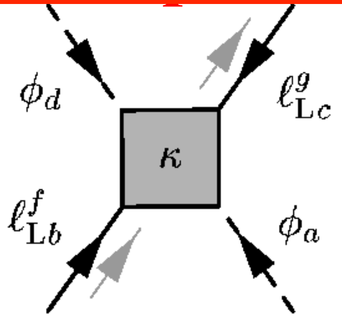
➔ see-saw type II, III

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

5) Higher dimensional operators: d=5, …



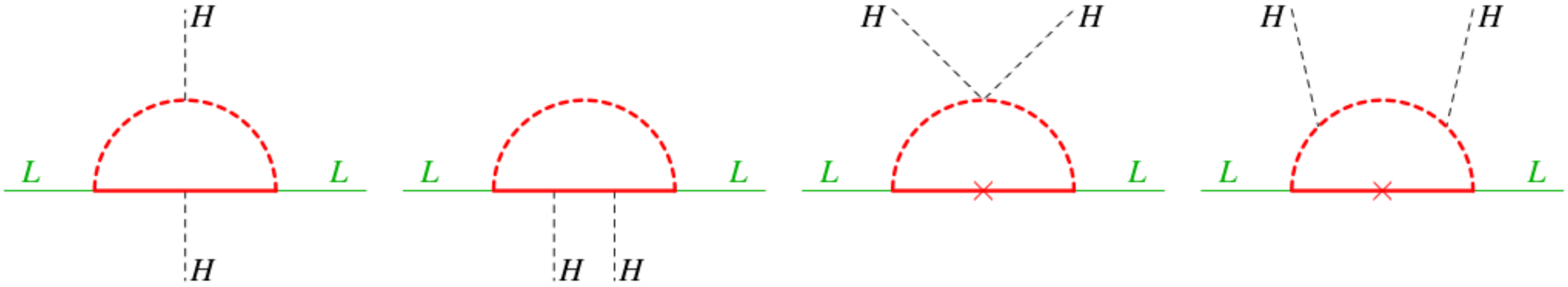
$\Rightarrow$



$\Leftrightarrow$ $\mathcal{L}_{mass} = \kappa \cdot \overline{\nu}_L^C \nu_L \Phi^T \Phi$

➔ $M_L \overline{L} L^c$

6) Radiative neutrino mass generation



7-N) SUSY, extra dimensions, …

➔ so many options...

Other effective Operators Beyond the SM

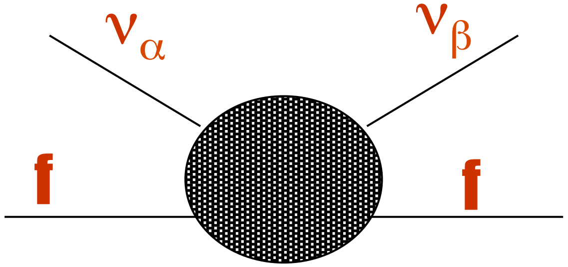
➔ effects beyond 3 flavours

➔ 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, …

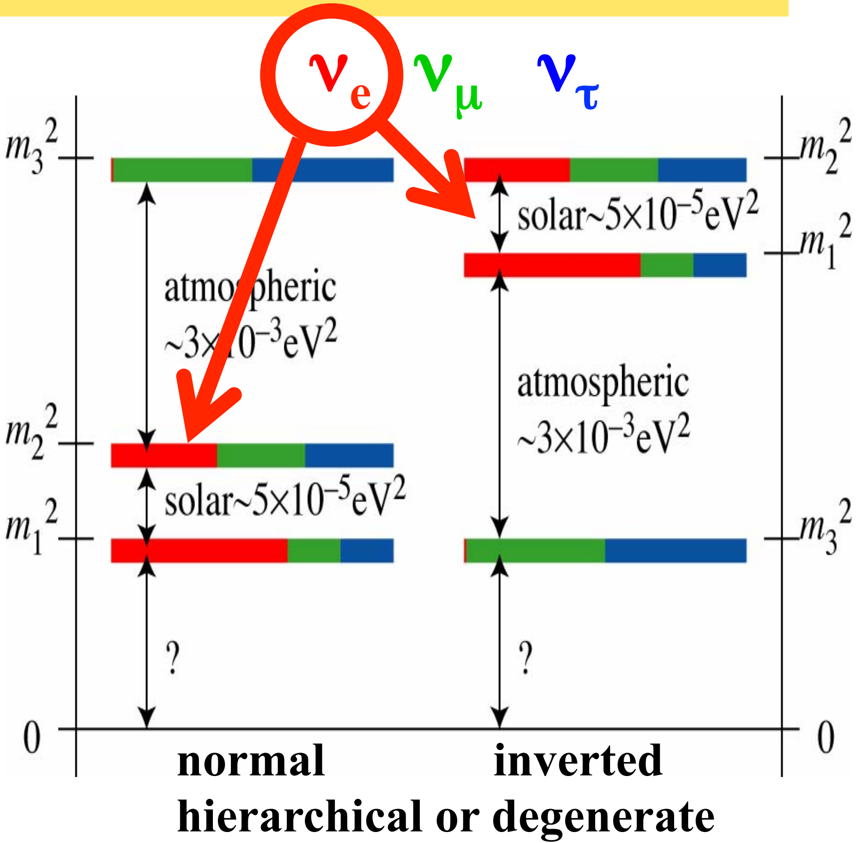
3 Light Neutrinos (...assumed)

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, …



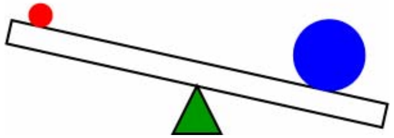
Suggestive Seesaw Features

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)



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

$m_h = M_R$

Numerical hints:

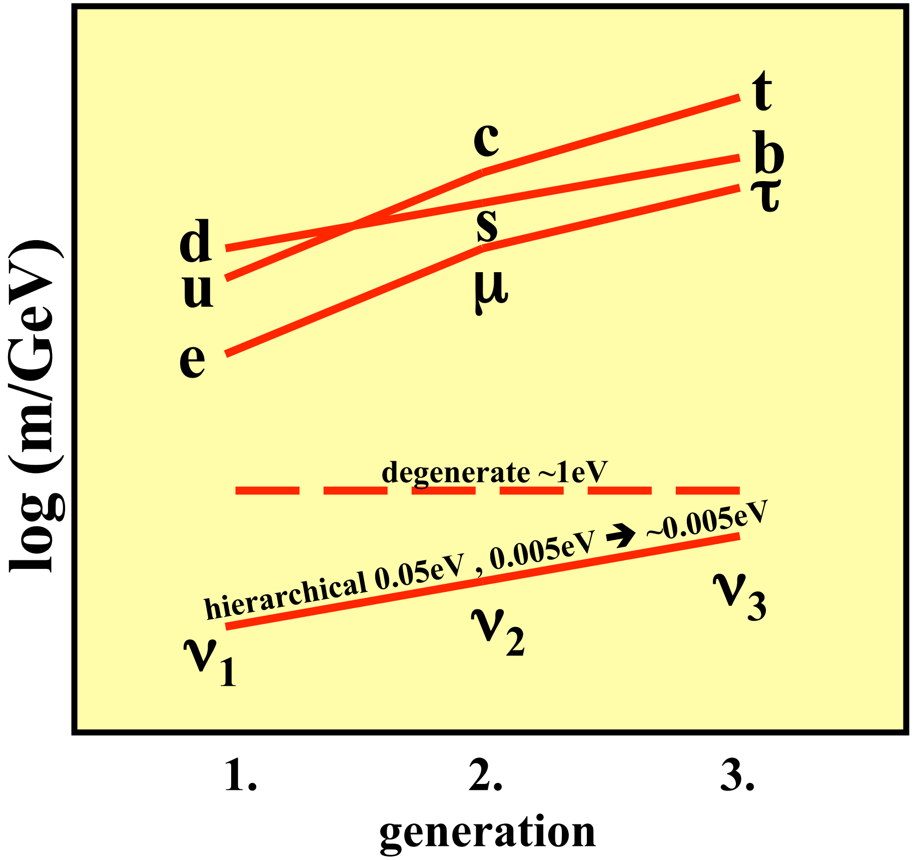
For $m_3 \sim (\Delta m^2_{atm})^{1/2}$, $m_D \sim$ leptons → $M_R \sim 10^{11}$ - 10^{16}GeV

→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	$\simeq$10	$\geq$20	?	$\geq$20

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

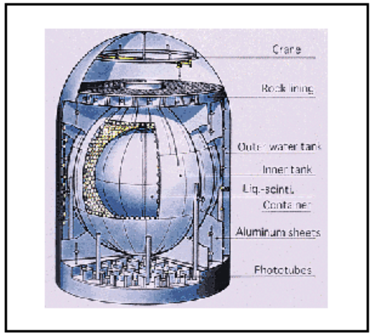
» other version of see-saw? ➔ type II, III, …?

» Dirac masses?

Neutrino Mass Determinations

Subtitle: What do we actually measure?

Status of Neutrino Oscillations



Reactors: KAMLAND

improved results

Beams: K2K → MINOS

→ T2K, OPERA

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

$$\Delta m^2_{31} = \begin{cases} -2.40 \pm 0.11 \; \left({}^{+0.37}_{-0.39}\right) \times 10^{-3}\ \text{eV}^2\ (\text{inve} \\ +2.51 \pm 0.12 \; \left({}^{+0.39}_{-0.36}\right) \times 10^{-3}\ \text{eV}^2\ (\text{nor} \end{cases}$$

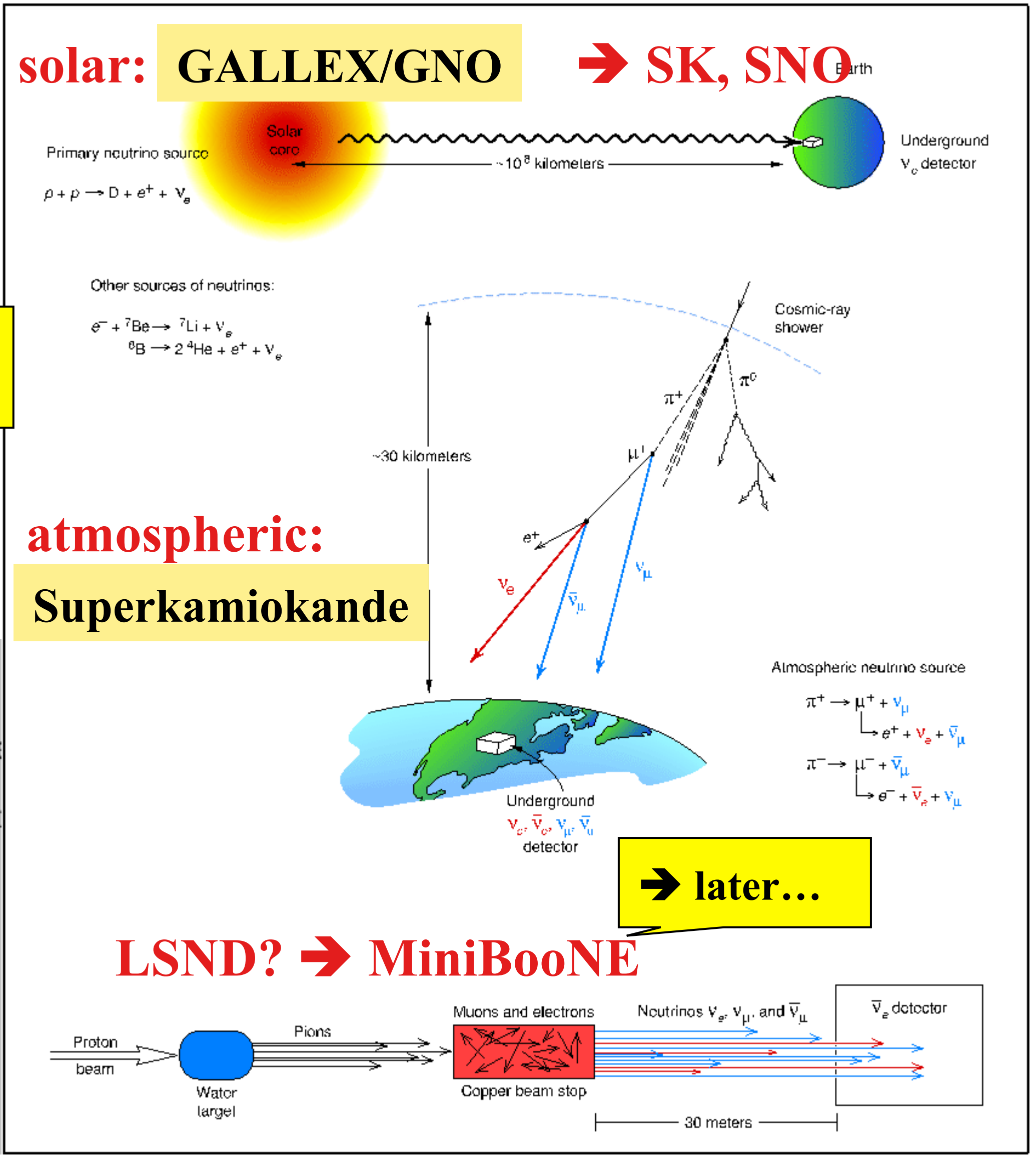
$$\theta_{12} = 34.4 \pm 1.0 \; \left({}^{+3.2}_{-2.9}\right)$$

$$\theta_{23} = 42.3\,{}^{+5.3}_{-2.8} \; \left({}^{+11.4}_{-7.1}\right)$$

$$\theta_{13} = 6.8\,{}^{+2.6}_{-3.6} \; (\leq 13.2)$$

$$\left[\sin^2\theta_{13} = 0.014\,{}^{+0.013}_{-0.011} \; (\leq 0.052)\right]$$

$$\delta_{\text{CP}} \in [0,\ 360]$$



solar: **GALLEX/GNO** → **SK, SNO**

atmospheric:

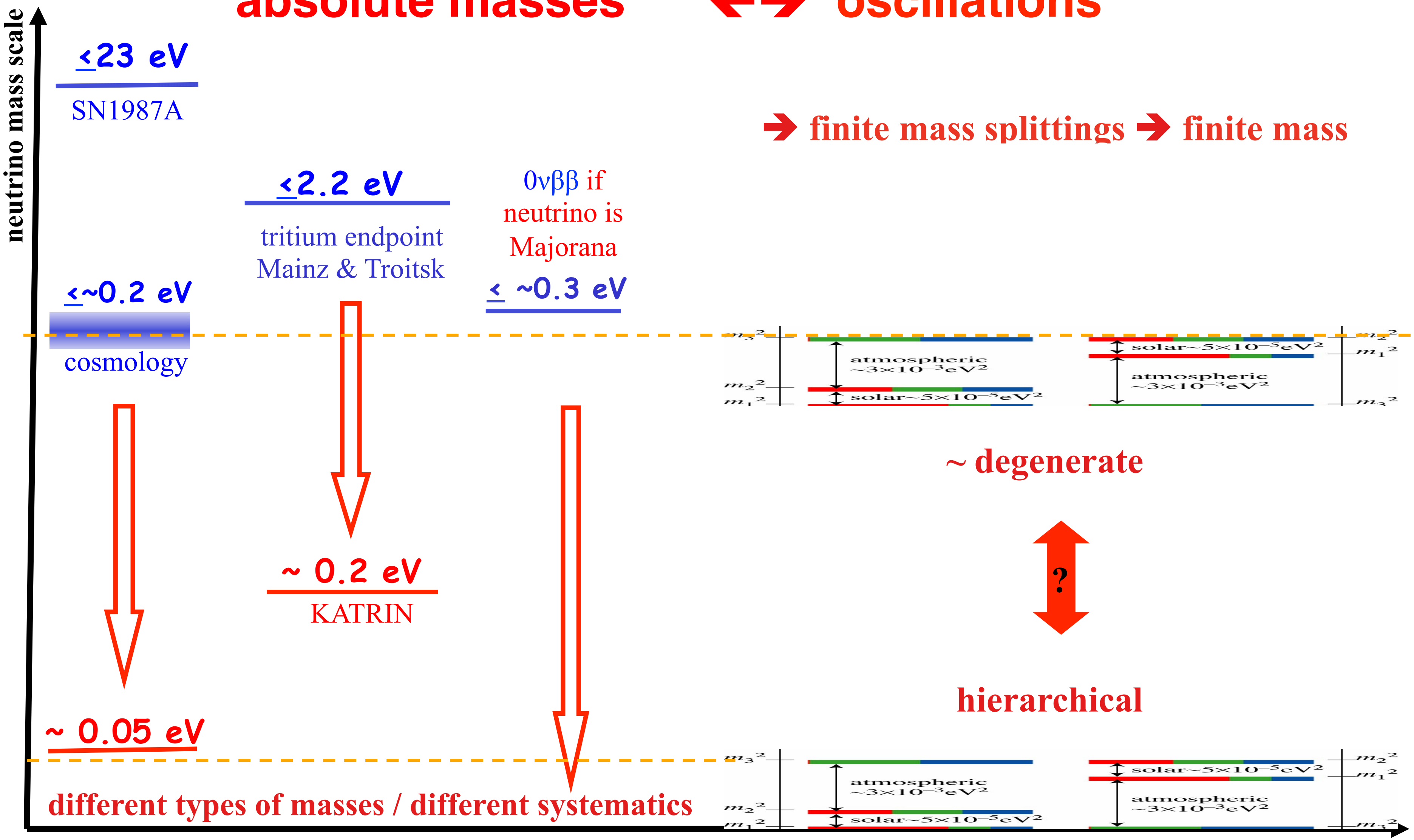
Superkamiokande

→ later…

LSND? → MiniBooNE

What is special about 50meV ?

absolute masses ↔ oscillations



neutrino mass scale

≤23 eV

SN1987A

≤2.2 eV

tritium endpoint
Mainz & Troitsk

0νββ if
neutrino is
Majorana

≤ ~0.3 eV

≤~0.2 eV

cosmology

~ 0.2 eV

KATRIN

~ 0.05 eV

different types of masses / different systematics

➔ finite mass splittings ➔ finite mass

~ degenerate

?

hierarchical

Four Methods of Mass Determination

- kinematical
- lepton number violation
  ↔ Majorana nature
- oscillations
- astrophysics & cosmology

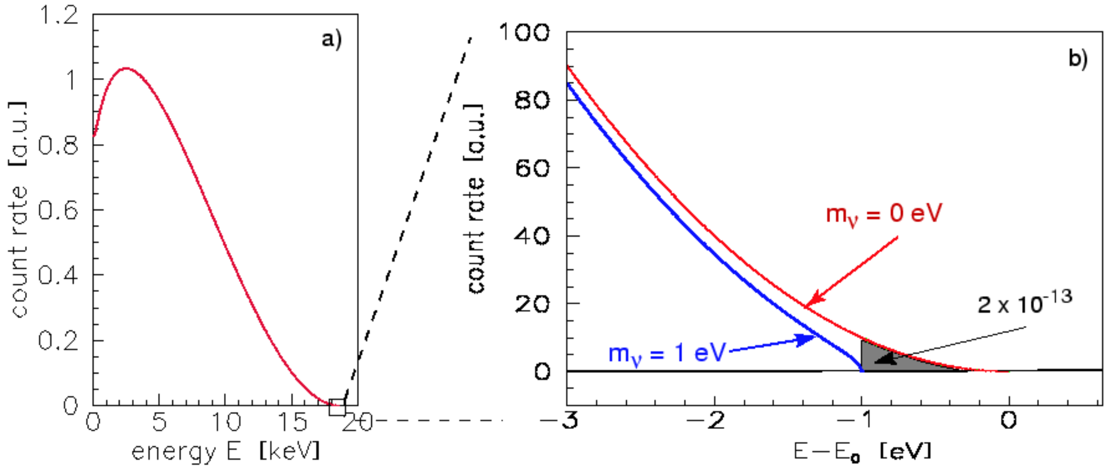
Kinematical Mass Determination

Relativistic kinematics:

$$E^2 = p^2 + m^2; \ \sum p_i^\mu = \sum p_f^\mu$$

Endpoint of decays:

Tritium $\rightarrow He^3 + e^- + \overline{\nu}_e$



Bounds:

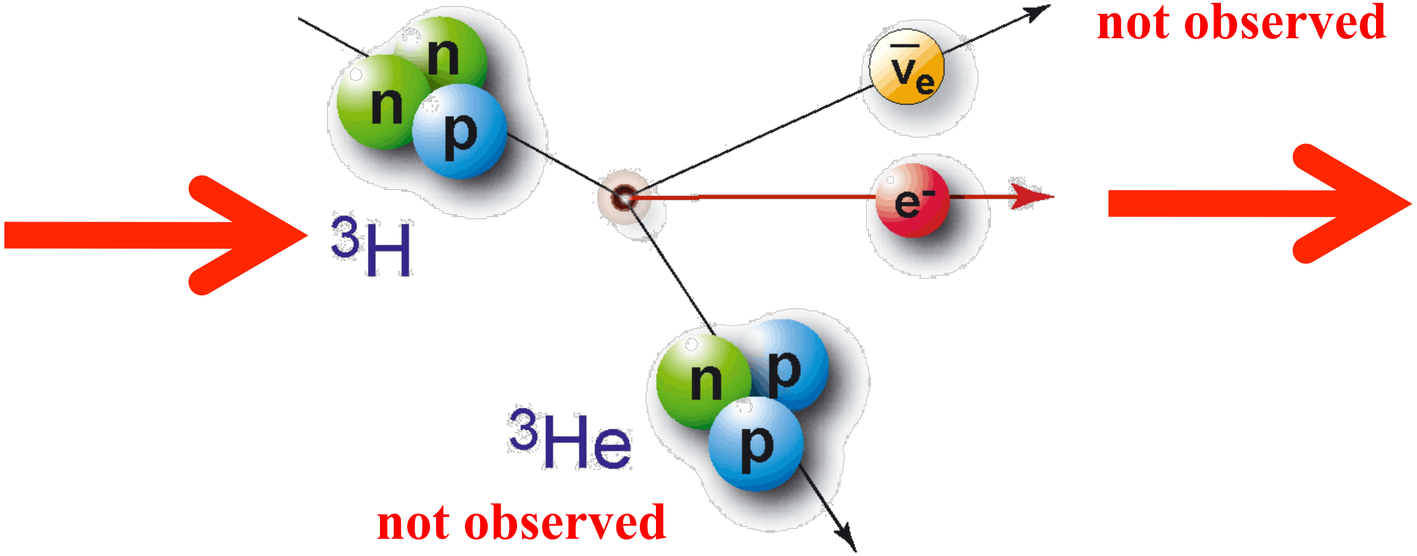
"Elektron-Neutrino": $m < 2.2$ eV (Mainz, Troitsk)
"Muon-Neutrino": $m < 170$ keV
"Tau-Neutrino": $m < 15.5$ MeV

Sensitivity ⇔ degenerate ν-spectrum

⇒ **Oscillations:** $\Delta m_{ij}^2 \ll m_i^2 \Rightarrow$ $\boxed{\sum m_i^2 |U_{ei}|^2 < (2.2 \text{ eV})^2}$

Future: **KATRIN → 0.20 eV** ←→ **c.f. comological bounds**

Other Options?



not observed

not observed

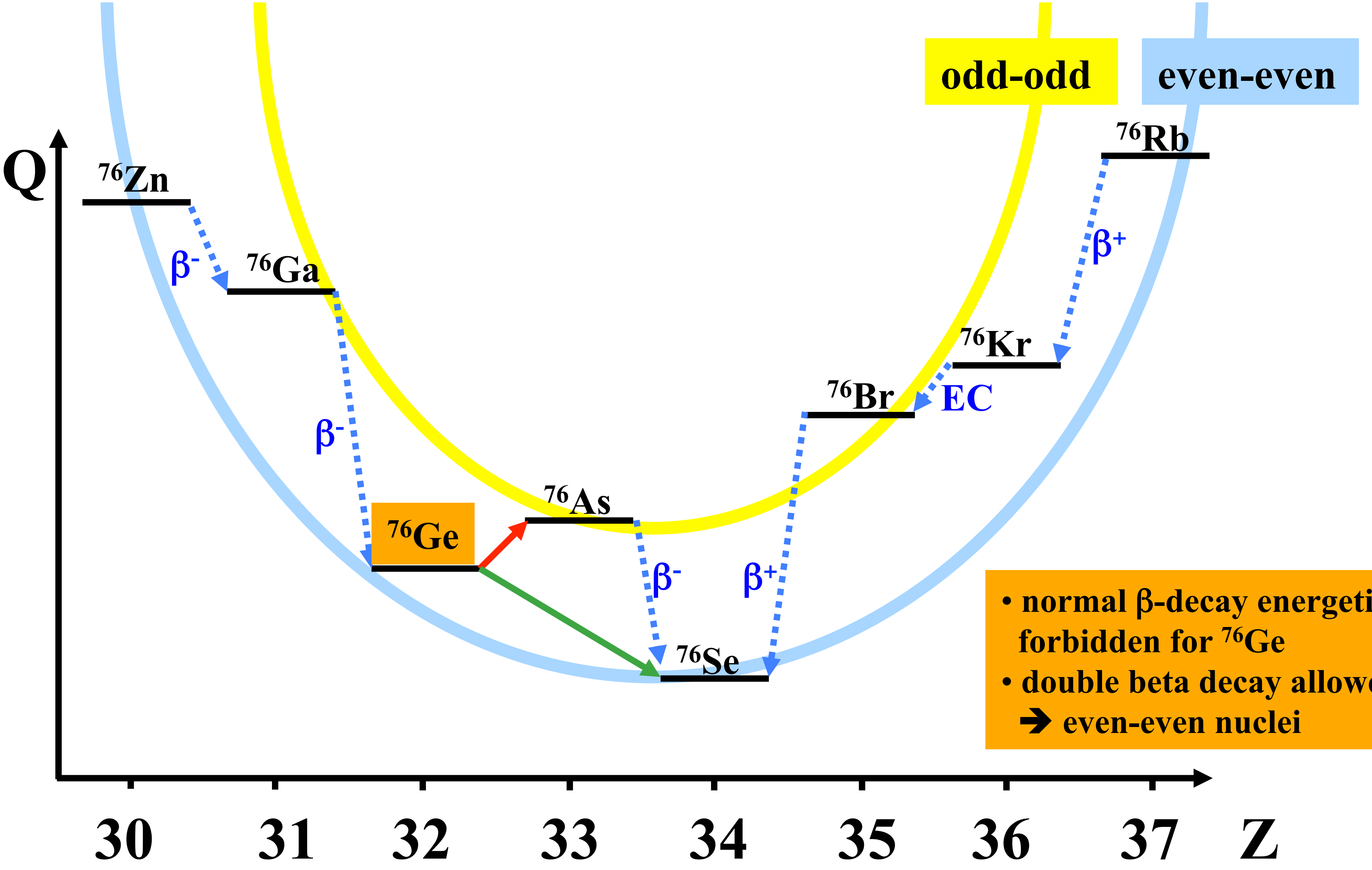
Other new physics which modifies kinematics of the endpoint?

➔ …

Four Methods of Mass Determination

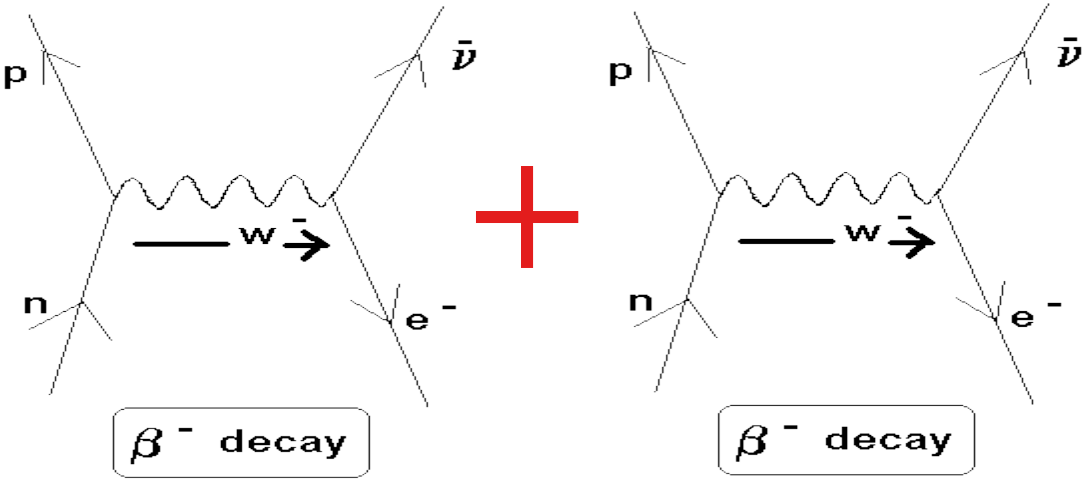
- kinematical
- lepton number violation
  ←→ Majorana nature
- oscillations
- astrophysics & cosmology

Double Beta Decay: Mass Parabolas

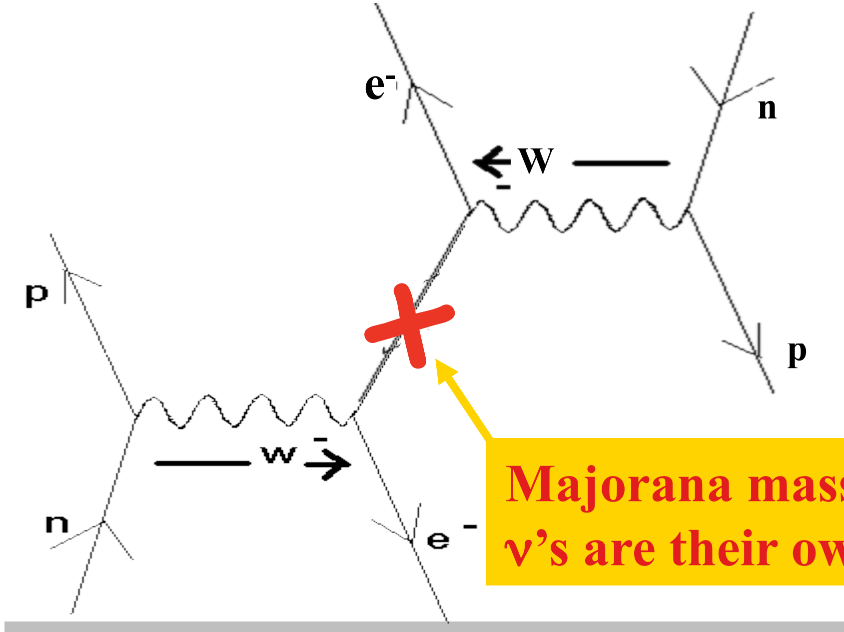


- normal β-decay energetically forbidden for ^{76}Ge
- double beta decay allowed ➔ even-even nuclei

Double Beta Decay



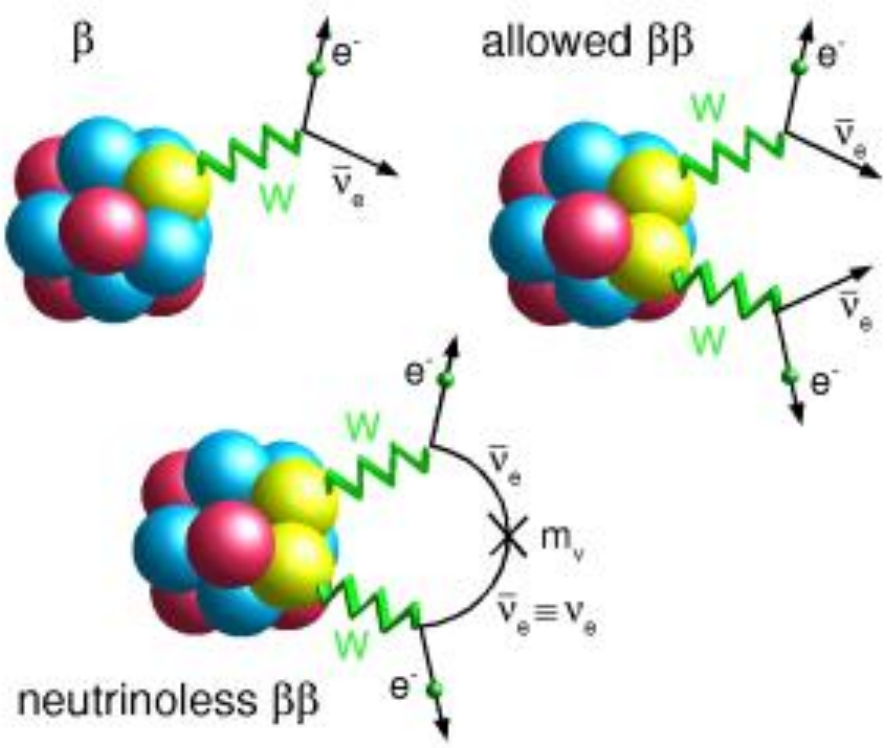
→ 2 neutrinos plus 2 electrons



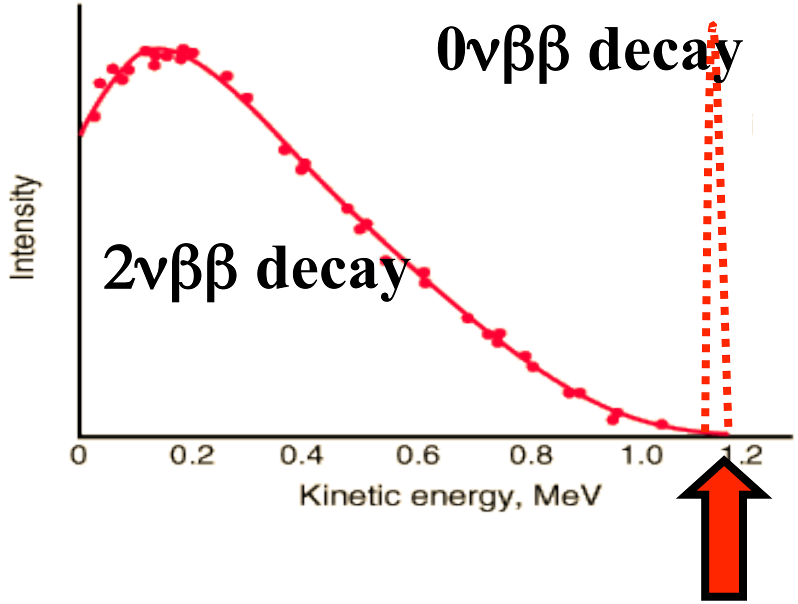
Majorana mass ←→
ν's are their own antiparticles

→no neutrinos just 2 electrons

0νββ Decay Kinematics



2νββ decay of ^{76}Ge observed:
$\tau = 1.5 \times 10^{21}$ y



Majorana ν ➔ 0νββ decay

<u>warning:</u>

other lepton number violating processes…

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

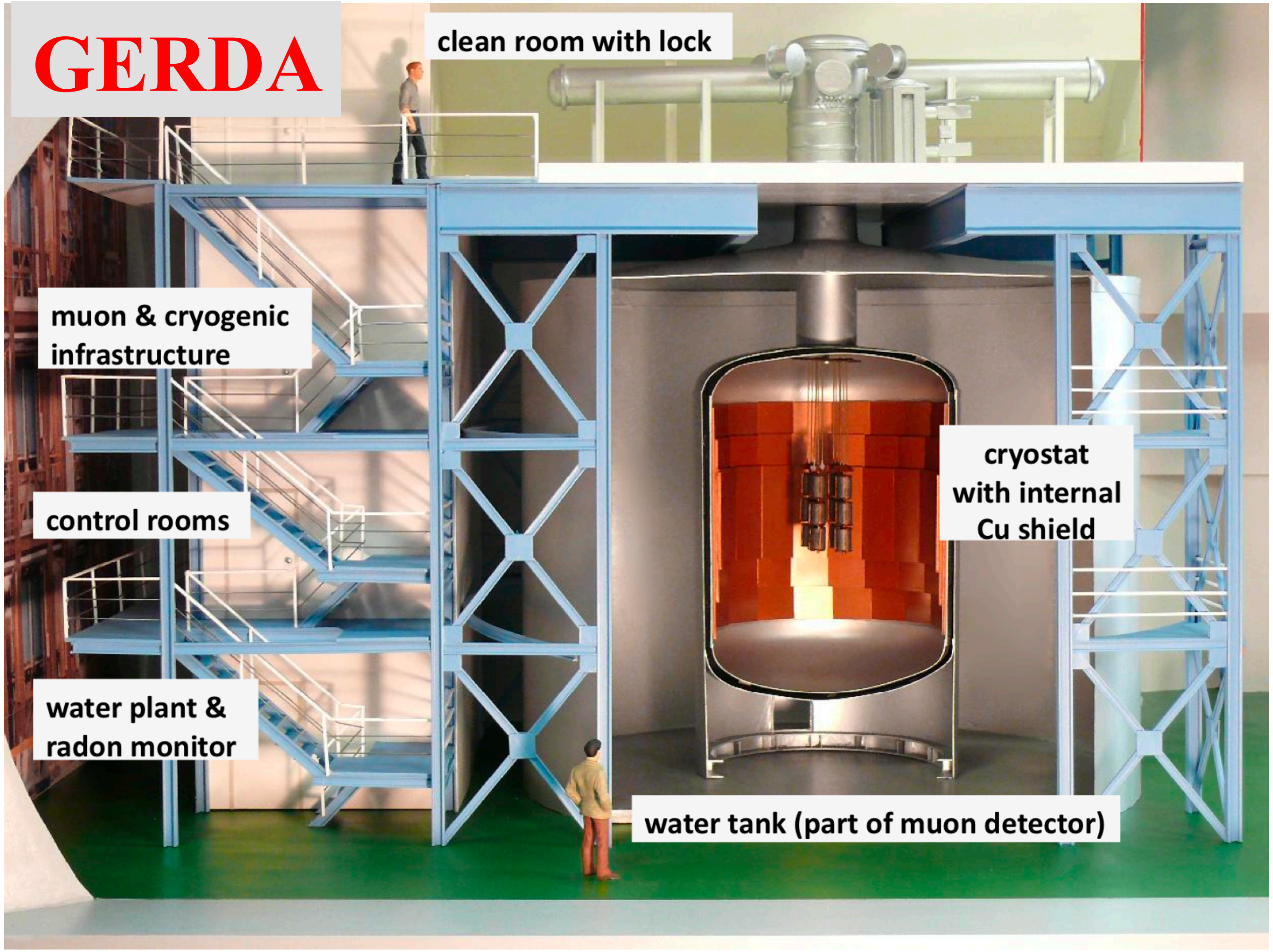
New Experiments

- GERDA (Ge76)
- EXO (Xe136)
- KamLAND-zen (Xe)

Construction:

- CUORE (Te-130)
- Majorana (Ge76)
- Super-NEMO (mult)

GERDA



➔ filled, commissioning with non-enriched Ge

➔ Start of phase I: Nov. 1, 2011(enriched)

Decay Rates

$2\nu 2\beta$:

$$\left[T_{\frac{1}{2}}^{2\nu}\,(0^+\to 0^+)\right]^{-1} = G^{2\nu}(E_0,Z)\left|M_{GT}^{2\nu}-\frac{g_V^2}{g_A^2}M_F^{2\nu}\right|^2$$

Phase space

nuclear matrix element

$0\nu 2\beta$:

(assuming that leading term is due to exchange of light Majorana-neutrinos)

$$\left[T_{\frac{1}{2}}^{0\nu}(0^+ \to 0^+)\right]^{-1} = G^{0\nu}(E_0,Z)\left|\,M_{GT}^{0\nu} - \frac{g_V^2}{g_A^2}M_F^{0\nu}\,\right|^2 <m_\nu>^2$$

Warning: other…

effective Majorana mass

Relating Rates / Lifetimes to Neutrino Masses

rate of 0νββ

phase space

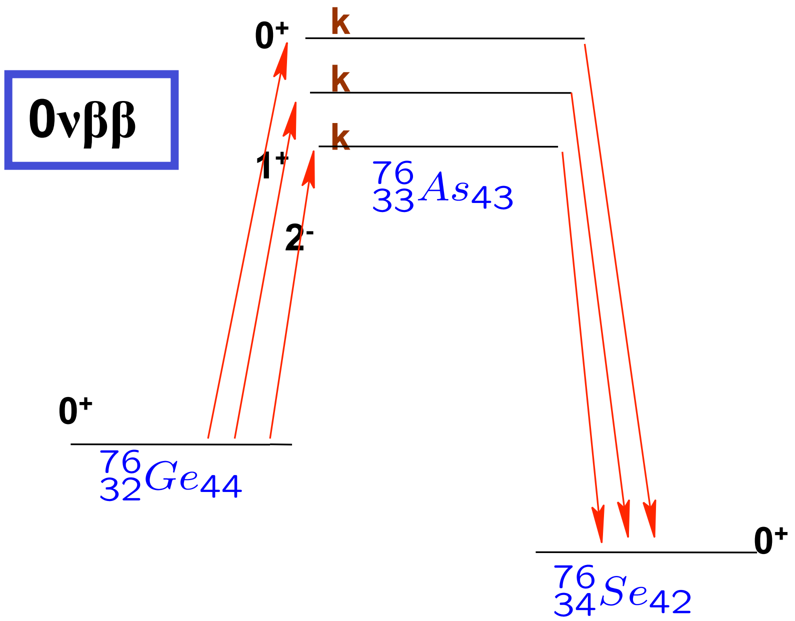
nuclear matrix elements

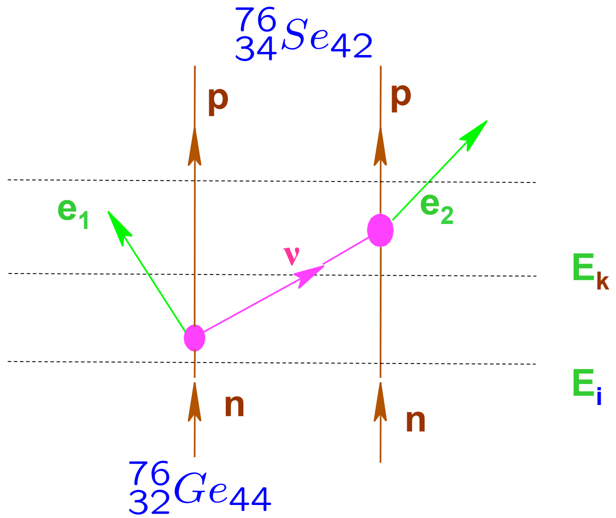
effectiveMajorana neutrino mass

$$1/\tau = G(Q,Z)\ |M_{nucl}|^2 <m_{ee}>^2$$

nuclear matrix elements: Fäßler et al., …

➔ virtual excitations of intermediate states





$$T = \Sigma_k \frac{< f|\hat{H}_W|k >< k|\hat{H}_W|i >}{E_i - E_k}$$

progress in TH errors ➔ reduced uncertainties

Nuclear Matrix Elements

0ν2β half-lives in units of 10^{26} years for <m_ν>=50 meV for nuclear matrix for different methods and authors

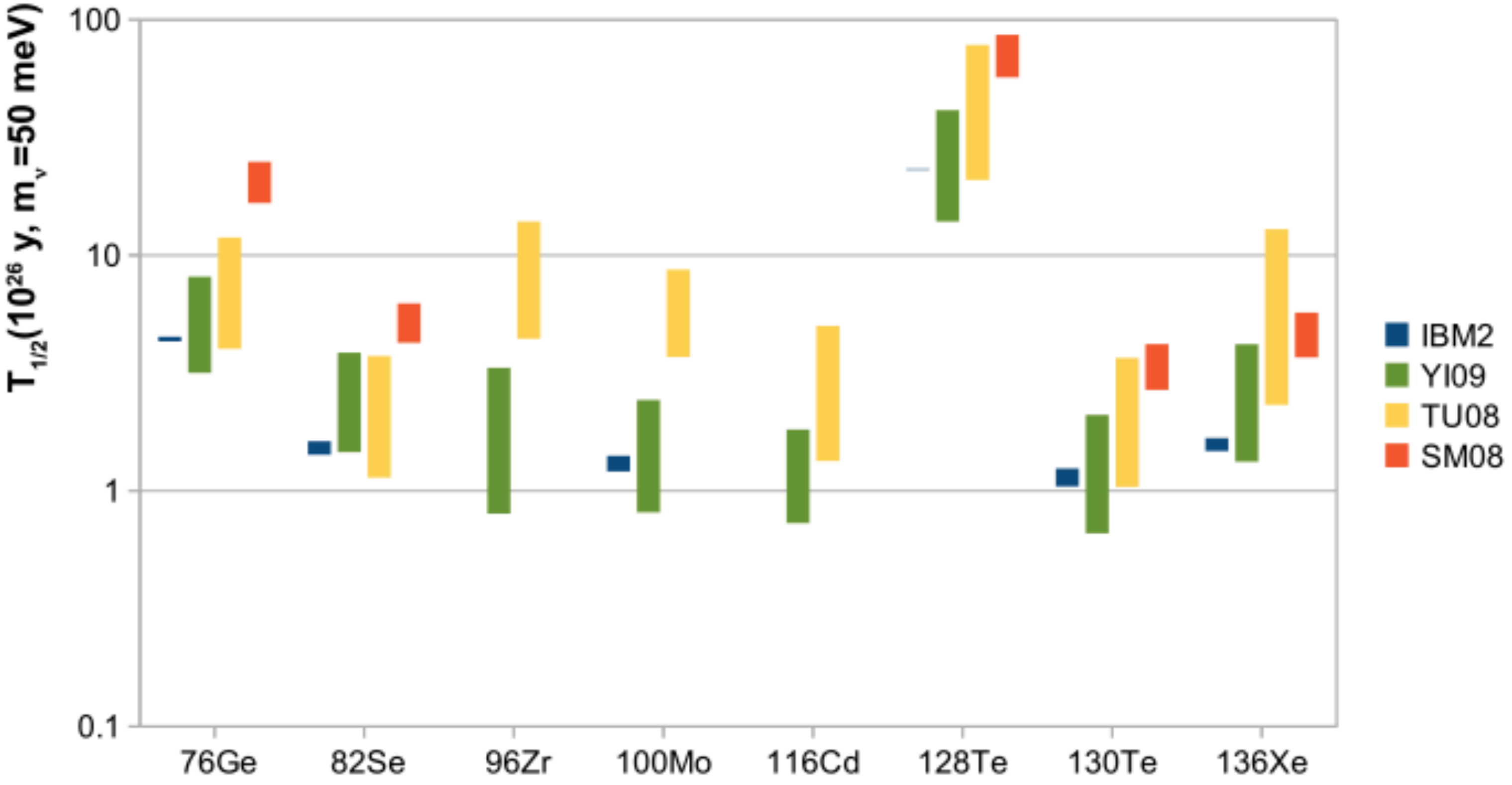
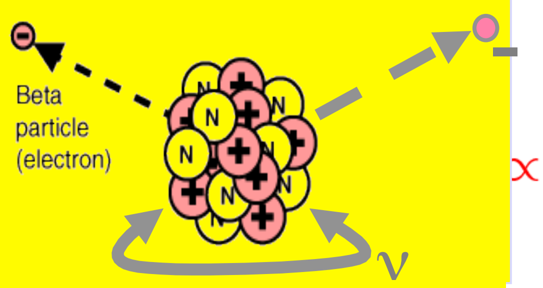


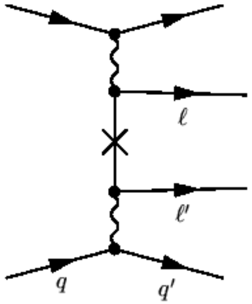
Figure 1: Expected $\beta\beta(0\nu)$ half lives for 50 meV effective neutrino mass and different NME calculations: IBM2 [17], YI09 [18], TU08 [19] and SM08 [20].

Effective Majorana Mass



Majorana ν ➔ 0ν2β decay

$\propto$

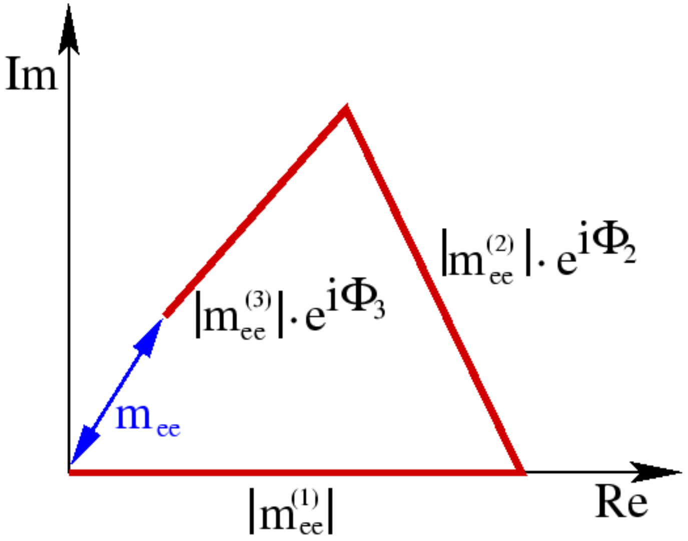


$$\propto |\langle m_{ee} \rangle| \;=\; |\textstyle\sum m_i U_{ei}^2| \quad \boxed{\leq 0.35 \text{ eV ?}}$$

Heidelberg-Moscow experiment

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

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



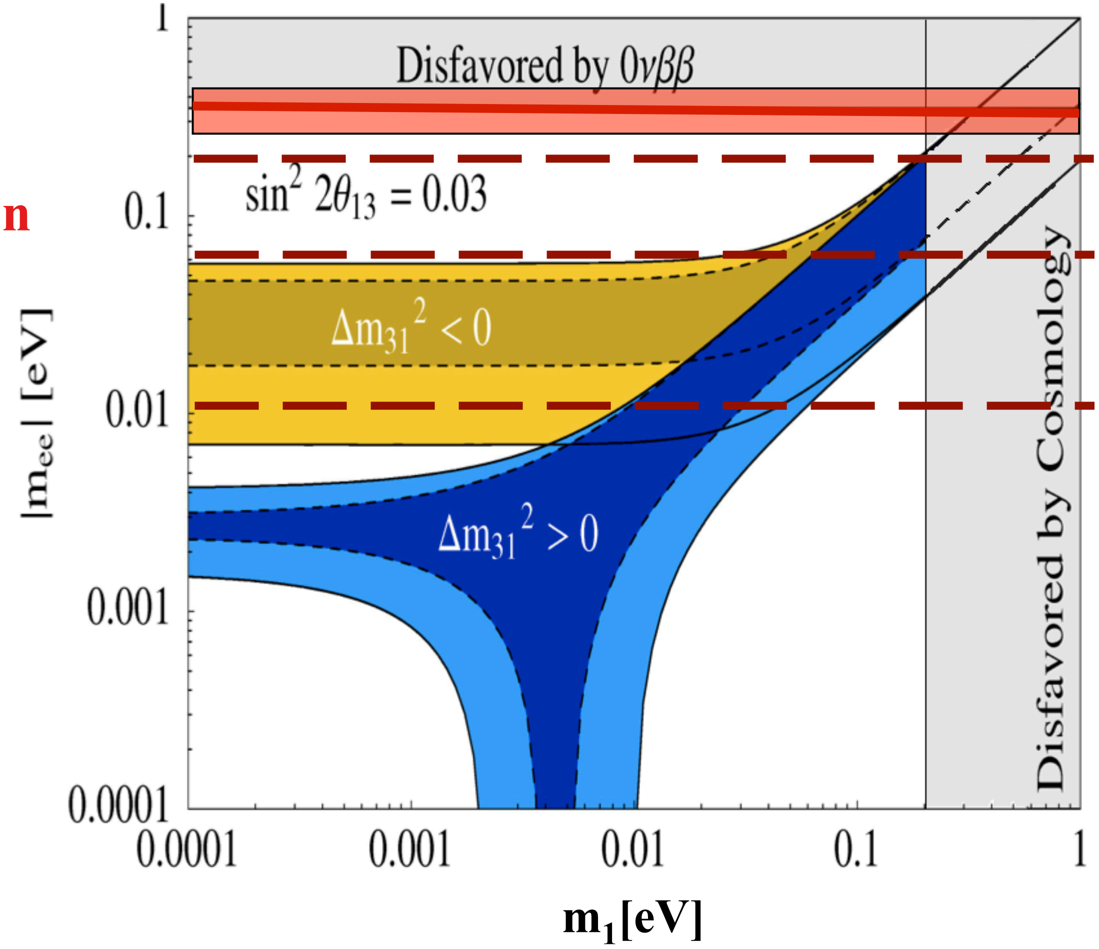
solar $\Rightarrow$ $|U_{e1}|^2, |U_{e2}|^2, \Delta m_{21}^2$ atmosph. $\Rightarrow$ $|\Delta m_{31}^2|$ CHOOZ $\Rightarrow$ $|U_{e3}|^2 < 0.05$

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

Claim of part of the original Heidelberg-Moscow collaboration $\Leftrightarrow$ cosmology ➔ ‚tension‘

aims of new experiments:

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



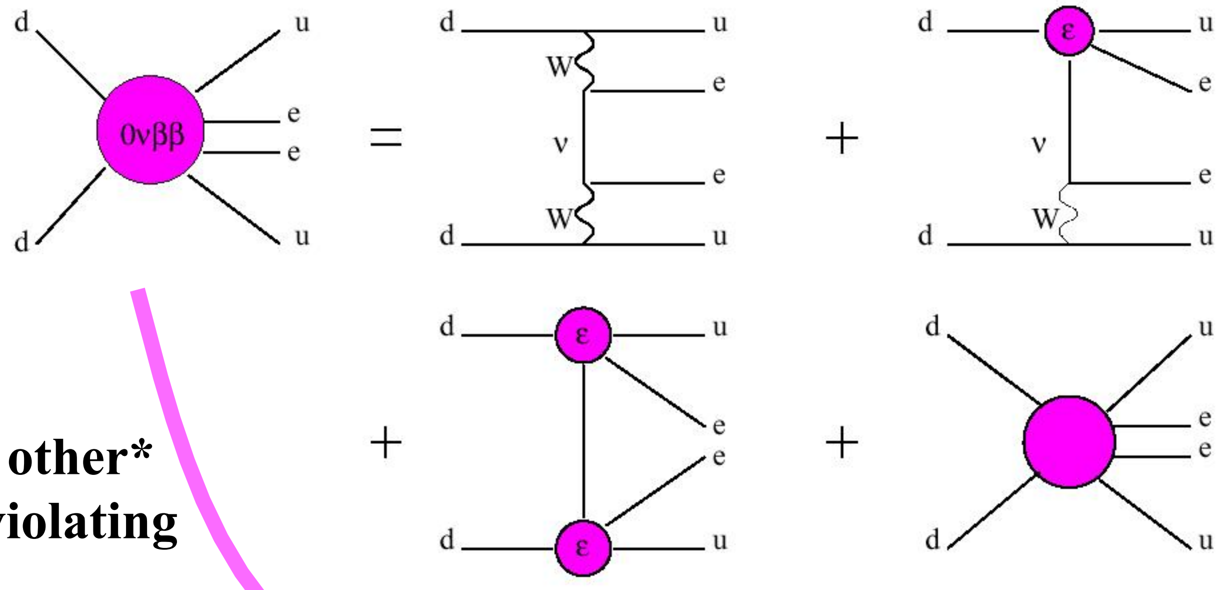
Comments:

- 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

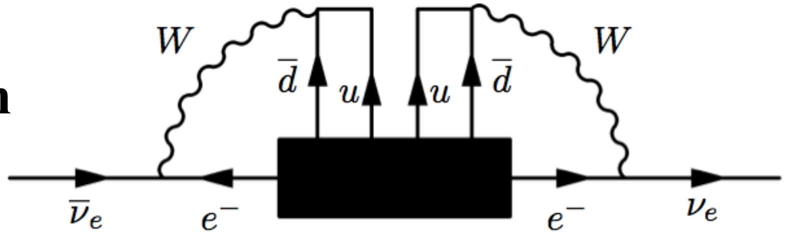
➔ very promising interplay of neutrino mass determinations, cosmology, LHC, LVF experiments and theory

Schechter + Valle: Any ΔL=2 violating operator

➔ radiative generation of Majorana mass term

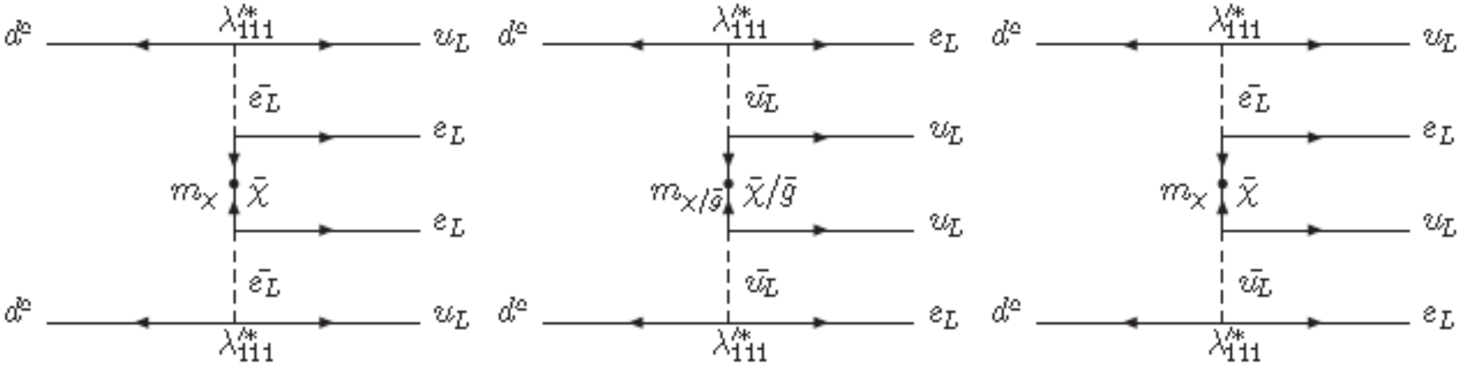
➔ Majorana nature of ν's guaranteed

➔ but how big is the mass?



SUSY Example

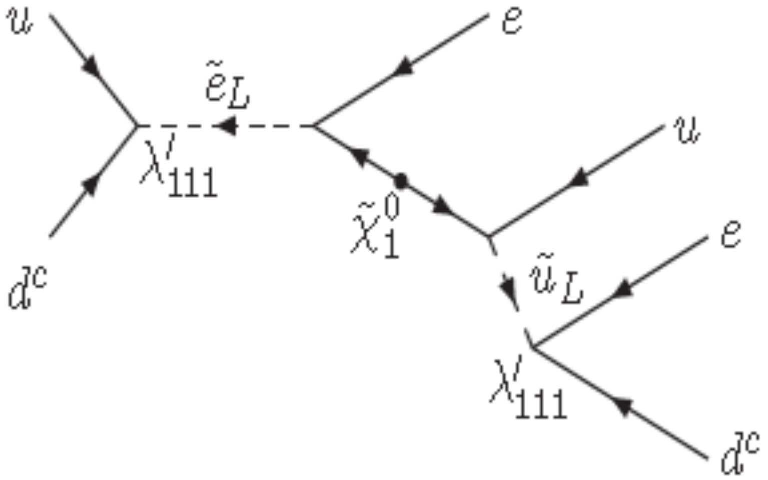
Direct, TeV scale short range mediation w/o intermediate light ν, e.g.



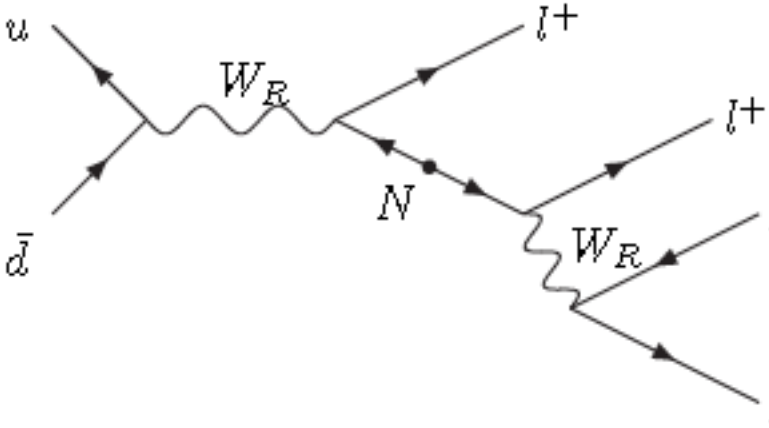
$$\begin{aligned}
\mathcal{L}^{eff,\,\Delta L_e=2}_{\lambda'_{111}\lambda'_{111}}(x) \quad &= \quad \frac{G_F^2}{2} m_p^{-1} [\bar{e}(1+\gamma_5)e^c] \\
&\quad \times \left[(\epsilon_{\tilde{g}} + \epsilon_\chi)(J_{PS}J_{PS} - \frac{1}{4} J_T^{\mu\nu} J_{T\mu\nu}) + (\epsilon_{\chi\tilde{e}} + \epsilon'_{\tilde{g}} + \epsilon_{\chi\tilde{f}}) J_{PS}J_{PS} \right] \\
\epsilon_i \quad &\sim \quad \pi\alpha_{(\mathrm{Strong,EW})} \frac{\lambda'^2_{111}}{G_F^2} \frac{m_P}{m_{(\tilde{g},\tilde{\chi})}} \frac{1}{m^4_{(\tilde{u},\tilde{d},\tilde{e})}} .
\end{aligned}$$

ΔL=2 Operators and TeV Scale Physics

SUSY: direct test of λ'$_{111}$

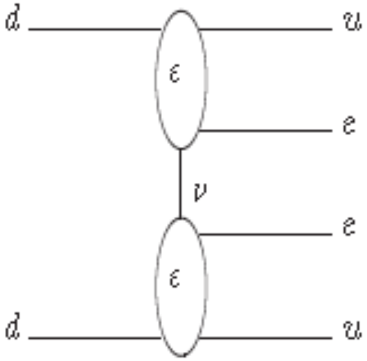


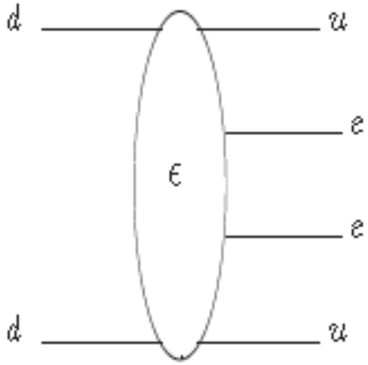
L-R symmetry: heavy N's



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

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





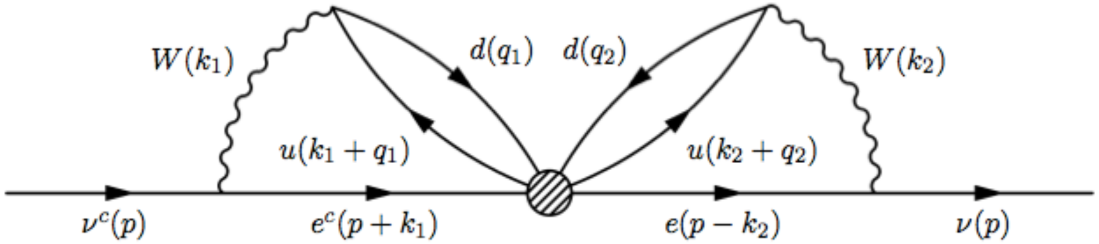
$$M_{\rm heavy} \sim G_F^2 \left(\frac{\lambda}{g_2}\right)^4 \frac{M_W^4}{\Lambda^5}$$

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

Four Methods of Mass Determination

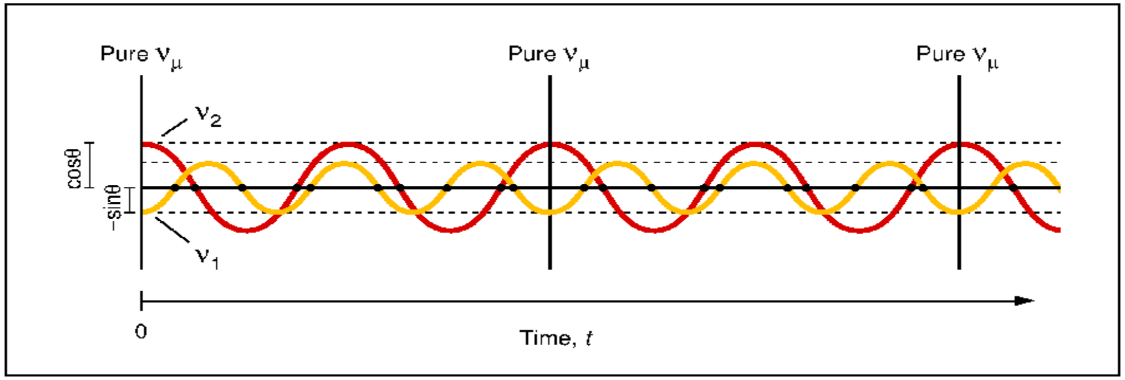
- **kinematical**
- **lepton number violation**

  ←→ Majorana nature
- **oscillations**
- **astrophysics & cosmology**

Two Neutrino Oscillations

2 Neutrinos: ν_e,ν_μ

$$\begin{aligned} |\nu_e(0)\rangle &= \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle \\ |\nu_\mu(0)\rangle &= -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle \end{aligned}$$



$$|\nu_\mu(t)\rangle = -\sin\theta\ \exp[-\frac{iE_1t}{\hbar}]\ |\nu_1\rangle + \cos\theta\ \exp[-\frac{iE_2t}{\hbar}]\ |\nu_2\rangle$$

$$E_i = \sqrt{p_i^2 + m_i^2} \quad \xrightarrow{p_i = p \gg m_i} \quad \simeq p + \frac{m_i^2}{2p} \quad \simeq p + \frac{m_i^2}{2E}$$

$$L = c \cdot t \qquad \Delta m^2 = m_2^2 - m_1^2 \Rightarrow \quad E_2 - E_1 = \frac{\Delta m^2}{2E}$$

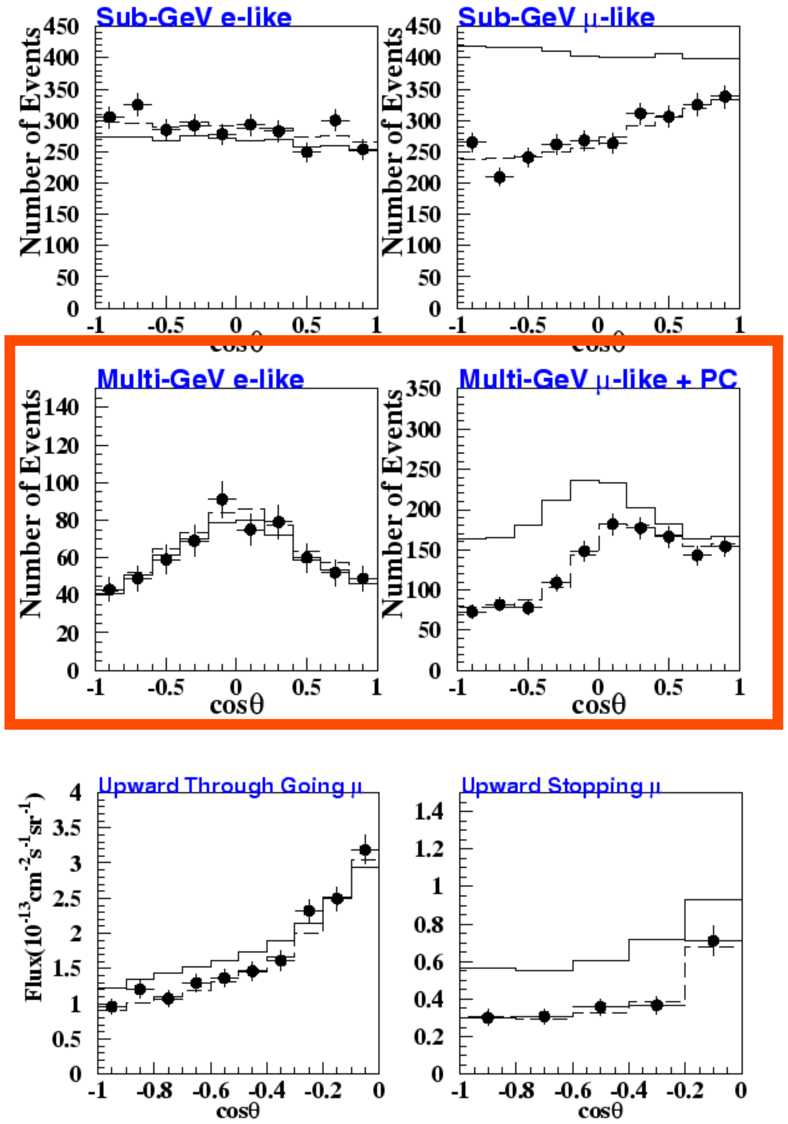
2ν-transition-probability:

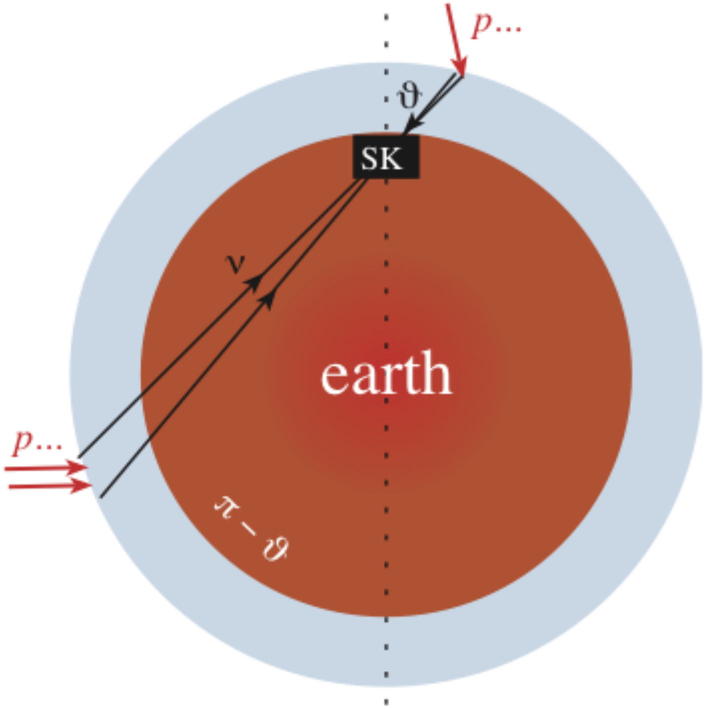
$$\boxed{P(\nu_\mu \to \nu_e) = |\langle \nu_\mu(t)|\nu_e(0)\rangle|^2 = \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2 L}{4E}\right)}$$

ν_e , ν_μ , ν_τ ➔ 9 oscillation channels for neutrinos

$\overline{\nu}_e$, $\overline{\nu}_\mu$, $\overline{\nu}_\tau$ ➔ 9 channels for anti-neutrinos (assuming 3ν !)

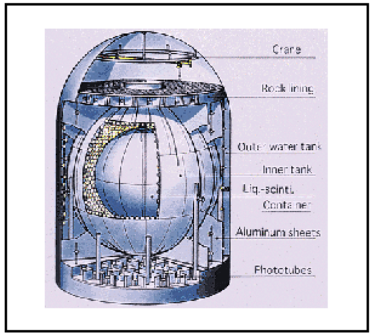
Atmospheric Oscillations @SuperK





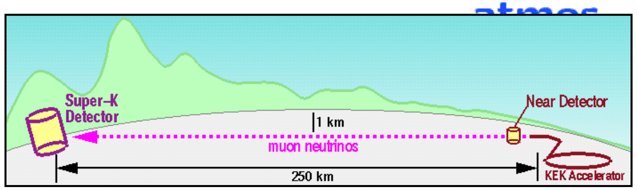
- 8σ signal for ν_μ disappearance
- NOT $\nu_\mu \longrightarrow \nu_e$ (consistent with Chooz)
- $\Rightarrow$ $\nu_\mu \longrightarrow \nu_\tau$ (some $\tau's$ seen)
- NOT $\nu_\mu \longrightarrow \nu_s$ from NC/CC comparison
- L/E confirmed by K2K ($\simeq 2\sigma$)
- sensitivity for L/E-dependence of oscillations

Status of Neutrino Oscillations

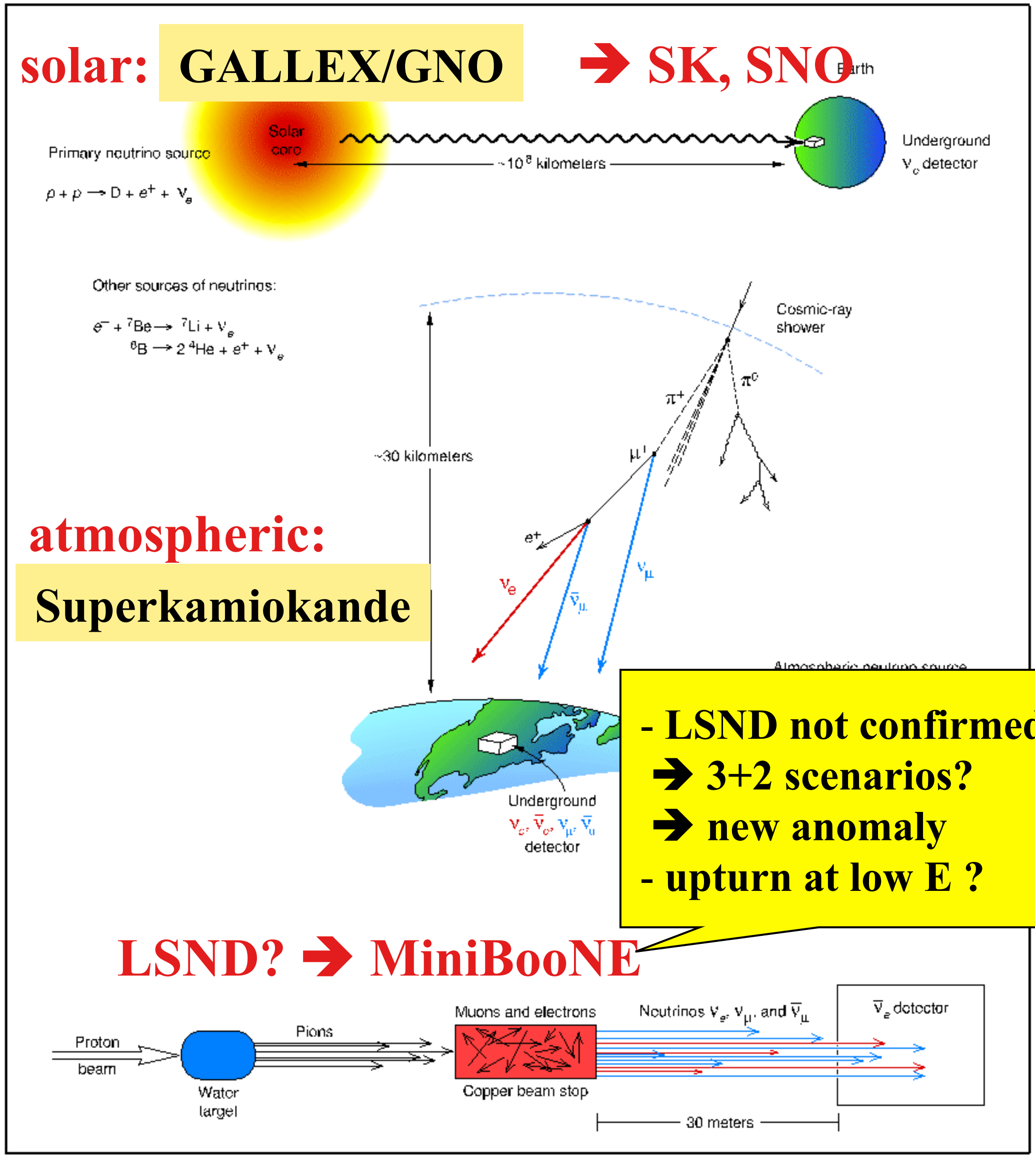


Reactors: KAMLAND

Beams: K2K ➔MINOS
➔ OPERA



$\Delta m^2_{21} = (7.9 \pm 0.3) * 10^{-5}\ \mathrm{eV}^2$
$\tan^2\theta_{12} = 0.39 \pm 0.05$
$\Delta m^2_{31} = (2.4 \pm 0.3) * 10^{-3}\ \mathrm{eV}^2$
$\tan^2\theta_{23} = 1.0 \pm 0.3$
$\sin^2 2\theta_{13} = 0.09 \pm \sim 0.02$



solar: GALLEX/GNO ➔ SK, SNO

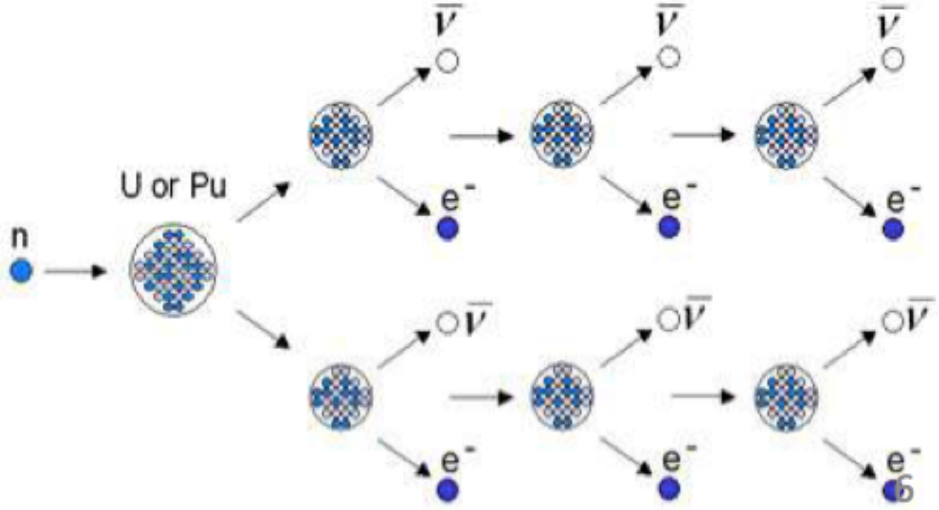
atmospheric: Superkamiokande

LSND? ➔ MiniBooNE

- LSND not confirmed !
  ➔ 3+2 scenarios?
  ➔ new anomaly
- upturn at low E ?

Nuclear Reactors as Antineutrino Source

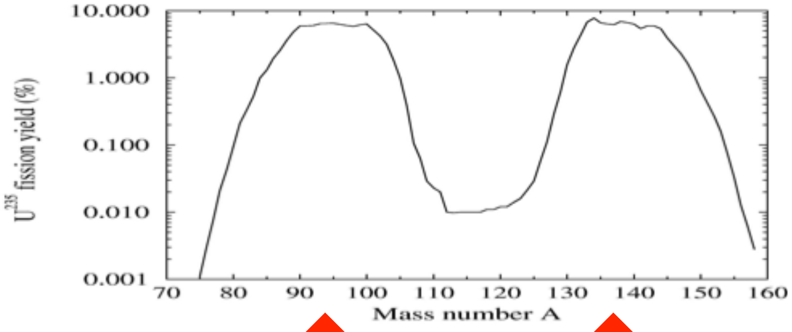
- **Reactors like Chooz A+B ➔ 8.5 GW_{th}**
- **Few percent of the released energy**
  ➔ escapes with anti-neutrinos
  ➔ $2 \cdot 10^{21} \bar{\nu}$/s ←→ O(1 kW/$m^2$) @fence



- **measured e^- spectrum of U^{235}, Pu^{239}, Pu^{241}**
  ➔ calculate $\bar{\nu}_e$ − spectrum ➔ precisions?

example: fission of U^{235}

$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$



most likely A

➔ <u>on average:</u>

- **6 neutrons β-decay t**
  6 protons to reach
  stable matter
- **1.5 ν_e emitted**
  with E > 1.8 MeV

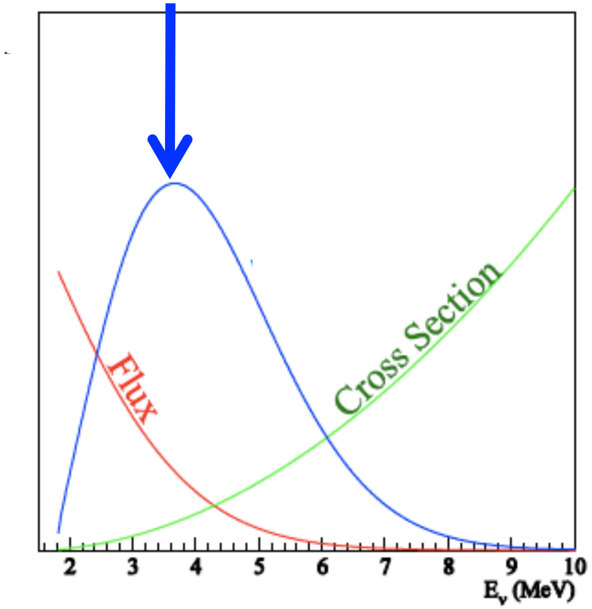
Anti-Neutrino Detection

Oscillations:

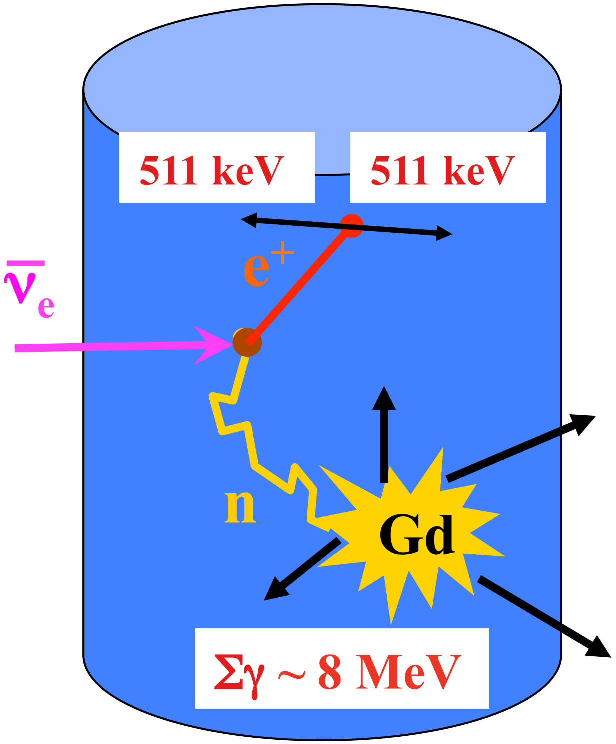
- affect rate & shape

Earlier reactor experiments:

- calculated spectrum
- rate normalized by $P_{thermal}$
- event rate = flux * x-section



- uncertainties in x-sections?



$\bar{\nu}_e + p \rightarrow e^+ + n$

prompt e^+ signal

delayed n capture
➔Gd doping
➔delayed γ (30 μs)

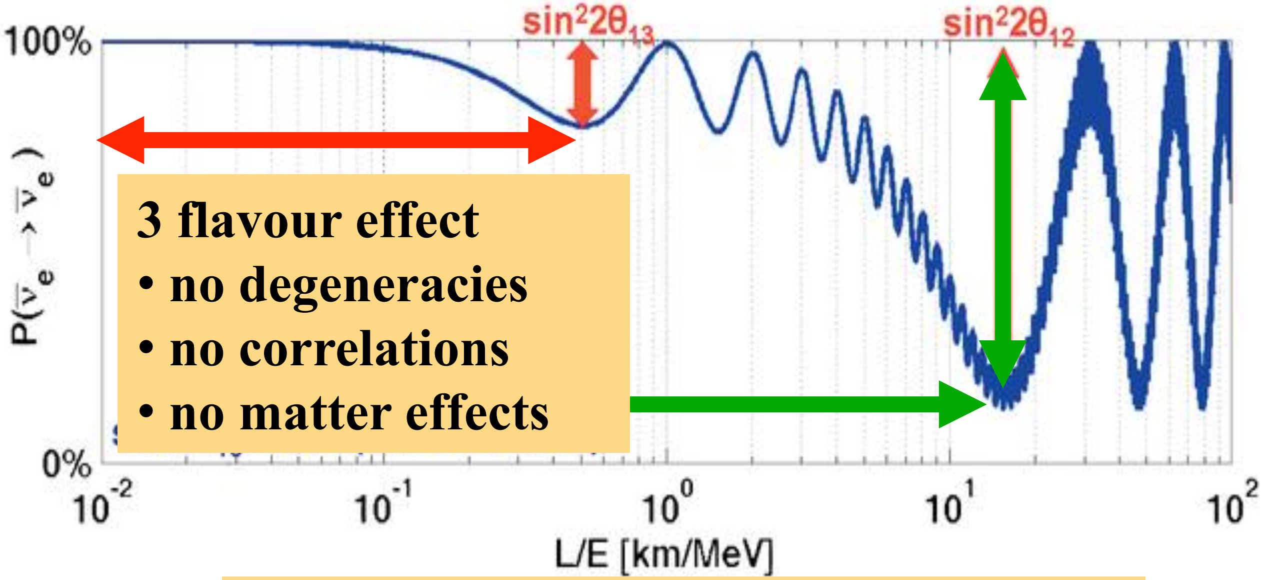
- position & time correlation
- delayed energy information
  ➔ background reduction!

Gd loaded liquid scintillator
  ➔ stability, transparency, WLS, …

Precision with Reactor Experiments

identical detectors → many errors cancel

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4 E_\nu} - \left(\frac{\Delta m^2_{21} L}{4 E_\nu}\right)^2 \cos^4 \theta_{13} \sin^2 2\theta_{12}$$



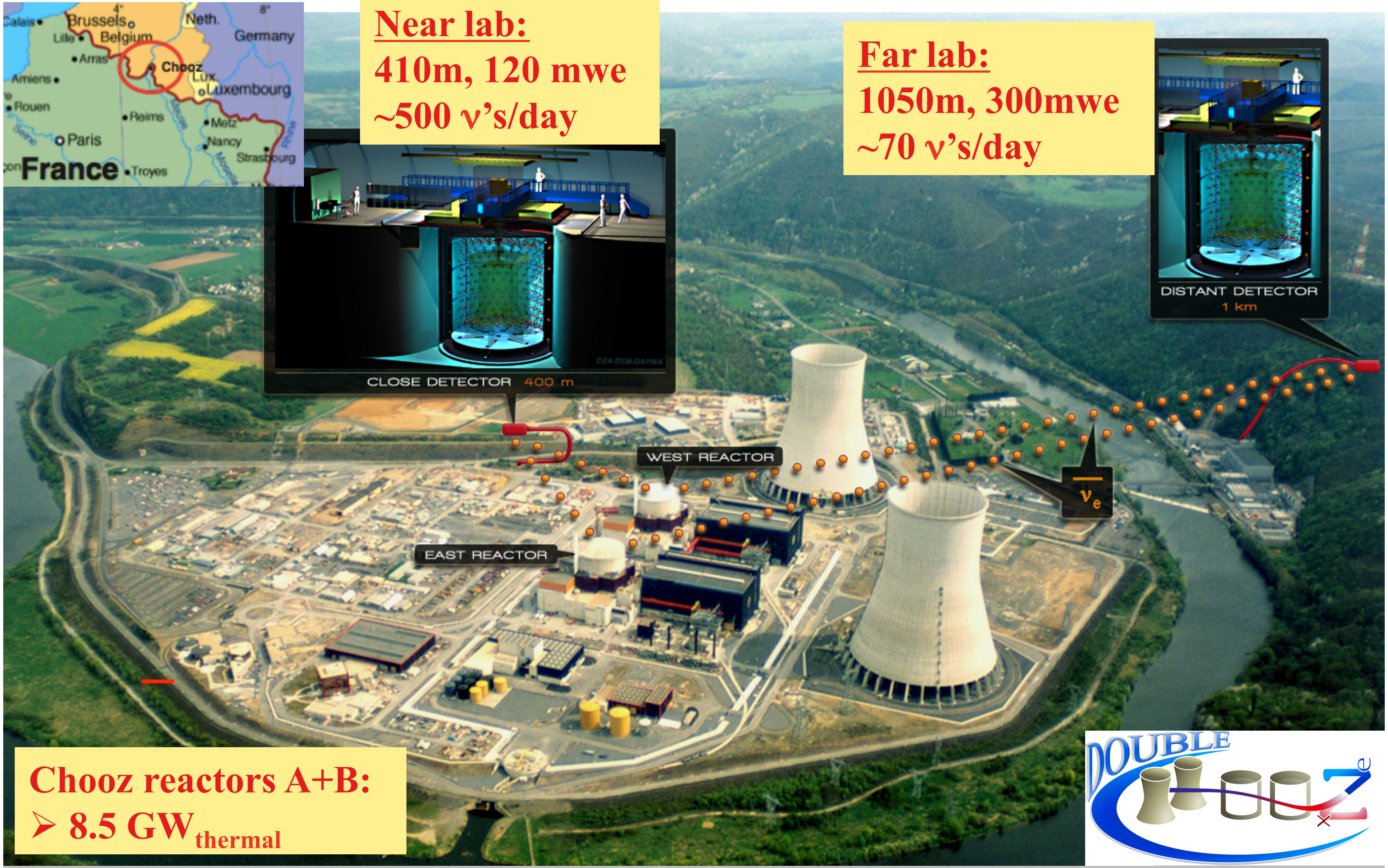
3 flavour effect
- **no degeneracies**
- **no correlations**
- **no matter effects**

E=4MeV → 1km 180km

clean & precise
θ_{13} measurments
←→ beams

→Double Chooz
→ Daya Bay
→ Reno

Double Chooz



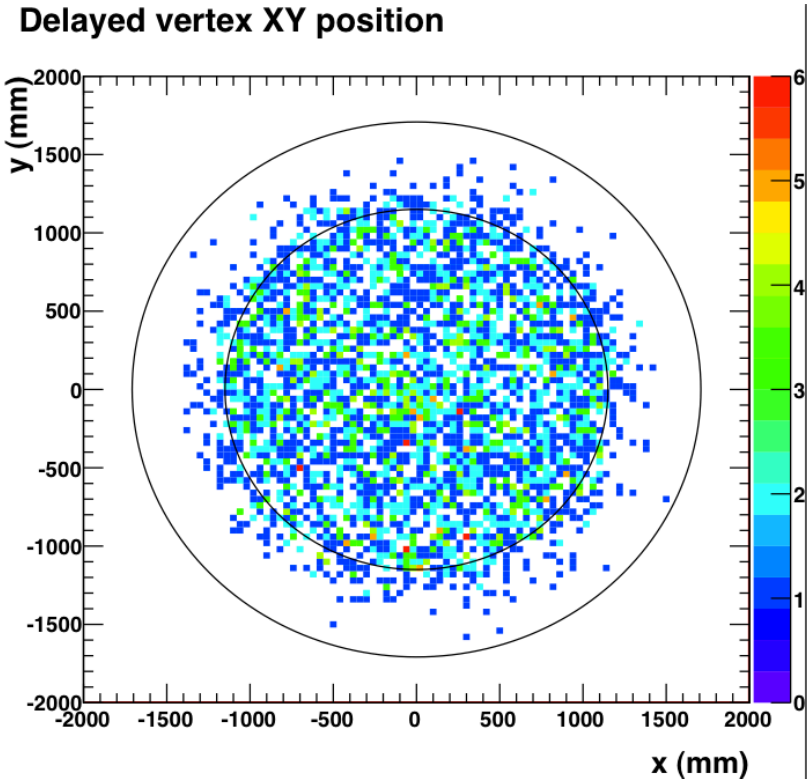
Near lab:
410m, 120 mwe
~500 ν's/day

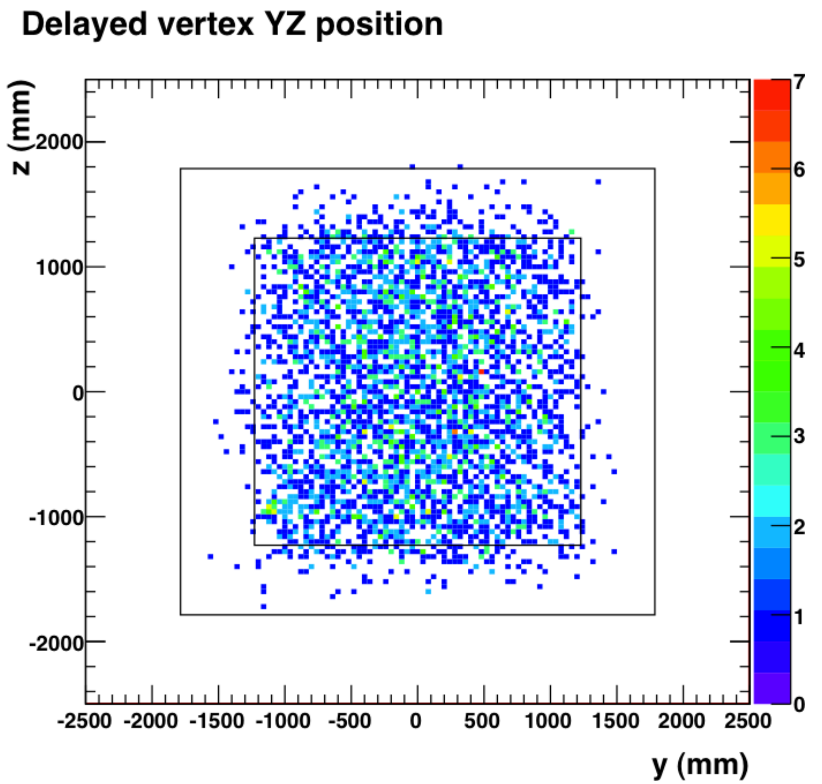
Far lab:
1050m, 300mwe
~70 ν's/day

Chooz reactors A+B:
- ➢ 8.5 $\mathrm{GW}_{\mathrm{thermal}}$

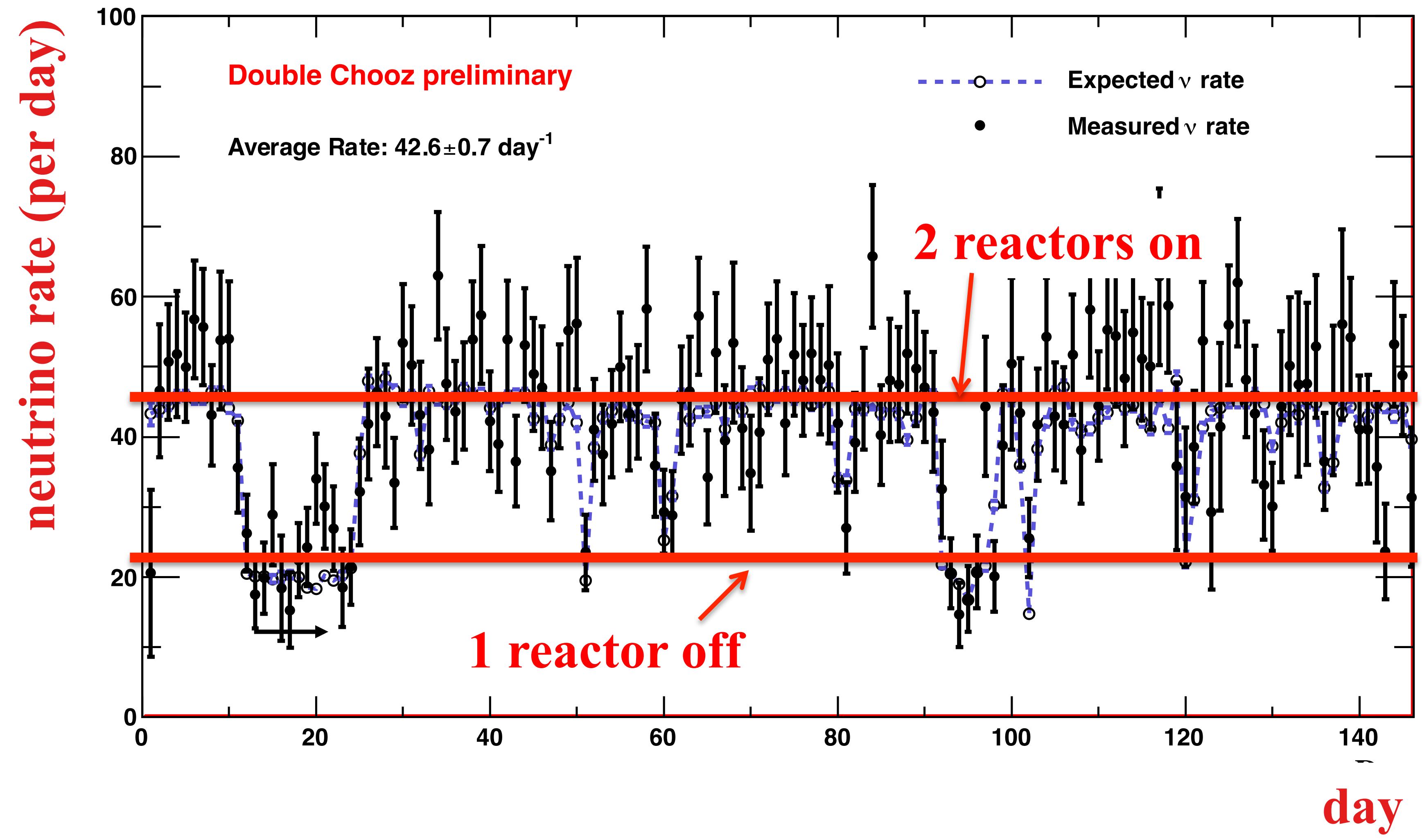
Neutrino Candidates n-Vertex Distribution

- Neutrino + Backgound selection
  - Prompt Energy Deposition
  - Delayed Energy Deposition
  - Time Correlation
  - No Muons





Measured Neutrino Rate & Reactors



Both reactors off for about 24 hours ➔ pure background measurment

First Results

Mid April - mid September 2011

➢ **4121 neutrino candidates**

➢ **328 background events**

➢ **4041 neutrinos expected without oscillations**

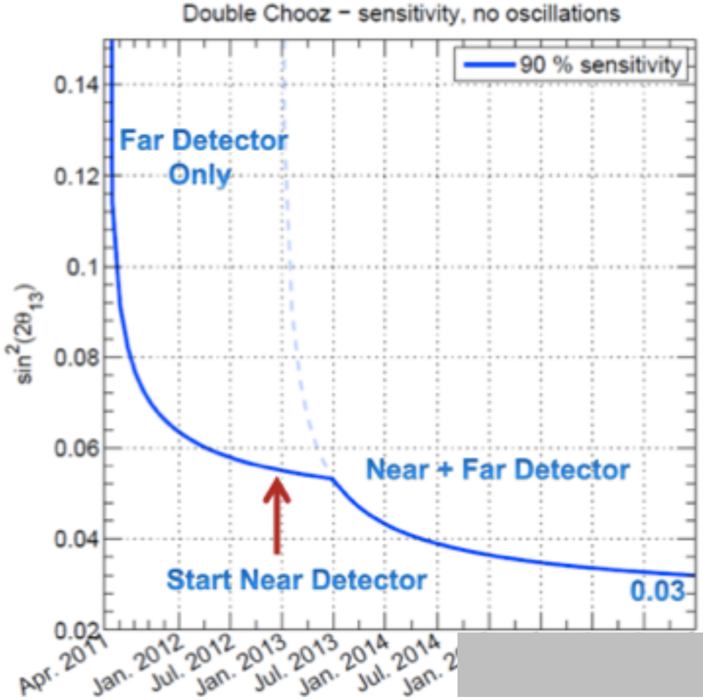
➢ **3793 neutrinos seen (94 %)**

➔ **$\sin^2(2\theta_{13}) = 0.085 \pm 0.051$**
>90% probability for $\theta_{13} > 0$

➔ **More data until next spring (5 months → 1 year)**

➔ **Further improved precision with 2 detectors**

H.de Kerret, Seoul, 9.November ´11



Further Results

Electron neutrinos from a ν_μ-beam

T2K: p → target @ J-PARC
Detector: Superkamiokande (50 kt)

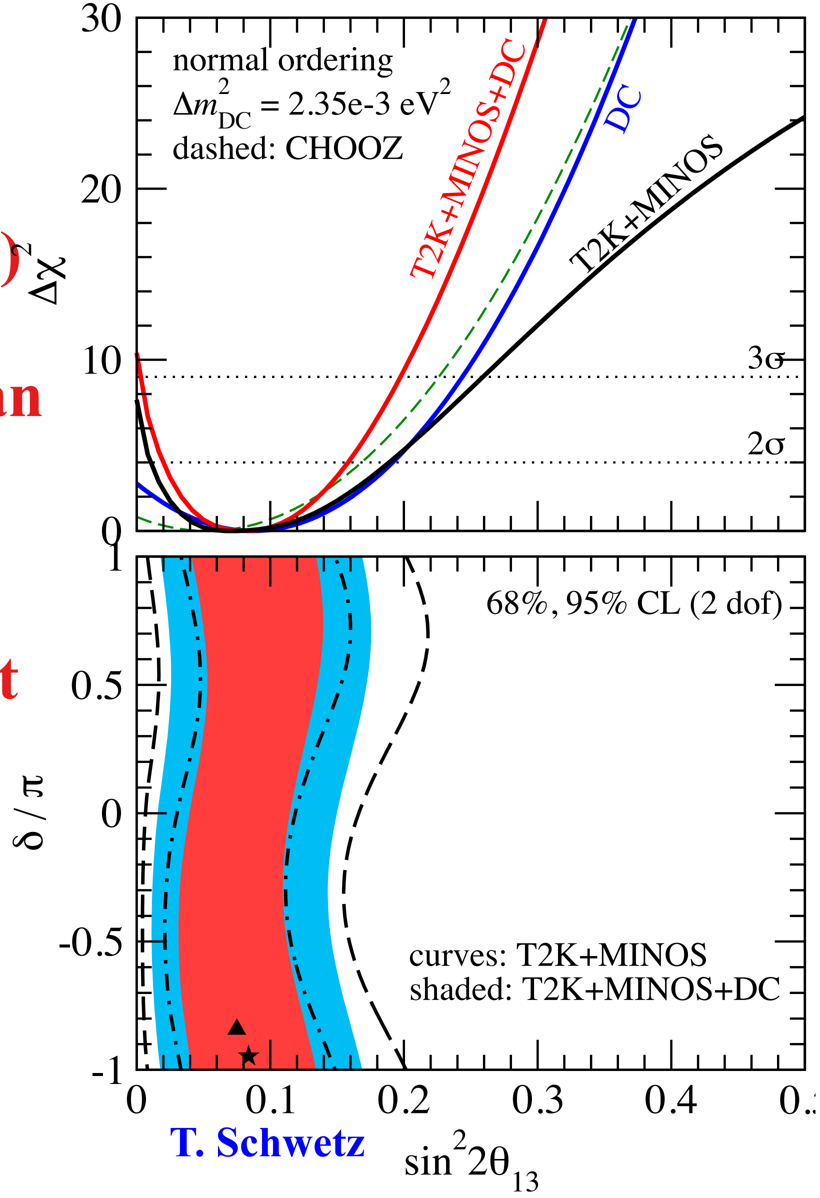
MIONS: Beam from FNAL to Soudan

Daya Bay: Reactor experiment

RENO: Reactor neutrino experiment

Double Chooz:
$\sin^2(2\theta_{13}) = 0.085 \pm 0.051$
will further improve very soon

All experiments: many sigma, CP...



T. Schwetz

Implications of sizable $\sin^2(2\theta_{13})$

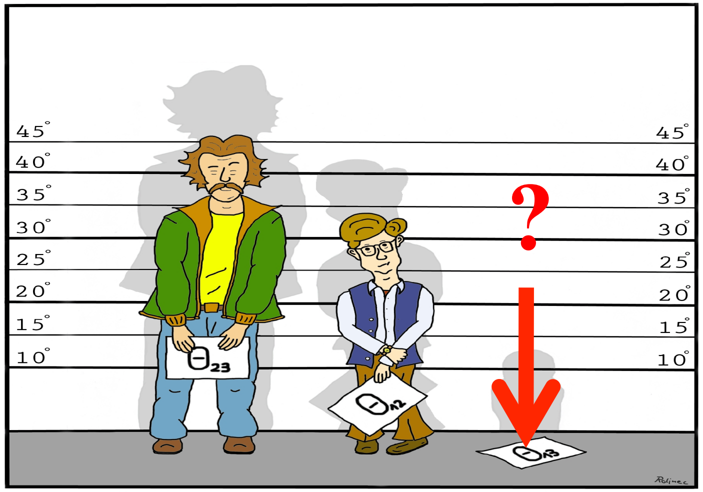
… in the standard 3 neutrino picture:

- **Experiment:**
  - good chances to measure θ_{13} soon with good precision
  - leptonic CP violation (Dirac phase δ) accessible

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}$$

  - standard neutrino factory out – matter uncertainties to big
  - low energy NF or beta beam or conventional beams

- **Theory:**
  - no apparent necessity for a special θ_{13} suppression (symmetry, …)
  - TBM ruled out ➔ sizable corrections, other starting points, …



- **…maybe not the complete story**

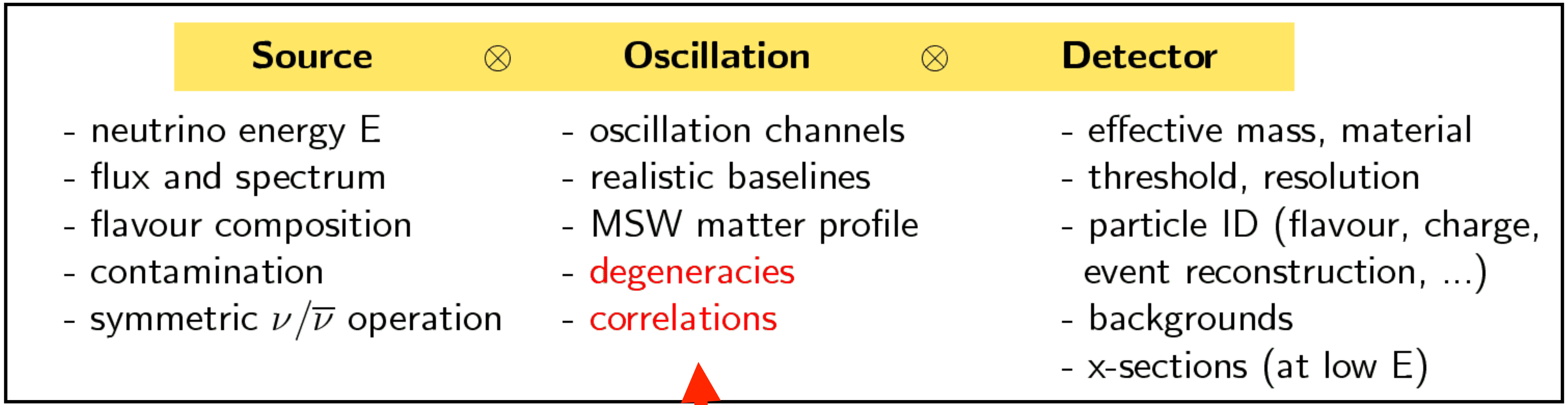
Potential Neutrinos Oscillation Surprises

… various assumptions: Majorana, 3 ν's, ΔL=2 ops mass mechanism

➔ examples:

- **extra light sterile neutrinos ➔ C. Rubbia's lectures**
- **how NSI's can fool precision experiments**

GLoBES simulation:



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		
- symmetric $\nu/\overline{\nu}$ operation		- correlations		- backgrounds
				- x-sections (at low E)

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)**

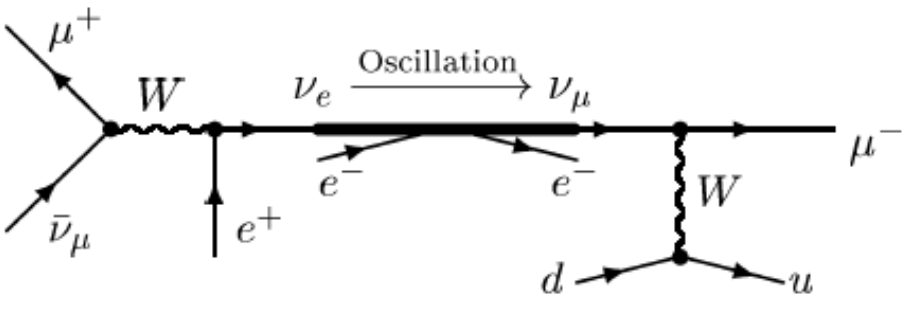
$$|\epsilon| \simeq \frac{M_W^2}{M_{NSI}^2}$$

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, …

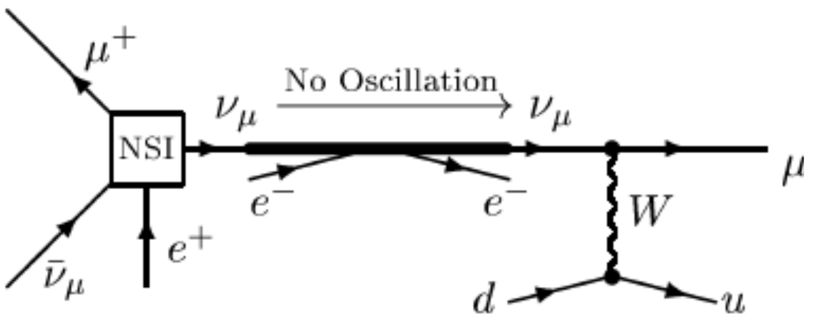
NSIs interfere with Oscillations

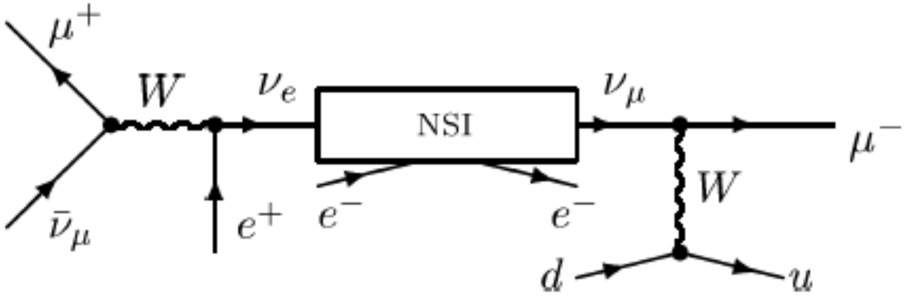
the "golden" oscillation channel

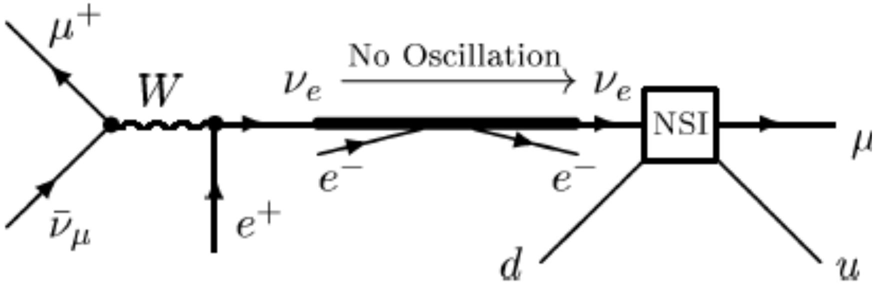
NSI contributions to the "golden" channel



(a)

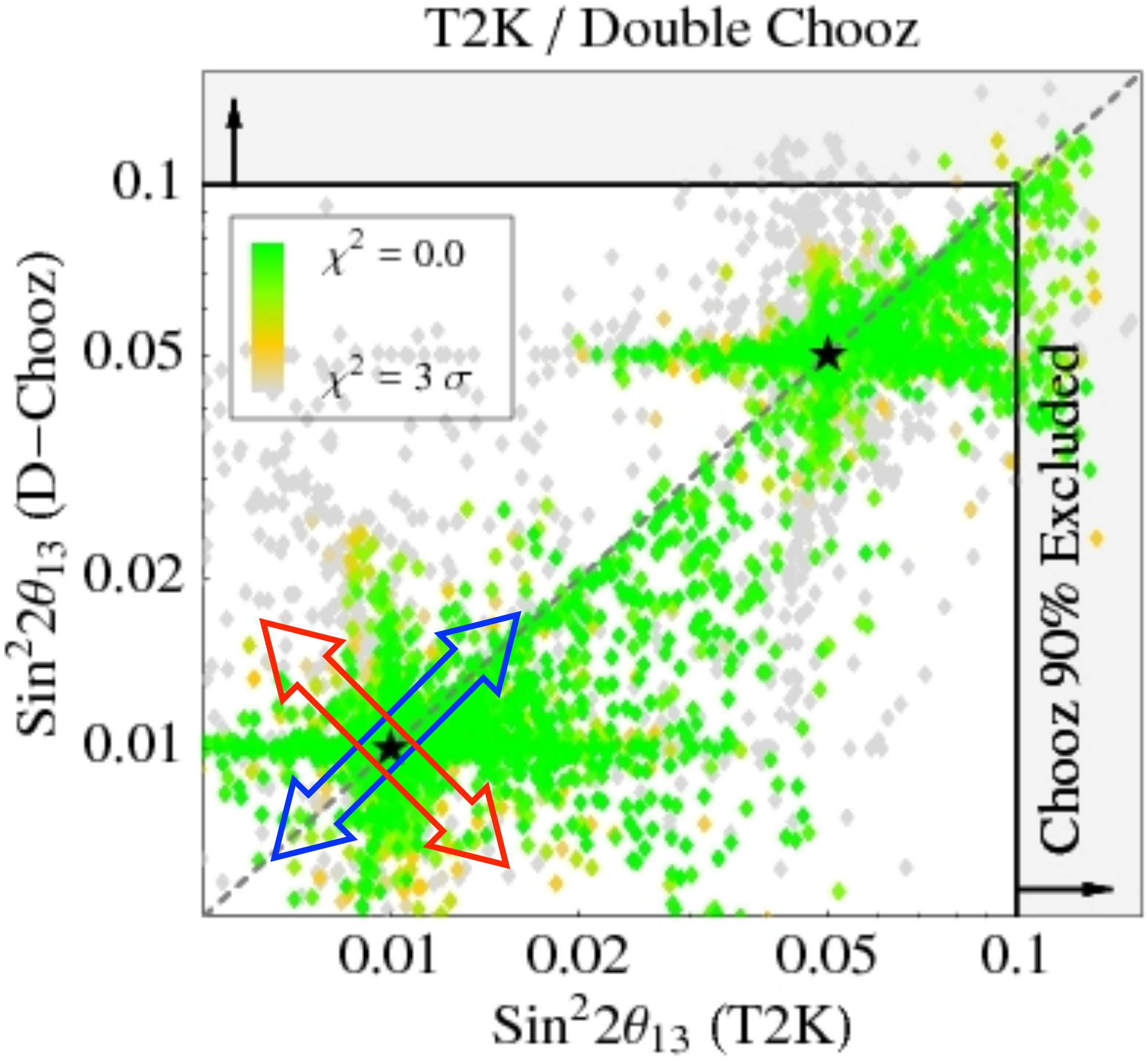






note: interference in oscillations $\sim\varepsilon$ $\Leftrightarrow$ FCNC effects $\sim\varepsilon^2$

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**

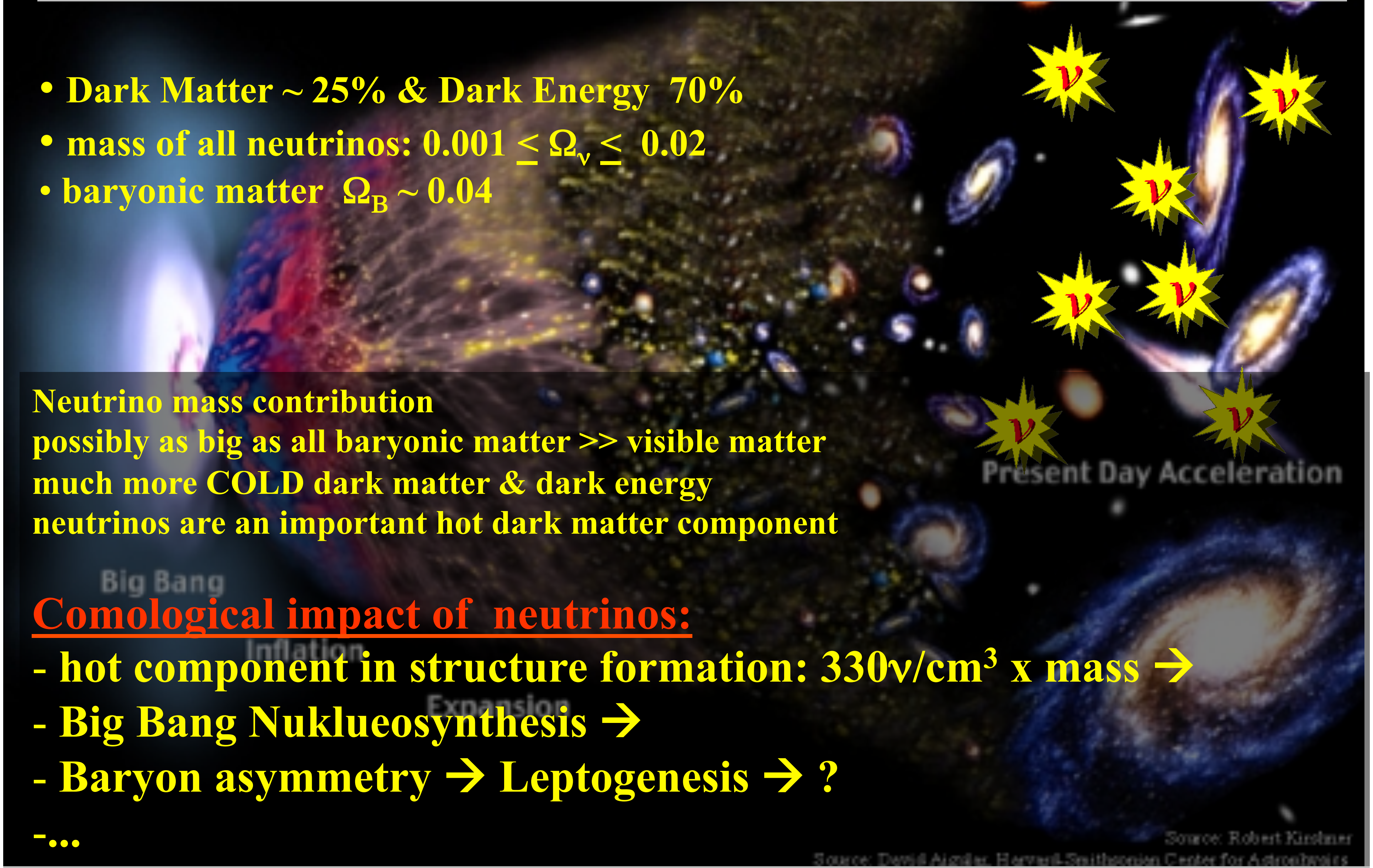
➔ redundancy

➔ interesting potential

Four Methods of Mass Determination

- kinematical
- lepton number violation
  ←→ Majorana nature
- oscillations
- astrophysics & cosmology

Neutrinos & Cosmology



- Dark Matter ~ 25% & Dark Energy 70%
- mass of all neutrinos: $0.001 \le \Omega_\nu \le 0.02$
- baryonic matter $\Omega_B \sim 0.04$

Neutrino mass contribution
possibly as big as all baryonic matter >> visible matter
much more COLD dark matter & dark energy
neutrinos are an important hot dark matter component

Comological impact of neutrinos:

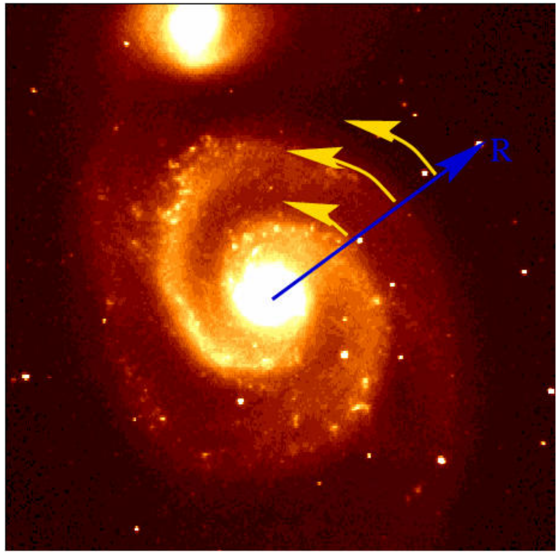
- hot component in structure formation: $330\nu/\text{cm}^3$ x mass →
- Big Bang Nuklueosynthesis →
- Baryon asymmetry → Leptogenesis → ?
-...

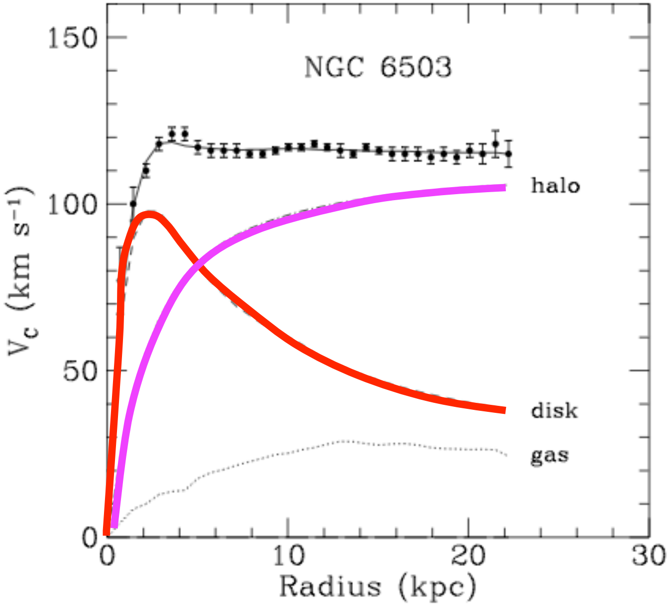
Neutrinos and Dark Matter

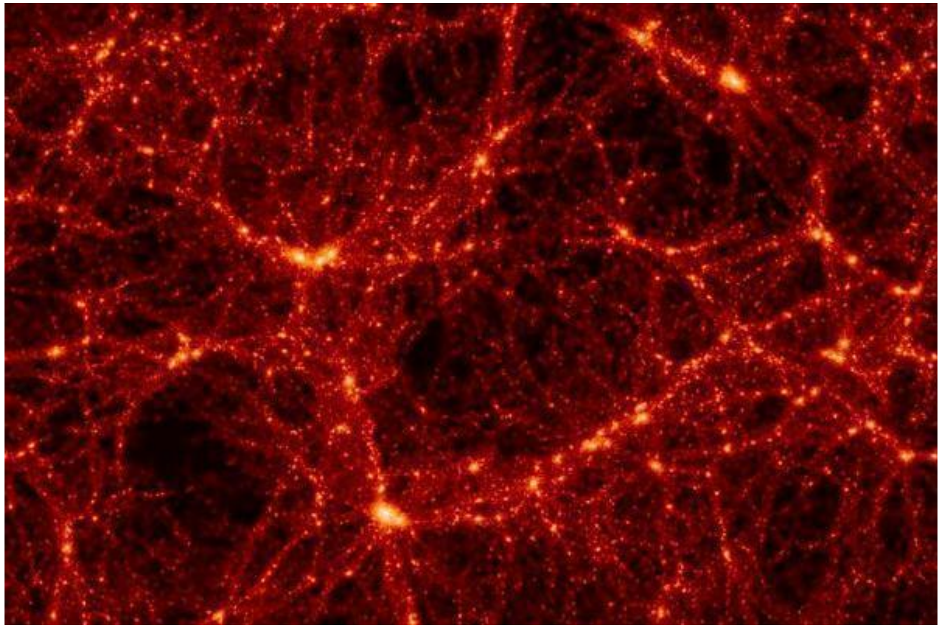
Dynamical Evidence for Dark Matter

F. Zwicky 1933
➔ proplem with galaxy clusters
➔ galaxies ➔

➔ galaxies have a large DM halo



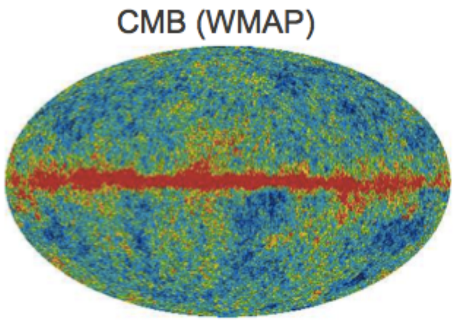


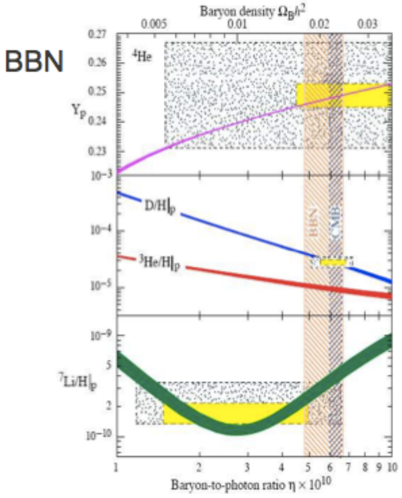


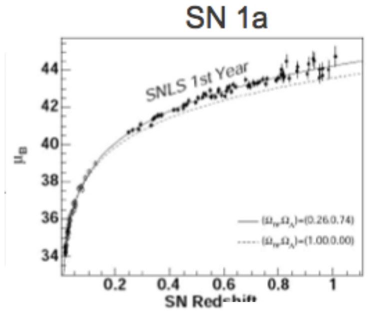
comparison of simulated and real structures
➔ cosmological DM dynamics

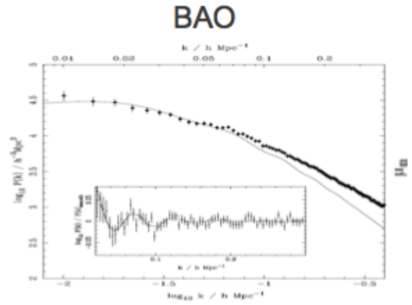
Many consistent Evidences for Dark Matter

- \+ Galactic rotation curves
- \+ Galaxy clusters & GR lensing
- \+ Bullet Cluster
- \+ Velocity dispersions of galaxies
- \+ Cosmic microwave background
- \+ Sky Surveys and Baryon Acoustic Oscillations
- \+ Type Ia supernovae distance measurements
- \+ Big Bang Nucleosynthesis (BBN)
- \+ Lyman-alpha forest
- \+ Structure formation

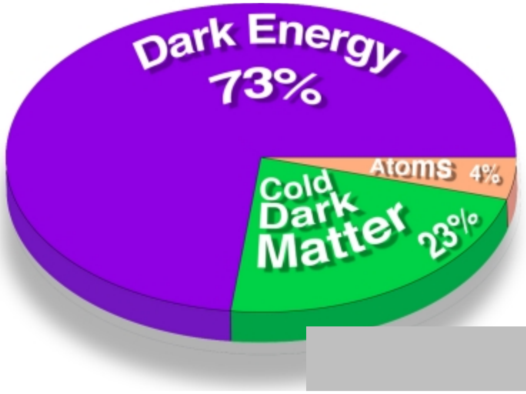








➔ Coherent picture of the composition of the Universe ➔



Sterile Neutrino Spectrum

<u>The standard picture:</u>

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

➔ leptogenesis, role in GUTs, …

some mechanism which makes
1 or 2 heavy sterile neutrinos light?
➔ keV sterile neutrino
➔ tiny heavy-light mixing

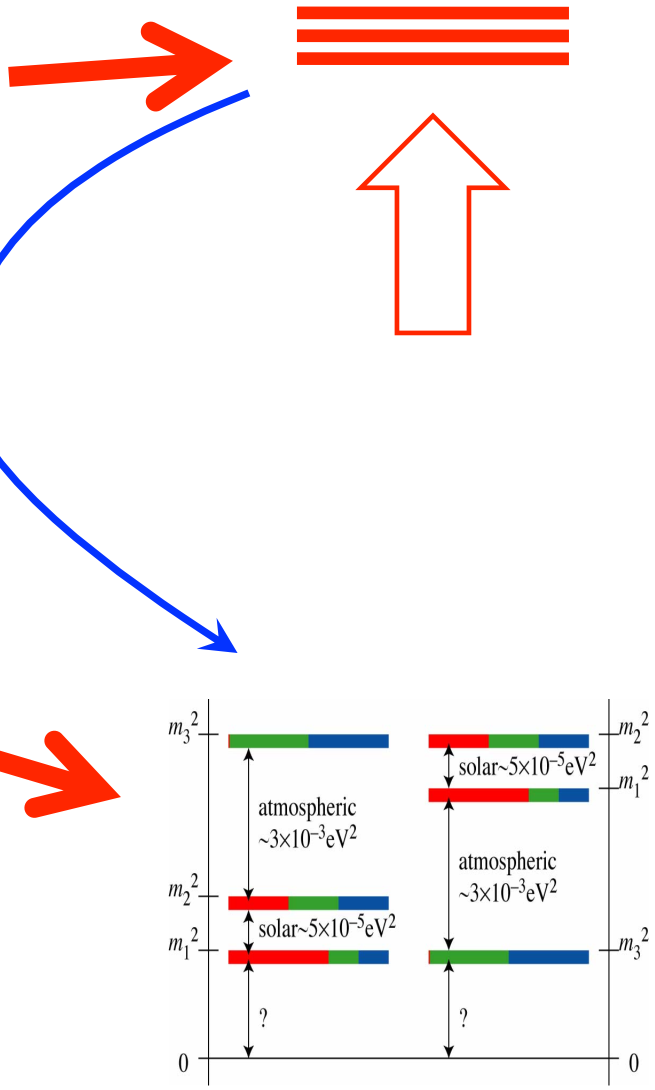
3 light active neutrinos

➔ this cold easily be wrong

- more than 3 N_R states, …

- M_R may have special eigenvalues, …

➔ light sterile neutrinos ?!



Evidences for Light Sterile Neutrinos ?

Particle Physics:

Reactor anomaly, LSND, MiniBooNE, MINOS, Gallex…

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

➔ maybe something exciting around the corner?

➔ but eV scale and sizable mixings

CMB: extra eV-ish neutrinos J. Hamann et al. , …

BBN: extra ν's possible: $N_\nu \simeq 3.7 \pm 1$

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

Astrophysics:

e.g. effects of keV-ish sterile neutrinos on pulsar kicks

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

Most likely not all of them are correct!

➔ consequences! ➔ assume first only 3 active neutrinos

Could Neutrinos be Dark Matter?

- **Active neutrinos would be perfect Hot Dark Matter** ➔ ruled out:
  - **destroys small scale structures in cosmological evolution**
  - **measured neutrino masses too small ➔ maybe 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 with very tiny mixing**
  - **reduced small scale structure ➔ smoother profile, less dwarf satellites**

  ➔ scenario where one sterile neutrino is keV-ish, the others heavy

  ➔ tiny active – sterile mixings $O(m_\nu/M_R)$

  ⇔ observational hints from astronomy
  - **hints that a keV sterile particle may exist ➔ right-handed neutrino?**

Note: Right-handed neutrinos exist probably anyway – just make one light!

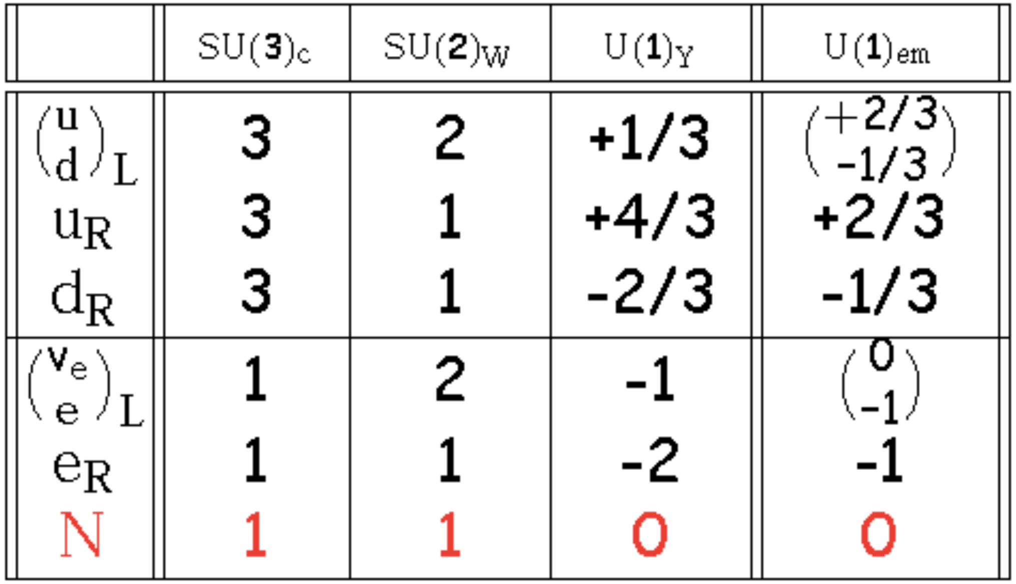
keV Neutrinos as WDM

The νMSM

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

Particle content:

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

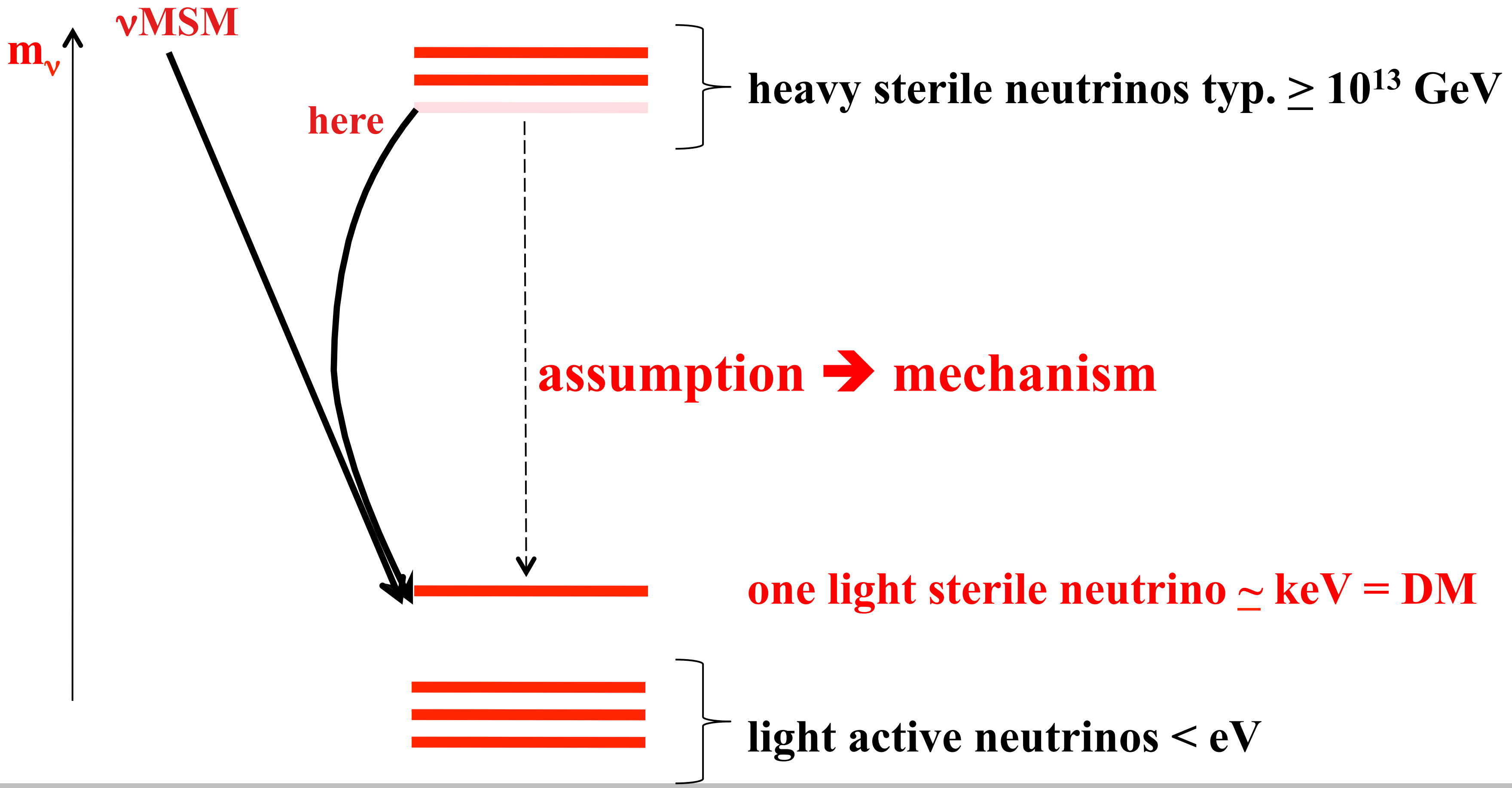
➔ choose for one sterile ν ~keV mass ➔ exceeds lifetime of Universe

Virtue and Problem of the νMSM

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

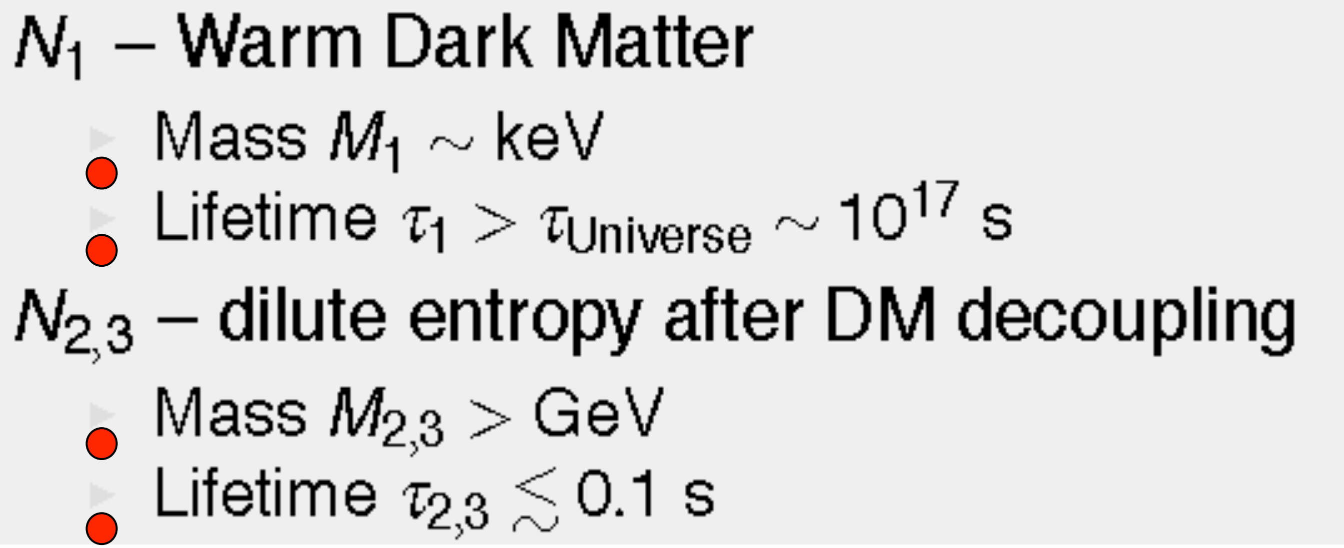


Alternative Scenario with Thermal Abundance

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 (~sterile)**
- **Specific example: LR-symmetry** $SU(3)_c$ x $SU(2)_L$ x $SU(2)_R$ x$U(1)_{B-L}$

Roles played by the sterile (~right-handed) neutrinos:



N_1 – Warm Dark Matter

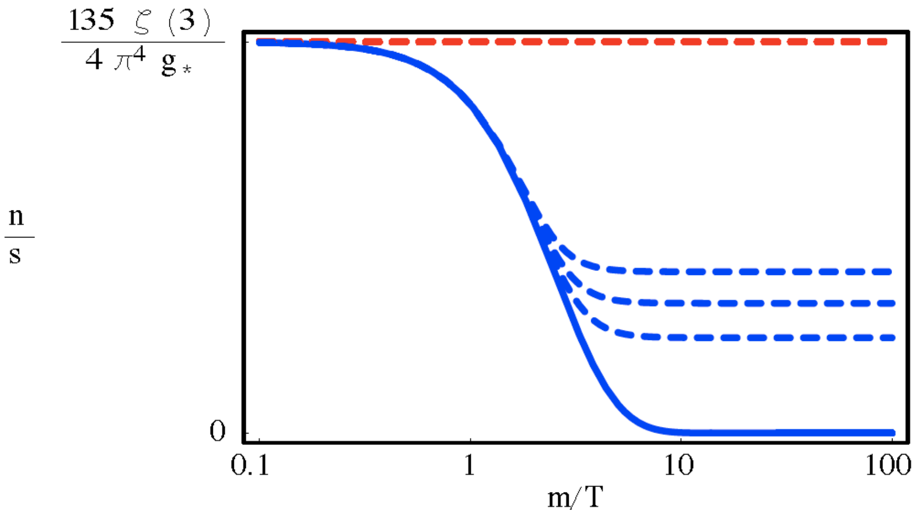
- Mass $M_1 \sim$ keV
- Lifetime $\tau_1 > \tau_{\text{Universe}} \sim 10^{17}$ s

$N_{2,3}$ – dilute entropy after DM decoupling

- Mass $M_{2,3} >$ GeV
- Lifetime $\tau_{2,3} \lesssim 0.1$ s

Obtaining the correct Abundance

Usual thermal case:



HDM:

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

Decoupled relativistic

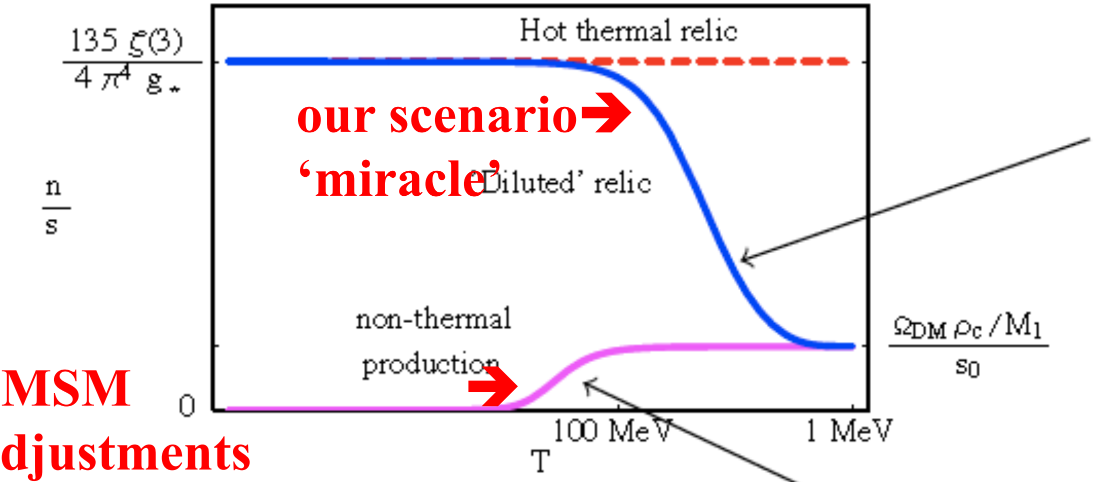
CDM:
(M>>MeV)

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

Decoupled

nonrelativistic

keV sterile neutrinos:



our scenario ➔
'miracle'

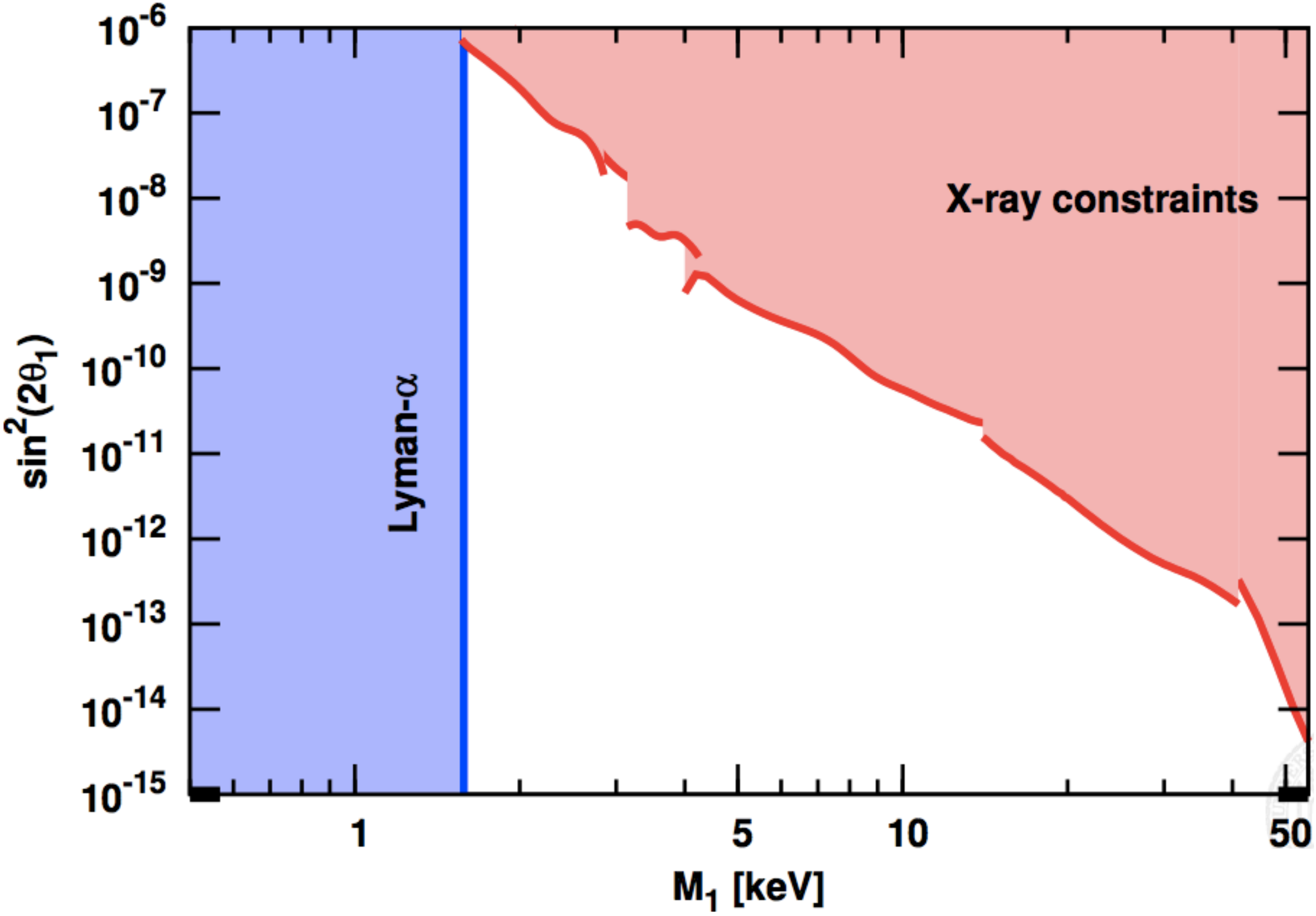
νMSM
adjustments ➔

Diluted after decoupling
(entropy generated by other
particle decay)

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

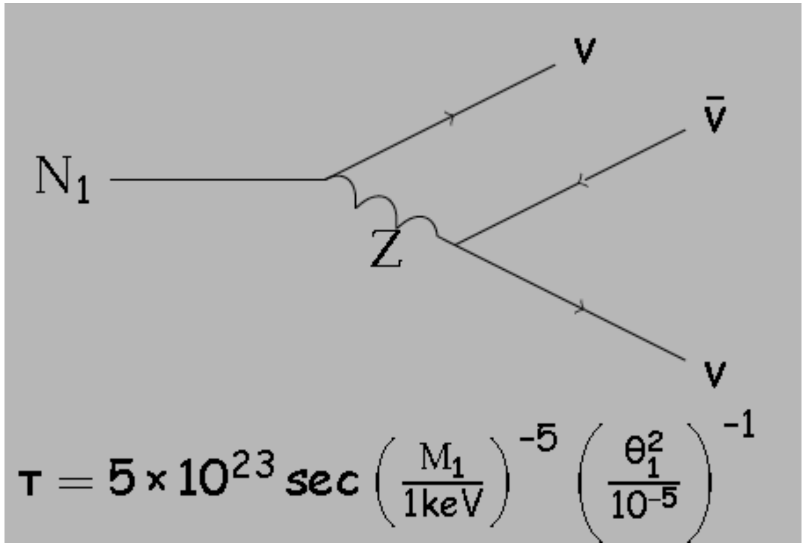
Never entered thermal equilibrium

Allowed Parameter Range



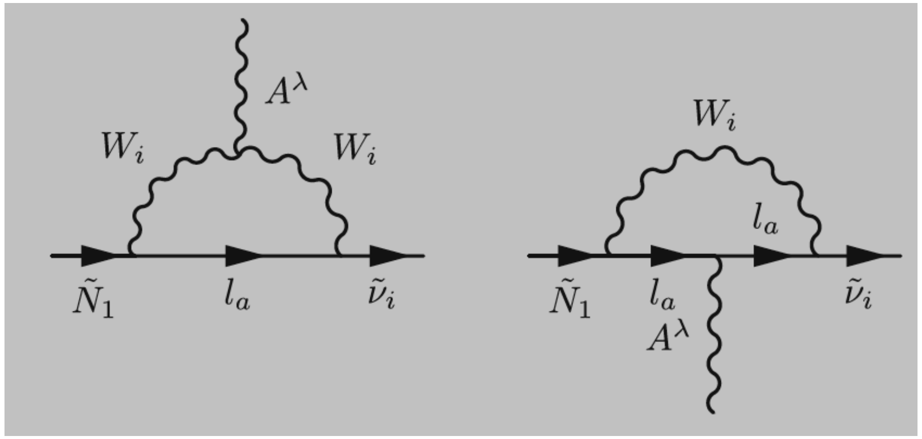
Observing keV-ish Neutrino DM

- LHC
  - sterile neutrino DM is not observable
  - WIMP-like particles still possible – but not DM
- direct searches
  - sterile ν DM extremely difficult; maybe in β-decay (MARE)
- astrophysics/cosmology ➔ at some level: keV X-rays
  ➔ sterile neutrino DM is decaying into active neutrinos
  - decay $N_1 \rightarrow \nu\bar{\nu}\nu$, $N_1 \rightarrow \nu\bar{\nu}\bar{\nu}$
  - not very constraining since $\tau \gg \tau_{\text{Universe}}$



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

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



- so far: observational limit on active-sterile mixing angle

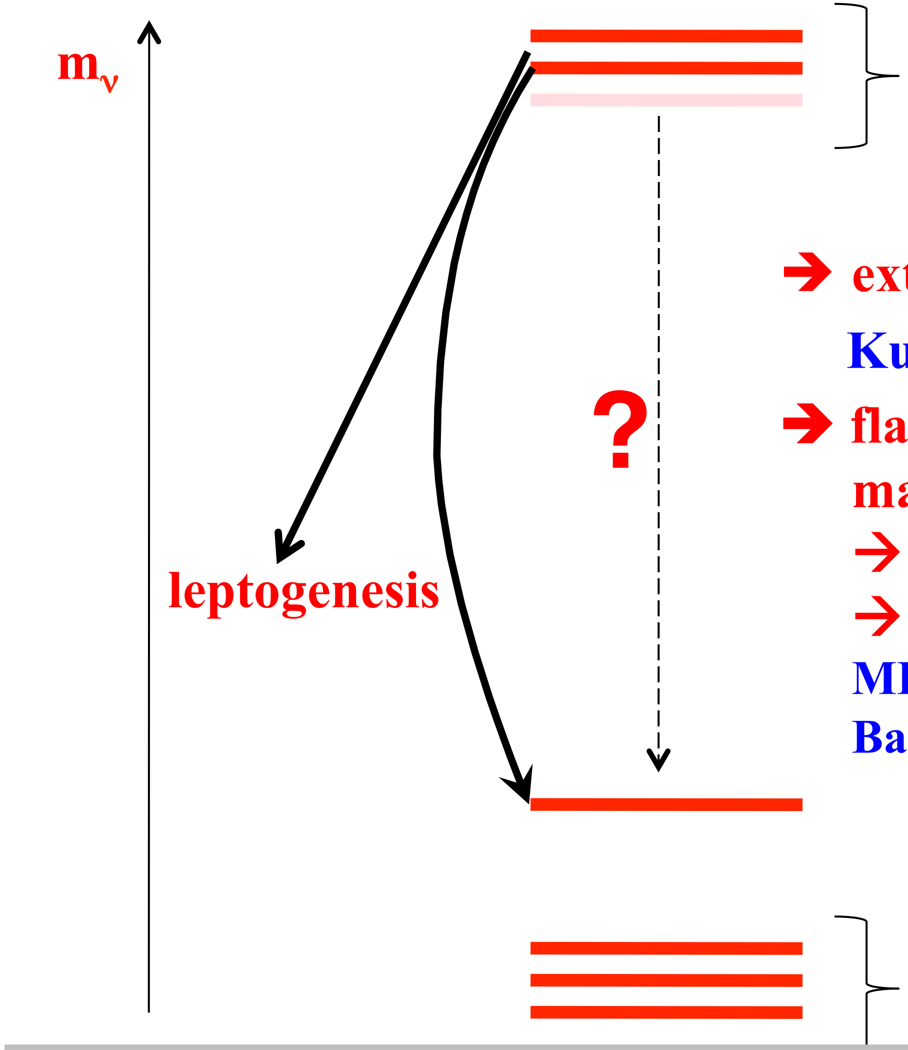
$$\Gamma_{N_1 \to \nu\gamma} \simeq 5.5 \times 10^{-22} \theta_1^2 \left(\frac{M_1}{1\ \mathrm{keV}}\right)^5 \mathrm{s}^{-1}$$

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

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

Explaining 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

- **Dark Matter exists**
- **But we cannot be sure if Dark Matter is**
  - made of particles (➔ smarter modified gravity ?)
  - particles → prefer scenarios with a 'miracle' (abundance)
    ➔ WIMPs (SUSY, …) - are very well motivated
    ➔ GIMPs – example: a keV-ish sterile neutrino very well motivated and good working Warm Dark Matter related to ν-masses

➔WIMP detection/limits down to 10^{-47}cm^{2} will be reached
- either find a WIMP or very strong constraint!
- combined with LHC searches
  ➔ excellent discovery potential!

Summary & Conclusions

- neutrinos provide **unique information & insight into new** physics
- three active neutrinos are still the paradigm

  ➔ Possibility to measure **leptonic CP-violation ←→** BAU…
- But maybe more…

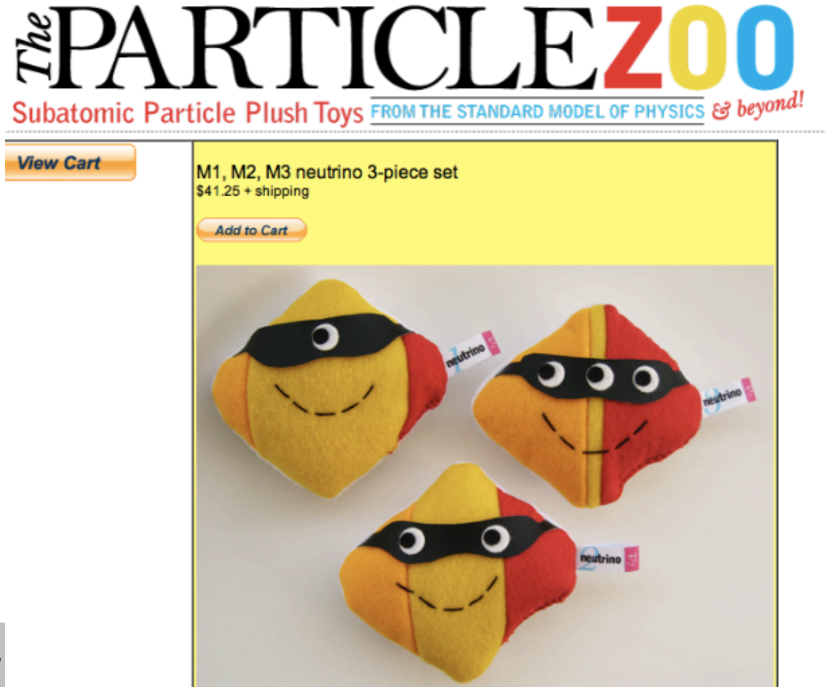
  ➔ **sterile neutrinos theoretically conceivable & quite natural**
- various **hints** which may point towards new surprises

  ➔ requires clarification

  ➔ **very interesting consequences**

  - neutrino mass generation

  - neutrinos as Dark Matter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Neutrinos have always been surprising

➔ **very interesting ν-times ahead!**