NEUTRINO PHYSICS

Oscillations and Majorana neutrino

31 may 2011

"Neutrino Physics": **http://www.roma1.infn.it/people/rahatlou/FNS3/**

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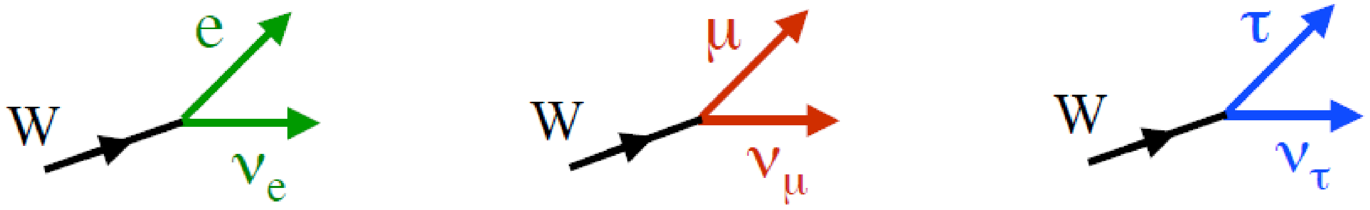
Corso di Fisica Nucleare e Subnucleare II, A.A.2010-2011

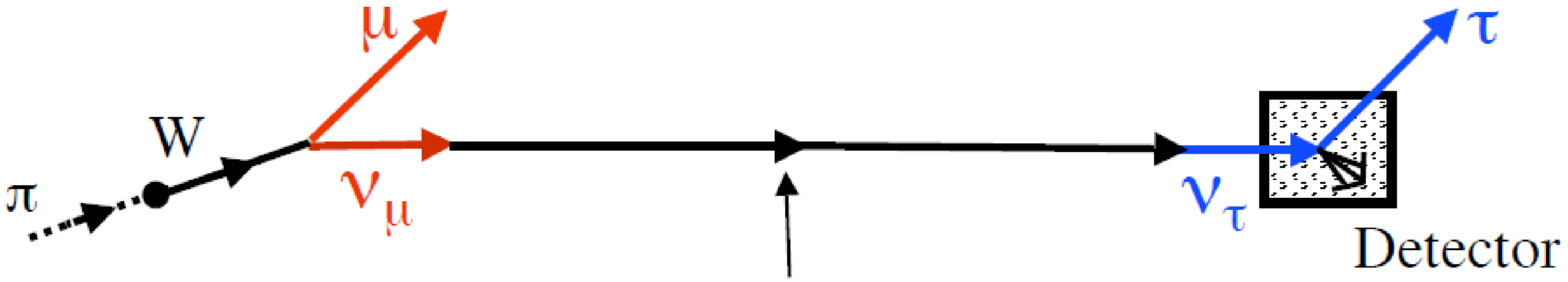
http://www.roma1.infn.it/people/luci/corso_fnsII.html

NEUTRINO OSCILLATION

- Neutrino flavour:



- Experimental observation:



Neutrino flavour change

- Implications:
  - Leptons mix: **lepton flavour not conserved**
  - Neutrinos have non zero mass: **there must be some ν mass spectrum**

- **Mixing angles? Neutrino masses? Dirac or Majorana ?**

NEUTRINOS IN THE STANDARD MODEL

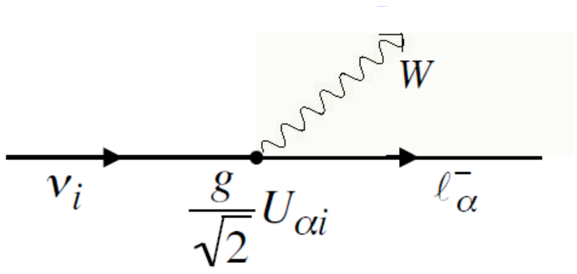
- Fermions described by a Dirac field Ψ
- Standard Model(MS): chiral theory $SU(2)_L \times U(1)_Y$
  - Chirality projector $P_L^{(R)}=(1\pm\gamma_5)/2$, $P_L^{(R)}\Psi=\Psi_L^{(R)}$
  - Ψ_L and Ψ_R have different properties under $SU(2)_L$
    - Ψ_R SU(2) singlet ⇒ doesn't couple with W,Z bosons
    - Ψ_L SU(2) doublet
    - Mass term (after EW symmetry breaking): $m\overline{\Psi}_L \Psi_R$ + h.c. ⇒ mix Ψ_L and Ψ_R
- Minimal Standard Model(MMS):
  - neutrinos are massless!
  - there are only 3 neutrinos lighter than $M_Z/2$
- Neutrino interaction:
  - Charged current: $$\mathcal{L}_W = -\frac{g}{\sqrt{2}} \sum_{\alpha=e,\mu,\tau} (\bar{\ell}_{L\alpha}\gamma^\lambda \nu_{L\alpha} W_\lambda^- + \bar{\nu}_{L\alpha}\gamma^\lambda \ell_{L\alpha} W_\lambda^+)$$
  - Neutral current: $$\mathcal{L}_Z = -\frac{g}{cos\theta_W} \sum_{\alpha=e,\mu,\tau} \bar{\nu}_{L\alpha}\gamma^\lambda \nu_{L\alpha} Z_\lambda$$

INCORPORATE MASS AND MIXING

- **Higgs mechanism** (like in the quark sector):
  - Introduce Dirac Mass Term and diagonalize the mass matrix
  - Unitary matrix appears in Interaction Lagrangian
  - Neutral current not affected: GIM mechanism

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} \sum_{\alpha=e,\mu,\tau\, i=1,2,3} (\bar{\ell}_{L\alpha}\gamma^{\lambda}U_{\alpha i}\nu_{Li}W_{\lambda}^{-} + \bar{\nu}_{Li}\gamma^{\lambda}U_{\alpha i}^{*}\ell_{L\alpha}W_{\lambda}^{+})$$

- **Amp($W^+ \rightarrow l_\alpha + \nu_i$)=$g/\sqrt{2}U_{\alpha i}^*$**



- **Orthogonality: 3 flavours ⇒ at least 3 mass eigenstates**

$$|\nu_\alpha\rangle = \sum_{i=1,2,3} U_{\alpha i}^{*}|\nu_i\rangle \qquad |\nu_i\rangle = \sum_{\alpha=e,\mu,\tau} U_{\alpha i}|\nu_\alpha\rangle$$

- **Flavour fraction of $|\nu_i\rangle = |U_{\alpha i}|^2$**

ν field: creates $\bar{\nu}$ and destroys ν
This is why U* appear when ket |ν> used

CHIRALITY AND HELICITY

Chirality (X)	**Helicity (H)**
Acts on Dirac Spinor Space	Acts on physical space: spin projection on momentum direction $H=\sigma\cdot p/\|p\|$
Projector: $P_L^{(R)}=(1\pm\gamma_5)/2$	Projector: $\Pi_L^{(R)}=(1\pm\sigma\cdot p/\|p\|)/2$
Lorentz invariant! Interactions don't depend on reference frame!!	Not Lorentz invariant for massive particle, momentum reversed if boost with $\beta>\beta_m=p/E$
Not conserved: mass term mixes right and left component	Conserved

If m=0 Helicity and Chirality coincide <u>(not the case for neutrinos!):</u> $X=H+O(m/E)$

Nature has related the Weak Force to chirality eigenstates

WHAT WE KNOW FROM EXPERIMENTS

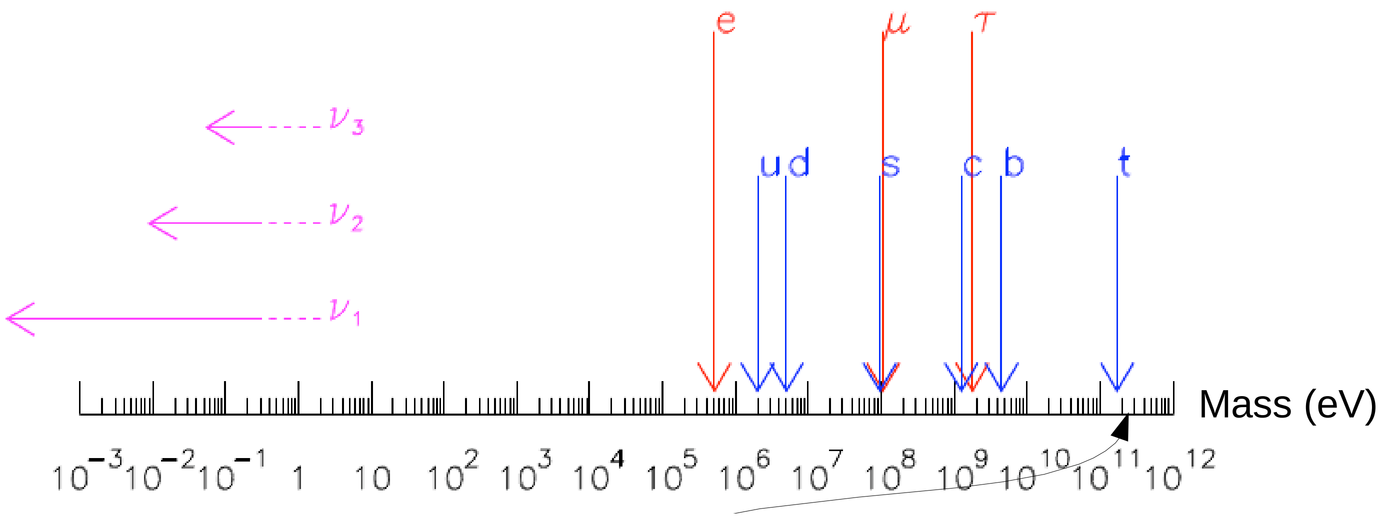
- **Neutrino mixing matrix:**

$$U_{PMNS} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} = \begin{bmatrix} 0.84 & 0.54 & 0.14 \\ 0.38 & 0.60 & 0.70 \\ 0.38 & 0.60 & 0.70 \end{bmatrix}$$

CKM

$$\begin{bmatrix} 0.97 & 0.22 & 0.003 \\ 0.22 & 0.97 & 0.04 \\ 0.009 & 0.04 & 0.99 \end{bmatrix}$$

- **Neutrino mass spectrum**

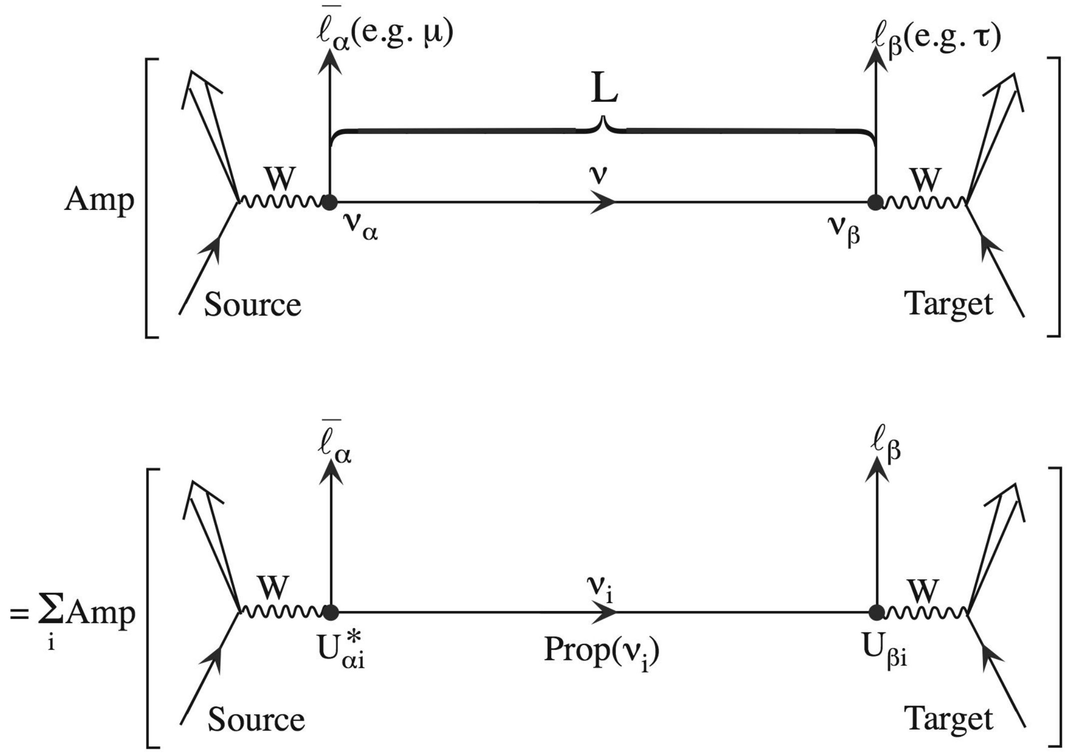


- **Quarks** and **charged leptons** produced as **mass eigenstates**
- **Neutrinos** as **flavour eigenstates**
- **Unitary triangles,** useful when measure sides and angles, **have no practical use in lepton flavour mixing**
  - **neutrino oscillation theory**

SPECIAL CASE: 2 NEUTRINOS

- Similar to K^0-$\bar{K}^0$ mixing: **weak eigenstates ≠ strong eigenstates**
  - but neutrinos don't decay (no exponential term)
  - always relativistic and tiny mass difference
    - **Flavour change in vacuum oscillates with L/E:**

      (macroscopic quantum coherence interference)
- Why quarks and charged leptons don't oscillate?



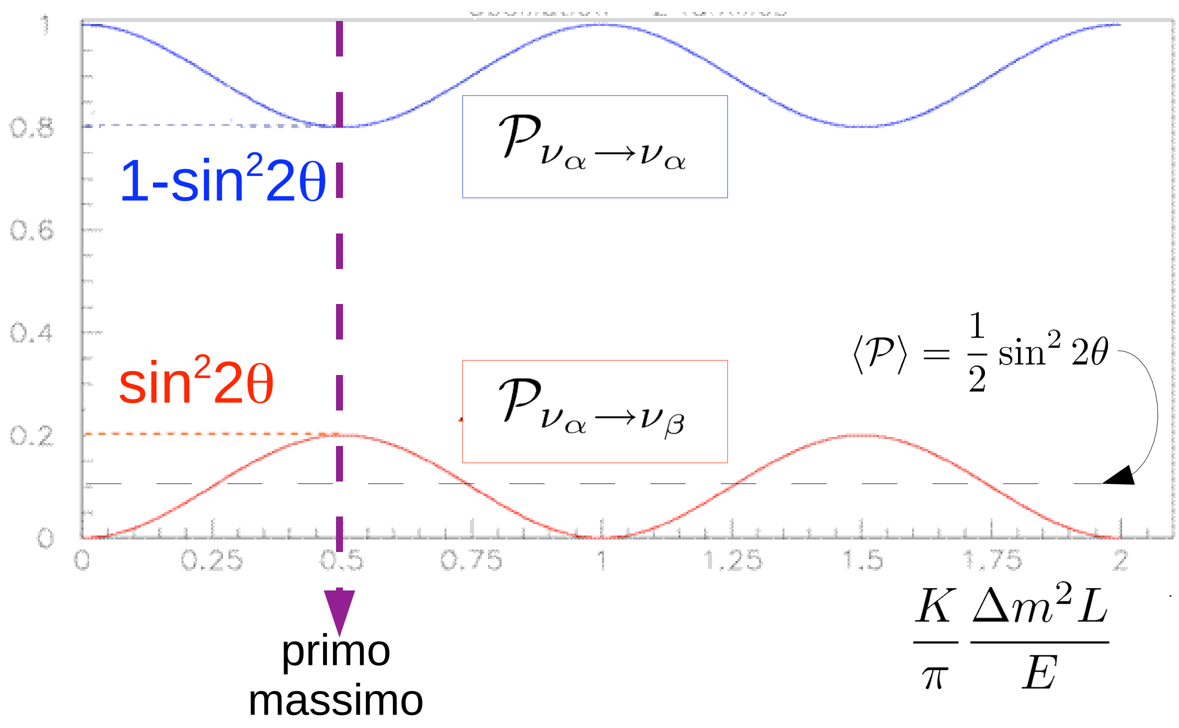
$$U = \begin{array}{ccc} & \nu_1 & \nu_2 \\ \nu_e & cos\theta & sin\theta \\ \nu_\mu & -sin\theta & cos\theta \end{array}$$

$$P[\nu_\alpha \rightarrow \nu_\beta] = sin^2(2\theta) sin^2(\Delta m^2 L/4E)$$

no distinction

$\theta \Leftrightarrow \pi/2-\theta$, $\Delta m^2 \Leftrightarrow -\Delta m^2$

if Δm or $\theta = 0$ $P(\nu_\alpha \Rightarrow \nu_\beta) = \delta_{\alpha\beta}$



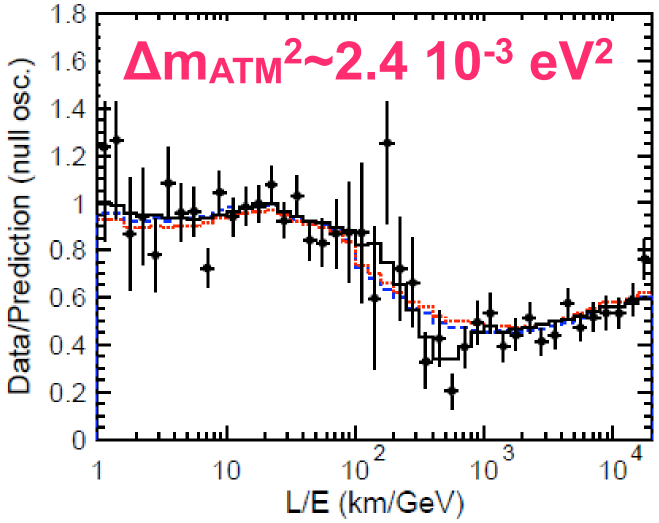
3 NEUTRINOS CASE

$$P[\nu_\alpha \rightarrow \nu_\beta] = \quad \delta_{\alpha\beta} - 4\sum_{i>j} Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})sin^2(\Delta m^2_{ij}L/4E) + 2\sum_{i>j} Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})sin^2(\Delta m^2_{ij}L/2E)$$

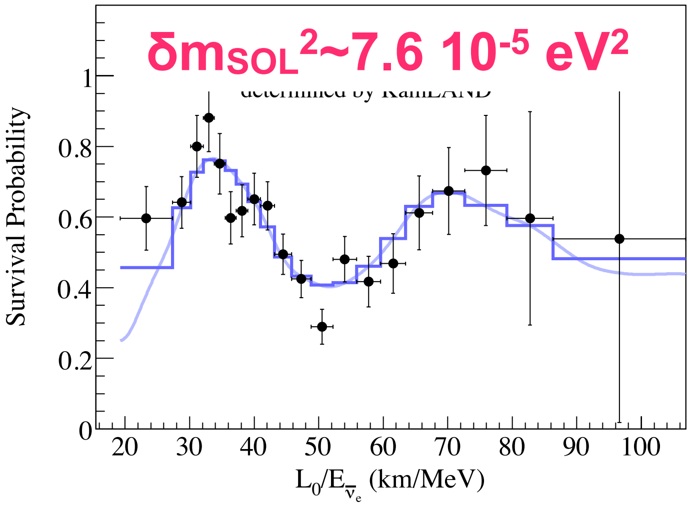
- Phenomenology simplified by two experimental results:

2 different mass scale: Δm_{ATM}^2~30*δm_{SOL}^2

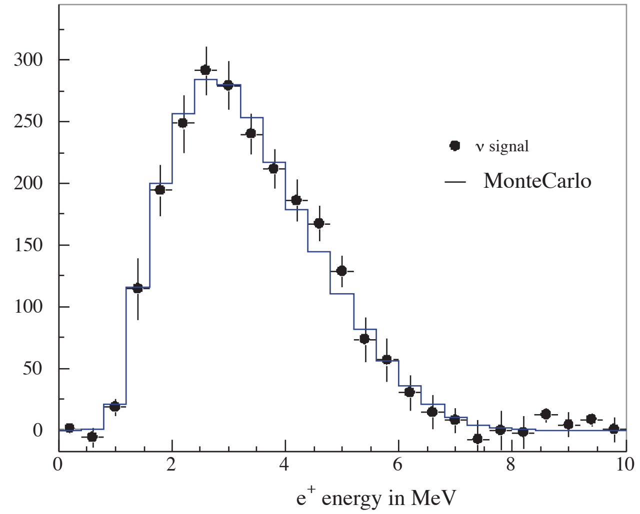
one small angle: $\vartheta_{13}<10°$


Δm_{ATM}^2~2.4 10^{-3} eV^2

SuperKamiokande

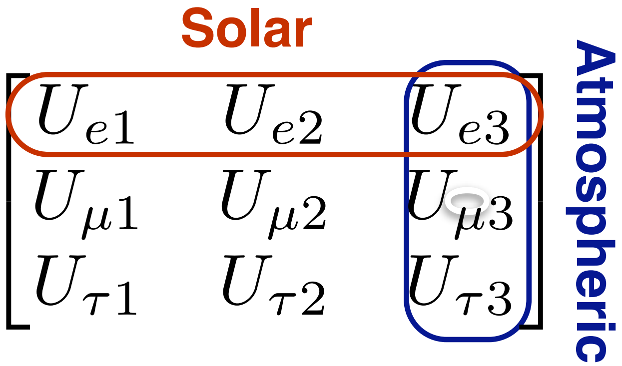

δm_{SOL}^2~7.6 10^{-5} eV^2

Kamland



Chooz

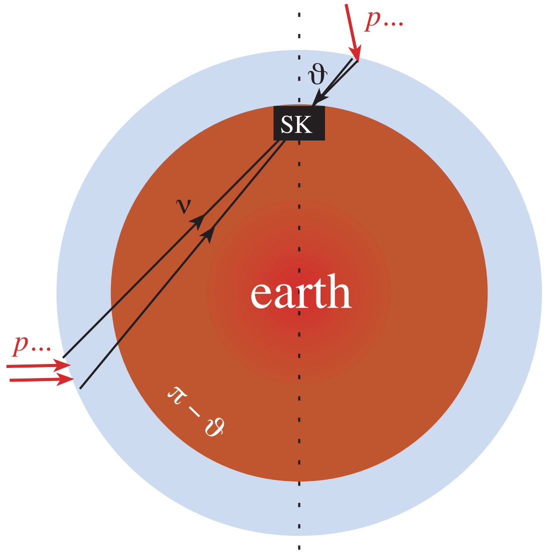
- **Experiments with $\Delta m^2L/E=O(1)$ can't distinguish δm_{SOL} eigeinstates (m_1 and m_2)**
  - **sensitive to 3rd column**
- **At solar energies (MeV)** μ,τ under production threshold:
  - **sensitive to 1st row**
- $|U_{e3}| = \sin(\vartheta_{13})$ ϑ_{13} only link between oscillations: $\vartheta_{13}<10°$
  - oscillations decoupled


Solar

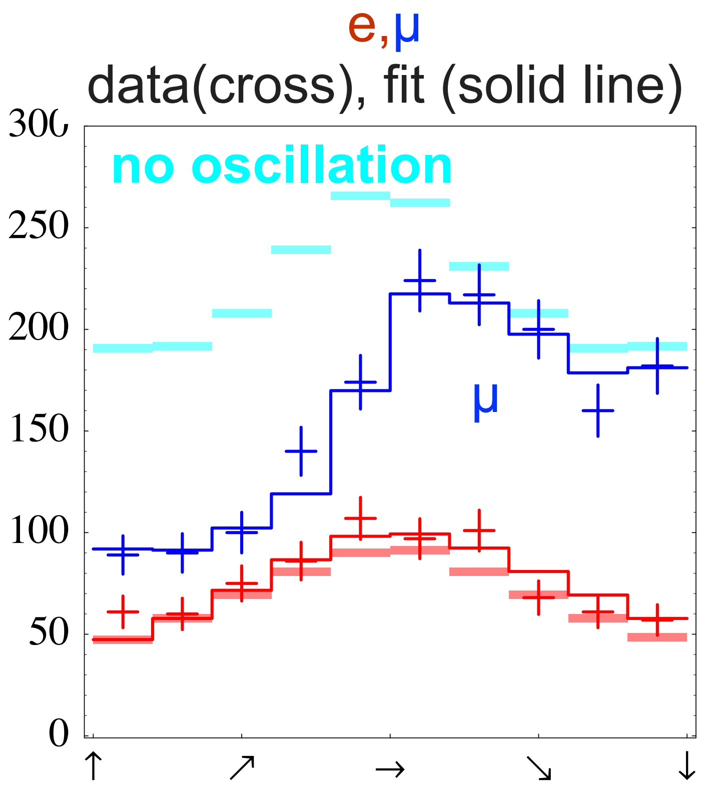
Atmospheric

$$\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

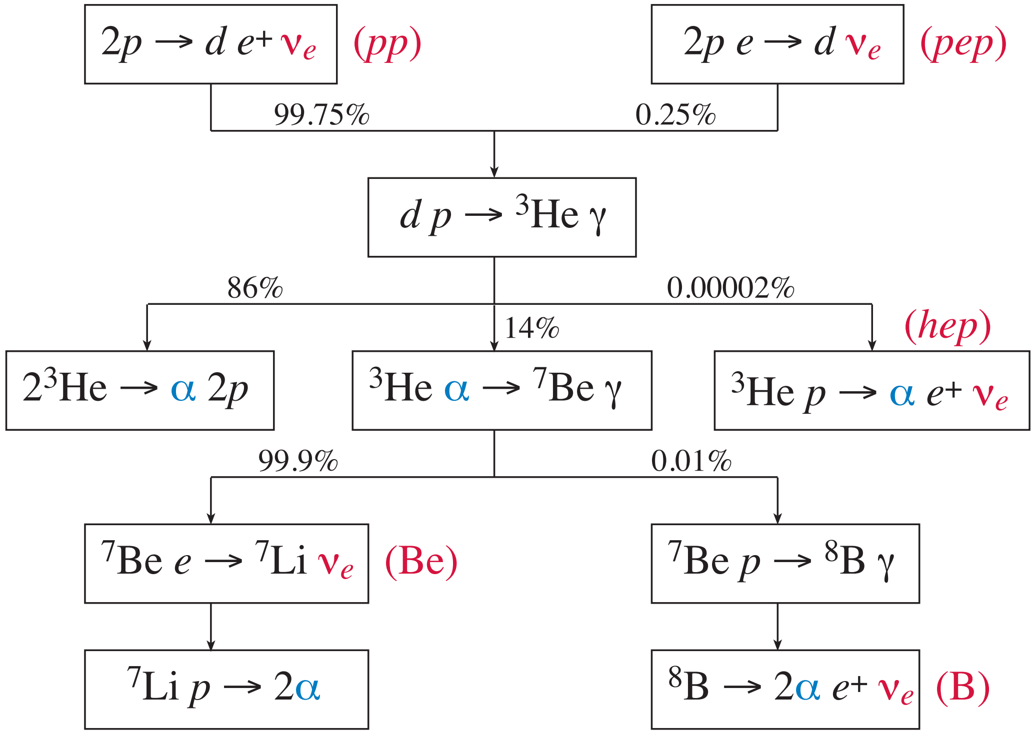
THE ATMOSPHERIC ANOMALY



- Primary cosmics produce π in the upper atmosphere:
  - $\pi \Rightarrow \mu\nu_\mu$, $\mu \Rightarrow e\nu_\mu\nu_e$ $\phi(\nu_\mu)=2\cdot\phi(\nu_e)$
- Isotropy of the >2GeV cosmic rays flux + Gauss' law :
  - **ν rate up/down symmetric (no need knowledge flux)**
- **Measuread Flux: $[\phi(\nu_\mu)/\phi(\nu_e)]/[\phi(\nu_\mu)/\phi(\nu_e)]_{MC}\sim 0.65$**
- **Anomaly even without relying on knowledge of neutrino fluxes**
  - $P_{ee}=1$, $P_{e\mu}=0$, $P_{\mu\mu}=1-\sin^2(2\vartheta_{Atm})\sin^2(\Delta m^2_{Atm}L/4E_\nu)$
  - **Zenith no oscillation, Nadir average oscillation**
    - $P_{\mu\mu}=1-0.5\cdot\sin^2(2\vartheta_{Atm})=1-0.5\ N^{\uparrow}/N^{\downarrow}\Rightarrow\vartheta=45°$
  - **Oscillations start horizontal:** $E_\nu\sim$GeV, $L\sim$1000km,
    - $\Delta m^2_{Atm}\sim E_\nu/L\ 3\cdot10^{-3}$ eV



NEUTRINOS FROM THE SUN



$2p \rightarrow d\, e^+ \nu_e$ (pp)

$2p\, e^- \rightarrow d\, \nu_e$ (pep)

99.75%

0.25%

$d\, p \rightarrow {}^3\mathrm{He}\, \gamma$

86%

14%

0.00002%

$2\,{}^3\mathrm{He} \rightarrow \alpha\, 2p$

${}^3\mathrm{He}\, \alpha \rightarrow {}^7\mathrm{Be}\, \gamma$

${}^3\mathrm{He}\, p \rightarrow \alpha\, e^+ \nu_e$ (hep)

99.9%

0.01%

${}^7\mathrm{Be}\, e \rightarrow {}^7\mathrm{Li}\, \nu_e$ (Be)

${}^7\mathrm{Be}\, p \rightarrow {}^8\mathrm{B}\, \gamma$

${}^7\mathrm{Li}\, p \rightarrow 2\alpha$

${}^8\mathrm{B} \rightarrow 2\alpha\, e^+ \nu_e$ (B)

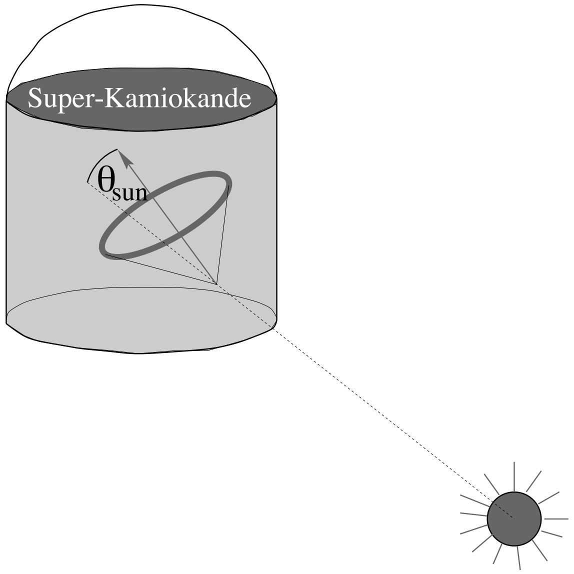
In the center of the sun

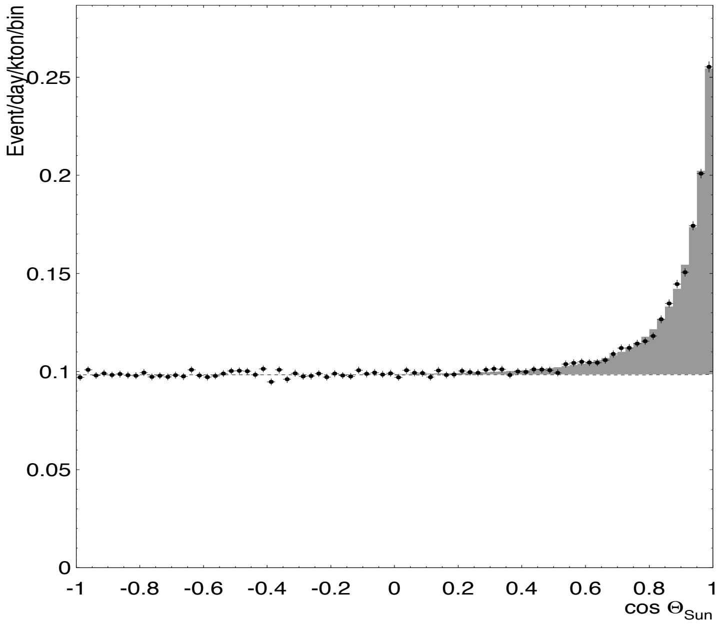
$4p + 2e^- \rightarrow {}^4\mathrm{He} + 2\nu_e$

Q=26.73 MeV

$\langle E_\nu \rangle \approx 0.3\,\mathrm{MeV}$

Solar $\Phi(\nu) \approx 6 \cdot 10^{10}\ \nu/\mathrm{cm}^2\mathrm{s}$





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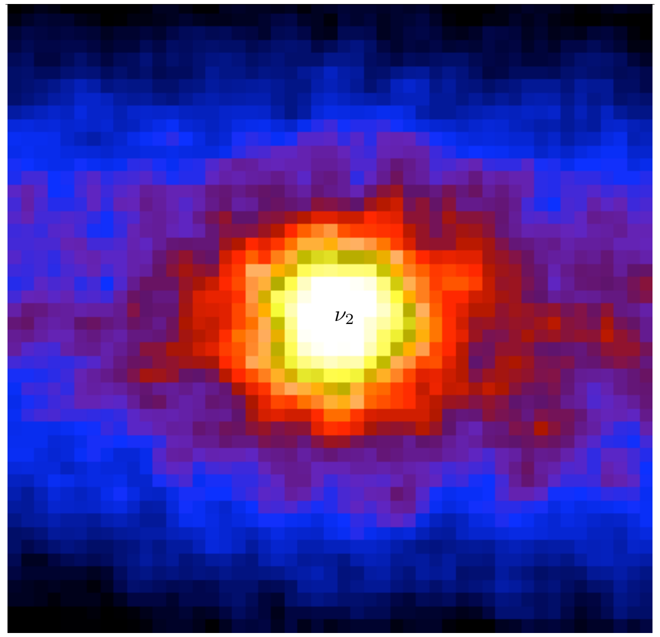
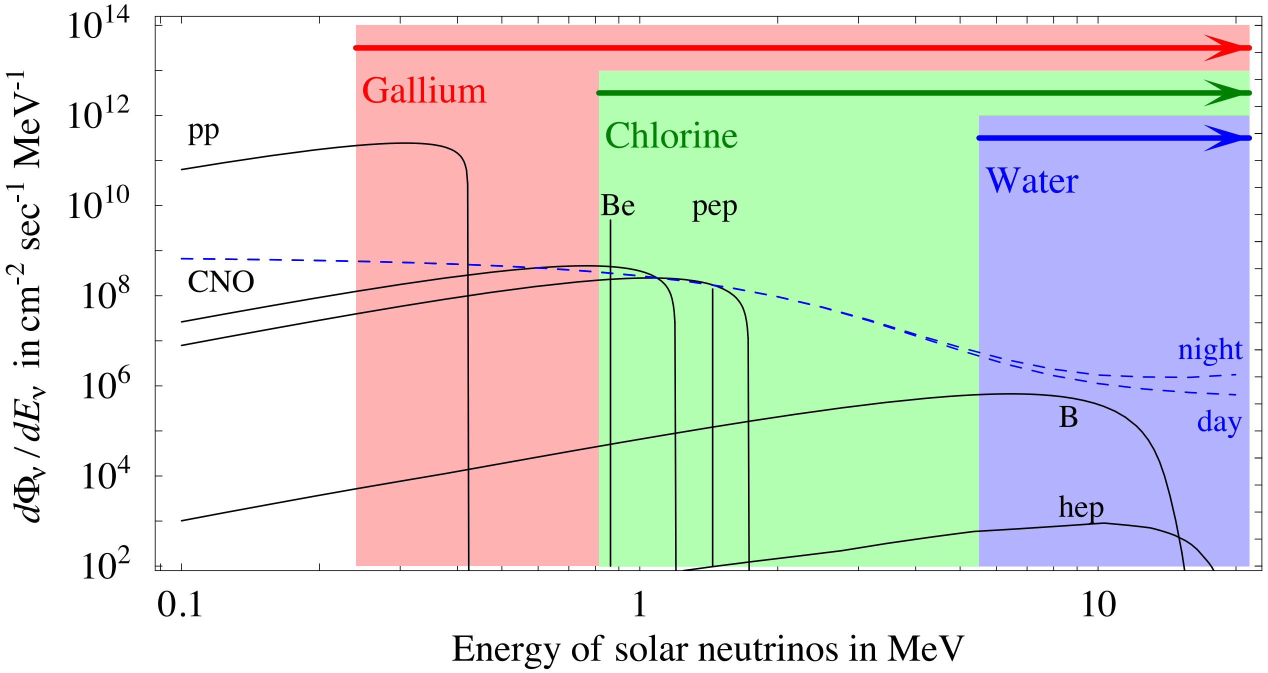
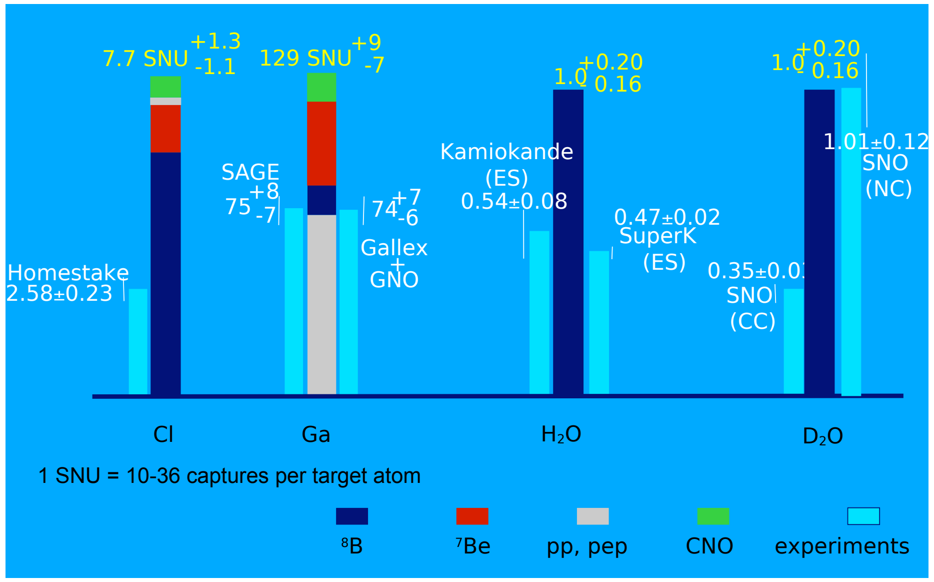


SOLAR ANOMALY

- Several experiments sensitive to different solar ν's measure a ν flux deficit: <u>problem with solar model?</u>

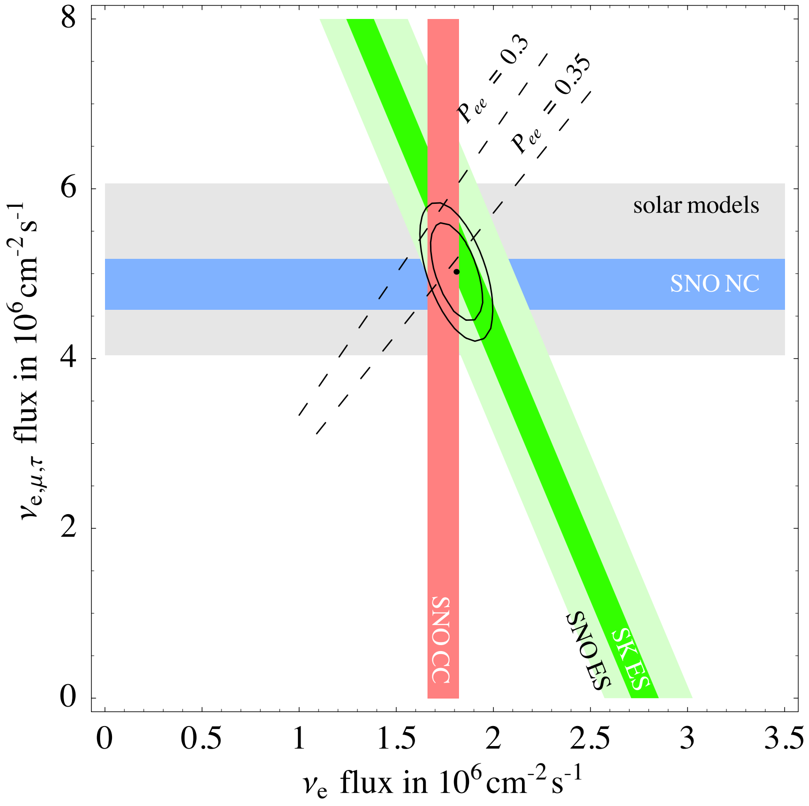




- SNO(D_20 Cerenkov detector) measure **both charged and total ν flux:**
  - **ES:** $\nu_{e,\mu,\tau} e \rightarrow \nu_{e,\mu,\tau} e \Rightarrow \Phi(\nu_e) + 0.155\ \Phi(\nu_{\mu,\tau})$
  - **CC:** $\nu_e D \rightarrow e^- pp \Rightarrow \Phi(\nu_e)$
  - **NC:** $\nu D \rightarrow \nu pn \Rightarrow \Phi(\nu_{e,\mu,\tau})$

- <u>NC rate as expected from Solar Model</u>

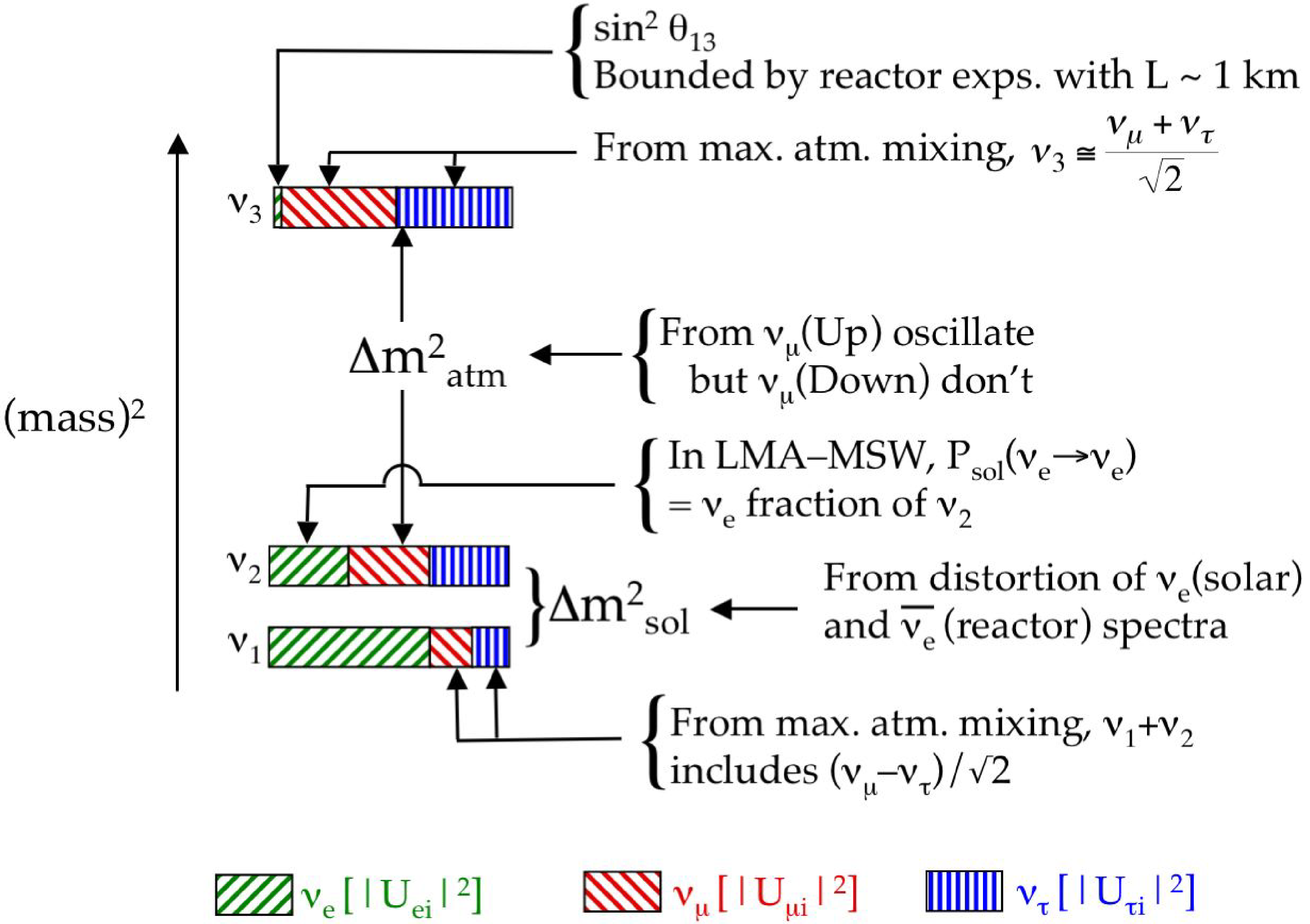
- CC/NC ratio: $$\frac{\phi(\nu_e)}{\phi(\nu_e) + \phi(\nu_{\mu,\tau})} = 0.357 \pm 0.030$$



THE WHOLE PICTURE

$\theta_{atm} \approx \theta_{13} \approx 45°$, $\theta_{sun} \approx \theta_{12} \approx 30°$, $\theta_{13} \lesssim 10°$

$|\Delta m^2_{13}| \approx |\Delta m^2_{23}| \approx |\Delta m^2_{atm}| \approx (2.40 \pm 0.15) \cdot 10^{-3}\ \text{eV}^2$ $\Delta m^2_{12} \approx \Delta m^2_{sol} \approx (7.58 \pm 0.21) \cdot 10^{-5}\ \text{eV}^2$



$\sin^2\theta_{13}$
Bounded by reactor exps. with L ~ 1 km

From max. atm. mixing, $\nu_3 \cong \dfrac{\nu_\mu + \nu_\tau}{\sqrt{2}}$

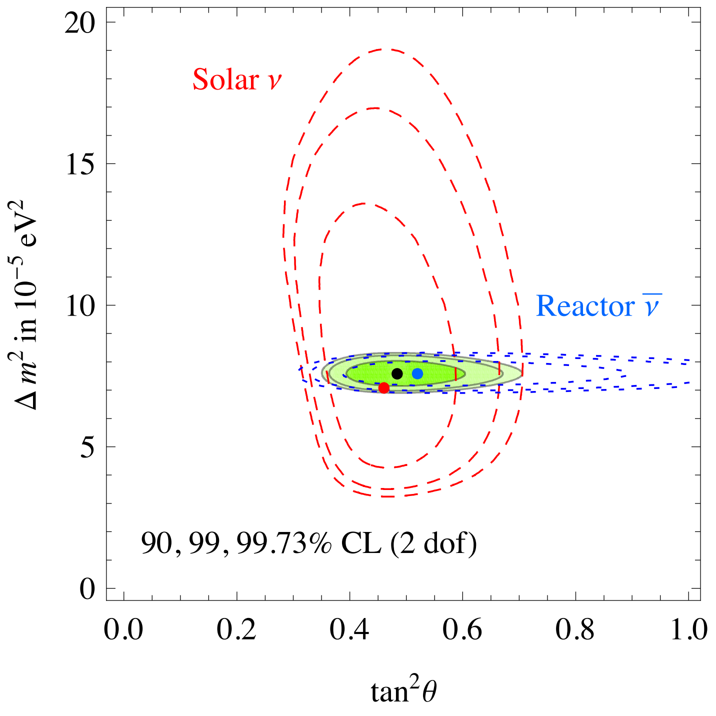
From ν_μ(Up) oscillate
but ν_μ(Down) don't

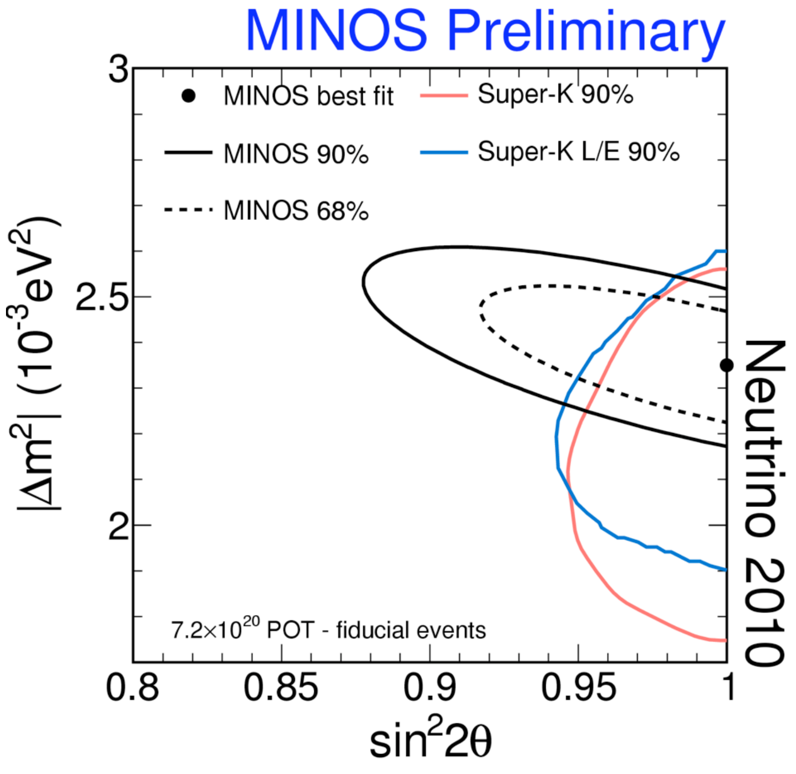
In LMA–MSW, $P_{sol}(\nu_e \to \nu_e)$
= ν_e fraction of ν_2

From distortion of ν_e(solar)
and $\overline{\nu}_e$ (reactor) spectra

From max. atm. mixing, $\nu_1 + \nu_2$
includes $(\nu_\mu - \nu_\tau)/\sqrt{2}$

▨ $\nu_e\ [\,|U_{ei}|^2]$ ▨ $\nu_\mu\ [\,|U_{\mu i}|^2]$ ▥ $\nu_\tau\ [\,|U_{\tau i}|^2]$





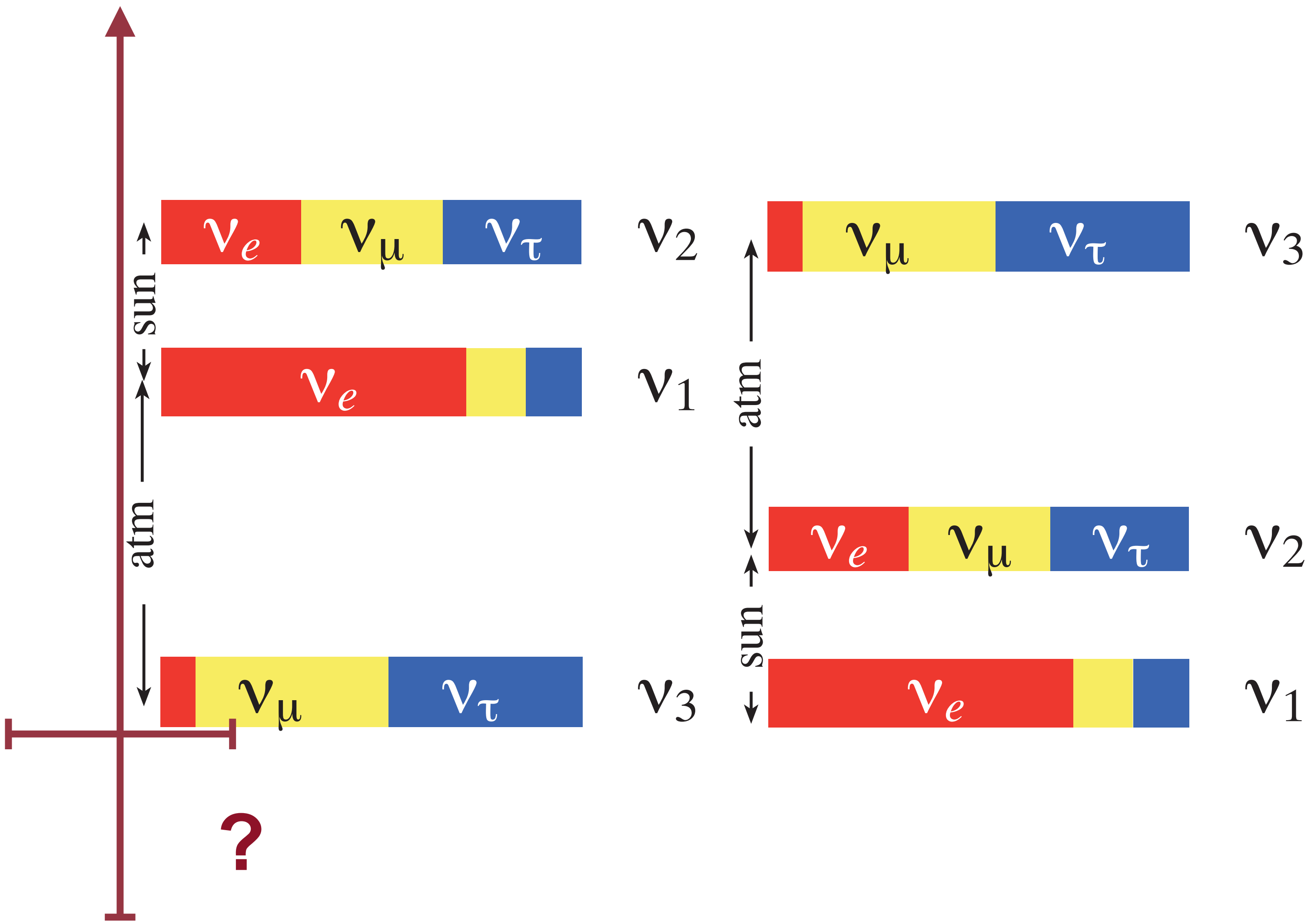
MASS SPECTRUM

- From oscillation experiments we know that neutrinos are massive:

  $|\Delta m^2_{13}| \approx |\Delta m^2_{23}| \approx |\Delta m^2_{atm}| \approx (2.40 \pm 0.15) \cdot 10^{-3}\ eV^2$ $\Delta m^2_{12} \approx \Delta m^2_{sol} \approx (7.58 \pm 0.21) \cdot 10^{-5}\ eV^2$

- Oscillation experiments are not sensitive to the absolute neutrino mass

- **Which is the absolute mass scale?**
  - **Cosmology**
  - **Beta Decay**
  - **Neutrinoless Double Beta Decay**

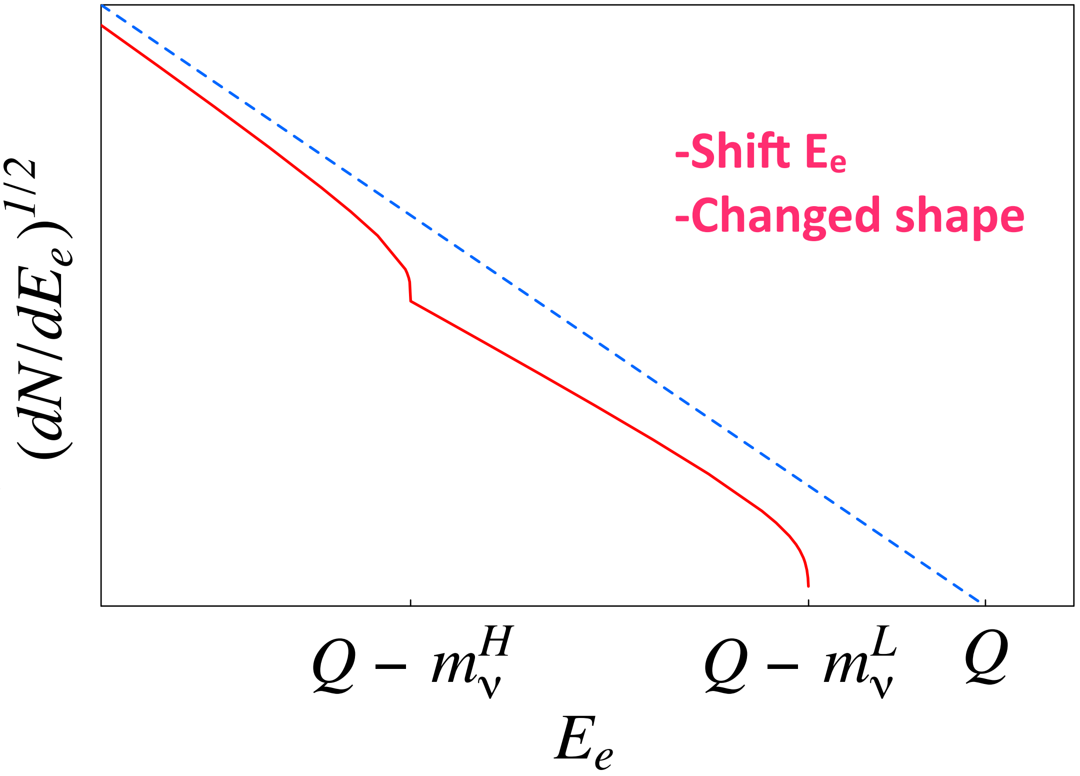


DIRECT MEASUREMENT

- **Based purely on kinematics without further assumptions**
  - Kinematically constrained measurement: π→μν,τ→5πν
    - Not competitive $m_\nu \leq O(100\ \text{keV})$ for π decay (MeV for τ decay)
  - Time of flight
    - long baseline ⇒ neutrino from supernovae explosion (emitted in 10 s) $m_\nu \leq O(10\text{eV})$
  - **Beta Decay**

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} = \sum_i |U_{ei}|^2 \frac{\mathrm{d}\Gamma_i}{\mathrm{d}E},$$

$$\frac{\mathrm{d}\Gamma_i}{\mathrm{d}E} = Cp(E+m_e)(E_0-E)\sqrt{(E_0-E)^2-m_i^2}F(E)\theta(E_0-E-m_i).$$



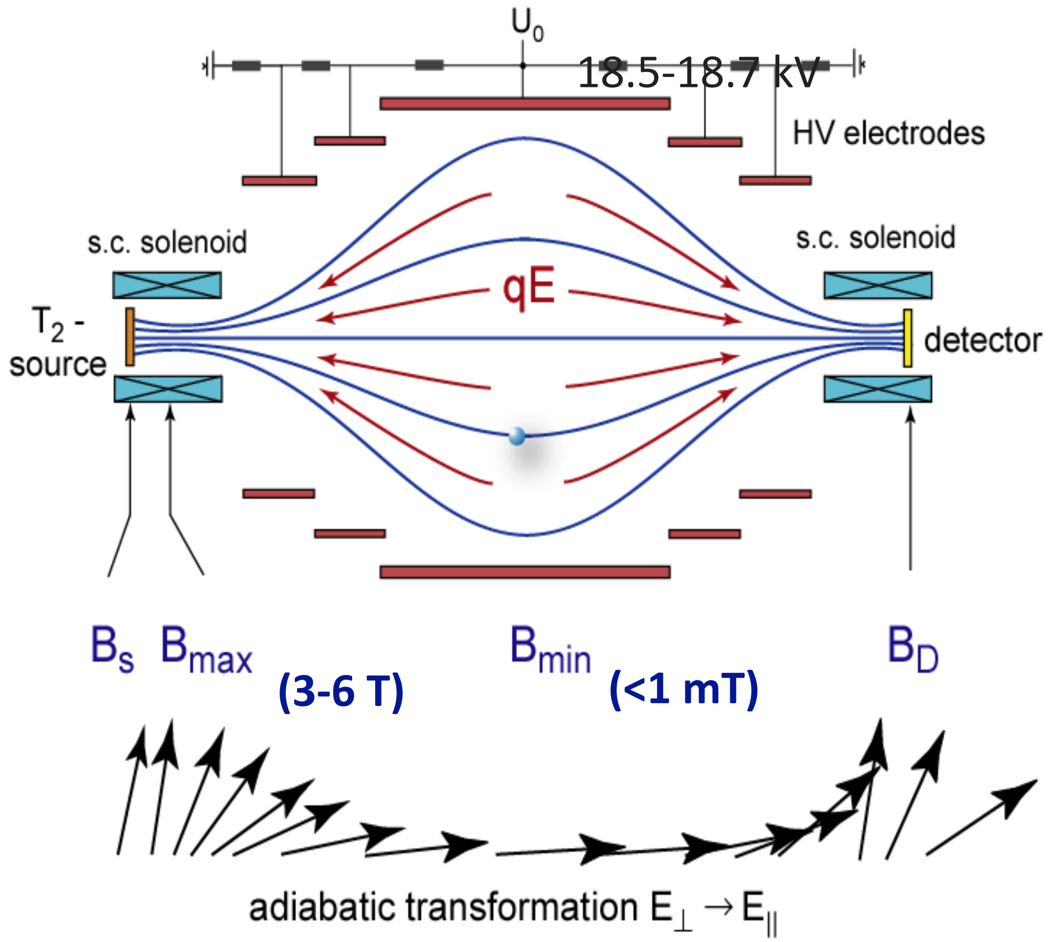
  - If different masses could not be resolved

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} = Cp(E+m_e)(E_0-E)\sqrt{(E_0-E)^2-m_\beta^2}F(E), \qquad m_\beta^2 = \sum_i |U_{ei}|^2 m_i^2$$

  - Events fraction near end-point ≈ $(m_\nu/Q)^3$: 10^{-13} for ^{3}H ⇒ low Q, high count rate & energy resolution

KATRIN

- **The MAC-E filter:**
  - Adiabatic guiding of electrons along magnetic field:
    - **$\mu = E_{K\perp}/B = \text{const}$**
    - **$E_e = E_{K\perp} + E_{K||} = \text{const}$**
    - **$E_{K\perp} \Rightarrow E_{K||}$**
    - **High energy pass filter** to due potential $E_{K||} > U_0$
  - High resolution **$\Delta E/E = B_{min}/B_{max} \approx 10^{-4}$**
  - Large solid angle: 2π



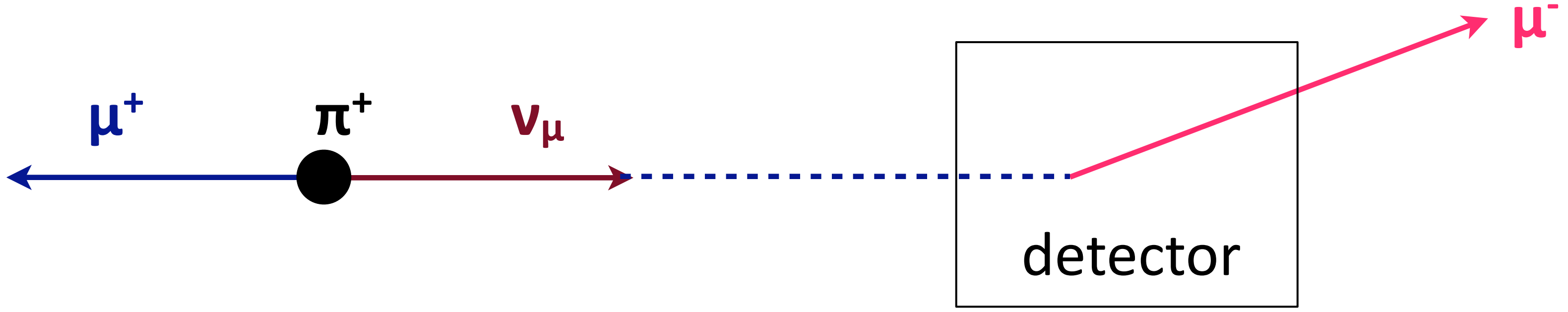
Actual limits $m_\nu \leq 2.3$ eV 90% CL
(Mainz,Troitsk)

Katrin points to $m_\nu \approx 0.2$.eV

MAJORANA OR DIRAC

LEPTON NUMBER CONSERVATION

- Experimental evidence:
  - **Particle produced together with μ^+ in π^+ decay produce a μ^- and never a μ^+**
  - Opposite for π^- decay



- **Conventional explanation**
  - ν_μ and $\bar{\nu}_\mu$ are distinct from each other
  - There exists a quantum number conserved during interactions: *the lepton number*
    - **Dirac fermion**

- **Alternative explanation**
  - Weak interactions couple to chirality eigenstates
  - *Left-handed* chirality particle interacts giving a μ^- (μ^+ opposite for right-handed chirality)
  - There exists only one particle with two chirality states
  - We don't see μ^+ because chirality flip is suppressed $\propto (m_\nu/E_\nu)^2$
    - **Majorana fermion**

MAJORANA NEUTRINO

- Dirac equation: $i(\gamma^{\mu}\partial_{\mu}-m)\Psi=0$
  - *Ψ_L, Ψ_R irreducible representations of Lorentz group* (Chirality $P_L^{(R)}=(1\pm\gamma_5)/2$, $P_L^{(R)}\Psi=\Psi_L^{(R)}$)
    - $\Psi=\Psi_L+\Psi_R$, $\boldsymbol{i\gamma^{\mu}\partial_{\mu}\Psi_L=m\Psi_R}$, $\boldsymbol{i\gamma^{\mu}\partial_{\mu}\Psi_R=m\Psi_L}$
    - Massless fermions described by two degrees of freedom: decoupled equations

- Minimal description of a massive neutral fermion with 2 degrees of freedom **(Majorana 1937)**:
  - **$\Psi\equiv\Psi^C$ particle and anti-particle coincide**

- C charge conjugation operator: **$\Psi^C=C\overline{\Psi}^T$, $C=i\gamma^2\gamma^0$**
  - Using γ properties: **Ψ^C_R is left-handed**
  - **$\Psi\equiv\Psi^C\Rightarrow$ $\Psi_L+\Psi_R=\Psi^C_L+\Psi^C_R$ $\Rightarrow$ $\Psi_R=\Psi^C_L$, $\Psi_L=\Psi^C_R$**
    - Only two independent components: **$\Psi^M=\Psi_L+\Psi^C_L$**
      - ➡ Majorana theory simpler ad more economical then Dirac theory

- **If $\Psi\equiv\Psi^C$**
  - ***No longer free to phase-redefine ν_i without consequences***
  - ***Mixing matrix U can contain addition CP-violating phases***
  - ***Affect only processes with lepton number violation***

$$U_{PMNS}\cdot\begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

MASS TERM

- MS: chiral theory $SU(2)_L$ X $U(1)_Y$
  - Ψ_L and Ψ_R have different properties under $SU(2)_L$: **Ψ_L doublet**, **Ψ_R singlet**

- *Ψ_L, Ψ_R irreducible representations of Lorentz group*
- General Lorentz invariant mass term includes:
  - **Dirac mass term: $L^D = -m_D \bar{\Psi}^D \Psi^D = -m_D (\bar{\Psi}_L \Psi_R + \bar{\Psi}_R \Psi_L)$**
    - Need a **Ψ^{ν}_R** *sterile* component
    - L^D creates/absorbs ν_L and absorbs/creates $\bar{\nu}_R$
    - L^D mixes chirality, **does not** mix particle/antiparticle component

  - **Majorana Mass term: $L^M = -1/2 m_M \bar{\Psi}^M \Psi^M = -1/2 m_M (\bar{\Psi}^C_L \Psi_L + \bar{\Psi}_L \Psi^C_L)$**
    - L^M create/absorbs **one** particle *with left and right chirality*
    - L^M mixes chirality, mixes charge conjugated components
      - ➡ **Violation of any additive quantum number** (Lepton number,etc...)
      - ➡ ***Only possible for totally (under all MS gauge groups) neutral particles***
      - ➡ Only neutrinos could have this mass term, they are very peculiar

MASS MATRIX

- Most general mass term **for 1 ν** compatible with Lorentz invariance: **$L^{D+M}=L^{D}+L^{M}_{L}+L^{M}_{R}$**
  - **$L^{D+M}=-m_D\bar{\Psi}_L\Psi_R-1/2m_M\bar{\Psi}^C_L\Psi_L-1/2m_M\bar{\Psi}_R\Psi^C_R$ +h.c.**

field notation change Ψ➛ν

$$L^{D+M}=-\frac{1}{2}\begin{bmatrix}\bar{\nu}_L^C & \bar{\nu}_R\end{bmatrix}\begin{bmatrix}m_L & m_D\\ m_D & m_R\end{bmatrix}\begin{bmatrix}\nu_L\\ \nu_R^C\end{bmatrix}+h.c.$$

Right components,sterile

Left components, active

$$\mathcal{L}^{\mathrm{D+M}}=\frac{1}{2}\,\overline{N_L^c}\,M\,N_L+\mathrm{H.c.}\,,\qquad M=\begin{pmatrix}m_L & m_{\mathrm{D}}\\ m_{\mathrm{D}} & m_R\end{pmatrix},\qquad N_L=\begin{pmatrix}\nu_L\\ \nu_R^c\end{pmatrix}.$$

  - ν_{L}, ν_R <u>are not mass eigenstates</u>, only neutrino fields in term of which the model is constructed
  - Diagonalizing the Mass Matrix:

$$N_L=U\,n_L\,,\qquad n_L=\begin{pmatrix}\nu_{1L}\\ \nu_{2L}\end{pmatrix},\qquad U^T\,M\,U=\begin{pmatrix}m_1 & 0\\ 0 & m_2\end{pmatrix},$$

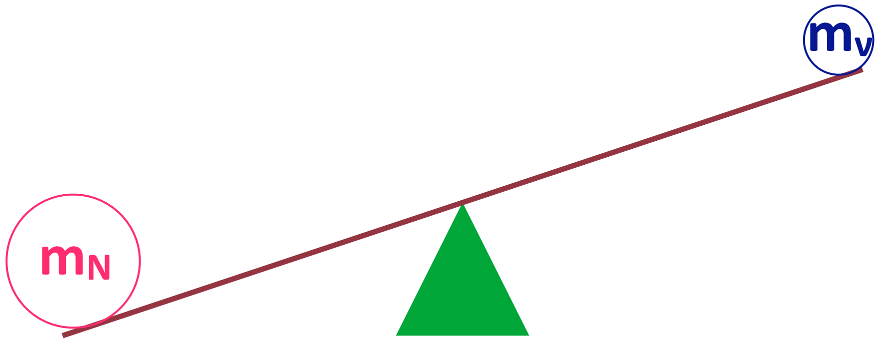
$$L^{D+M}=-\frac{1}{2}\sum_{k=1,2}m_k\bar{\nu}_{kL}^C\nu_{kL}+h.c$$

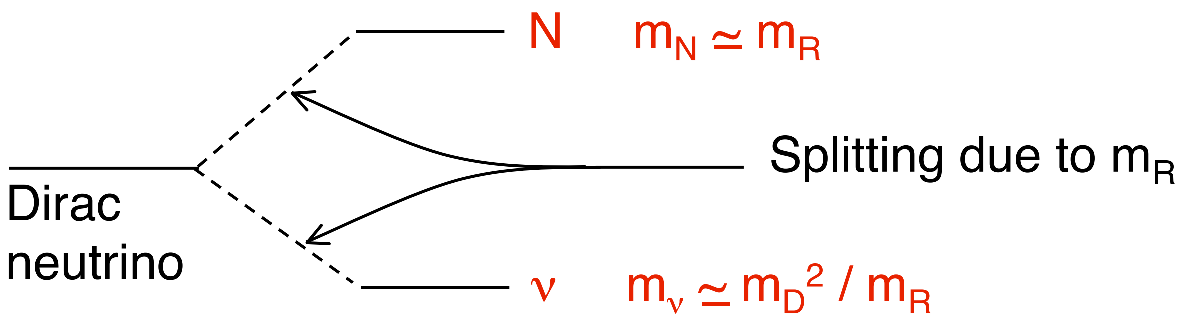
$$\nu_k=\nu_{kL}+\nu_{kL}^c\qquad (k=1,2)\,.$$

- **Most general D+M mass term = Sum of 2 Majorana mass term for the fields $\nu_k=\nu_k^C$**
- As a result of $\bar{K}^0K^0$ mixing, the neutral K mass eigenstates are K_L, $K_S=0.5(\bar{K}^0\pm K^0)$. As a result of neutrino mixing (induced by Majorana mass term) **ν mass eigenstates are Majorana neutrino**
- $N_L=Un_L\Rightarrow\nu_L$, ν_R^C combination of ν_{1L}, ν_{2L}, *<u>possible oscillation between sterile and active states</u>*

SEE-SAW

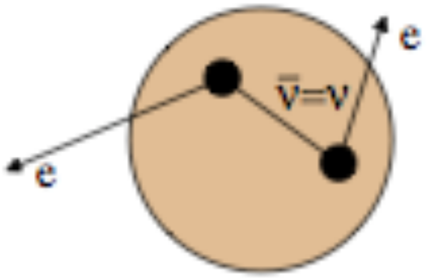
- **Majorana masses cannot** come from the progenitor of the **Dirac Mass term**: $H_{SM}\bar{\nu}_R\nu_L$
- Possibles progenitors of Majorana mass term:
  - $H_{SM}H_{SM}\bar{\nu}_L^C\nu_L$: not renormalizable ($\nu_L^C\nu_L$ isospin triplet)
  - $H_{Isospin=1}\bar{\nu}_L^C\nu_L$: excluded by Standard Model measurements (Z,W couplings and widths)
  - $m_R\bar{\nu}_R^C\nu_R$: **ok** ($\bar{\nu}_R^C\nu_R$ Isospin singlet)
    - $m_L=0$
    - m_D: order of magnitude EW symmetry breaking scale **≈100 GeV**
    - m_R: unprotected by any symmetry
      - ➡ If MS is a low energy effective theory of a more general gauge group, it's reasonable to expect m_R of the order of this new symmetry breaking scale
      - ➡ **$m_R \approx m_D^2/m_\nu \approx 10^{15}$ GeV ≈GUT scale!**
  - 2 Majorana neutrinos, one big mass sterile neutrino **($m_N=m_R$)**, one light neutrino **($m_\nu=m^2_D/m_R$)**
    - Explanation of the smallness of neutrino mass
    - Sterile neutrinos are very heavy and therefore decoupled from the active ones

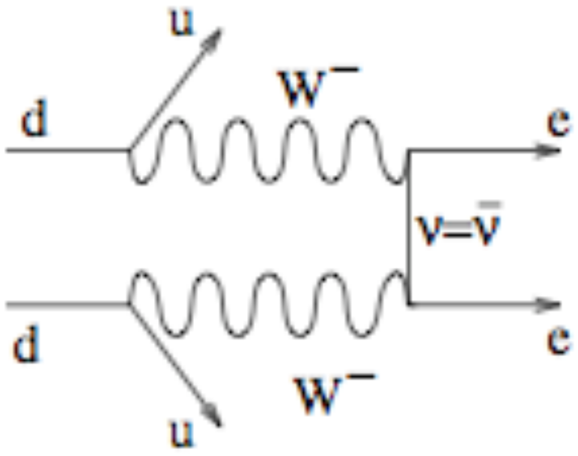




HOW TO TEST MAJORANA NATURE

- The most sensitive LNV process: Neutrinoless Double Beta Decay ($0\nu\beta\beta$)
- Second order weak nuclear process: (A,Z) → (A,Z+2) + 2 e^-
  - (A,Z) → (A,Z+2) + 2 e^- + 2$\bar{\nu}$ allowed by the MS





Only if:

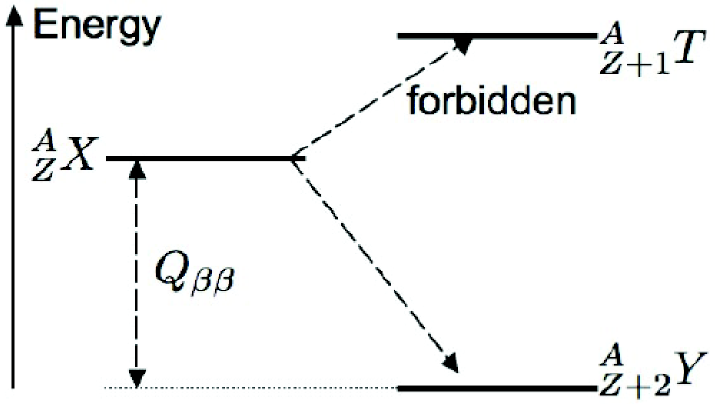
massive neutrinos → chirality flip

Majorana neutrino

$\Delta L=2$

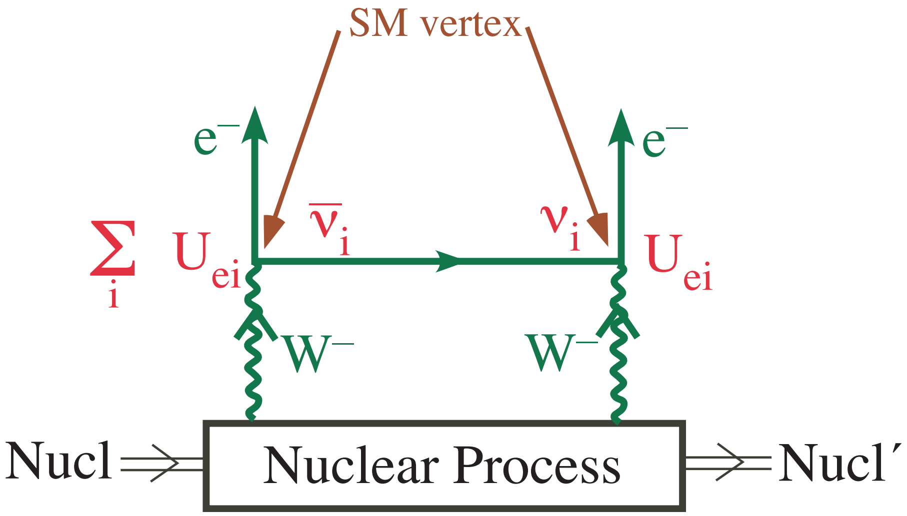
- Possible only in few even-even nuclei:

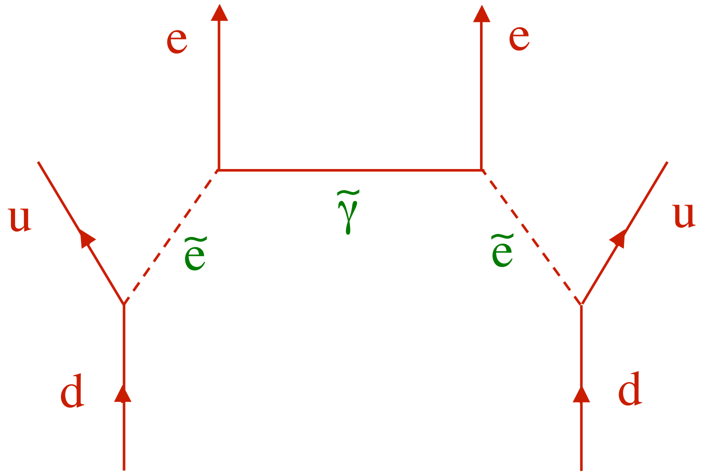
^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe, ^{150}Nd



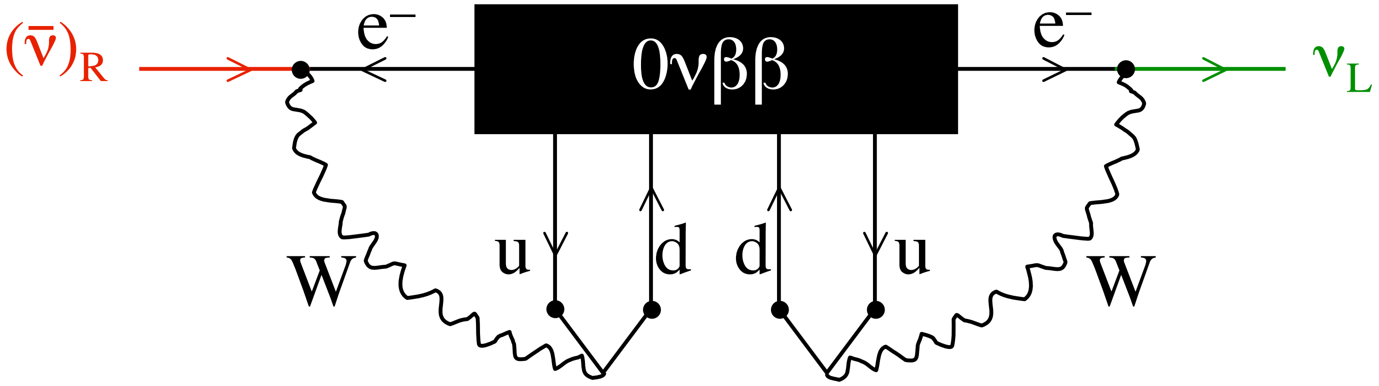
NEUTRINOLESS DOUBLE BETA DECAY: 0νββ

- Many diagrams can contribute:





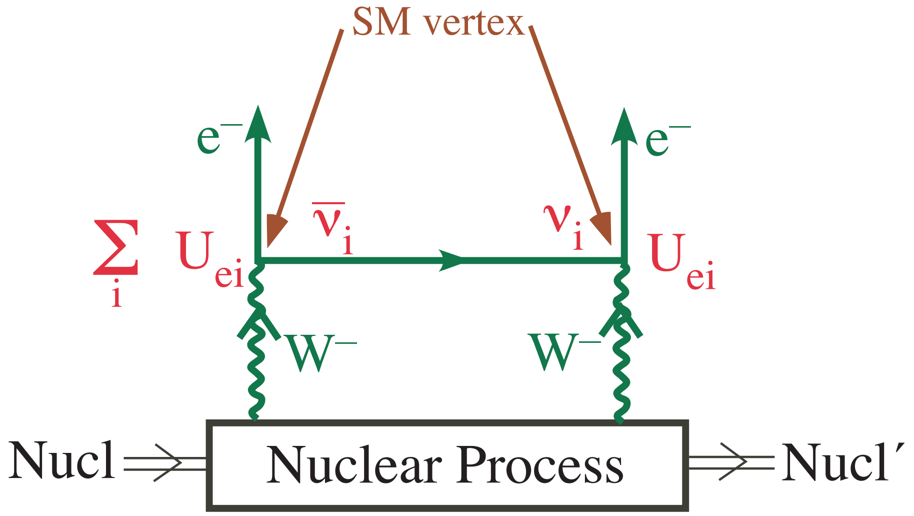
Whatever diagram causes 0νββ, it's observation would imply Majorana mass



Schetcher, Valle Phys. Rev. D25 2951 1982

NEUTRINOLESS DOUBLE BETA DECAY: 0νββ

- Assuming the dominant mechanism is:



- **Chirality flip ⇒ Amp(0νββ)∝|$\sum m_i U_{ei}^2$|≡$m_{\beta\beta}$**
  - This is what you expect,the only term that violates L in the lagrangian is the ν mass term

$$m_{\beta\beta} = \cos^2\theta_{13}(m_1\cos^2\theta_{12} + m_2 e^{2i\alpha}\sin^2\theta_{12}) + m_3 e^{2i\beta}\sin^2\theta_{13}$$

  - **Due to Majorana phases cancellations may occur**

0νββ ⇔ ν MASS

- The measurable quantity is the half life:

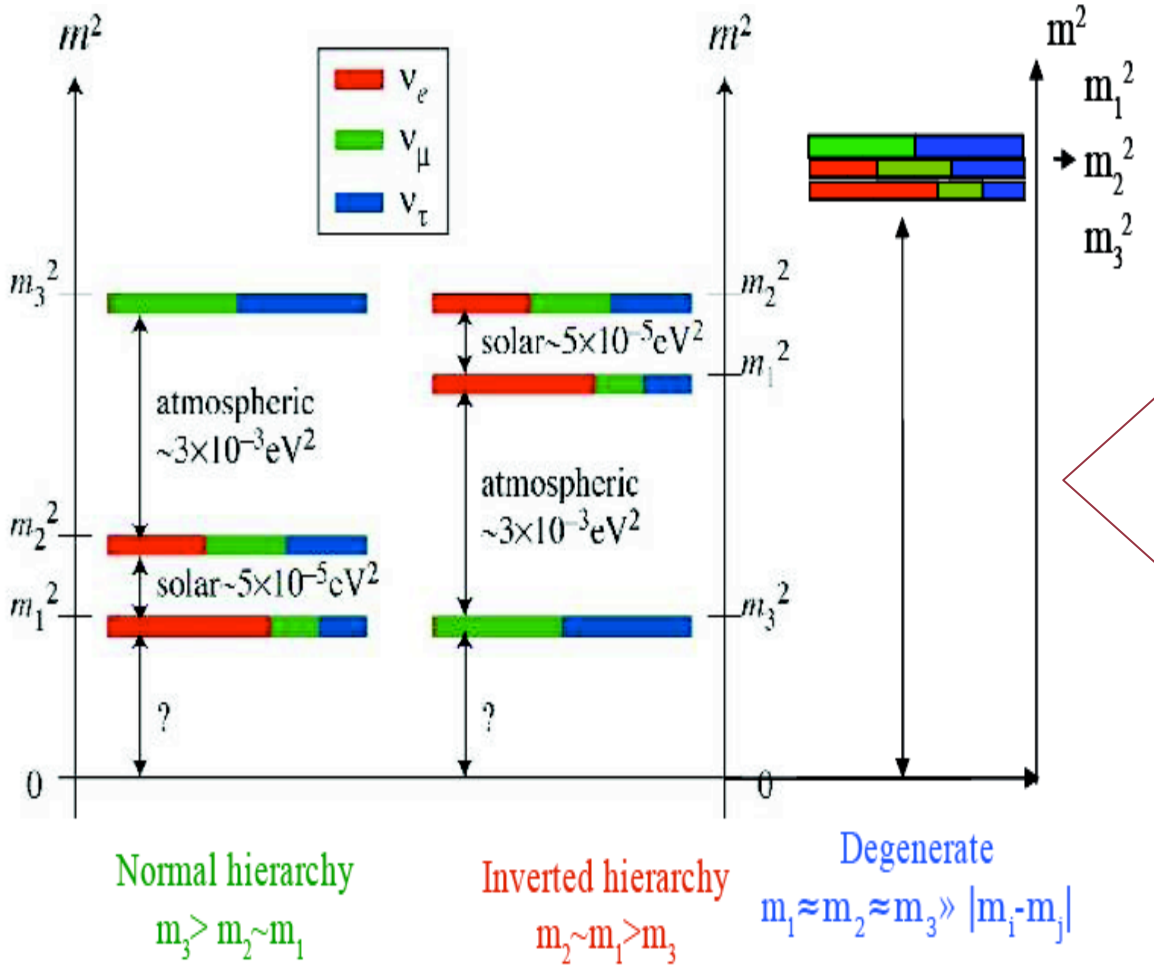
Phase space factor~Q^5 **Nuclear Matrix Element** **Effective neutrino mass**

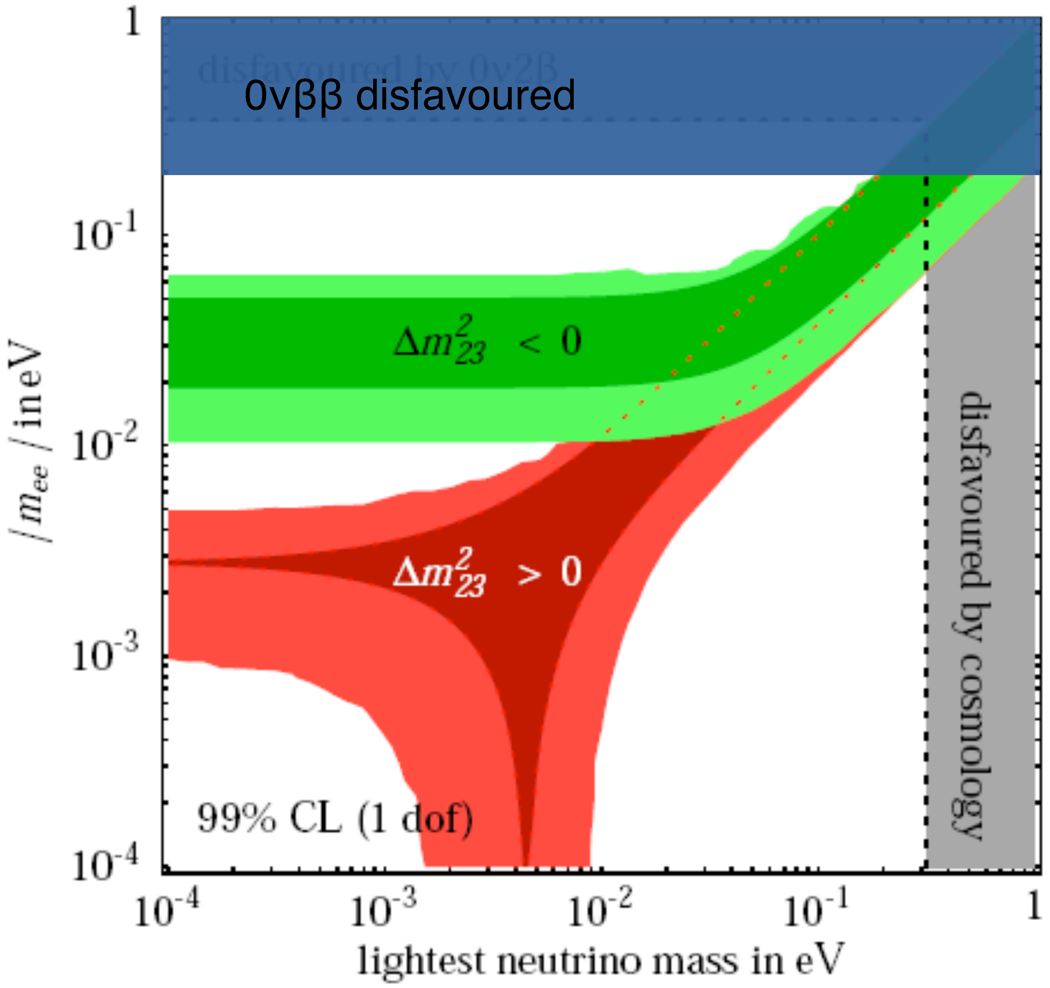
$$(\tau^{0\nu}_{1/2})^{-1} = G(Q,Z)|M_{nucl}|^2|m_{\beta\beta}|^2$$

$$m_{\beta\beta} = |\sum_i m_i \cdot U_{ie}^2|$$

(light neutrino exchange mode)

$$m_{\beta\beta} = \cos^2\theta_{13}(m_1\cos^2\theta_{12} + m_2 e^{2i\alpha}\sin^2\theta_{12}) + m_3 e^{2i\beta}\sin^2\theta_{13}$$

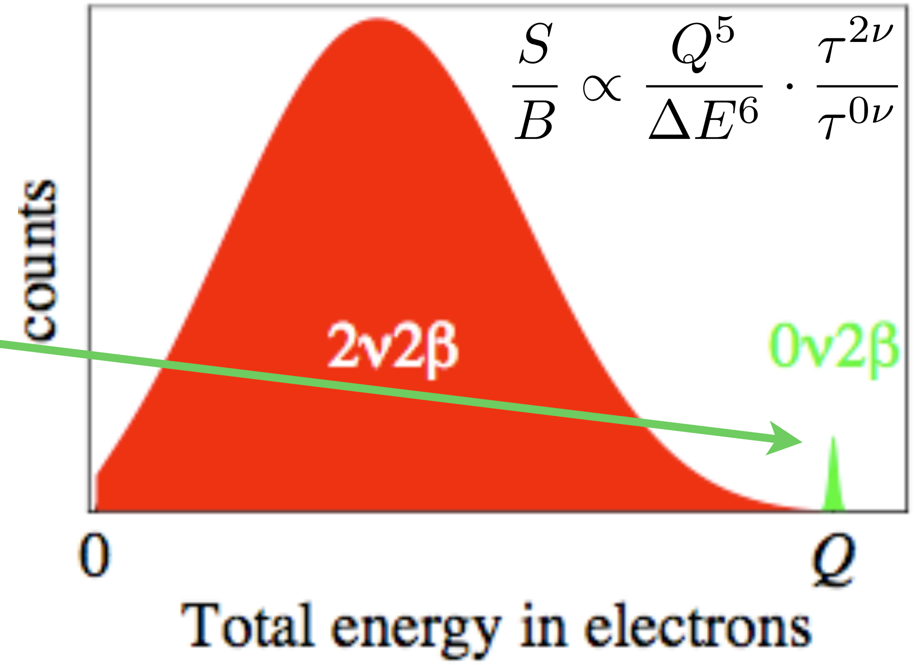




Strumia, Vissani hep/ph 0606054

0νDBD IN EXPERIMENTS

- Experiments measure the sum of the kinetic energies of the two emitted electrons
- Signature: monochromatic line at the Q-value of the decay (2-3 MeV)



$$\frac{S}{B} \propto \frac{Q^5}{\Delta E^6} \cdot \frac{\tau^{2\nu}}{\tau^{0\nu}}$$

Detector mass (kg)

Isotopic abundance

Measurement time (y)

$$S^{0\nu\beta\beta} = \ln 2 N_A \cdot \frac{a}{A} \left(\frac{Mt}{B \Delta E} \right)^{1/2} \cdot \epsilon$$

Efficiency

Atomic mass

Energy Resolution (keV)

Background (counts/keV/kg/y)

$\tau_{0\nu} \approx \geq 10^{24}$ y
$\tau_{2\nu} \approx 10^{19/22}$ y
τ primordial(Ur,Th)$\approx 10^{10}$ y

- Remember: $m_{\beta\beta} \propto (\tau^{0\nu})^{-1/2}$

THE ISOTOPE CHOICE

Parent Isotope	$Q_{\beta\beta}$ (KeV)	Ab(%)
^{48}Ca	4271	0.187
^{76}Ge	2039	7.8
^{82}Se	2995	9
^{100}Mo	3034	9.6
^{116}Cd	2902	7.5
^{130}Te	2530	33.9
^{136}Xe	2479	8.9
^{150}Nd	3367	5.6

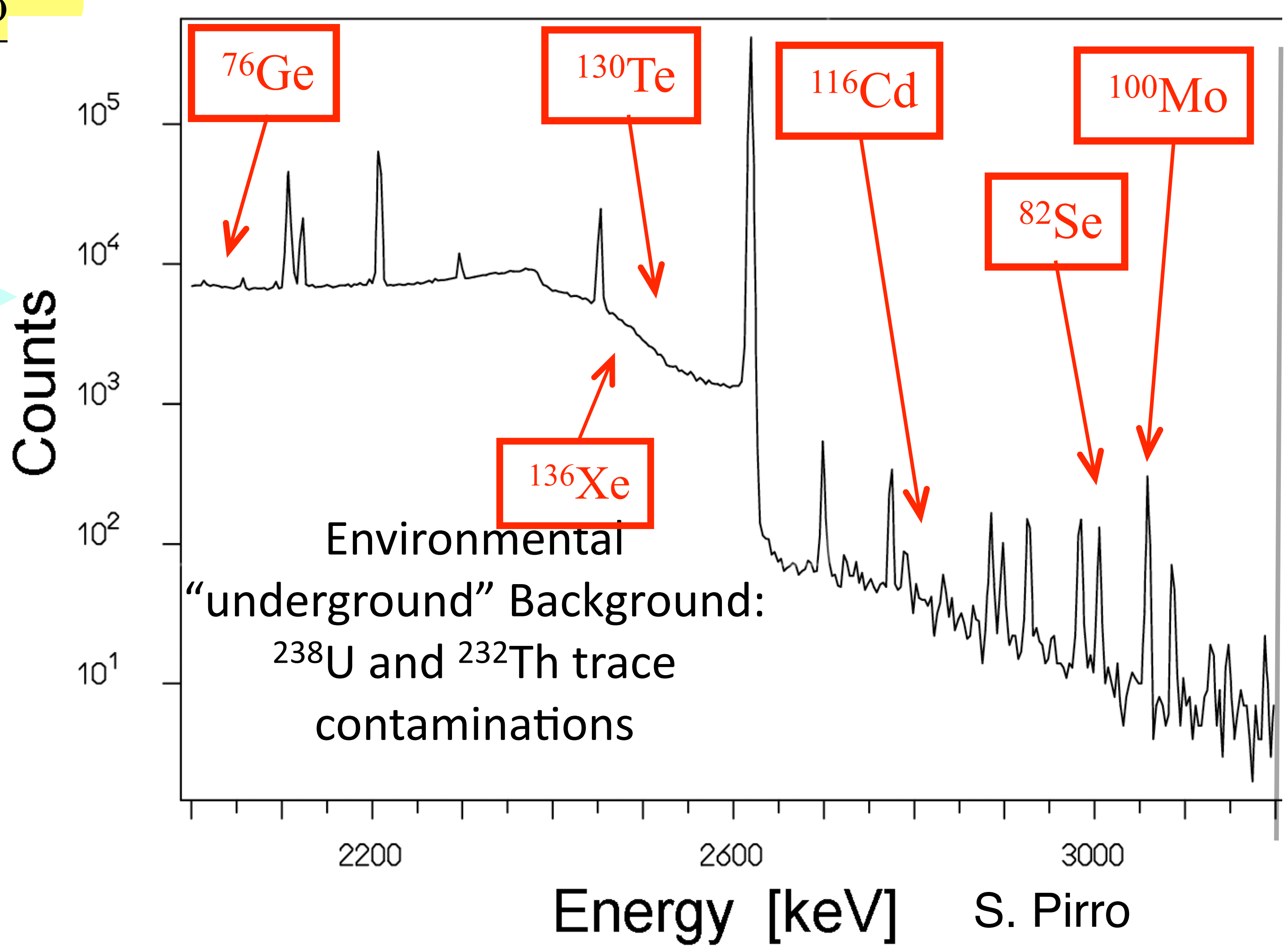
Isotopic abundance: **<10%**

(only exception ^{130}Te)

Gain ~ 100

if **$Q_{\beta\beta}$ > 2615 keV**

end of γ radioactivity (^{208}Tl)

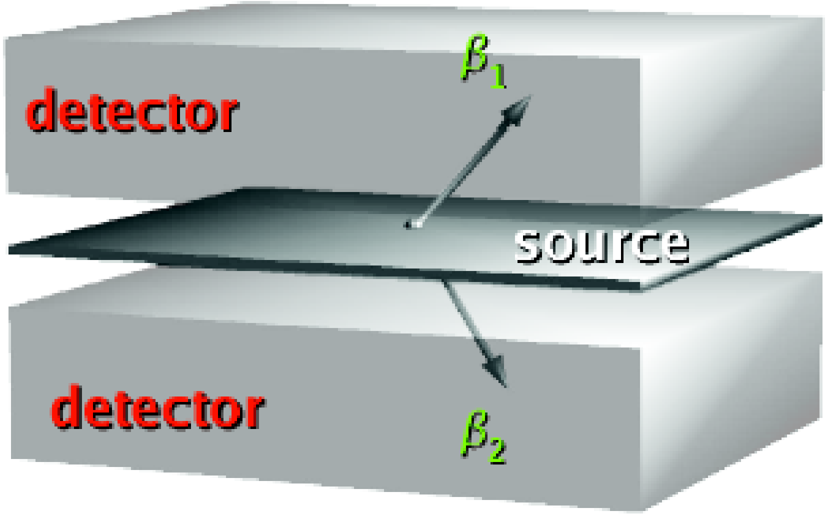


Environmental "underground" Background: ^{238}U and ^{232}Th trace contaminations

S. Pirro

EXPERIMENTAL STRATEGIES

source ≠ detector

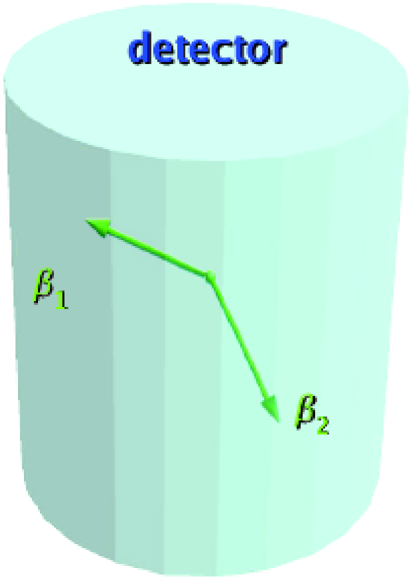


+++ Topology, Bkgd(2νββ exception)

--- M, ΔE, ε

Calo-tracko detectors
(NEMO, MOON,DCBA)

source = detector

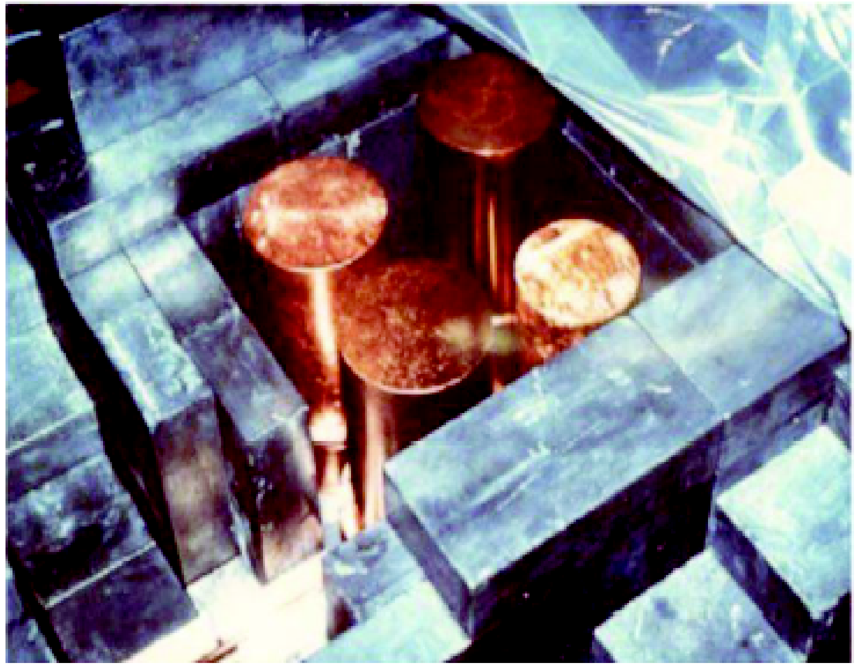


+++ M, ΔE, ε

--- Topology, Bkgd(2νββ exce.)

Diodes (MAJORANA, GERDA)
Bolometers (CUORE, LUCIFER)
Solid-state devices scintillators (COBRA)
Solid scintillators(CANDLES)
Liquid loaded scintillator(SNO++,Kamland)
Gaseous/Liquid TPC (EXO)

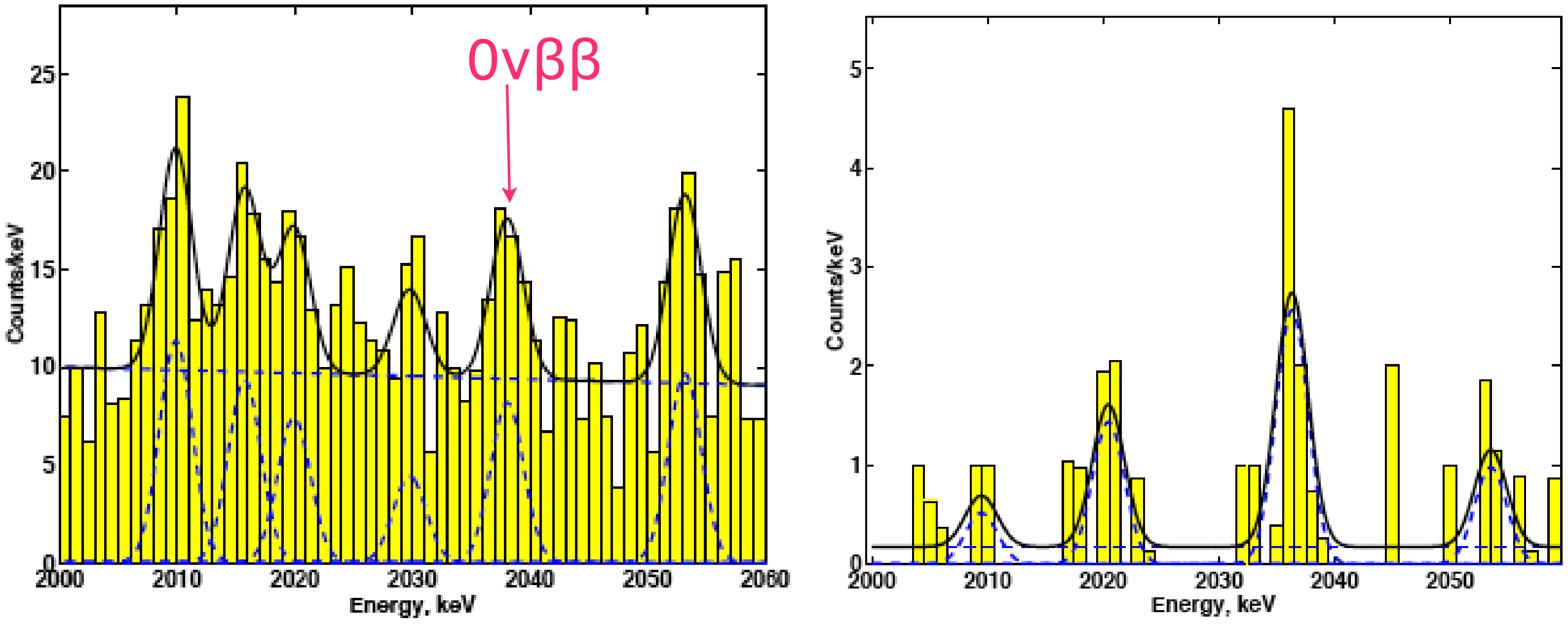
HEIDELBERG-MOSCOW: KLAPDOR CLAIM



source = detector

- 5 HP-Ge diodes: 10.9 kg (86% enriched ^{76}Ge)
  - Exposure: 53.9 kg y (1990-2001)
  - $\Delta E_{FWHM} \sim$ 4 keV @ $Q_{\beta\beta} \approx$2039 keV
  - $\tau^{0\nu}_{1/2} > 1.9 \cdot 10^{25}$ y $\Leftrightarrow$ $\langle m_{\beta\beta} \rangle < 0.35$ eV

Klapdor et al. Phys. Lett. B 586 (198) 2004



- Exposure: 71.7 kg y(1990-2003)
  - Background ~0.11 counts/keV/kg/y

$\tau^{0\nu}_{1/2} = 1.2 \cdot 10^{25}$ y

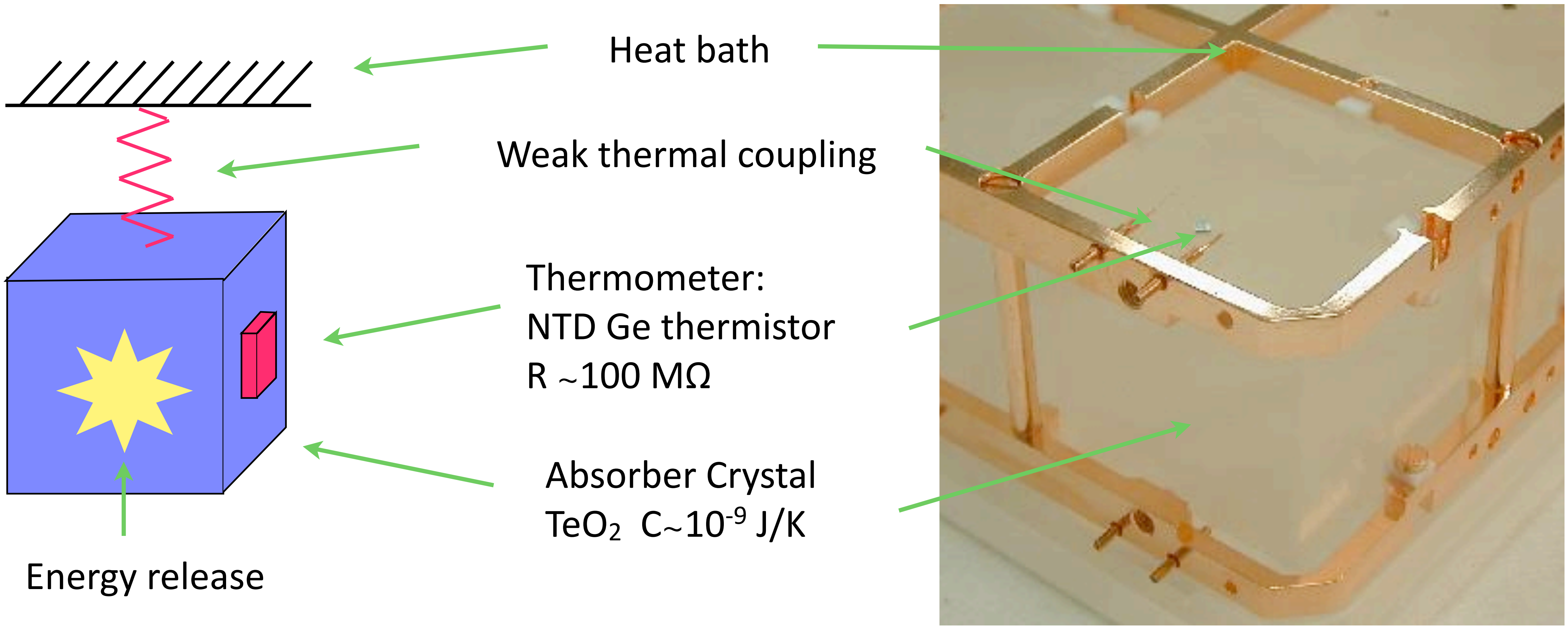
$\Leftrightarrow$

$\langle m_{\beta\beta} \rangle = 0.44$ eV

CUORICINO

- Particle energy converted into phonons → temperature variation **$\Delta T = E/C$**
- Need very low heat capacity: TeO_2 crystals (dielectric, diamagnetic) **@~8mK**

source = detector



Heat bath

Weak thermal coupling

Thermometer:
NTD Ge thermistor
R ~100 MΩ

Absorber Crystal
TeO_2 $C \sim 10^{-9}$ J/K

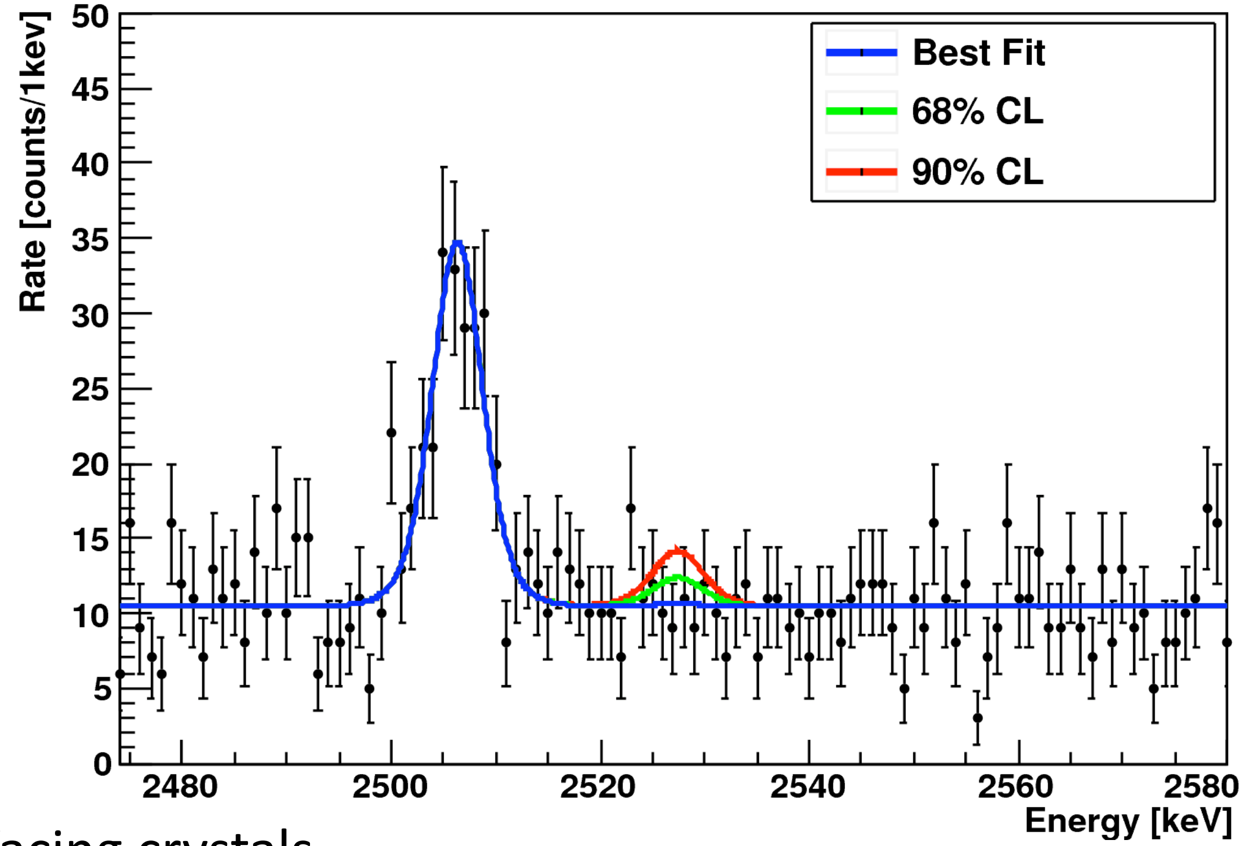
Energy release

- Detector response in this configuration: **≈ 0.1 mK/MeV ≈ 0.3 mV/MeV**

CUORICINO RESULTS

- Exposure (2003-2008):

$$M \cdot t = 19.75 \text{ kg } {}^{130}\text{Te} \cdot \text{y}$$



- Background level:

$$(0.16 \pm 0.01)\text{counts/keV/kg/y}$$

  - ~50% from degraded α from inert material (Cu) facing crystals
  - ~40% from ^{208}Tl multi-Compton (cryostat contamination)

- **ΔE_{FWHM}~7.5 keV @ $Q_{\beta\beta}$ ~2527 keV**

$$\tau_{1/2}^{0\nu} > 2.8 \cdot 10^{24}\,\text{y}\ @90\%CL \quad \Leftrightarrow \quad m_{\beta\beta} < 0.3 \div 0.7\,\text{eV}$$

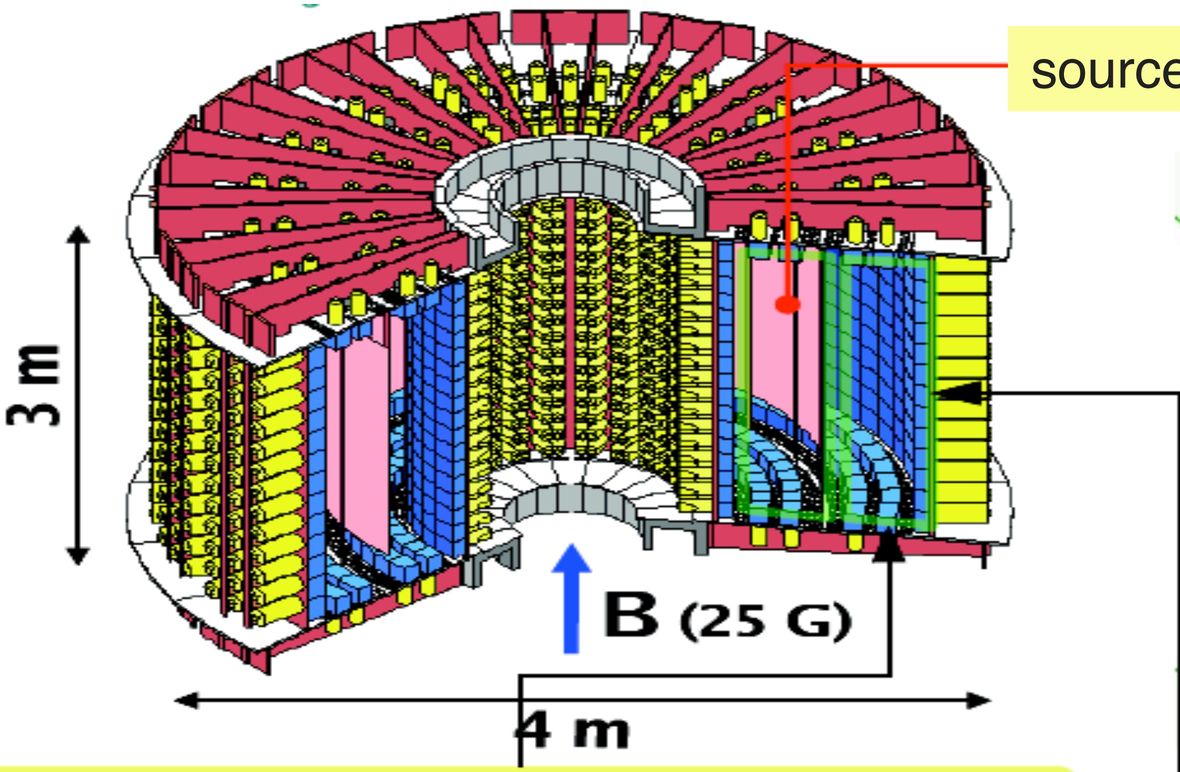
NEMO 3

- Tracking detector: ~6000 Geiger mode drift chambers (95%He+4%alcohol+1%Ar)
- Calorimeter:~2000 plastic scintillators + PMTs
  - **$\Delta E_{FWHM}/E \sim 8\%$ @ 3MeV $\sigma_T \sim$ 300 ps @ 1MeV**
  - 3-5% charge confusion

source ≠ detector

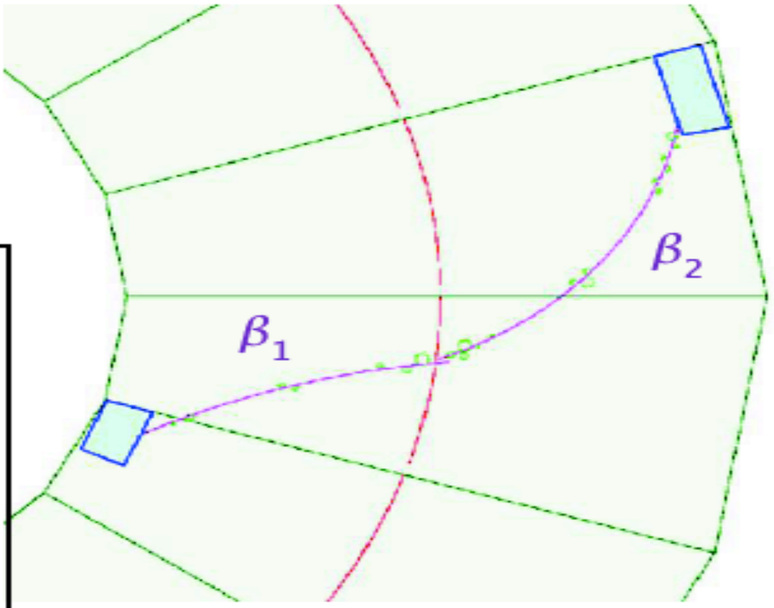
Source	Mass	
^{100}Mo	6.9 kg	0νββ
^{82}Se	0.9 kg	
^{130}Te	0.45 kg	
^{116}Cd	0.4 kg	
^{150}Nd	37g	2νββ
^{96}Zr	9.4g	
^{48}Ca	7.0g	

source in foils 40-60 mg/cm2



tracking volume (drit wire chamber)

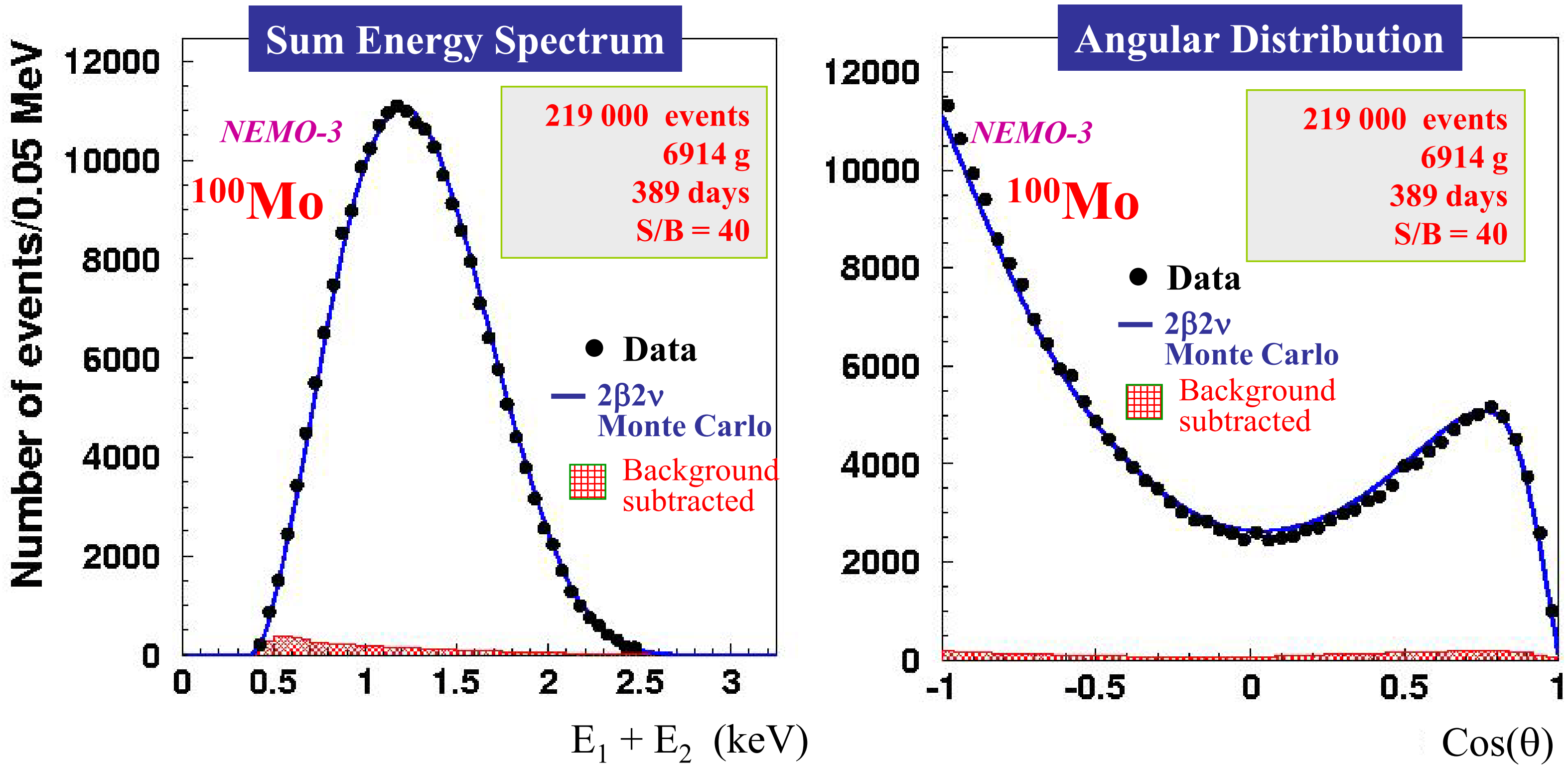
calorimeter (scintillators)

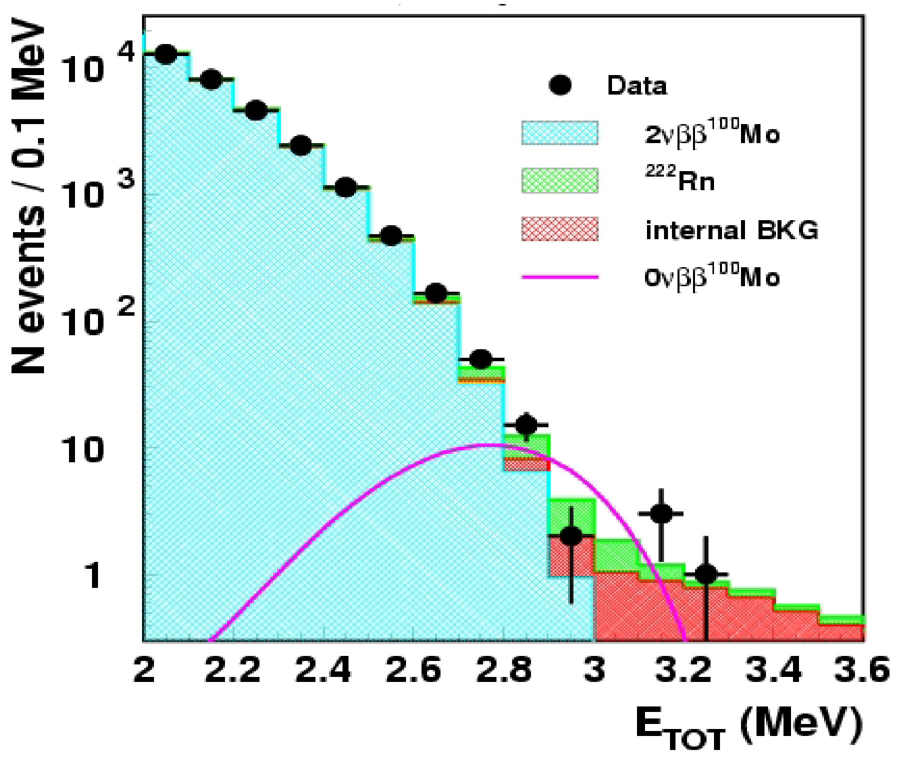


NEMO 3 RESULTS

^{100}Mo: $\tau^{2\nu}_{1/2}$ =(7.11±0.02±0.54)·10^{18} y

^{100}Mo: $\tau^{0\nu}_{1/2}$ >1.1·10^{24} y





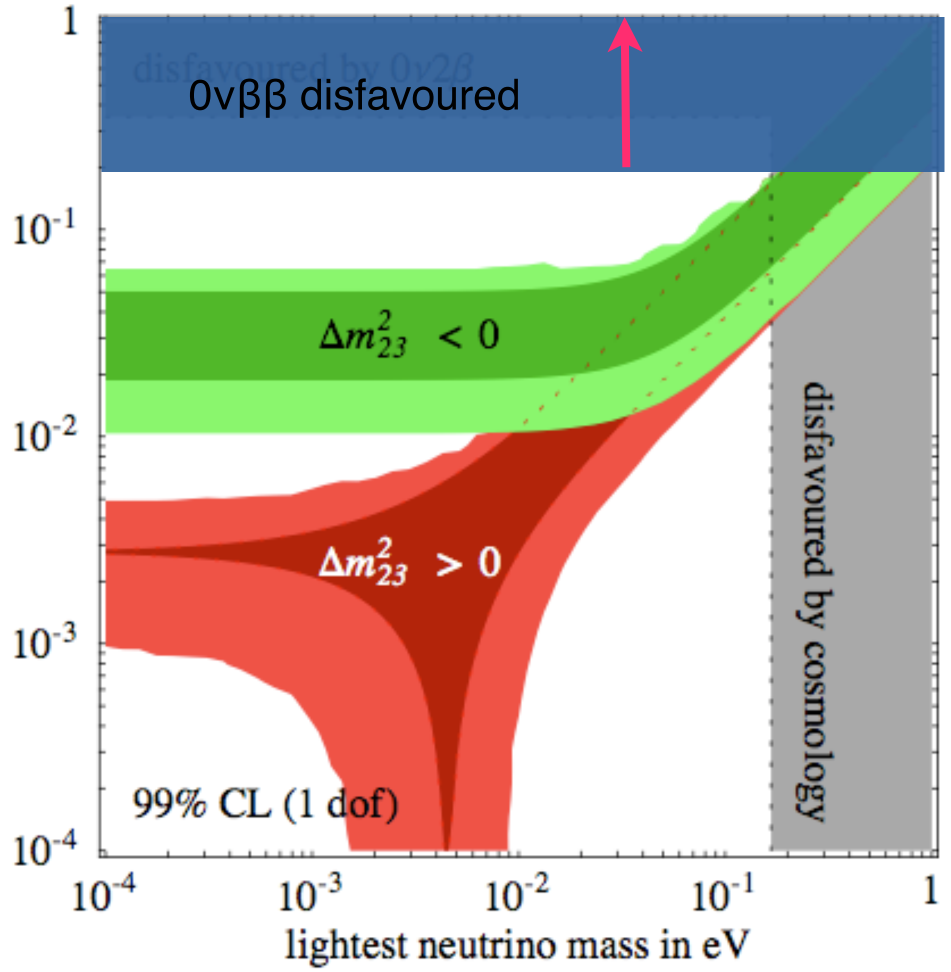
Isotope	Exposure (kg·y)	$T_{1/2}(0\nu\beta\beta)$, y	$\langle m_\nu \rangle$, eV [NME ref.]
^{100}Mo	26.6	> 1.1 · 10^{24}	< 0.45 – 0.93 [1-3]
^{82}Se	3.6	> 3.6 · 10^{23}	< 0.9 – 1.6 [1-3]; < 2.3 [7]
^{150}Nd	0.095	> 1.8 · 10^{22}	< 1.7 – 2.4 [4,5] ;< 4.8 – 7.6 [6]
^{130}Te	1.4	> 9.8 · 10^{22}	< 1.6 – 3.1 [2,3]
^{96}Zr	0.031	> 9.2 · 10^{21}	< 7.2 – 19.5 [2,3]
^{48}Ca	0.017	> 1.3 · 10^{22}	< 29.6 [7]

Isotope	S/B	(2νββ), y (NEMO 3)
^{100}Mo	40	(7.11 ± 0.02(stat)±0.54(syst))·10^{18} (SSD favoured) [1]
^{100}Mo(0^+_1)	3	($5.7^{+1.3}_{-0.9}$(stat))±0.8(syst))·10^{20} [2]
^{82}Se	4	(9.6± 0.3(stat)±1.0(syst))·10^{19} [1]
^{116}Cd	7.5	(2.8± 0.1(stat)±0.3(syst))·10^{19} [3]
^{130}Te	0.35	(6.9± 0.9(stat)±1.0(syst))·10^{20} [6]
^{150}Nd	2.8	($9.11^{+0.25}_{-0.22}$(stat)±0.63(syst))·10^{18} [4]
^{96}Zr	1.0	(2.35± 0.14(stat)±0.16(syst))·10^{19} [5]
^{48}Ca	6.8	($4.4^{+0.5}_{-0.4}$(stat)±0.4(syst))·10^{19} [6]

Background: natural radioactivity, mainly ^{214}Bi and ^{208}Tl, Rn, neutrons (n,γ), muons

FUTURE STRATEGIES

$$S^{m_{\beta\beta}} = \left(\frac{A}{\ln 2 N_A a \epsilon G}\right)^{1/2} \frac{1}{|M_{nucl}|} \left(\frac{B \Delta E}{Mt}\right)^{1/4}$$



- Enrichment: difficult and expensive

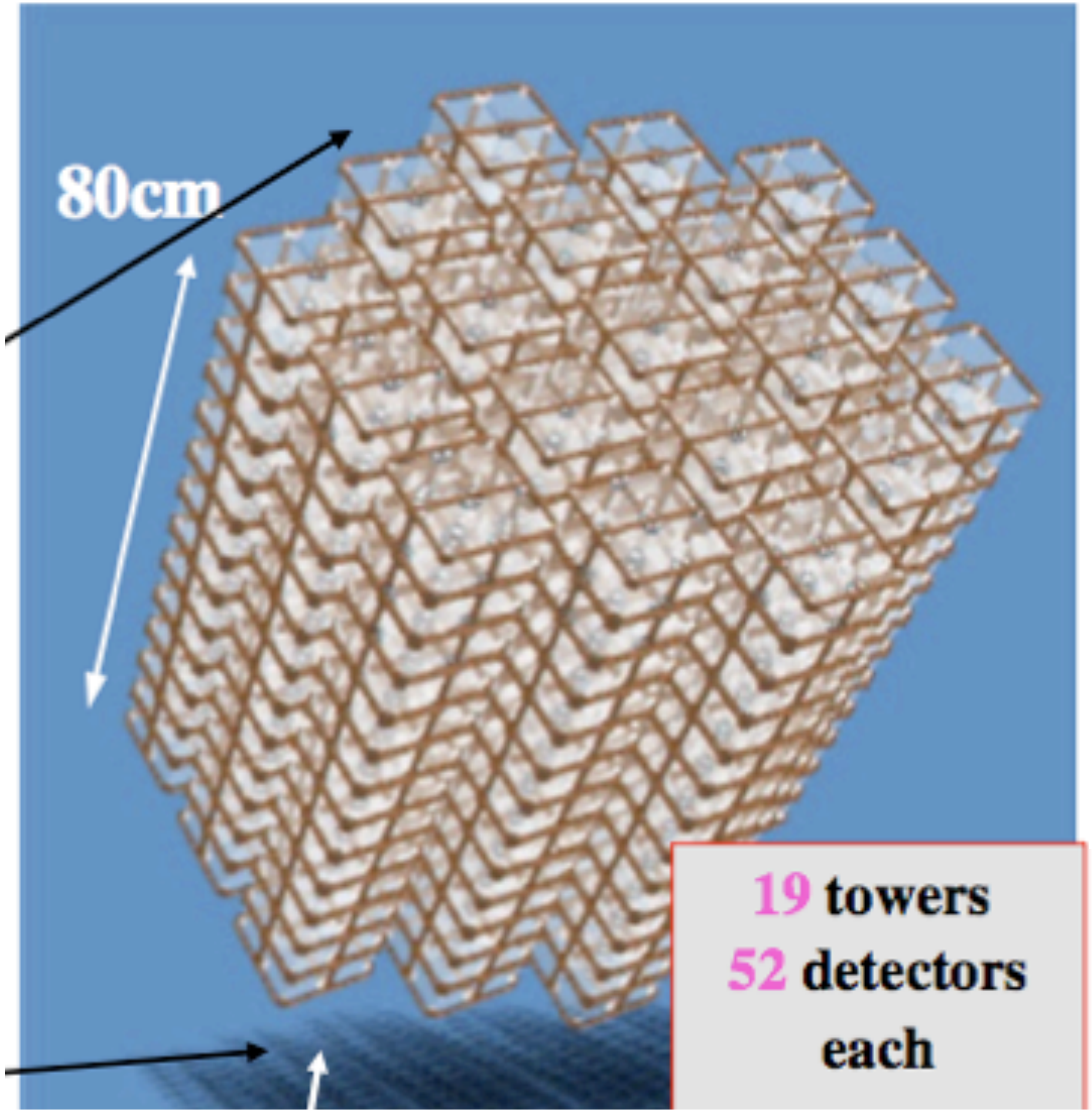
- To start to explore(cover) inverted hierarchy:
  - M~0.1(1) Ton
  - B~10^{-2}(10^{-3}) counts/keV/kg/y

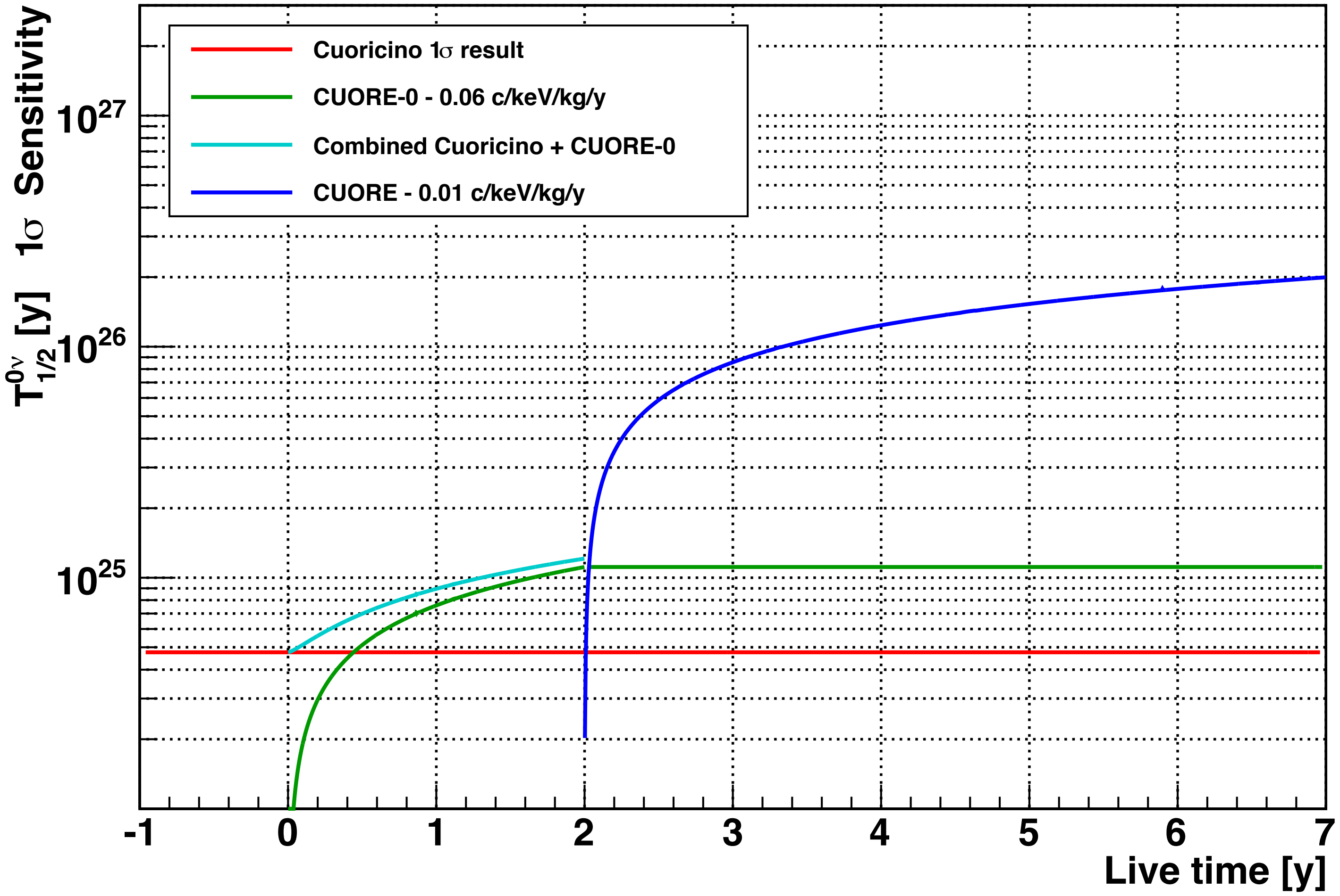
- Background sources:
  - Natural radioactivity: U, Th(τ~10^{10} y) in detector and surroundings
    - ➡ Contamination ~10^{-13} g/g (close or below detectability of HPGE, NAA, ICPMS)
  - Neutrons: from radioactivity and muon-induced
  - Cosmic rays: (in)direct interaction and activation

CUORE

source = detector

Closed packed array of 988 TeO_2 crystals **≈200 Kg ^{130}Te ~10^{27} nuclides**





Background: 10^{-2} counts/keV/kg/y

$\tau^{0\nu}_{1/2} = 2.0 \cdot 10^{26}$ y

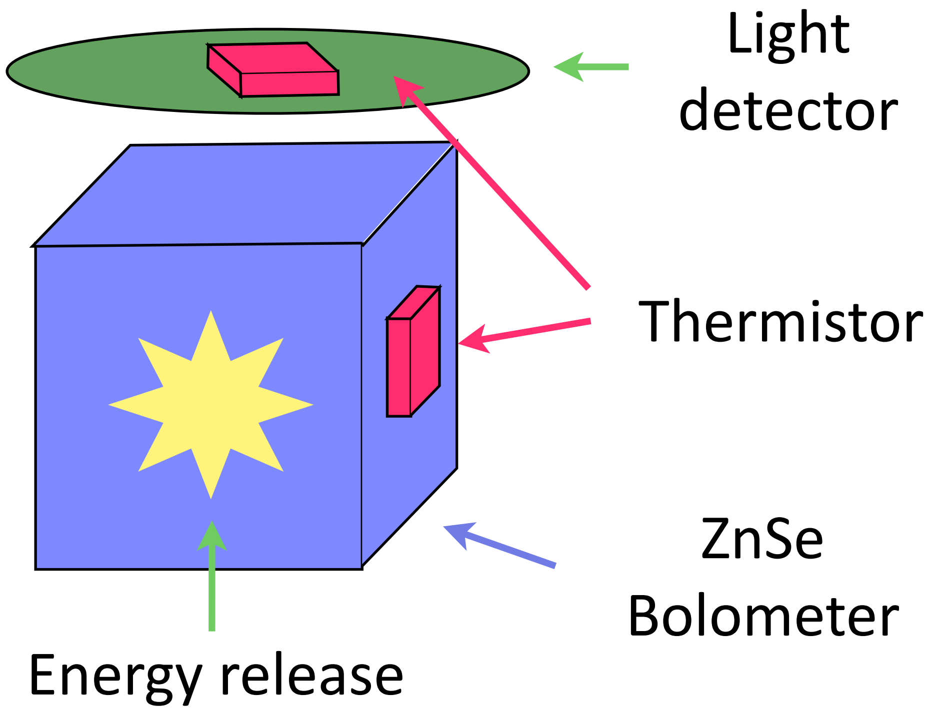
$\langle m_{\beta\beta} \rangle$ = 44-87 meV

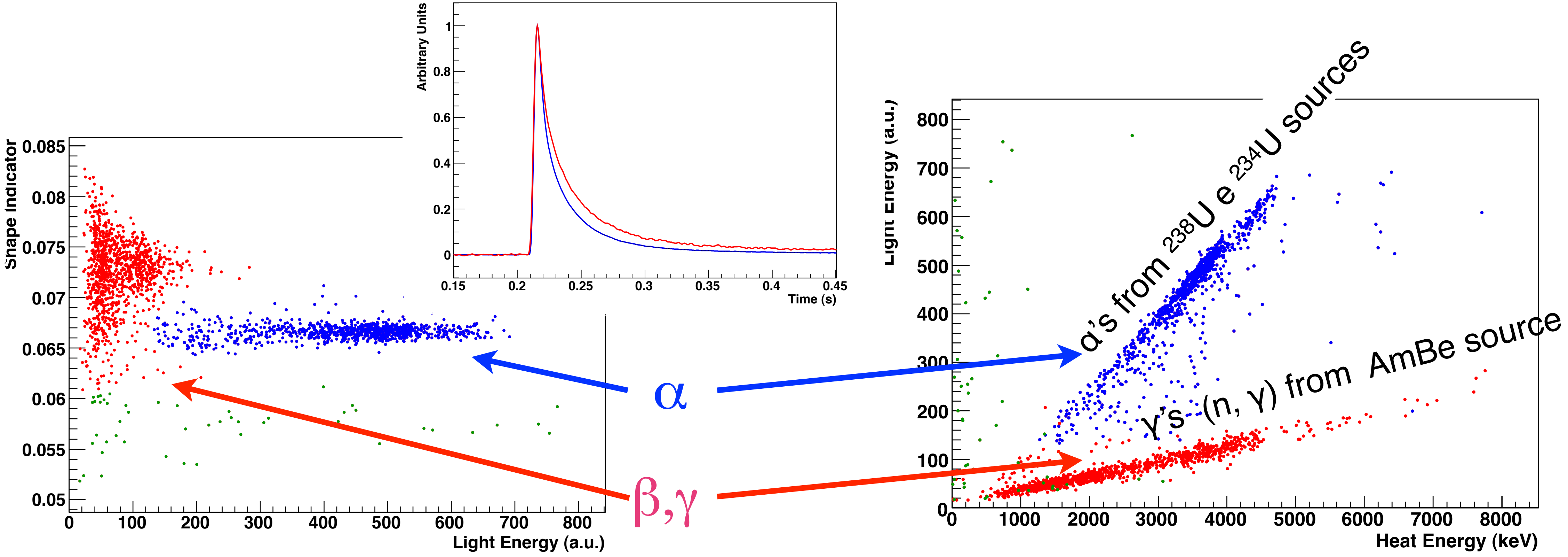
LUCIFER

- **Scintillating bolometers**: use different α/γ light emission for background discrimination
  - Quenching factor **≈4**
  - α discrimination **>99%**
  - **≈20 kg ^{82}Se** + background **10^{-3} counts/kg/keV/y**

$$\tau^{0\nu}_{1/2} = 2.3 \cdot 10^{26}\ \mathrm{y}$$

$$\langle m_{\beta\beta} \rangle = 49\text{-}61\ \mathrm{meV}$$

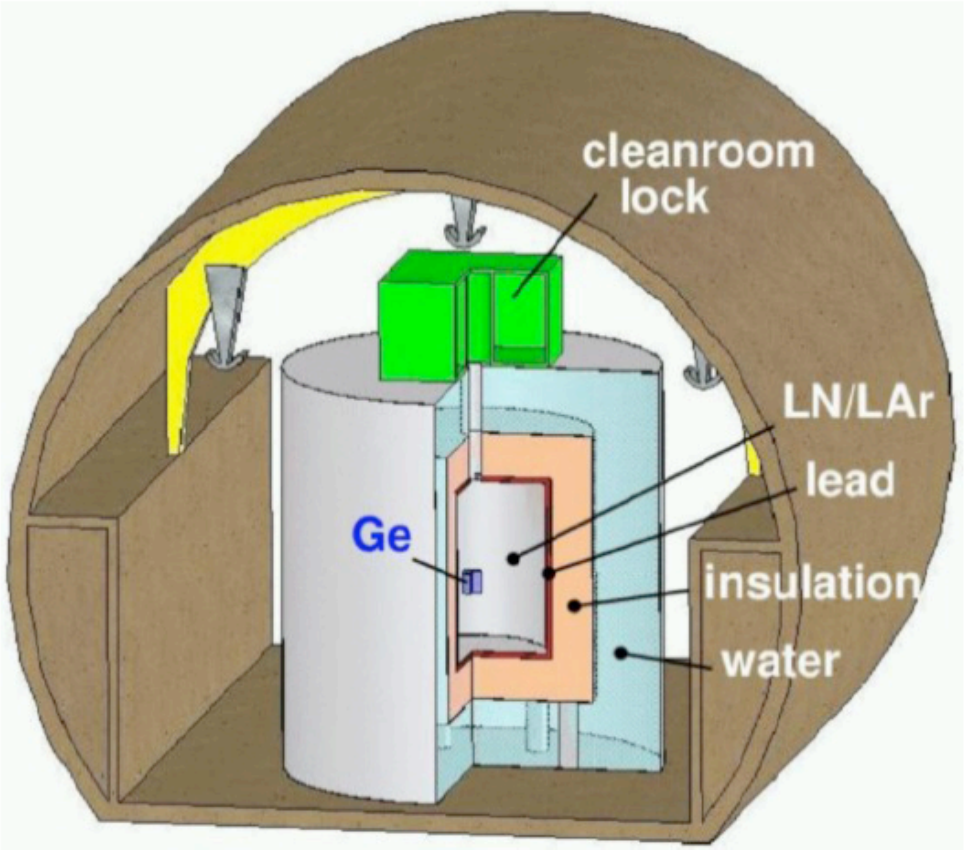




GERDA

- Background: detector surroundings & Ge cosmogenic activation

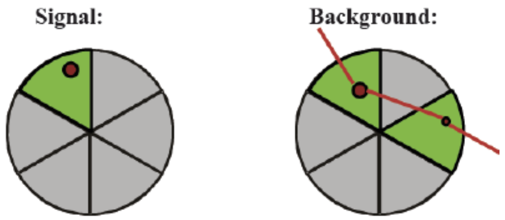
source = detector

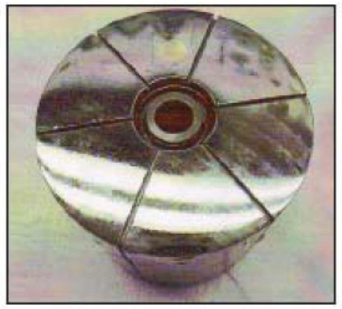


- Phase 1:
  - 18 kg bare (HM+IGEX) ^{76}Ge diodes in LAr
  - Background $\sim 10^{-2}$ **counts/keV/kg/y**
  - Scrutinize KK-HM claim in 1 year
  - Commissioning started Nov 2010

- Phase 2:
  - 40 Kg enriched segmented diodes
  - Background $\sim 10^{-3}$ **counts/keV/kg/y**
  - Sensitivity: $\tau^{0\nu}_{1/2} \sim 2 \cdot 10^{26}$ **y**

    $\langle m_{\beta\beta} \rangle < 90\text{-}200$ **meV**

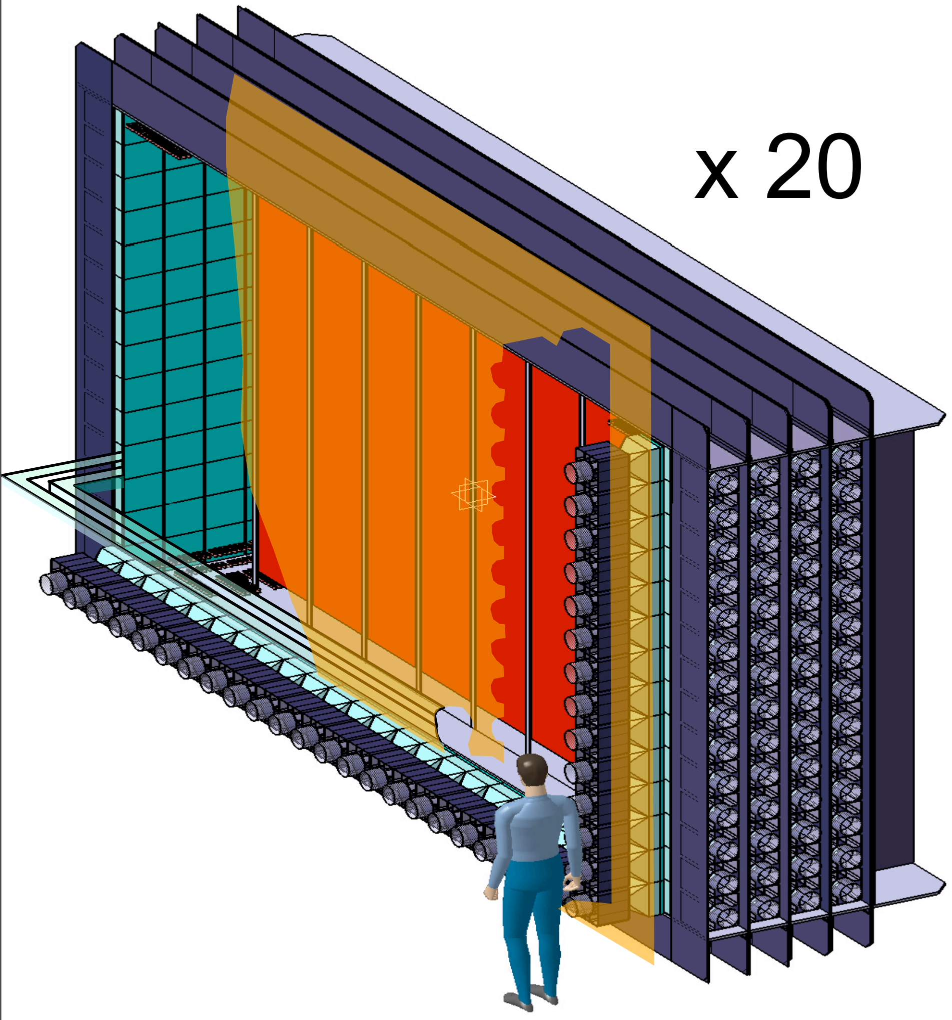




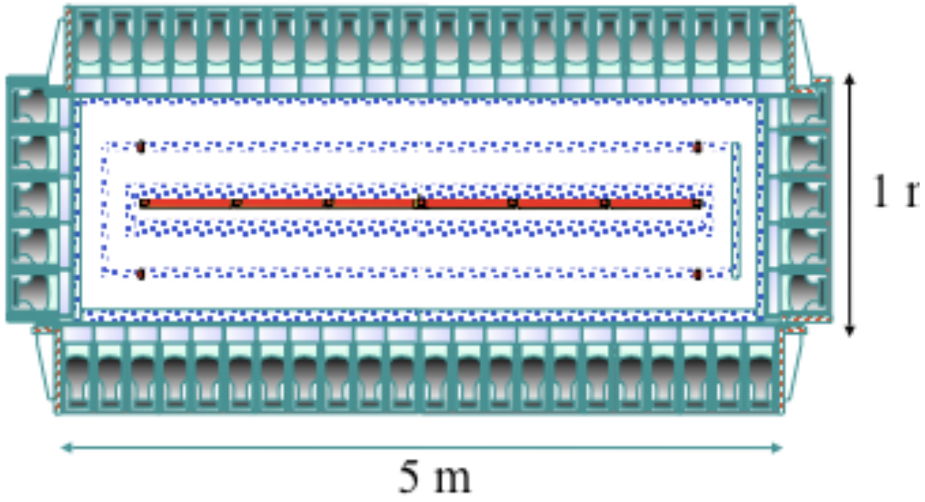
SUPERNEMO

source ≠ detector

First prototype module in 2011



NEMO-3		**SuperNEMO**
^{100}Mo $T_{1/2}(\beta\beta2\nu) = 7.\ 10^{18}$ y	Choice of isotope	**^{82}Se (and/or ^{150}Nd)** $T_{1/2}(\beta\beta2\nu) = 10^{20}$ y
7 kg	Isotope mass **M**	**100 - 200** kg
$\varepsilon(\beta\beta0\nu) = 8\ \%$	Efficiency ε	$\varepsilon(\beta\beta0\nu) \sim 30\ \%$
^{214}Bi < **300** μBq/kg ^{208}Tl < 20 μBq/kg (^{208}Tl, ^{214}Bi) ~ **1** evt/ 7 kg /y	N_{exclu} = f(BKG) *Internal contaminations* *^{208}Tl and ^{214}Bi in the ββ foil*	^{214}Bi < **10** μBq/kg ^{208}Tl < 2 μBq/kg (^{208}Tl, ^{214}Bi) ~ **1** evt/ 100 kg /y
FWHM(calo)=**8%** @3MeV	2νββ	FWHM(calo)=**4%** @3MeV
$T_{1/2}(\beta\beta0\nu) > 2.\ 10^{24}$ y **$<m_\nu> < 0.3 - 0.7$ eV**	**SENSITIVITY**	**$T_{1/2}(\beta\beta0\nu) > 2\ 10^{26}$ y** **$<m_\nu> < 50$ meV**



1) ββ source production

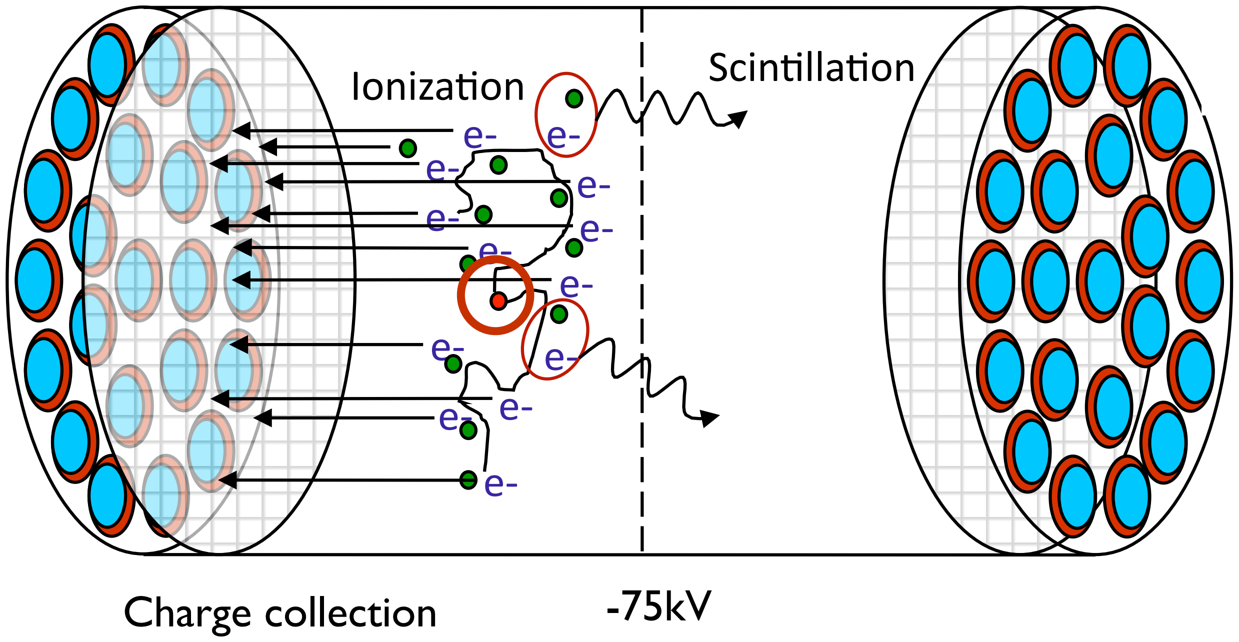
2) Energy resolution

3) Radiopurity

4) Tracking

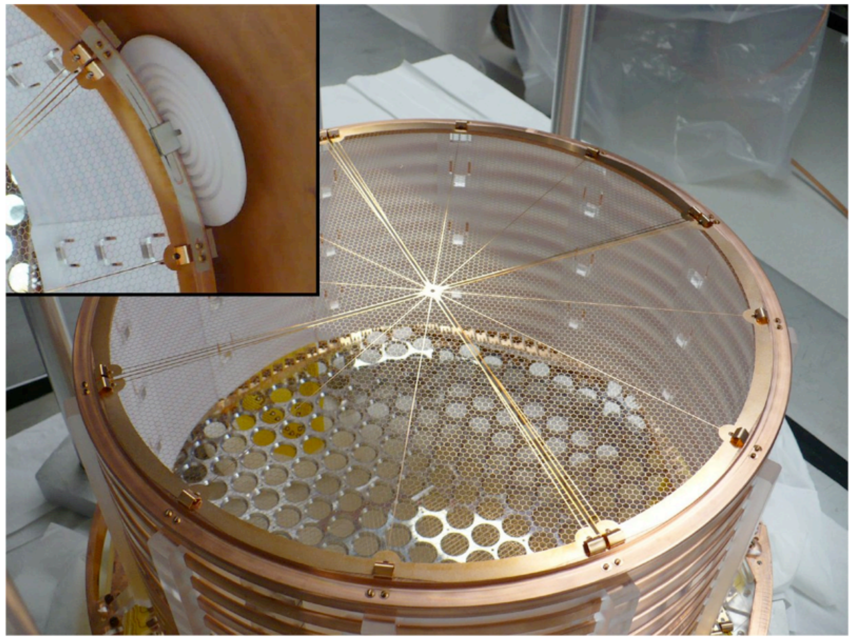
EXO-200

- 200 kg Liquid (80% ^{136}Xe) Xe TPC + scintillation: $^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Ba}^{++} + 2e^{-} (+ 2\nu_e)$

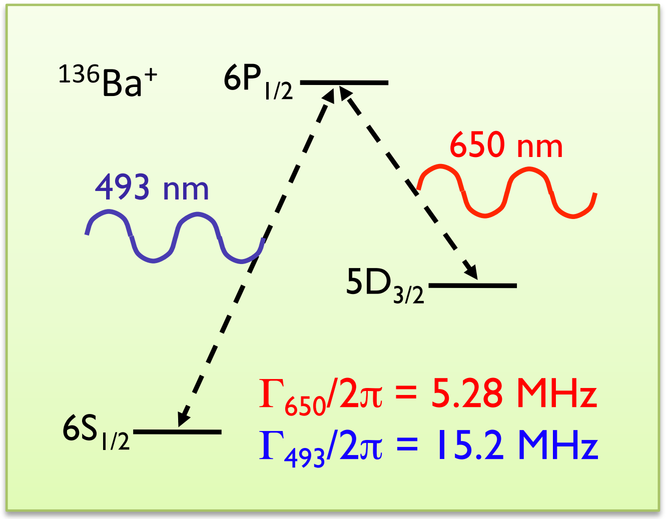


Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	Radioactive Background (events)	$T_{1/2}^{0\nu\beta\beta}$ (yr, 90%CL)	$m_{\beta\beta}$ (meV)
0.2	70	2	1.6	40	6.4×10^{25}	133-186

source = detector



^{136}Ba^{+} level structure



- Full EXO ~Ton scale gas or liquid TPC
- Single Ba^{+} tagging in real time
  - Ion extraction from TPC and trapping
  - Ion identification with Laser Induced Fluorescence

LOADED LIQUID SCINTILLATORS

- Poor resolution but hugh mass and low background compensate

source = detector

Data taking foreseen in 2011

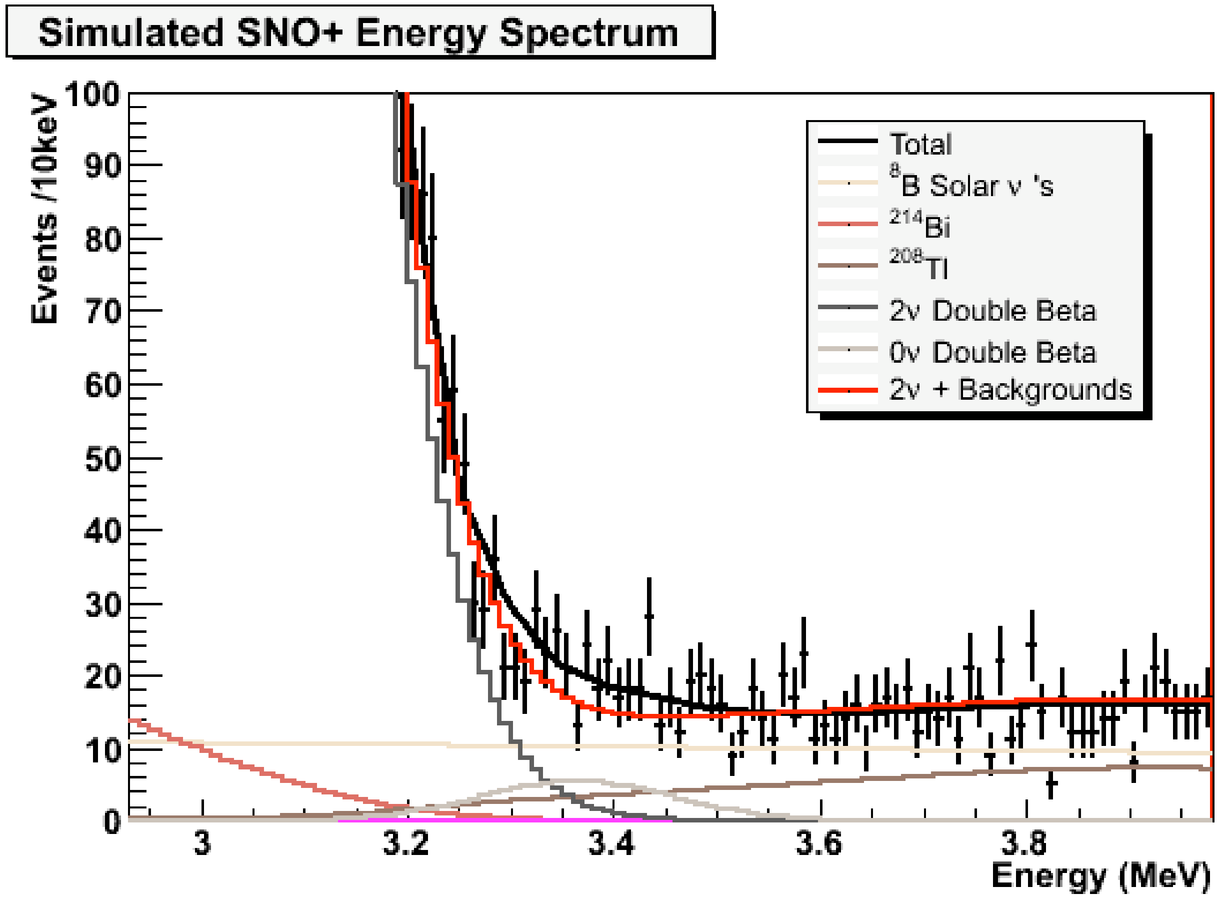
SNO++

^{150}Nd (i.a.=5.6%)

0.1% natural load Nd ~56 kg ^{150}Nd

ΔE_{FWHM}~ 6.4% @ 3367 keV

Sensitivity(3y): **$\langle m_{\beta\beta} \rangle$ ~100 meV**



Kamland -Xe

^{136}Xe (i.a.=8.9%)

200-400 kg enriched ^{136}Xe

ΔE_{FWHM} ~5% @ 2479 keV

Sensitivity(5y): **$\langle m_{\beta\beta} \rangle$ <150 meV**