What you didn't know about
Neutrinos

Nicole Ackerman
SASS: October 7, 2009

Today's Talk...

- History
- Background Physics

- New Physics
- Earth and Sun
- Atomic Physics

- Majorana Center

Neutrino History

- 1930: Fermi proposes fix to beta decay
- 1935: M. Goeppert-Mayer calculates $2\nu\beta\beta$
- 1937: Majorana proposes neutral fermion

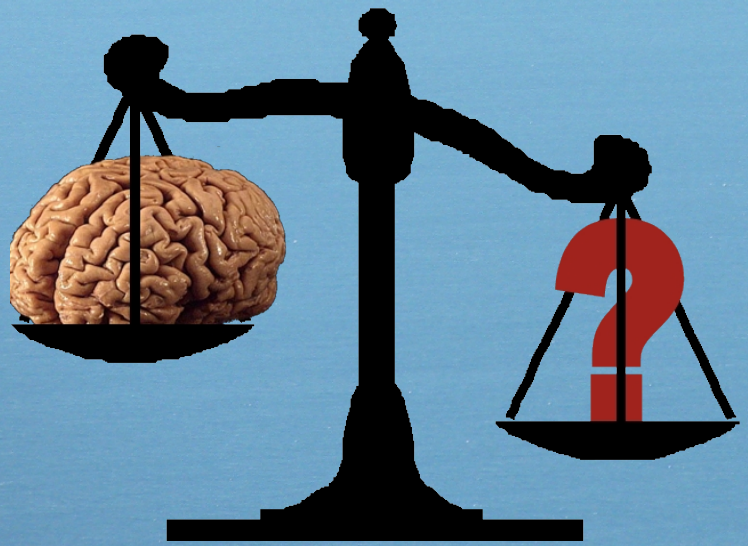
- 1956: e neutrino found with beta decay
- 1957: Pontecorvo proposes flavor oscillation
- 1962: mu neutrino found
- 1967: Homestake Solar Neutrino experiment started

- 2000: tau neutrino detected
- 2001: SNO decisively proves neutrino oscillation

Neutrino Basics

"Known"

- Neutral
- Small mass (<1 eV)
- 3 types (e,μ,τ)
- Mixing (large)



Unknown

- Actual Mass
- "Hierarchy"
- If own antiparticle
- Why there is mass
- Sterile neutrinos?
- Why large mixing
- CP violation?

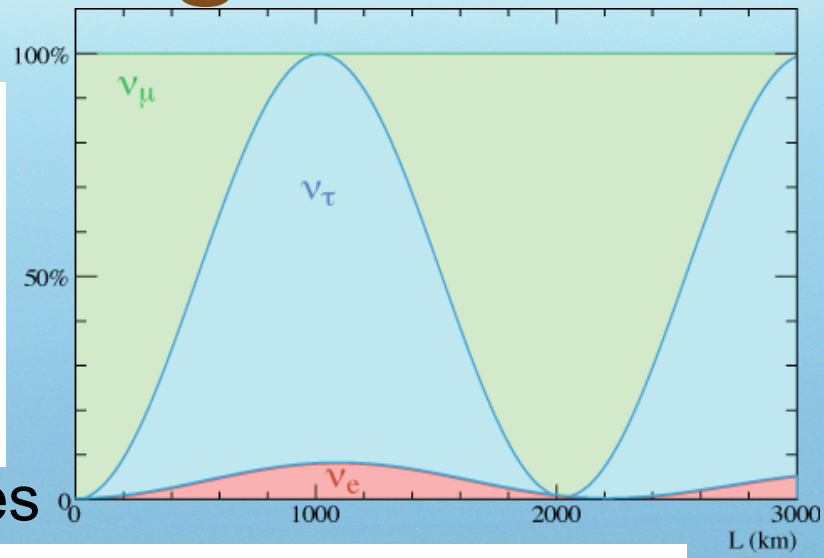
Neutrino Mixing

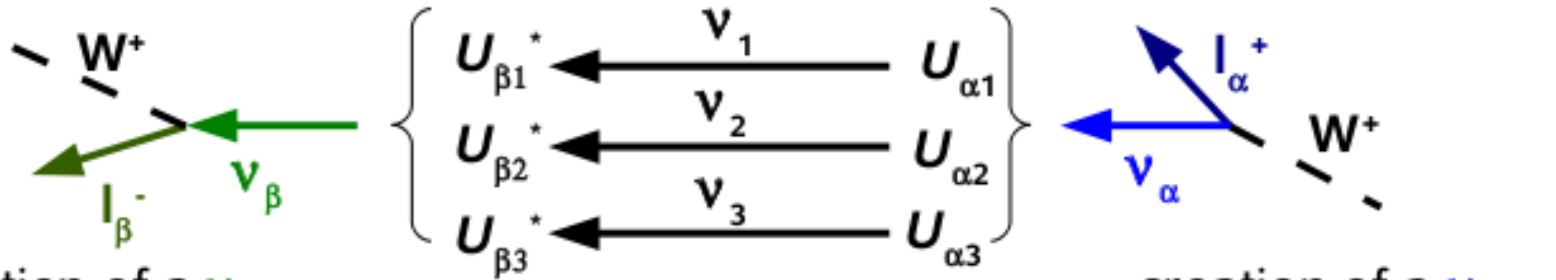
PMNS Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Weak Eigenstates (flavor)

Mass eigenstates





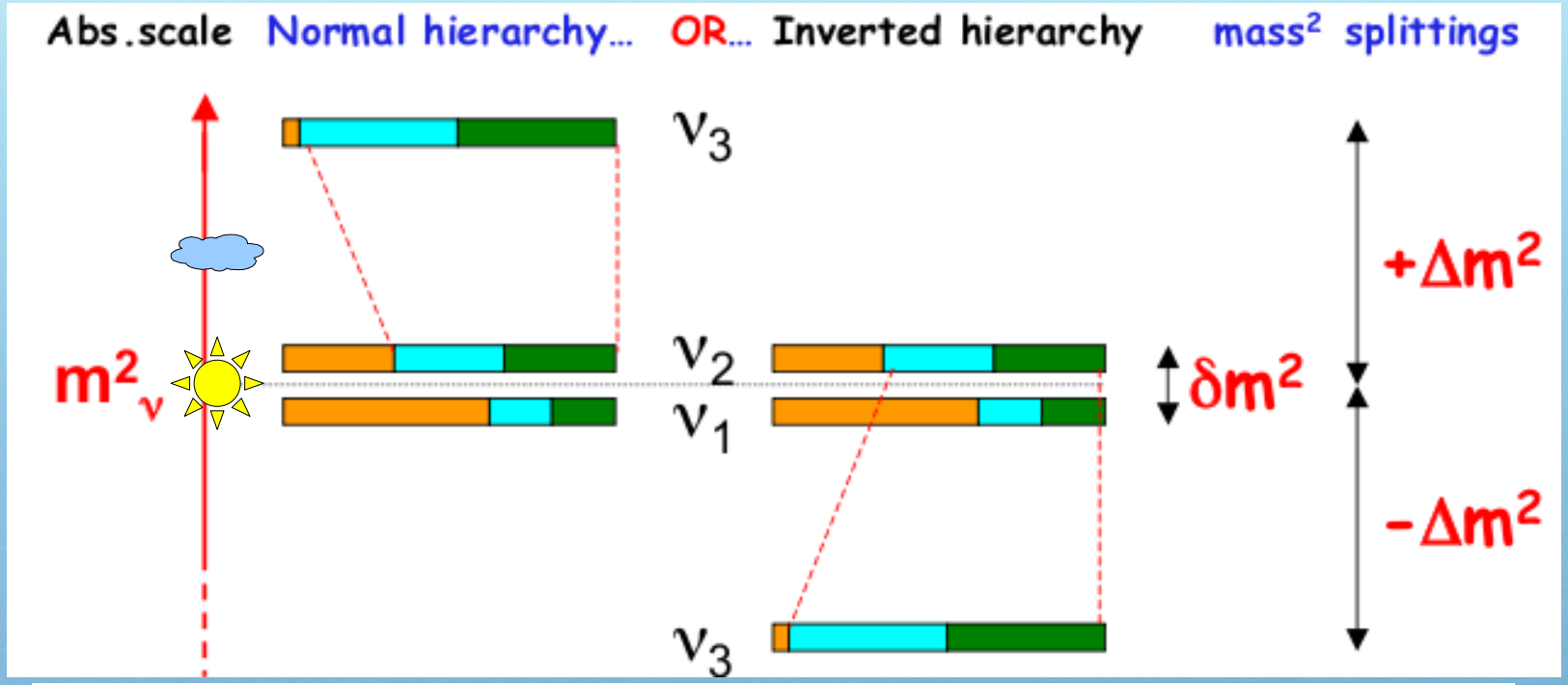
detection of a ν_β via weak interaction

propagation as coherent superposition of mass states

creation of a ν_α via weak interaction

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_i U_{\alpha i}\, e^{-iE_i t}\, U_{\beta i}^* \right|^2 = \underbrace{\sin^2(2\theta) \cdot \sin^2 \frac{|m_2^2 - m_1^2| \cdot L}{4E}}_{\text{2 flavor mixing}}$$

Neutrino Mixing



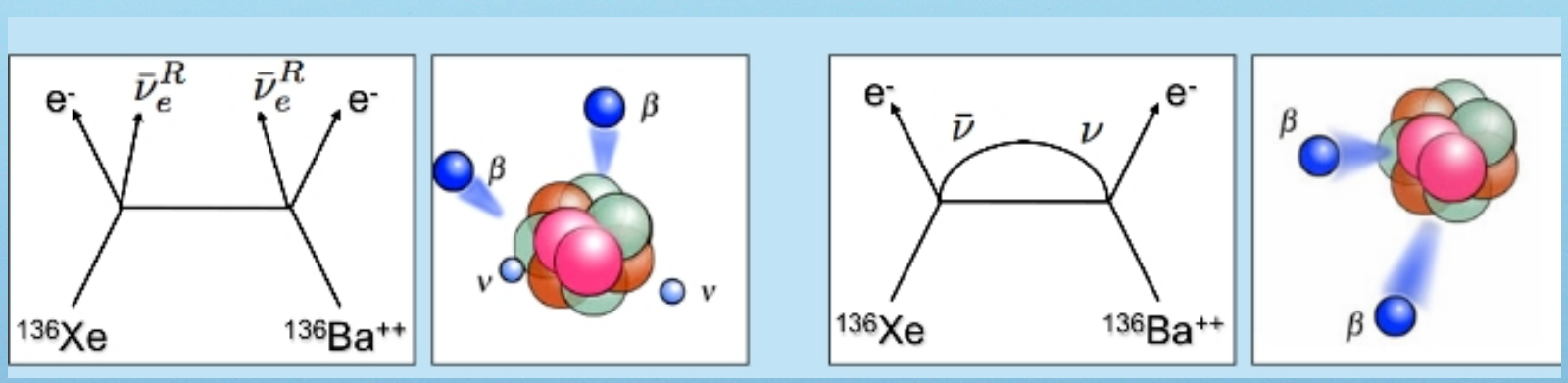
$$U_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & s_{13}e^{i\delta} \\ -0.4 & 0.6 & 0.7 \\ 0.4 & -0.6 & 0.7 \end{pmatrix} \qquad |s_{13}| < 0.2$$

Can be expressed in terms of angles θ_{ij}

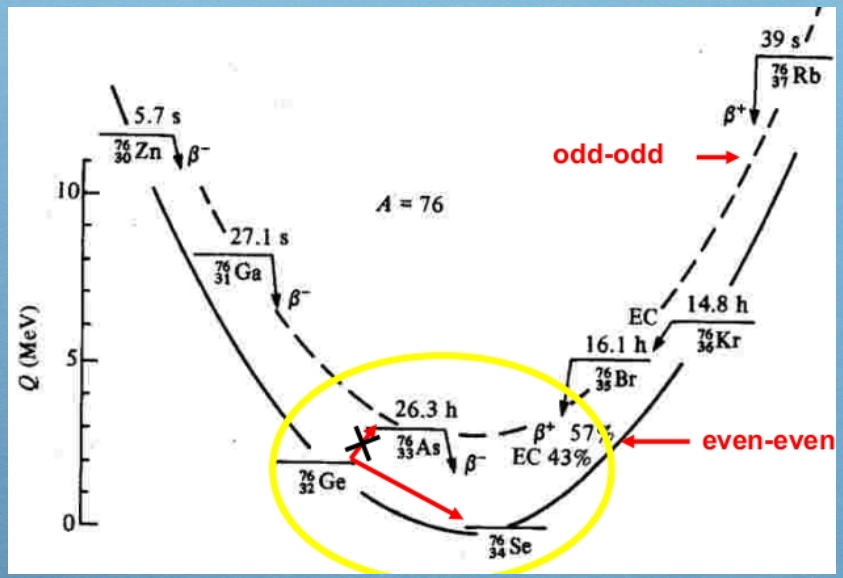
Double Beta Decay

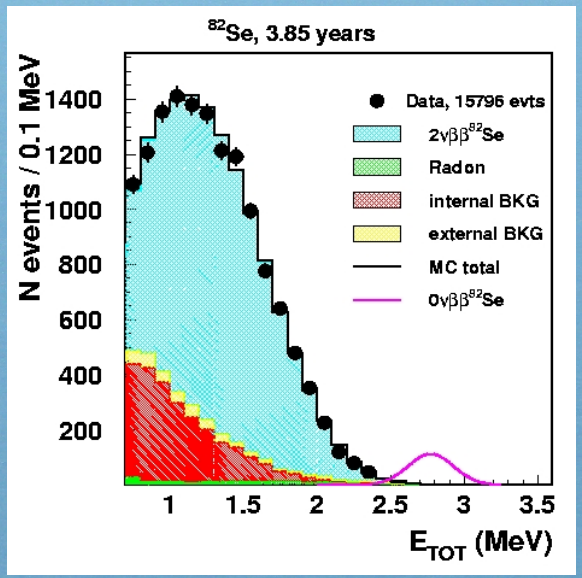
2-neutrino Double Beta Decay
(Standard Model)

Neutrinoless Double Beta Decay
(New physics)

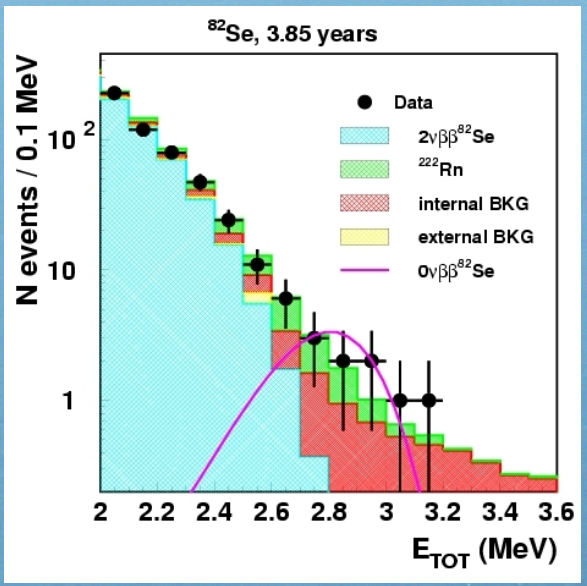


NEMO Collaboration Data





Measured spectrum

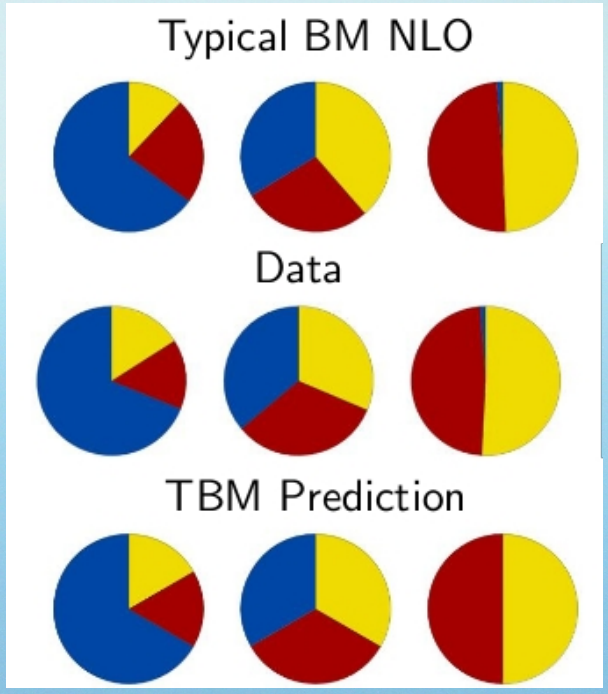


Neutrinoless region

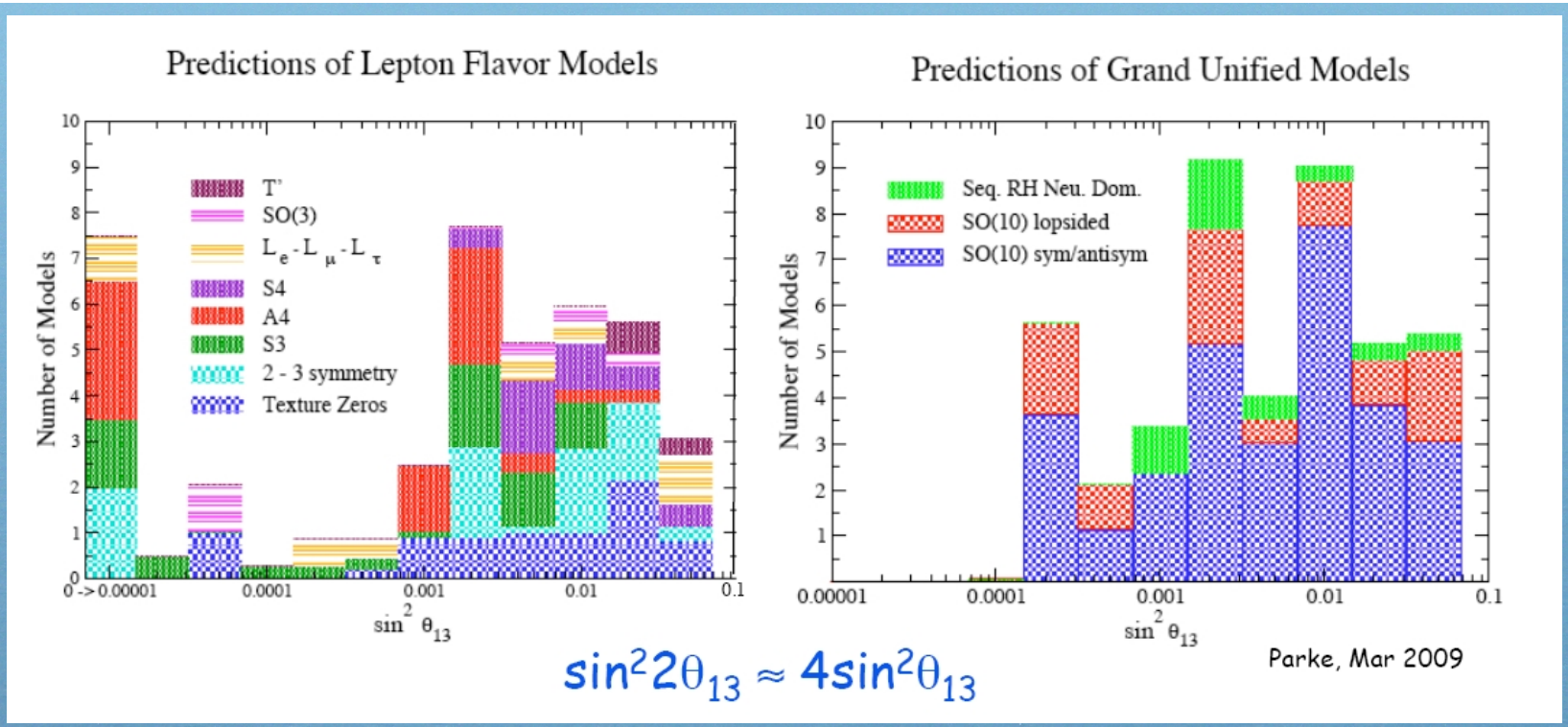
New Physics

- Neutrino masses
  - Best mechanism introduces higher scale and new particles
- θ_{13}
  - Currently “upper limit”
  - If “0” allows for symmetries
  - CP violating term
- Double Beta Decay
  - Existence breaks lepton number symmetry
  - Can be mediated by a variety of non-SM particles

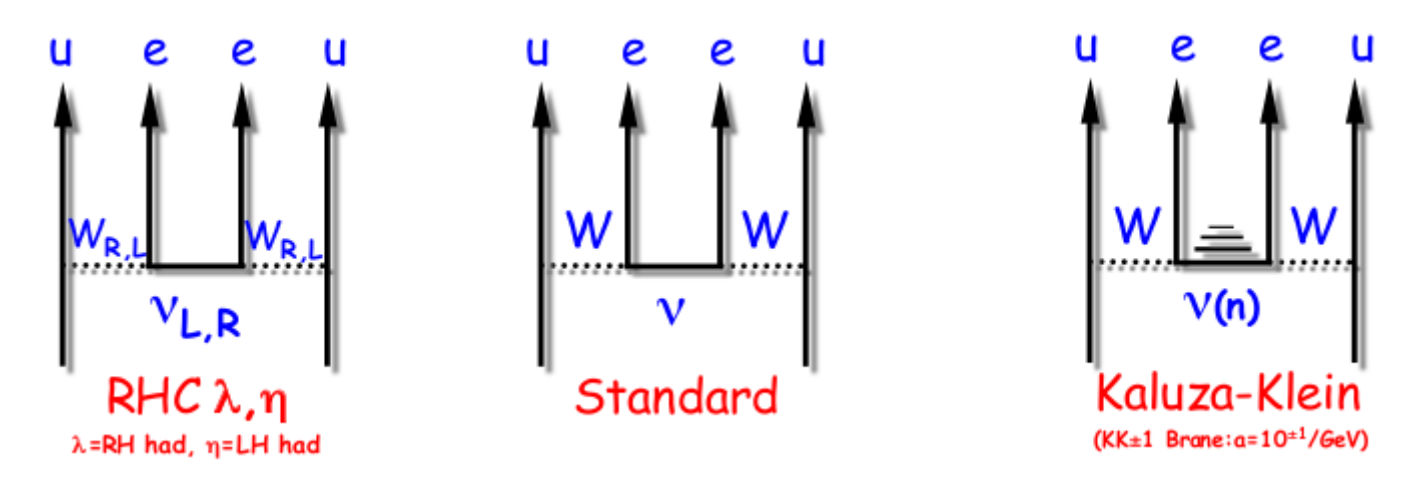
- Current: 0.02 +/- 0.01 Θ_{13}
- "future" limit: 0.008
- Important for CP violation
- New physics models make a variety of predictions
- Comes from reactor measurements



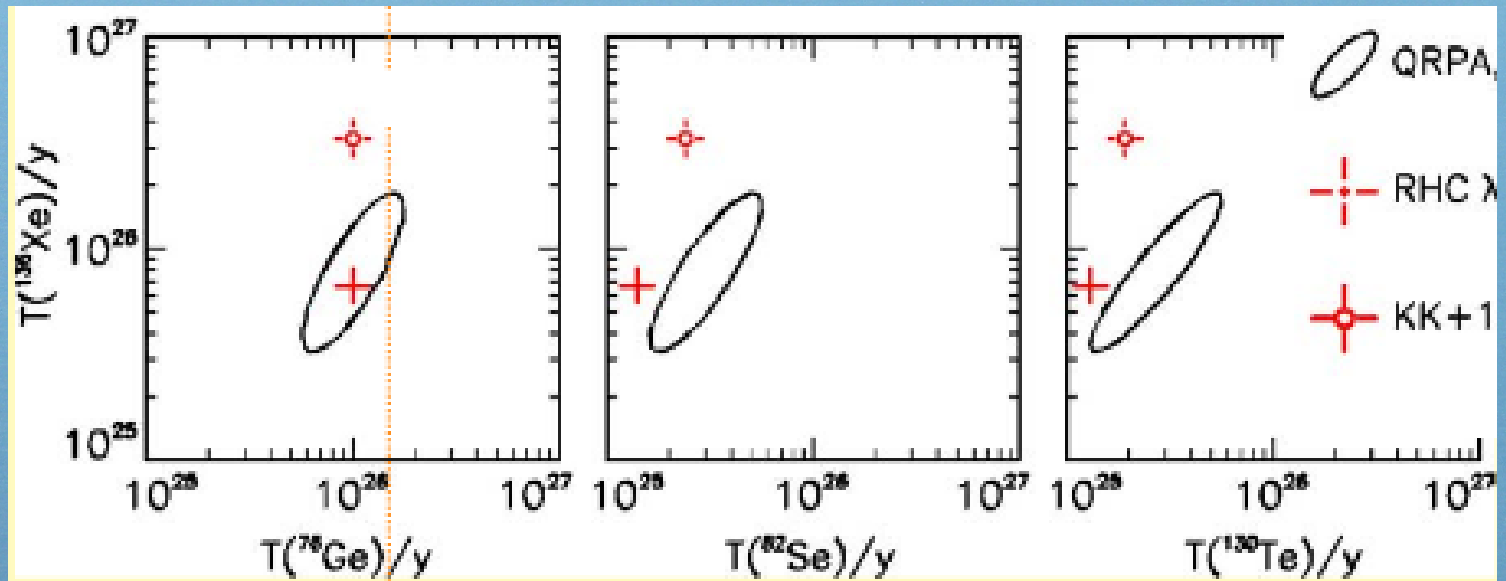
$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\right)$$



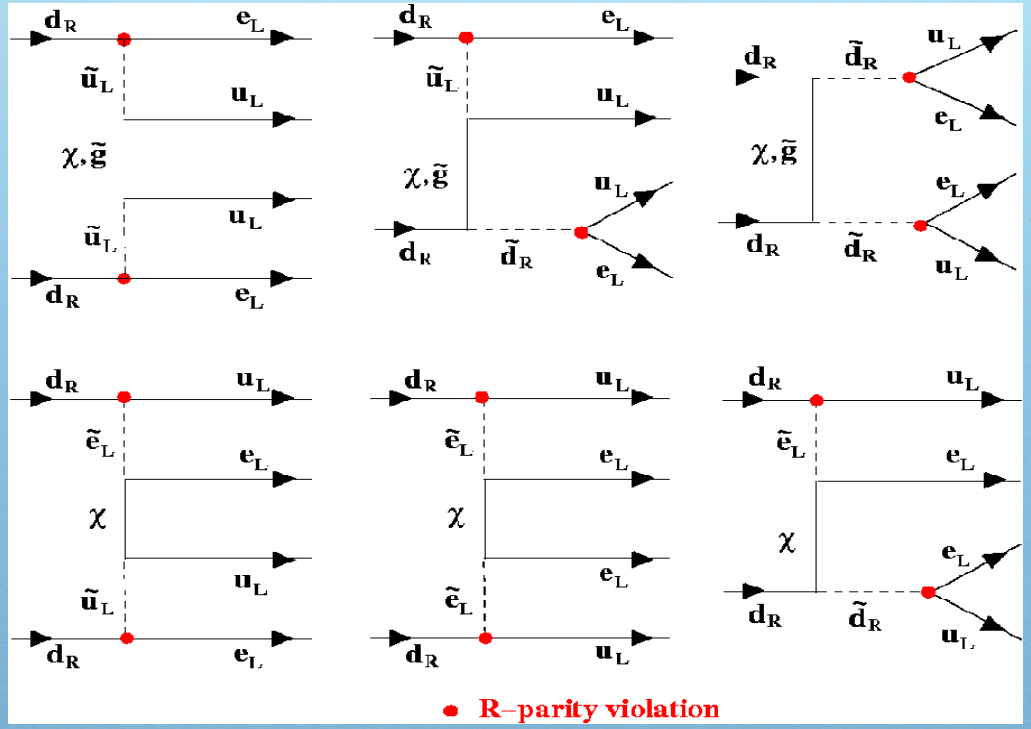
ββ0ν Mode Discrimination

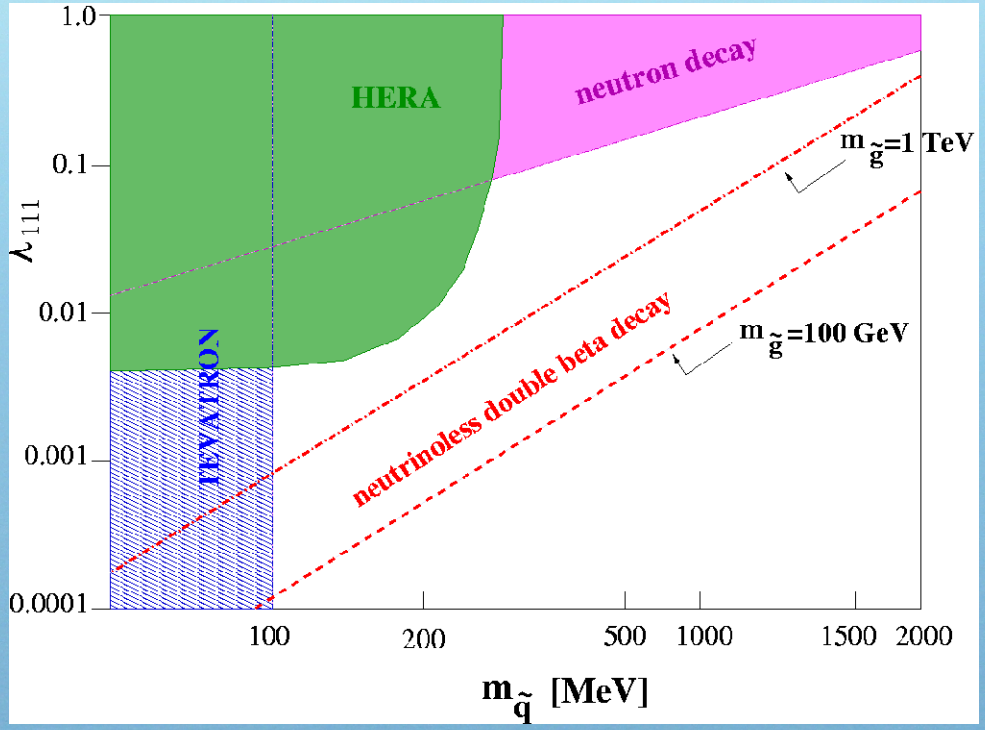


Ratio of different isotopes can determine mediation mechanism (also angular info)



0νββ with SUSY





nucl.	$T_{1/2}^{0\nu-exp}$ [Ref.] (years)	$\eta^{11}_{(q)LR}$	$\lambda'_{111}\lambda'_{111}$	$\lambda'_{112}\lambda'_{121}$	$\lambda'_{113}\lambda'_{131}$
^{76}Ge	$\geq 1.9\ 10^{25}$ [2]	$8.5\ 10^{-9}$	$1.5\ 10^{-5}$	$8.0\ 10^{-7}$	$3.3\ 10^{-8}$
^{100}Mo	$\geq 5.8\ 10^{23}$ [4]	$1.8\ 10^{-8}$	$3.2\ 10^{-5}$	$1.7\ 10^{-6}$	$7.0\ 10^{-8}$
^{130}Te	$\geq 3.0\ 10^{24}$ [5]	$9.5\ 10^{-9}$	$1.7\ 10^{-5}$	$9.0\ 10^{-7}$	$3.7\ 10^{-8}$

Earth and Sun

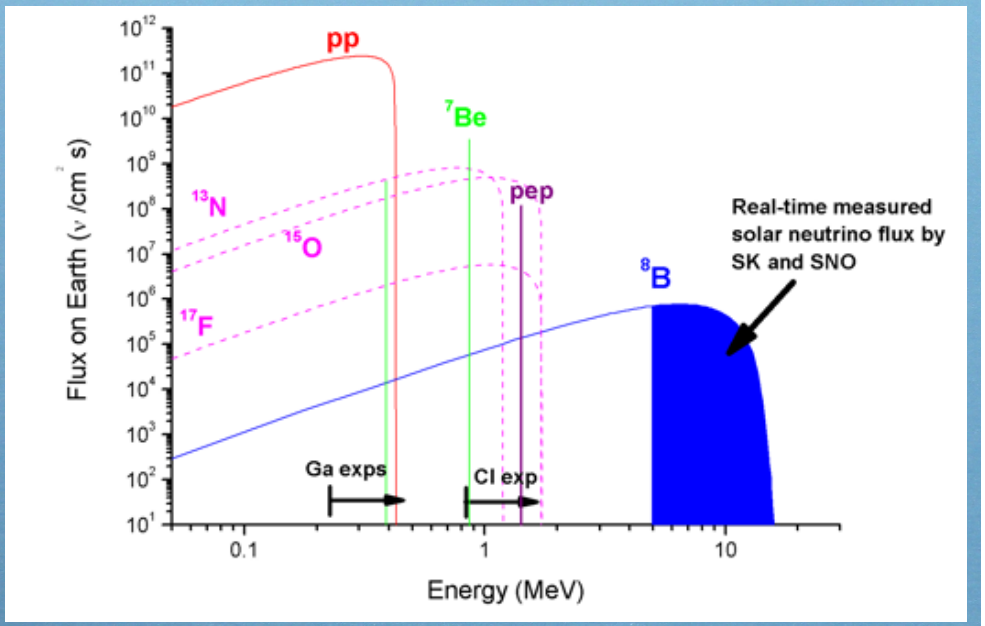
- First measured in 2005
- ν from U/Th decays
- Complimentary to heat measurements
- Future experiments proposed

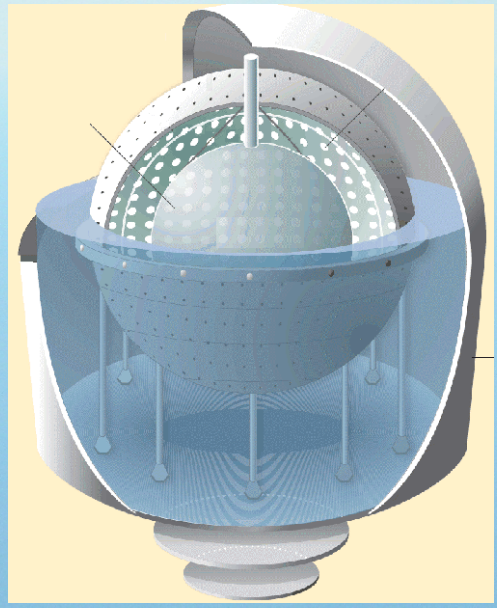
- First measured in 1968
- ν from solar cycles
- Complimentary to light measurements
- Led to discovery of oscillations

Solar Neutrinos

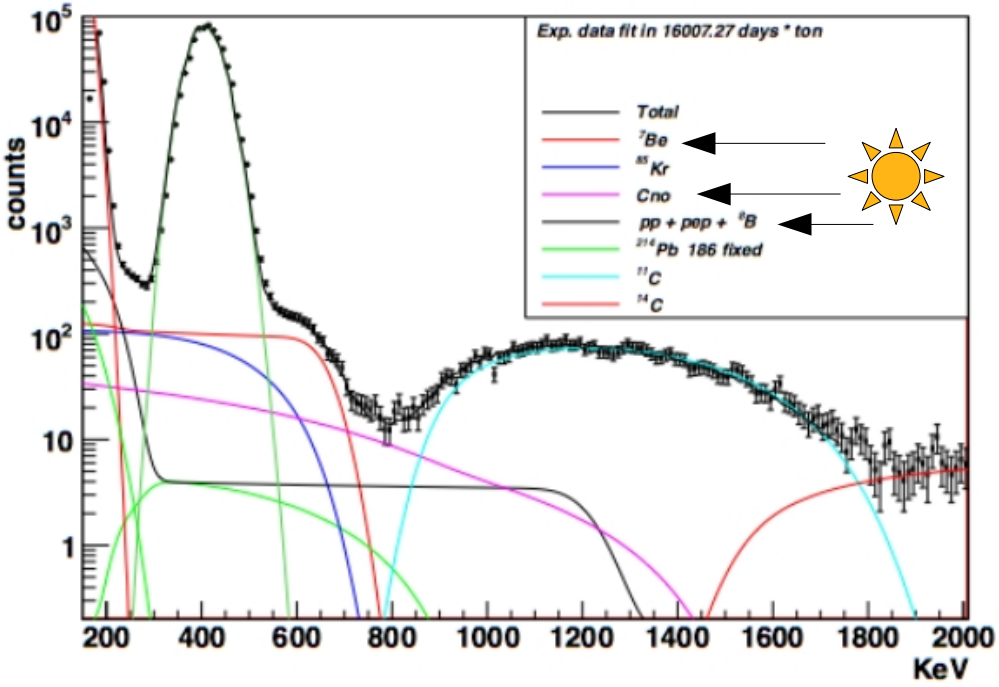
Standard Solar Model

	Proton-Proton Chain:	ν Energy (MeV)
	$H + H \rightarrow D + e^+ + \nu$	Spectrum: 0 to 0.420
I	$H + D \rightarrow {}^3He + \gamma$	
I	$H + H + e^- \rightarrow D + \nu$	Line: 1.44
I	${}^3He + {}^3He \rightarrow {}^4He + 2H$	
	${}^3He + {}^4He \rightarrow {}^7Be + \gamma$	
II	${}^7Be + H \rightarrow {}^7Li + \nu$	**Lines: 0.816, 0.383**
II	${}^7Li + H \rightarrow {}^8Be + 2{}^4He + \gamma$	
	${}^7He + H \rightarrow {}^8B + \gamma$	
III	${}^8B \rightarrow {}^8Be^* + e^+ + \nu$	Spectrum: 0 to 14
III	${}^8Be^* \rightarrow 2{}^4He + \gamma$	

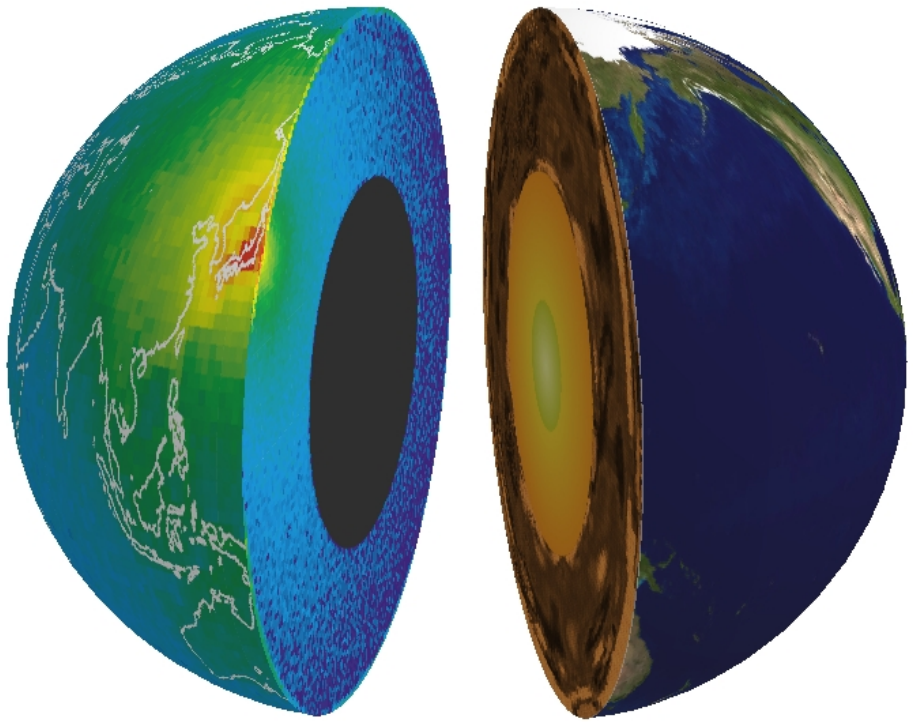


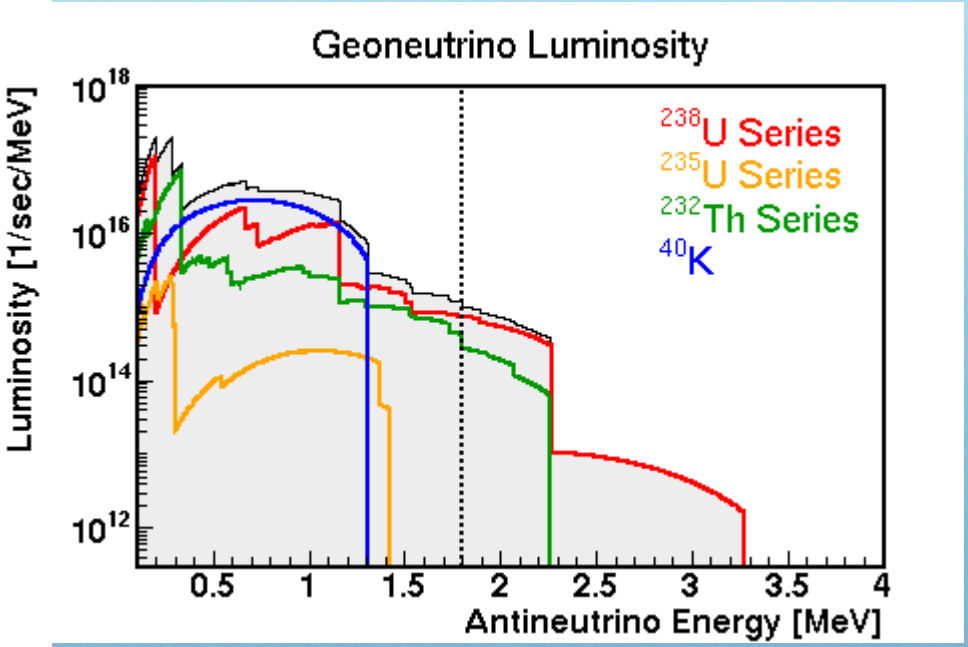


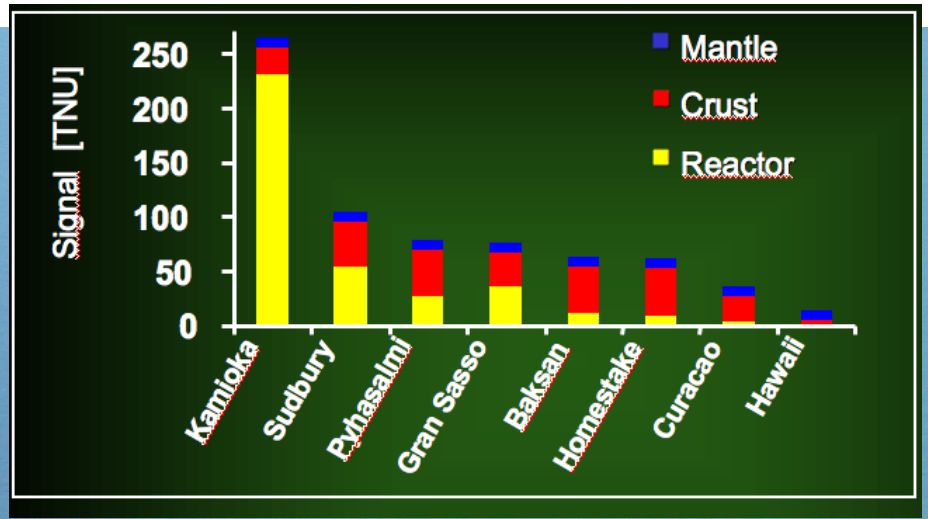
Borexino



Geo-Neutrinos







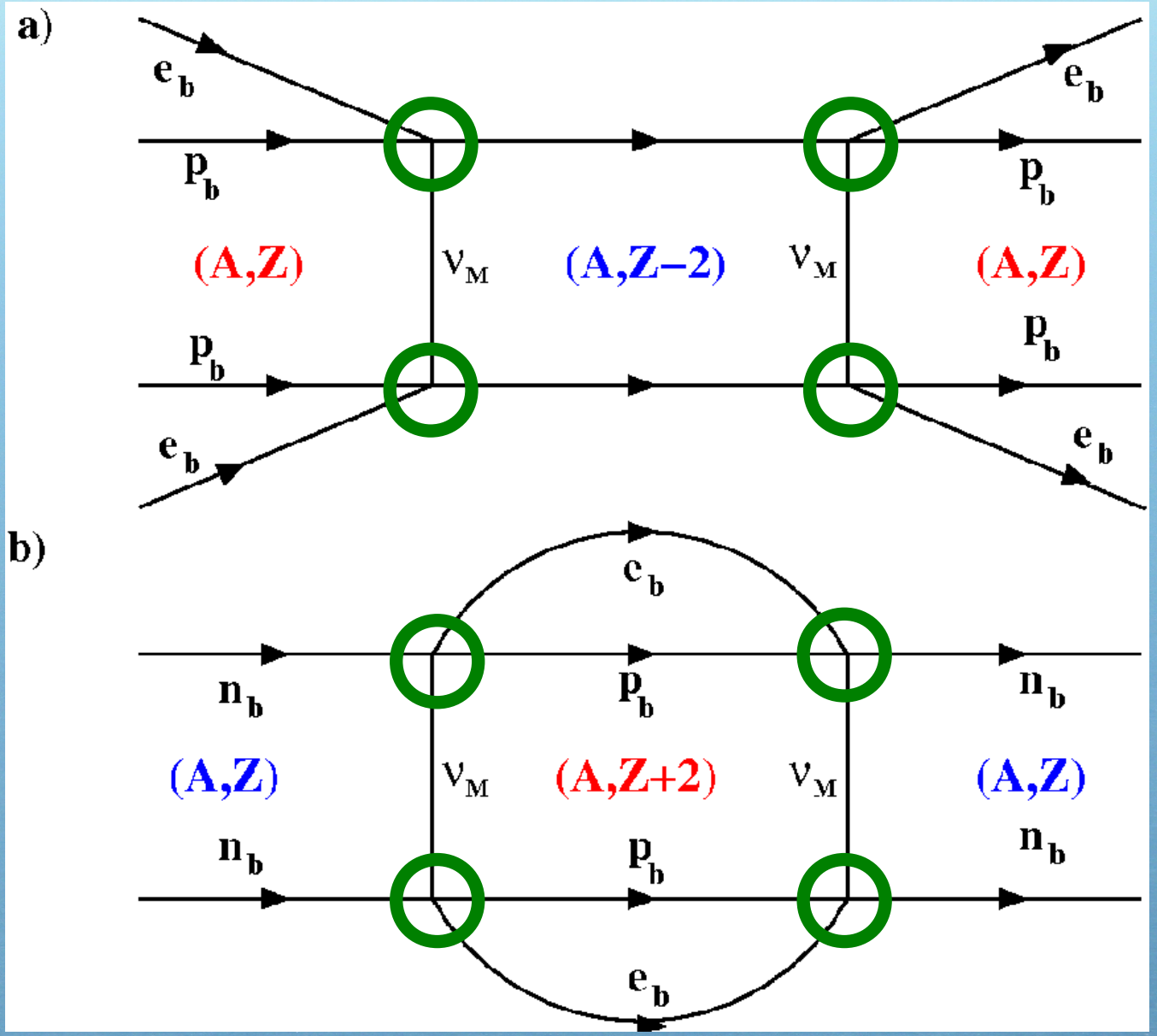
- Measure flux from crust and mantle
- Determine U/Th ratio
- Measure earth fission reactor power (1-10TW)

Atomic Physics

- Nuclei/atoms oscillate by +/-2 electrons and protons
- Box-diagram oscillations occur in many mesons
- Would change atomic properties

Vertices are the same as $\beta\beta0\nu$:

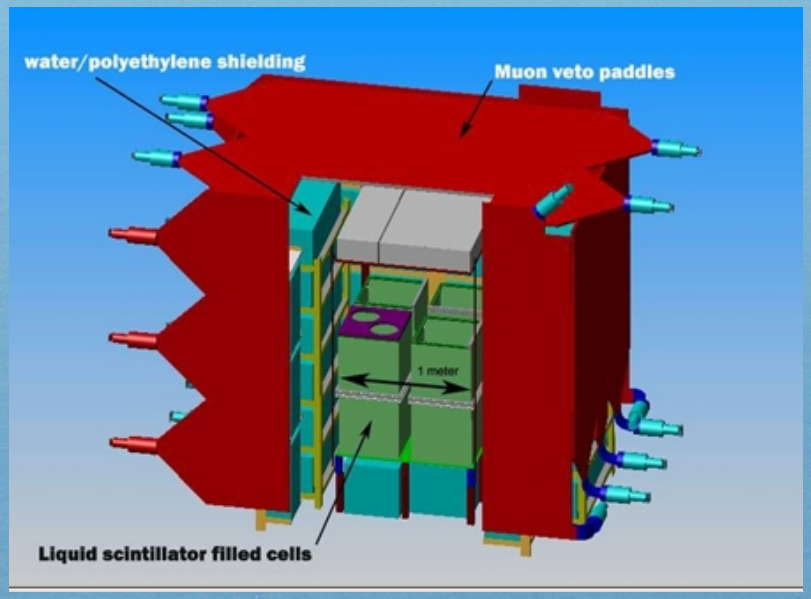
- Require Majorana type
- Depends on ν mass
- Rate is small

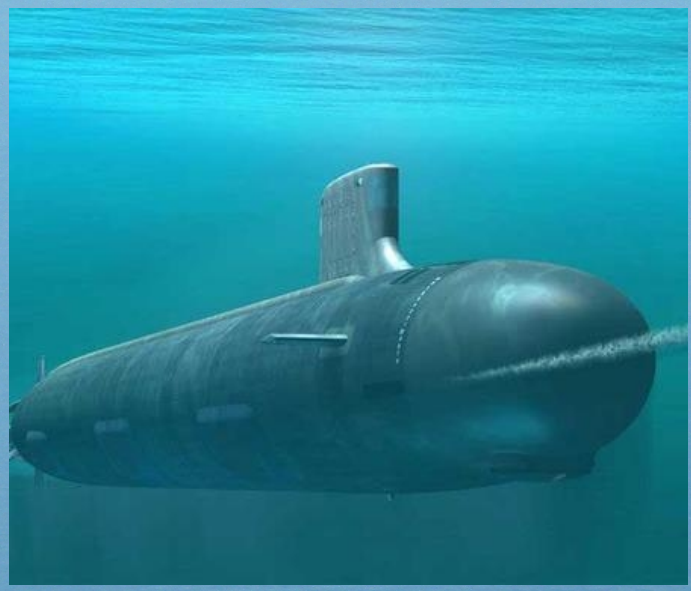


Phys.Part.Nucl.Lett.6:298-303,2009

Actual “Practicality”

- Anti-nuke beam (arXiv:hep-ph/0305062v2 and arXiv:0805.3991v3)
- Submarine Communication *(arXiv:0909.4554v1)*
- Reactor Monitoring





Physics Summary

- **Still learning** about neutrinos
- Already using neutrinos for
  - New Physics
  - Solar Physics
  - Geo-physics
- Neutrino interactions can have mesoscopic implications
- Neutrinos are proposed for future technologies.

Majorana Center

- Started in 1963
- Hosted Pope in 1993
- Ran by Prof. Zichichi
- 123 Schools
- Occupies monasteries in Erice, a mountain town in Sicily

Schools Include

International School of...

- Hadrontherapy
- Radiation Damage and Protection (protection for medical accelerators)
- Mathematics (variational analysis)
- Crystallography (high pressure crystallography)
- Biological Magnetic Resonance (Biophysics)
- **Atomic and Molecular Spectroscopy (Bio-photonics)**
- Scientific Journalism and Communication (communicating energy)
- **Complexity (grains, friction, faults)**
- **Subnuclear Physics (LHC)**
- Fusion Reactors Technology (superconducting magnets)
- **Nuclear Physics (neutrinos)**

Erice is called the “Mountain of God”

Historic Town of Erice

Exciting Trips!

Physicists (of course)

Marsala Room

Thank You!

Physics From:
R. de Adelhart Toorop,
G. Bellini, H. Ejiri,
J. Jochum, S. Kim,
M. Linder, E. Lisi,
R. McKeown, L. Simard,
F. Simkovic, S. Smith,
F. Suekane,
C. Weinheimer

Pictures From:
T. Koettig, O. Micu, S. Smith, T. Strauss

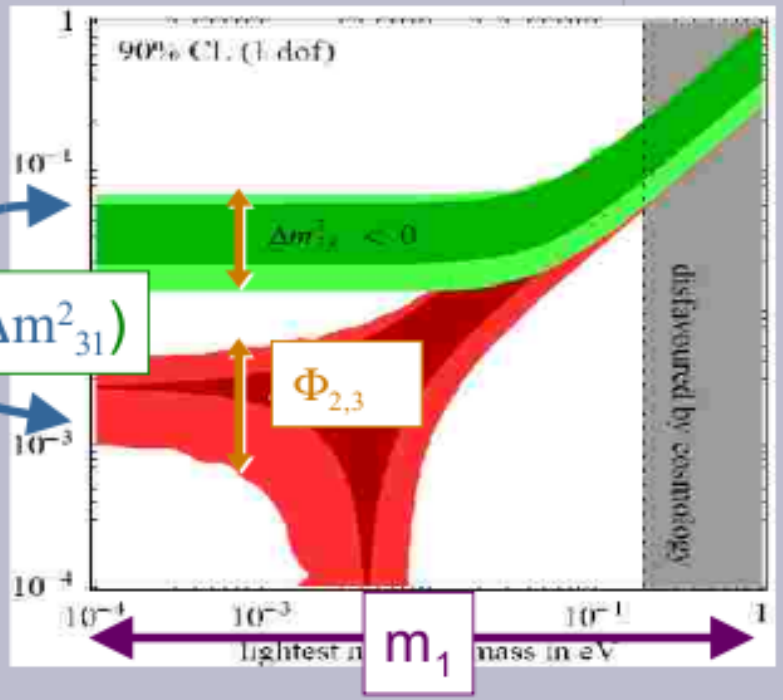
$0\nu2\beta$ decay – effective neutrino mass $m_{\beta\beta}$

GERDA @ Erice

$0\nu2\beta$-decay $\propto$ $\propto |\langle m_{\beta\beta} \rangle| - |\sum m_i U_{ei}^2|$

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

$$|m_{\beta\beta}^{(1)}| - |U_{e1}|^2 m_1$$
$$|m_{\beta\beta}^{(2)}| - |U_{e2}|^2 \sqrt{m_1^2 + \Delta m_{21}^2}$$
$$|m_{\beta\beta}^{(3)}| - |U_{e3}|^2 \sqrt{m_1^2 + \Delta m_{31}^2}$$



solar $\Rightarrow$ $|U_{e1}|^2, |U_{e2}|^2, \Delta m_{21}^2$

atmosph. $\Rightarrow$ $|\Delta m_{31}^2|$

CHOOZ $\Rightarrow$ $|U_{e3}|^2 < 0.05$

➔unknown parameters: m_1

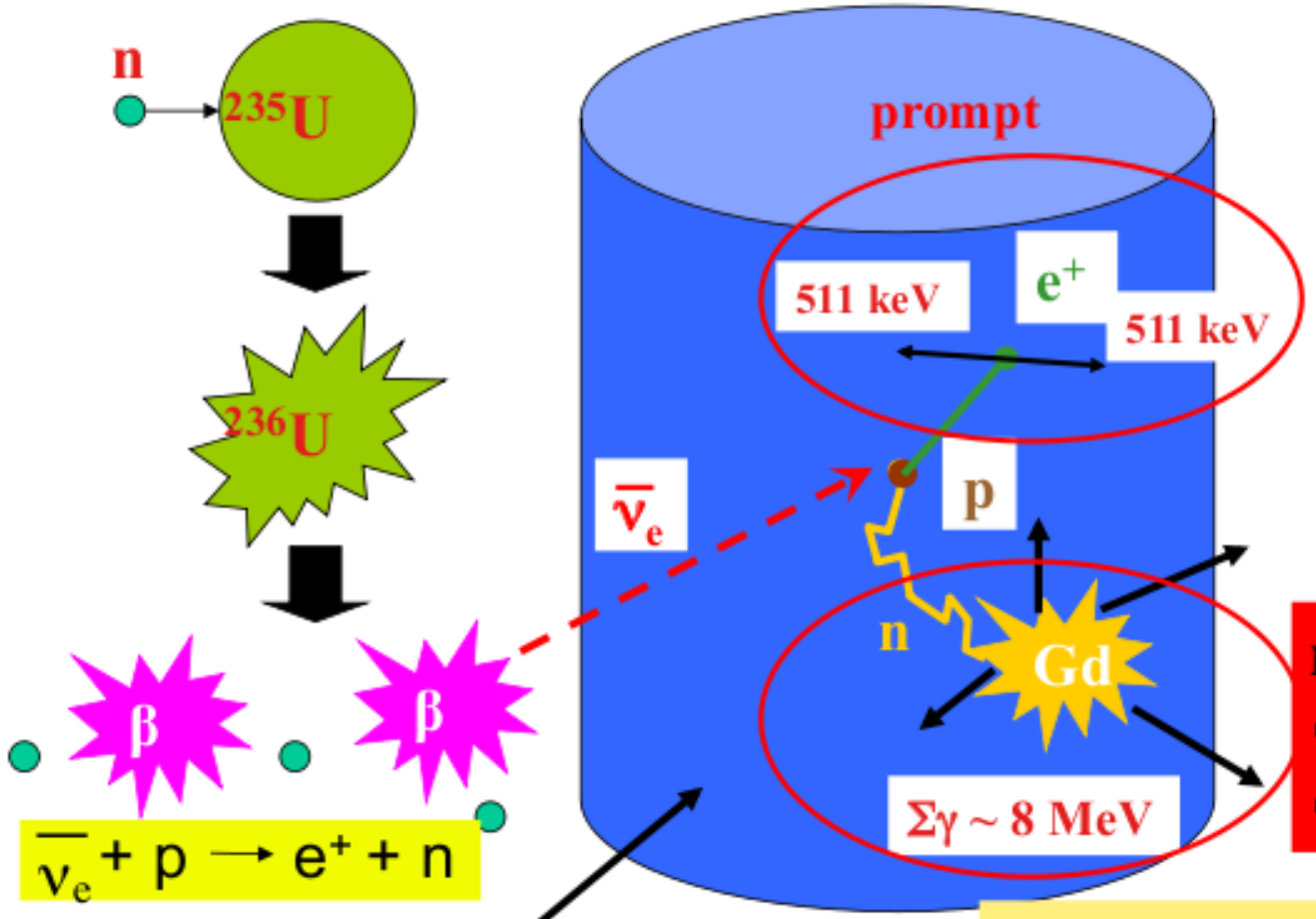
sign(Δm^2_{31})

CP-phases Φ_2, Φ_3

Present limits/values on 0ν β β rates and the ν masses

Isotope	$Q_{\beta\beta}$ (MeV)	$G^{0\nu}$ (10^{-14} y^{-1})	$T^{0\nu}_{1/2}$ (10^{24})	$\langle m_\nu \rangle$ (eV)	
^{48}Ca	4.276	4.46	> 0.014	< 7.2–45	
^{76}Ge	2.039	0.44	> 19(12*)	< 0.35 (≈ 0.44*)	22 0.32 HM
^{76}Ge	2.039	0.44	> 16	< 0.33–1.35	IGEX
^{82}Se	2.992	1.89	> 0.19	< 1.3–3.2	
^{100}Mo	3.034	3.17	> **0.58**	< **0.8 – 1.3**	NEMO3
^{116}Cd	2.804	3.24	> 0.17	< 1.7	
^{128}Te	0.876	0.12	> 7.7	< 1.1–1.5	Geochemical
^{130}Te	2.529	2.86	> **3**	< **0.46**	CUORITINO
^{136}Xe	2.467	3.03	> 0.44	< 1.8–5.2	
^{150}Nd	3.368	13.4	> 0.0012	< 3	

Anti-Neutrino Production and Detection



prompt e^+ signal

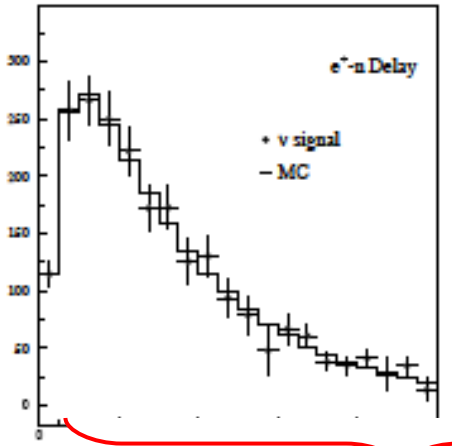
neutron capture
➔ Gd doping
➔ delayed γ (30 μs)

Target: Gd loaded liquid scintillator
transparency, stability, density, matching

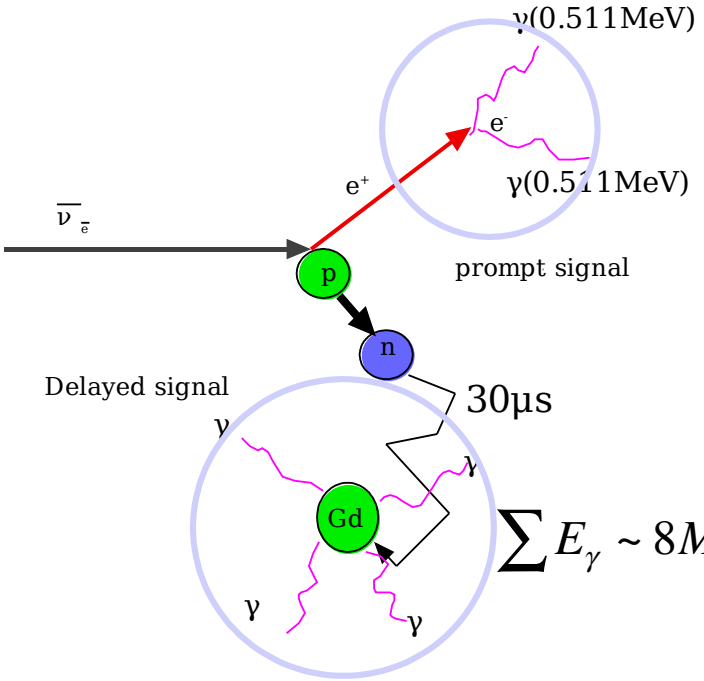
position & time correlation
and delayed energy information
➔ enormous background reduction!

Detection of Reactor Neutrinos

data from CHOOZ
hep-ex/0301017v1

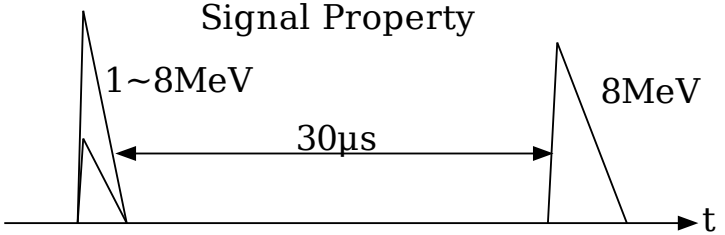


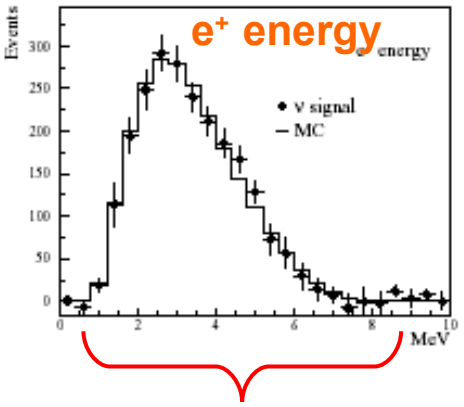
(3) $1\mu s < \Delta T < 200\mu s$



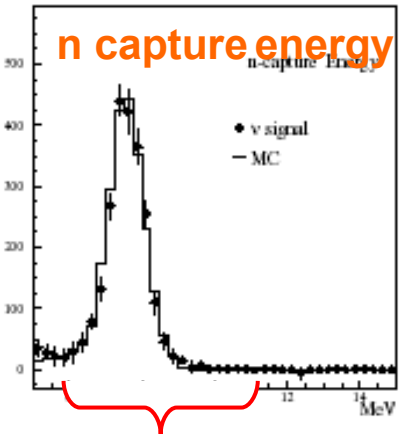
$\sum E_\gamma \sim 8MeV$

Signal Property





(1) $0.7 < E_{prompt} < 9MeV$



(2) $5 < E_{delayed} < 11MeV$

TriBiMaximal mixing

- Many models use tribimaximal mixing to model the neutrino mixing P. F. Harrison, D. H. Perkins and W. G. Scott, Phys. Lett. B **530** (2002) 167

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

$$\theta_{12} = 35^\circ, \quad \theta_{13} = 0^\circ, \quad \theta_{23} = 45^\circ.$$

- This describes the data really well ...

Data

TBM Prediction

Different types of Oscillations (Effective Hamiltonian)

$$H_{eff}^{K_0\overline{K_0}} = \begin{pmatrix} M - \frac{i}{2}\Gamma & M_{12} - \Gamma_{12} \\ M_{12}^* - \Gamma_{12}^* & M - \frac{i}{2}\Gamma \end{pmatrix}$$

Oscillations of ν_l-$\nu_{l'}$ (lepton flavor)

Oscillation of K_0-anti{K_0} (strangeness)

$$H_{eff}^{n\bar{n}} = \begin{pmatrix} M & V^{BNV} \\ V^{BNV} & M - \frac{i}{2}\Gamma \end{pmatrix}$$

Oscillation of n-anti{n} (baryon number)

$$H_{eff}^{atom} = \begin{pmatrix} M_i & V^{LNV} \\ V^{LNV} & M_f - \frac{i}{2}\Gamma \end{pmatrix}$$

Oscillation of atoms (total lepton number)

Full width of unstable atom/nucleus

Eigenvalues

$$\lambda_+ = M_i + \Delta M - \frac{i}{2}\Gamma_1,$$

$$\lambda_- = M_f - \frac{i}{2}\Gamma - \Delta M + \frac{i}{2}\Gamma_1$$

$$\Delta M = \frac{V^2(M_i - M_f)}{(M_i - M_f)^2 + \frac{1}{4}\Gamma^2},$$

$$\Gamma_1 = \frac{V^2\Gamma}{(M_i - M_f)^2 + \frac{1}{4}\Gamma^2}.$$

Oscillations of stable atoms ($\Gamma = 0$)

$$|< f|e^{-iH_{eff}t}|i >|^2 = \frac{4V^2}{(M_i - M_f)^2} \sin^2 [t\ (M_i - M_f)/2]$$

$[t\ (M_i - M_f)] \leq 1$ $\qquad |< f|e^{-iH_{eff}t}|i >|^2 = V^2 t^2$

$[t\ (M_i - M_f)] \geq 1$ $\qquad |< f|e^{-iH_{eff}t}|i >|^2 \approx \frac{V^2}{(M_i - M_f)^2}$

$^{164}_{68}Er \rightarrow {}^{164}_{66}Dy$

$(M_i - M_f) = 24.1\ keV$ $\qquad |< f|e^{-iH_{eff}t}|i >|^2 \leq 3\ 10^{-55}$

Double electron capture ($\Gamma \neq 0$) (resonant enhancement of atom)

$\Gamma = 4 \times 10^{-7}\ Z^4$ eV

$= 0.3\ eV \quad (Z = 30)$

$R_{max} = \frac{1\ \text{ton}}{M_i} \times \frac{4V^2}{\Gamma} \sim 10^4\ yr^{-1}$

Mass difference >> Γ

$\Gamma_1 = \frac{4V^2}{4(M_i - M_f) + \Gamma^2}\ \Gamma$

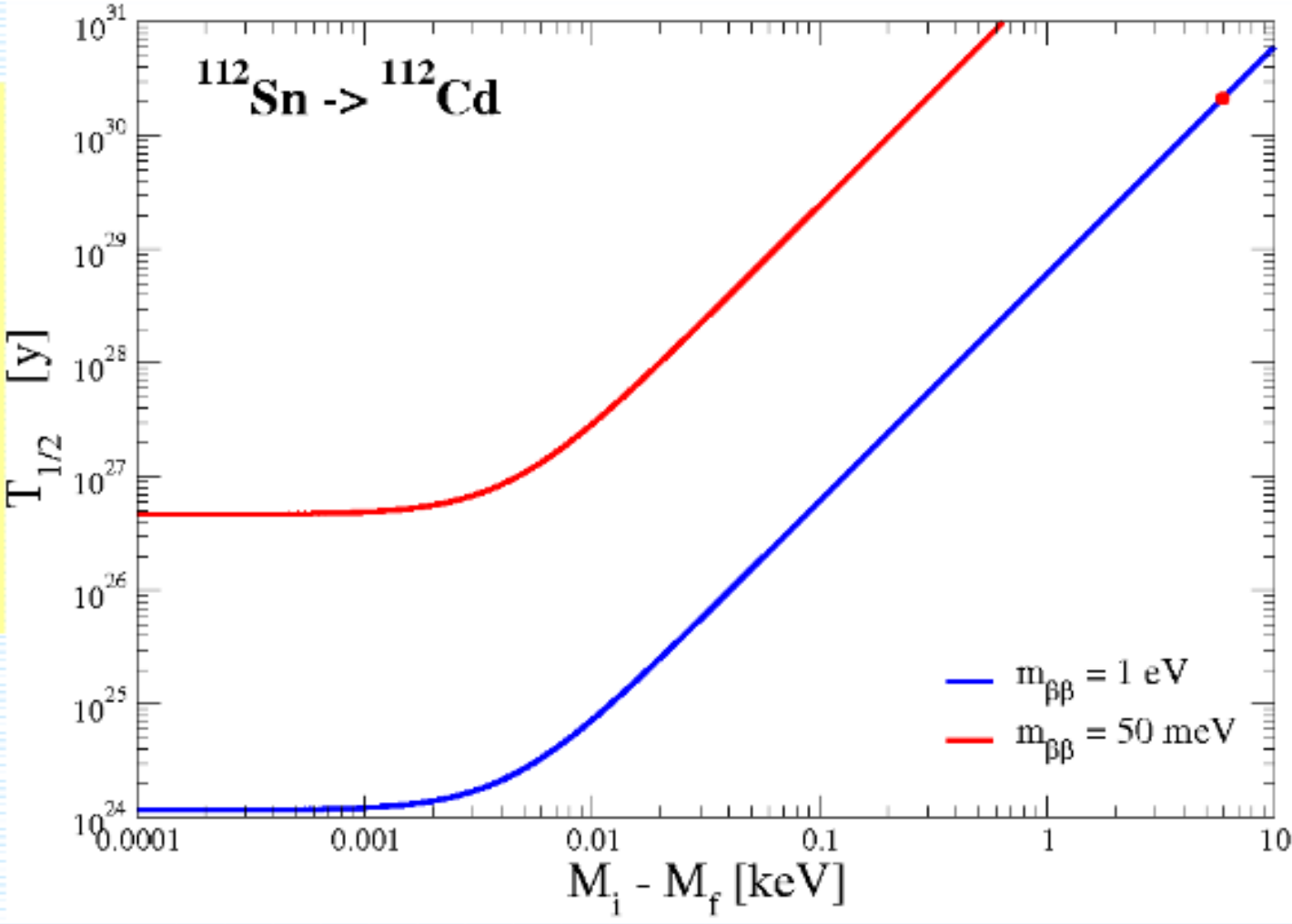
$R \sim R_{max} \frac{\Gamma^2}{(M_i - M_f)^2} \sim 10^{-3}\ yr^{-1}$

Mass difference ~ keV

Double electron capture of ^{112}Sn (perspectives of search)

F. Šimkovic, M. Krivoruchenko, A. Faessler, to be submitted

M_i-M_f	$T_{1/2}^{ECEC}$ ($m_{\beta\beta}$ = 50 meV)
1 keV	$2.44\ 10^{31}$ years
100 eV	$2.45\ 10^{29}$ years
10 eV	$2.91\ 10^{27}$ years
0 eV	$4.67\ 10^{26}$ years



$T_{1/2}^{0\nu}$ (^{76}Ge)= (2.95 – 5.74) 10^{26} years for $m_{\beta\beta}$ = 50 meV