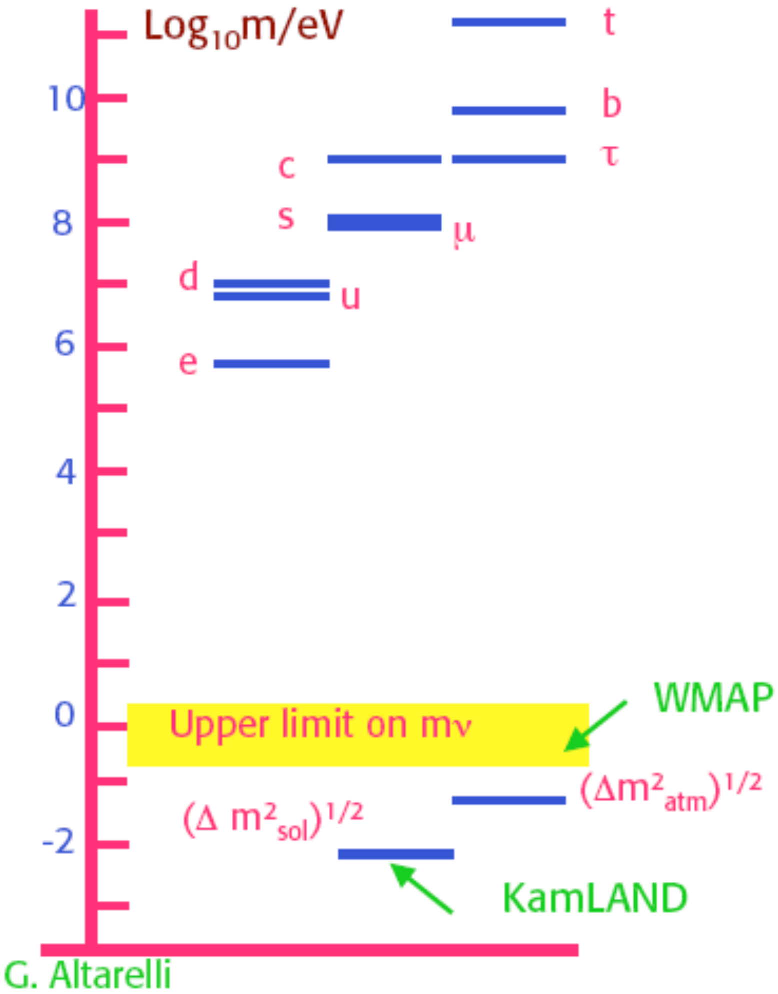
ASTROPARTICLE PHYSICS

The problem with neutrinos…

Neutrino masses

- Neutrino oscillation data has been extensively covered in Particle Physics Major option, and also reviewed in Lecture 5
- Here, consider the Majorana hypothesis: "Neutrinos are their own antiparticles"

Masses of fermions



Fermion masses supposed to come from couplings to Higgs.

Common Dirac mass term of O(10 GeV) with corrections?

Neutrinos appear to stand out from the crowd.

Arxiv:0901.2492

Majorana masses

Notation follows Griffiths, Intro to Elementary Particles

- SM has Dirac particles, and fermions have two states, ψ_L and ψ_R with different interactions .
- Dirac equation

$$-i\hbar\gamma^{\mu}\partial_{\mu}\psi + mc\psi = 0$$

The spinor ψ contains L - and R - handed helicity states: $\psi = \psi_L + \psi_R$

where $\psi_L = \frac{1}{2}\left(1-\gamma^5\right)\psi$ and $\psi_R = \frac{1}{2}\left(1+\gamma^5\right)\psi$

- Consider electron spin-up state:

$$U_1 = \sqrt{E+m}\begin{pmatrix} 1 \\ 0 \\ p_z/E+m \\ p_x+ip_y/E+m \end{pmatrix} \Rightarrow \sqrt{E+m}\begin{pmatrix} 1 \\ 0 \\ p_z/E+m \\ 0 \end{pmatrix} \quad \text{for } p_x = p_y = 0$$

$$U_1^L = \frac{1}{2}\left(1-\gamma^5\right)U_1 = \frac{\sqrt{E+m}}{2}\begin{pmatrix} 1-p_z/E+m \\ 0 \\ -1+p_z/E+m \\ 0 \end{pmatrix}$$

$$U_1^R = \frac{1}{2}\left(1+\gamma^5\right)U_1 = \frac{\sqrt{E+m}}{2}\begin{pmatrix} 1+p_z/E+m \\ 0 \\ 1+p_z/E+m \\ 0 \end{pmatrix}$$

These are not eigenstates: the electron will have equal probability of being in either one.

Dirac particle masses

The L,R states are coupled via the particle mass:

$$\overline{U}_1^R U_1^L = U_1^{R^\dagger} \gamma^0 U_1^L = m$$

$$\overline{U}_1^R U_1^R = 0$$

Dirac spinor mass terms correspond to diagrams where the state changes from L to R and vice versa.

If the mass were zero, this could not happen and the L and R states would decouple into two fixed helicity states

For finite mass, the L/R states and the +-helicity states are different, and not eigenstates.

In the standard model, the interaction proceeds via the Higgs field and the value of mass is given by the Higgs coupling.

Particle anti-particle spinors

$$V_2 = \sqrt{E+m}\begin{pmatrix} p_z/E+m \\ 0 \\ 1 \\ 0 \end{pmatrix} \qquad \text{for } p_x = p_y = 0$$

$$\overline{V}_2^R U_1^L = m$$

Also get mass term from transition between electron and positron!

This is forbidden by conservation of electric charge and lepton number. Can never happen for charged fermion in SM.

Majorana masses

The neutrino has no electric charge, so it is possible that it is its own antiparticle. Then the process

Allowed if lepton number is not conserved. The neutrino can therefore have both Dirac and Majorana mass terms.

$$\overline{V}_2^R U_1^L = M \quad \text{and since} \quad \overline{V}_2^R \equiv U_1^L$$

RH-antiparticle=>LH-particle

$$U_1^L U_1^L = M_L$$

$$U_1^R U_1^R = M_R$$

Majorana masses come from LL and RR transitions.

Dirac masses come from LR and RL transitions.

Neutrino mass matrix

- Connect L, R states to mass eigenstates ν_1 and ν_2

$$\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = \begin{pmatrix} M_L & m \\ m & M_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

- Eigenvalues are then

$$m_{1,2} = \frac{1}{2}\left\{ \left(M_R + M_L\right) \pm \sqrt{\left(M_R - M_L\right)^2 + 4m^2} \right\}$$

The see-saw mechanism

- Weak interaction prefers LH states, and has small mass scale (relative to M_{GUT}).
- Possible explanation of parity violation is that RH interactions have large mass scale (eg heavy right-handed W would produce no effect at current energies).
- This would lead to $M_R >> M_L$, m and hence

$$m_1 \approx \frac{m^2}{M_R} \qquad m_2 \approx M_R$$

- As M_R increases, m_1 falls and m_2 rises.
- Very light neutrino state, with dominantly LH interactions, and very heavy RH state.
- We know m is of order 10 GeV from observed fermions, and m_1 is consistent with 0.1 eV so would require

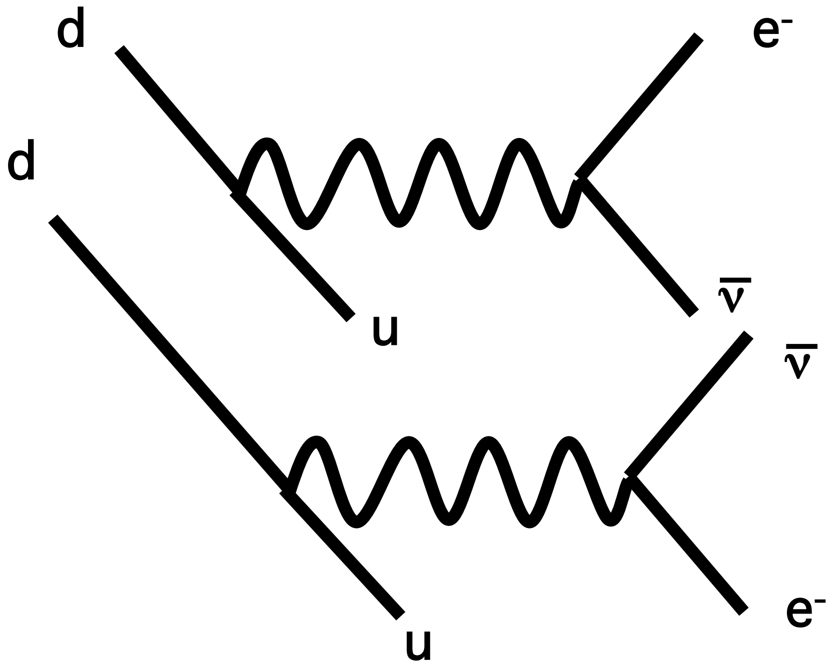
$$M_R \approx \frac{m^2}{m_1} = \frac{\left(10\ \mathrm{GeV}^2\right)}{10^{-10}\mathrm{GeV}} = 10^{12}\ \mathrm{GeV}$$

consistent with values in typical GUT models.

Also, lepton number violation can lead to leptogenesis and then baryogenesis.

Double beta decay

- Distinguish between Dirac and Majorana neutrinos by looking for lepton-number violating processes, forbidden in the SM. DBD is the rarest radioactive decay mode, only observed in 10 isotopes.

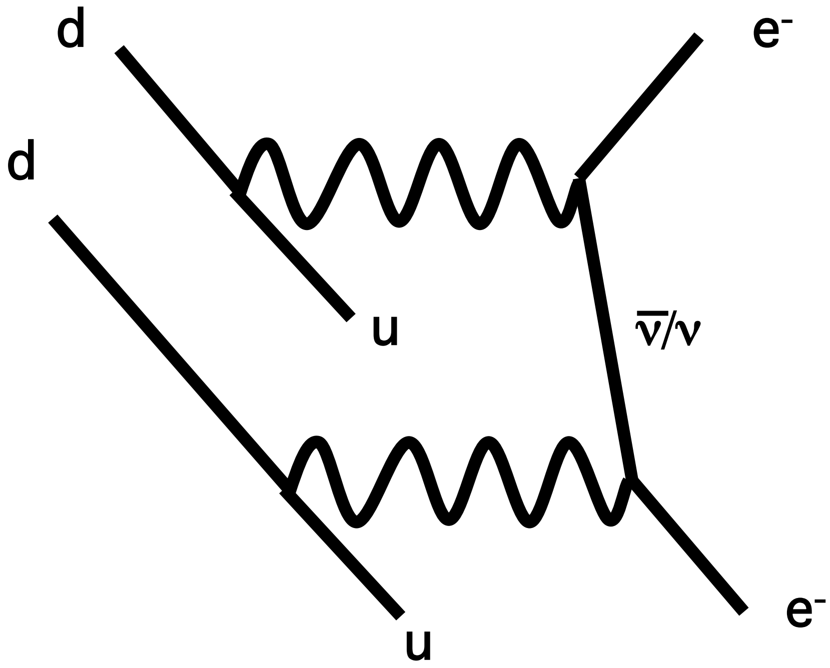


SM allows double beta decay: nucleus with Z, A transmutes to Z+2, A

Two antineutrinos emitted. Lepton number conserved. Electrons emitted with variable energies.

Neutrino-less double beta decay

- Neutrino state exchanged. Lepton number changes by 2 units. Electrons emitted at fixed energy.



One neutrino state has "wrong" helicity, so rate is suppressed by

$$\left(1-\frac{v}{c}\right) \approx \frac{(m_\nu c^2)^2}{2E^2}$$

Hence $0\nu\beta\beta$ allows the neutrino mass to be inferred if the nuclear matrix element is known.

$0\nu\beta\beta$ experiments

- Require:
  - Large detector mass to raise event rate
  - Very good energy resolution to isolate signal at expected energy
  - Very low background from radioactivity in detector and surroundings
  - Good shielding from cosmic rays
- Very similar to dark matter searches – use similar detectors, Xe and semiconductors

The Moscow-Heidelberg result

- Only positive result to date
- ^{76}Ge detector
- 11 kg target mass
- 13 years of running (1990-2003)
- Located in Gran Sasso road tunnel

Background dominated by radioactivity in detector, with gamma rays producing electrons by Compton scattering.

Example background processes

Diagram from NEMO experiment (see later)
Similar for M-H experiment

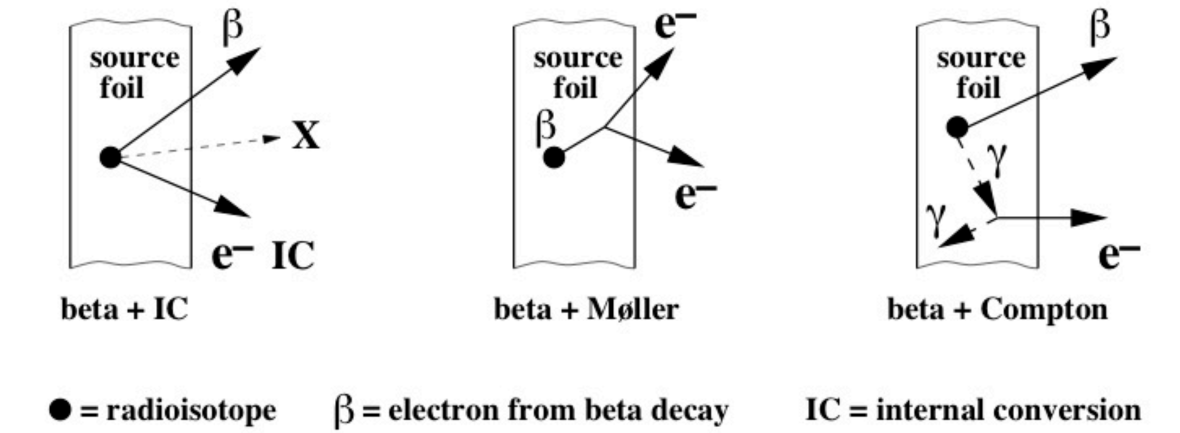


Fig. 2. Internal background production in the source foil.

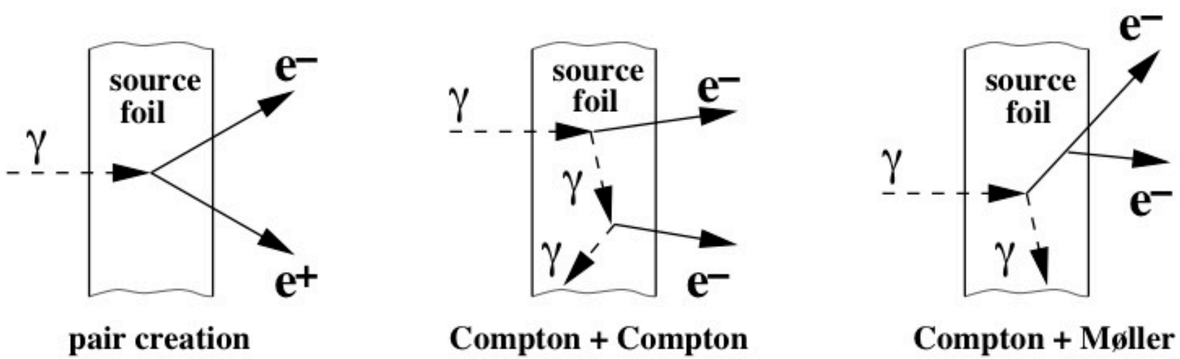


Fig. 3. External background production in the source foil.

Background sources

Non-trivial to understand all sources from radioactive isotopes

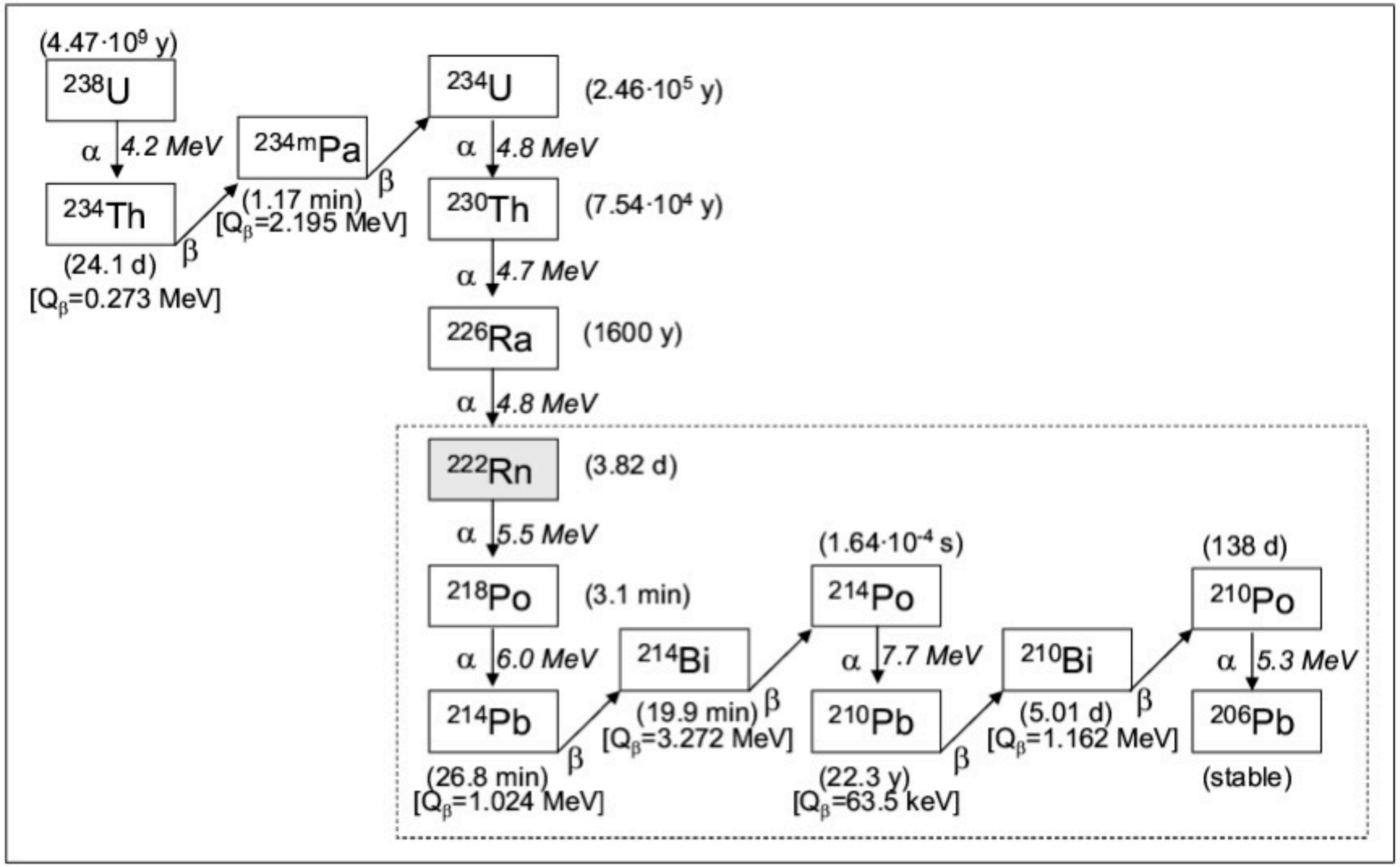
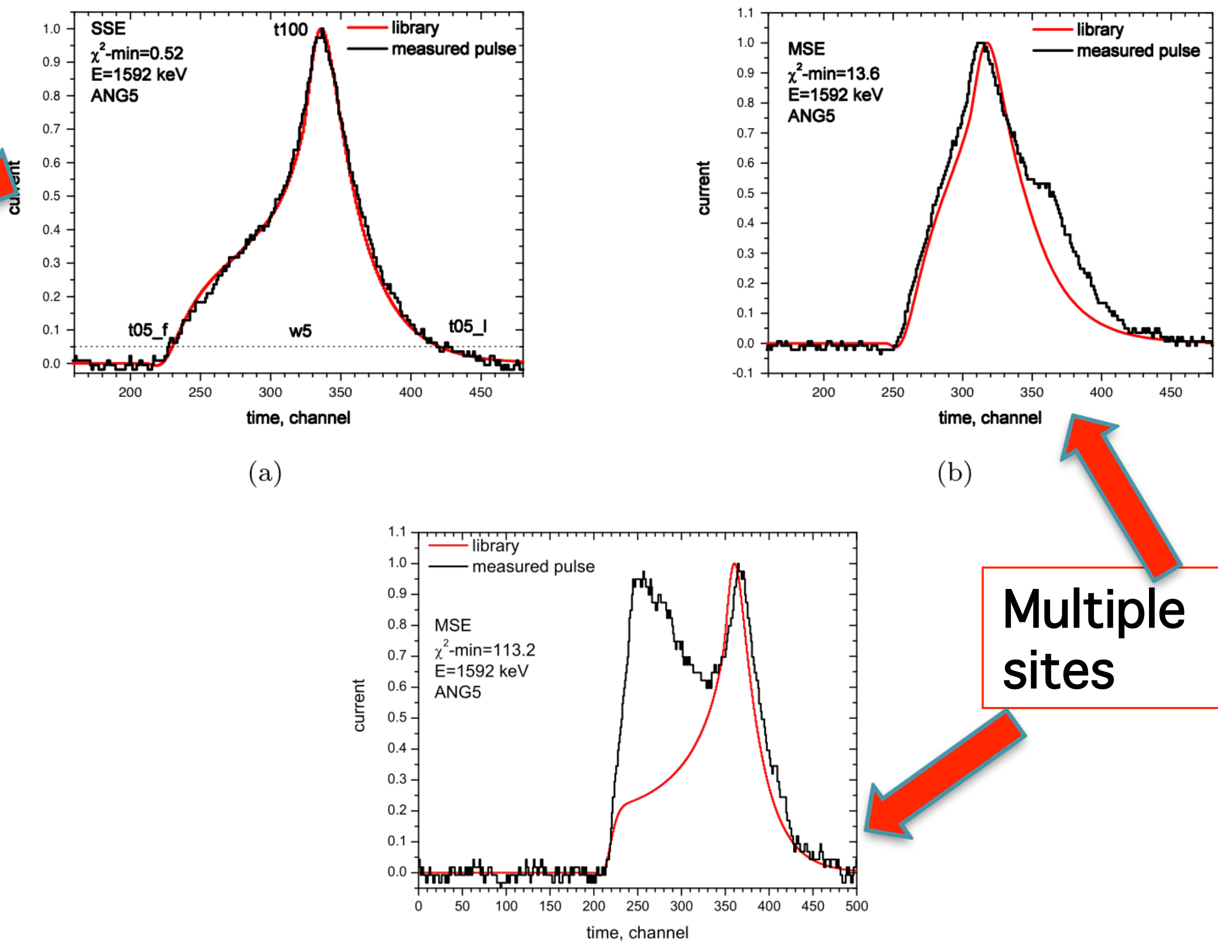


Fig. 4. Decay chain of the radioactive family of ^{238}U. The half-lives and decay energies are taken from [5].

Analysis relies heavily on analysis of pulse shapes. Events depositing energy at a single site (plot a) differ from those where energy comes from multiple sites.

Single site



(a) (b) (c)

Multiple sites

Final result, after detailed analysis of pulse shapes, shows a peak at the expected energy for double beta decay, with a claimed significance of 6.4 sigma from 7 events. Result widely disputed and not yet confirmed, but strongly defended by authors.

$\tau_{0\nu}$= (2.23+0.44) × 10^{25} y

⟨m⟩ = (0.32+0.03) eV
with assumptions

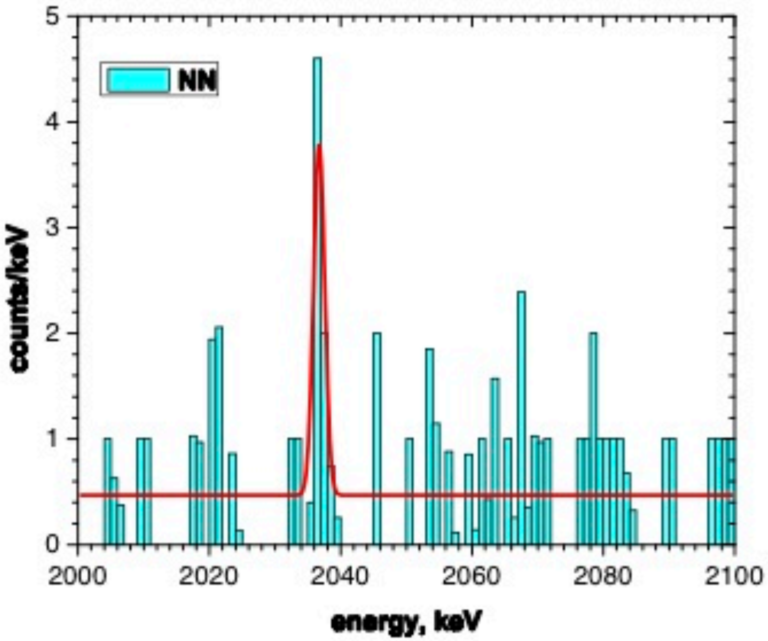


Fig. 8. The pulse shape selected spectrum (selected by neuronal net-NN) with detectors 2, 3, 4, 5 from 1995 to 2003 in the energy interval 2000–2100 keV (see Refs. 3 and 4). The signal at $Q_{\beta\beta}$ has a confidence level of 6.4σ (7.05 ± 1.11 events).

Modern Physics Letters A Vol. 21, No. 20 (2006) 1547–1566

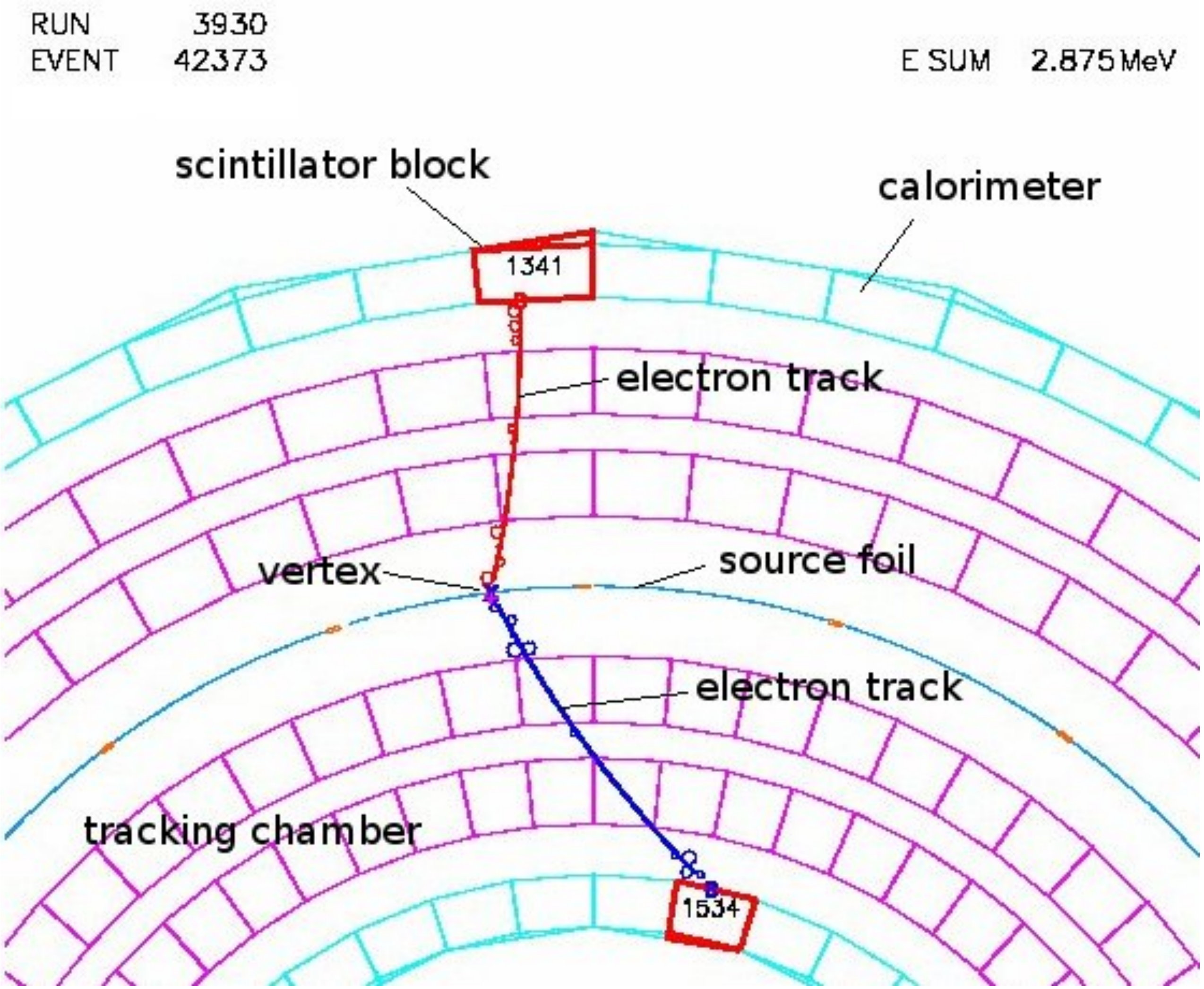
Future experiments

- Active field of research – 15 experiments active or planned. For example NEMO-3 active (10 kg), Super-NEMO planned (100 kg). NEMO-3 can reach 10^{24} years, SuperNEMO 10^{26} years half-life.

NEMO-3 event

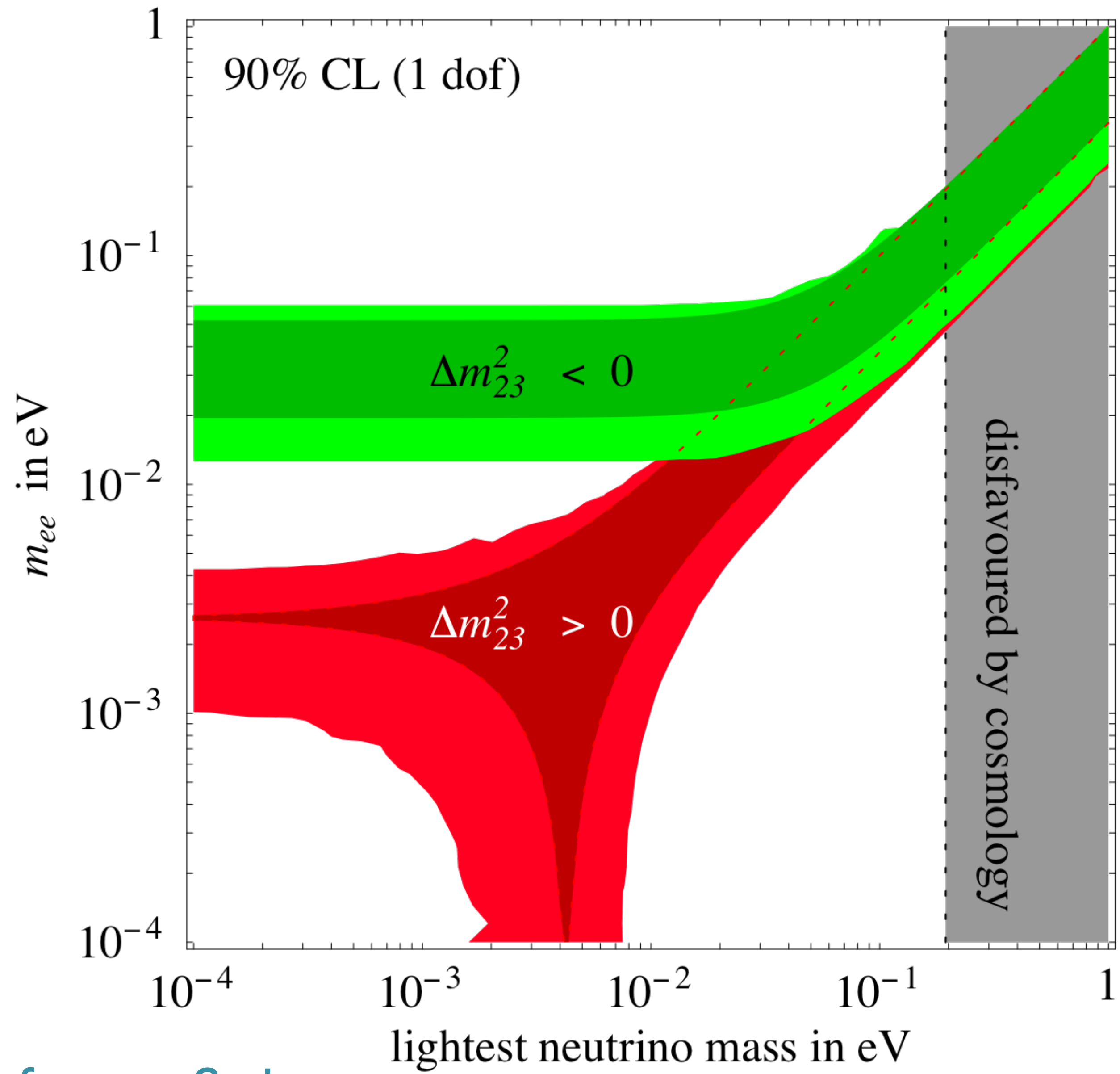
NEMO can track particles to show common origin of electrons

Sources in foils interleaved with detectors



arXiv: 0903.2277v1

Mass resolution needed to distinguish mass hierarchy



Journal of Physics: Conference Series 203 (2010) 012014

Cosmic Neutrinos

- Cosmic neutrinos would have begun to propagate 1s after the BB when T=1 MeV
- Expect neutrinos energies of 5×10^{-4} eV and 56 neutrinos/cm^3 based on standard cosmology.

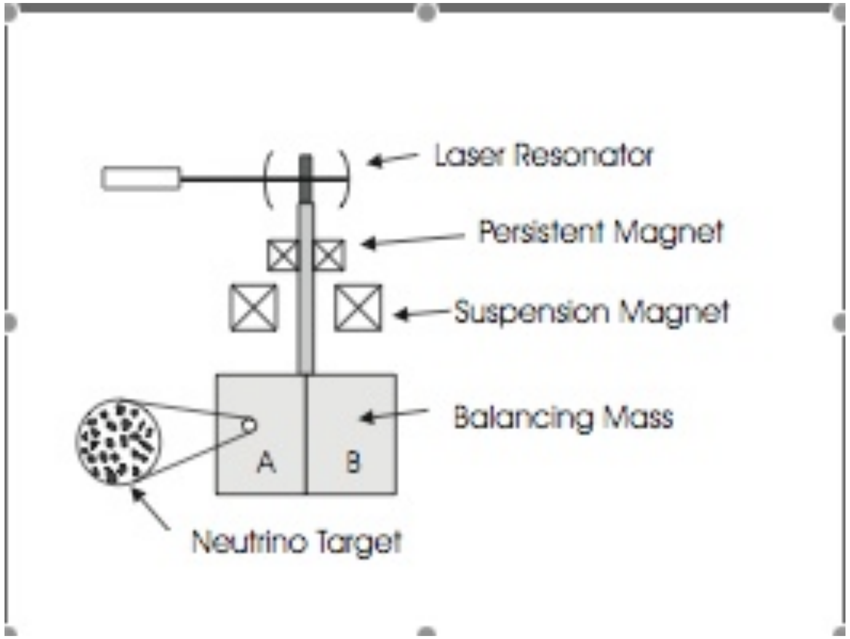
- But neutrino cross section rises linearly with energy, so if $m_\nu = 0.1$ eV,

$\sigma = 2 \times 10^{-58}$ cm^2 on a nuclear target

giving 5×10^{-8} events per year per kiloton of target

Torsion balance method?

- Use two materials with same density but different neutrino scattering cross-sections, suspended from SC magnetic bearing. Detect neutrino wind
- Since wavelength of neutrinos is 2.3 mm, get coherent scattering



Coherence gives N^2 enhancement to σ
Acceleration = 4×10^{-29} cms^{-2}
16 orders of magnitude better than current balances

Use cosmic ν as target?

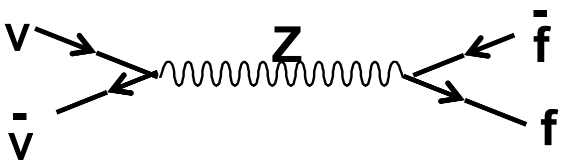
- Neutrino cross-section is very small, but rises linearly with CoM energy.
- Consider hitting neutrinos with high energy beam…
- Centre of mass energy = sqrt(2 m E) where m is target mass and E is beam energy.

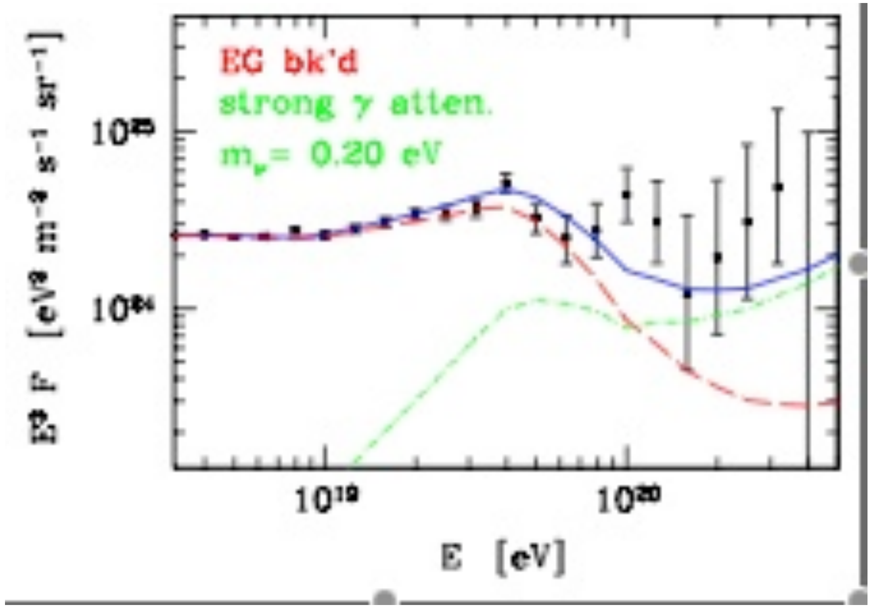
- Cross-section rises to 3×10^{-46} cm^2 for an LHC beam at 7 TeV…
- … but event rate is still $<10^{-12}$ events per year

- No hope with current or planned accelerator

Ultra-High-Energy Cosmic ν

- UHE cosmic rays have been observed up to energies of 10^{20} eV
- If neutrinos exist with these energies then at $4\text{x}10^{22}$ eV, it is possible to produce Z bosons on resonance with a cross-section of $4\text{x}10^{-32}$ cm^2

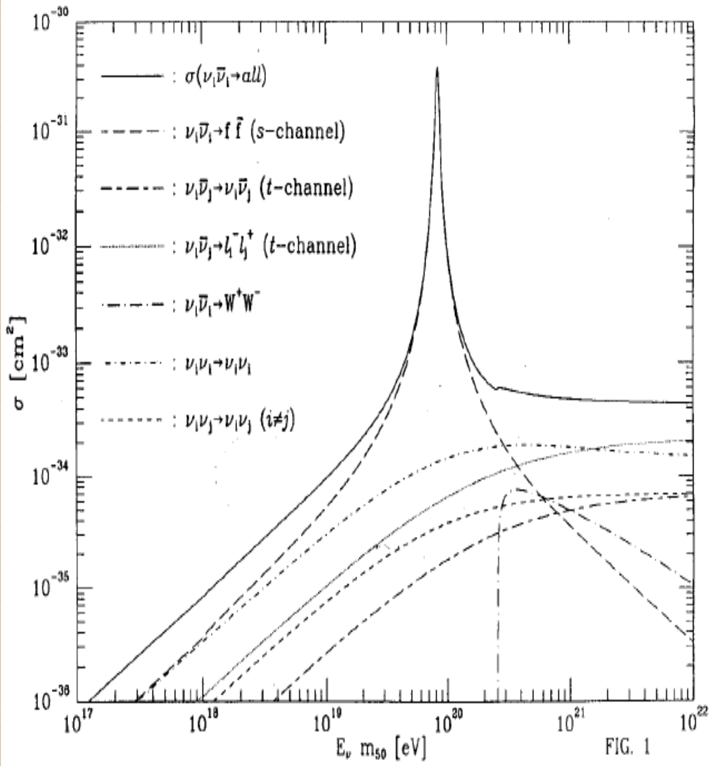


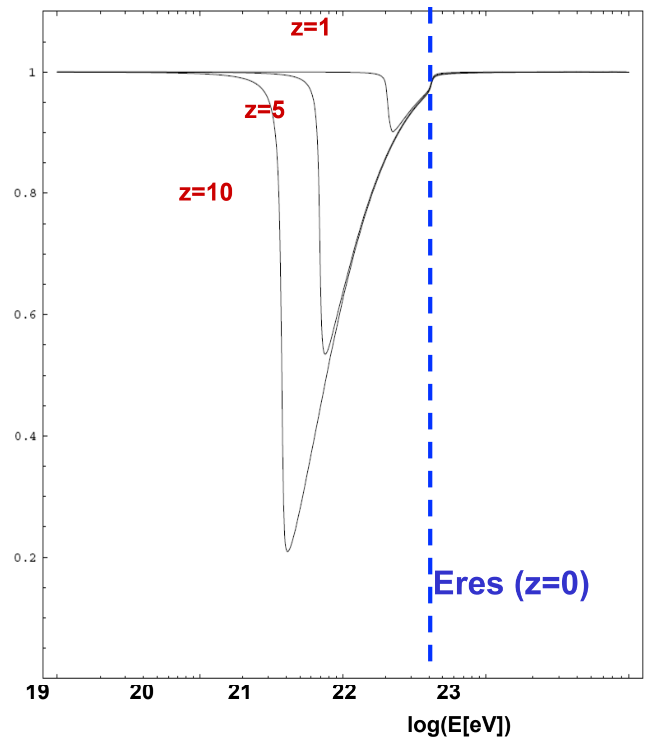


Mean free path of UHE ν = $1.4\text{x}10^5$ Mpc = $4.5\text{x}10^{11}$ light years

cf age of Universe = $13.7\text{x}10^9$ years

Absorption lines

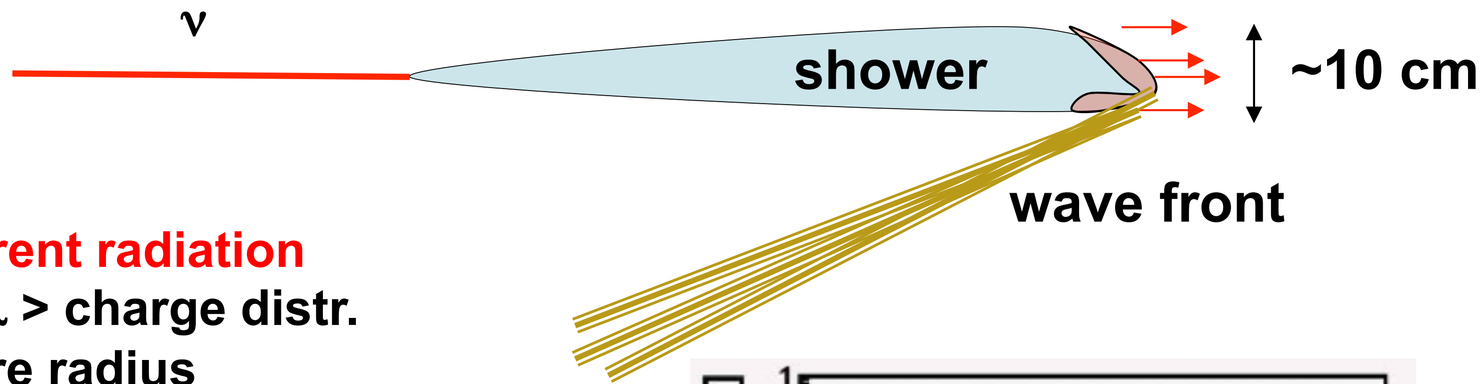




- Presence of Z resonance creates absorption lines in UHE ν flux. Position depends on redshift z of source

Askaryan effect: radio waves from neutrinos

ν interaction → cascade in the material strips off electrons that move with cascade



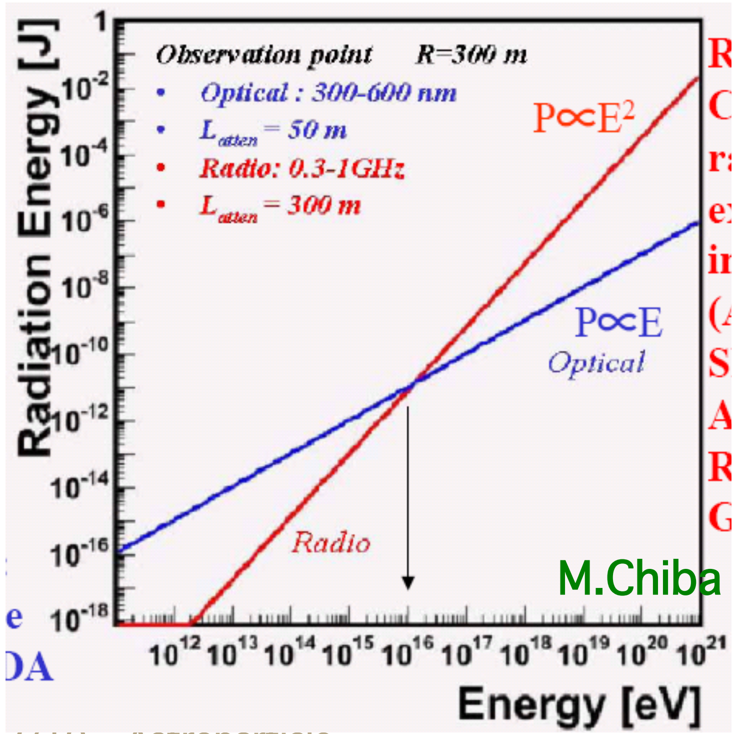
Cherenkov **coherent radiation** **for wave length λ > charge distr. = shower Molière radius**

r_M**~10 cm**

→ radio wave lengths

→ power ~ $(N\ Q_e)^2 \sim E^2$ of primary energy

→ dominates incoherent optical output above 10^{16}-10^{18} eV



Existing experiments

- RICE-Cube – using Antartic ice for light and radio
- ANITA – balloon over Antartic looking for radio emission from ice
- GLUE – Goldstone radio telescopes observing moon in coincidence

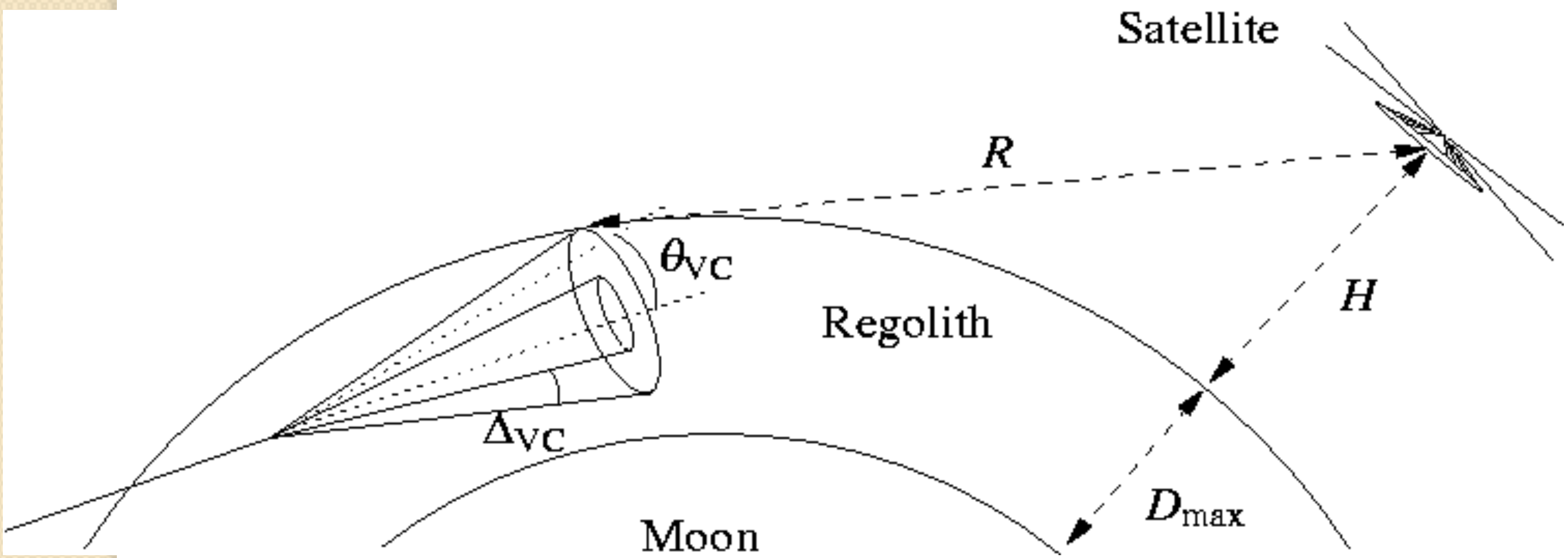
Moon as neutrino target

Askaryan 1962:

**"… use ice,
permafrost,
very dry
rock"**

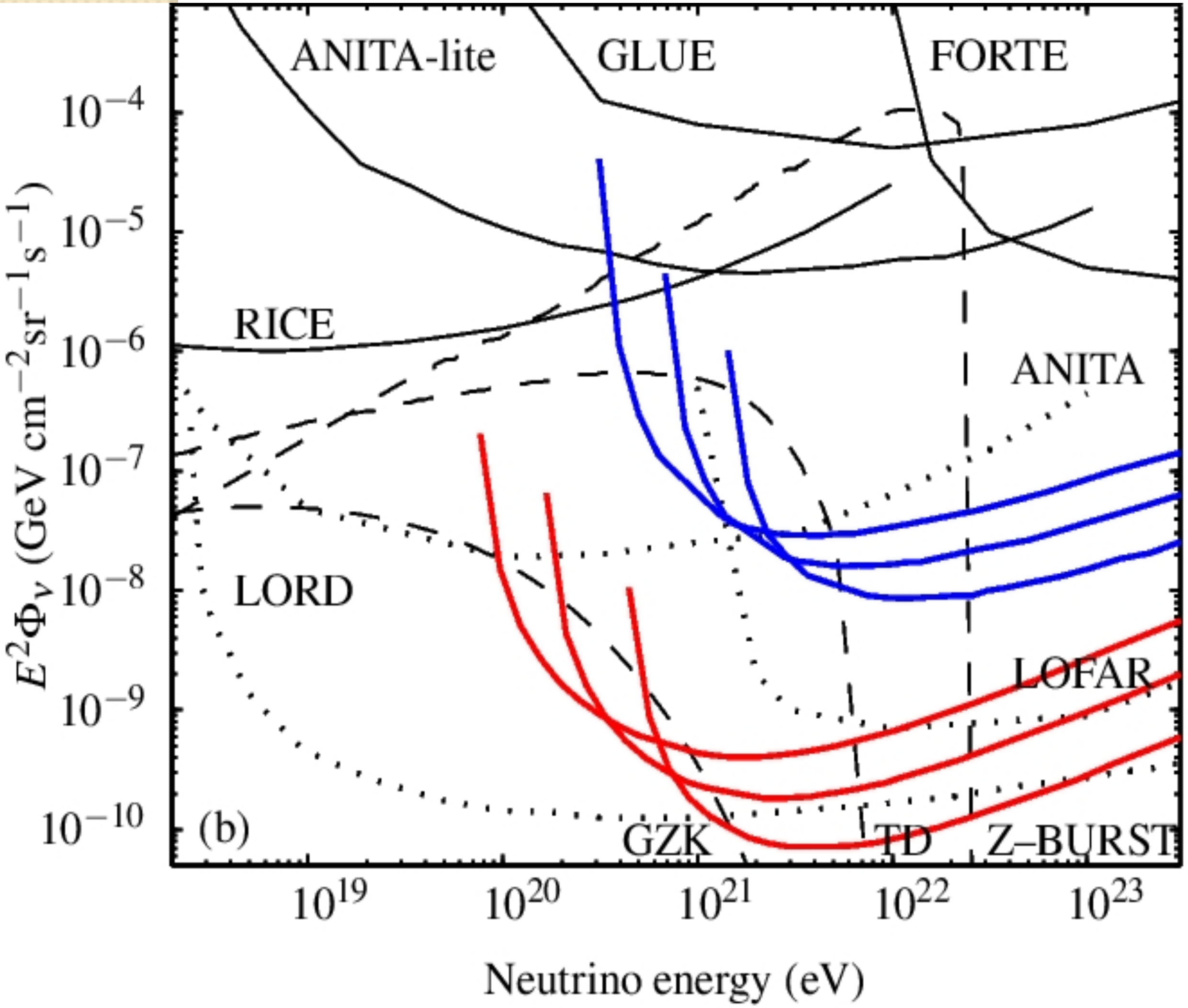
Moon provides huge target

Future satellite mission?



- Gain factor of 10^7 in signal power, and observe continuously for >1 year
- Reduce background noise from Earth (especially on far side

Flux limits for *beam-filling* antenna in 1 year



O. Stål et al., PRL 2007

ν [GHz]	H [km]
1	100
	250
	1000
0.1	100
	250
	1000

Beam-filling antenna observes full Moon → higher sensitivity

Suppressed galactic noise → optimum at low observation frequency