Measuring directionality in double-beta decay and neutrino interactions with kiloton-scale scintillation detectors

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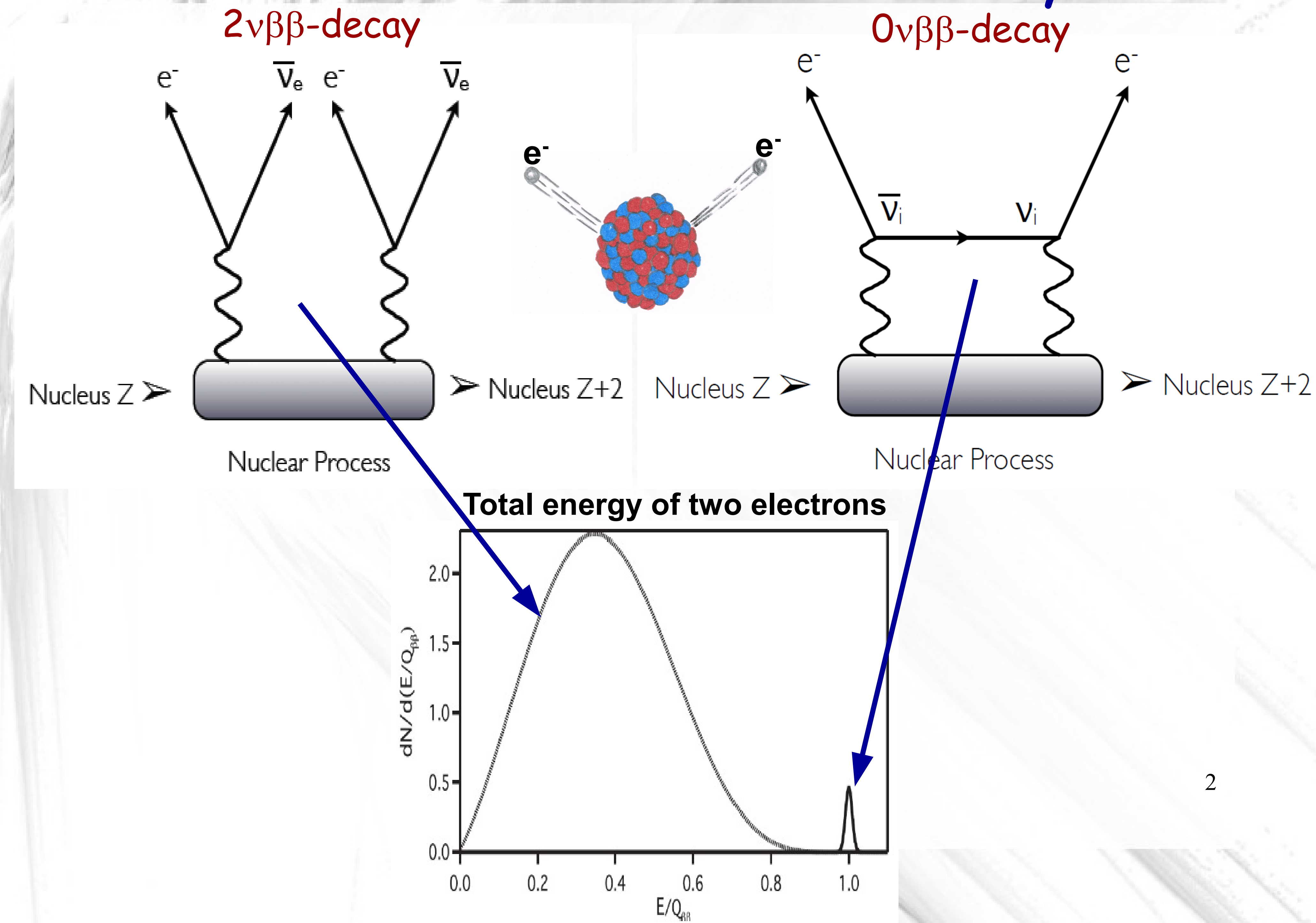
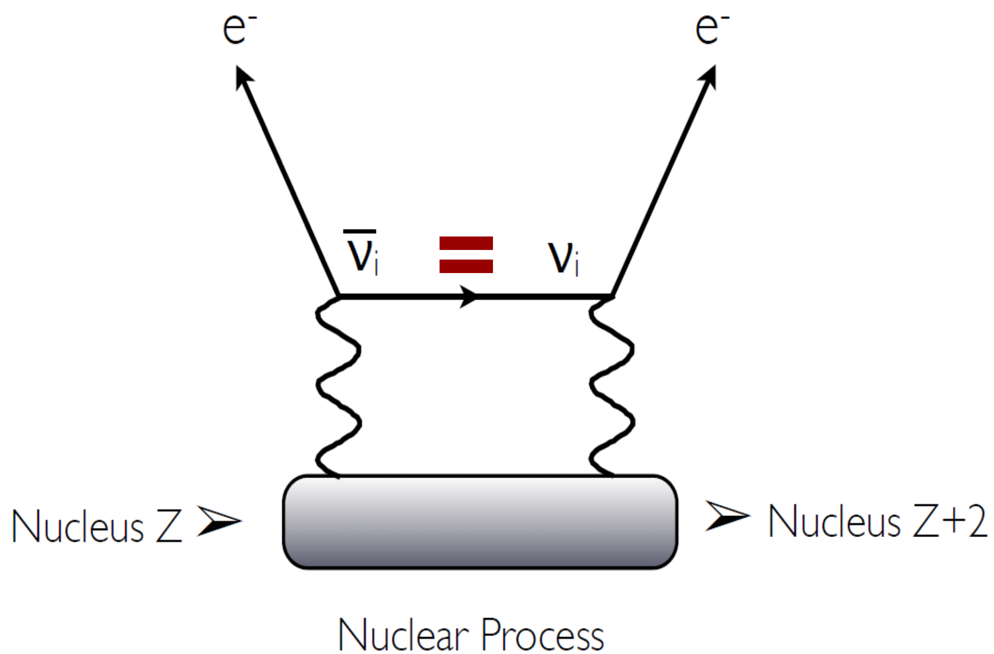
What Is Double Beta Decay?



Why Is It Interesting?

$0\nu\beta\beta$-decay is only possible if the neutrino is its own antiparticle (i.e. Majorana particle)



Is neutrino its own antiparticle?

- It is possible because the neutrino has no electric charge
- No other fermion can be its own antiparticle
- It is not only possible, but may be necessary
  - origin of matter-antimatter asymmetry in the universe
  - why the neutrino mass is so tiny?

How to Find $0\nu\beta\beta$-decay?

1) Choose isotope where $0\nu\beta\beta$-decay is allowed

2) Wait for emission of two electrons with the right total energy

Isotopes	Q-value (Total energy of 2 electrons), MeV	Natural abundance, %
Ca 48	4.271	0.187
Ge 76	2.039	7.8
Se 82	2.995	9.2
Zr 96	3.350	2.8
Mo 100	3.034	9.6
Pd 110	2.013	11.8
Cd 116	2.802	7.5
Sn 124	2.288	5.64
Te 130	2.529	34.5
Xe 136	2.479	8.9
Nd 150	3.367	5.6

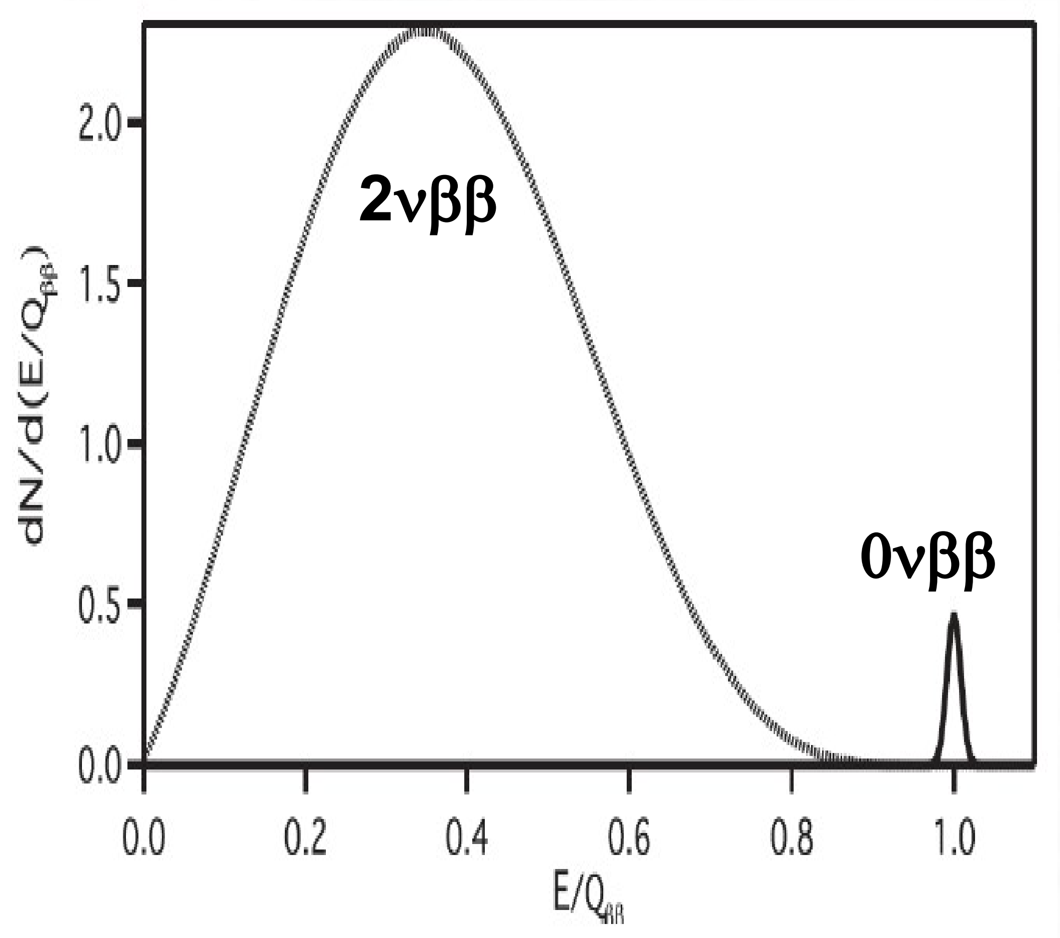
Challenge 1: Decay Probability

Life-time for $0\nu\beta\beta$-decay is more than > 10^{26} years

This is much longer than the age of the universe

Solution: look at many atoms at the same time
- Avogadro number is large $N_A = 6 x 10^{23}$
- one ton of material can have >10^{27} atoms
- even with one ton we are talking about ~10 events per year

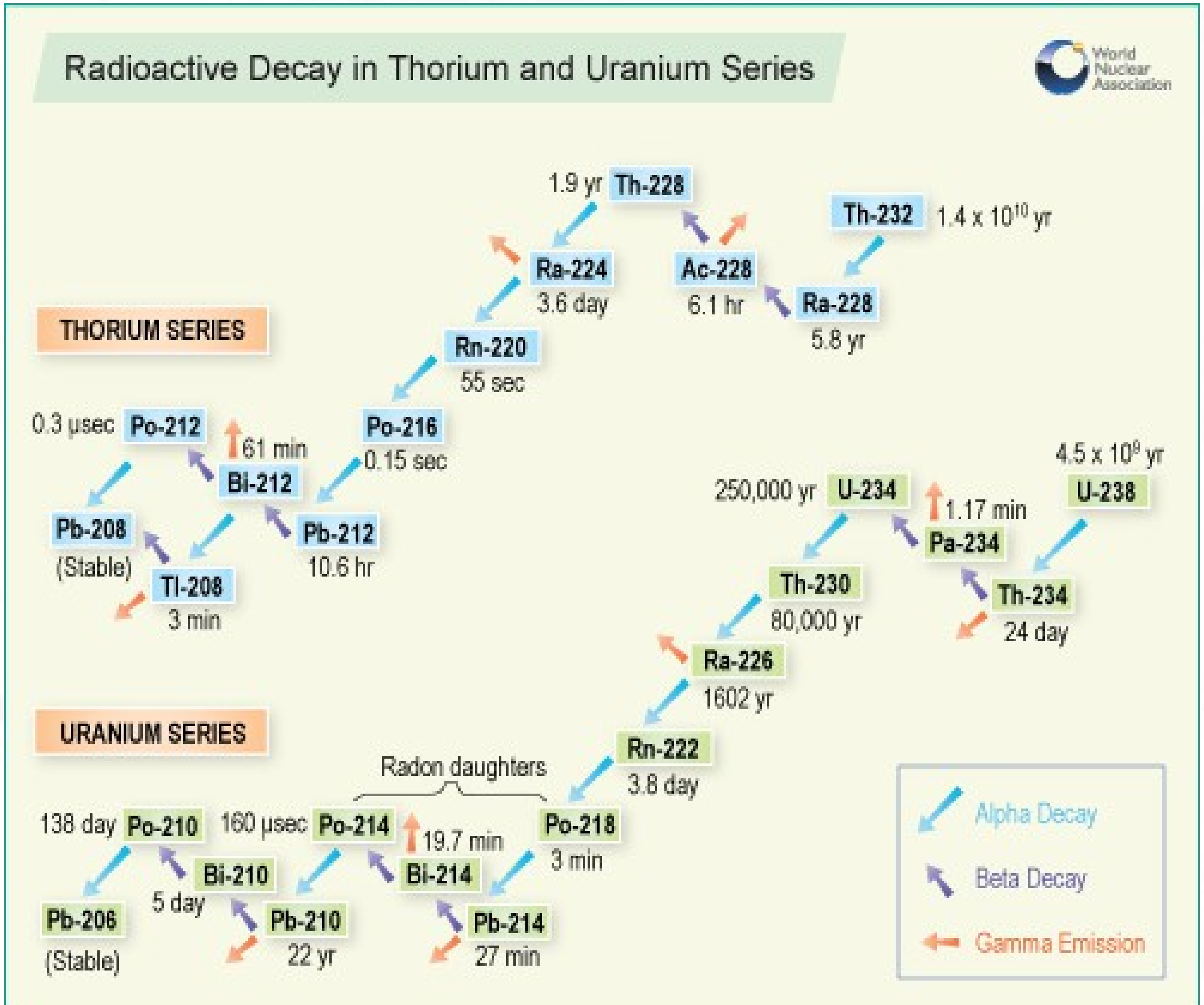
Challenge 2: Background from $2\nu\beta\beta$



Solution: good energy resolution

Challenge 3: Natural Radioactivity

There are 3g U-238 and 9g of Th-232 per ton of rock



These decays are a factor of ~10^{16} more likely than $0\nu\beta\beta$-decay

Solution: *good event selection using proper instruments*

Ideal Experiment

1) Large mass (more nuclei at the same time)

2) Good energy resolution (discriminate from $2\nu\beta\beta$-decay)

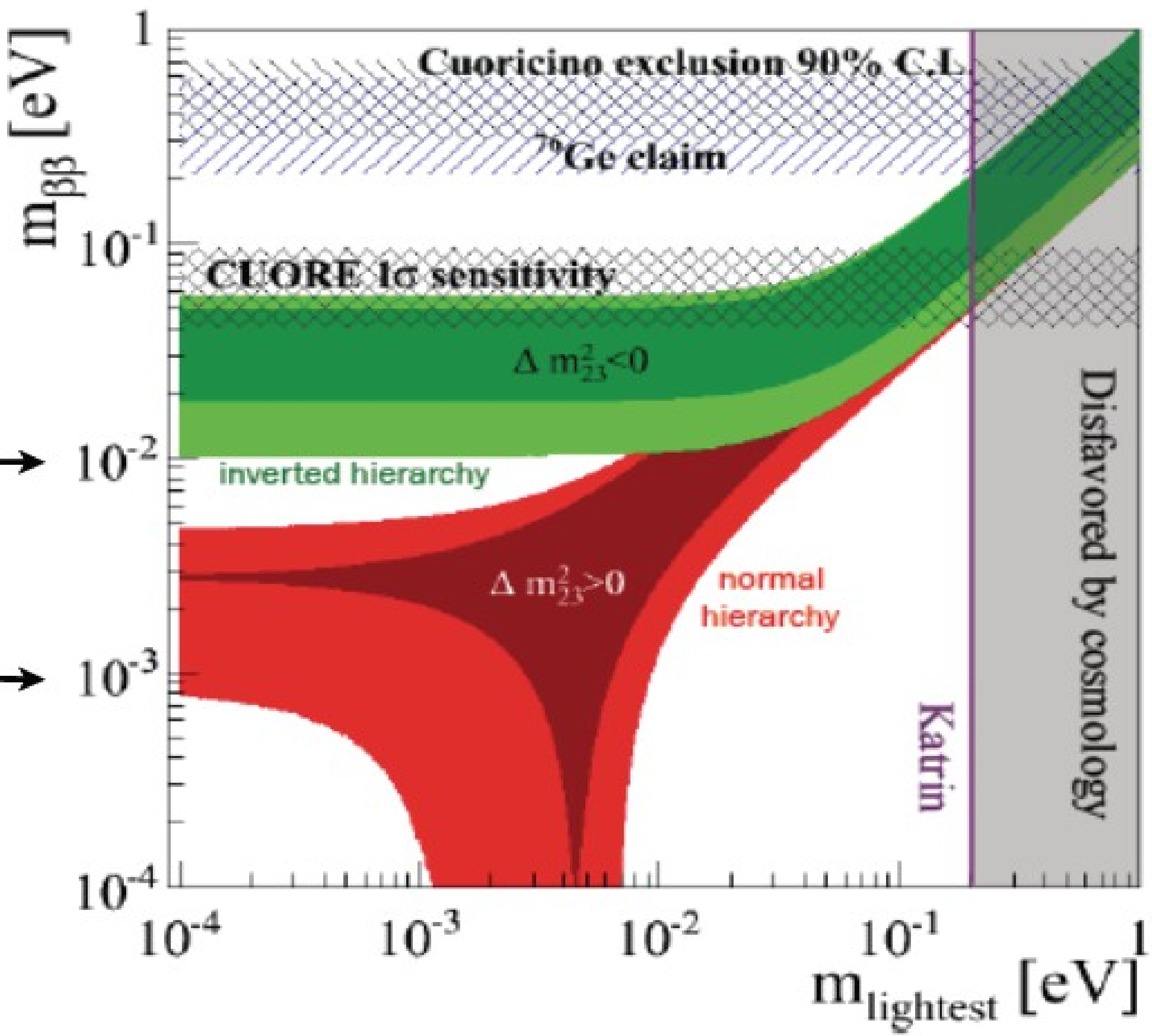
3) Good event selection (natural radioactivity)

Real-Life Experiments Sensitivity

EXO ~32 kg yr

1 ton

10 ton

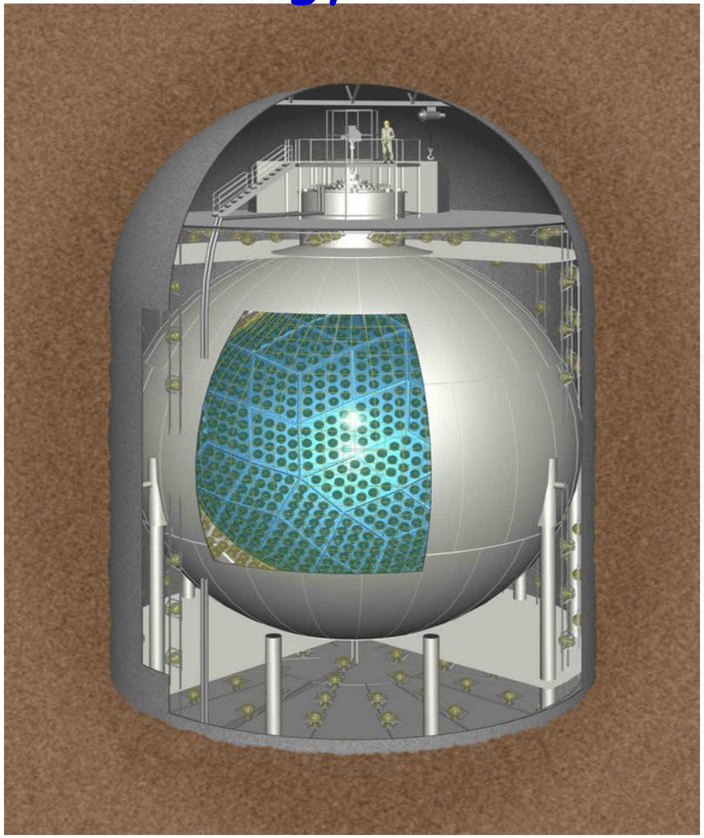


None of the currently running or planned experiments is sensitive to $m_{\beta\beta} \sim 10^{-3}$ eV

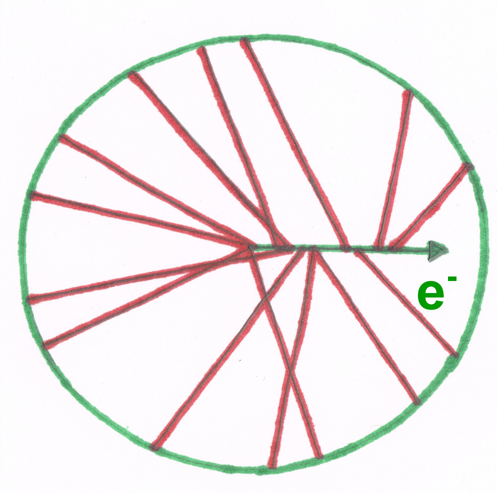
How to Make a Better Experiment?

Learn what other people have done already

KamLAND experiment:
- liquid scintillator
  ("easy" to build big)
- scintillation light is used
  for energy measurement



Scintillation light

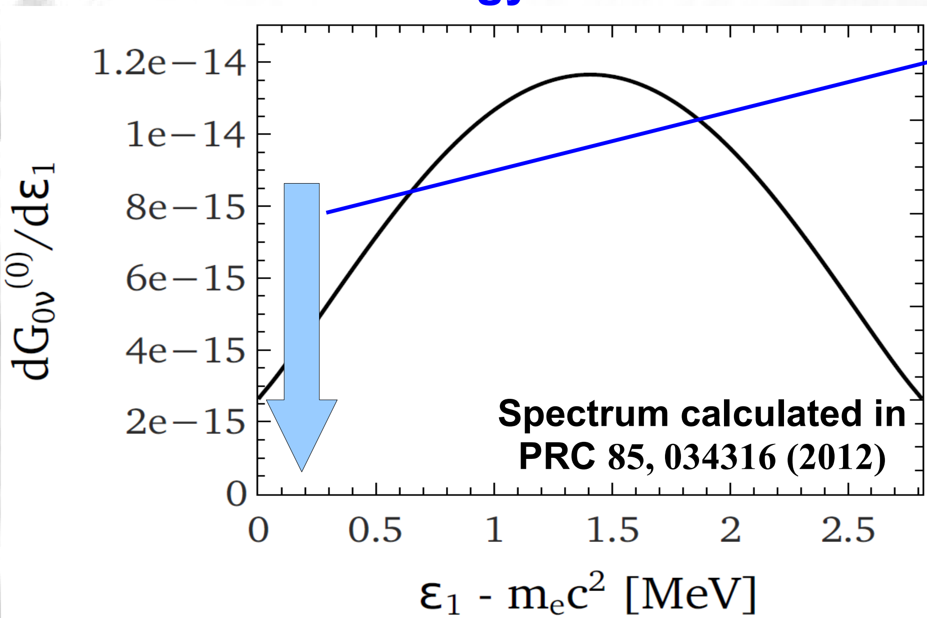


- Produced by a charged particle in a scintillation media
- Delayed
- Isotropic

How to Make a Better Experiment?

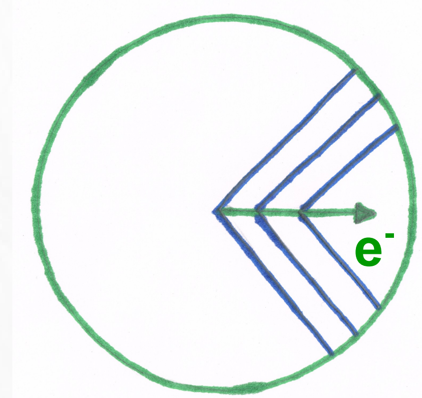
Bring new ideas

Kinetic energy of one electron

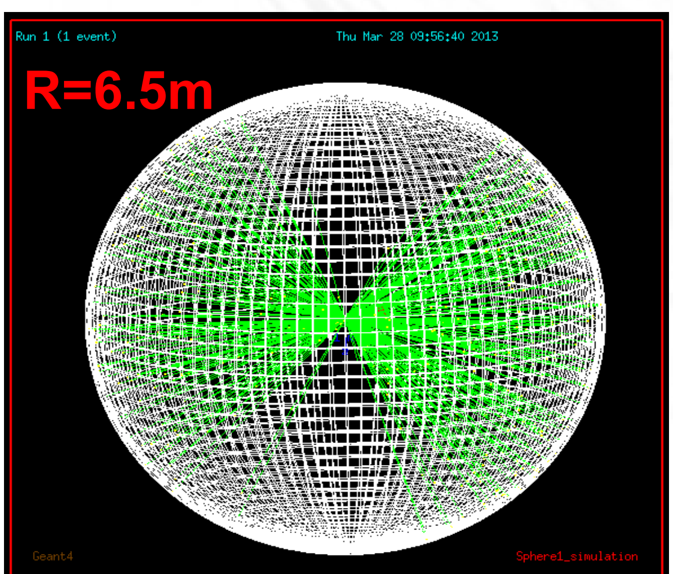


Cherenkov threshold for n=1.47

Cherenkov light



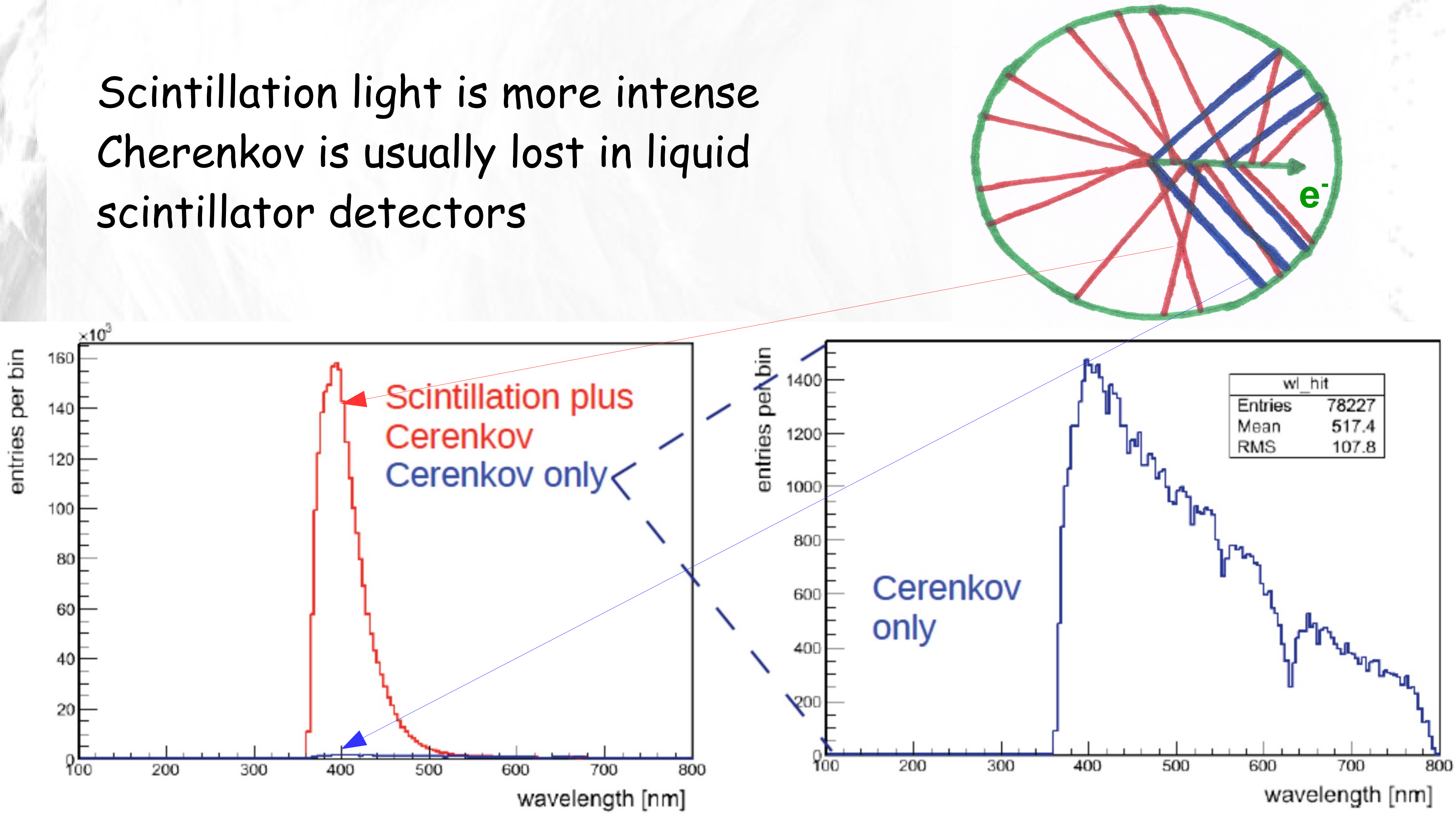
Simulation of ^{116}Cd $0\nu\beta\beta$ event



- Produced by a charged particle in a media whenever particle's speed exceeds the speed of light in that media
- Prompt
- Directional (e.g. ~42° for cosmic muons in water)

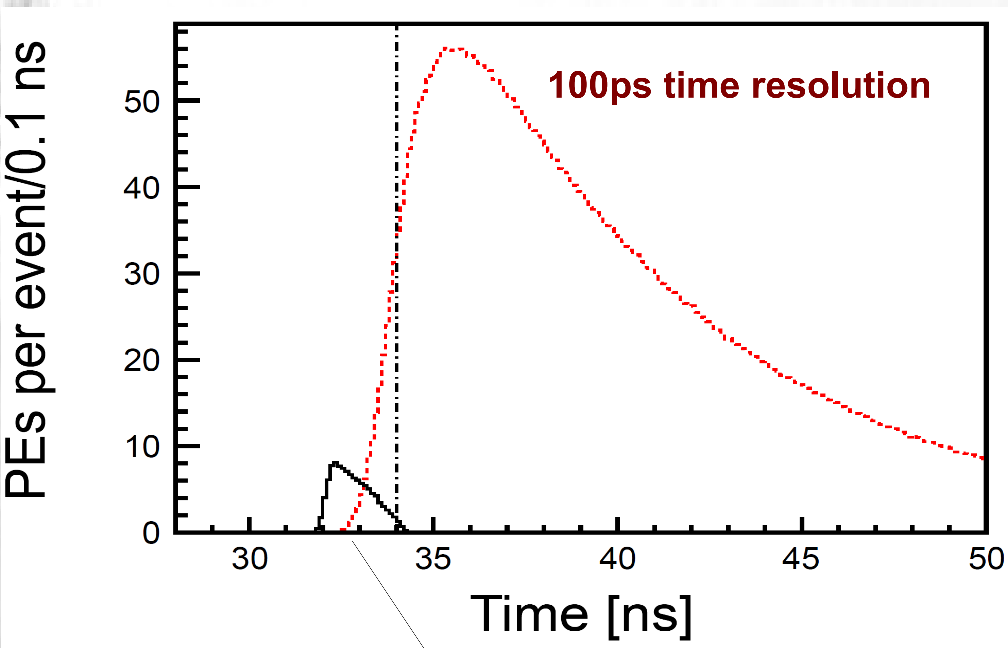
Can We Detect Cherenkov Light?

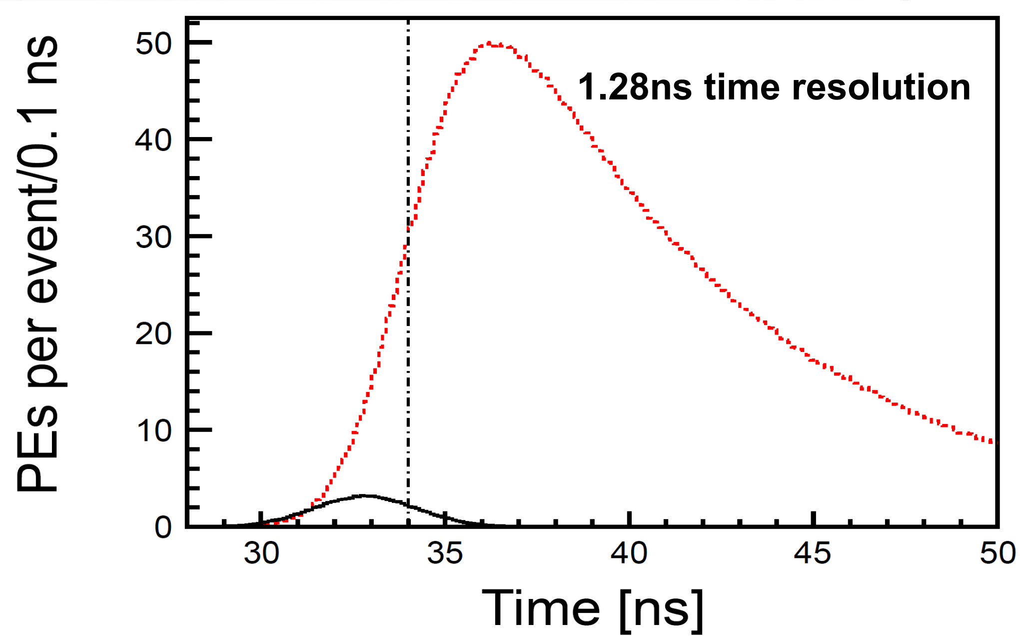
Scintillation light is more intense
Cherenkov is usually lost in liquid scintillator detectors

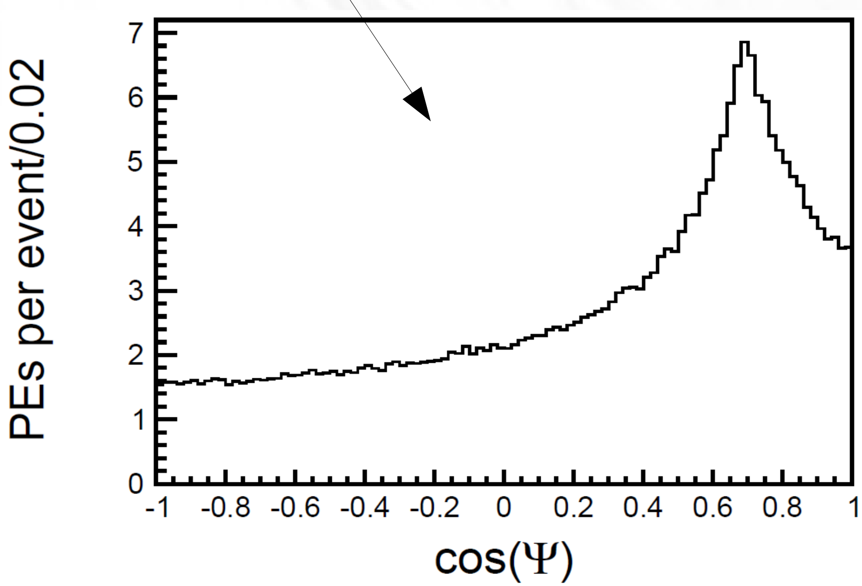


- Longer wavelengths travel faster
- Cherenkov light arrives earlier

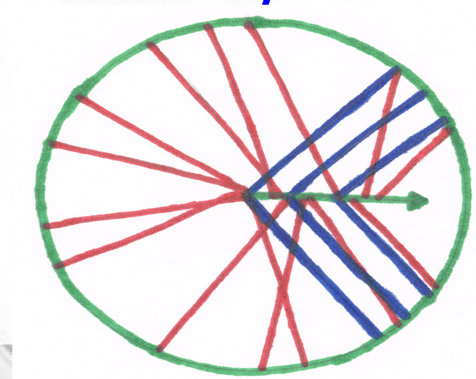
Use Early Light







Early light contains directionality information



First Step Towards a New Experiment

Measuring Directionality in Double-Beta Decay and Neutrino Interactions with Kiloton-Scale Scintillation Detectors

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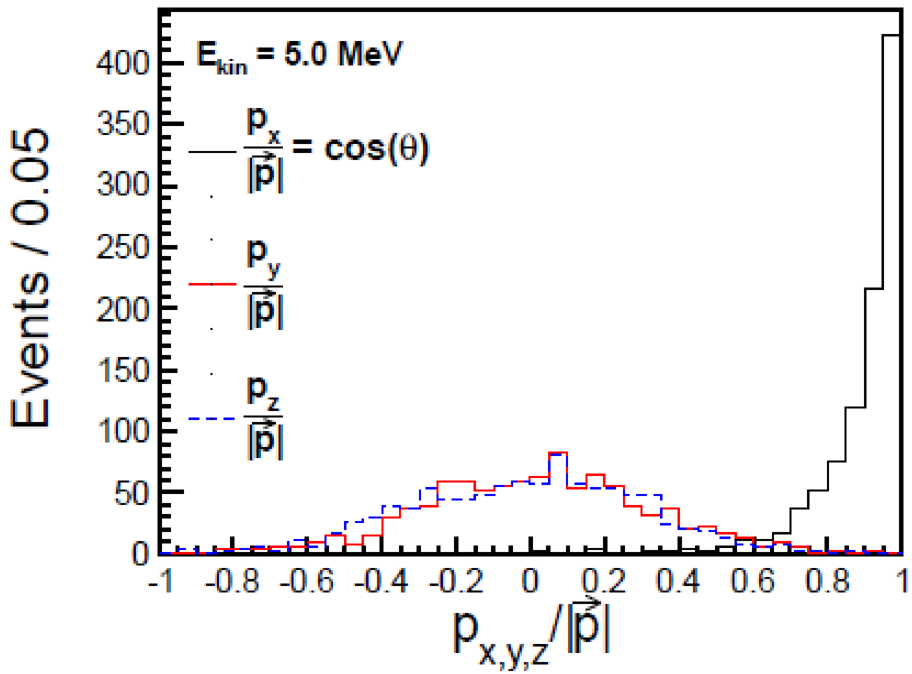
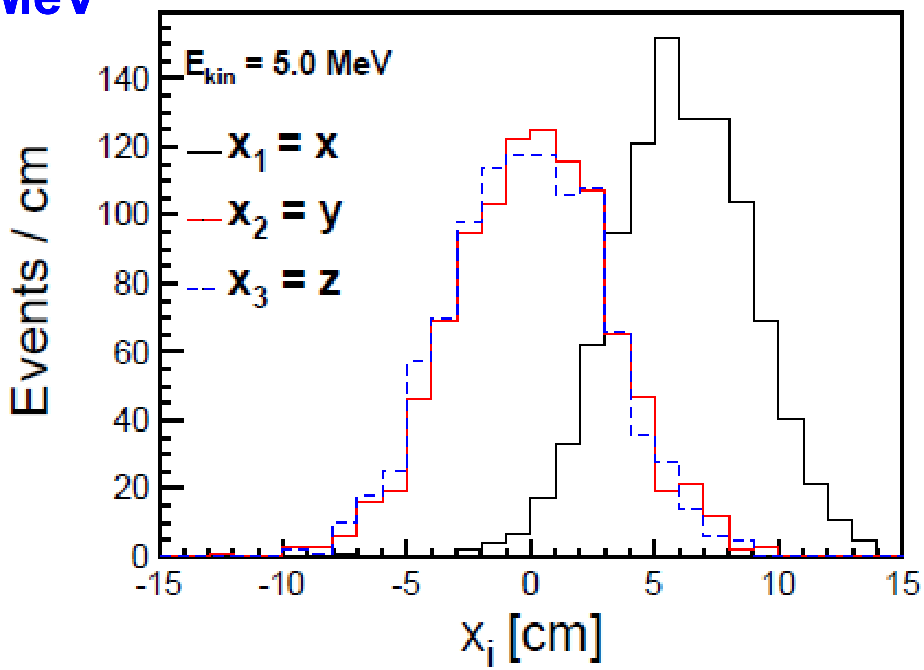
(Dated: July 23, 2013)

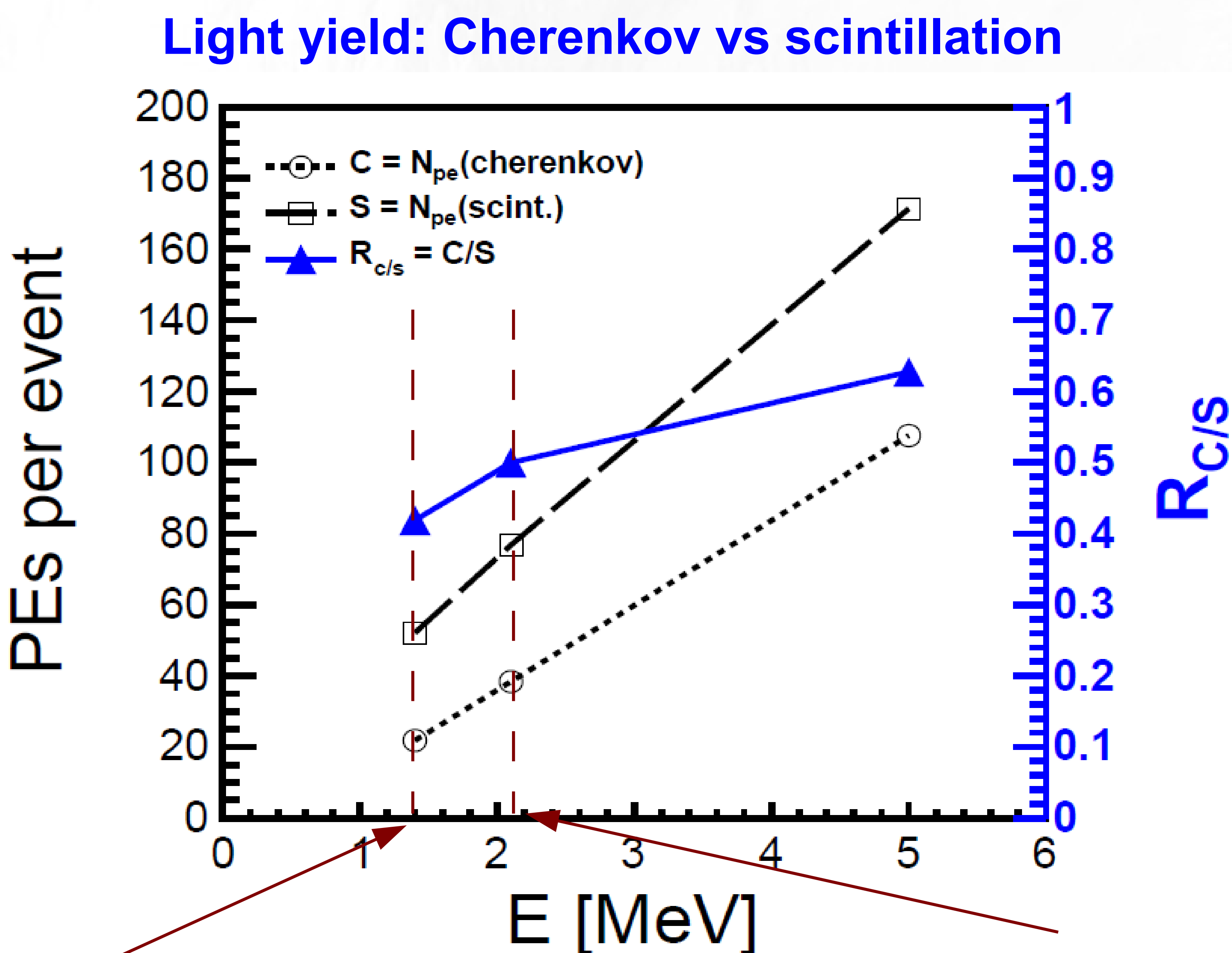
Large liquid-scintillator-based detectors have proven to be exceptionally effective for low energy neutrino measurements due to their good energy resolution and scalability to large volumes. The addition of directional information using Cherenkov light and fast timing would enhance the scientific reach of these detectors, especially for searches for neutrino-less double-beta decay. In this paper, we develop a technique for extracting particle direction using the difference in arrival times for Cherenkov and scintillation light, and evaluate several detector advances in timing, photodetector spectral response, and scintillator emission spectra that could be used to make direction reconstruction a reality in a kiloton-scale detector.

5.0 MeV





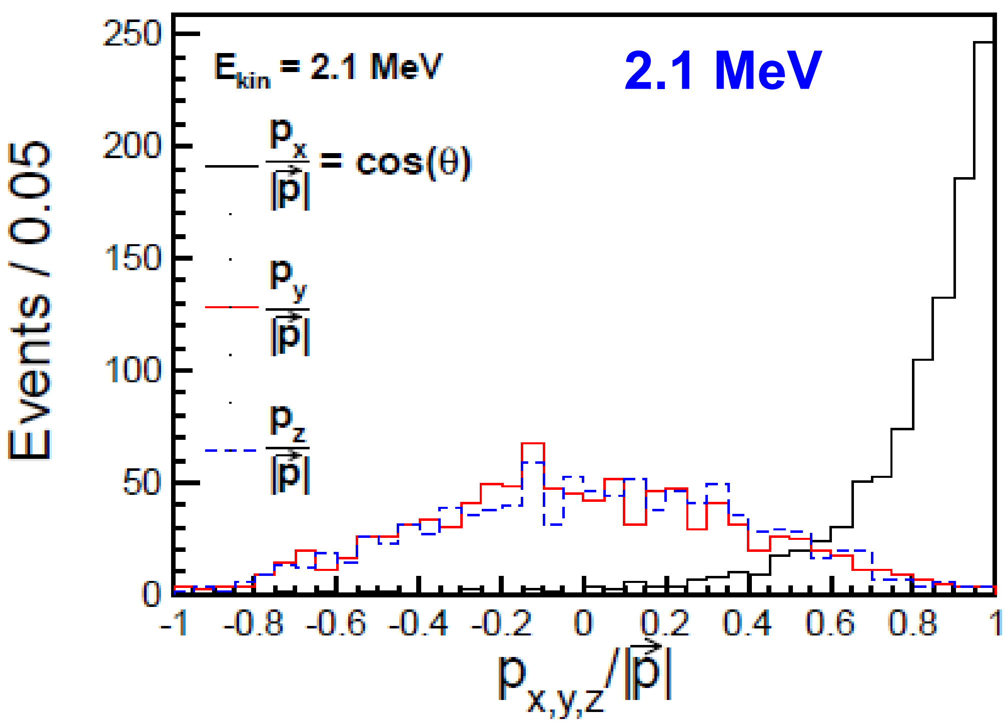
What About Lower Energies?

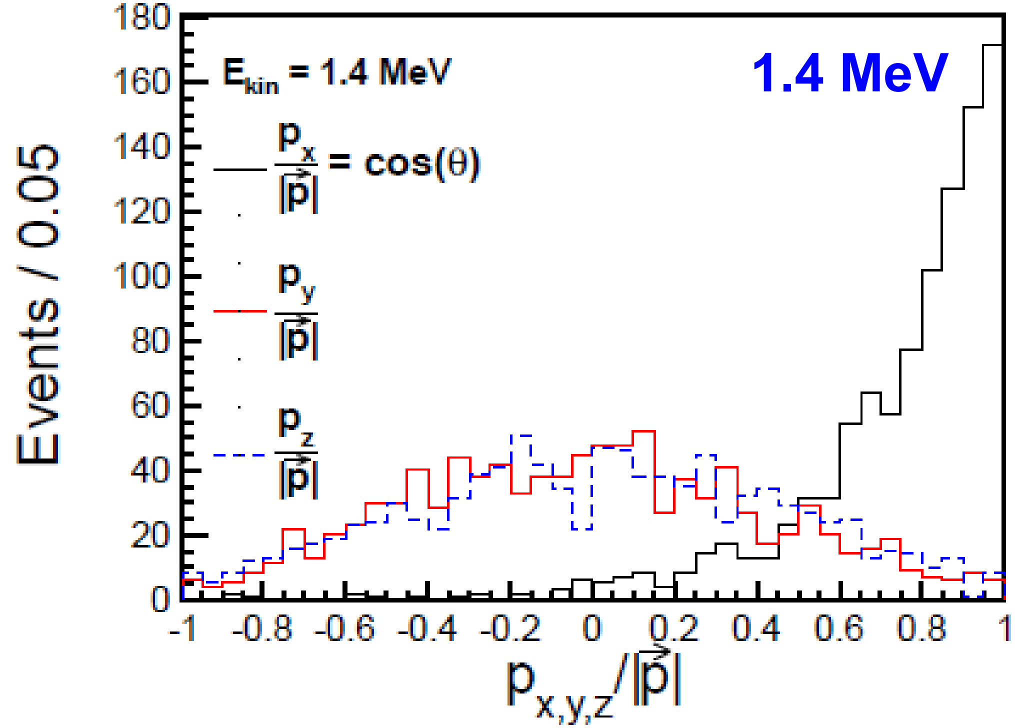


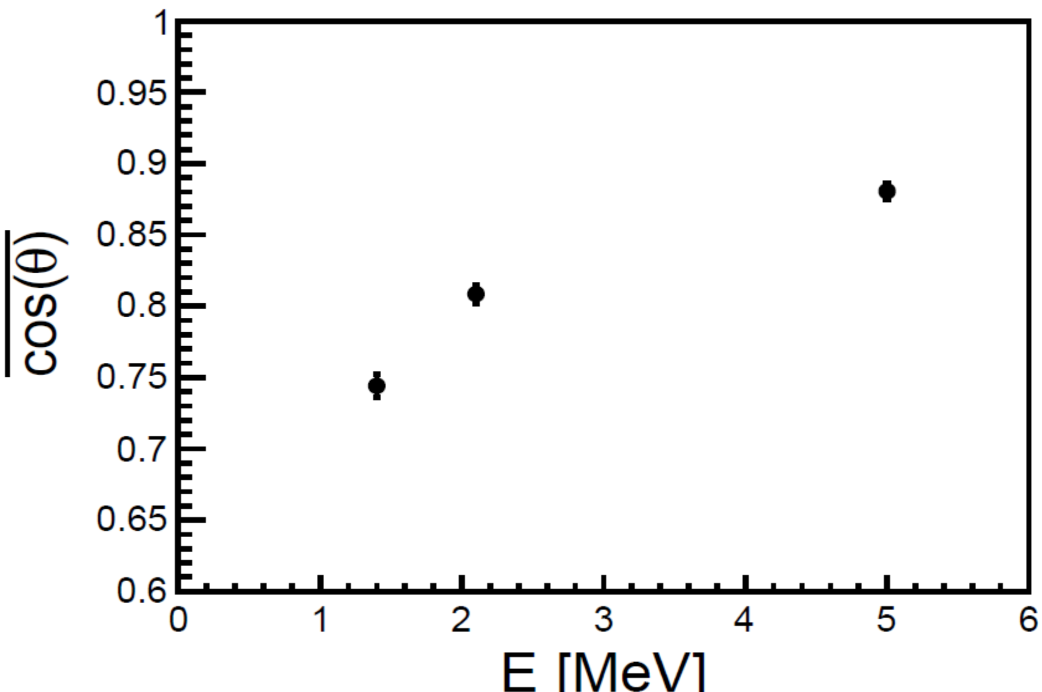
½ Q (^{116}Cd) =1.4 MeV

½ Q (^{48}Ca) =2.1 MeV

What About Lower Energies?







With 100ps timing the vertex is constrained within ~6 cm and the directional information can be extracted even for ~1MeV electrons

Summary

Large detector mass is required to search for neutrino-less double beta decay
- liquid scintillator detectors scale well to large masses

We propose to use Cherenkov light to reconstruct double beta decay event topology in a kilo-ton liquid scintillator detector
- double beta decay electrons are above Cherenkov threshold
- Cherenkov light travels faster than scintillation light
- early light contains directional information

Fast Photo-Detectors with TTS of ~100ps are needed to separate Cherenkov from scintillation light (see slides/posters by the LAPPD team for an example of such photo-detector)