Directional Liquid Scintillator Detector

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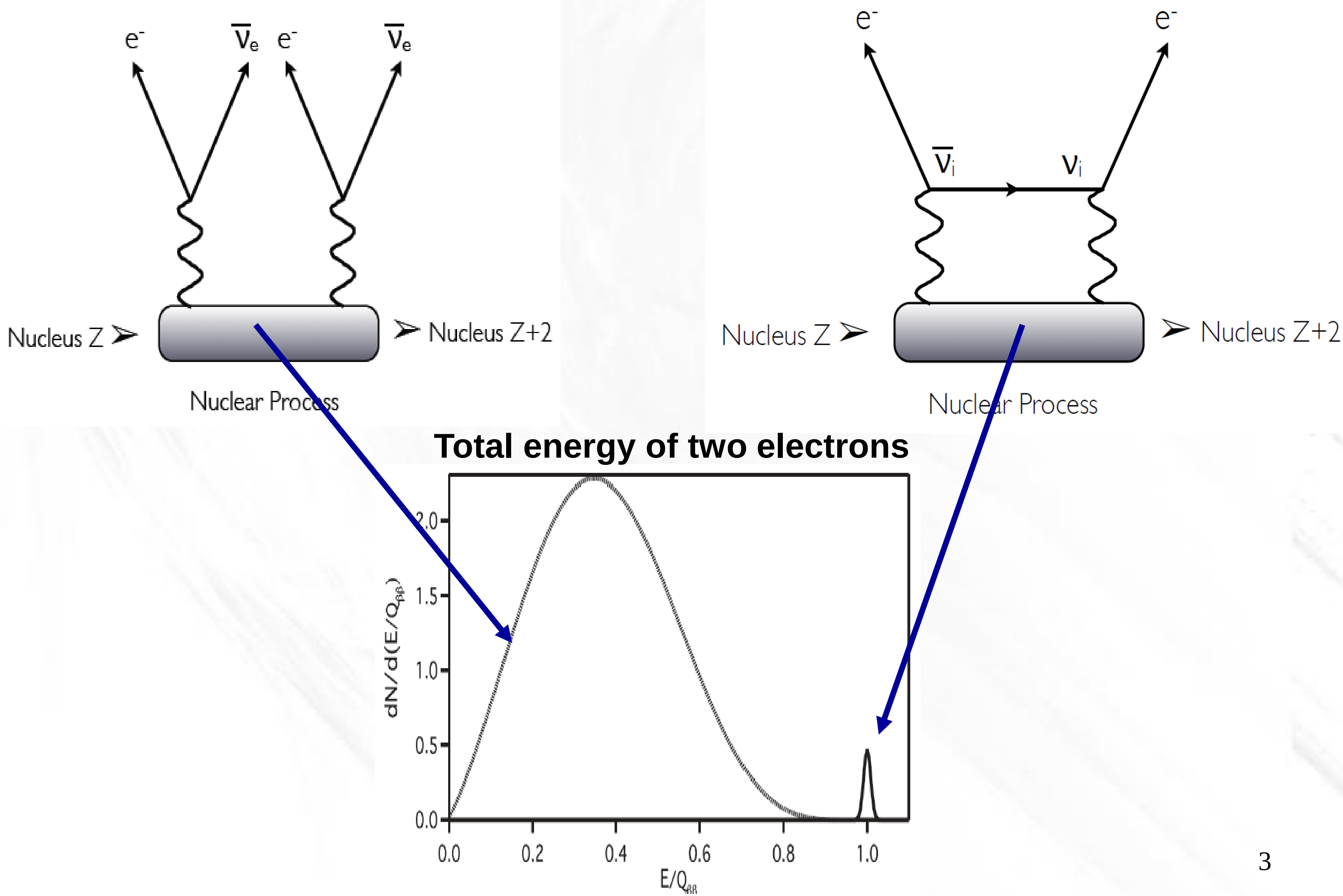
Outline

- Motivation – $0\nu\beta\beta$-decay
- Event topology reconstruction by Cherenkov/scintillation light separation
- NuDot – 1m^3 prototype of directional LS detector
  - work done by MIT/UCLA L. Winslow group:
  D. Gooding (MIT), B. Naranjo (UCLA), J. Ouellet (MIT), R. Schofield (UCLA), L. Winslow (MIT), T. Wongjirad (MIT)

Double Beta Decay



Search for neutrino-less double beta decay (0νββ-decay) is the most feasible way to determine if the neutrino is its own antiparticle

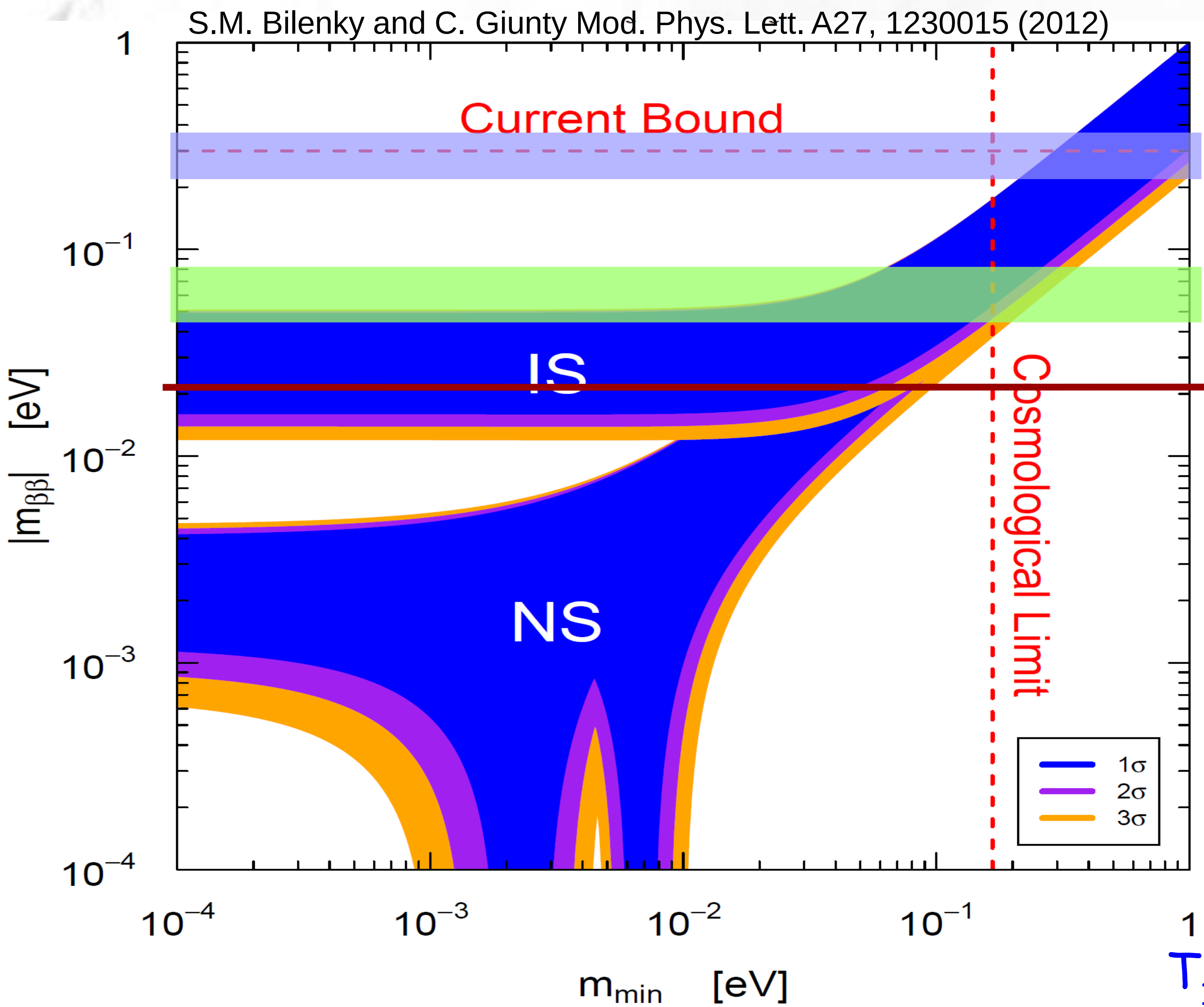
How to Find 0νββ-decay?

1) Choose isotope where 0νββ-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

Experimental Sensitivity



Limits by
EXO (~200kg ^{136}Xe)
KamLAND-Zen (~300 kg ^{136}Xe)
GERDA (~20 kg ^{76}Ge)

Projections by
CUORE (~200kg ^{130}Te)
SNO+ (0.8 ton ^{130}Te)

SNO+ (8 ton ^{130}Te)

Assuming that light neutrino exchange is the dominant 0νββ-decay mechanism

$T_{1/2}^{-1} = G^{0\nu} \times |M^{0\nu}|^2 \times m_{\beta\beta}^2$

Getting down to $m_{\beta\beta}$~10^{-3} eV is very difficult

Why is it difficult?

- Need very large mass

  - could be a few events per year even in a kilo-ton scale detector

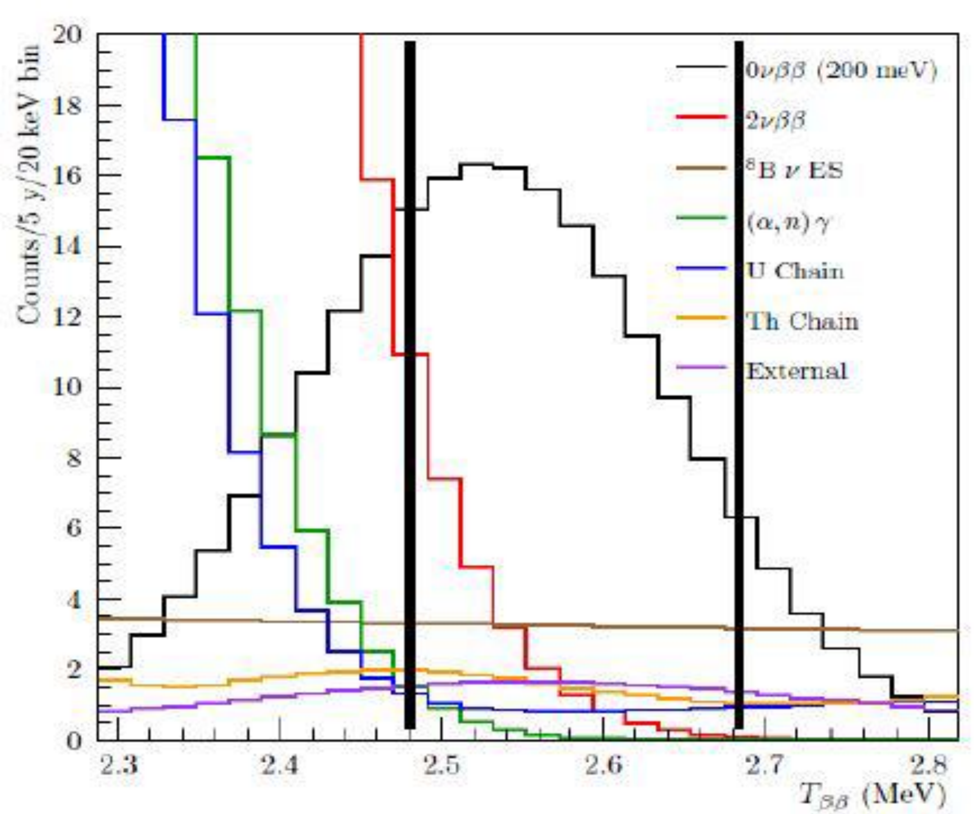
- Need "zero" background

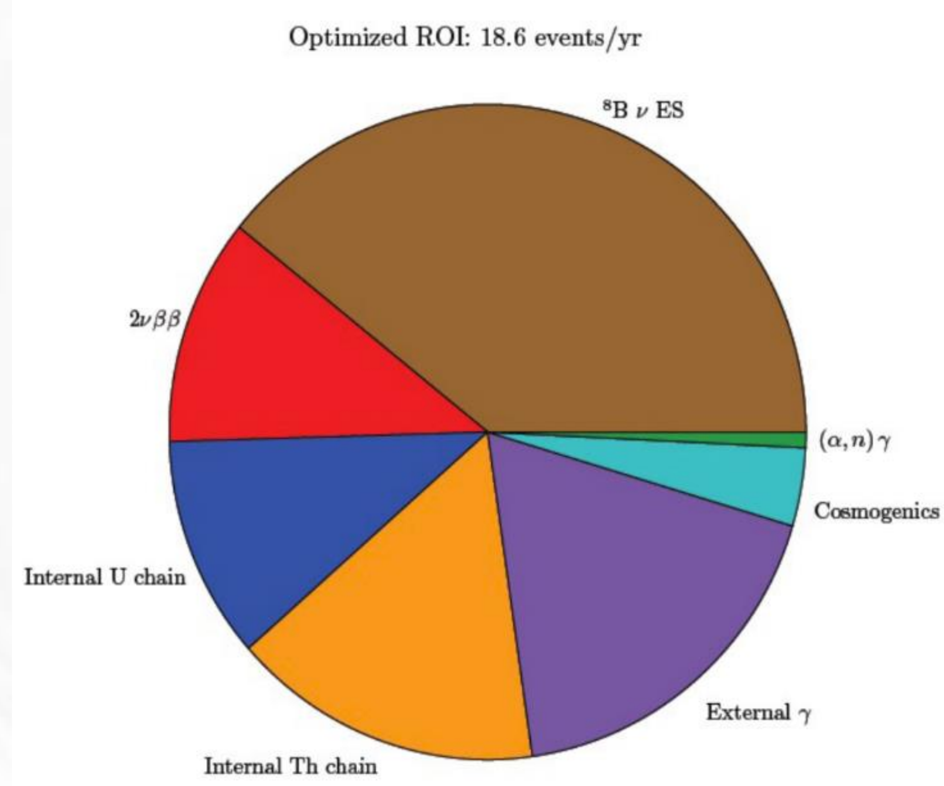
  - high purity
  - good energy resolution
  - good particle ID and event topology reconstruction at ~1 MeV

- Liquid scintillator detectors scale well to very large masses

  - purification and self-shielding may allow for "zero" reducible background
  - high light yield and collection efficiency may allow for low $2\nu\beta\beta$ background
  - ^{8}B solar neutrino becomes dominant background
    - nearly flat energy spectrum around Q-value
    - this is irreducible background without event topology reconstruction

Background Budget at SNO+





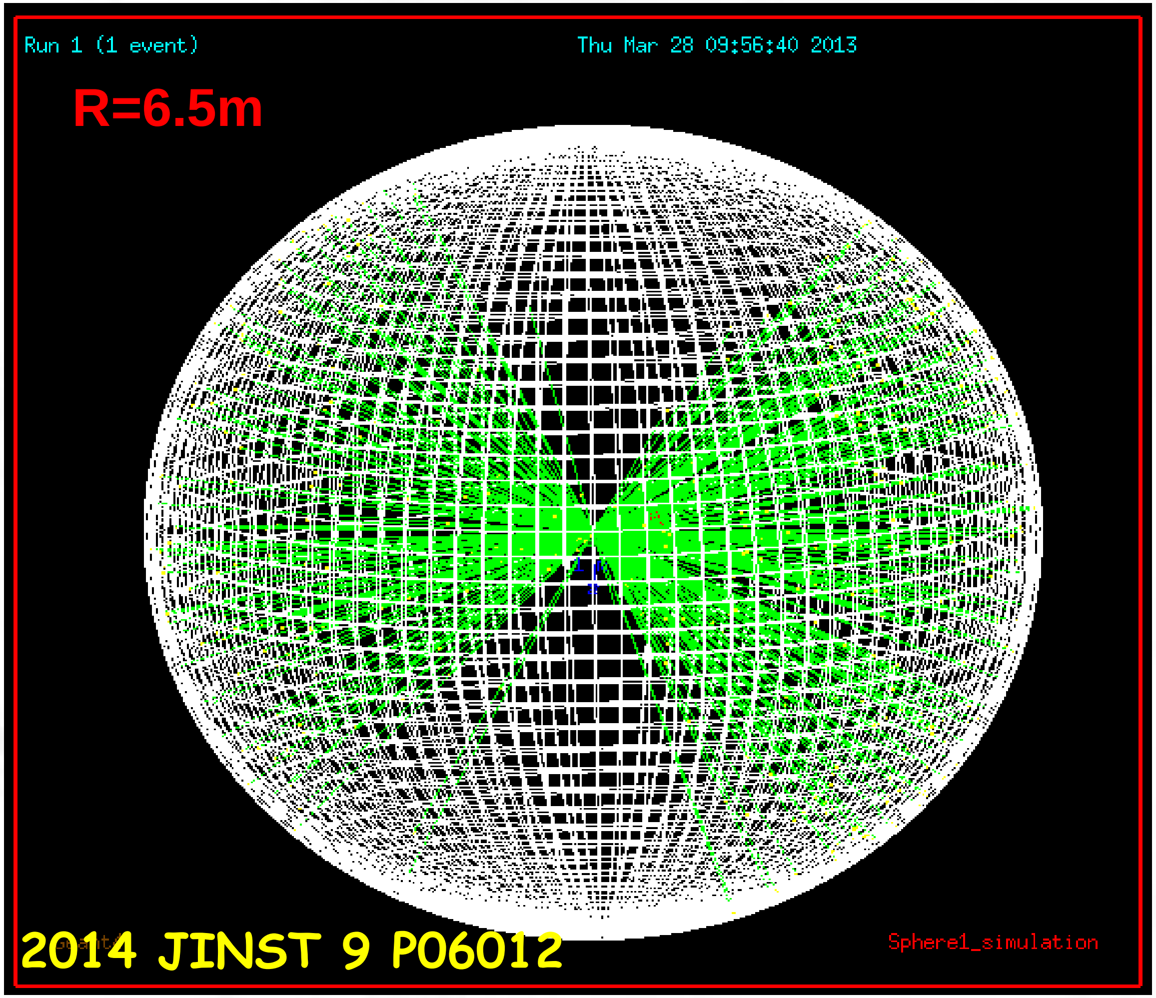
The largest background is coming from ^{8}B solar neutrinos
It has only 1 electron, while $\nu\beta\beta$-decay has 2 electrons

Is it possible to separate two-track and one-track events using Cherenkov light in a liquid scintillator detector?

Figures are borrowed from SNO+ presentations

Can We See This?

Simulation of a back-to-back $0\nu\beta\beta$ event

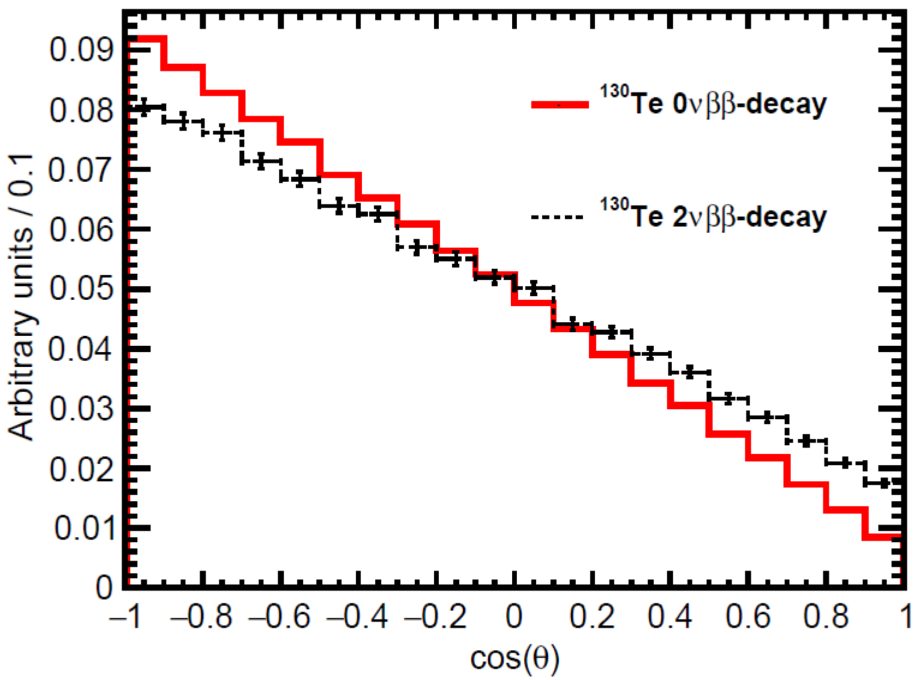


- I started thinking about this in 2012 in the context of new applications for LAPPD
- I think it's quite possible to reconstruct $0\nu\beta\beta$-decay event topology in a large liquid scintillator detector using fast timing
- It will take very challenging instrumentation development

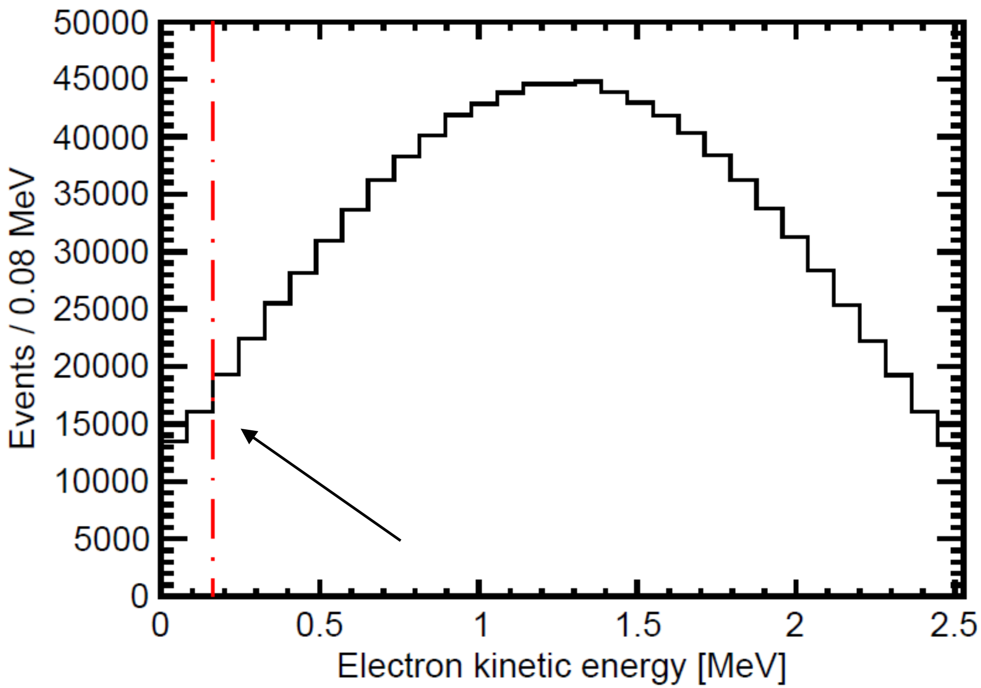
Double beta decay kinematics

- Distinct two track topology with preference to be back-to-back
- Electrons are above Cherenkov threshold

Angle between two electrons



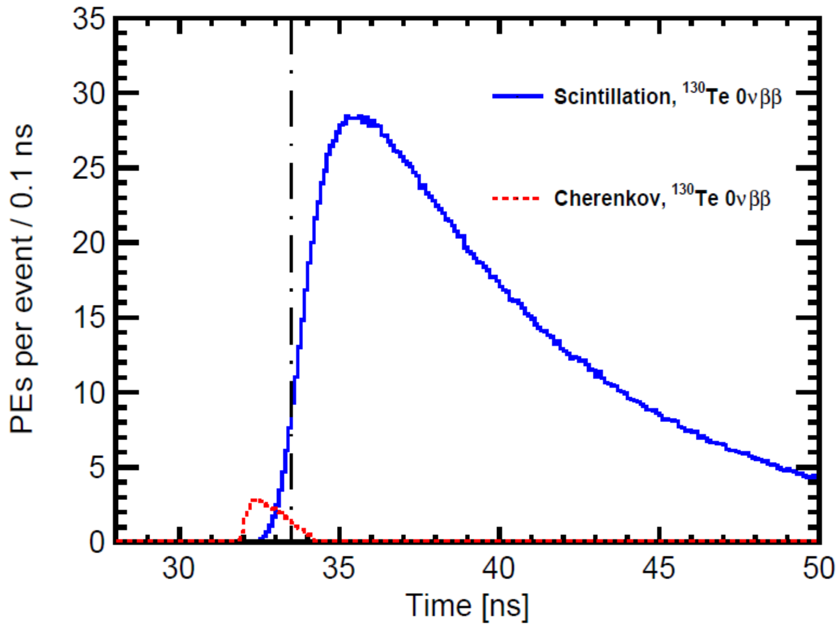
Kinetic energy of each electron



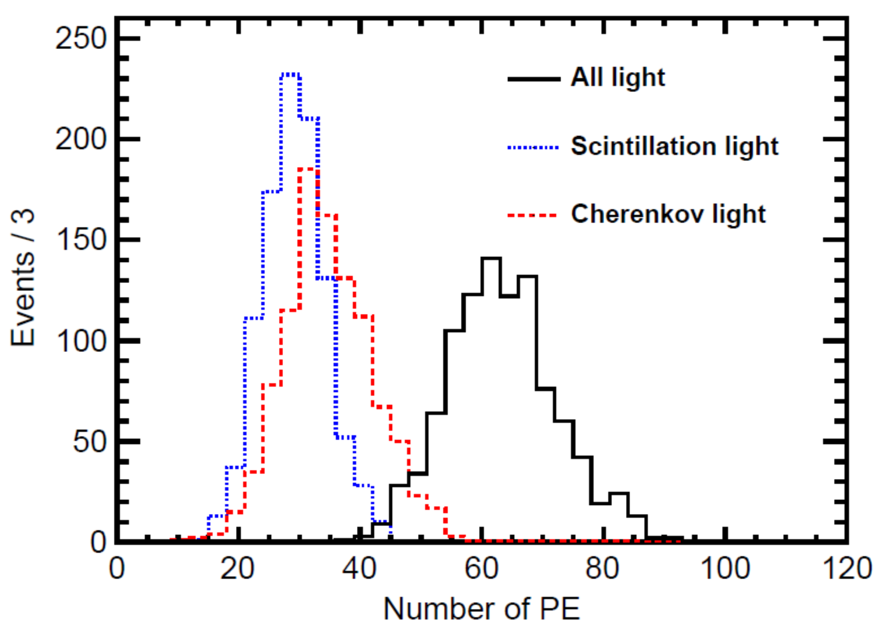
What about scintillation light?

- Scintillation is "slow" compared to Cherenkov
  - Cherenkov emission is prompt
  - red tail of Cherenkov photons travels faster
- Early light is directional due to Cherenkov component

PE arrival times

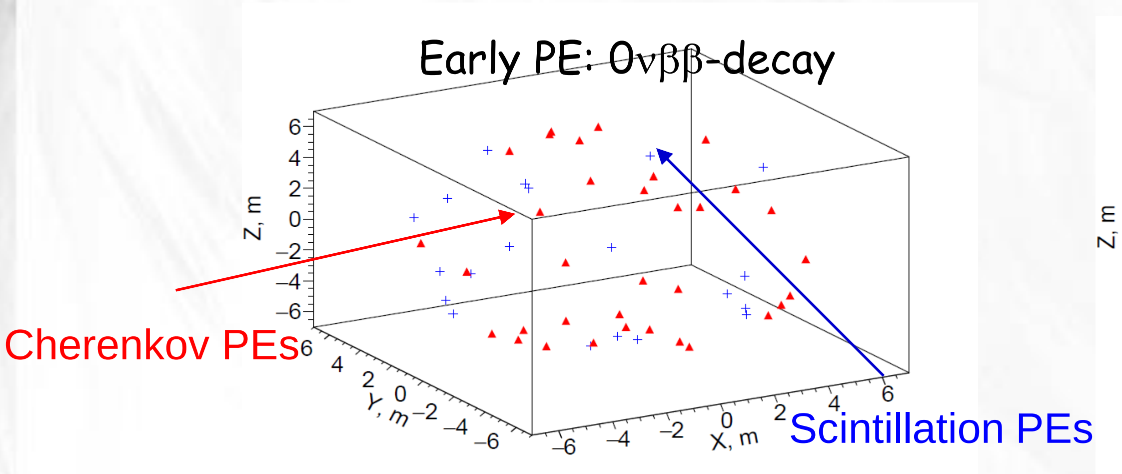


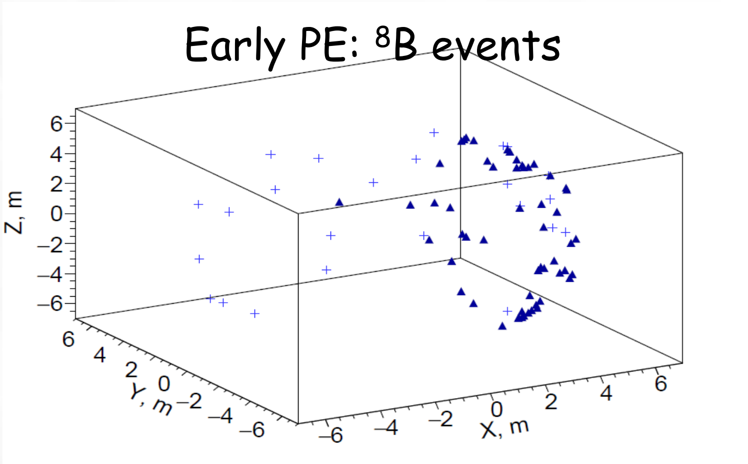
Early PE sample



Early Light Topology

- A good pattern recognition algorithm should pick up the difference between two track and one track topologies
- E.g., a spherical harmonics analysis can separate signal and background on a statistical basis
  - see arXiv:1609.09865 for details (submitted to NIM)



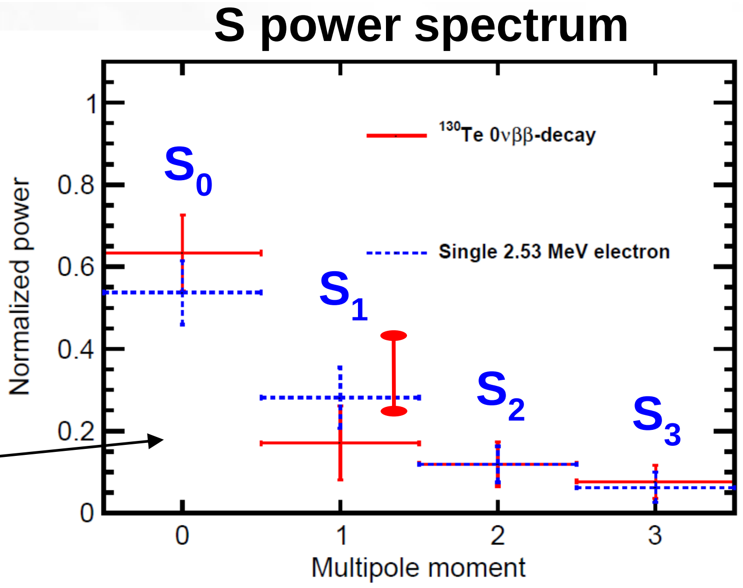


Spherical harmonics analysis

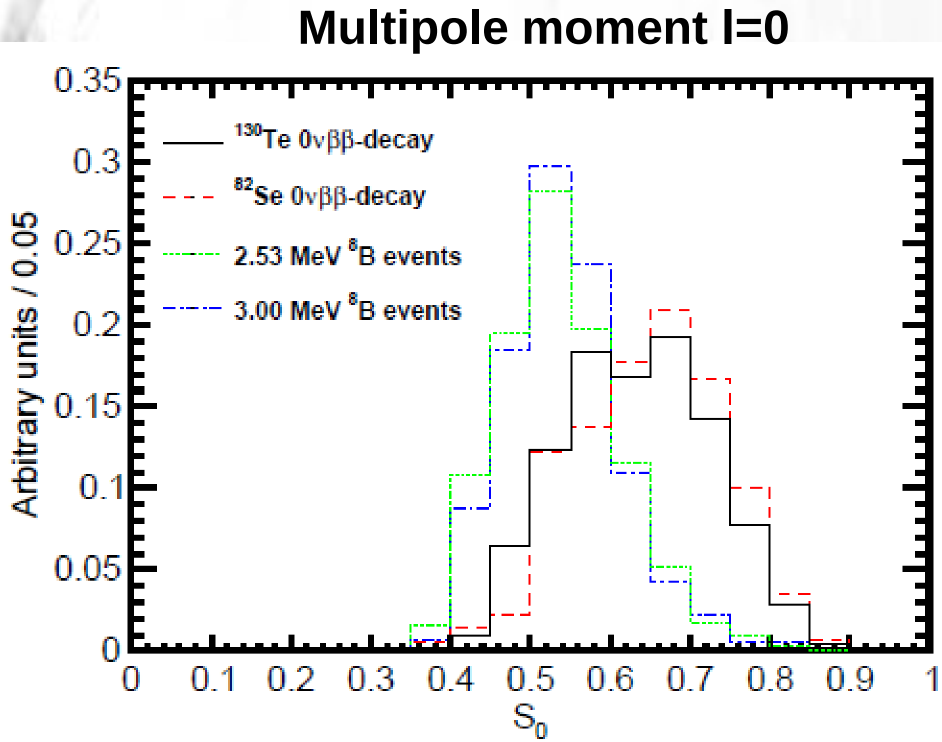
$$f(\theta, \varphi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} f_{\ell m} Y_{\ell m}(\theta, \varphi).$$

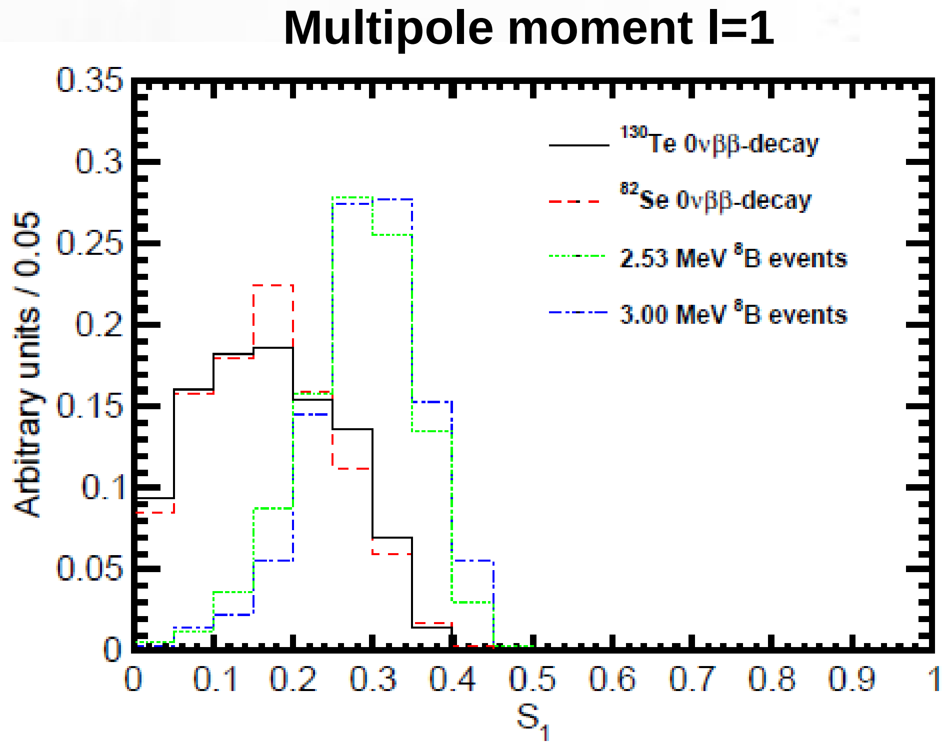
Rotation invariant power spectrum

$$S_{ff}(\ell) = \sum_{m=-\ell}^{\ell} |f_{\ell m}|^2$$



$0\nu\beta\beta$ vs ^8B





Simulation details:

- 6.5m radius detector, scintillator model from KamLAND simulation
- TTS=100 ps, 100% area coverage, QE(che) ~12, QE(sci) ~23%

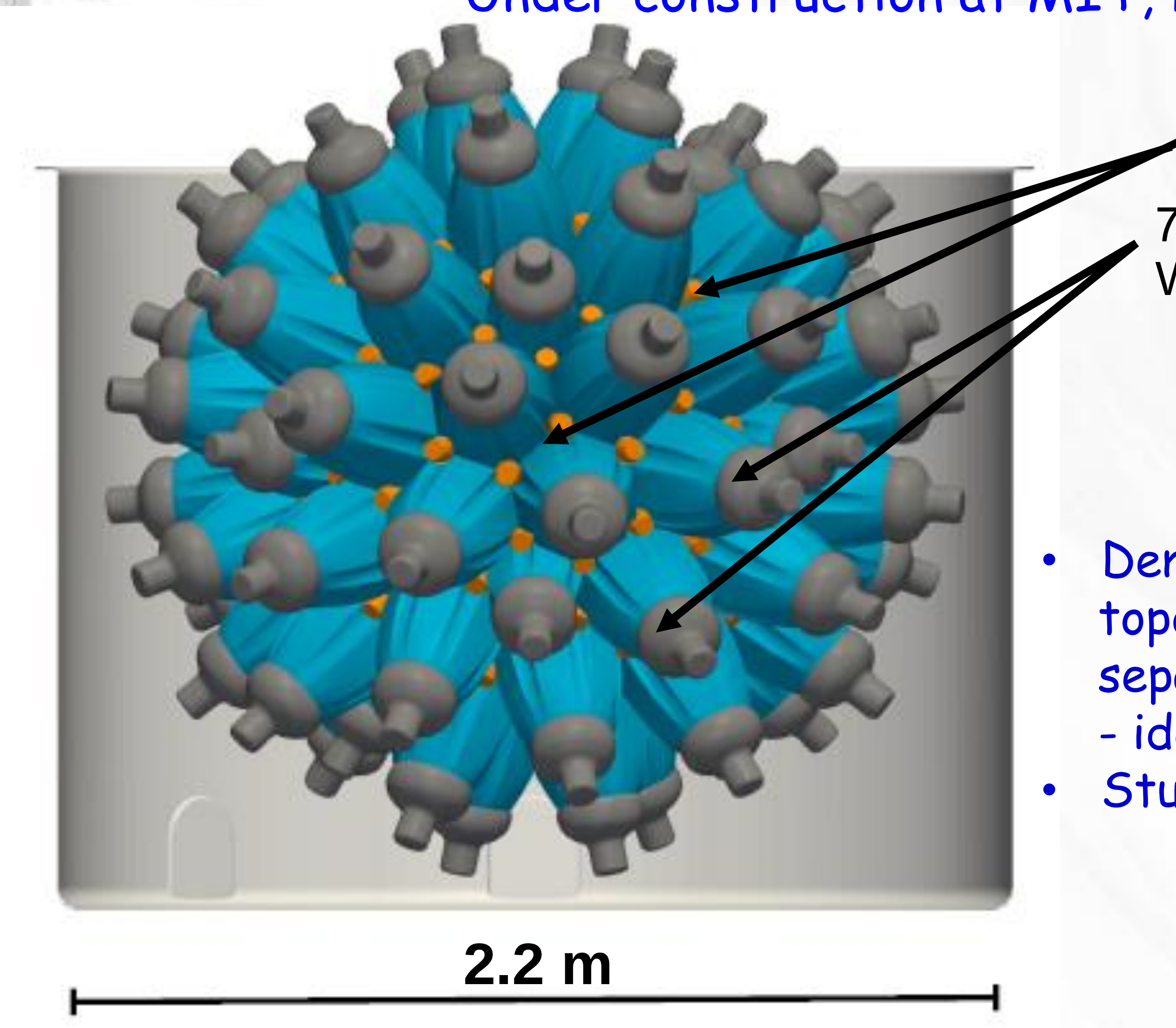
Key parameters determining separation of $0\nu\beta\beta$-decay from ^8B:

- Scintillator properties (narrow spectrum, slow rise time)
- Photo-detector properties (fast, large-area, high QE)
- Measuring photon color and timing with high precision would be even better…

NuDot - Directional Liquid Scintillator

R&D Towards Large Scale Detector for 0$\nu\beta\beta$-decay

Under construction at MIT, led by L. Winslow

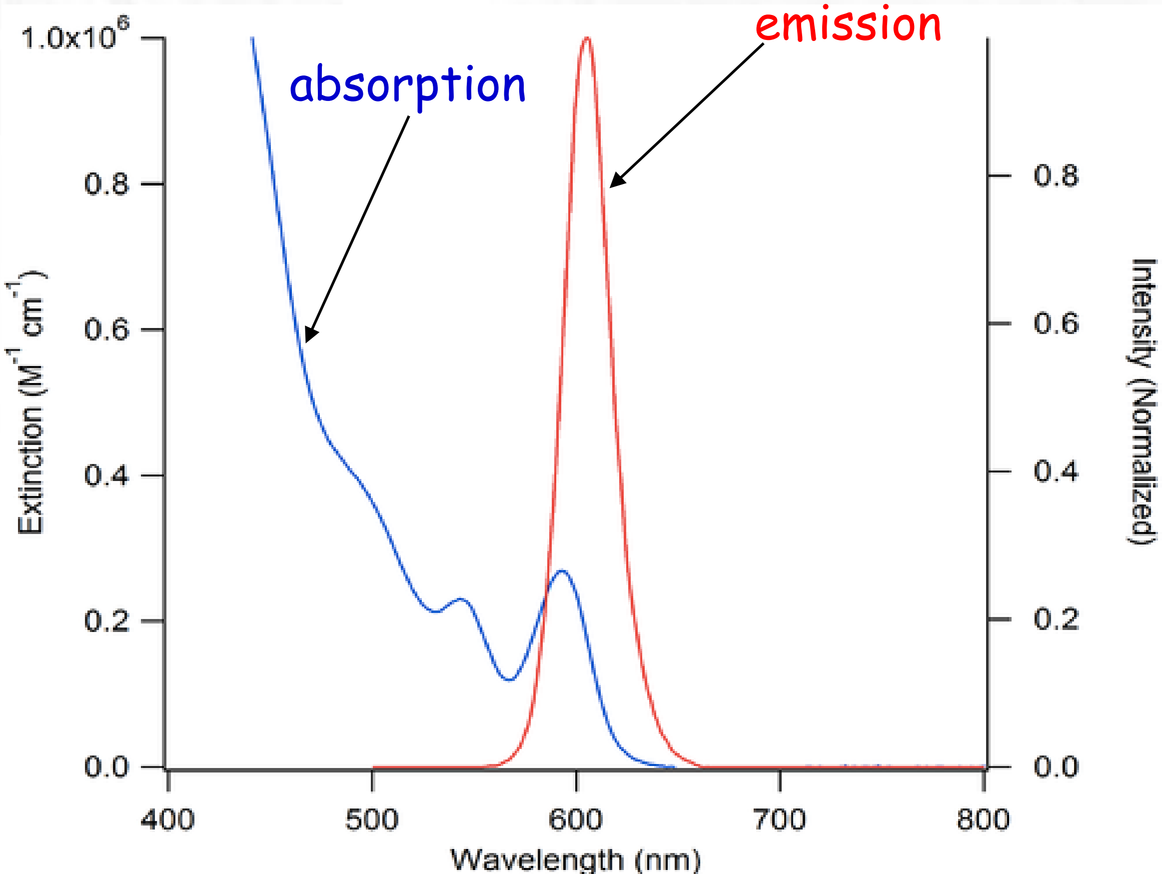


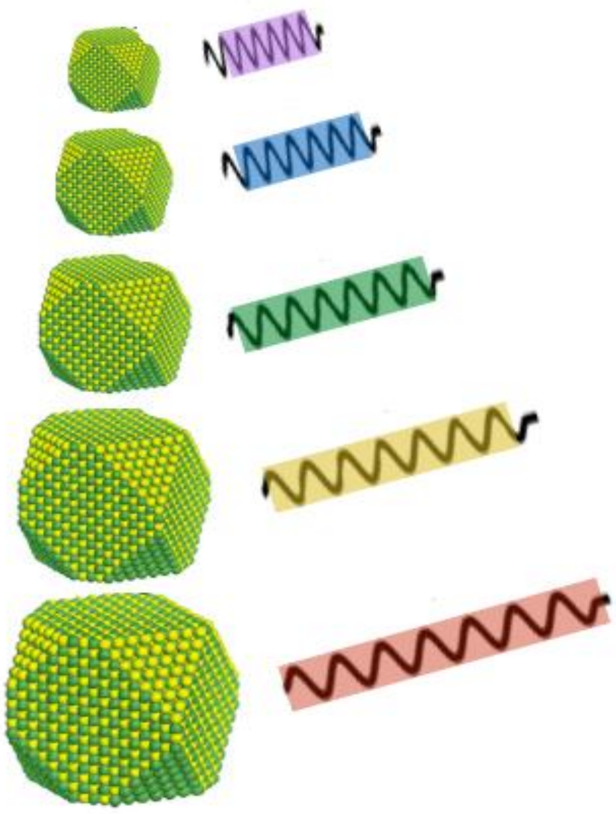
Goals

- Demonstrate directionality and event topology reconstruction using che/sci separation by fast timing
  - ideally by measuring 2$\nu\beta\beta$-decay
- Study scintillators, including quantum dots

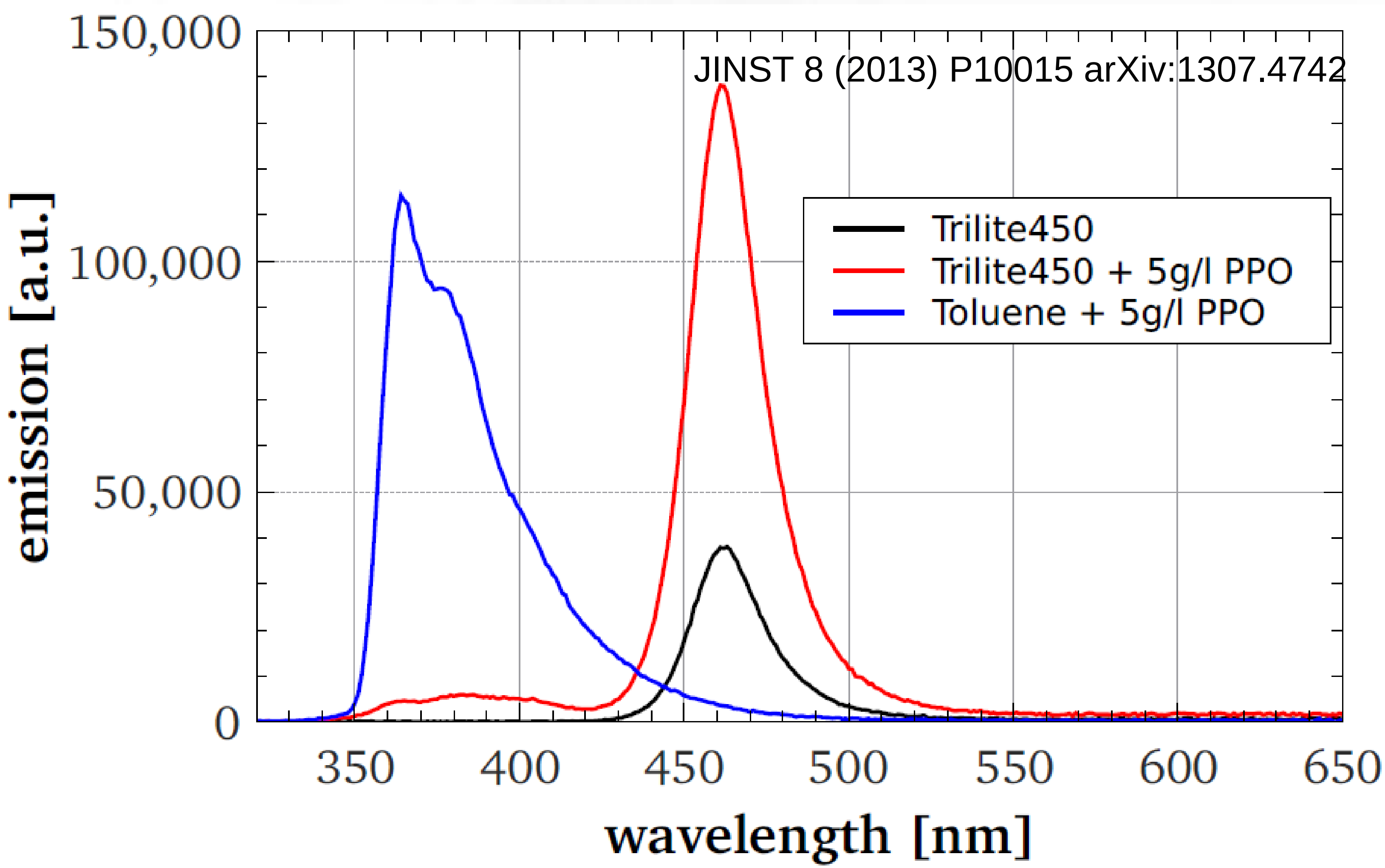
What Are Quantum Dots?

- Q-dots are nanocrystals of semiconductor with interesting optical properties
- Common crystals are CdS, CdSe, CdTe – interesting for $\nu\beta\beta$-decay
- Q-dots can be suspended in organic solvents and water





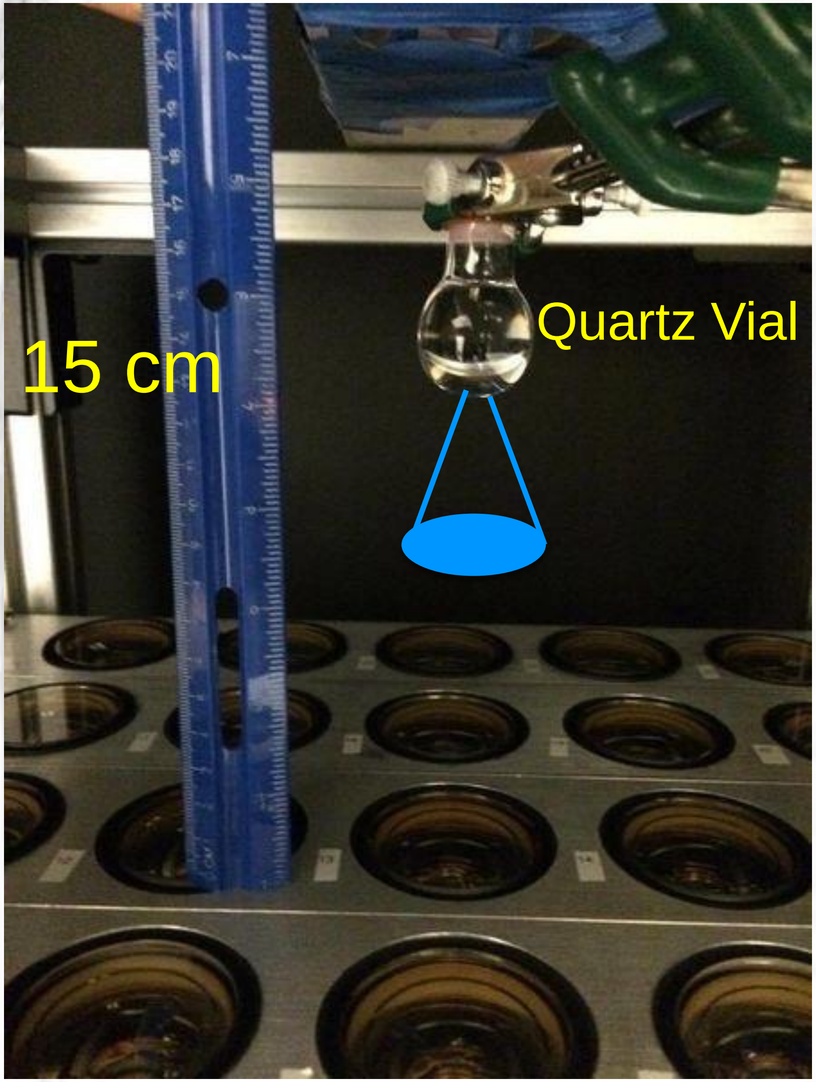
Q-dots



- Optical properties and 0νββ-decay compatibility are very interesting
- Still quite expensive
- More in-depth R&D is needed to evaluate potential of Q-dots

FlatDot Demonstration

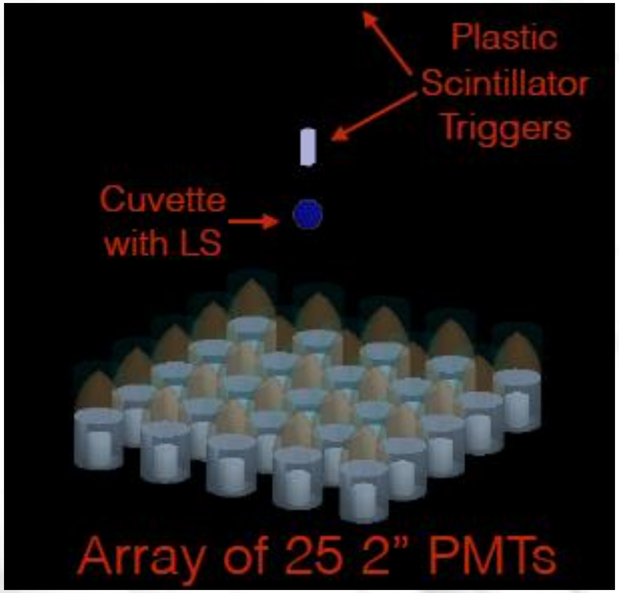
A grid of 5x5 PMTs (2", TTS 300ps)



Goals

- Intermediate step towards 1m3 spherical NuDot
  - e.g. detection of Cherenkov "rings" from low energy electrons using a tagged Compton source
- Testing different scintillator cocktails
- Readout testing

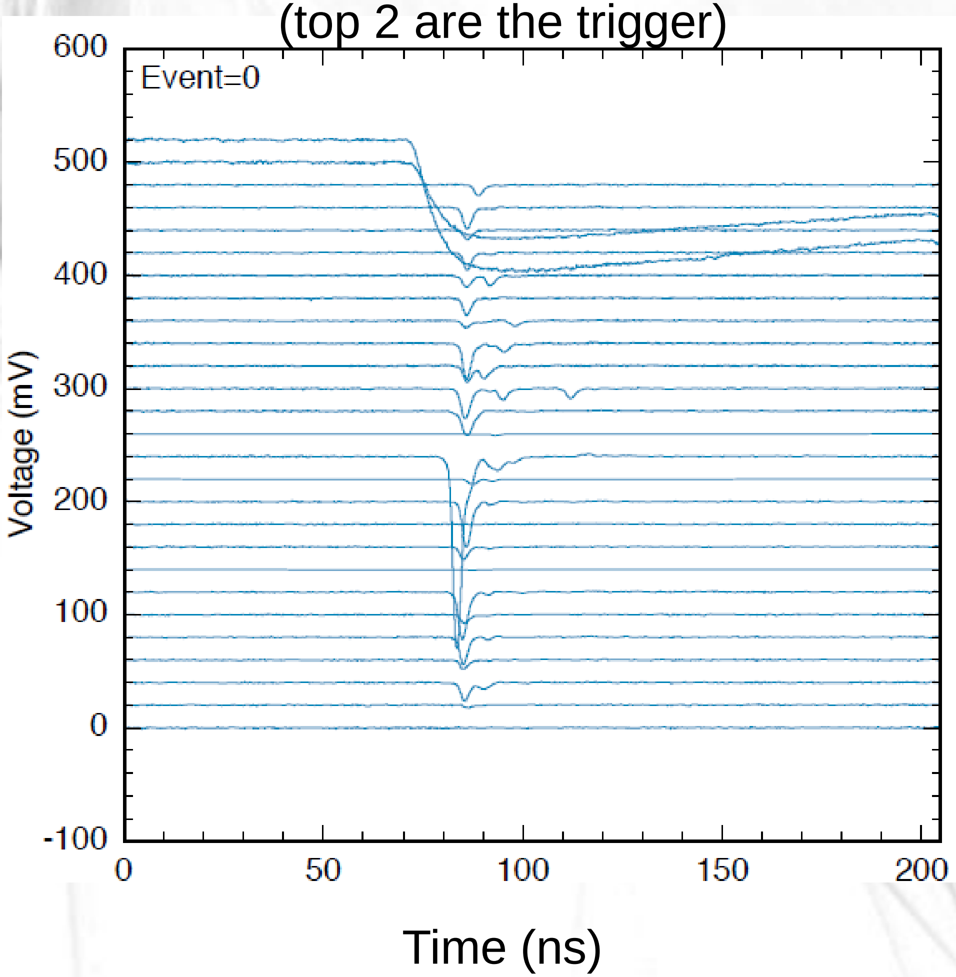
Geant-4 based MC



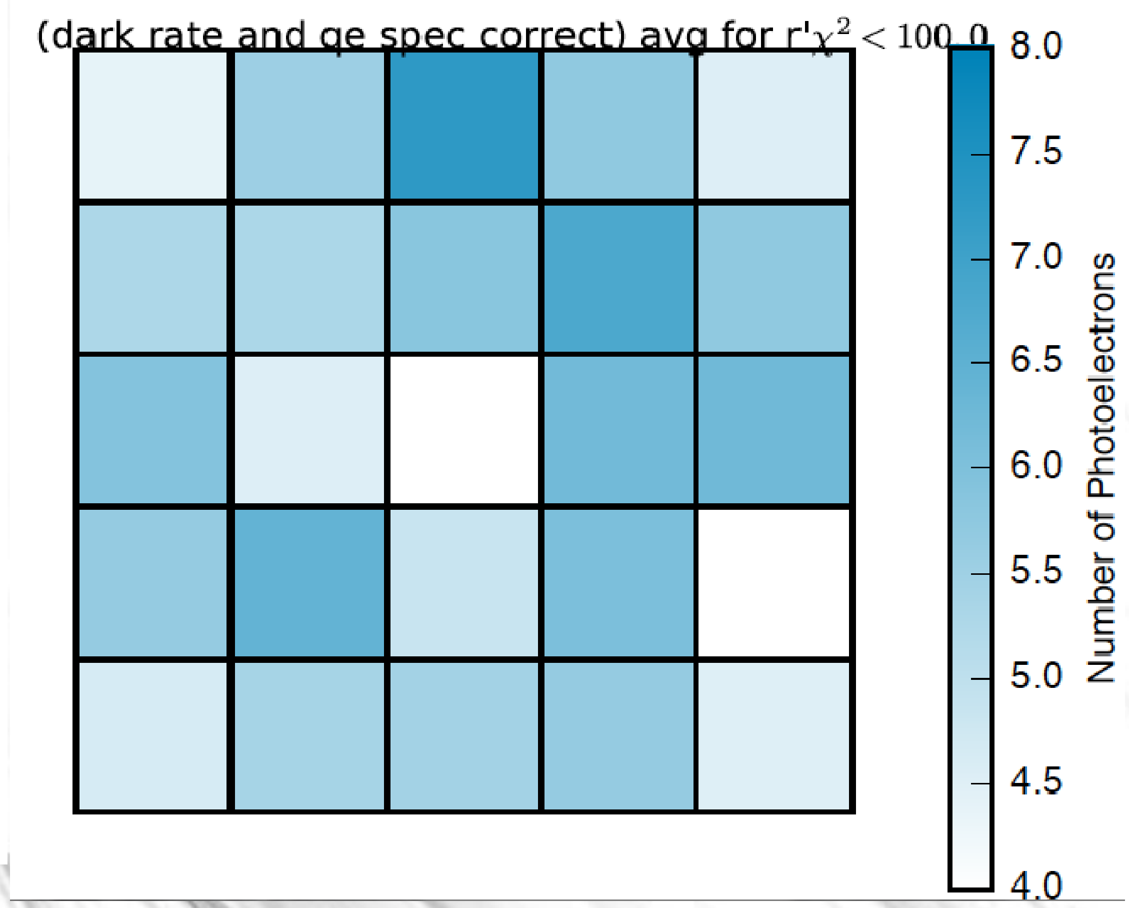
FlatDot Status

- Commissioned with cosmic muons
- Trigger using plastic scintillators with SiPMs
- Currently pure toluene, adding PPO next
- Simulation of the setup works too

Raw pulses from DRS-4
(top 2 are the trigger)



Event display after corrections



Summary

Dirac/Majorana nature of the neutrino is a fundamental question

Search for $0\nu\beta\beta$-decay is the most feasible approach to answer this question

Very large detector mass (kilo-ton) is required to probe small $m_{\beta\beta}$

^{8}B solar neutrinos become dominant background - traditionally viewed as irreducible

Directionality and event topology provide handles on ^{8}B and other backgrounds

Detector R&D is on going to demonstrate event topology reconstruction using Cherenkov/scintillation light separation