High Energy Analysis at KamLAND and Application to Dark Matter Search

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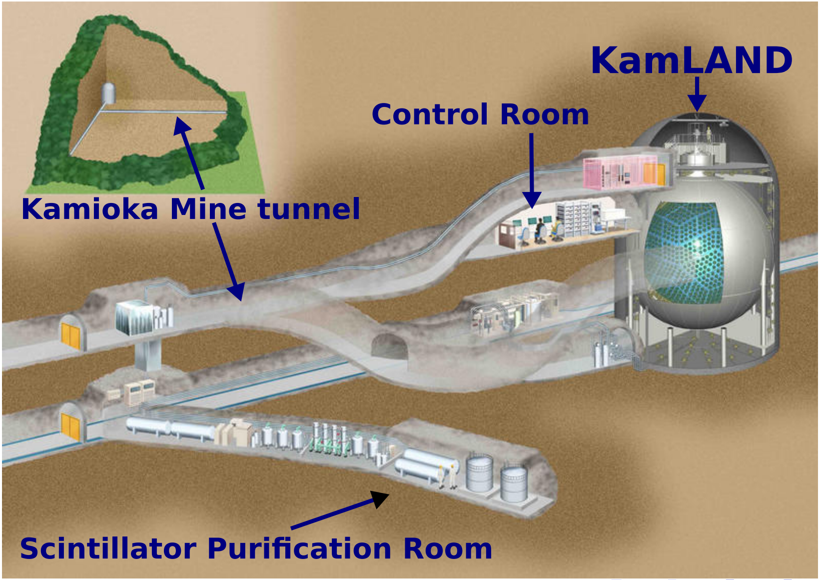
Overview

KamLAND: ν detector in Japan



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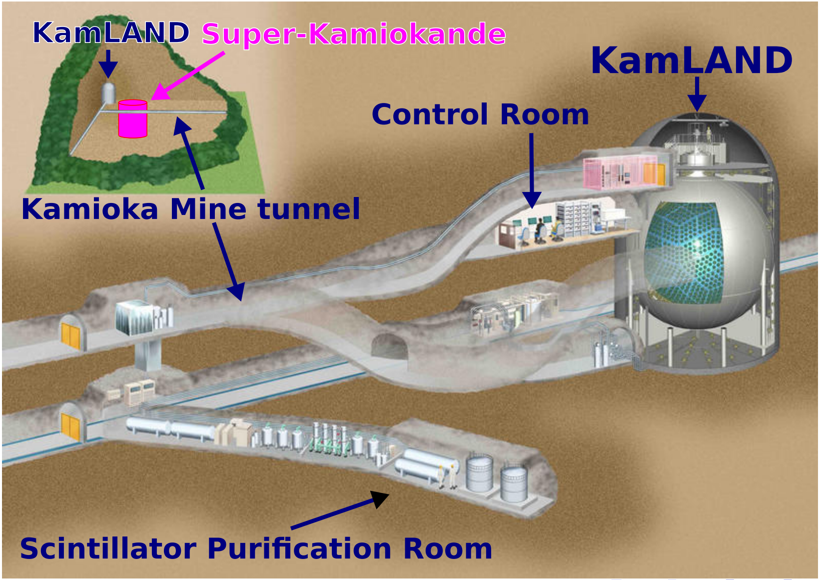

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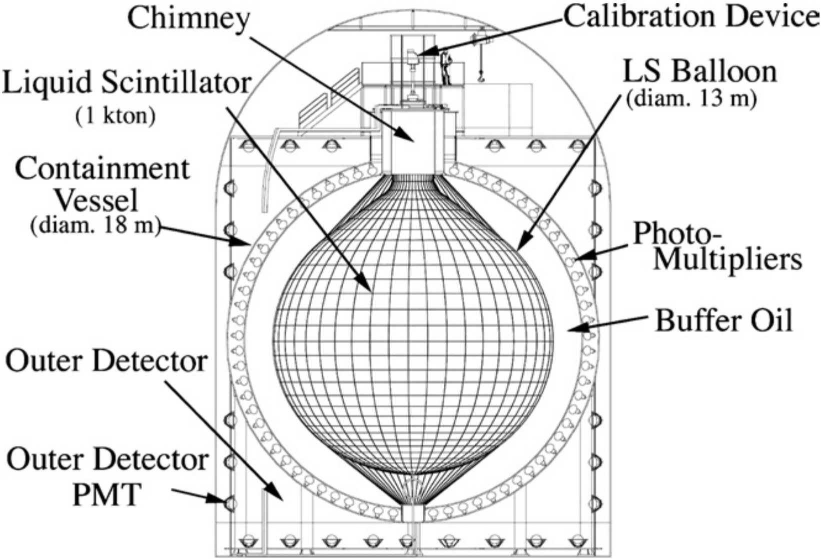

KamLAND: features

- Commissioned: 2001
- Medium: liquid scintillator
- Size: 1 kt
- Photomultiplier tubes (Hamamatsu):
  - 1325 17-inch, 7 ns rise-time
  - 779 20-inch, 10 ns rise-time
- Analysis: $\sim$MeV $\overline{\nu}_e$ (inverse-beta decay)
- Energy resolution: $7.0 \pm 0.1\,\%/\sqrt{E(\mathrm{MeV})}$
- Vertex resolution: $13.8 \pm 2.3\,\mathrm{cm}$

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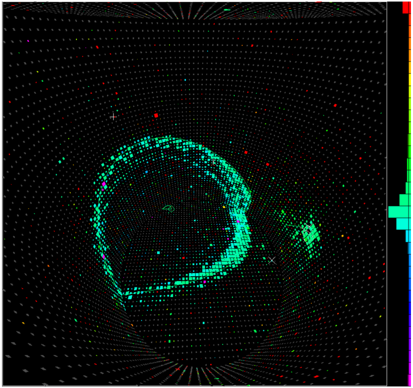
- Directional sensitivity: thought to be NONE
- No analysis at higher energies

Directionality in water

Super-Kamiokande



- Cherenkov ring

Directionality in water

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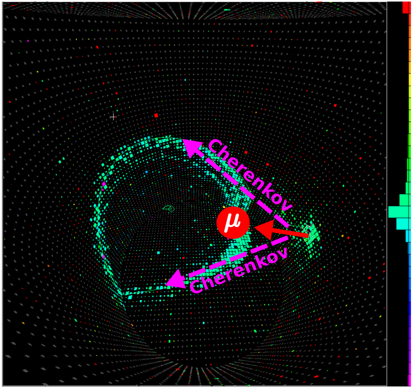
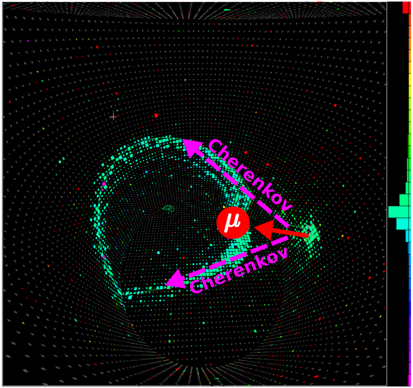


- Cherenkov ring
- shows charged particle direction

Directionality in water

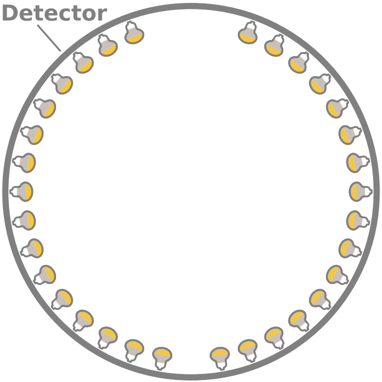
Super-Kamiokande



- Cherenkov ring
- shows charged particle direction
- Can we do something similar in scintillator?

In scintillator...

KamLAND



In scintillator...

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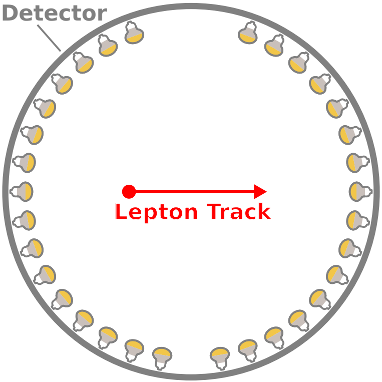

In scintillator...

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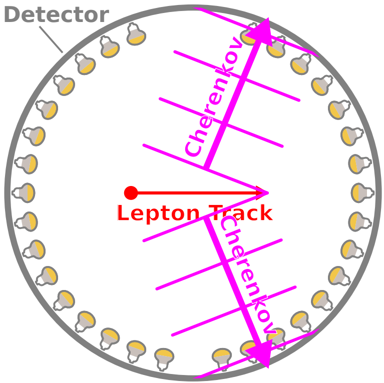
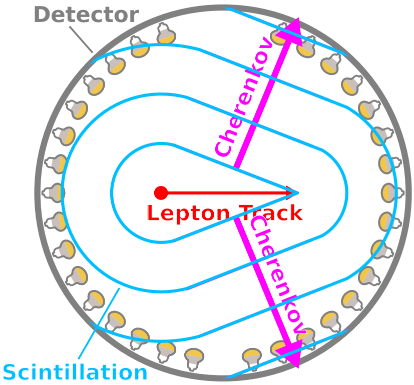


- Cherenkov is emitted

In scintillator...

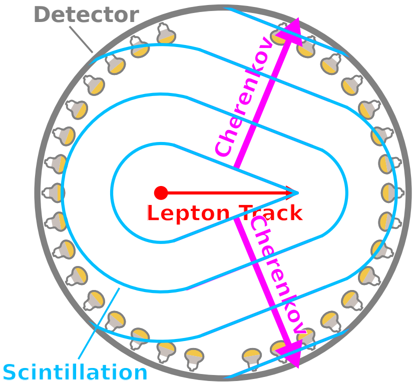
KamLAND



- Cherenkov is emitted
- Along with isotropic scintillation

In scintillator...

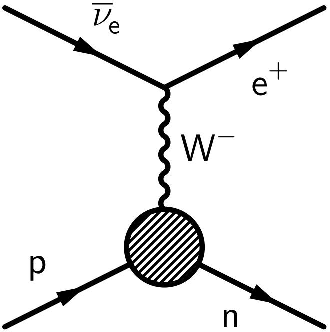
KamLAND



- Cherenkov is emitted
- Along with isotropic scintillation
- $\implies$ Cannot simply use Cherenkov for directionality

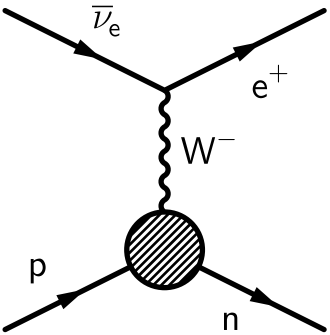
Furthermore...

Inverse-beta decay



Furthermore...

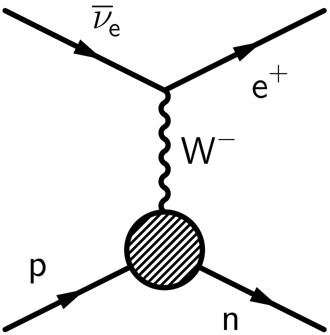
Inverse-beta decay



- KamLAND is used to seeing simple kinematics at low energies ($\sim$ MeV)

Furthermore...

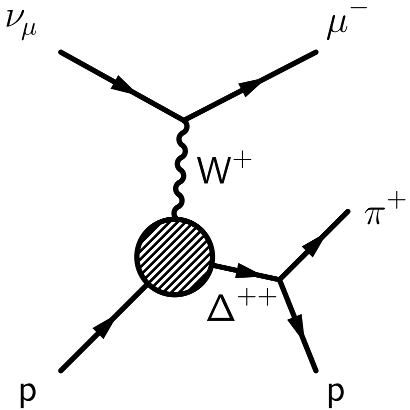
Inverse-beta decay



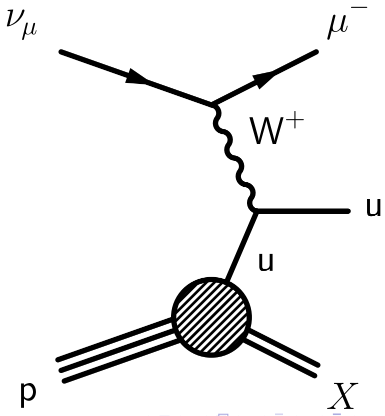
- KamLAND is used to seeing simple kinematics at low energies ($\sim$ MeV)
- Single final-state lepton

But at higher energies, the kinematics is not so simple

Resonance production

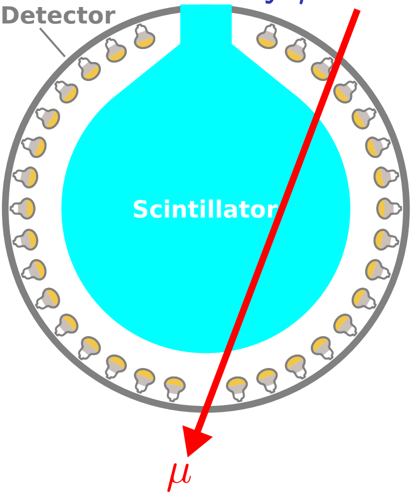


Deep inelastic scattering

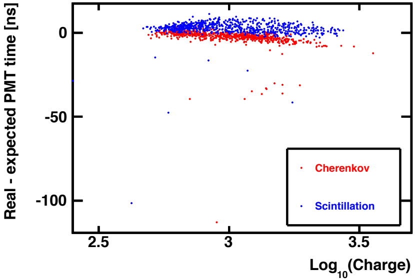


Many photons at high energy in scintillator

Cosmic ray μ



Hit time vs energy (data)



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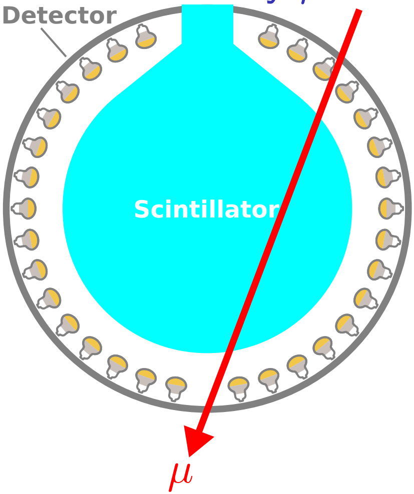

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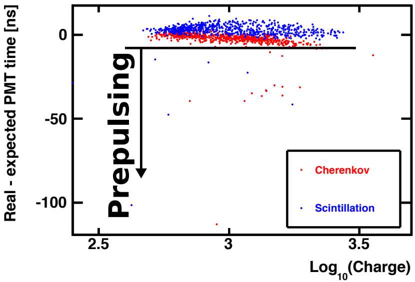

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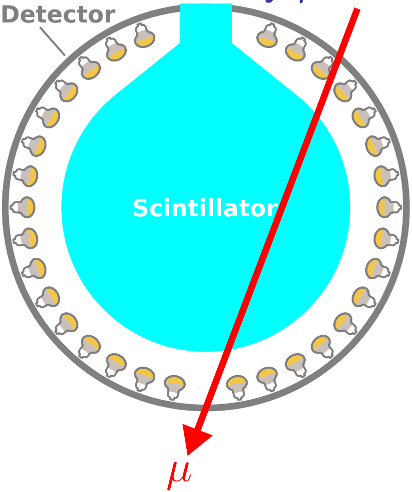

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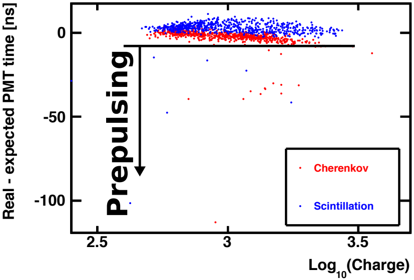

- Fitters must to be robust against these statistical outliers

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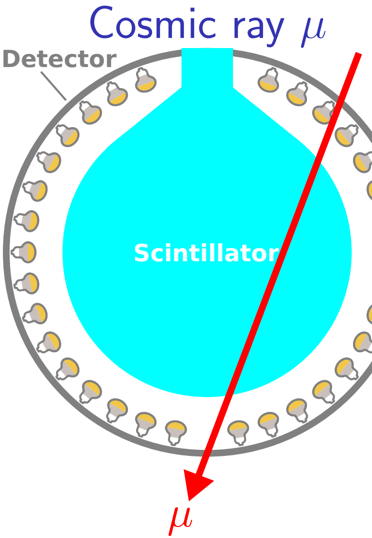

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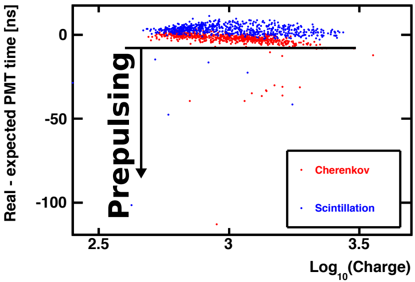
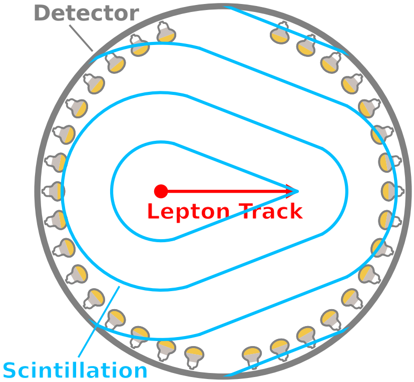


- Fitters must to be robust against these statistical outliers
- Or we can just use **LAPPD**s!

Direction reconstruction technique

Fit direction with charge and time



Idea: John Learned

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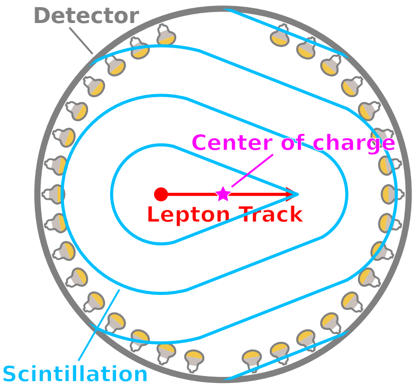

Idea: John Learned

- Use center of charge to fit middle of track

Direction reconstruction technique

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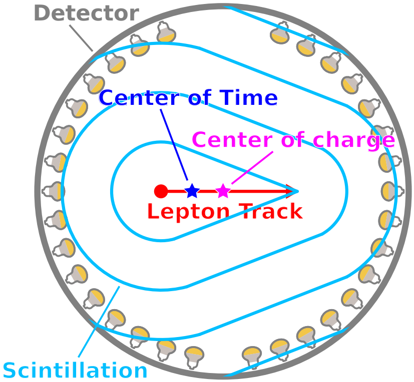
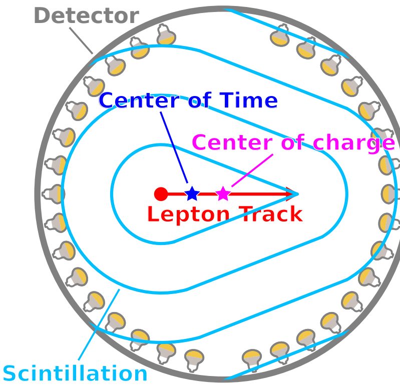


Idea: John Learned

- Use center of charge to fit middle of track
- Use center of time to fit near end of track

Direction reconstruction technique

Fit direction with charge and time



Idea: John Learned

- Use center of charge to fit middle of track
- Use center of time to fit near end of track
- And just connect dots to find direction!

Question:

Question:

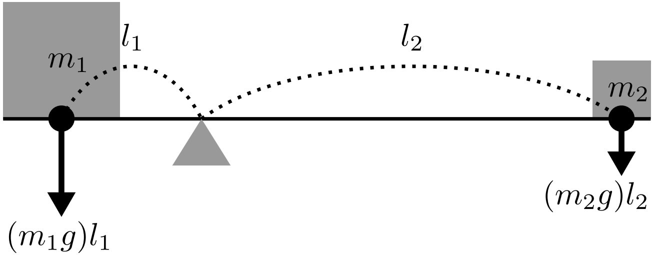
- But, what do we use for the weights in the **weighted mean**:

$$\frac{\sum_i w_i x_i}{\sum_i w_i}$$

when calculating center of charge and time?

Let's review some basic physics...

What weight is used for *center of gravity*?



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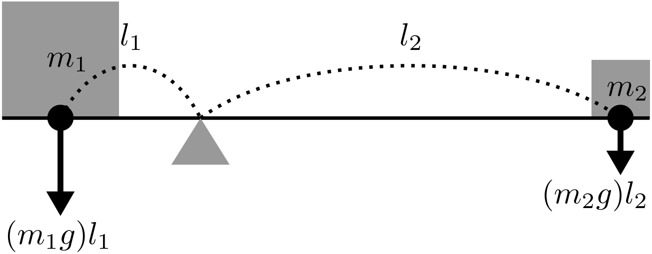

To find center of gravity:

net torque $= -(m_1 g) l_1 + (m_2 g) l_2 = 0$

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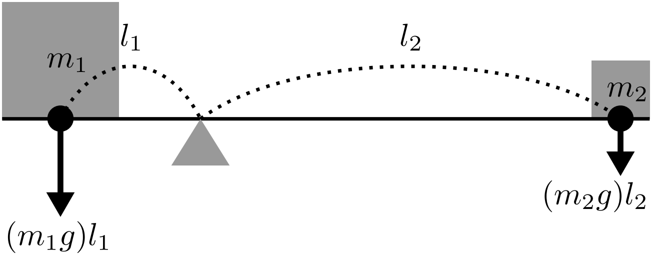

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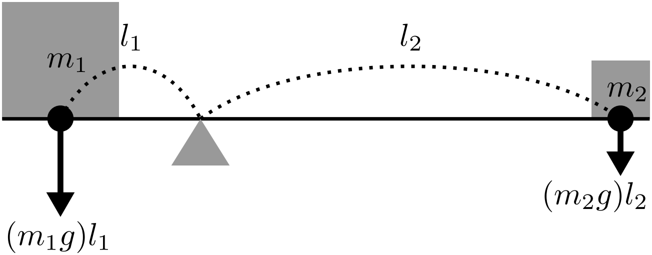

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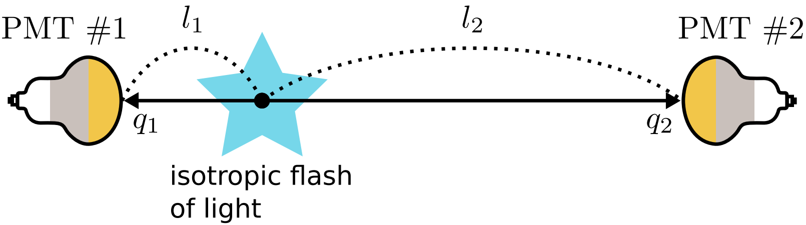
$\implies -(m_1)l_1 + (m_2)l_2 = 0$

$\therefore$ weight is **mass**: $w_i = m_i$

What weight is used for *center of charge*?



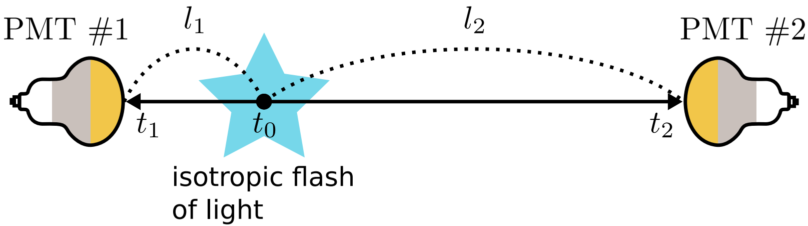
$$q_1 \propto \frac{1}{l_1^2}, \quad q_2 \propto \frac{1}{l_2^2}$$

$$\implies \sqrt{q_1} \propto \frac{1}{l_1}, \quad \sqrt{q_2} \propto \frac{1}{l_2}$$

$$\implies -(\sqrt{q_1})l_1 + (\sqrt{q_2})l_2 = 0$$

$\therefore$ weight is $\sqrt{\textbf{charge}}$: $w_i = \sqrt{q_i}$

What weight is used for *center of time*?



Let $\Delta t_i \equiv t_i - t_0$

$$\implies \Delta t_1 = \frac{l_1}{c}, \quad \Delta t_2 = \frac{l_2}{c}$$

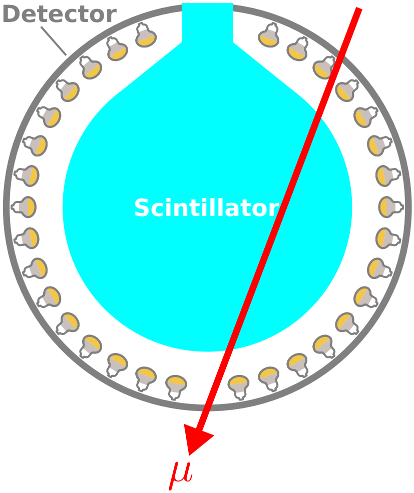
$$\implies -\left(\frac{1}{\Delta t_1}\right)\frac{l_1}{c} + \left(\frac{1}{\Delta t_2}\right)\frac{l_2}{c} = 0$$

$$\implies -\left(\frac{1}{\Delta t_1}\right)l_1 + \left(\frac{1}{\Delta t_2}\right)l_2 = 0$$

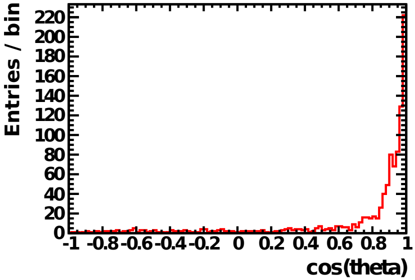
$\therefore$ weight is **inverse of time**: $w_i = \frac{1}{\Delta t_i}$

Test algorithm against μ (data)

Cosmic ray μ

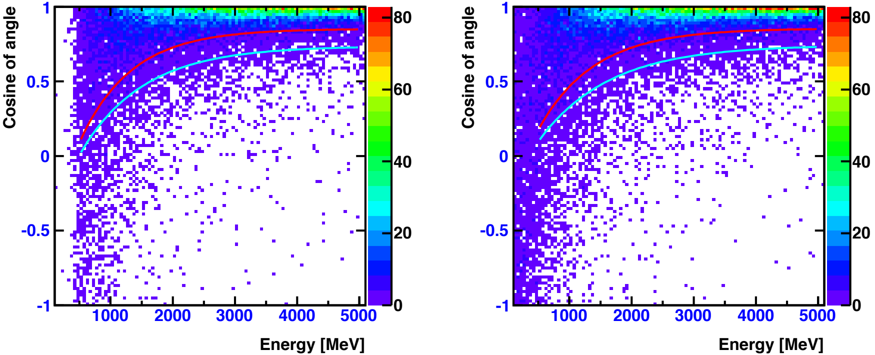


Agreement with μ-fitter which uses entry/exit points



Test algorithm against ν (MC)

$\nu_e + {}^{1}\mathrm{H} \xrightarrow{\mathrm{CC}} e^- + ?$ $\qquad$ $\nu_e + {}^{12}\mathrm{C} \xrightarrow{\mathrm{CC}} e^- + ?$



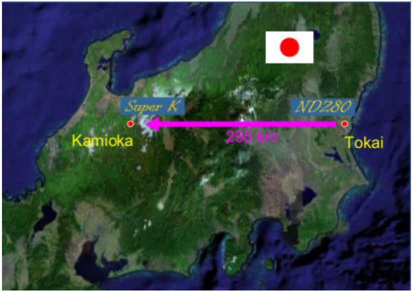
Legend:

- red line: $1\,\sigma$ of reconstructed angle from ν direction
- cyan line: $1\,\sigma$ of lepton angle from ν direction

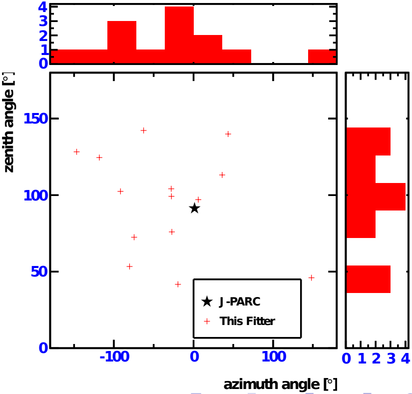
Test algorithm against T2K events (data)

(Selected with spill-time so no backgrounds)

Map



Agreement with J-PARC direction



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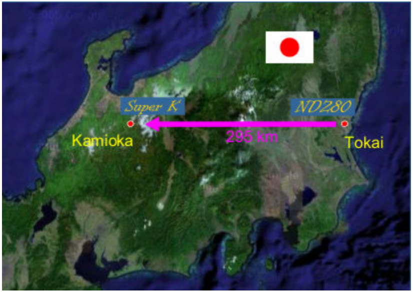
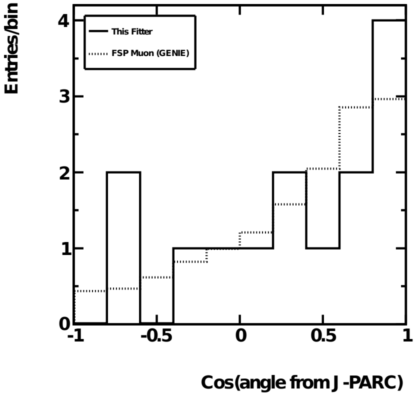


Agreement with MC
(K-S test: p-value $= 0.96$)



Track Reconstruction and Particle ID

Hellgartner's algorithm

(former LENA grad student)

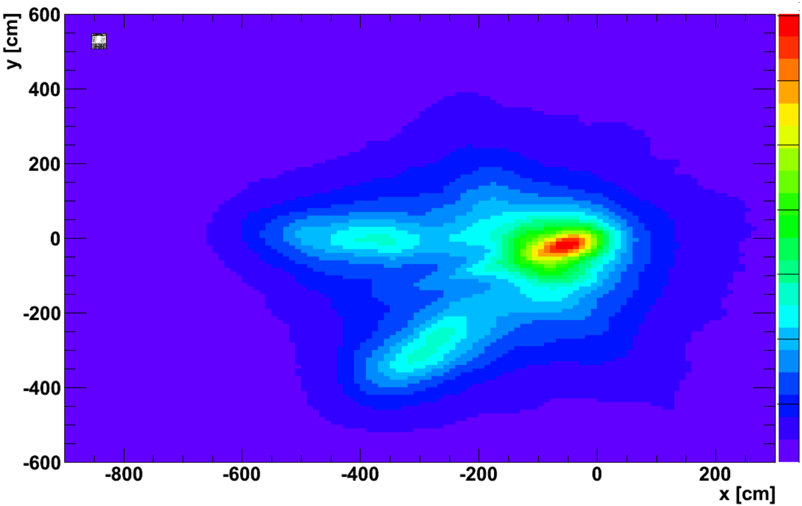
$$h(\vec{x}, t) = \sum_{i=1}^{N_{\mathsf{PMT}}} \Theta(q_i - q_{\mathsf{threshold}}) \sum_{j=1}^{N_\gamma} f(t_{ij} - t_i^{\mathsf{TOF}}, t)$$

$$\begin{cases} N_{\mathsf{PMT}} & \text{(number of PMTs)} \\ N_\gamma & \text{(number of photon hits to count per PMT)} \\ q_i & \text{(charge on } i\text{-th PMT)} \\ q_{\mathsf{threshold}} & \text{(minimum charge for analysis)} \\ t_{ij} & (j\text{-th hit time on } i\text{-th PMT)} \\ t_i^{\mathsf{TOF}} & \text{(expected time-of-flight between } i\text{-th PMT and } \vec{x}) \end{cases}$$

$$f(\Delta t, t) \propto (t - \Delta t) \exp\left[-\frac{(\Delta t - t)^2}{2\sigma_{\mathsf{tts}}} \right]$$

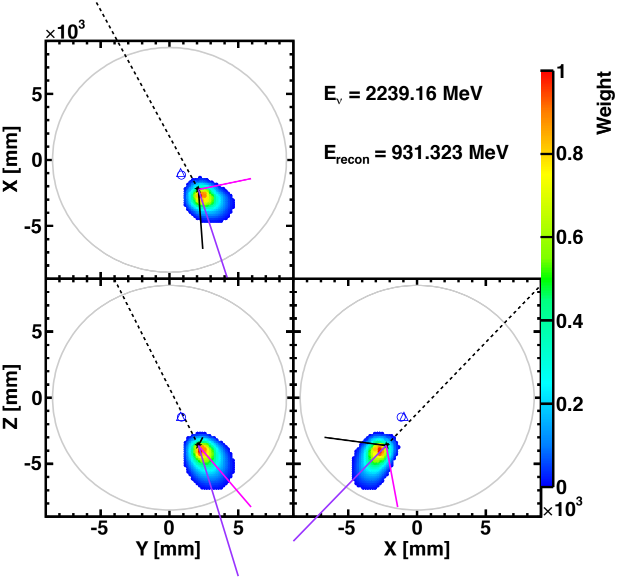
Figure of merit for each test point in space $= \int_{-\infty}^{\infty} |h(\vec{x}, t)|^2 \, \mathrm{d}t$

Test Hellgartner on double 1 GeV muons (MC)



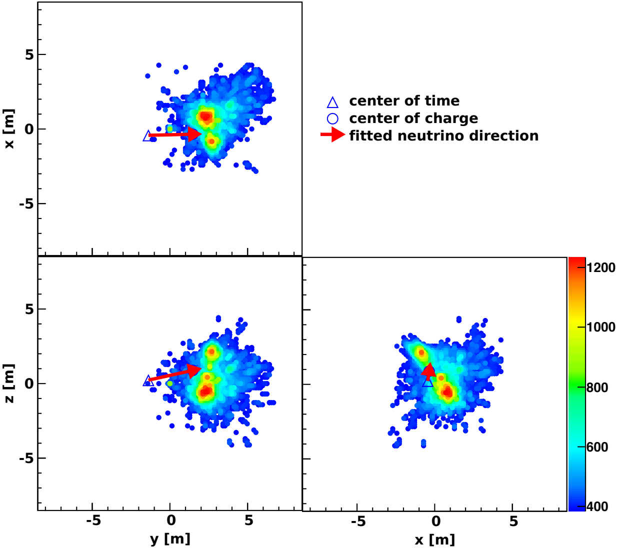
Dominikus Hellgartner

Test Hellgartner on 2 GeV ν_e (MC)



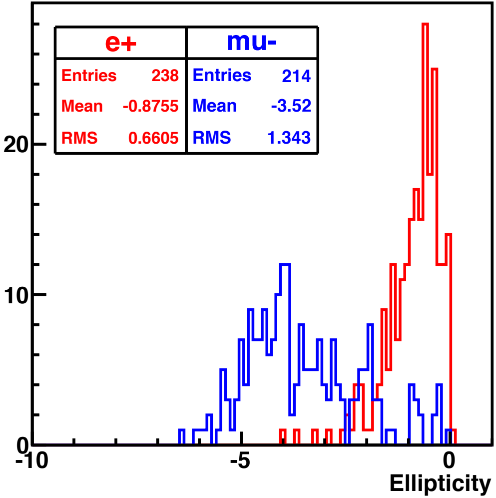
Test Hellgartner on T2K events (data)

($E_{\text{reconstructed}} = 363\,\text{MeV}$)



Test lepton discrimination (MC)

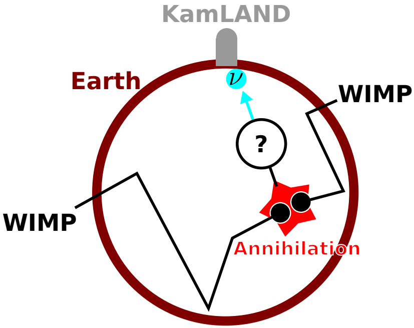
(Using track ellipticity)



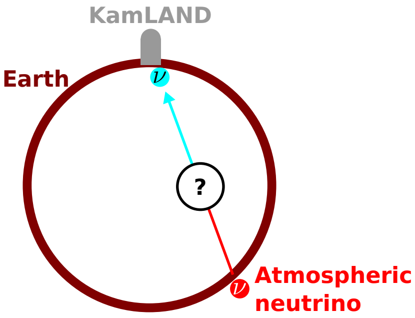
Search for dark matter

Dark matter detection scheme

Signal: Dark matter (WIMP) annihilation induced ν

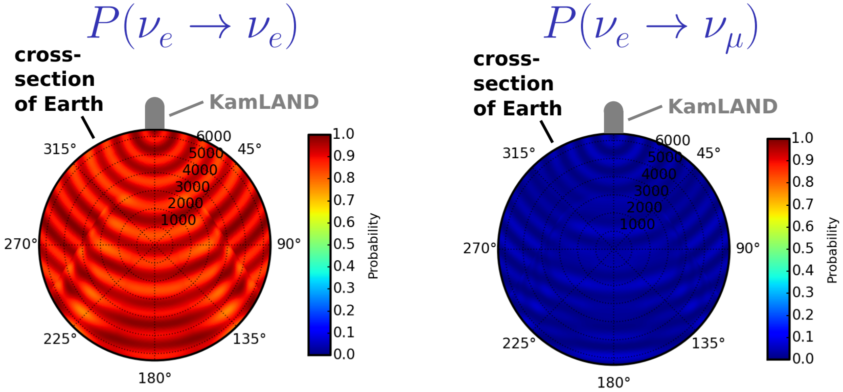


Background: atmospheric ν



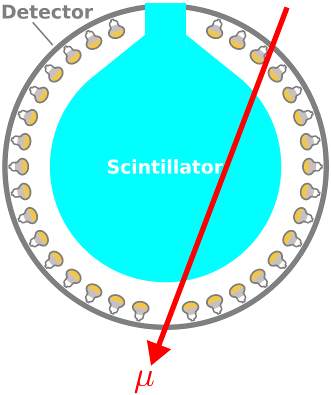
1 GeV ν_e oscillation probability $P(\nu_e \to \nu_x)$ from inside Earth to KamLAND

(PDG 2014 oscillation parameters, PREM)

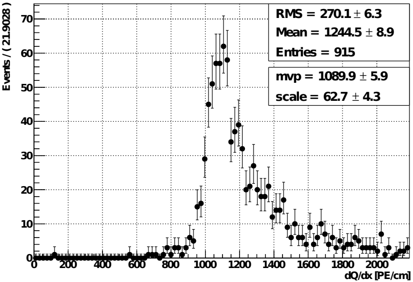


High energy ($\gtrsim$ GeV) calibration

Cosmic ray μ traversing scintillator



$\frac{\mathrm{d}Q}{\mathrm{d}x}$ [p.e./MeV] (data)



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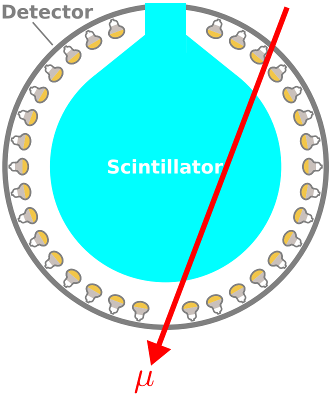
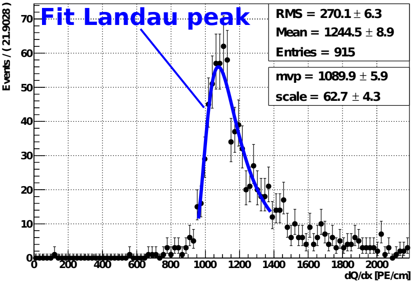
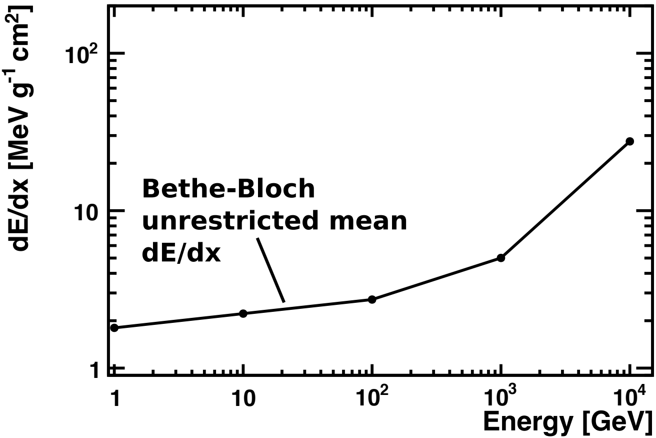


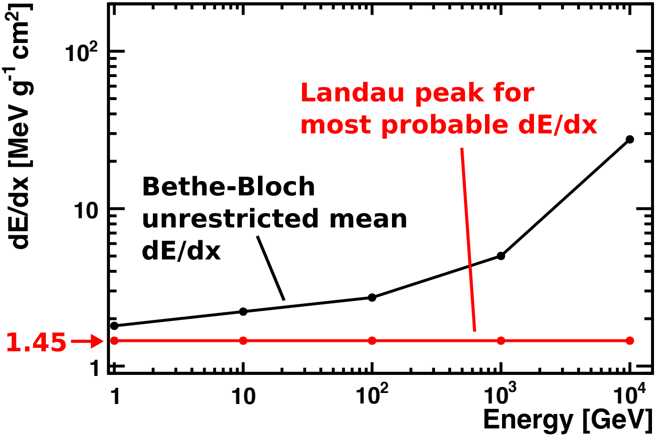
$\frac{\mathrm{d}Q}{\mathrm{d}x}$ [p.e./MeV] (data)



Fit $\frac{\mathrm{d}E}{\mathrm{d}x}$ for μ in scintillator (MC)

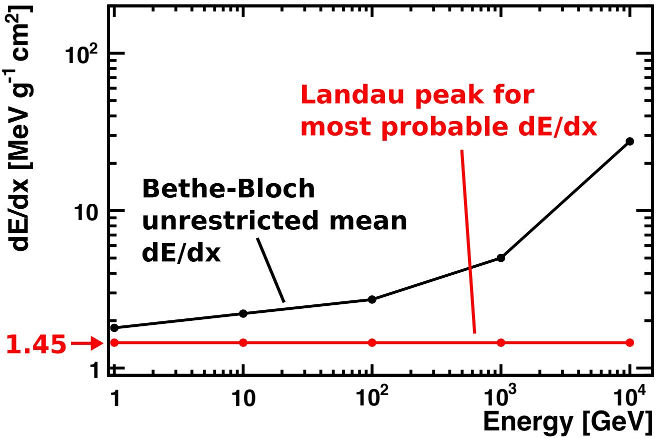


Fit $\frac{\mathrm{d}E}{\mathrm{d}x}$ for μ in scintillator (MC)



- Peak is stable across huge energy range!

Fit $\frac{\mathrm{d}E}{\mathrm{d}x}$ for μ in scintillator (MC)



- Peak is stable across huge energy range!
- $\Longrightarrow$ Use **peak** instead of mean for calibration

Data selection

- Live time: 3671 days ($\sim$ 10 years)

Data selection

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- Event selection criteria:

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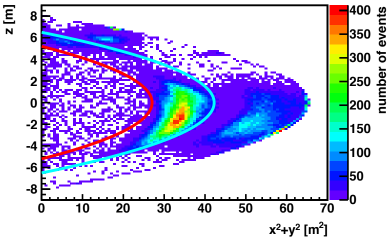
Data selection

- Live time: 3671 days ($\sim$ 10 years)
- Event selection criteria:
  - Fully contained events
    $\Longrightarrow$ Outer detector PMT hits < 5
  - $E_{\text{reconstructed}} > 1\,\text{GeV}$ (theoretically preferred)

Reconstructed Vertex (data)

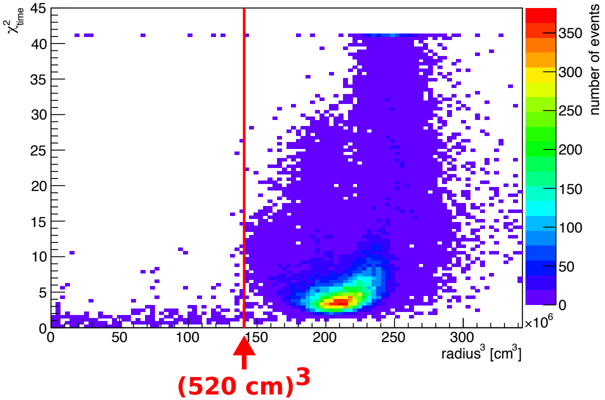
$E_{\text{reconstructed}} > 30\,\text{MeV}$ $\quad$ $E_{\text{reconstructed}} > 1\,\text{GeV}$



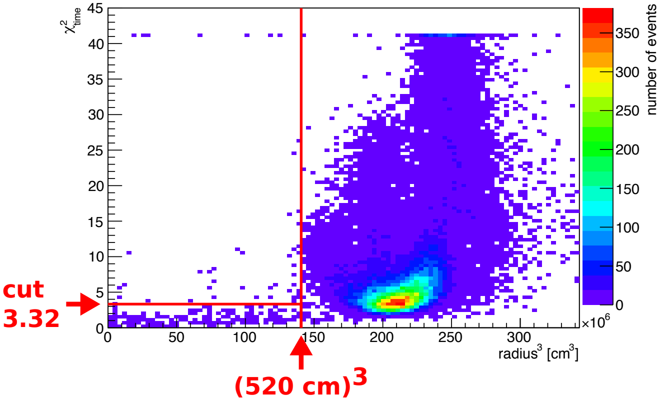
Legend:

- 5.2 m radius fiducial volume cut
- 6.5 m radius balloon edge

Vertex χ^2_{time} (test of event point-likeness)



Vertex χ^2_{time} (test of event point-likeness)

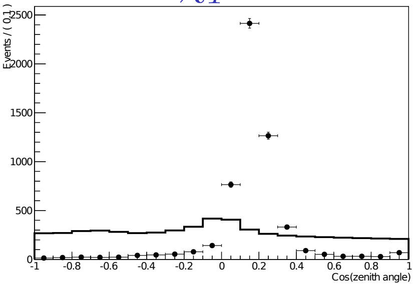


- Reject events above $\chi^2_{\text{time}} = 3.32$ that are too elongated in shape (most likely μ)

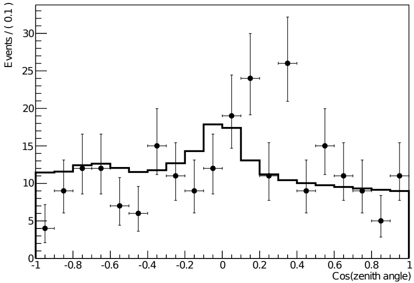
Fit data to background model

(with $\chi^2_T < 3.32$ cut)

No χ^2_T cut



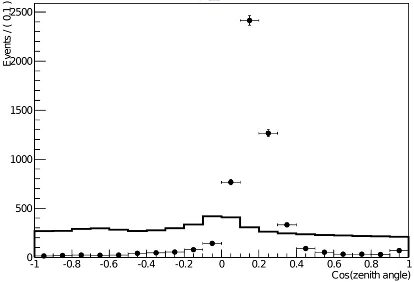
$\chi^2_T < 3.32$



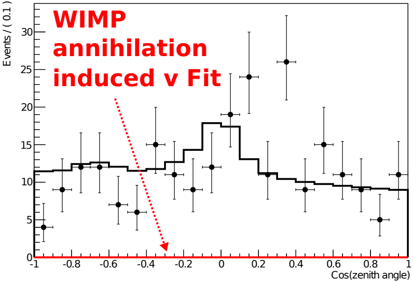
Fit data to background model

(with $\chi^2_T < 3.32$ cut)

No χ^2_T cut



$\chi^2_T < 3.32$



Signal event rate equation

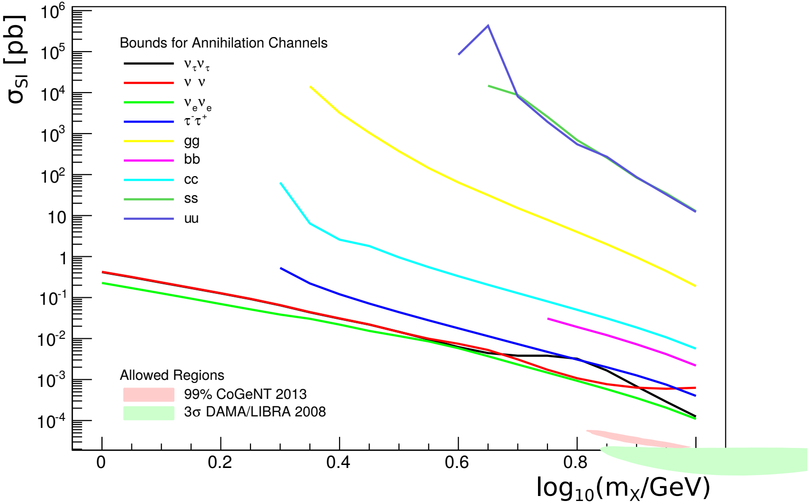
$$\text{rate}_{\text{signal}} = \Gamma_{\text{A}} \times \sum_{\substack{\text{channel}=i \\ \nu-\text{flavor}=\alpha}} \left[B_i \int dE_\alpha \frac{dN_{i,\alpha}}{dE_\alpha} \frac{\sigma_{\text{effective}}(E_\alpha)}{4\pi R_{\text{Earth}}^2} \right]$$

$$\begin{cases} \Gamma_A = \frac{1}{2}\Gamma_C & (\chi\overline{\chi} \text{ annihilation rate at equilibrium}) \\ \Gamma_C = \sigma_{\chi-\text{nucleon}} C_0 & (\chi \text{ capture rate}) \\ E_\alpha & (\text{energy of neutrino for flavor } \alpha) \\ N_{i,\alpha} & (\text{neutrino yield of flavor } \alpha \text{ per annihilation for channel } i) \\ \sigma_{\text{effective},\alpha}(E_\alpha) & (\text{effective detector cross-section}) \\ R_{\text{Earth}} & (\text{Earth radius}) \end{cases}$$

bound on $\text{rate}_{\text{signal}} \implies$ bound on $\sigma_{\chi-\text{nucleon}}$

WIMP $\sigma_{\rm SI}$ bounds (preliminary)

(90 % C.L.)



Summary

- Developed and tested **directionality** and **track reconstruction** techniques for high energy ν in scintillator.
- Studied **lepton flavor discrimination** algorithms in scintillator.
- Studied **high-energy calibration** using cosmic ray μ.
- Placed bounds on **dark-matter-nucleon cross-sections** by looking at annihilation induced ν from Earth's core (preliminary).
- One of **first physics application** of ν directionality in scintillator.

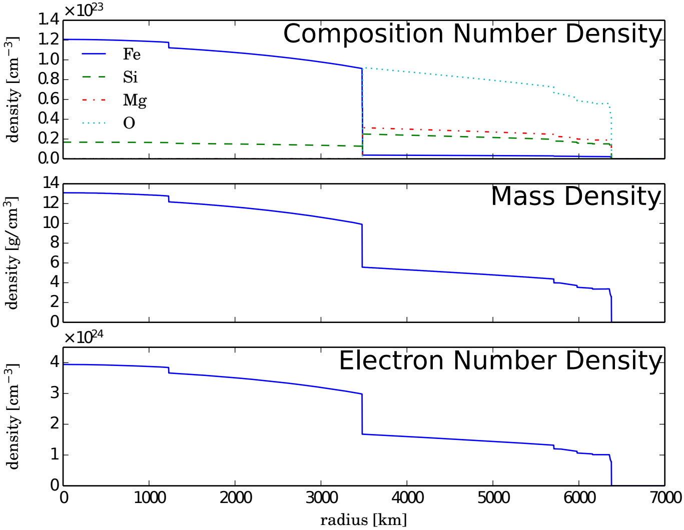
Thank you for listening!

Backup slides

KamLAND: features

- Commissioned: 2001
- Medium: liquid scintillator
  - Decay constants: $\tau_1 = 4.0\,\mathrm{ns}$, $\tau_2 = 8.6\,\mathrm{ns}$
- Size: 1 kt
- Photomultiplier tubes (Hamamatsu):
  - 1325 17-inch, 7 ns rise-time, 3.5 ns TTS
  - 779 20-inch, 10 ns rise-time, 5.5 ns TTS
  - 34 % photocathode coverage
- Analysis: $\sim$MeV $\overline{\nu}_\mathrm{e}$ (inverse-beta decay)
- Energy resolution: $7.0 \pm 0.1\,\%/\sqrt{\mathrm{E(MeV)}}$
- Vertex resolution: $13.8 \pm 2.3\,\mathrm{cm}$
- Directional sensitivity: thought to be NONE
- No analysis at higher energies

Earth Model (PREM)



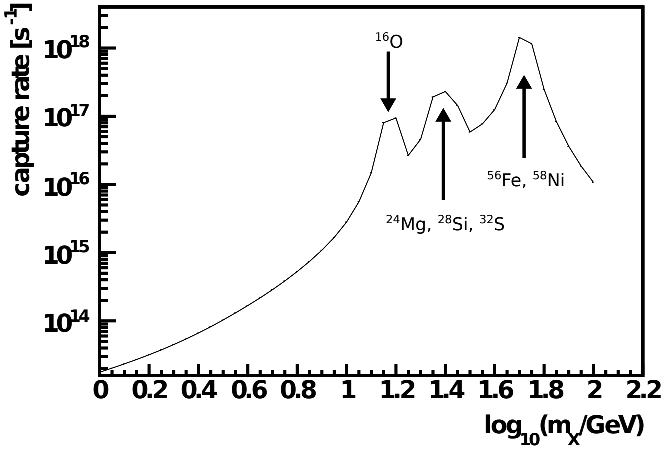
Neutrino Oscillation Parameters

(normal hierarchy, PDG 2014)

- $\sin^2(2\theta_{12}) = 0.846 \pm 0.021$
  $\Longrightarrow \theta_{12} = 33.45^\circ$
- $\sin^2(2\theta_{13}) = (9.3 \pm 0.8) \times 10^{-2}$
  $\Longrightarrow \theta_{13} = 8.88^\circ$
- $\sin^2(2\theta_{23}) = 0.999^{+0.001}_{-0.018}$
  $\Longrightarrow \theta_{23} = 44.09^\circ$
- $\Delta m^2_{21} = 7.53 \pm 0.18 \times 10^{-5}$ eV
- $\Delta m^2_{31} = 2.52 \pm 0.06 \times 10^{-3}$ eV

Dark matter capture in Earth vs mass m_x

(Spin-independent cross-section $\sigma_{\mathrm{SI}} = 1 \times 10^{-40}\,\mathrm{cm}^2$)



Fit data to background model