

# High Energy Analysis at KamLAND and Application to Dark Matter Search

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# Overview

Introduction

Neutrino directionality

Issues

Algorithm

Validation

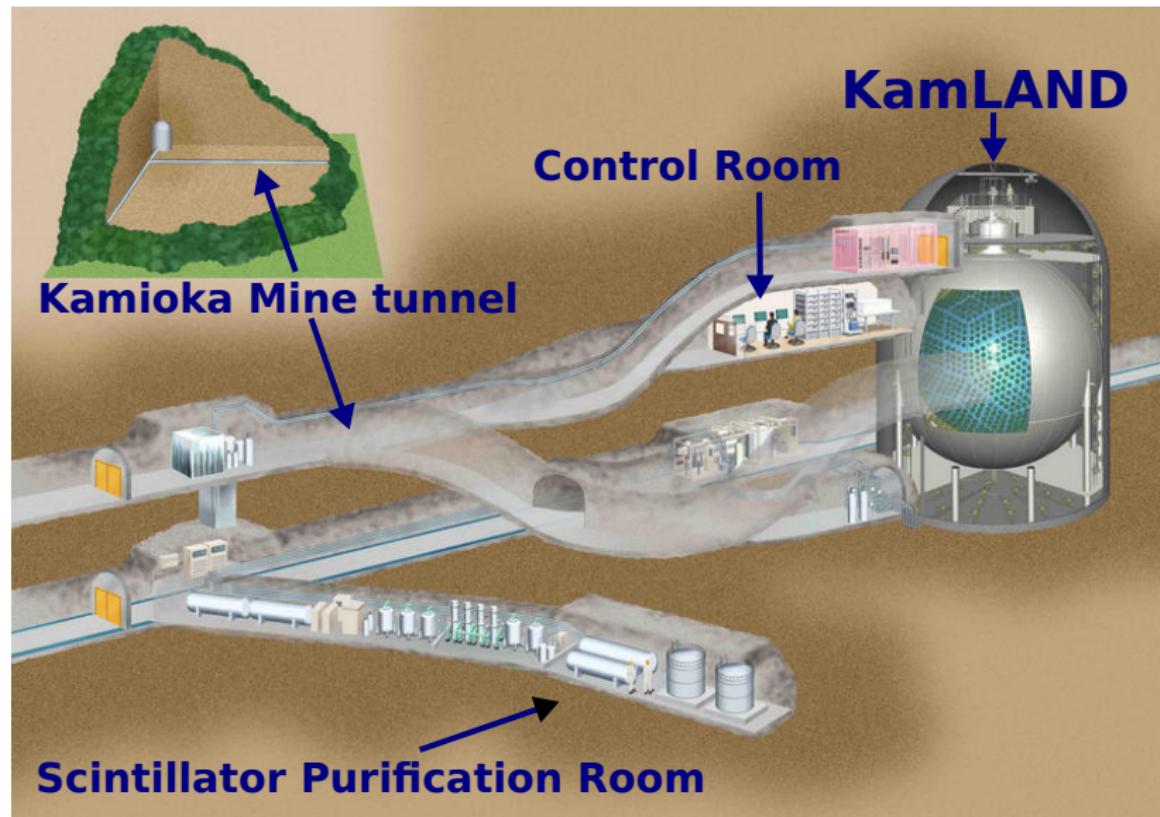
Track reconstruction and particle discrimination

Algorithm

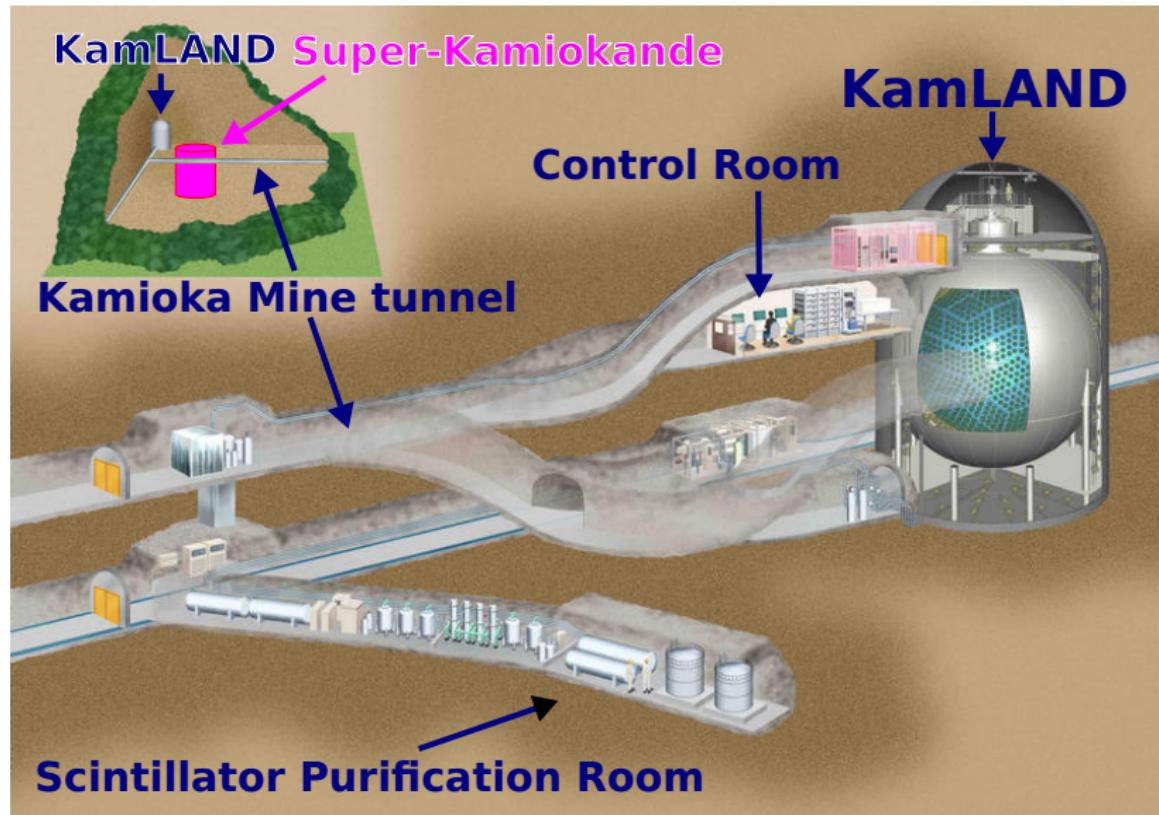
Validation

Search for dark matter

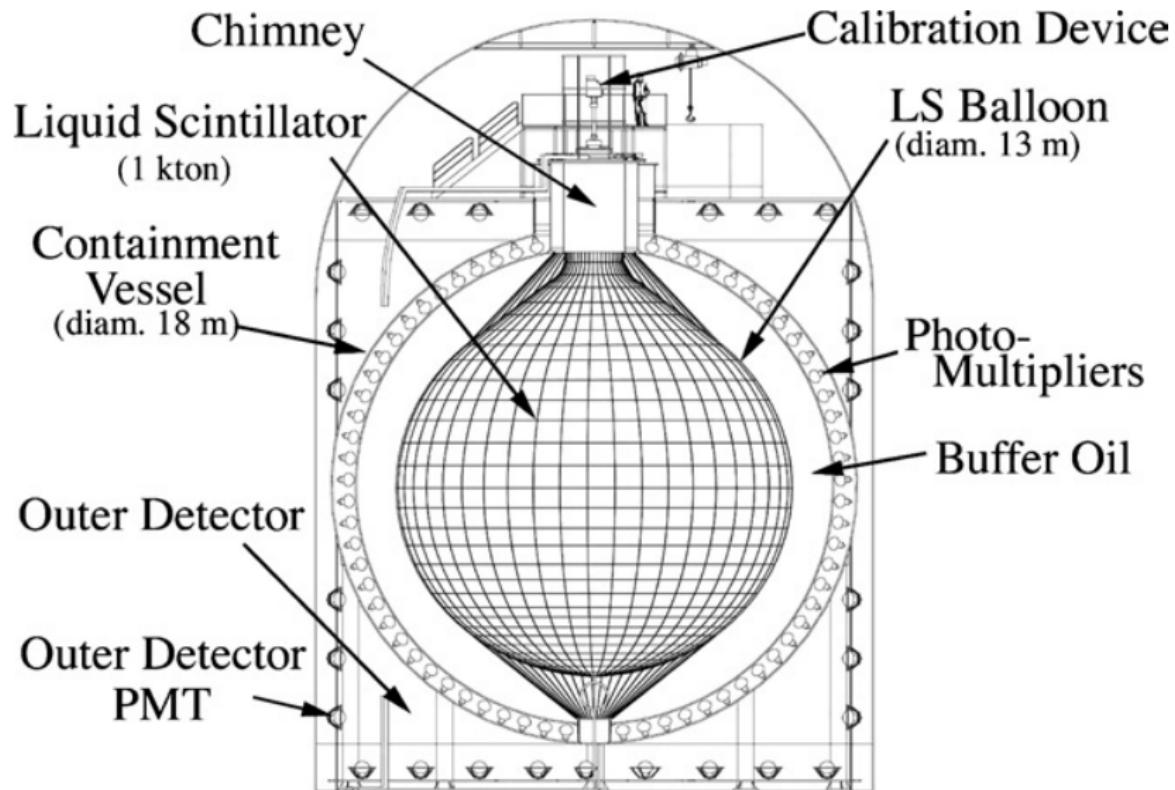
# KamLAND: $\nu$ detector in Japan



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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:  $\sim \text{MeV } \bar{\nu}_e$  (inverse-beta decay)
- ▶ Energy resolution:  $7.0 \pm 0.1\% / \sqrt{E(\text{MeV})}$
- ▶ Vertex resolution:  $13.8 \pm 2.3 \text{ cm}$

# KamLAND: features

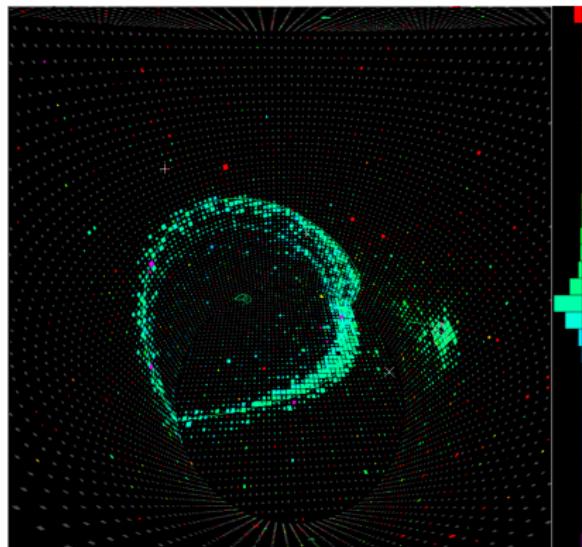
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- ▶ No analysis at higher energies

# Directionality in water

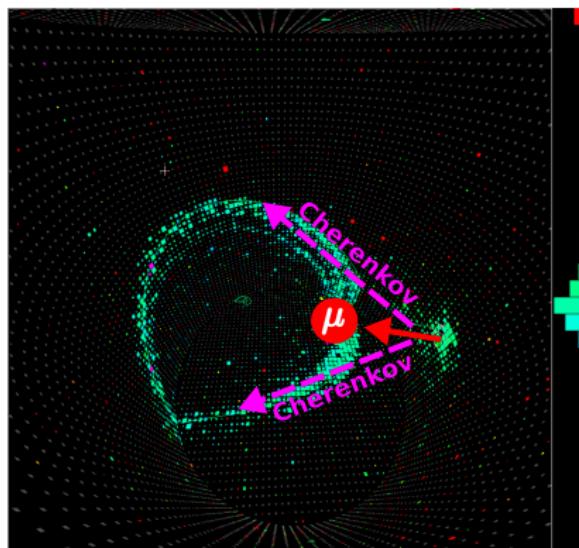
Super-Kamiokande



► Cherenkov ring

# Directionality in water

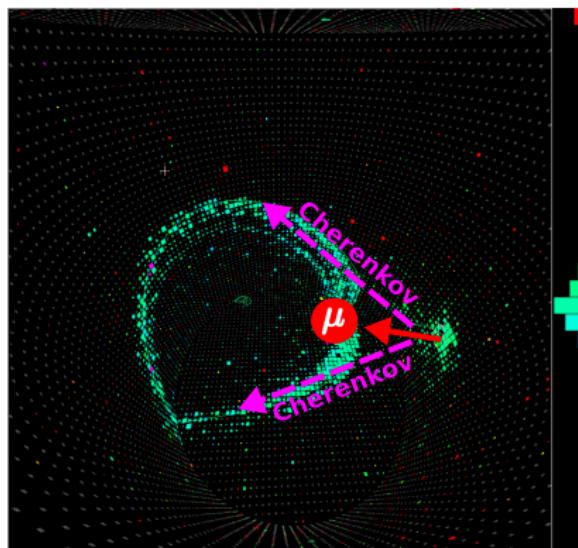
## Super-Kamiokande



- ▶ Cherenkov ring
- ▶ shows charged particle direction

# Directionality in water

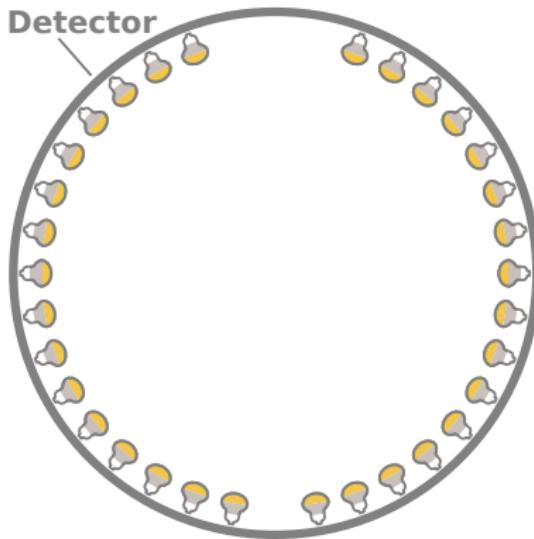
## Super-Kamiokande



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

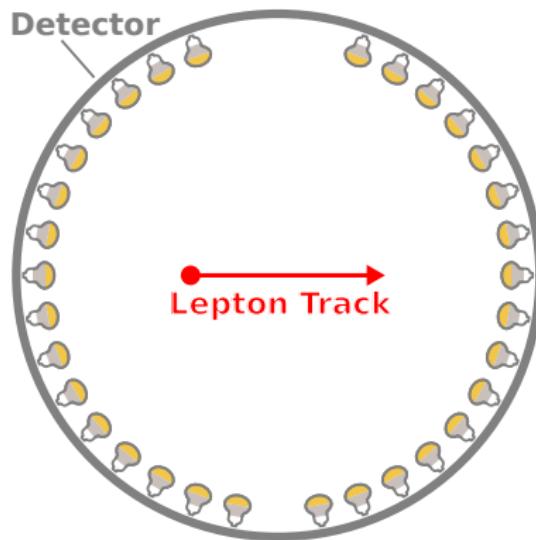
# In scintillator...

## KamLAND



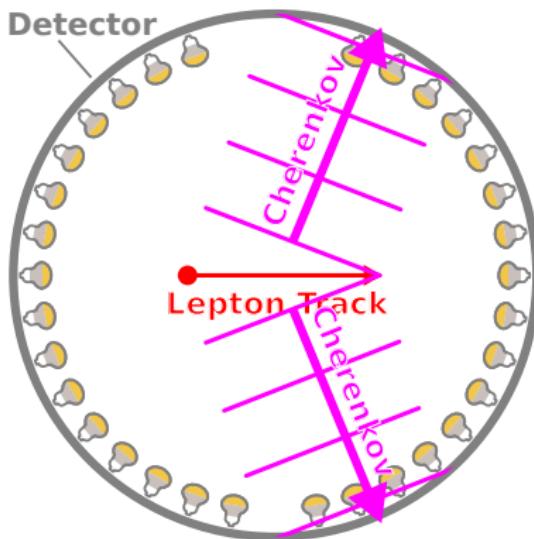
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## KamLAND



# In scintillator...

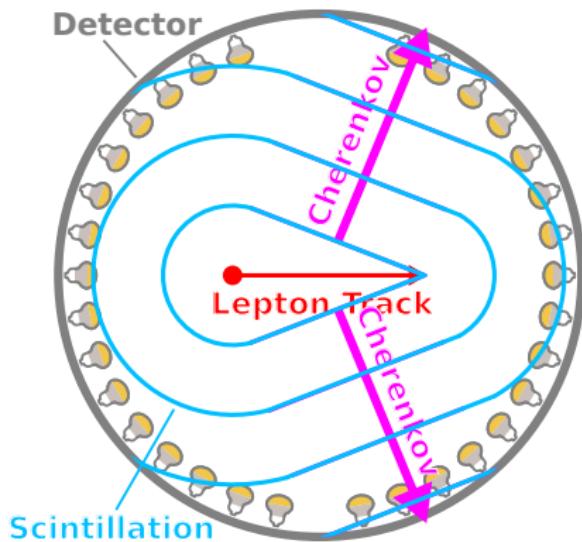
## KamLAND



► Cherenkov is emitted

# In scintillator...

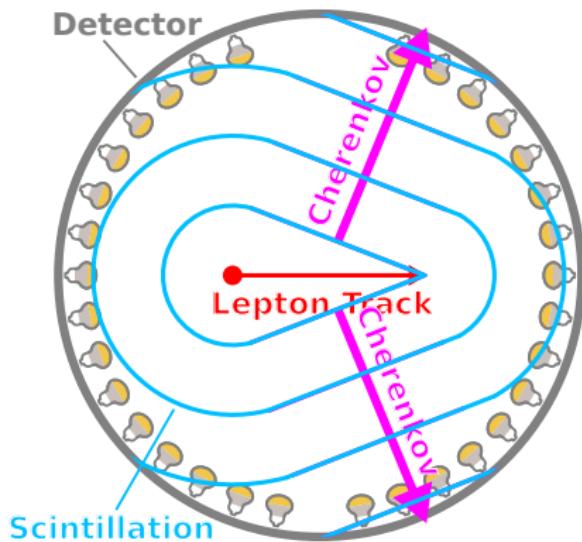
## KamLAND



- ▶ Cherenkov is emitted
- ▶ Along with isotropic scintillation

# In scintillator...

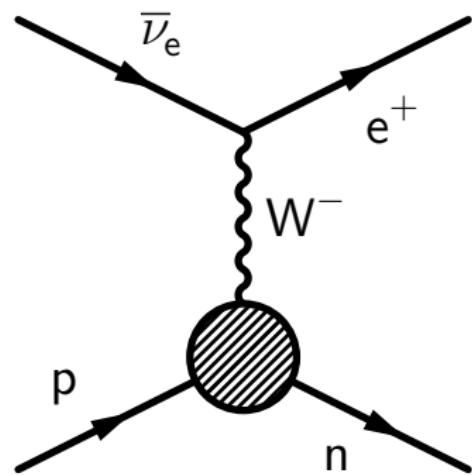
## KamLAND



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

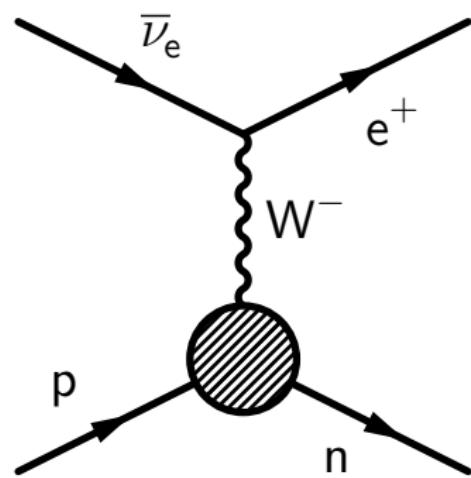
# Furthermore...

## Inverse-beta decay



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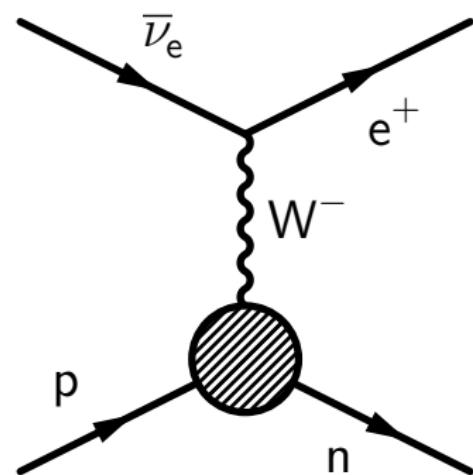
## Inverse-beta decay



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

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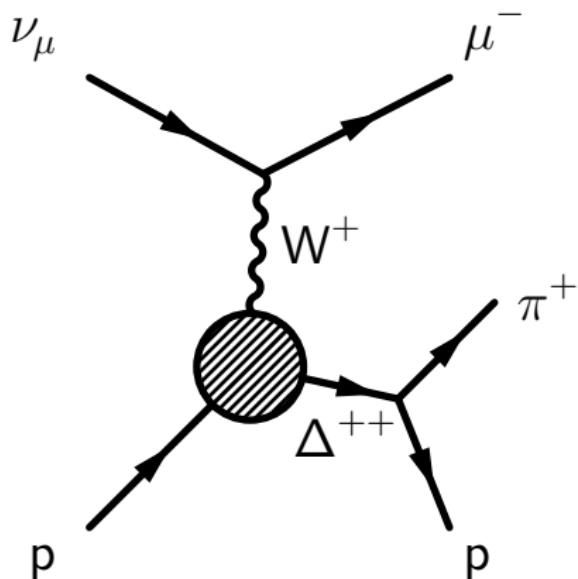
## Inverse-beta decay



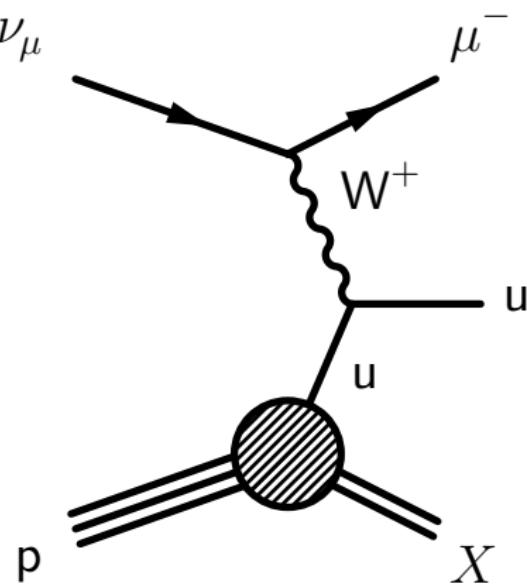
- ▶ KamLAND is used to seeing simple kinematics at low energies ( $\sim$  MeV)
- ▶ Single final-state lepton

But at higher energies, the kinematics is not so simple

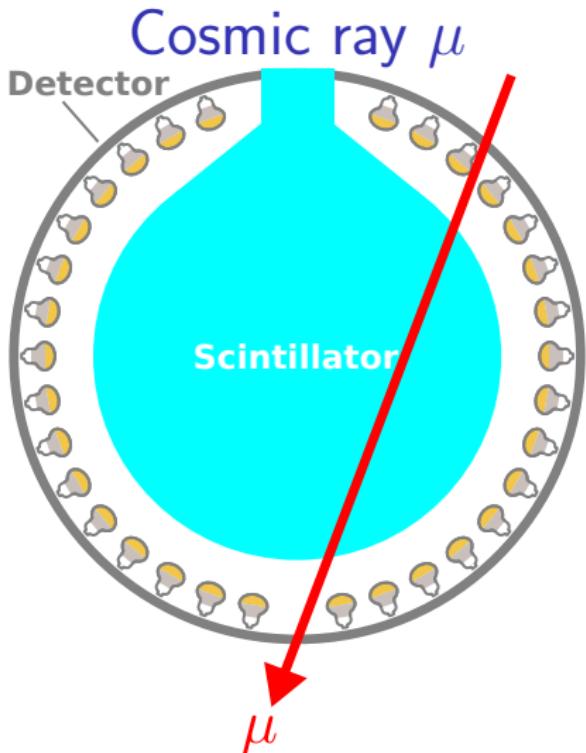
Resonance production



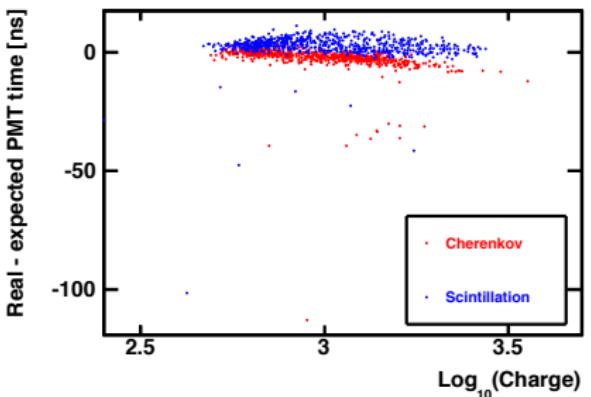
Deep inelastic scattering



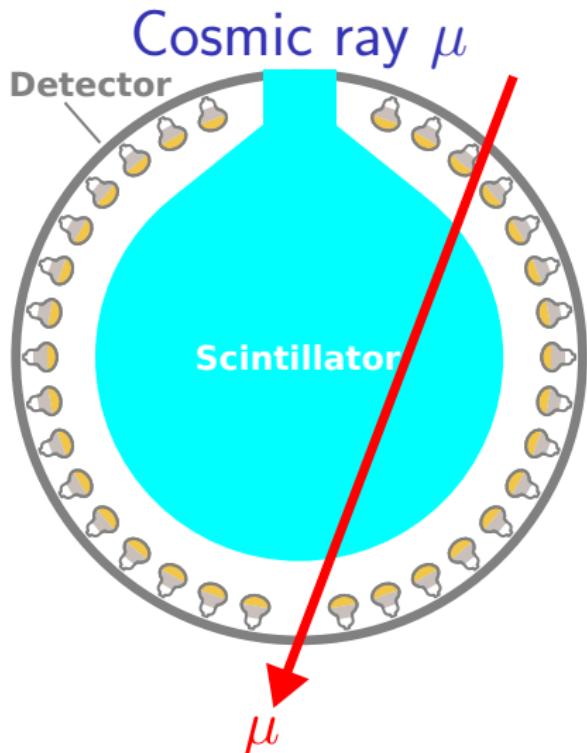
# Many photons at high energy in scintillator



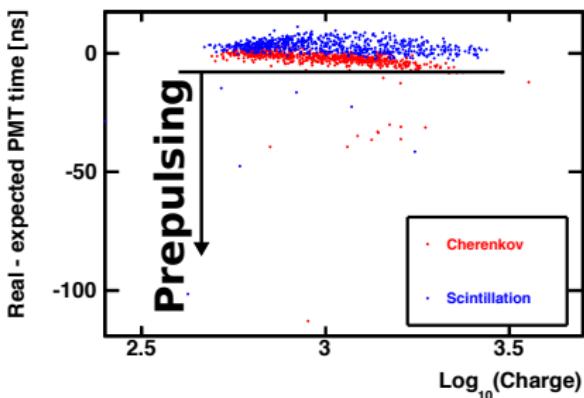
Hit time vs energy (data)



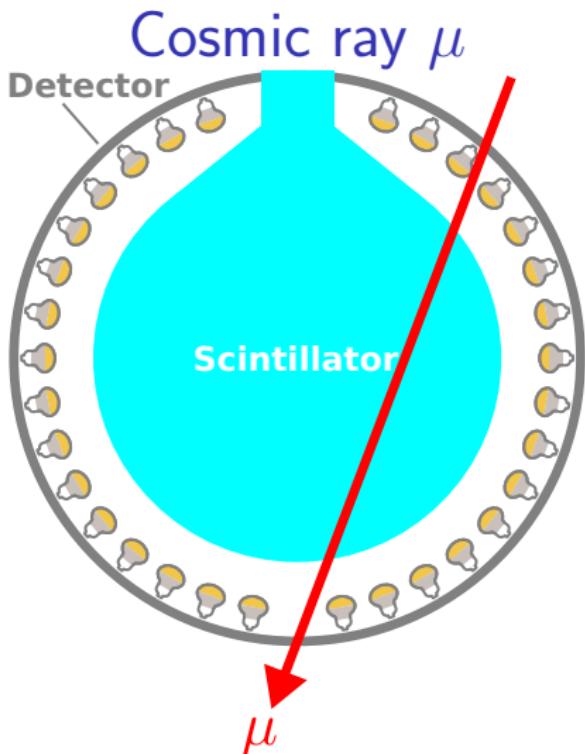
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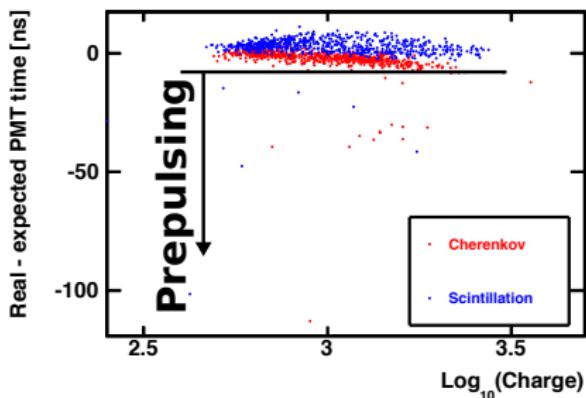
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# Many photons at high energy in scintillator

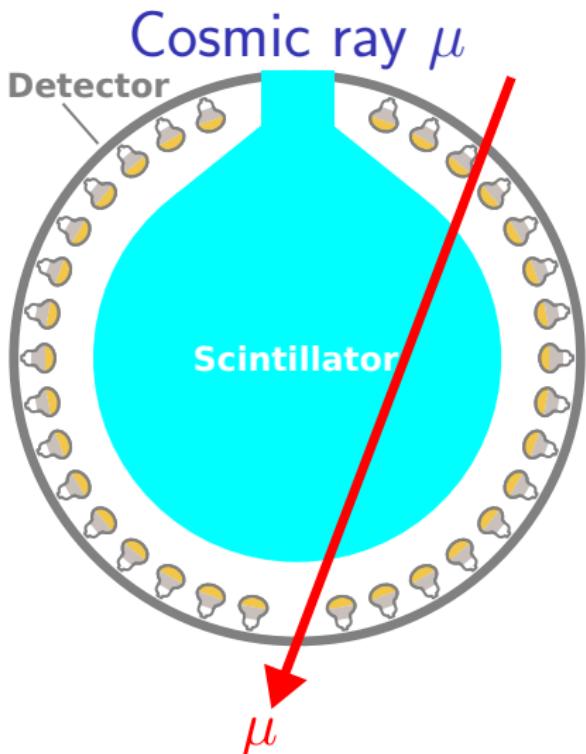


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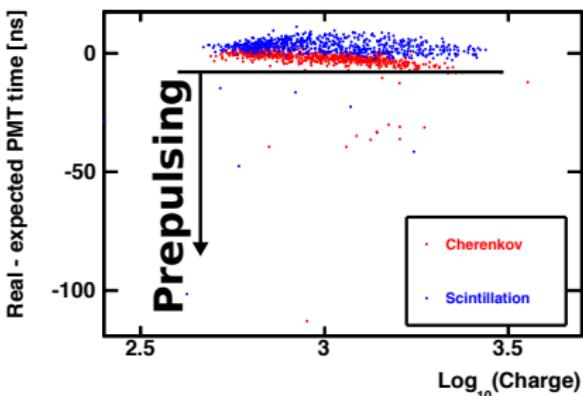


- ▶ Fitters must be robust against these statistical outliers

# Many photons at high energy in scintillator



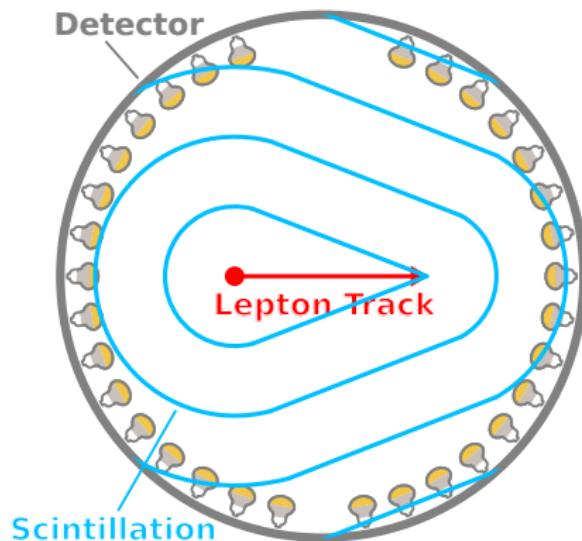
Hit time vs energy (data)



- ▶ Fitters must be robust against these statistical outliers
- ▶ Or we can just use **LAPPDs!**

# Direction reconstruction technique

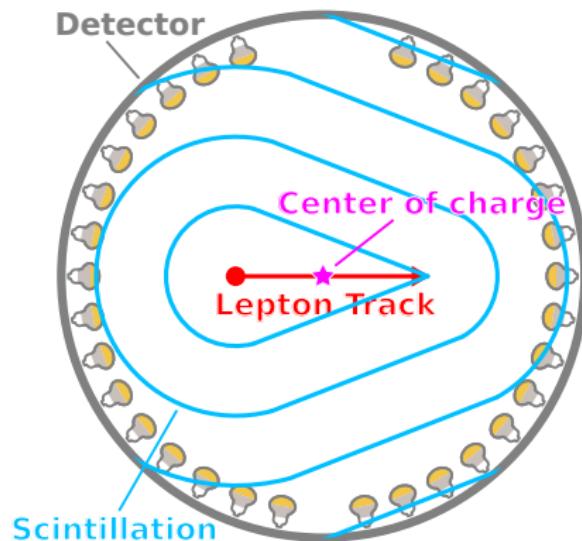
Fit direction with **charge** and **time**



Idea: John Learned

# Direction reconstruction technique

Fit direction with charge and time

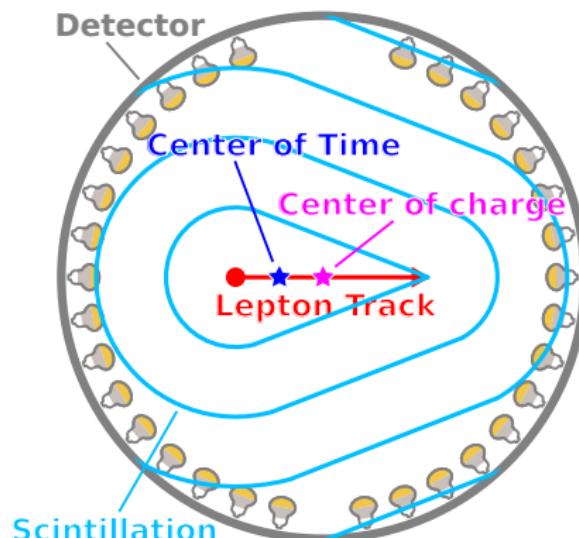


- ▶ Use center of charge to fit middle of track

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# Direction reconstruction technique

Fit direction with charge and time

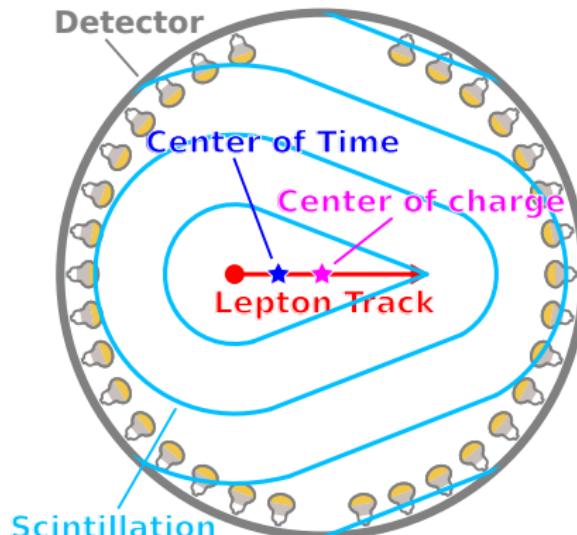


- ▶ Use center of charge to fit middle of track
- ▶ Use center of time to fit near end of track

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# Direction reconstruction technique

Fit direction with charge and time



- ▶ 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!

Idea: John Learned

# Question:

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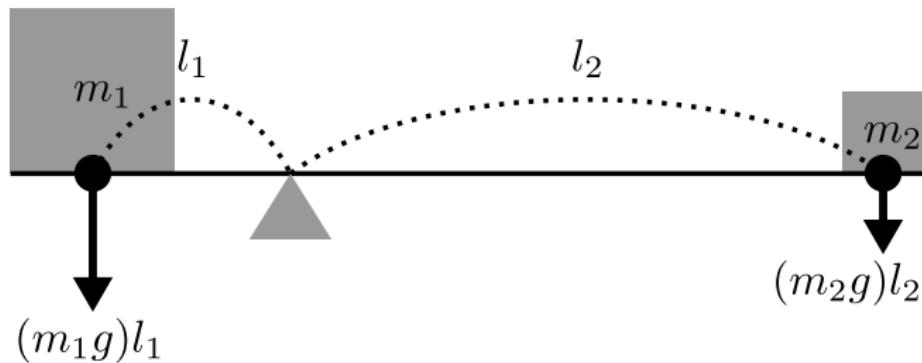
- ▶ But, what do we use for the weights in the **weighted mean**:

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

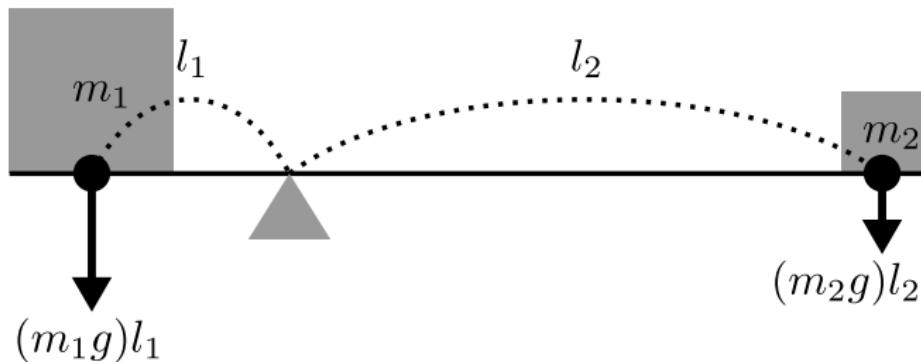
when calculating center of charge and time?

Let's review some basic  
physics...

# What weight is used for *center of gravity*?



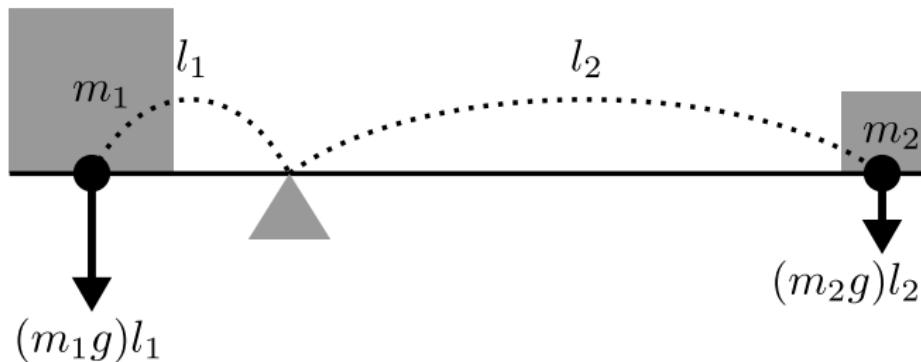
# What weight is used for *center of gravity*?



To find center of gravity:

$$\text{net torque} = -(m_1g)l_1 + (m_2g)l_2 = 0$$

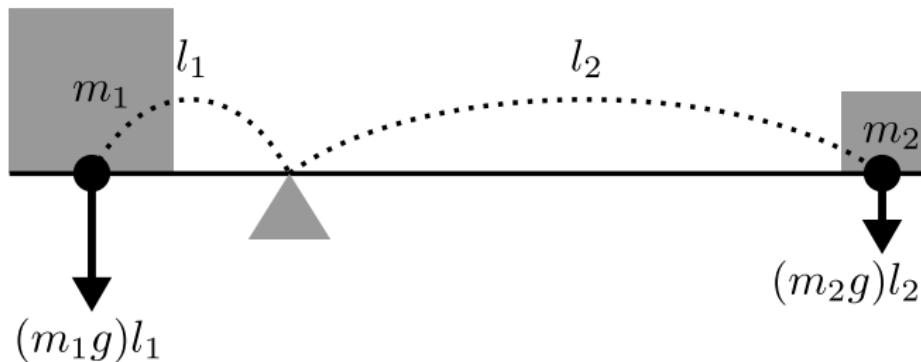
# What weight is used for *center of gravity*?



To find center of gravity:

$$\begin{aligned}\text{net torque} &= -(m_1g)l_1 + (m_2g)l_2 = 0 \\ \implies -(m_1)l_1 + (m_2)l_2 &= 0\end{aligned}$$

# What weight is used for *center of gravity*?



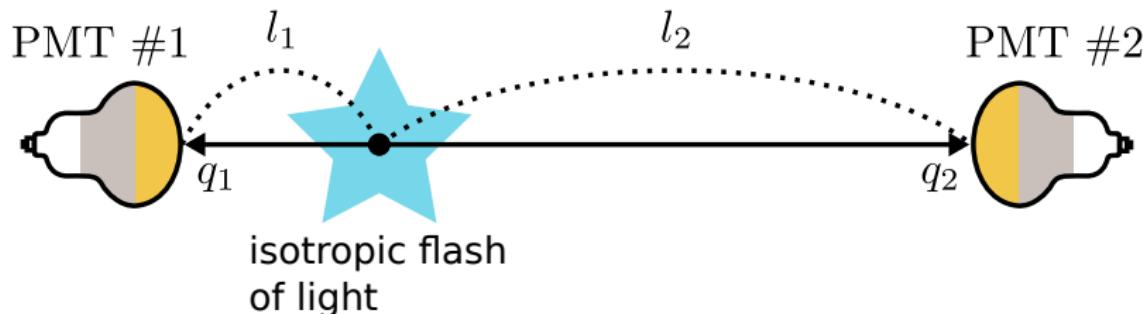
To find center of gravity:

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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*?



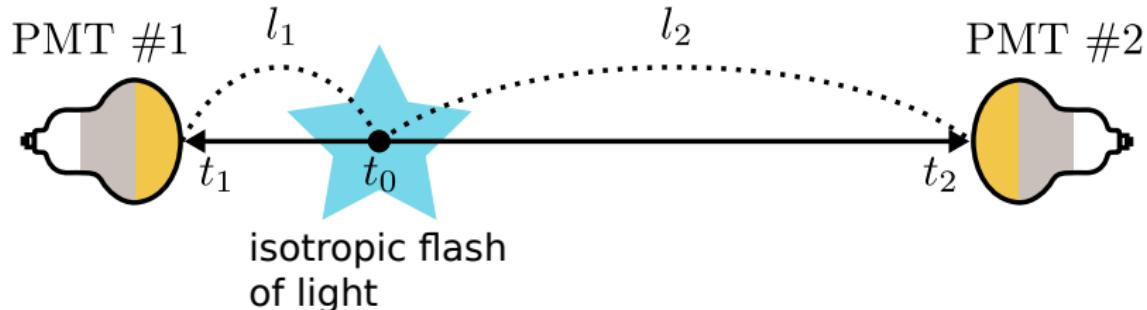
$$q_1 \propto \frac{1}{l_1^2}, \quad q_2 \propto \frac{1}{l_2^2}$$

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

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

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

# What weight is used for *center of time*?



$$\text{Let } \Delta t_i \equiv t_i - t_0$$

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

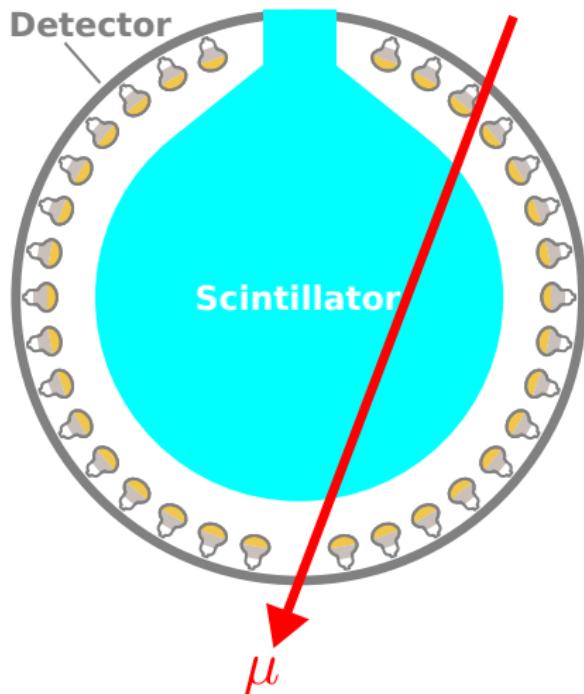
$$\implies -\left(\frac{1}{\Delta t_1}\right)\frac{l_1}{c} + \left(\frac{1}{\Delta t_2}\right)\frac{l_2}{c} = 0$$

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

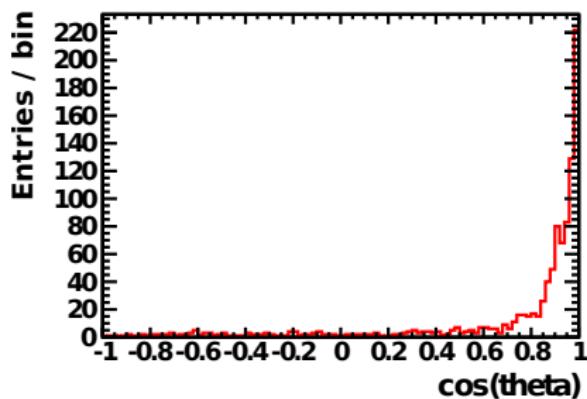
$\therefore$  weight is **inverse of time**:  $w_i = \frac{1}{\Delta t_i}$

# Test algorithm against $\mu$ (data)

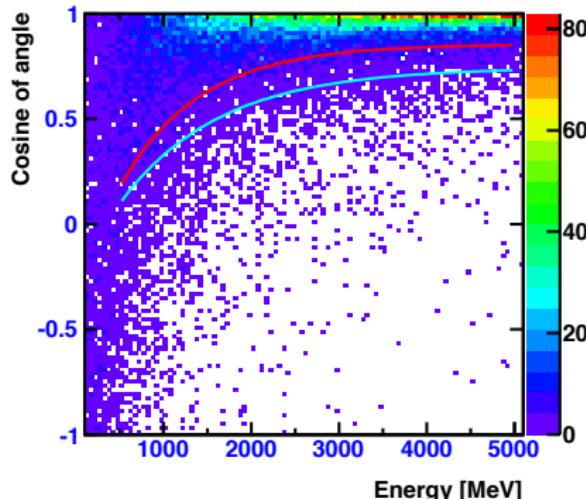
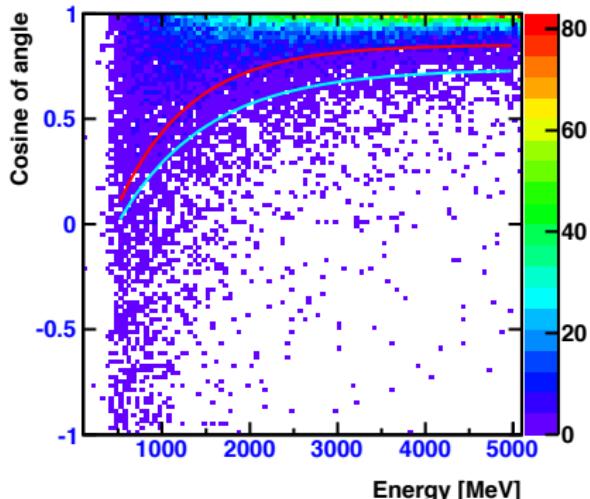
Cosmic ray  $\mu$



Agreement with  $\mu$ -fitter  
which uses  
entry/exit points



# Test algorithm against $\nu$ (MC)



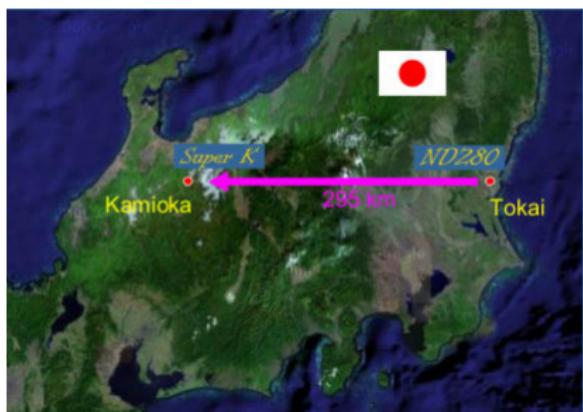
Legend:

- $1\sigma$  of reconstructed angle from  $\nu$  direction
- $1\sigma$  of lepton angle from  $\nu$  direction

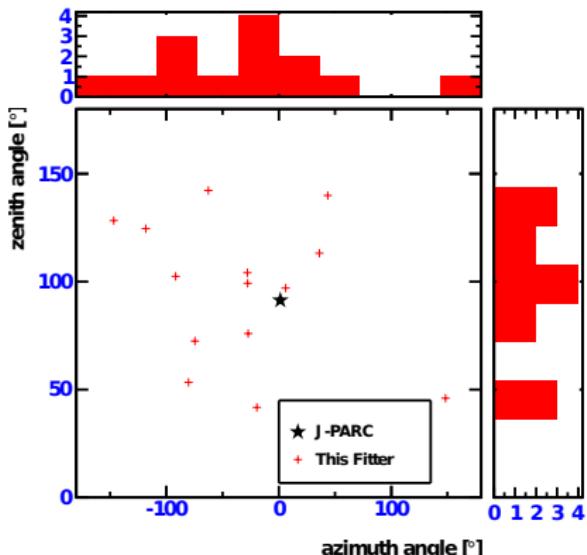
# Test algorithm against T2K events (data)

(Selected with spill-time so no backgrounds)

Map



Agreement with J-PARC  
direction



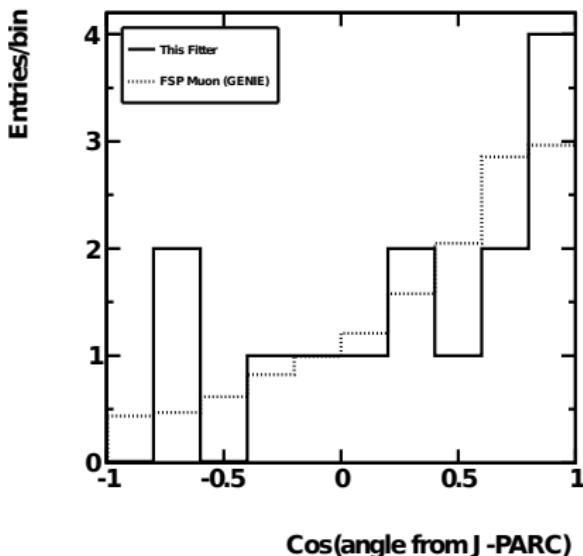
# Test algorithm against T2K events (data)

(Selected with spill-time so no backgrounds)

Map



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



# Track Reconstruction and Particle ID

# Hellgartner's algorithm

(former LENA grad student)

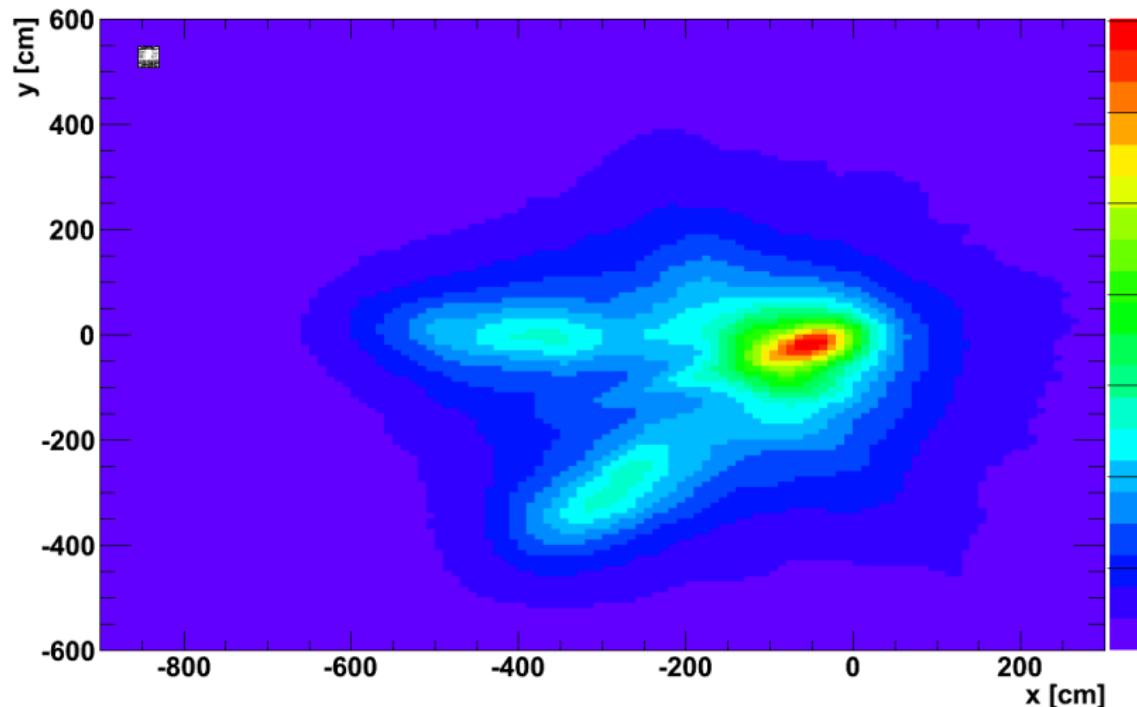
$$h(\vec{x}, t) = \sum_{i=1}^{N_{\text{PMT}}} \Theta(q_i - q_{\text{threshold}}) \sum_{j=1}^{N_{\gamma}} f(t_{ij} - t_i^{\text{TOF}}, t)$$

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

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

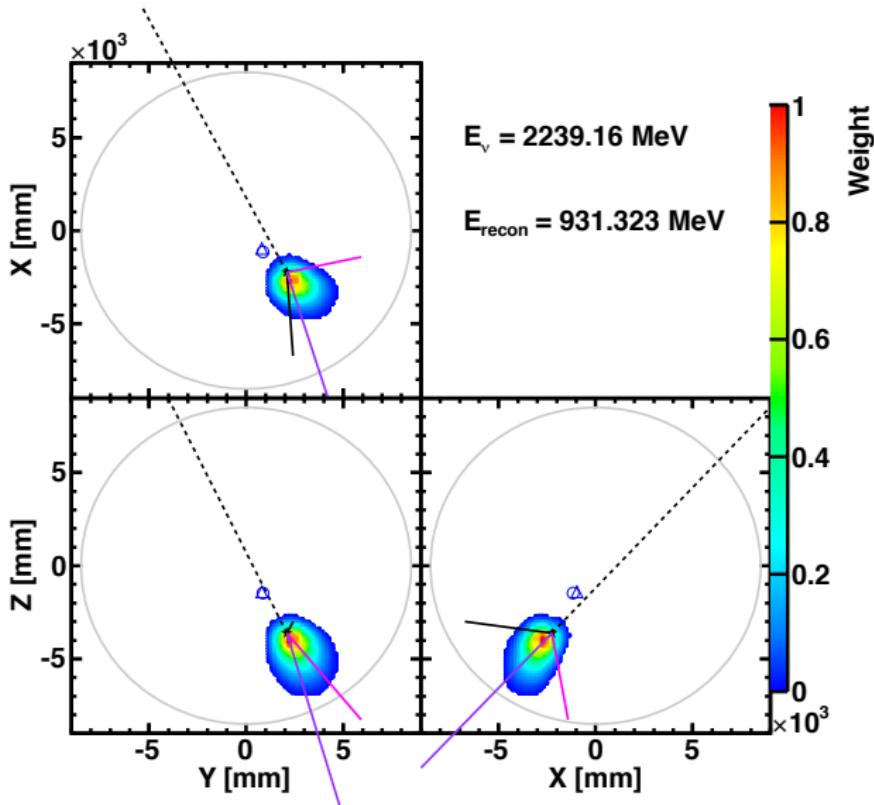
**Figure of merit** for each test point in space  $= \int_{-\infty}^{\infty} |h(\vec{x}, t)|^2 dt$

# Test Hellgartner on double 1 GeV muons (MC)



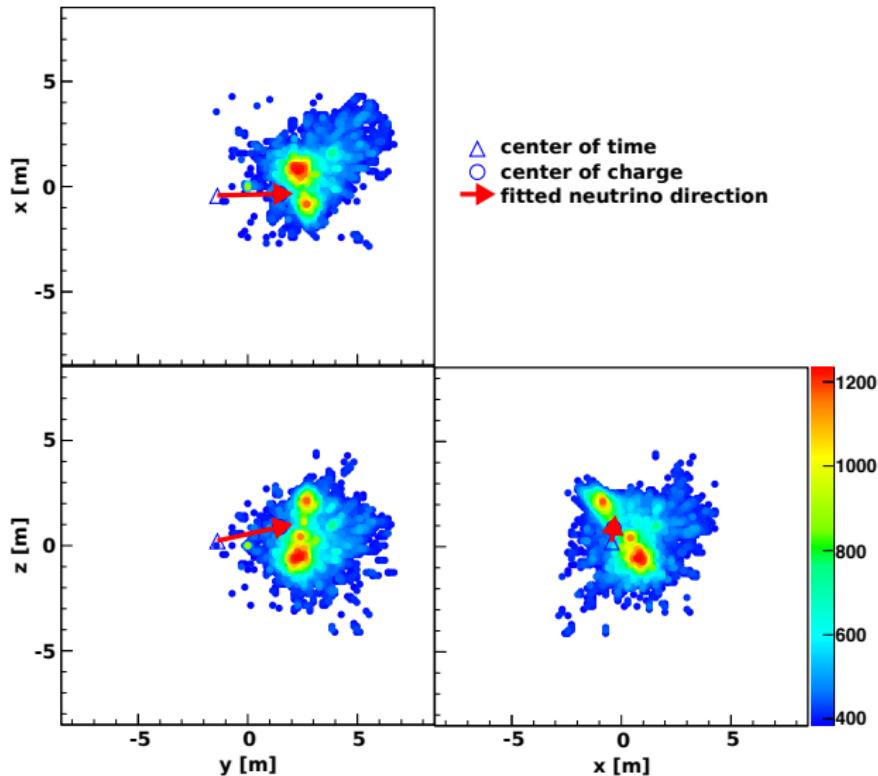
Dominikus Hellgartner

# Test Hellgartner on 2 GeV $\nu_e$ (MC)



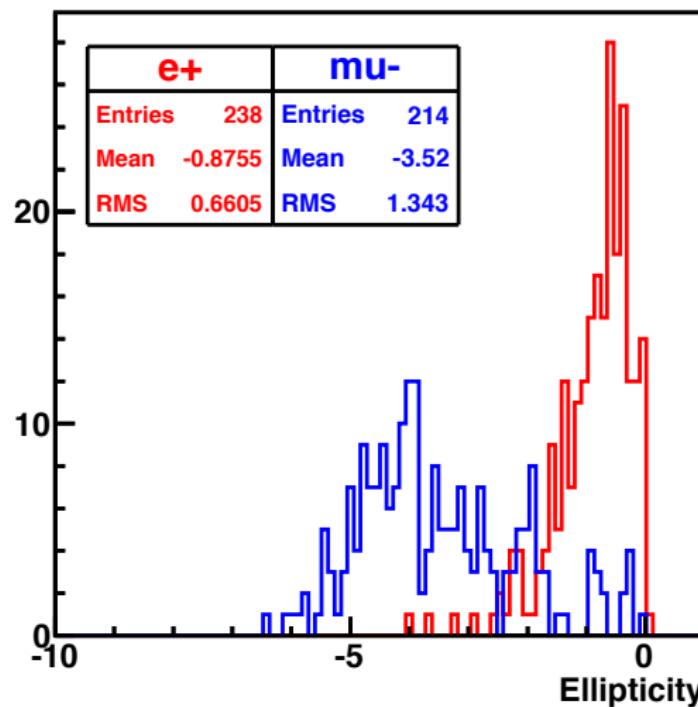
# Test Hellgartner on T2K events (data)

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



# Test lepton discrimination (MC)

(Using track ellipticity)

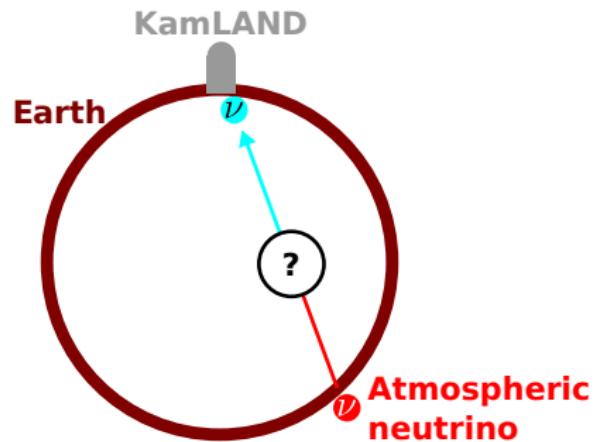
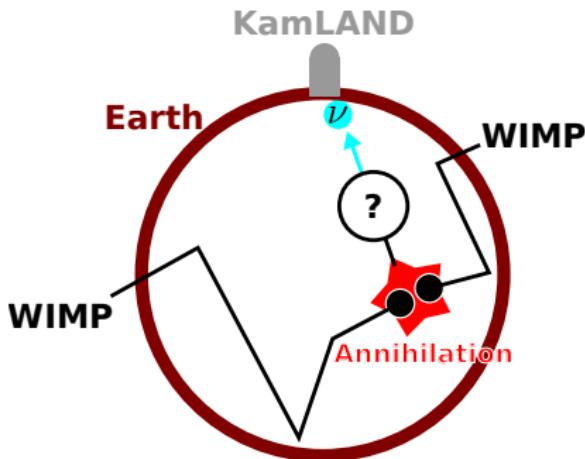


# Search for dark matter

# Dark matter detection scheme

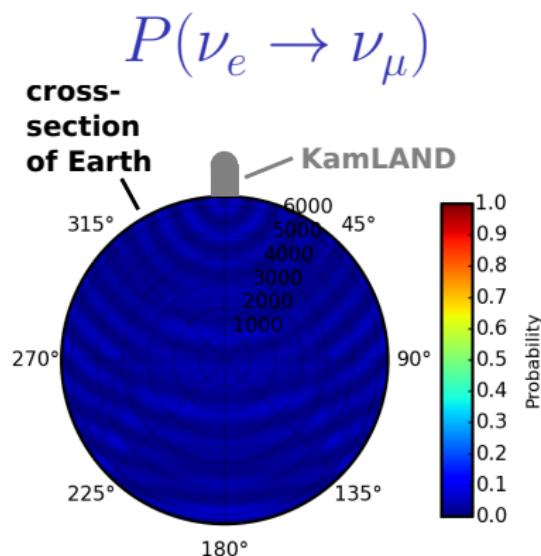
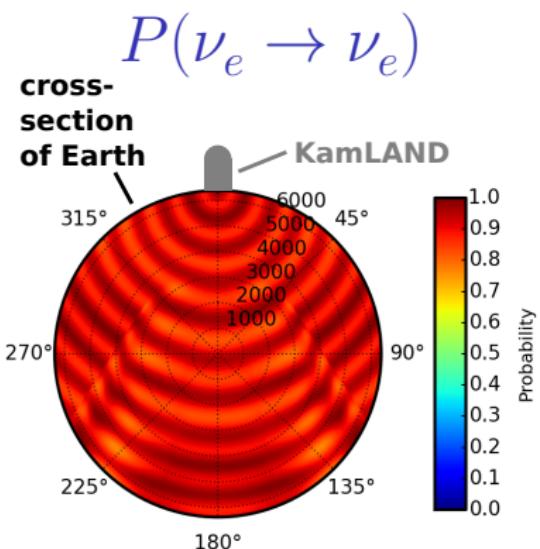
Signal: Dark matter (WIMP)  
annihilation induced  $\nu$

Background: atmospheric  $\nu$



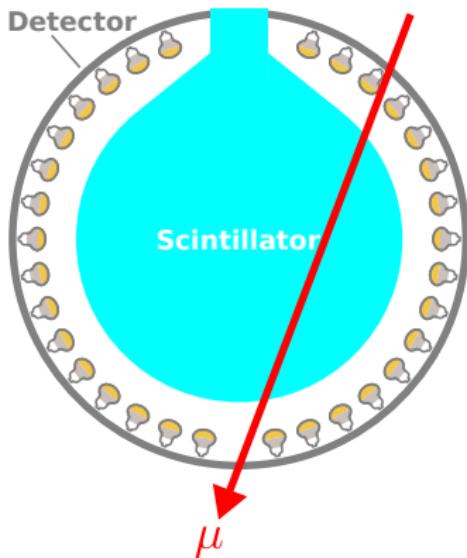
# $1 \text{ GeV } \nu_e$ oscillation probability $P(\nu_e \rightarrow \nu_x)$ from inside Earth to KamLAND

(PDG 2014 oscillation parameters, PREM)

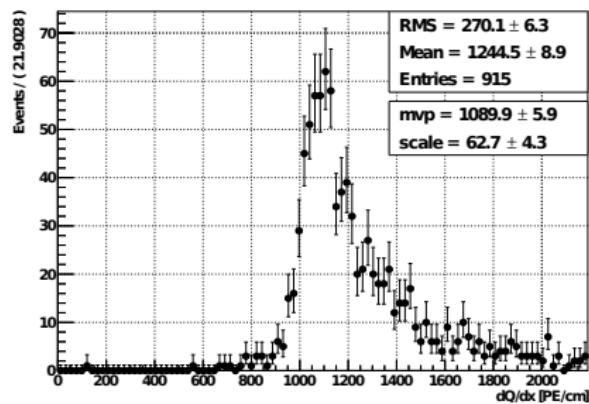


# High energy ( $\gtrsim$ GeV) calibration

Cosmic ray  $\mu$   
traversing scintillator

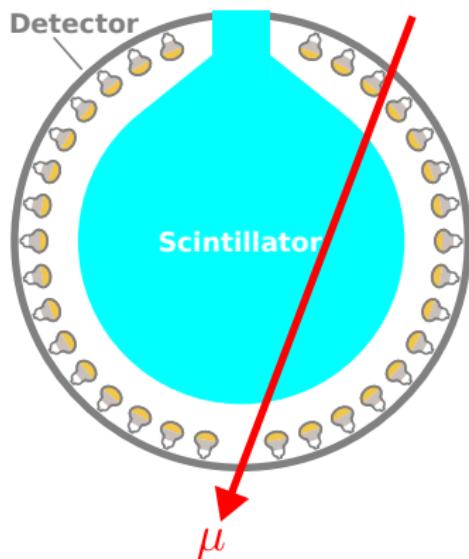


$\frac{dQ}{dx}$  [p.e./MeV] (data)

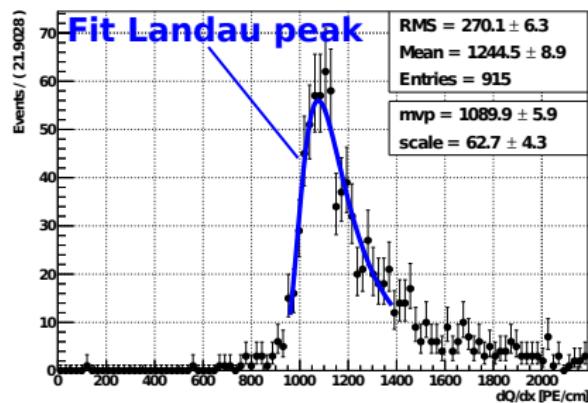


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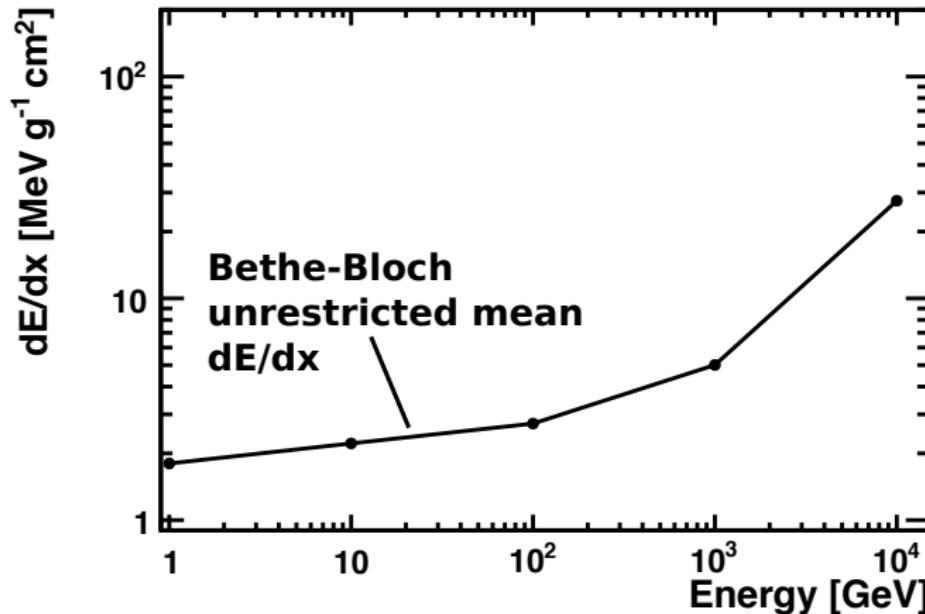
Cosmic ray  $\mu$   
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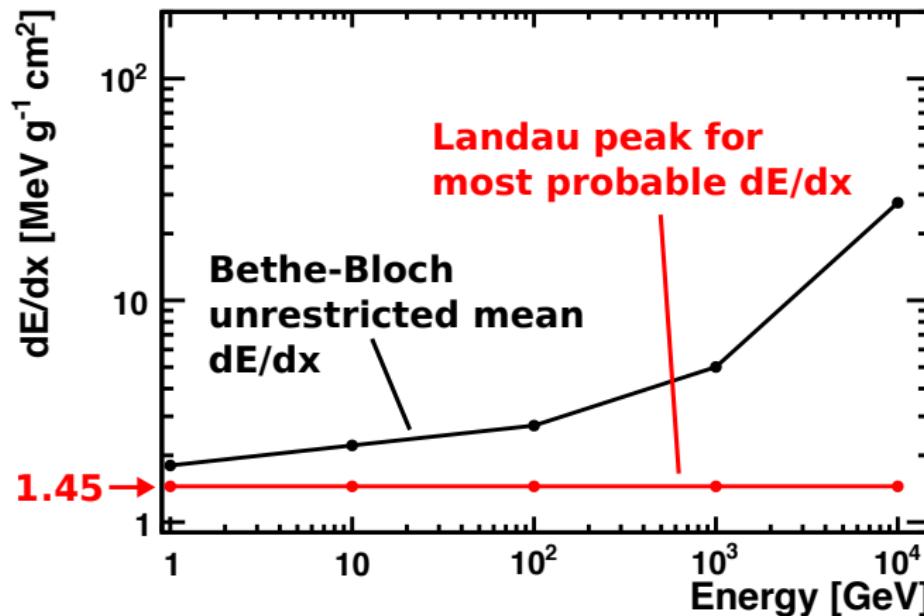
$\frac{dQ}{dx}$  [p.e./MeV] (data)



# Fit $\frac{dE}{dx}$ for $\mu$ in scintillator (MC)

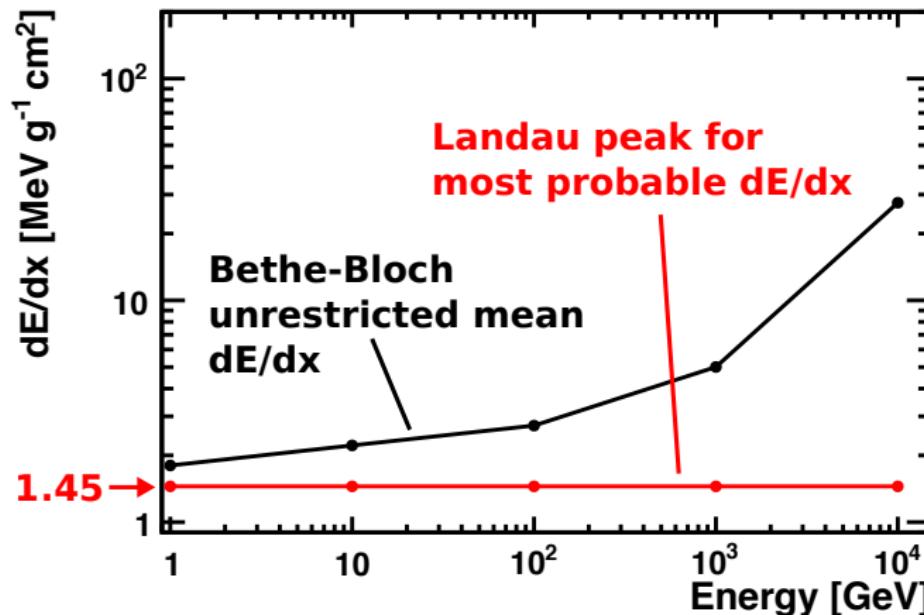


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- ▶ Peak is stable across huge energy range!

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- ▶ Peak is stable across huge energy range!
- ▶ ⇒ Use **peak** instead of mean for calibration

# Data selection

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

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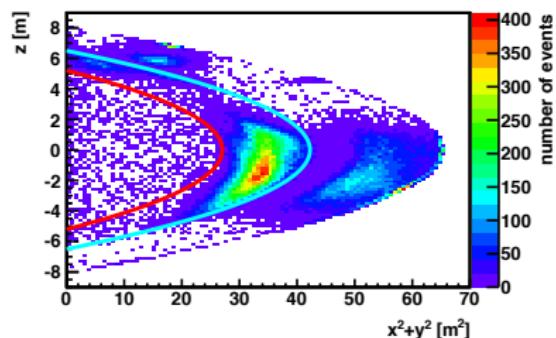
- ▶ Live time: 3671 days ( $\sim 10$  years)
- ▶ Event selection criteria:
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 $\implies$  Outer detector PMT hits  $< 5$

# Data selection

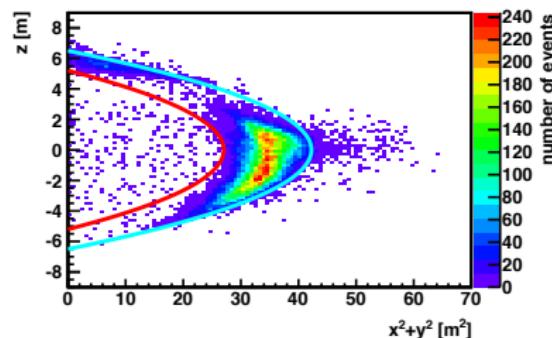
- ▶ Live time: 3671 days ( $\sim 10$  years)
- ▶ Event selection criteria:
  - ▶ Fully contained events
    - $\implies$  Outer detector PMT hits < 5
  - ▶  $E_{\text{reconstructed}} > 1 \text{ GeV}$  (theoretically preferred)

# Reconstructed Vertex (data)

$E_{\text{reconstructed}} > 30 \text{ MeV}$



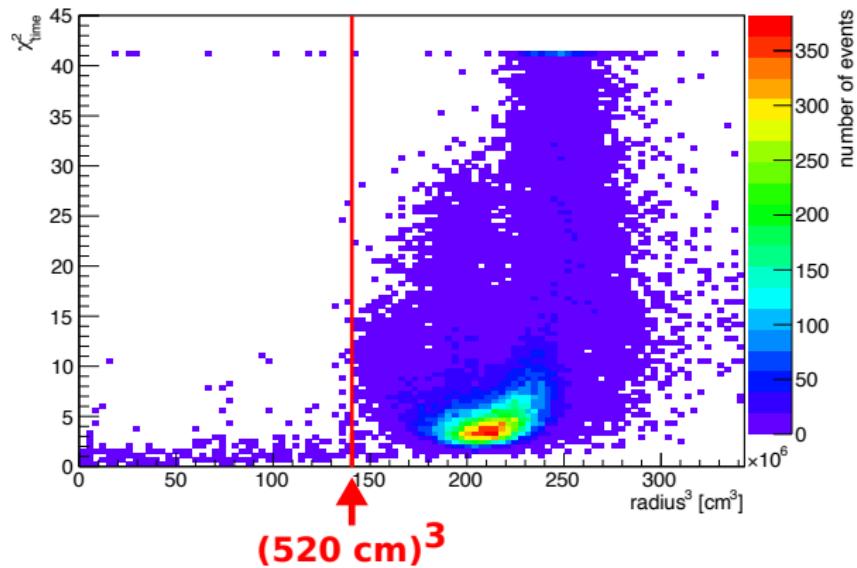
$E_{\text{reconstructed}} > 1 \text{ GeV}$



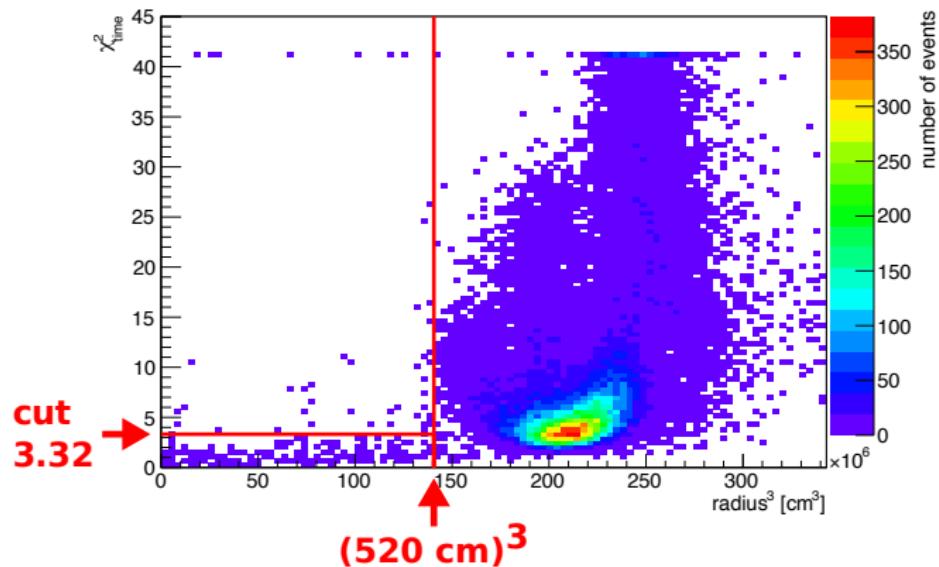
Legend:

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

# Vertex $\chi^2_{\text{time}}$ (test of event point-likeness)



# Vertex $\chi^2_{\text{time}}$ (test of event point-likeness)

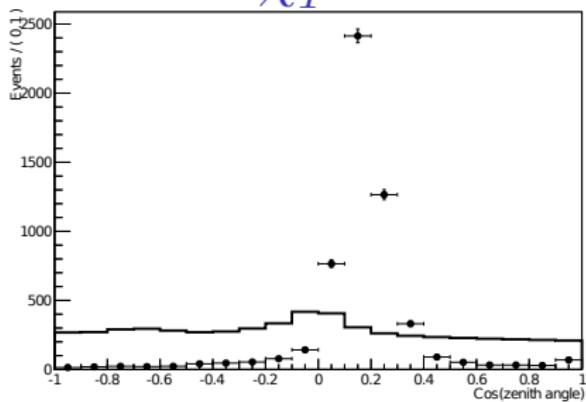


- ▶ Reject events above  $\chi^2_{\text{time}} = 3.32$  that are too elongated in shape (most likely  $\mu$ )

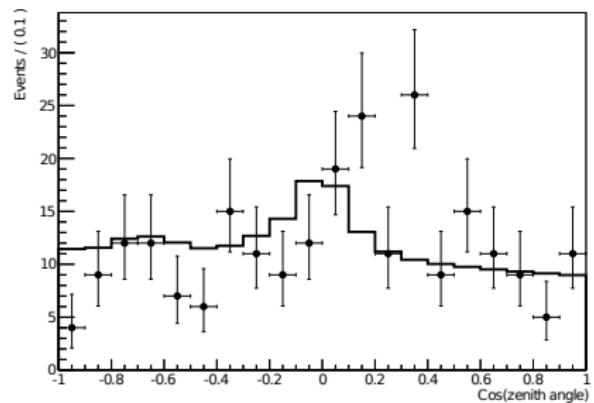
# Fit data to background model

(with  $\chi_T^2 < 3.32$  cut)

No  $\chi_T^2$  cut



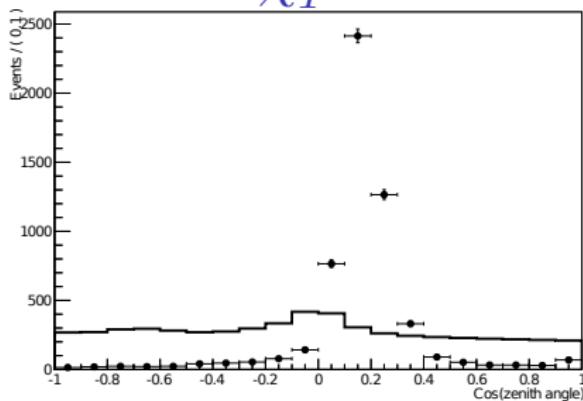
$\chi_T^2 < 3.32$



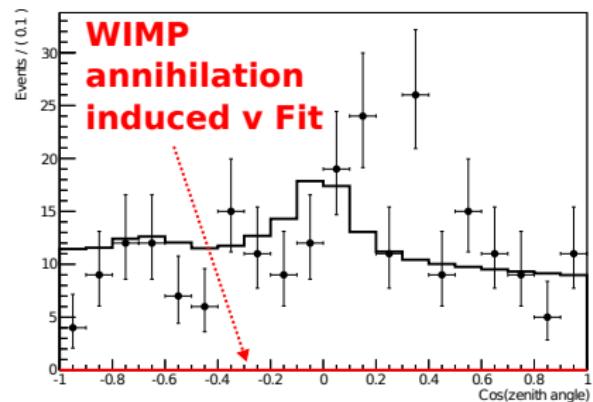
# Fit data to background model

(with  $\chi_T^2 < 3.32$  cut)

No  $\chi_T^2$  cut



$\chi_T^2 < 3.32$



# Signal event rate equation

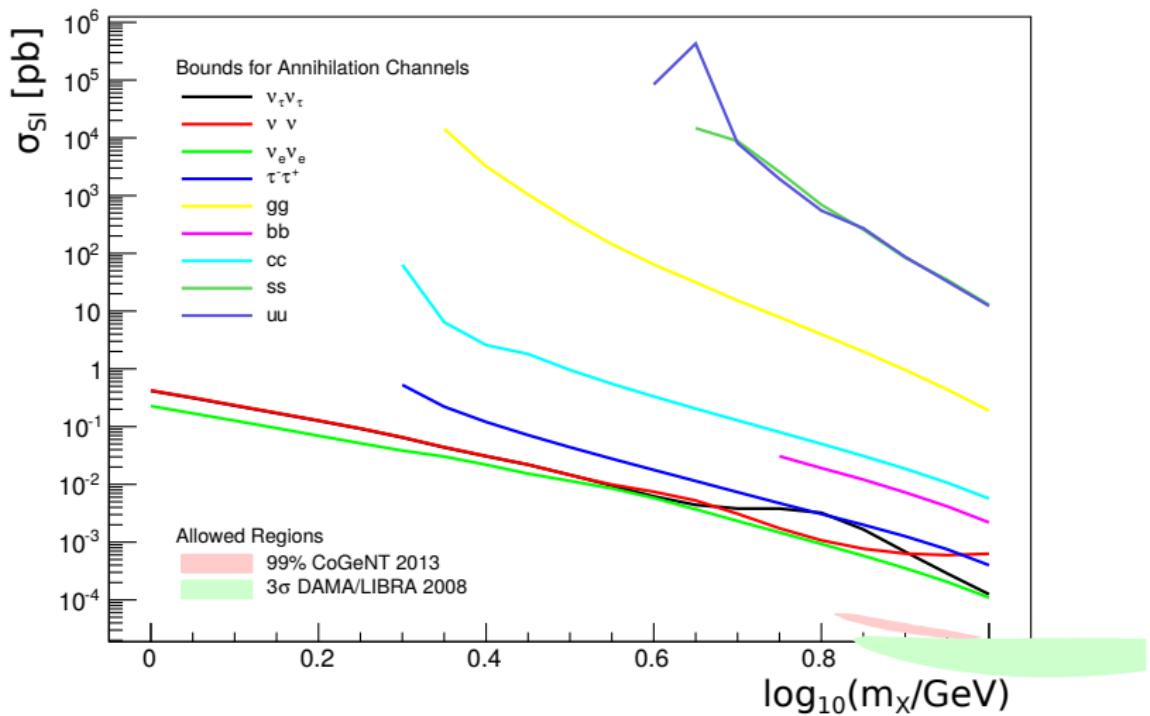
$$\text{rate}_{\text{signal}} = \Gamma_A \times \sum_{\substack{\text{channel}=i \\ \nu-\text{flavor}=\alpha}} \left[ B_i \int dE_\alpha \frac{dN_{i,\alpha}}{dE_\alpha} \frac{\sigma_{\text{effective}}(E_\alpha)}{4\pi R_{\text{Earth}}^2} \right]$$

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

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

# WIMP $\sigma_{\text{SI}}$ bounds (preliminary)

(90 % C.L.)



# Summary

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

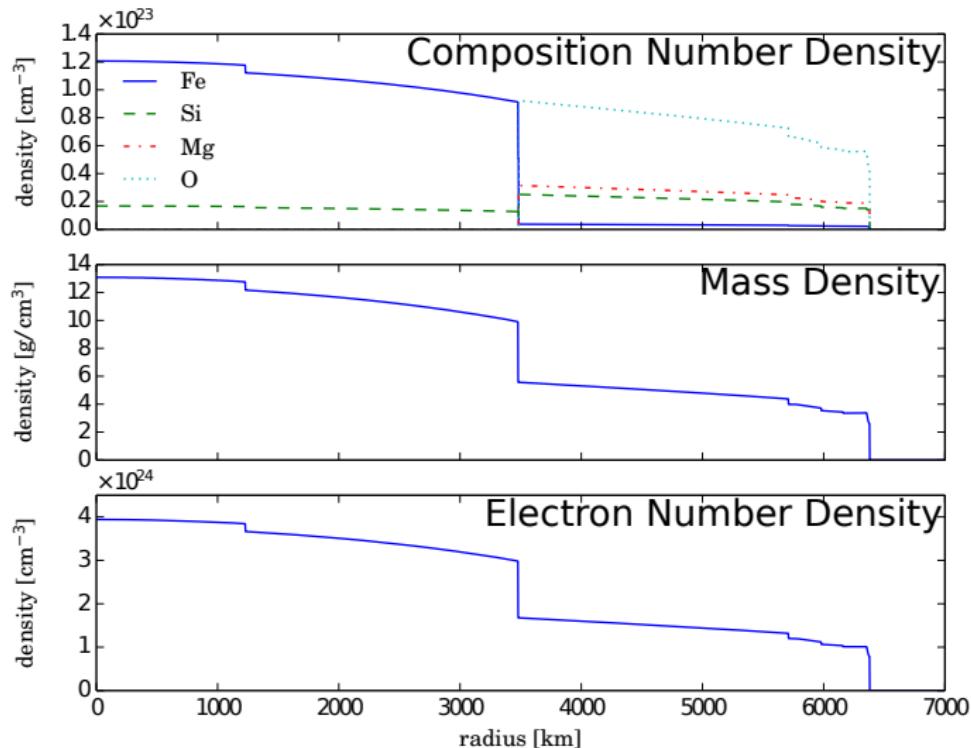
# Thank you for listening!

# Backup slides

# KamLAND: features

- ▶ Commissioned: 2001
- ▶ Medium: liquid scintillator
  - ▶ Decay constants:  $\tau_1 = 4.0 \text{ ns}$ ,  $\tau_2 = 8.6 \text{ ns}$
- ▶ 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:  $\sim \text{MeV } \bar{\nu}_e$  (inverse-beta decay)
- ▶ Energy resolution:  $7.0 \pm 0.1 \% / \sqrt{E(\text{MeV})}$
- ▶ Vertex resolution:  $13.8 \pm 2.3 \text{ cm}$
- ▶ Directional sensitivity: thought to be **NONE**
- ▶ No analysis at higher energies

# Earth Model (PREM)



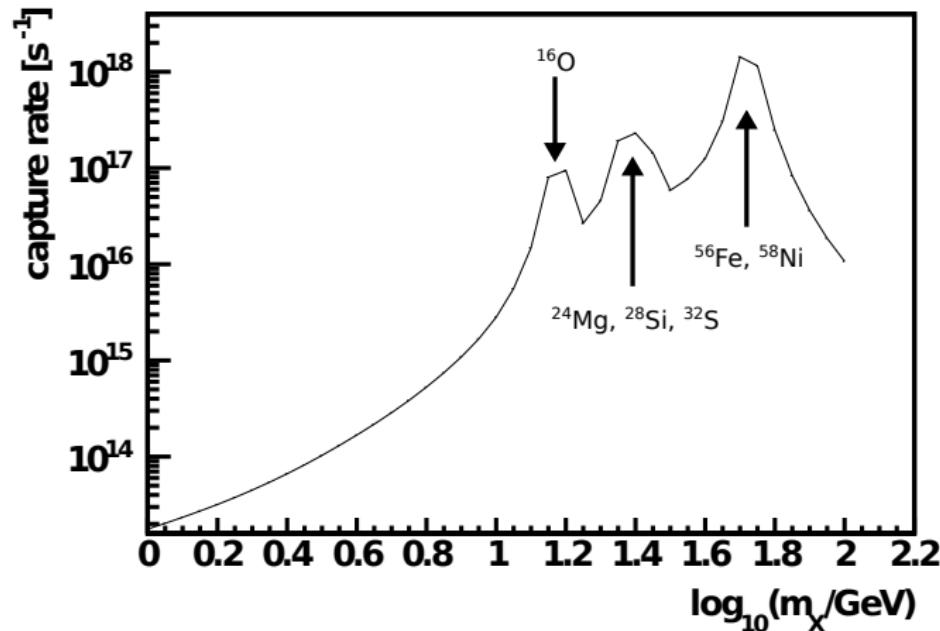
# Neutrino Oscillation Parameters

(normal hierarchy, PDG 2014)

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

# Dark matter capture in Earth vs mass $m_x$

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



# Fit data to background model

