Spallation at Super-Kamiokande: the good, the bad, and the ugly

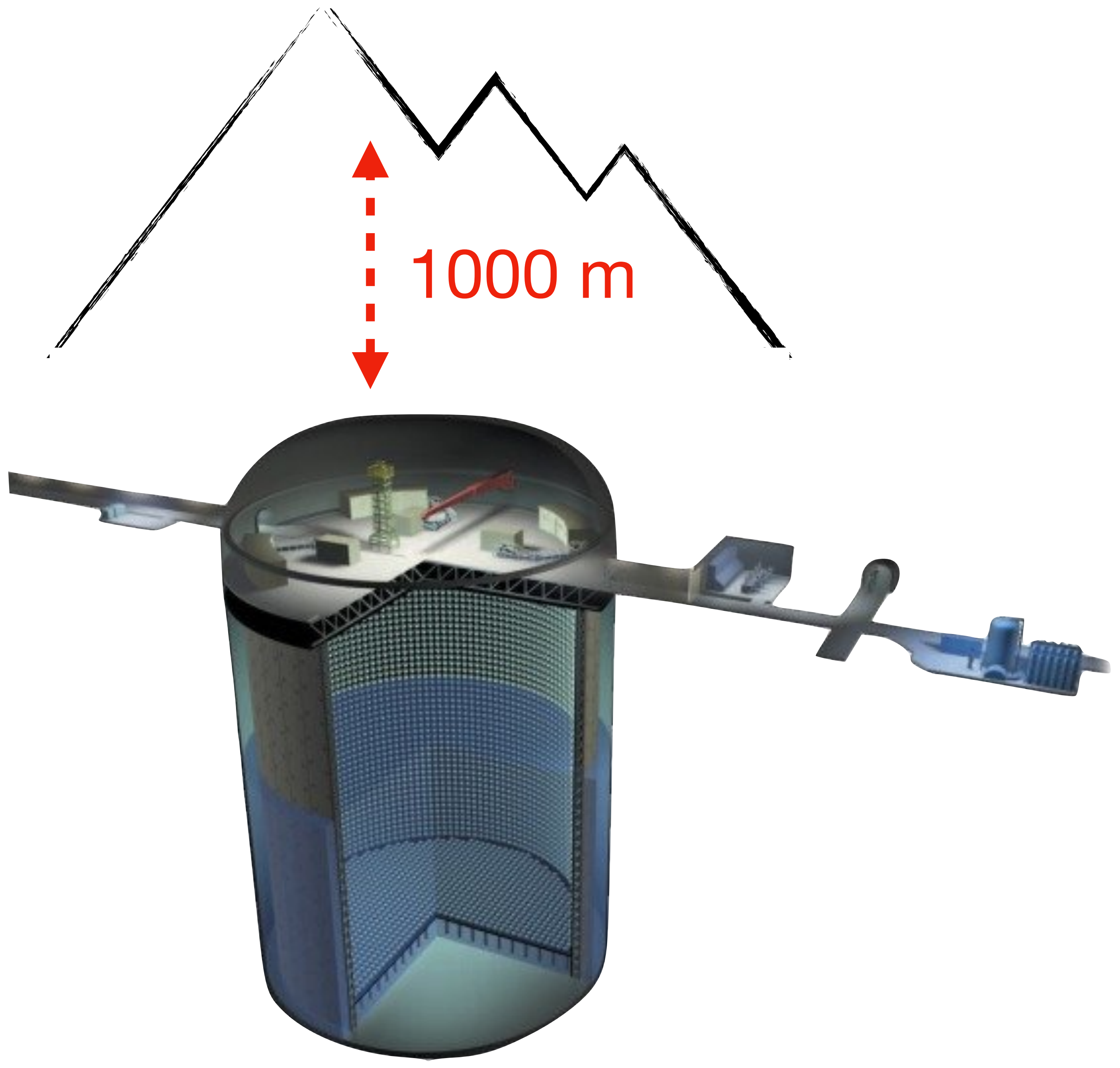
MITP topical workshop

Sonia El Hedri — 20/09/2024

Work done at Laboratoire Leprince-Ringuet
and with the Super-Kamiokande Collaboration

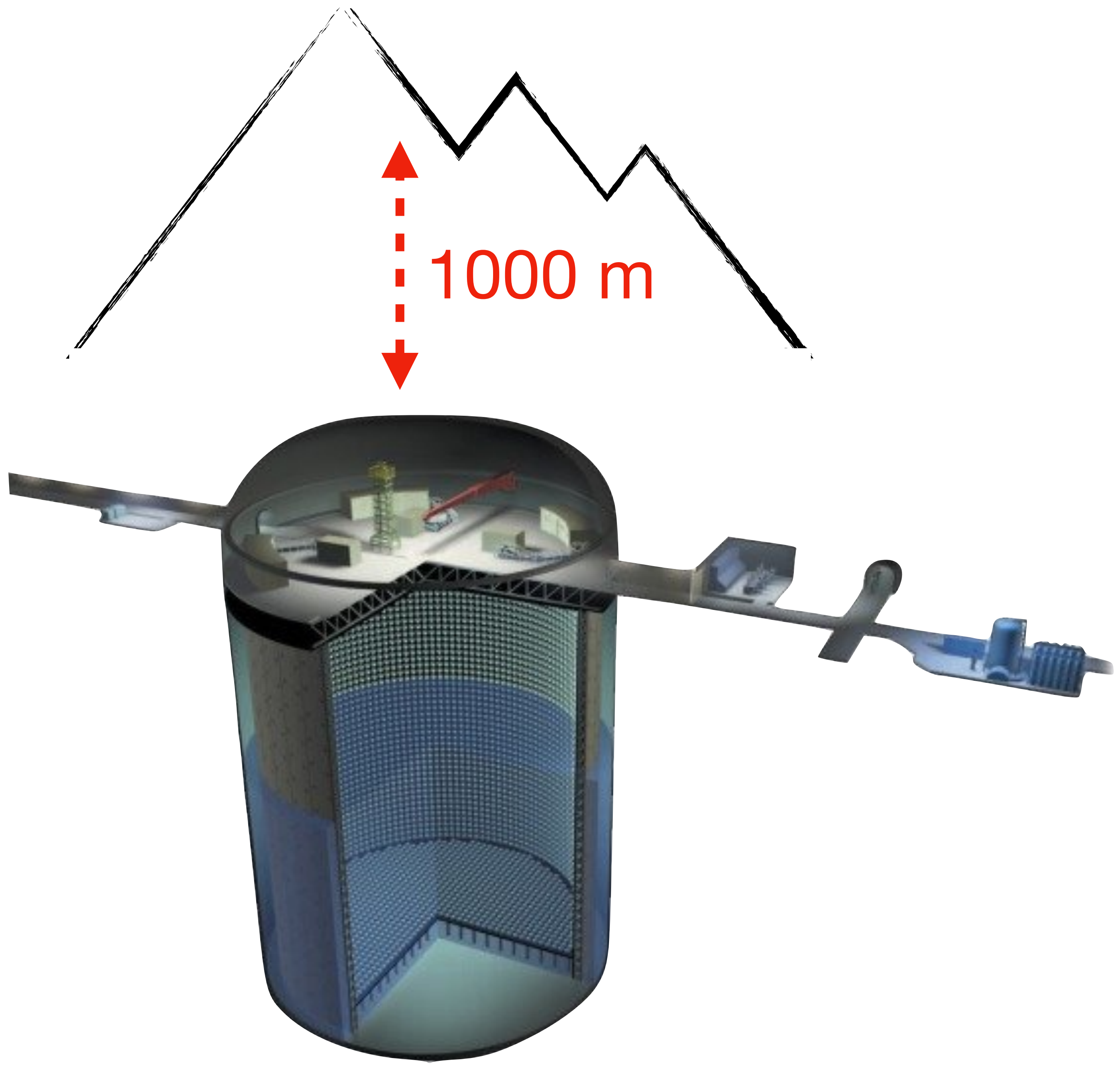
Water Cherenkov detectors for DSNB detection

The Kamiokande family



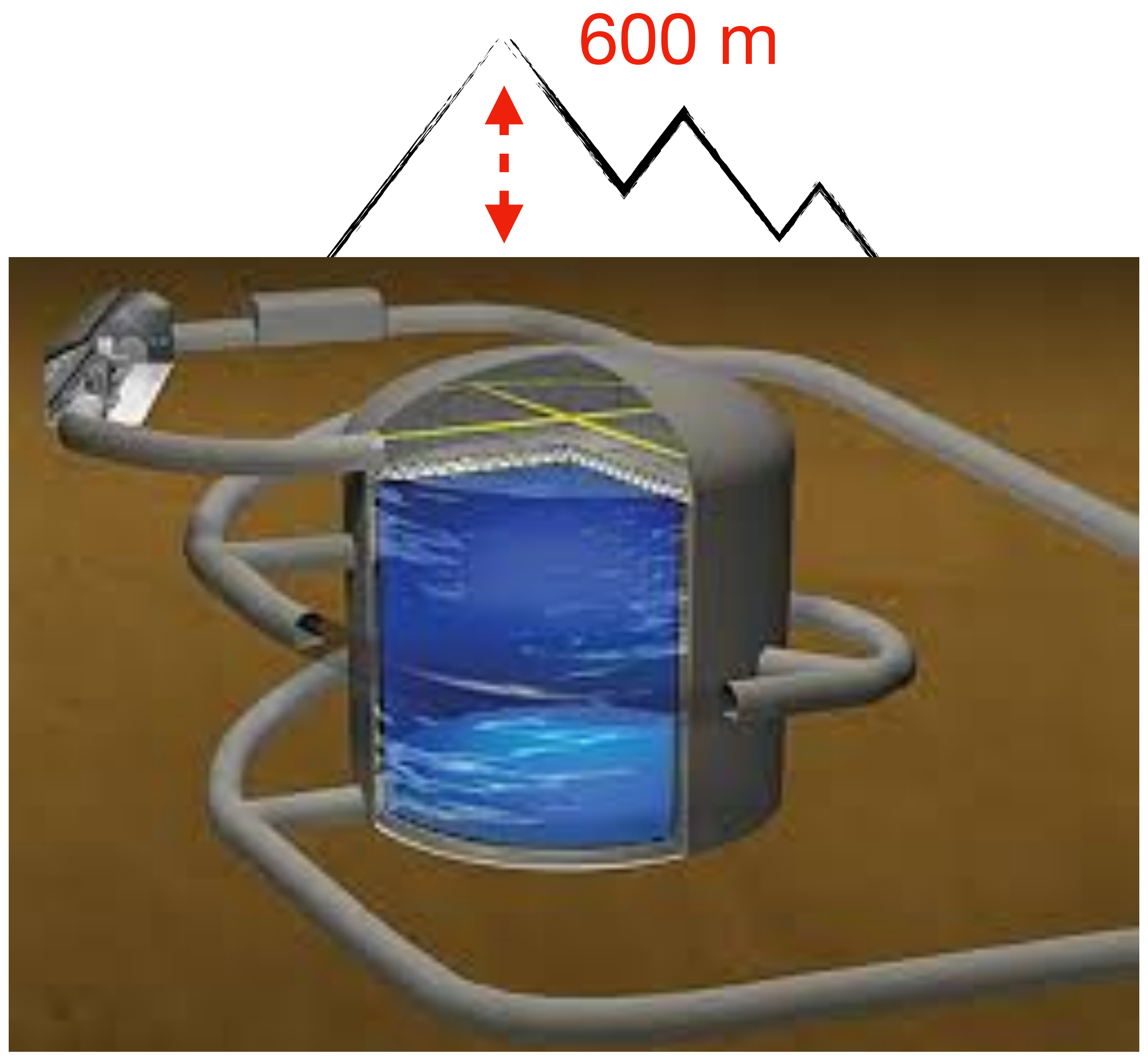
Super-Kamiokande

22.5 kt fiducial volume
11129 photomultipliers
4.5 MeV to ~1 TeV



Super-K Gd

22.5 kt fiducial volume
11129 photomultipliers
4.5 MeV to ~1 TeV
0.033% Gd in water



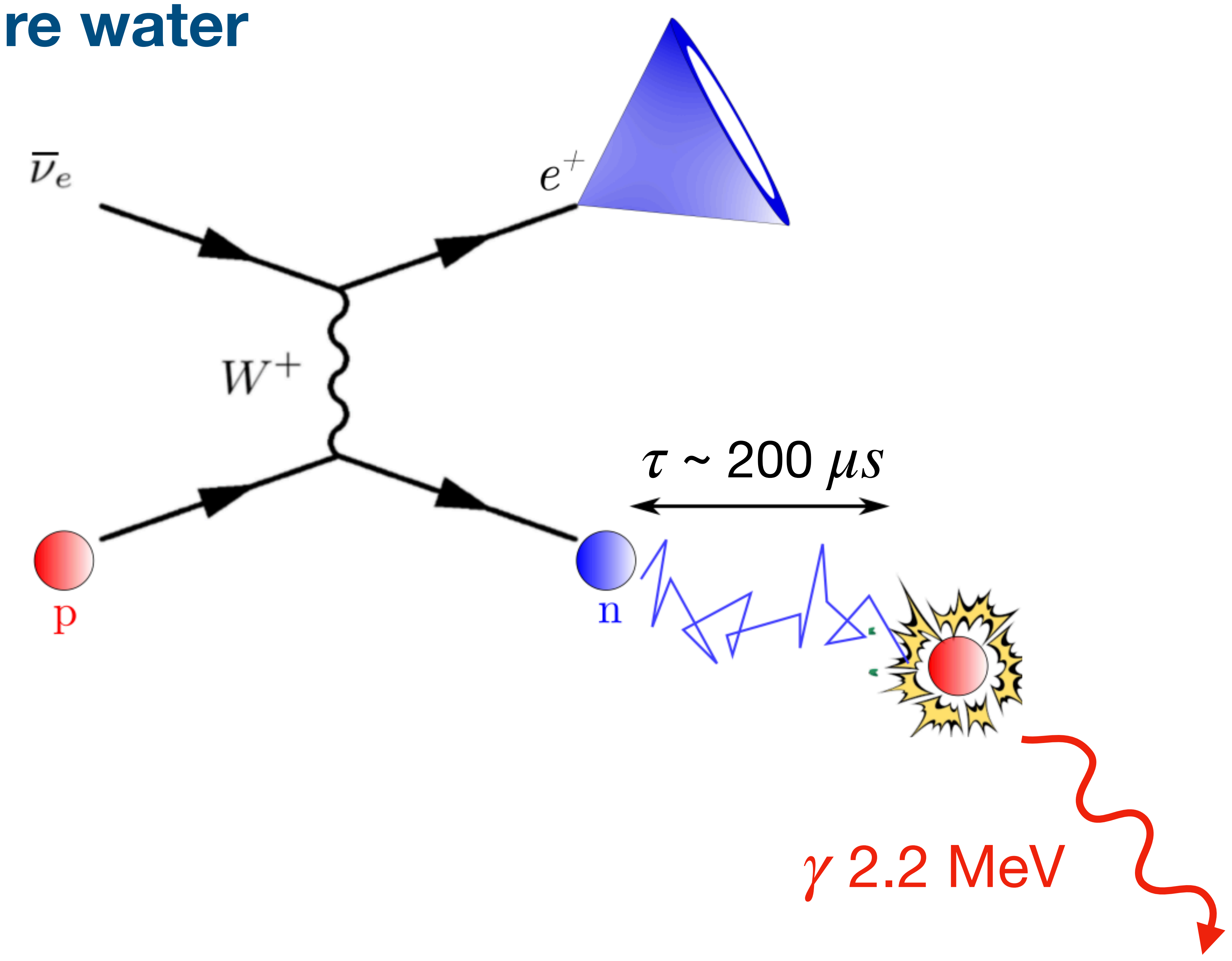
Hyper-Kamiokande

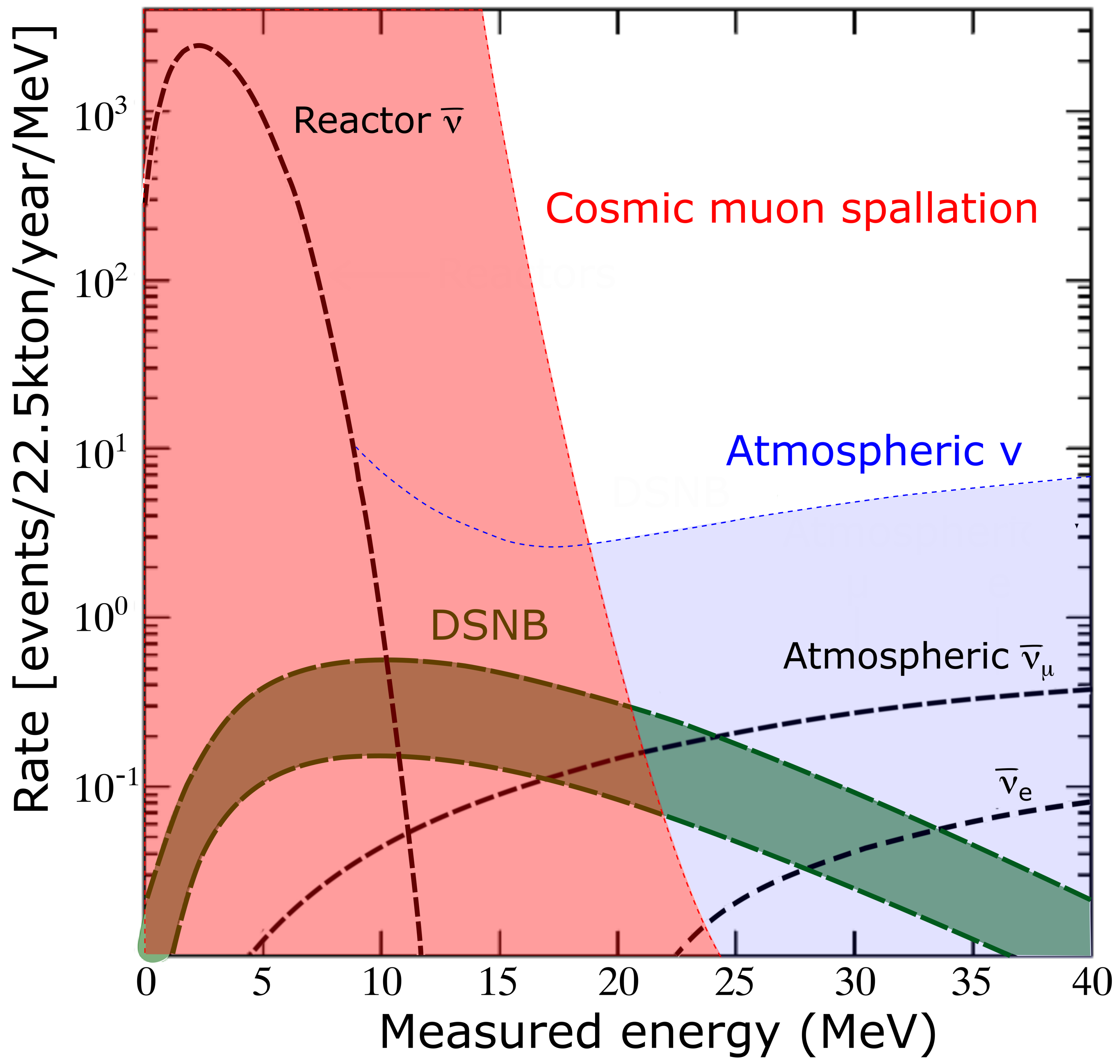
175 kt fiducial volume
~21000 photomultipliers
4.5 MeV to ~1 TeV

DSNB in Water Cherenkov detectors

Inverse beta decay — Main backgrounds

Pure water



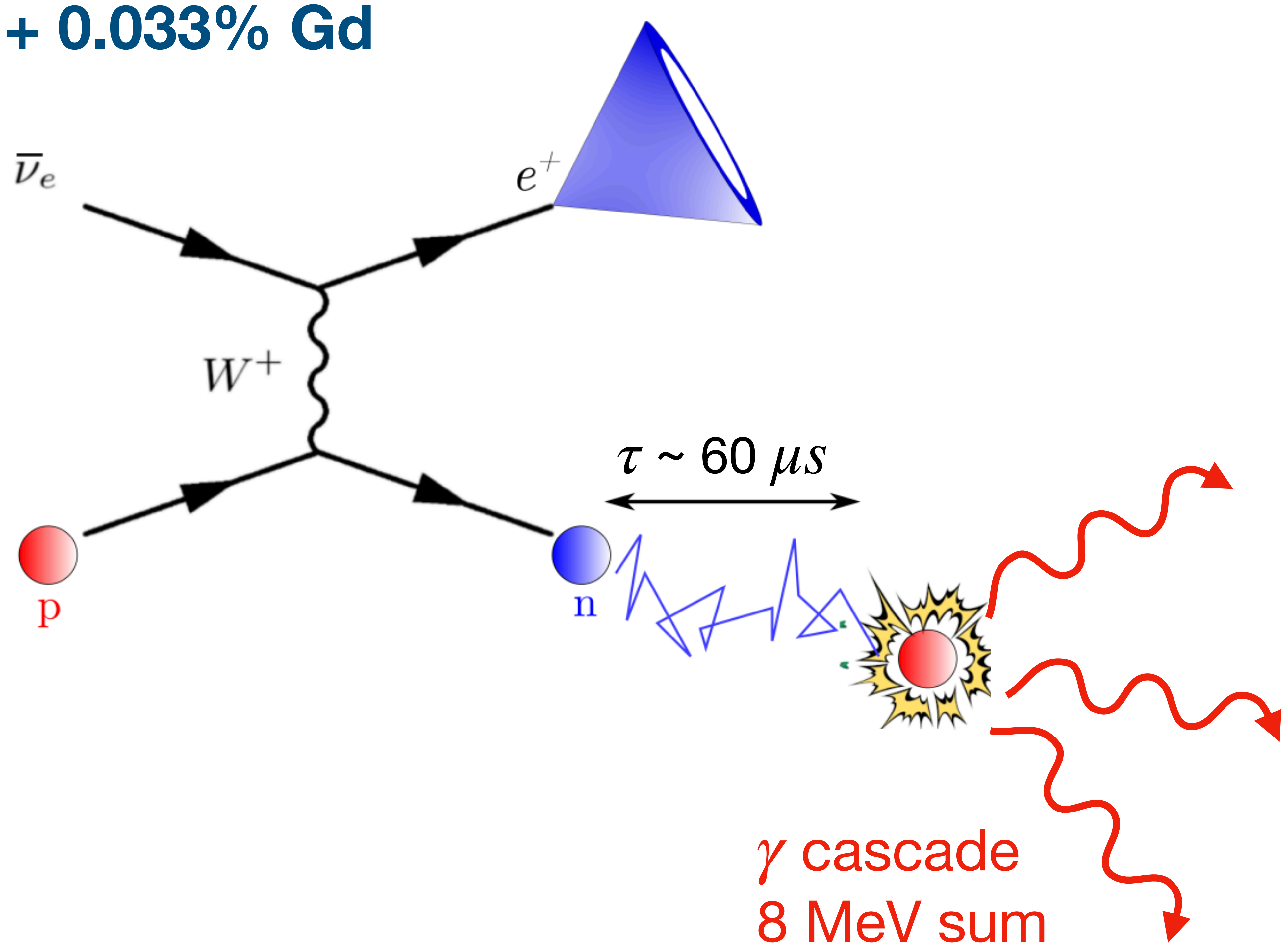


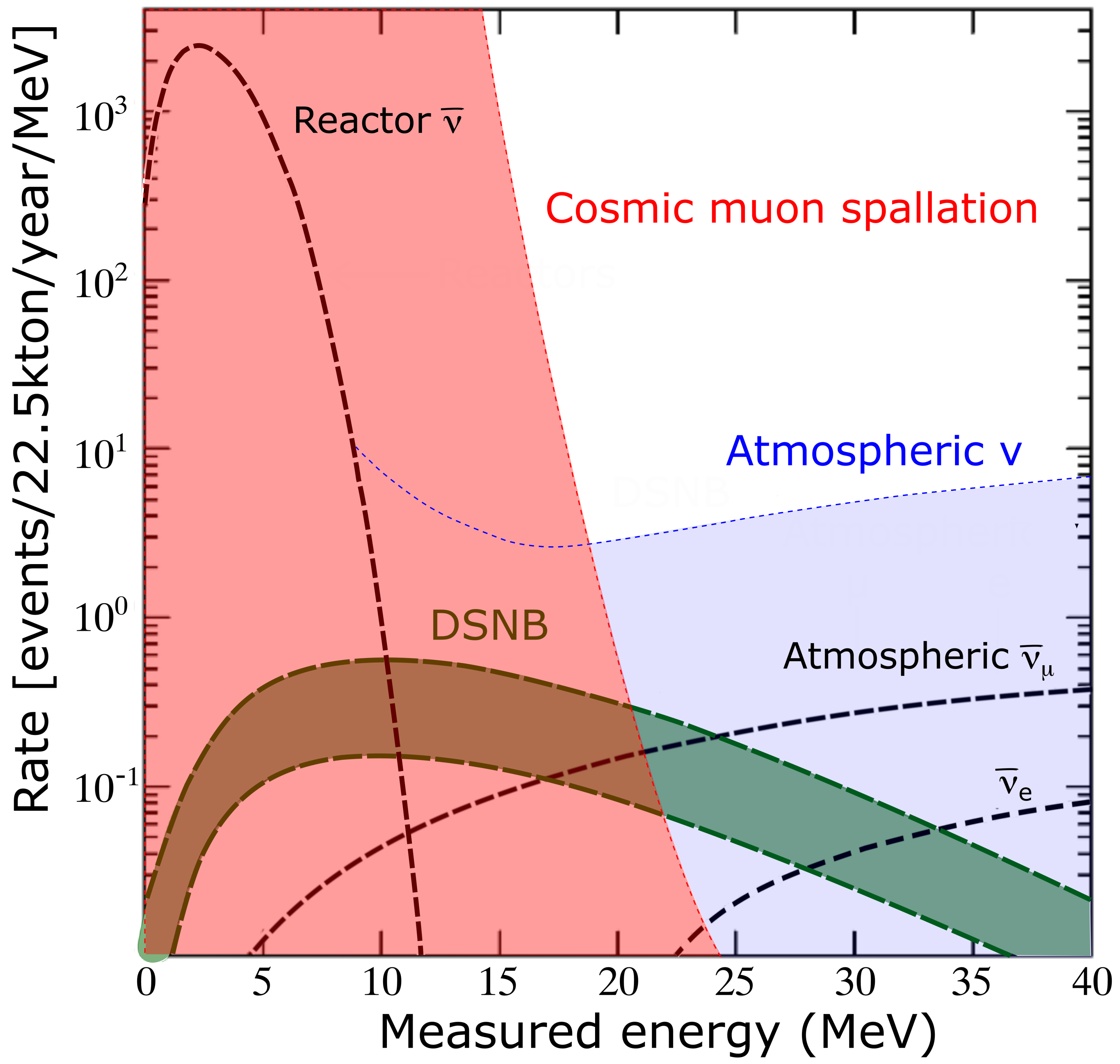
From Beacom and Vagins, Phys. Rev. Lett., 93:171101, 2004

DSNB in Water Cherenkov detectors

Inverse beta decay — Main backgrounds

Water + 0.033% Gd





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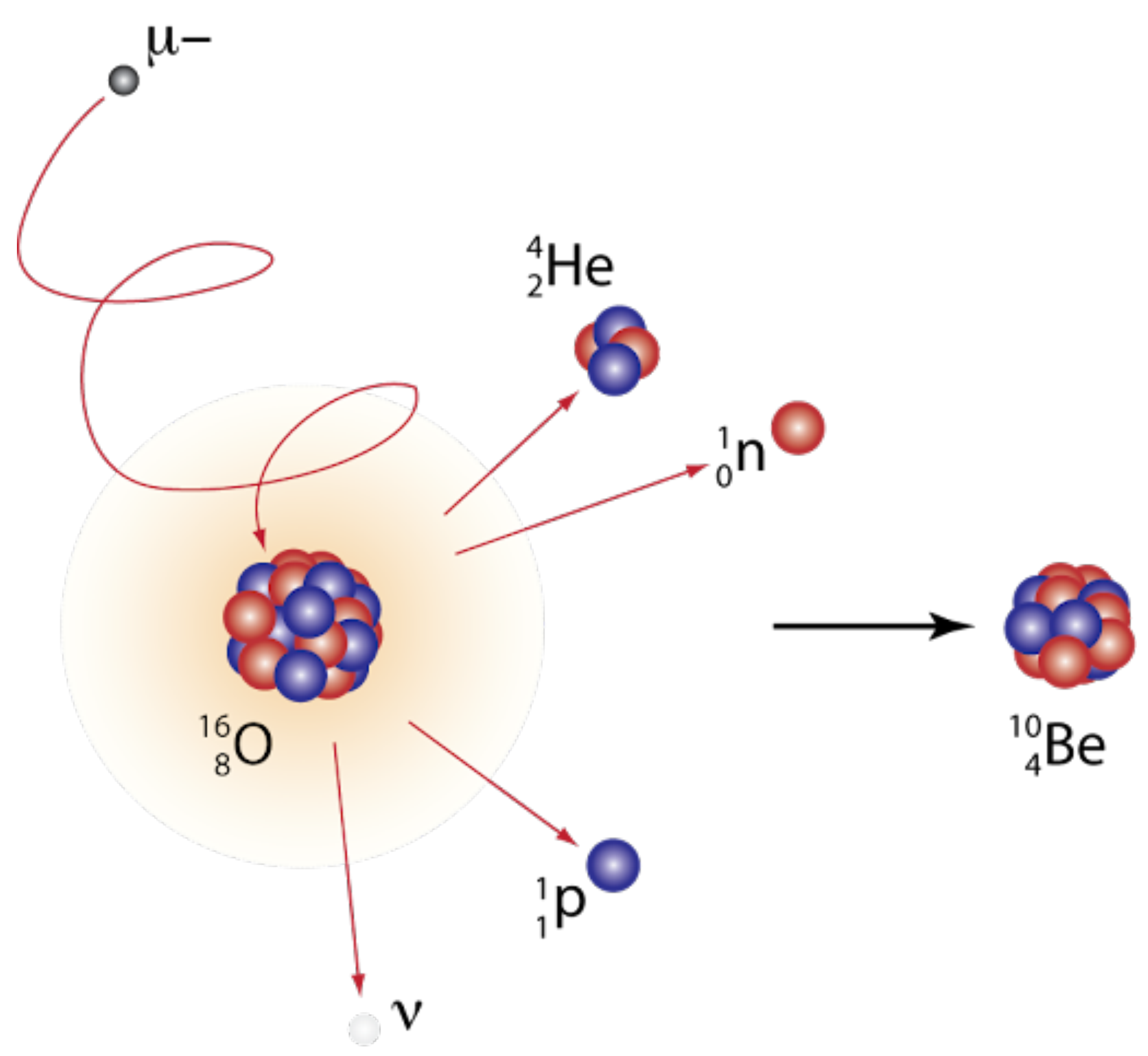
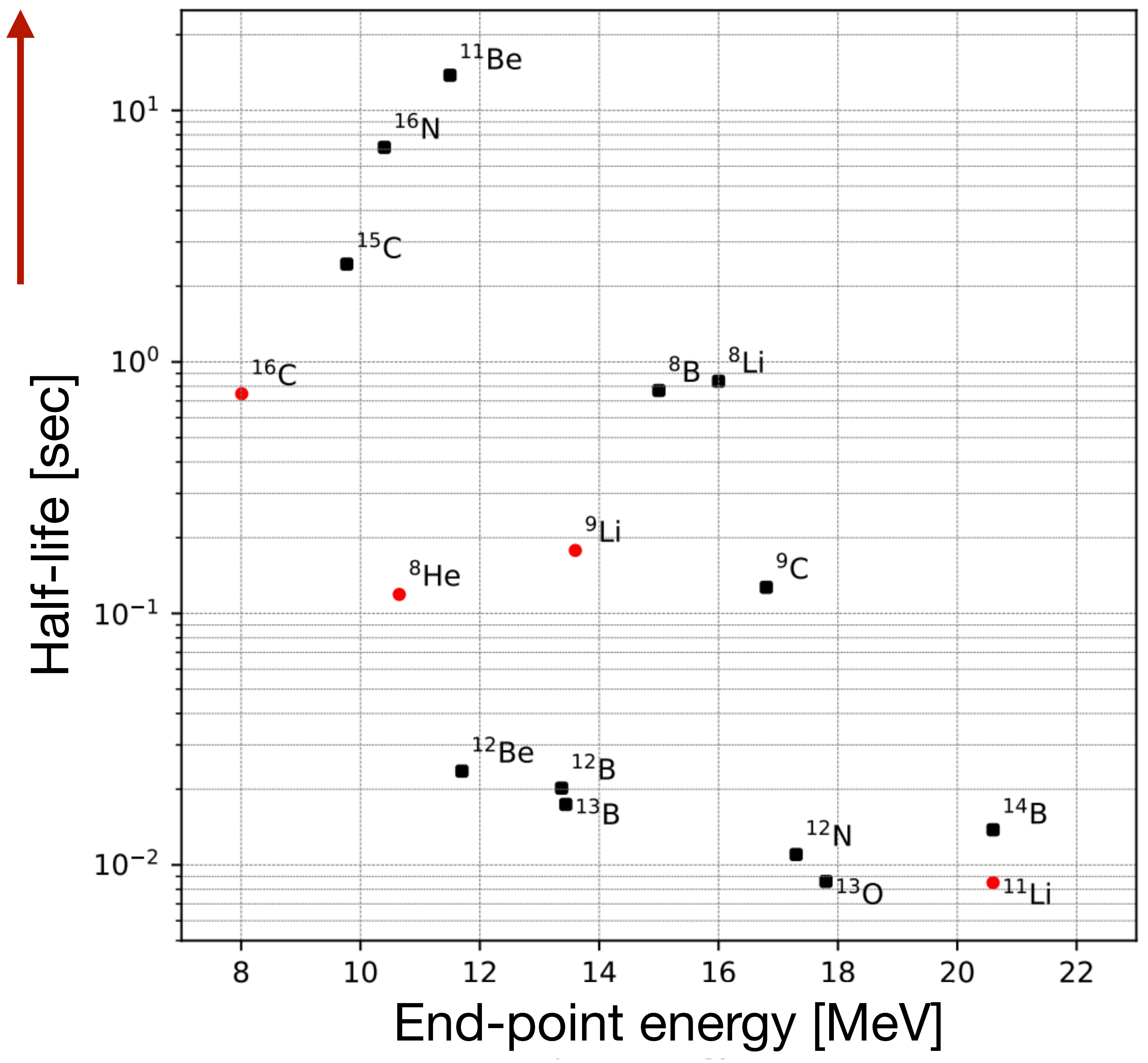
Cosmic muon spallation in water

Production of radioactive isotopes from Oxygen atoms



Half-life larger than time between μs

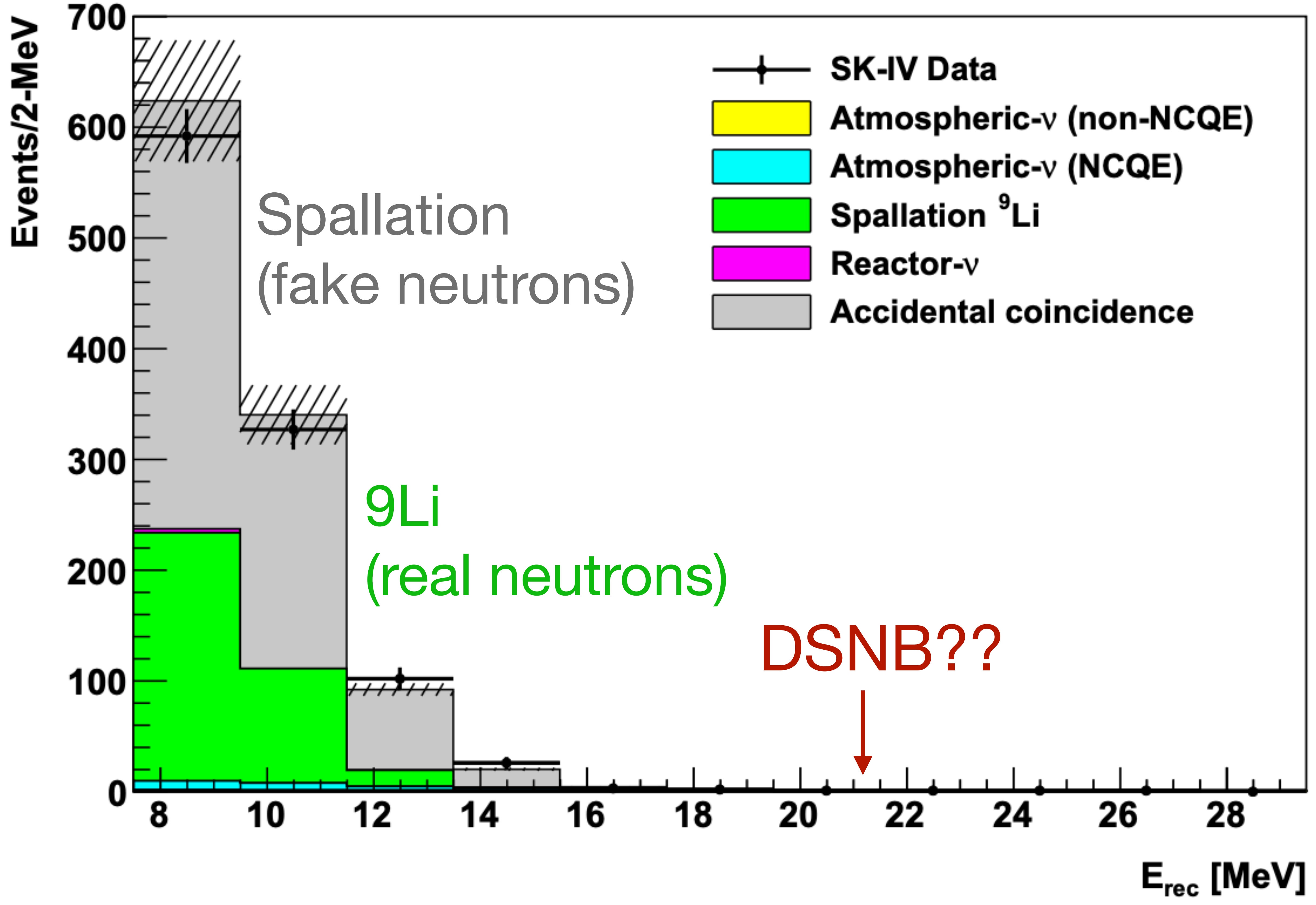


Covers bulk of DSNB spectrum

K. Abe et al (SK collaboration) Phys. Rev. D 104 (2021) 12

Muon-isotope pairing: what if we do not care?

Example: Super-Kamiokande IV DSNB search



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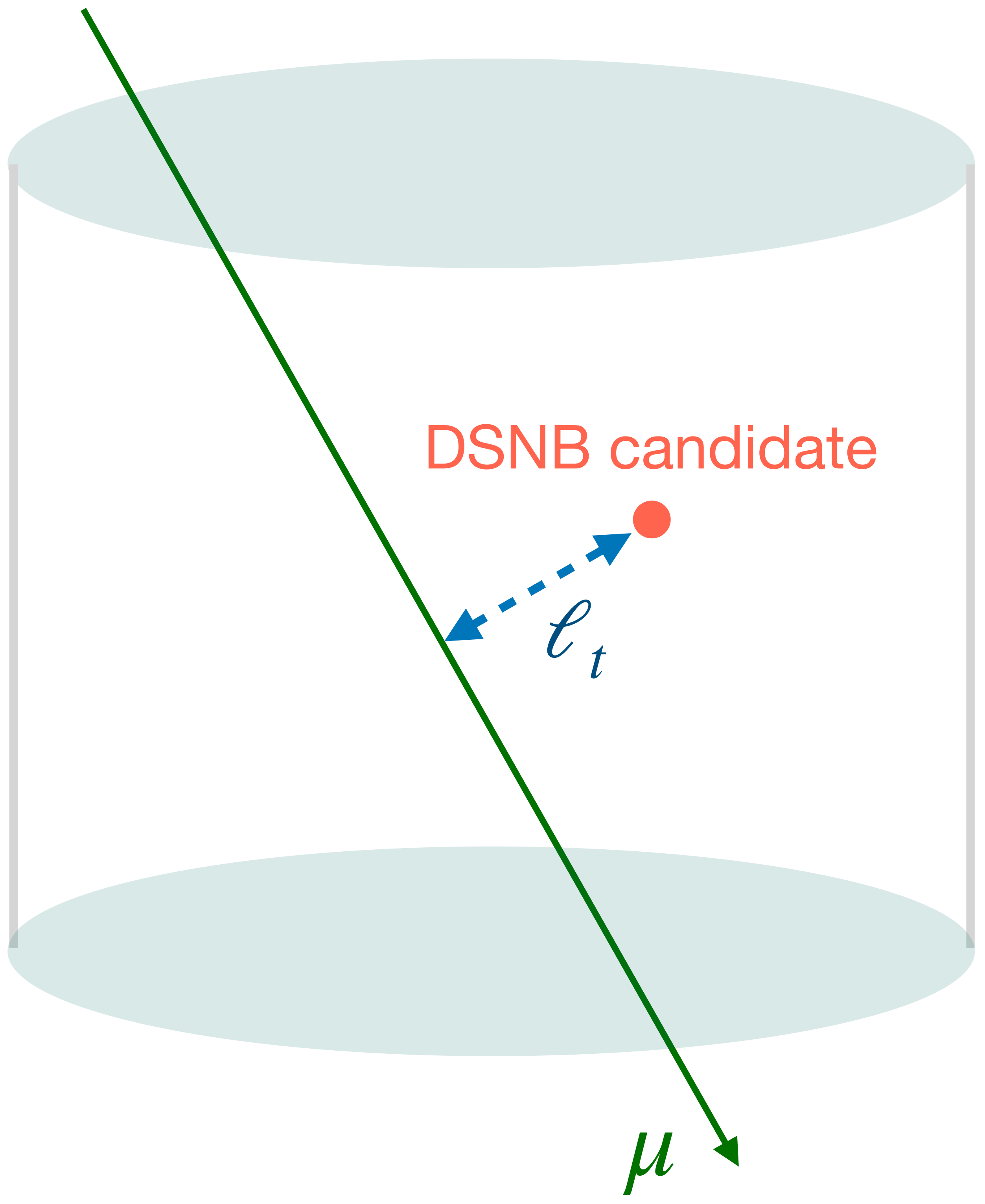
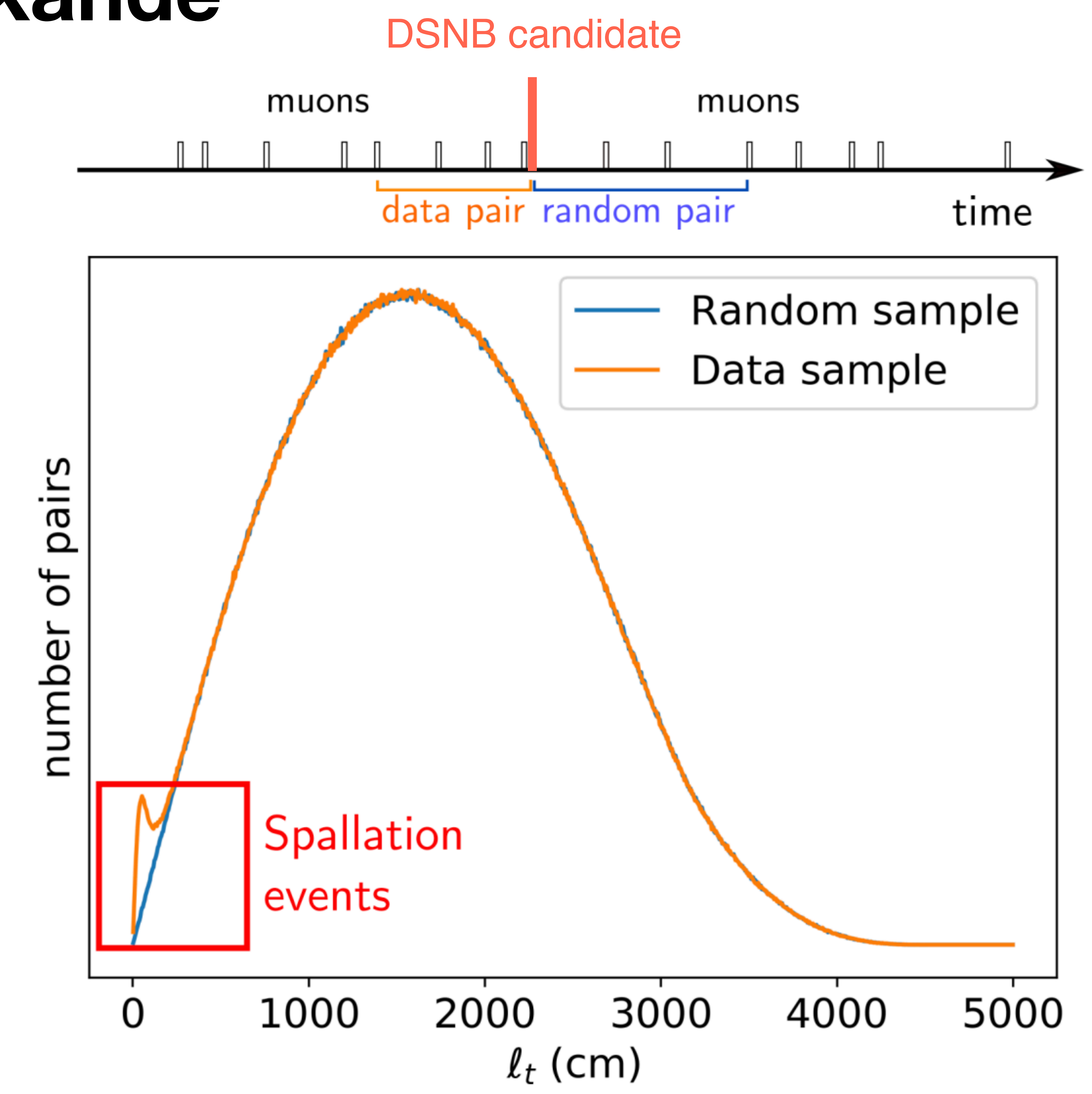
Pairing MeV-scale events with muons

First spallation cuts at Super-Kamiokande



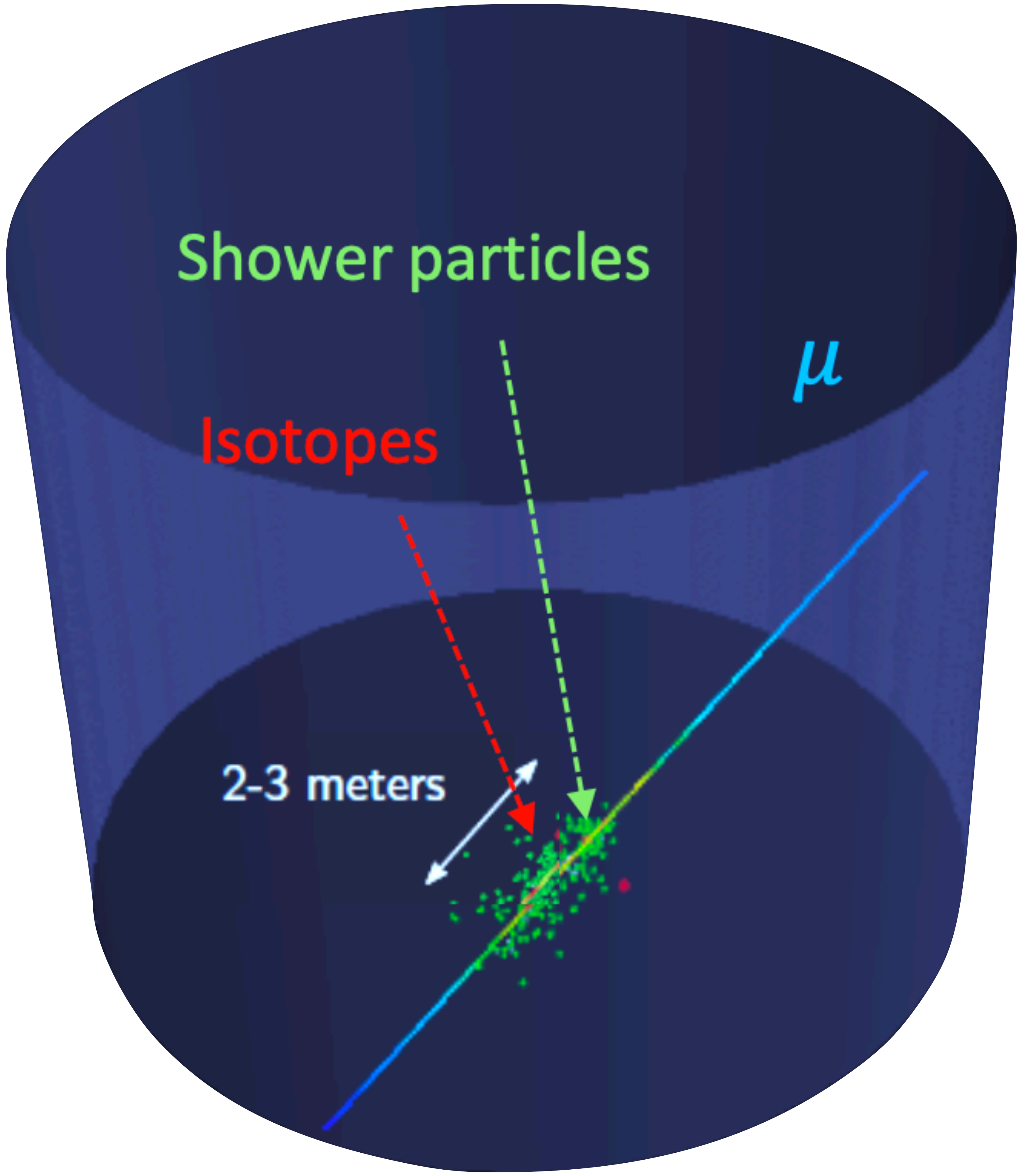


- Likelihood cut based on ℓ_t, Δt and total light
- 90% background removed, 20% deadtime
- No isotope-by-isotope information!

First muon spallation simulations in water

Work by Shirley Li and John Beacom

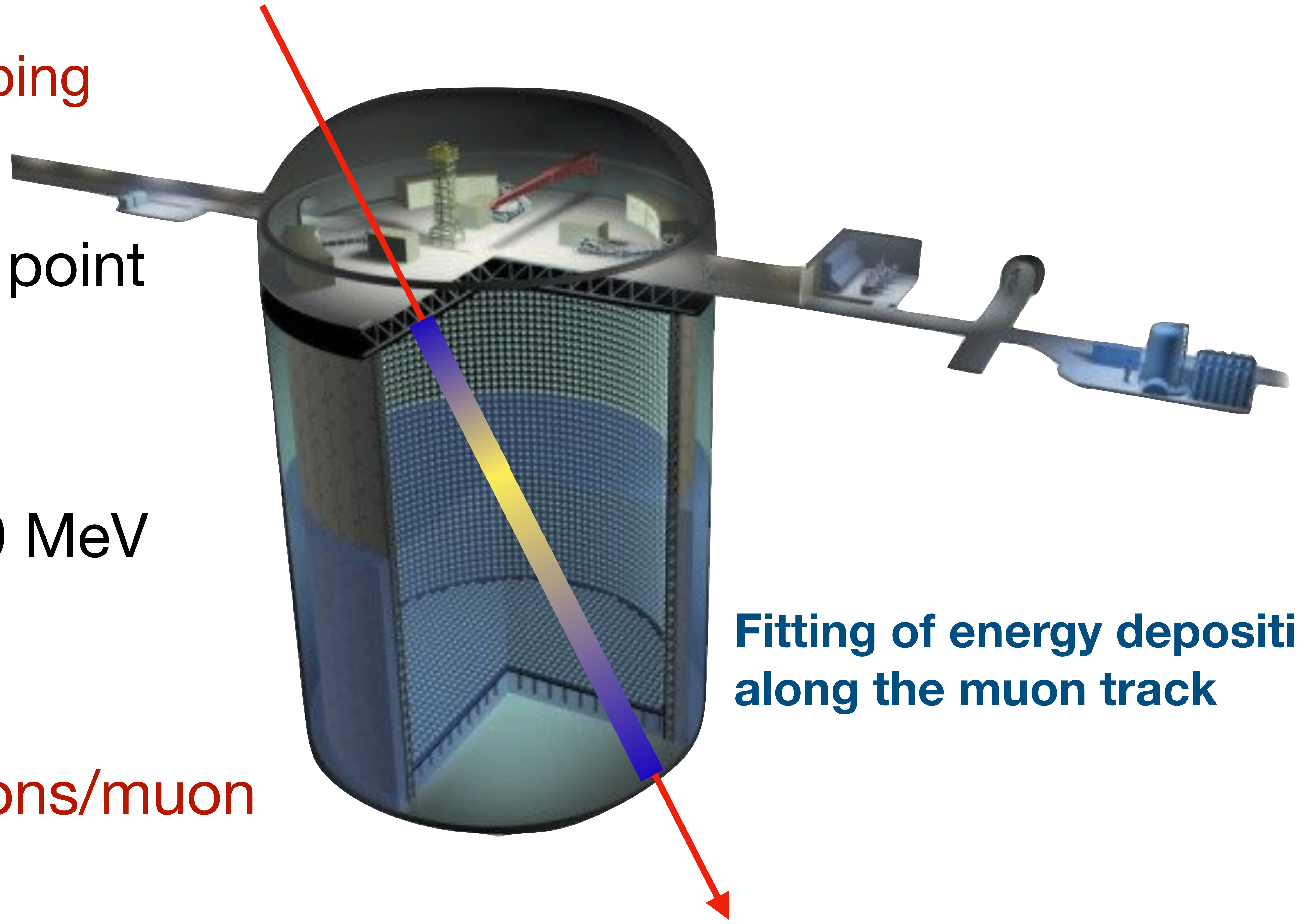
- Vertical downgoing muons in cylinder of 22.5 kt volume
- Most spallation isotopes are produced in hadronic showers
- Isotope distance to μ track depends on parent particle: $\pi^{\pm}, \gamma$ (<1m) or neutron (~3m)
- Locate the shower ⇒ remove isotopes with minimal deadtime



Improving spallation cuts at Super-Kamiokande

The SK detector capabilities — Pure water

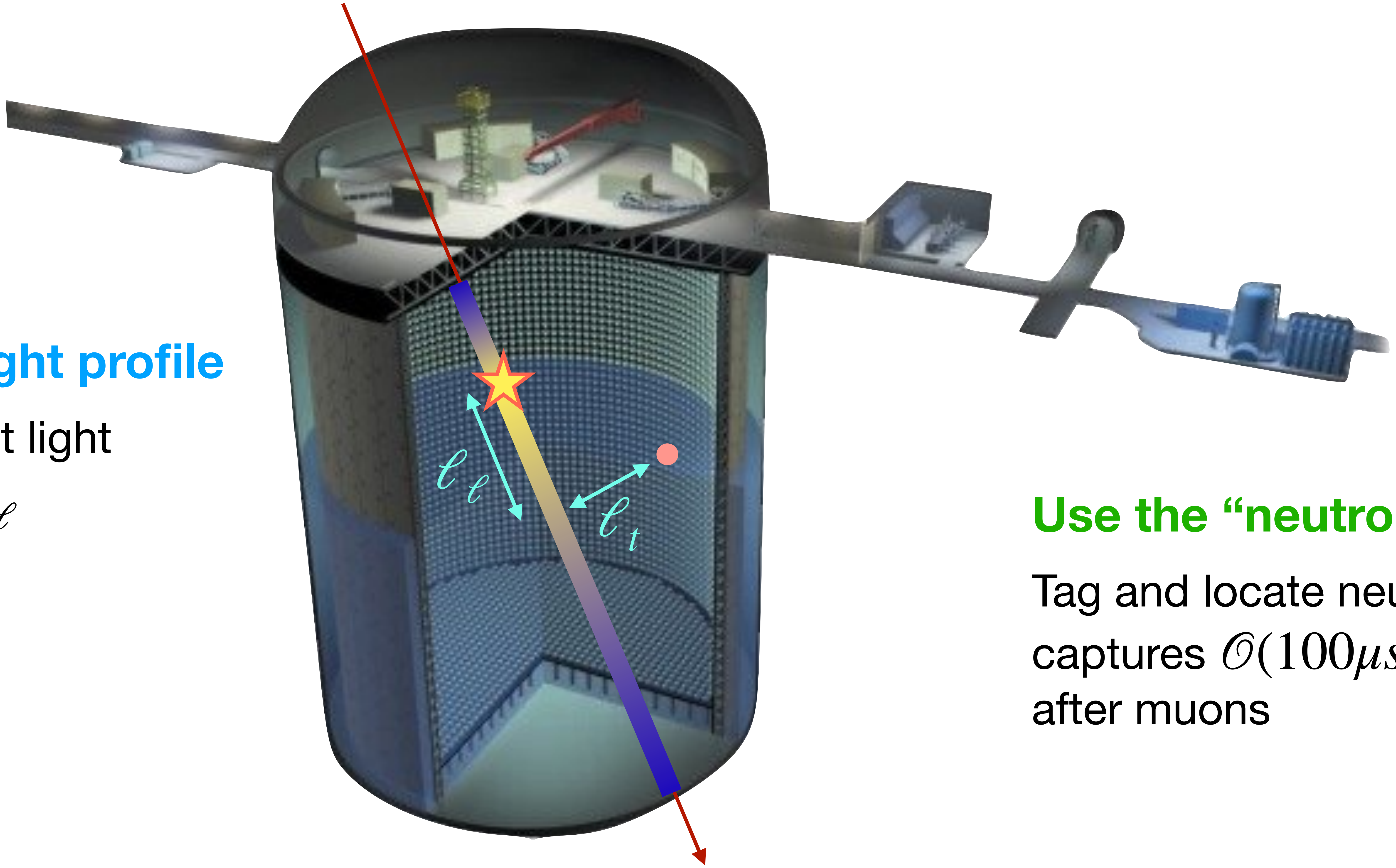
- **Muons:** 2Hz
  82% single through-going, 7% stopping
  7% bundles, 4% corner-clipping
- **Muon fitter resolution:** 1m entry point
  6° direction (single muons)
- **Low-energy event resolution:**
  50 cm vertex, 14.2% energy @ 10 MeV
- **Muon-neutron coincidences:**
  Wideband Intelligent Trigger
  6.5% efficiency, 0.044 fake neutrons/muon



Fitting of energy deposition along the muon track

Improving spallation cuts at Super-Kamiokande

Shower localization: two complementary strategies



Use the muon light profile

Distance to highest light deposition point ℓ_ℓ
Charge deposited

Use the "neutron clouds"

Tag and locate neutron captures $\mathcal{O}(100\mu s)$ after muons

Improving spallation cuts at Super-Kamiokande

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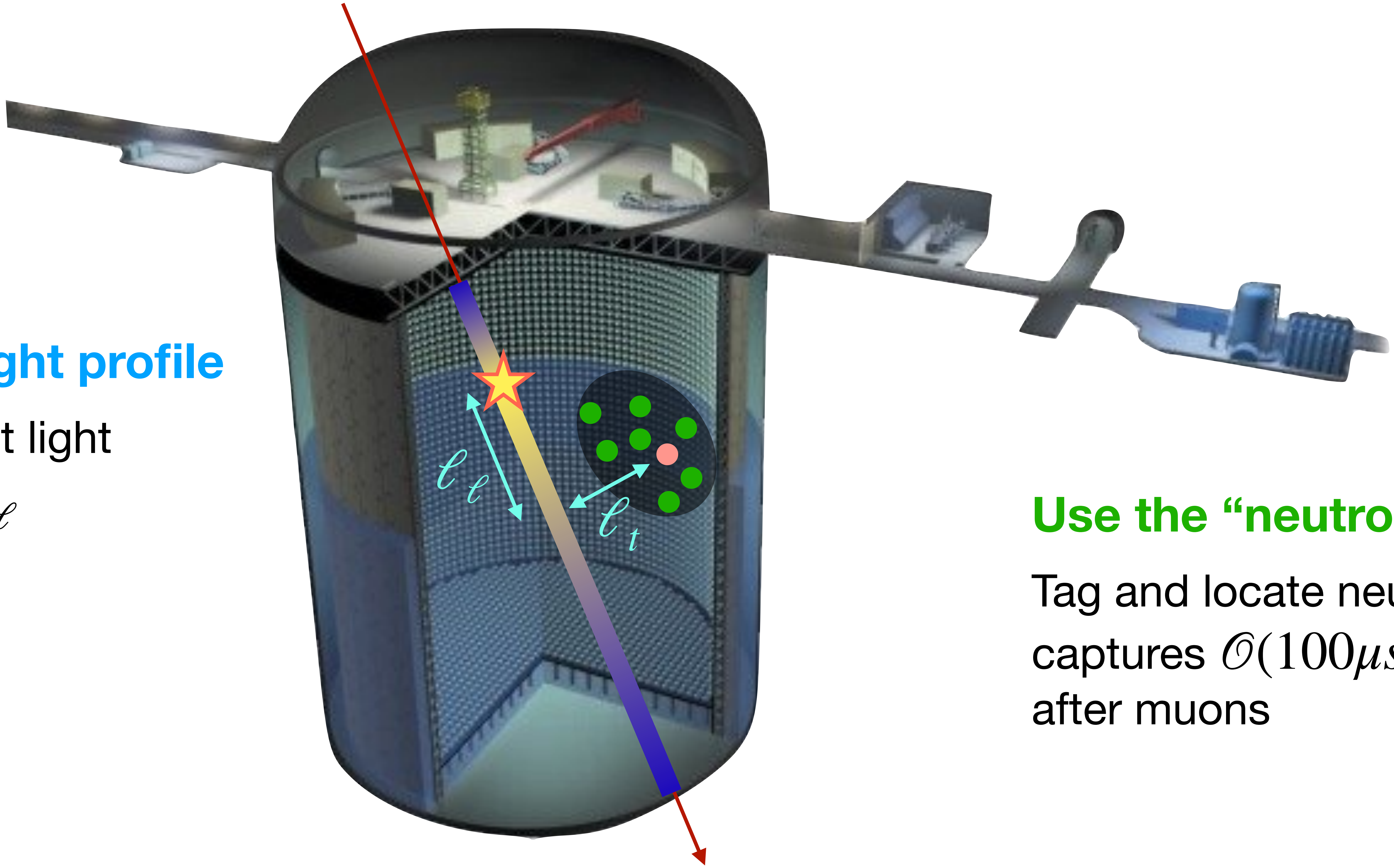


Use the "neutron clouds"

Tag and locate neutron captures $\mathcal{O}(100\mu s)$ after muons

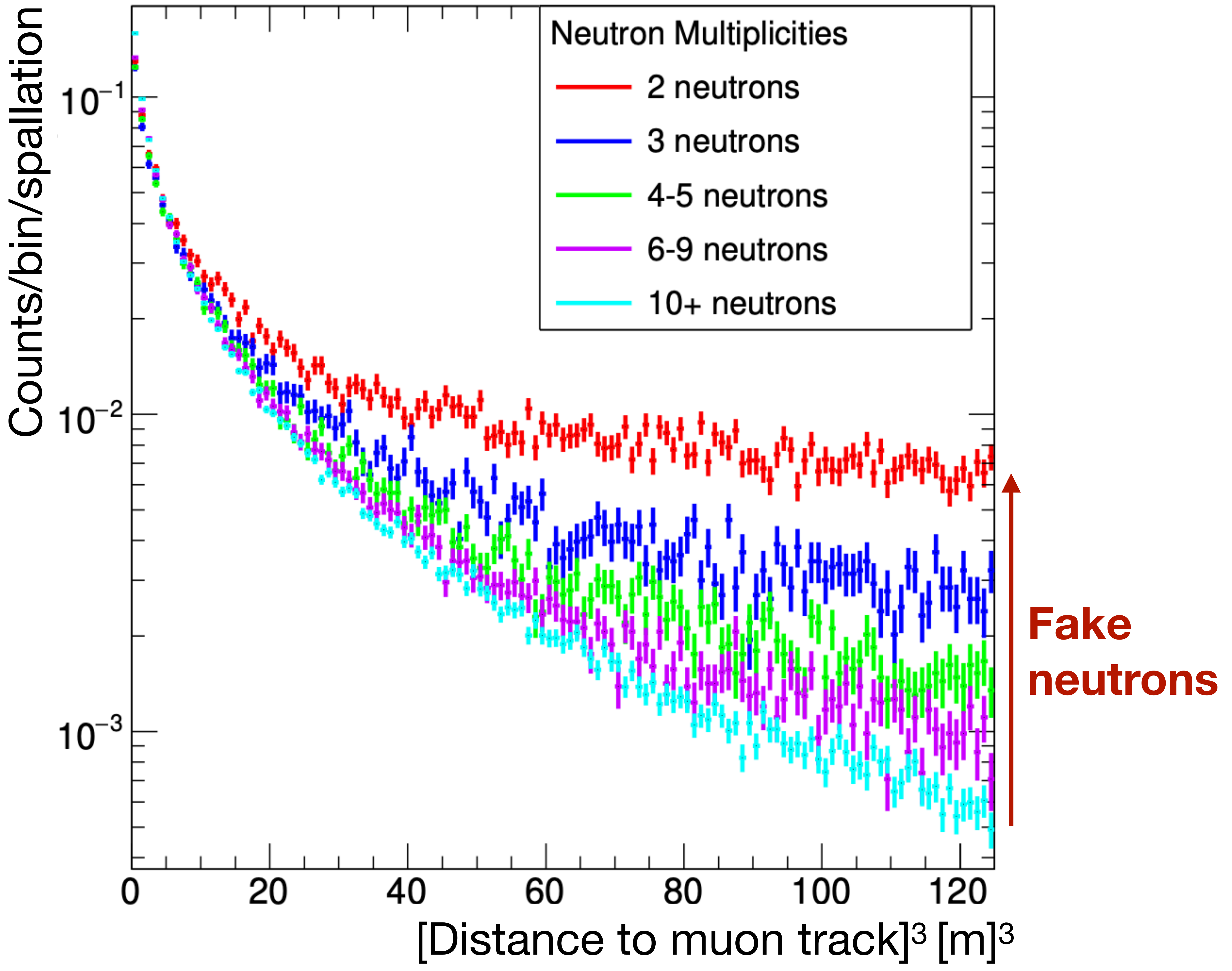
Application: Super-Kamiokande IV

Isotope clustering and neutron cloud identification

- Test new spallation cuts: 2970 day livetime 5.49-19.5 MeV (solar neutrinos)

- **Multiple spallation:** remove events within 4m and 60 of each other
  45% background rejection, 1.3% deadtime

- **Neutron clouds:** elliptical cuts
  Vary with neutron multiplicity & $\Delta_t^{\mathrm{event}-\mu}$
  37% background rejection, ~1% deadtime



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Application: Super-Kamiokande IV

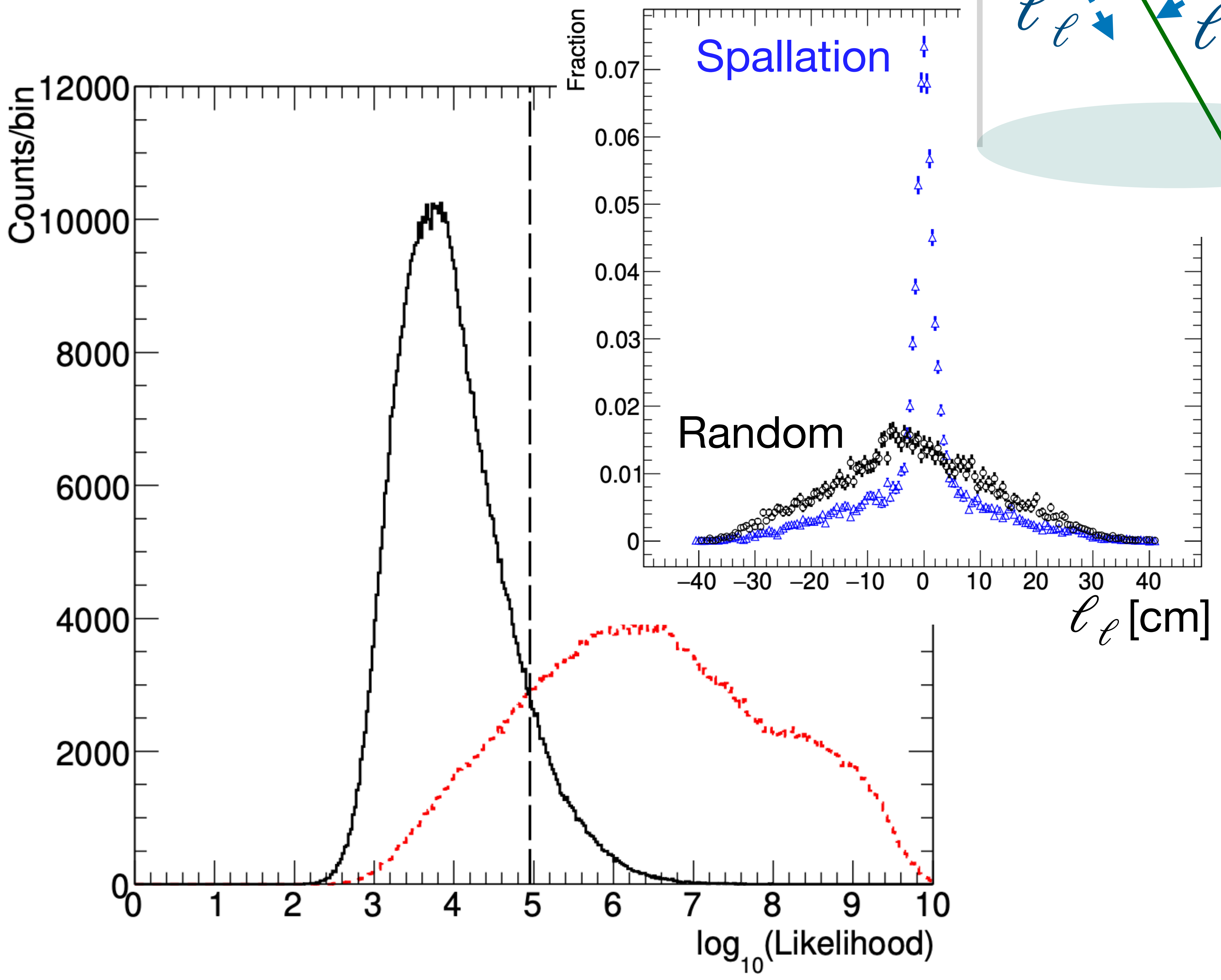
Using muon light: likelihood analysis

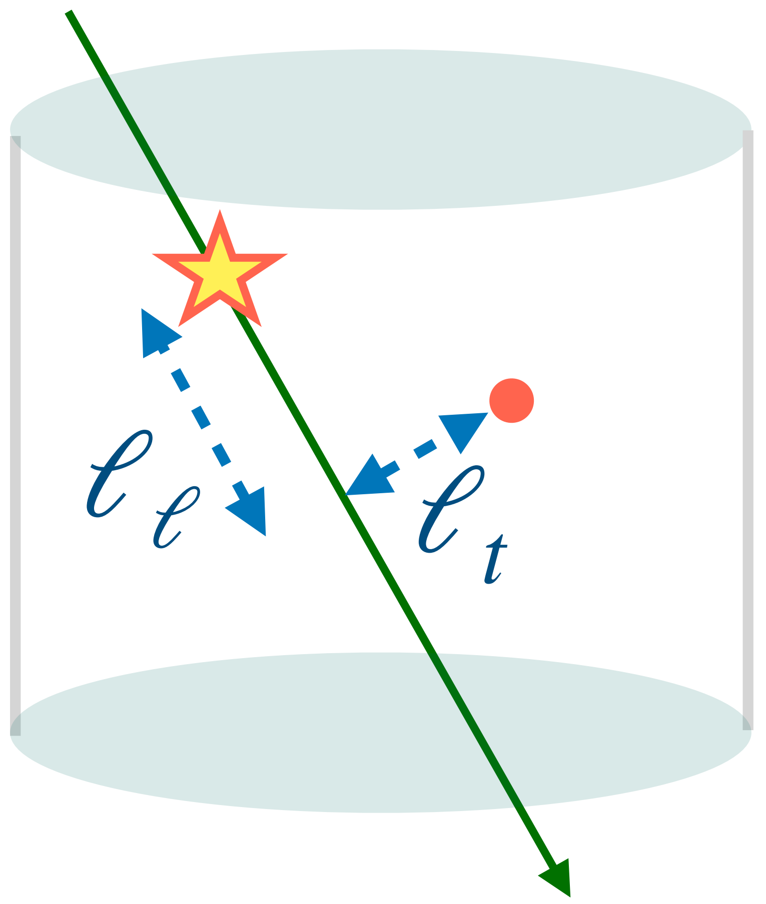
- Geometric observables: ℓ_t and ℓ_ℓ
  Improved ℓ_ℓ determination based on [S. Li & J. Beacom, PRD 92 (2015)]
- Light deposited: residual charge

$$Q_{\mathrm{res}} = Q_{\mathrm{total}} - Q_{\mathrm{min\ ionizing}}$$

- Time difference between muon and DSNB candidate

90% rejection for 10% deadtime





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Spallation simulation for Super-Kamiokande

Muon generation

Modified Gaisser parameterization

—

MUSIC: transport to SK depth

Propagation in SK

FLUKA

—

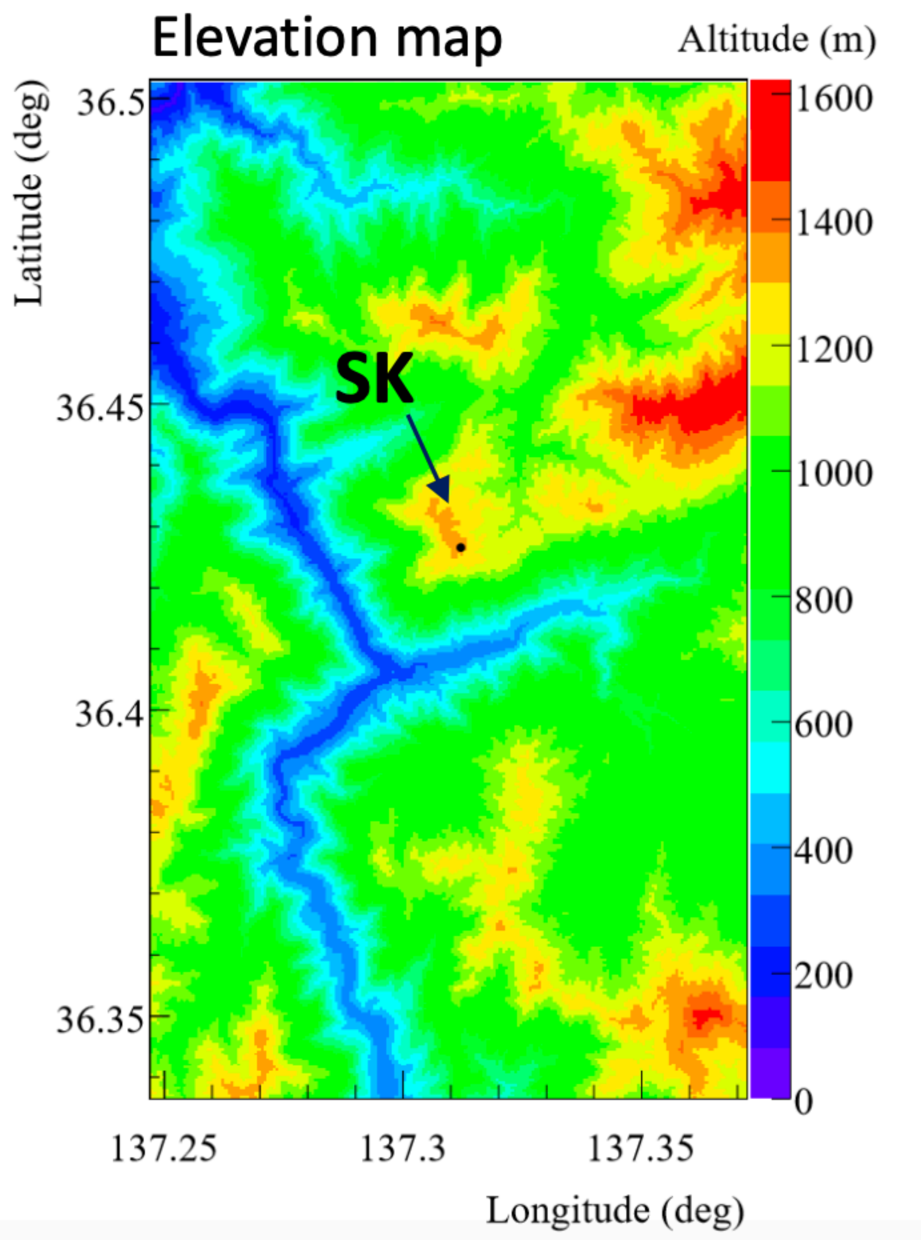
Full SK volume
2m rock

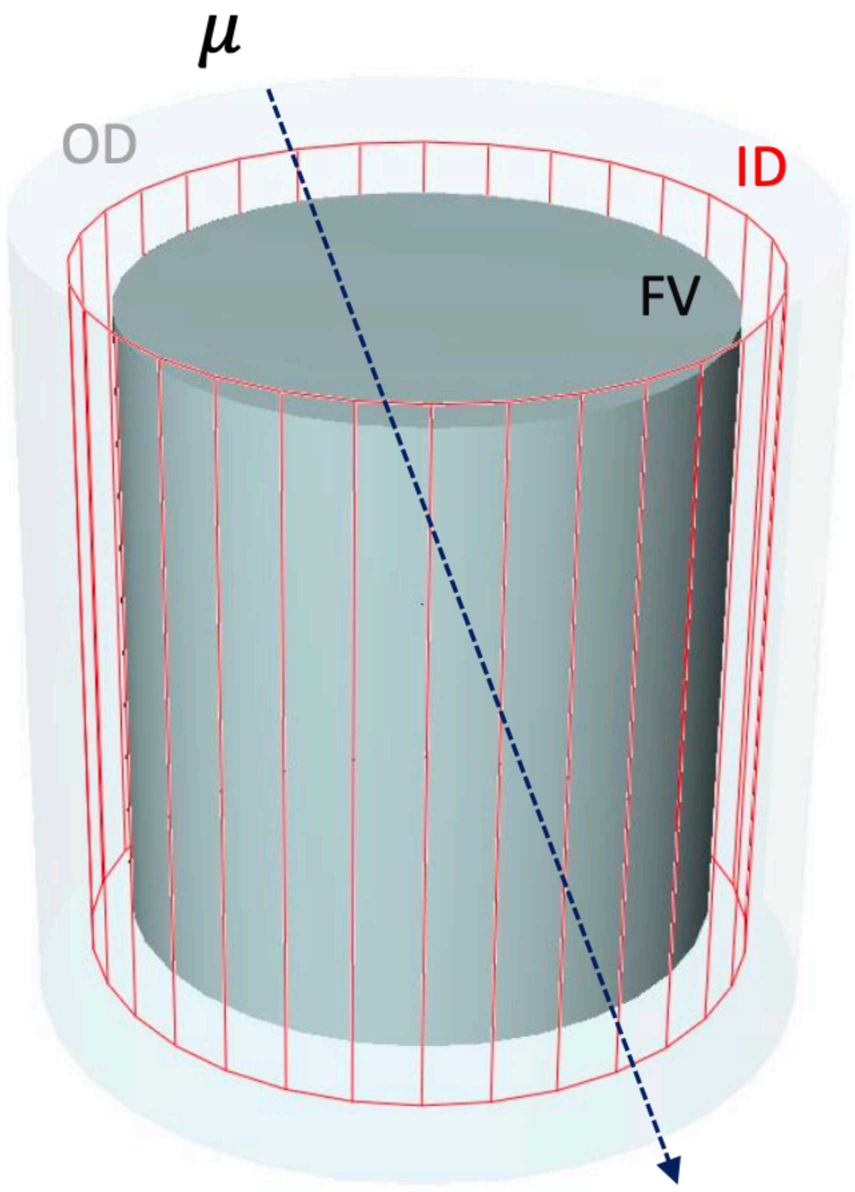
Detector simulation

SKDetSim (GEANT3)

—

Isotope decays
Neutron captures



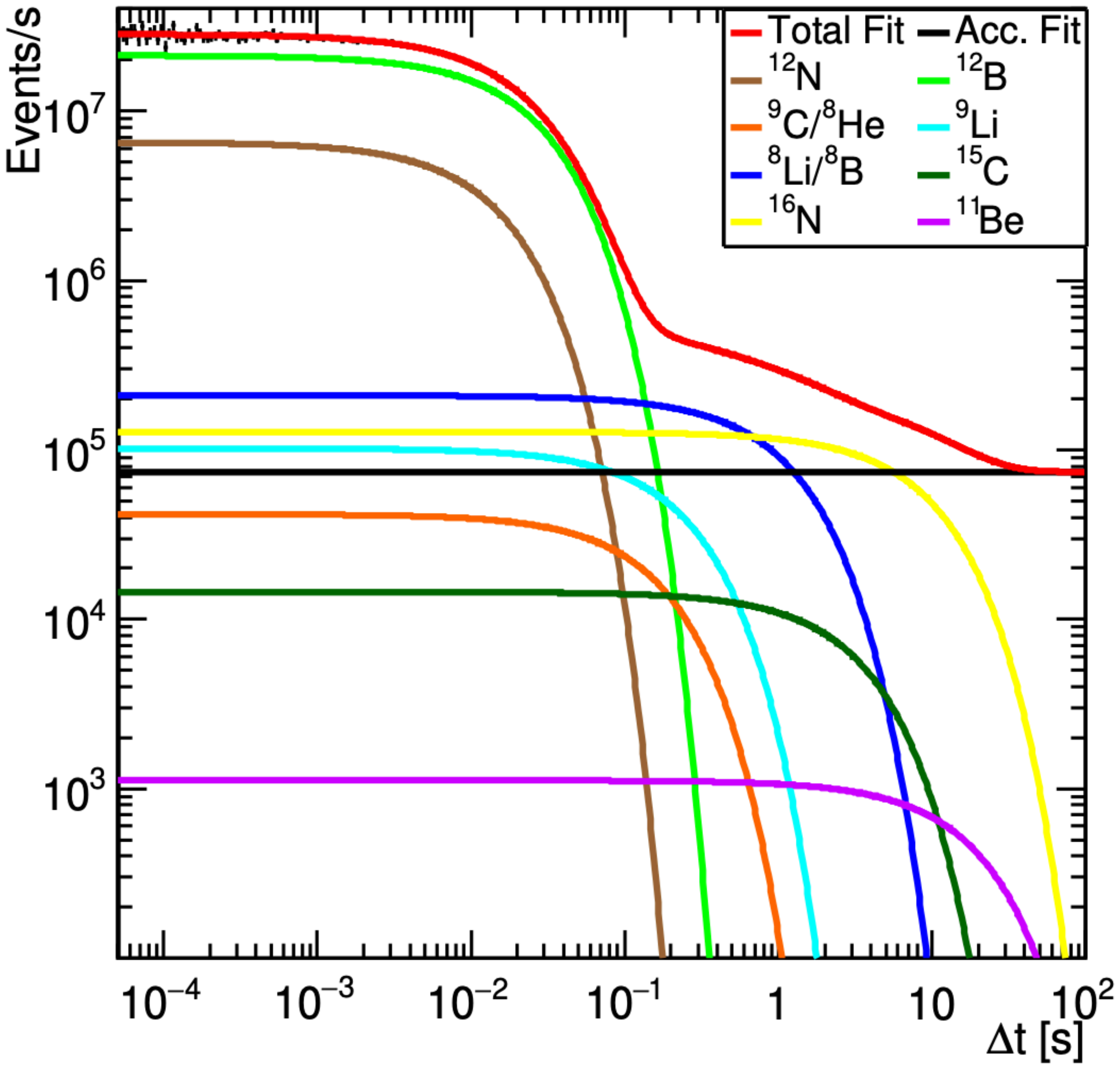


Spallation simulation @ Super-Kamiokande

...mit MUSIC

Comparison to data: isotope yields

Estimate yields from data using muon-event time difference



Isotope	Yields $[10^{-7}\text{cm}^2\mu^{-1}\text{g}^{-1}]$ Calculated	Observed	Rates $[\text{kton}^{-1}.\text{day}^{-1}]$
^{12}N	0.92	1.72	$3.04 \pm 0.06 \pm 0.028$
^{12}B	8.6	12.9	$22.86 \pm 0.11 \pm 0.21$
^{9}C/^{8}He	0.8	<0.61	<1.08
^{9}Li	1.5	0.67	$1.19 \pm 0.33 \pm 0.010$
^{8}Li/^{8}B	13.4	5.11	$9.04 \pm 0.17^{+0.60}_{-1.1}$
^{15}C	0.55	1.57	$2.78 \pm 0.45 \pm 0.032$
^{16}N	14.5	27.3	$48.43 \pm 0.60 \pm 0.49$
^{11}Be	0.61	<1.05	<1.9

Differences of 50-100%

- Need to reweight simulation results
- Minor incidence on geometric observables

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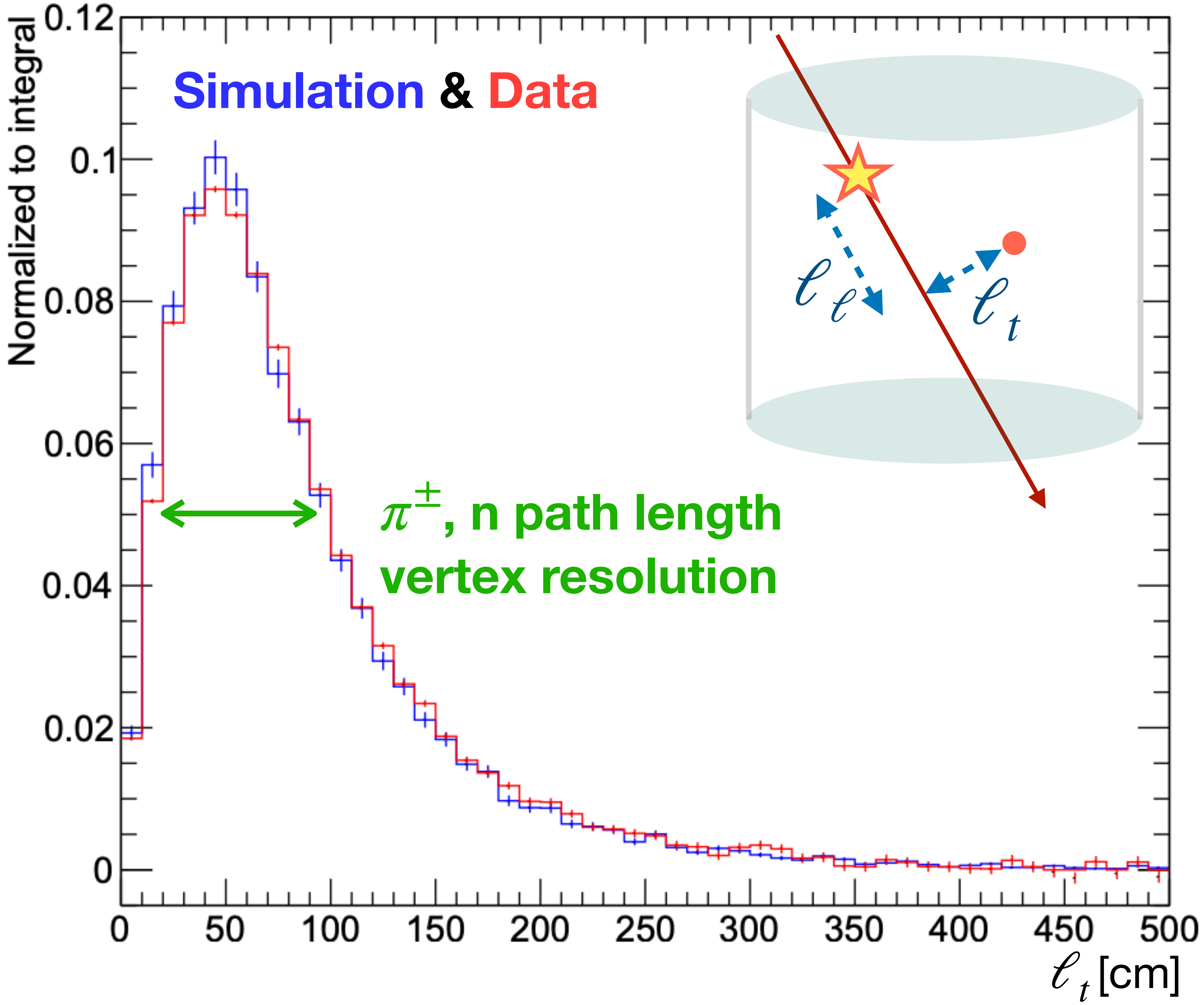
Comparison to data: shower localization

Isotope distance to muon track

- Simulation and data agree within 5%
- Simulation can already be used to assess the performance of cylindrical muon cuts



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Comparison to data: neutron clouds

Neutron multiplicity

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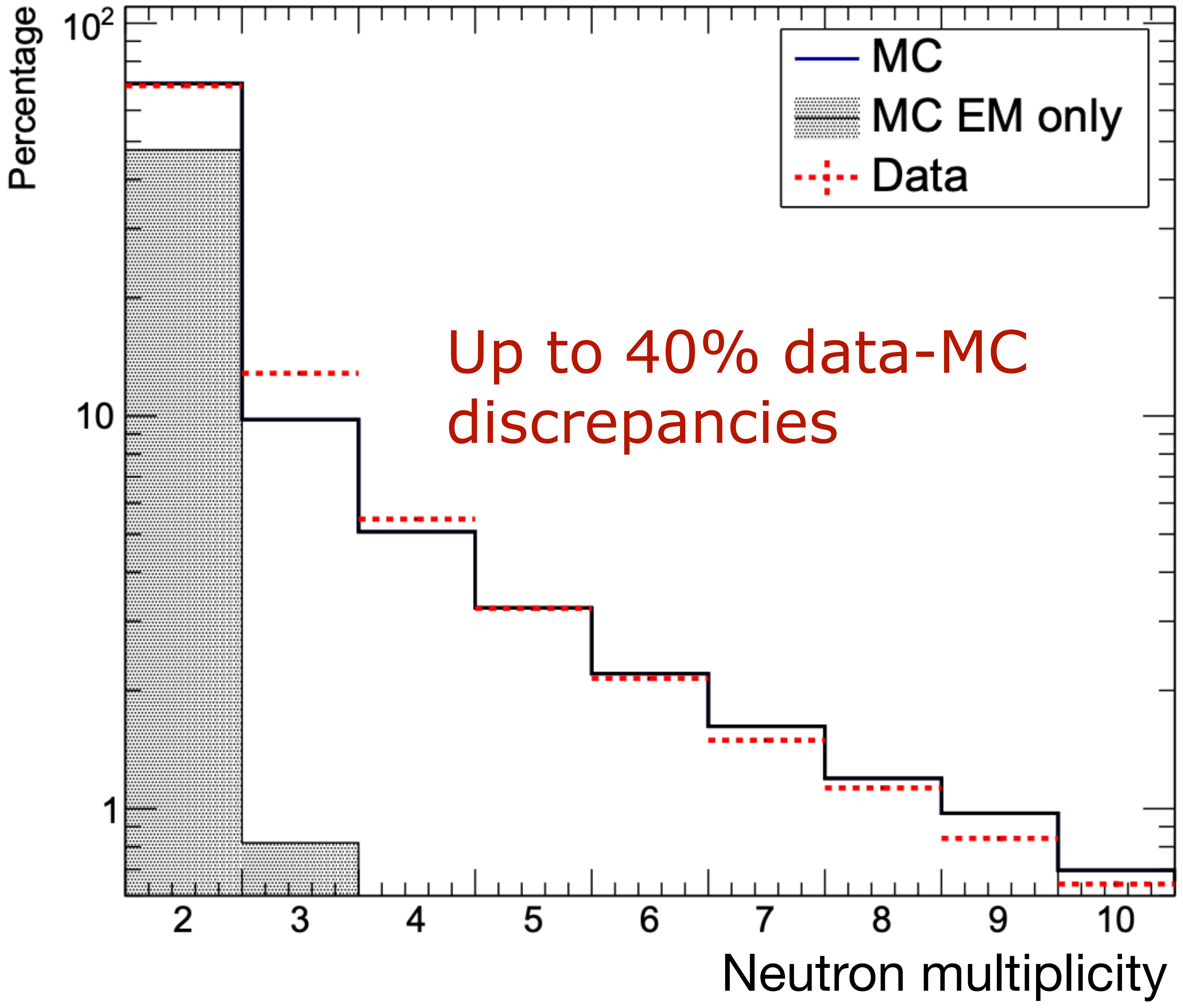
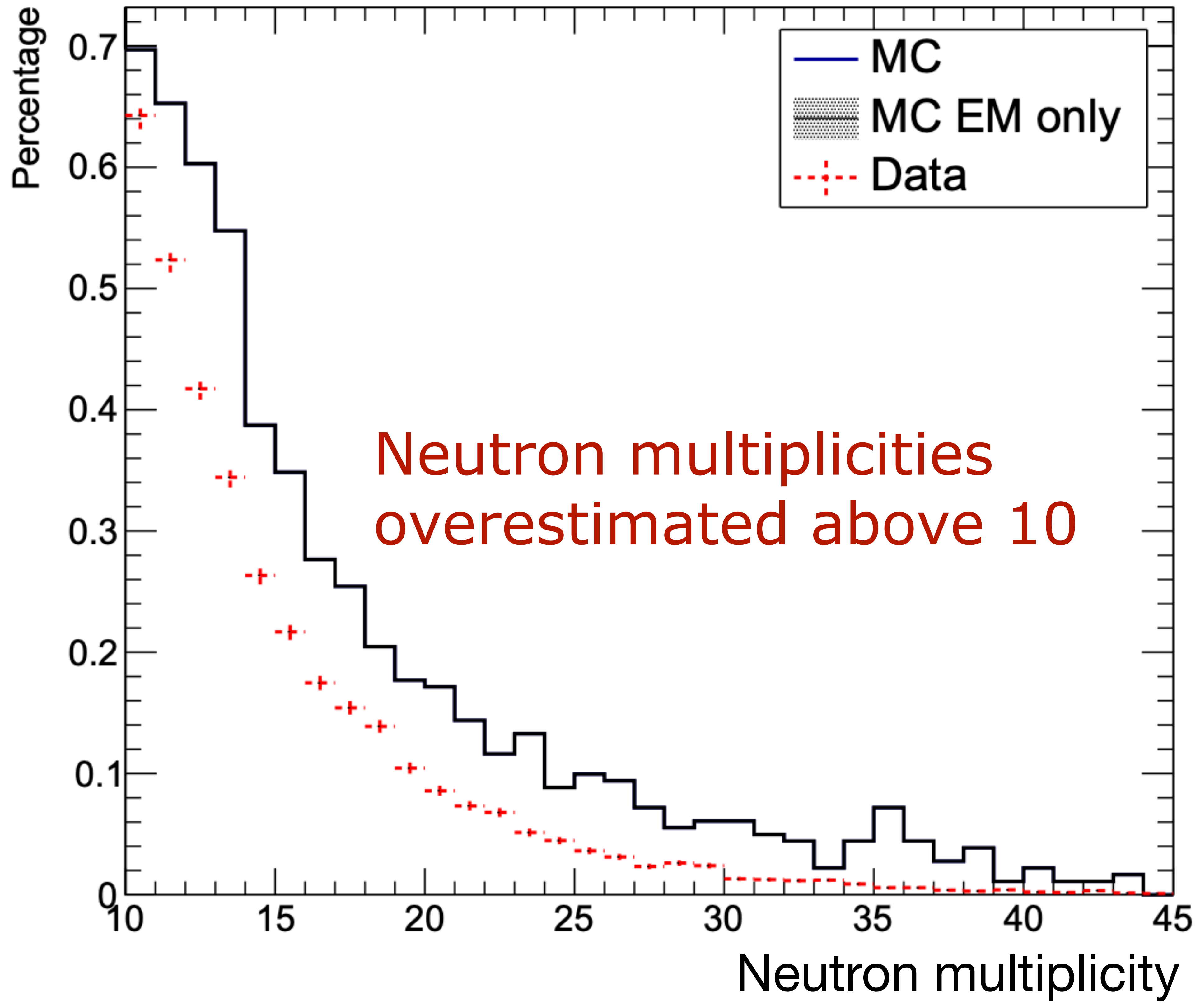
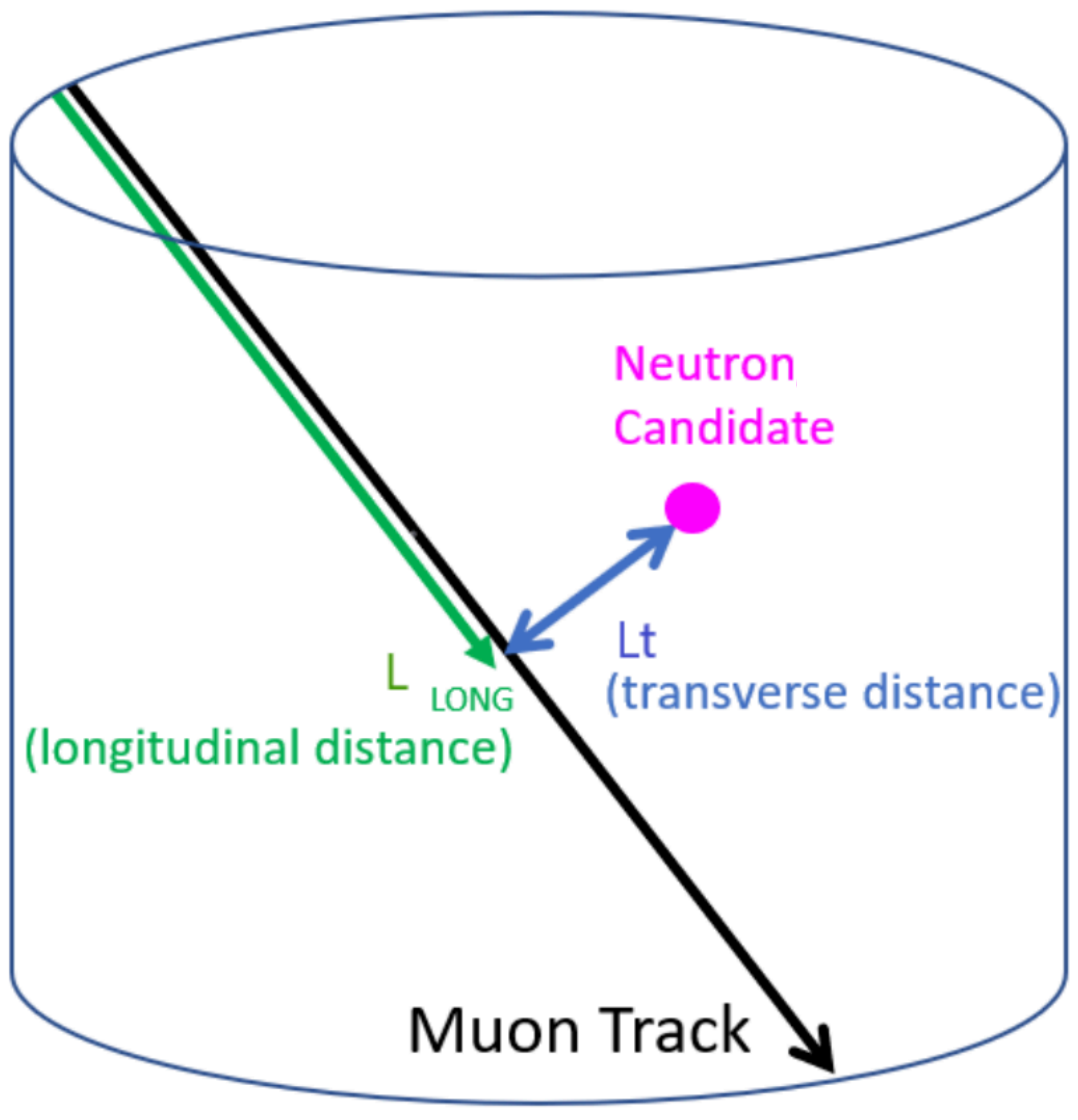


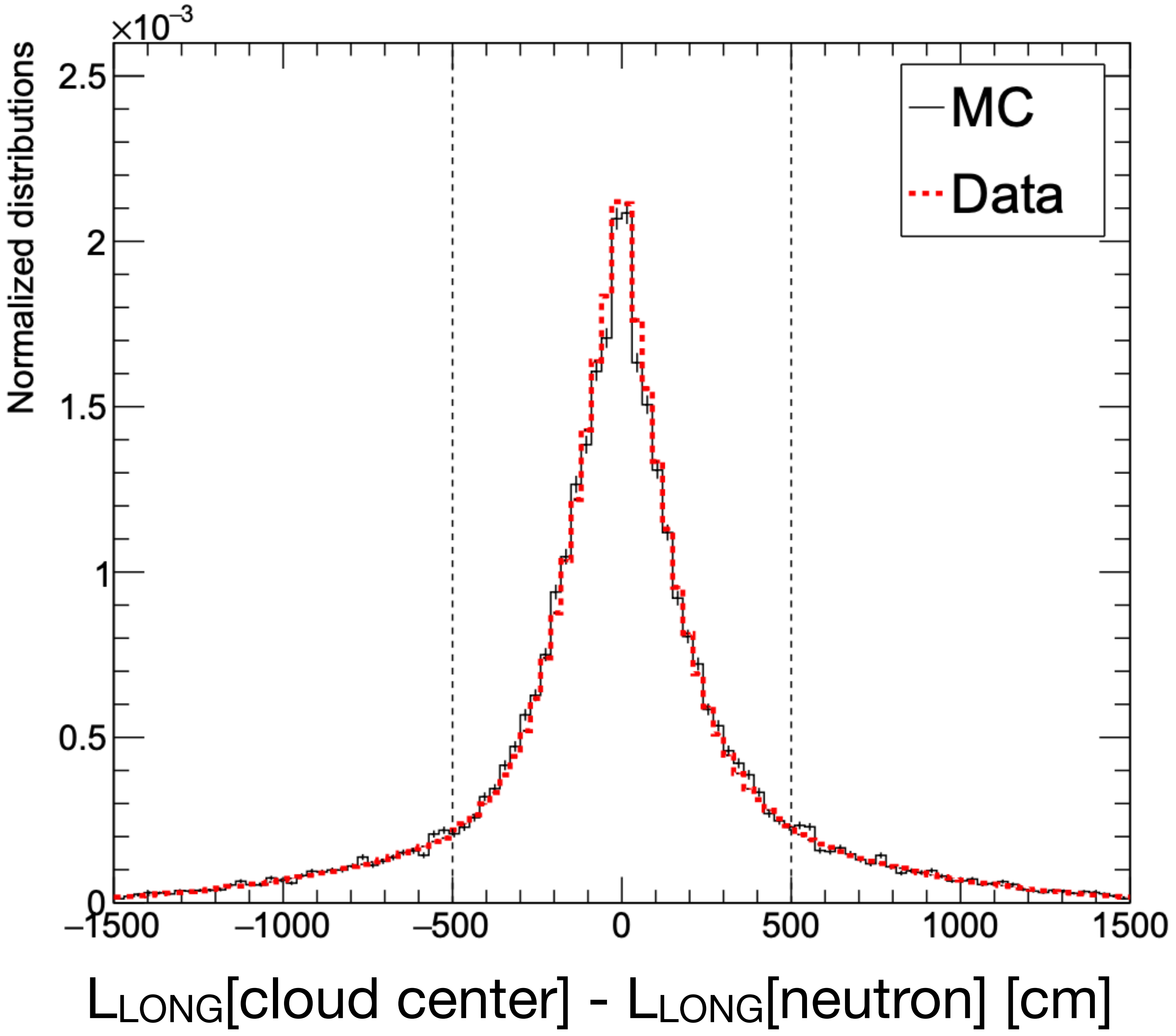


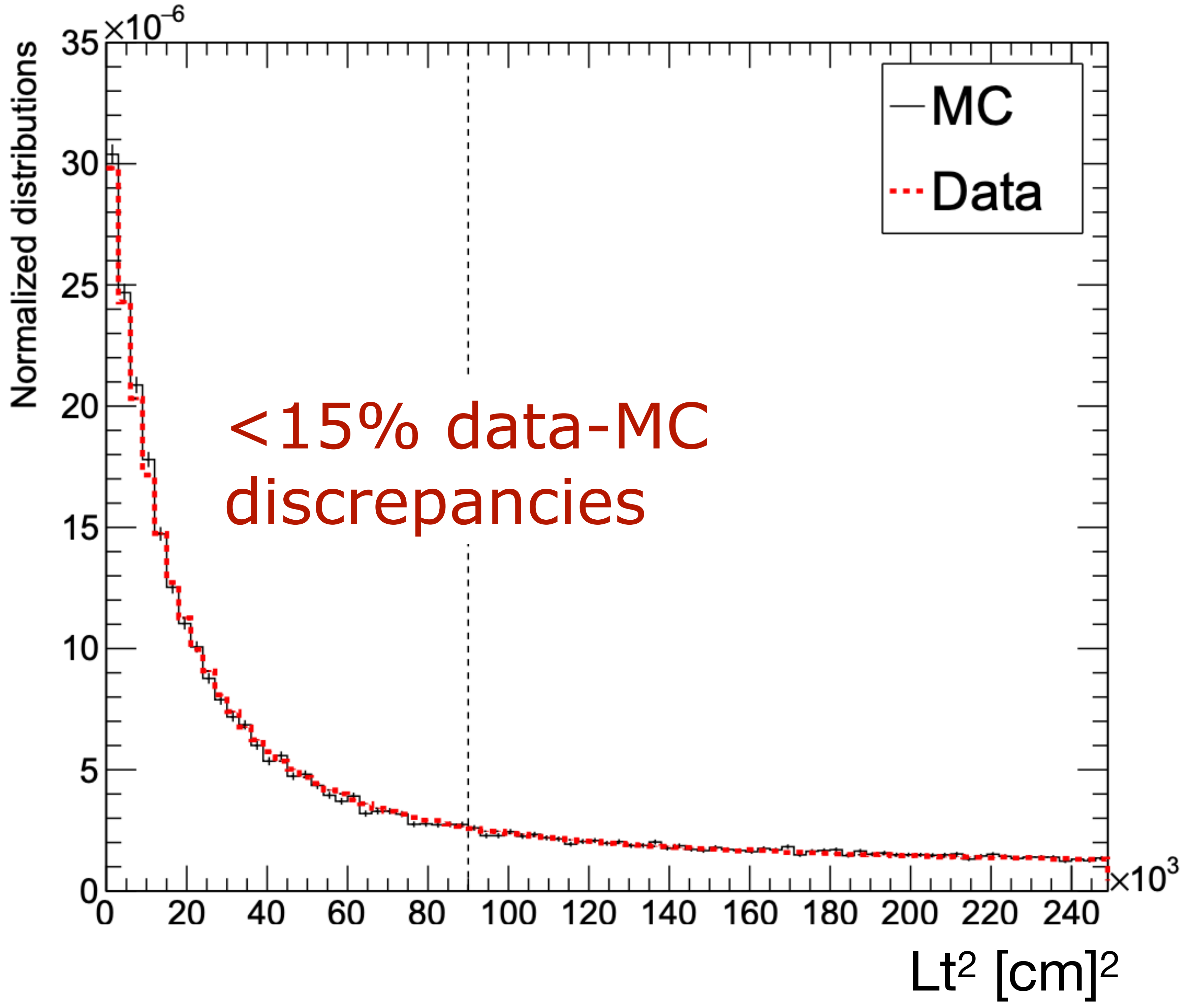
Discrepancies need to be accounted for: systematic uncertainties or reweighting

Comparison to data: neutron clouds

Neutron cloud shape







The simulation can be used to test neutron cloud cuts @ SK-Gd

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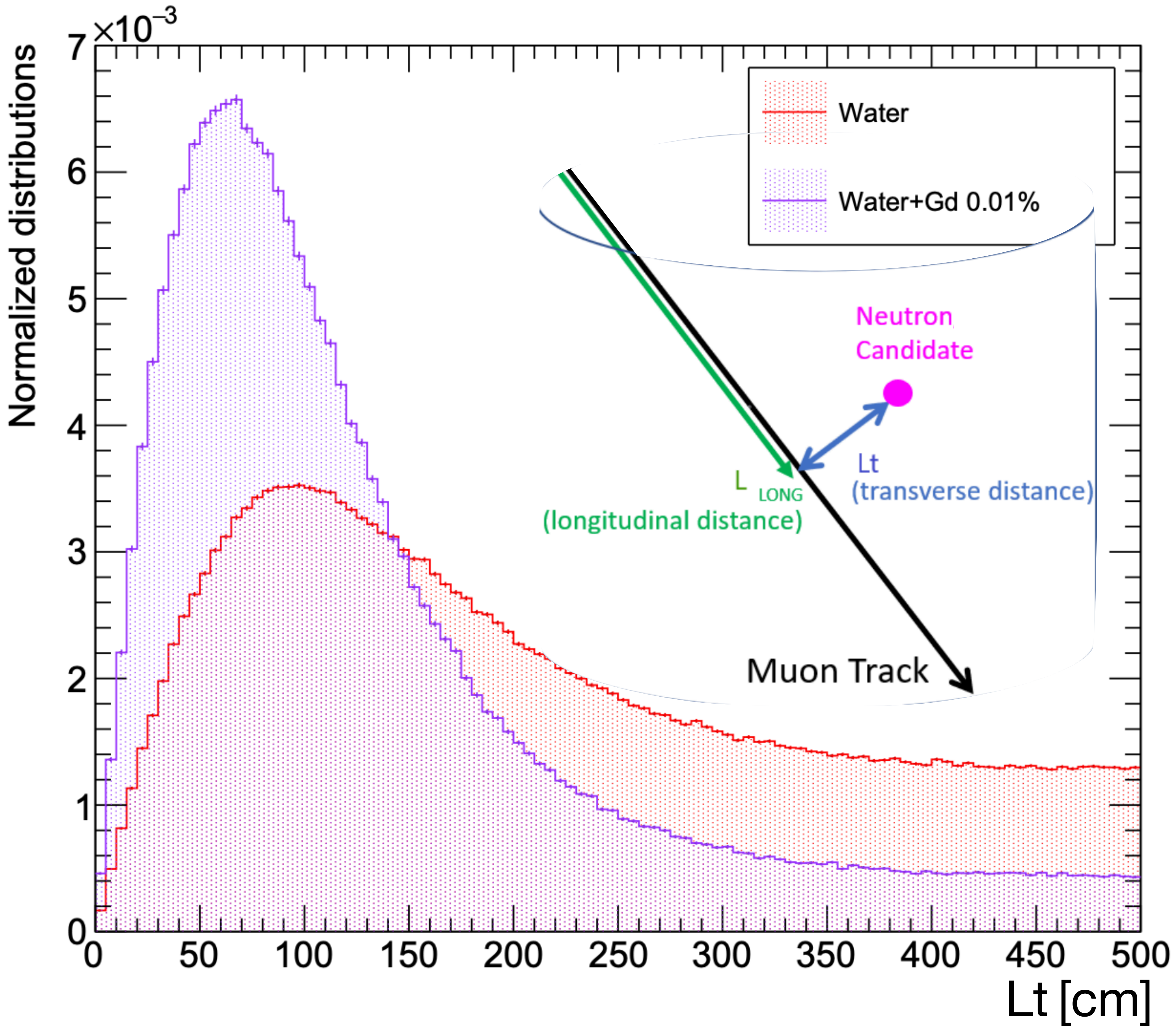
Perspective: neutron clouds at SK-Gd

FLUKA-based simulation at SK-Gd — Preliminary results

- **Summer 2020:** incorporation of 13 tons of $Gd_2(SO_4)_3$ (0.011% Gd in water)
- **FLUKA simulation with Gd**
  GEANT4 photofission model for neutron capture
- **Neutron identification efficiency**
  from 6.5% to 26.9%
  (increase of fake neutron rate due to temporary noise increase)

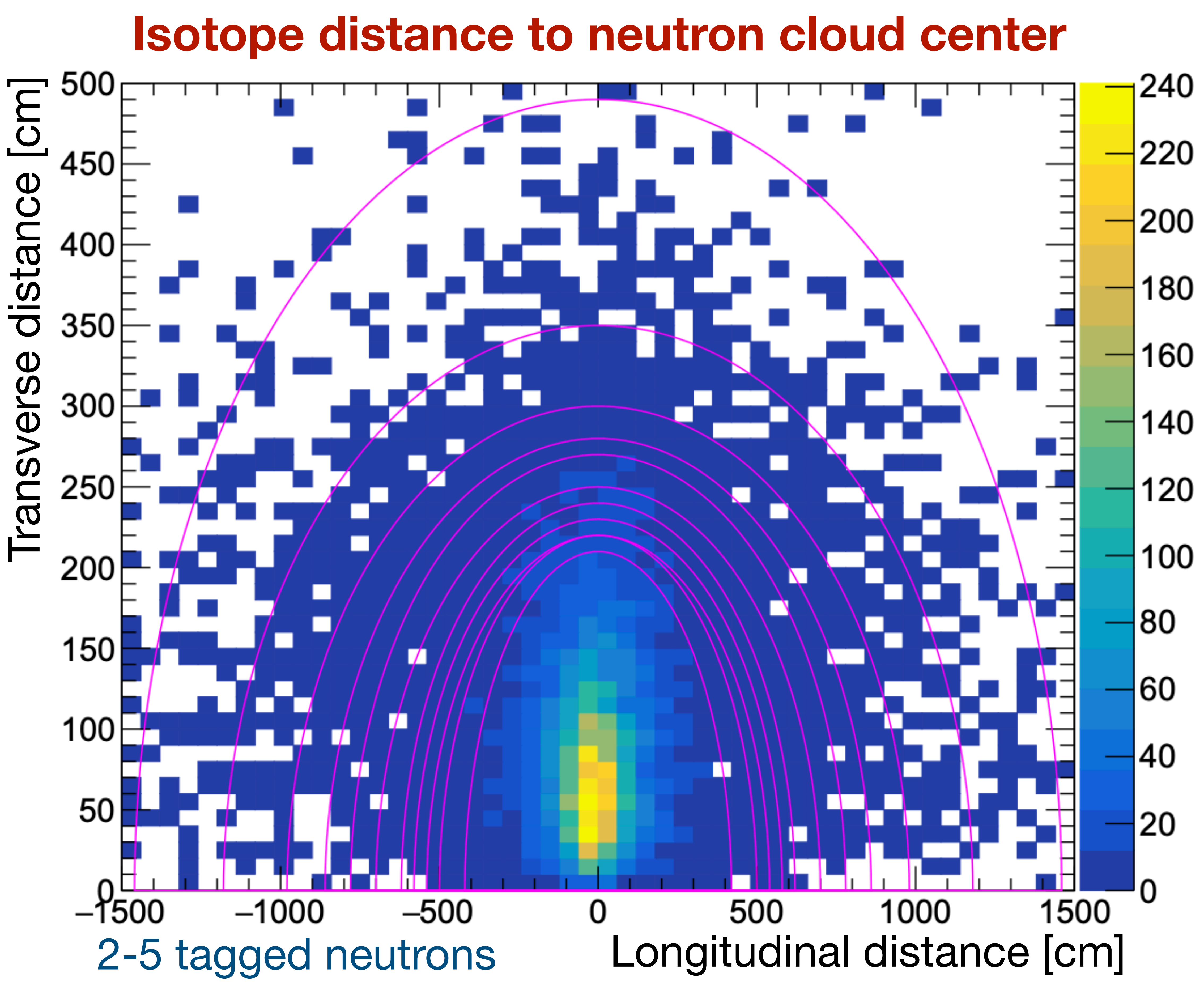


A. Coffani, Ph. D thesis

Perspective: neutron clouds at SK-Gd

Identifying spallation isotopes using neutron clouds

- **Multiplicity classes:**
  2-5, 6-10, 11-30, 31-55, >55 neutrons
- **Elliptical cuts:** ellipses containing 100%, 99%…79% of the isotopes
- **Spherical cuts:** additional cuts depending on $\Delta_t^{\text{muon}-\text{isotope}}$



A. Coffani, Ph. D thesis

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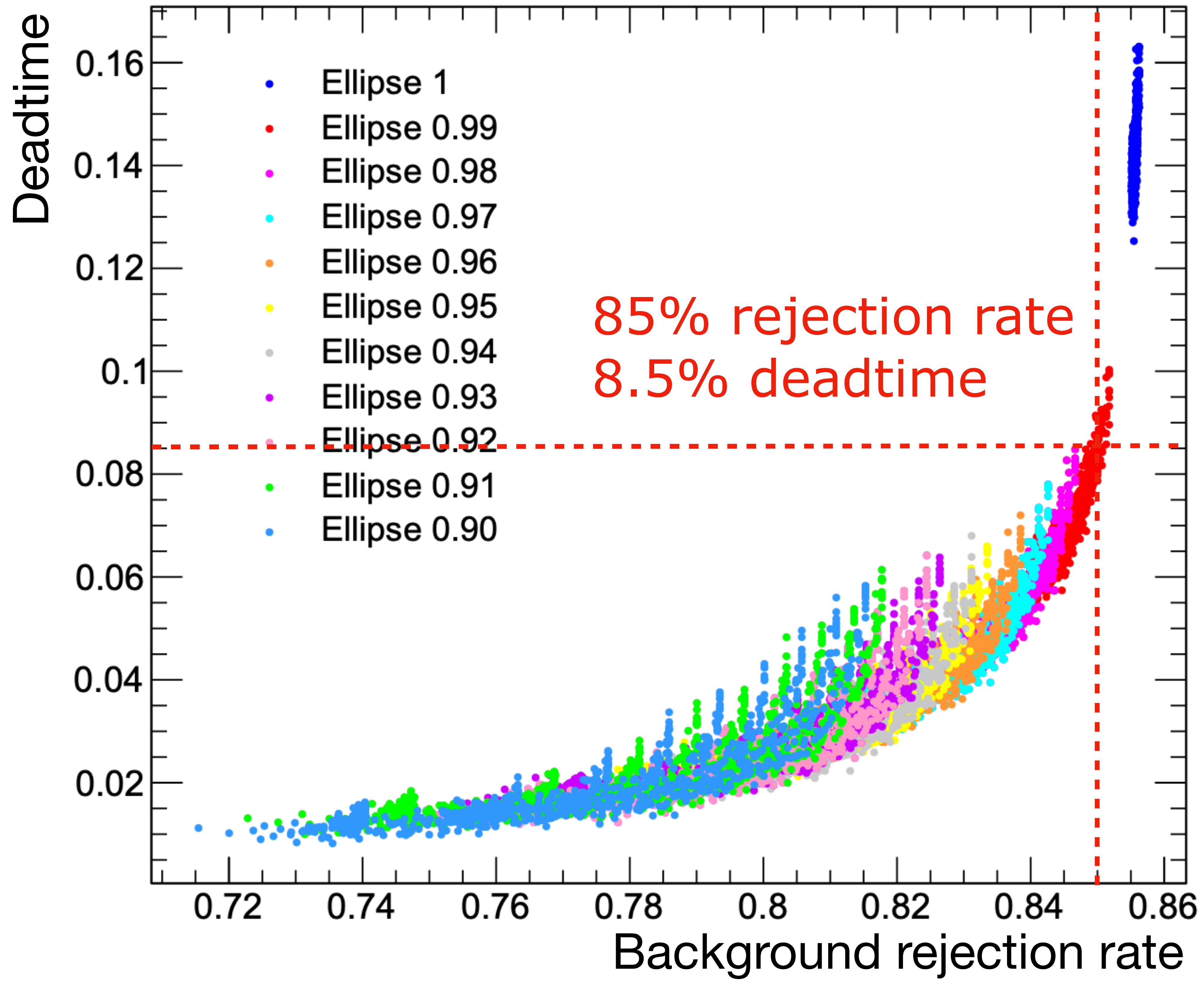
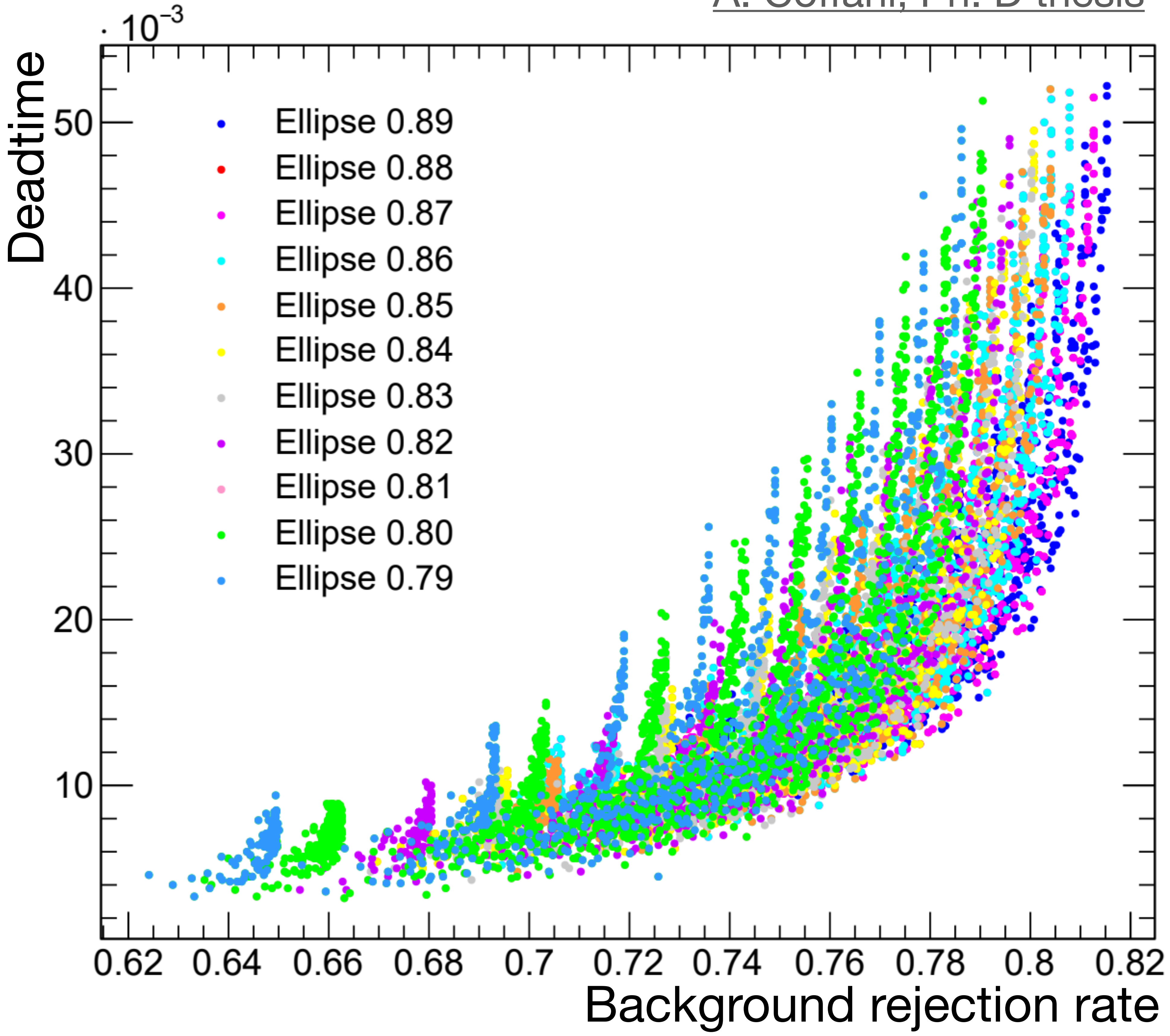




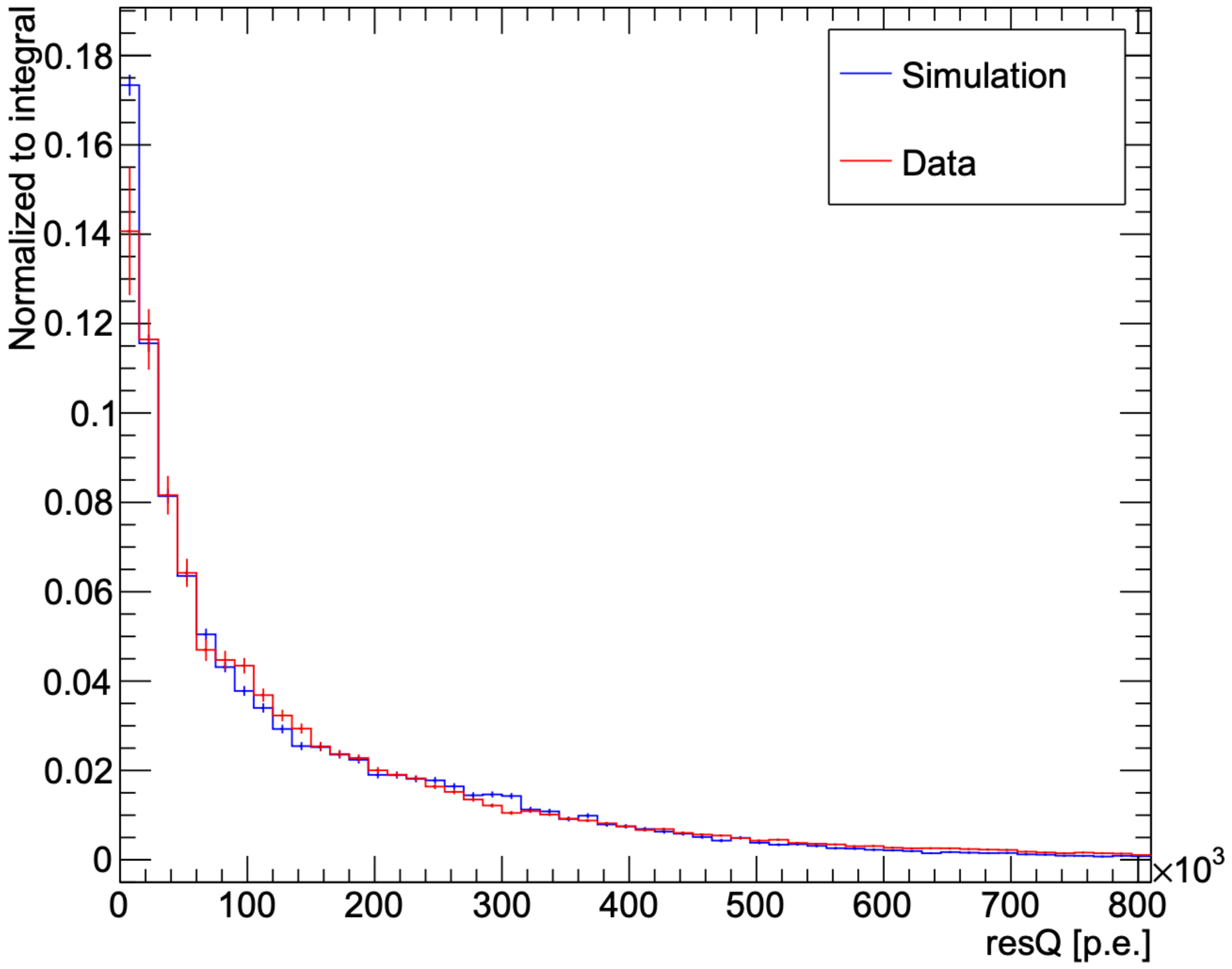
Promising prospects for SK-Gd with 0.033% concentration

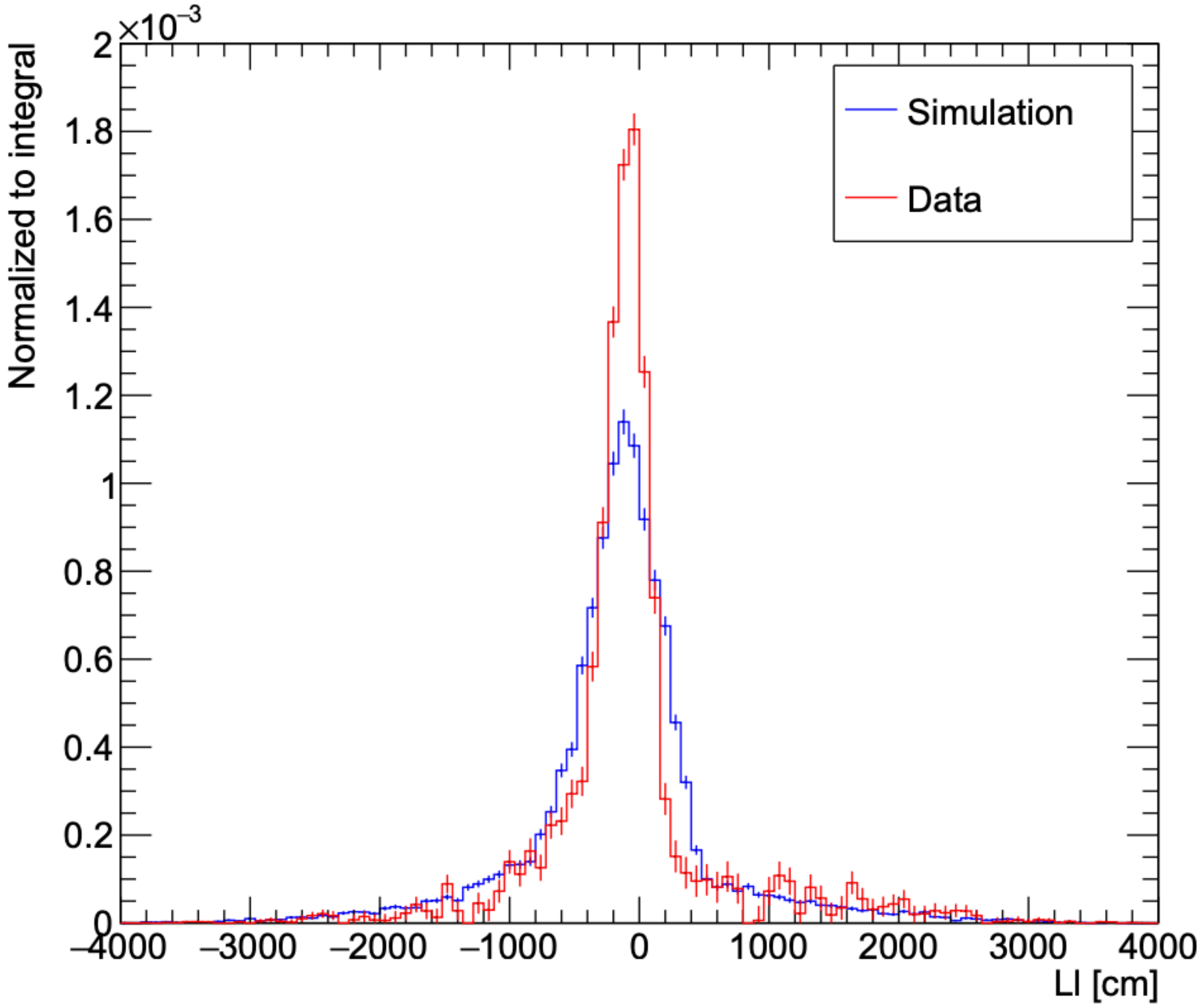
Conclusion

- Spallation reduction and isotope-by-isotope studies are essential for both Super- and Hyper-Kamiokande
- Spallation simulations have already allowed SK to cut the deadtime in half for solar neutrino searches
- In-house FLUKA-based simulations accurately model the isotope and neutron cloud spatial distributions — Promising projections for SK-Gd
- **Missing piece #1:** FLUKA-GEANT interface to predict light deposition along the muon track
- **Missing piece #2:** simulate propagation and showering of muon bundles
  MUPAGE generator, Carminati et al []

Comparison to data: shower light deposition

Very prelimary — Interface between FLUKA and SKDetSim





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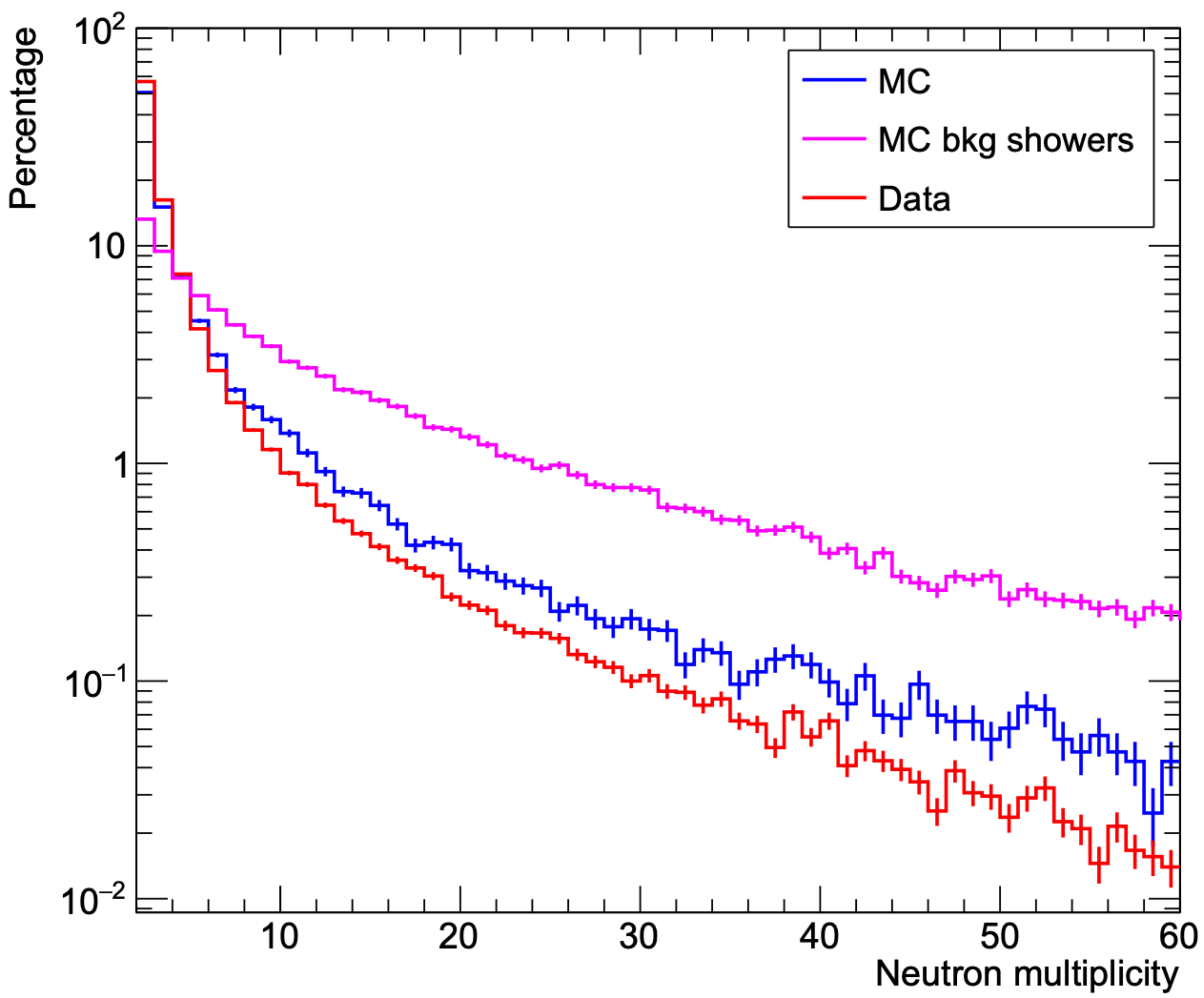
Neutron clouds with Gd — Multiplicities



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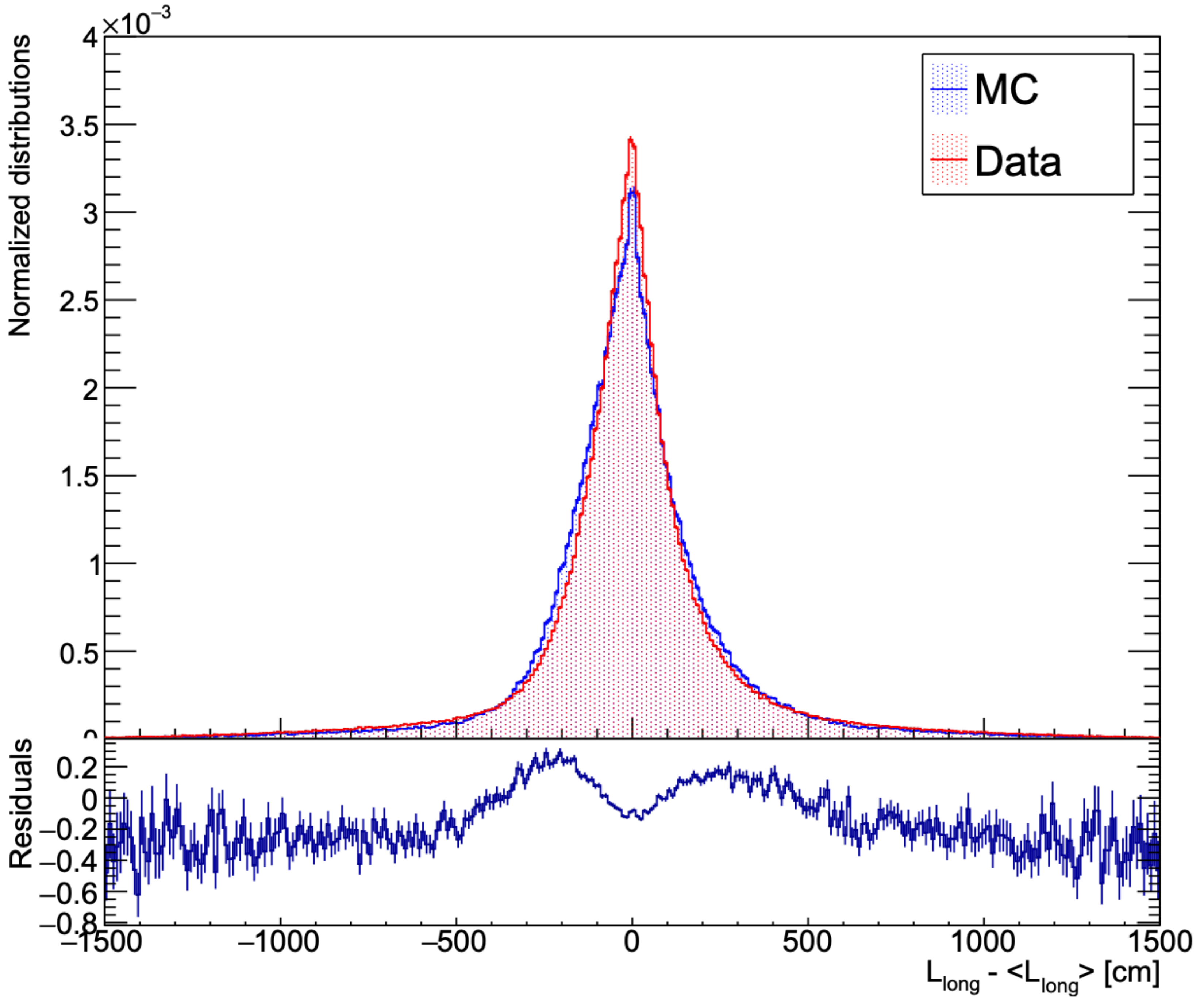
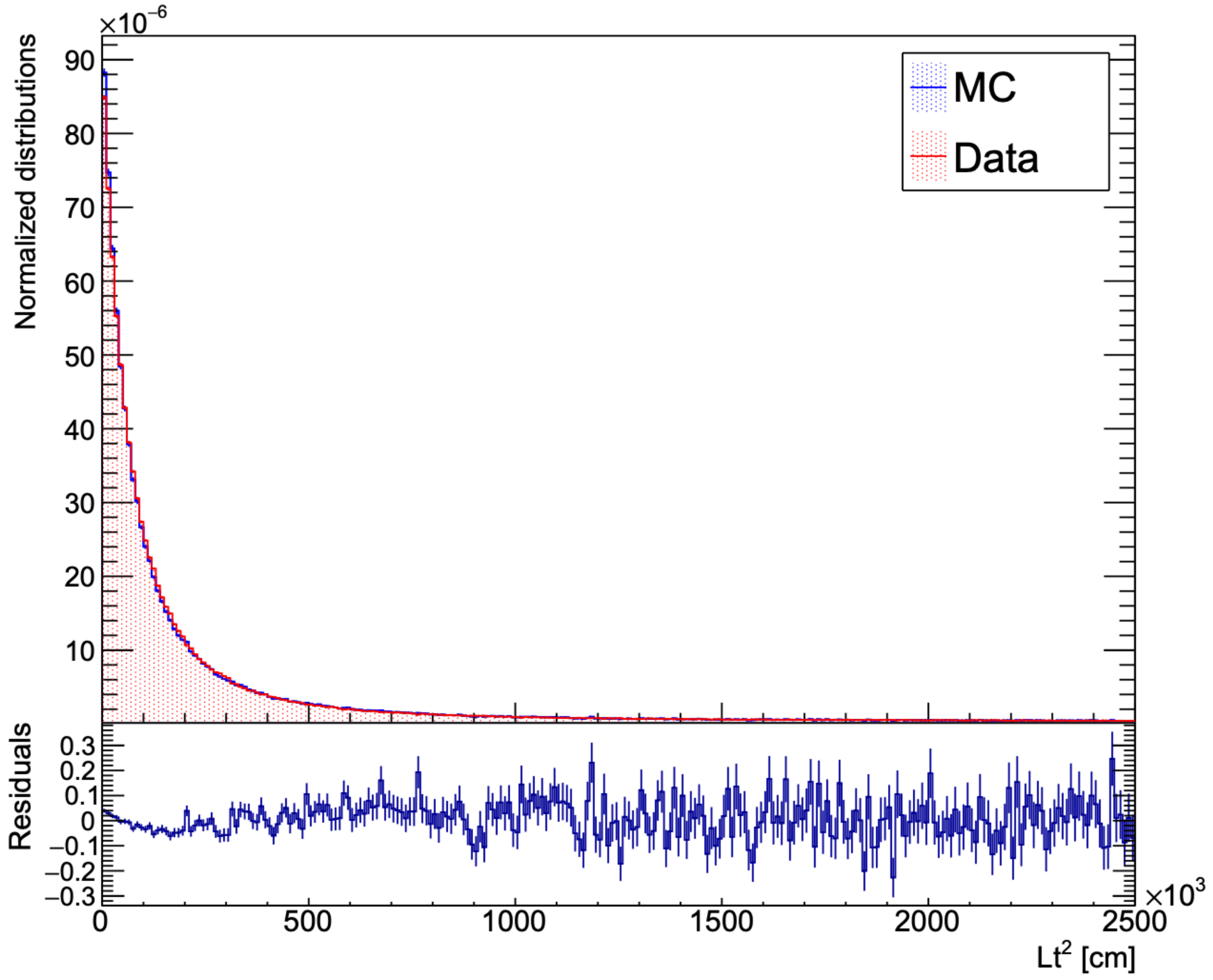
Neutron clouds with Gd — Shapes





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