Status and Perspectives of Solar Neutrino Research at Super-Kamiokande

Conference on Neutrino and Nuclear Physics, 2017.10.30

Michael Smy, UC Irvine

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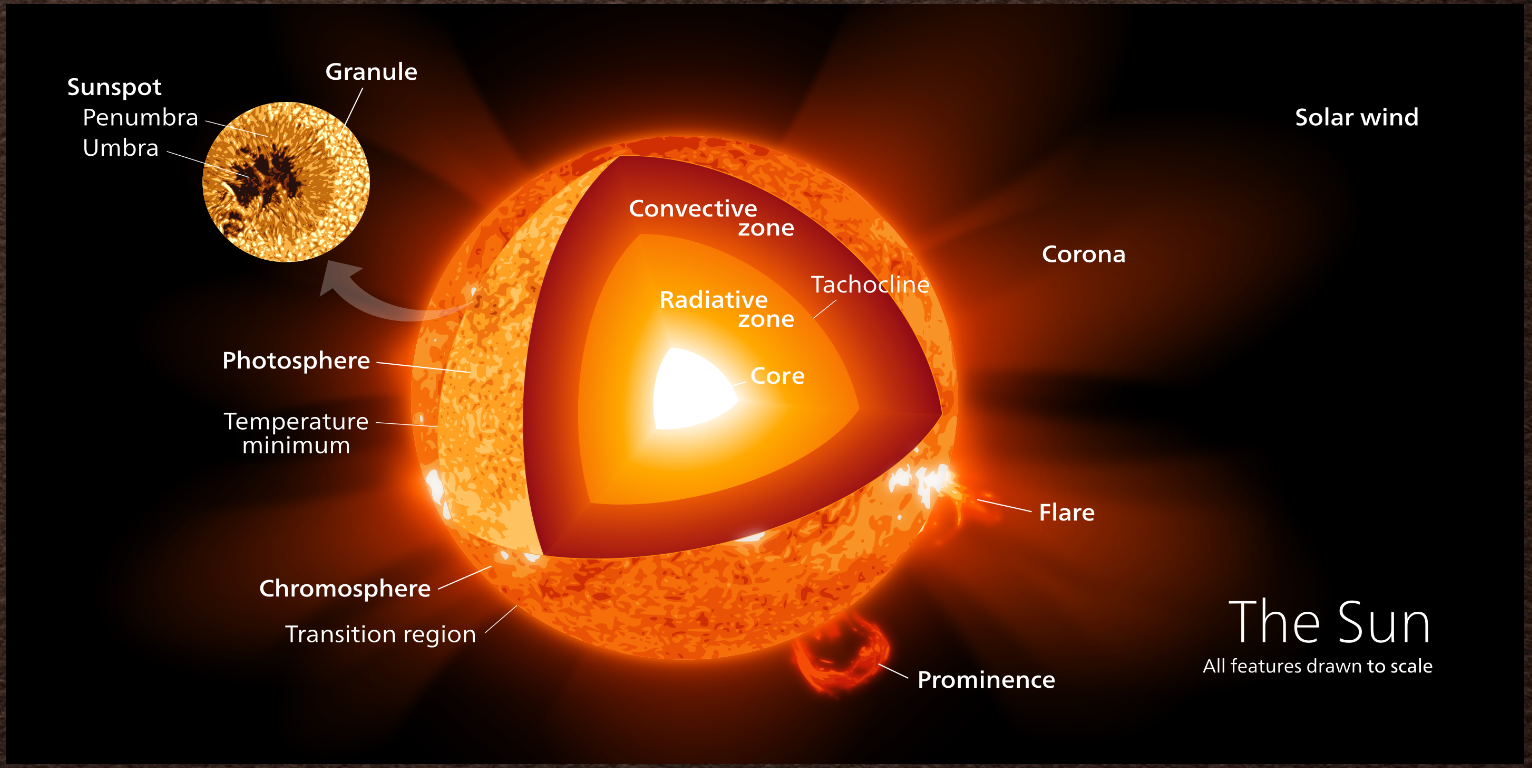
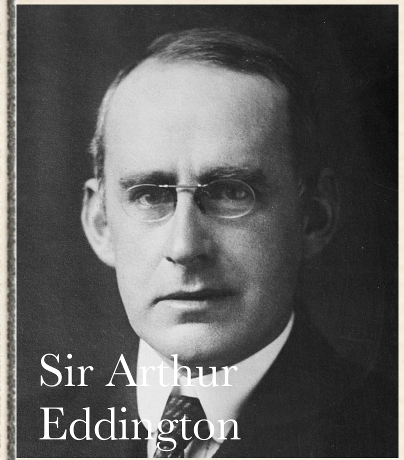
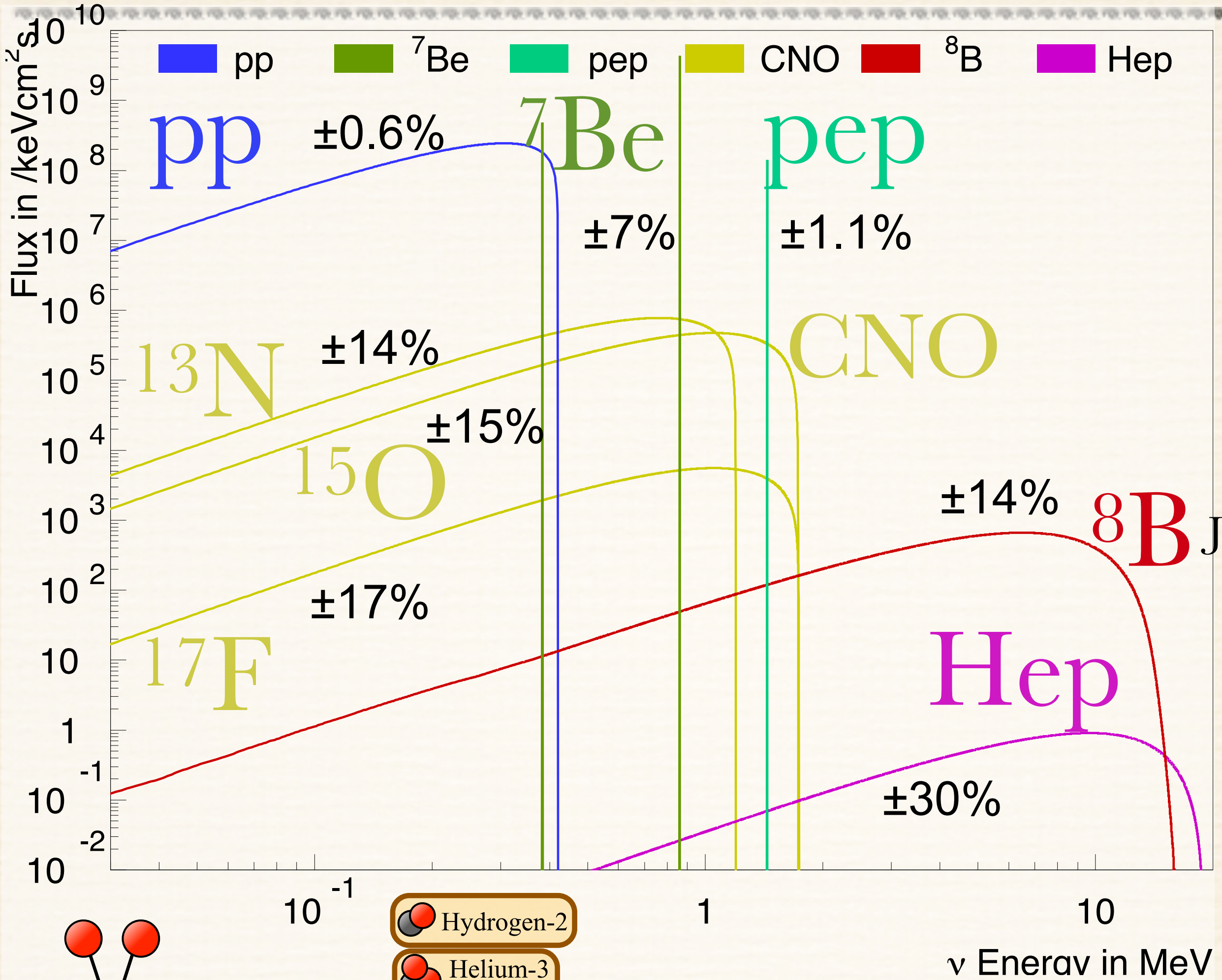


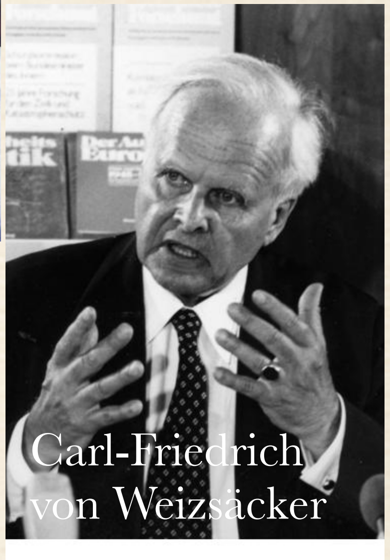
Solar Neutrino Physics

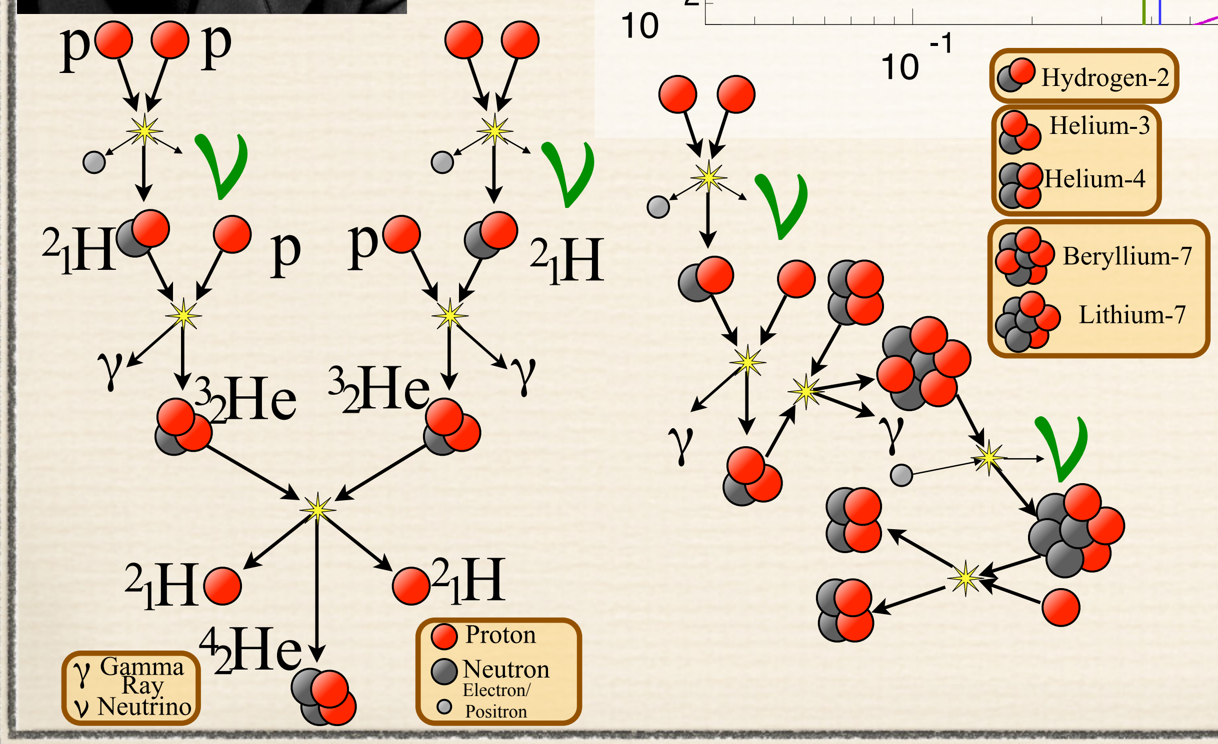
- particle physics:
  - original motivation for neutrino oscillation scenario
  - flavor transformation: test MSW effect in the sun by comparison of low and high energy solar neutrinos
  - directly test matter effects on neutrino oscillations (in the earth) by comparing day- and night-time interaction rates
  - neutrino magnetic moment
- nuclear physics/astrophysics
  - sun shines via nuclear fusion
  - solar core temperature and stability
  - test (evolutionary) solar models (and some of the assumptions)

Solar Fusion and Solar Neutrinos

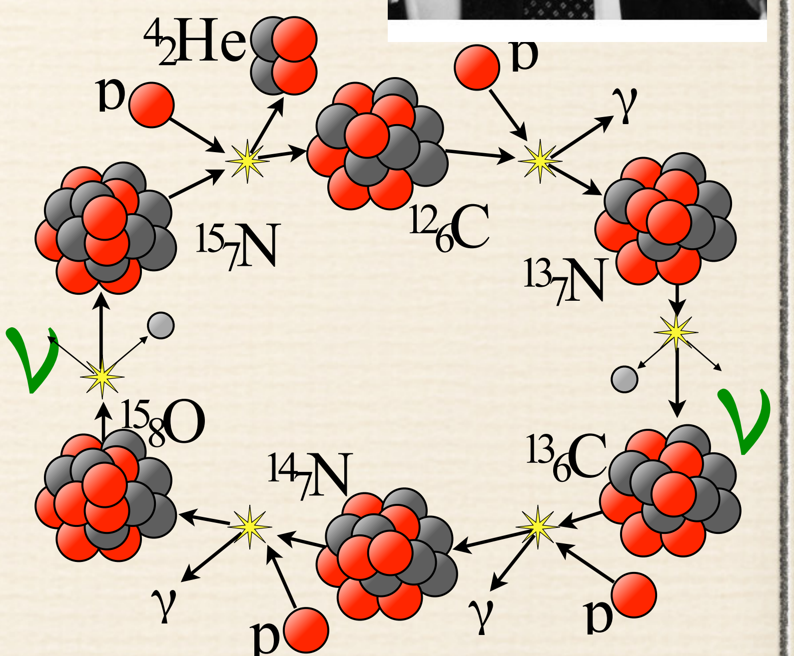




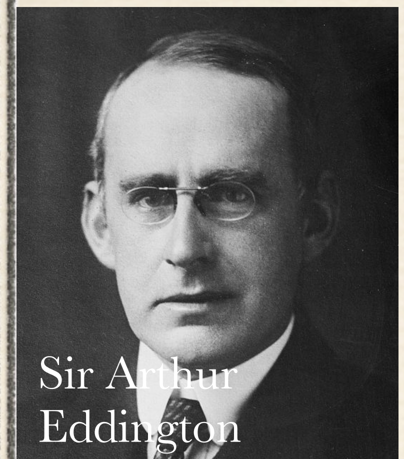


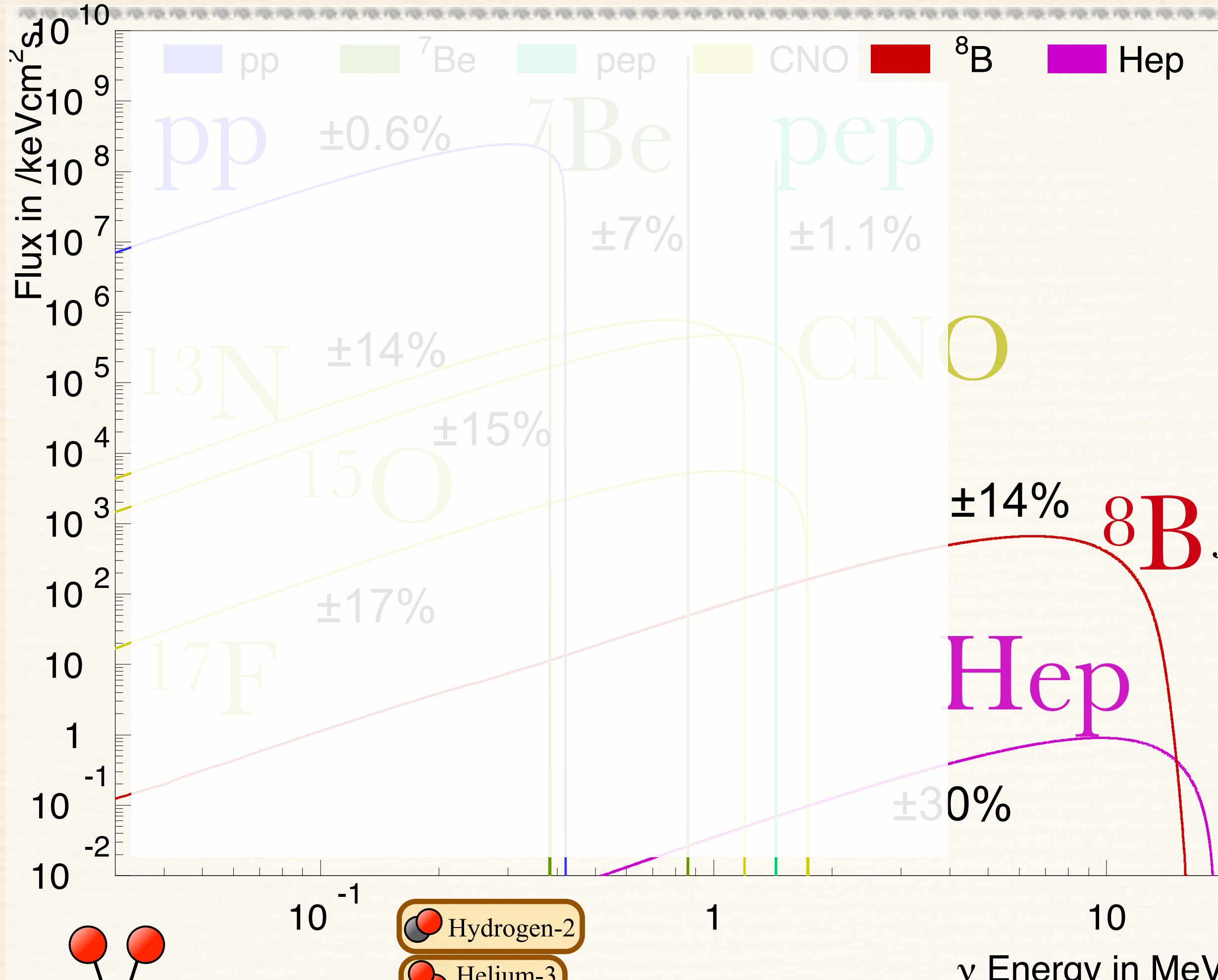


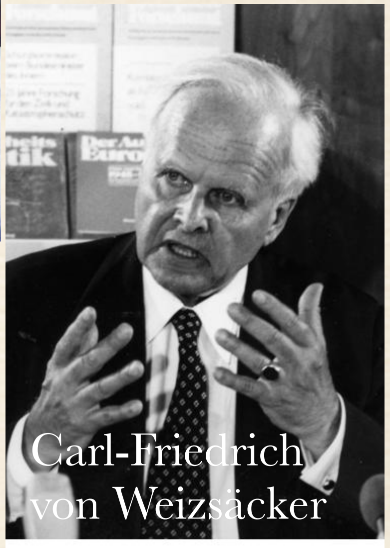
$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e$$

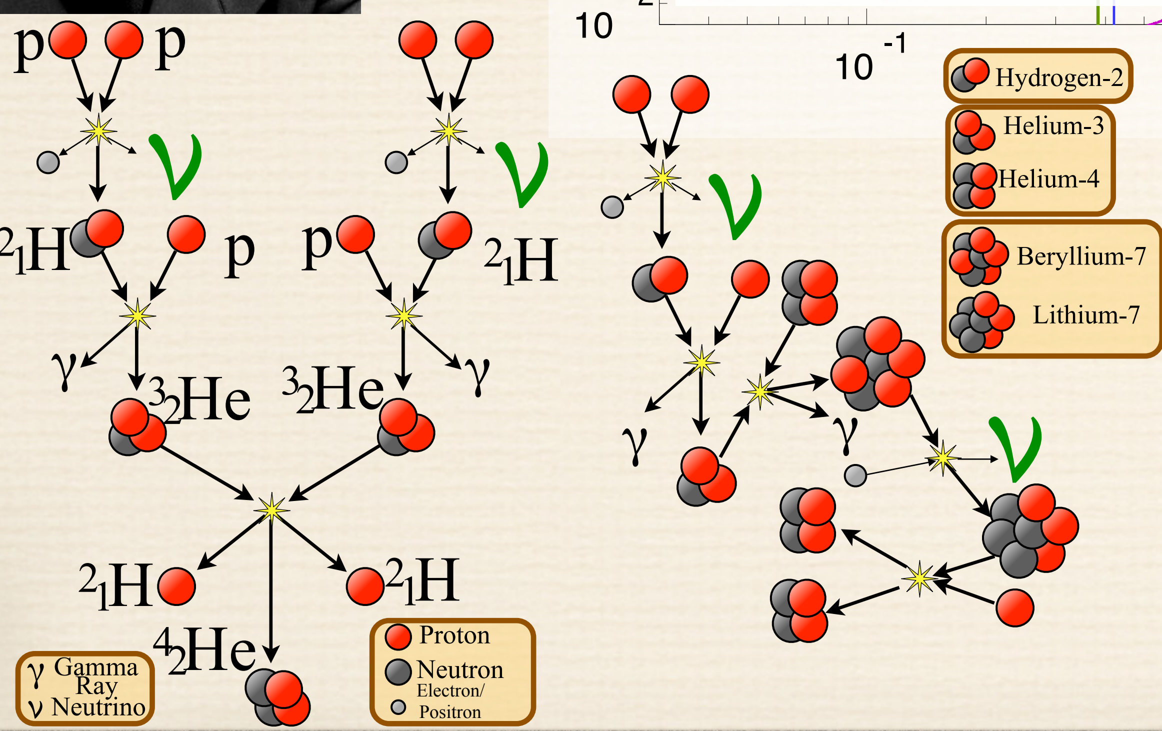


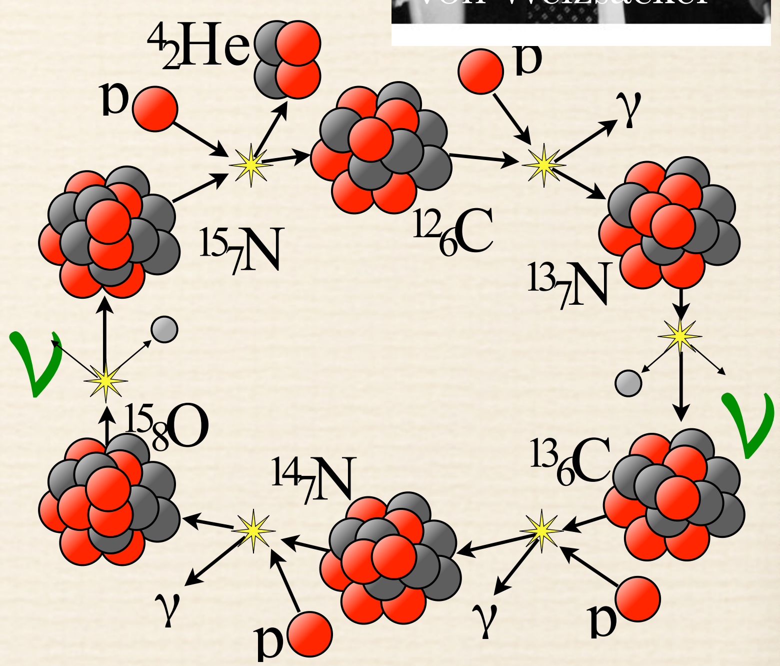
Solar Fusion and Solar Neutrinos











$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e$$

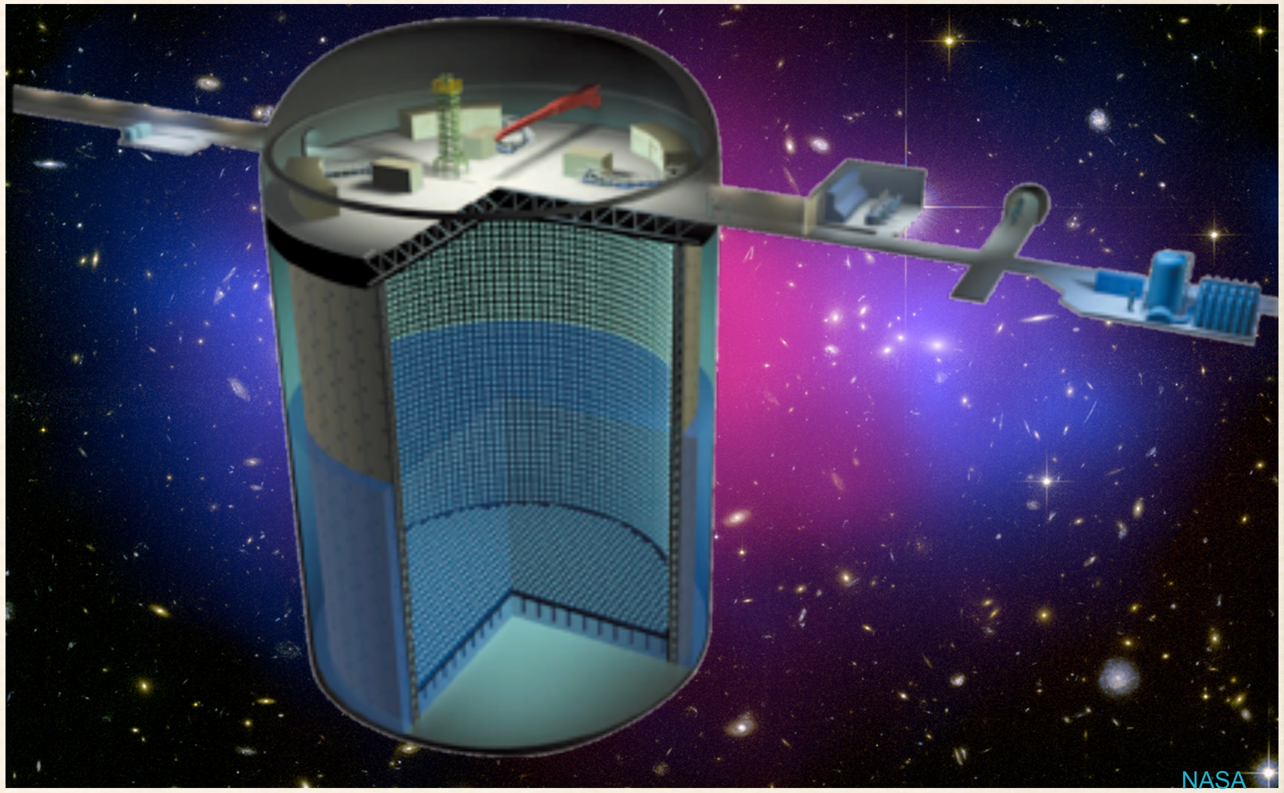
21 Years of Super-Kamiokande!

96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14

4 Super-Kamiokande-I 6 Accident 12 SK-II 5,182 PMTs 11 full repair 7 SK-III 9 Super-Kamiokande-IV

K2K-I K2K-II earth-quake T2K

- 1998: discovery of atmospheric neutrino flavor transformation and neutrino mass
- 2000: solar mixing angle is large
- 2001: discovery of solar neutrino flavor transformation with SNO; uniquely measure oscillation parameters (with all solar data)
- 2004: discovery of atmospheric ν oscillation; confirmation from K2K with ν_μ beam
- 2011: first indication of positive θ_{13} from T2K with ν_μ neutrino beam
- 2012: first evidence for τ appearance
- 2013: first direct indication of matter effects on ν oscillations (solar ν day/night effect)
- 2013: first observation of $\nu_\mu \rightarrow \nu_e$ appearance
- 2017: first hint of CP violation in ν oscillations

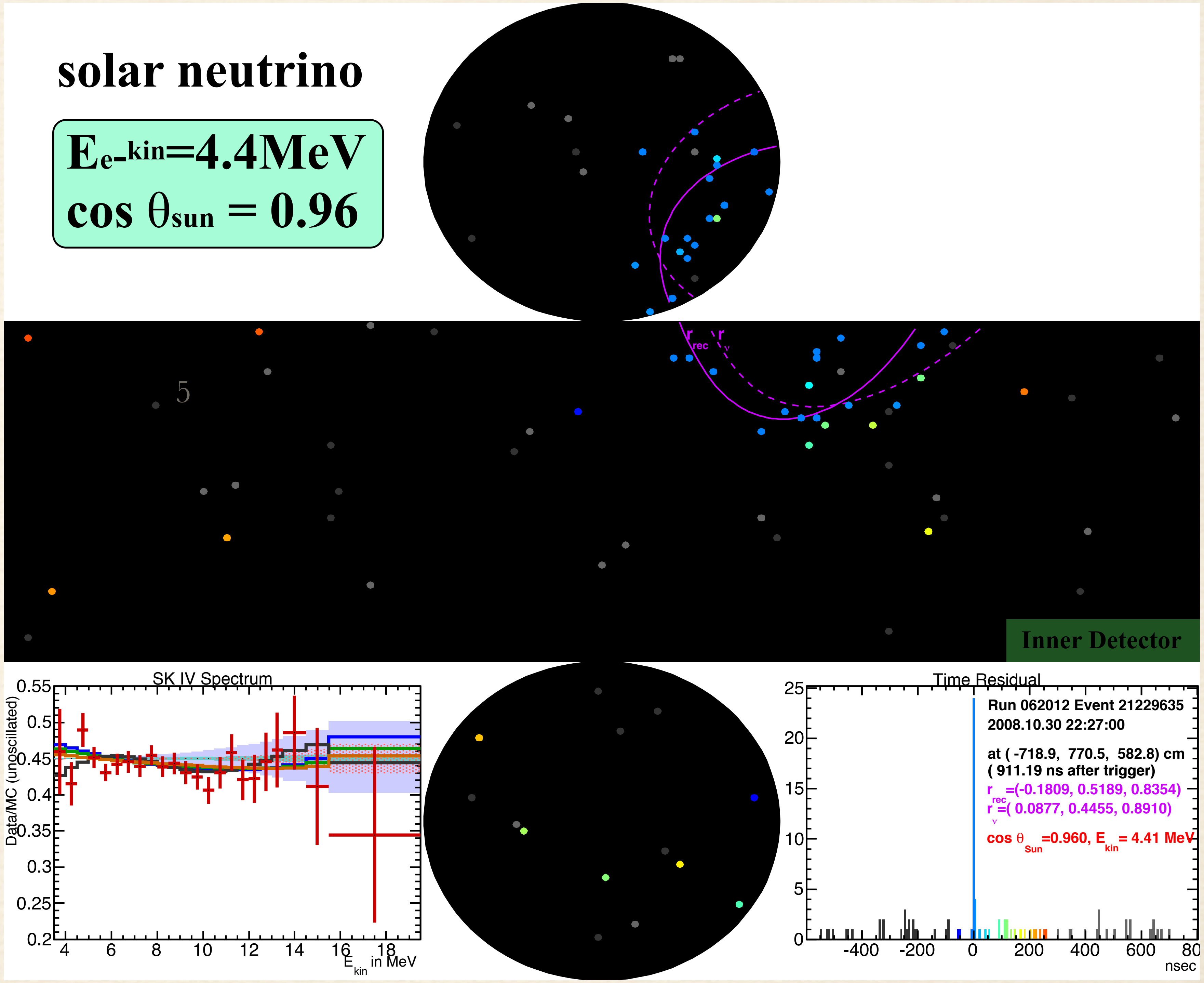


- 50,000 ton water Cherenkov detector
  - ID: 32,000 tons (FV 22,500 tons); 11,129 PMTs (SK-I 11,146 PMTs)
  - OD: 18,000 tons; 1,885 PMTs

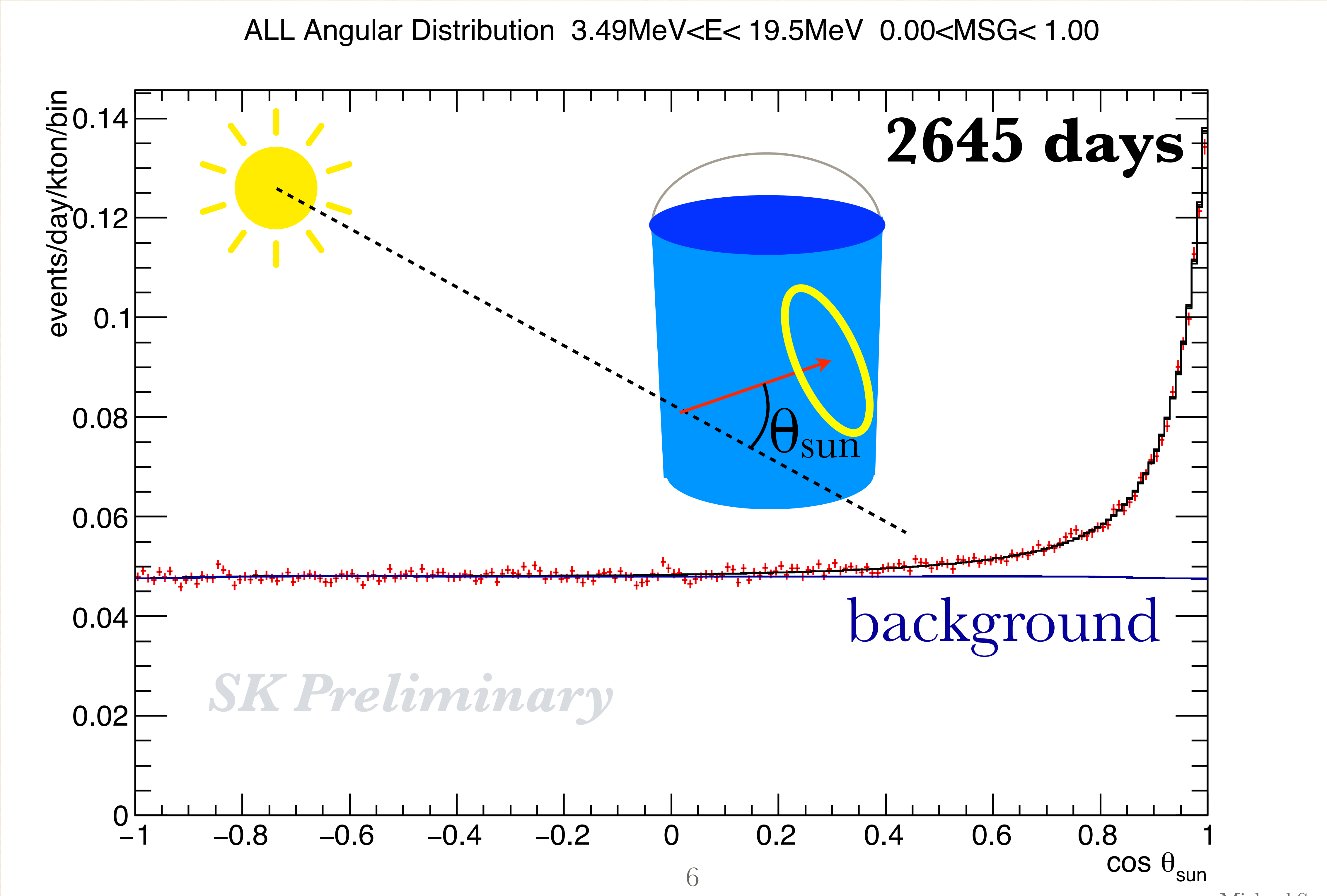
layout by Y. Suzuki, ICRR (Michael Smy, UC Irvine)

Low Energy Electron Detection in Super-Kamiokande

- PMT timing ➛ vertex reconstruction: **20cm (high energy)-60cm (low energy electrons)**
- hit pattern ➛ particle ID and direction reconstruction: **few (high energy muons) to 30⁰ (low energy electrons)**
- brightness ➛ energy: **14% @ 10 MeV** (≈6 hits/MeV above threshold)



Super-Kamiokande IV Data



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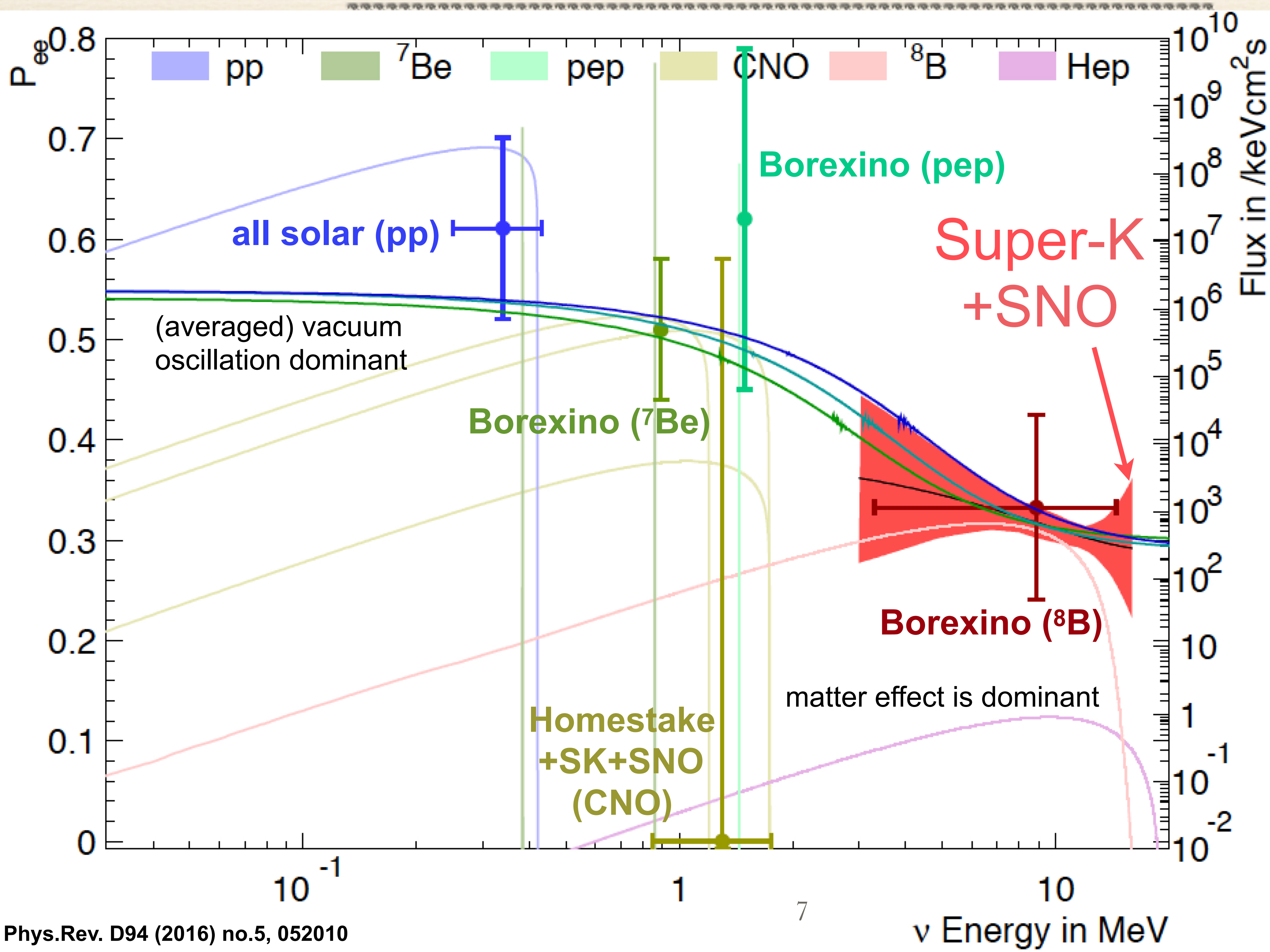
Solar Neutrino Flavor Conversion



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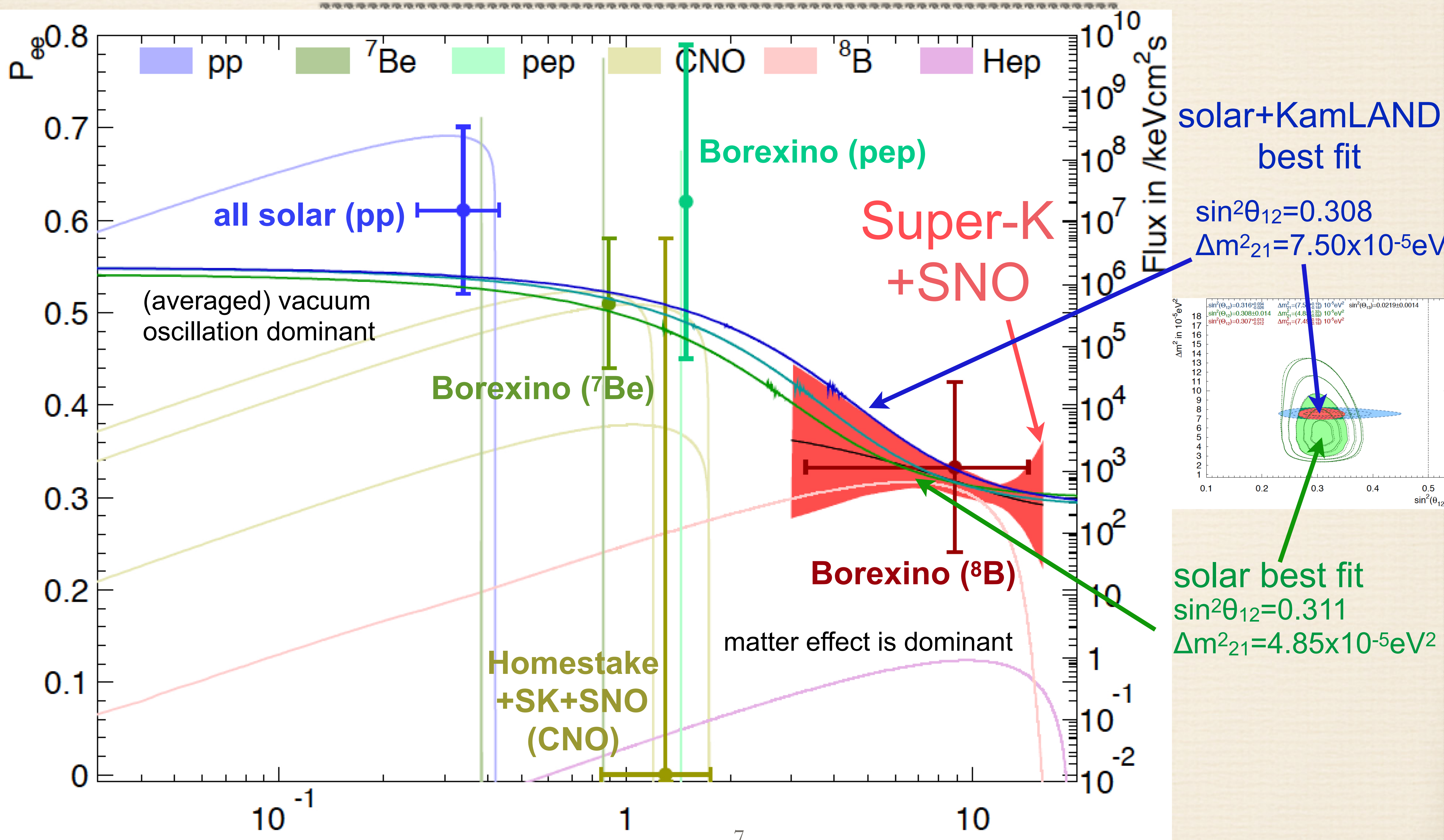
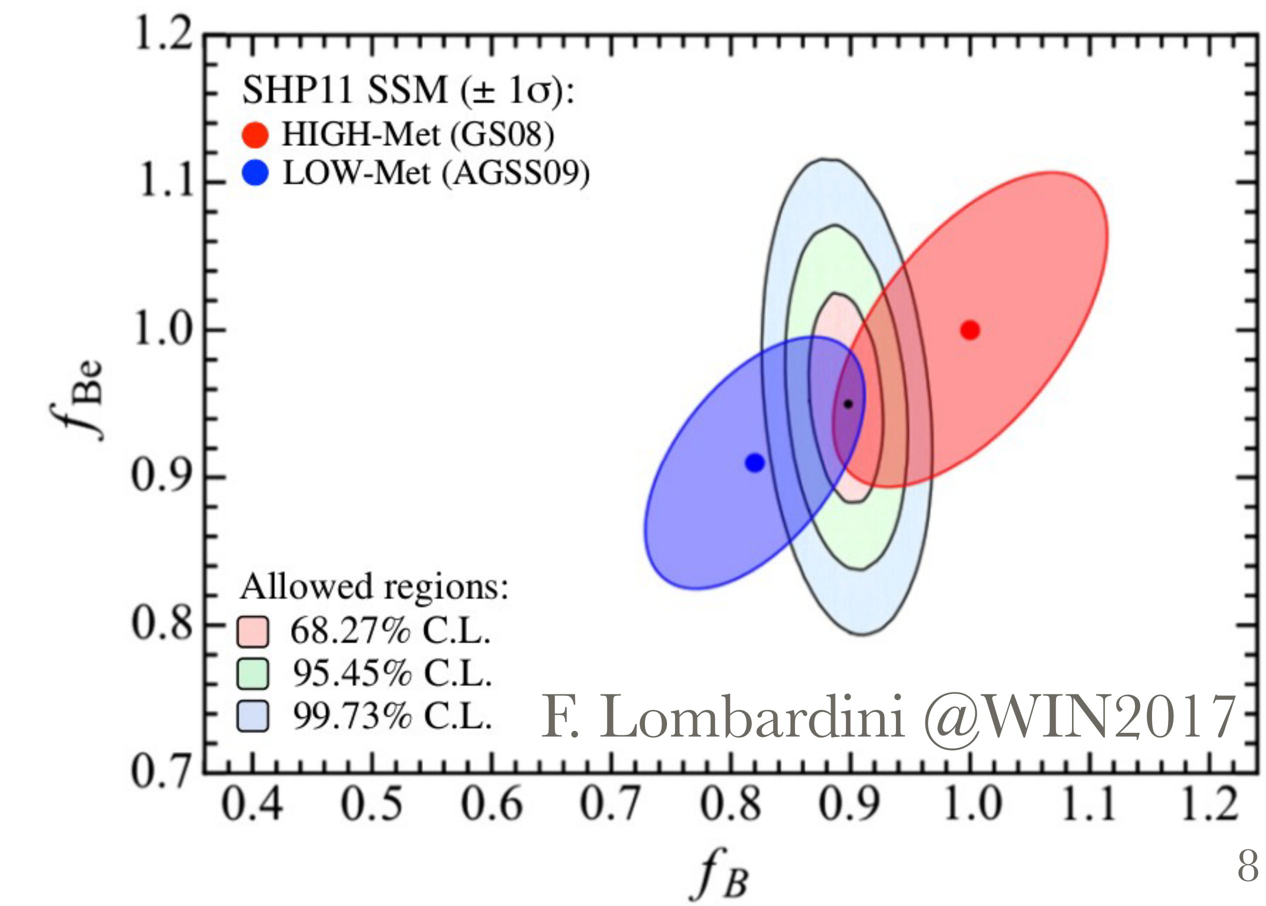
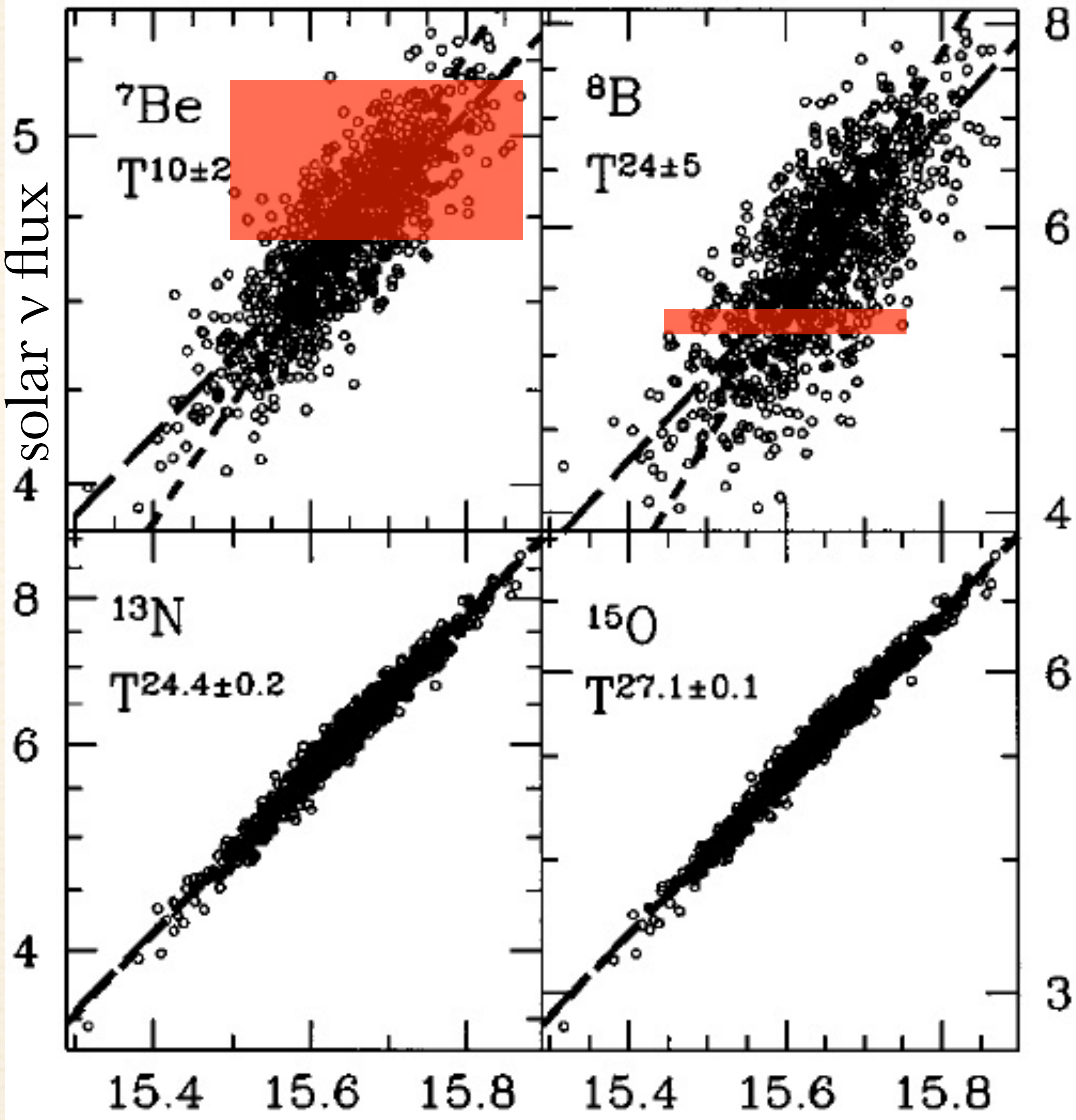


Phys.Rev. D94 (2016) no.5, 052010

Solar ^{8}B ν's and Solar Models

- in essence, measure value (and stability) of solar core temperature
- can't discriminate between high- and low-metallicity models
- CNO value could select one class and break degeneracy with opacity





J. N. Bacall, A. Ulmer, PRD 53, 4202 (1996)

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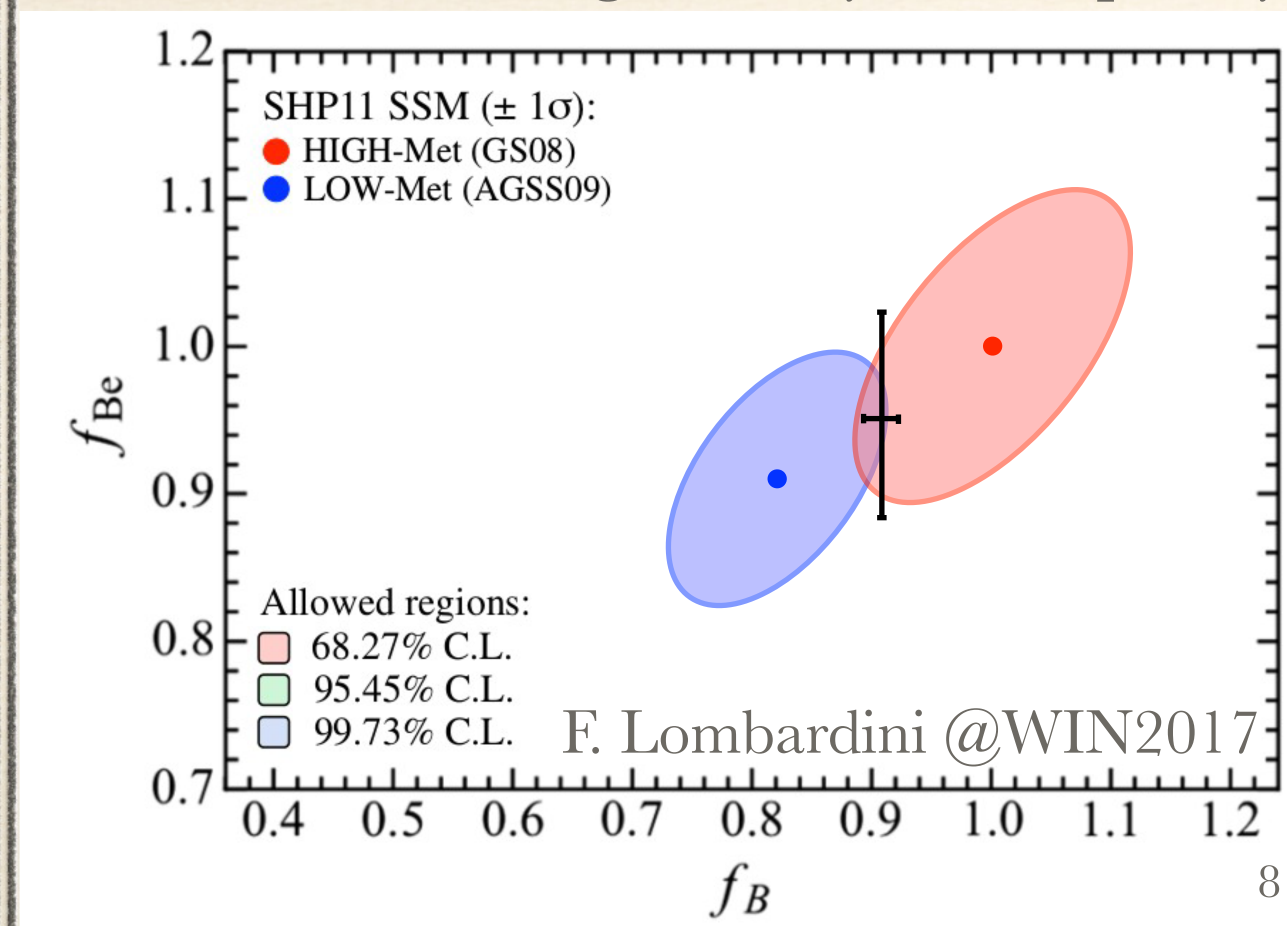

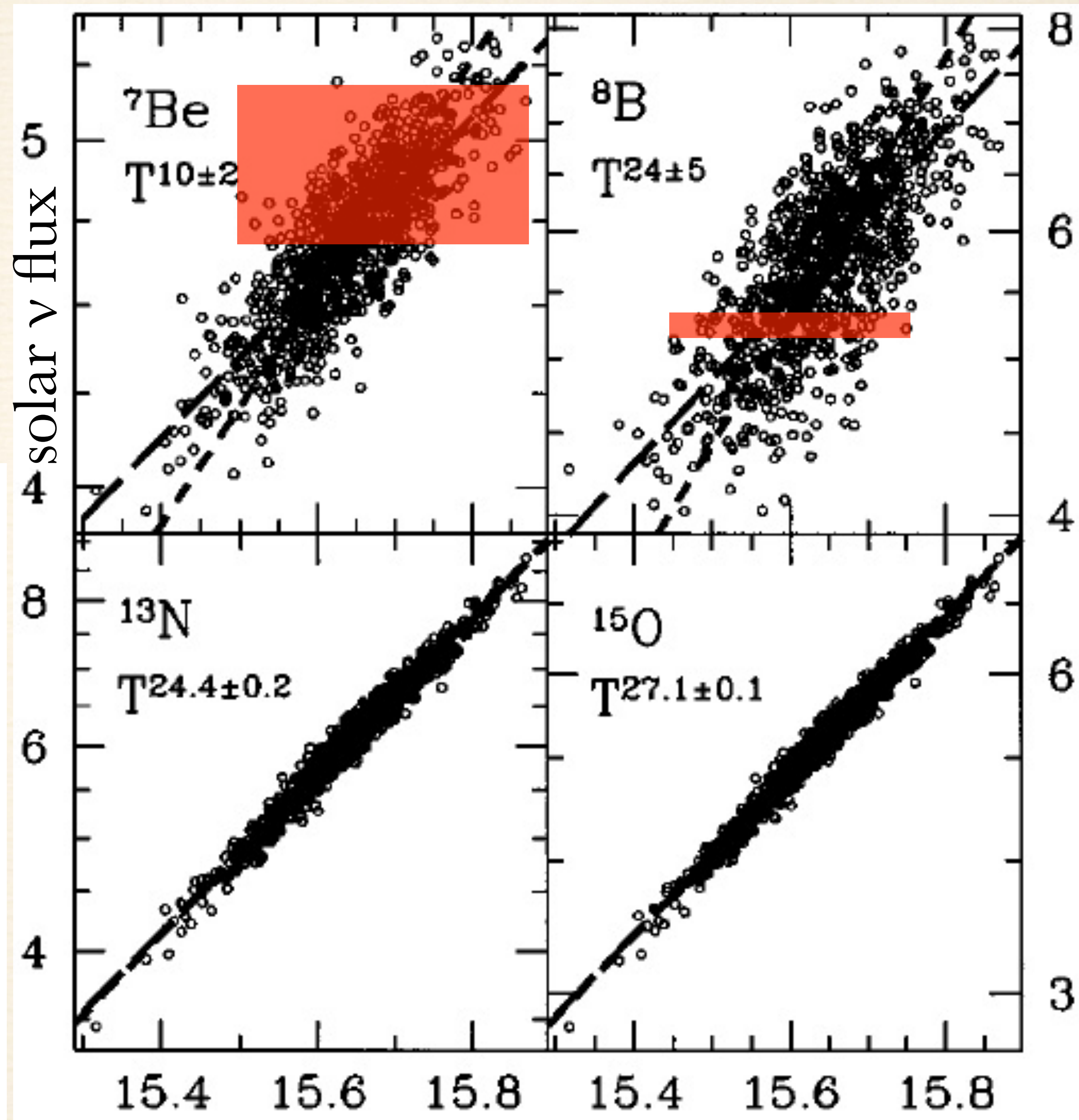

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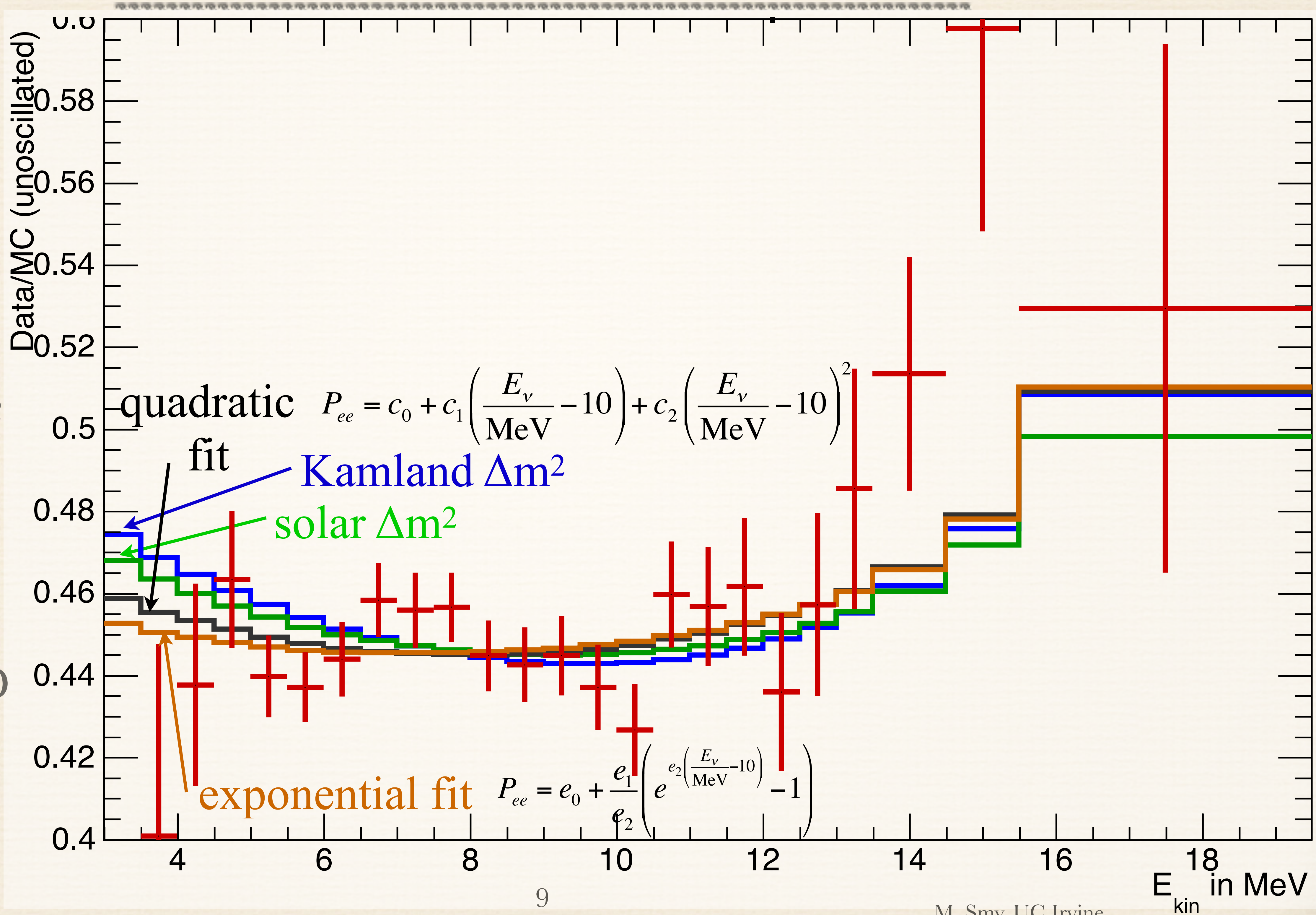
Test Resonant Conversion in the Sun (MSW)

latest Super-K recoil e- spectral data: consistent with solar best fit Δm² within 1σ, but ~2σ tension with KamLAND measurement



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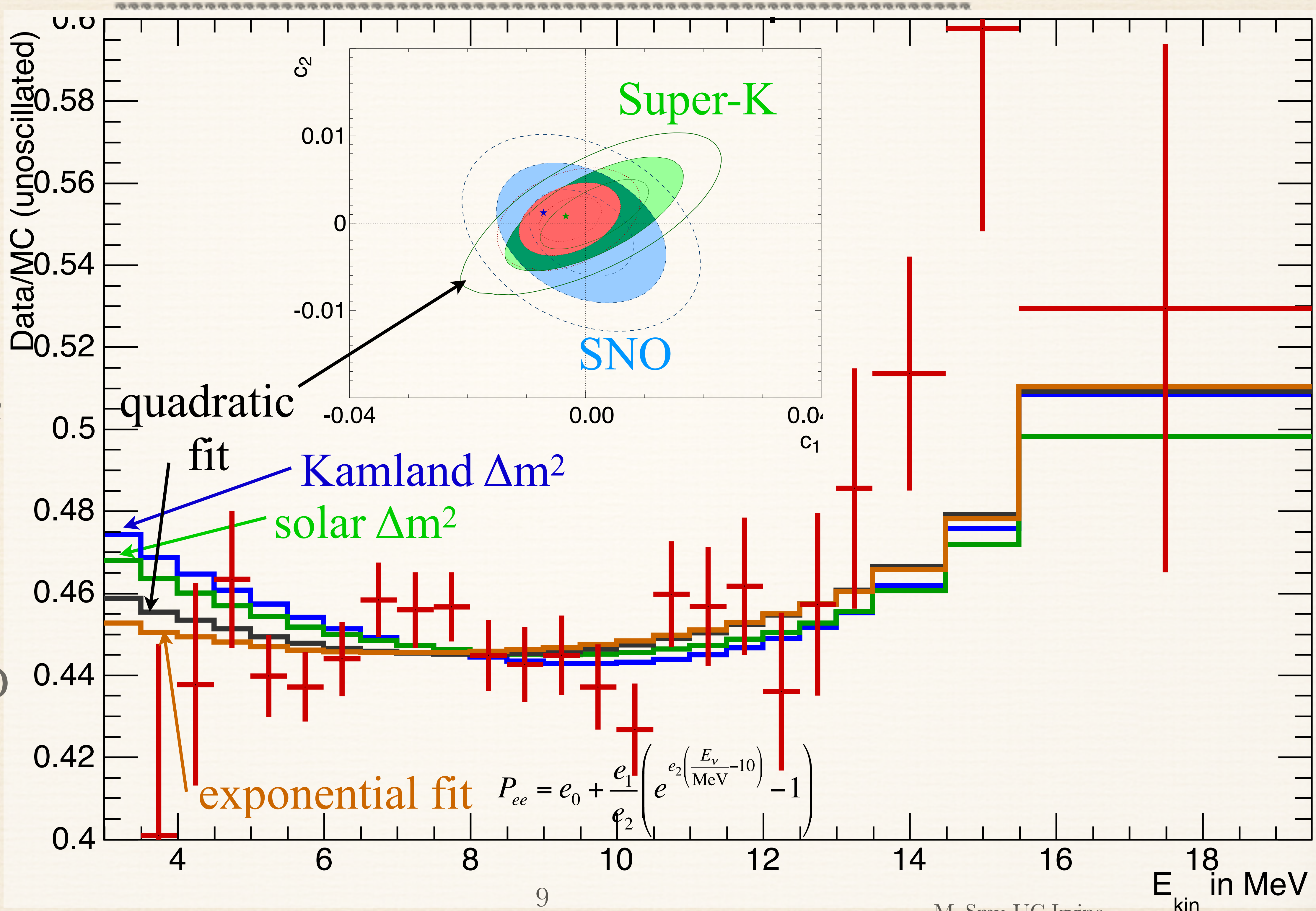

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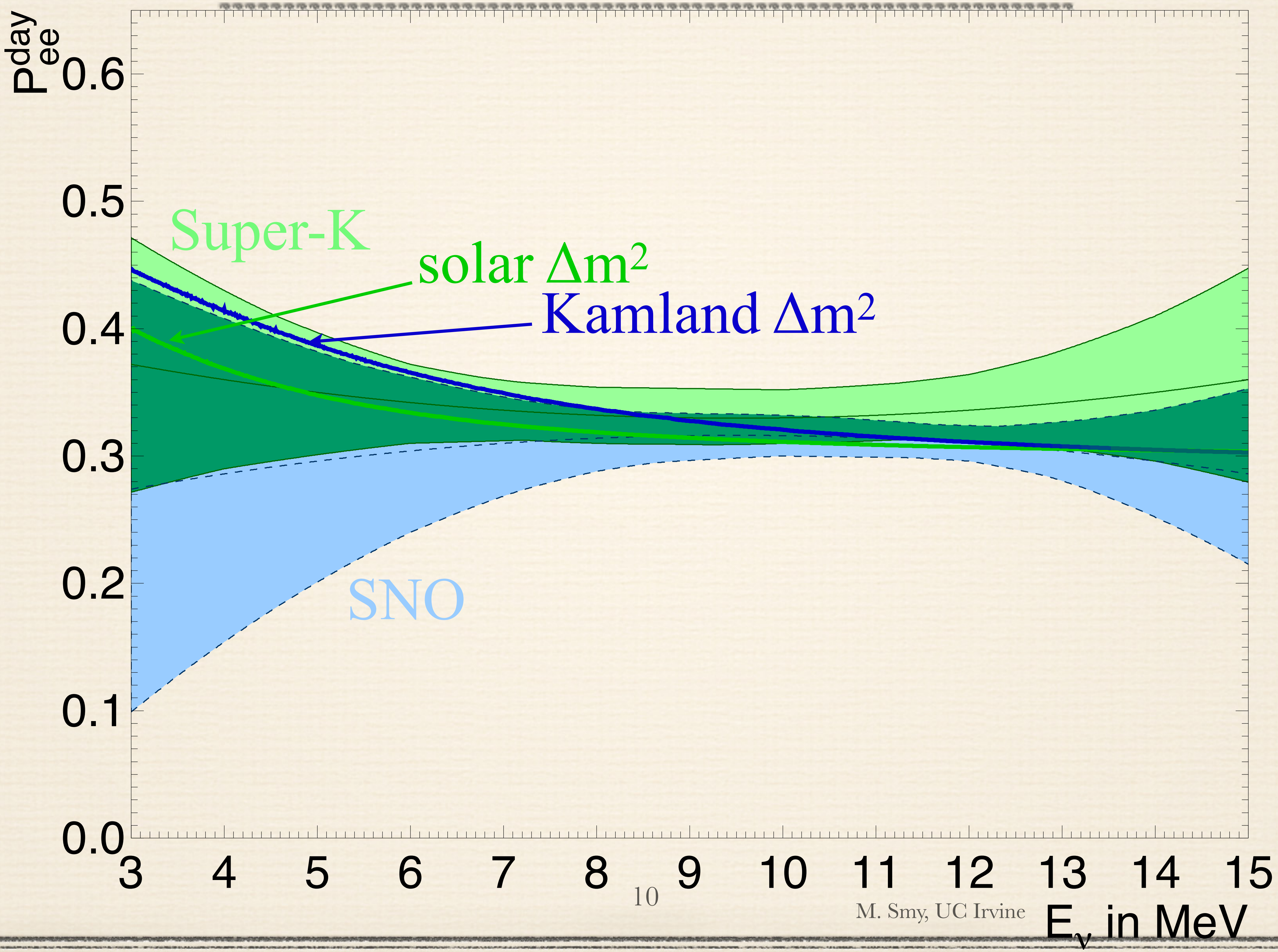
Super-K and SNO: resulting P_{ee}



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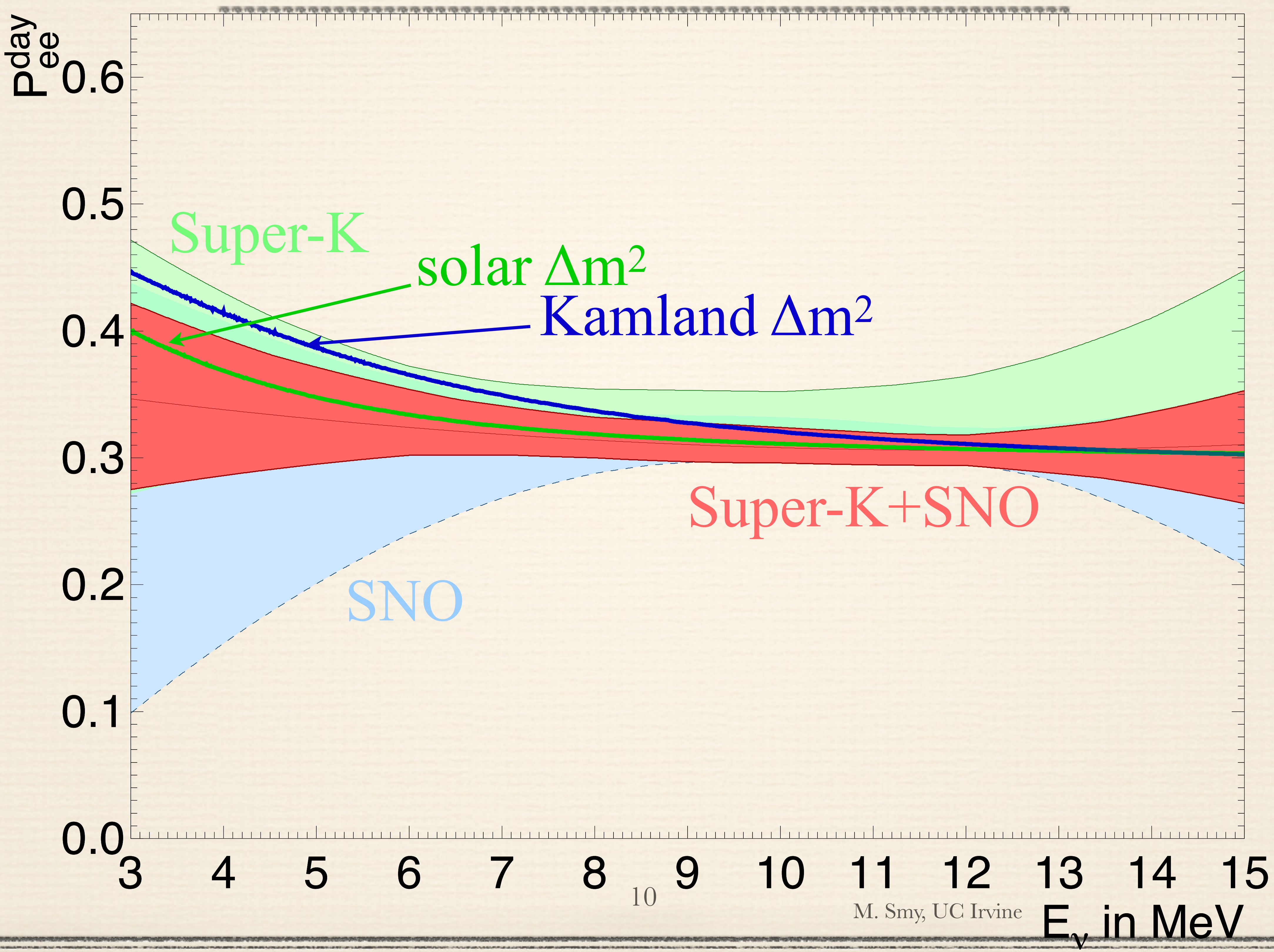

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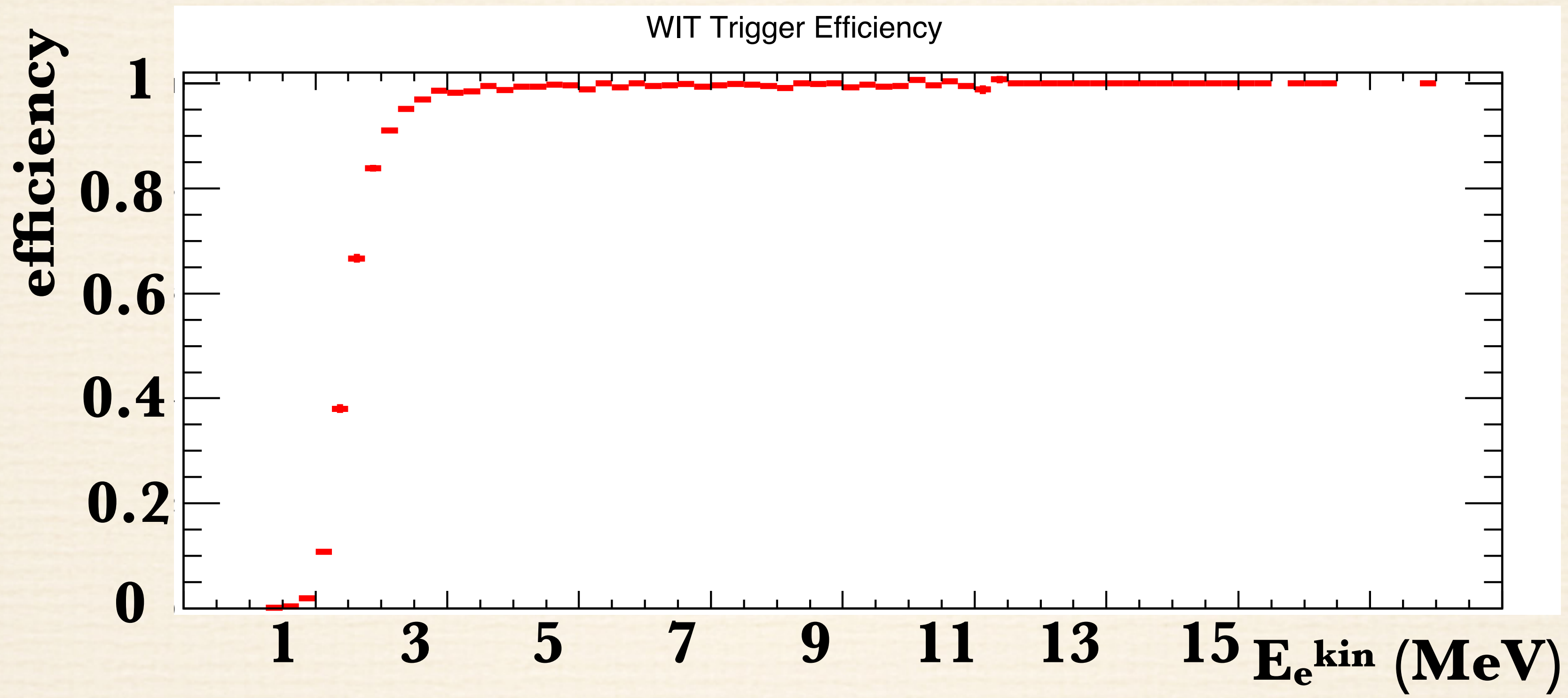
Probe MSW: Future Improvements

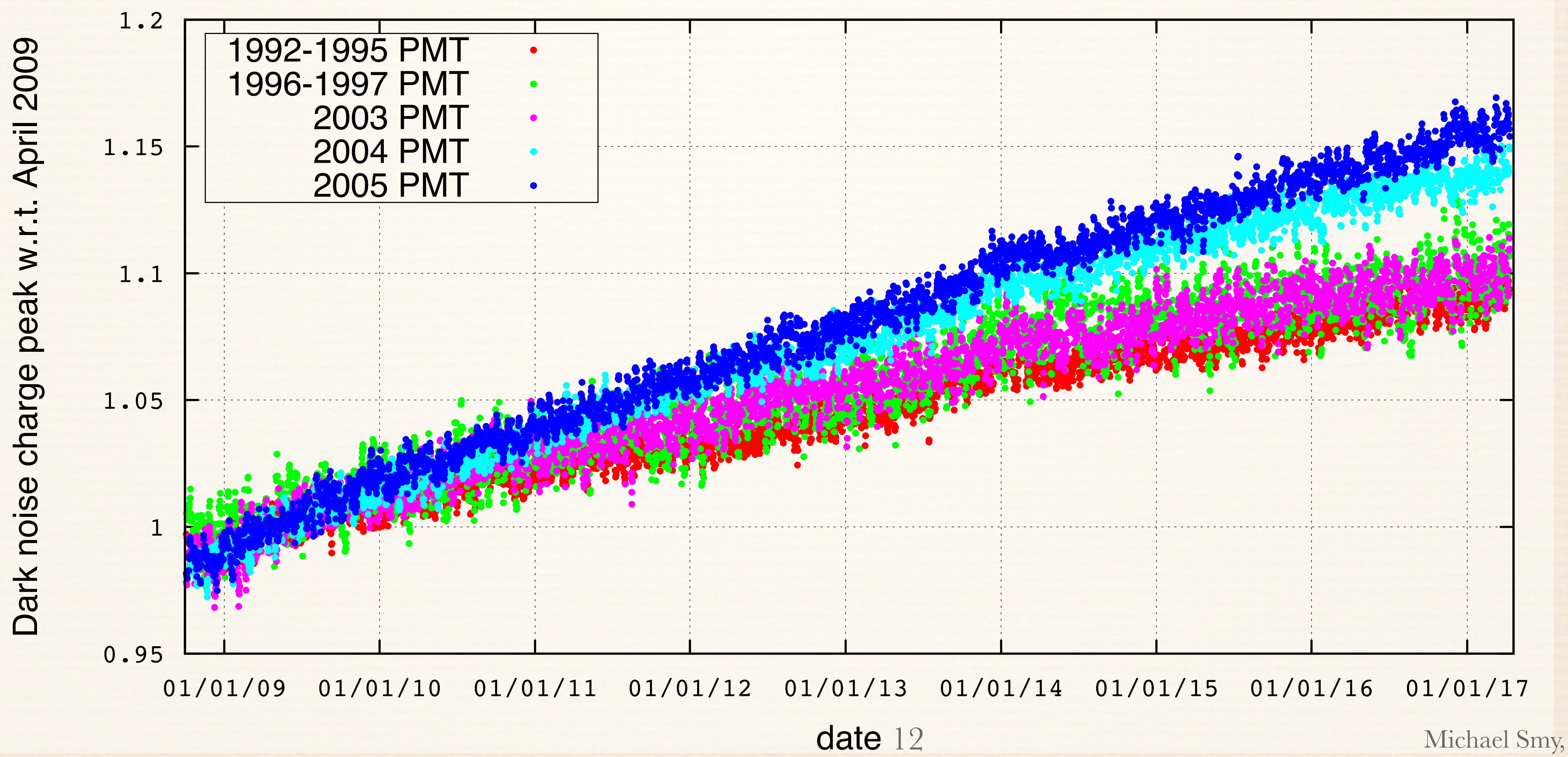
- lower threshold: Wideband Intelligent Trigger has >90% efficiency for kinetic energies >2.5 MeV



- smaller spectral systematic uncertainty with better calibration:
  - linear accelerator injecting single electrons with E=5-18 MeV
  - Deuterium-Tritium generator to make ^{16}N with 14 MeV n's

Energy Scale: PMT Gain Variation

- single photo-electron peak (from dark noise) changes with time
- effective single pe efficiency changes (threshold effect)
- have started implementing this effect for the energy scale



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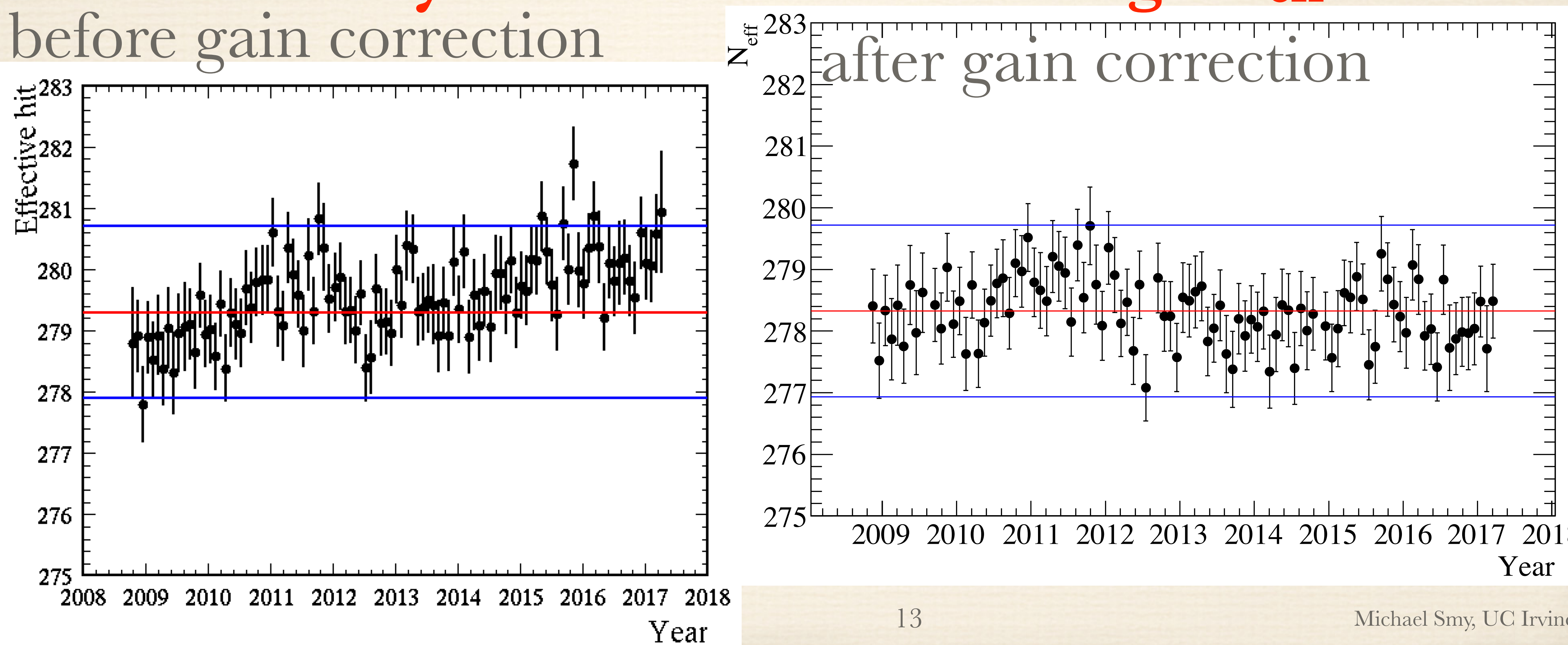
Energy Scale: PMT Gain Variation

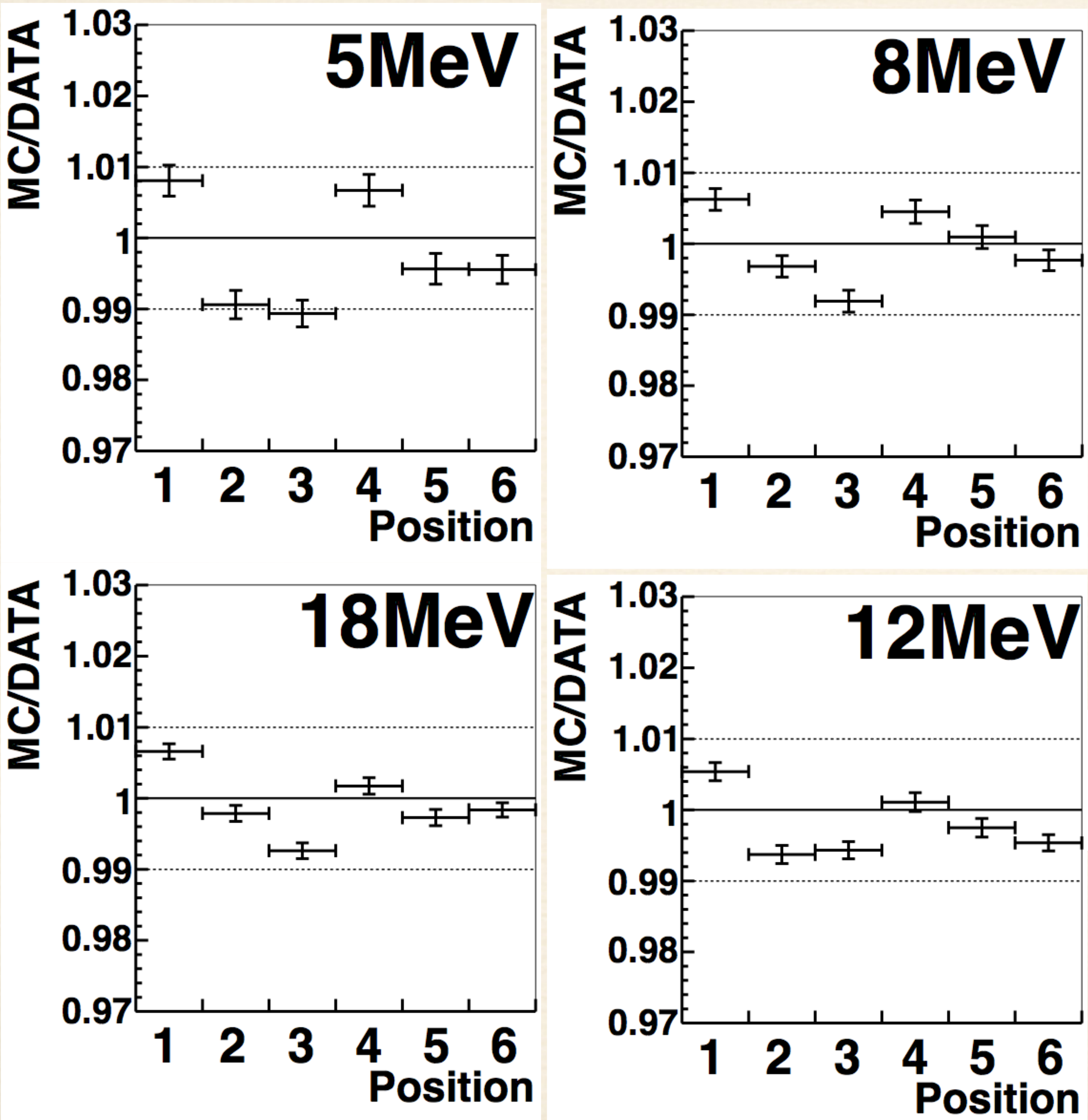
- gain drift changes the fit to the optical parameters and the effective number of signal PMT hits (N_{eff}) used for energy reconstruction
- energy scale becomes more stable in time

Decay Electron Data: Average N_{eff}

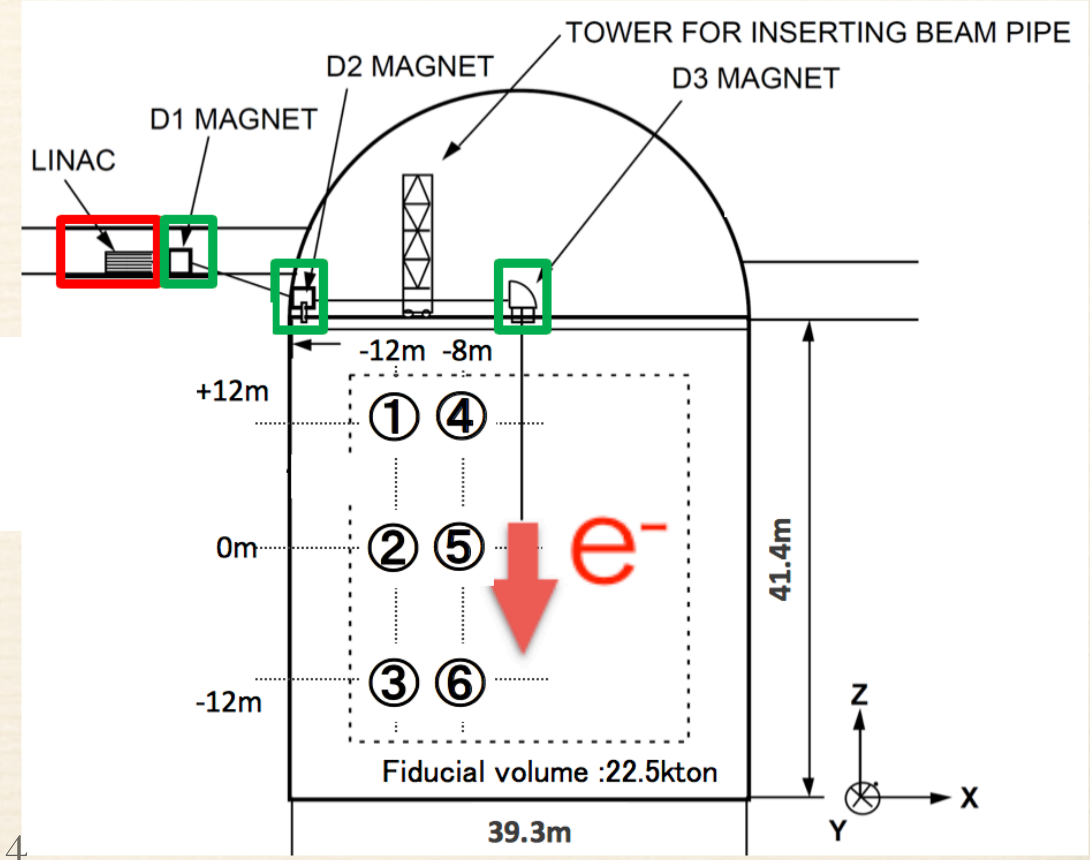
before gain correction



Energy Scale: LINAC Calibration

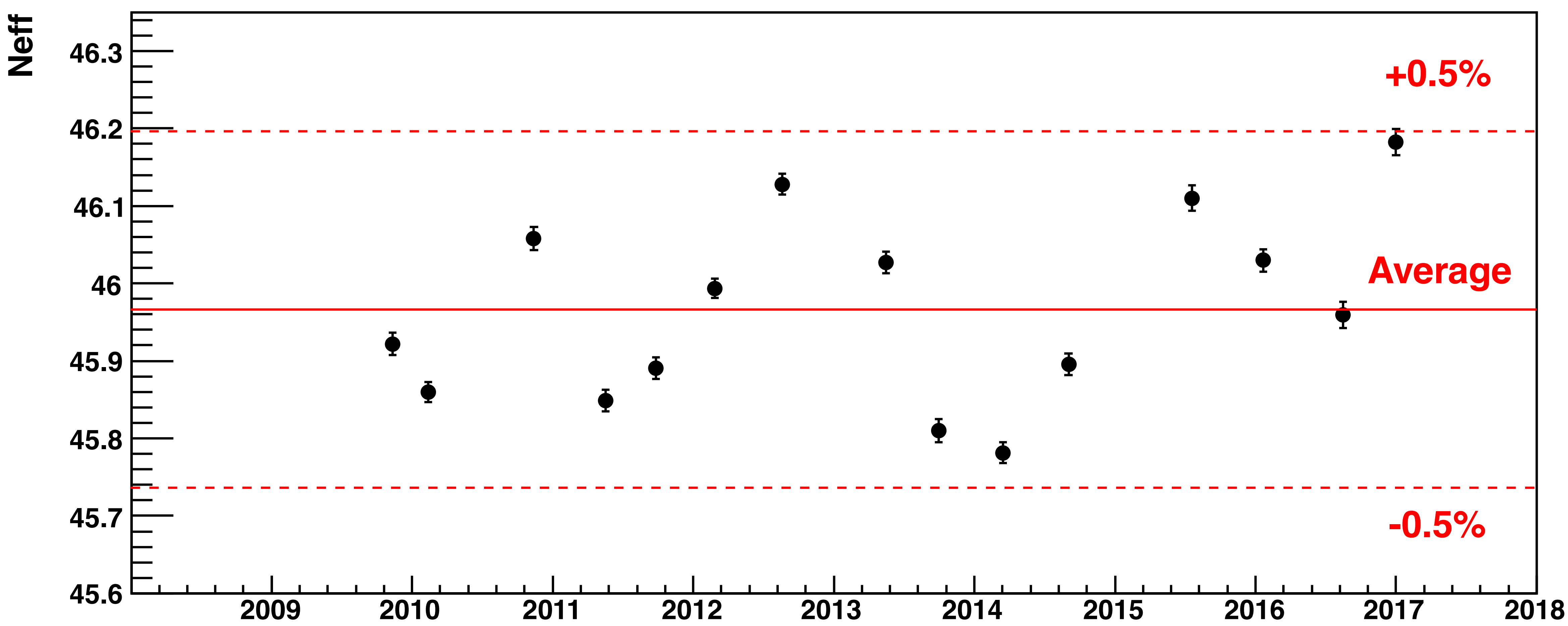


- linear accelerator injecting single electrons
- E=5-18 MeV, nine positions
- still analyzing latest data



Energy Scale: DT Calibration

- Deuterium-Tritium generator to make ^{16}N with 14 MeV n's
- many more positions
- check directionality

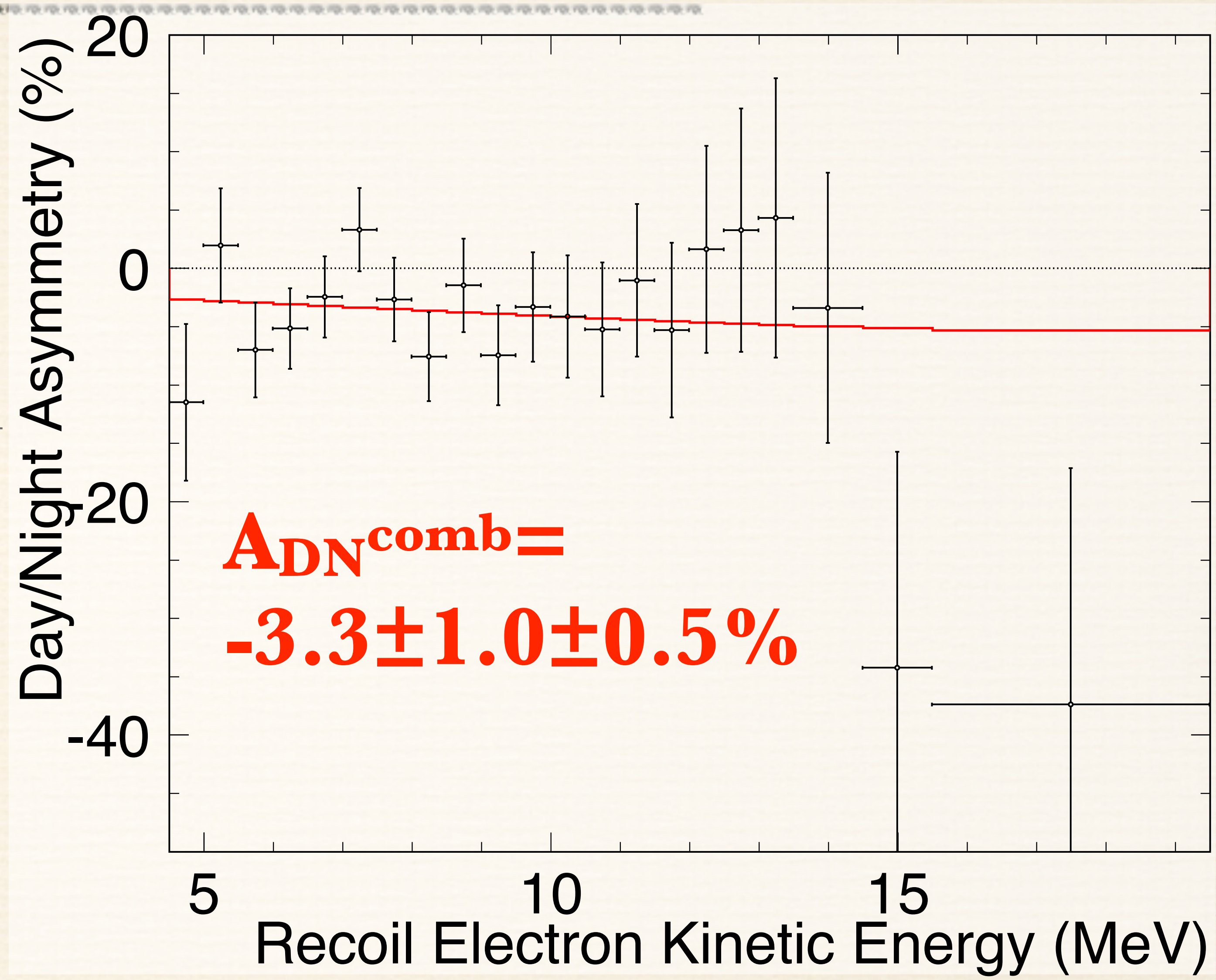


Earth Matter Effects

- direct test: compare flavor content of the same "beam" with and without matter being present
- with current parameters: no effect below few MeV; large effect near ~50 MeV, a few % for ^{8}B neutrinos
- form asym. $A_{DN}=2(D-N)/(D+N)$
- mostly a "regeneration" effect: $P_{ee}^{night}>P_{ee}^{day}$ $(A<0)$
- searched for by Super-K, SNO (E_ν>few MeV) and BOREXINO (E_ν=0.86 MeV)
- no significant non-zero A_{DN} from SNO or BOREXINO
- 2.8σ indication from Super-K

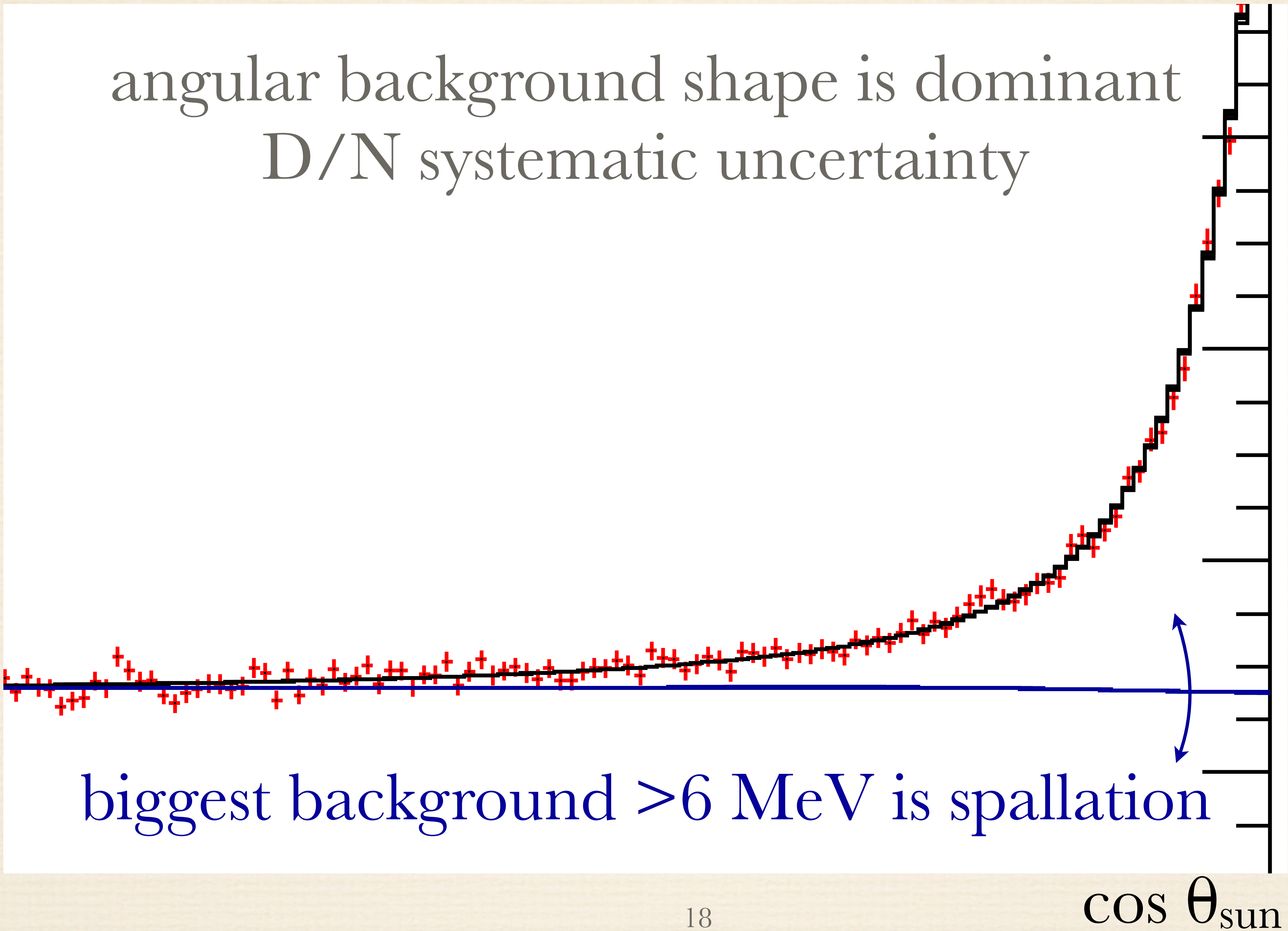
Super-K Result and its Future

- currently ~3σ significance for $A_{DN}\neq 0$
- Super-K-IV uncertainty by itself is ±1.6±0.6%, with full data set (60% more data), it should reach ±1.3±0.4%
- combined $\sigma_{A_{DN}}$=0.9±0.4%
- expect ~3.4σ significance, if same central value



to reach >5σ in reasonable time, need larger event rate, reduction in systematic uncertainty, better control of spallation background will achieve both

D/N Systematic Uncertainty



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Nuclear Spallation Background in Water

- mechanism: muon occasionally starts showers,
- some showers contain hadrons; e.g. neutrons or, $\pi^{\pm}$
- these break up the oxygen nucleus and change them to radioactive elements: ^{16}N, ^{12}B, and many others
- after some msec's to sec's, these elements βγ decay and make background
- the decay locations are close to the muon tracks, but directly correlate with the volume covered by the shower

★^{16}O

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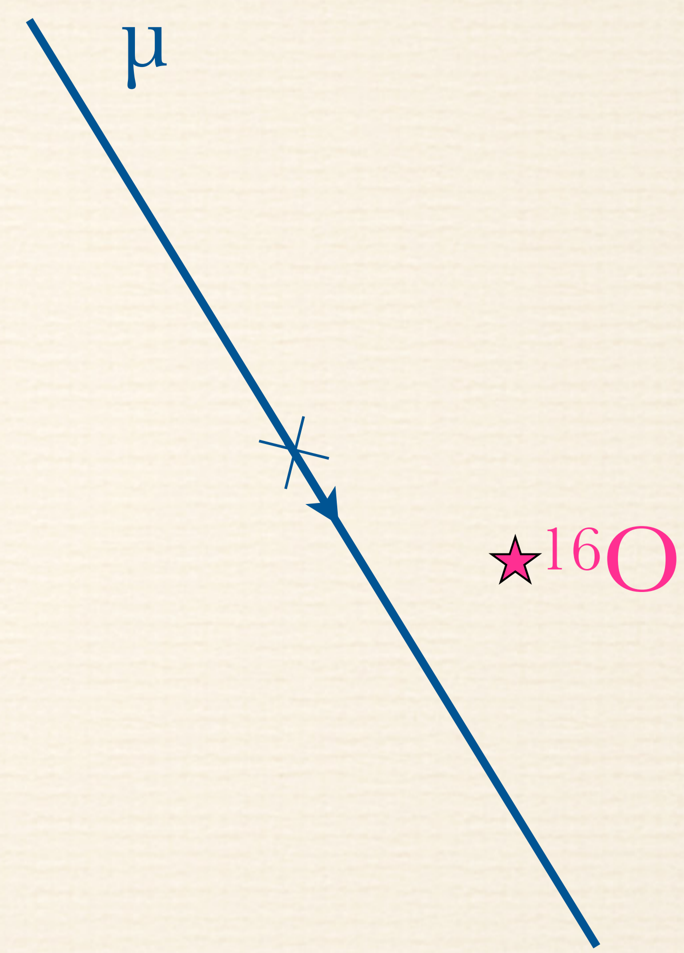

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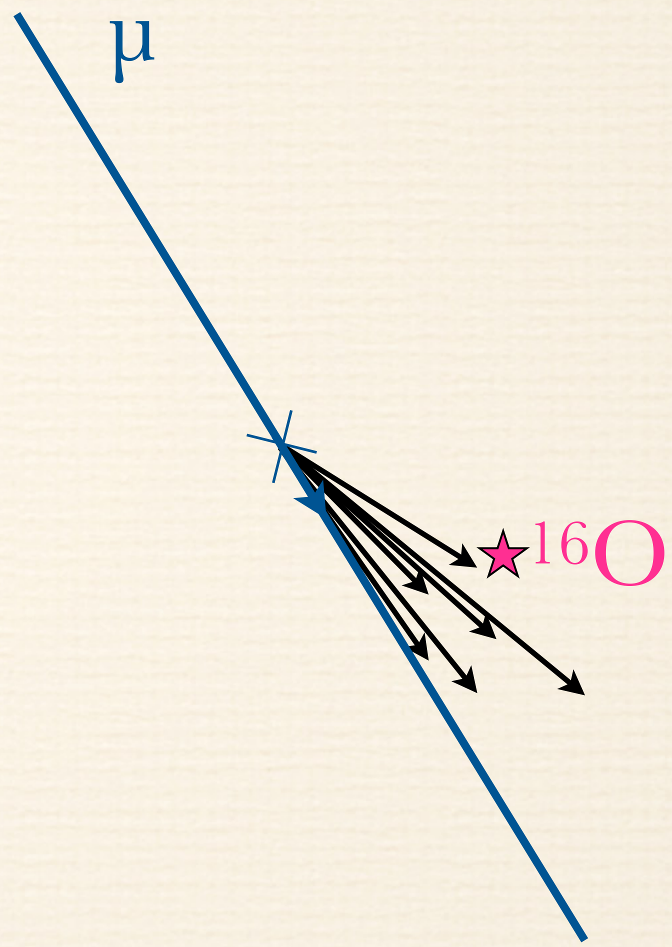

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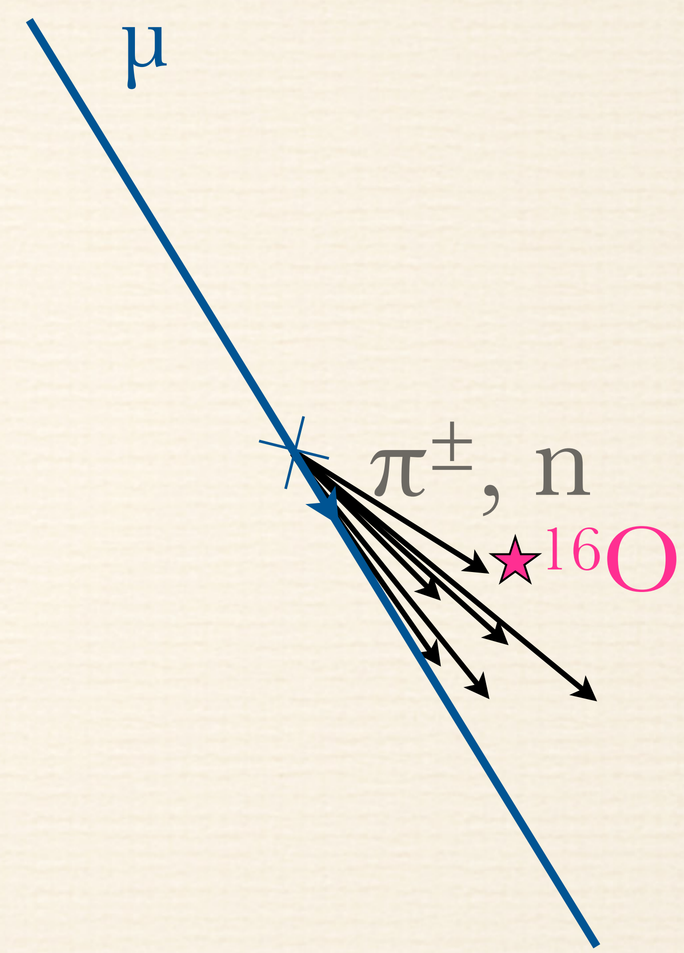

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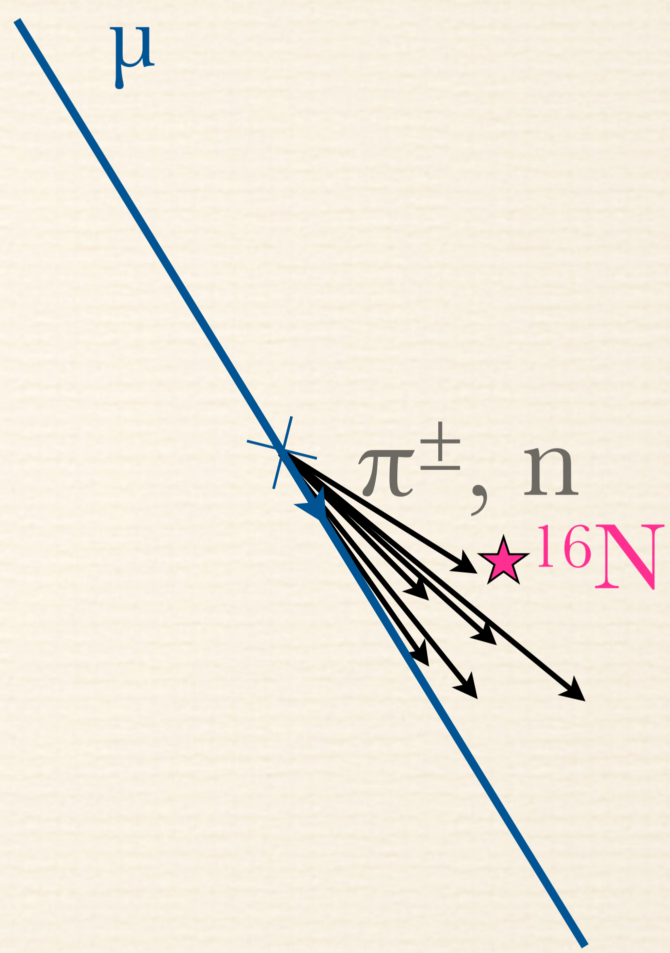

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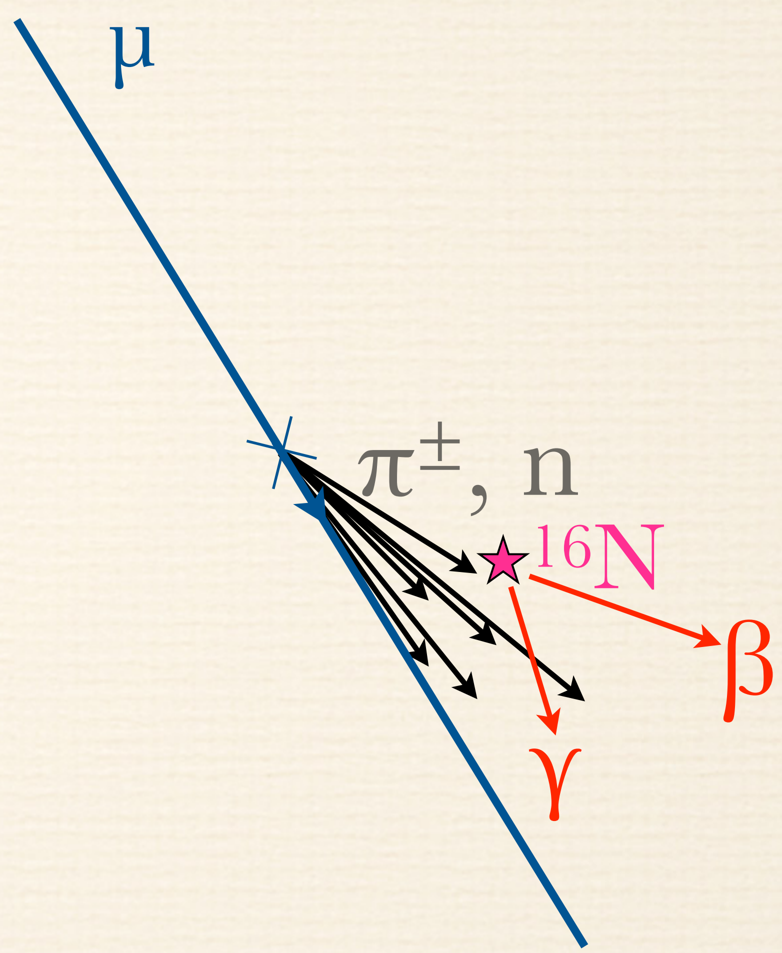
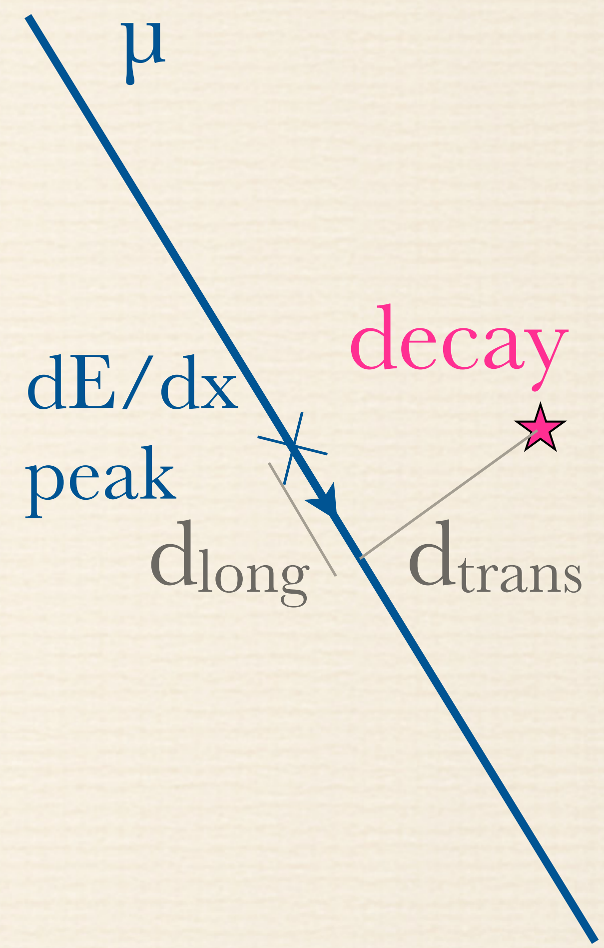


Nuclear Spallation Tagging

- traditionally, form likelihood based on time difference to muon, distance to muon track, and excess light of the muon above the MIP expectation (from electromagnetic component of the showers)
- in 2012, we invented a new method for the distant supernova neutrino search: the muon dE/dx profile (using water Cherenkov detectors as a TPC) points out the spallation location



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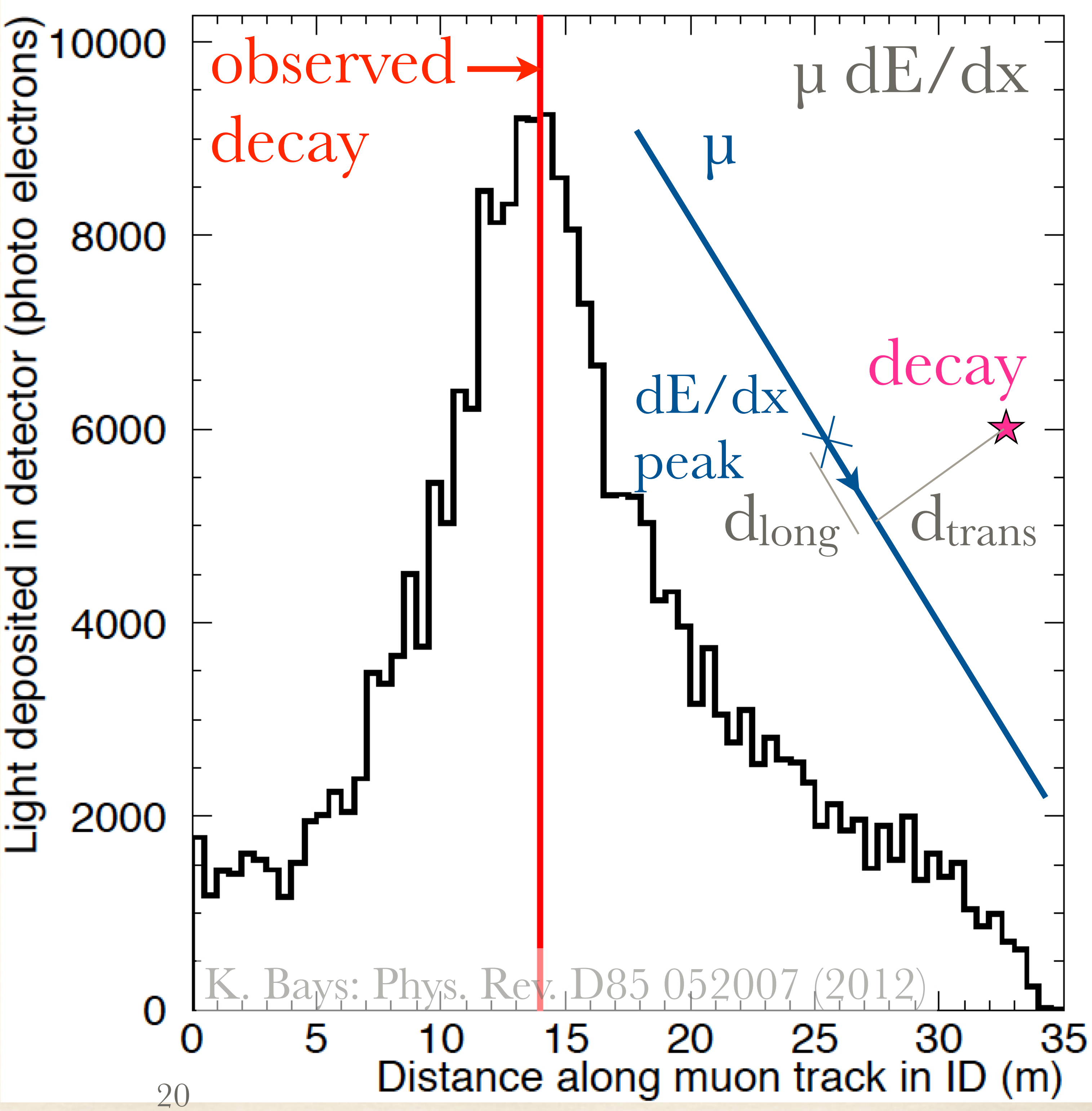
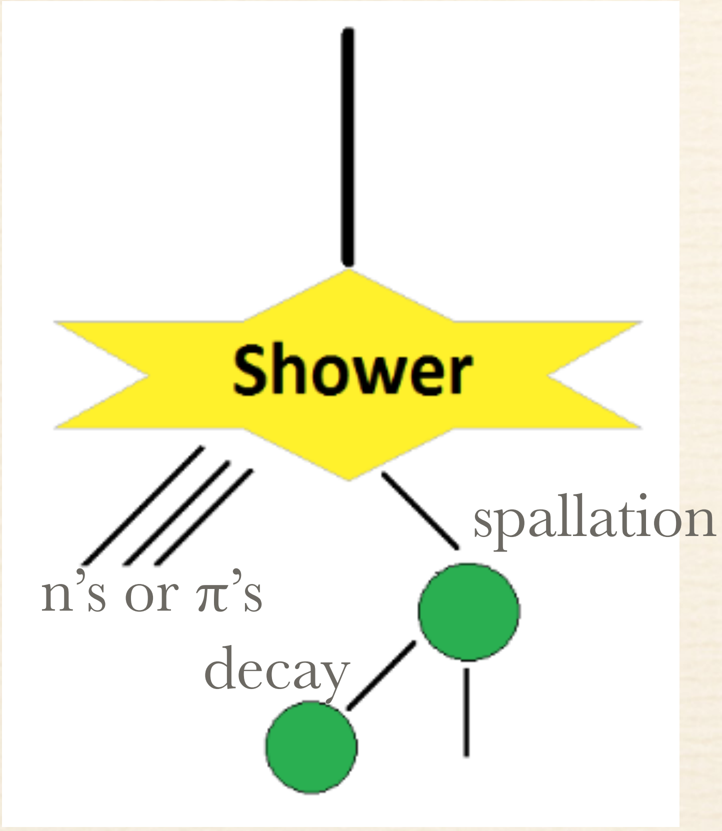
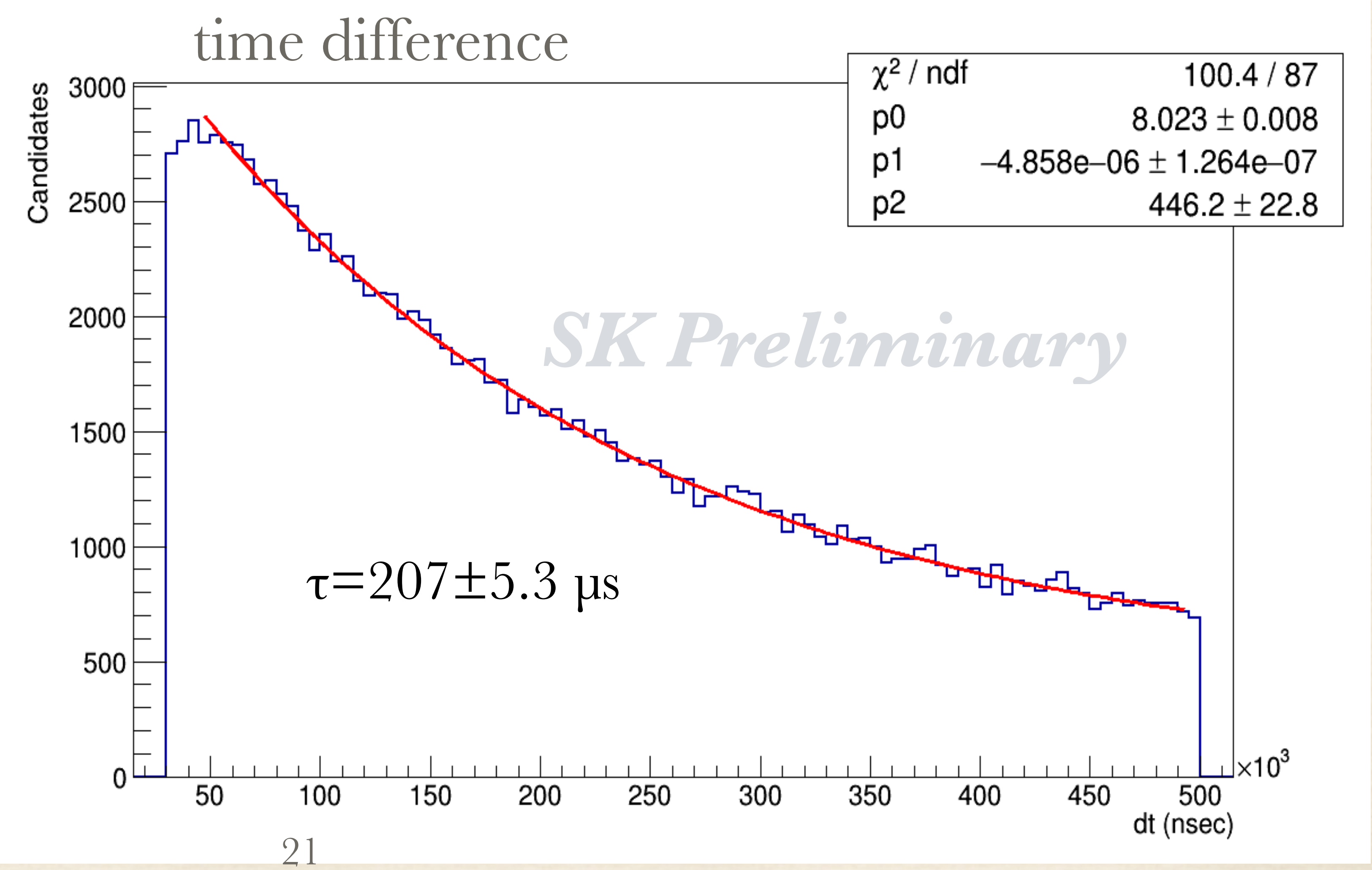


Detecting Hadronic Showers

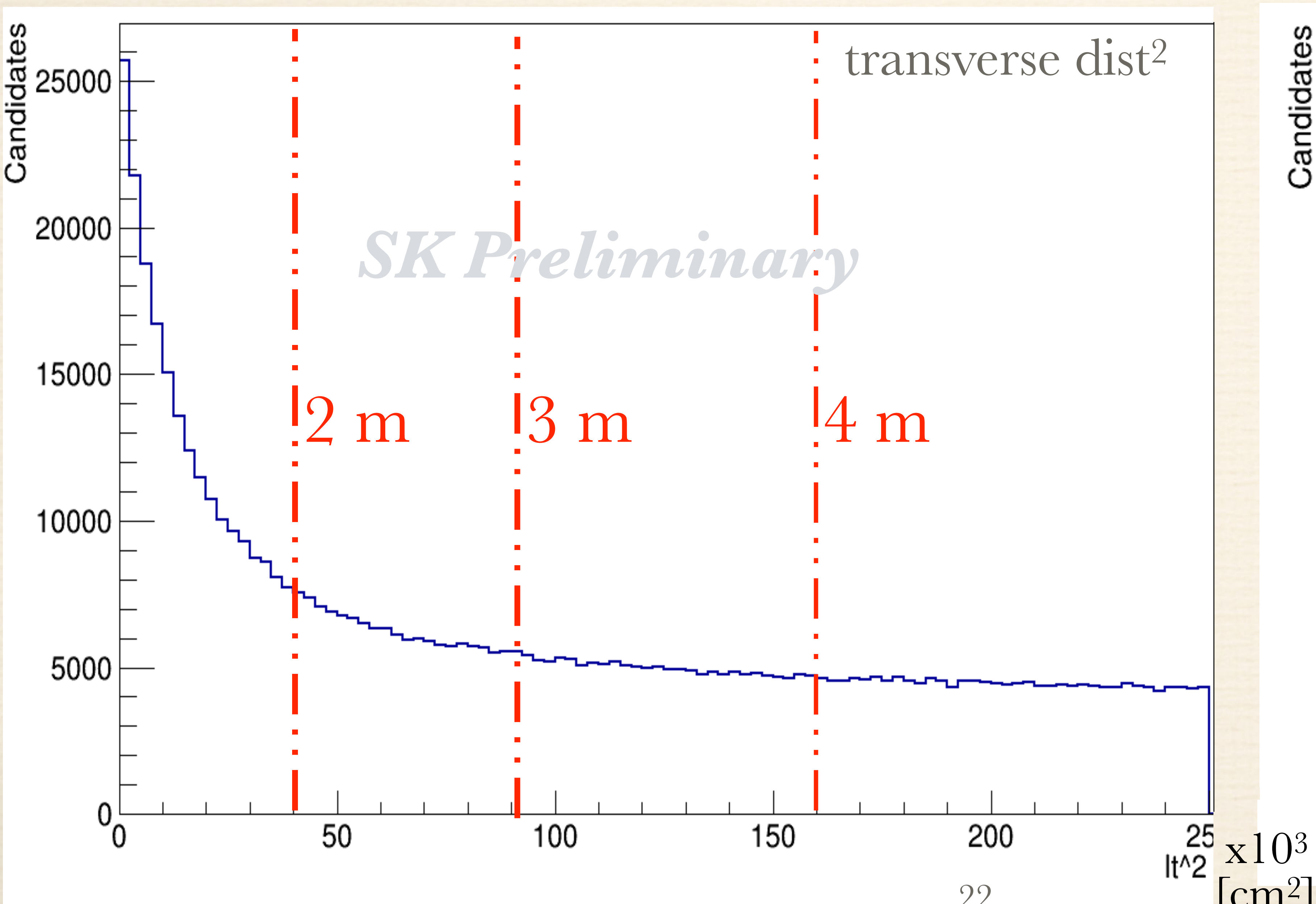
- J. Beacom, S. Li (Phys. Rev. C 89, 045801, 2014): investigate how spallation nuclei are produced in hadronic showers
- S. Locke (TeVPA 2017): observed 2.2 MeV γ's from many neutron captures on hydrogen after muons using Super-K's new software trigger (threshold ~2.5 MeV kinetic electron energy; 2.2 MeV γ efficiency ~13%)

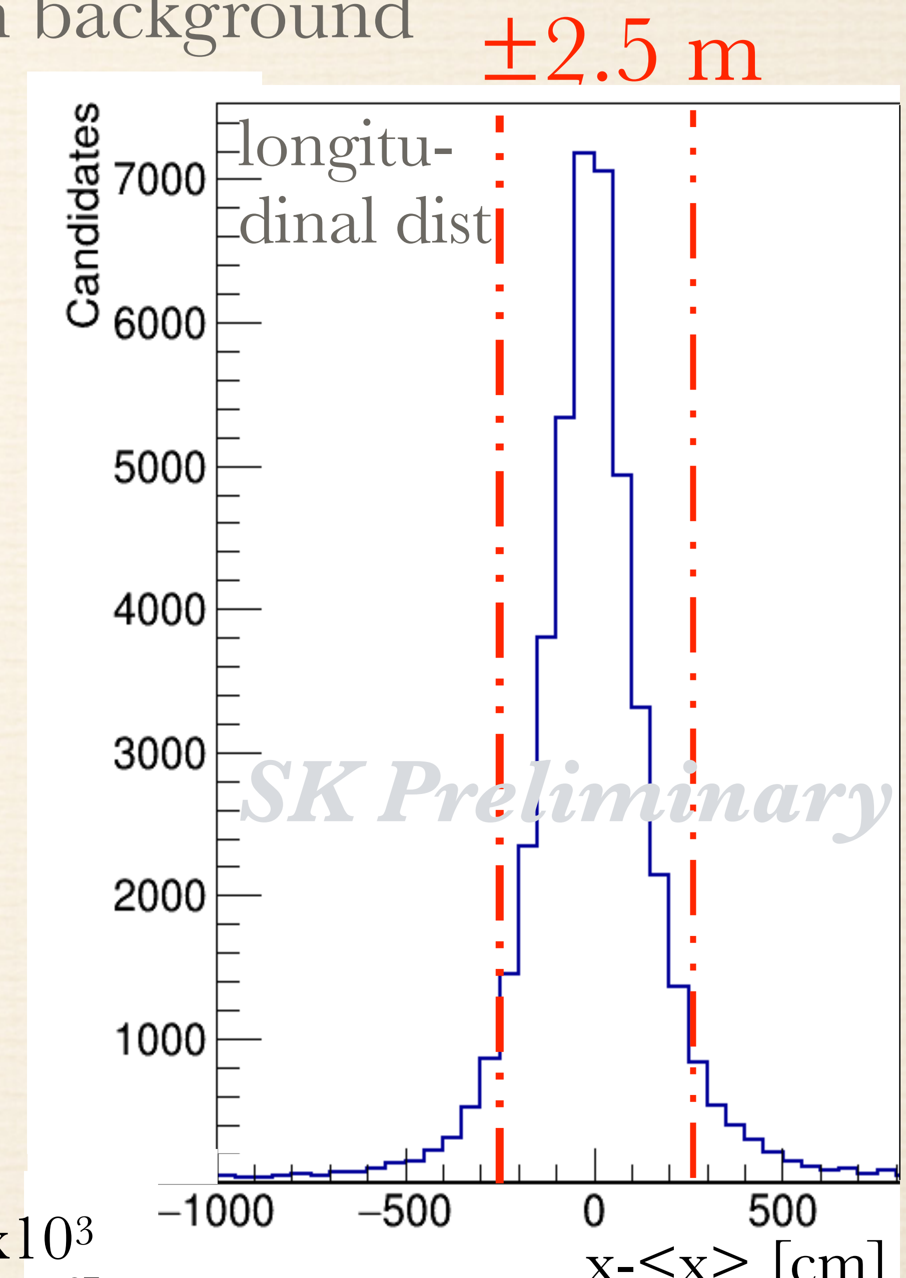




Hadronic Showers

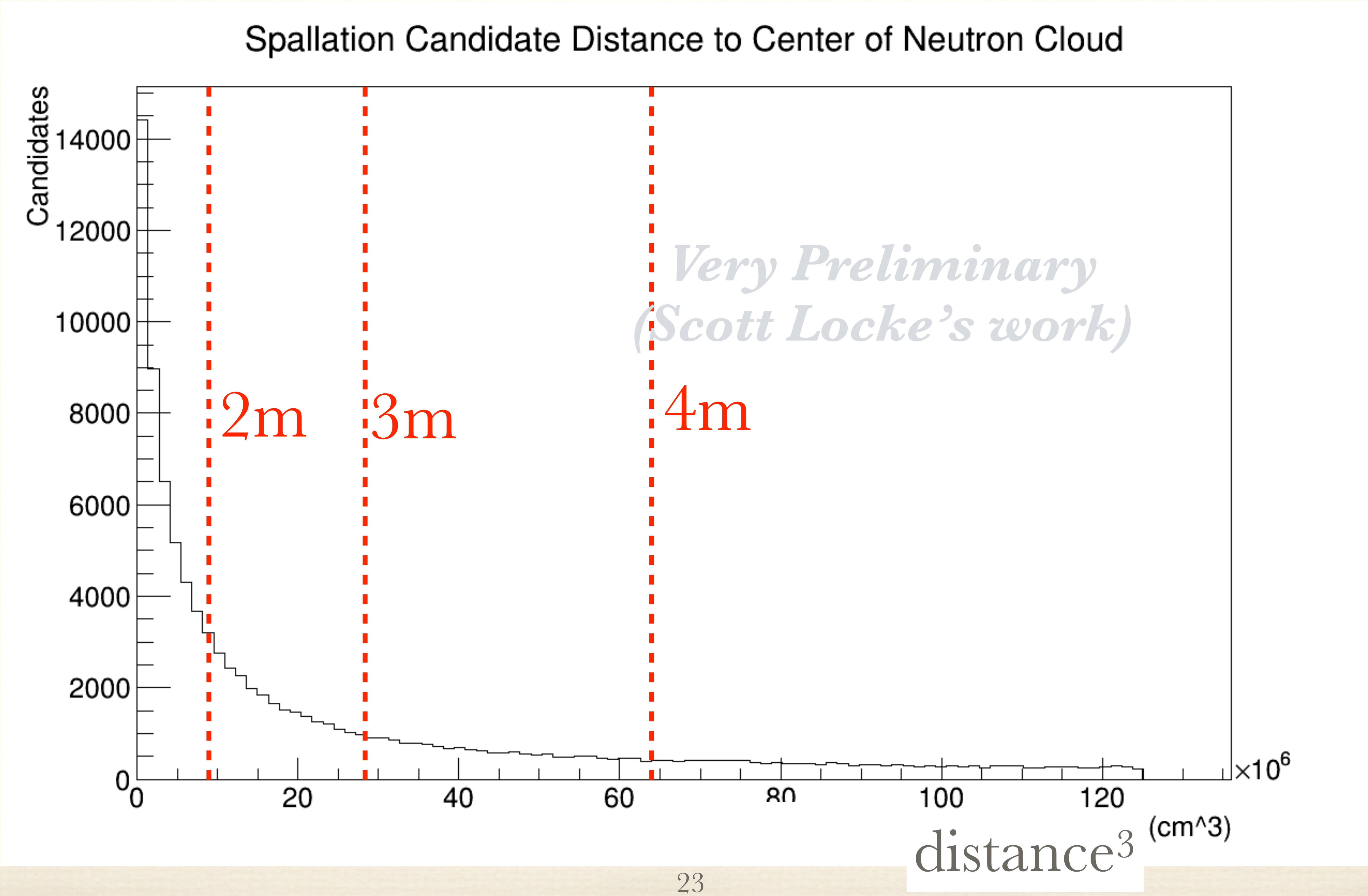
- neutrons after muons are spatially correlated with neutrons and each other: neutrons tag ^{16}N production as well as indicate the 3D location of the decay
- reduce Super-Kamiokande's dominant spallation background





Finding Spallation Decays

- simplest way: events within 1 minute near the average neutron capture vertices



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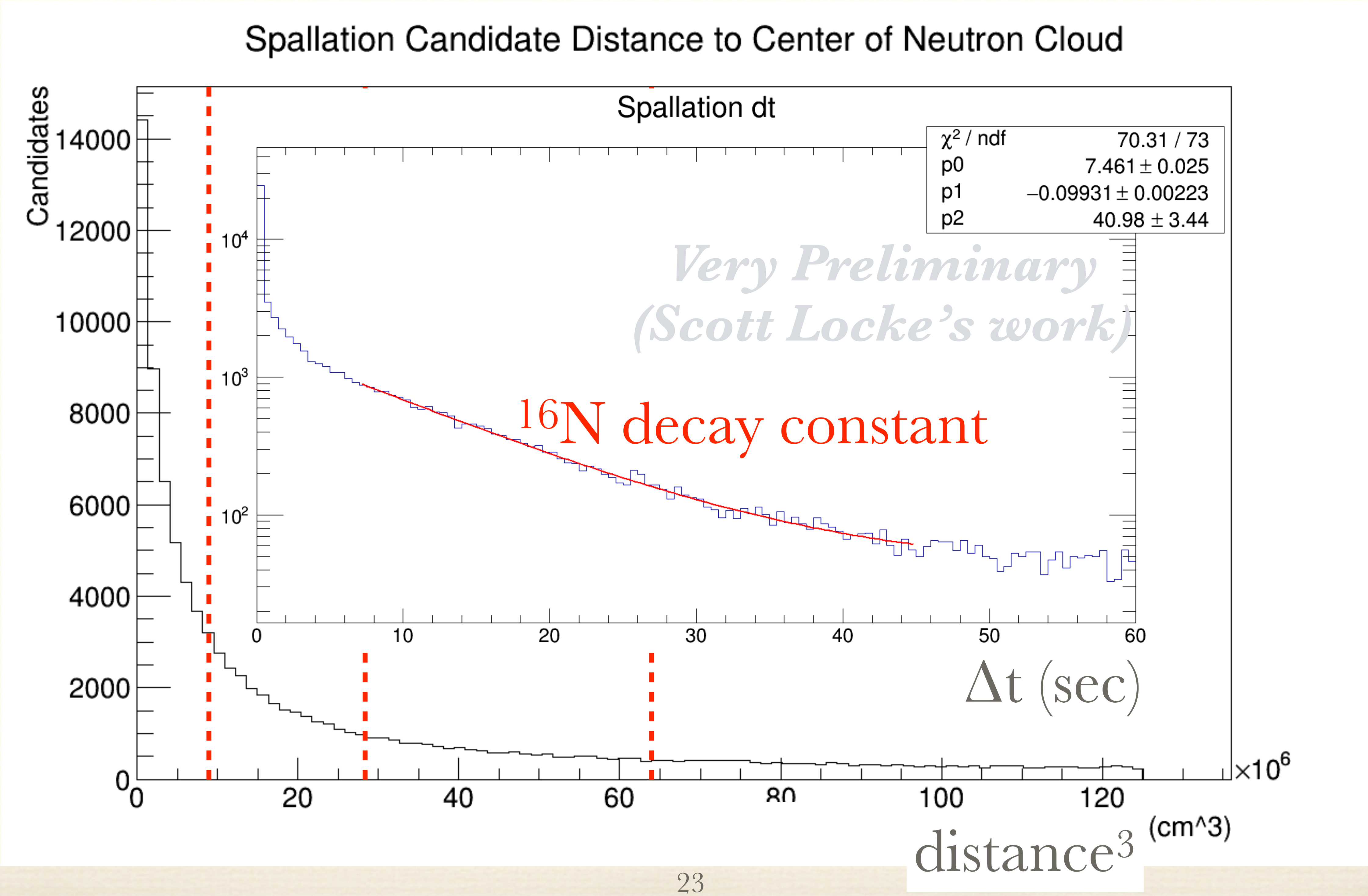
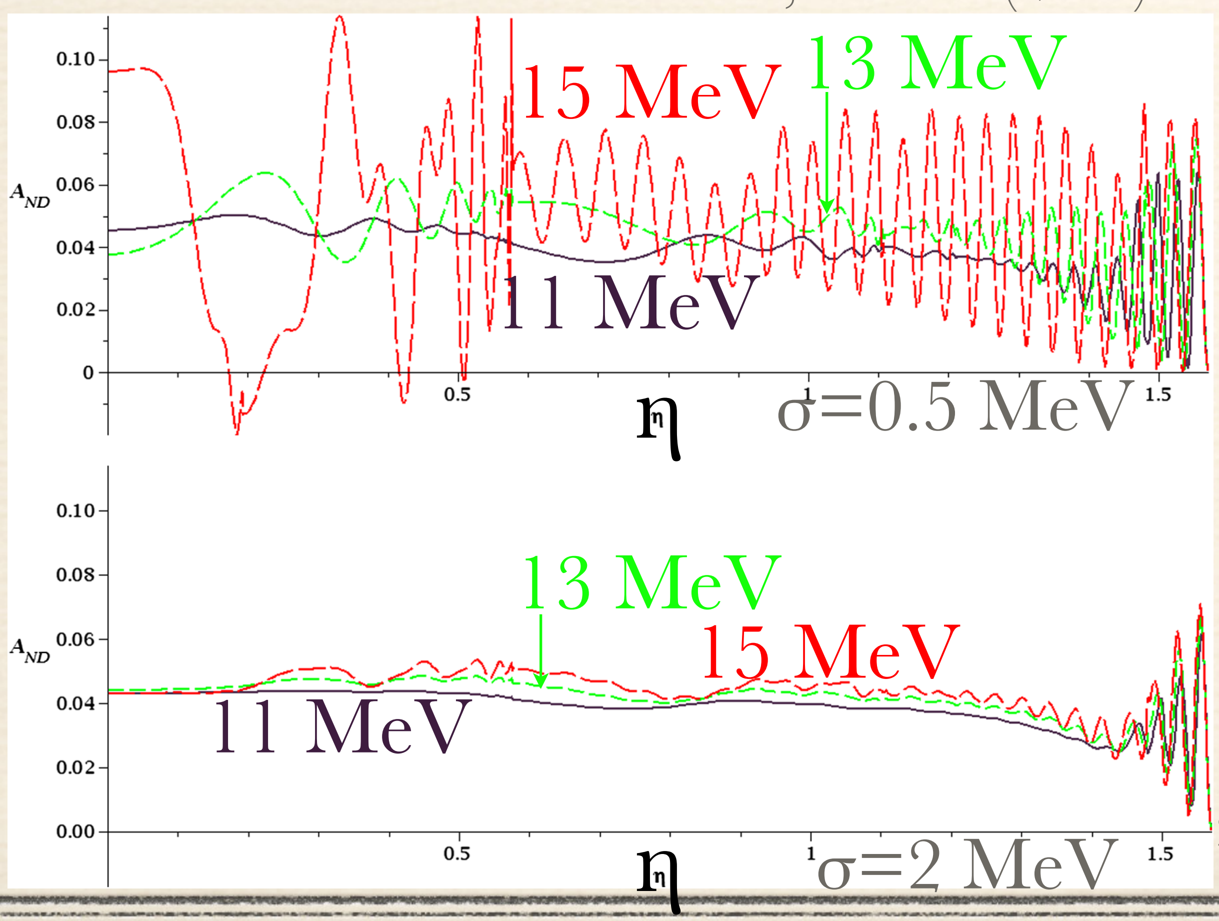


Future D/N Structure Measurement

- Super-K: evidence for existence, but cannot study it beyond that
- need Hyper-K, DUNE or Theia to resolve structure
- it principle, can reconstruct earth electron density profile
- problem: energy resolution wash out phase of oscillations

DUNE

Ioannisian, Smirnov, Wyler
PRD 96, 036005 (2017)



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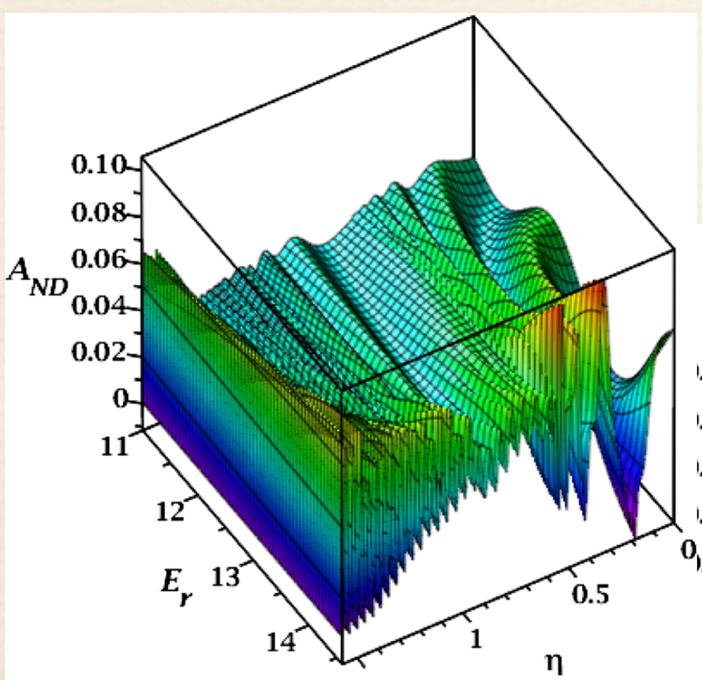
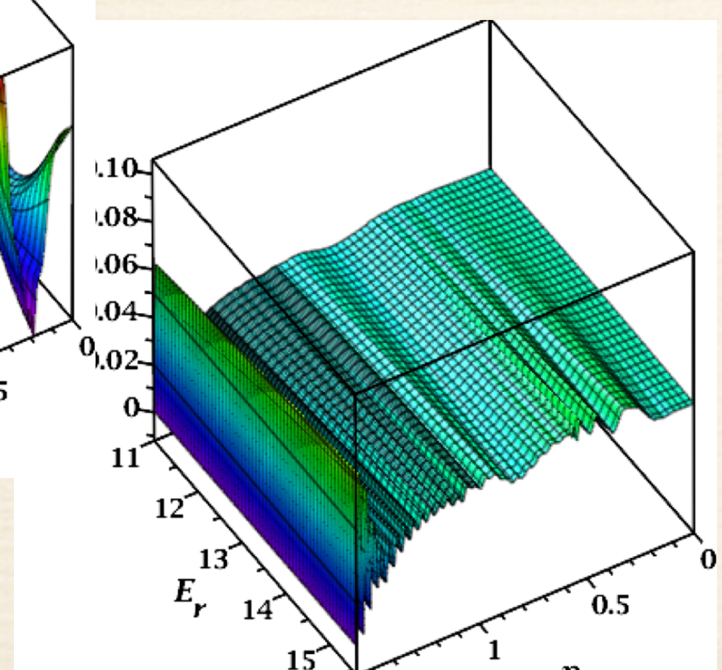


σ=0.5 MeV

σ=2 MeV



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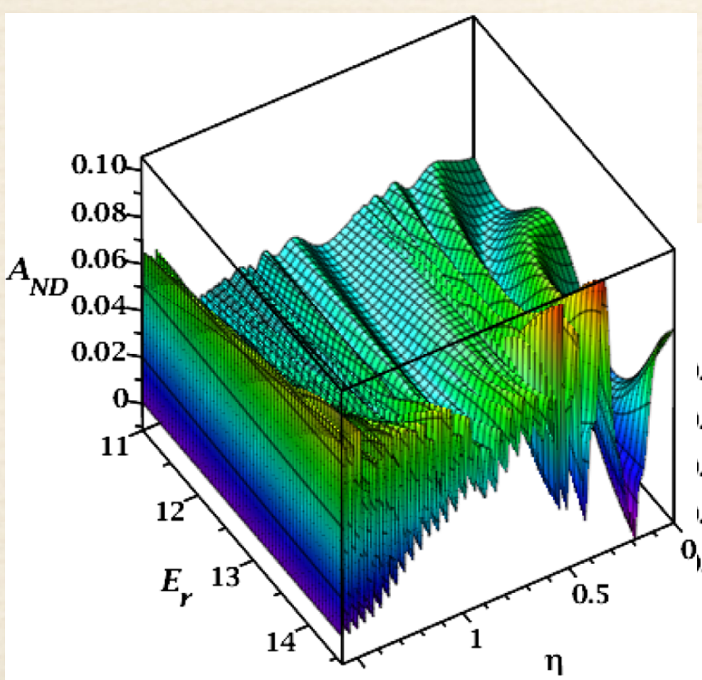
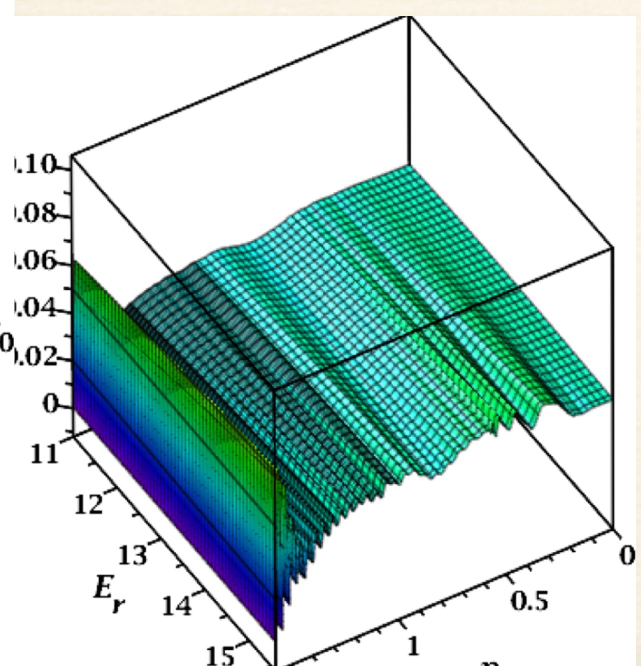
PRD 96, 036005 (2017)

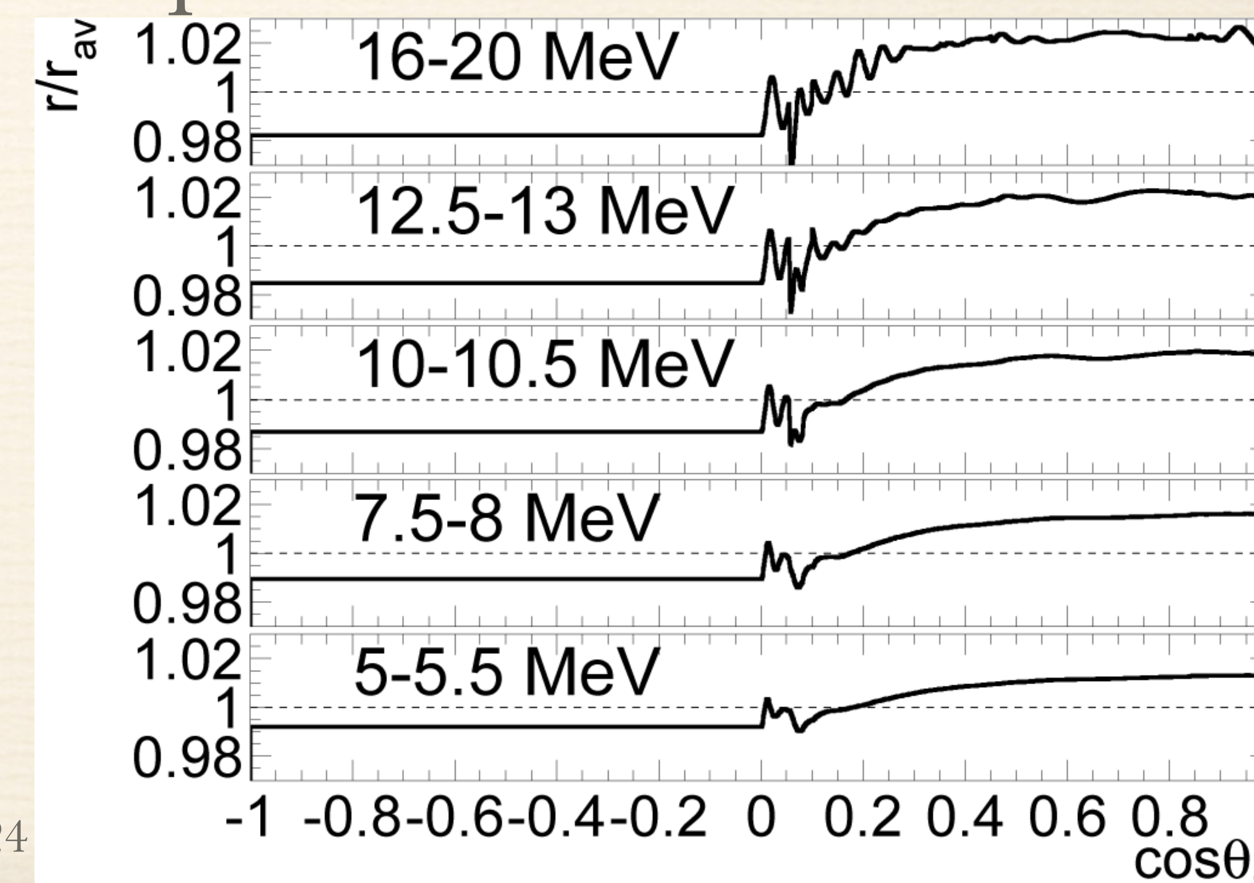
Super-Kamiokande



σ=0.5 MeV

σ=2 MeV





Future Measurement: Argon vs. Water

- DUNE offers tag, larger cross section, larger depth, and event-by-event neutrino energy, but
  - 10kt is not enough (only ~25/day cf Super-K's ~20/day)
  - can CC interactions on Argon be triggered and reconstructed (~5 MeV electrons + few MeV in de-exciation γ's)?
  - what about ^{39}Ar background (on the MHz scale)?
  - what about very long-lived spallation products?
- water provides more target mass, but only measures "integral" spectrum using the recoil electrons from elastic scattering
  - differential spectrum can still be extracted statistically, so detector energy resolution is still important
  - Li doping could help, but works best with water-based LS

Outlook

- still many interesting questions in solar neutrino land
  - particle physics: solar MSW effect, terrestrial matter effects, CPT invariance (compare KamLAND/JUNO oscillation parameters governing $\overline{\nu}_e$'s with solar fit)
  - solar and astrophysics: metallicity, solar models
  - terrestrial physics: reconstruct electron density and earth's chemical composition (by comparison with matter density from seismic measurements)
- can still learn a lot from Super-K data
- Hyper-K could have large impact, if backgrounds and systematics can be controlled

Thank You!

Thank you for your attention!