Solar and Supernova Neutrinos in Super-Kamiokande

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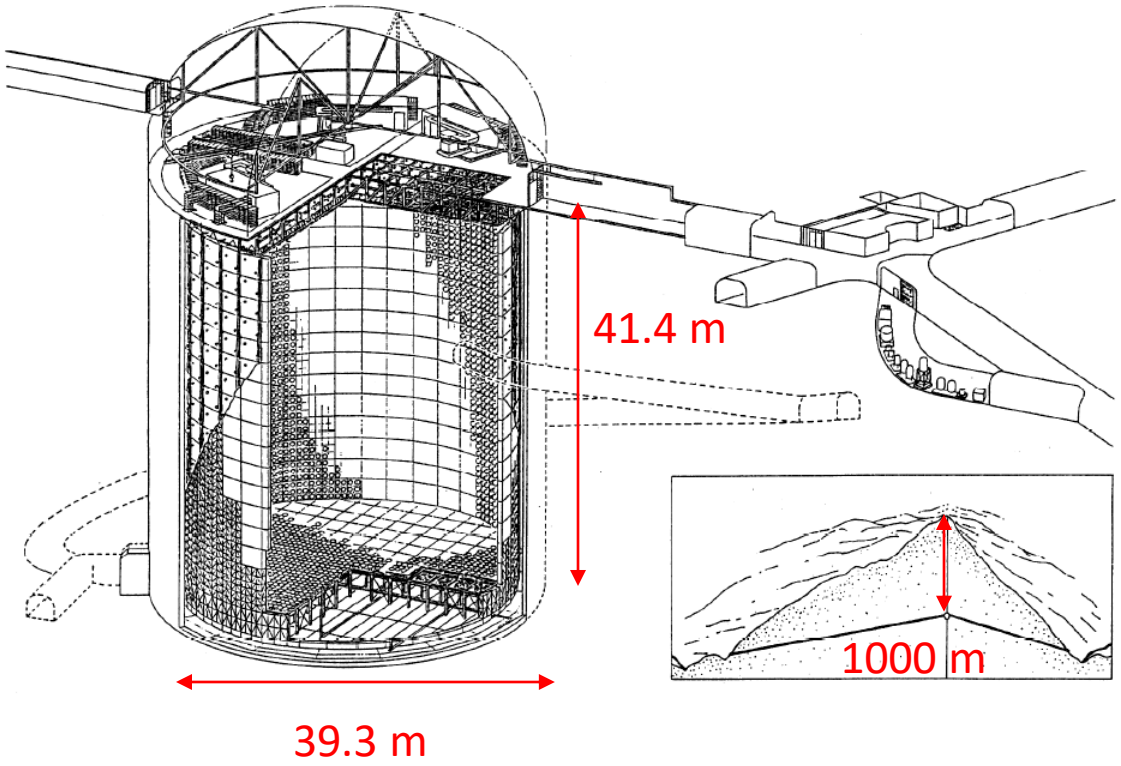
APS DPF 2017, Fermilab

Super Kamiokande Detector



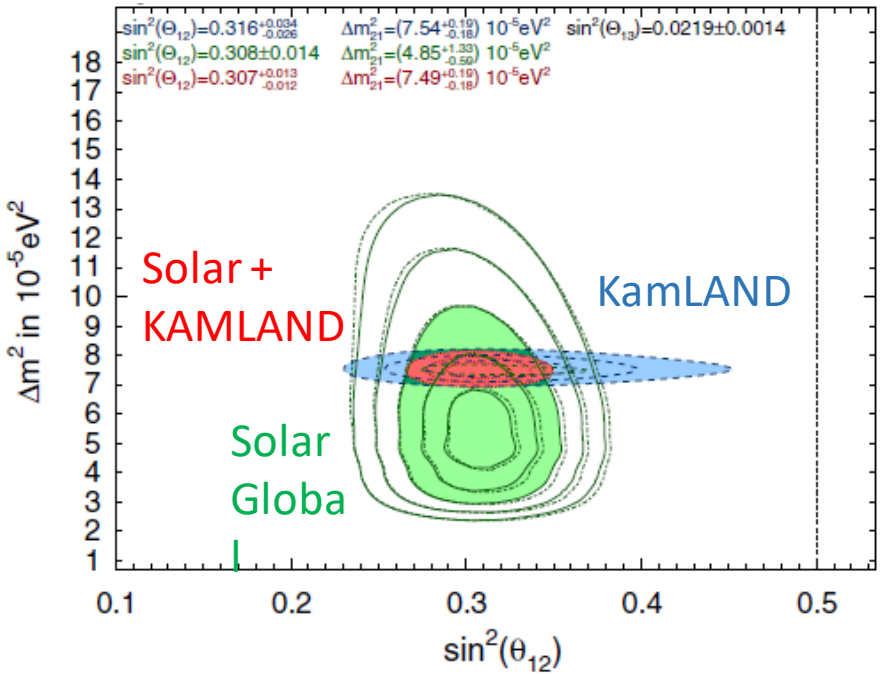
- 50kton water Cherenkov
  - Ultrapure Water
- 22.5 kton fiducial volume (32 kton for SN burst)
- 11, 129 20-inch PMTs (inner), 1885 of 8-inch PMTs (outer)

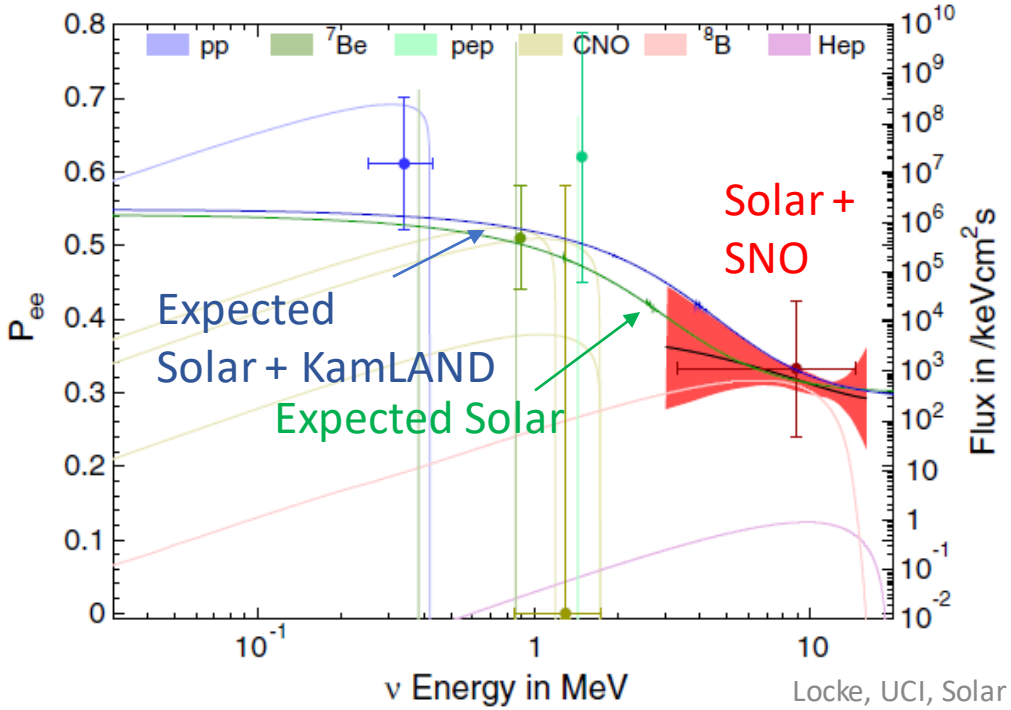
Phase	Period	inner PMTs	coverage
SK-I	1996-2001	11,146	40%
SK-II	2002-2005	5,182	19%
SK-III	2006-2008	11,129	40%
SK-IV	2008-2018	(same as SK-III with new electronics)	

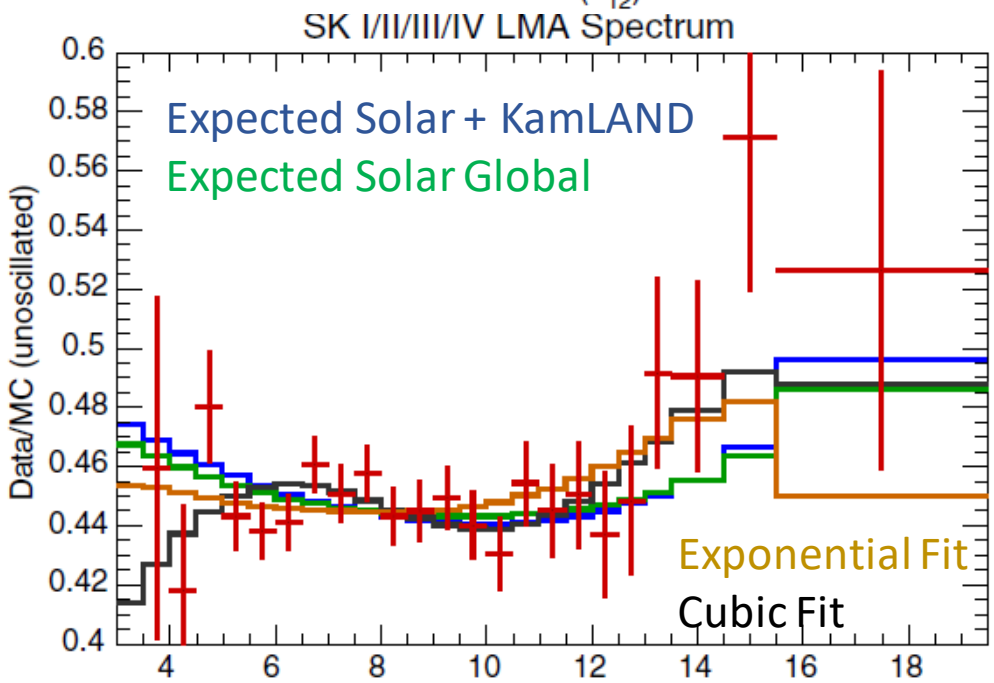
- SK-Gd 20XX-
- ~300 kt-years exposure
- Detects neutrinos from many sources
- T2K far detector

Solar Neutrinos

- Recently published results
  - PRD94, 052010 (Shown this slide)
- Neutrino oscillations
  - Solar MSW
  - Terrestrial Effects





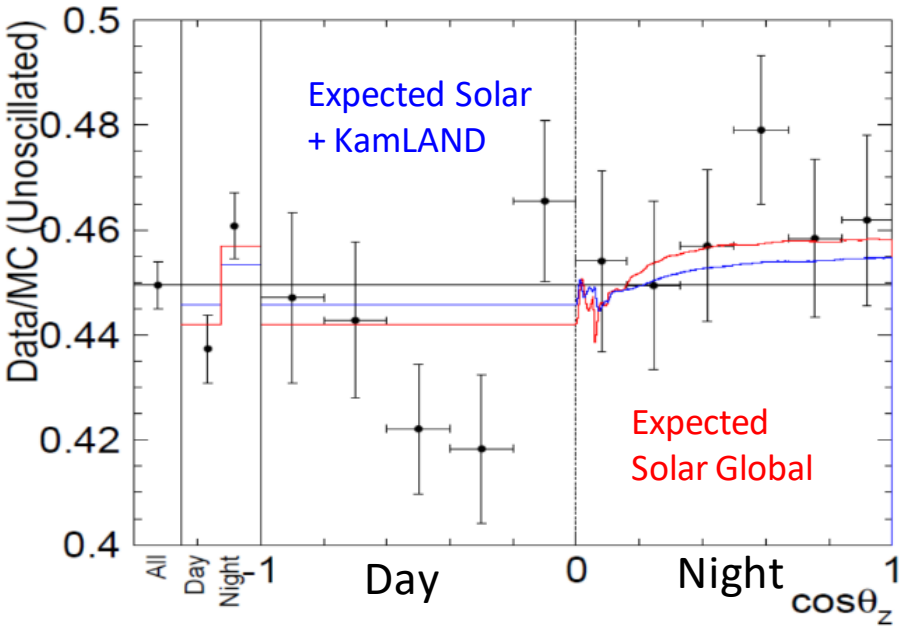


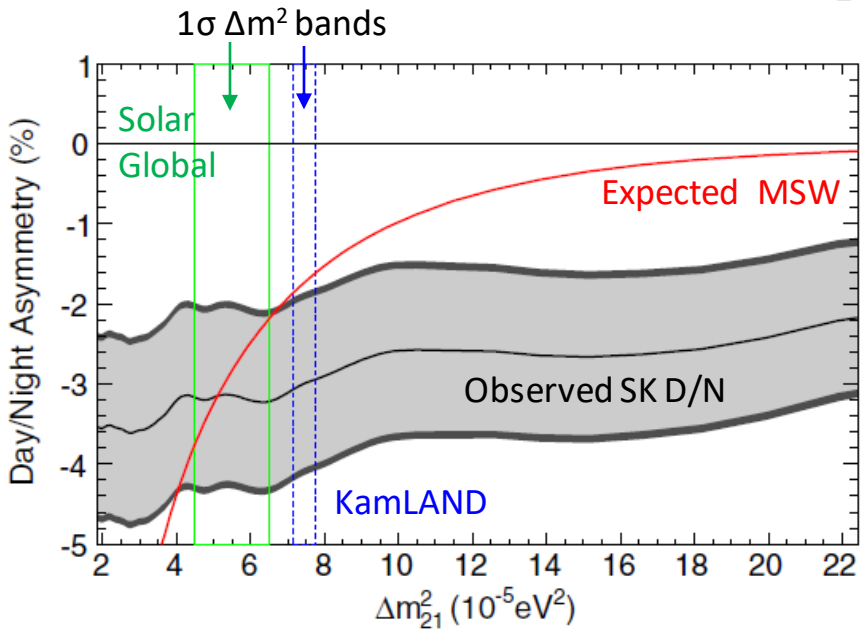
Day/Night Asymmetry

- Look for differences in neutrino flux seen from day/night
  - Effects of earth matter on neutrino oscillation
- Asymmetry defined as difference between day and night flux:

$$A = \frac{D-N}{\frac{1}{2}(D+N)}$$

A. Renshaw, Phys. Rev. Lett. 112, 091805 (2014)





PRD94, 052010

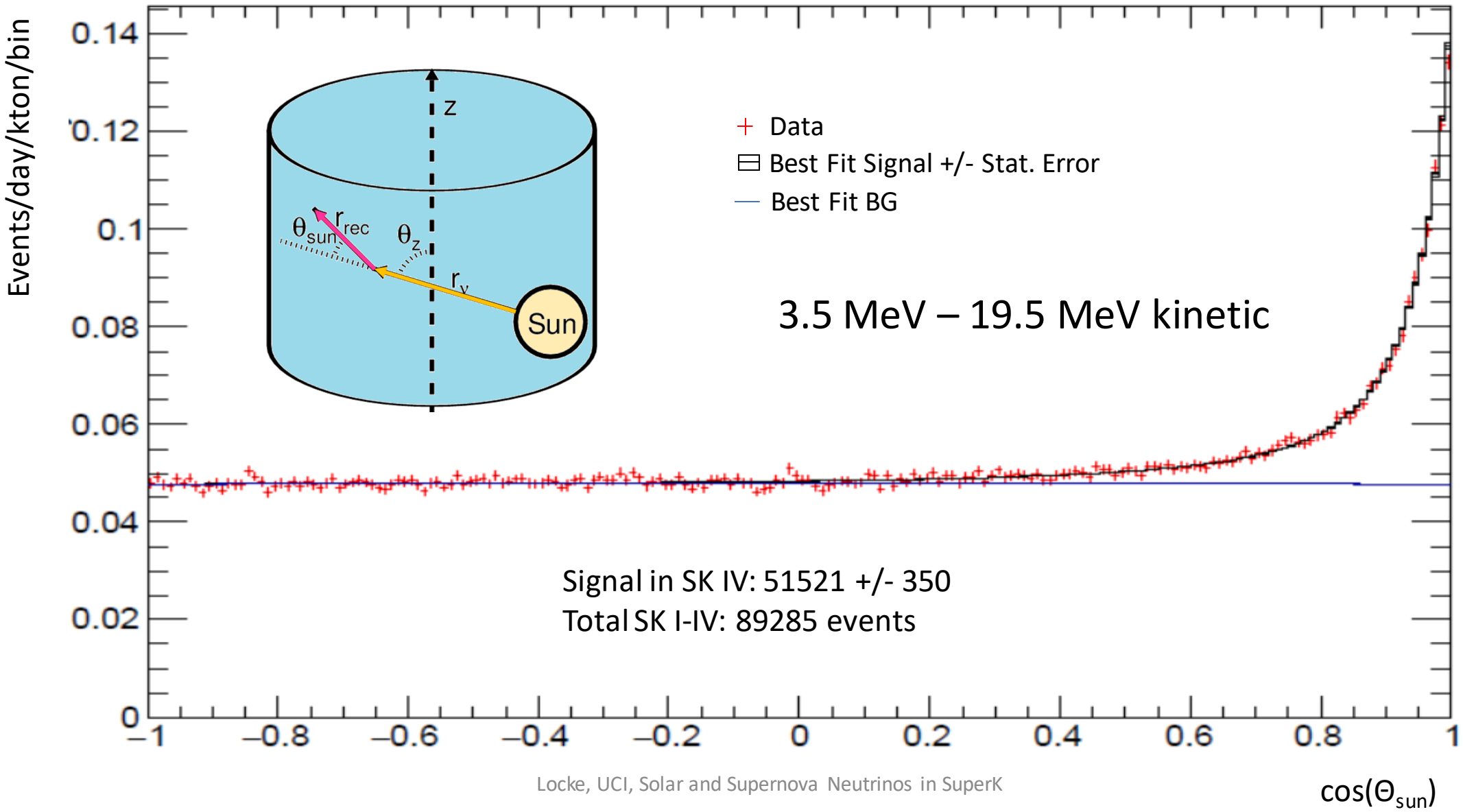
Data Set for Combined Analysis

- Published Data (PRD 94, 052010 (2016))

Phase	Days	Spectrum E (MeV kin)	D/N E ≥ (MeV kin)
I	1496	4.5-19.5	4.5
II	791	6.5-19.5	7.0
III	548	4.0-19.5	4.5
IV	1664	3.5-19.5	4.5

- SNO: PRC88,025501 (2013)
- Radiochemical : Cl, Ga
  - Ga rate: 66.1+/-3.1 SNU (All Ga global) (PRC80, 015807(2009))
  - Cl rate: 2.56+/-0.23 SNU (Astrophys. J. 496, 505 (1998))
- Borexino : ^{7}Be flux (PRL107, 141302 (2011))
- KamLAND : reactor measurement (PRD88, 033001 (2013))
- ^{8}B spectrum : Winter 2006 (PRC73, 025503 (2006))

SK-IV Solar Neutrino Signal [$\cos(\Theta_{sun})$ distribution]

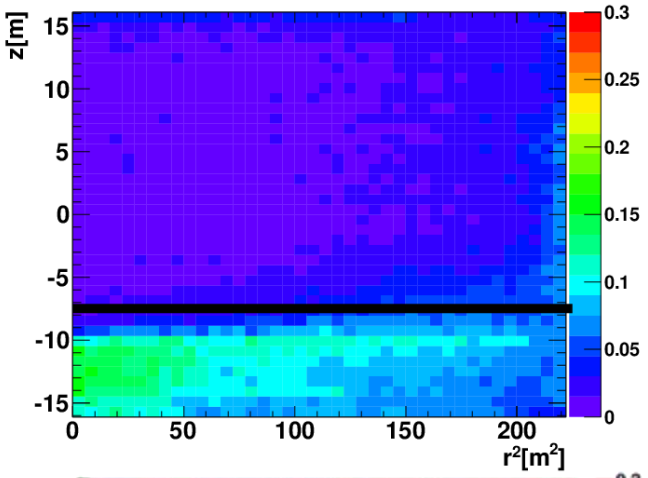


Preliminary
June 2017
2645 Days

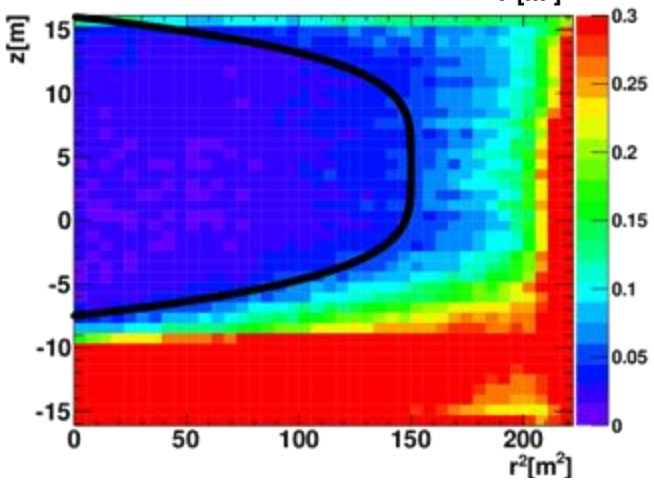
Vertex Distribution

- Shown at right, plot area is normal 22.5 kton FV of SK
  - Above 5.0 MeV Kinetic, use usual 22.5 kton FV
- Below 5.0 MeV, tighter FV cuts are applied
- Scale: (events/day/bin)
  low→high

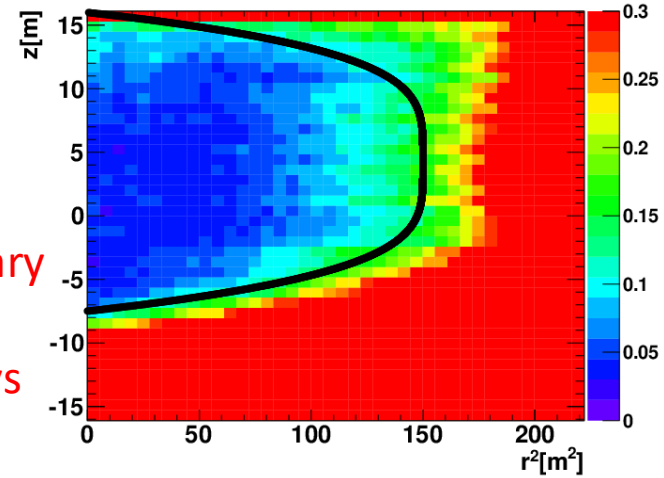
4.5 – 5.0 MeV
Z > -7.5m (16.5kt)



4.0 – 4.5 MeV
(8.8 kt)



3.5 – 4.0 MeV
(8.8 kt)

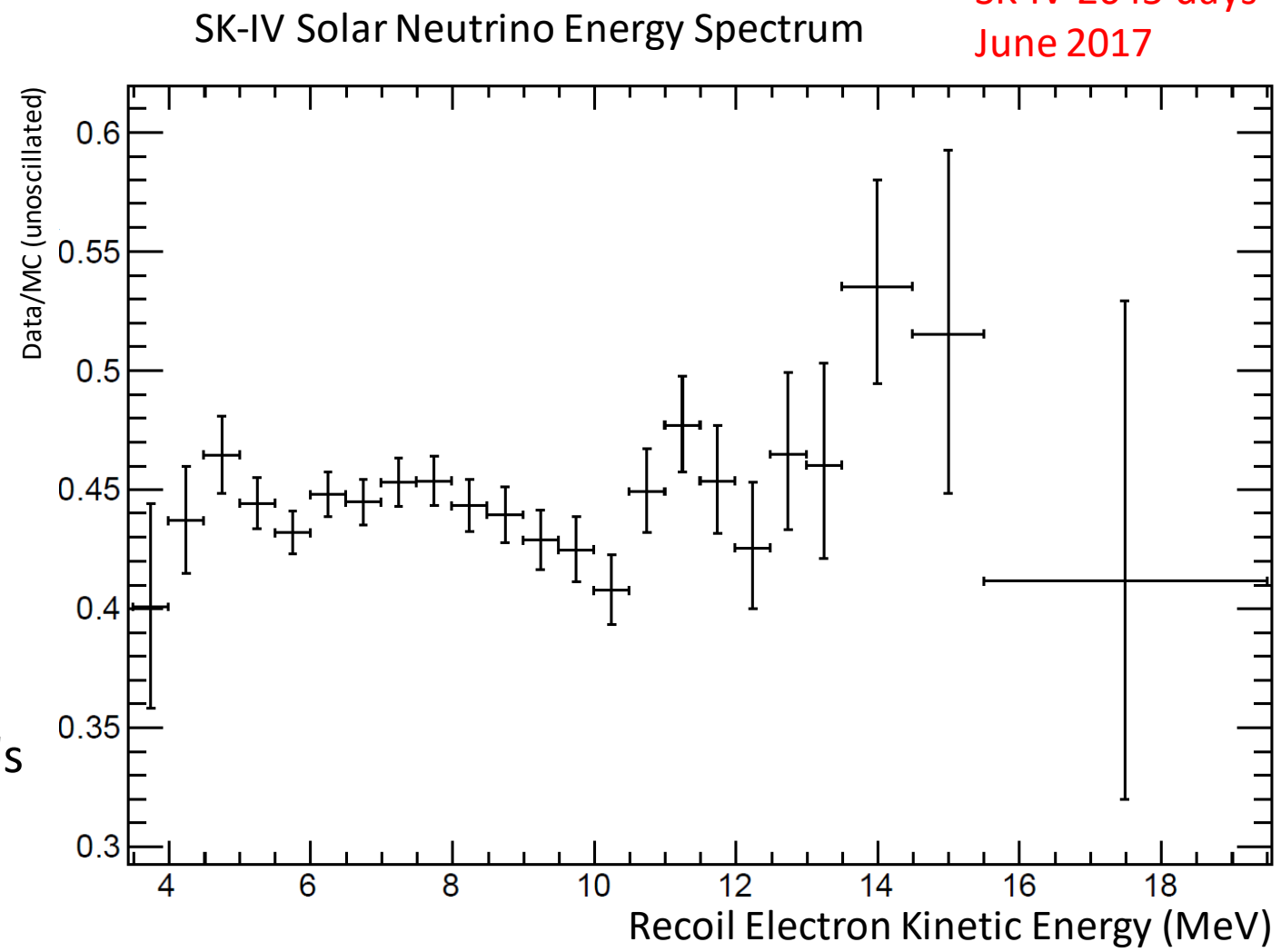


Preliminary
2017
2645 Days

Solar Analysis Updates

- Updated spectrum analysis
  - Total live time: 5480 days
  - SK-IV: now 2645 days
  - PRD94, 052010: 1664
- Preliminary periodic modulation analysis
- Energy scale improvement
- Spallation Studies
- Radon BG
  - "Measurement of Radon Concentration in Super-Kamiokande's Buffer Gas", NIM A, in press (DOI: 10.1016/j.nima.2017.04.037)

Preliminary
SK-IV 2645 days
June 2017



(MC flux = 5.25×10^6 cm^2/s from SNO NC)

SK I-IV Spectral Data

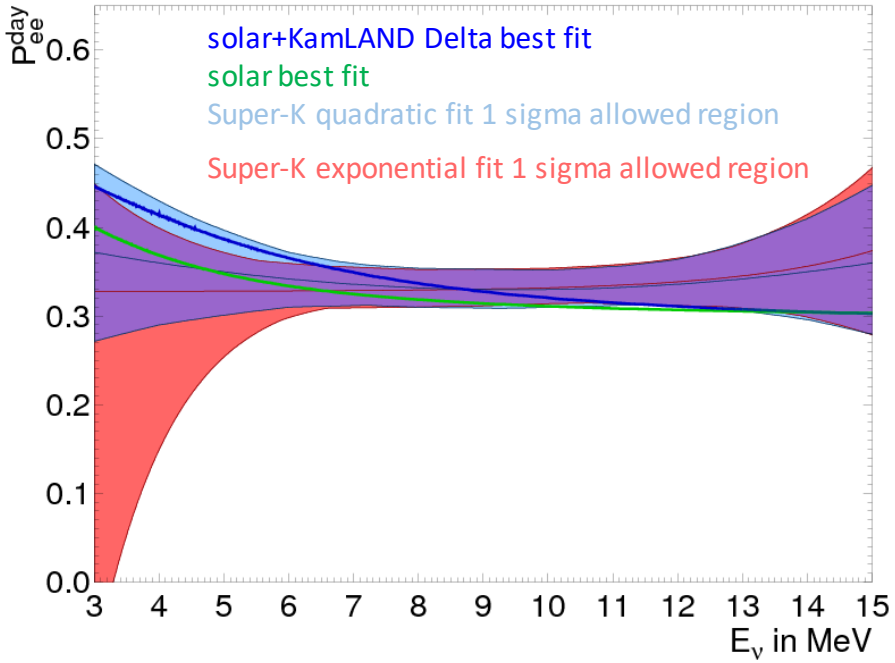
Preliminary
June 2017

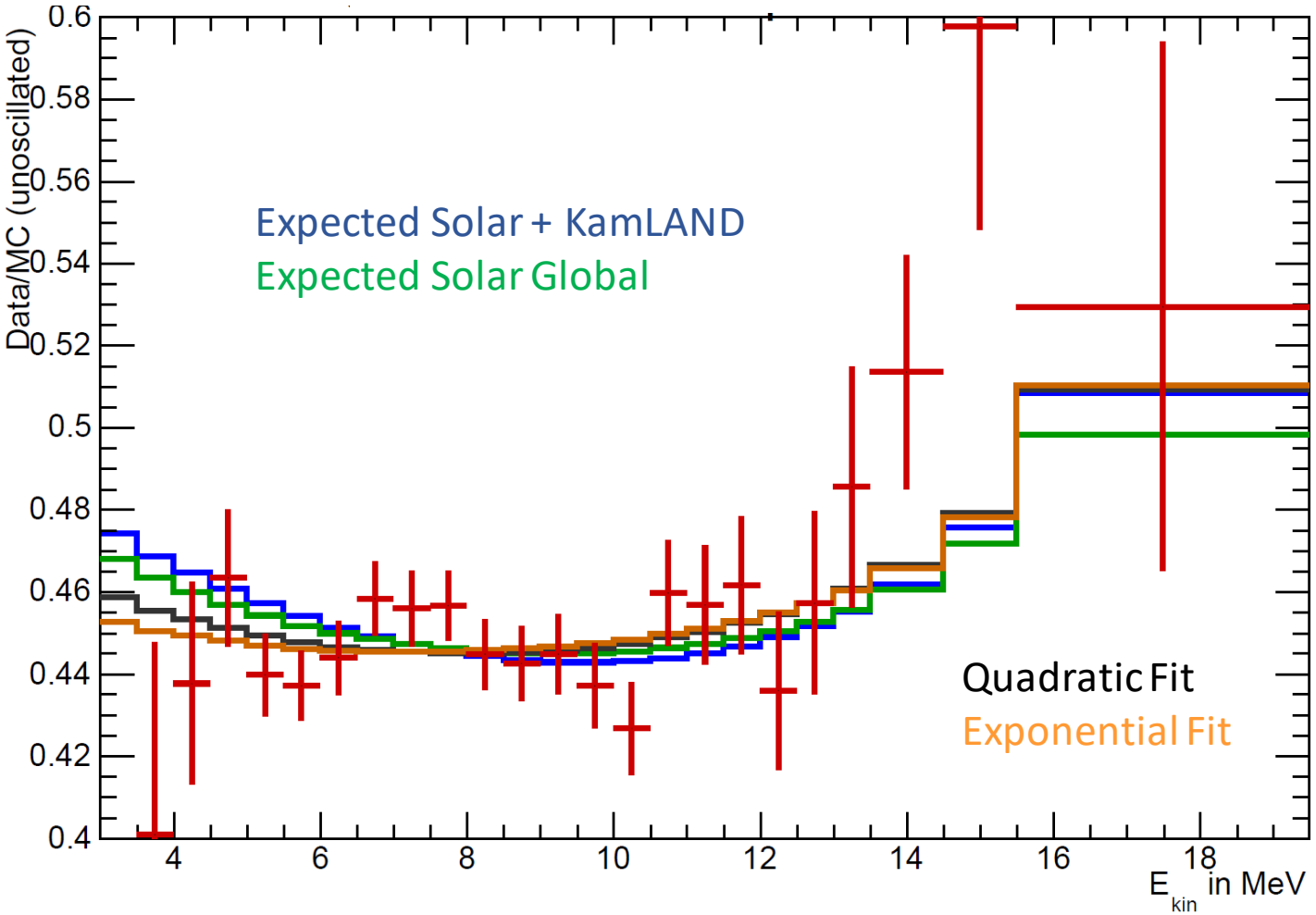
- Spectrum is:
  - Consistent to within ~1σ of the MSW upturn for Solar best fit
  - ~2σ tension of the MSW upturn for Solar + KamLAND best fit parameters
- SK I-IV: 83 Bins
- Quadratic Fit:

$$\chi^2 = 75.5/80 \text{ d.o.f.}$$

- Exponential Fit:

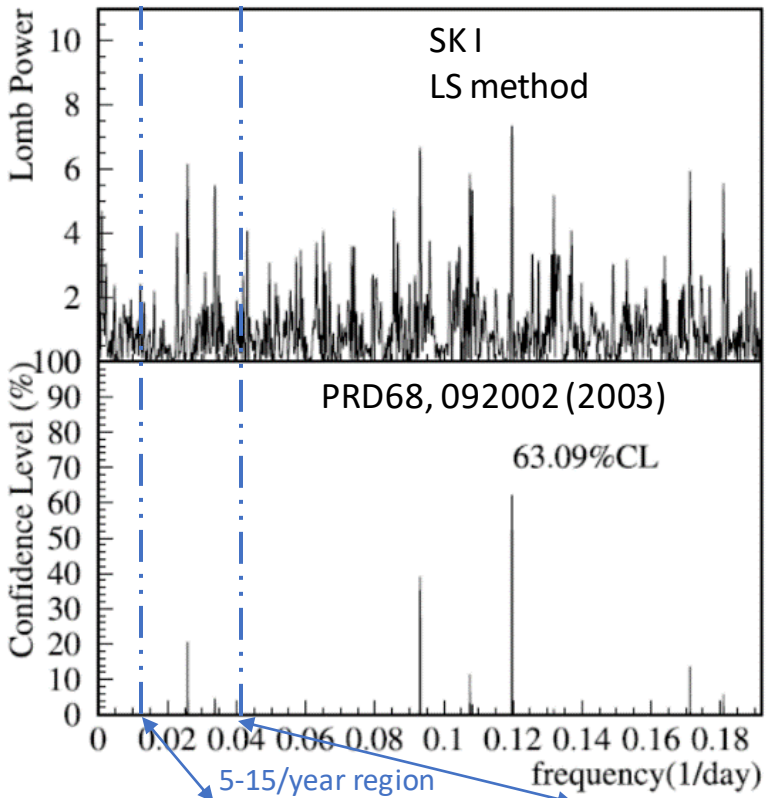
$$\chi^2 = 75.5/80 \text{ d.o.f.}$$

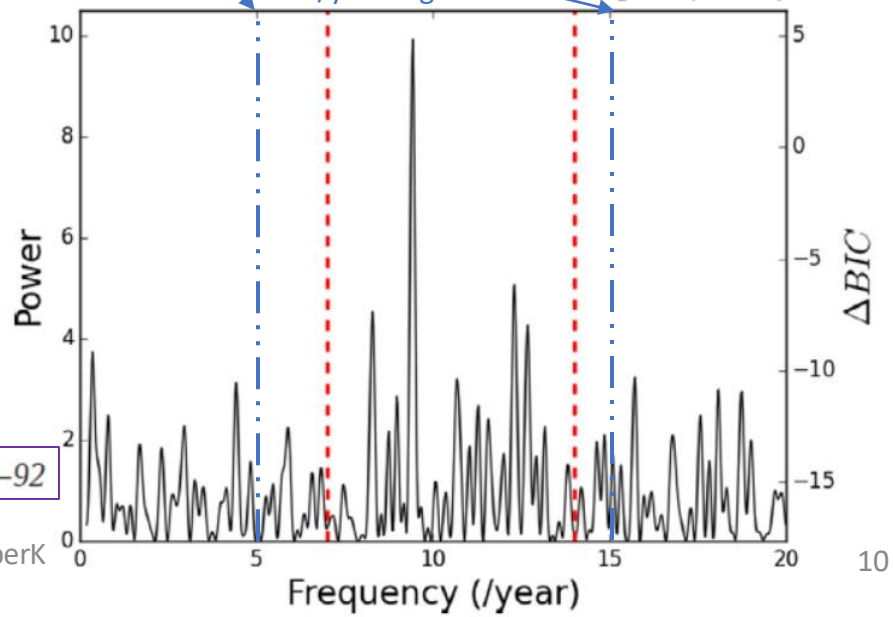




Periodic Modulation in SK IV

- Look for periodicity of frequency, f
- Previously visited in PRD68, 092002 (2003)
  - SK I, 1496 days data with 4.5-19.5 MeV kinetic
  - 5-day long samples
  - Lomb-Scargle (LS) method to check power
- Peak referenced by researchers at roughly 9.43/year
  - Improved analysis
- With new method, revisited SK I data with Generalized LS method
- Preliminary search in SK-IV for frequency region 5-15/year

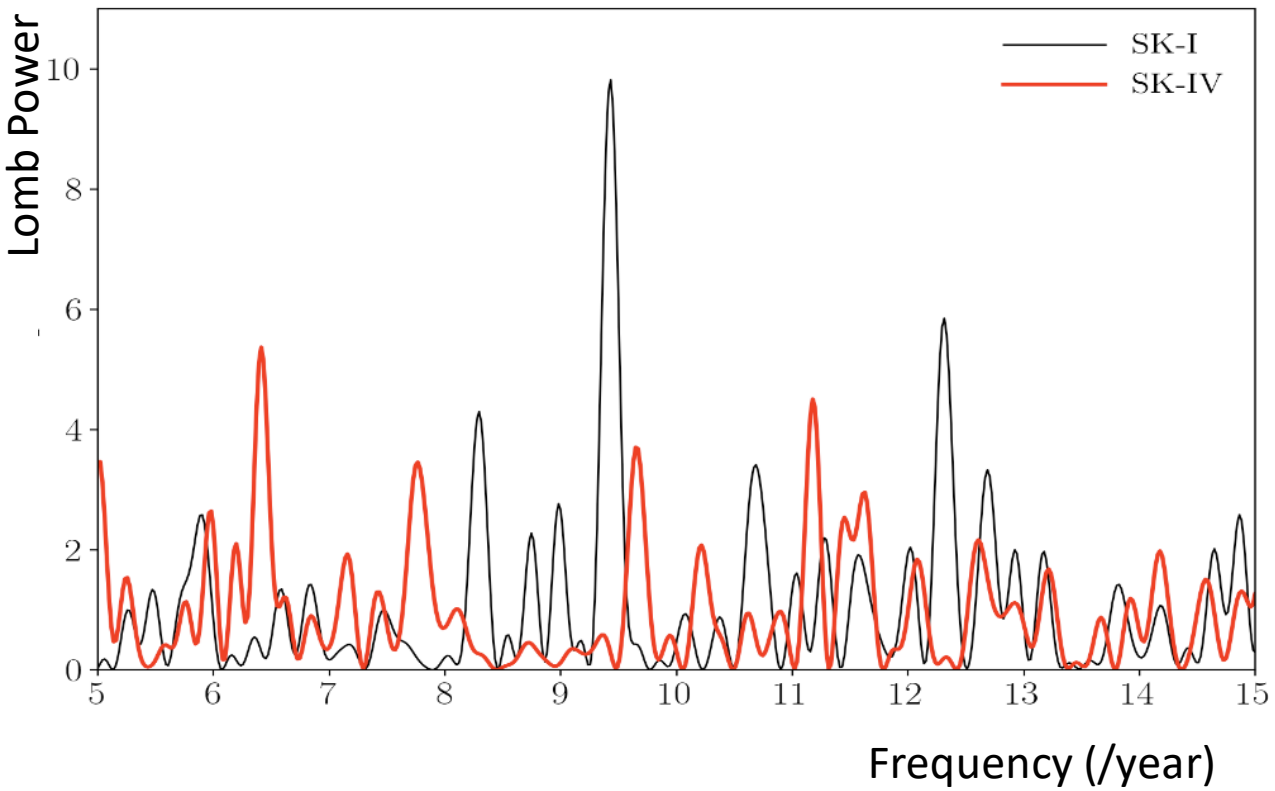




S. Desai, D.W. Liu / Astroparticle Physics 82 (2016) 86–92

Periodic Modulation in SK IV

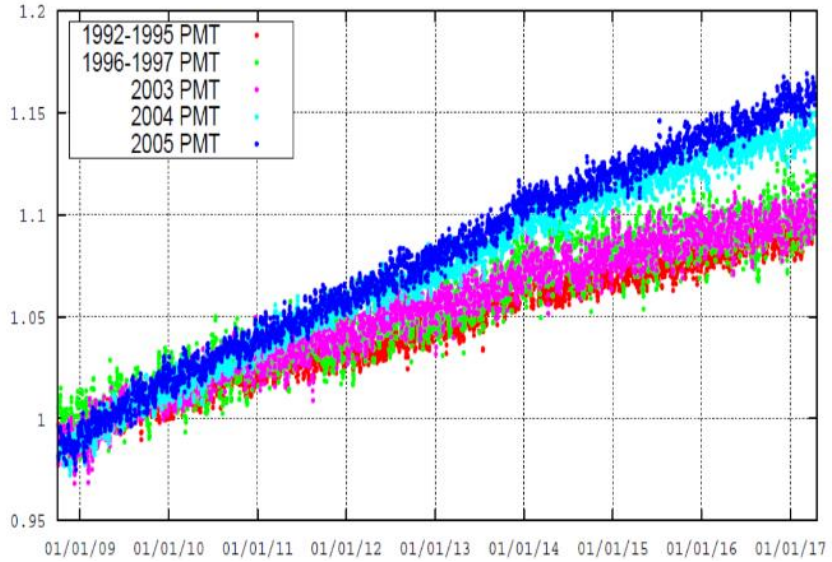
- Data:
  - SK-I: 1496days, 5-day long sample, 4.5-19.5 MeV kinetic
  - SK-IV: 1664 days, 5-day long sample, 4.5-19.5 MeV kinetic
  - Generalized LS method (with symmetric error)
  - 5 – 15/year
- Maximum not found at 9.43/year for SK IV data set

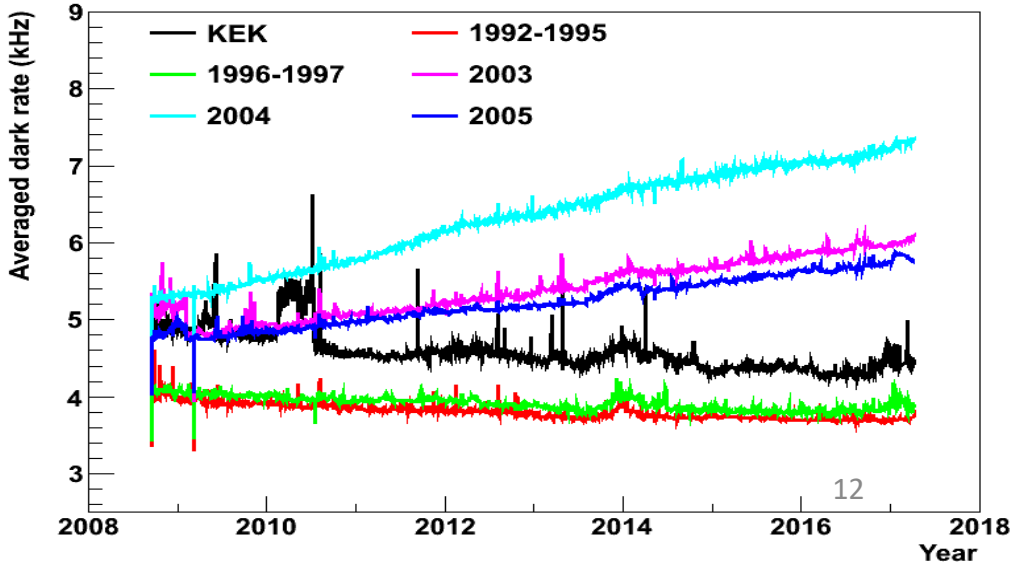


Improvements to Energy Scale

Preliminary
June 2017

- PMT Gain increasing with time
- Dark Rate changing with time as well
- Currently implementing these effects in simulation and energy resolution scale for reduction in energy scale uncertainty
- These variations are not currently used for low energy scale calculations. Working to implement in the future

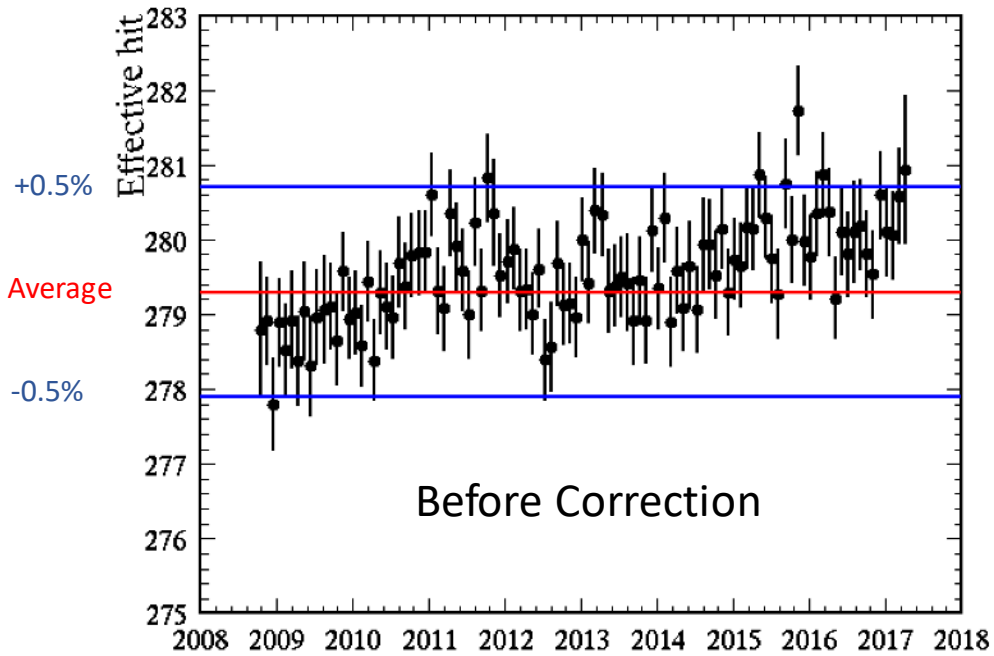


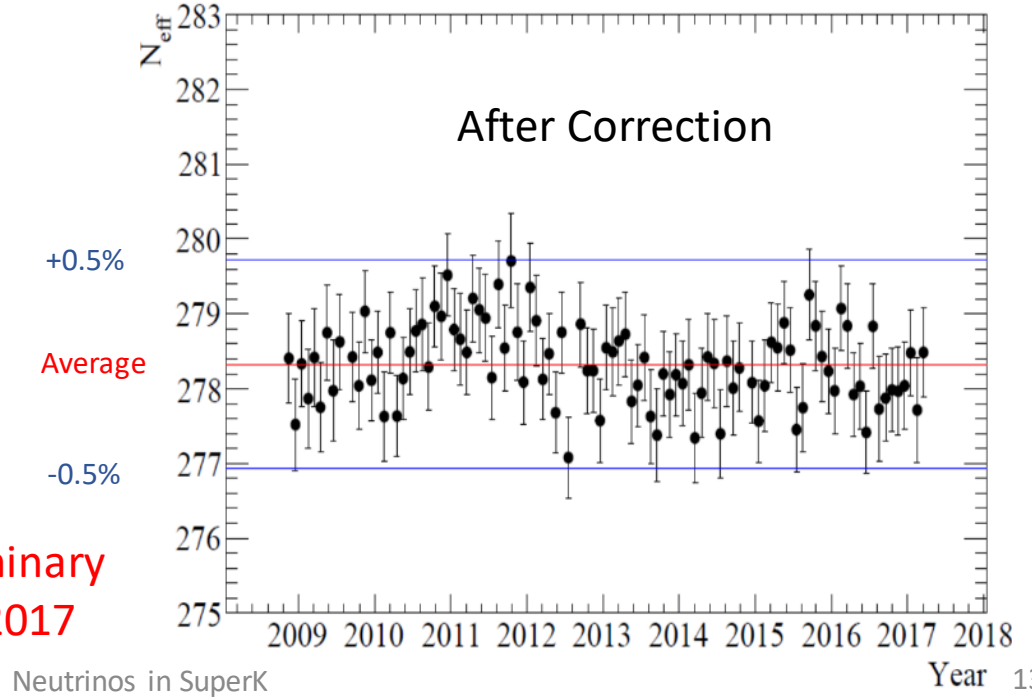


Energy Scale (Cont'd)

- Examine decay electrons from stopping muons
- Spectrum becomes more stable.
- Reminder, gain correction not yet implemented

(Looking at N_{eff}, effective number of hit PMTs used for energy scale for low energy events)

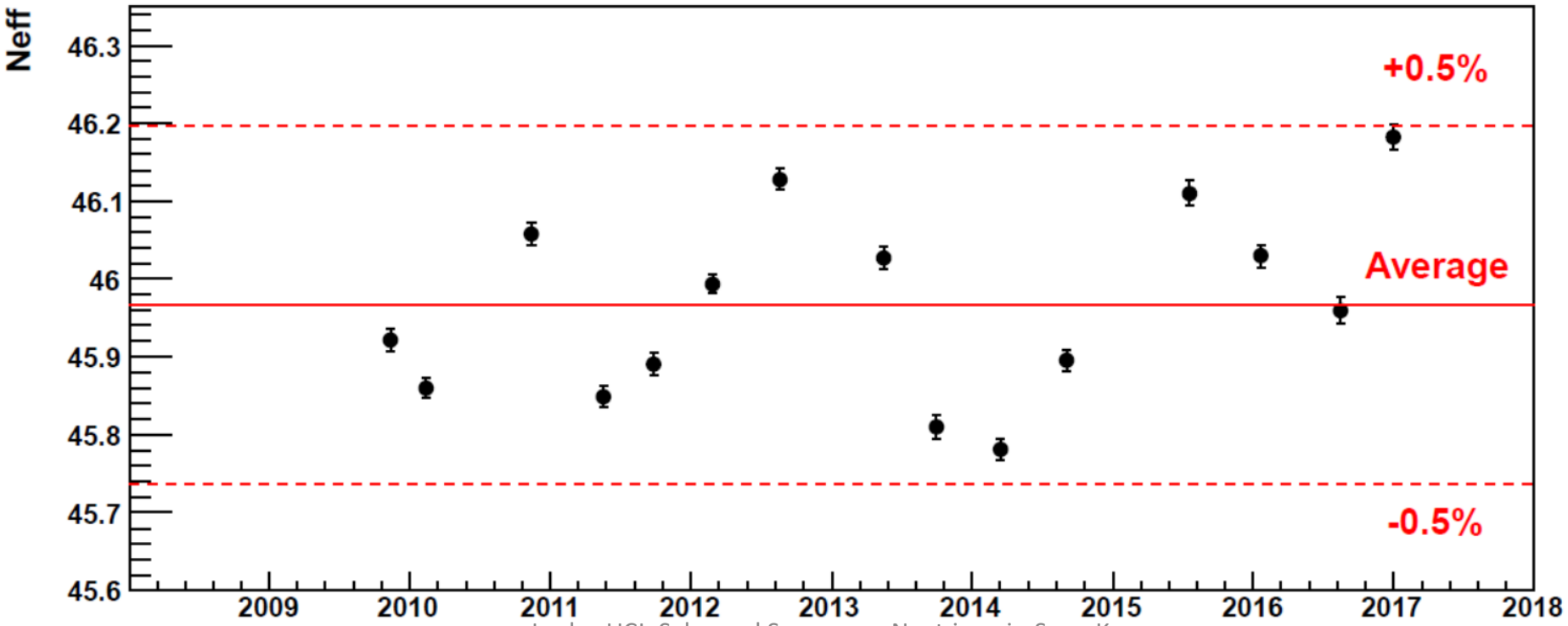




Preliminary
June 2017

DT Energy Calibration

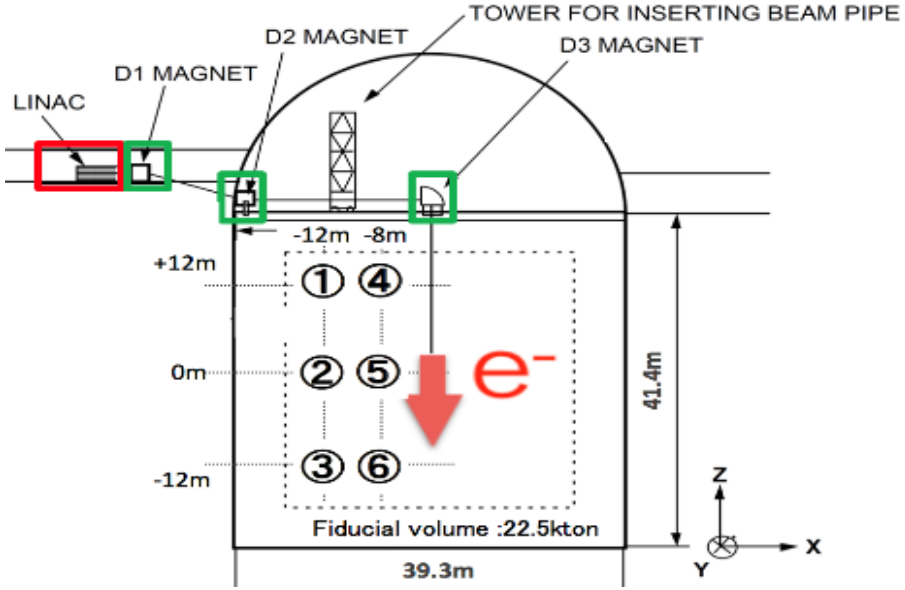
- Deuterium-Tritium Generator produces thousands of 14 MeV neutrons which interact with ^{16}O in water to make ^{16}N
  - ^{16}N beta decays back to ^{16}O (τ = 10.3s)
- Stable after gain correction



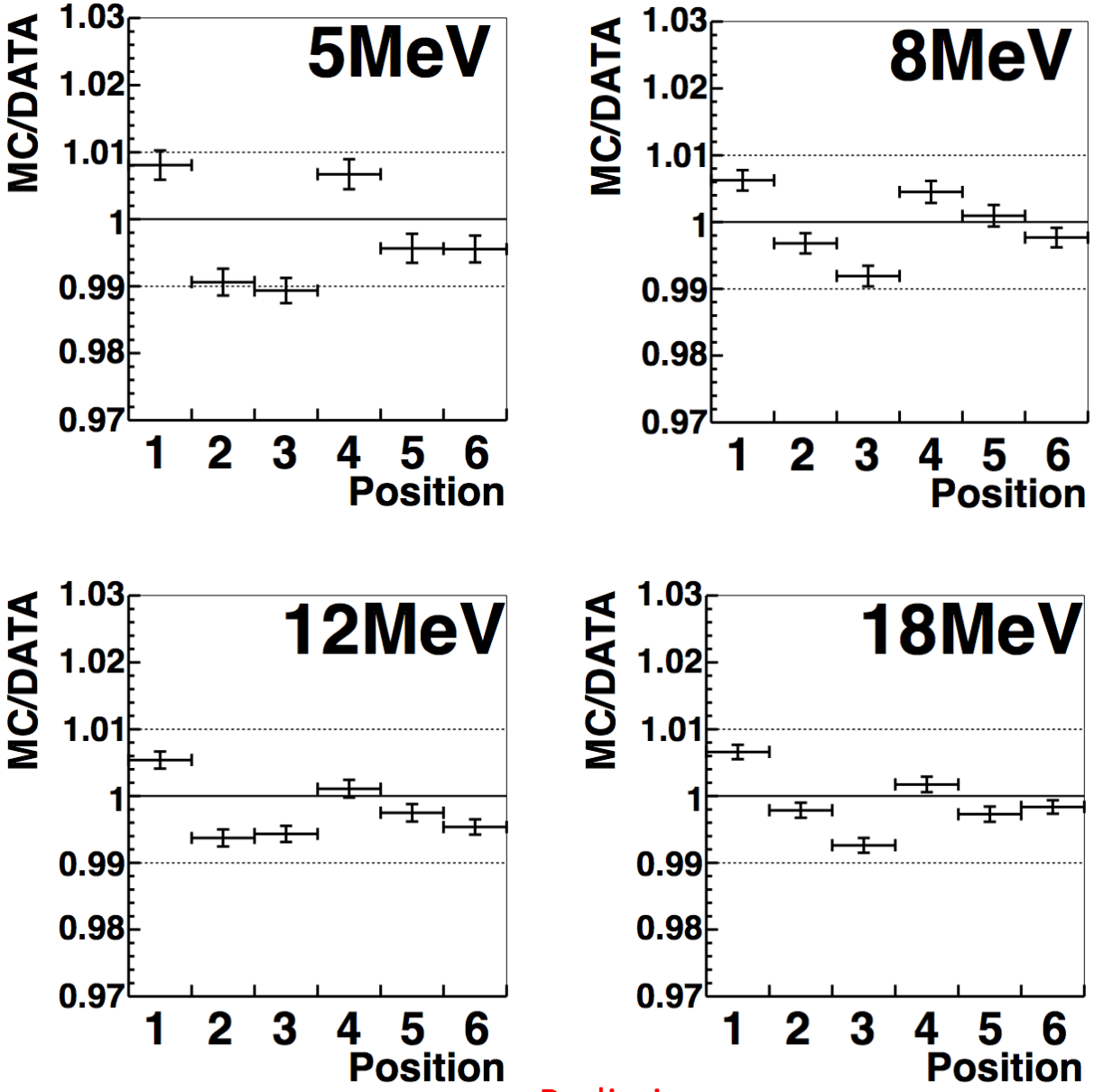
Preliminary
June 2017

LINAC Calibration

- Monochromatic Electrons
  - Ranging in energy from 4-20 MeV
- Remain stable after gain correction



After Gain Correction

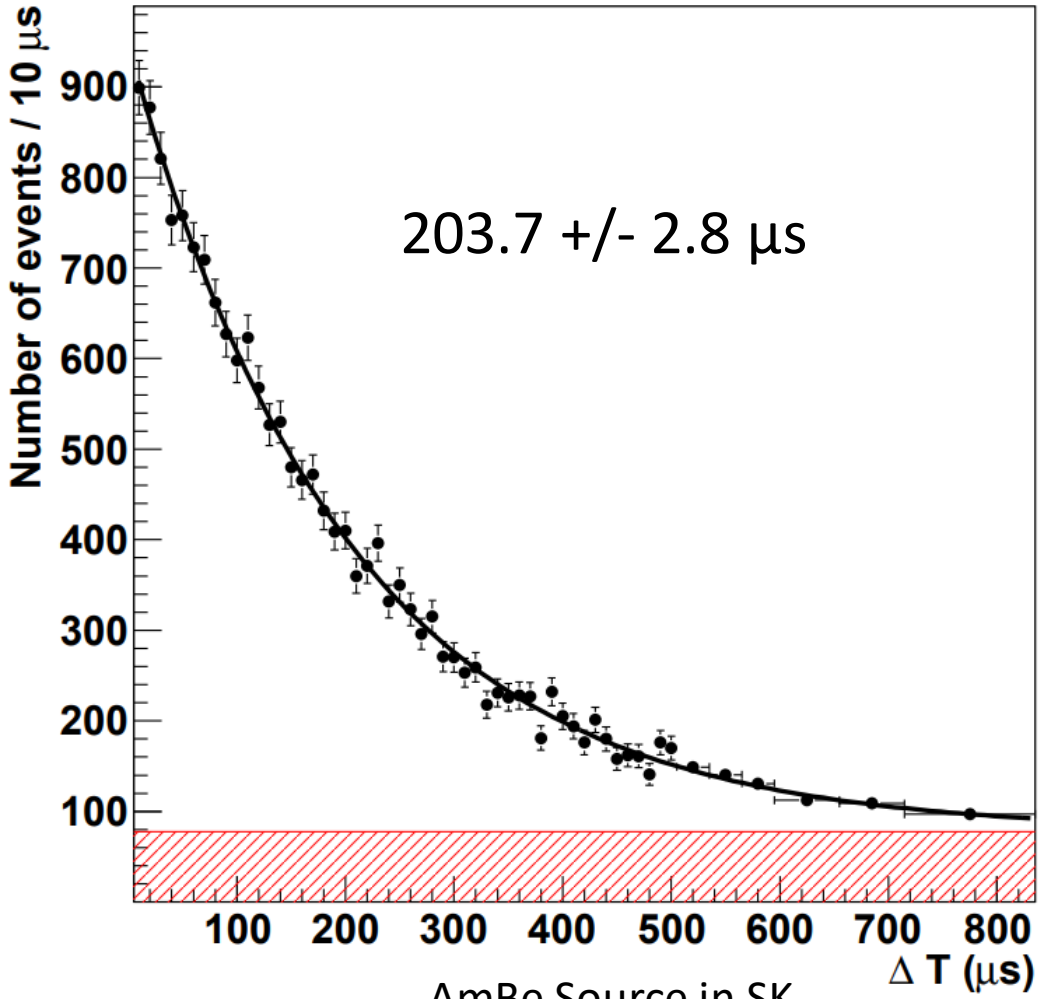


Preliminary
June 2017

Spallation Studies

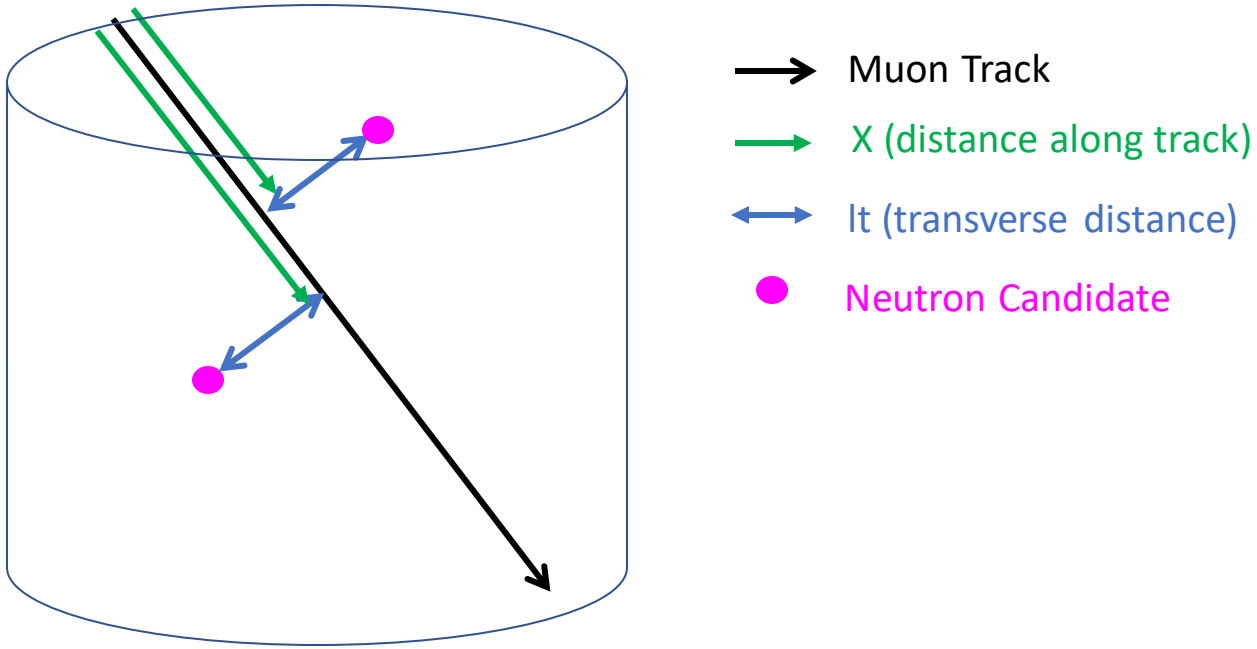
- Spallation is one of the leading backgrounds in solar and DSNB analysis
- Beacom and Li predict many neutrons produced in the hadronic shower from a spallation causing muon
- Using Wideband-Intelligent Trigger (WIT), we have a lower threshold to look for 2.2 MeV gammas from n+p production (Astropart. 60 (2015) 41)

Astropart. 60 (2015) 41

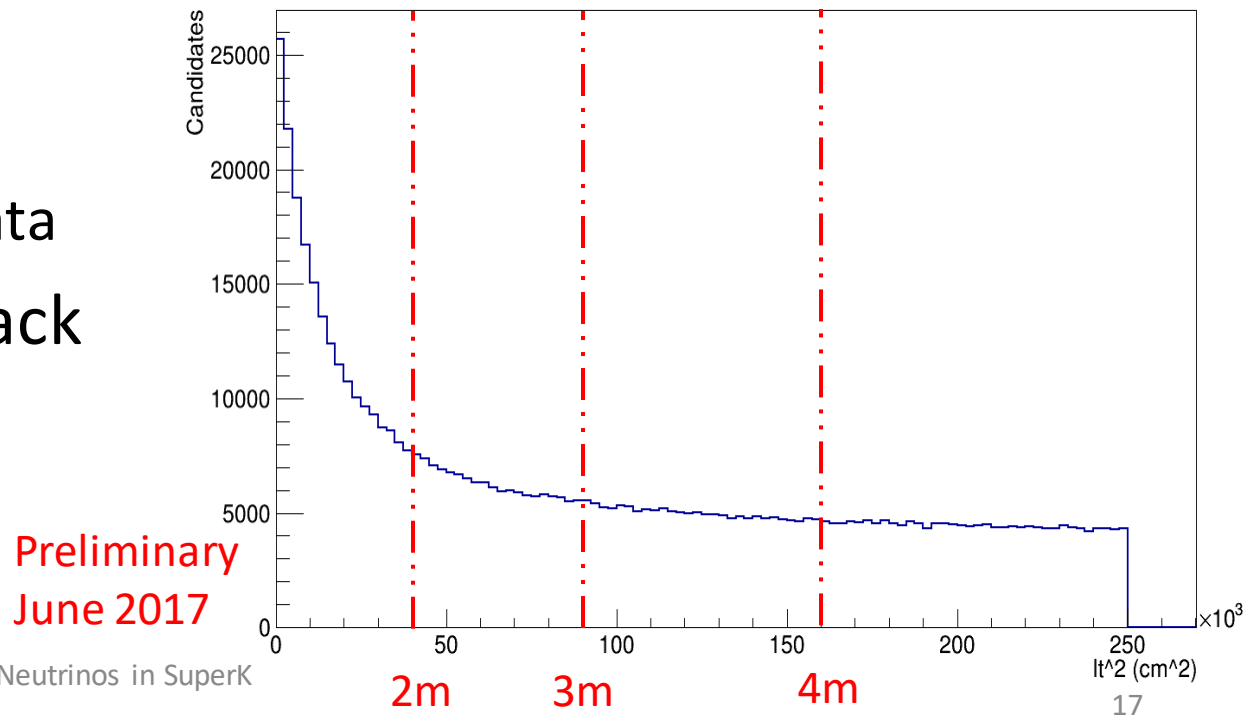


AmBe Source in SK

Spallation Studies

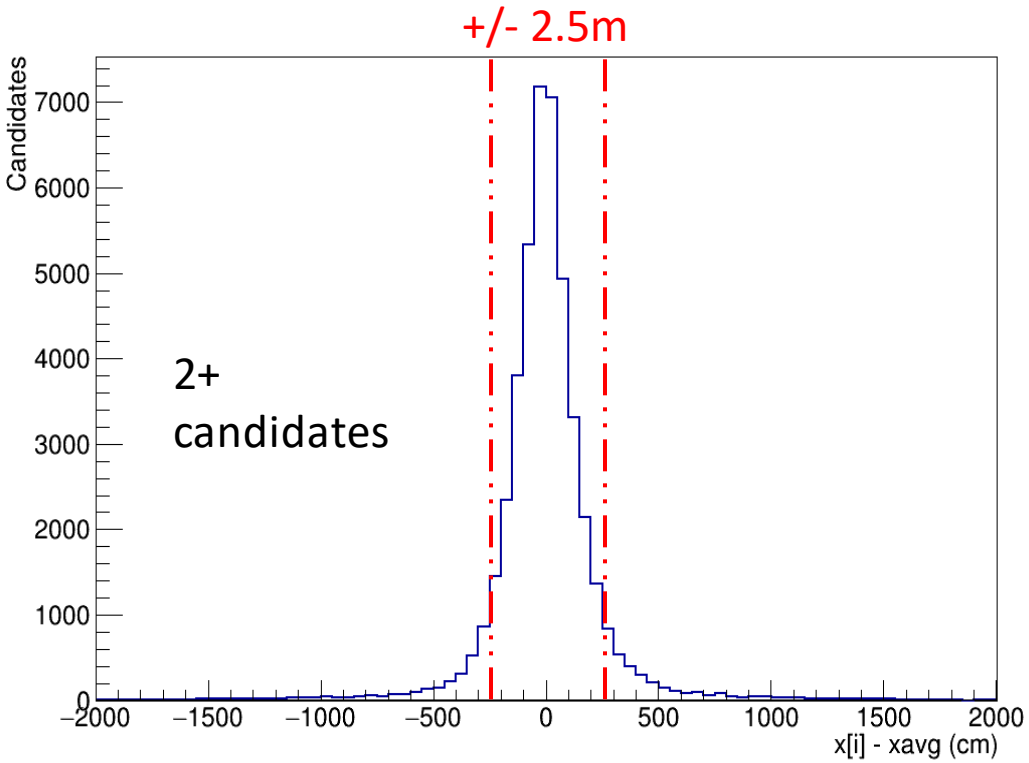


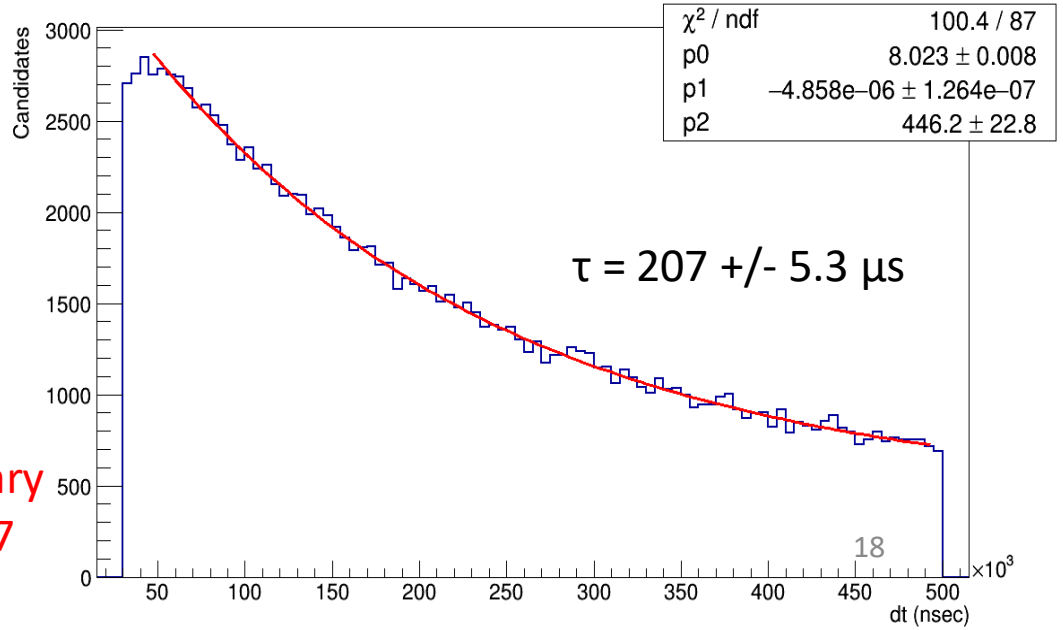
- Initial Data Set:
  - ~6 weeks of data
  - 20-500 μs after muon
  - E < 5.5 MeV kin
  - <5m from track
  - Basic cut used on some of the data
- Sharply peaked closer to the track



Spallation Studies

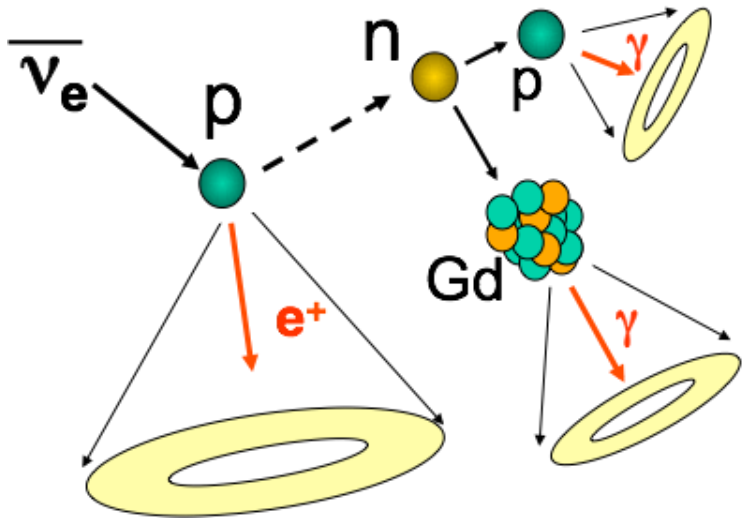
- Candidates tightly correlated to each other
- dt spectrum consistent with AmBe
- We see the neutron candidates
- Need to investigate further





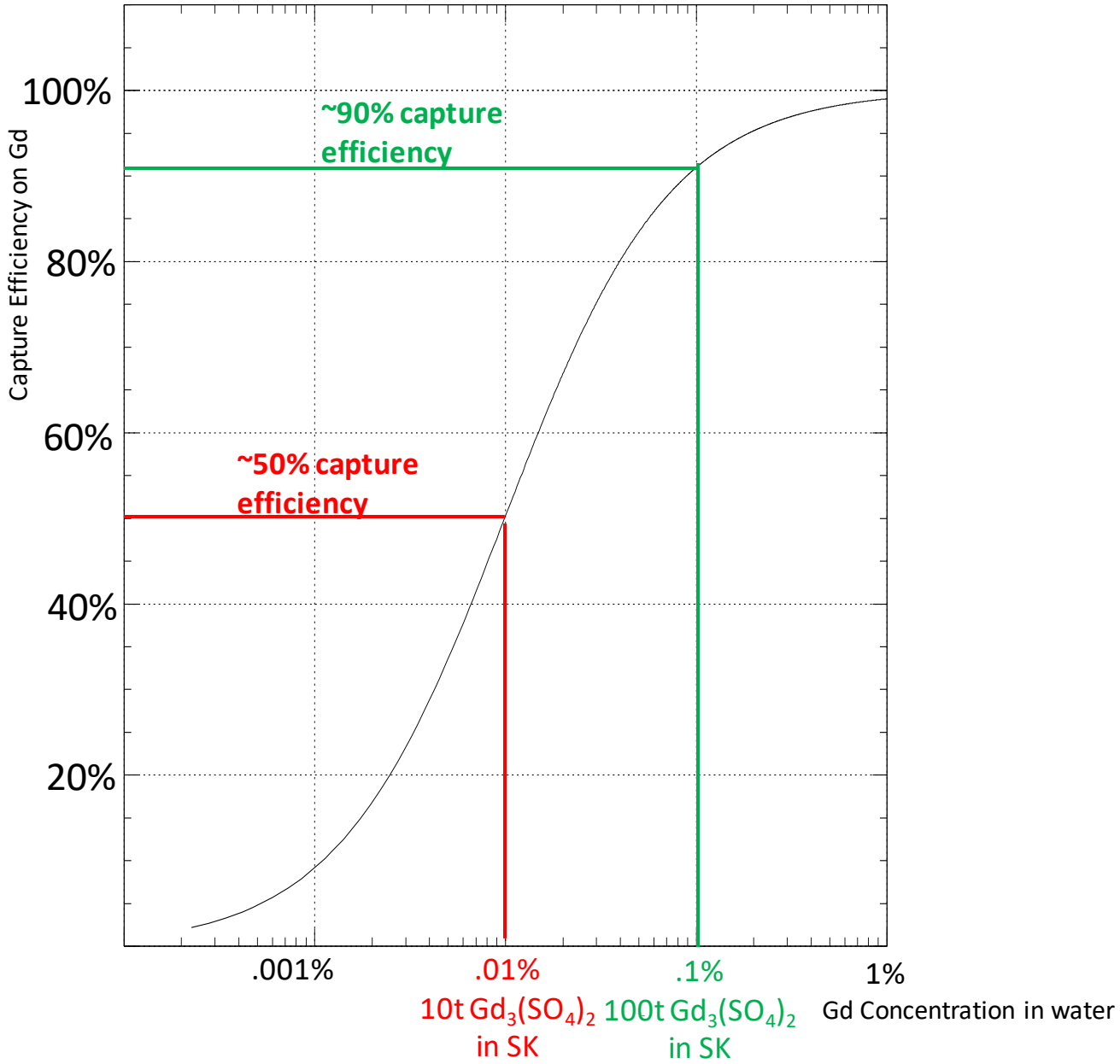
Preliminary
June 2017

SK-GD



- Dope Water with $Gd_2(SO_4)_3$
  - Reduce ν_e-bar BG
  - ~10k events for 8.5 kpc (galactic center) supernova
- Signal:
  - Prompt positron followed by 8 MeV gamma cascade (~4.5 MeV reconstructed) or 2.2 MeV gamma
  - ΔT ~ 30μs
  - ~50cm vertex correlation

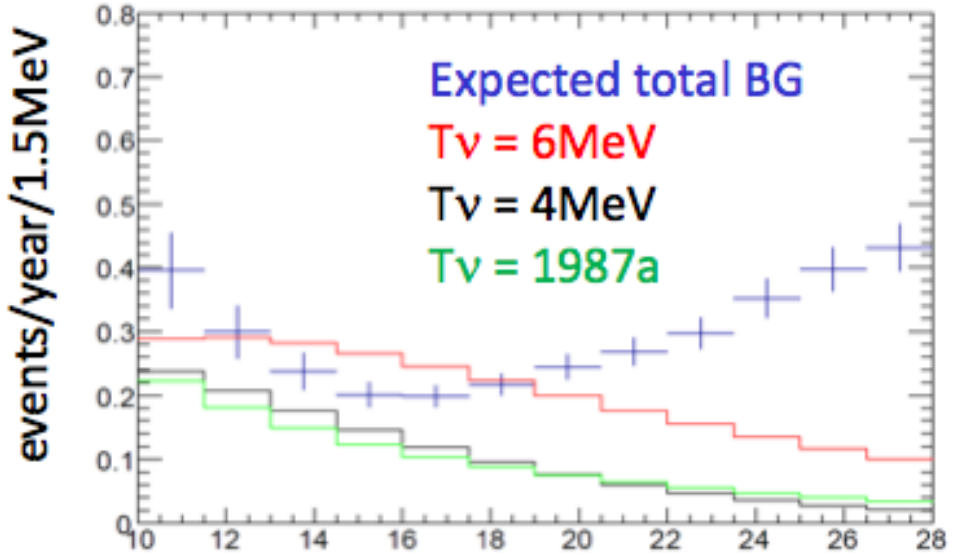
Dissolve Gadolinium into SK J. Beacom and M. Vagins, PRL93, 171101 (2004)



SK-GD Expected Sensitivity

DSNB flux:
Horiuchi, Beacom and Dwek, PRD, 79, 083013 (2009)

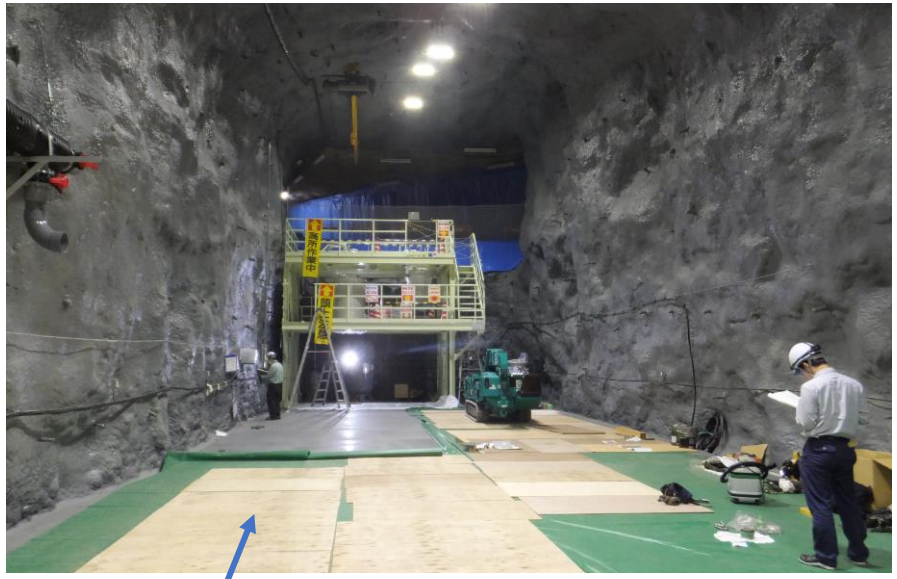
- It depends on typical/actual SN emission spectrum



DSNB events number with 10 years observation

HBD models	10-16MeV (evts/10yrs)	16-28MeV (evts/10yrs)	Total (10-28MeV)	significance (2 energy bin)
T_{eff} 8MeV	11.3	19.9	31.2	5.3 σ
T_{eff} 6MeV	11.3	13.5	24.8	4.3 σ
T_{eff} 4MeV	7.7	4.8	12.5	2.5 σ
T_{eff} SN1987a	5.1	6.8	11.9	2.1 σ
BG	10	24	34	----

SK-GD: New Water System

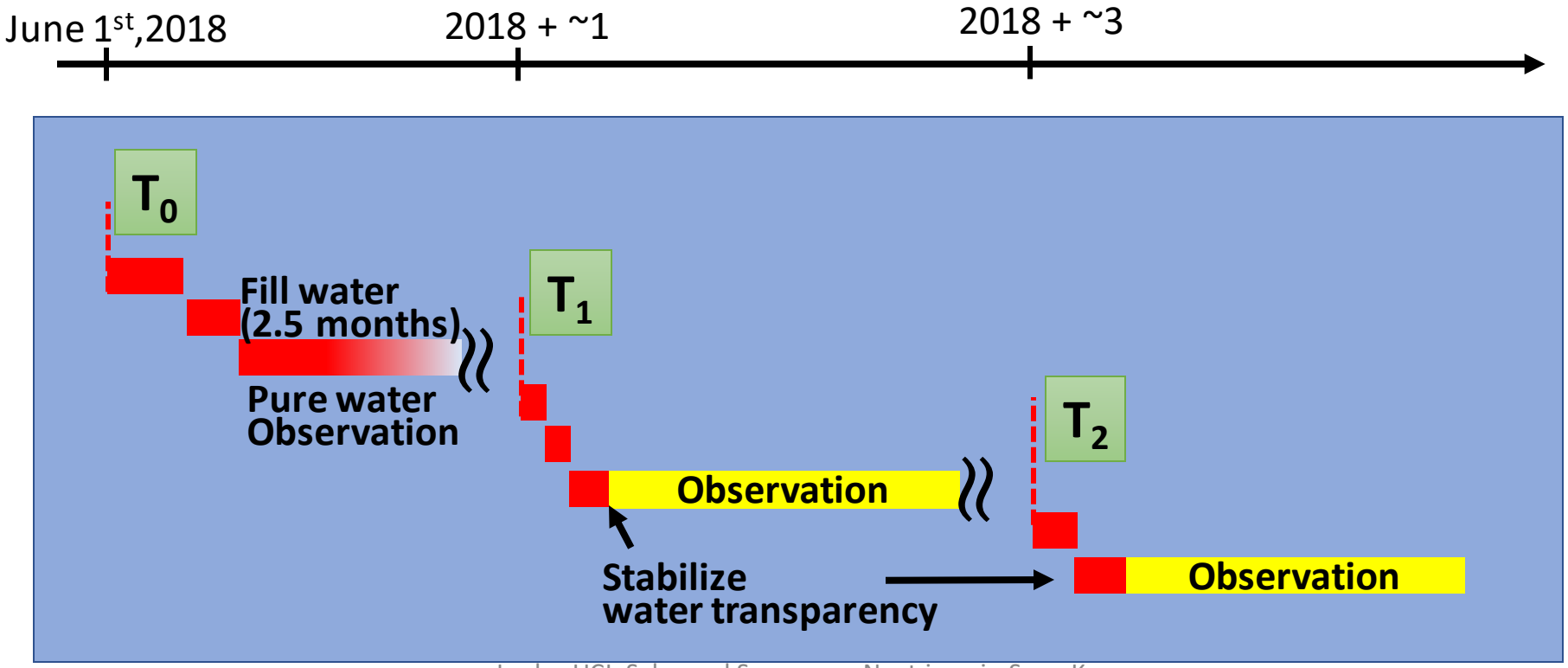


2015 2016 2017

- Progressing on pace for target tank opening

SK-Gd: Moving Forward

- T_0 : Open tank, fix leak, fill, and check pure water results
- T_1 : Begin loading Gd, up to 0.01% (10 tons $Gd_2(SO_4)_3$) and take observation
- T_2 : Further load with Gd, to .1% (100 tons $Gd_2(SO_4)_3$)
- Constant monitoring of water transparency needed



Summary

- Solar and Supernova neutrinos are the main focus of the Low Energy group
  - Spectrum consistent to within ~1σ of the MSW upturn for Solar best fit
  - Tension of ~2σ of the MSW upturn for Solar + KamLAND best fit parameters
- Partial updates for the 2645 day sample, and SK IV modulation analysis.
- Improvements are underway for the energy spectrum, with ongoing efforts for gain correction and various continual calibration data.
- Efforts in removing spallation BG are progressing
- SK-Gd is on track, tank opening slated for 2018

Super-Kamiokande Collaboration

- 10 nations
- ~42 institutions
- ~160 Researchers
- As of June 2017