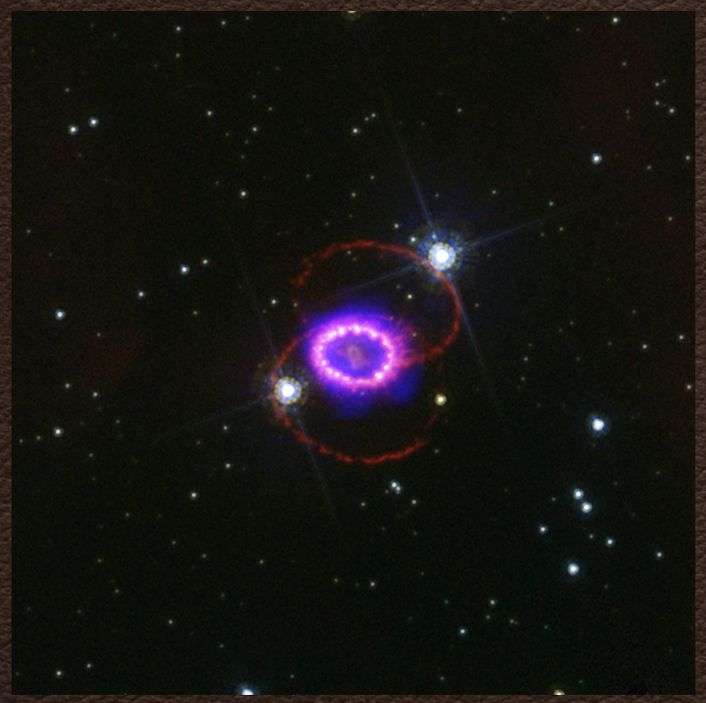
Low Energy Neutrino Astrophysics in Super-Kamiokande with Gd



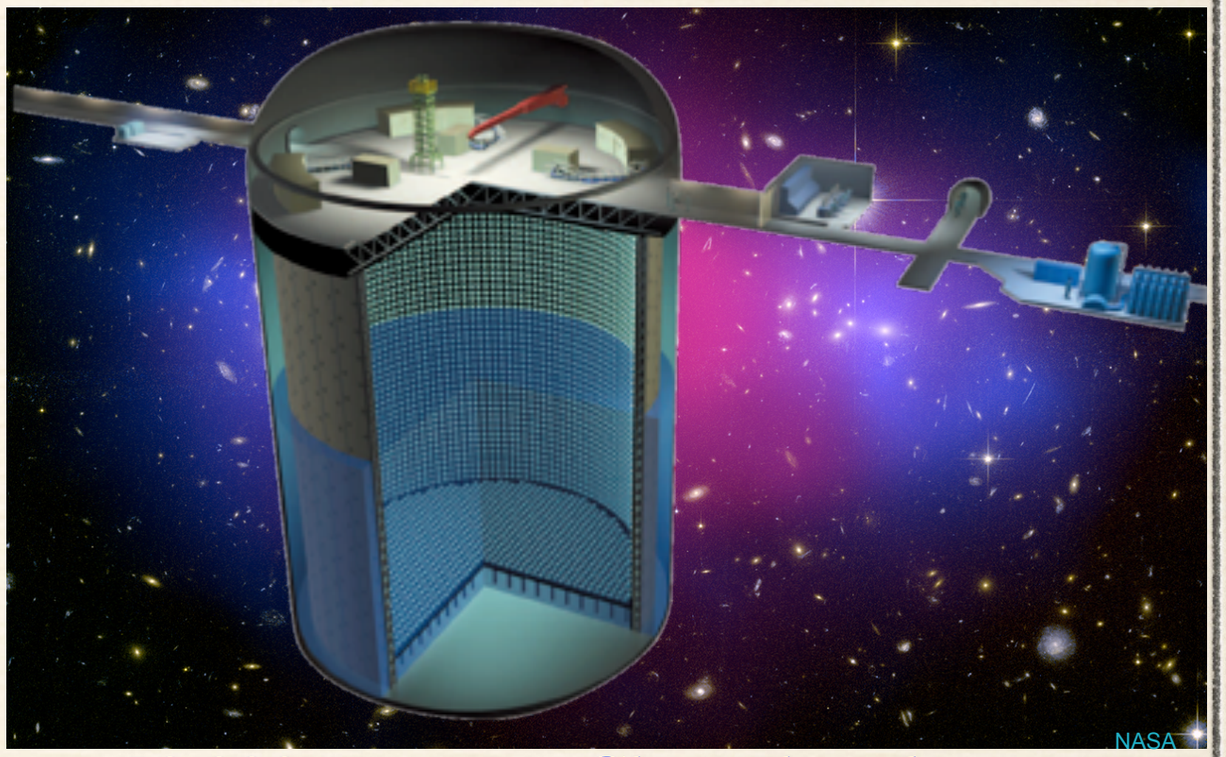
Michael Smy, UC Irvine

Topics in Cosmic Neutrino Physics

October 10th 2019

23 Years of Low Energy Astrophysics with Super-Kamiokande!

- 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

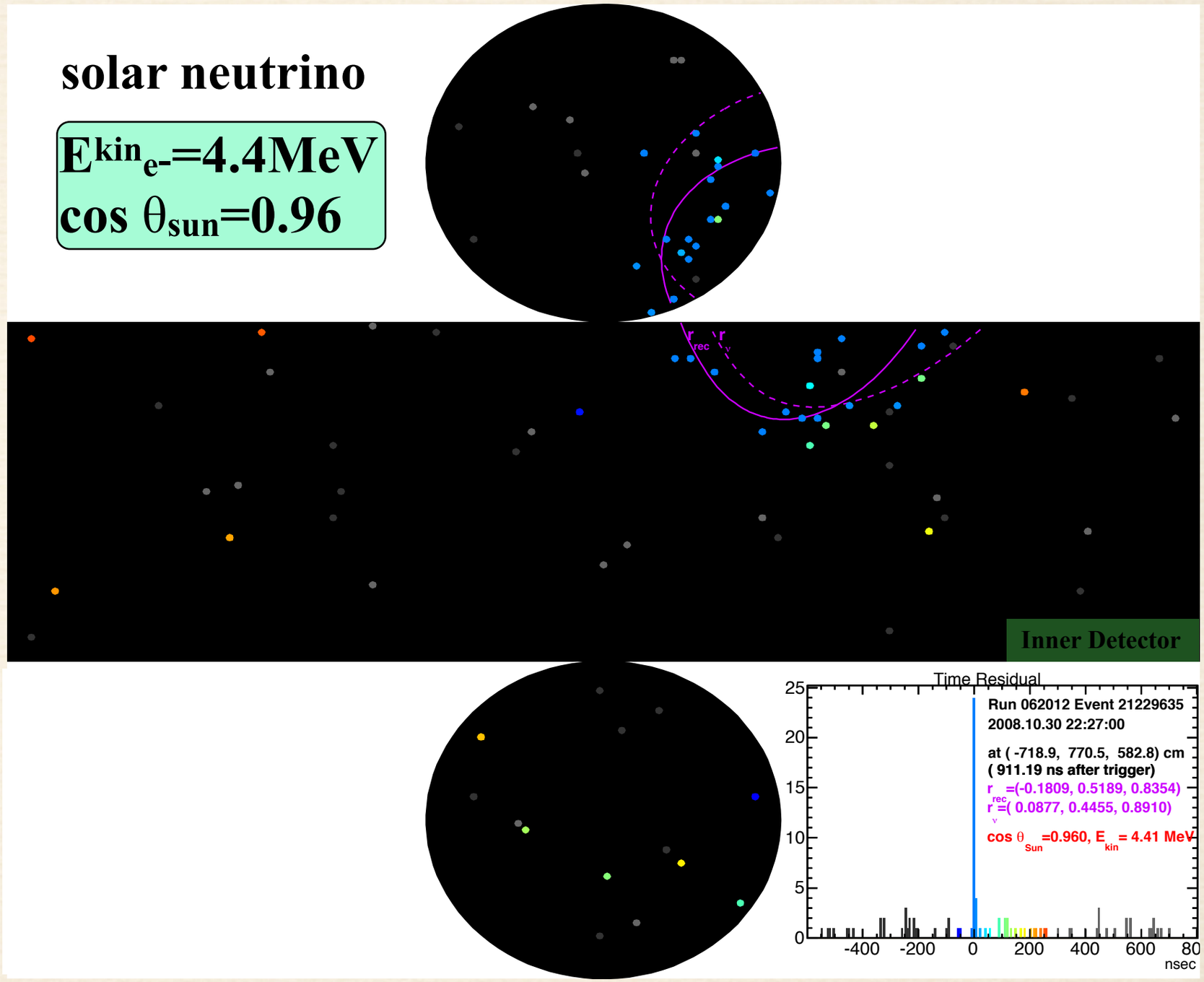


- 50,000 ton water Cherenkov detector
  - ID: 32,000 tons (FV 22,500 tons); 11,129 PMTs (SK-I 11,146 PMTs)
  - OD: 18,000 tons; 1,885 PMTs

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

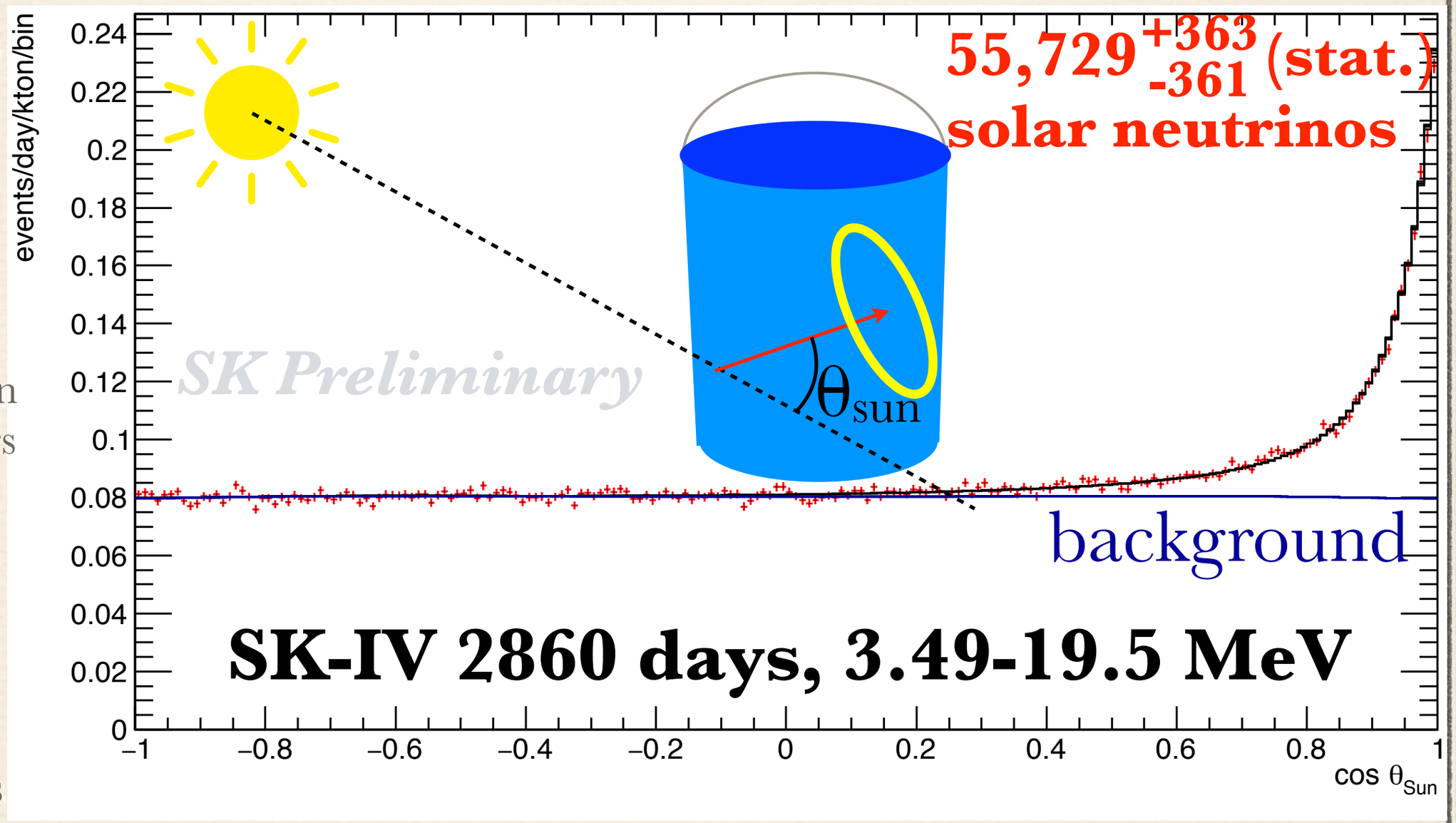
Low Energy Electron Detection in Super-Kamiokande

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



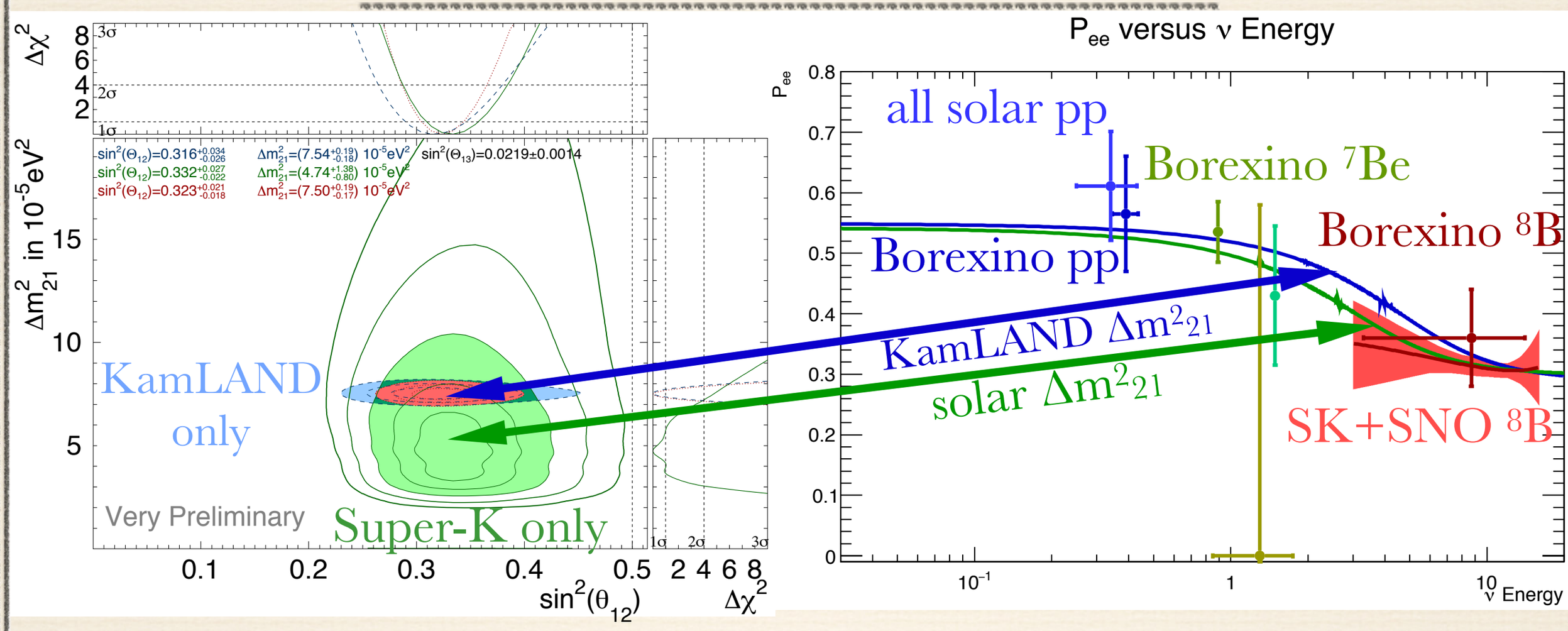
Solar ^{8}B Neutrinos

- high statistics observations
- solar core temperature
- observe solar ν oscillation; determination of parameters
- investigate solar matter effects
- study terrestrial matter effects



- found ν osc.: θ_{12} consistent with SNO, Δm^2_{21} a bit larger than KamLAND
- no evidence of MSW energy "edge", hint of terrestrial matter effects

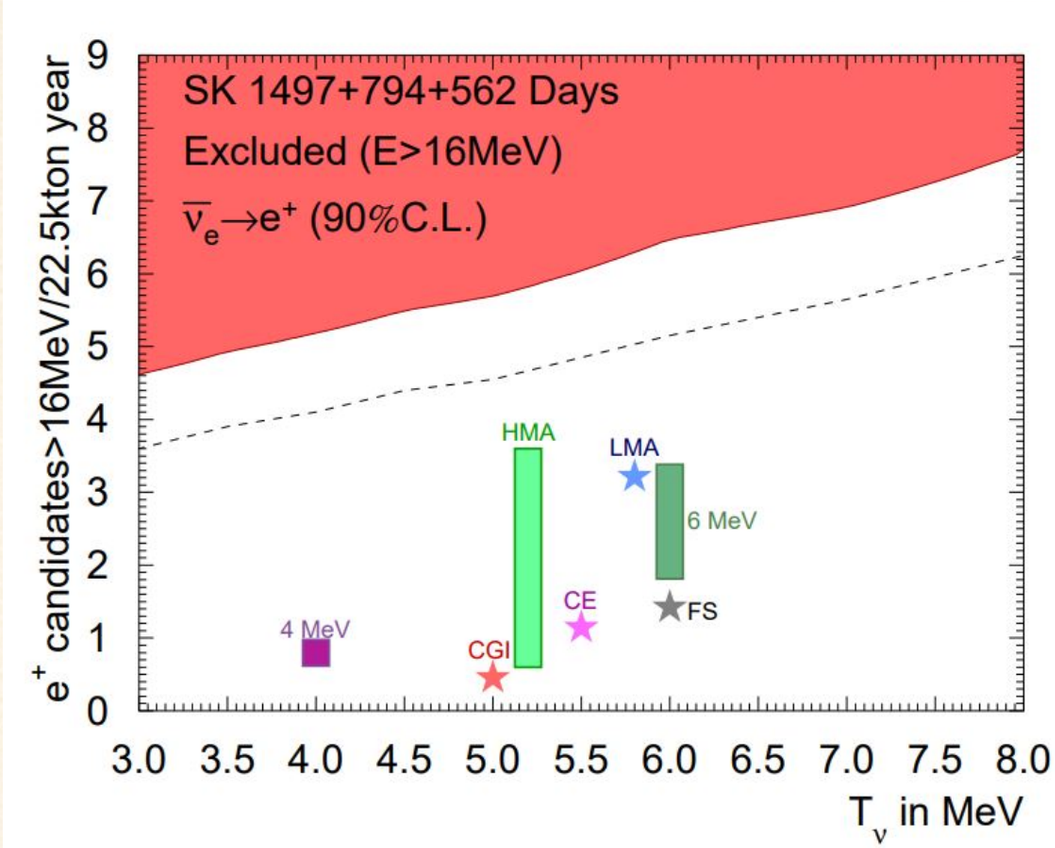
Solar ^{8}B Neutrinos

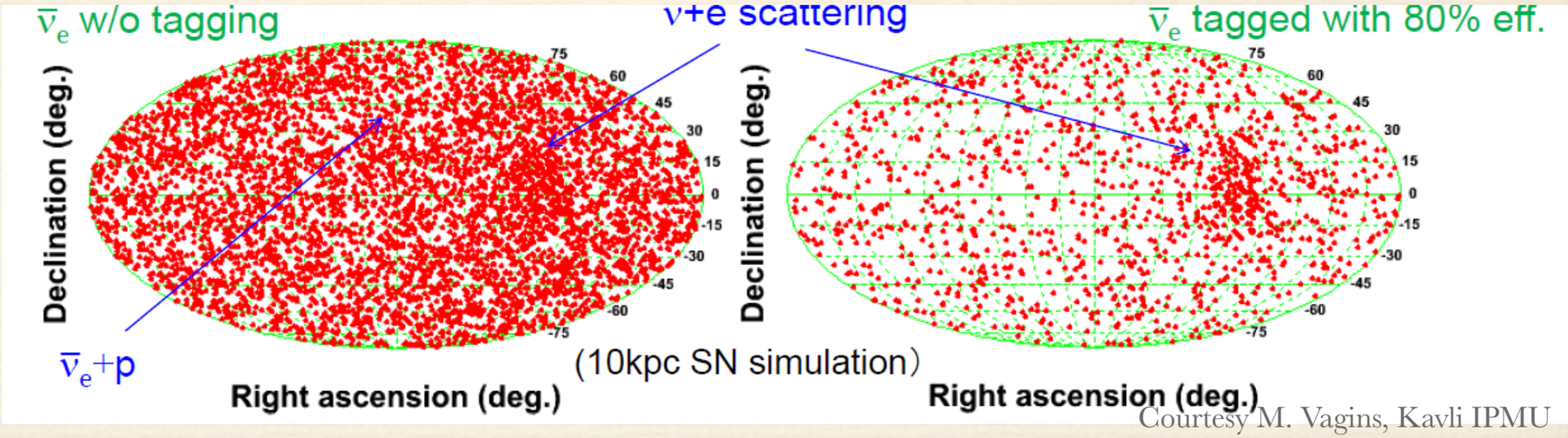


- SK ^{8}B spectrum and day/night asymmetry is strongest solar neutrino constraint on Δm^2_{21}: lower than KamLAND anti-neutrino measurement by ~2σ
- SK Low E ^{8}B data give strongest constraints on MSW energy dependence: disfavor presence of MSW lower edge by ~2σ for KamLAND Δm^2_{21}

Supernova Neutrinos

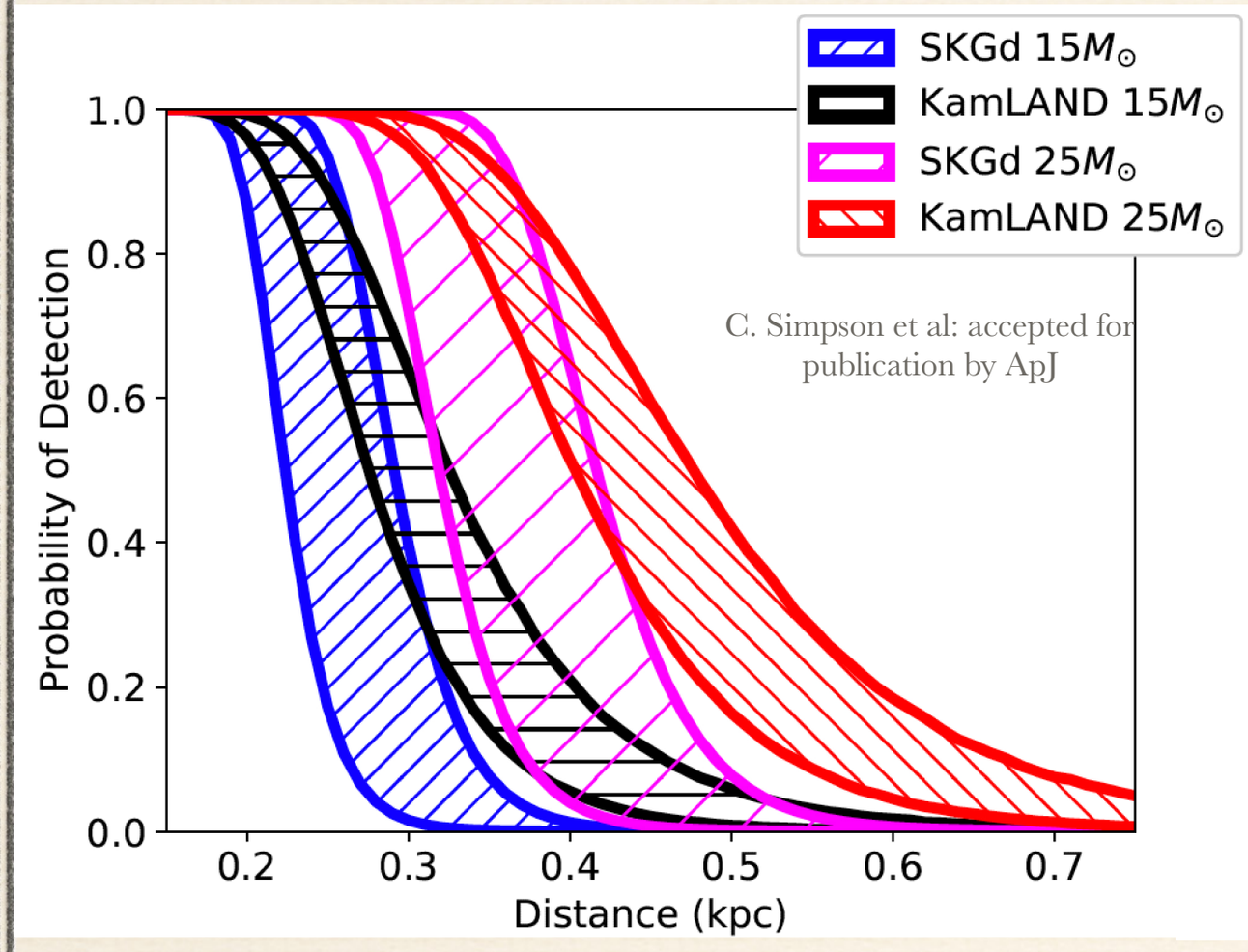
- no SN ν detection by Super-K so far
- no galactic bursts
- only ~1σ (~2±2 ev/year) excess over background from search for diffuse, distant SN ν interactions
- March 2020: add $Gd_2(SO_4)_3$ to Super-K to enhance search via delayed coincidence technique of IBD detection suggested by Beacom and Vagins (Phys. Rev. Lett., 93:171101, 2004)
- 3x more light for neutrons capturing on Gd compared to hydrogen
- culmination of a 15 year R & D program
- improved flavor separation and pointing for galactic burst



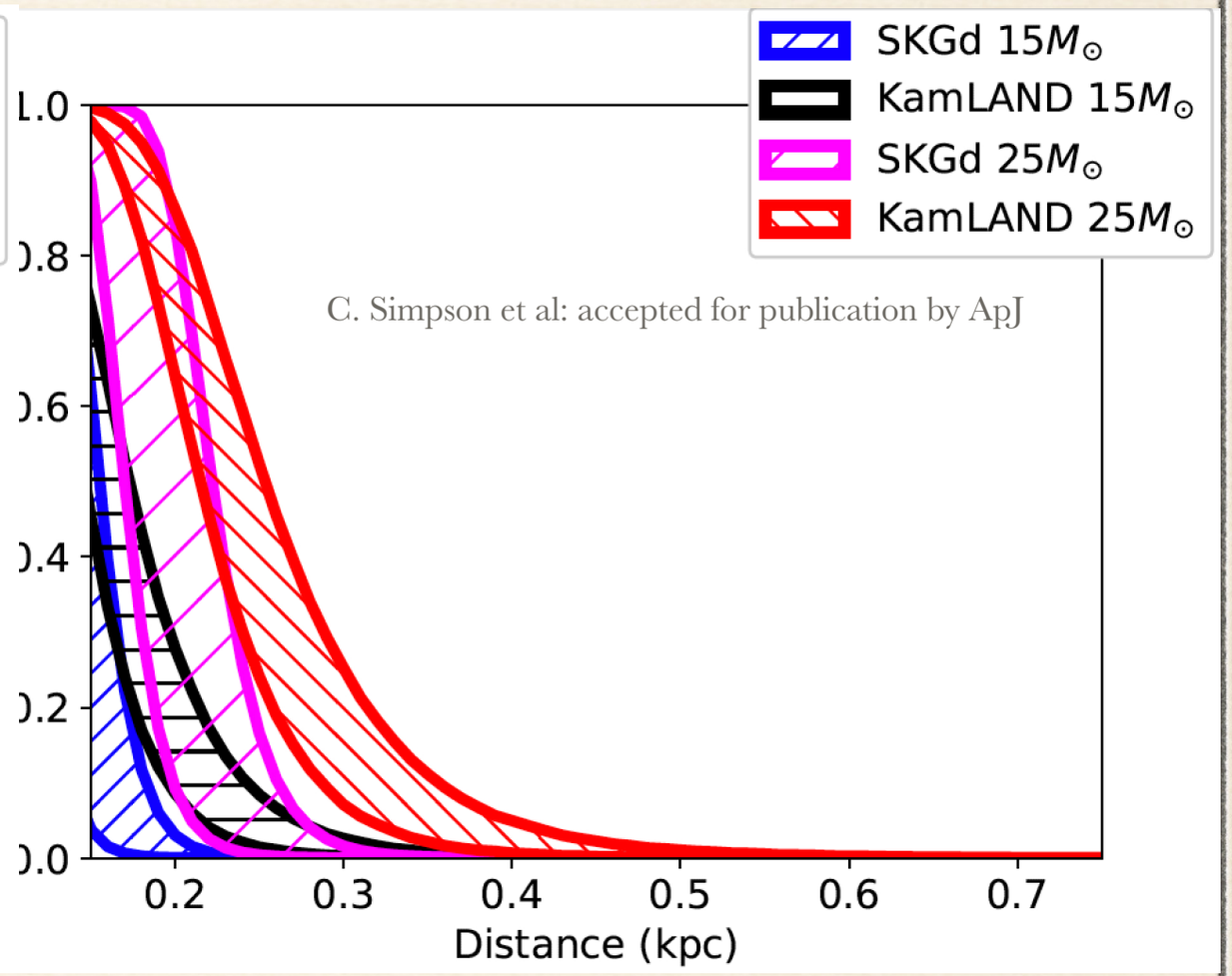


Courtesy M. Vagins, Kavli IPMU

Added Benefit: Pre-SN Alert from Si-Burning ν's



normal mass ordering

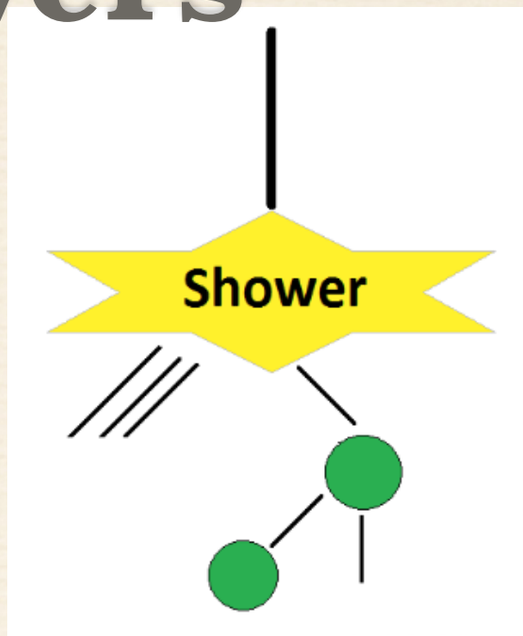


inverted mass ordering

- detection in ~48 hour period before SN
- only viable for massive stars in the neighborhood (e.g. Betelgeuse)
- some model dependence of 5σ detection range; it is similar to KamLAND's

Reduce Spallation Background: Tagging Hadronic Showers

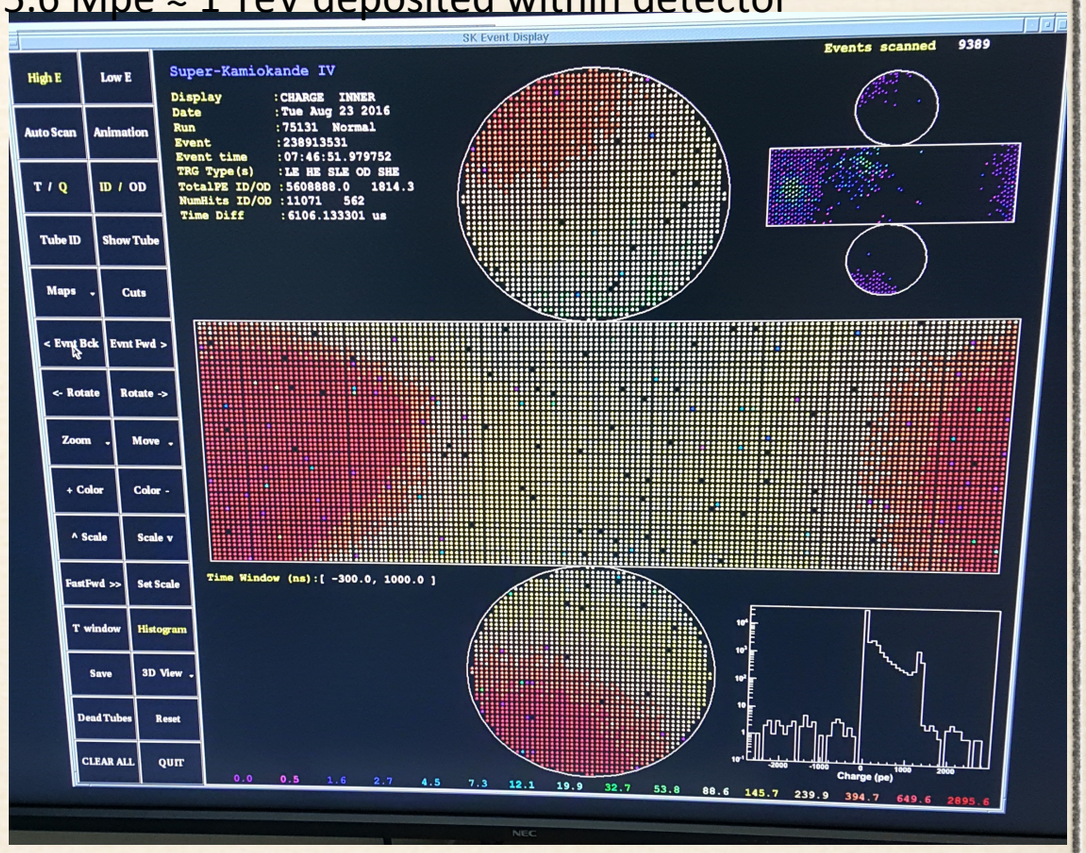
- some muons initiate showers of secondary particles (e, γ, n, π , …); hadrons (n, π) in those break up ^{16}O and the decays of unstable resulting isotopes feign ν interactions
- lifetime ranges from O(0.01s) to O(10s)



Radioactive isotope	τ (s)	Decay mode	$E_{\text{kin.}}$ (MeV)	Primary process
^{11}Be	19.9	β^-	11.51	$^{16}O(n,\alpha+2p)^{11}Be$
		$\beta^-\gamma$	9.41+2.1(γ)	
^{16}N	10.3	β^-	10.44	$^{16}O(n,p)^{16}N$
		$\beta^-\gamma$	4.27+6.13(γ)	
^{15}C	3.53	β^-	9.77	$^{16}O(n,2p)^{15}C$
		$\beta^-\gamma$	4.51+5.30(γ)	
^{8}Li	1.21	β^-	~13.0	$^{16}O(\pi^-,\alpha+{}^2H+p+n)^{8}Li$
^{8}B	1.11	β^+	~13.9	$^{16}O(\pi^+,\alpha+2p+2n)^{8}B$
^{12}B	0.029	β^-	13.37	$^{16}O(n,\alpha+p)^{12}B$

Radioactive isotope	ϵ_i	R_i (kton^{-1}day^{-1})
^{12}B	45.5%	19.8±0.1±1.0
^{12}N	56.2%	2.8±0.1±0.1
^{16}N	45.0%	39.7±3.3±2.8
^{11}Be	38.1%	<16.9
^{9}Li	39.2%	0.9±0.3±0.3
^{8}He/^{9}C	22.2%, 50.2%	<1.4
^{8}Li/^{8}B	42.8%, 51.3%	8.3±0.3±0.3
^{15}C	31.8%	<6.7

5.6 Mpe ≈ 1 TeV deposited within detector

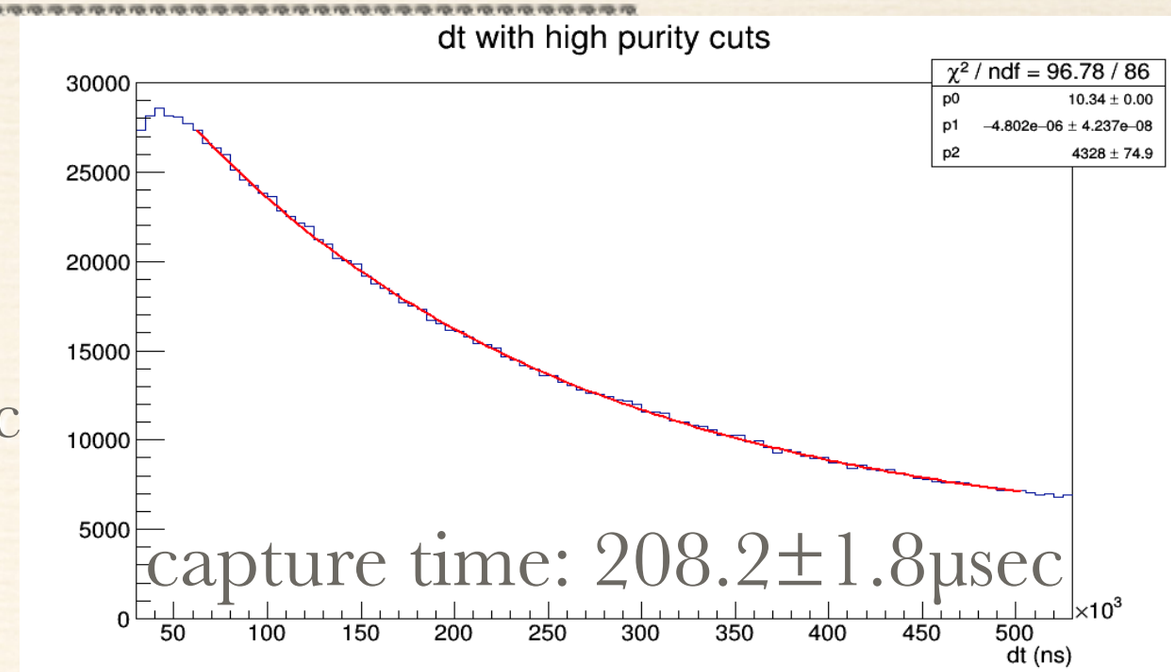


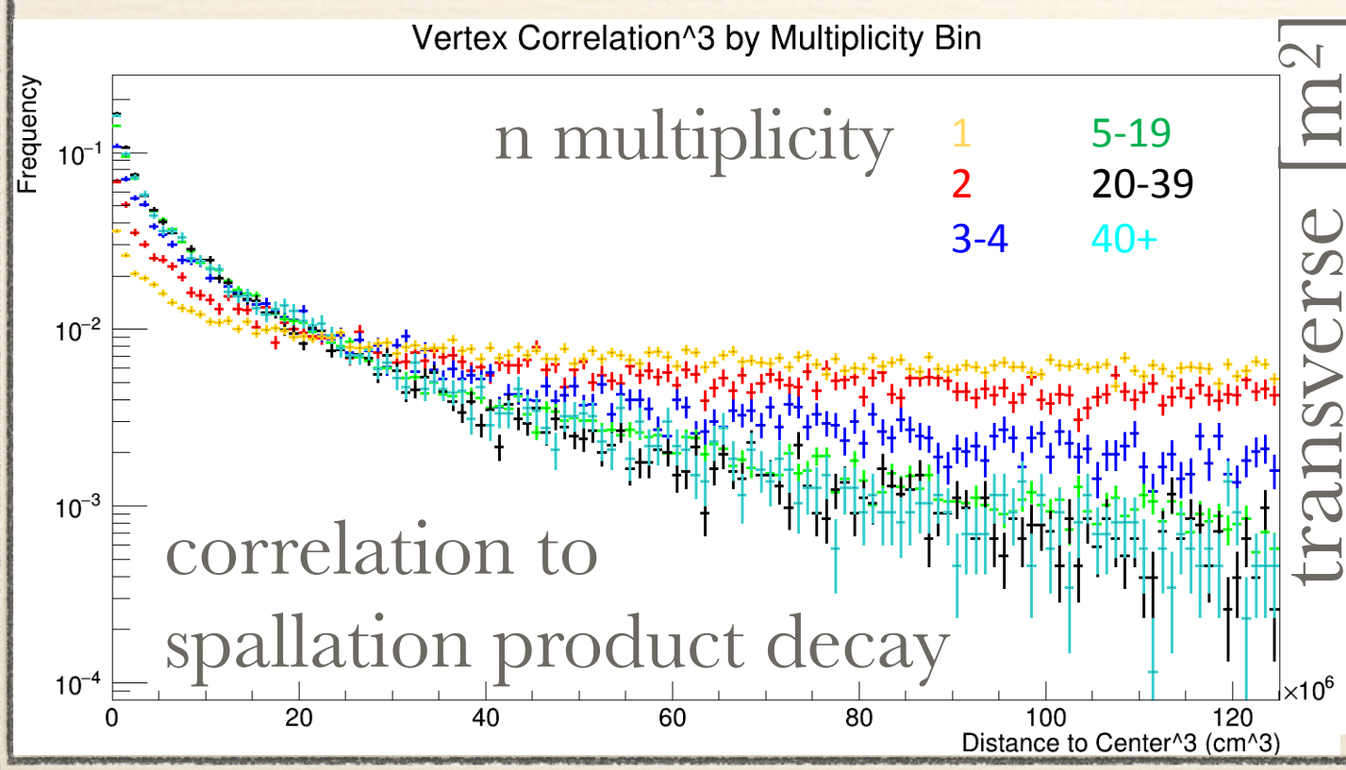
Y. Zhang et al. Phys. Ev. D 93, 012004 (2016) and Beacom and Li: Phys Rev C 89, 045801 (2014)

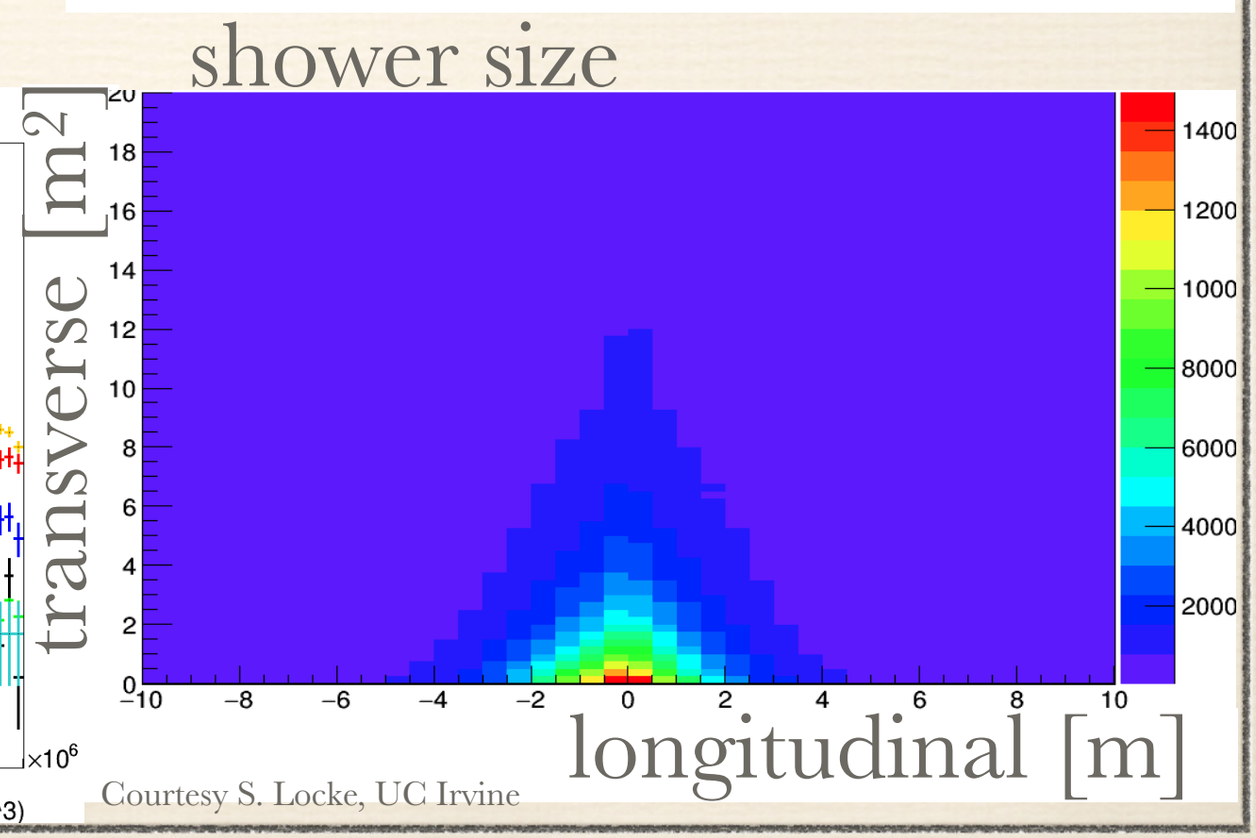
Courtesy S. Locke, UC Irvine

Reduce Spallation Background: Tagging Hadronic Showers

- very low threshold WIT system triggers on 2.2 MeV γ's from hadronic shower neutrons **capturing on hydrogen**
- multiple spallation: several events >5.49 MeV within 60sec and 4m tag a hadronic shower, even without a detected muon
- ~45% of spallation background is from multiple spallation





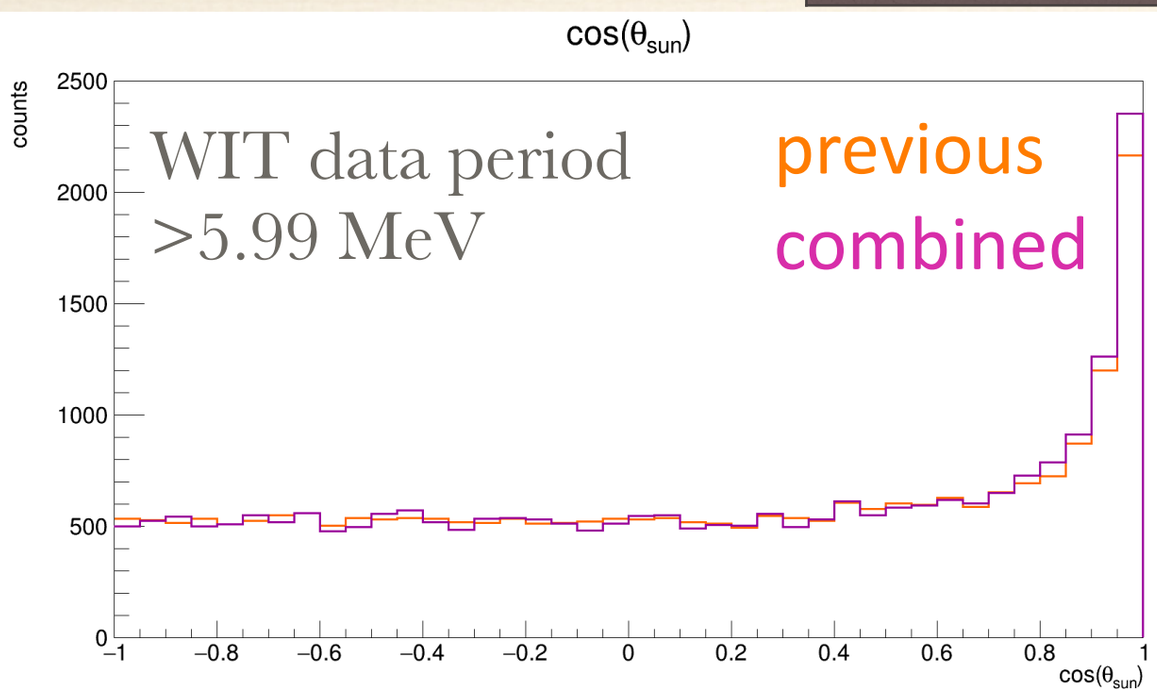


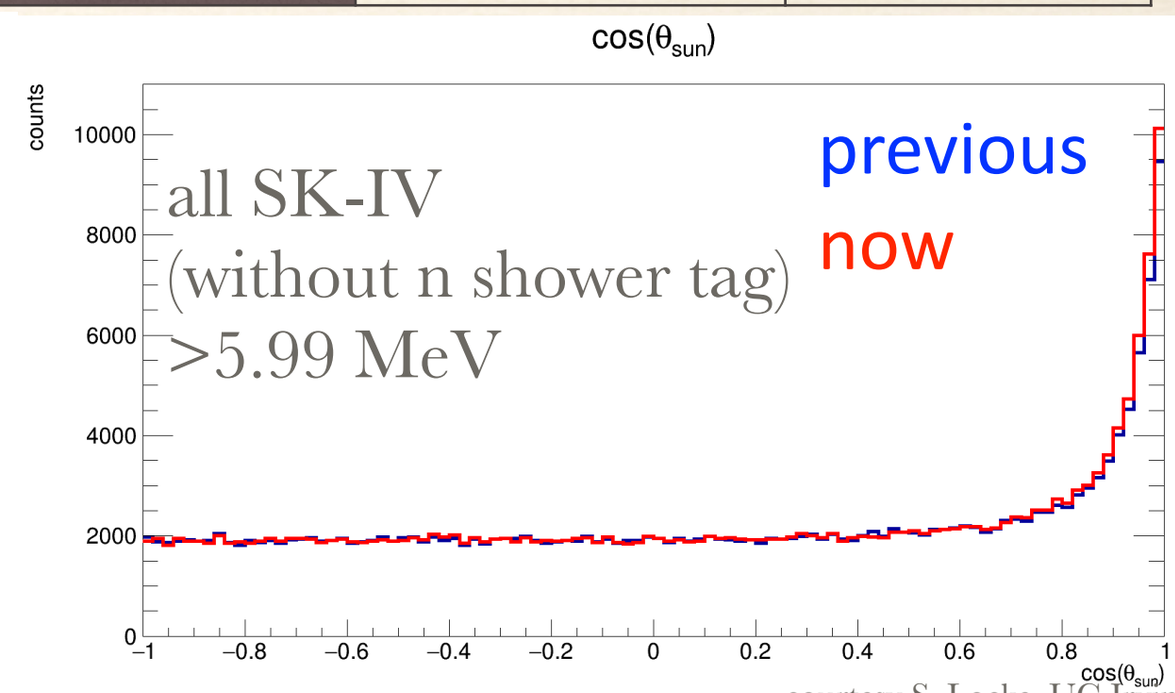
Courtesy S. Locke, UC Irvine

Reduce Spallation Background: Tagging Hadronic Showers

- in WIT data period use n shower, multi-spa & track, rest of data just multi-spa & track
- only half the dead time in WIT data period!
- gain ~250 days exposure in SK-IV!

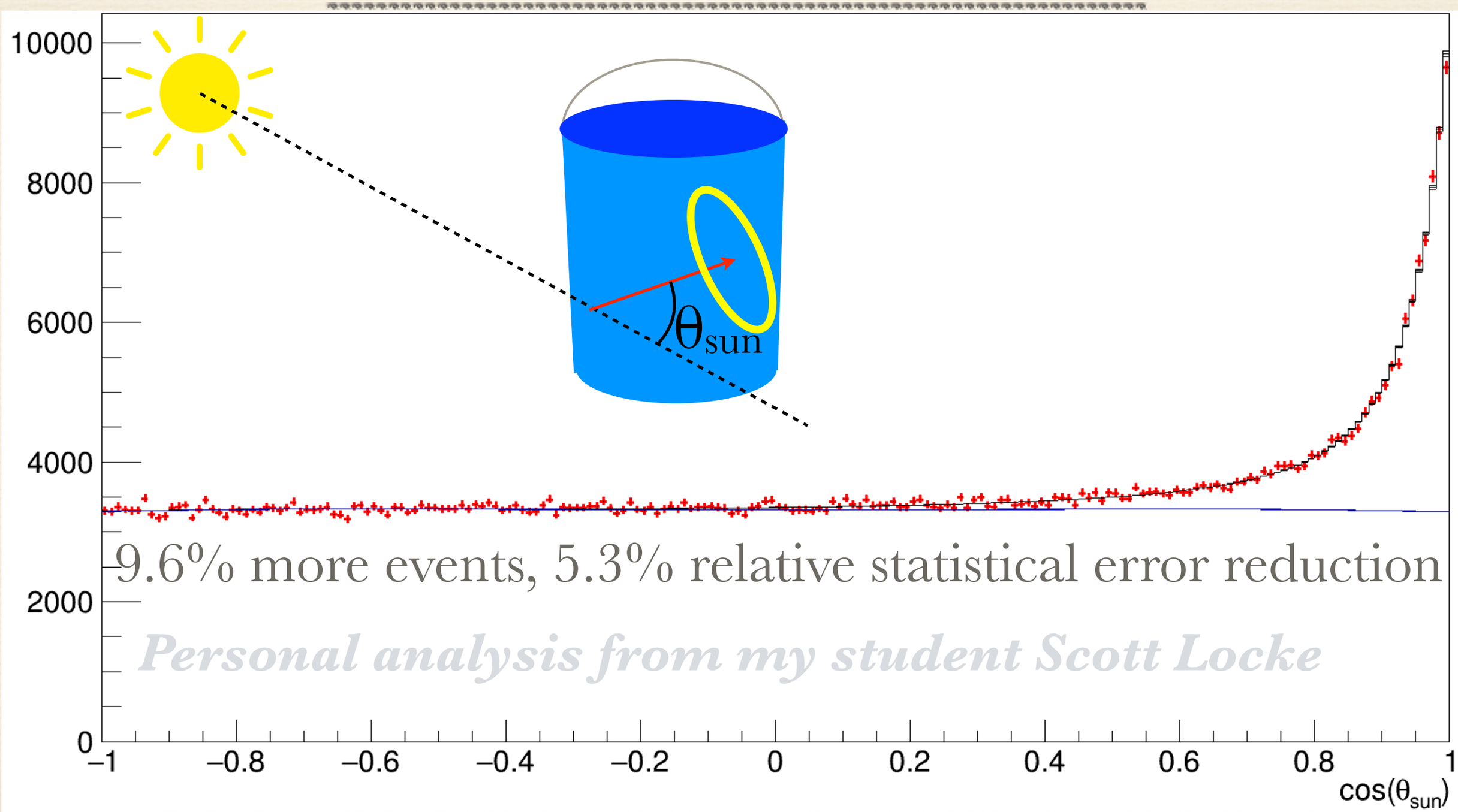
Method	effectiveness [%]	deadtime [%]
n shower tag (on H)	54.34	1.18
multiple spall. tag	46.48	1.27
muon track likelihood	81.08	7.70
combined	90.05	**9.65**
previous muon track likelihood	89.97	**19.61**





courtesy S. Locke, UC Irvine

Reduce Spallation Background: Tagging Hadronic Showers

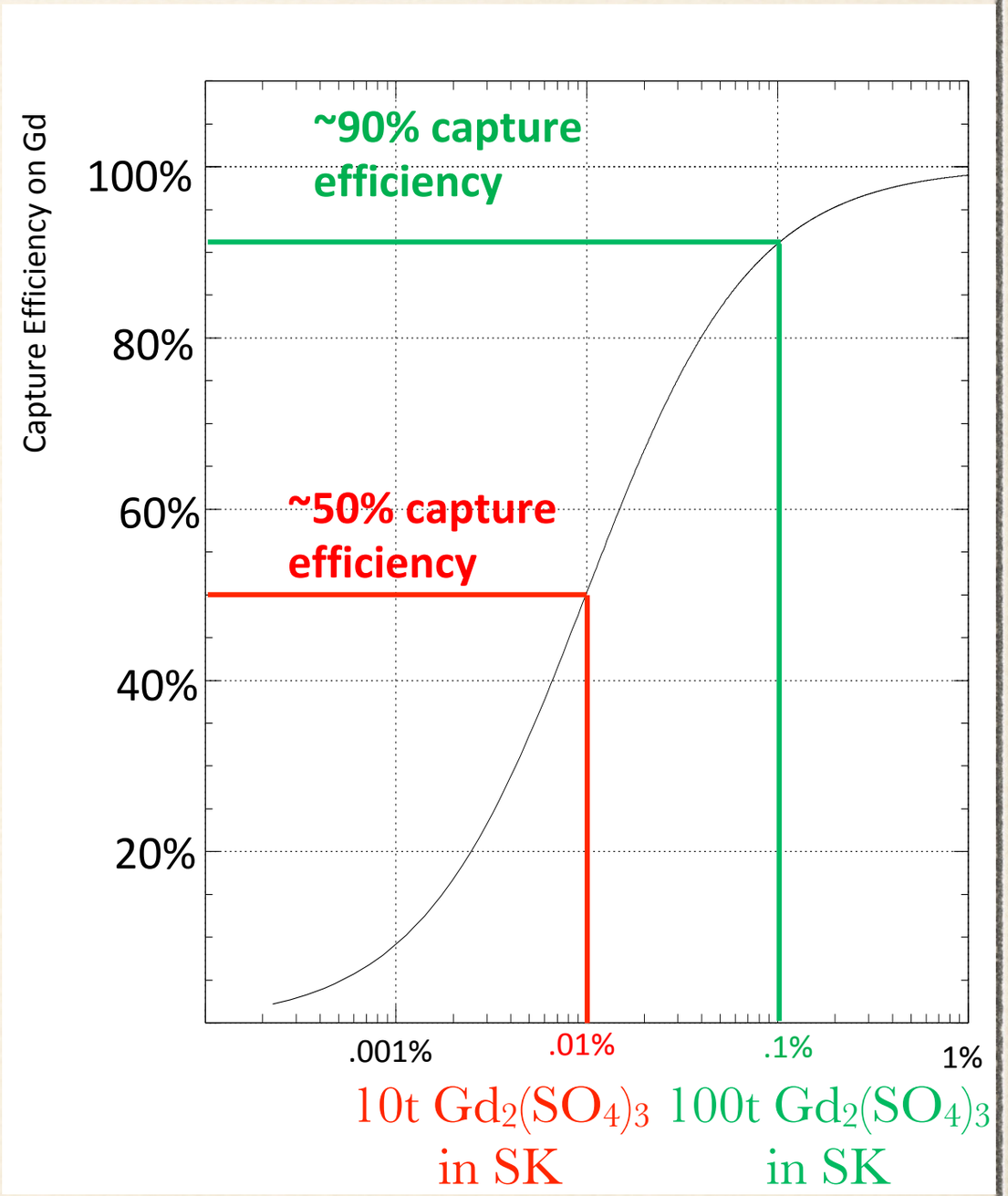


9.6% more events, 5.3% relative statistical error reduction

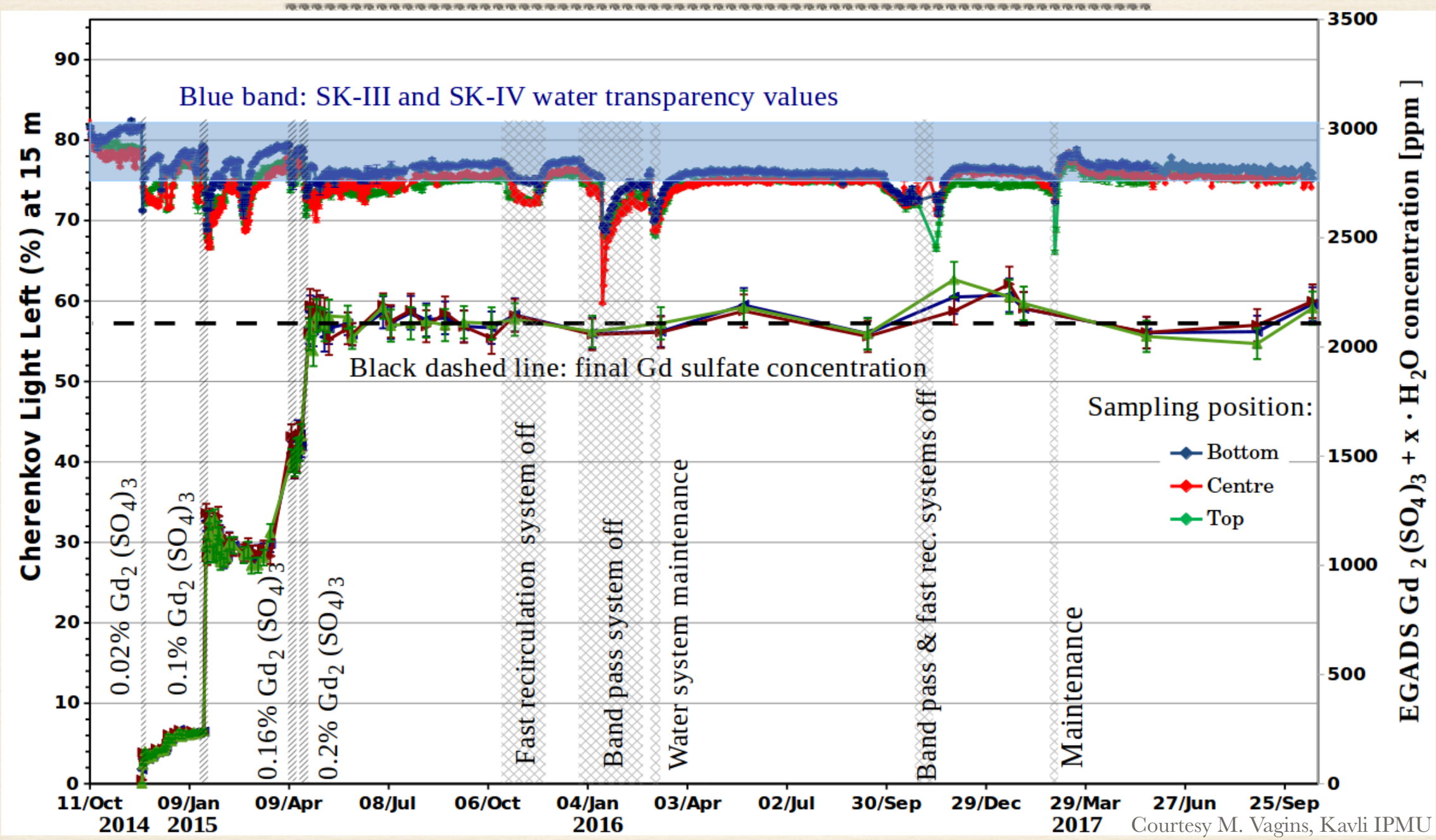
Personal analysis from my student Scott Locke

Hadronic Shower Neutron Tagging: Capturing on Gd

- next March we will dissolve 10t of $Gd_2(SO_4)_3$: ~50% Gd n captures with ~90% detection efficiency!
- capture time reduced to O(100 μsec); bigger overlap with 15 μsec PMT after pulse
- can tag showers with lower n multiplicity: possibility of larger fraction of spallation removal via n tag (less dead time)
- get better accuracy on shower shape and therefore spallation position



EGADS: Study Detector Effects and Water transparency in 200t Detector



Courtesy M. Vagins, Kavli IPMU

two and a half years 0.1% Gd loading: no Gd loss; EGADS water transparency is in the SK ultra-pure range during stable operation of water filtration

2018 SK Tank Work: Preparing to Dissolve $Gd_2(SO_4)_3$

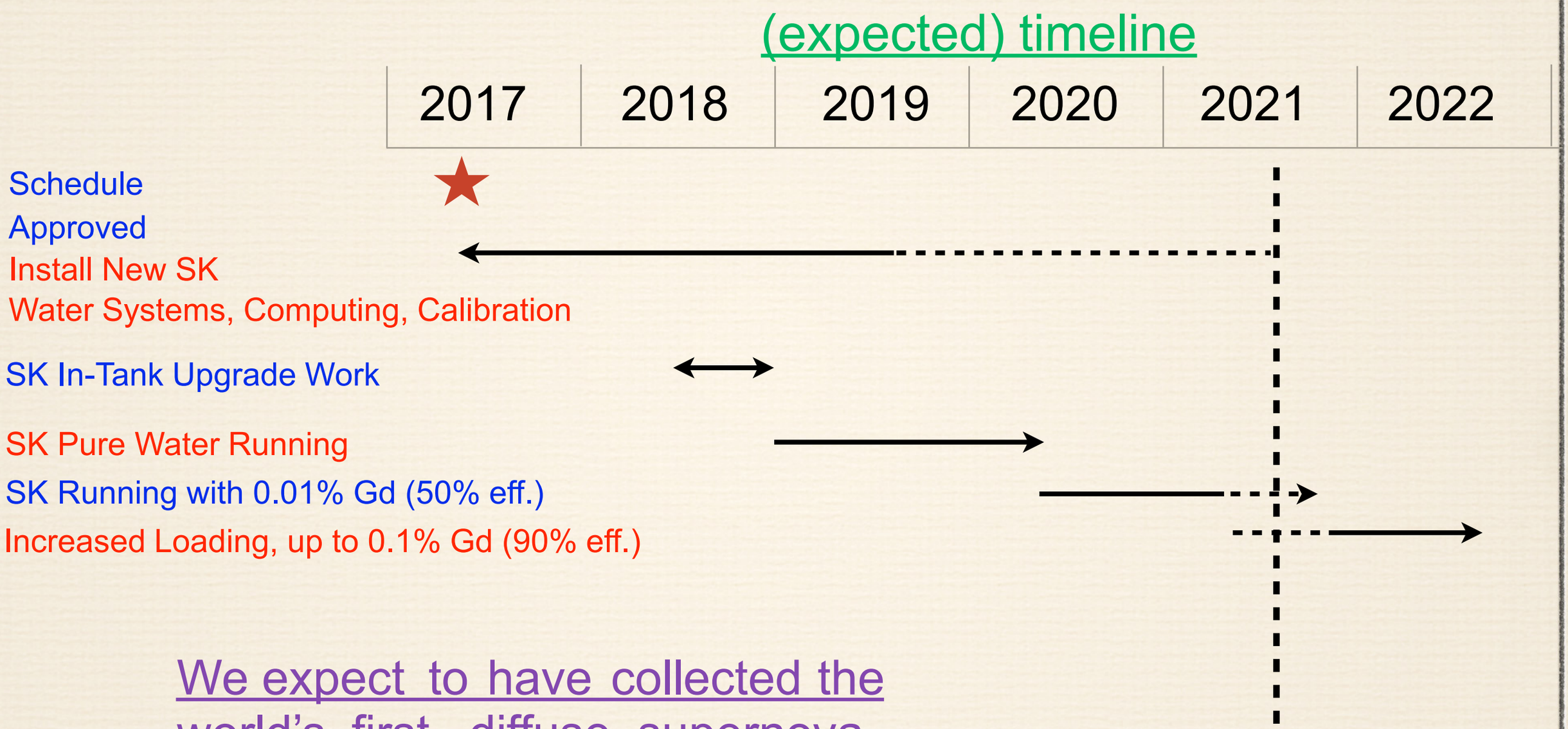
Impact of $Gd_2(SO_4)_3$ Addition on Radiopurity for Solar ν's

Goal [mBq/kg]	Instrument	Batch 1	Batch 2	Batch 3
^{238}U: <5	ICPMS	<0.02	0.02	0.04
	Ge	<9.45	<9.89	<28.4
^{232}Th: <0.05	ICPMS	0.04	0.02	0.04
	Ge	<0.20	<0.21	<0.16
^{226}Ra: <0.5	Ge	0.46±0.24	<0.33	<0.2

Courtesy M. Vagins, Kavli IPMU

- found a company capable of producing $Gd_2(SO_4)_3$ of sufficient purity
- tested with underground mass spectrometer and Ge detector
- purchase ~15 tons in 2019 for March 2020

SK-Gd Schedule



We expect to have collected the world's first diffuse supernova neutrino interactions before 2022!

Courtesy M. Vagins, Kavli IPMU

Summary

- Super-K has also a rich neutrino astrophysics program
- next March we will move to a new era: taking advantage of enhanced neutron detection capabilities from the addition of $Gd_2(SO_4)_3$ to Super-K's water
- our goal is the discovery of neutrino interactions from the combined neutrino emissions of all SN within a redshift of about one
- also expect improvements for the solar neutrino physics program
- many other physics benefits, e.g. reactor neutrino detection, solar antineutrino search, atmospheric neutrino physics, proton decay, long baseline accelerator neutrino program, …