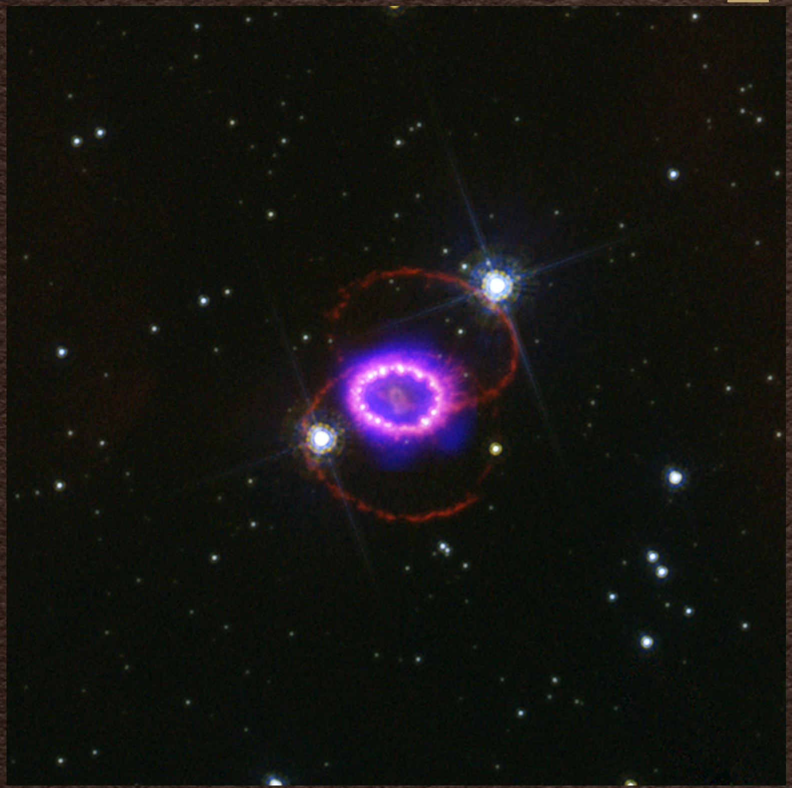
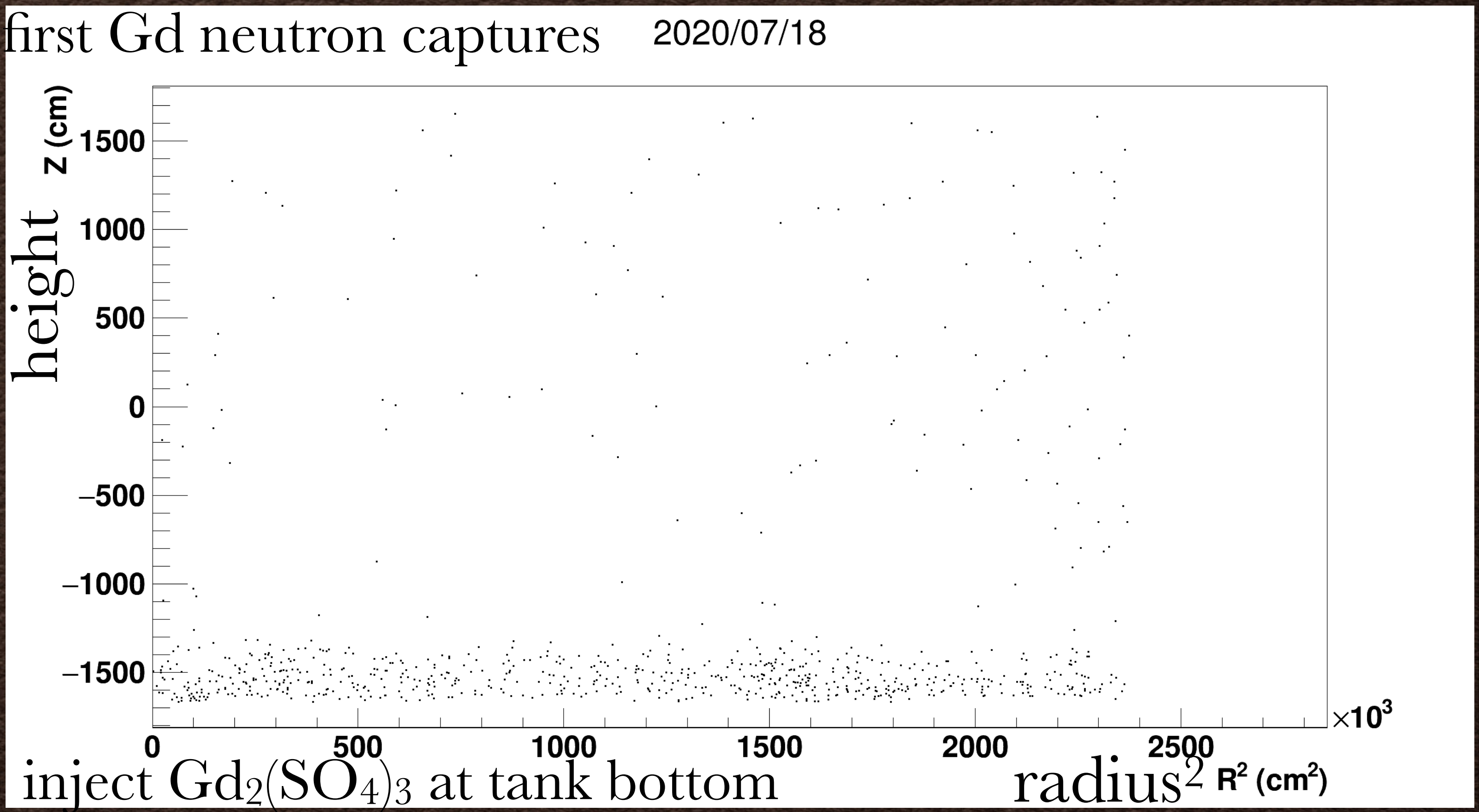
First Results from Gd Running in Super-Kamiokande



Michael Smy, UC Irvine
14th Conference on the Intersections of Particle and Nuclear Physics
September 1st 2022



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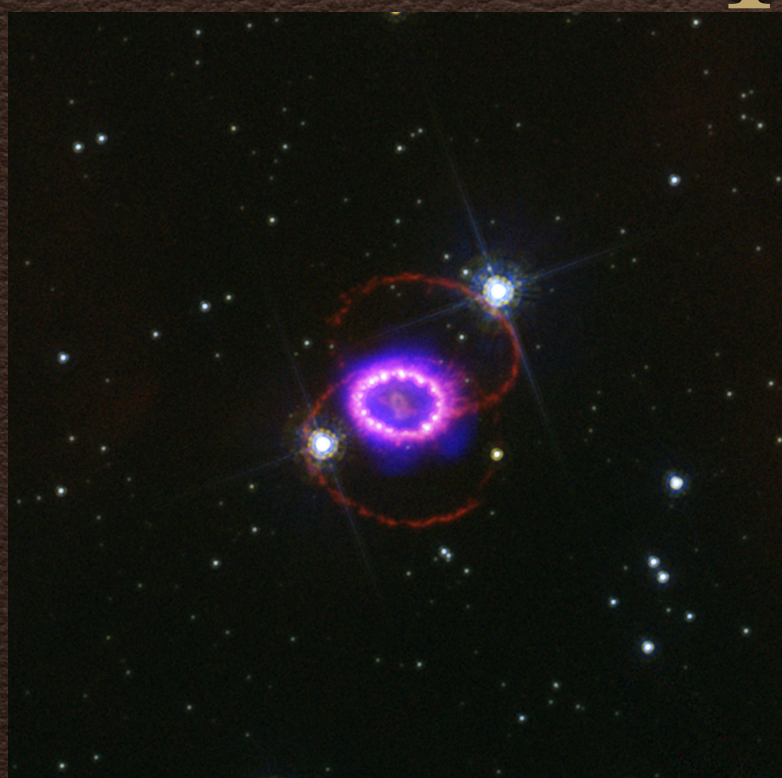

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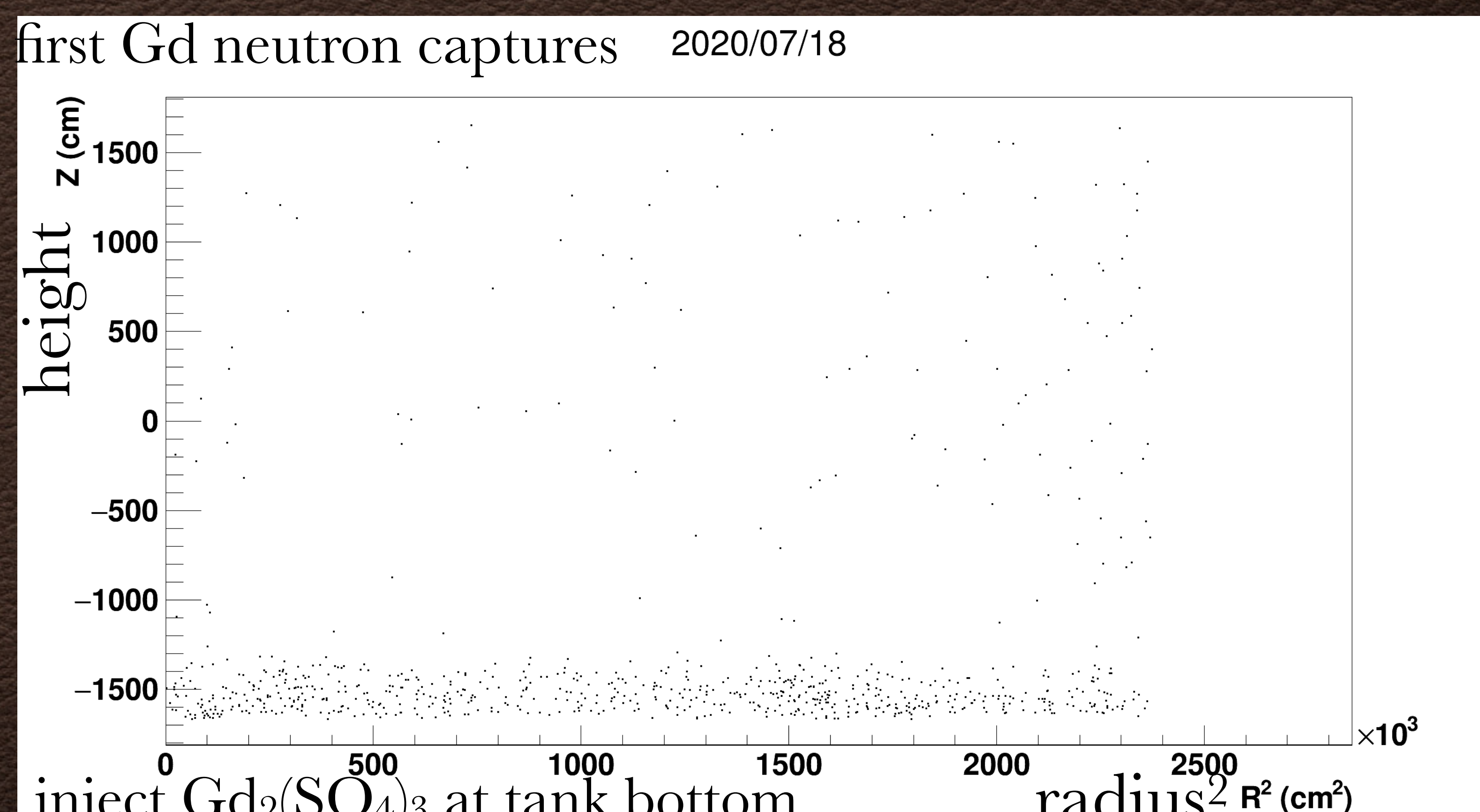
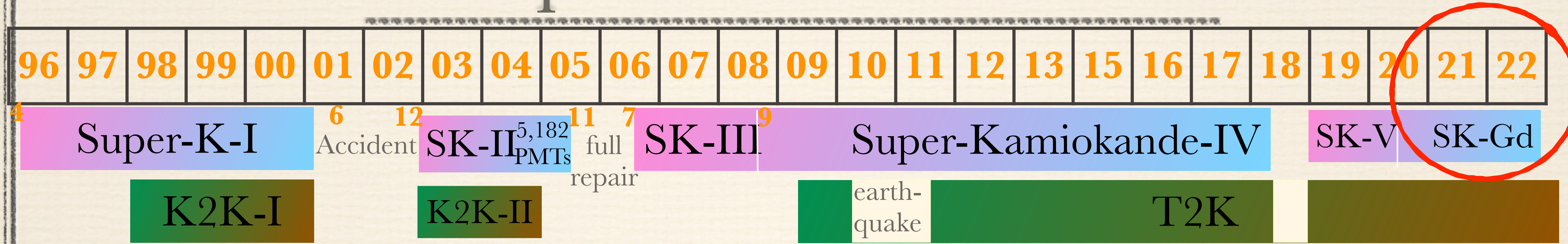
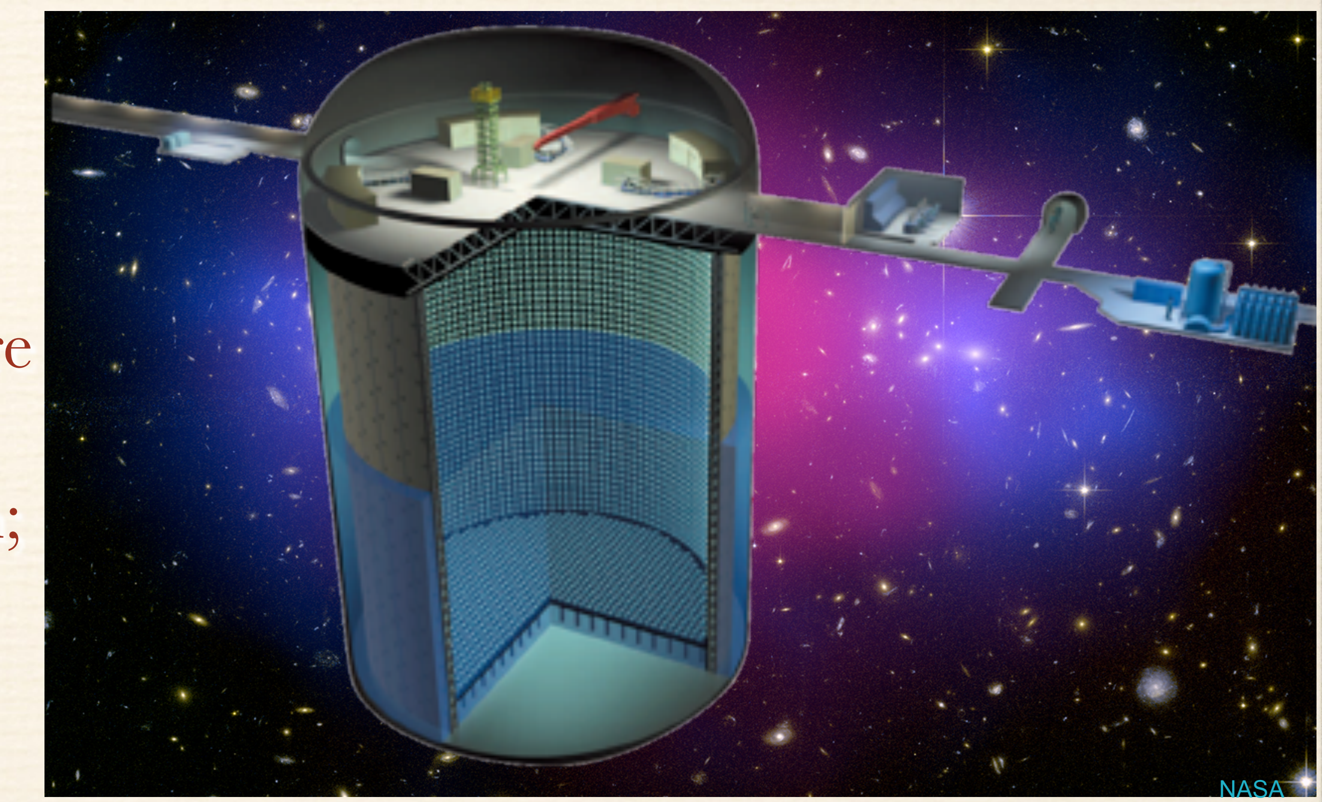


26 Years of Neutrino- and Astrophysics with Super-Kamiokande!



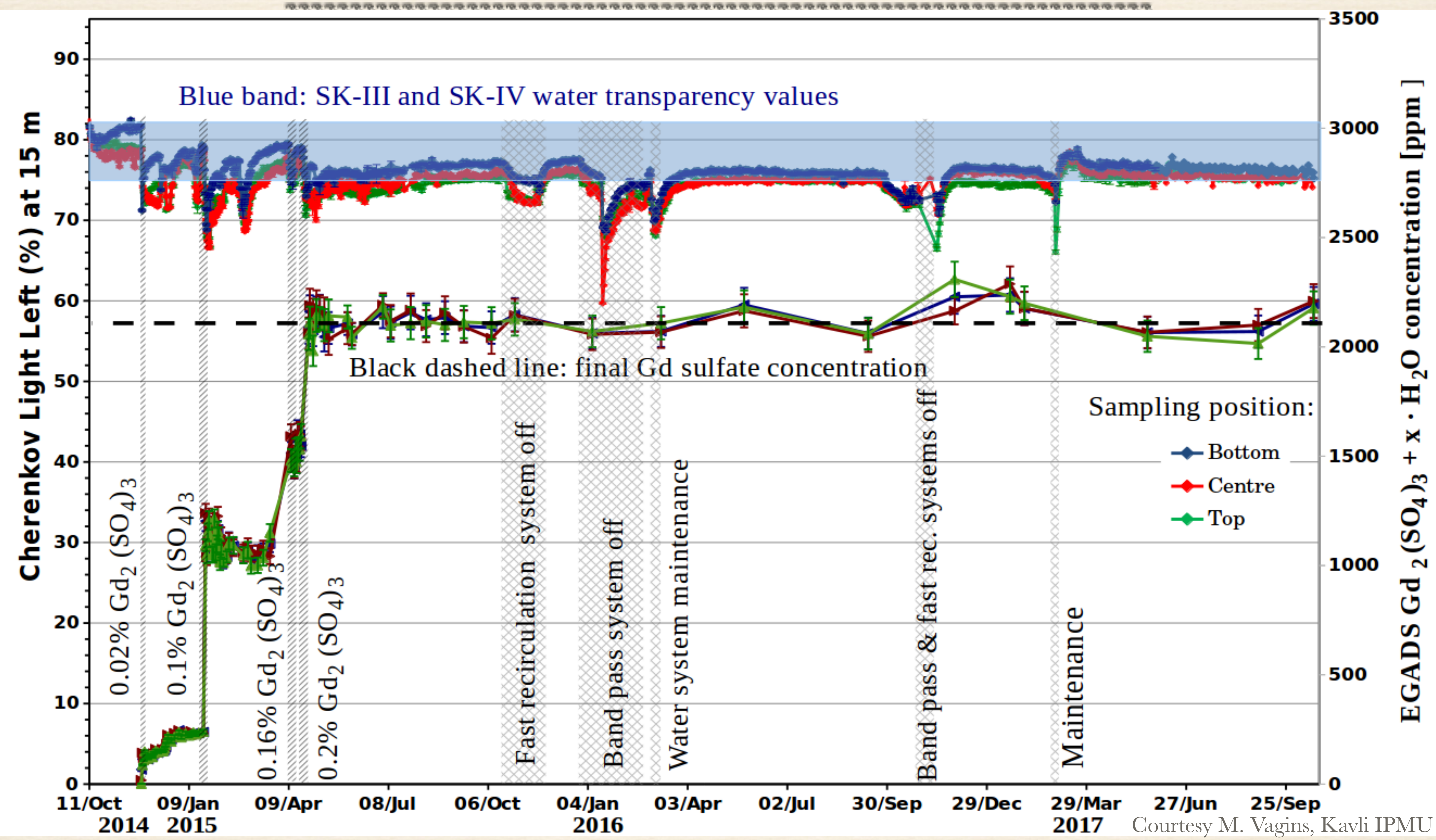
- 1998: discovery of atmospheric neutrino flavor transformation and neutrino mass
- 2000: solar mixing angle is large
- 2001: discovery of solar neutrino flavor transformation with SNO; uniquely measure oscillation parameters (with all solar data)
- 2004: discovery of atmospheric ν oscillation; confirmation 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

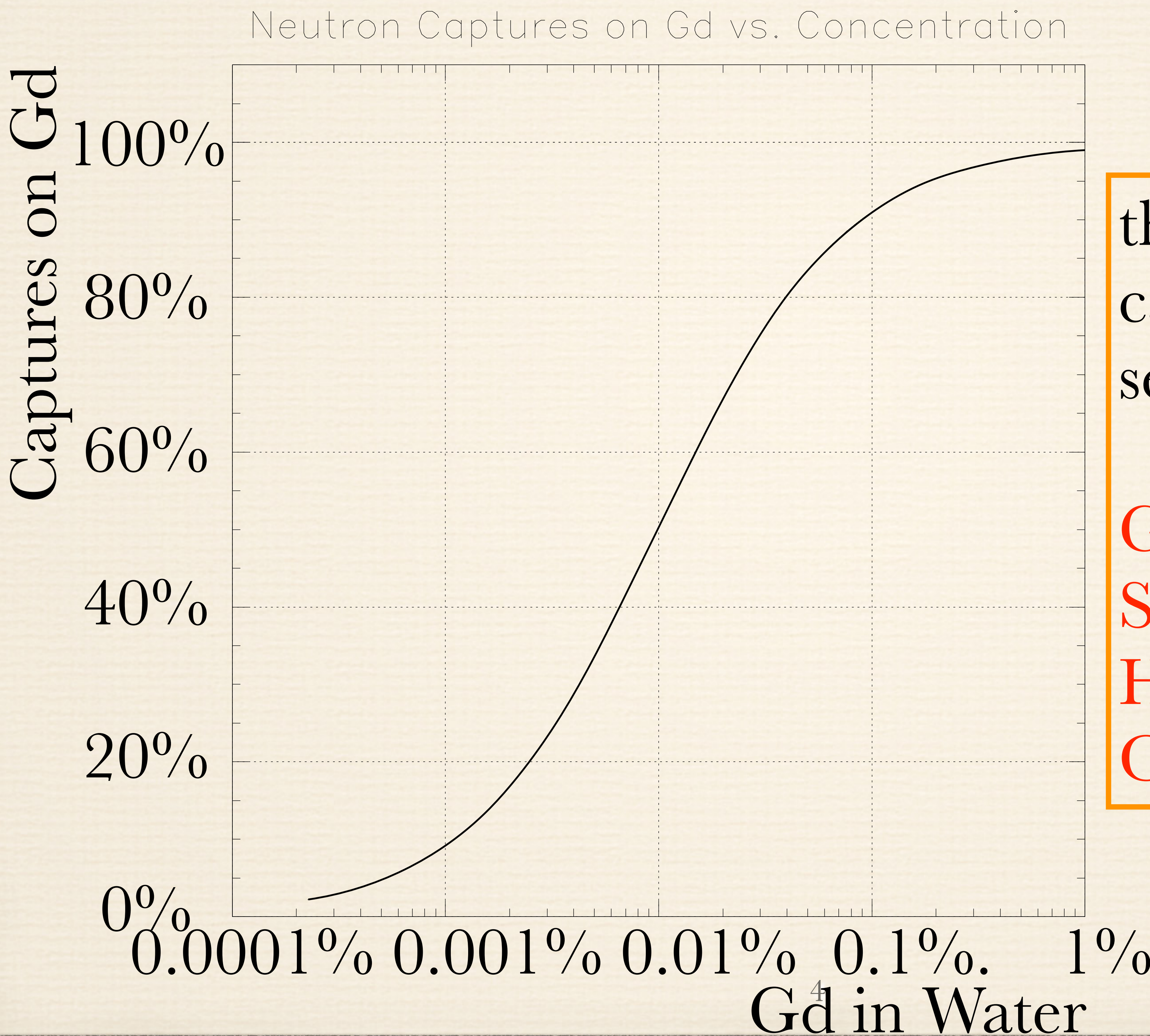
layout by Y. Suzuki, ICRR (Michael Smy, UC Irvine)

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



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

Gadolinium Loading of Super-Kamiokande

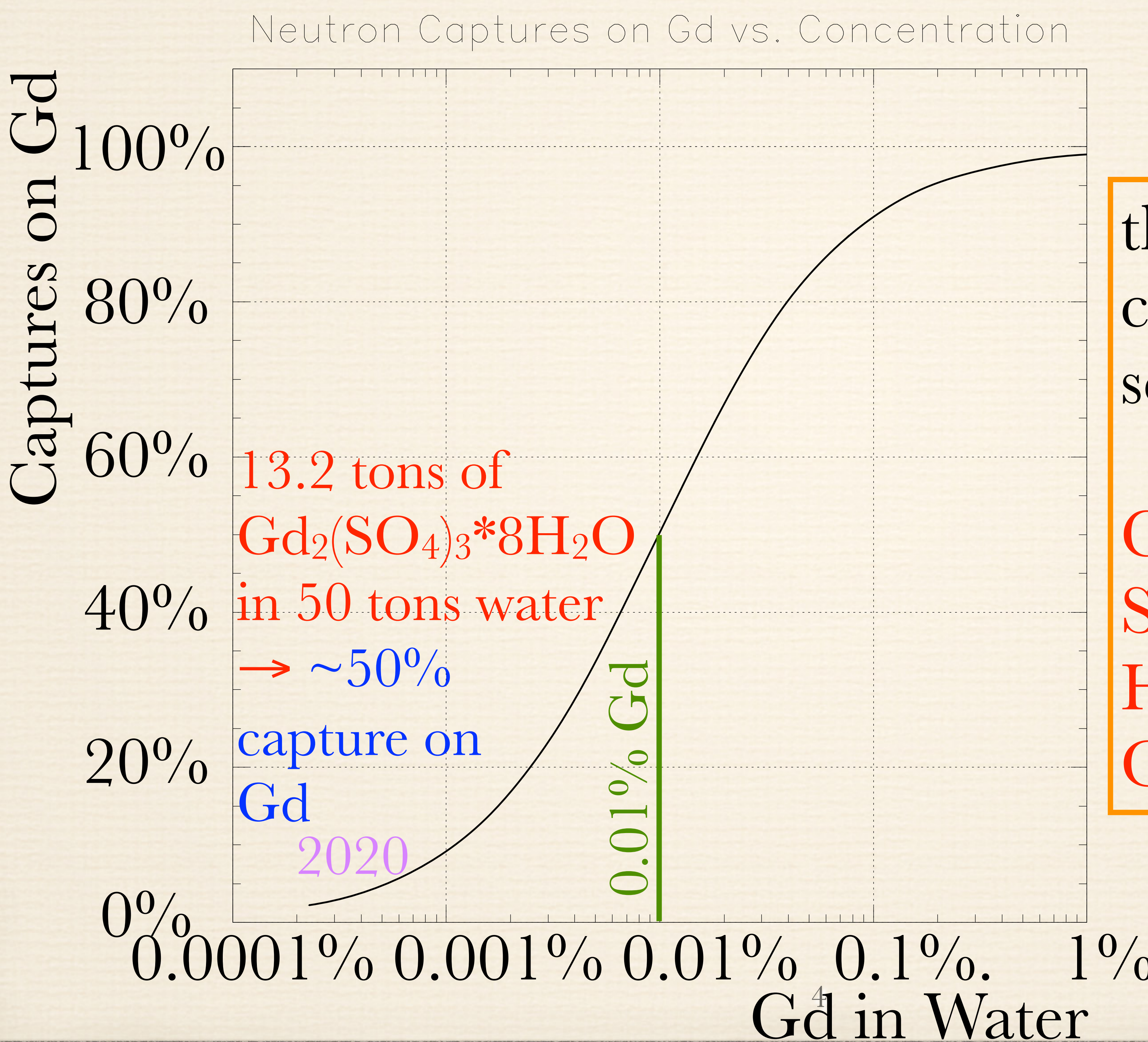


thermal neutron capture cross section

Gd = 49,700 barns
S = 0.53 barns
H = 0.33 barns
O = 0.0002 barns

Courtesy M. Vagins, Kavli IPMU

Gadolinium Loading of Super-Kamiokande



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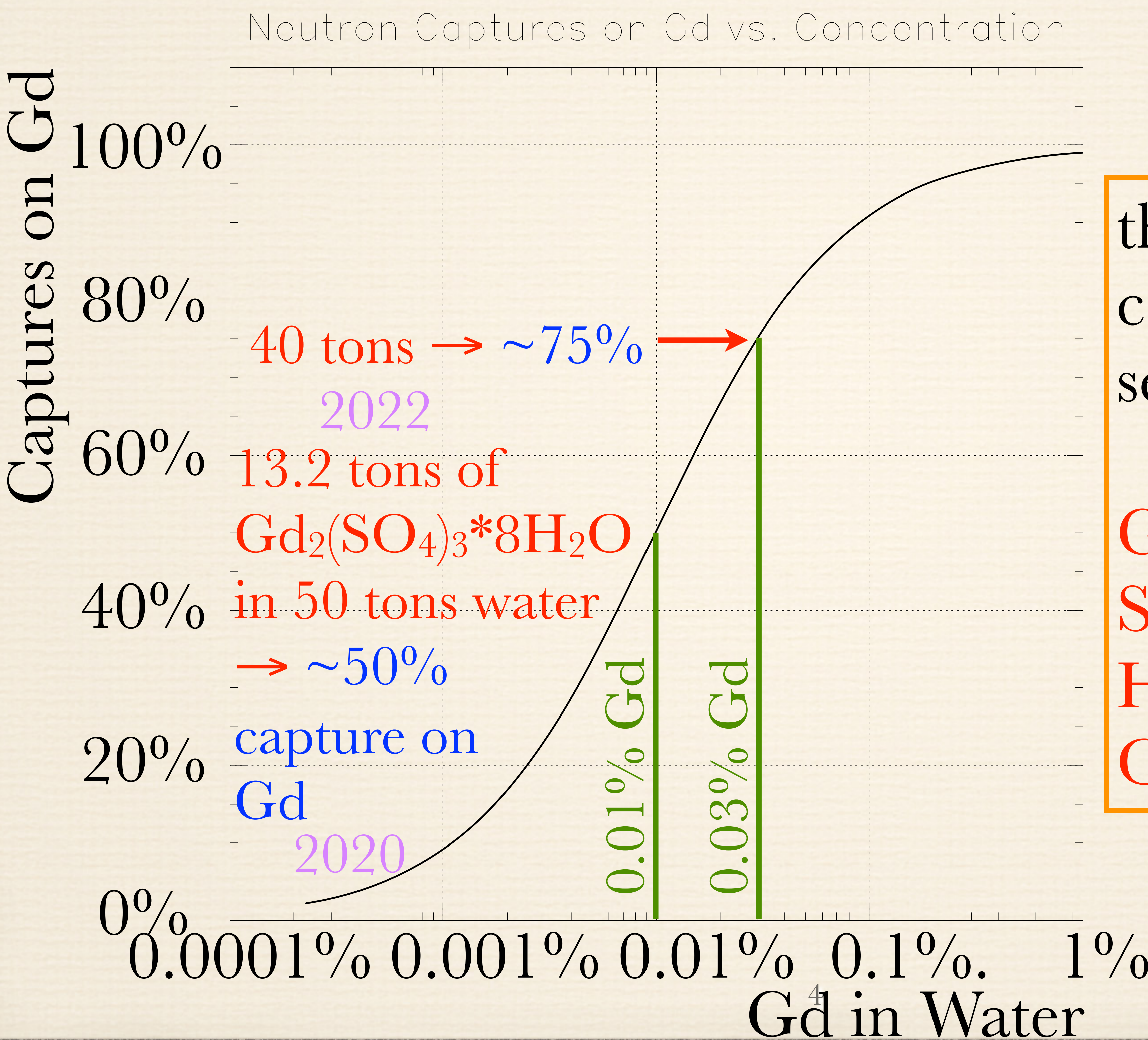

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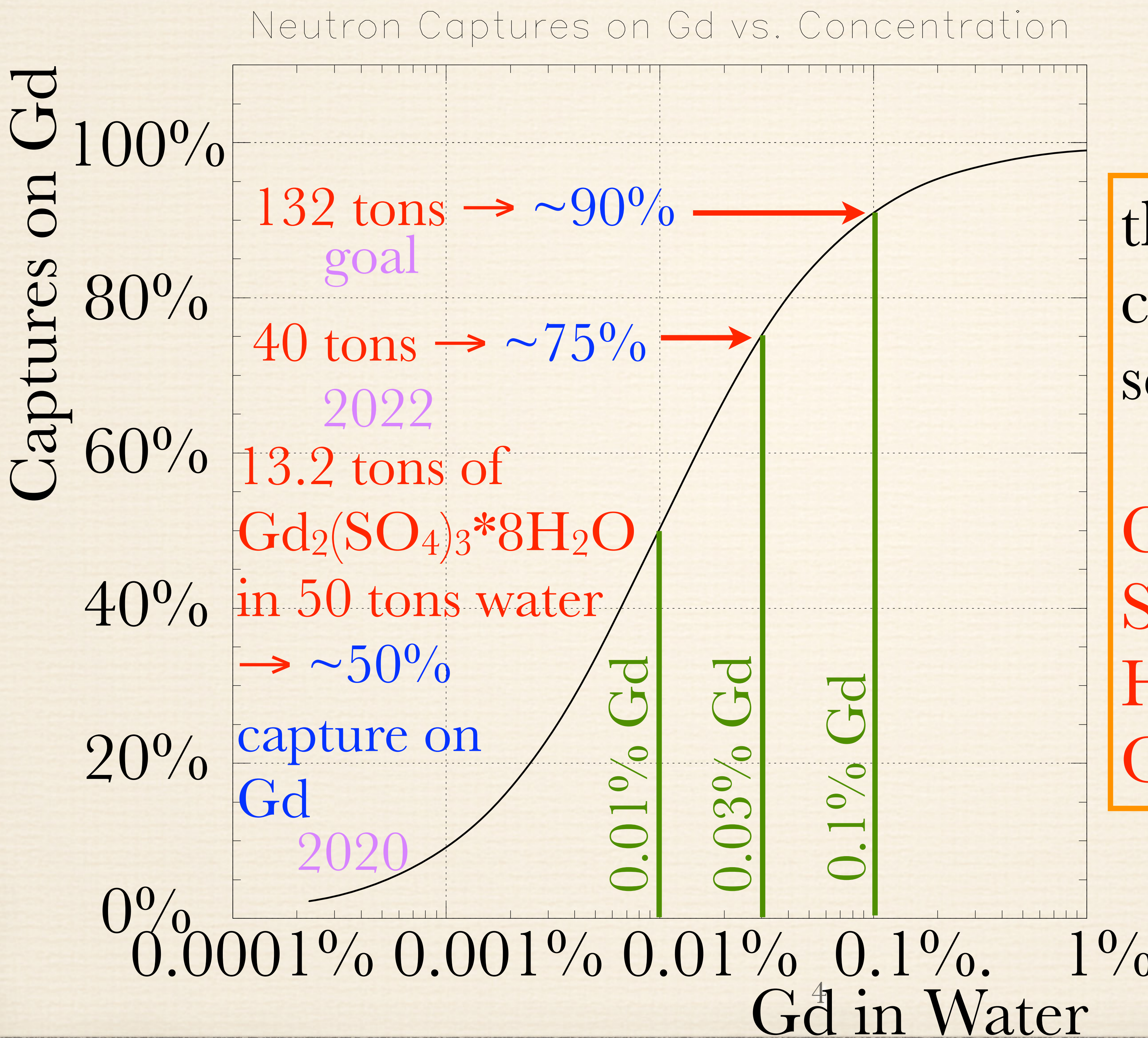

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Gd = 49,700 barns
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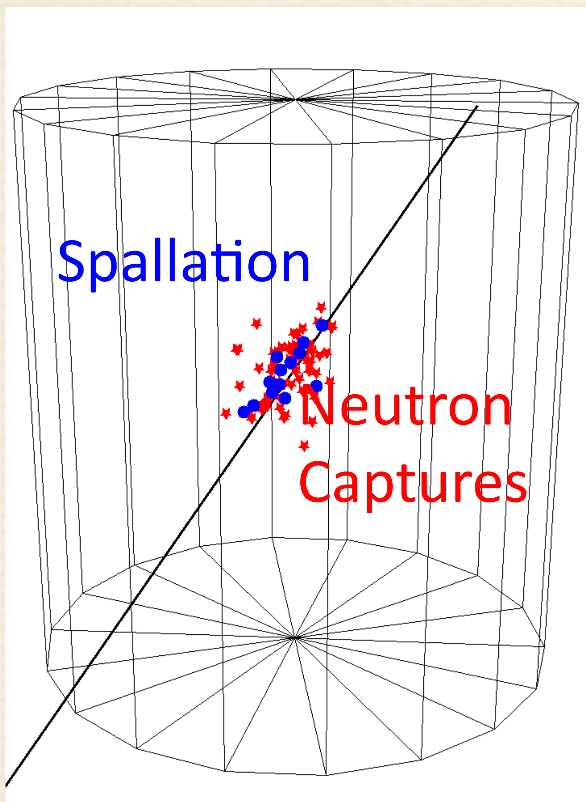
Courtesy M. Vagins, Kavli IPMU

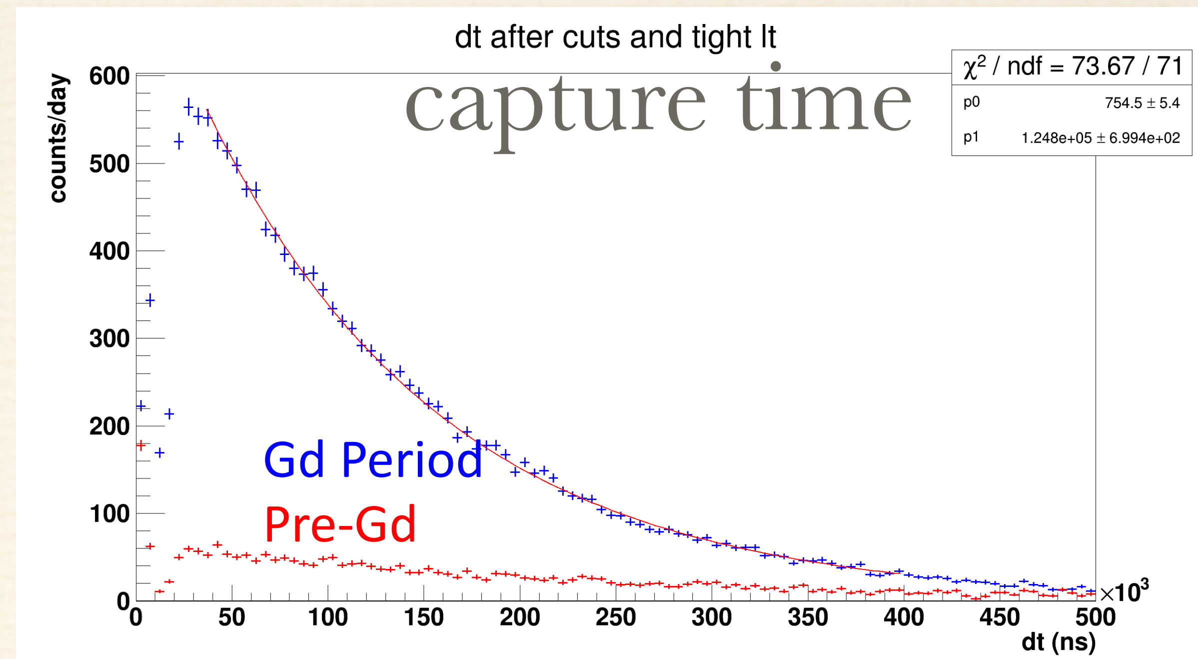
July 2020: First Gd Neutron Signal

Super-K injecting $Gd_2(SO_4)_3$ to reach 0.011% Gd concentration

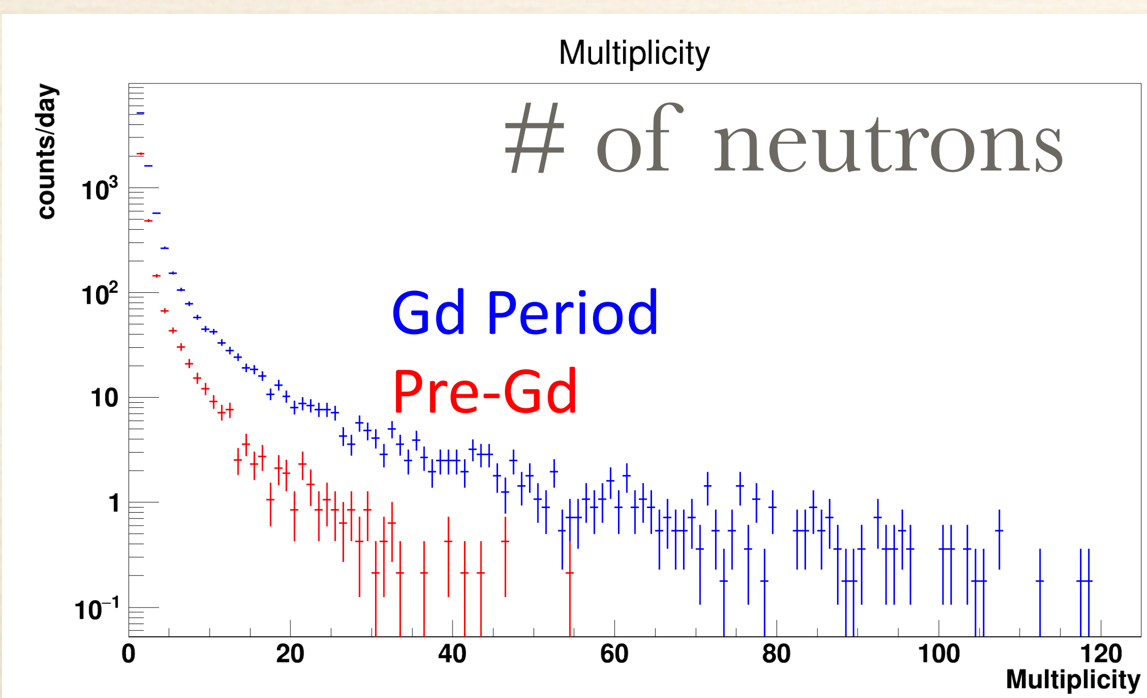


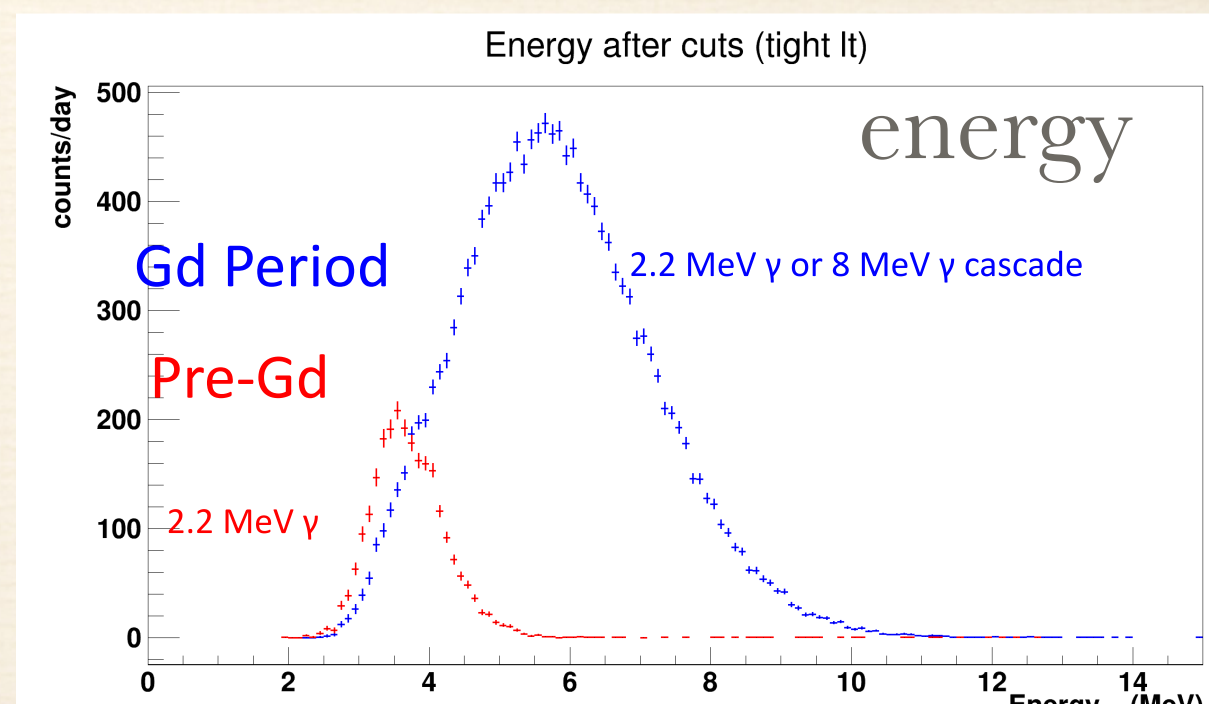
use neutrons generated by showering muons to compare Gd with H captures

showers containing neutrons produce radioactive nuclei (spallation); important bkgd for MeV physics



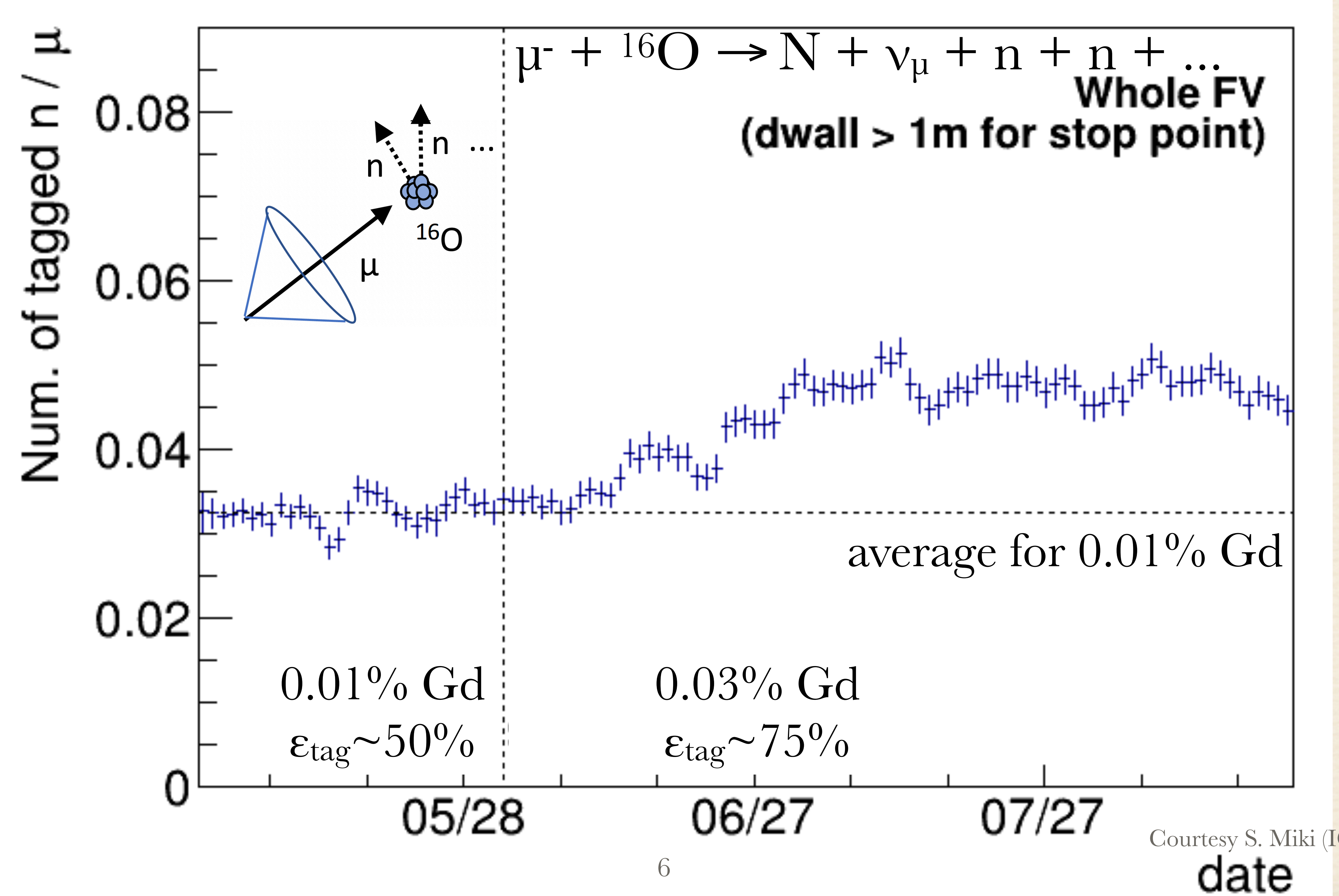
Courtesy S. Locke, UCI





Courtesy S. Locke, UC Irvine

June 2022: Increase Gd Concentration to 0.03%



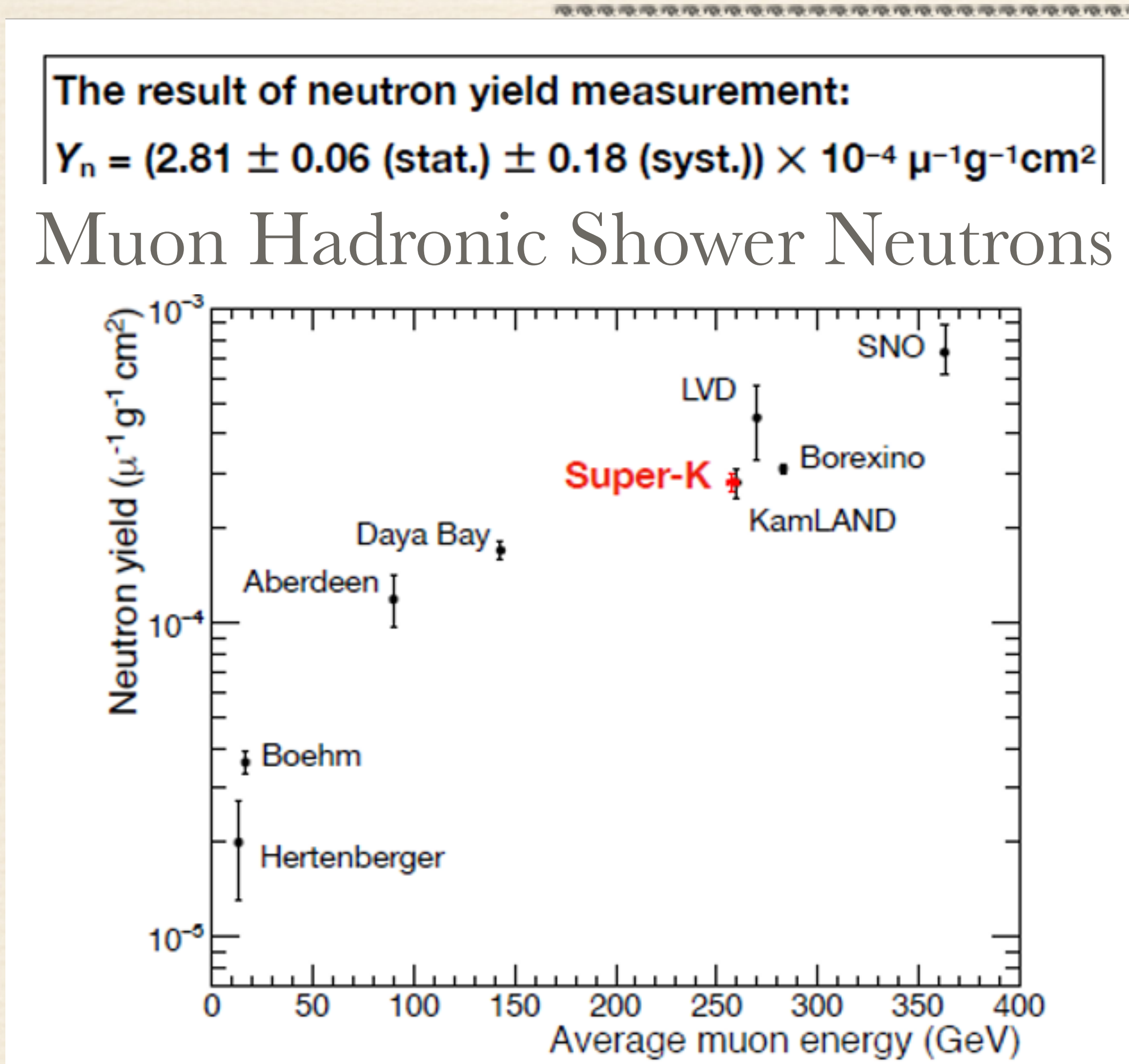
Courtesy S. Miki (ICRR)

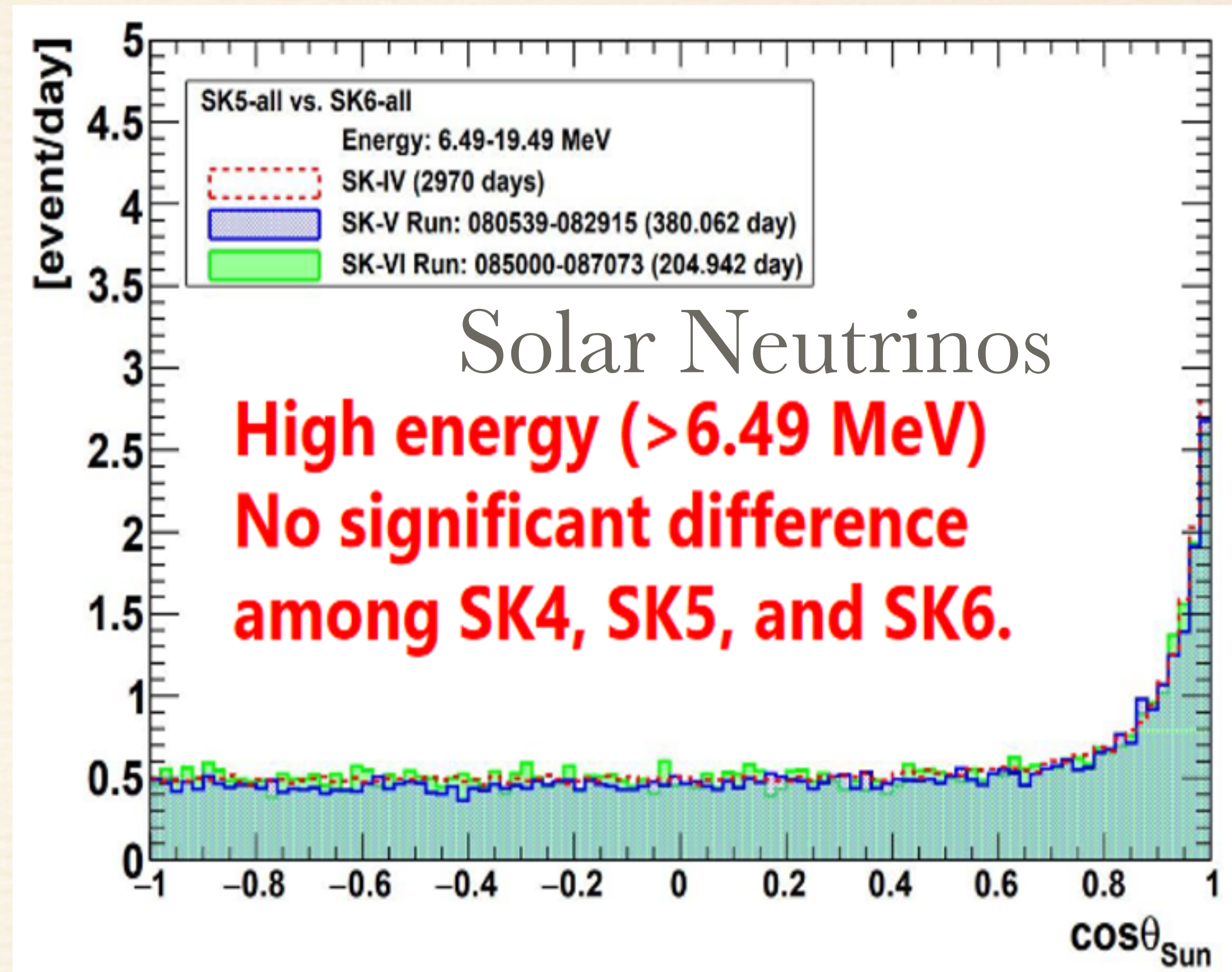
June 2022: Adding 26 more tons of $Gd_2(SO_4)_3*8H_2O$ to Super-K

- largest (ultra radio-pure) Gd order ever!
- preparing a paper…

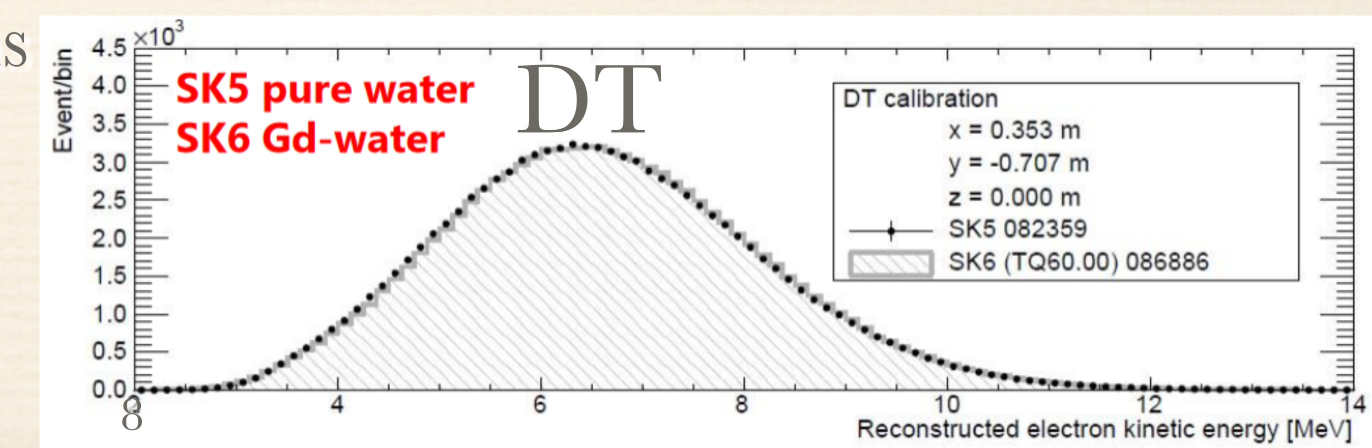
Courtesy M. Vagins, Kavli IPMU

Two years of 0.01%Gd Operation



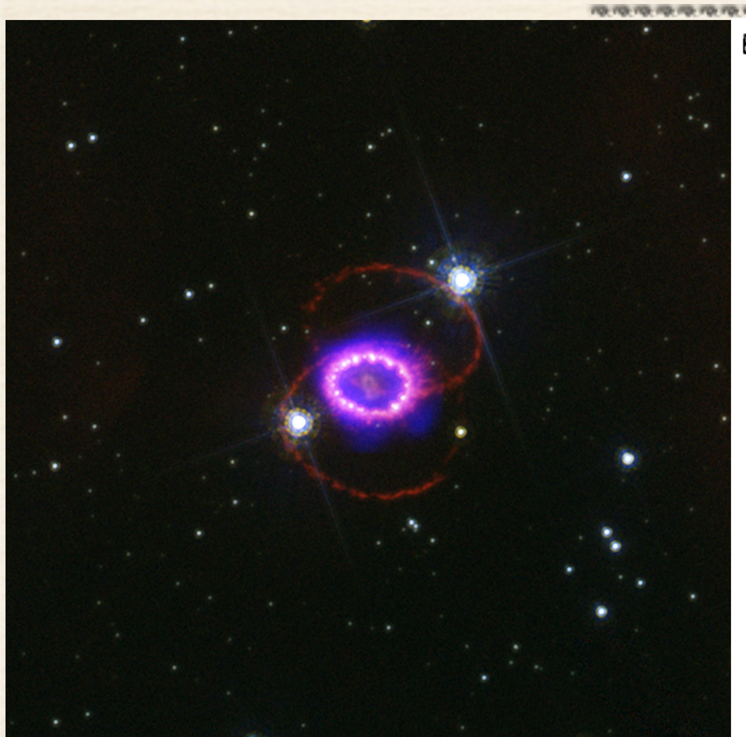


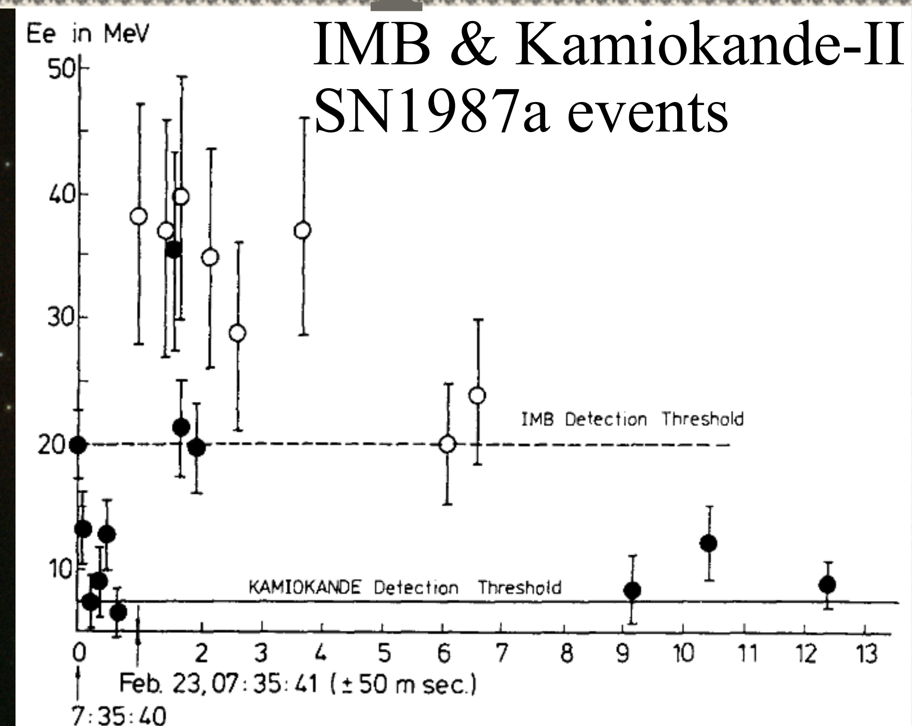
- measured neutron yield of muons
- still see solar neutrinos
- well-calibrated energy scale with DT neutron generator



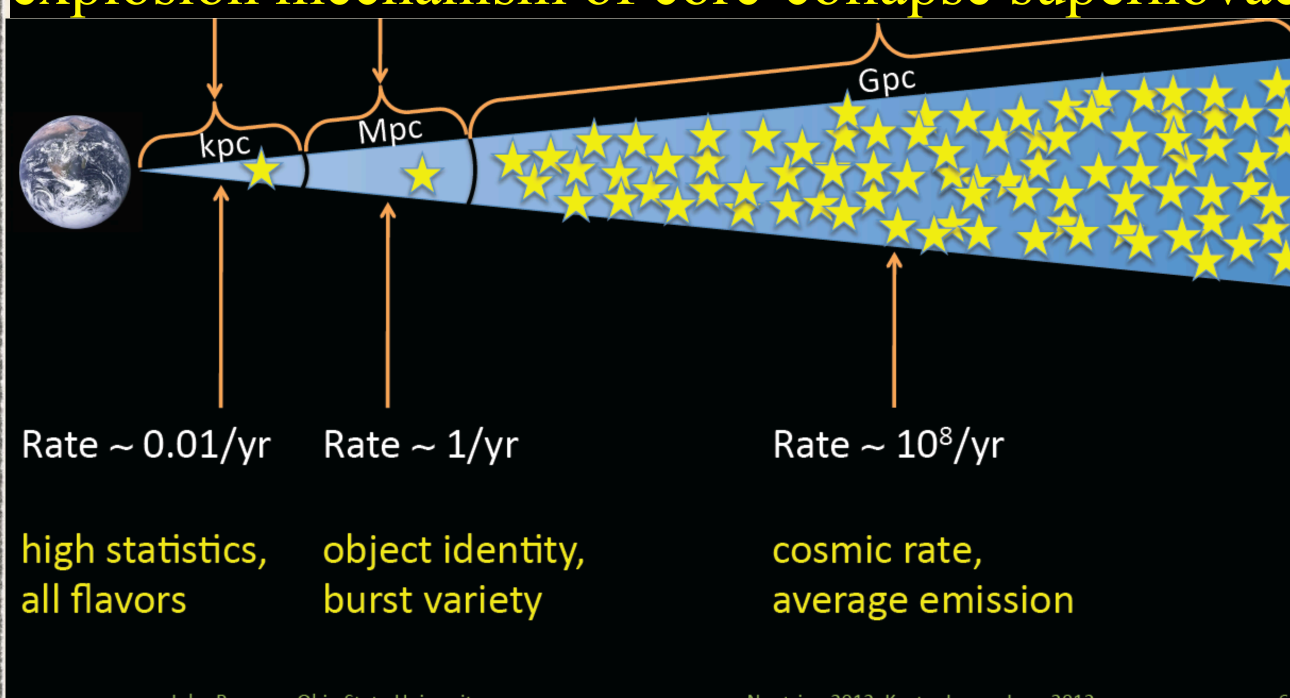
Courtesy M. Vagins, Kavli IPMU

Neutrinos from Core-Collapse Supernova





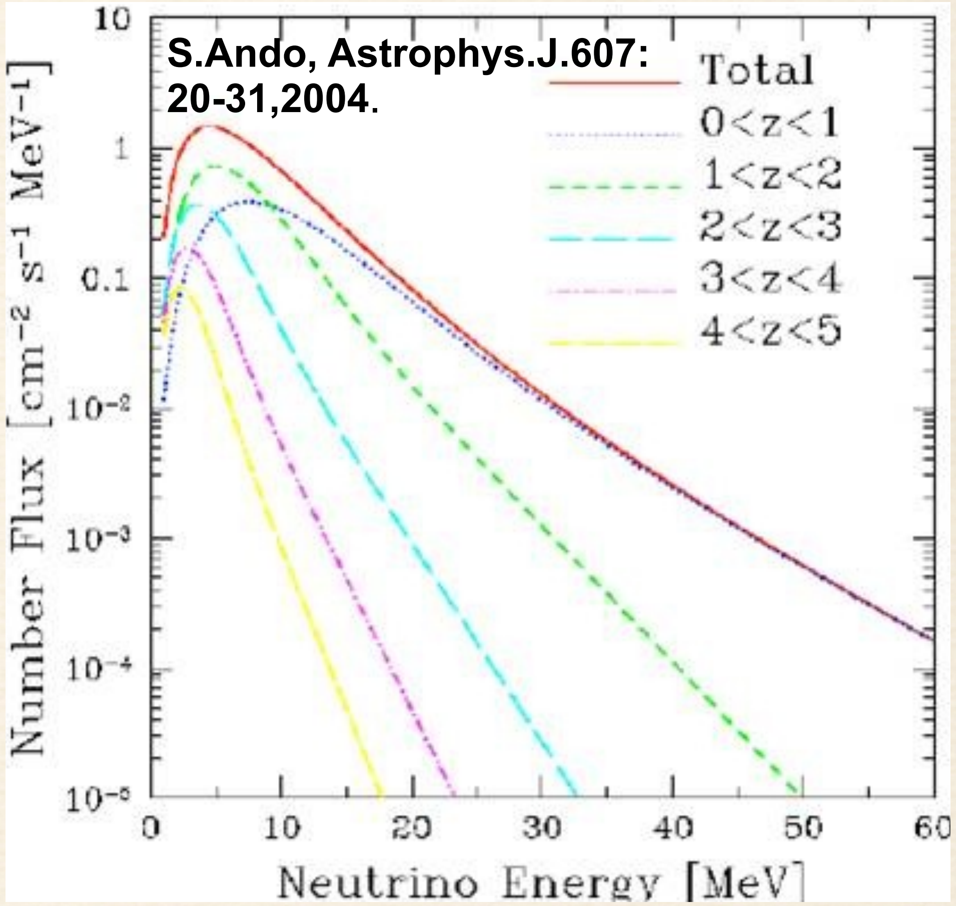
These few events confirmed the basic picture about the explosion mechanism of core-collapse supernovae



- iron core build-up at the end of stellar fusion
- collapse of that core once electron degeneracy pressure is overcome via neutronization
- explosion releasing $\sim 10^{53}$erg in 10s (>99% ν's): or ~1sextillion YW
- $\sim 10^4$ events in Super-K at galactic center
- ~2-3/galaxy/century!
- mini-bursts? (~ only 1 event at Andromeda)
- diffuse, distant supernova ν flux

Search for Distant Supernova Neutrinos

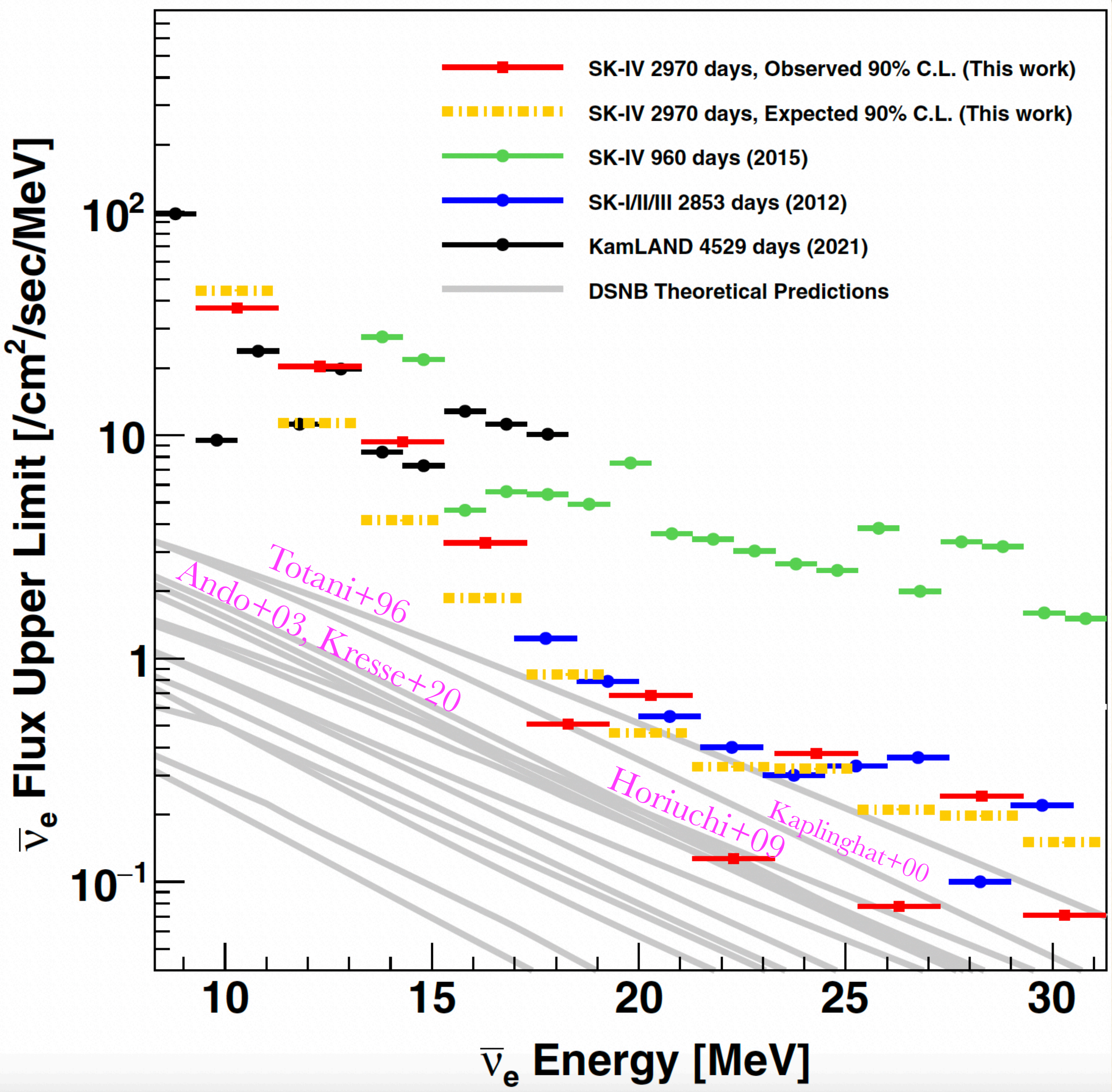
- "distant": farther than Andromeda (M31, NGC224), $z \lesssim 1$ (to be above reactor spectrum) with $\ll 1$ exp. interactions
- constant, diffuse (isotropic positrons from IBD), and low (~few/year) signal rate between 10 and 30 MeV



- delayed coincidence of neutron capture is import handle to distinguish from radioactive and neutrino backgrounds
- flux=cosmic star formation history ⊗ initial mass function ⊗ supernova fraction ⊗ neutrinos/supernova

Michael Smy, UC Irvine

Spectrum-Independent Search for Distant Supernova Neutrinos

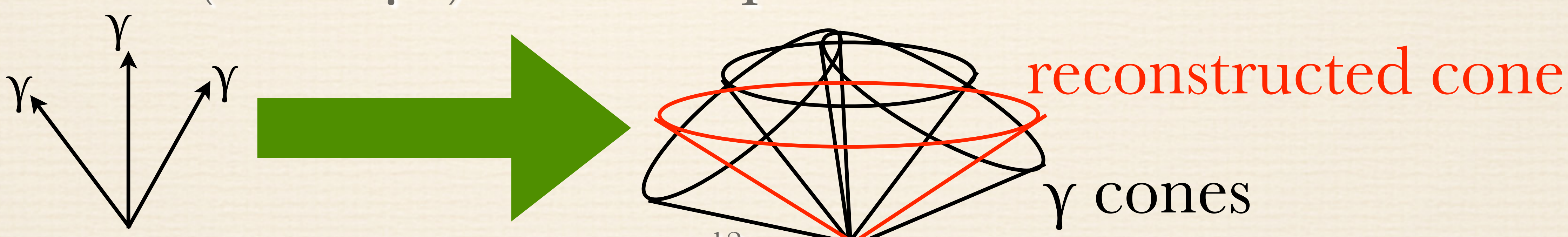


PRD **104**, 122002 (2021)

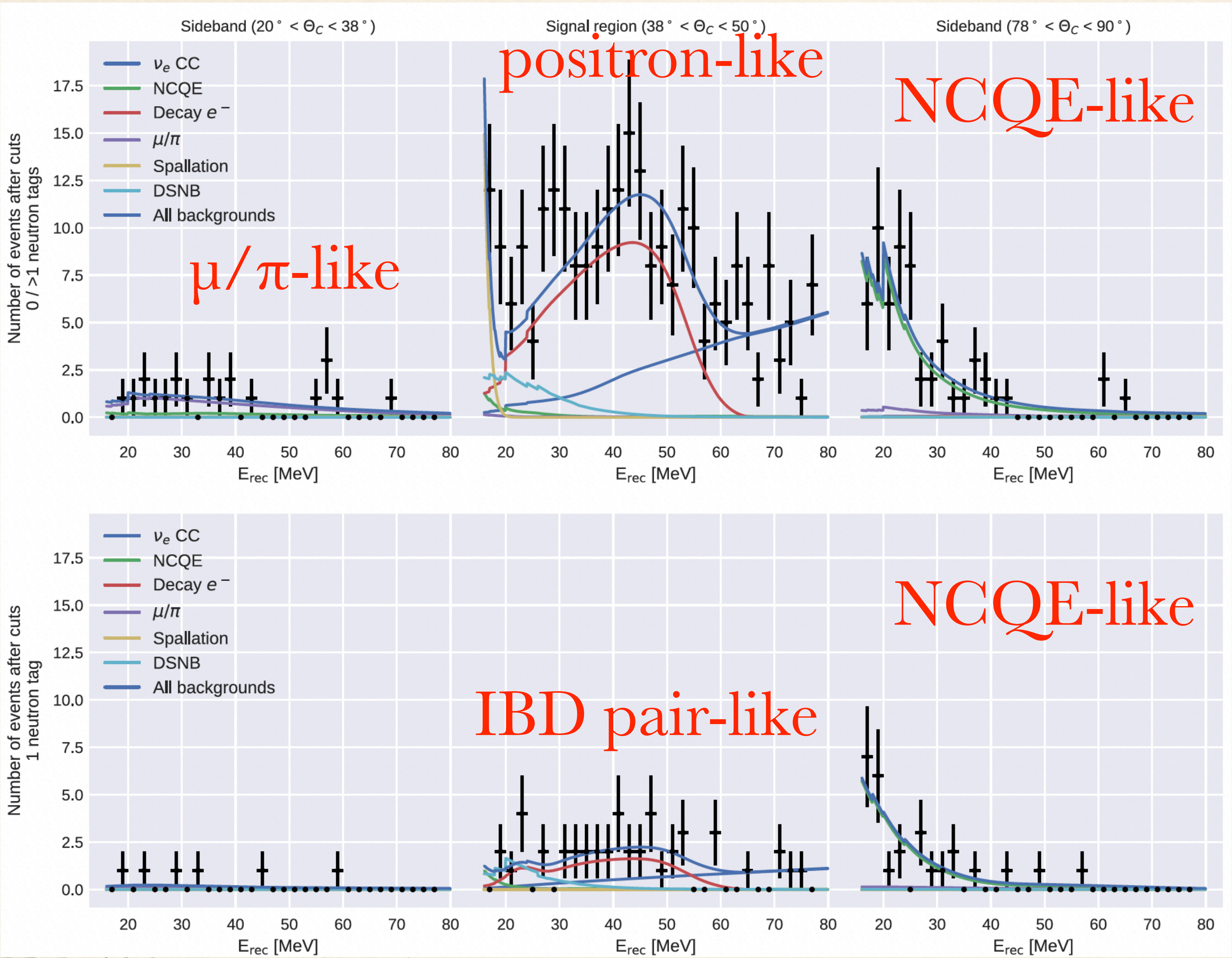
- SK-I/II/III limits based on positron signal only (uses background spectrum model)
- SK-IV limits with 2.2 MeV γ n tag is similar due to low n tagging efficiency
- KamLAND search is less sensitive due to smaller detector size

Signal and Sidebands in SK-IV w/o Gd

- one and only one 2.2 MeV γ candidate, ε_{tag}=O(0.1)
- reconstruct Cherenkov angle:
  - signal region: a positron Cherenkov cone opening angle reconstructs as 38^0-50^0
  - low energy muons/pions: smaller opening angle
  - large angles: overlay of multiple Cherenkov cones (from γ's) in atmospheric ν NC interactions



Distant Supernova Search without Gd



- O(10%) efficiency to tag IBD with 2.2 MeV γ
- fit spectra for singles and pairs for three regions of Cherenkov angle

PRD **104**, 122002 (2021)

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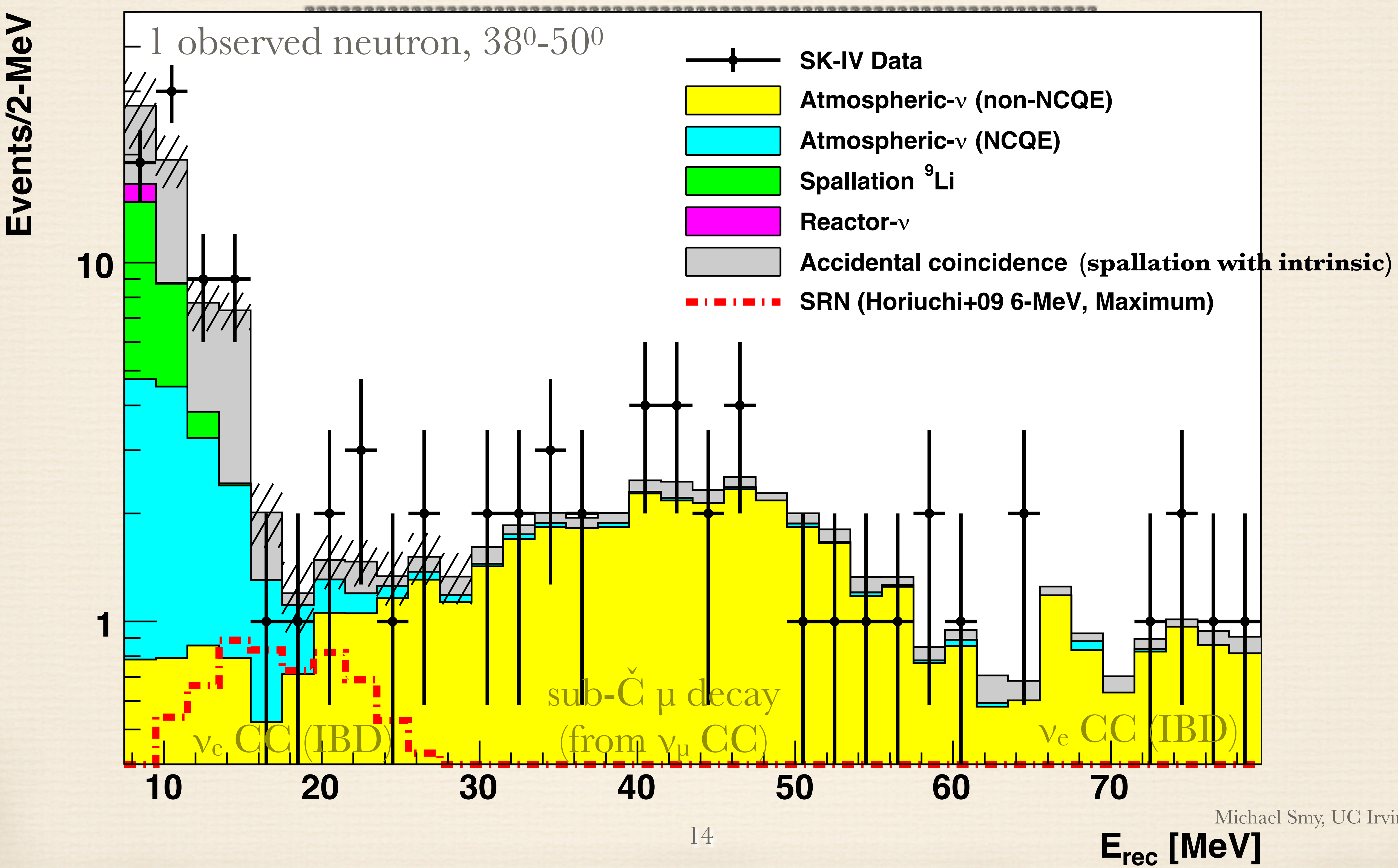
SK-IV Data, Signal and Background



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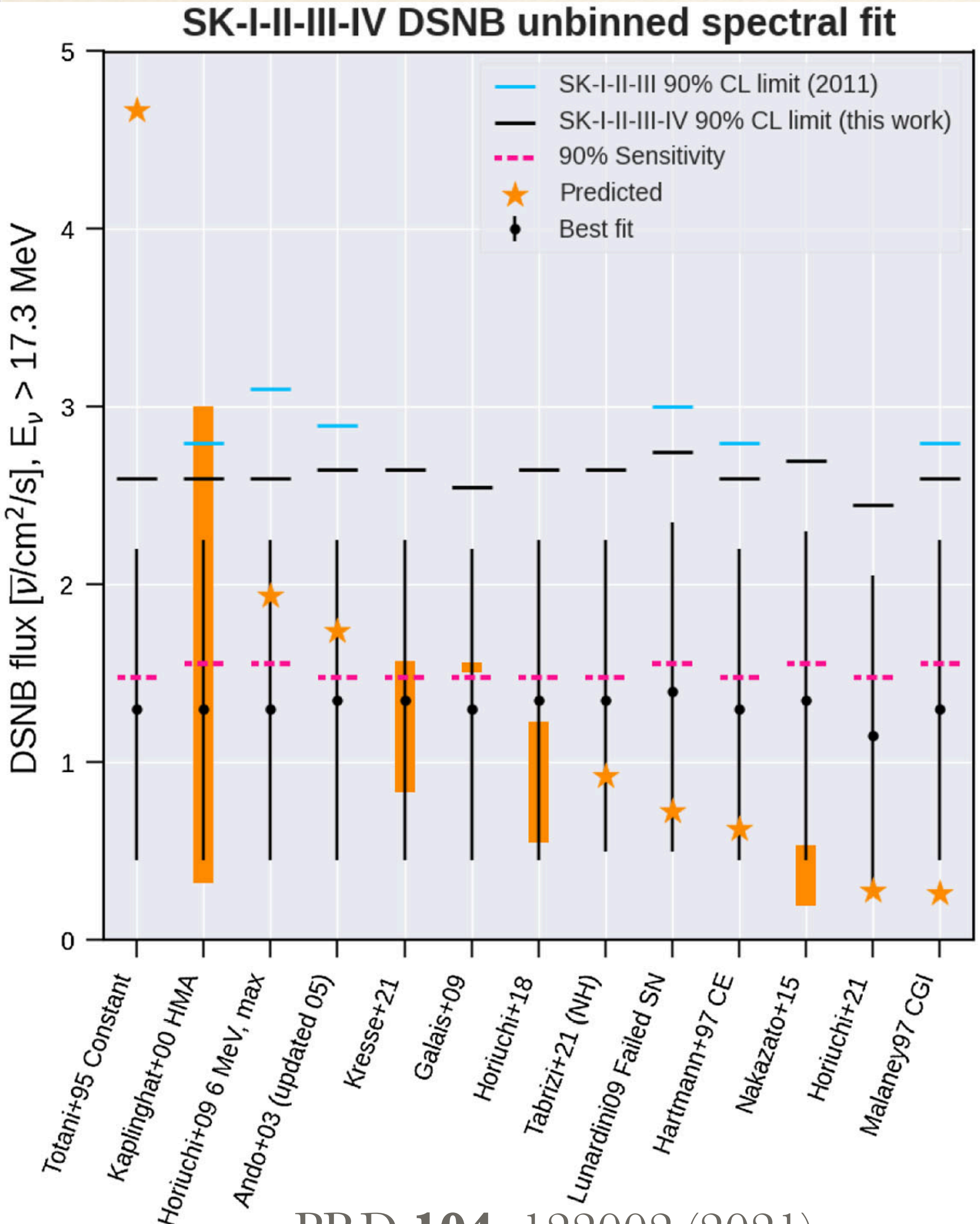

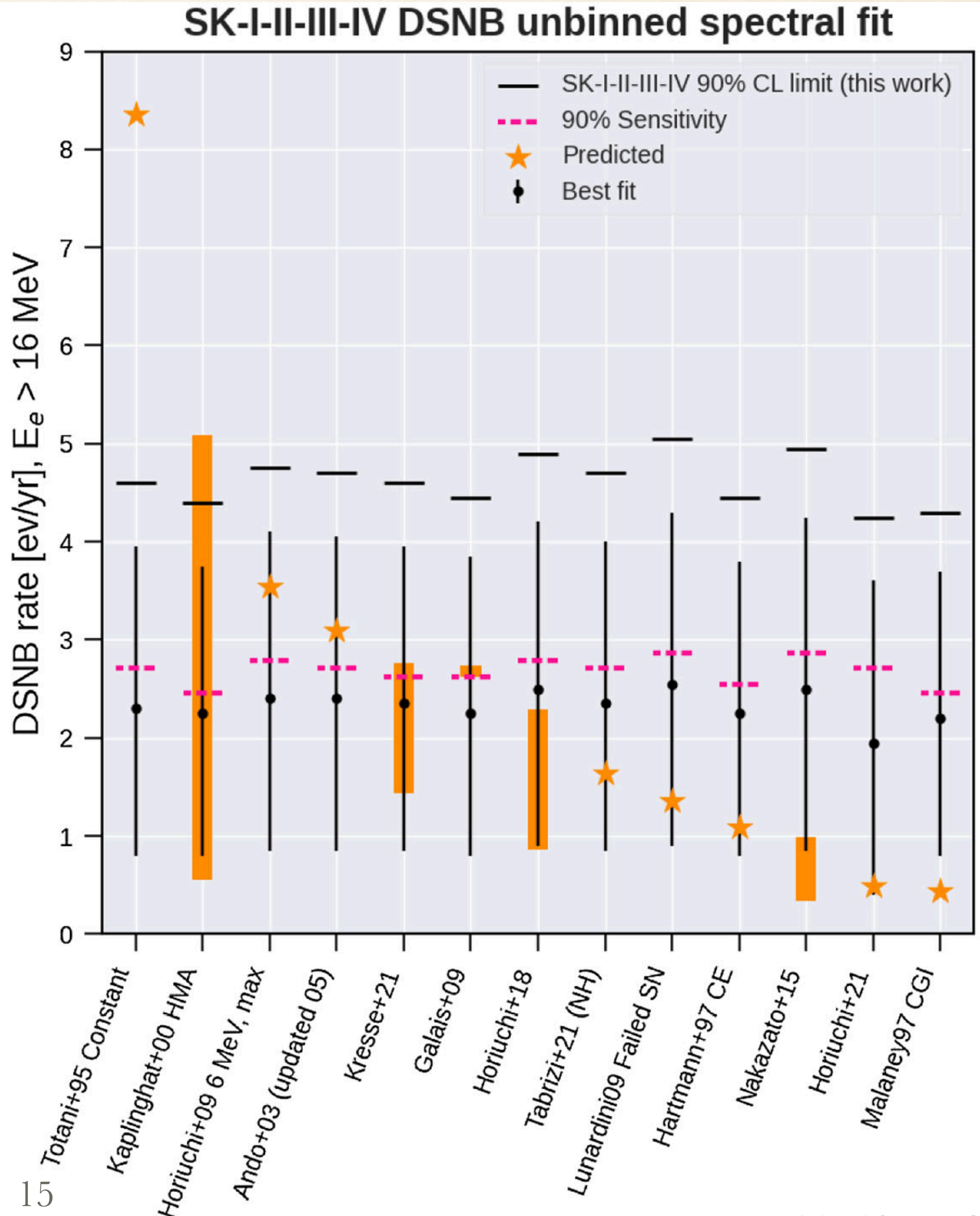

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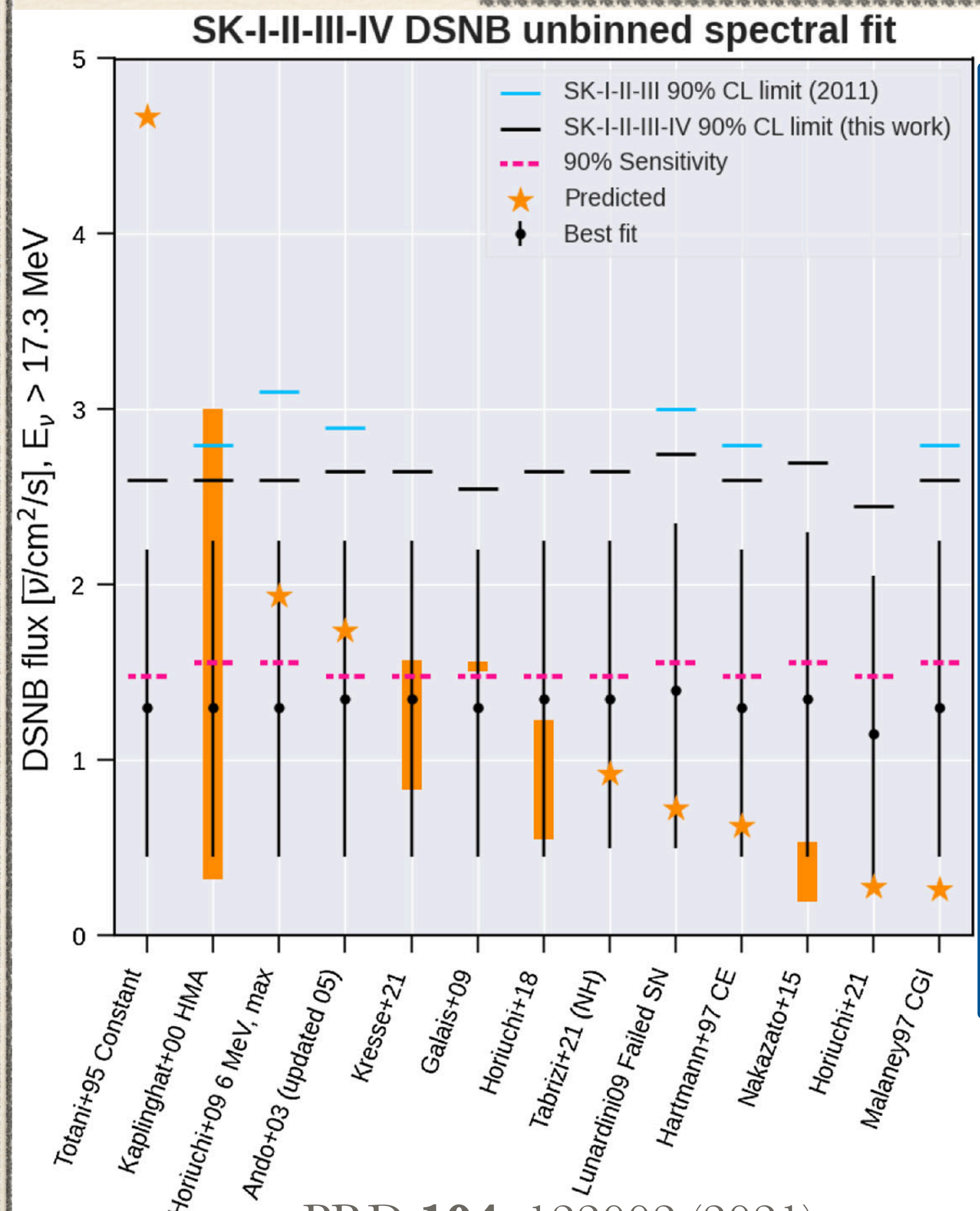

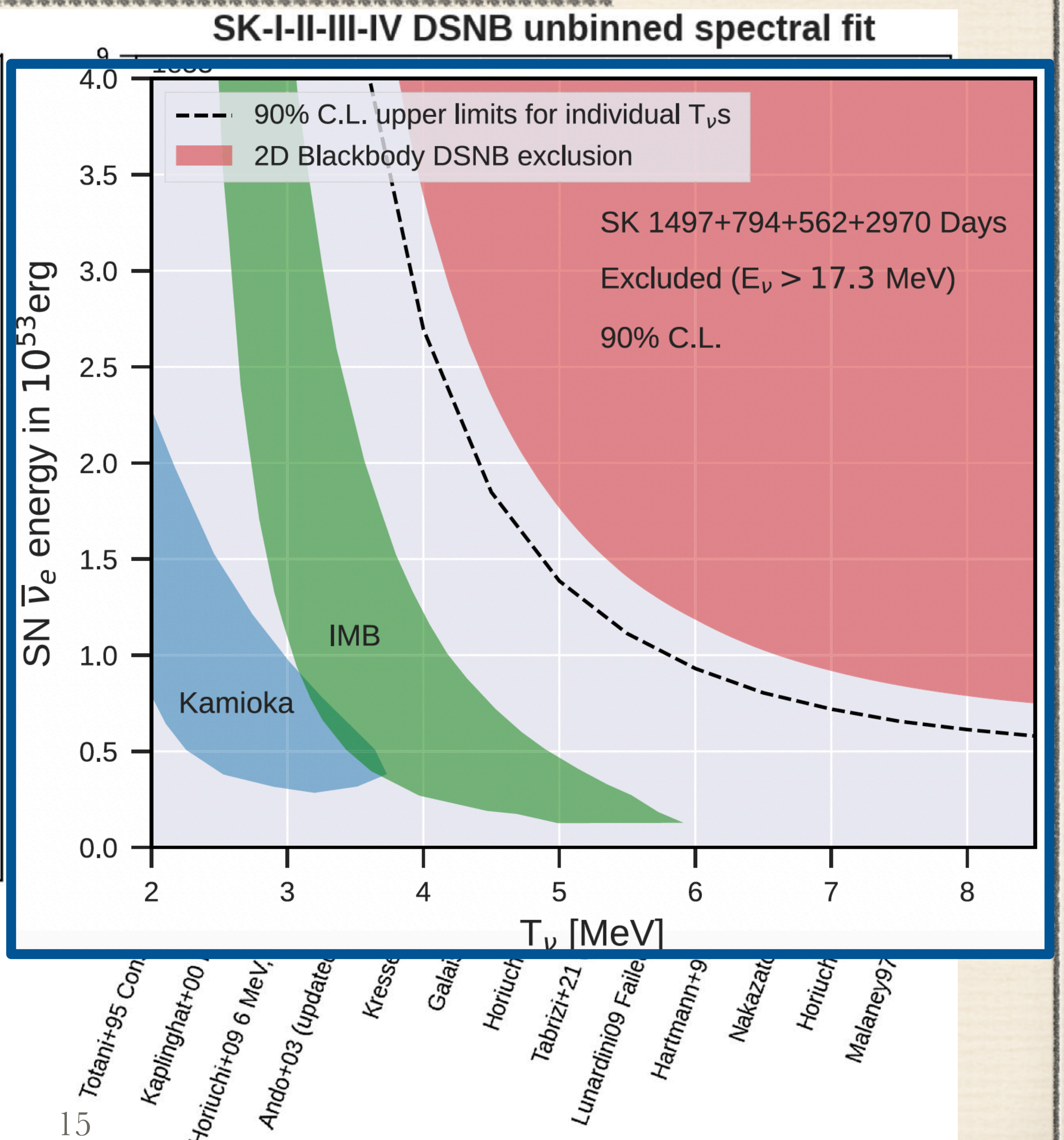

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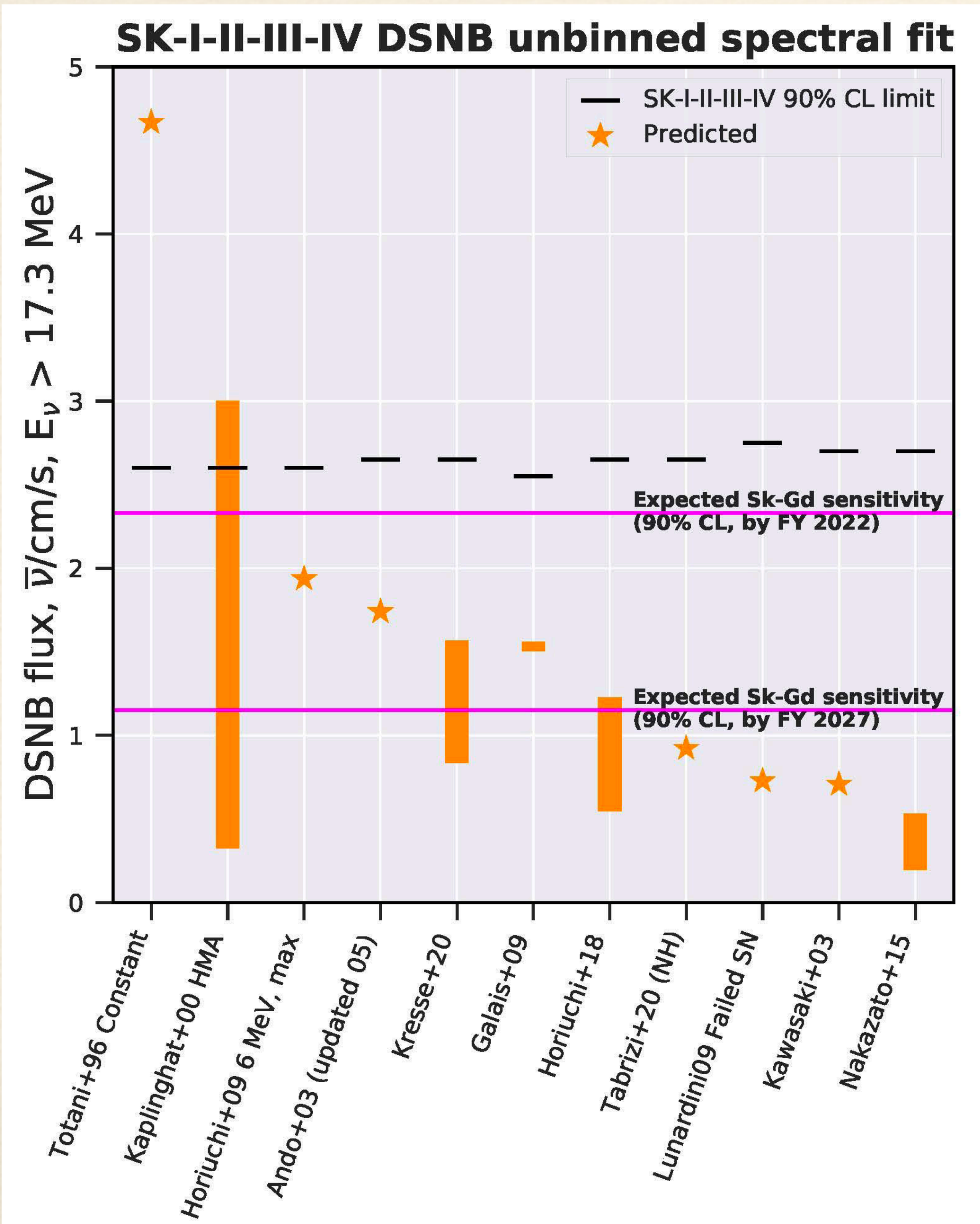
Distant Supernova Search with Gd



- ~50% to ~70% to ~80% efficiency to tag IBD with Gd γ's/2.2 MeV γ
- Gd analysis results are not yet released, need to study detector stability carefully, in particular transparency and noise

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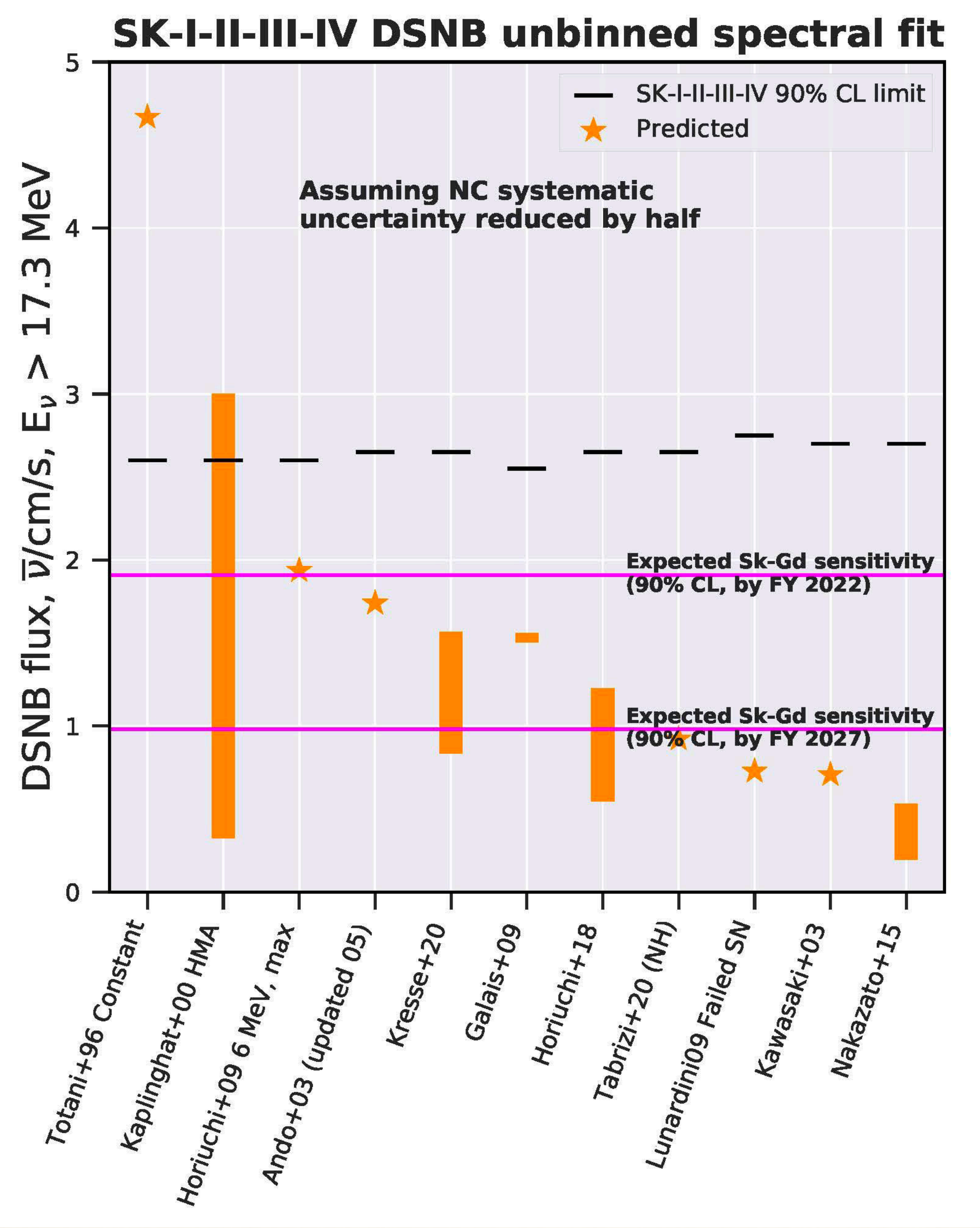

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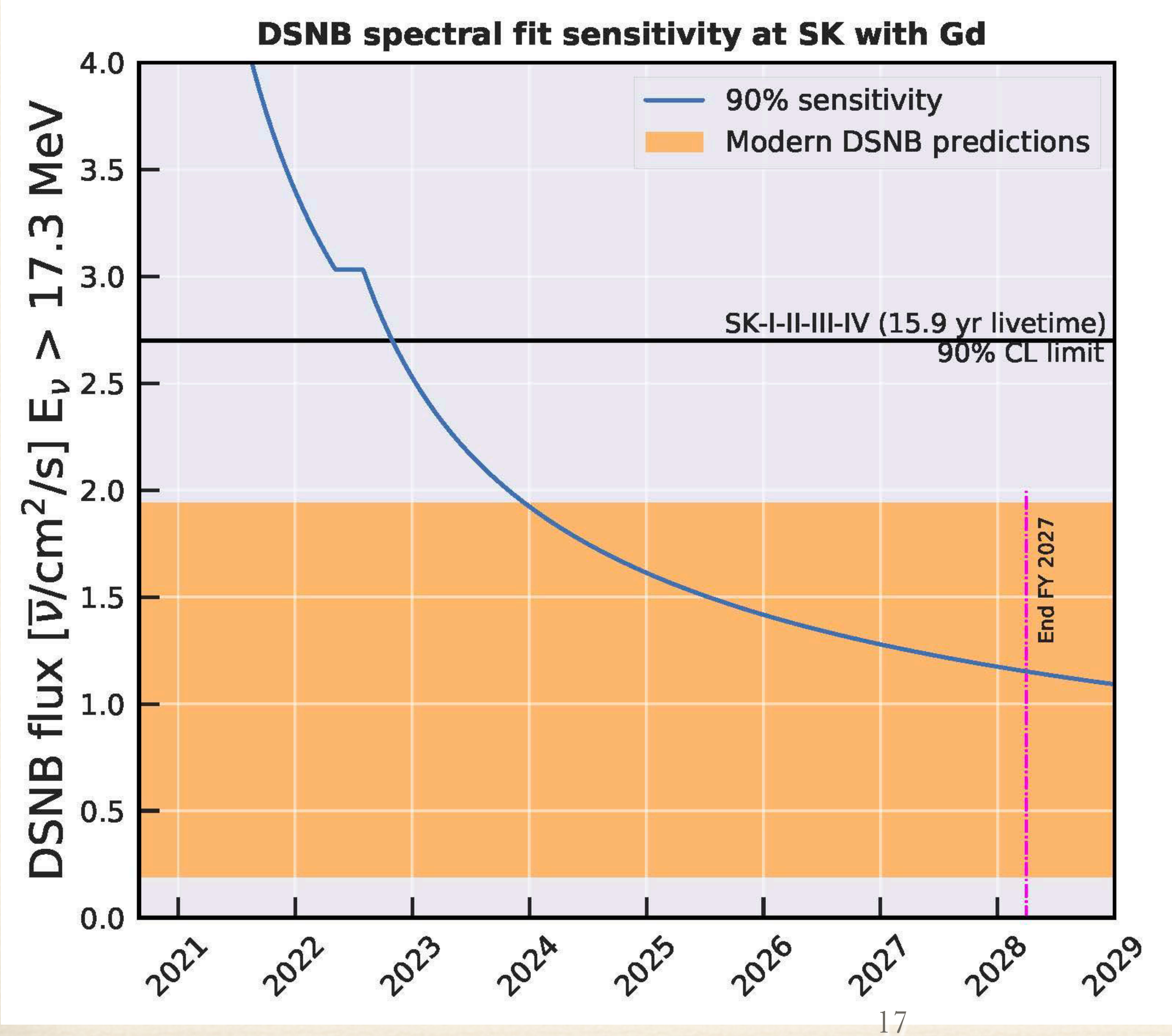
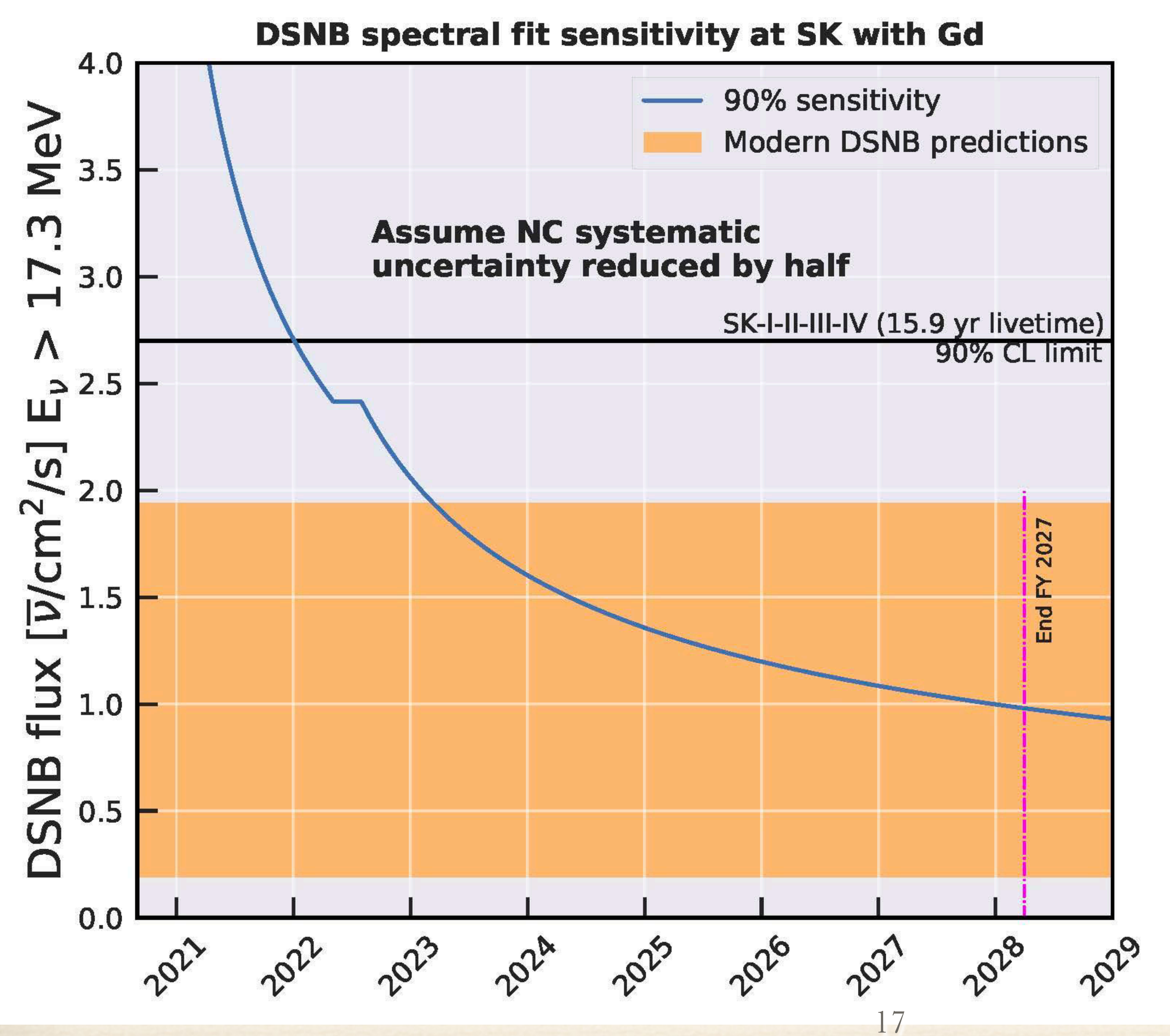


- decent chance of discovery by the end of SK in 2027

Michael Smy, UC Irvine

Distant Supernova Search with Gd



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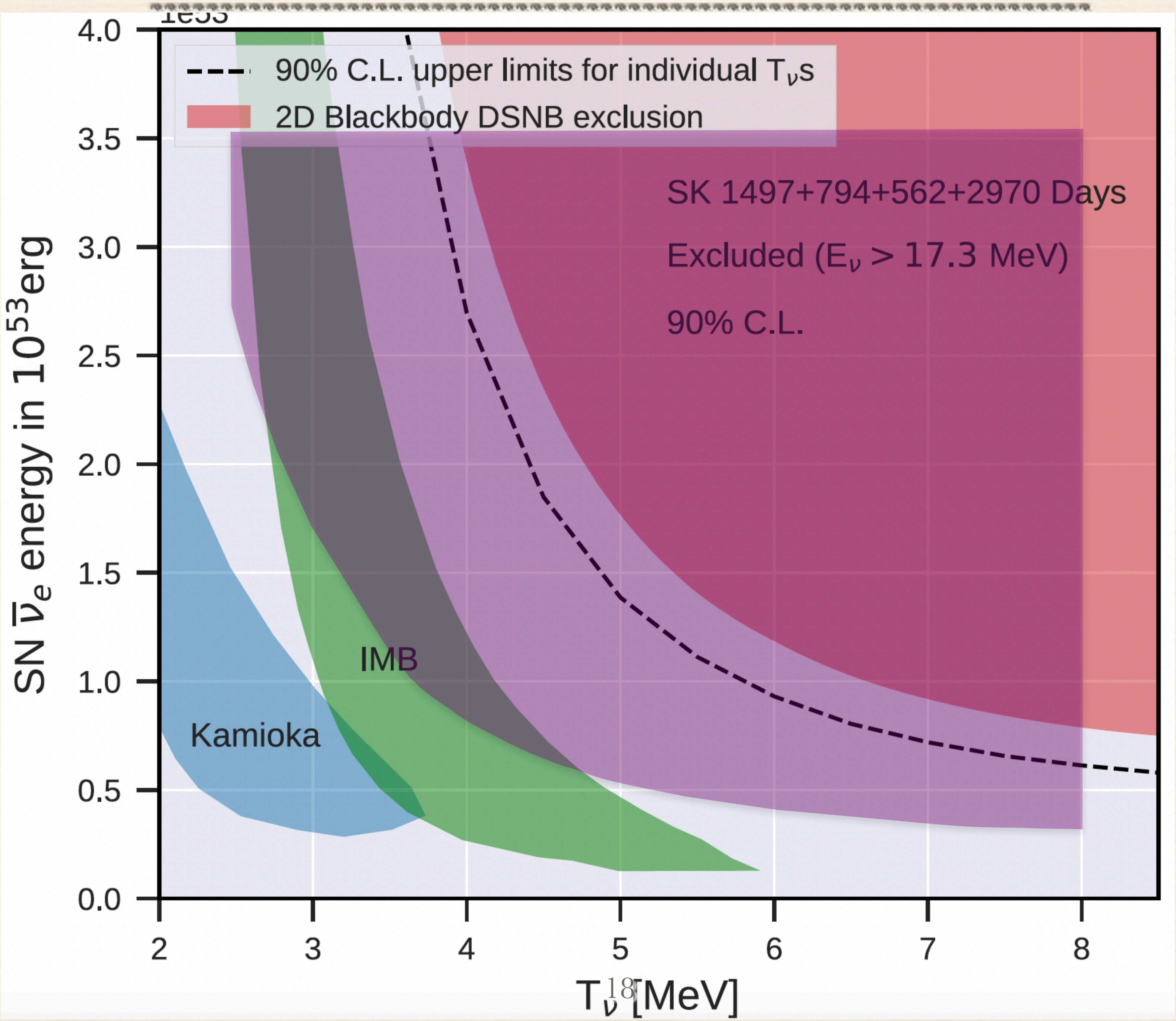
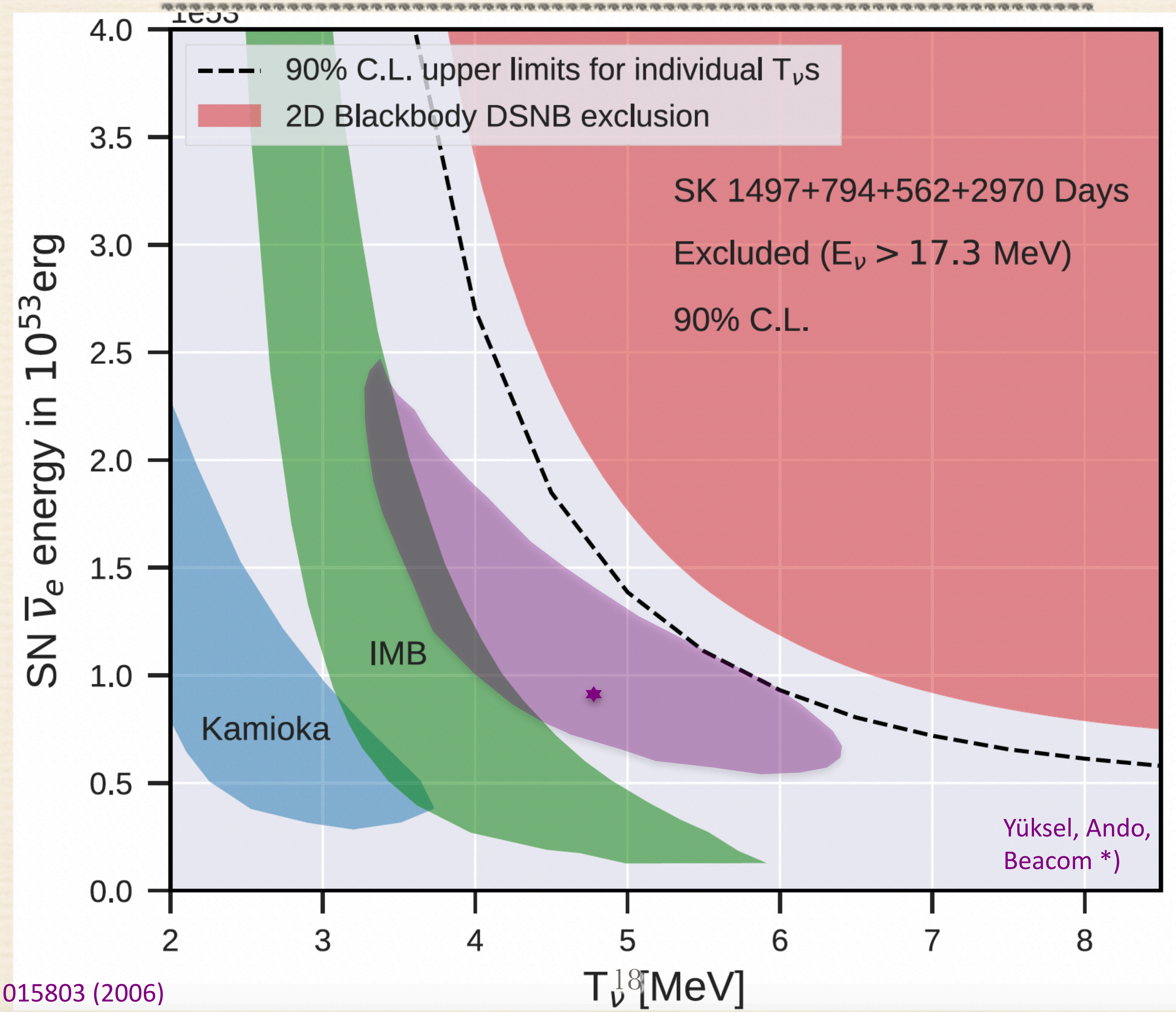
Michael Smy, UC Irvine

Distant Supernova Search with Gd: Determine Typical SN ν Emission



Michael Smy, UC Irvine

Distant Supernova Search with Gd: Determine Typical SN ν Emission



*) Phys. Rev. C 74 015803 (2006)

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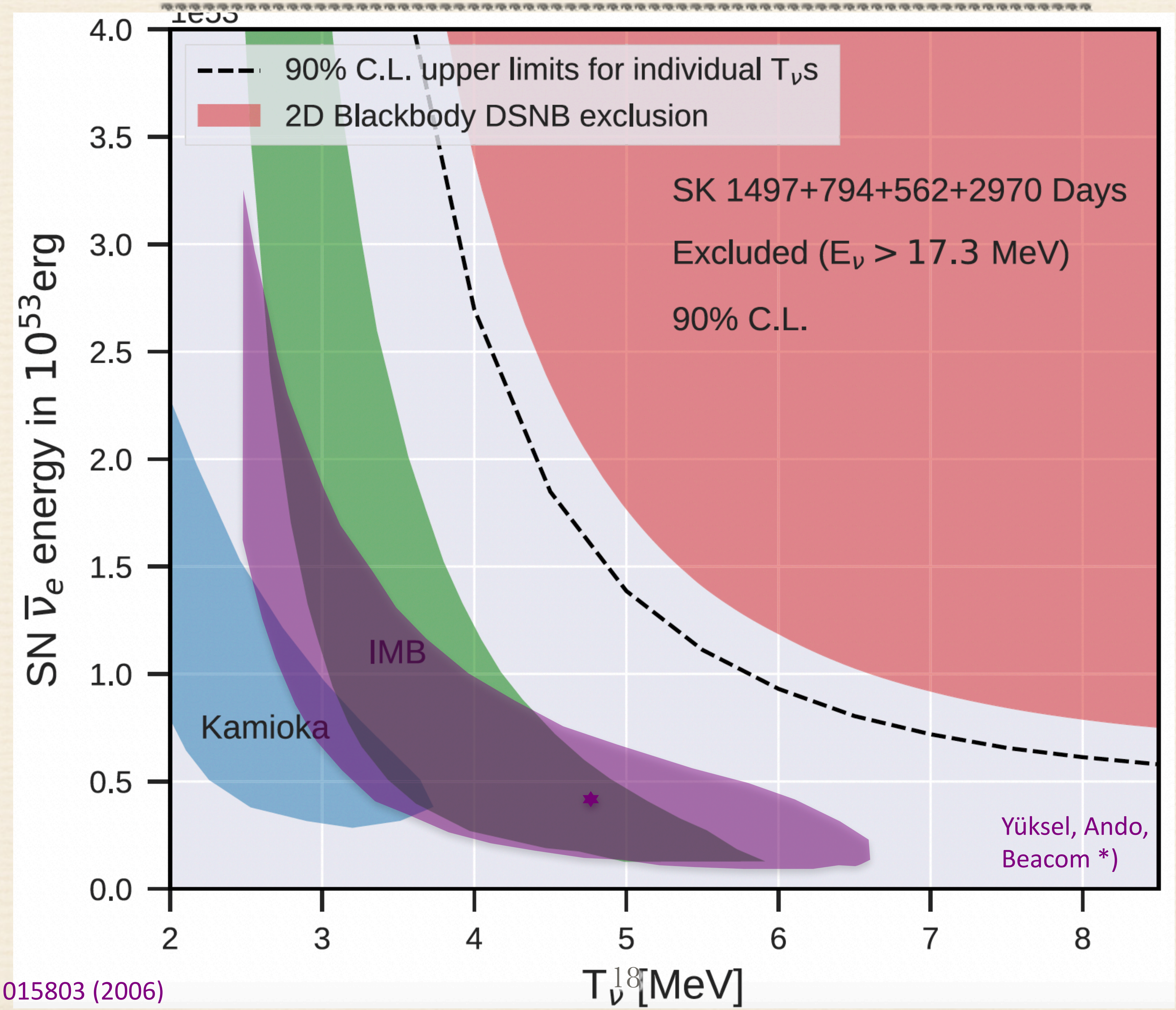

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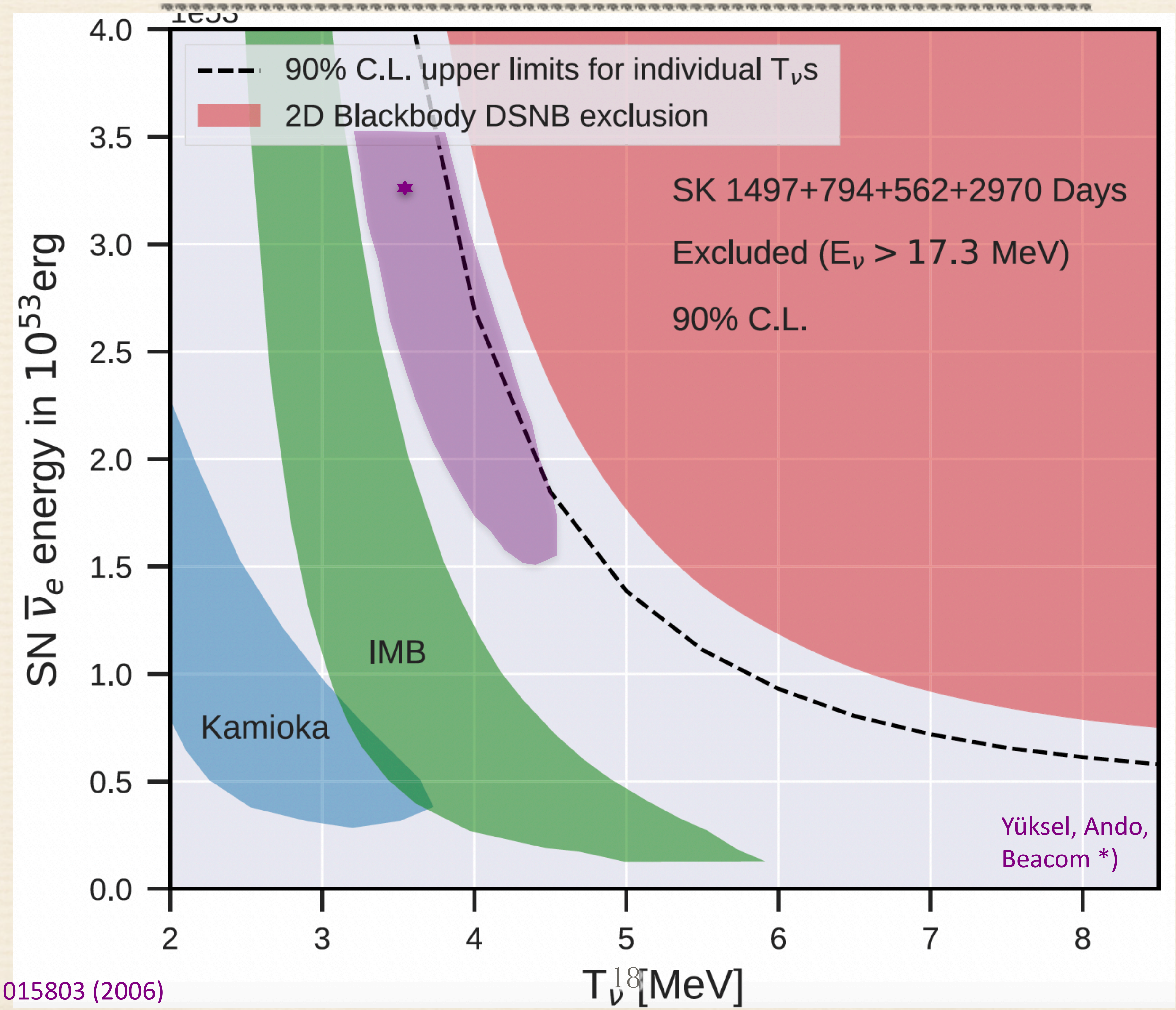
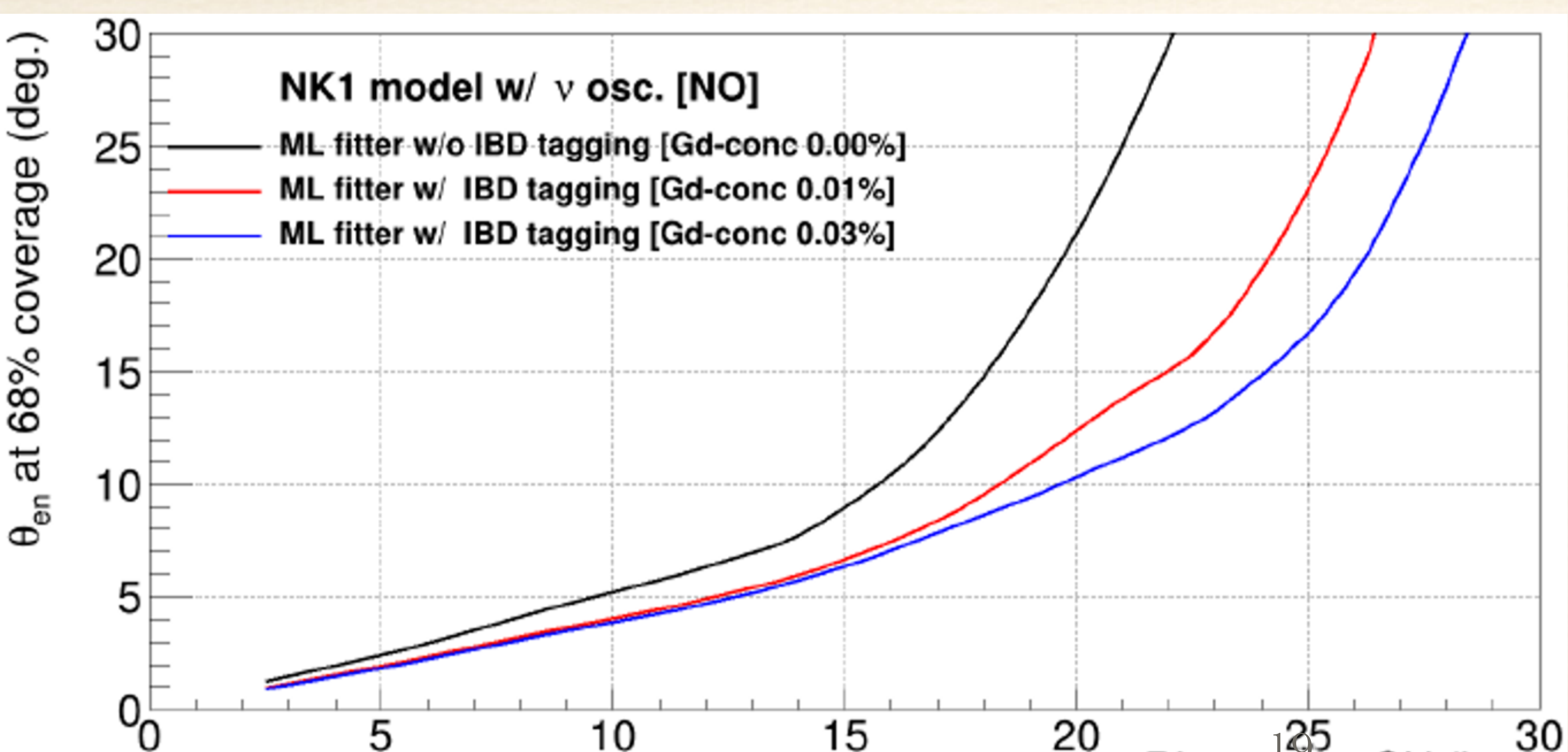


*) Phys. Rev. C 74 015803 (2006)

Galactic Supernova Alerts with Supernova Direction

- IBD signature adds confidence to SN identification: since December 2021, SK sends fully automated alerts to GCN within <1 minute of the burst detection
- direction includes in these alerts makes use of separation of electron elastic scattering events

system test in May 2022

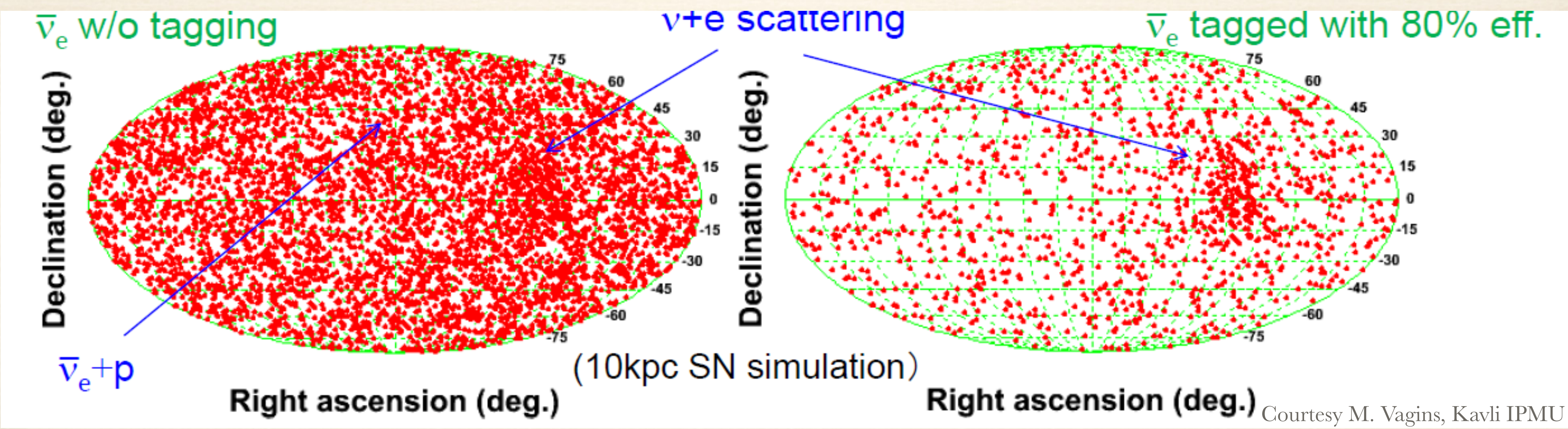


Courtesy M. Vagins, Kavli IPMU

```
TYPE:           SK-SN Golden event
SUBMISSION_DATE:  2022/05/09 03:26:44 UT
MESG_REALITY: test
TRIGGER_NUMBER: SK_SN_1
EVENT_DATE: 19708 TJD;  129 DOY;  2022/05/09
EVENT_TIME: 10792.64 SOD {02:59:52.64} UT
N_EVENTS:   60135  (number_of_detected_neutrinos_events)
ENERGY_LIMIT: 7.0 MeV (Visible energy)
DURATION:   18.6 seconds
SRC_RA:     42.88d {02h 51m 31s} (J2000),
SRC_DEC:    34.23d {+34d 13m 47s} (J2000),
ERROR68:    0.66 [deg]
ERROR90:    0.97 [deg]
ERROR95:    1.13 [deg]
DISTANCE:   2.23 3.05 [kpc]  (min_max_assuming_as_SN1987A_like)
COMMENTS:   The EVENT_TIME corresponds to the detection time of
COMMENTS:   the first neutrino event at 2022/May/09 02:59:52 641948 [us] UT
```

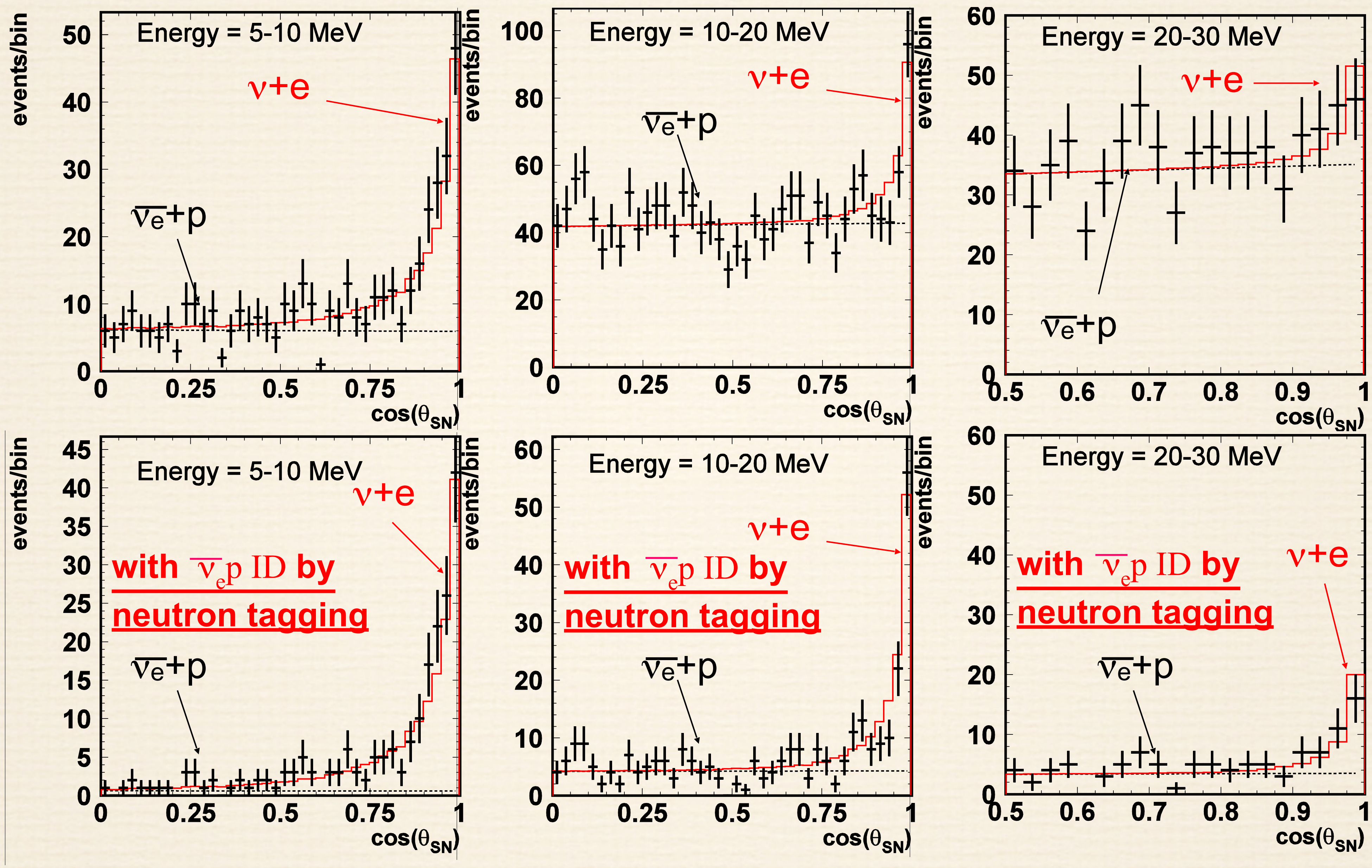
Direction Fitting and Gd

- use maximum likelihood and machine-learning methods
- electron elastic scattering events are highly directional; IBD events are slightly forward-peaked at higher energies
- also: ES is dominated by electron neutrinos, IBD is exclusively electron antineutrinos (flavour separation)



Courtesy M. Vagins, Kavli IPMU

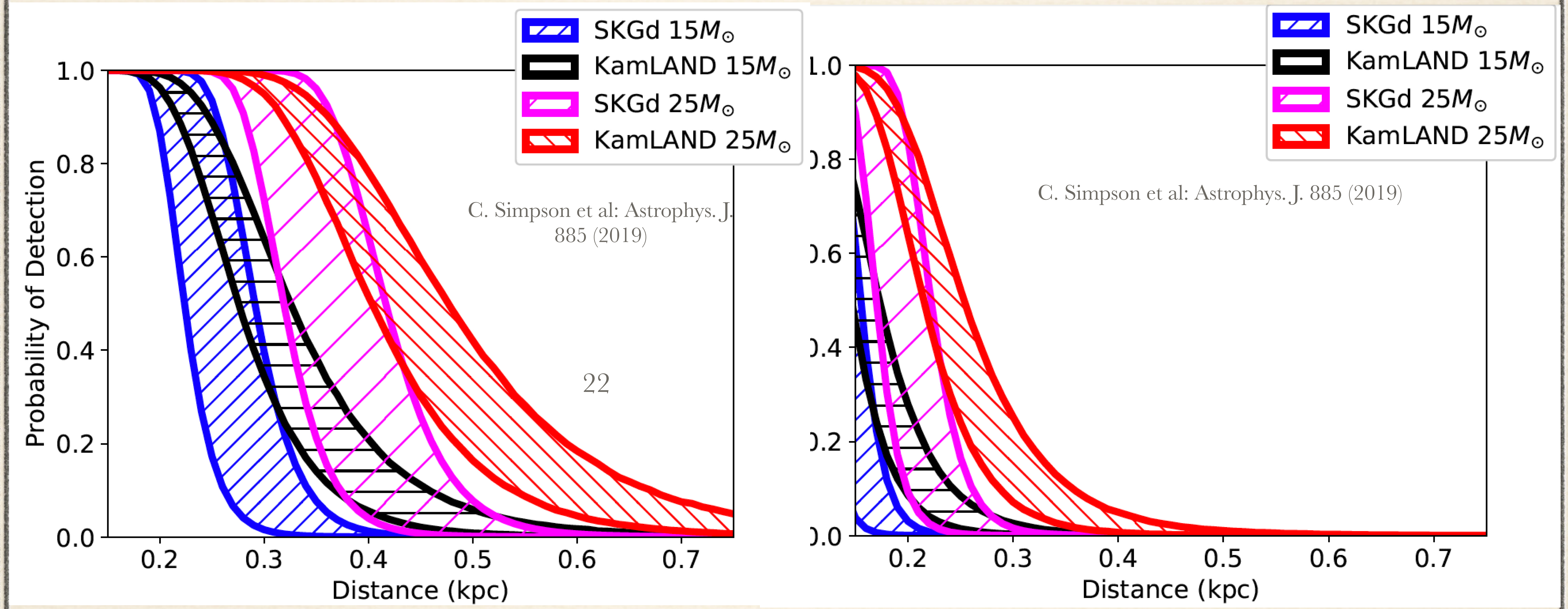
Galactic Supernova Neutrinos



- improve ES signal and flavor decomposition of galactic SN ν burst
- improve angular resolution by factor of two!

Courtesy M. Nakahata, ICRR

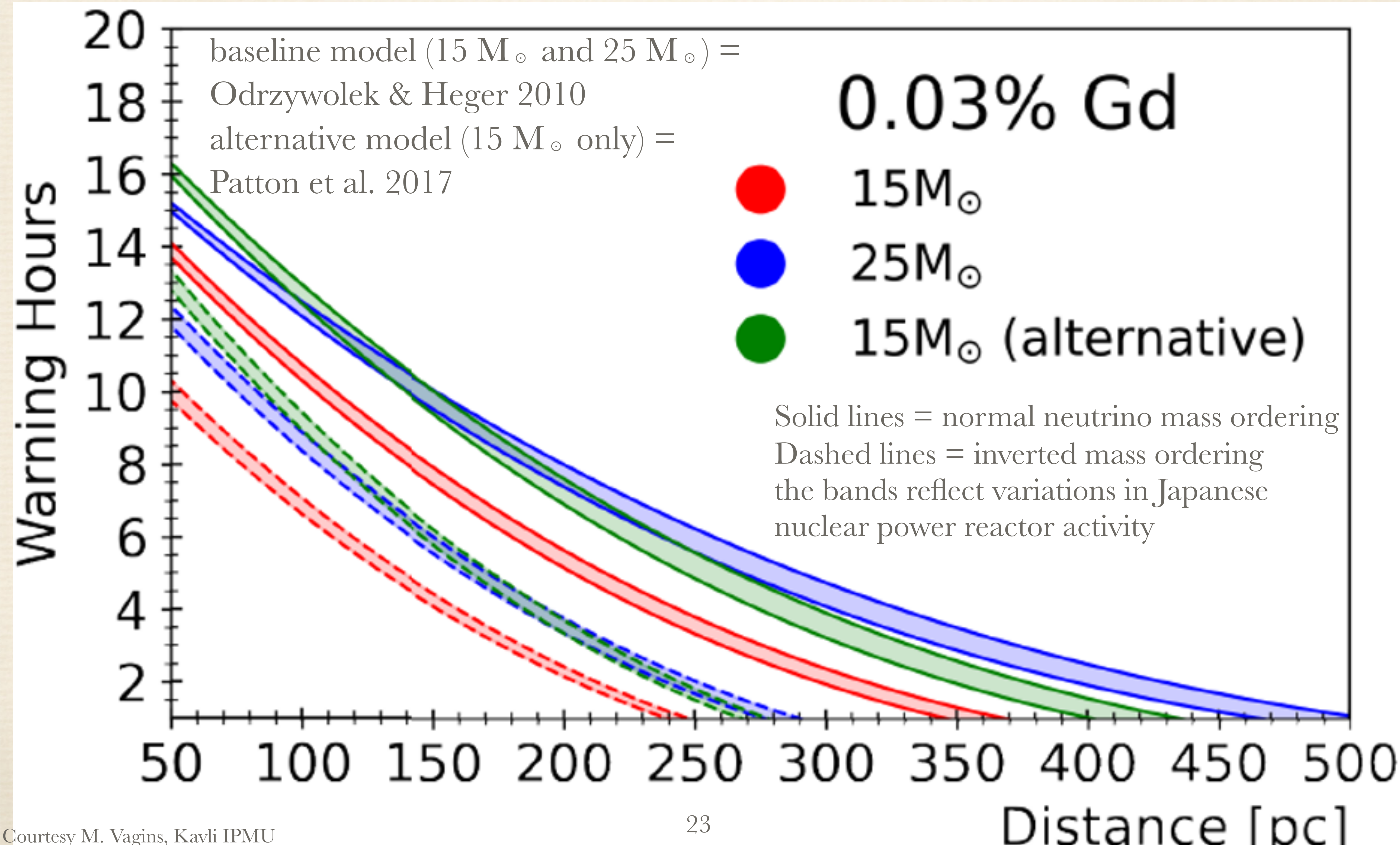
Galactic Supernovae: Pre-SN Alert from Si-Burning ν's



normal mass ordering | inverted mass ordering

- last stage of nuclear fusion in a star, lasts O(1 week)
- 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

Galactic Supernovae: Pre-SN Alert from Si-Burning ν's



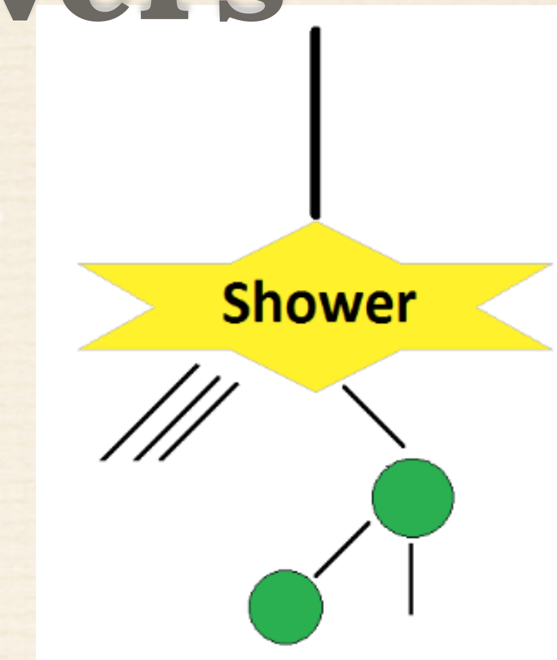
Courtesy M. Vagins, Kavli IPMU

Reduce Spallation Background: Tagging Hadronic Showers

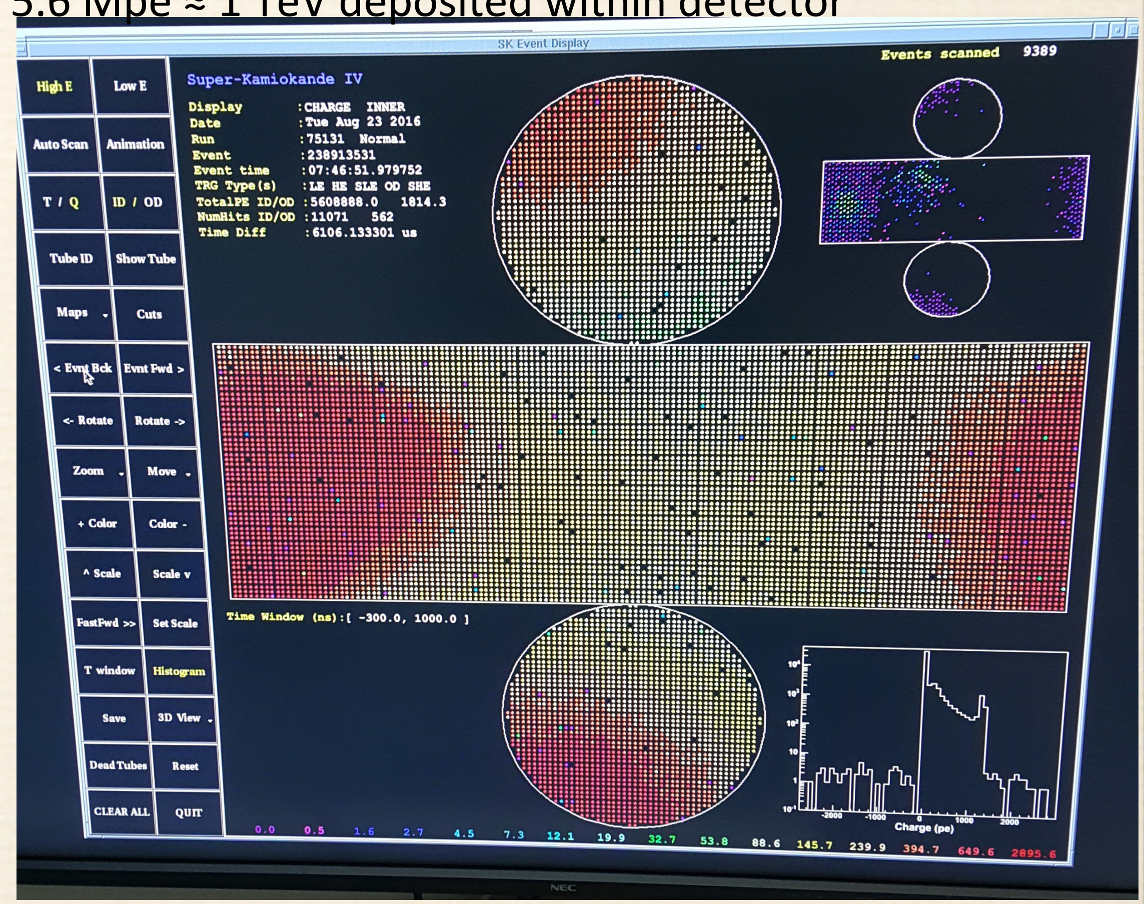
- some muons initiate showers of secondary particles (e, γ, n, π , …); hadrons (n, π) in those break up ^{16}O and the decays of unstable resulting isotopes feign ν interactions
- lifetime ranges from O(0.01s) to O(10s)

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

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



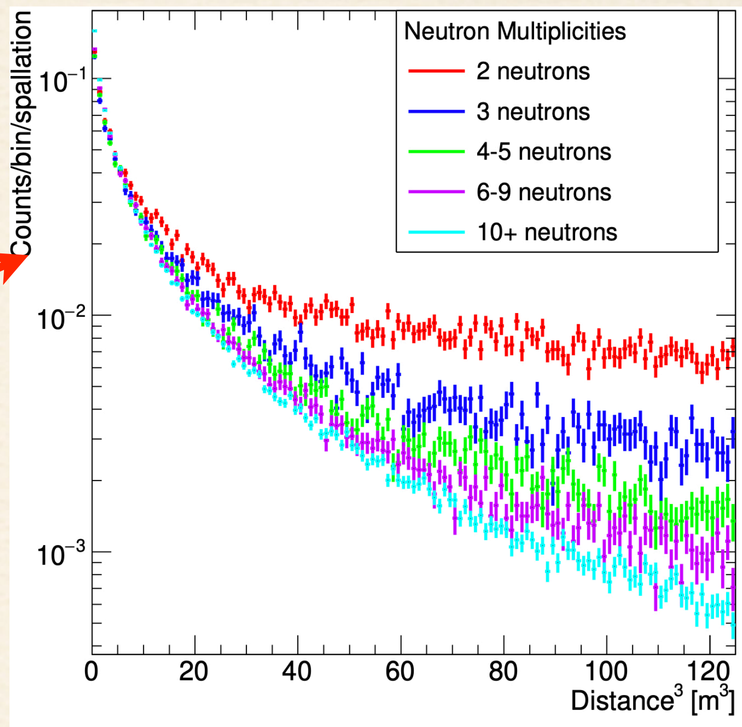
Y. Zhang et al. Phys. Ev. D 93, 012004 (2016) and Beacom and Li: Phys Rev C 89, 045801 (2014)

Courtesy S. Locke, UC Irvine

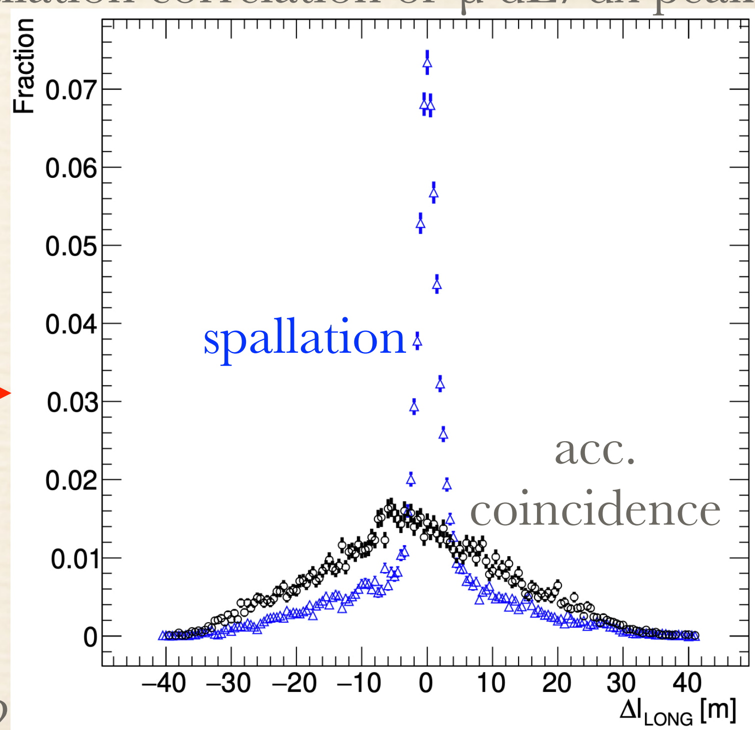
Spallation Decay Tagging in Super-K

- most cosmogenic radioactivity is produced in hadronic showers initiated by energetic muons
- invented three tagging methods:
  - neutron clouds: hadronic showers make many neutrons ("clouds") capturing near muon track
  - multiple spallation: ~50% of spallation results in more than one decay → time and spatial correlation: decays tag each other without need to use muon track
  - reconstruct optical muon "dE/dx" to identify showers and find shower position along track
- results in efficient tag without loosing much signal

spallation correlation of neutron cloud



spallation correlation of μ dE/dx peak

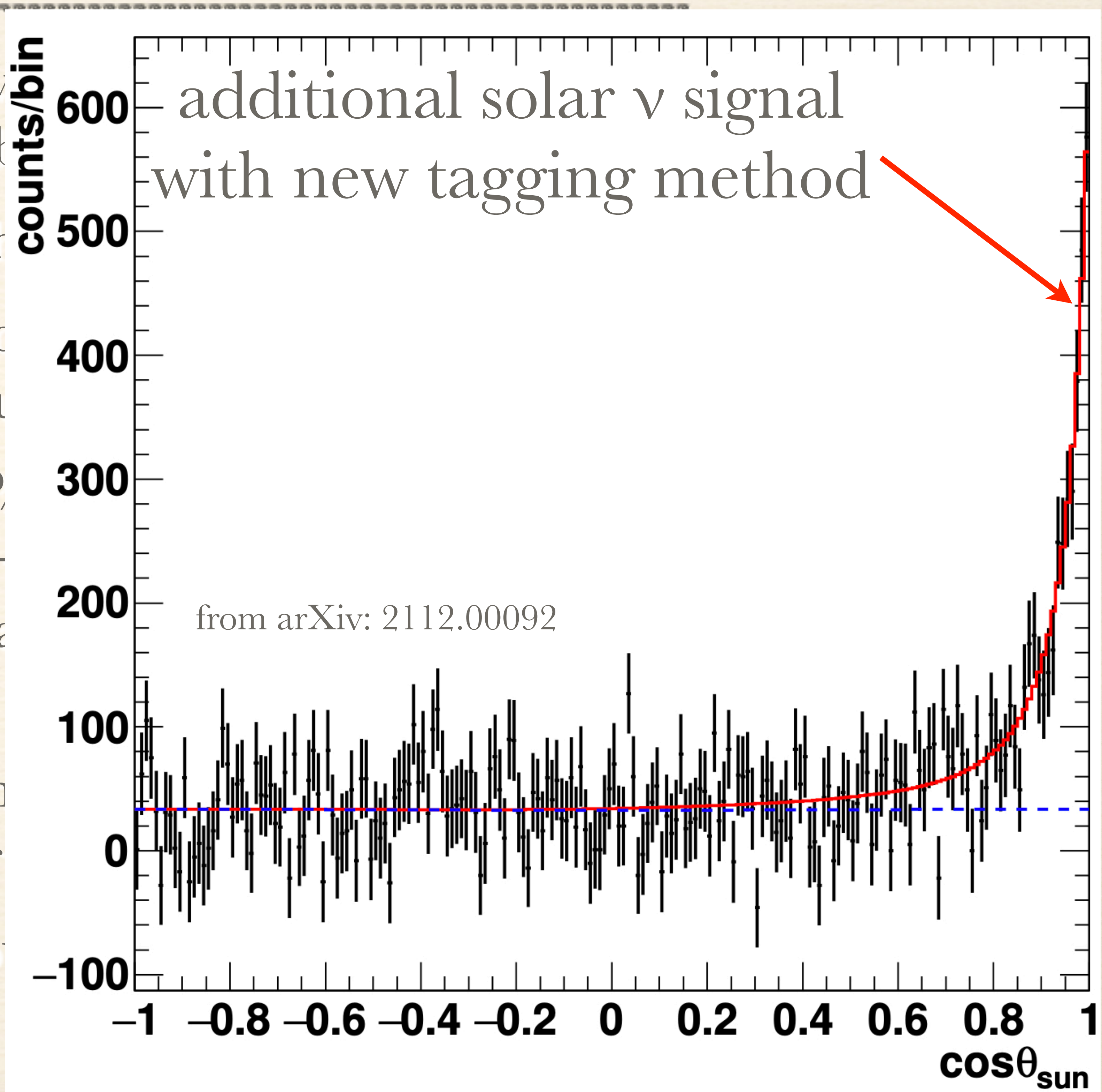


from arXiv: 2112.00092

Michael Smy, UC Irvine

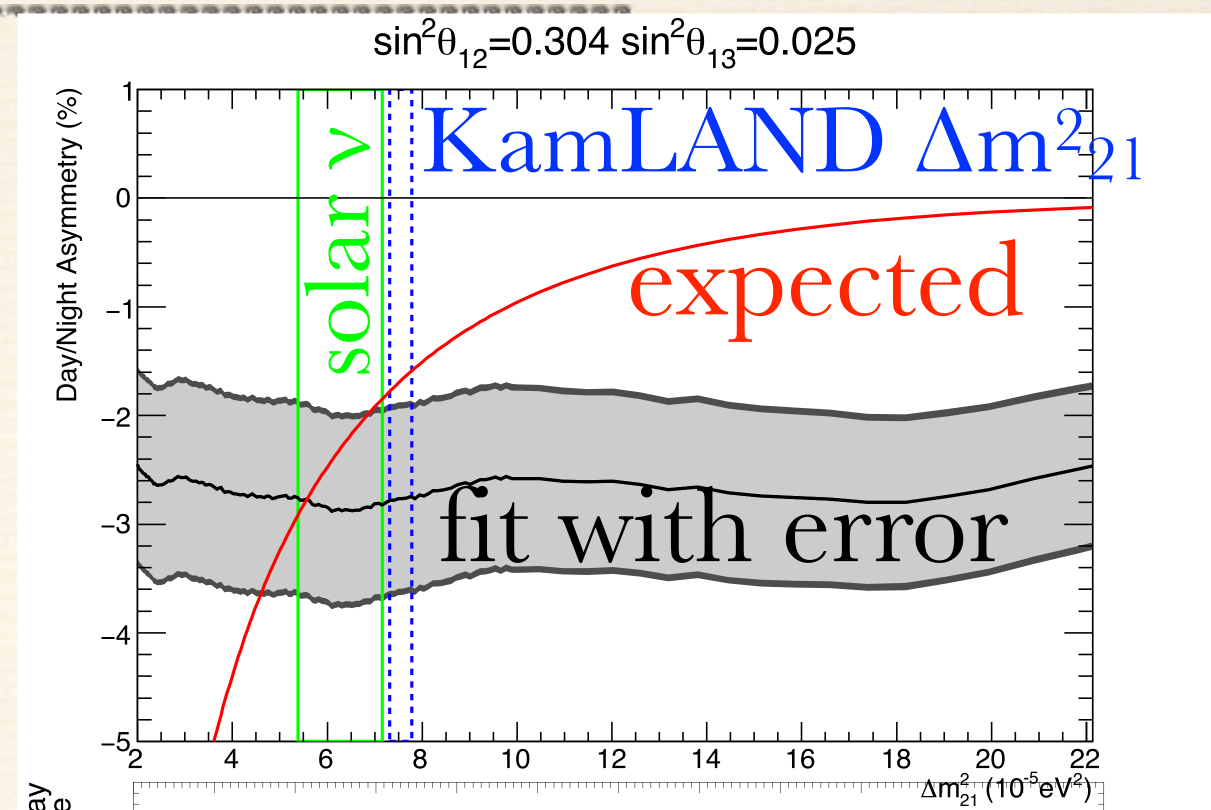
Spallation Decay Tagging in Super-K

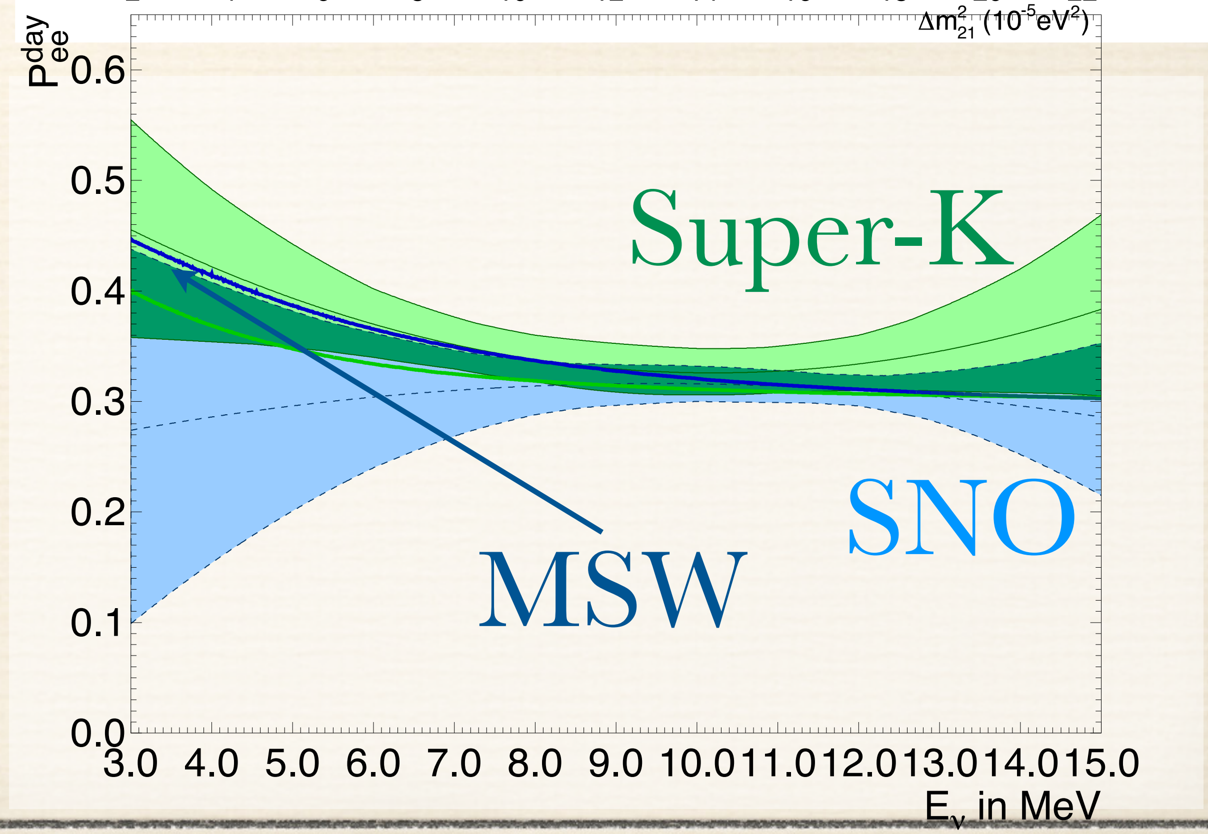
- most cosmogenic radioactiv
  hadronic showers initiated b
- invented three tagging meth
  - neutron clouds: hadronic
    neutrons (“clouds”) captu
  - multiple spallation: ~50%
    in more than one decay
    correlation: decays tag ea
    to use muon track
  - reconstruct optical muon
    showers and find shower
- results in efficient tag witho



Benefit of Exposure Gain

- evidence of earth matter effect (non-zero day/night asymmetry)
  - A_{DN}=-(2.88±0.85±0.32)% (3.2σ) for solar ν favoured Δm^2_{21}
  - A_{DN}=-(2.88±0.85±0.32)% (3.1σ) for KamLAND Δm^2_{21}
- better constraint of solar matter effect (MSW): $P_{ee}(E_\nu)$ from recoil electron spectrum favours transition from vacuum oscillations to matter-domination region





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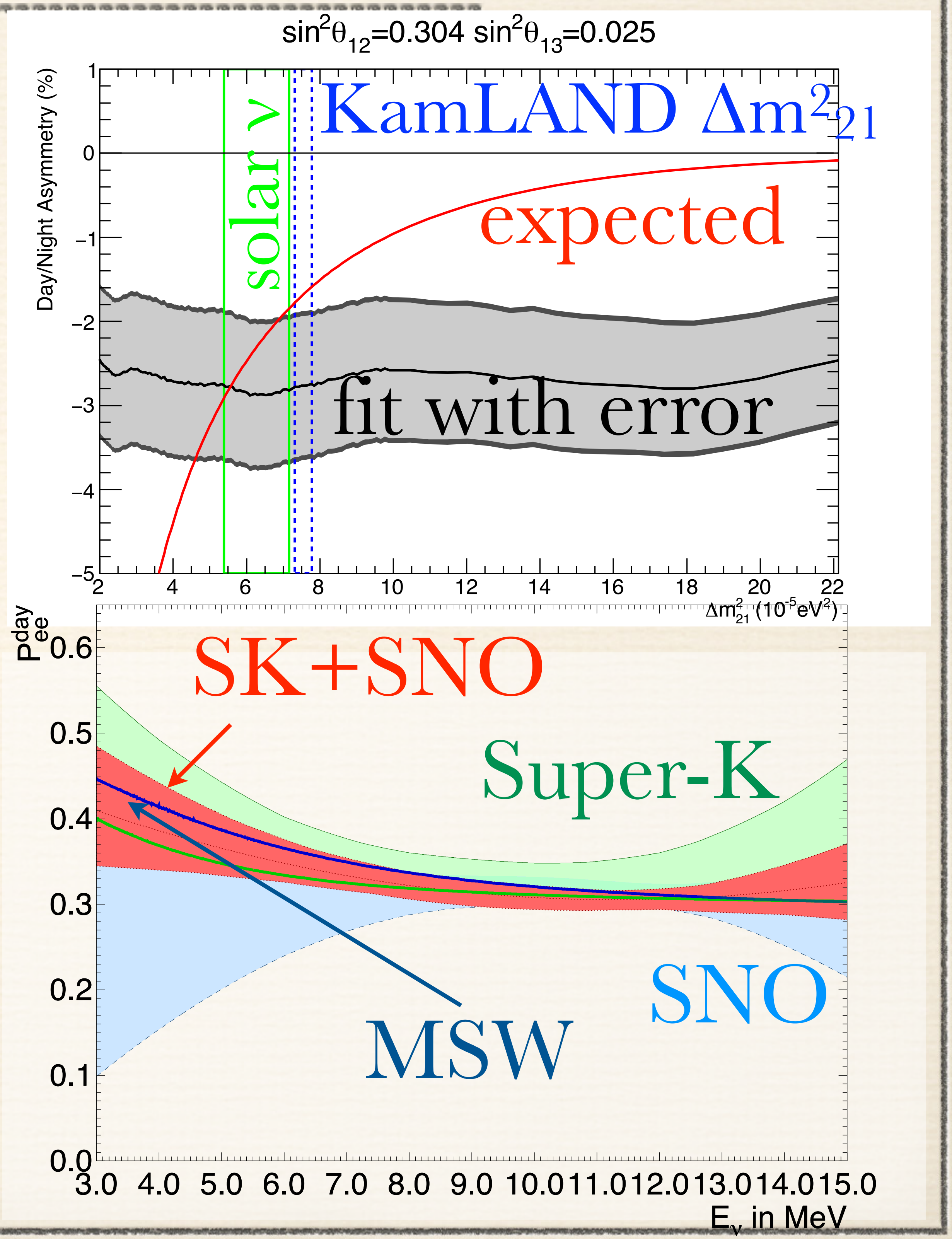
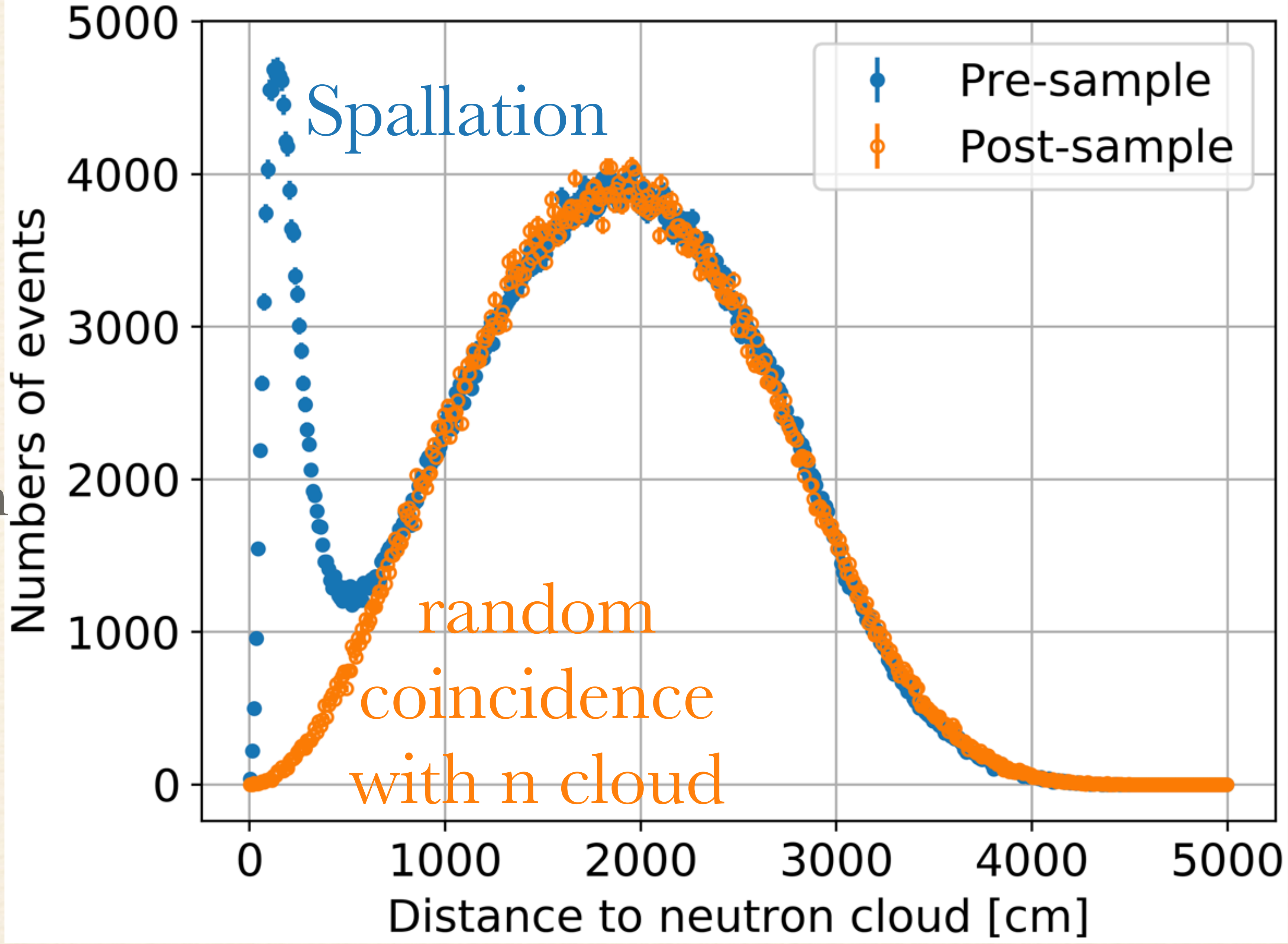


Spallation: Also Dominant Background for Distant SN ν's

- "neutron cloud" method was already used in PRD **104**, 122002 (2021)
- expect much better rejection with "Gd n clouds":
  - better statistics (n multiplicity)
  - better vertex resolution



Michael Smy, UC Irvine

Summary

- Super-K has a rich neutrino astrophysics program
- in July 2020 we started a new era: taking advantage of enhanced neutron detection capabilities from the addition of $Gd_2(SO_4)_3$ to Super-K's water
- the 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, …
  - see talk by Thomas Wester on Tuesday 13:00 on atmospheric ν's
  - a planned, dedicated T2K talk was unfortunately cancelled