DSNB Neutrinos: Overview and New Results

Neutrino 2022

S13: Solar/DSNB Neutrinos

June 2, 2022

Andy Mastbaum

Rutgers University

mastbaum@physics.rutgers.edu

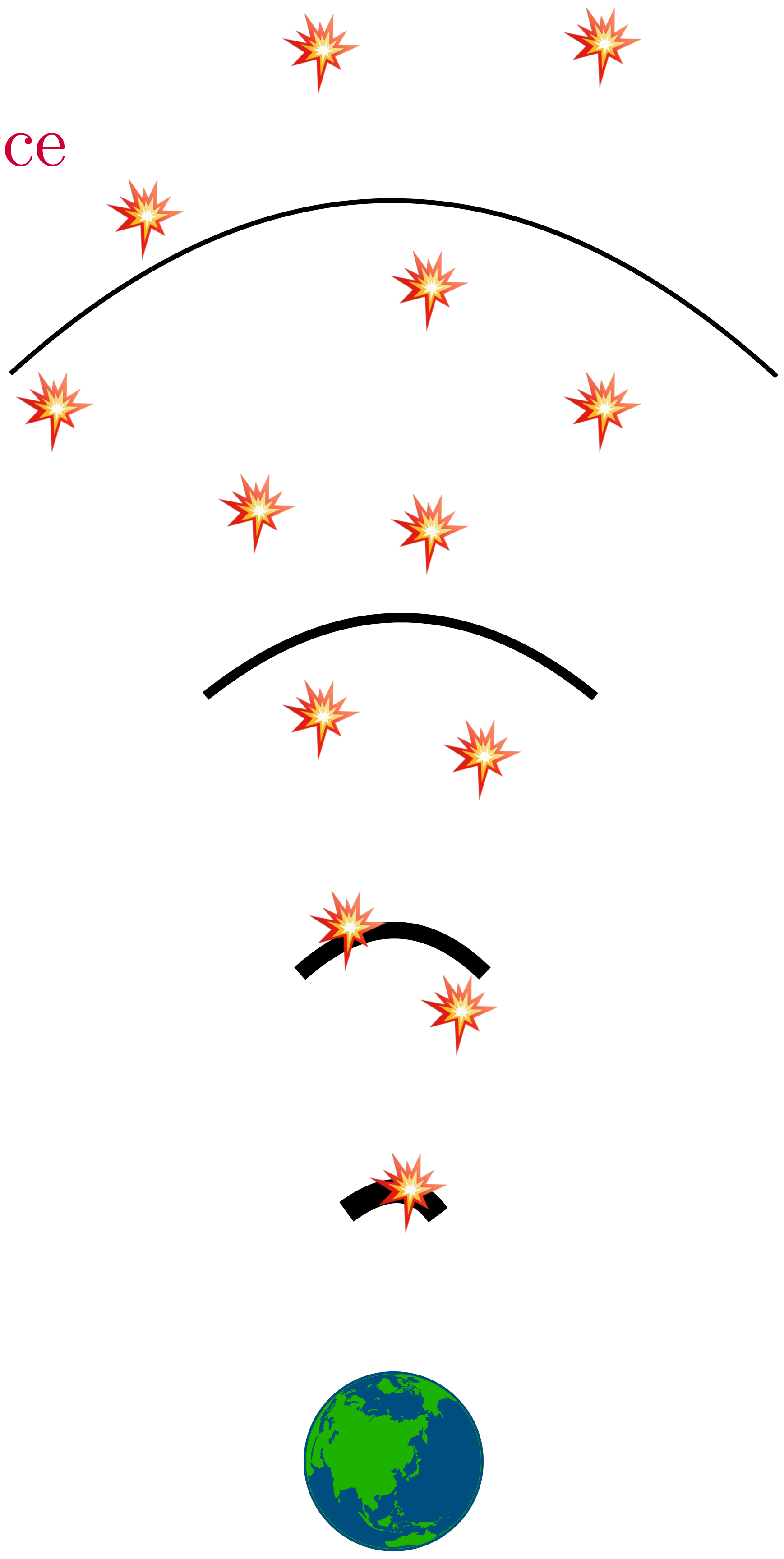
on behalf of the SNO Collaboration

Outline

- **DSNB Overview**
  - What is the diffuse supernova neutrino background?
  - Why is it interesting to measure?
  - Through what mechanisms can we detect this signal?
- **Recent Searches**
  - What are the latest experimental findings?
  - Where are we now relative to model predictions?
- **Future Prospects**
  - What will upcoming and next-generation experiments offer?
  - What does the future hold for this field?

Supernova Neutrinos

The Diffuse Supernova Neutrino ~~Background~~ Source



Core-Collapse Supernovae

- Most energy loss through neutrinos (~10^{53} erg)
- Rich physics in neutrino bursts from nearby CCSNe — detectors are ready (cf. SNEWS)! (snews2.org)
- Detectable bursts are rare events
  - **kpc:** ~few/century → ≫ 1 event
    - One detection: SN1987A
  - **Mpc:** ~once a year → ~1 event
  - **Observable universe:** ~1 Hz → ≪ 1 event

Diffuse Supernova Neutrino Background (DSNB)

also Supernova Relic Neutrinos (SRN) —

The diffuse "glow" of neutrinos from distant core-collapse supernovae

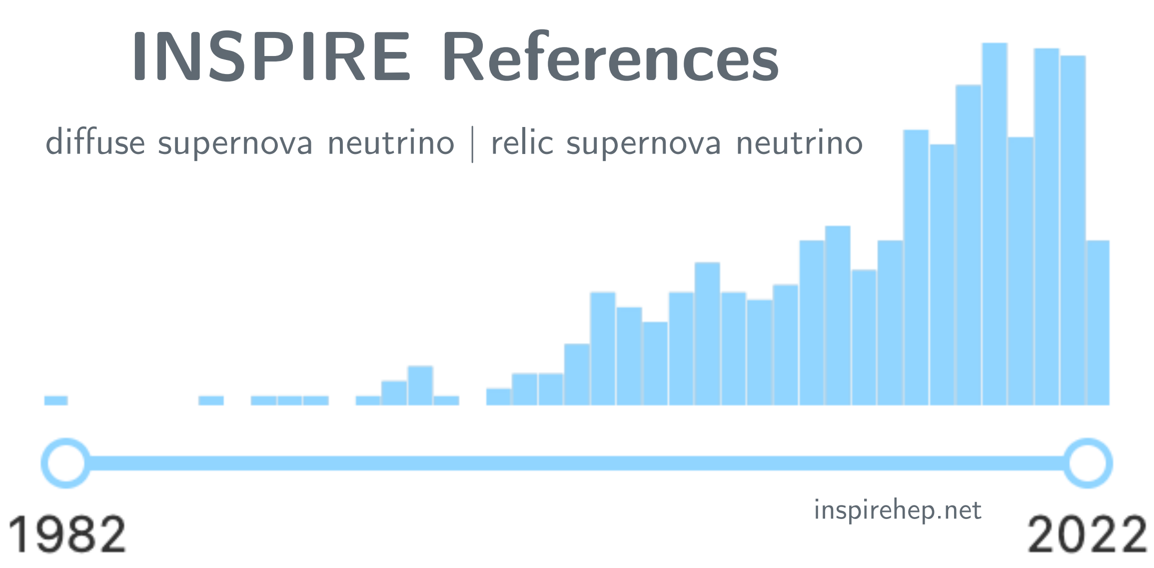
Unique Physics Insights

The Diffuse Supernova Neutrino ~~Background~~ Source

The DSNB is a uniquely informative neutrino source.

Supernova Physics & Cosmology

- Spectrum and flux → *average* temperature and luminosity
  - Typical SNe dynamics
  - Rate of failed SNe
  - Universe's history and evolution



Elementary Particle Physics

- Neutrino oscillations in dense media, ν–ν interactions, NSI
- Fundamental neutrino physics
  - Lifetime, pseudo-Dirac nature [PRD 102, 123012 (2020)]
  - MSW oscillations, decay [PRD 105, 043008 (2022); JCAP05(2021)011]
- A complete picture requires measuring the DSNB *spectrum* and *flavor composition*

DSNB: Source

Modeling & Inputs

See also: Session S14: Astrophysical Neutrinos I
Meng-Ru Wu, "Neutrinos in supernovae and binary neutron star mergers"

Line-of-sight integral in redshift

$\rightarrow$ *New SNe & particle physics effects!*

Neutrino emission spectrum

$$\frac{d\Phi(E_\nu)}{dE_\nu} = \int_0^{z_{\max}} R_{\mathrm{SN}}(z) \frac{dN[E(1+z)]}{dE} (1+z) \left| \frac{dt}{dz} \right| dz$$

DSNB Flux

CC SNe rate

$\rightarrow$ *Cosmology and star formation!*

(ΛCDM) Cosmology

$\rightarrow$ *Cosmological effects!*

DSNB: Source

Modeling & Inputs

See also: Session S14: Astrophysical Neutrinos I
Meng-Ru Wu, "Neutrinos in supernovae and binary neutron star mergers"

Line-of-sight integral in redshift

→ *New SNe & particle physics effects!*
Neutrino emission spectrum

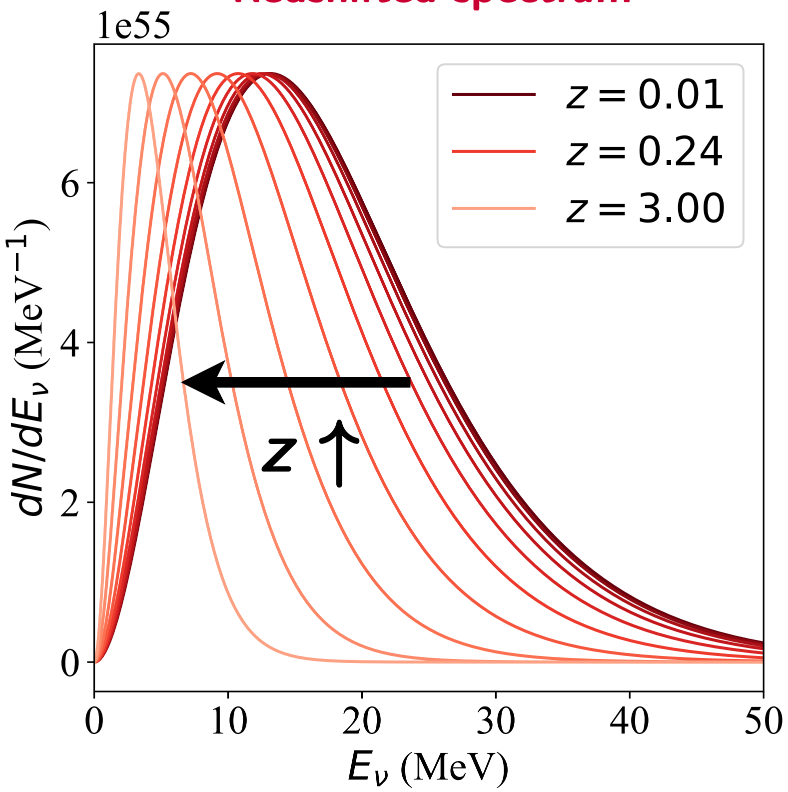
$$\frac{d\Phi(E_\nu)}{dE_\nu} = \int_0^{z_{\max}} R_{\rm SN}(z) \frac{dN[E(1+z)]}{dE} (1+z) \left| \frac{dt}{dz} \right| dz$$

DSNB Flux

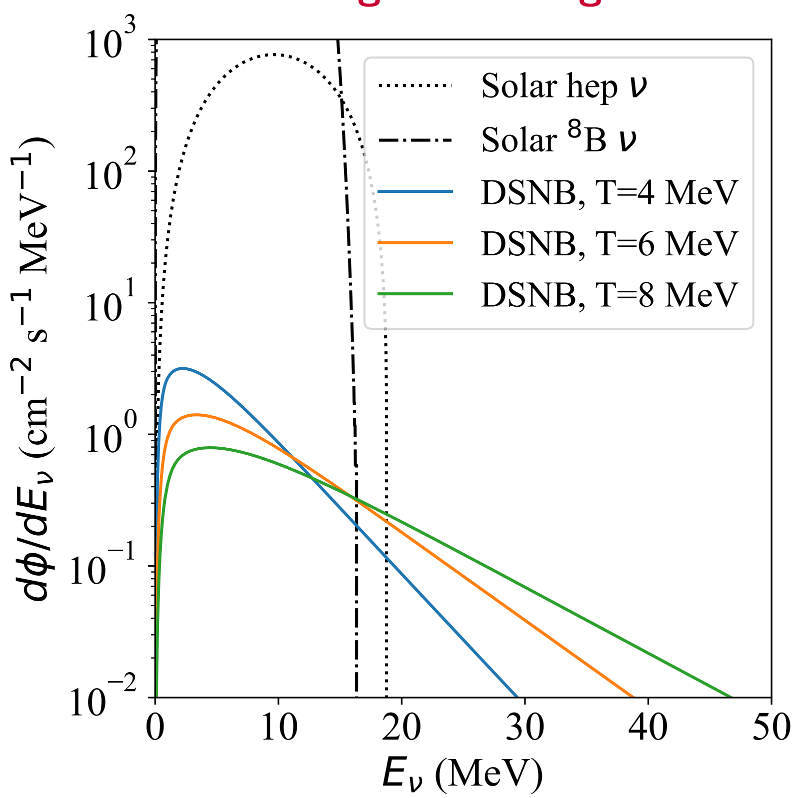
CC SNe rate
→ *Cosmology and star formation!*

(ΛCDM) Cosmology
→ *Cosmological effects!*

Redshifted spectra...



...integrated along z.



DSNB: Source

Modeling & Inputs

See also: Session S14: Astrophysical Neutrinos I
Meng-Ru Wu, "Neutrinos in supernovae and binary neutron star mergers"

Line-of-sight integral in redshift

→ New SNe & particle physics effects!
Neutrino emission spectrum

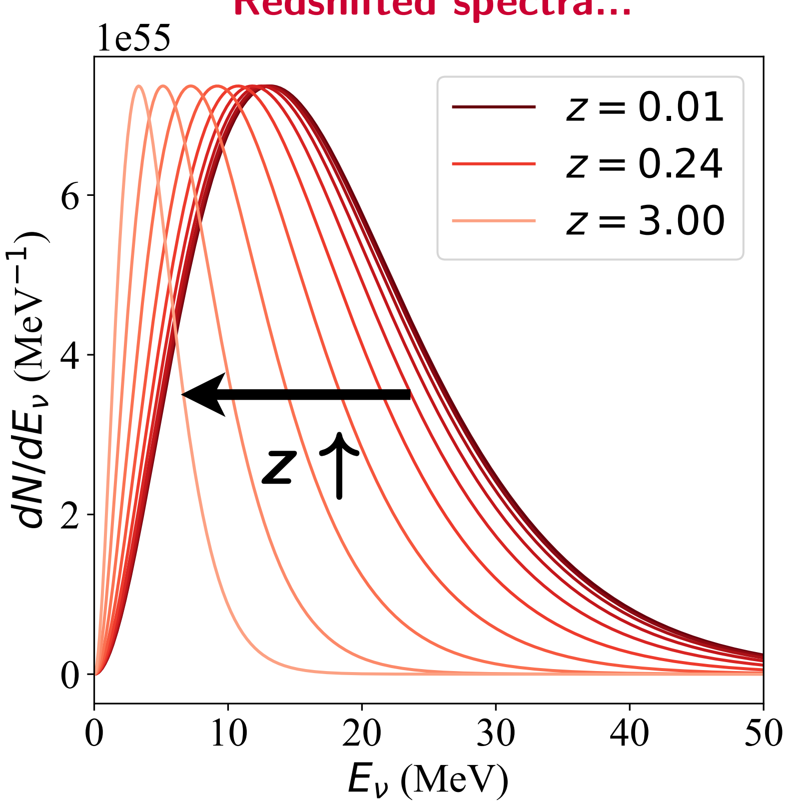
$$\frac{d\Phi(E_\nu)}{dE_\nu} = \int_0^{z_{\max}} R_{\rm SN}(z)\frac{dN[E(1+z)]}{dE}(1+z)\left|\frac{dt}{dz}\right| dz$$

DSNB Flux

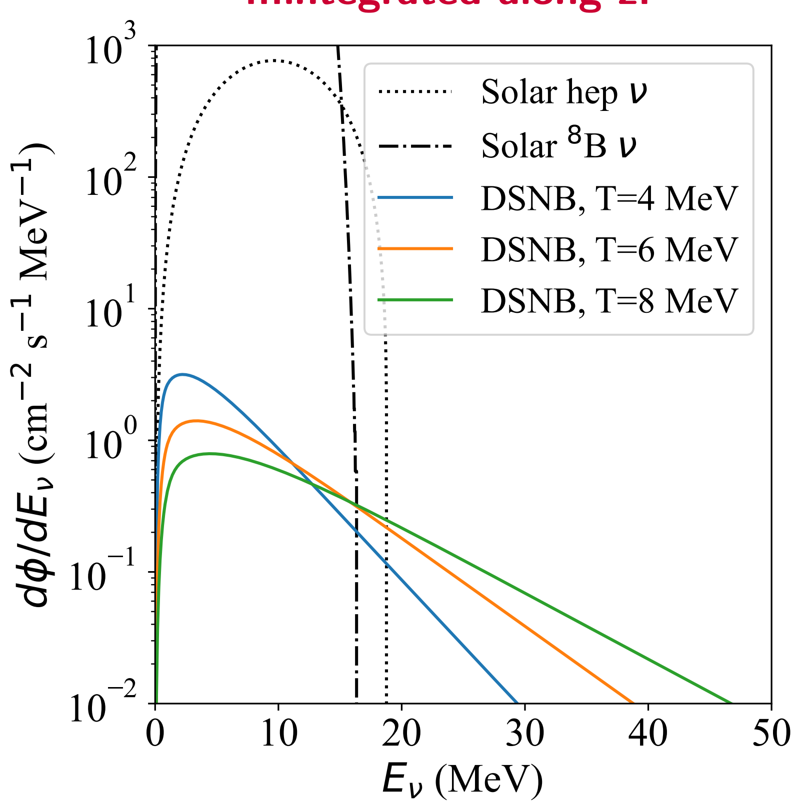
CC SNe rate
→ Cosmology and star formation!

(ΛCDM) Cosmology
→ Cosmological effects!

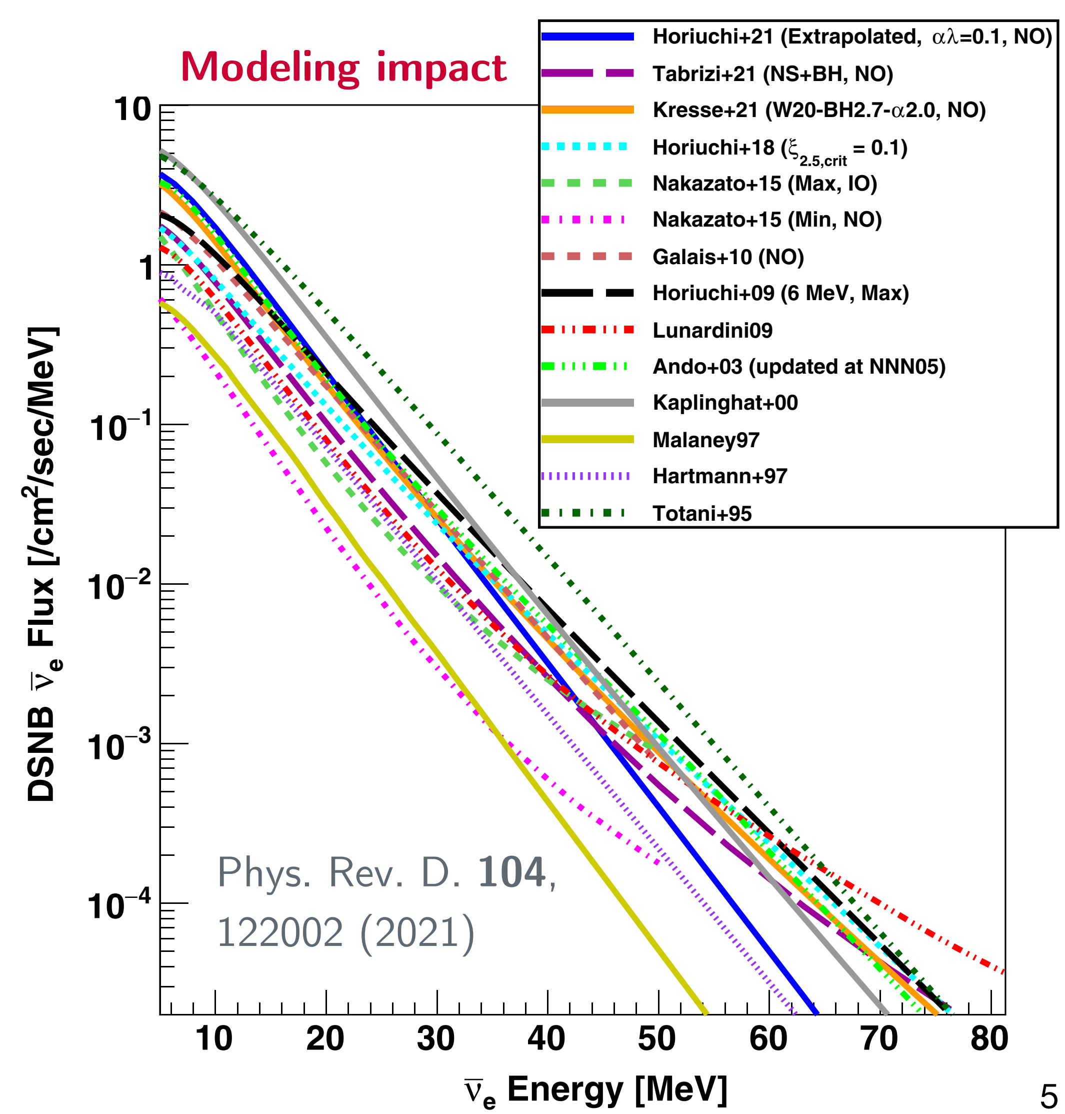
Redshifted spectra...



...integrated along z.

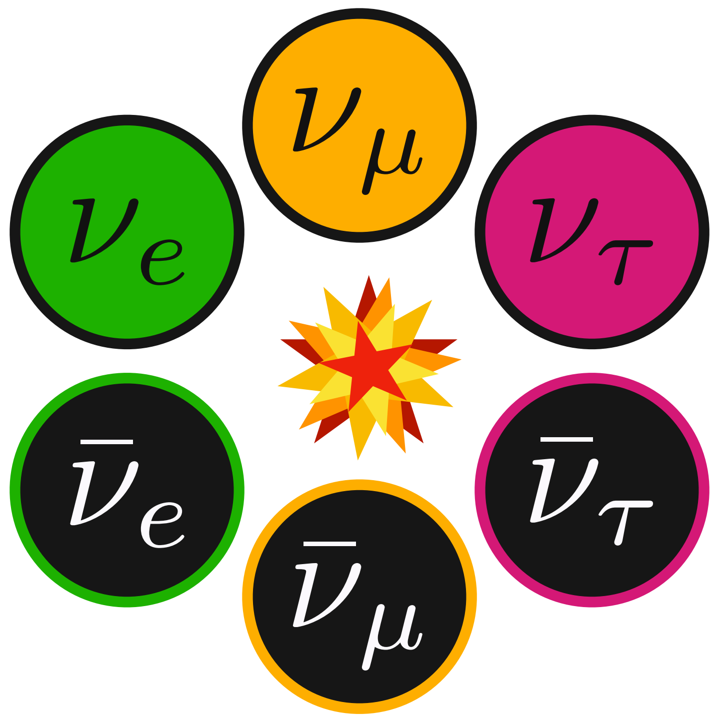


Modeling impact



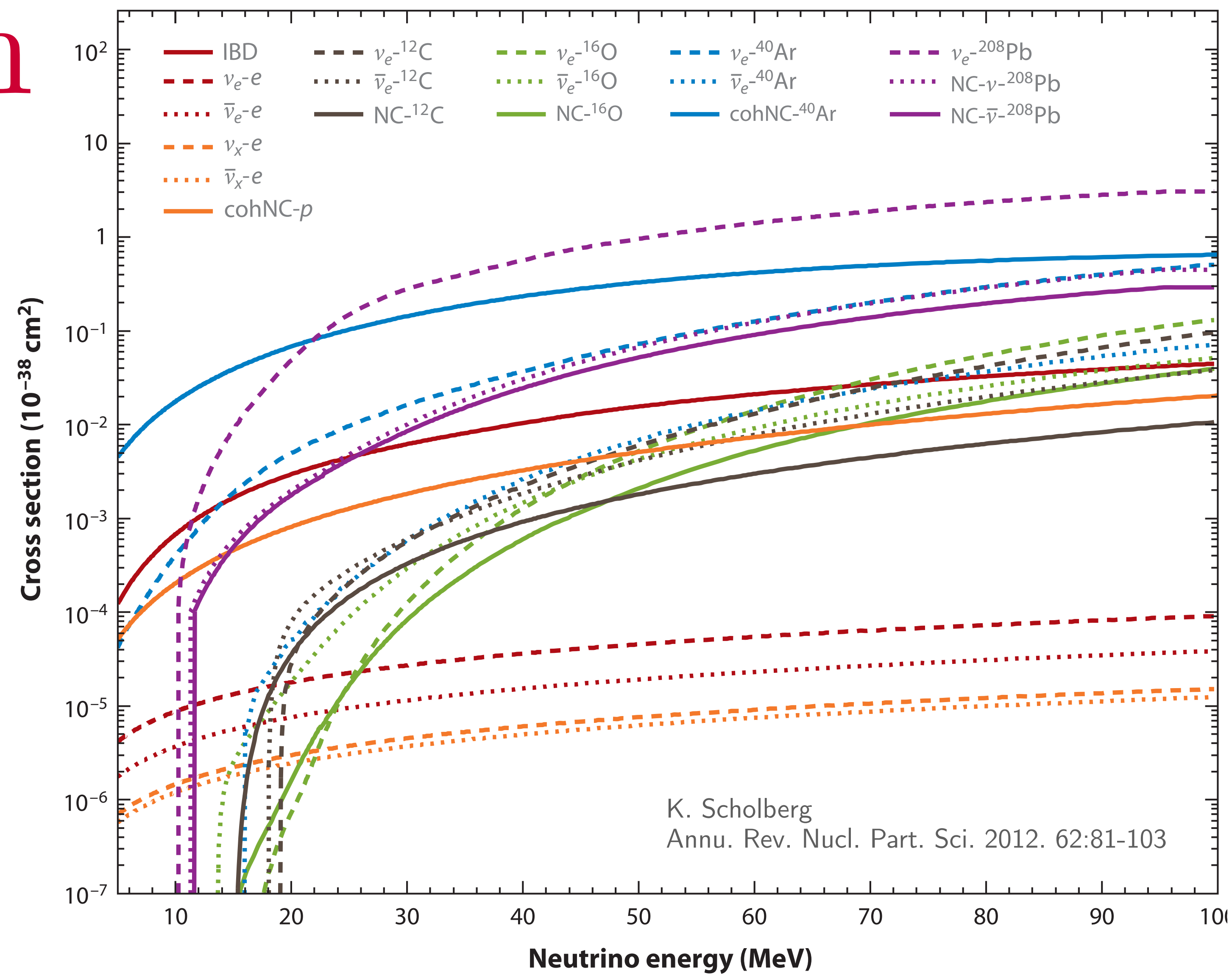
DSNB: Detection

Mechanisms & Approaches



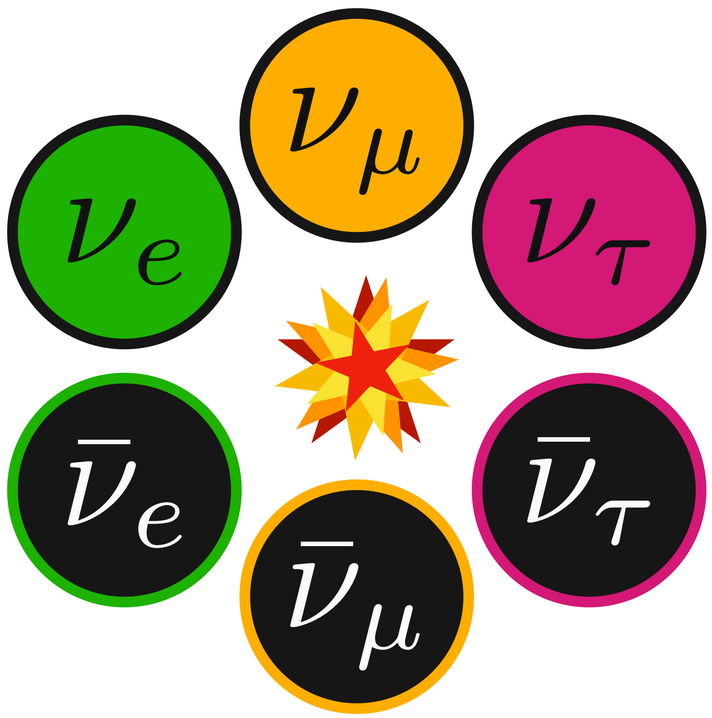
Roughly equal luminosity in each flavor

(Under standard modeling assumptions)



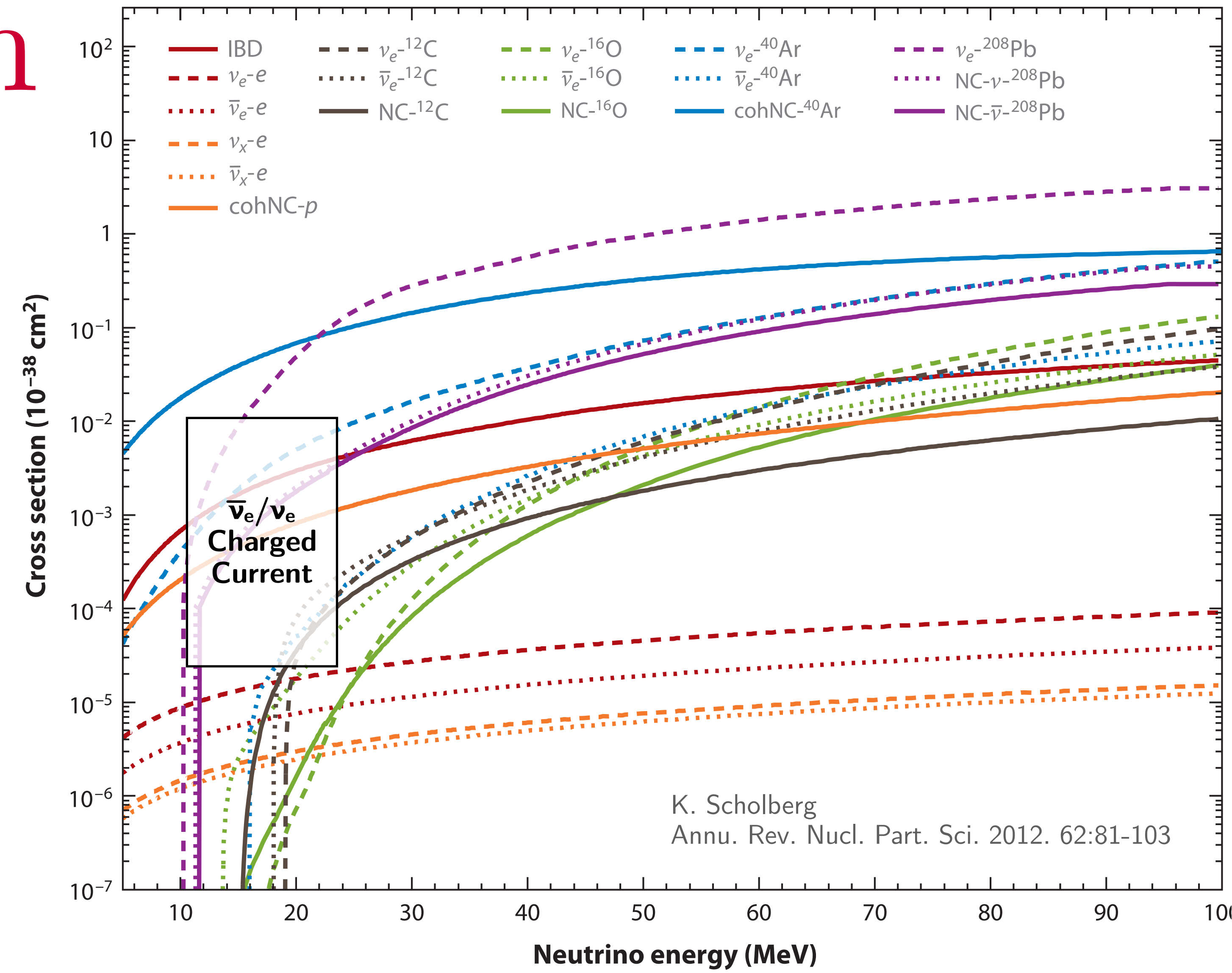
DSNB: Detection

Mechanisms & Approaches

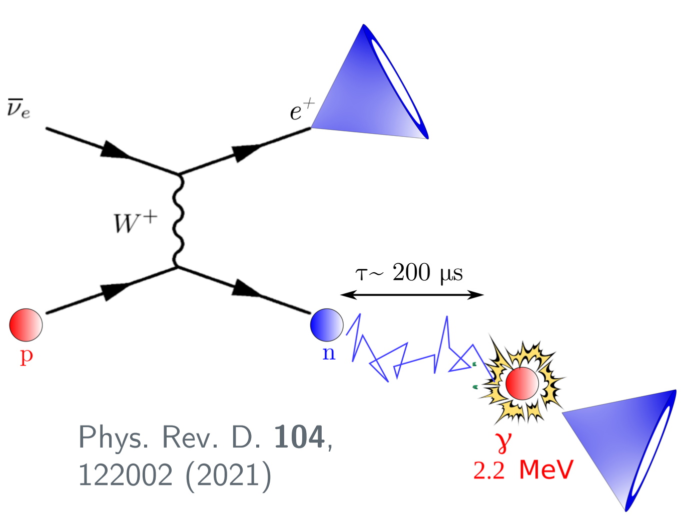


Roughly equal luminosity in each flavor

(Under standard modeling assumptions)

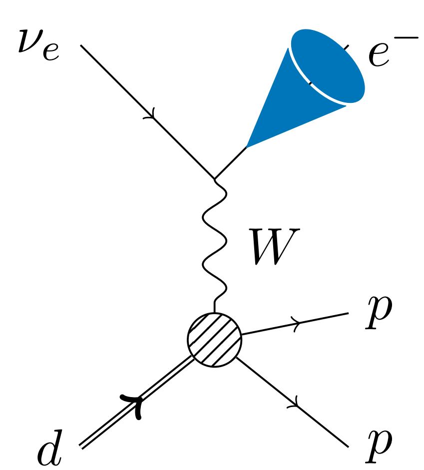


$\bar{\nu}_e$ Inverse Beta Decay (IBD)



Phys. Rev. D. **104**, 122002 (2021)

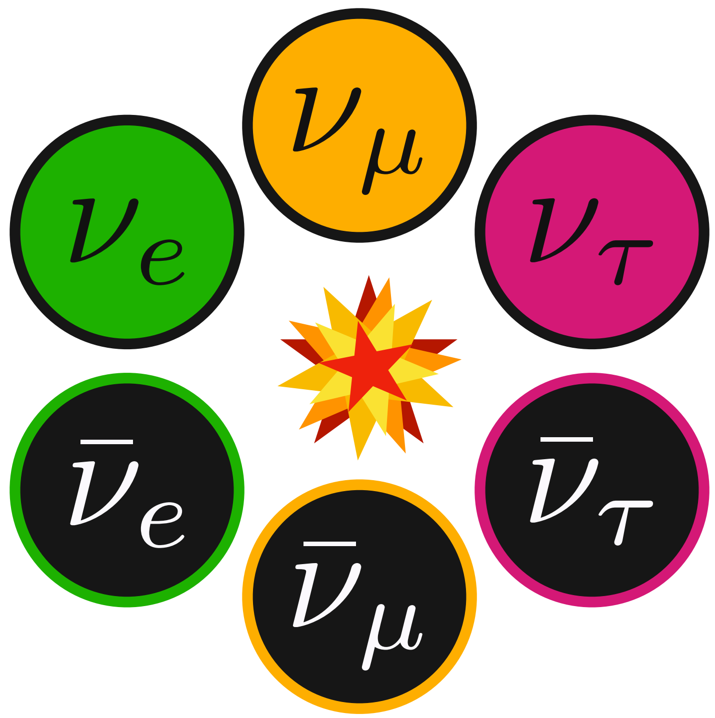
ν_e Charged Current



(Ex. Deuterium)

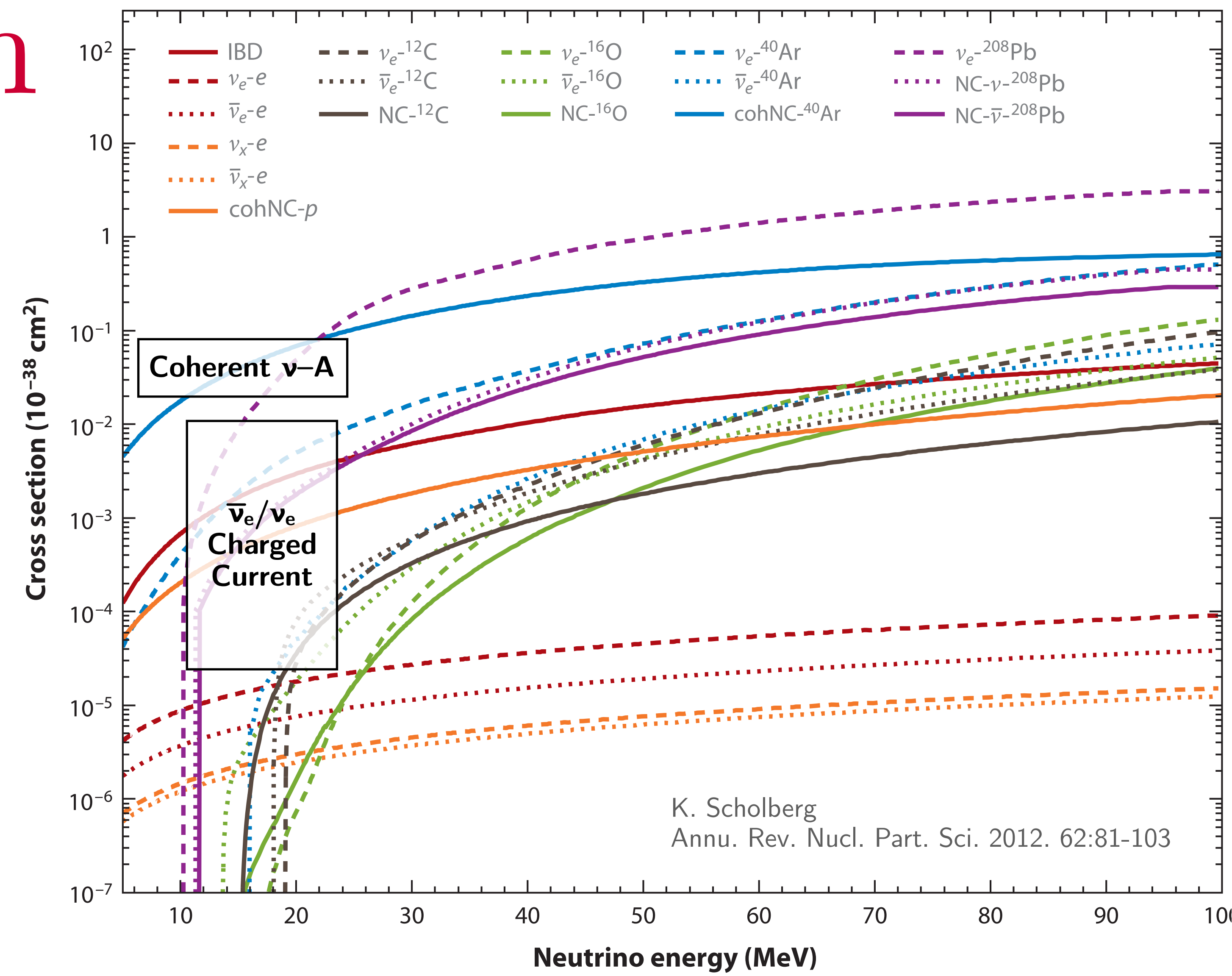
DSNB: Detection

Mechanisms & Approaches

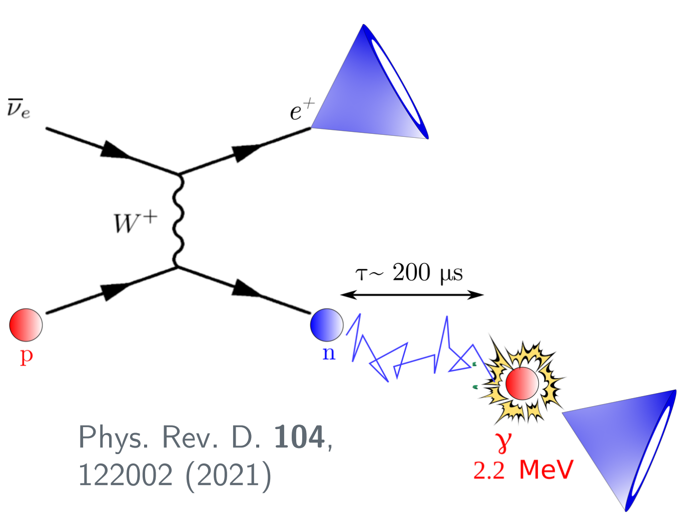


Roughly equal luminosity in each flavor

(Under standard modeling assumptions)

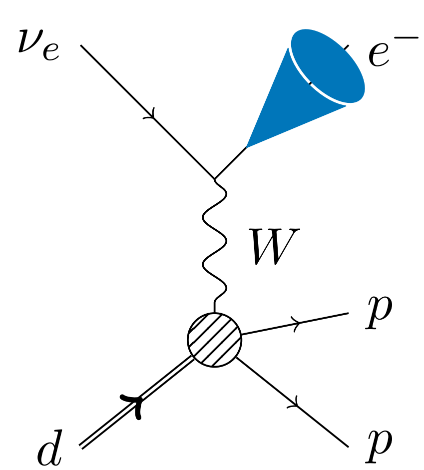


$\bar{\nu}_e$ Inverse Beta Decay (IBD)



Phys. Rev. D. **104**, 122002 (2021)

ν_e Charged Current



(Ex. Deuterium)

NC Coherent ν–A

Suliga, Beacom, Tamborra, PRD **105**, 043008 (2022) [Xe/Pb]

Pattavina, Iachellini, Tamborra, PRD **102**, 063001 (2020) [Pb]

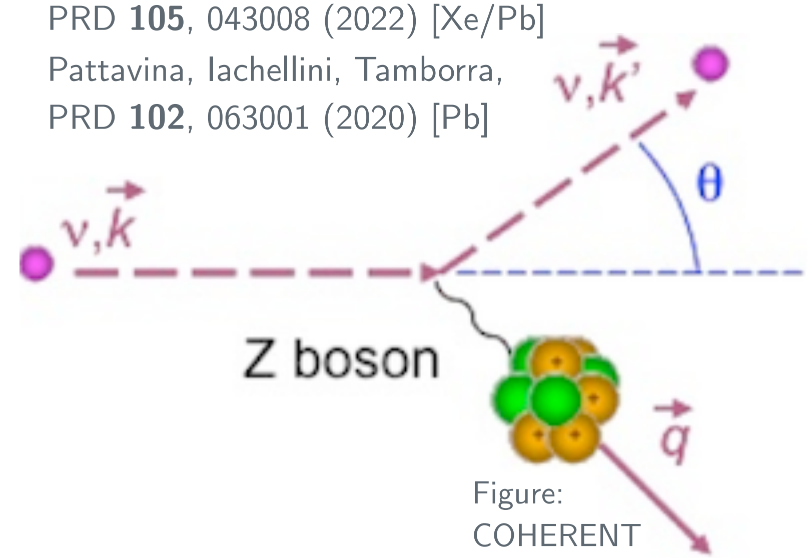
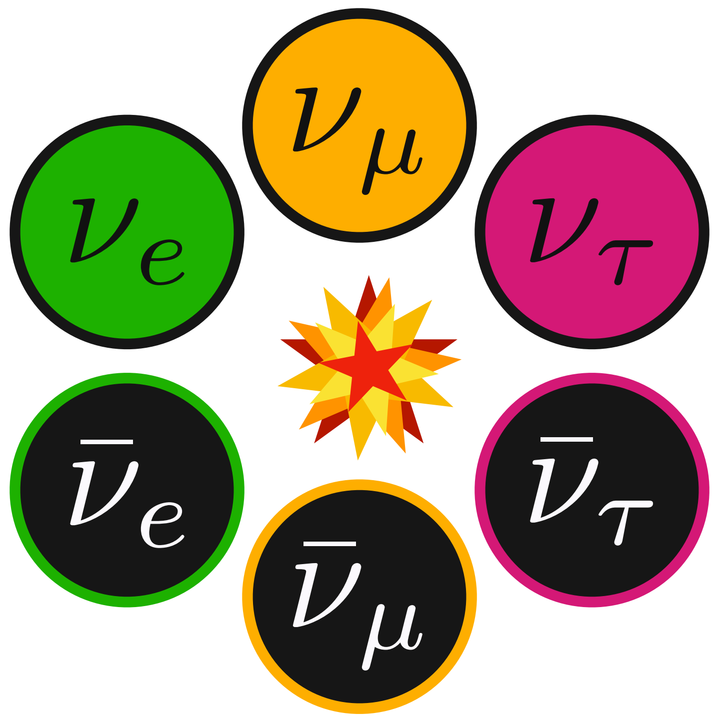


Figure: COHERENT

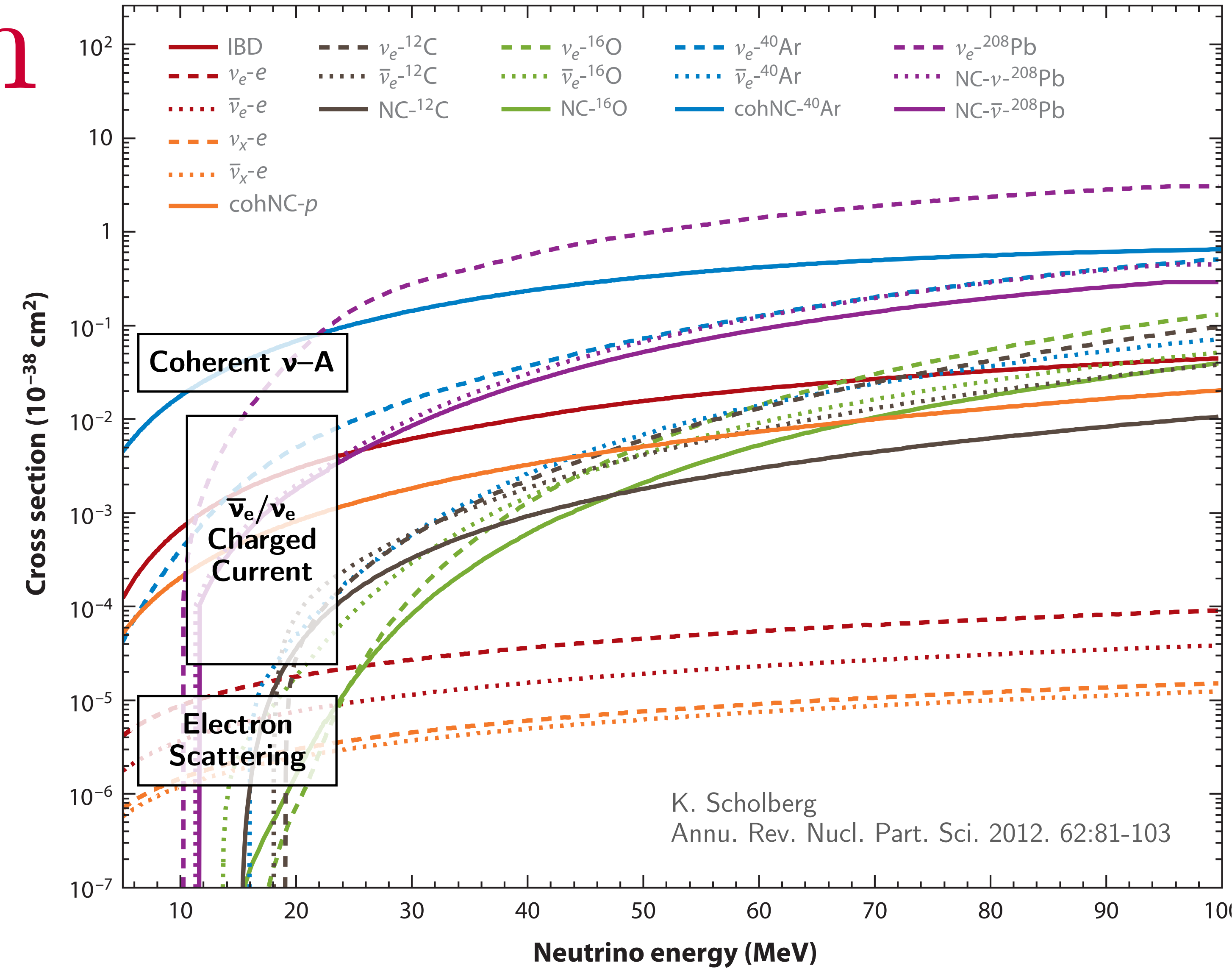
DSNB: Detection

Mechanisms & Approaches

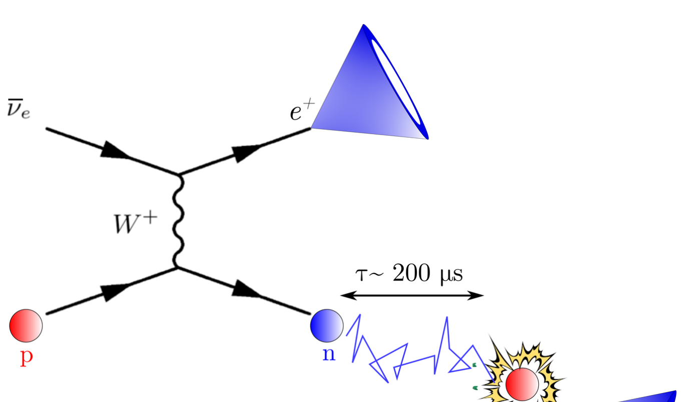


Roughly equal luminosity in each flavor

(Under standard modeling assumptions)

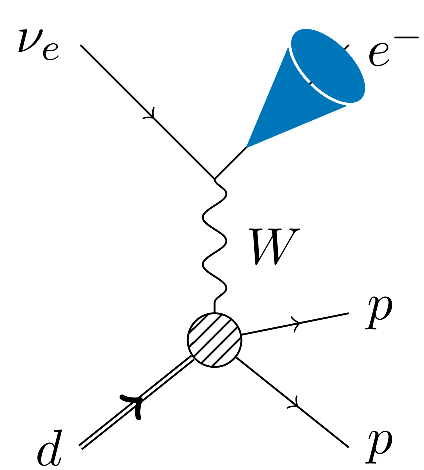


$\bar{\nu}_e$ Inverse Beta Decay (IBD)



Phys. Rev. D. **104**, 122002 (2021)

ν_e Charged Current



(Ex. Deuterium)

NC Coherent ν–A

Suliga, Beacom, Tamborra, PRD **105**, 043008 (2022) [Xe/Pb]

Pattavina, Iachellini, Tamborra, PRD **102**, 063001 (2020) [Pb]

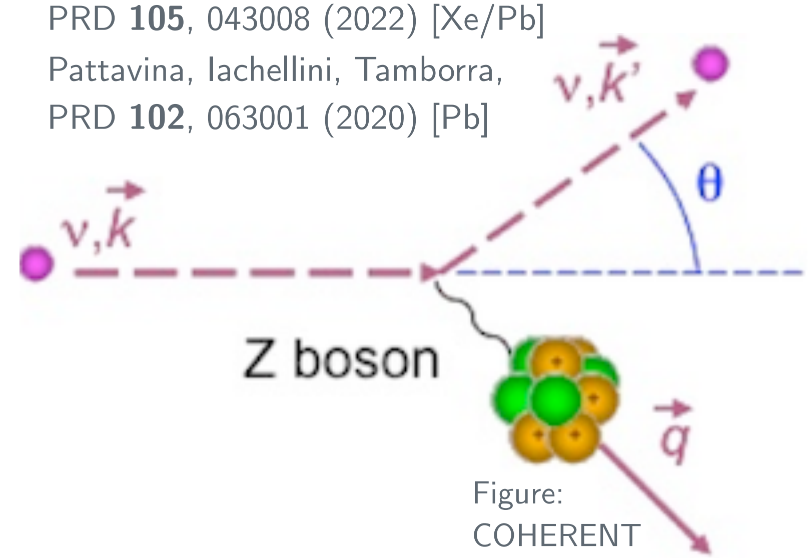
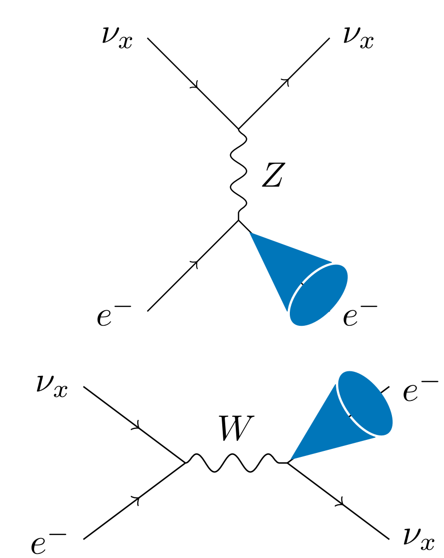


Figure: COHERENT

Electron Scattering



Tabrizi, Horiuchi, JCAP05(2011)011 [ν–e, ν–p ES]

DSNB Searches

Recent Highlights

Super-Kamiokande

Joint SK I–IV $\overline{\nu}_e$ search

Phys. Rev. D. **104**, 122002 (2021)

Sudbury Neutrino Observatory

Full dataset ν_e

Phys. Rev. D. **102**, 062006 (2020)

Borexino

Astrophysical $\overline{\nu}_e$

Astropart. Phys. **125**, 102509 (2021)

KamLAND

Astrophysical $\overline{\nu}_e$

Astrophys. J. **925**:14 (2022)

SuperK

The Experiment

Super-Kamiokande
(SuperK)

Location: Kamioka Mine, Japan

Type: Water Cherenkov

Channel: $\bar{\nu}_e$ IBD

Mass: 50 kton (22.5 fiducial)

Exposure: 22.5 kton $\times$ 5823 days

Depth: 2700 mwe

- Phases I–III (1996 – 2008 $\rightarrow$ 3033 d)
- Phase IV (2008 – 2018 $\rightarrow$ 2790 d)
  - Improved triggering $\rightarrow$ neutron tagging
- Phase VI (Jul. '20 – present)
  - **Gd** loading $\rightarrow$ next talk!

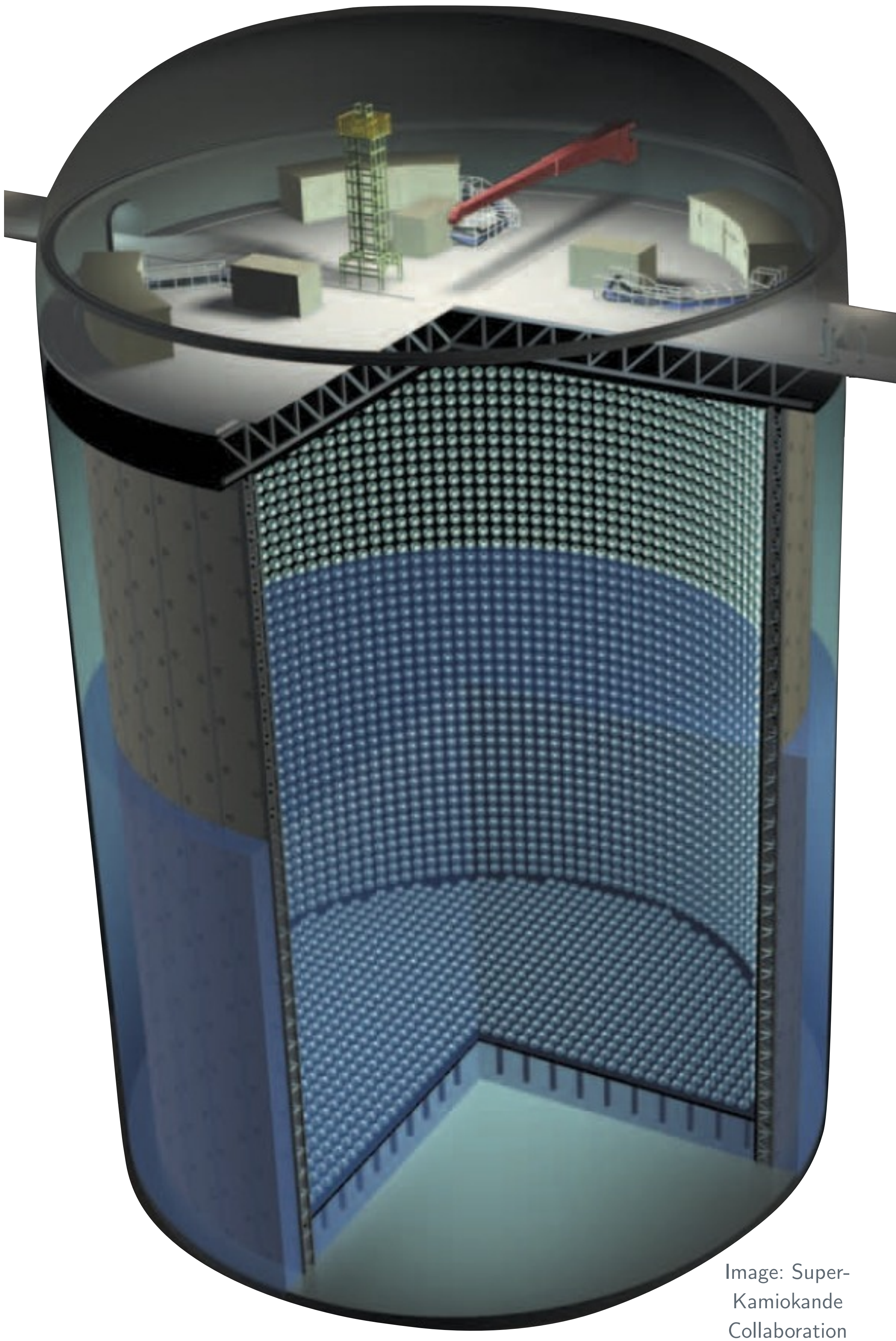


Image: Super-Kamiokande Collaboration

SuperK
DSNB Search Analysis

Super-Kamiokande Collaboration, Phys. Rev. D **104**, 122002 (2021)

Channel: $\bar{\nu}_e$ Inverse Beta Decay (IBD)
Signatures: Prompt e^+ (SKI–IV) and neutron (SKIV)
Exposure: 22.5 kton × [3033 (I–III) + 2790 (IV)] days

Analysis Highlights:

- Huge exposure in SK I–IV
- Enhanced trigger with 500 μs window for neutron captures
- Improved analysis algorithms
  - Neutron capture selection
  - Multivariate likelihood reduces spallation backgrounds significantly
  - Angle/scattering-based solar neutrino rejection

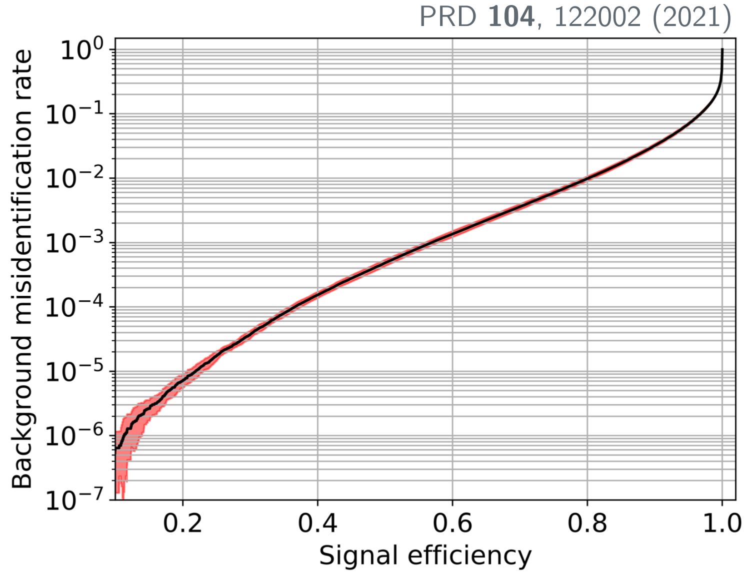
} Neutron captures via BDT-based search of low-energy event clusters, tuned with AmBe source data

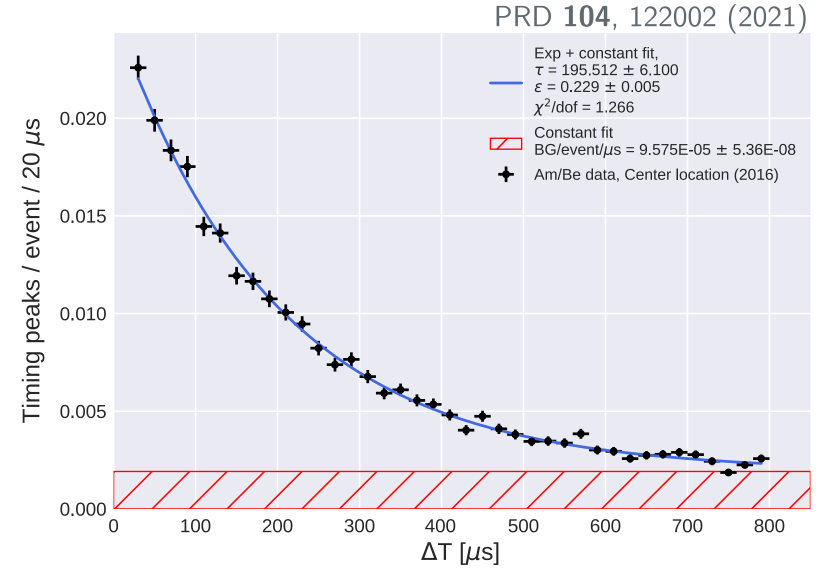
Model-Independent Analysis (SK IV, $N_n = 1$)

- Differential upper limit, $9.5 < E_\nu < 29.5$ MeV
- Atmospherics constrained with high-energy sideband
- Data-driven estimates for modeling of neutron multiplicity (T2K), ^{9}Li (SK), accidentals (SK)

Spectral Analysis (SK I–IV)

- Fit to a benchmark model, $15.5 < E_\nu < 79.5$ MeV
- Six samples: (3×Cherenkov angle)×(2×N_n)
  - Separates signal IBD, invisible/visible μ/π, NCQE, and spallation backgrounds
- Likelihood fit in normalizations, PDF shapes
- Combined fit with SK I–III data (PRD **85**, 052007, 2012), using SK IV model to account for spallation





SK IV neutron tagging

SuperK

DSNB Search Results: Model-Independent

Model-Independent Results (SK IV, $N_n = 1$)

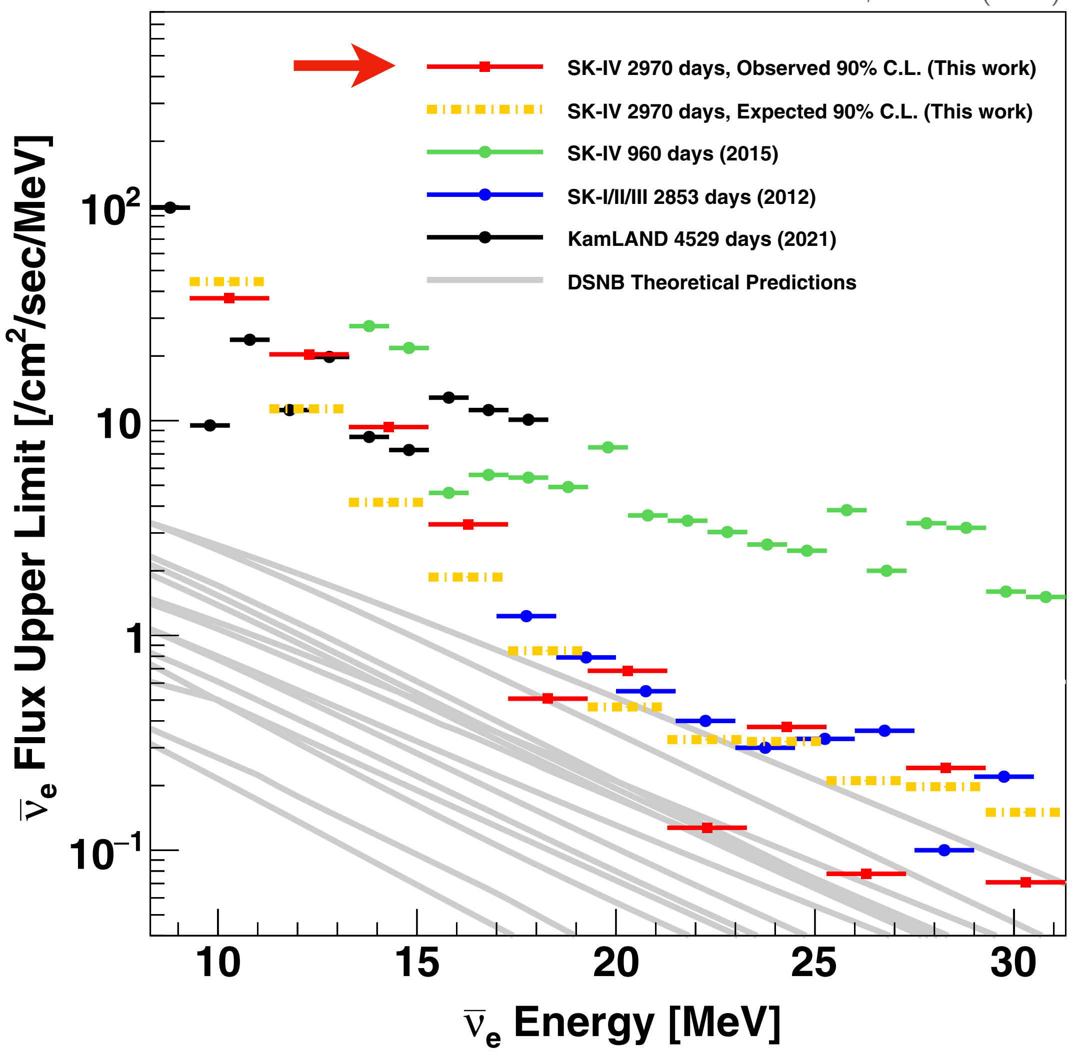
- No excess observed
- No single bin above 2σ relative to backgrounds
- Strongest constraints for $E_\nu > 11.3$ MeV
- Disfavors the most optimistic DSNB models

TABLE V. Summary on the 90% CL expected sensitivities and observed upper limits as well as the corresponding p-values in each electron antineutrino energy bin ($E_\nu = E_{rec} + 1.8$ MeV).

E_ν (MeV)	Expected (cm^{-2} sec^{-1} MeV^{-1})	Observed ($cm^{-2}sec^{-1}$ MeV^{-1})	p-value
9.3–11.3	4.44×10^{1}	3.71×10^{1}	0.346
11.3–13.3	1.14×10^{1}	2.04×10^{1}	0.886
13.3–15.3	4.17×10^{0}	9.34×10^{0}	0.938
15.3–17.3	1.87×10^{0}	3.29×10^{0}	0.830
17.3–19.3	8.48×10^{-1}	5.08×10^{-1}	0.243
19.3–21.3	4.64×10^{-1}	6.84×10^{-1}	0.686
21.3–23.3	3.28×10^{-1}	1.27×10^{-1}	0.073
23.3–25.3	2.11×10^{-1}	3.75×10^{-1}	0.597
25.3–27.3	2.13×10^{-1}	7.77×10^{-2}	0.051
27.3–29.3	1.98×10^{-1}	2.42×10^{-1}	0.605
29.3–31.3	1.50×10^{-1}	7.09×10^{-2}	0.126

PRD **104**, 122002 (2021)

PRD **104**, 122002 (2021)

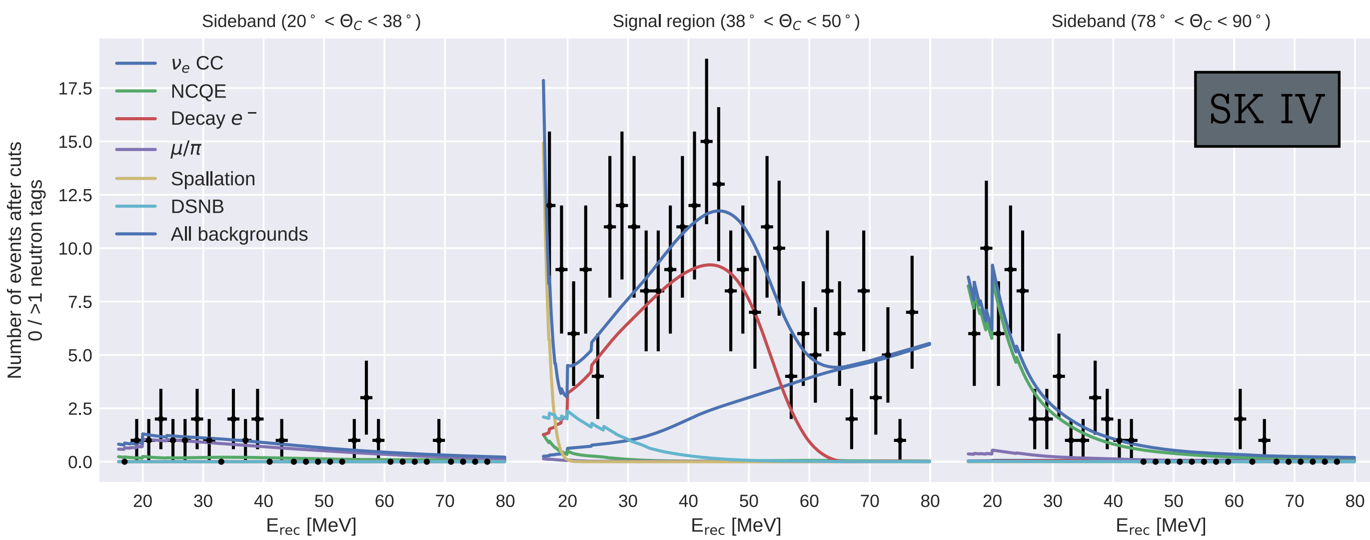


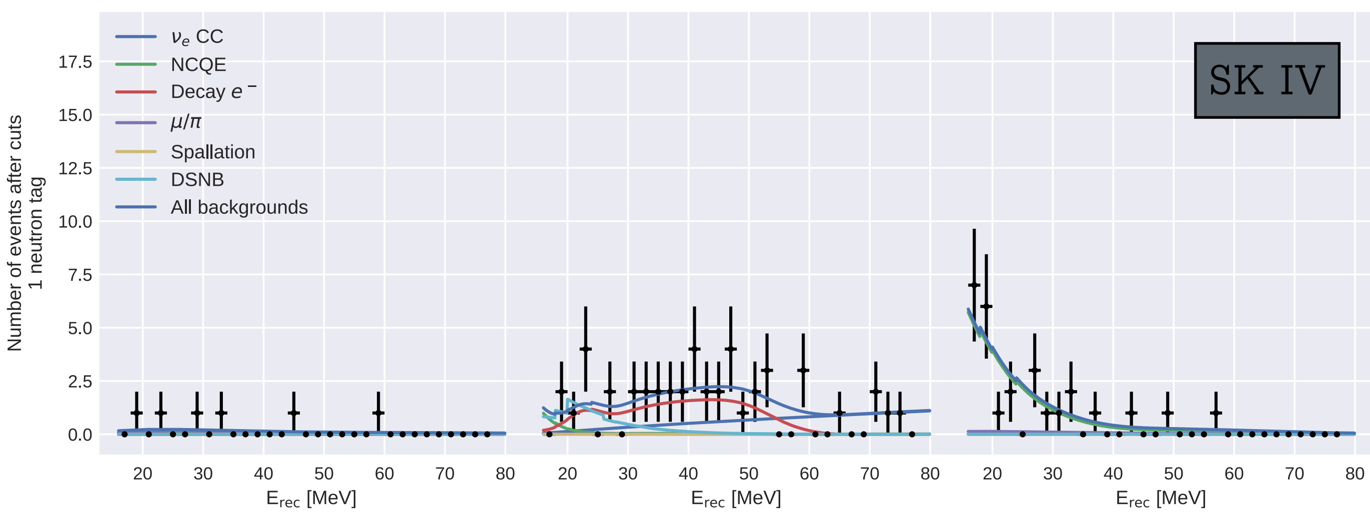
Super-Kamiokande Collaboration, Phys. Rev. D **104**, 122002 (2021)

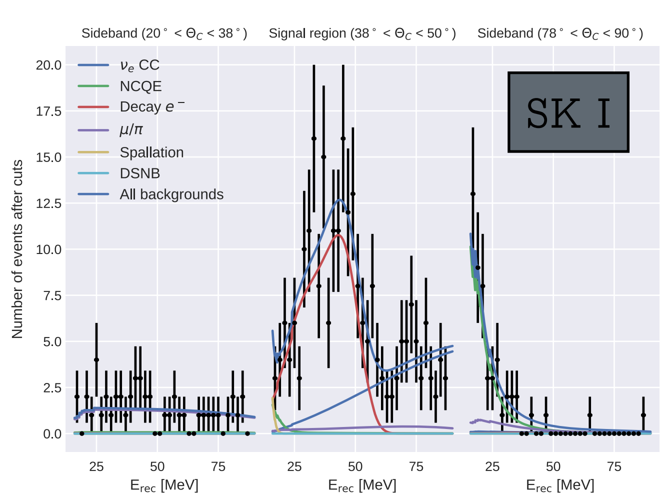
SuperK

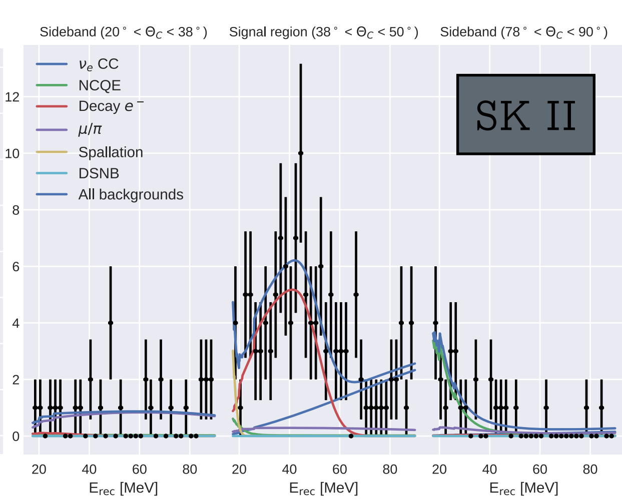
DSNB Search Results: Spectral Analysis

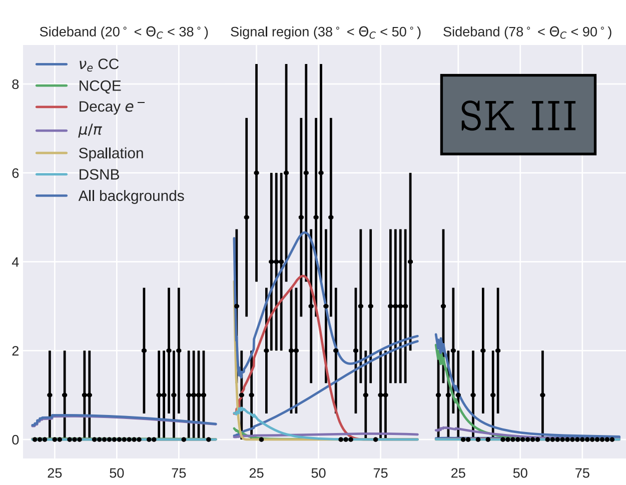
Super-Kamiokande Collaboration, Phys. Rev. D **104**, 122002 (2021)











Spectral Analysis Results **(SK I–IV)**

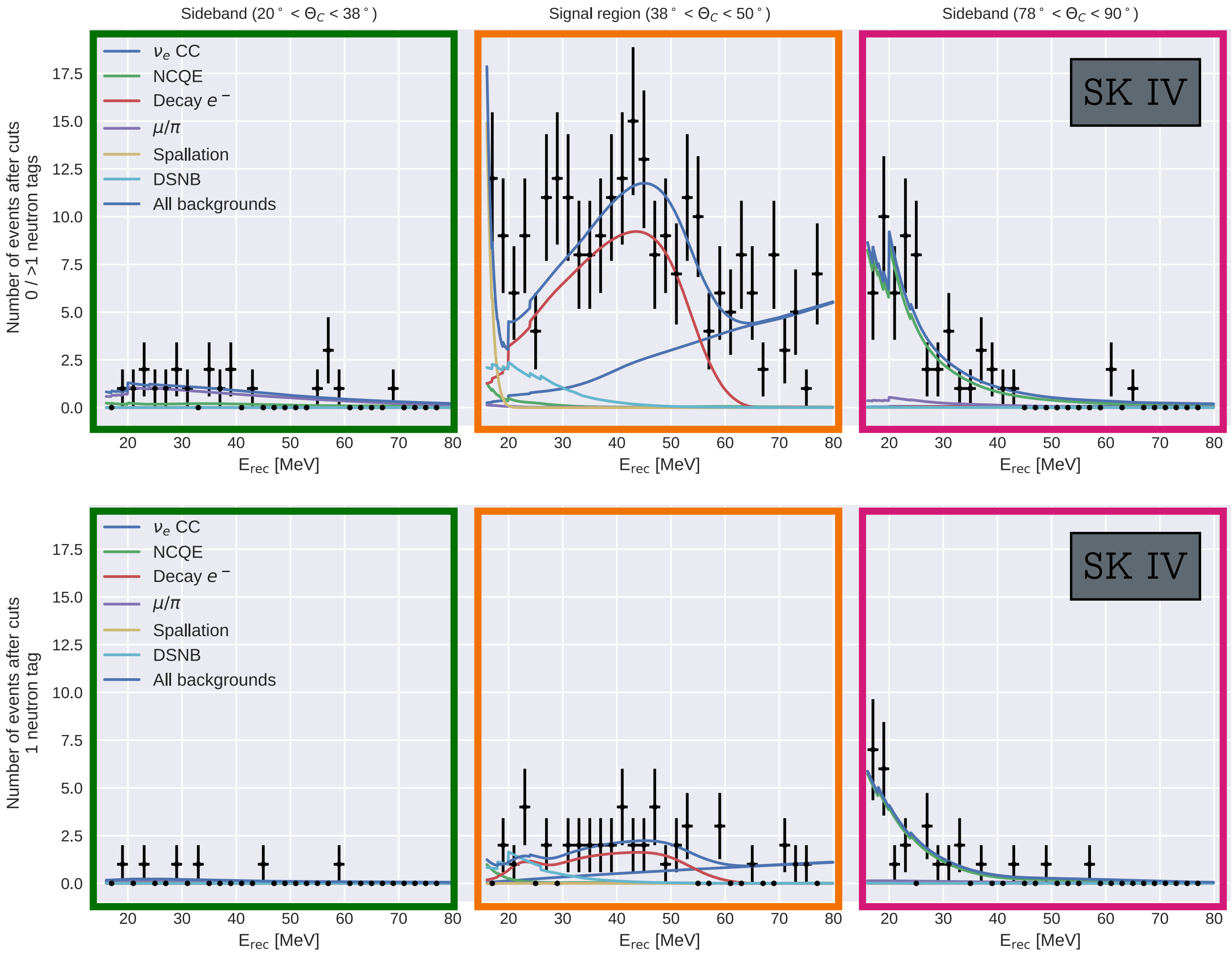
- Sensitive to 1.5 $\overline{\nu}_e/\mathrm{cm}^2/\mathrm{s}$, Horiuchi+09 model is 1.9
- Combined upper limit of 2.6 $\overline{\nu}_e/\mathrm{cm}^2/\mathrm{s}$
  - Most optimistic signals are excluded
- Best fit is $1.3^{+0.90}_{-0.85}$ $\overline{\nu}_e/\mathrm{cm}^2/\mathrm{s}$
  - 1.5σ excess over background expectation

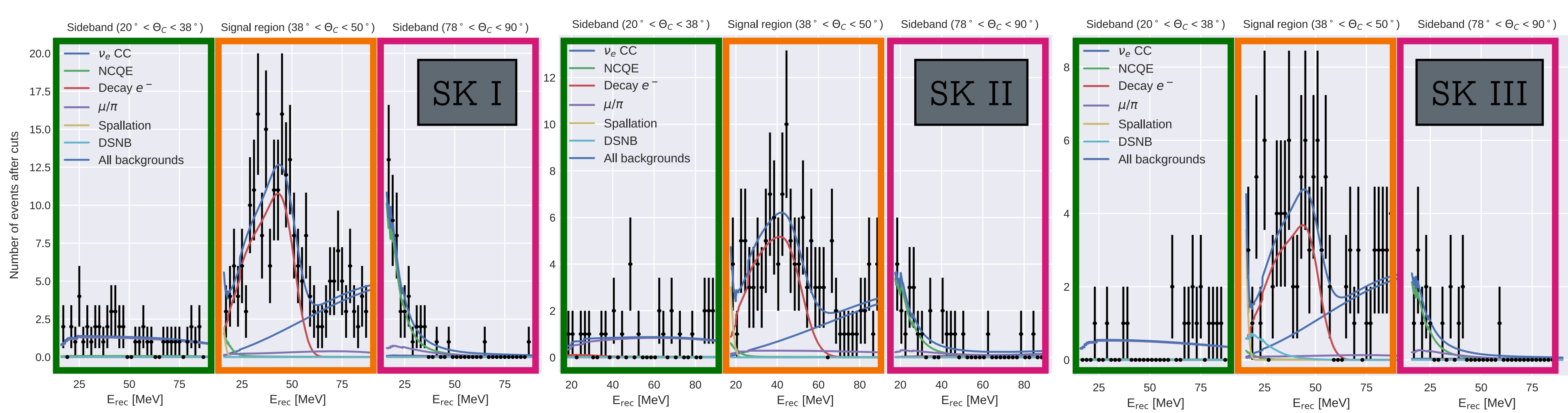
SuperK

DSNB Search Results: Spectral Analysis

Super-Kamiokande Collaboration, Phys. Rev. D **104**, 122002 (2021)

20° < θ_c < 38°: μ & π   38° < θ_c < 50°: Signal rich   78° < θ_c < 90°: NCQE, γ





Spectral Analysis Results (SK I–IV)

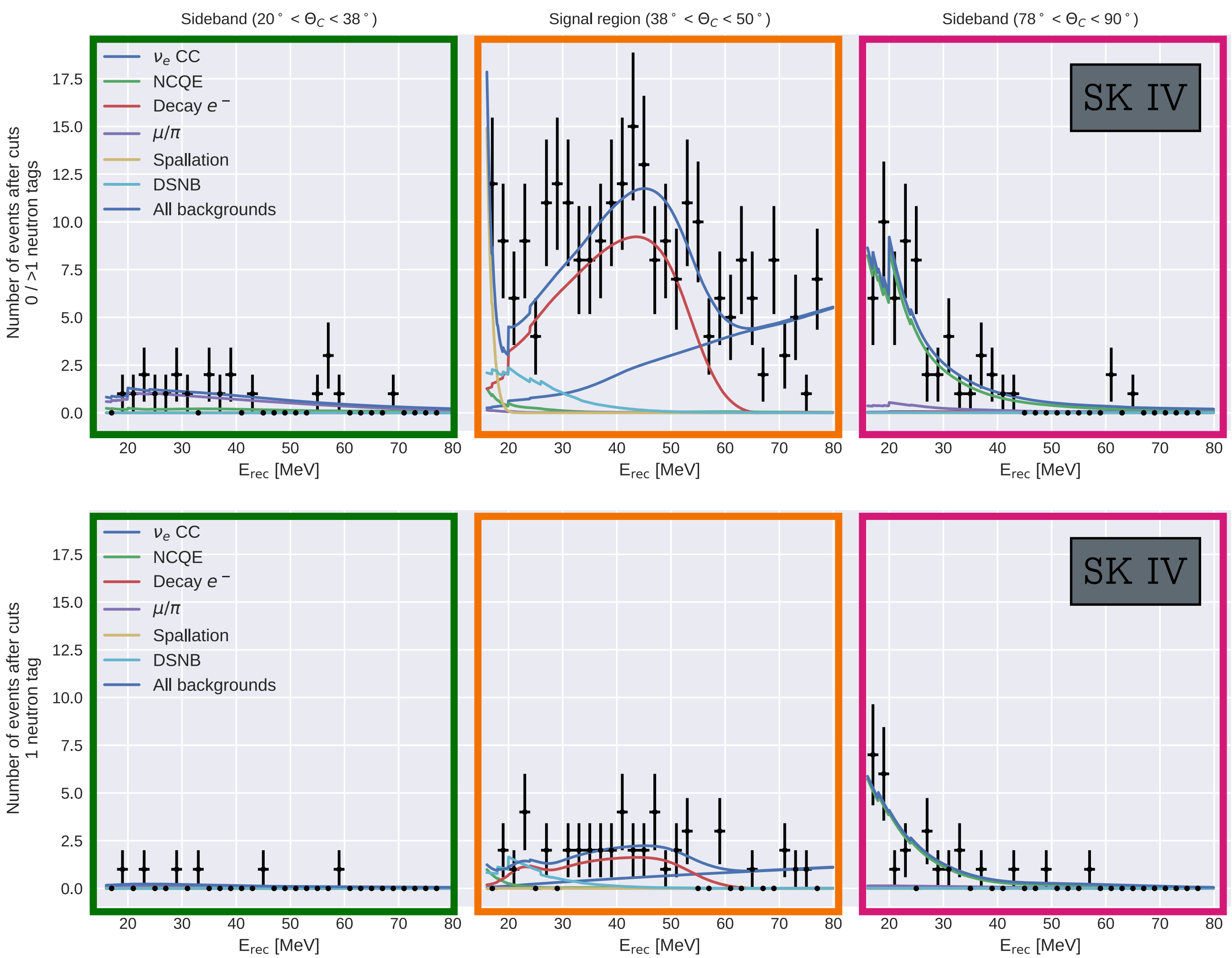
- Sensitive to 1.5 $\overline{\nu}_e$/cm²/s, Horiuchi+09 model is 1.9
- Combined upper limit of 2.6 $\overline{\nu}_e$/cm²/s
  - Most optimistic signals are excluded
- Best fit is $1.3^{+0.90}_{-0.85}$ $\overline{\nu}_e$/cm²/s
  - 1.5σ excess over background expectation

SuperK

DSNB Search Results: Spectral Analysis

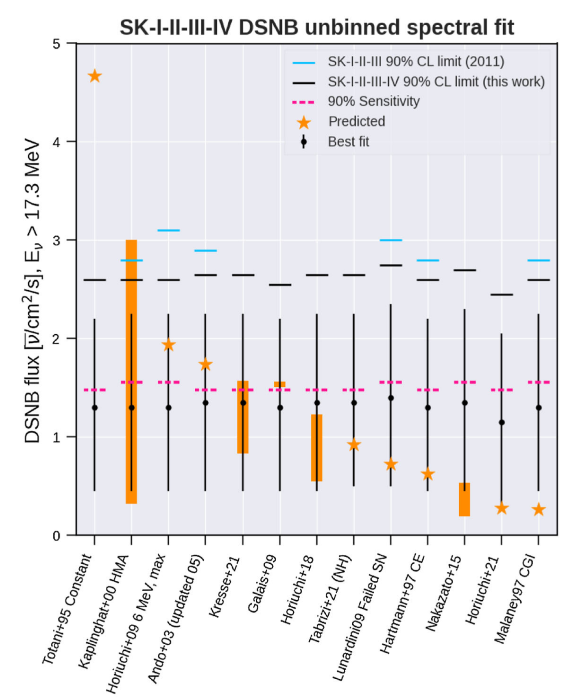
Super-Kamiokande Collaboration, Phys. Rev. D **104**, 122002 (2021)

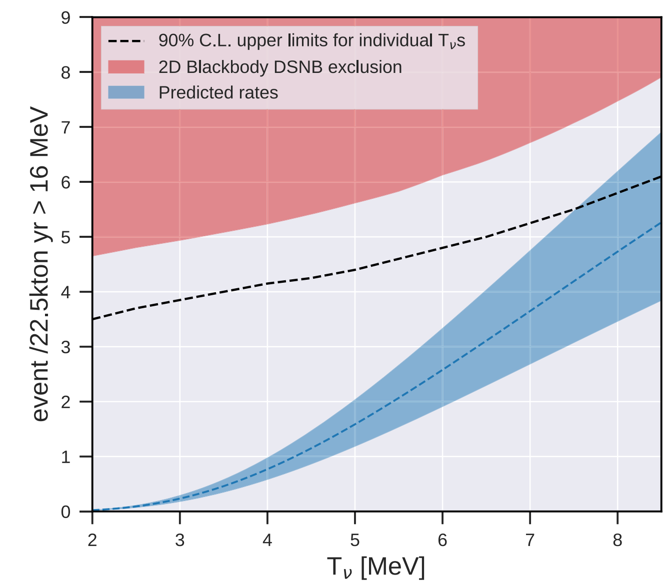
$20^\circ < \theta_c < 38^\circ$: μ & π $38^\circ < \theta_c < 50^\circ$: Signal rich $78^\circ < \theta_c < 90^\circ$: NCQE, γ

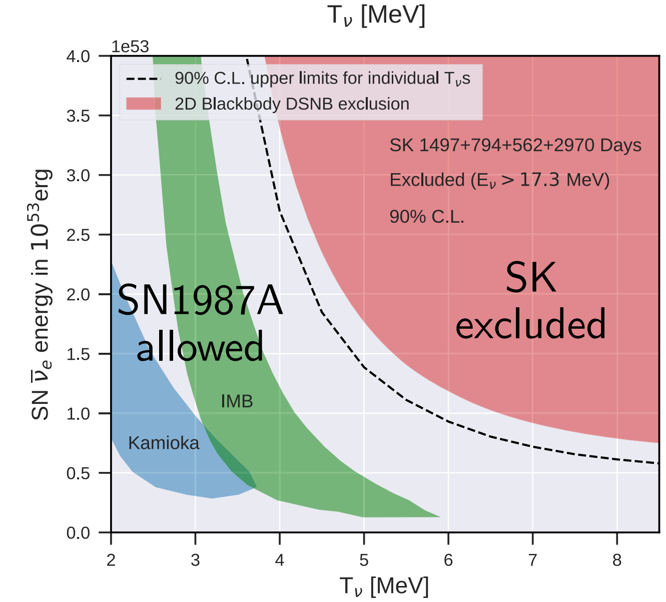


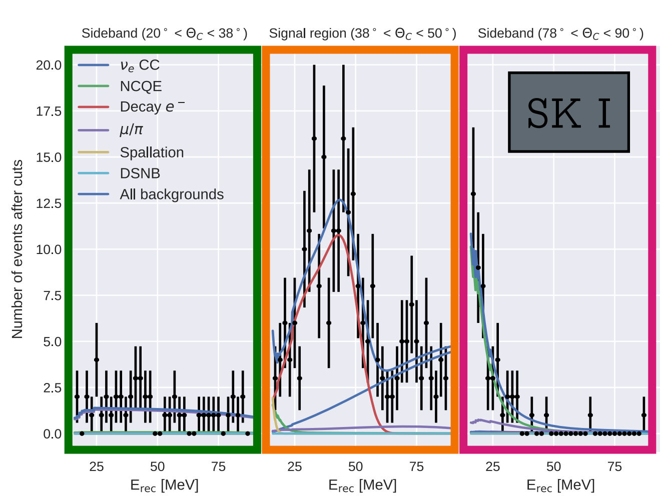
Spectral Analysis Results (SK I–IV)

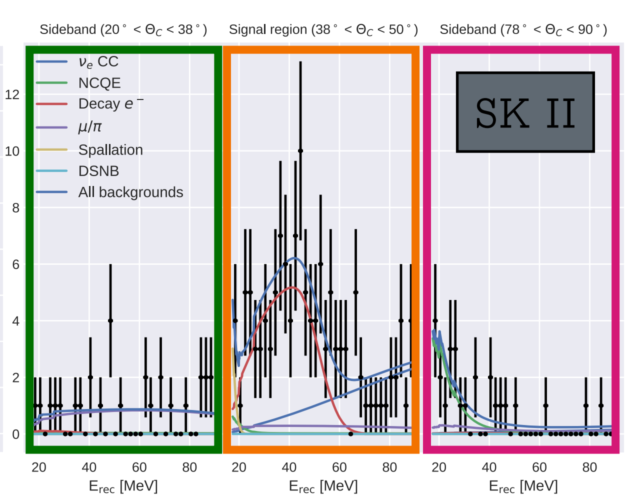
- Sensitive to 1.5 $\overline{\nu}_e/\mathrm{cm}^2/\mathrm{s}$, Horiuchi+09 model is 1.9
- Combined upper limit of 2.6 $\overline{\nu}_e/\mathrm{cm}^2/\mathrm{s}$
  - Most optimistic signals are excluded
- Best fit is $1.3^{+0.90}_{-0.85}$ $\overline{\nu}_e/\mathrm{cm}^2/\mathrm{s}$
  - 1.5σ excess over background expectation

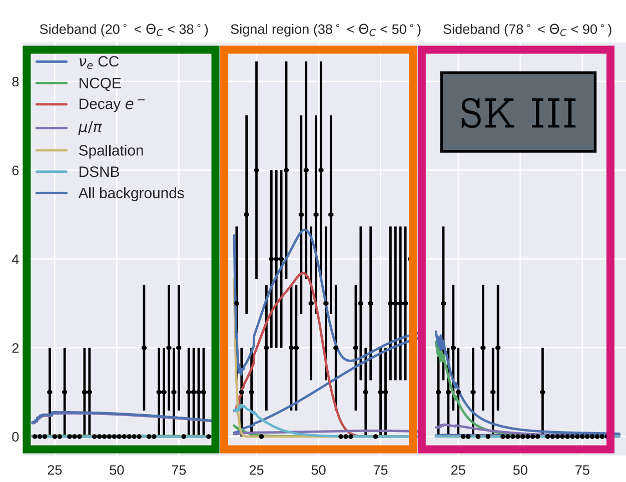










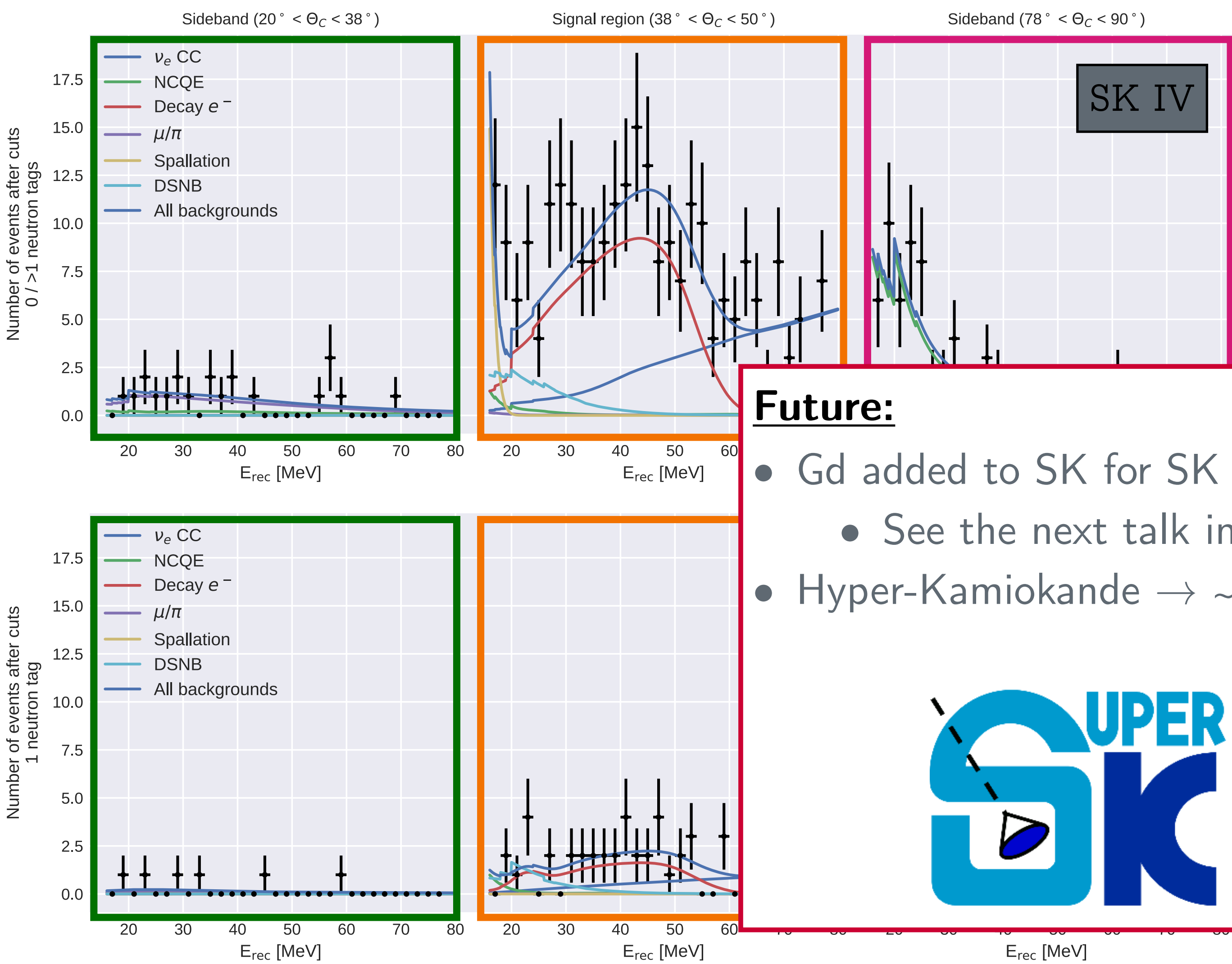


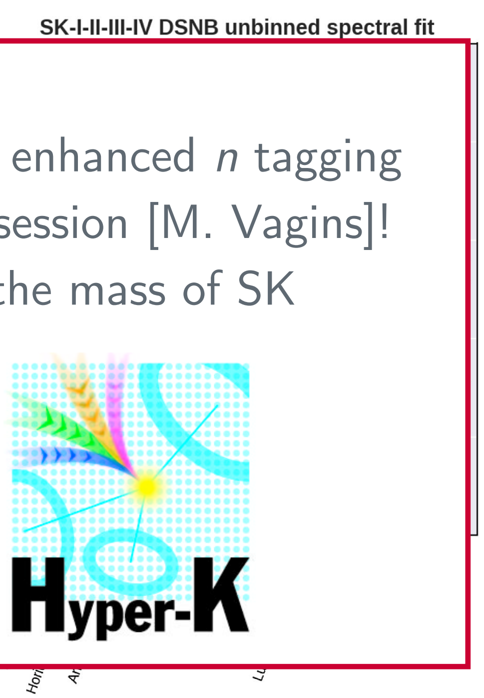
SuperK

DSNB Search Results: Spectral Analysis

Super-Kamiokande Collaboration, Phys. Rev. D **104**, 122002 (2021)

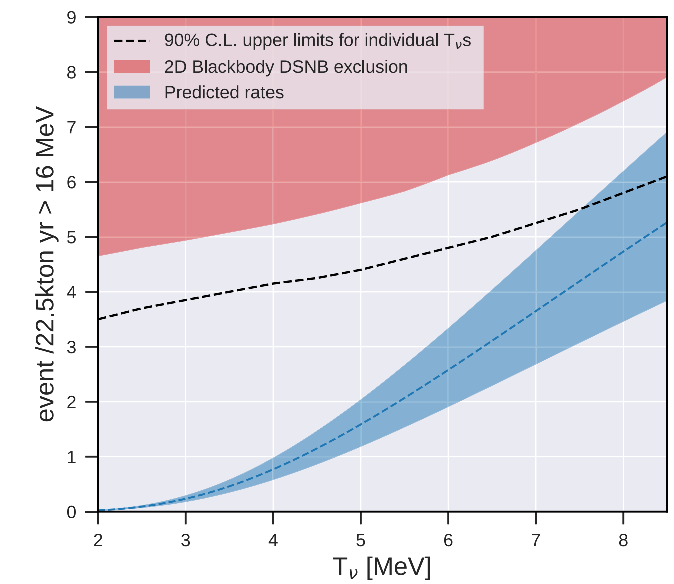
$20^\circ < \theta_c < 38^\circ$: μ & π $38^\circ < \theta_c < 50^\circ$: Signal rich $78^\circ < \theta_c < 90^\circ$: NCQE, γ

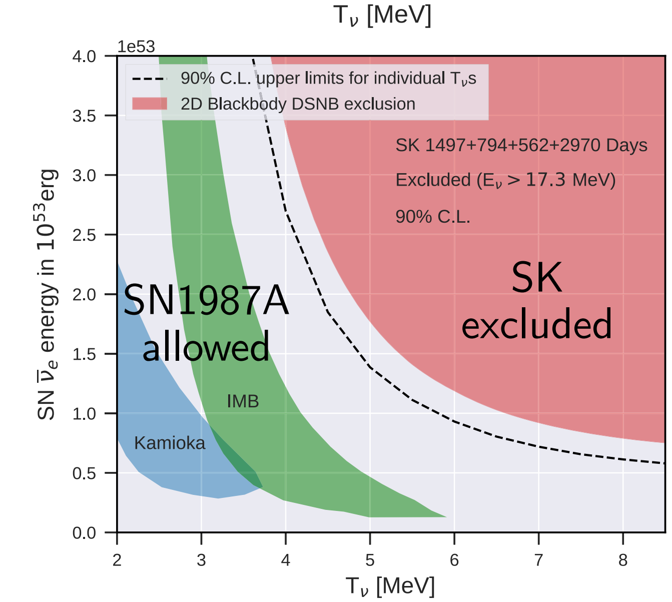




Spectral Analysis Results (SK I–IV)

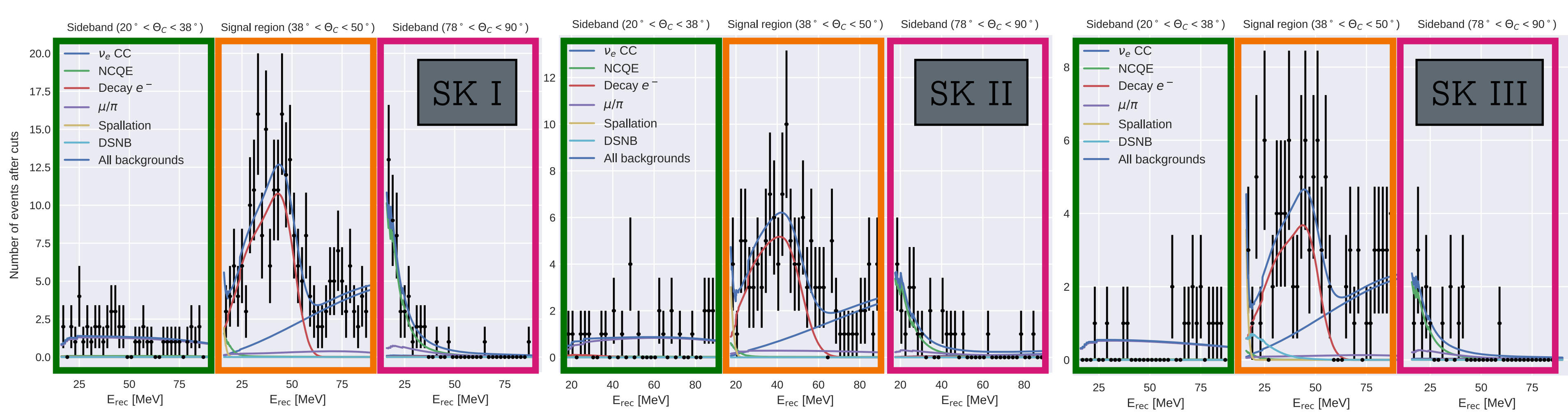
- Sensitive to 1.5 $\overline{\nu}_e/\text{cm}^2/\text{s}$, Horiuchi+09 model is 1.9
- Combined upper limit of 2.6 $\overline{\nu}_e/\text{cm}^2/\text{s}$
  - Most optimistic signals are excluded
- Best fit is $1.3^{+0.90}_{-0.85}$ $\overline{\nu}_e/\text{cm}^2/\text{s}$
  - 1.5σ excess over background expectation





Future:

- Gd added to SK for SK VI → enhanced *n* tagging
  - See the next talk in this session [M. Vagins]!
- Hyper-Kamiokande → ~10× the mass of SK



Sudbury Neutrino Observatory

The Experiment

Sudbury Neutrino Observatory (SNO)

Location: Sudbury, Canada

Type: Heavy Water Cherenkov

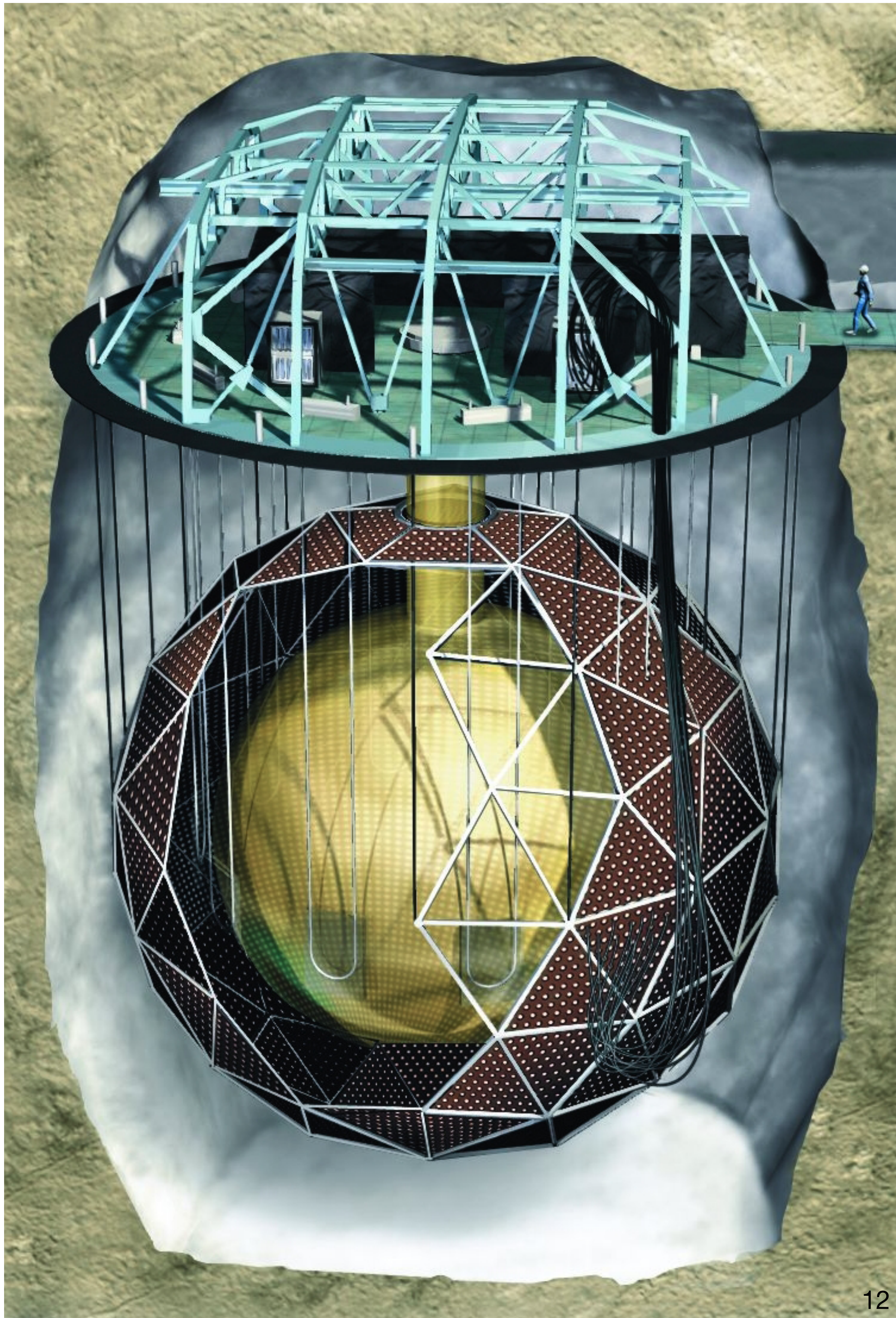
Channel: ν_e – d CC

Mass: 1 kton (770 t fiducial)

Exposure: 902 kton·days

Depth: 5980 mwe

- Phase I (Nov. '99 – May '01)
  - D_2O target
- Phase II (Jul. '01 – Sep '03)
  - D_2O + 2 tonnes NaCl
- Phase III (Nov. '04 – Dec '06)
  - D_2O + 40 ^{3}He counters (NCDs)



SNO
DSNB Search Analysis

SNO Collaboration, *ATM*, et al.
Phys. Rev. D **102**, 062006 (2020)

Channel: Electron neutrino CC

Signatures: Prompt electron

Exposure: 2.47 kton·years

Signal selection targets single electron ring events well-isolated in space and time.

Analysis Highlights:

- Heavy water target → ν_e via CC interaction with deuterium
- Analysis of the full SNO dataset
- Simulation, energy response model updates
  - GENIE-based MC, updated calibration

(GENIE: NIM A **614**, 87-104, 2010)

Key Backgrounds:

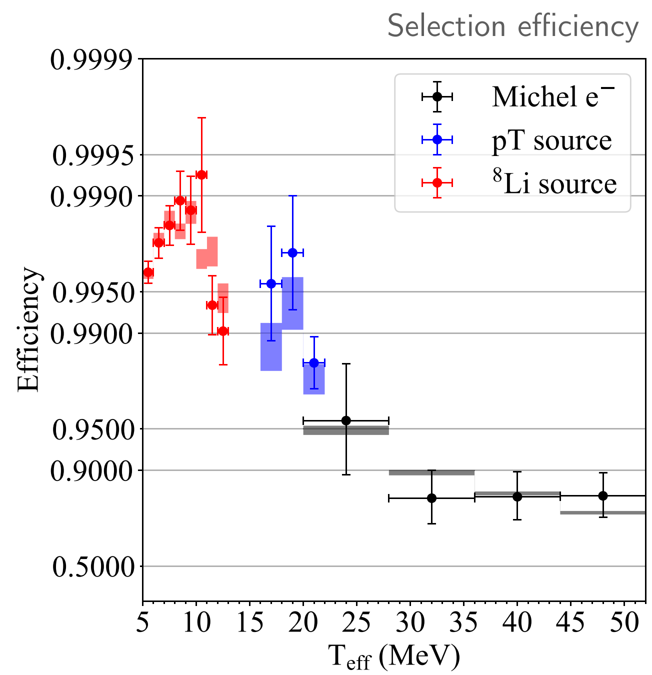
Atmospheric Neutrinos
- Sub-threshold $\mu \to e$ and $\pi \to \mu \to e$ decays
- Atmospheric ν_eCC
- NCQE 1γ

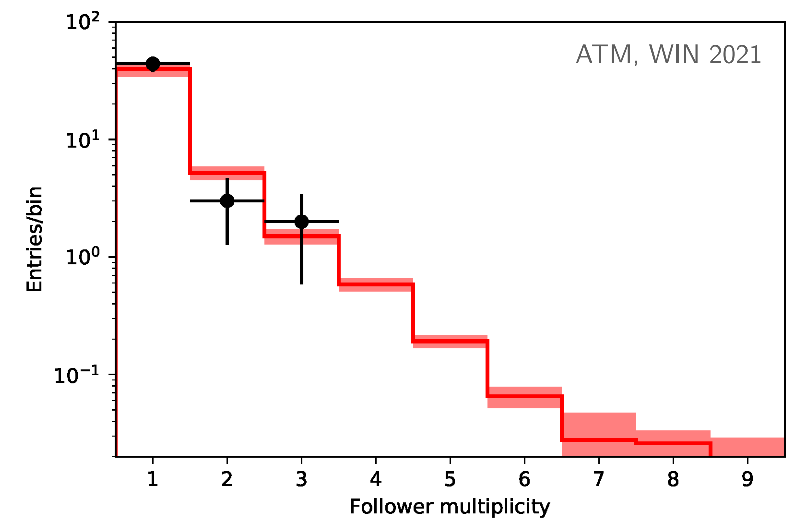
Solar Neutrinos
- Irreducible background from ^{8}B and *hep* CC
- Sets lower energy threshold of 20 MeV

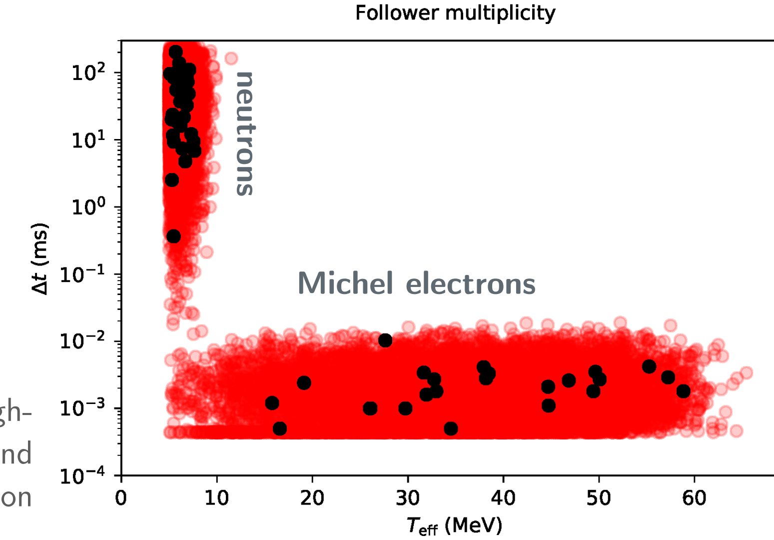
Cosmic-Ray Spallation Products
- Low cosmic rate at 5980 mwe
- Large time cuts around muons

Counting Analysis

- Count relative to a benchmark model, $20 < E_\nu < 40$ MeV
  - Beacom & Strigari, T=6 MeV [PRC **73**, 035807 (2006)]
- Key systematics:
  - Atmospheric neutrinos → GENIE MC & FC validation
  - Energy response → new source + Michel calibration
- Bayesian upper limit, marginalized over background PDFs
- Sensitive to signals ~52× the benchmark model







Atmospheric ν high-energy sideband validation

SNO

DSNB Search Results

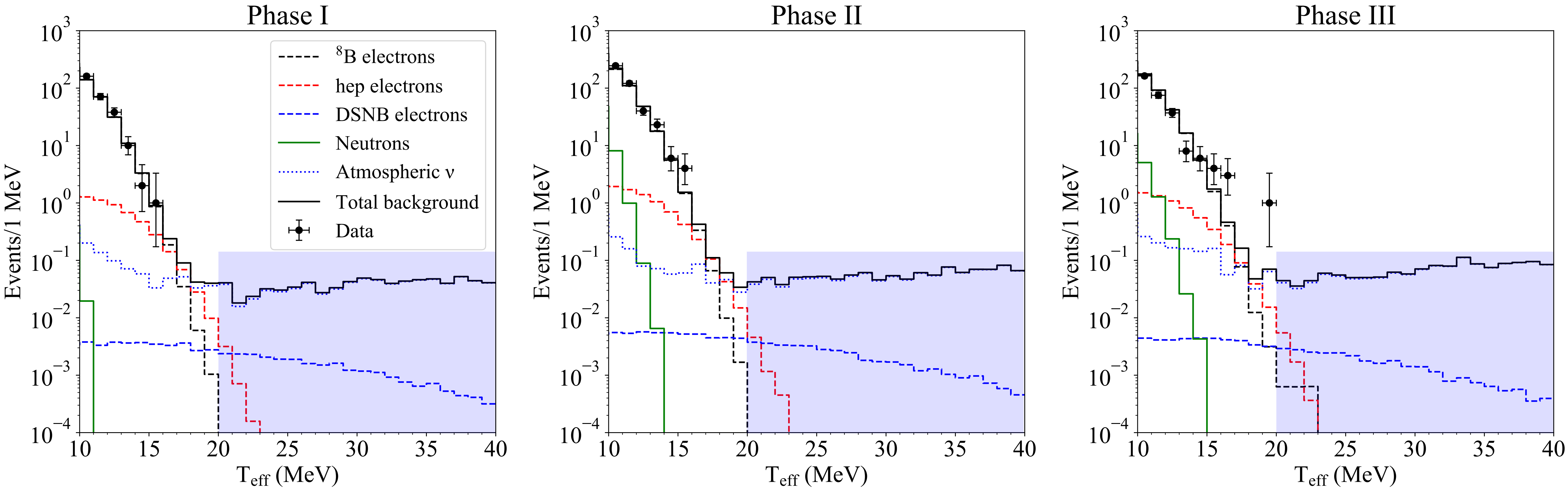
SNO Collaboration, *ATM*, et al.
Phys. Rev. D **102**, 062006 (2020)

Counting Analysis Results

- Sensitive to 34 ν_e/cm²/s in $22.9 < E_\nu < 36.9$ MeV
- 2.58 background + 0.08 signal events expected
- No events observed → 90% CI upper limit: 19 ν/cm²/s
- Direct constraint on DSNB ν_e

	Expected signal	Expected background	Events observed
Phase I DSNB	0.02 ± 0.00	0.62 ± 0.10	0
Phase II DSNB	0.03 ± 0.00	0.91 ± 0.15	0
Phase III DSNB	0.02 ± 0.00	1.06 ± 0.17	0
Total DSNB	0.08 ± 0.00	2.58 ± 0.26	0

(± systematic uncertainty on rate)



LS-Based Searches

Astrophysical Neutrinos in Liquid Scintillator

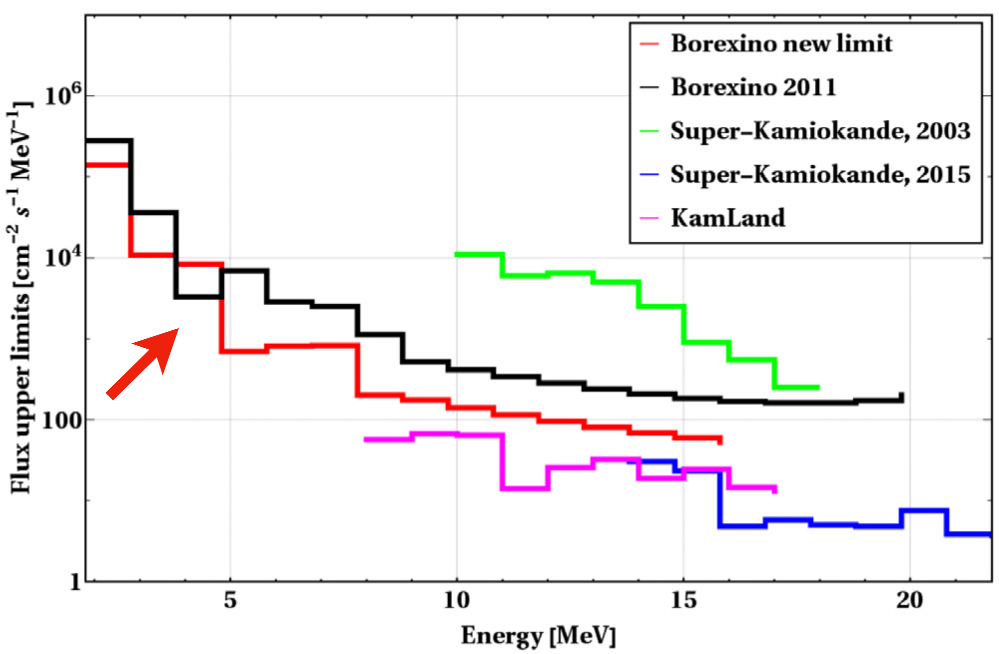
Borexino

Location: LNGS, Italy
Type: Liquid Scintillator
Channel: $\bar{\nu}_e$ IBD
Mass: 278 tons (~231 t fiducial)
Exposure: 546 kton·days
Depth: 3800 mwe

KamLAND

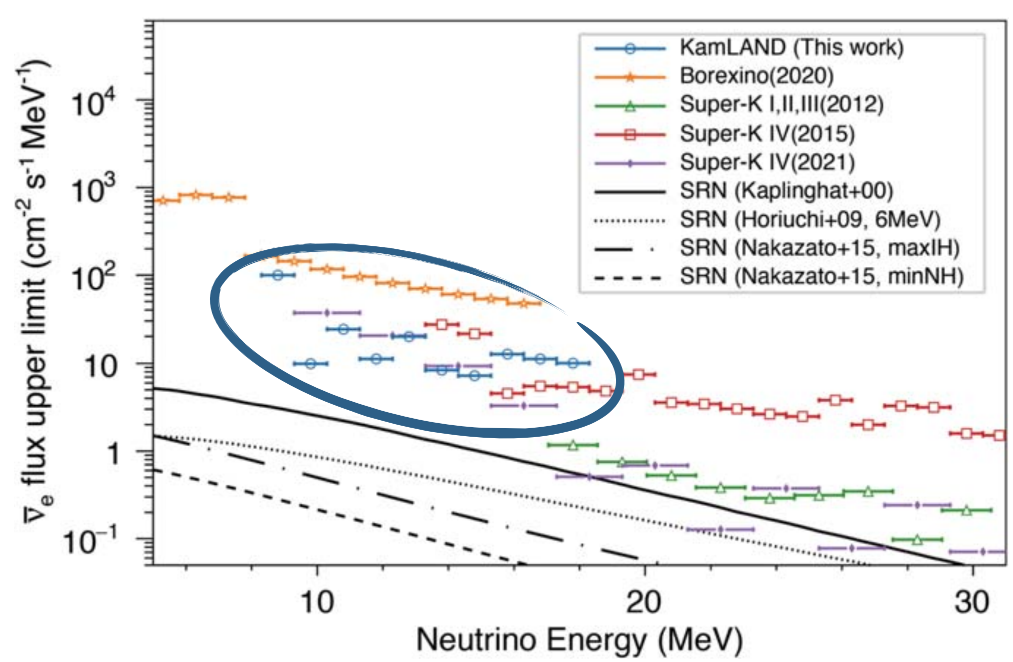
Location: Kamioka, Japan
Type: Liquid Scintillator
Channel: $\bar{\nu}_e$ IBD
Mass: 1 kt (~606 t fiducial)
Exposure: 2454 kton·days
Depth: 2700 mwe

Astropart. Phys. **125**, 102509 (2021)



	Nakazato [53]	Hüdepohl [54]
E[MeV]	$\Phi[\mathrm{cm^{-2}s^{-1}}]$	$\Phi[\mathrm{cm^{-2}s^{-1}}]$
2.8–16.8	$< 2.4\ (1.7) \times 10^3$	$< 2.6\ (1.8) \times 10^3$
7.8–16.8	$< 106.0\ (38.2)$	$< 112.3\ (40.5)$

Astrophys. J. **925**:14 (2022)



Model	F_{90} (cm^{-2} s^{-1})	Expected Flux (cm^{-2} s^{-1})
Kaplinghat+00	74.5	19.9
Horiuchi+09 (6 MeV)	61.6	5.8
Nakazato+15 (max, IH)	108	5.1
Nakazato+15 (min, NH)	105	2.2

DSNB Searches

Future Prospects

SK +Gd	JUNO	Hyper-K	DUNE	THEIA
Enhanced n tagging capabilities in SK	Large-mass liquid scintillator	Massive scale Water Cherenkov detector arxiv:1805.04163	Unique opportunity for ν_e sensitivity with ^{40}Ar target arxiv:2002.03005 JCAP12(2004)002	LS + Cherenkov analysis with Water-based LS

A new generation of experimental capabilities

DSNB Searches

Future Prospects

SK +Gd

Enhanced n tagging capabilities in SK

JUNO

Large-mass liquid scintillator

Hyper-K

Massive scale Water Cherenkov detector

arxiv:1805.04163

DUNE

Unique opportunity for ν_e sensitivity with ^{40}Ar target

arxiv:2002.03005
JCAP12(2004)002

THEIA

LS + Cherenkov analysis with Water-based LS

A new generation of experimental capabilities

DSNB In JUNO

Coming Soon

JUNO Collaboration, arXiv:2205.08830v1

Jiangmen Underground Neutrino Observatory (JUNO) *coming 2023*

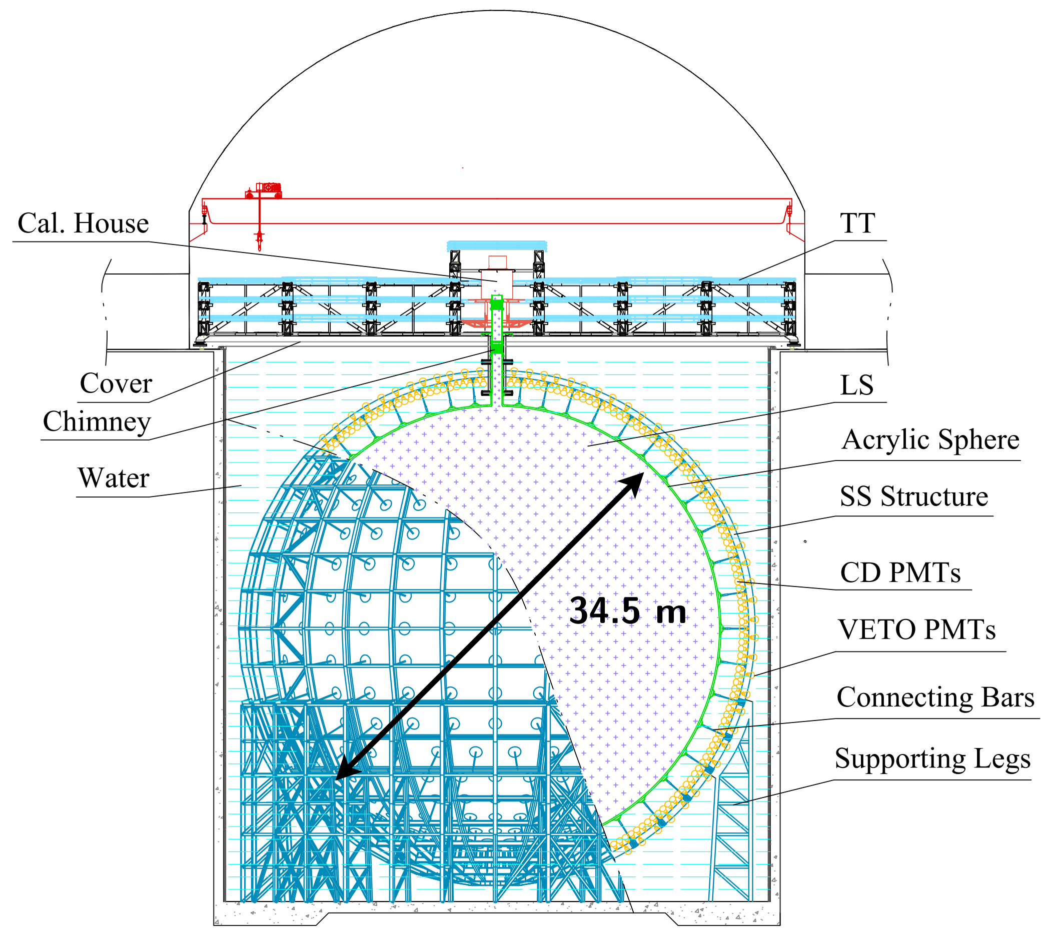
Location: Jiangmen, China

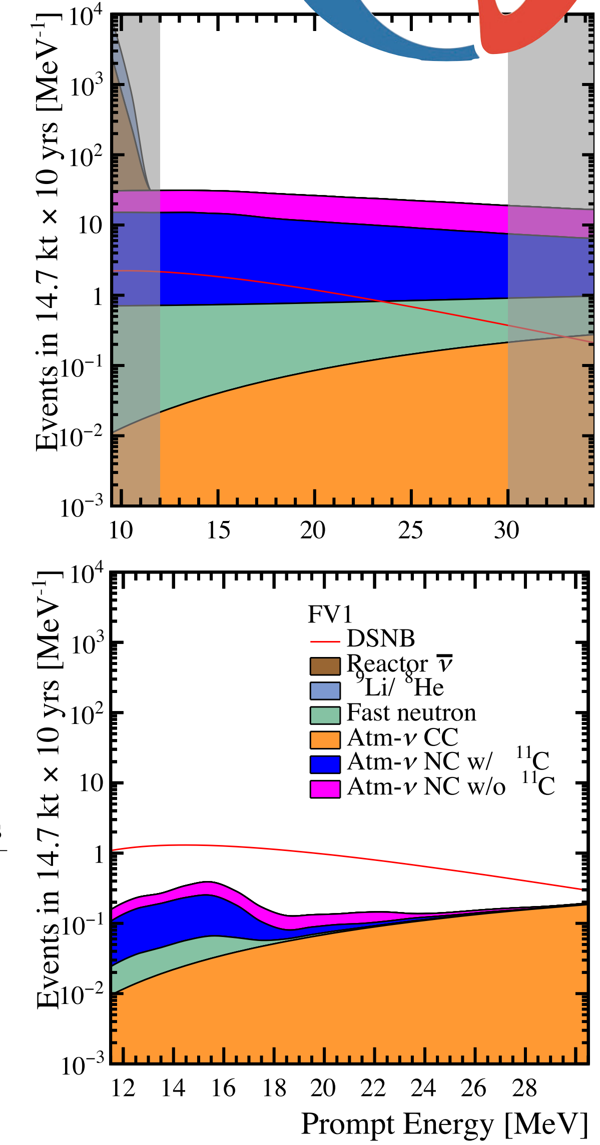
Type: Liquid Scintillator ☀

Channel: $\bar{\nu}_e$ IBD

Mass: 20 kton

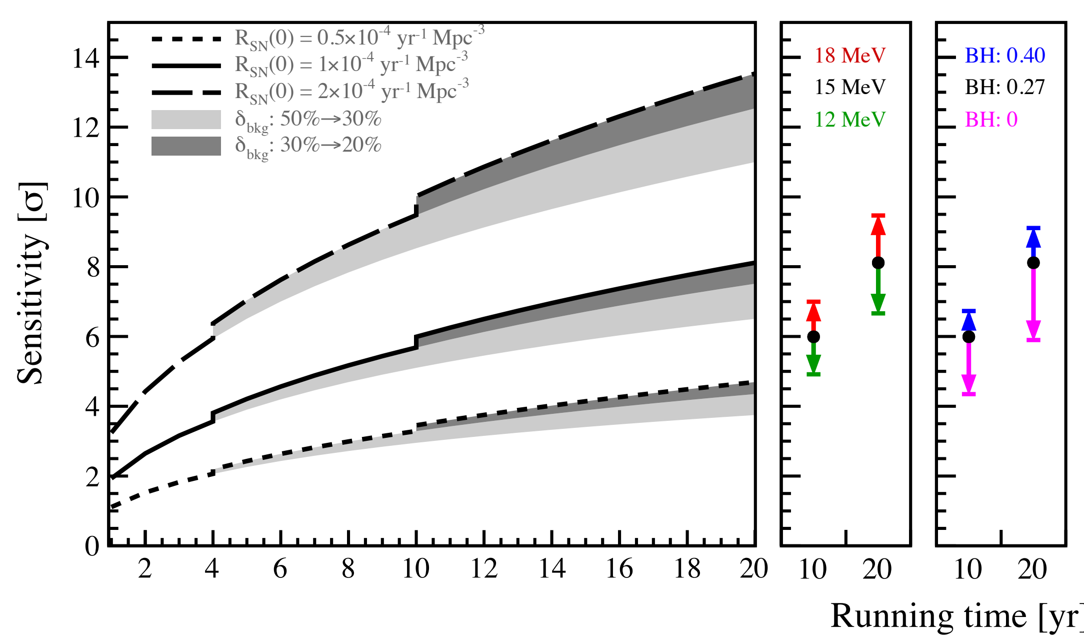
Depth: 1800 mwe

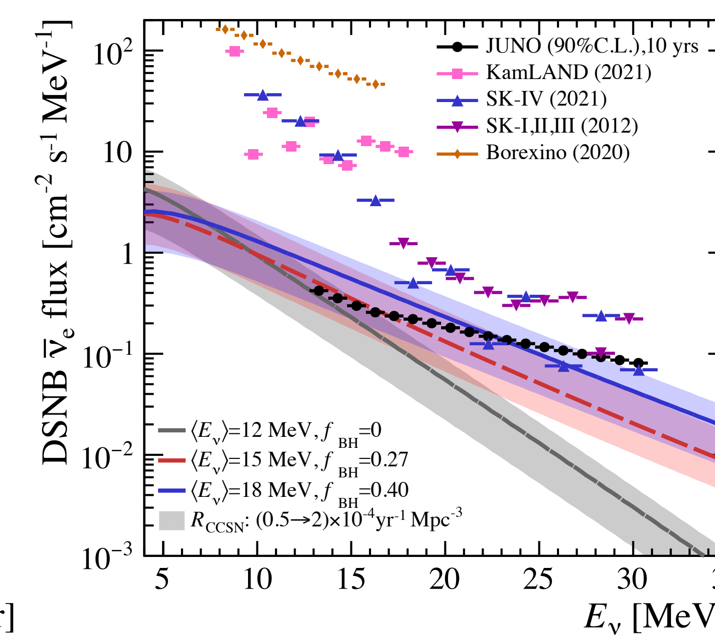




Analysis Highlights:

- Very large mass LS detector
- Exceptional coverage/ resolution, low threshold
- Strong μ tagging capabilities
- Powerful PSD and triple coincidence tagging capability
  - Minimal spallation backgrounds





See also: Jie Zhao, "JUNO Status and Prospects," Session S7

DSNB In Theia

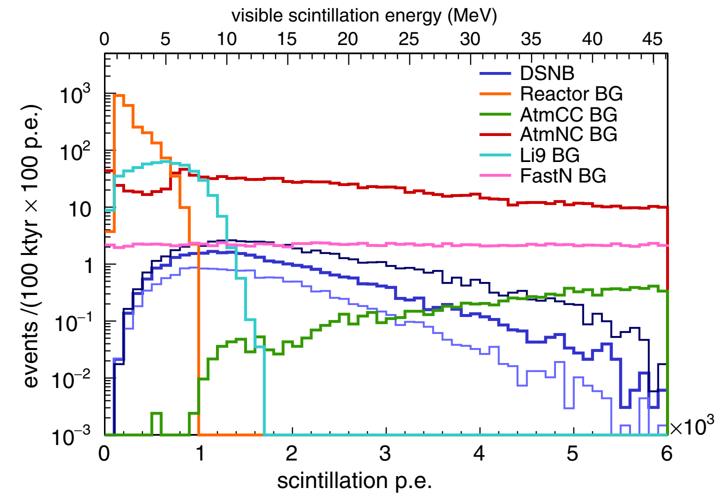
Future Prospects

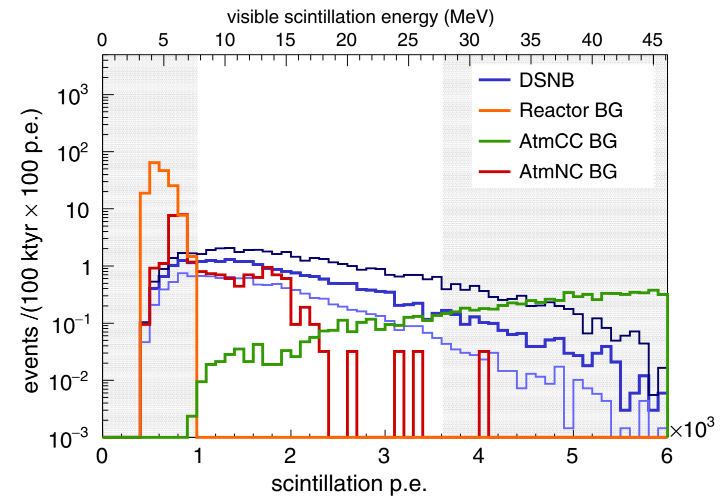
Sawatzki, Wurm, Kresse,
Phys. Rev. D **103**, 023021 (2021)

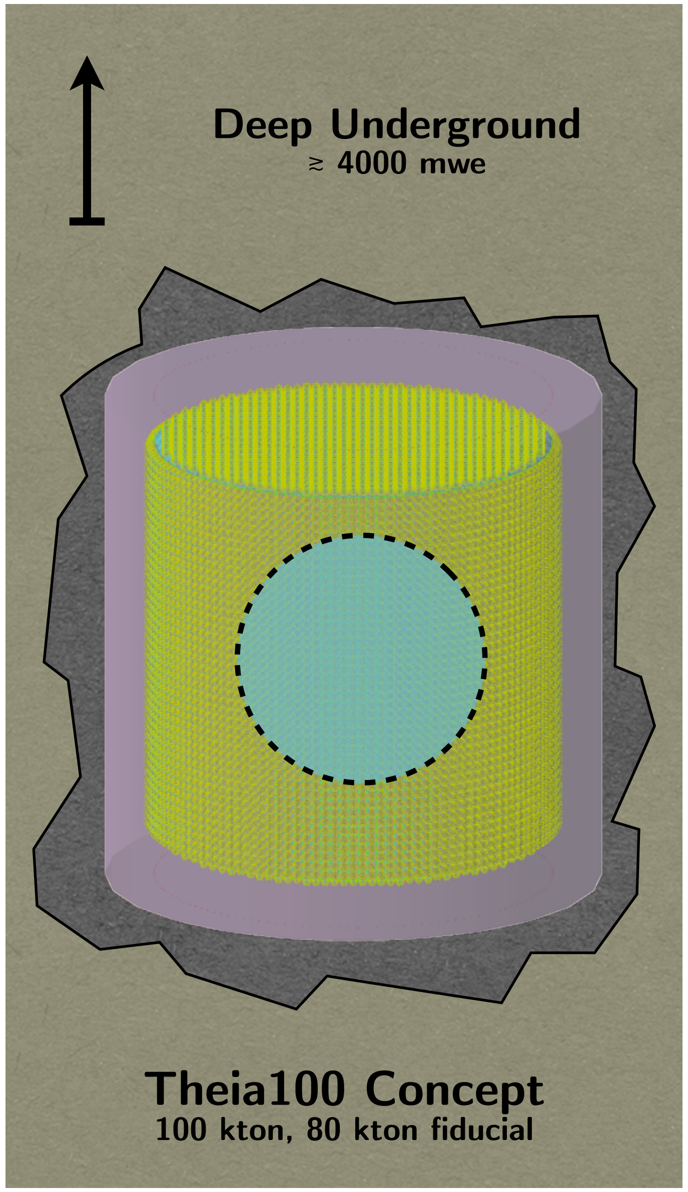
THEIA EPJC **80**:416 (2020)

future concept

Location: TBD, possibly SURF
Type: Water-based Liquid Scintillator
Channel: $\bar{\nu}_e$ IBD
Mass: 50–100 kton
Depth: ~4000 mwe

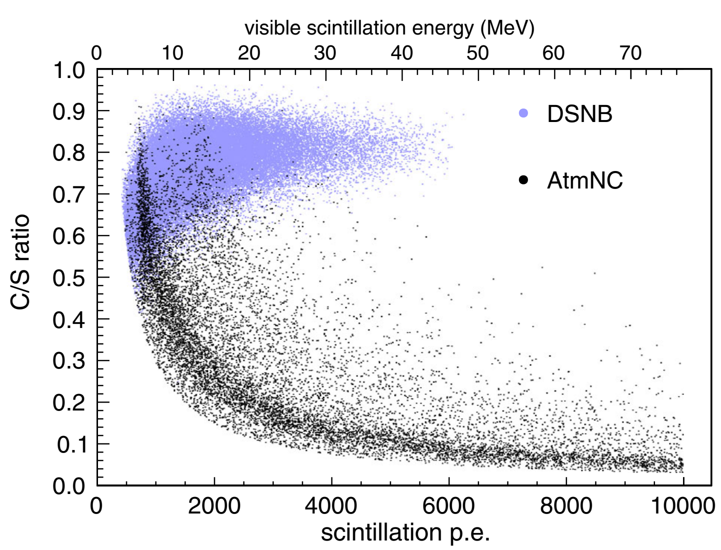


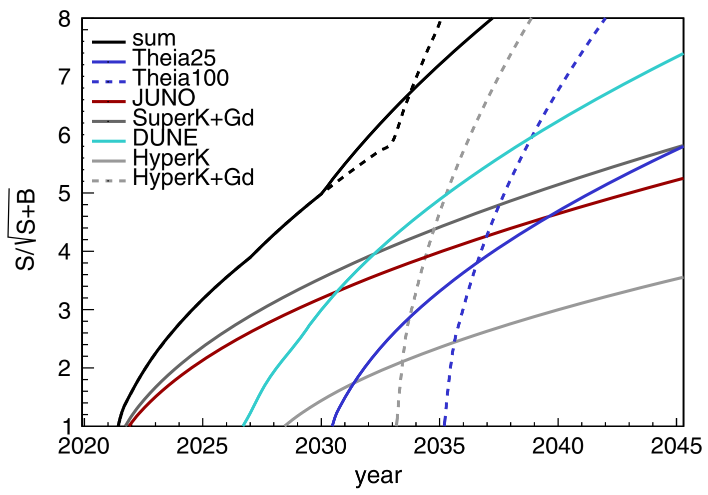




Analysis Highlights:

- WbLS provides efficient IBD neutron tag, Cherenkov ring counting, and sub-threshold NCQE tag
- Tagging of long-lived low-E decays



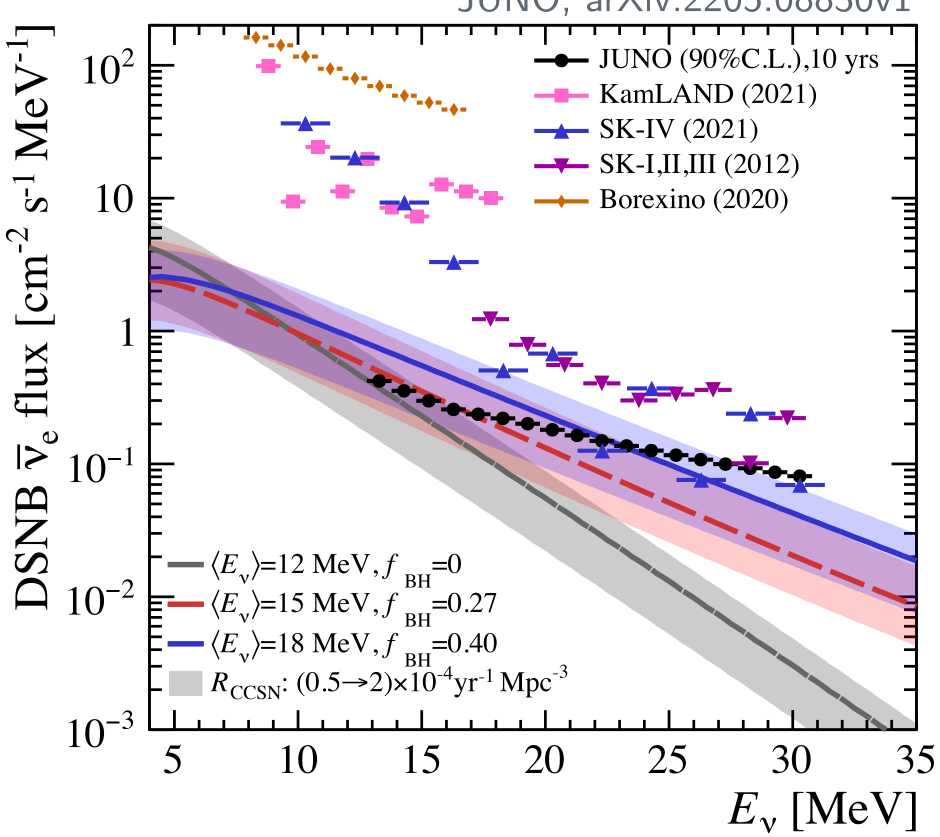


DSNB Searches

Where We Stand

- **Null results are closing in on the theory expectation**
  - 3σ appears achievable within a few years in SK+Gd, JUNO
  - Optimistic scenarios, excesses already disfavored
  - Robust searches in $\nu_{e,}\, \bar{\nu}_e$: Different detectors, channels, backgrounds, systematics, etc.
- **The DSNB signal remains elusive**
  - Despite exceptional detectors and analysis, no detection yet
  - Measuring spectral features will require much larger statistics than a first detection
  - Promising path with new, next-generation detectors
- **A rich array of measurements ahead**
  - Average supernova dynamics will provide crucial SNe physics context
  - Neutrino & SM/BSM physics: oscillations, properties, NSI, ...
- **The future is ~~bright~~ a dim *but informative* glow!**

JUNO, arXiv:2205.08830v1



Thank You!

<u>Posters including DSNB:</u>

Pruthvi Mehta, P0588: "Neutron tagging with SK-Gd for neutral current quasielastic interaction measurements with the T2K neutrino beam"
Jie Cheng, P0113: "Prospects for Detecting the Diffuse Supernova Neutrino Background in JUNO"
Xiaojie Luo, P0123: "Pulse Shape Discrimination for Diffuse Supernova Neutrino Background Search at JUNO"
Seiya Sakai, P0579: "The performance evaluation of Geant4-based simulation in SK- Gd experiment"
Tomohiro Tano, P0661: "Measurement of neutron-oxygen interaction cross section using neutron beam"
ATM, P0200: "Theia: An advanced optical detector concept"
Min Li, P0237: "Atmospheric neutrino neutral current background at JUNO: from reactor neutrinos to diffuse supernova neutrino background"

Image: Cassiopeia A, Chandra X-Ray Observatory. X-ray: NASA/CXC/SAO; Optical: NASA/STScI; Infrared: NASA/JPL-Caltech/Steward/O.Krause et al.