Deep Background Material

John Beacom, The Ohio State University

Happy 60th Birthday
to Mark Vagins!

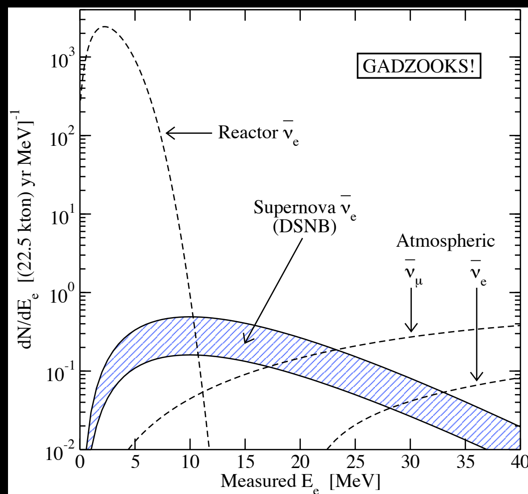
The Ohio State University's Center for Cosmology and AstroParticle Physics
CCAPP
NSF

Outline

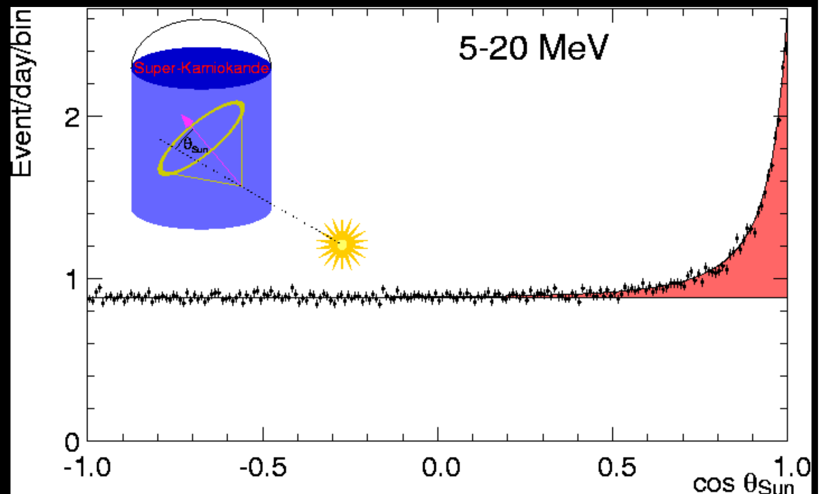
How I know Mark

Adding 383 grams $Gd_2(SO_4)_3$ to 191 liters of H_2O; January 5th, 2011

DSNB research



DSNB+Solar research



How I know Mark

One,

+ I started grad school in Wisconsin doing collider physics theory, but this was not the right fit for me

+ Then I got interested in neutrinos. One step was a seminar I randomly went to by some guy named Mark Vagins (hosted by Charles Sukenik)

+ I finished grad school doing neutrino astrophysics theory with Baha Balantekin

Two,

Dear Prof. Vagins:

17 June 1998

I have recently written a paper on supernova neutrino detection in SK (hep-ph/9802424), and would like to talk to some of the SK members about it. However, I really have no idea who I should talk to. Is there a supernova group inside of SK? I was directed to you by Prof. Svoboda.

Thanks,

John Beacom beacom@citnp.caltech.edu

- Triangulation Conclusions:
  - Best information in the leading edge.

    risetime ~ 0s $\longrightarrow$ $\boxed{\begin{array}{l}\delta(\Delta t) \simeq 8\,\mathrm{ms} \\ \delta(\cos\alpha) \simeq 0.25\end{array}}$

    risetime ~ 30ms $\longrightarrow$ $\boxed{\begin{array}{l}\delta(\Delta t) \gtrsim 15\,\mathrm{ms} \\ \delta(\cos\alpha) \gtrsim 0.5\end{array}}$

  - Error $\sim \frac{1}{\sqrt{N}} \sim \left[\frac{D}{10\ \mathrm{kpc}}\right]$
  - Use network just to suppress false alarms.

Three…

Simple story of GADZOOKS!

2002: initial ideas at Neutrino 2002 (Munich); Mark visited me at Fermilab

2003: infinitely more emails, paper submitted to arXiv

2004: paper accepted for PRL

More complicated story of GADZOOKS!

We had many serious concerns and setbacks

We faced many hard questions from the community

The referee process was … ehto … difficult

The paper required our theory-experiment collaboration

Nakahata-sensei provided crucial help and encouragement

Infinity

How knowing Mark has shaped my career

- We have been very close friends for decades
- He believed in me when I was just getting started
- He strongly connected me to Super-Kamiokande
- He encouraged my work at the theory-experiment interface
- I copied his haircut and Hawaiian shirts

DSNB Research

Theoretical Framework for the Signal

Signal rate spectrum in detector in terms of measured energy

$$\frac{dN_e}{dE_e}(E_e) \;=\; N_p\,\sigma(E_\nu)\,\int_0^\infty \Big[(1+z)\;\varphi[E_\nu(1+z)]\Big]\;\Big[R_{SN}(z)\;\Big]\;\left[\left|\frac{c\,dt}{dz}\right|dz\right]$$

Third ingredient: Detection capabilities
(well understood)

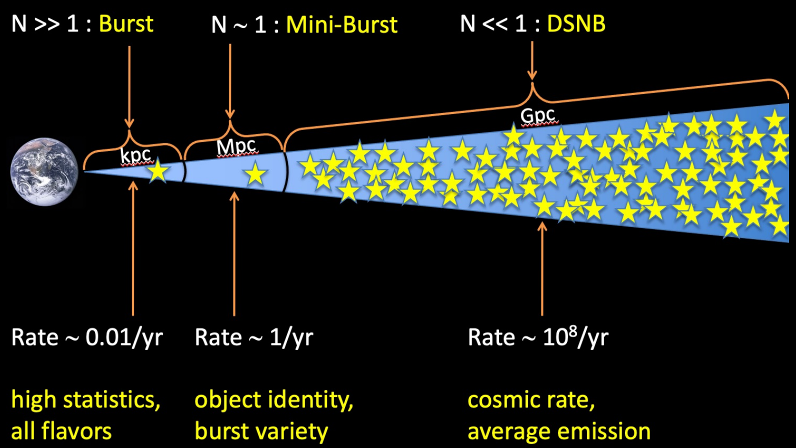
Second ingredient: Core-collapse rate
(known with reasonable precision)

First ingredient: Neutrino spectrum, including mixing effects
(this spectrum is the key unknown)

Beacom review (2010)

Why Focus on the Neutrino Spectrum?

Neutrino spectrum is the only part that *cannot* be measured by astronomers



Neutrino spectrum:

Can be *predicted* multiple ways

Can be *measured* multiple ways

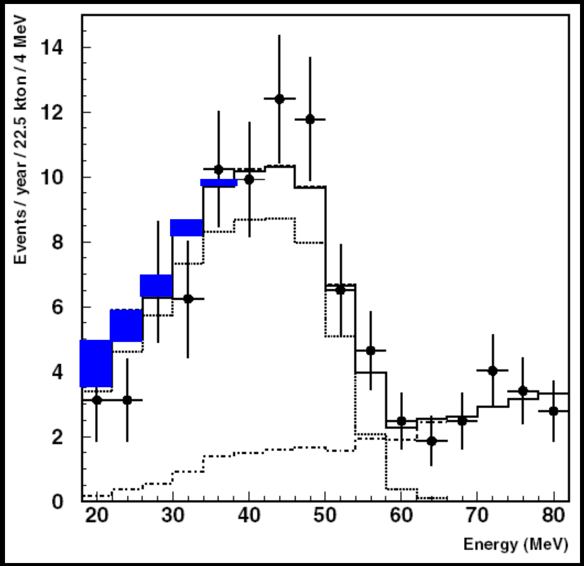
Has multiple *observational* signatures

Very rich scientific focus

These comparisons have crucial implications for astrophysics and physics

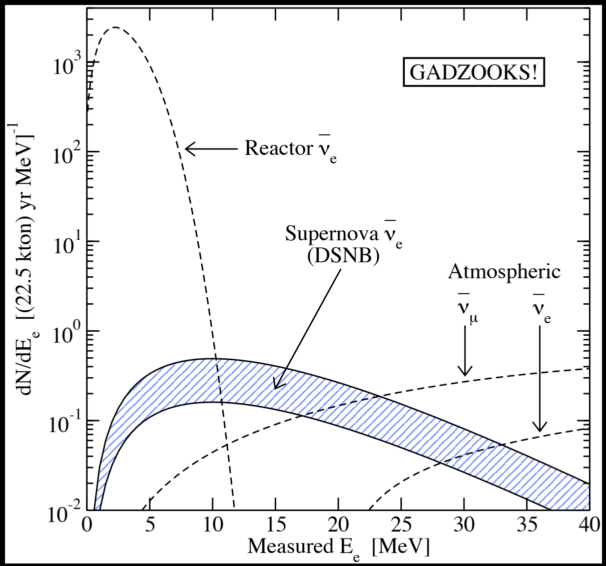
GADZOOKS! Prospects

The challenge:



Malek et al. (SK, 2003)

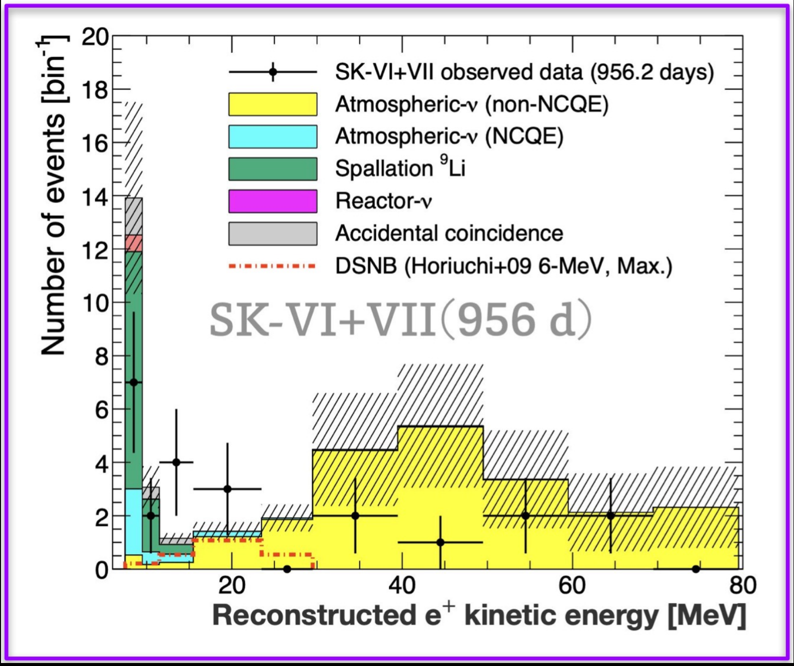
The opportunity:



Beacom, Vagins (2003)

See Horiuchi talk for signal predictions

Most Important Detector Backgrounds



Super-K (2024)

Why do backgrounds matter so much?

Most serious problems:

1. Reactor antineutrinos
   Can never go below ~10 MeV
2. Atmospheric NC interactions
   Should be reducible
3. Atmospheric CC interactions
   Should be reducible
4. Spallation decays
   Should be reducible

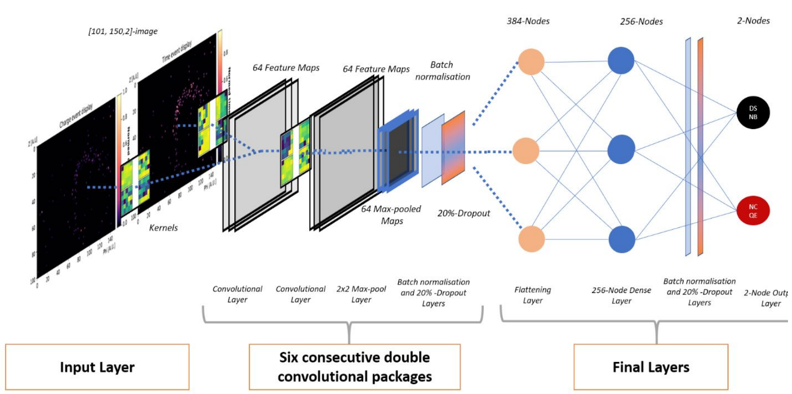
Atmospheric NC Interactions

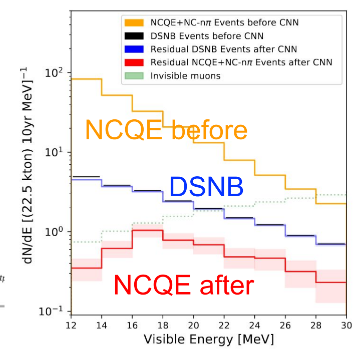
Atmospheric Neutrinos

Towards better discrimination

- Machine-learning based DSNB vs. NCQE discrimination
  [Maksimovic *et al.*, JCAP11 (2021) 051]

Fig 9 from
Maksimovic *et al.*





➔ Studies inspired by this paper have been developed within Super-K and are currently in the validation stage

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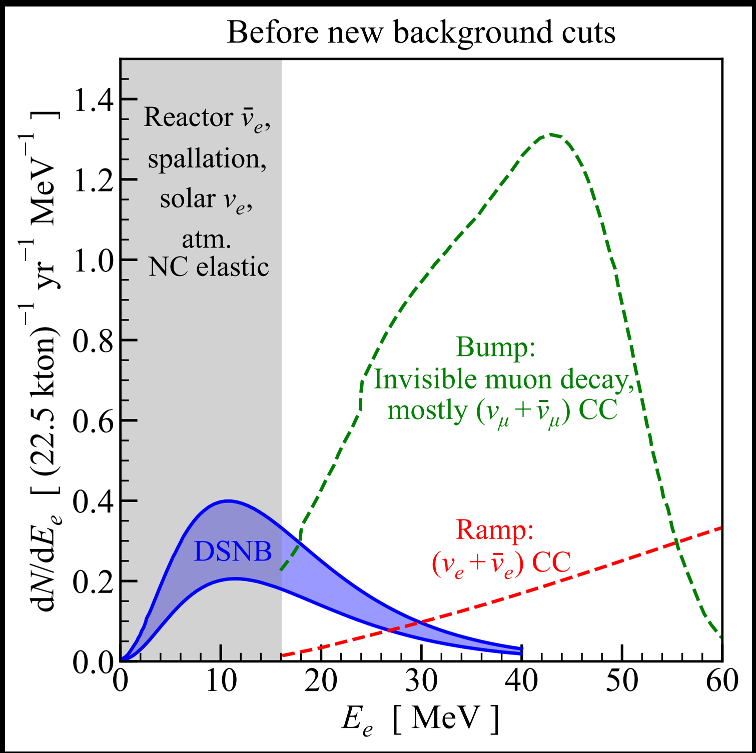
Fujita slide

Atmospheric CC Interactions: Challenge



Zhou, Beacom (2024)

Key points:

Super-K uses fixed shapes, floating normalizations

Approximate calculation in Beacom and Vagins (2003)

First detailed calculation in Zhou and Beacom (2024)

Reducing backgrounds depends on understanding them

Bei Zhou,
lead author

Atmospheric CC Interactions: Setup and Validation

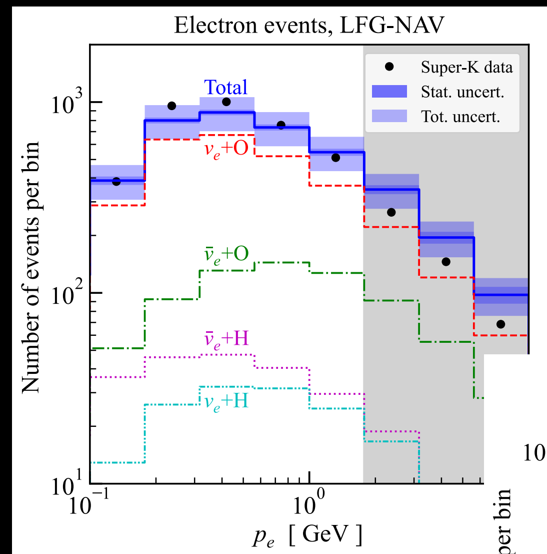
Key inputs:

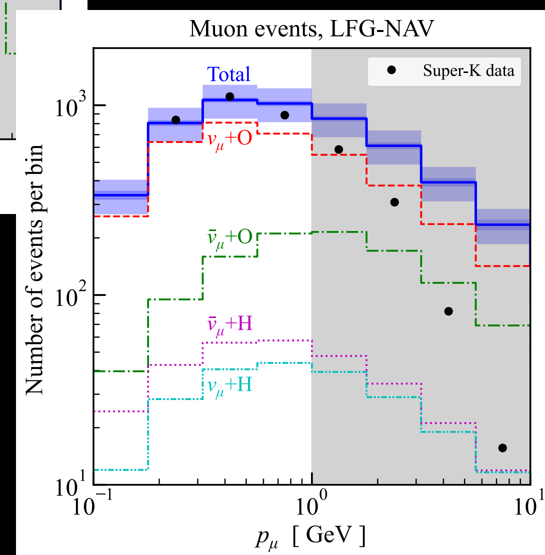
Predicted atmospheric neutrino fluxes

Neutrino mixing (vacuum, matter effects)

Cross section simulation with GENIE

Particle propagation with FLUKA

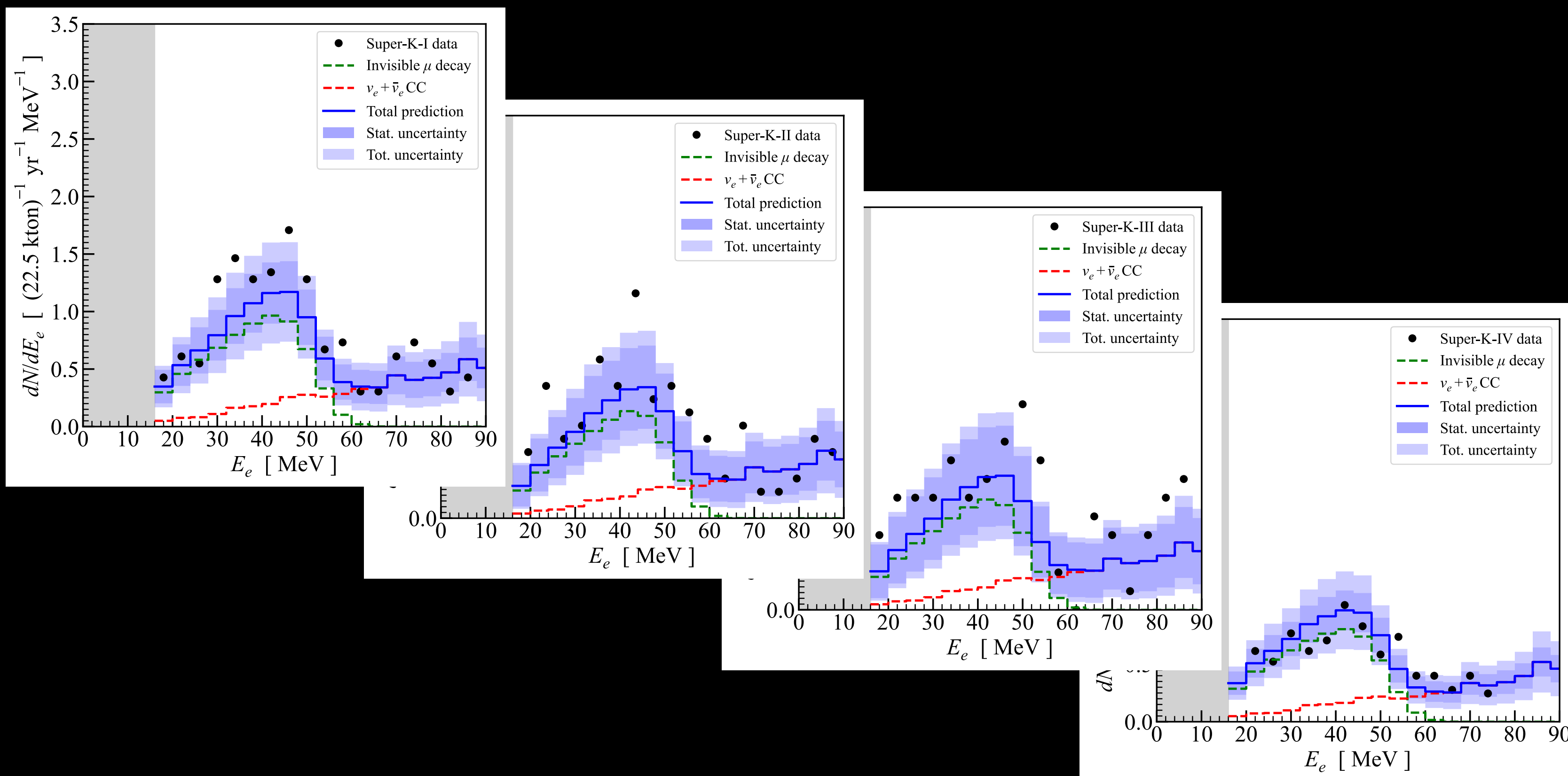




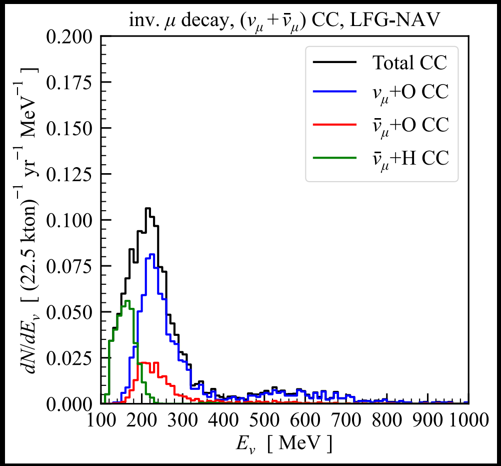
Atmospheric CC Interactions: Key Corrections

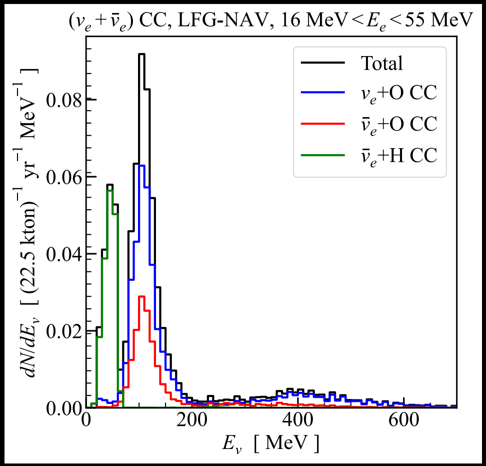
Interaction channel	$Br_\gamma = 50\%,\ \epsilon_\gamma = 0\%$				$Br_\gamma = 50\%,\ \epsilon_\gamma = 100\%$		
	Naive	Standard	Coulomb	Threshold	Standard	Coulomb	Threshold
ν_μ+O CC	159	107	107	143	56	56	75
$\bar{\nu}_\mu$+O CC	35	30	30	39	14	14	19
ν_μ+H CC	7	0	0	0	0	0	0
$\bar{\nu}_\mu$+H CC	24	23	23	30	23	23	30
NC π^+		92	84	107	51	46	61
Total	226	253	245	319	145	140	**185**
Total/Super-K-IV (155)	1.45	1.63	1.58	2.05	0.93	0.90	**1.19**

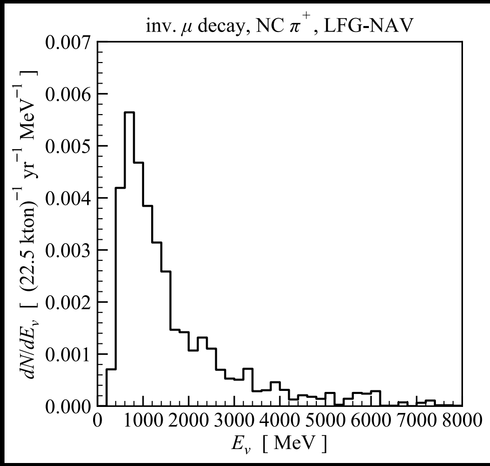
Atmospheric CC Interactions: Results

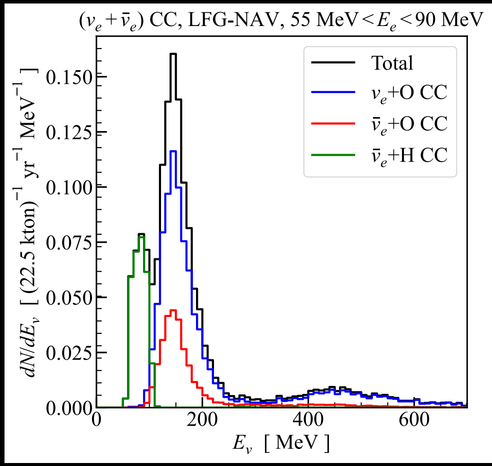


Atmospheric CC Interactions: Parent Neutrinos









Atmospheric CC Interactions: Expected Impact

In this paper, we perform the first detailed calculations of the dominant atmospheric-neutrino backgrounds for DSNB searches in Super-K, taking into account neutrino mixing, neutrino-nucleus interactions, and how events register in Super-K. As a bottom line, our calculations can reasonably reproduce Super-K's observed atmospheric-neutrino backgrounds in the range $E_e = 16$–90 MeV, which are mostly produced by neutrinos in the range up to about 400 MeV. Our key results are shown in Fig. 6, Table I, and Table II. Achieving this agreement required taking into account several physical and detector effects, as well as checking that our calculations reasonably reproduce Super-K's GeV-range atmospheric-neutrino data. The detailed results and comprehensive roadmap provided in this paper will help Super-K improve sensitivity to the DSNB. In our next paper [54], we go further by detailing proposed new cuts that take advantage of our new knowledge of how different processes contribute to the observed backgrounds.

This program of work will not only be useful for reducing backgrounds for DSNB (and dark matter [8, 47, 136]) searches. Put another way, Super-K has a large atmospheric-neutrino dataset below about 100 MeV that has never been exploited as a signal. The counts are large, about 50 events/year after cuts for about 25 years, so about 1250 events in total. Without cuts, these event counts would be more than a factor of two larger. Combined with data from other detectors, an exciting new frontier in low-energy atmospheric neutrinos could be opened [42, 44, 79, 137–145]. This would allow new tests of neutrino mixing and neutrino-nucleus interactions.

Selected recent activity on low-E atmospherics:
Kelly et al. (2019)
Newstead et al. (2021)
Cheng et al. (2021, 2021)
Chauhan, Dasgupta (2022)
Suliga, Beacom (2023)
Meighen-Berger et al. (2023)

Atmospheric CC Interactions: Tasks for Super-K

It would be very helpful for future Super-K DSNB papers to provide details comparable to what we do above. In addition, key questions to resolve include:

1. For invisible-muon events *with* nuclear gamma rays, what are the gamma-ray probabilities and energies? For $(\nu_e + \bar{\nu}_e)$ CC interactions, can nuclear gamma rays be identified?

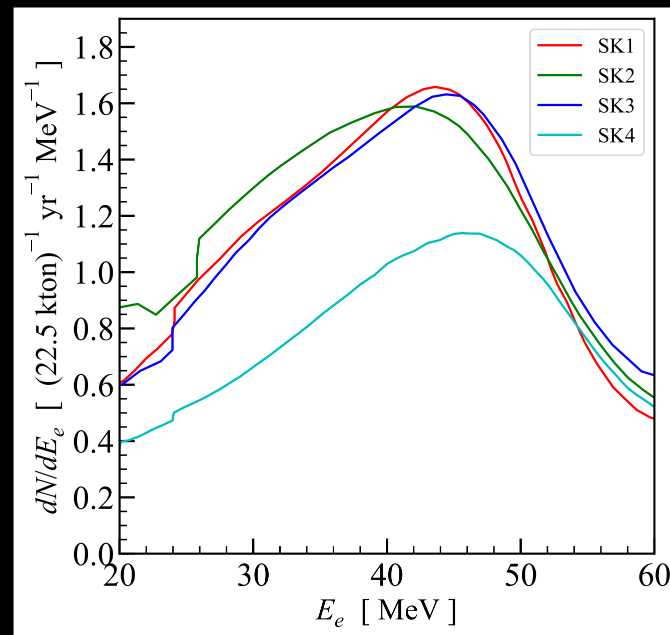
2. How do the spectra of the low-energy events (<100 MeV) in detected energy connect to those at energies up through a few hundred MeV?

3. What are detection thresholds for barely relativistic muons and pions (Sec. IV A 4)?

4. Why are the low-energy spectra observed in Super-K stage IV inconsistent with those in earlier stages (Sec. IV A 4)?

5. Thinking ahead to future analyses, what are the details of the spallation and atmospheric NC events below 16 MeV, both before and after cuts?

Last, it would be helpful if Super-K would provide full event data for every low-energy event, as this would enable independent analyses.



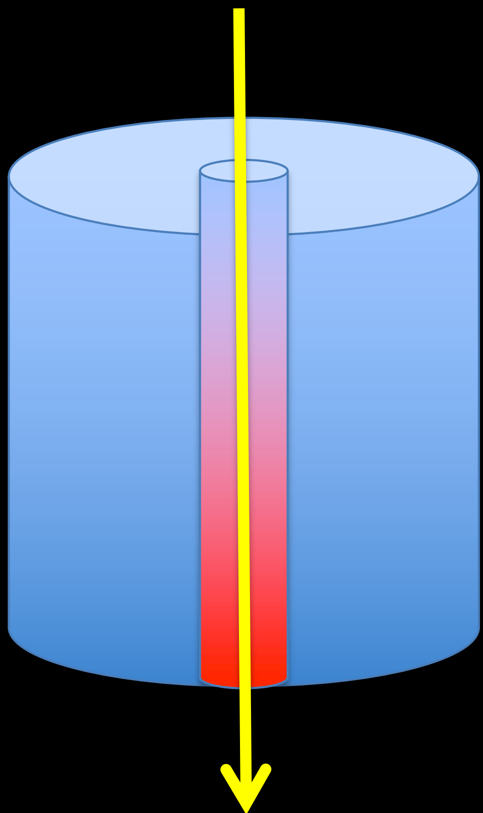
DSNB+Solar Research

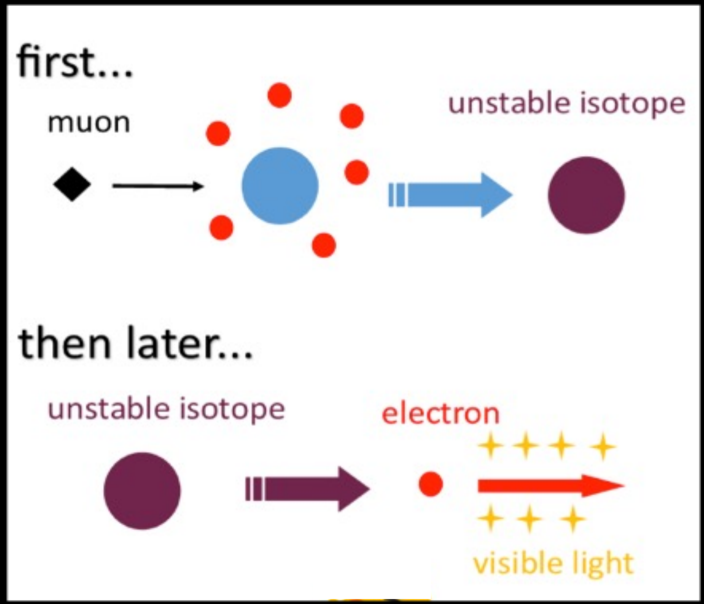
Open Questions in Solar Neutrinos

Particle physics
Neutrino mixing
Neutrino new physics
Etc.

Astrophysics
Solar metallicity
Solar T, ρ (Zaidel, Beacom, 2025)
Etc.

Spallation Decays: Challenge

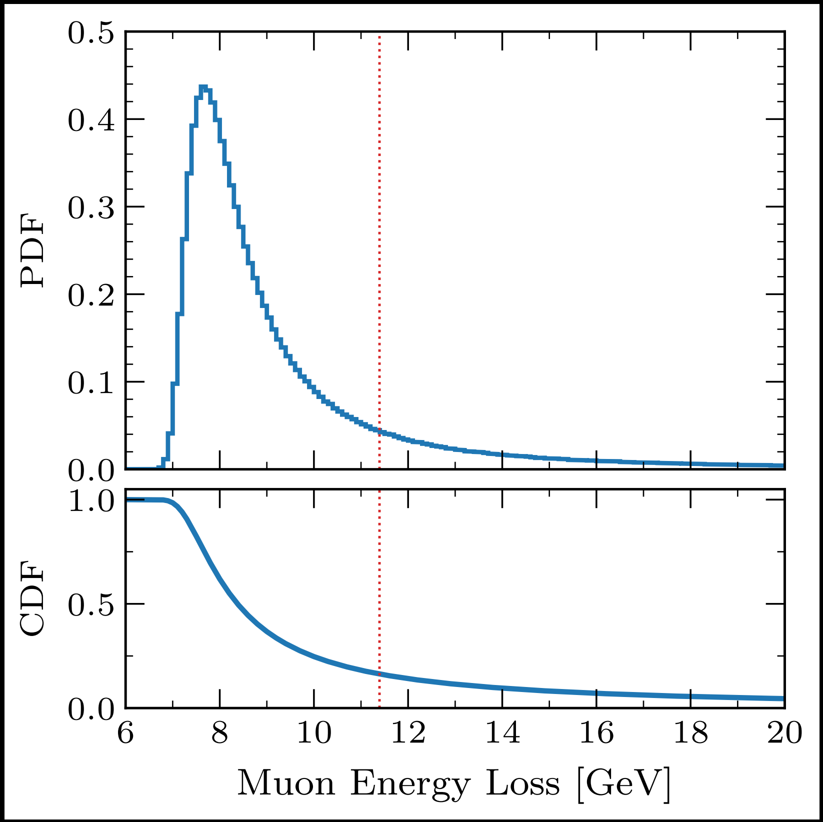




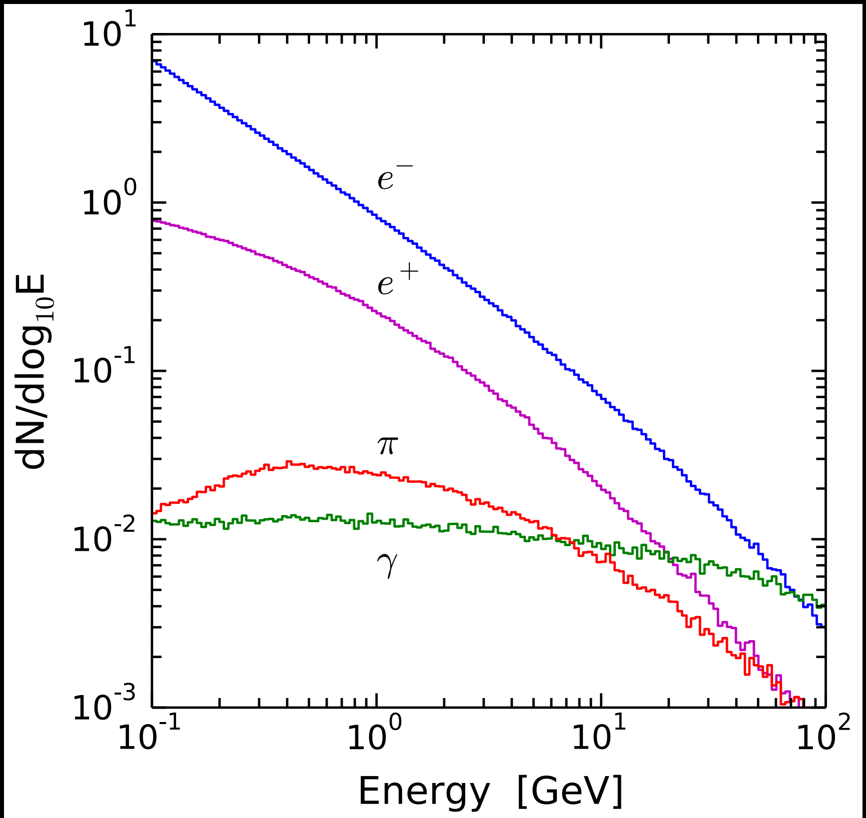
Spallation Decays: Key Steps

Experimental side	Theoretical side
Empirical studies over decades	Galbiati and Beacom (2005)
Kirk Bays (Ph.D., 2012)	Li and Beacom (2014)
	Li and Beacom (2015)
Scott Locke (Ph.D., 2020)	Li and Beacom (2015)
Alice Coffani (Ph.D., 2021)	Li et al. (2016)
And many Super-K papers	And private communications

Spallation Decays: Muon Energy Losses

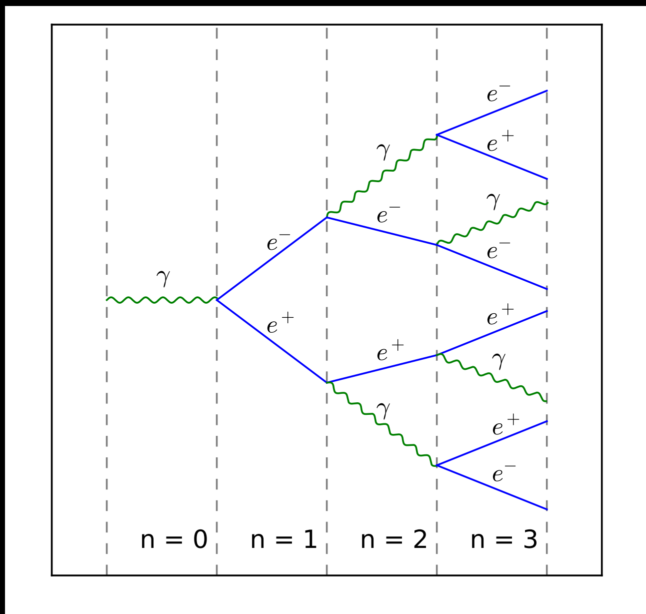


Nairat, Beacom, Li (2024)

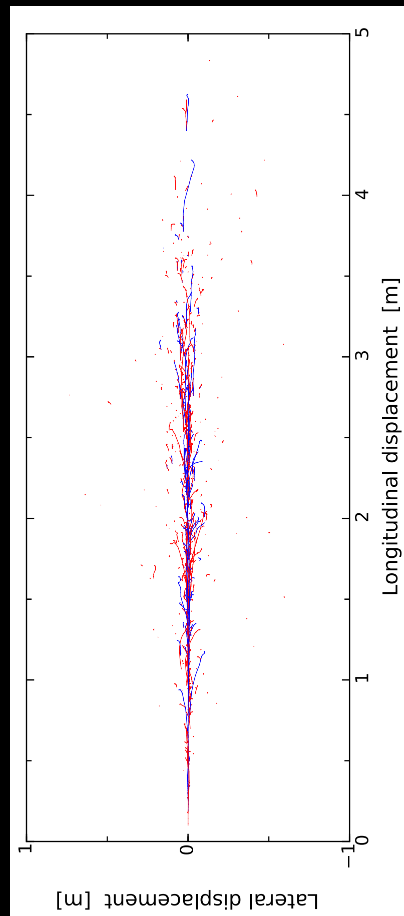


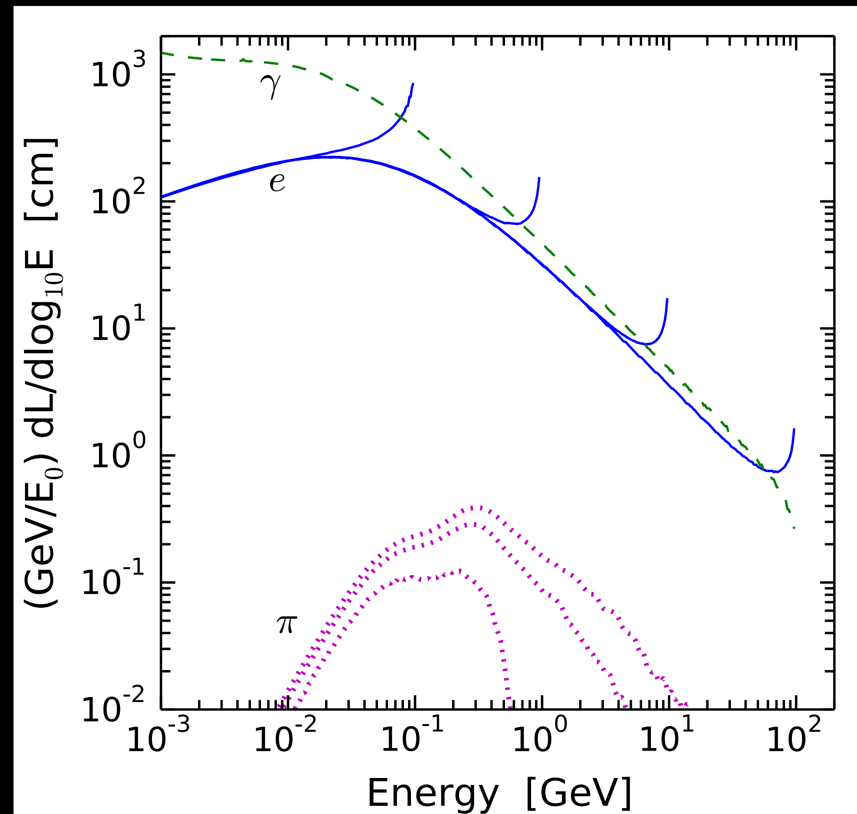
Li, Beacom (2015)

Spallation Decays: Showers



Li, Beacom (2015)

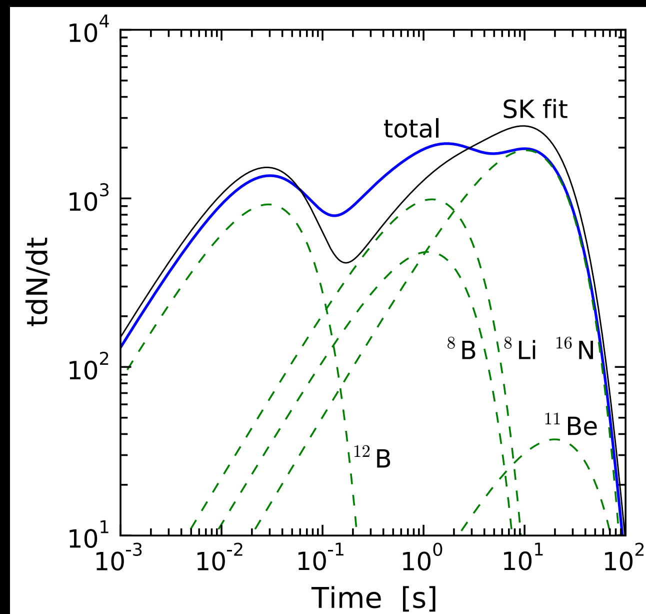


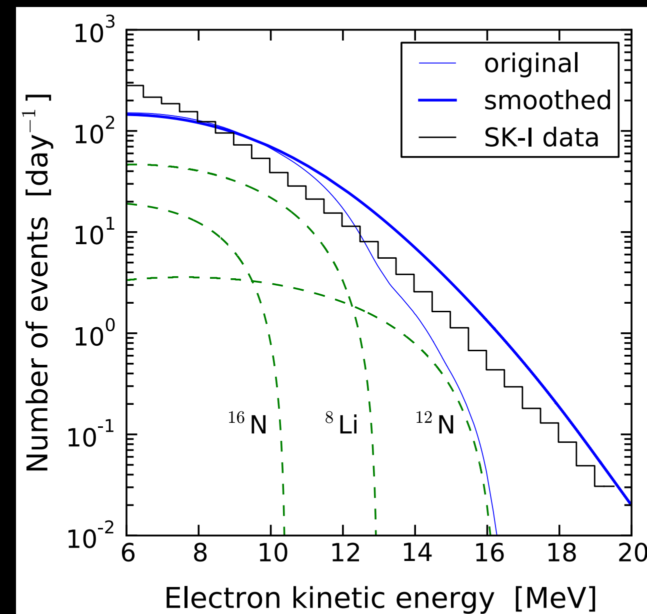


Spallation Decays: Production Rates

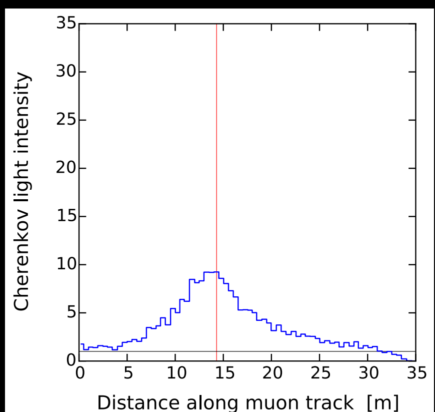
Isotope	Half-life (s)	Yield (E > 3.5 MeV) ($\times 10^{-7} \mu^{-1} \mathrm{g}^{-1} \mathrm{cm}^2$)	Primary process
n			
^{18}N	0.624	0.01	^{18}O(n,p)
^{17}N	4.173	0.02	^{18}O(n,n+p)
^{16}N	7.13	18	(n,p)
^{16}C	0.747	0.003	(π^-,n+p)
^{15}C	2.449	0.28	(n,2p)
^{14}B	0.0138	0.02	(n,3p)
^{13}O	0.0086	0.24	(μ^-,p+2n+μ^-+π^-)
^{13}B	0.0174	1.6	(π^-,2p+n)
^{12}N	0.0110	1.1	(π^+,2p+2n)
^{12}B	0.0202	9.8	(n,α+p)
^{12}Be	0.0236	0.08	(π^-,α+p+n)
^{11}Be	13.8	0.54	(n,α+2p)
^{11}Li	0.0085	0.01	(π^+,5p+π^++π^0)
^{9}C	0.127	0.69	(n,α+4n)
^{9}Li	0.178	1.5	(π^-,α+2p+n)
^{8}B	0.77	5.0	(π^+,α+2p+2n)
^{8}Li	0.838	11	(π^-,α+^{2}H+p+n)
^{8}He	0.119	0.16	(π^-,^{3}H+4p+n)

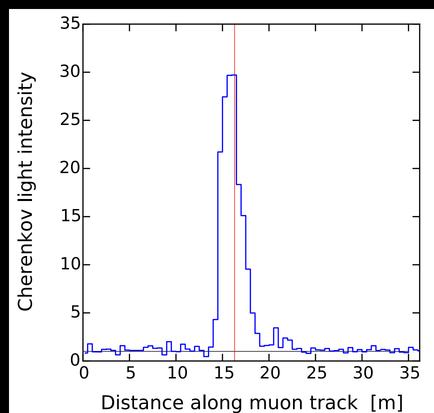
Li, Beacom (2014)

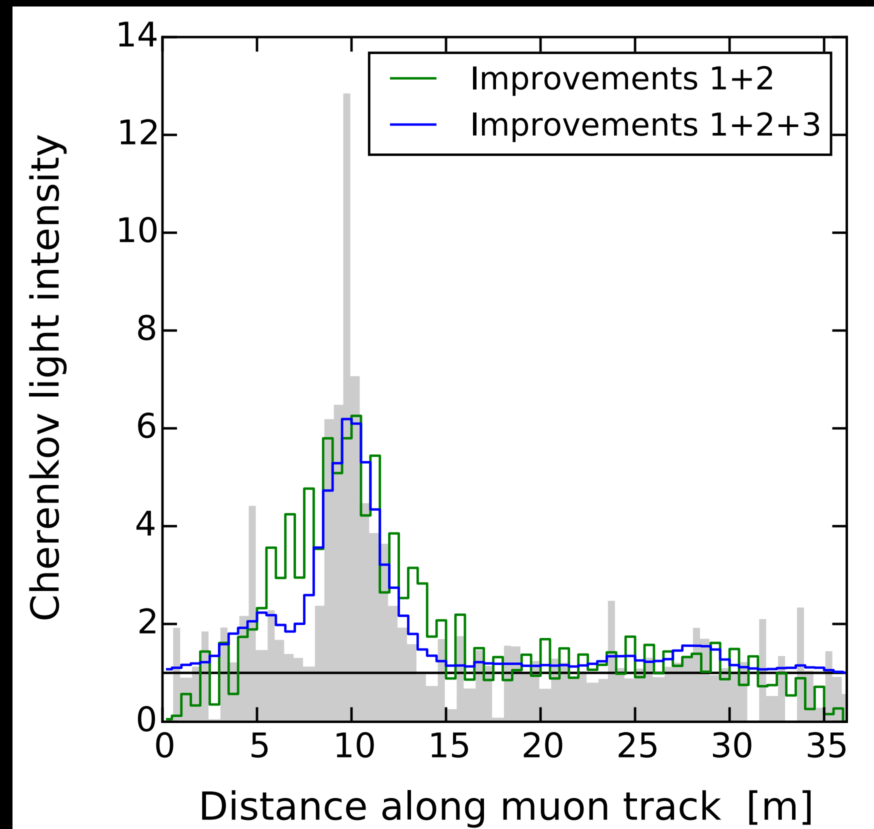




Spallation Decays: Shower Localization

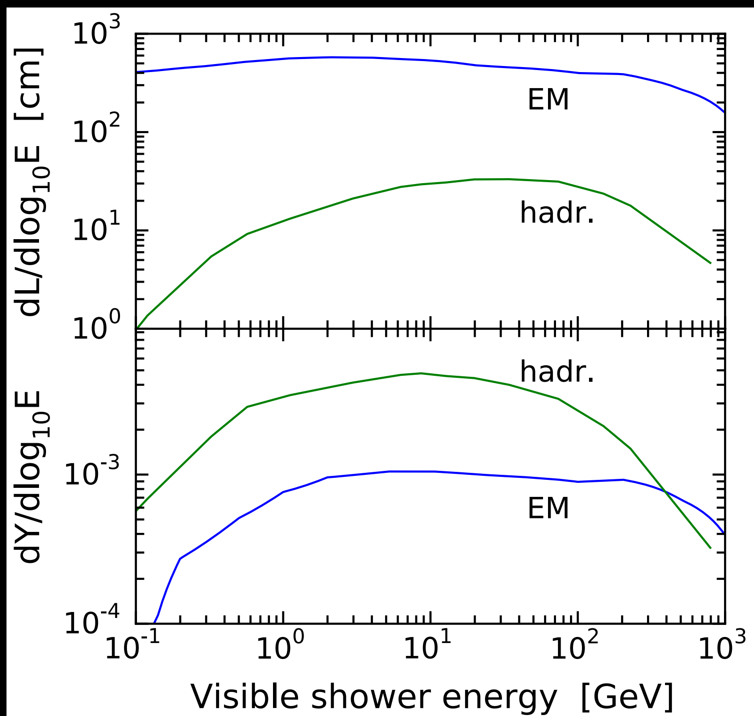


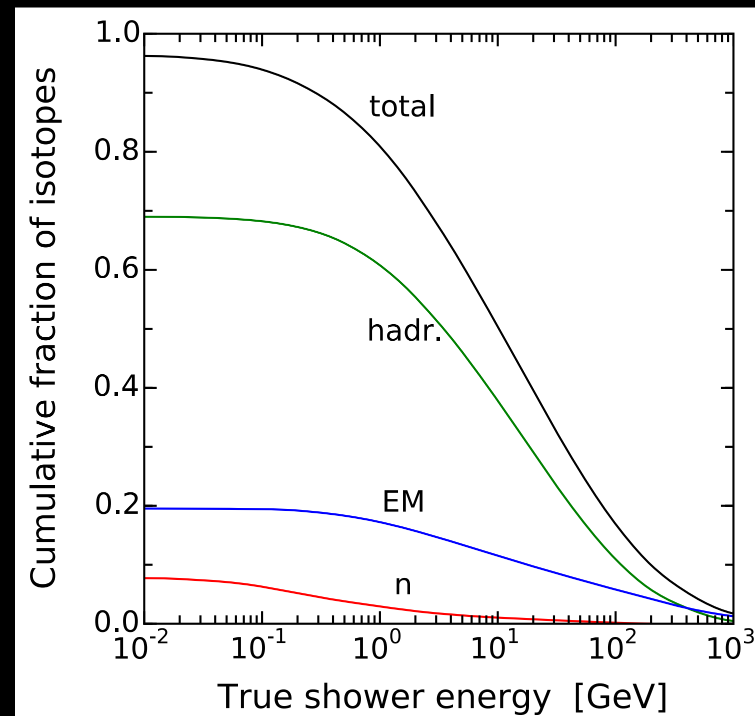




Li, Beacom (2015)

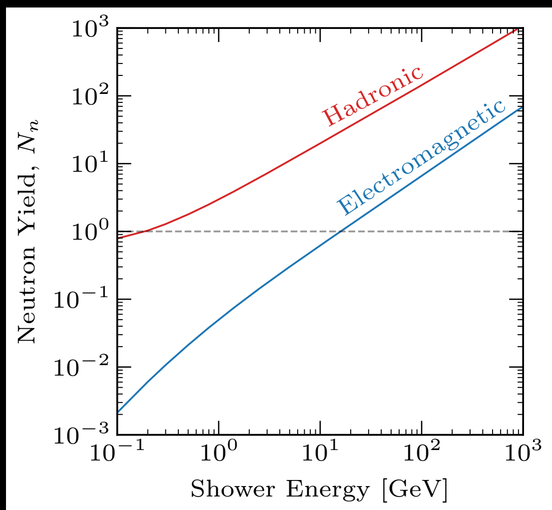
Spallation Decays: Shower Type



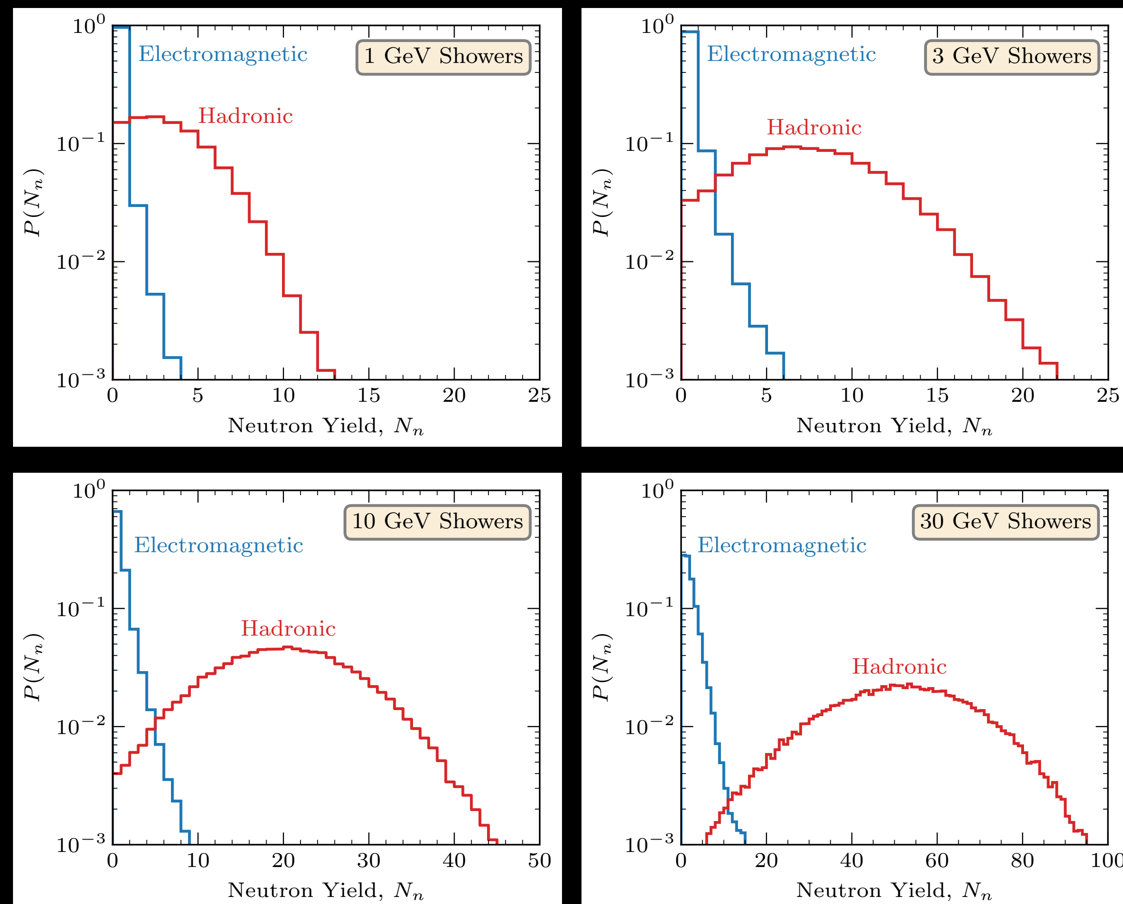


EM showers make lots of light but not isotopes; hadronic showers do the opposite

Spallation Decays: Neutron Production

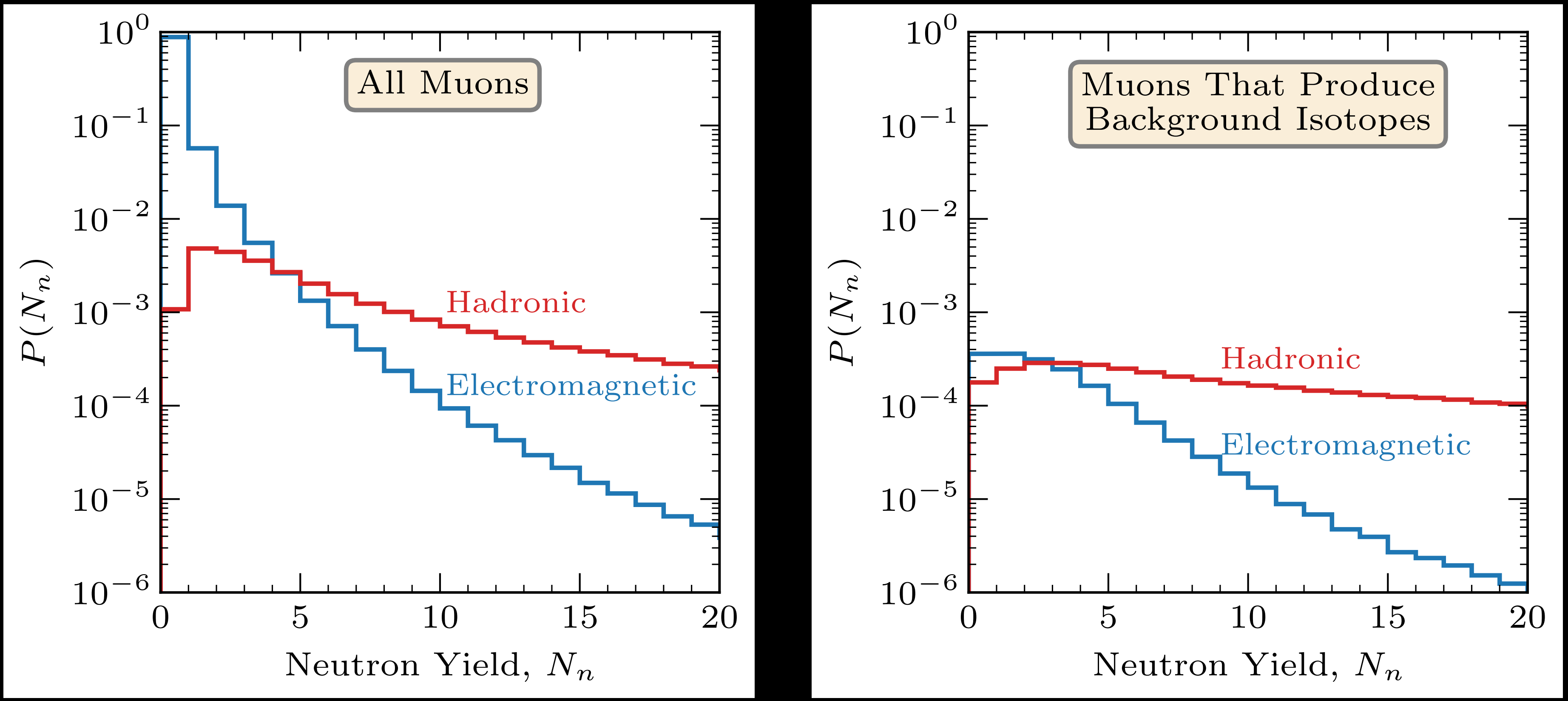


Nairat, Beacom, Li (2024)

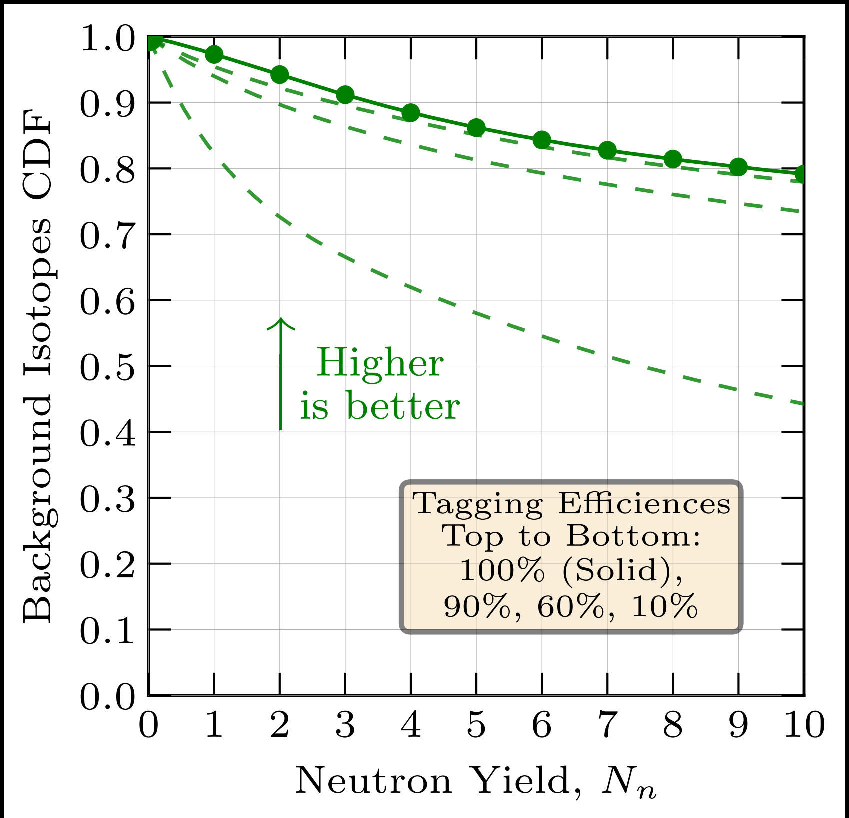


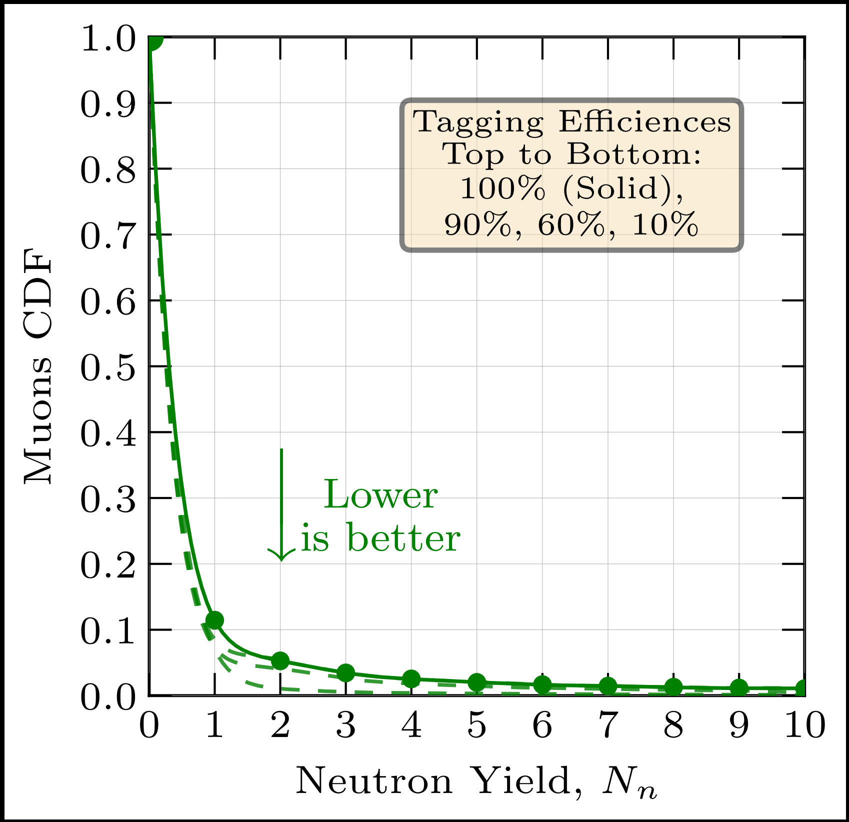
Obada Nairat,
lead author

Spallation Decays: Neutrons and Showers



Spallation Decays: Neutrons and Isotopes





Spallation Decays: Expected Impact

Main Results:

1. Super-K with Gd

Reduce spallation by factor ~4

2. Super-K with pure water

Promising to help big dataset

3. Hyper-K

Would increase the effective depth

Bonus Results:

1. JUNO and other detectors

Paper in preparation

2. Fake supernova bursts

New technique to test readiness

Spallation Decays: Tasks for Super-K

+ Study role of muon bundles

+ Redo analyses of spallation yields

+ Base geometric cuts on showers

+ Implement our methods

+ Get our help (for free)

→

Greatly reduce backgrounds

Improve sensitivity for DSNB, solar, reactor, other searches

Concluding Remarks

A Dream Scenario for MeV Neutrino Astronomy

Experimental side:

JUNO start
Hyper-K start
DSNB signals in Super-K, JUNO
DUNE start
Milky Way supernova
…

Other sides:

Star aspects measured well
Supernova aspects measured well
Supernova models advance well
Neutrinos measured well
Peace on Earth
…

→ High-statistics measurement of DSNB in HK-Gd

A Realistic Nightmare Scenario

present and near future

large detectors
used to measure
neutrino mixing

beyond that

maybe not
anymore

time

Who will build detectors for supernova neutrinos?

What Should We Do?

Make a strong, positive, forward-looking case for supernova physics
Why we need multiple detectors for multiple supernova flavors
Why THEY need supernova neutrinos to do their work

Make a strong, positive, forward-looking case for gadolinium technology
Why this is the best route towards discoveries in supernova science
Why THEY need gadolinium to do their work

Take clear, effective actions to show a unified community
If we divide, we will be ignored

Closing Message

Neutrinos take patience, but they reward it richly