The Diffuse Supernova Neutrino Background in Super-Kamiokande

Sonia El Hedri

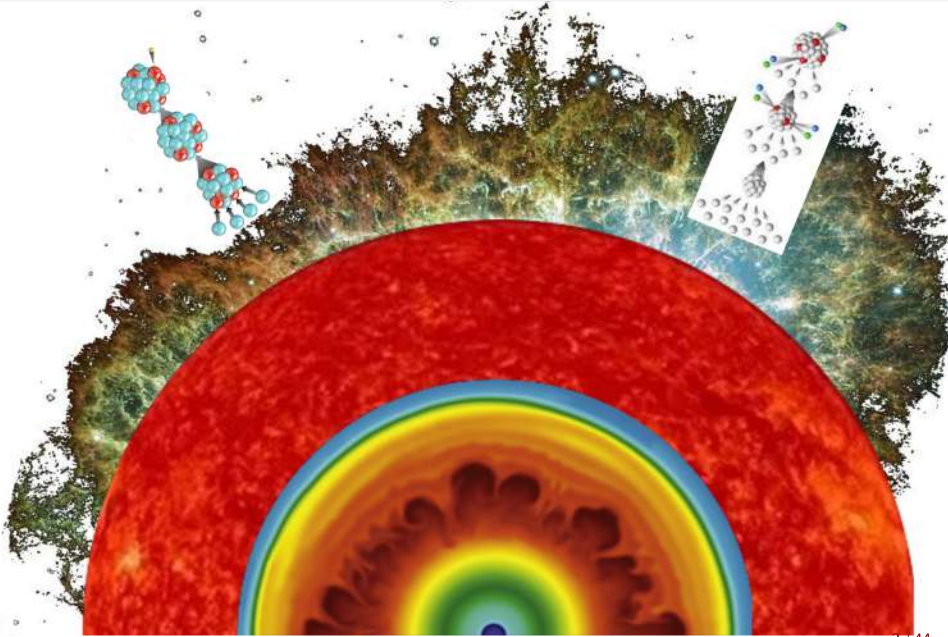
LPNHE Seminar

November 2, 2020

Not-so-diffuse supernovae

Not-so-diffuse supernovae

Core-Collapse Supernovae



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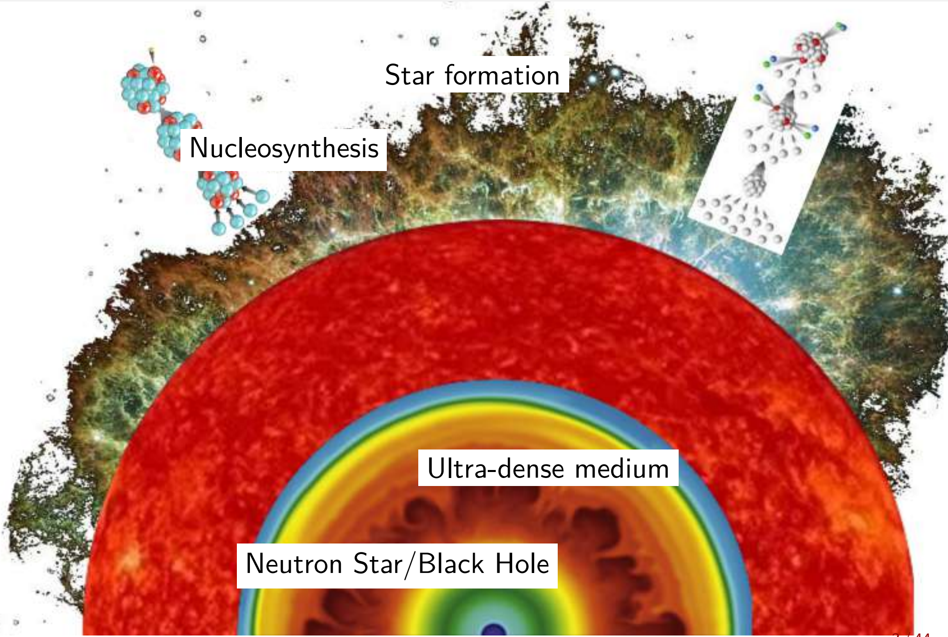
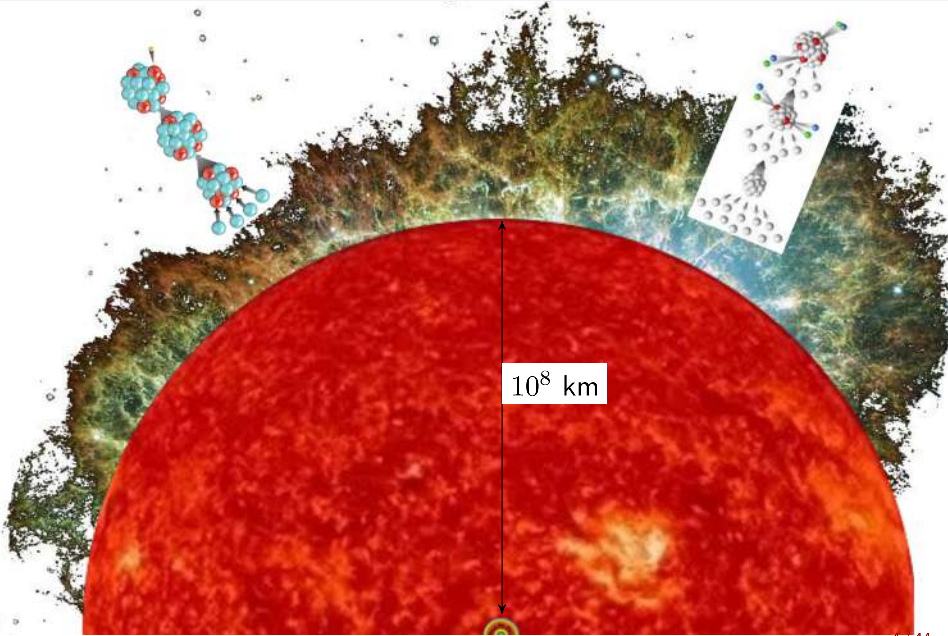
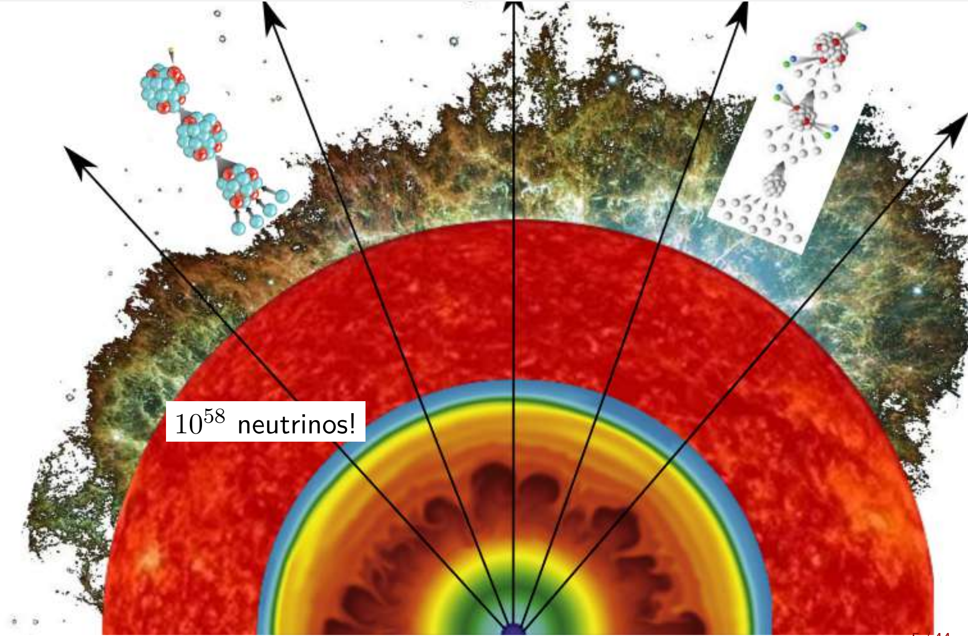


Probing core-collapse



Neutrinos to the rescue



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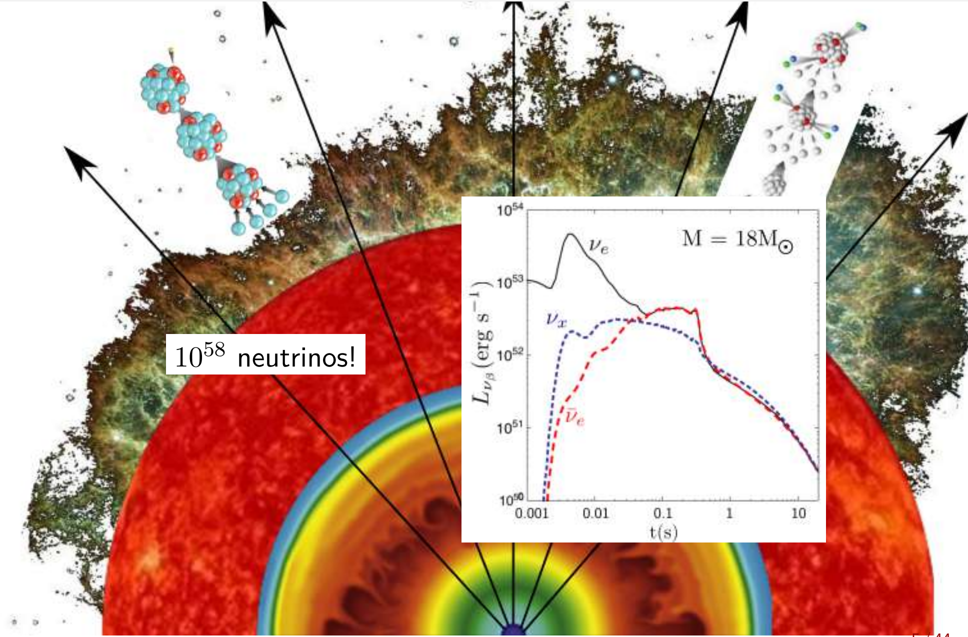

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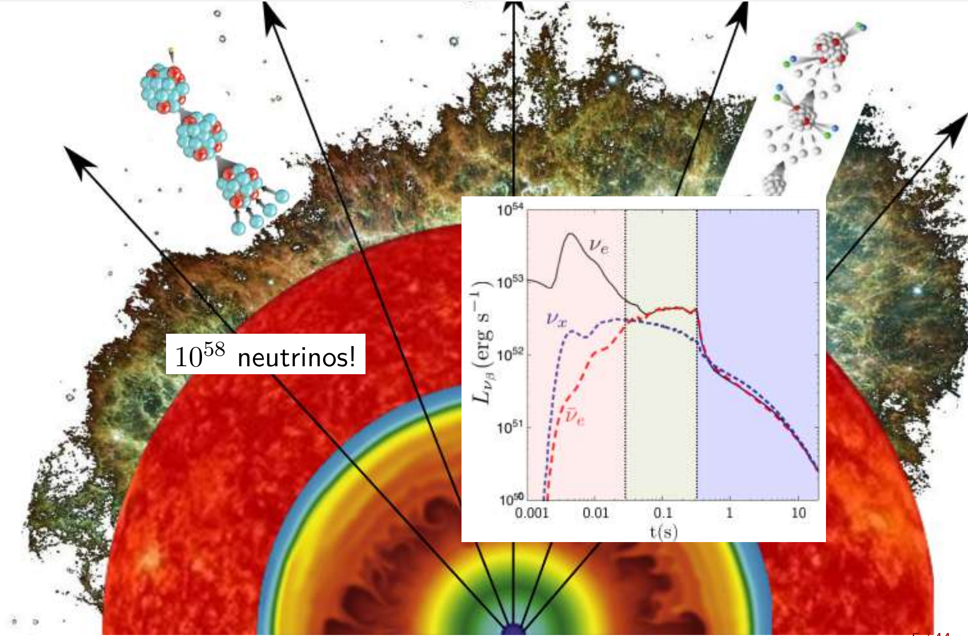
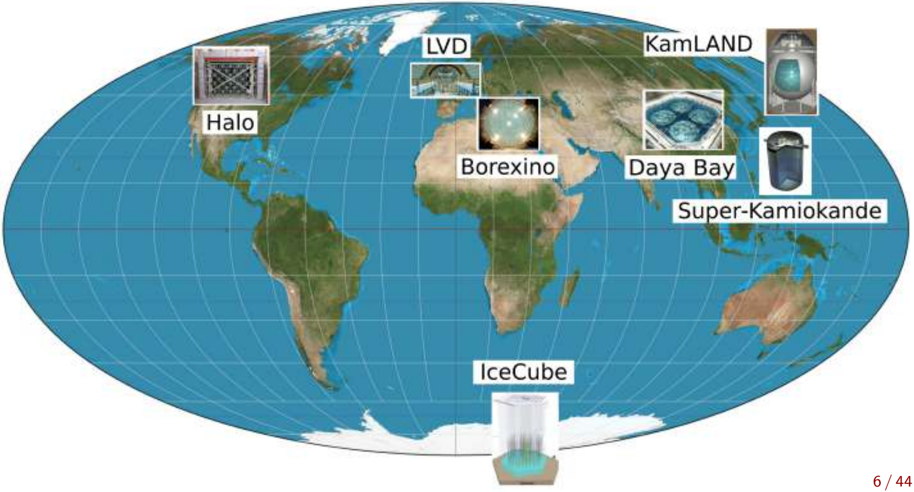


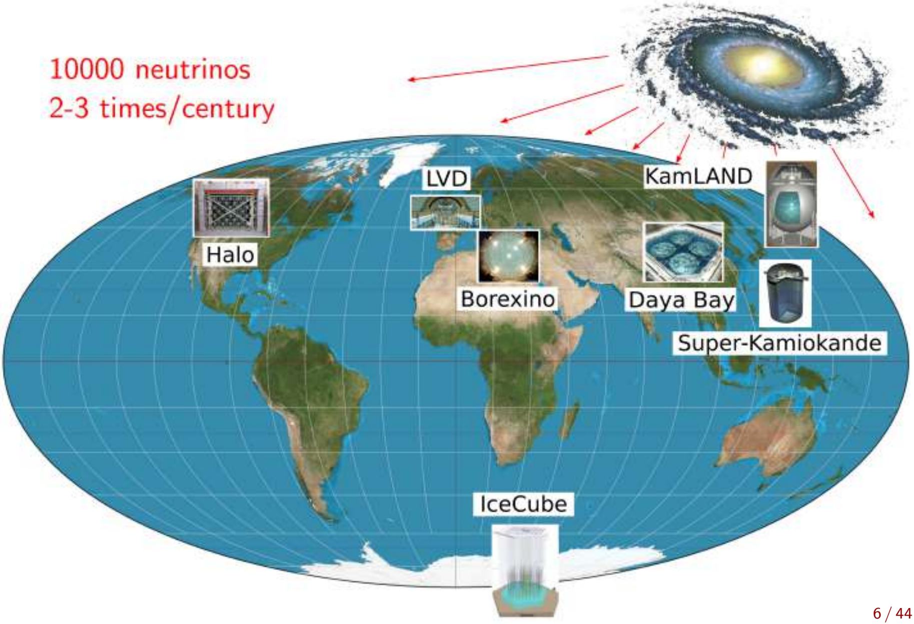
Supernovae with neutrinos: the problem

SNEWS



Supernovae with neutrinos: the problem

10000 neutrinos
2-3 times/century

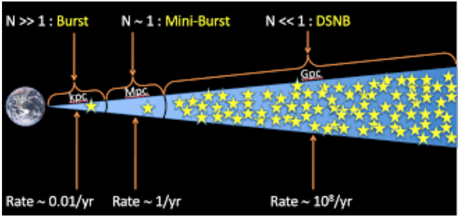


The Diffuse Supernova Neutrino Background

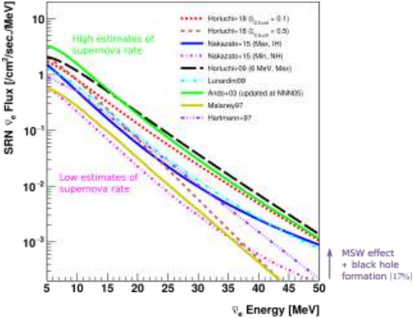
Neutrino flux from all distant core-collapse supernovae

2-3 galactic supernovae/century

1 SN/s in the observable Universe



J. Beacom



Y. Ashida

$$\Phi(E) = \frac{c}{H_0}\int_0^{z_{max}} R_{\mathsf{SN}}(z)\, F_\nu[E(1+z)]\,\frac{\mathrm{d}z}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}$$

- Aggregate properties of core-collapse supernovae
- All flavors of neutrinos, redshifted
- Elusive low energy signal

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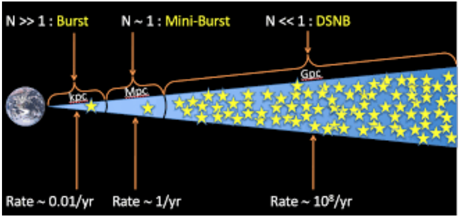

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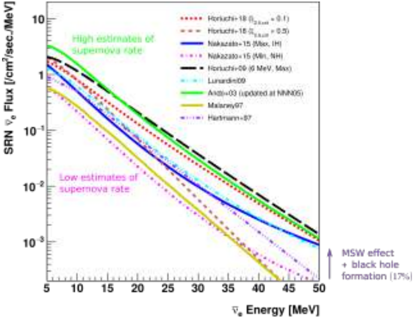


Y. Ashida

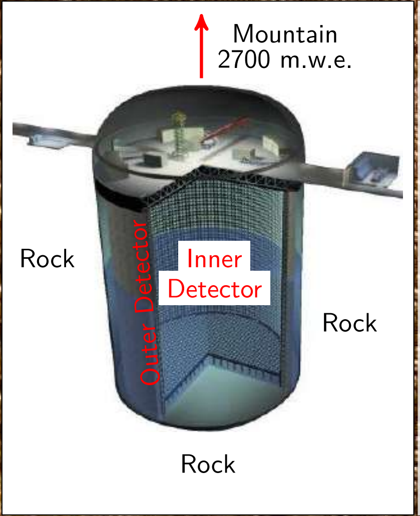
$$\Phi = \int \left[\begin{array}{c} \nu \text{ emission} \\ \text{(black hole} \\ \text{fraction)} \end{array} \right] \otimes \left[\begin{array}{c} \text{Star} \\ \text{formation} \end{array} \right] \otimes \left[\begin{array}{c} \text{Universe} \\ \text{expansion} \end{array} \right]$$

- Aggregate properties of core-collapse supernovae
- All flavors of neutrinos, redshifted
- Elusive low energy signal

Outline

1. Super-Kamiokande and the DSNB
2. The DSNB analysis in SK-IV
   - Spallation backgrounds
   - Atmospheric neutrino backgrounds
   - Neutron tagging
   - Analysis results
3. The future: Super-K Gd and Hyper-Kamiokande

Super-Kamiokande: A cheat sheet



- Kamioka Mine, Japan
- 50 kton Water Cherenkov detector
- Water constantly recirculated and purified
- 11129 Inner Detector PMTs
  50 cm, 3 ns resolution
- Currently in phase VI, doping with Gadolinium just started!
- Current study: phase IV
  longest data-taking period (2008-2017)
  2790.1 live days

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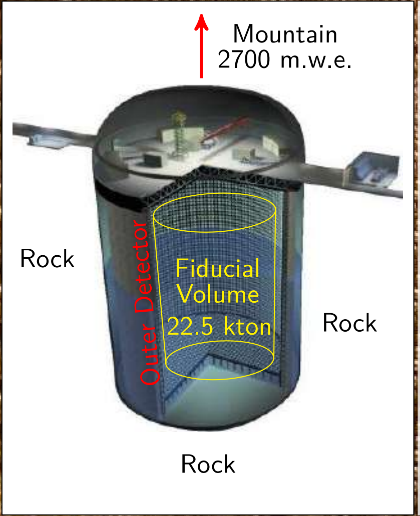

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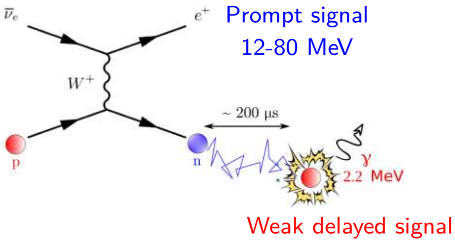
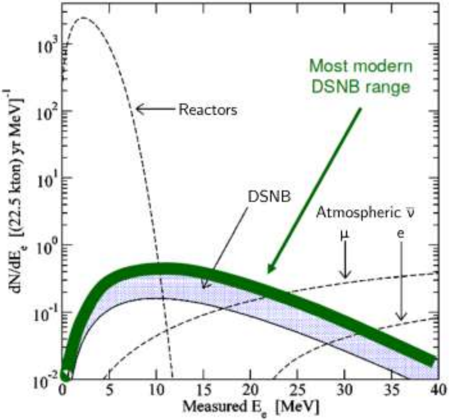
The DSNB in Super-Kamiokande

Detecting antineutrinos via Inverse Beta Decay (IBD)





[Beacom and Vagins, Phys. Rev. Lett., 93:171101, 2004]

- 5-20 events/year – Preferred detection window $10 - 20$ MeV
- Overwhelming cosmogenic and atmospheric backgrounds
  unless we identify IBD neutrons

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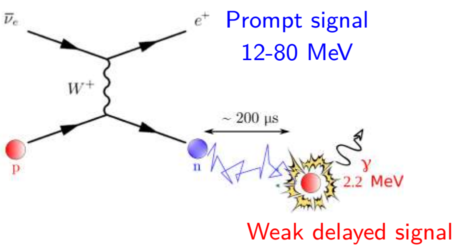

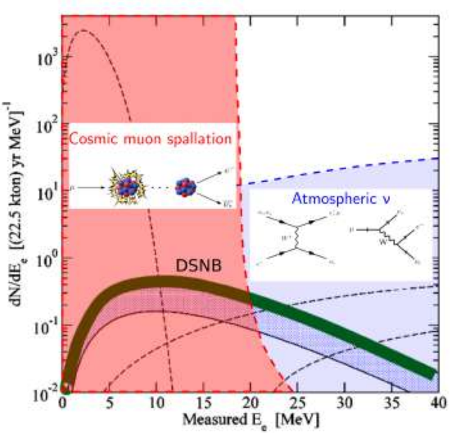

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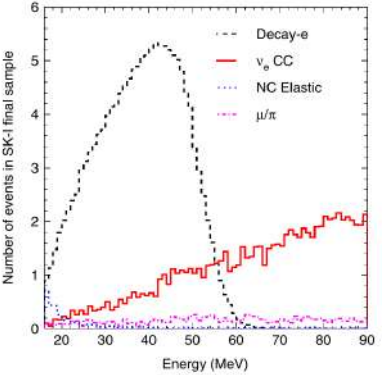
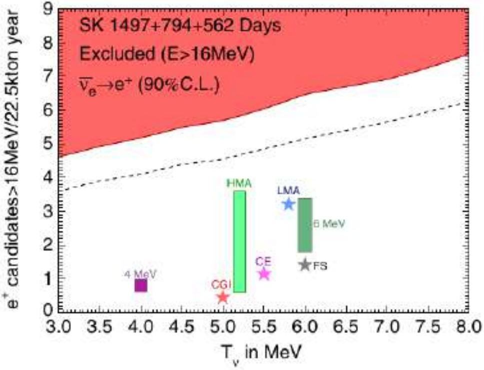
Spectral analysis in SK-I,II,III

Spectral shape fitting using SK-I,II,III data
2853 live days – No neutron identification





[K. Bays et al, Phys. Rev. D. 85, 052007 (2012)]

- "Only" a factor of two above the first models
- Energy threshold: 17.3 MeV – Atmospheric background region
- Goal in SK-IV: access the low energy region

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The DSNB analysis in SK-IV

2790 days of data – Energy range 12-80 MeV

I - Spallation cuts

- Remove radioactive isotopes produced by cosmic muons

II - Atmospheric background reduction/characterization

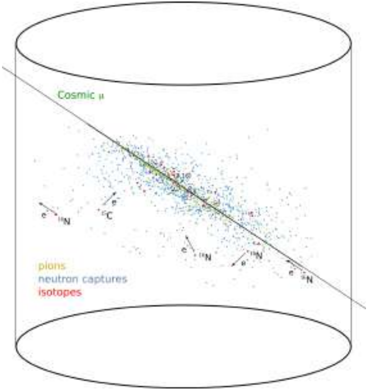
- Remove atmospheric signals with pions/muons/gammas
- Characterize atmospheric neutrino spectra

III - Neutron tagging

- Possible only since SK-IV
- Identify neutron capture signal in water

Spallation backgrounds

Radioactivity induced by cosmic muon spallation in water – 1.3 μ/s in SK

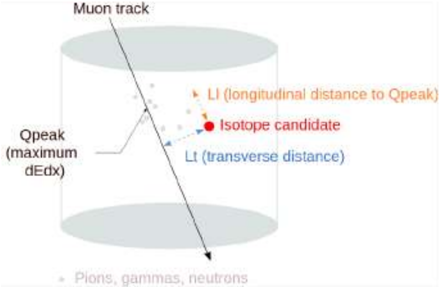


- Isotope decays often appear in clusters (50% of spallation events)
- 1% of spallation events are IBD-like (^{9}Li): $A \to e^- + n$
- 10^5 spallation events in our signal window $\Rightarrow$ Need $\mathcal{O}(10^4)$ reduction
- Isotopes spread over up to 5 meters – Decays times up to 30 s

Spallation: hunting for correlations

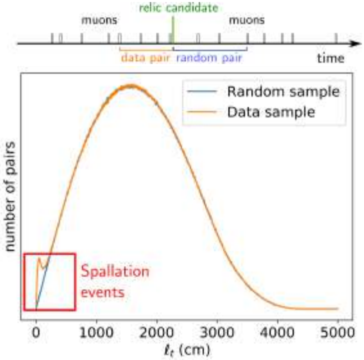
Pair each DSNB candidate with muons up to 30 s before
Investigate correlations using a likelihood analysis

Observables



- Δt, L_t, L_l: distance and time difference
- resQ: charge deposited by the muon in addition to minimum ionization

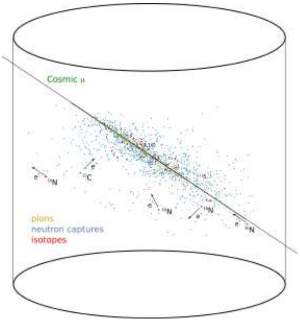
Distributions from data

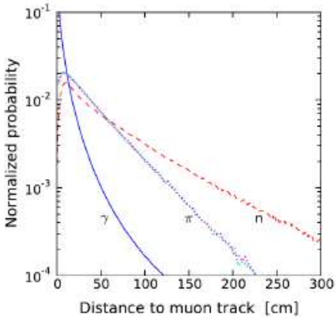


Going further: simulation studies

Considerable insight gained from FLUKA simulations of vertical muons
S. Li and J. Beacom, Phys.Rev. D91 (2015) no.10, 105005

- Most isotope production processes involve pions or neutrons



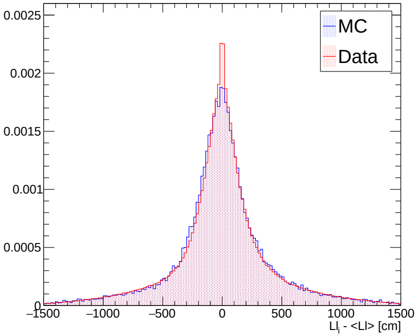


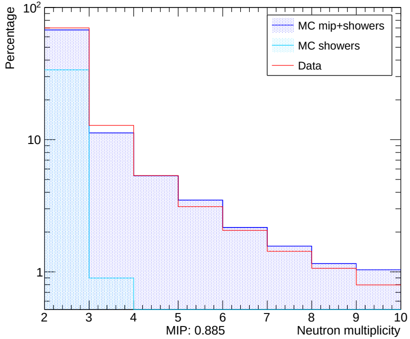
S. Li and J. Beacom, Phys.Rev. D91 (2015) no.10, 105005

- Ongoing effort: realistic FLUKA simulations interfaced with the SK detector simulation (GEANT-3). With A. Coffani and L. Bernard, LLR

A recent application: neutron clouds

Identify muon shower by tagging neutron capture processes





- Track PMT hit clusters in sample of ultra low energy events from 2014 to 2017 [S. Locke, UC Irvine]
- Preliminary results: excellent agreement between data and simulations for cloud size and neutron multiplicity
- New handle to remove isotopes produced far from muon tracks

Spallation: the final SK-IV strategy

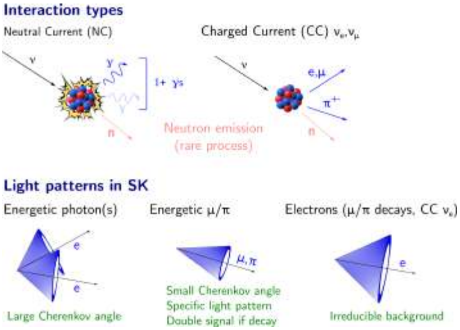
- A three-pronged analysis using insights from simulations:
  - Remove clustered low energy events
  - Remove events next to neutron clouds
  - Identify correlations with preceding muons

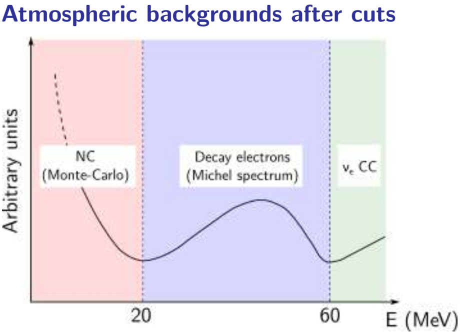
- $90 - 98\%$ background rejection ($> 99\%$ on ^{9}Li)
  $40 - 90\%$ signal efficiency (depending on reconstructed energy)

- Promising directions to explore in the future phases of SK
  - Machine-learning studies using simulations
  - Extended neutron identification capabilities

Atmospheric neutrino backgrounds

Dominant background above 20 MeV



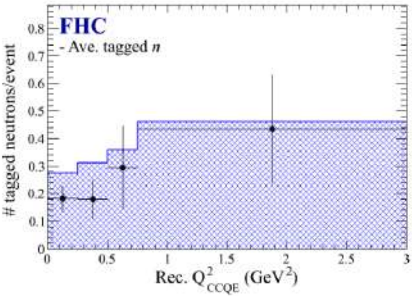


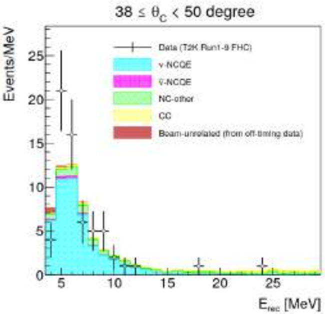
Categorization and reduction in SK:

- Categories: NC and μ/π (reducible), ν_e CC and decay electrons (irreducible).
- For NC and μ/π: high efficiency cuts on the Cherenkov light pattern.

Characterizing atmospheric neutrino backgrounds

Atmospheric backgrounds are poorly known below 100 MeV
Only available measurements: T2K studies





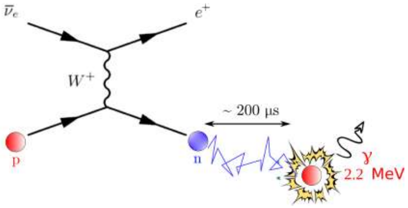
[Y. Ashida, Ph D. thesis (2019)]

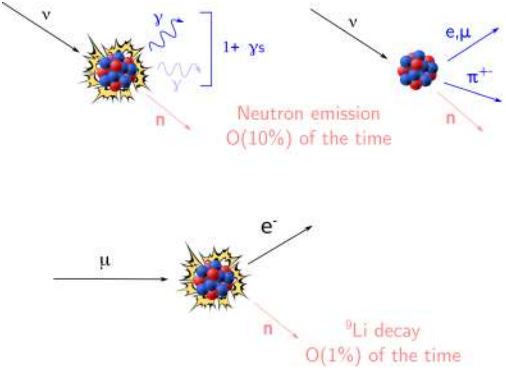
Large uncertainties in fluxes and spectral shapes:

- Final state types and multiplicities: pions, neutrons, ...
- Number of secondary gamma rays from fast neutron interactions
- Only the decay electron spectrum is well-characterized

The ultimate background removal technique

Neutron tagging can remove more than 99% of the backgrounds



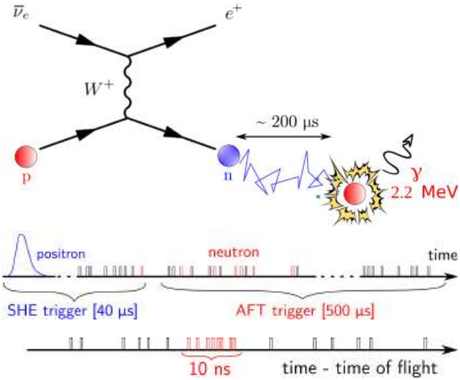


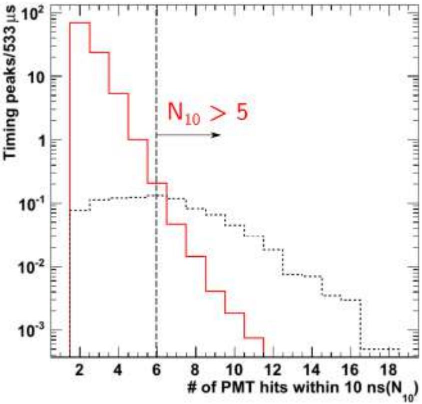
A challenging signal to detect:

- In pure water: large capture time, faint capture signal
- In SK-IV: define $500\ \mu$s "AFT" trigger windows after each positron-like event..then look for a needle in a haystack

Selecting neutrons: a needle in a haystack

Neutron capture occurs **near the positron vertex**





- New in SK-IV: "AFT" trigger window after the positron window
- Sensitivity to dark noise: inject random trigger data into MC simulation (SKDetSim – GEANT3) for cut optimization.
- Preselection: define **candidate neutron peaks** with $N_{10} > 5$

Weed out candidate peaks

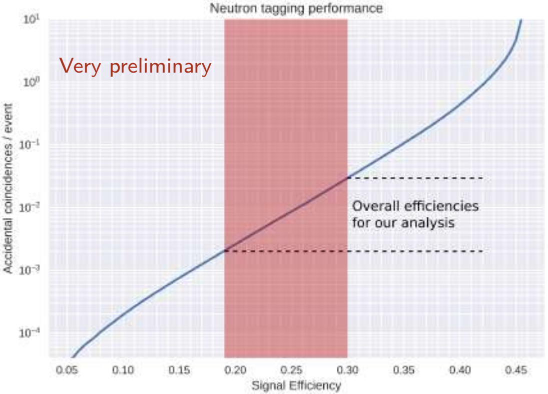
About 10 candidate peaks per event...most of them are noise
Study candidate peaks one by one
Use a **Boosted Decision Tree** (BDT) with 22 observables

- Neutron capture position
  Further exploit proximity to the positron vertex
  Reconstructed neutron vertex, time spread
- Background contamination
  Clusters, high charge hits, unusually high activity
- Ring shape
  Cherenkov angle, azimuthal symmetry, backward hits

Need to reduce the background by a factor of 10^4
Extreme sensitivity to signal and noise modeling!

Selecting neutrons: final step

Use a Boosted Decision Tree (BDT) to tag neutron candidates.



- **Final performance**: $0.3 - 3\%$ background acceptance
  $18 - 30\%$ signal efficiency.
- Expect considerable performance enhancement in the current SK-VI phase, with Gadolinium doping.

Analysis procedures

Supernova model-independent analysis

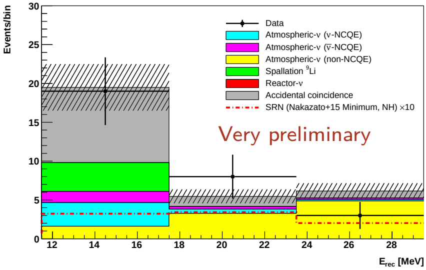
- Low energy analysis: $12 - 30$ MeV reconstructed positron energy
- Atmospheric CC: estimate by fitting Michel spectrum in $[30, 80]$ MeV
- Atmospheric NC: estimate using T2K data $\Rightarrow$ define 3 large energy bins
  50% uncertainties for NC backgrounds
- Bin-by-bin cut optimization and limit calculation

Spectral analysis

- Fit observed energy spectrum by DSNB + atmospheric spectra
- Two analyses, with and without neutron tagging
- Need to eliminate spallation + solar backgrounds
  $\Rightarrow [16, 80]$ MeV energy range
- Atmospheric spectral shapes: use sidebands in Cherenkov angle for NC and μ/π. Assume $\mathcal{O}(100\%)$ uncertainties on normalizations and shapes **except for Michel spectrum**.

Supernova model-independent analysis

No excess observed – Significantly improved exclusion bounds at low energy



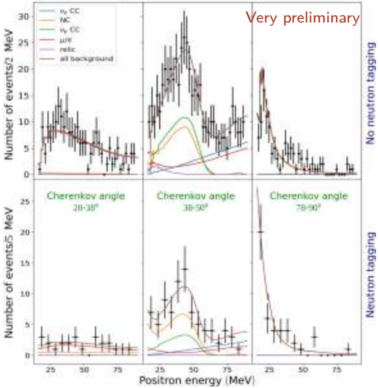
Search Results & Integrated SRN Electron Antineutrino Flux [/cm²/sec.]

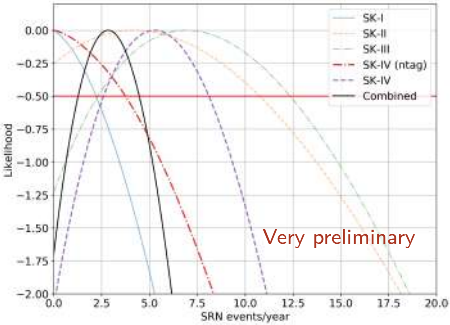
E_ν region [MeV]	13.3–19.3	19.3–25.3	25.3–31.3
SK-IV 2970 days (Expected)	9.48	1.35	0.82
SK-IV 2970 days (Observed)	9.08	2.22	0.35
Nakazato+15 (Minimum, NH)	0.337	0.089	0.026
Horiuchi+09 (6 MeV, Maximum)	2.534	0.887	0.314
Ando+03 (updated at NNN05)	2.652	0.796	0.261

- Neutron tagging allowed to bring the analysis threshold from 16 to 12 MeV (limit set by reactor neutrinos and atmospheric backgrounds)
- Current limits within a factor of a few of optimistic DSNB scenarios.
- Better neutron tagging would allow to probe a significant fraction of the DSNB parameter space
- Even with improved neutron tagging, important uncertainties from NC γ emission and neutron multiplicity

Spectral analysis

Combination of SK-I to IV for the Ando (optimistic) model





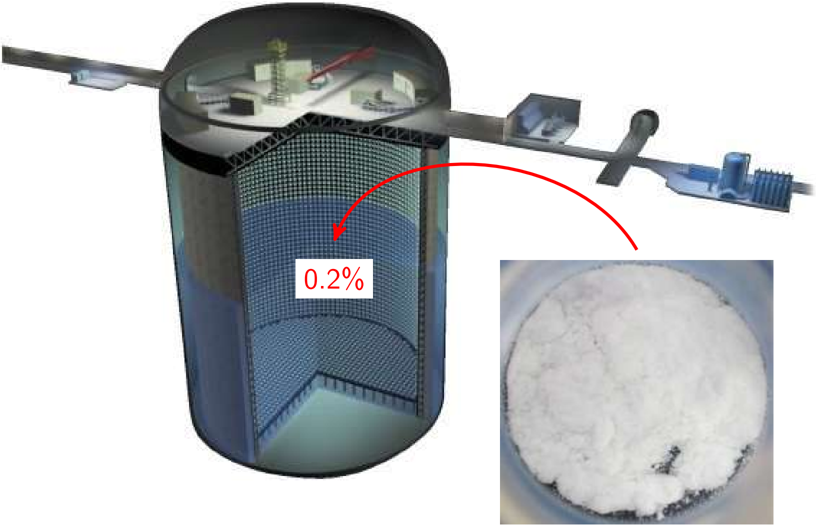
- Slight excess at low energy without neutron tagging
- Current 90% C.L. limits on the Ando model flux (1.7 cm^{-2}/s):

SK-IV (no neutron tagging) :	$\Phi_{90} = 4.9$ cm^{-2}/s
SK-IV (neutron tagging):	$\Phi_{90} = 3.8$ cm^{-2}/s
Combined (22.5×2853 kton.day) :	$\Phi_{90} = 2.7$ cm^{-2}/s

The DSNB in SK-IV: summary

- Expand on the 2012 analysis by using neutron tagging to fully characterize IBD processes
- Neutron tagging reduces backgrounds by a factor of 10^3 but removed more than two thirds of the signal
- Interesting possibilities to expand the spallation reduction algorithm using simulations and neutron clouds
- Current sensitivity close to the predictions of optimistic DSNB models
- Need to make neutron tagging more efficient
- Need to decrease the atmospheric neutrino systematics

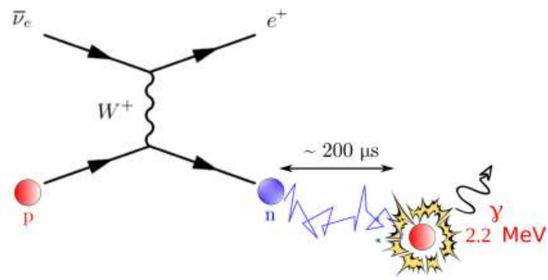
One spoonful of Gadolinium



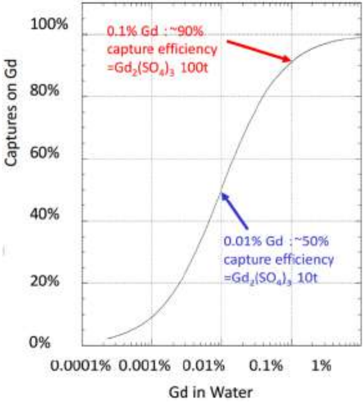
Gadolinium Sulfate

Why Gadolinium?

High neutron capture rate, small capture time, visible signal



[Nucl.Part.Phys.Proc. 273-275 (2016) 353-360]



- 0.1% Gd leads to 90% capture probability
- Neutron tagging signal much more visible

We just needed to convince people to dissolve 150 T of Gd powder in a pure water Cherenkov detector...

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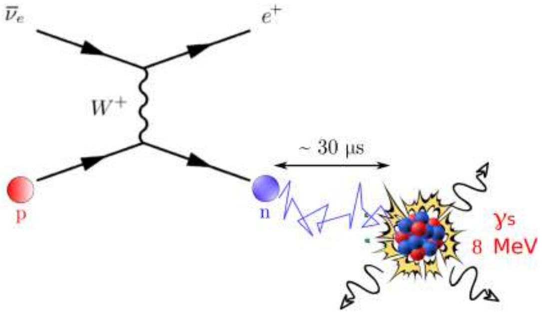

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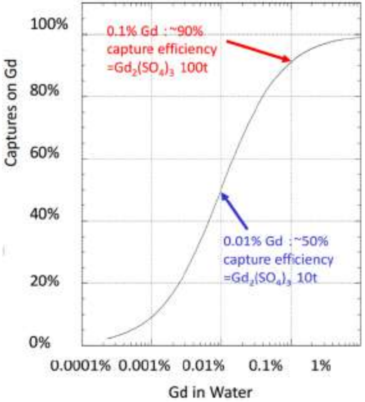

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The steps towards gadolinium

EGADS (or baby-SK)

SK refurbishment

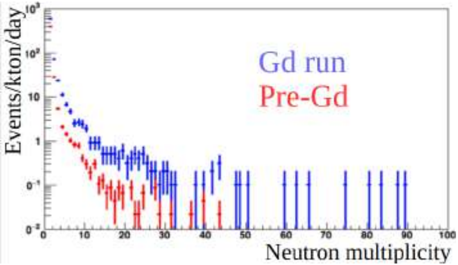
Final repairs

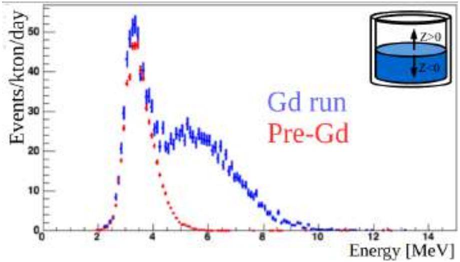
Radiopurity

The final timeline

- October 2018: New water system implemented for SK
- September 2019: 13T ultra-pure $GdSO_4$ delivered at Super-K
- July-August 2020: dilution 0.02% $(Gd)_2(SO_4)_3$
- Some time in 2021: dilution 0.2% $(Gd)_2(SO_4)_3$ [nominal]
- 2020 – ?: data-taking

It's raining neutrons!



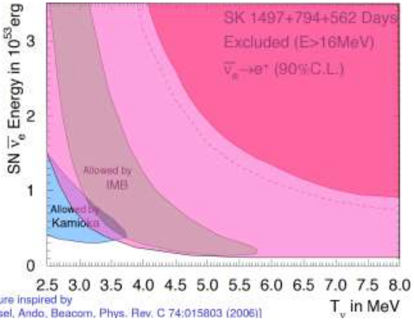


- Identification of neutron clouds following muons
- Significant increase in tagged neutron multiplicity
- Capture energies larger than the SK low energy threshold

Expectations for the DSNB

If we make the most of neutron tagging...

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	----



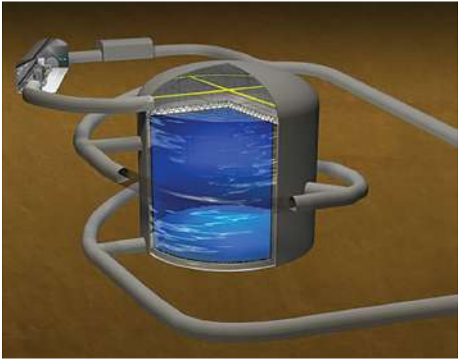
[Figure inspired by Yuksel, Ando, Beacom, Phys. Rev. C 74:015803 (2006)]

- Sensitivity up to regions favored by SN 1987A!
- Will probe many DSNB models and can lead to first discovery
- "On/Off" study: proof of existence but no spectral study
- The atmospheric NC systematics will still be alive and well

Going further: Hyper-Kamiokande

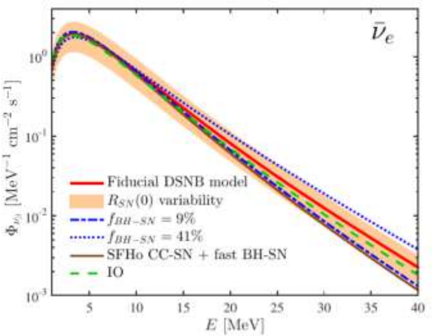
Next generation of Water Cherenkov detector

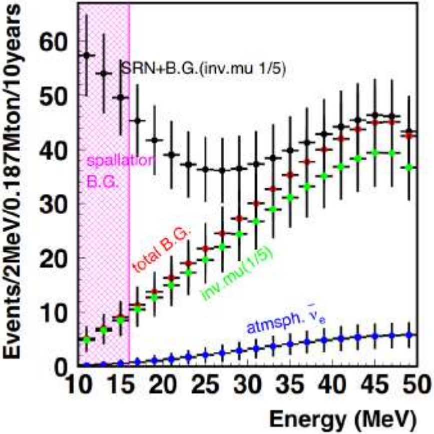
- 187 kton of fiducial volume (22.5 kton for SK)
- 20% PMT coverage
  x2 efficiency
- Close to Super-Kamiokande



- Approved by the Japanese government in January
- Expected start around 202X for more than 10 years of data-taking

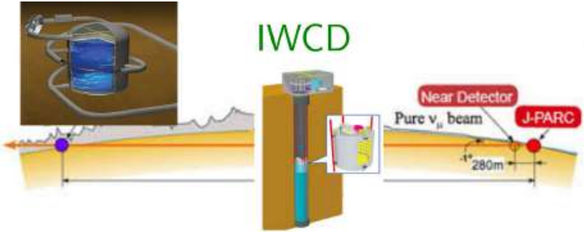
Unique sensitivity to the DSNB spectral features





- Spectral study now possible: determine black hole fraction? constrain star formation rate?
- The informations extracted crucially depend on the **lower energy threshold** of the DSNB search...

Hyper-K: the future



Low energy DSNB search in HK:

- IWCD's cross-section studies
  - ⇒ Characterize neutrino-nucleus interactions
  - ⇒ Reduce atmospheric neutrino systematics
- Use of multi-PMTs
  - ⇒ Improve vertex resolution?
  - ⇒ Impact on neutron tagging?
- Doping HK with gadolinium?

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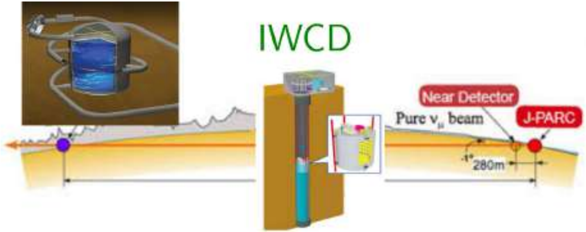

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A phenomenological study will be necessary

Conclusion

- Close-by supernova bursts are spectacular but rare...
- The DSNB is a unique probe of global supernova properties and the history of our Universe
- Important backgrounds in traditional WC detectors
- Significant room for improvement in spallation studies
- Neutron tagging is a powerful tool, maximum potential in SuperK-Gd
- Current sensitivity in SK comparable to optimistic DSNB models
- SuperK-Gd and Hyper-K have a unique chance to discover and characterize the DSNB

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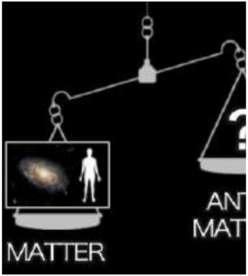
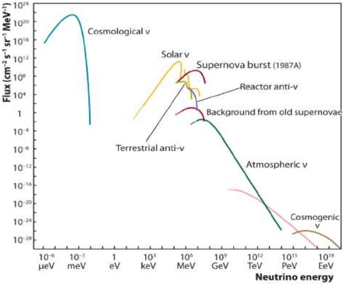
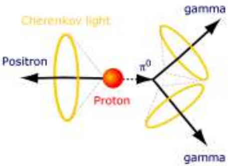
Thank you for your attention!

Physics potential







CP violation
Sterile neutrinos
CPT violation, symmetries...

δ_{CP} measurement
Mixing angles and $|\Delta m^2|$
Mass hierarchy

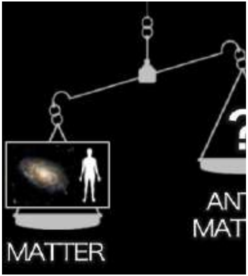
Astrophysics

Solar neutrinos
Supernova burst(s)
Supernova relics
Blazars

Great Unification
dark matter, ...

Proton decay
Exotic signatures

Physics potential



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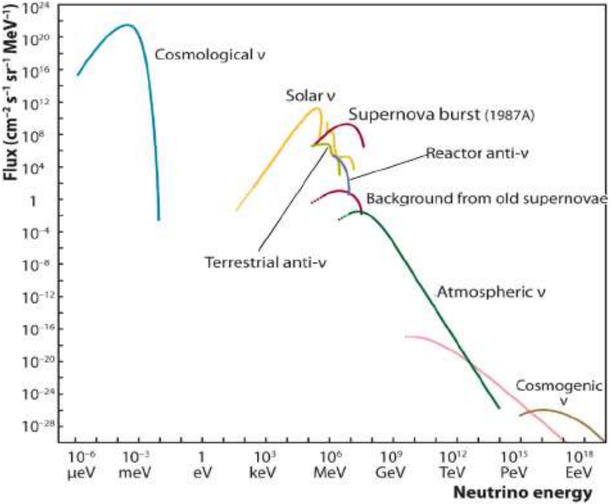

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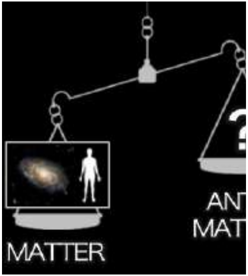

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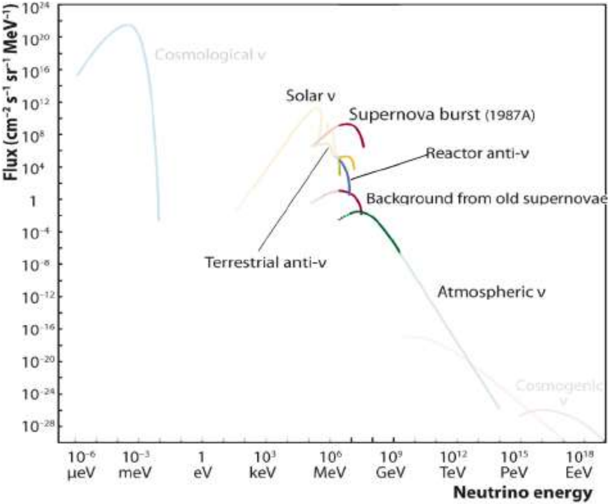

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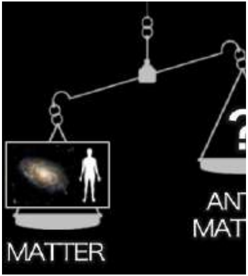

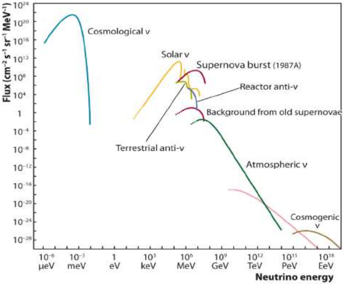

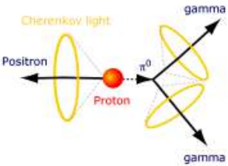

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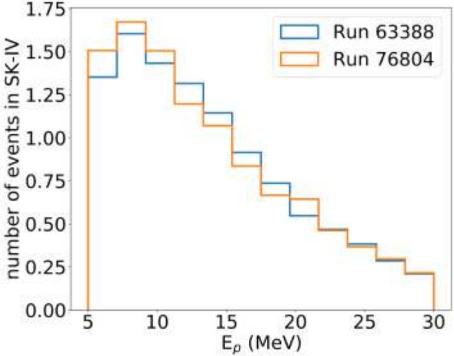
Signal and background modeling

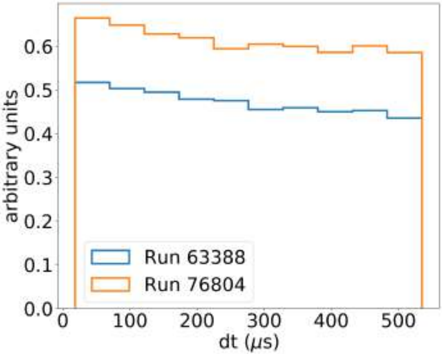
Time-dependent Monte-Carlo simulation (GEANT3)

- **Signal:** positron + neutron propagation/capture in GEANT
- **Background:** electronic noise, flashers, radioactivity...
  Inject real data (random trigger) in **7-month bins**

Positron energy



Neutron candidate time delay



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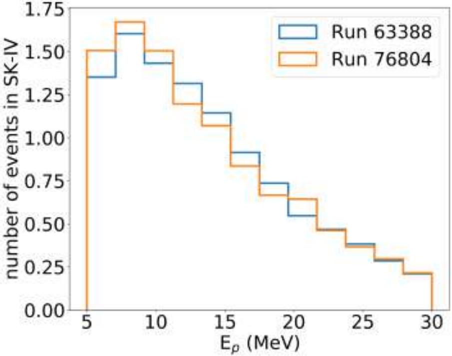

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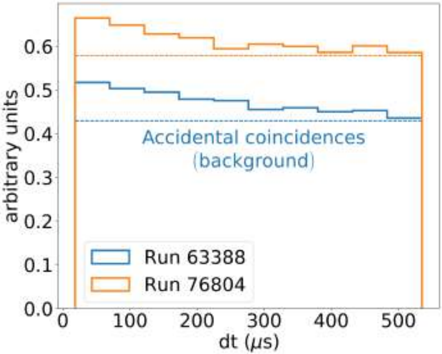

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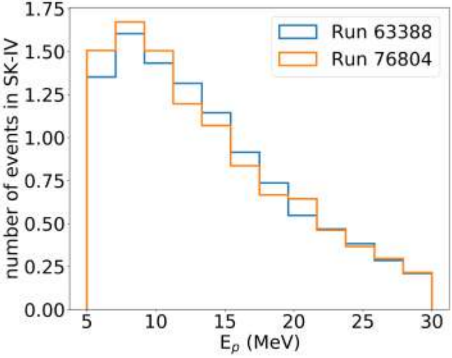

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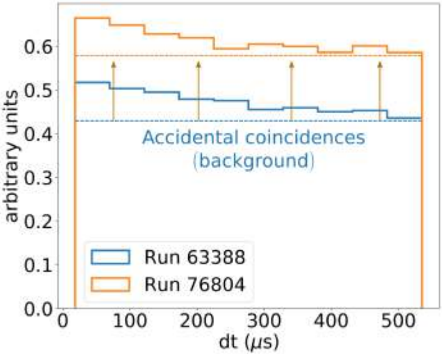
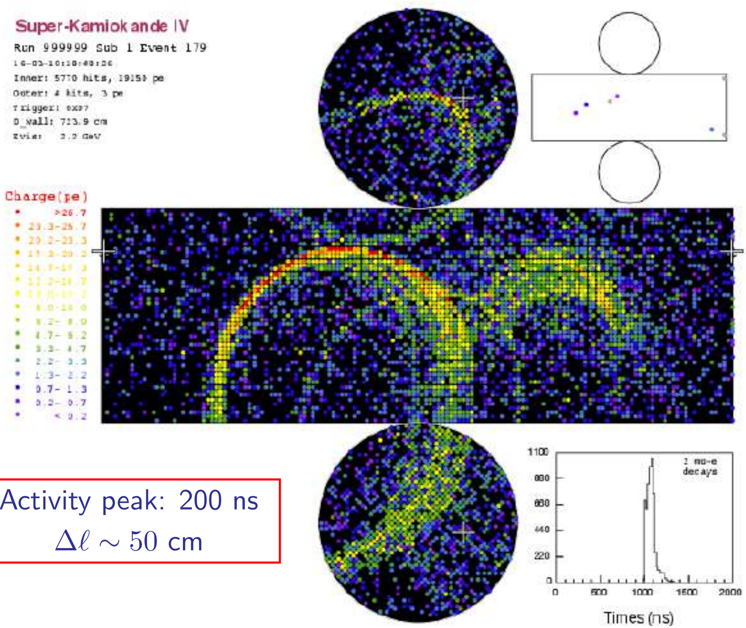


Capabilities



Activity peak: 200 ns

$\Delta\ell \sim 50$ cm

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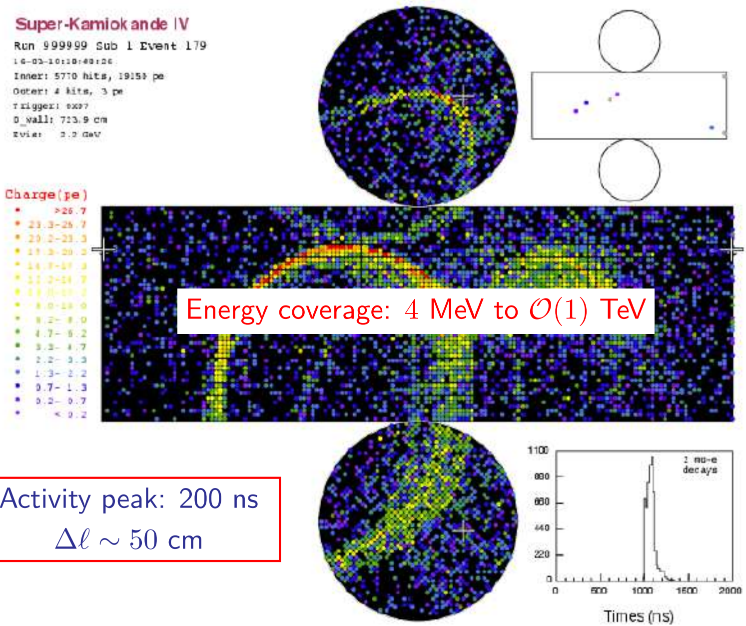

Energy coverage: 4 MeV to $\mathcal{O}(1)$ TeV

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