DSNB detection in Water-based Liquid Scintillator

ECT* Workshop
Trento, 16 May 19

Julia Sawatzki (TUM)
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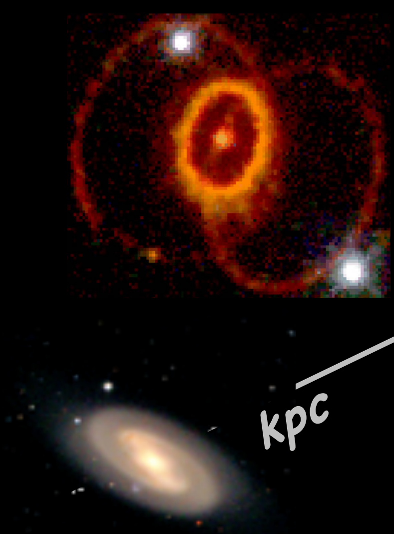
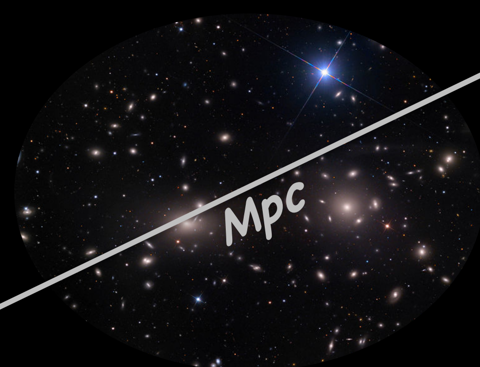
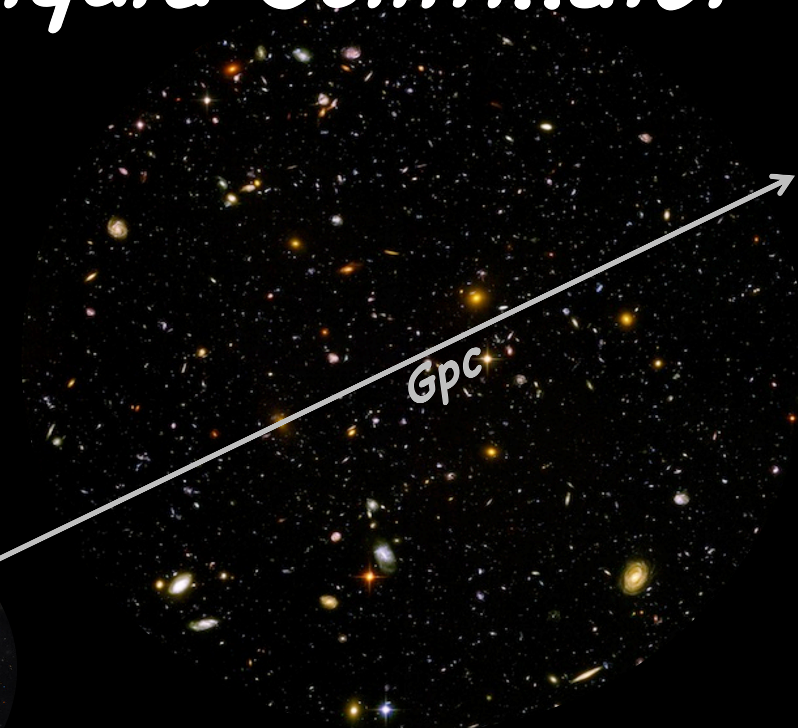


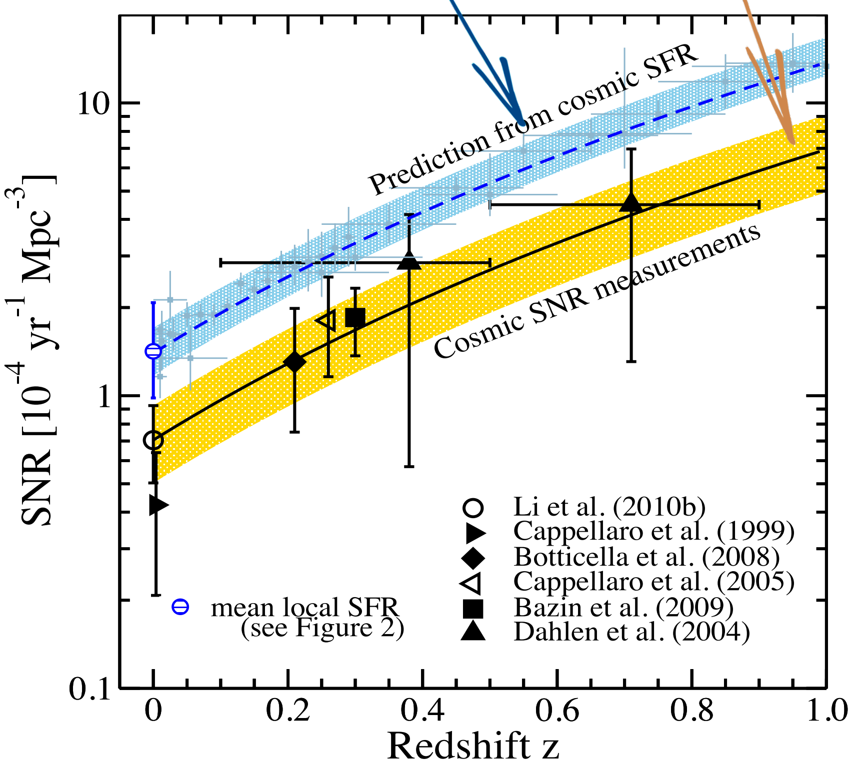


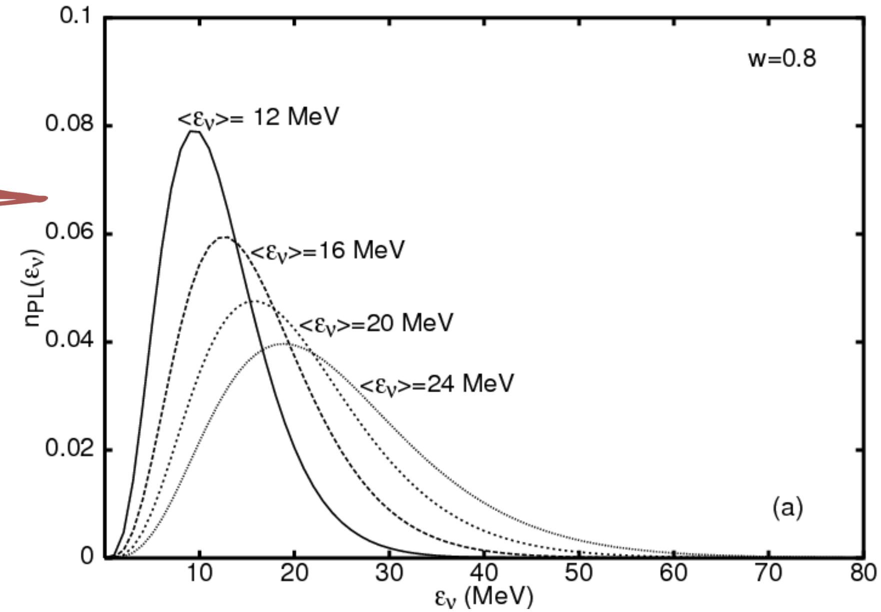


DSNB prediction

DSNB prediction depends on

- SN neutrino spectrum, $\langle E_\nu \rangle$
- redshift-dependent **Supernova rate** *(or* ***star formation and IMF****)*





Objectives of a DSNB measurement

→ first of all: discovery

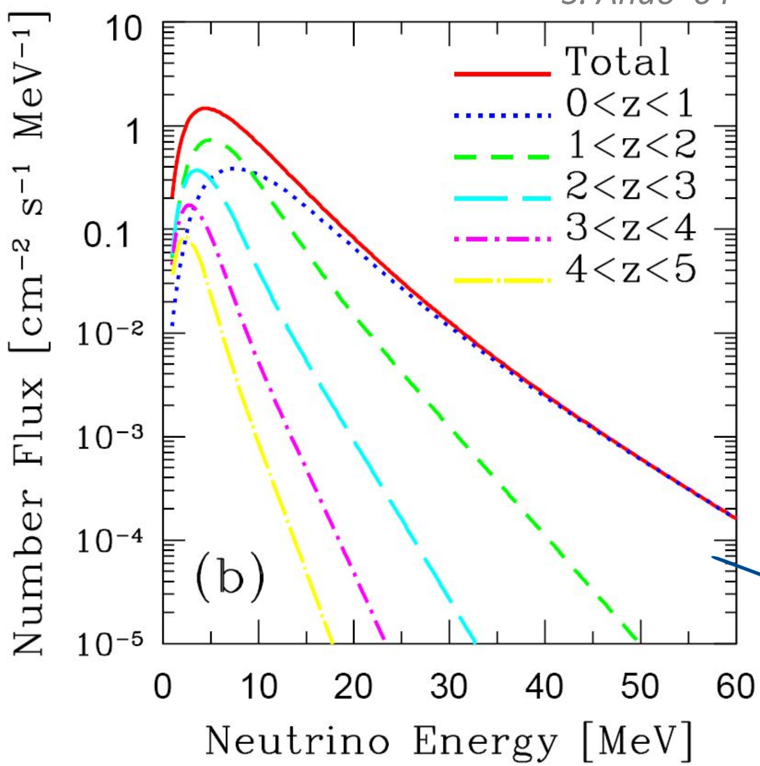
→ average Supernova ν spectrum (large variation on type expected)

→ redshift-dependent SN rate

→ fraction of hidden/failed SNe

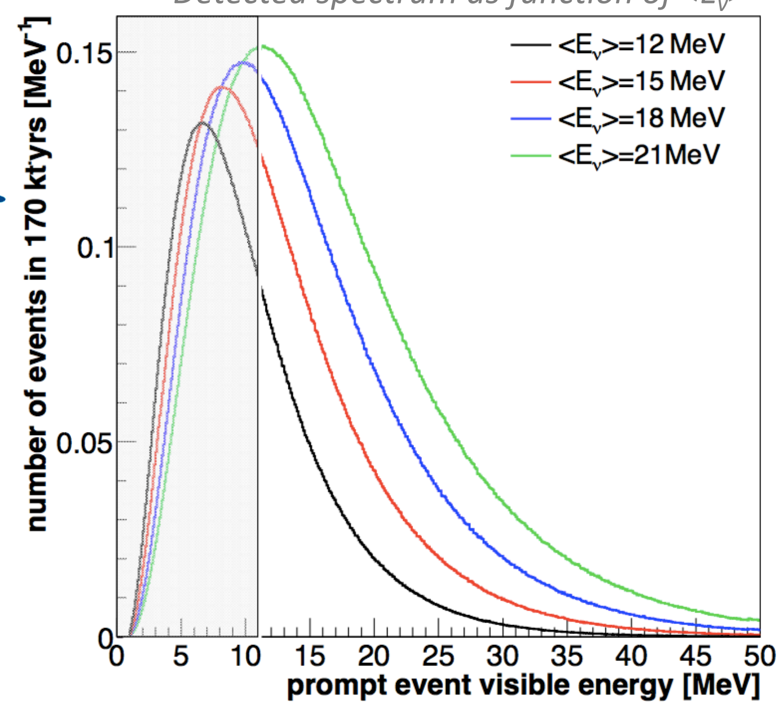
DSNB spectrum and flux

S. Ando '04



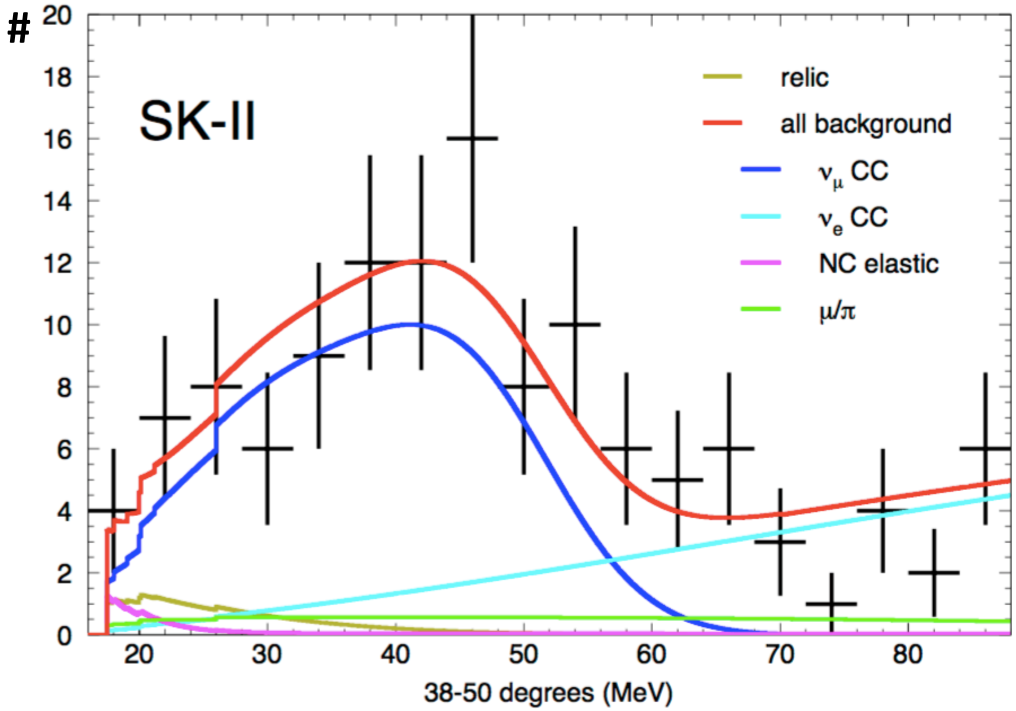
- DSNB flux: ~10^2 /cm^{2}s
- equipartition between flavors
- best possibility for detection in water and LS: **inverse beta decay**
- expected rate: ~1 per 10 kt·yrs

Detected spectrum as function of <E$_\nu$>



Current status of DSNB (non-)detection

- DSNB provides for a very faint signal: ~1 IBD per year and 10 kt water (LS)
- Super-K only able to provide an upper limit → efficient IBD neutron tag missing



positron energy [MeV]

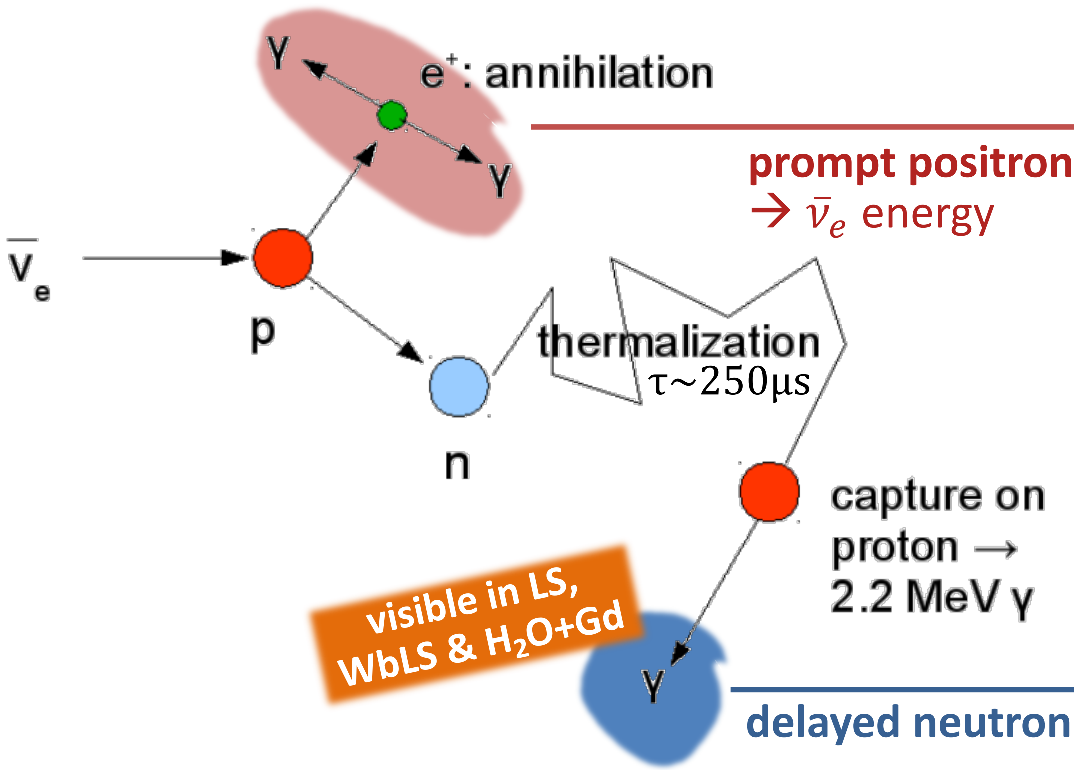
Backgrounds in pure water

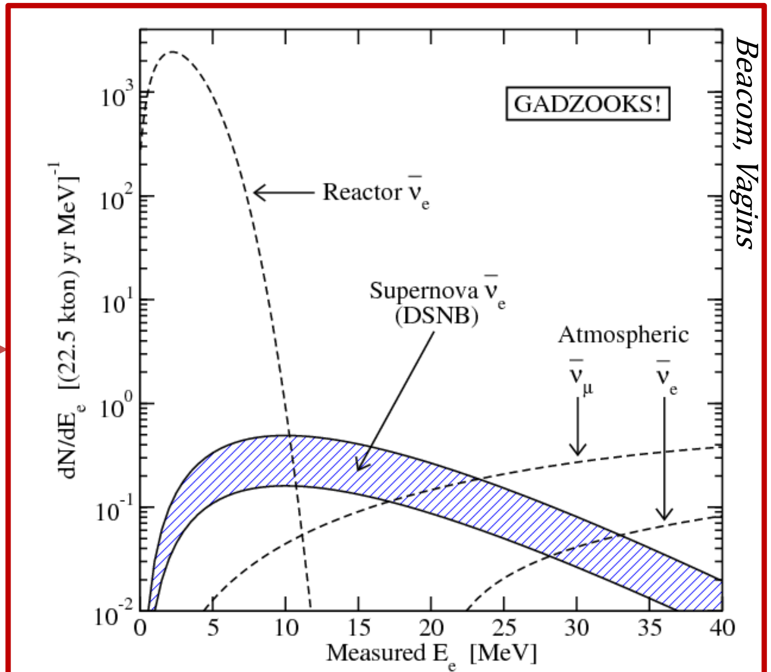
- solar neutrinos (^{8}B): E>16MeV
- IBDs from **atmospheric ν_e's**
- Michel electrons from CC of low-energy atmospheric ν_μ's (a.k.a. "**invisible muons**")
- **NC elastic scattering** of atm. ν's
- **π misidentifcation**

→ resulting limit from SKI-III:
ϕ_ν < 2.9 cm^{-2}s^{-1} for E(e$^+$)>16MeV

DSNB $\bar{\nu}_e$ signal in water+Gd/scintillator

Inverse Beta Decay on H:
rate: ~1 IBD per 10 kt x yrs



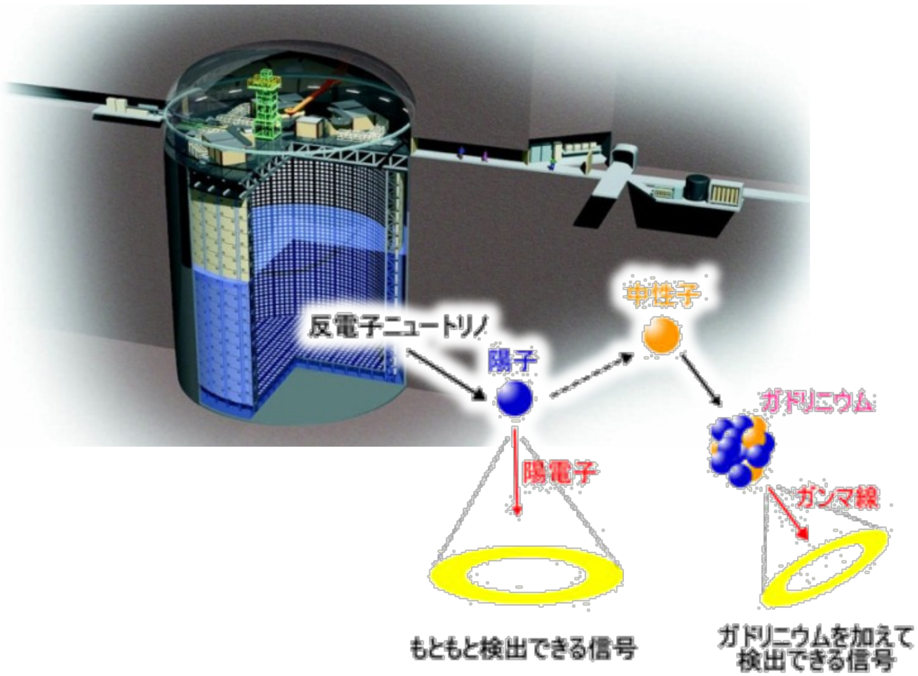


background discrimination:
removes **single events**
(e.g. invisible muons)

→ **residual background:** anything mimicking a fast coincidence signal (delayed neutron)

Current efforts towards DSNB discovery

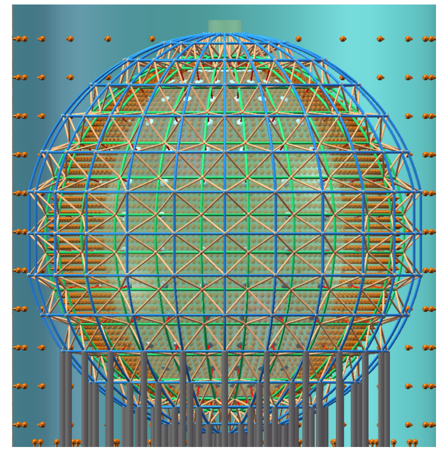
Super-Kamiokande+Gadolinium



→ add gadolinium
→ **enhanced neutron tag** ($\Sigma E_\gamma \approx 8\,\mathrm{MeV}$)
→ **detection efficiency: 65-80%**

[atm. NC likely to pose some BG for water+Gd]

JUNO



→ lower detection threshold
→ **sees p(n,γ)d directly**
→ **detection efficiency** close to 100%

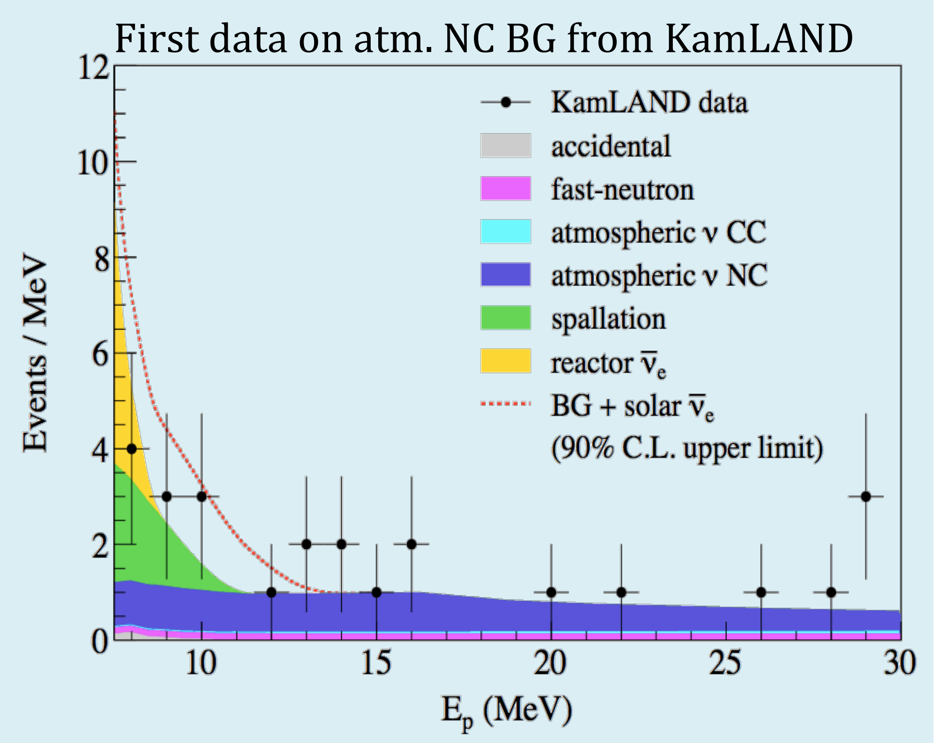
BUT: nasty atm. ν NC background
→ needs pulse shape discrimination
→ **detection efficiency: ≥50%**

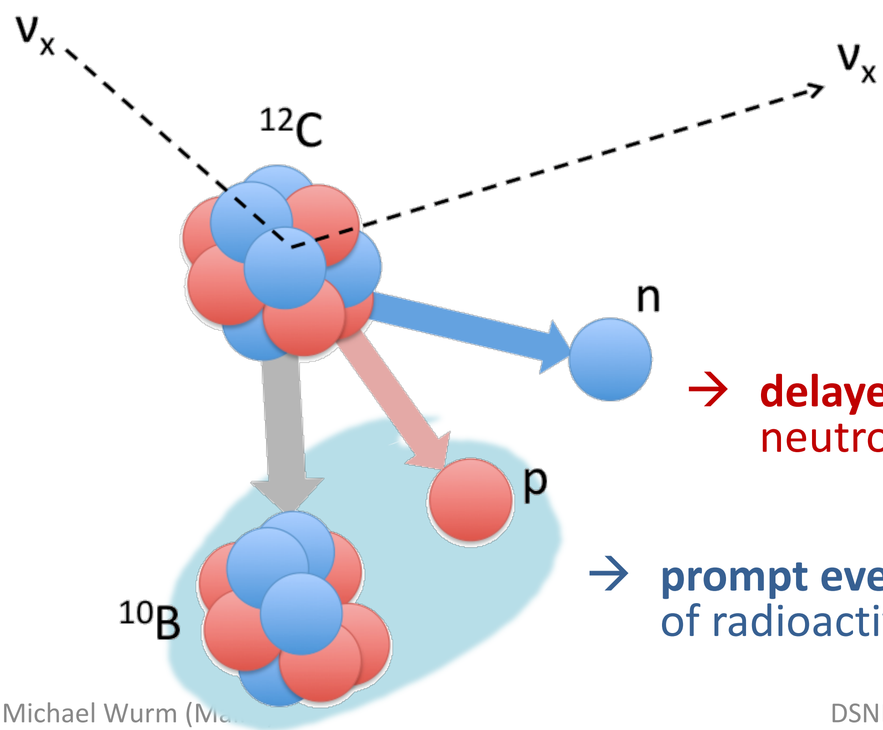
Atmospheric neutrino NC background

Atmospheric neutrinos: high energy (GeV+) → no problem in CC, but sometimes in NC ...

Background in liquid scintillator: quenched signals of p, α, γ … mimic prompt in right E range → needs PSD

Background in H2O+Gd: excited oxygen nuclei may produce prompt gamma rays



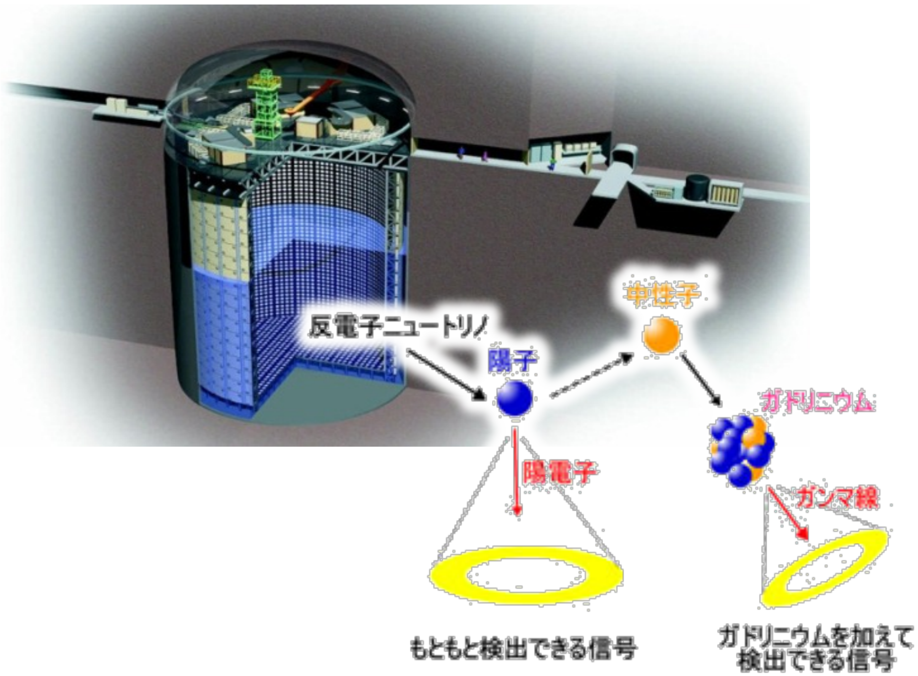


→ **delayed event:** neutron capture on hydrogen

→ **prompt event:** quenched signal of radioactive decay + protons

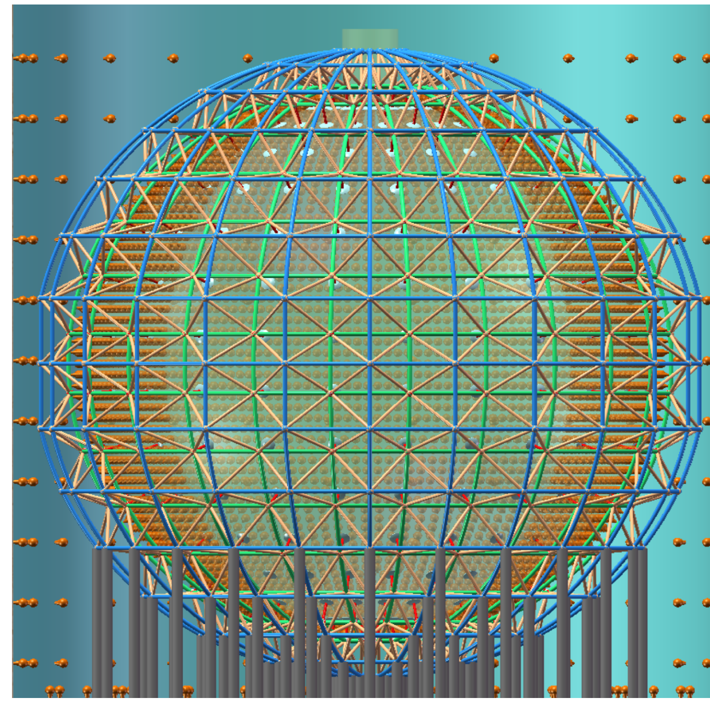
Current efforts towards DSNB discovery

Super-Kamiokande+Gadolinium



Detection efficiency: 65-80%
Atm. NC BG: probably not too bad

JUNO



Detection efficiency: >50% (PSD)
Atm. NC BG: S:B > 1:1

→ Both have a very realistic perspective to detect the DSNB
→ Acquiring statistics for DSNB spectroscopy needs a lot of time: SK-Gd+JUNO → 3-4 yr^{-1}
→ How to improve this situation?

Cherenkov detection in scintillator

courtesy of Ben Land

→ Cherenkov light is particularly useful for reconstruction of direction and (multiple) tracks

→ Cherenkov photons are produced in liquid scintillators (~5%)

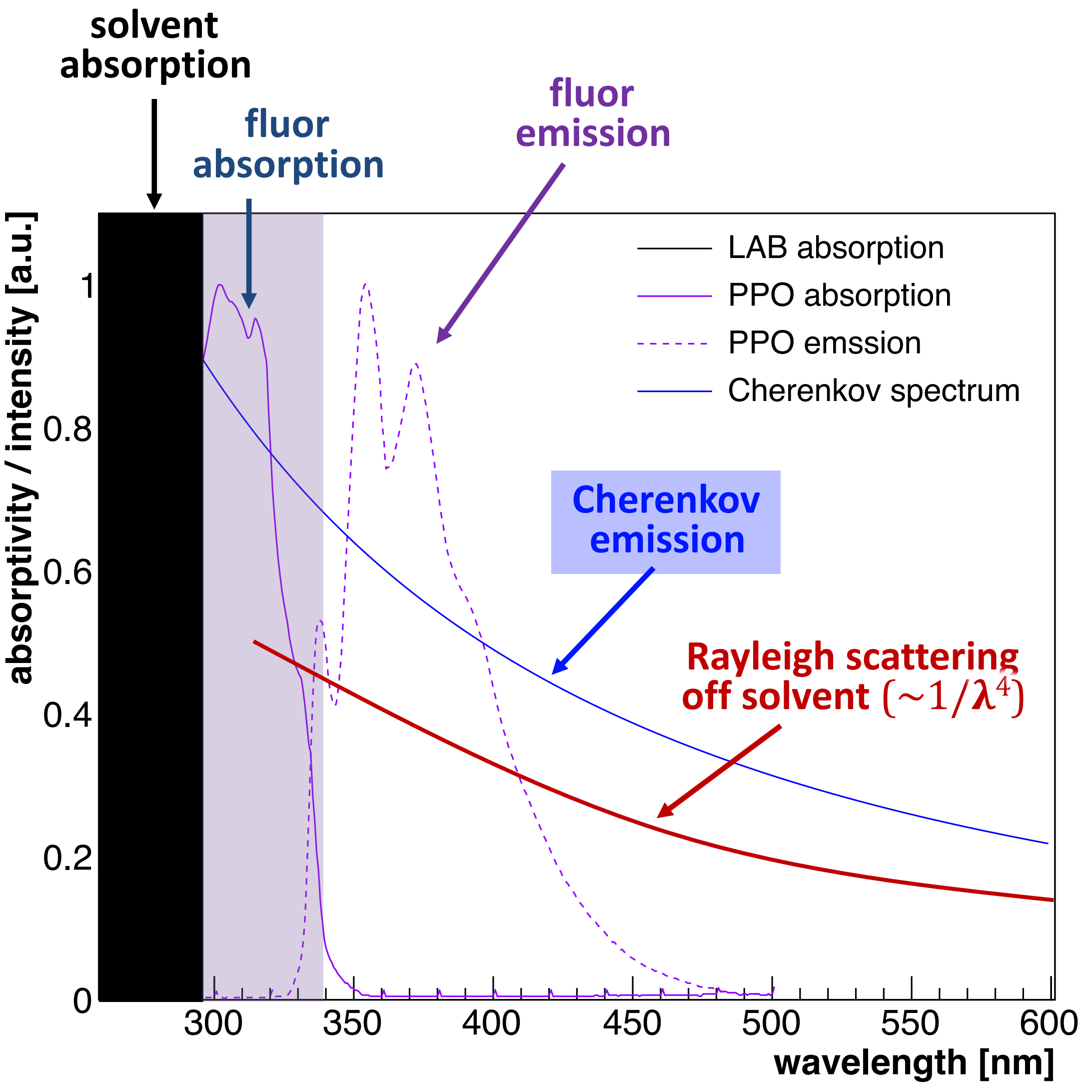
→ the majority is scattered or absorbed before reaching PMTs

To make use of it:

→ reduce scattering/absorption

→ separation of Cherenkov and scintillation photons

Light propagation in organic scintillators



How to improve the (relative) Cherenkov photoelectron yield?

→ **reduce fluor concentration**

- impacts scintillation yield
- slows down scintillation (good! → see next slide)

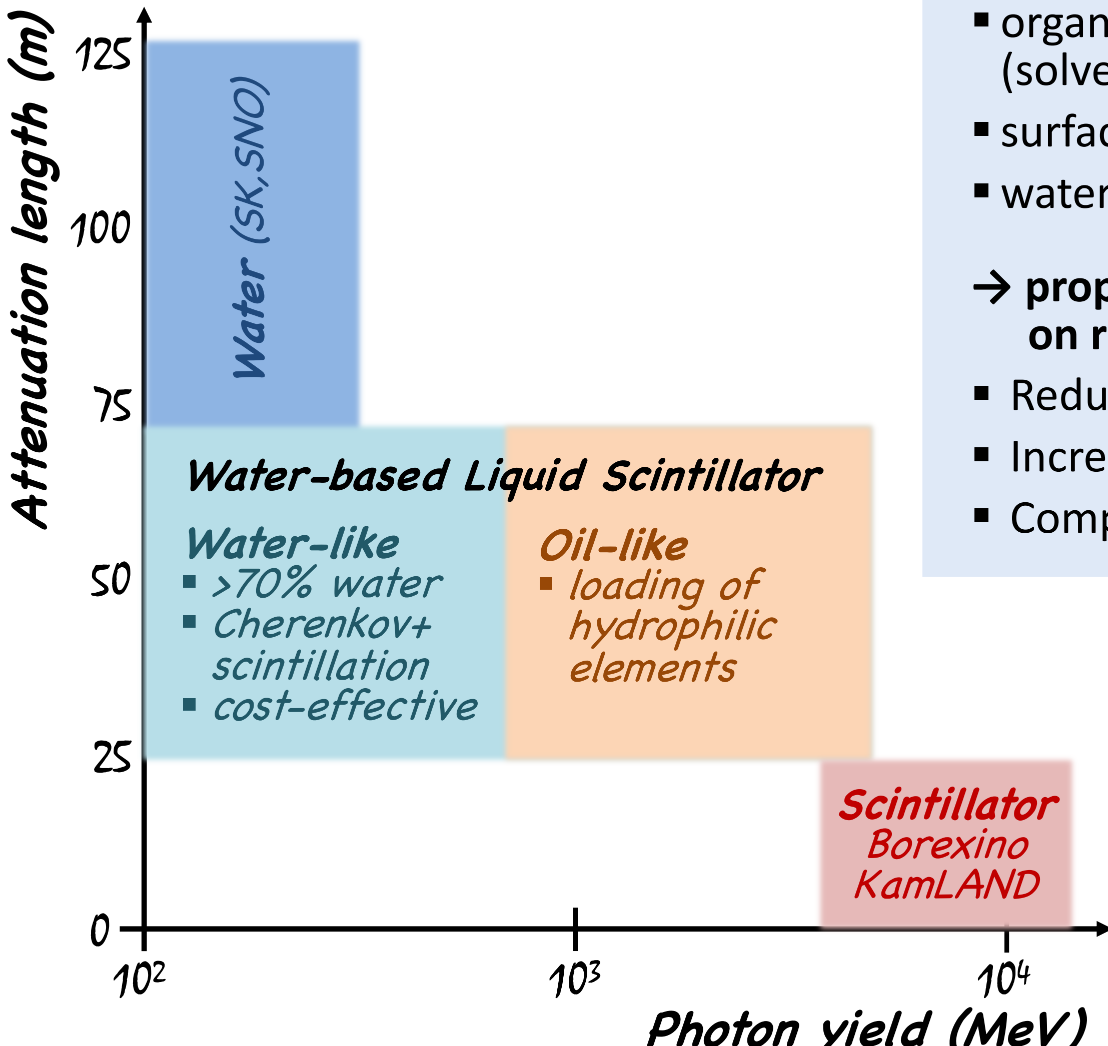
→ **reduce Rayleigh scattering**

- new transparent solvent, e.g. LAB (~20m)

  and/or

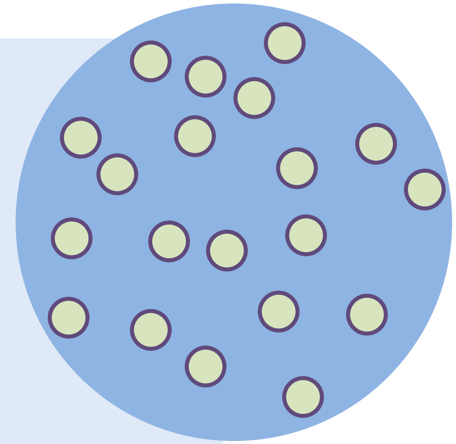
- dilution of solvent:
  Water-based scintillators
  Oil-diluted LS (LSND …)

Water-based Liquid Scintillators (WbLS)



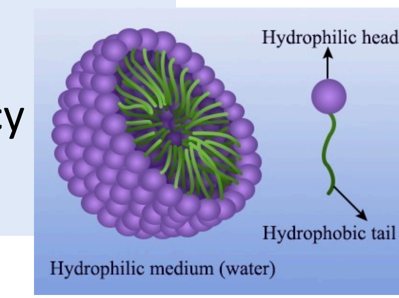
WbLS composition

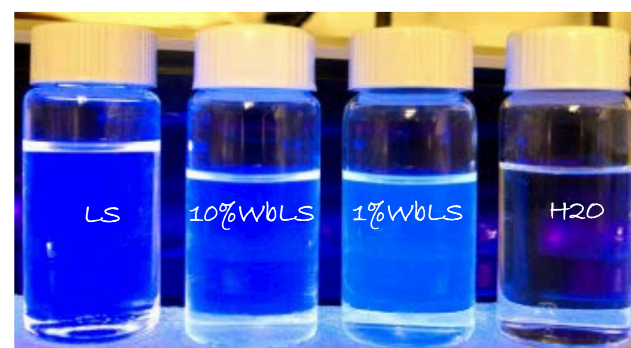
- organic LS droplets (solvent+fluor)
- surfactant
- water



→ **properties depend on relative fractions:**

- Reduced light yield
- Increased transparency
- Comparable timing





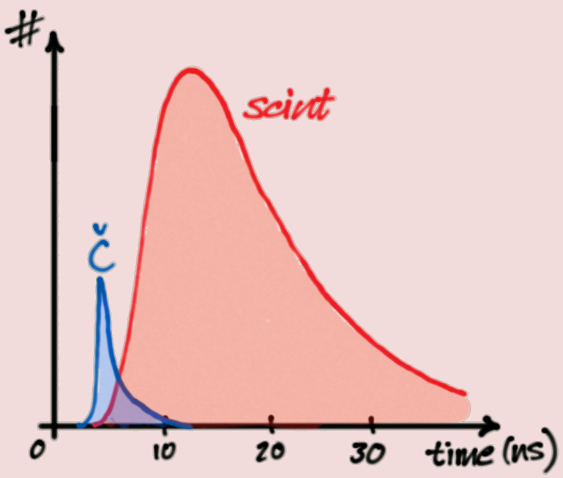
Minfang Yeh, BNL

Separation of Cherenkov/scintillation photons

Several handles available for discrimination of **Cherenkov** and **scintillation** photons:

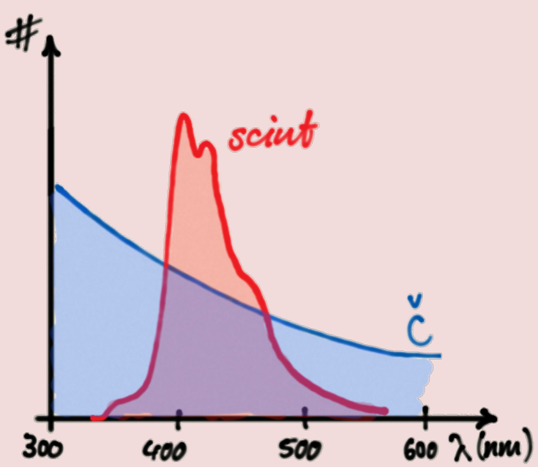
Timing

"instantaneous" Cherenkov vs. delayed scintillation light
→ ns resolution or better



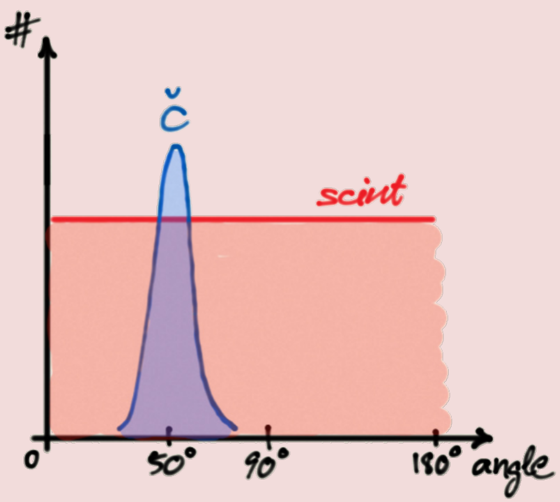
Spectrum

UV/blue scintillation vs. blue/green Cherenkov
→ wavelength-sensitivity



Angular distribution

increased PMT hit density under Cherenkov angle
→ sufficient granularity



DSNB in WbLS

Julia Sawatzki (TUM)

MW (MZ)

- Julia's PhD: detailed MC study of DSNB detection in JUNO
- Study for WbLS performed for THEIA project (see later)
- JUNO-like detector w/ WbLS target (10% organic fraction)
  - Cherenkov (C) to Scintillation (S) – 3:4
  - High PMT coverage of >70%

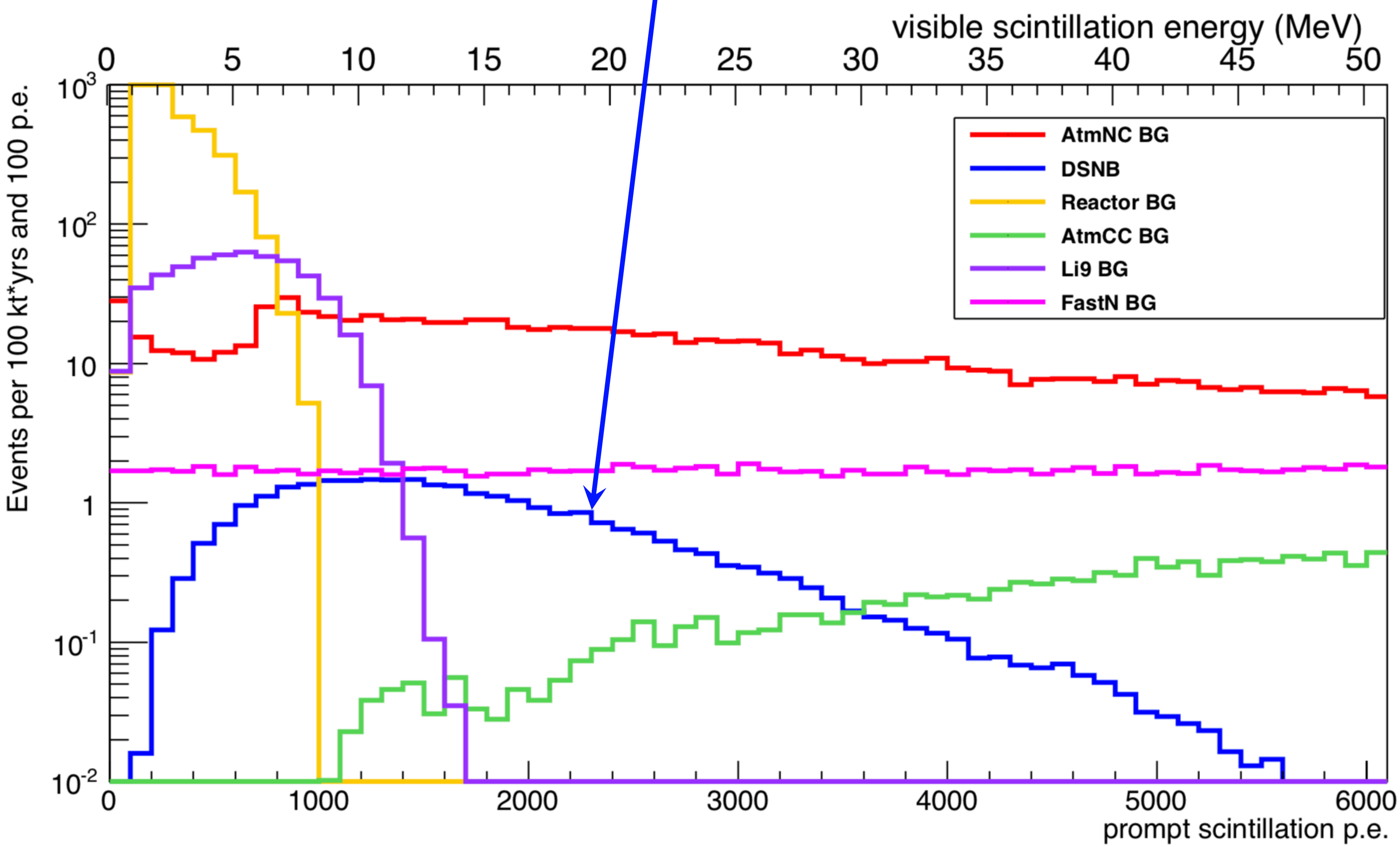
    → 90pe (C) + 120pe (S) / MeV → $\Delta E/E \sim 7\%/\sqrt{E}$
  - No explicit event reco, assume C/S can be separated
- Important: detailed modeling of the atm. NC BG:
  - Neutrino interactions by GENIE
  - Nuclear excitations by TALYS
- Publication in preparation

- Note: Similar study on **DSNB detection in slow scintillator** (Jinping Neutrino Experiment) → finds very good signal/BG discrimination based on Cherenkov/scintillation ratio
- Wei, Wang, Chen, Phys.Lett. B769 (2017) 255-261

Signals and backgrounds in THEIA

Simulated spectra of signal plus all backgrounds that may **mimic the IBD signature**:

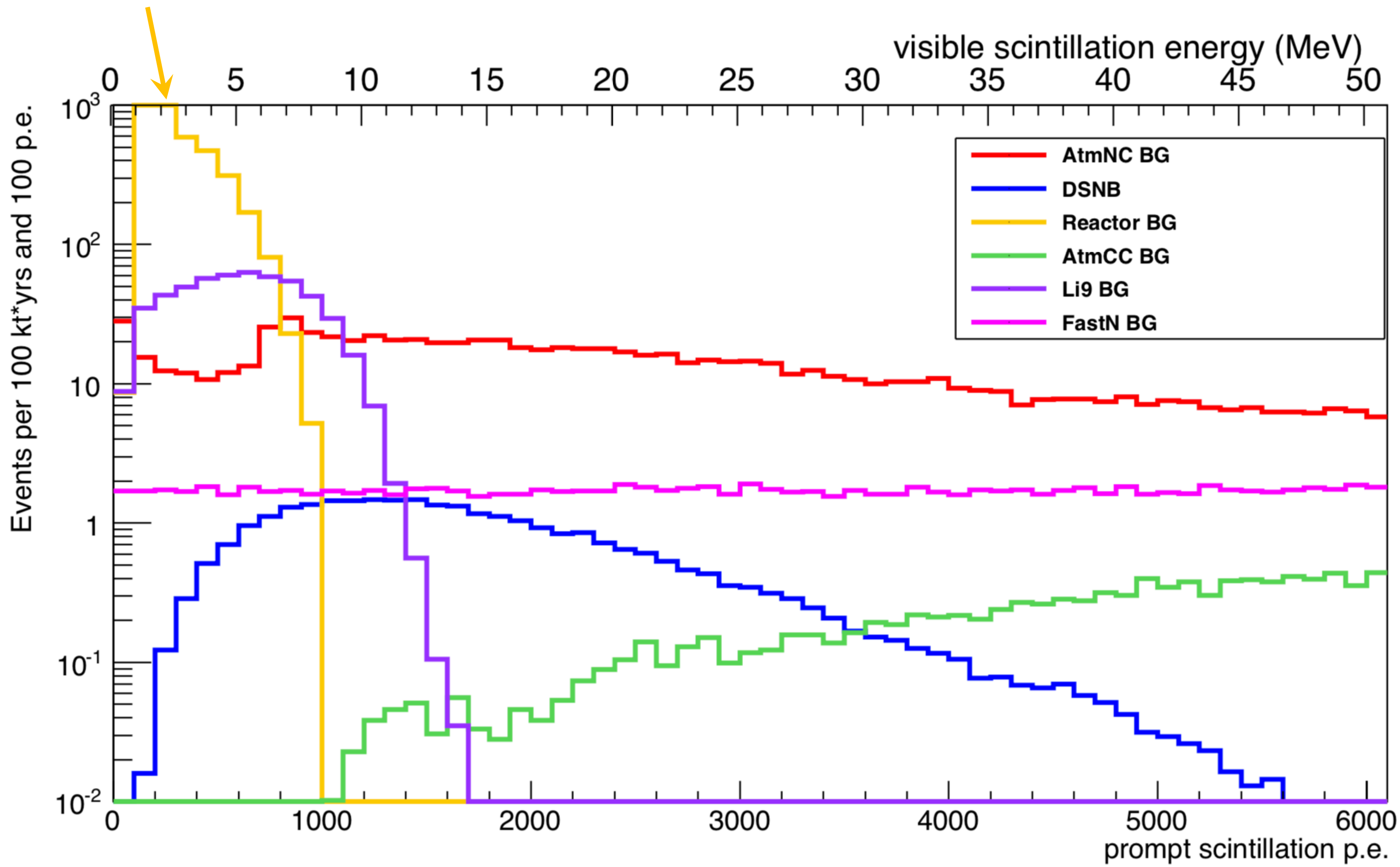
DSNB signal: based on model by Kresse, Ertl, Janka (in prep.) : ~3 IBDs per 10 kt·yr



Signals and backgrounds in THEIA

Simulated spectra of signal plus all backgrounds that may **mimic the IBD signature**:

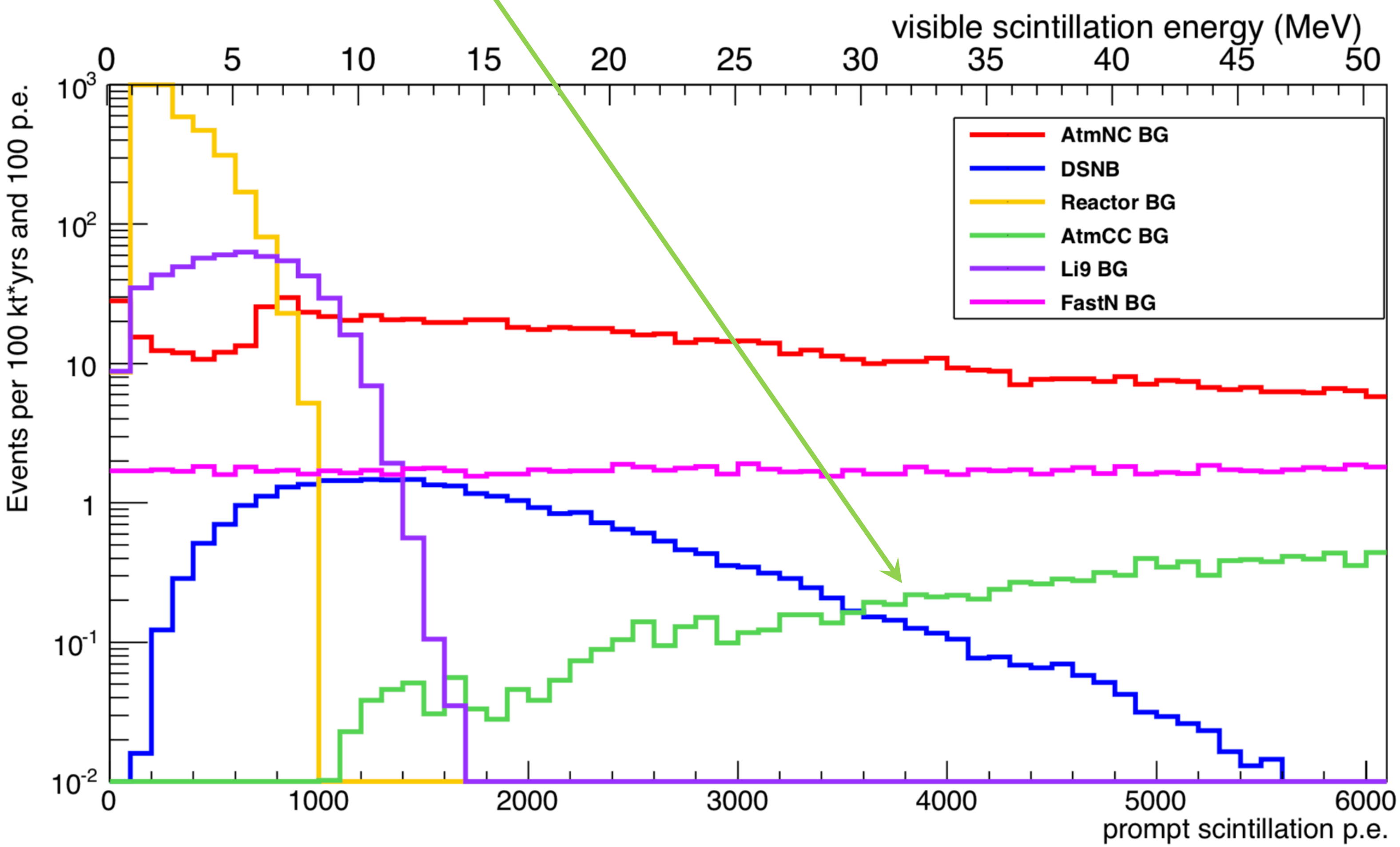
Reactor neutrinos (for Homestake, by Steve Dye): irreducible background



Signals and backgrounds in THEIA

Simulated spectra of signal plus all backgrounds that may **mimic the IBD signature**:

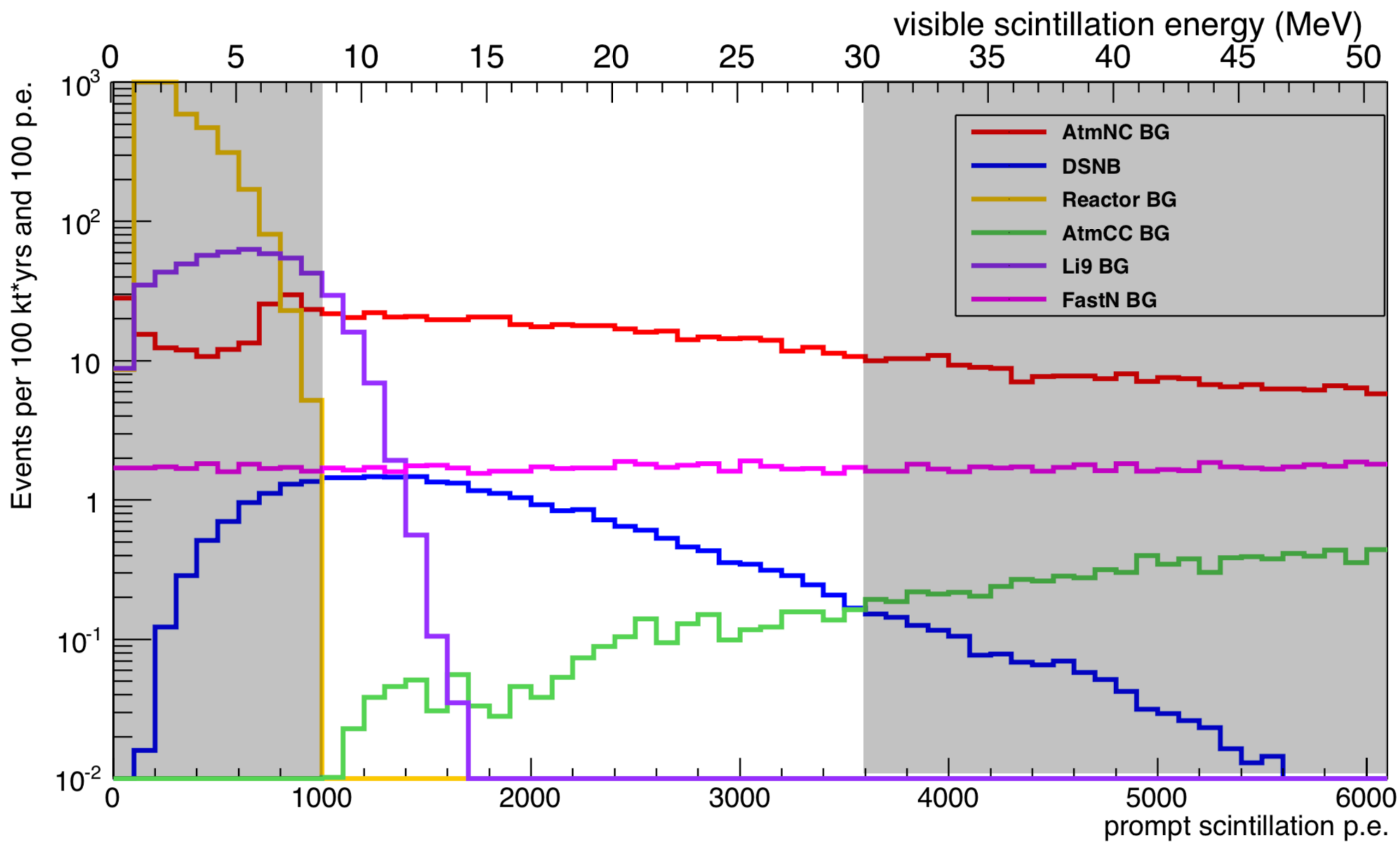
Atmospheric neutrino IBDs (for Homestake): irreducible background



Signals and backgrounds in THEIA

Simulated spectra of signal plus all backgrounds that may **mimic the IBD signature**:

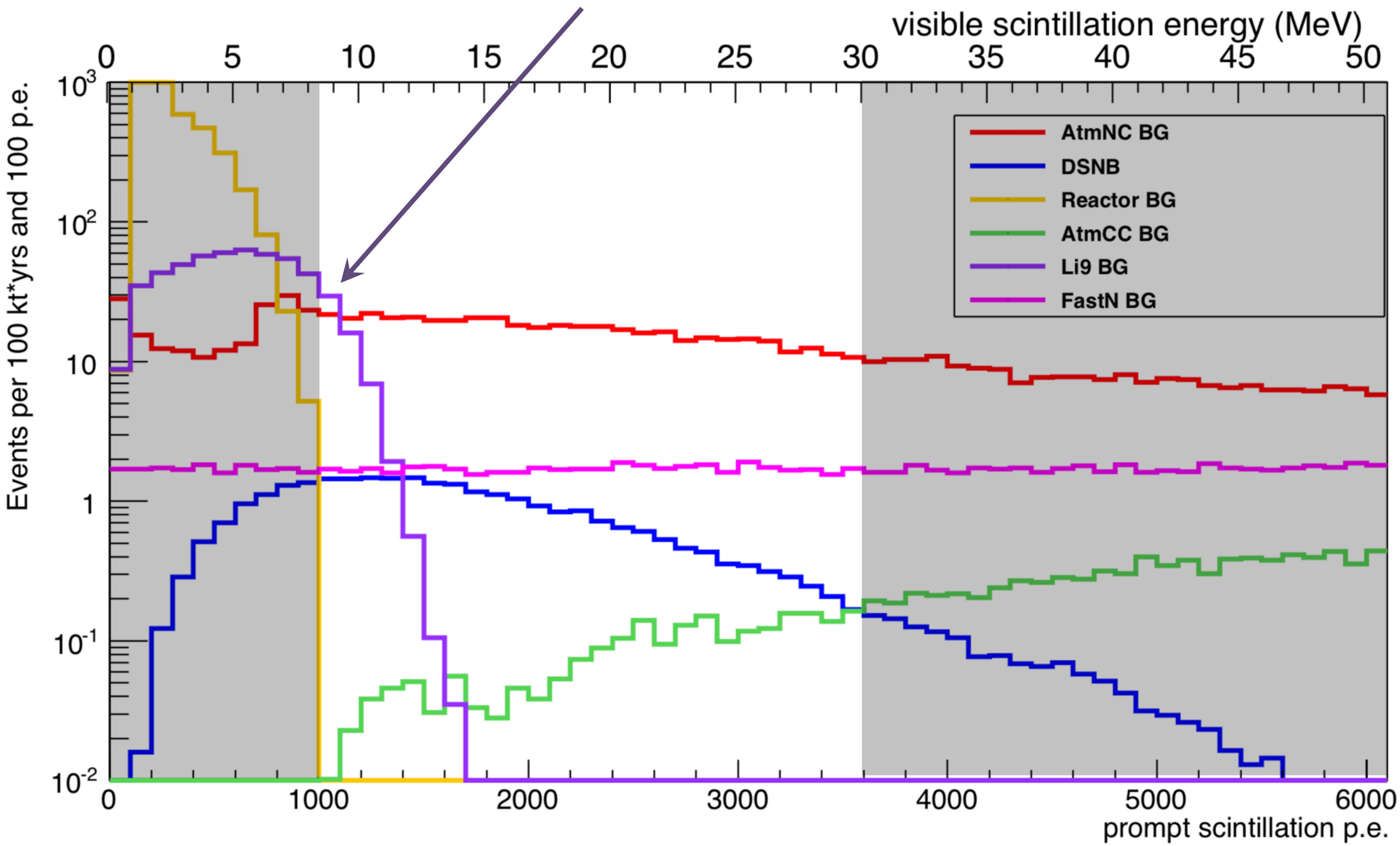
Defines DSNB observation window from 9 to 30 MeV



Signals and backgrounds in THEIA

Simulated spectra of signal plus all backgrounds that may **mimic the IBD signature**:

Cosmogenic ^{9}Li: βn-emitter
→ can be reduced by depth and muon coincidence veto scheme



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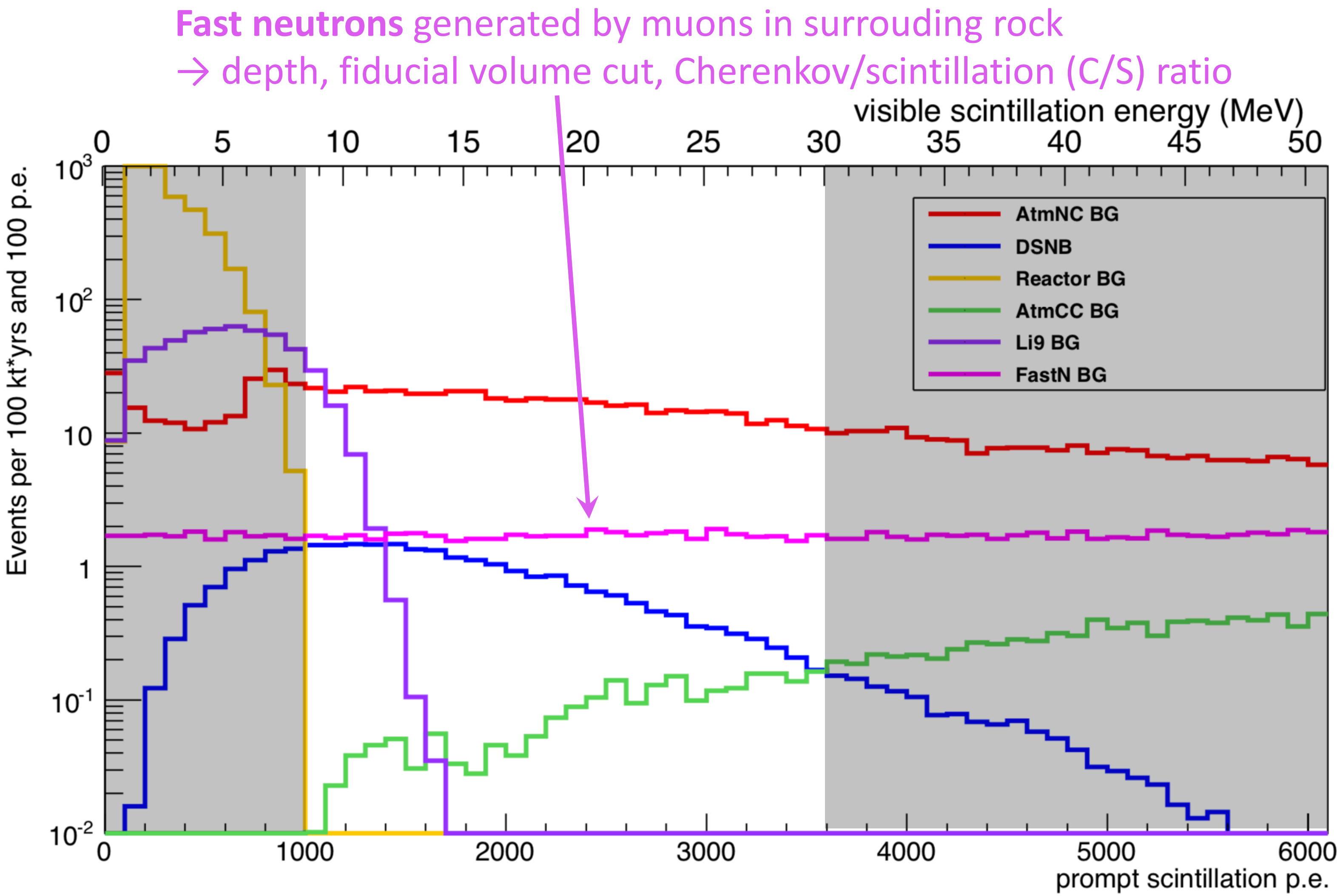
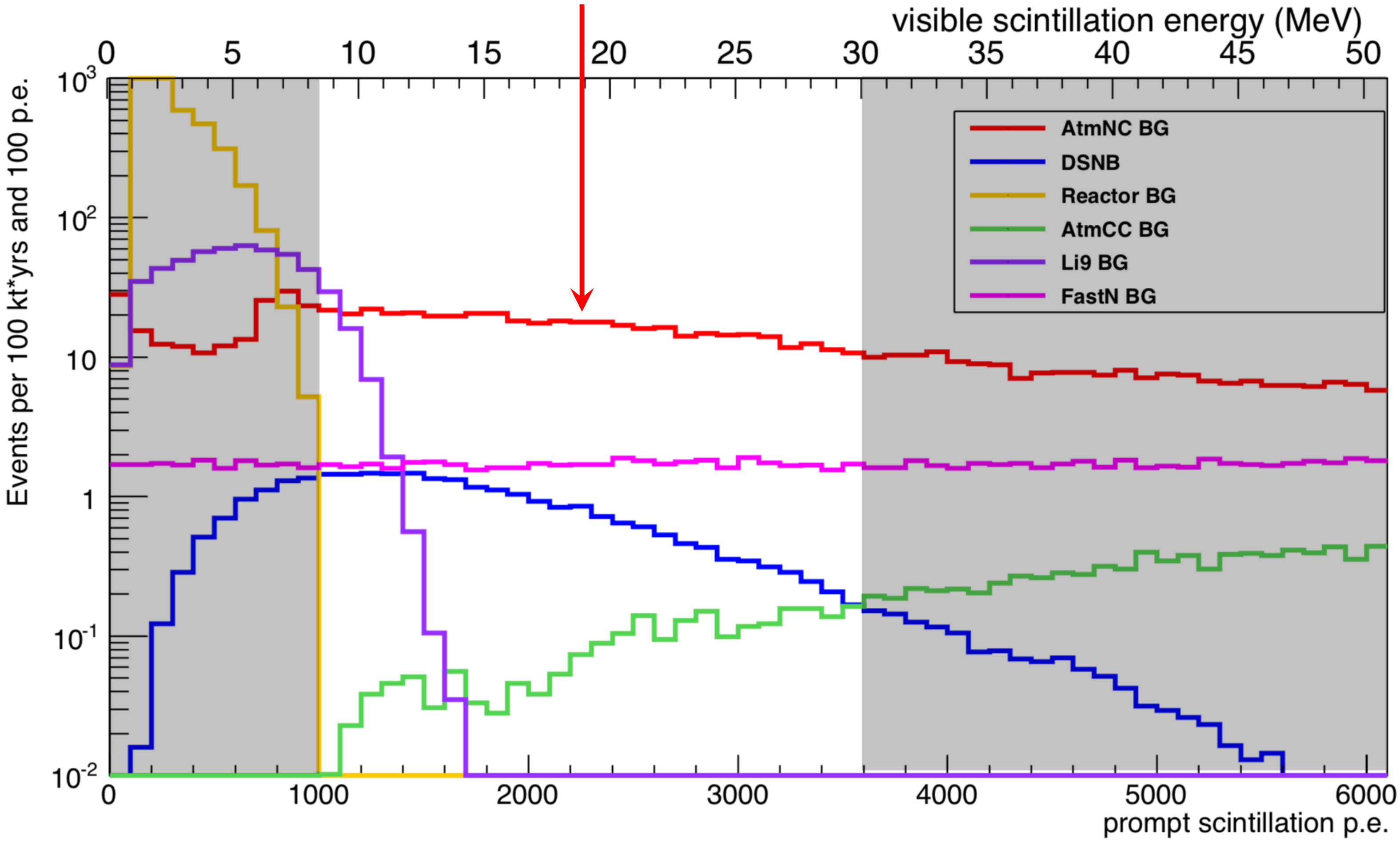


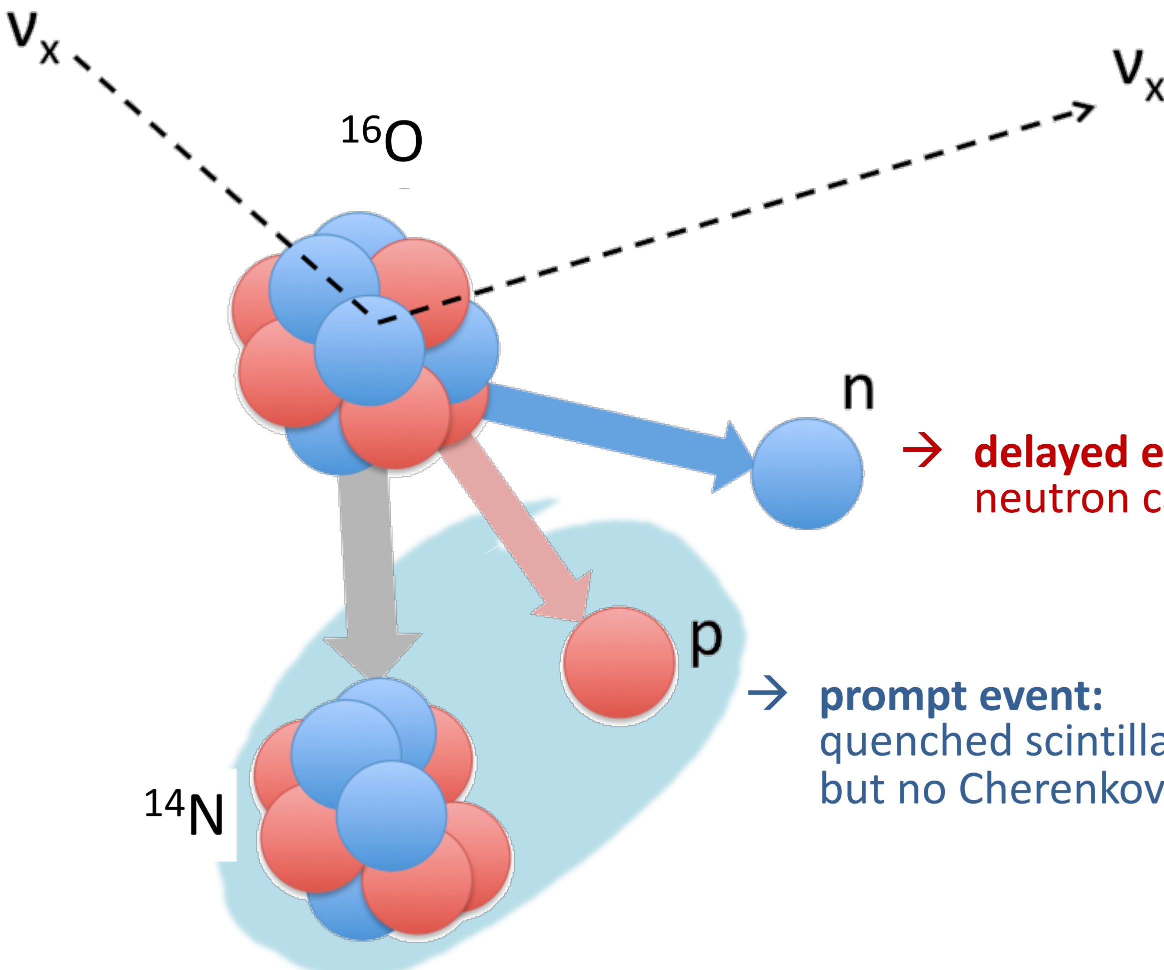
Signals and backgrounds in THEIA

Simulated spectra of signal plus all backgrounds that may **mimic the IBD signature**:

Atmospheric NC events: 1-2 OoM higher than DSNB signal
→ C/S ratio, multi-ring selection, triple coincidence veto



AtmNC BG and C/S ratio



→ **delayed event:**
neutron capture on hydrogen

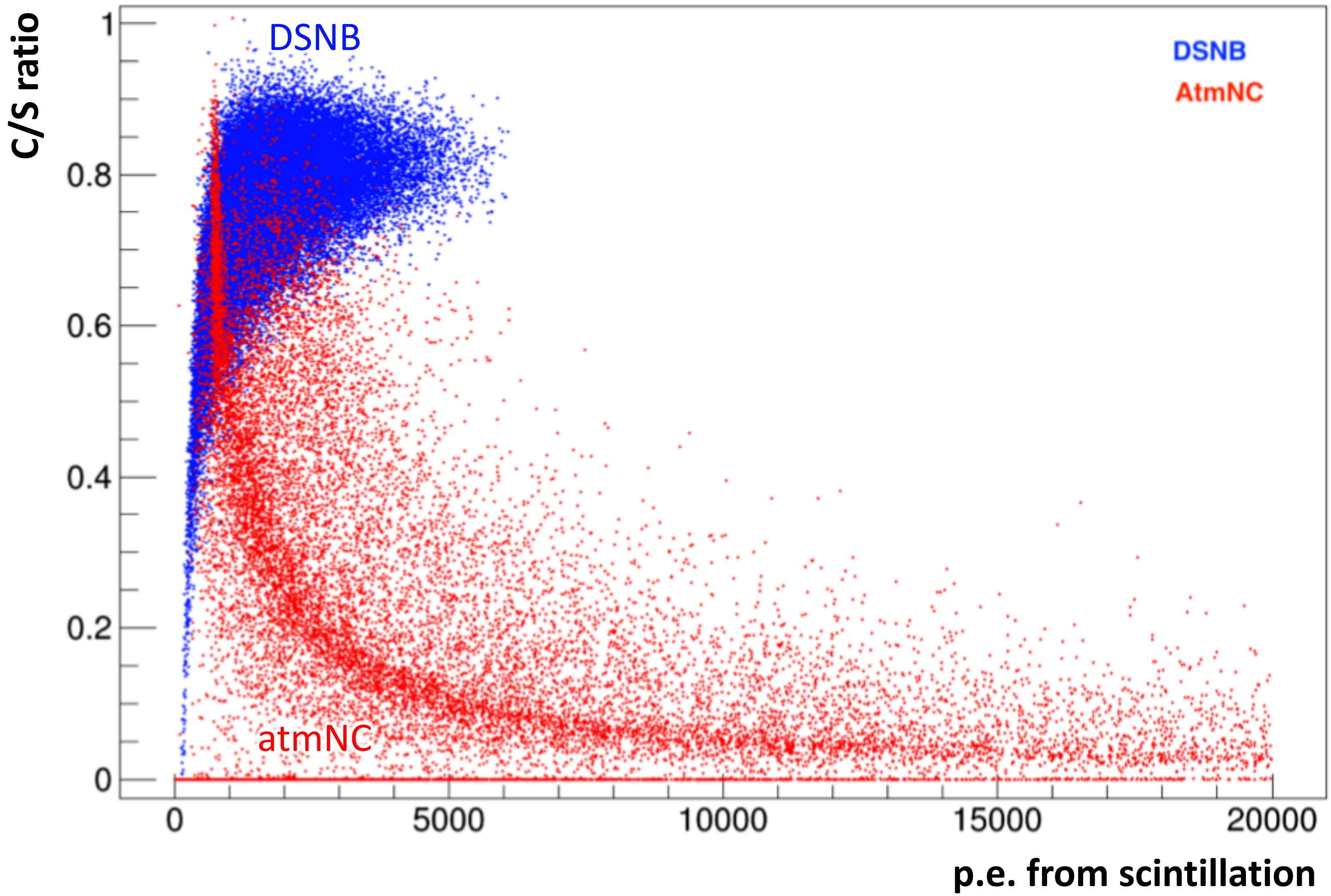
→ **prompt event:**
quenched scintillation signal
but no Cherenkov signal

vs. IBD: large Cherenkov signal from prompt positron

→ discrimination based on Cherenkov/Scintillation (C/S) ratio

Background discrimination with C/S ratio

Large MC sample of DSNB signal and atmospheric NC events with **1! neutron in final state**



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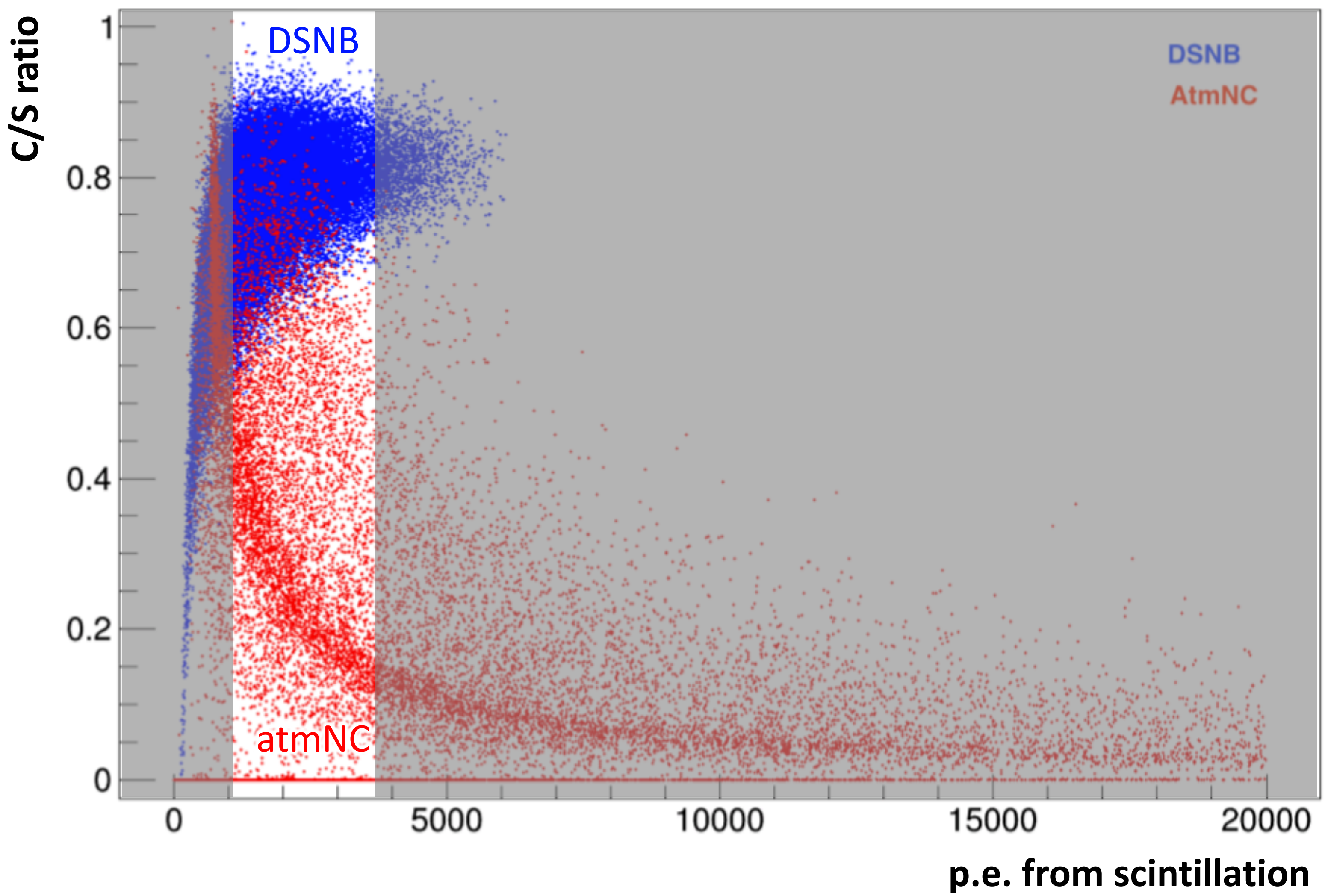

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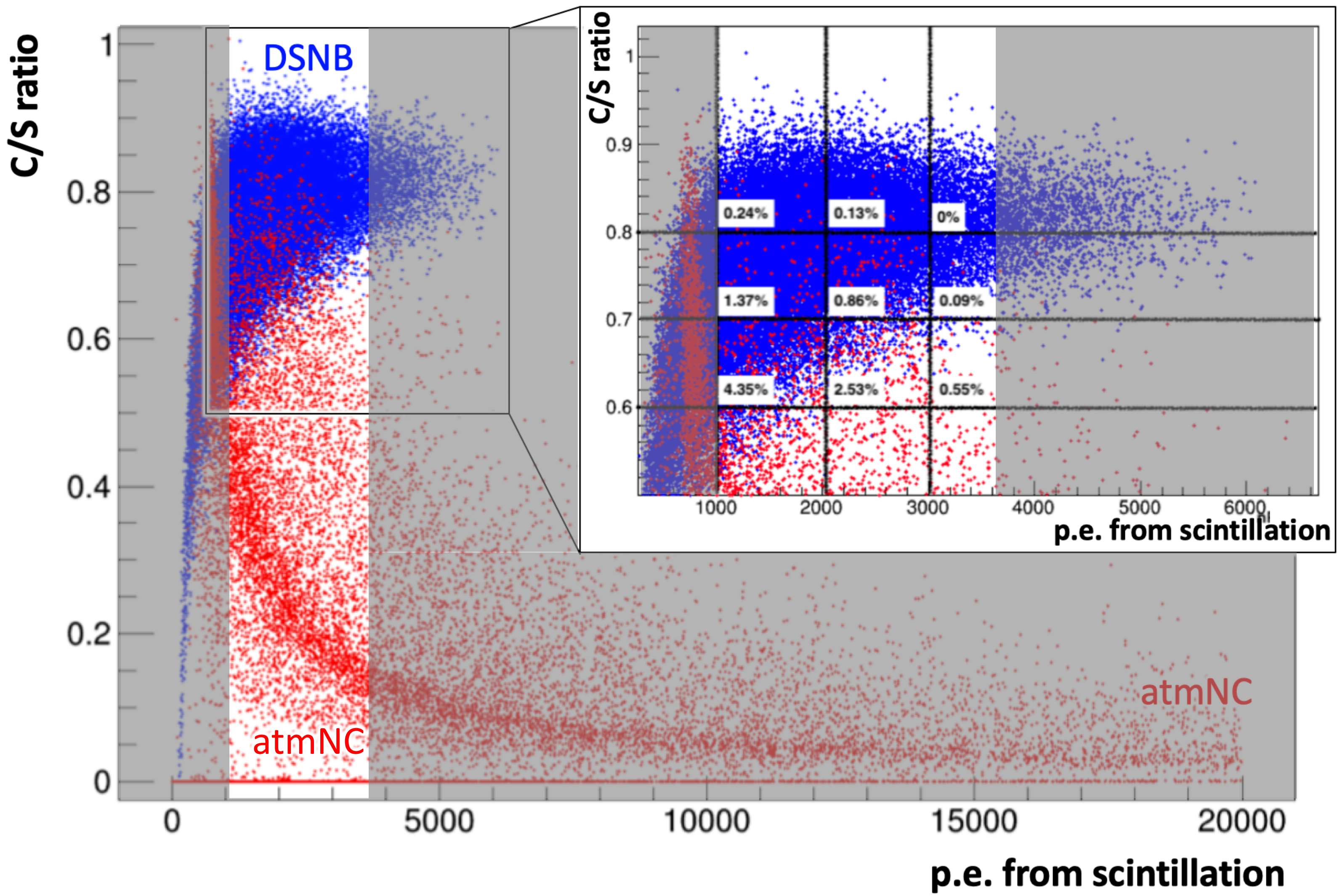

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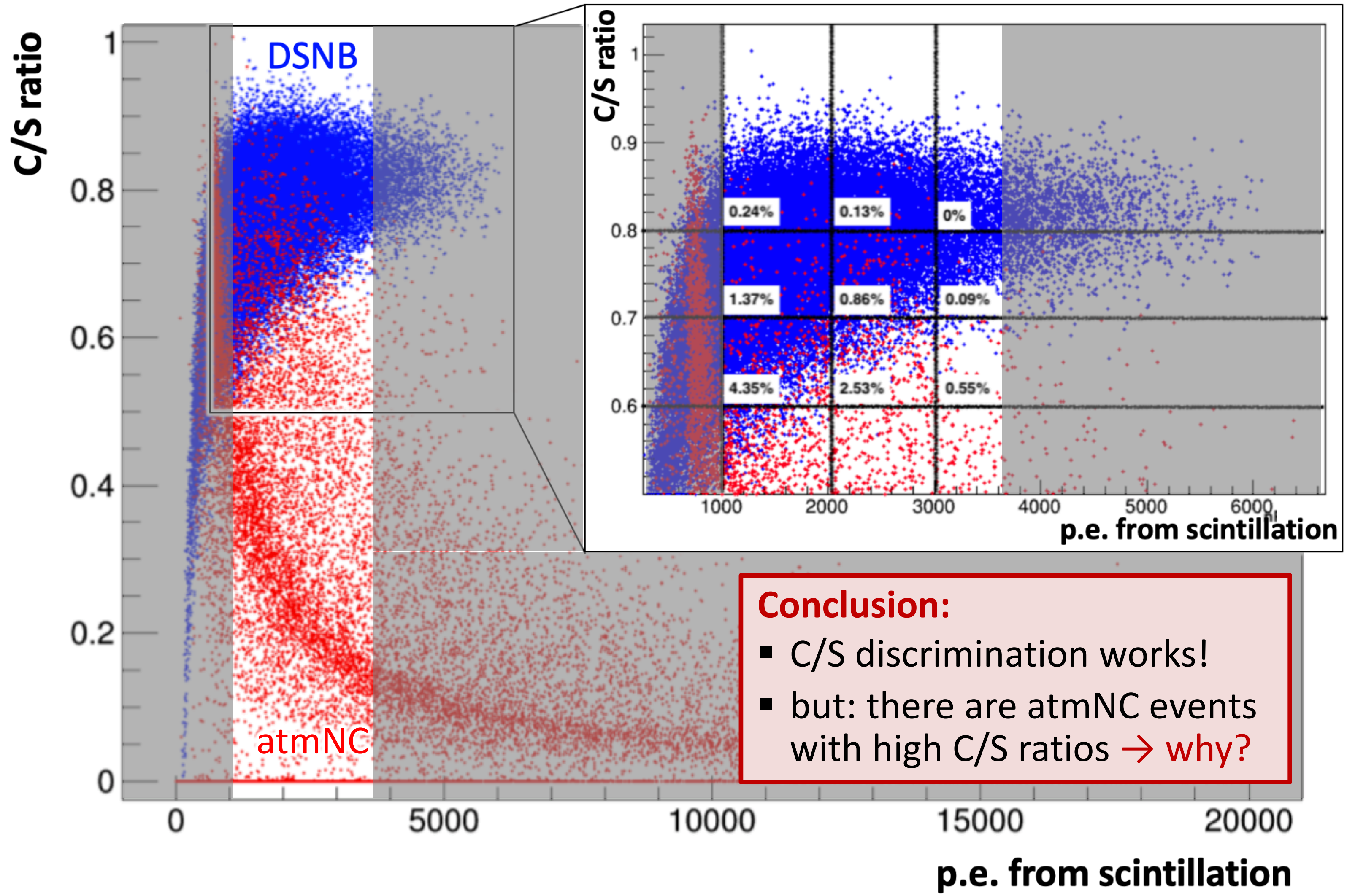


Conclusion:

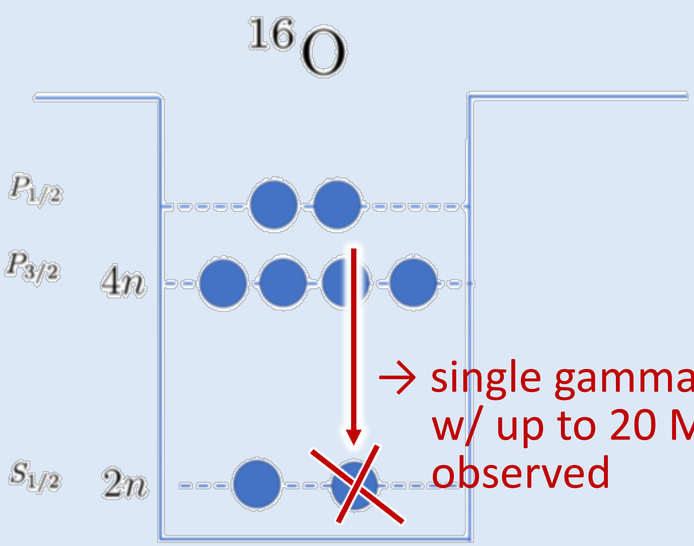
- C/S discrimination works!
- but: there are atmNC events with high C/S ratios → why?

AtmNC events with high C/S ratio

Two event populations contributing:

(1) Oxygen de-excitation gammas

- atmospheric neutrino removes $1s_{1/2}$ neutron
- high-energy de-excitation γ's



→ single gammas w/ up to 20 MeV observed

(2) High-energy neutrons

- depositing 15-50 MeV in WbLS
- creating secondary particles: e,γ

e.g. two or more

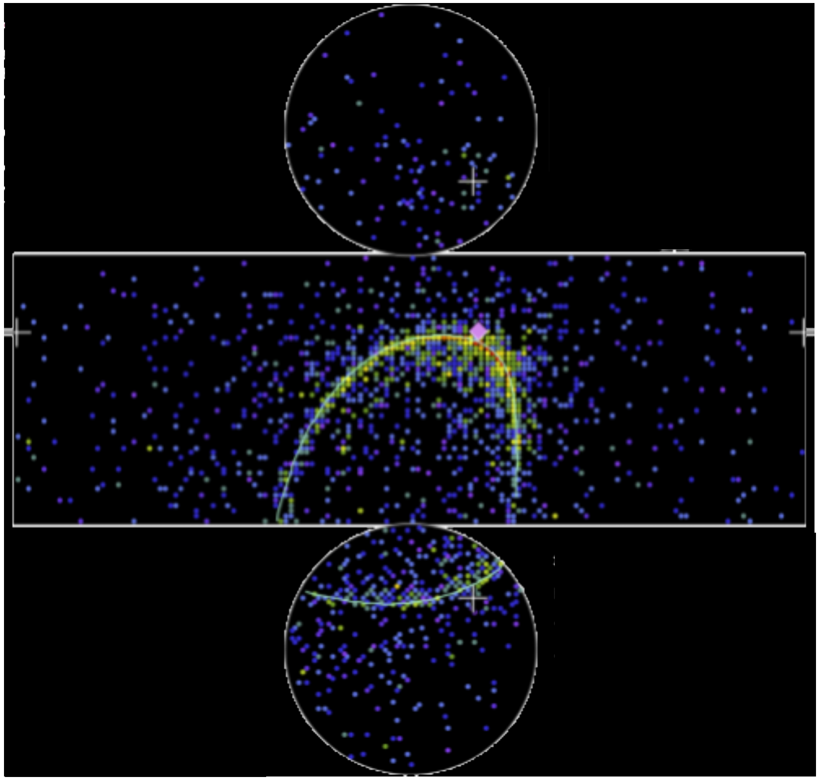
- $^{16}O(n,n)^{16}O^*$ → 6.13 MeV
- $^{16}O(n,2n)^{15}O^*$ → 6.18 MeV
- $^{16}O(n, np)^{15}N^*$ → 6.32 MeV

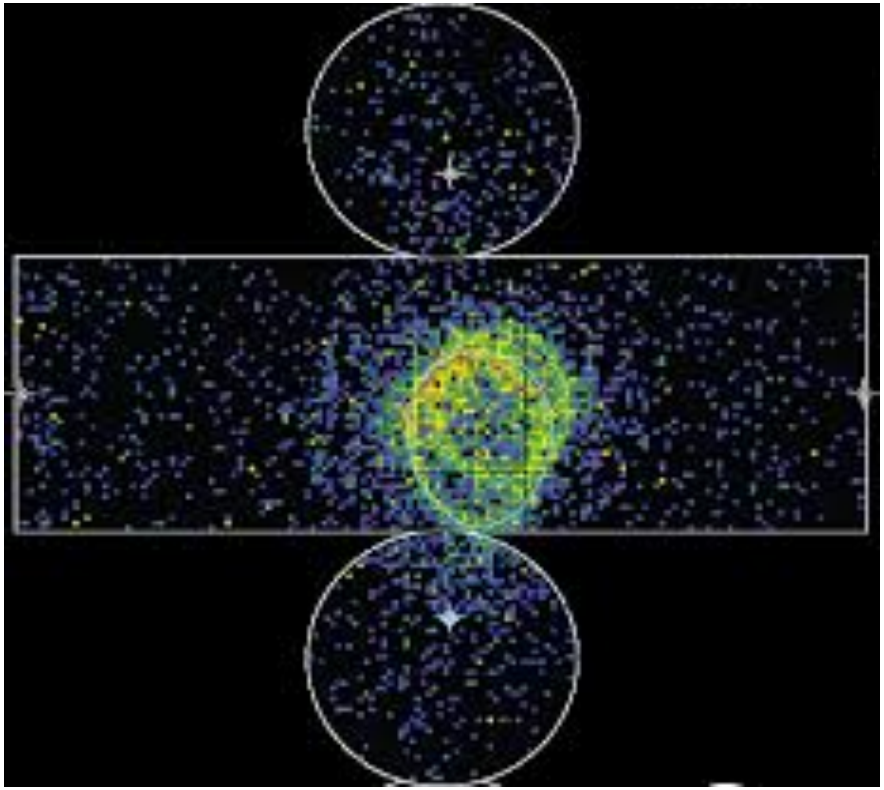
→ these events form a potential background for water+Gd detection, too

Ring-counting for BG discrimination

IBD prompt positrons:
single Cherenkov ring

AtmNC background:
multiple particles (γ's) → ≥1 ring





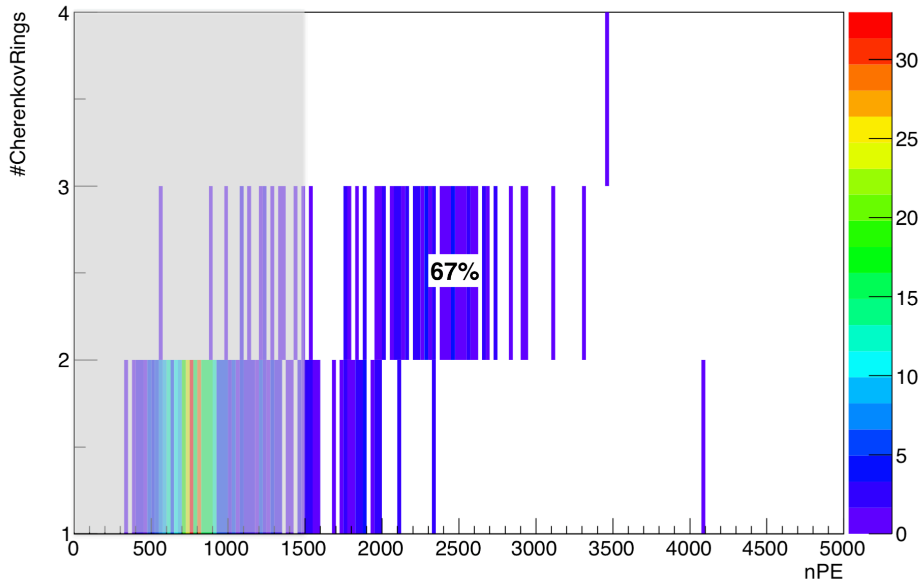
High-energy event displays from SK: real life will be much harder ...

→ ring counting can be used for **discrimination of BG with high C/S ratio**

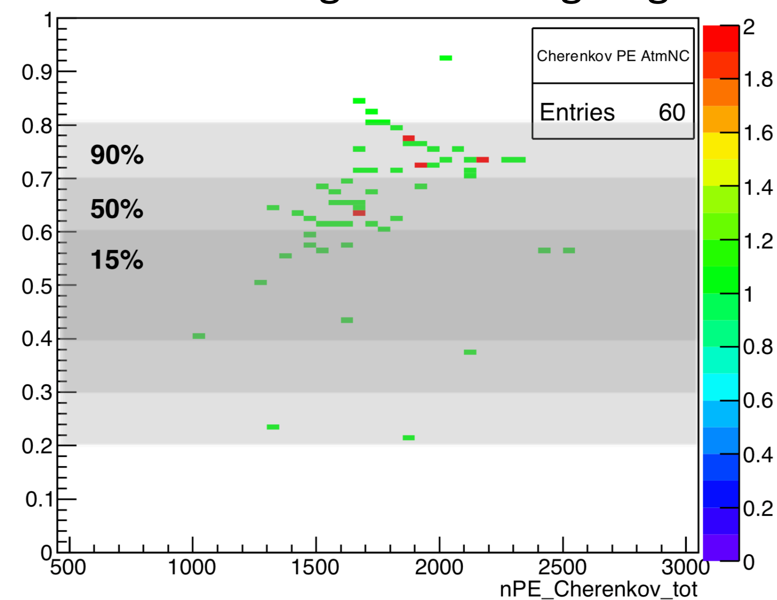
Multi-ring tagging

Simulation study: no ring reconstruction yet,
so counting of final state particles that produce Cherenkov light

number of Cherenkov rings vs. energy



fraction of light in leading ring



→ fraction of multi-ring AtmBG events: ~2/3 of high C/S events feature 2+ rings

→ what is required for recognizing 2nd ring? assuming 20% of all C photons is sufficient, **60% of all AtmBG events can be tagged** as multi-ring background

Delayed decay tagging

Signature for background tagging:
→ three-fold coincidence of prompt, neutron and delayed decay signal

Reaction channel $\nu_x + {}^{16}\mathrm{O} \longrightarrow \nu_x +$					ratio in %	
(1)	n			$+ \; {}^{15}\mathrm{O}$	45.9	taggable
(2)	n	+	p	$+ \; {}^{14}\mathrm{N}$	19.7	stable
(3)	n	+	2p	$+ \; {}^{13}\mathrm{C}$	14.7	stable
(4)	n	+	p	$+ \; d + {}^{12}\mathrm{C}$	9.1	stable
(5)	n	+	p	$+ \; d + \alpha + {}^{8}\mathrm{Be}$	2.0	too fast
(6)	n	+	3p	$+ \; {}^{12}\mathrm{B}$	1.8	taggable
(7)	n			$+\alpha + {}^{3}\mathrm{He} + {}^{8}\mathrm{Be}$	1.6	too fast
(8)	n	+	p	$+\alpha + {}^{10}\mathrm{B}$	1.4	stable
(9)	n	+	2p	$+\alpha + {}^{9}\mathrm{Be}$	1.2	stable

→ β^+: Q = 2.8 MeV
τ = 2.2min

→ β^-: Q = 13.4 MeV
τ = 20 msec

→ tagging of delayed decays provides **48% AtmBG rejection efficiency**

Signal vs. background rates

Rates in observation window (i.e. 8-30 MeV) in 100 kt x yrs at Homestake

multi-neutron events already rejected

Spectral contribution	before cuts	Li veto	delayed decays	C/S cut	single-ring
DSNB signal	21.1	20.9	20.9	20.5	20.5
Reactor neutrinos	–	–	–	–	–
Atmospheric CC	2.1	2.1	2.1	2.0	2.0
Atmospheric NC	436	432	230	11.5	6.2
βn-emitters (^{9}Li)	55.1	–	–	–	–
fast neutrons	0.65	0.65	0.65	–	–
Signal-to-background	0.043	0.048	0.090	1.52	2.50

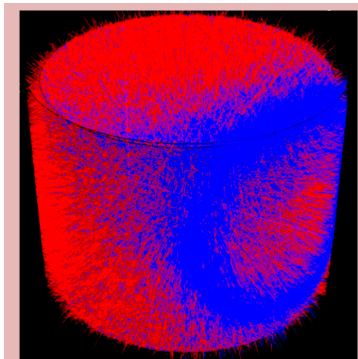
→ Signal efficiency at >95% **→ virtually full signal statistics!**

→ AtmBG background rejection by a factor 70!
(stronger suppression can be bought in exchange for reduced signal efficiency)

→ All other BGs reduced to negligible level

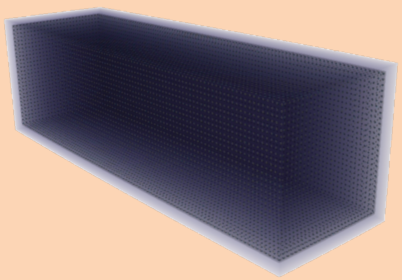
→ Final S:B ratio of 5:2

Prospects for WbLS in THEIA



Reference design

- Fiducial mass: 50-100 kt
- WbLS or oil-diluted LS
- up to 80% photo-coverage (90% PMTS / 10% LAPPDs)
- Isotope loading (Gd, Li, Te, Xe)



Reduced design

- fits into a free DUNE cavern
- Fiducial mass: ~20 kt
- 40% photo-coverage w/ possible LAPPD upgrade

THEIA proto-collaboration:
~30 PI's from 5 countries (US,DE,UK,CA,FI)

Staged Approach

Phase 1	Long-baseline neutrinos (LBNF) with "thin" WbLS (1%)
Phase 2	Low-energy neutrino observation with "oily" LS
Phase 3	multi-ton scale $0\nu\beta\beta$ search with loaded LS in suspended vessel

Physics Goals → arXiv:1409.5864

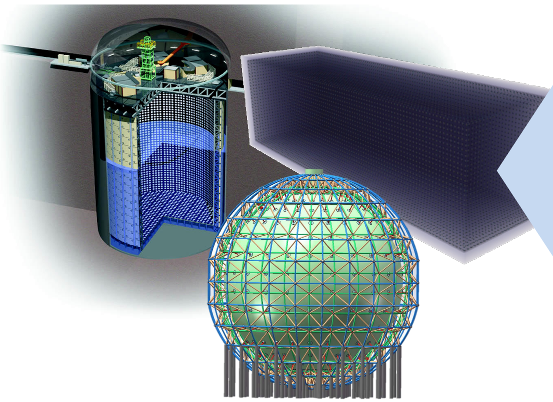
- LBL: **CP violation**
- **Proton decay** ($K^+\nu/\pi^0e^+$)

- **Supernova neutrinos** pointing ($\Delta\theta\sim1°$)
- **Diffuse SN neutrinos** atm. NC BG reduction
- **Solar neutrinos** CNO, Li loading → CC
- **Geoneutrinos**

- **$0\nu\beta\beta$** on <10meV scale

Prospects for DSNB spectroscopy

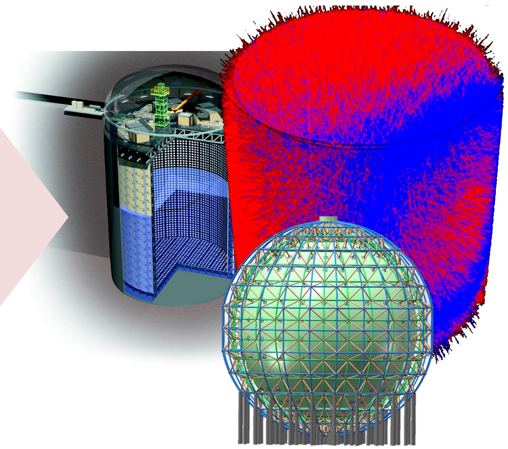
Main aspects: event statistics, understanding of residual background.



Minimal scenario

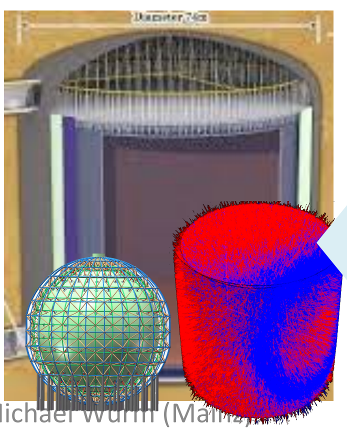
- **Det.Mass:** SK-Gd 16kt* + JUNO 10kt* + small THEIA 18kt*
  → Integral DSNB rate: **9 events per year** (4 from THEIA)
- WbLS: improved understanding of systematics for H_2O+Gd and oLS, too, because of C/S information

** already including detection efficiencies*



Present detectors + reference THEIA

- **Det.Mass:** SK-Gd 16kt* + JUNO 10kt* + THEIA 95kt*
  → Integral DSNB rate: **25 events per year** (20 from THEIA)
- order 100 events after 4 years! → DSNB spectroscopy



Optimistic scenario: HK+JUNO+THEIA

- **Det.Mass:** HK-Gd 200kt* + JUNO 10kt* + THEIA 95kt*
  → Integral DSNB rate: **60 events per year** (40 from HK)
- WbLS still adds to understanding of most relevant BG

Conclusions

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DSNB detection in WbLS

- **C/S ratio** gives a powerful handle to discriminate atmNC background signals
- can be supported by **delayed-decay tag** or **multi-ring identification**

→ **S:B ratios of 2:1 or better** are possible w/o significant loss of signal efficiency

- Even small WbLS detector (20kt) means **substantial increase in event statistics** when added to SK-Gd and JUNO
- In anya case, WbLS can be expected to have a large impact on the **understanding of BG systematics** for H_2O+Gd and oLS

Backup Slides

Table of Events Rates (all techniques)

Wei, Wang, Chen, arXiv:1607.01671

Table 2: Summary of the numbers of backgrounds and SRN events at neutrino energies of 10.8-30.8 MeV with an exposure of 20 kton-year of water, Gd-doped water, a typical liquid scintillator, and a slow liquid scintillator (LAB) at Jinping.

20 kton-year	Water [a]	Gd-w [a]	LS	Slow LS
Atmos. $\bar{\nu}_e$	0.040	0.21	0.28	0.26
Atmos. $\bar{\nu}_\mu/\nu_\mu$ CC	0.33	1.8	3.6	0.025
Atmos. NC	0.095	0.49	62	0.35
Total backgrounds	0.47	2.5	66	0.64
Signal[b]	0.54	2.8	4.2	4.1
Signal efficiency	13%	70%	92%	90%
S/B	1.1	1.1	0.064	6.4

[a] with neutron tagging.

[b] HBD model; water and Gd-w results corrected by a factor of ~0.9 due to differences in the fractions of free protons in water and LAB.

Different flavors of atm. NC background

There is a long list of final states with single neutrons ...

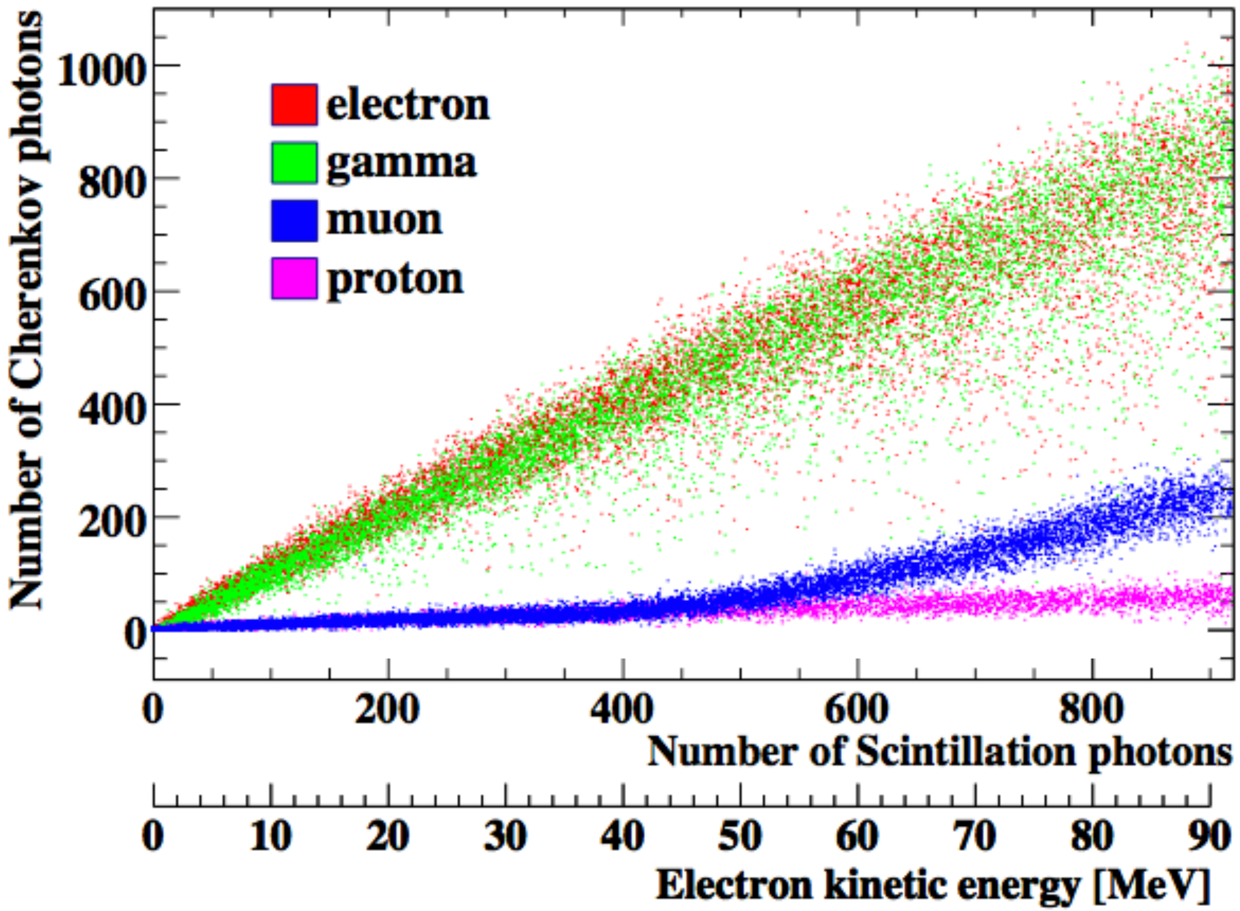
Reaction channel	Branching ratio
(1) $\nu_x + {}^{12}C \rightarrow \nu_x + n + {}^{11}C$	38.8 %
(2) $\nu_x + {}^{12}C \rightarrow \nu_x + p + n + {}^{10}B$	20.4 %
(3) $\nu_x + {}^{12}C \rightarrow \nu_x + 2p + n + {}^{9}Be$	15.9 %
(4) $\nu_x + {}^{12}C \rightarrow \nu_x + p + d + n + {}^{8}Be$	7.1 %
(5) $\nu_x + {}^{12}C \rightarrow \nu_x + \alpha + p + n + {}^{6}Li$	6.6 %
(6) $\nu_x + {}^{12}C \rightarrow \nu_x + 2p + d + n + {}^{7}Li$	1.3 %
(7) $\nu_x + {}^{12}C \rightarrow \nu_x + 3p + 2n + {}^{7}Li$	1.2 %
(8) $\nu_x + {}^{12}C \rightarrow \nu_x + d + n + {}^{9}B$	1.2 %
(9) $\nu_x + {}^{12}C \rightarrow \nu_x + 2p + t + n + {}^{6}Li$	1.1 %
(10) $\nu_x + {}^{12}C \rightarrow \nu_x + \alpha + n + {}^{7}Be$	1.1 %
(11) $\nu_x + {}^{12}C \rightarrow \nu_x + 3p + n + {}^{8}Li$	1.1 %
other reaction channels	4.2 %

Total rate found in KamLAND: **3.6±1.0 $kt^{-1}yr^{-1}$**

→ none of the final state particles will produce Cherenkov light! (except γ's)

DSNB study performed for Jinping

Wei, Wang, Chen, arXiv:1607.01671



→ electron-like (positrons)

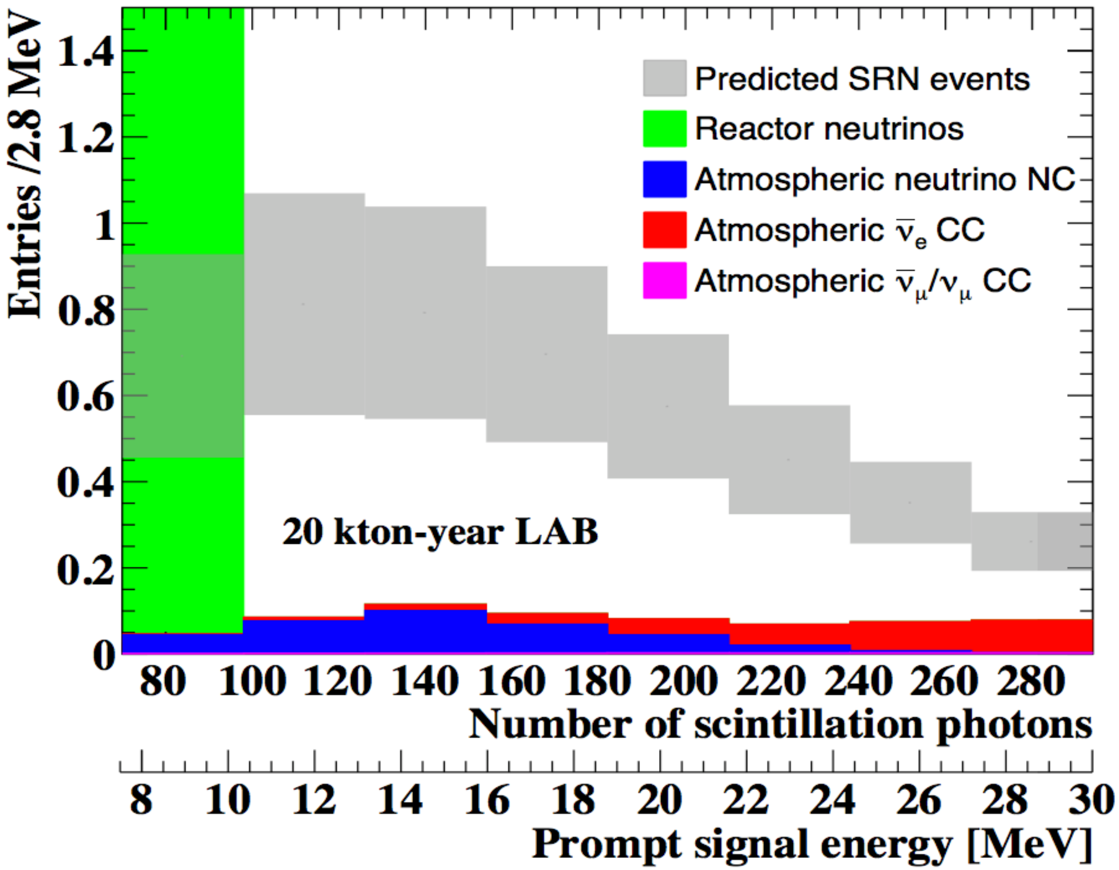
→ protons and heavier nuclear fragments

→ discrimination of e⁺ and NC-prompt seems effortless above 10 MeV

DSNB event spectrum in sLS

Wei, Wang, Chen, arXiv:1607.01671

Expected energy spectrum: $\langle E_\nu \rangle$=18MeV



Event rates in observation window

$E_\nu \in$ [10.8;30.8] MeV

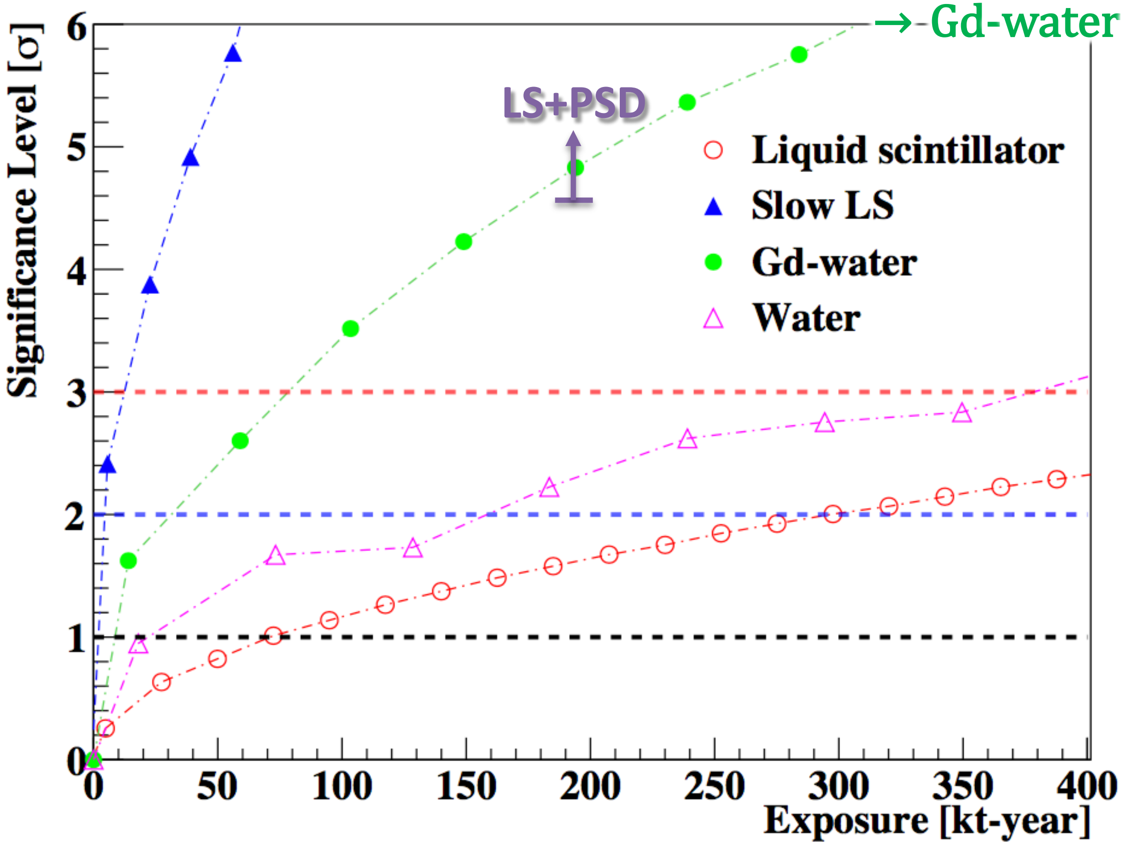
20 kt·yr	# [11-31 MeV]
atm. $\bar{\nu}_e$	0.26
atm. ν_μ	0.025
atm. NC	0.35
total BG	0.64
signal	4.1
efficiency	90%
S/B	6.4

→ comes close to **background-free** observation (excl. terrestrial $\bar{\nu}_e$ sources)

LSCDs vs. other techniques

Wei, Wang, Chen, arXiv:1607.01671
JUNO Yellow Book, arXiv:1507.0561

Significance of DSNB discovery vs. exposure



some caveats:

→ **Gd-water:** BG 2.5/20kt·yr, ε~70%
S/B ~ 1.1

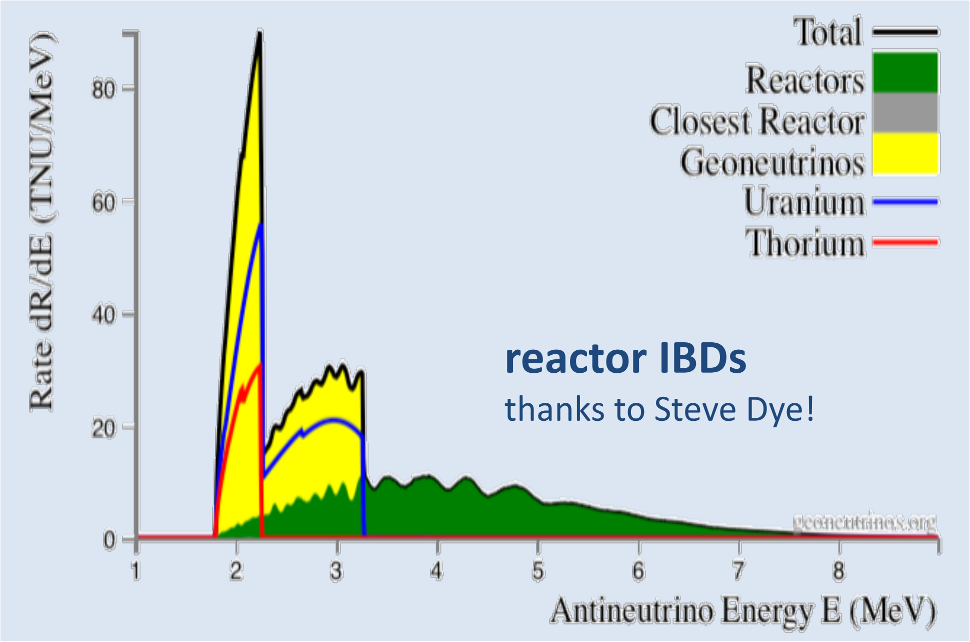
→ **LS+PSD:** S/B ~ 2.3

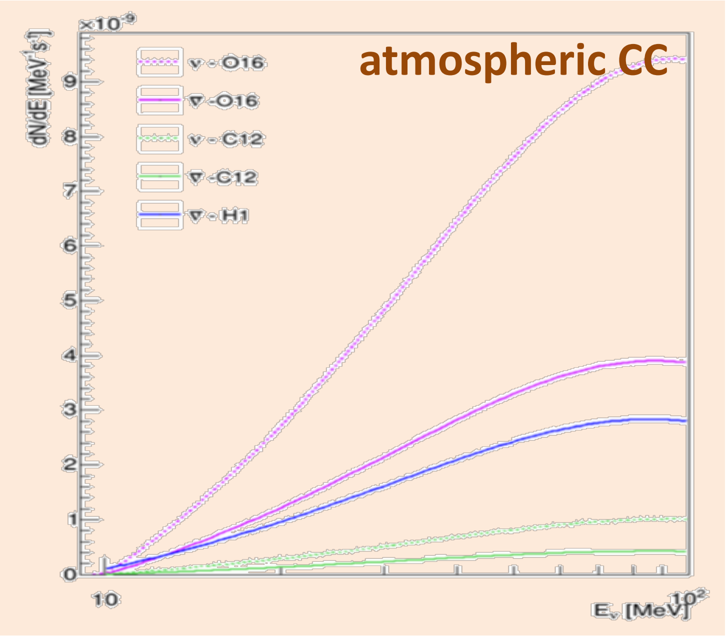
→ **LS:** no PSD!
S/B ~ 0.064

Signals and backgrounds in THEIA

Julia performed a detailed study of all backgrounds that may **mimic the IBD signature**:

- Reactor antineutrinos -- irreducible
- Cosmogenic βn-emitters: $^{9}Li/^{8}He$ -- somewhat reduced compared to oLS/muon veto
- Fast neutrons from rock muons -- can be rejected by fiducial volume cut, but better to use C/S ratio
- Atmospheric **ν** CC interactions -- in part irreducible
- Atmospheric **ν** NC interactions -- the headache





Fast light detectors: LAPPDs

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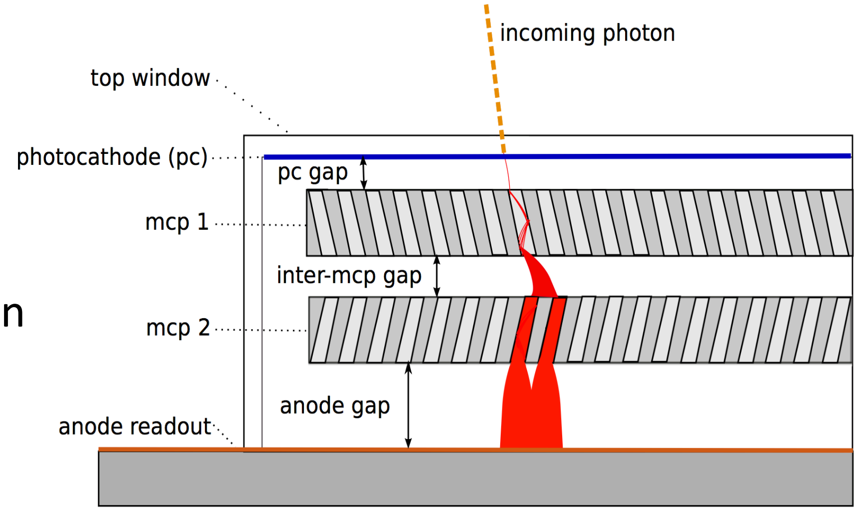
For fast scintillators (e.g. WbLS),
sub-ns time resolution will be crucial

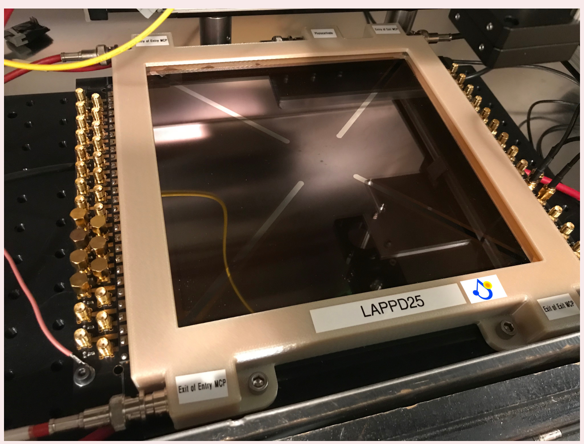
Large-Area Picosecond Photo-Detectors:

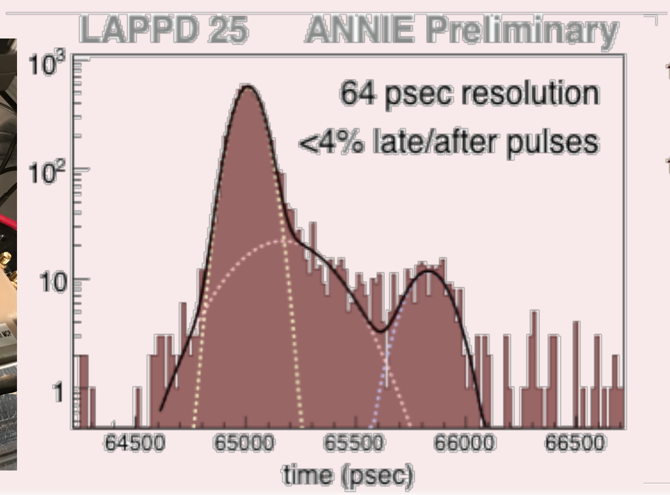
- flat, large area (20cm x 20cm) detectors
- standard photocathode, MCP-based amplification
- time resolution: ~60 ps
- spatial resolution: <1cm
- Manufactured by US company, Incom Inc.

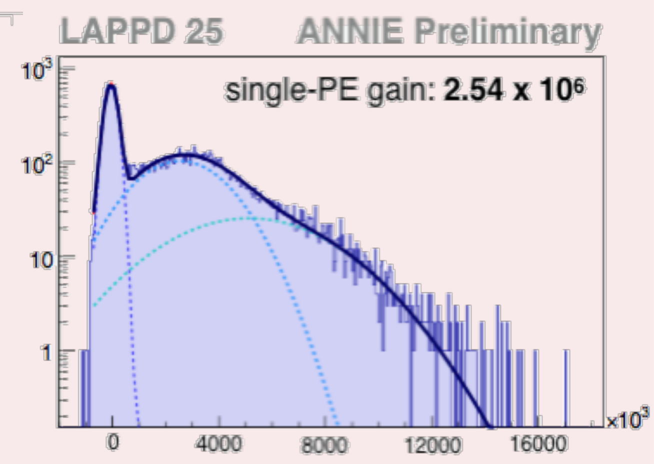


Schematic of LAPPD

LAPPD test for ANNIE





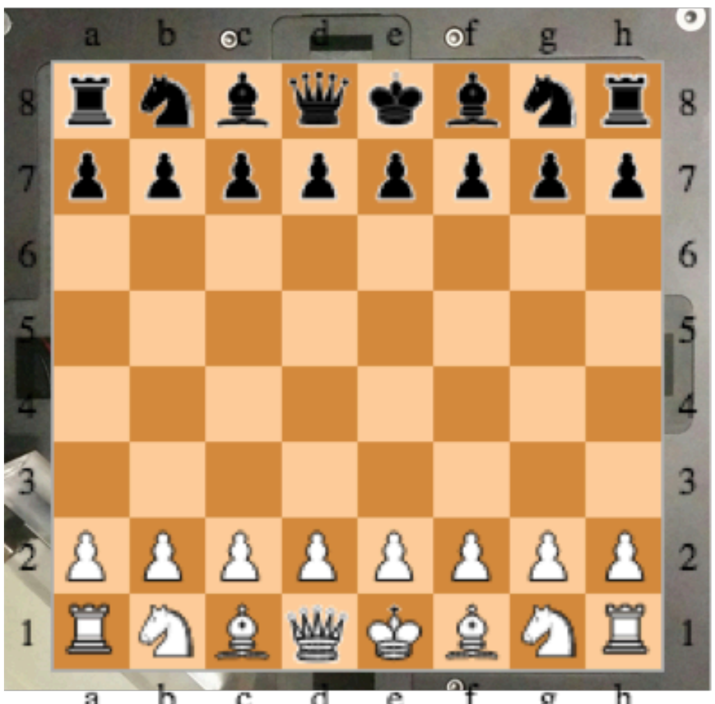


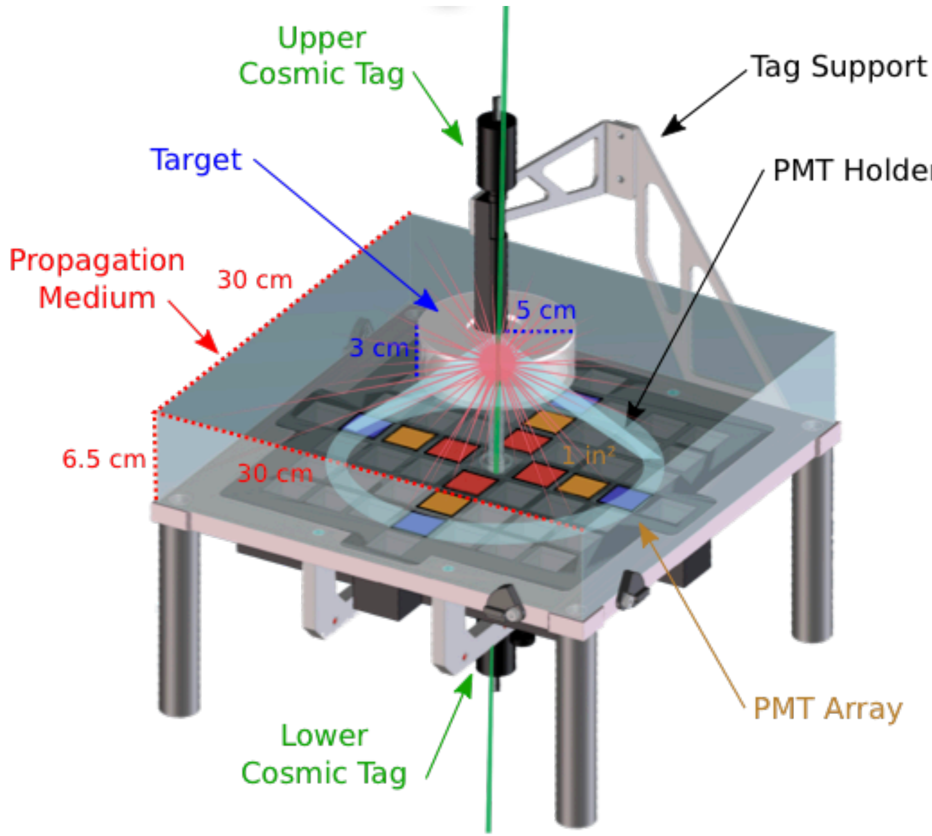
→ posters by A. Elagin, M. Wetstein

Select vertical cosmic muon events

Image Cherenkov ring in Q and T on fast-PMT array

Allows charge- and time-based separation



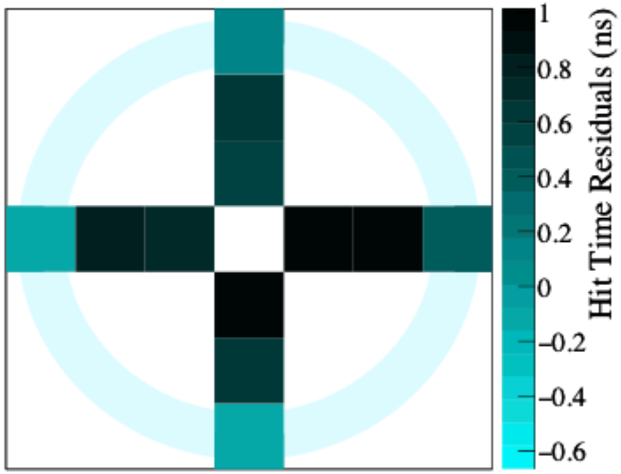


12 1-inch H11934 PMTs (300ps FWHM, 42% QE)
CAEN V1742 (5GHz)
675 samples (135ns window)
CAEN V1730 (500MHz)

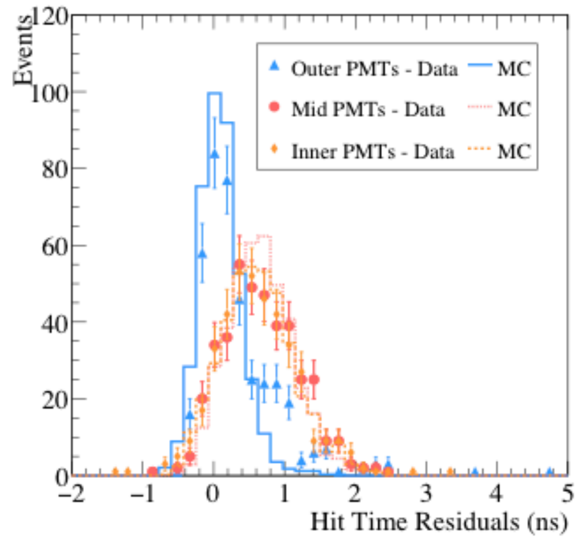
X

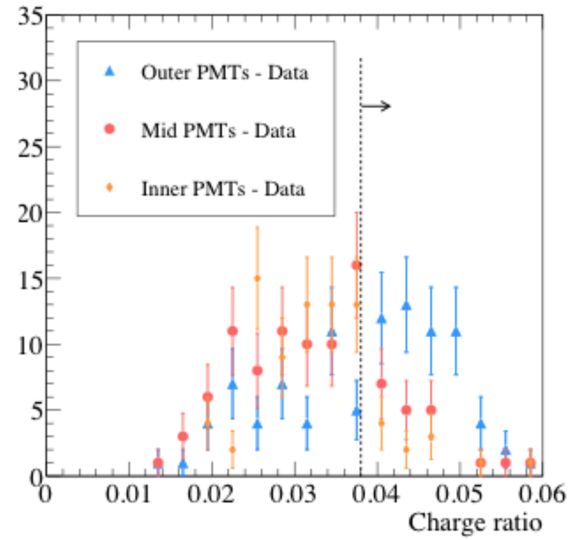
CHESS results on LAB+PPO

Caravaca et al., Eur. Phys. J. C (2017) 77: 811



Typical ring candidate event





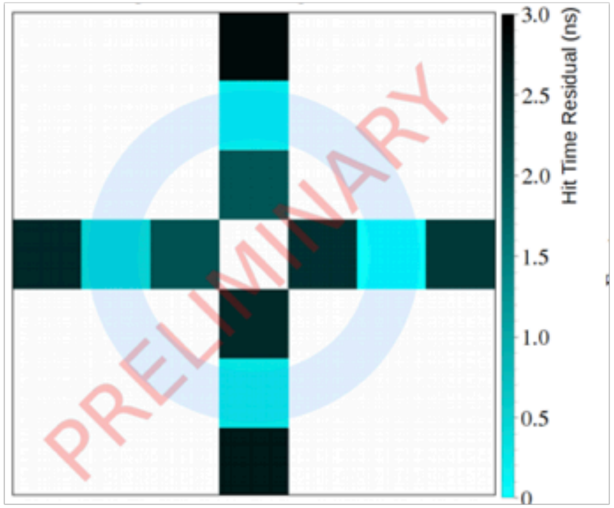
NOTE: Rise time = 0.75 ± 0.25 ns

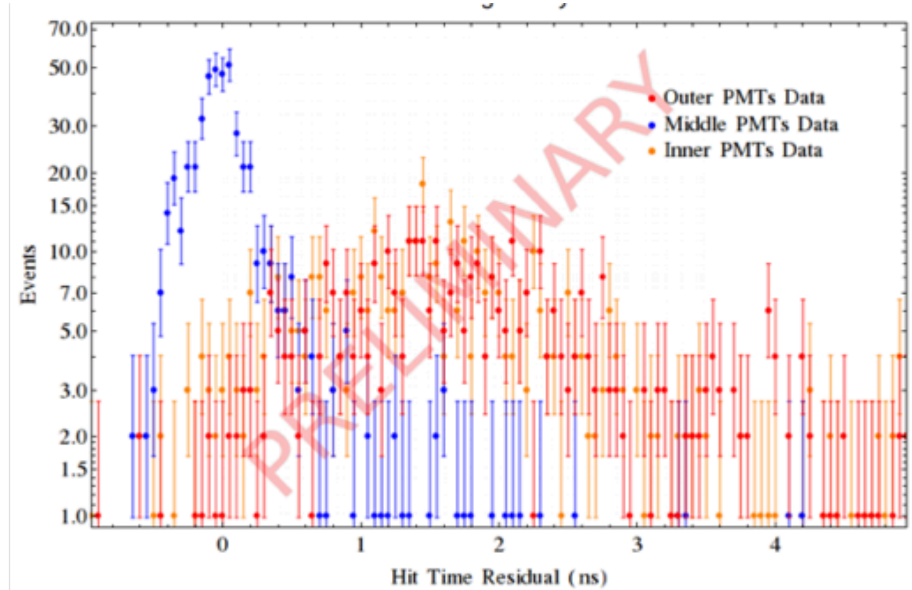
Time at fixed threshold Corrected by ToF, channel delays

Ratio of charge in prompt, 5ns window to charge in total (135ns) window

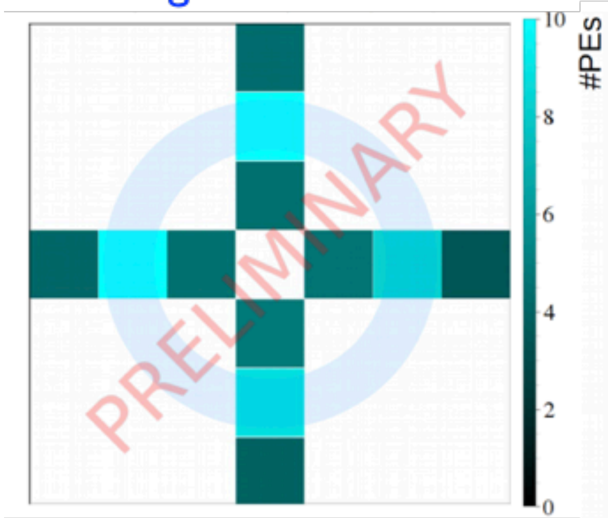
	LAB (time)	LAB (charge)	LAB/PPO (time)	LAB/PPO (charge)
Cherenkov detection efficiency	83 ± 3 %	96 ± 2 %	70 ± 3 %	63 ± 8 %
Scintillation contamination	11 ± 1 %	6 ± 3 %	36 ± 5 %	38 ± 4 %

CHESS results on WbLS (1%)

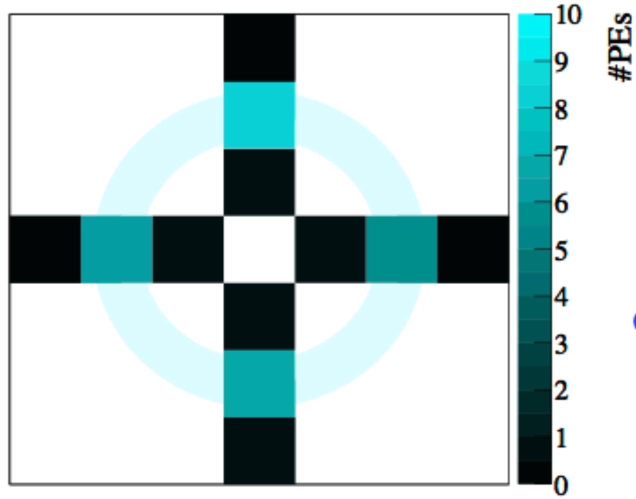




Average of WbLS data set



Average of water data set

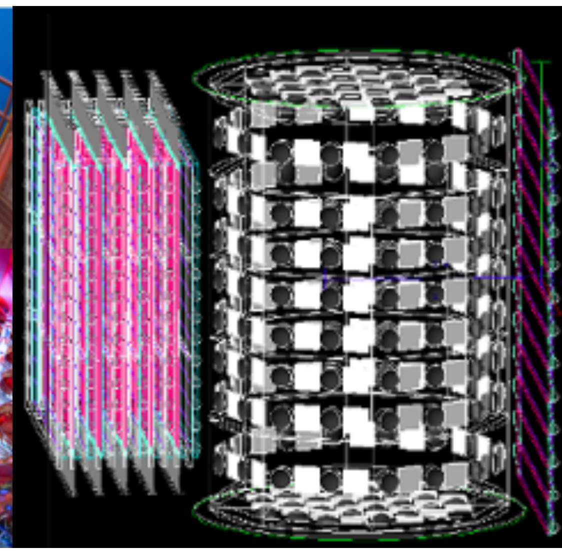
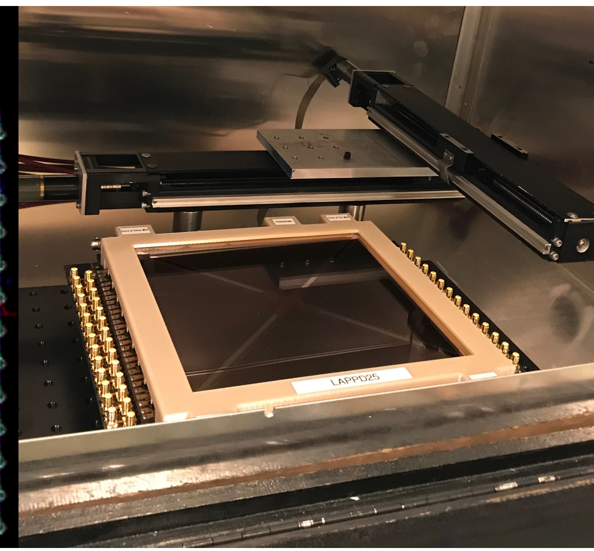


Charge rings:
Clearly seeing
scintillation light
even at 1% LS fraction

WbLS development path → ANNIE

ANNIE: Accelerator Neutrino Neutron Interaction Experiment

- Fermilab-based R&D facility for Water-Cherenkov(+Gd)/scintillator detection
- Physics motiviation: measurement of nuclear final states from neutrino interactions (NuMi-beam) in water: production and multiplicity of final-state neutrons

Phase I an engineering run of the detector and measurement of beam correlated neutron backgrounds, was completed in summer of 2017

Phase II the full physics and R&D run, starts construction this summer with the data taking to planned start in Fall 2018

Phase III (planned) R&D run with WbLS fill or separated target vessel (ton-scale)

→ posters by J. Eisch/M. Wetstein

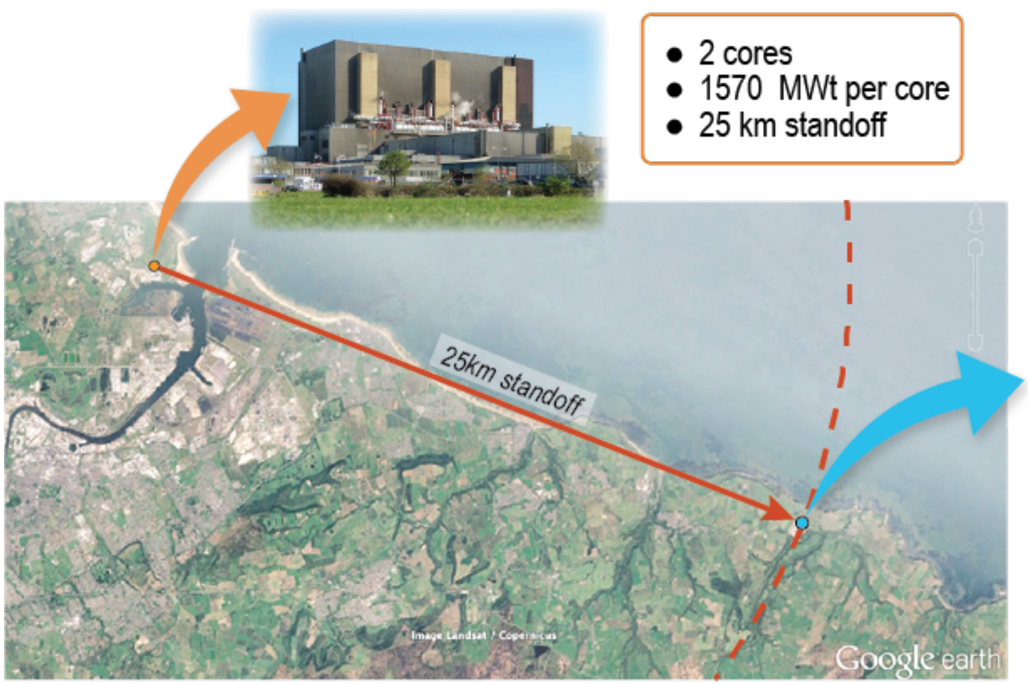
WbLS development path → WATCHMAN/AIT

WATCHMAN: WATer Cherenkov Monitor for Anti Neutrinos

- Phase I of the Advanced Instrumentation Testbed (AIT)
- kiloton-scale H_2O+Gd Cherenkov detector for reactor monitoring
- from 2022: detection of ON/OFF power cycle of single reactor (3σ at 25km)

→ later phases (2024+): upgrade with WbLS and LAPPDs

HARTLEPOOL REACTORS



WATCHMAN detector at the Boulby mine

- 3500 tons, ~3000 photomultiplier tubes
- Water Cherenkov detector, doped with gadolinium
- Detects antineutrinos via the process $\bar{\nu} + p = e^+ + n$

→ poster by E. Kneale