How to detect the Diffuse Supernova Neutrino Background?

Seminar talk
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9 Dec 2022
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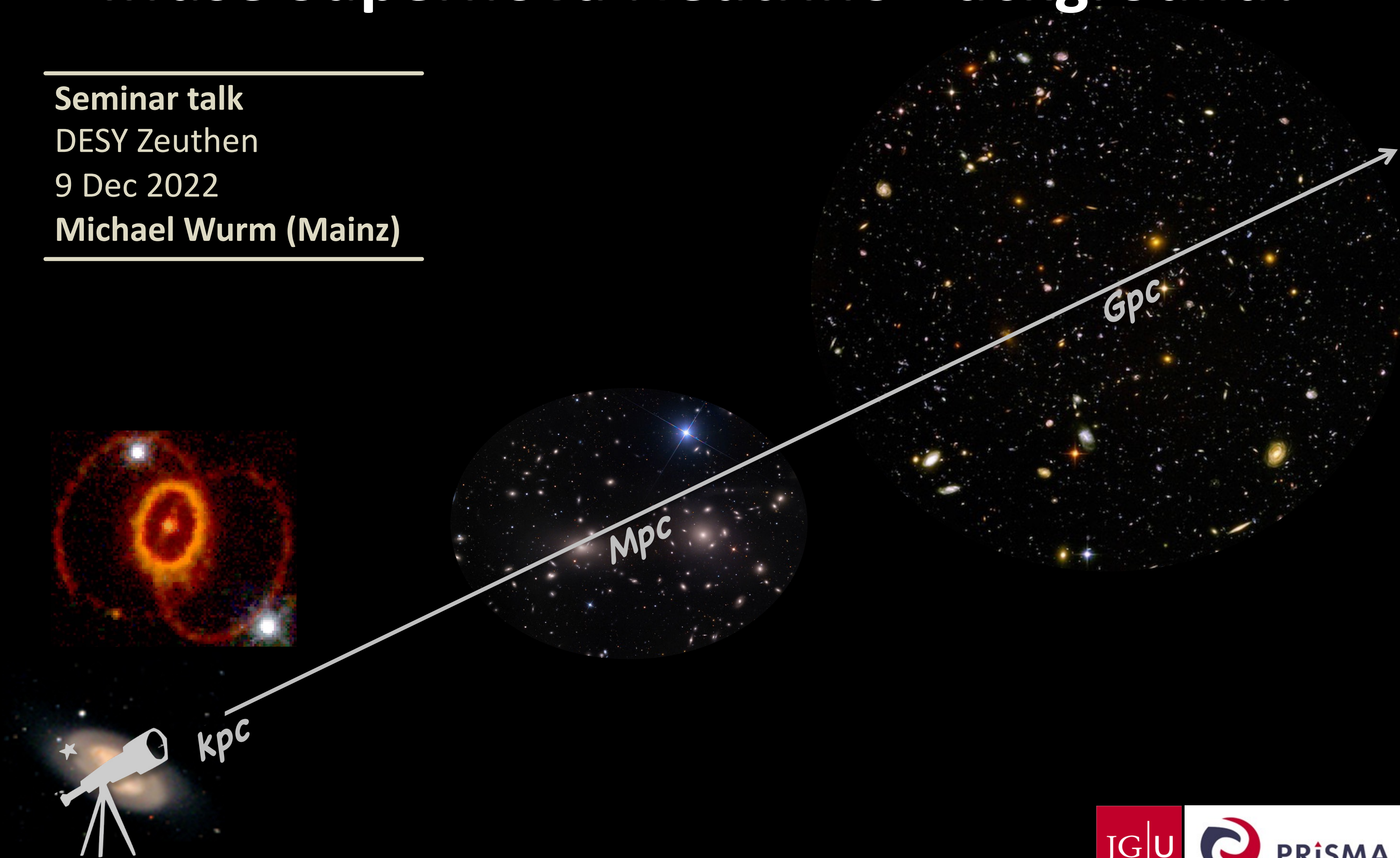
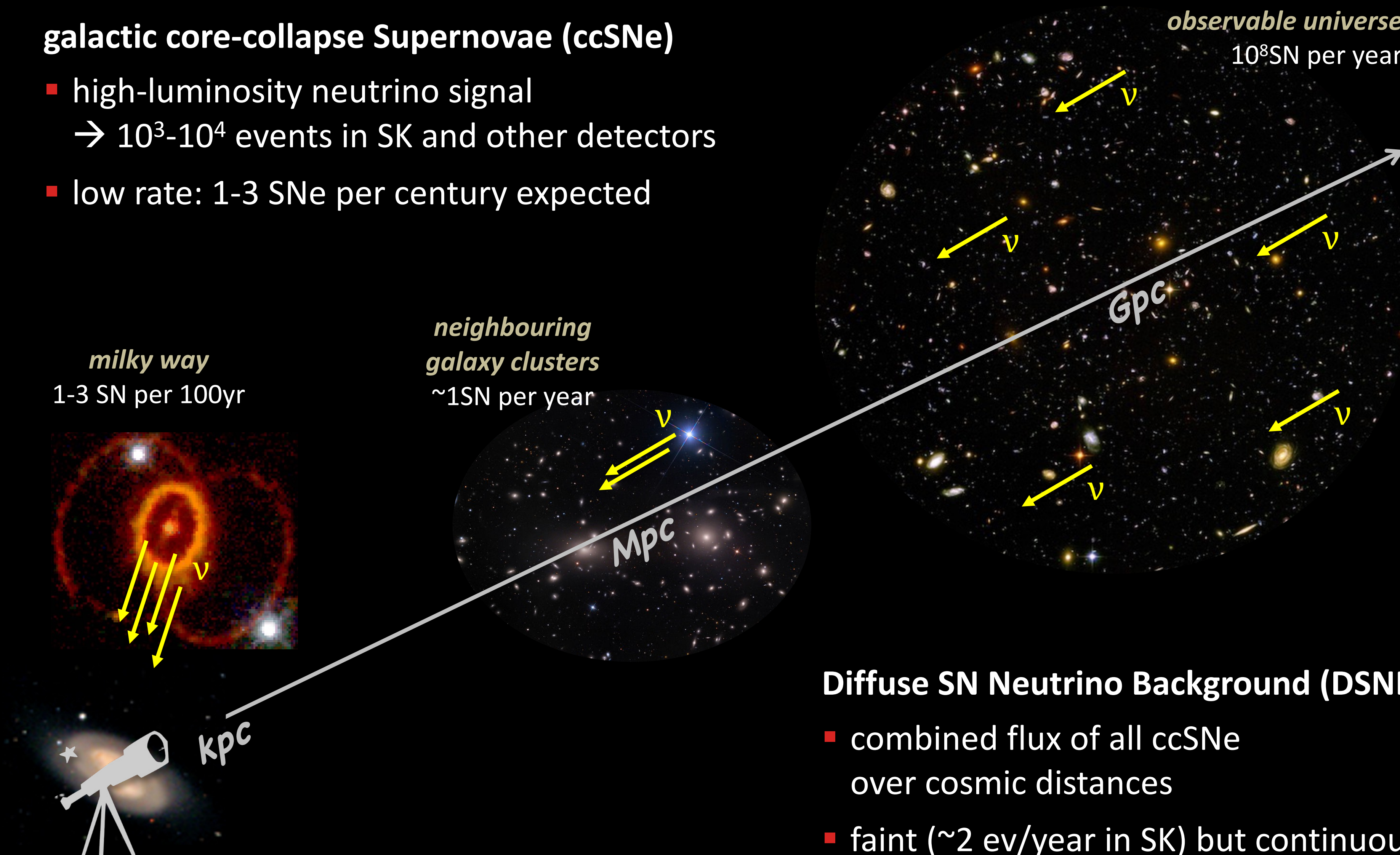


Observation of Supernova neutrinos

galactic core-collapse Supernovae (ccSNe)

- high-luminosity neutrino signal
  → 10^3-10^4 events in SK and other detectors
- low rate: 1-3 SNe per century expected

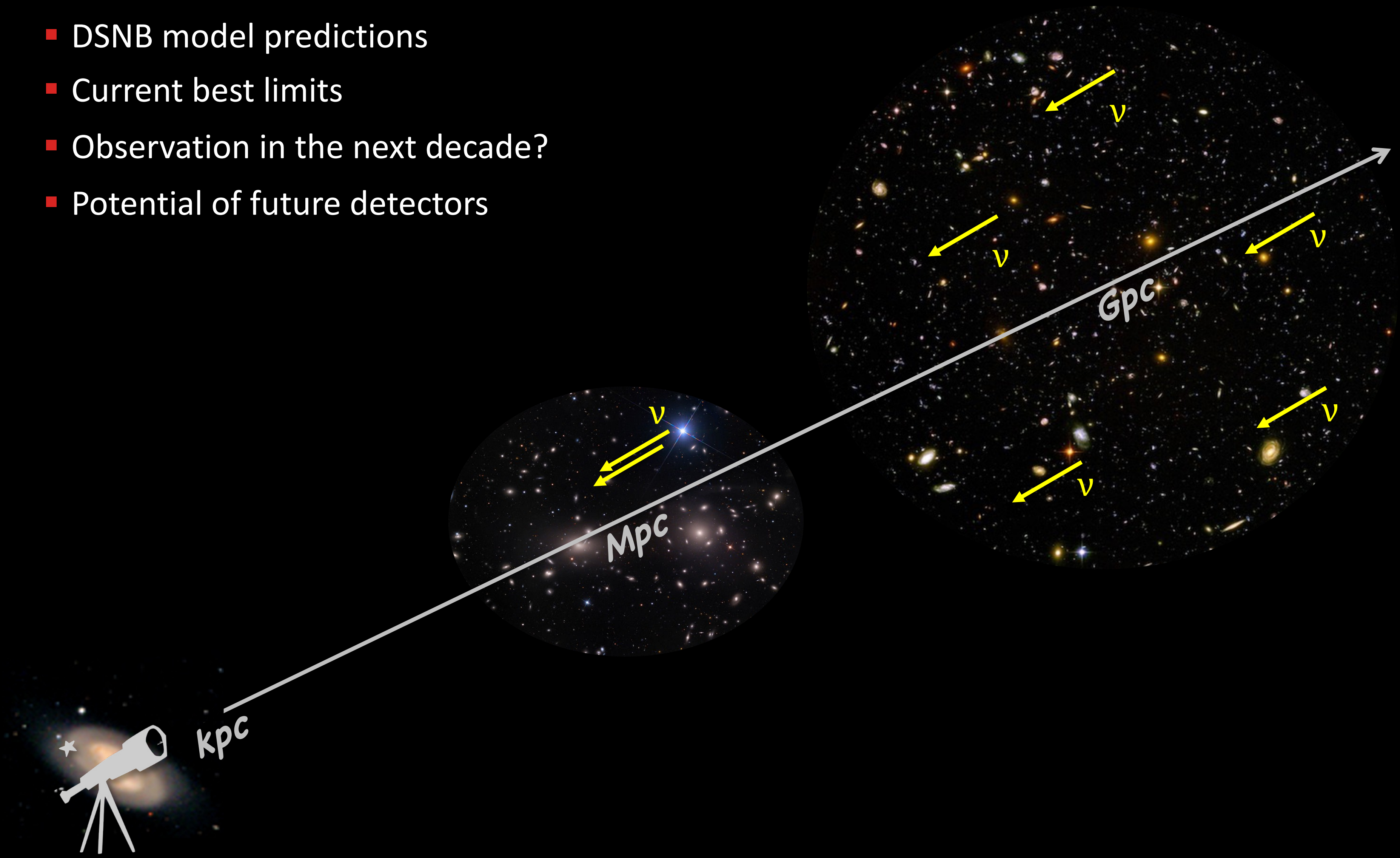


Diffuse SN Neutrino Background (DSNB)

- combined flux of all ccSNe over cosmic distances
- faint (~2 ev/year in SK) but continuous

Outline of this talk

- DSNB model predictions
- Current best limits
- Observation in the next decade?
- Potential of future detectors



1 DSNB Models: Basic Ingredients

red-shift dependent
Star Formation Rate

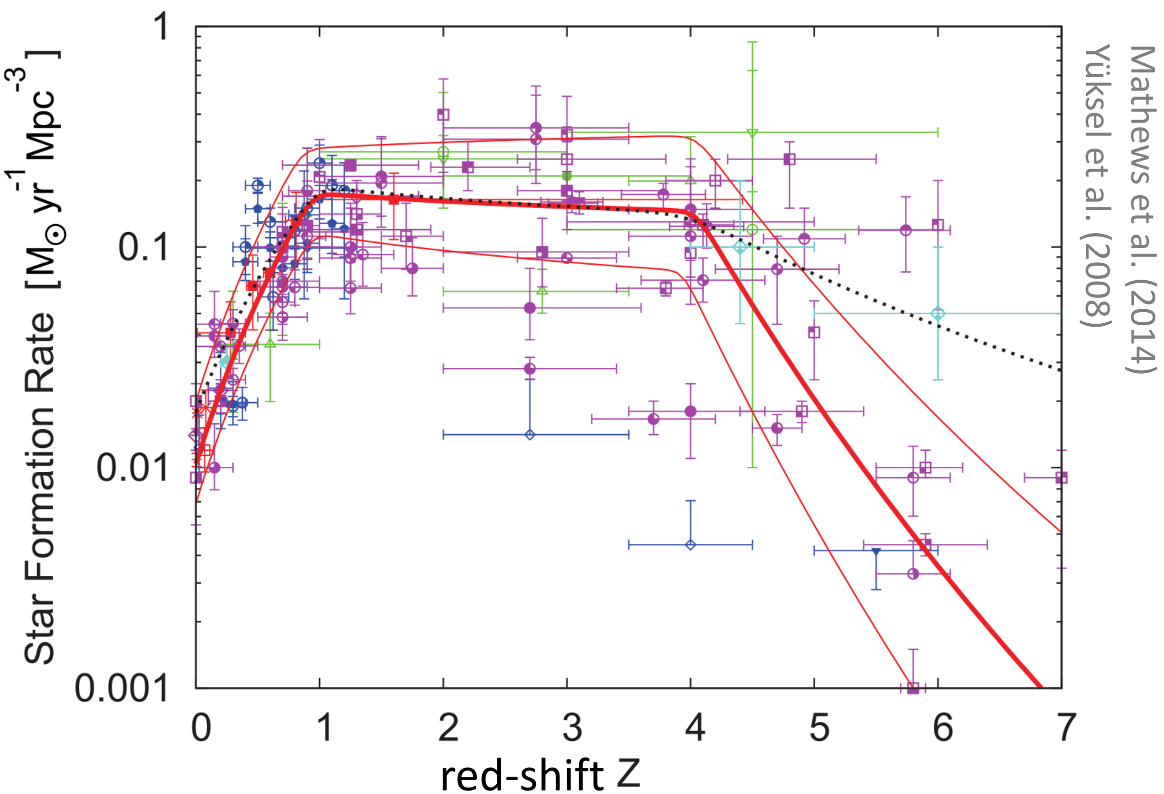
red-shift dependent
Supernova Rate

Initial Mass Function
of forming stars

Supernova Neutrino Spectrum
-- depending on progenitor mass
-- red-shifted by cosmic expansion

Star Formation History

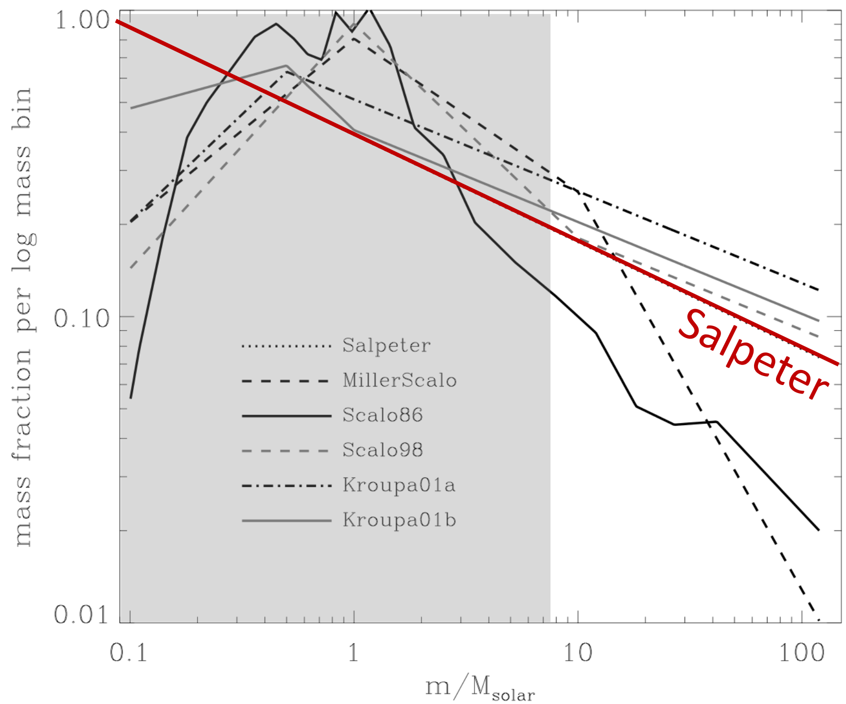
i.e. the red-shift dependent Star Formation Rate (SFR)



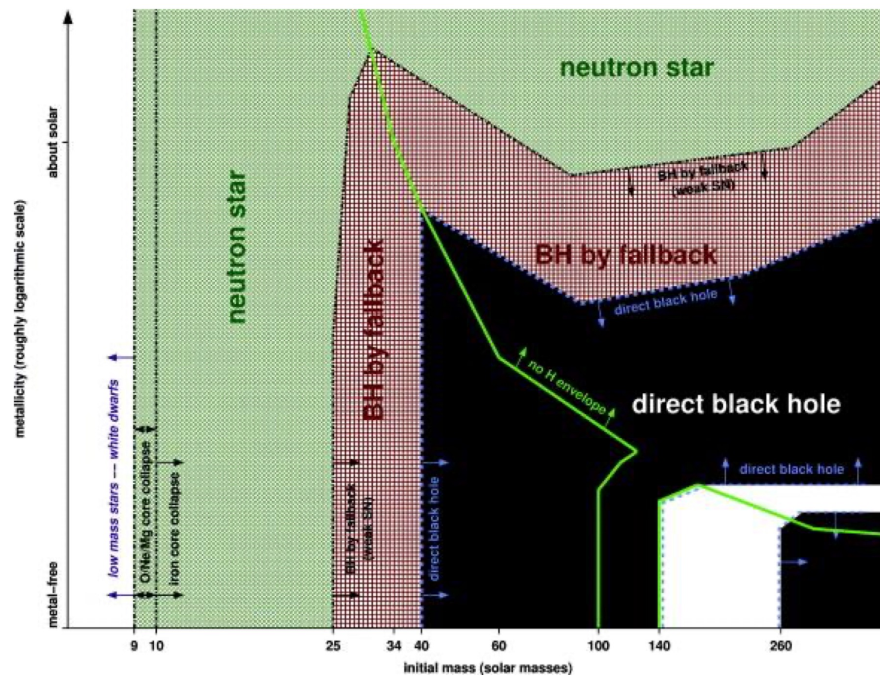
- astronomical observation of star formation regions by photons (UV→radio)
- relatively well constrained up to red-shifts z ≈ 1-2 → most relevant for DSNB

Initial Mass Function

i.e. distribution of progenitor star masses



Baldry, Glazebrook (2003)



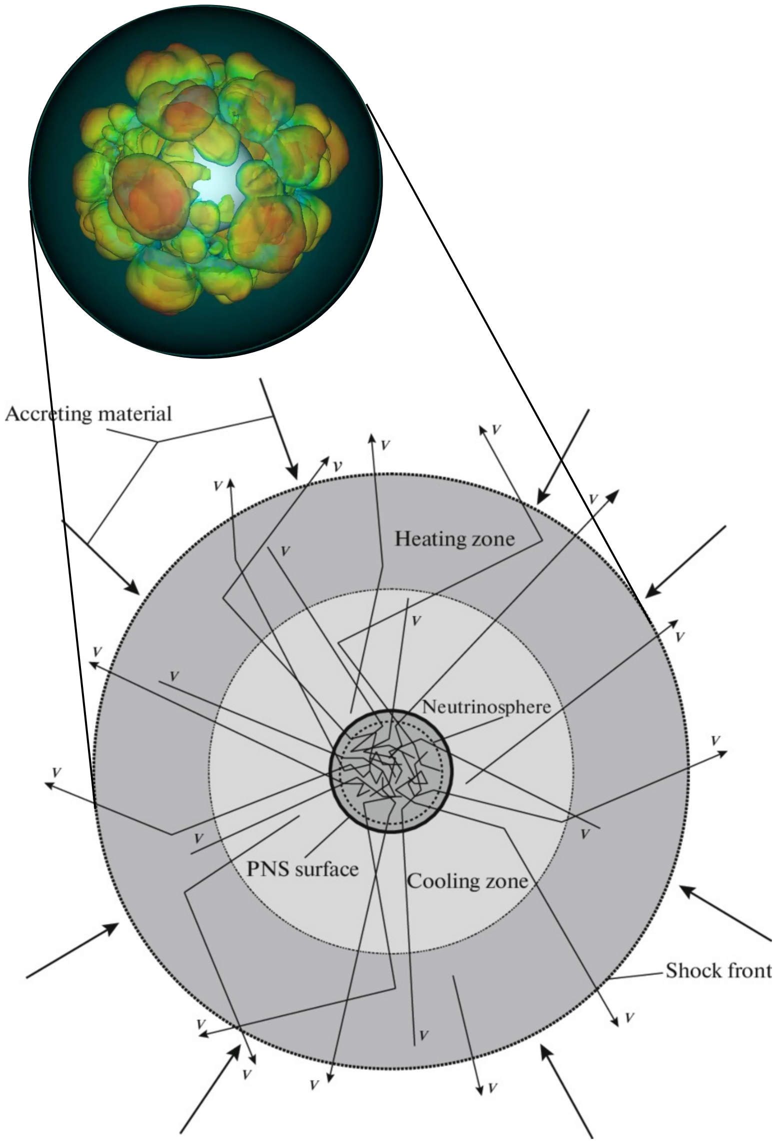
Heger et al. (2003)

- stars that end in a ccSN: typically only 8 M_{solar} and higher → small fraction (~10%)
- DSNB modeling: commonly used (broken) Salpeter parametrization

progenitor mass influences

- final state: neutron star, black hole
- temperature of proto-neutron star → SN neutrino spectrum

Supernova Neutrino Emission in a Nut Shell

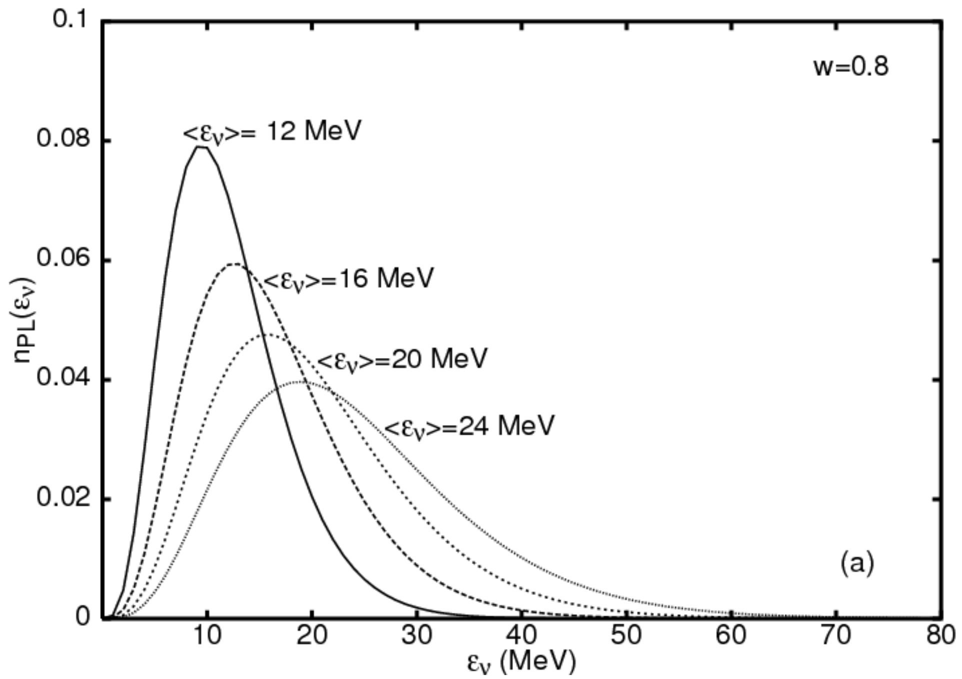


- neutrino emission from core-collapse Supernovae comes in three batches
  - neutronization: $p + e^- \rightarrow n + \nu_e$
  - accretion: ν_e & $\bar{\nu}_e$
  - PNS cooling: $\nu\bar{\nu}$-pair production (all flavors!)
- Proto Neutron Star (PNS) cooling is the dominant contribution
- Total ν luminosity: ~99% of gravitational energy released in Fe core collapse
- event numbers expected for Super-K:
  - $\sim 10^4$ for center of Milky Way (10 kpc)
  - ~ 1 for Andromeda (1 Mpc)

Supernova Neutrino Spectrum

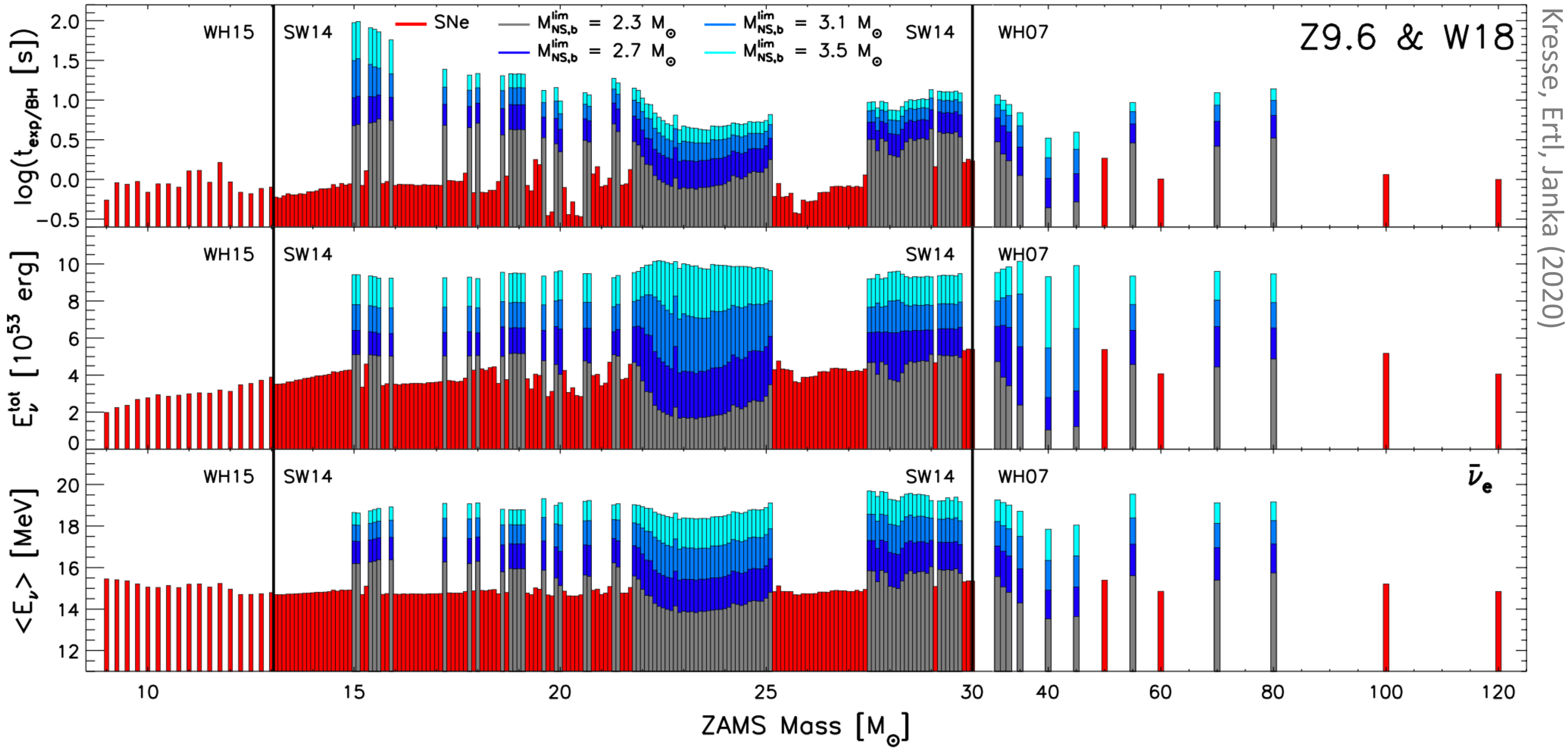
standard parametrization (Keil, Raffelt, Janka)

$$\frac{dN_\nu}{dE_\nu} = \frac{(1+\beta_\nu)^{1+\beta_\nu} L_\nu}{\Gamma(1+\beta_\nu)\langle E_\nu\rangle^2} \left(\frac{E_\nu}{\langle E_\nu\rangle}\right)^{\beta_\nu} e^{-(1+\beta_\nu)E_\nu/\langle E_\nu\rangle}$$



- thermal Fermi-Dirac spectrum (T ~4-5 MeV) with
- pinching β_ν to take into account thickness of neutrino sphere

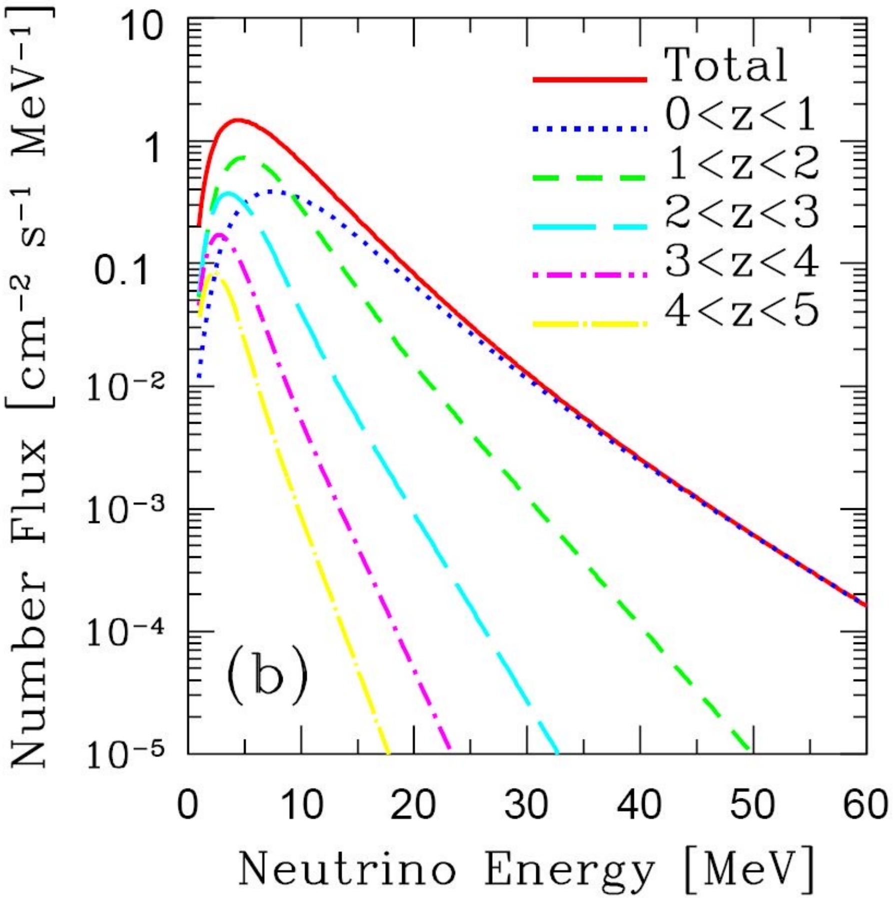
New: Mass-dependent Neutrino Spectra

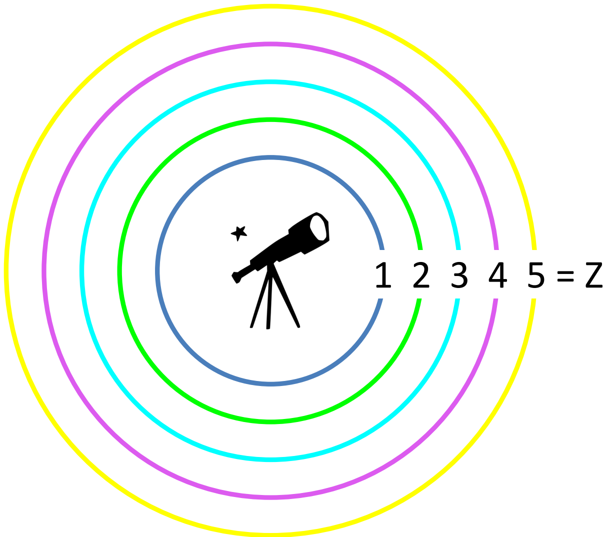


- figures show time to explosion/BH formation, total energy, mean neutrino energy as a function of Zero-Age Main Sequence (ZAMS) mass
- red: successful SNe, grey-blue: failed SNe with dependence on EoS of neutron star

Impact of Cosmological Red-Shift

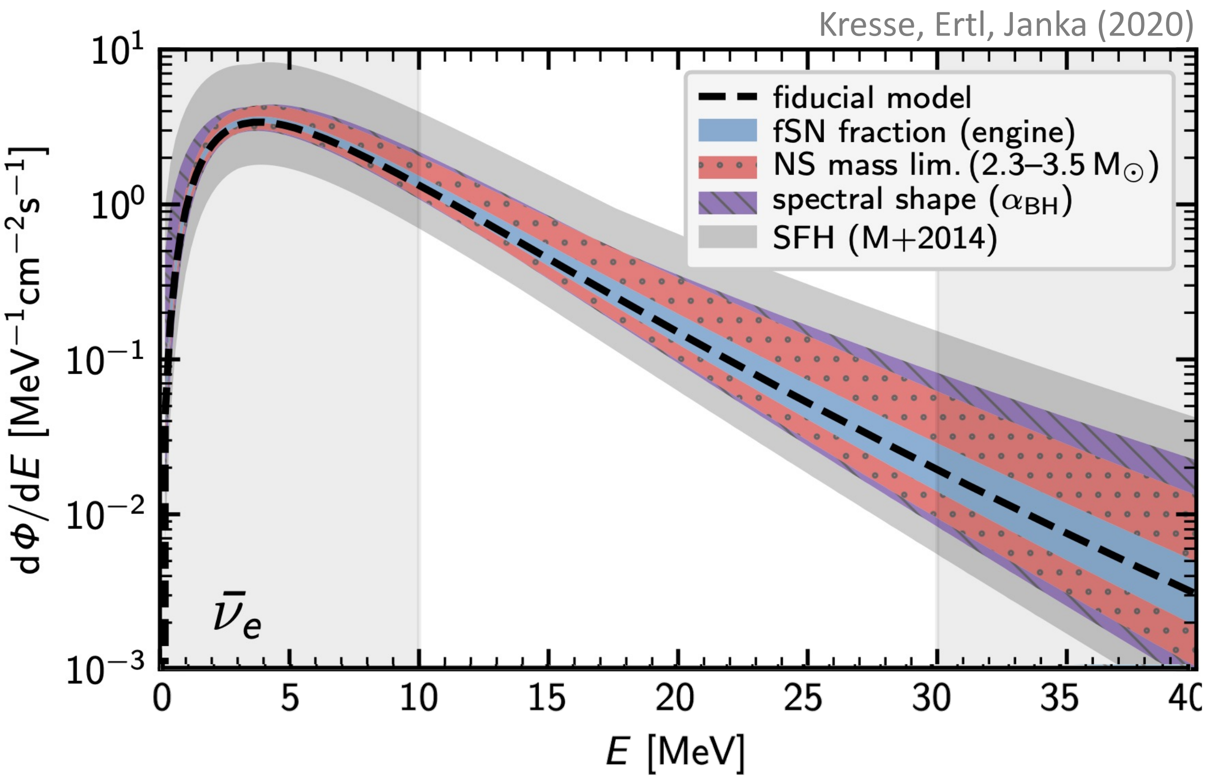
S. Ando '04





- DSNB spectrum at Earth is composite of SN spectra emitted from different red-shift shells
- only SNe at red-shifts <2 contribute to signal region above 10 MeV (see later)

Range of predictions

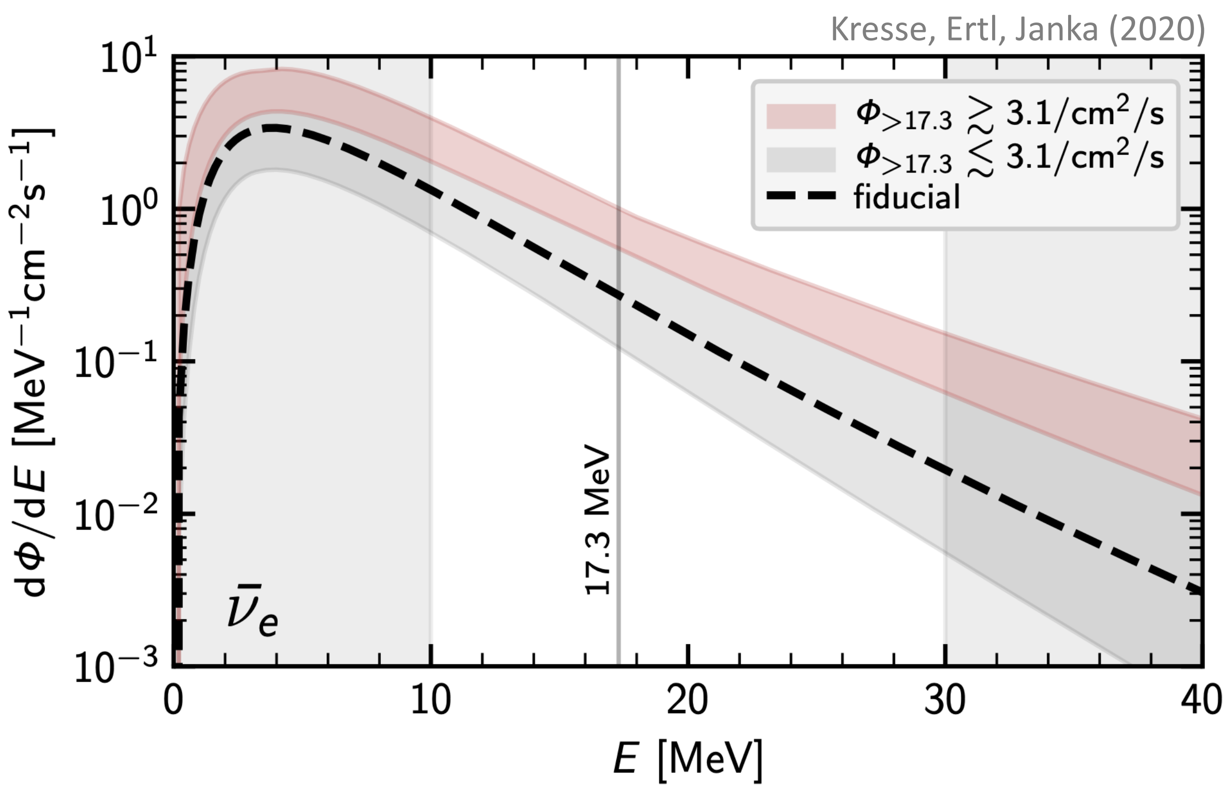


uncertainties shown here:

- fraction of failed SN
- mass limit of neutron stars
- spectral shape of black-hole forming SN
- normalization of Star Formation Rate

- DSNB flux predictions feature large intrinsic uncertainties
- predictions by many different groups
  → no substantial differences on flux/spectral shape

Range of predictions and upper limit



effect of upper limit by Super-Kamiokande

- DSNB flux predictions feature large intrinsic uncertainties
- predictions by many different groups
  → no substantial differences on flux/spectral shape
- upper limit from experiment: part of parameter space already ruled out!

Why is the DSNB interesting?

→ discovery of the only „permanent“ SN neutrino signal

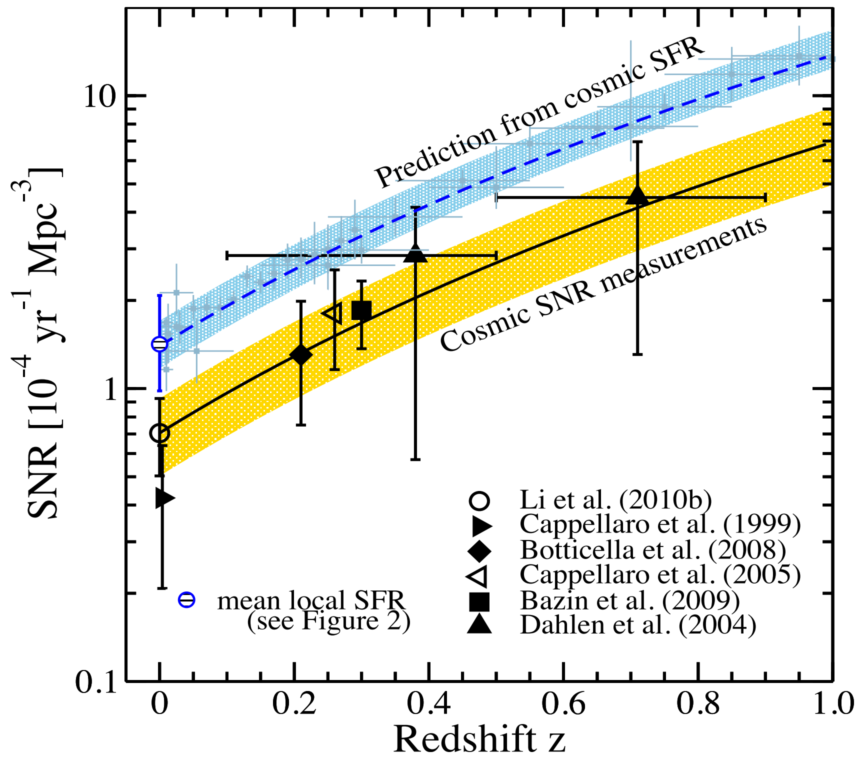
→ signal normalization

- redshift-dependent SN rate
- fraction of hidden/failed SNe

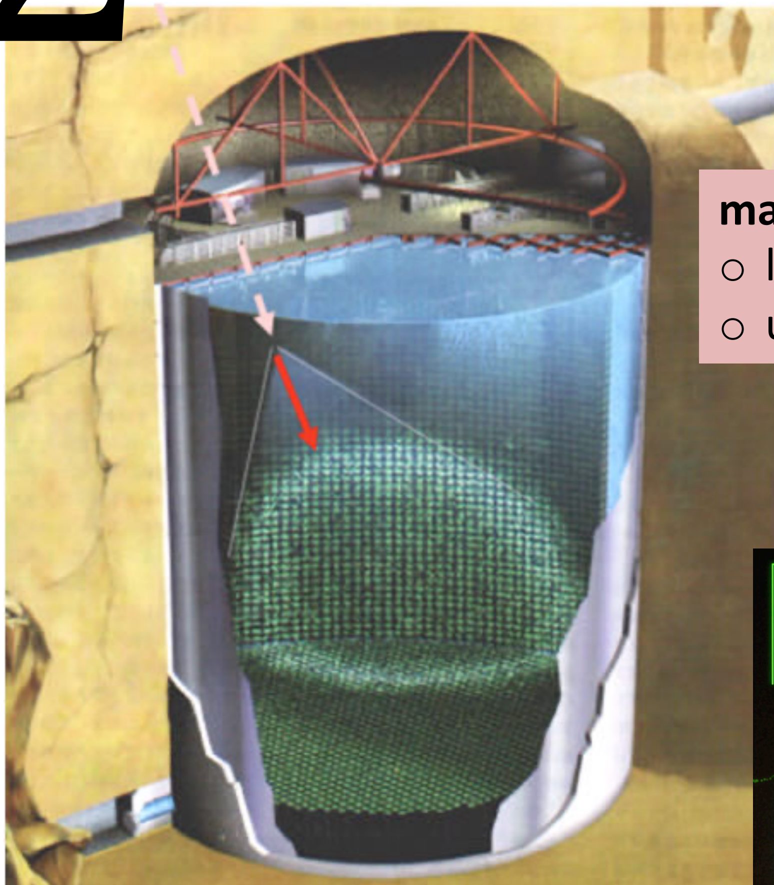
→ spectral shape

- large variability in PNS temperatures expected → average SN neutrino spectrum
- astrophysical parameters, e.g. neutron star equation of state

Beacom



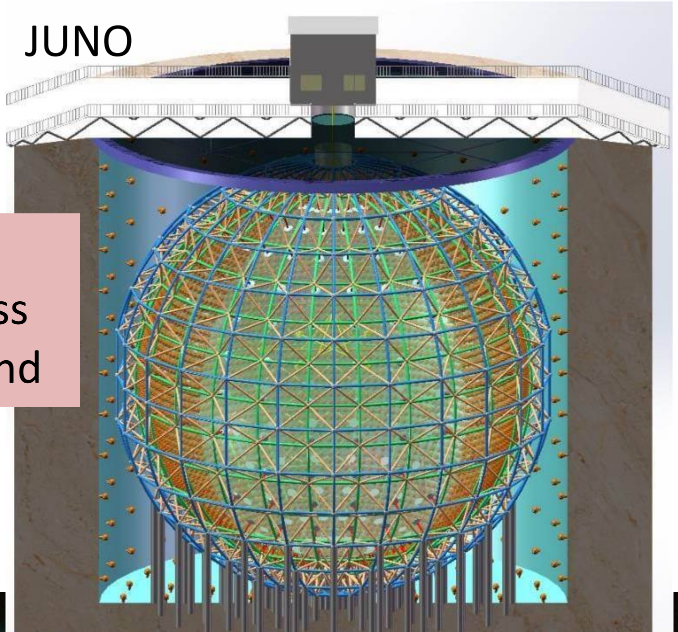
2 Detectors for DSNB detection

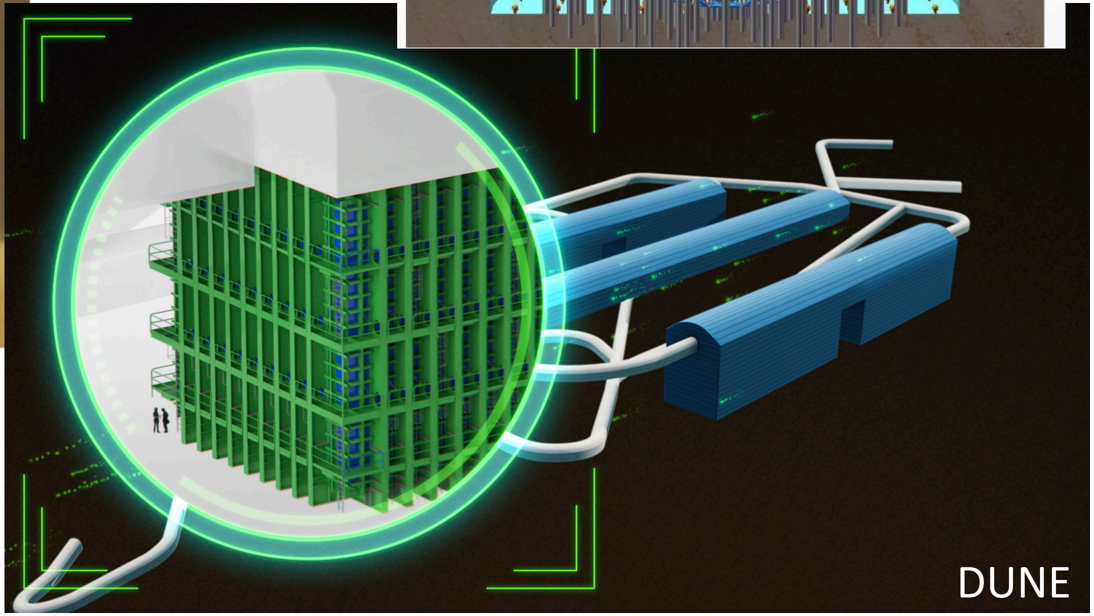


Super-Kamiokande

main requirements:
- large detection mass
- ultra-low background

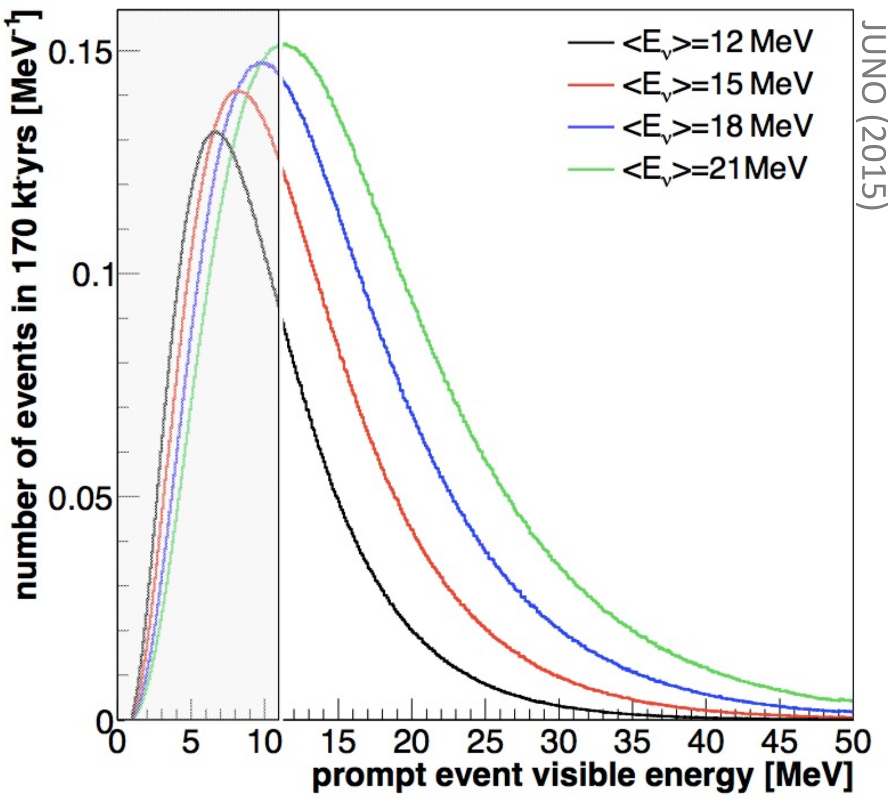
JUNO





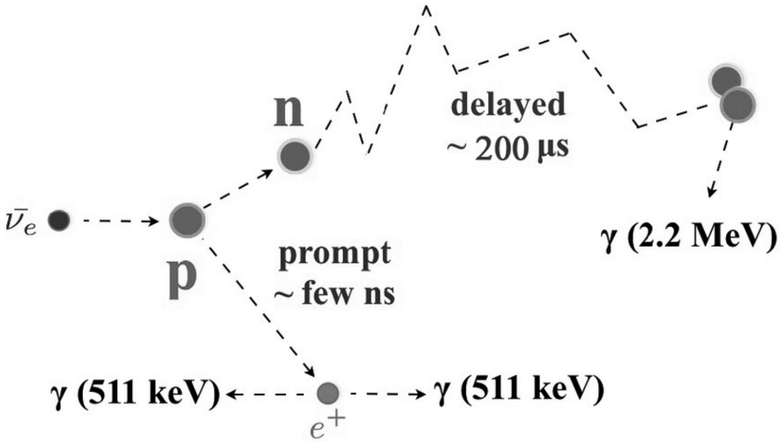
DUNE

Detecting the DSNB antineutrino component



- DSNB flux: ~10^2 /cm^{2}s
- equipartition between ν flavors
- best possibility for detection in water and liquid scintillator (LS)

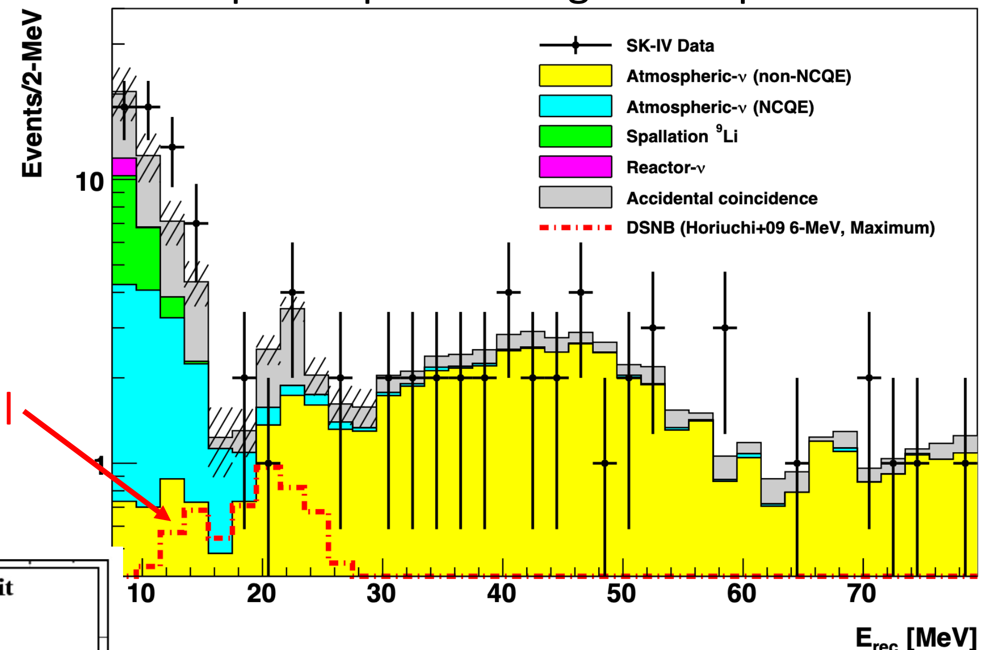
  $\bar{\nu}_e$ via **inverse beta decay** on free protons (H)
- expected event rate:
  1—2 events per 10 kt·yrs



Current experimental results

Experiment	Type	Mass
Borexino	LS	270t
KamLAND	LS	1kt
Super-K	WC	22.5kt

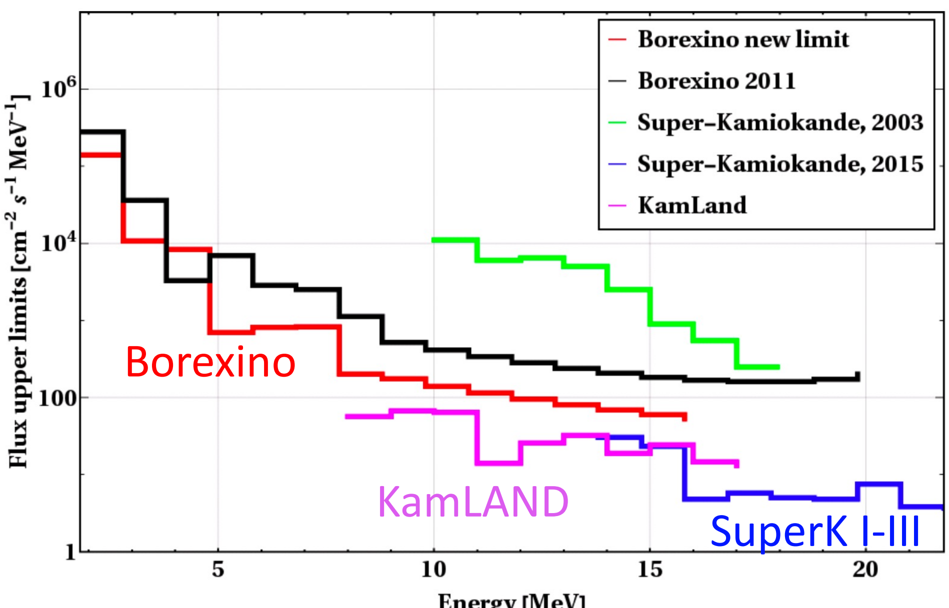
Example: Super-K background spectra



Super-Kamiokande (2021)

DSNB signal

State of current experimental limits

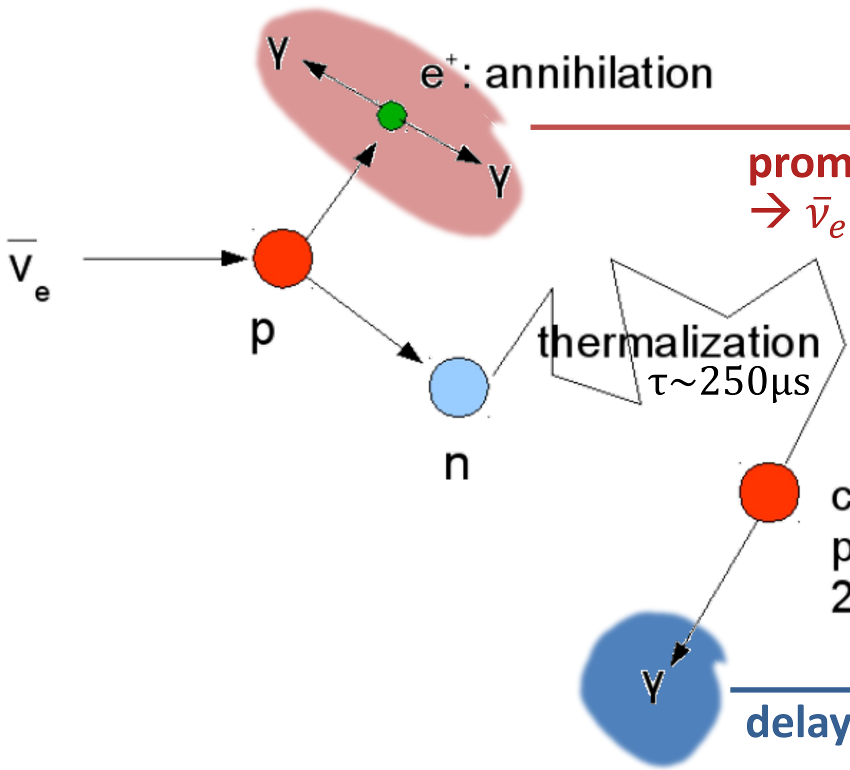


Borexino (2019)

→ current experiments are either too small or feature too much background for a detection

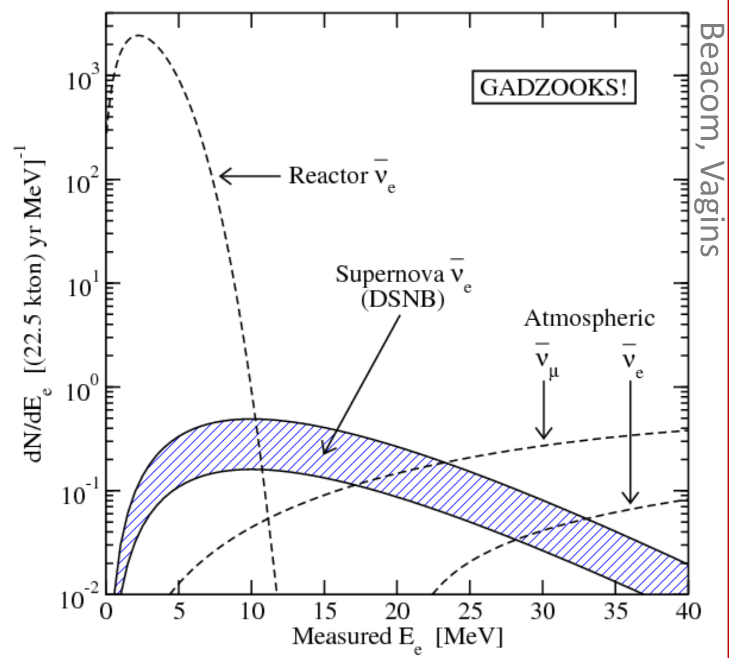
Important improvement: Neutron Tag

irreducible backgrounds
detection window 10-30 MeV



prompt positron
→ $\bar{\nu}_e$ energy

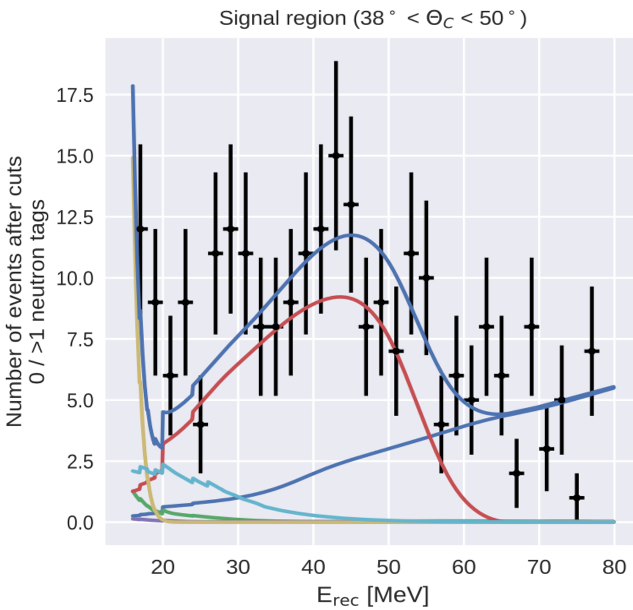
delayed neutron



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

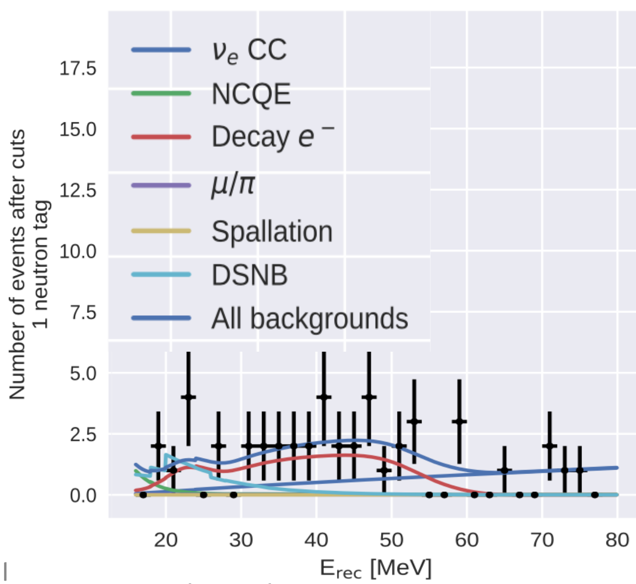
→ **n-detection** inherent to liquid scintillators but hard to achieve in pure water

Neutron Tag in current SK-IV



Recent publication on latest SK-IV data with long acquisition window after trigger that results in ~20% delayed neutron tag efficiency

← events with 0/2+ detected neutrons background levels as in SK I-III analyses



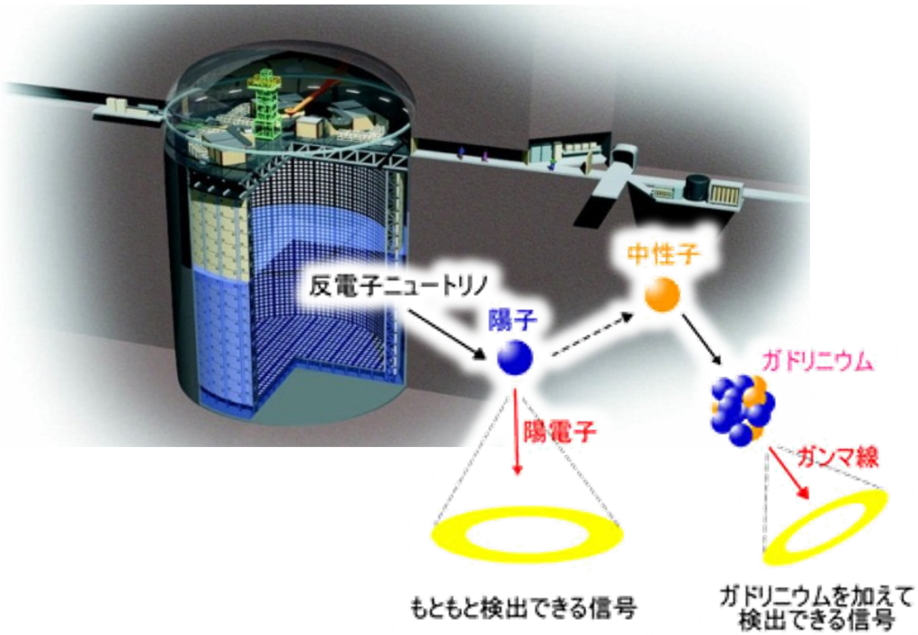
← events with **1** detected neutrons single background levels suppressed but also low signal efficiency

Side note: both data samples prefer a small non-zero DSNB contribution.

How to enhance delayed neutron tagging?

JG|U

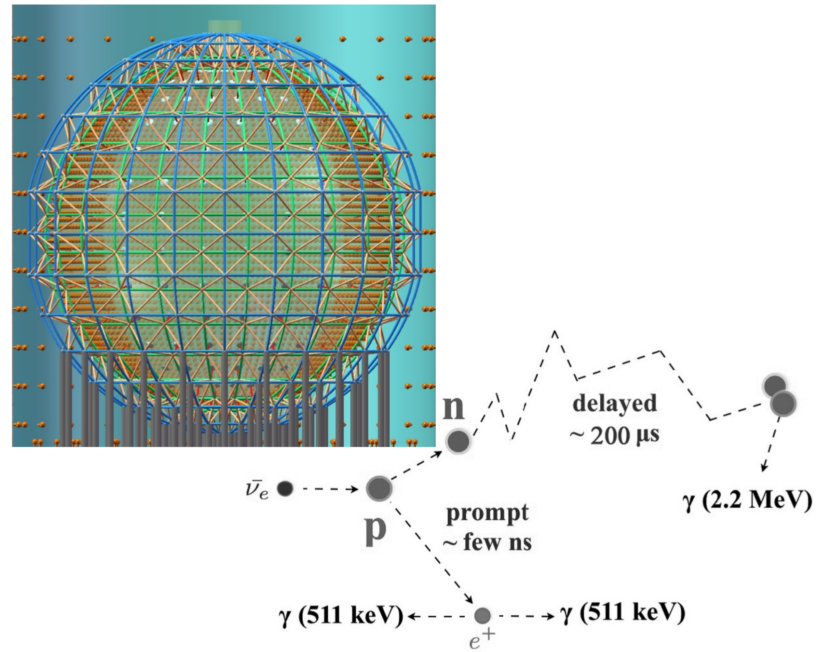
Super-Kamiokande+Gadolinium



- add low concentration of gadolinium (10^{-3})
- **enhanced neutron tag by gamma cascade** (τ~30µs, 4-5 gammas with $\Sigma E_\gamma \approx$8MeV)
- **detection efficiency**: **65-80%**

→ running since fall 2020!

JUNO



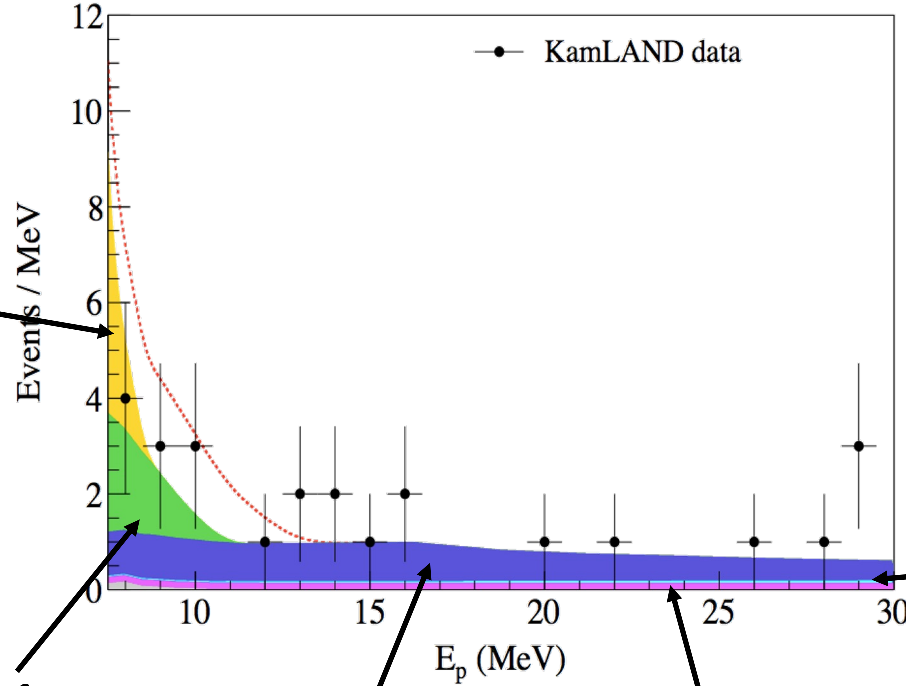
- liquid scintillator: high light yield & low detection threshold
- **large signal by n capture on H**
- **detection efficiency** close to 100%

→ will start in 2023

→ successfully removes all single-event backgrounds – **but:** there are correlated BGs …

Backgrounds mimicking IBDs

In 2011, KamLAND published results from an extraterrestrial $\bar{\nu}_e$ search in 10-30 MeV range:



reactor electron antineutrinos (irreducible)

spallation isotopes (^{9}Li) from cosmic muons in the target

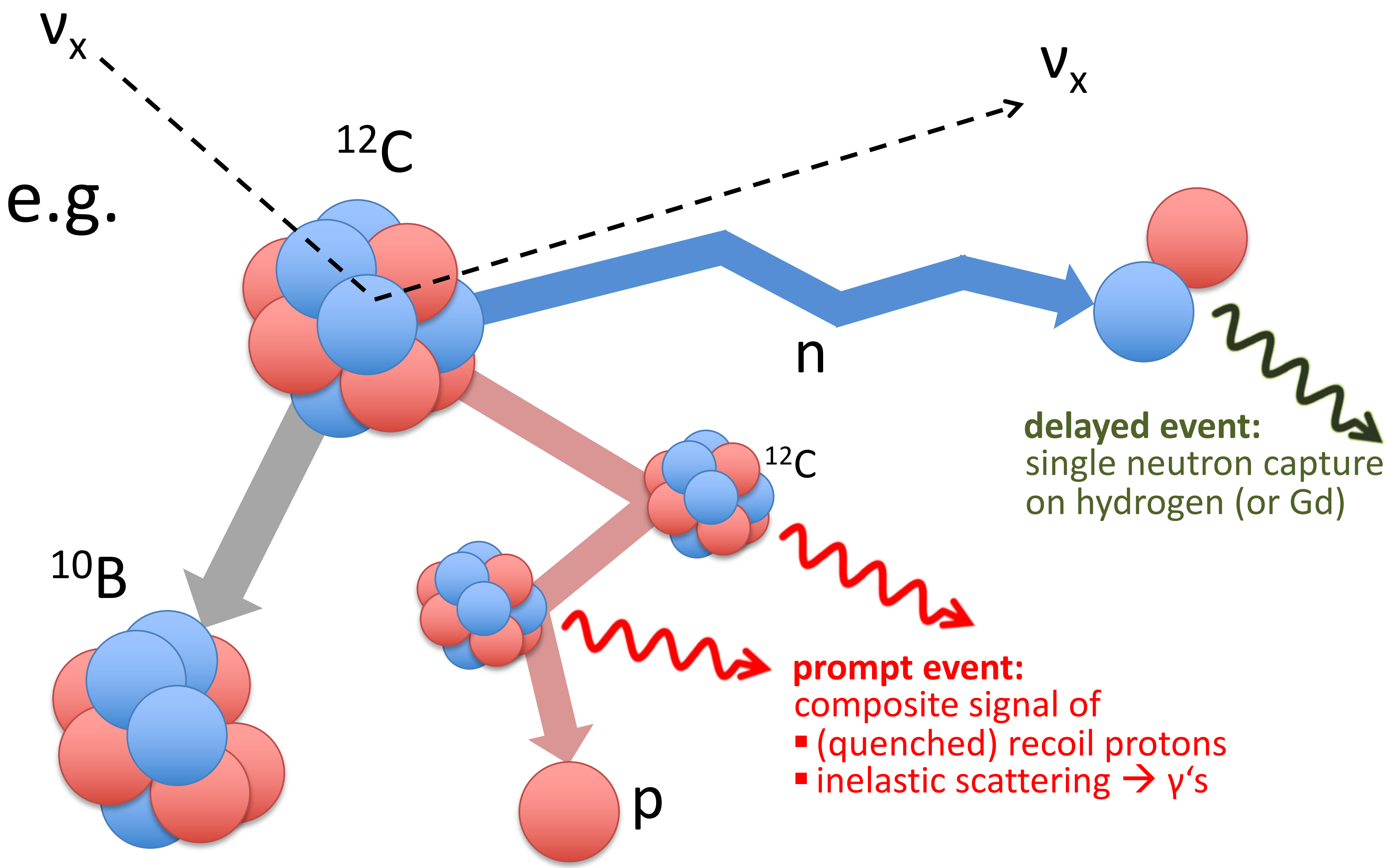
who ordered this?

fast neutrons from muons crossing surrounding rock (can be shielded/tagged)

atmospheric antineutrinos (irreducible)

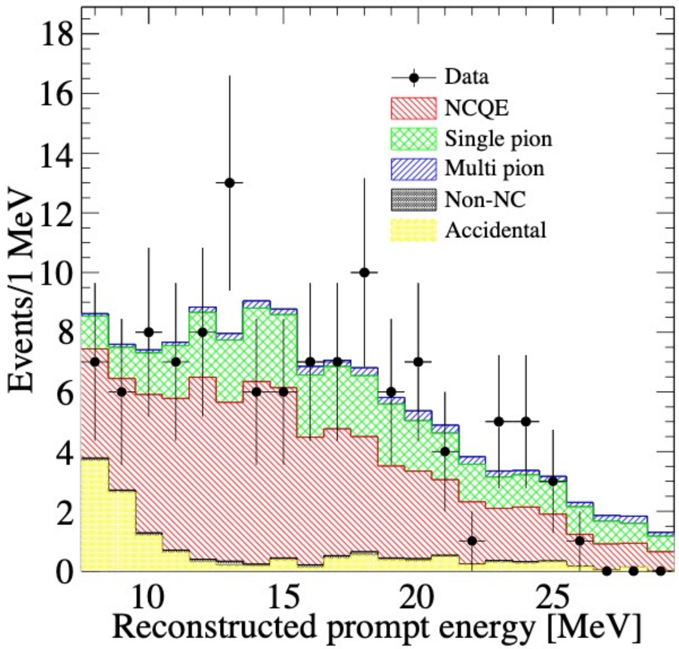
Atmospheric neutrino NC background

caused by NC reactions of GeV atmospheric neutrinos on carbon/oxygen

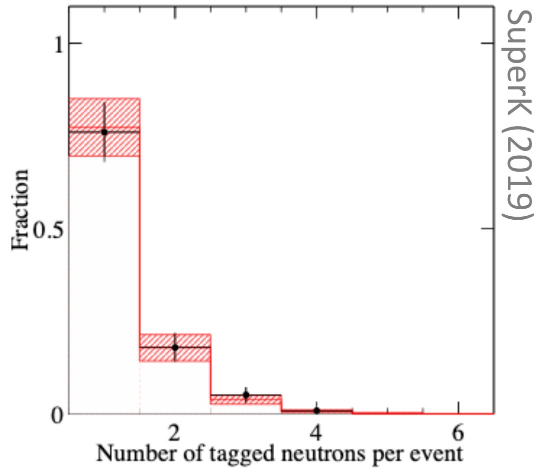


Atmospheric NC background in SK-Gd

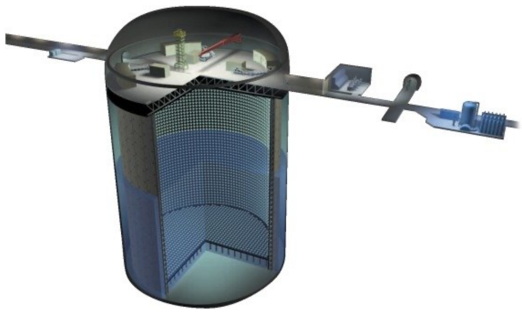
prompt NC event spectrum



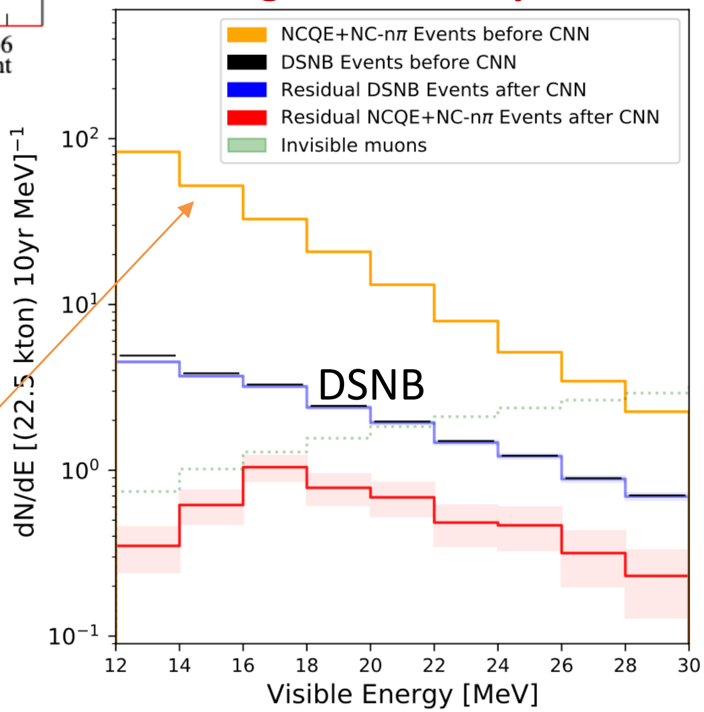
number of delayed neutron captures



Maksimovic, Nieslony, Wurm (2021)



DSNB signal & BG expectation



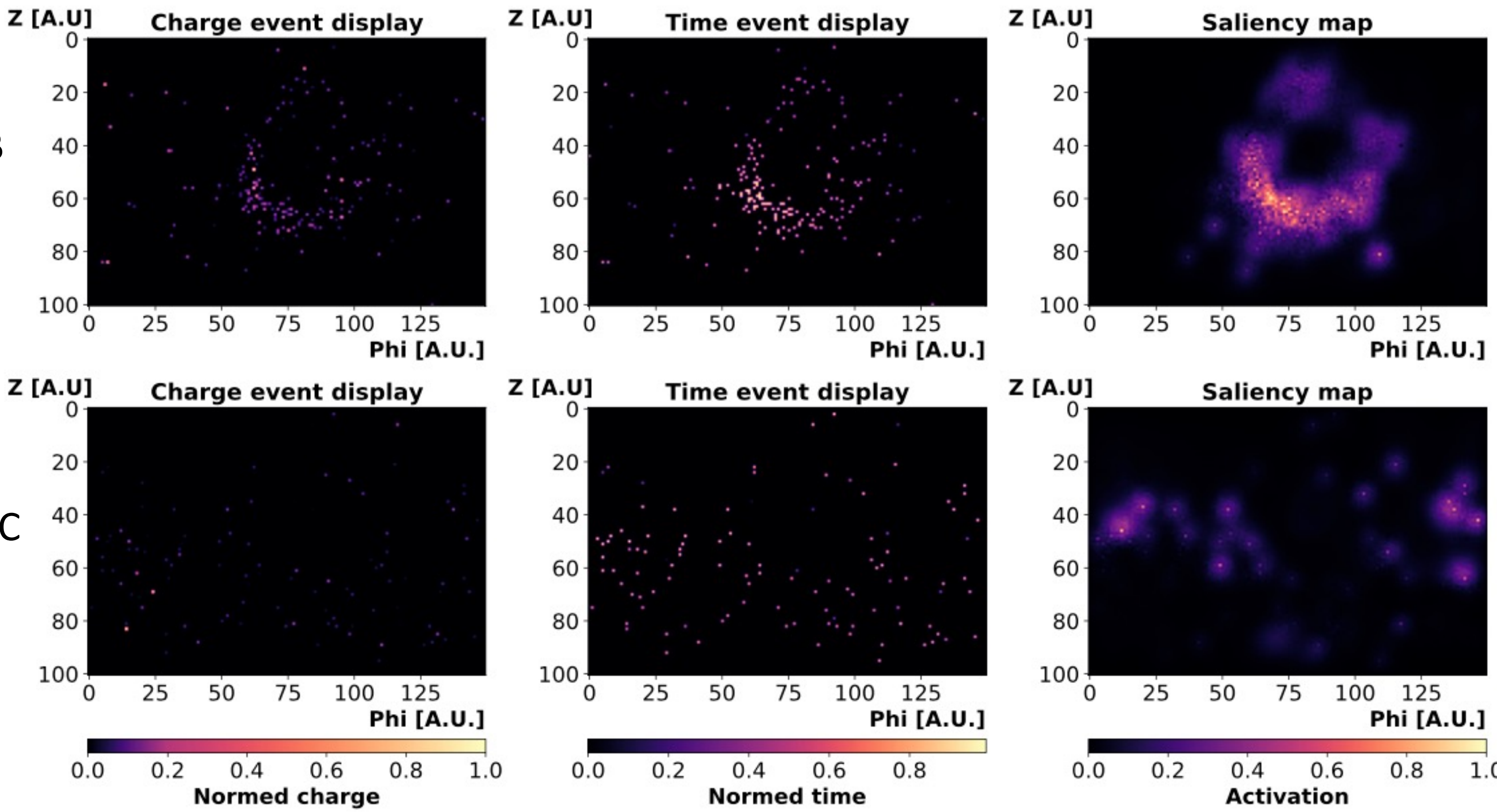
- atmospheric NC background rate and spectrum measured by SK IV
- also neutron multiplicity has been measured, but with low efficiency (~10%)
- can be scaled as background for DSNB search using Gd-neutron tag → **relevant!**

Discrimination based on light patterns

distinguishing charge and timing patterns with Convolutional Neural Network (CNN)

DSNB (e^+)

atm.NC (γ's)

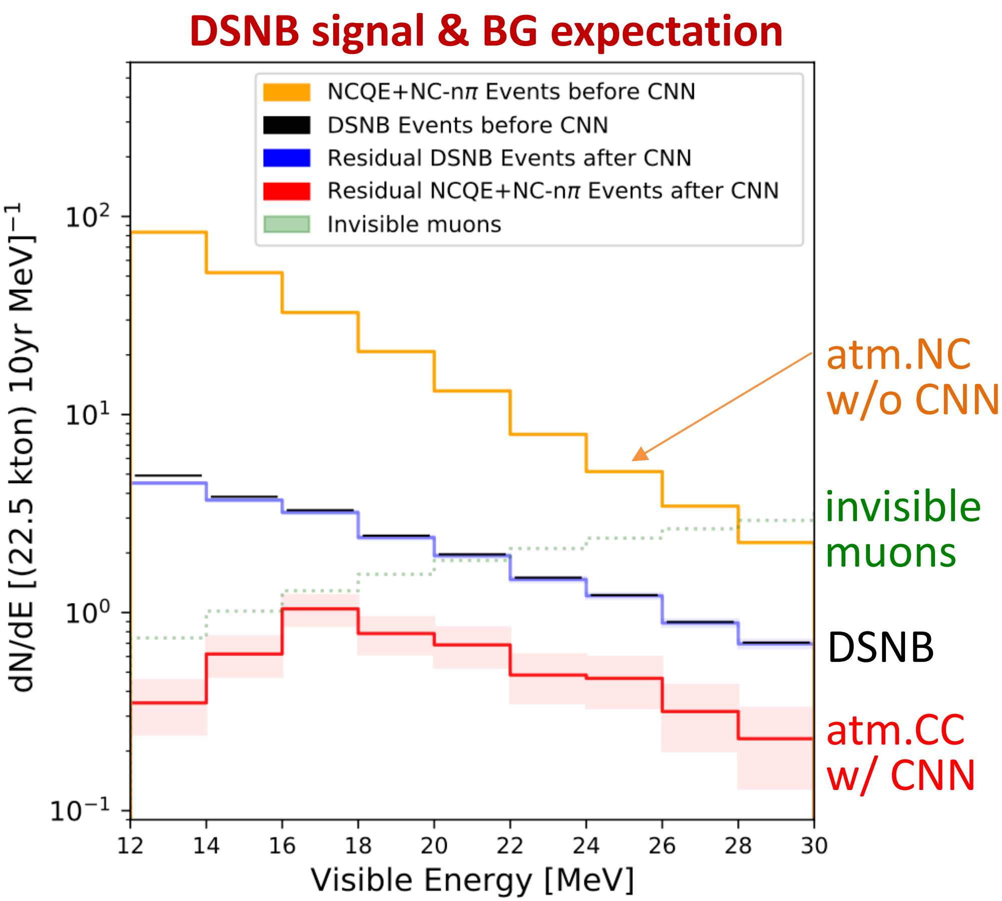


Maksimovic, Nieslony, Wurm (2021)

→ single rings for DSNB, more complex structures for atmospheric NC events

SK-Gd expectation after CNN

Maksimovic, Nieslony, Wurm (2021)



- CNN performance:
  - signal efficiency: 96%
  - residual background: 2%
- resulting S:B ratio of 4:1 in the energy range of interest (12-30) MeV
- residual background by invisible muons (Michel electrons from low-E atm. ν_μ's)

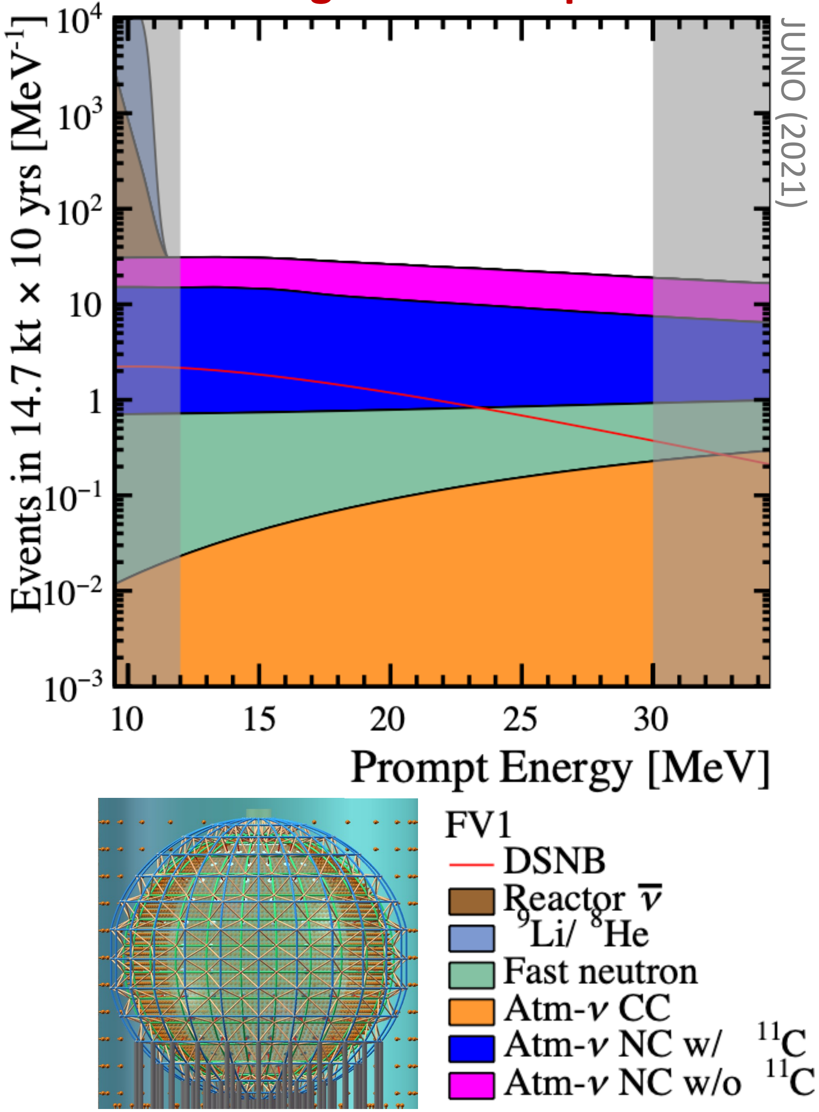
expected event rate for SK-Gd:

- **signal:** **2.0 IBD/yr** *(large model uncertainty)*
- **background:** **0.9 /yr**

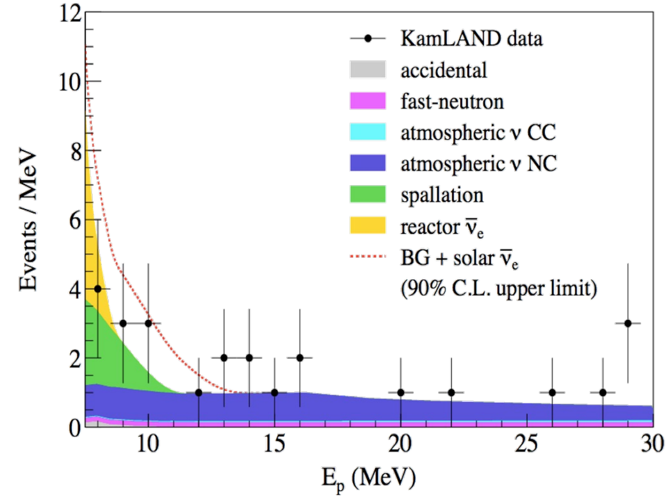
DSNB search in JUNO

JG|U

DSNB signal & BG expectation



BG measured in KamLAND

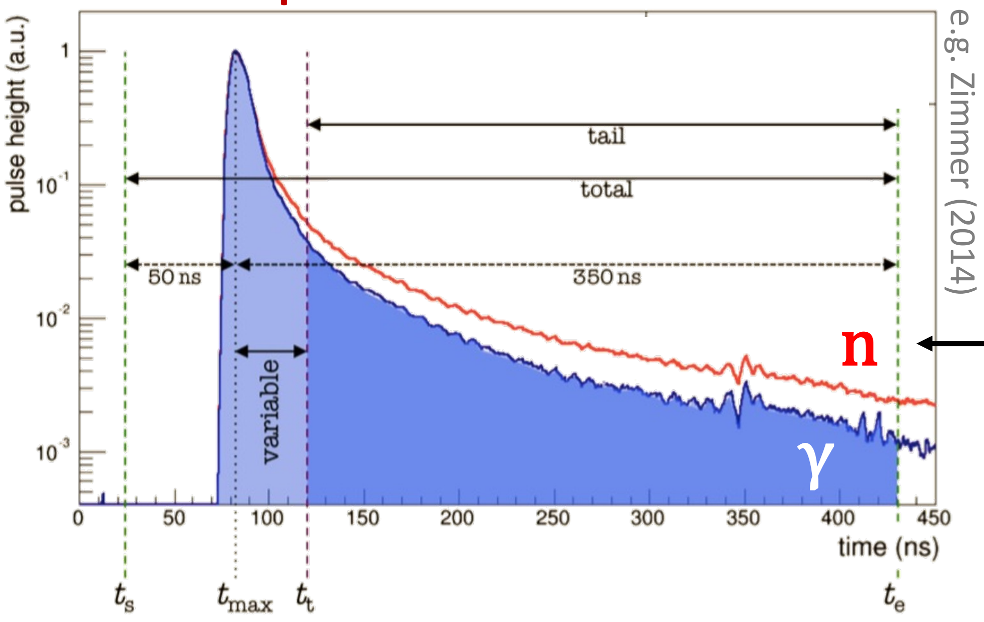


- BG levels in KamLAND almost directly translate to situation in JUNO
- atm. NC BG has been re-evaluated based on available neutrino generators (GENIE, NuWro)

→ BGs surpass DSNB signal by at least an order of magnitude ...

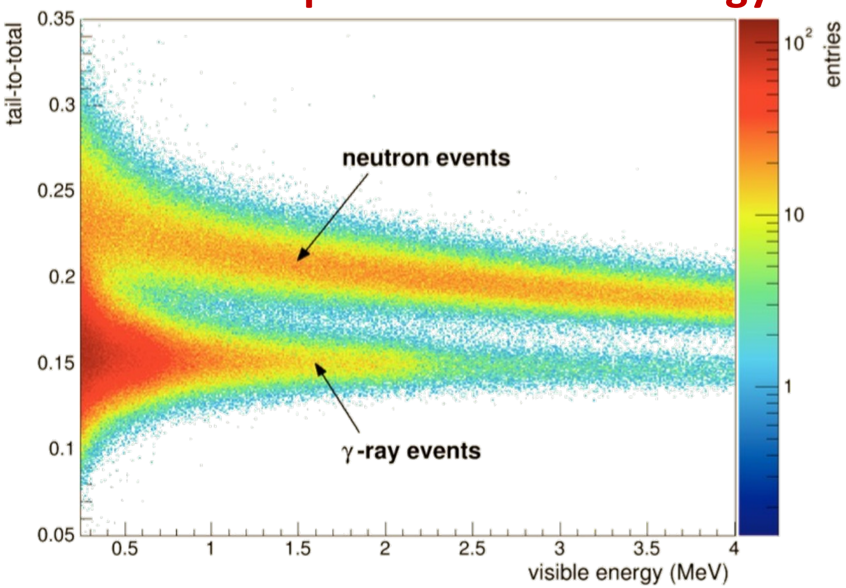
Pulse Shape Discrimination (PSD) in LS

Pulse Shapes of Gammas and Neutrons



- in liquid scintillators, pulse shapes (and light yield) of highly ionizing particles (n,p,α's) differs from light particles (e,γ's)
- can be exploited for discrimination, e.g. by **tail-to-total ratio** of time-of-flight corrected pulses

PSD performance vs. energy



- example shown here for 11 MeV neutrons vs. 4 MeV gammas
- efficiency rises with energy/number of photons detected
- JUNO is a high light yield experiment! → expect ~1300 pe/MeV

DSNB expectation in JUNO after PSD

2015: based on tail-to-total pulse shape discrimination and old LENA studies, expected performance for JUNO was

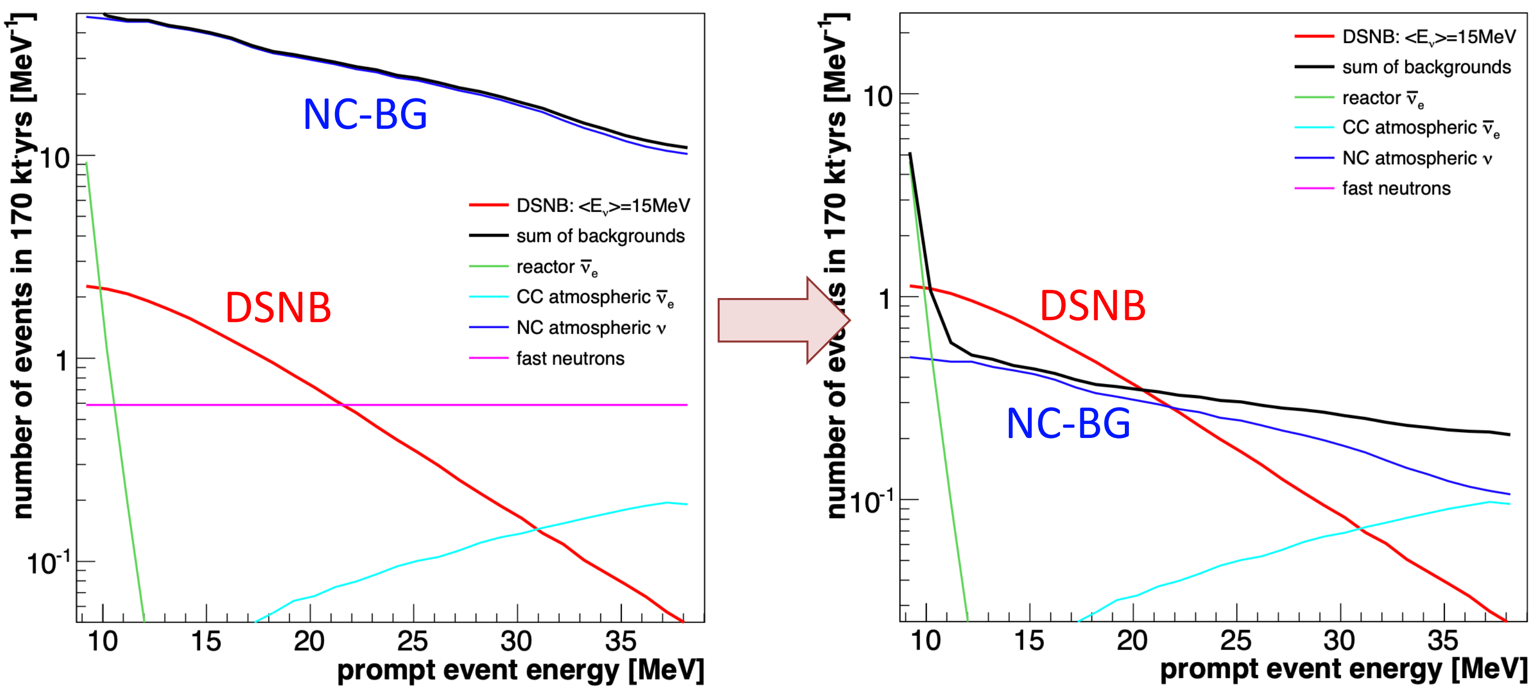
- DSNB signal efficiency: 50%
- NC background residual: 1.1%

expected event rate for JUNO:

- **signal: 2.0 IBD/yr**
  (large model uncertainty)
- **background: 0.8 /yr**

i.e. roughly comparable to SK-Gd expectation

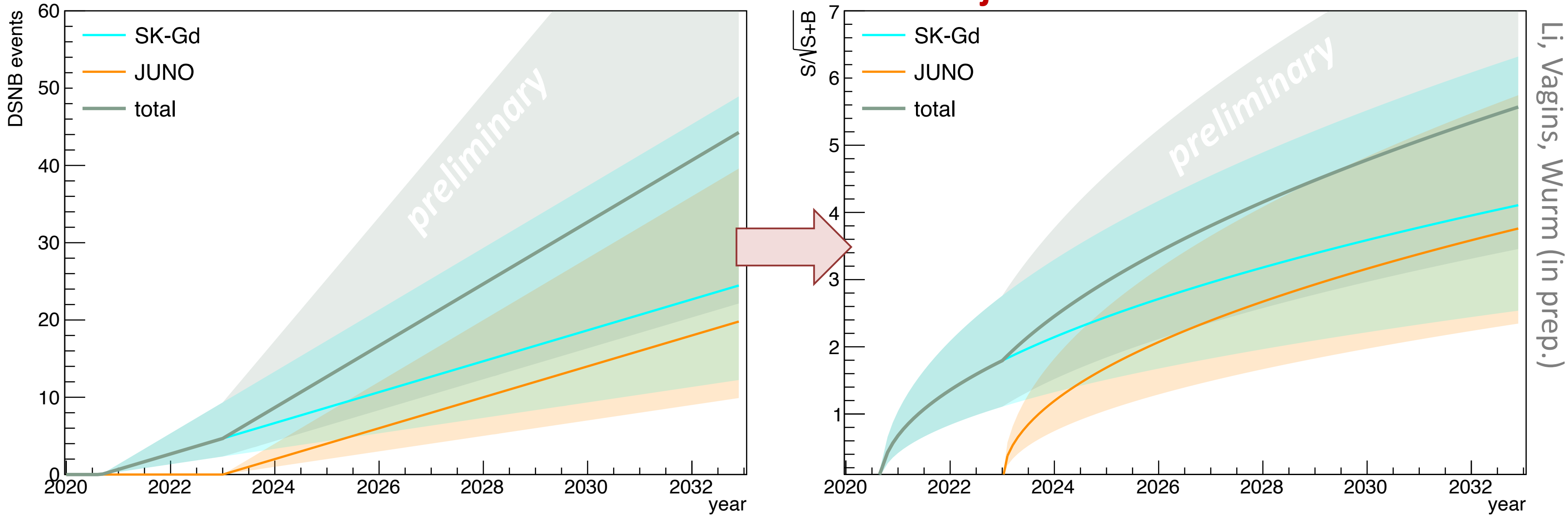
DSNB signal and background before/after PSD



First observation of DSNB within 10 years?

SK-Gd started data taking in 2020, JUNO will follow soon → projected DSNB sensitivity?

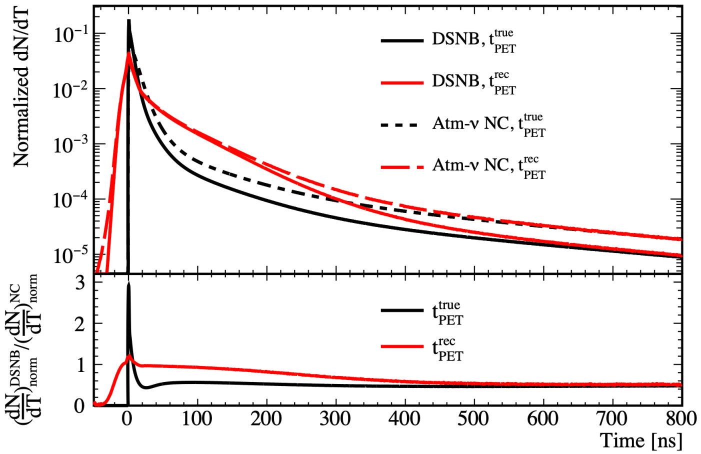
Events accumulated in SK-Gd/JUNO | **Projected statistical sensitivities**



- after 10 years, sensitivity of individual experiments at 3σ level
- combined sensitivity will reach 5σ level for a positive DSNB detection
- many caveats: DSNB (and BG) rate uncertainty, systematic effects
- but as well synergies: complementary measurements of atm. NC BG in water/scintillator will improve understanding of this background

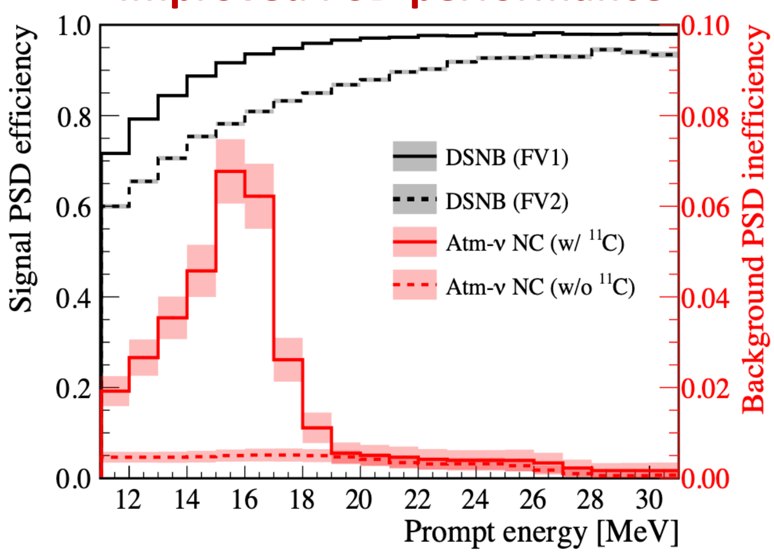
Updated JUNO study with better PSD

Improved knowledge of pulse shapes

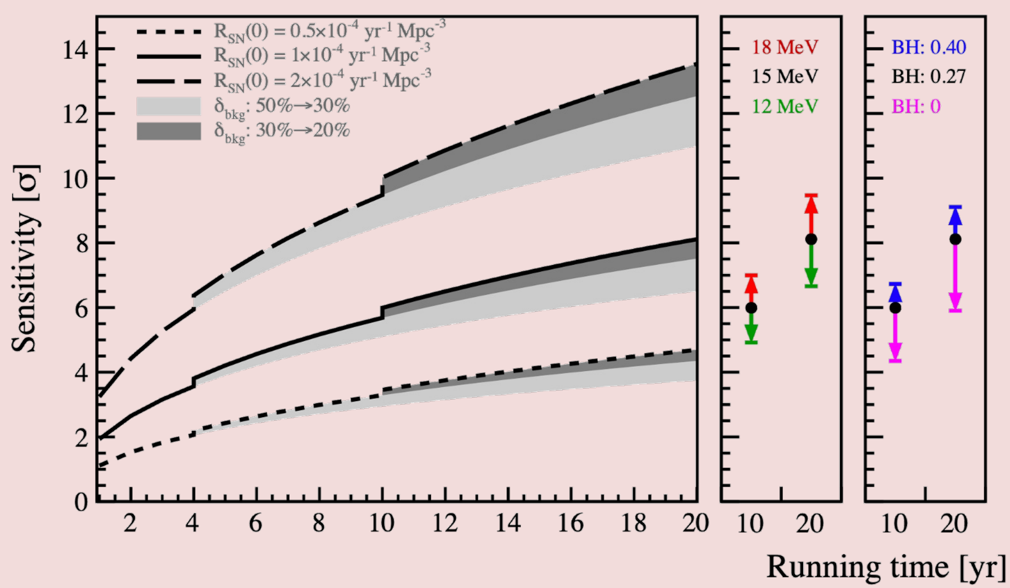


- state-of-the art modeling of NC final states and LS fluorescence parameters
- improved PSD techniques (radius-dep. Tail-to-Total, machine learning TMVA) promises excellent BG suppression
- atm.NC reactions with ^{11}C in final state are harder to discriminate by PSD but can be tagged based on delayed β^+-decay

Improved PSD performance



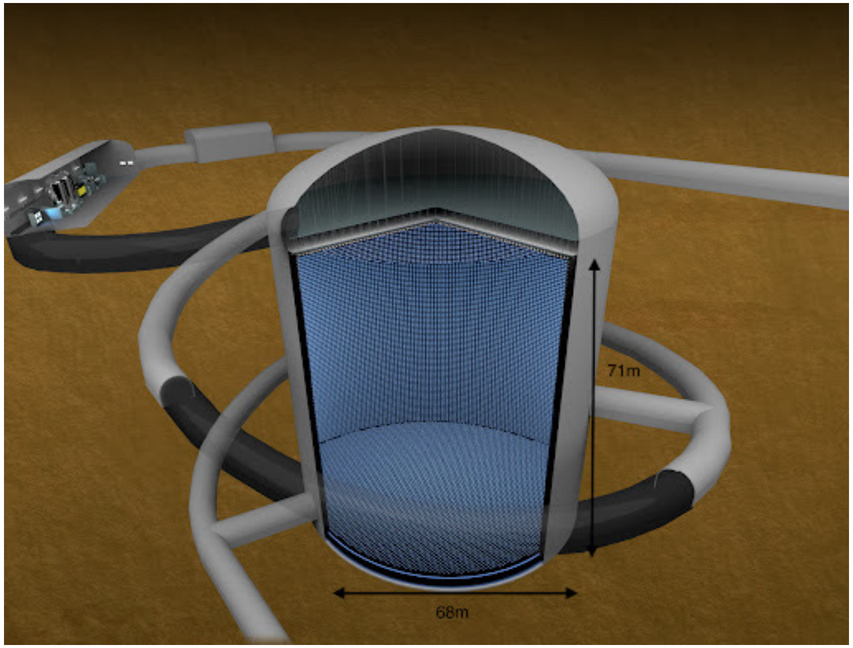
→ substantially improved sensitivity!



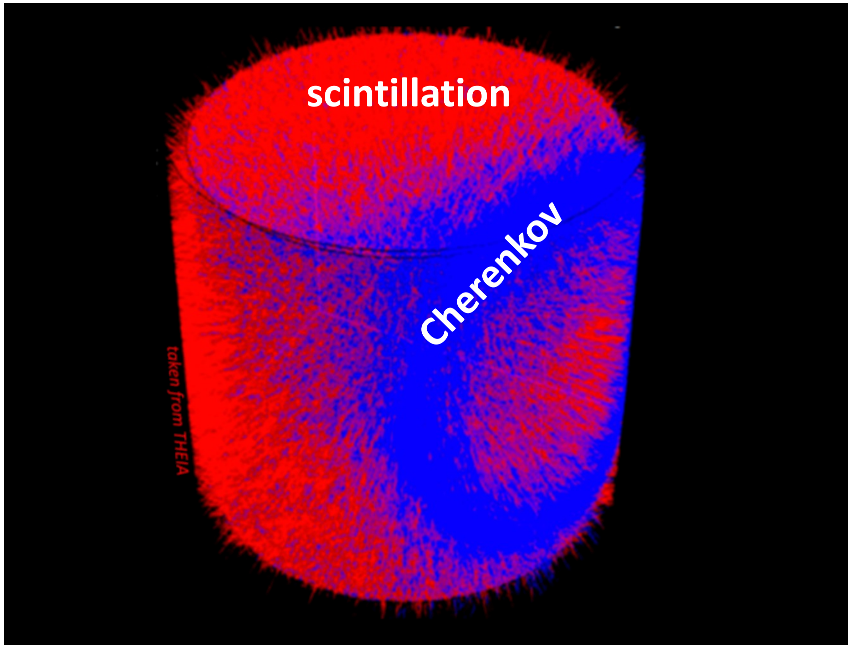
JUNO (2022)

3 Future detection strategies

Next generation of experiments can discover the DSNB signal
→ **how do we get to spectroscopic measurements?**



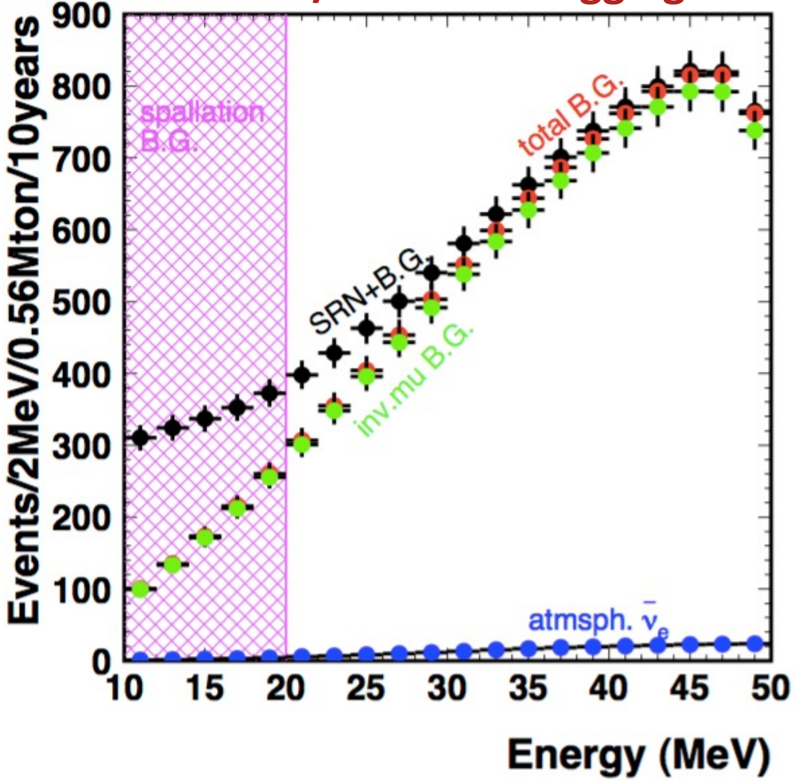
→ huge water-Cherenkov detectors, i.e. **Hyper-Kamiokande**



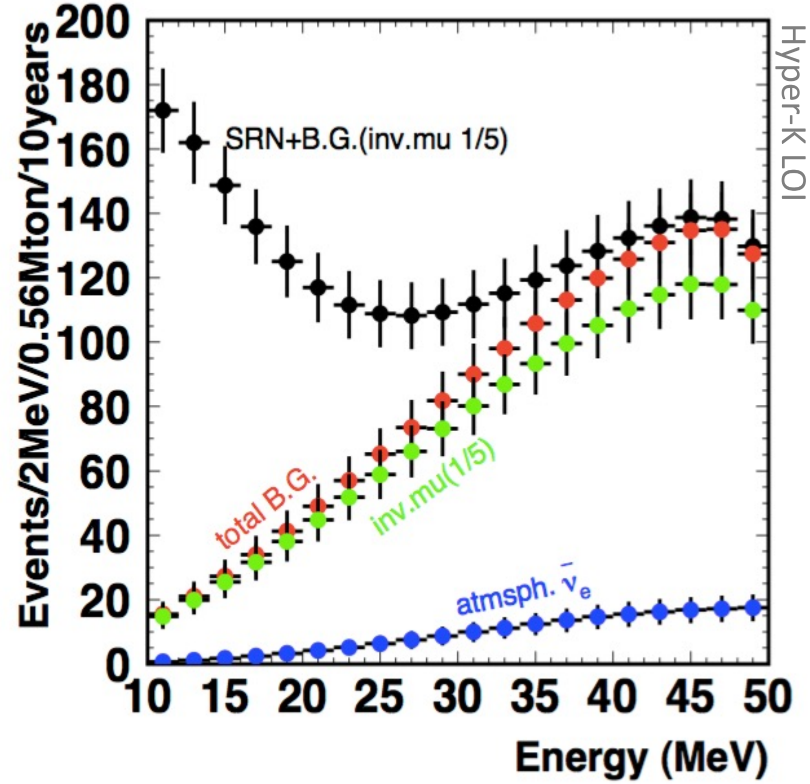
→ advanced scintillator detectors with hybrid signal readout, i.e. **Theia**

Prospects for Hyper-Kamiokande

HK w/o neutron tagging



HK+Gd

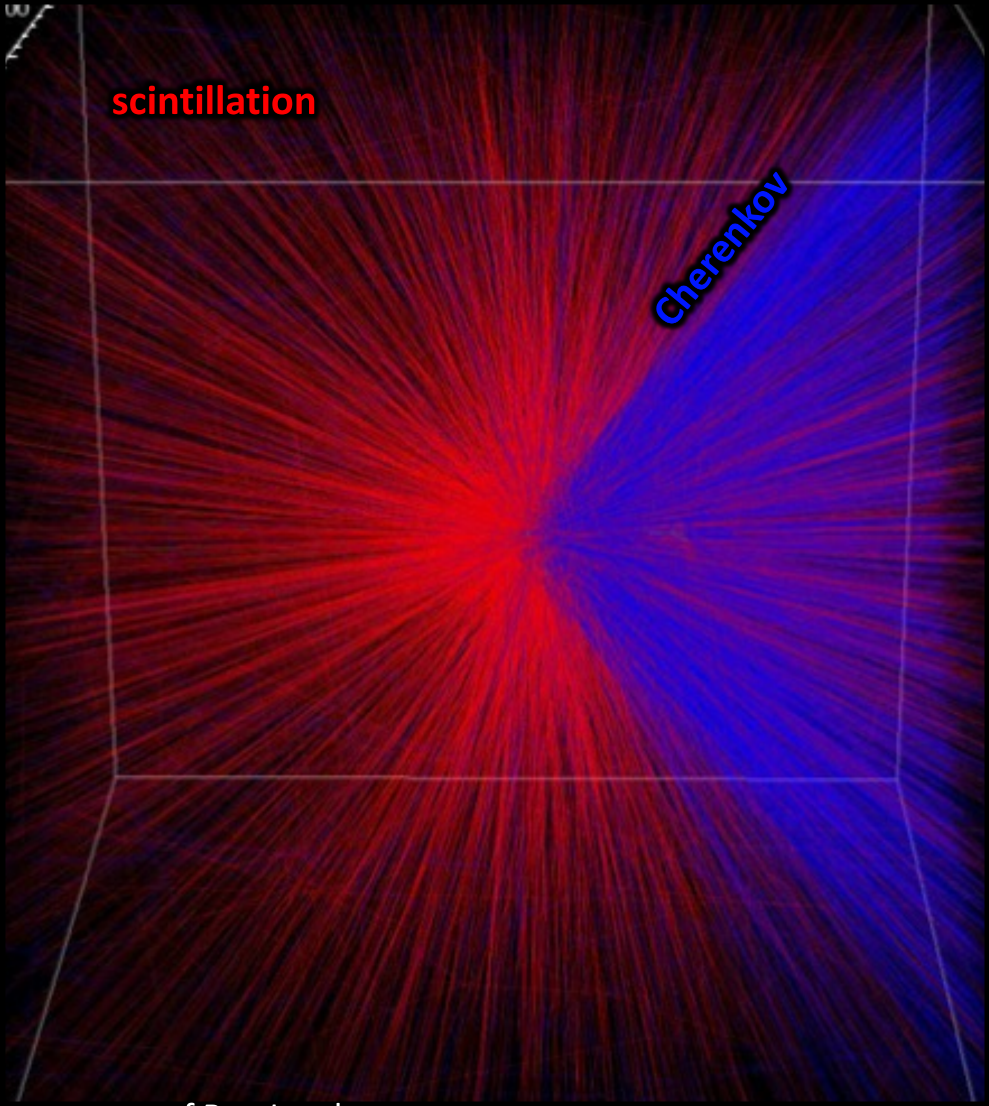


- 10x larger volume: statistics will drastically increase!

→ detection becomes possible without addition of gadolinium

- **but:** full potential is reached only if gadolinium is added (this is no longer the standard scenario)

Hybrid Cherenkov-scintillation detectors



courtesy of Ben Land

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

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

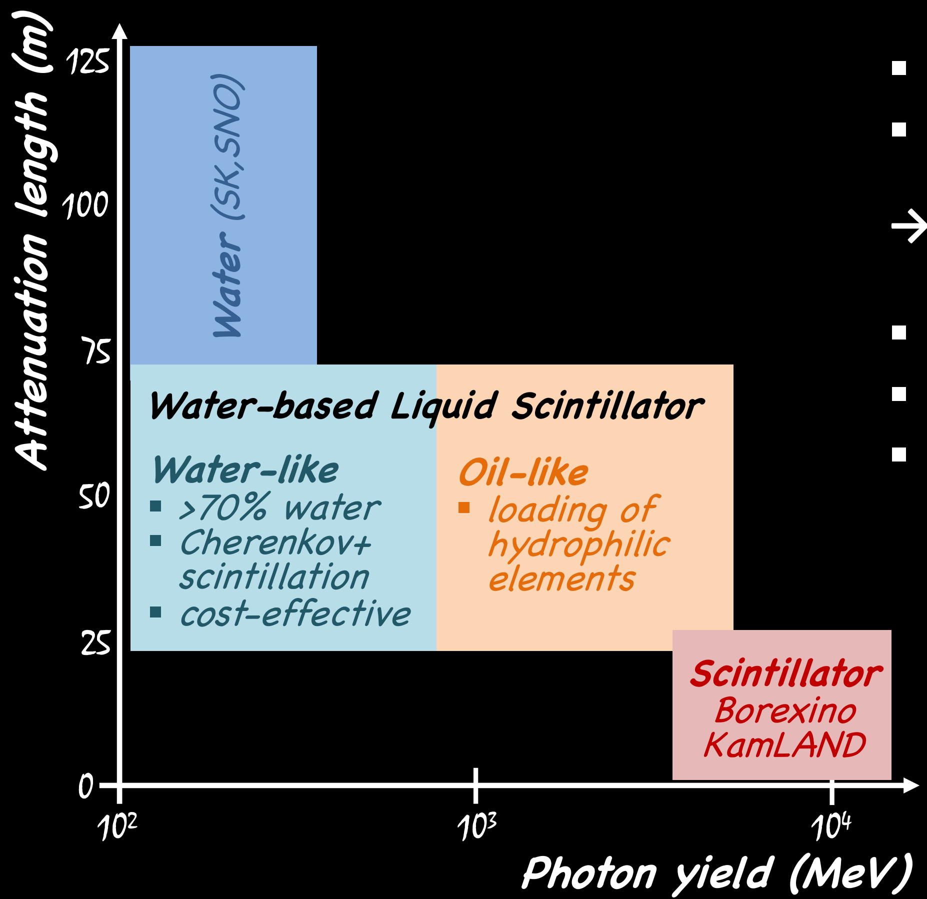
→ the majority is scattered or absorbed before reaching PMTs

To make use of it:

→ reduce scattering/absorption

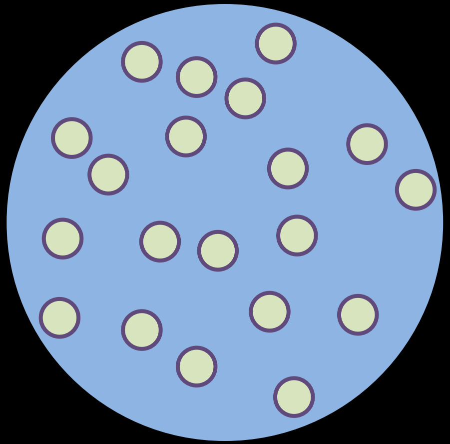
→ separation of Cherenkov and scintillation photons

Water-based Liquid Scintillators (WbLS)



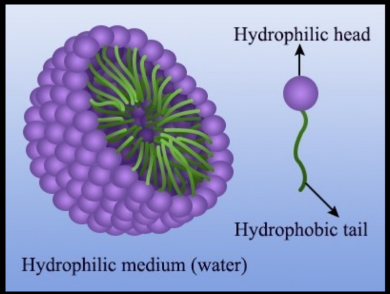
WbLS composition

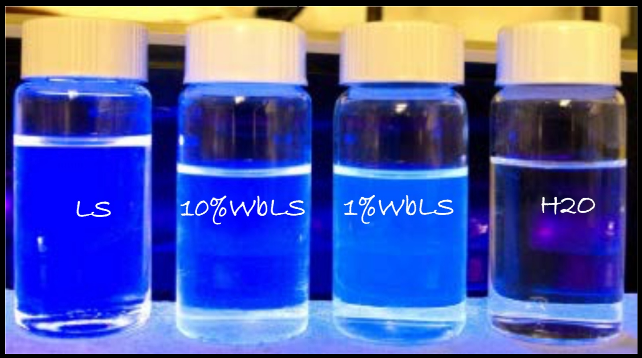
- organic LS mycels (solvent+fluor)
- surfactant
- water



→ **properties depend on relative fractions:**

- Reduced light yield
- Increased transparency
- Comparable timing

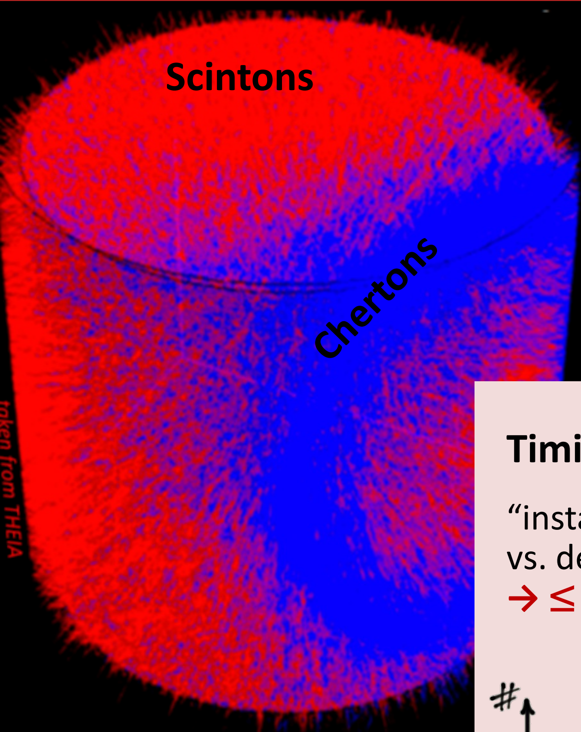




Minfang Yeh, BNL

Separating Chertons and Scintons

JG|U

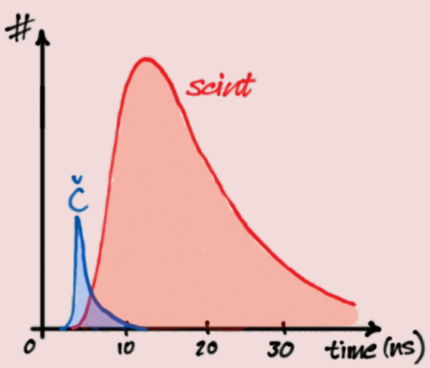


→ how to resolve the Cherenkov/scintillation signals?

Timing

"instantaneous chertons" vs. delayed "scintons"

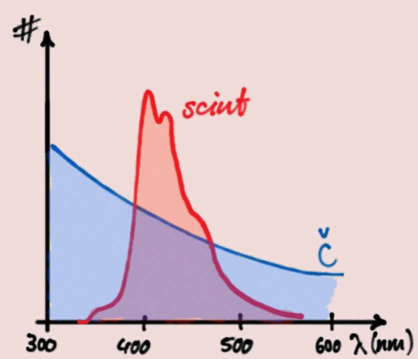
→ ≤ 1 nanosec resolution



Spectrum

UV/blue scintillation vs. blue/green Cherenkov

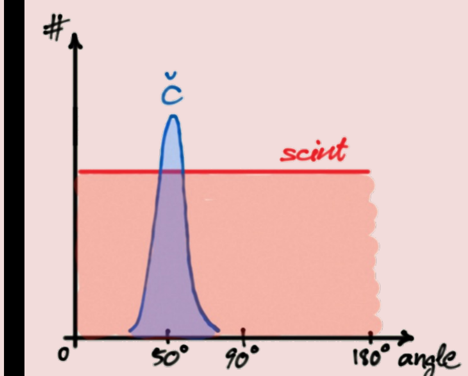
→ wavelength-sensitivity



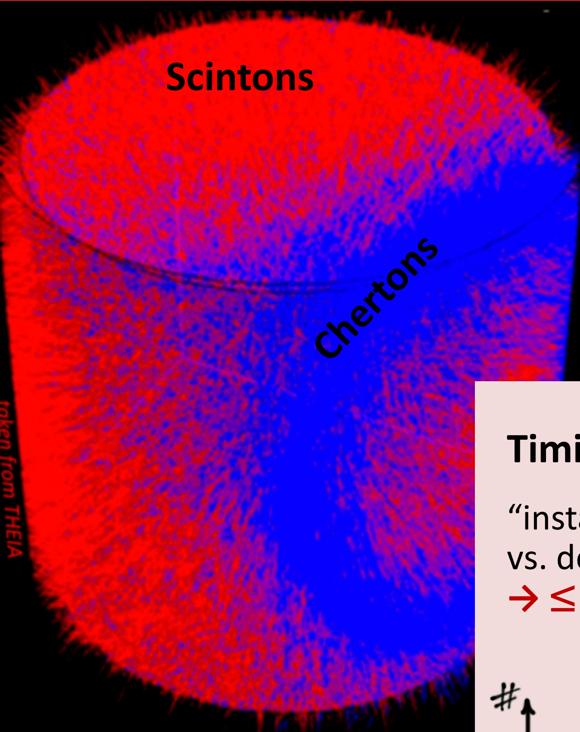
Angular distribution

increased PMT hit density under Cherenkov angle

→ sufficient granularity



Separating Chertons and Scintons



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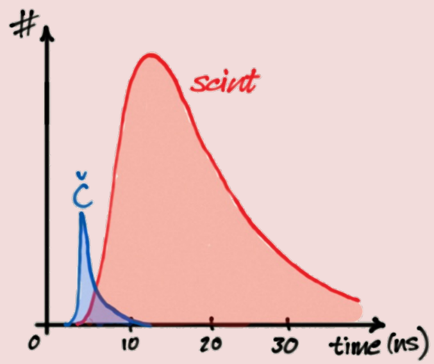

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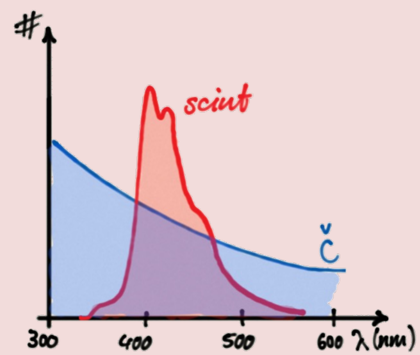

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increased PMT hit density under Cherenkov angle

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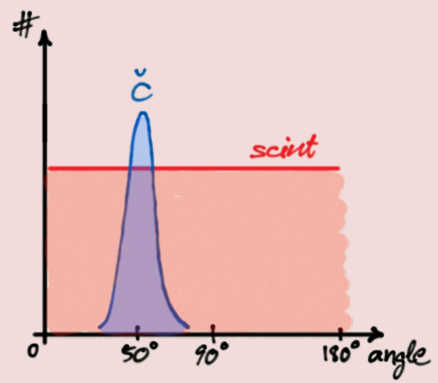


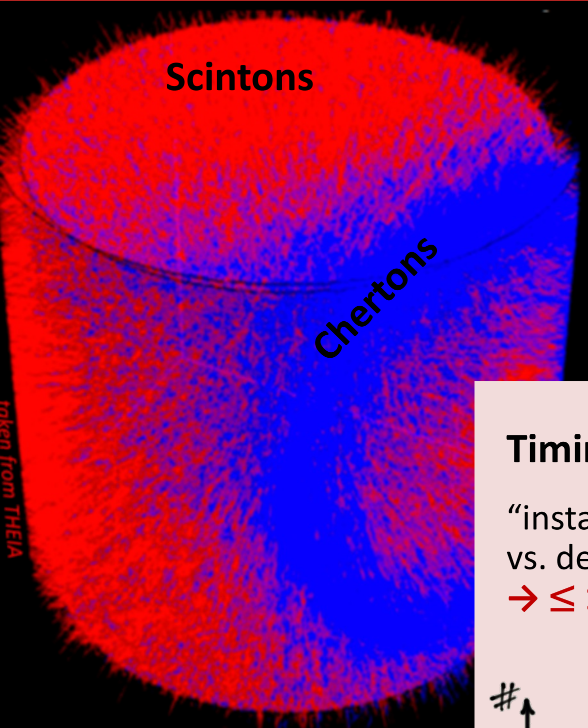
e.g.

LAPPDs: ~60ps timing

Dichroic filters

Standard PMTs

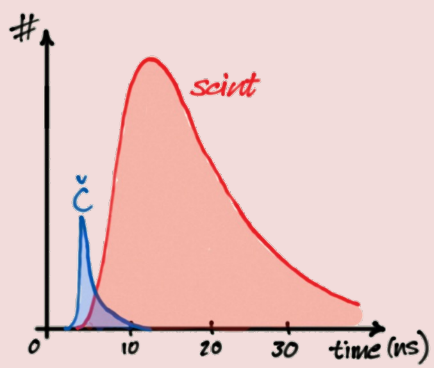
Separating Chertons and Scintons



→ how to resolve the Cherenkov/scintillation signals?

Timing

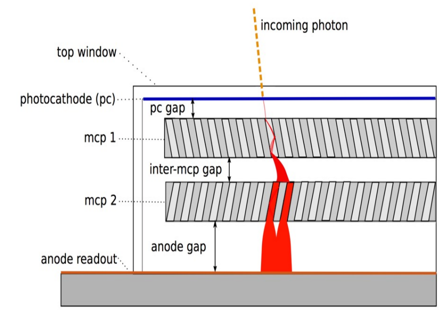
"instantaneous chertons" vs. delayed "scintons"
→ ≤ 1 nanosec resolution

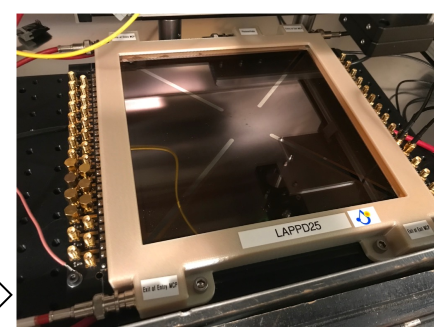


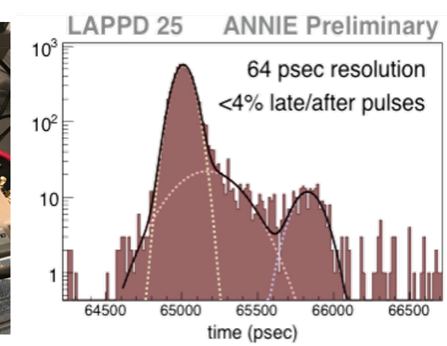
LAPPDs: ~60ps timing

Large Area Picosecond Photon Detectors

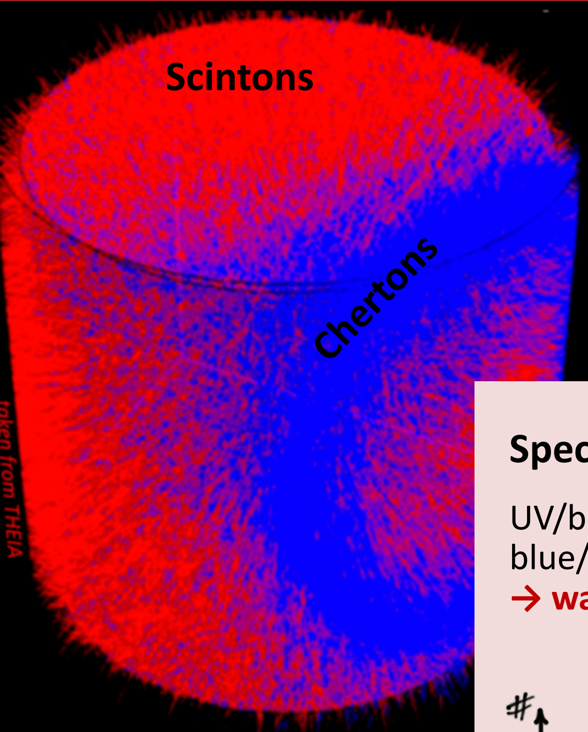
- Area: 20-by-20 cm^2
- Amplification of p.e. by two MCP layers
- Flat geometry: ultrafast timing ~65ps
- Strip readout: spatial resolution ~1cm
- Commercial production by Incom, Ltd.





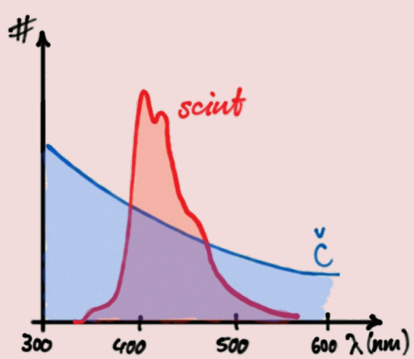


Separating Chertons and Scintons

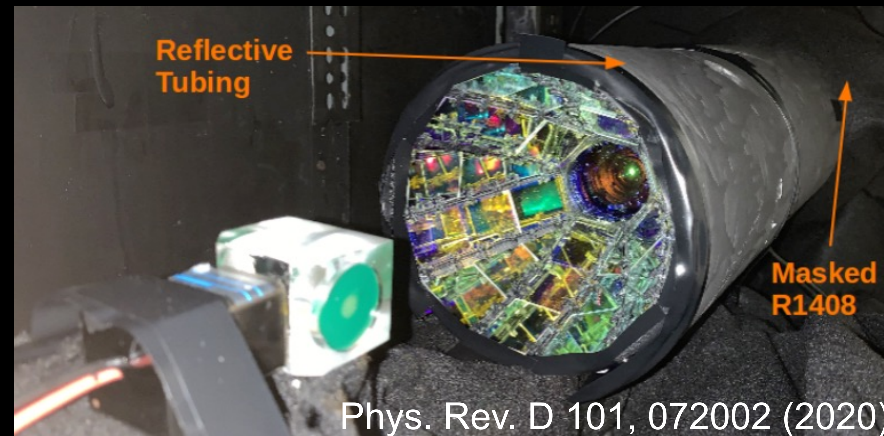


Spectrum

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

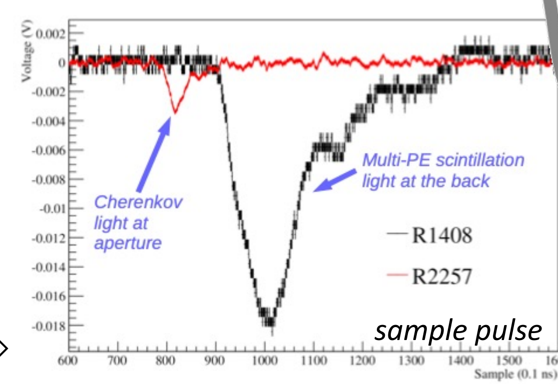


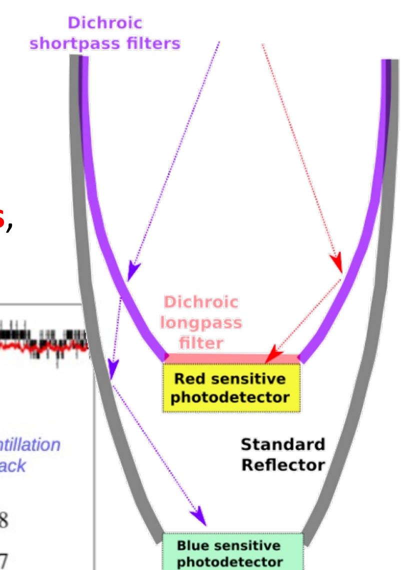
Dichroic filters



Dichroicons (Josh Klein's group @ U Penn)

- two PMTs in sequence separated by a Winston cone assembled from shortpass filters (<460nm)
- front PMT collects **Chertons**, back PMT **scintons**

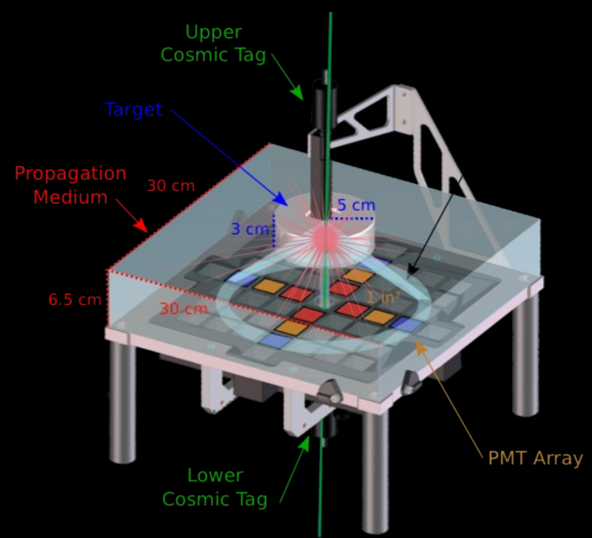




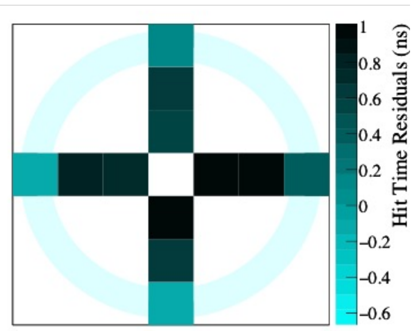
Chertons and Scintons with CHESS

[arXiv:2006.00173]

Setup at UC Berkeley (Gabriel Orebi Gann)



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

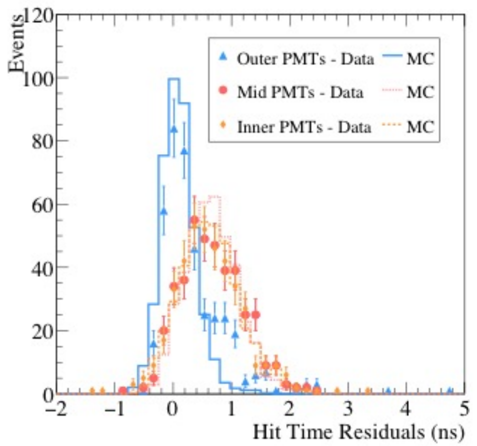


Hit pattern expected on the PMT array for a muon crossing the scintillator target

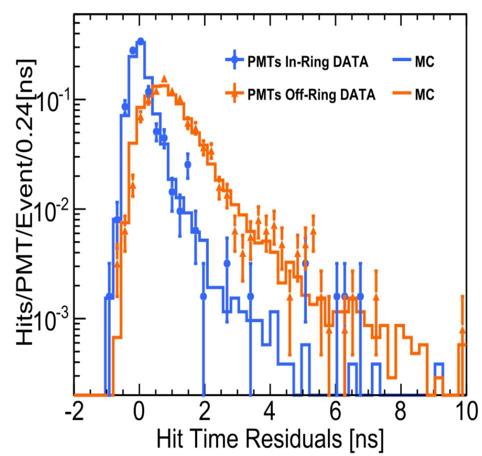
→ angular and fast timing information

Results for timing distributions in different rings:

LAB + 2g/l PPO



WbLS (5% organic)

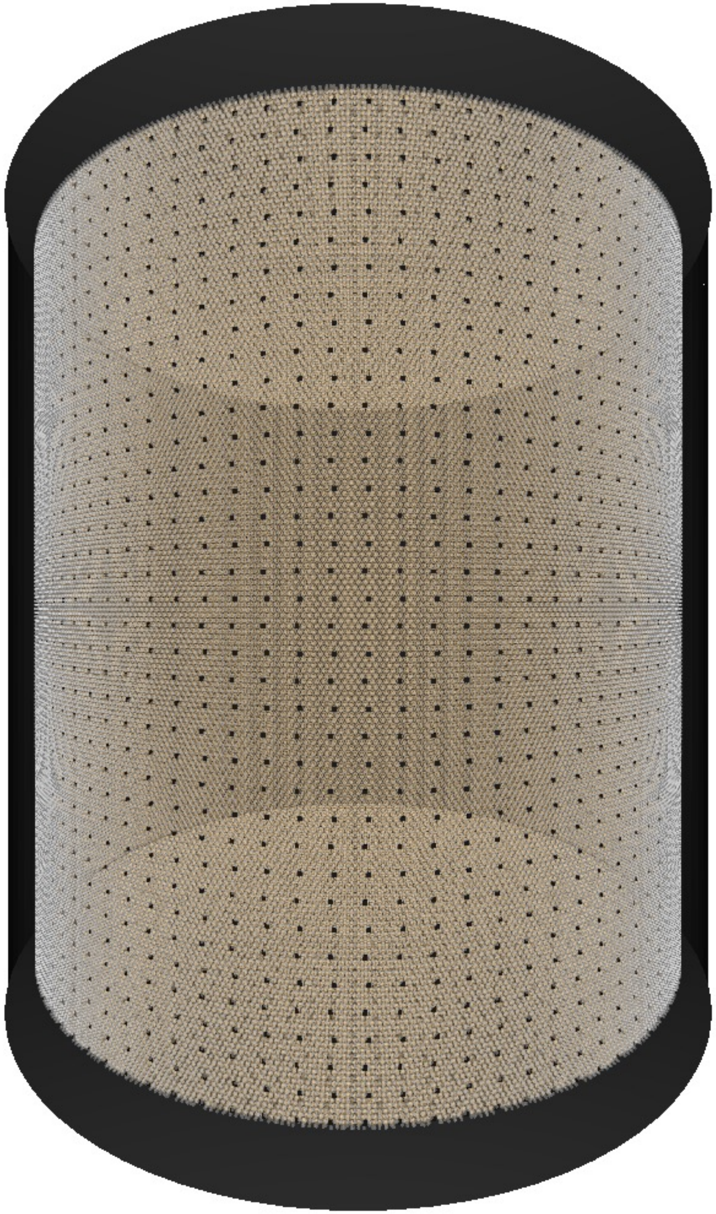


→ **ring and timing pattern clearly visible!**

→ WbLS is found to be faster than pure LAB LS

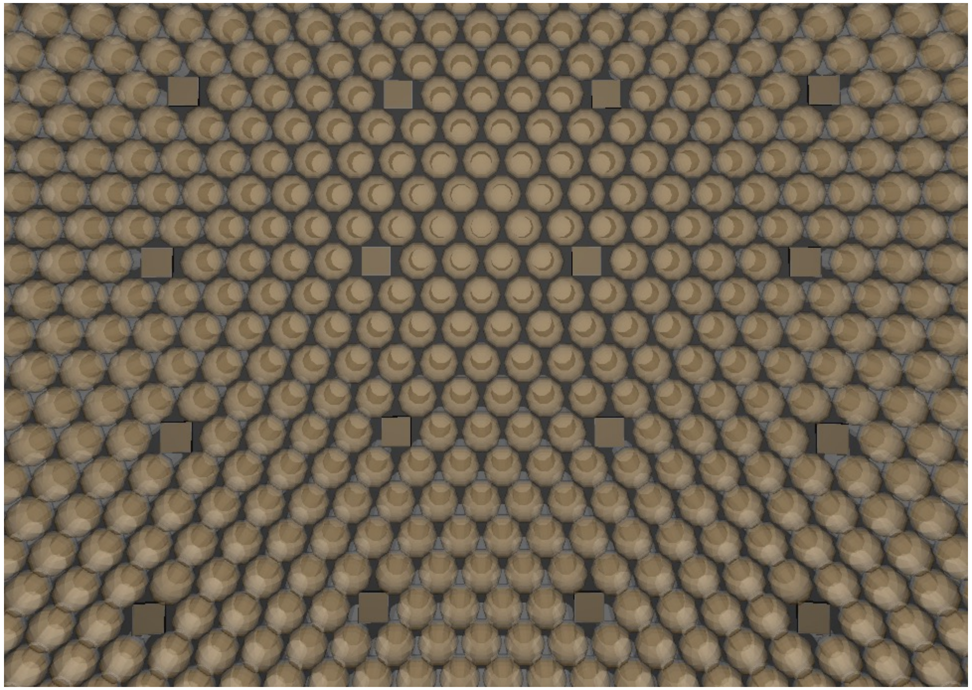
WbLS	1%	5%	10%
τ_1 [ns]	2.25 ± 0.15	2.35 ± 0.11	2.70 ± 0.16
τ_2 [ns]	15.1 ± 7.5	23.2 ± 3.3	27.1 ± 4.2
R_1	0.96 ± 0.01	0.94 ± 0.01	0.94 ± 0.01

A large WbLS detector? → THEIA100



Detector Specifications

- **Detector mass:** ca. 100 kt
- **Dimensions:** 50-by-50 m? (WbLS transparency)
- **Photosensors:** mix of conventional PMTs (light collection) and LAPPDs (timing)
- **Location:** deep lab with neutrino beam (Homestake, Pyhäsalmi, Swedish sites?)



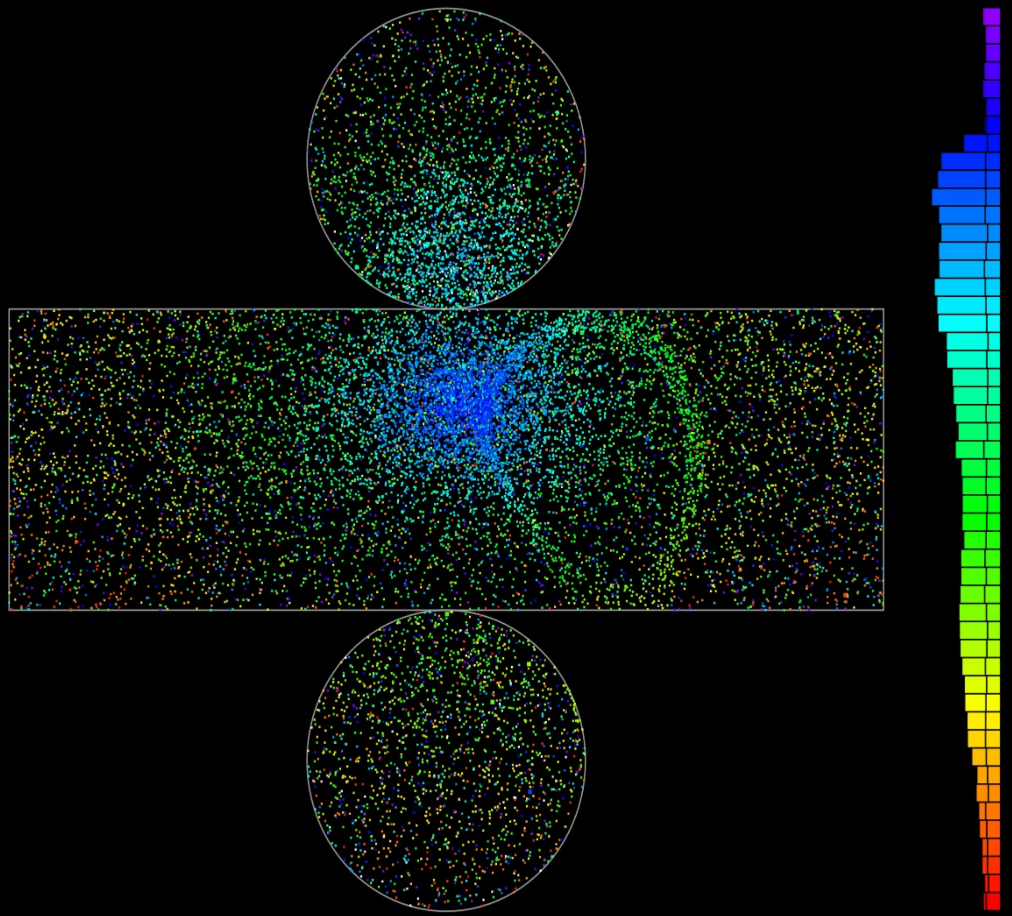
WbLS: Impact on MeV neutrino detection

[arXiv:2007.14999]

Water Cherenkov
- High transparency → enhanced light collection
- Directionality from cone reco
- Particle ID from ring counting
- Enhanced metal loading

Combined: Particle ID based on **Cherenkov/scintillation (C/S) ratio** (p, α below Č threshold)

Organic scintillator mycels
- Low (sub-Cherenkov) threshold
- Increased light yield
- Enhanced vertex reconstruction
- Particle ID by pulse shape
- Enhanced cleanliness



DSNB/background discrimination in WbLS

Atmospheric NC events remain as the most important background.

Several handles for BG discrimination:

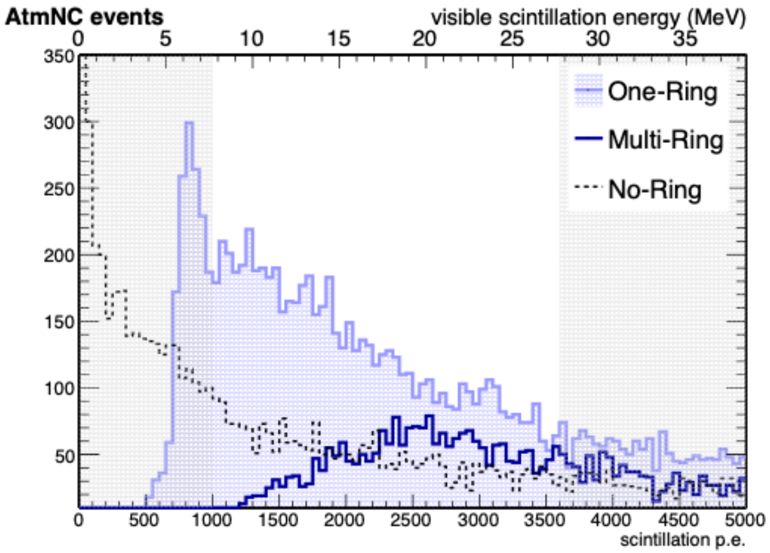
- ring counting
- **Cherenkov/Scintillation (C/S) ratio**
- Tagging of delayed decays

Result of MC study using realistic BG model and basic event reco

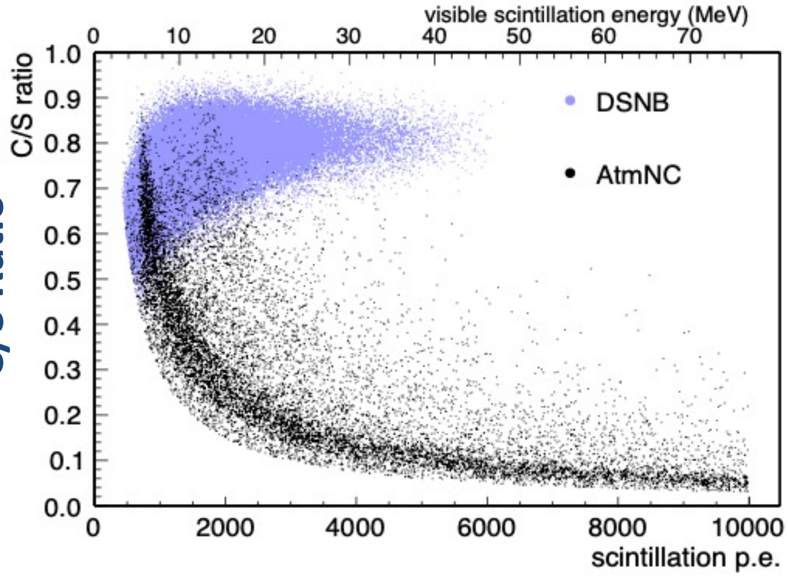
→ signal efficiency: ~ 80%

→ residual background: ~ 1%

Ring-Counting



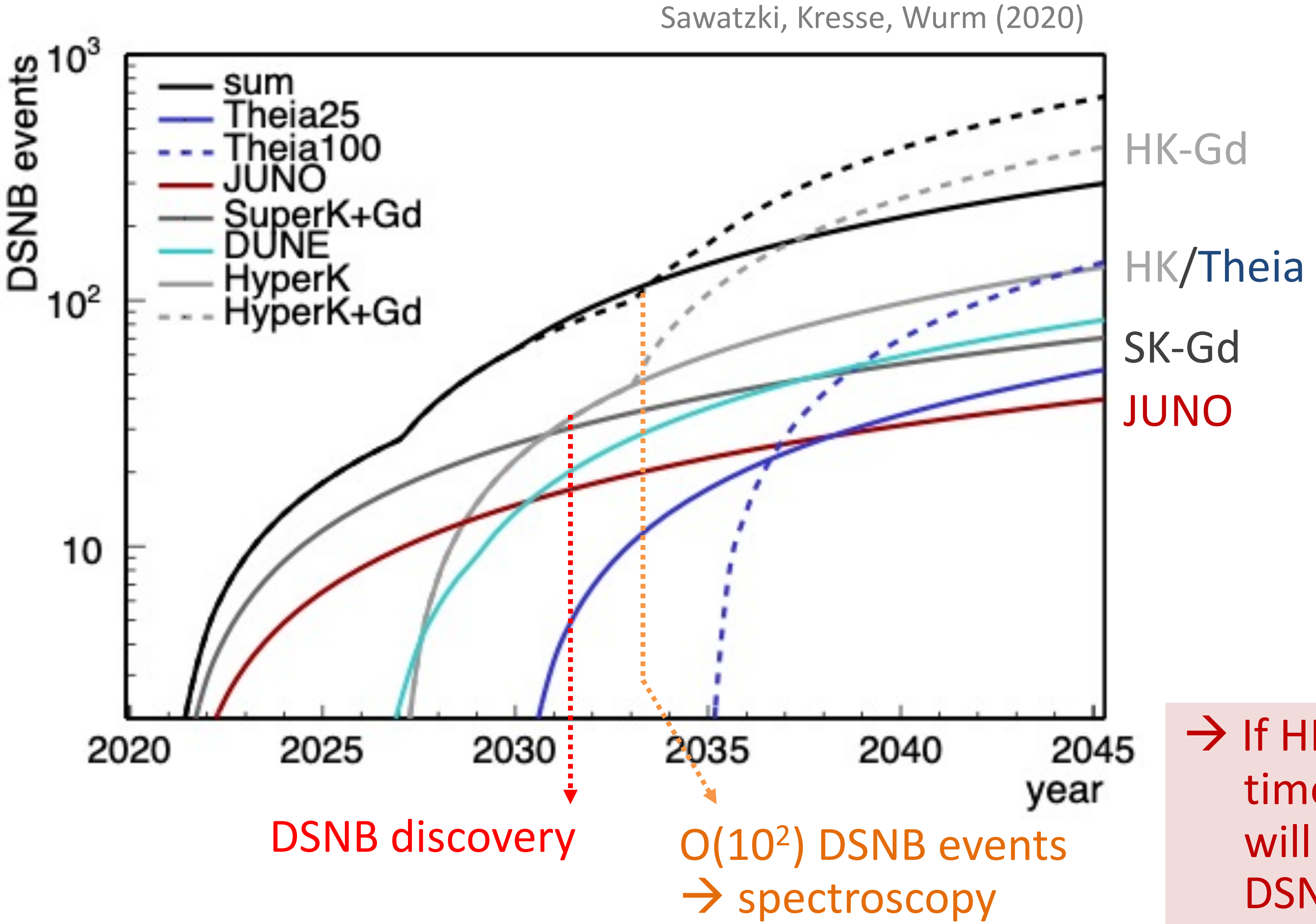
C/S Ratio



Sawatzki, Kresse, Wurm (2020)

Collecting event statistics for spectroscopy

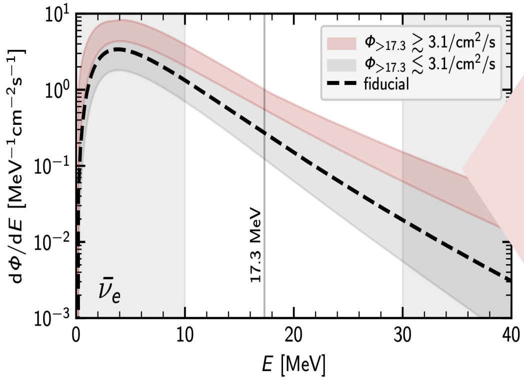
How long do we have to wait to collect 10 → 100 → 1000 events?



→ If HK-Gd arrives on time, spectroscopy will start soon after DSNB discovery.

Conclusions

JG|U



Diffuse Supernova Neutrino Background depends on from

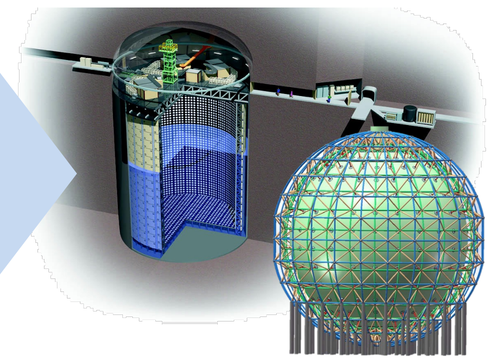
- red-shift dependent star-formation/Supernova rate
- **average spectrum** of Supernova neutrinos (fraction of failed SNe, EoS of neutron stars etc.)

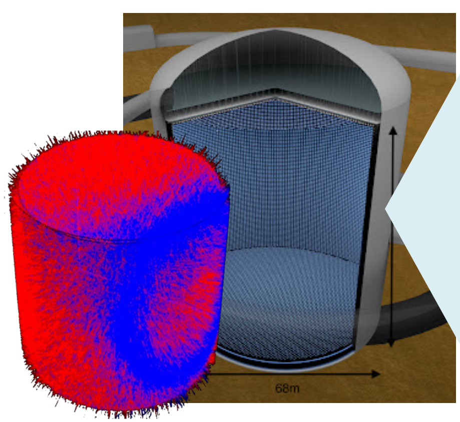
→ complementary information to next galactic Supernova!

Upcoming generation of DSNB experiments

- **SK-Gd and JUNO** can both hope to collect 2 IBDs/yr with relatively low background levels (S:B > 2:1)

→ **DSNB discovery** expected after about 10 years





Future DSNB experiments

- **HK** and especially **HK-Gd** would mean a huge increase in sensitivity and event statistics
- new hybrid detector concepts like Theia will further improve detection/BG suppression capabilities

→ **spectroscopy of DSNB** is within reach

Backup Slides

Table of Event Rates (all techniques)

JG|U

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

JG|U

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

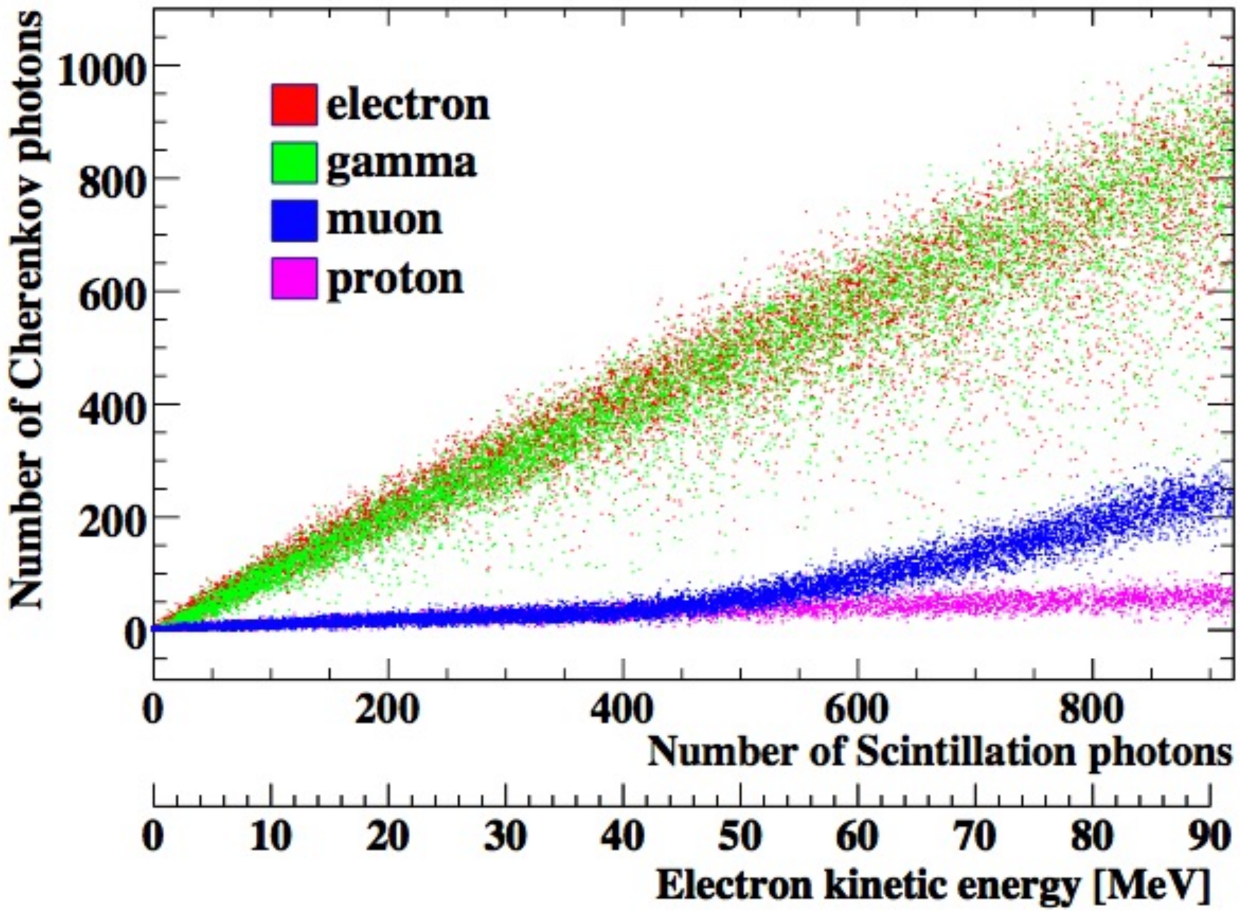
Reaction channel	Branching ratio
(1) $\nu_x + {}^{12}C \rightarrow \nu_x + n + {}^{11}C$	38.8 %
(2) $\nu_x + {}^{12}C \rightarrow \nu_x + p + n + {}^{10}B$	20.4 %
(3) $\nu_x + {}^{12}C \rightarrow \nu_x + 2p + n + {}^{9}Be$	15.9 %
(4) $\nu_x + {}^{12}C \rightarrow \nu_x + p + d + n + {}^{8}Be$	7.1 %
(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

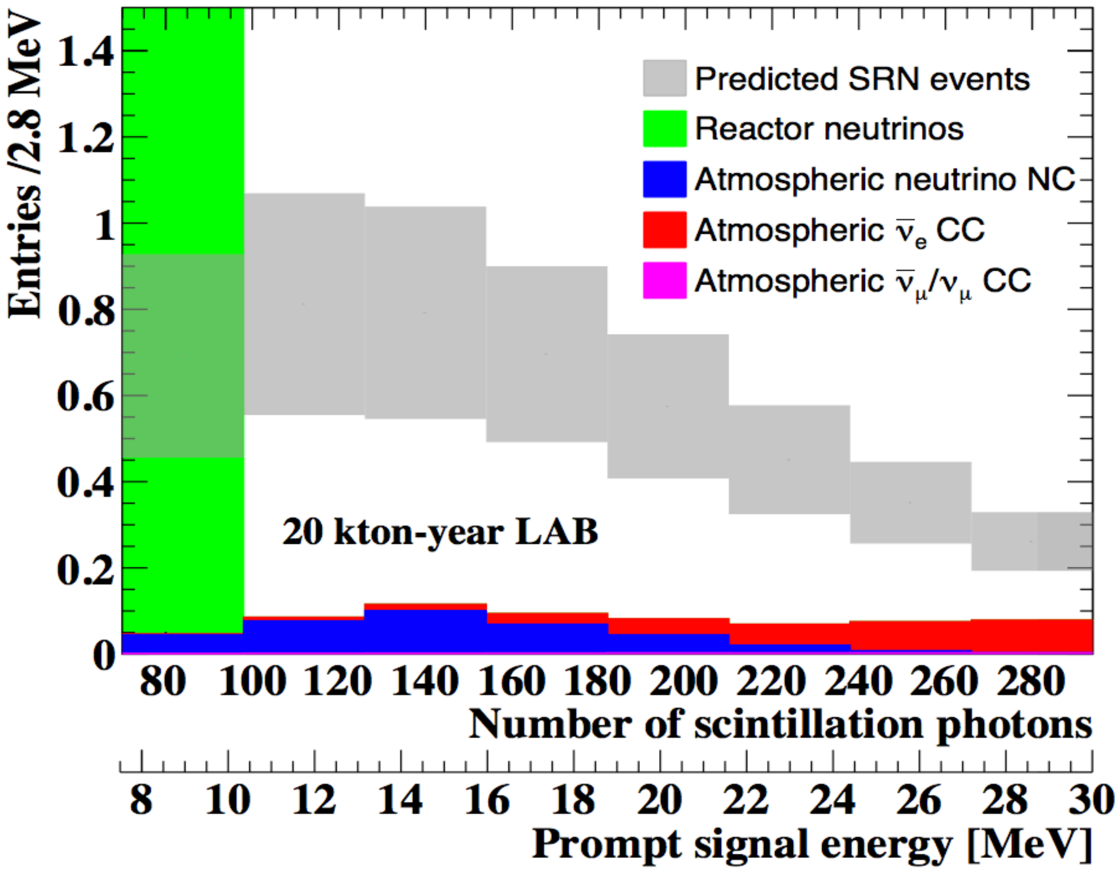
→ discrimination of e^+ and NC-prompt seems effortless above 10 MeV

DSNB event spectrum in sLS

JG|U

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

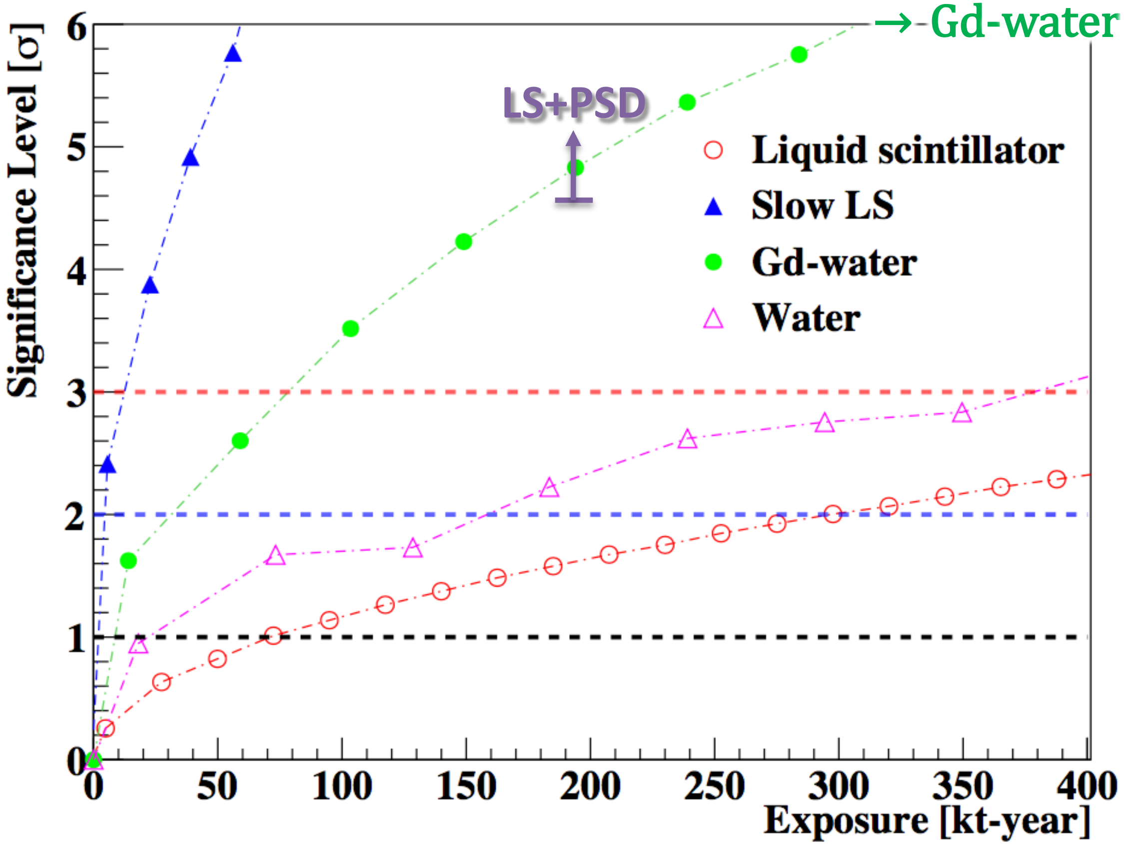
→ comes close to **background-free** observation (excl. terrestrial $\bar{\nu}_e$ sources)

LSCDs vs. other techniques

JG|U

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

Significance of DSNB discovery vs. exposure



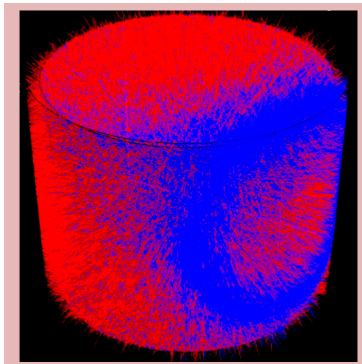
some caveats:

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

→ **LS+PSD:** S/B ~ 2.3

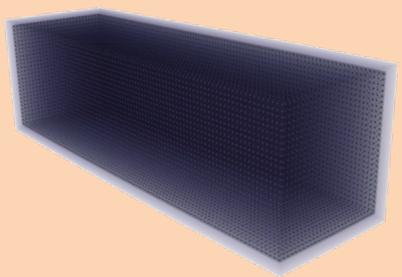
→ **LS:** no PSD!
S/B ~ 0.064

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

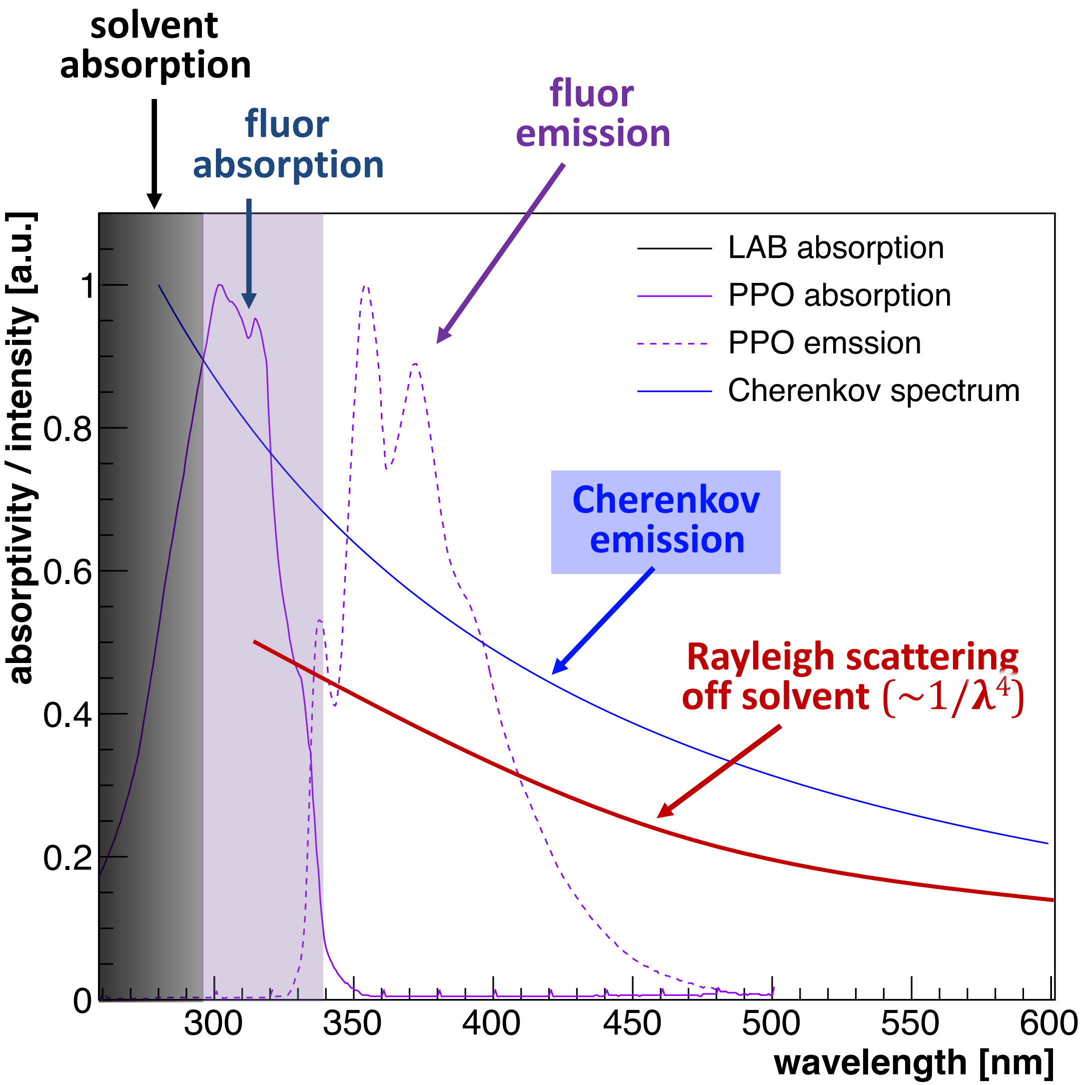
Physics Goals → arXiv:1409.5864

- 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

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 …)

Delayed decay tagging

JG|U

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

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

→ β^+: Q = 2.8 MeV
τ = 2.2min

→ β^-: Q = 13.4 MeV
τ = 20 msec

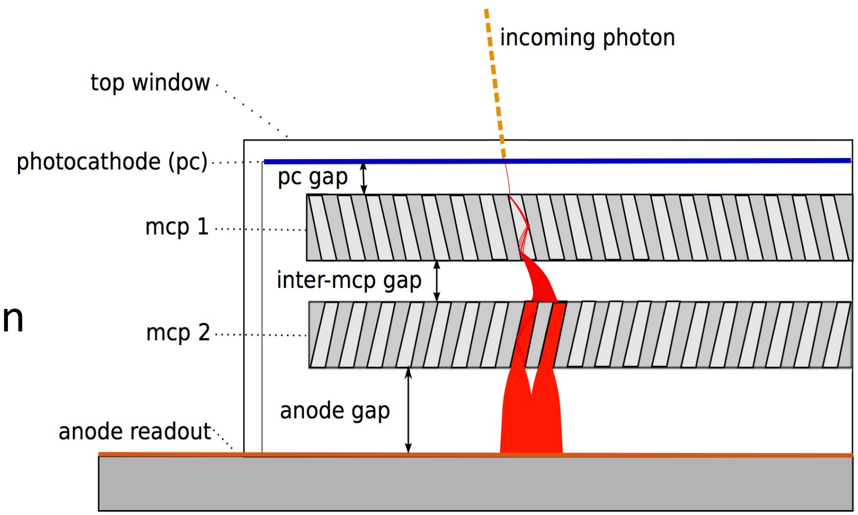
→ tagging of delayed decays provides **48% AtmBG rejection efficiency**

Fast light detectors: LAPPDs

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

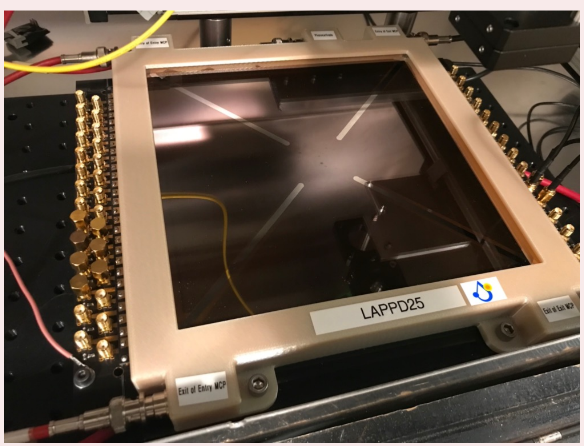
Large-Area Picosecond Photo-Detectors:

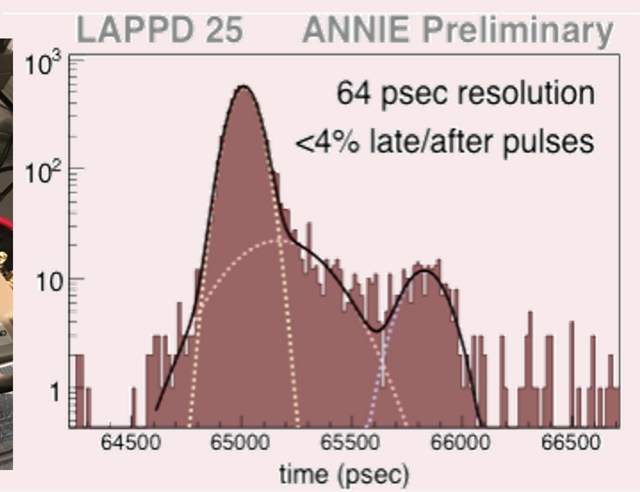
- flat, large area (20cm x 20cm) detectors
- standard photocathode, MCP-based amplification
- time resolution: ~60 ps
- spatial resolution: <1cm
- Manufactured by US company, Incom Inc.

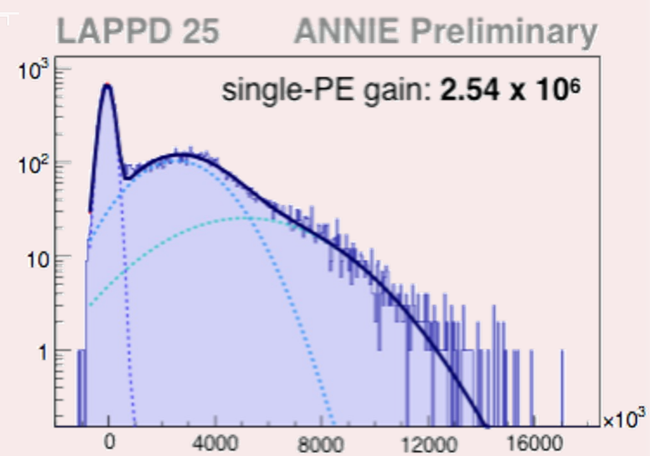


Schematic of LAPPD

LAPPD test for ANNIE





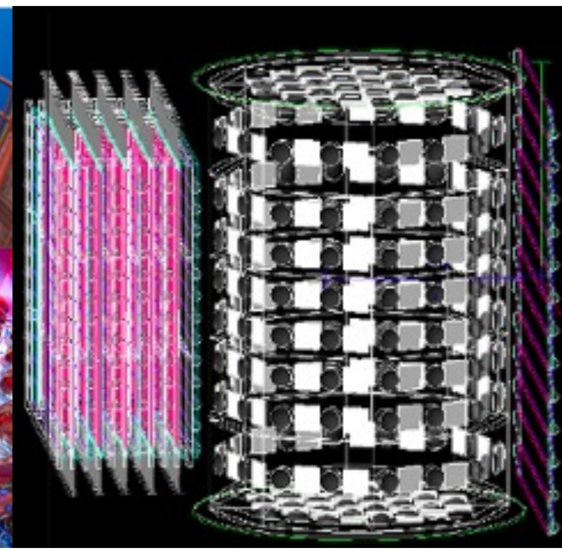


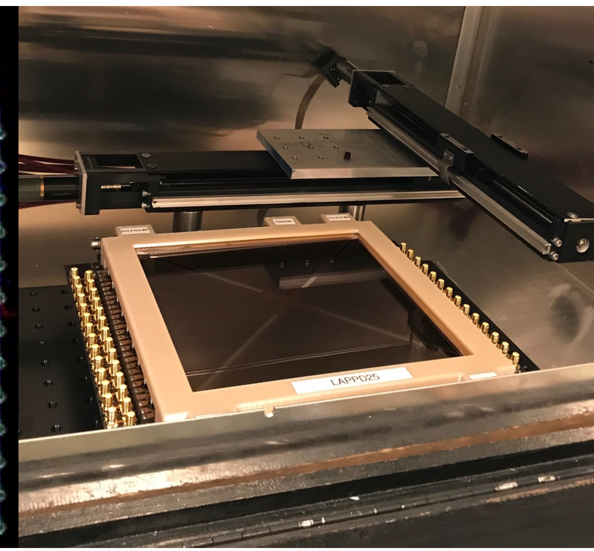
→ posters by A. Elagin, M. Wetstein

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)

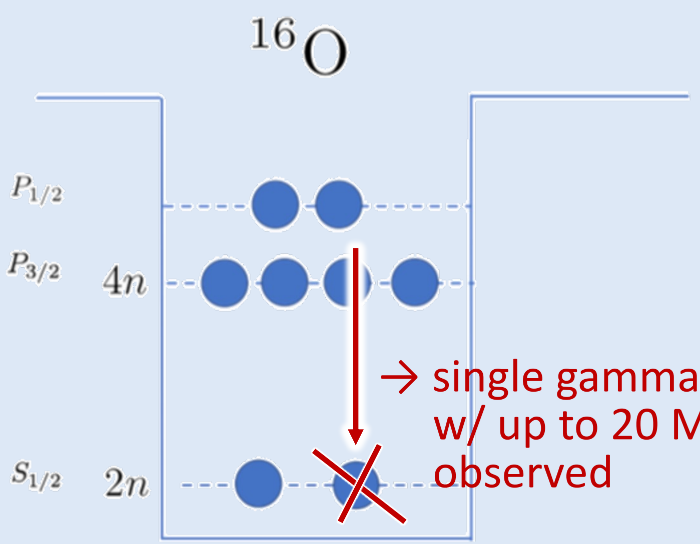
→ posters by J. Eisch/M. Wetstein

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