Prospects for detecting the DSNB in JUNO

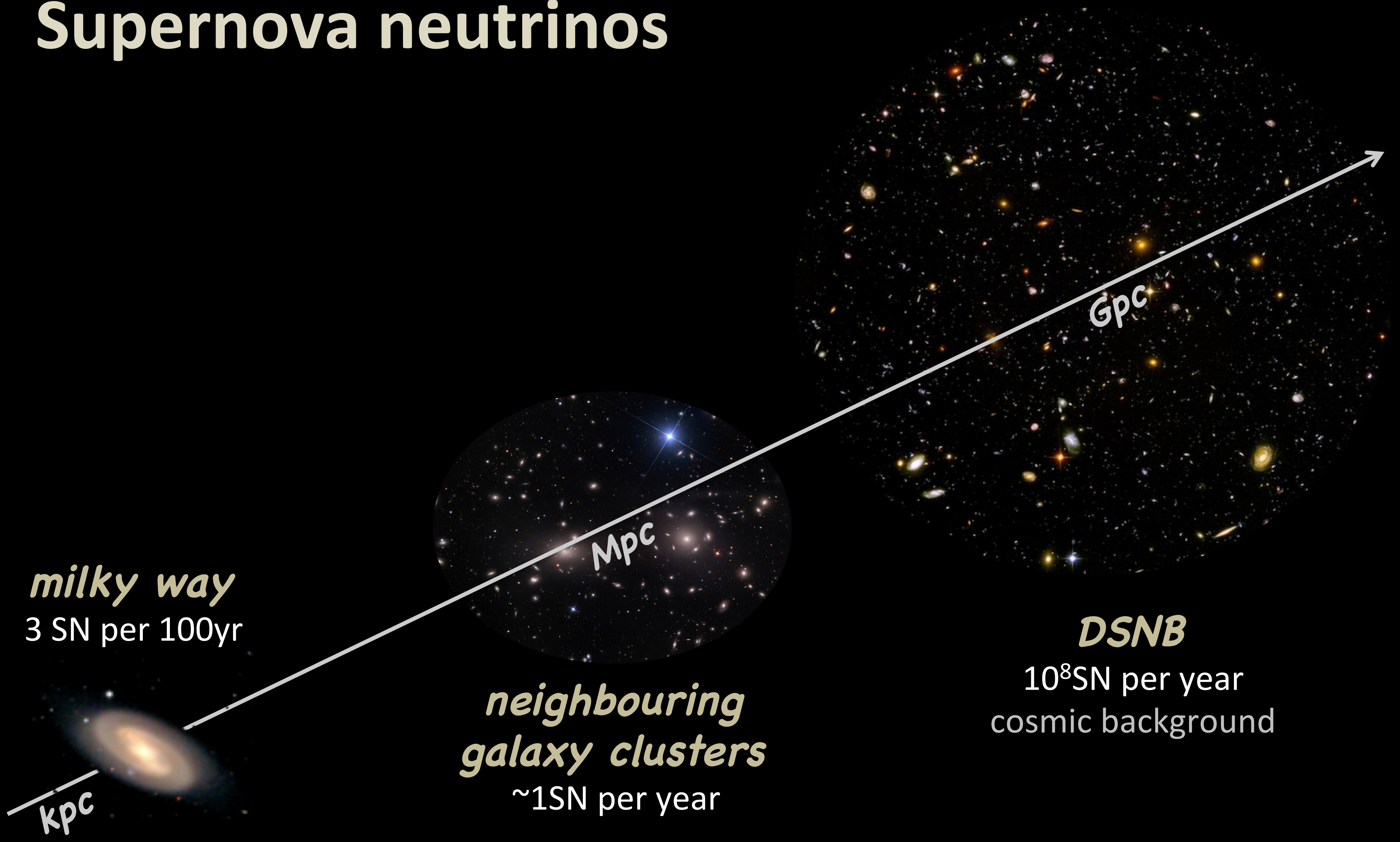
Workshop on Underground Physics

Tokyo University, 13 May 16

Michael Wurm (JGU Mainz)

on behalf of the JUNO collaboration

Supernova neutrinos

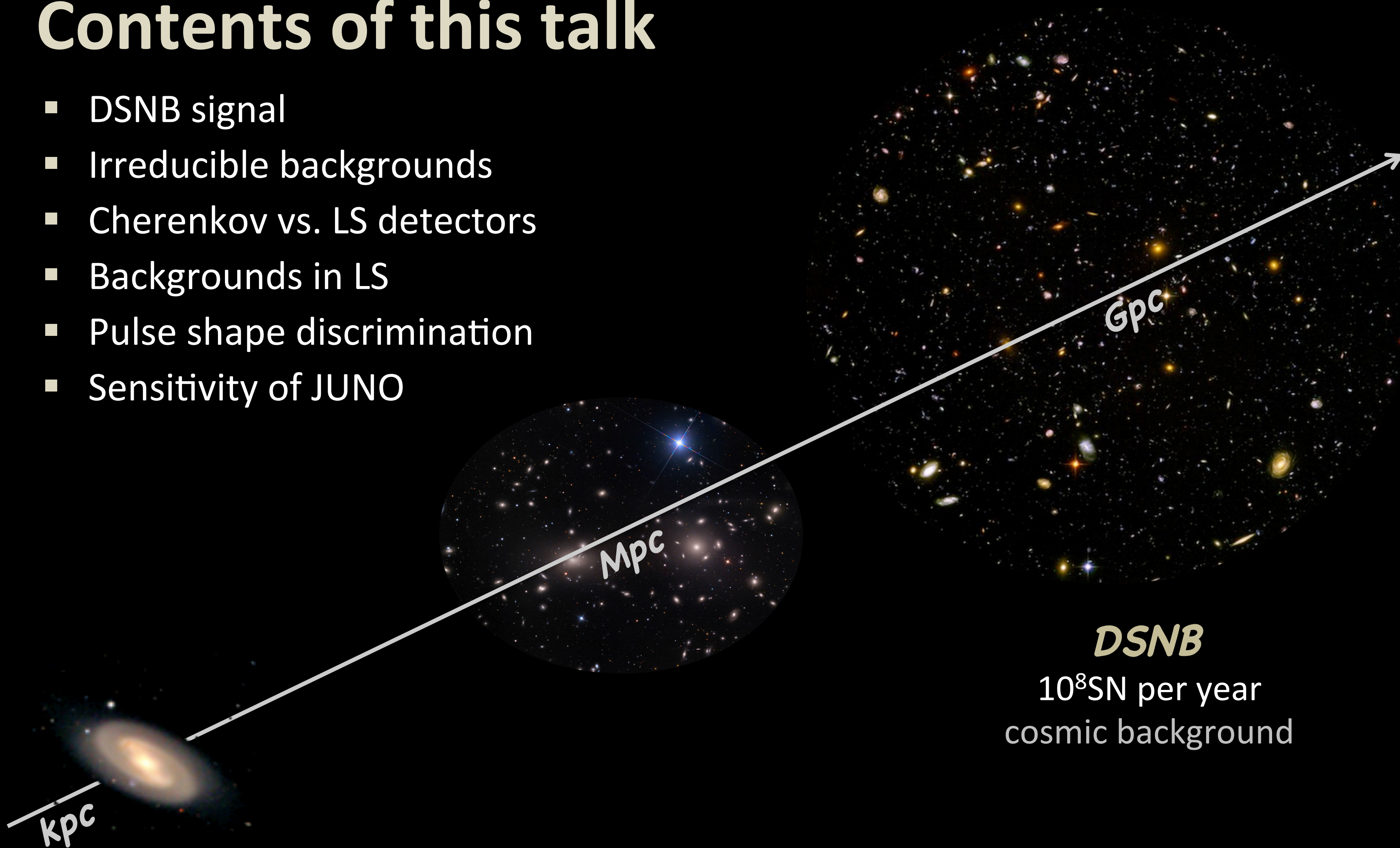


250 IBDs/kt → 1 IBD/(10kt·yrs)

present detectors | Mton++ detectors | low-background ν-observatories

Contents of this talk

- DSNB signal
- Irreducible backgrounds
- Cherenkov vs. LS detectors
- Backgrounds in LS
- Pulse shape discrimination
- Sensitivity of JUNO



DSNB

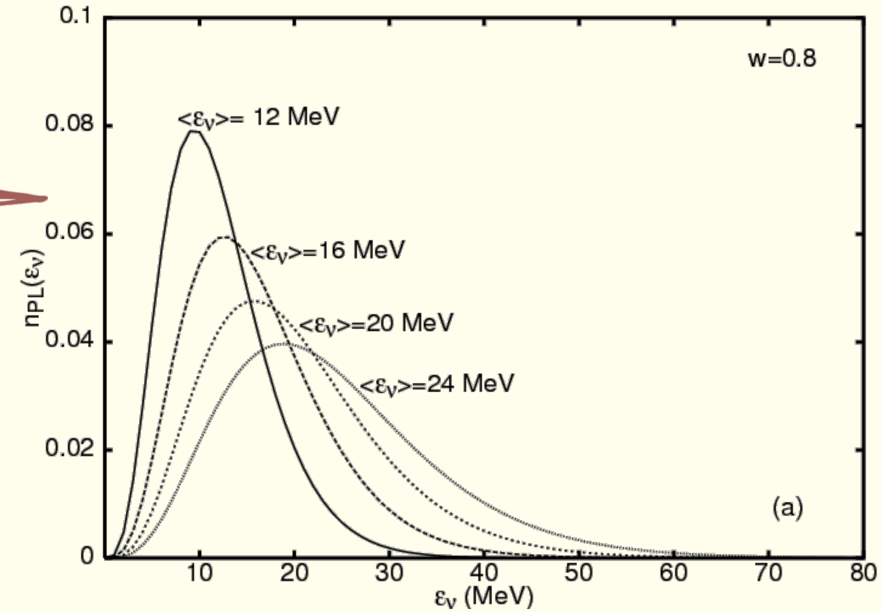
10^8SN per year

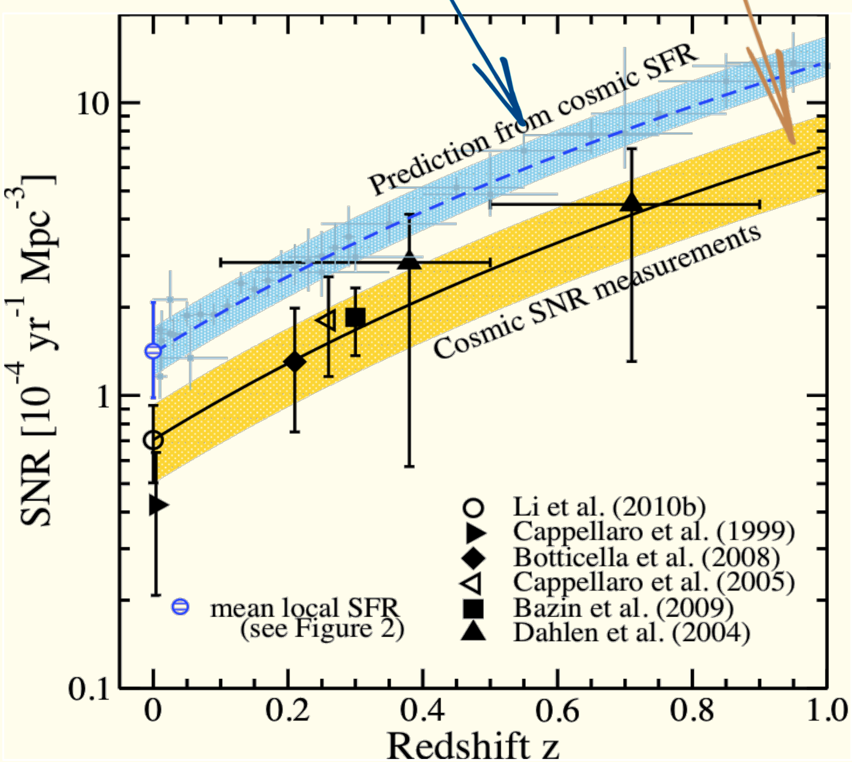
cosmic background

DSNB prediction

DSNB prediction depends on

- SN neutrino spectrum, *<E_ν>*
- redshift-dependent **Supernova rate** *(or **star formation and IMF**)*





Objectives of a DSNB measurement

→ first of all: discovery

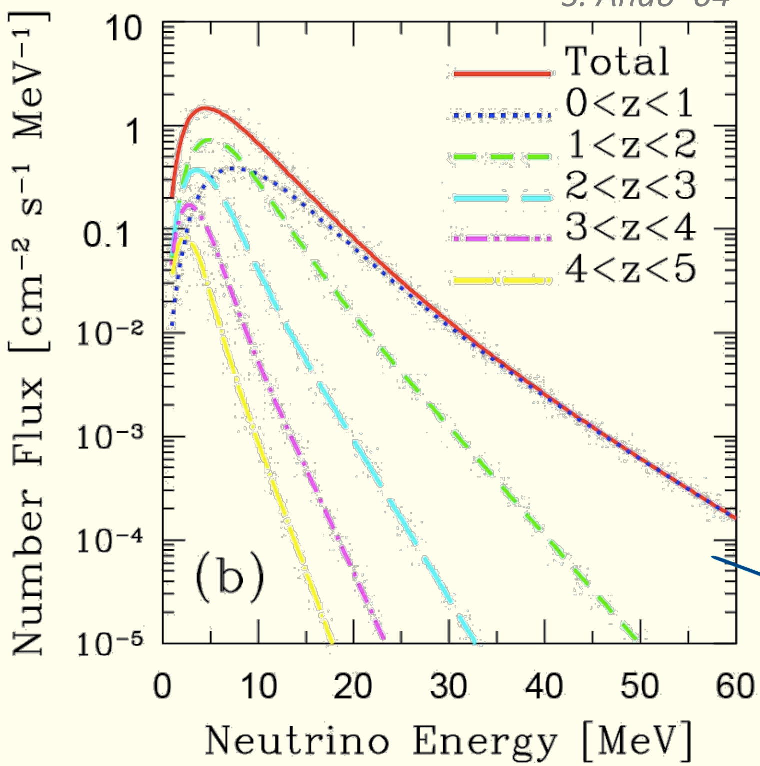
→ average Supernova ν spectrum (large variation on type expected)

→ redshift-dependent SN rate

→ fraction of hidden/failed SNe

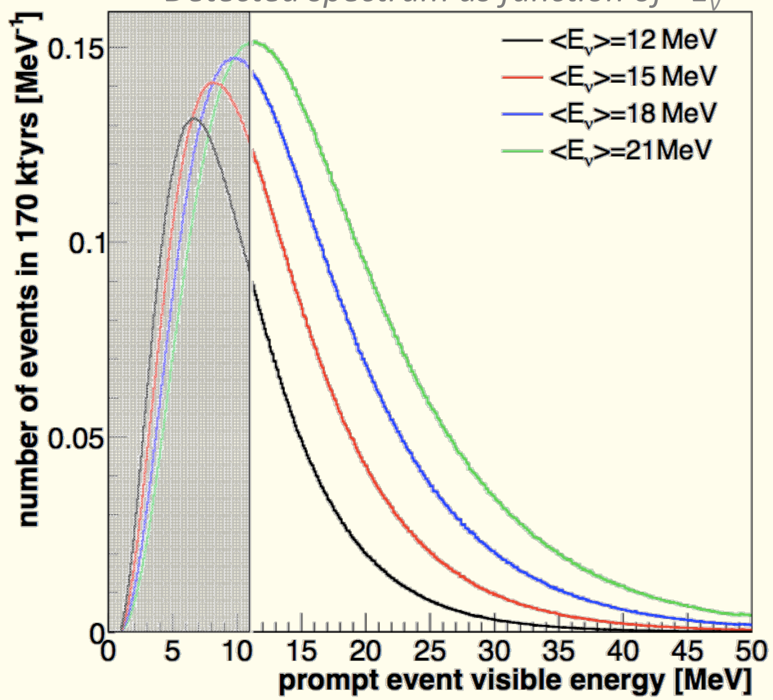
DSNB spectrum and flux

S. Ando '04

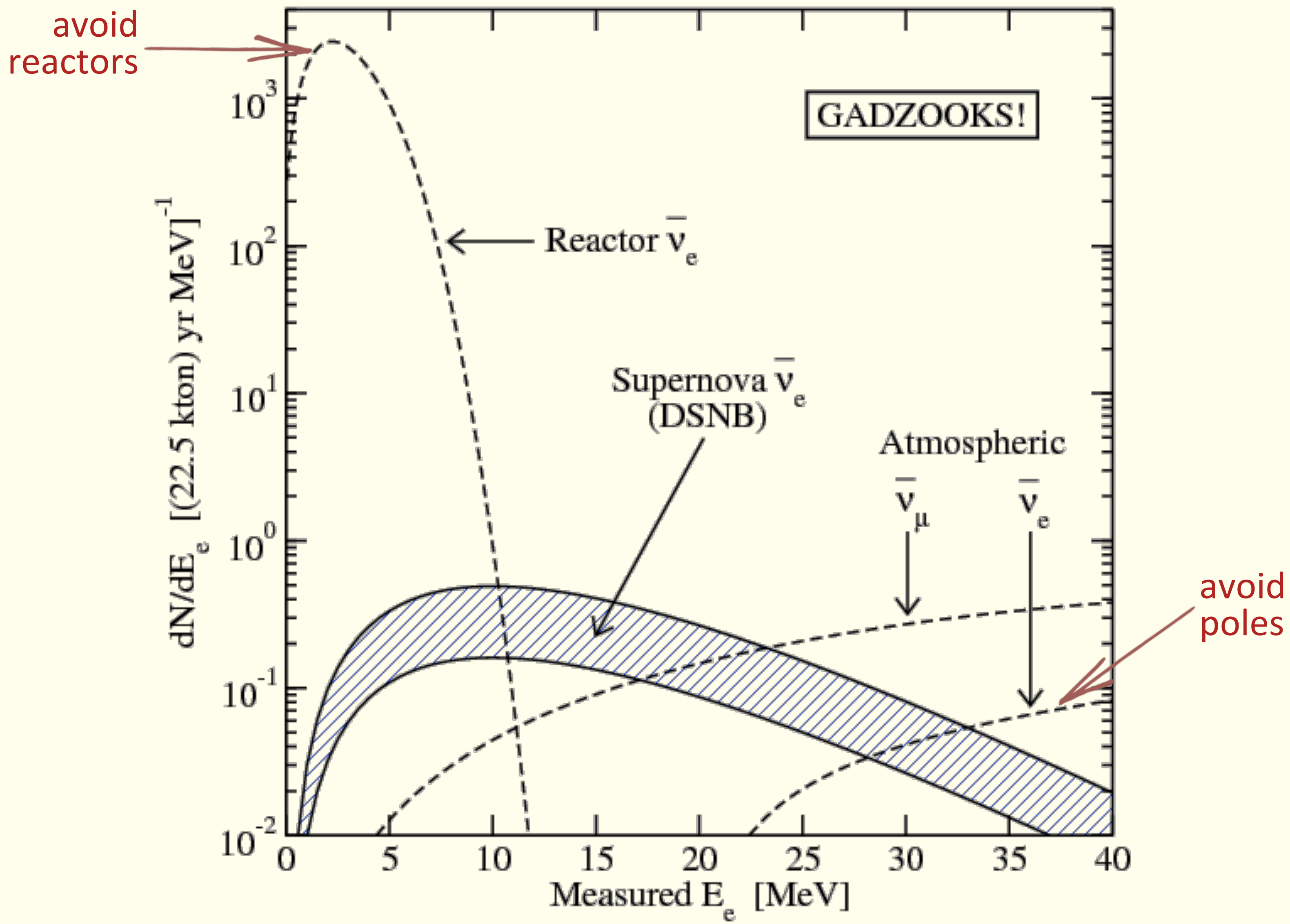


- DSNB flux: ~10^2 /cm^2s
- equipartition between flavors
- best possibility for detection in water and LS: **inverse beta decay**
- expected rate: ~1 per 10 kt·yrs

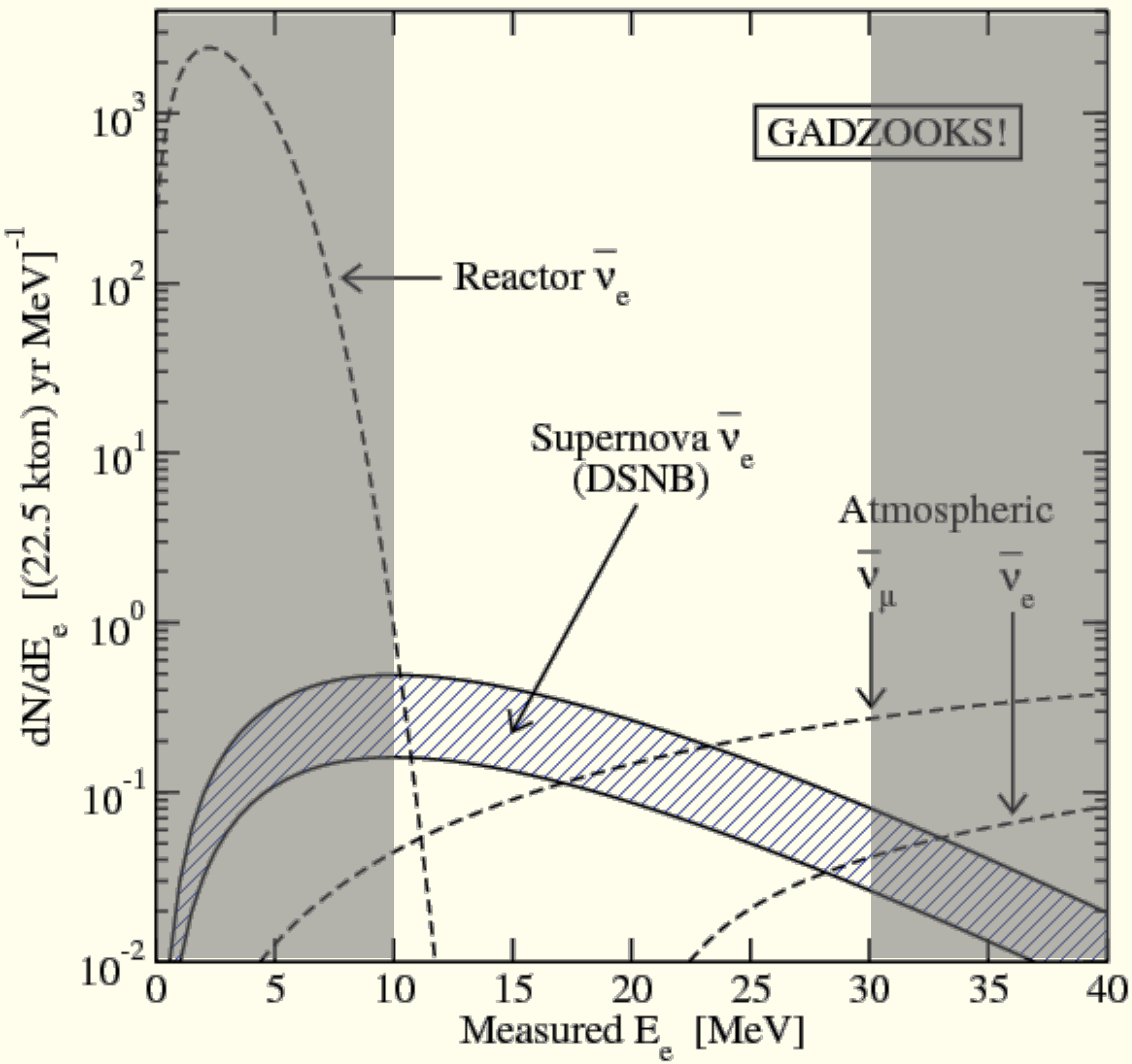
Detected spectrum as function of <Eν>



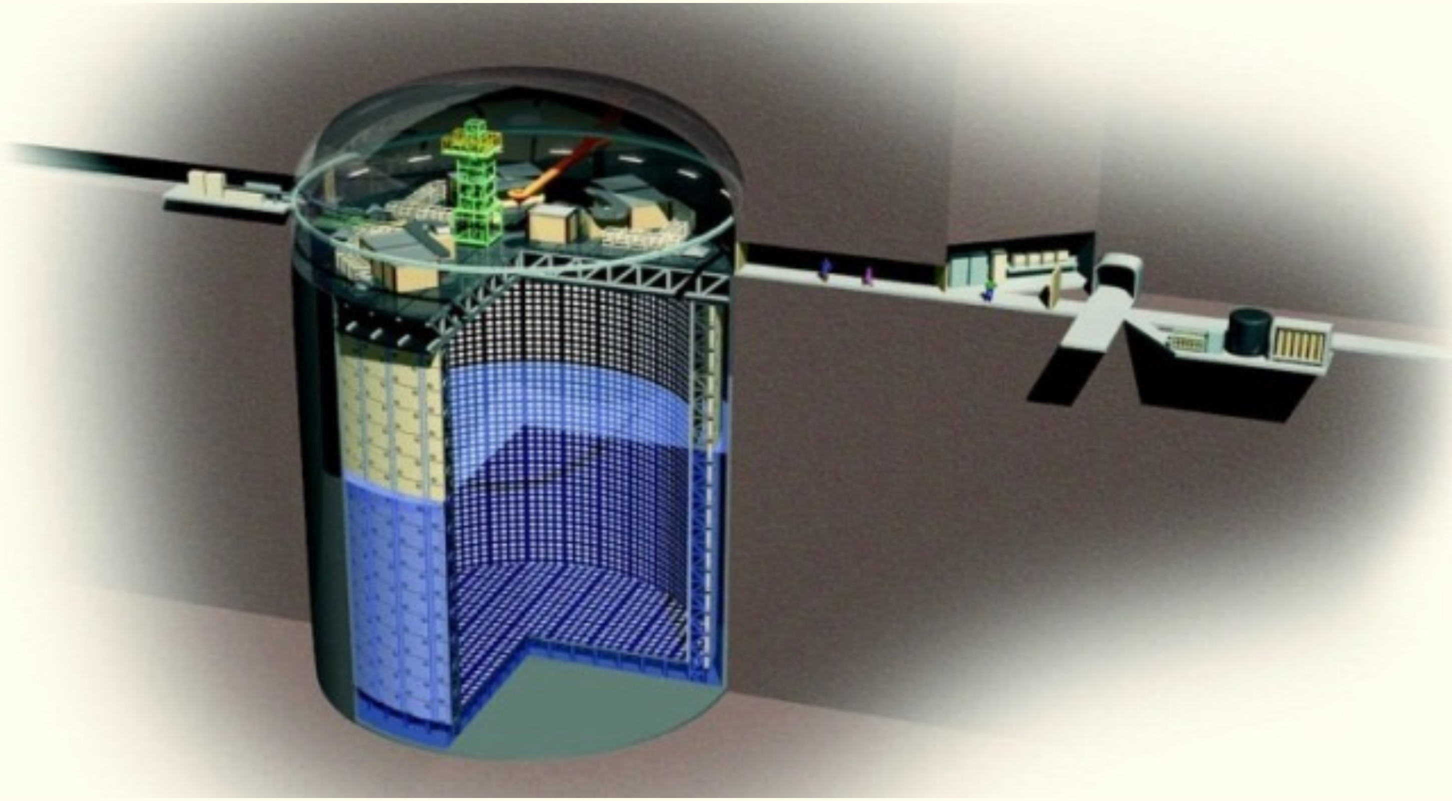
DSNB irreducible backgrounds



DSNB detection window



DSNB detection in Super-Kamiokande

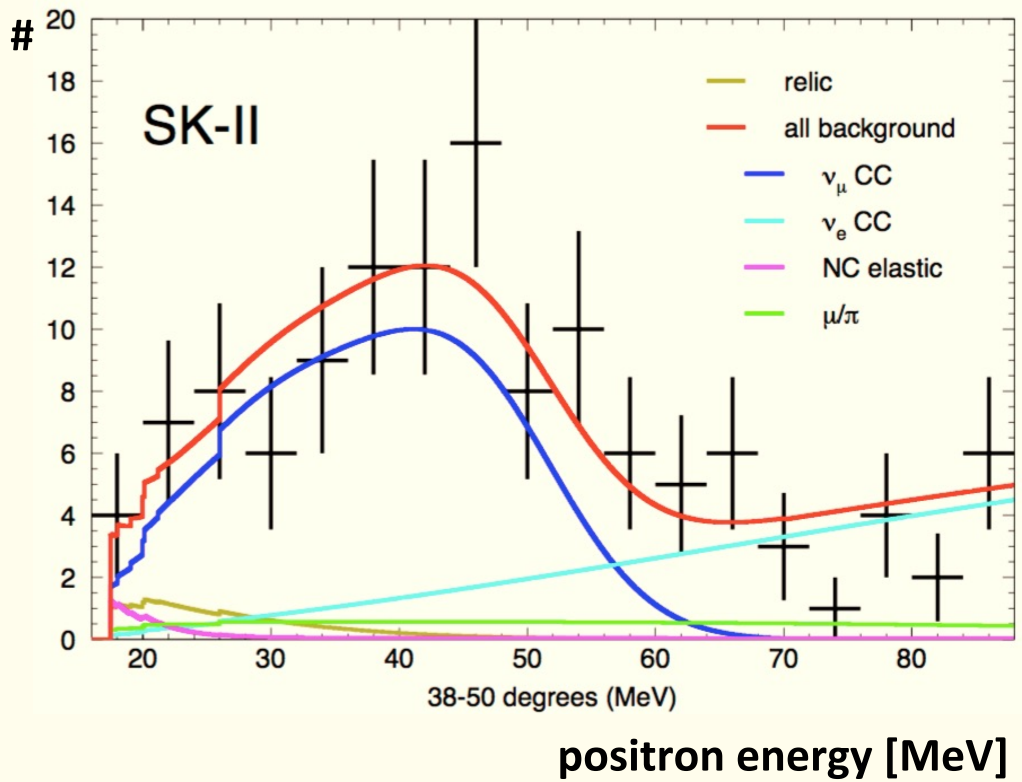


- large target mass: 25 kt
  → order 2-3 events/yr expected
- but: delayed neutron capture in IBDs hard to tag (see later)
  → additional backgrounds

Most recent limit from SK 2011 analysis

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**



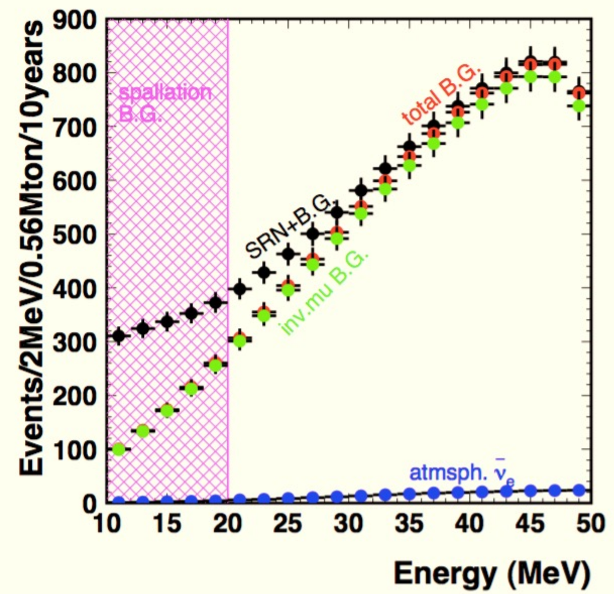
→ resulting limit from SKI-III:
ϕ_ν < 2.9 cm^{-2}s^{-1} for E(e^+)>16MeV

Prospects of detection in water

Several options:

- increase statistics drastically
  → Hyper-Kamiokande

HK w/o neutron tagging

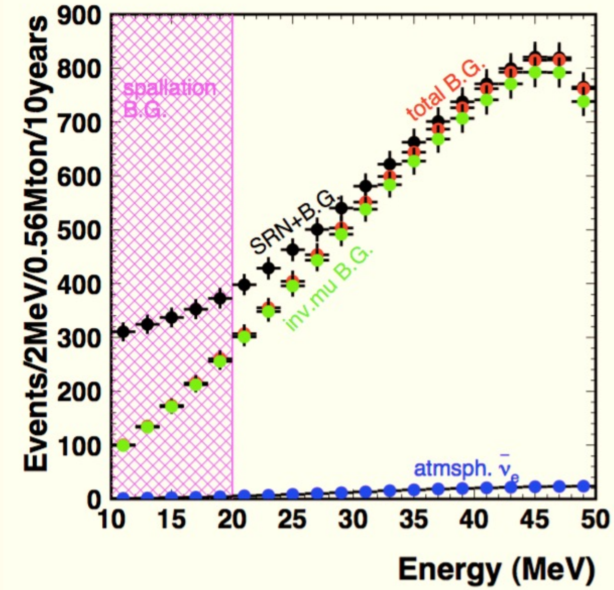


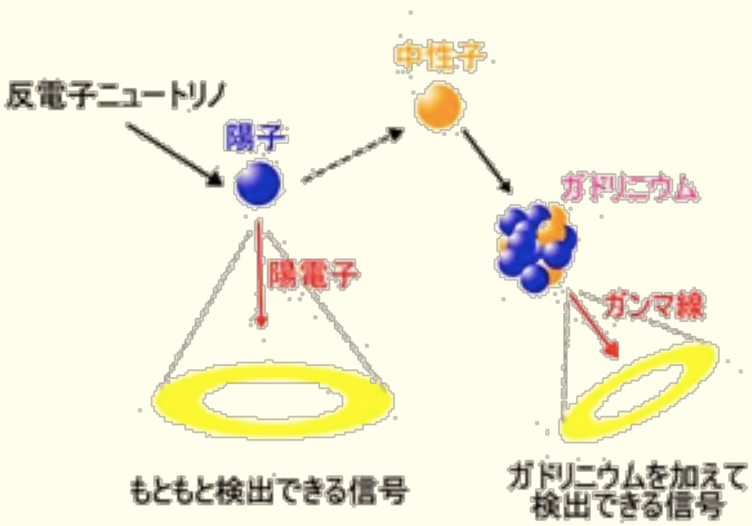
Prospects of detection in water

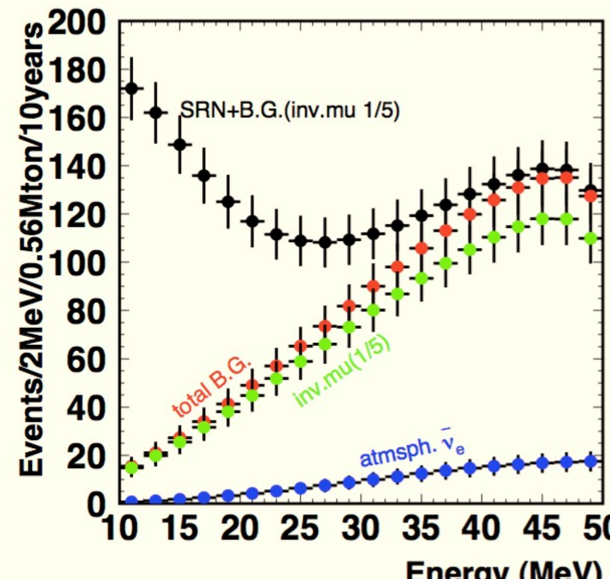
Several options:

- increase statistics drastically
  → Hyper-Kamiokande
- tag the delayed neutron
  → by clever trigger logic
  (efficiency ~20%) → applied in SK
  → by doping with gadolinium
  (efficiency ~60%) → GADZOOKS!

HK w/o neutron tagging







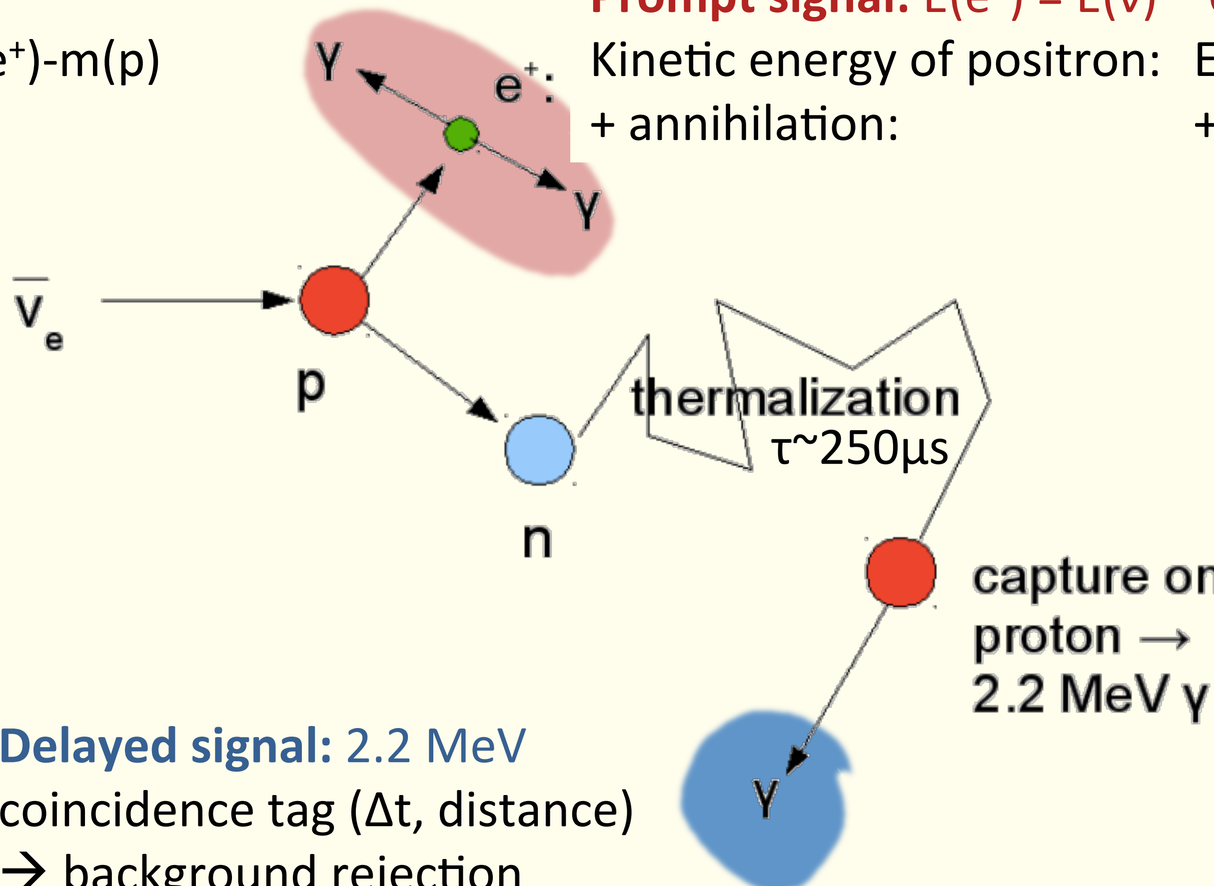
HK+Gd

Alternative: Liquid scintillator (LS) detectors

main advantage: neutron tagging in IBD comes for free
→ all single-event backgrounds can be easily rejected

Threshold:
$Q = m(n)+m(e^+)-m(p)$
$= 1.8$ MeV

Prompt signal: $E(e^+) = E(\nu) - 0.8$ MeV
Kinetic energy of positron: $E(\nu) - Q$
+ annihilation: $+ 2m(e^{\pm})$



Delayed signal: 2.2 MeV
coincidence tag (Δt, distance)
→ background rejection

Alternative: Liquid scintillator (LS) detectors

main advantage: **neutron tagging in IBD comes for free**
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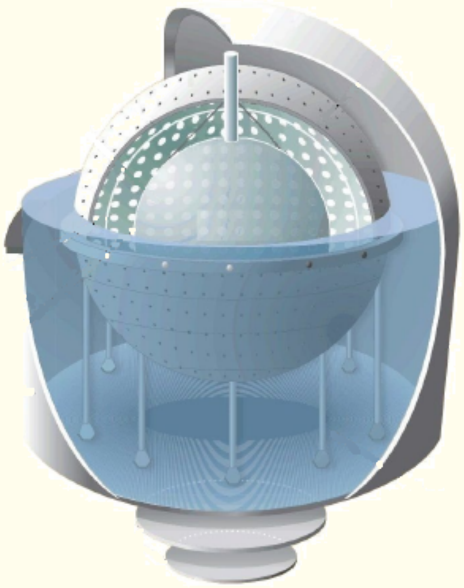
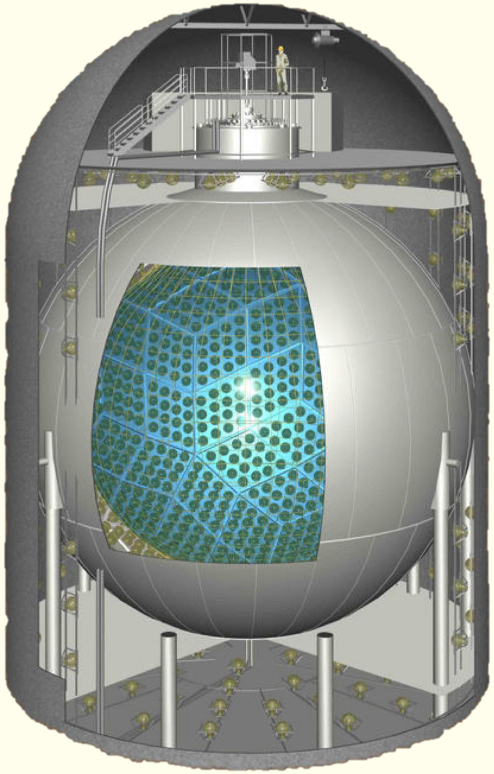
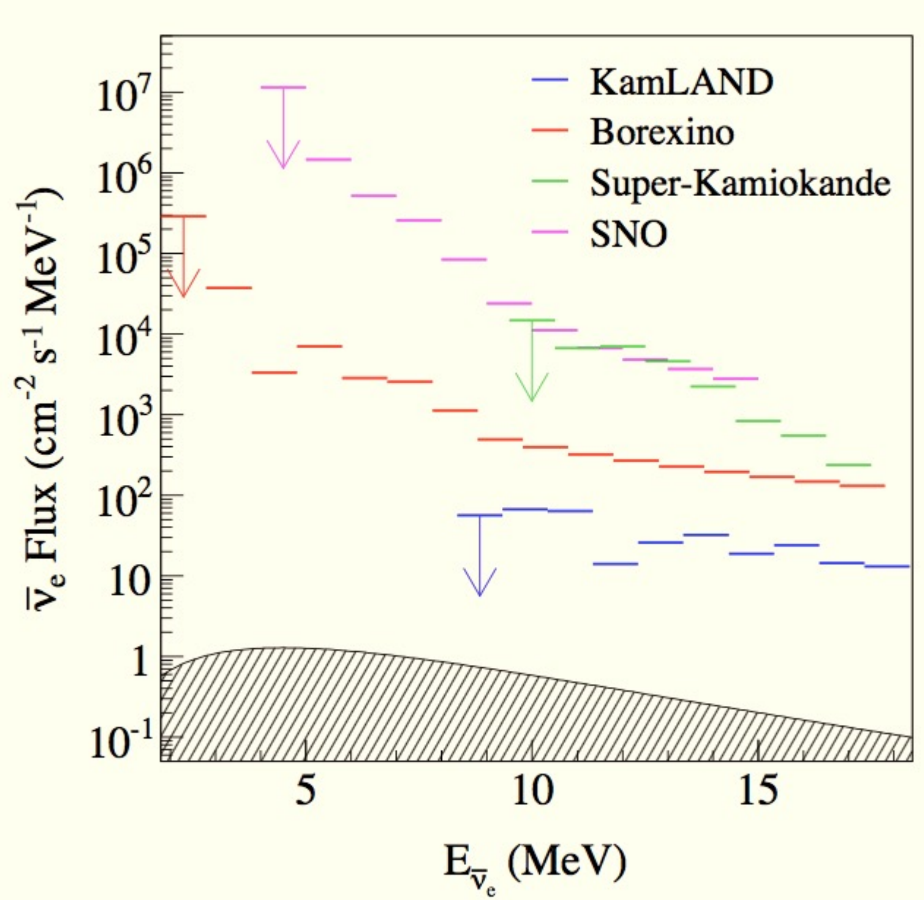
present LS detectors:
→ Borexino (270t)
→ KamLAND (1000t)

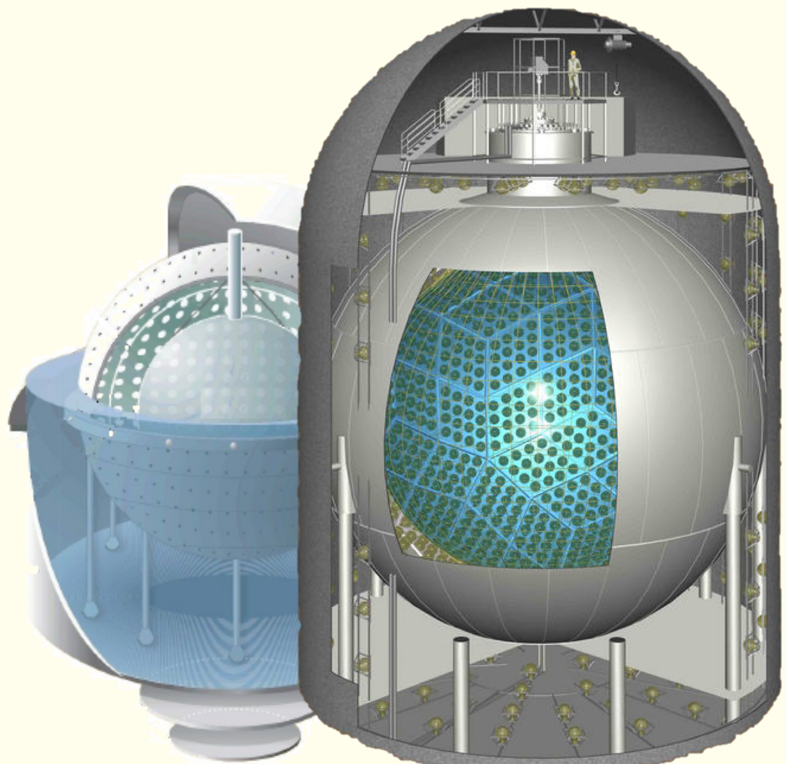




DSNB signal in today's LS detectors?

- Search for extraterrestrial antineutrino sources: [arXiv:1105.3516]
- At low energies (E_ν<8MeV): dominated by reactor background
- At high energies (E_ν>18MeV): SK provides better limits



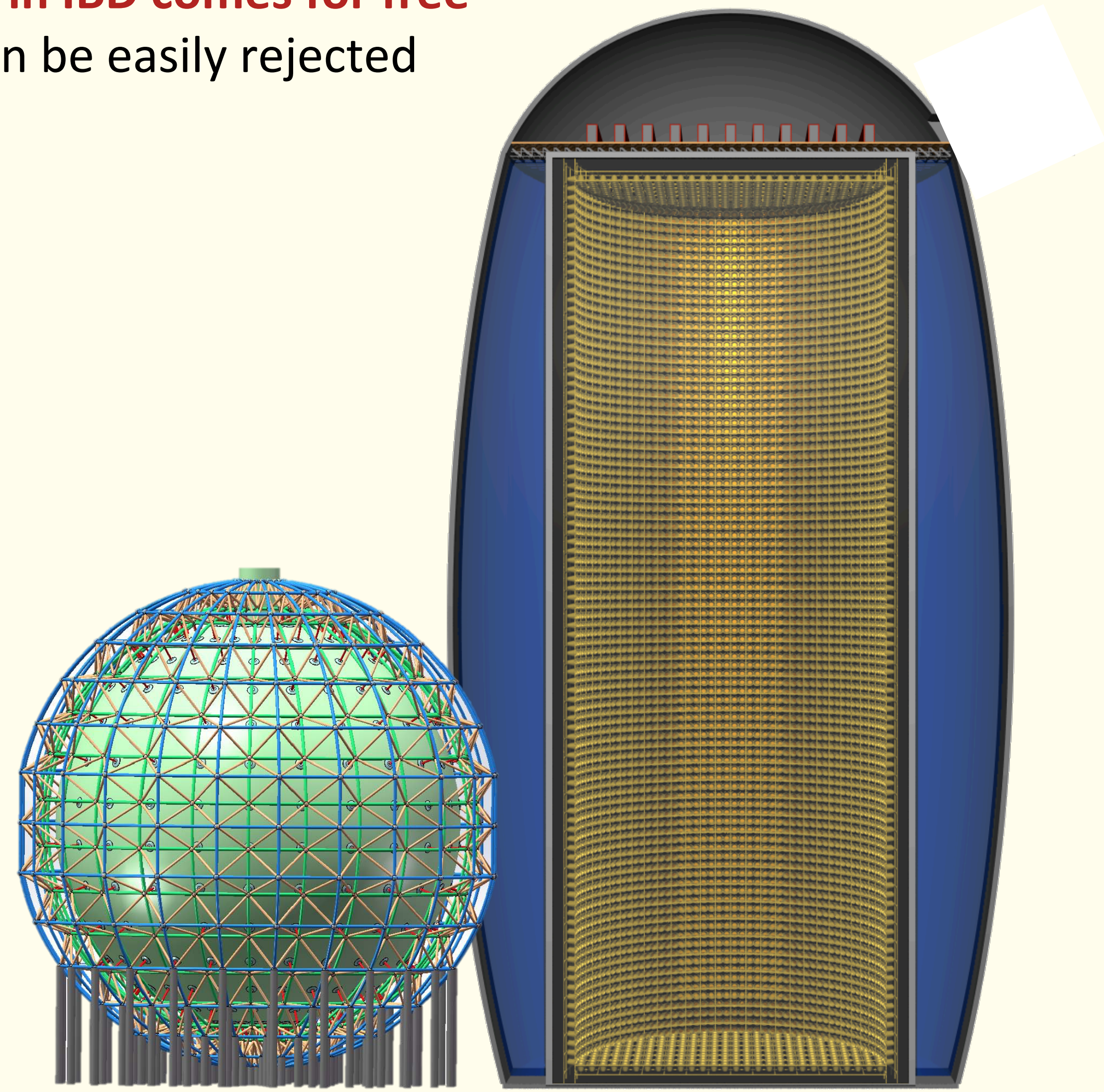


Alternative: Liquid scintillator (LS) detectors

main advantage: **neutron tagging in IBD comes for free**
→ all single-event backgrounds can be easily rejected

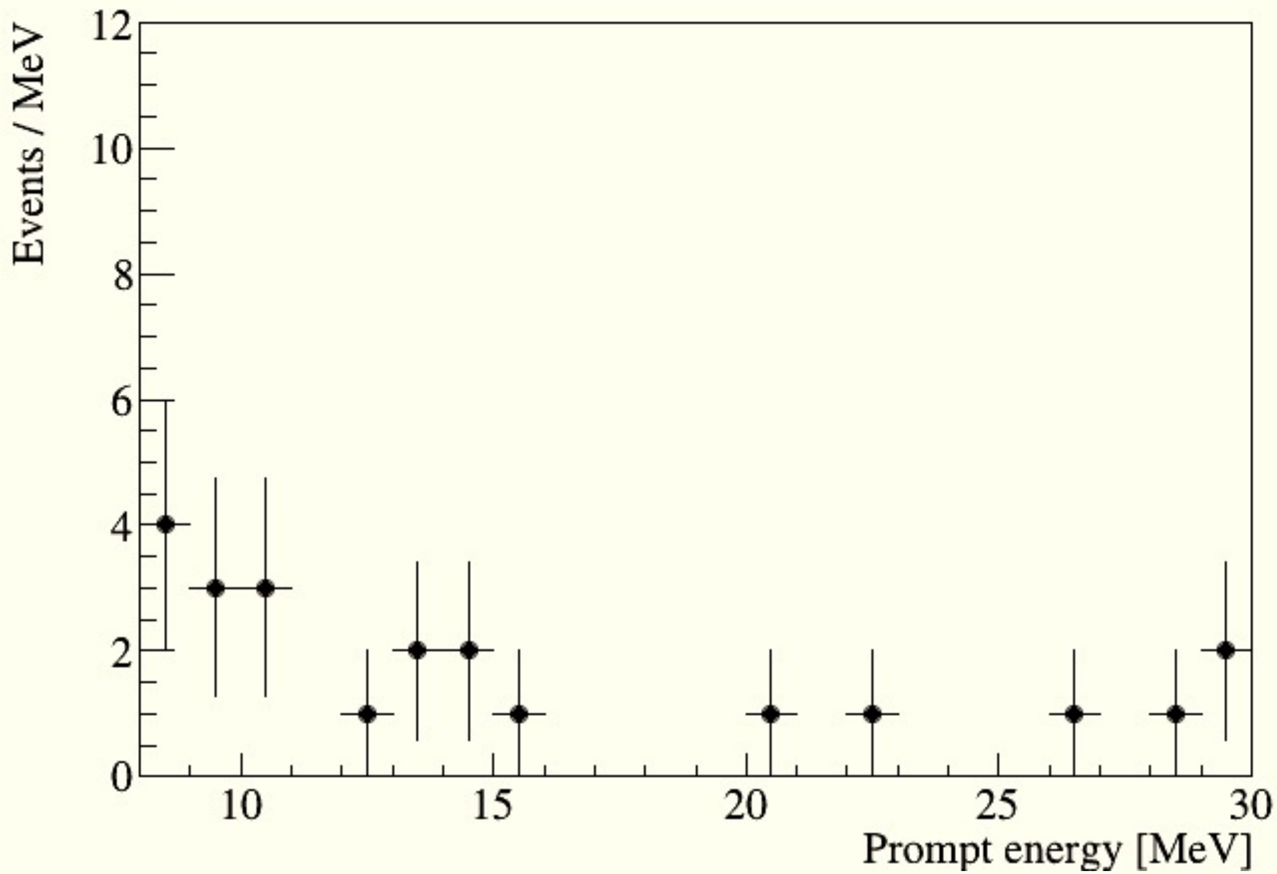
present LS detectors:
→ Borexino (270t)
→ KamLAND (1000t)

future LS detectors:
→ JUNO (20kt)
→ RENO-50 (18kt)
→ LENA (50kt)



KamLAND's "high energy IBD" events

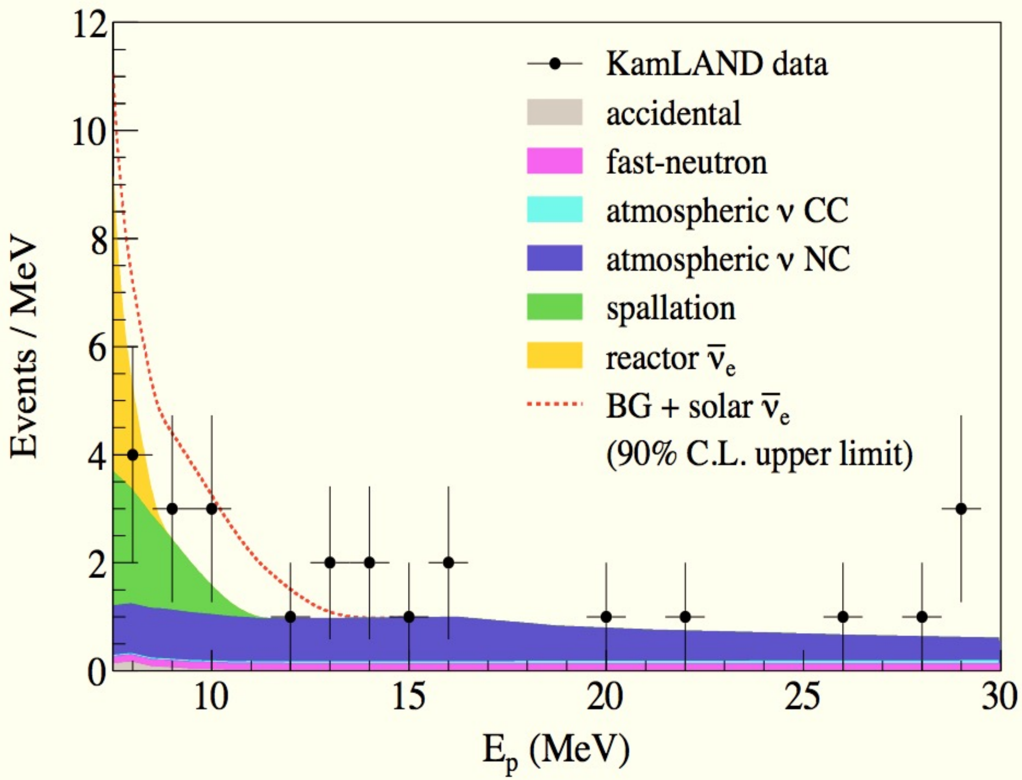
- target volume too small to discover the DSNB signal (only 0.1 $kt^{-1}yr^{-1}$)
- but sufficiently large to check for backgrounds



KamLAND "high energy" data (2011)

exposure: 4.53 kt

Background: The usual suspects



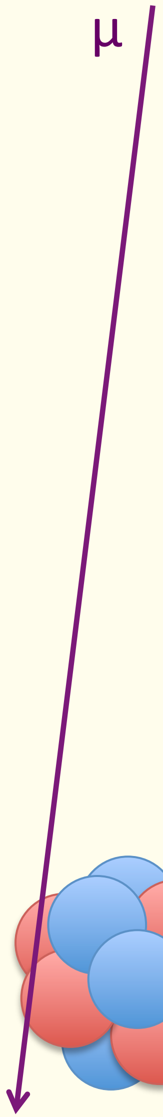
Other inverse beta decays

- reactor antineutrinos
- atmospheric antineutrinos
  → defines observation window

Cosmogenic backgrounds

- βn-emitters: ^{9}Li & ^{8}He
- fast-neutrons

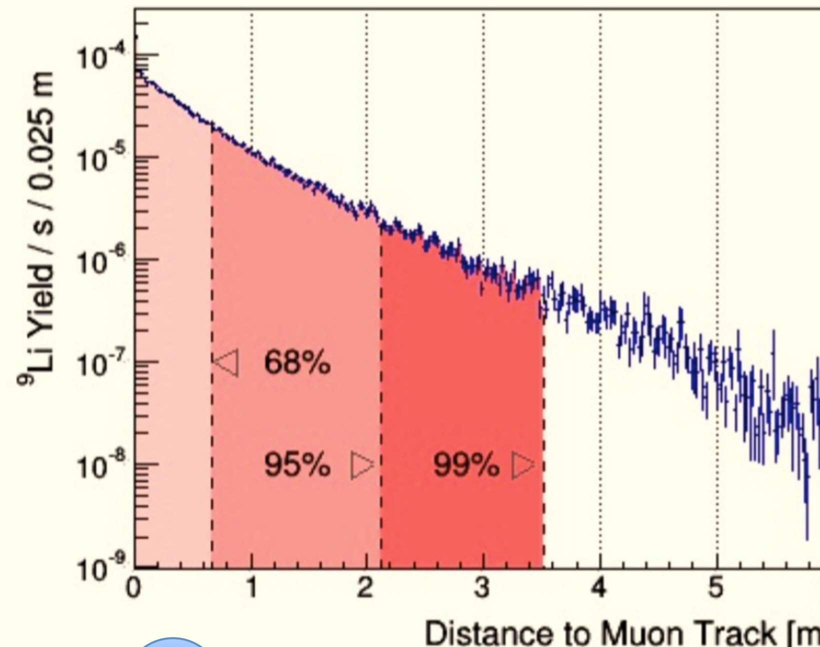
Cosmogenic βn-emitters: ^{9}Li + ^{8}He



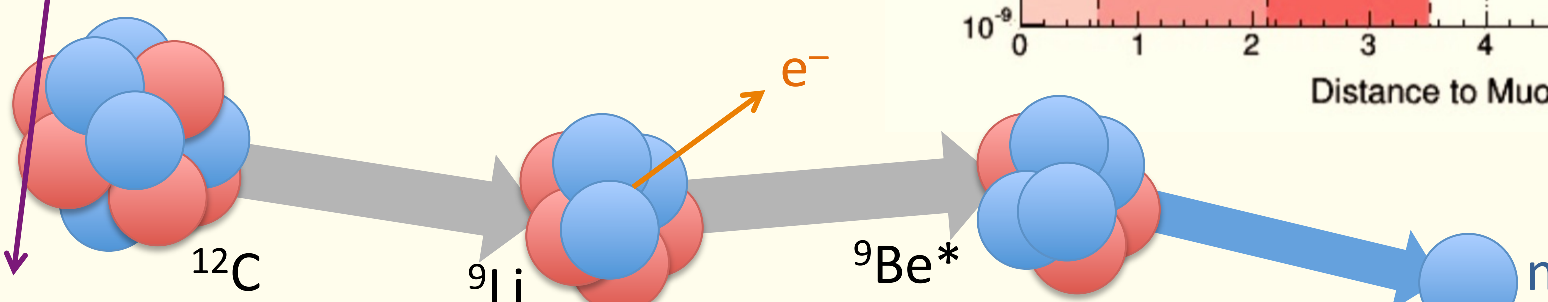
- Cosmic muon spallation on ^{12}C in LS target: radioactive isotopes
- Neutron-rich isotopes: ^{9}Li (τ=257ms, $Q_{\beta n}\approx$10.5MeV), ^{8}He
- β^{-}-decay to excited state of daughter: neutron emission
- prompt β-like event followed by n-capture → IBD signature

Background reduction

- time-cut after each muon (e.g. for 5τ ~ 1.25s)
- spatial cut relative to parent muon track

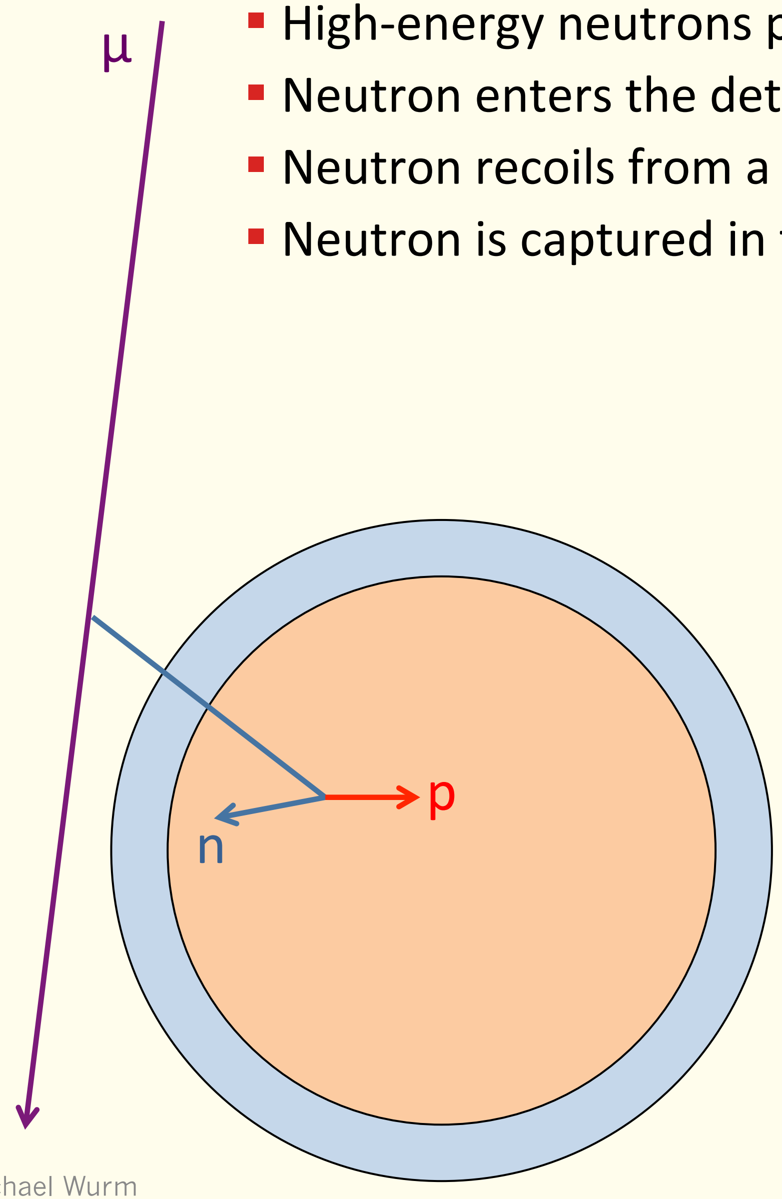


M. Grassi et al., arXiv:1505.05609



Fast neutrons

- High-energy neutrons produced by muons in surrounding rocks
- Neutron enters the detector w/o triggering vetoes
- Neutron recoils from a proton in the LS → prompt signal
- Neutron is captured in the LS → delayed signal

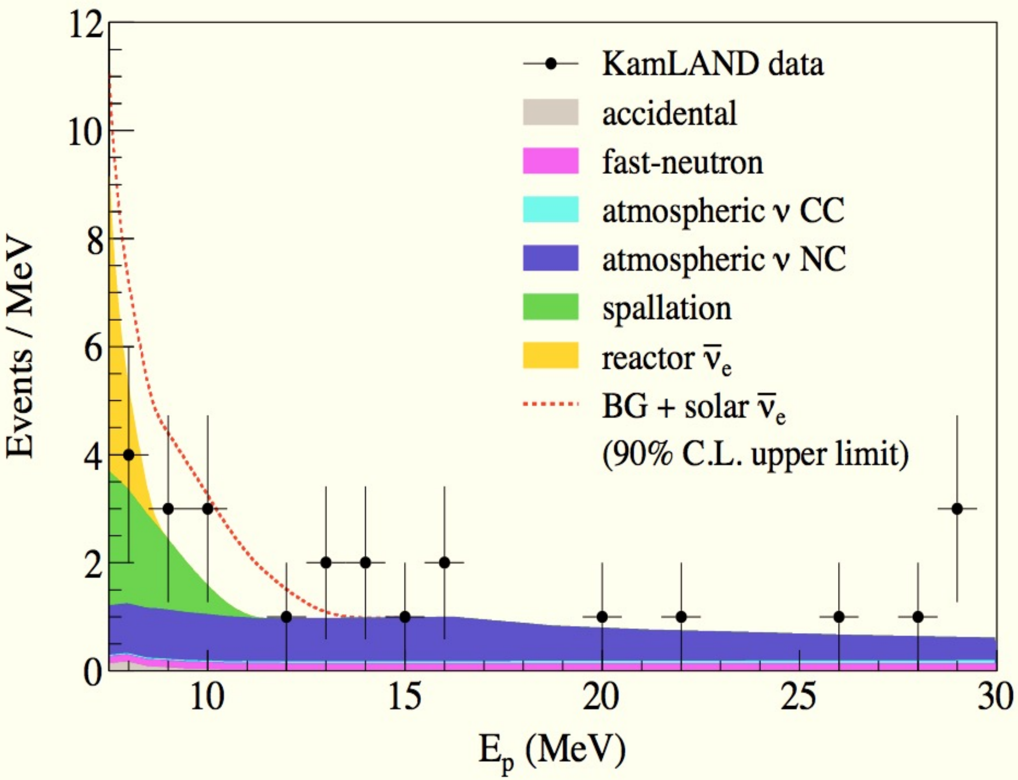


Background reduction

- surrounding muon veto
- passive shielding or fiducial volume cut:

  e.g. in JUNO (Jilei Xu):
  cut of 1m: 40 yr^{-1} → 2 yr^{-1}
- pulse shape discrimination for prompt event

Background: The usual suspects



Other inverse beta decays

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- atmospheric antineutrinos
  → defines observation window

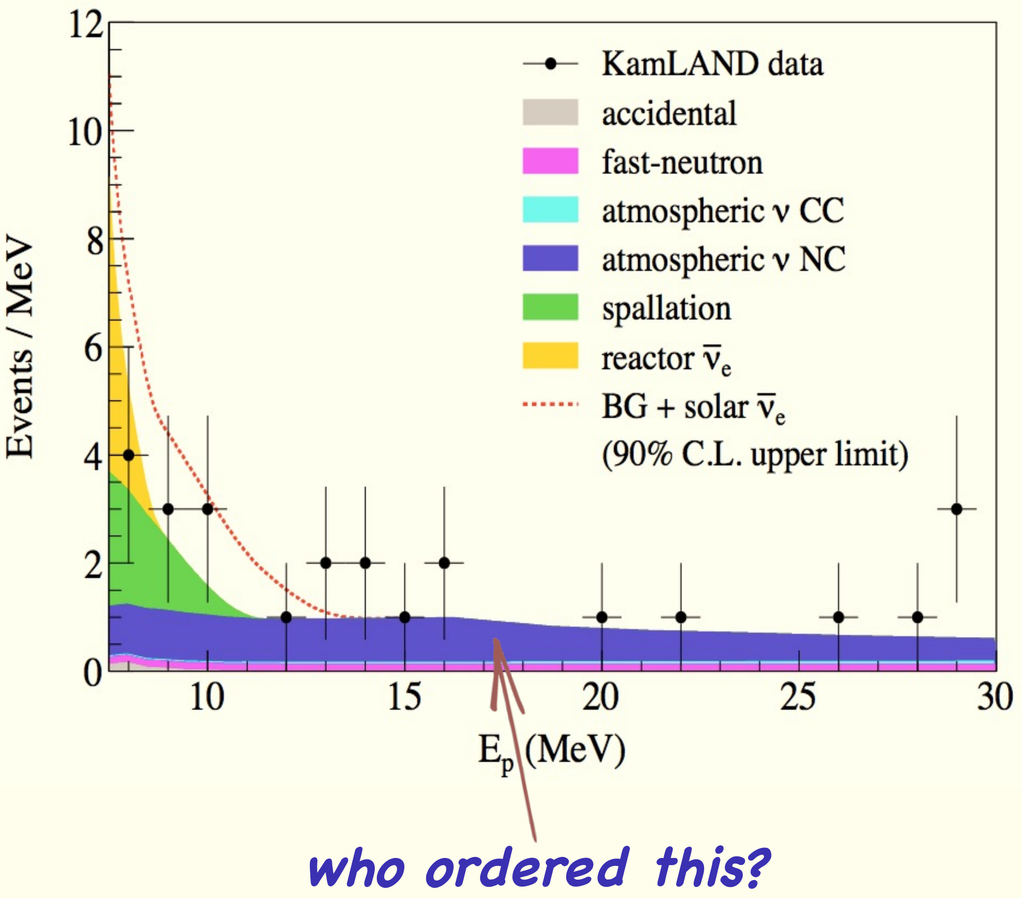
μ-induced spallation isotopes

- βn-emitters: ^{9}Li & ^{8}He
  → depth
  → veto using time,distance-correlation to parent muon

External neutrons (μ-induced)

- fast-neutrons
  → depth
  → fiducial volume cut

Background: The usual suspects



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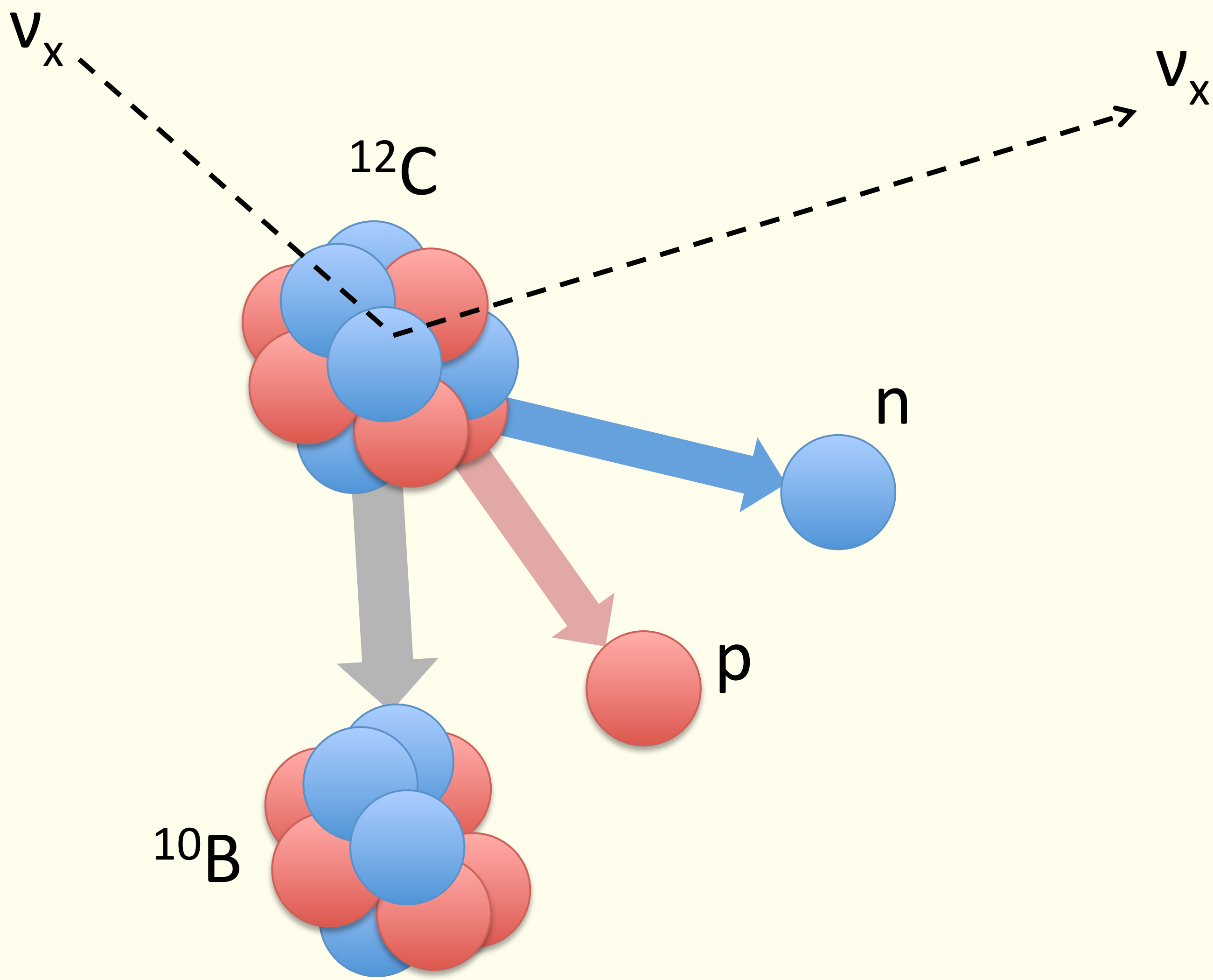
Atmospheric neutrino NC reactions

Background: NC neutrino-nucleon scattering **with neutron in final state**



Atmospheric neutrino NC reactions

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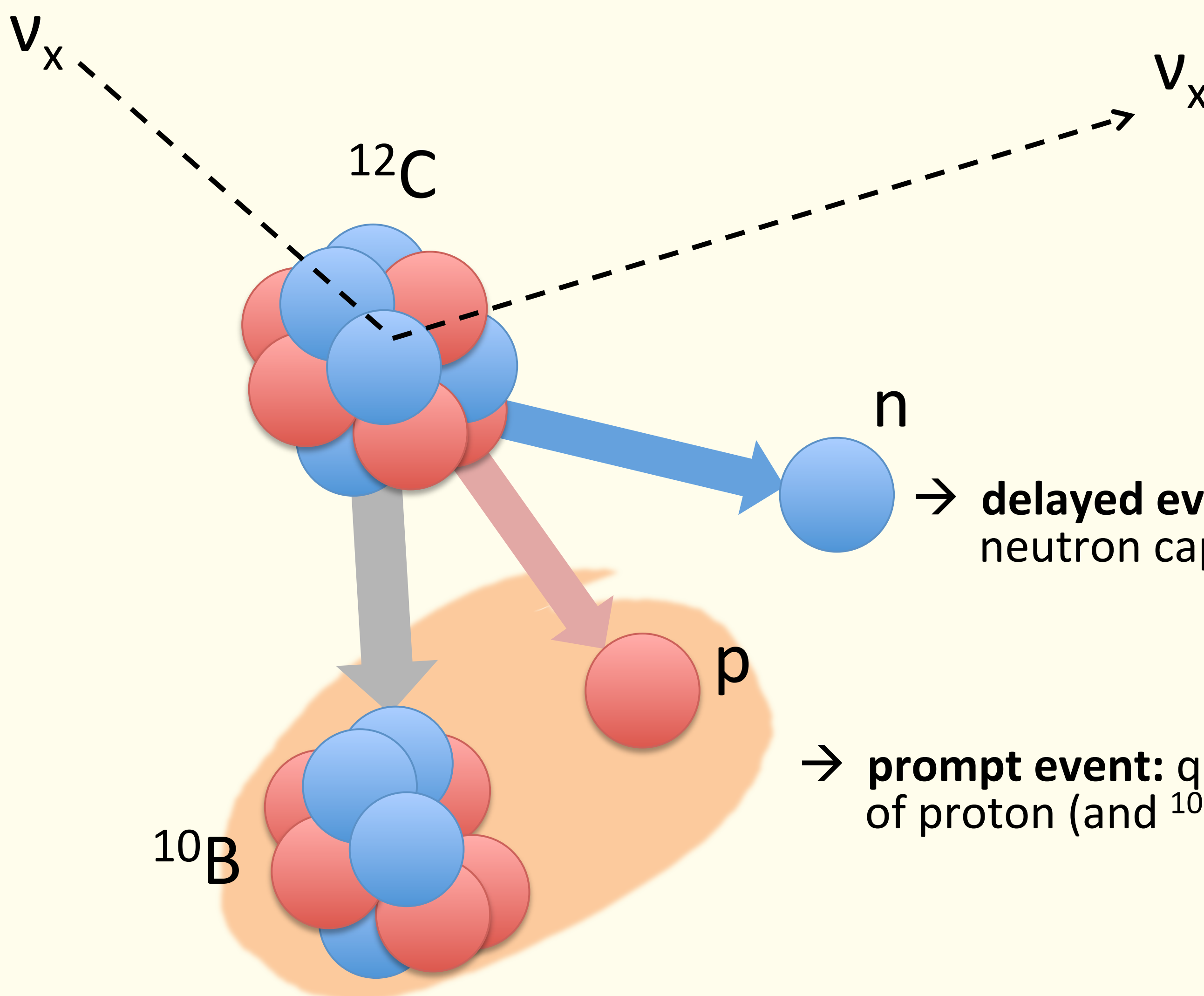


→ **delayed event:** neutron capture on hydrogen

→ **prompt event:** quenched signal of proton (and ^{10}B) recoil

Possible compositions of final states

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

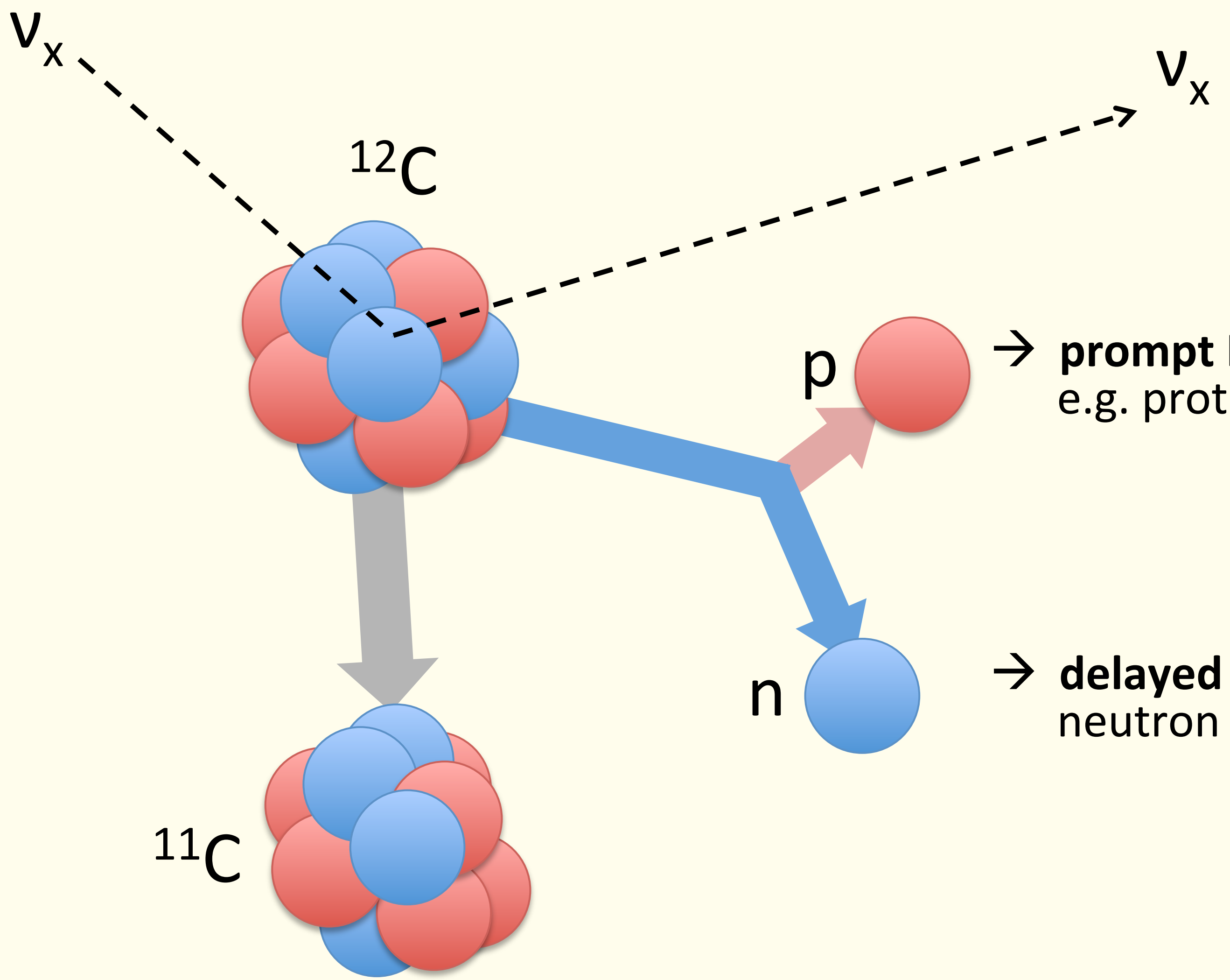
Reaction channel	Branching ratio
(1) $\nu_x + {}^{12}C \rightarrow \nu_x + n + {}^{11}C$	38.8 %
(2) $\nu_x + {}^{12}C \rightarrow \nu_x + p + n + {}^{10}B$	20.4 %
(3) $\nu_x + {}^{12}C \rightarrow \nu_x + 2\,p + n + {}^{9}Be$	15.9 %
(4) $\nu_x + {}^{12}C \rightarrow \nu_x + p + d + n + {}^{8}Be$	7.1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

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

→ more than an order of magnitude greater than DSNB signal!

BG rejection: Delayed decays

Discrimination based on delayed signal from **decay of the final state nucleus**:

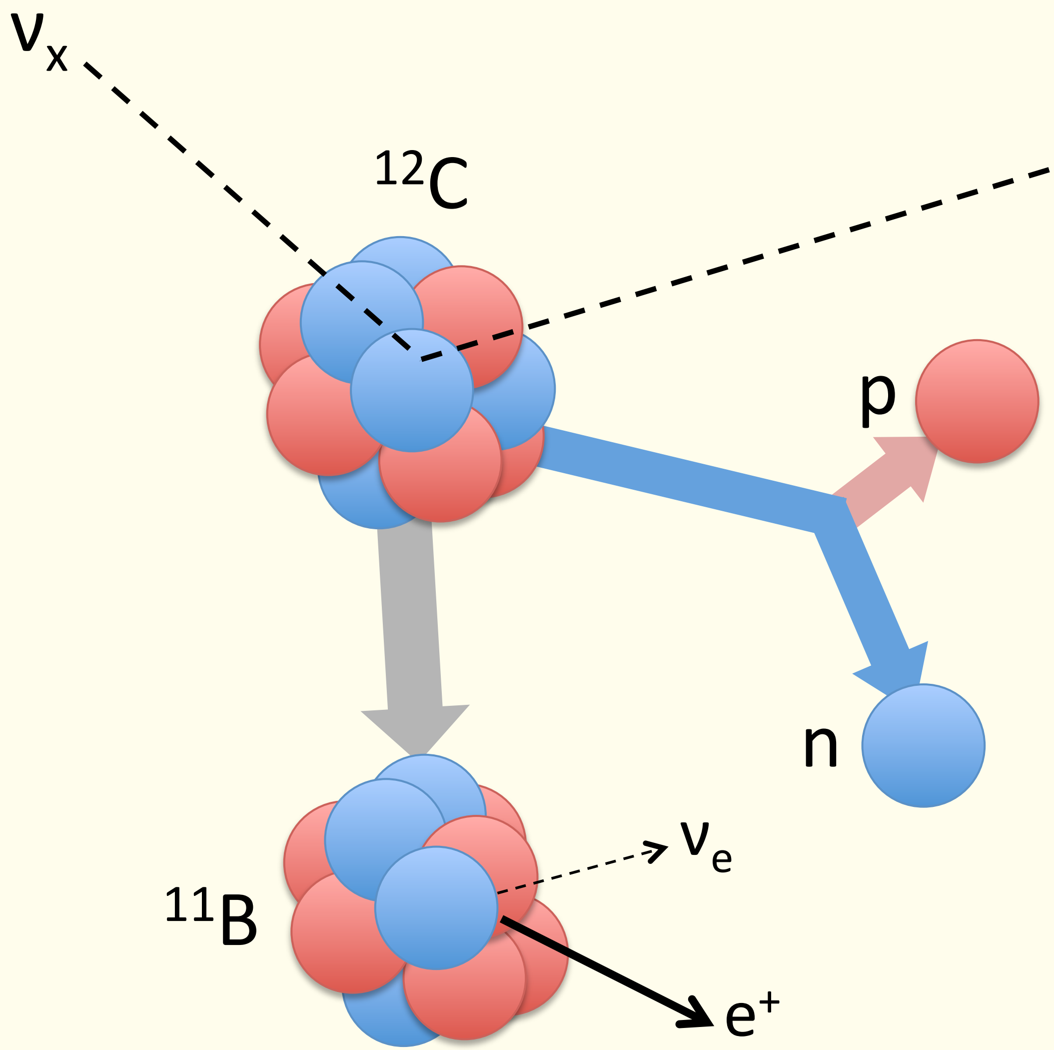


→ **prompt IBD-like event:**
e.g. proton recoil

→ **delayed IBD-like event:**
neutron capture on H

BG rejection: Delayed decays

Discrimination based on delayed signal from **decay of the final state nucleus**:



→ **prompt IBD-like event:**
e.g. proton recoil

→ **delayed IBD-like event:**
neutron capture on H

→ **late β-decay of ^{11}C**
($T_{1/2}$~20min)

NC BG reduction 1: Delayed Decays

Several of the spallation isotopes produced are not stable:

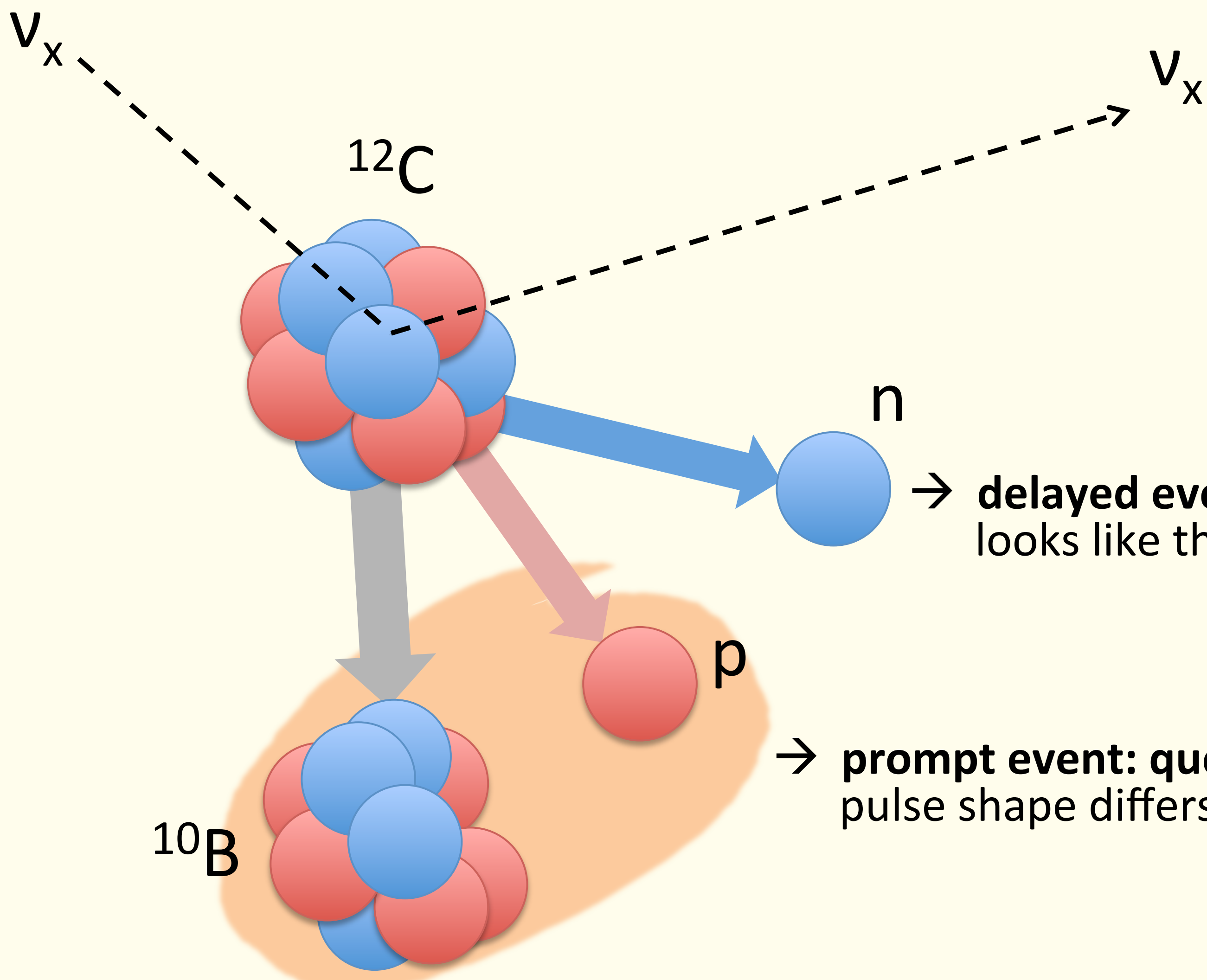
Reaction channel	Branching ratio	
(1) $\nu_x + {}^{12}C \rightarrow \nu_x + n + {}^{11}C$	38.8 %	→ taggable
(2) $\nu_x + {}^{12}C \rightarrow \nu_x + p + n + {}^{10}B$	20.4 %	→ stable
(3) $\nu_x + {}^{12}C \rightarrow \nu_x + 2p + n + {}^{9}Be$	15.9 %	→ stable
(4) $\nu_x + {}^{12}C \rightarrow \nu_x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

→ potentially allows to tag about 40% of the NC background events

→ remaining amount is still several times the DNSB signal

NC BG reduction 2: Pulse Shape

Background: NC neutrino-nucleon scatterings **with neutron in final state**



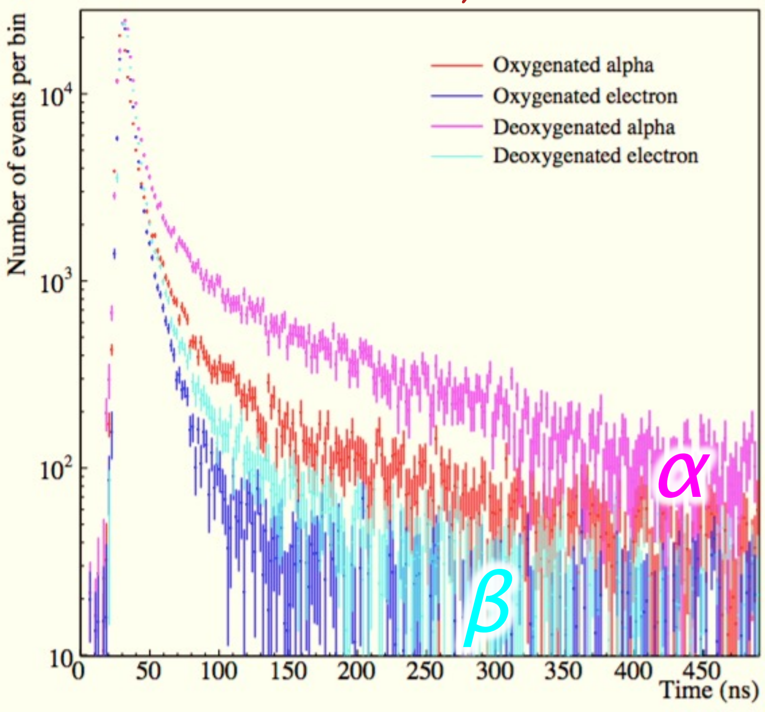
→ **delayed event: neutron**
looks like the real thing

→ **prompt event: quenched fragments**
pulse shape differs significantly from e^+

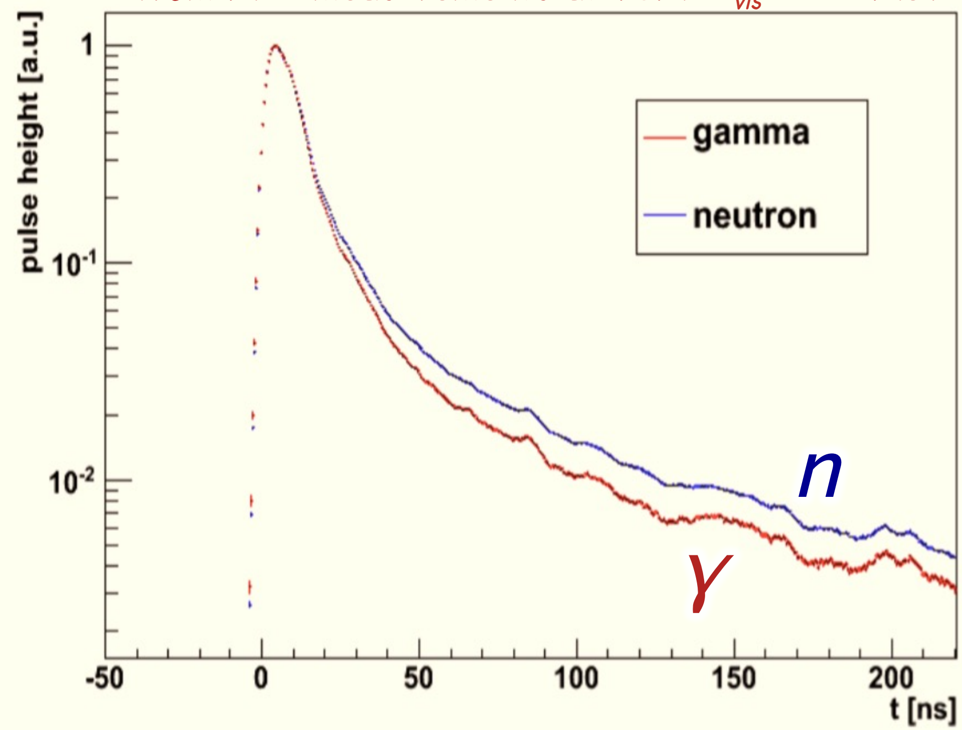
Pulse Shape measurements

Light emission of LS depends on particle type:

O'Keeffe et al., arXiv:1102.0797



from MLL measurements at TUM: E_{vis}=2-2.5MeV

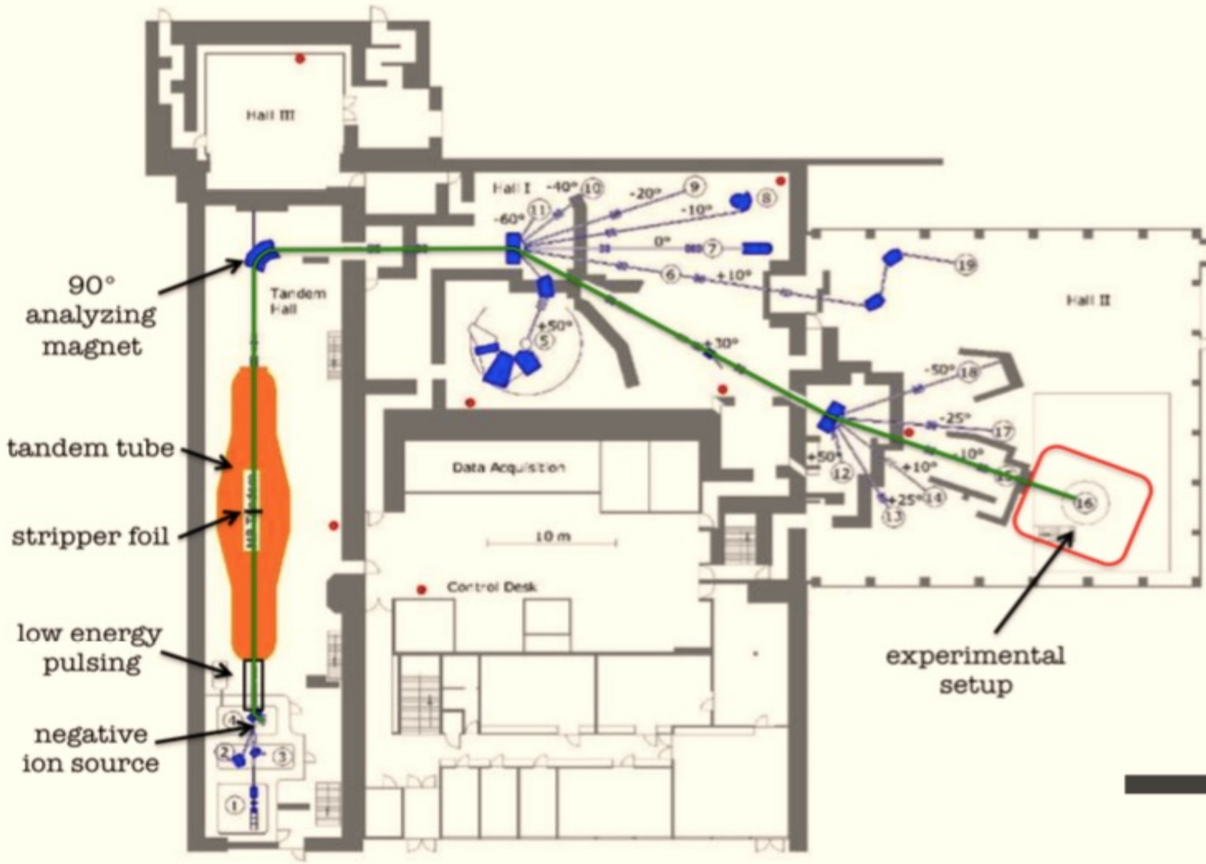


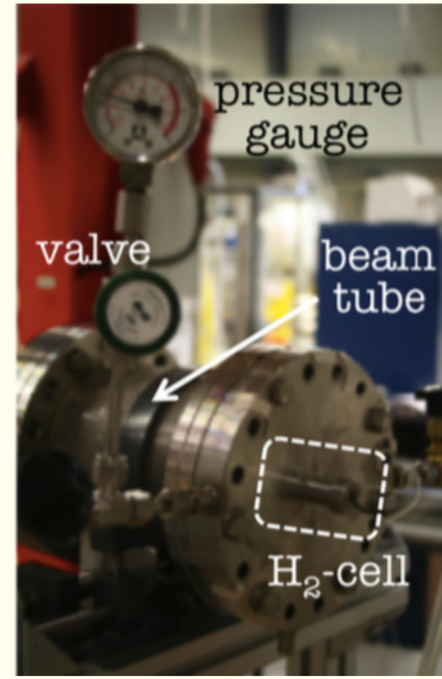
LS samples studied here: LAB + 2-3 g/l PPO [+20mg/l Bis-MSB]
used in SNO+, JUNO, LENA

→ **long fluorescence components increase with dE/dx of particles**

The beam setup at TUM

J. Winter, V. Zimmer

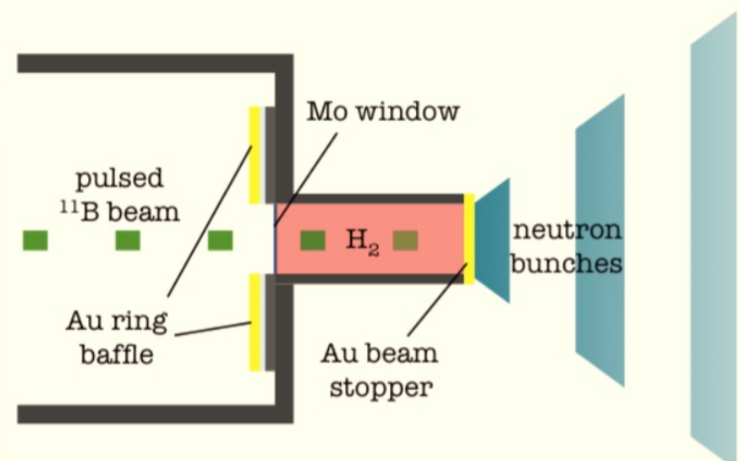




Tandem van-de-Graaf accelerator at MLL

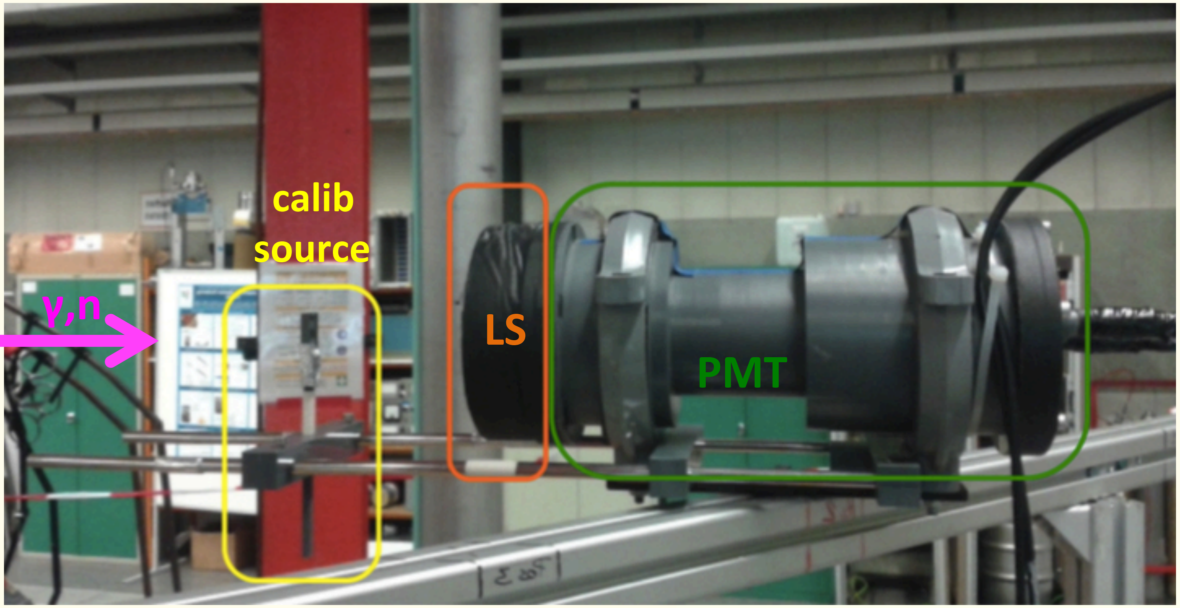
- ^{11}B (61.5MeV) on fixed proton (H_2) target
- neutrons of 11.2 MeV, γ's of <4 MeV

→ measure **pulse shapes** (and quenching)



Scintillator sample for γ,n-scattering

J. Winter, V. Zimmer



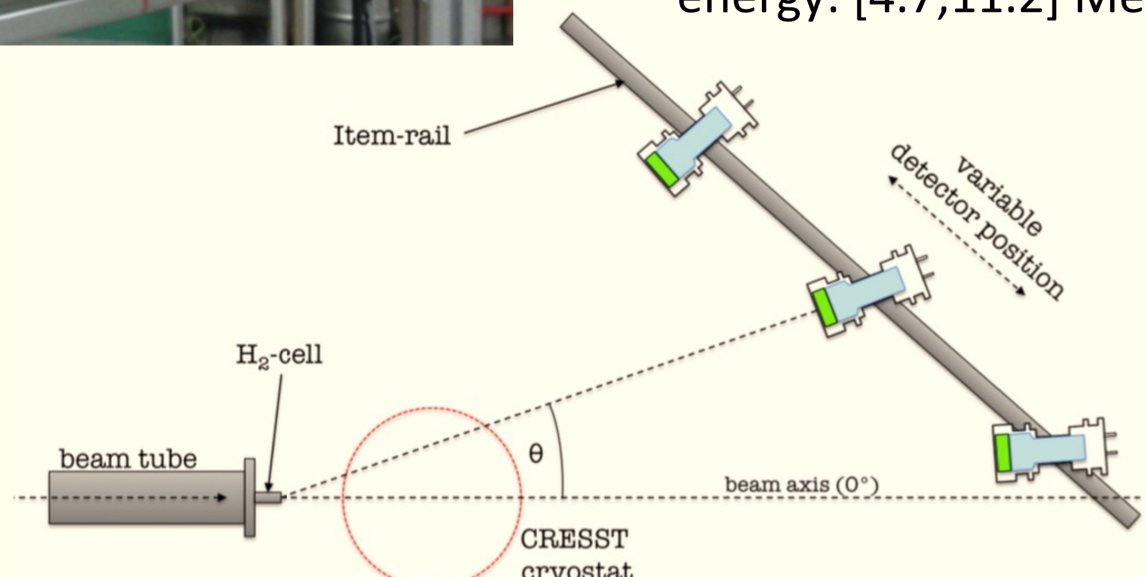
Rail system

- test cell can be moved from on-axis position
- selection of neutron energy: [4.7;11.2] MeV

Test cell

- Container with LS sample, light read-out by PMT
  [ΔE/E ~7% at 1MeV]
- gammas and neutrons scatter in the LS sample

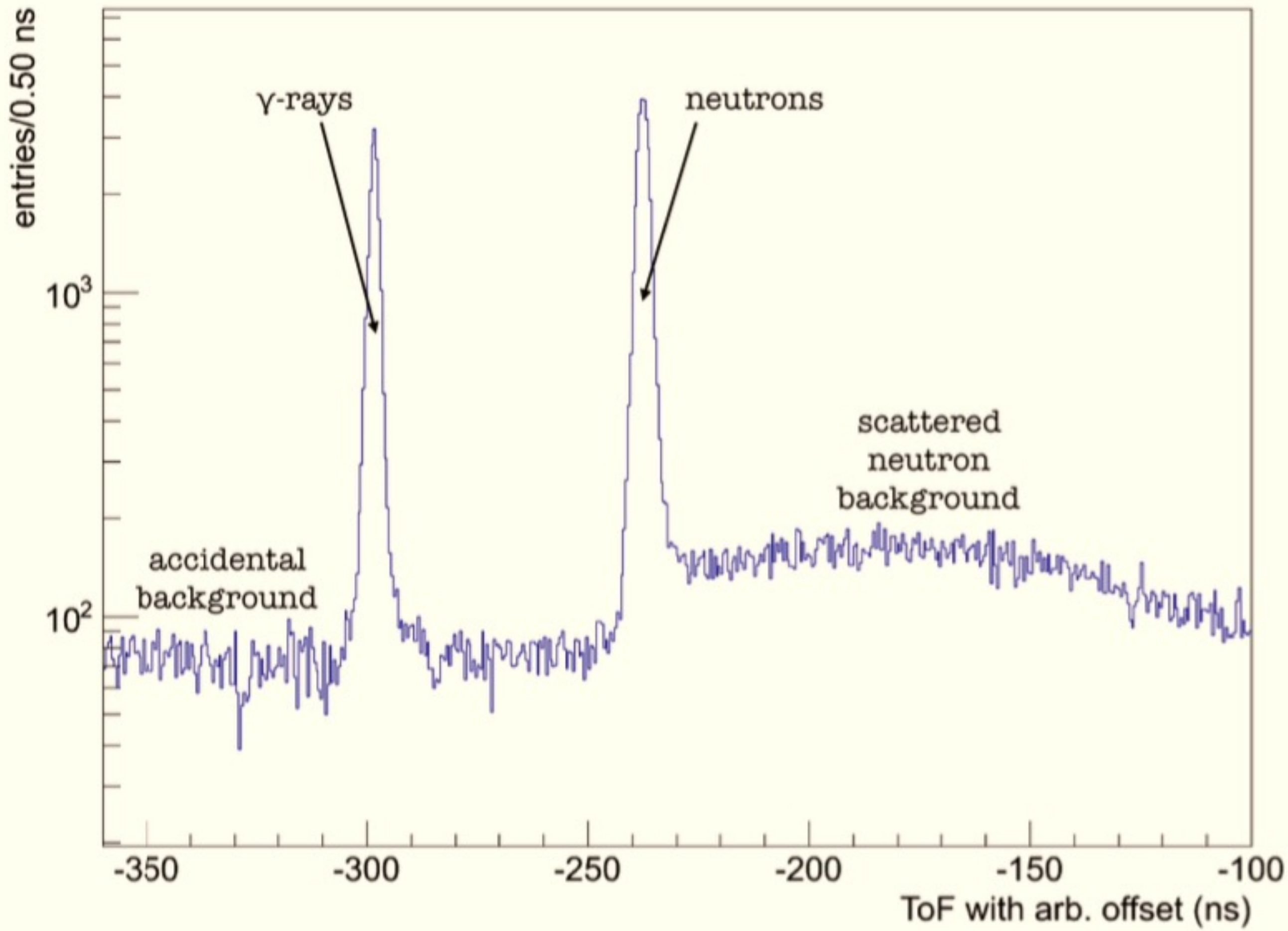
→ recoil electrons, protons



Gamma/Neutron separation by timing

J. Winter, V. Zimmer

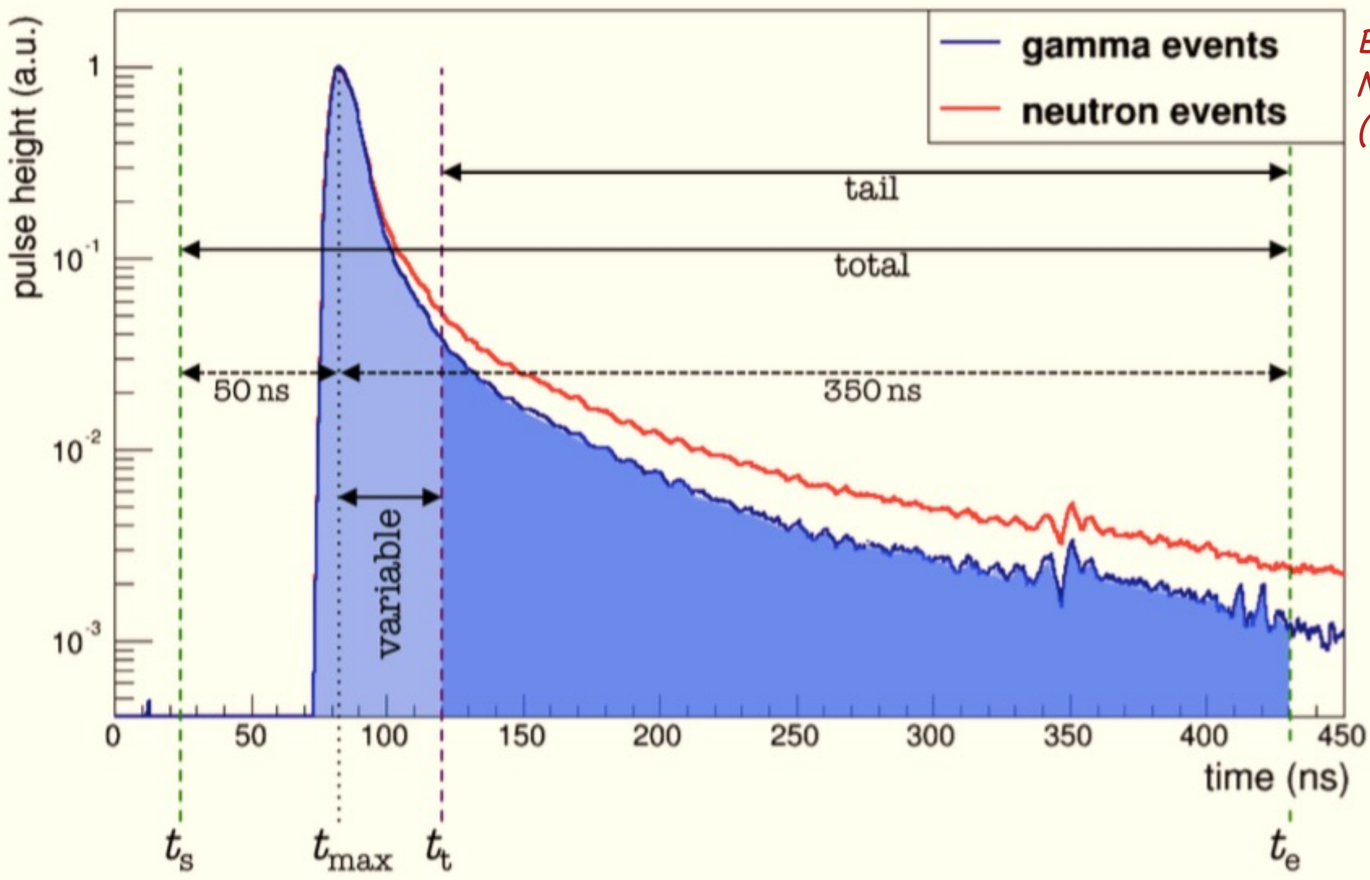
Time of flight from neutron source to LS sample



→ unambiguous samples of gamma (e) and neutron (p) events

Analyzing pulse shapes

Simple method: Ratio of tail area to total area (tail-to-total)

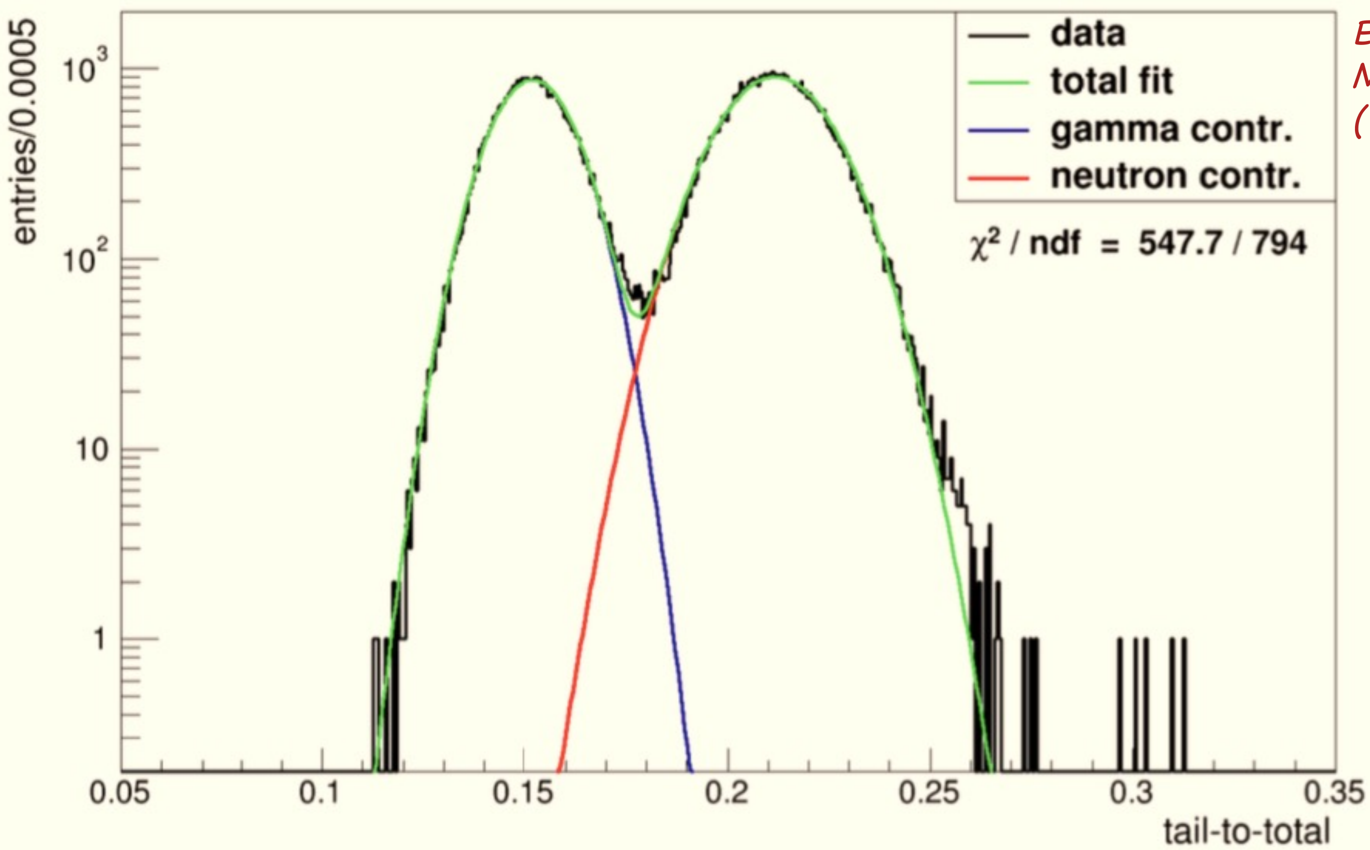


Example from MLL measurements (V. Zimmer)

→ α's and neutrons feature higher t2t-ratios than β's and γ's

Neutron-gamma separation at low energies

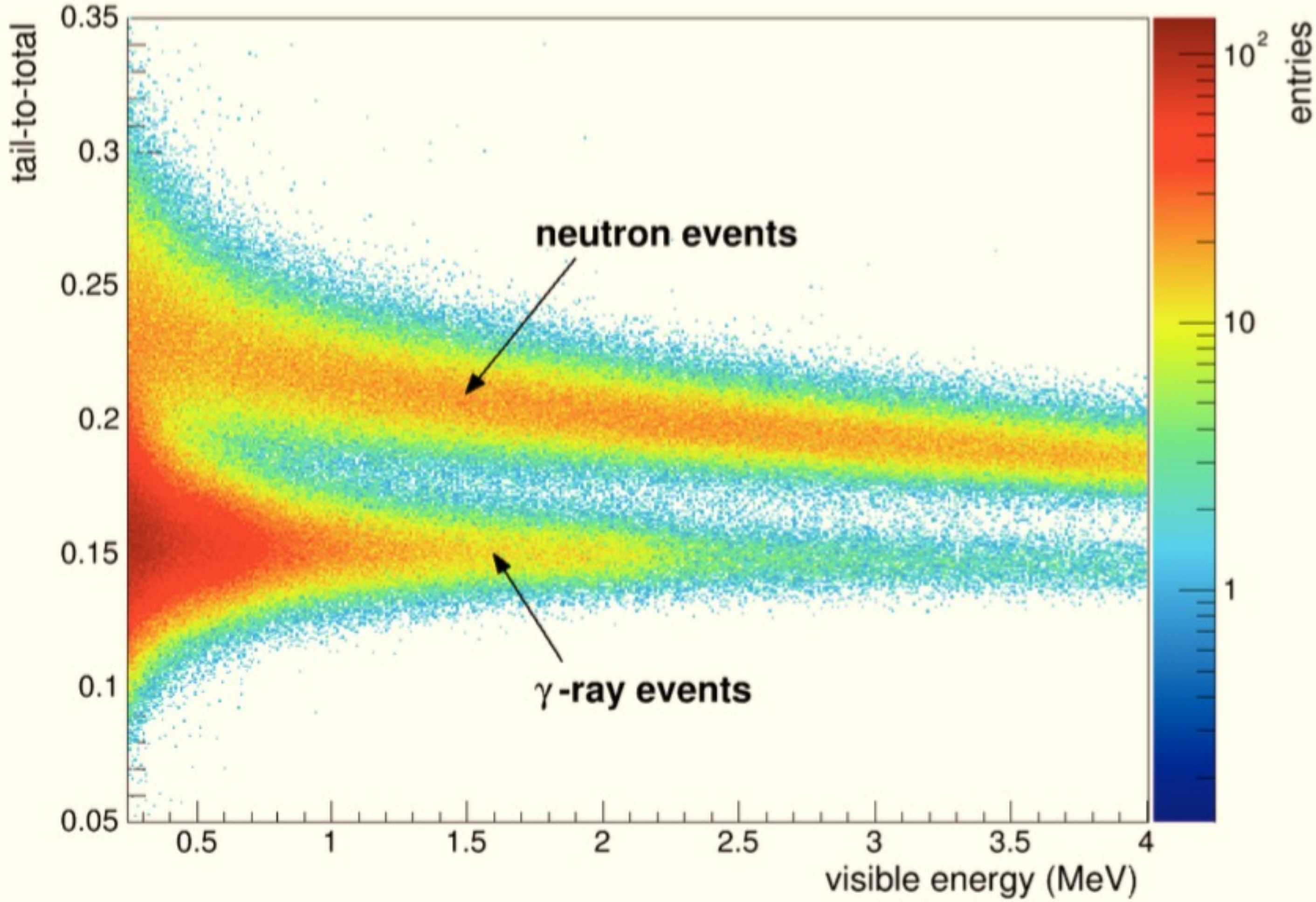
Simple method: Ratio of tail area to total area (tail-to-total)



Example from MLL measurements (V. Zimmer)

→ separation possible, but overlap of distributions

Separation power vs. visible energy (1)



→ pulse shapes become more distinct with increasing photon statistics

→ separation capability improves with energy

Separation power vs. visible energy (2)

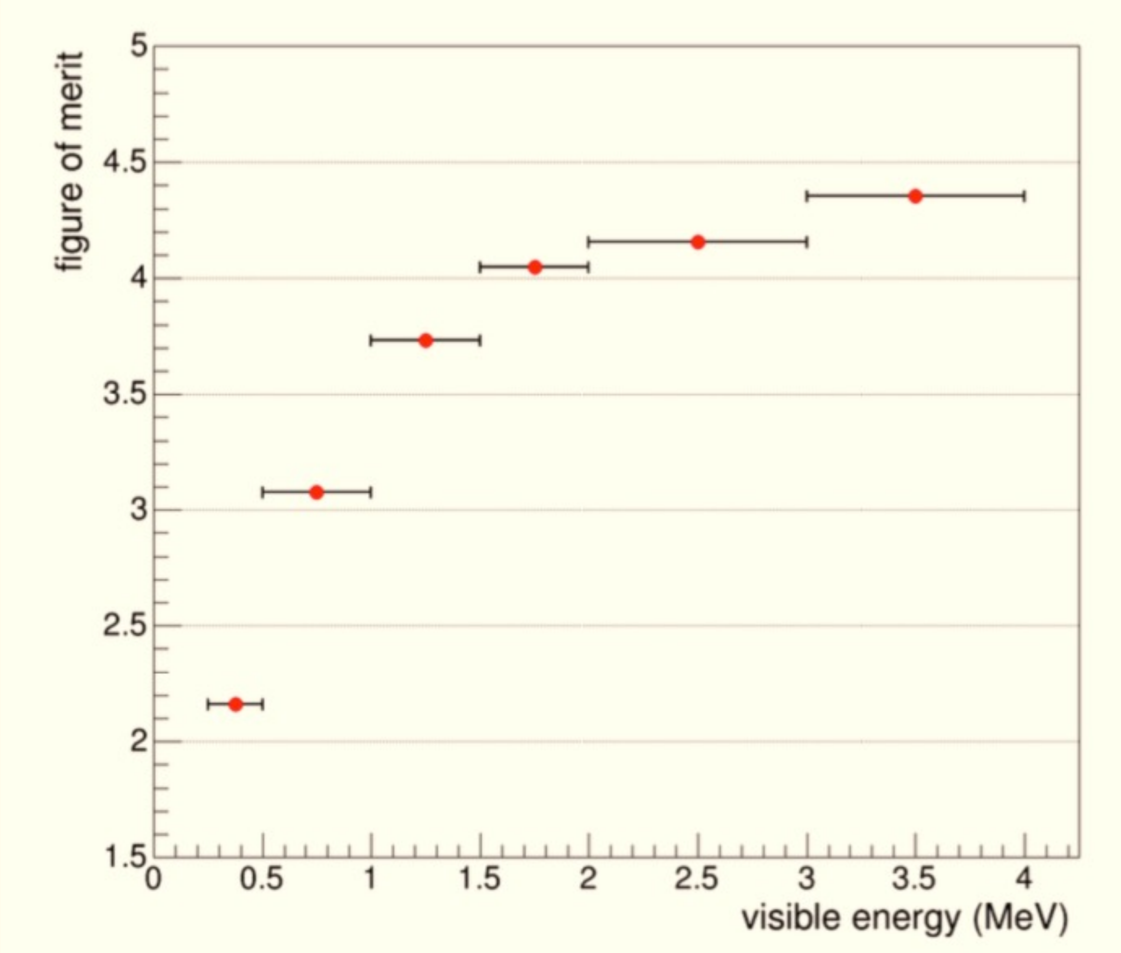


figure of merit

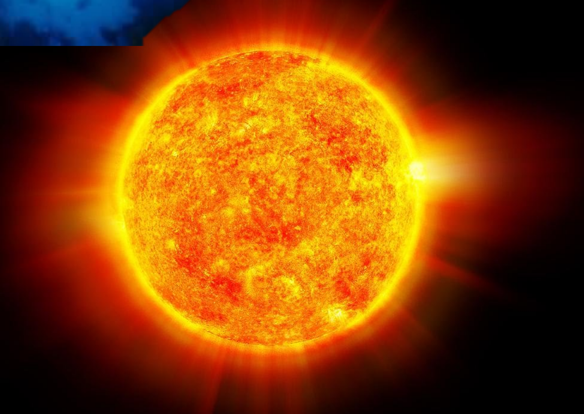
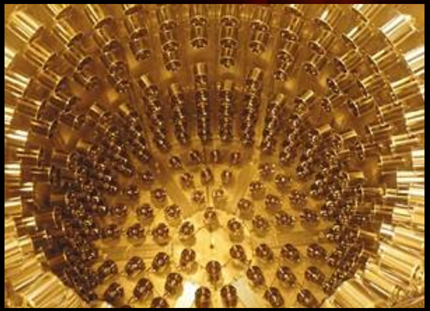
$$\frac{\mu_n - \mu_\gamma}{\sqrt{\sigma_n^2 + \sigma_\gamma^2}}$$

→ **in lab-scale samples**, separation between electrons and hadrons improves steeply with visible energy of the events

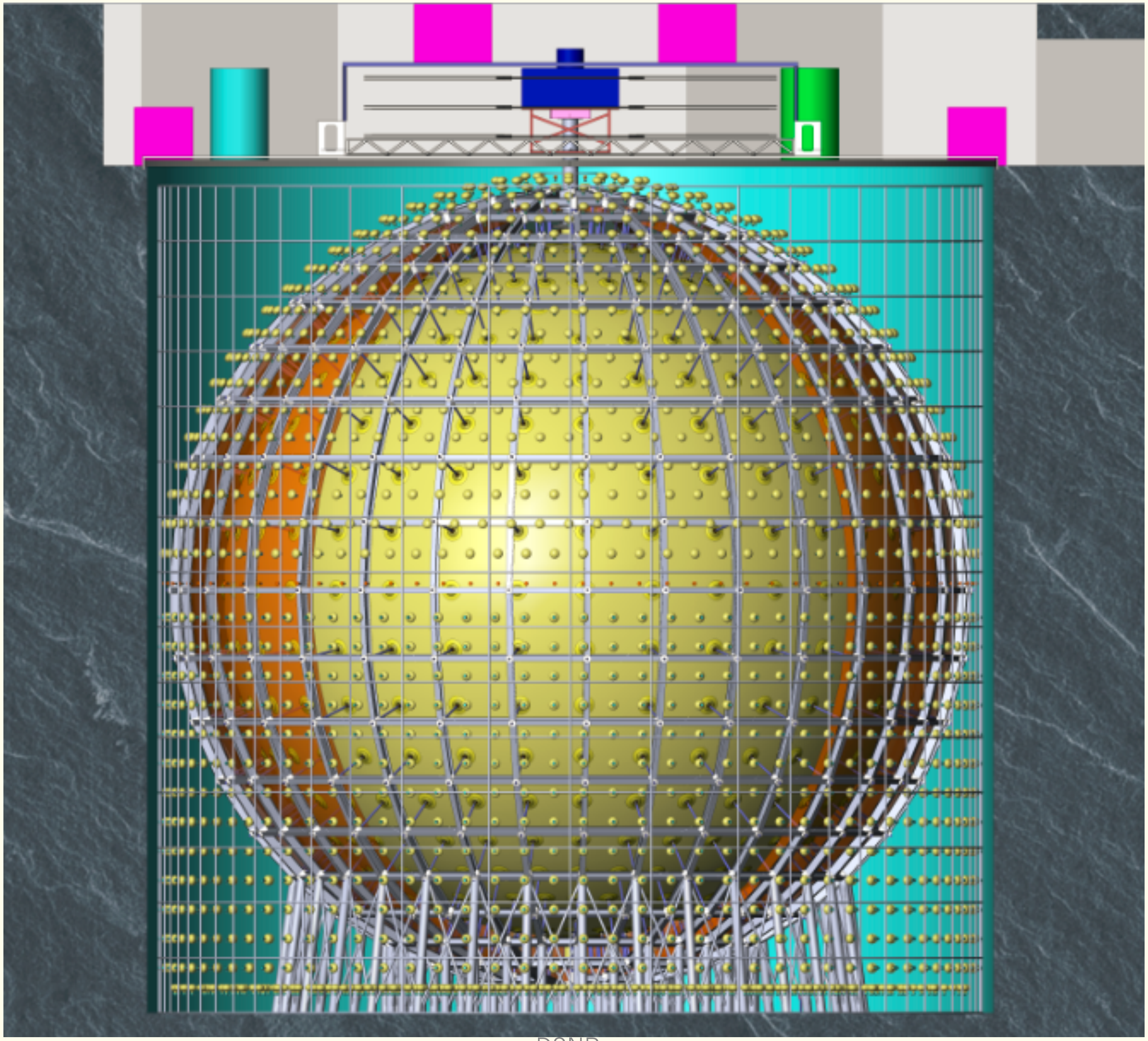
JUNO physics program

- Reactor neutrino oscillations
  - neutrino mass hierarchy
  - precise measurement of osc. parameters: Δm^2_{21}~0.6%, Δm^2_{ee}~0.4%, $\sin^2\theta_{12}$~0.7%
- Neutrinos from natural sources
  - Galactic Supernova neutrinos
  - Diffuse Supernova Neutrino Background
  - Solar neutrinos
  - Geoneutrinos
  - Neutrinos from dark matter annihilation
  - Atmospheric neutrinos
- Short-baseline oscillations (sterile ν's)
- Proton decay into $K^+\bar{\nu}$

→ JUNO Yellow Book, arXiv:1507.05613

JUNO detector layout



JUNO detector layout – details

Calibration

Top muon veto
Scintillator panels

Outer water tank
Muon Cherenkov veto

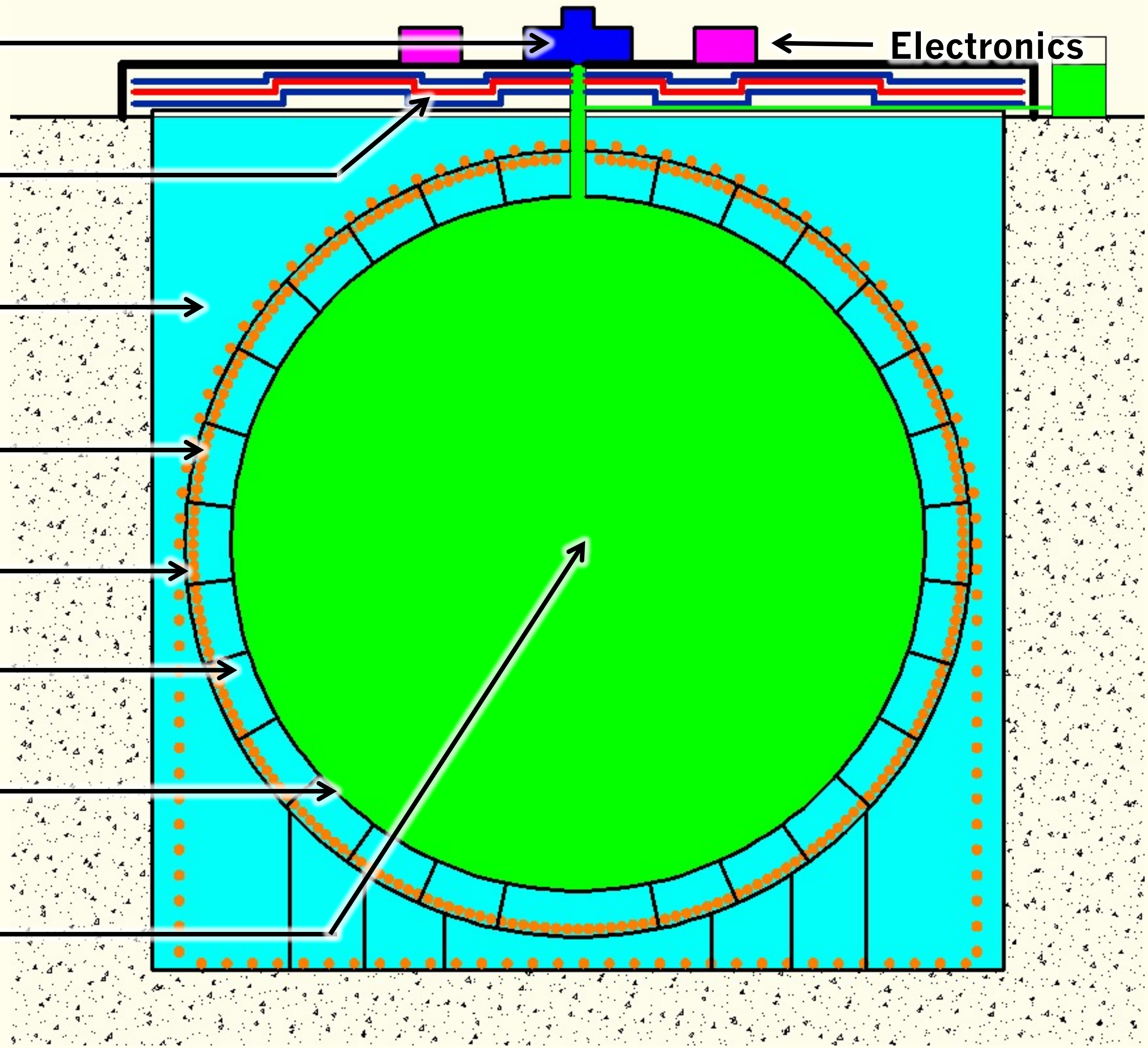
Steel support structure
optical separation

17,000 PMTs (20‘‘)

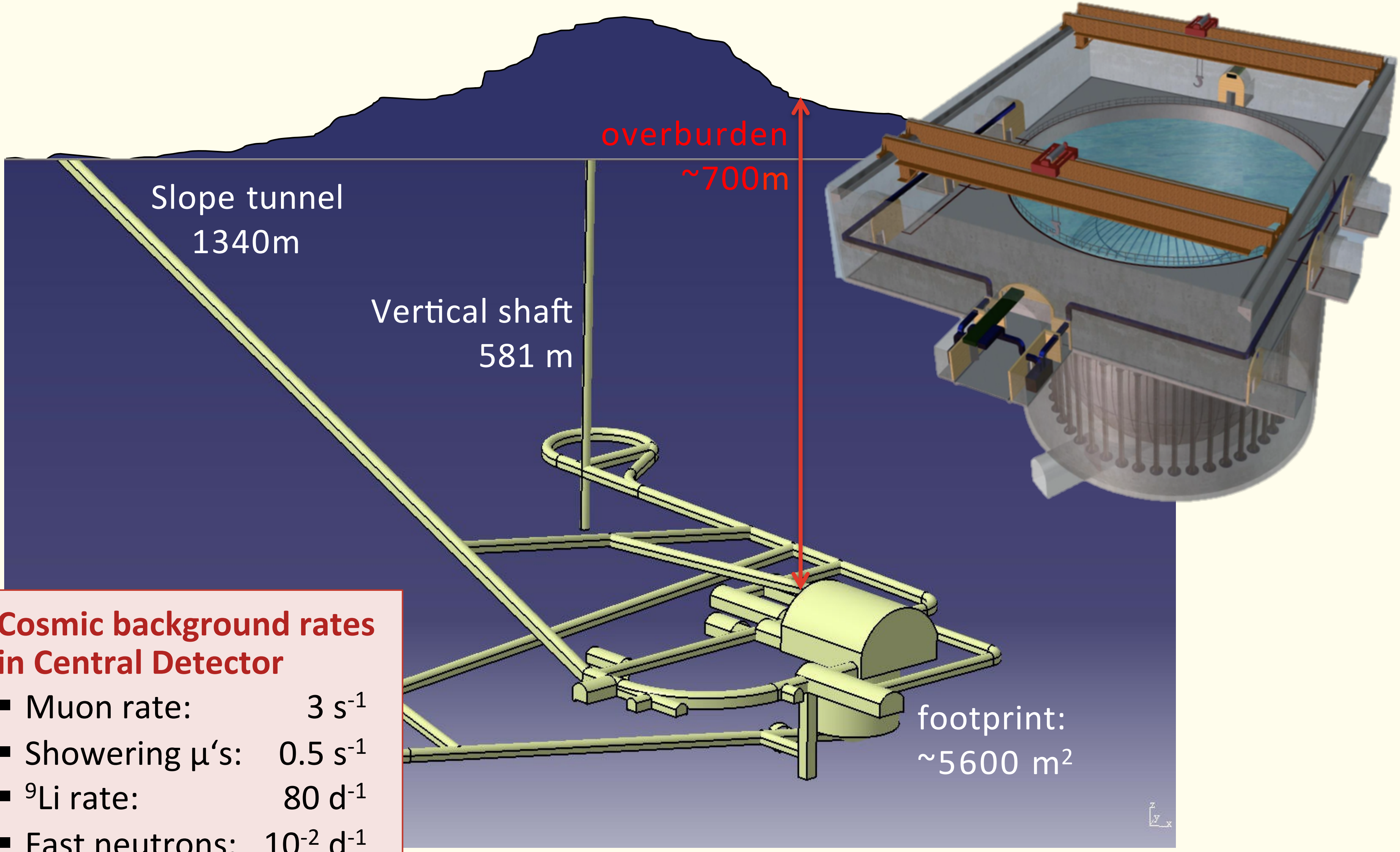
water buffer (2m)

Acrylic sphere
diameter: 35.4m

Liquid scintillator
20 kt of LAB



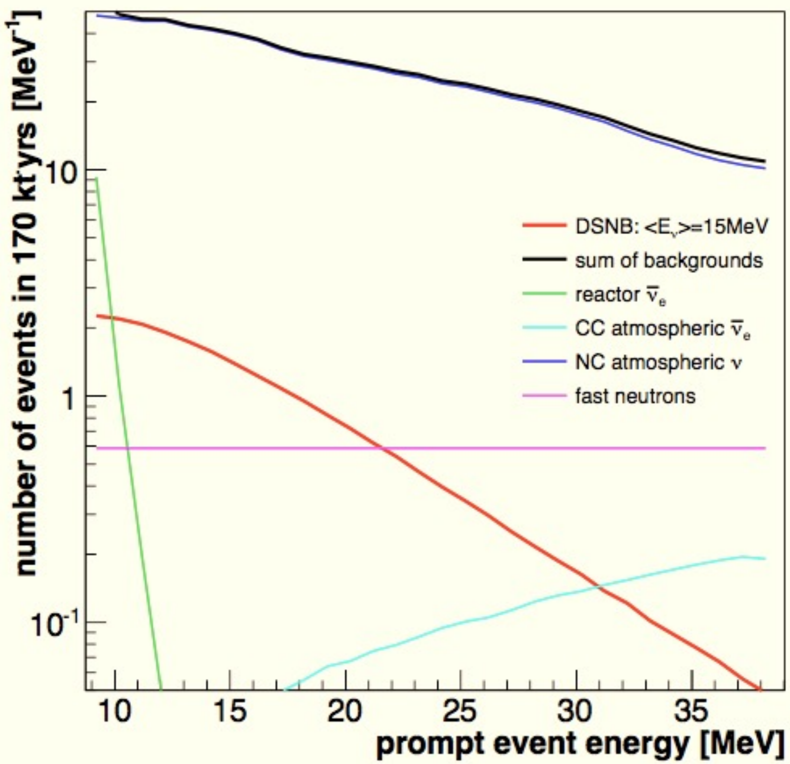
JUNO rock shielding



Cosmic background rates in Central Detector

- Muon rate: $3\ s^{-1}$
- Showering μ's: $0.5\ s^{-1}$
- ^{9}Li rate: $80\ d^{-1}$
- Fast neutrons: $10^{-2}\ d^{-1}$

Backgrounds to DSNB detection



Event rates in the 11-30MeV range:

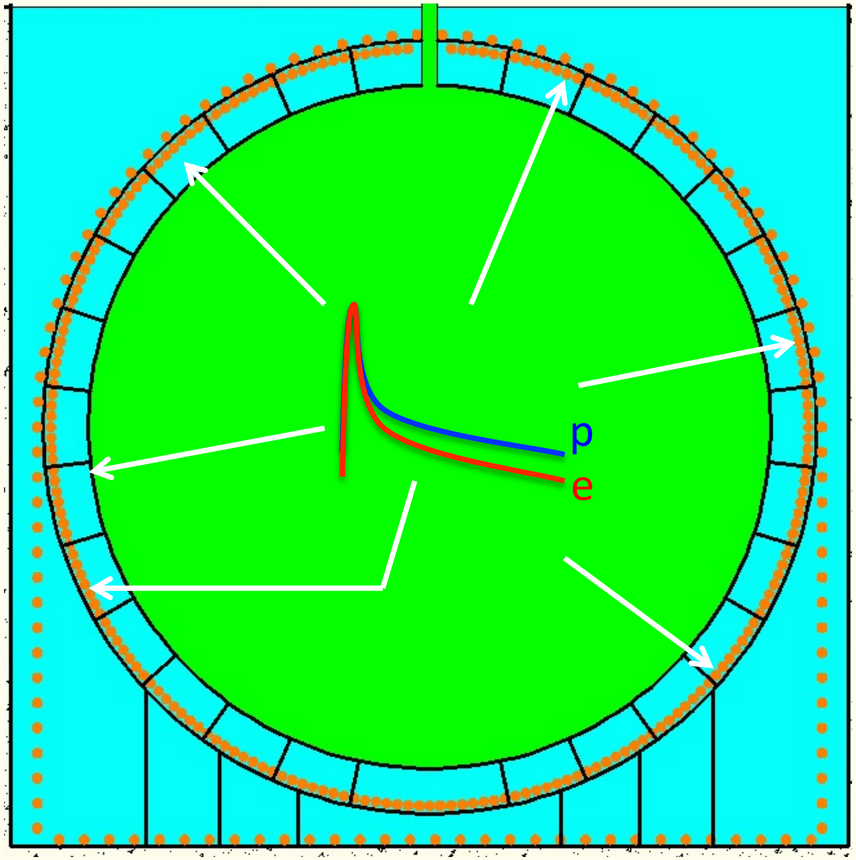
	Contribution	Rate [yr^{-1}]
DSNB Signal	$<E_\nu>=12MeV$	1.3
	$<E_\nu>=15MeV$	2.3
	$<E_\nu>=18MeV$	3.3
	$<E_\nu>=21MeV$	3.9
Backgrounds	Reactor ν's	0.03
	Atm. ν's CC	0.13
	Atm. ν's NC	60
	Fast neutrons	2.0
	Total	**62**

w/o pulse shape discrimination:

- atmospheric ν NC reactions
- fast neutrons

dominate the DSNB signal

Pulse shape discrimination in large detectors



From lab experiments to JUNO

- starting point: light emission curves aquired in lab experiment
- add light propagation effects to PMTs (scattering, n(λ) etc.)
- PMT time resolution effects

→ signal as observed in experiment

Pulse shape analysis in JUNO

- reconstruction of event vertex from photon arrival time distribution
- subtraction of photon TOF effects

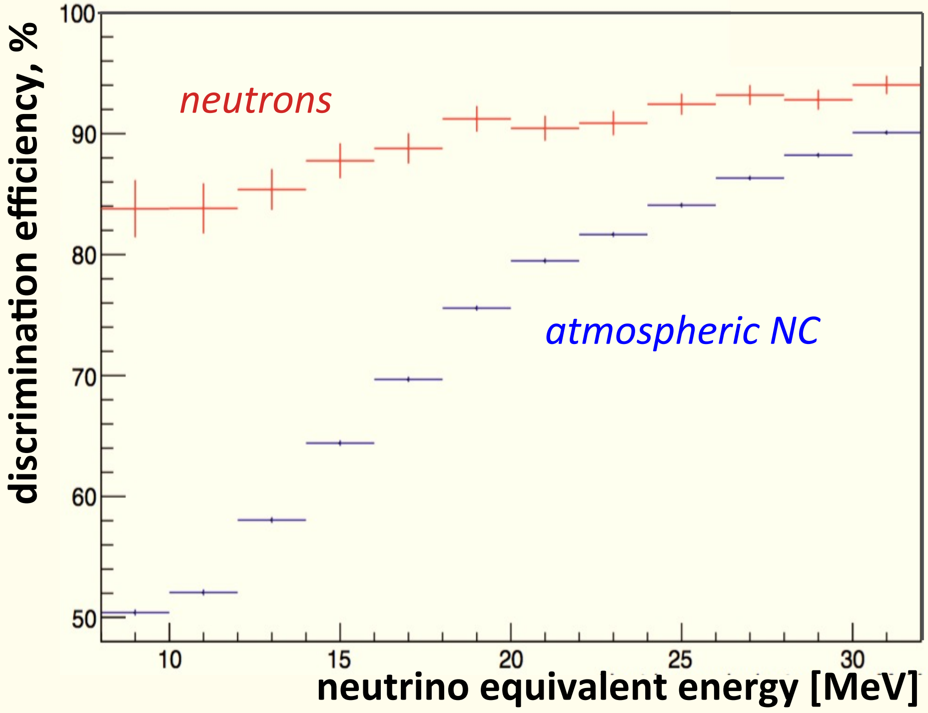
→ original fluorescence profile

Up to now: PSD performance based on LENA MC (~1/4 of JUNO light yield)

Pulse Shape Discrimination for DSNB

PSD to be used not only for **atmospheric NC** but also **fast neutron** background:

PSD discrimination efficiency vs.E_{vis}
DSNB signal acceptance: **95%**



PSD efficiencies vs. signal acceptance

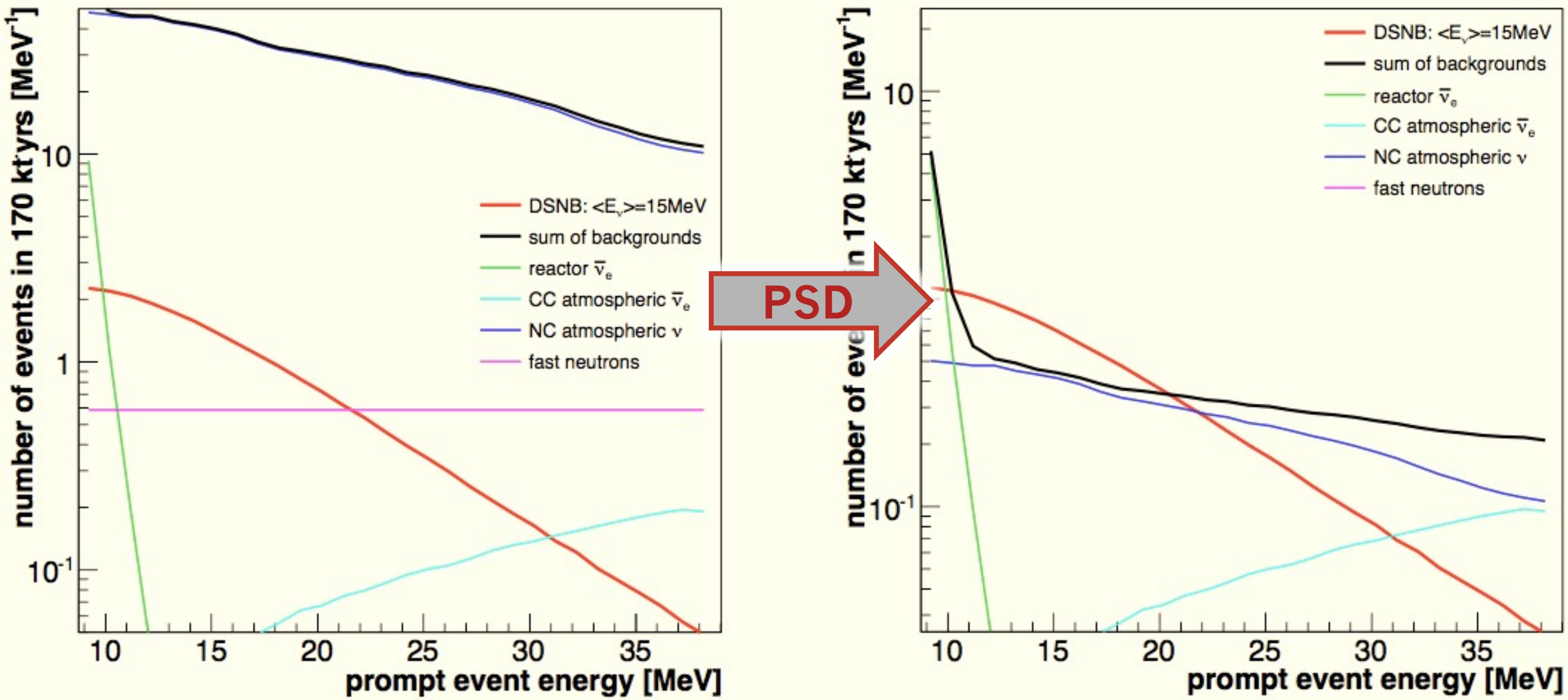
IBD acceptance	FN rejection	NC rejection
95%	84.3%	66.6%
90%	91.8%	87.4%
80%	95.2%	94.8%
55%	97.8%	98.9%
50%	98.1%	99.1%
40%	98.5%	99.3%

→ IBD acceptance has to be reduced to ~50% to obtain sufficient BG rejection

→ fast neutron detection allows to use almost the entire scintillator volume

DSNB backgrounds after PSD

from JUNO Yellow Book



before PSD:

- atmospheric ν NC reactions
- fast neutrons

dominate the DSNB signal

after PSD:

- atm. NC & FN greatly reduced
- reactor & atmospheric IBDs define observation window

Predicted DSNB signal and background rates

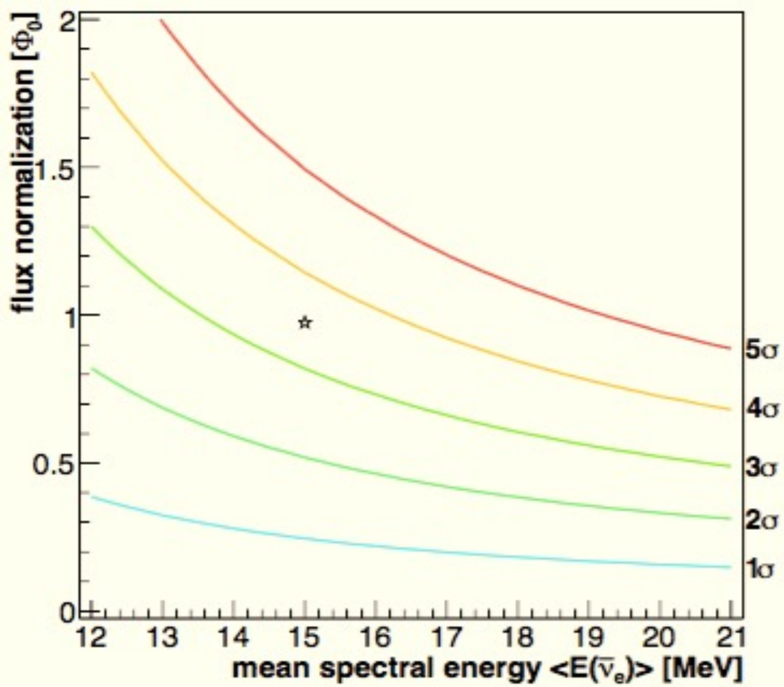
	Contribution	Rate [yr^{-1}]	PSD efficiency	Rate w/ PSD [yr^{-1}]
DSNB Signal	$\langle E_\nu \rangle$=12MeV	1.3	50%	0.7
	$\langle E_\nu \rangle$=15MeV	2.3		1.2
	$\langle E_\nu \rangle$=18MeV	3.3		1.6
	$\langle E_\nu \rangle$=21MeV	3.9		1.9
Backgrounds	Reactor ν's	0.03	50%	0.01
	Atm. ν's CC	0.13	50%	0.07
	Atm. ν's NC	60	1.1%	0.62
	Fast neutrons	2.0	1.3%	0.02
	Total	**61**		**0.7**

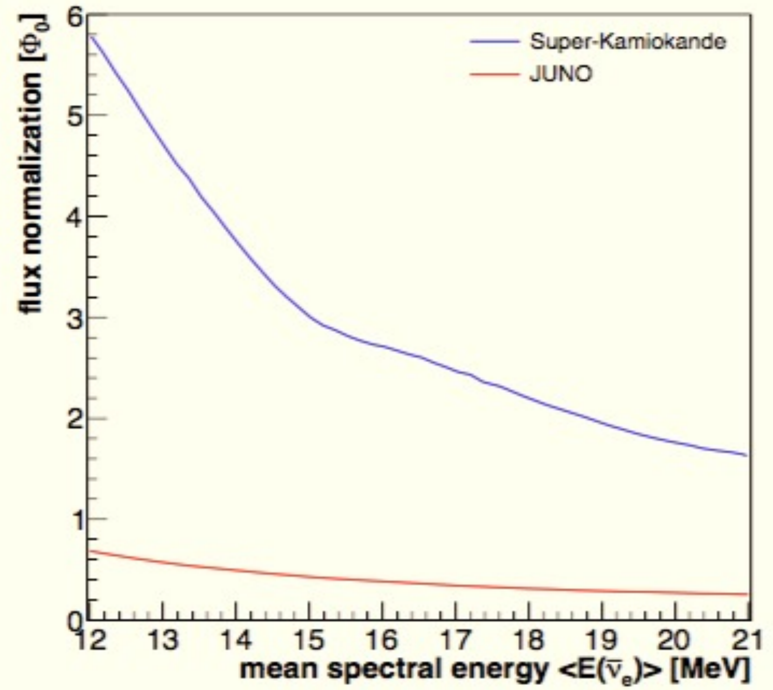
→ DSNB statistics reduced to half the original value, but S:B ≥ 1

→ collecting statistics for several years, spectral information becomes available

DSNB sensitivity of JUNO (preliminary)

from JUNO Yellow Book [arXiv:1507.05613]





- **Discovery potential**
  - **exposure: 17kt x 10 yrs**
  - syst. uncertainty on BG rate: 5%

  → **possibility for evidence of DSNB signal at 3σ level**

- **Exclusion plot**
  - same assumptions as before
  - only BG prediction detected

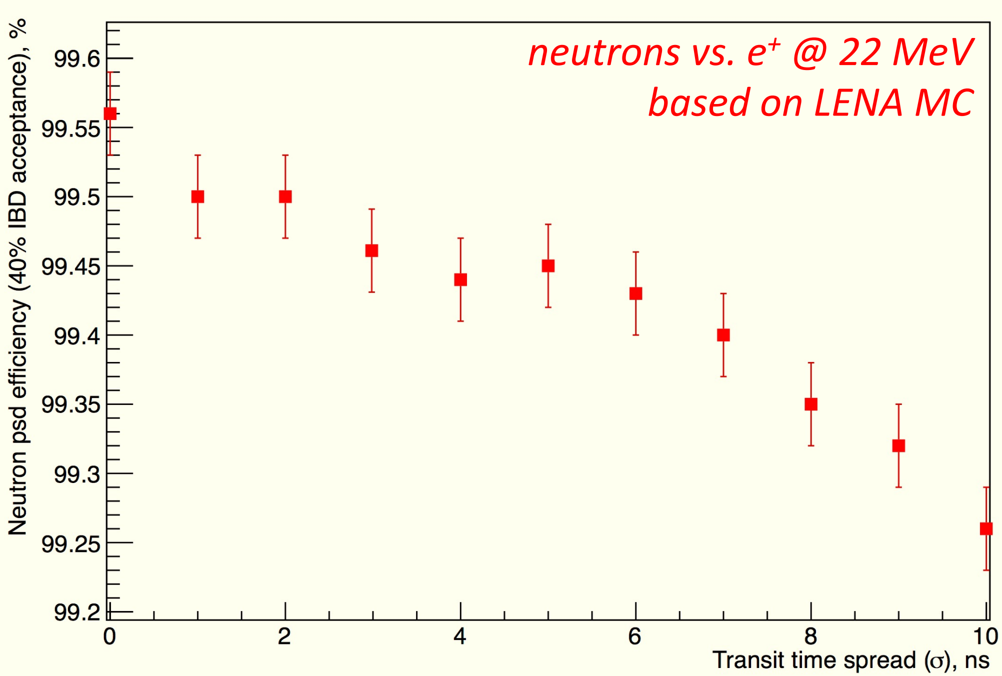
  → **significant improvement over current Super-K limit**

Current activities in JUNO

→ porting the full analysis to JUNO MC framework

→ evaluate the JUNO-specific impact on PSD

- 4x larger photoelectron yield:
  improved discrimination power
- 2/3 of CD-PMTs with transit time spread of 12ns:
  mild reduction of PSD power expected



tts ~ 3ns

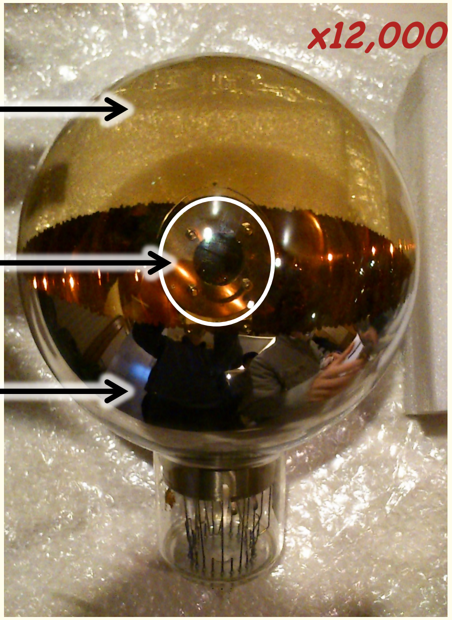
Hamamatsu R12860 (20"PMT)

front cathode transmission

MCP doublet back-to-back

back cathode reflection

tts ~ 12ns



20'' MCP-PMT (prototype)

Conclusions

- Detection of the DSNB will provide information on the average SN neutrino spectrum and the cosmic SN rate
- Positive evidence for the DSNB is just within reach of present and upcoming few-10kt detectors
- **Liquid scintillator** and especially **JUNO** will be able to contribute
- The primary background, **atmospheric neutrino NC reactions**, dominates the DSNB signal, but can be greatly reduced based on the **excellent pulse-shaping capabilites** expected for JUNO
- Preliminary study suggests **3σ evidence in JUNO after 10 years**
- More detailed studies are on-going.

Thank you!

The JUNO Collaboration

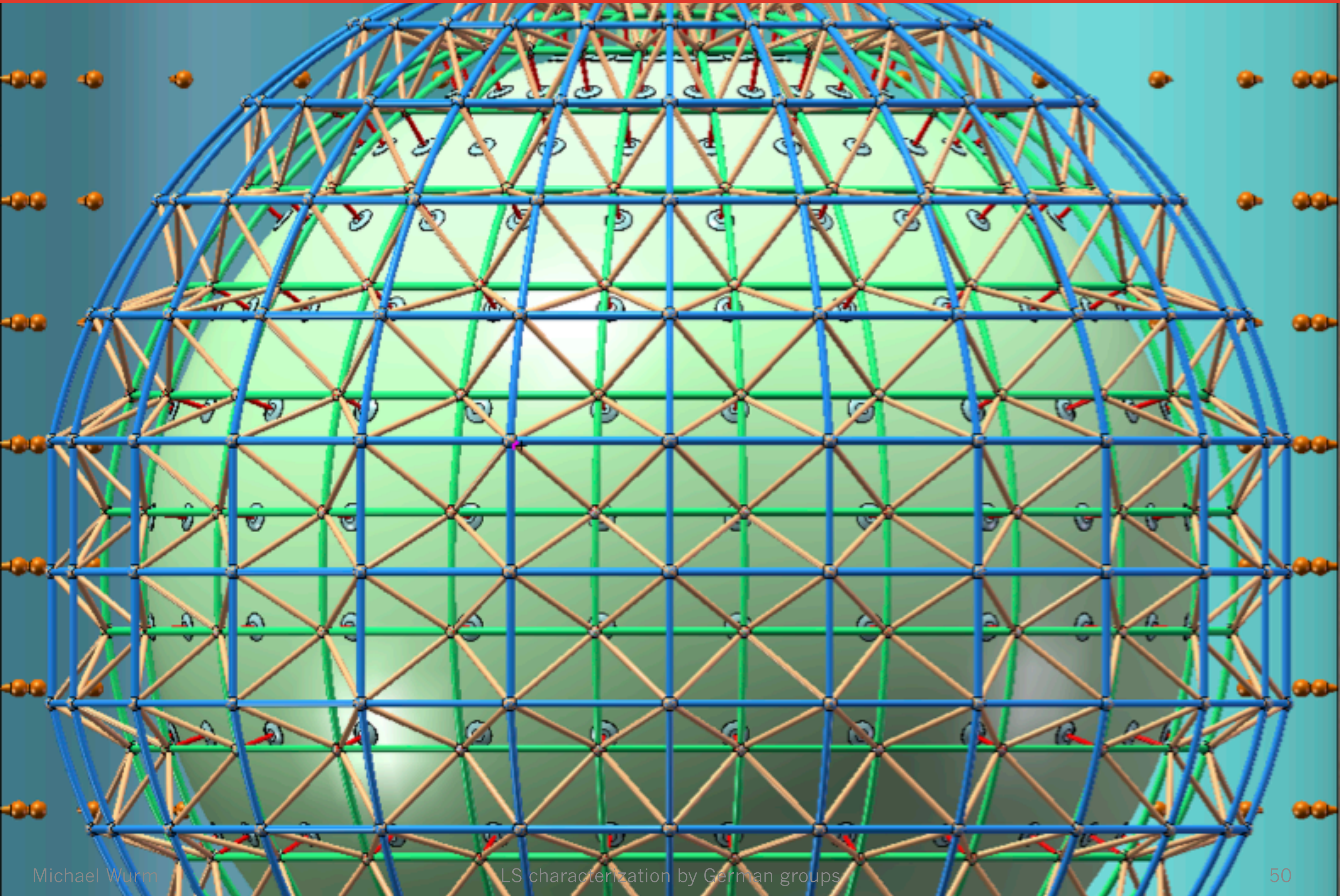
380 scientists, 60 institutions, 1/3 from Europe

Armenia, Austria, Belgium, Brazil, Chile, Chinese Republic, Czech Republic, Germany, Finland, France, Italy, Japan, Korea, Russia, Taiwan, and the United States

German institutes

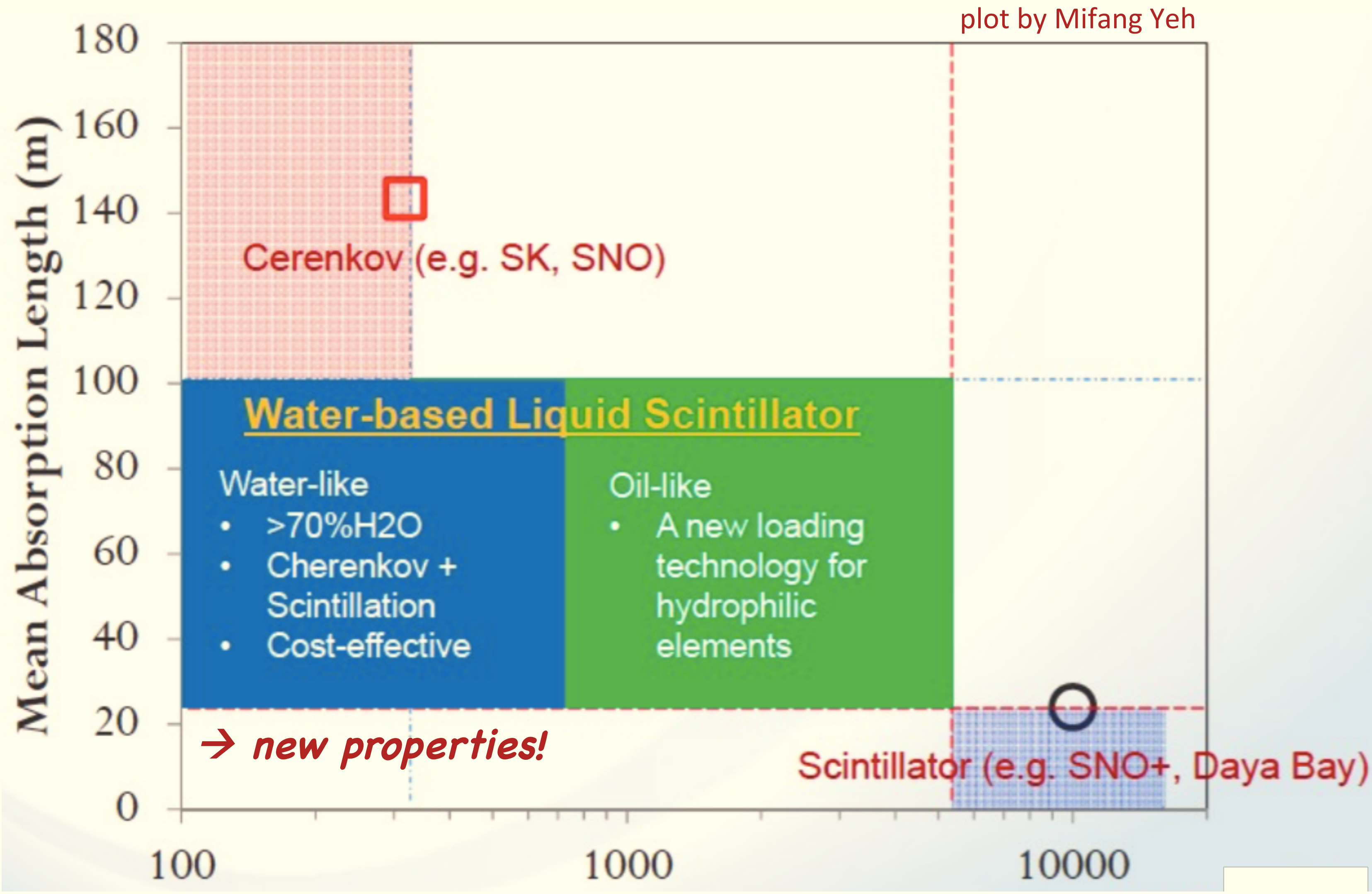
- RWTH AACHEN UNIVERSITY
- Universität Hamburg – DER FORSCHUNG | DER LEHRE | DER BILDUNG
- JÜLICH FORSCHUNGSZENTRUM
- JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ
- TUM Technische Universität München
- EBERHARD KARLS UNIVERSITÄT TÜBINGEN

Backup Slides

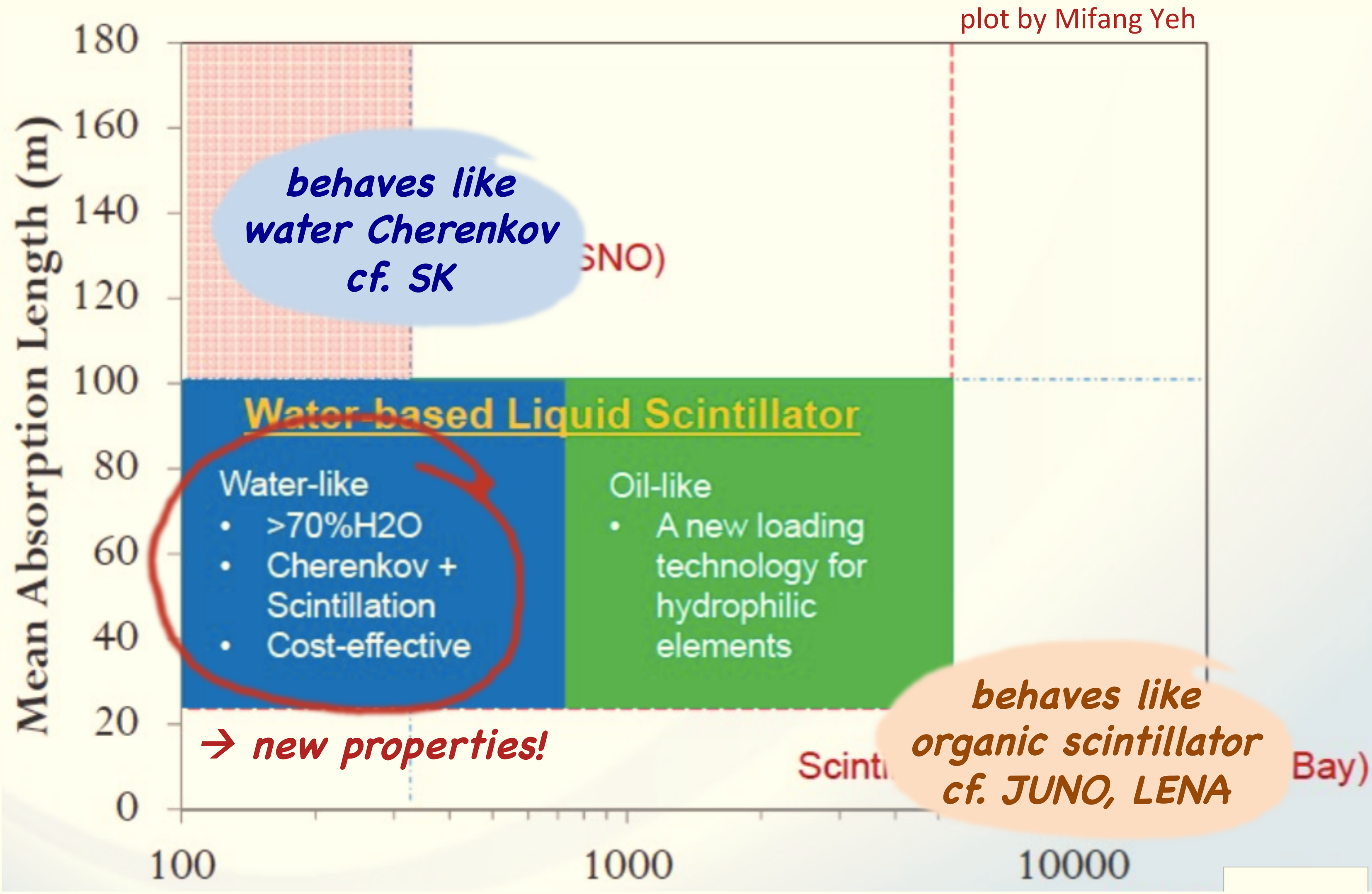


Potential of water-based scintillators

plot by Mifang Yeh



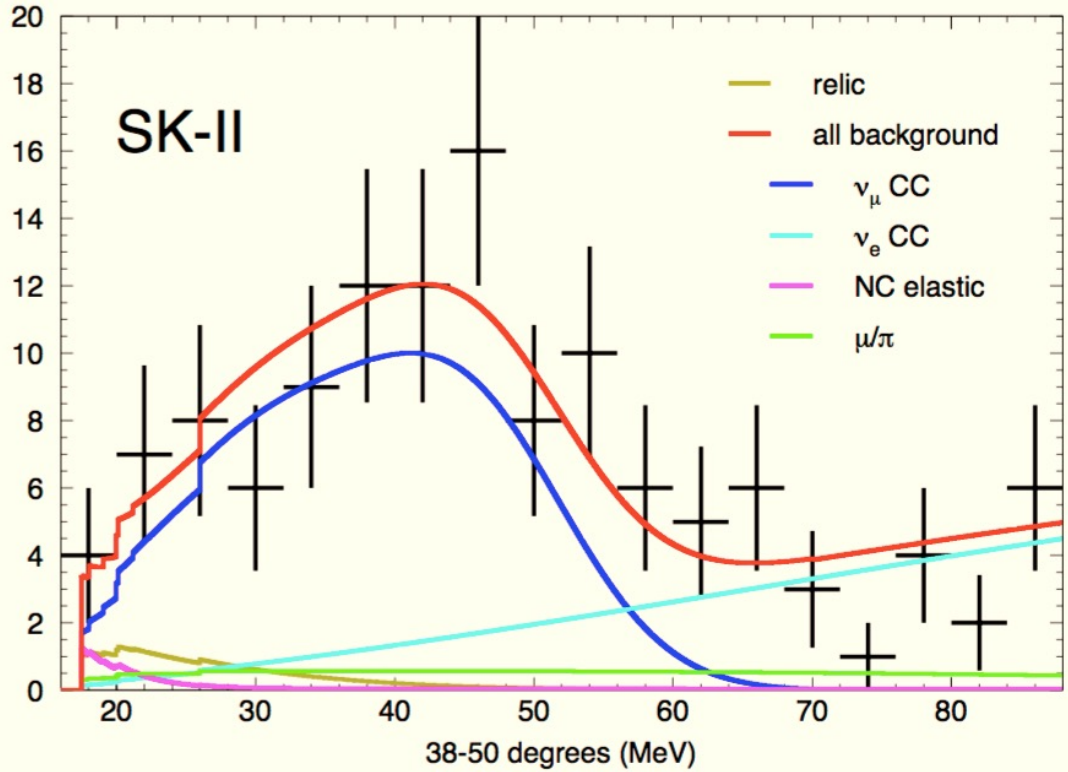
Potential of water-based scintillators



Adding scintillation to Cherenkov detector

compared to pure water

- adds neutron detection tag
- **"invisible muons"** no longer invisible

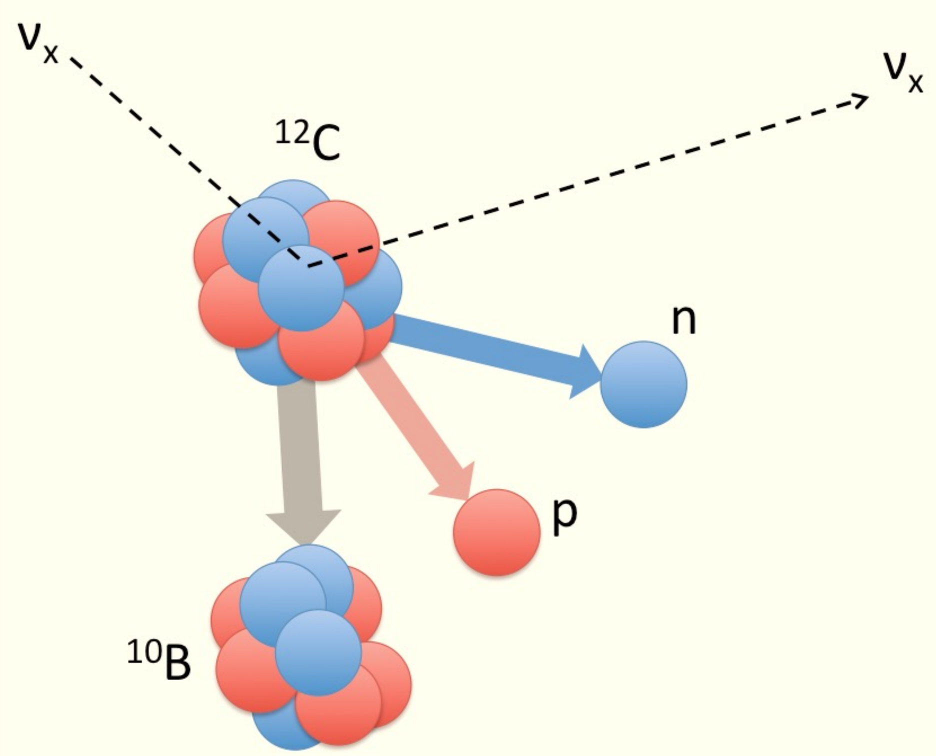


positron energy [MeV]

Adding scintillation to Cherenkov detector

compared to pure water

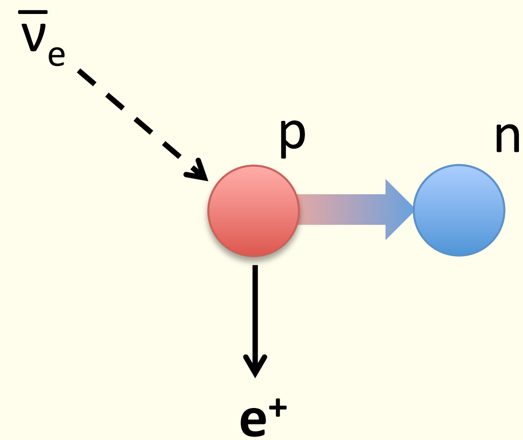
- adds neutron detection tag
- **"invisible muons"** no longer invisible
- but: appearance of atmospheric NC background?



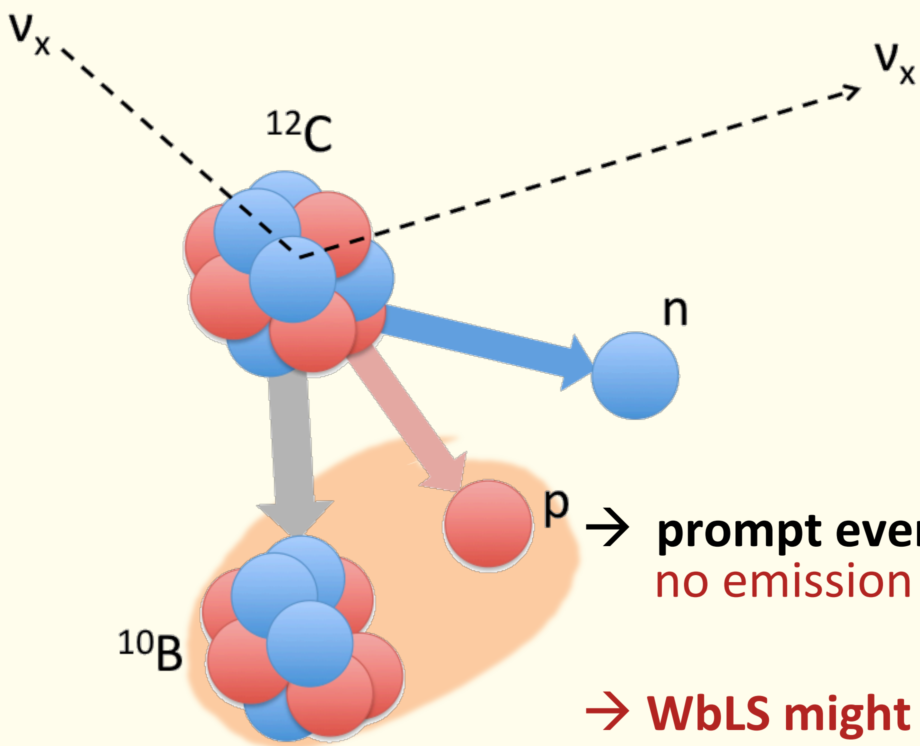
Adding Cherenkov to scintillation detector

compared to pure water

- adds neutron detection tag
- **"invisible muons"** no longer invisible
- but: appearance of atmospheric NC background?



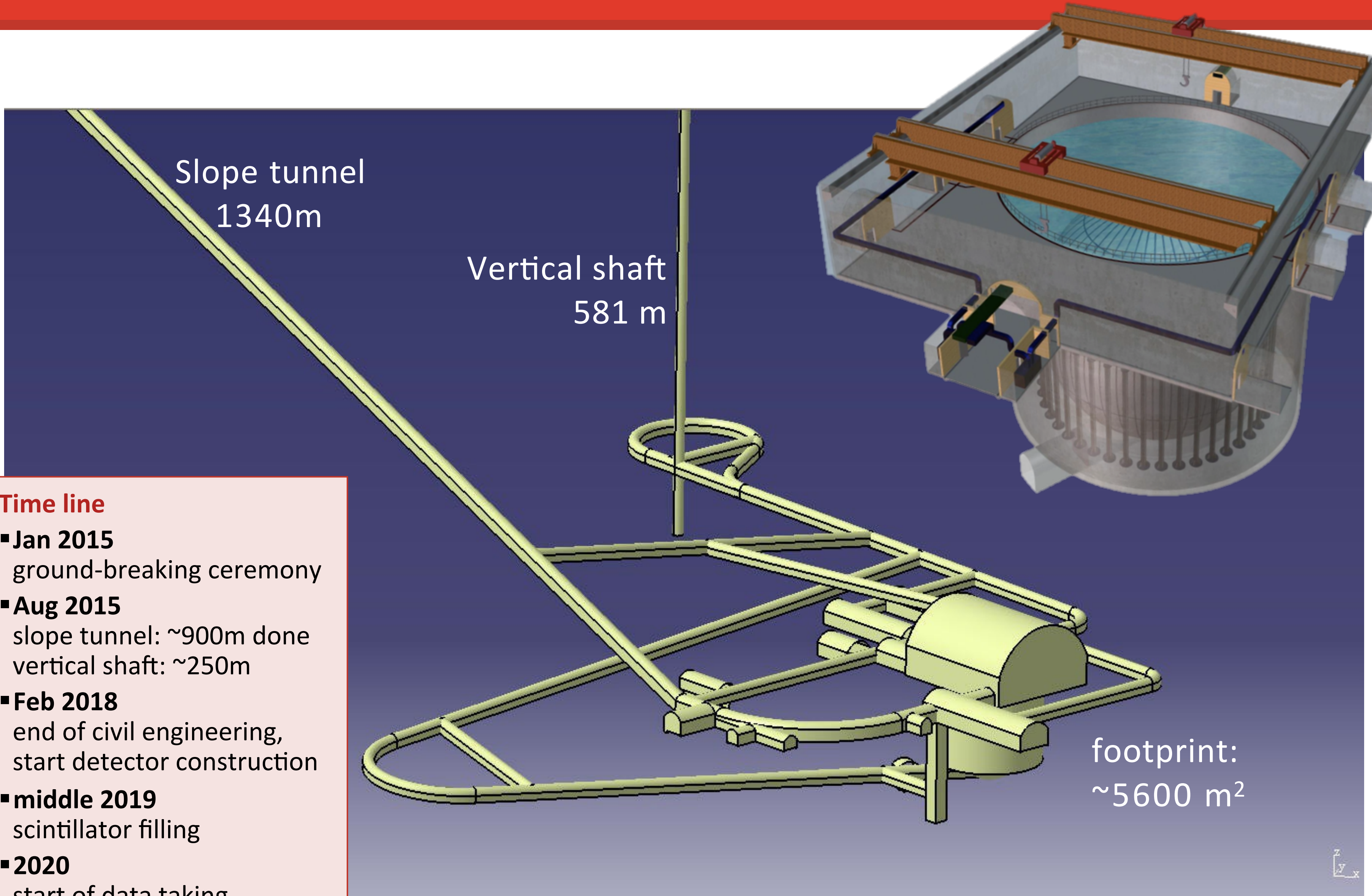
→ **prompt event:** positron emits both scintillation and Cherenkov



→ **prompt event:** low-energy protons (α's, nuclei): no emission of Cherenkov light!

→ **WbLS might provide very efficient discrimination!**

Schedule

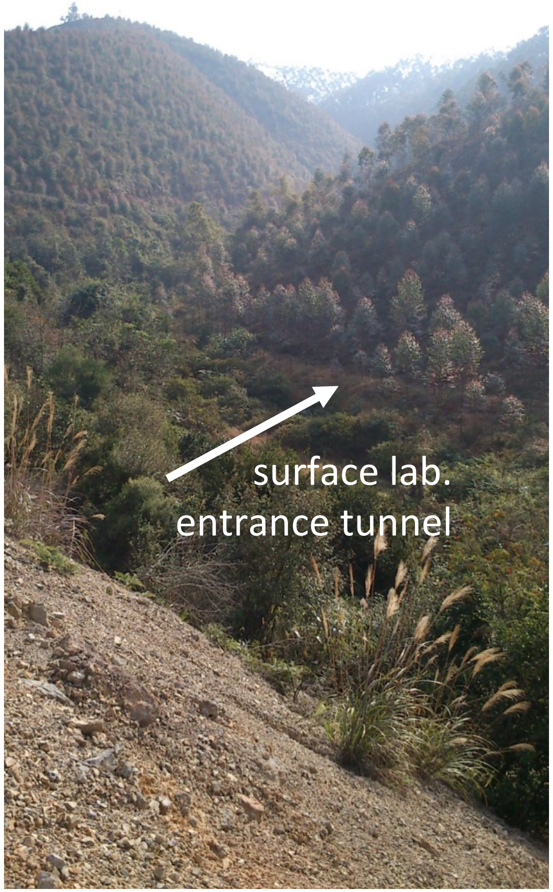


Time line

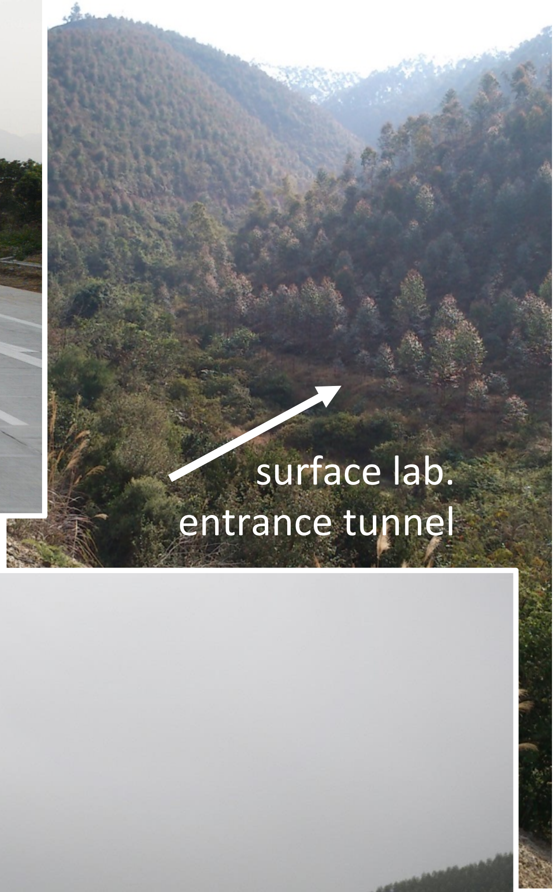
- **Jan 2015**
  ground-breaking ceremony
- **Aug 2015**
  slope tunnel: ~900m done
  vertical shaft: ~250m
- **Feb 2018**
  end of civil engineering,
  start detector construction
- **middle 2019**
  scintillator filling
- **2020**
  start of data taking

Slope tunnel

Surface facilities

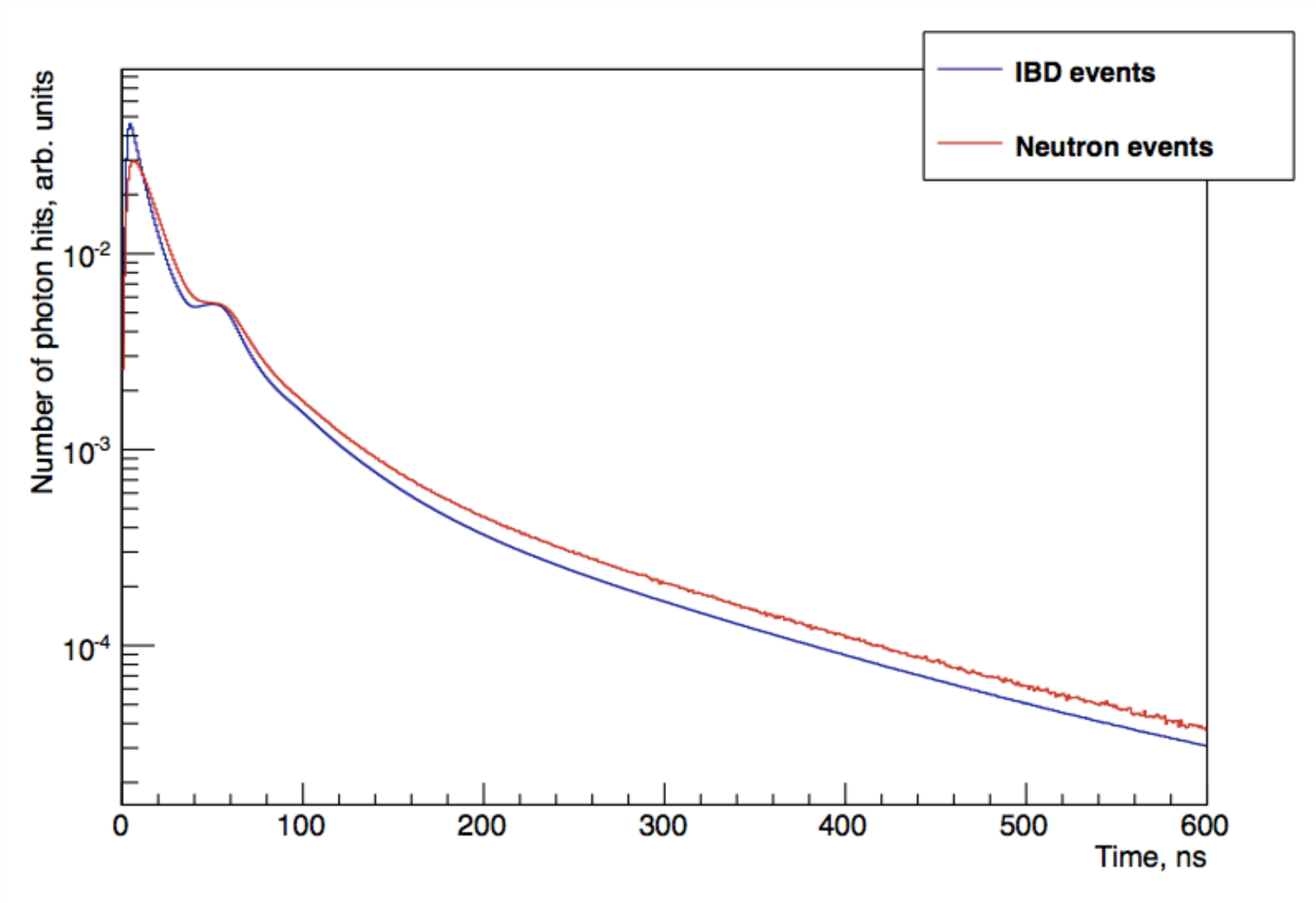


Surface facilities



Surface facilities

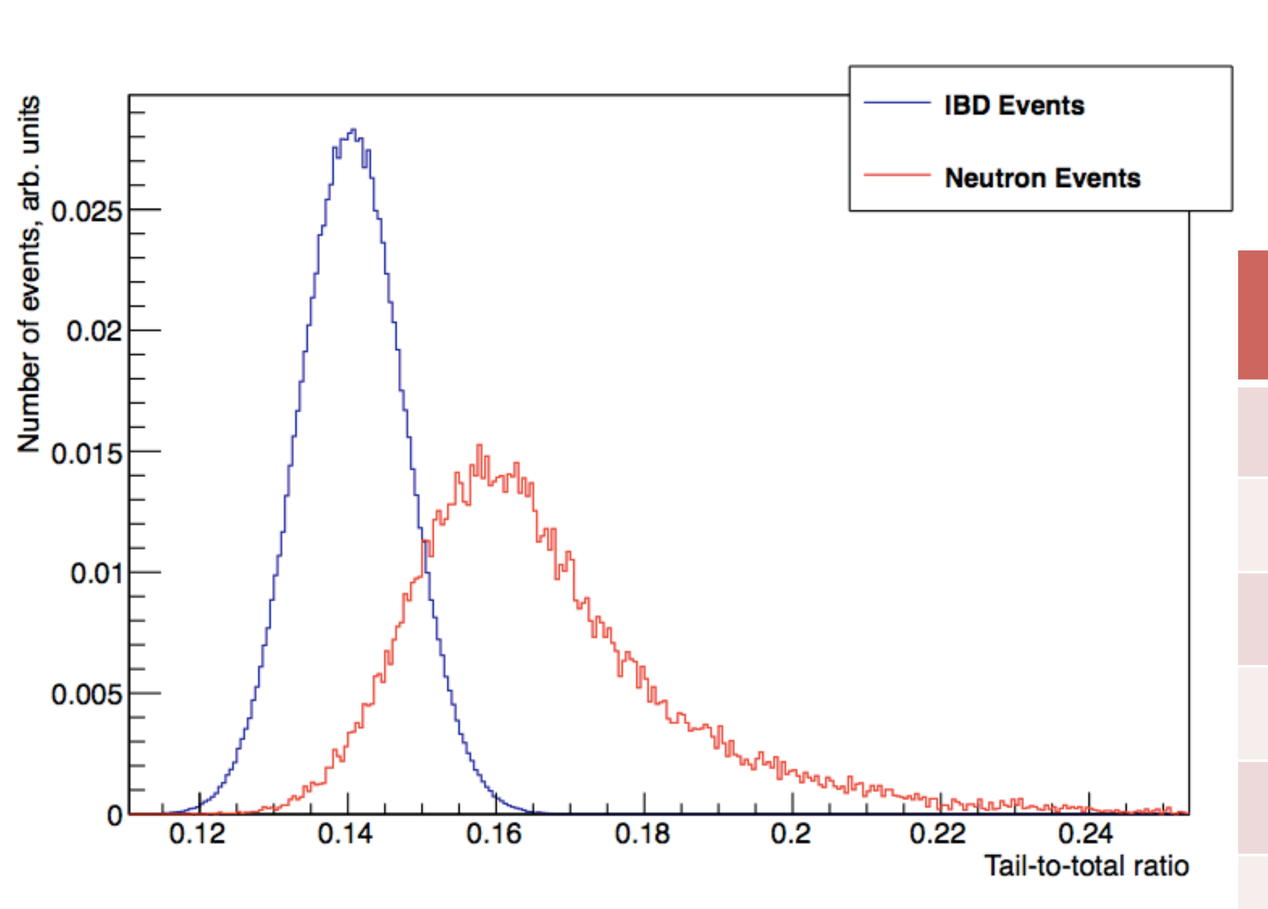
Pulse-shape discrimination (PSD) I



based on LENA MC:

- same scintillator (LAB + 3g/l PPO + 20 mg/l bisMSB)
- lower photoelectron yield: 250 pe/MeV
- better PMT timing: ~1ns (1 σ)

Pulse-shape discrimination (PSD) II



IBD Acceptance	FN Rejection
95%	15.7%
90%	8.2%
80%	4.8%
55%	2.2%
50%	1.9%
40%	1.5%

- based on tail-to-total ratio (&Gatti par)
- for 50% acceptance:
  DSNB rate: 0.7–1.9 yr^{-1}, BG rate: 0.6 yr^{-1}