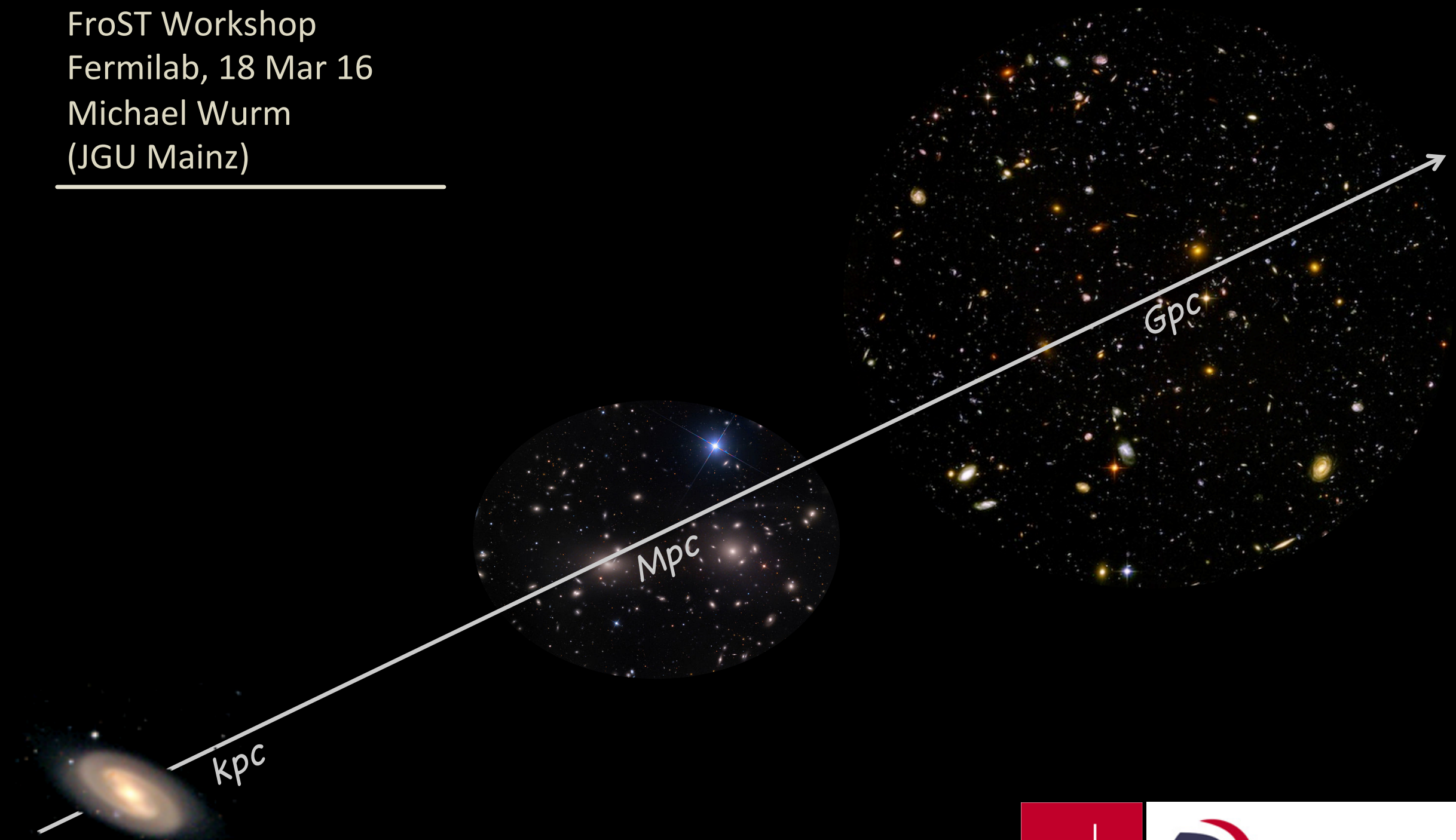
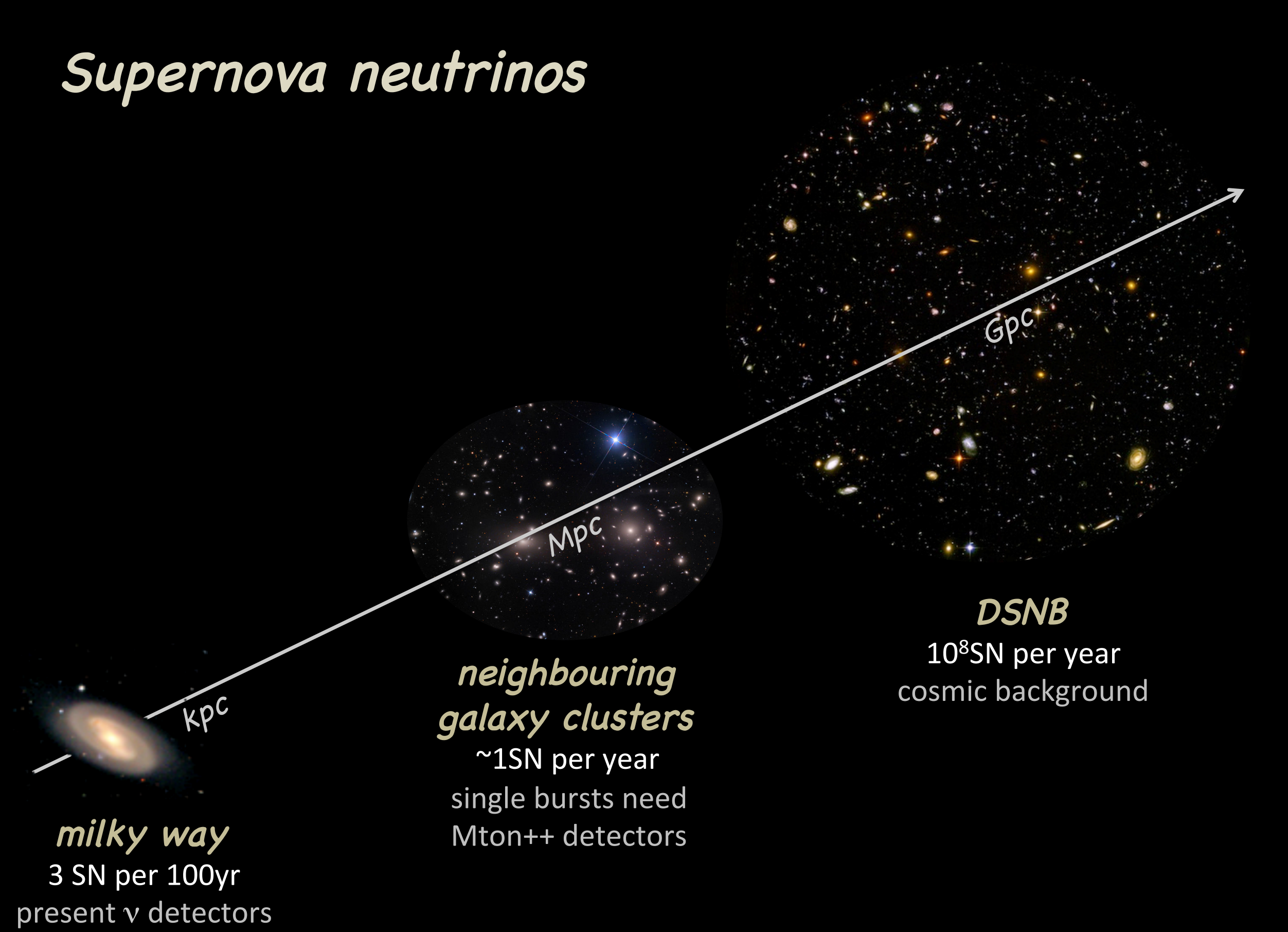
DSNB detection in Liquid Scintillator

FroST Workshop
Fermilab, 18 Mar 16
Michael Wurm
(JGU Mainz)

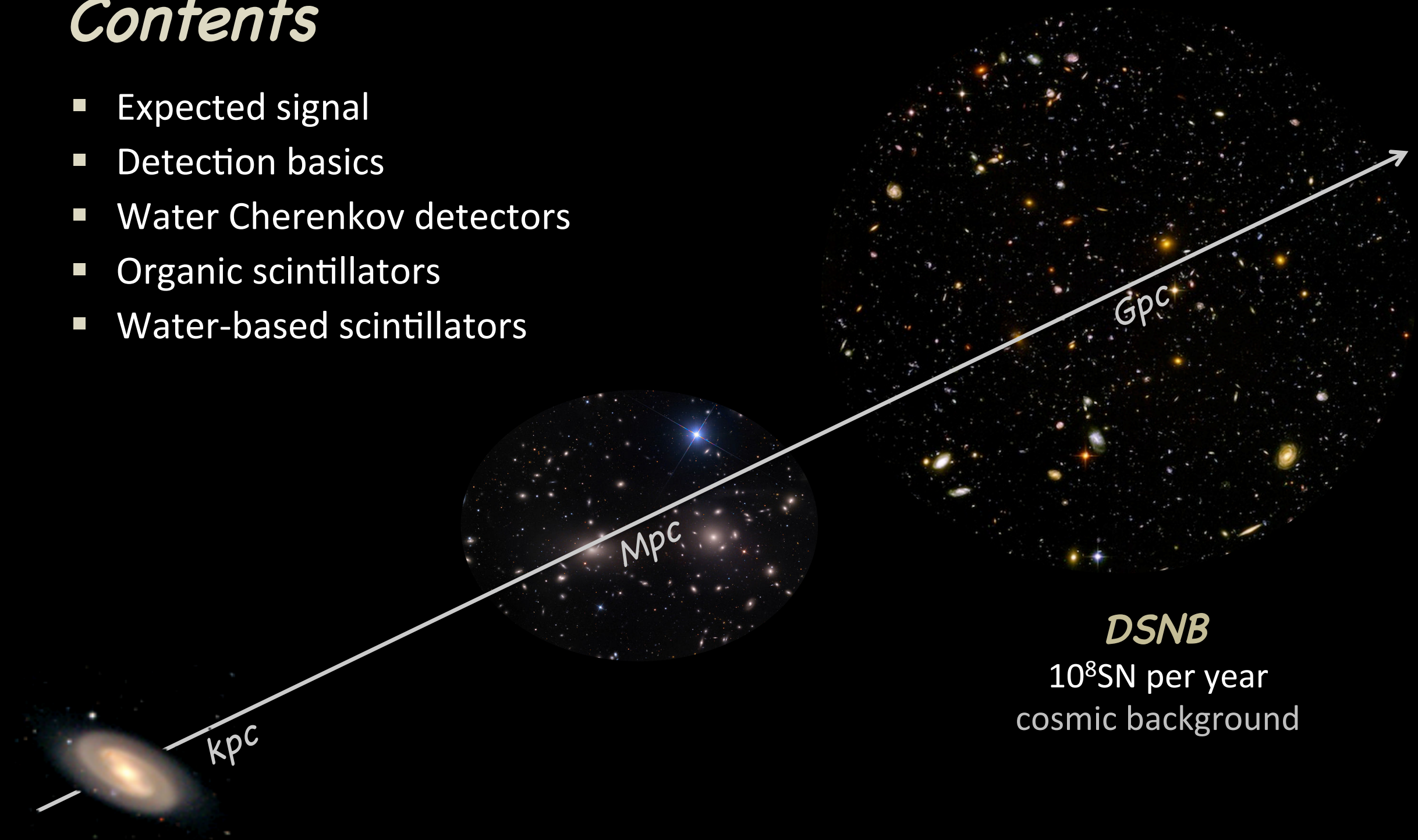


Supernova neutrinos



Contents

- Expected signal
- Detection basics
- Water Cherenkov detectors
- Organic scintillators
- Water-based scintillators



DSNB

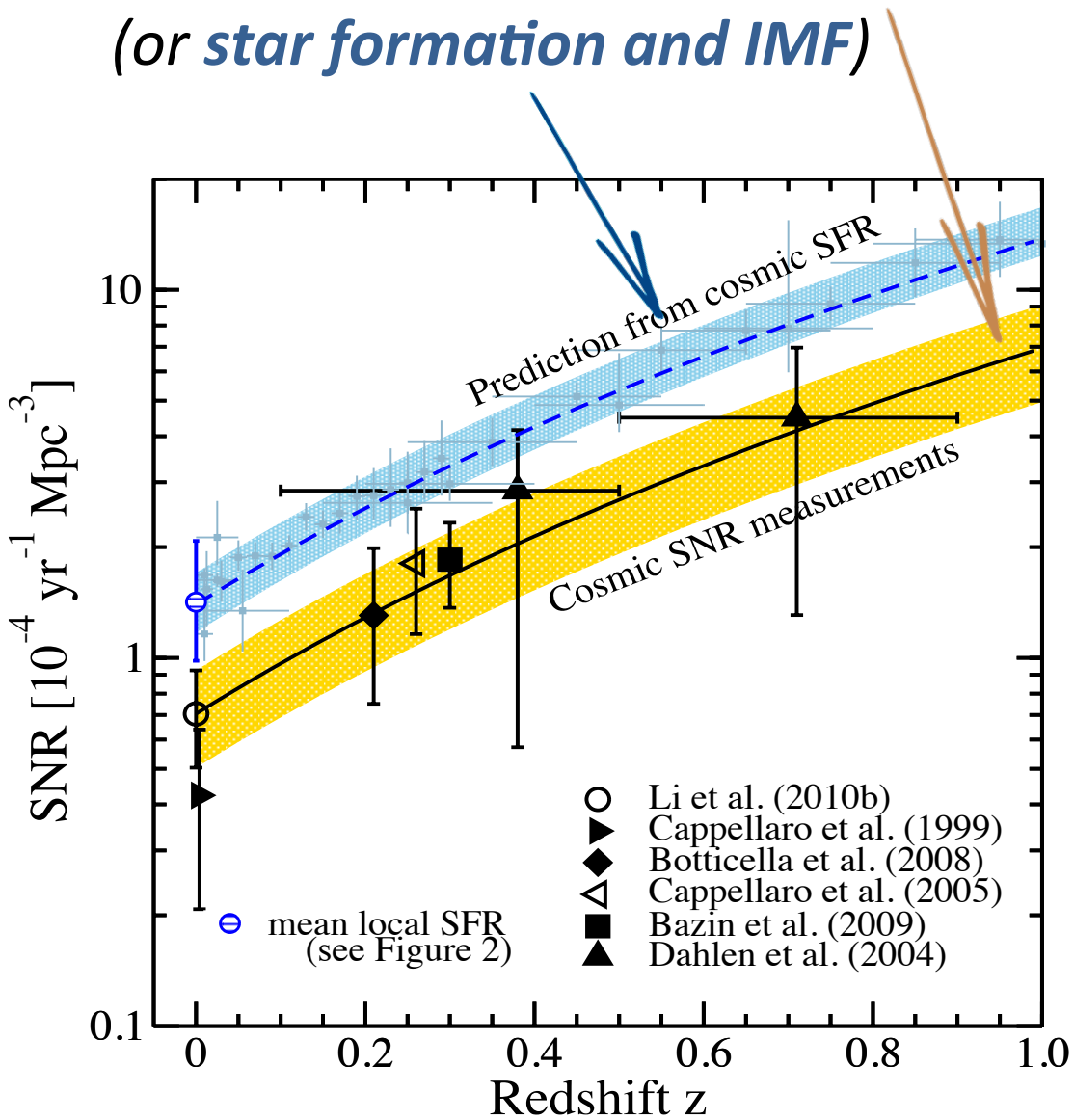
10^8SN per year

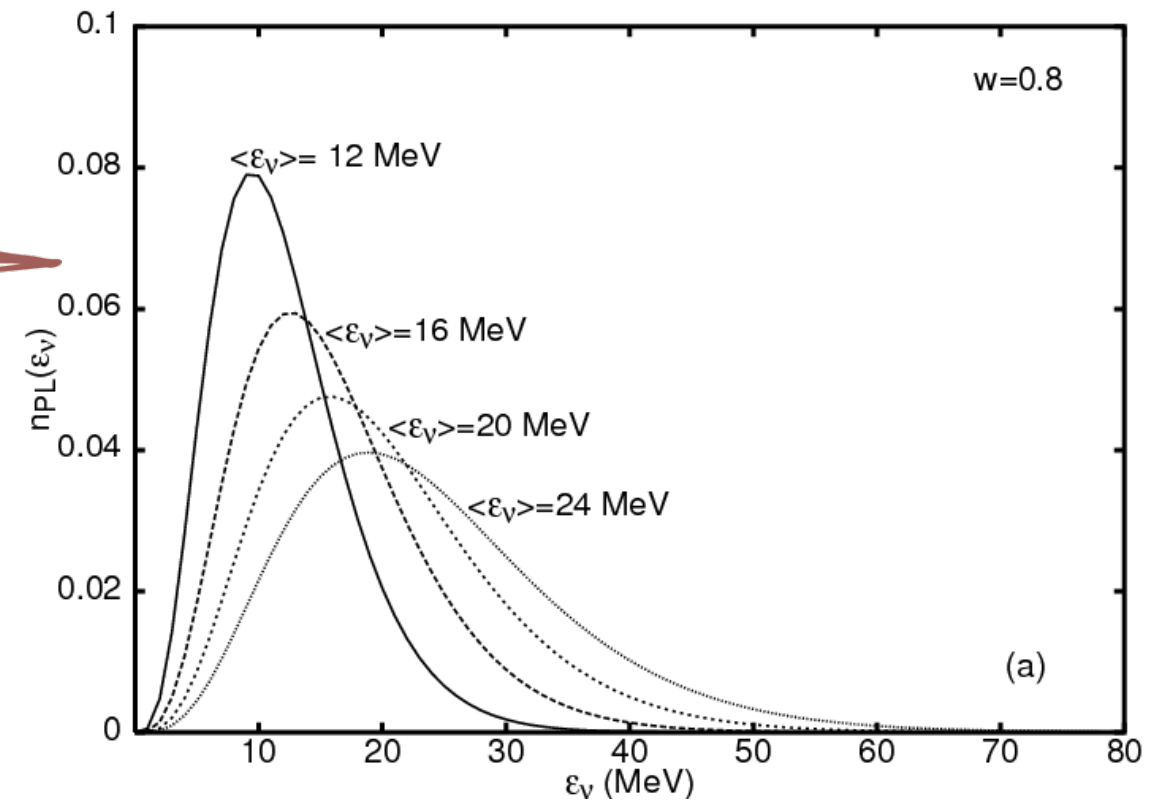
cosmic background

DSNB prediction

DSNB prediction depends on

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





Objectives of a DSNB measurement

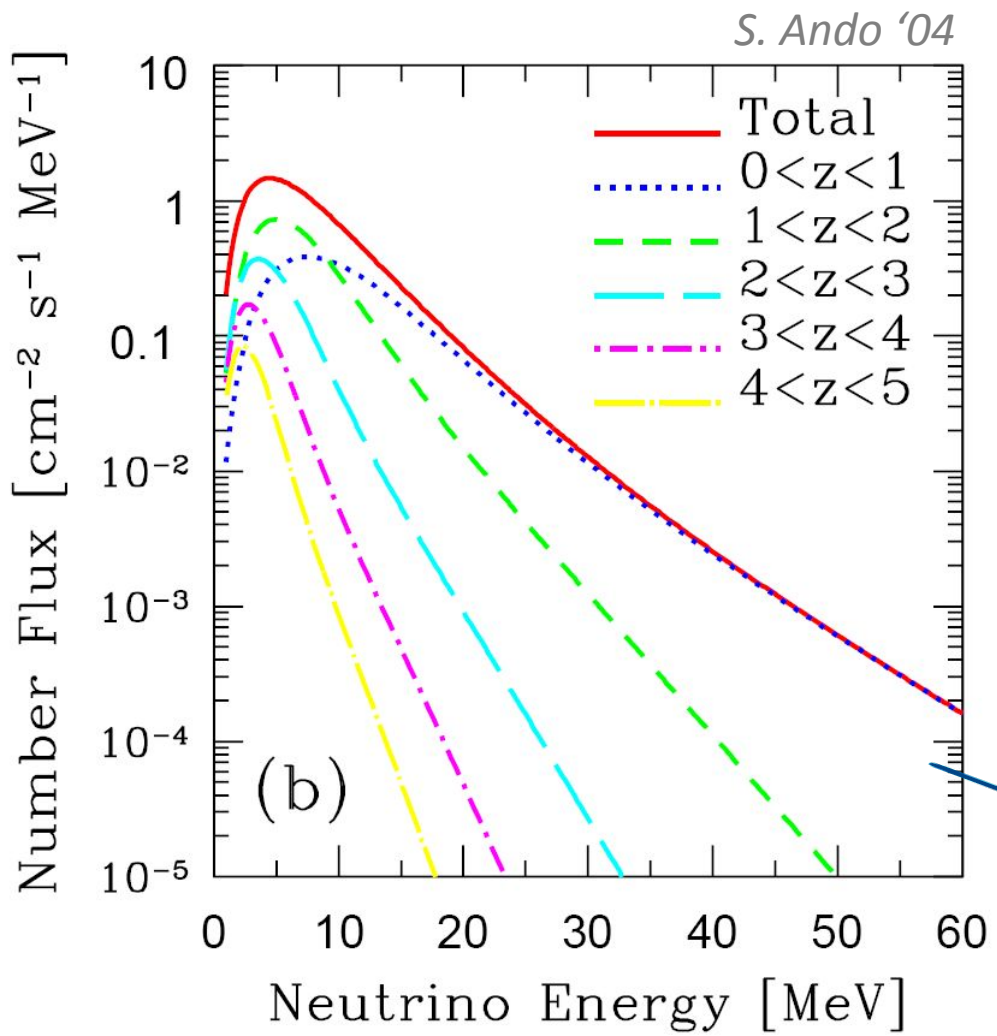
→ first of all: discovery

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

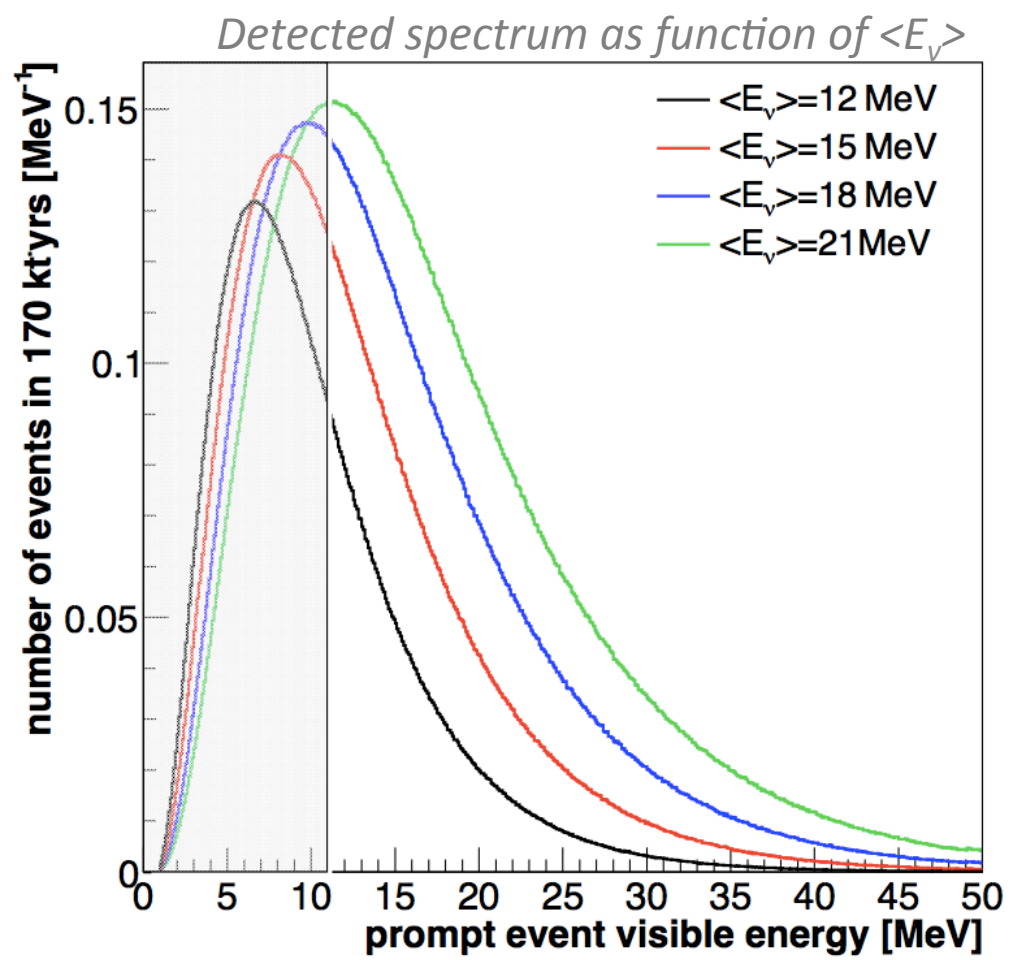
→ redshift-dependent SN rate

→ fraction of hidden/failed SNe

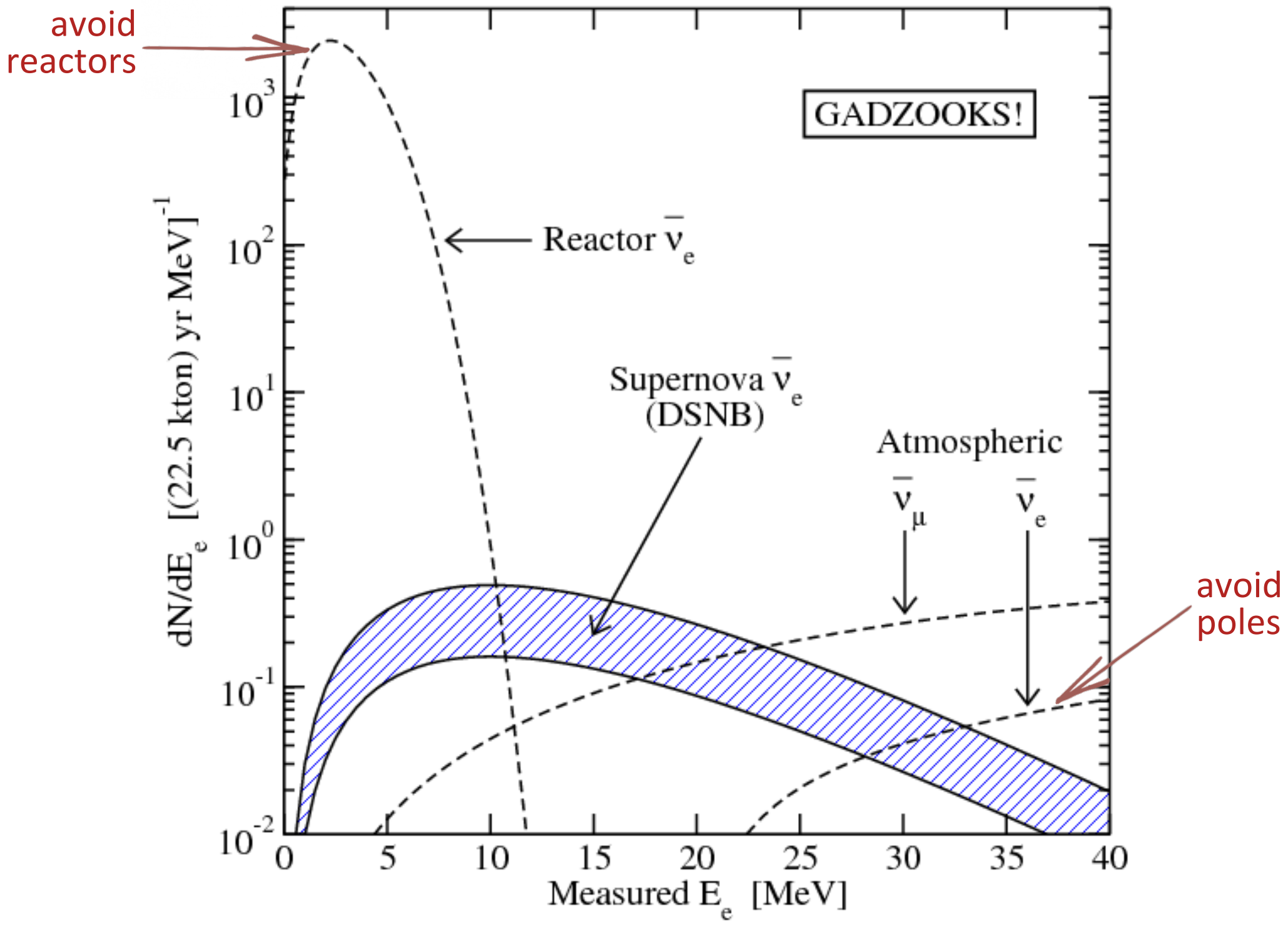
DSNB spectrum and flux



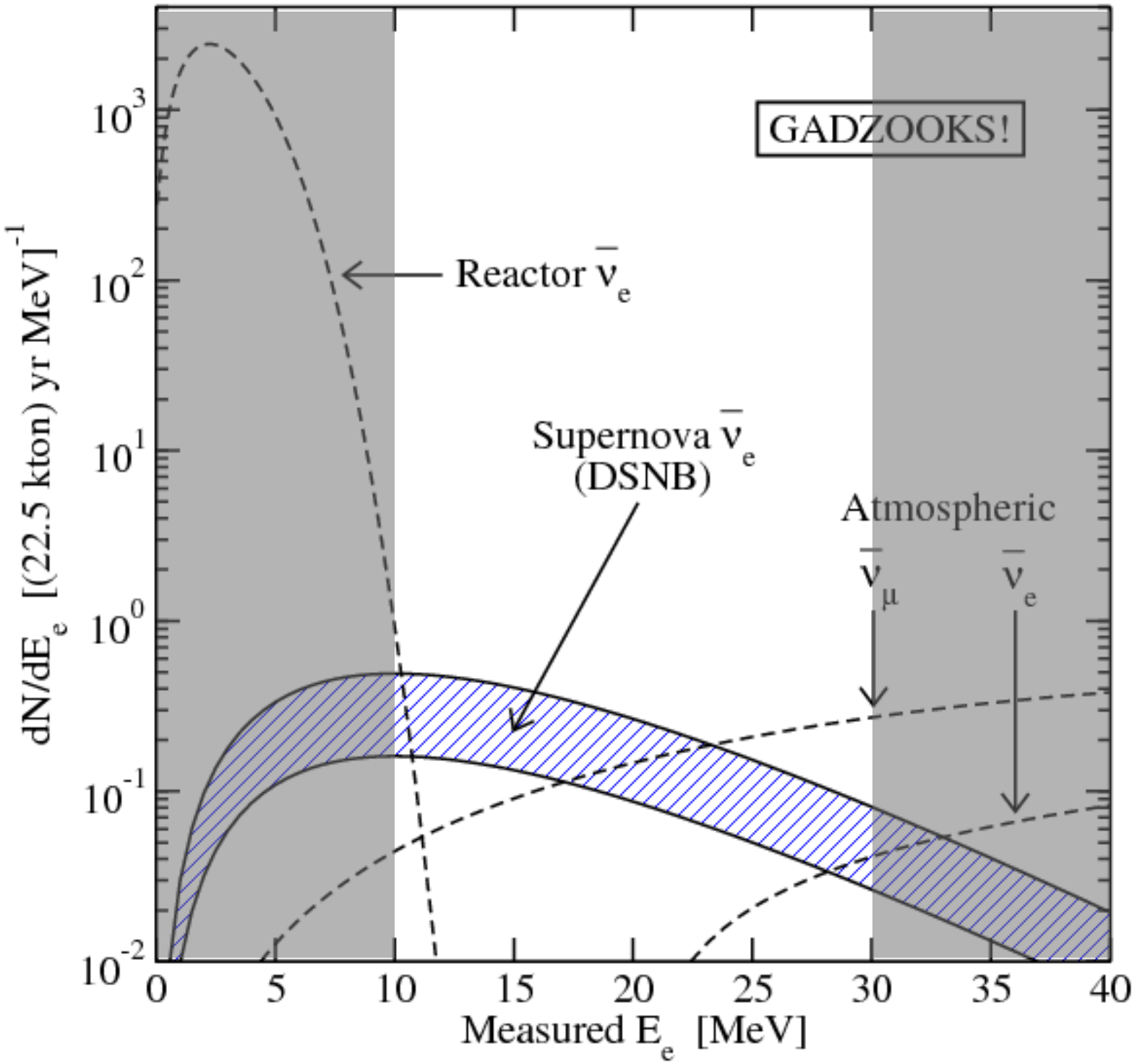
- DSNB flux: ~10^2 /cm^{2}s
- equipartition between flavors
- best possibility for detection in water and LS: **inverse beta decay**
- expected rate: ~1 per 10 kt·yrs



DSNB irreducible backgrounds

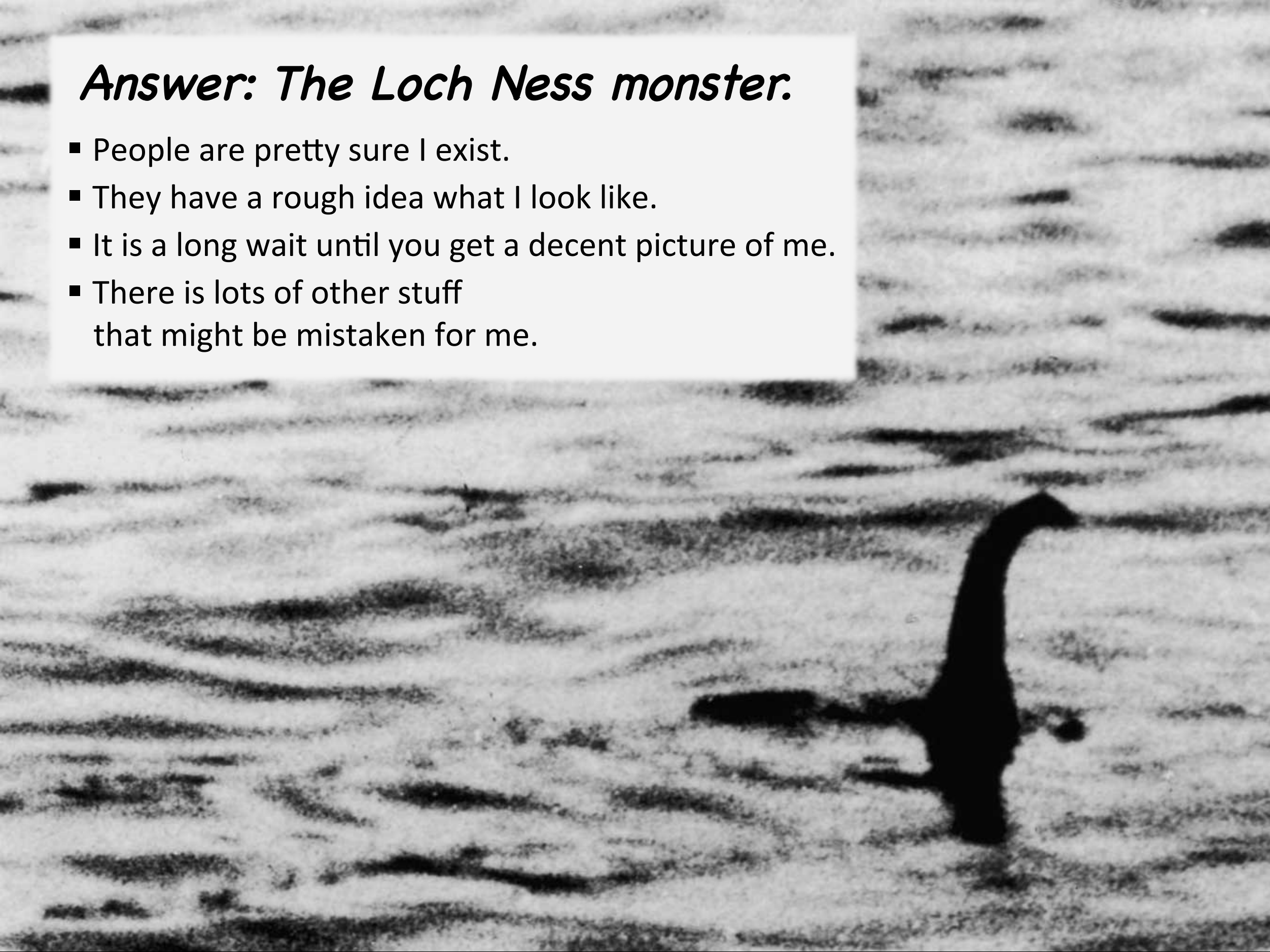


DSNB detection window



Quickie: What am I?

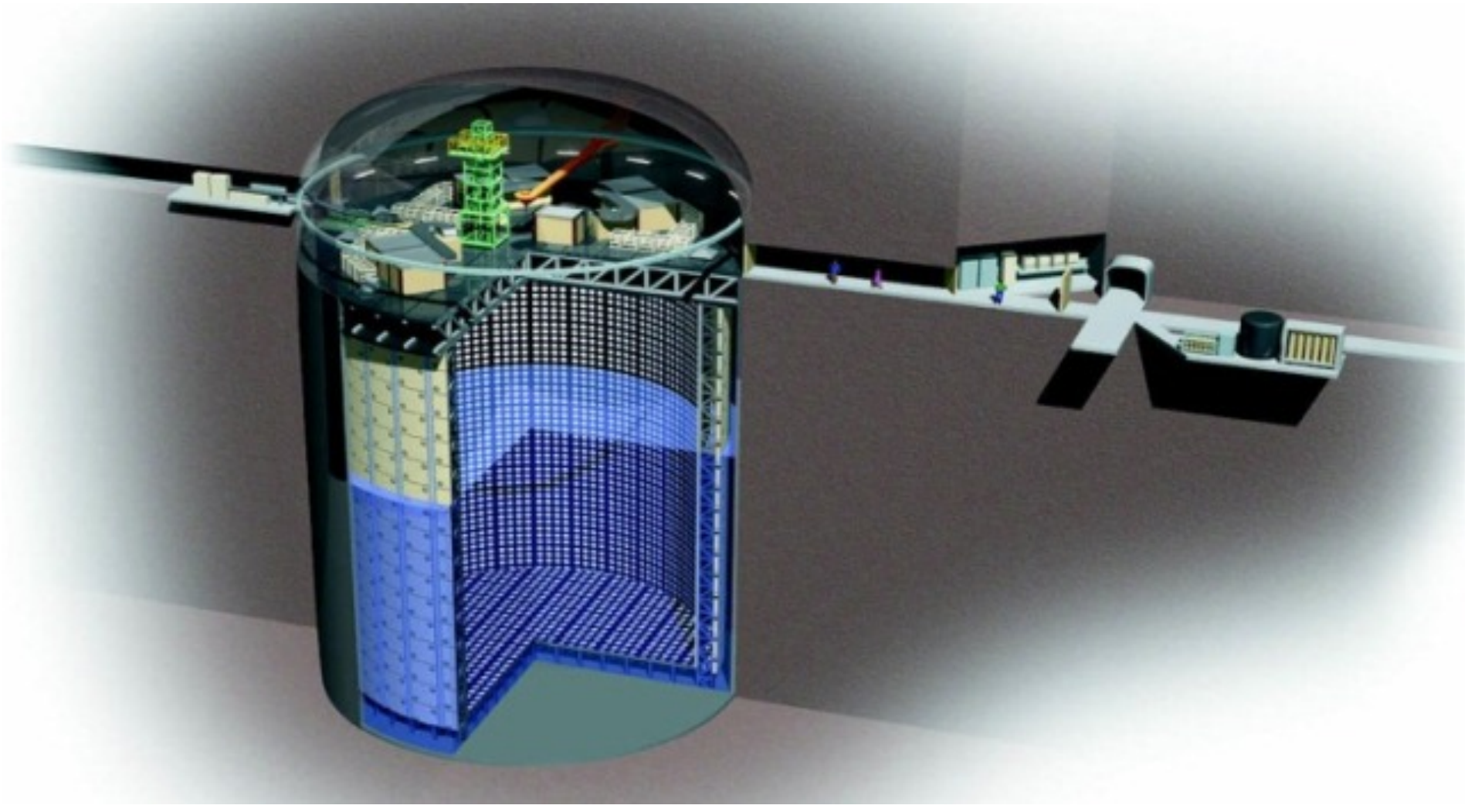
- People are pretty sure I exist.
- They have a rough idea what I look like.
- It is a long wait until you get a decent picture of me.
- There is lots of other stuff
  that might be mistaken for me.



Answer: The Loch Ness monster.

- People are pretty sure I exist.
- They have a rough idea what I look like.
- It is a long wait until you get a decent picture of me.
- There is lots of other stuff
  that might be mistaken for me.

DSNB detection in Super-Kamiokande

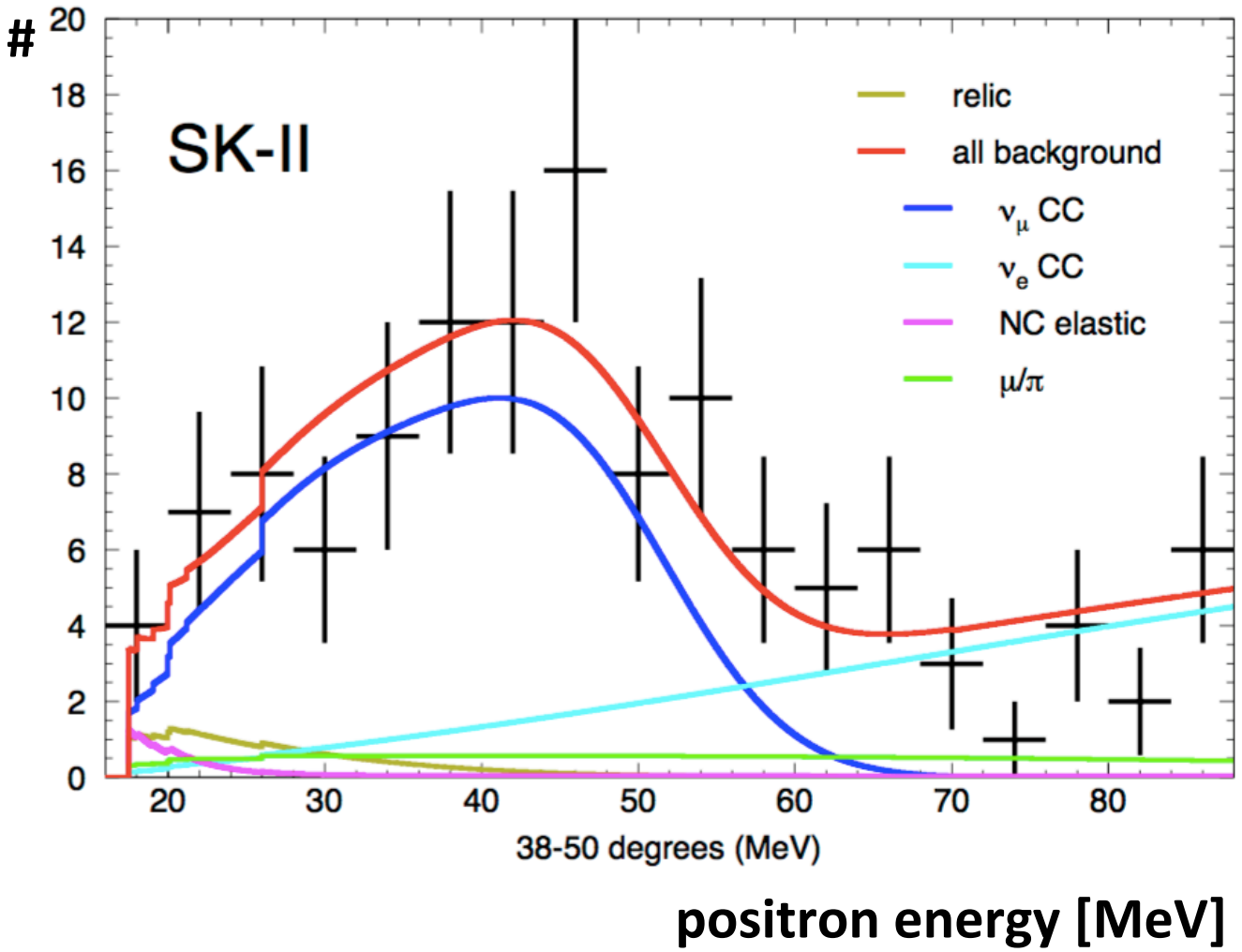


- large target mass: 25 kt
  → order 2-3 events/yr expected
- but: delayed neutron capture in IBDs hard to tag (see later)
  → additional backgrounds

Best 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

Best limit from SK 2011 analysis

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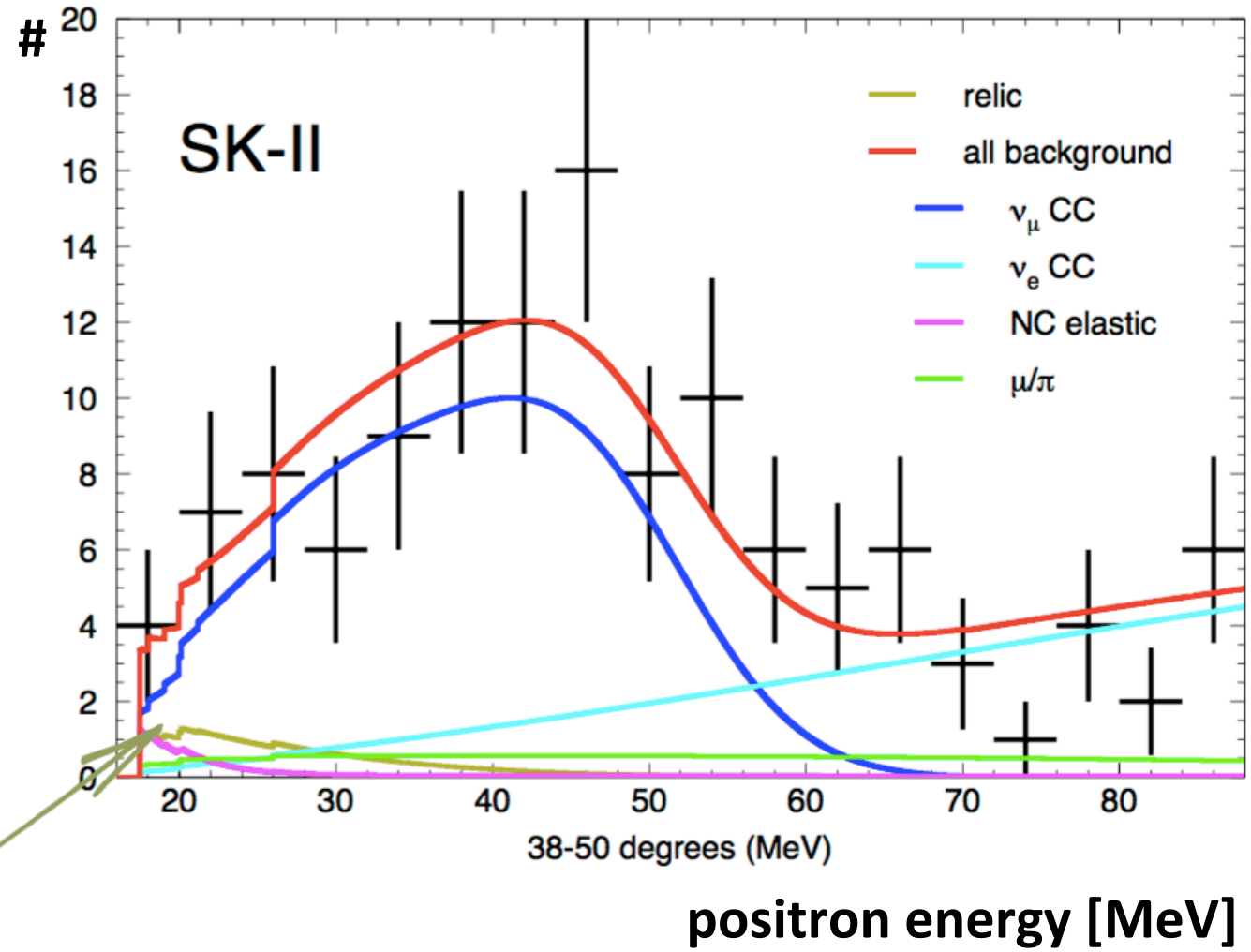


→ resulting limit from SKI-III:
ϕ_ν < 2.9 cm^{-2}s^{-1} for E(e$^+$)>16MeV

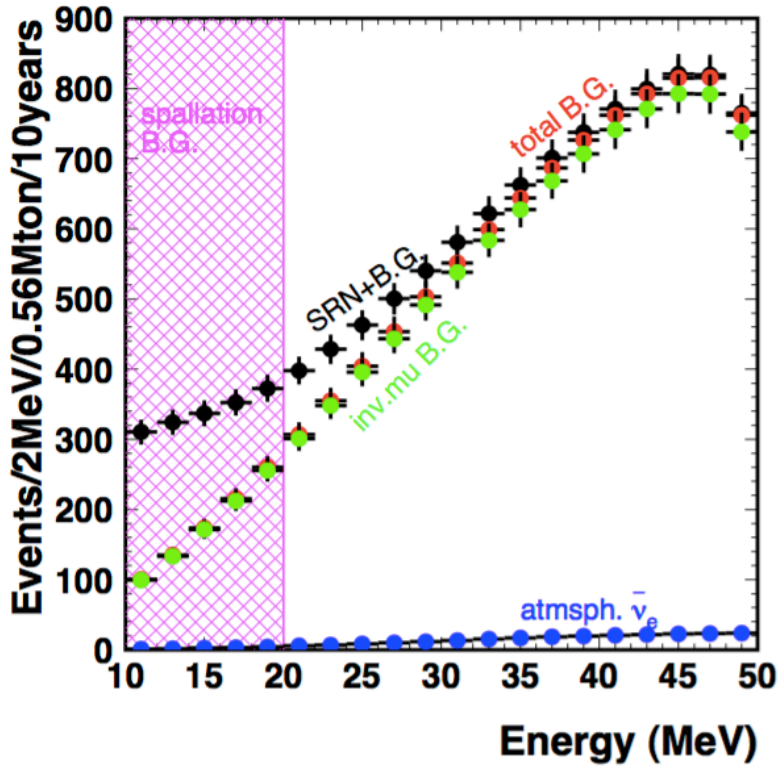
Approach 1: Use more water!

Prospects of detection in water

Several options:

- increase statistics drastically
  → Hyper-Kamiokande

HK w/o neutron tagging



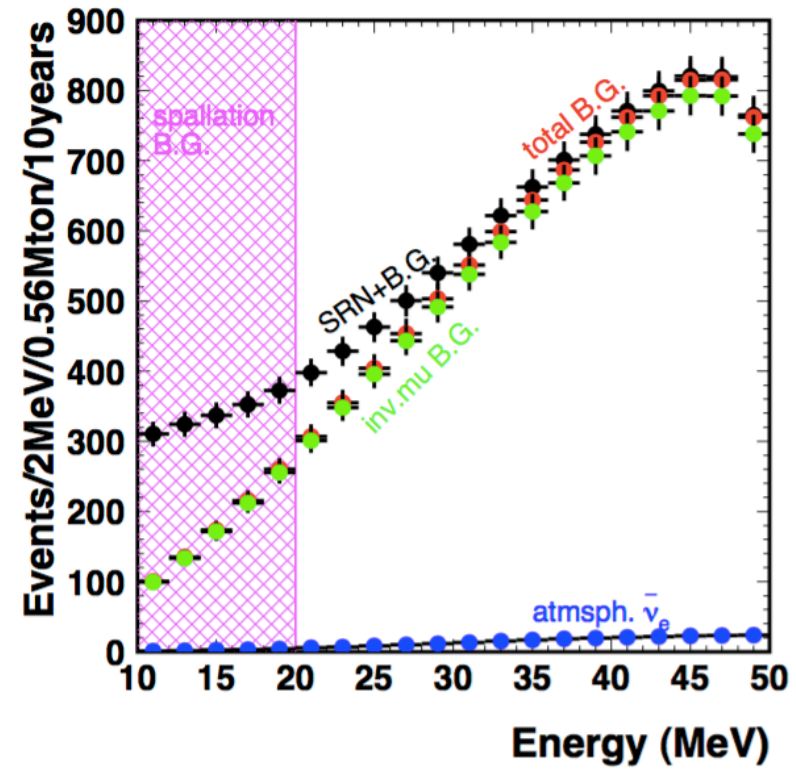
Approach 2: Increase contrast

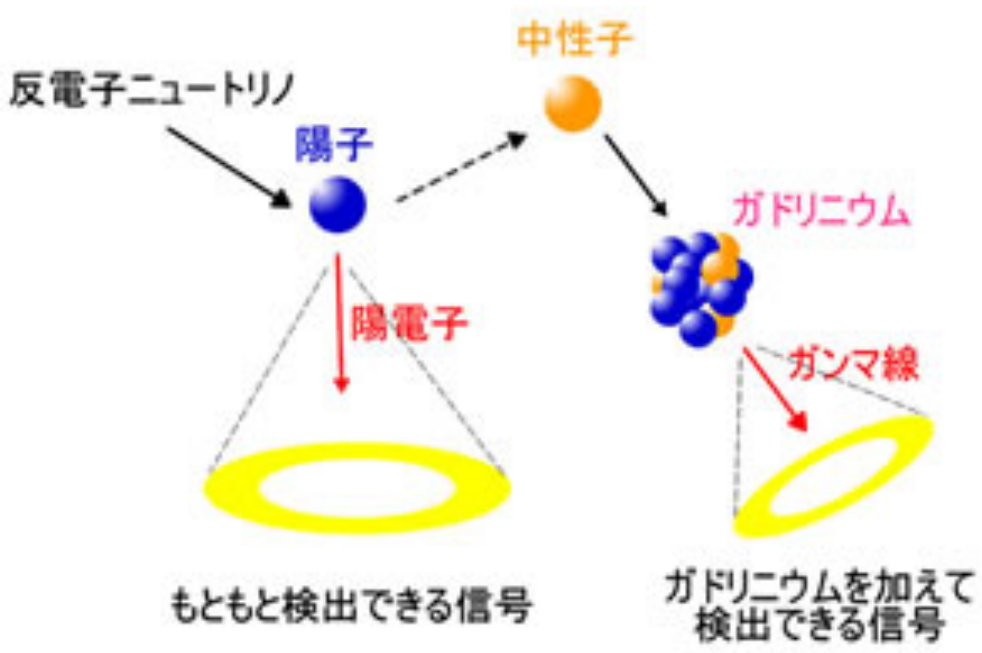
Prospects of detection in water

Several options:

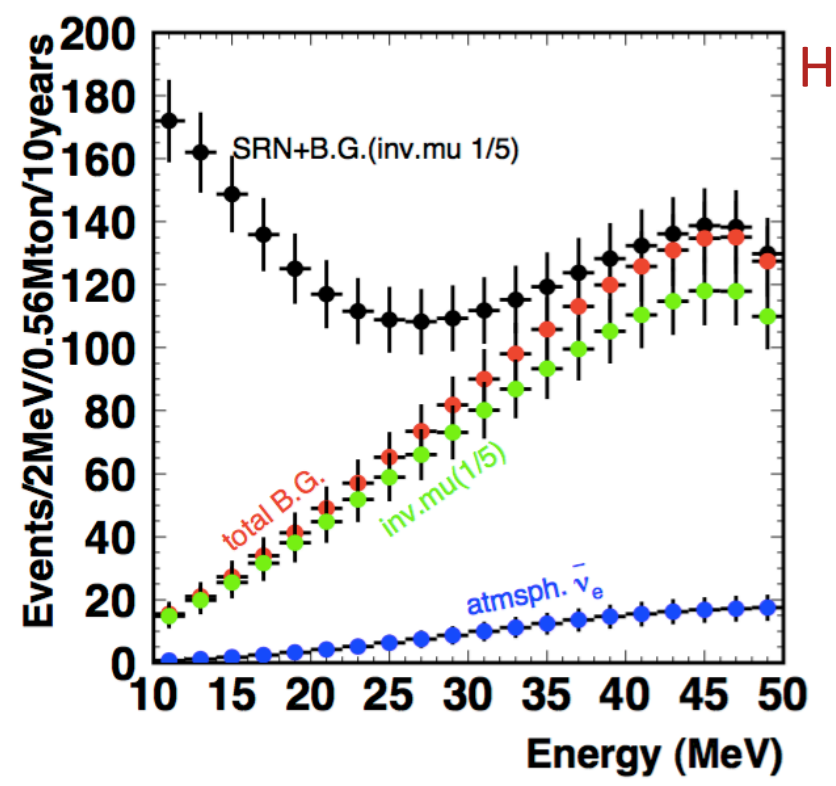
- increase statistics drastically
  → Hyper-Kamiokande
- tag the delayed neutron
  → by clever trigger logic
  (efficiency ~20%) → applied in SK
  → by doping with gadolinium
  (efficiency ~60%) → GADZOOKS!

HK w/o neutron tagging



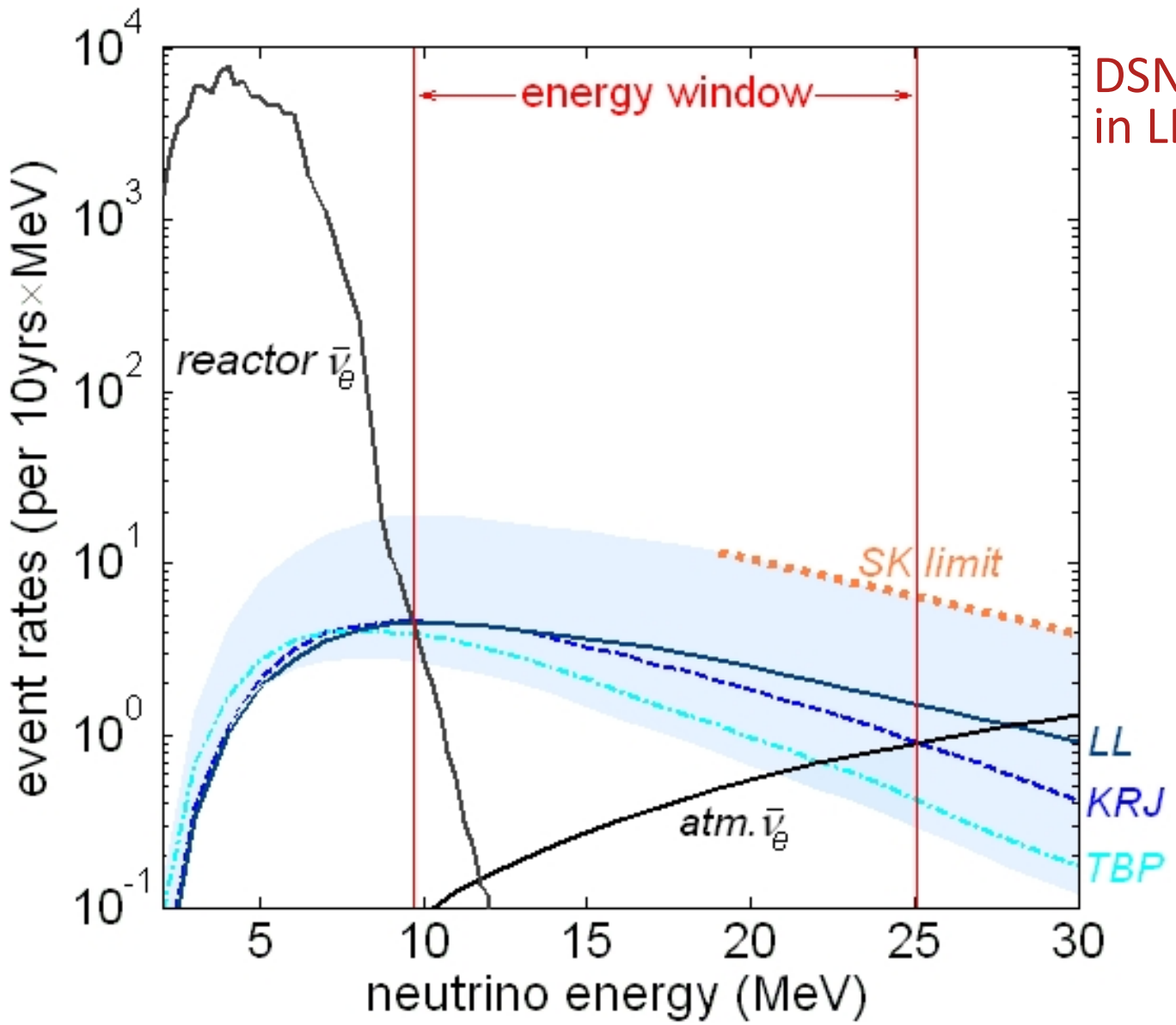


HK+Gd



Alternative: Organic liquid scintillator

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

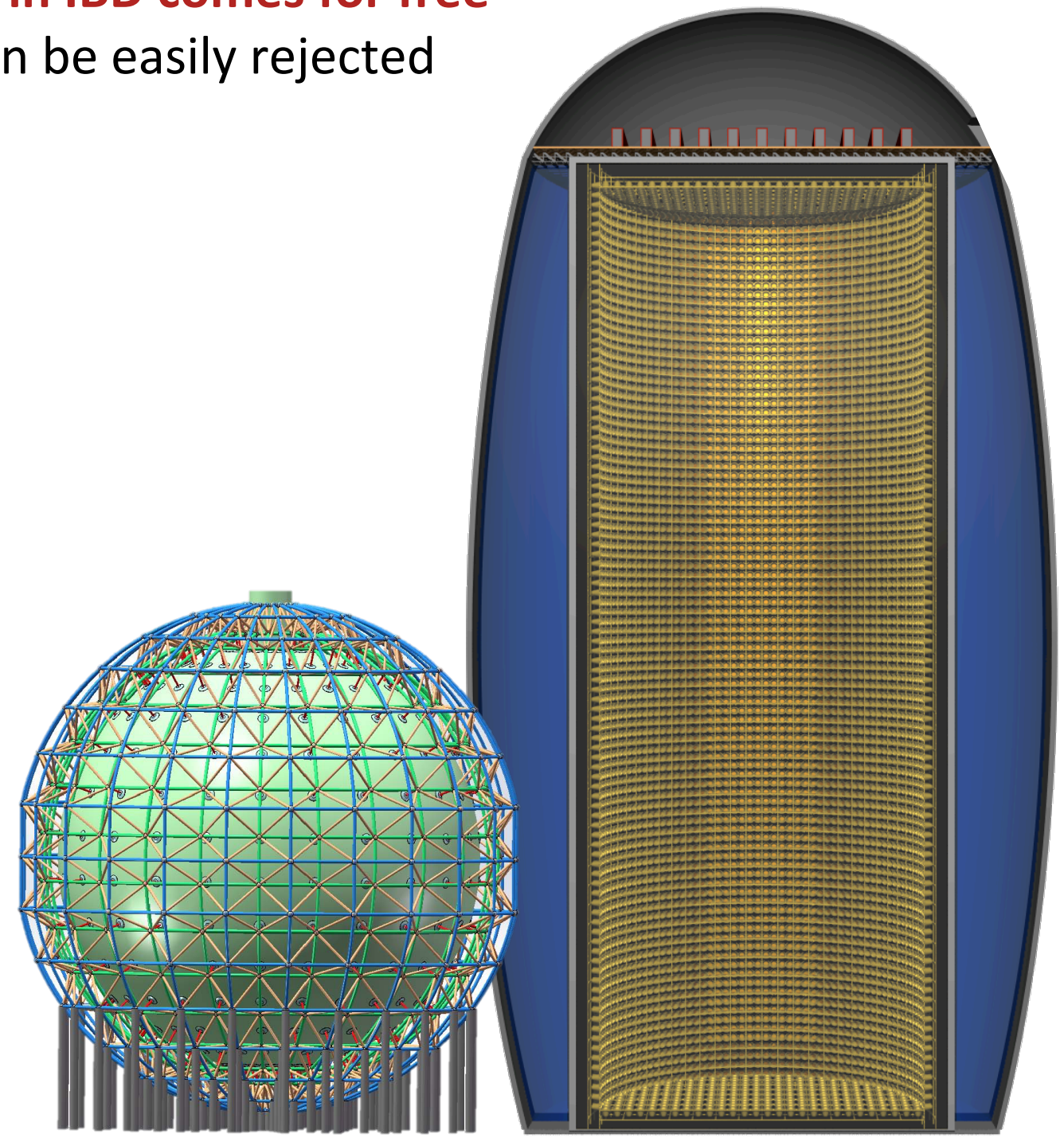


DSNB detection in LENA (2006)

Alternative: Organic liquid scintillator

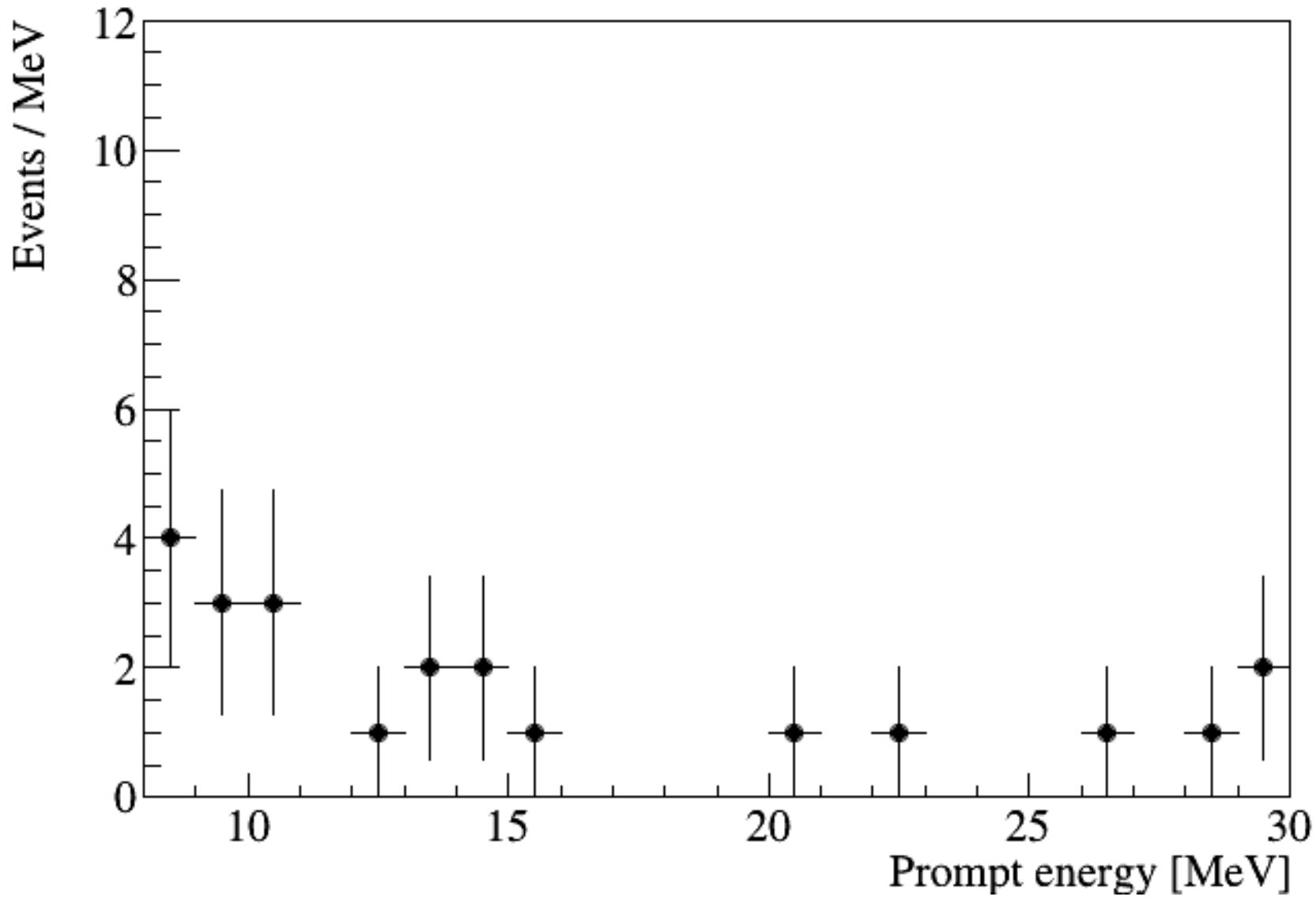
main advantage: neutron tagging in IBD comes for free
→ all single-event backgrounds can be easily rejected

still, large target mass required:
→ LENA (50kt)
→ JUNO (20kt)
→ RENO-50 (18kt)



KamLAND extraterrestrial antineutrino search

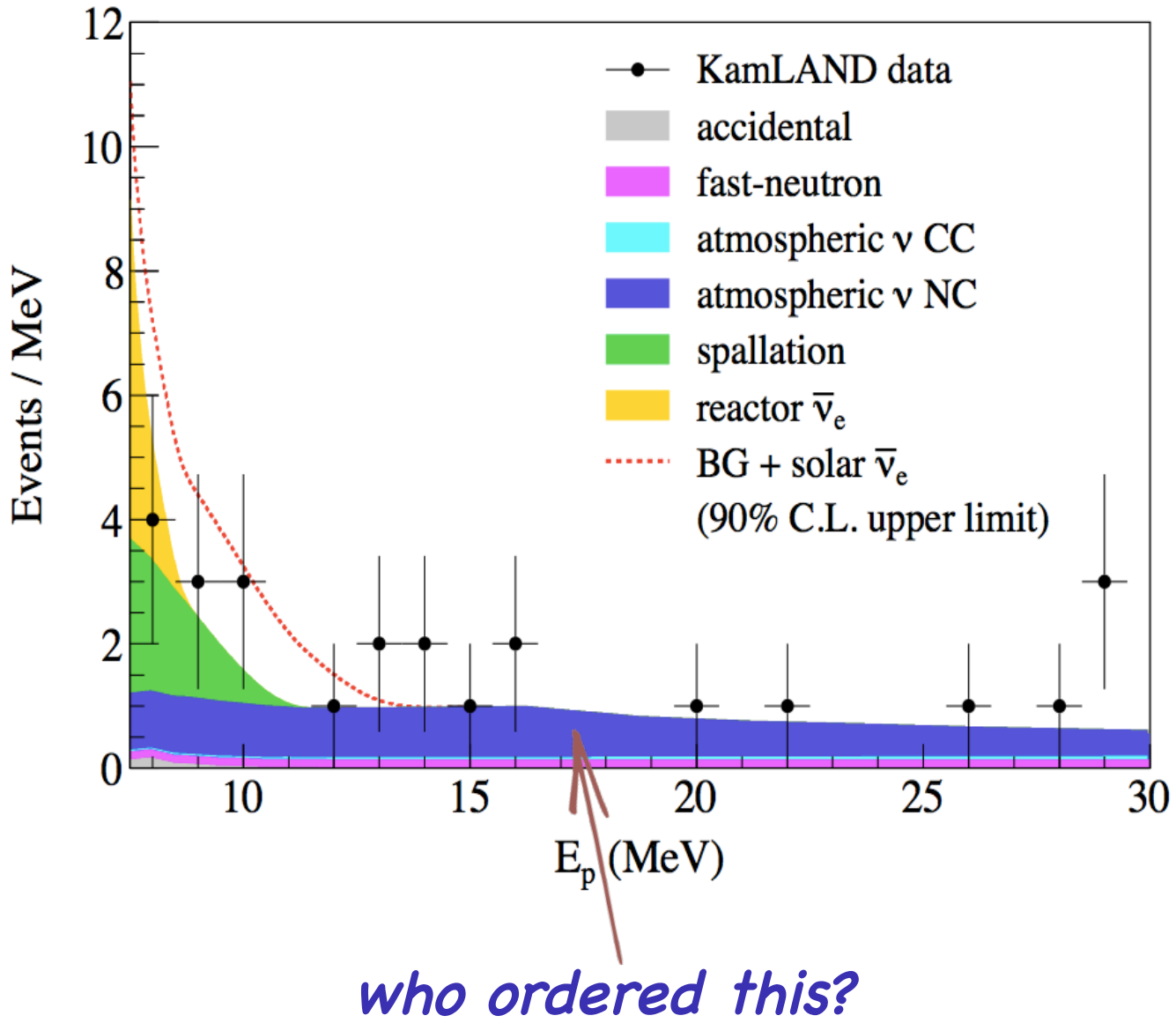
- target volume too small to discover the DSNB signal (order 0.1 $kt^{-1}yr^{-1}$)
- but sufficiently large to check for backgrounds



KamLAND
"high energy"
data (2011)

exposure:
4.53 kt

Background: The usual suspects



Other inverse beta decays

- reactor antineutrinos
- atmospheric antineutrinos
  → defines observation window

Spallation isotopes

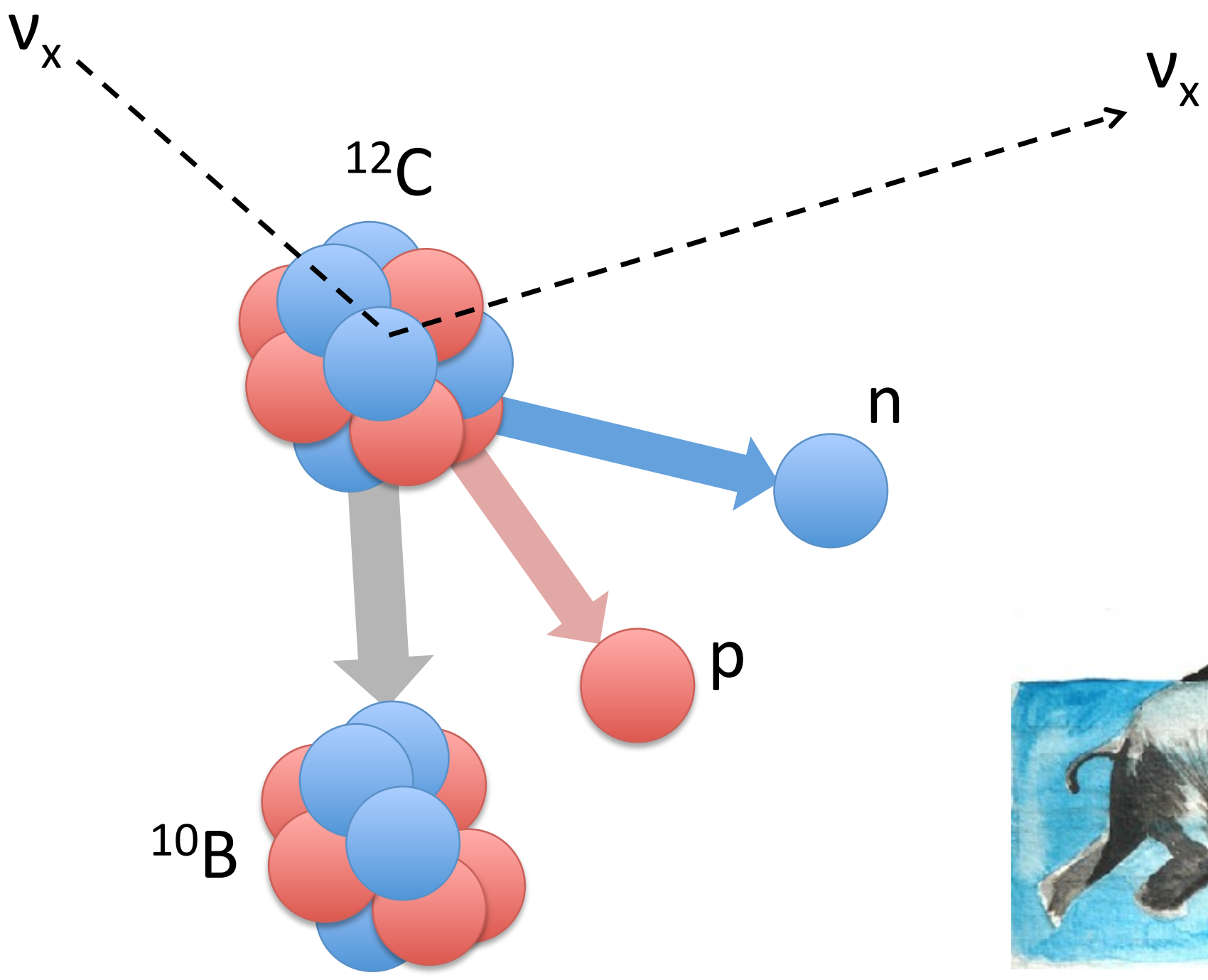
- βn-emitters: ^{9}Li & ^{8}He
  → depth
  → veto using time,distance-correlation to parent muon

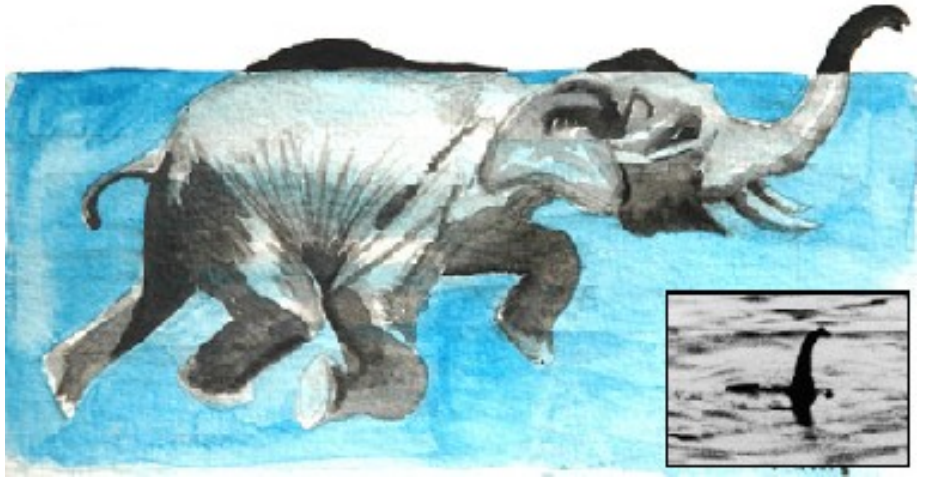
External neutrons

- fast-neutrons
  → depth
  → fiducial volume cut

Atmospheric neutrino NC reactions

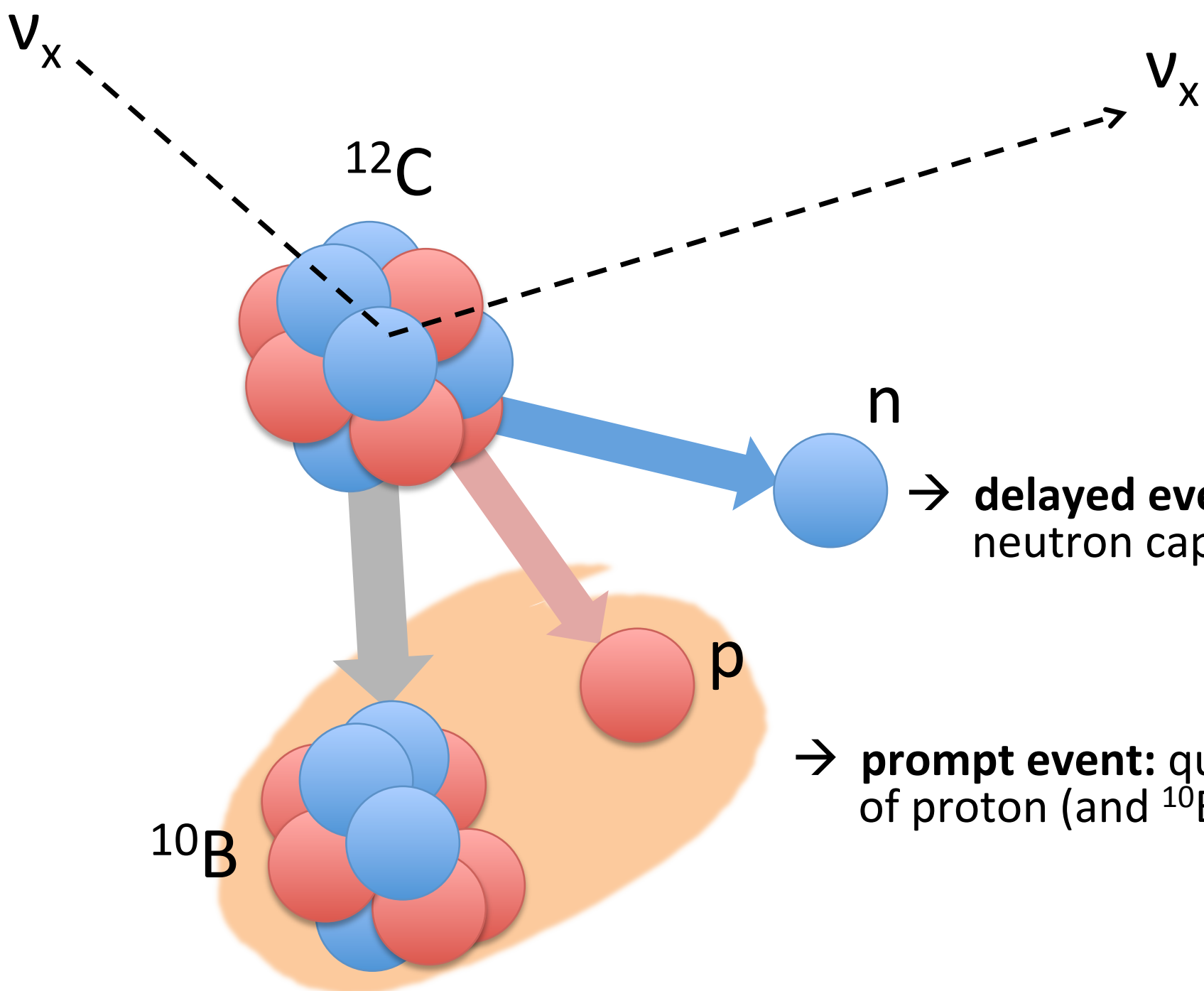
Background: NC neutrino-nucleon scattering **with neutron in final state**





Atmospheric neutrino NC reactions

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



→ **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) $\nu_x + {}^{12}C \rightarrow \nu_x + 2p + n + {}^{9}Be$	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 $kt^{-1}yr^{-1}$**

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

NC BG reduction 1: Delayed Decays

Several of the spallation isotopes produced are not stable:

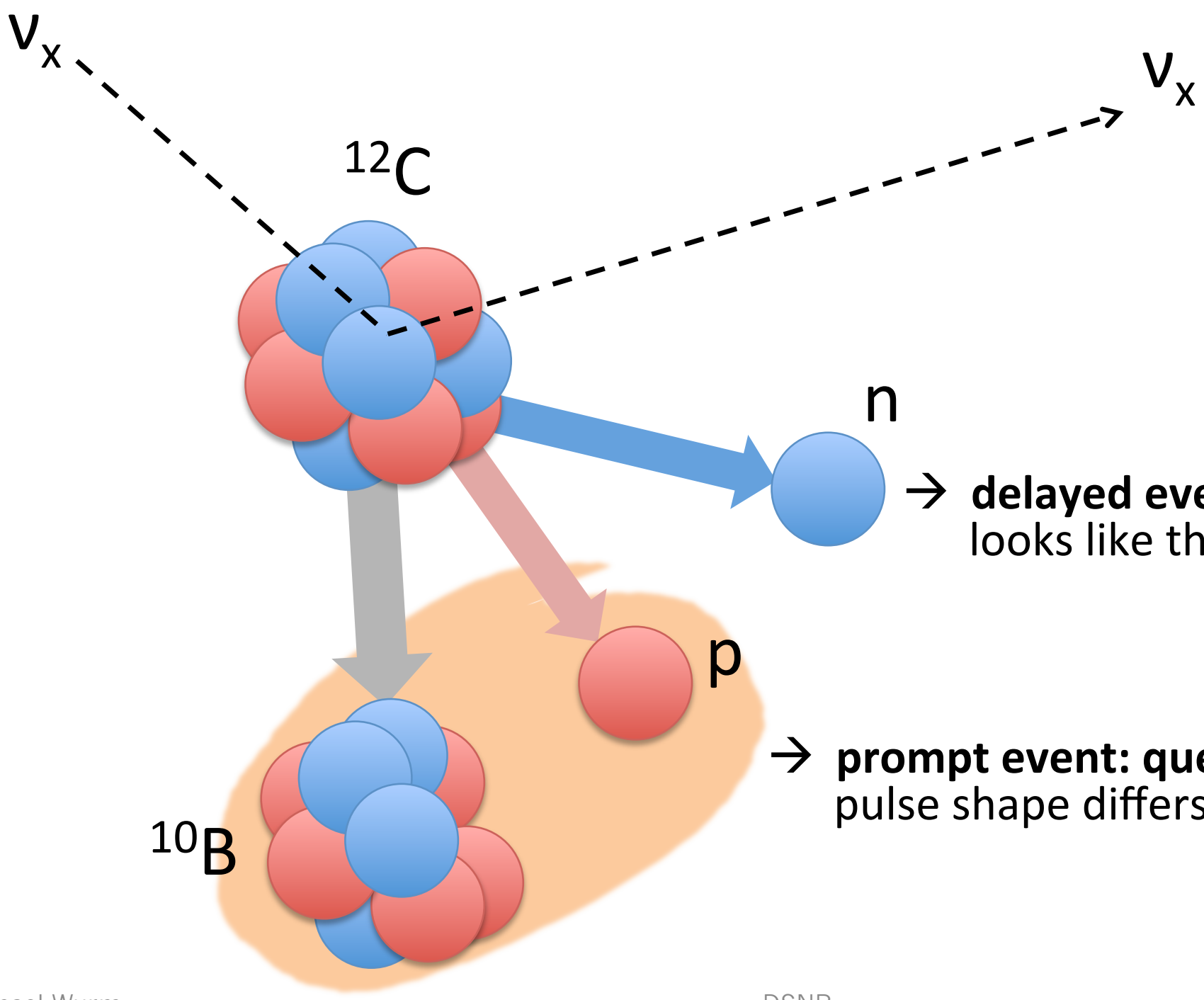
Reaction channel	Branching ratio	
(1) $\nu_x + {}^{12}C \rightarrow \nu_x + n + {}^{11}C$	38.8 %	→ *taggable*
(2) $\nu_x + {}^{12}C \rightarrow \nu_x + p + n + {}^{10}B$	20.4 %	→ *stable*
(3) $\nu_x + {}^{12}C \rightarrow \nu_x + 2p + n + {}^{9}Be$	15.9 %	→ *stable*
(4) $\nu_x + {}^{12}C \rightarrow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



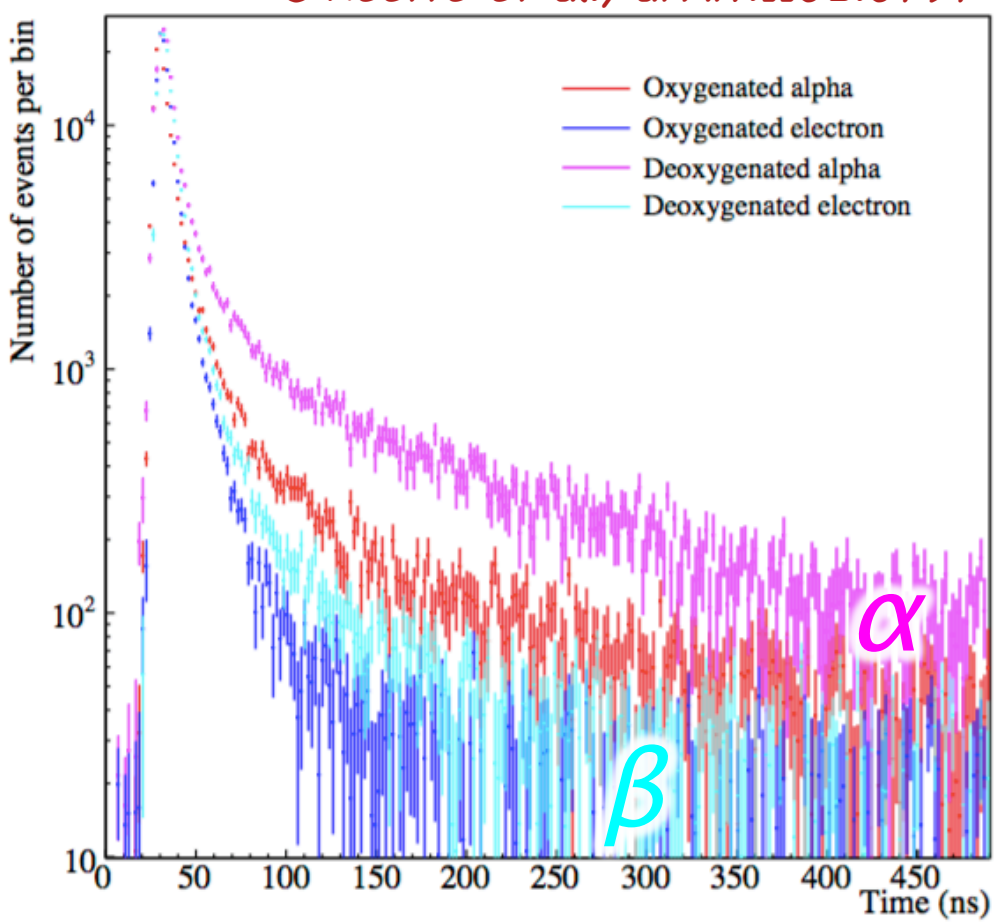
→ **delayed event: neutron**
looks like the real thing

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

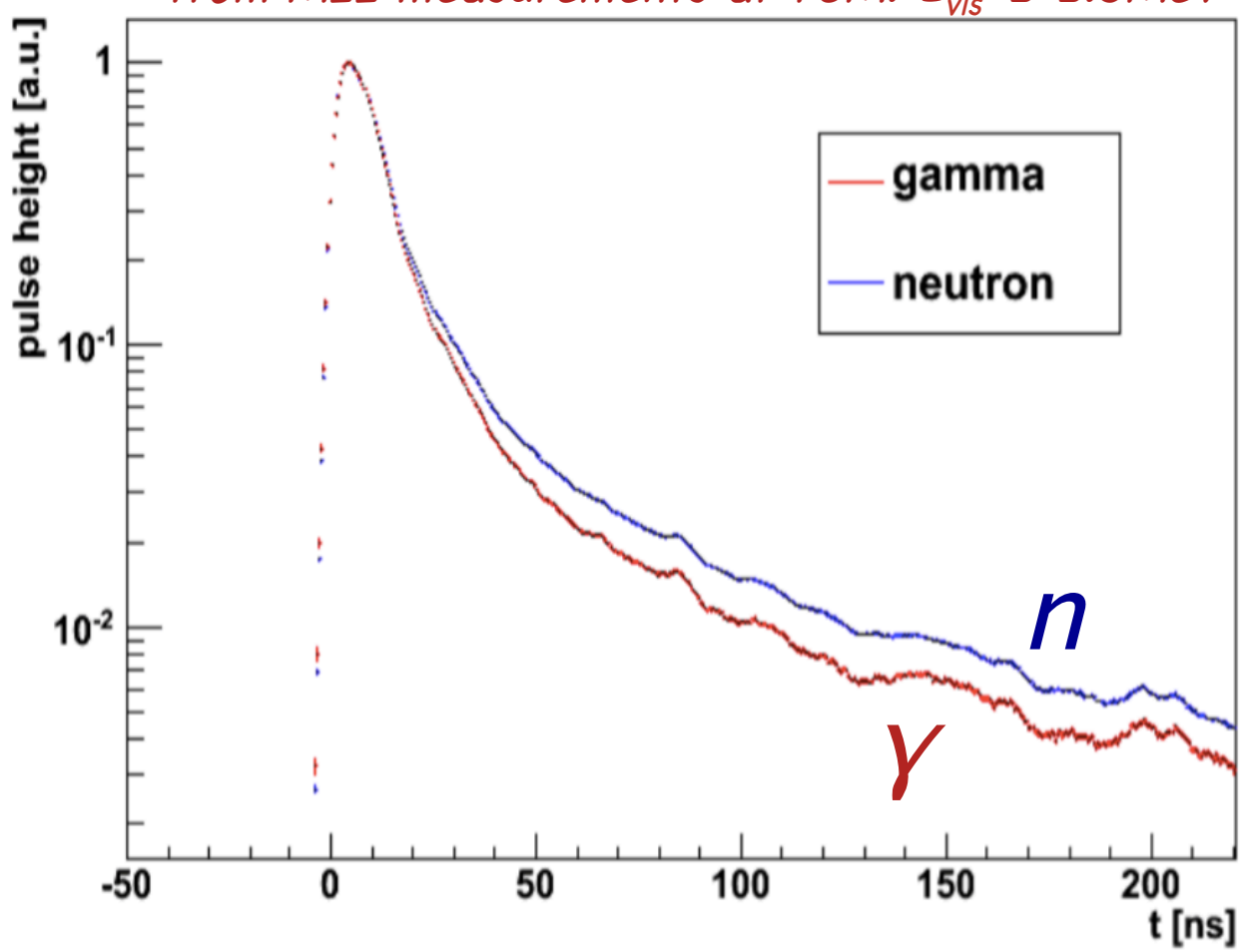
Pulse Shape measurements

Pulse shapes in linear alkyl-benzene (LAB) were studied for SNO, LENA and JUNO:
→ scintillator composition: LAB + 2-3 g/l PPO (+ 20mg/l bis-MSB)

O'Keeffe et al., arXiv:1102.0797



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

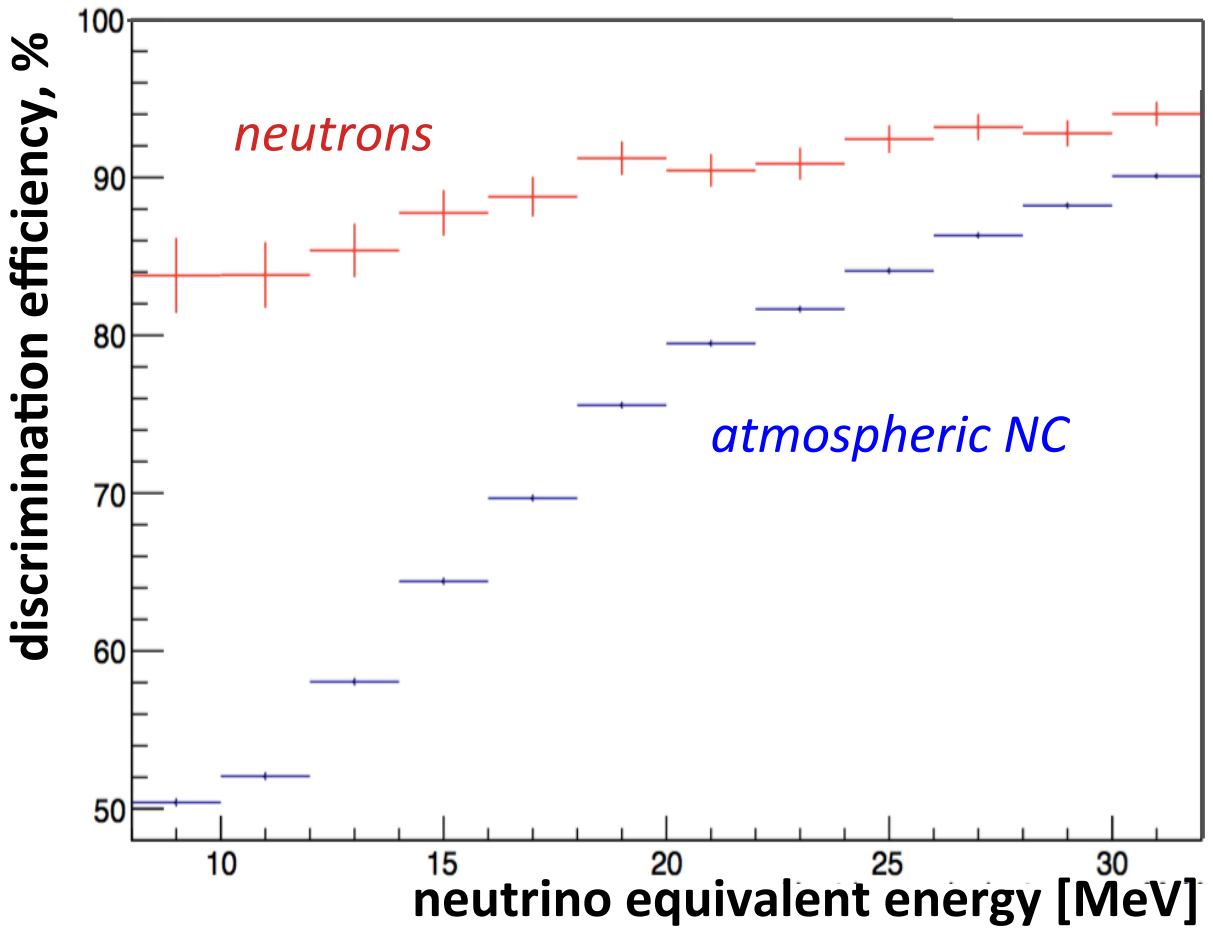


→ excellent particle discrimination properties

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

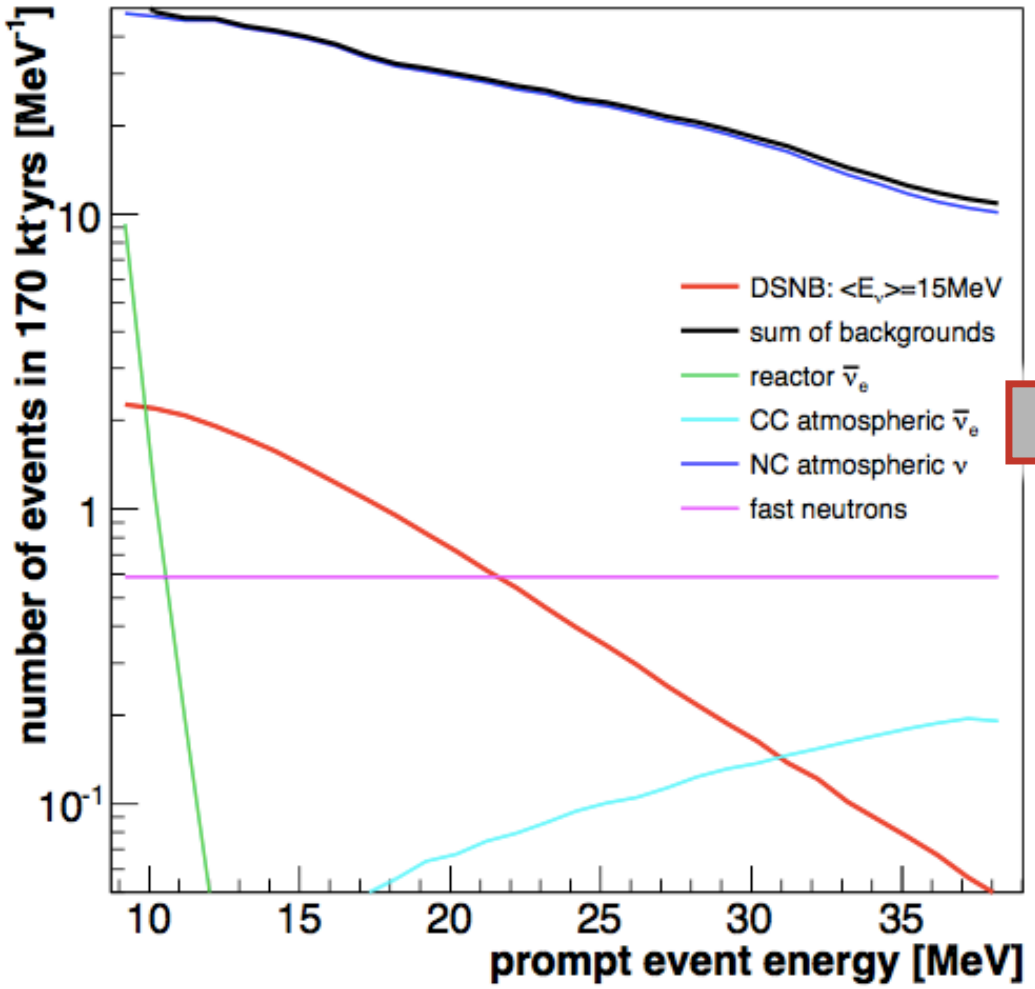
IBD acceptance	FN rejection	NC rejection
95%	84.3%	66.6%
90%	91.8%	87.4%
80%	95.2%	94.8%
55%	97.8%	98.9%
50%	98.1%	99.1%
40%	98.5%	99.3%

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

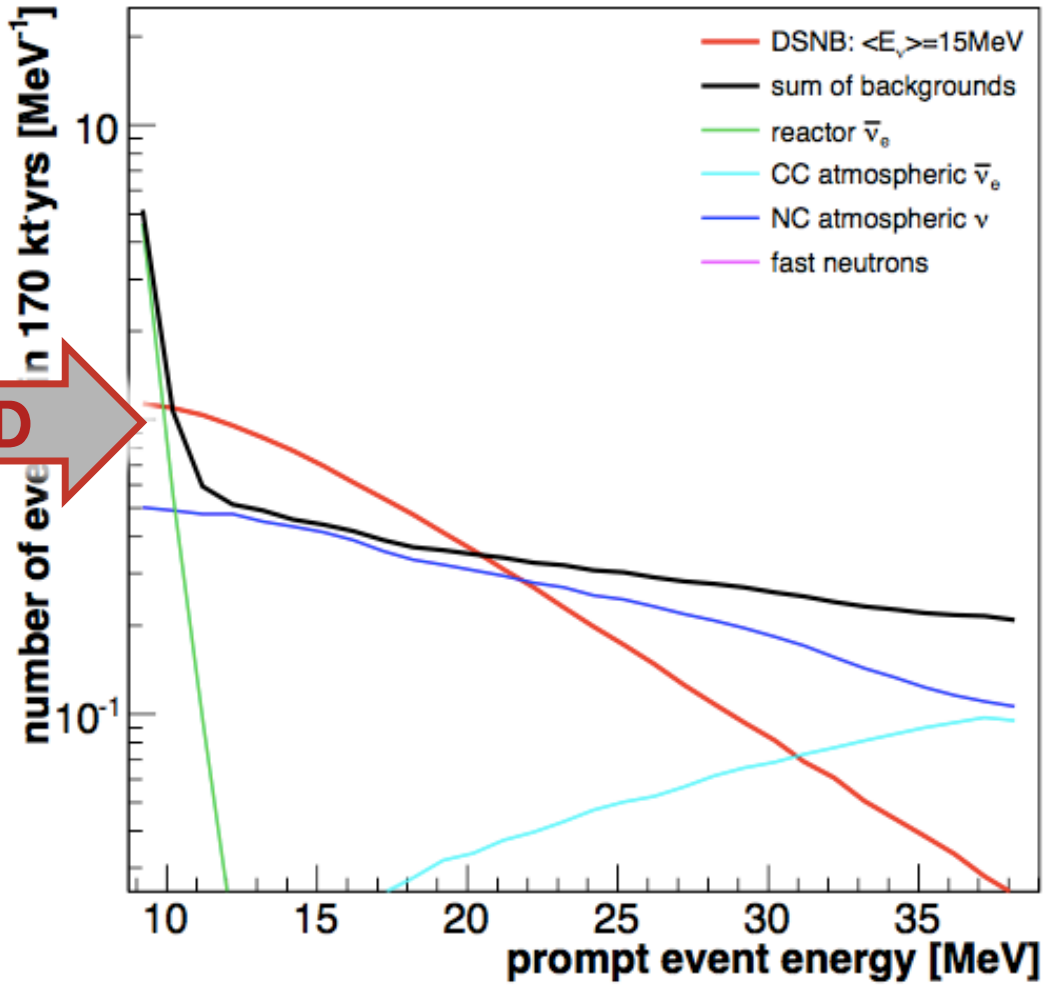
→ fast neutron detection allows to use almost the entire scintillator volume

Backgrounds to DSNB detection

from JUNO Yellow Book



PSD



before PSD:

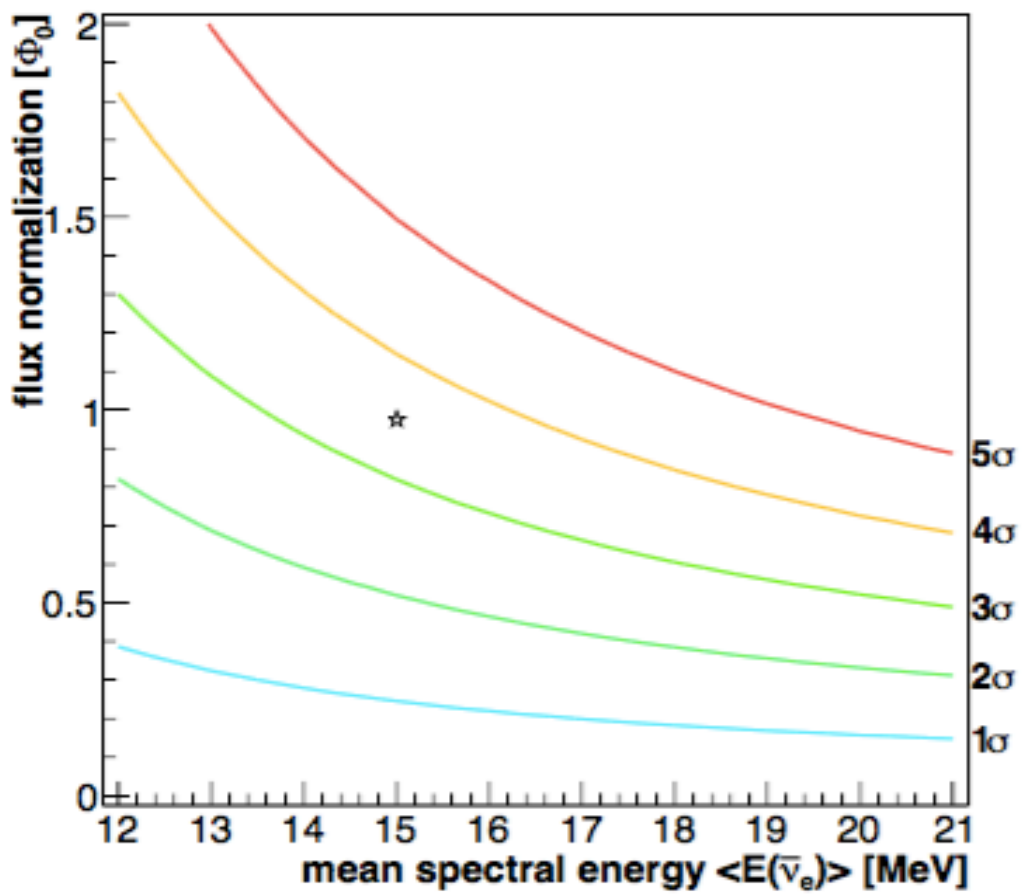
- atmospheric ν NC reactions
- fast neutrons

dominate the DSNB signal

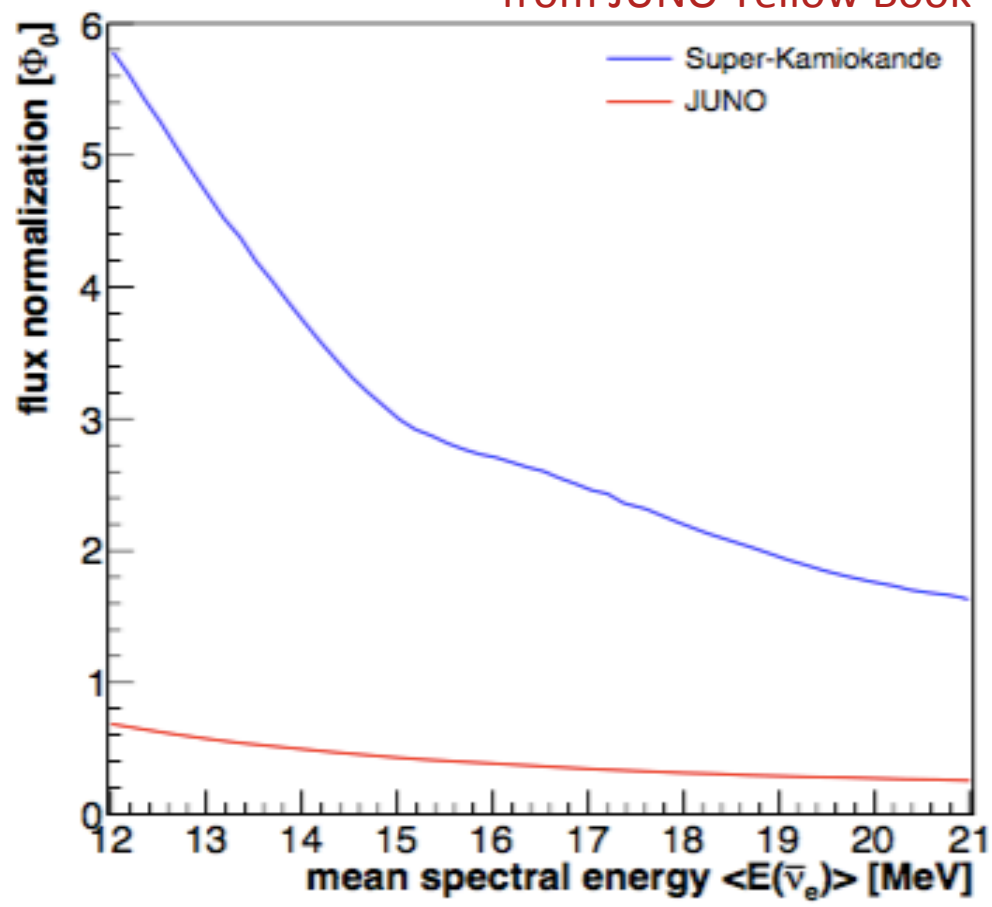
after PSD:

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

DSNB discovery/exclusion in JUNO



from JUNO Yellow Book



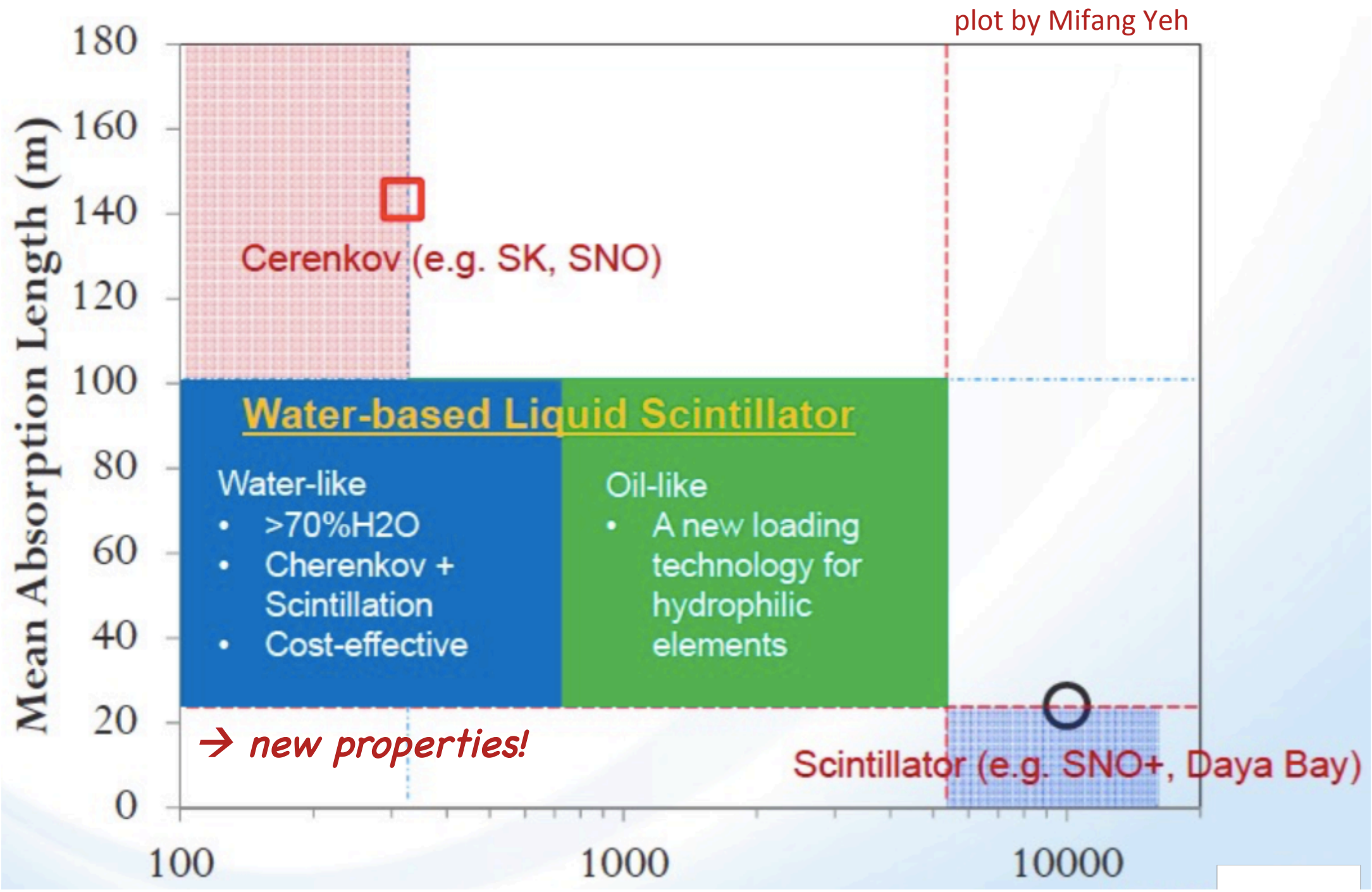
- **Discovery potential**
  - esposure: 17kt x 10 yrs
  - syst. uncertainty on BG: 5%

  → **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**

Potential of water-based scintillators



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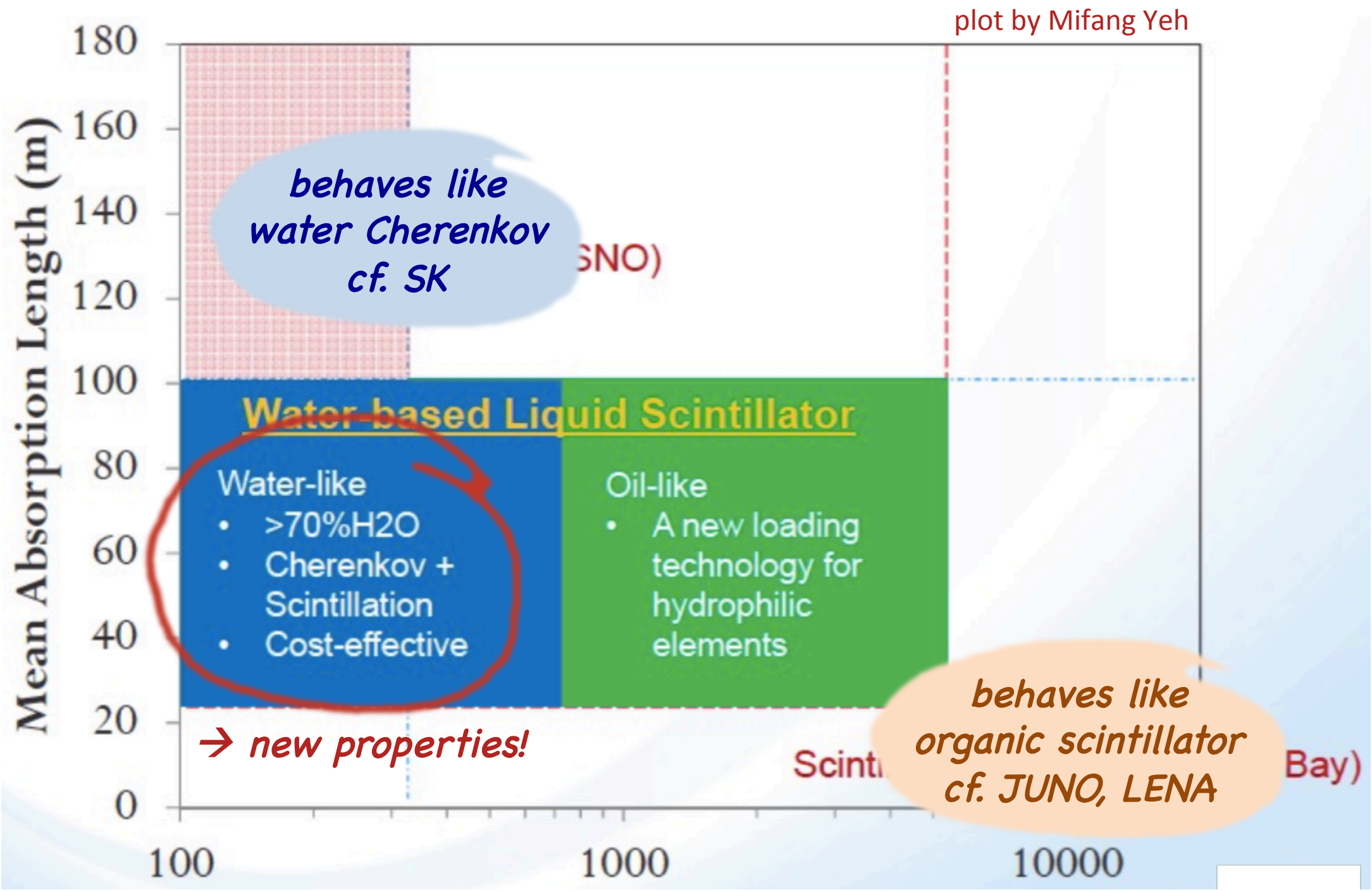
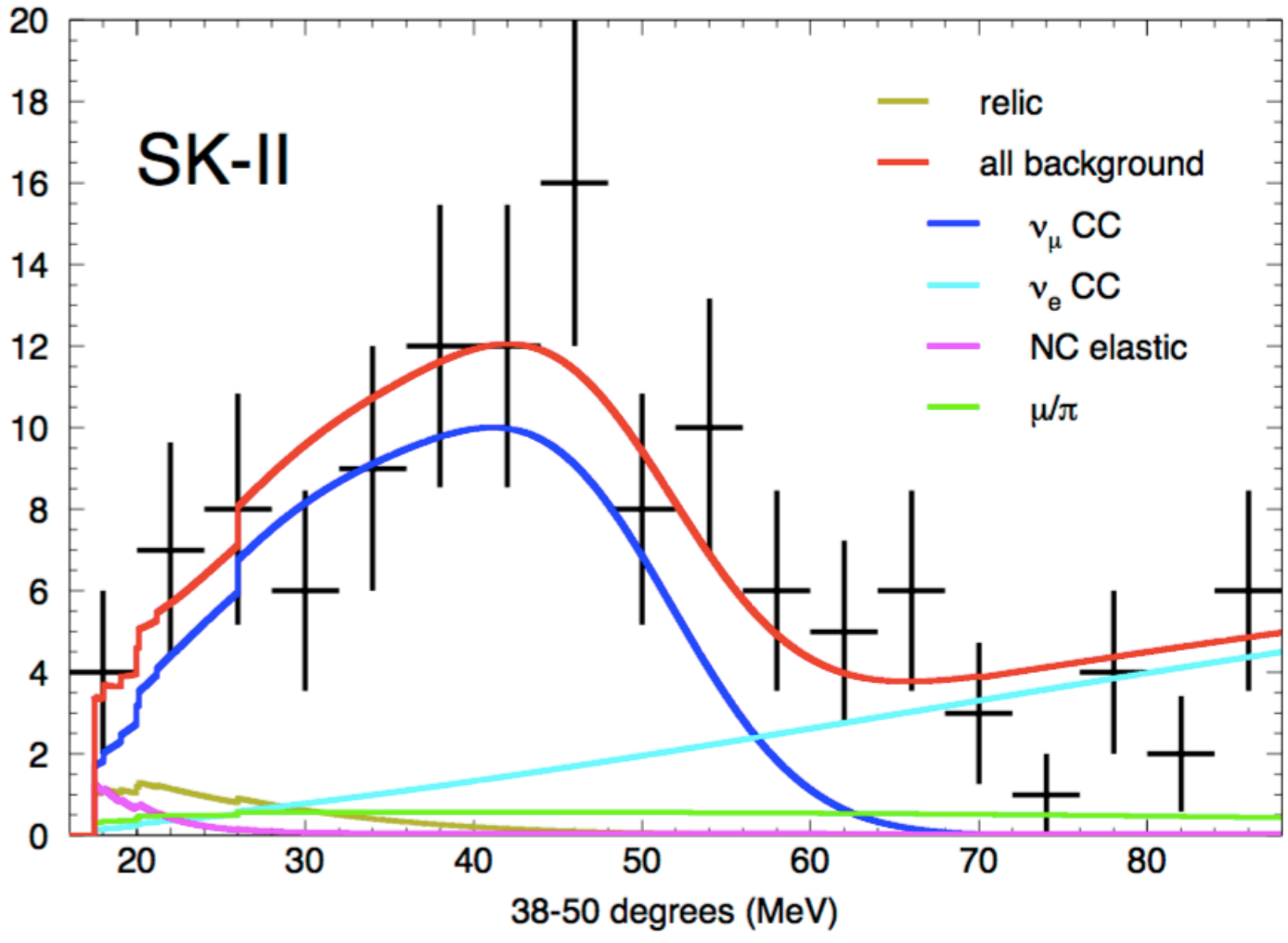


Adding scintillation to Cherenkov detector

compared to pure water

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

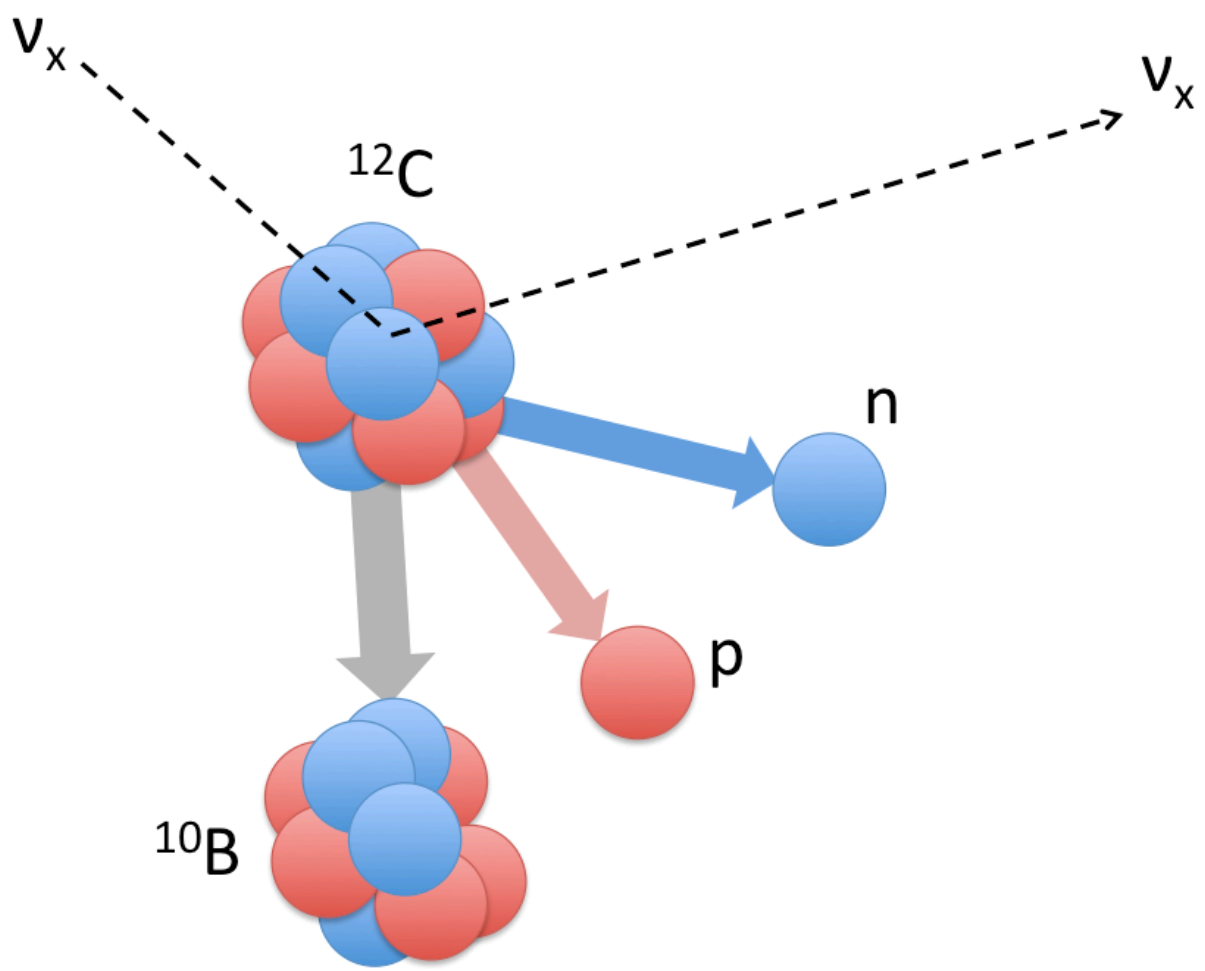


positron energy [MeV]

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
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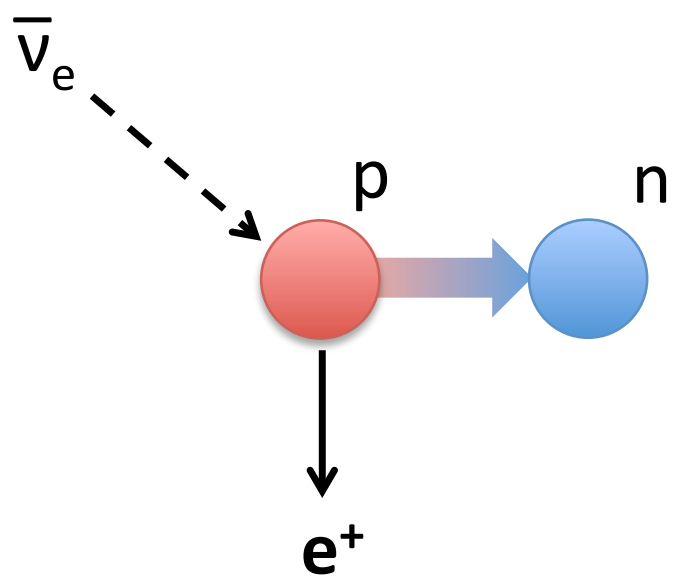
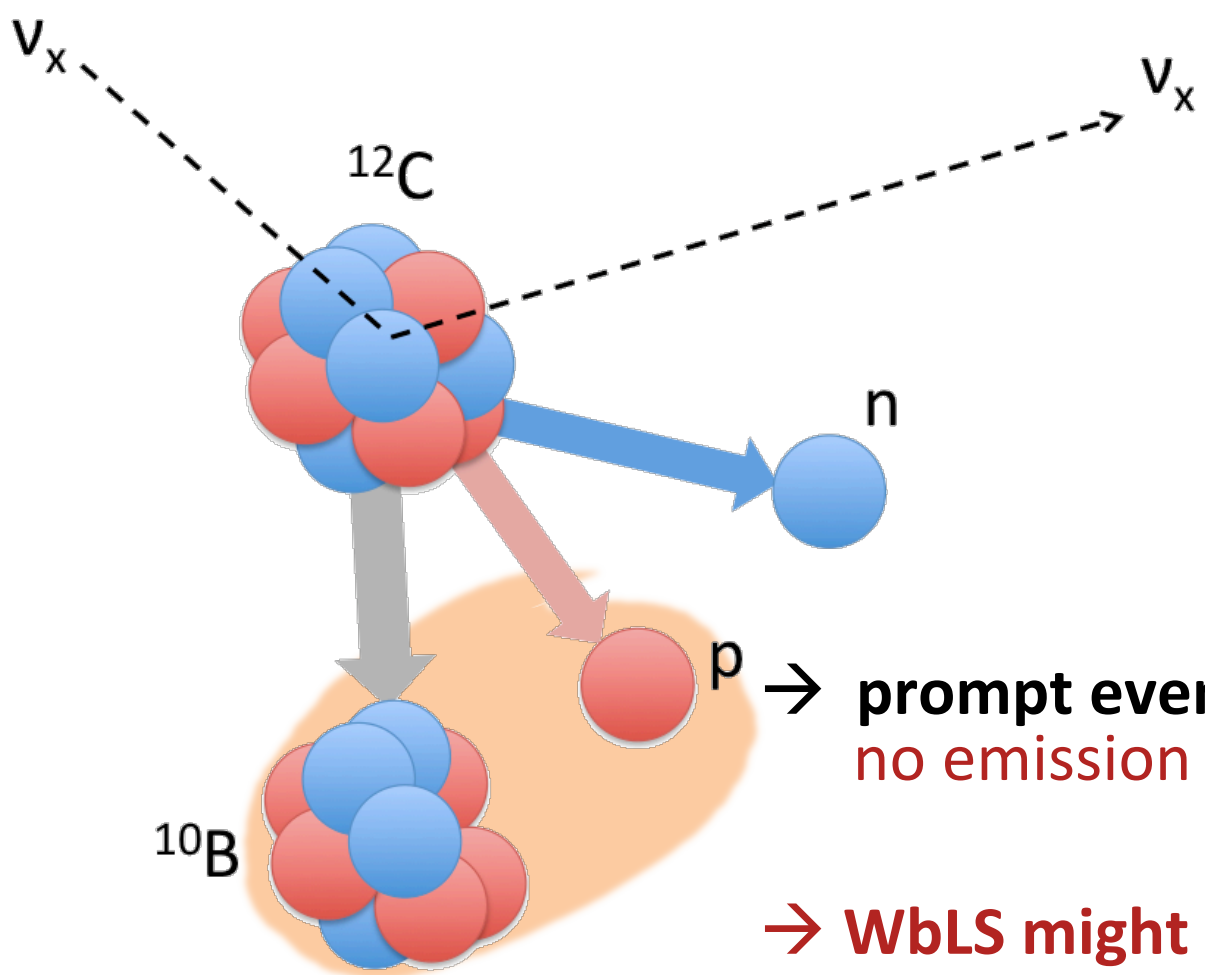


→ **prompt event:** positron emits both scintillation and Cherenkov

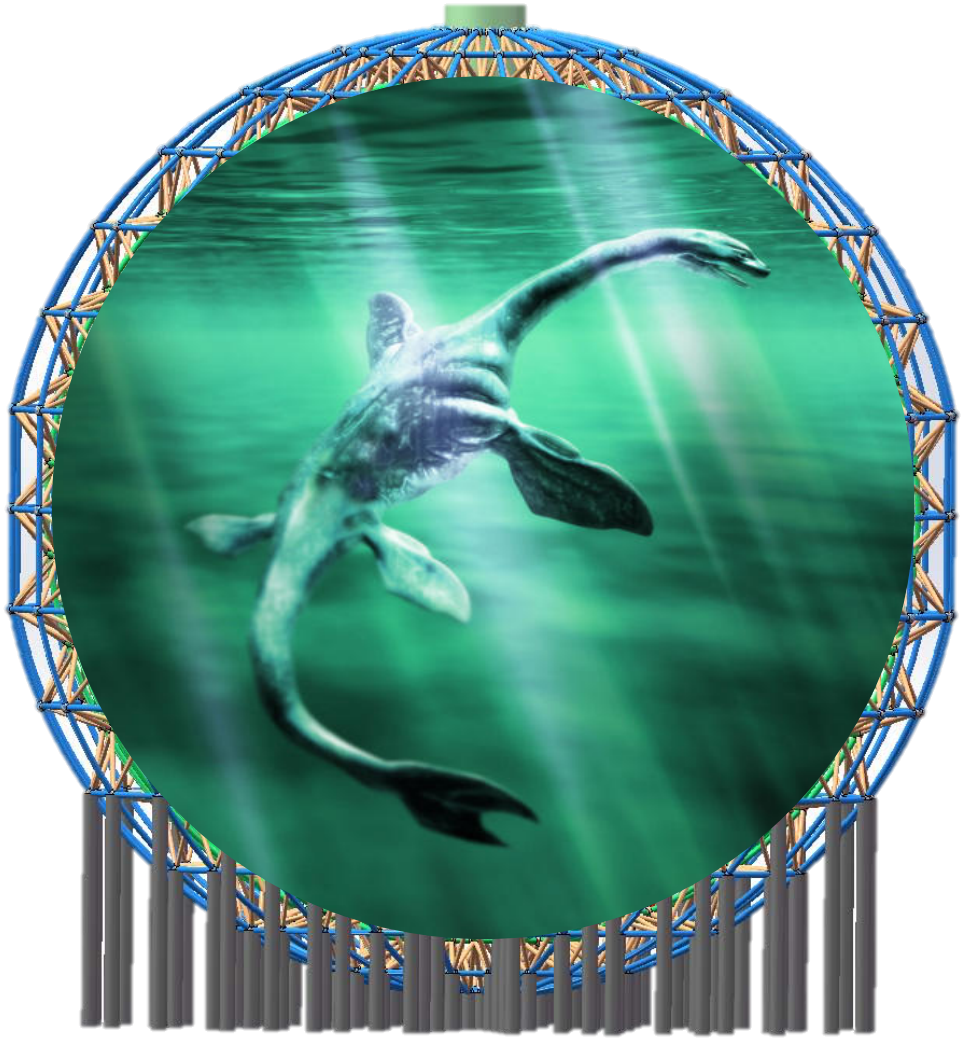


→ **prompt event:** low-energy protons (α's, nuclei): no emission of Cherenkov light!

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

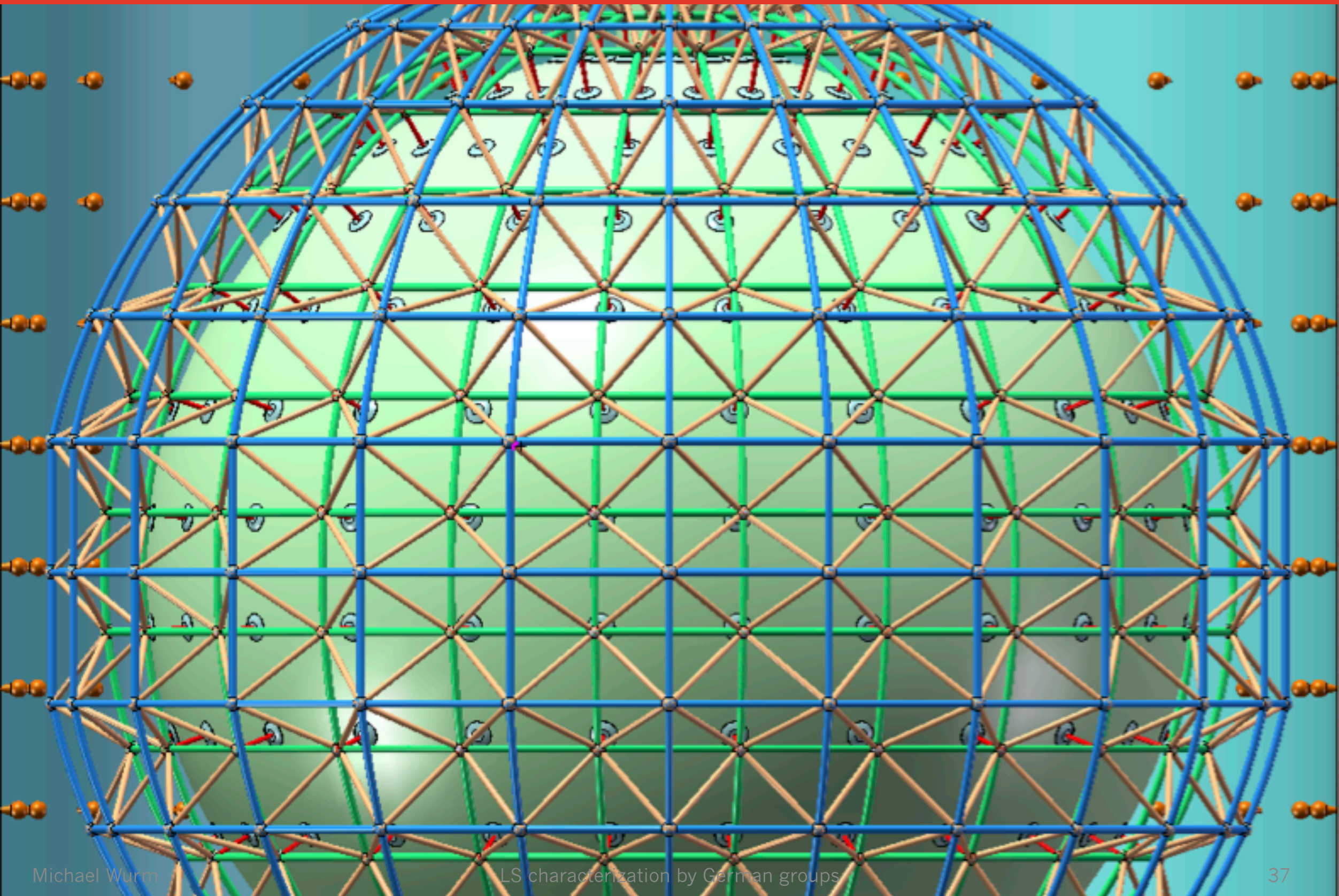
Requirements of a future DSNB detector

- large target mass (>>25kt) for
  - guaranteed discovery at 5σ level
  - measurement of mean spectral energy
- far away from nuclear reactors
- close to the equator (reduce atmospheric BG)
- sufficient depth and/or water shielding for fast neutron suppression
- possibility to tag delayed neutrons (Gd,LS)
- some means of prompt event discrimination:
  - pulse shape discrimination (LS)
  - Cherenkov/scintillation (WbLS)

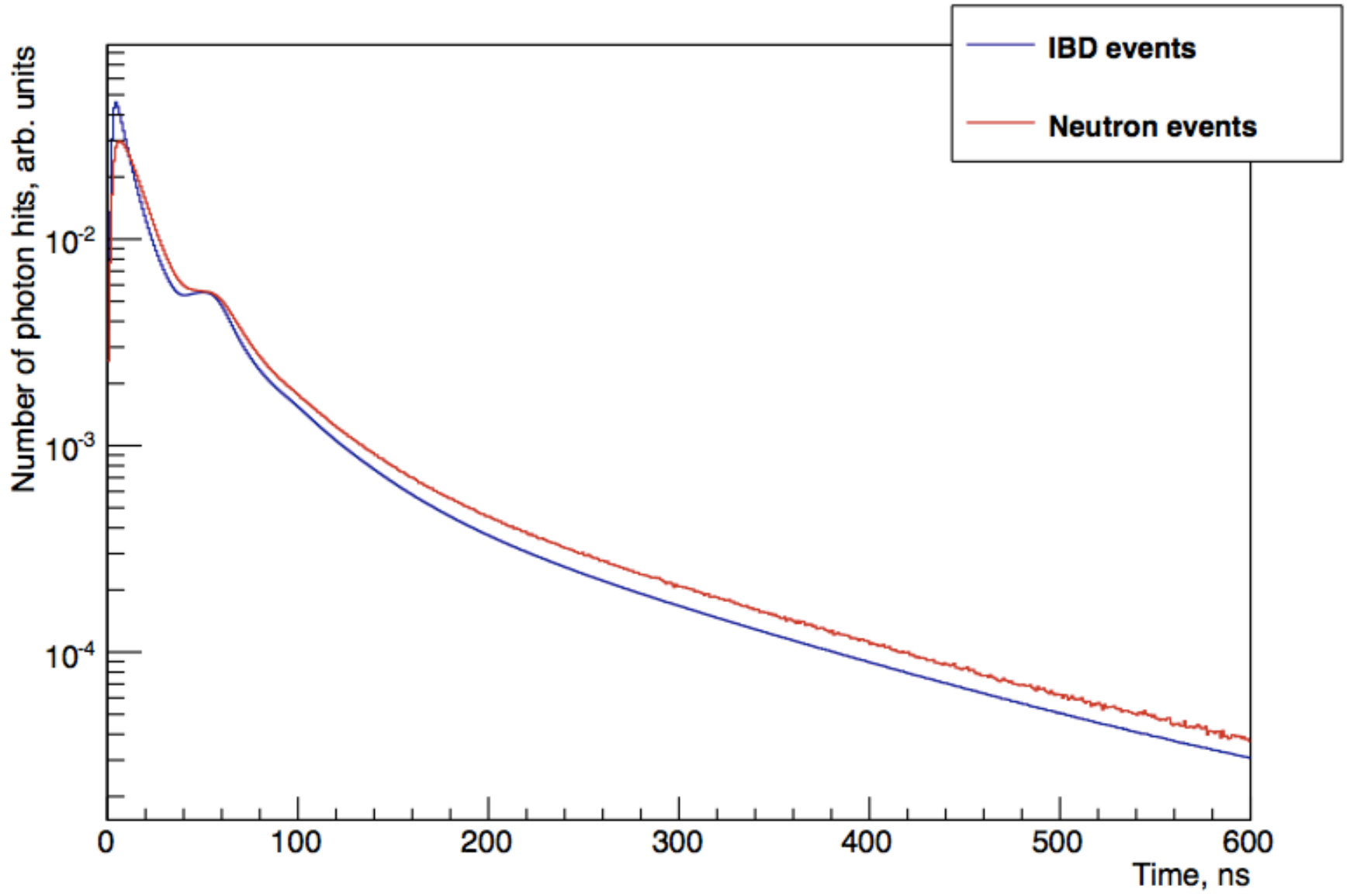


Thank you!

Backup Slides



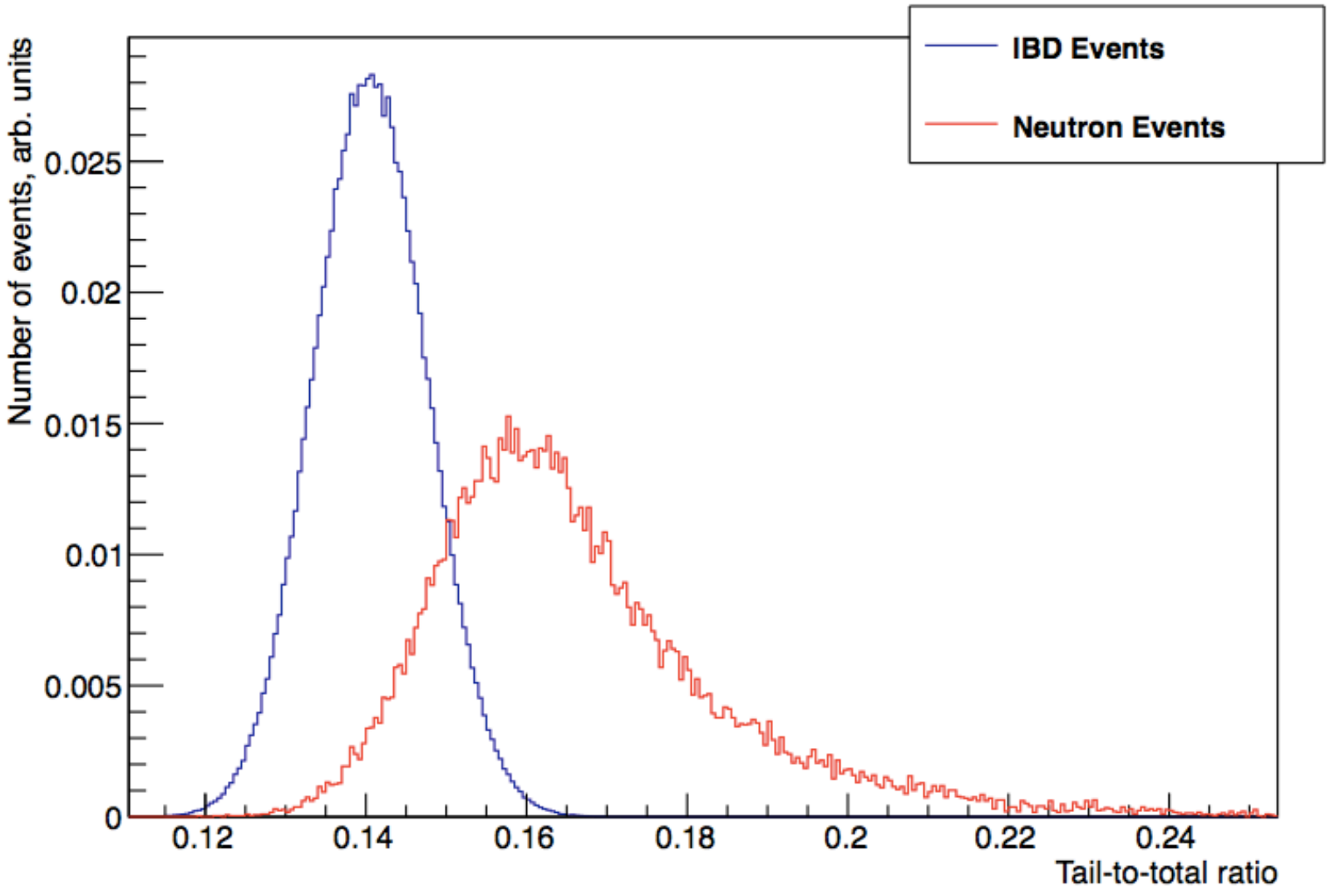
Pulse-shape discrimination (PSD) I



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}