Detection of Supernova Relic Neutrinos with Slow Liquid Scintillator

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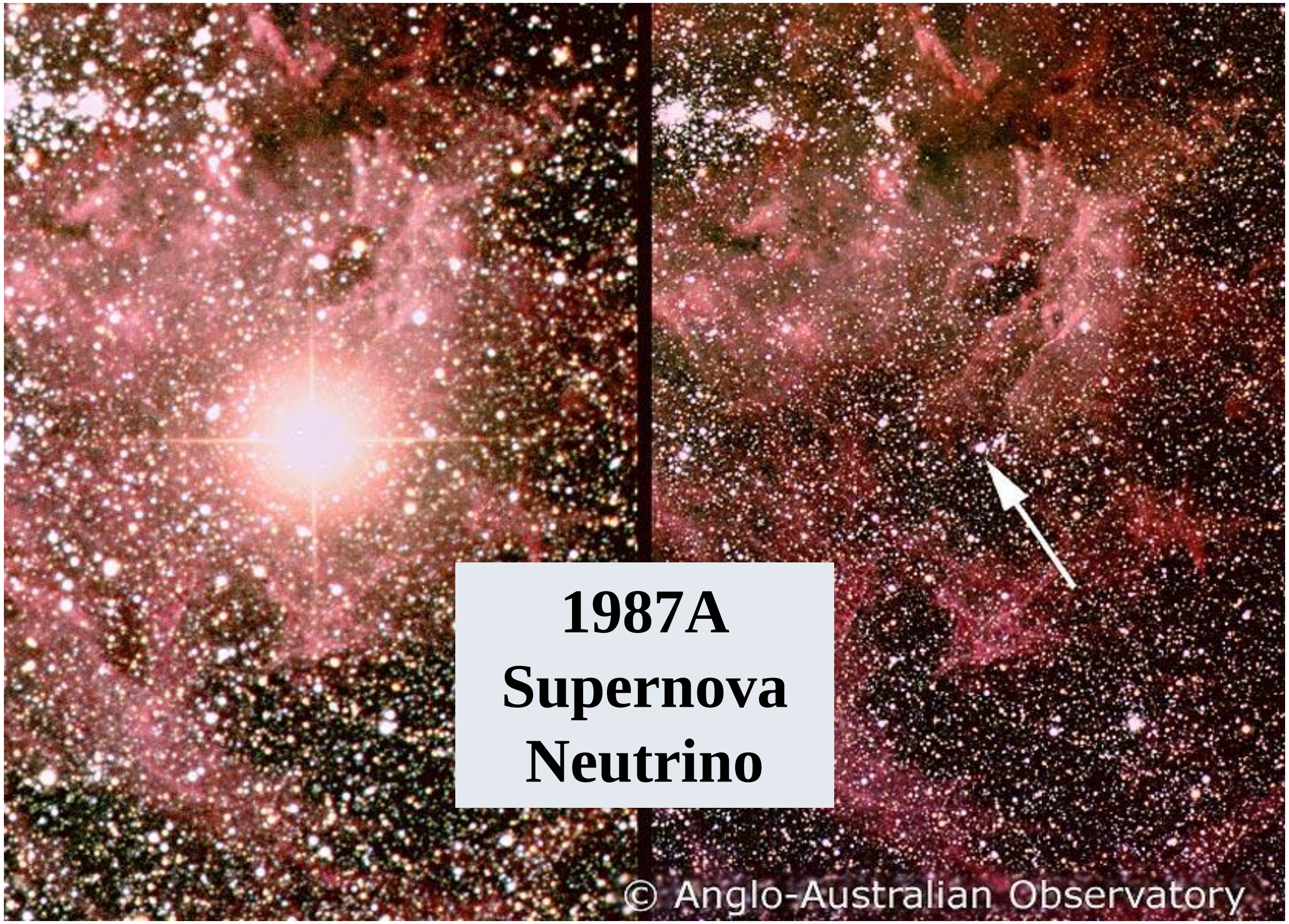
Supernova Neutrino



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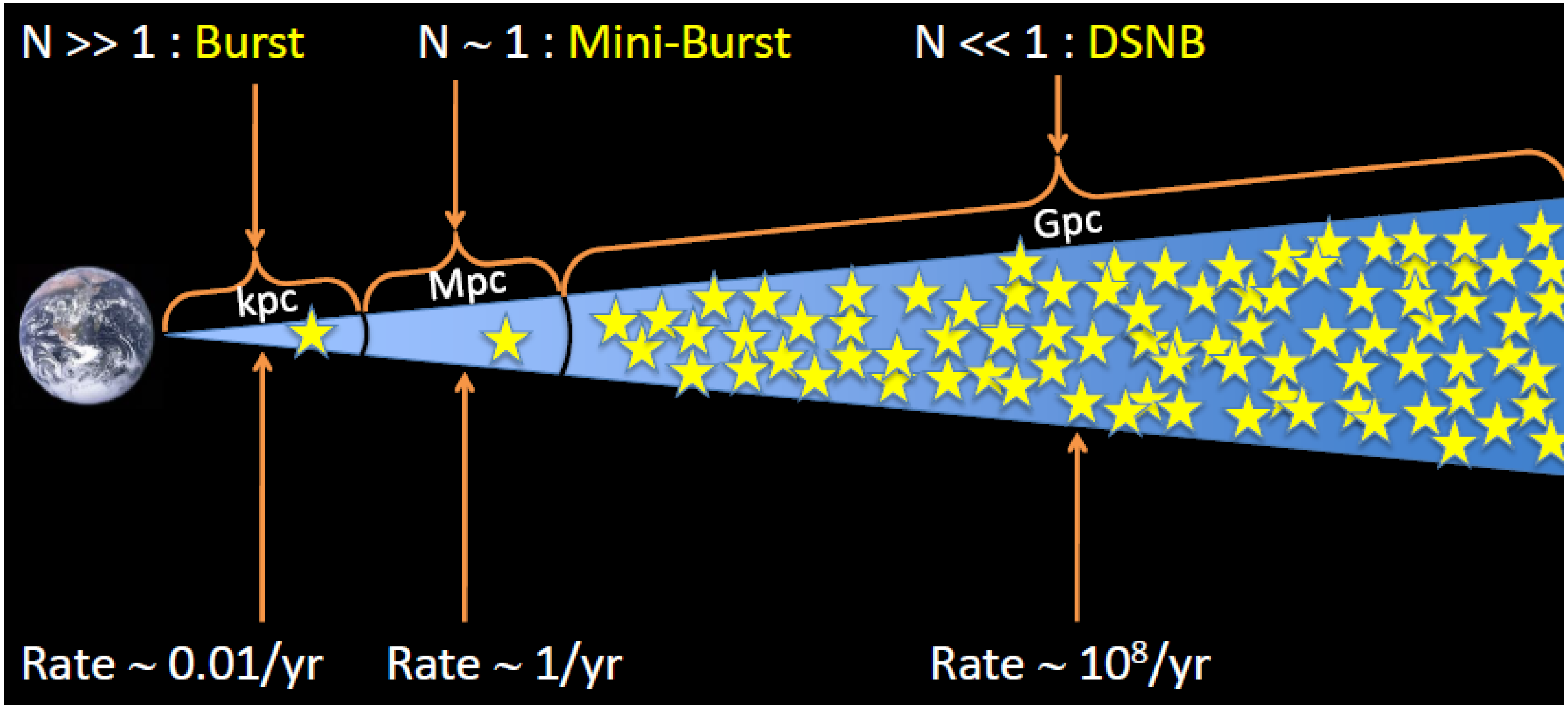
1987A
Supernova
Neutrino

- Supernova burst neutrino detection is hard
  -- about one chance per century.

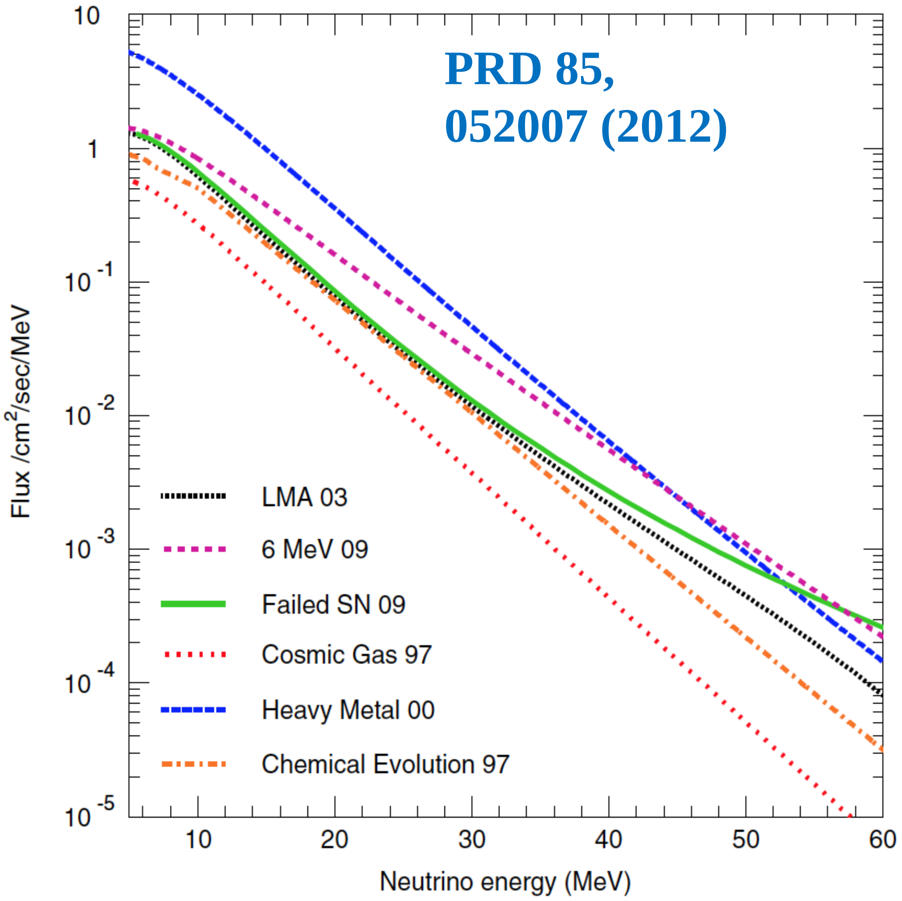
Supernova relic neutrino (SRN)

Or Diffused Supernova Neutrino Background (DSNB)



Neutrino-rich Core collapse supernova's (ccSN) are the main contributors

SRN spectrum

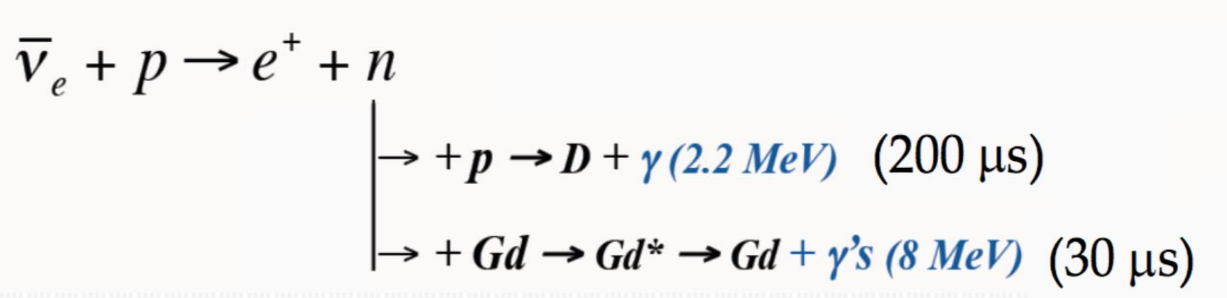


$$\frac{d\phi(E)}{dE} = \int R_{\mathrm{ccSN}}(z)\frac{dN(E')}{dE'}(1+z)\left|\frac{dt}{dz}\right|dz$$

1. R_{ccSN} - supernova rate (known with precision)
2. dN/dE' - neutrino spectrum (Some knowledge)
3. Others: redshift or constant

SRN Detection

- Equal amount for each flavors;
- SRN are identified primarily through IBD interactions in a hydrogen-rich detector



$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$\hookrightarrow + p \rightarrow D + \gamma\,(2.2\ MeV) \quad (200\ \mu s)$$

$$\hookrightarrow + Gd \rightarrow Gd^* \rightarrow Gd + \gamma\text{'s}\,(8\ MeV) \quad (30\ \mu s)$$

✓ Liquid scintillator – KamLAND [scintillation light]

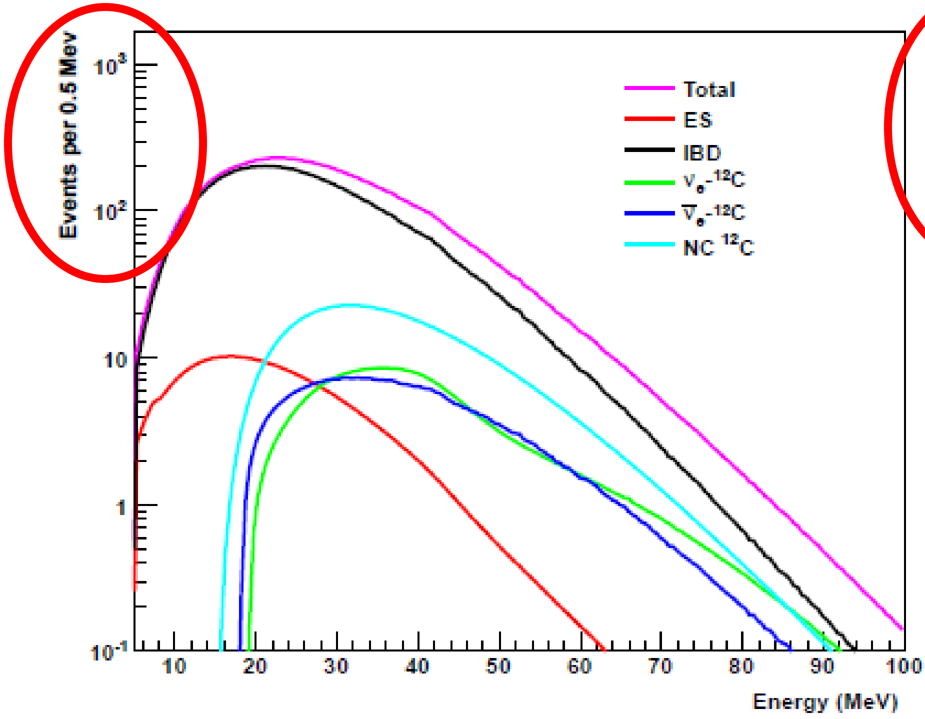
✓ Water – SuperK w/ or w/o neutron tagging [Cherenkov light]

✓ Gd-Water - Super K with neutron tagging [Cherenkov light]

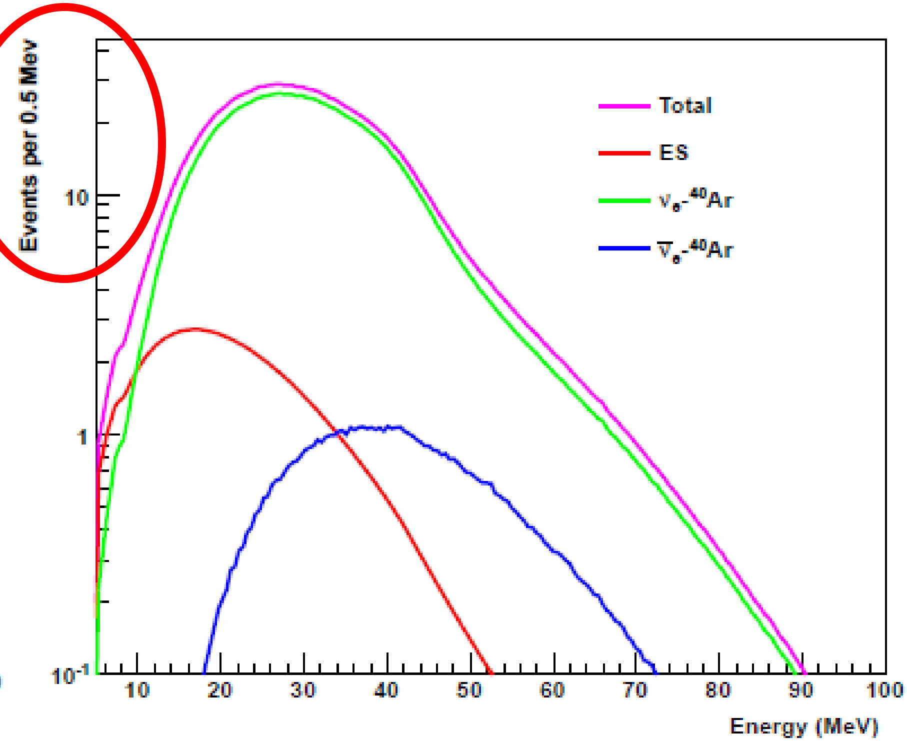
- LAr-TPC - DUNE $\bar{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{Cl}^*$

  Elastic scattering $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$

Statistical comparison for H or Ar



50 kt LS

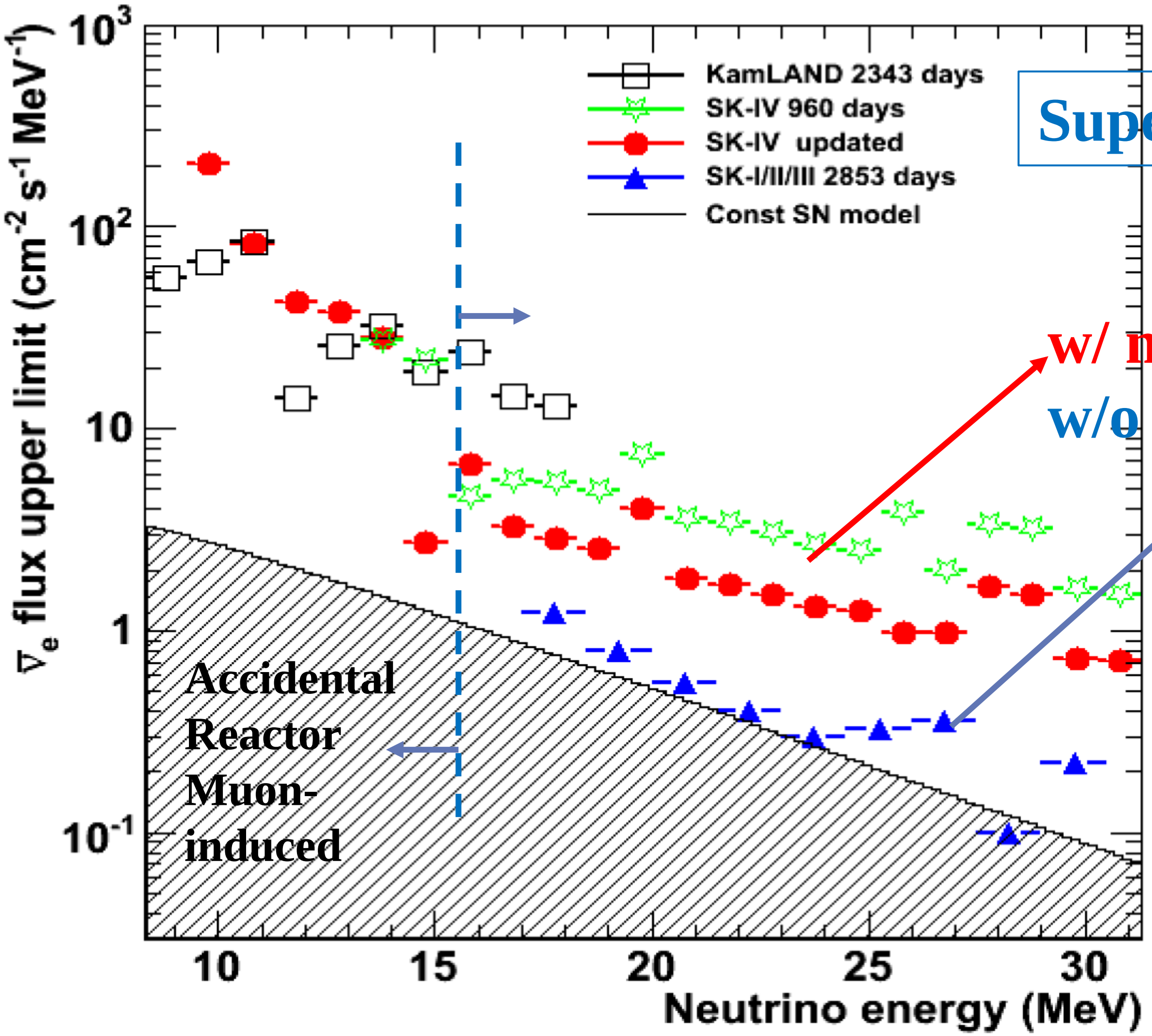


17 kt LAr

Water case is similar with LS

arxiv:1205.6003

Experimental results



Accidental
Reactor
Muon-induced

Super K result

w/ n-tag ~1900 days

w/o n-tag 2853 days

KamLAND result can be found at Astrophys. J. 745, 193 (2012)

Backgrounds for SRN detection

Site dependent:

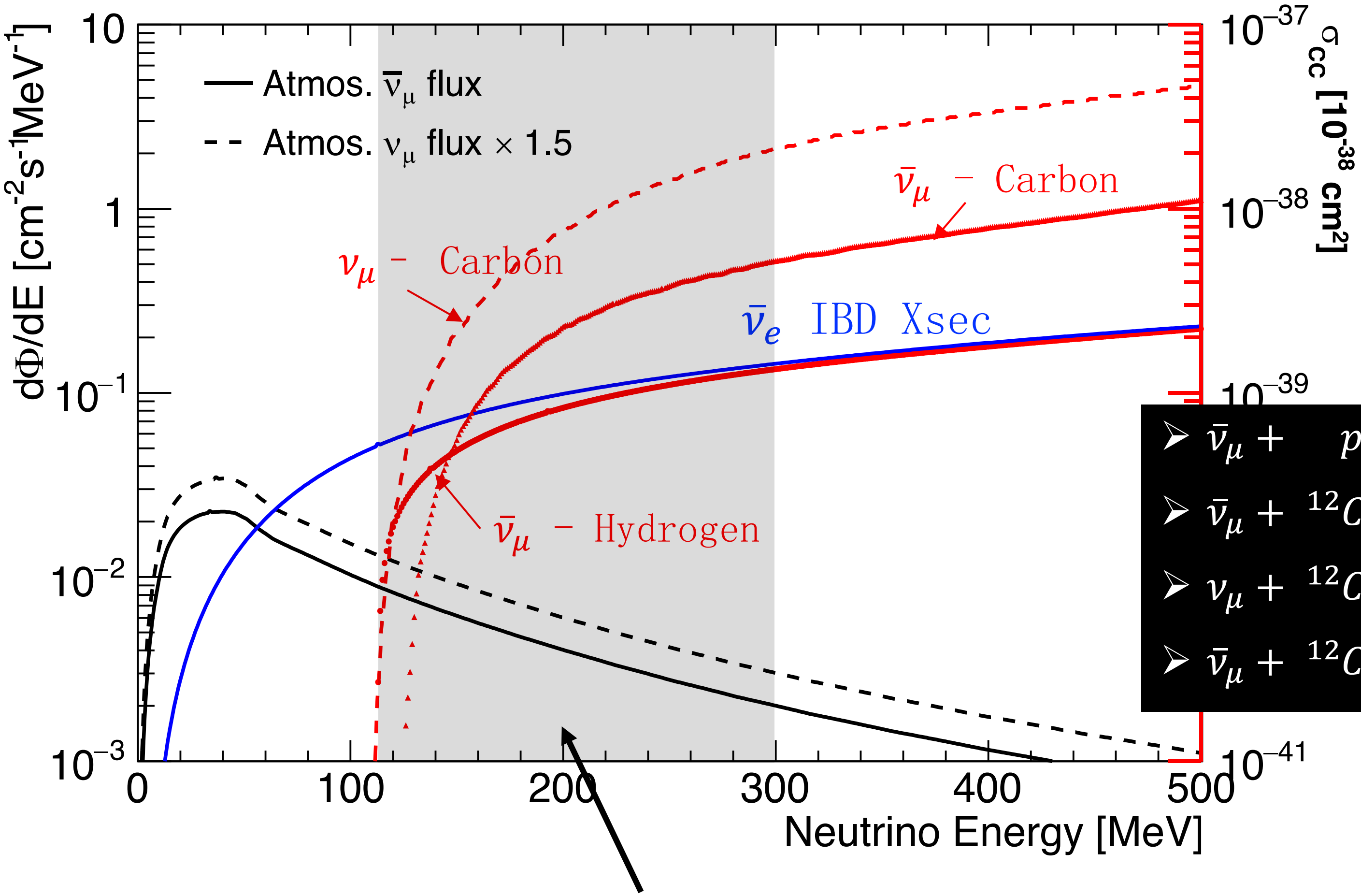
- ✓ Reactor neutrino E < 10 MeV
- ✓ Cosmogenic muons, Li9/He8 E < 15 MeV

Irreducible:

- ✓ Atmospheric ν_e background, E> 25-30 MeV

=> Signal window [10, 30] MeV

Atmospheric $\bar{\nu}_\mu/\nu_\mu$ charged current (CC) Bkg.

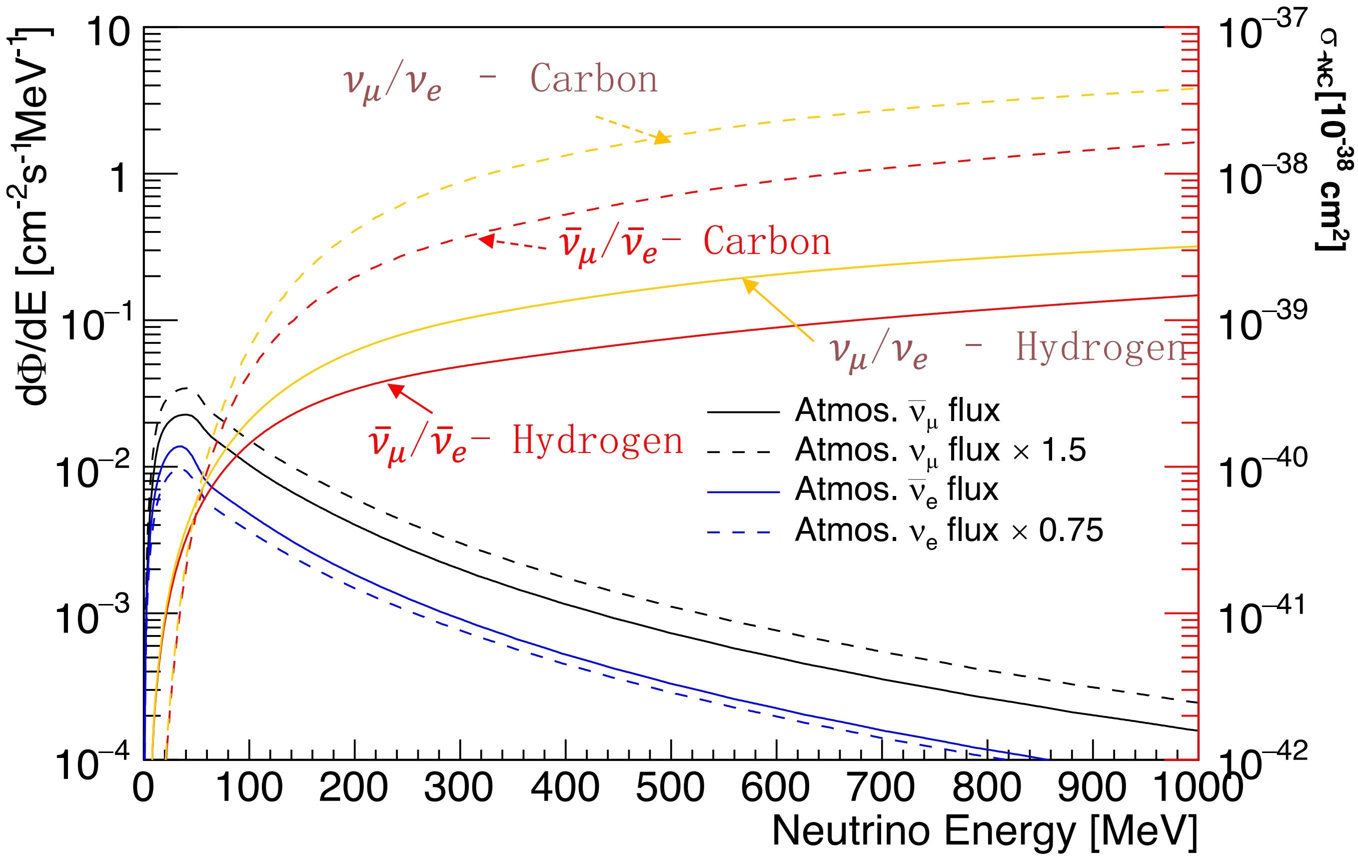


- ✓ Total CC cross section
- ✓ Quasi-elastic scattering (QES) dominated < 500 MeV

- ➢ $\bar{\nu}_\mu + p \rightarrow \boxed{\mu^+} + \boxed{n}$
- ➢ $\bar{\nu}_\mu + {}^{12}C \rightarrow \boxed{\mu^+} + \boxed{n} + {}^{11}B(+\gamma)$
- ➢ $\nu_\mu + {}^{12}C \rightarrow \boxed{\mu^-} + \boxed{n} + {}^{11}N$
- ➢ $\bar{\nu}_\mu + {}^{12}C \rightarrow \boxed{\mu^+} + \boxed{n} + {}^{7}Li + \alpha$

Shaded area: Atmospheric $\bar{\nu}_\mu/\nu_\mu$ CC background responsible for 10-30 MeV SRN detection

Atmospheric $\nu/\bar{\nu}$ neutral current (NC) Bkg.



- ✓ Total NC cross section
- ✓ NC elastic scattering dominated
- ✓ Quite a few percent resonant/coherent single π production and ν–e scattering

<1 GeV Atmospheric $\nu/\bar{\nu}$ NC background responsible for 10-30 MeV SRN detection

- ➢ $\nu(\bar{\nu}) + {}^{12}C \rightarrow \nu(\bar{\nu}) + \boxed{n} + {}^{11}C + \gamma$
- ➢ $\nu(\bar{\nu}) + {}^{12}C \rightarrow \nu(\bar{\nu}) + \boxed{n} + {}^{10}B + p$
- ➢ $\nu(\bar{\nu}) + {}^{12}C \rightarrow \nu(\bar{\nu}) + \boxed{n} + {}^{6}Li + \alpha + p$

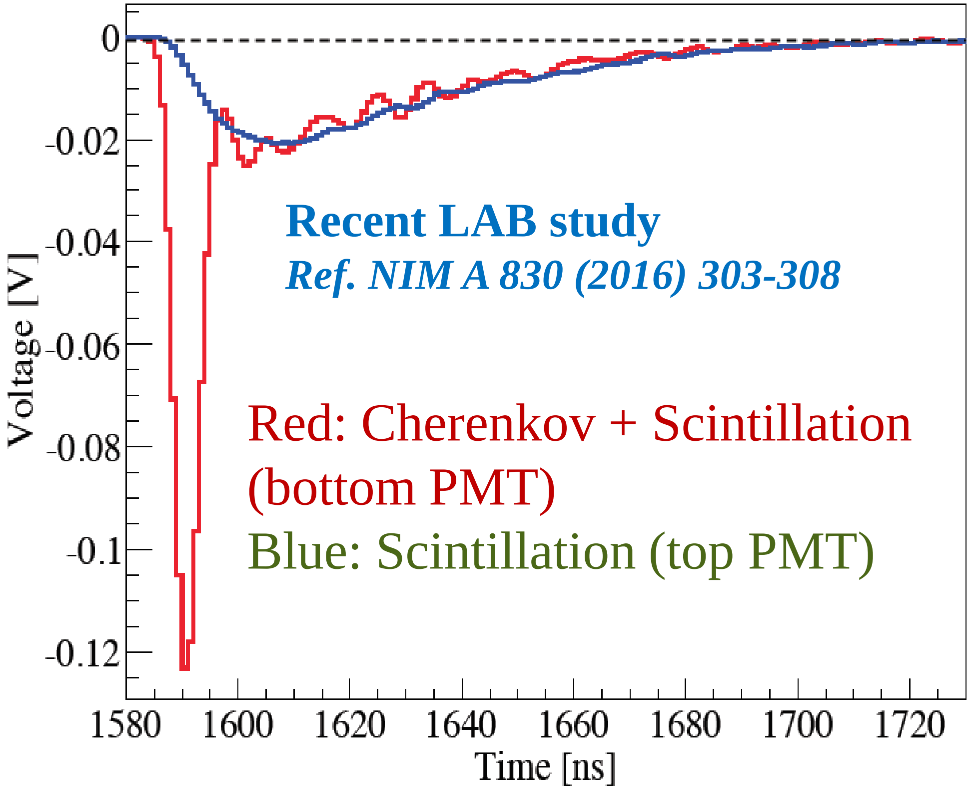
Key issues on SRN detections

	effi	Atmos. CC	Atmos. NC	Optical
LS	**~90%**	**triple coin. from $\mu^{\pm}$, decay $e^{\pm}$, and neutron capture.** **$\mu^{\pm}$ visible in 10-30 MeV**	**Energetic neutrons from high energy atmos. Neutrinos**	**Scintillation**
water w/o n-tag	**~75%**	**Decay $e^{\pm}$ from invisible $\mu^{\pm}$,** **$\mu^{\pm}$ invisible in 10-30 MeV**	**Secondaries (decays) of n or $\pi^{\pm}/\pi^{0}$ below Cherenkov threshold or different hit pattern**	**Cherenkov**
water w/ n-tag	**~13%**	**Reduced a lot by neutron tagging. The efficiency is increased a lot in Gd-water.**	**Further reduced by neutron tagging.**	
Gd-water	**~70%**			

- **Green: advantage / Blue: disadvantage**

Slow liquid scintillator candidate - LAB

- Other candidates: oil-based or water-based
- Feature: scintillation components slow enough
- Distinguish Cherenkov and scintillation



Recent LAB study

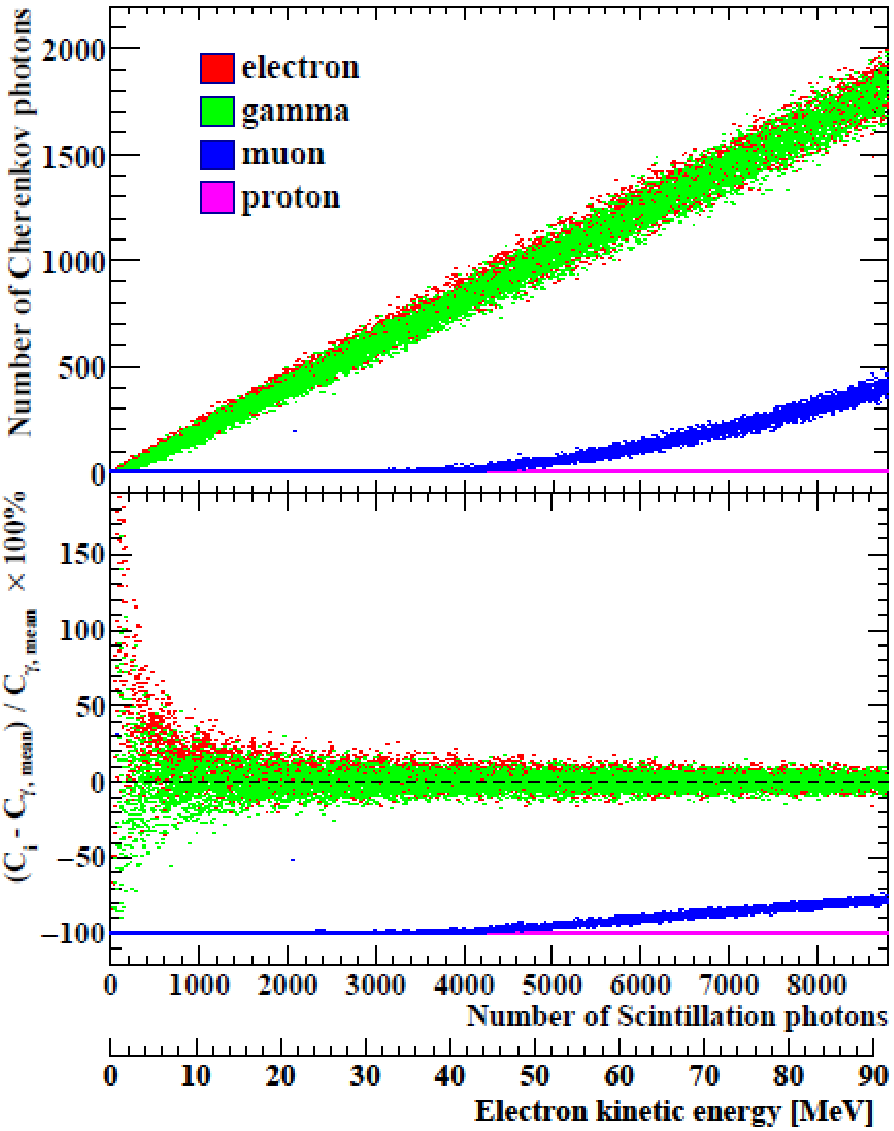
Ref. NIM A 830 (2016) 303-308

Red: Cherenkov + Scintillation (bottom PMT)

Blue: Scintillation (top PMT)

- **Rising time (τ_r): 7.7 ± 3.0 ns**
- **Decay time (τ_d): 36.6 ± 2.4 ns**
- **PMT time resolution: ~2ns**
- **Scintillation light yield: ~1000/MeV**

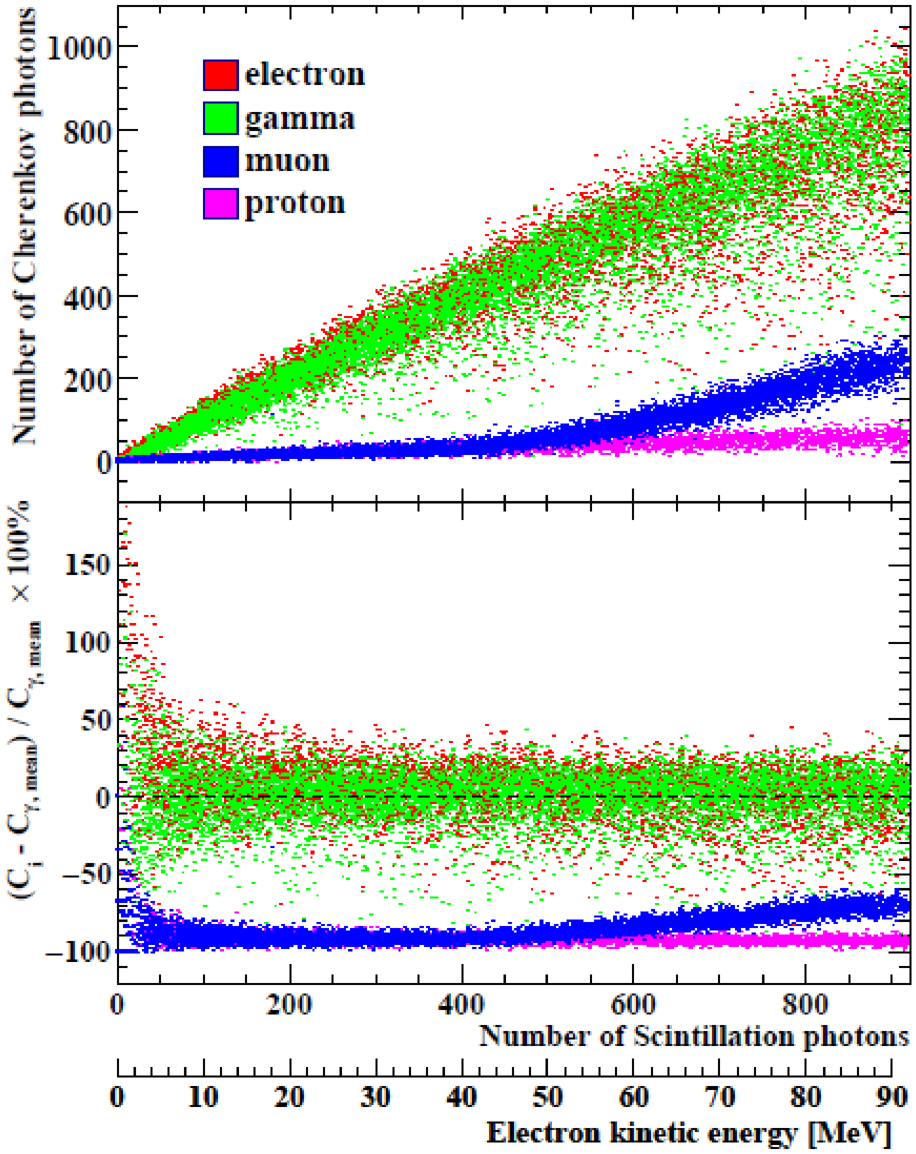
Separation of particles with LAB



Simulation of all types of particles

- Geant4 true information
- 10% QE efficiency for all photons
- No other detector effect

Separation of particles with LAB



More realistic:

- 10 ns cut for Cherenkov counting
- Attenuation in a10 m R detector (Eff: 10% for S and 50% for C)
- 10% efficiency for all photons

Simulation study

- [Detector response] Use LAB, PID in the realistic case
- [Signal flux] HBD model for SRN prediction
- [Background flux] Atmospheric neutrino flux
  1. > 100 MeV (Honda)
  2. < 100 MeV (Barr), basically for atmos. $\bar{\nu}_e$, ($\bar{\nu}_\mu/\nu_\mu$ CC interaction threshold ~105 MeV, NC neutron mainly contributed from >100 MeV atmos. flux)
  3. MSW effect considered, which would reduce the flux of $\bar{\nu}_\mu/\nu_\mu$ by 30%-50% in the interested energy range for SRN study
- GENIE cross sections for neutrino interactions
- *Simulation validated by KamLAND SRN result (2012)*

Suppression of Atmos. nu backgrounds

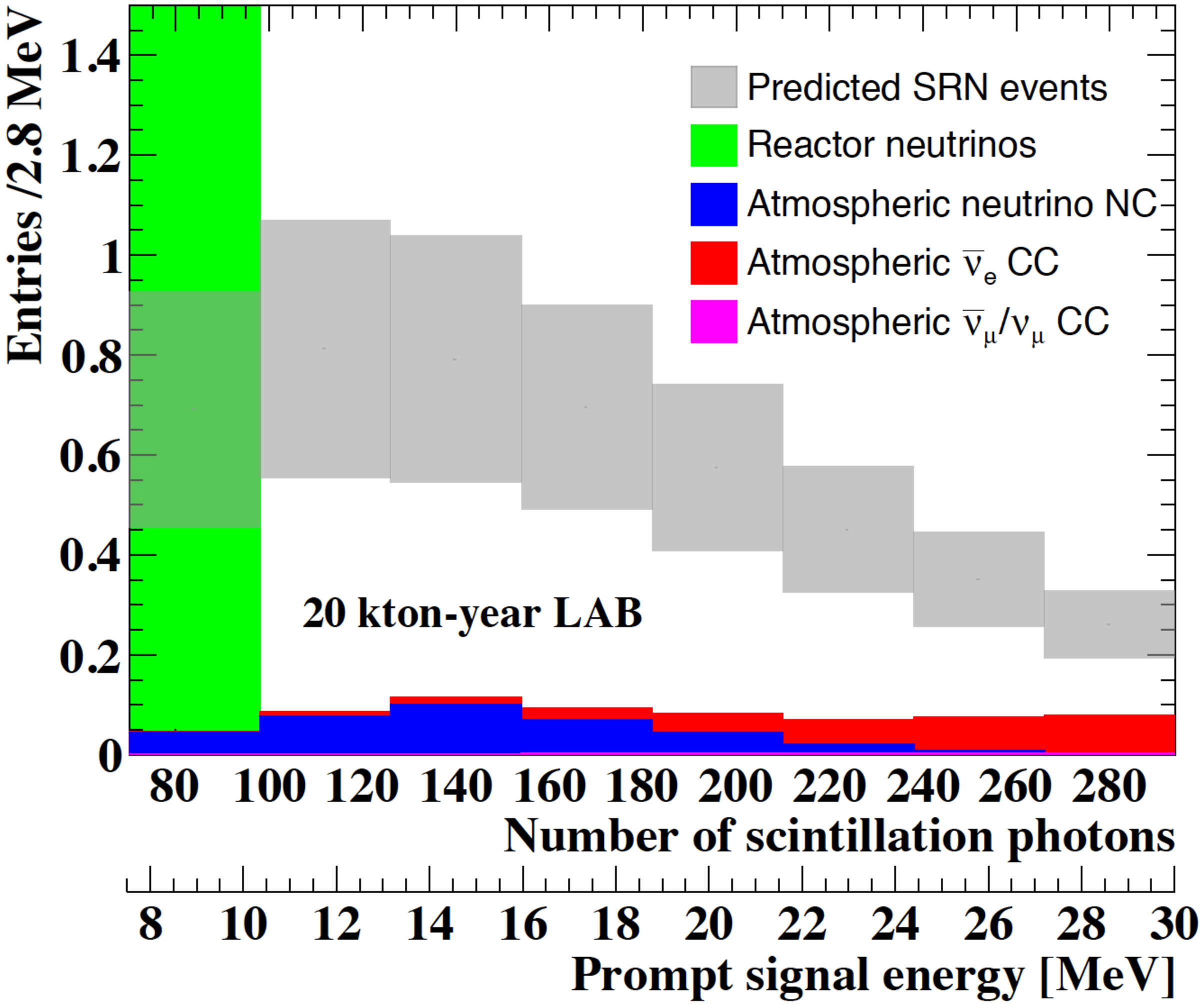
- CC background is suppressed as liquid scintillator to tag muon

  - $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$
  - $\bar{\nu}_\mu + {}^{12}C \rightarrow \mu^+ + n + {}^{11}B(+\gamma)$
  - $\nu_\mu + {}^{12}C \rightarrow \mu^- + n + {}^{11}N$
  - $\bar{\nu}_\mu + {}^{12}C \rightarrow \mu^+ + n + {}^{7}Li + \alpha$

- NC background is suppressed with particle id for electron and neutron recoils and others

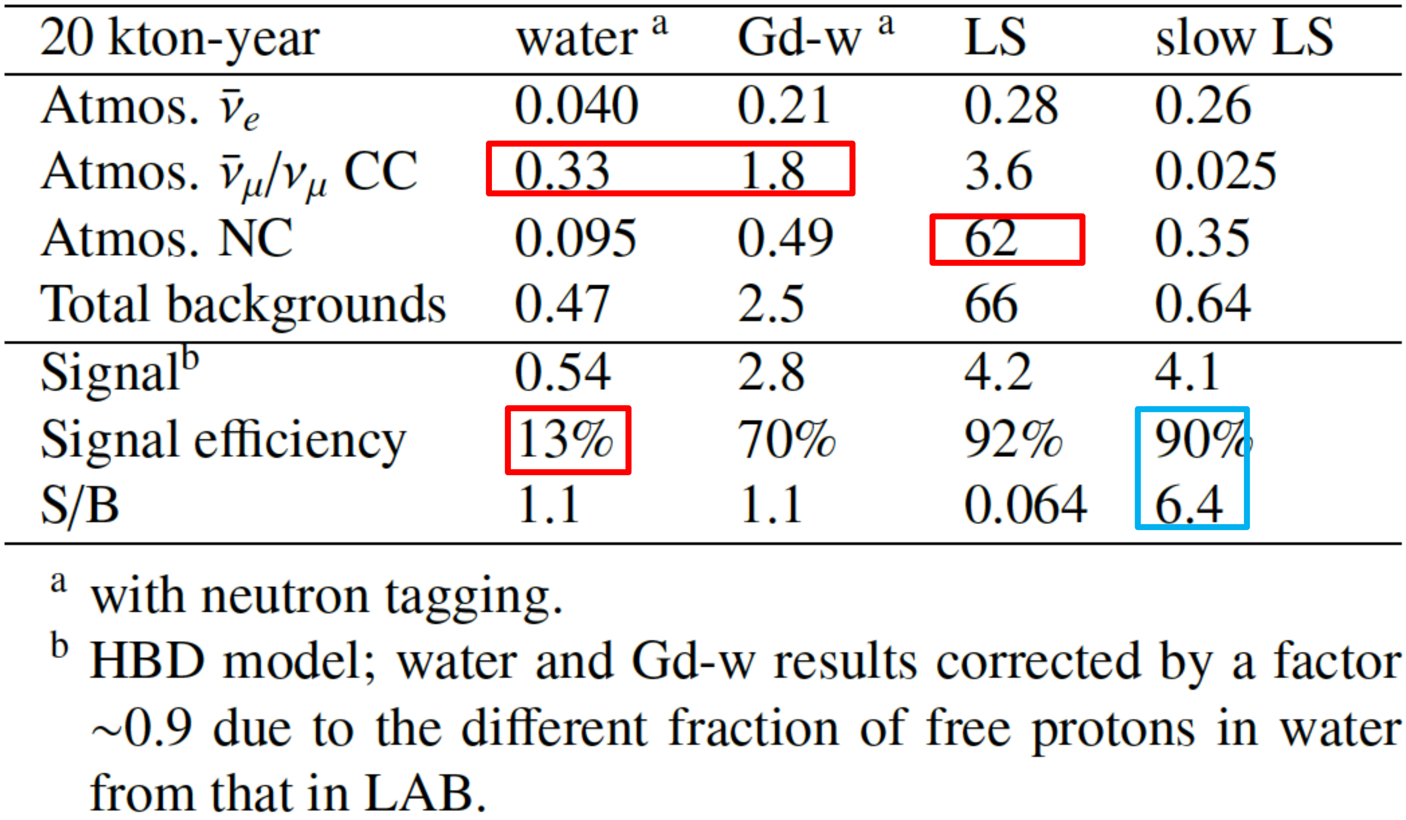
  - $\nu(\bar{\nu}) + {}^{12}C \rightarrow \nu(\bar{\nu}) + n + {}^{11}C + \gamma$
  - $\nu(\bar{\nu}) + {}^{12}C \rightarrow \nu(\bar{\nu}) + n + {}^{10}B + p$
  - $\nu(\bar{\nu}) + {}^{12}C \rightarrow \nu(\bar{\nu}) + n + {}^{6}Li + \alpha + p$

Result in a 20 kton-year detector



Environmental background at Jinping level

Comparison with other techniques



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

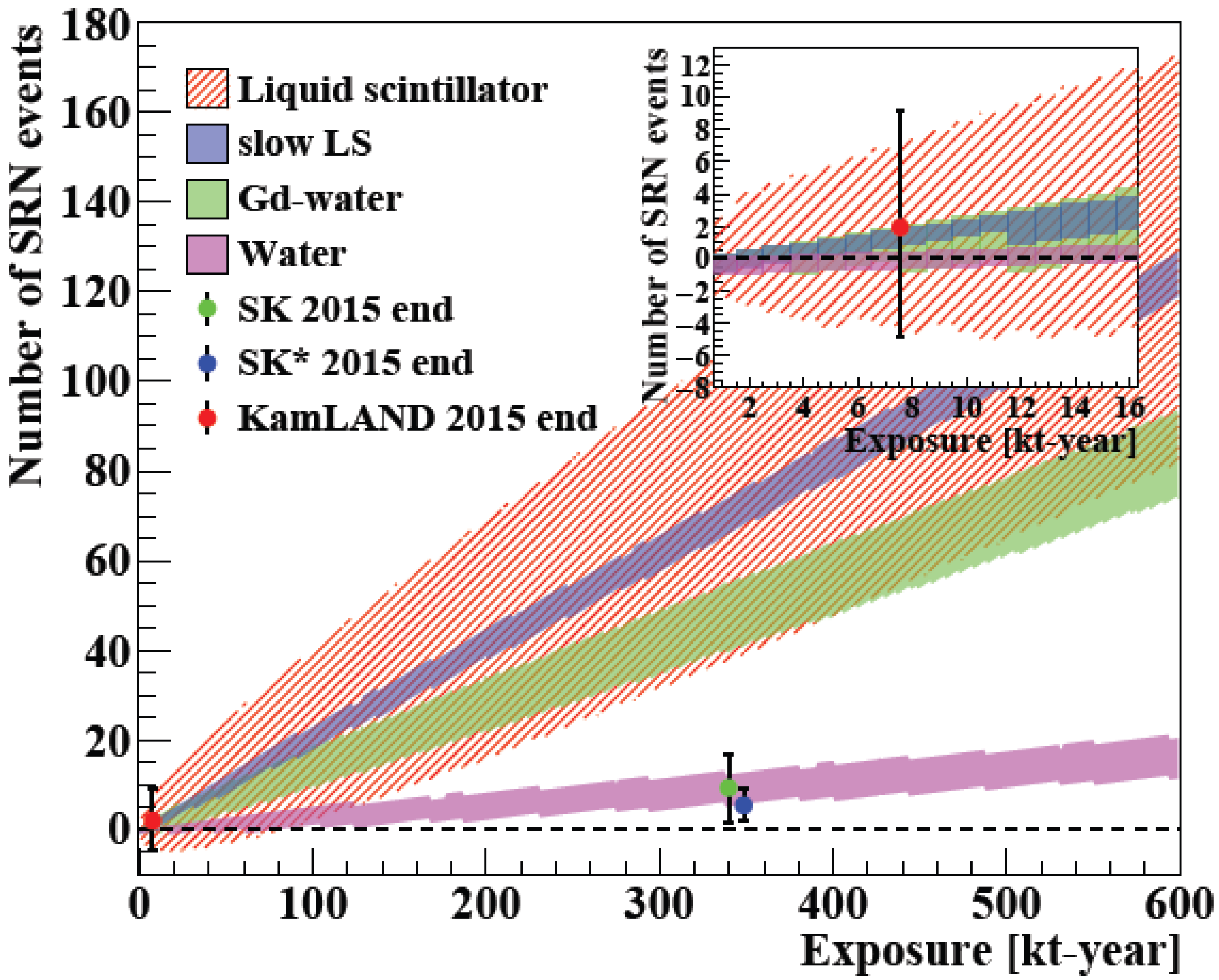
[a] with neutron tagging.

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

Note:

1. Traditional PSD in LS should improve the LS result.
2. For LAr, we expect the same S/N and Eff.

Comparison in a plot



Band is background only uncertainty at 1 sigma

Final comments on the result

The information is valid for a wide range of slow liquid scintillators.

- What about water-based LS? Insufficient scintillation?
  - Fine, as long as a little scintillation components is added
- What about oil-based LS? Separation is poor
  - A little separation is still needed.

Thank you.

More detail of the work can be found at arXiv:1607.01671.