Preliminary

# Potential of Supernova Relic Neutrino Search by *Slow Liquid Scintillator*

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April 17, 2016
Workshop on JUNO Neutrino Astronomy and Astrophysics

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- Current experimental upper limits
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- Slow liquid scintillator (slow LS)
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- SRN sensitivity study
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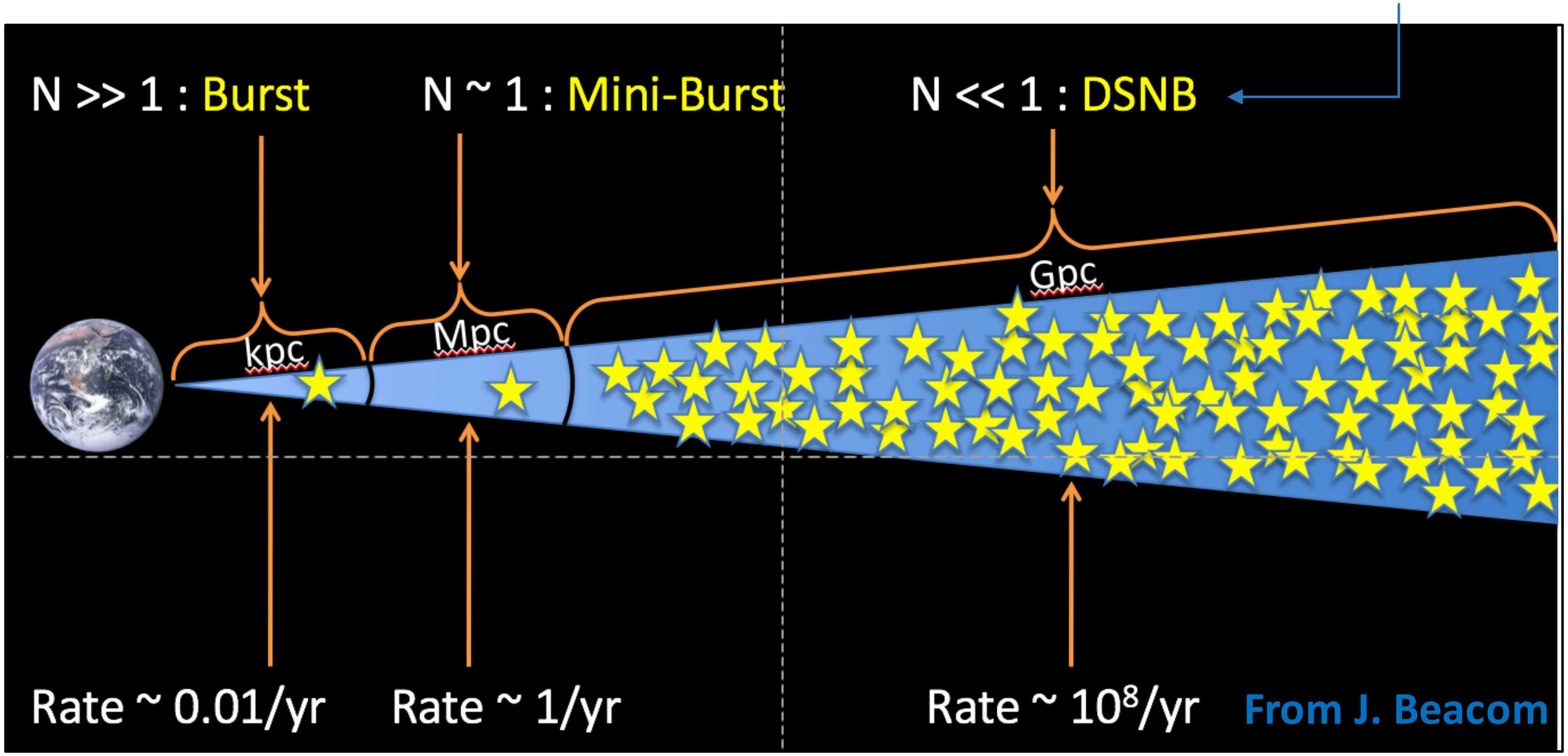
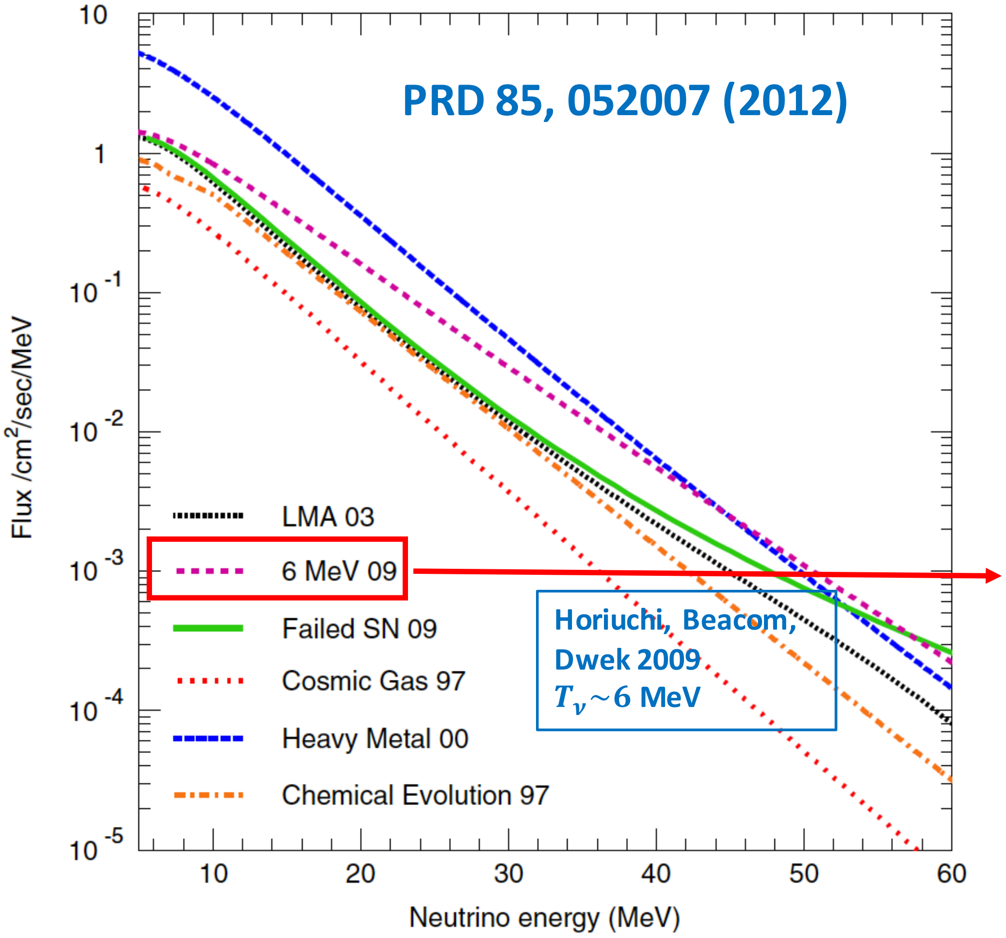
# Supernova relic neutrinos (SRN)

- Collective supernova burst neutrinos from all the past supernova explosions throughout the history of the Universe
- Also known as diffuse supernova neutrino background (DSNB)



From J. Beacom

# SRN theoretical spectrum

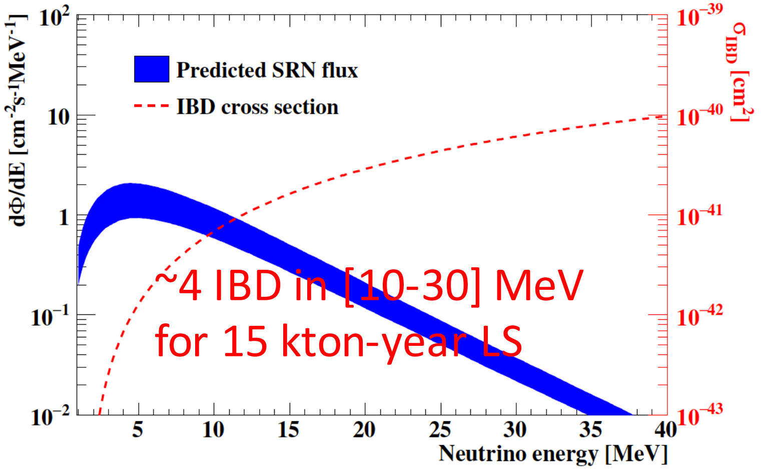


**PRD 85, 052007 (2012)**

**Horiuchi, Beacom, Dwek 2009**
**$T_\nu \sim 6$ MeV**

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

- Rate of core-collapse supernova explosions
- Neutrino emission per supernova
- Redshift, cosmic time and other cosmological parameters



~4 IBD in [10-30] MeV
for 15 kton-year LS

# Detection of SRN

- SRN are identified primarily through **IBD** interactions in a hydrogen-rich detector

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

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

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

Large cross section (10-20x second largest)

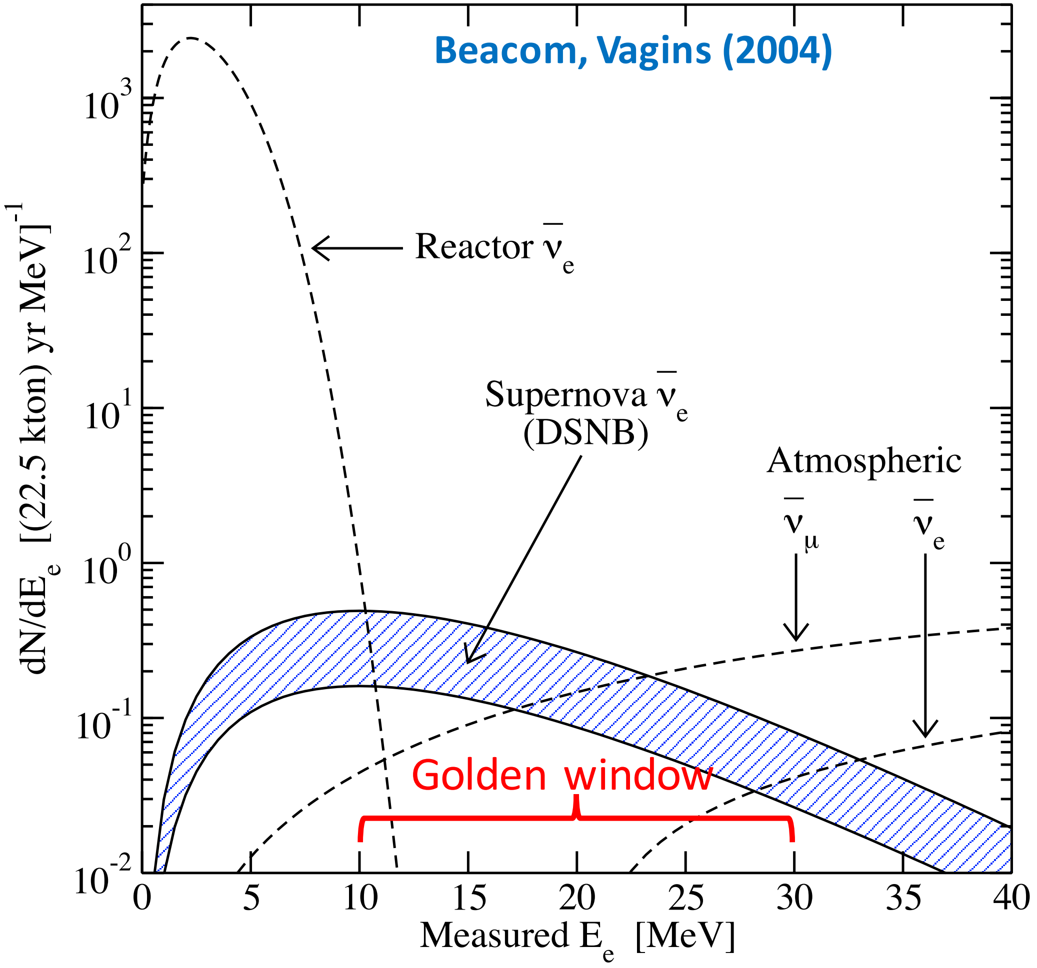
Prompt-delayed coincidence: low backgrounds from accidentals, radioactivity and other neutrino sources and interactions

✓ Liquid scintillator - KamLAND [scintillation light]
✓ Water - SuperK (Gd-doped) with neutron tagging [Cherenkov light]

Only positron signal

✓ Water - SuperK without neutron tagging [Cherenkov light]

# Backgrounds for SRN detection



**Background sources**

**Cosmogenic muon**

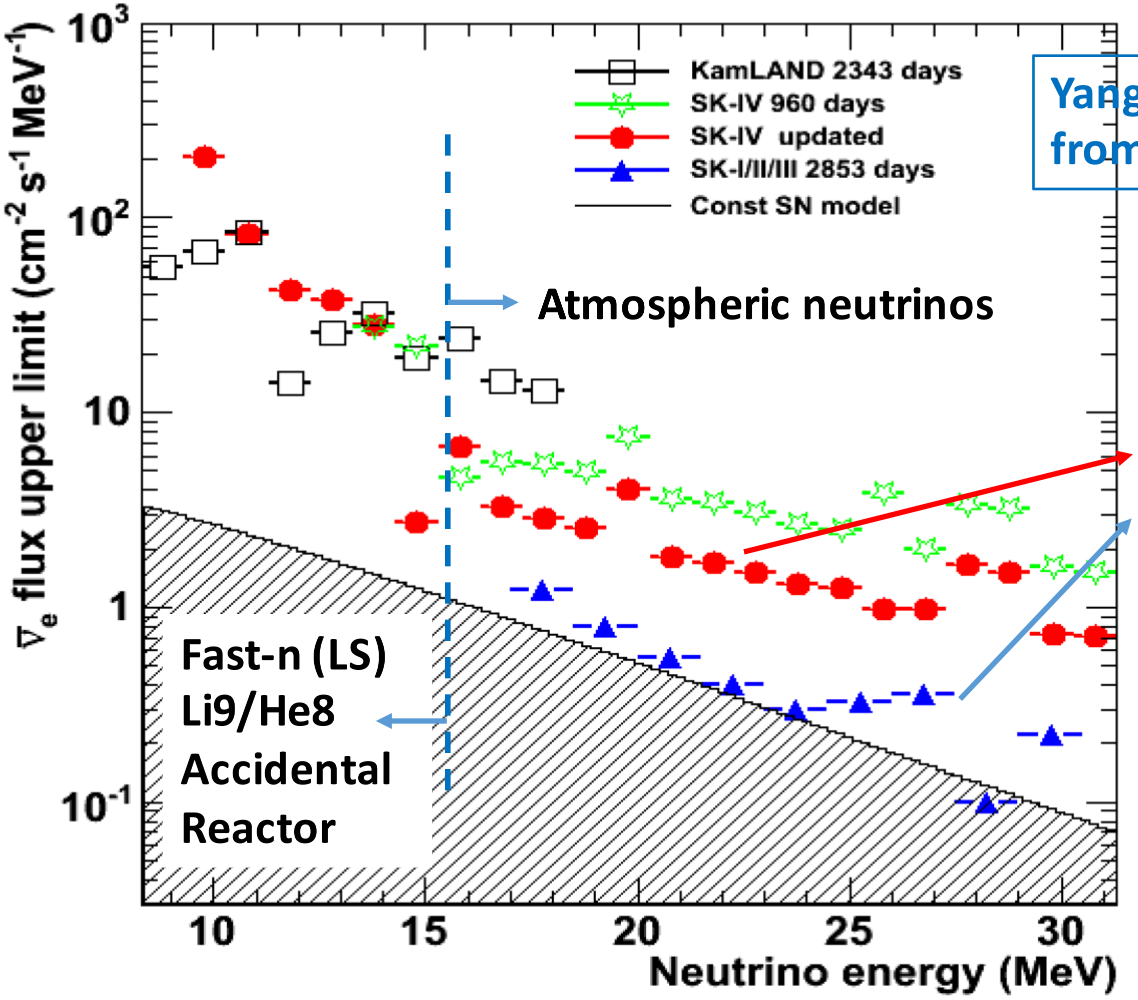
- ✓ **Fast neutron (LS)**
- ✓ **Li9/He8**

**Reactor neutrino**

**Atmospheric neutrinos (Irreducible)**

- ✓ $\bar{\nu}_e$ **CC (intrinsic)**
- ✓ $\bar{\nu}_\mu/\nu_\mu$ **CC (**$\mu$ **produced,** $E_{th}\sim m_\mu$**)**
- ✓ **NC (energetic** $n, \pi^\pm, \pi^0$ **produced)**

# Current experimental upper limits



Atmospheric neutrinos

Fast-n (LS)
Li9/He8
Accidental
Reactor

Yang Zhang's thesis
from Super-K

w/ n-tag ~1900 days
w/o n-tag 2853 days

Constant SN rate model (1995) predicts a SRN flux about 2-3 times larger than other recent models

# Key issues in SRN study

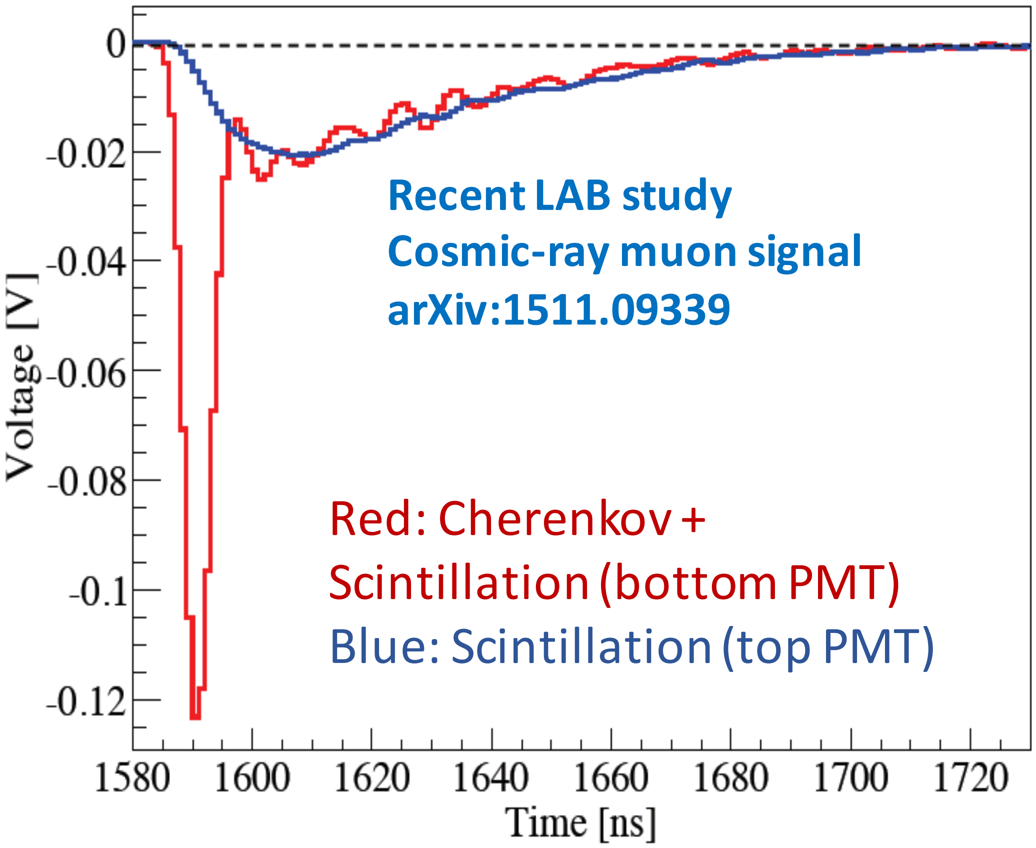
✓ Ignore the backgrounds induced by cosmic muons and reactor neutrinos, which are basically negligible at Jinping context.

| | efficiency | Atmos. CC | Atmos. NC | Optical Photon to PMT |
|---|---|---|---|---|
| LS | ~90% | triple coin. from $\mu^\pm$, Michel $e^\pm$, and neutron capture<br>$\mu^\pm$ visible in 10-30 MeV | Energetic neutrons (< 1GeV atmos. neutrinos considered due to strong quenching of neutron in LS) | Scintillation |
| water w/o n-tag | ~75% | Michel $e^\pm$ from invisible $\mu^\pm$, **reduced a lot by n-tag**<br>$\mu^\pm$ invisible in 10-30 MeV | Secondaries (decays) of $\boldsymbol{n}$ or $\boldsymbol{\pi^\pm/\pi^0}$ **(reduced by n-tag)** below Cherenkov thresh or different hit pattern | Cherenkov |
| water w/ n-tag | ~10% | | | |
| Gd-water | ~70% | | | |

**Green: advantage / Blue: disadvantage** **Invisible muon: below Cherenkov threshold**

✓ **Solution: both Cherenkov lights and Scintillation lights are utilized, and further reduce CC and NC backgrounds?**

# Slow liquid scintillator



**Recent LAB study**
**Cosmic-ray muon signal**
**arXiv:1511.09339**

Red: Cherenkov + Scintillation (bottom PMT)
Blue: Scintillation (top PMT)

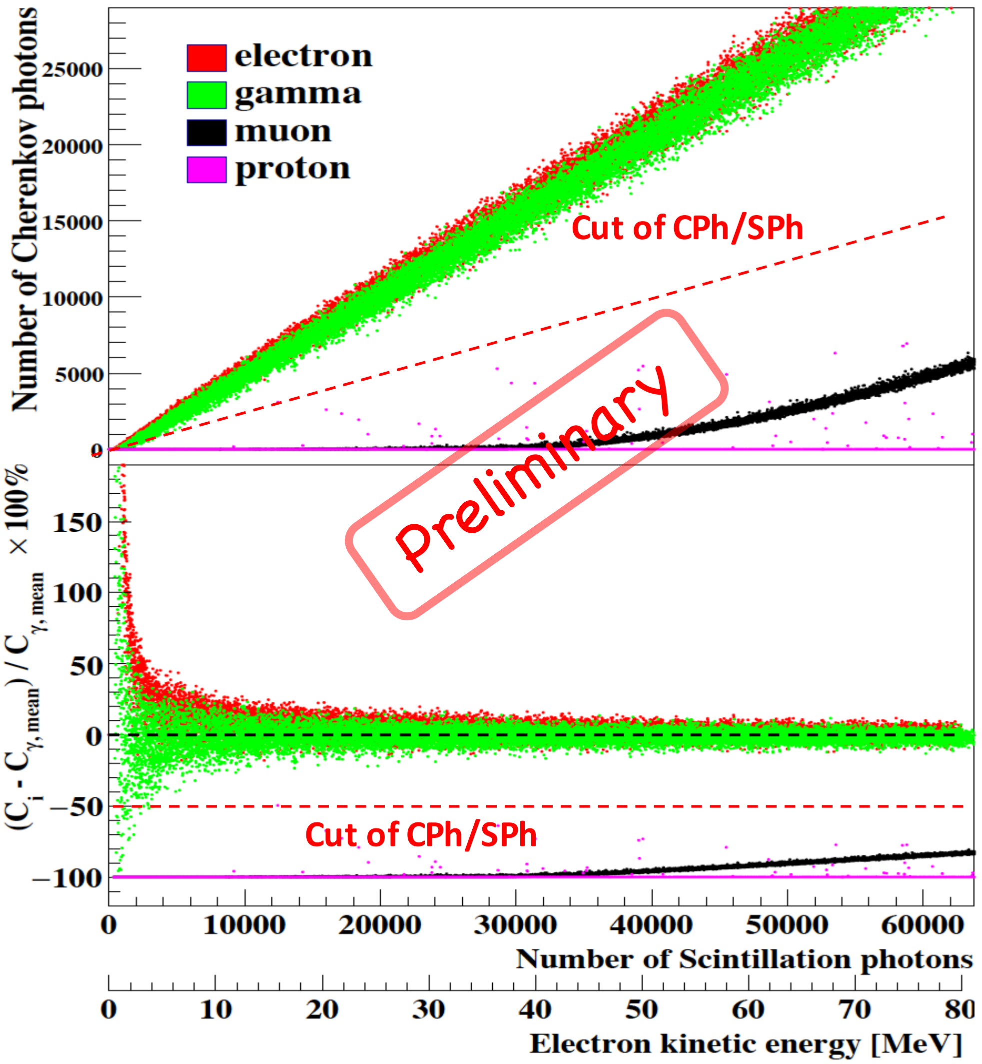
✓ Separation of Cherenkov and scintillation lights in linear alkyl benzene (LAB), as a slow LS candidate

LAB Scintillation light time profile:

$$n(t) = \frac{\tau_r + \tau_d}{\tau_d^2}(1 - \mathrm{e}^{-t/\tau_r}) \cdot \mathrm{e}^{-t/\tau_d},$$

- Rising time ($\tau_r$): 7.7 $\pm$ 3.0 ns
- Decay time ($\tau_d$): 36.6 $\pm$ 2.4 ns
- PMT time resolution: ~2ns
- Scintillation light yield: ~1000/MeV
  - 3% $E_{res}$ @10 MeV assuming a PMT quantum eff. & coverage~10%

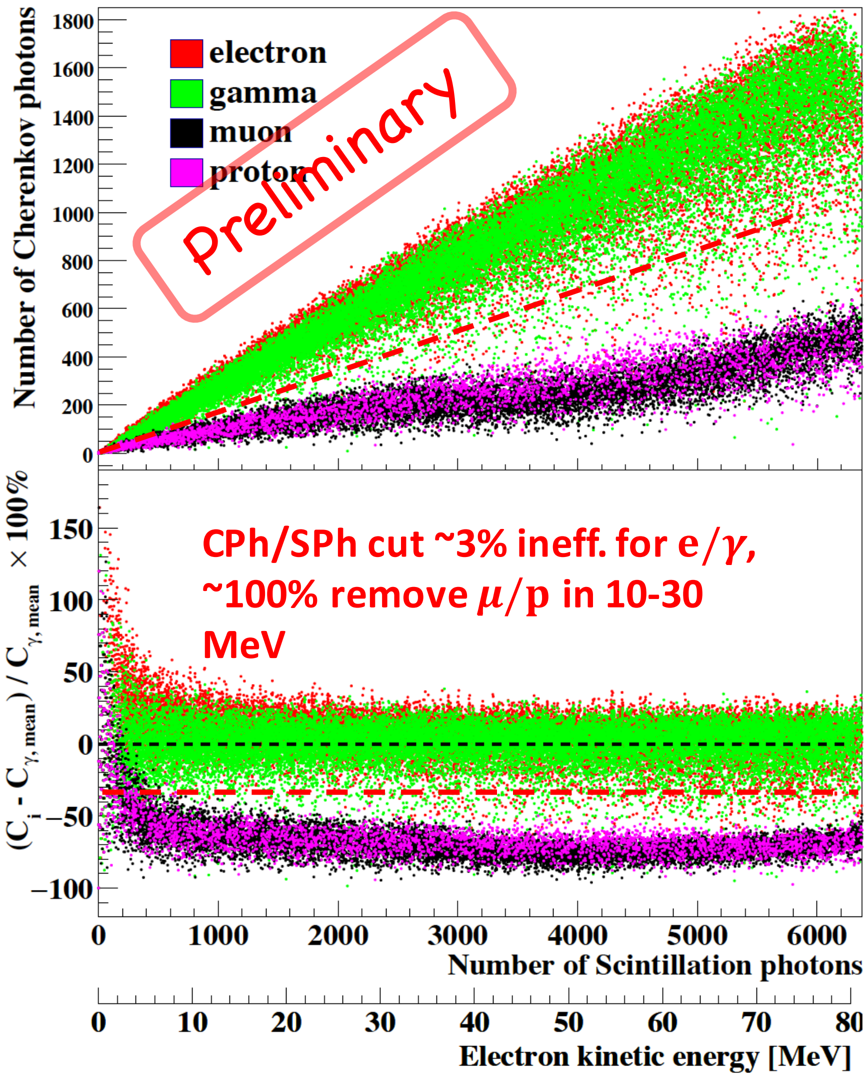
# Particle identification - ideal



1. >250 nm Cherenkov
2. True Chrenkov photon number (CPh.) and scintillation photon number (SPh.)

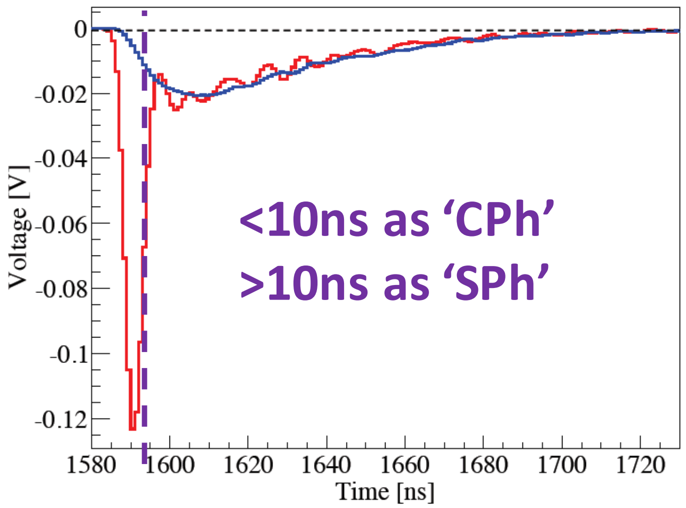
Note: secondary gamma from neutron inelastic scattering would introduce Cherenkov

# Particle identification- realistic



CPh/SPh cut ~3% ineff. for e/$\gamma$, ~100% remove $\mu$/p in 10-30 MeV

1. 300-500 nm Cherenkov
2. PMT coverage & quantum eff ~10%
3. Consider Contamination between CPh. and SPh.



<10ns as 'CPh'
>10ns as 'SPh'

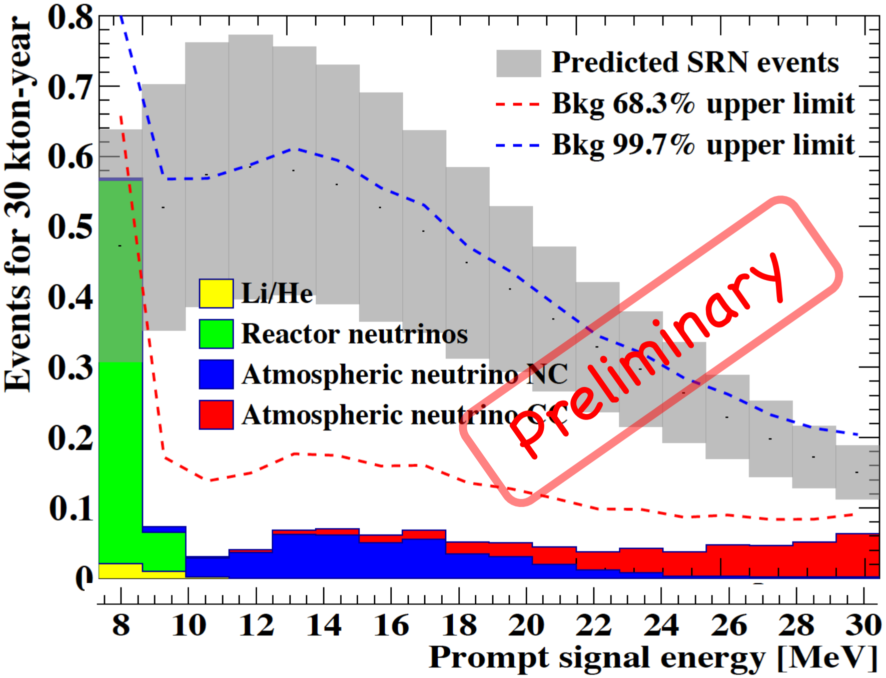
Considering pulse shape (timing spectrum), it will have a better PID

# Sensitivity study

- [Detector response] Use LAB, PID from true Cherenkov and Scintillation photons
- [Signal flux] HBD model on page 4 for SRN prediction
- [Background flux] Atmospheric neutrino flux
    - > 100 MeV
    - < 100 MeV, 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)
    - 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)*

# Selection cuts and results

- Crucial selection criteria:
  - Prompt signal: $N_{\mathrm{SPh}}$ (number of scintillation photons)
  - Ratio of Cherenkov/Scintillation photons: $N_{\mathrm{CPh}}/N_{\mathrm{SPh}}$
  - Double-coincidence cut

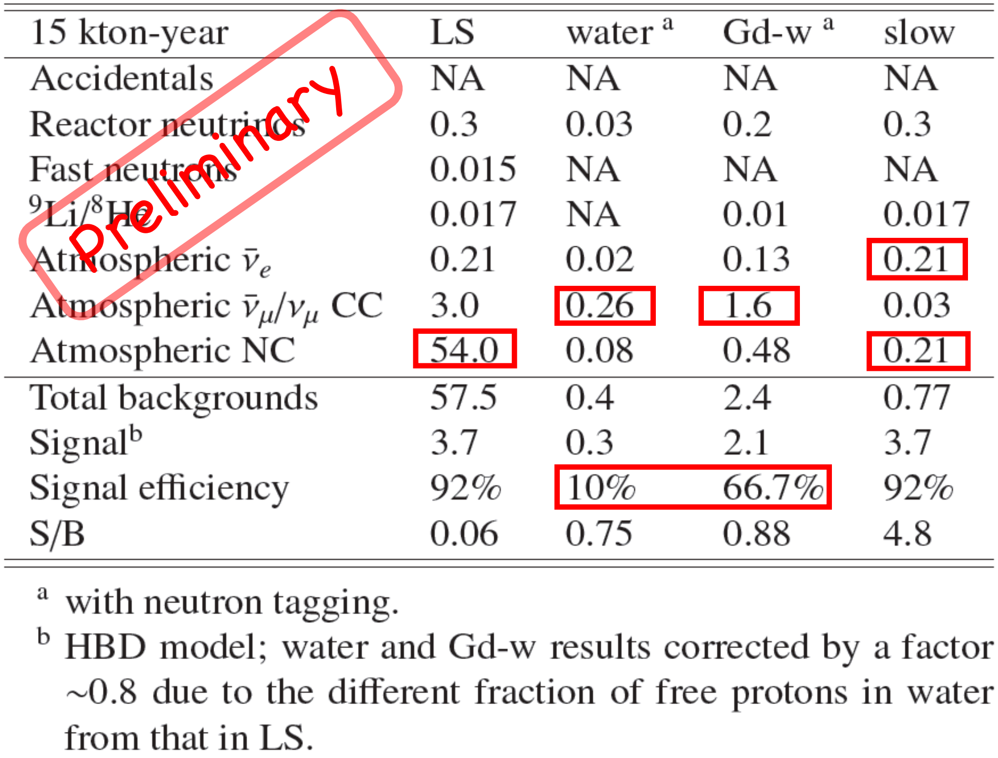


Atmos. CC bkg:
mainly atmos. $\bar{\nu}_e$ and quite a few atmos. $\bar{\nu}_\mu/\nu_\mu$

Atmos. NC bkg:
due to secondary $\gamma$'s from neutron inelastic scattering with carbon nuclei, (additional cut for Cherenkov light hit pattern).

# Comparison

- 8.3-30.8 MeV neutrino energy
- Liquid scintillator (LS), slow liquid scintillator (slow), water Cherenkov (water), and Gd-water (Gd-w)



| 15 kton-year | LS | water [a] | Gd-w [a] | slow |
|---|---|---|---|---|
| Accidentals | NA | NA | NA | NA |
| Reactor neutrinos | 0.3 | 0.03 | 0.2 | 0.3 |
| Fast neutrons | 0.015 | NA | NA | NA |
| $^9$Li/$^8$He | 0.017 | NA | 0.01 | 0.017 |
| Atmospheric $\bar{\nu}_e$ | 0.21 | 0.02 | 0.13 | 0.21 |
| Atmospheric $\bar{\nu}_\mu/\nu_\mu$ CC | 3.0 | 0.26 | 1.6 | 0.03 |
| Atmospheric NC | 54.0 | 0.08 | 0.48 | 0.21 |
| Total backgrounds | 57.5 | 0.4 | 2.4 | 0.77 |
| Signal[b] | 3.7 | 0.3 | 2.1 | 3.7 |
| Signal efficiency | 92% | 10% | 66.7% | 92% |
| S/B | 0.06 | 0.75 | 0.88 | 4.8 |

[a] with neutron tagging.

[b] HBD model; water and Gd-w results corrected by a factor ~0.8 due to the different fraction of free protons in water from that in LS.

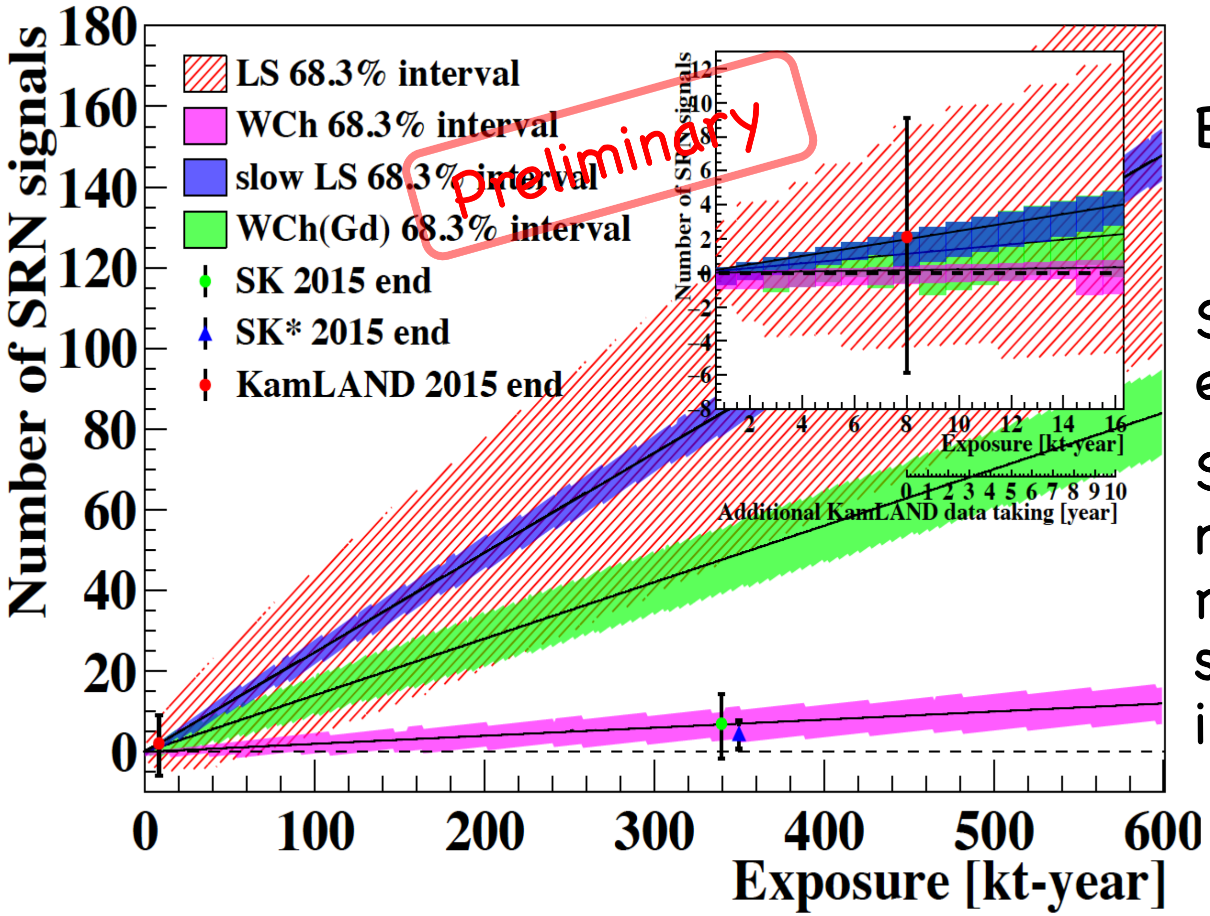
Jinping context (~6400 w.m.e.)

**Slow LS**

Less CC than LS due to $N_{\mathrm{CPh}}/N_{\mathrm{SPh}}$ cut

less NC than (Gd-)water due to $N_{\mathrm{SPh}}$ cut

# Sensitivity



Error band is bkg-only.

SK*: 15-30 MeV neutrino energy

Slow LS: if 10-30 MeV neutrino energy (remove reactor neutrino), sensitivity (rate analysis) increased by ~30%

# Conclusions

- Based on the capability of the separation of Cherenkov and scintillation lights in slow LS (eg. LAB), atmospheric neutrino CC and NC backgrounds could be reduced significantly.
- A kilo-ton scale detector with LAB has the sensitivity to make a discovery of SRN, which is a key consideration in the future Jinping neutrino experiment. Based on my calculation,

| 10-year sensitivity | Jinping (2x 1kt LAB) | SK-Gd (20kt Gd-water) | JUNO (w/ PSD*, 20kt LS) |
|---|---|---|---|
| | 3.5$\sigma$ 10–30 MeV | 3$\sigma$ 15–30 MeV | 4$\sigma$ 15–30 MeV |
| Ignore cosmogenic muons and reactor neutrinos | | 4$\sigma$ 10–30 MeV | 5$\sigma$ 10–30 MeV |

*PSD: Pulse Shape Discrimination