

Discovery potential for supernova relic neutrinos with slow liquid scintillator detectors

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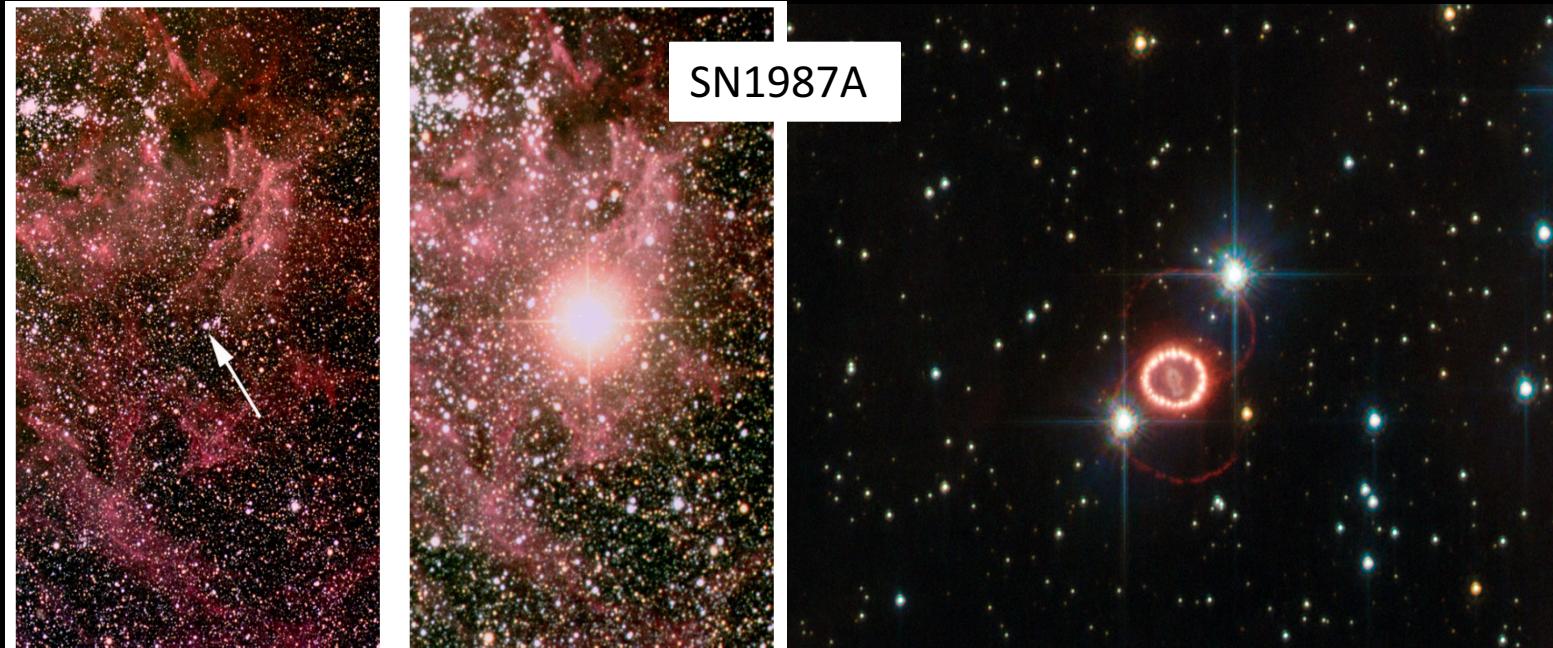
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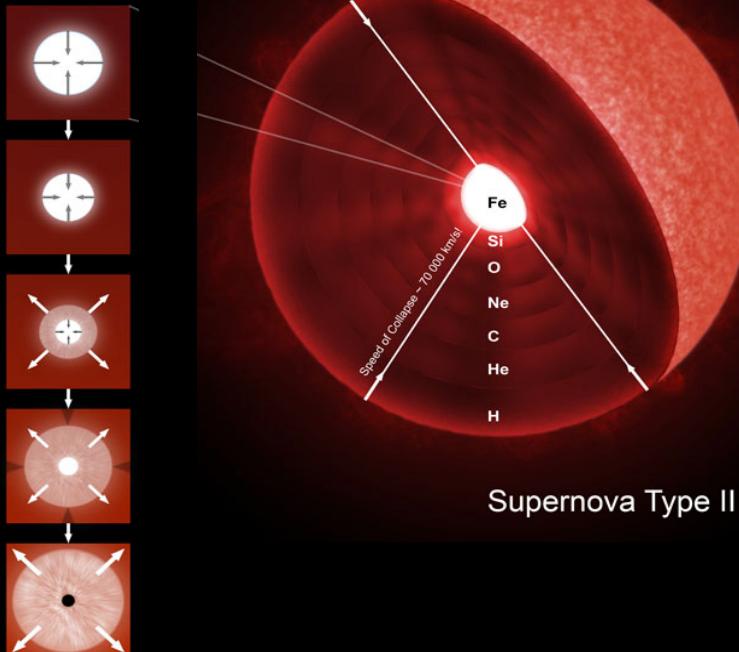
What is a supernova



- ✓ Evolved massive star
- ✓ Outshines
- ✓ Fades from view
- ✓ Material blasted out
- ✓ Stellar core transforms into a neutron star, black hole, etc.

Core-collapse supernova (CCSN)

- ~70% of the observed supernova explosions
 - Type II, Type Ib, Type Ic (light curve, spectrometer characteristics)
- 30% Type Ia is not core-collapse

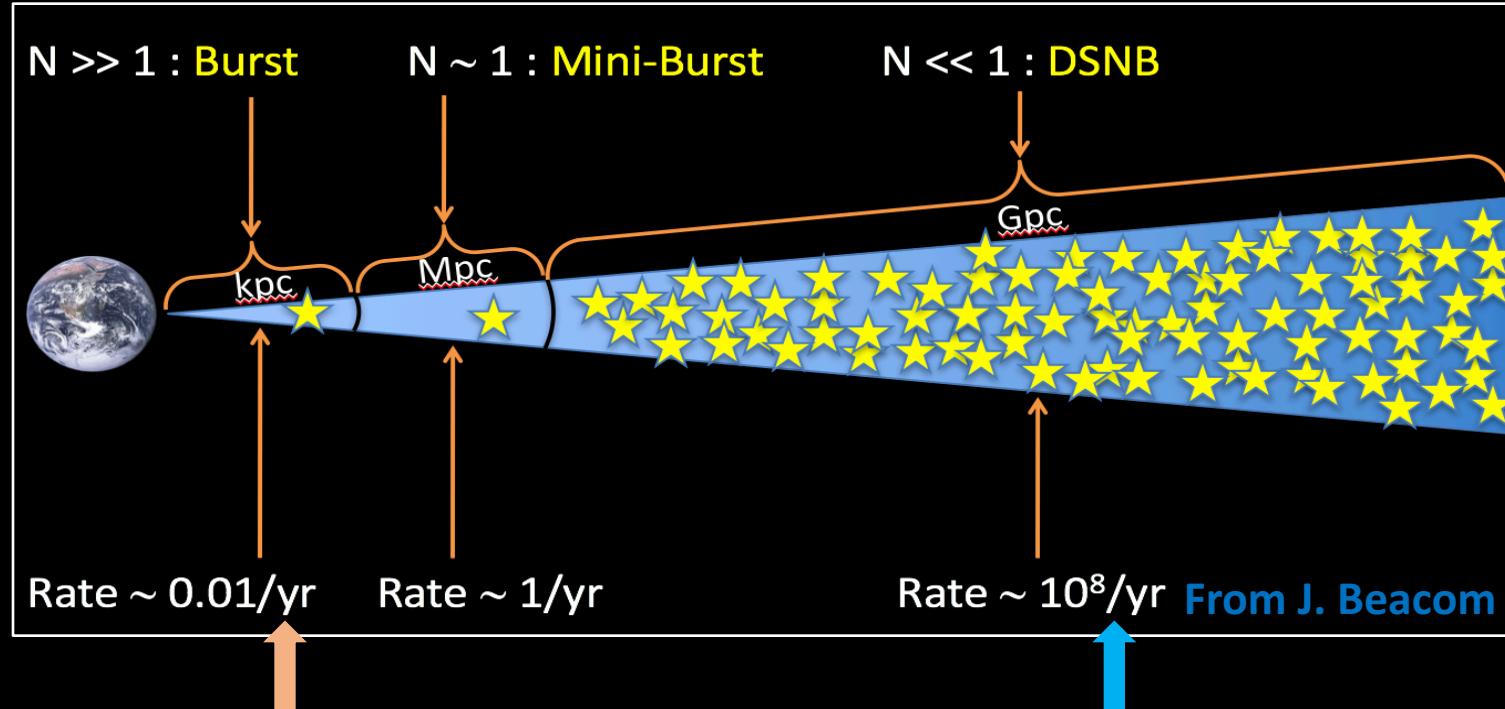


- Core collapse of an evolved massive star
 - Onion-like layers
 - Iron core $\rightarrow 1.44 M_{\odot}$
- ~99% gravitational potential energy ($\sim 0.2 M_{\odot}$) carried away by neutrinos within $\sim 10s$
 - $\sim 10^{58}$ neutrinos

Importance of supernovae

- Standard candles to indicate astronomical distances
- Stellar evolution
- Heavy elements production
- Source of astronomical neutrinos
- Source of gravitational waves
- Cosmology ...
- Supernova neutrinos -- messenger
 - ✓ ~99% gravitational binding energy of a supernova explosion
 - ✓ Travel freely in the Universe
 - ✗ Weak interaction
- Milestone: SN1987A (~20 neutrinos observed)
 - ✓ A large range of limits on neutrino physics
 - ✓ A crucial test for SN theory
 - ✓ Foundation of neutrino astronomy and recent supernova models
- Still uncertain supernova models

How big chance to detect supernova neutrinos?



✓ Once-in-a-lifetime opportunity to detect a few supernova burst neutrinos (e.g. 1987A)

✓ Possible to detect the supernova relic neutrinos (aka. diffuse supernova neutrino background)

Theoretic spectrum of supernova relic neutrinos (SRN)

Detected energy spectrum

$$\frac{dN_e}{dE_e}(E_e) = N_p \sigma(E_\nu) \int_0^\infty \left[(1+z) \varphi[E_\nu(1+z)] \right] \left[R_{SN}(z) \right] \left[\left| \frac{c dt}{dz} \right| dz \right]$$

3. Detector target
mass/capability and cross
section

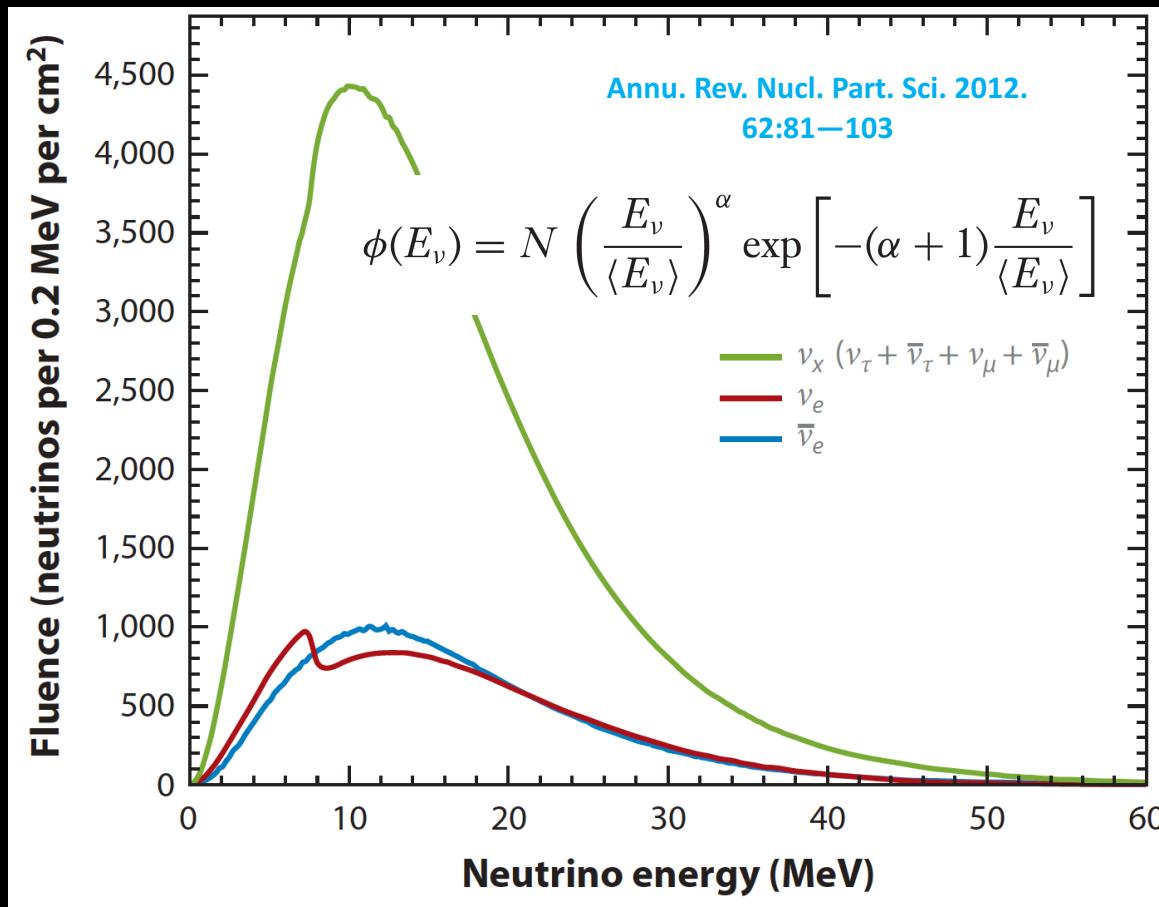
2. CCSN rate
(known with precision)

1. Neutrino spectrum E_ν (unknown)
 $Z \sim$ redshift, softer neutrino energy

Cosmology
parameters

A few SRN in Super-K (22.5 kt water) per year !!!

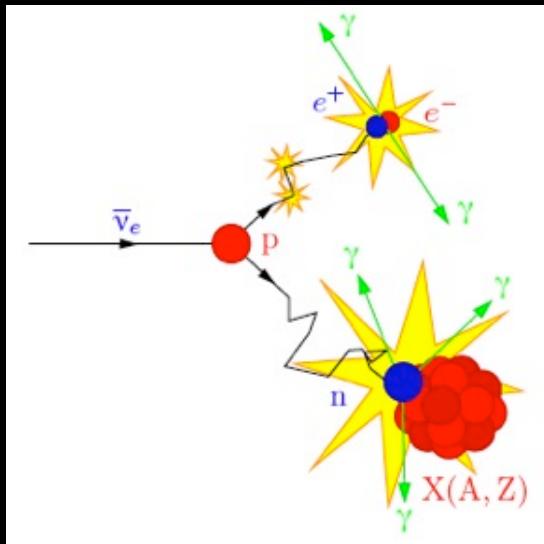
Supernova neutrino spectrum



$$E_{\bar{\nu}_e} \sim 3-4 \times T_{\bar{\nu}_e} \sim 12-15 \text{ MeV.} \quad \langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$$

Detection of SRN (in hydrogen-rich detectors)

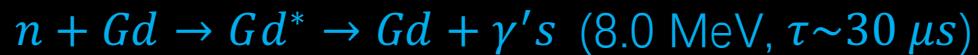
- SRN ($\bar{\nu}_e$) are identified primarily through inverse beta decay (IBD, $\bar{\nu}_e + p \rightarrow e^+ + n$) interactions



Large cross sections!!

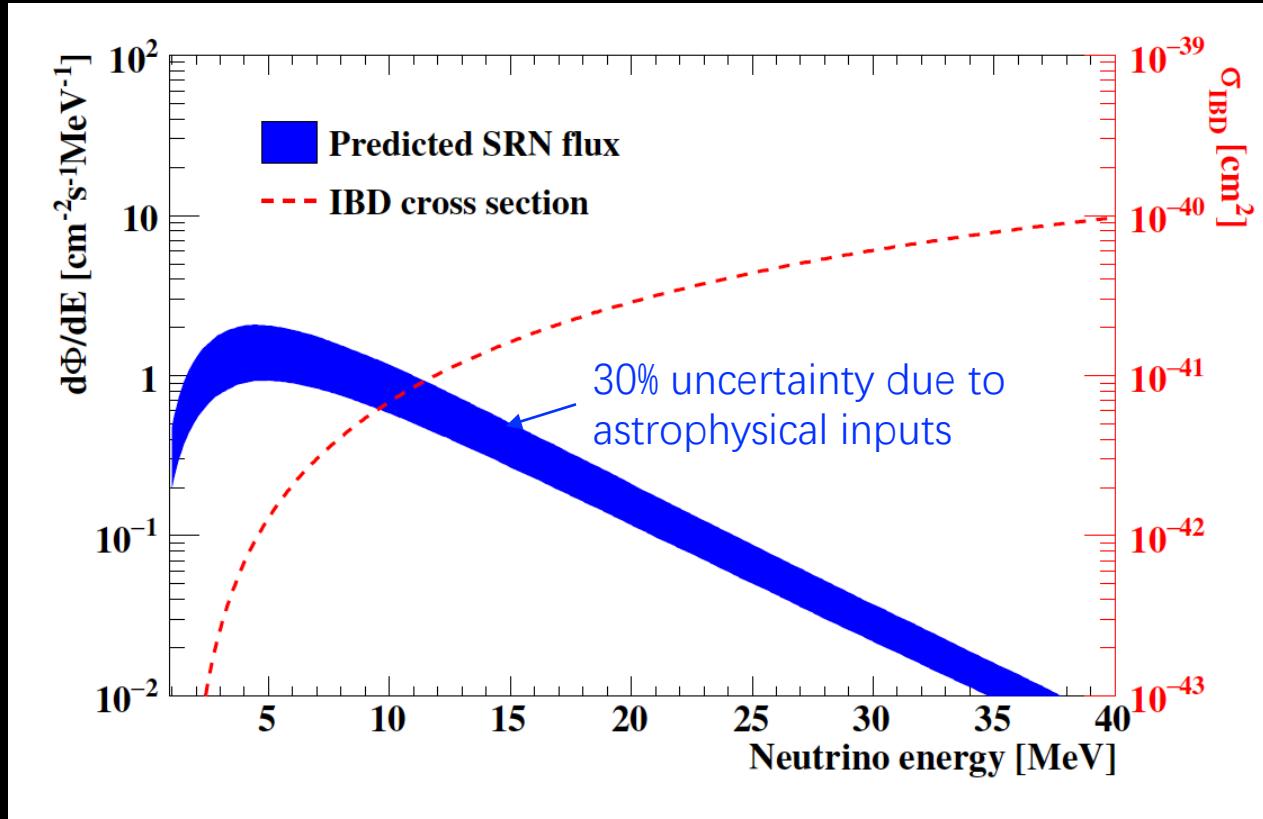
Prompt: e^+ kinetic and annihilation

Delayed:



- Prompt-delayed coincidence: reduce accidentals, radioactivity and other neutrino sources and interactions
 - ✓ Liquid scintillator – KamLAND [scintillation light]
 - ✓ Water – SuperK with neutron tagging (*Astroparticle Physics 31 (2009) 320–328*) [Cherenkov light]

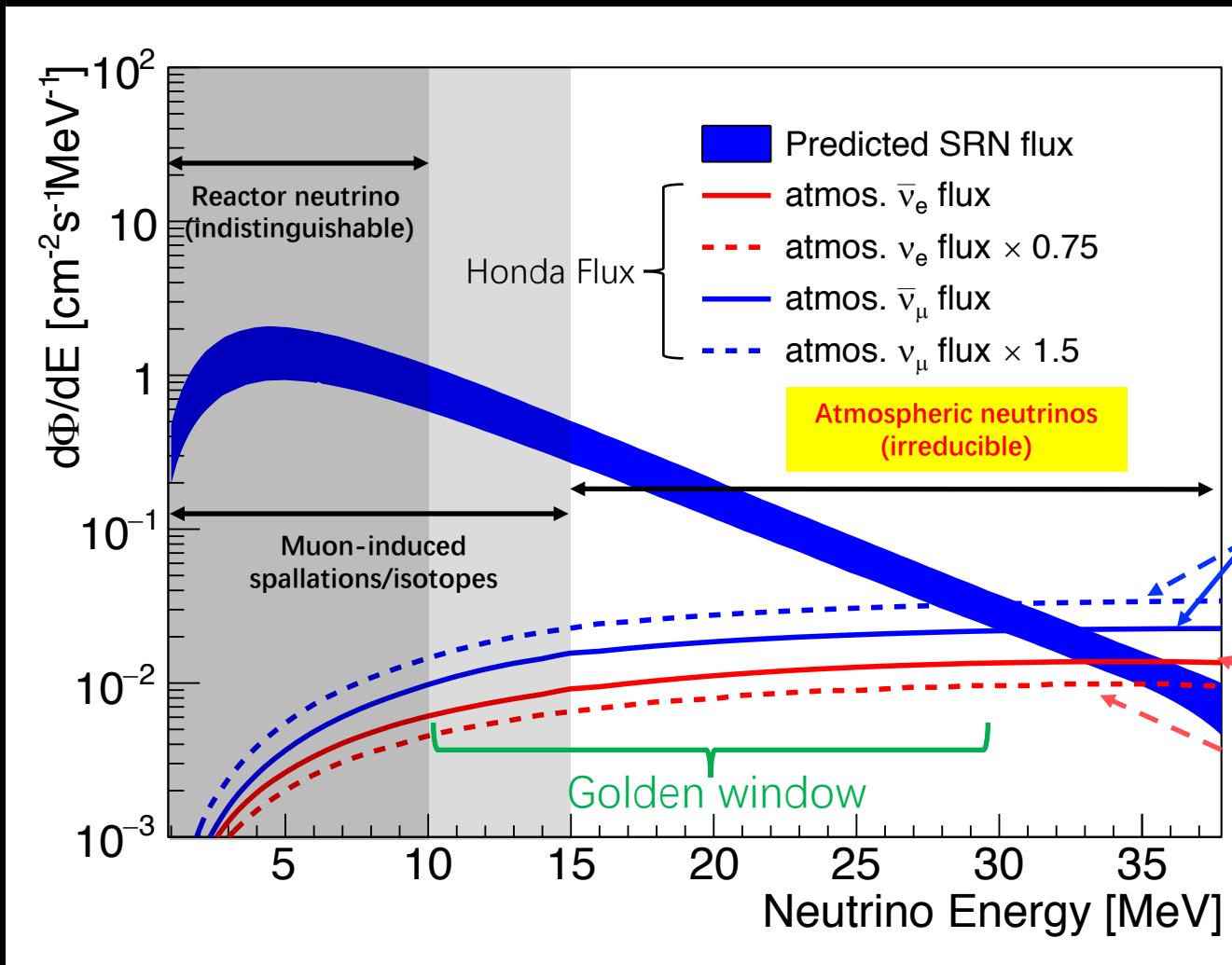
SRN spectrum



~4 IBD in 10-30 MeV
for 15 kton-year
typical liquid
scintillator

Horiuchi, Beacom, Dwek 2009 model
 $T_\nu \sim 6$ MeV, oscillation included

SRN vs backgrounds



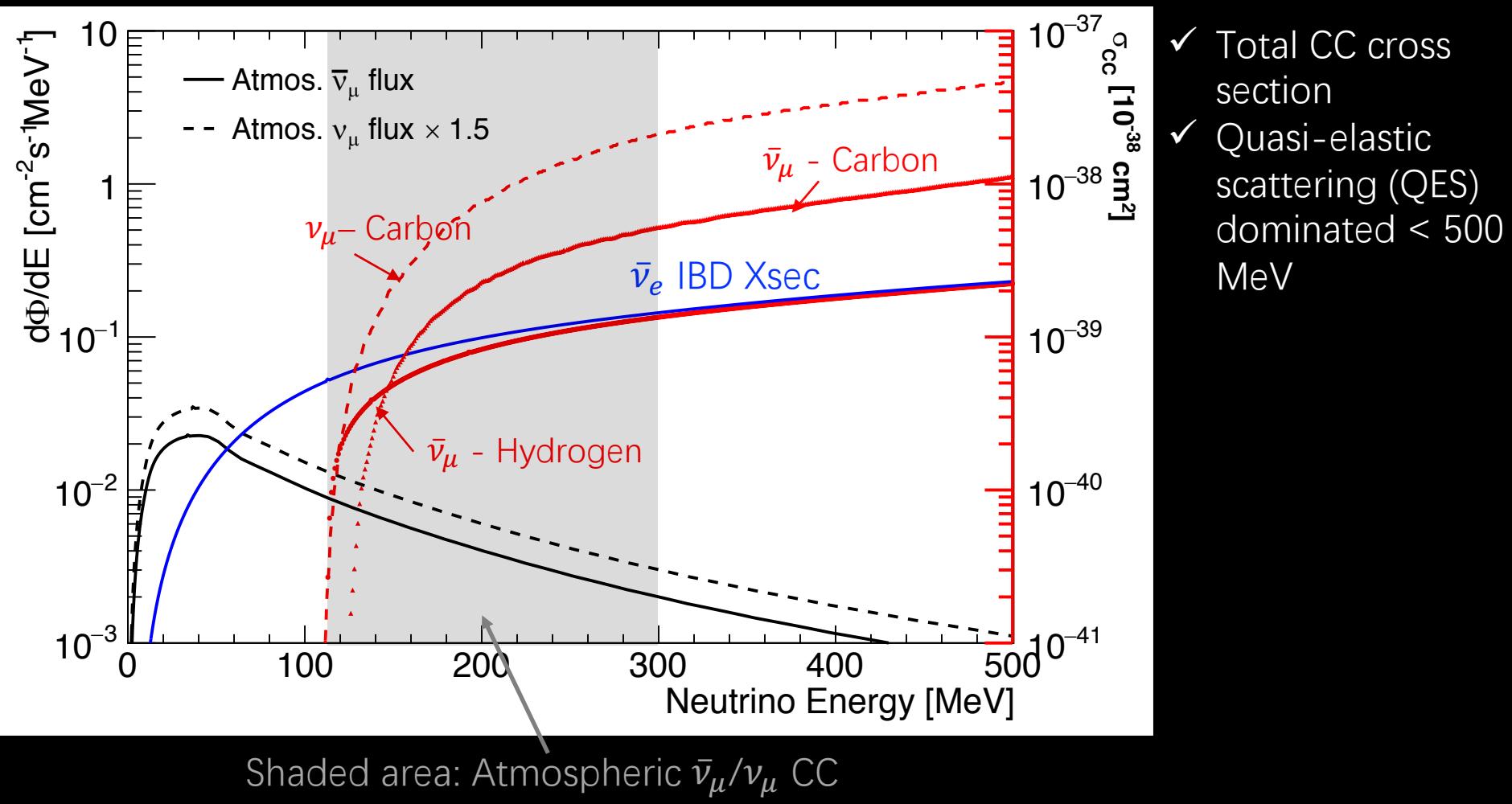
Charged current

Atmos. $\bar{\nu}_\mu/\nu_\mu$
 ✓ Energy threshold?
 ✓ Final states?

Intrinsic atmos. $\bar{\nu}_e$
 Ignored atmos. ν_e (small cross section)

Neutral current ?

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



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

Reactions in liquid scintillator

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

(Analogous in water, carbon → oxygen)

Detection

Liquid scintillator detector

- ✓ μ is visible
- ✓ Reduce by triple coincidence
(prompt + μ decay + neutron capture)
- ✗ Unable to distinguish μ and e^+

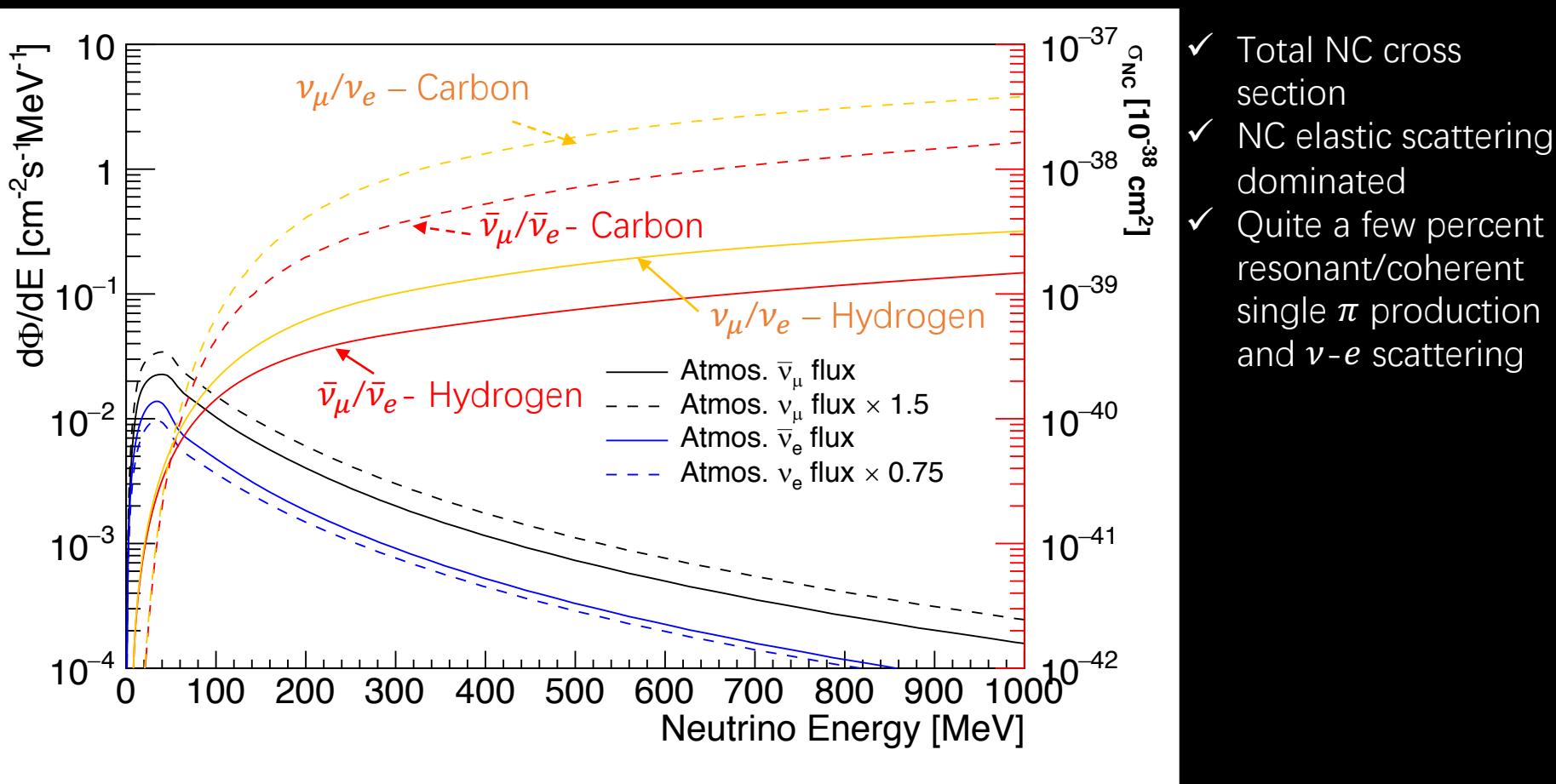
Water Cherenkov detector

- ✗ μ with <54 MeV kinetic energy
(Cherenkov threshold) invisible
- ✗ Michel electrons from μ decays

If liquid scintillation light +
Cherenkov light?

- ✓ μ and e^+ distinguishable

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



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

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

Reactions in liquid scintillator

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

a small fraction of deposited energy visible in either liquid scintillator or water

Complicated intranuclear transport and final state interactions (FSI)

(Analogous in water, carbon \rightarrow oxygen)

Detection

Liquid scintillator detector

- ✗ Unable to distinguish high energy neutrons from low energy e^+

Water Cherenkov detector

- ✓ No Cherenkov from neutron
- ✓ Reduce secondary γ induced by energetic neutron by Cherenkov hit pattern (number and angle of Cherenkov ring)
- ✗ No neutron energy information

If Cherenkov light + scintillation light?

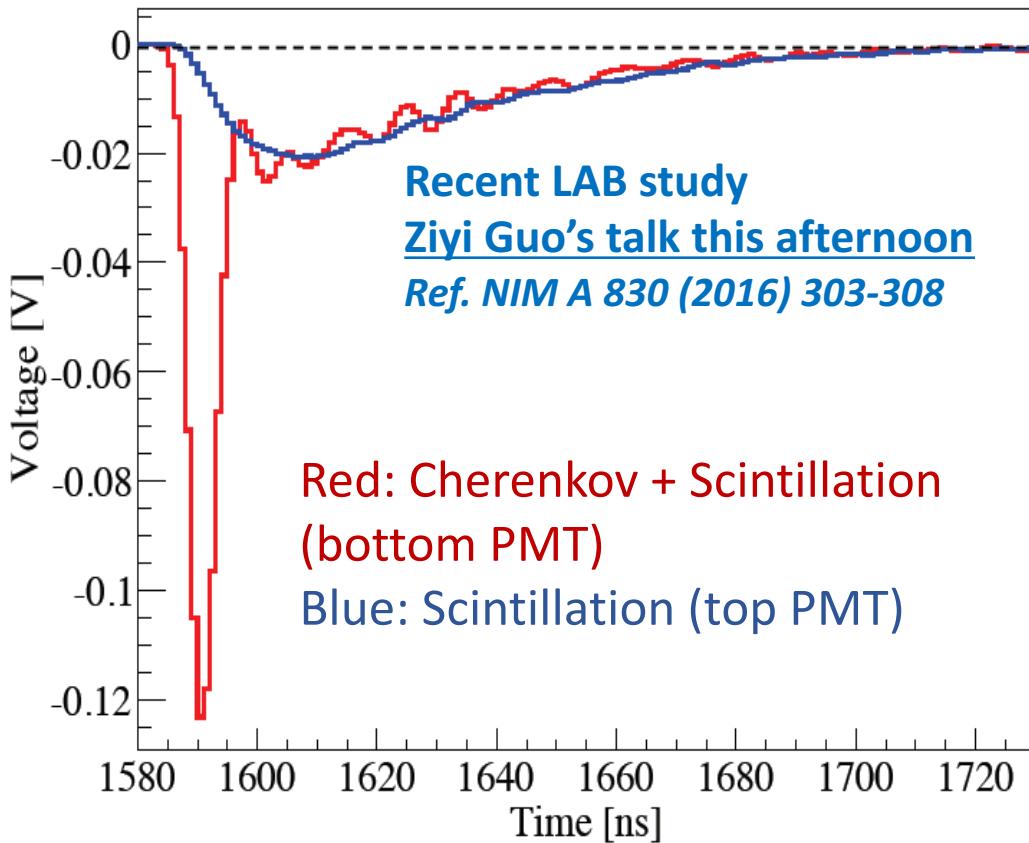
- ✓ Energy information + water capability

Cherenkov + Scintillation

---- To kill atmospheric neutrino backgrounds

Note: Muon-induced spallations could also be suppressed.

Slow liquid scintillator



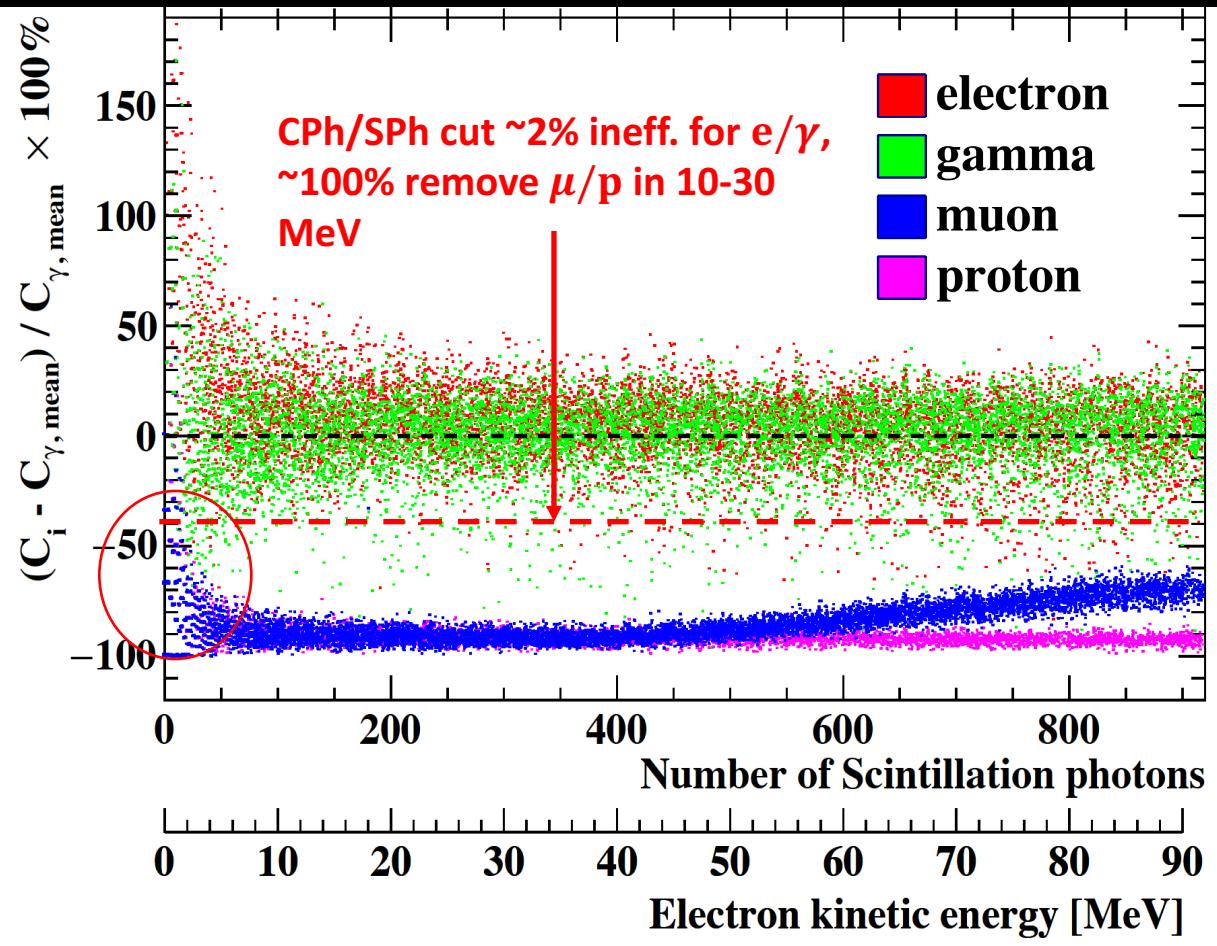
- ✓ Separation of Cherenkov and scintillation lights in linear alkyl benzene (LAB), as a slow LS candidate

LAB Scintillation light time profile:

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

- 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

Particle identification- realistic



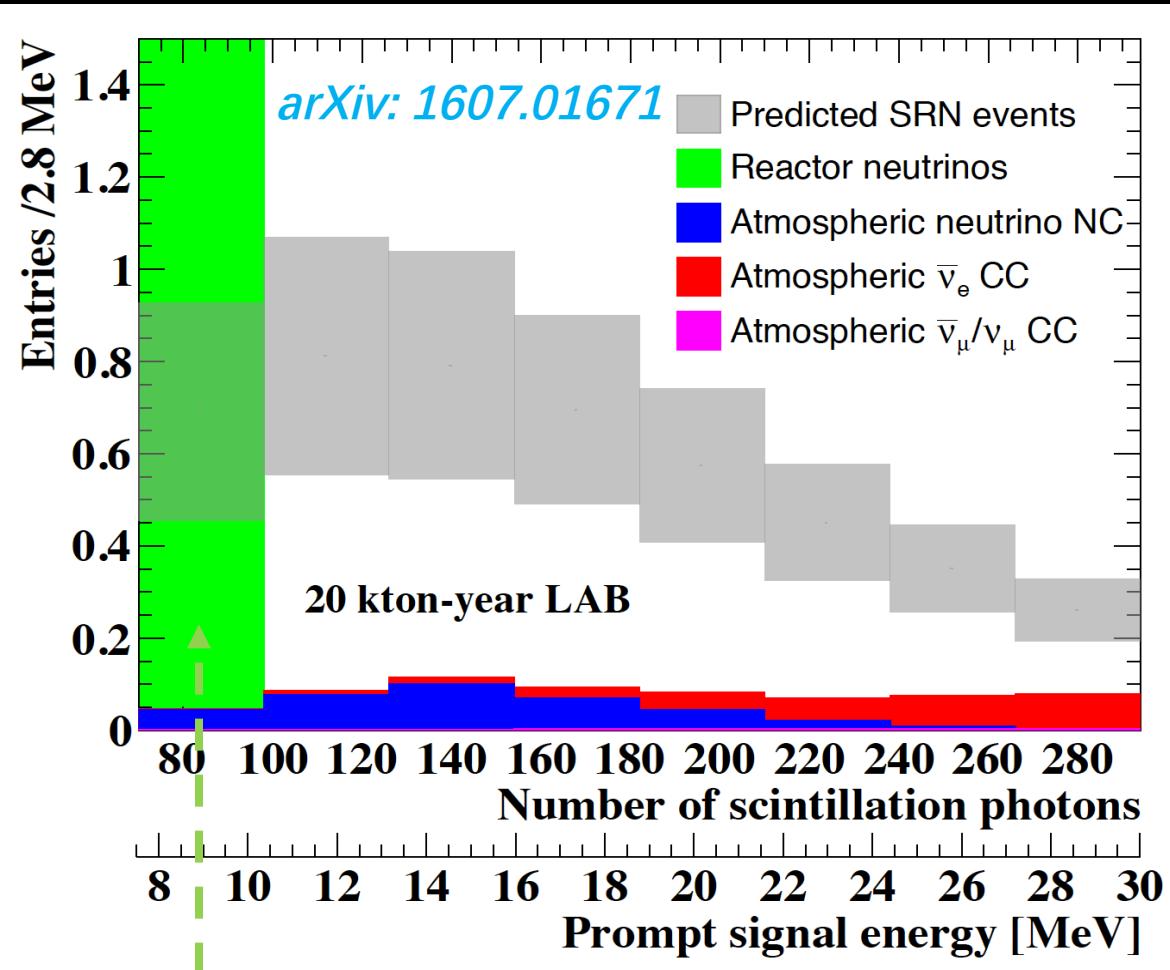
Geant4-based simulation

1. 300-500 nm Cherenkov
2. PMT collection & quantum eff $\sim 10\%$ in total
3. Scintillation quenching effect
4. Photon attenuation in LAB. 10% (50%) of scintillation (Cherenkov) photons remains in a 10-m level detector.
5. Consider contamination between CPh. and SPh. (before and after 10ns)

Discovery potential for SRN

- *arXiv: 1607.01671*
- [Detector response] Use LAB, PID in the realistic case
- [Signal flux] HBD model for SRN prediction
- [Background flux] Atmospheric neutrino 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)

Results



With Jinping environment assumption.

- ✓ Extremely low muon flux
- ✓ Quite low reactor neutrino flux

Reactor neutrino background: higher than expected due to the worse energy resolution.

Comparison

- 10.8-30.8 MeV neutrino energy
- Liquid scintillator (LS), slow liquid scintillator (slow), water Cherenkov (water), and Gd-water (Gd-w)

arXiv: 1607.01671

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

Low efficiency of
tagging 2.2 MeV γ

**With neutron
tagging**

Slow LS:

Less CC than LS due to
 $N_{\text{Cherenkov}}/N_{\text{Scintillation}}$
less NC than (Gd-)water due
to $N_{\text{Scintillation}}$

Note:

*Liquid scintillator with pulse shape
discrimination (eg. JUNO) \gtrsim Gd-water*
*Liquid argon time projection chamber (eg.
DUNE) assumed \approx slow LS ?*

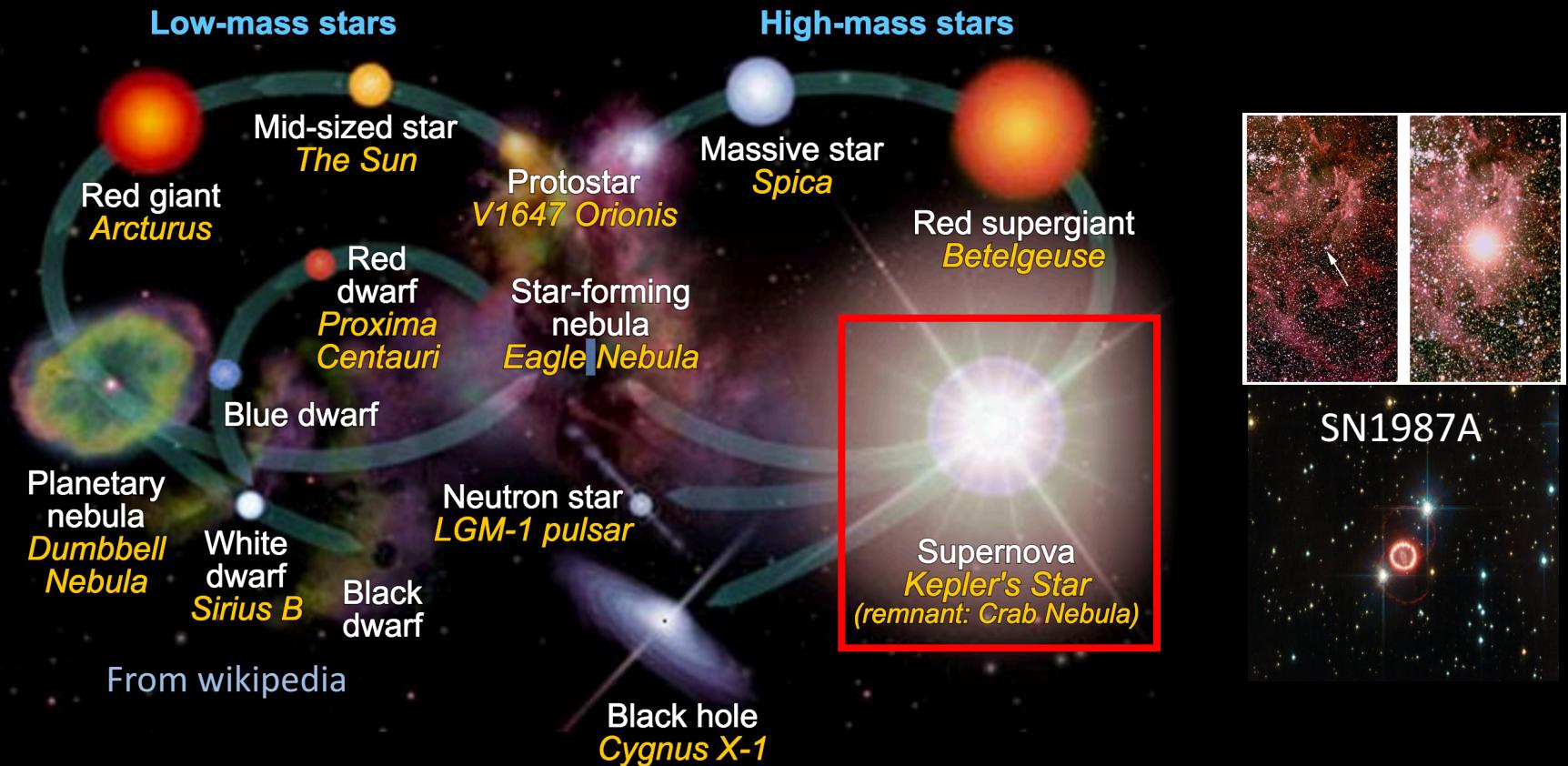
Conclusions

- Based on the ability 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 as well as some kilo-ton scale detectors.

10-year sensitivity	Jinping (2x 1kt LAB)	SK-Gd (20kt Gd-water)
	3.5σ 10-30 MeV	3σ 15-30 MeV
Ignore cosmogenic muons and reactor neutrinos		4σ 10-30 MeV

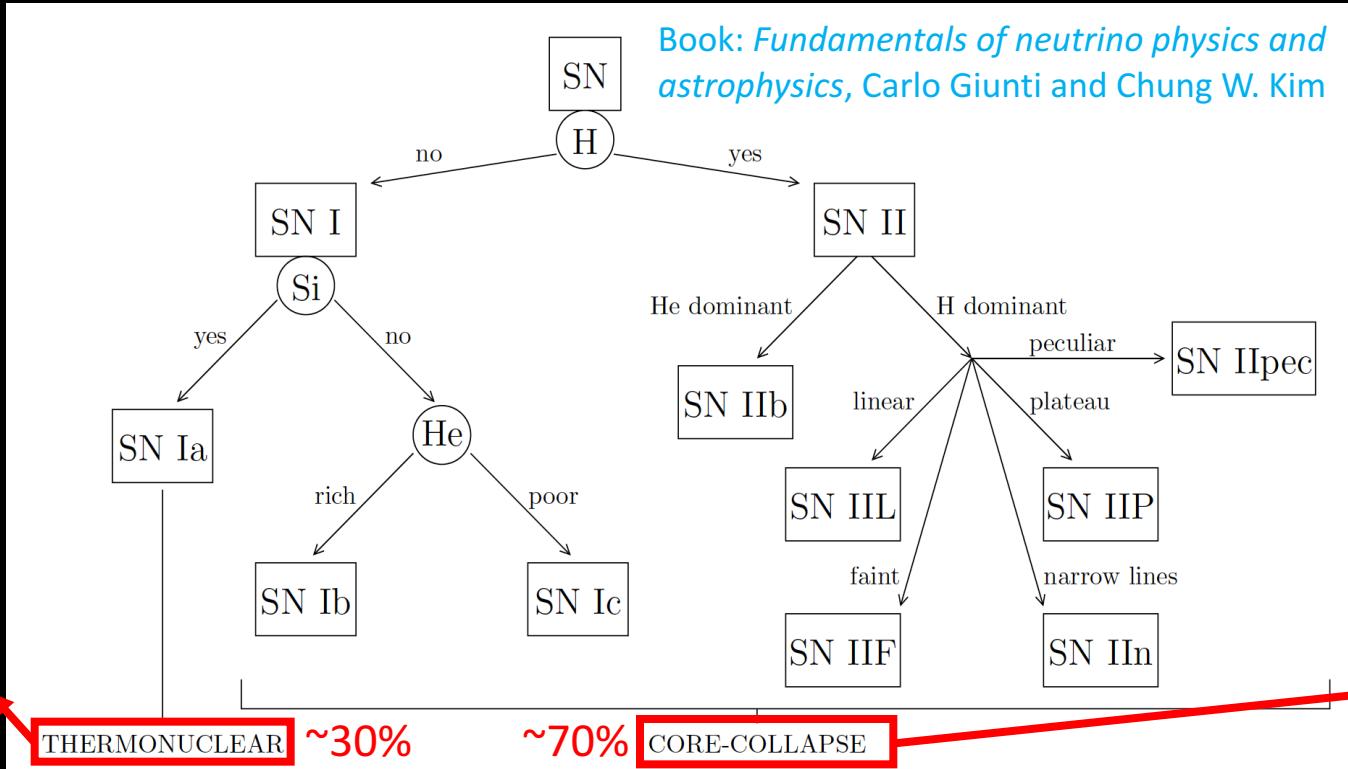
Back up

Stellar evolution



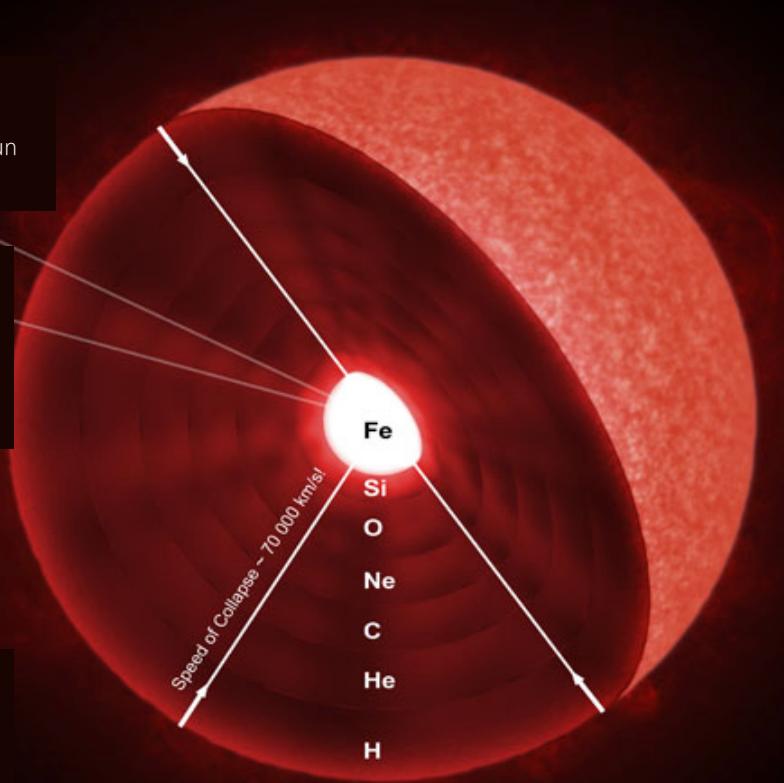
A star changes during its lifetime (from a few million years for the most massive to trillions of years for the least massive), depending on the mass of the star.

Supernova types



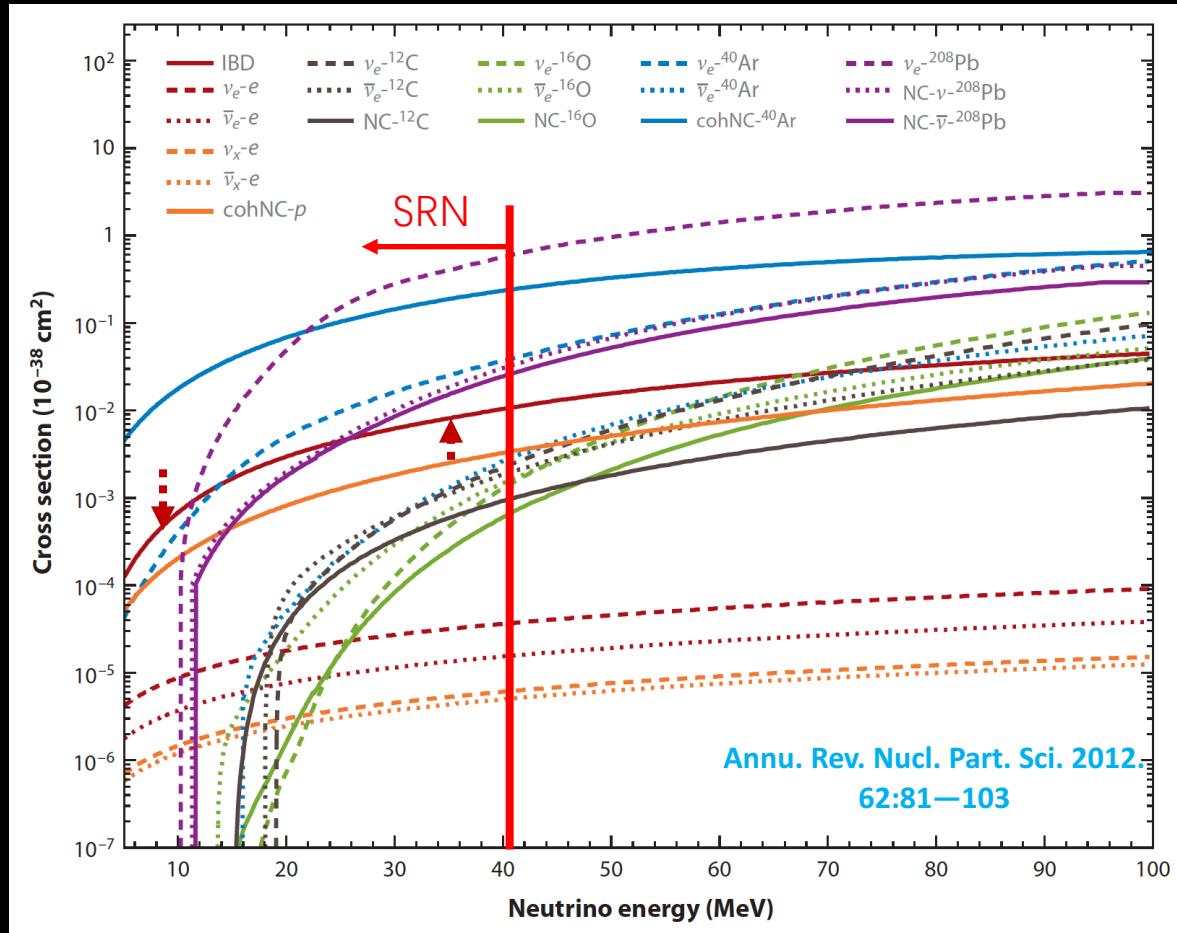
- ✓ Depend on the composition of the envelope of the SN progenitor star
- ✓ By spectroscopic characteristics near maximum luminosity
- ✓ By properties of the light curve

Core-collapse Supernova (CCSN) mechanism



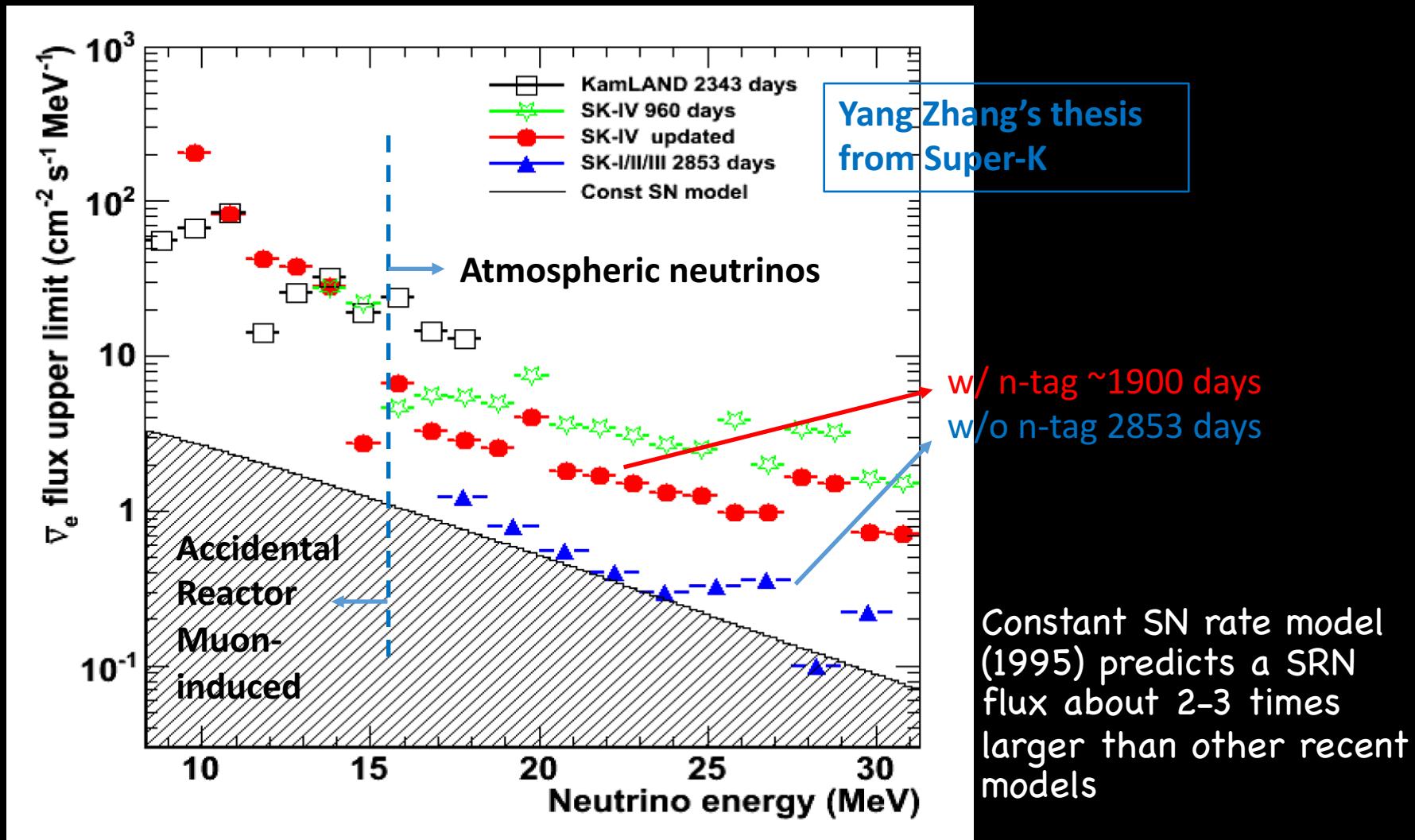
Supernova Type II

Cross sections

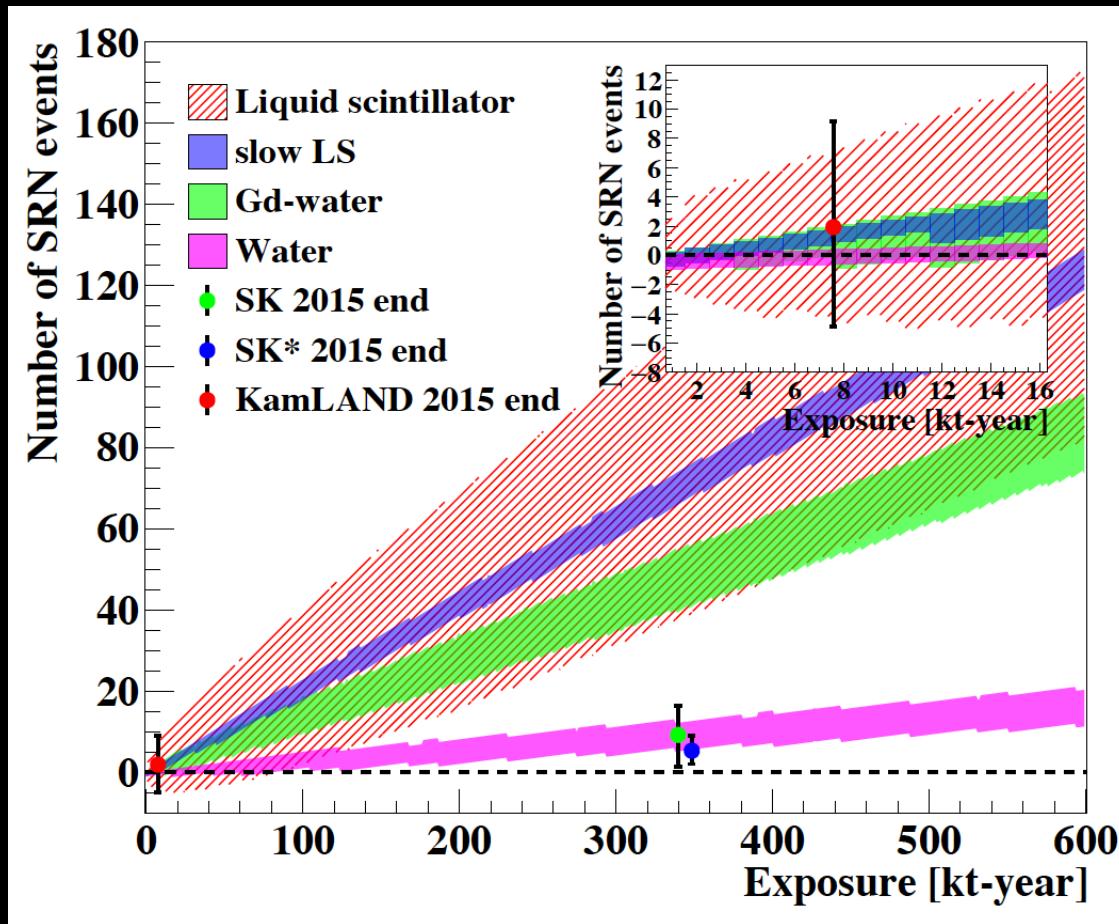


- Purple lines: interact with lead. Detect produced neutron. E.g. HALO experiment
- Blue lines: interact with Argon. Detect produced gamma. E.g. future DUNE experiment.
- IBD: inverse beta decay. Mature & widely used technique mainly in **hydrogen-rich** detectors.
- Orange lines: coherent elastic scattering. Quite low recoil energy. For dark matter experiment.

Current experimental upper limits



Sensitivity @Jinping



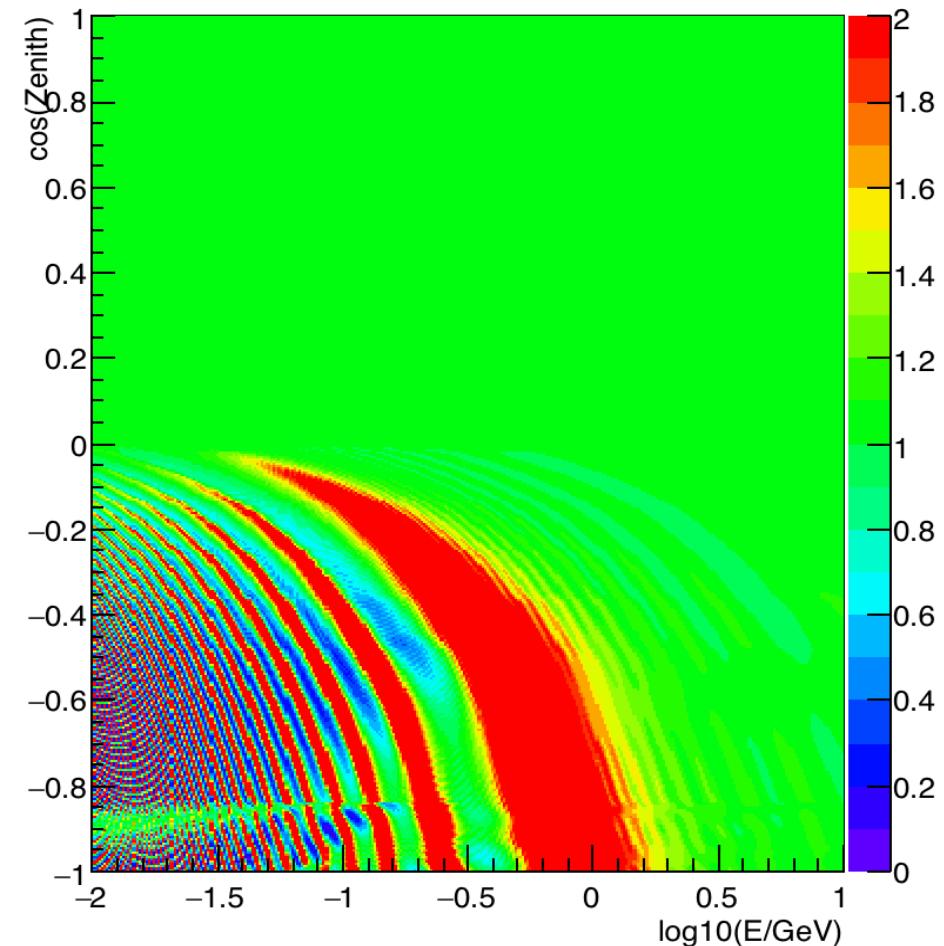
✓ Error band is 68.3% C.L. bkg-only (toothed due to discrete distribution).

✓ SK*: 15-30 MeV neutrino energy

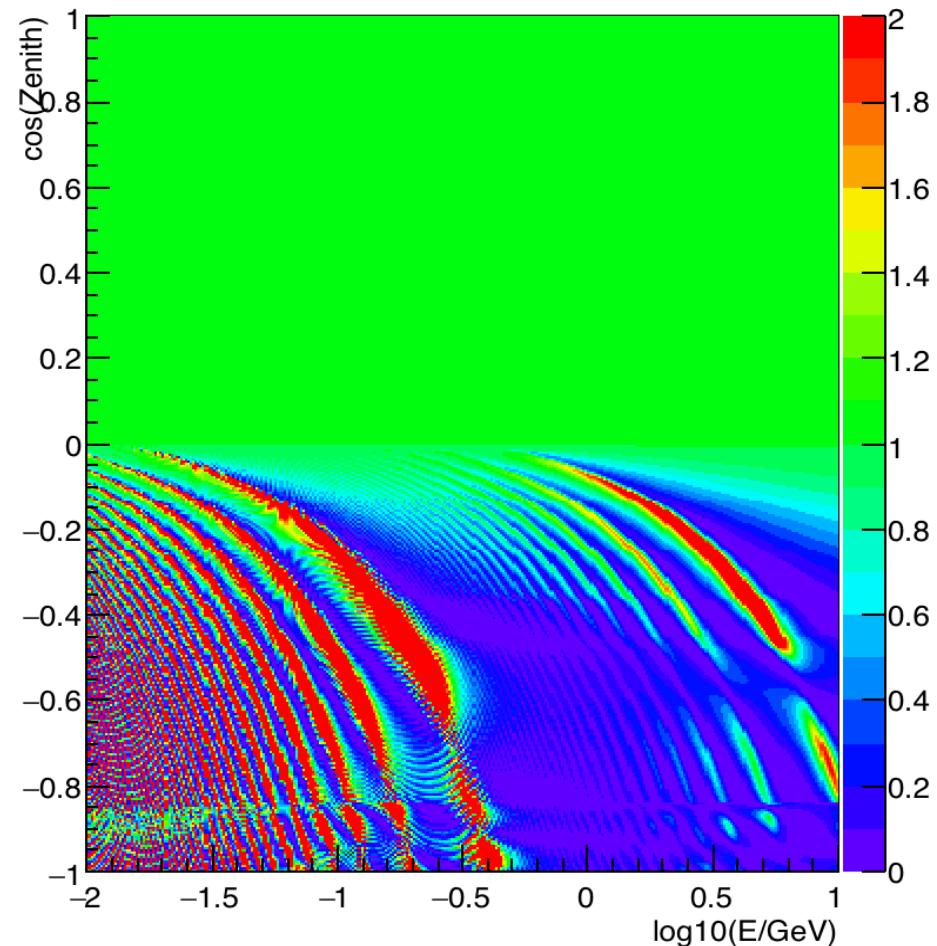
In a kiloton-scale LAB detector at Jinping, a 99.95% confidence-level (3.5-sigma) discovery will be obtained with an exposure of 20 kton-years.

Ratio of MSW/no-MSW ($\bar{\nu}_e$)

E-Er

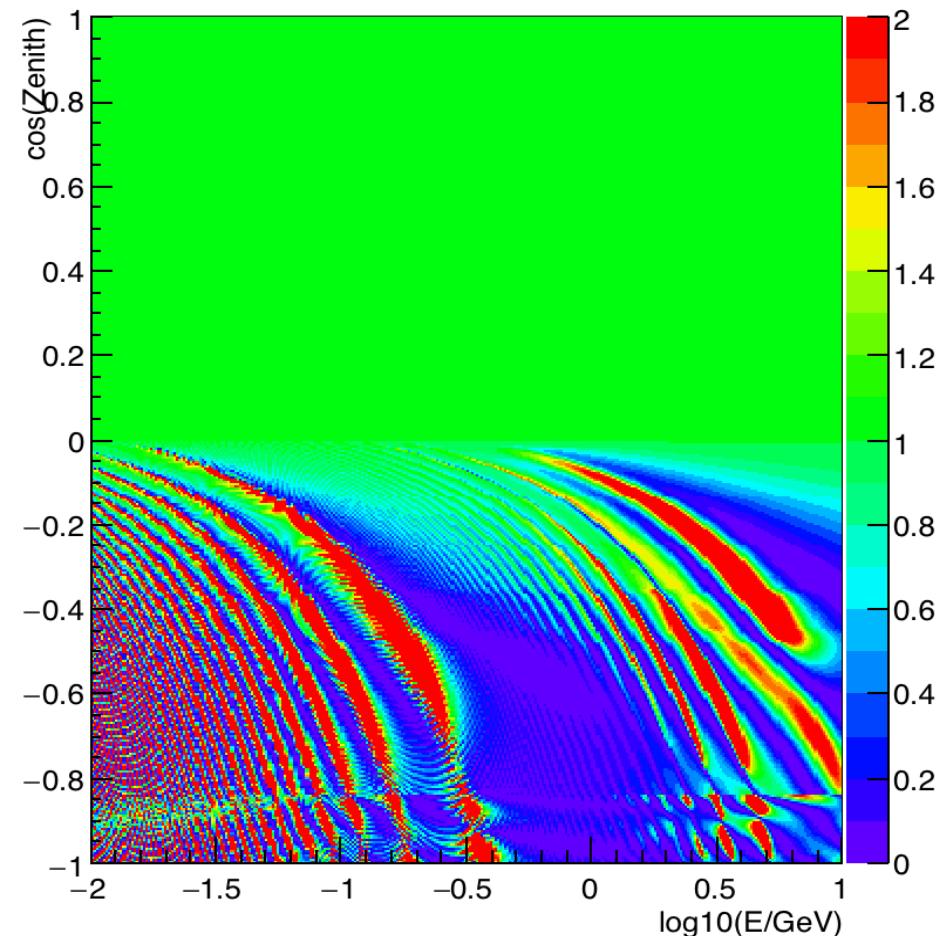


E-Mur

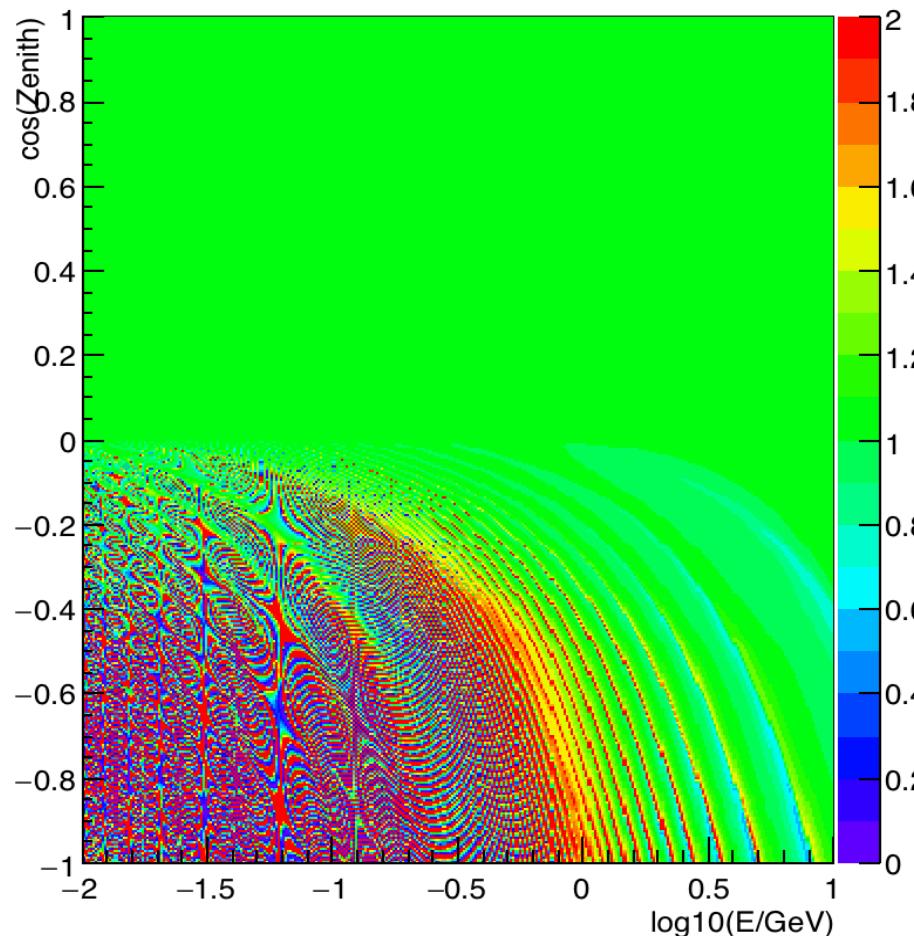


Ratio of MSW/no-MSW ($\bar{\nu}_\mu$)

Mu-Er



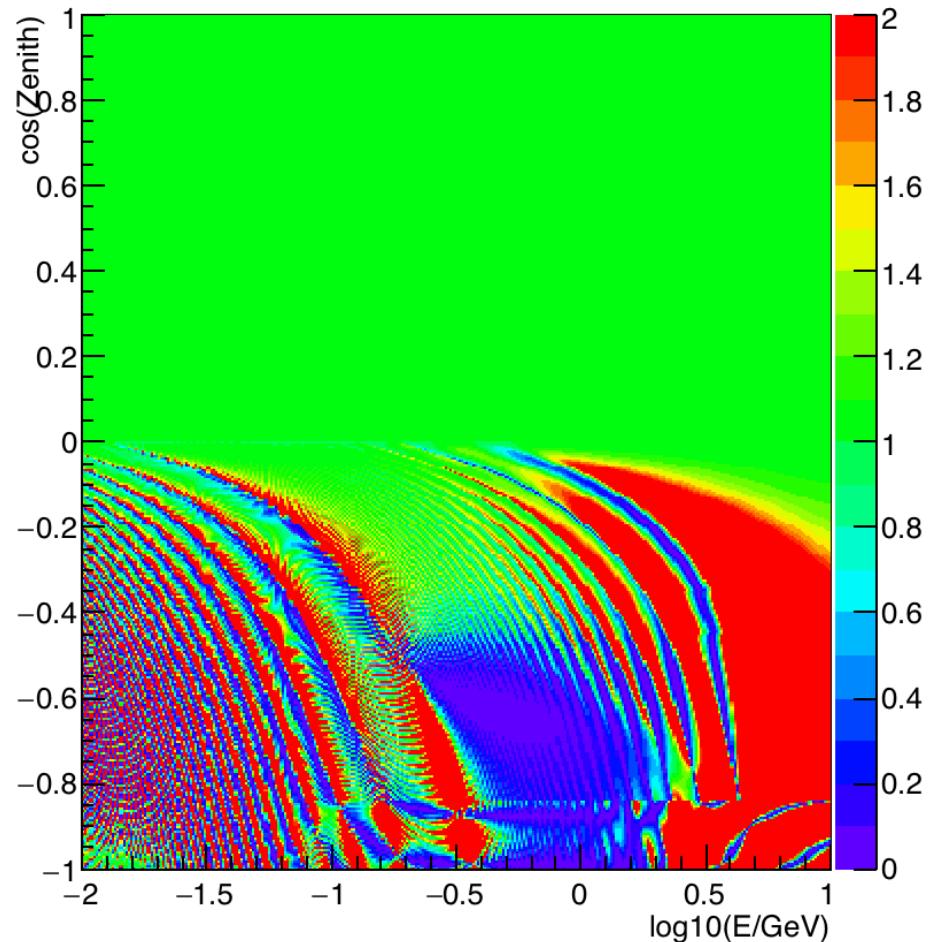
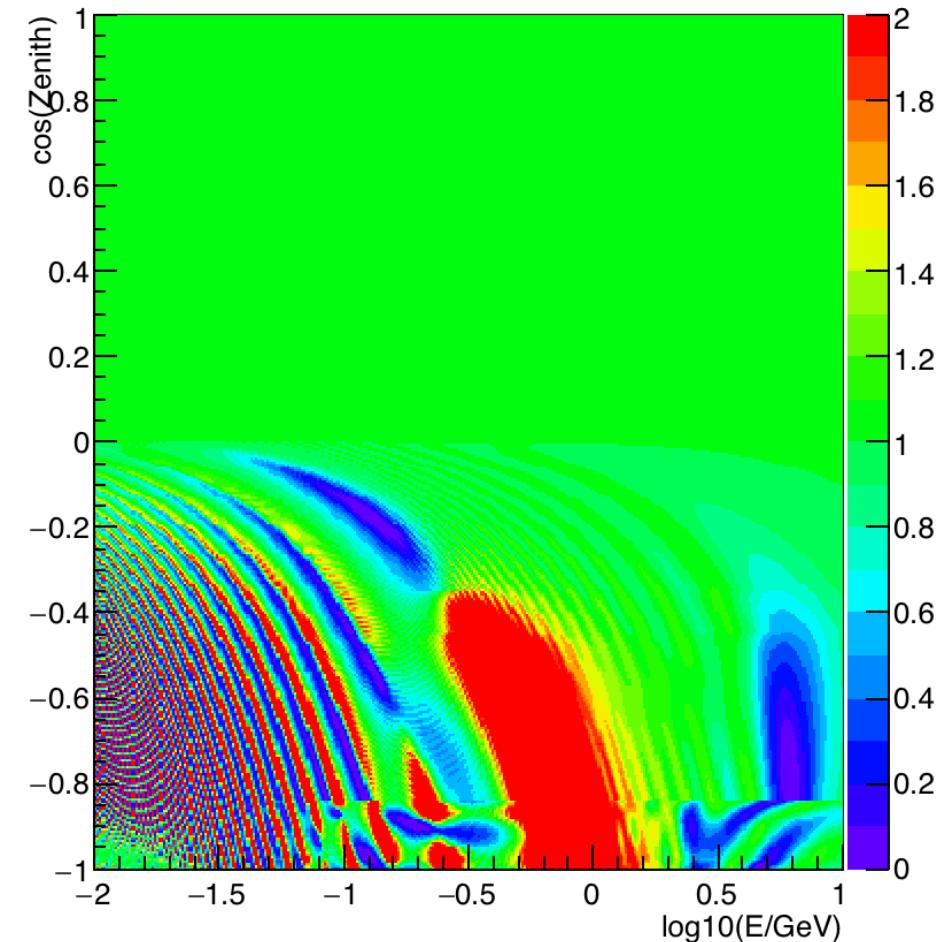
Mu-Mur



Ratio of MSW/no-MSW (ν_e)

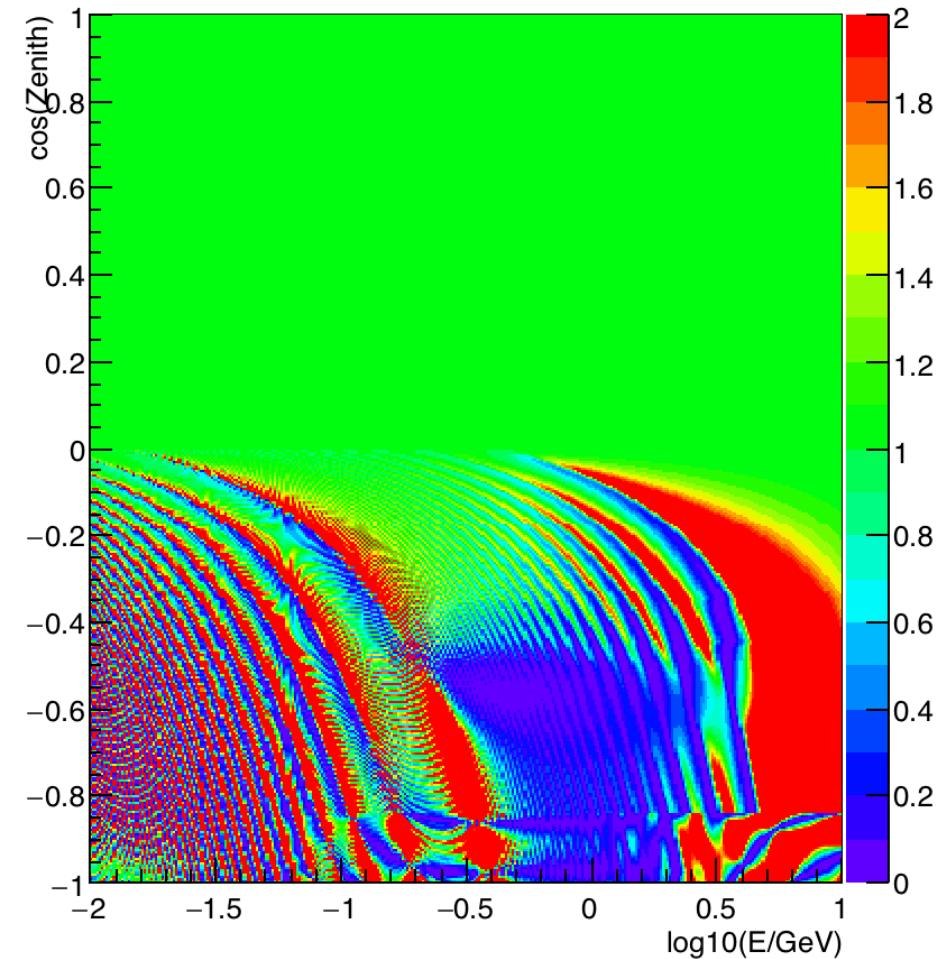
E-Er

E-Mur

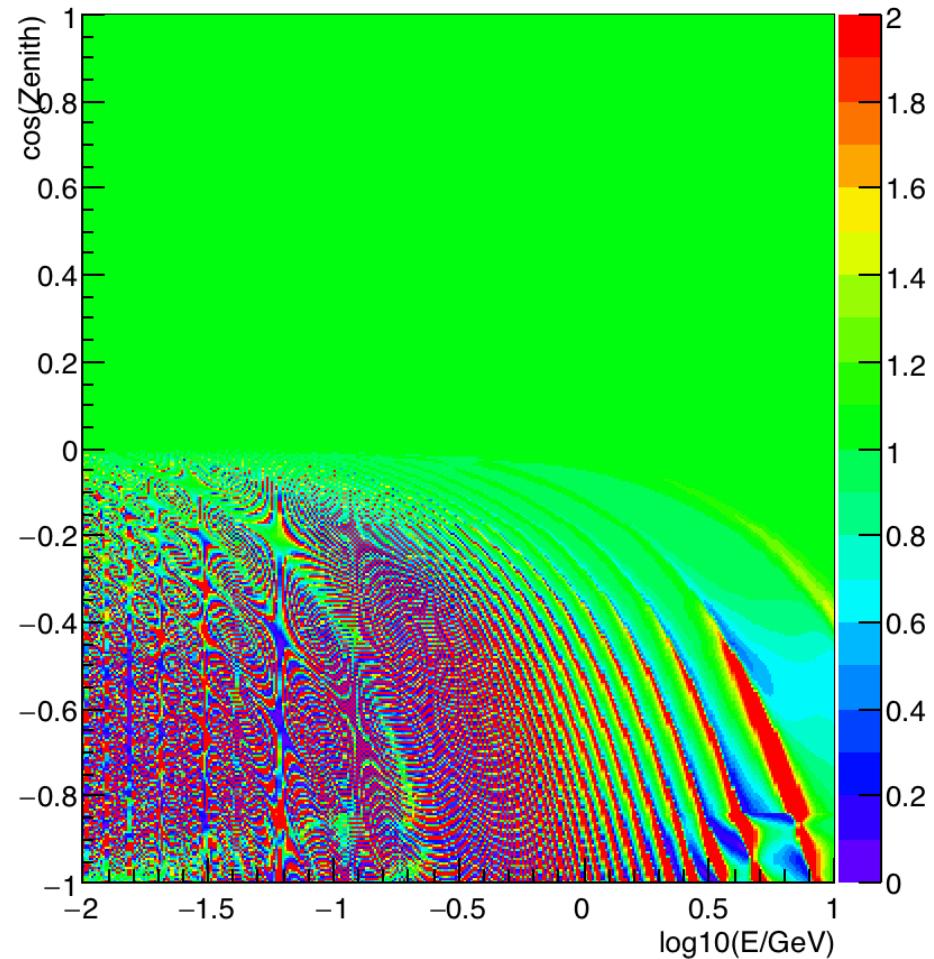


Ratio of MSW/no-MSW (ν_μ)

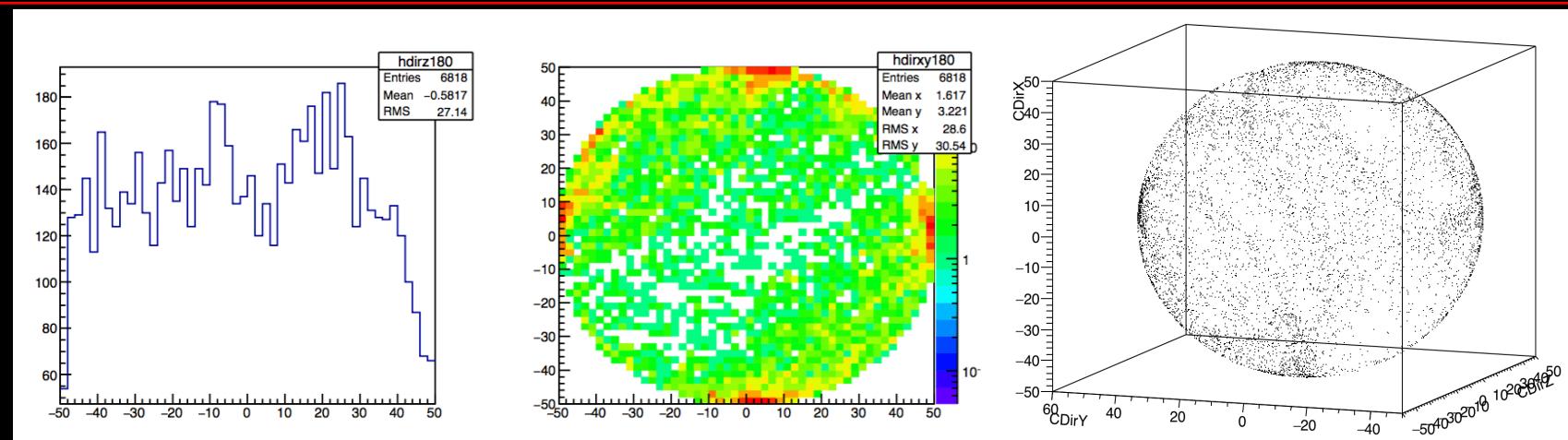
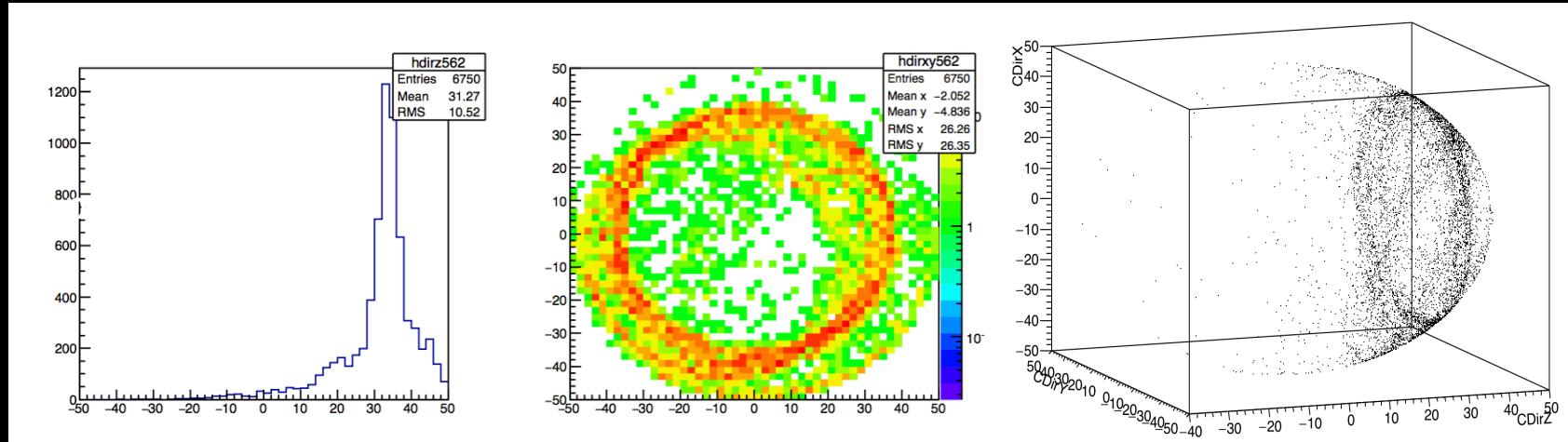
Mu-Er



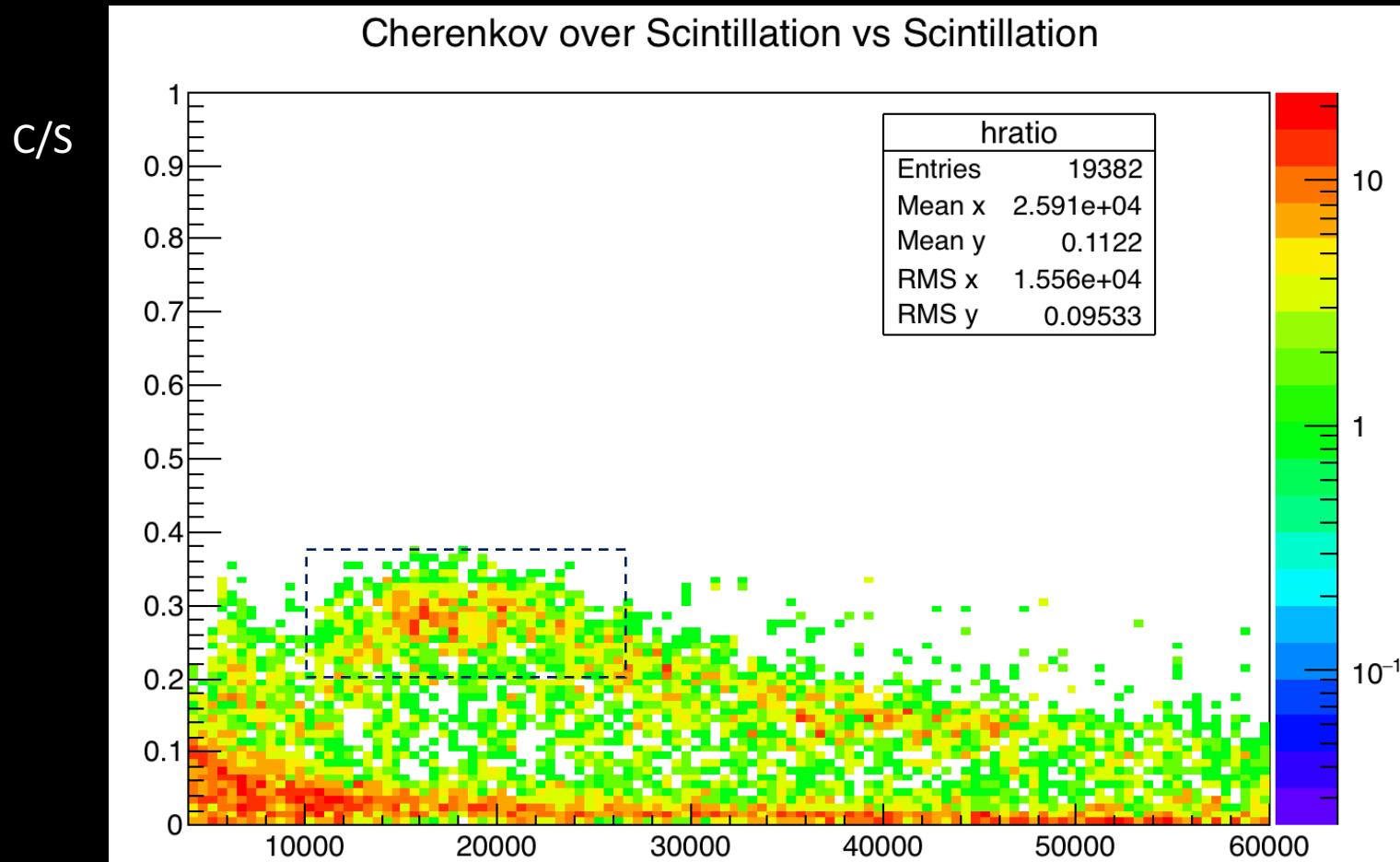
Mu-Mur



e^+ / n – Cherenkov pattern



Neutron Cherenkov vs. Scintillation



- $8800 < \text{SPh} < 36000$ is signal region.