Supernova Neutrino Searches in Water and LS

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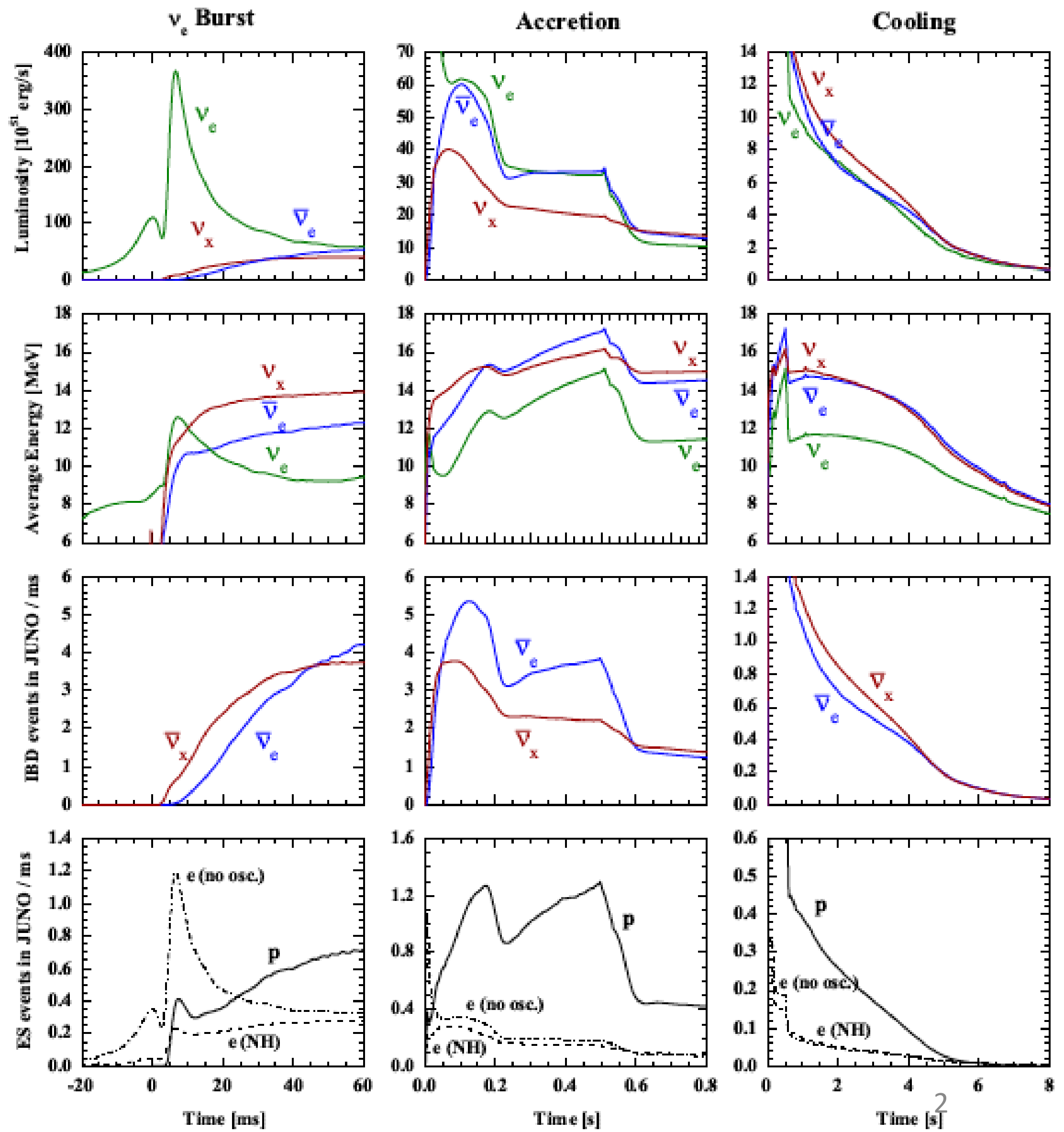
What do we need for SN？

arXiv:1507.05613



1. **Prompt trigger**
2. **Direction**
3. **Energy**
4. **Time**
5. $\nu_e/\overline{\nu_e}$ **separation**
6. **Statistcis**

Event rates

ApJ.496,216(1998)

	WS (/kton)	LS(/kton)
IBD	228	300
ν e scattering	10	20
^{16}O or ^{12}C CC	3	60
ν p scattering	-	300

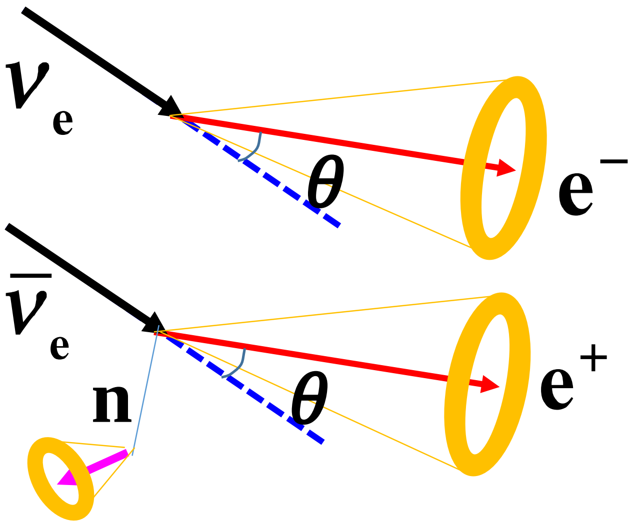
Note: This is for a 10kpc supernova.

- ✓ **32 kton for SK @4.5 MeV;**
- ✓ **1 kton for KamLAND @0.35 MeV**

Comment: High SBN rate may paralyze the online system, special caution is needed.

Signal signature

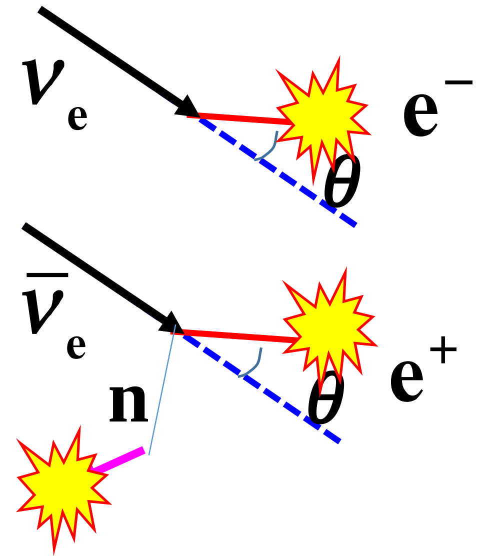
WC



2.2 MeV γ or ~8.0 MeVγ's

- ✓ **Direction**
- ✓ **Energy**
- ✓ **Time**
- ✓ $\nu_e / \overline{\nu_e}$ **(w/Gd)**

LS

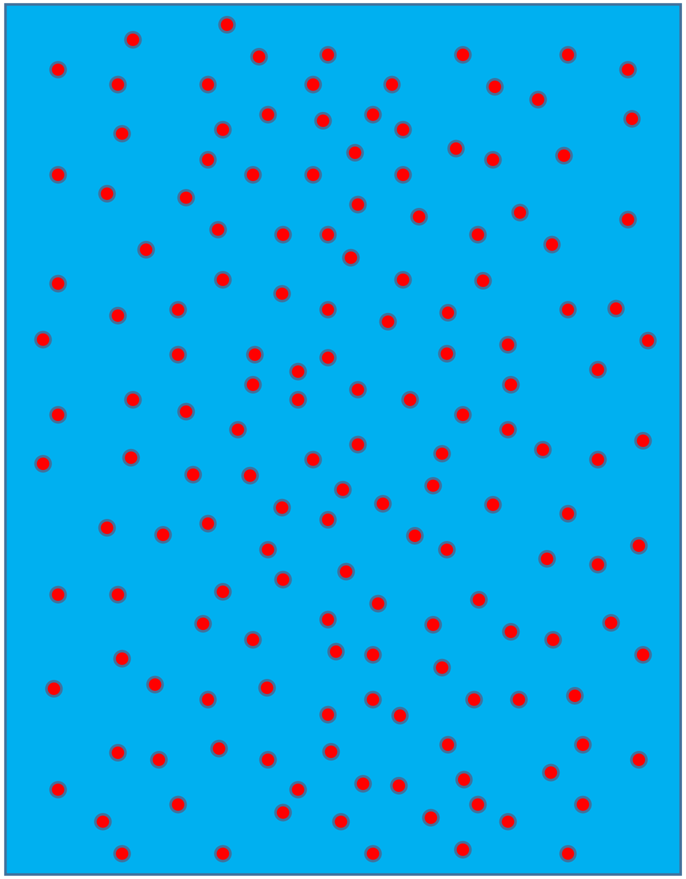


2.2 MeV γ or ~8.0 MeVγ's

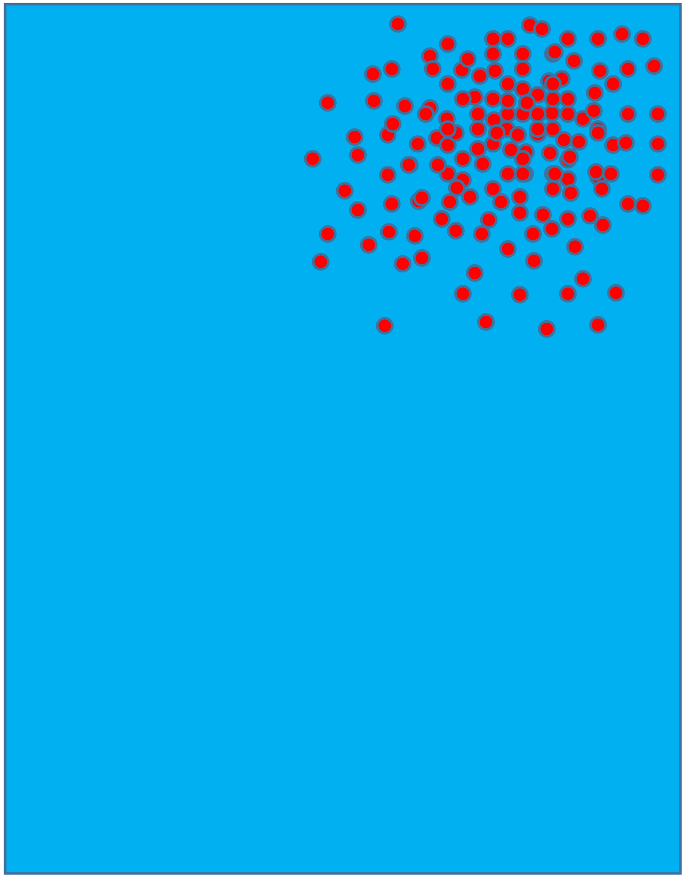
- × **Direction**
- ✓ **Energy**
- ✓ **Time**
- ✓ $\nu_e / \overline{\nu_e}$

Bkg. for SN online trigger

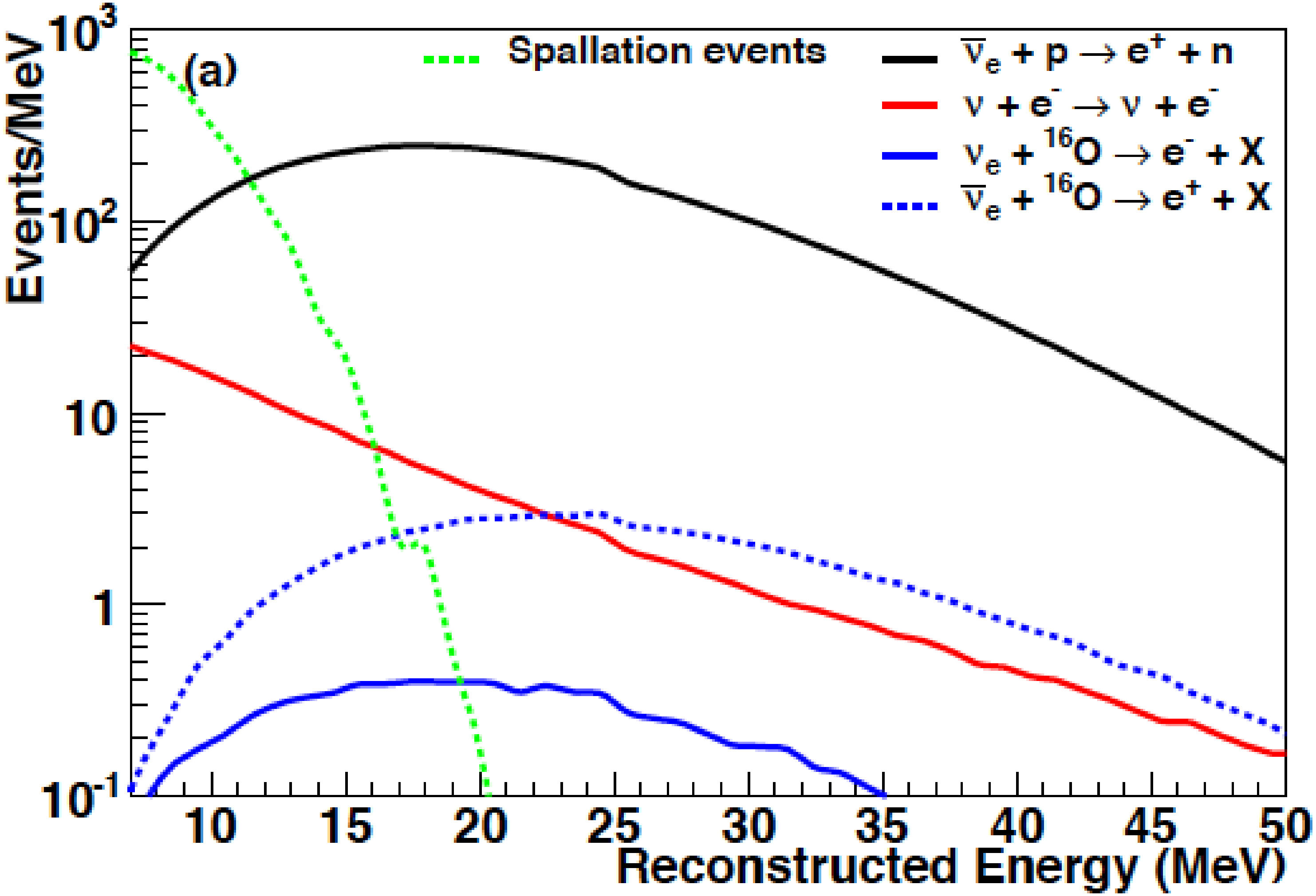
Uniform vertexes of SN neutrino events in a short time window



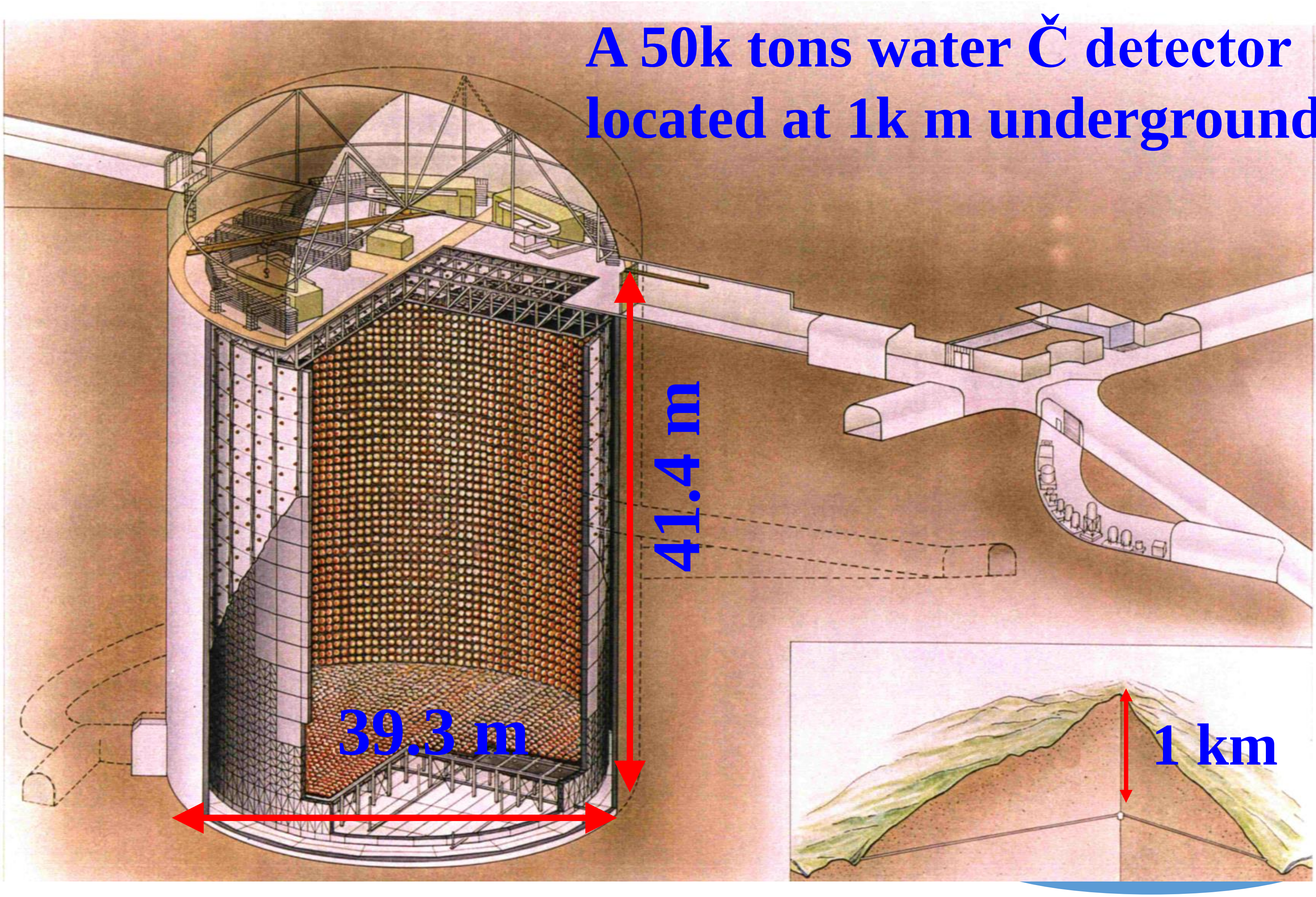
Vertexes of spallation events in a short time window



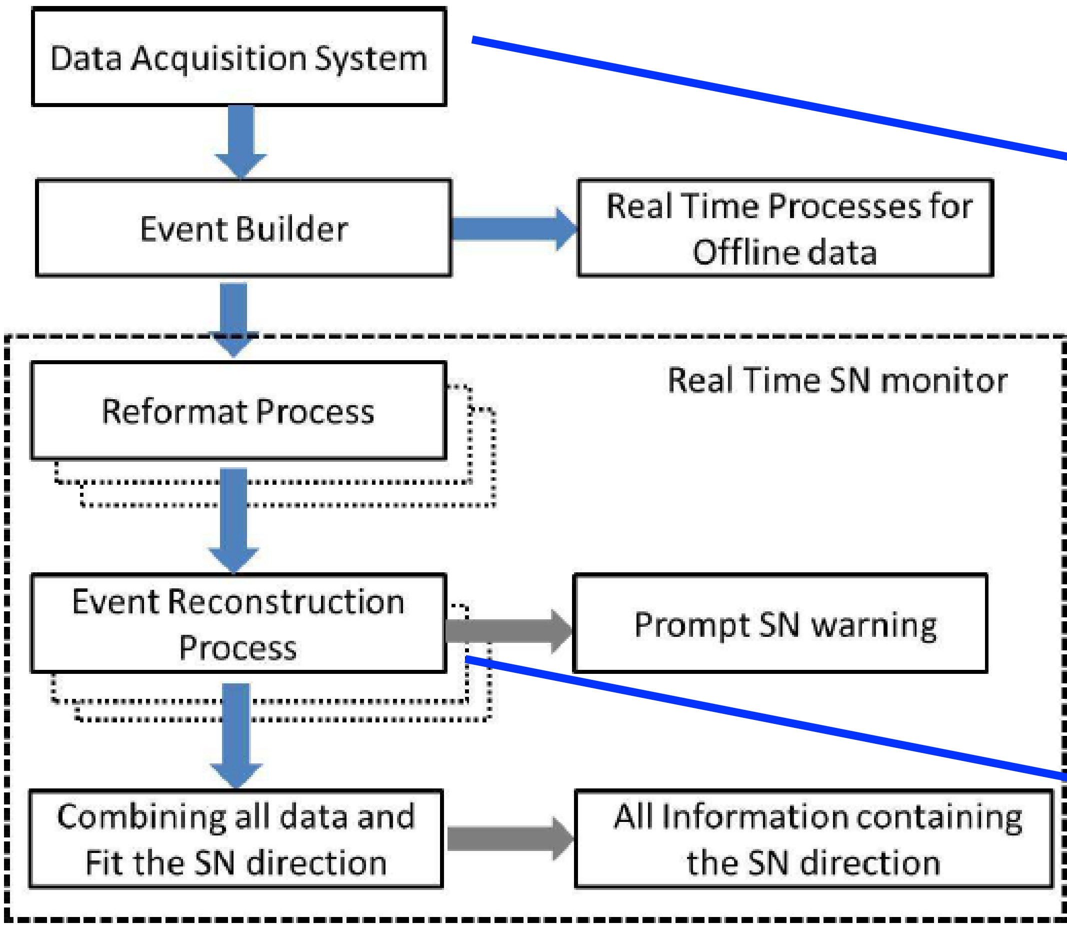
Signal and background shapes

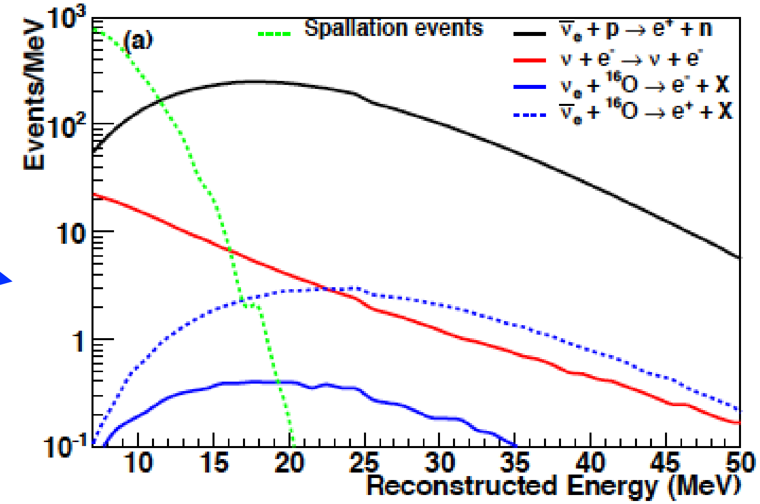


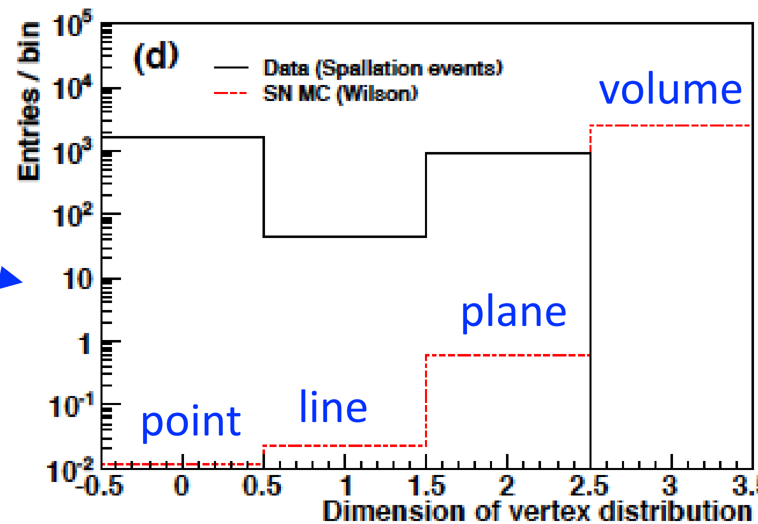
The Super-Kamiokande Experiment



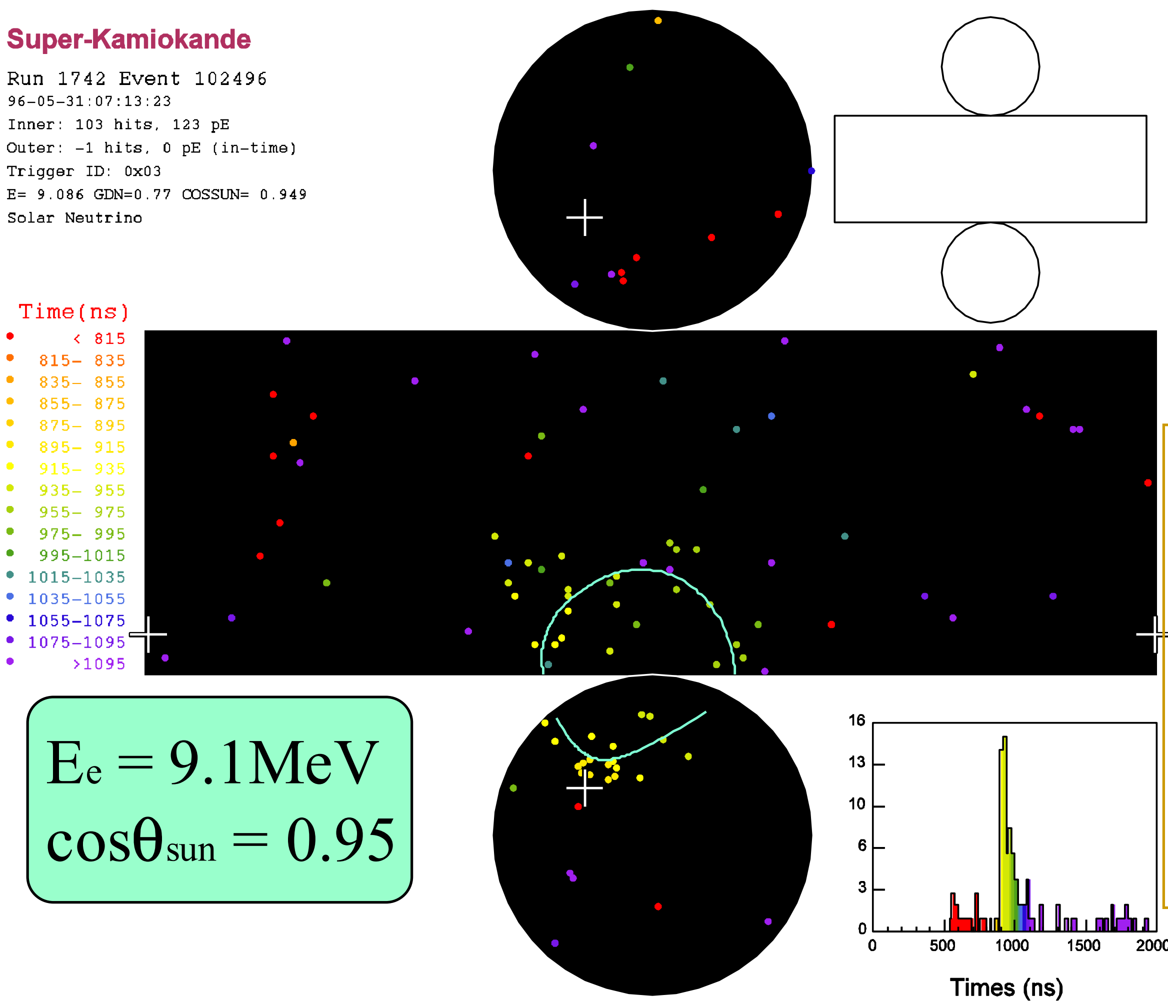
Real-Time Burst Monitor







LE Elastic Scattering Event @SK



$E_e = 9.1\mathrm{MeV}$
$\cos\theta_{sun} = 0.95$

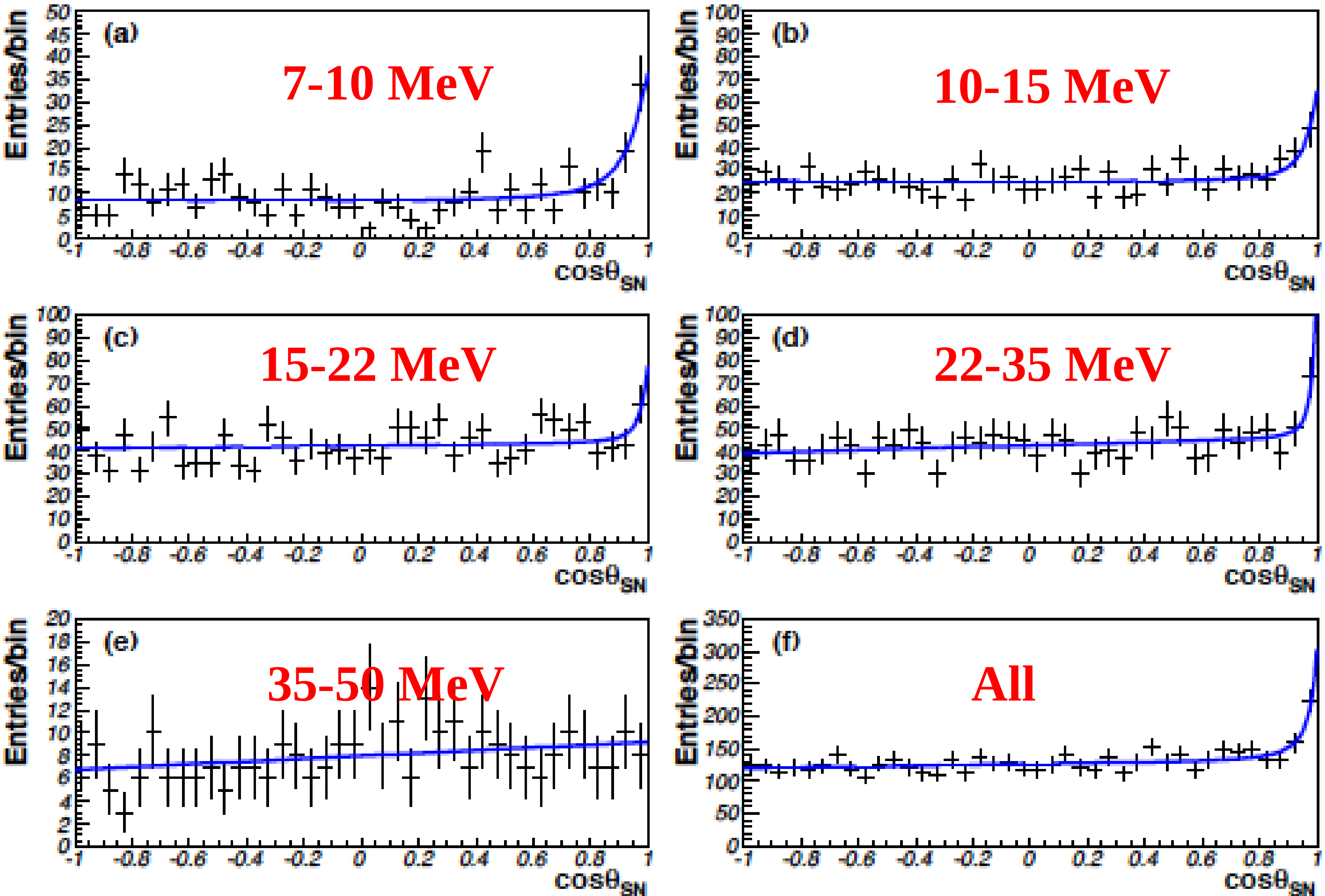
$\nu + e^- \rightarrow \nu + e^-$

Sensitive to ν_e, ν_μ, ν_τ

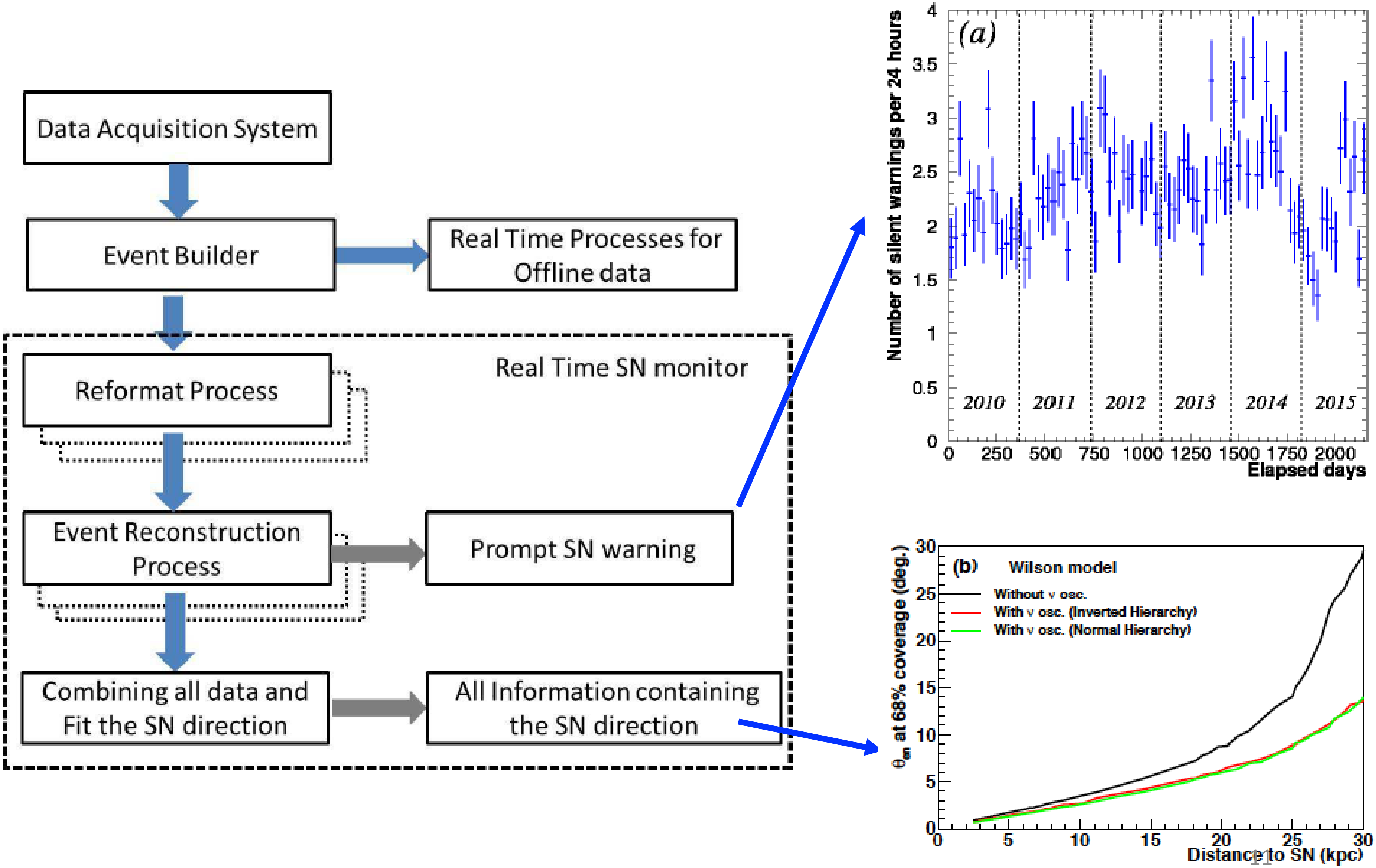
$\sigma(\nu_{\mu(\tau)}e^-) = \sim 0.15 \times \sigma(\nu_e e^-)$

- Timing information
  ➡ vertex position
- Ring pattern
  ➡ direction
- Number of hit PMTs
  ➡ energy

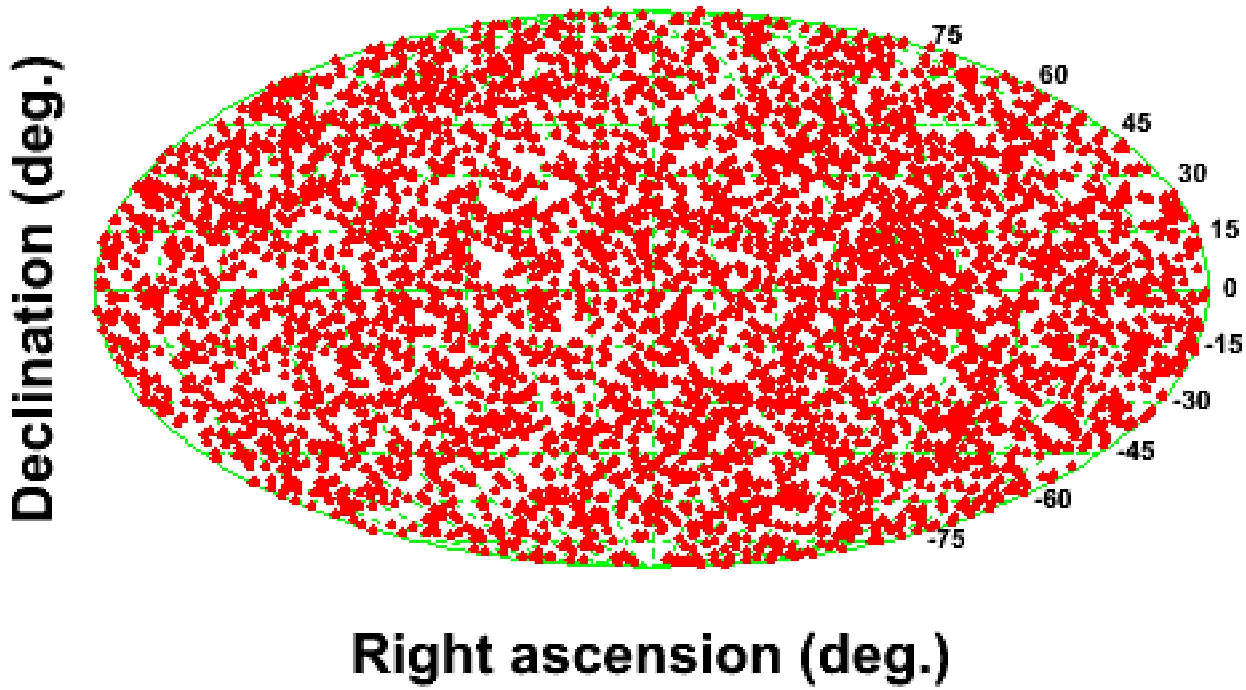
SN direction



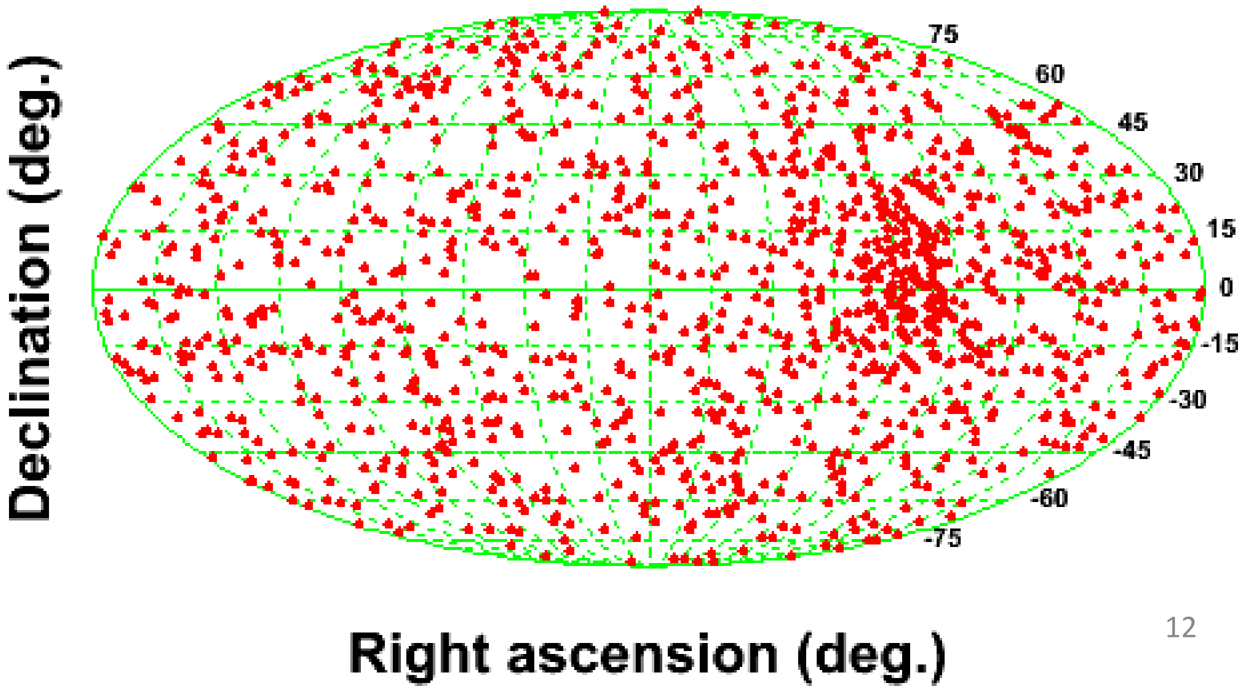
Real-Time Burst Warning



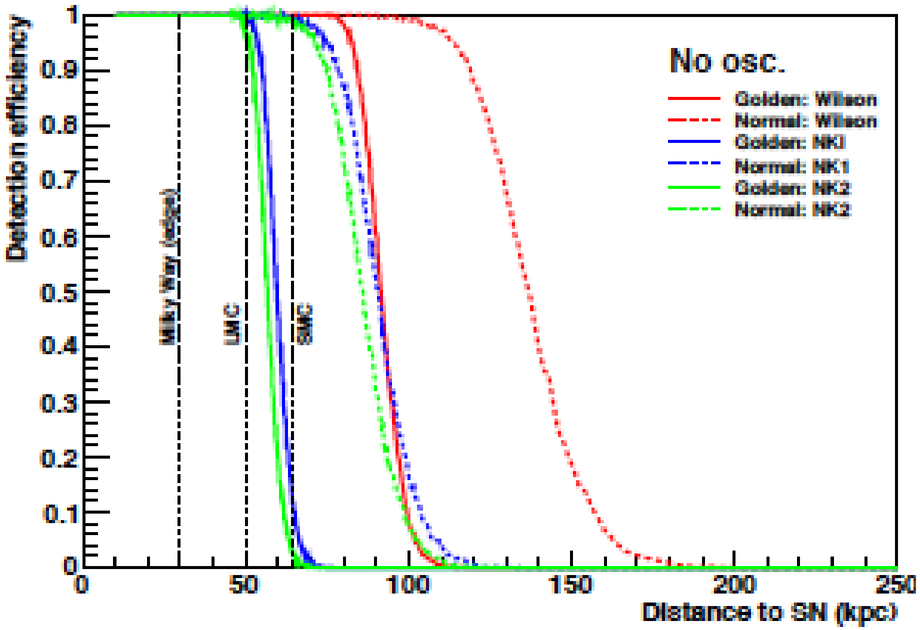
W/O n tag

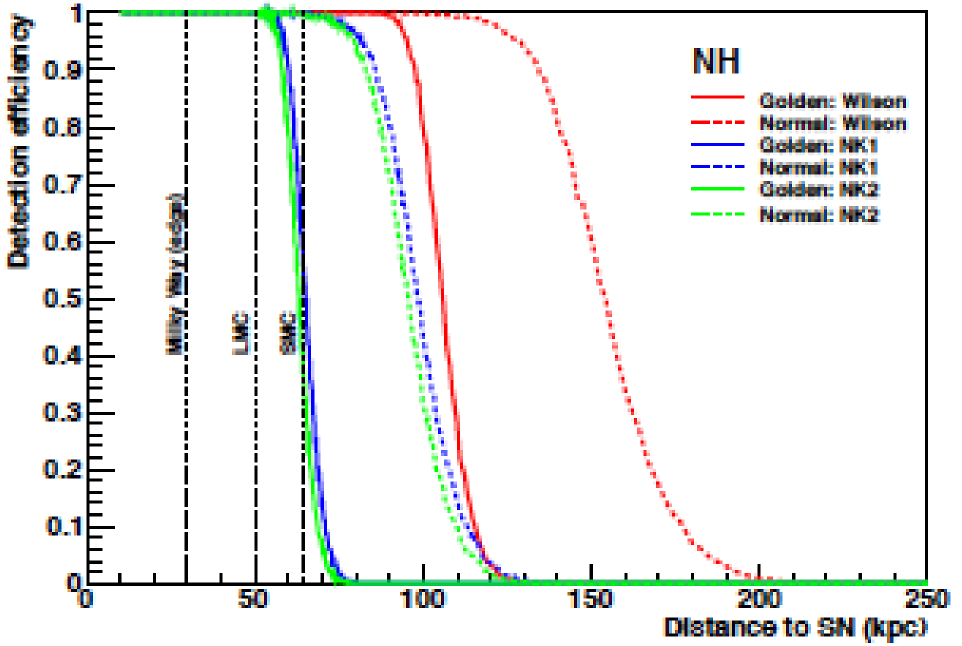


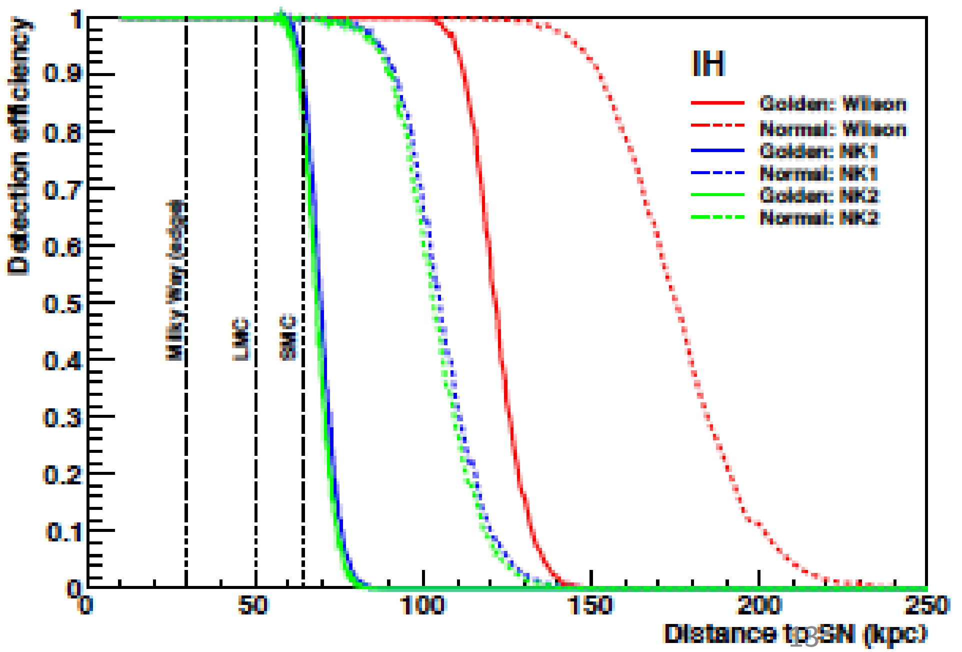
W/ n tag



Sensitivity



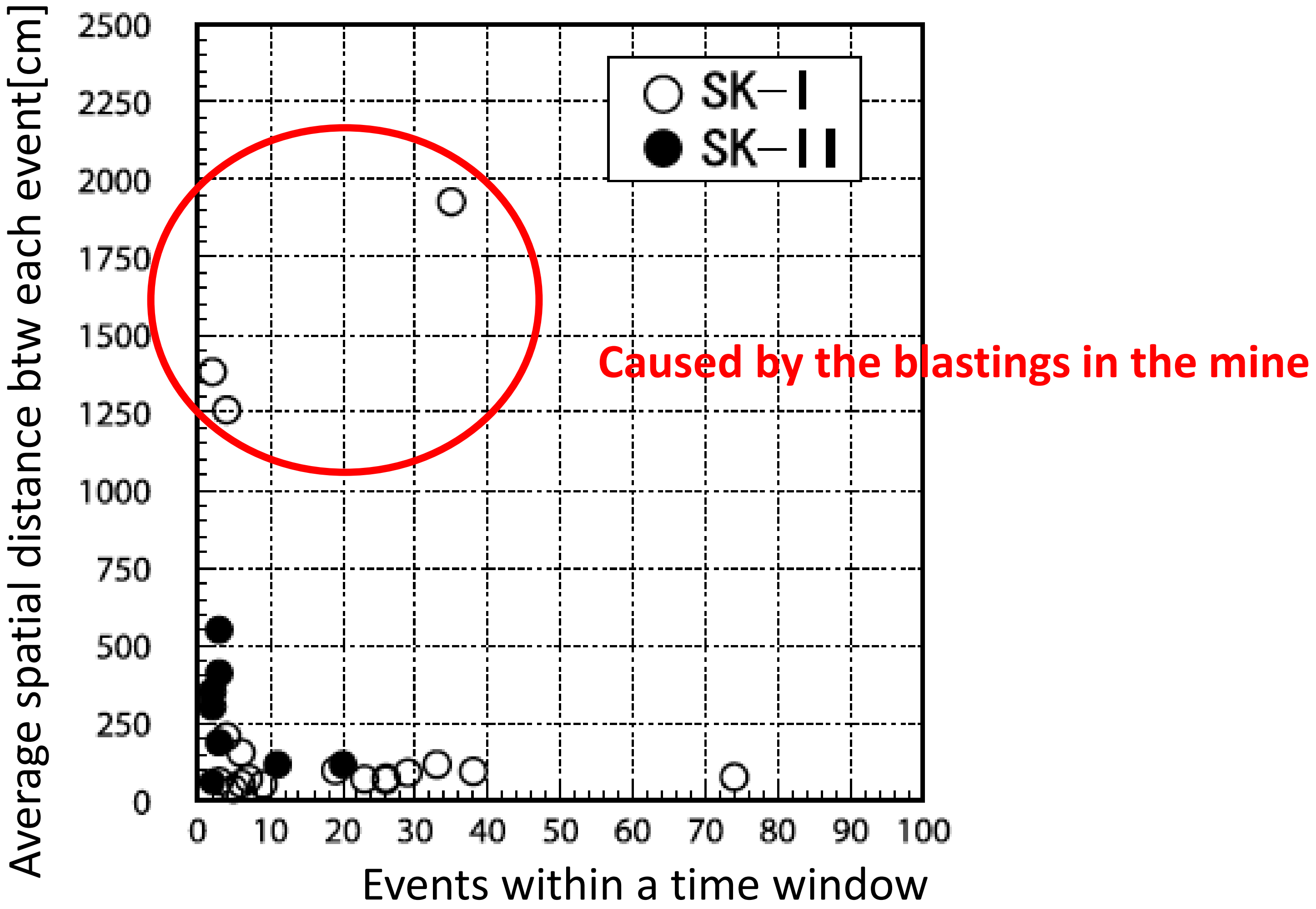




Since other flavor anti-neutrinos are converted to electron anti-neutrinos, the average neutrino energy increase, resulting in a high rate of IBD.

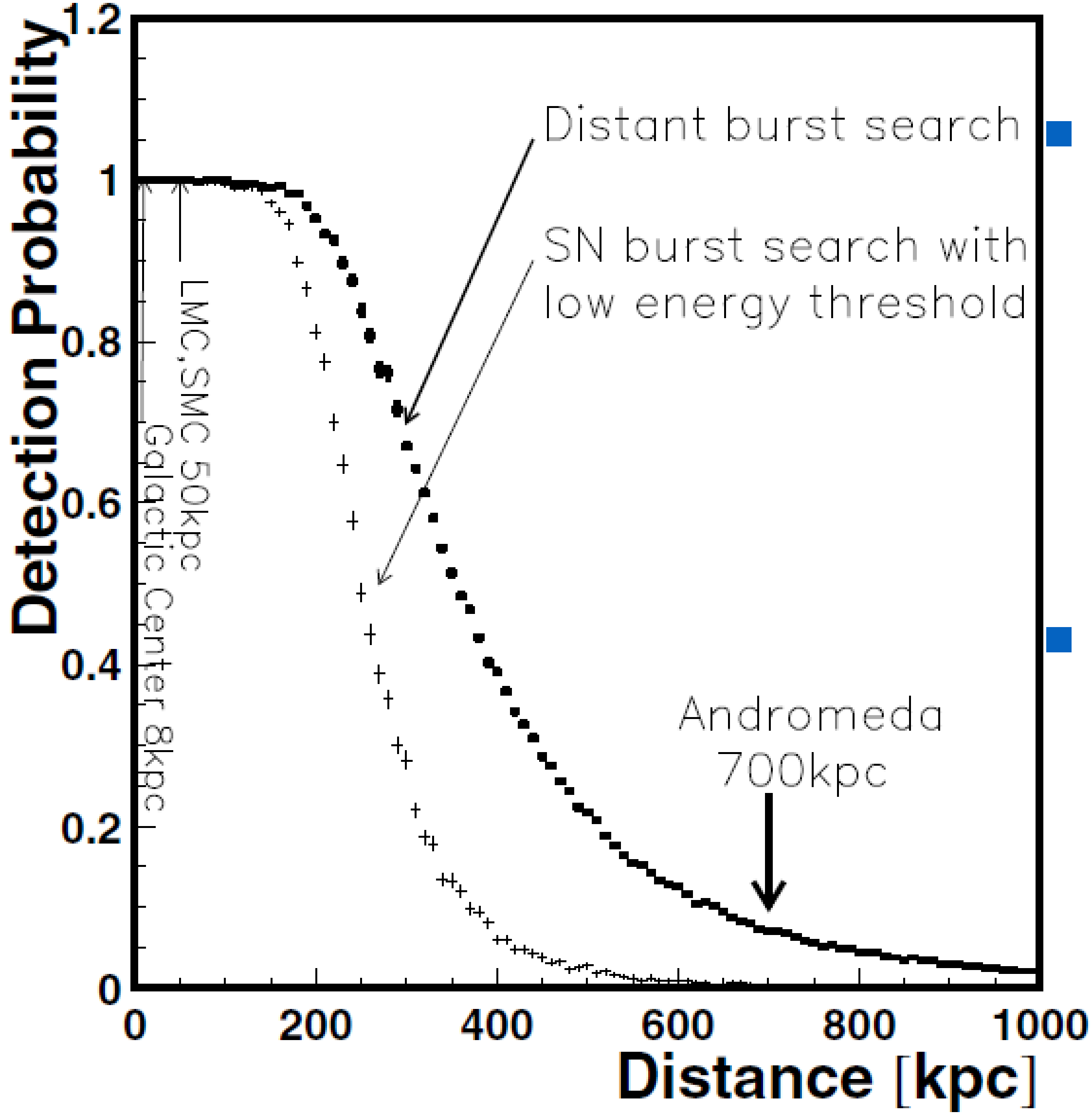
Offline search @ SK-I, II

Sophisticated cuts can be applied to suppress background



The Astrophysical Journal, 669:519Y524, 2007

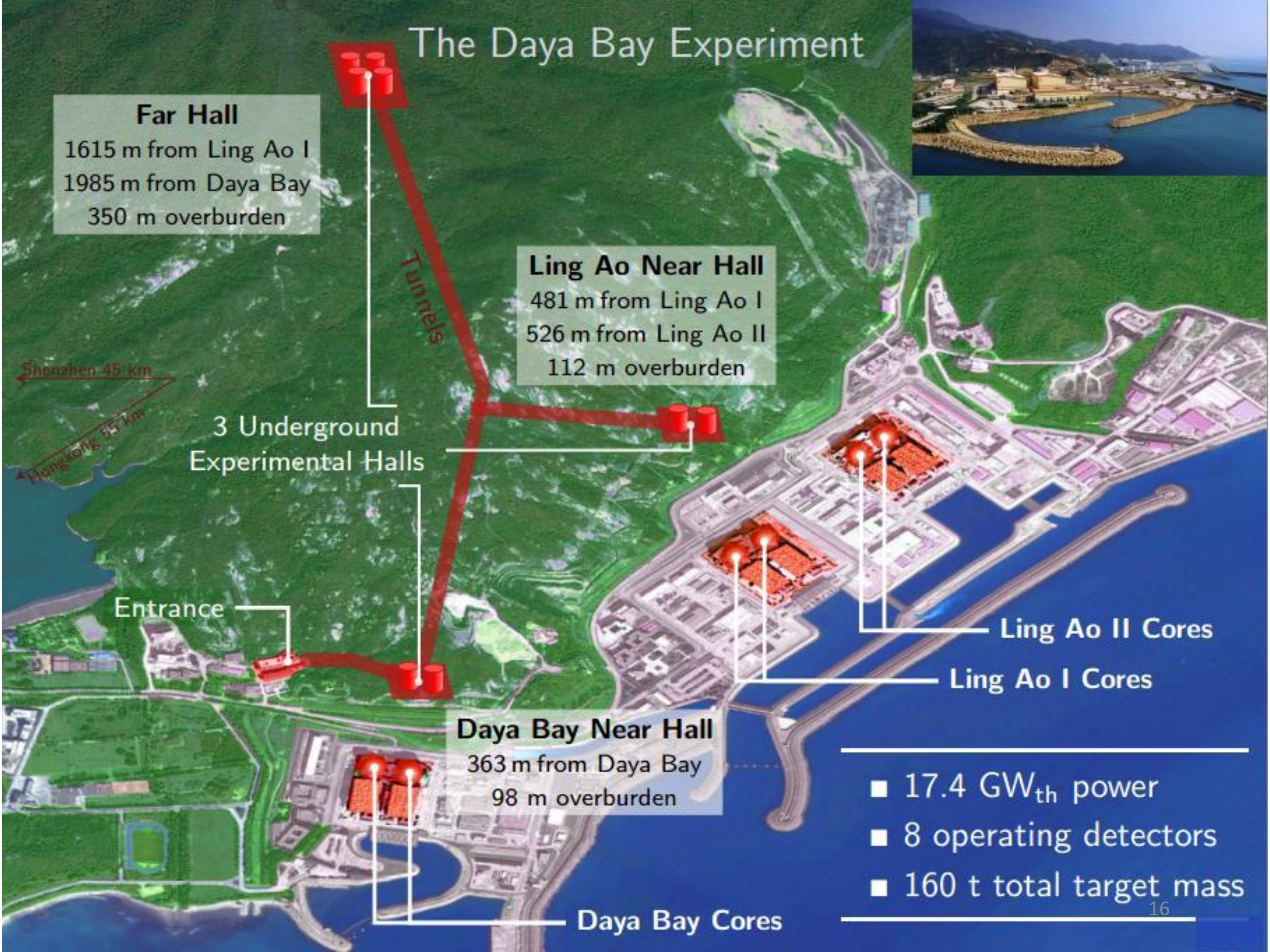
Limit for Galactic SN @SK



- **~10% probability at Andromeda was achieved in the distant search**
- **Upper limit: (90%CL)**

  0.32 Galactic SN per year

The Astrophysical Journal, 669:519Y524, 2007


The Daya Bay Experiment
Far Hall
1615 m from Ling Ao I
1985 m from Daya Bay
350 m overburden
Tunnels
Ling Ao Near Hall
481 m from Ling Ao I
526 m from Ling Ao II
112 m overburden
Shenzhen 45 km
3 Underground
Experimental Halls
Entrance
Ling Ao II Cores
Ling Ao I Cores
Daya Bay Near Hall
363 m from Daya Bay
98 m overburden
■ 17.4 GW_{th} power
■ 8 operating detectors
■ 160 t total target mass
Daya Bay Cores

Target mass comparison

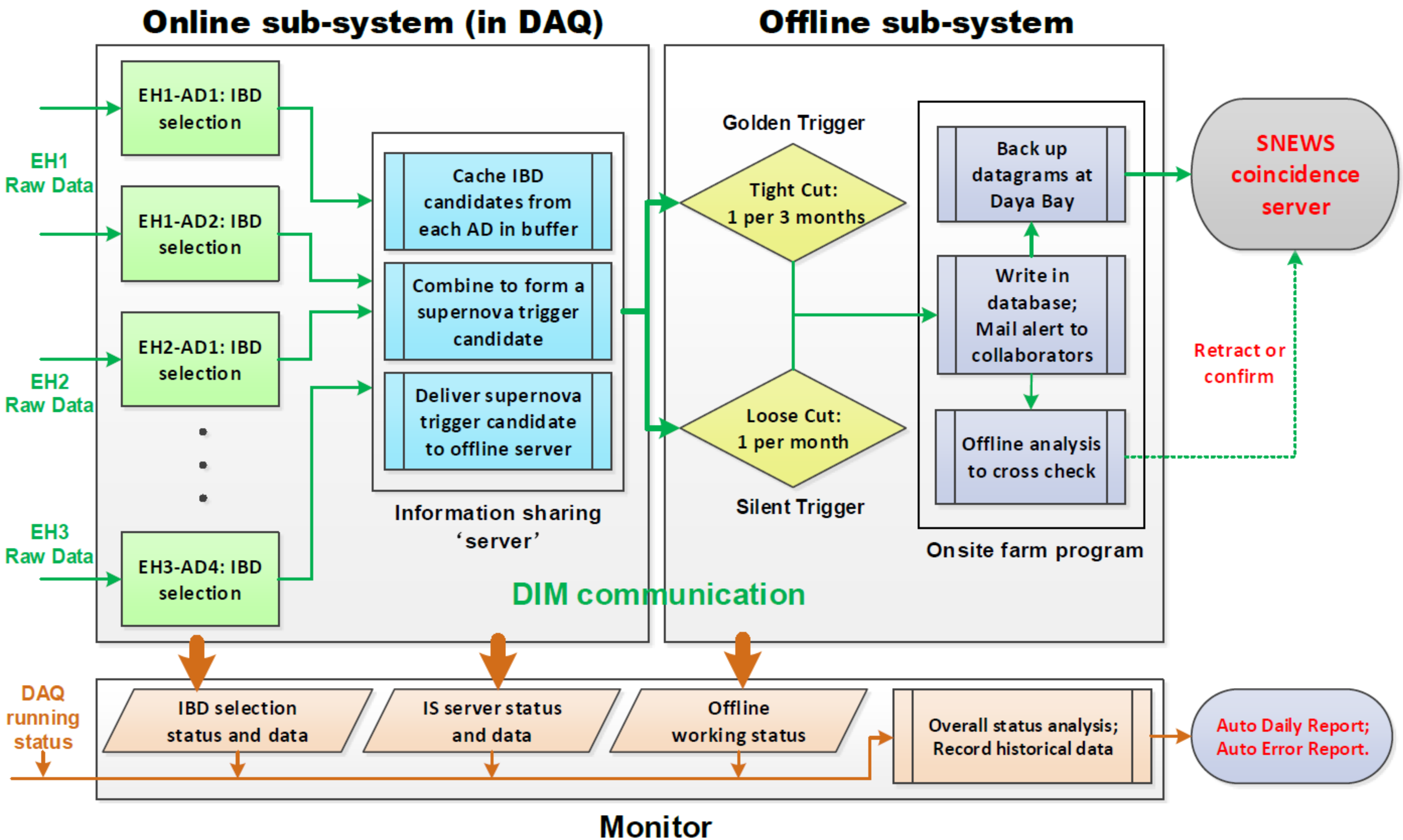
Table 1: Supernova neutrino detectors in SNEWS and their capabilities. N_{IBD} is the expected number of IBD events from a SN at 10 kpc, with an emission of 5×10^{52} erg in $\bar{\nu}_e$'s, and an average $\bar{\nu}_e$ energy around 12 MeV, which is compatible with SN 1987A measurements.

Detector	Type	Location	Mass (kt)	N_{IBD}	E_{th} (MeV)
IceCube	*L.S. Ch.	Antarctic	0.6/PMT	N/A	-
Super-K	Water Ch.	Japan	32	7000	7.0
LVD	Scint.	Italy	1	300	4.0
KamLAND	Scint.	Japan	1	300	0.35
Borexino	Scint.	Italy	0.3	100	0.2
Daya Bay	†M.S. Scint.	China	0.33	110	0.7

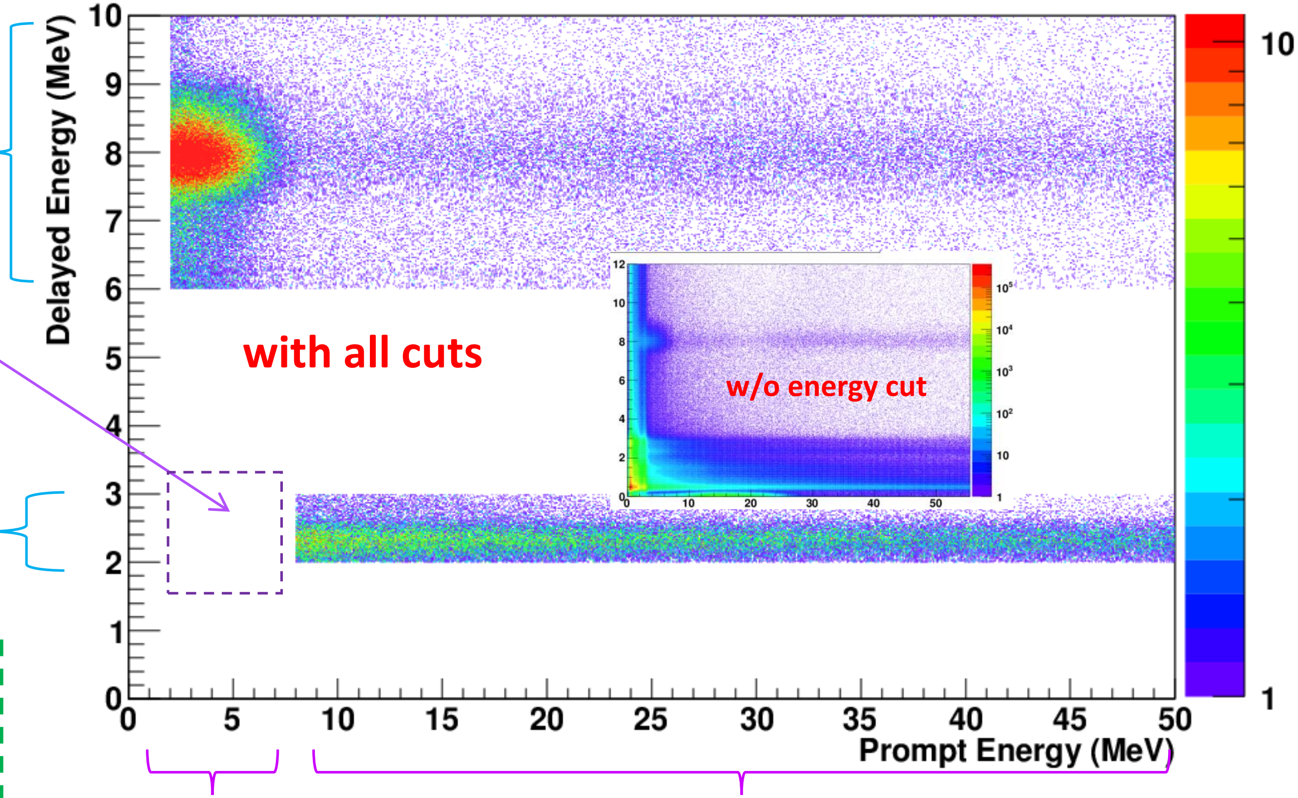
* Long-String Cherenkov † Multiple-Site Scintillator

	Daya Bay	Super-K
Energy Resolution	0.3 MeV @10 MeV	1.6MeV @10 MeV
Threshold	2 MeV (online) 0.7 MeV(offline) Sensitive to full spectrum and other models	~10 MeV
Multiple sites or single site/detector	8 ADs deploying in three sites: robust against cosmogenic backgrounds	Single detector
	Prompt online trigger ~10s Increase online/offline sensitivity	Need complicated reconstruction for online
Detection probability	100% within 30 kpc	100% within 100 kpc

Algorithm for IBD trigger only



Online selection



Selection Cuts:

1. PMT Flasher
2. Muon Veto
3. Time Coin.~400us
4. Multiplicity ~2
5. Prompt-Delayed Distance~1000mm
6. Energy cut

Single AD trigger rate:
DYB ~0.015Hz LA ~0.012Hz
FAR ~0.0012Hz

Expect ~10/AD SN$\overline{\nu}_e$ @10 kpc in 10s (after 70% eff.)

- ADs from different experimental halls (EHs) are independent
- An approach was developed to handle the correlation between two ADs in one experimental hall
- A table is generated for all IBD candidate combinations in multiple ADs and sorted according to the predicted rate of occurrence.

EH1		EH2		EH3				Rate (Hz)
AD1	AD2	AD1	AD2	AD1	AD2	AD3	AD4	($r_i > r_{i+1}$)
0	0	0	0	0	0	0	0	r_1
0	1	0	0	0	0	0	0	r_2
⋮		⋮		⋮				⋮
0	0	0	1	0	1	0	0	r_n
2	0	0	1	0	0	0	0	r_{n+1}
⋮		⋮		⋮				⋮

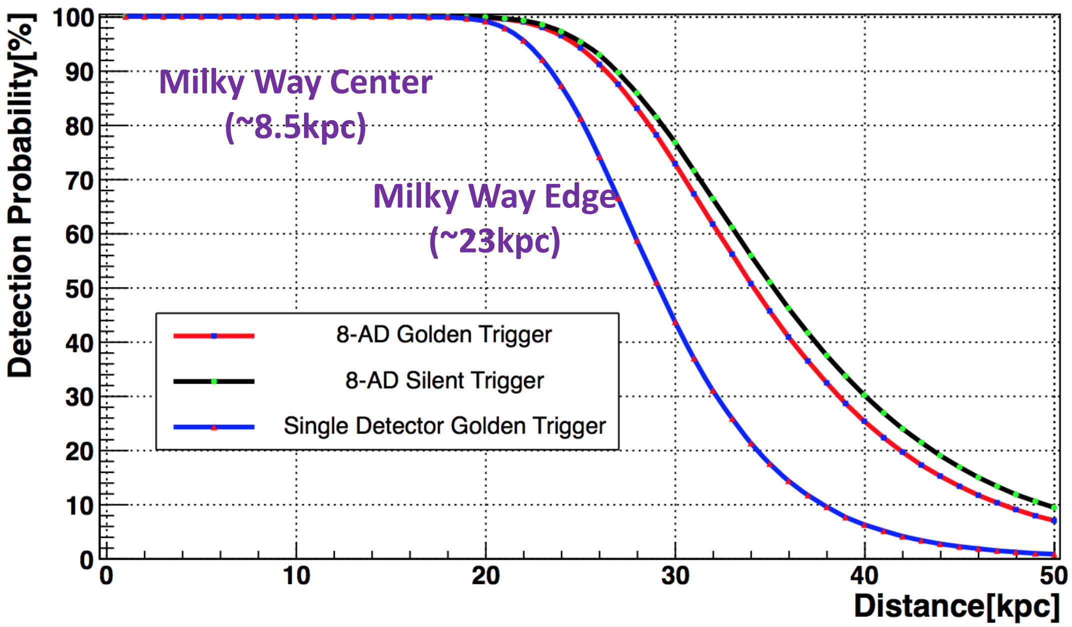
For a false alarm rate threshold (P_{DYB} =1/3months),
kth row as a cut satisfies:

$$\sum_{i=k+1}^{\infty} r_i \leq P_{DYB} \quad \text{and} \quad \sum_{i=k}^{\infty} r_i \geq P_{DYB}.$$

- The combinations below kth row would be a SN candidate
    - Loose trigger: 1/month
    - Golden trigger: 1/3-months

Sensitivity

- Assuming a 1987A-type SN explosion at some distance, summation of the probabilities of the combinations surviving from the trigger cut.
- The IBD selection efficiency for supernova burst neutrinos is about 70%.
- Fully sensitive to 1987A-type supernova explosions throughout most of the Milky Way



Single Detector curve:

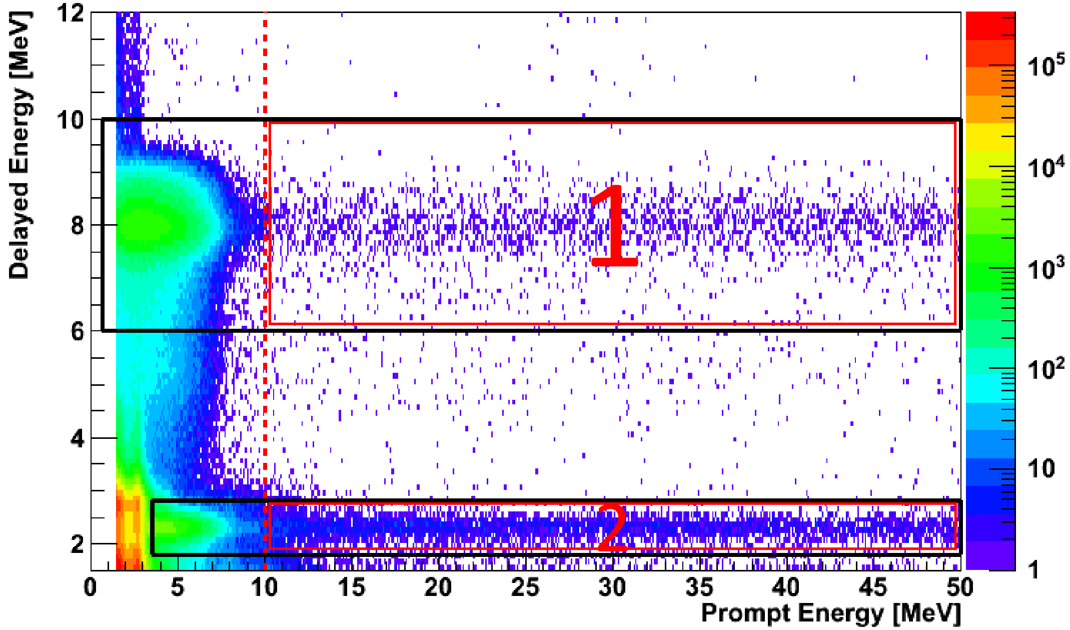
- Target mass of all 8 ADs combined into a single detector with the sum of bkg rates in 8 ADs
- Illustrate the significant gain in sensitivity of multiple detectors

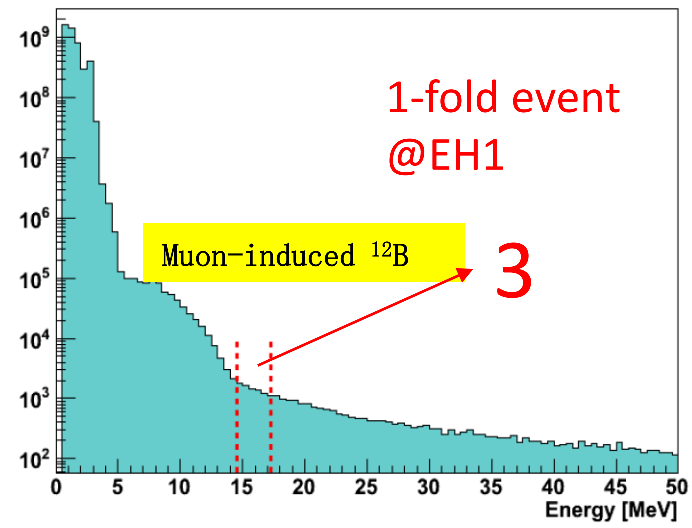
Offline searching at Daya Bay

- **Analogous to online watching but**
  - **Good data quality & reconstruction, less background**
- **IBD channel**
  - **75% efficiency**
- **Include NC-^{12}C channel (a 3-sigma energy range cut on one-fold event after IBD selection)**
  - **expect 2/AD SNν @10 kpc after 40% eff.**
  - **40% eff. in full volumes including GdLS (20t), LS(22t), and mineral oil (~40t, used for radiation shielding, contribute <0.1% IBD, but a large fraction of single gamma spill into LS)**
  - **Background: ~8(6)$\times 10^{-5}$ Hz/AD, far site ~6$\times 10^{-6}$ Hz/AD**

Offline analysis

NC-^{12}C (all flavors, 15.11-MeV de-excitation γ)

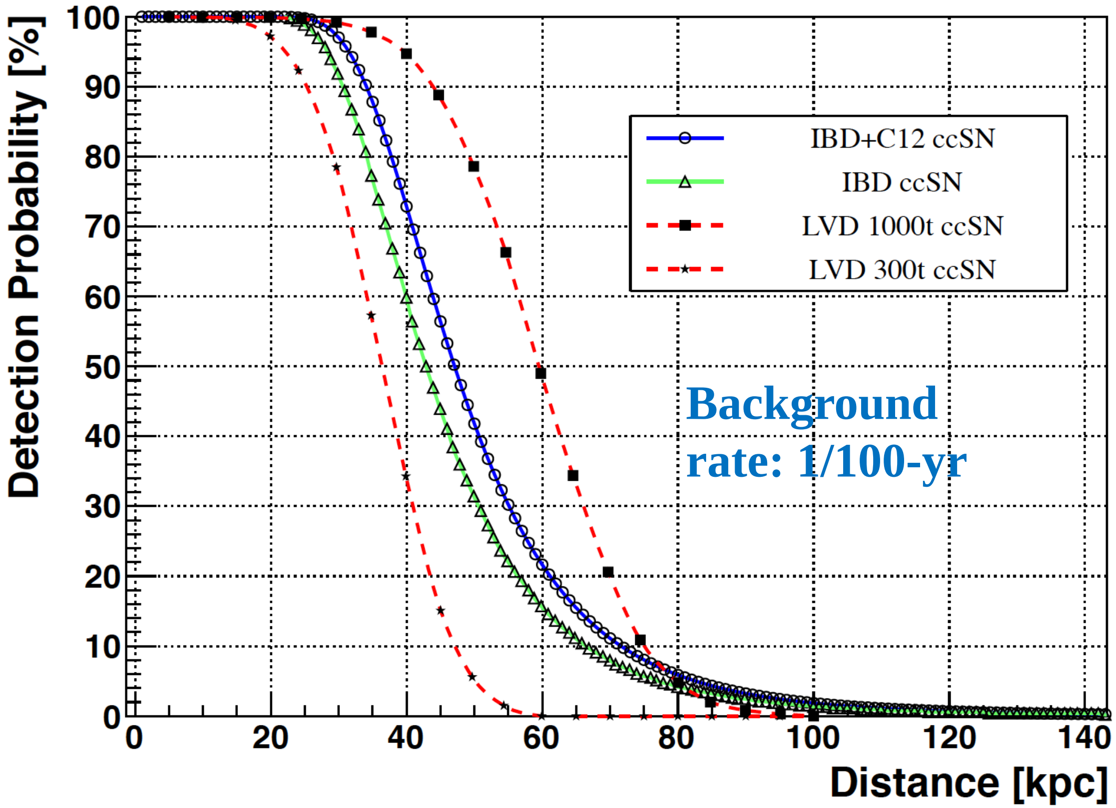


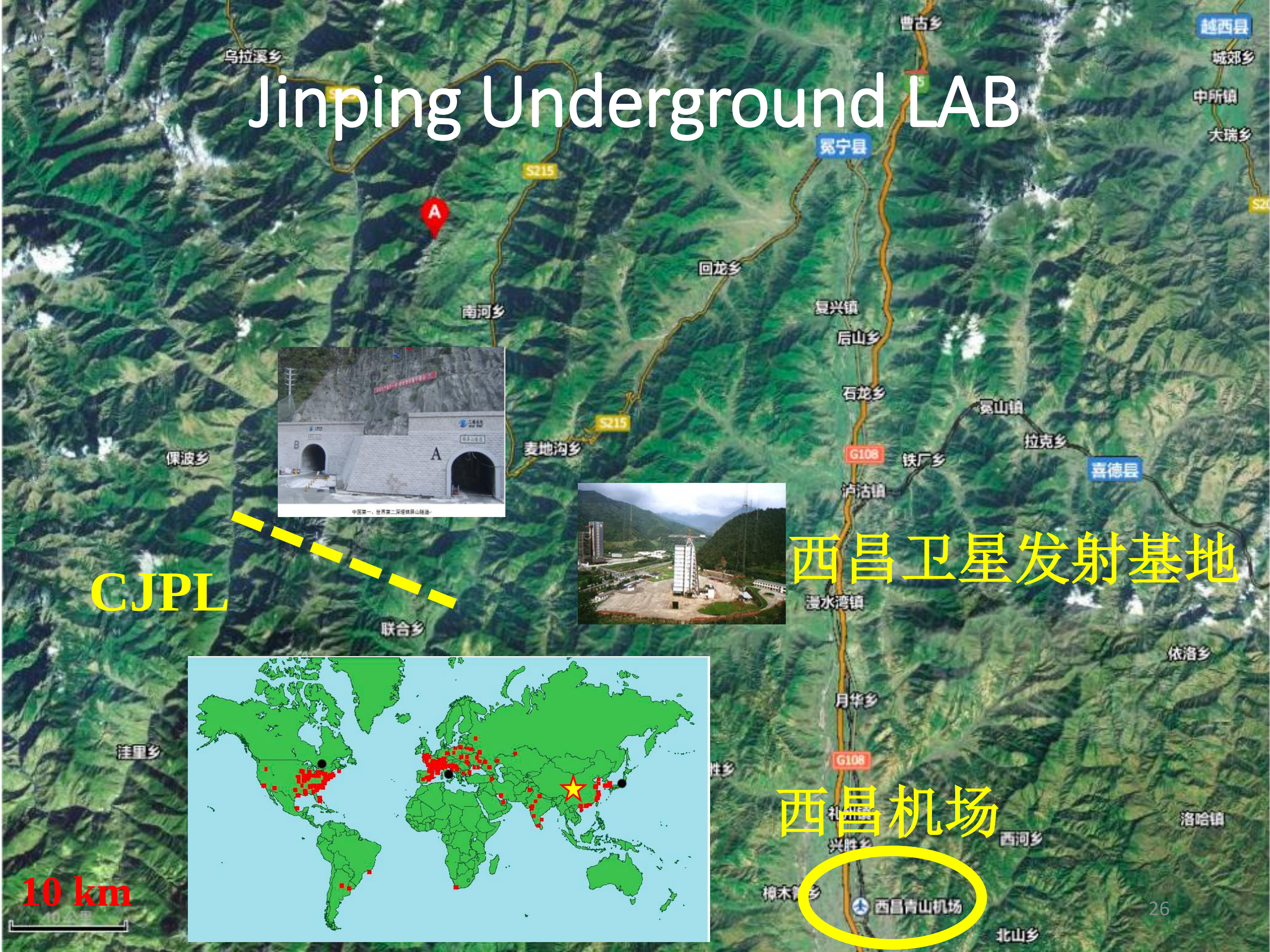


✓**Energy threshold >10 MeV [1+2+3] -- high signal-to-background ratio (high sensitivity)**

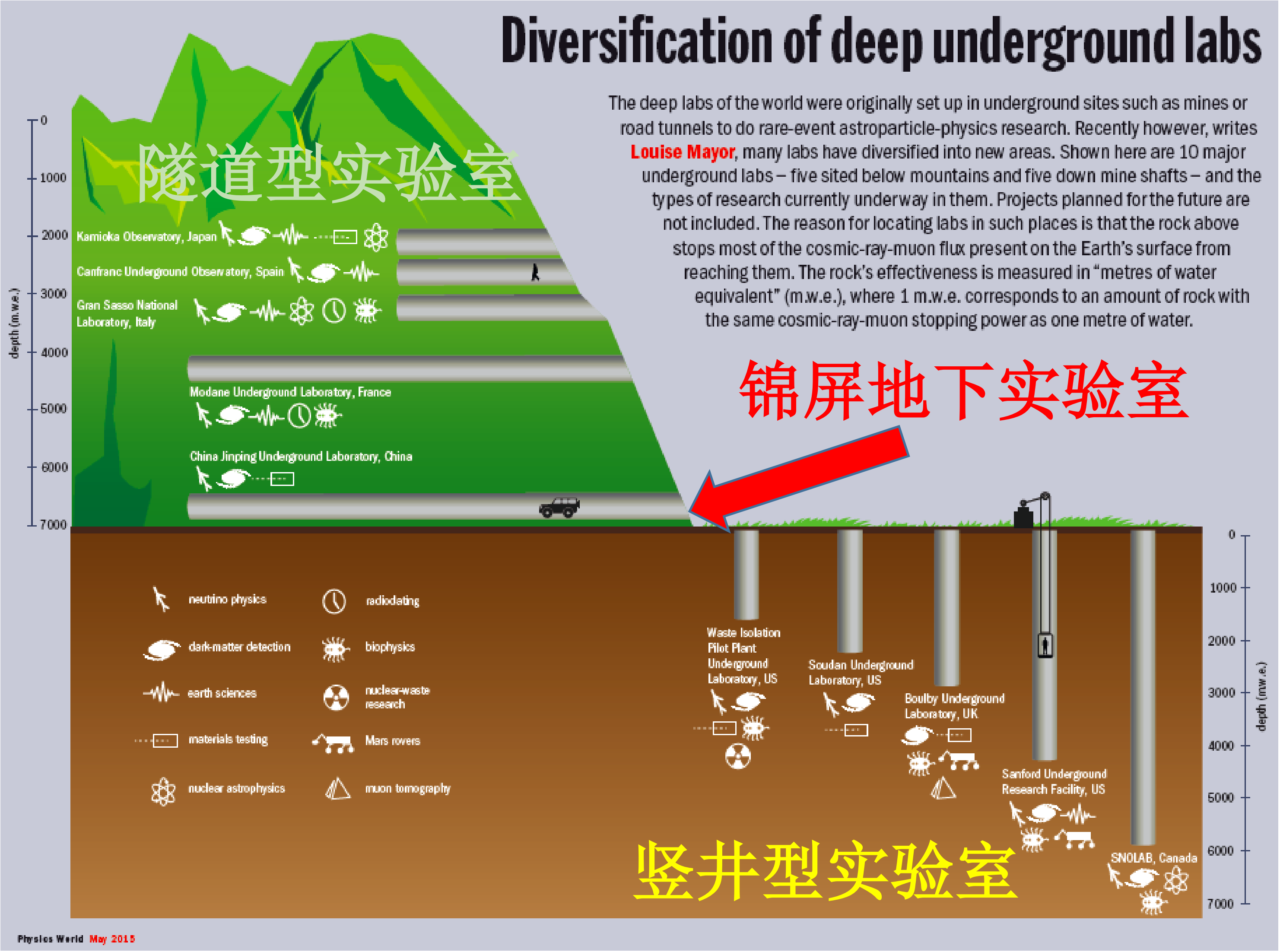
Sensitivity (8AD configuration)

Compared with LVD (1kt LS + 0.85kt Fe, 840 tanks, trigger-level analysis containing all kinds of interaction channels, 10-100 MeV, 21-yr data, world-wide most stringent upper limit 0.114/yr)

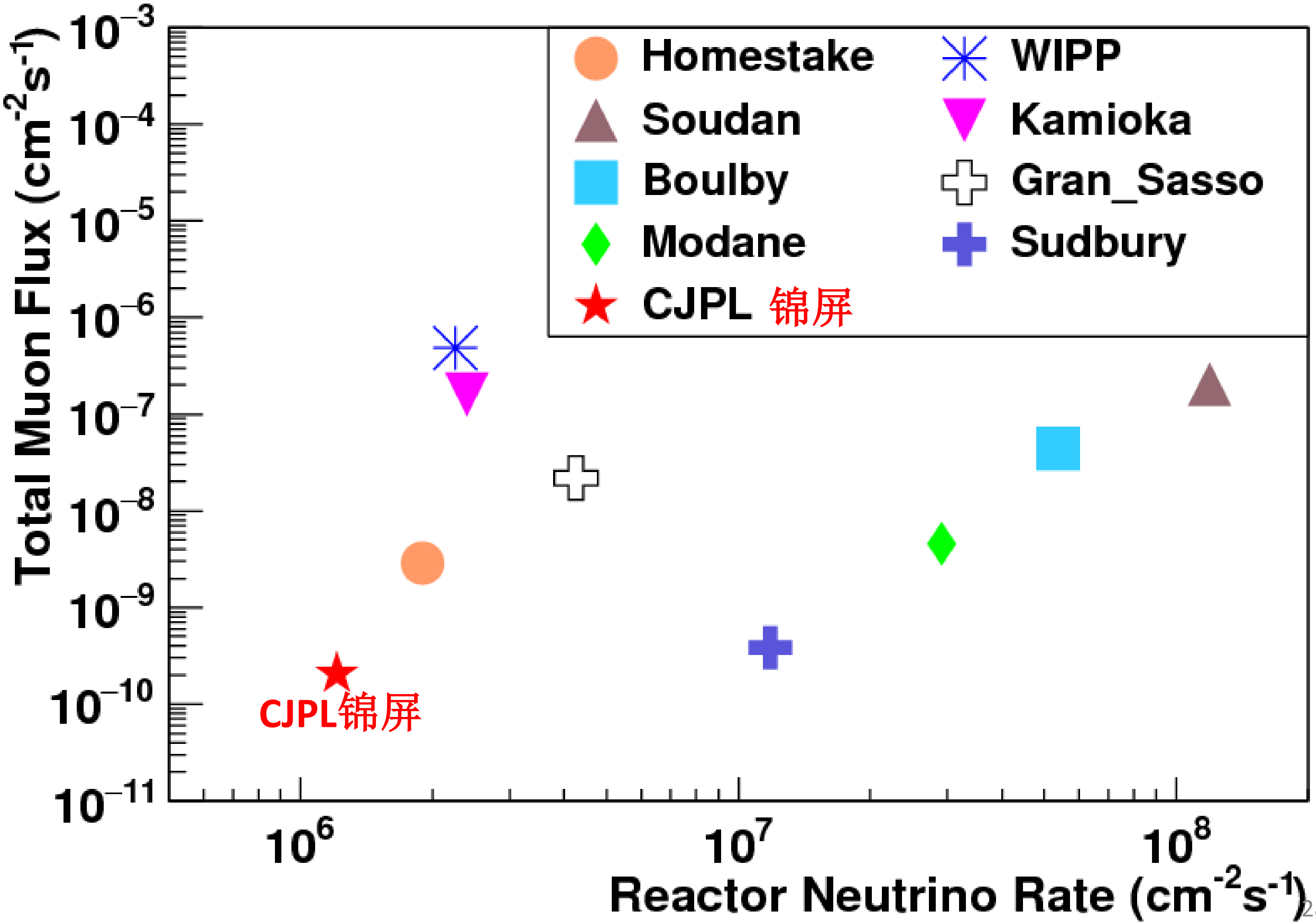



Jinping Underground LAB
CJPL
西昌卫星发射基地
西昌机场
10 km
乌拉溪乡
冕宁县
越西县
城郊乡
中所镇
大瑞乡
回龙乡
南河乡
复兴镇
后山乡
石龙乡
麦地沟乡
泸沽镇
铁厂乡
拉克乡
喜德县
漫水湾镇
联合乡
依洛乡
月华乡
洛哈镇
西河乡
西昌青山机场
北山乡
S215
G108
A
B

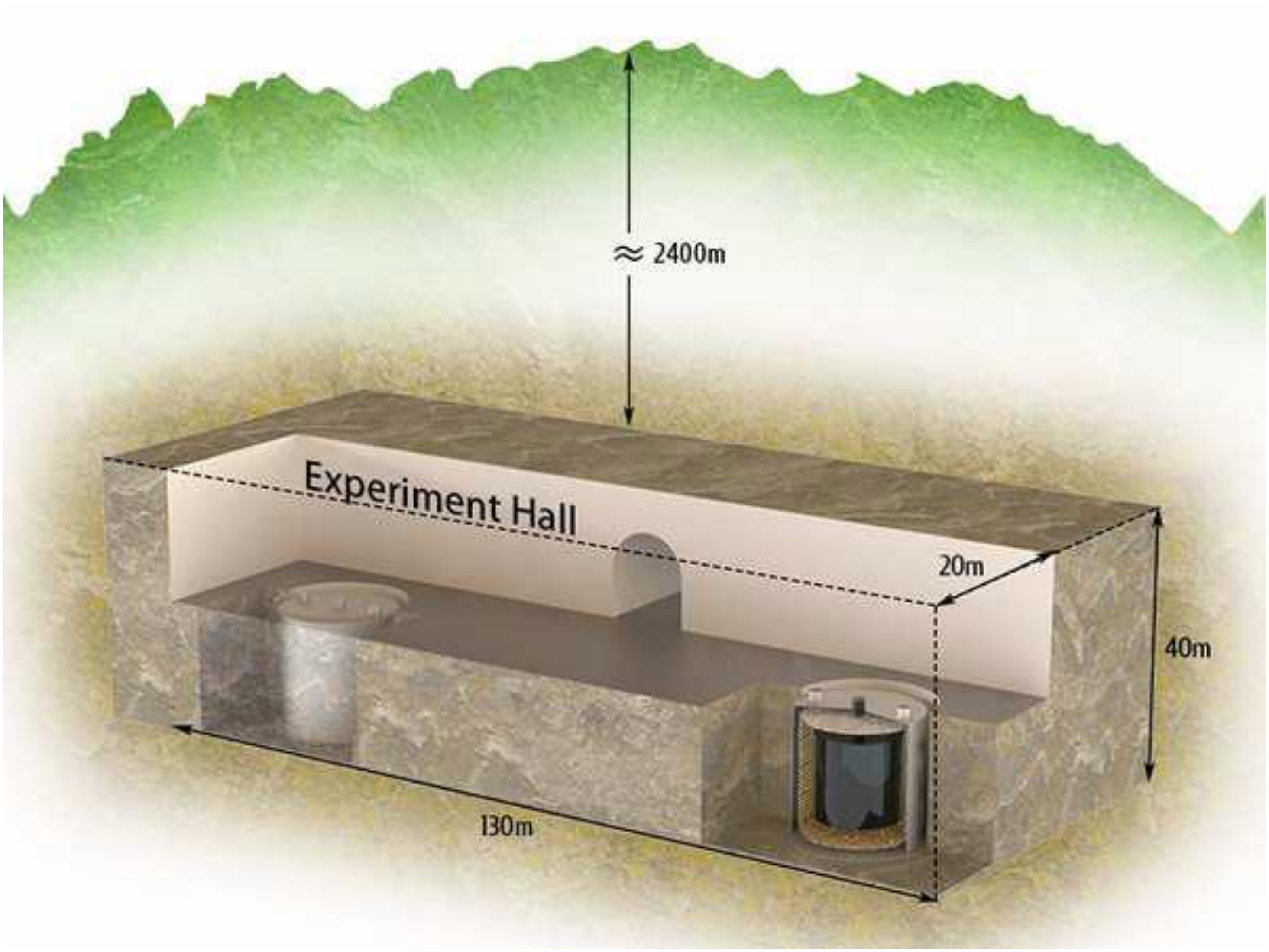
Jinping Underground Lab



Low Background at CJPL

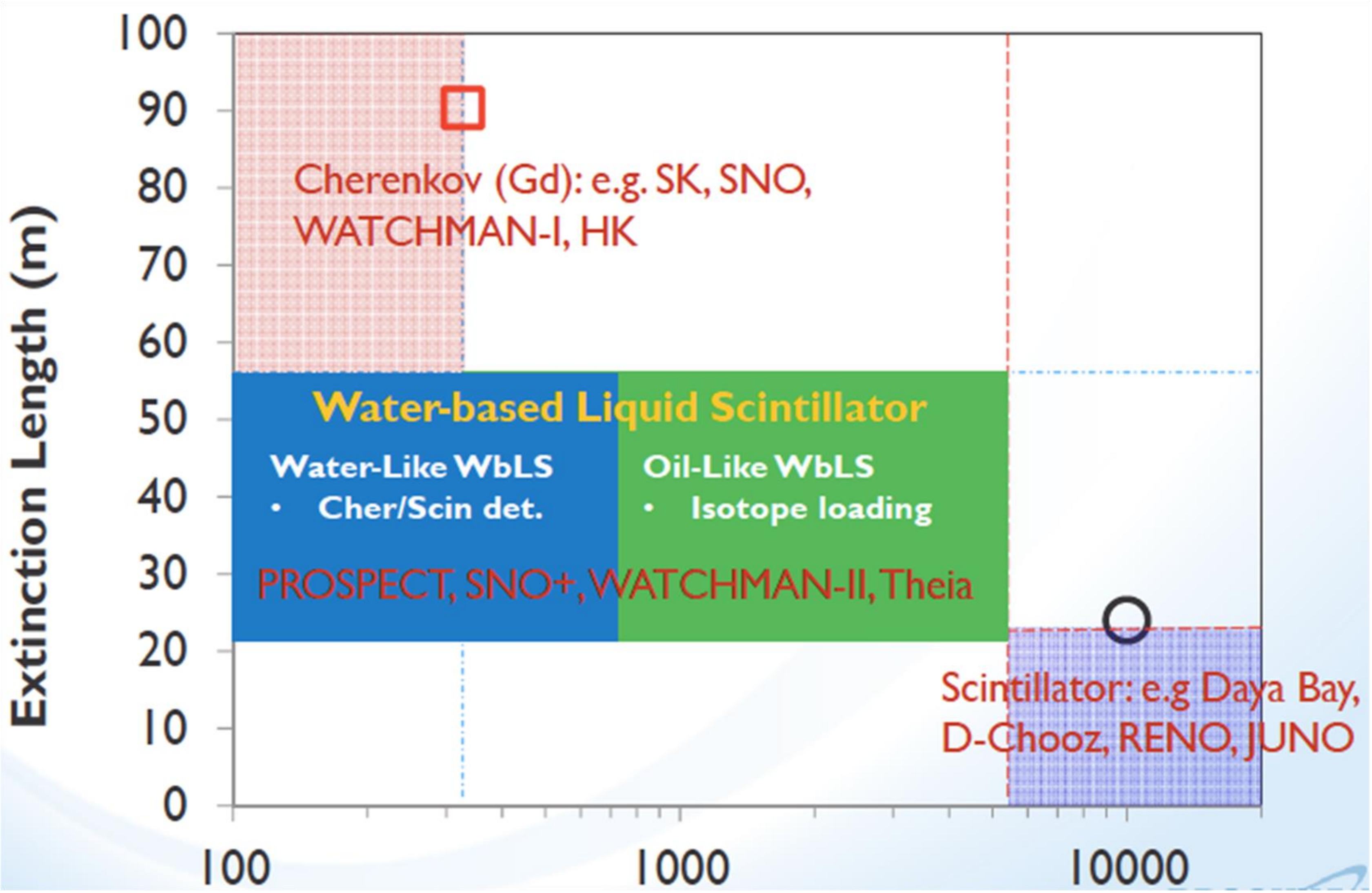


Plan to build two kton detectors

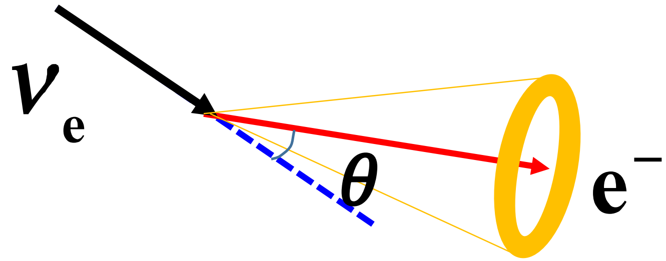


Cavities under construction

With slow liquid scintillator

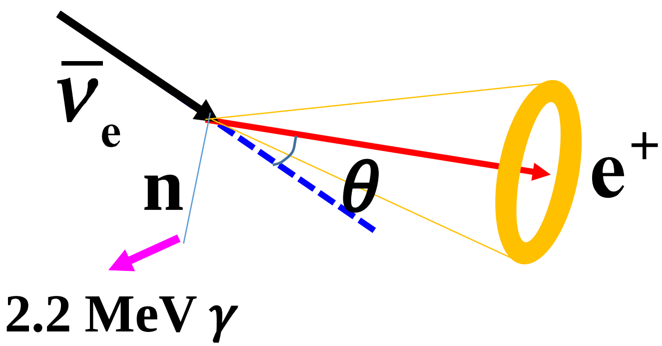


Photons/MeV

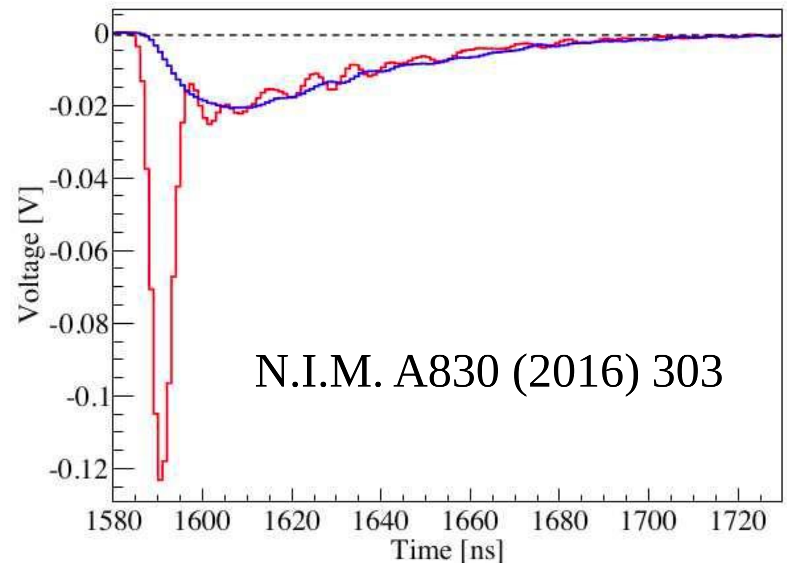


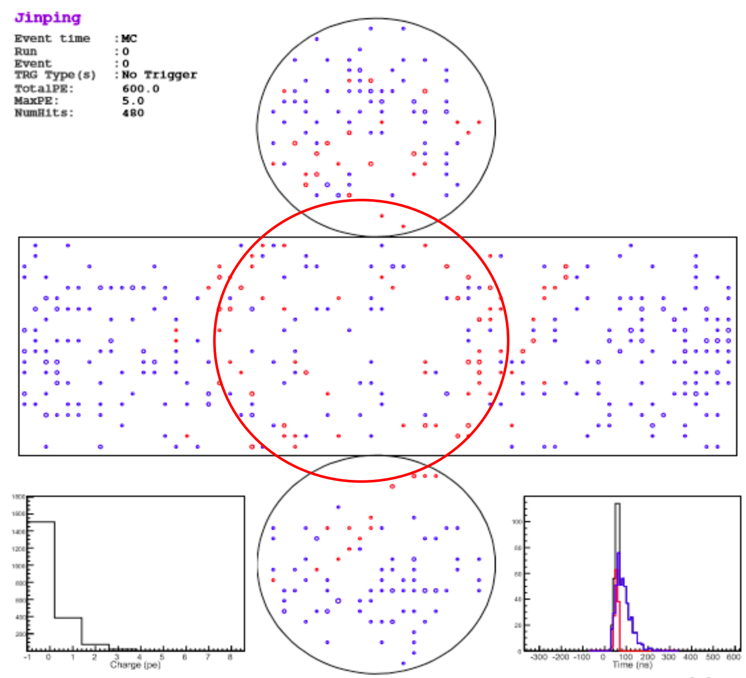
$$\cos\theta = \frac{1 + m_e / E_{\nu_e}}{\sqrt{1 + 2m_e / T_e}},$$

$$T_e^{\max} = \frac{E_{\nu_e}}{1 + m_e / 2E_{\nu_e}}$$

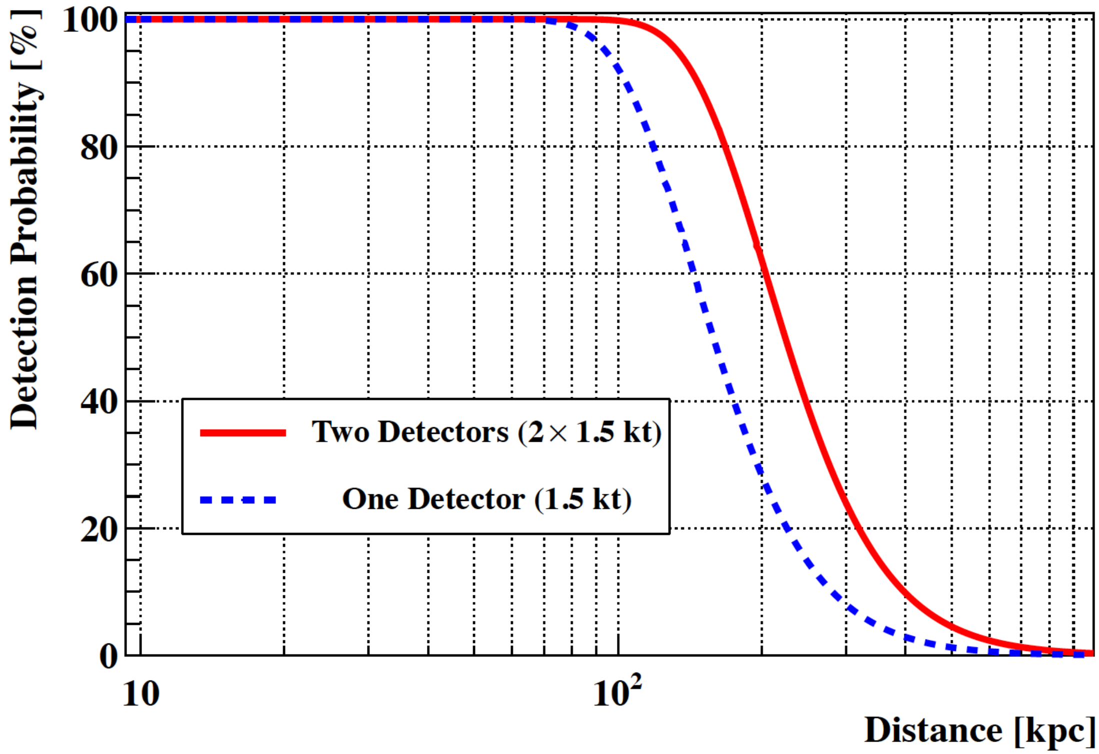


$$E_{\bar{\nu}_e} = T_e + 1.8\,\text{MeV}$$





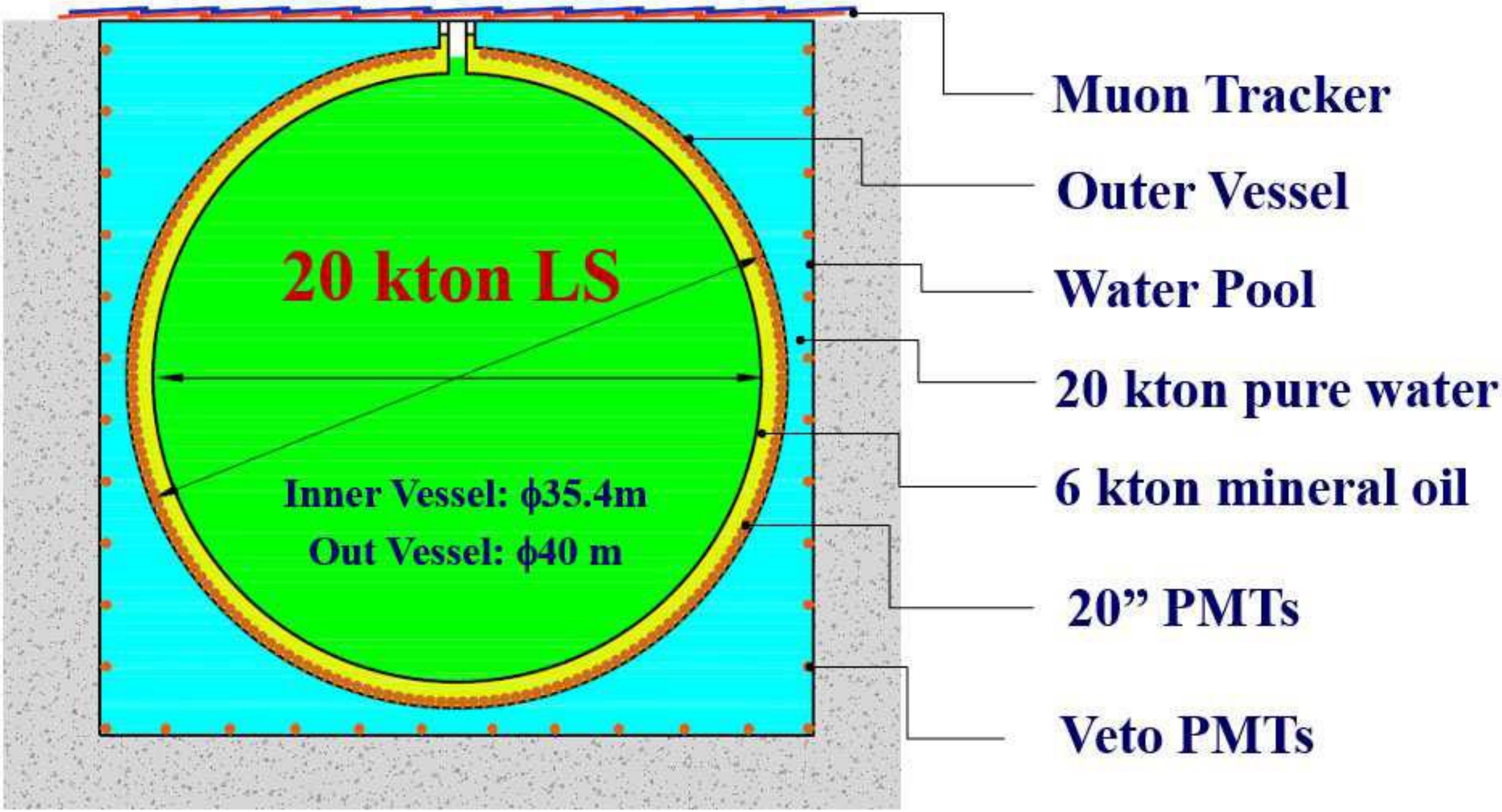
Expected sensitivity



Kilo-ton detector @Jinping 100% detection probability within 100 kpc comparable to Super-K

Clean measurement of supernova burst neutrinos ~1000 (3 kt LS) SNν @10kpc

JUNO Experiment



20 kton LS
Inner Vessel: ϕ35.4m
Out Vessel: ϕ40 m
Muon Tracker
Outer Vessel
Water Pool
20 kton pure water
6 kton mineral oil
20” PMTs
Veto PMTs

Summary

- **Experimentally, we have tried our best to search SN in either WC or LS detectors. No signal has been observed yet.**
- **Next phase of experiments are aiming at increasing target mass, adding neutron tagging and improving/providing both directional and energy measurements.**
- **For few tens of MeV neutrinos, we are still working on getting correct neutrino energy.**

Thanks!