Core-collapse SN, the contribution from Underground Laboratories

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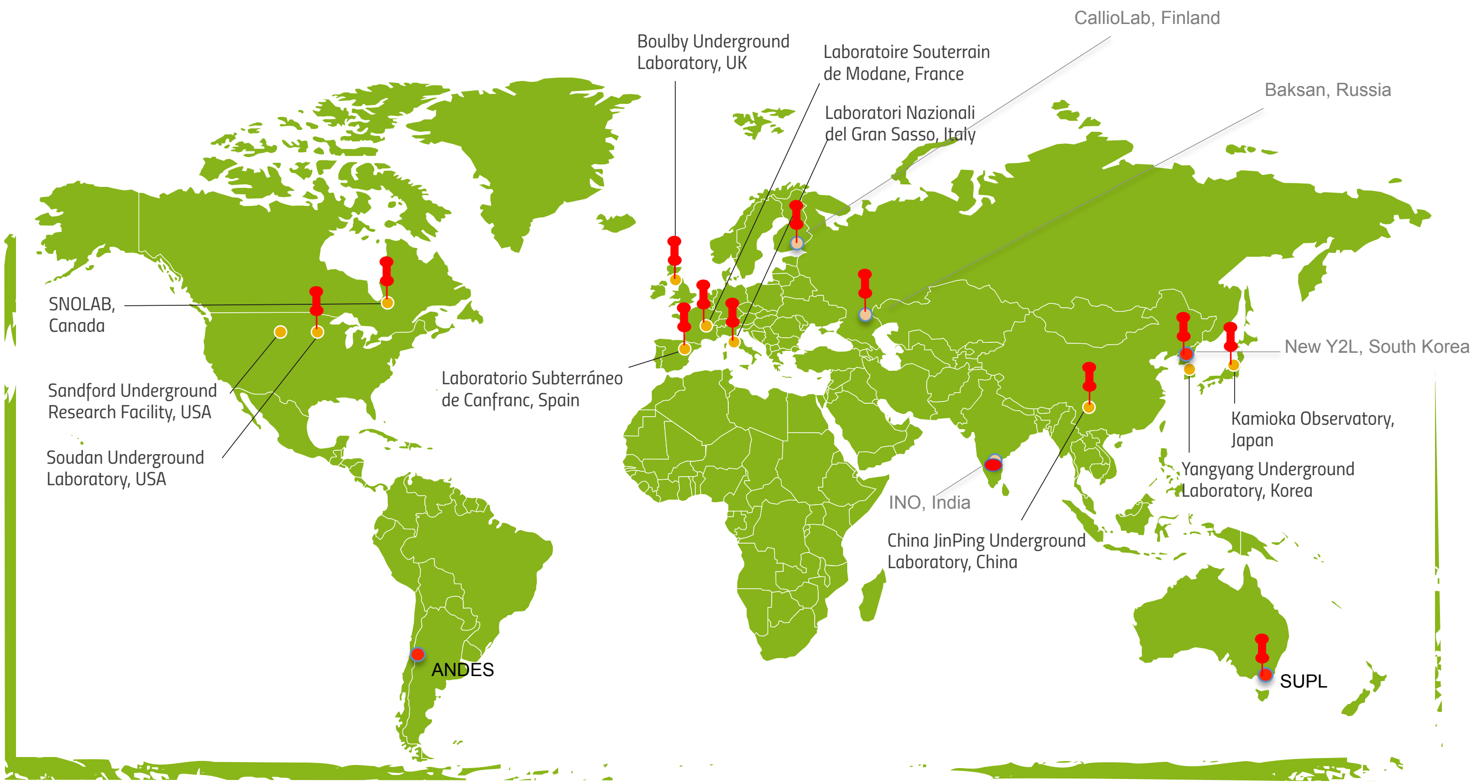
Multi-messenger Astrophysics Workshop

EGO, Pisa, 11th Oct. 2022

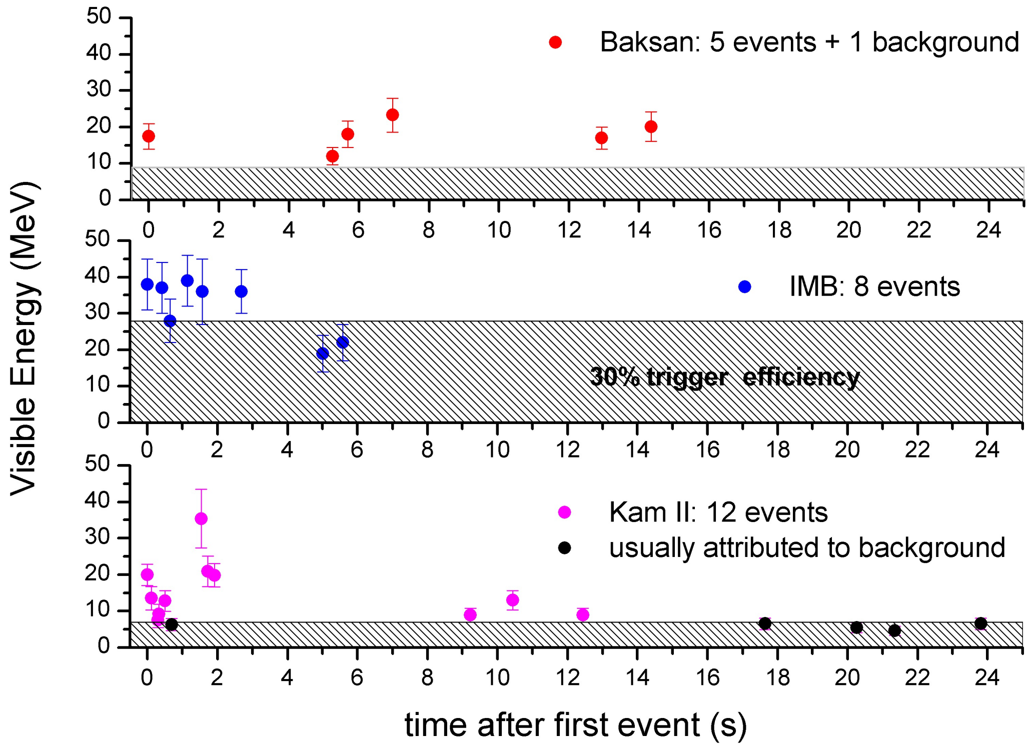
Map of Underground Labs

13 operating infrastructures
Plenty of experiments on DM, DBD, and neutrino physics



SN1987A: 1st SN ν observation

- 23rd Feb 1987
- ~ 50 kpc
- Only 29 events
  - 16 Kamiokande (Cherenkov)
  - 8 IMB (Cherenkov)
  - 5 Baksan (LS)



Estimation of the binding energy and neutrino energy from SN1987A

- Consider:
  - 12 neutrino observed in Kamiokande in 10^3 tons of water
  - $\langle E_\nu \rangle \sim 10$ MeV

$$12 = N_{\text{target}} \cdot F_\nu \cdot \sigma$$

$$\sigma \approx 9.3 \cdot 10^{-42}\ \text{cm}^2$$

$$N_{\text{target}} = 6.7 \cdot 10^{31}$$

$$E_B \equiv \Delta E \approx \frac{3}{5} G \frac{M_{NS}^2}{R_{NS}} \sim 2 \cdot 10^{53} erg \left(\frac{M_{NS}}{M_{Sun}} \right)^2 \left(\frac{10km}{R_{NS}} \right)$$

$$N_\nu = F_\nu \left(4\pi D^2 \right) = 5.7 \cdot 10^{57}\ \bar{\nu}_e$$

$$E_b = \langle E_\nu \rangle N_\nu = 5.7 \cdot 10^{58}\ \text{MeV} \approx 10^{53}\ \text{ergs for}\ \bar{\nu}_e$$

The Supernova model

$$F^0_{\nu_i}(E_\nu) = \frac{Es}{4\pi d^2}\left(\frac{E_\nu}{E_{0,i}}\right)^\alpha \frac{(\alpha+1)^{\alpha+2}}{E^2_{0,i}} \frac{e^{-(\alpha+1)E/E_{0,i}}}{\Gamma(\alpha+2)} \ \mathrm{cm^{-2}MeV^{-1}}$$

$$E_{0,i} = T_i(\alpha+1)$$

$$\alpha = 3$$

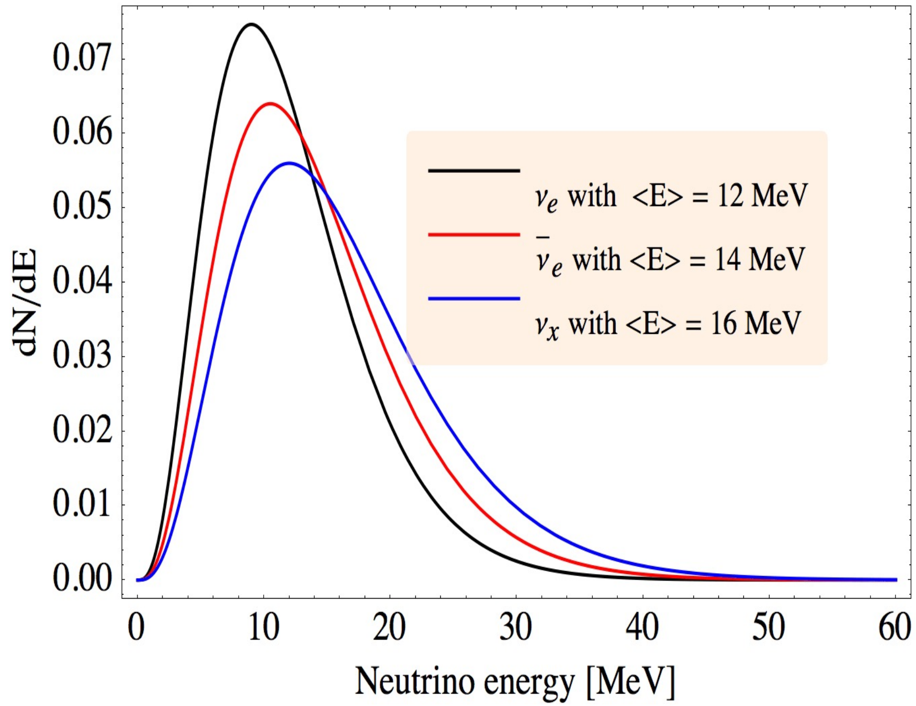
$$d = 10 \text{ kpc}$$

$$\sum_i 4\pi d^2 \int dE_\nu E_\nu F_{\nu_i}(E_\nu) = 3\cdot 10^{53} \text{ erg}$$

$$\mathrm{N}_{\nu,i} = 4\pi d^2 \int dE_\nu F_{\nu_i}(E_\nu) = \begin{cases} N_{\nu_e} = 2.6\cdot 10^{57} \\ N_{\bar{\nu}_e} = 2.2\cdot 10^{57} \\ N_{\nu_x} = 7.8\cdot 10^{57} \end{cases}$$

$F^{Tot}_\nu = 1.1\cdot 10^{12}\ \mathrm{cm^{-2}}$ @ 10 kpc

SN Signal duration ~ O(10) s

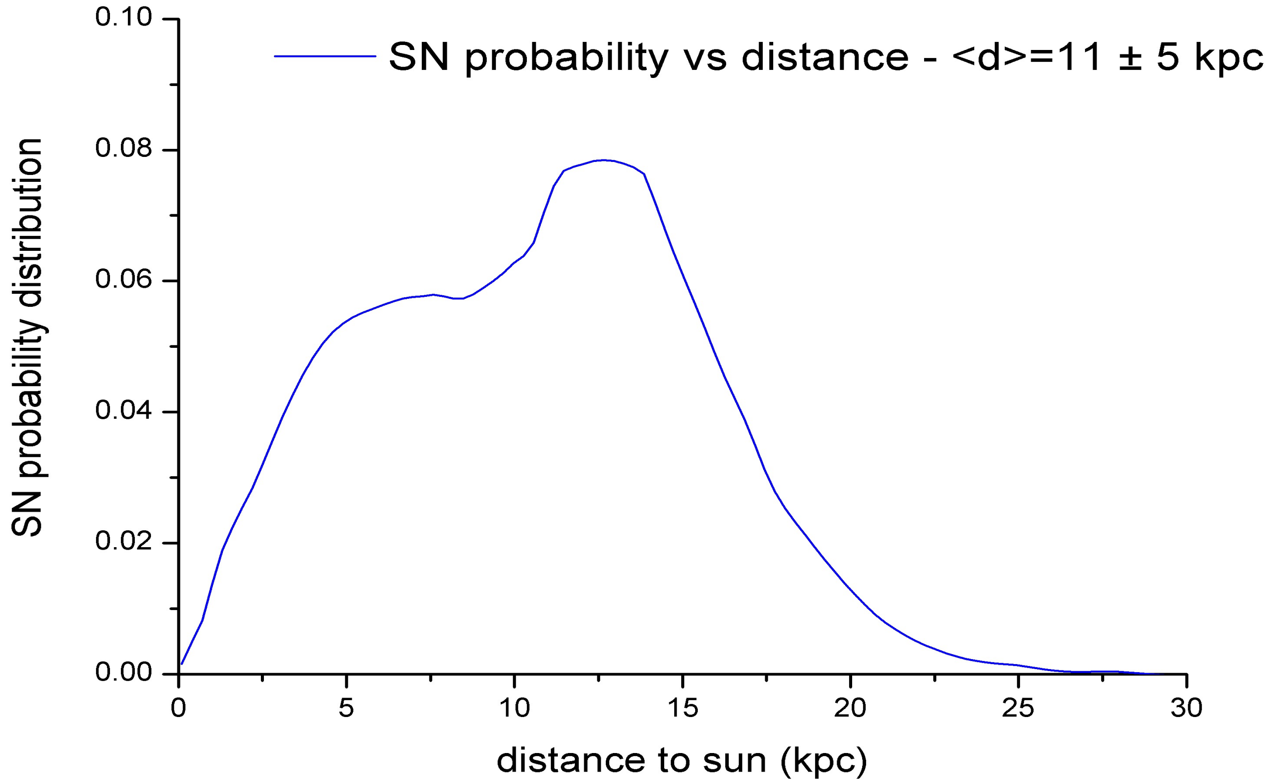


Average energy expected to change as:
ν_e : ~12-14 MeV
bar-ν_e : ~14-16 MeV
ν_x : ~14-16 MeV

SN neutrinos and neutrino oscillations

- Assume $2\phi_x = \phi_{\nu\mu} + \phi_{\nu\tau}$
- $\phi_{\nu_e} = P_{ee}\,\phi^0_{\nu_e} + (1 - P_{ee})\phi^0_{\nu_x}$
- $2\phi_{\nu_x} = (1 - P_{ee})\phi^0_{\nu_e} + (1 + P_{ee})\phi^0_{\nu_x}$
- $2\phi_{\nu_x} + \phi_{\nu_e} = 2\phi^0_{\nu_x} + \phi^0_{\nu_e}$
- Pee depends on mass ordering and particle anti-particle nature

Probability of a galactic SN vs distance to the Sun



Mirizzi, Raffelt and Serpico, JCAP 0605,012(2006)

Underground Laboratories and SN neutrinos

ULs offer a unique opportunity to detect SN neutrinos by different and complementary techniques

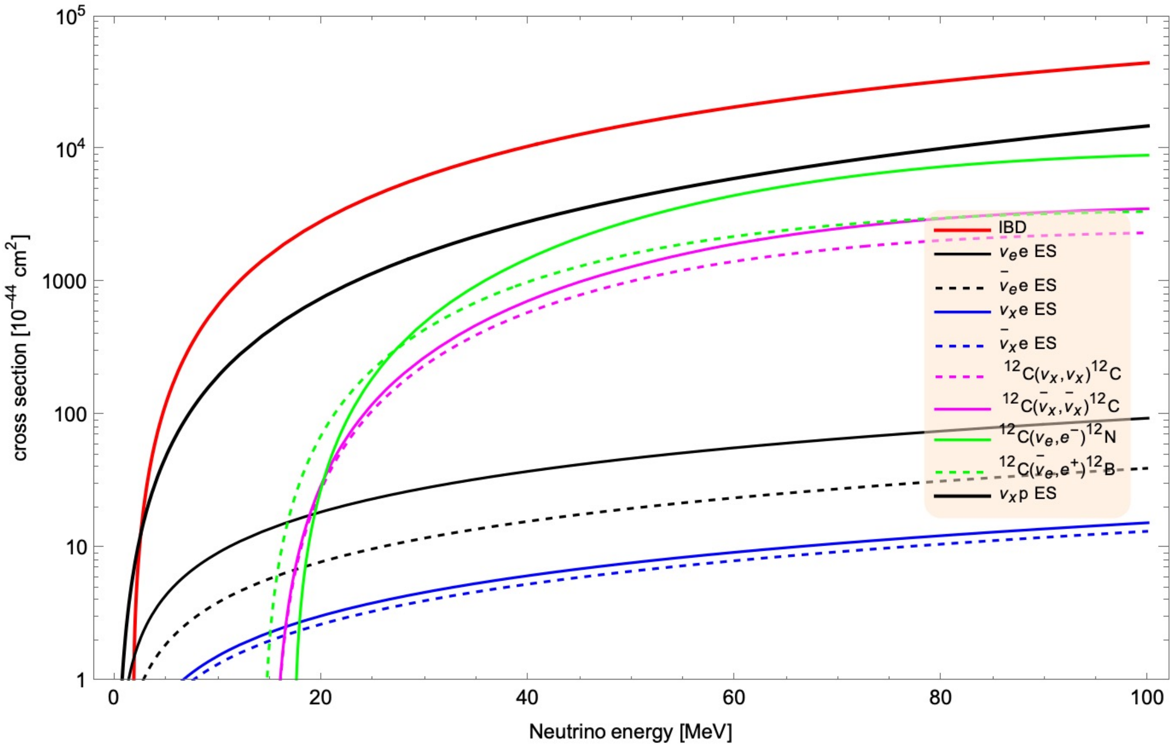
- Core-collapse SN emits different cosmic messengers: **neutrinos**, gravitational wave, electromagnetic emission and cosmic rays in a late stage
- Neutrinos are a unique probe to trigger multi-messengers observation/correlation
- Present sensitivity goes beyond Milky Way edge
- **Rare event: ~ 1.6 /century**

- Detectors
  - Liquid scintillators (LS) such as LVD, Borexino, KamLAND, Juno, SNO+, others in CJPG and Yemilab
  - Water Cherenkov such as SNO, SuperKamiokande, Hyper-Kamiokande
  - LXe and LAr detectors such as LZ, XENONnT,XMASS, DarkSide-20k, DUNE
  - IceCube and Km3NET

Liquid Scintillators

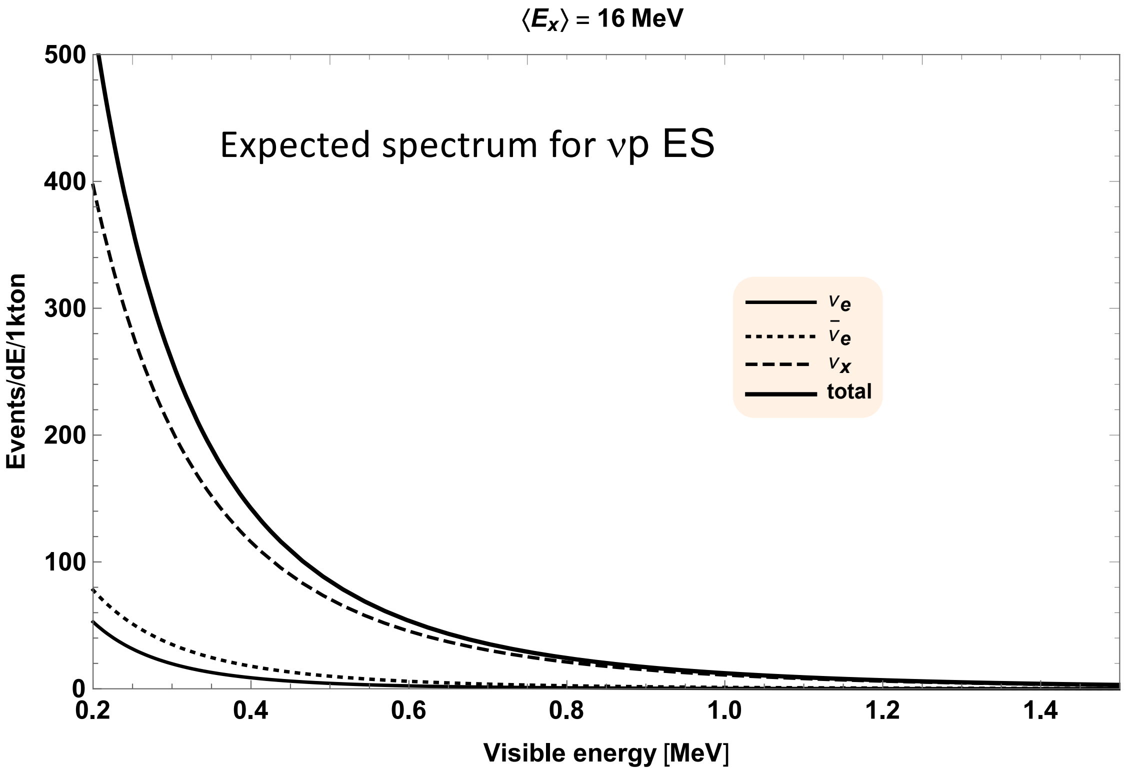
- SN at 10 kpc with $E_b = 3 \times 10^{53}$ erg
- Main detection channel IBD
  - ~ 200 events/kton
- ES ~ 20 events/kton above 200 keV
- CC on ^{12}C ~ 15 events/kton
- Neutrino-proton ES ~ 100 events/kton above 200 keV

Cross sections in LS detectors



Neutrino-proton ES

- A unique opportunity for NC interactions
- Need sensitivity to low visible energy (<1 MeV) due to quenching effect
- ~80% of the signal above 200 keV thereshold is due to ν_x's
- crucial to disentangle the average energy of ν_x neutrinos



Water Cherenkov detectors

- Main detection channel is IBD
- ES sub-dominant but with pointing capability
- CC on ^{16}O for ν_e
- 10 kpc SN in Super-Kamiokande gives about 5^0 pointing accuracy, this improves to about 3^0 with Gd (better IBD selection, so isolate ES events). With Hyper-Kamiokande expected 1^0 accuracy

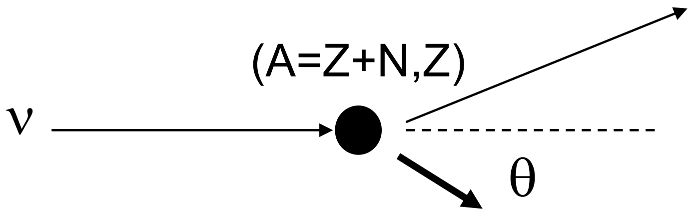
Super-Kamiokande

- Water Cherenkov with 22.5 kt fiducial mass
- Energy threshold 7 MeV
- Golden signal with a cluster of ≥60 candidates in 20s
- Main signal from IBD with ~10^4 events for 10 kpc SN
- Other channels:
  - ES (directionality)
  - ν_e capture on ^{16}O
- Gd loading enhances IBD detection opening new opportunities
  - Pointing
  - Pre-supernova alert

- Recently the horizon became larger

- Observation of neutrino-nucleus coherent scattering
    - COHERENT Collaboration, Science, Aug. 3, 2017

Coherent neutrino-nucleus elastic scattering



$$\frac{d\sigma}{dE_r} = \frac{G_F^2}{4\pi} Q_W^2 M \left(1 - \frac{ME_r}{2E_\nu^2}\right) F^2\left(Q^2\right)$$

$$Q^2 = 2E_\nu^2\left(1-\cos\theta\right)$$

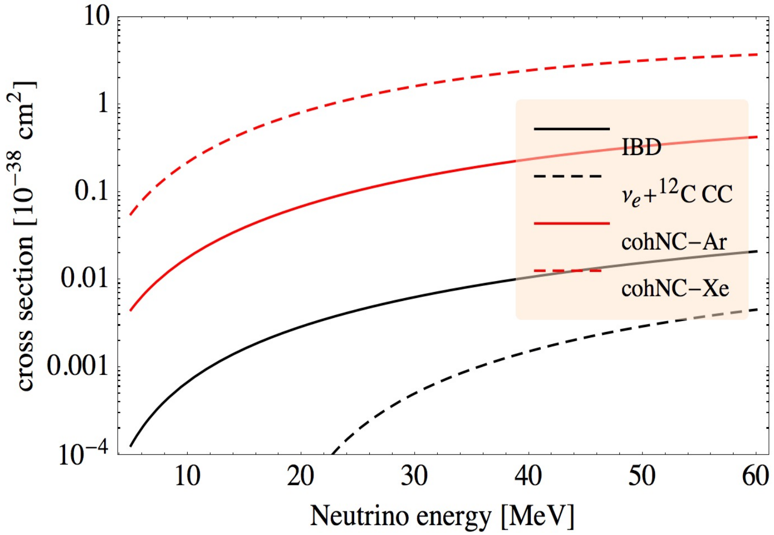
$$Q_W = \left(1 - 4\sin^2\theta_W\right)Z - N$$

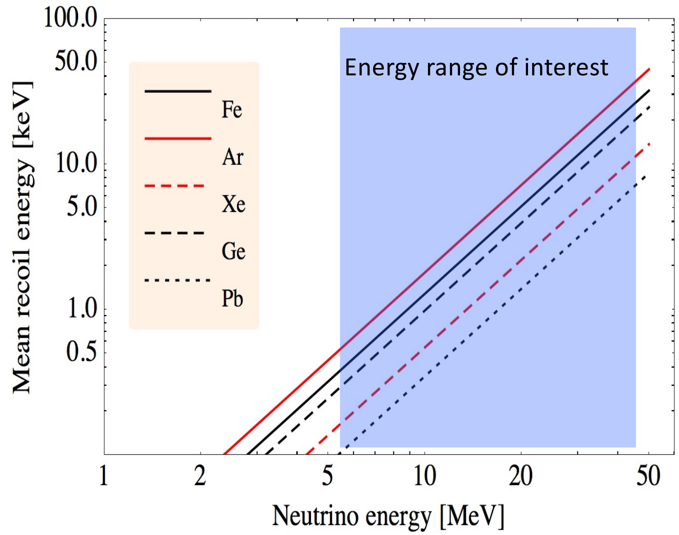
$$\sigma = \frac{G_F^2}{4\pi} Q_W^2 E_\nu^2 \approx 4.215\times10^{-45} Q_W^2 \left(\frac{E_\nu}{\text{MeV}}\right)^2 \text{cm}^2 \approx 4.215\times10^{-45} N^2 \left(\frac{E_\nu}{\text{MeV}}\right)^2 \text{cm}^2$$

Condition of coherence

$$Q\left(E_\nu\right)\cdot\left(r_0 A^{1/3}\right) \le 1$$

CohNS vs IBD and CC ν interactions





Trade off between

1. large A for larger σ
2. low A for larger recoil energy

Basic requirement to detect cohNS

$$\sigma \approx 2.539 \times 10^{-18} \frac{N^2}{A} \left(\frac{E_\nu}{MeV} \right)^2 \ \mathrm{cm}^2 / kg$$

For the sake of the discussion:
E_ν = 15 MeV and $\phi_\nu = 10^{12}\ \mathrm{cm}^{-2}$

Target	Mean recoil energy [keV]	Number of events [ton^{-1}]
Si	5.7	4.0
Ne	8.0	2.9
Na	7.0	3.6
Ge	2.2	13.0
Ar	4.0	6.9
Xe	1.2	26.0
Te	1.3	25.6
Cs	1.2	26.1
I	1.2	24.6

Dark Matter Detectors to the rescue

✓Designed

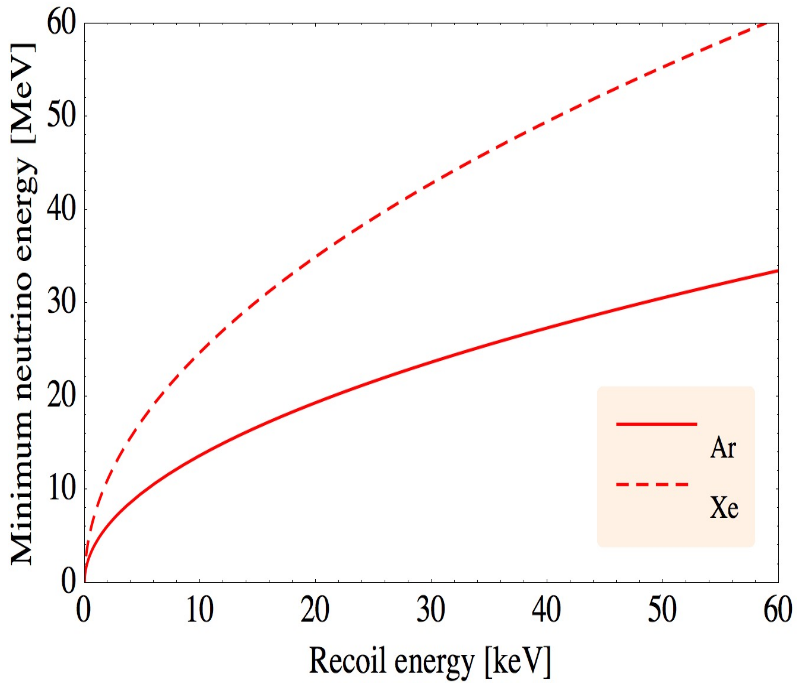
- to detected low energy nuclear recoils (< 100 keV)
- to have high discrimination power between Electron Recoils (ER) and Nuclear Recoils (NR)
- to have intrinsic low background due to the radio-purity of selected detector components
- To have good fiducial mass determination

✓Look ideal for cohNS measurement and SN neutrino observation

SN signal in Ar and Xe

$$\frac{dN}{dE_r} = C \int_{E_{\min}(E_r)}^{\infty} dE_r \frac{d\sigma}{dE_r}(E_\nu, E_r) \sum_{i=\nu_e,\bar{\nu}_e,4\nu_x} F^0_{\nu_i}(E_\nu)$$

Threshold [keV]	Ar [events/ton]	Xe [events/ton]
0	7.4 ±20%	26.2 ±20%
5	3.9	4.0
10	2.3	1.0
20	1.0	0.09



Signal gets reduced due to smearing from detection efficiency
For LXe ~x5 reduction

Massive LAr and LXe detectors

- Joining the underground network of detectors to probe for core-collapse SN neutrinos
- Considering efforts made to search for DM and neutrinos these detectors become crucials for some ULs
- Main detectors using LXe and LAr for DM direct detection
  - LZ at SURF: ~ 360 events/7 t LXe for 10 kpc SN from ν-nucleus coherent ES
  - XENONnT at LNGS: ~ 100 events with 700 t Water Cherenkov veto IBD; ~300 events from ν-nucleus coherent ES
- To massive LAr detectors belongs DUNE
  - 4 x 10 kt detectors
  - Special CC channel: $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$ (E>1.5 MeV), order of 2×10^3 events
  - Other channels: ES, NC, bar- $\nu_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*$
  - Absence of photons from de-excitation to distinguish ES (about 300 events)
  - DUNE TPC can also exploit directionality on ES at about 5^0

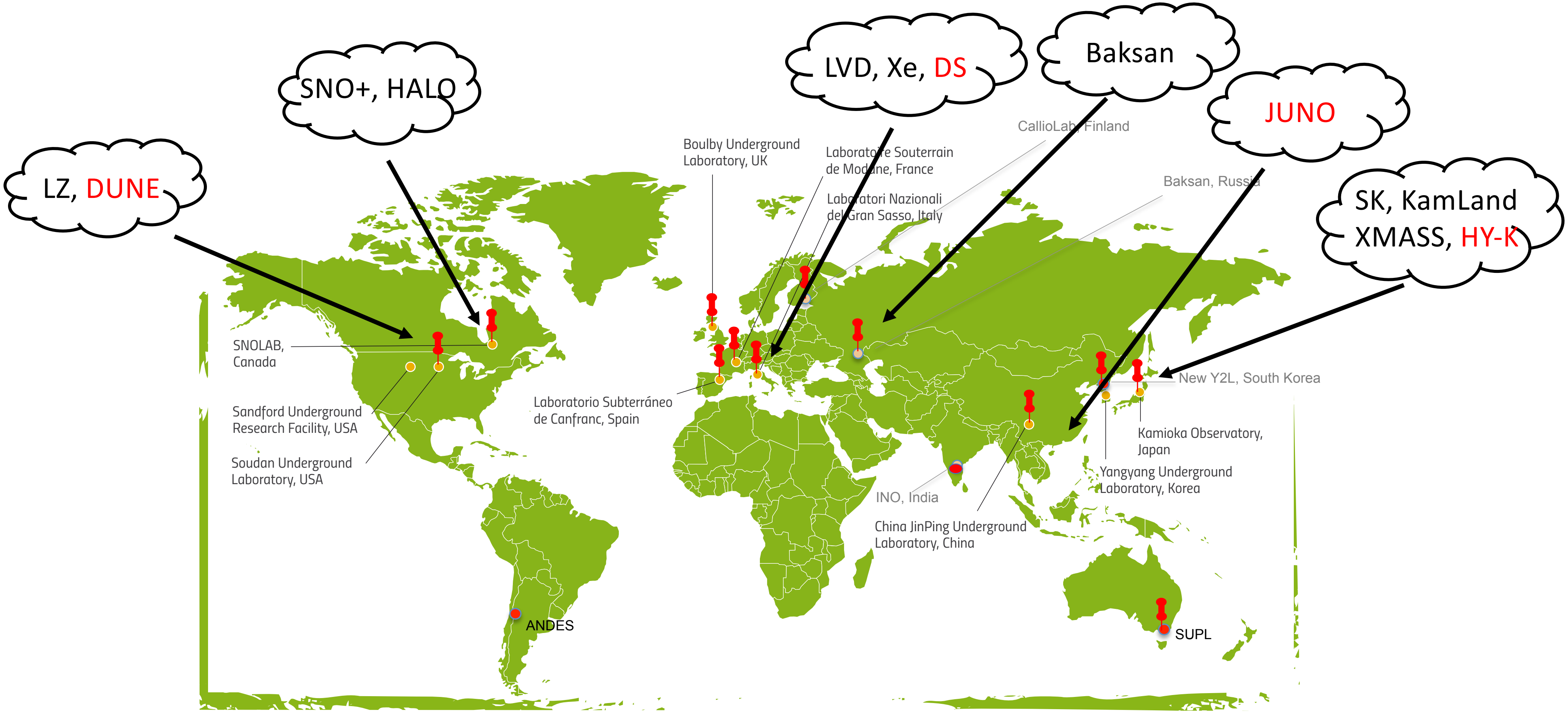
More opportunities

- HALO at SNOlab with Pb target mass and ^3H counters
  - SN neutrinos will produce CC and NC on Pb
  - Neutrons in final stage detected by counters

- CC on ^{13}C in organic LS
  - 1% abundance
  - Large cross section
  - Specific for ν_e

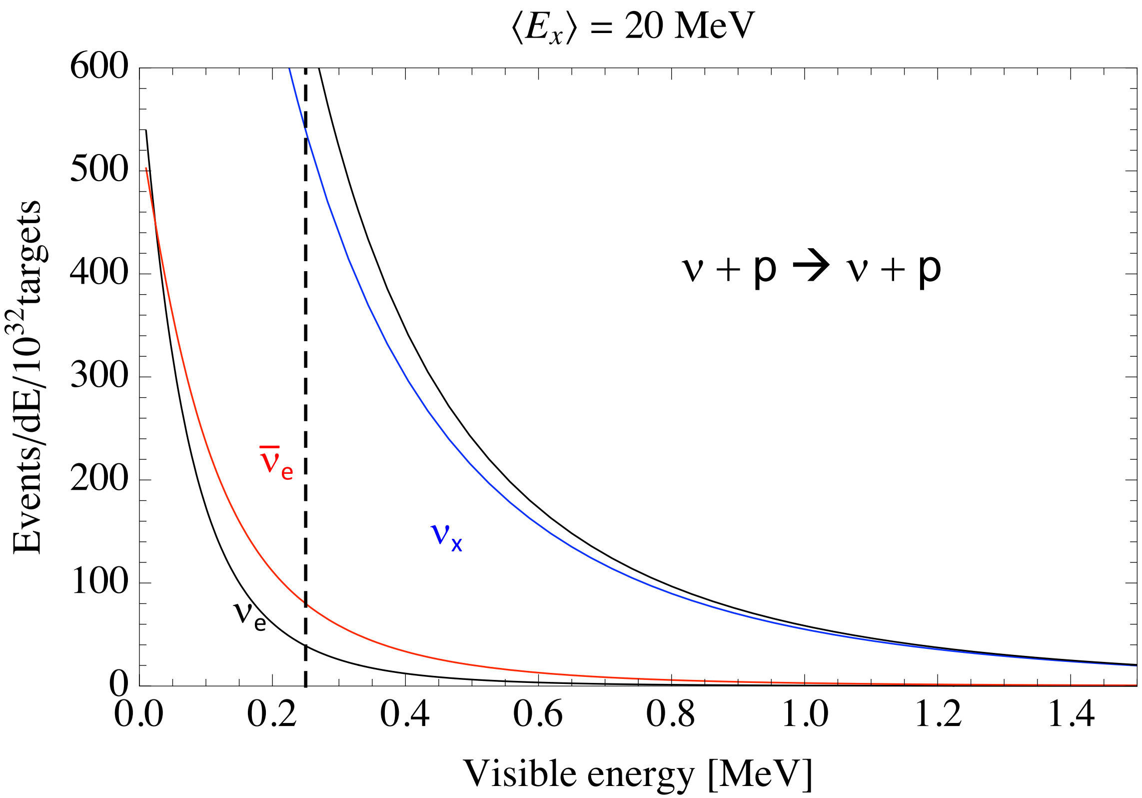
- CC on ^{56}Fe in LVD tanks
  - Large cross section
  - Specific for ν_e

Map of Underground Labs: SN detectors



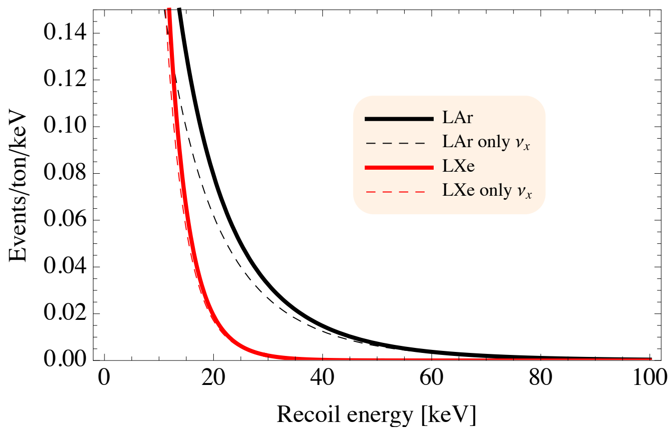
- IBD «golden» channel with Super-Kamiokande leading the field
    - electron anti-neutrino observation
- Future massive LAr detectors to probe electron neutrinos in CC interactions
- A second «golden» channel is coherent neutrino-proton scattering

Neutrino-proton ES and the Supernova



Exploit cohNS with a SN: main feature

The measured number of events has a typical NC degeneracy problem



$$N_{events} \propto \langle \sigma \rangle \frac{E_{binding\_x}}{\langle E_x \rangle}$$

Due to the fact that the cohNC spectrum is mainly from ν_x above threshold, by measuring the spectrum we break the degeneracy between $\langle E_x \rangle$ and $E_{binding\_x}$.

This was pointed out by J. Beacom et al. for the ν-p elastic scattering in organic liquid scintillators in 2002

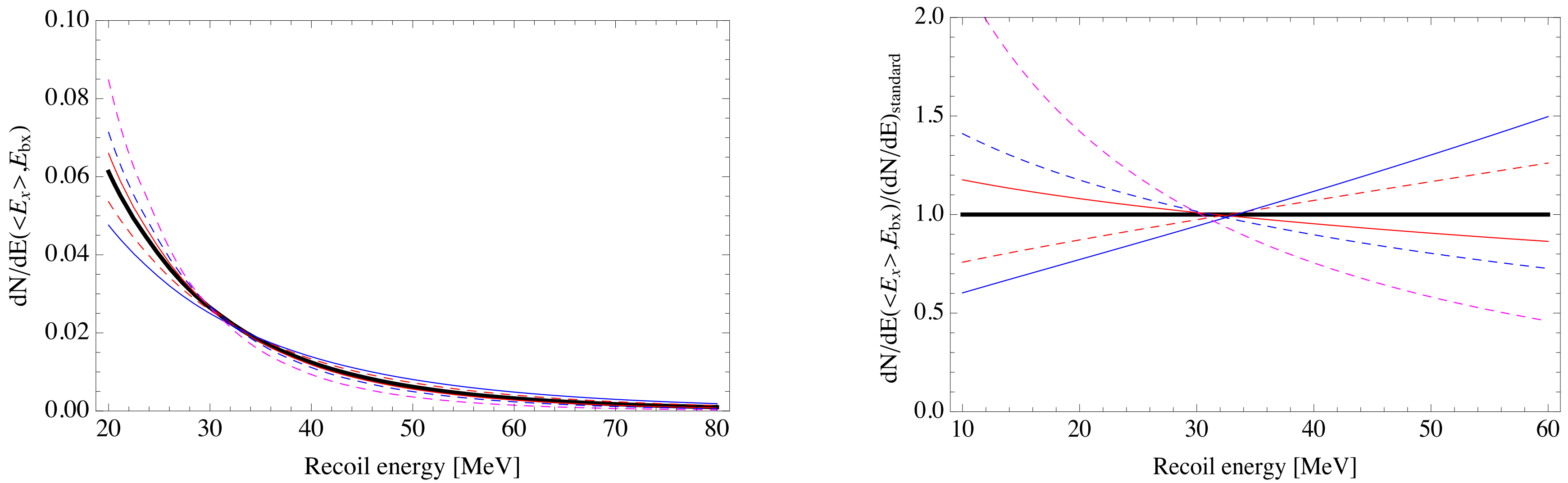
Breaking <E_x> and E_{b_x} degeneracy

Reference SN: E_x=16 MeV; $E_{b\text{-}x}$=0.5x10^{52}erg (total energy is 10^{53} erg)

LAr with ROI = [20,80] keVr

Select different E_x and E_{bx} to give the same number of events above threshold

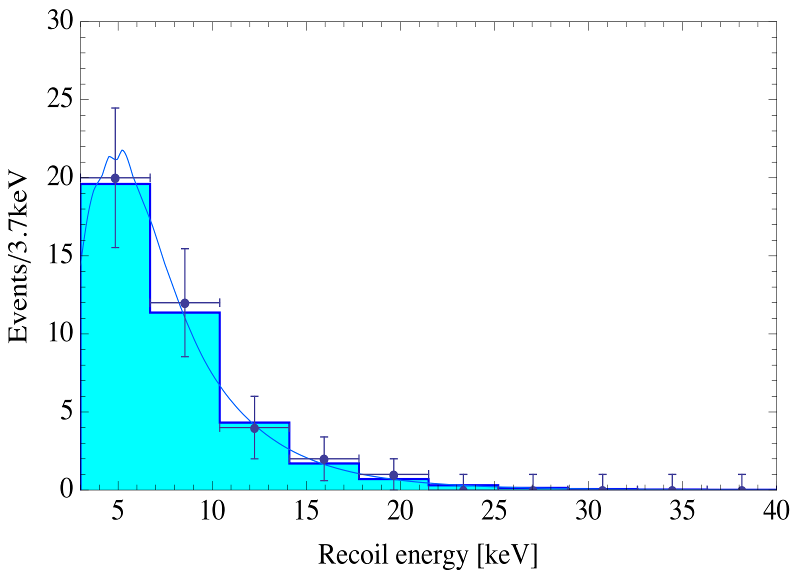
E_x changing from 12 to 20 MeV

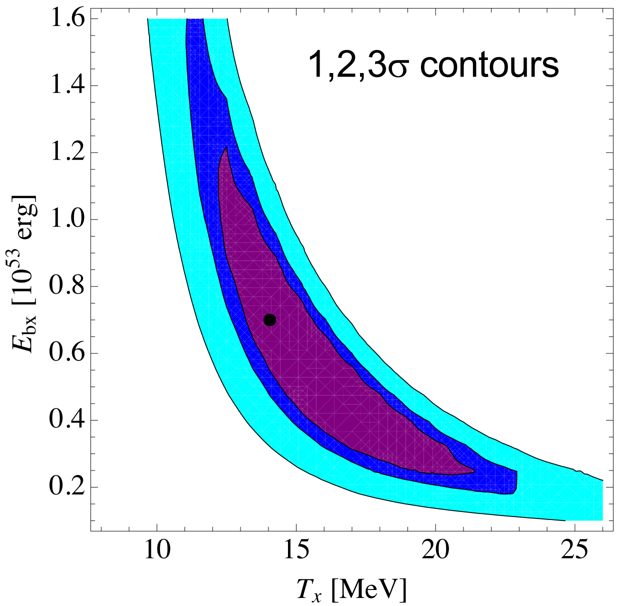


Probe SN parameters

Standard NR selection in LXe above 3 keVr with 10 tons of LXe

Testing a measured energy spectrum



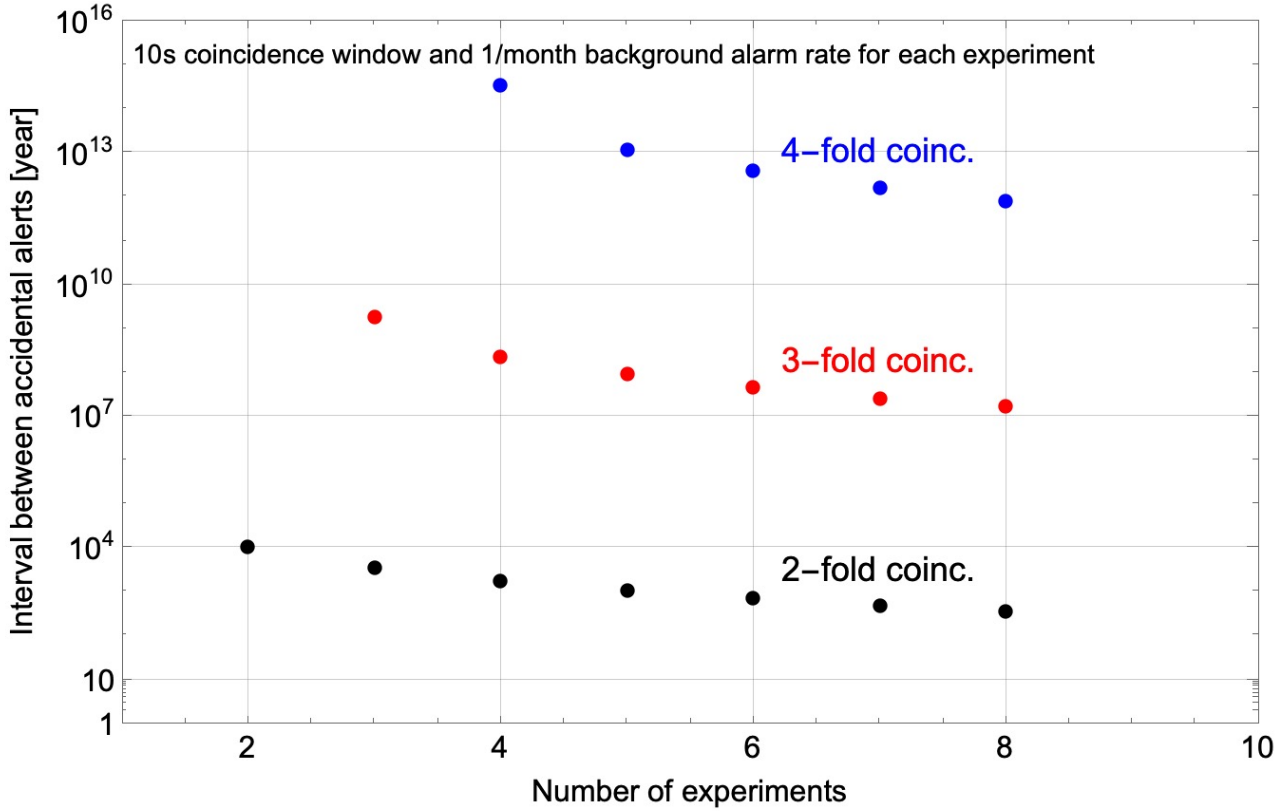


Pre-supernova neutrinos

- Emitted before collapse begins: O(180 days) and Si(2 days) burning
- Neutrino produced by fusion reactions, electron-positron annihilation
- Only ~1% of core-collapse event
  - at the same detection sensitivity, SN distance reduced x10
  - closer stars such as Betelgeuse and Antares can be observed
- << 10 MeV energy, peaked at a few MeV
  - O burning: ~ 1 MeV
  - Si burning: ~ 2 MeV
  - detection more challenging, more background from natural radioactivity
- KamLAND and Super-Kamiokande have implemented an alert for this signal
- Super-Kamiokande with 0.01% Gd has a significant enhanced sensitivity
  - 9 hours before collapse for Betelgeuse
  - NO with x2 events wrt IO
- Large detectors with LAr/LXe could also attempt this observation
- Very important to prepare multi-messenger observation

A netwrok to provide a robust early alert for a SN event

- In each experiment an alert corresponds to a cluster of M events within 10s with specific characteristics
    - E.g.: LVD with backg. = 0.03/s in ROI for M≥10, f_{acc} = 1/100 years
- Intrinsic background rate limits the sensitivity
- A network reduces significantly the false alert rate



Supernova Early Warning System (SNEWS)

- Considering the multi-messenger nature of a core-collapse event
- Considering the low rate of about 1.6/century

  - A network was established SNEWS1.0 (New J. Phys. 6 114, 2004) to provide a prompt, pointing, and positive (3P) alert for a core-collapse event (see Kate Scholberg, AN 329, No. 3, 337-339, 2008)
  - First meeting on this topic in 1998
  - In 2013: LVD, Super-Kamiokande, Borexino, KamLAND, and IceCube
  - In 2015: added HALO and Daya Bay
  - The network is being improved (SNEWS2.0) including new detectors from ULs and enhancing the efficiency, gravitational waves detectors

    (*New J.Phys.* 23 (2021) 3, 031201)

Hyper-Kamiokande

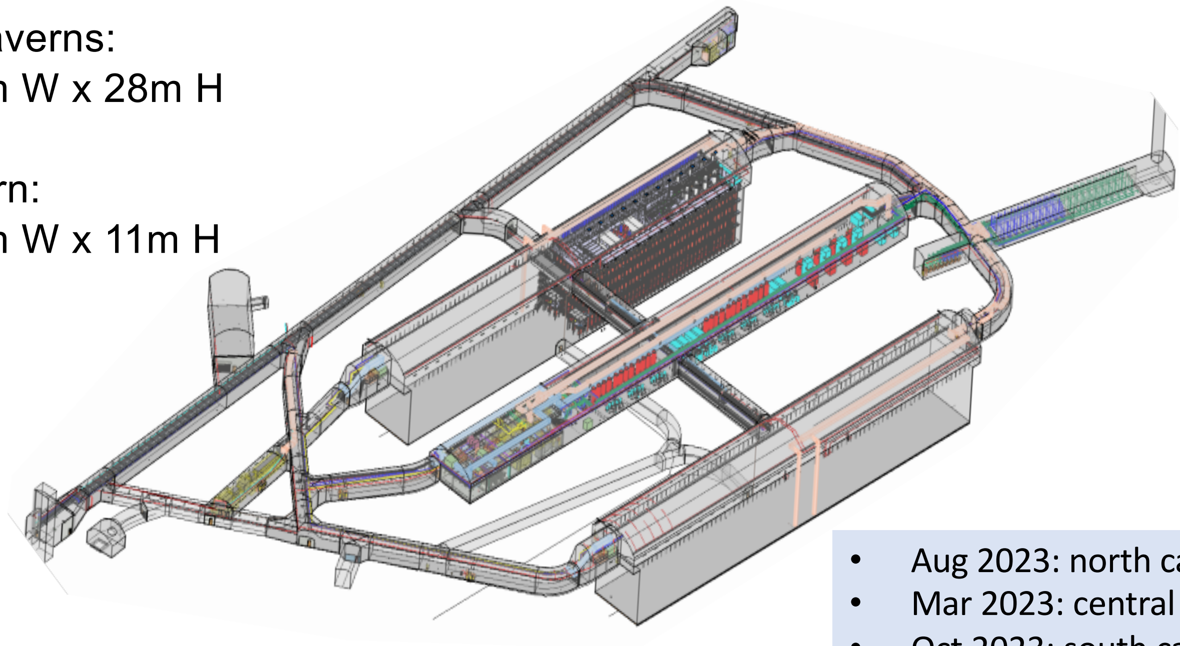
- Water Cherenkov with 217 kt fiducial mass
- For a 10 kpc SN about 10^6 IBD events and 10^3 ES events
- High directionality capability through ES channel
- Tunnel excavation (2 km) started in 2021
- Tunnel reached the center of HK cavern in June 2022
- HK cavern excavation 2022-2024
- Start operation 2027

The center of HK dome, July 2022

Long-baseline neutrino facility @ SURF

2 Detector Caverns:
145m L x 20m W x 28m H

1 Utility Cavern:
190m L x 20m W x 11m H



"Module of Opportunity"
(73m L x 20m W x 28m H)
Temporary use of 50% of one of the LBNF caverns

- Aug 2023: north cavern excavation complete
- Mar 2023: central utility cavern excavation complete
- Oct 2023: south cavern excavation complete
- Mar 2024: all concrete complete
- May 2024: infrastructure outfitting (18 months), cryostat construction (24 months)

Conclusions

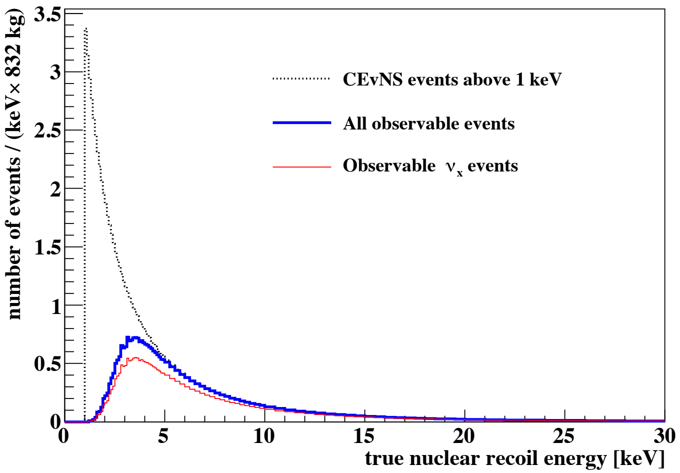
- A core-collapse SN event offers a unique opportunity for a multi-messenger event
- Wrt to 1987 we expect order of x10^3 events with different detection channels
- A network of sensitive detectors is being established to provide an early and robust alert for a core-collapse SN event: SNEWS2.0
- New detectors for DM and neutrino physics being included in the network
- Pointing capability improving significantly
- Crucial pre-supernova signal: challenging but feasible
- Detectors in ULs playing a crucial role to not miss such a unique event

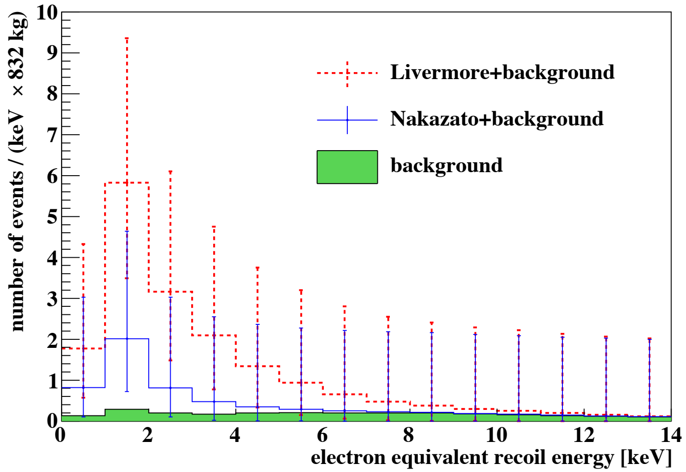
Acknowledgments:

Marco Selvi (XENONnT), Elise McCarthy(LZ), Walter Fulgione (LVD), Jeffrey Tseng (SNEWS), Giulia Pagliaroli (LNGS), Shigetaka Moriyama (Super-Kamiokande)

XMASS as SN detector

XMASS coll., Astrop. Phys. 89, 2017





Only cohNS events with 832 LXe active mass for a 10kpc SN
Number of SN events very much depend on the SN model.
Due to threshold effect XMASS is mainly sensitive to neutrinos above ~ 15 MeV

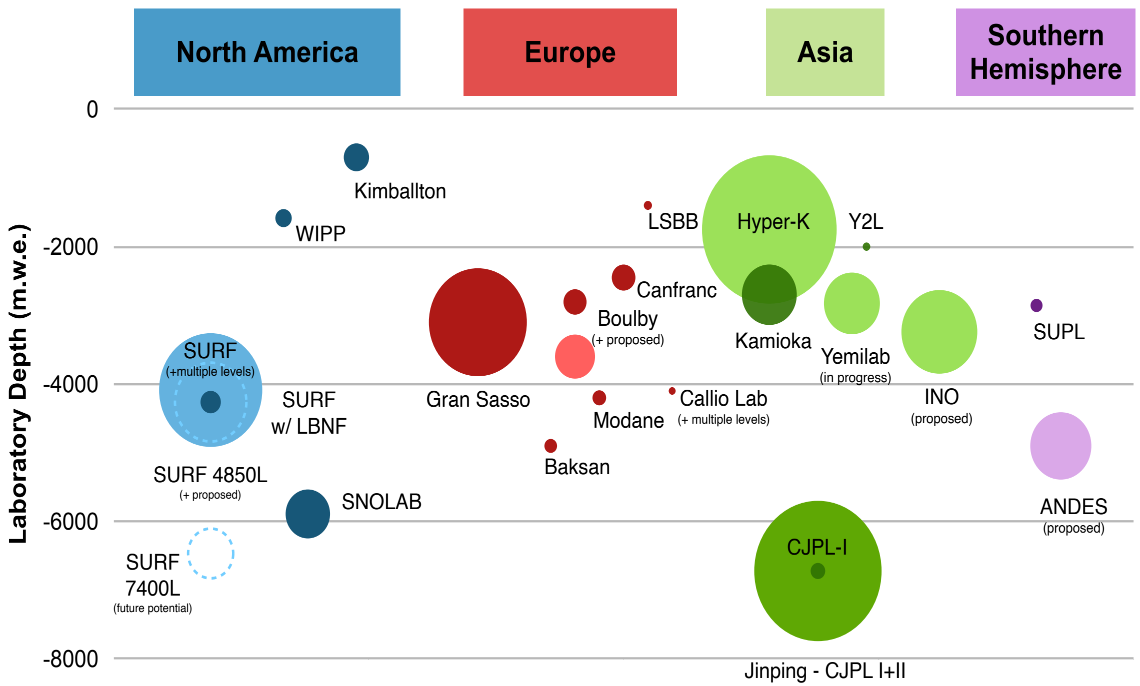
Gold alert

- 2-fold or greater coincidence in 10s depending on number of experiments in the network
- Two experiments at different laboratoriesù
- Rate of false alarms (acc. coinc.) in involved experiments < 1/century
- Gold alert delivered to astronomical comunity

Underground Facilities

UG Facilities can provide:

- Unique environments for multi-disciplinary research
- Local radiation shielding
- Assay capabilities
- Material production/purification
- Environmental control
- Implementation and operations support
- Above-ground and underground support facilities (CR, Rn-free CR, ICP-MS, HPGe, ….)
- Advance training



Note: Circles represent volume of science space

Adapted from Jaret Heise @ Snomass CSS 2022