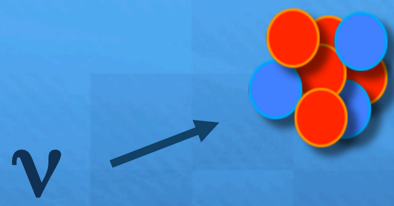
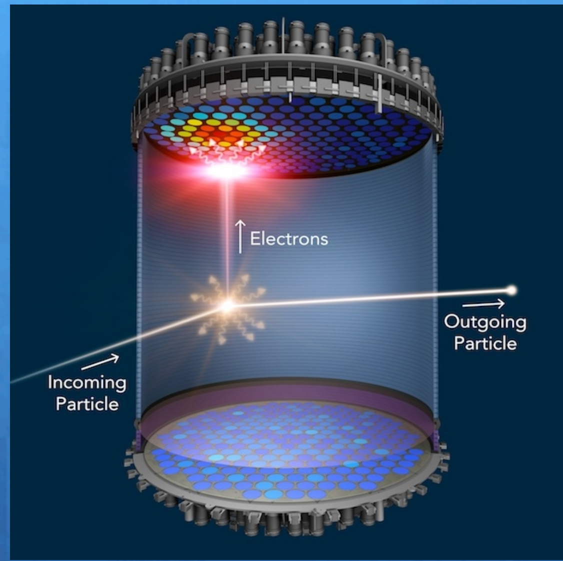




Supernova Neutrino Detection with Dark Matter Experiments

Recent development in neutrino physics and astrophysics
LNGS, Sept. 4-7, 2017

Aldo Ianni, Laboratorio Subterraneo de Canfranc and LNGS

Outline

- Neutrino-Nucleus Coherent Scattering (cohNS) in Dark Matter detectors
- Supernova Neutrinos (SN)
- Detection of Supernova Neutrinos in Xe and Ar using cohNS
- Conslusions

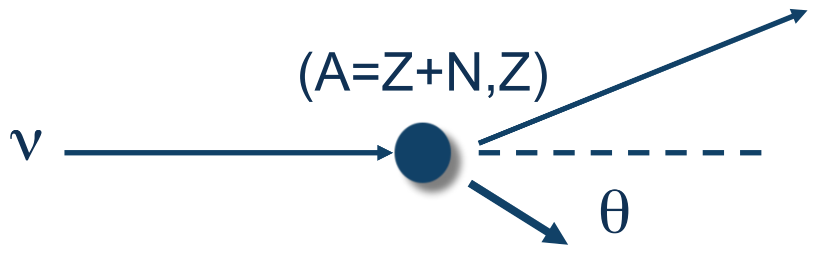
Early literature (not a complete list)

- ✓ D.Z. Freedman, PRD 9, 1977 proposes the cohNS
- ✓ A. Drukier and L. Stodolsky, PRD 30, 1984 propose NC ν-nucleus scattering to detect MeV range neutrinos from
  - spallation sources (ν_μ, bar-ν_μ, ν_e from π^+ and μ^+ decays)
  - reactors and geo-neutrinos (bar-ν_e from β^- decays)
  - solar neutrinos (ν_e)
  - supernova neutrinos (all flavors)
- ✓ M.W. Goodman and E. Witten, PRD 31, 1985 realize that detectors for cohNS can be used to search for DM particles
- ✓ B. Cabrera, L.M. Krauss, F. Wilczek, PRL 55, 1985 propose bolometer detectors to implement ν-nucleus scattering for reactor antineutrinos, solar and supernova ν's
- ✓ ….

Recent literature (not a complete list)

- ✓ J.F. Beacom et al., PRD 66, 2002 discuss neutrino-proton elastic scattering to detect supernova neutrinos
- ✓ C.J. Horowitz et al, PRD 68, 2003 study in detail detection of SN neutrinos through cohNS in different targets (including Xe and Ar)
- ✓ A.J. Anderson et al., PRD 84, 2011 propose to discover cohNS in DM detectors
- ✓ K. Arisaka et al., Astrop. Phys. 36, 2012 discuss SN neutrino detection in Ar and Xe DM detectors
- ✓ R.F. Lang et al., PRD 94, 2016 discuss SN neutrino detection in DM xenon experiments (Xenon1t and larger proposals)
- ✓ K. Abe et al., XMASS Collaboration, Astrop. Phys. 89, 2017, discuss SN neutrino detection in Xe using cohNS
- ✓ D. Akimov et al., COHERENT coll., Science 2017, first observation of cohNS in a spallation source

Coherent neutrino-nucleus scattering



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

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

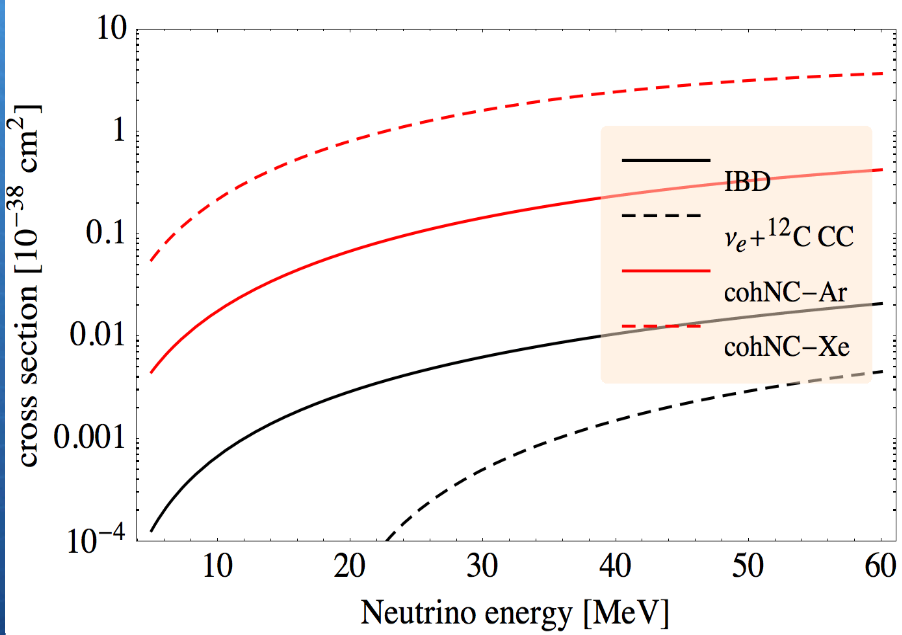
$$Q_W = \left(1 - 4\sin^2\theta_W\right) Z - N$$

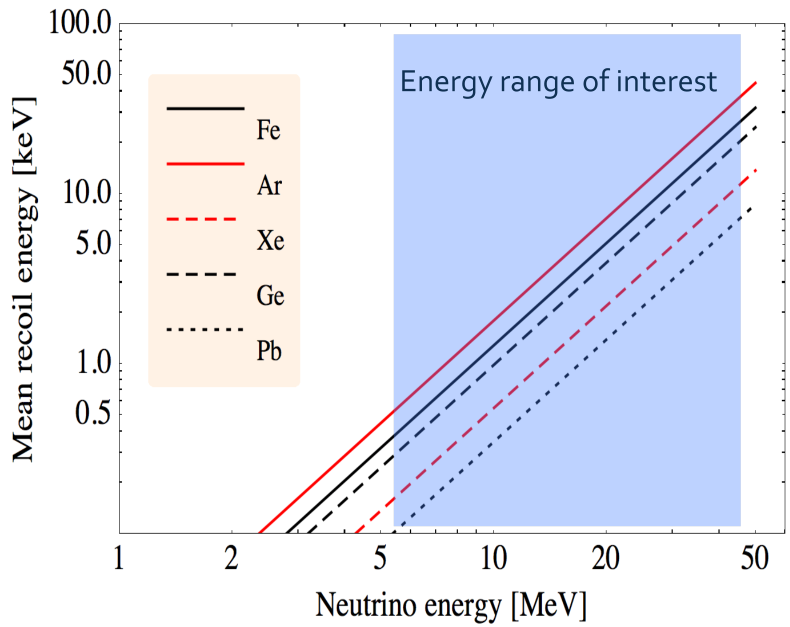
$$\sigma = \frac{G_F^2}{4\pi} Q_W^2 E_\nu^2 \approx 4.215\times 10^{-45} Q_W^2 \left(\frac{E_\nu}{\text{MeV}}\right)^2 \text{cm}^2 \approx 4.215\times 10^{-45} N^2 \left(\frac{E_\nu}{\text{MeV}}\right)^2 \text{cm}^2$$

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





$$\lambda \approx \frac{262\ \text{m}}{\rho / 10^{13}\text{g cm}^{-3}} \quad \text{for 10 MeV cohNS neutrino in Fe}$$

$$\lambda \approx \frac{3.8 \cdot 10^{4}\ \text{m}}{\rho / 10^{13}\text{g cm}^{-3}} \quad \text{for 10 MeV neutrino-electron ES in Fe}$$

Trade off between

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

Basic requirement to detect cohNS

$$\sigma \approx 2.539\times10^{-18}\frac{N^2}{A}\left(\frac{E_\nu}{MeV}\right)^2 \text{ cm}^2/kg$$

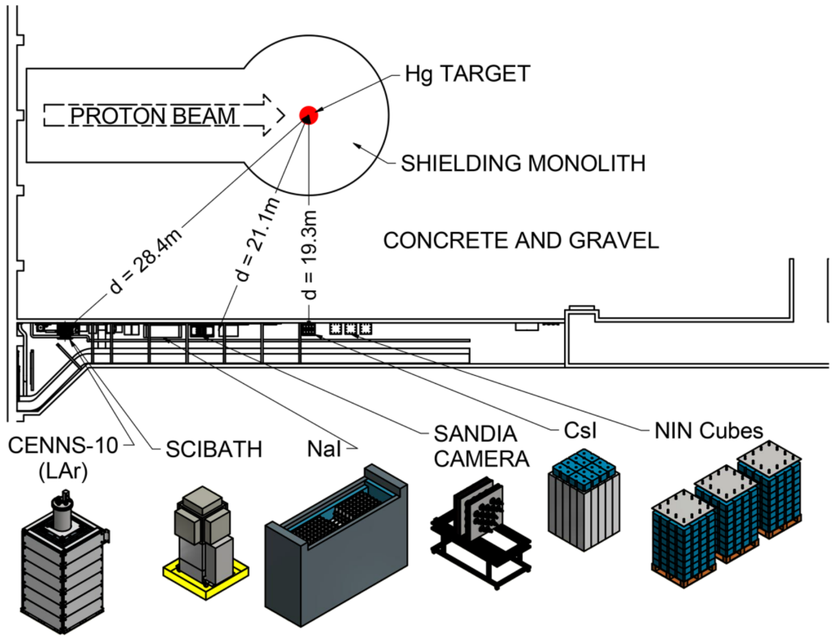
For the sake of the discussion:
E_ν = 15 MeV and $\phi_\nu = 10^{12}$ cm^{-2}

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

Observation of ν-nucleus scattering [1]

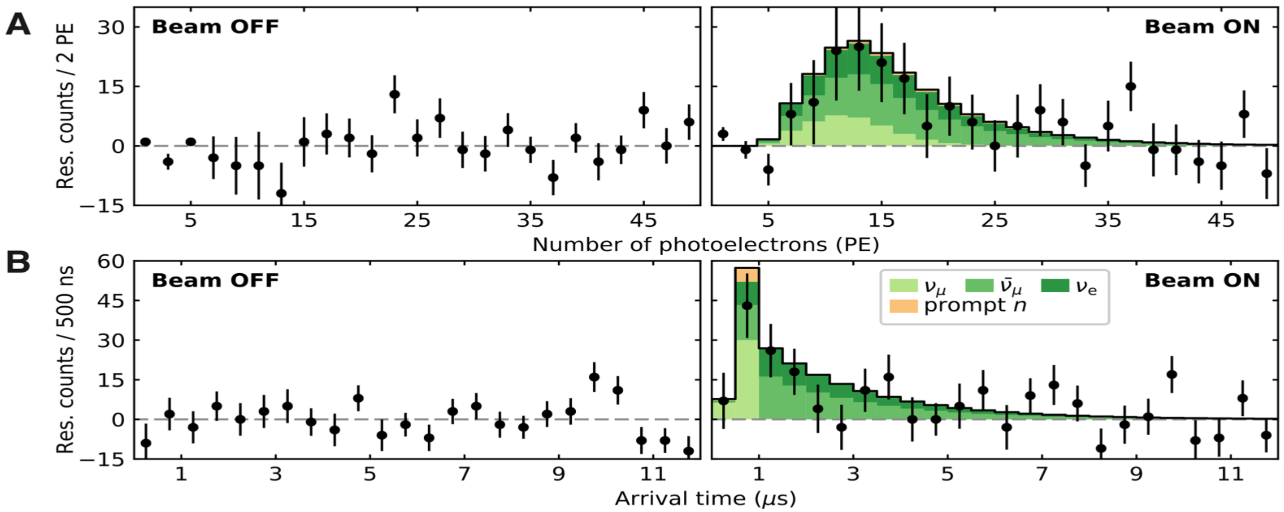
D. Akimov et al., COHERENT Collaboration, Science, Aug. 3, 2017
Using neutrino emission from the Spallation Source at the Oak Ridge Laboratory
Using 14.6 kg of CsI(Na) scintillator

1. 8 m.w.e. overburden
2. effective shielding against beam-related neutrons
3. 1.76×10^{23} POT in 308 live-days
4. ~ 3×10^{14} ν/cm^2 per flavor



Observation of ν-nucleus scattering [2]

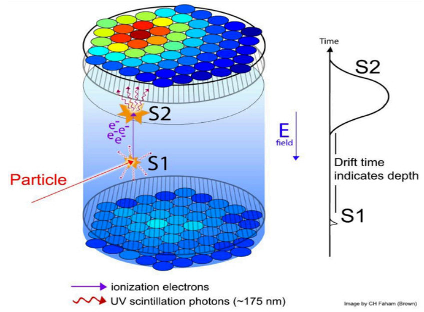
- 134±22 events observed and 173±48 events predicted
- 153.5 live-days of beam off and 308.1 live-days of beam on
- Events excess following cohNS correlated with beam activity
- Energy and time likelihood study determine the presence of cohNS at 6.7σ



Why are we interested in Dark Matter Detectors for WIMPs for cohNS ?

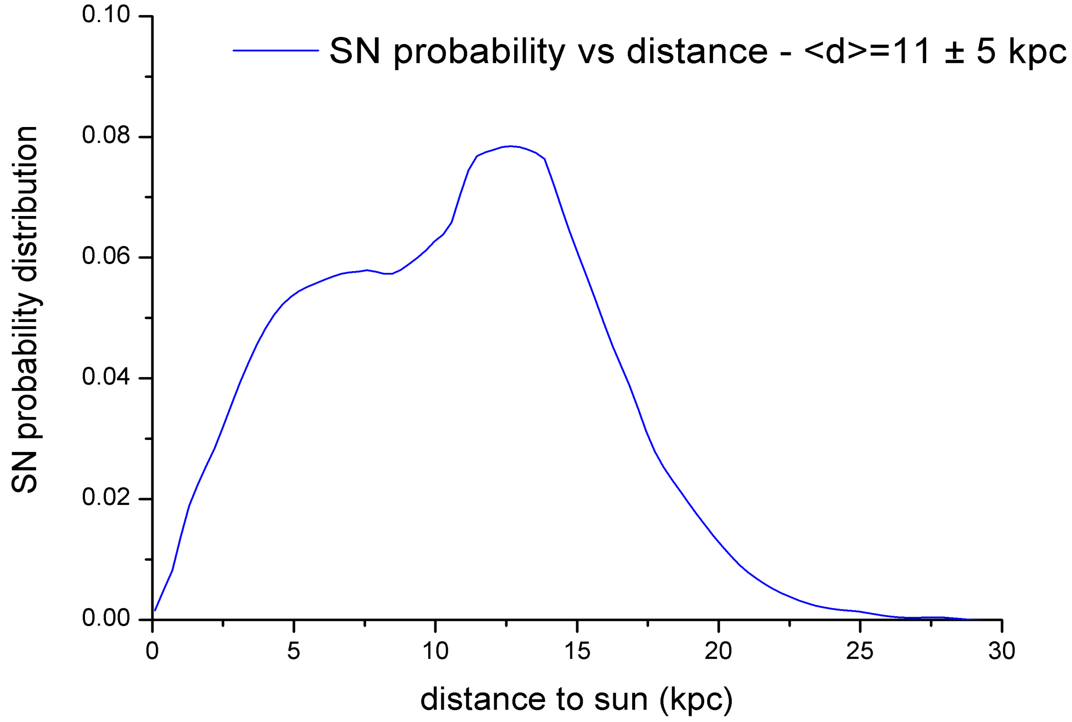
- ✓ Designed
  - to detected low energy nuclear recoils (< 100 keV)
  - to have high discrimination power between Electron Recoils (ER) and Nuclear Recoils (NR)
  - to have intrinsic low background due to the radio-purity of selected detector components
  - To have good fiducial mass determination
- ✓ Look ideal for cohNS measurement and SN neutrino observation

Two-phase LXe and LAr DM detectors



- **GOAL**: detect nuclear recoils
- Detect S1 (liquid) and S2 (gas) signals
- High discrimination power between NR and ER based on S2/S1 vs S1 measurement or timing PSD on S1 (mainly Ar)
  - ~ 1/200 in LXe above ~3 keVr
  - ~ $1/10^7$ in LAr above ~ 50 keVr
- 3D vertex reconstruction, based on S2-S1 timing and PMTs hit pattern, for fiducial volume definition
- Low background

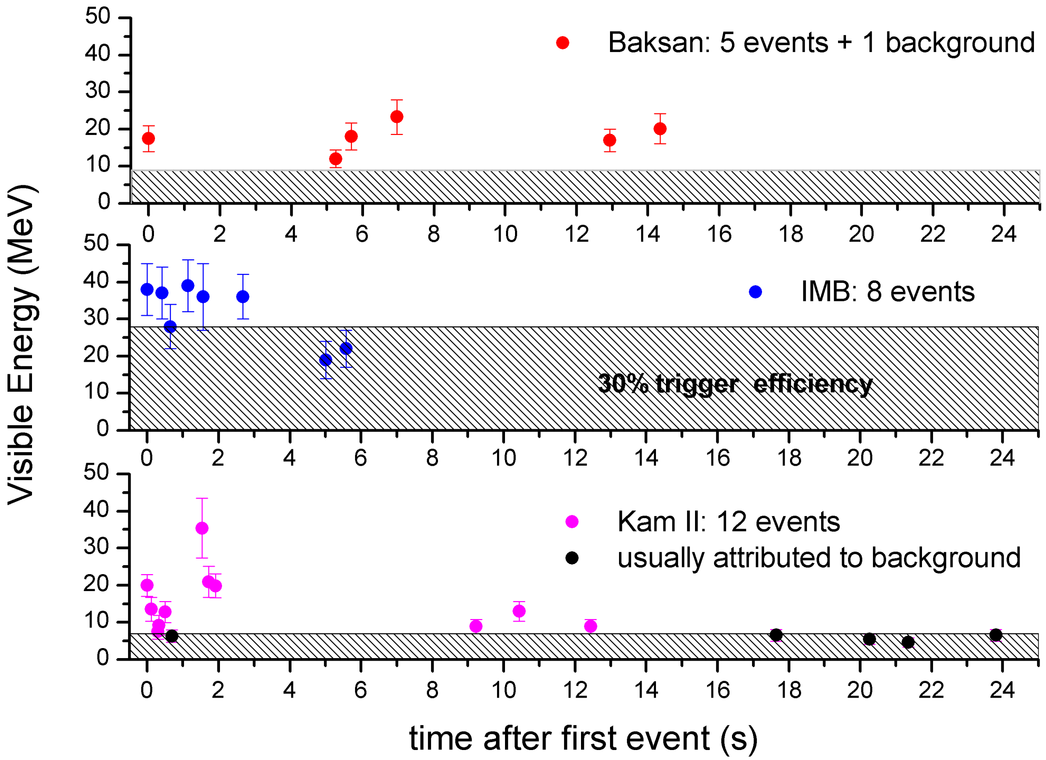
Probability of a galactic SN vs distance to the Sun



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

SN1987A: 1st SN ν observation

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



See talk by M. Nakahata for more details

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

Expected

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

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

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

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

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

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

The SuperNova model

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

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

$$\alpha=3$$

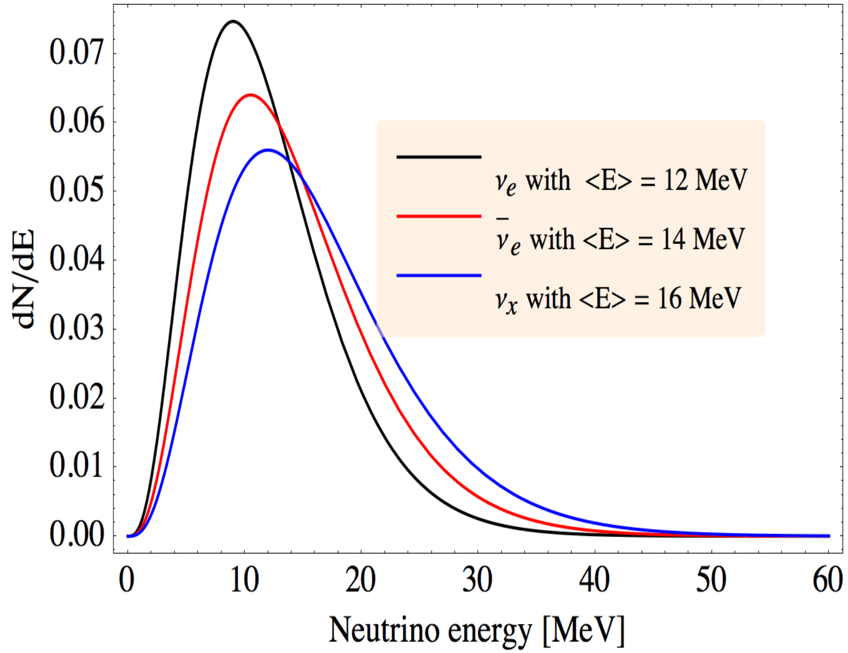
$$d=10\ \mathrm{kpc}$$

$$\sum_i 4\pi d^2\int dE_\nu E_\nu F_{\nu_i}\left(E_\nu\right)=3\cdot10^{53}\ \mathrm{erg}$$

$$\mathrm{N}_{\nu,i}=4\pi d^2\int dE_\nu F_{\nu_i}\left(E_\nu\right)=\quad N_{\nu_e}=2.6\cdot10^{57},\quad N_{\bar{\nu}_e}=2.2\cdot10^{57},\quad N_{\nu_x}=7.8\cdot10^{57}$$

$$F^{Tot}_\nu=1.1\cdot10^{12}\ \mathrm{cm^{-2}}$$

SN Signal duration ~ O(10) s



Average energy expected to change as:

ν_e : ~12-14 MeV

bar-ν_e : ~14-16 MeV

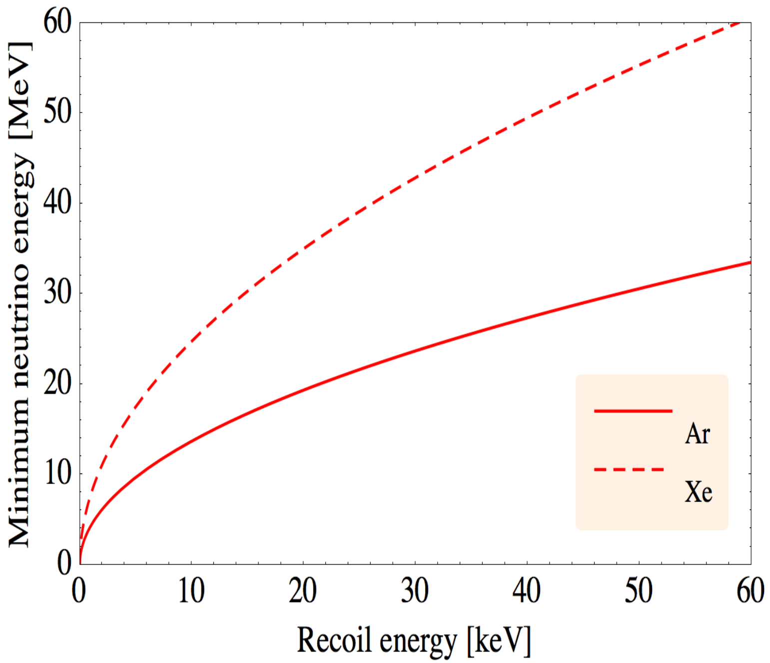
ν_x : ~14-16 MeV

A. Summa et al. Astrophys. J 825 (2016)

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

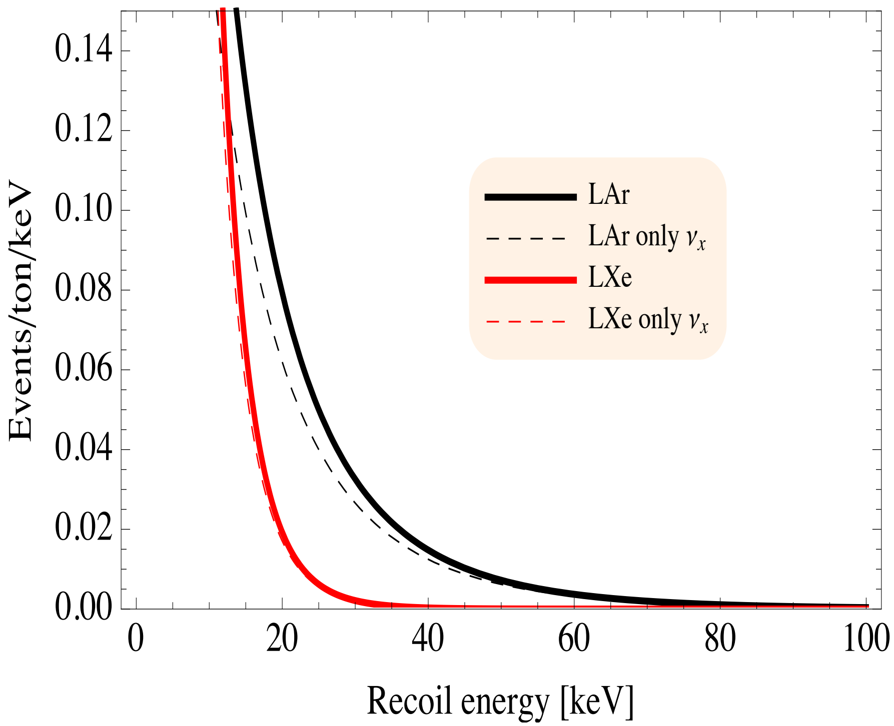


The SN neutrino spectrum in Ar and Xe

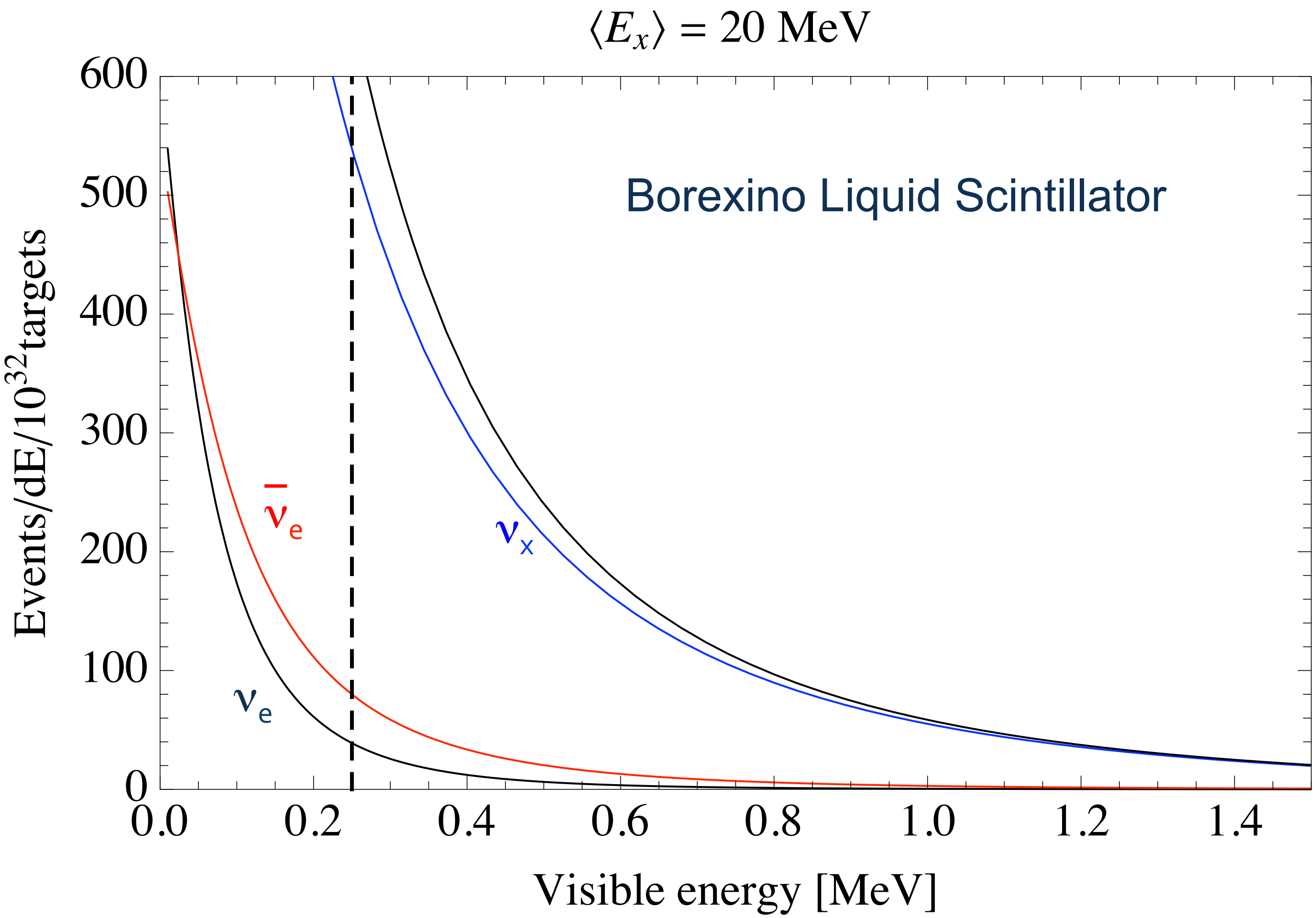
The neutrino signal is mainly due to ν_x contribution similarly to neutrino-proton interaction in a Borexino-like detector

This allows to break the degeneracy between the $E_{binding}$ and T_x

(see also F. Vissani et al arXiv:1708.00876 to measure the binding energy in SuperKamiokande)

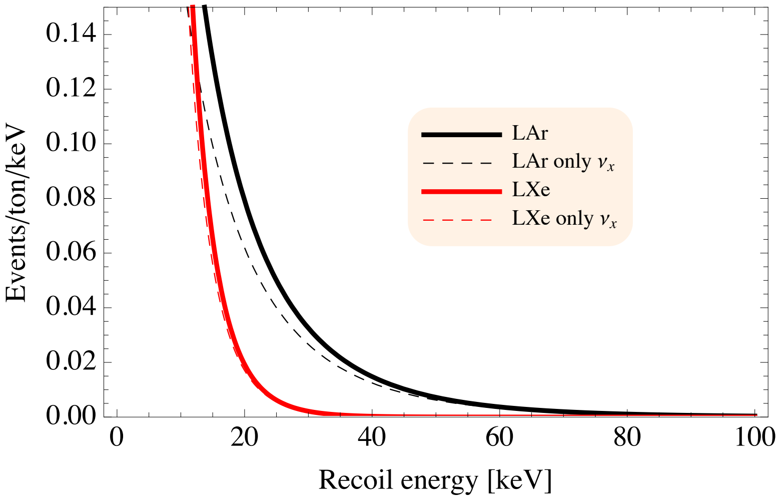


The SN neutrino spectrum in a Borexino-like detector for ν-p scattering



Exploit cohNS with a SN: main feature

The measured number of events has a typical NC degeneracy problem



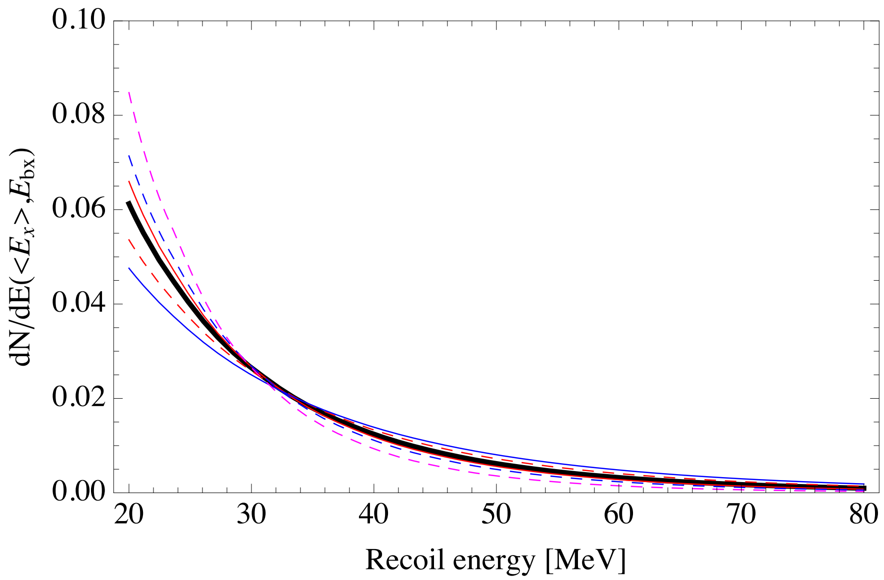
$$N_{events} \propto \langle \sigma \rangle \frac{E_{binding\_x}}{\langle E_x \rangle}$$

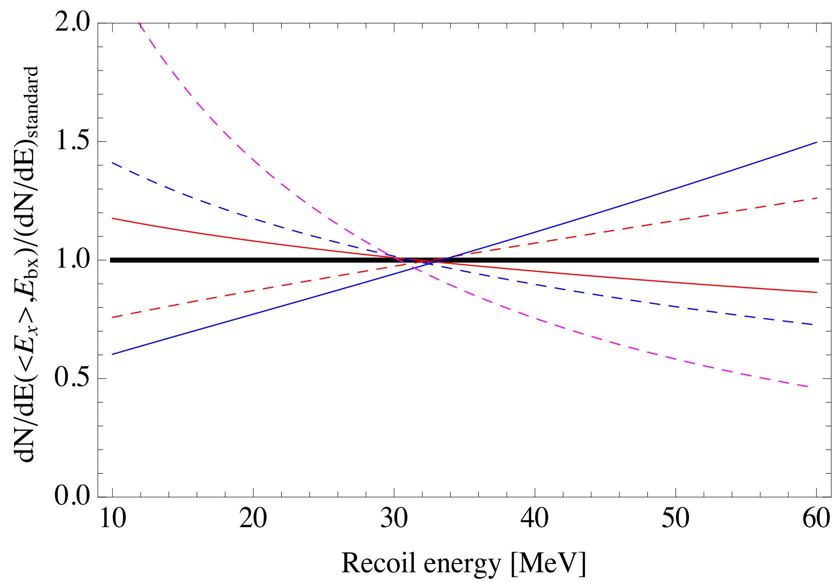
Due to the fact that the cohNC spectrum is mainly from ν_x above threshold, by measuring the spectrum we break the degeneracy between $\langle E_x \rangle$ and $E_{binding\_x}$.

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 $E_{binding\_x}$ 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

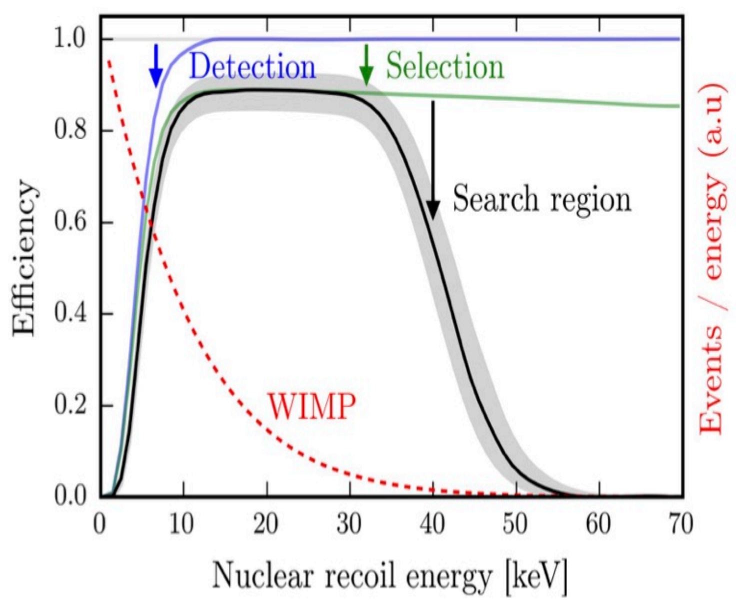


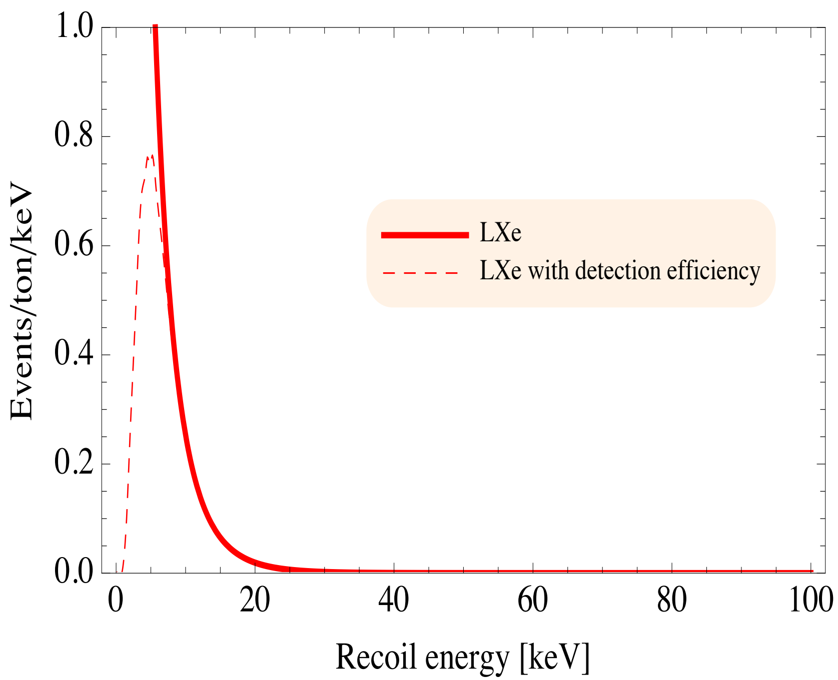


Considering detector properties

NR detection efficiency in the fiducial mass in Xenon1t, 2017, as an example

SN events: 26 → 5 ton^{-1}

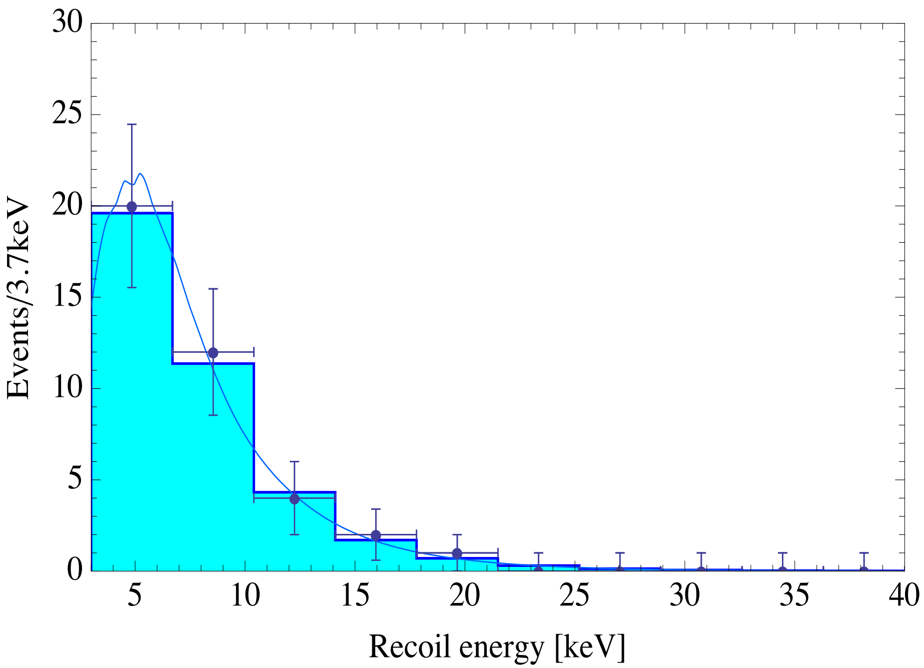


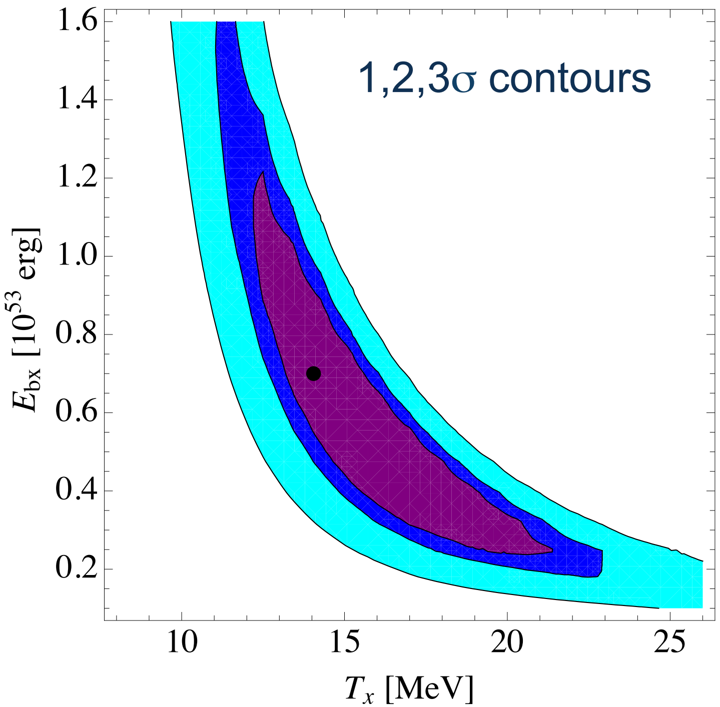


Probe SN parameters

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

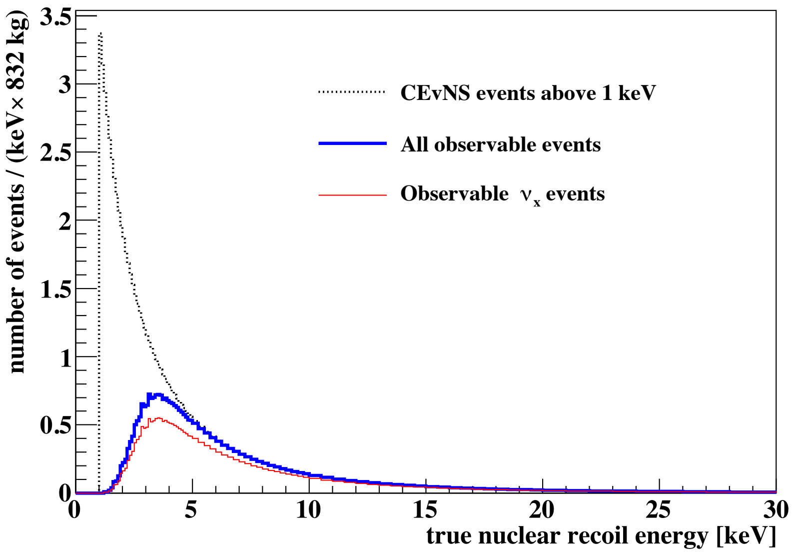
Testing a measured energy spectrum

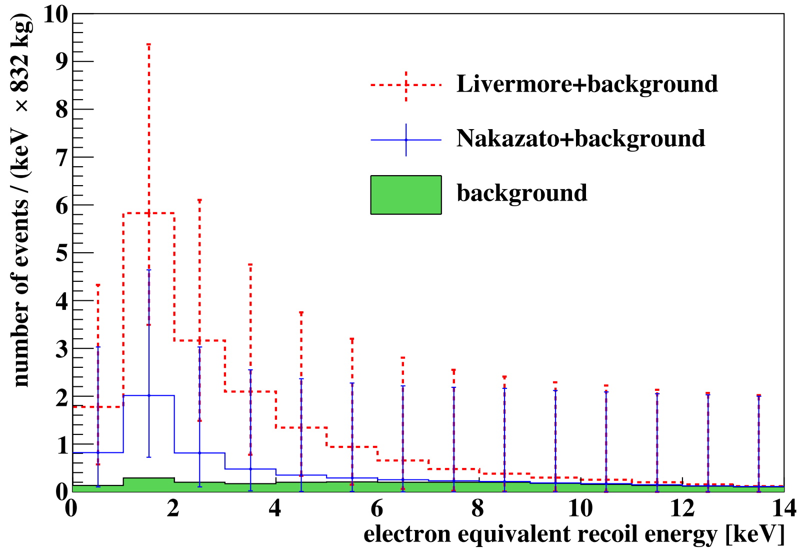




XMASS as SN detector

XMASS coll., Astrop. Phys. 89, 2017

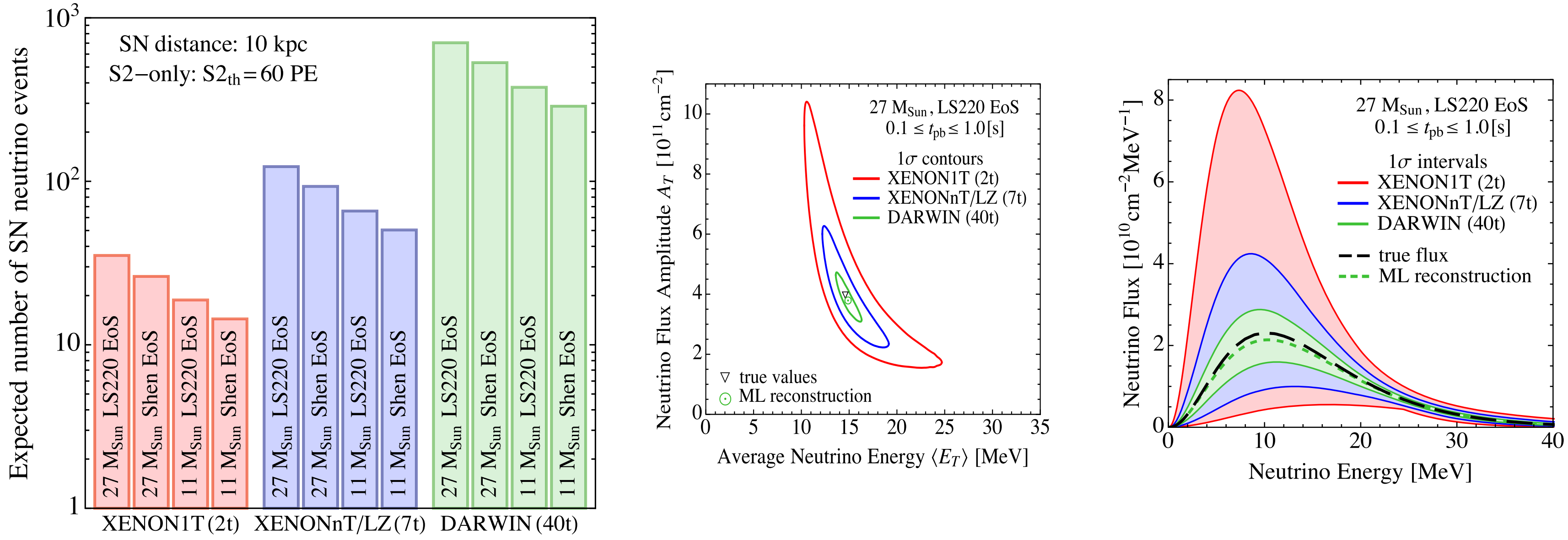




Only cohNS events with 832 LXe active mass for a 10kpc SN
Number of SN events very much depend on the SN model.
Due to threshold effect XMASS is mainly sensitive to neutrinos above ~ 15 MeV

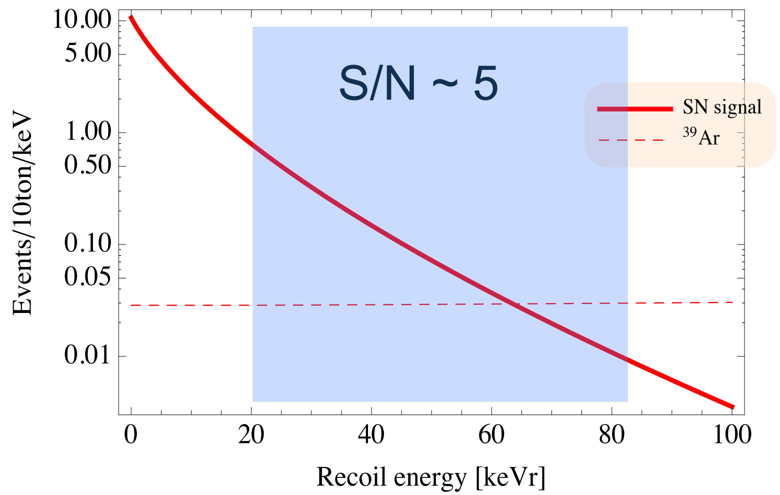
SN events in two-phase LXe detectors

- Xenon1t has measured ~ 2 x10^{-4} events/kg/day/keVe
- This background measurement turns into a background-free detector for SN neutrinos with cohNS in the ROI with a 50% acceptance for NR
- As suggested by R.L. Lang et al. PRD 94, 2016 an **S2-only analysis** could make possible to lower the detection threshold and increase the number of events observed from a SN: for 1 keV deposition <S1> ~ 0.5pe and <S2> ~ 150pe



UAr for cohSC SN detection

- DarkSide-50, ArDM and DEAP have shown a huge PSD efficiency for ER (reduction factor ~ 10^7) in LAr
- DarkSide-50 has measured a depletion factor for UAr of the order of 1400 with respect to AAr (~ 1 Bq/kg)
- In 10 ton of UAr we expect 70 ^{39}Ar events in 10 sec.
- For a window of [20,80] keVr ~ [5,20] keVe we expect some 6/1000 events, therefore the acceptance for NR (~100% above 50 keVr) could be much larger than what measured at present in the ROI for SN cohNS events
- Implement S2-only analysis to lower analysis threshold



Conclusions

- Dark Matter LXe and LAr detector offer an opportunity to detect SN neutrinos by means of cohNS
  - In this respect they become multi-purpose experiments and help to guarantee the SN detection in underground labs
- These detectors will offer a complementary measurement to liquid scintillator low threshold detectors (Borexino-like)
  - In this respect they offer the opportunity to understand better the SN model and parameters in combination with high rates detectors such as SuperKamiokande where CC interactions can be exploited
    - see also F. Vissani et al arXiv:1708.00876 to measure the binding energy in SuperKamiokande
  - At present it has been shown that Xenon1t with S2-only analysis can start probing the SN model

Thank you for your attention

Happy ten years to Borexino!