Astrophysical neutrinos with DUNE, HK and JUNO

(Opportunities with Neutrinos from Supernovae)

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EXCELENCIA MARÍA DE MAEZTU

European Neutrino "Town" Meeting and European Strategy Preparation 2019
22-24 October 2018

CERN

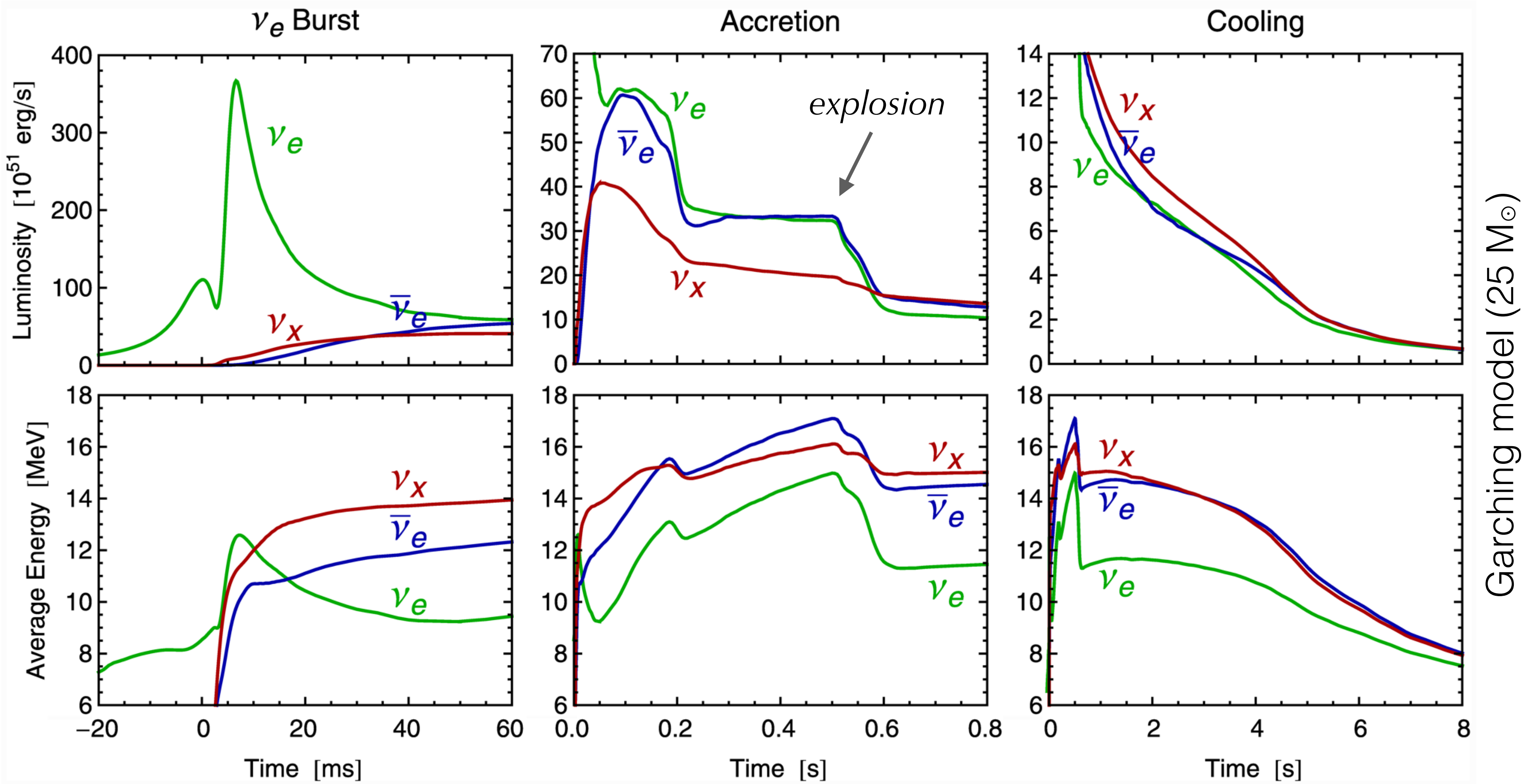
Scientific motivation

- Supernova neutrino detection is **one of the main goals** included in the physics program of current & future large underground neutrino projects
- Measurement of the neutrino **energy** spectra, **flavor** composition and **time** distributions from supernova will provide information about:

- **Supernova physics**:
  - Core collapse mechanism
  - Supernova evolution in time
  - Cooling of the proto-neutron star
  - Nucleosynthesis of heavy nuclei
  - Black hole formation
- **Neutrino (other particle) physics**:
  - Neutrino flavor transformation in SN core and/or in Earth
  - Neutrino absolute mass (not competitive)
  - Other neutrino properties: sterile vs, magnetic moments,…
  - Axions, extra dimensions,…
- **Early alert** for astronomers (SNEWS)

First multi-messenger event:
neutrinos and light from SN1987

Three phases of SN ν emission



Neutronization burst

- Shock breakout
- De-leptonization of outer core layers

Accretion phase

- Shock stalls ~150 km
- Neutrinos powered by infalling matter

Cooling phase

- Cooling on neutrino diffusion time scale

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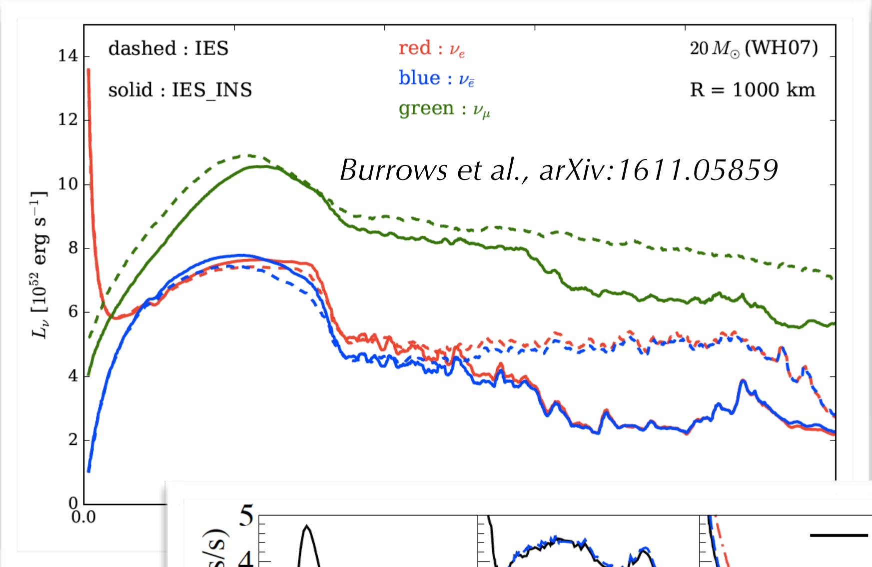
SN neutrino fluxes

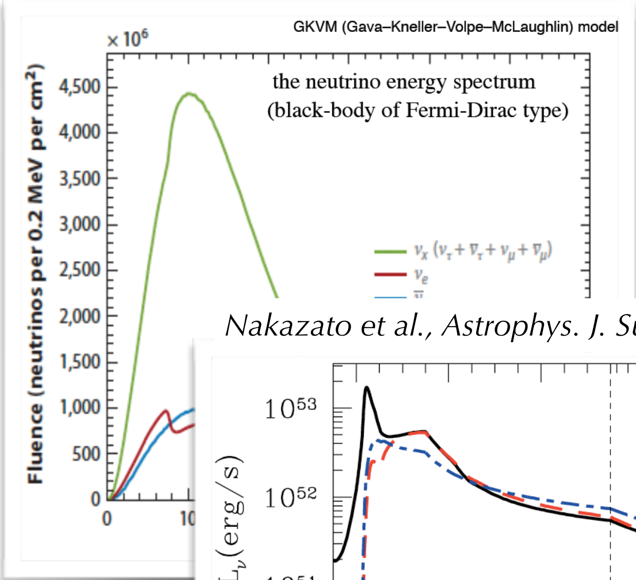
Many theoretical models…

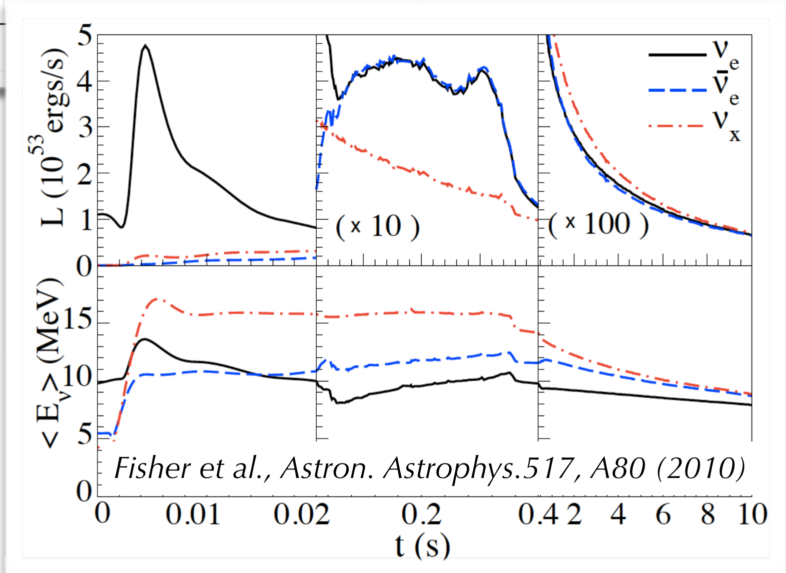
$$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$$

Generic feature



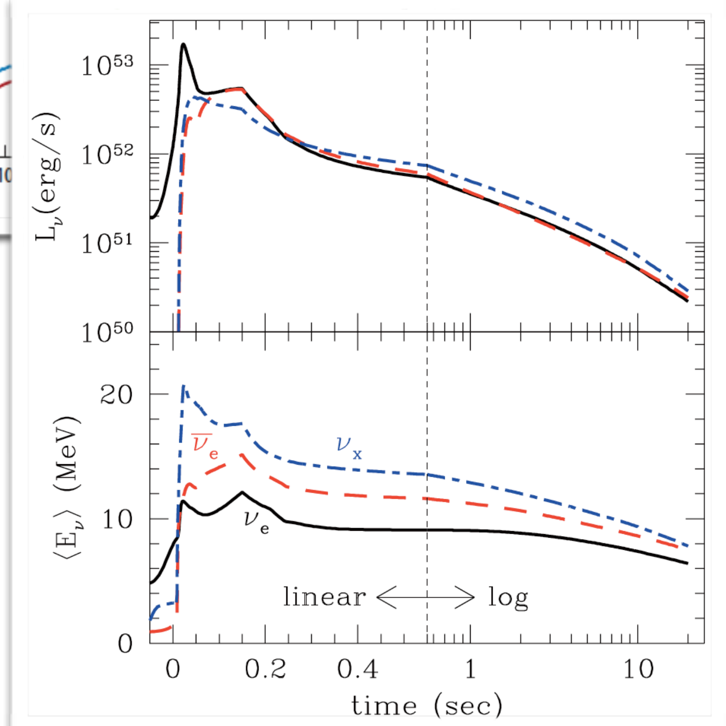
Burrows et al., arXiv:1611.05859





Fisher et al., Astron. Astrophys.517, A80 (2010)

Nakazato et al., Astrophys. J. Suppl.205 (2013) 2



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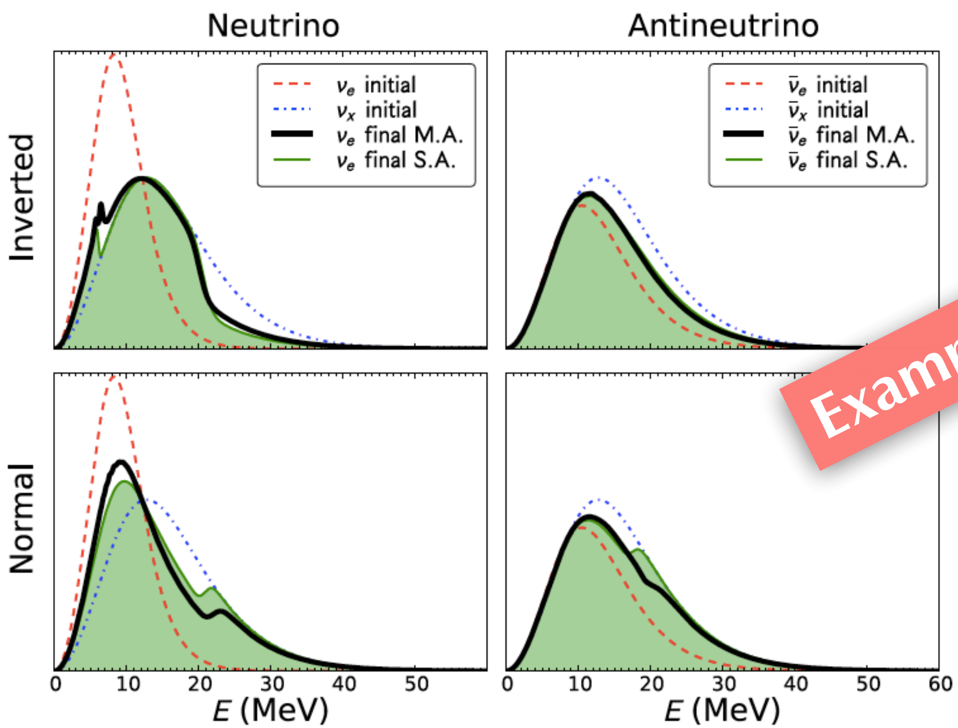
SN ν flavor oscillation physics

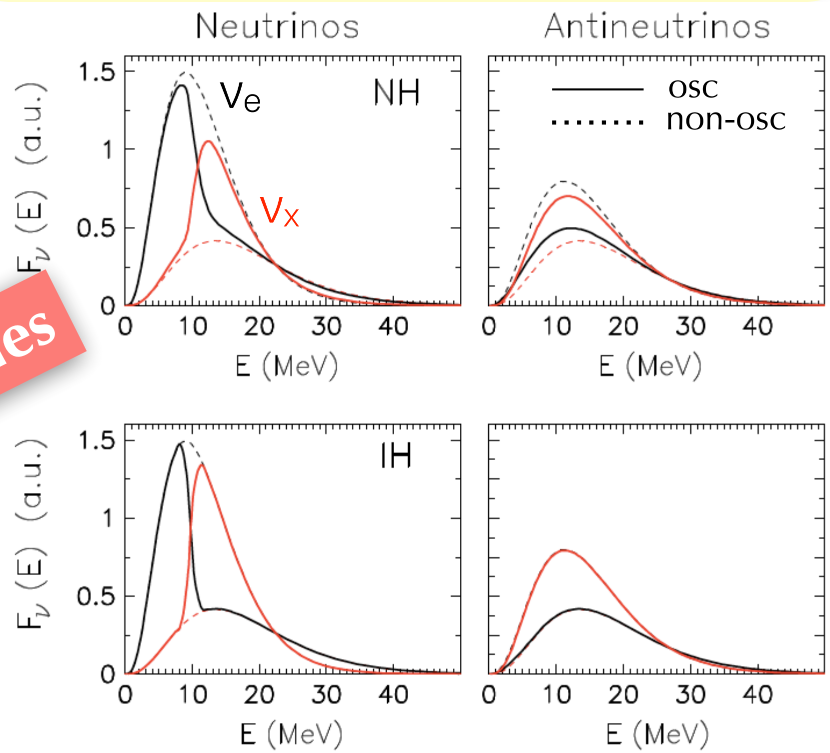
Collective oscillations (r < 200 km) + **MSW flavor transformations** (r > 200 km) imprint the neutrino signal

Information about the **mass hierarchy** (and **SN mechanisms**) can be obtained from neutrino time and energy spectra evolution



Duan & Friedland, Phys. Rev. Lett. 106 (2011) 091101

Examples

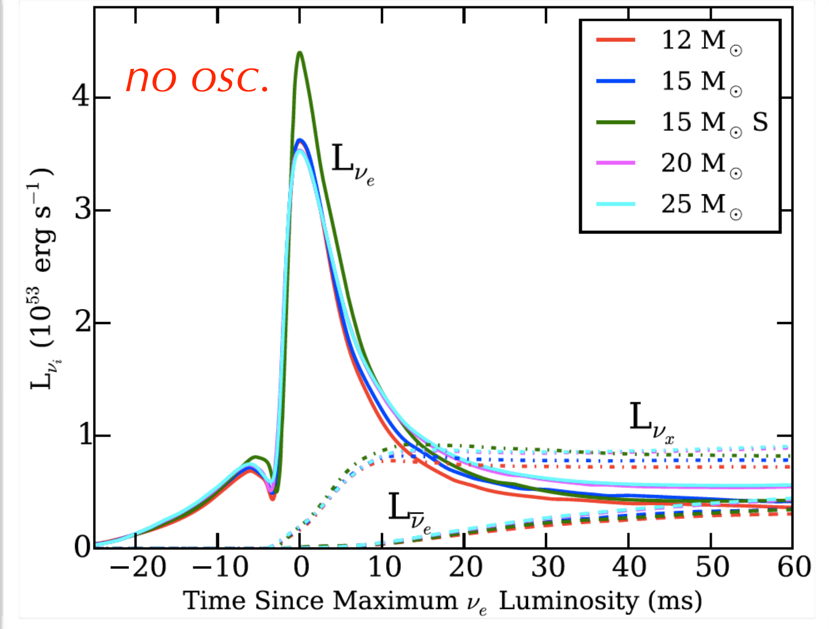


S. Chakraborty and A. Mirizzi, Phys. Rev. D90, 033004 (2014)

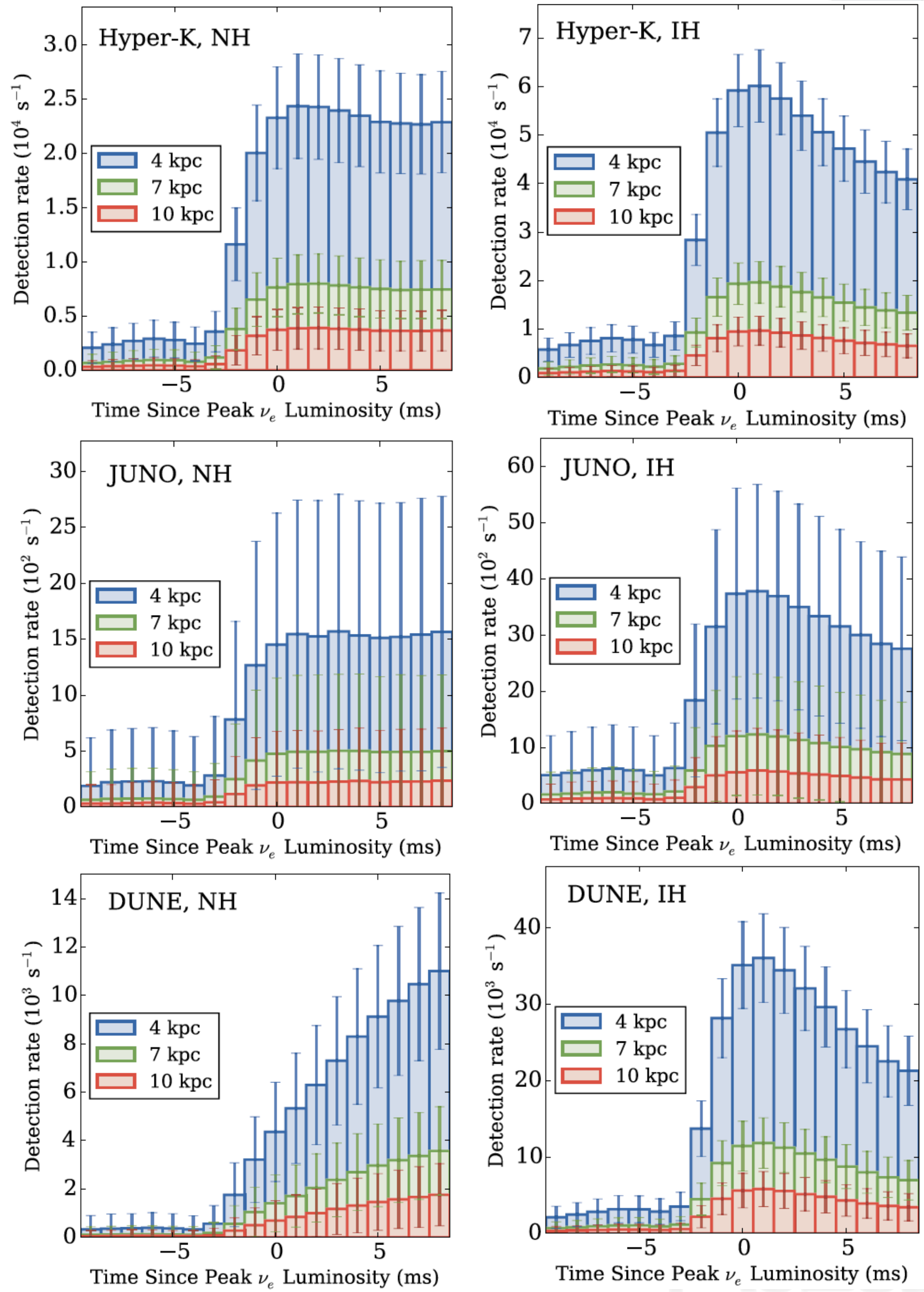
It is important to identify robust, **model-independent observable signatures** of supernova neutrino flavour conversions: self-induced spectral splits, Earth matter effects, neutronization burst, …

Detection of SN breakout burst

J. Wallace et al., Astrophys. J. 817 (2016), 182



- Robust **time signature** during the first few tens of ms after the core bounce
- Strongly dominated by electron neutrinos
- **MSW oscillations**: presence or absence of **ν_e burst allowing to distinguish between different mixing scenarios**
  - **NH**: strong suppression of ν_e
  - **IH**: ν_e suppressed by $\sin^2\theta_{12}$



Main experimental challenges

Detector requirement	Purpose
Large mass (~ktons)	Enough statistics
Low energy threshold (few MeV)	Detection of the low E SN neutrino spectra
Sensitivity to different neutrino flavors	Distinguish different SN effects and neutrino oscillations
Good knowledge of low-E cross sections and neutrino interactions (particle ID)	Tag different interactions
Accurate neutrino energy reconstruction	SN features
Good timing resolution	SN features
Good angular resolution	SN direction
Separation from backgrounds	Identification of SN signal
Good trigger efficiency/DAQ	Large data acquisition in a few seconds

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Complementarity

One single detector generally cannot meet all these requirements

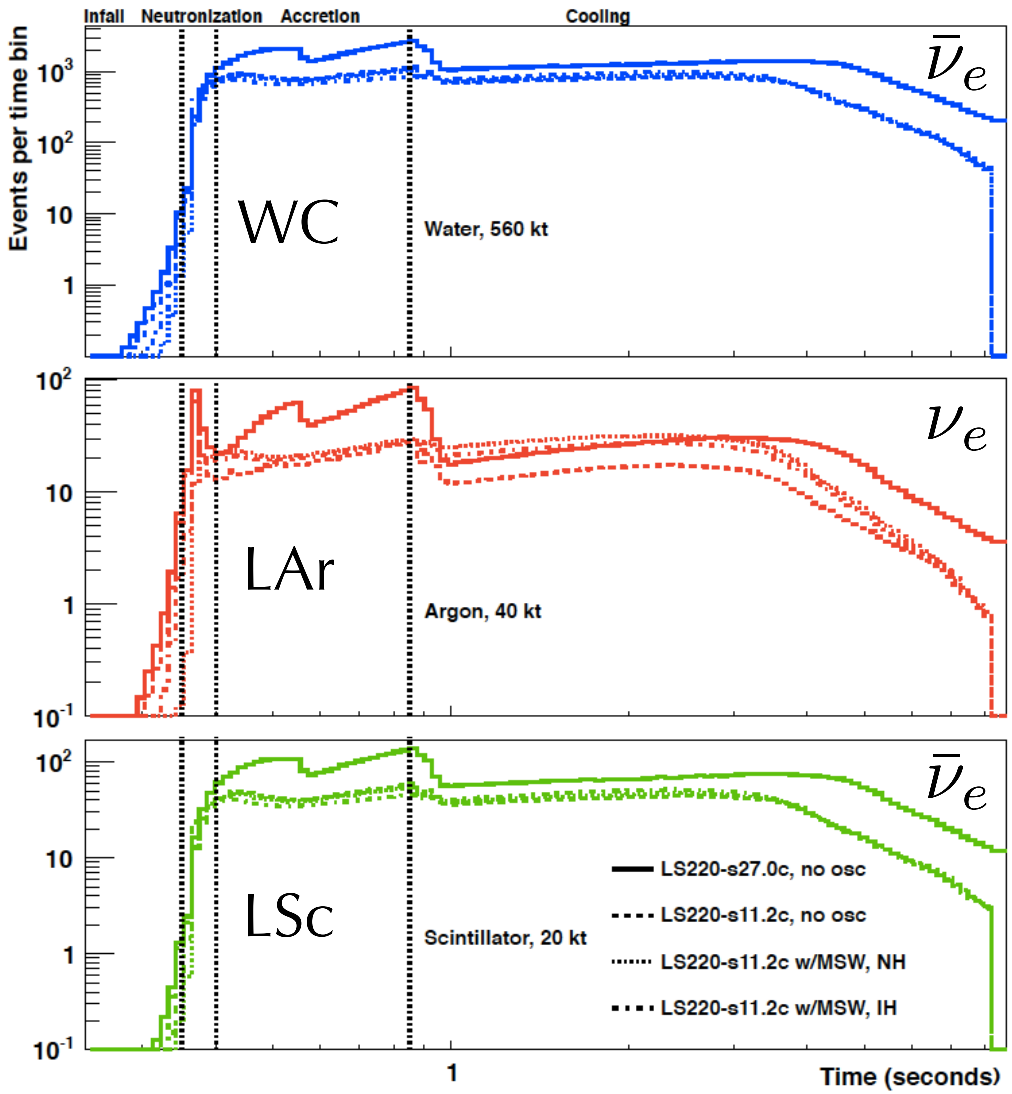
- Specially three flavour sensitivity

Different simultaneous observations are needed by multiple detectors

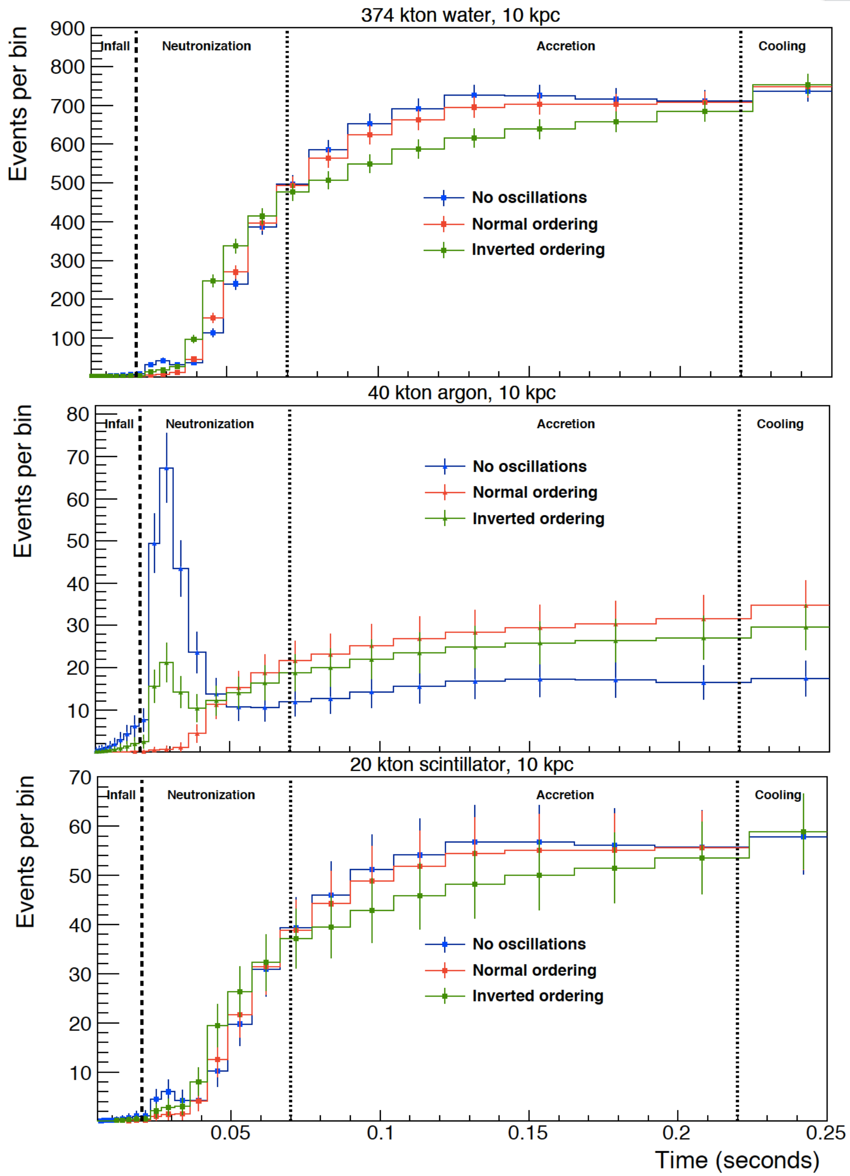
Comparison between technologies

Total event rates per time bin for 27 and 11 M⊙ SN progenitors

Neutronization burst



Mirizzi et al., Riv. Nuov. Cim. 39, N. 1-2 (2016)



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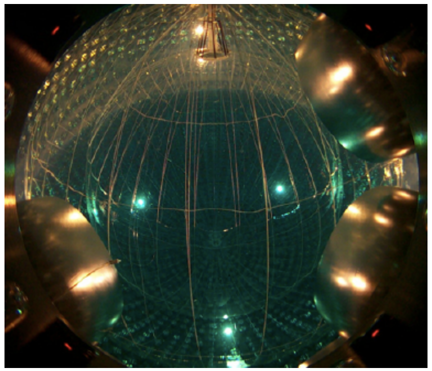
SN neutrino detectors

@10 kpc

Detector	Type	Mass (kt)	Location	Events	Status
Super-Kamiokande	H_2O	32	Japan	7,000	Running
LVD	C_nH_{2n}	1	Italy	300	Running
KamLAND	C_nH_{2n}	1	Japan	300	Running
Borexino	C_nH_{2n}	0.3	Italy	100	Running
IceCube	Long string	(600)	South Pole	(10^6)	Running
Baksan	C_nH_{2n}	0.33	Russia	50	Running
HALO	Pb	0.08	Canada	30	Running
Daya Bay	C_nH_{2n}	0.33	China	100	Running
NOνA*	C_nH_{2n}	15	USA	4,000	Running
MicroBooNE*	Ar	0.17	USA	17	Running
SNO+	C_nH_{2n}	0.8	Canada	300	Near future
DUNE	Ar	40	USA	3,000	Future
Hyper-Kamiokande	H_2O	374	Japan	75,000	Future
JUNO	C_nH_{2n}	20	China	6000	Future
RENO-50	C_nH_{2n}	18	Korea	5400	Future
PINGU	Long string	(600)	South Pole	(10^6)	Future

K. Scholberg, J.Phys. G45 (2018) no.1, 014002

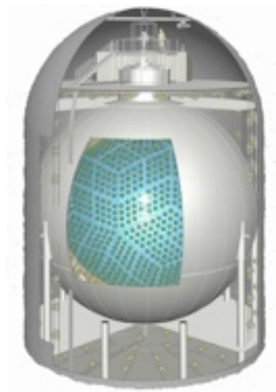
Liquid Scintillator Detectors

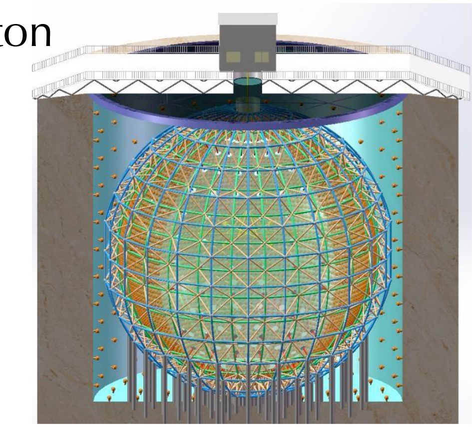


Borexino: 0.33 kton

SNO+: 1 kton

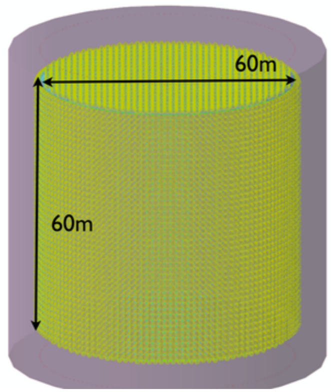
KamLAND: 1 kton





JUNO: 20 kton

THEIA: 50 kton



LVD: 1 kton

NOvA: 14 kton

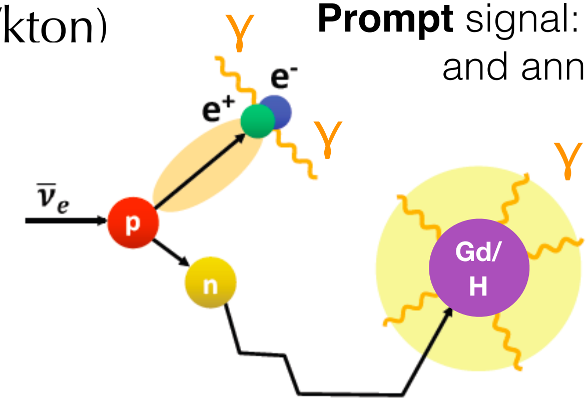
LSc interaction channels

- **Main channel:** (few hundred events/kton)

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

  - **Low energy threshold**: 1.8 MeV
  - Good neutron tagging
  - Good energy resolution (7.25% /√E KamLAND)
  - Some pointing capability JCAP08 (2015) 032

Prompt signal: e+ scintillation and annihilation



Delayed signal: n capture on H (2.2 MeV γ, Δt ~200 μs or Gd (8 MeV γ, Δt ~30 μs)

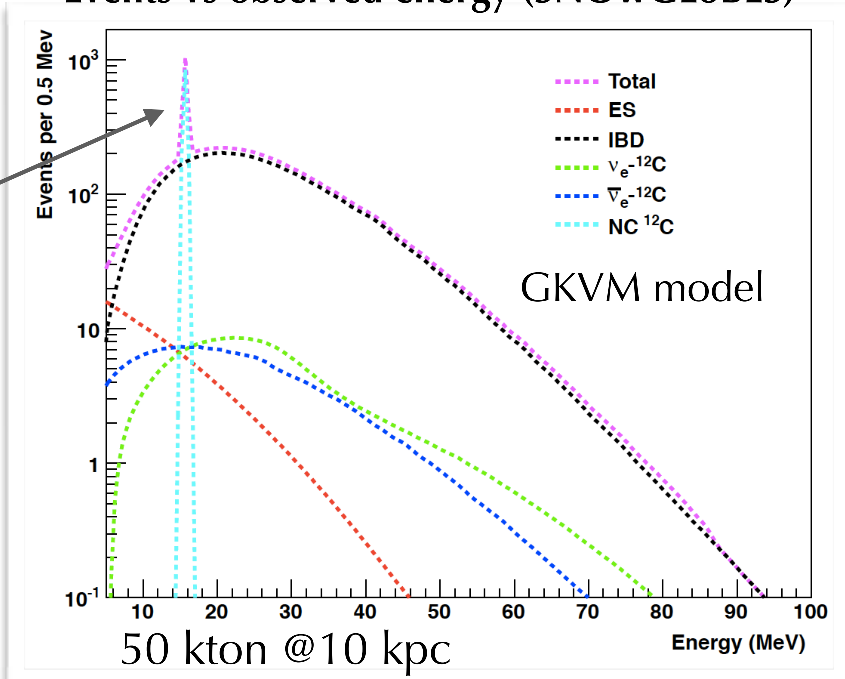
- Other channels:

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

$$\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + {}^{12}\mathrm{N}^{(*)}$$
$$\bar{\nu}_e + {}^{12}\mathrm{C} \rightarrow e^+ + {}^{12}\mathrm{B}^{(*)}$$
$$\nu_x + {}^{12}\mathrm{C} \rightarrow \nu_x + {}^{12}\mathrm{C}^*$$

15 MeV de-excitation peak from NC

Events vs observed energy (SNOwGLoBES)



- Coherent elastic NC scattering on protons

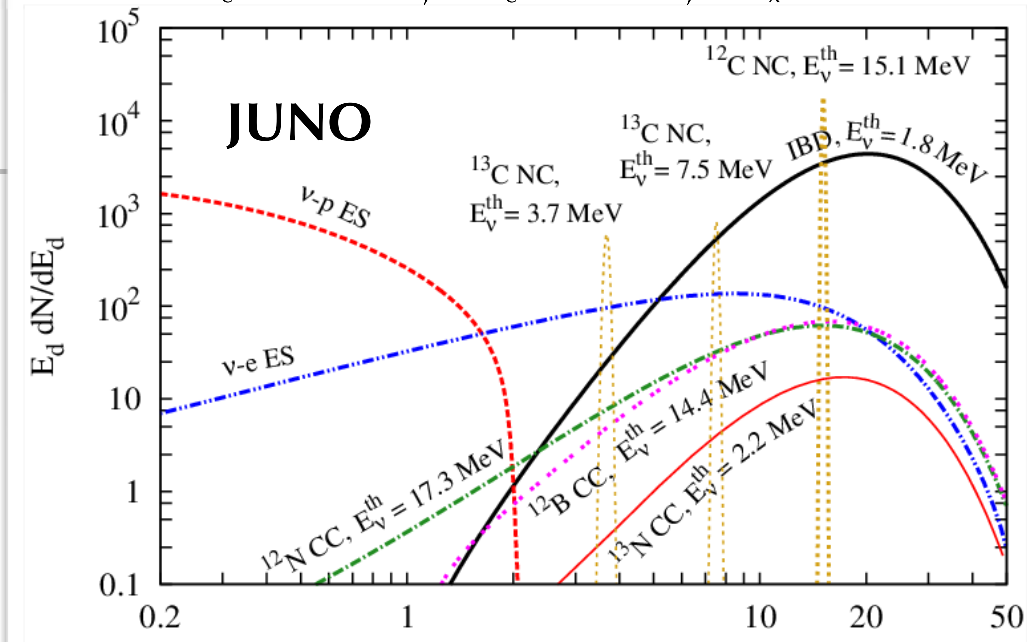
$$\nu_x + p \rightarrow \nu_x + p$$

JUNO

Thanks to Liangjian Wen

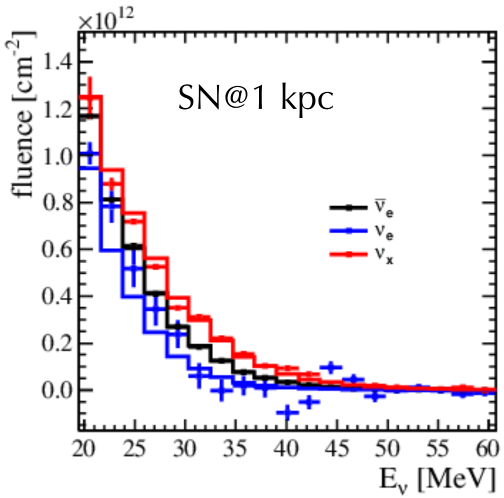
- Current detectors: LVD, Borexino, KamLAND, SNO+, reactors, NOvA (at surface)
  - **~300 events** (per 1 kton) from a SN at 10 kpc
- Future: JUNO (20 kton)
  - **~6000 events** for SN @10 kpc

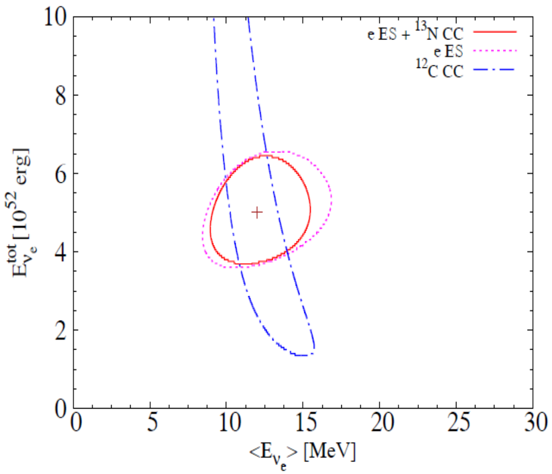
<Eν_e> = 12 MeV, <E$\bar{\nu}_e$>=14 MeV, <Eν_x> = 16 MeV



J. Phys. G 43 (2016) 030401

H.L Li et al, Phys. Rev. D 97, 063014 (2018)
JS Lu et al, Phys. Rev. D 94, 023006 (2016)





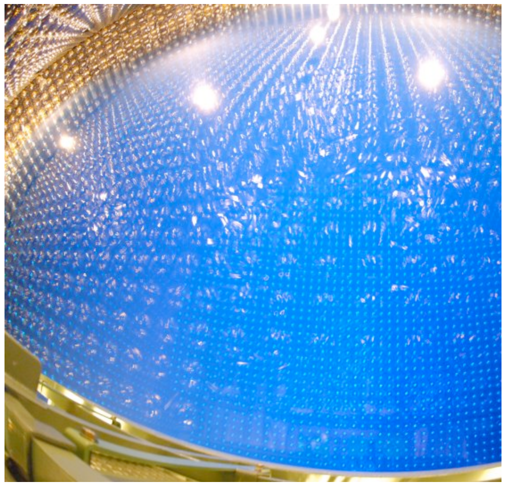
- Constrains on *absolute neutrino masses* via SN neutrino detection in JUNO:

  JCAP 05 (2015) 044

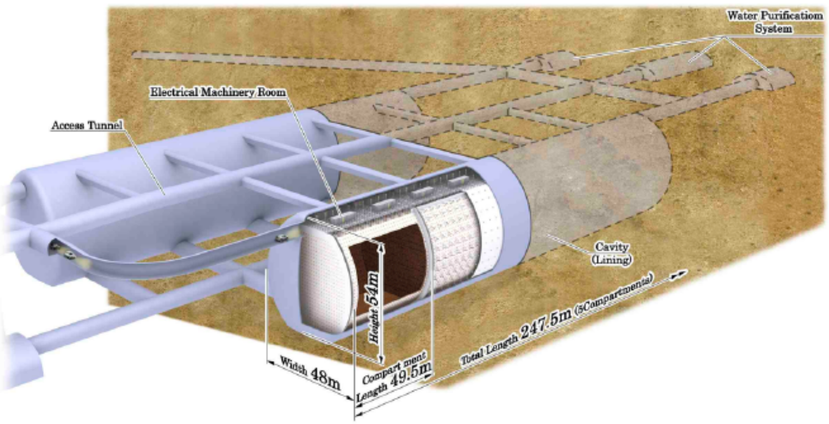
  - **m_ν < (0.83 ± 0.24) eV at 95% CL** for a SN at 10 kpc, assuming nearly-degenerates neutrino mass spectrum and NH

- Energy spectra of all flavor SN neutrinos can be extracted by combining IBD, pES and eES
- The average energy of SN $\bar{\nu}_e$, ν_e & ν_x can be reconstructed with precision 1%, 10% and 5% respectively

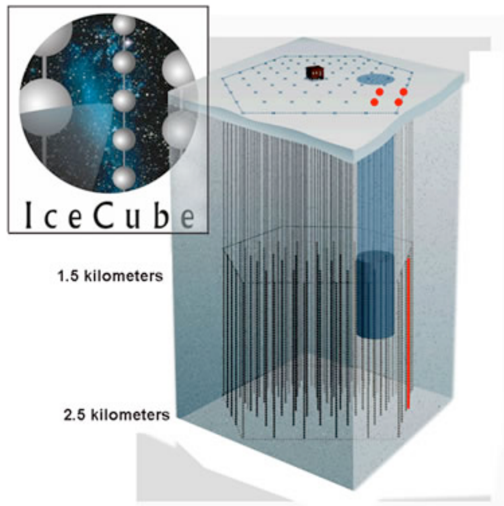
Water Cherenkov Detectors



SK: 32 kton fid. volume



HK: 374 kton fid. volume

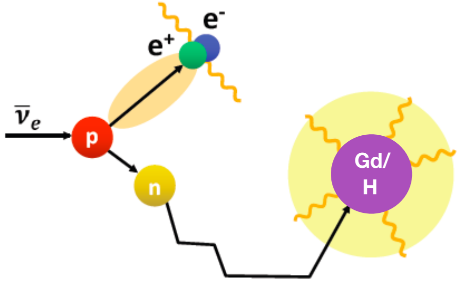


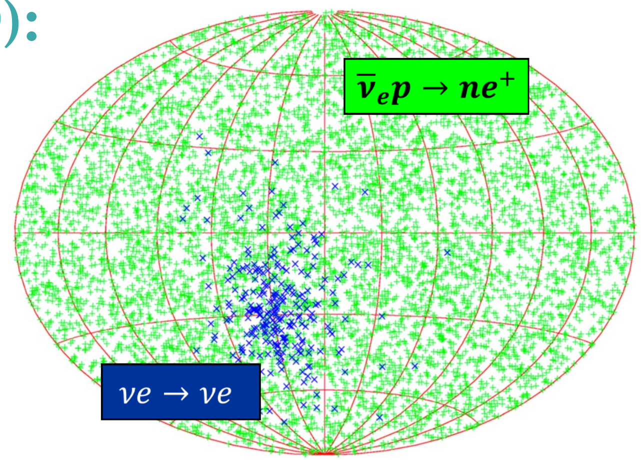
IceCube: 1 km^3

WC interaction channels

- **Main channel (IBD):**

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





Detection:

- Cherenkov light emission
- Neutron tagging: observation of γ-Compton scatters

(SK-IV 20% n tagging efficiency)

Advantages:

- Huge size detectors
- Mainly sensitive to electron antineutrinos
- Pointing information

- **Elastic scattering (ES):**

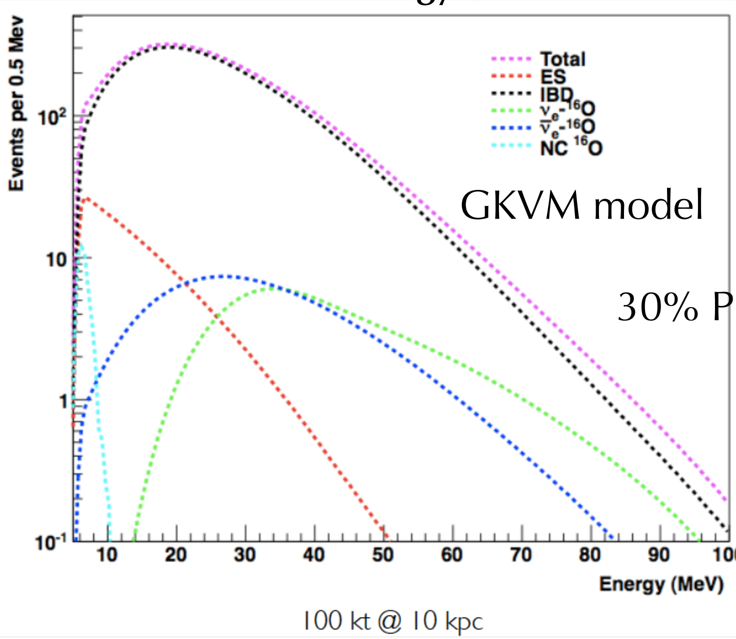
  $\nu_x + e^- \rightarrow \nu_x + e^-$

  - Pointing to the supernova

- Other channels

$$\nu_e + {}^{16}\mathrm{O} \rightarrow e^- + {}^{16}\mathrm{F}^{(*)}$$
$$\bar{\nu}_e + {}^{16}\mathrm{O} \rightarrow e^+ + {}^{16}\mathrm{N}^{(*)}$$
$$\nu_x + {}^{16}\mathrm{O} \rightarrow \nu_x + {}^{16}\mathrm{O}^*$$

Events vs observed energy (SNOwGLoBES)



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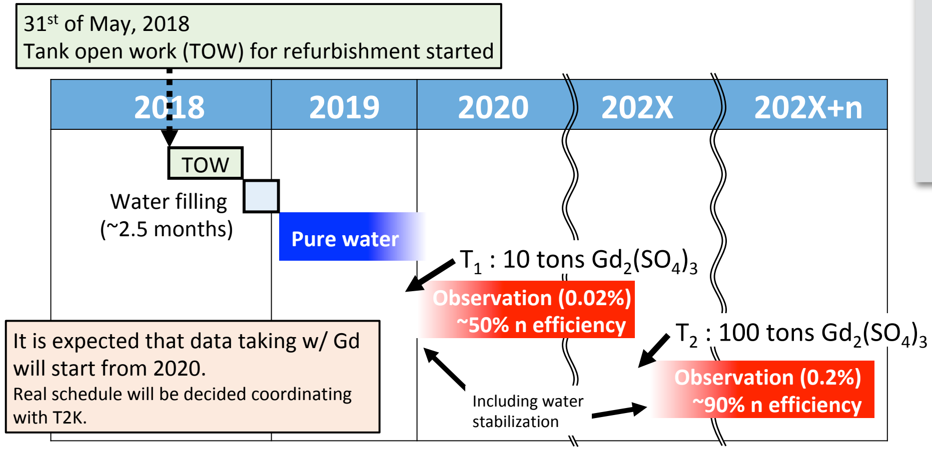
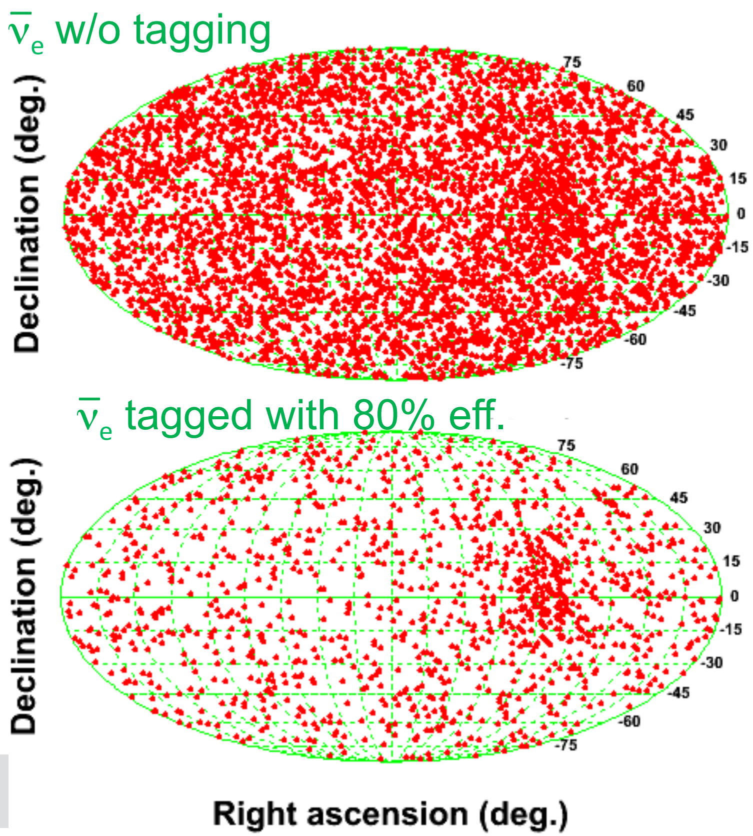
Super-K/Super-K Gd

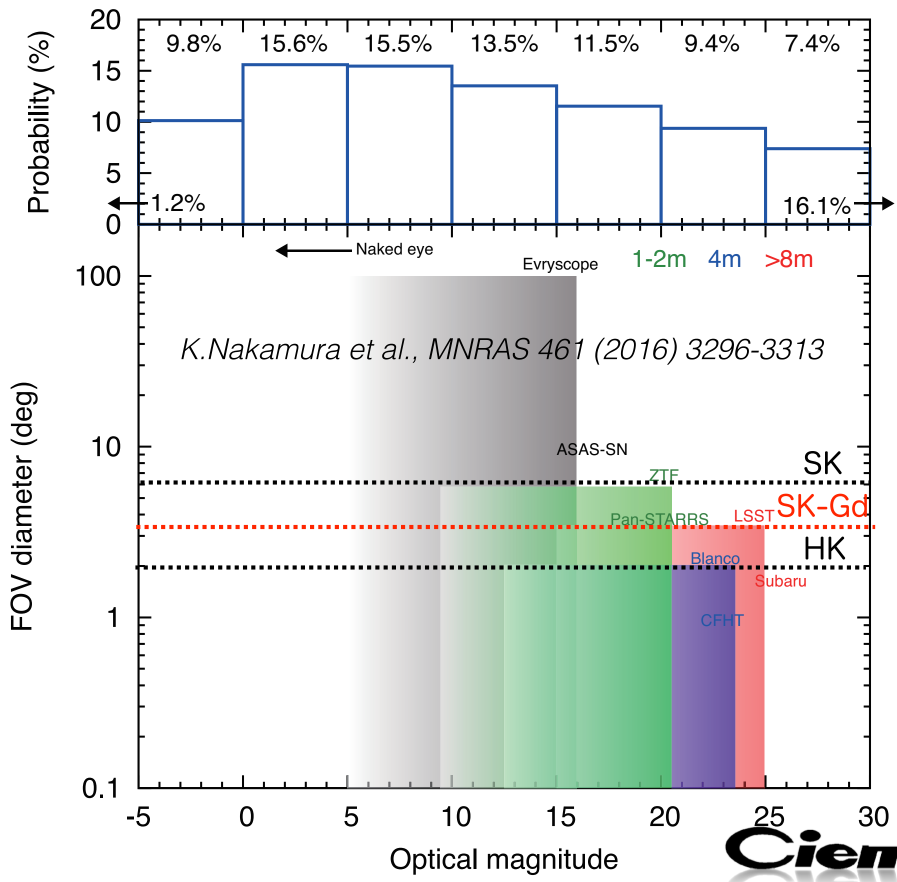
Thanks to Yusuke Koshio & Takatomi Yano

- **Super-K rates**: ~8000 evts (5 MeV thr.) for Livermore model and no-osc.
- Possibility to **improve neutron tagging with Gd** (0.1% Gd gives >90% efficiency for n-capture)

J.Beacom and M.Vagins, Phys.Rev.Lett.93 (2004) 171101

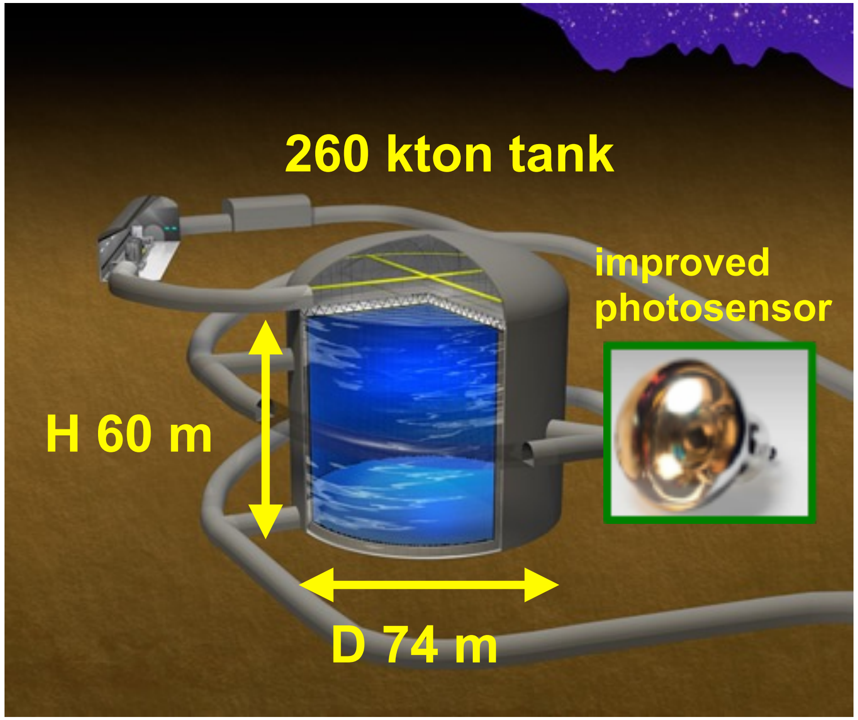


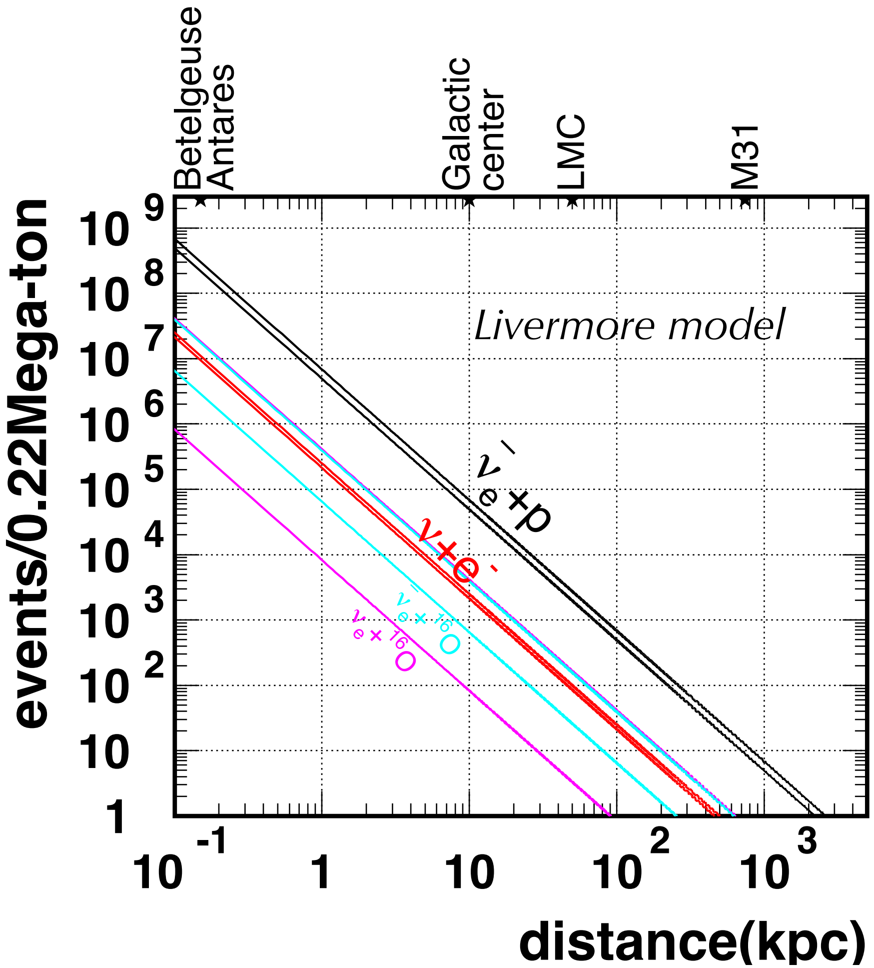




Hyper-K

Thanks to Yusuke Koshio & Takatomi Yano

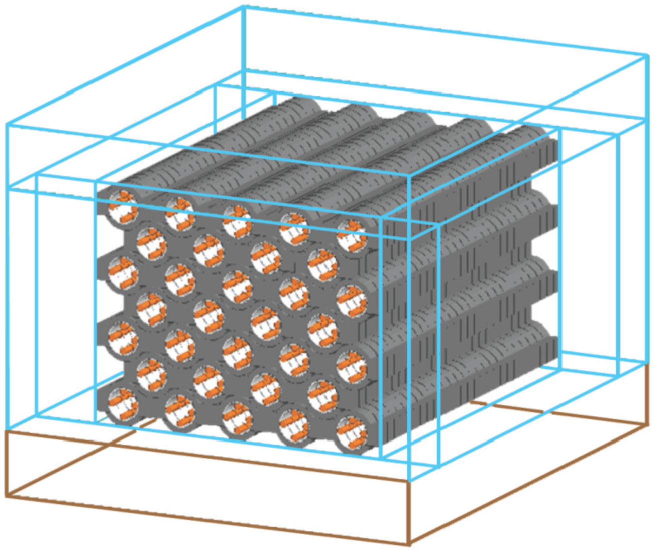




Hyper-K Design Report: arXiv:1805.04163

- High-statistics (x10 Super-K fiducial mass) keeping low energy threshold
- Aiming to start observation in 2027
- **Expected #events** (@10 kpc):
  - 49-68 kevts (IBD)
  - 2.1-2.5 kevts (ES) (6-40 neutronization)
  - 80-4100 evts (nue CC)
  - 650-3900 evts (anti-nue CC)

Heavy-nuclei detectors

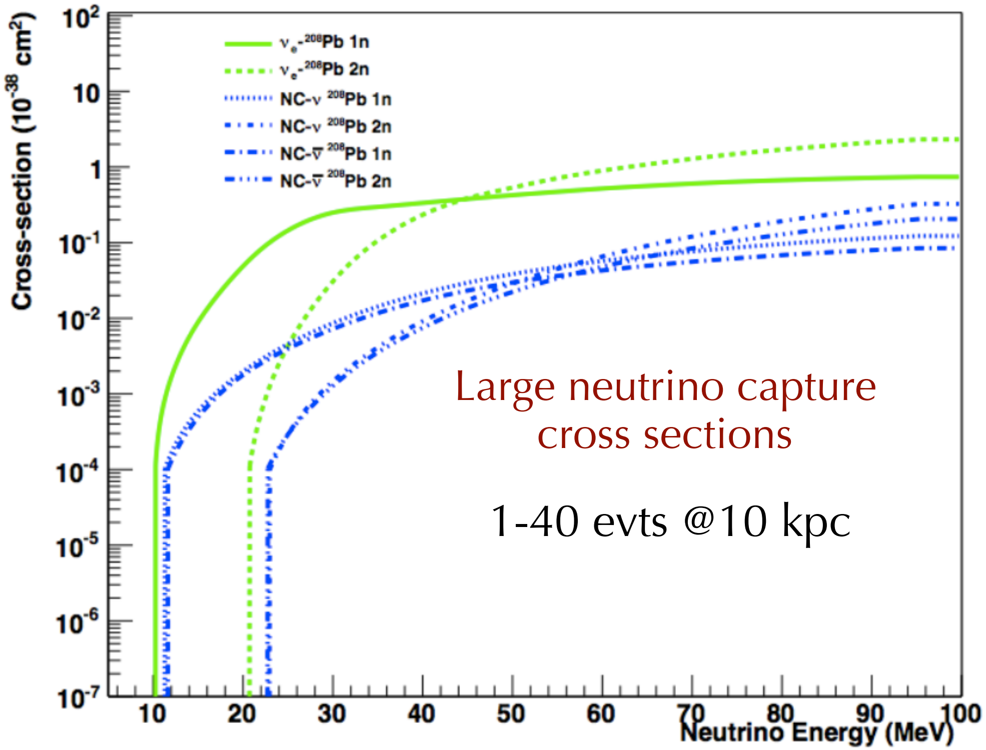


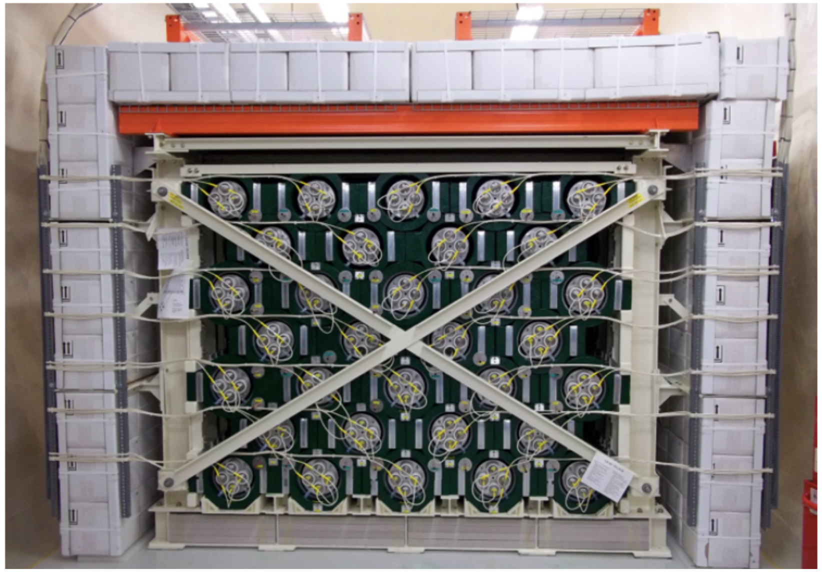
HALO (Helium and Lead Observatory)

- Lead-based SN detector at SNOLAB: SNO ^{3}He counters + 79 tons of Pb
- CC: $\nu_e + {}^{208}Pb \rightarrow e^- + {}^{208}Bi^*$
  - $\rightarrow$ (1n, 2n) + γ
- NC: $\nu_x + {}^{208}Pb \rightarrow \nu_x + {}^{208}Pb^*$
  - $\rightarrow$ (1n, 2n) + γ
- Running since 2013
- Integrated in SNEWS in 2015

Detection:

- **Neutron tagging**
  $^{3}He + n \rightarrow {}^{3}H + p + 764$ keV
- Low neutron capture cross section
- Not possible to distinguish between CC & NC





HALO-1kT at Gran Sasso: 1 kton lead detector (from OPERA decommissioning): ~300 interactions for a SN @10 kpc

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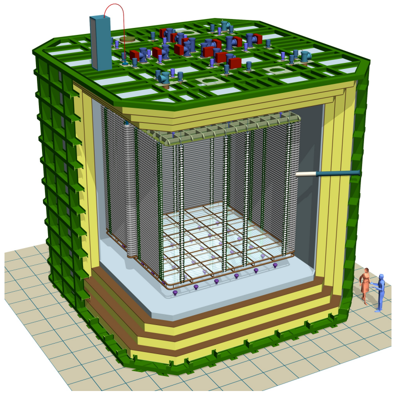
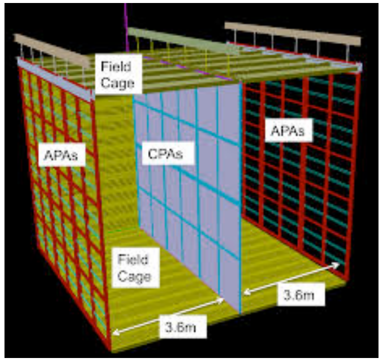
LAr TPC detectors

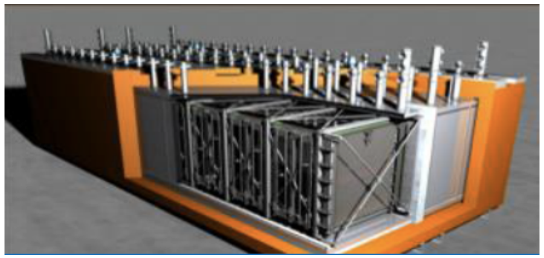
MicroBooNE: 89 ton



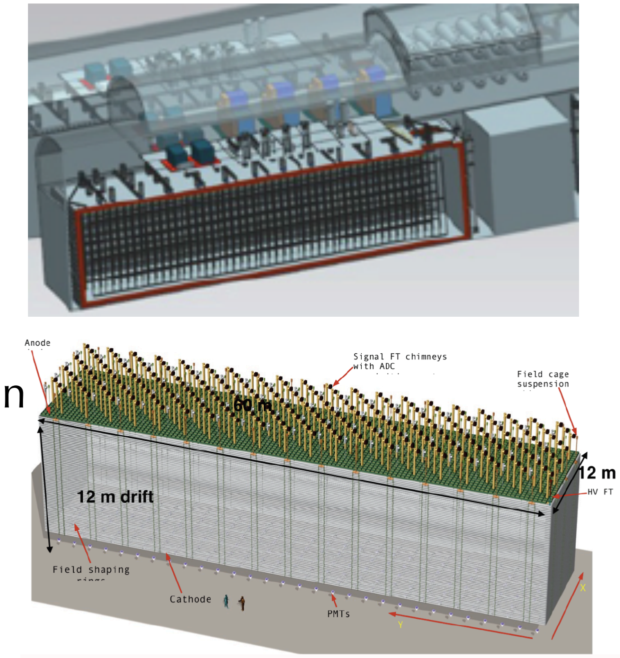
protoDUNE-DP: 300 ton



protoDUNE-SP: 300 ton



ICARUS: 476 ton



DUNE: 40 kton

SN neutrino signal in LAr

hep-ph/0307222
JCAP 10 (2003) 009
JCAP 08 (2004) 001
I.Gil-Botella & A.Rubbia

- Elastic scattering (ES) on electrons

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

- Charged-current (CC) interactions on Ar

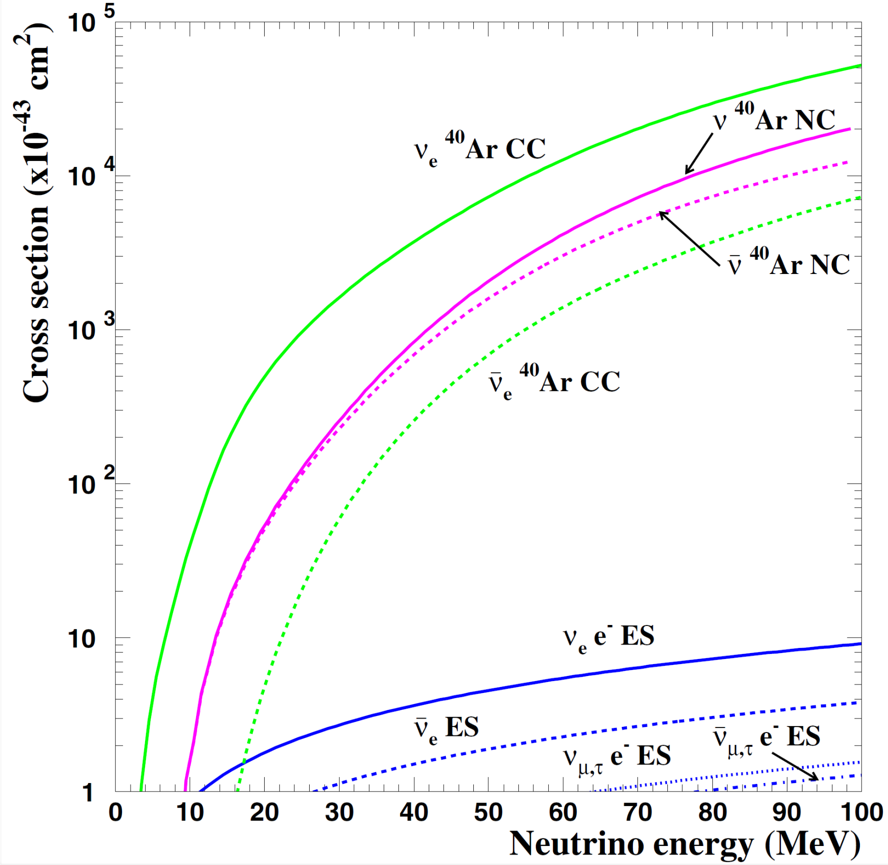
$$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^- \qquad E\nu_e > 1.5\ MeV$$

$$\bar{\nu}_e + {}^{40}Ar \rightarrow {}^{40}Cl^* + e^+ \qquad E\bar{\nu}_e > 7.48\ MeV$$

- Neutral current (NC) interactions on Ar

$$\nu + {}^{40}Ar \rightarrow \nu + {}^{40}Ar^* \qquad E\nu > 1.46\ MeV$$

SN ν cross sections on Ar



Possibility to separate the different channels by a classification of the associated photons from the K, Cl or Ar de-excitation (specific spectral lines for CC and NC) or by the absence of photons (ES)

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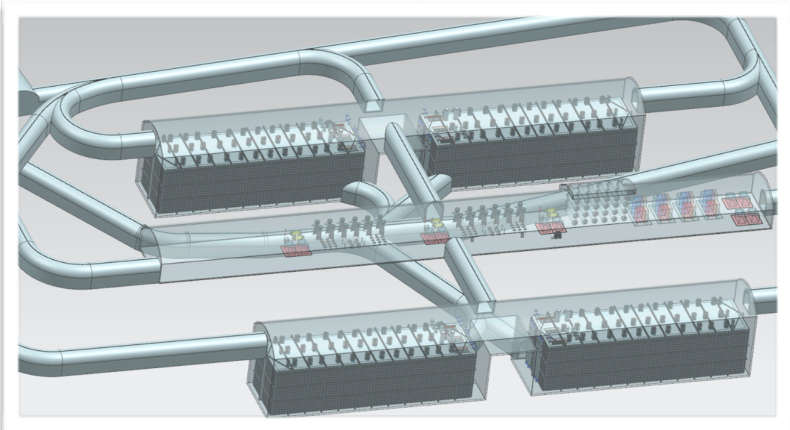
DEEP UNDERGROUND NEUTRINO EXPERIMENT

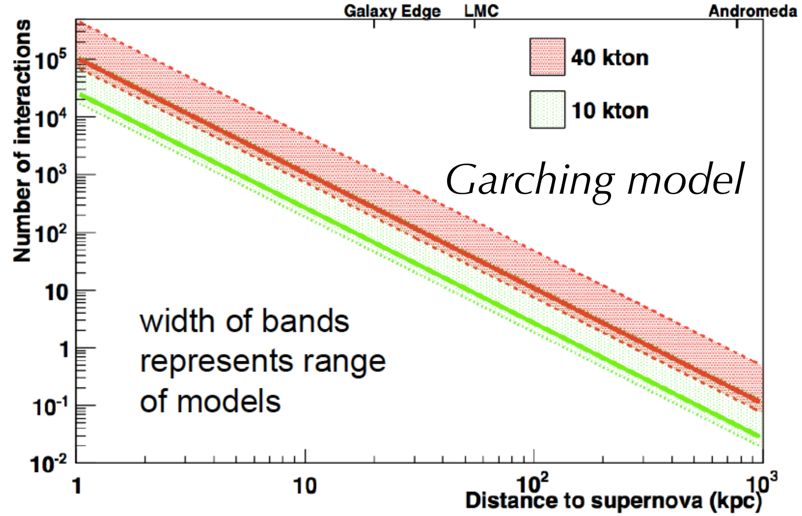
Far Detector at SURF

- **Deep Underground Neutrino Experiment**: **40 kton LAr TPC** detector at 1480 m depth (4300 mwe)
  - 4 x 10 kton (single/dual-phase) LAr TPCs with ability to detect SN burst neutrinos (+ nucleon decay, LBL osc., atmospheric neutrinos)
  - First module installation begins in 2022



- Unique sensitivity to **electron neutrinos**
- Event **rates in DUNE for a core-collapse SN at 10 kpc**

Channel	Events "Livermore" model	Events "GKVM" model
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	2720	3350
$\overline{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	230	160
$\nu_x + e^- \rightarrow \nu_x + e^-$	350	260
Total	3300	3770
	no oscillations	*collective effects*



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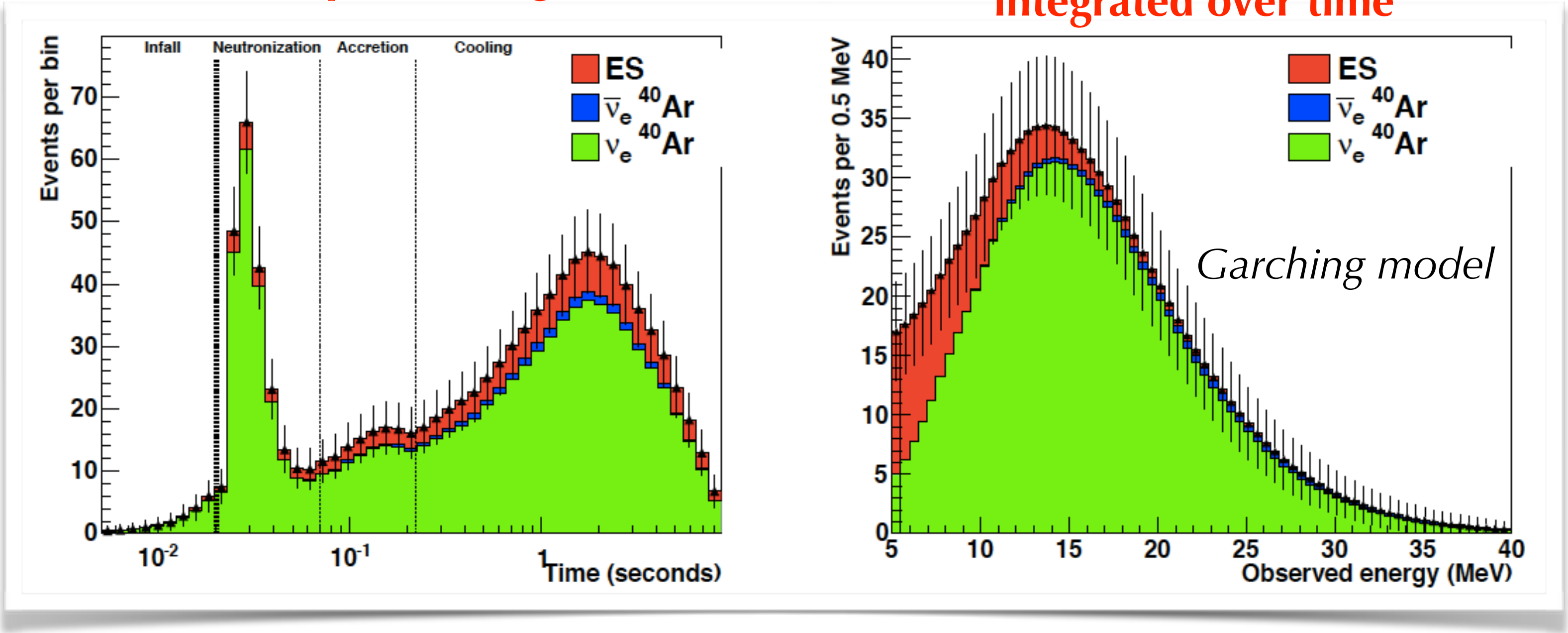
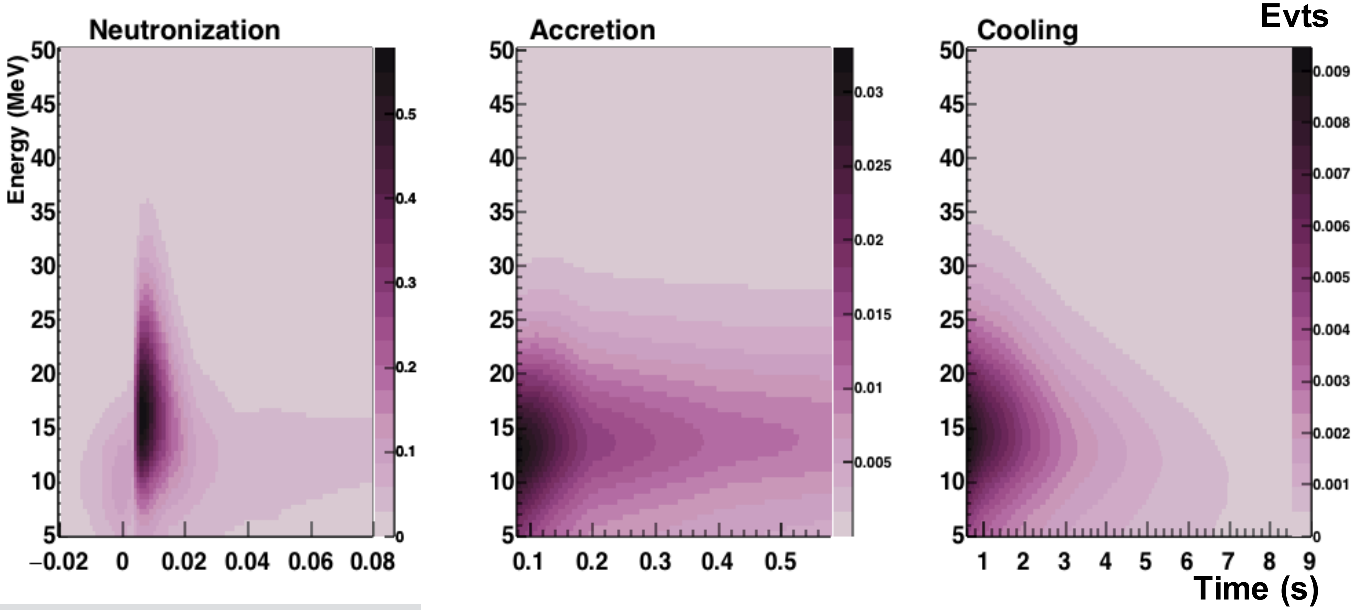
40 kton LAr (SN @10 kpc)

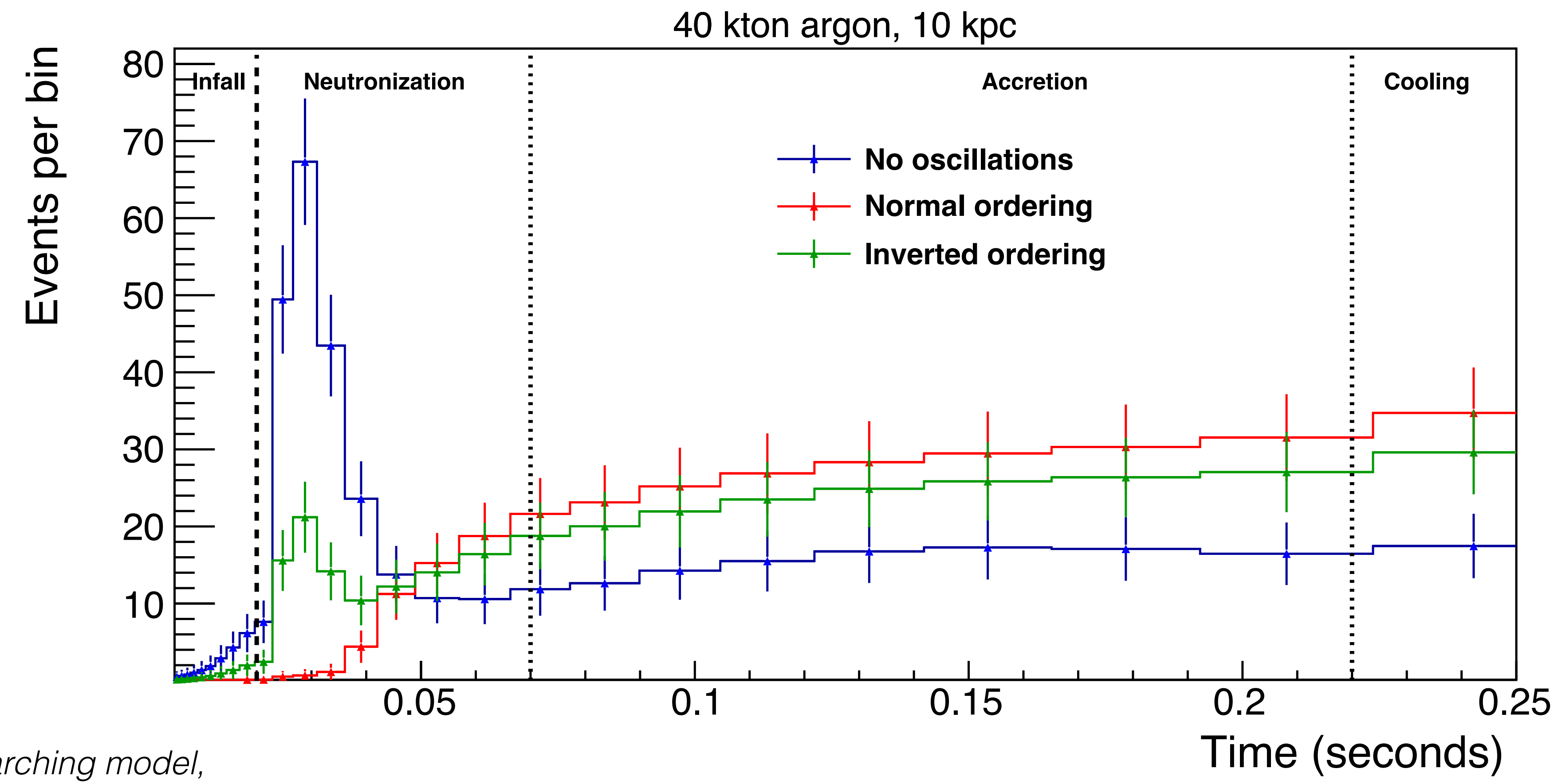
Time-dependent signal *no oscillations* **Expected event spectrum integrated over time**





Neutronization burst

DUNE will provide unique information about the early breakout pulse thanks to its sensitivity to electron neutrinos



Garching model, MSW transitions only, total events (mostly ν_e)

Robust mass ordering signature

Pros & cons

😊	😩	😊	😩
Liquid scintillators		**Water Cerenkov**	
• Electron antineutrino sensitivity • Good n tagging • Low energy threshold • Good energy resolution • Very well known IBD int.	• Poor directionality • Low energy vulnerable to backgrounds	• Electron antineutrino sensitivity • Potentially good n tagging w/ Gd • Directionality • Very large mass • Good timing (long strings)	• Cherenkov threshold limits reconstruction • Relatively high energy threshold • Difficult to disentangle channels • No event-by-event reconstruction (long-strings)
Heavy nuclei		**Liquid Argon**	
• Electron neutrino sensitivity • Cheap material	• No event-by-event reconstruction • No tagging • No directionality • Small mass	• Electron neutrino sensitivity • Some other flavours • Potentially good tagging • Potentially good reconstruction • Some directionality	• Technology under development • Capabilities still unknown • Statistics limited

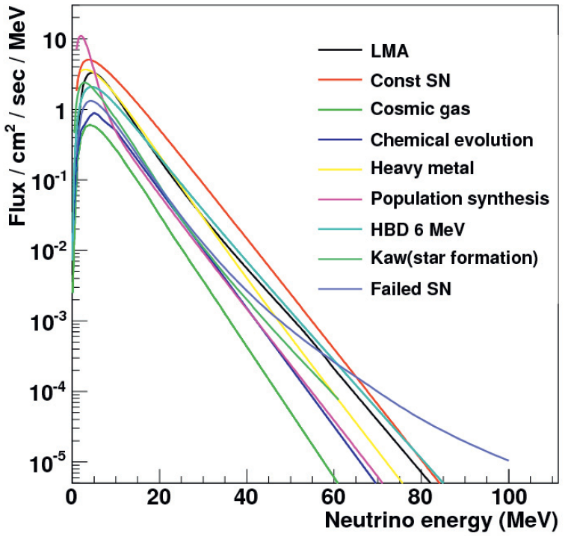
Complementarity

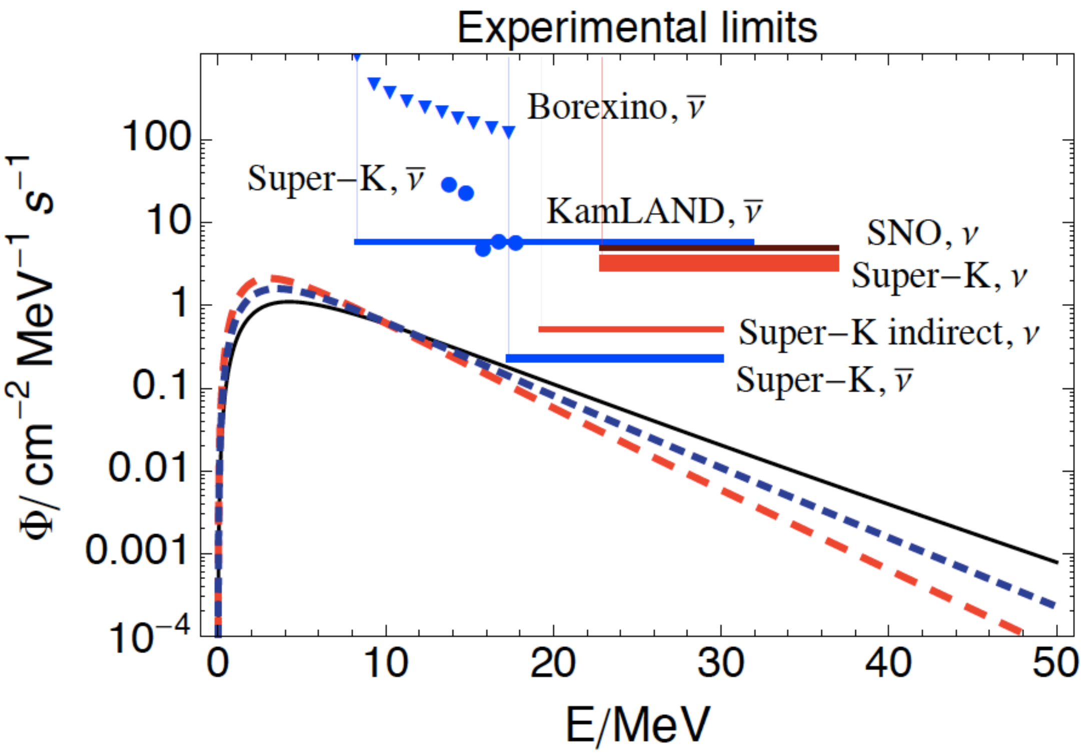
Ciemat

Diffuse Supernova Neutrino Background

- Diffuse SN neutrino background (DSNB) from all the SN explosions in the Universe → **guaranteed steady source of SN neutrinos**
- **Not detected yet** (same detection interactions as for burst νs)
- Main experimental issue: **backgrounds**

Different theoretical DSNB models





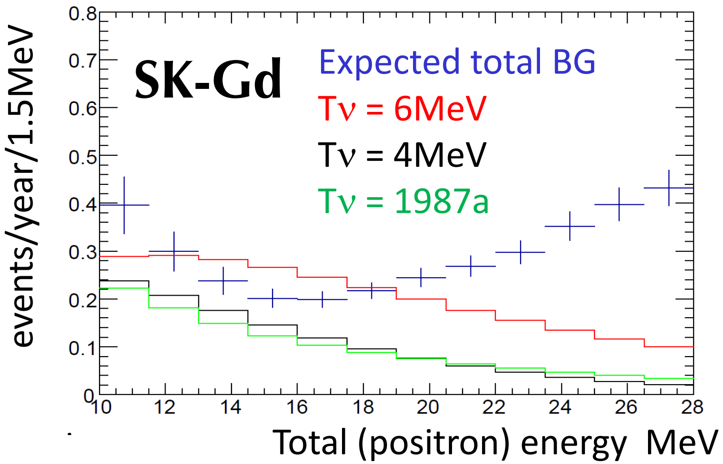
C. Lunardini, Astropart. Phys. 79 (2016) 49-77

DSNB in WC

Thanks to Yusuke Koshio & Takatomi Yano

DSNB flux:
Horiuchi, Beacom and Dwek,
PRD, 79, 083013 (2009)

- It depends on typical/actual SN emission spectrum

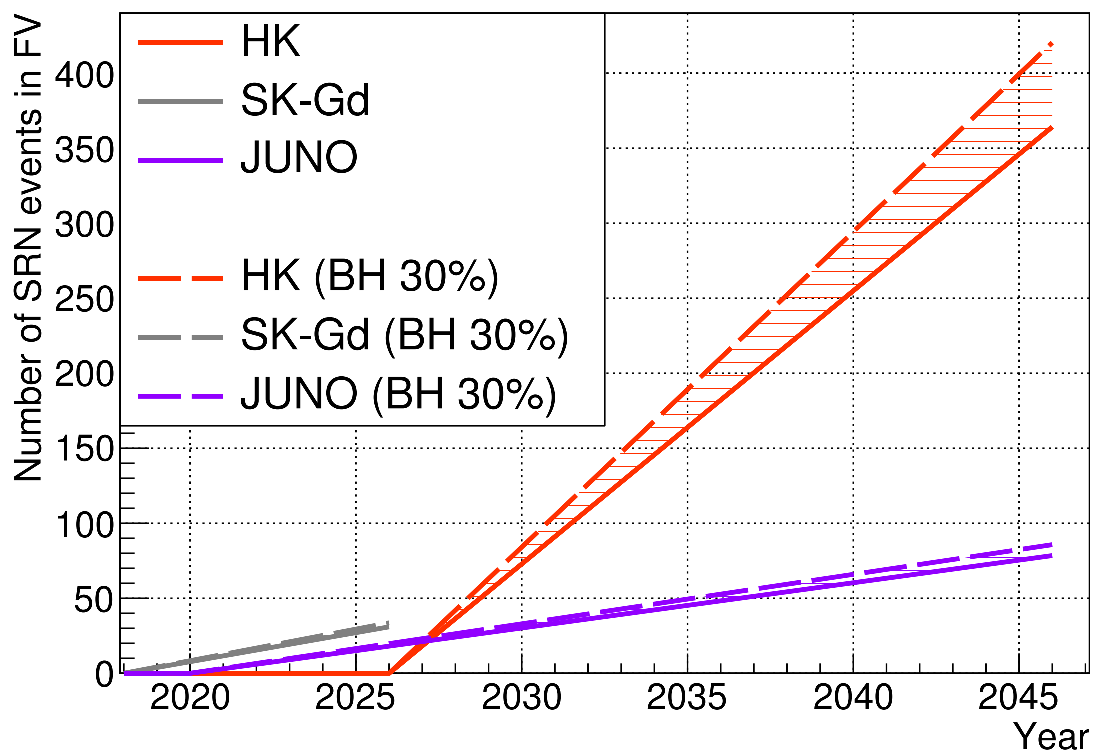


Hyper-K aims to measure the spectrum of DSNB

DSNB events number with 10 years observation

HBD models	10-16MeV (evts/10yrs)	16-28MeV (evts/10yrs)	Total (10-28MeV)	significance (2 energy bin)
T_{eff} 8MeV	11.3	19.9	31.2	5.3 σ
T_{eff} 6MeV	11.3	13.5	24.8	4.3 σ
T_{eff} 4MeV	7.7	4.8	12.5	2.5 σ
T_{eff} SN1987a	5.1	6.8	11.9	2.1 σ
BG	10	24	34	----

detection efficiency is not considered



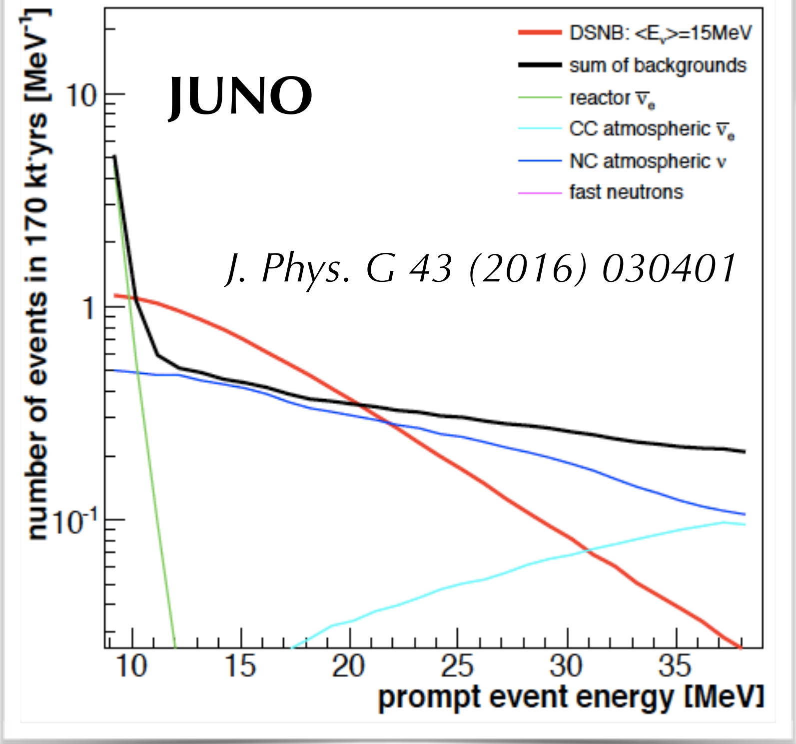
DSNB in LSc

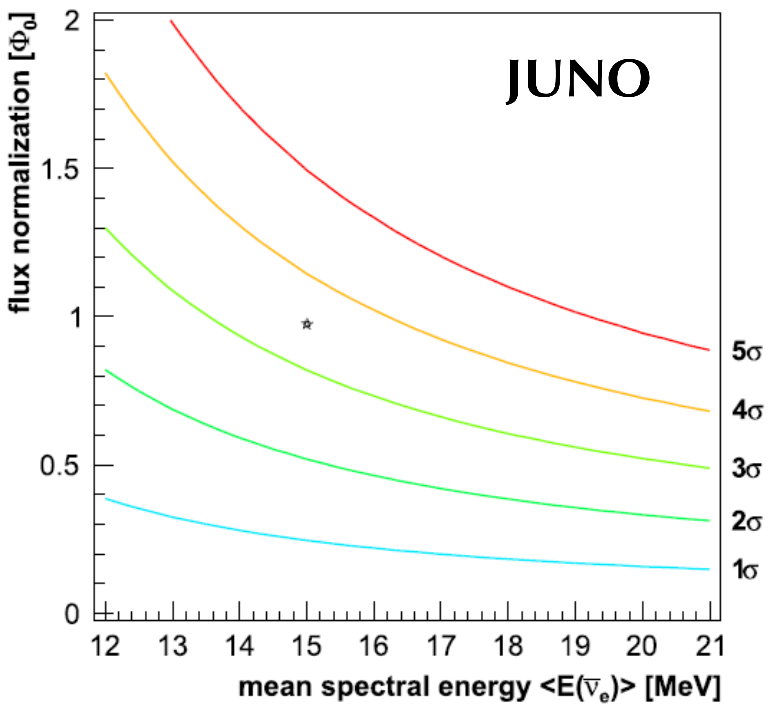
Thanks to Liangjian Wen

KamLAND best limit (90% CL):
$f(\nu_e) < 3.7 \times 10^2\ cm^{-2}s^{-1}$ for $8.3 < E_\nu < 14.8$ MeV

- Few events per year are expected in JUNO
- *Main backgrounds*: atmospheric and reactor ν_e
  - atm NC & fast neutrons can be identified and reduced
- Discovery potential: 3σ level for 17 kton x 10 y (syst uncertainty on BG: 5%)

Pulse shape discrimination applied





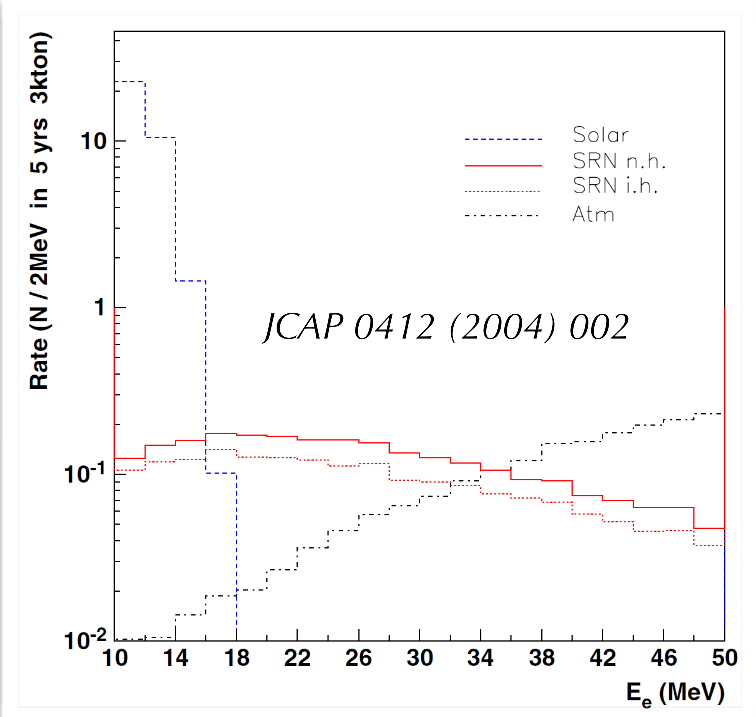
10 Years' sensitivity

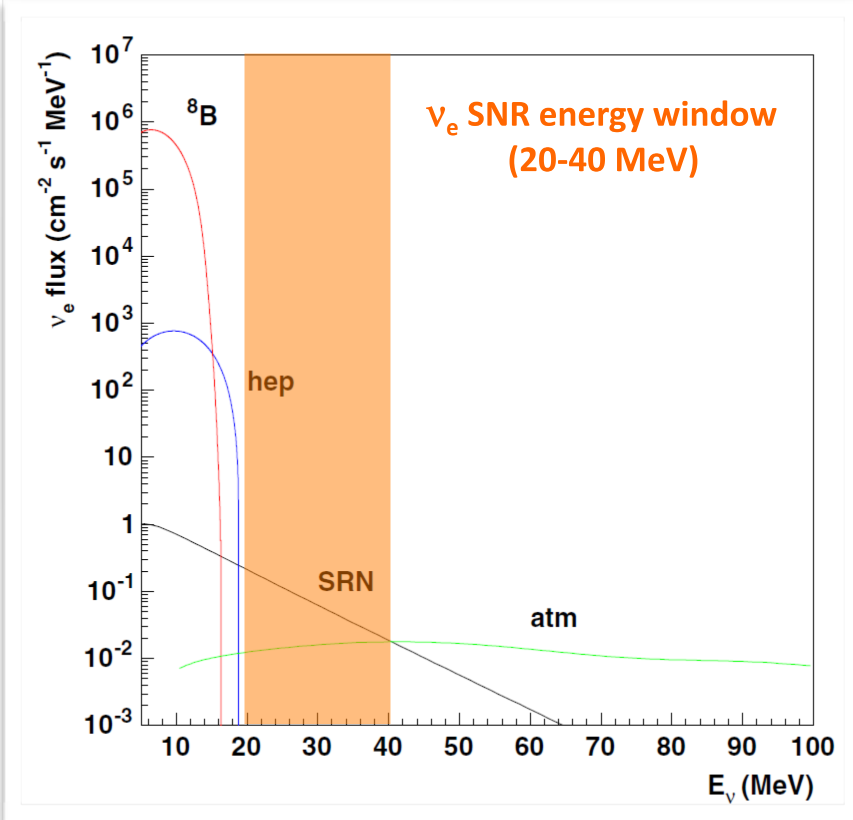
Syst. uncertainty BG	5%		20%	
$\langle E_{\bar{\nu}_e} \rangle$	Rate only	Spectral fit	Rate only	Spectral fit
12 MeV	2.3 σ	2.5 σ	2.0 σ	2.3 σ
15 MeV	3.5 σ	3.7 σ	3.2 σ	3.3 σ
18 MeV	4.6 σ	4.8 σ	4.1 σ	4.3 σ
21 MeV	5.5 σ	5.8 σ	4.9 σ	5.1 σ

Ciemat

DSNB in LAr

- LAr TPCs can detect relic neutrinos through **ν_eCC interactions**
- *Main background*: solar and atmospheric neutrinos
- **DUNE**, in 10 years, n.h.
  N_{DSNB}= 46 ± 10 (16 MeV ≤ E_e ≤ 40 MeV)





DSNB flux prediction based on Strigari et al., JCAP03 (2004) 007

3 kton, 5y, n.h.

N_{DSNB} = 1.7 ± 1.6 evts (16 ≤ E_e ≤ 40 MeV)
$f(\nu_e) < 1.6$ $cm^{-2}s^{-1}$ (90% CL)

100 kton, 5y, n.h

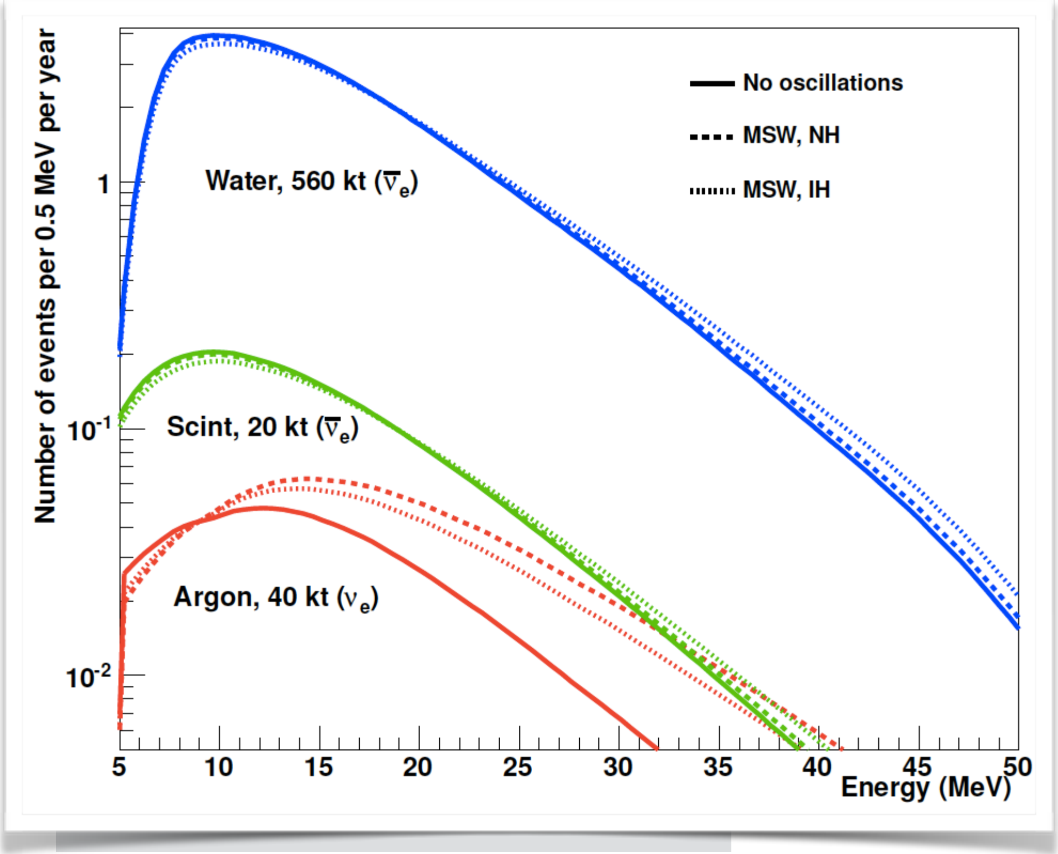
N_{DSNB} = 57 ± 12 evts (16 ≤ E_e ≤ 40 MeV) 4σ measurement

Comparison between technologies

LAGUNA Design Study
JCAP 0711 (2007) 011

Interaction	Exposure	Energy Window	Signal/Bkgd
GLACIER $\nu_e + {}^{40}Ar \to e^- + {}^{40}K^*$	0.5 Mton year 5 years	$[16-40]$ MeV	(40-60)/30
LENA at Pyhasalmi $\bar{\nu}_e + p \to n + e^+$ $n + p \to d + \gamma$ (2 MeV, 200 μs)	0.4 Mton year 10 years	$[9.5-30]$ MeV	(20-230)/8
1 MEMPHYS module + 0.2% Gd (with bkgd at Kamioka) $\bar{\nu}_e + p \to n + e^+$ $n + Gd \to \gamma$ (8 MeV, 20 μs)	0.7 Mton year 5 years	$[15-30]$ MeV	(43-109)/47

Expected DSNB interaction rates



Mirizzi et al., Riv. Nuov. Cim. 39, N. 1-2 (2016)

Conclusions

- Detection of SN neutrino events is one of the main goals of current and future large underground detectors
- SN neutrinos can provide information about fundamental processes related to SN physics and neutrino properties
- The understanding of the SN explosion mechanism and the neutrino flavor transformations is still in progress (spectacular advance of theoretical models) but new experimental inputs are needed
- Important to understand the different SN ν detection channels (cross-sections, signatures, directionality, reconstruction, timing, etc.) and a good detector response in terms of time, flavor and energy
- Complementarity between different detector technologies will be crucial