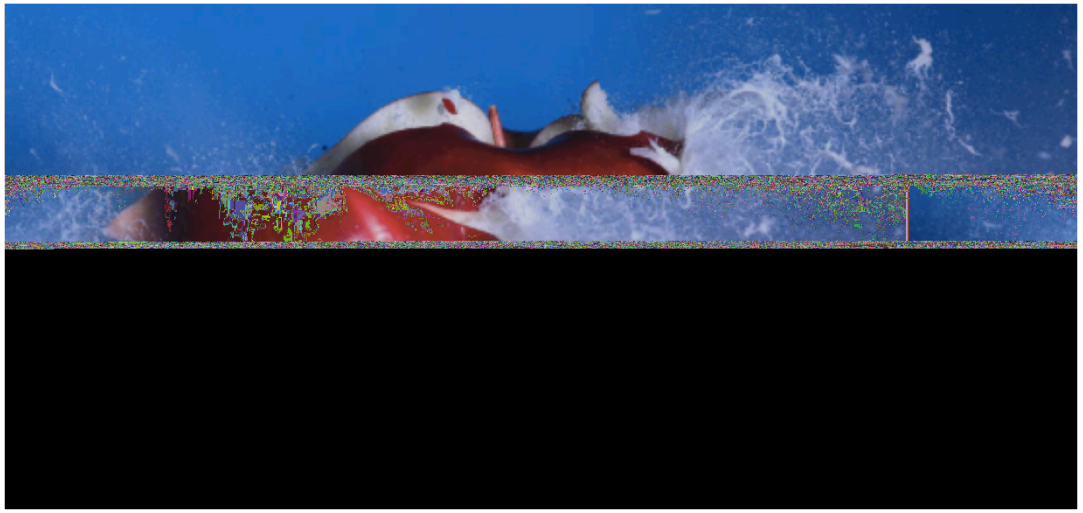
Lecture overview

Lecture 1: general principles of neutrino interactions and particle detection

Lecture 2: neutrinos at GeV energies

Lecture 3: neutrinos at MeV energies

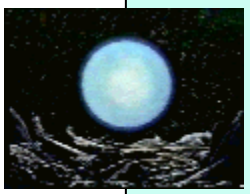
Moving to a (somewhat) gentler regime...



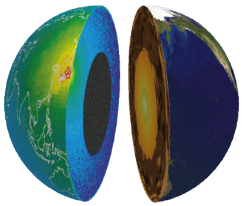
~GeV+ neutrinos can create a quite a mess ...

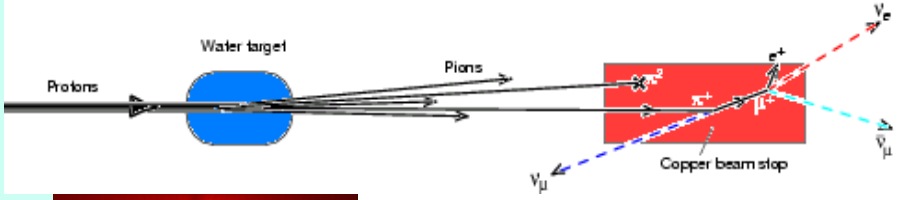
~tens of MeV neutrinos are not as disruptive, but still leave non-trivial debris ...

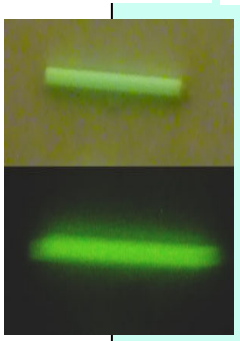
Zoom in to the ~ MeV energy range

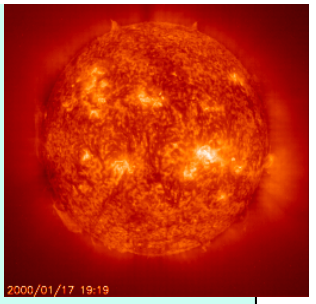


eV keV MeV GeV TeV

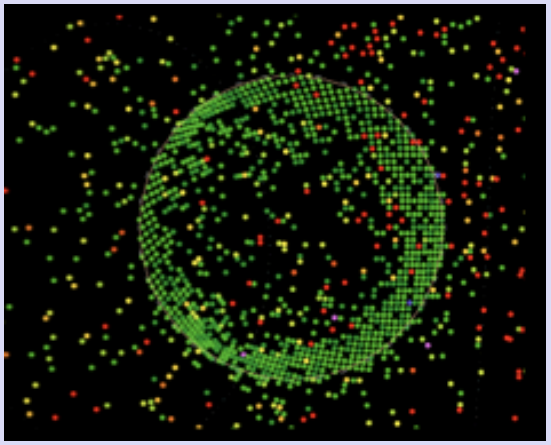


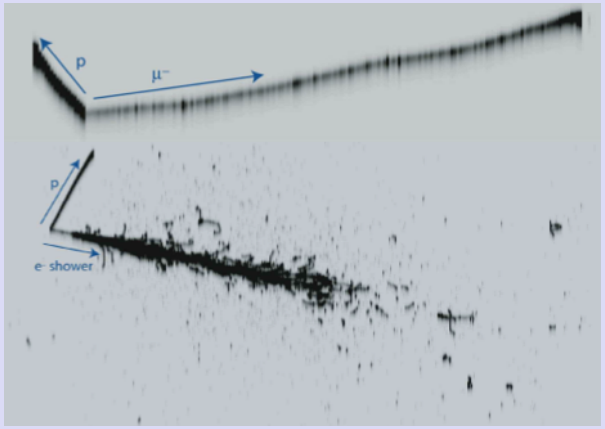




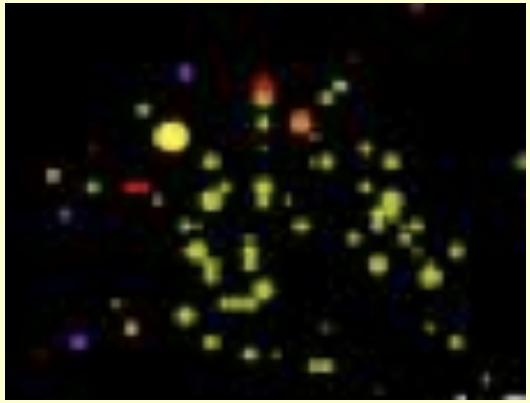


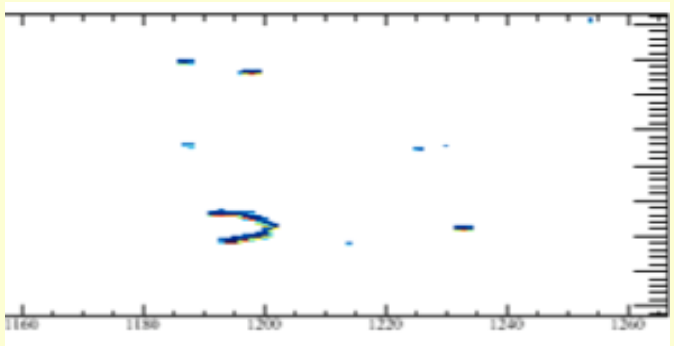
GeV-scale events: handsome and distinctive





MeV-scale events: crummy little stubs

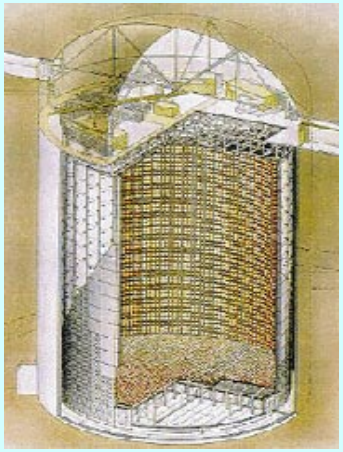


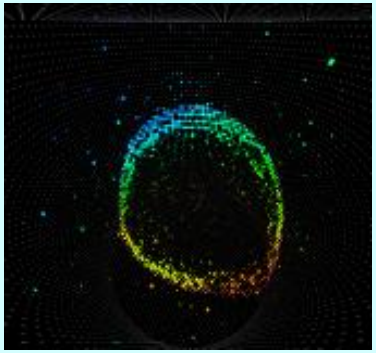


hungry for visible dE/dx!

Large (multi-kton) detector for low energy neutrinos?

Water Cherenkov

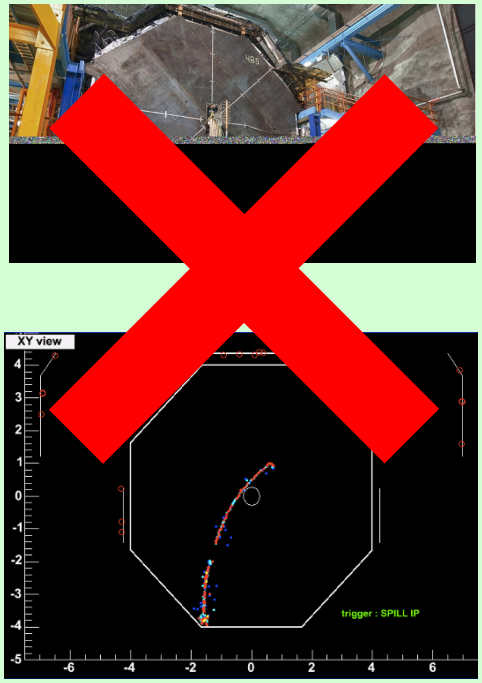




Cheap material, proven at very large scale

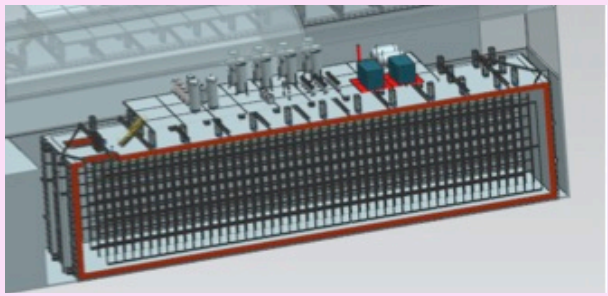
Trackers

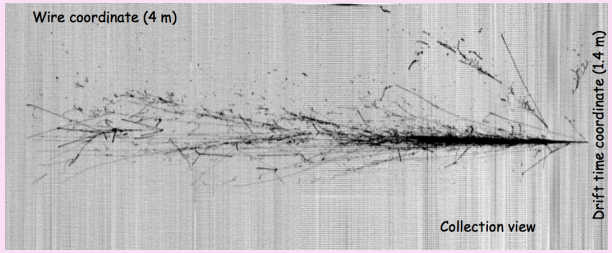
(a diverse category)



Not good for low energies (with some exceptions)

Liquid Argon

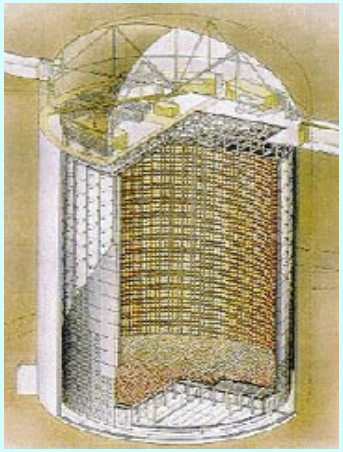


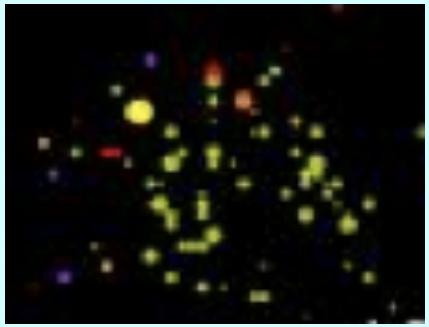


Excellent particle reconstruction

Large (multi-kton) detector technologies for low energies

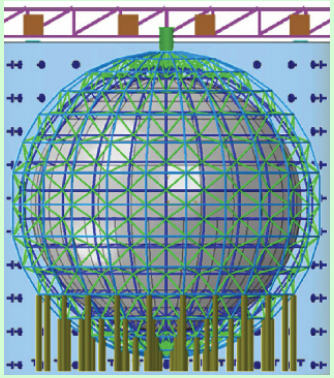
Water Cherenkov

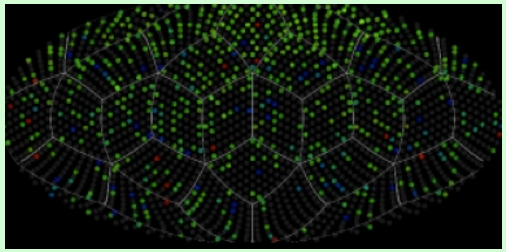




Cheap material, proven at very large scale

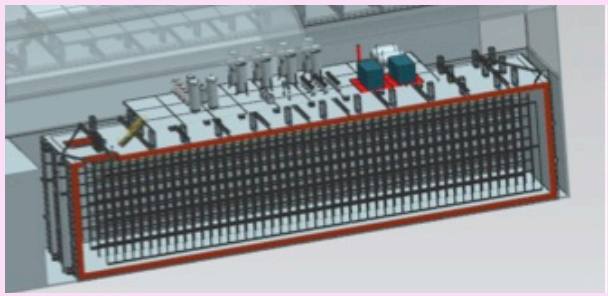
Liquid scintillator

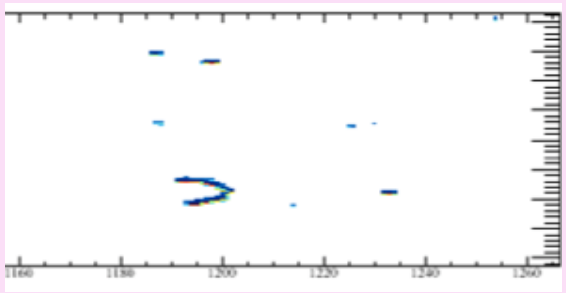




Low threshold, good energy resolution

Liquid Argon





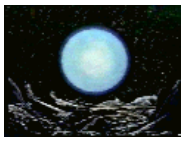
Good particle reconstruction

+ some other detector types for specific uses

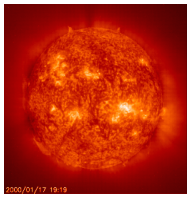
Low energy neutrinos are much more vulnerable to background (cosmogenics, radioactivity)

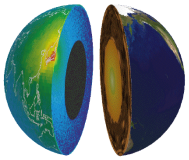
Almost always need some overburden, or else good signal selection strategy (or both...)
... and often need extreme cleanliness

Physics/astrophysics of interest in this energy range (few to few tens of MeV)



Supernova neutrinos: burst and “relic”

Solar neutrinos 



Geoneutrinos

Reactor neutrinos

Radioactive sources

Stopped-pion neutrinos

} today

I will start with supernova neutrinos and go into more detail for those...
in large part, similar techniques for the others.
Will discuss physics to motivate detection technique

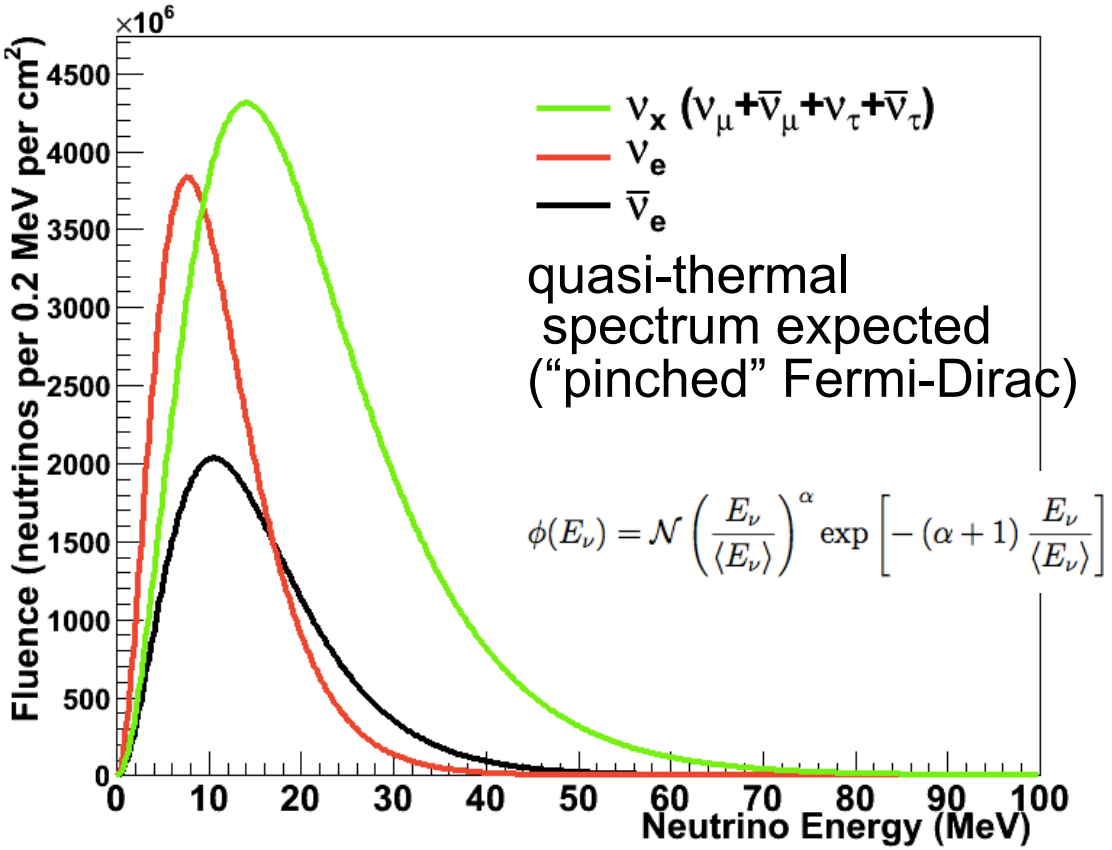
Neutrinos from core collapse

When a star's core collapses, ~99% of the gravitational binding energy of the proto-nstar goes into ν's of ***all flavors*** with **~tens-of-MeV energies**

(Energy *can* escape via ν's)

Mostly ν-$\bar{\nu}$ pairs from proto-nstar cooling

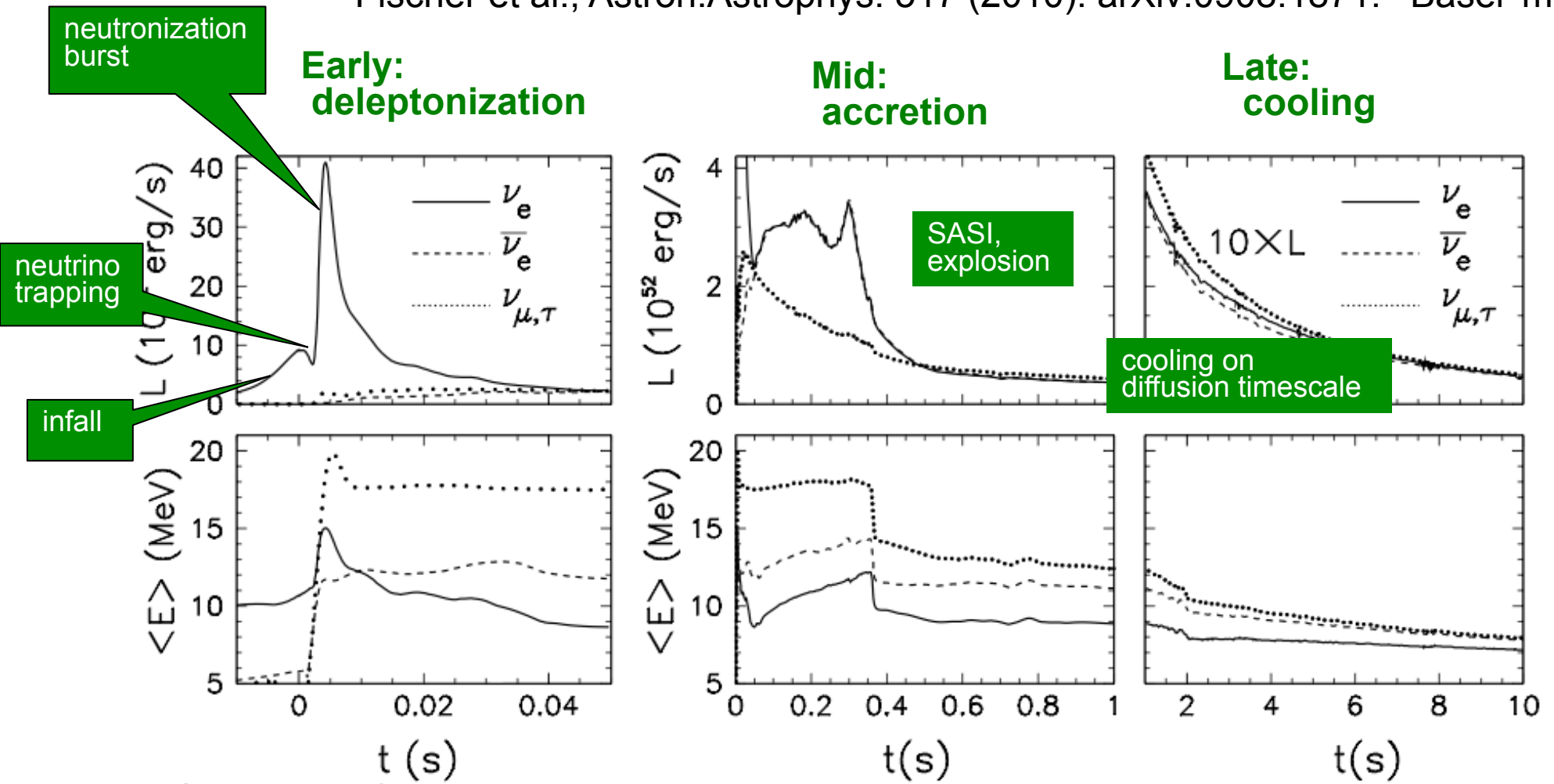
Timescale: ***prompt*** after core collapse, overall **Δt~10's of seconds**



Expected neutrino luminosity and average energy vs time

Vast information in the *flavor-energy-time profile*

Fischer et al., Astron.Astrophys. 517 (2010). arXiv:0908.1871: 'Basel' model



Generic feature:
(may or may not be robust)

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

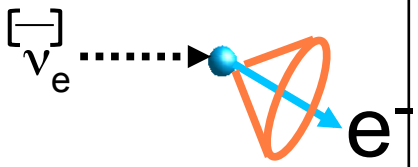
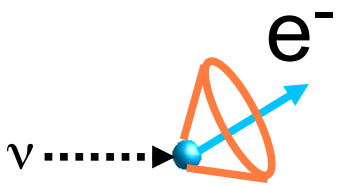
What do you want in a detector for a supernova burst?

Information is in the ***energy, flavor, time*** structure of the supernova burst

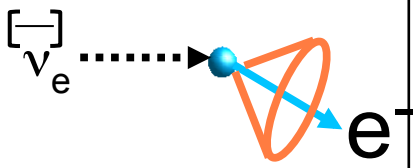
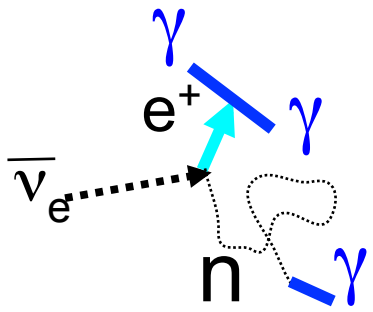
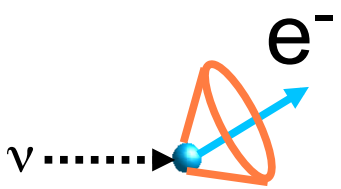
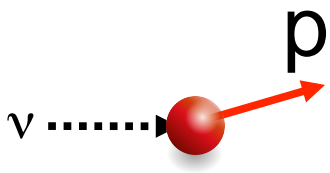
Size	~kton detector mass per 100 events @ 10 kpc
Low energy threshold	~Few MeV if possible
Energy resolution	Resolve features in spectrum
Angular resolution	Point to the supernova! (for directional interactions)
Timing resolution	Follow the time evolution
Low background	BG rate << rate in burst; underground location usually excellent; surface detectors conceivably sensitive
Flavor sensitivity	Ability to **tag** flavor components
High up-time and longevity	Can't miss a ~1/30 year spectacle!

Note that many detectors have a "day job"...

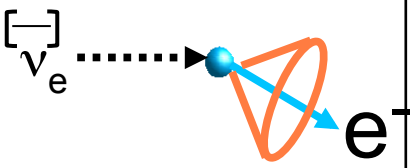
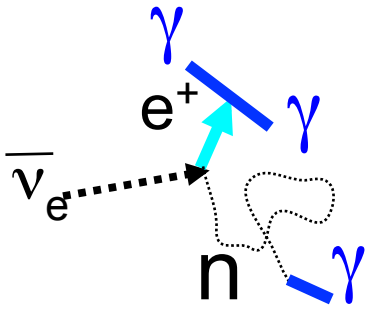
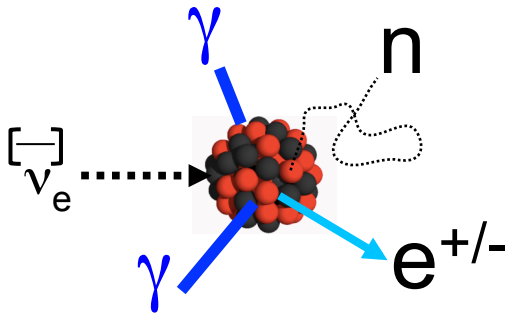
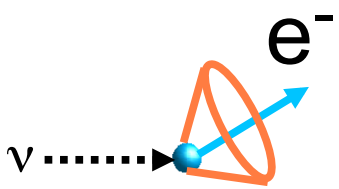
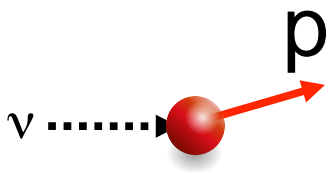
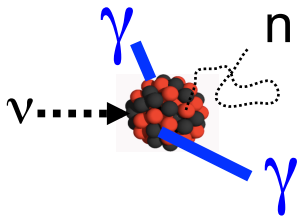
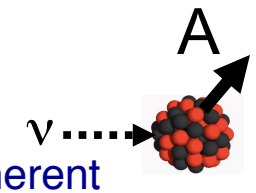
Neutrino interactions in the ~10 MeV range

	Electrons		
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 		
Neutral current	 Useful for pointing		

Neutrino interactions in the ~10 MeV range

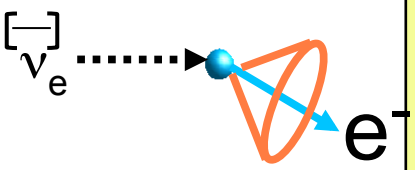
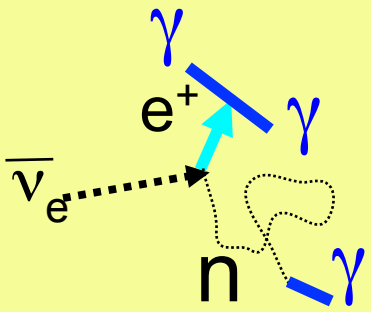
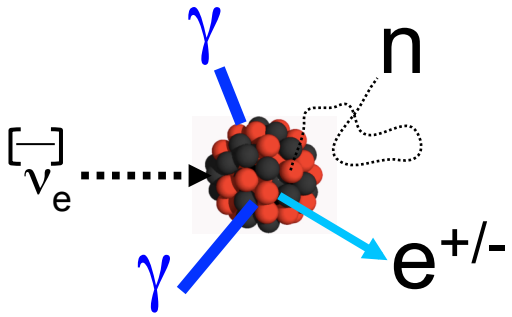
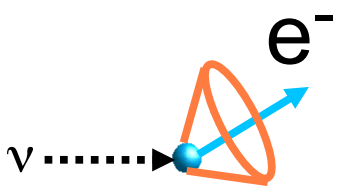
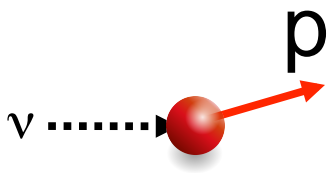
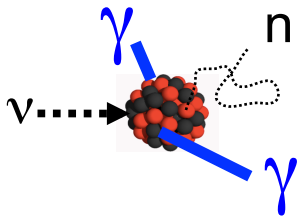
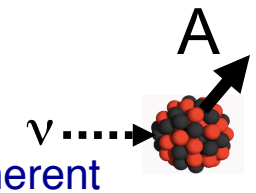
	Electrons	Protons	
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	

Neutrino interactions in the ~10 MeV range

	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	$\nu_e + (N,Z) \rightarrow e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N,Z) \rightarrow e^+ + (N+1, Z-1)$ 
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	$\nu + A \rightarrow \nu + A^*$  $\nu + A \rightarrow \nu + A$  Coherent elastic (CEvNS)

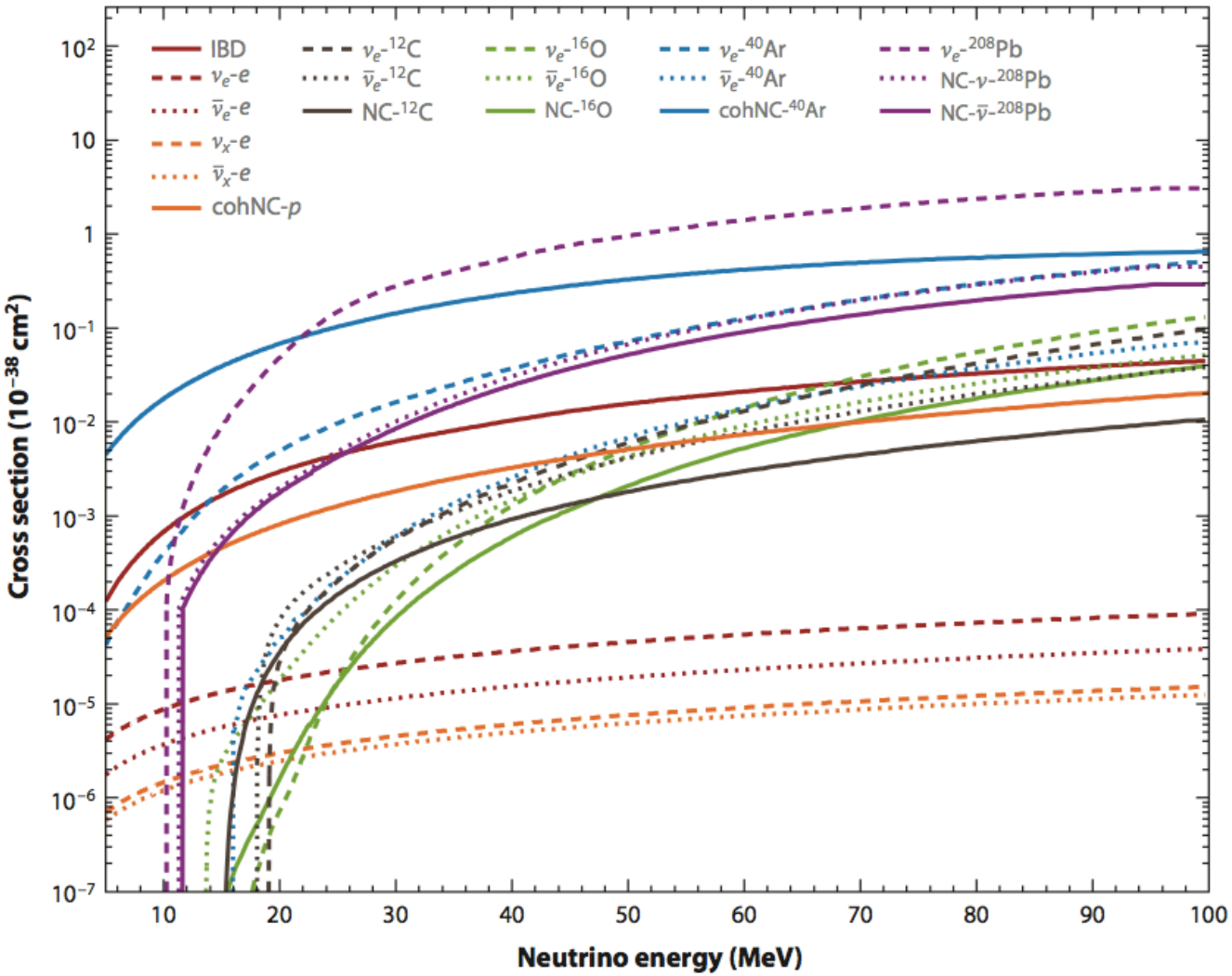
Various possible ejecta and deexcitation products

Neutrino interactions in the ~10 MeV range

	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	$\nu_e + (N, Z) \rightarrow e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	$\nu + A \rightarrow \nu + A^*$  $\nu + A \rightarrow \nu + A$  Coherent elastic (CEvNS)

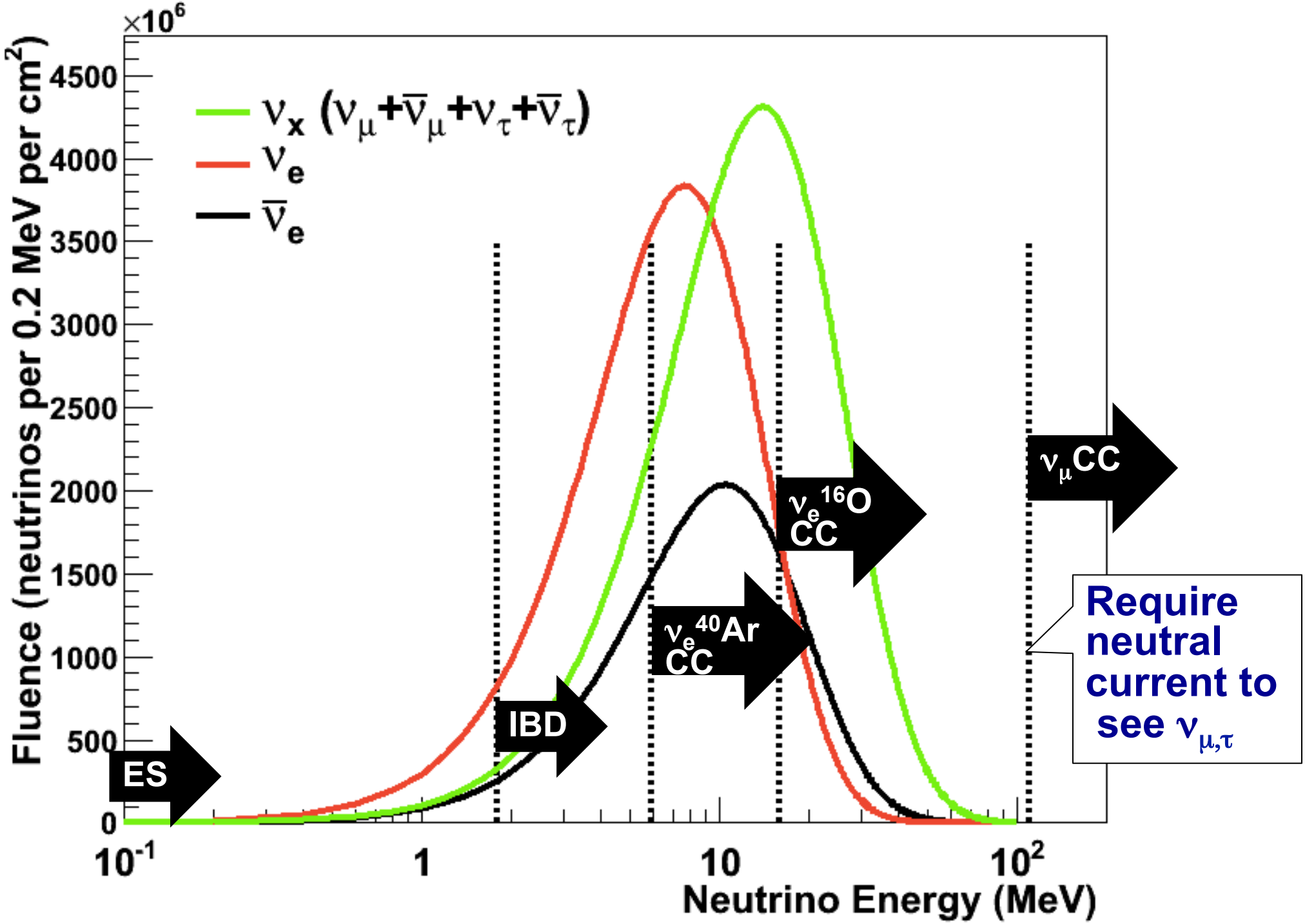
IBD (electron *anti*neutrinos) dominates for current detectors

Cross-sections in this energy range



Of these, only IBD and ES on electrons well understood theoretically (or experimentally)...

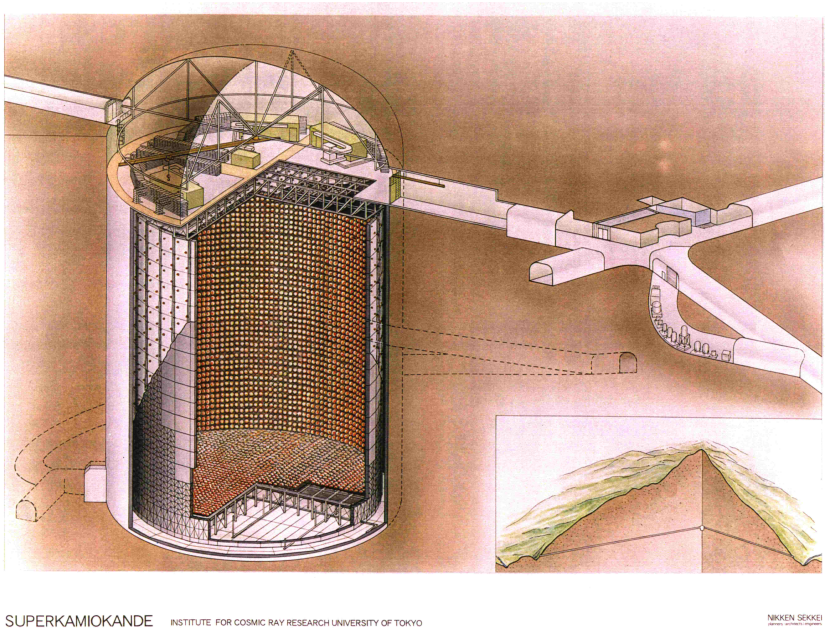
Neutrino interaction thresholds



Current main supernova neutrino detector types

Water	Scintillator
Argon	**Lead**

+ some others (e.g. DM detectors)



Super-Kamiokande

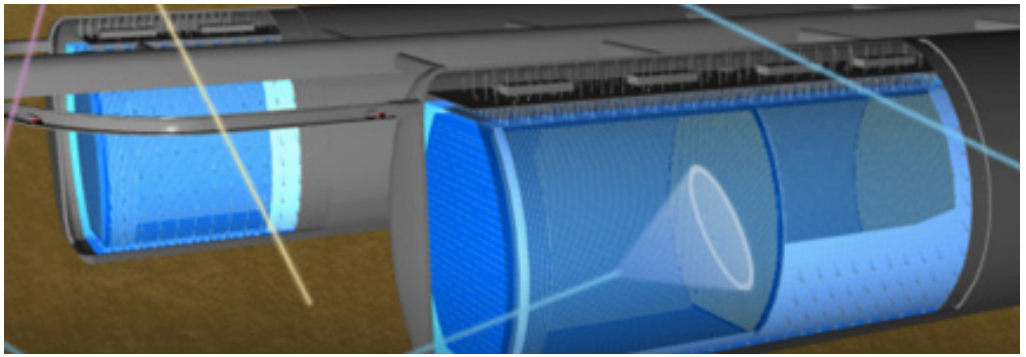
Mozumi, Japan

22.5 kton fid. volume (32 kton total)

~5-10K events @ 10 kpc

(mostly anti-ν_e)

~5^o pointing @ 10 kpc



Hyper-Kamiokande

560 kton fiducial volume

Design & site-selection underway

~half photocoverage, but still good efficiency for SN

Neutron tagging in water Cherenkov detectors

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

detection of neutron tags event as *electron antineutrino*

- especially useful for DSNB (which has low signal/bg)
- also useful for disentangling flavor content of a burst
  (improves pointing, and physics extraction)

R. Tomas et al., PRD68 (2003) 093013
KS, J.Phys.Conf.Ser. 309 (2011) 012028; LBNE collab arXiv:1110.6249
R. Laha & J. Beacom, PRD89 (2014) 063007

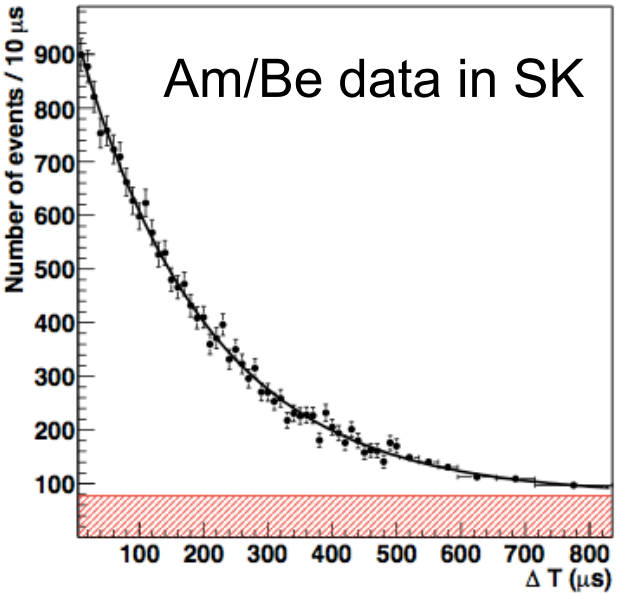
"Drug-free" neutron tagging

$$n + p \rightarrow d + \gamma(2.2\ \mathrm{MeV})$$

~200 μs thermalization & capture, observe Cherenkov radiation from γ Compton scatters

➔ with SK-IV electronics, ~18% n tagging efficiency

SK collaboration, arXiv:1311.3738;



Enhanced performance by doping!

use gadolinium to capture neutrons

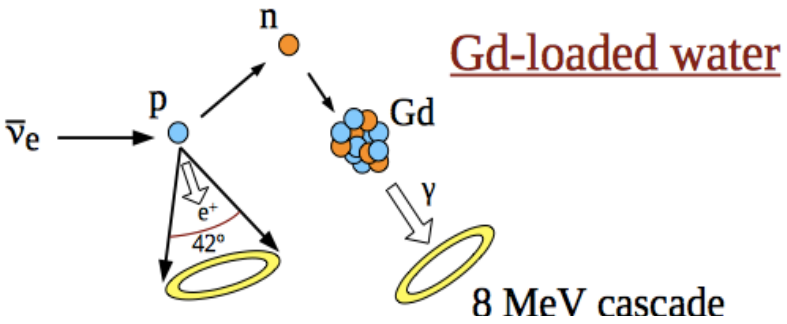
(common strategy for scintillator)

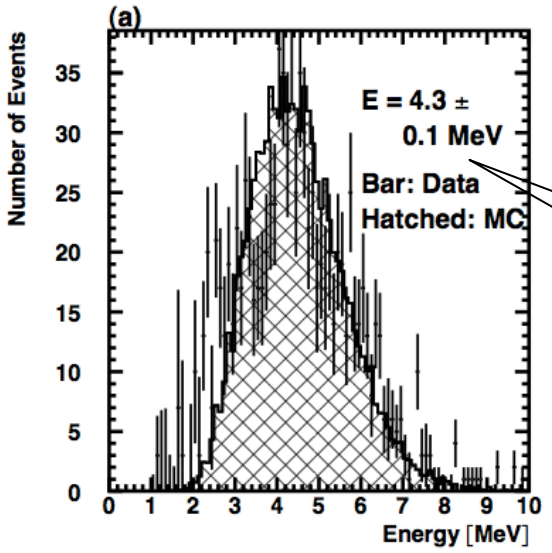
J. Beacom & M. Vagins, PRL 93 (2004) 171101

Gd has a huge n capture cross-section:

49,000 barns, vs 0.3 b for free protons

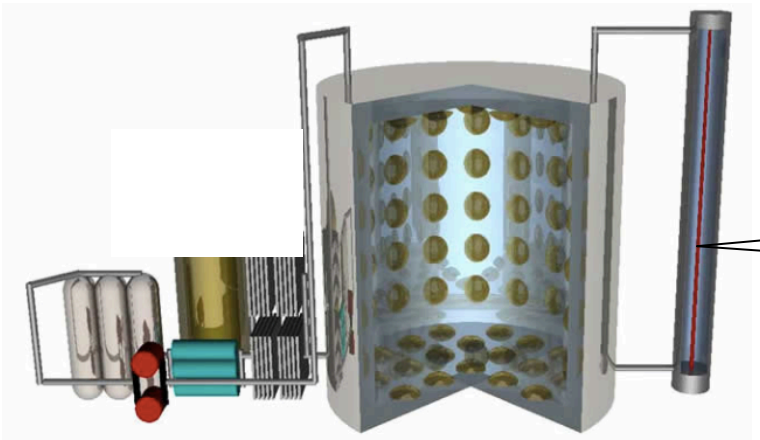
$n + Gd \rightarrow Gd^{*} \rightarrow Gd + \gamma \qquad \sum E_{\gamma} = 8\,MeV$





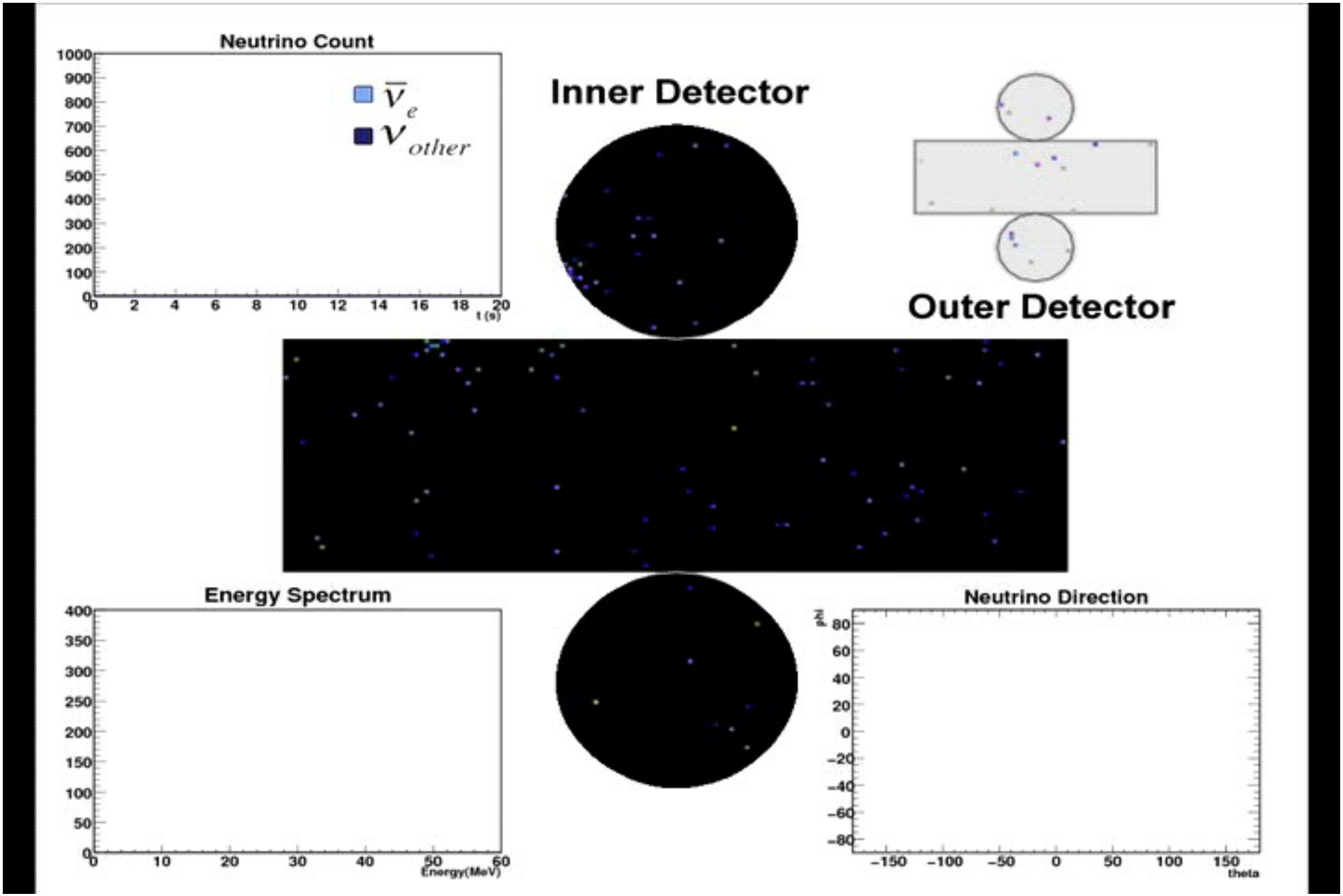
H. Watanabe et al., Astropart. Phys. 31, 320-328 (2009)

About 4 MeV visible energy per capture; ~67% efficiency in SK



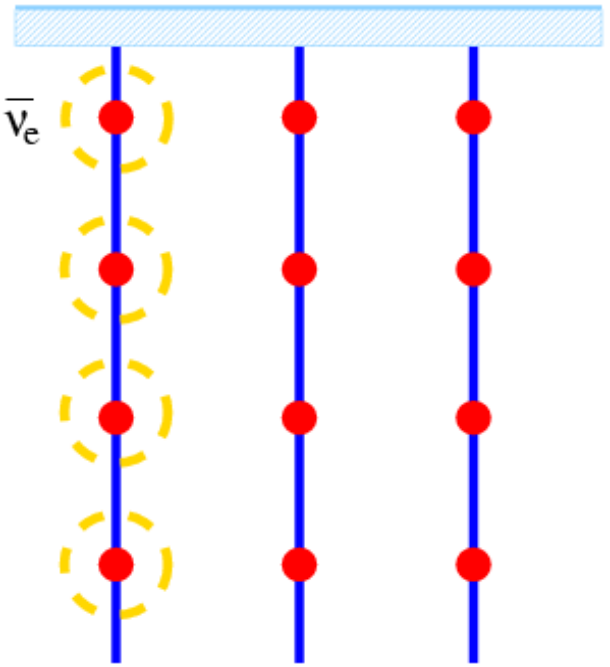
ADS: test tank in the Kamioka mine for R&D

Going forward as **"SK-Gd"**



http://snews.bnl.gov/snmovie.html

Long string water Cherenkov detectors

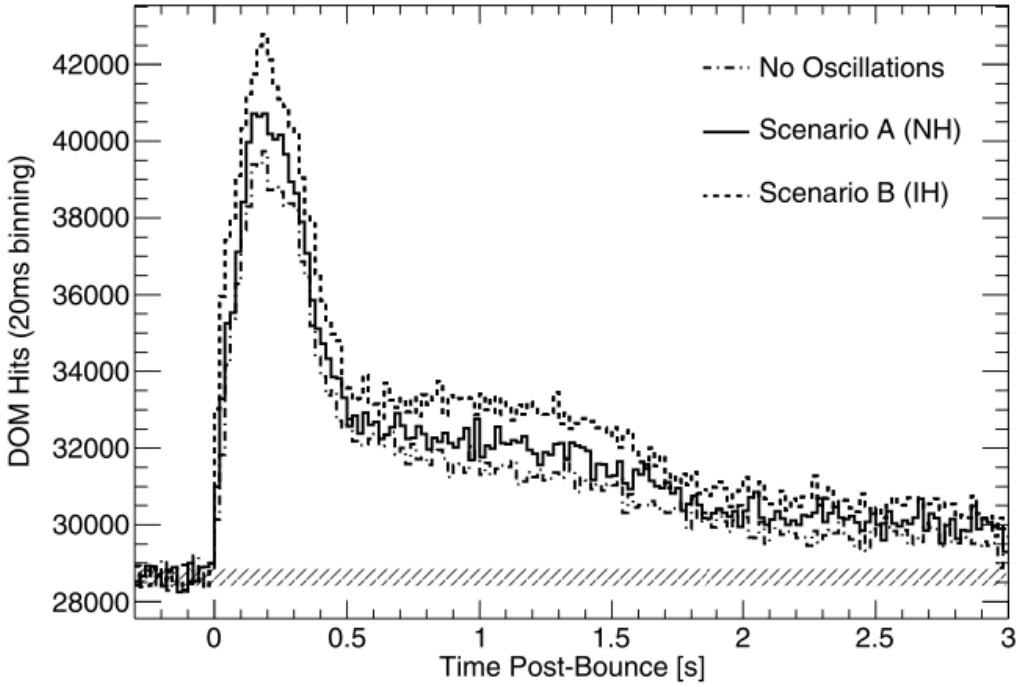


~kilometer long strings of PMTs in very clear water or ice
(IceCube/PINGU, ANTARES)

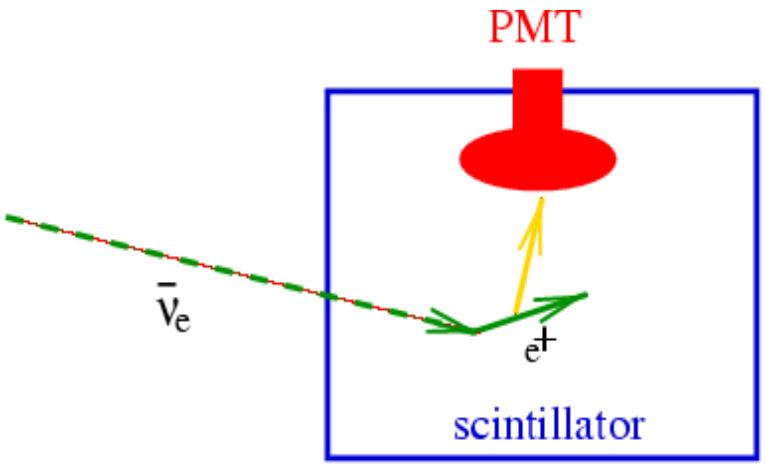
Nominally multi-GeV energy threshold... but, may see burst of low energy $\bar{\nu}_e$'s as ***coincident increase in single PMT count rates*** (M_{eff}~ 0.7 kton/PMT)

Map overall time structure of burst

IceCube collaboration, A&A 535, A109 (2011)

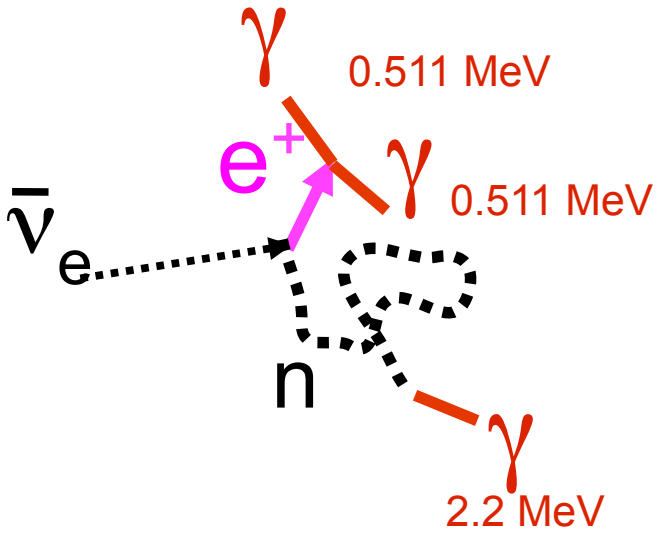


Scintillation detectors



Liquid scintillator (C_nH_{2n}) volume surrounded by photomultipliers

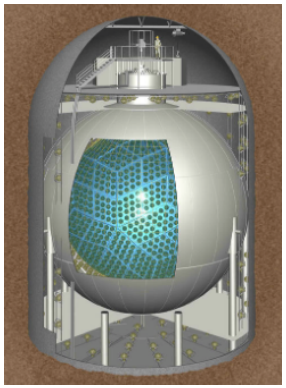
- **lots of photons:**
  few 100 pe/MeV
  ➔**low threshold, good energy resolution**
- little pointing capability
  (light is ~isotropic
  even if interaction were directional...)
- can also dope with Gd



retrieve the energy of the n-capture and annihilation γ's

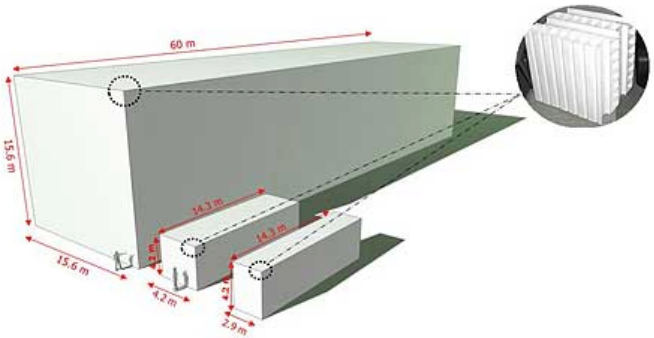
Current and near-future scintillator detectors

KamLAND
(Japan)
1 kton



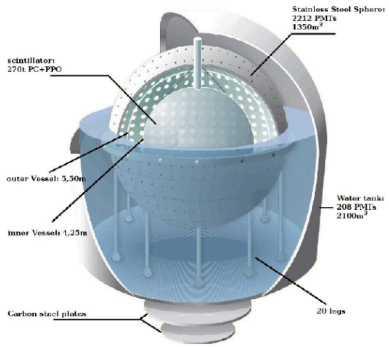
LVD
(Italy)
1 kton

NOvA
(USA)
14 kton

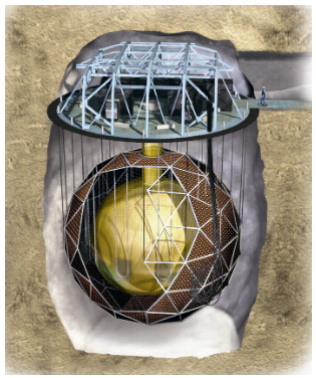


(on surface, but may be possible to extract counts for known burst)

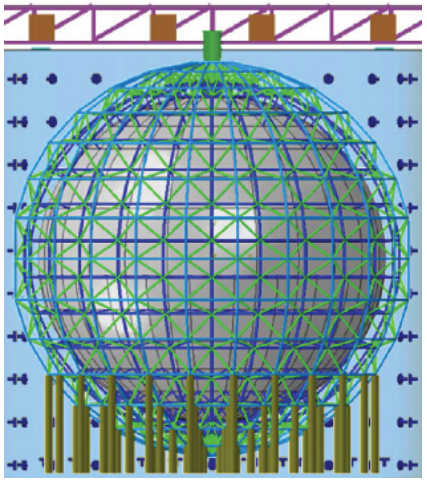
Borexino
(Italy)
0.33 kton



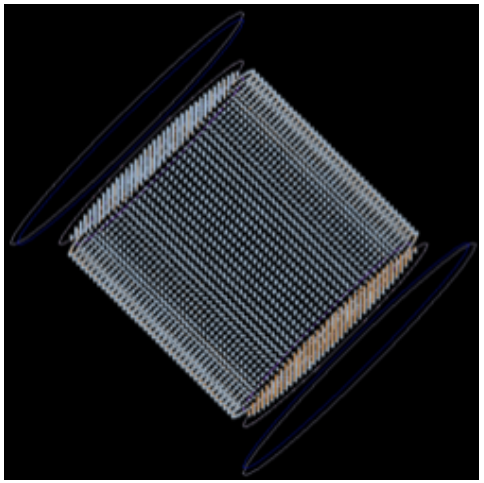
SNO+
(Canada)
1 kton



Future detector proposals



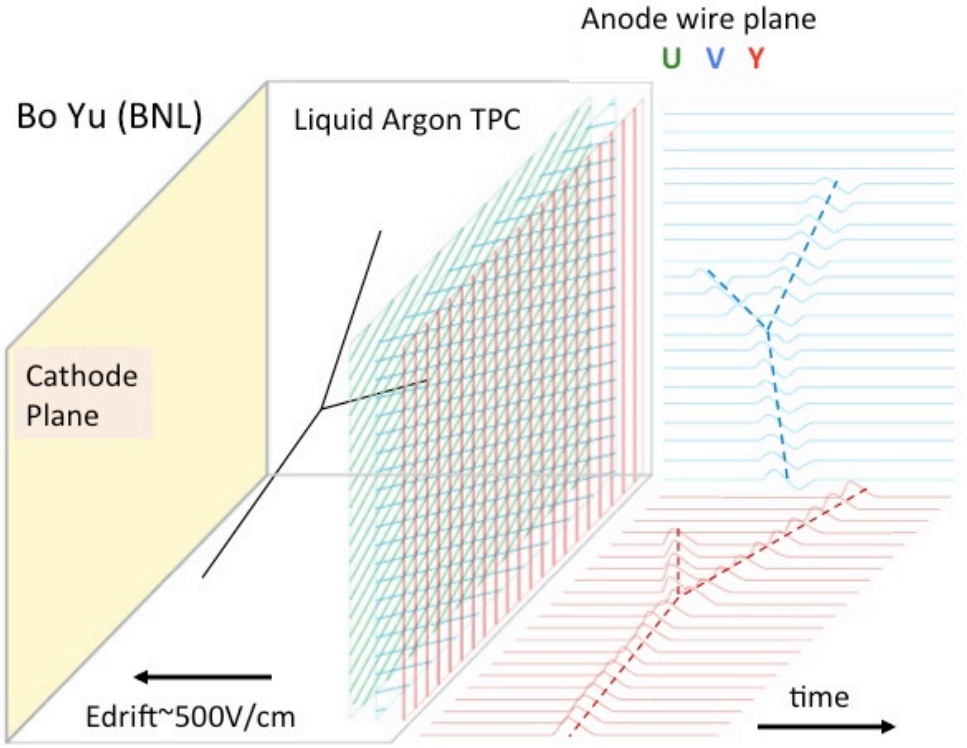
JUNO
(China)
20 kton



RENO-50
(S. Korea)
18 kton

(LENA)
(Finland)
50 kton

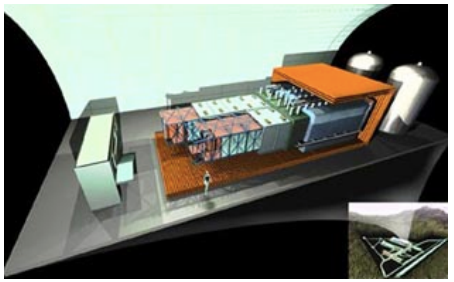
Liquid argon time projection chambers



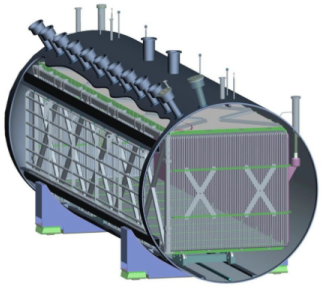
- fine-grained trackers
- no Cherenkov threshold
- **high ν_e cross section**

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

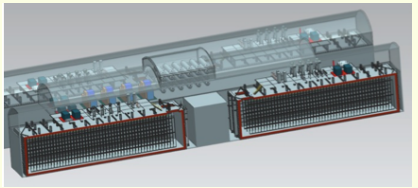
ICARUS
(Italy...)
0.6 kton



MicroBooNE
(USA)
0.2 kton

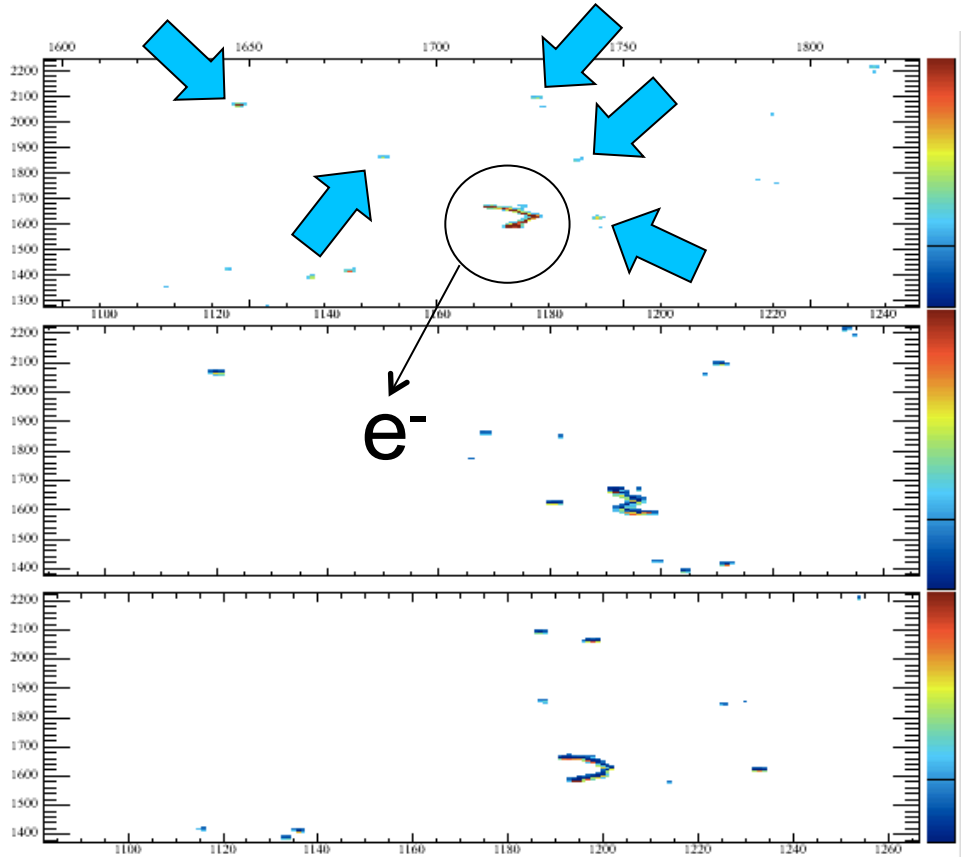


DUNE
(USA)
40 kton

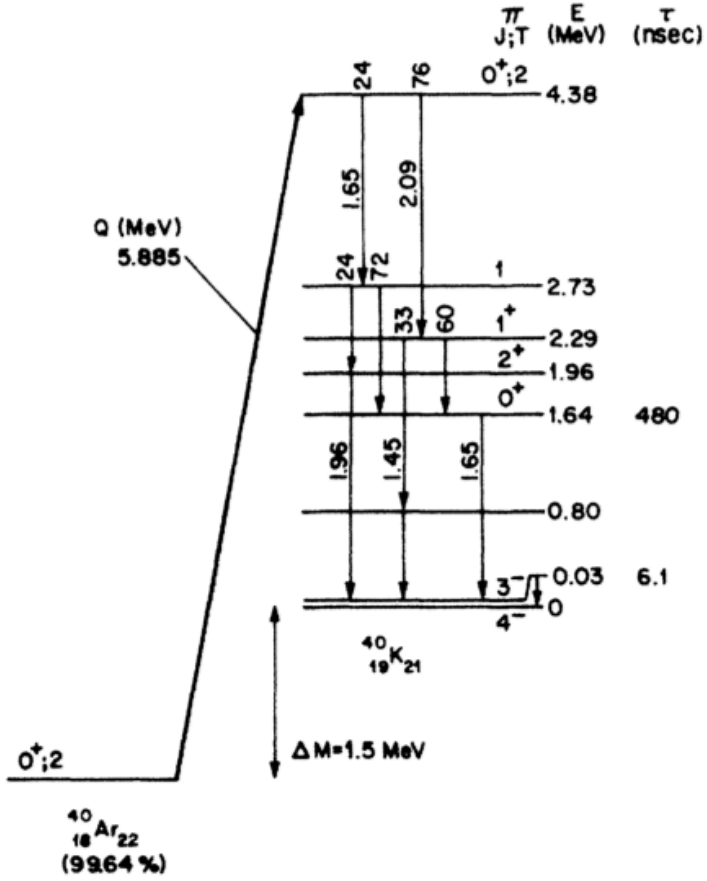


Can we tag ν_e CC interactions in argon using nuclear deexcitation γ's?

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$



MicroBooNE geometry (LArSoft)



20 MeV ν_e , 14.1 MeV e^-, simple model based on R. Raghavan, PRD 34 (1986) 2088
Improved modeling based on ^{40}Ti (^{40}K mirror) β decay measurements in progress
Direct measurements (and theory) needed!

… in fact there can be transitions to intermediate states, adding to the cross section (and complicating the γ-tag)

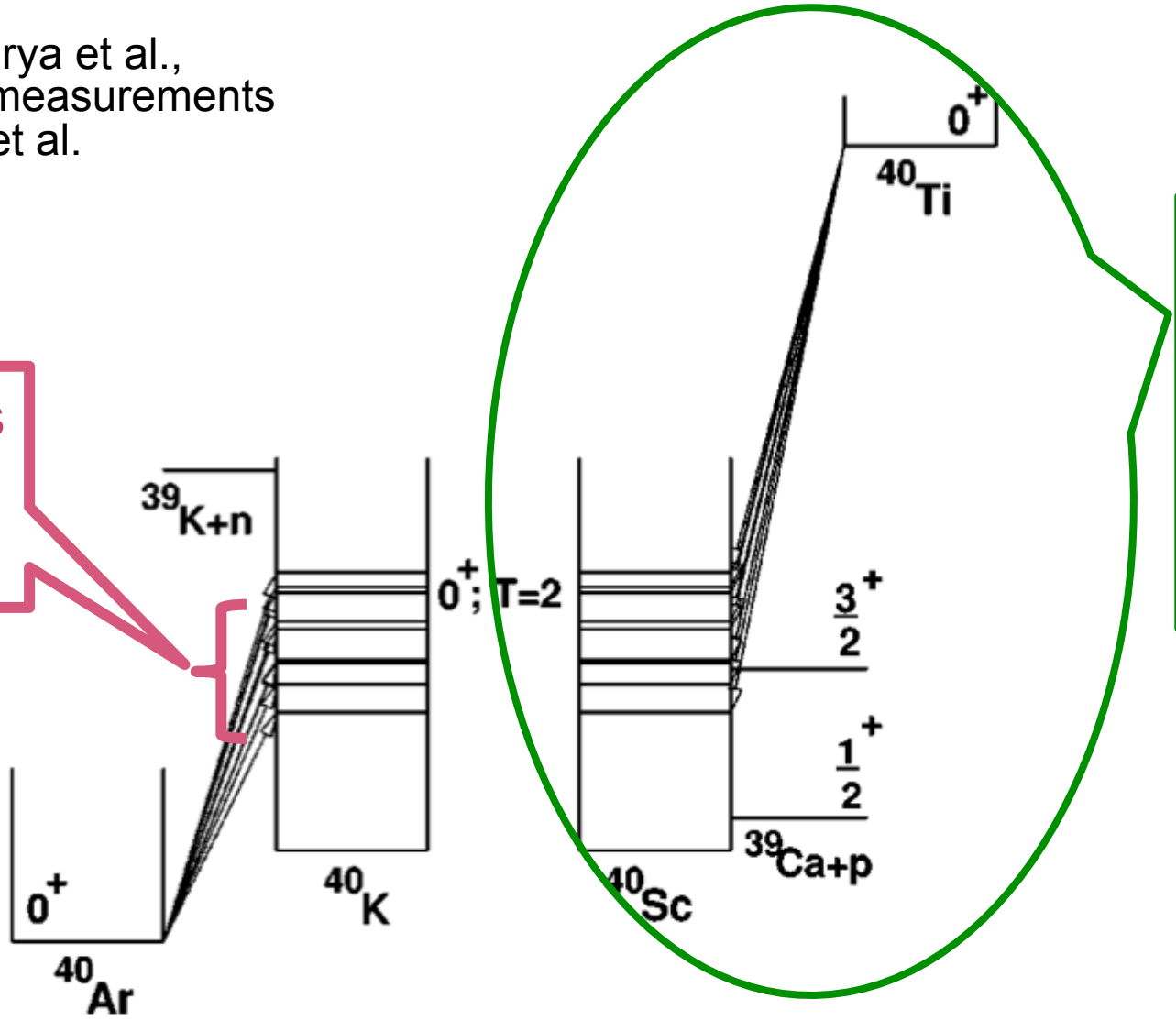
PHYSICAL REVIEW C VOLUME 58, NUMBER 6 DECEMBER 1998

Neutrino absorption efficiency of an ^{40}Ar detector from the β decay of ^{40}Ti

M. Bhattacharya et al.,
and newer measurements
by Trinder et al.

these states can be populated

measure relative strengths with βdk of ^{40}Ti to mirror nucleus



… in fact there can be transitions to intermediate states, adding to the cross section (and complicating the γ-tag)

PHYSICAL REVIEW C VOLUME 58, NUMBER 6 DECEMBER 1998

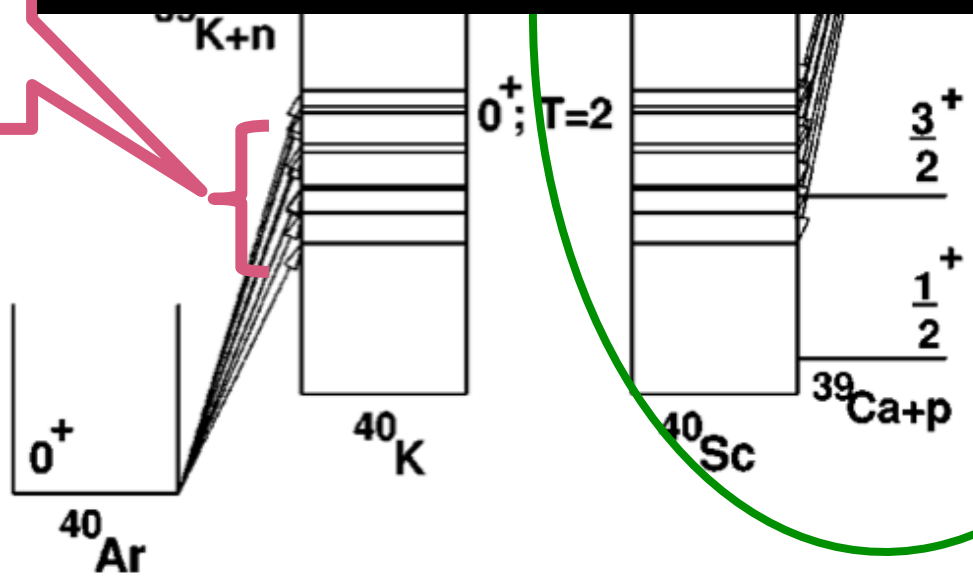
Neutrino absorption efficiency of an ^{40}Ar detector from the β decay of ^{40}Ti

M. Bhattacharya et al.,
and newer me
by Trinder et

Nuclear physics of specific targets matters @ ~10 MeV energies (nuclear energy-level scale)

these states can be populated

measure relative strengths with βdk of ^{40}Ti to mirror nucleus



Lead-based supernova detectors

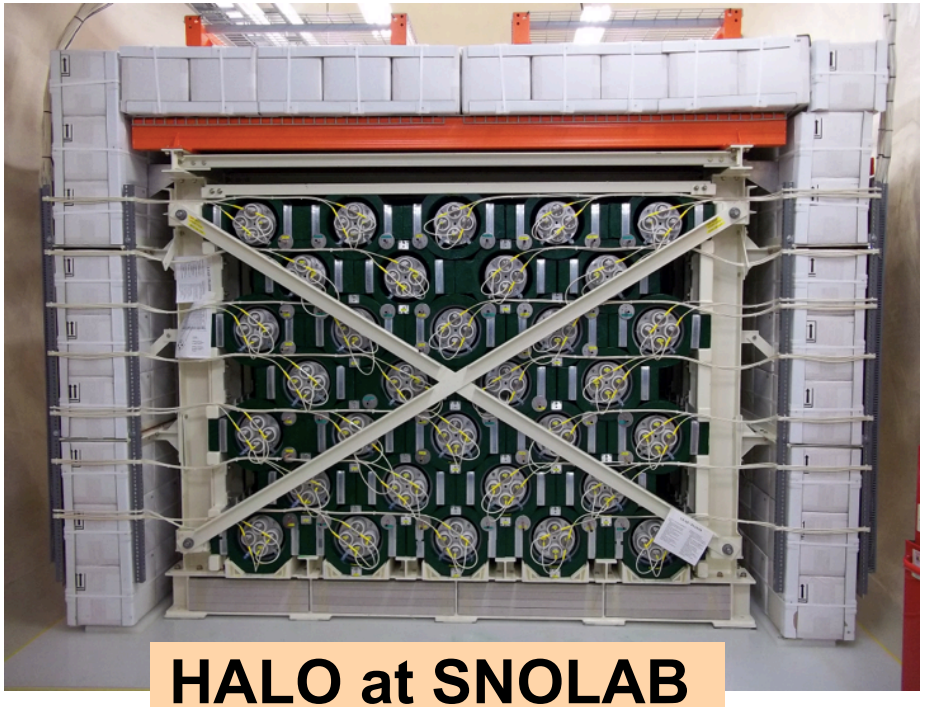
$\nu_e + {}^{208}Pb \rightarrow {}^{208}Bi^* + e^-$ CC

↘ 1n, 2n emission

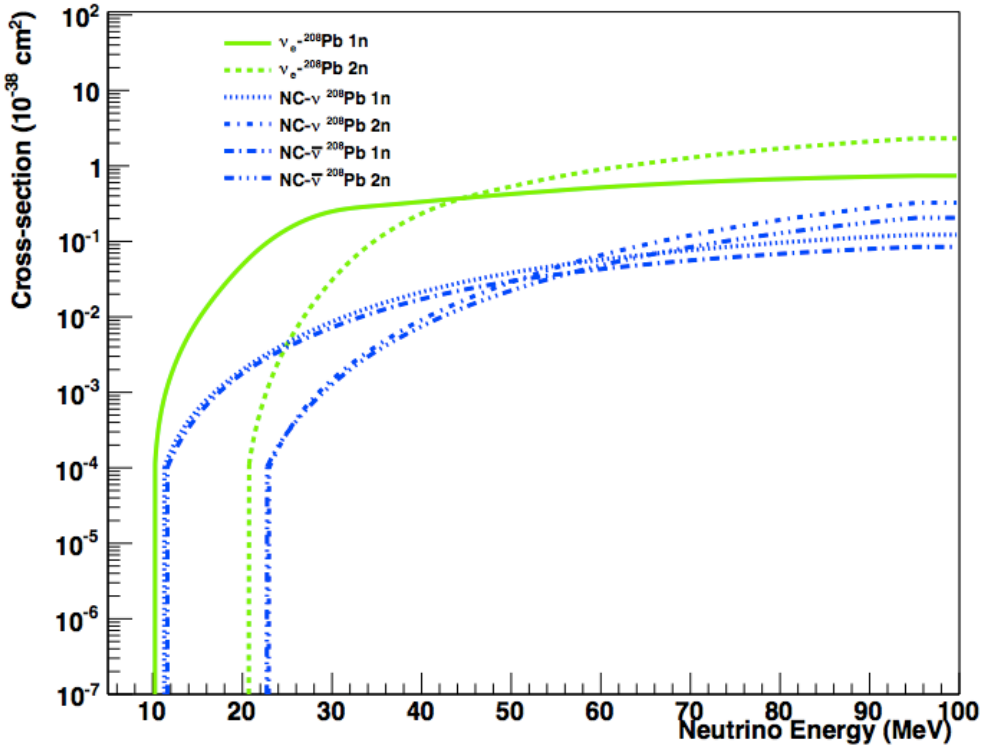
$\nu_x + {}^{208}Pb \rightarrow {}^{208}Pb^* + \nu_x$ NC

↘ 1n, 2n, γ emission

Relative 1n/2n rates
sharply dependent on neutrino energy
⇒ spectral sensitivity

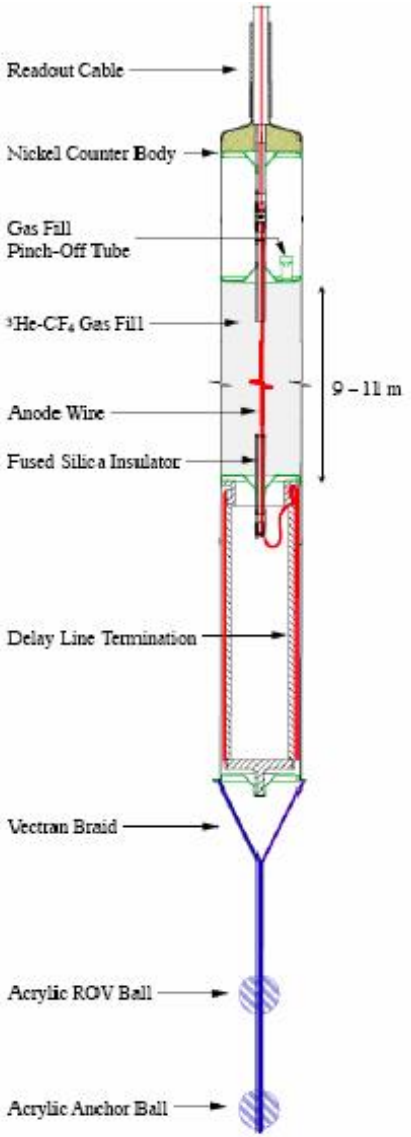


HALO at SNOLAB



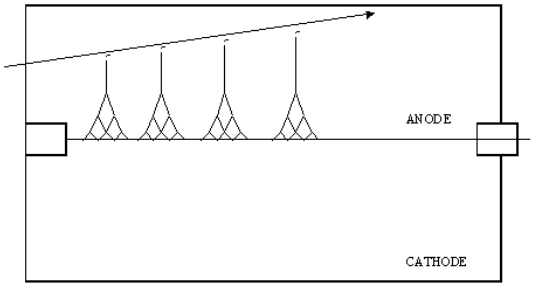
SNO ^{3}He counters + 79 tons of Pb: ~1-40 events @ 10 kpc

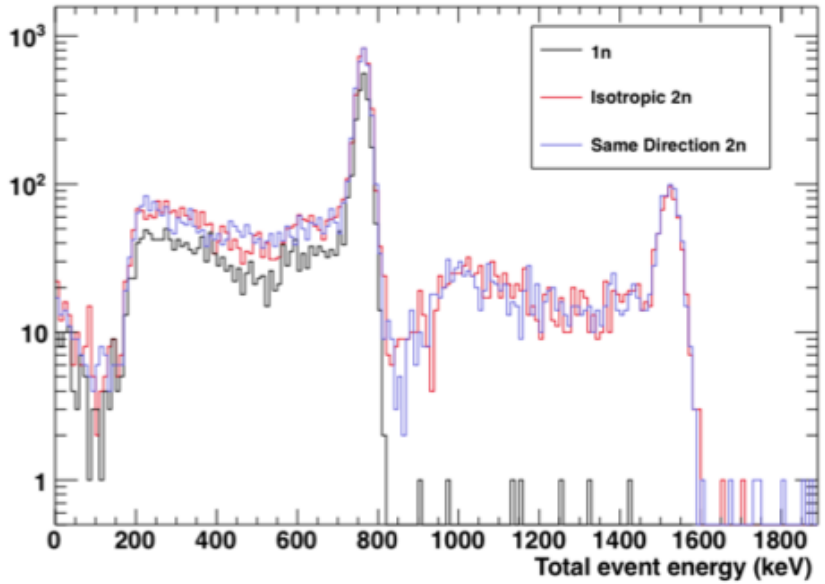
^{3}He counters for neutron detection



$$^3\mathrm{He} + n \rightarrow p + t + 764\ \mathrm{keV}$$

proportional counter
measures ionization deposition by p, t final state charged particles





Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

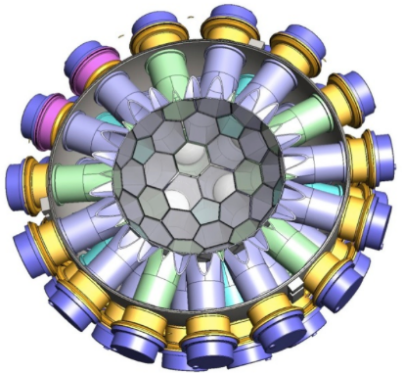
$\nu_x + A \rightarrow \nu_x + A$

C. Horowitz et al., PRD68 (2003) 023005

High x-scn but *very* low recoil energy (10's of keV)

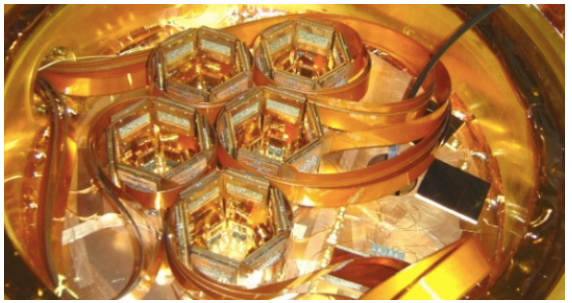
$\Rightarrow$ observable in DM detectors

~ few events per ton for Galactic SN



ν_x energy information from recoil spectrum

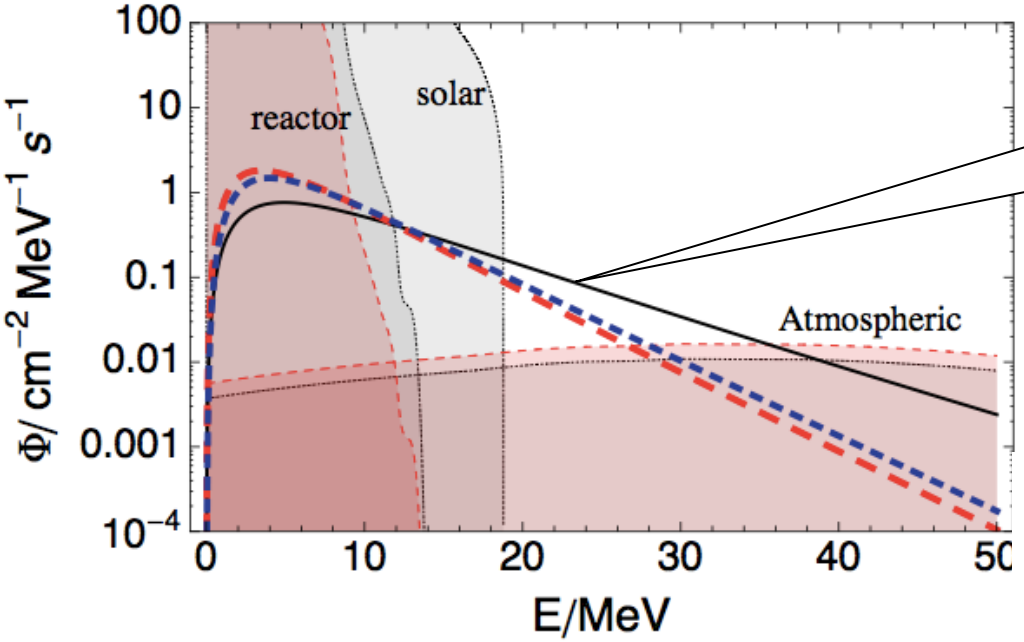
e.g., Ar, Ne, Xe, Ge, ...



DM detectors,
e.g., LUX/LZ, Super-CDMS, ...

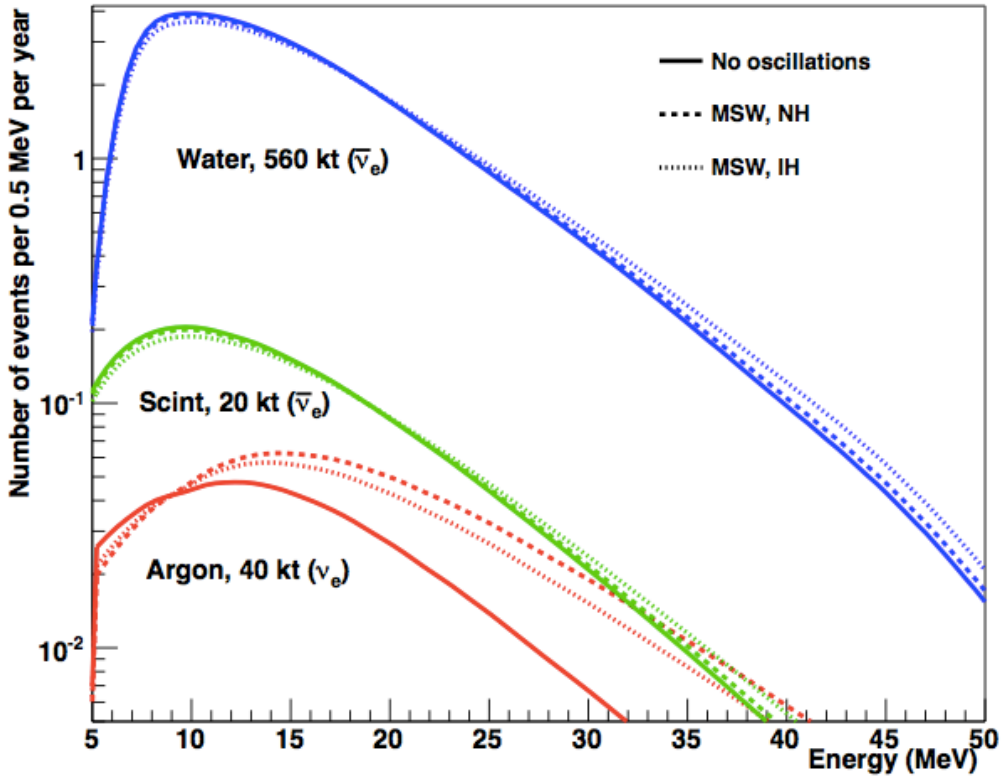
More on this tomorrow...

And going even farther out: we are awash in a sea of ***'relic'* or diffuse SN ν's (DSNB)**, from ancient SNae ...



Window with low ν bg, 20-40 MeV

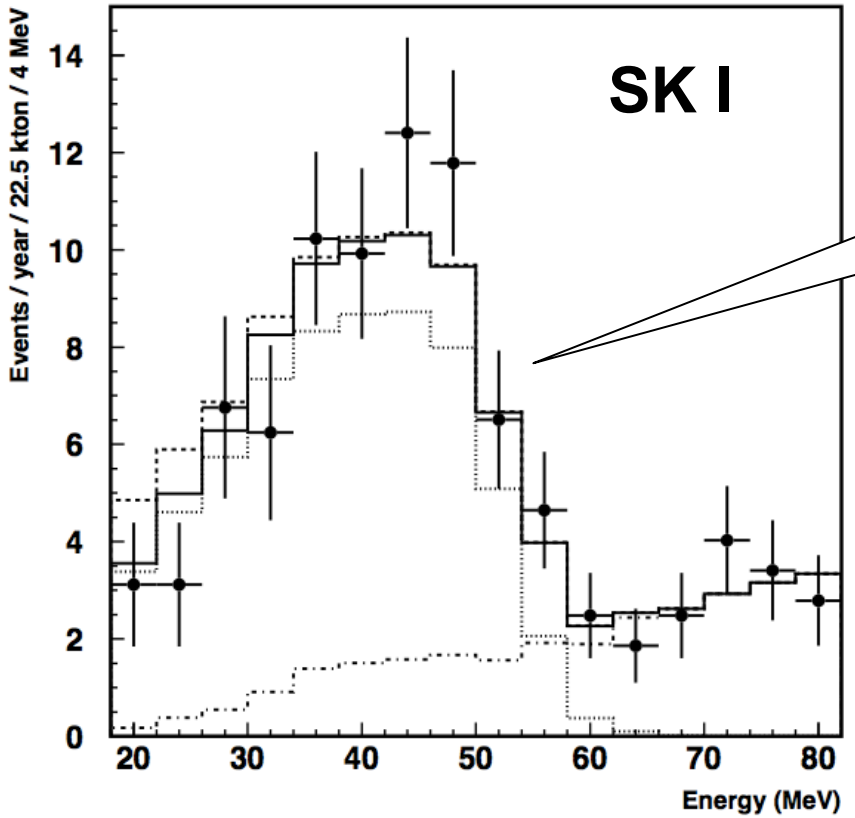
~few events per year in SK



Difficulty is tagging for decent signal/bg (no burst, coincidences w/ optical SNae...)

it's all about the backgrounds

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



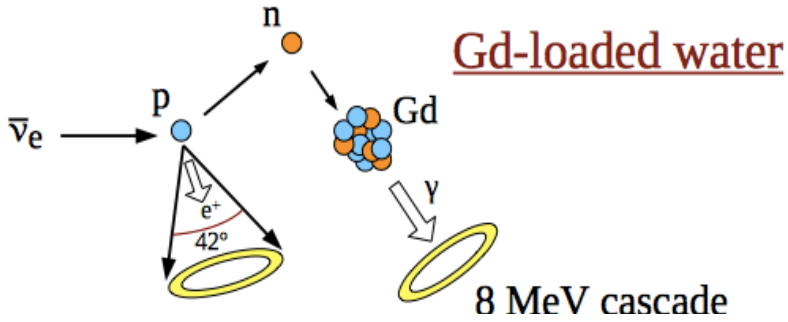
Michel electrons from decays of sub-Cherenkov threshold muons

- Worst background is from decaying 'invisible muons' from atmospheric neutrinos
  → ***reduce by tagging electron antineutrinos with Gd***
- But for a big detector requires low energy threshold ($)

LAr? Electron flavor,
but low rate... bg unknown

Scintillator?

Good IBD tagging, but NC bg...



Summary of supernova neutrino detectors

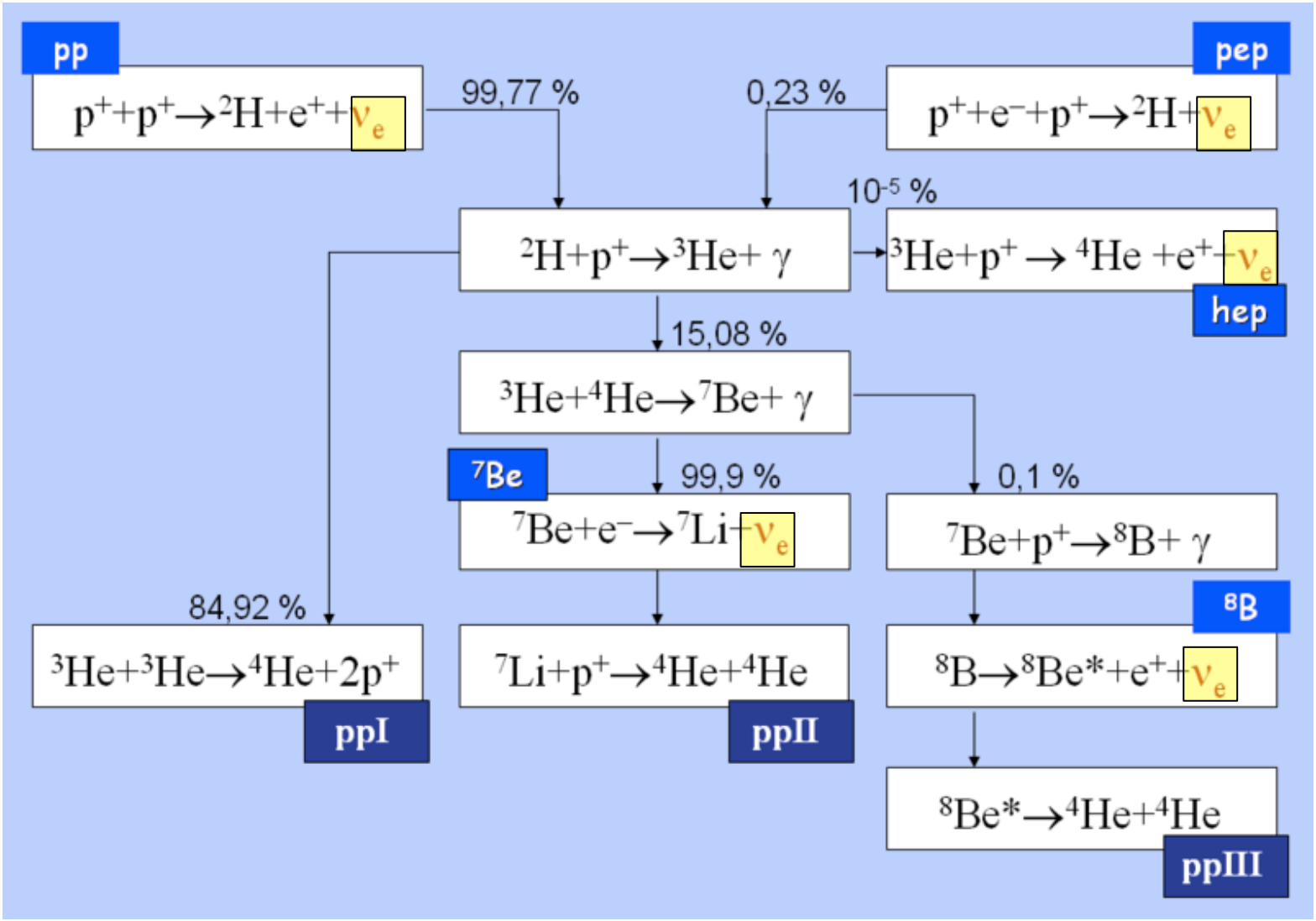
Galactic sensitivity

Extragalactic

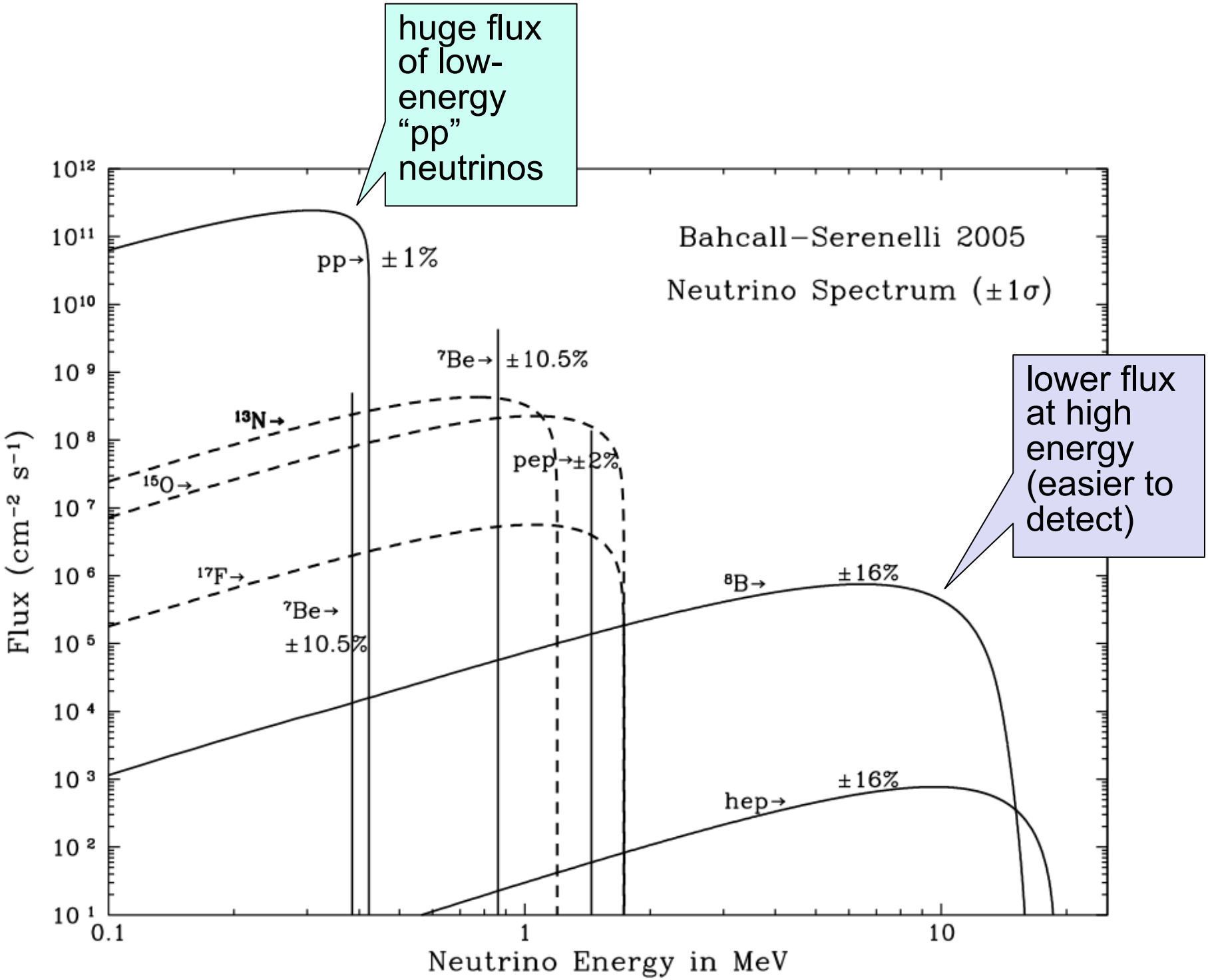
Detector	Type	Location	Mass (kton)	Events @ 10 kpc	Status
Super-K	Water	Japan	32	8000	Running (SK IV)
LVD	Scintillator	Italy	1	300	Running
KamLAND	Scintillator	Japan	1	300	Running
Borexino	Scintillator	Italy	0.3	100	Running
IceCube	Long string	South Pole	(600)	(10^6)	Running
Baksan	Scintillator	Russia	0.33	50	Running
Mini-BooNE	Scintillator	USA	0.7	200	(Running)
HALO	Lead	Canada	0.079	20	Running
Daya Bay	Scintillator	China	0.33	100	Running
NOνA	Scintillator	USA	15	3000	Turning on
SNO+	Scintillator	Canada	1	300	Under construction
MicroBooNE	Liquid argon	USA	0.17	17	Under construction
DUNE	Liquid argon	USA	40	3000	Proposed
Hyper-K	Water	Japan	540	110,000	Proposed
JUNO	Scintillator	China	20	6000	Proposed
RENO-50	Scintillator	South Korea	18	5400	Proposed
PINGU	Long string	South pole	(600)	(10^6)	Proposed

plus reactor experiments, DM experiments...

Detecting solar neutrinos



Electron flavor neutrinos generated in solar fusion; spectrum is pretty well understood from weak physics


huge flux of low-energy "pp" neutrinos
lower flux at high energy (easier to detect)
Bahcall–Serenelli 2005
Neutrino Spectrum (±1σ)
pp→ ±1%
⁷Be→ ±10.5%
¹³N→
¹⁵O→
pep→±2%
¹⁷F→
⁷Be→ ±10.5%
⁸B→ ±16%
hep→ ±16%
Flux (cm⁻² s⁻¹)
Neutrino Energy in MeV
0.1
1
10

What do you want in a detector for solar neutrinos?

Information is in the ***energy*** and ***flavor***

Size	always want this!
Low energy threshold	~Few MeV at least, <1 MeV best!
Energy resolution	Resolve features in spectrum
Angular resolution	Point to the Sun (for directional interactions)
Timing resolution	Precision timing not needed, but “real time” good
Low background	BG rate << solar neutrino rate; underground location needed, must be clean
Flavor sensitivity	Ability to **tag** flavor components

This is (was) the “day job” of many detectors...

Homestake chlorine radiochemical detector

$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

600 tons of cleaning fluid

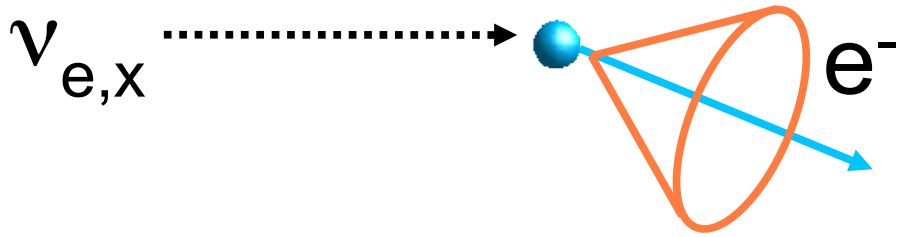
Threshold: 0.81 MeV

Extract atoms of ^{37}Ar every few months
and count decays (35-day half life): ~ 12 per month!

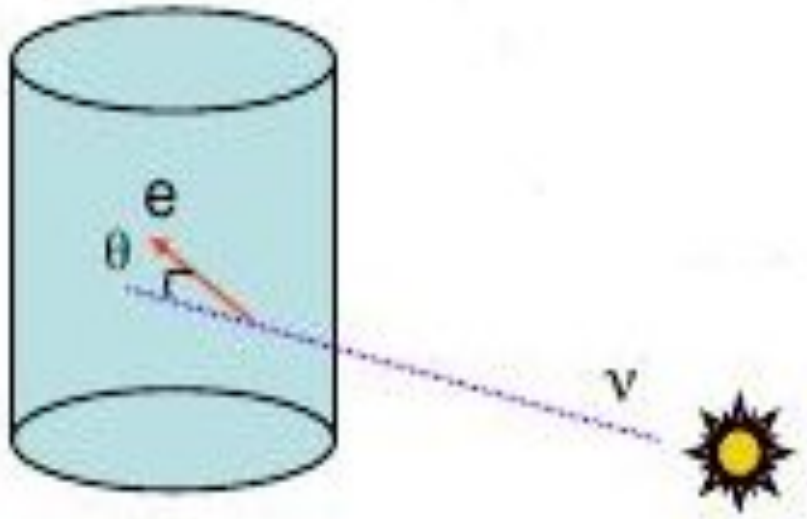
Water Cherenkov detectors for solar neutrinos

Elastic scattering of ~MeV solar ν's on electrons

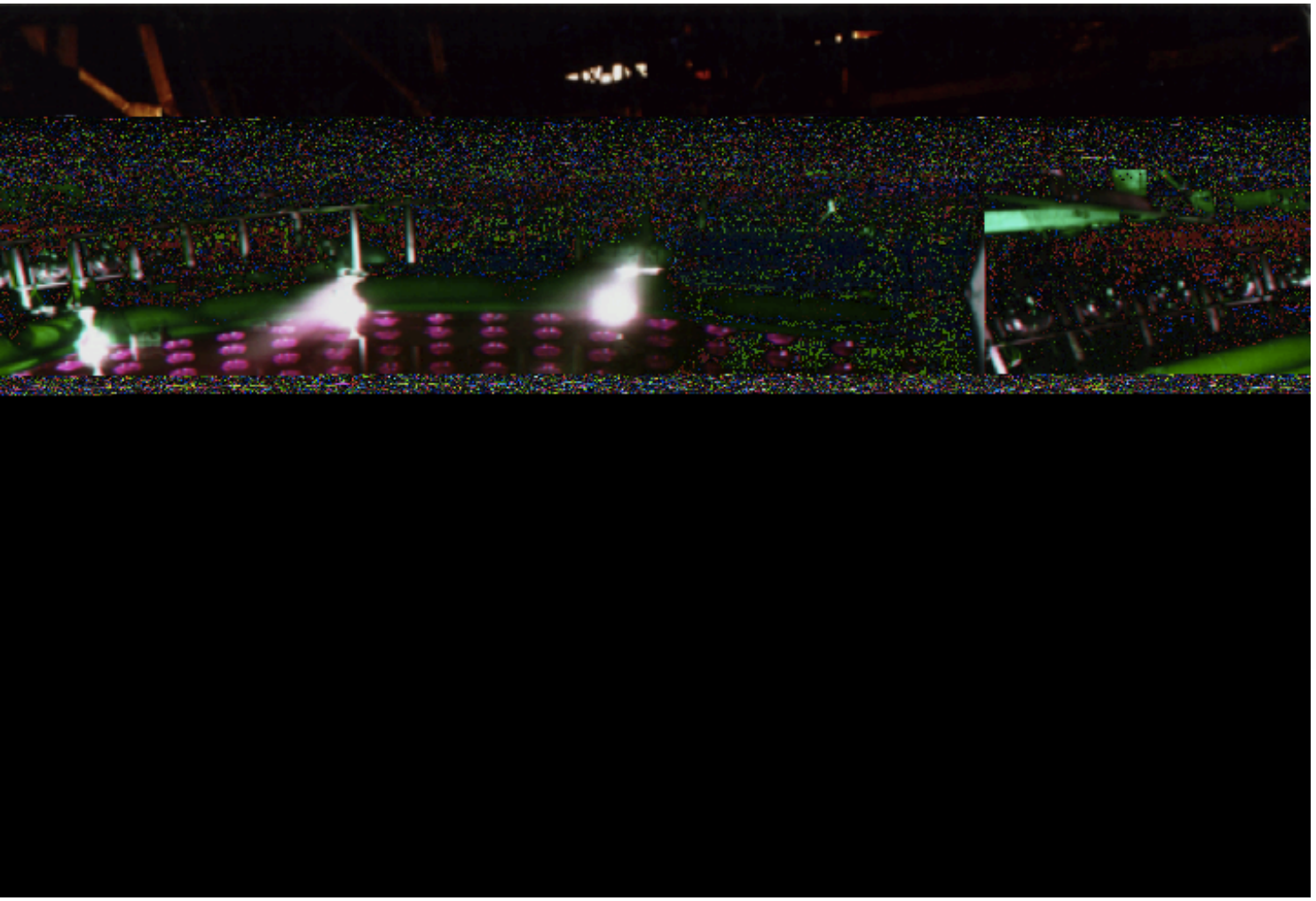
real time detection, with *directionality*

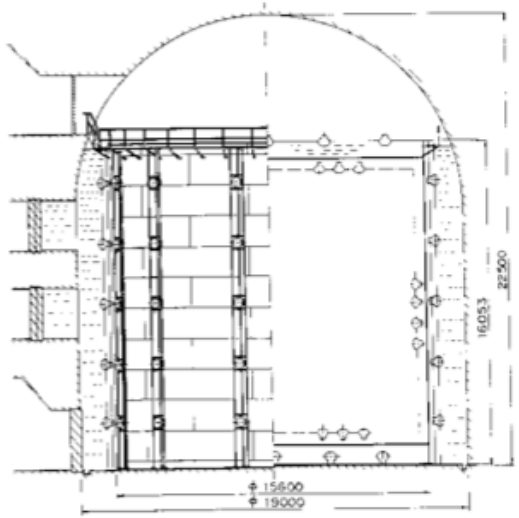


$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$

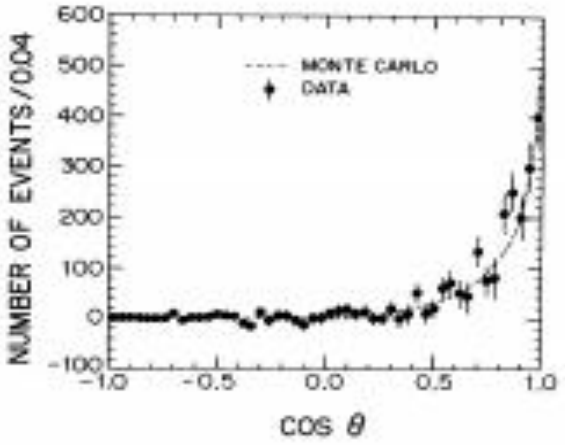


Kamiokande II in Japan
(original motivation: search for proton decay)



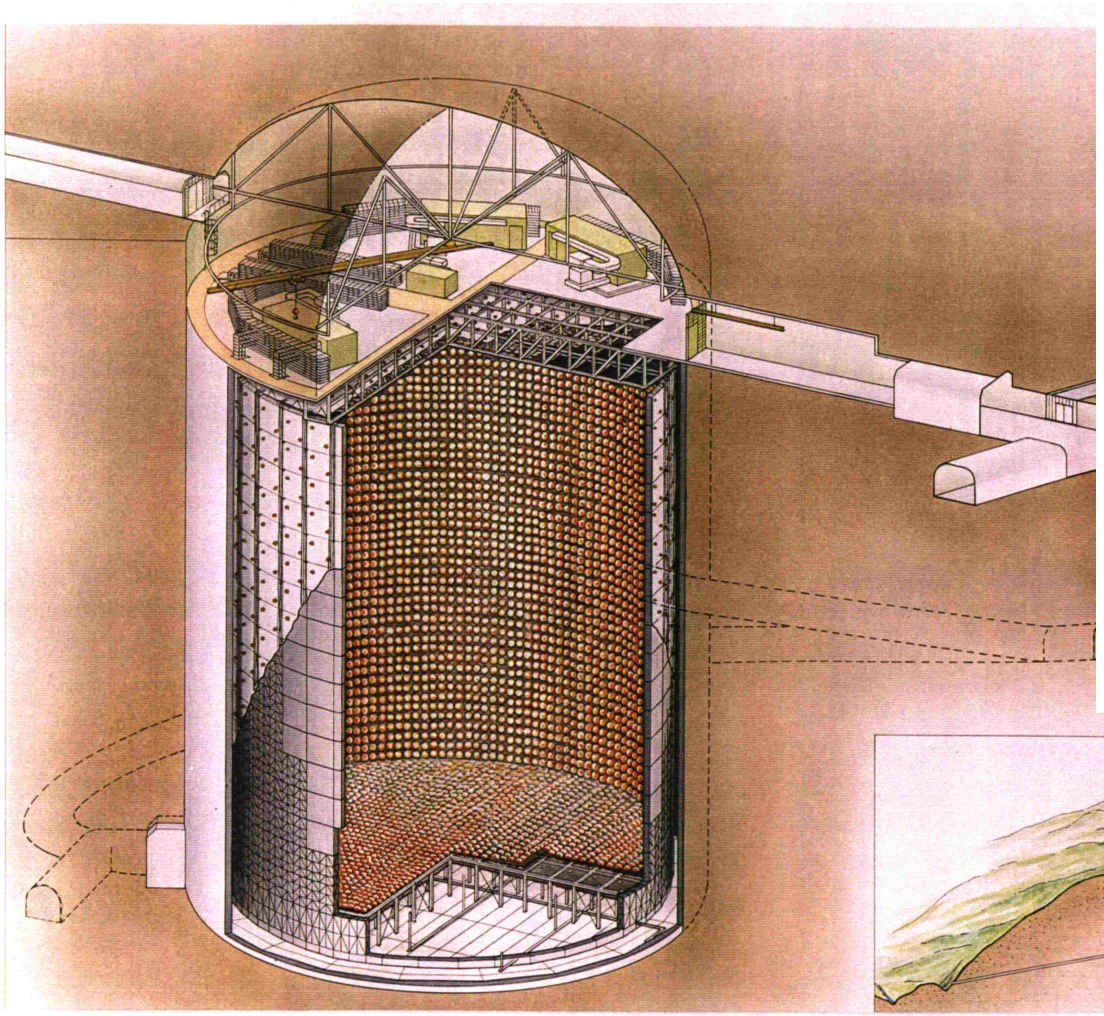


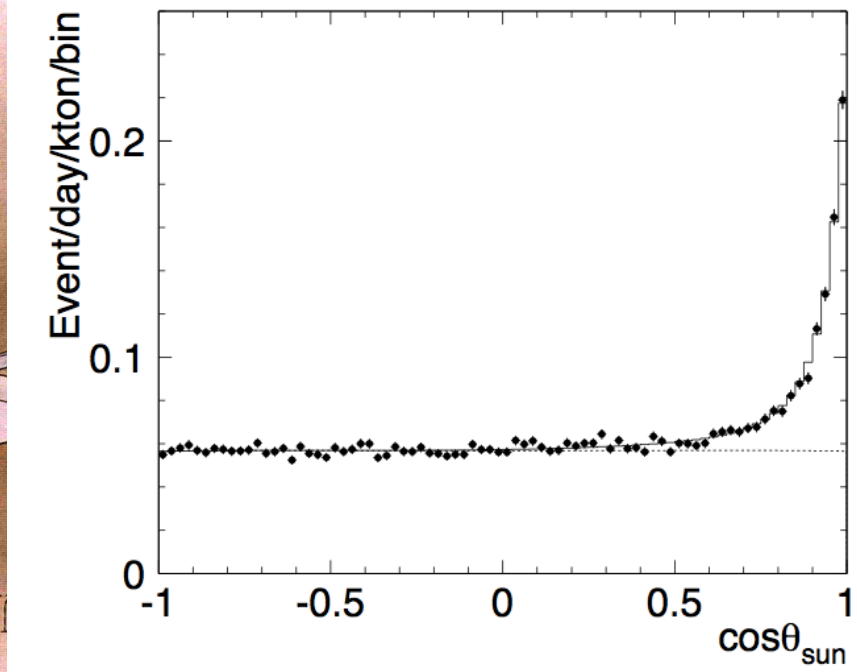
2.1 kton



E>~7 MeV : sensitive to ^{8}B tail of spectrum

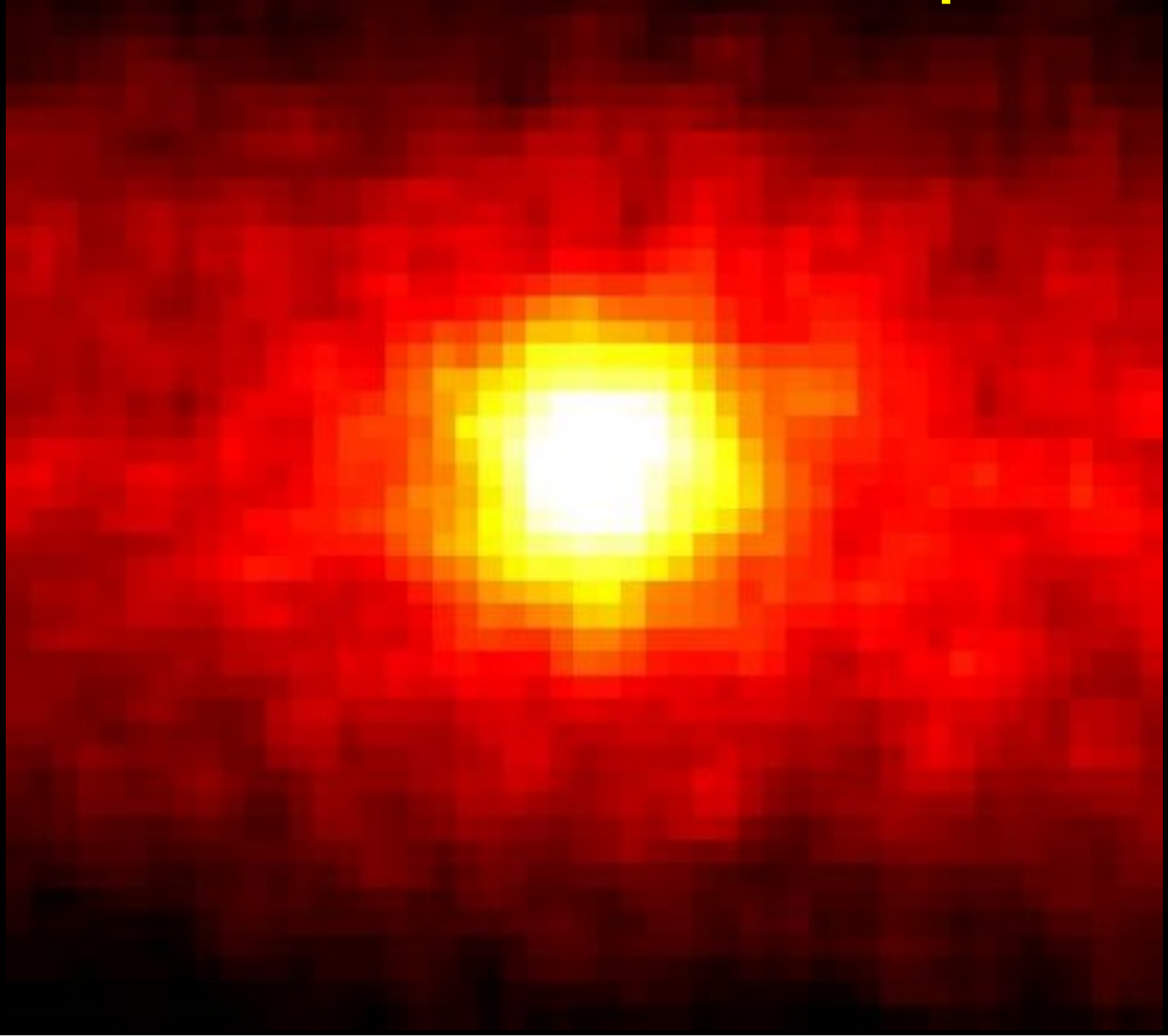
Later: significant improvement from Super-K
(consistent with earlier results)



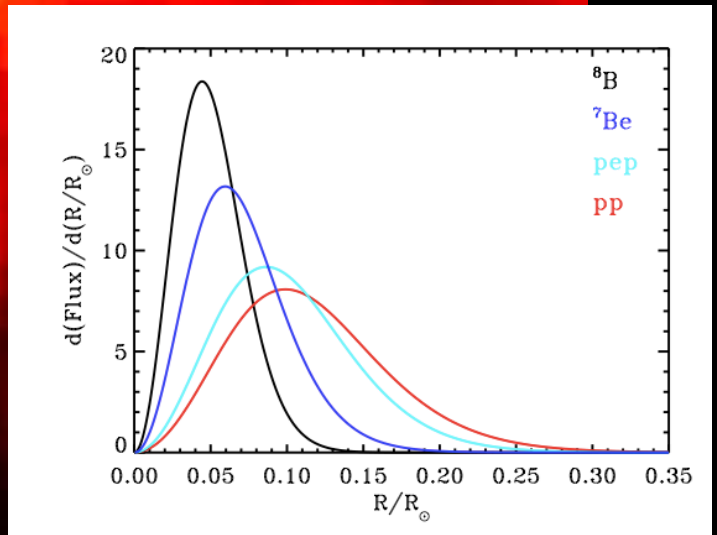


22.5 kton, <~ 5 MeV threshold

The Sun in neutrinos from Super-K

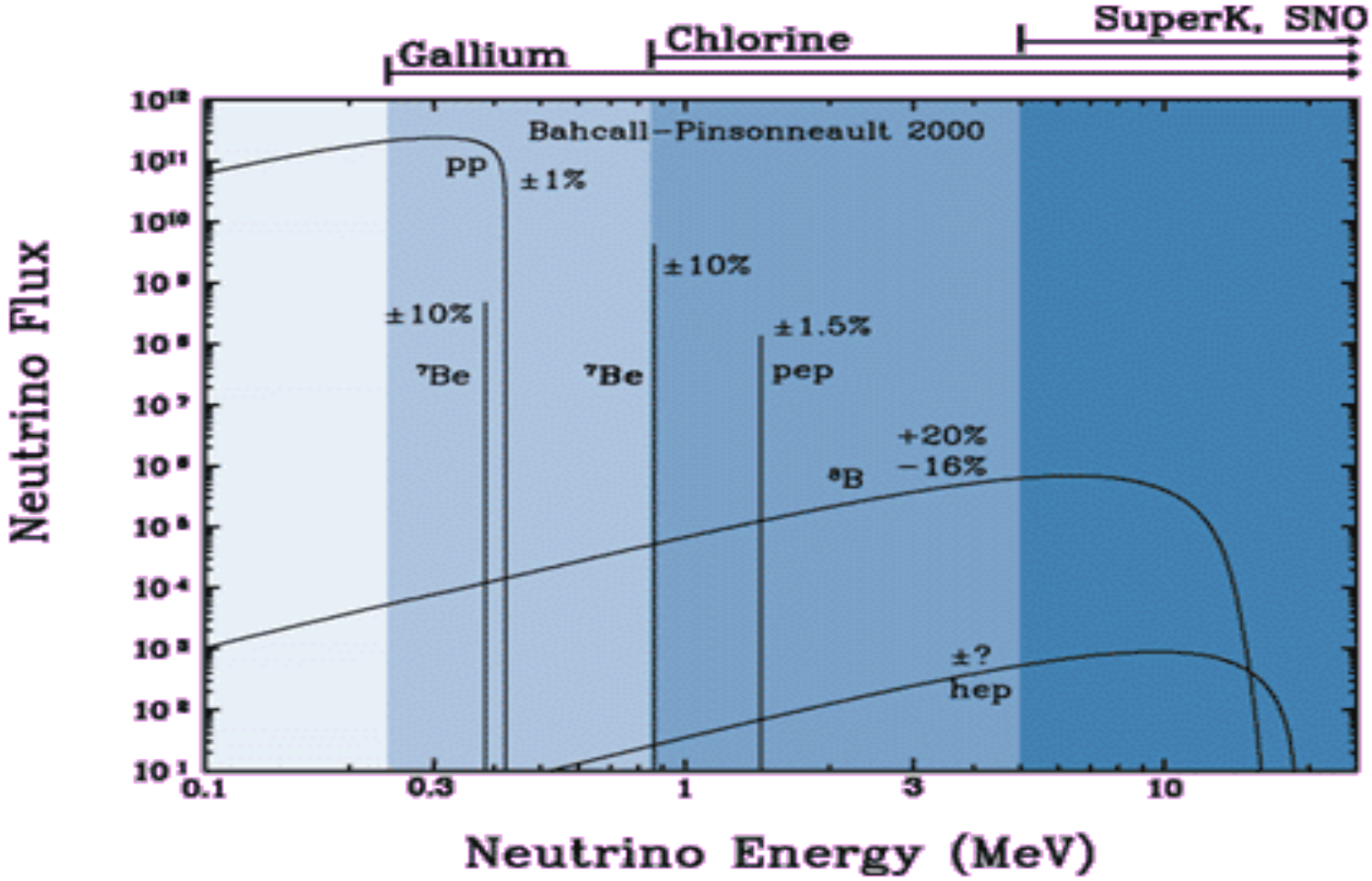


Disclaimer: the visible Sun occupies < 1 pixel,
and neutrinos emerge from an even smaller region!



Another radiochemical experiment: gallium

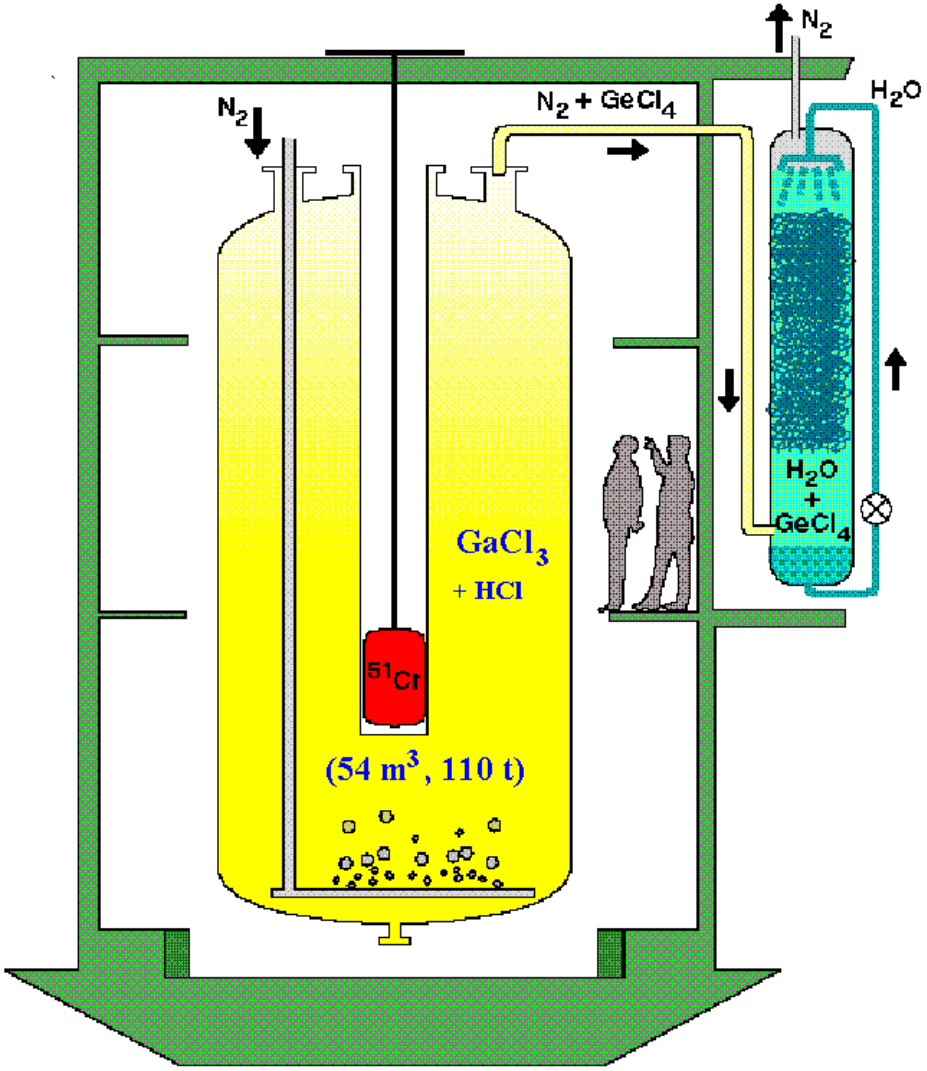
$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$$



Threshold: 0.23 MeV, 11 day half-life

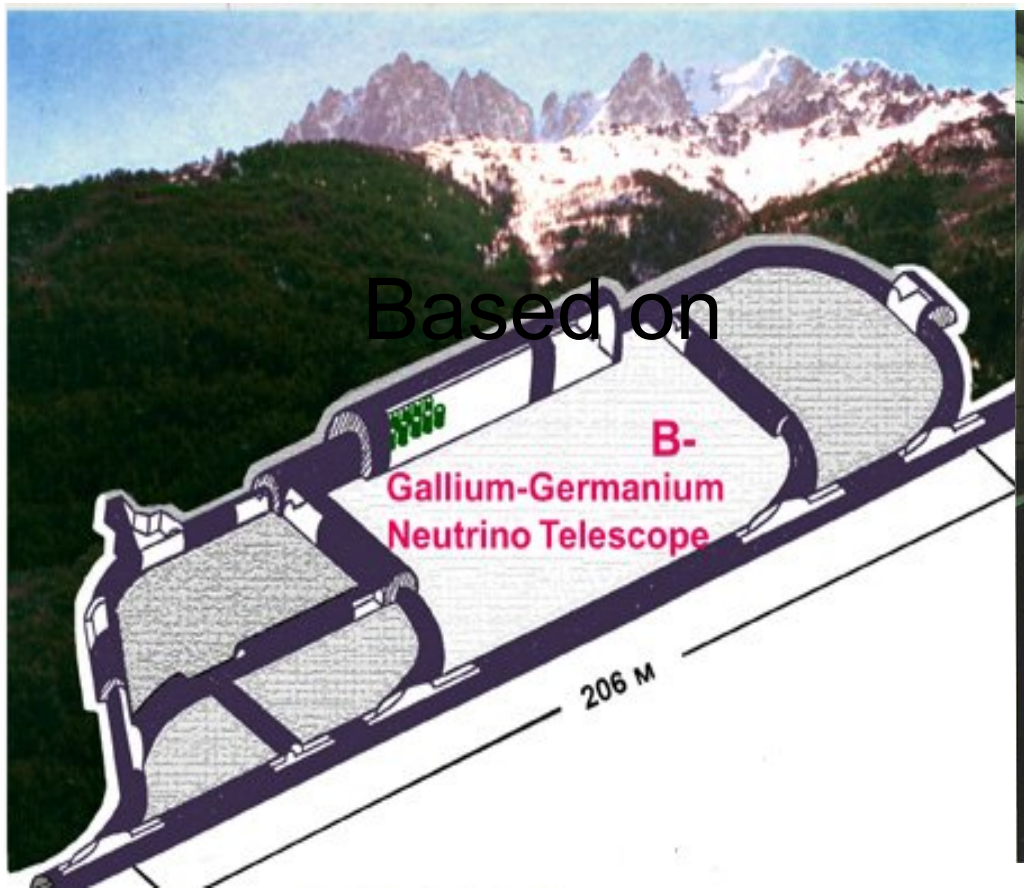
Sensitive to *pp neutrinos*

Gallex/GNO (Gallium Neutrino Observatory)
at LNGS, Italy: 1991-2006

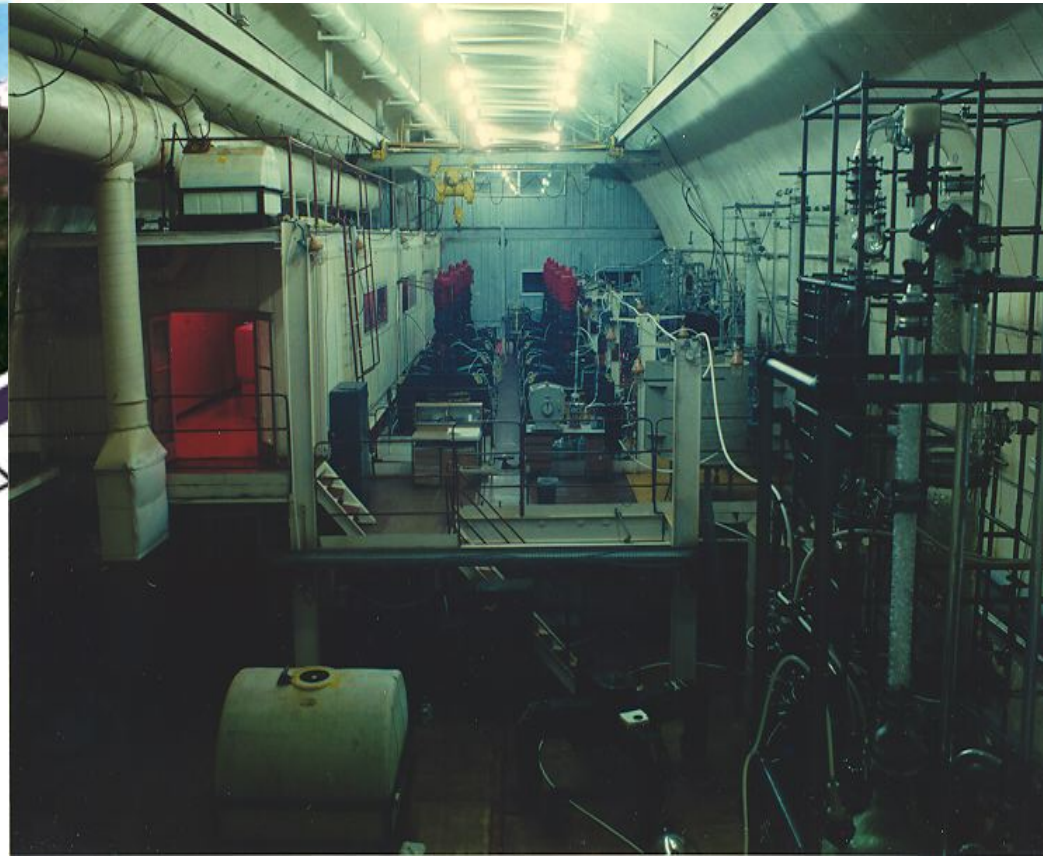


Used gallium chloride (30 tons of Ga)

The SAGE Experiment



Caucasus mountains, Russia

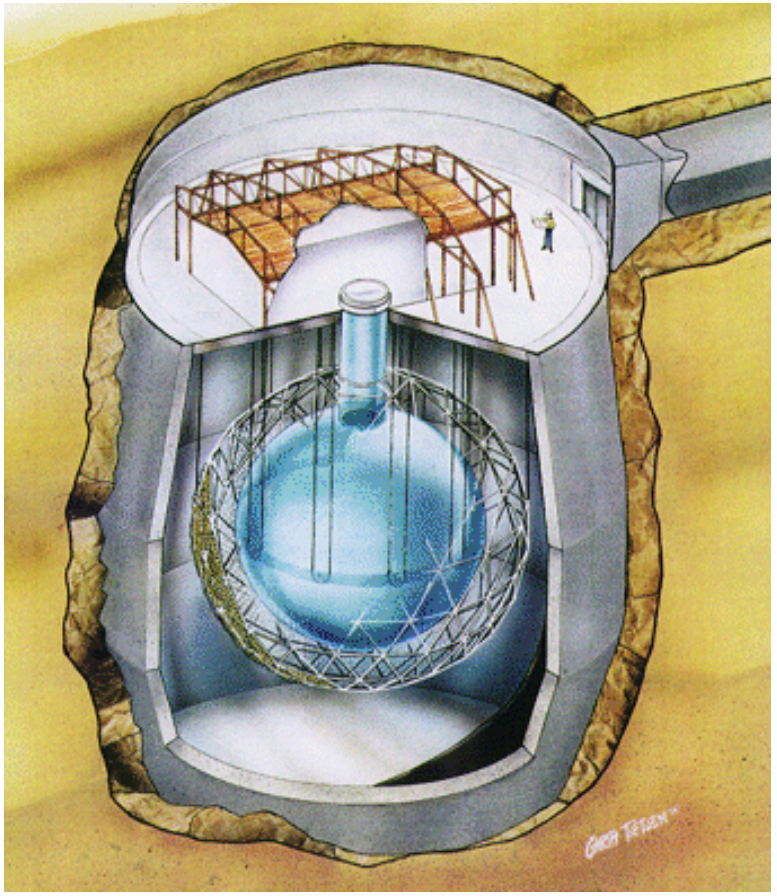


Based on liquid gallium
50 tons

1990-2007

For many years: the “solar neutrino problem”
... ν_e’s disappearing...
How do we know for sure they are oscillating?

The Sudbury Neutrino Observatory



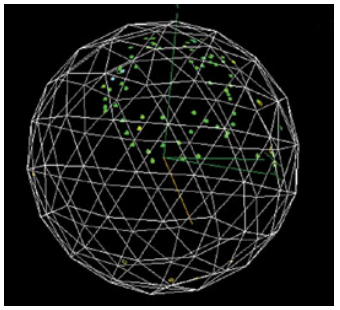
Sudbury, Canada

1 kton D_2O, 1.7 kton H_2O

$\nu_e + d \rightarrow p + p + e^-$ CC

$\nu_x + d \rightarrow \nu_x + p + n$ NC

$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$ Elastic scattering (CC, NC)



Cherenkov light from e^- and **neutron detection** for NC

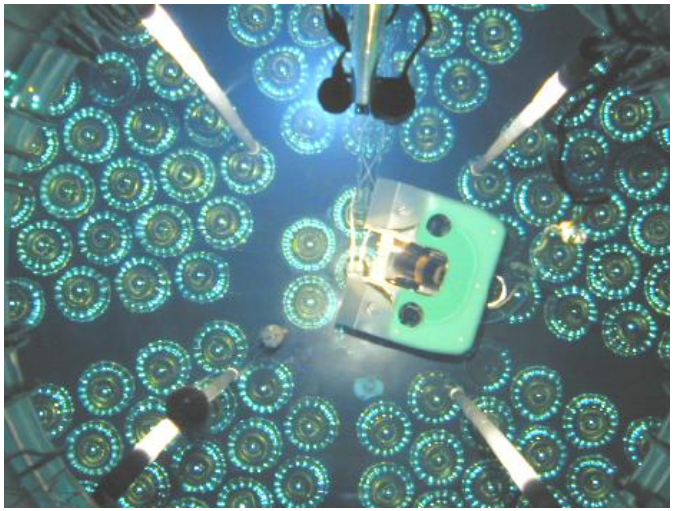
SNO's unique feature: NC detection

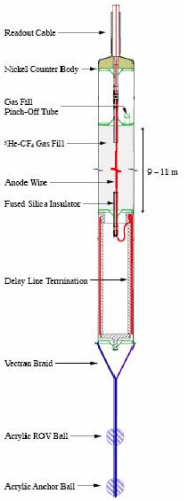
$$\nu_x + d \rightarrow \nu_x + p + n$$

flavor-blind

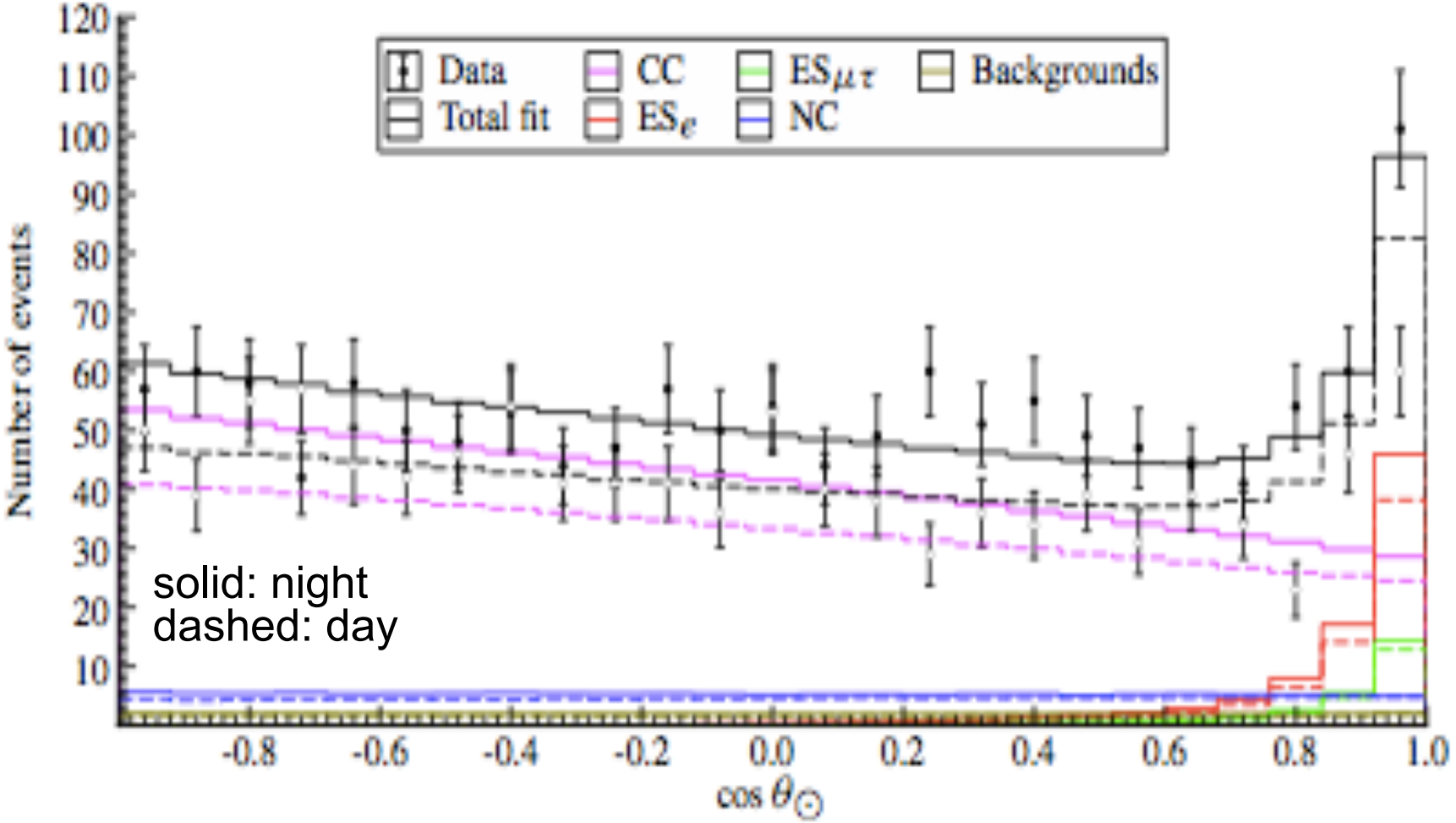
Tag NC via detection of neutron

- Phase I: capture on d (D_2O) $n + d \rightarrow t + \gamma + 6.25$ MeV
- Phase II: capture on Cl (salt, NaCl) $n + {}^{35}Cl \rightarrow {}^{36}Cl + \gamma + 8.6$ MeV
- Phase III: neutron detectors (NCD) $n + {}^{3}He \rightarrow p + t + 0.76$ MeV





SNO data



Use **angle** and **energy** distributions to fit data for CC, NC, ES components

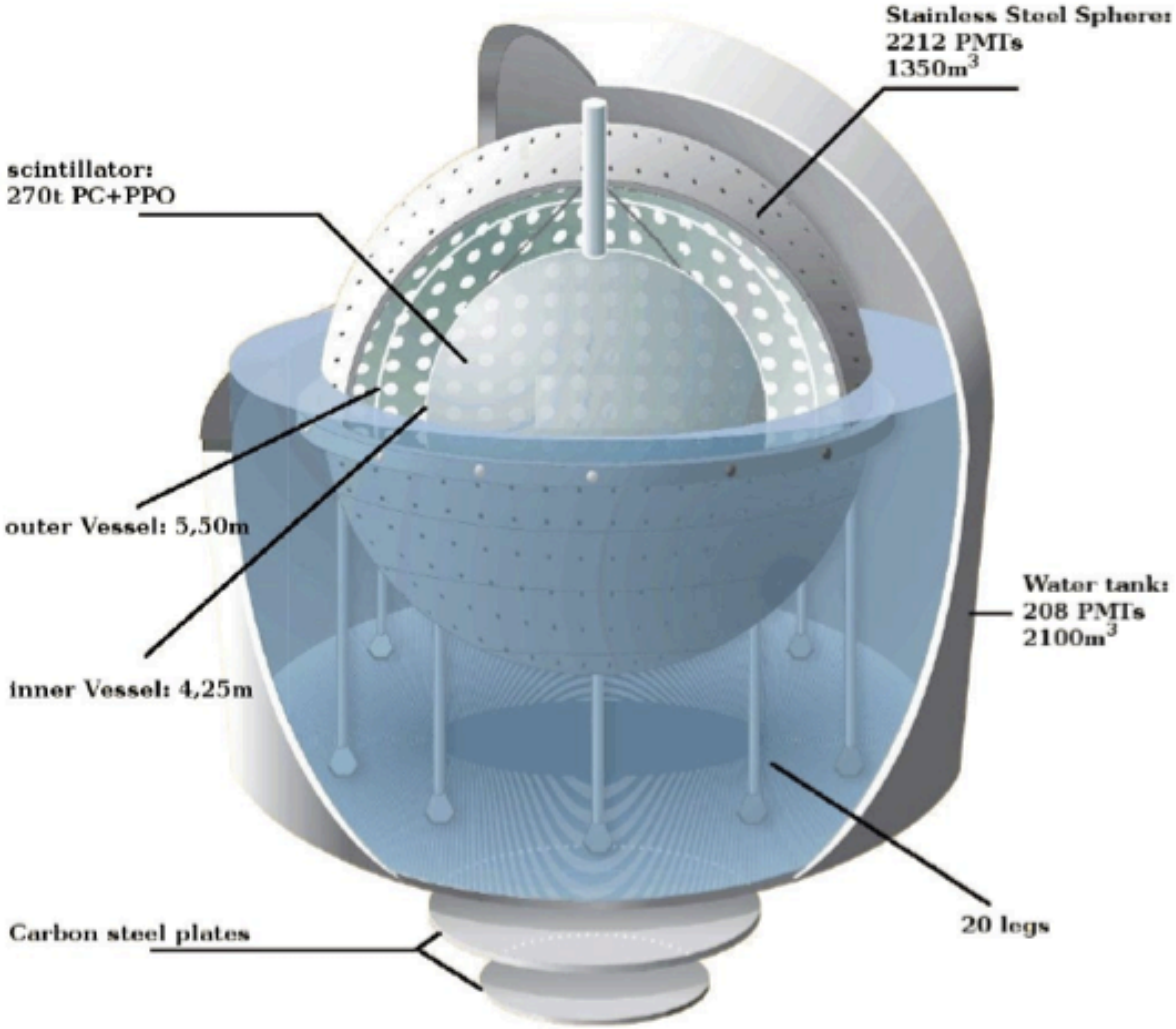
slightly backscattered

isotropic

forward scattered

But there's more: the Borexino Experiment

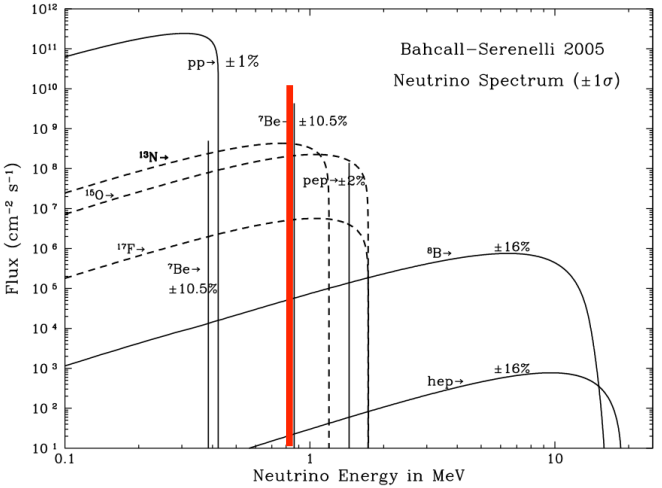
Gran Sasso, Italy

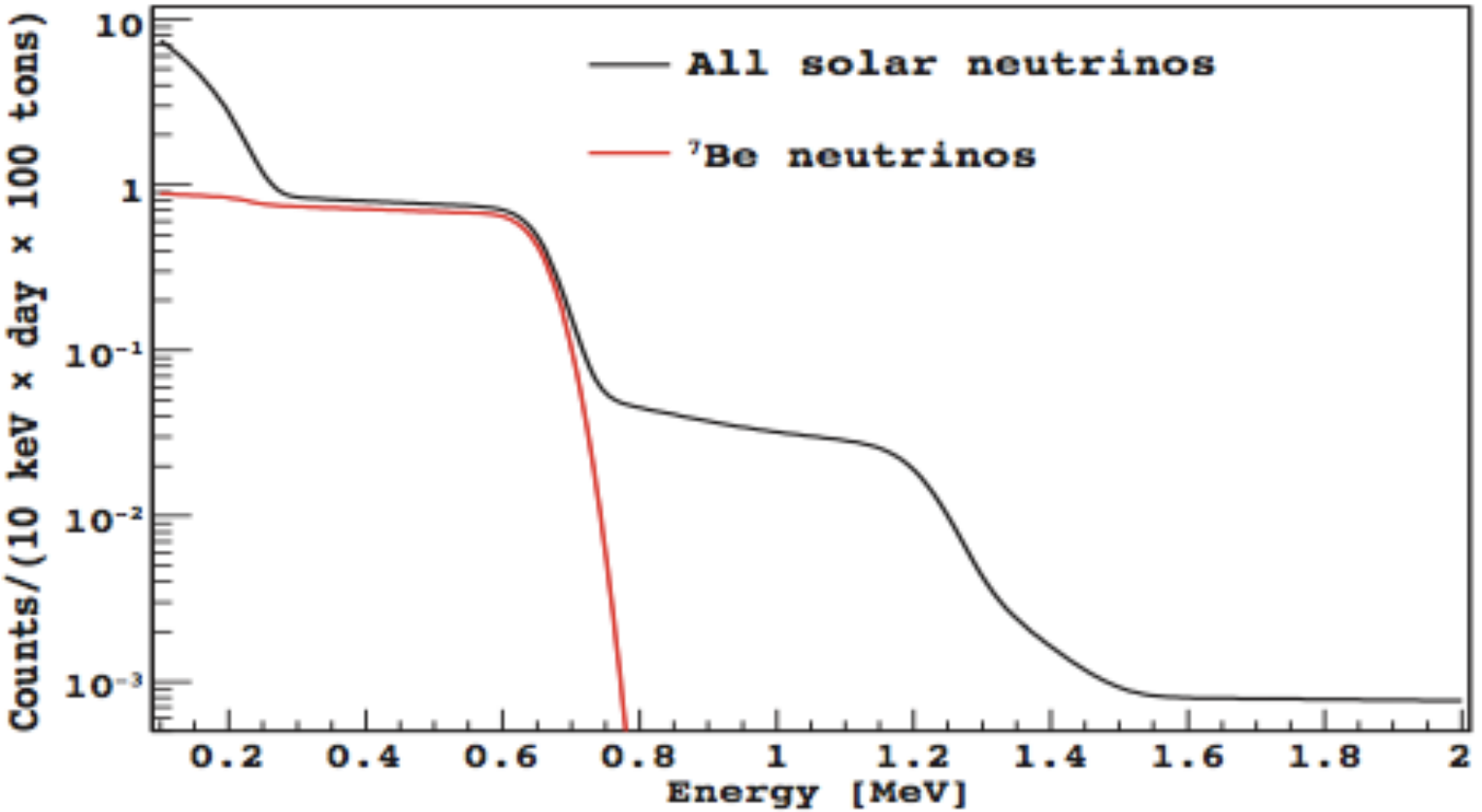


$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$

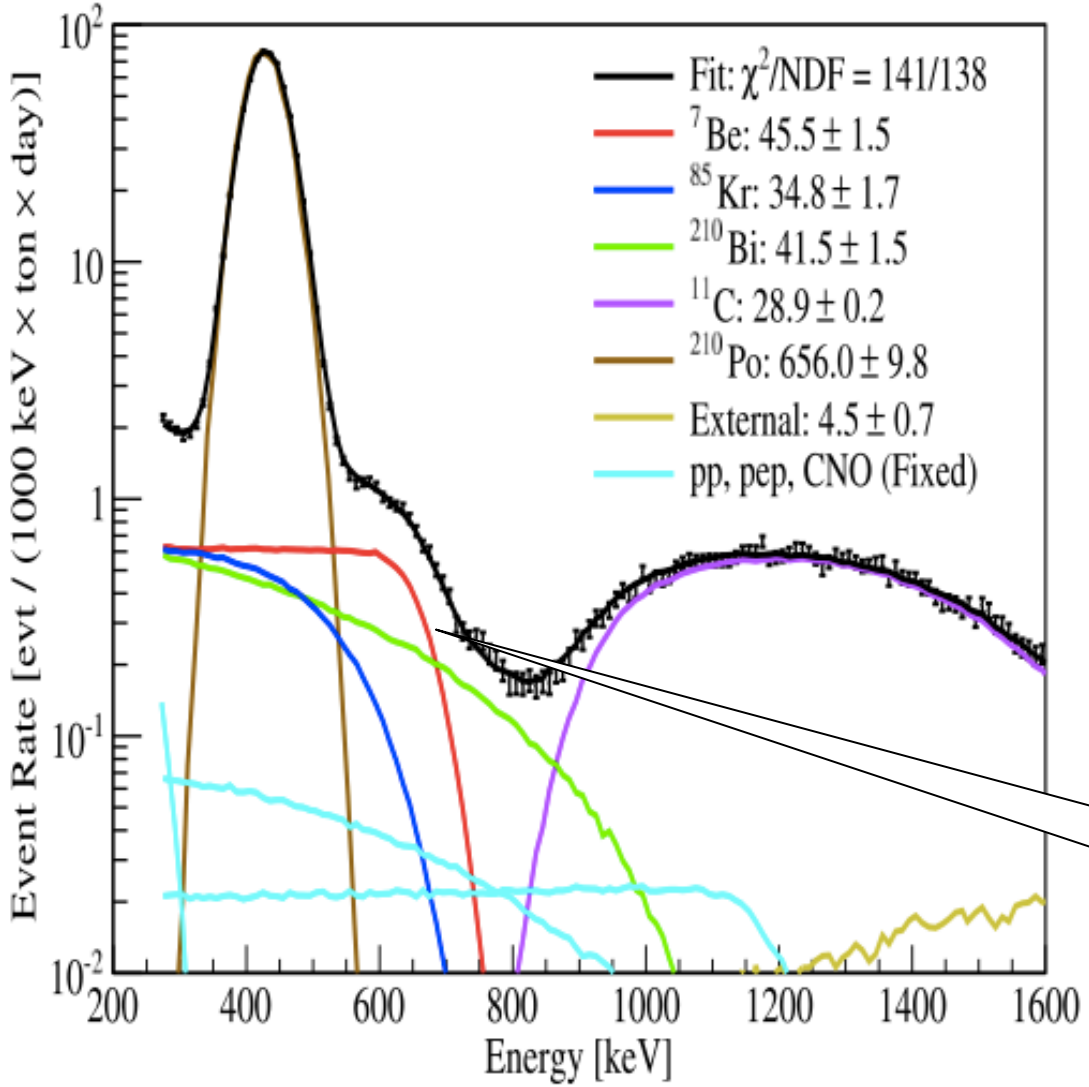
- Scintillator (300 ton)
- Very low threshold (down to ~200 keV)
- Very low radioactivity
- Real time

Go after recoil electrons from the ^{7}Be line





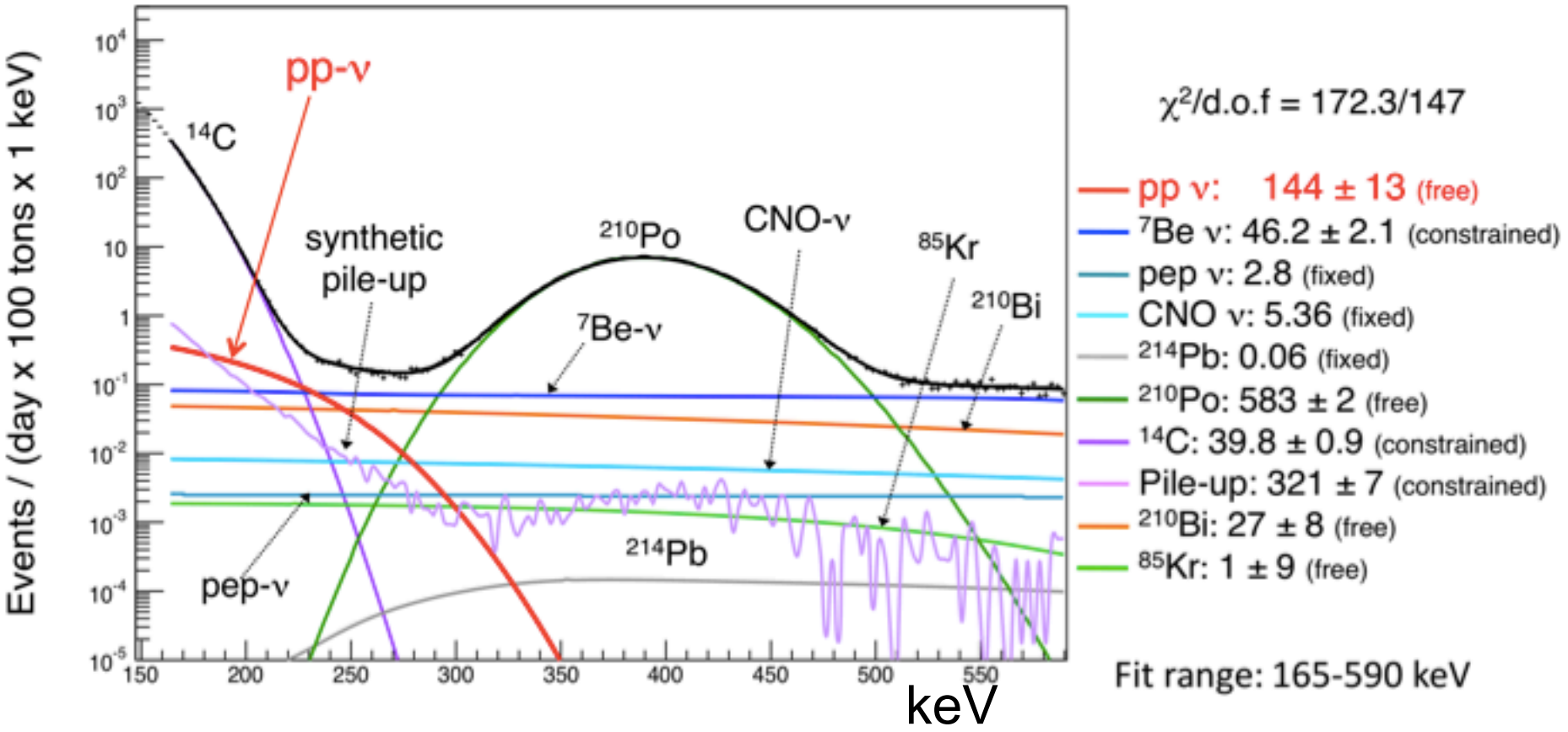
Heroic (and successful) struggle with radioactive (ambient & cosmogenic) backgrounds



it's all about the backgrounds

^{7}Be neutrinos identified

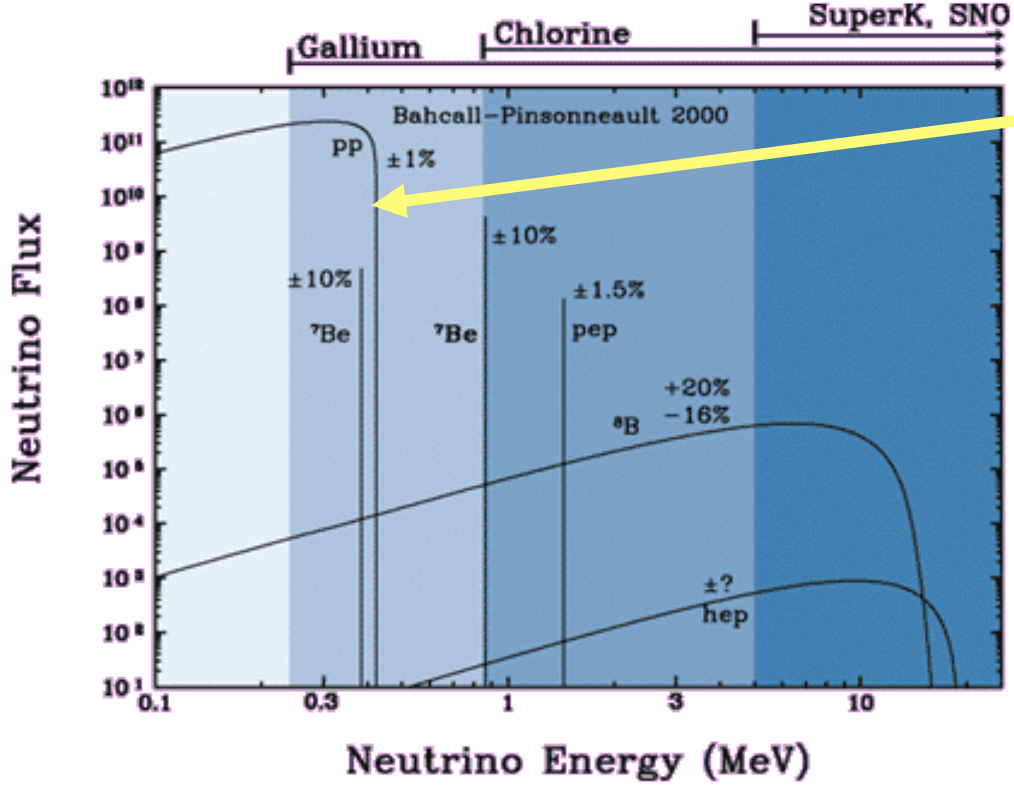
Even more heroic extraction of pp rates:



it's all about the backgrounds ...

The Future? Large water, argon, scint... (WbLS?)

Ideas for ultra-low energy (sub MeV) ?
real-time solar pp ν detectors

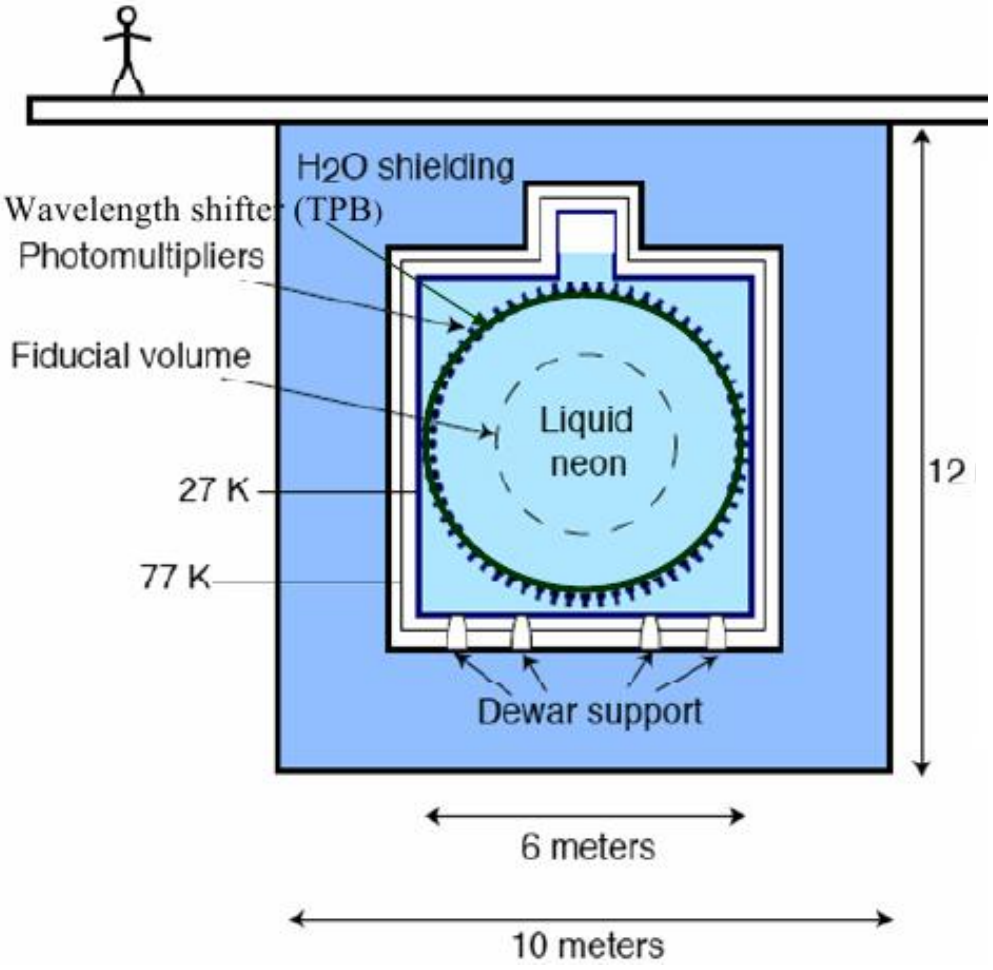


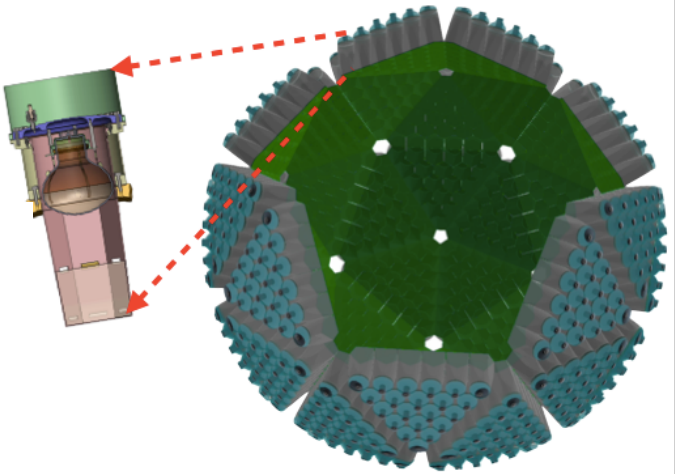
Vast pp neutrino flux barely touched!

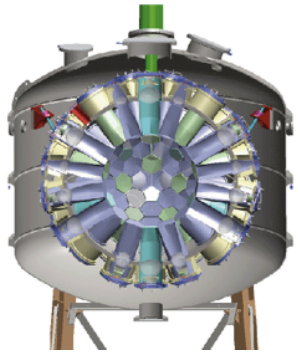
- detectors can be relatively small (~10 tons) thanks to huge pp flux
- want real-time energy resolution
- **must be ultra-clean** to defeat radioactive background

it's all about the backgrounds ...

CLEAN: liquid neon (argon)

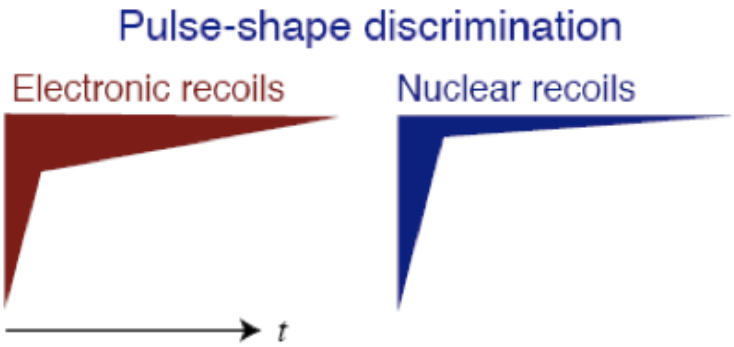






MiniCLEAN

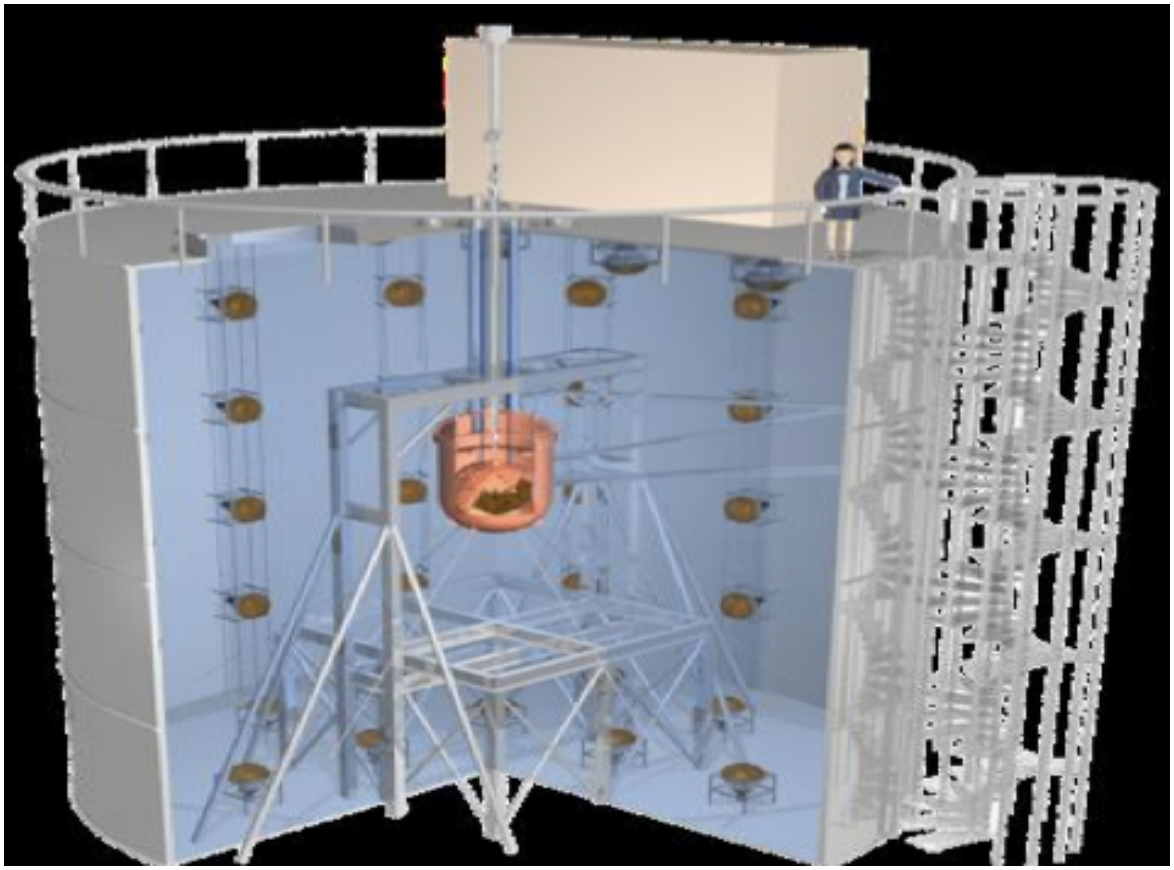
$$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$$



Fast component: < 10 ns
Slow component: 1.6 μs (LAr), 15 μs (LNe)
Discriminate based on fraction of light in first 100 ns (Fprompt)

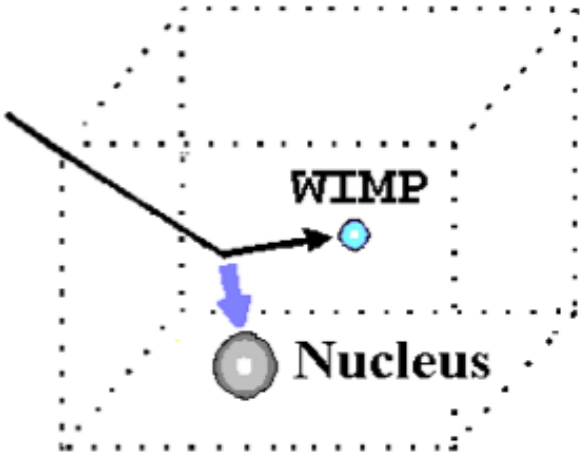
XMASS: liquid xenon

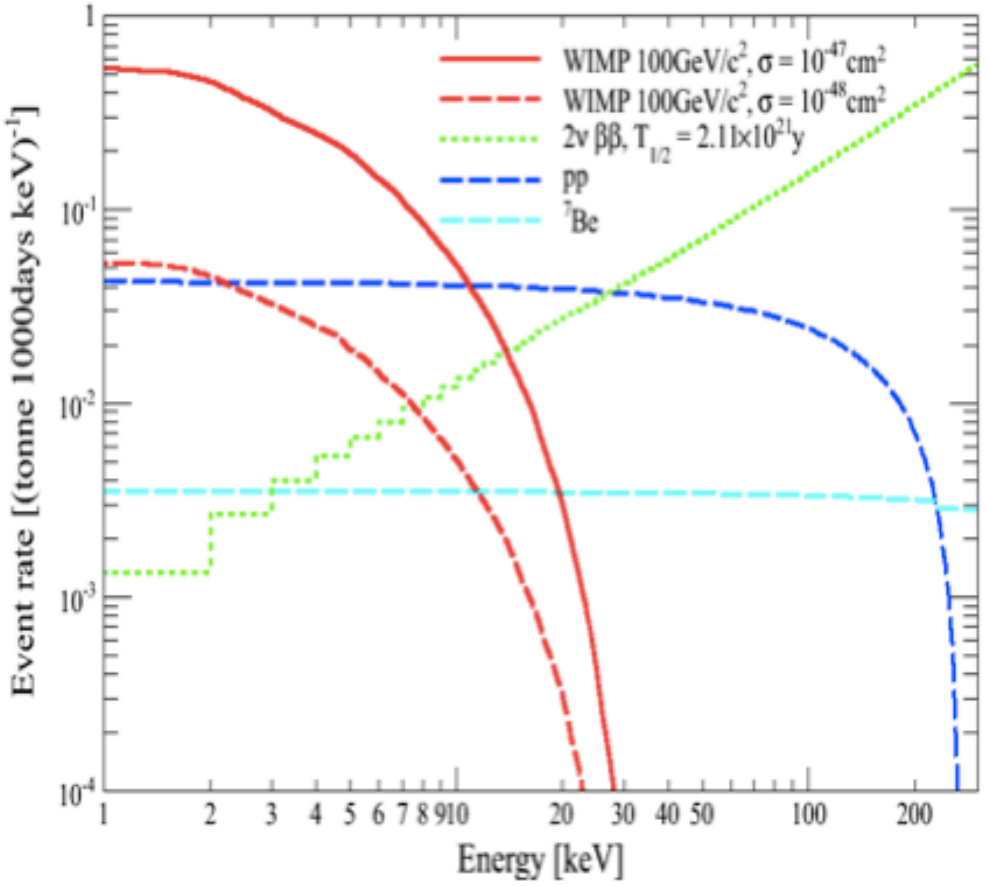
$$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$$



But note: noble liquid detectors have gotten “distracted” by **WIMP searches**...

Measured recoil energy spectrum in xenon





Nuclear recoils induced by DM may be an easier signal!.. and CEvNS of solar neutrinos may be a *background* for them...

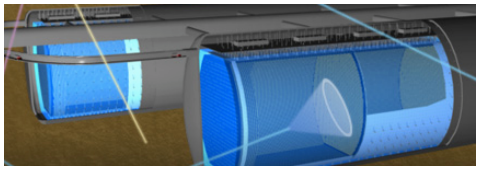
What to take away from this lecture

At low energy (<100 MeV):

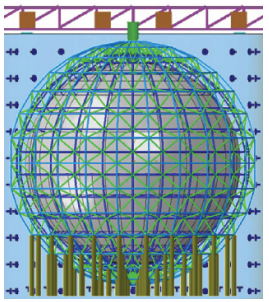
- Still want **energy** (quantity/resolution)**, angular resolution**
- Still want **flavor tagging**... but
  can only distinguish ν_e vs $\bar{\nu}_e$ vs ν_x
- Interactions w/ nuclei poorly understood;
  details of nuclear physics matter
- Background is critical... must be deep & clean

it's all about the backgrounds ...

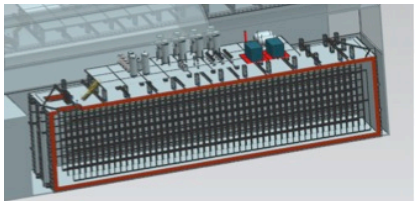
Water: cheap, proven, directional,
OK reconstruction, but low light yield,
hard to go <few MeV, neutron tagging w/Gd



Scintillator: proven, non-directional,
good light yield ➔energy resolution,
low threshold, neutron tagging



LArTPC: OK reconstruction,
directional, **unique ν_e sensitivity**



Lecture overview

Lecture 1: general principles of neutrino interactions and particle detection

Lecture 2: neutrinos at GeV energies

Lecture 3: neutrinos at MeV energies: supernova, solar, geo (the “wild” ones)

Lecture 4: more on detecting MeV neutrinos: (geo, reactor, source, accelerator) plus some other topics if time permits