What Stubs and Sparkles in Vast Vats of Liquid Can Tell Us About Exploding Stars

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BNL Physics Colloquium
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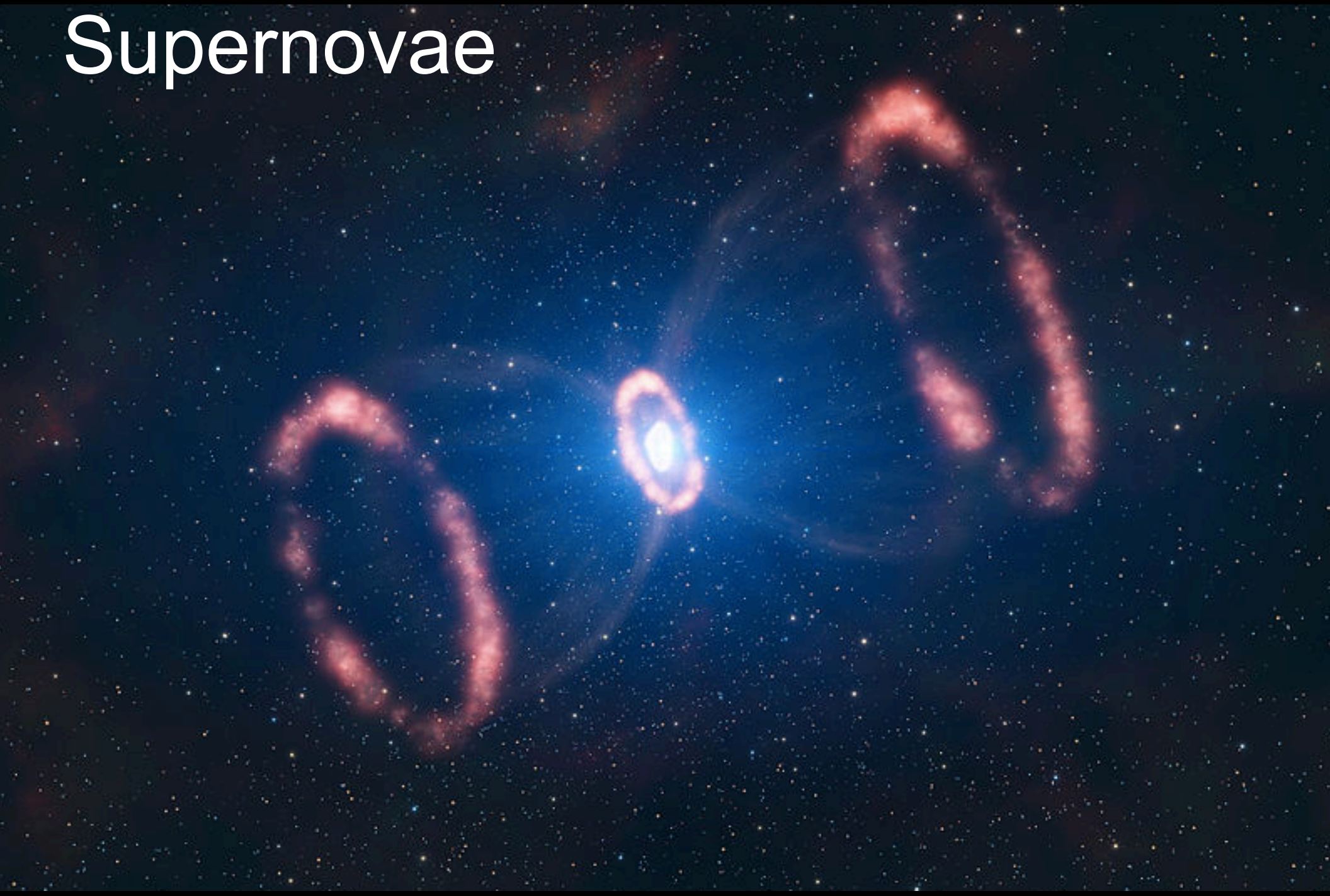
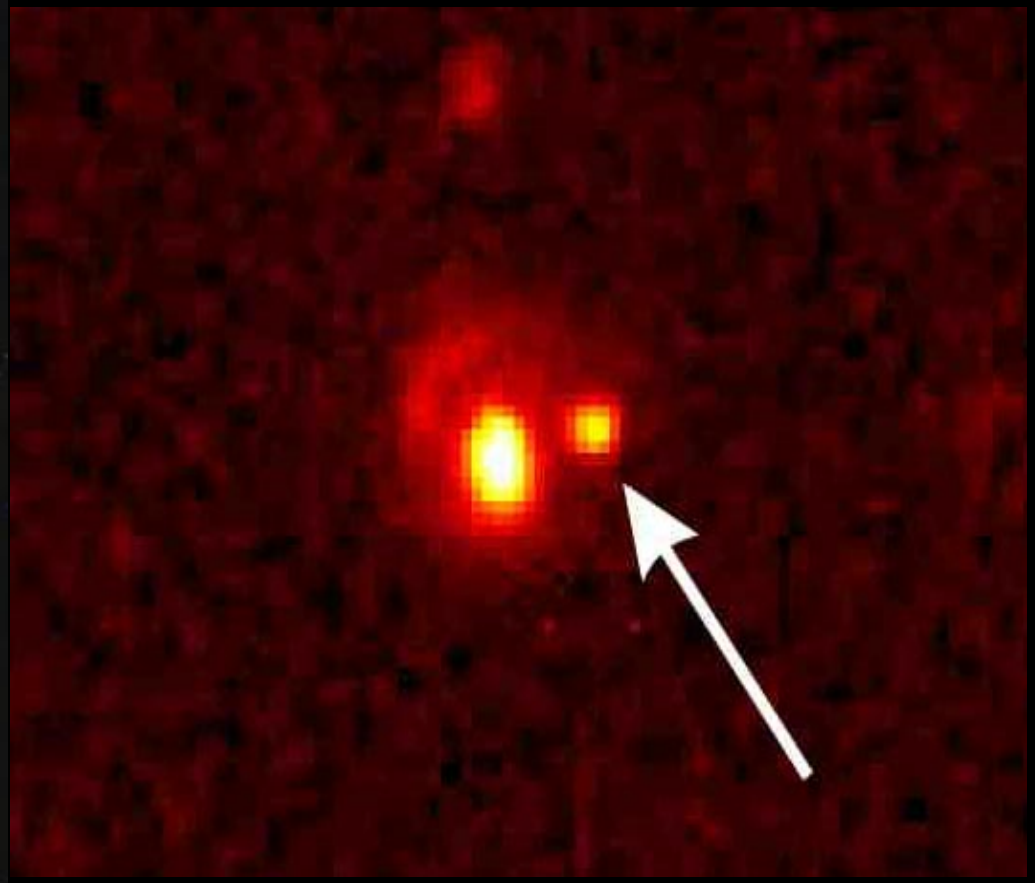
OUTLINE

- Supernovae
- Neutrinos
- Neutrinos from Supernovae
  - The signal
  - What we will learn
- Detecting Neutrinos from Supernova
  - Interactions
  - Detector types & Instances
- Future prospects
  - An early alert
- Summary

Supernovae



Supernova: An energetic outburst resulting in the disruption of a star



For a while, as luminous (in photons) as a galaxy!

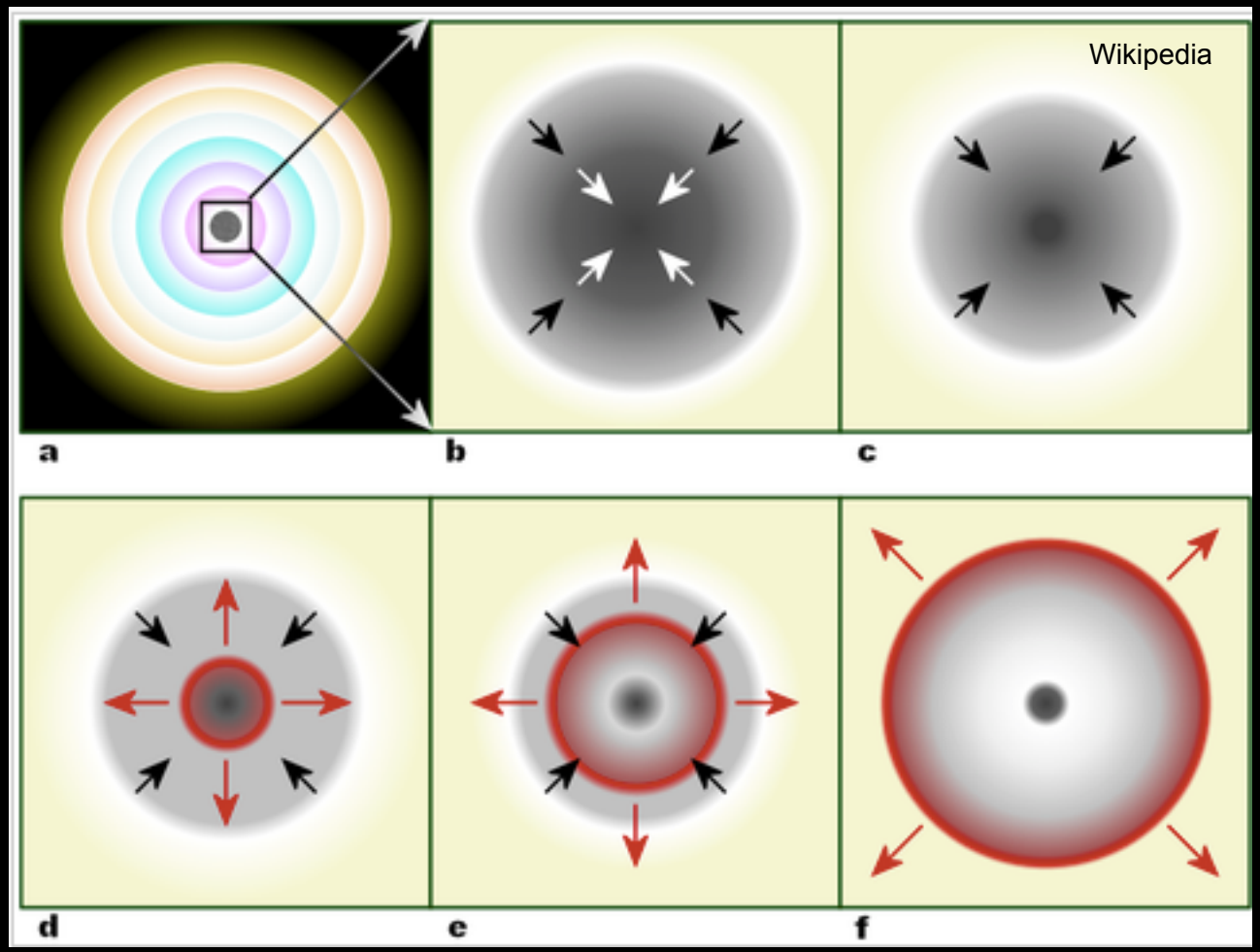
(well, some galaxies)

Type II

H lines present in spectra

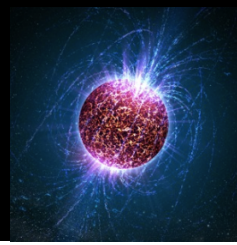
(also Type Ib,c)

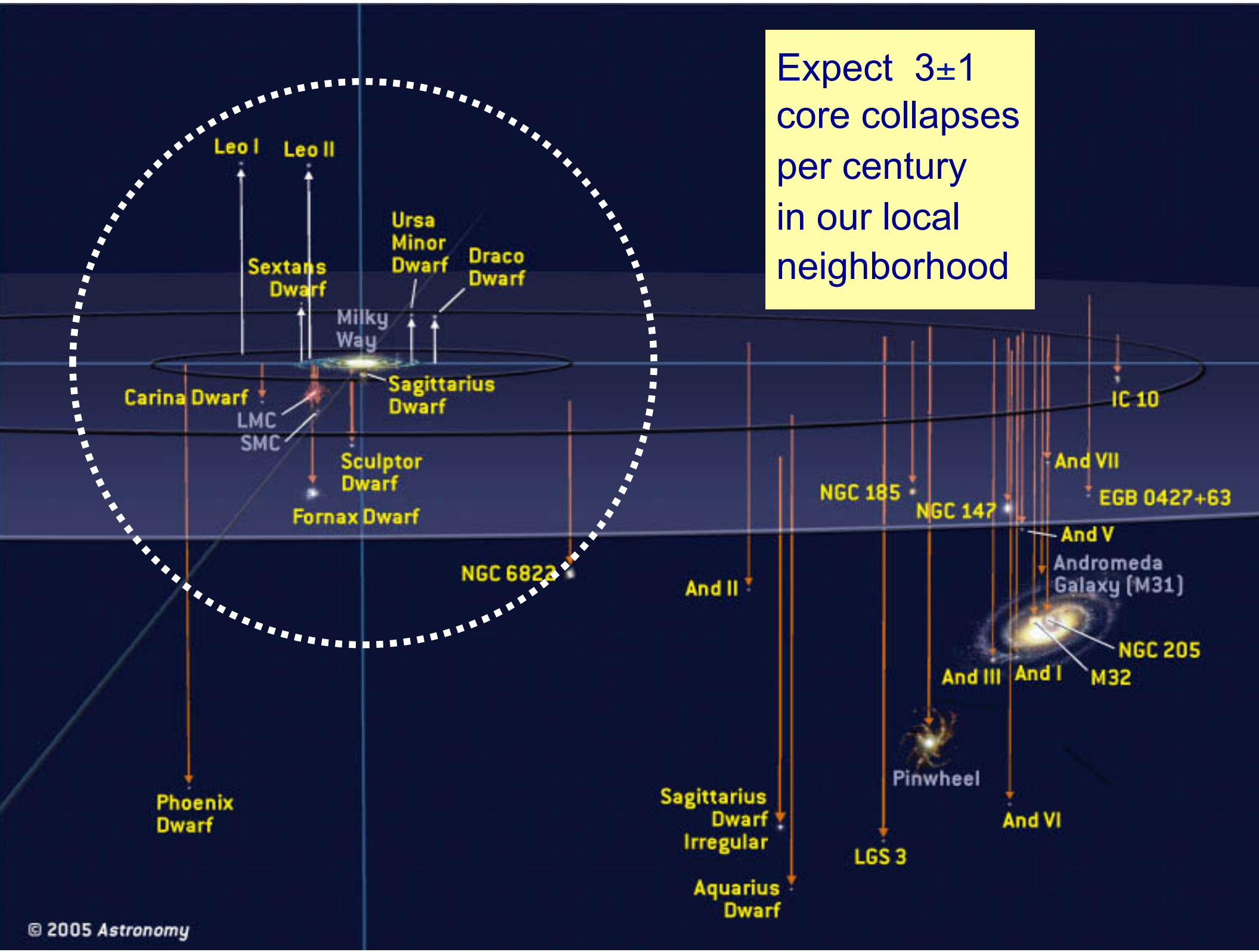
Model: *gravitational collapse* of a massive star at the end of its life



Core-collapse supernovae are copious producers of neutrinos!

Creates ***compact remnant***: neutron star or black hole



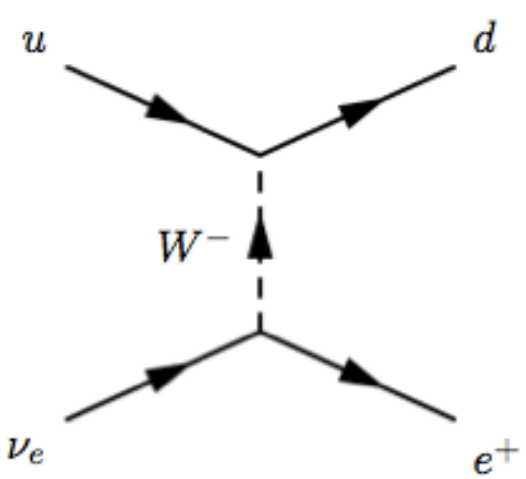

Expect 3±1
core collapses
per century
in our local
neighborhood
Leo I
Leo II
Ursa
Minor
Dwarf
Draco
Dwarf
Sextans
Dwarf
Milky
Way
Sagittarius
Dwarf
Carina Dwarf
LMC
SMC
Sculptor
Dwarf
Fornax Dwarf
NGC 6822
Phoenix
Dwarf
And II
Sagittarius
Dwarf
Irregular
Aquarius
Dwarf
LGS 3
Pinwheel
NGC 185
NGC 147
And VII
EGB 0427+63
And V
Andromeda
Galaxy (M31)
NGC 205
M32
And III
And I
And VI
IC 10
© 2005 Astronomy

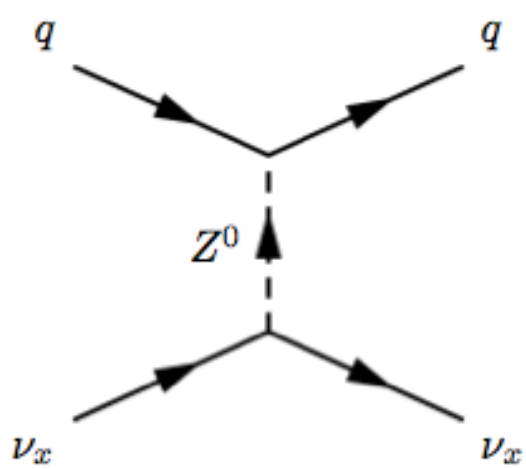
NEUTRINOS

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

neutral partners
to the charged leptons

- Three flavors (families), neutrinos and antineutrinos
- Tiny masses (< 1 eV) and oscillations (flavor change)
- Interact *only* via *weak interaction* (& gravity)

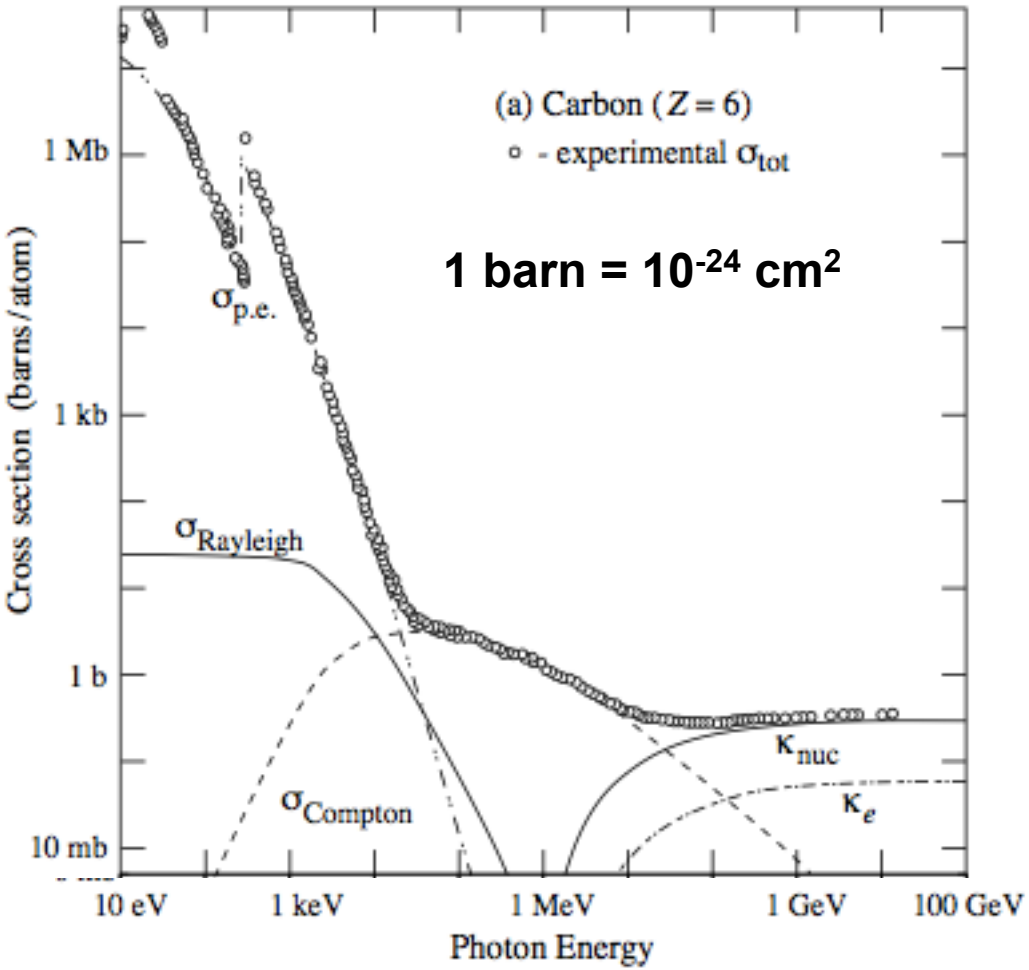




Exchange of
W and Z bosons in
weak interactions

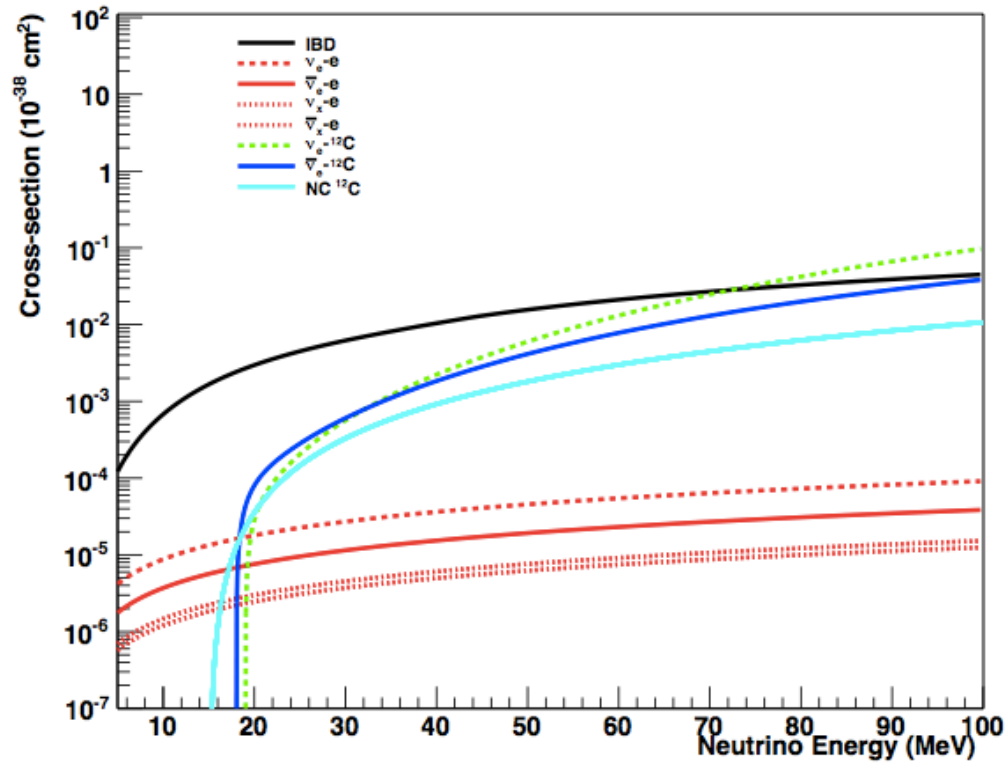
It's called the weak interaction for a reason

Photon-matter cross sections



~10^{-24} cm^2

Neutrino-matter cross sections



~10^{-40} cm^2

~16-17 orders of magnitude smaller

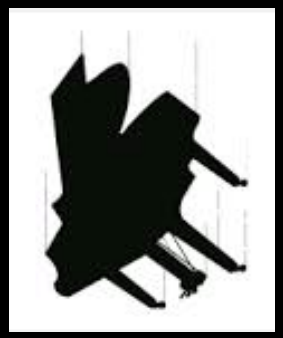
In astrophysics, the weakness of the interaction is both a blessing and a curse...

- neutrinos bring information from deep inside objects, from regions where photons are trapped

- but they require heroic efforts to detect!

Neutrinos from core collapse

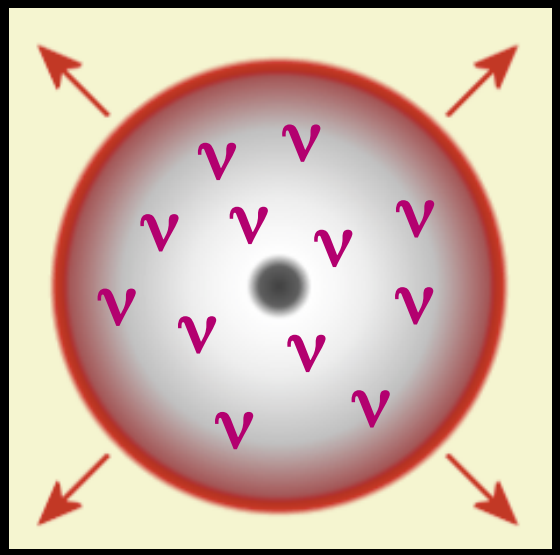
Just as gravitational potential energy turns into kinetic (and thermal) energy when an object falls,



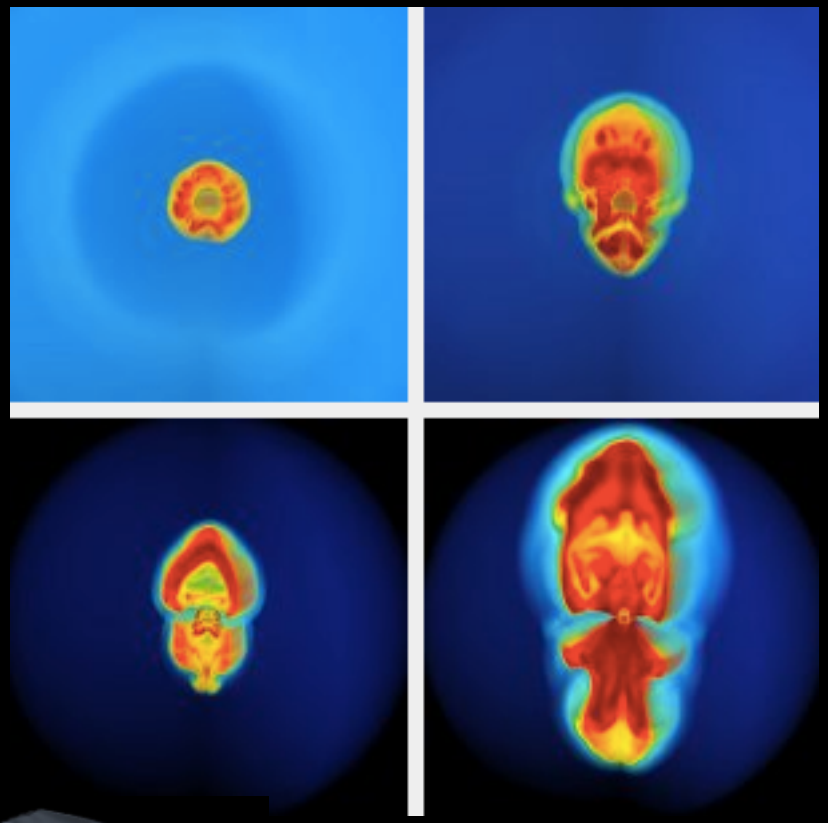
.... as the star falls inward, the gravitational energy *must go somewhere*...

The energy *can* escape via neutrinos, thanks to the weakness of the neutrino interactions

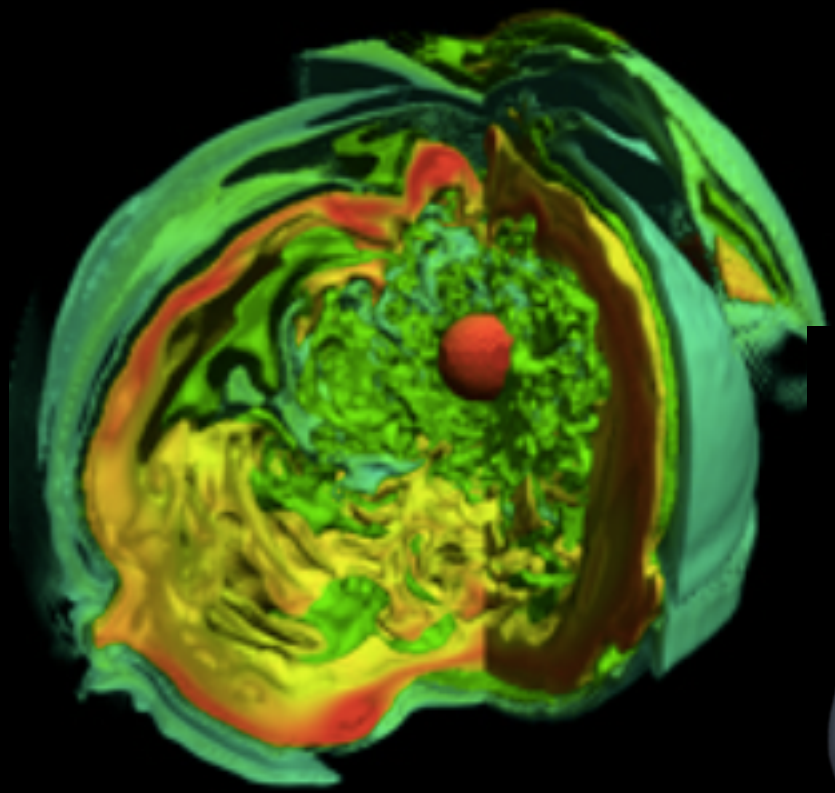
~99% of the vast binding energy of the proto-neutron star is shed within ~10 seconds in the form of *neutrinos and antineutrinos of all flavors*



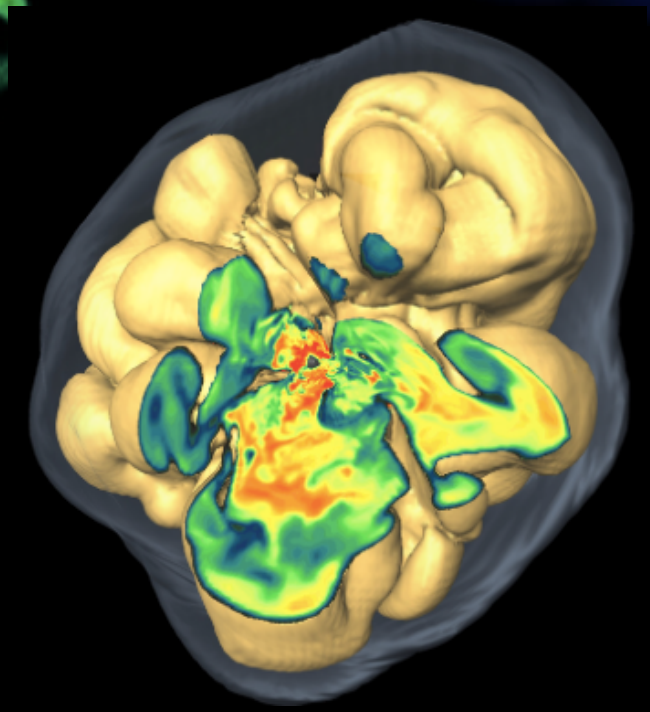
The core-collapse
supernova explosion
is still not well understood...
numerical study ongoing



Marek & Janka



Blondin, Mezzacappa, DeMarino

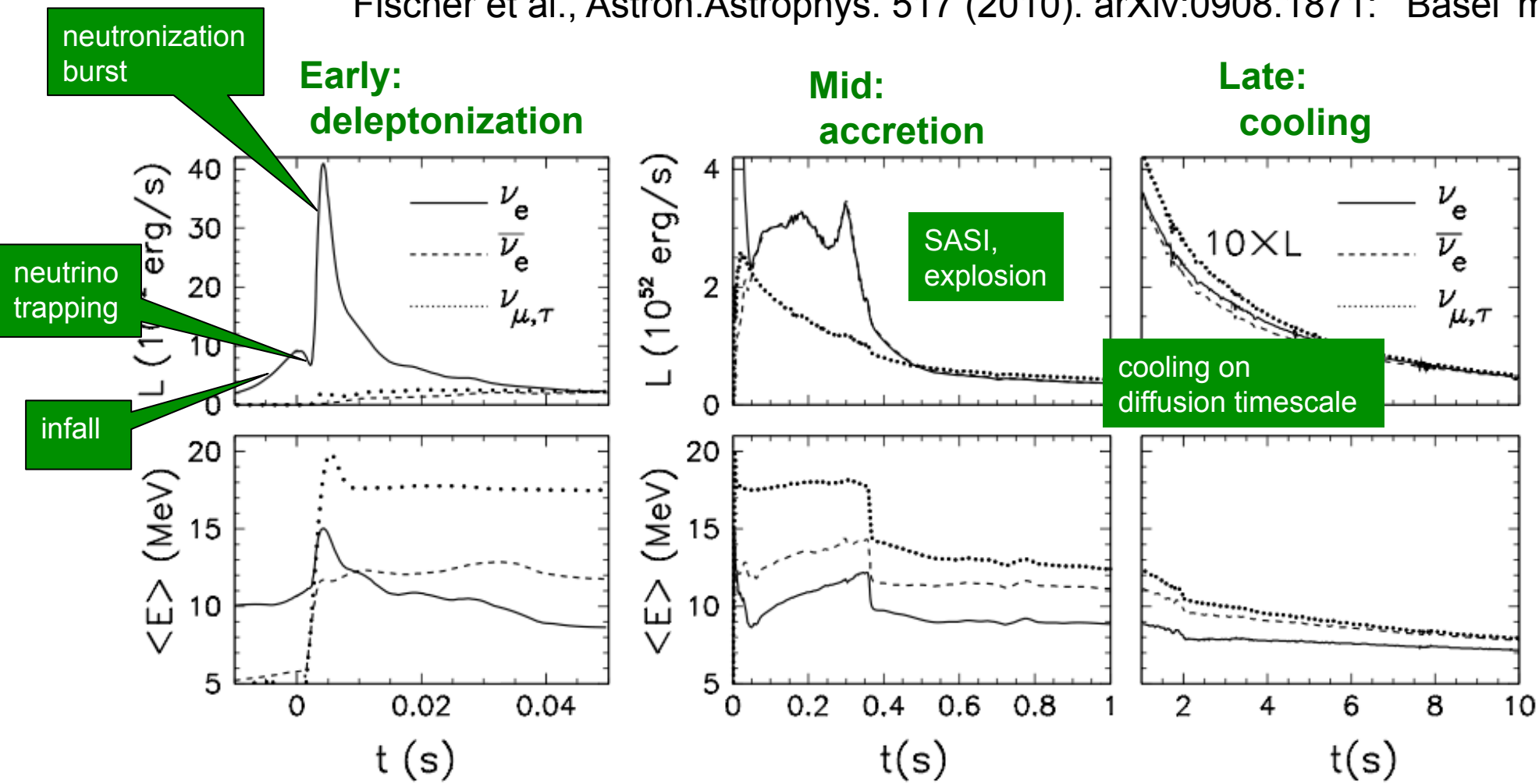


Neutrinos are
intimately
involved

Expected neutrino luminosity and average energy vs time

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

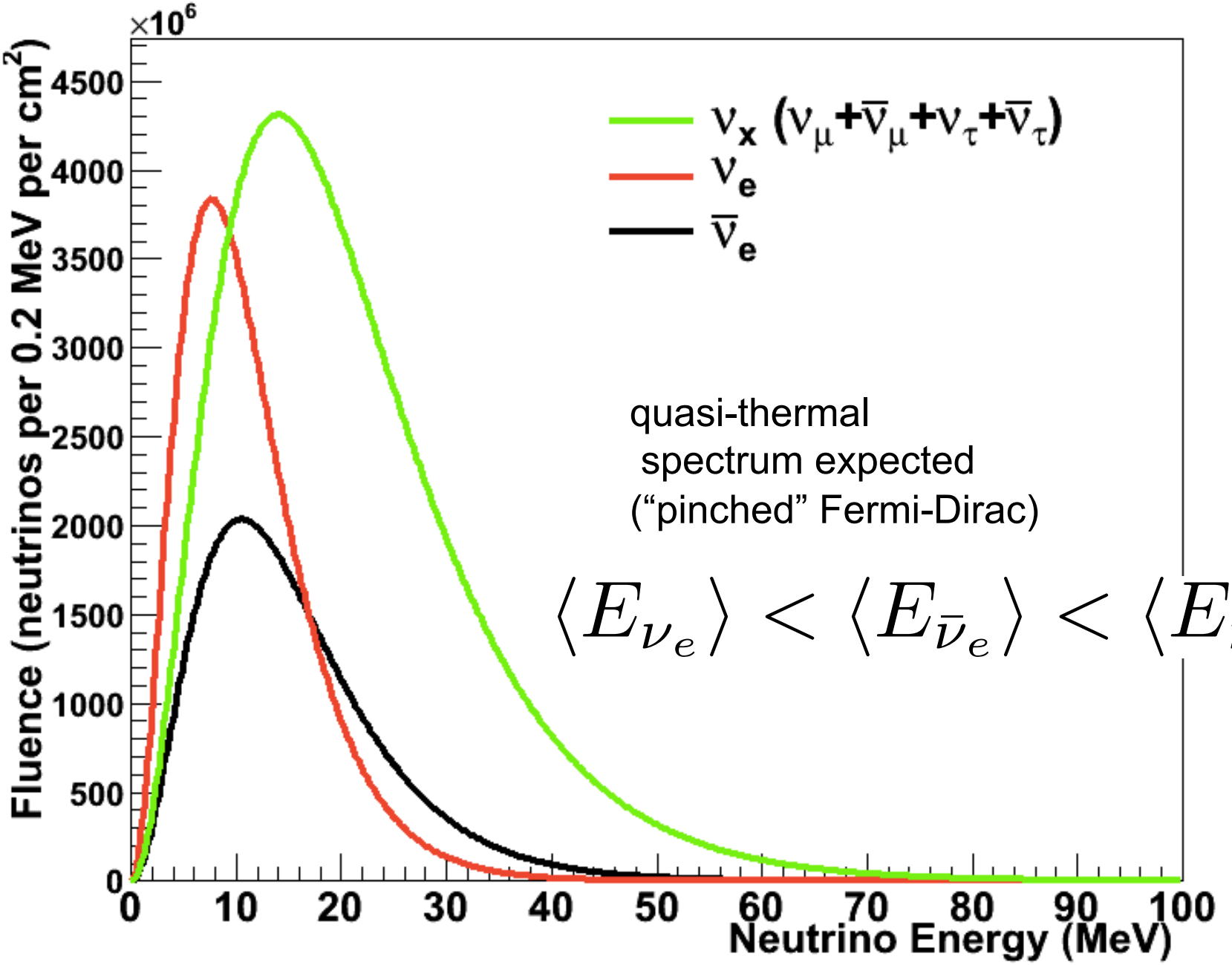
Fischer et al., Astron.Astrophys. 517 (2010). arXiv:0908.1871: 'Basel' model



Generic feature:
(may or may not be robust)

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

Neutrino spectrum from core collapse



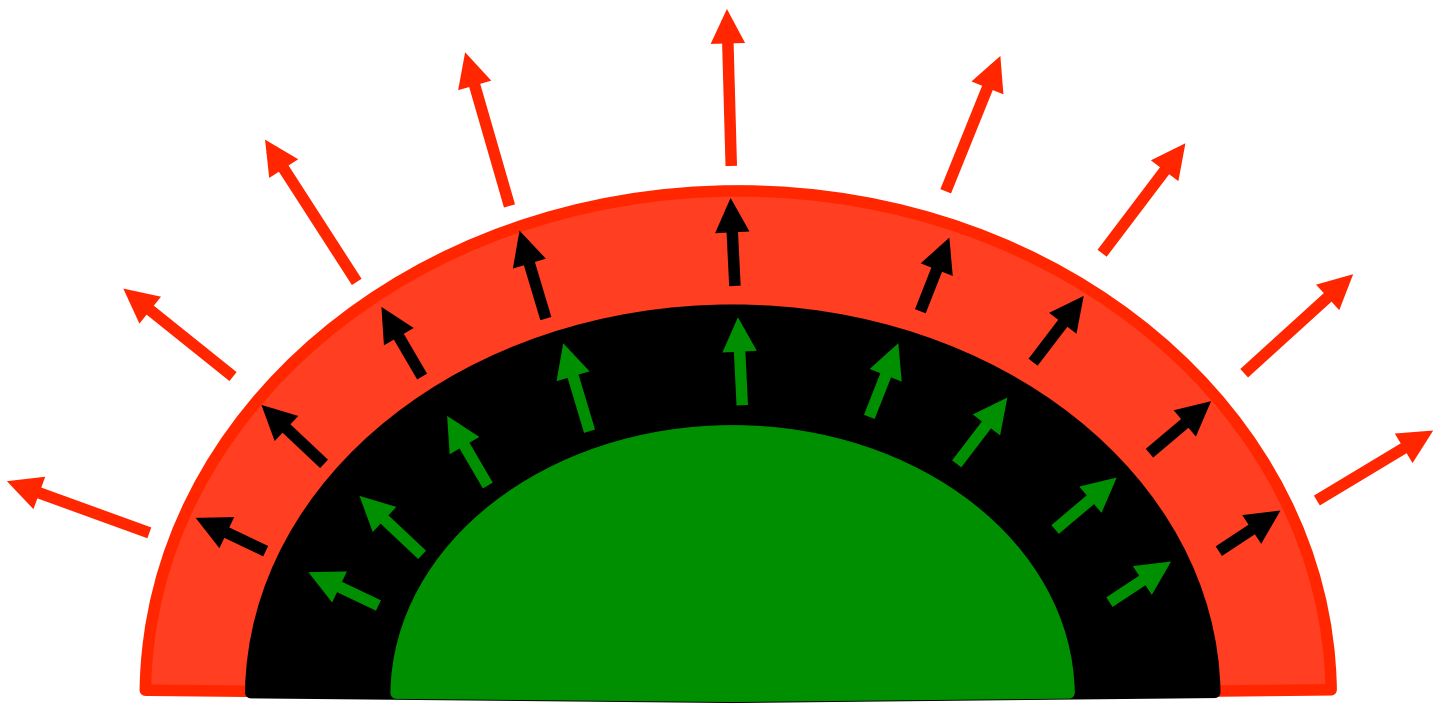
quasi-thermal
spectrum expected
("pinched" Fermi-Dirac)

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

Nominal expected flavor-energy hierarchy

Fewer interactions
w/ proto-nstar
⇒ deeper ν-sphere
⇒ hotter ν's

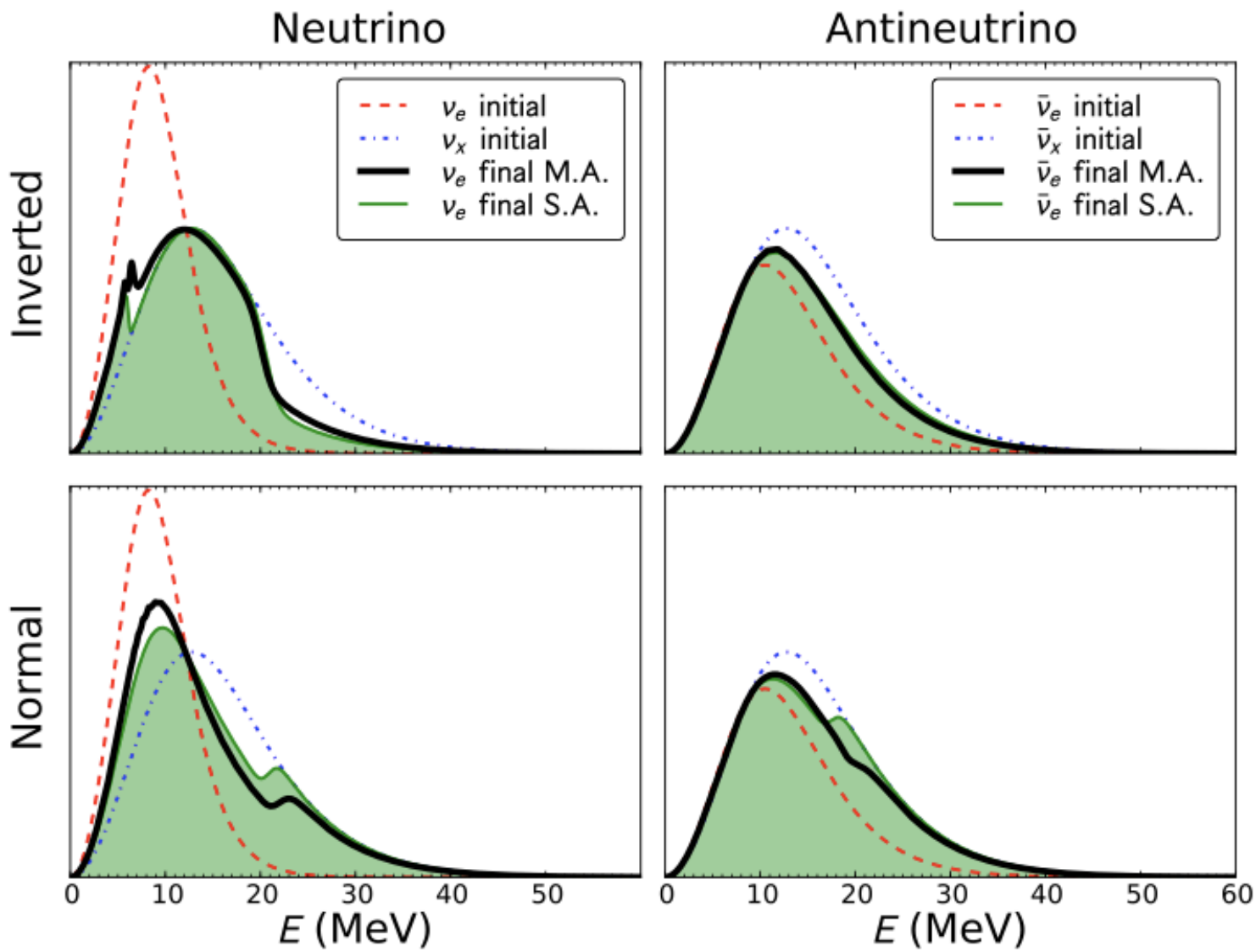
$\langle E\nu_e \rangle \sim 12$ MeV
$\langle E\bar{\nu}_e \rangle \sim 15$ MeV
$\langle E\overset{(-)}{\nu}_{\mu,\tau} \rangle \sim 18$ MeV



May or may not be robust...

Neutrino flavor oscillations (governed by fundamental neutrino parameters) will modify the spectra

Example of oscillation effects: Duan & Friedland, arXiv:1006.2359



Distinctive spectral swap features depend on neutrino mass hierarchy, for neutrinos vs antineutrinos

Experimentally, can we tell the difference?

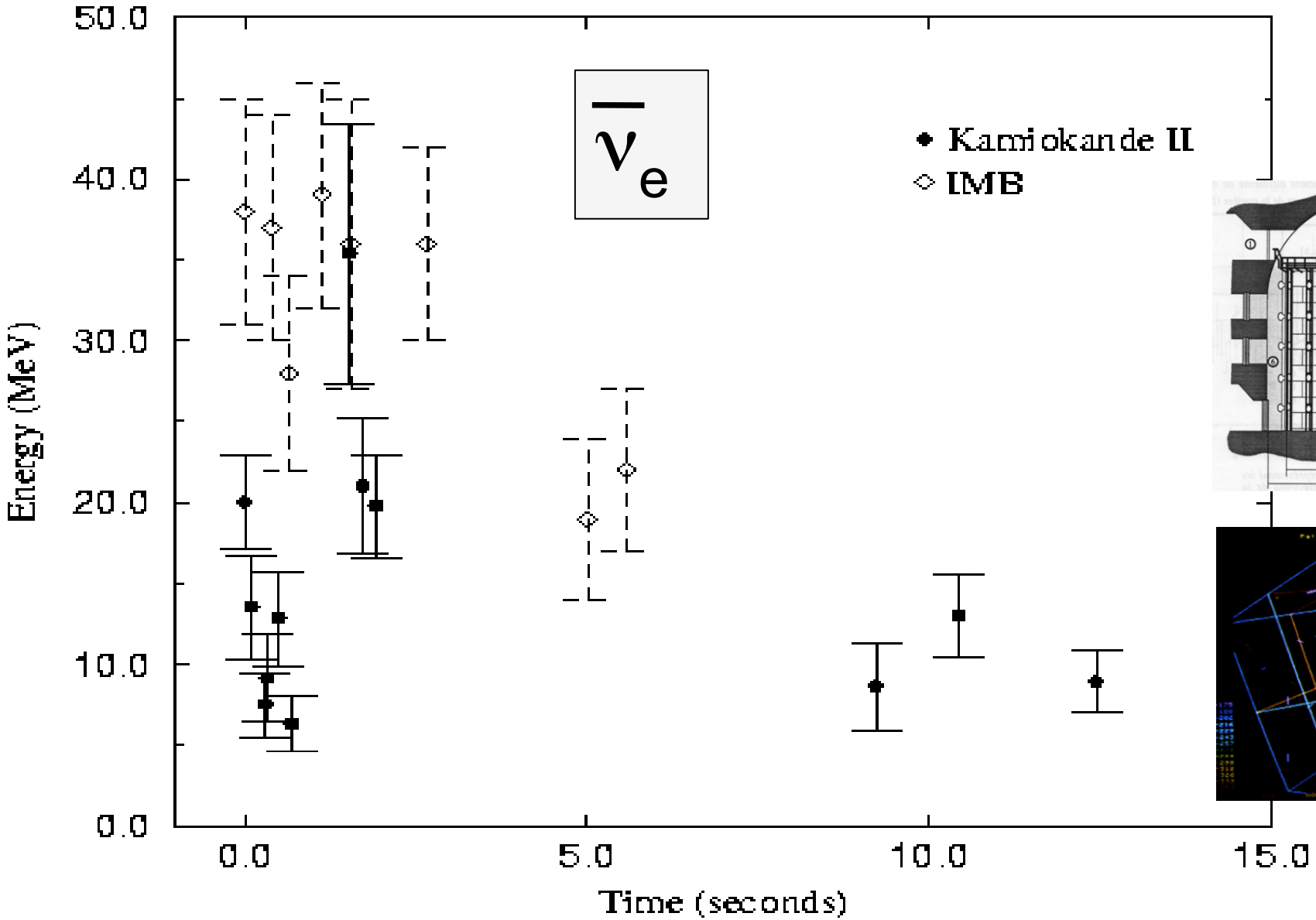
Supernova 1987A

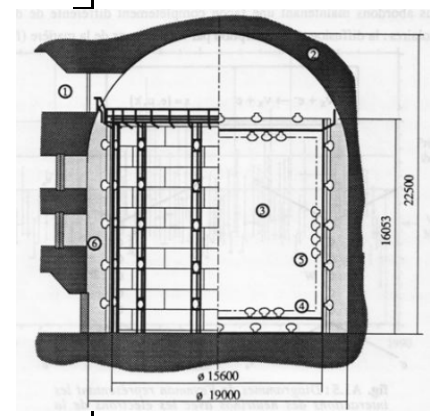
in the Large Magellanic Cloud (55 kpc away)

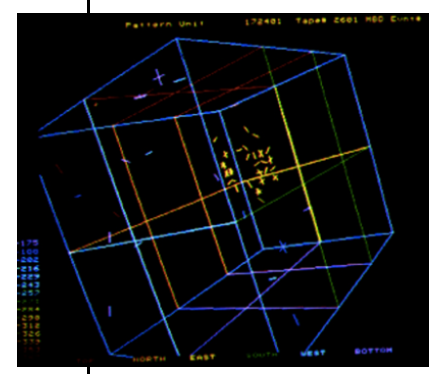
~two dozen neutrino interactions observed!

SN1987A in LMC

ν's seen ~2.5 hours before first light



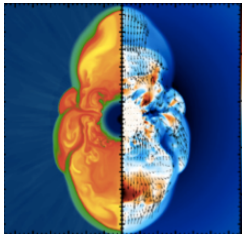




Confirmed baseline model... but still many questions

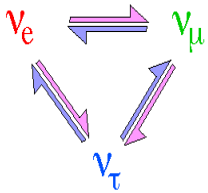
What can we learn from the next neutrino burst?

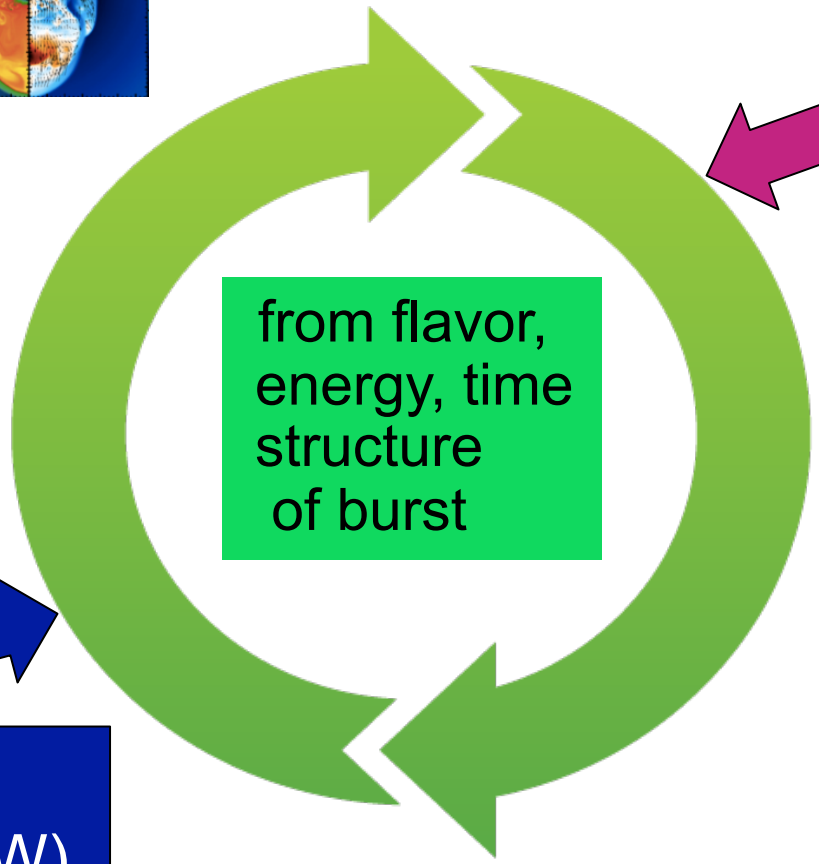
CORE COLLAPSE PHYSICS



explosion mechanism
proto nstar cooling,
quark matter
black hole formation
accretion, SASI
nucleosynthesis
....

input from neutrino experiments





from flavor, energy, time structure of burst

NEUTRINO and OTHER PARTICLE PHYSICS

ν absolute mass (not competitive)
ν mixing from spectra:
flavor conversion in SN/Earth
(mass hierarchy)
other ν properties: sterile ν's,
magnetic moment,...
axions, extra dimensions,
FCNC, ...

input from photon (GW) observations

+ EARLY ALERT

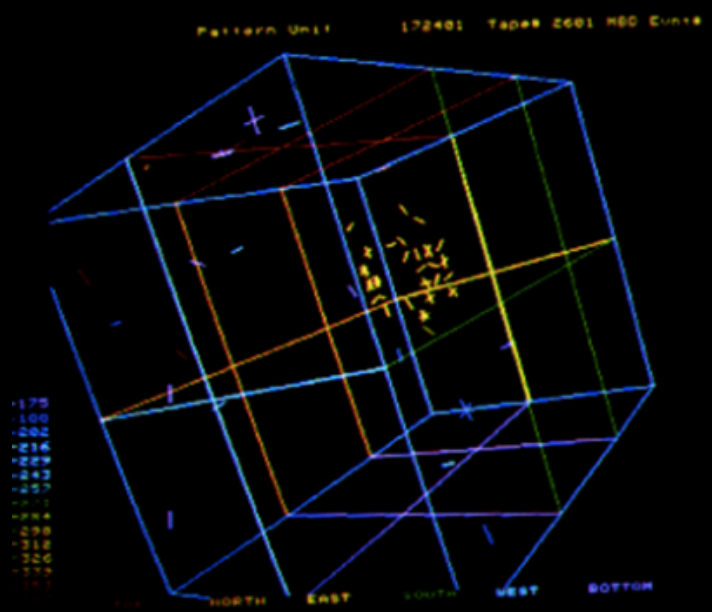
Jargon alert!

In particle physics,
an “event” is *not* this...

~$10^{52\text{-}53}$ ergs

It’s an individual *recorded neutrino interaction*:

few times
10^{-5} ergs

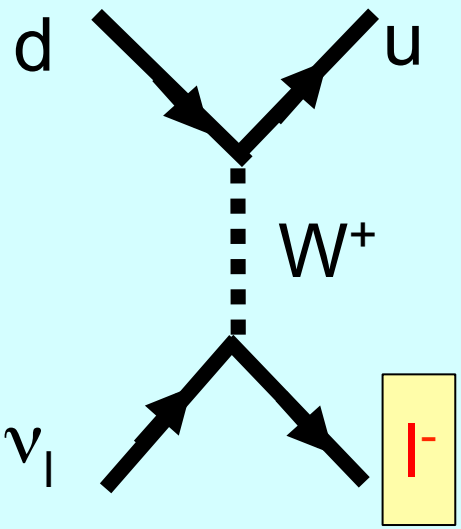


e.g., “the IMB neutrino detector saw 8 events from 1987A”

Reminder on Neutrino Interactions with Matter

Neutrinos are aloof but not *completely* unsociable

Charged Current (CC)

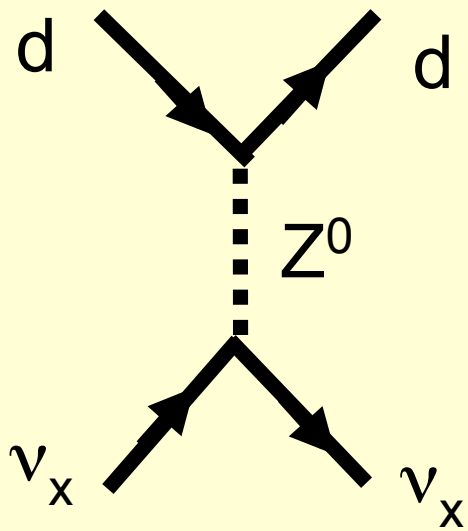


$$\nu_l + N \rightarrow l^{\pm} + N'$$

Produces lepton
with flavor corresponding
to neutrino flavor

(must have enough energy to make lepton)

Neutral Current (NC)



Flavor-blind

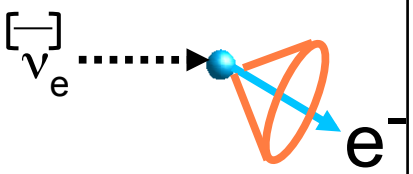
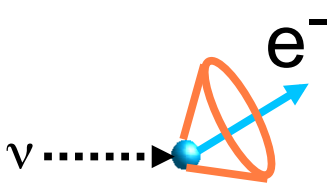
Information is in the ***energy, flavor, time*** structure of the burst

What do you want in a detector?

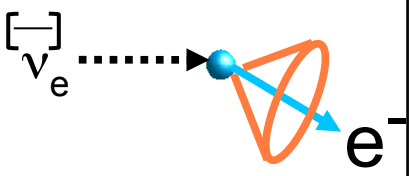
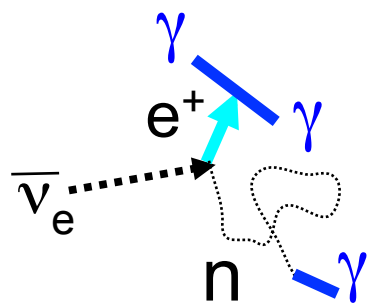
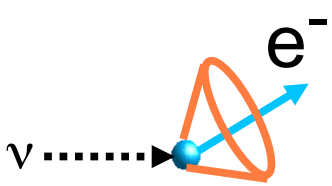
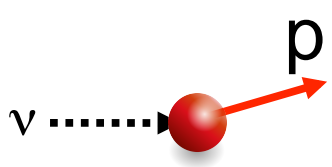
Size	~kton detector mass per 100 events @ 10 kpc
Low energy threshold	~Few MeV if possible
Energy resolution	Resolve features in spectrum
Angular resolution	Point to the supernova! (for directional interactions)
Timing resolution	Follow the time evolution
Low background	BG rate << rate in burst; **underground 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"...

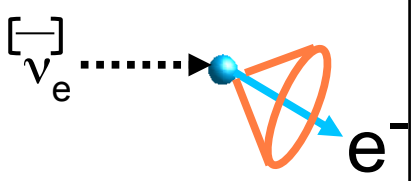
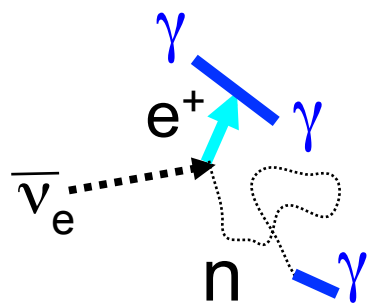
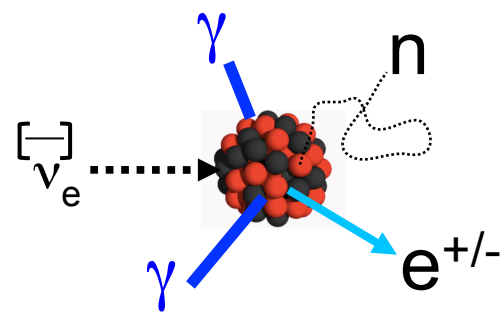
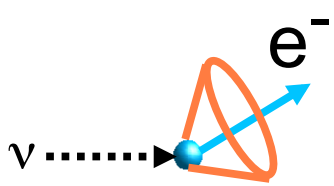
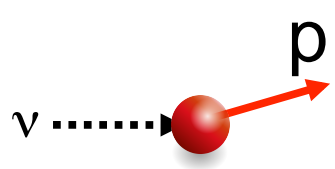
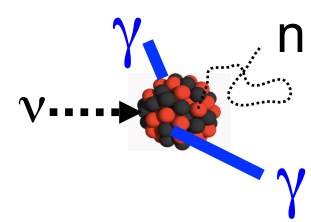
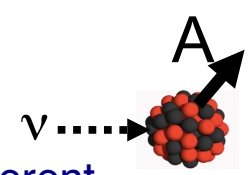
Supernova-relevant neutrino interactions

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

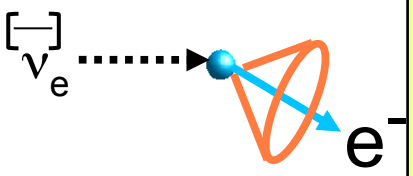
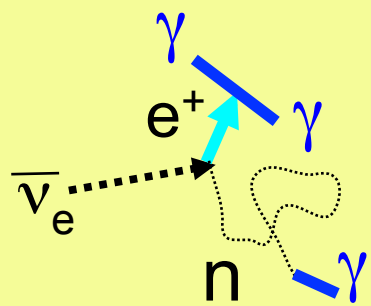
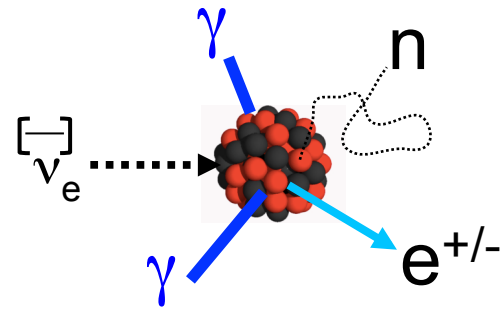
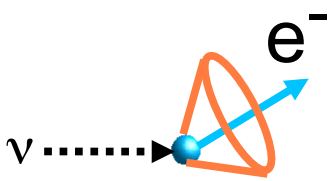
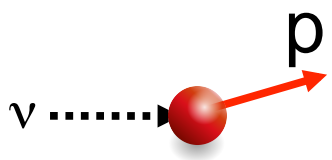
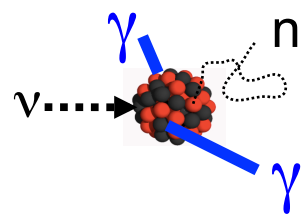
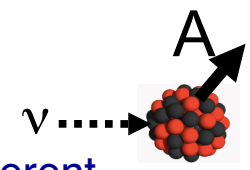
Supernova-relevant neutrino interactions

	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	

Supernova-relevant neutrino interactions

	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)

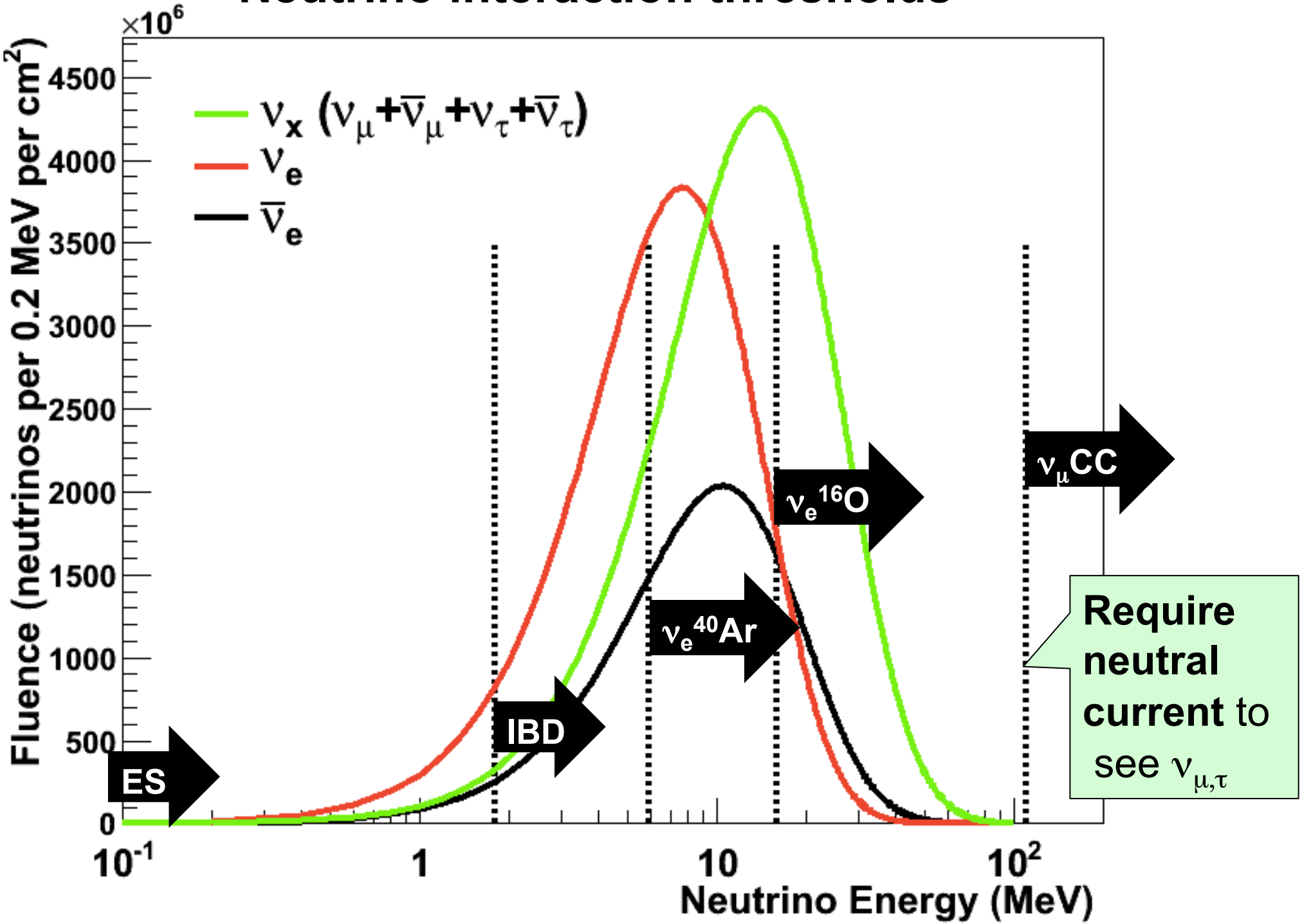
Supernova-relevant neutrino interactions

	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

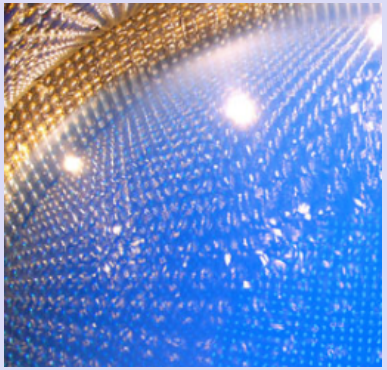
IBD (electron *anti*neutrinos) dominates for current detectors

Neutrino interaction thresholds

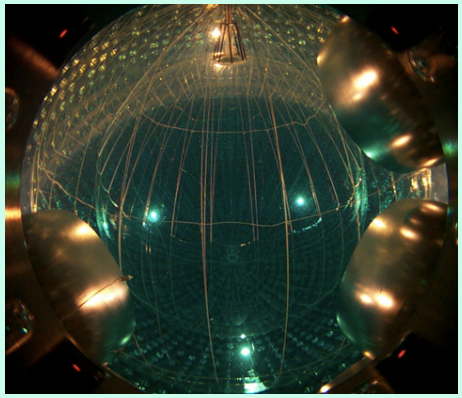


Current main supernova neutrino detector types

Water



Scintillator

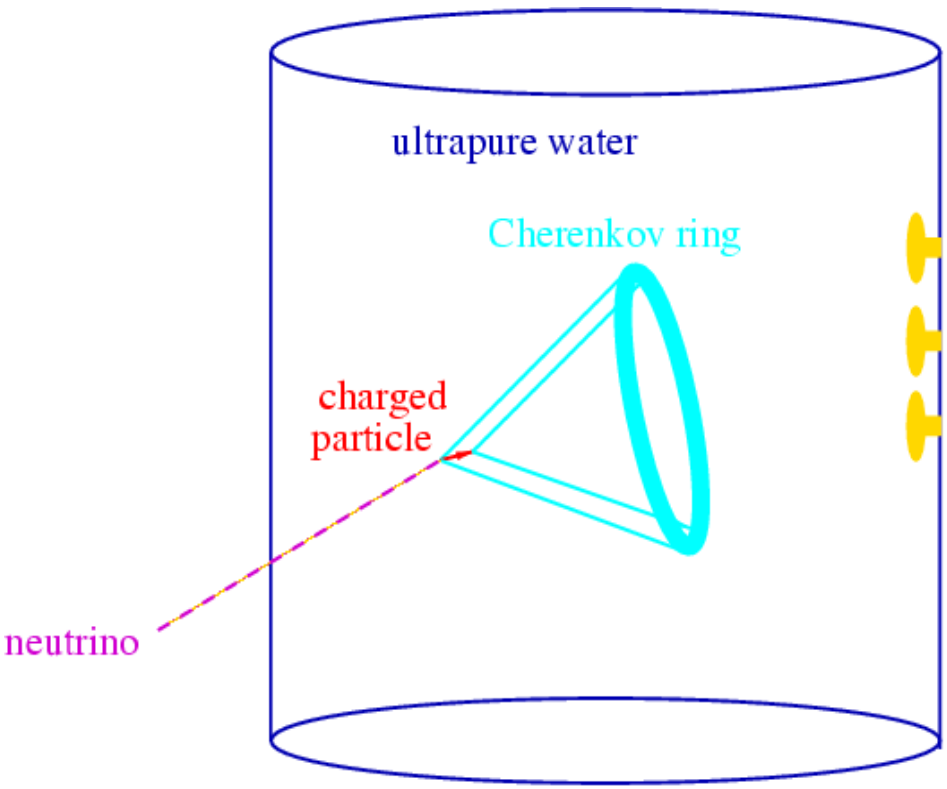


Argon

Lead

+ some others (e.g. DM detectors)

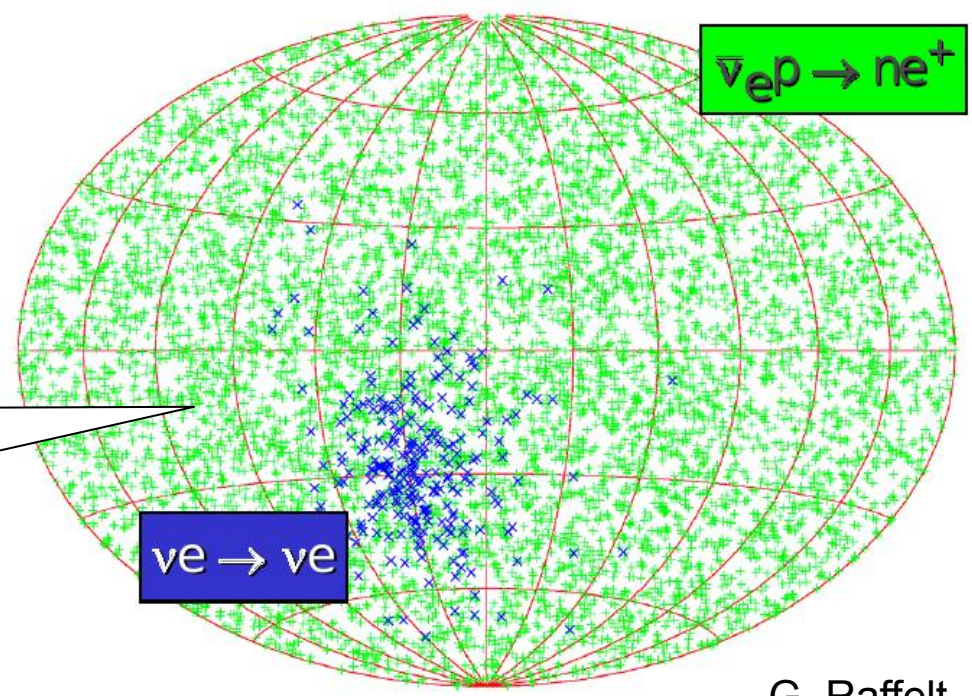
Water Cherenkov detectors



Inverse Beta Decay (CC)

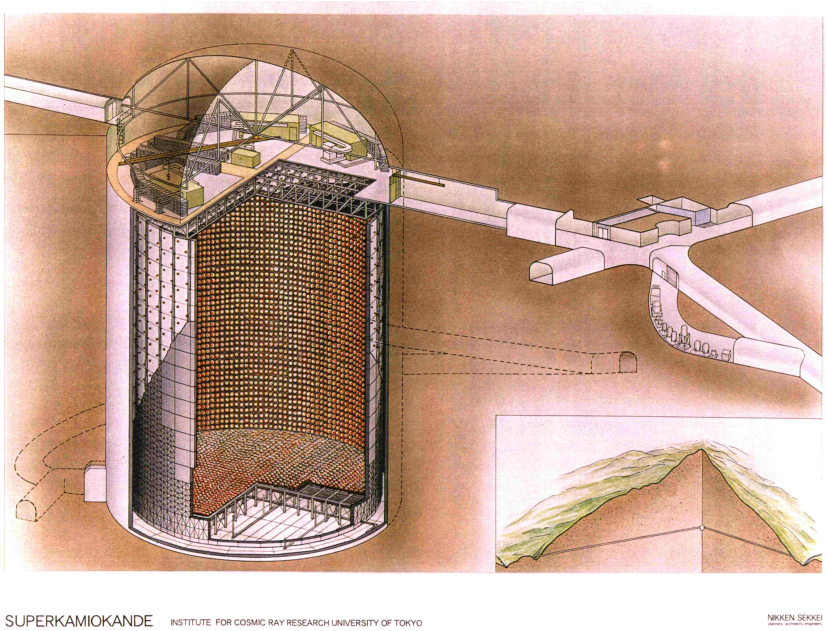
$\bar{\nu}_e + p \rightarrow e^+ + n$ **dominates**

E_{thr}=1.8 MeV



Pointing from neutrino-electron elastic scattering

G. Raffelt



Super-Kamiokande

Mozumi, Japan

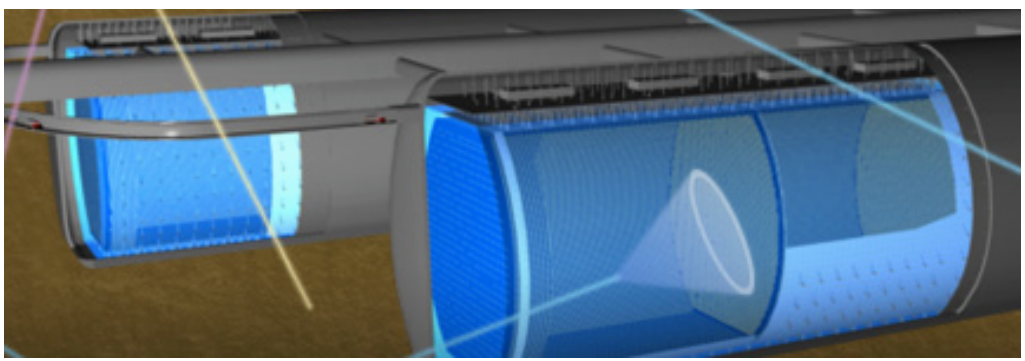
22.5 kton fid. volume (32 kton total)

~5-10K events @ 10 kpc

(mostly anti-ν_e)

~5° pointing @ 10 kpc

Future: SK-Gd



Hyper-Kamiokande

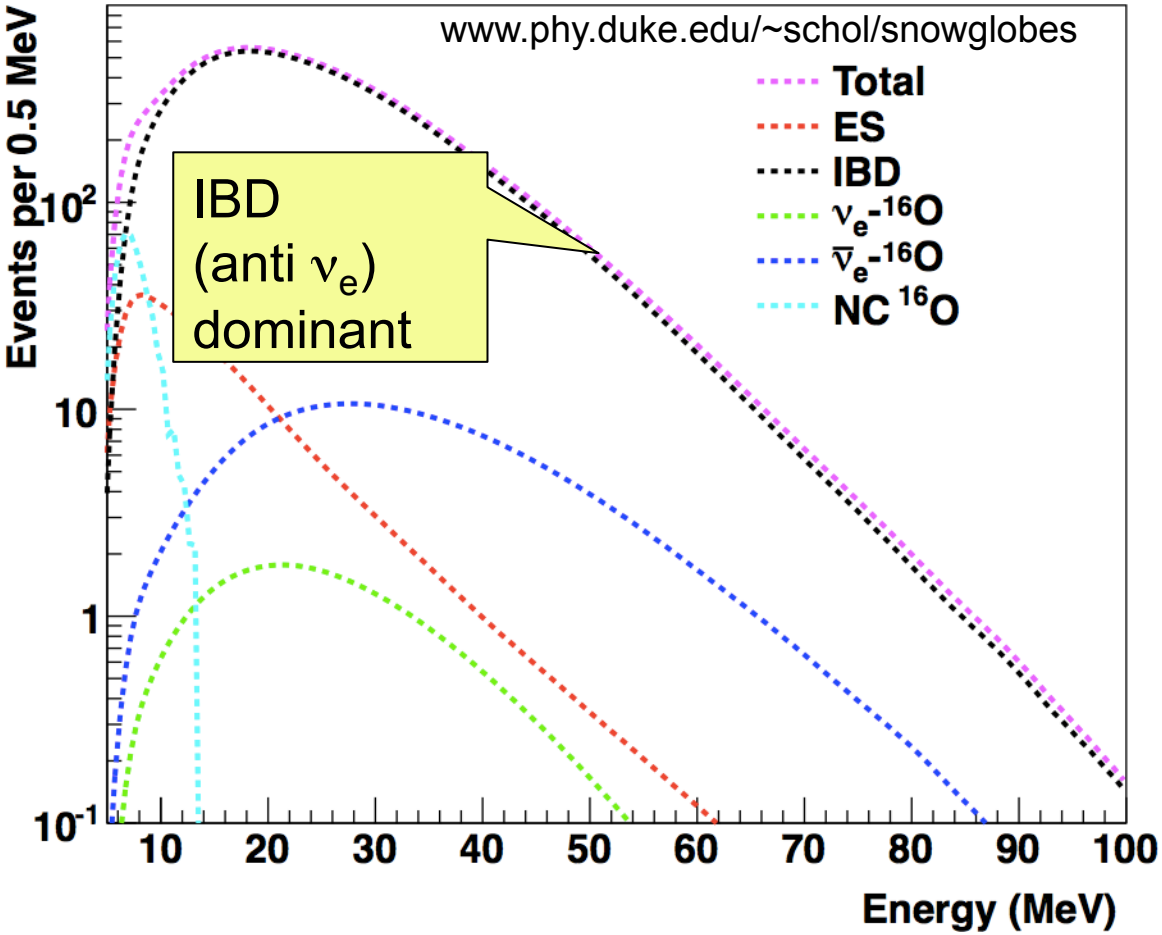
560 kton fiducial volume

Design & site-selection underway

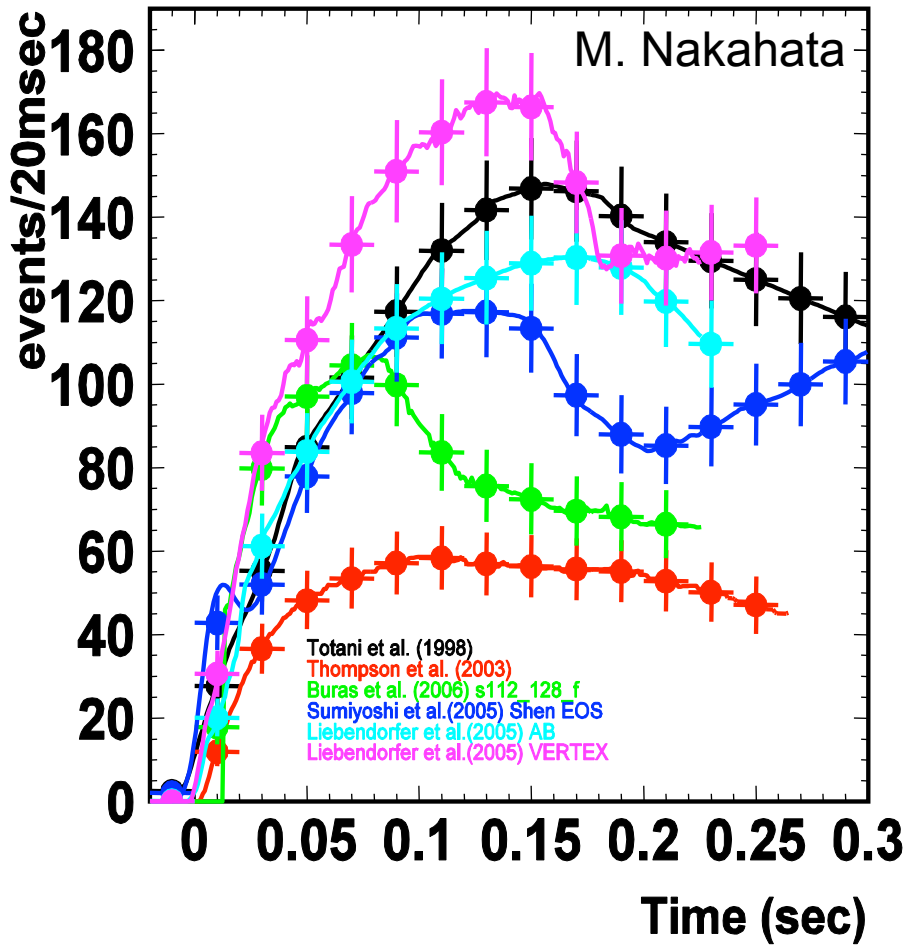
~half photocoverage, but still good efficiency for SN

Supernova signal in a water Cherenkov detector

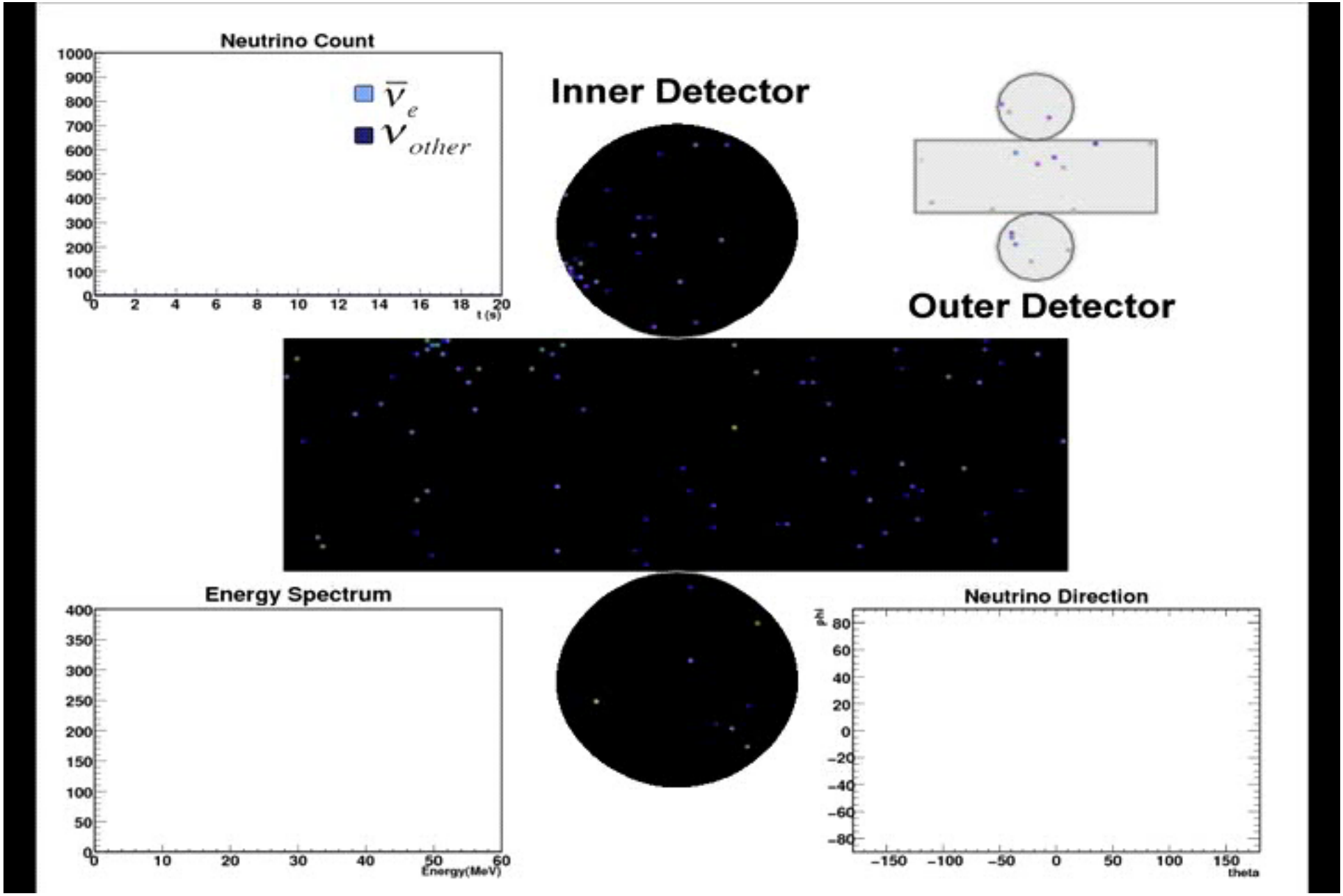
Events seen, as a function of observed energy



For 100 kton.
30% PMT coverage
@ 10 kpc

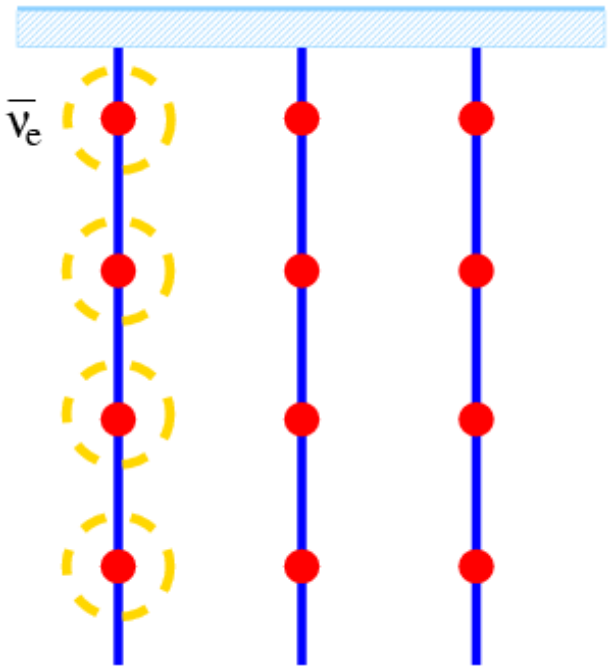


Events vs time
for SK, for
different models



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

Long string water Cherenkov detectors

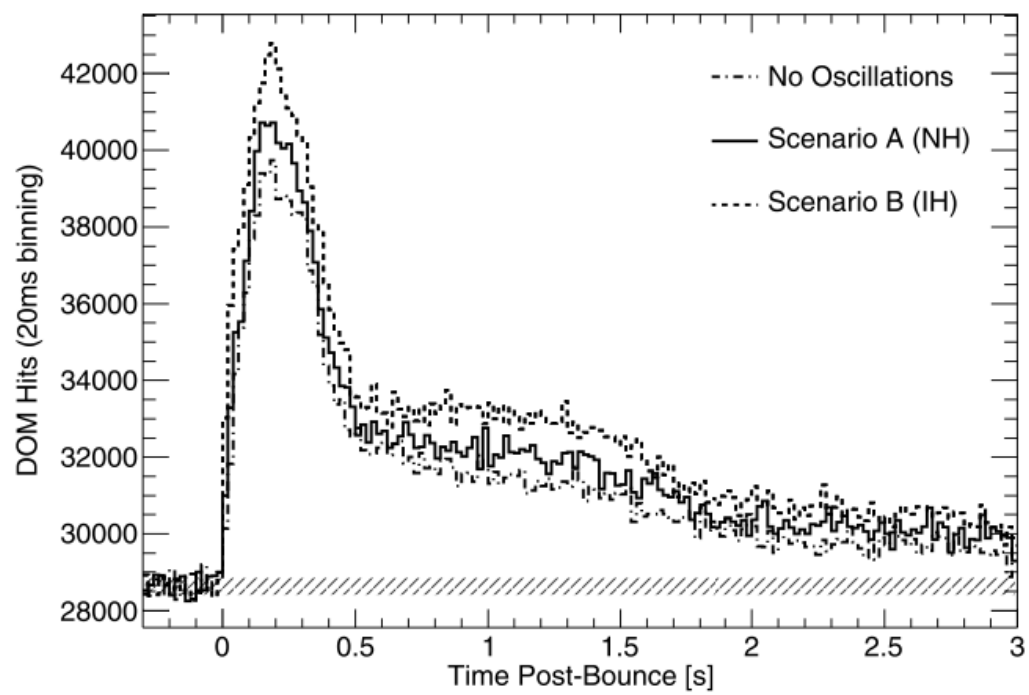


~kilometer long strings of PMTs in very clear water or ice
(IceCube/PINGU, ANTARES)

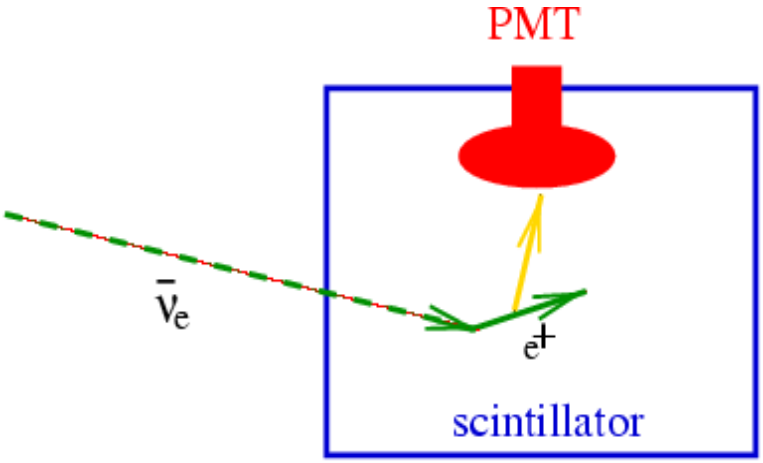
Nominally multi-GeV energy threshold... but, may see burst of low energy $\bar{\nu}_e$'s as *coincident increase in single PMT count rates* (M_{eff}~ 0.7 kton/PMT)

Map overall time structure of burst

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

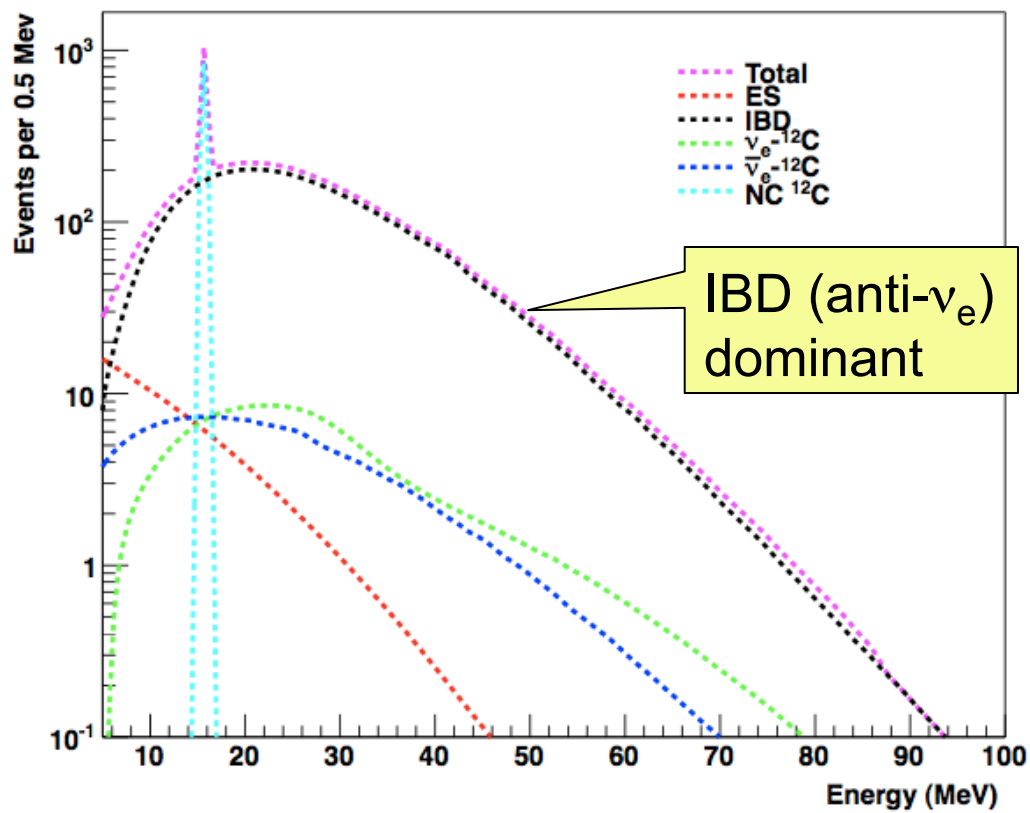


Scintillation detectors



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

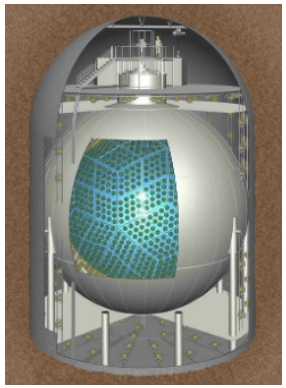
- few 100 events/kton (IBD)
- low threshold, good energy resolution
- little pointing capability (light is ~isotropic)



50 kt @ 10 kpc

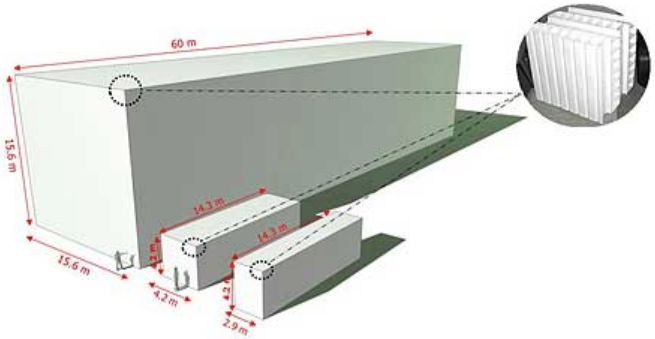
Current and near-future scintillator detectors

KamLAND
(Japan)
1 kton



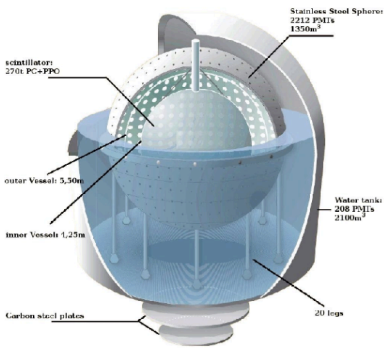
LVD
(Italy)
1 kton

NOvA
(USA)
14 kton

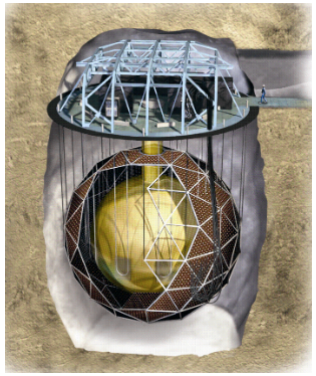


(on surface, but may be possible to extract counts for known burst)

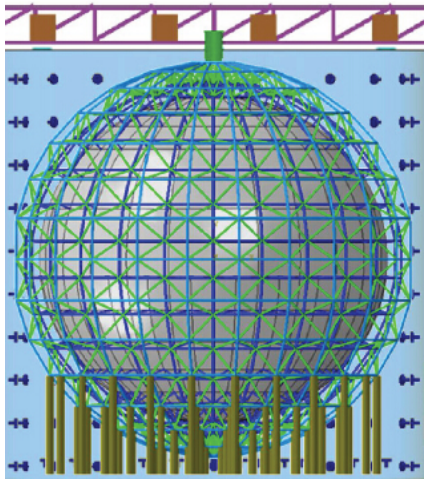
Borexino
(Italy)
0.33 kton



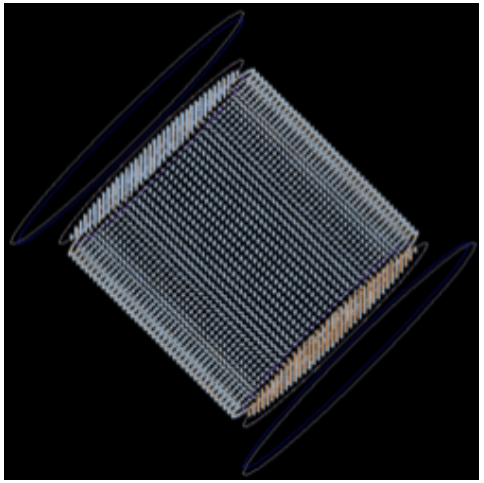
SNO+
(Canada)
1 kton



Future detector proposals



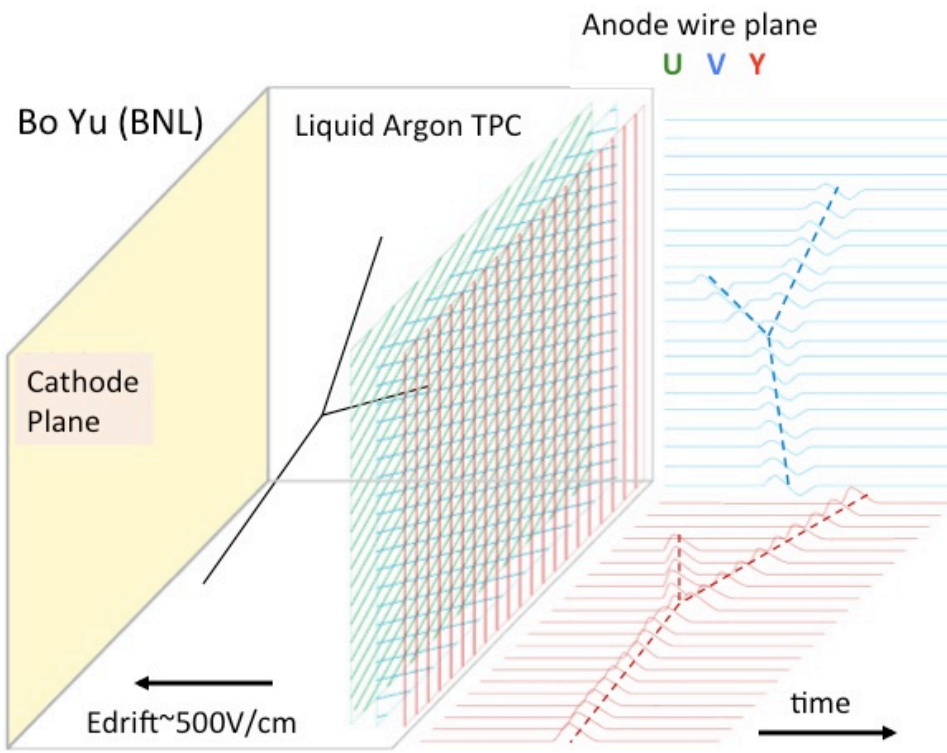
JUNO
(China)
20 kton



RENO-50
(S. Korea)
18 kton

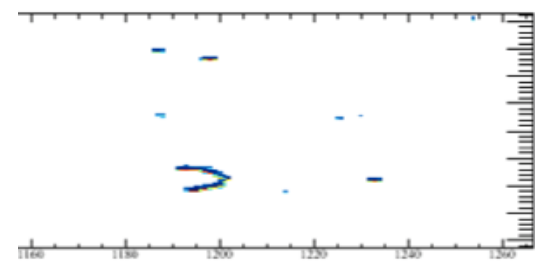
LENA
(Finland)
50 kton

Liquid argon time projection chambers

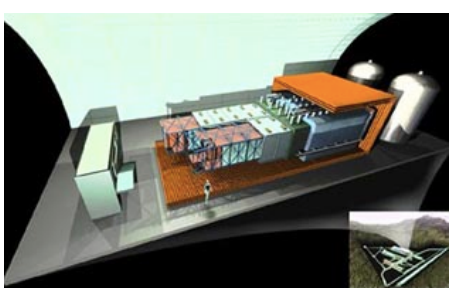


- fine-grained trackers
- no Cherenkov threshold
- high ν_e cross section

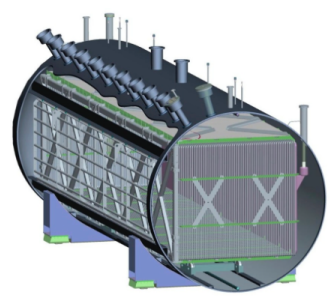
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$



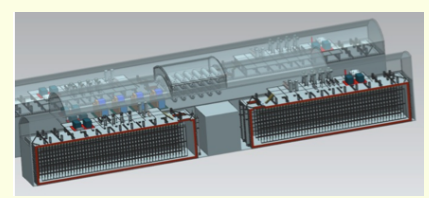
ICARUS
(Italy...)
0.6 kton



MicroBooNE
(USA)
0.2 kton

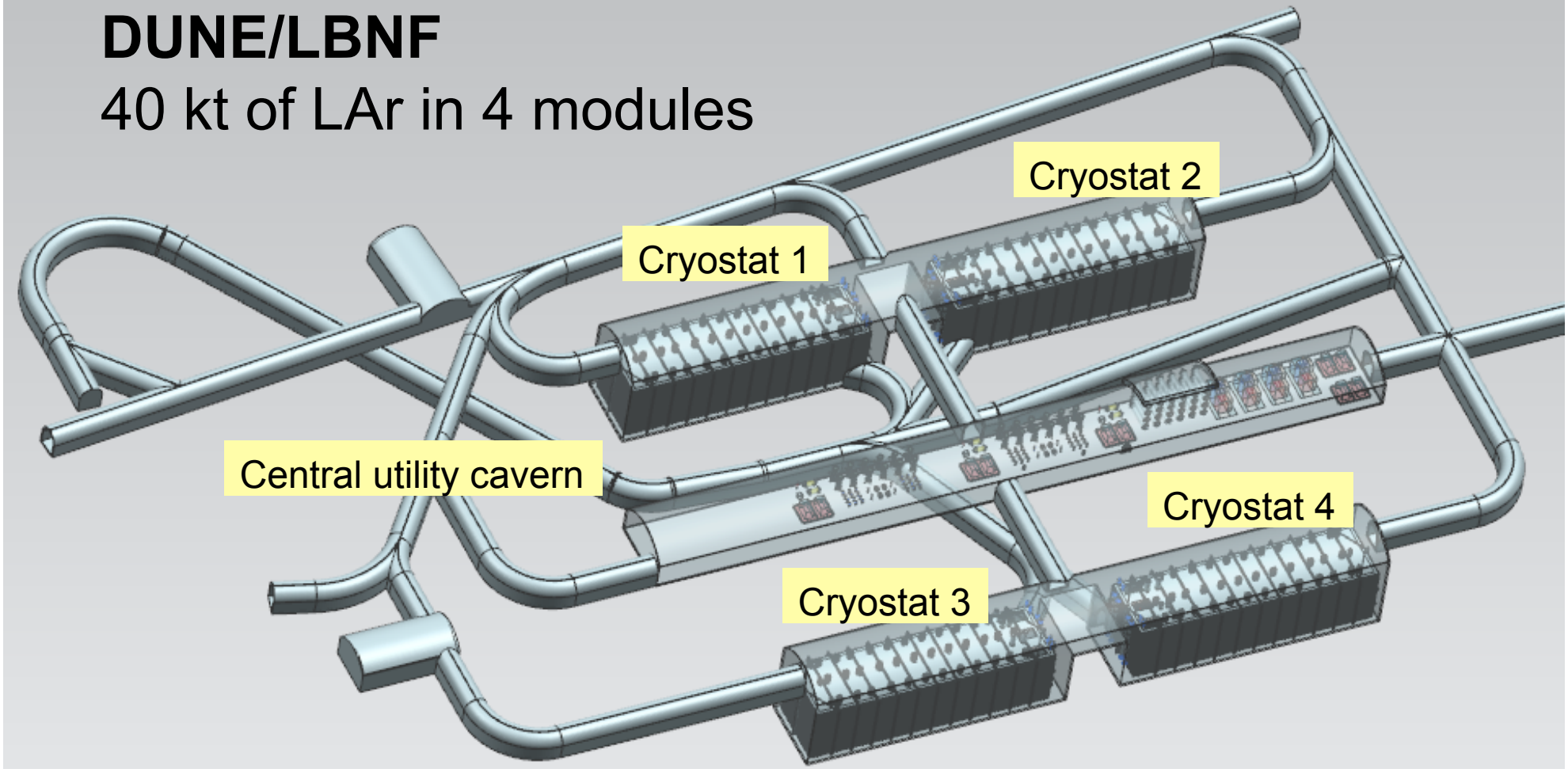


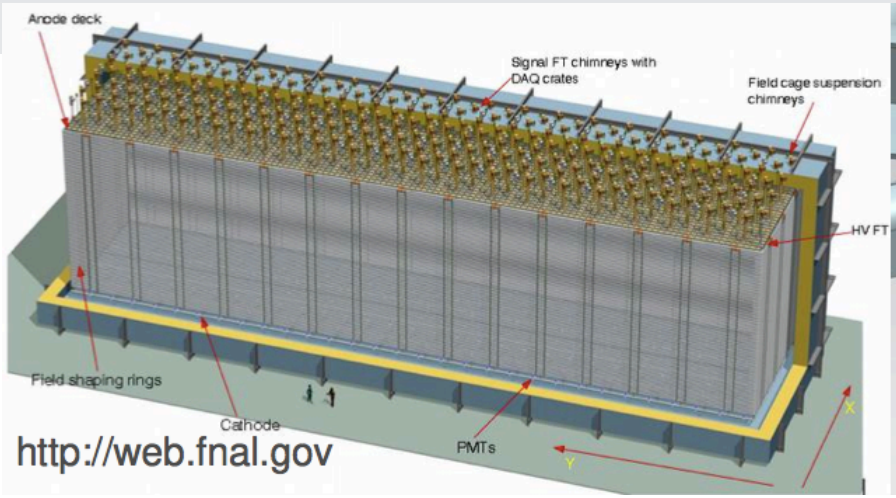
DUNE
(USA)
40 kton

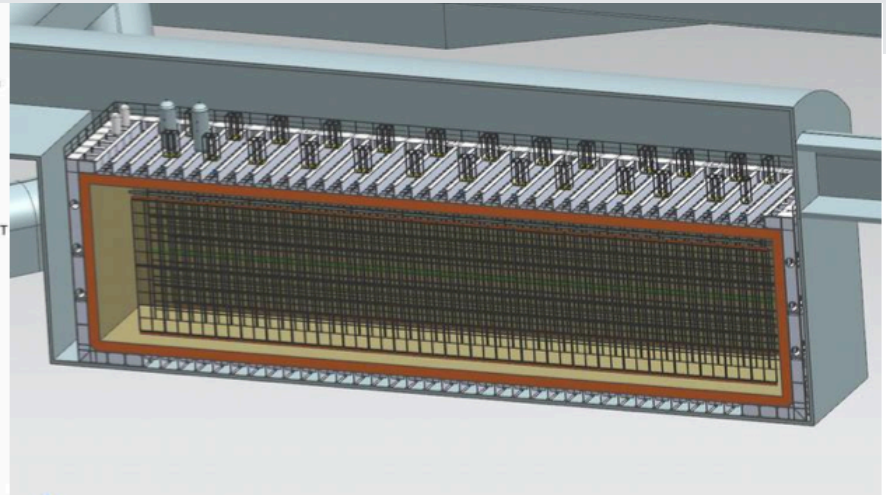


DUNE/LBNF

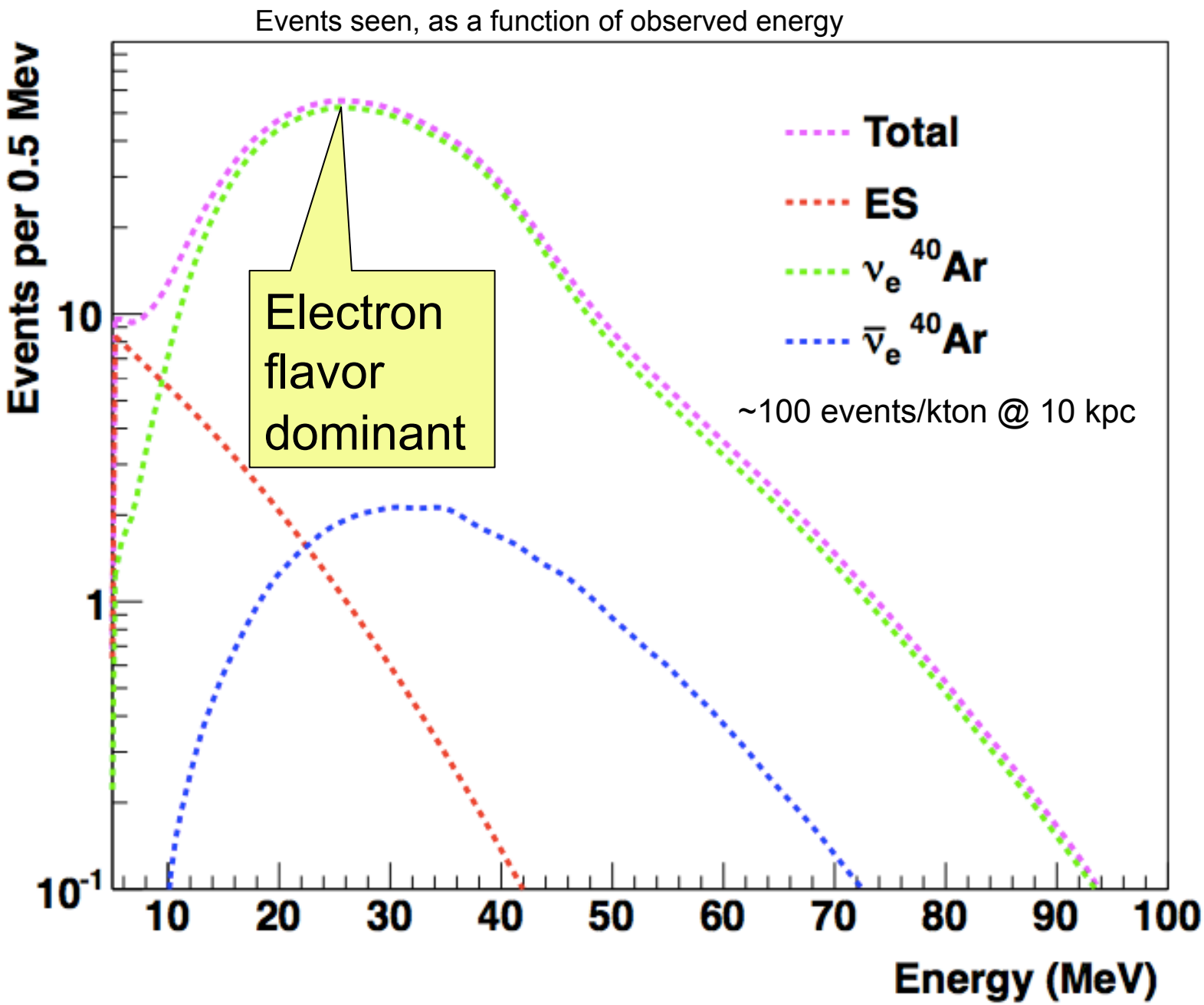
40 kt of LAr in 4 modules



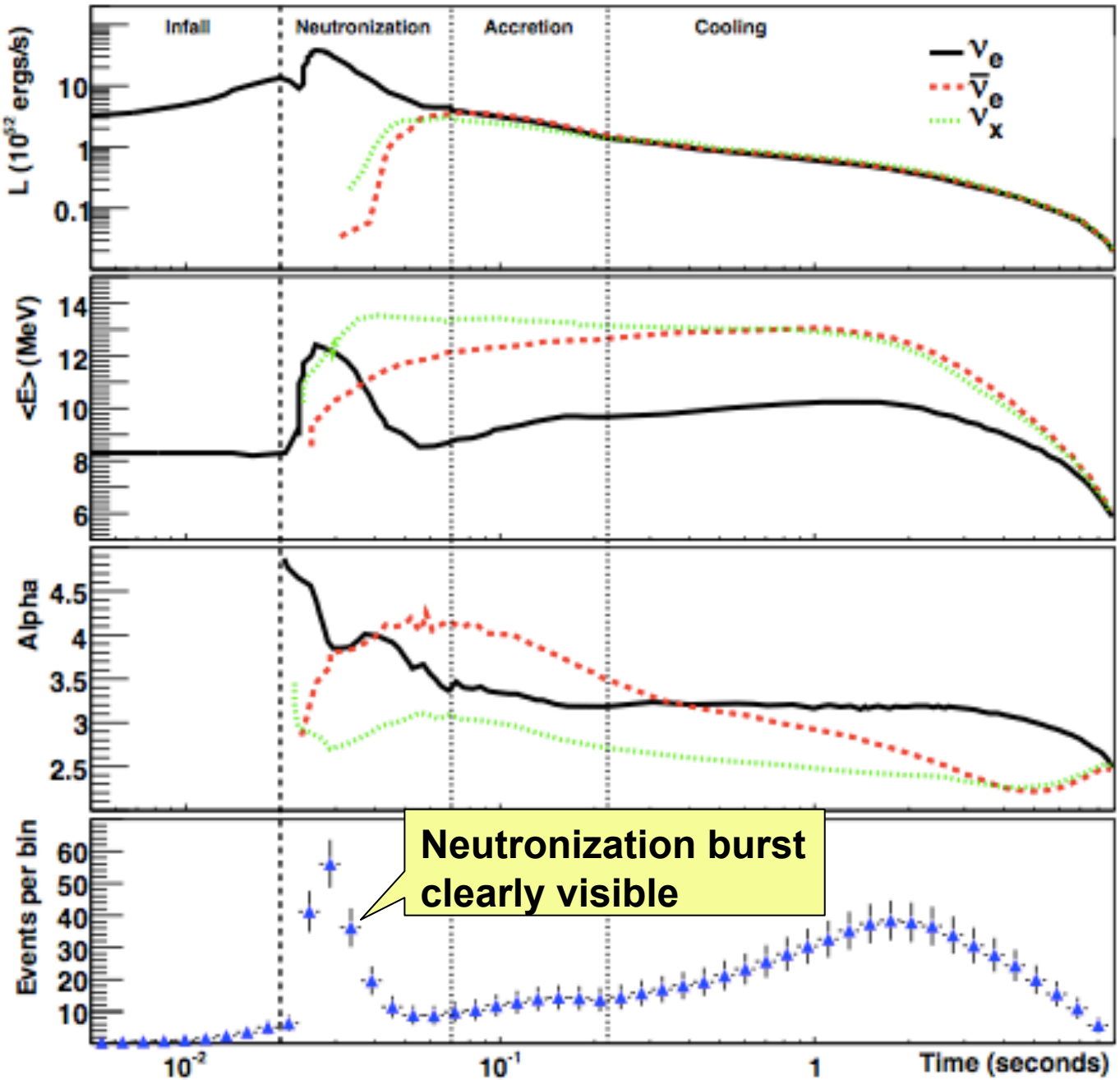




Supernova signal in a liquid argon detector



Example of supernova burst signal in 34 kton of LAr

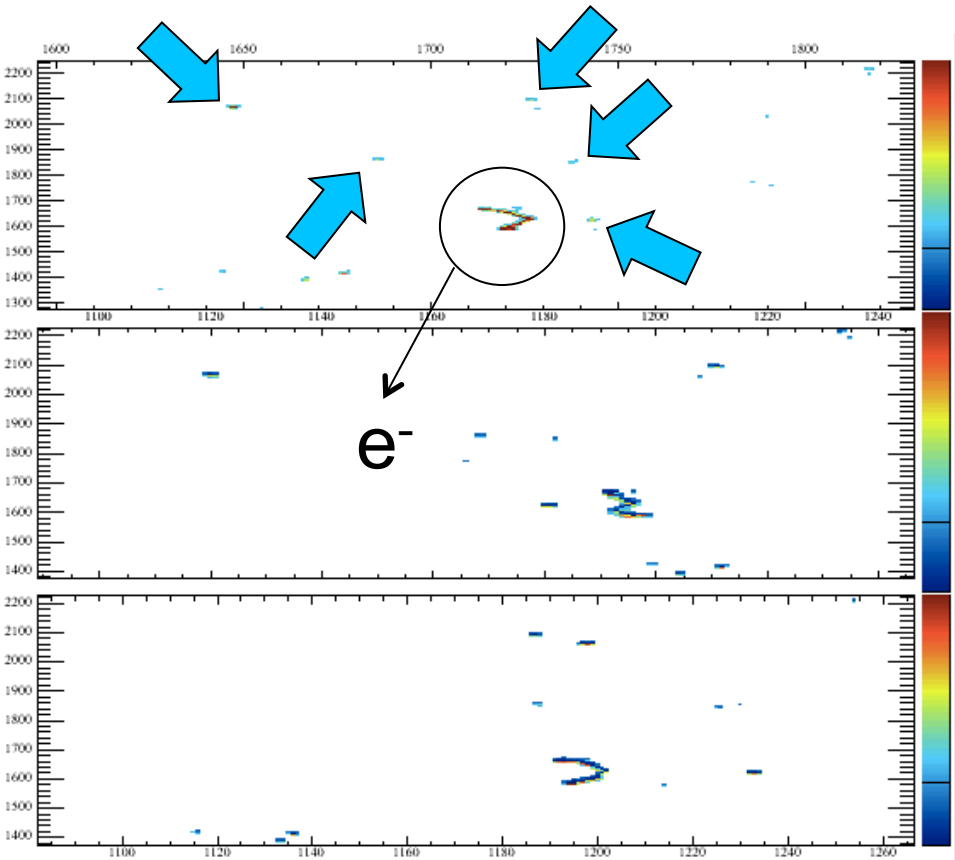


Flux from Huedepohl et al., PRL 104 (2010) 251101 ("Garching") @ 10 kpc

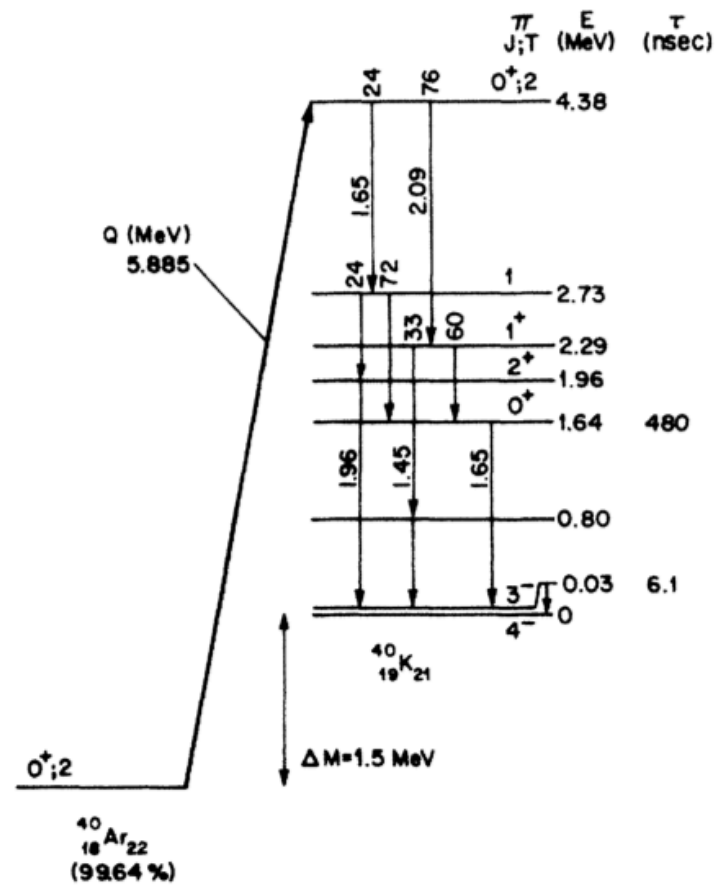
See the ν_e light curve!

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!

Lead-based supernova detectors

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

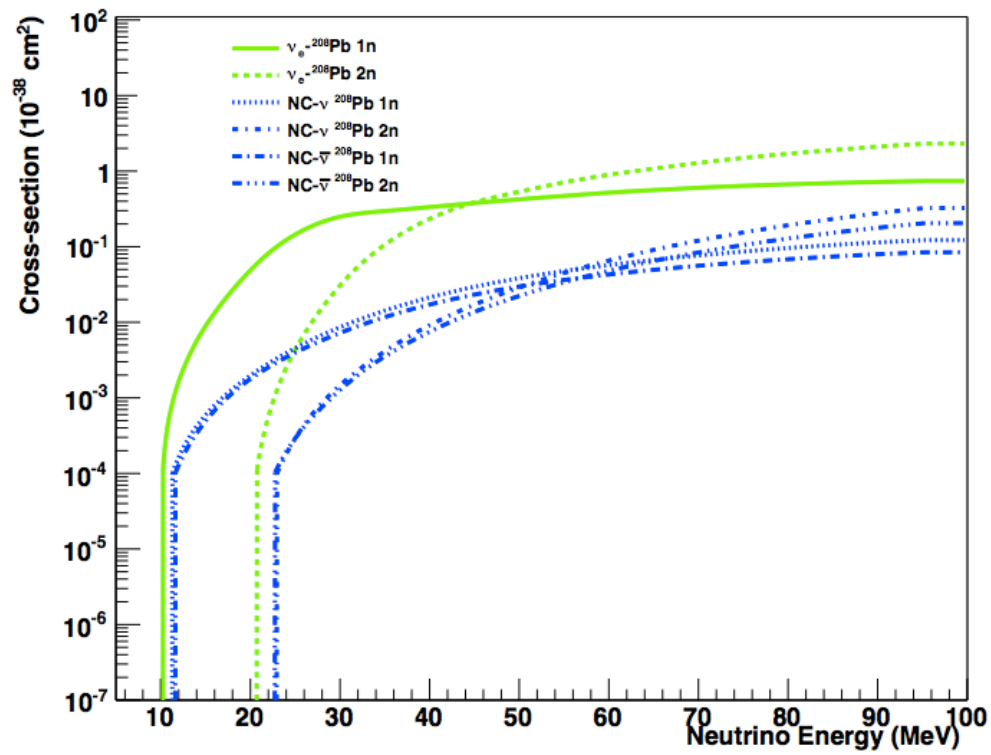
↘ 1n, 2n emission

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

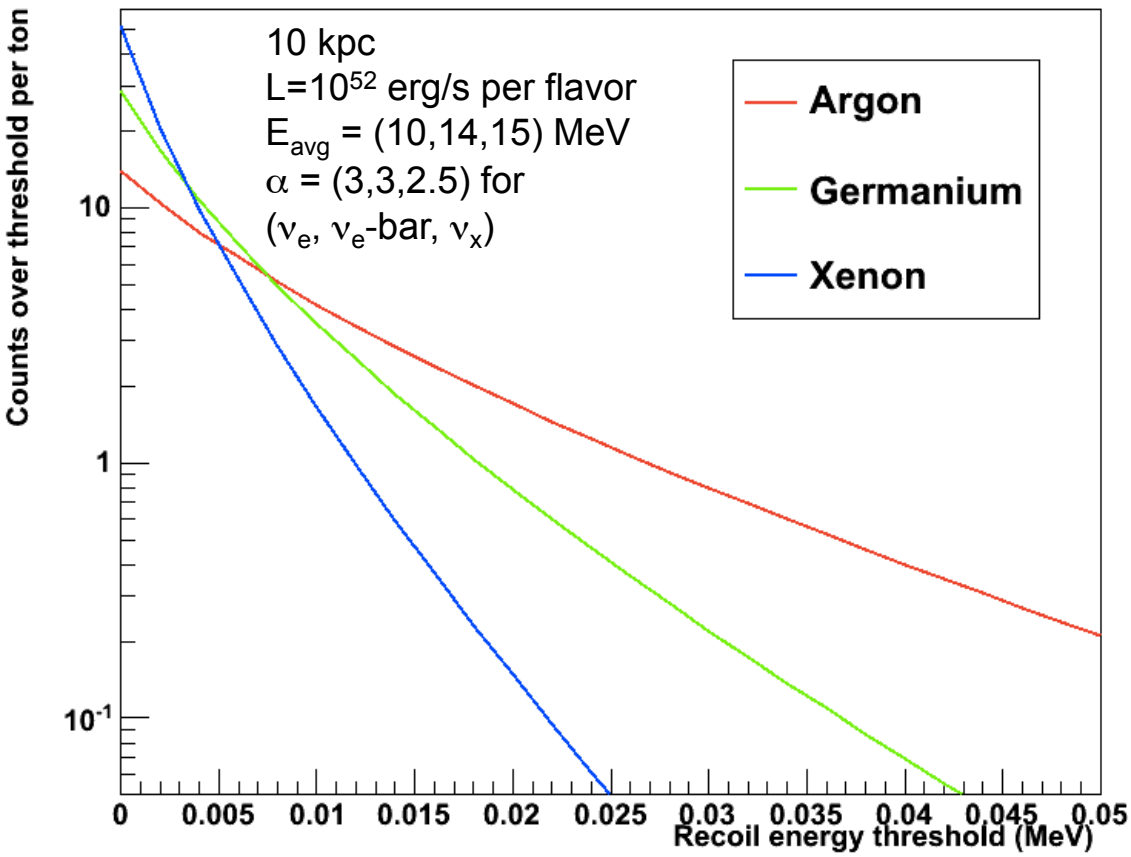
Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

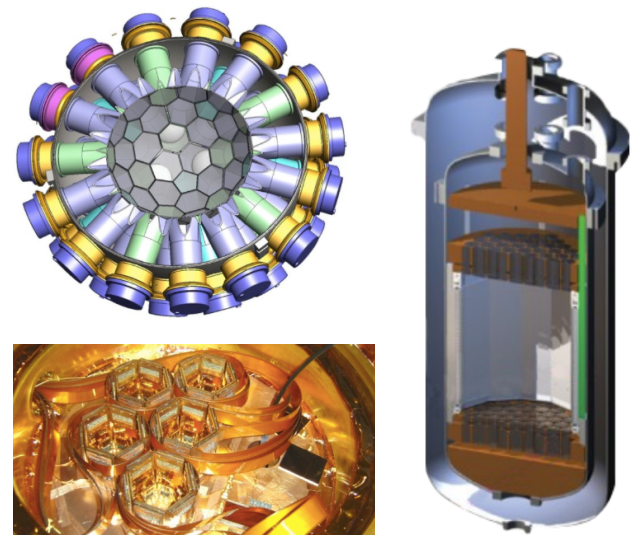
$$\nu_x + A \rightarrow \nu_x + A$$

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

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

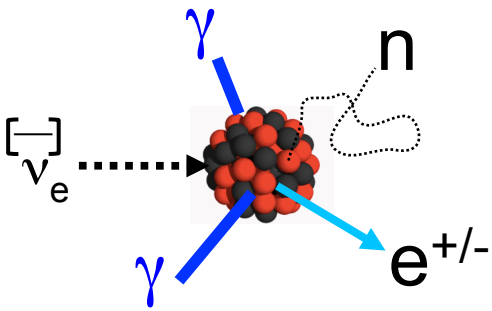
$\Rightarrow$ observable in dark matter detectors





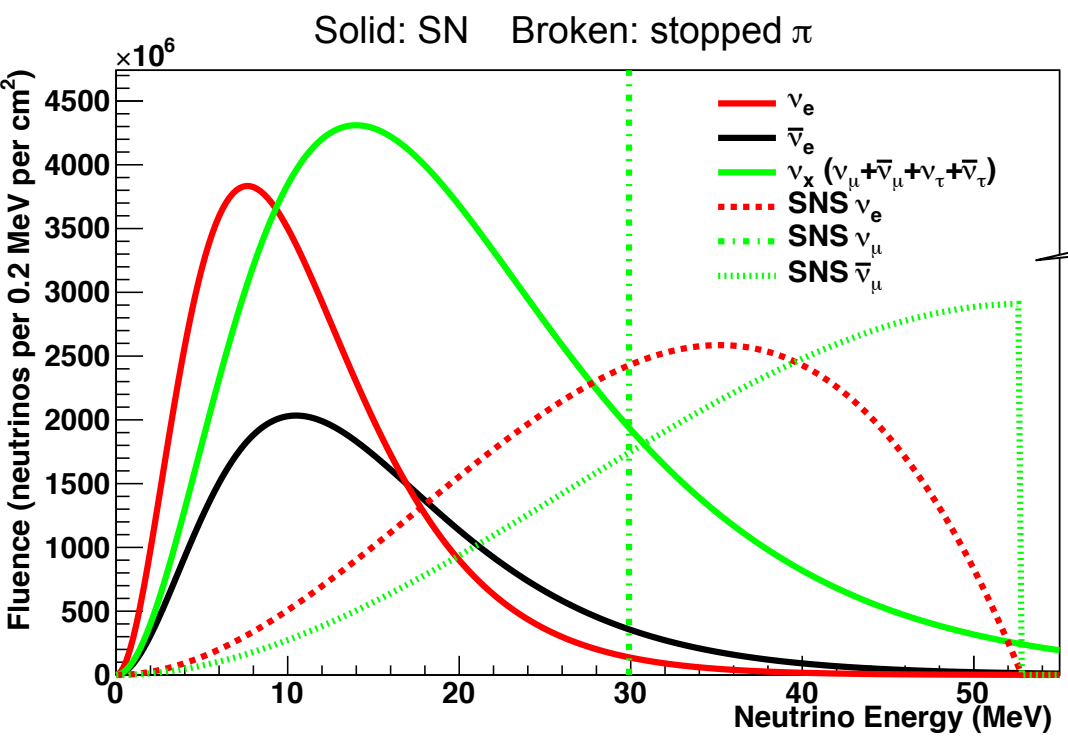
~ handful of events per tonne
@ 10 kpc: sensitive to
all flavor components *of the flux*

\begin{aside}



Interactions with nuclei
(cross sections & products)
very poorly understood...
sparse theory & experiment
(*only* measurements at better than ~50% level are for ^{12}C)

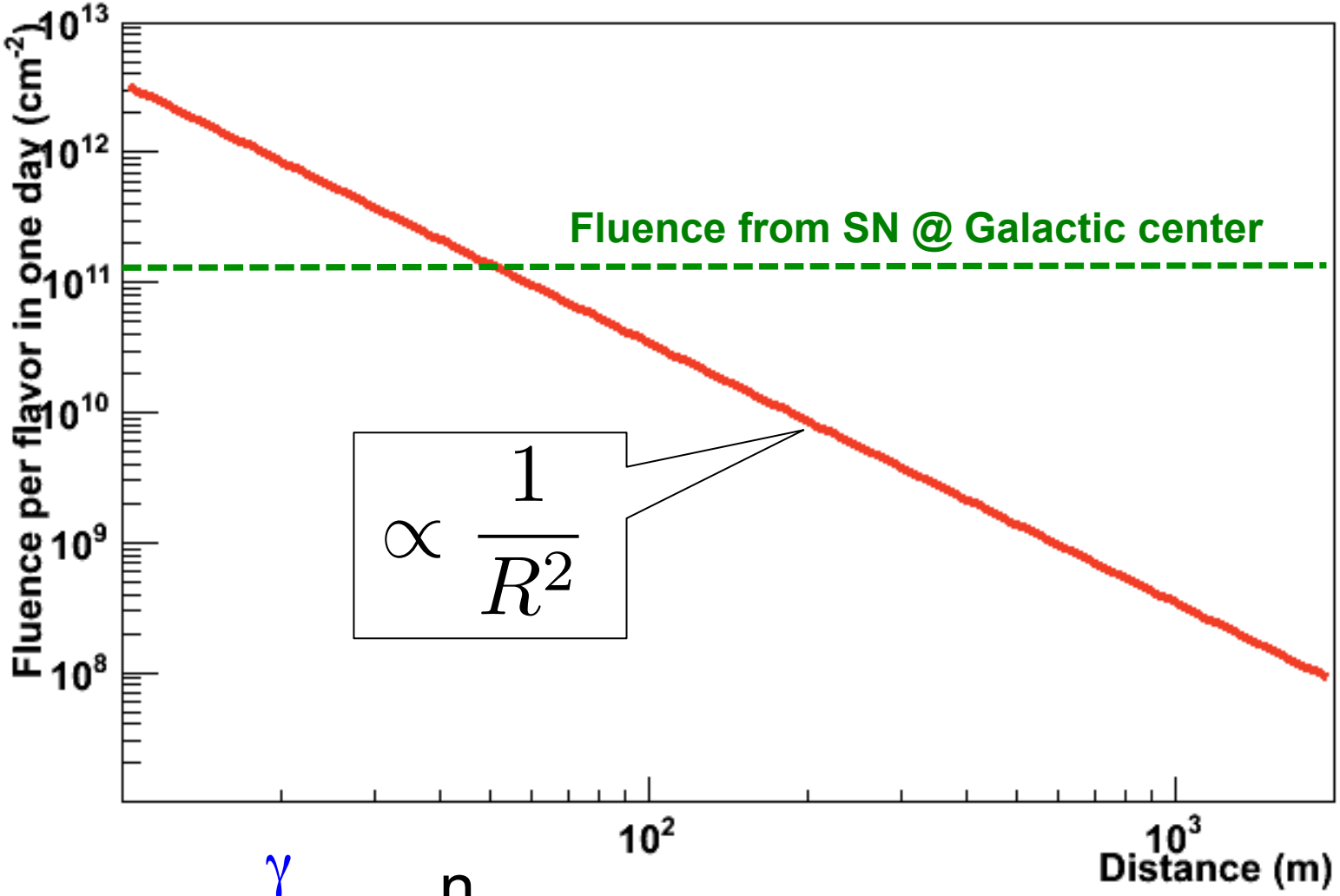
Neutrinos from pion decay at rest have spectrum overlapping with SN ν spectrum, e.g., at ORNL Spallation Neutron Source and far off-axis at the Fermilab BNB

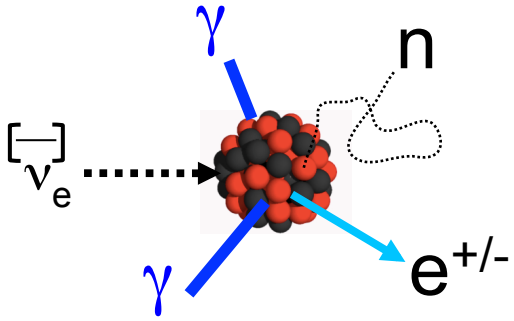


A. Bolozdynya et al., arXiv:1211.5199

Fluence at ~50 m from the stopped pion source amounts to ~ a supernova a day!

(or 0.2 microsupernovae per pulse, 60 Hz of pulses)





This is an excellent opportunity to study poorly understood neutrino-nucleus interactions in the supernova energy range

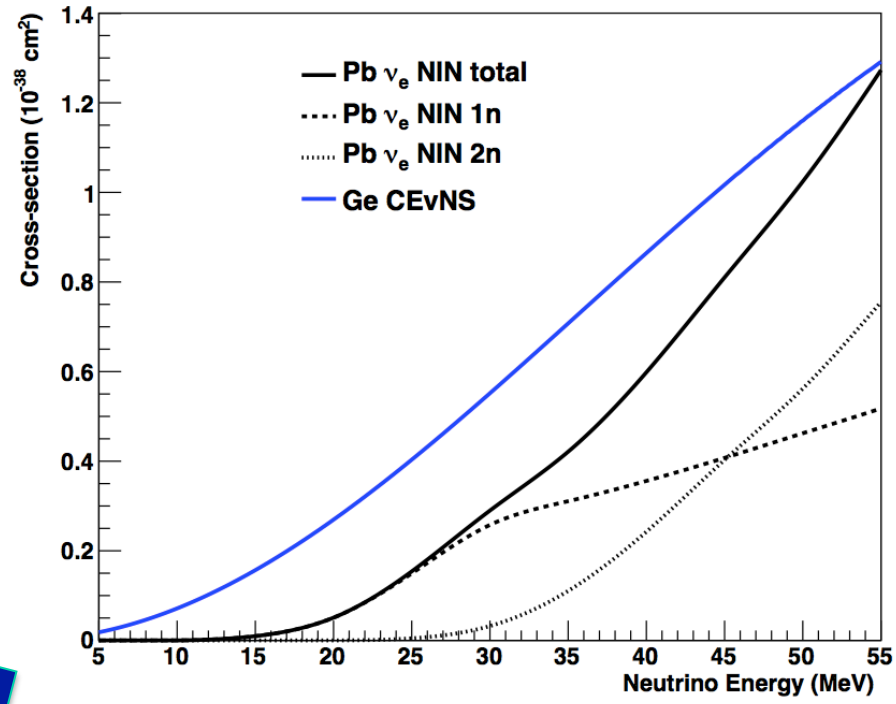
Currently measuring *neutrino-induced neutrons* in lead, (iron, copper), ...

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

$\searrow$ 1n, 2n emission

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

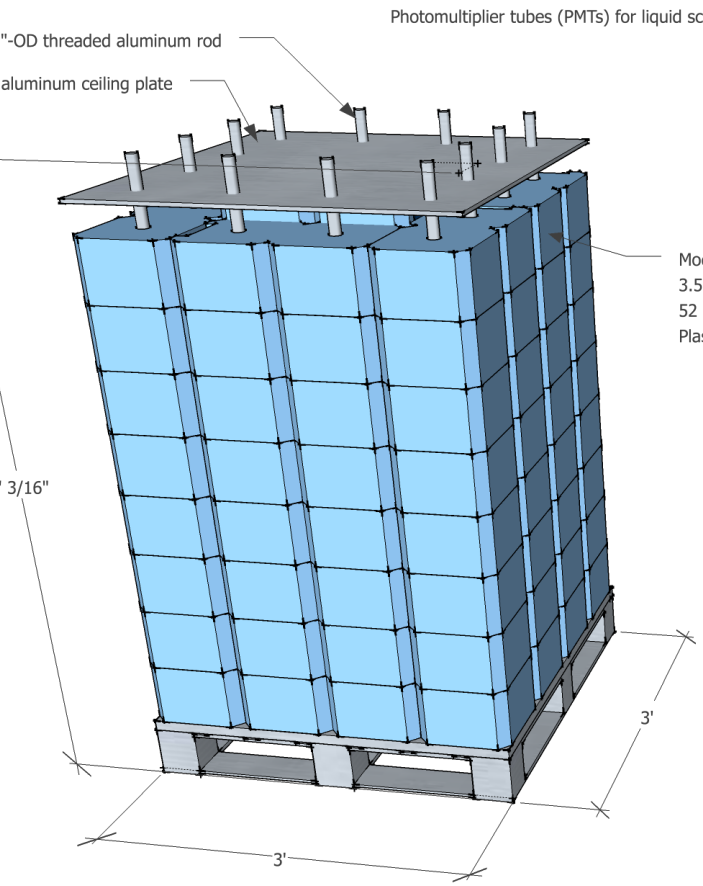
$\searrow$ 1n, 2n, γ emission

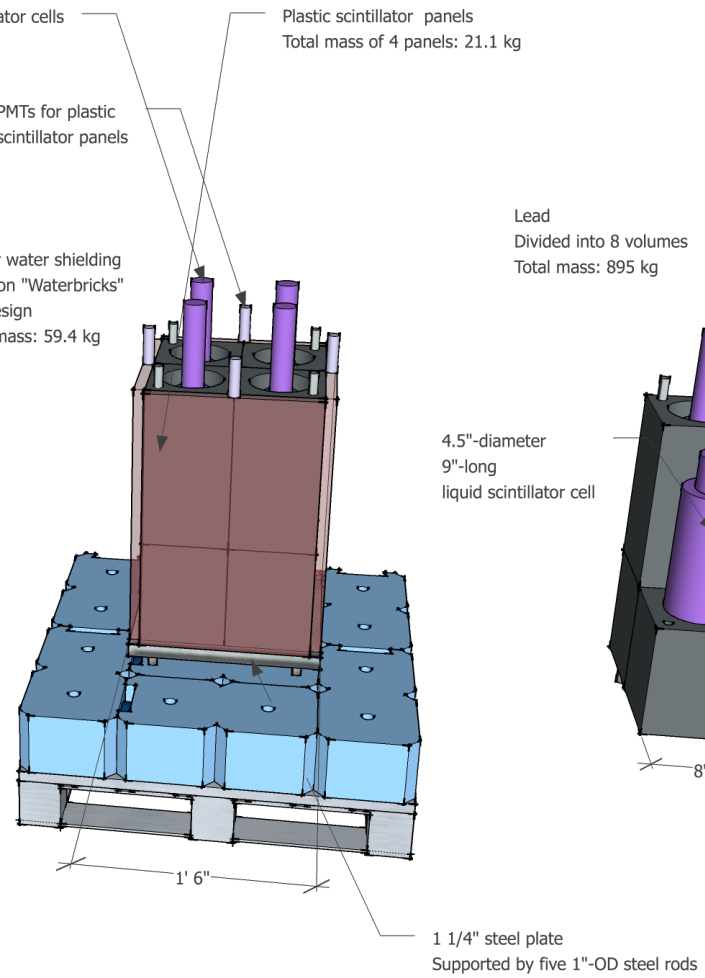


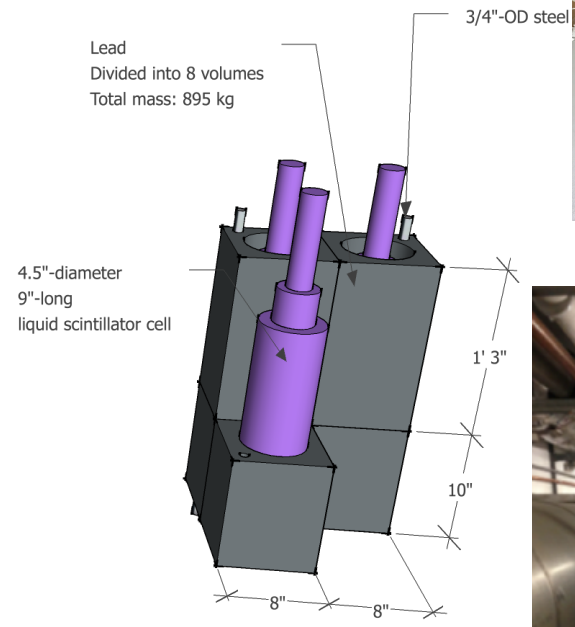
Likely a non-negligible background to CEvNS, especially in lead shield

NIN measurement in SNS basement

- Scintillator inside CsI detector lead shield (now)
- Liquid scintillator surrounded by lead (swappable for other NIN targets) inside water shield







Phil Barbeau

\end{aside}

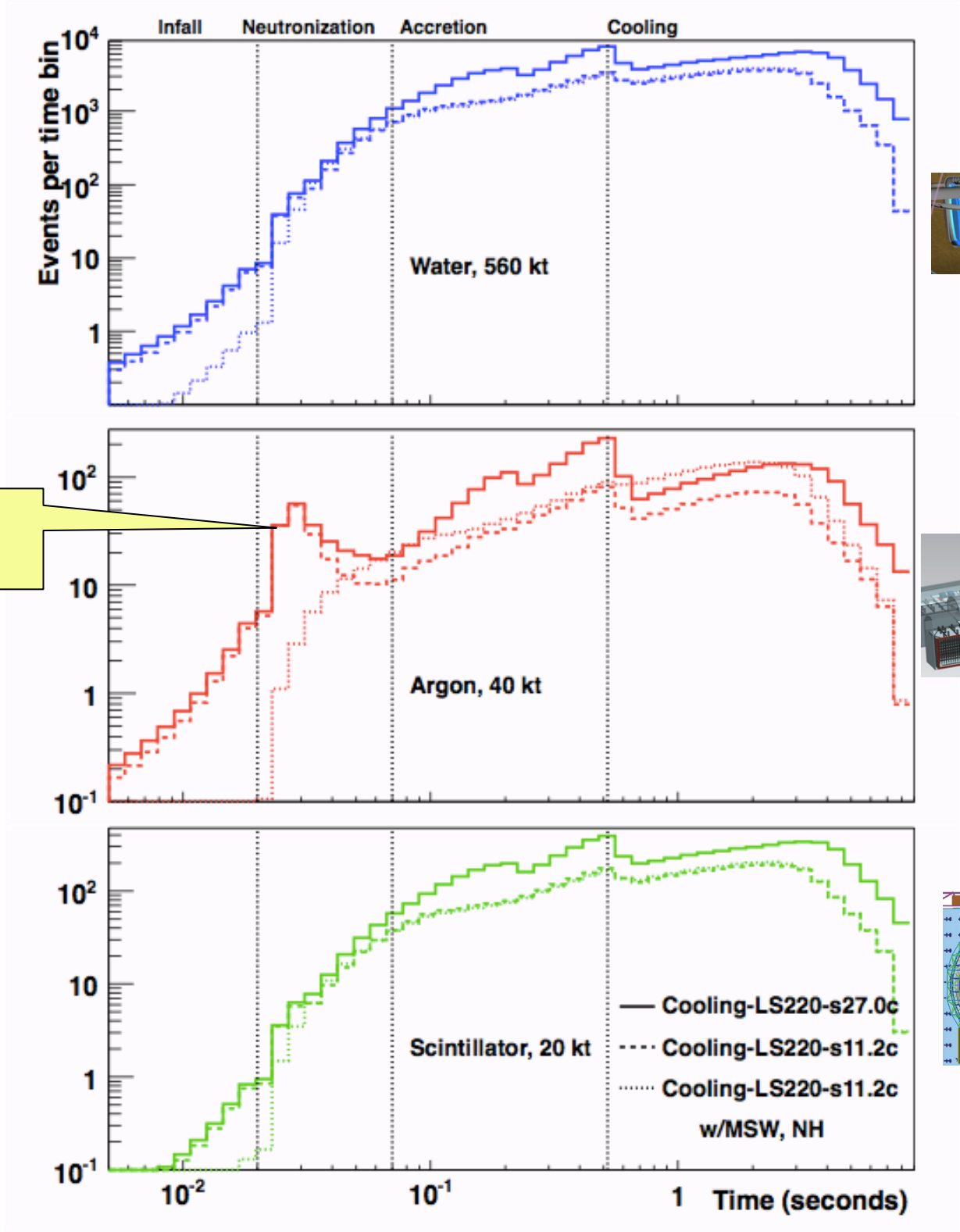
Summary of supernova neutrino detectors

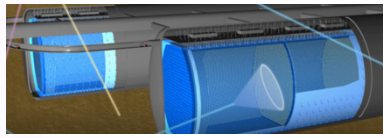
	Detector	Type	Location	Mass (kton)	Events @ 10 kpc	Status
Galactic sensitivity	Super-K	Water	Japan	32	8000	Running (SK IV)
	LVD	Scintillator	Italy	1	300	Running
	KamLAND	Scintillator	Japan	1	300	Running
	Borexino	Scintillator	Italy	0.3	100	Running
	IceCube	Long string	South Pole	(600)	(10^6)	Running
	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
Extragalactic	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

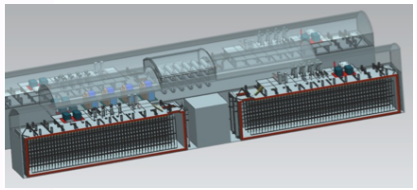
plus reactor experiments, DM experiments...

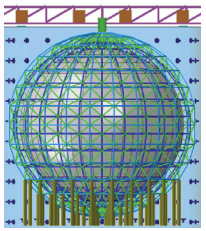
Example signals in future detectors

Neutronization burst in argon



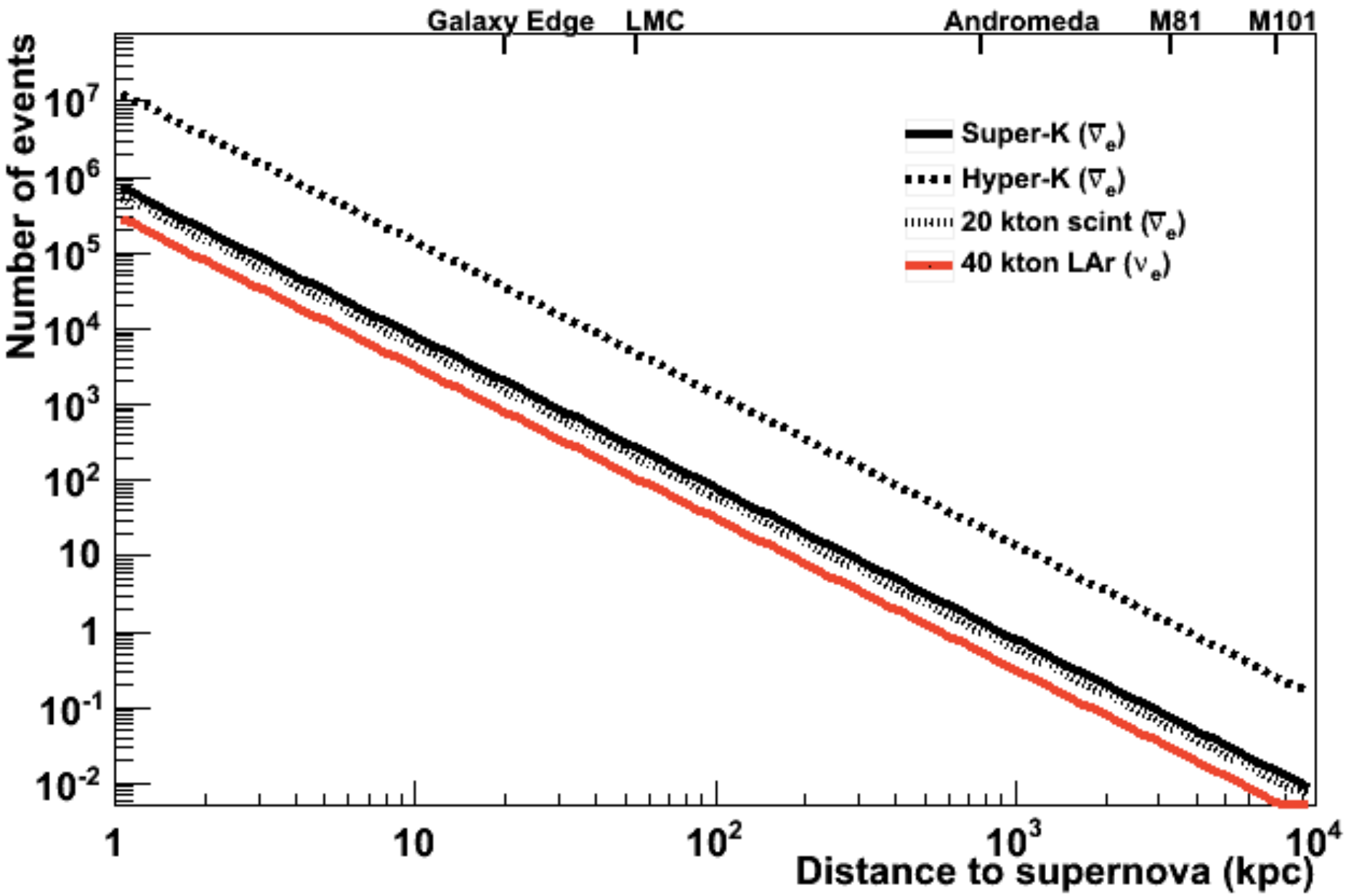






(note logarithmic time bins)

Distance reach for future detectors

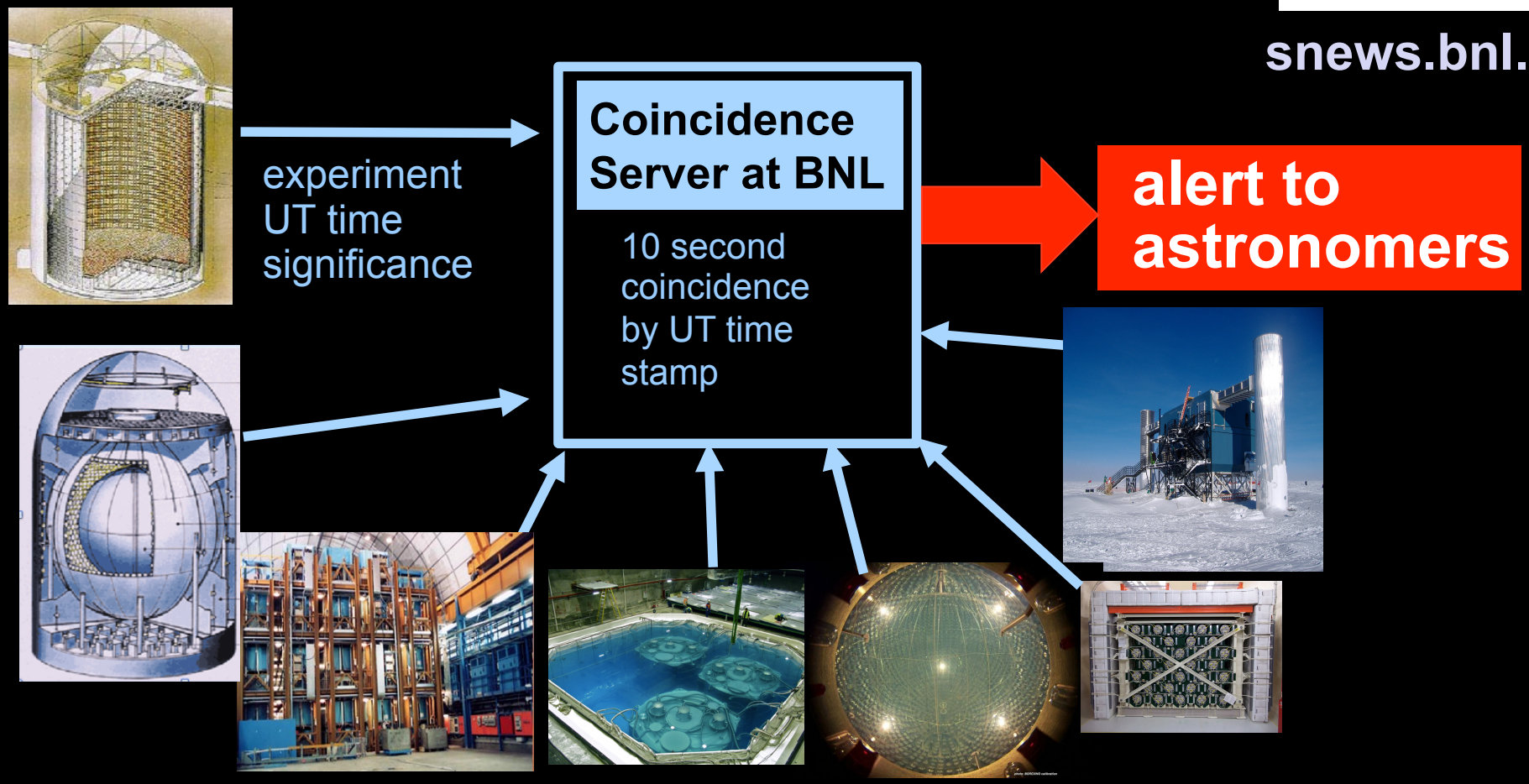


SK will see ~1 event from Andromeda; HK will get a ~dozen

SNEWS: SuperNova Early Warning System

- Neutrinos (and GW) precede em radiation by hours or even days
- For promptness, require ***coincidence*** to suppress false alerts

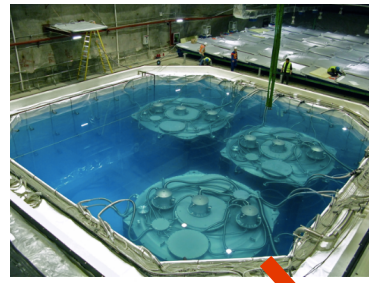
snews.bnl.gov



- Running smoothly for more than 10 years, automated since 2005

SNEWS: SuperNova Early Warning System

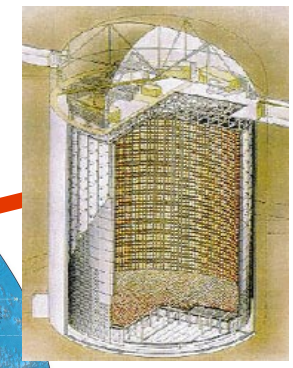
LVD



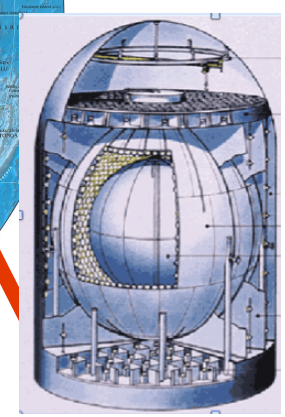
Daya Bay

snews.bnl.gov

HALO

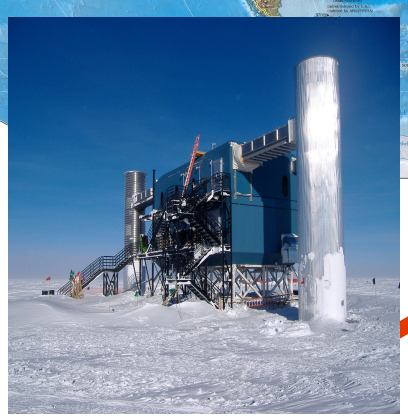


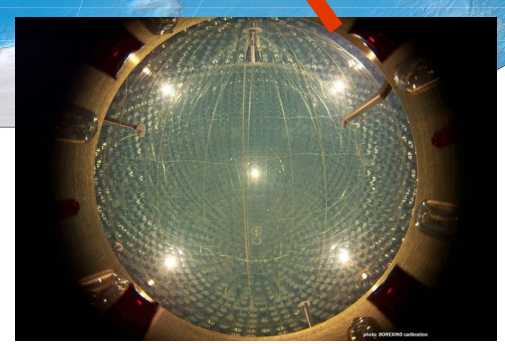
Super-K



KamLAND

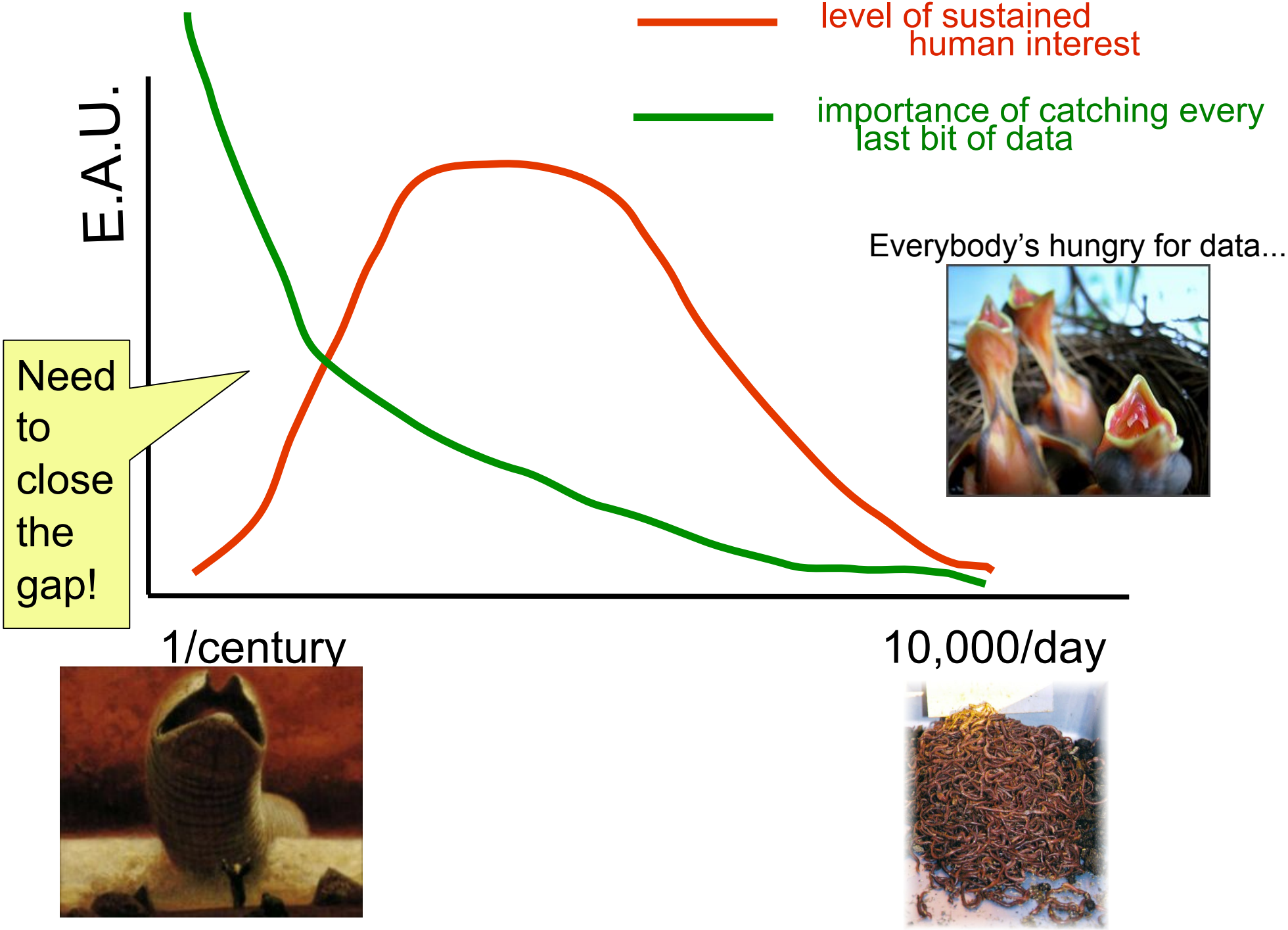
IceCube





Borexino

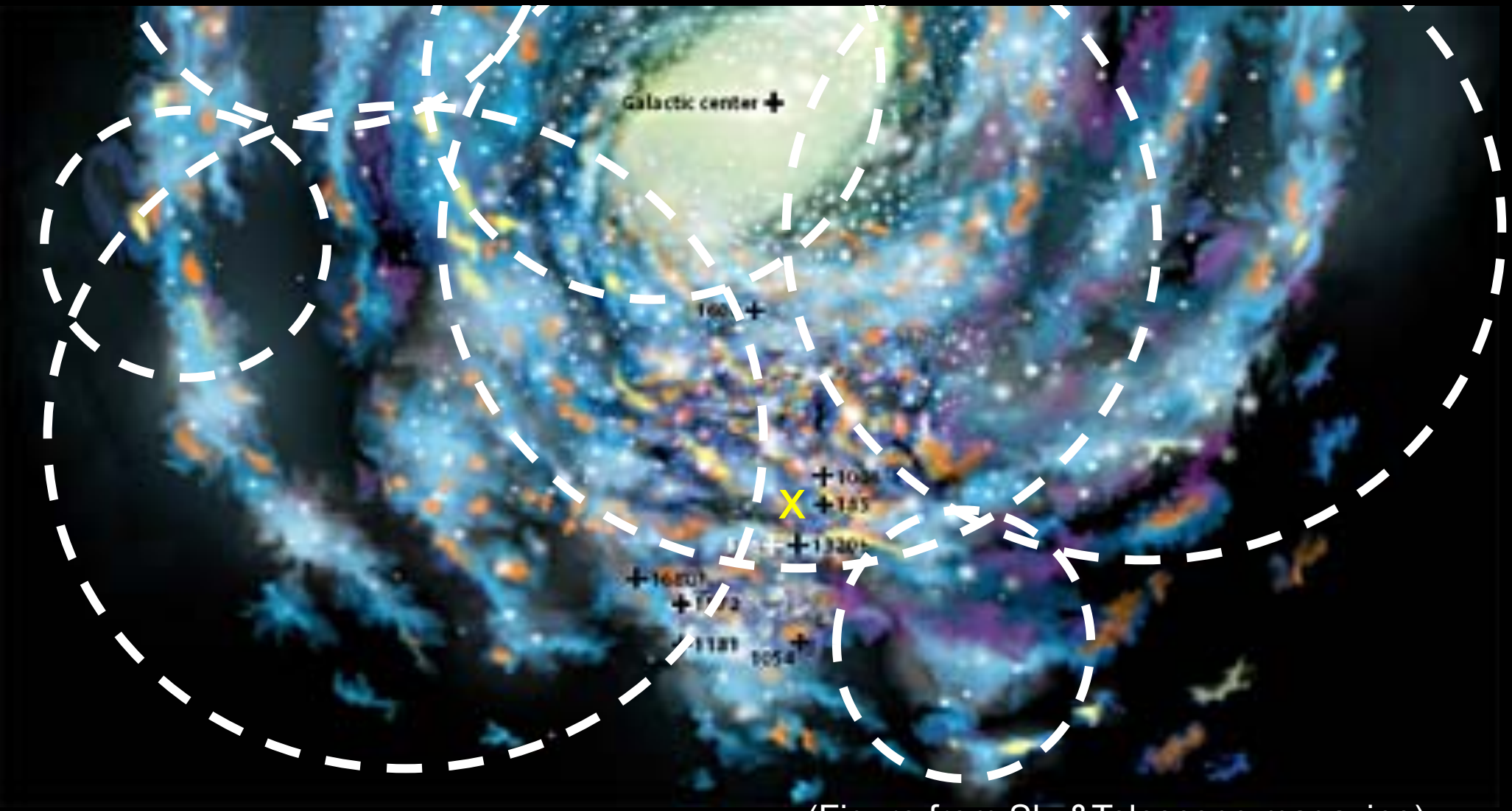
Sociological comments...



The neutrinos are coming!

Far side of the Milky Way is ~650 light-centuries away...

... ~2000 core collapses have happened already....



(Figure from Sky&Telescope magazine)

Summary

Vast information to be had from a core-collapse burst!

- Need energy, flavor, time structure

Current & near future detectors:

- ~Galactic sensitivity
  (SK reaches barely to Andromeda)
- sensitive mainly to the $\bar{\nu}_e$ component of the SN flux
- excellent timing from IceCube
- early alert network is waiting !
- we need to measure some x-scns

Farther future megadetectors

- huge statistics: extragalactic reach
- richer flavor sensitivity (e.g. ν_e in LAr)
- multimessenger prospects

Extras/backups

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

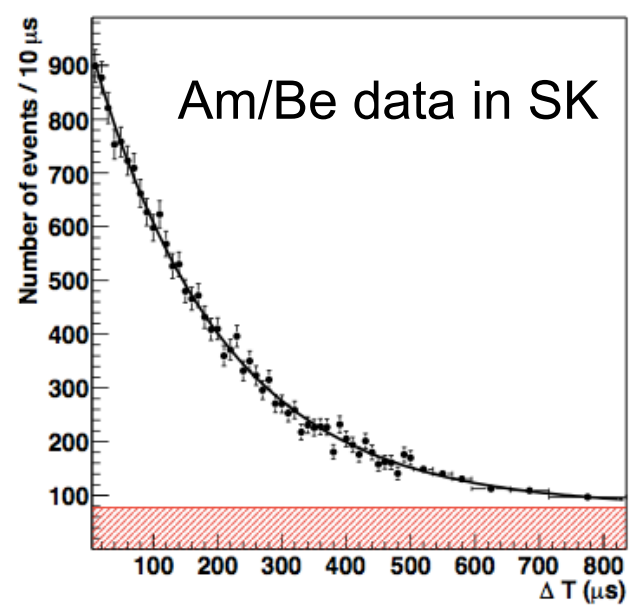
"Drug-free" neutron tagging

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

~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 (like for scintillator)

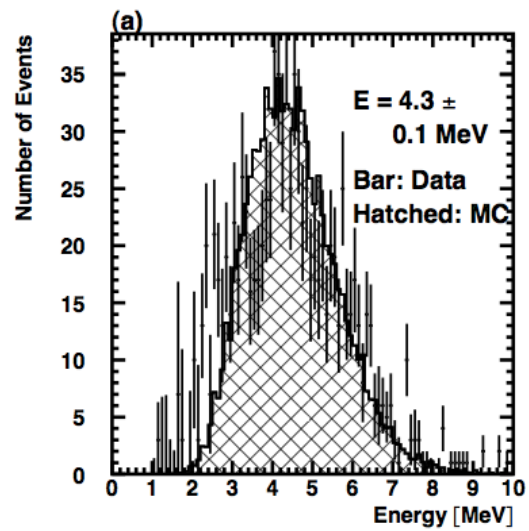
J. Beacom & M. Vagins, PRL 93 (2004) 171101

Gd has a huge n capture cross-section:

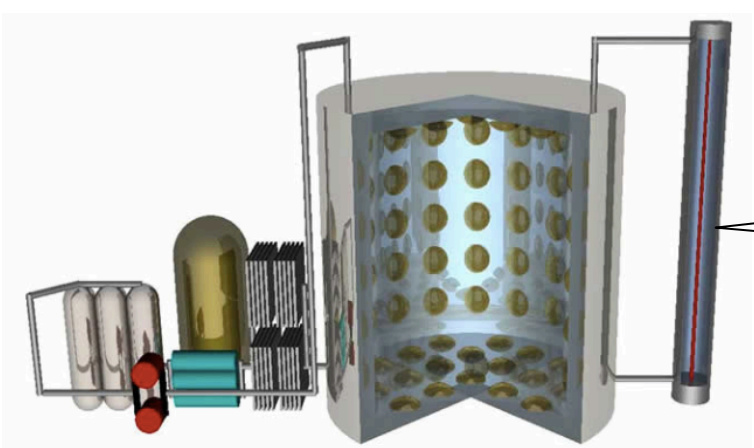
49,000 barns, vs 0.3 b for free protons

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

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



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



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

SK-Gd now approved to go forward

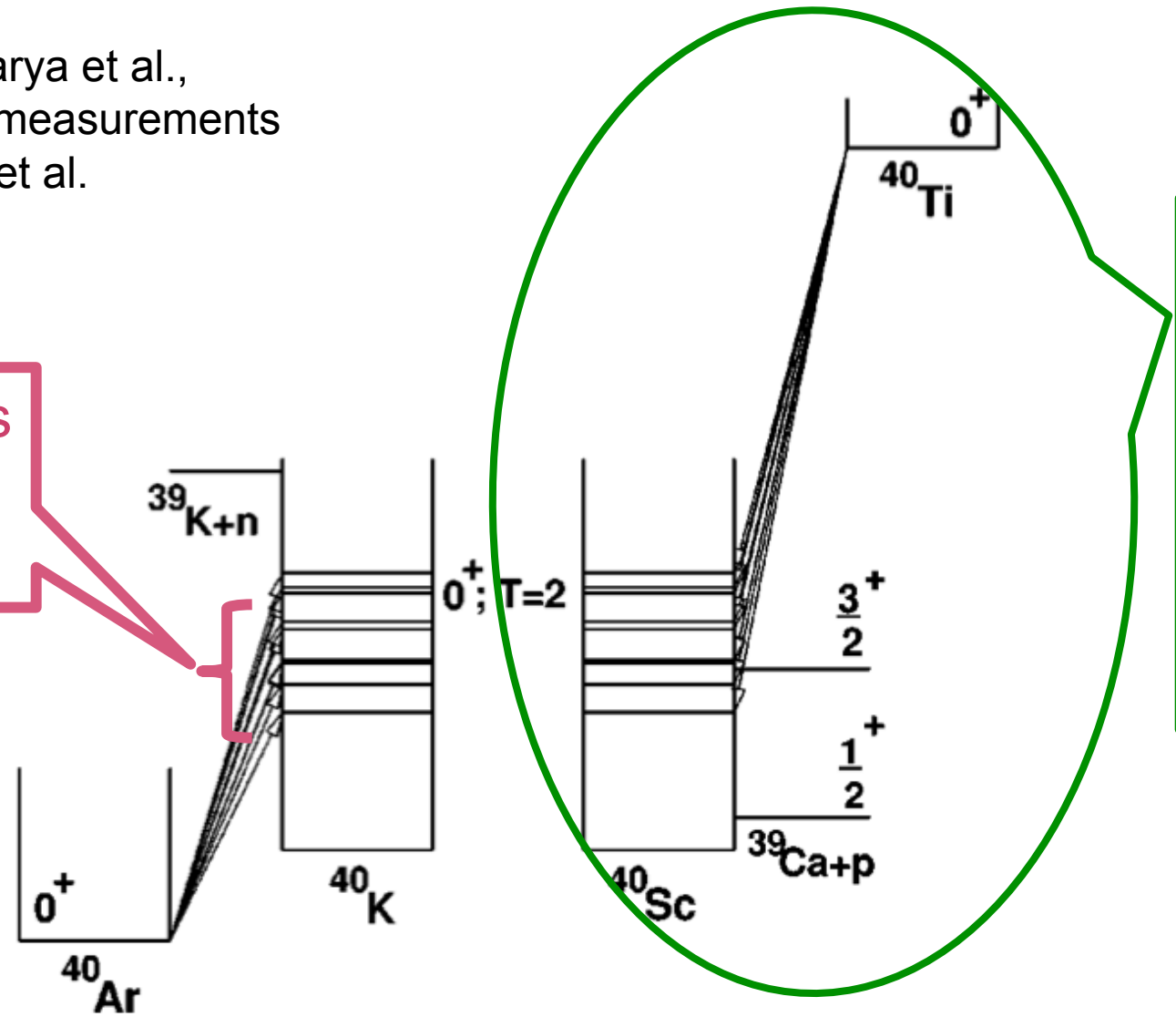
… in fact there can be transitions to intermediate states, adding to the cross section (and complicating the γ-tag)

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

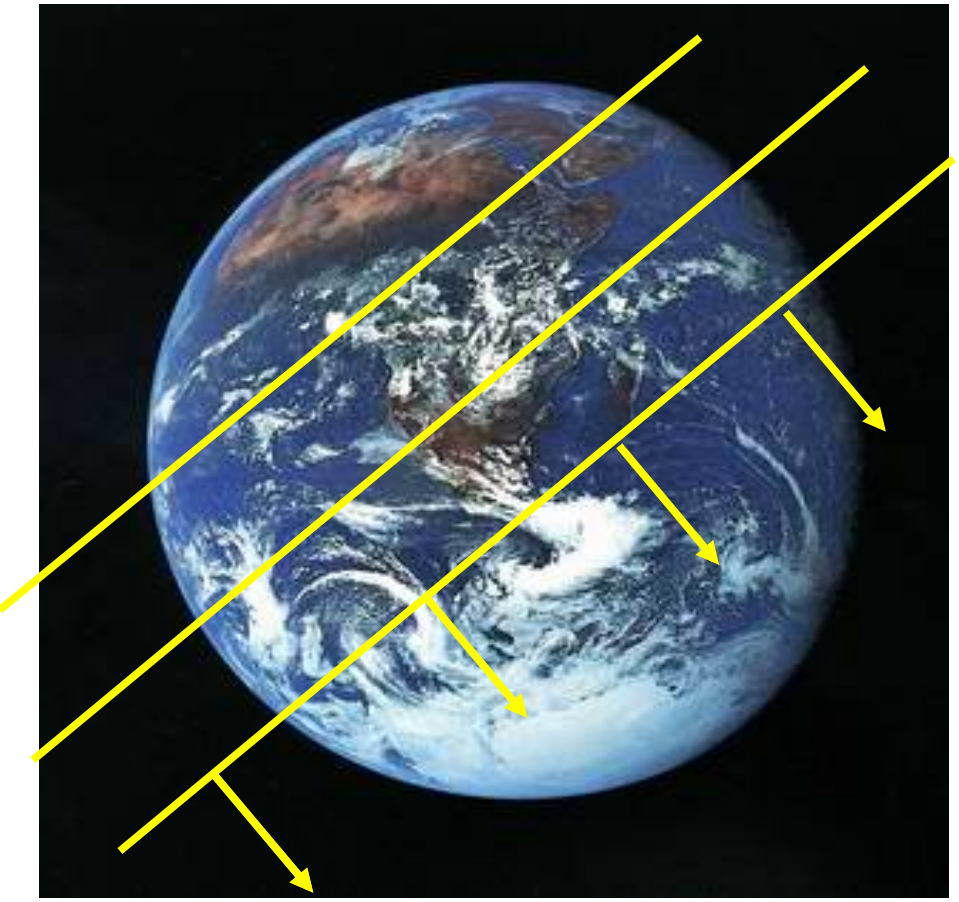


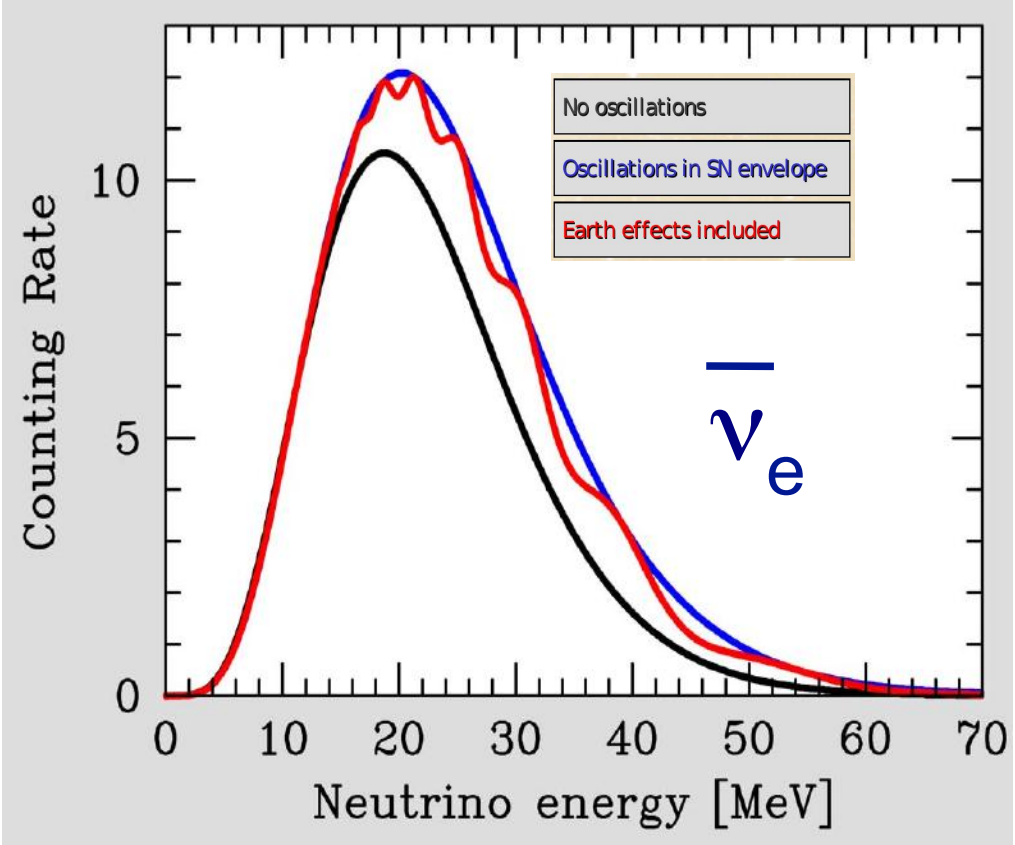
measure relative strengths with βdk of ^{40}Ti to mirror nucleus

Another possibility:

Flavor transformation *in the Earth* can give a handle on oscillation parameters (less SN-dependence)

Kachelreiss, Raffelt et al.

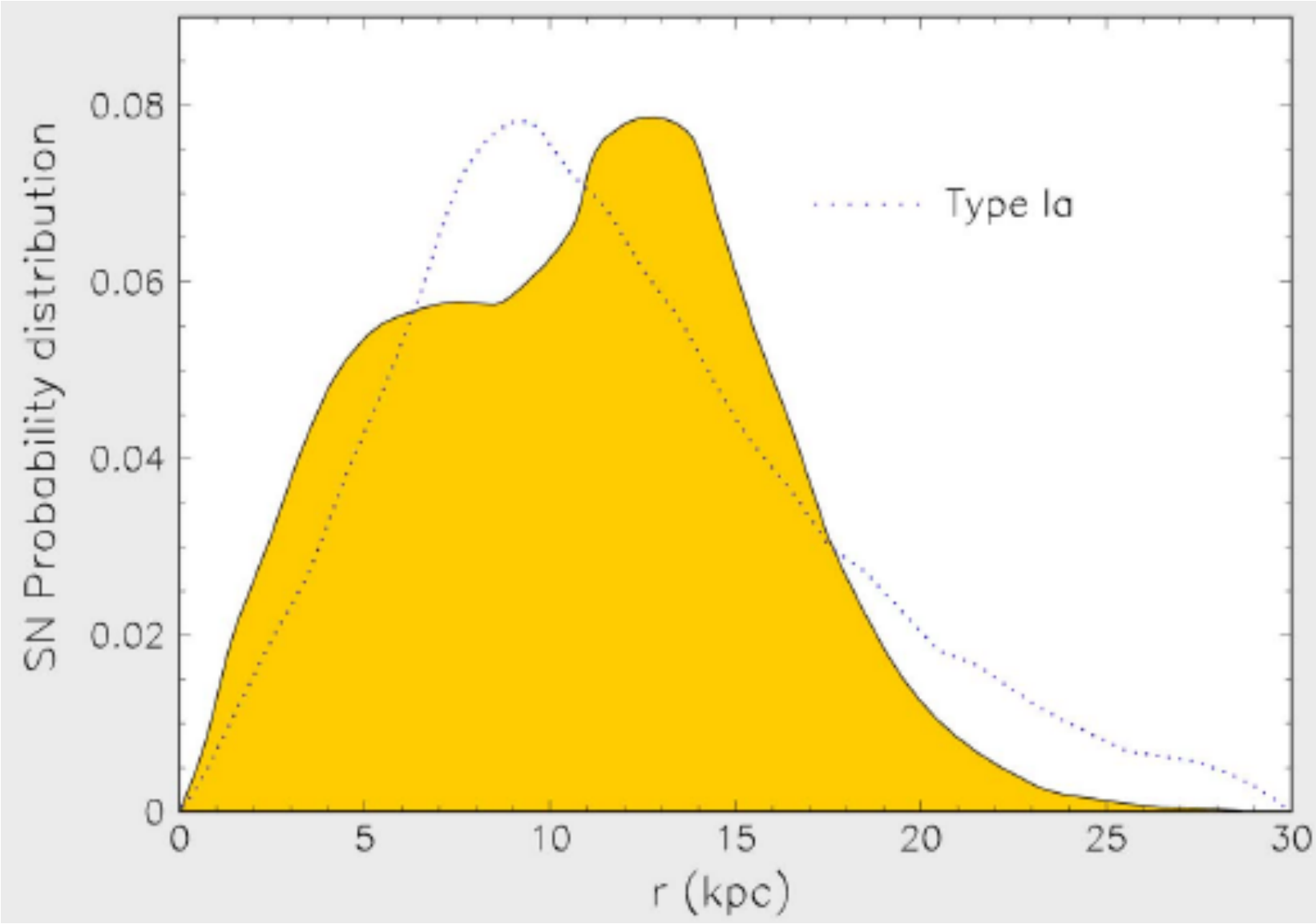




Compare fluxes of different flavors a different locations; or, look for spectral distortions in a single detector

Typical distance from us: ~10-15 kpc

(10 kpc is "standard distance")



Mirizzi, Raffelt and Serpico , astro-ph/0604300

Also on the surface: reactor experiments w/ Gd-doped (and undoped) scintillator

Detector	Type	Location	Mass (ton)	Events @ 10 kpc
Double Chooz	Scintillator	France	20	**7**
RENO	Scintillator	South Korea	30	**11**
Daya Bay	Scintillator	China	330	**100**

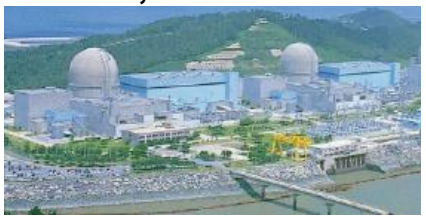
Although signal numbers are small, for low bg rates and good tagging, there will be good S/B

Also: coincidence between multiple detectors makes a SN trigger possible

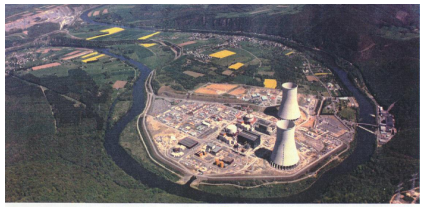
Daya Bay, arXiv:1310.5783

See poster #87 by H. Wei

RENO, South Korea



Double CHOOZ, France

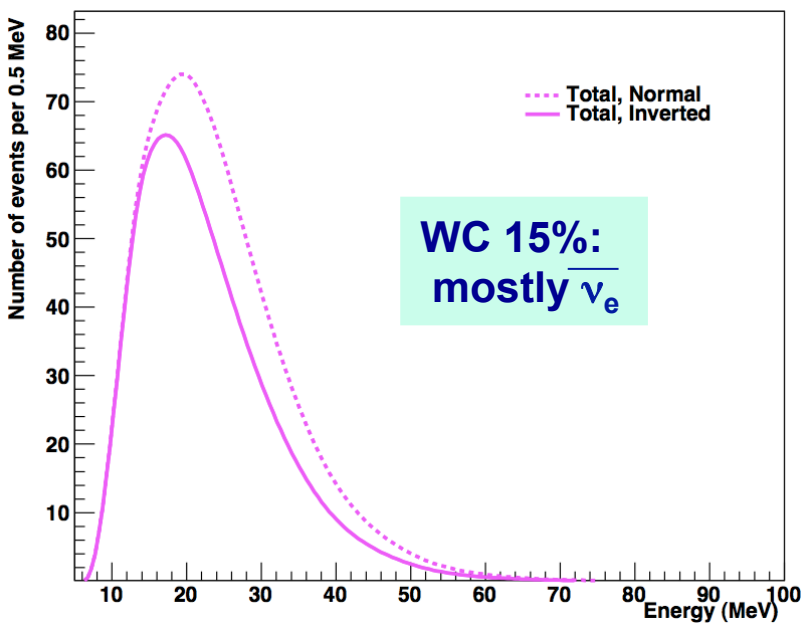


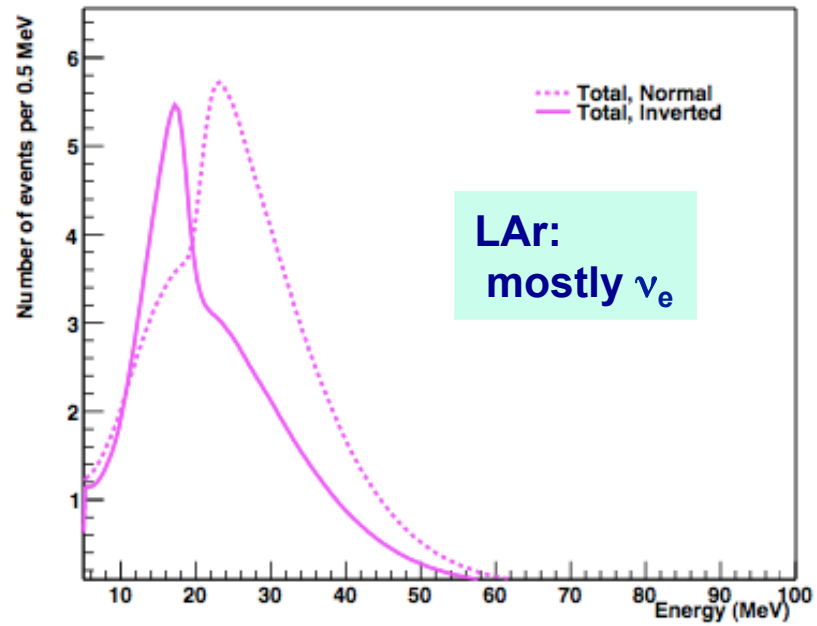
Daya Bay, China

Sensitivity to neutrino oscillation parameters: example

Can we tell the difference between normal and inverted mass hierarchies?

(1 second late time slice, flux from H. Duan w/collective effects)





Differences, but no sharp features

LAr shows dramatic difference

`Anecdotal' evidence...

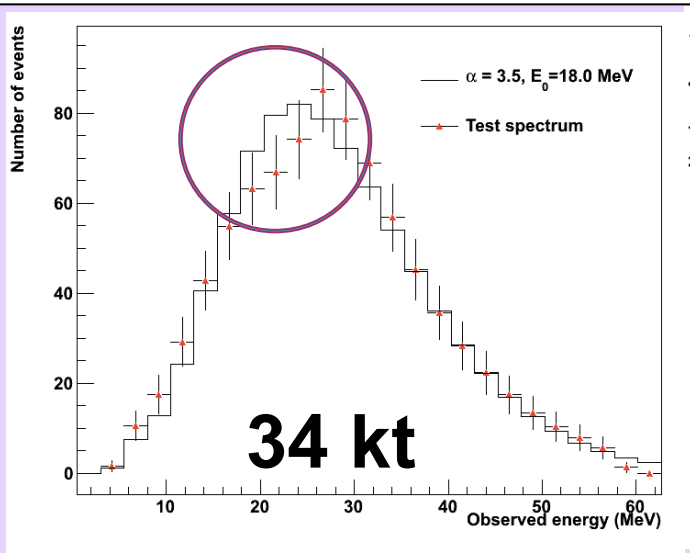
Diverse supernova detectors are desirable for getting the most physics from the burst

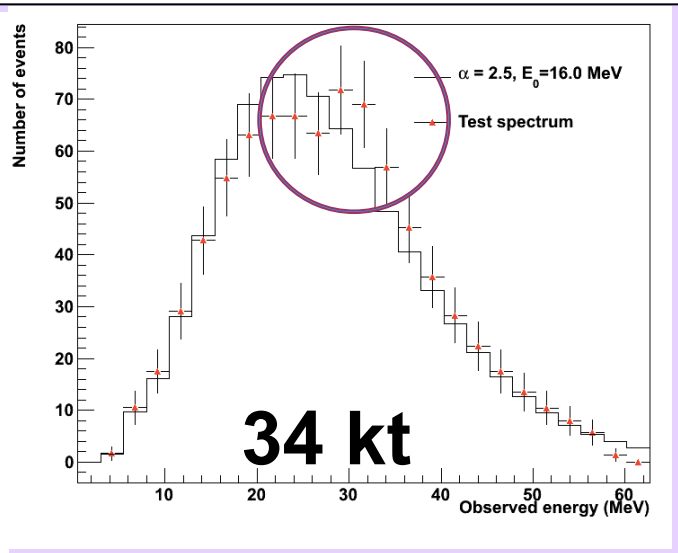
Hierarchy signature in SN shock w/LAr

Preliminary: work in progress

Snapshots at ~ 1 second intervals (1 s integration) for cooling phase w/ shock, NMH

10 kpc spectra from A. Friedland/JJ Cherry/H. Duan smeared w/ SNOwGLoBES response
Based on Keil, Raffelt, Janka spectra, astro-ph/0208035, w/ collective oscillations + shock
Black line: best fit to pinched thermal spectrum



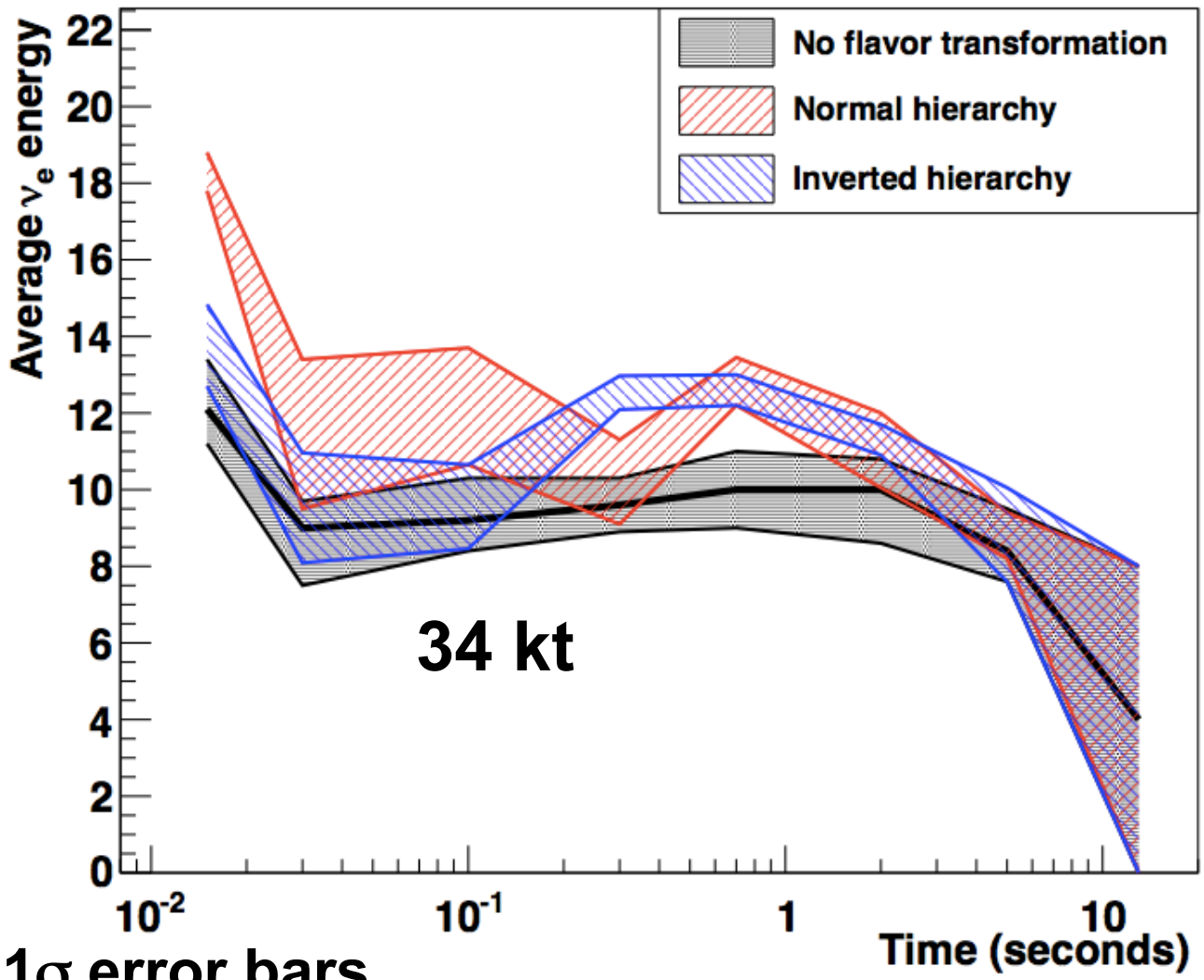


For NMH (*not* for IMH), "non-thermal" features clearly visible, and change as shock moves through the SN

Measuring SN ν_e temperature vs time w/Lar

10 kpc spectra from A. Friedland/JJ Cherry/H. Duan smeared w/ SNOwGLoBES response, fit to pinched thermal spectrum

Based on Keil, Raffelt, Janka spectra, astro-ph/0208035, w/ collective oscillations (NH & IH)



1σ error bars

Solid line: original $\langle E_\nu \rangle$

Preliminary: work in progress