

Neutrinos from Core-Collapse Supernovae

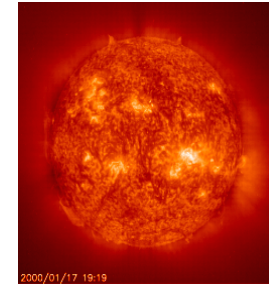
Kate Scholberg, Duke University
NNPSS 2014

Lecture Plan

Lecture #1: Neutrino Mass and Oscillations



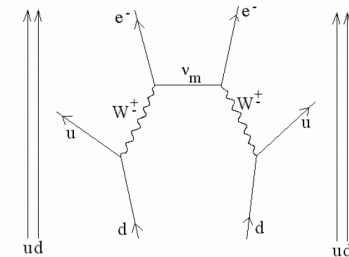
Lecture #2: Solar Neutrinos



Lecture #3: Supernova Neutrinos



Lecture #4: Absolute Mass and Neutrinoless Double Beta Decay



OUTLINE

Neutrinos, supernovae & neutrinos from SNa

What can be learned

Supernova neutrino detection

Inverse beta decay

Other CC interactions

NC interactions

Summary of current and near future detectors

Future detection

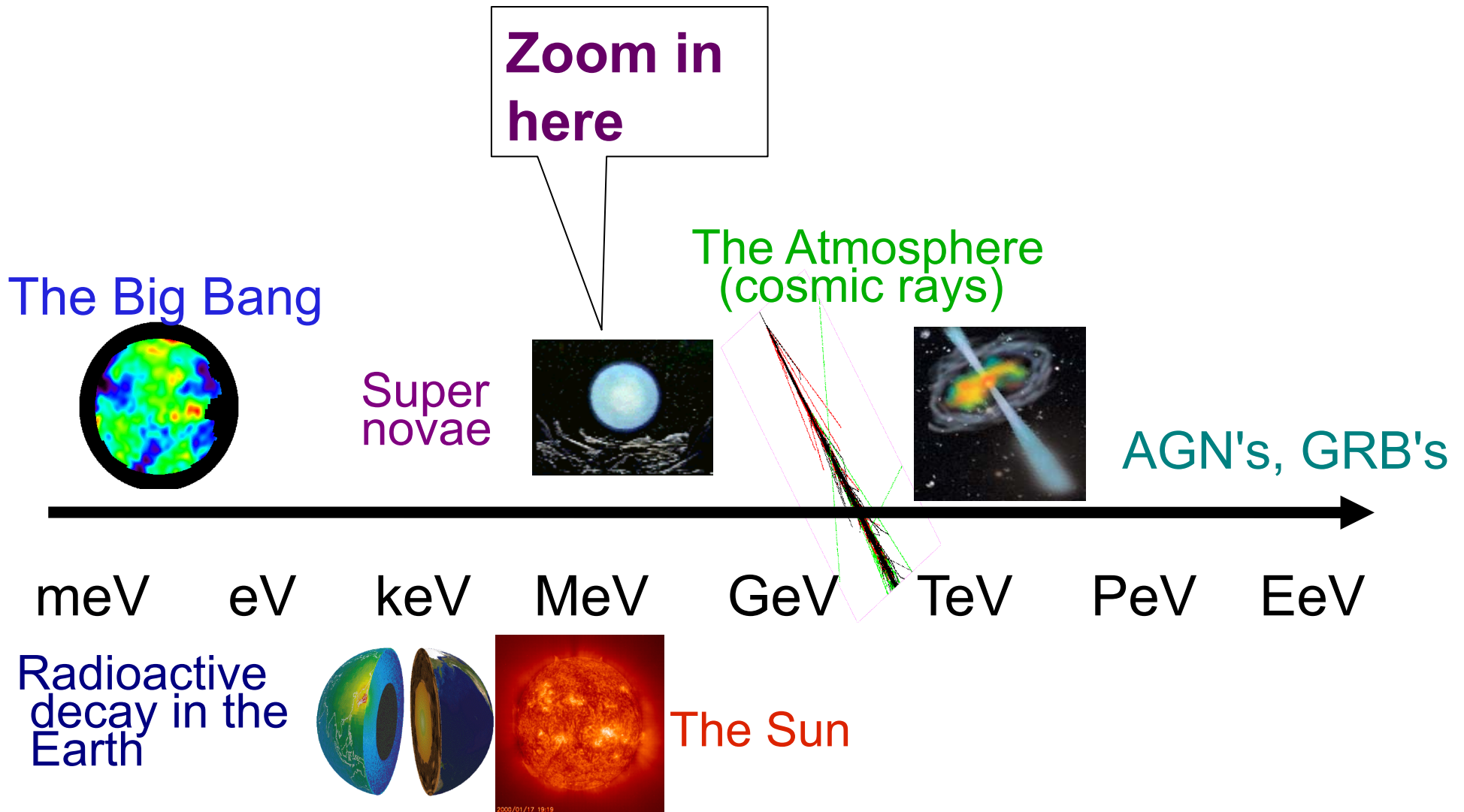
Extragalactic neutrinos

Diffuse background neutrinos

Note on xscn measurements

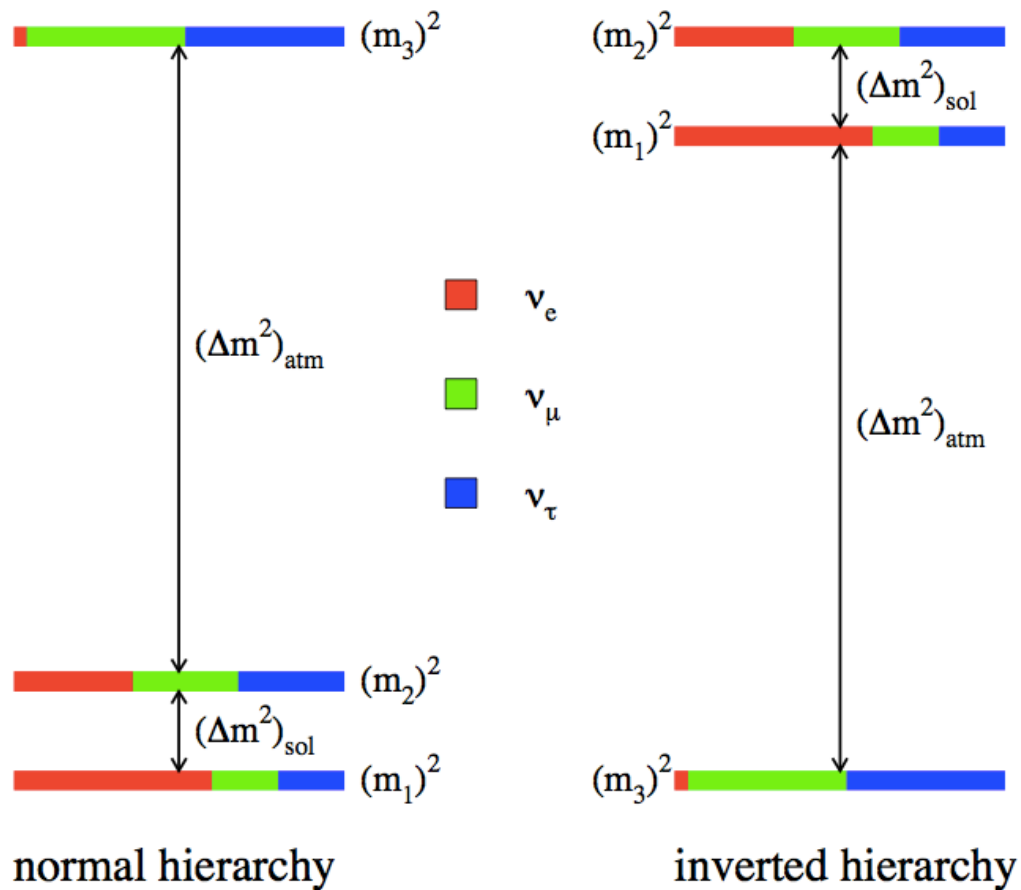
Summary

Sources of wild neutrinos



Next on the list to go after experimentally: mass hierarchy

(sign of Δm^2_{32})



$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$$

Neutrinos from core collapse

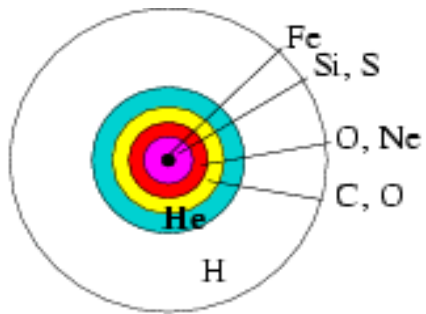
When a star's core collapses, ~99% of the gravitational binding energy of the proto-nstar goes into ν 's of *all flavors* with ~tens-of-MeV energies

(Energy *can* escape via ν 's)

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

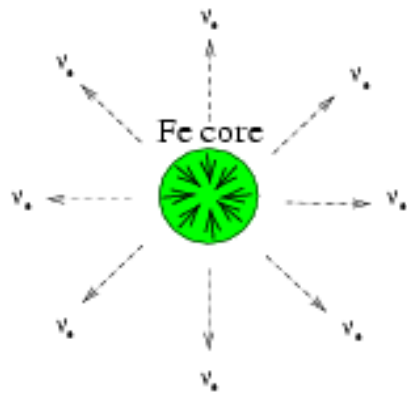
Timescale: *prompt*
after core collapse,
overall $\Delta t \sim 10$'s
of seconds





PRE-SUPERNOVA

"onion-skin"



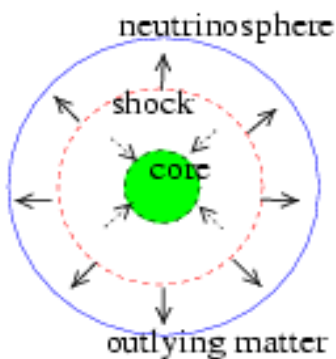
CORE INFALL

$$M_{\text{core}} > \sim M_{\text{Ch}}$$

"neutronization" $e^- + p \rightarrow n + \nu_e$

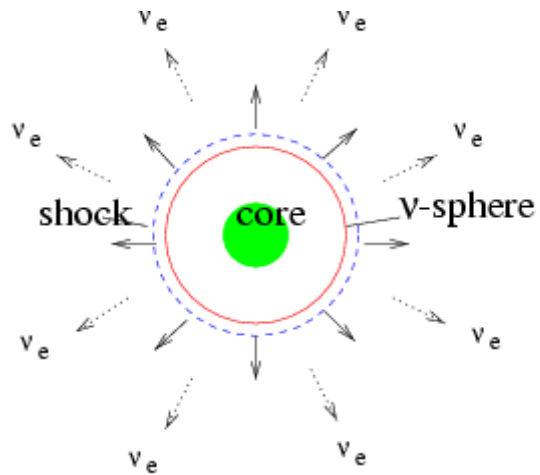


NEUTRINO TRAPPING



CORE BOUNCE

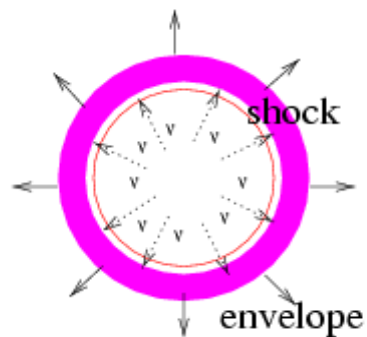
shock formation



NEUTRINO "BREAKOUT"

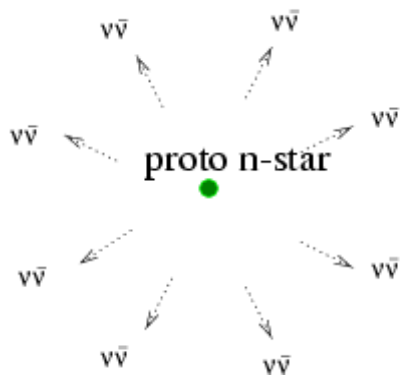
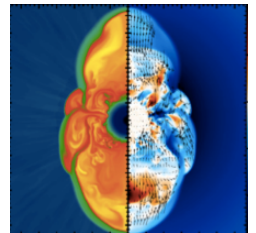
shock hits " ν -sphere"

(radius such that
 ν mean free path is ∞)



ACCRETION and/(or) EXPLOSION

star disrupted (or fizzles...)
 ν 's may be important



COOLING

energy shed
via $\nu\bar{\nu}$ pairs

Visible aftermath after
~hours or days



SN ν spectrum parameterizations:

“pinched thermal” is decent description

Fermi-Dirac (T, η, Φ)

$$F_{\nu_\alpha}^0(E) = \frac{\Phi_{\nu_\alpha}}{T_{\nu_\alpha}^3 f_2(\eta_{\nu_\alpha})} \frac{E^2}{e^{E/T_{\nu_\alpha} - \eta_{\nu_\alpha}} + 1}$$

$$f_n(\eta_{\nu_\alpha}) \equiv \int_0^\infty \frac{x^n}{e^{x - \eta_{\nu_\alpha}} + 1} dx$$

$$\langle E_{\nu_\alpha} \rangle = [f_3(\eta_{\nu_\alpha}) / f_2(\eta_{\nu_\alpha})] T_{\nu_\alpha}$$

Garching $(\langle E \rangle, \beta, \Phi)$

preferred by
Garching SN modelers

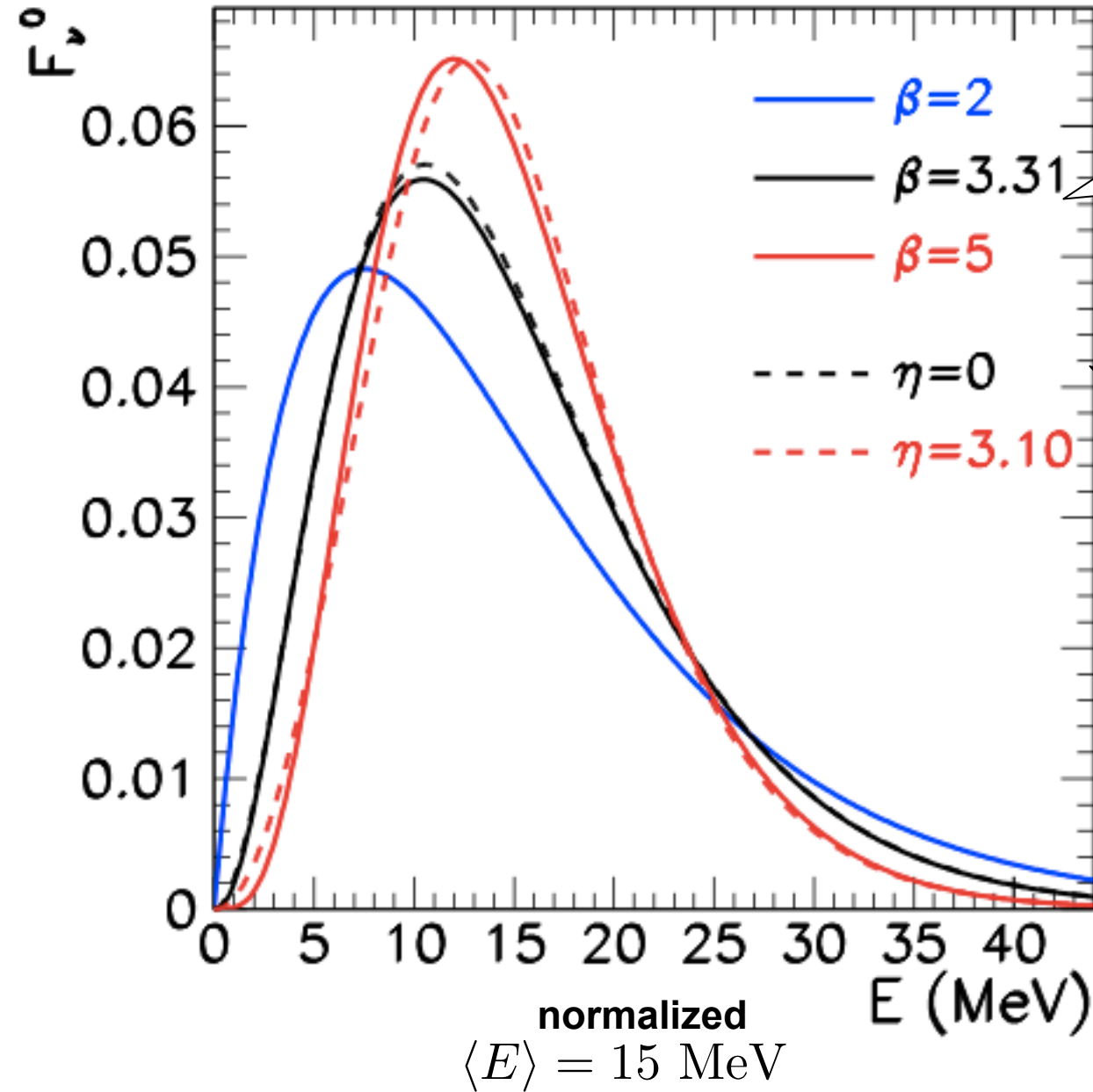
$$F_{\nu_\alpha}^0(E) = \frac{\Phi_{\nu_\alpha}}{\langle E_{\nu_\alpha} \rangle} \frac{\beta_{\nu_\alpha}^{\beta_{\nu_\alpha}}}{\Gamma(\beta_{\nu_\alpha})} \left(\frac{E}{\langle E_{\nu_\alpha} \rangle} \right)^{\beta_{\nu_\alpha} - 1} \exp \left(-\beta_{\nu_\alpha} \frac{E}{\langle E_{\nu_\alpha} \rangle} \right)$$

see e.g. arXiv:0802.1489

$$\Phi_{\nu_x} = \Phi_{\nu_\mu} = \Phi_{\bar{\nu}_\mu} = \Phi_{\nu_\tau} = \Phi_{\bar{\nu}_\tau}$$

$$E_{\nu_\alpha}^{\text{tot}} = \Phi_{\nu_\alpha} \langle E_{\nu_\alpha} \rangle$$

$$F_{\nu_\alpha}^0(E) = \frac{\Phi_{\nu_\alpha}}{\langle E_{\nu_\alpha} \rangle} \frac{\beta_{\nu_\alpha}^{\beta_{\nu_\alpha}}}{\Gamma(\beta_{\nu_\alpha})} \left(\frac{E}{\langle E_{\nu_\alpha} \rangle} \right)^{\beta_{\nu_\alpha}-1} \exp \left(-\beta_{\nu_\alpha} \frac{E}{\langle E_{\nu_\alpha} \rangle} \right)$$



“Pinching”
controlled
by β for
Garching

“Pinching”
controlled
by η for FD

$$F_{\nu_\alpha}^0(E) = \frac{\Phi_{\nu_\alpha}}{T_{\nu_\alpha}^3 f_2(\eta_{\nu_\alpha})} \frac{E^2}{e^{E/T_{\nu_\alpha} - \eta_{\nu_\alpha}} + 1}$$

Expected neutrino luminosity and average energy vs time

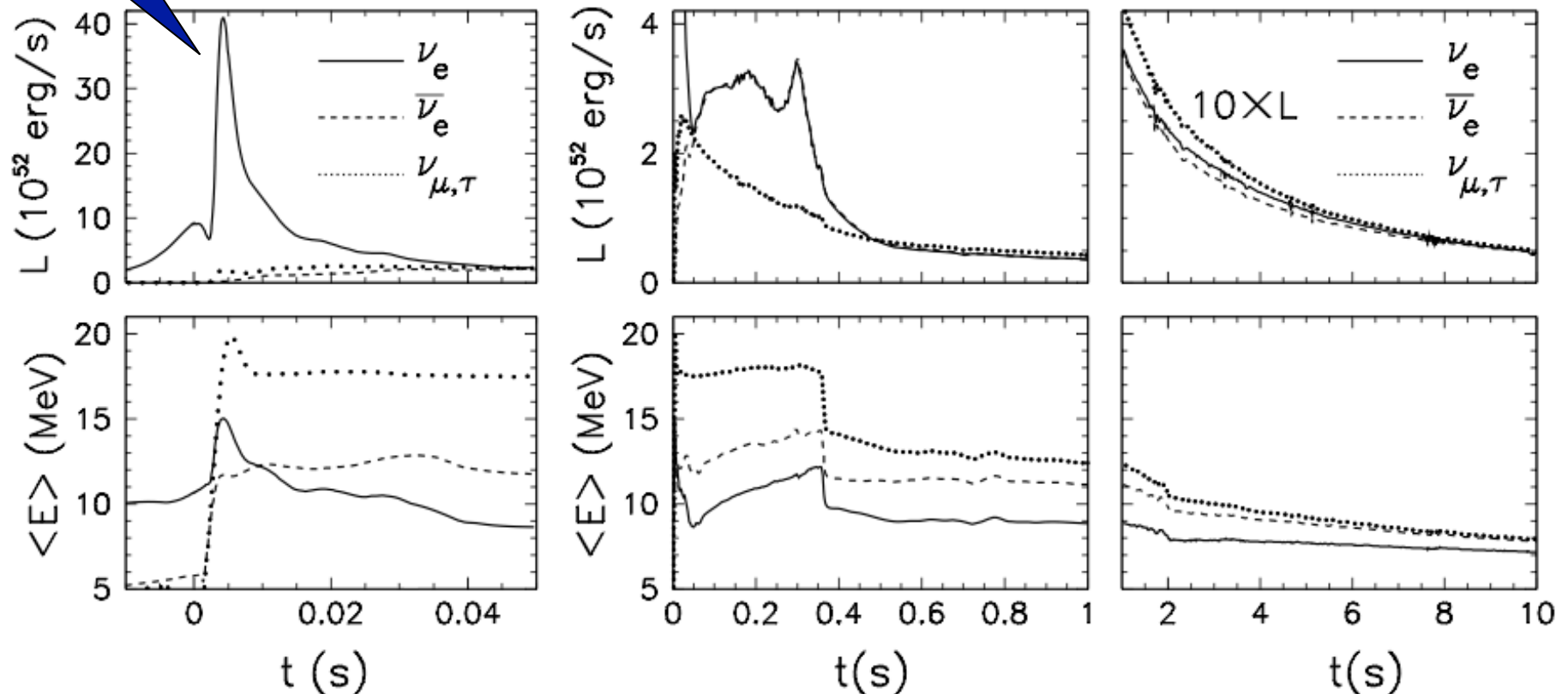
Fischer et al., arXiv:0908.1871: 'Basel' model

neutronization burst

Early:
deleptonization

Mid:
accretion

Late:
cooling



Generic feature:
(may or may not be robust)

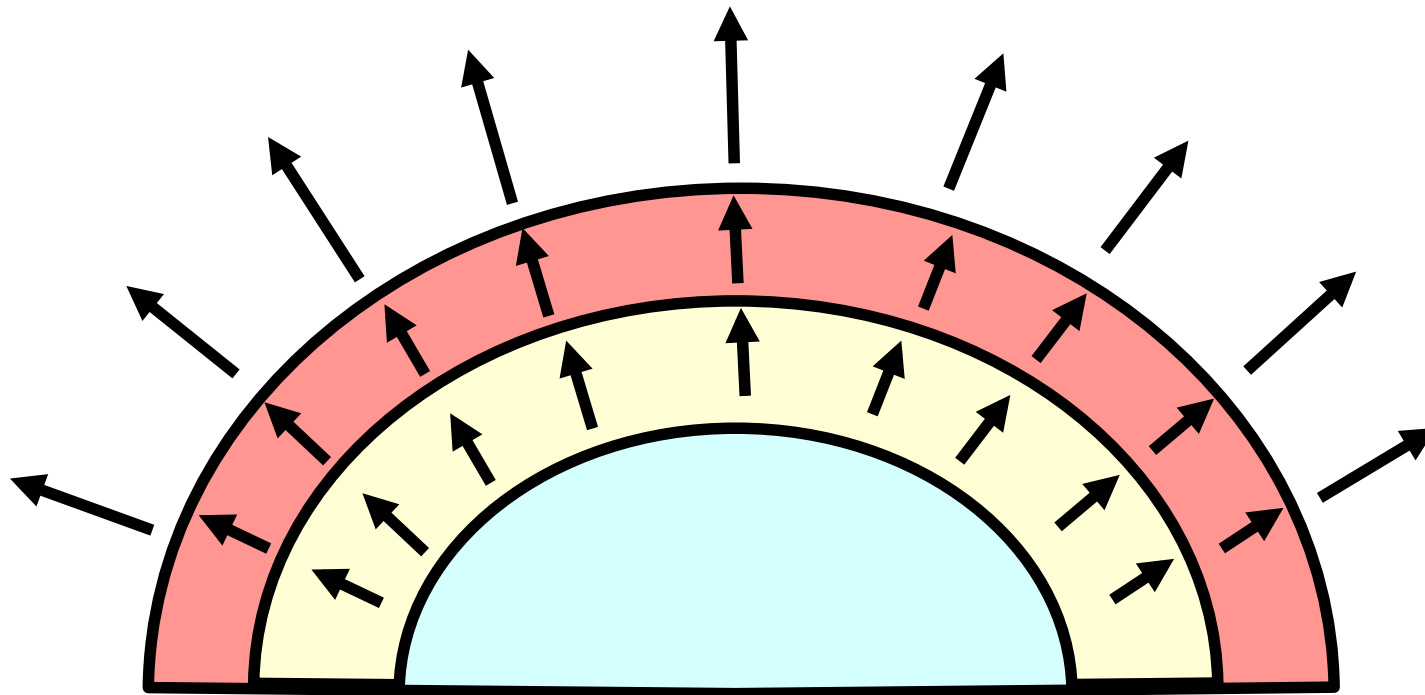
$$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$$

Nominal expected flavor-energy hierarchy

Fewer interactions
w/ proto-nstar
 $\Rightarrow$ deeper ν -sphere
 $\Rightarrow$ hotter ν 's

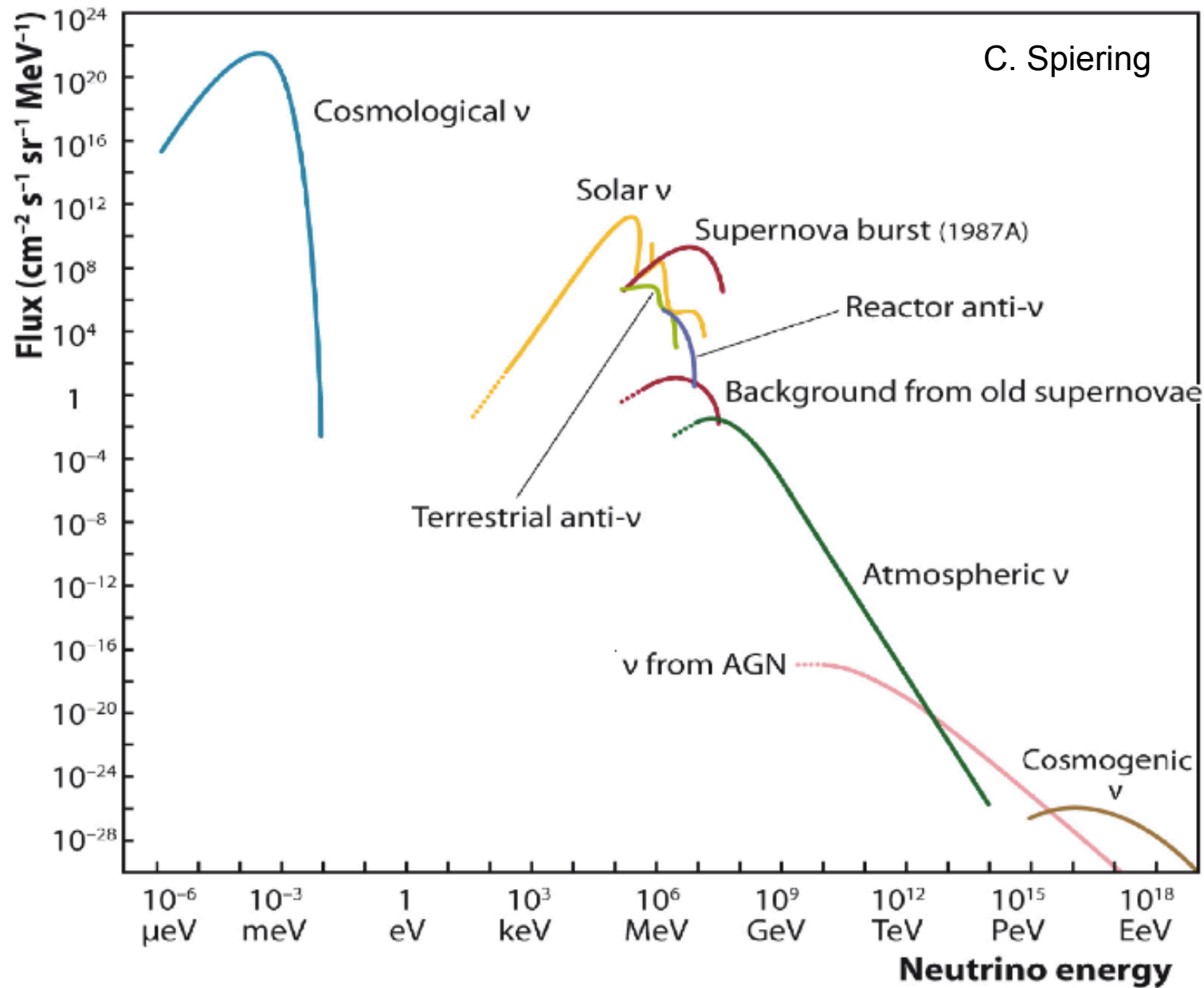


$$\begin{aligned} \langle E \nu_e \rangle &\sim 12 \text{ MeV} \\ \langle E \bar{\nu}_e \rangle &\sim 15 \text{ MeV} \\ \langle E \bar{\nu}_{\mu,\tau} \rangle &\sim 18 \text{ MeV} \end{aligned}$$



May or may not be robust (neutrinos which decouple deeper may lose more energy)

The supernova neutrino signal



Enormous, transient flux of tens-of-MeV neutrinos of all flavors

Supernova 1987A

in the Large Magellanic Cloud (55 kpc away)



SN1987A in LMC

at 55 kpc

ν 's seen ~ 2.5 hours before first light

Water Cherenkov: IMB

Kam II

$E_{th} \sim 29$ MeV, 6 kton

$E_{th} \sim 8.5$ MeV, 2.14 kton

8 events

11 events

Liquid Scintillator: Baksan

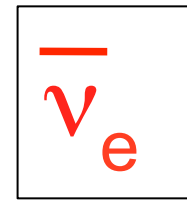
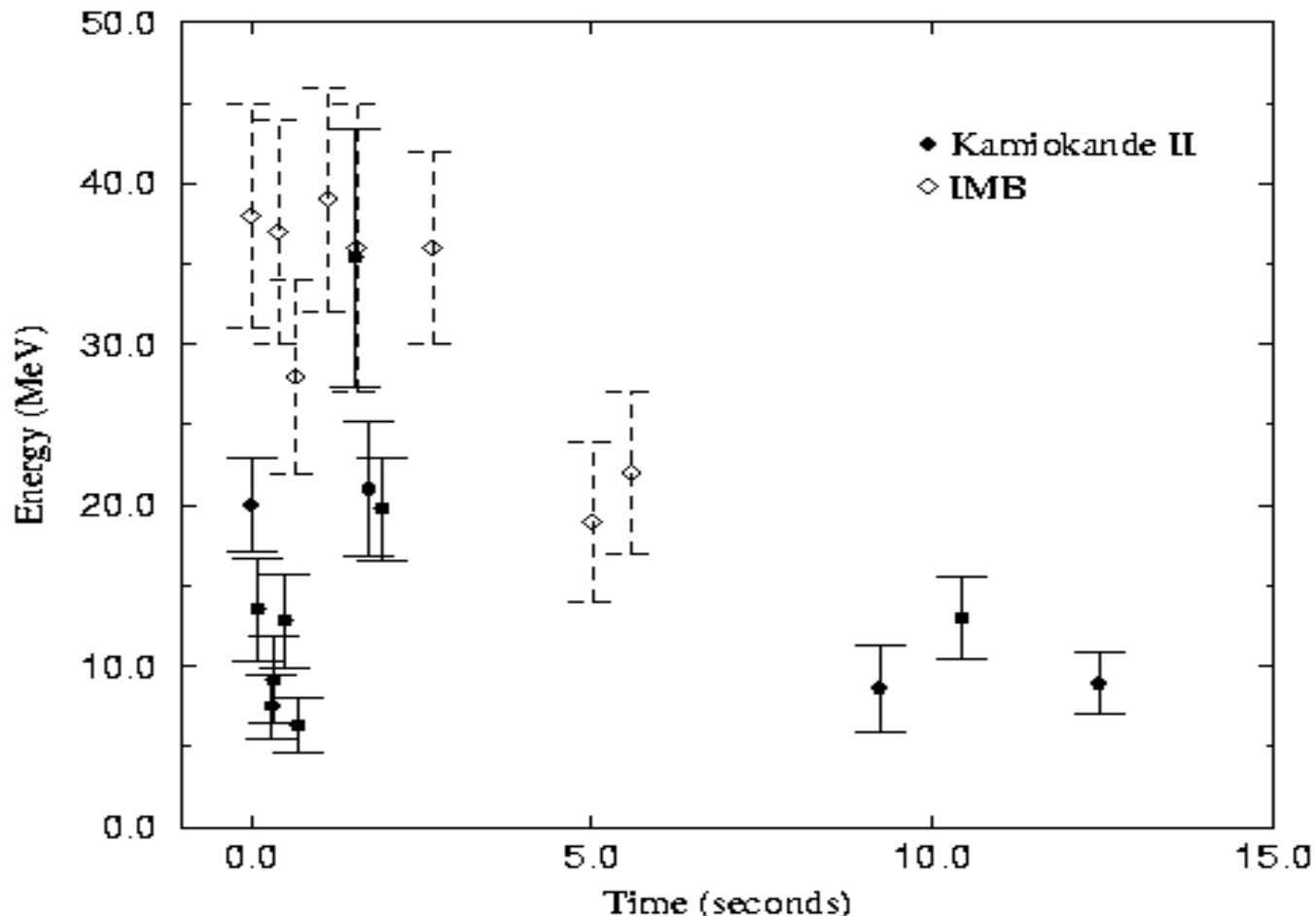
Mont Blanc

$E_{th} \sim 10$ MeV, 130 ton

$E_{th} \sim 7$ MeV, 90 ton

3-5 events

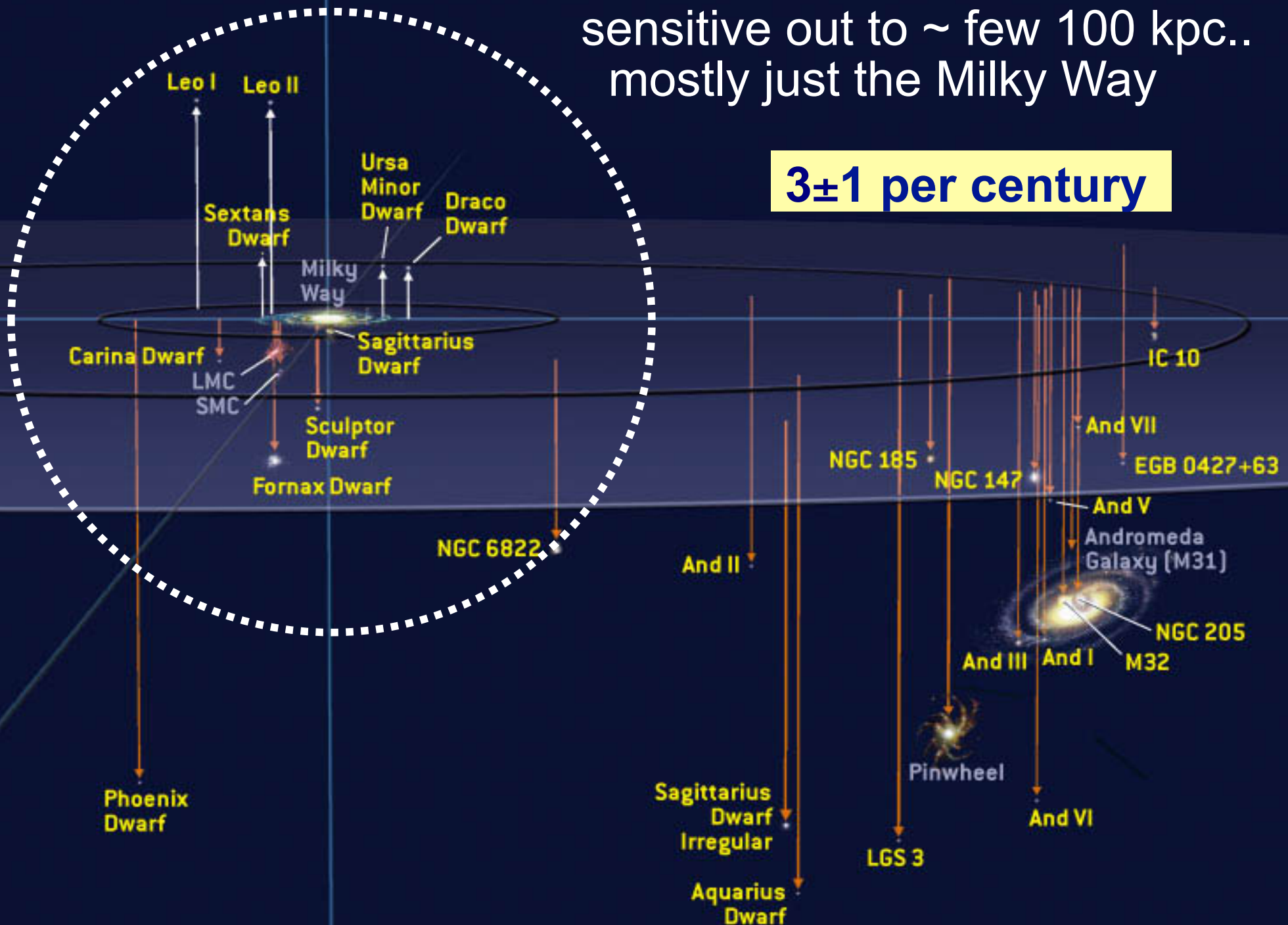
5 events??



Confirmed
baseline
model...
but still
many
questions

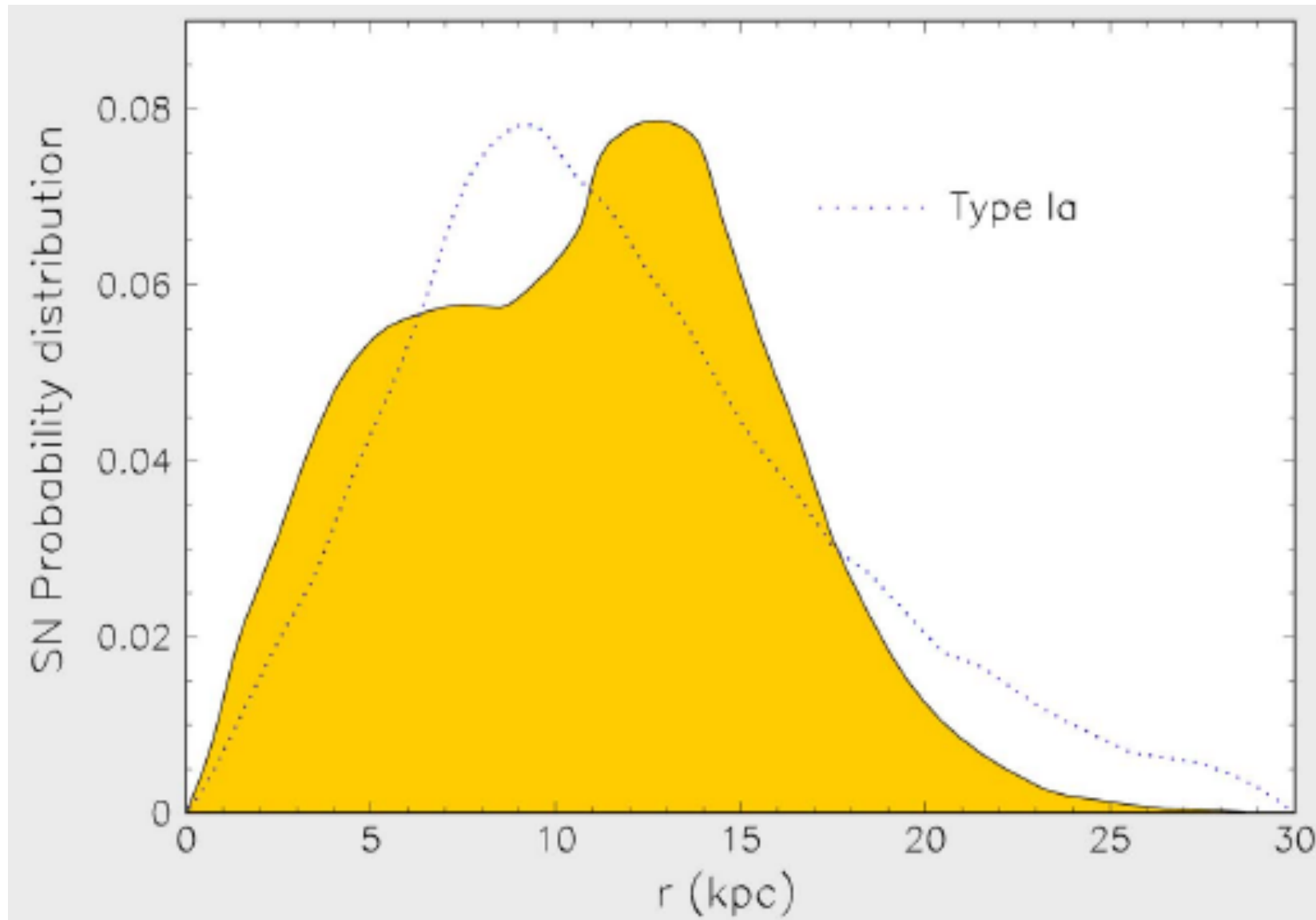
Current best neutrino detectors
sensitive out to ~ few 100 kpc..
mostly just the Milky Way

3 ± 1 per century



Typical distance from us: ~10-15 kpc

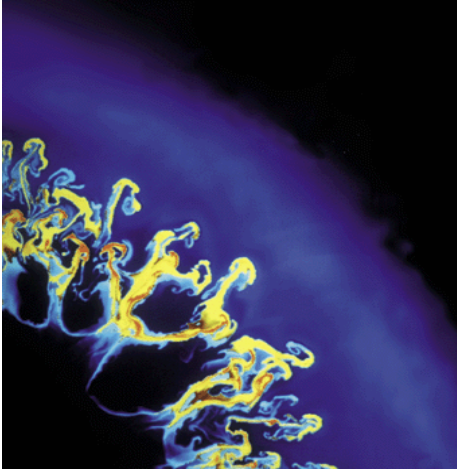
(10 kpc is “standard distance”)



Mirizzi, Raffelt and Serpico , astro-ph/0604300

What We Can Learn

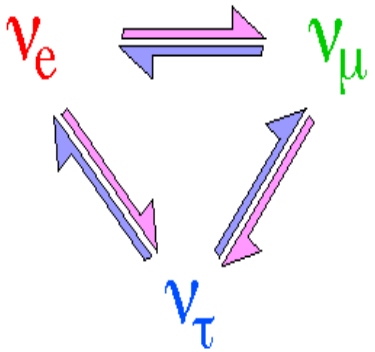
CORE COLLAPSE PHYSICS



- explosion mechanism
- proto nstar cooling, quark matter
- black hole formation
- accretion disks
- nucleosynthesis

from flavor,
energy, time
structure
of burst

NEUTRINO/OTHER PARTICLE PHYSICS



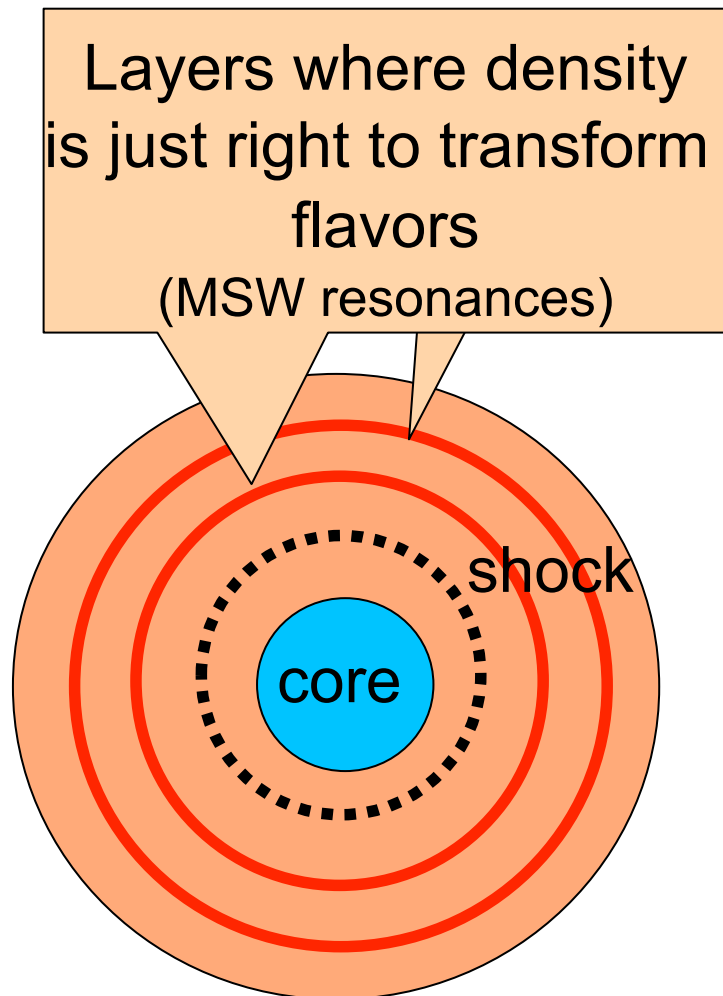
- ν absolute mass (not competitive)
- ν mixing from spectra: flavor conversion in SN/Earth
- other ν properties: sterile ν 's, magnetic moment, ...
- axions, extra dimensions, FCNC, ...

+ EARLY ALERT

Getting at neutrino oscillation parameters, e.g. $\text{sign}(\Delta m^2)$

Flavor transitions in the supernova itself may leave an imprint of the oscillation parameters on the supernova signal

There is some model dependence; understanding of the supernova will help



For example, depending on parameters, spectra can get swapped; signature could be e.g. *anomalously hot* ν_e ; also shock wave can have effect

'Collective effects' matter

- ν - ν interactions
- nonlinear effects
- 'multi-angle' effects

How can we learn about unknown neutrino oscillation parameters from a core collapse signal?

In the proto-neutron star the neutrino density is so high that *neutrino-neutrino interactions* matter

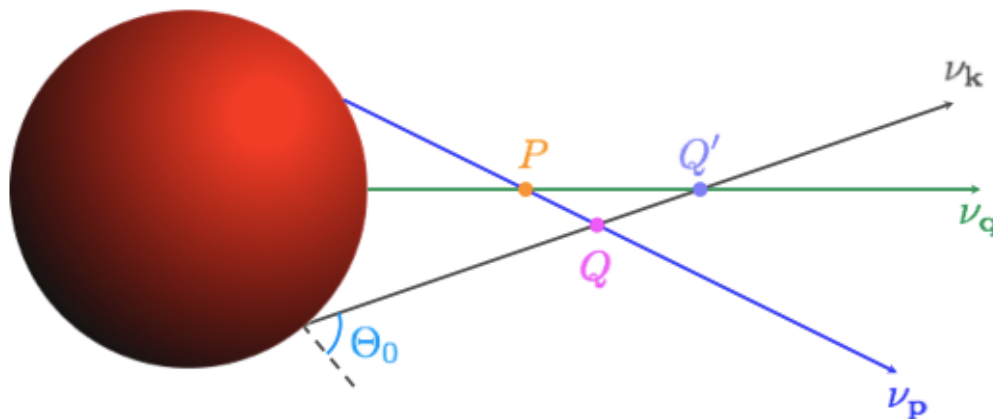
From G. Fuller

$$\psi_{\nu,i} = \begin{bmatrix} \text{amplitude to be } \nu_e \\ \text{amplitude to be } \nu_{\mu,\tau} \end{bmatrix}$$

$$i \frac{\partial}{\partial t} \psi_{\nu,i} = (\mathcal{H}_{\text{vac},i} + \mathcal{H}_{e,i} + \mathcal{H}_{\nu\nu,i}) \psi_{\nu,i}$$

neutrino-electron
charged current
forward exchange
scattering

neutrino-neutrino
neutral current
forward scattering

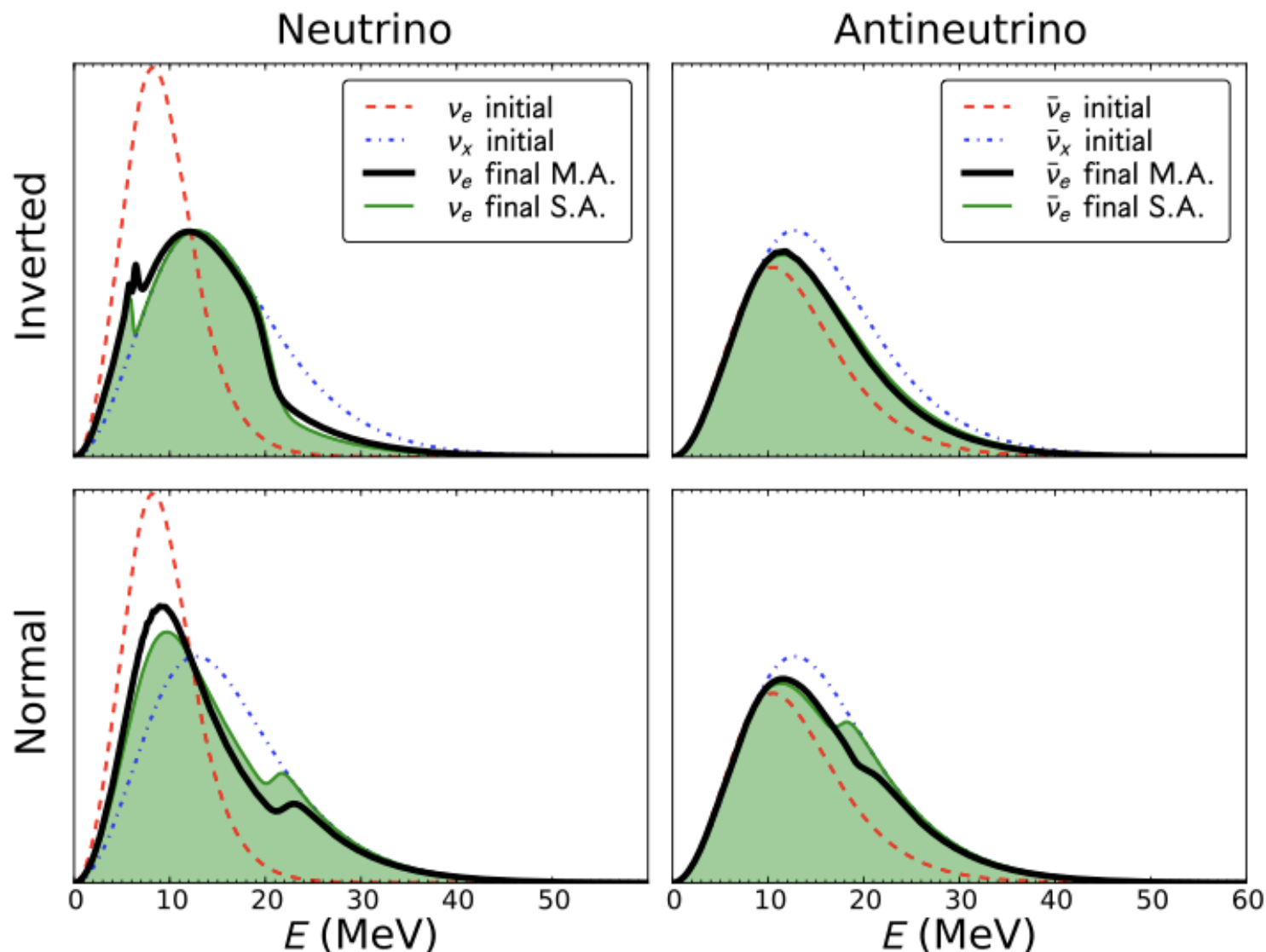


Anisotropic, nonlinear
quantum coupling of all
neutrino flavor evolution
histories:
“collective effects”

Must solve many *millions* of coupled, nonlinear partial differential equations!!

“The physics is addictive” -- G. Raffelt

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



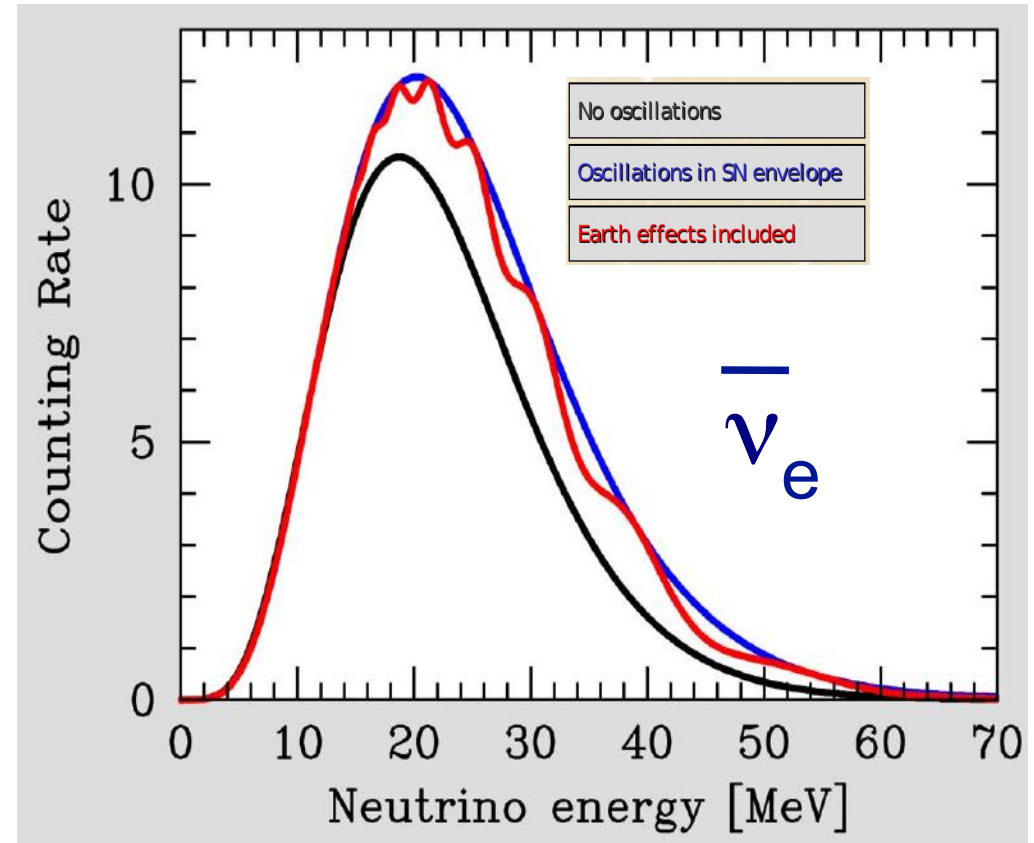
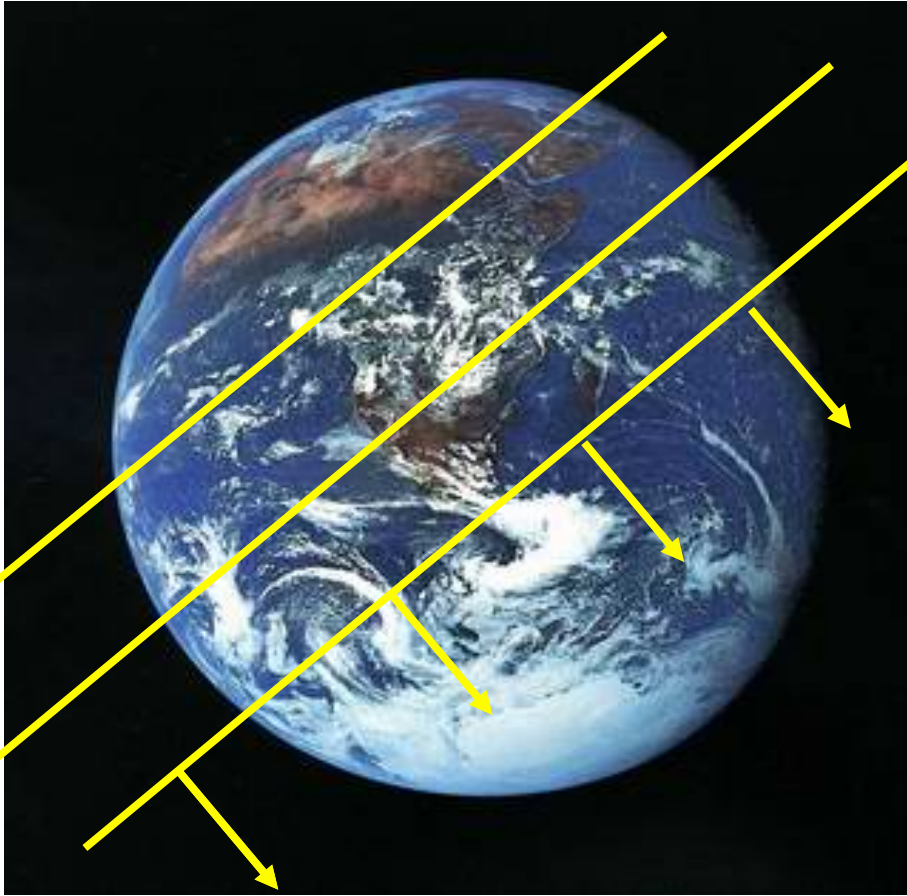
Distinctive spectral swap features depend on neutrino mass hierarchy, for neutrinos vs antineutrinos

Experimentally, can we tell the difference?

Another possibility:

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

Kachelreiss, Raffelt et al.



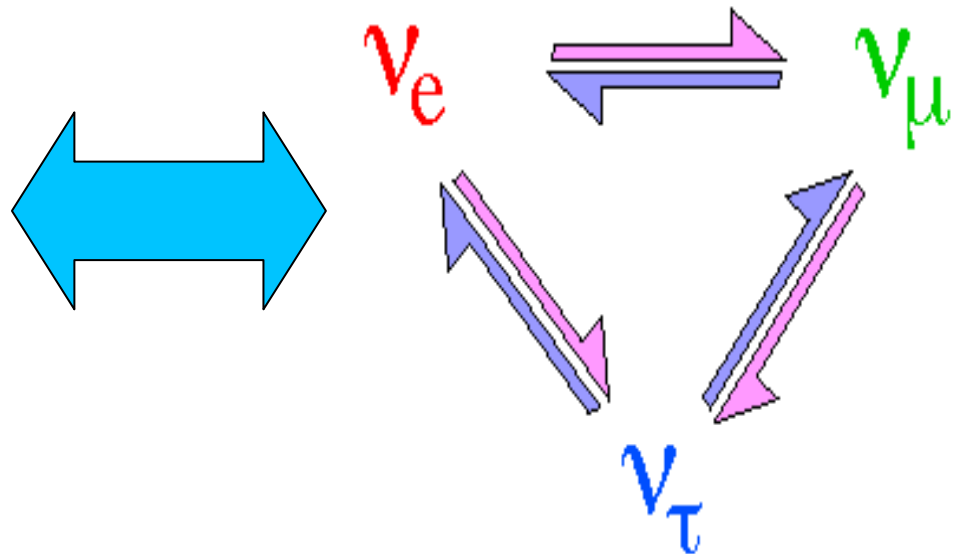
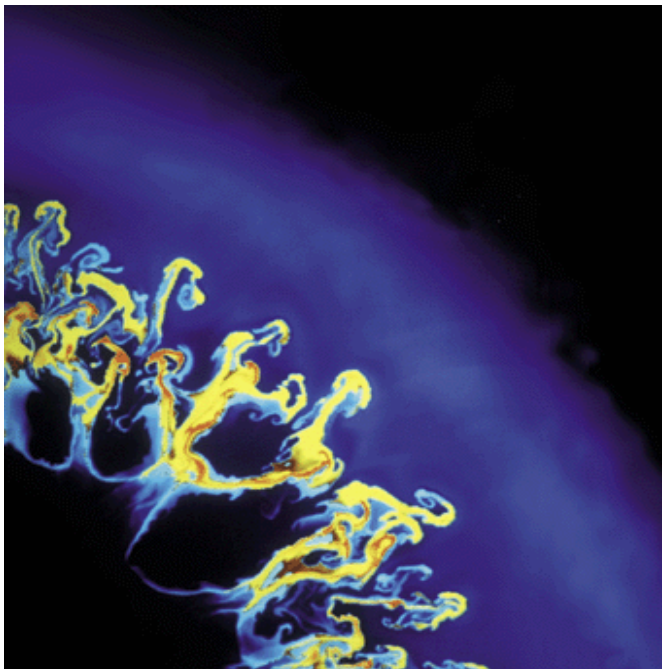
Compare fluxes of different flavors at different locations; or, look for spectral distortions in a single detector

My message here:

Sensitivity to (and ability to tag) different flavors

will be key for disentangling
core collapse & neutrino physics
information from the observed signal

Detector locations around the globe desirable, too!



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

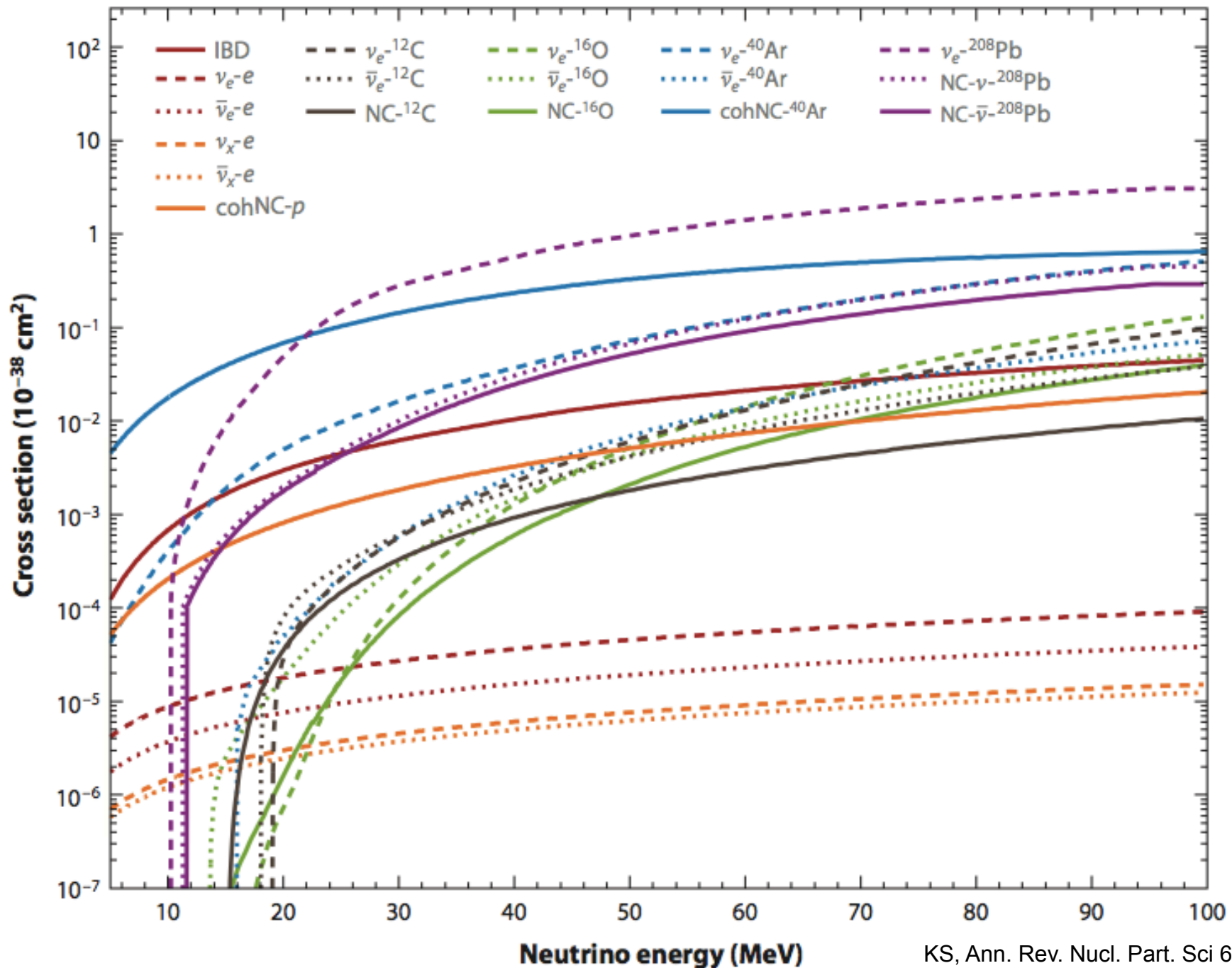


What do you want in a detector?

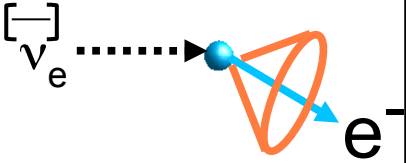
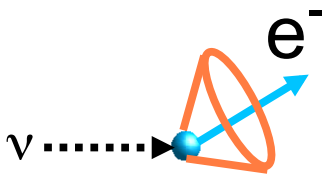
Size	~kton detector mass per 100 events
Low energy threshold	~Few MeV if possible
Energy resolution	Resolve features in spectrum
Angular resolution	Point to the supernova! (for directional interactions)
Timing resolution	Follow the time evolution
Low background	BG rate $\ll$ rate in burst; underground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

Note that many detectors have a “day job”...

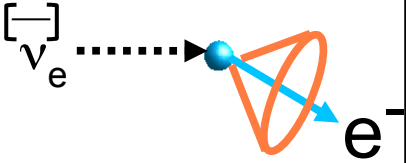
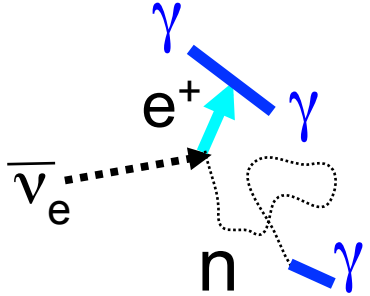
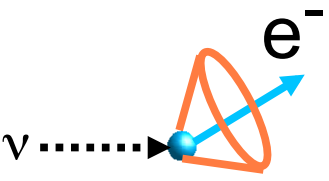
Relevant interaction cross sections in the 5-100 MeV range



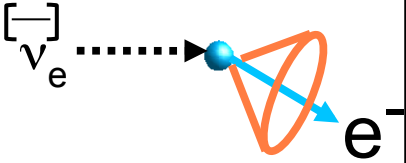
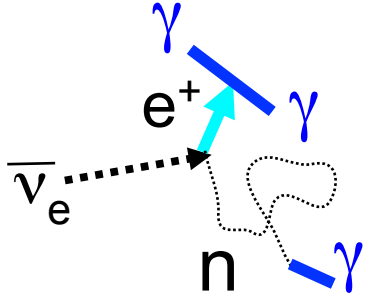
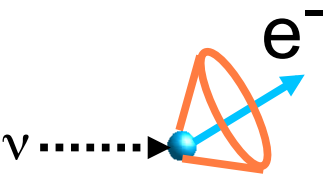
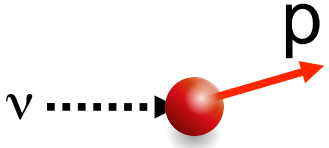
Supernova-relevant neutrino interactions

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

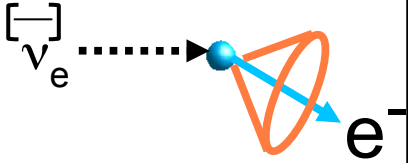
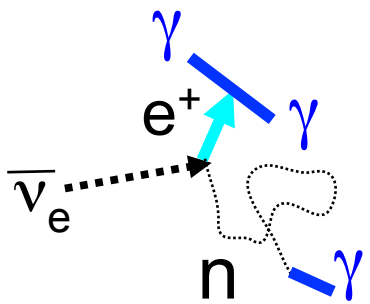
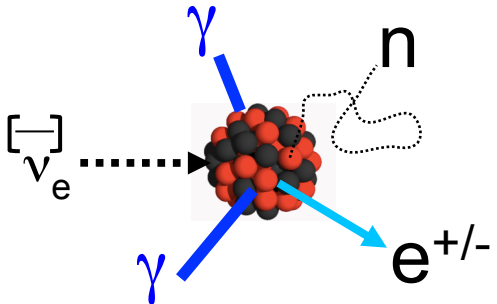
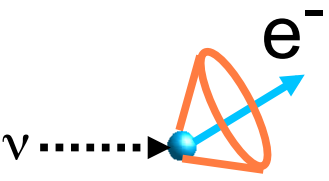
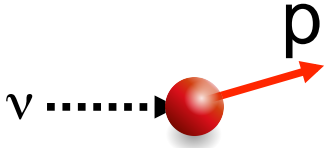
Supernova-relevant neutrino interactions

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Neutral current	 Useful for pointing		

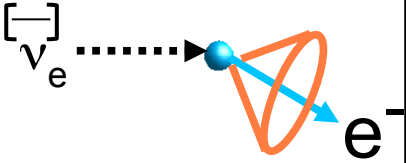
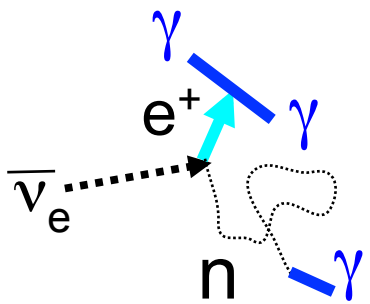
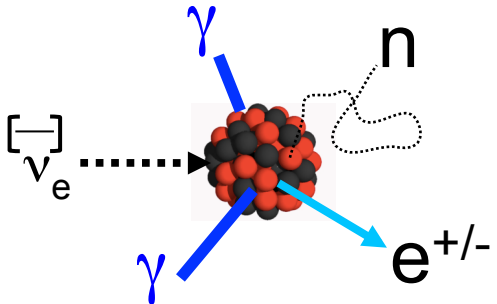
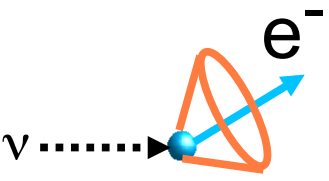
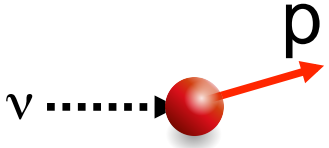
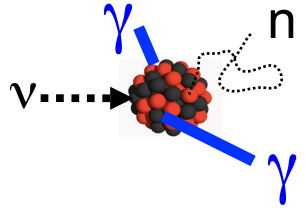
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Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	

Supernova-relevant neutrino interactions

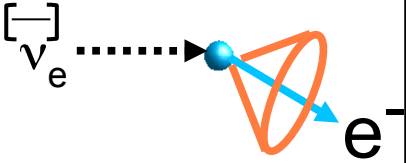
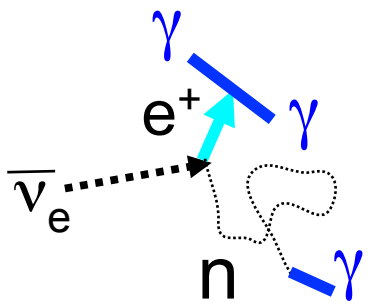
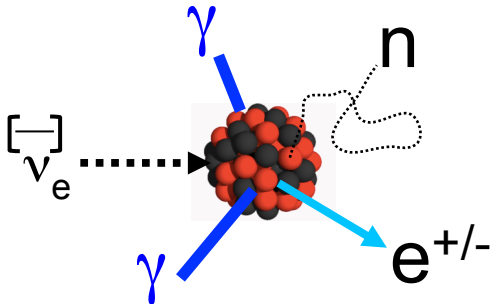
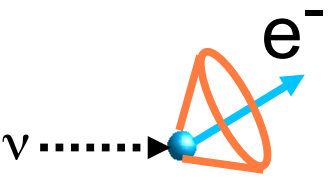
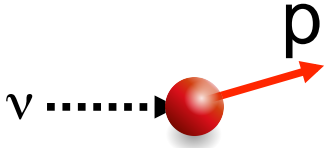
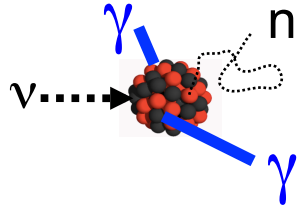
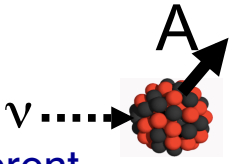
	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	$\nu_e + (N, Z) \rightarrow e^- + (N - 1, Z + 1)$ $\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N + 1, Z - 1)$  Various possible ejecta and deexcitation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

Supernova-relevant neutrino interactions

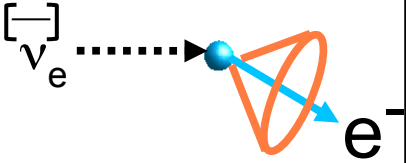
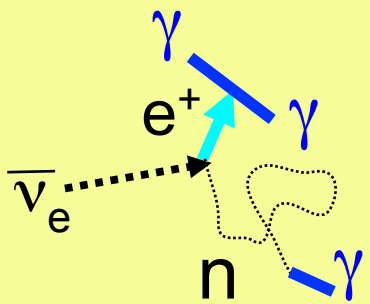
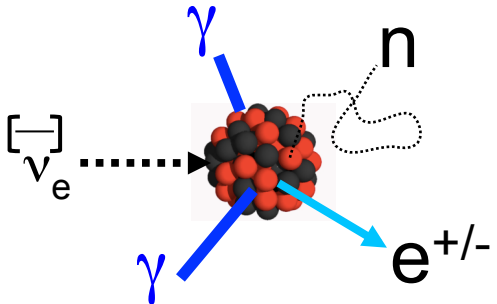
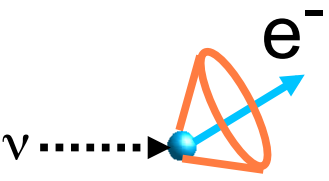
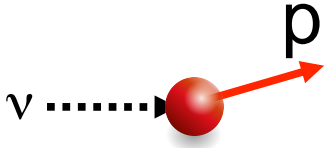
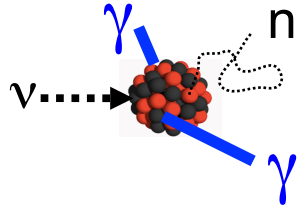
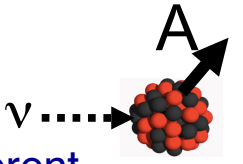
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Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	$\nu + A \rightarrow \nu + A^*$ 

Various possible ejecta and deexcitation products

Supernova-relevant neutrino interactions

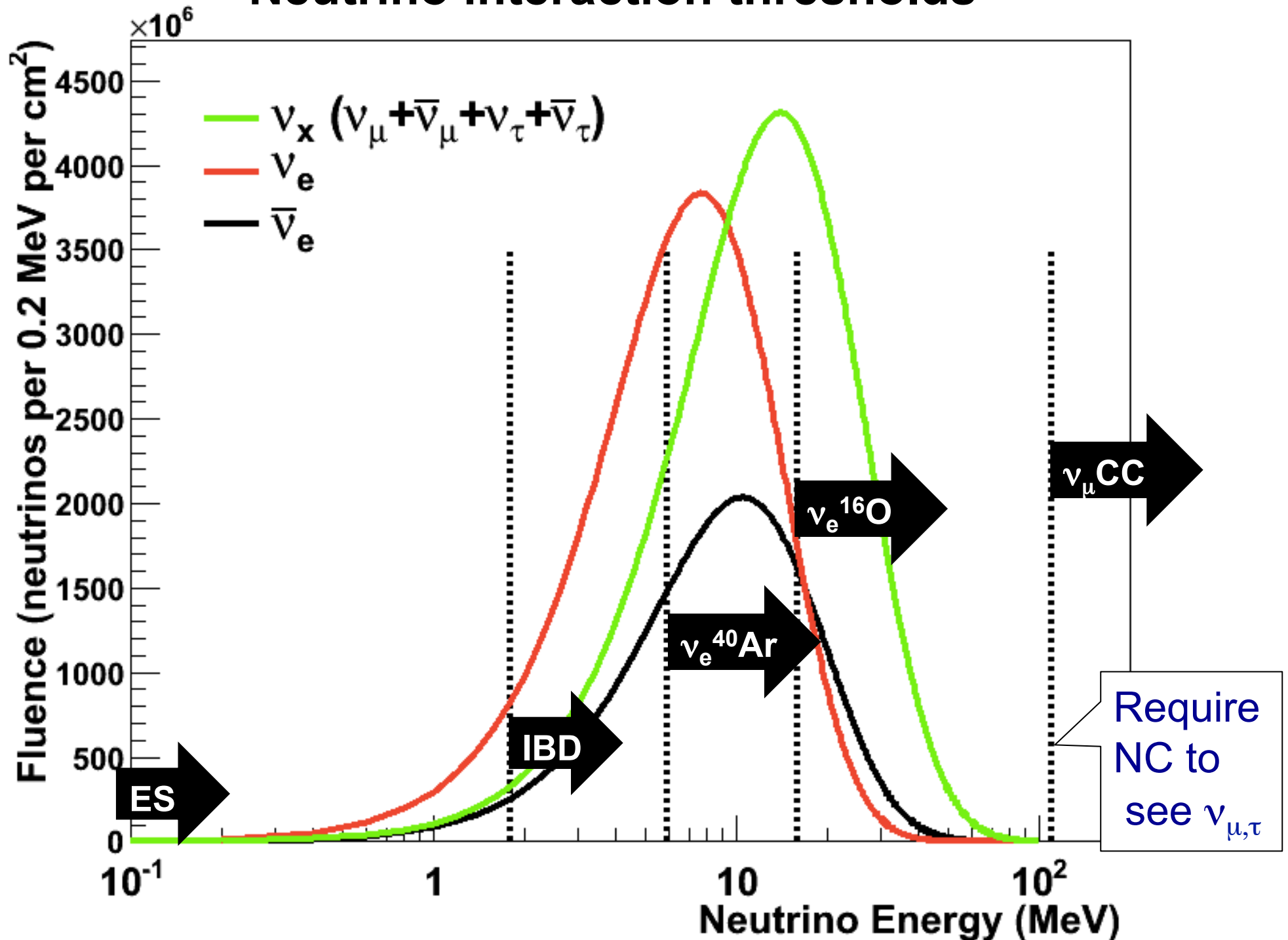
	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	$\nu_e + (N, Z) \rightarrow e^- + (N - 1, Z + 1)$ $\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N + 1, Z - 1)$  Various possible ejecta and deexcitation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

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IBD (electron antineutrinos) dominates for current detectors

Neutrino interaction thresholds



Interaction rates in a detector material

The diagram shows the equation $R = \Phi \sigma N_t$ where the variables are highlighted in colored boxes and labeled with callouts. Φ is in a light green box with a callout labeled 'Flux'. σ is in a light yellow box with a callout labeled 'Cross section'. N_t is in a light purple box with a callout labeled 'Number of targets'.

$$R = \Phi \sigma N_t$$

$\propto$ detector mass, $1/D^2$

Event spectrum as a function of observed energy E' , for a realistic detector

flux $\otimes$ xscn $\otimes$ detector response

The diagram shows the equation for the event spectrum with four color-coded components in the integrand, each with a callout box:

- Flux** (green box) points to $\Phi(E)$
- Cross section** (yellow box) points to $\sigma(E)$
- Interaction products (physics)** (purple box) points to $k(E - \hat{E})$
- Detector response (detector simulation)** (orange box) points to $T(\hat{E})V(\hat{E} - E')$

$$\frac{dn}{dE'} = N \int_0^\infty \int_0^\infty dE d\hat{E} \Phi(E) \sigma(E) k(E - \hat{E}) T(\hat{E}) V(\hat{E} - E')$$

E' : observed energy

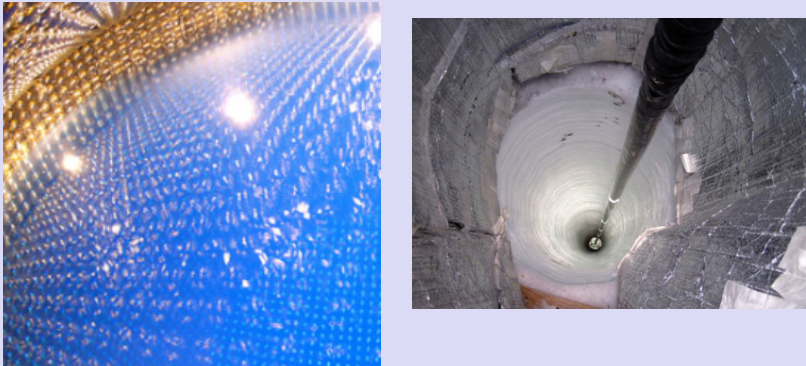
k : observed energy for given neutrino energy

T : detector efficiency

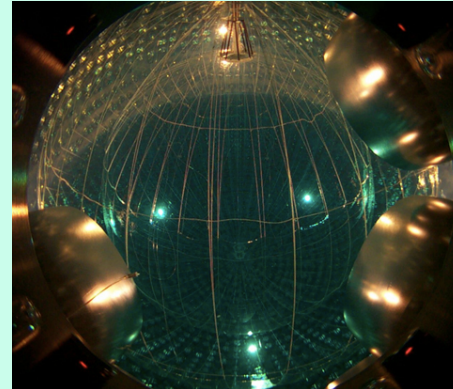
V : detector resolution

Current main supernova neutrino detector types

Water



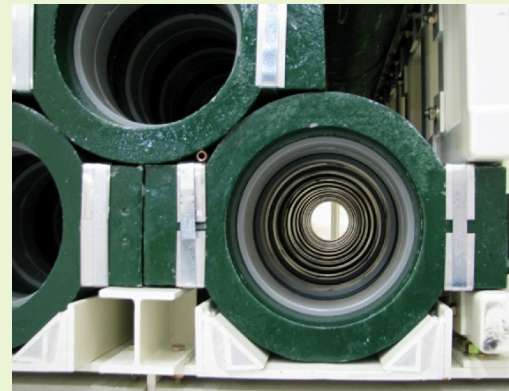
Scintillator



Argon

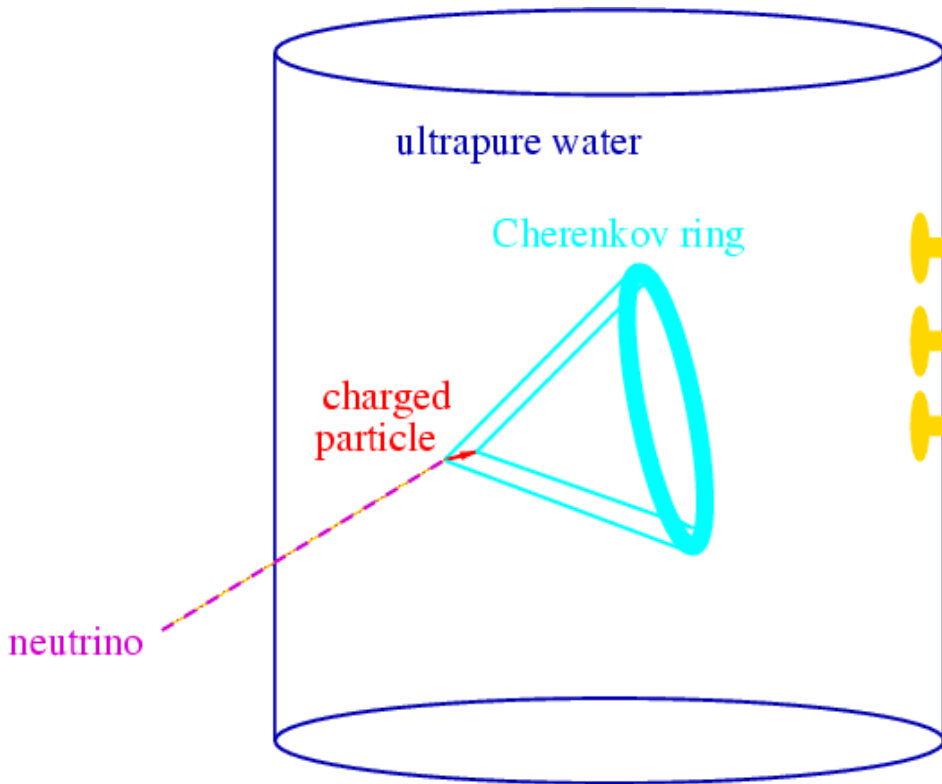


Lead

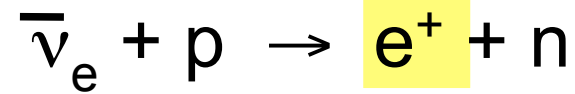


+ some others (e.g. DM detectors)

Water Cherenkov detectors

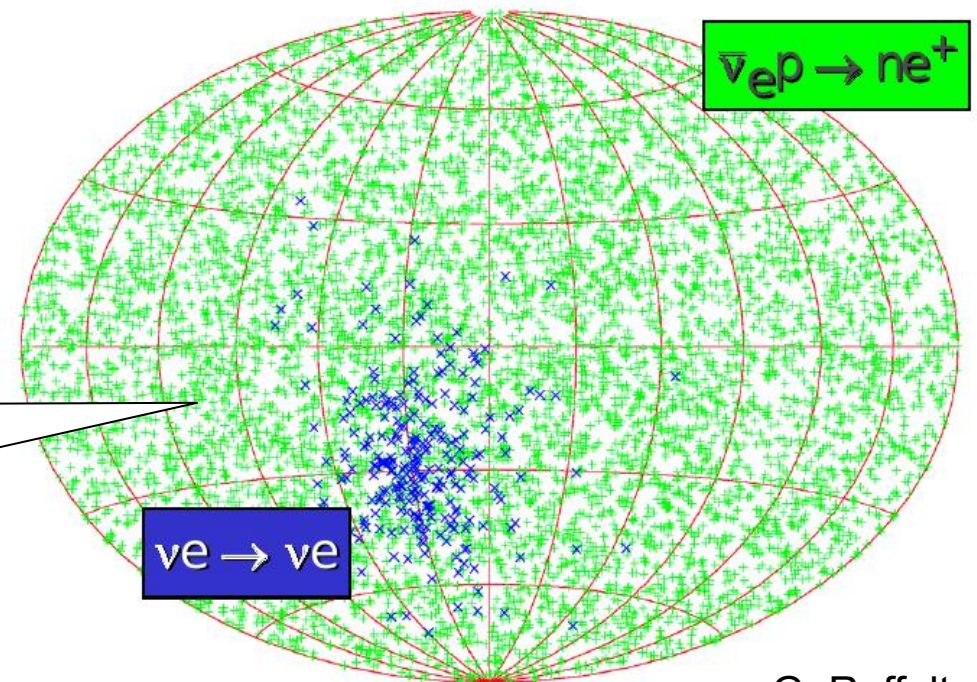


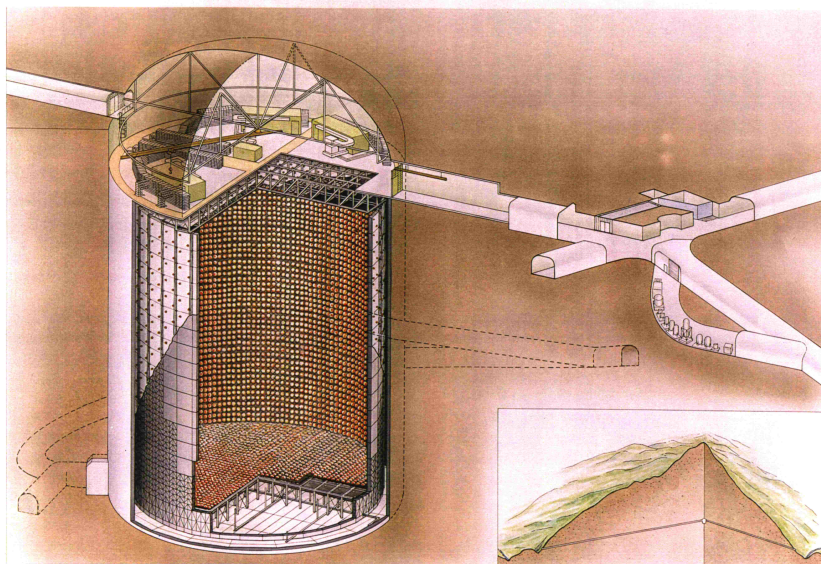
Inverse Beta Decay (CC)
dominates



$$E_{\text{thr}} = 1.8 \text{ MeV}$$

Pointing from
neutrino-electron
elastic scattering





SUPERKAMIOKANDE INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO

NIKKEN SOKKI

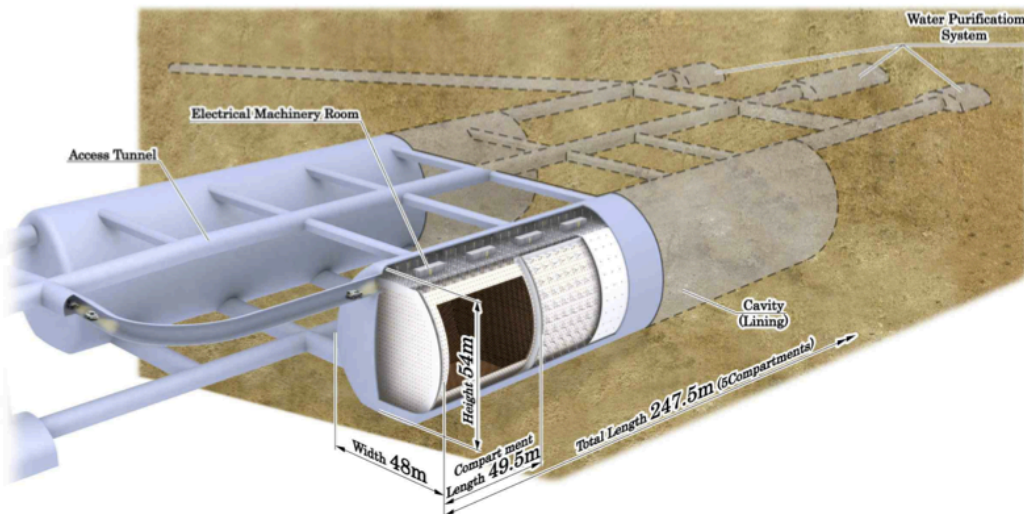
Super-Kamiokande

Mozumi, Japan

22.5 kton fid. volume (32 kton total)

~5-10K events @ 10 kpc
(mostly anti- ν_e)

New: "SN recorder" will lower threshold during burst for improved sensitivity



Hyper-Kamiokande

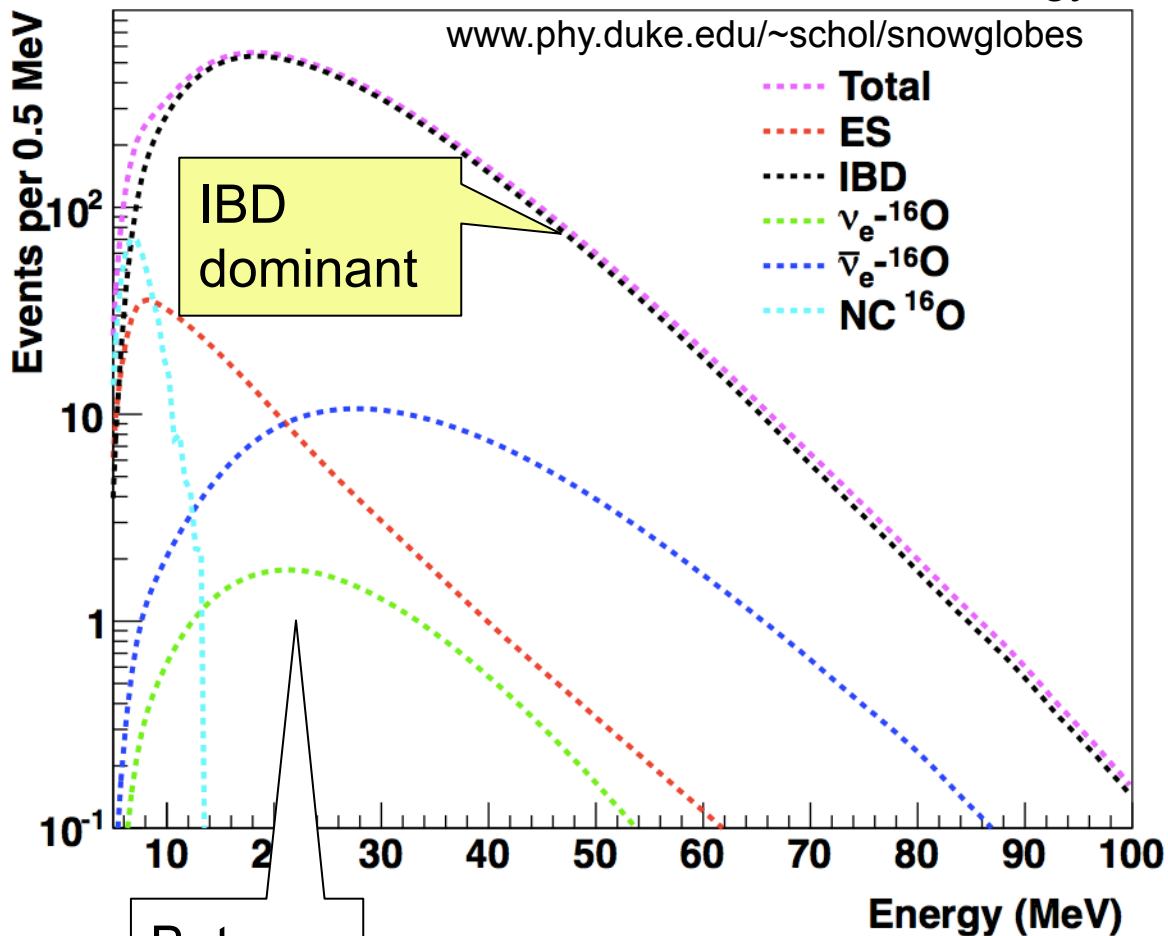
560 kton fiducial volume

Design & site-selection underway

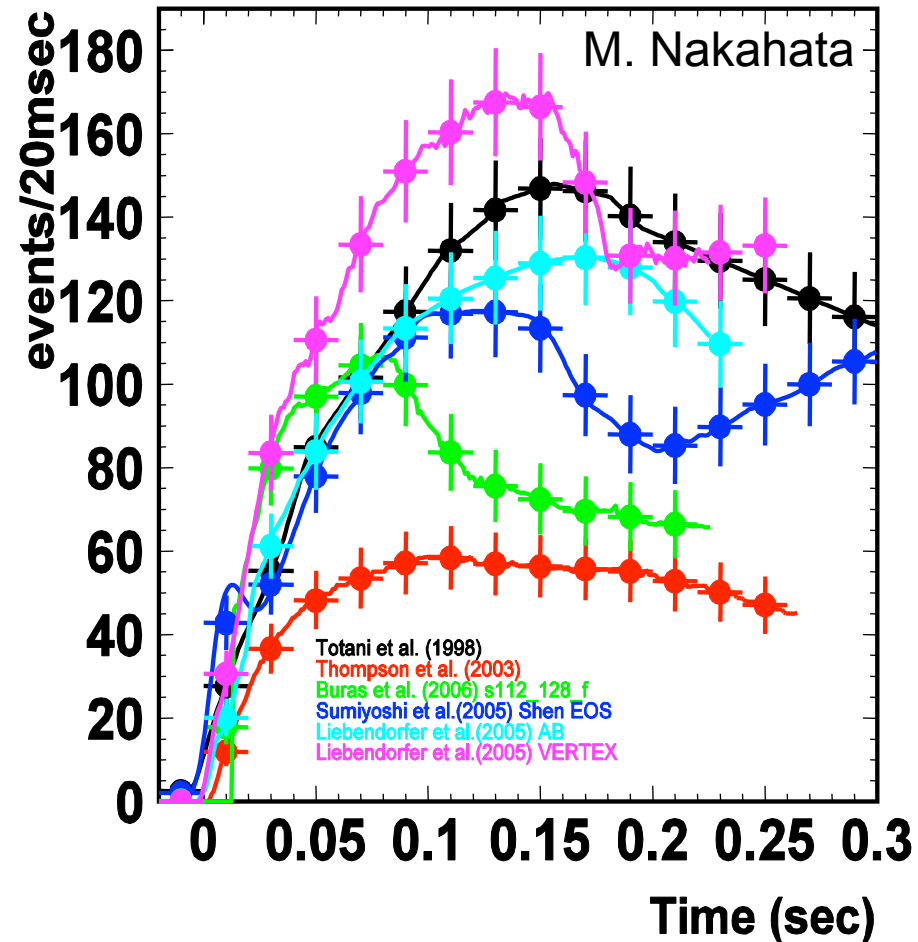
~half photocoverage, but still good efficiency for SN

Supernova signal in a water Cherenkov detector

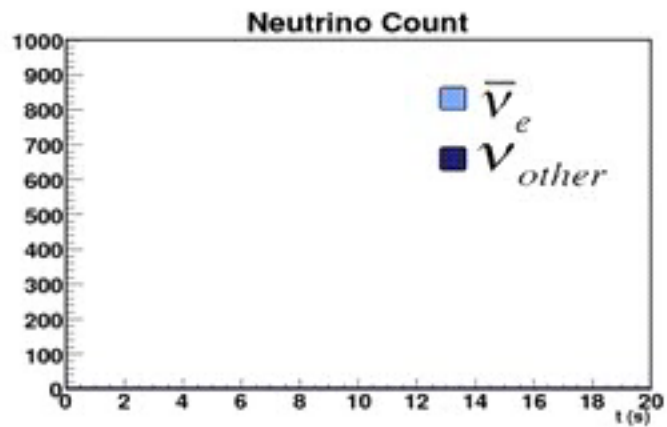
Events seen, as a function of observed energy



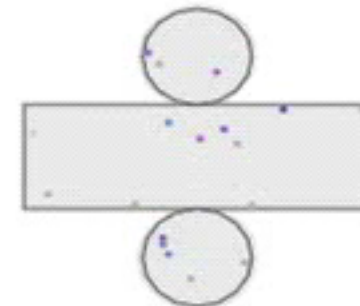
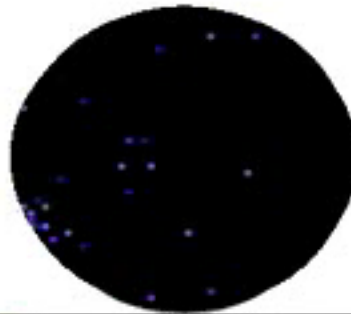
For 100 kton.
30% PMT coverage
@ 10 kpc



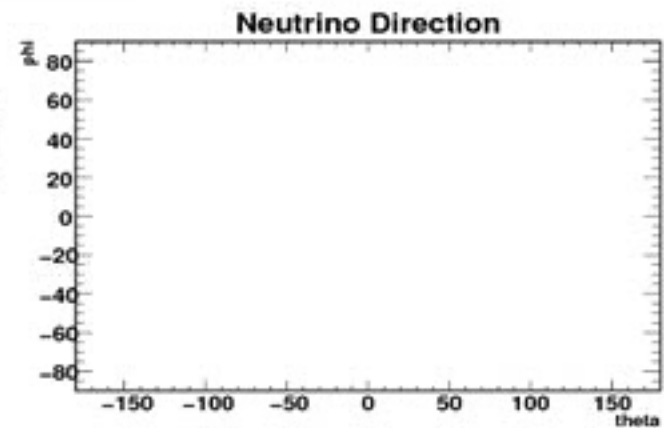
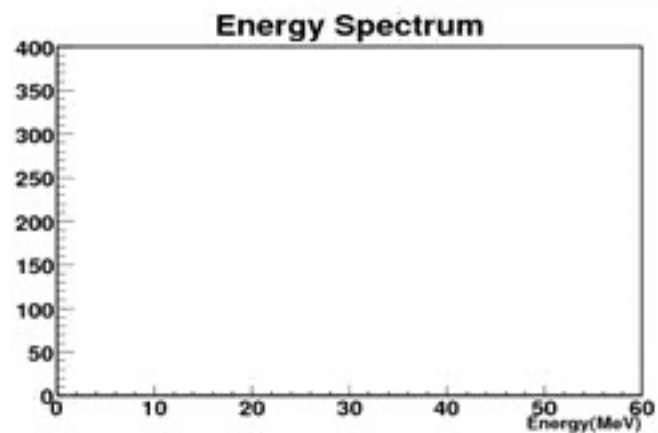
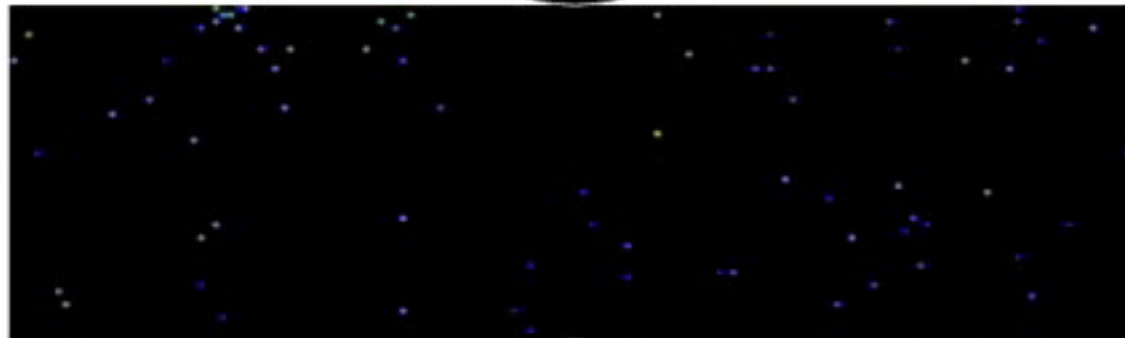
Events vs time
for SK, for
different models



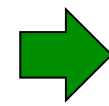
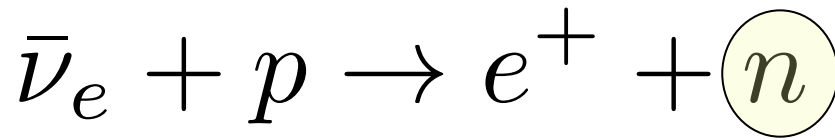
Inner Detector



Outer Detector



Neutron tagging in water Cherenkov detectors



detection of neutron tags
event as *electron antineutrino*

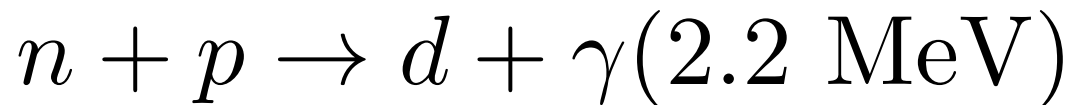
- especially useful for DSNB (which has low signal/bg)
- also useful for disentangling flavor content of a burst
(improves pointing, and physics extraction)

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

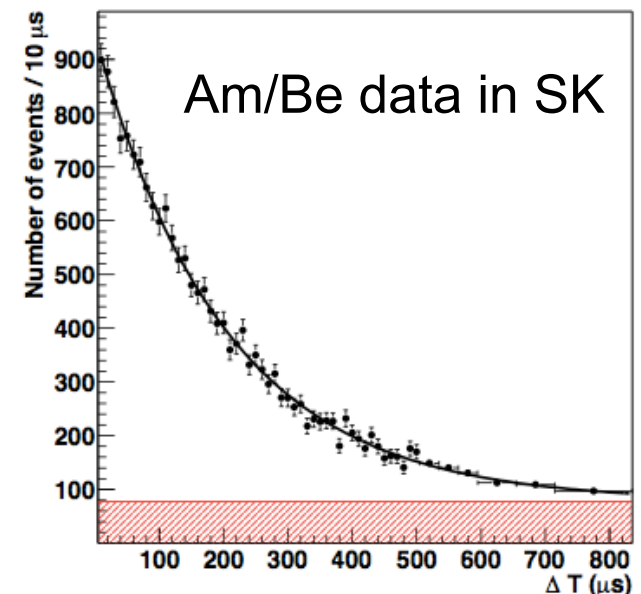
“Drug-free” neutron tagging



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

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

SK collaboration, arXiv:1311.3738;
see also R. Wendell talk



Enhanced performance by doping!

use gadolinium to capture neutrons

(like for scintillator)

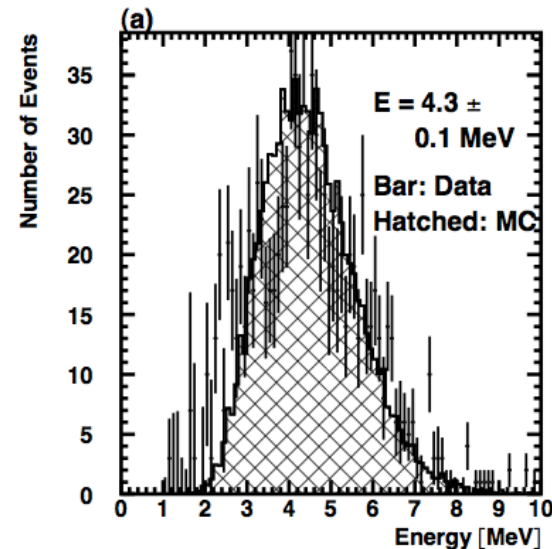
J. Beacom & M. Vagins, PRL 93 (2004) 171101

Gd has a huge n capture cross-section:
49,000 barns, vs 0.3 b for free protons

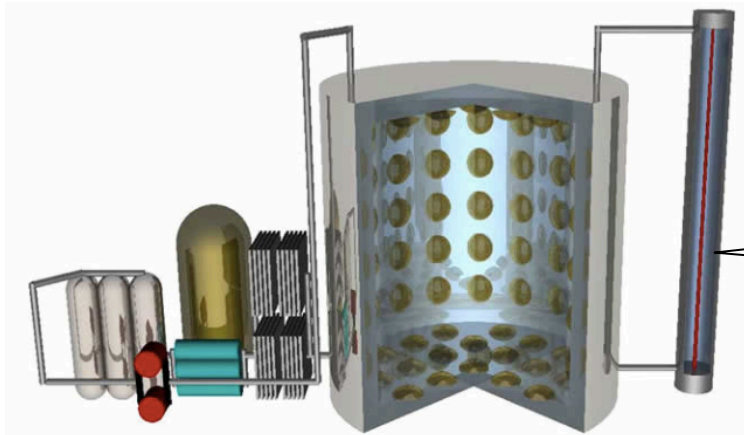


$$\sum E_{\gamma} = 8 \text{ MeV}$$

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

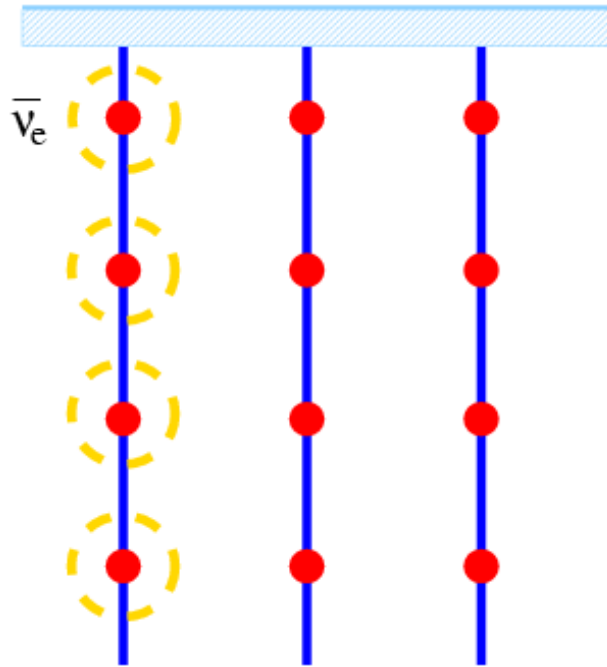


H. Watanabe et al.,
Astropart. Phys. 31,
320-328 (2009)



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

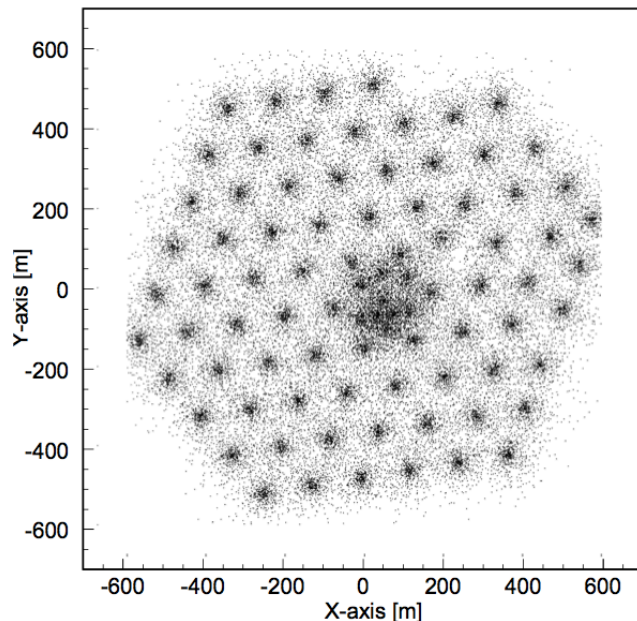
Long string water Cherenkov detectors



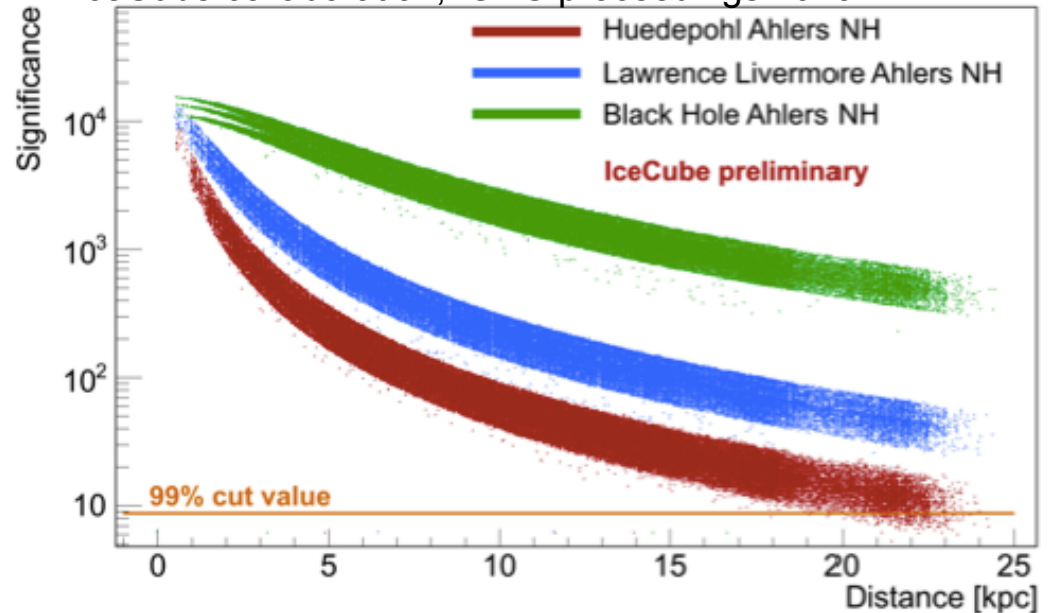
~kilometer long strings of PMTs
in very clear water or ice
(IceCube/PINGU, ANTARES)

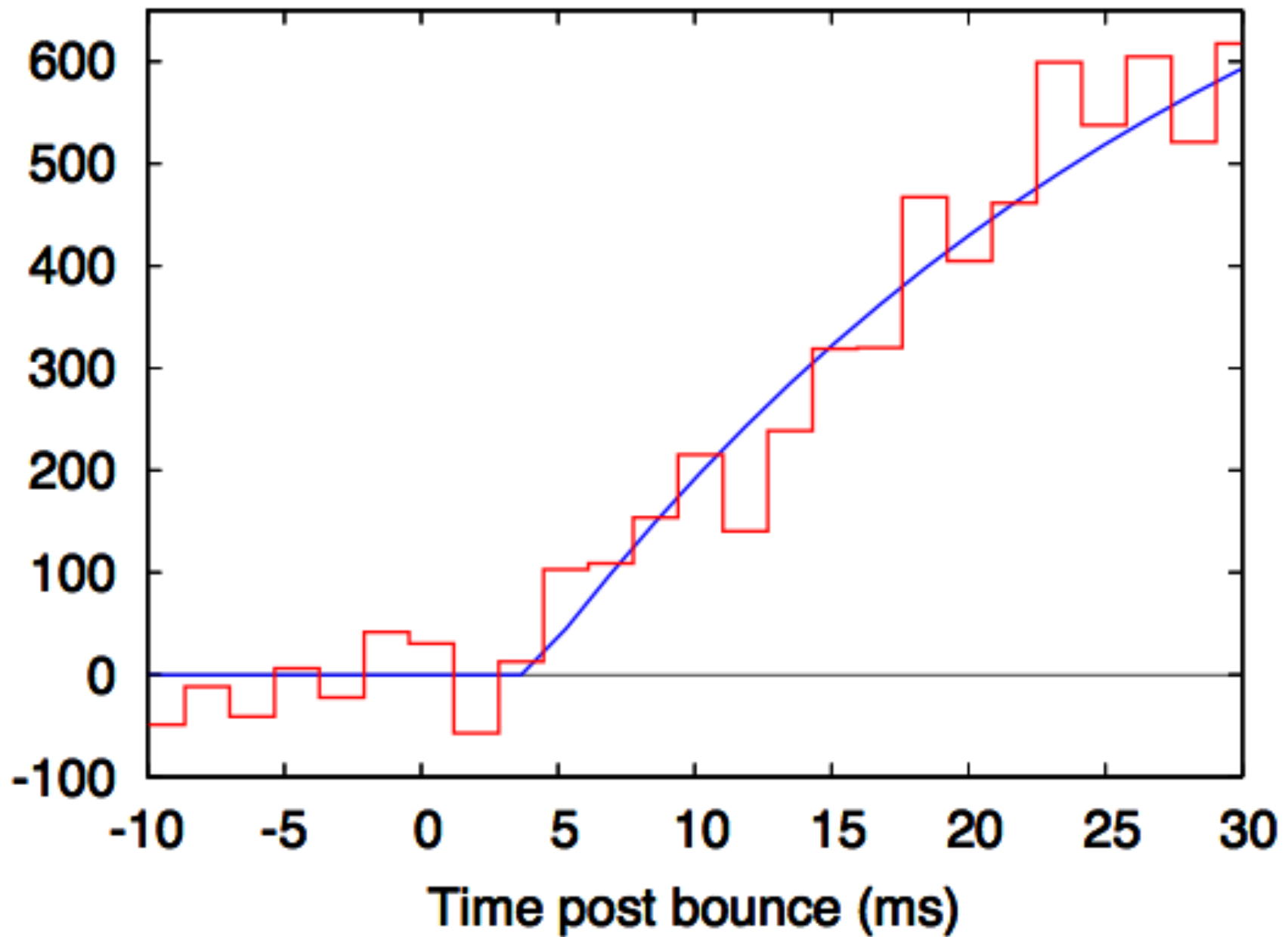
Nominally multi-GeV energy
threshold... but, may see burst
of low energy $\bar{\nu}_e$'s as *coincident
increase in single PMT count
rates* ($M_{\text{eff}} \sim 0.7$ kton/PMT)

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



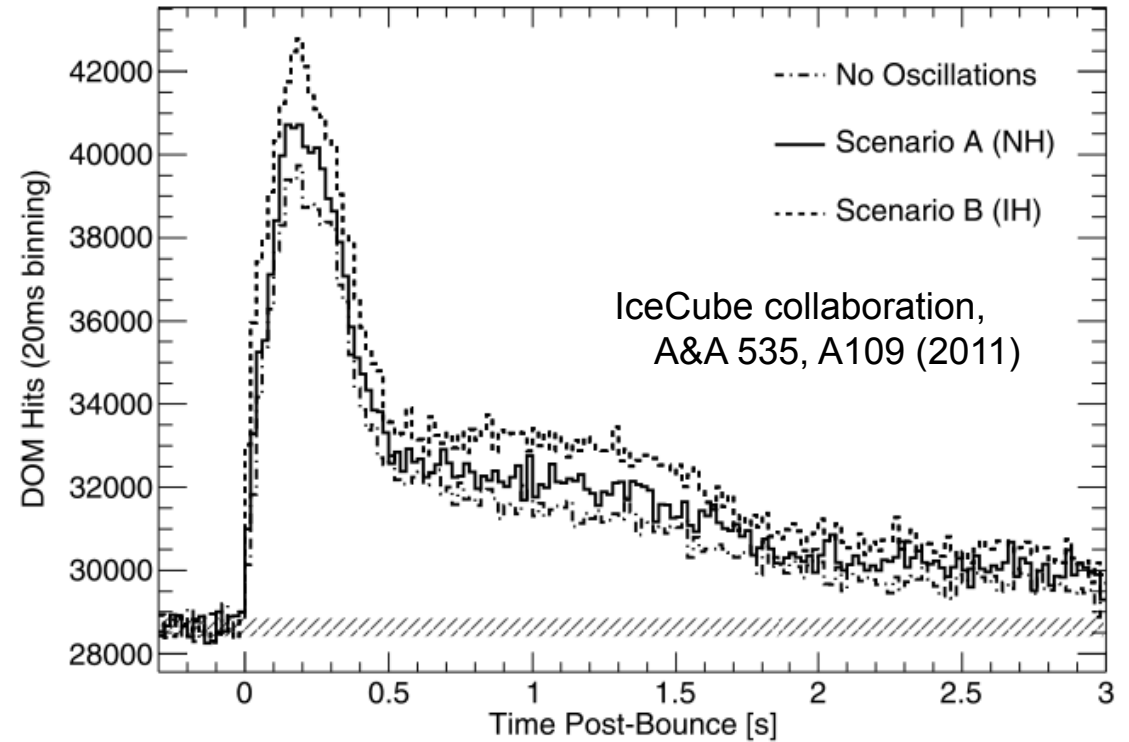
IceCube collaboration, ICRC proceedings 2013





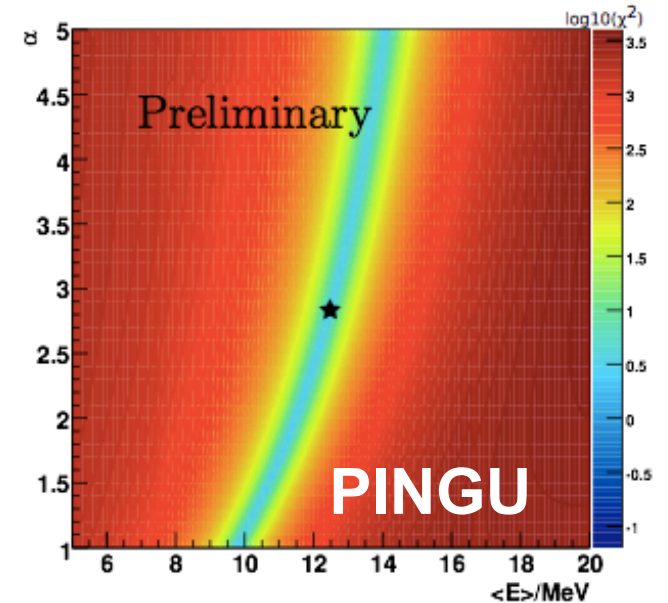
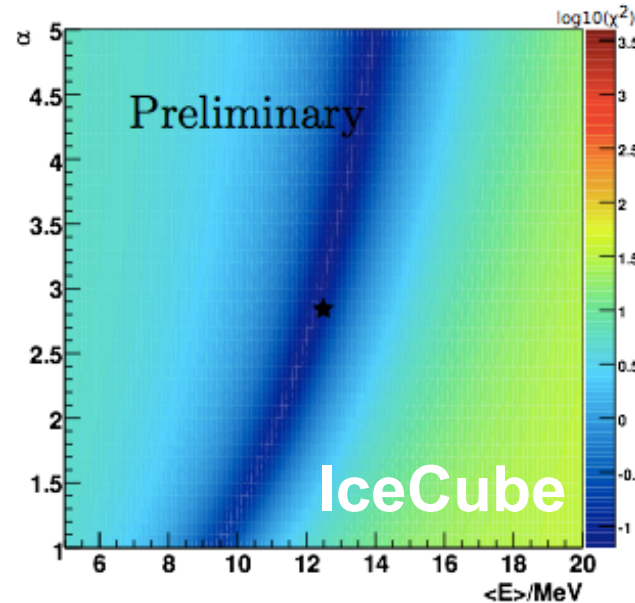
Few ~ms timing may be possible @ 10 kpc w/IceCube

Cannot tag flavor,
or other event-by-event
info, but map overall
burst time structure



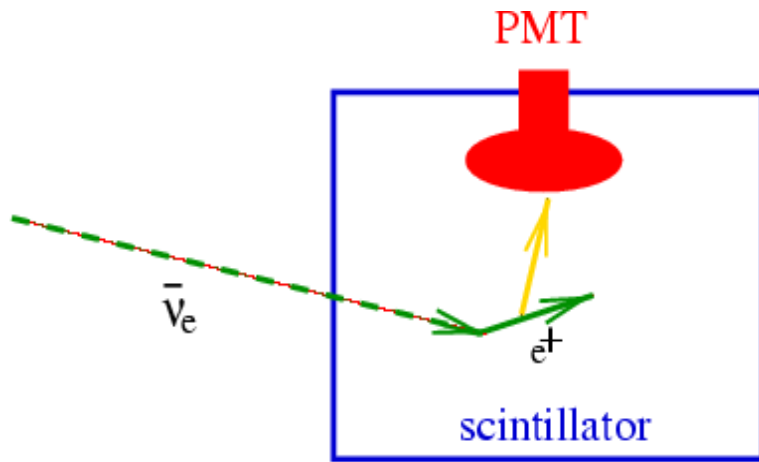
Also: T. Lund et al., PRD82 (2010) 063007

Some spectral
info using
multiple-
vs-single
hits, especially
w/ PINGU infill



PINGU LOI, arXiv:1401.2046

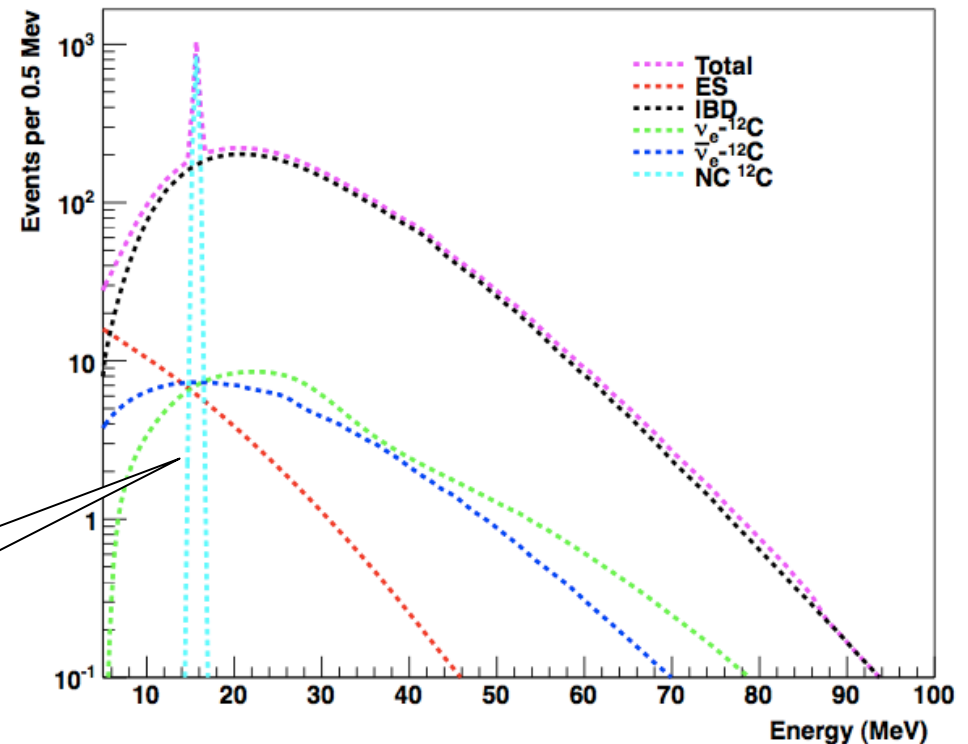
Scintillation detectors



Liquid scintillator $C_n H_{2n}$
volume surrounded by
photomultipliers

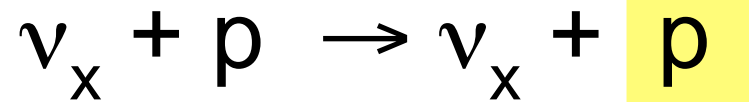
- few 100 events/kton (IBD)
- low threshold, good neutron tagging possible
- little pointing capability (light is $\sim$ isotropic)
- coherent elastic NC scattering on protons for ν spectral info

NC tag from 15 MeV
deexcitation γ
(no ν spectral info)

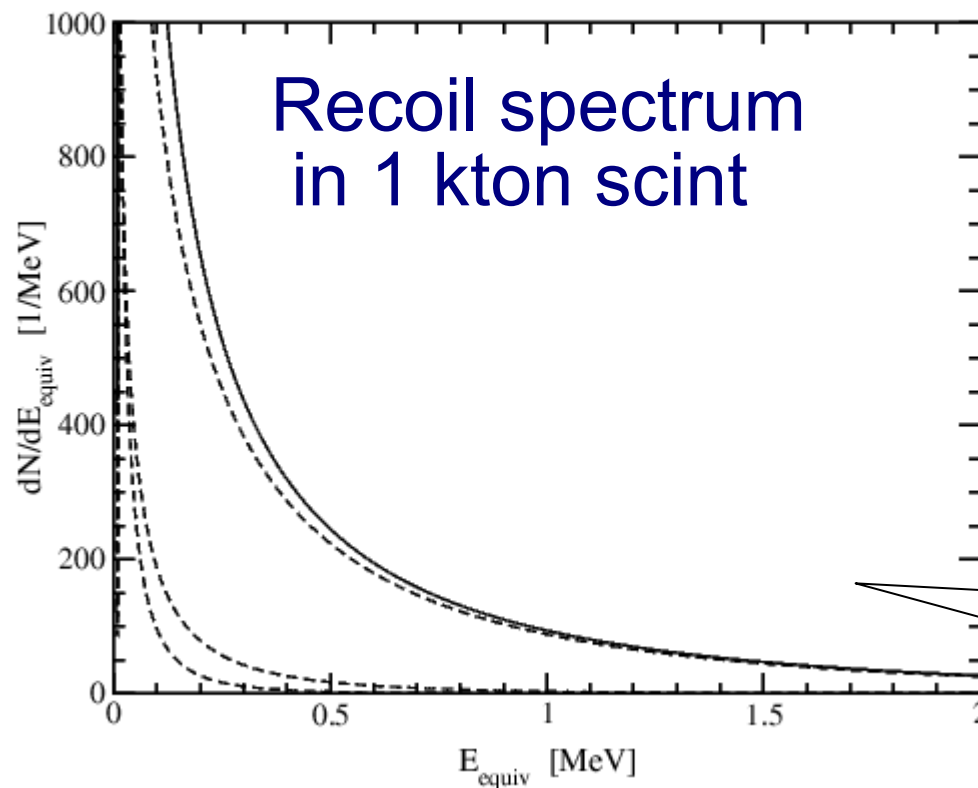


50 kt @ 10 kpc

NC neutrino-proton elastic scattering



Recoil energy small, but visible in scintillator
(accounting for 'quenching')

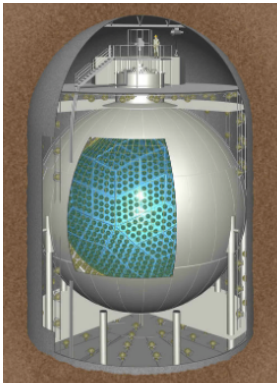


Expect ~few 100
events/kton
for 8.5 kpc SN

Neutrino spectral information
from recoil energies

Current and near-future scintillator detectors

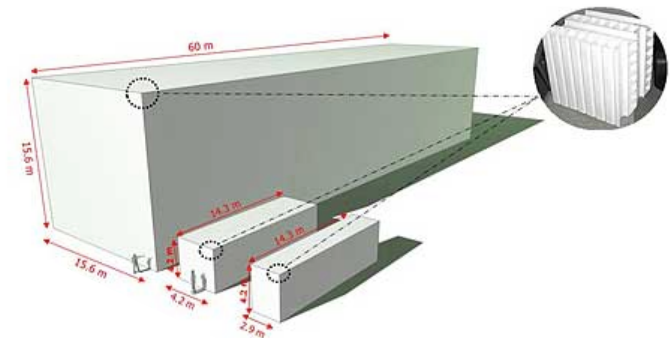
KamLAND
(Japan)
1 kton



LVD
(Italy)
1 kton

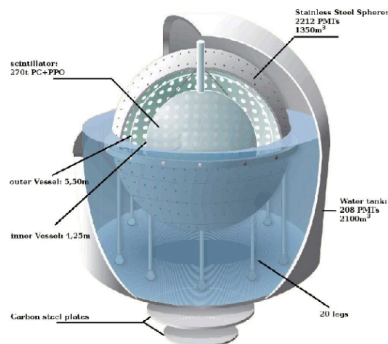


NOvA
(USA)
14 kton

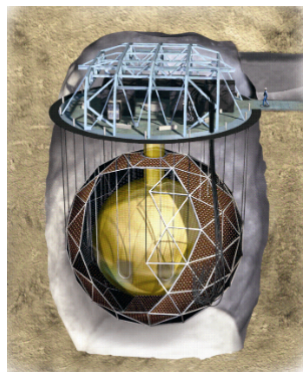


(on surface, but
may be possible
to extract counts
for known burst)

Borexino
(Italy)
0.33 kton



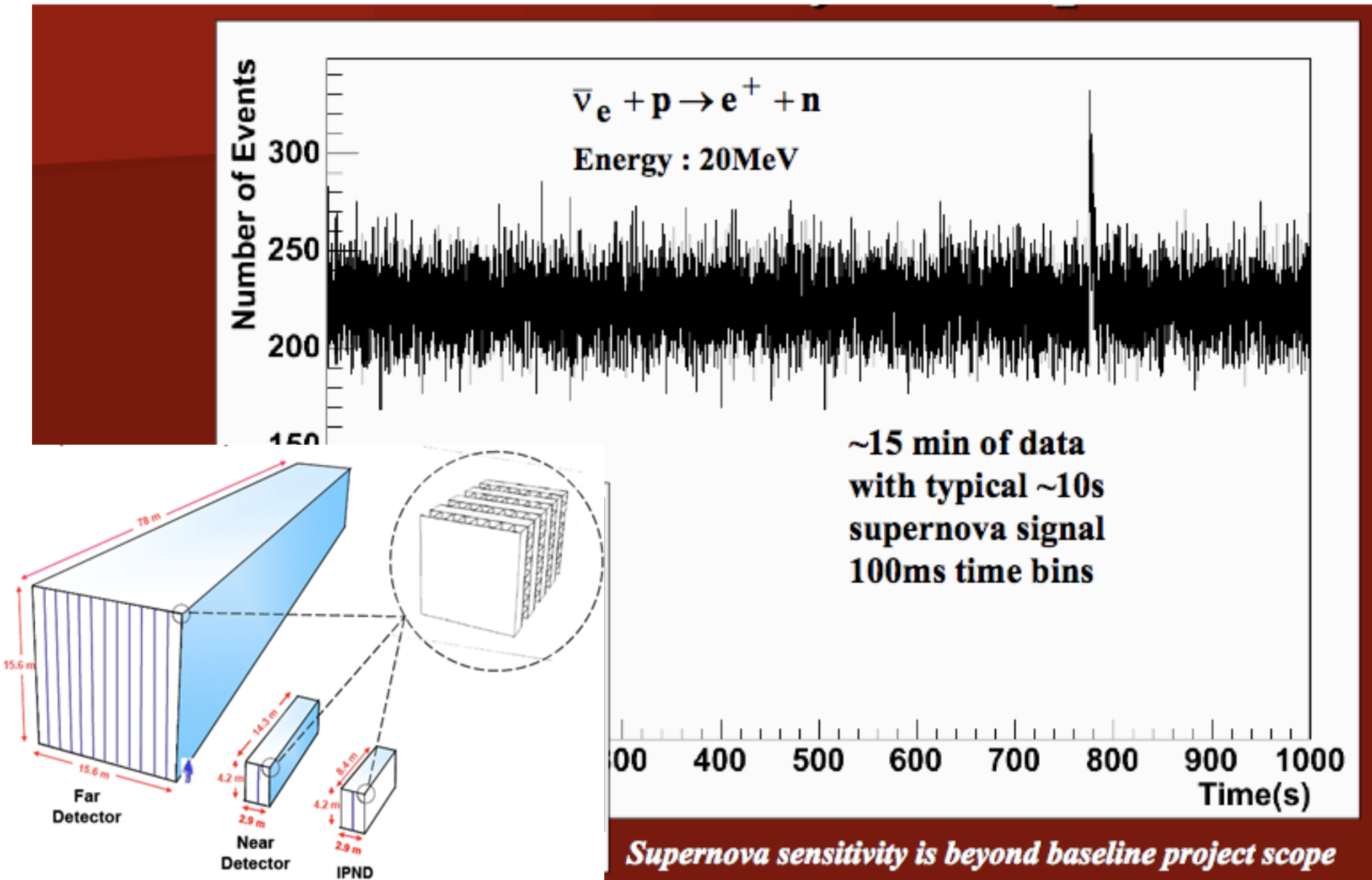
SNO+
(Canada)
1 kton



NOvA: long baseline oscillation experiment (Ash River, MN)

15 kton scintillator, near surface

K. Arms, CIPANP '09



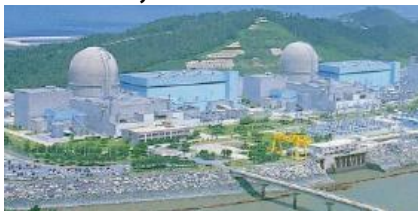
Also on the surface: reactor experiments w/ Gd-doped (and undoped) scintillator

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

RENO, South Korea



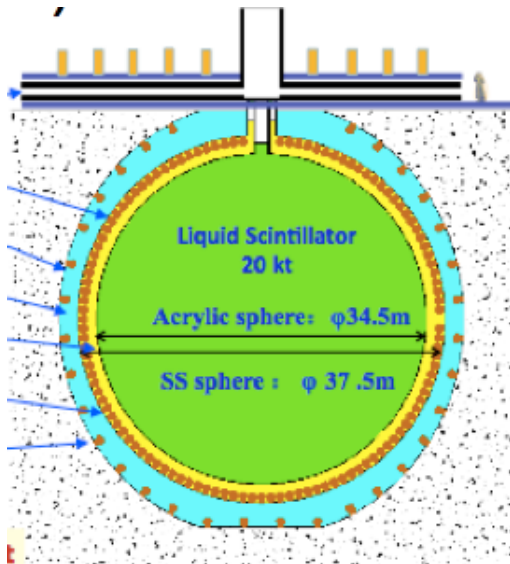
Double CHOOZ, France



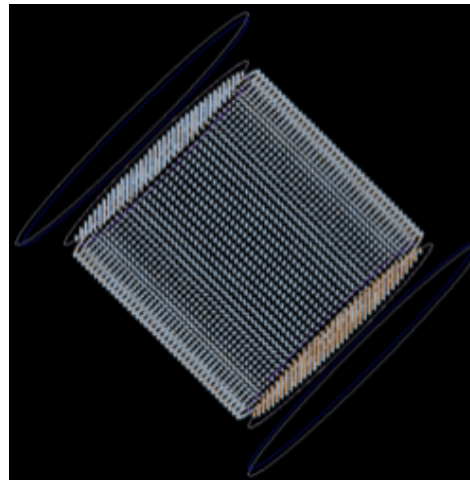
Daya Bay, China



Future detector proposals



JUNO
(China)
20 kton

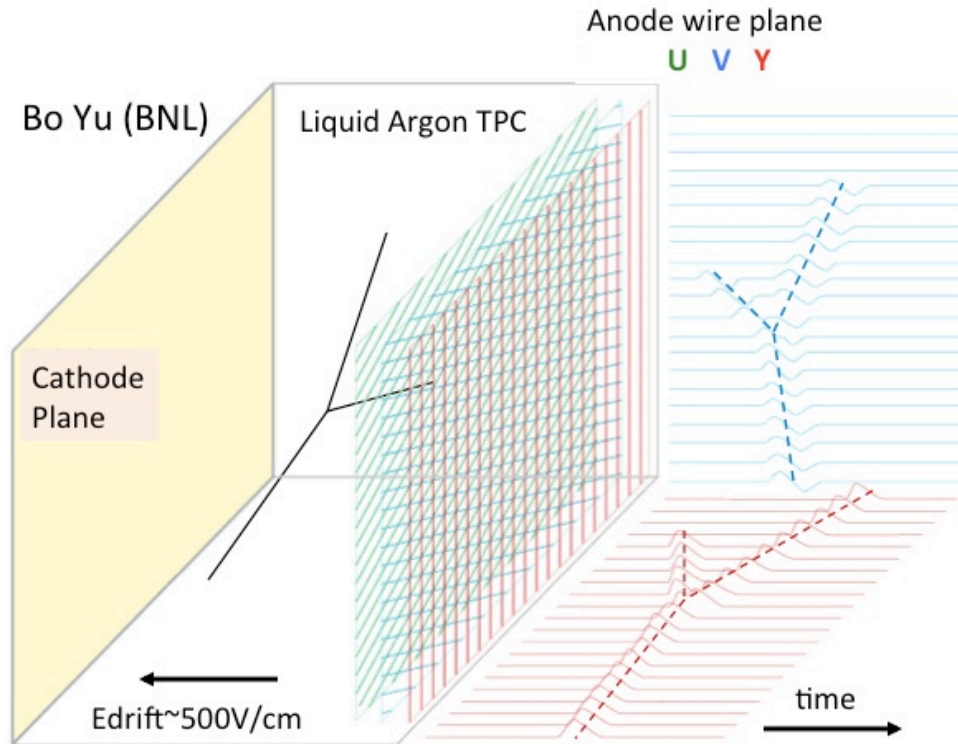


RENO-50
(S. Korea)
18 kton



LENA
(Finland)
50 kton

Liquid argon time projection chambers



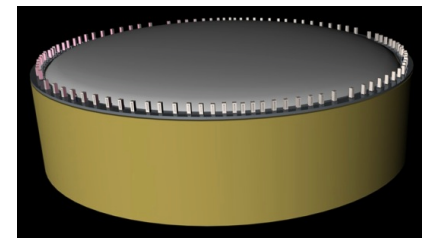
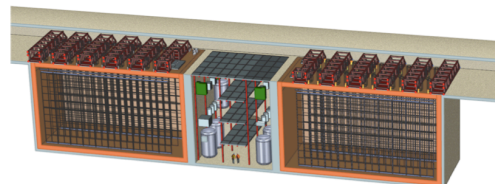
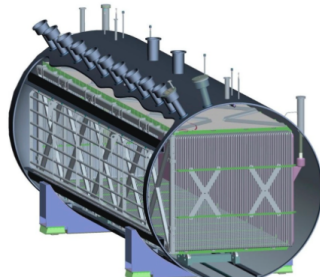
- fine-grained trackers
- no Cherenkov threshold
- high ν_e cross section

ICARUS
(Italy...)
0.6 kton

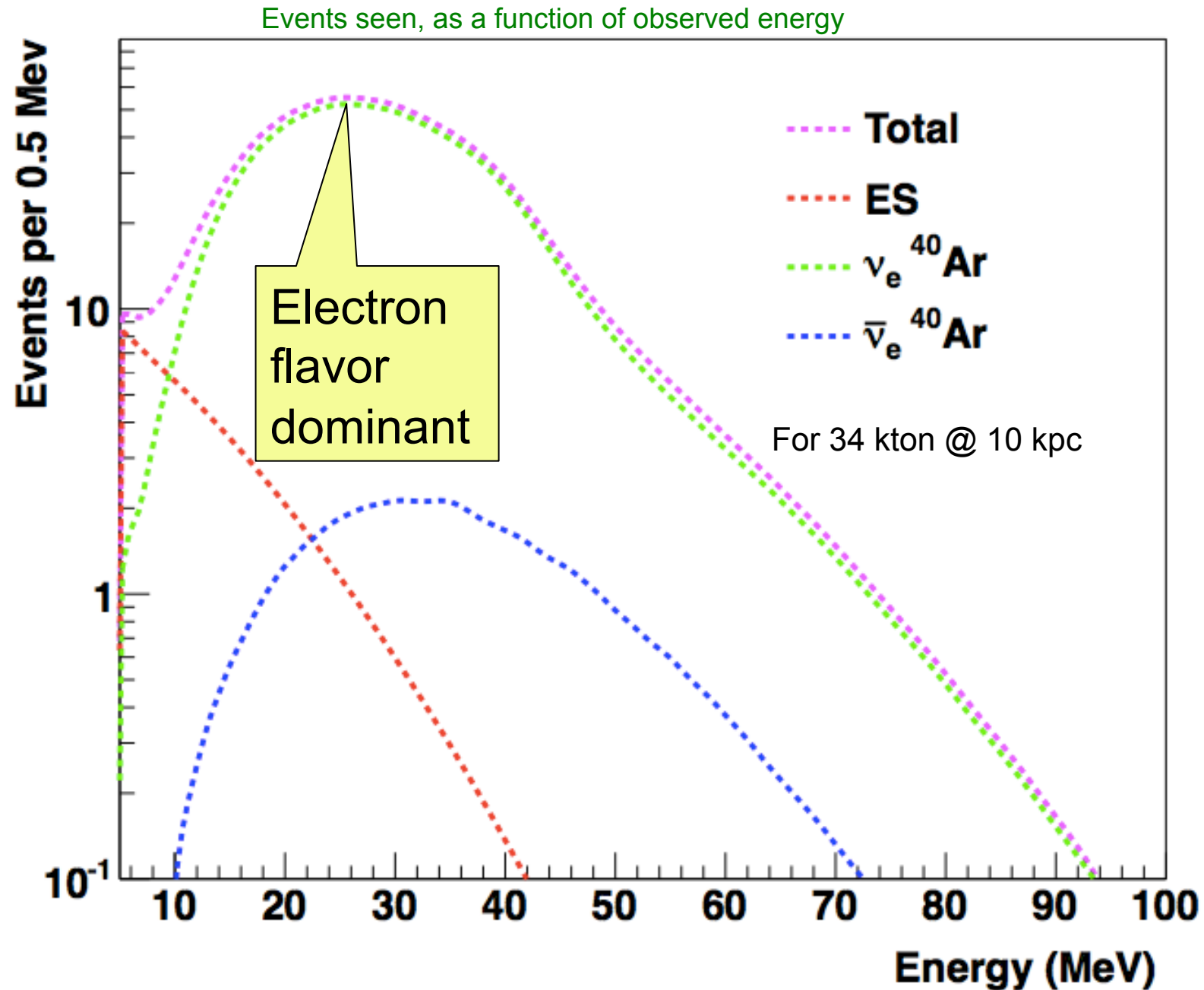
MicroBooNE
(USA)
0.2 kton

LBNE
(USA)
34 kton

GLACIER
(Europe)
100 kton

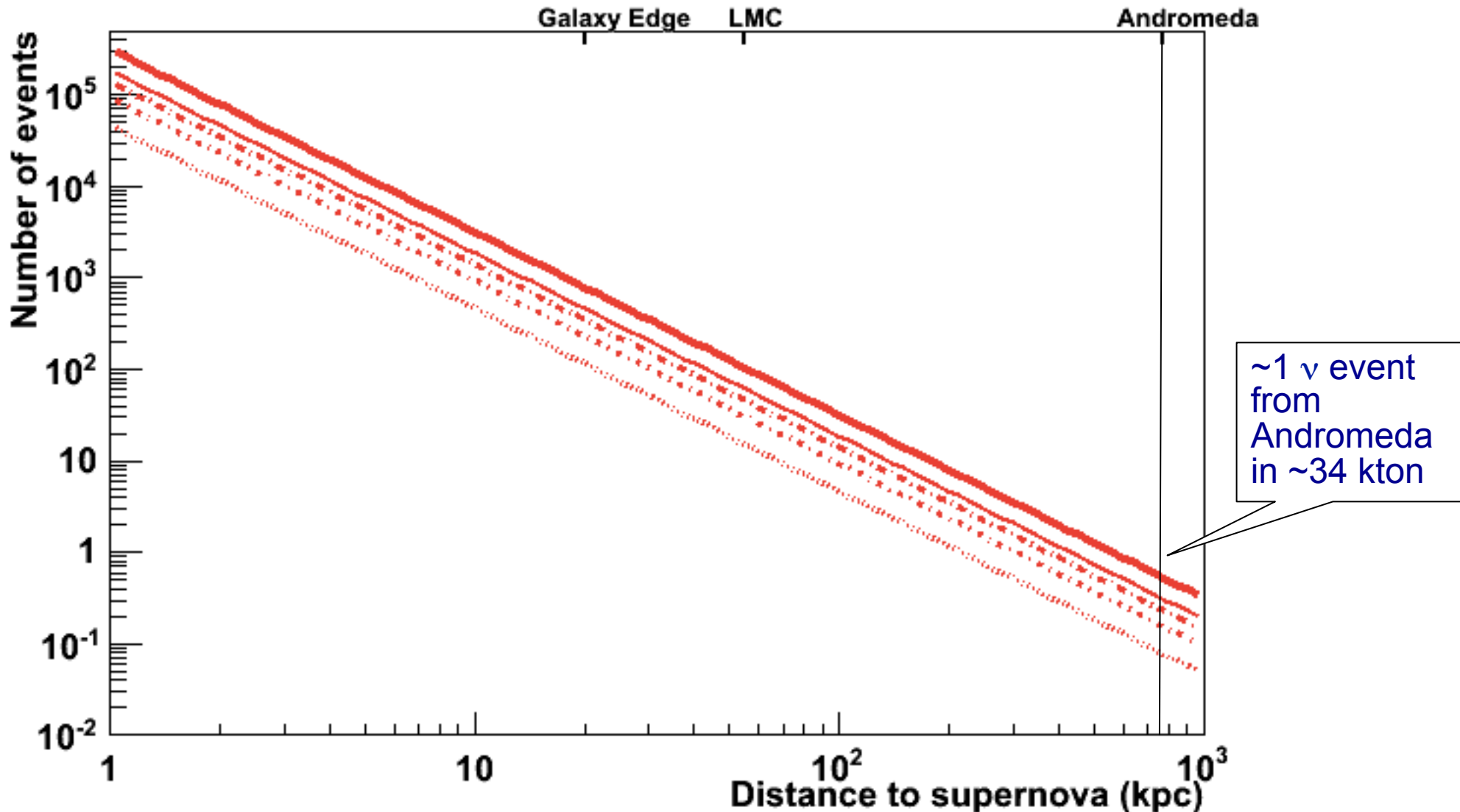


Supernova signal in a liquid argon detector



Signal rates vs distance for LBNE configurations

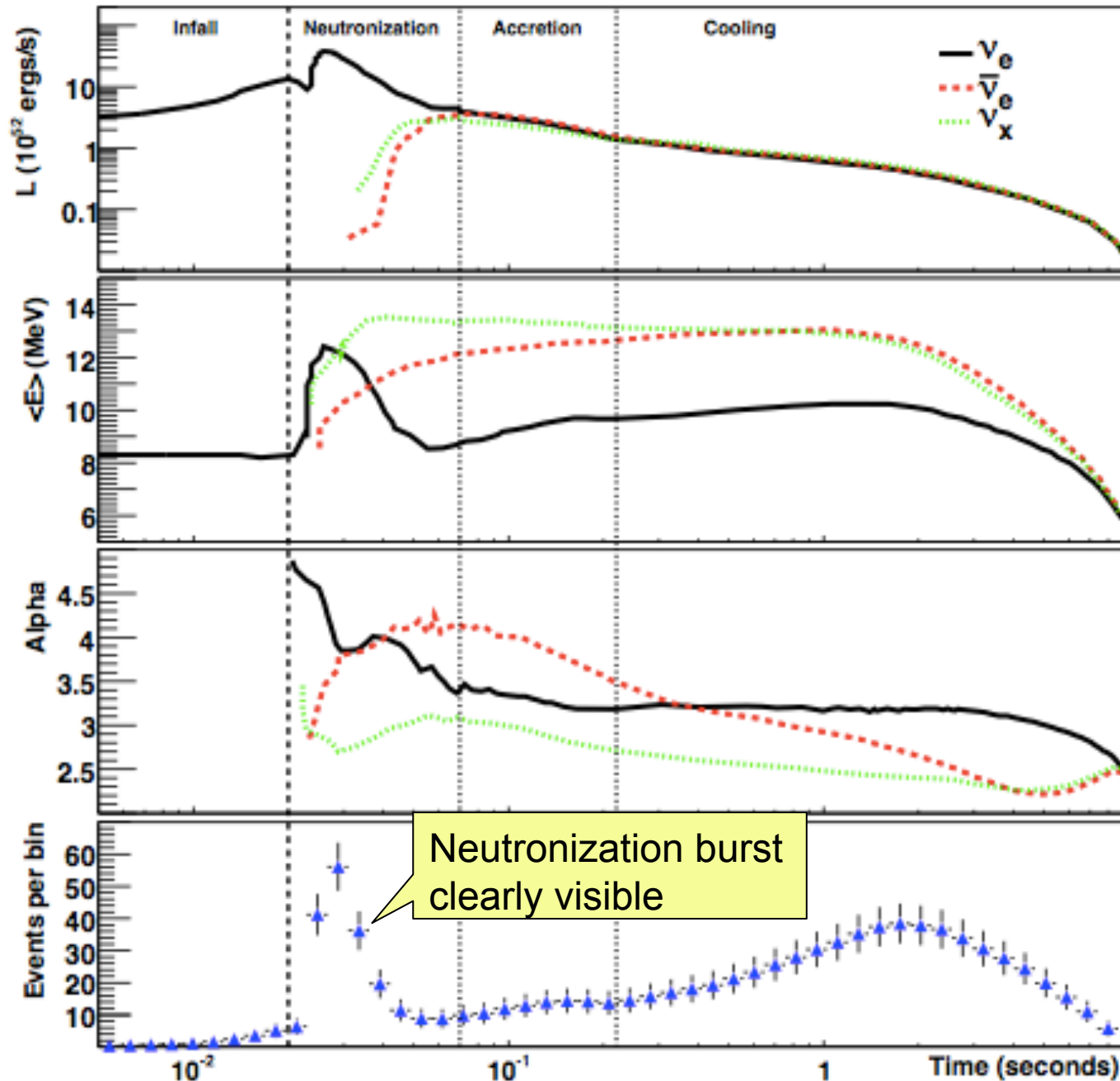
Supernova neutrinos in argon



5, 10, 15, 20, 34 kton

Example of supernova burst signal in 34 kton of LAr

arXiv:1307.7335



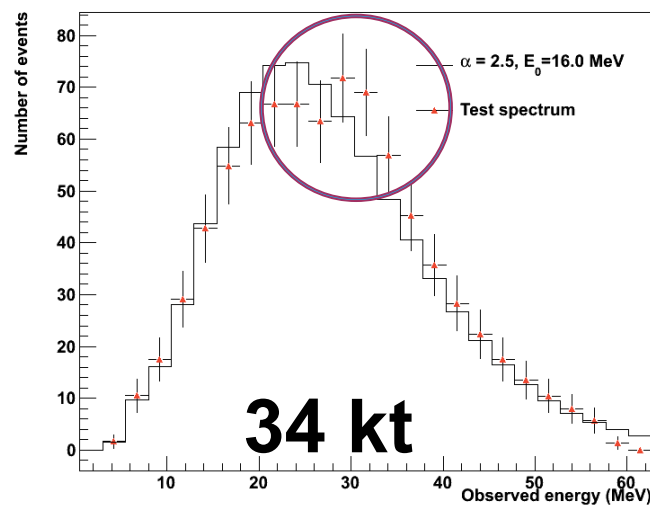
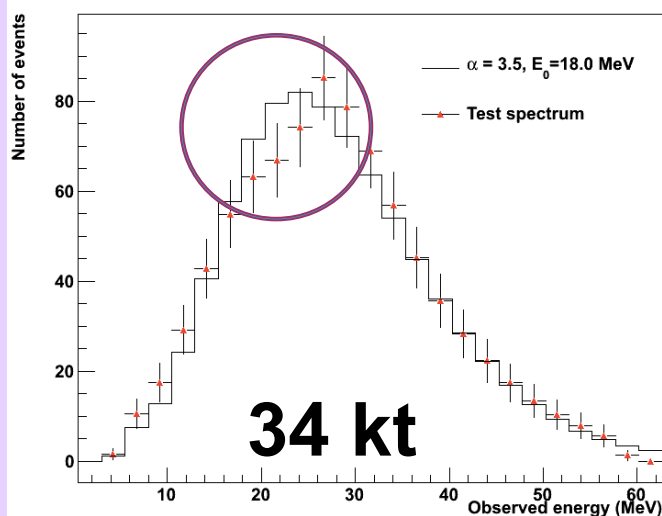
Flux from Huedepohl et. al, PRL 104 (2010) 251101 @ 10 kpc

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

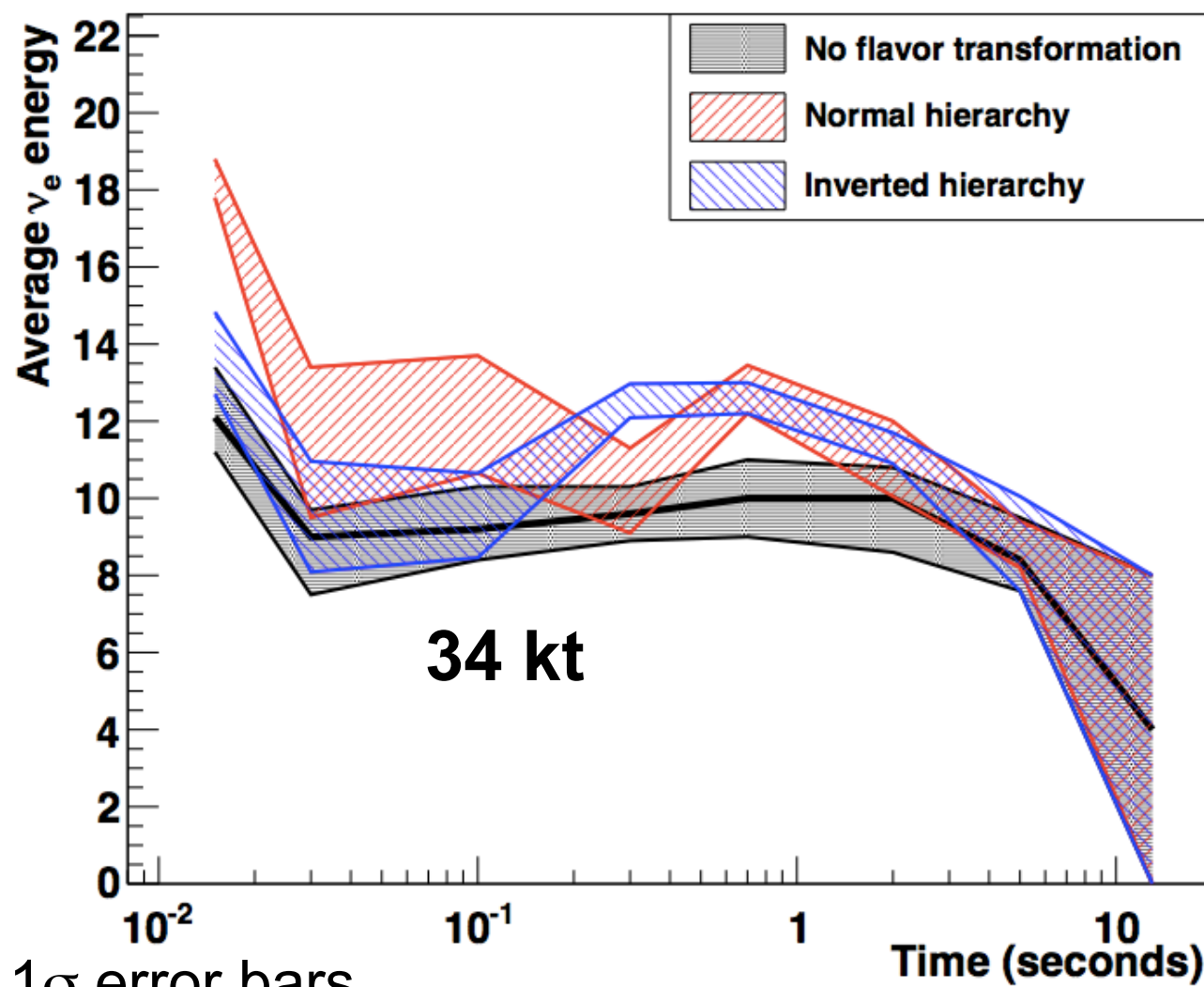


For NMH (*not* for IMH),
“non-thermal” features
clearly visible,
and change as shock
moves through the SN

Measuring SN ν_e temperature vs time w/Lar

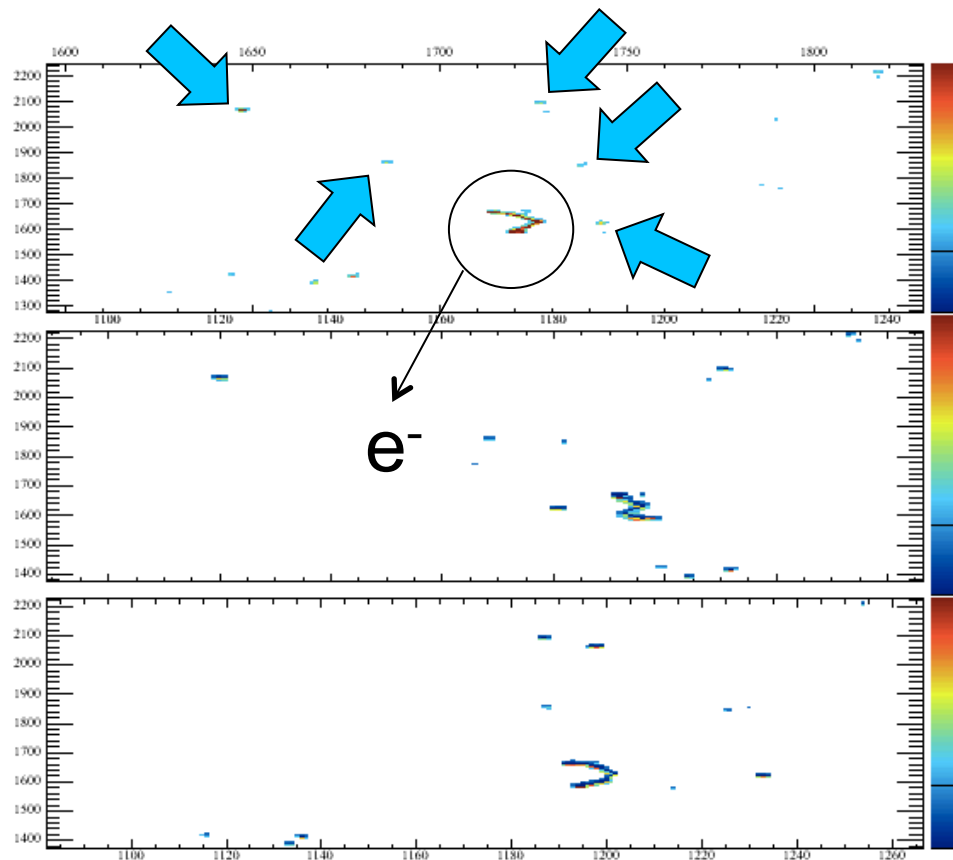
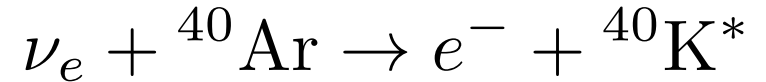
10 kpc spectra from A. Friedland/JJ Cherry/H. Duan smeared w/ SNOwGLoBES response,
fit to pinched thermal spectrum

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

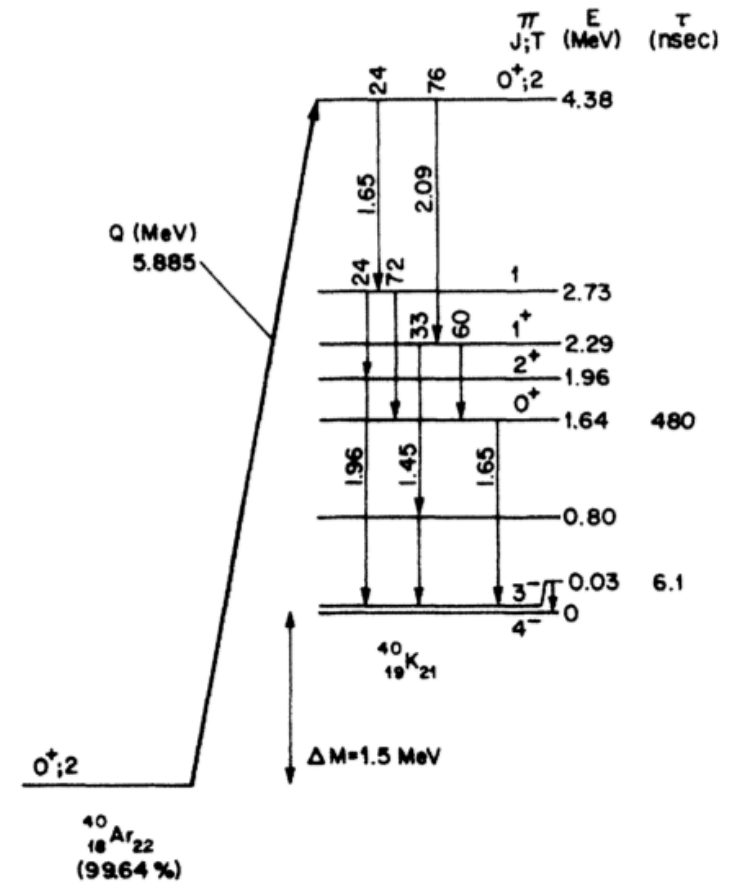


Preliminary: work in progress

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



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

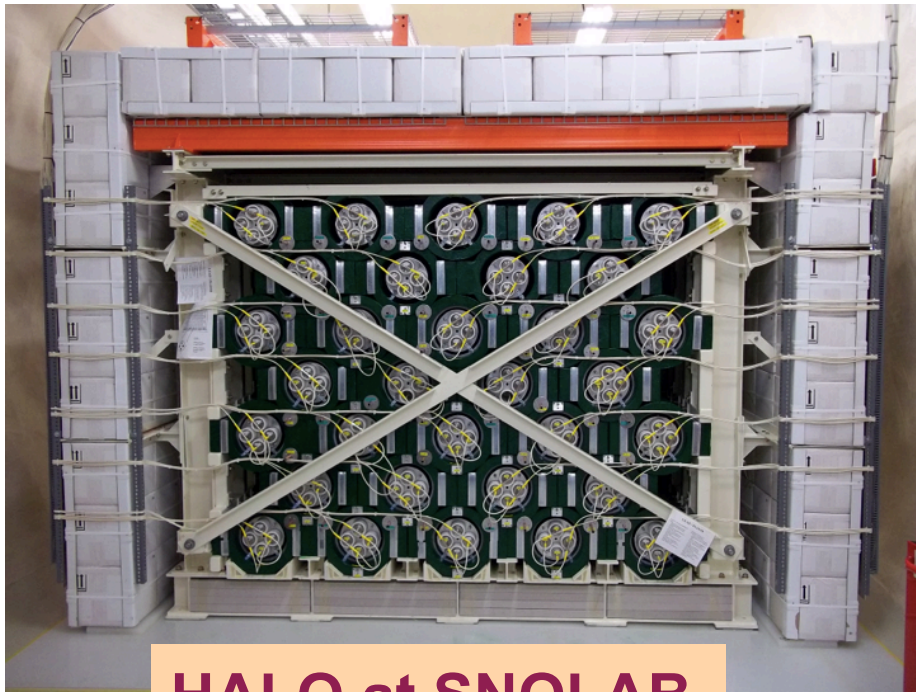


↓
1n, 2n emission

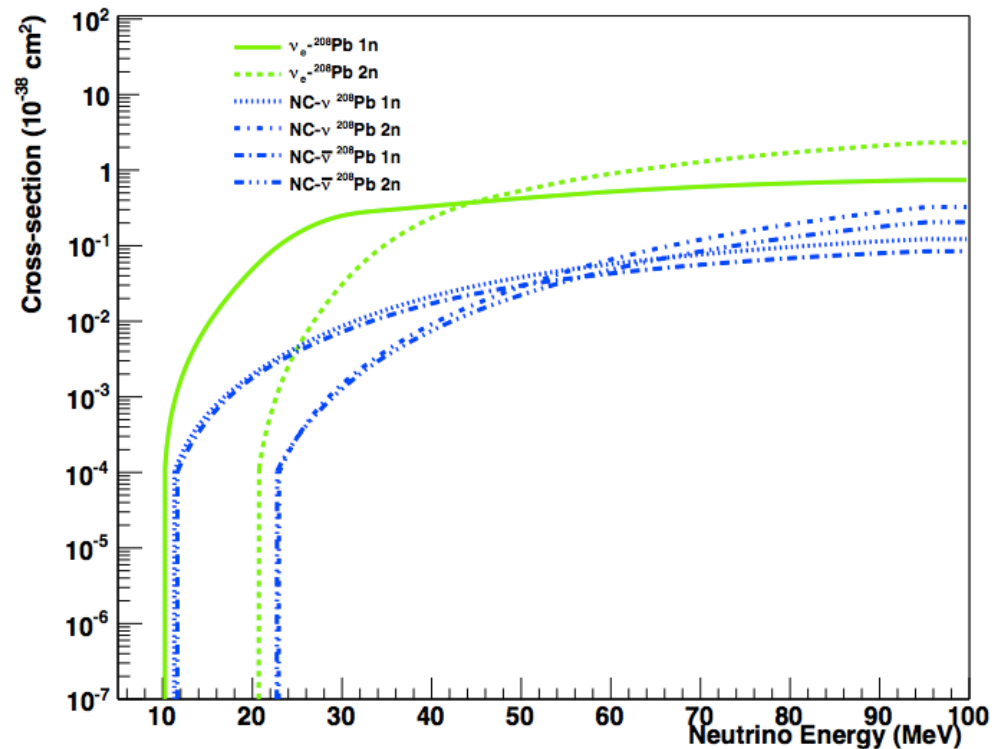


↓
1n, 2n, γ emission

Relative 1n/2n rates
sharply dependent
on neutrino energy
 $\Rightarrow$ spectral
sensitivity



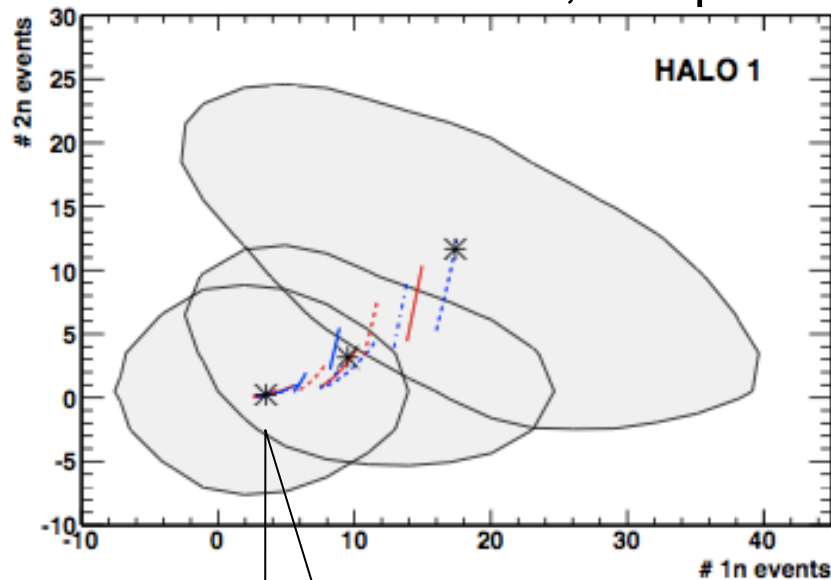
HALO at SNOLAB



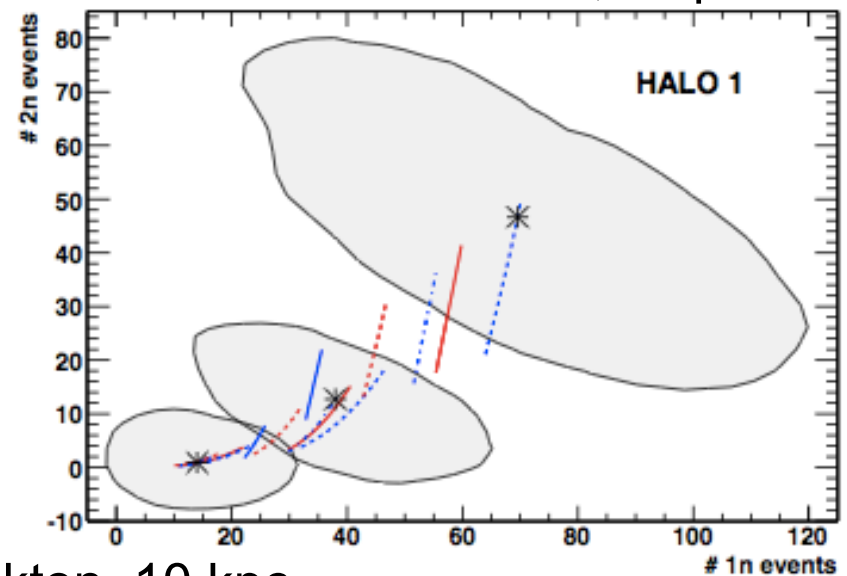
SNO ${}^3\text{He}$ counters + 79 tons of Pb: ~1-40 events @ 10 kpc

HALO sensitivity

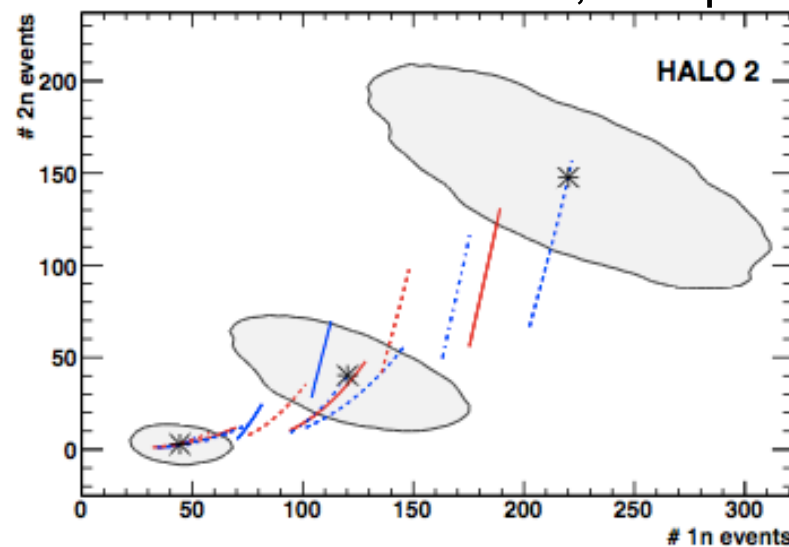
79 tons, 10 kpc



79 tons, 5 kpc



1kton, 10 kpc



Note that
measuring
few events
will give
significant
information

- Curves represent predictions for a range of models with different fluxes and oscillation parameters, from Vaananen & Volpe arXiv:1105.6225
- Shaded regions enclose 90% of HALO inferred values, for simulated neutron detection efficiencies (~40% efficiency)

Coherent Elastic Neutrino Nucleus Scattering

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

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

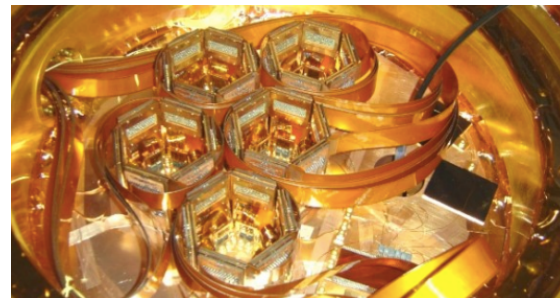
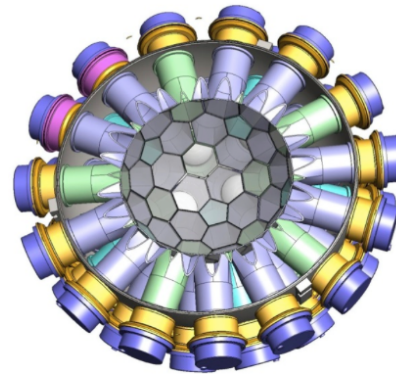
High x-scn but *very* low recoil energy (10's of keV)

⇒ observable in DM detectors

~ few events per ton
for Galactic SN

ν_x energy information
from recoil spectrum

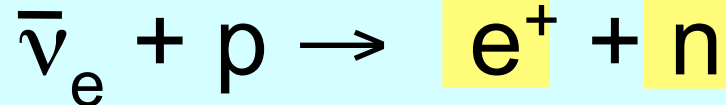
e.g. Ar, Ne, Xe, Ge, ...



DM detectors,
e.g. CLEAN/DEAP, LUX, ...

Summary of SN neutrino detection channels

Inverse beta decay:



- dominates for detectors with lots of free p (water, scint)
- $\bar{\nu}_e$ sensitivity; good E resolution; well known x-scns; some tagging, poor pointing

CC interactions with nuclei:

- lower rates, but still useful, ν_e tagging useful (e.g. LAr)
- cross-sections not always well known

Elastic scattering: few % of $\text{inv}\beta\text{dk}$, but point!

NC interactions with nuclei:

- very important for physics, probes μ and τ flux
- some rate in existing detectors, new observatories
- some tagging; poor E resolution; x-scns not well known
- coherent ν -p, ν -A scattering in low thresh detectors

Table 1 Summary of relevant interactions for current and near-future detectors

KS, arXiv:1205.6003

Channel	Observable(s) ^a	Interactions ^b
$\nu_x + e^- \rightarrow \nu_x + e^-$	C	17/10
$\bar{\nu}_e + p \rightarrow e^+ + n$	C, N, A	278/165
$\nu_x + p \rightarrow \nu_x + p$	C	682/351
$\nu_e + {}^{12}\text{C} \rightarrow e^- + {}^{12}\text{N}^*$	C, N, G	3/9
$\bar{\nu}_e + {}^{12}\text{C} \rightarrow e^+ + {}^{12}\text{B}^*$	C, N, G, A	6/8
$\nu_x + {}^{12}\text{C} \rightarrow \nu_x + {}^{12}\text{C}^*$	G, N	68/25
$\nu_e + {}^{16}\text{O} \rightarrow e^- + {}^{16}\text{F}^*$	C, N, G	1/4
$\bar{\nu}_e + {}^{16}\text{O} \rightarrow e^+ + {}^{16}\text{N}^*$	C, N, G	7/5
$\nu_x + {}^{16}\text{O} \rightarrow \nu_x + {}^{16}\text{O}^*$	G, N	50/12
$\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$	C, G	67/83
$\bar{\nu}_e + {}^{40}\text{Ar} \rightarrow e^+ + {}^{40}\text{Cl}^*$	C, A, G	5/4
$\nu_e + {}^{208}\text{Pb} \rightarrow e^- + {}^{208}\text{Bi}^*$	N	144/228
$\nu_x + {}^{208}\text{Pb} \rightarrow \nu_x + {}^{208}\text{Pb}^*$	N	150/55
$\nu_x + A \rightarrow \nu_x + A$	C	9,408/4,974

(Livermore/GKVM)

C: energy loss of a charged particle

N: neutrons

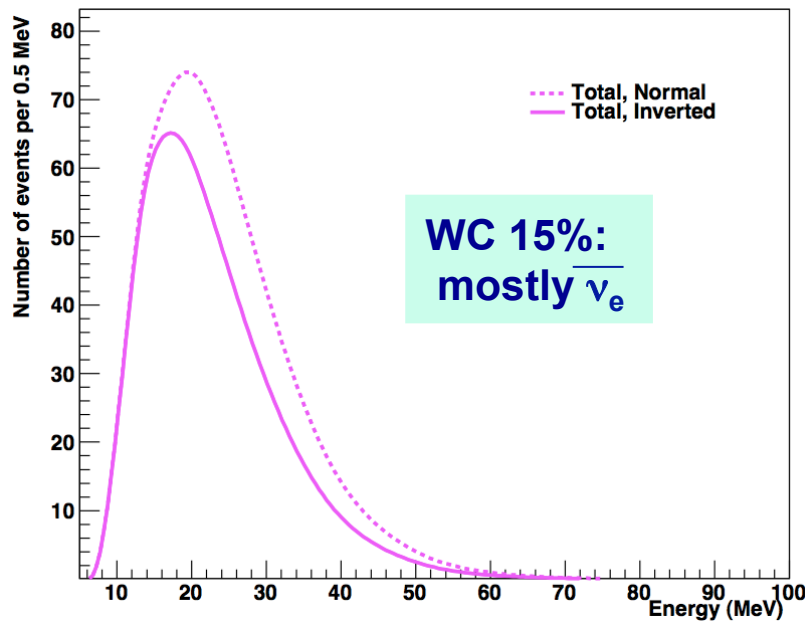
A: annihilation gammas

G: de-excitation gammas

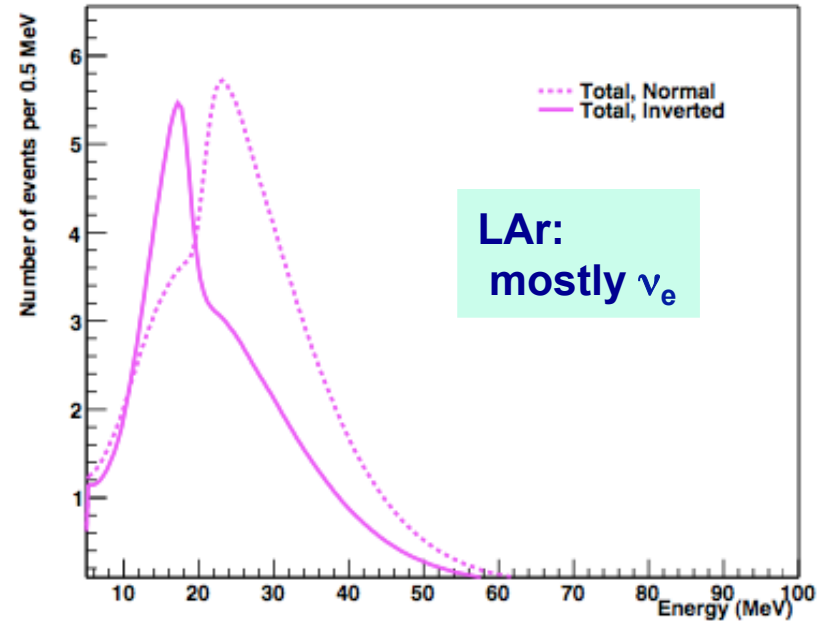
Sensitivity to neutrino oscillation parameters: example

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

Comments on extracting information from the supernova signal:

The signatures of physics and astrophysics are `rich': many complex features in energy spectrum, flavor and time evolution depending on progenitor,

SN type, oscillation parameters, model assumptions...

... models aren't identical, and individual SN explosions may also vary but there *are* generic features of e.g. mass hierarchy

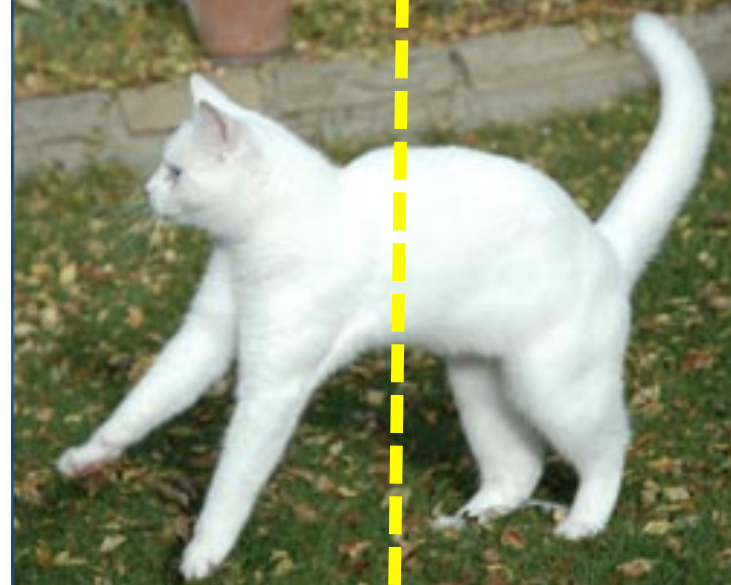
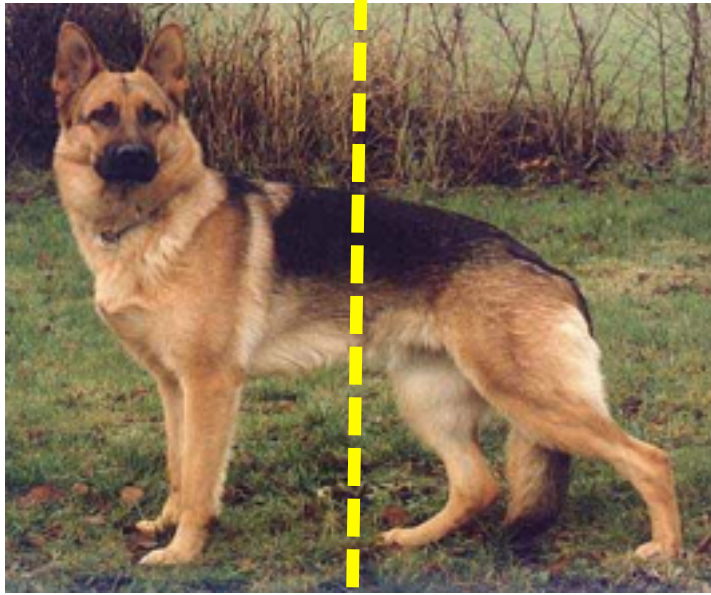
An analogy: testing ability to determine the mass hierarchy from the SN burst flux is like



testing ability of an algorithm to tell a picture of a cat from a picture of a dog



Having both electron neutrino and antineutrino signals
is like having pictures of both front and
back ends of the animal to help you identify it



Looking at one model is like testing whether you can tell
a *particular* cat and a particular dog apart,
knowing features of the individuals in advance

If your algorithm works, that's a good sign, and you get
a reasonable suggestion about whether the front
or the back picture is more useful, but:

- doesn't prove that you can always do it for all cats and dogs
- doesn't really say much about whether or
not you can do it in general or in common cases

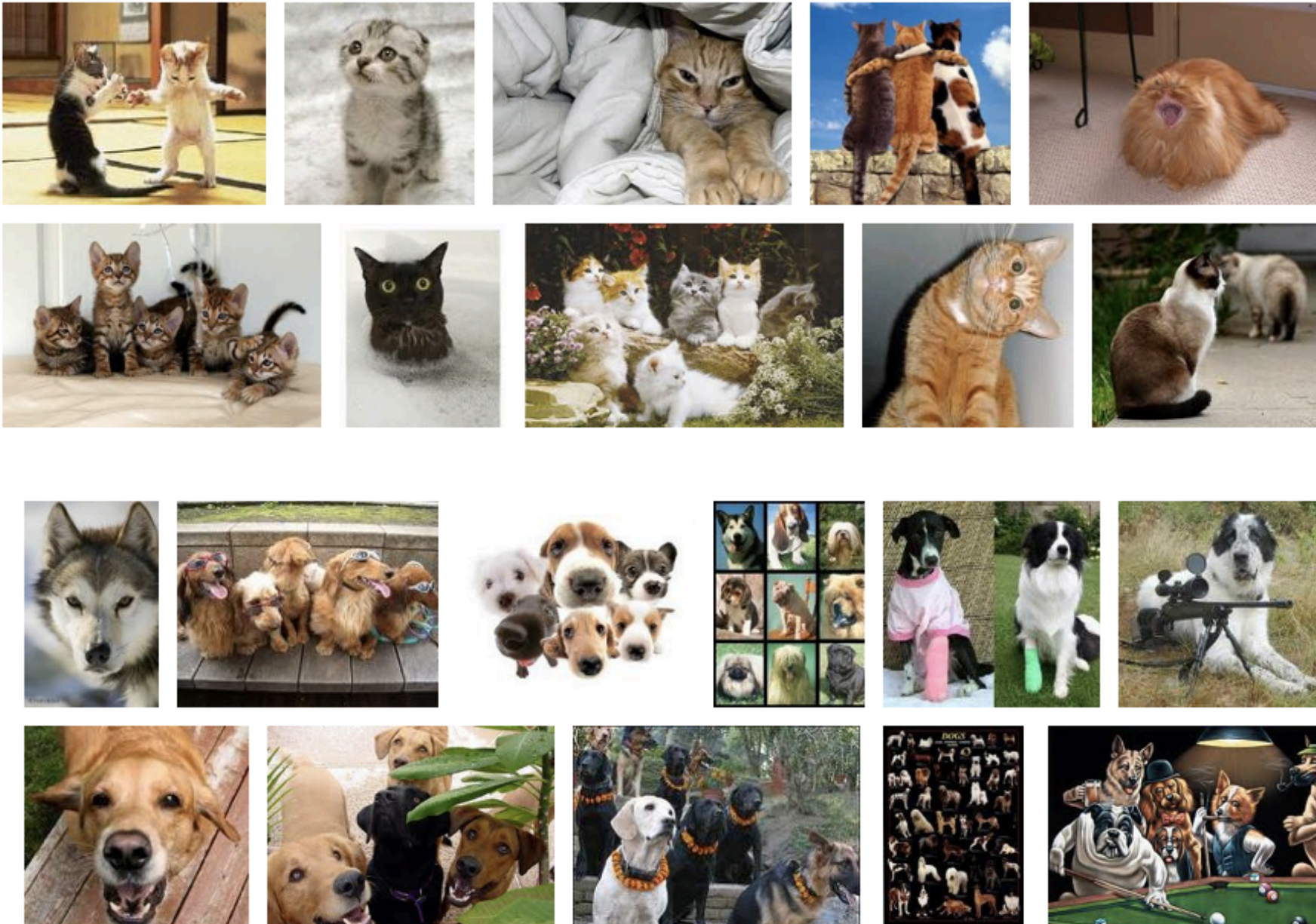
What about this one?





Having *both* the front and back
will very likely help!

We need to test a range of cases...

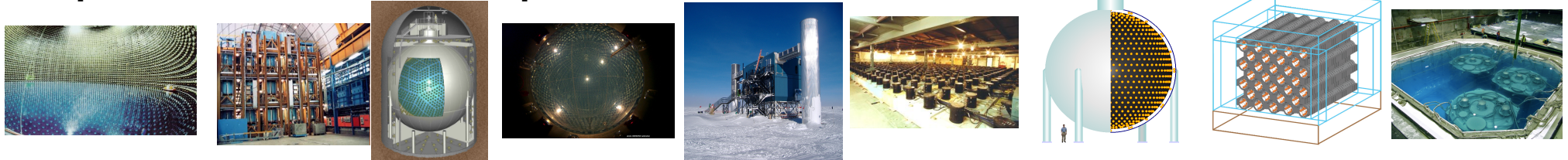


A wide sampling of models is needed

Current & near-future supernova neutrino detectors

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
NOvA	Scintillator	USA	15	3000	Starting
SNO+	Scintillator	Canada	1	300	Under construction
MicroBooNE	Liquid argon	USA	0.17	17	Under construction

plus other reactor, DM experiments...



Primary sensitivity is to electron antineutrinos

via inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$

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
NOvA	Scintillator	USA	15	3000	Turning on
SNO+	Scintillator	Canada	1	300	Under construction
MicroBooNE	Liquid argon	USA	0.17	17	Under construction
LBNE	Liquid argon	USA	34	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...

World SN flavor sensitivity

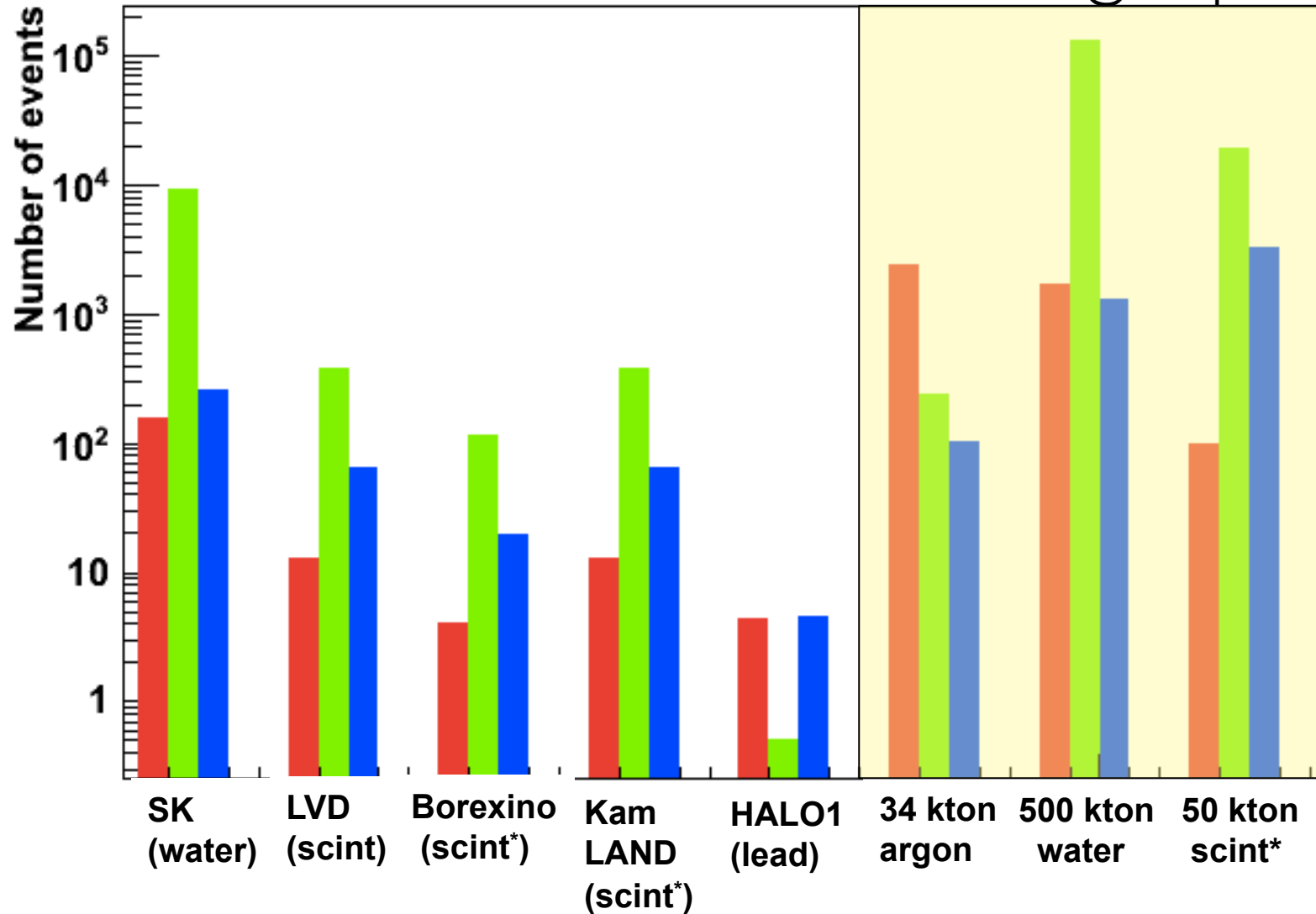
Electron neutrino

Electron antineutrino

Muon and tau neutrino and antineutrino

for ~largest existing or proposed detectors
of each class

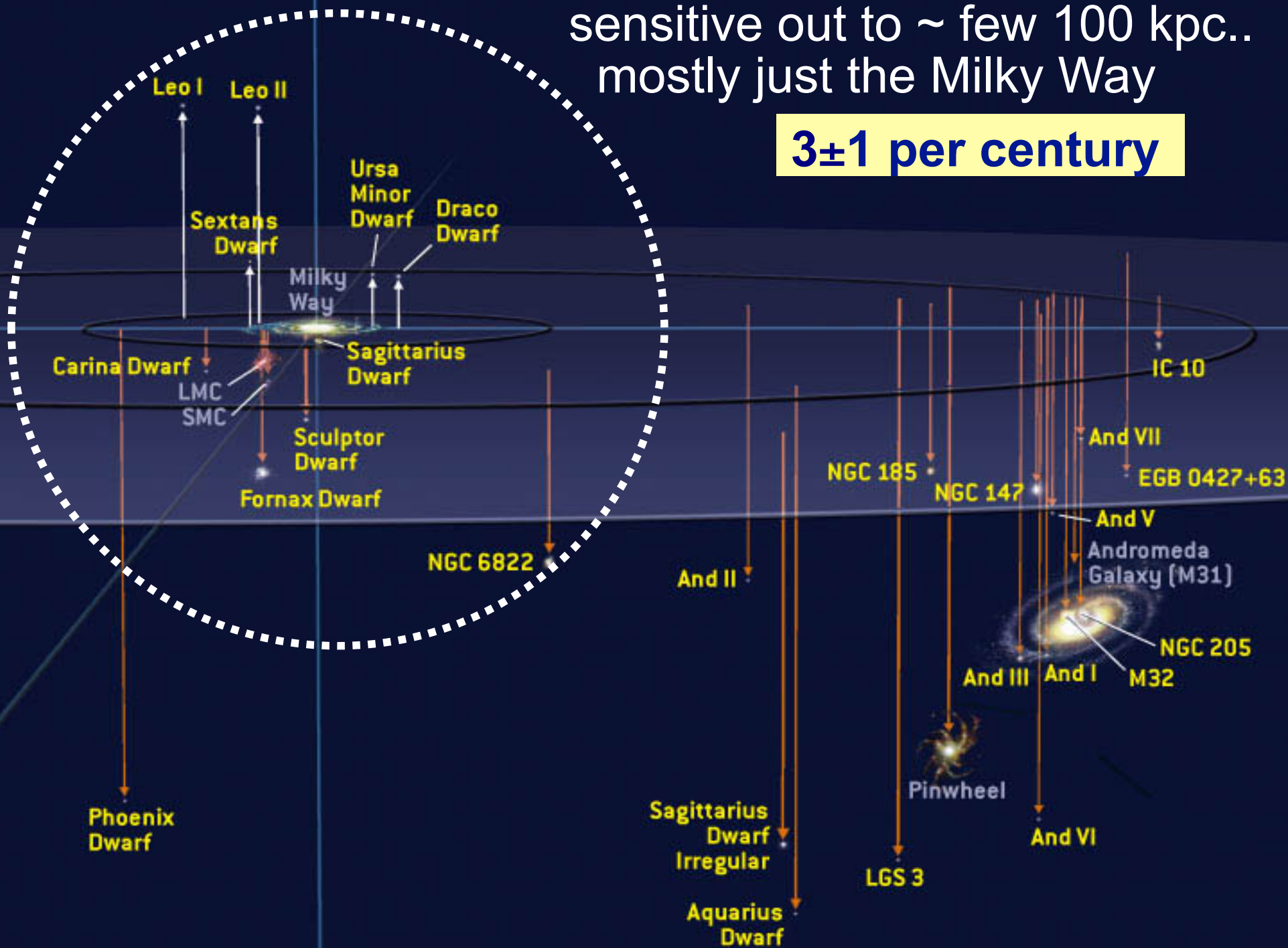
Livermore model
@ 10 kpc



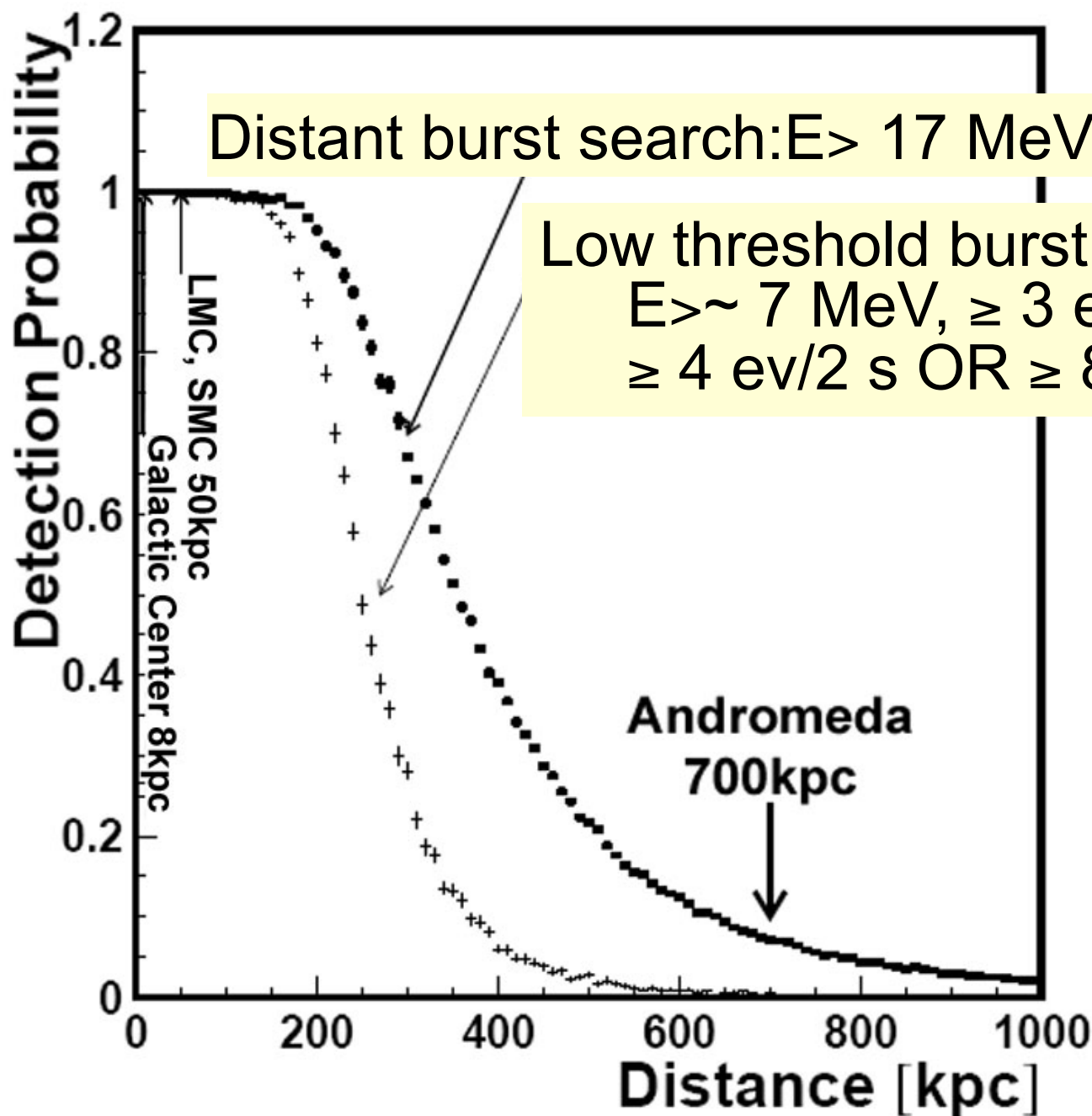
* plus NC ν -p scattering

Current best neutrino detectors
sensitive out to ~ few 100 kpc..
mostly just the Milky Way

3 ± 1 per century



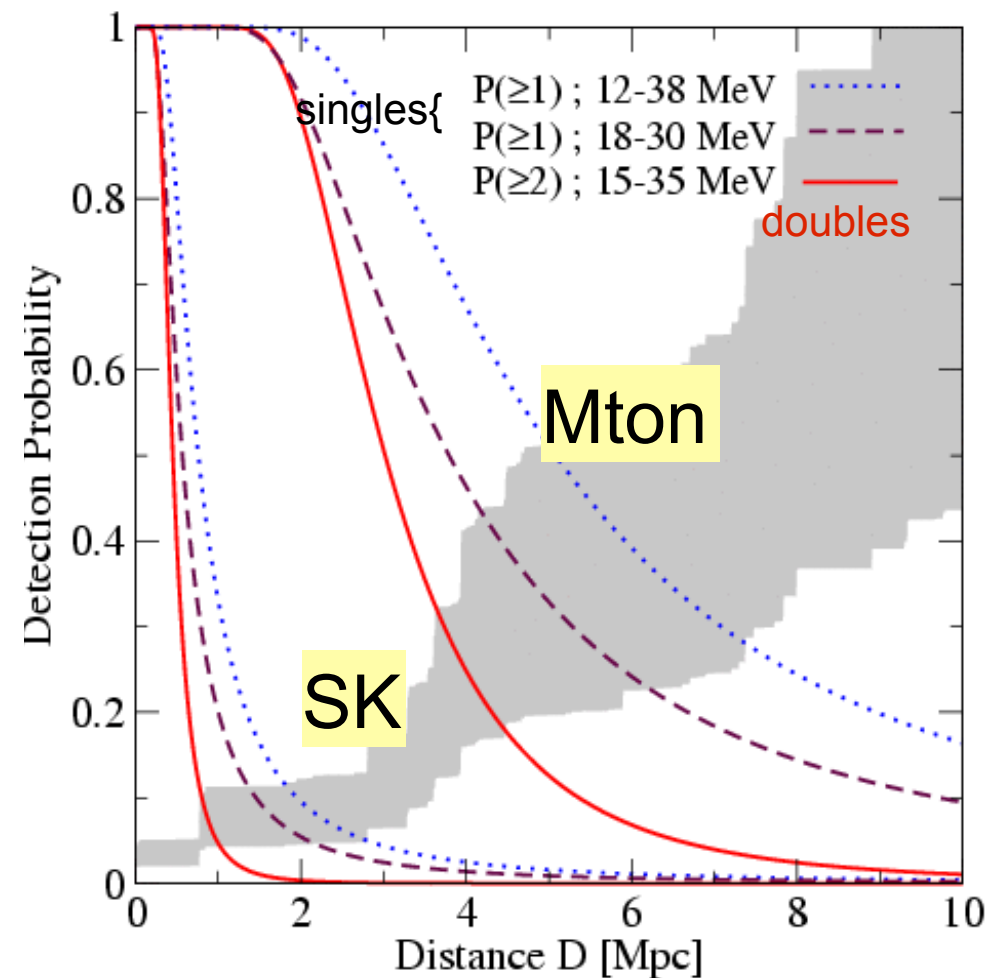
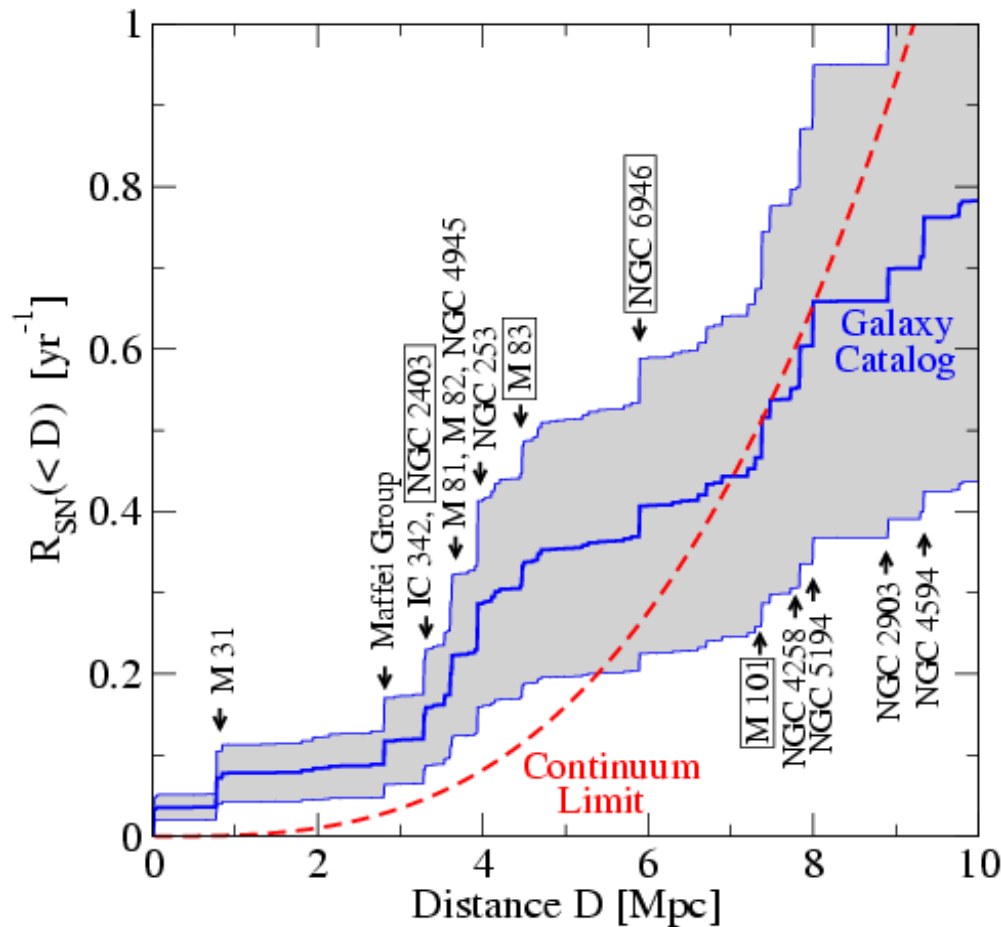
How far can we look out? SK has farthest reach now



For “untriggered” distant search, it’s all about the background...

Looking beyond: number of sources $\propto D^3$

S. Ando et al., astro-ph/0503321



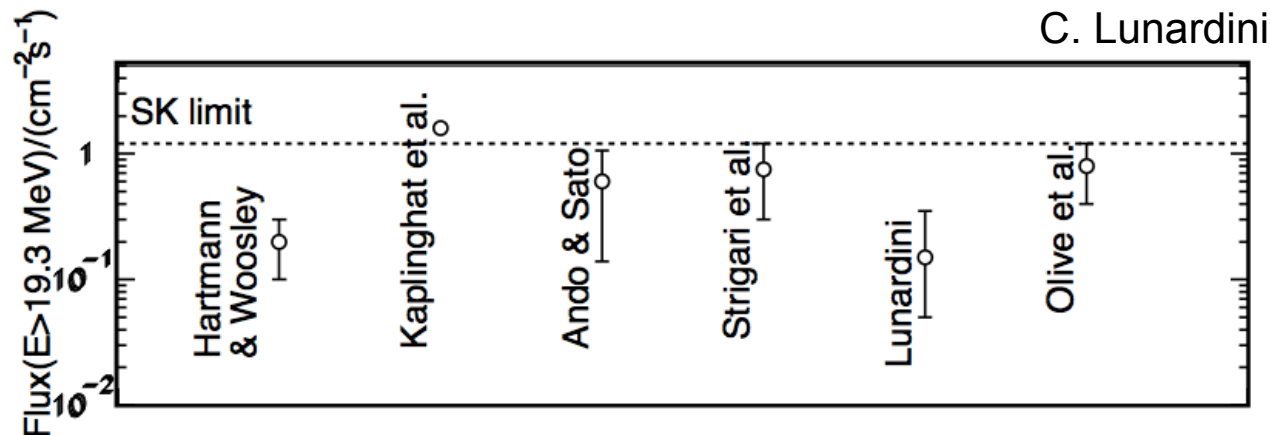
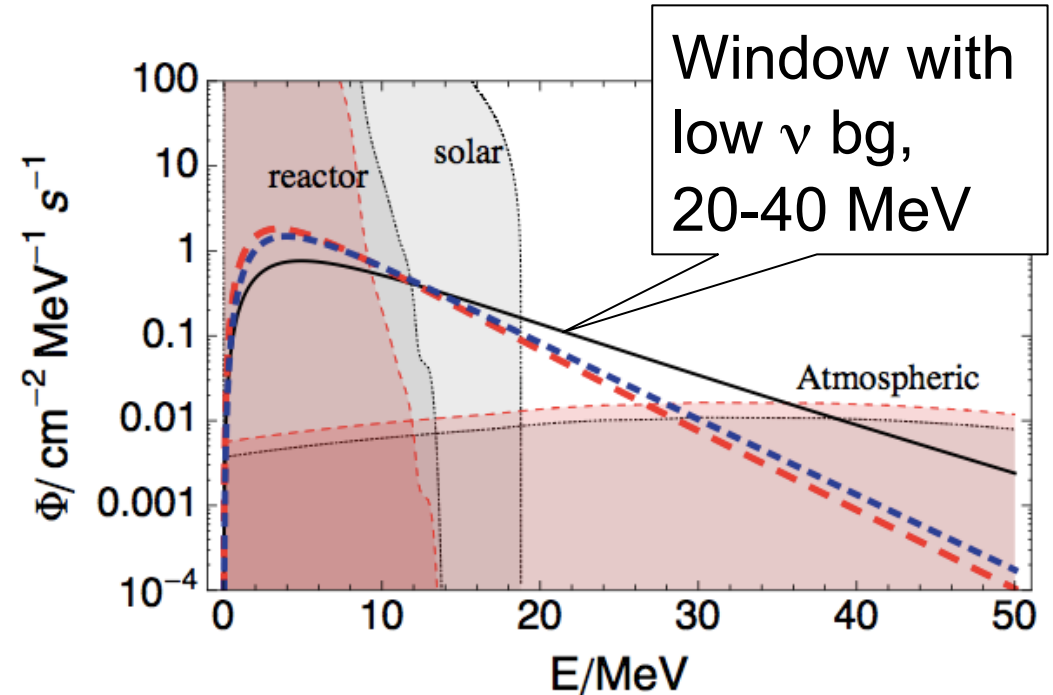
With Mton scale detector, probability of detecting 1-2 events reasonably close to ~ 1 at distances where rate is $< \sim 1/\text{year}$

Tagging signal over background becomes the issue
 $\Rightarrow$ require double ν 's or grav wave/optical coincidence

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

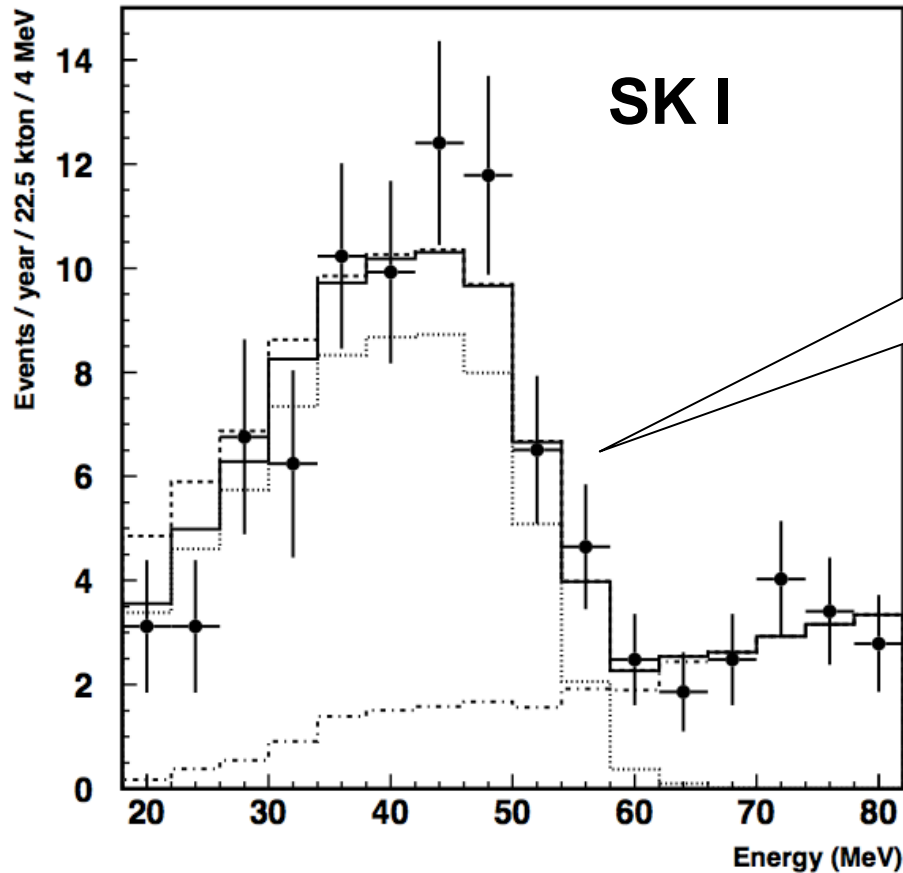
Learn about average supernova properties over cosmic history

Difficulty is tagging for decent signal/bg (no burst, 2 ν coincidences optical SNaE...)



~few events per year in SK

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

DSNB

~0.1 event/kt/year

more background

low rate of return,
but a sure thing

Galactic SN

~300 events/kt/30 year

~10 events/kt/yr

less background

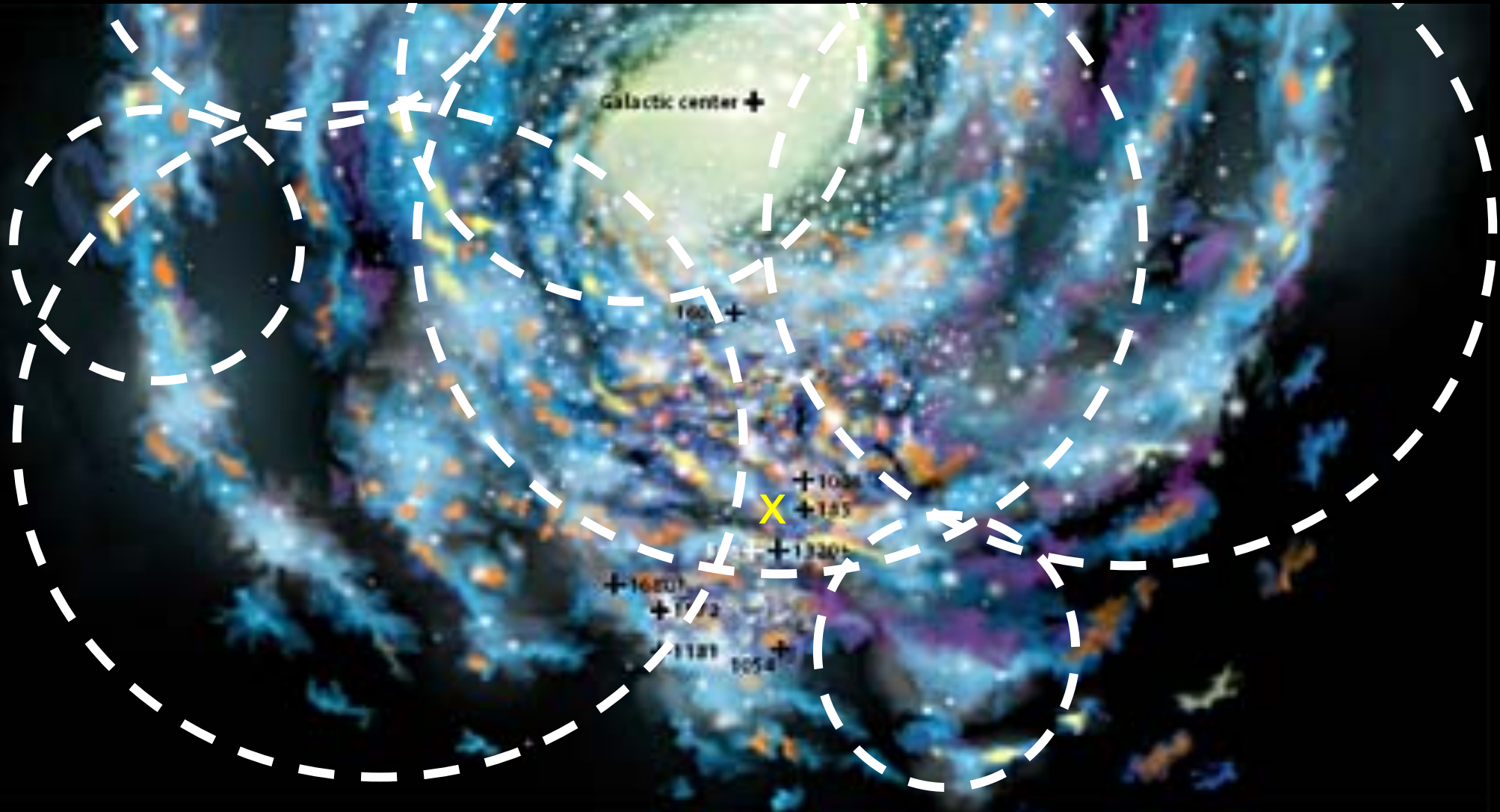
risky in the short term, but you
win in the very long term

bonds vs stocks...

(Of course if you build a big detector and run
it a long time, you may get both! Diversify!)

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)

Any information saved, in any channel,
may be valuable

- all em wavelengths
- neutrinos (low and high energy)
- gravitational waves
- ...

Combining information with other detectors
sensitive to SNaE is important! (alert & later)

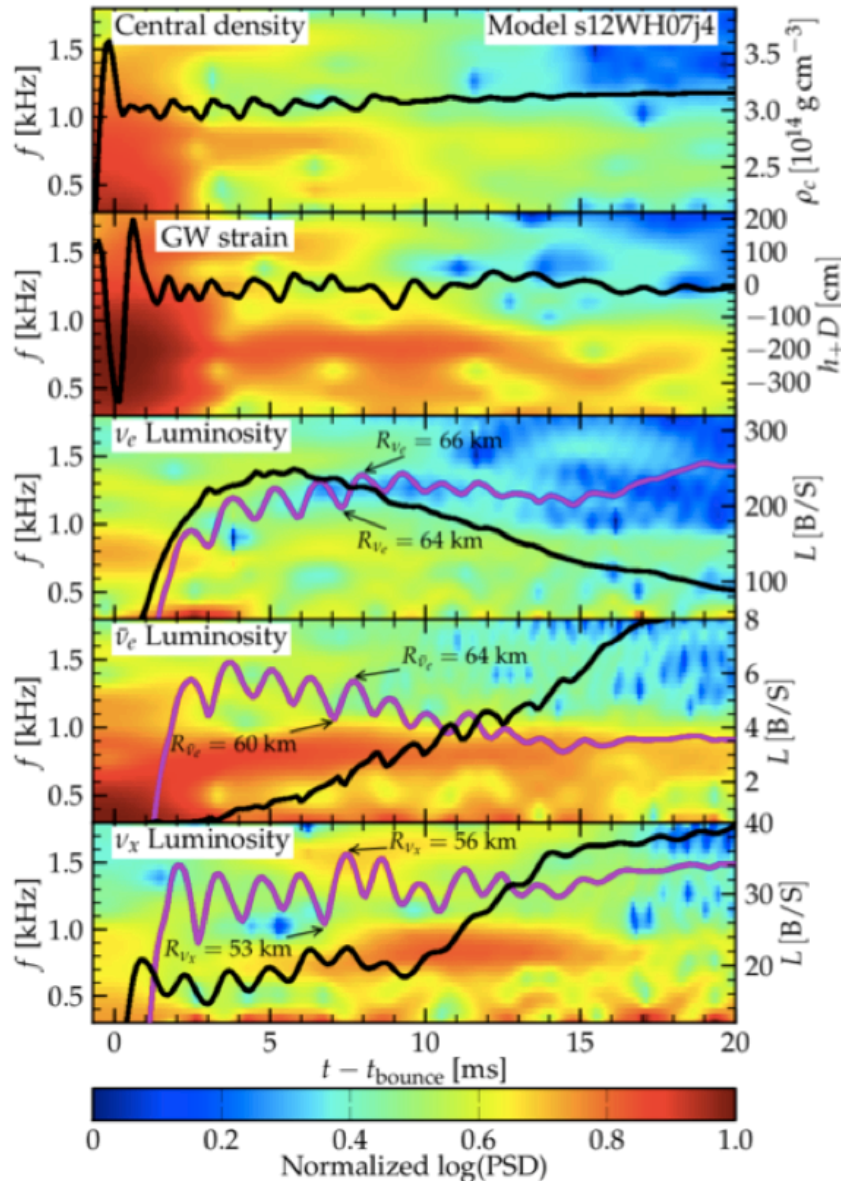


gravitational waves



multiwavelength astronomy

Gravitational wave signals from core collapse



C. Ott, et al. (GWPAW 2012):
correlated oscillations

Correlations
between GW & ν 's
potentially extremely
interesting

➔ physics potential from
nearby collapse

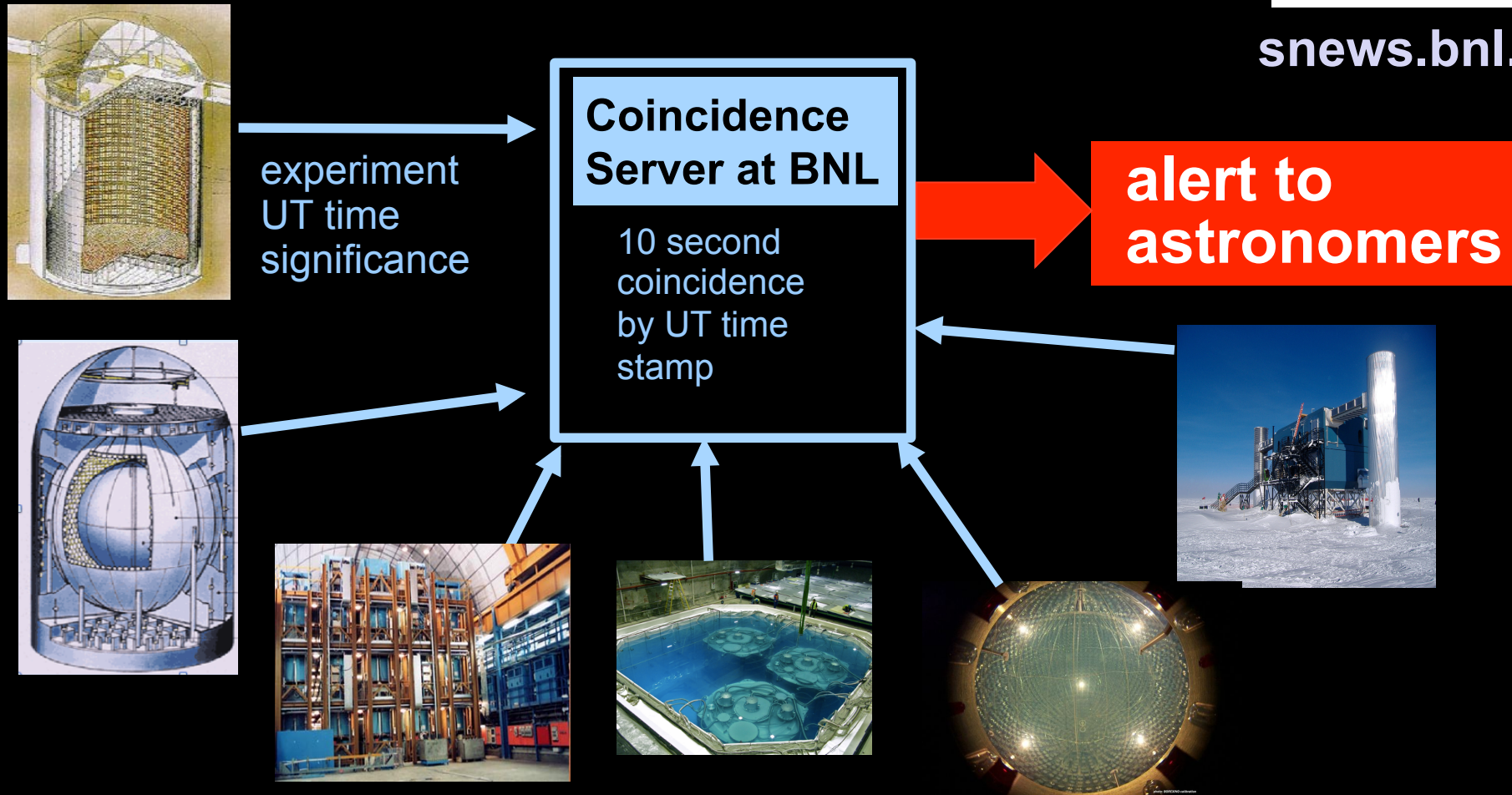
➔ improvement in
sensitivity from
correlation analysis with
existing data

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

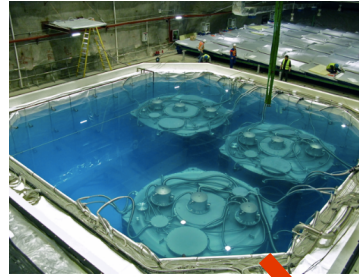


- Running smoothly for more than 10 years, automated since 2005
- Amateur astronomer connection

SNEWS: SuperNova Early Warning System



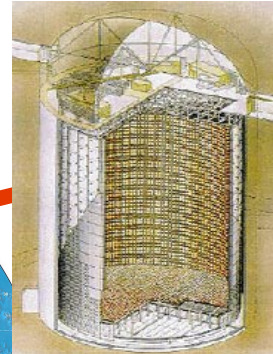
LVD



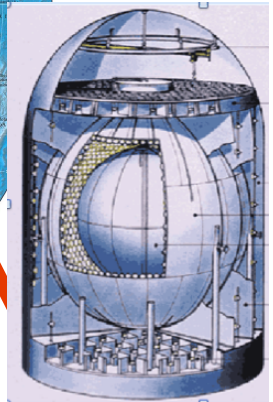
Daya Bay
(soon)



snews.bnl.gov

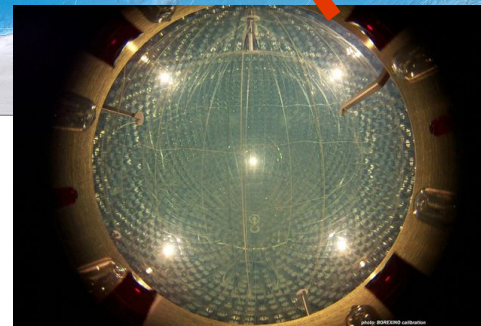
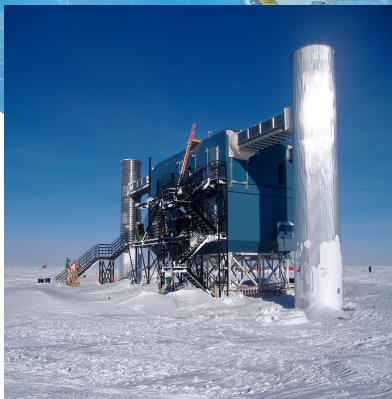


Super-K



KamLAND

IceCube



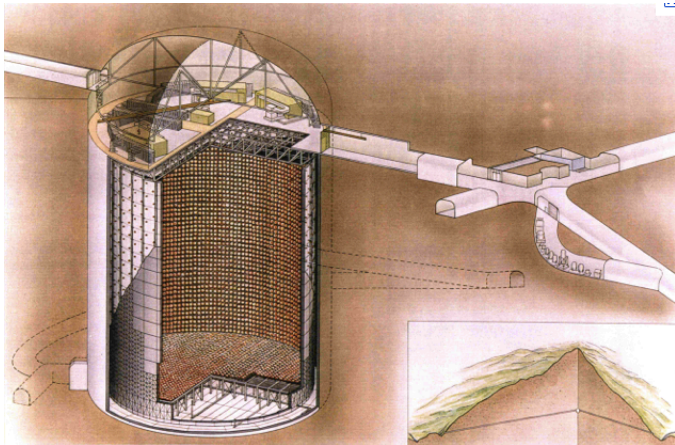
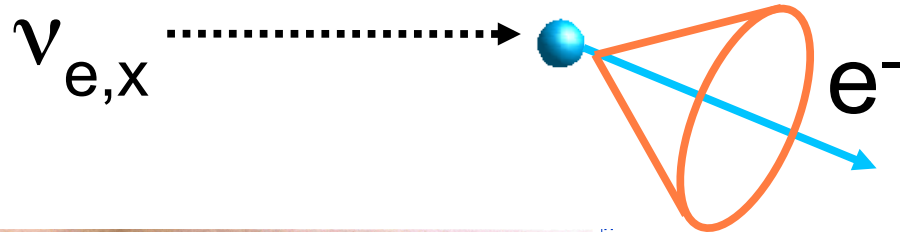
Borexino

POINTING to the supernova with future detectors

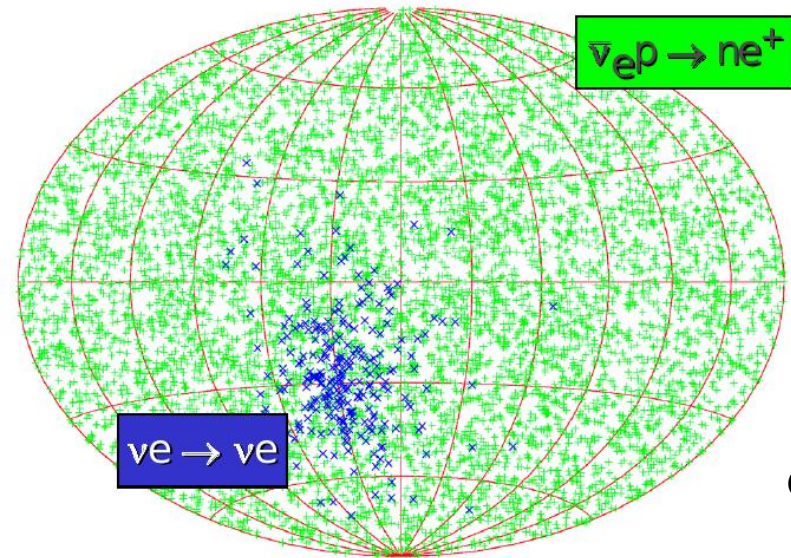
(should be prompt if possible)

Elastic scattering off electrons is the best bet

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



In water Cherenkov
few % of total rate



G. Raffelt

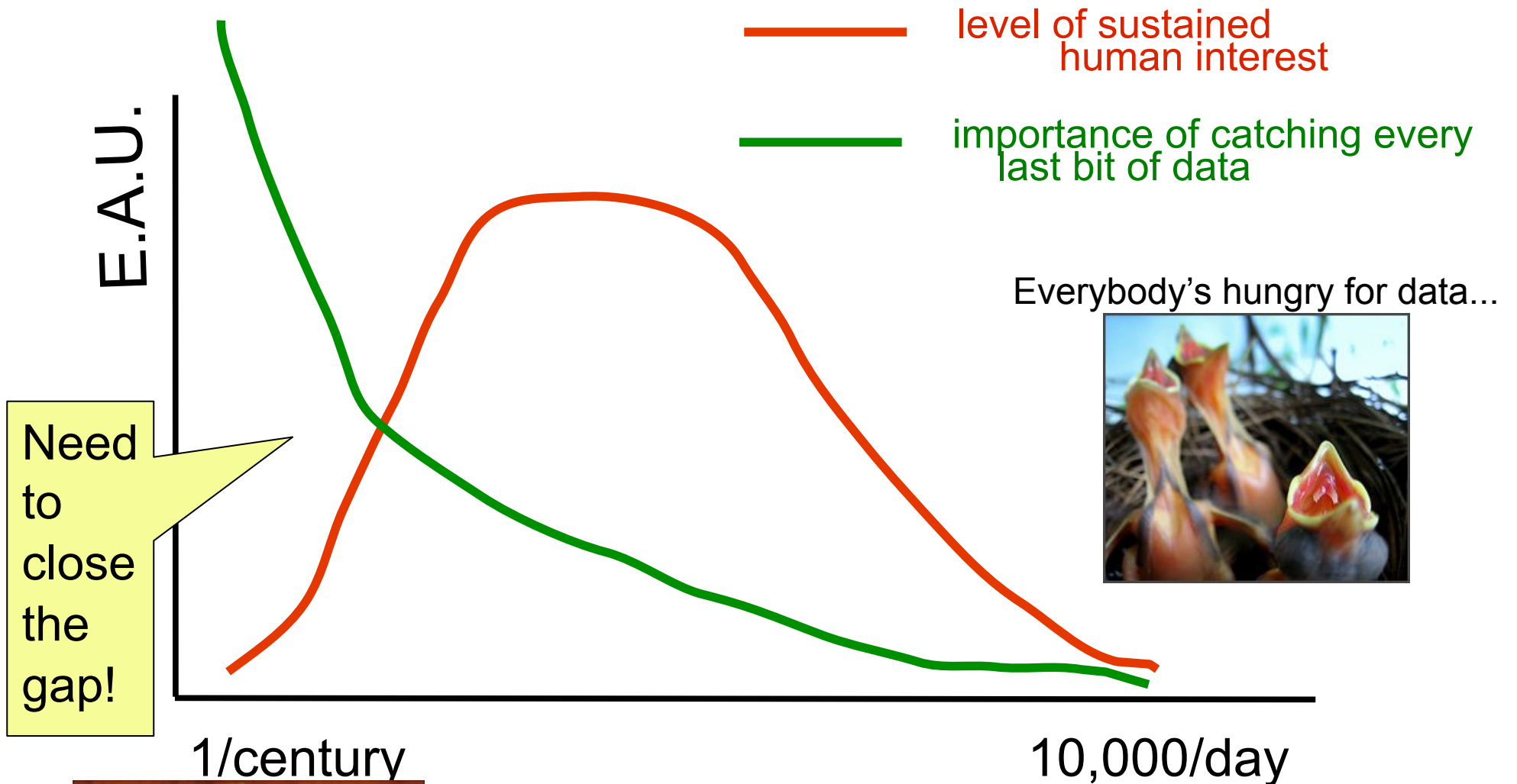
Super-K: $\sim 8^\circ$ pointing

- Other possibilities:
- time triangulation
 - matter oscillation pattern
 - inv. β dk e^+n separation
 - $\sim$ TeV neutrinos (delayed)

KS, A. Burgmeier, R. Wendell
arXiv: 0910.3174

Tomas et al., hep-ph/0307050

Sociological comments...



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

Farther future megadetectors

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

