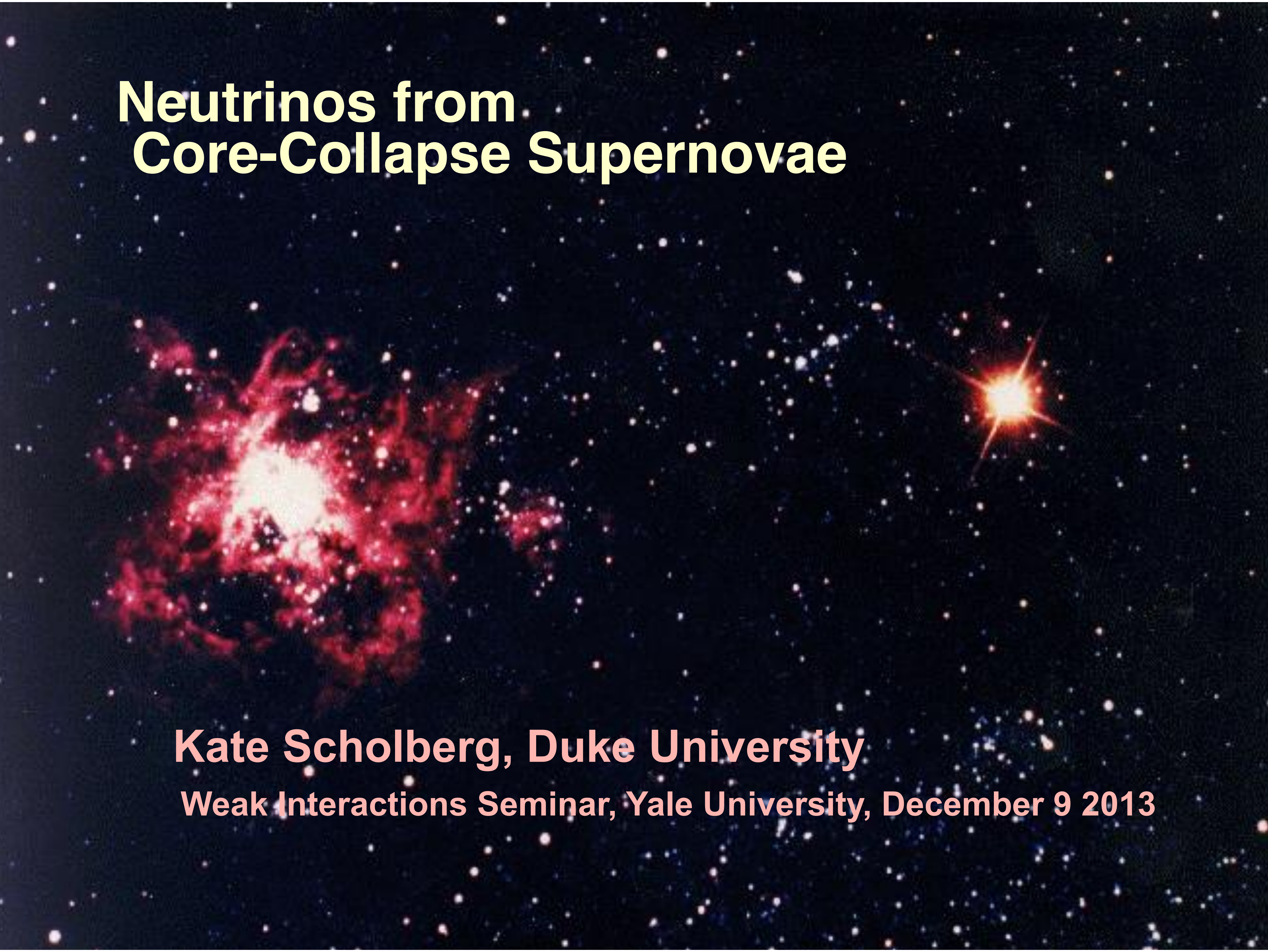
Neutrinos from Core-Collapse Supernovae



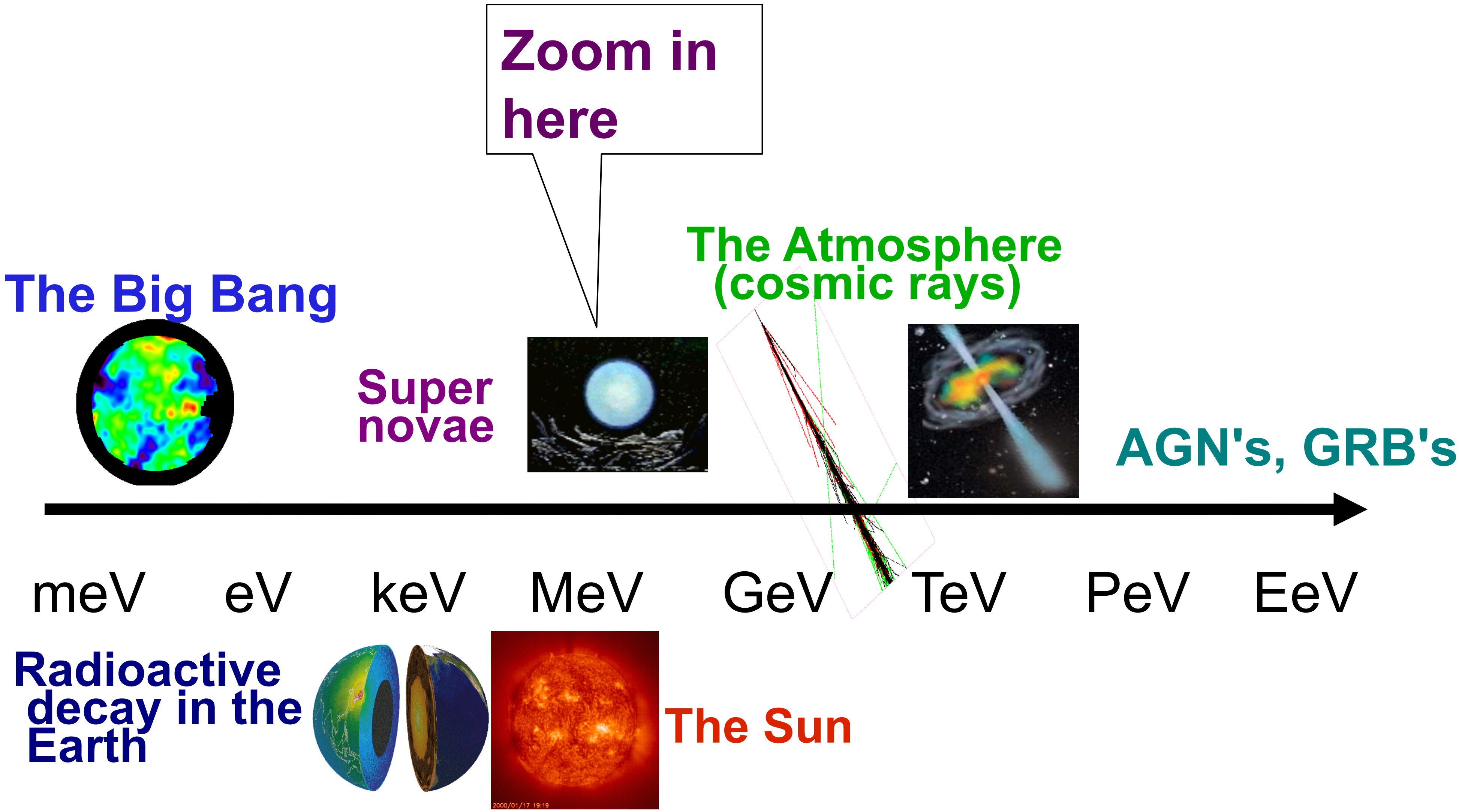
Kate Scholberg, Duke University

Weak Interactions Seminar, Yale University, December 9 2013

OUTLINE

- **Neutrinos, supernovae & neutrinos from SNae**
  - **What can be learned**
- **Supernova neutrino detection**
  - **Inverse beta decay**
  - **Other CC interactions**
  - **NC interactions**
- **Summary of current and near future detectors**
- **Future detection**
- **Summary**

Sources of wild neutrinos



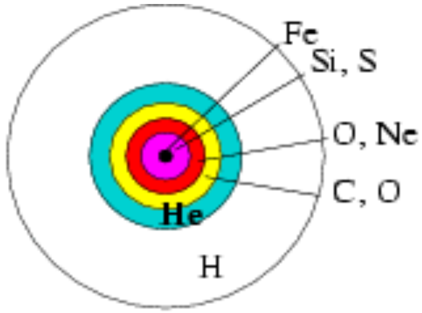
Neutrinos from core collapse

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

(Energy *can* escape via ν's)

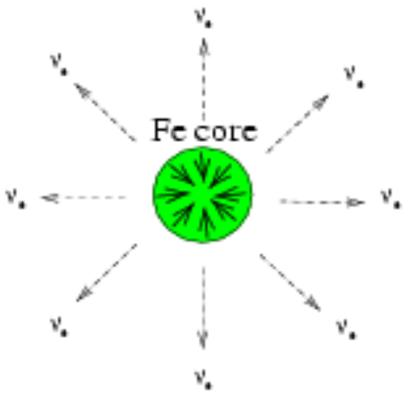
Mostly ν-$\bar{\nu}$ pairs from proto-nstar cooling

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



PRE-SUPERNOVA

"onion-skin"

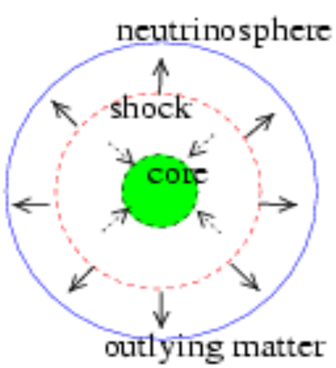


CORE INFALL

M_{core} >~ M_{Ch}

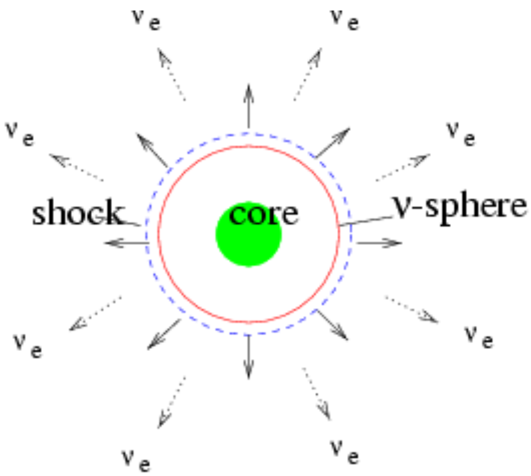
"neutronization" $e^- + p \rightarrow n + \nu_e$

NEUTRINO TRAPPING



CORE BOUNCE

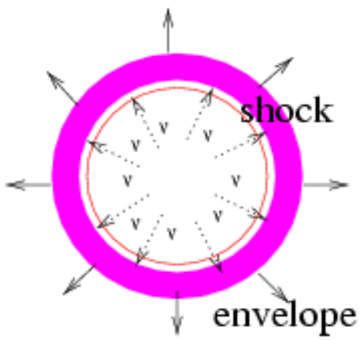
shock formation



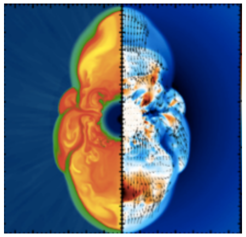
NEUTRINO "BREAKOUT"

shock hits "ν-sphere"

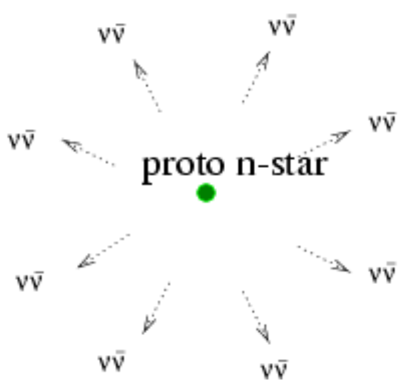
(radius such that
ν mean free path is ∞)



ACCRETION and/(or)
EXPLOSION



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



COOLING

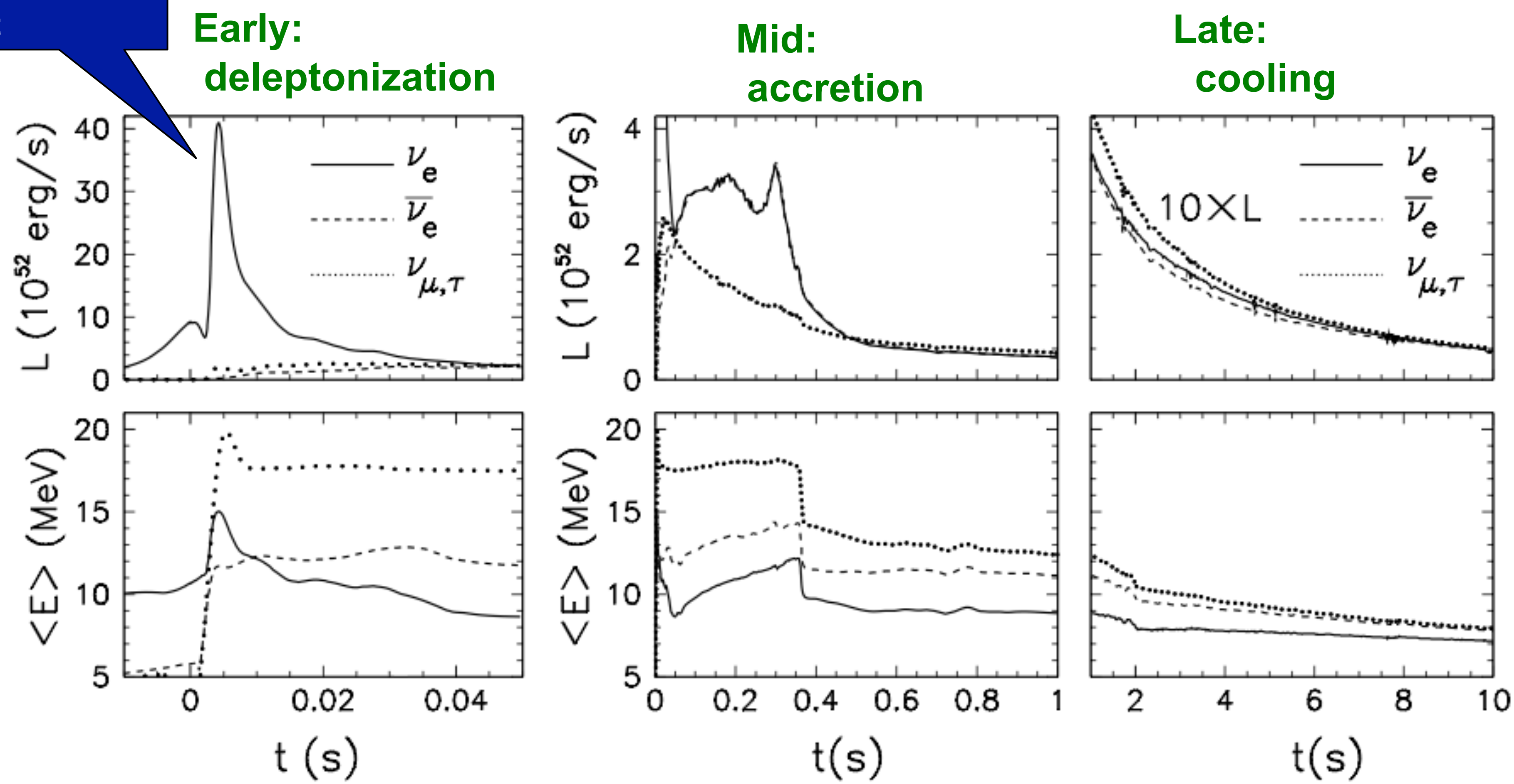
energy shed
via $\nu\bar{\nu}$ pairs

Visible aftermath after
~hours or days

Expected neutrino luminosity and average energy vs time

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

neutronization burst



Generic feature:
(may or may not be robust)

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

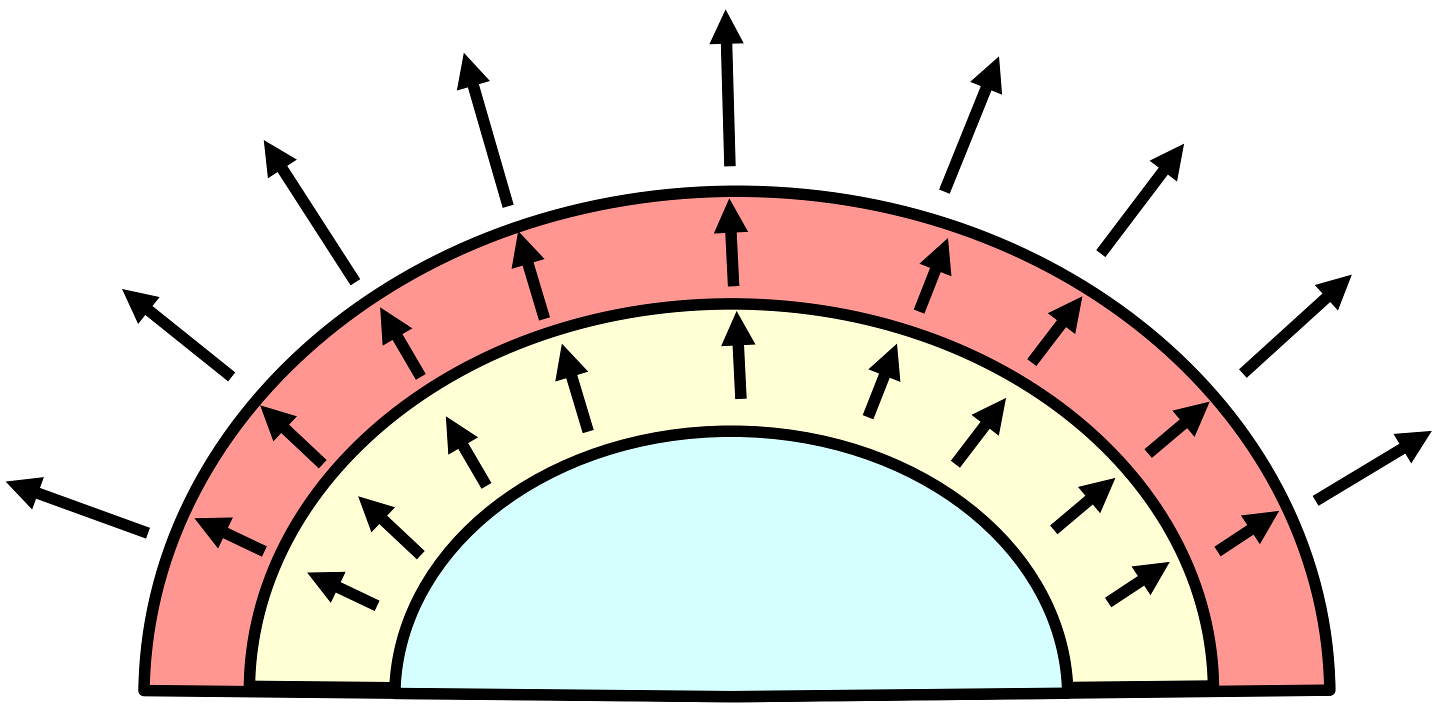
Nominal expected flavor-energy hierarchy

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

$\langle E\nu_e \rangle \sim$ 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 (neutrinos which decouple deeper may lose more energy)

Raffelt, astro-ph/0105250; Keil, Raffelt & Janka astro-ph/0208035

Supernova 1987A

in the Large Magellanic Cloud (55 kpc away)

SN1987A in LMC

at 55 kpc

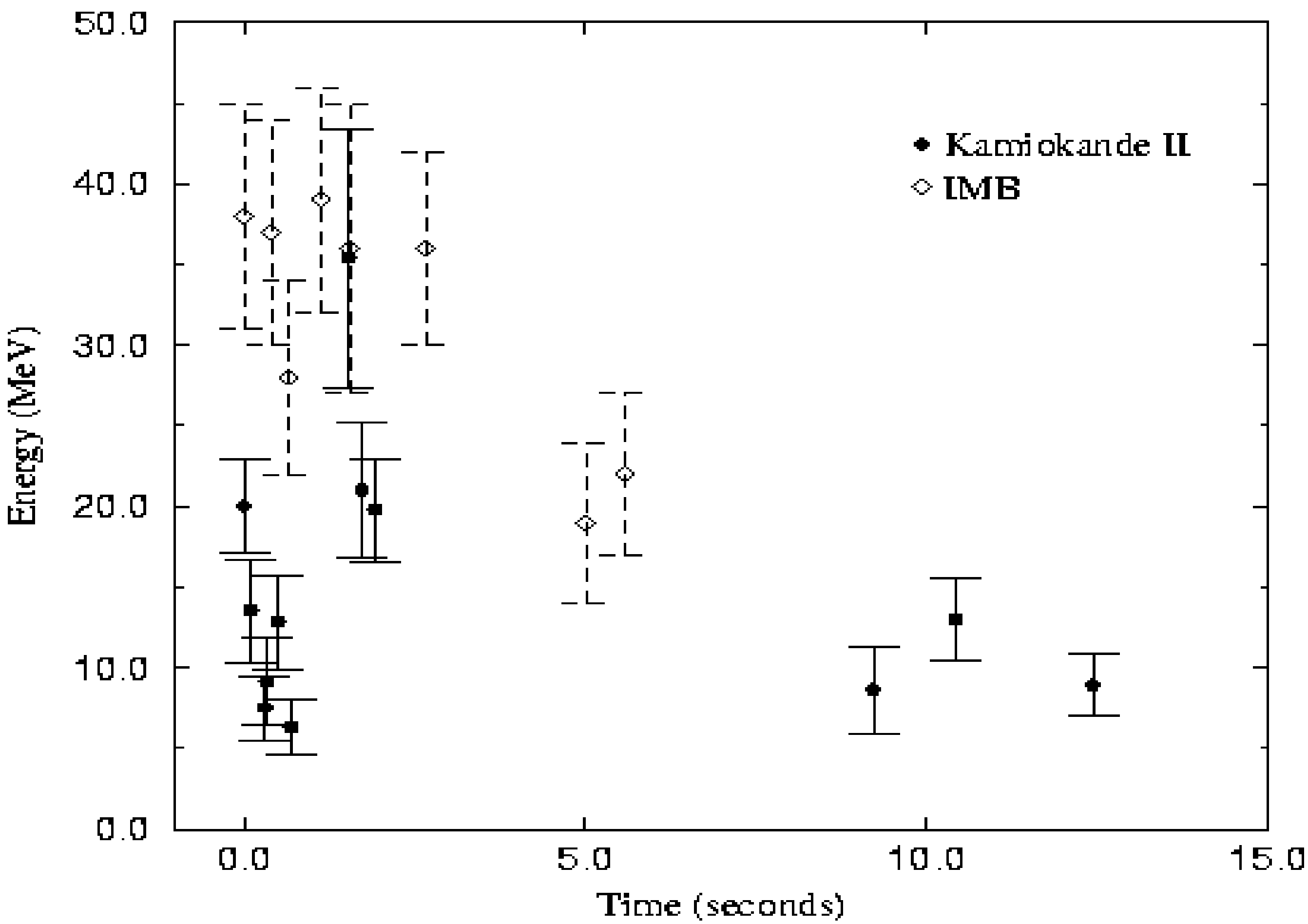
ν's seen ~2.5 hours before first light

Water Cherenkov: IMB E_{th}~ 29 MeV, 6 kton 8 events

Kam II E_{th}~ 8.5 MeV, 2.14 kton 11 events

Liquid Scintillator: Baksan E_{th}~ 10 MeV, 130 ton 3-5 events

Mont Blanc E_{th}~ 7 MeV, 90 ton 5 events??

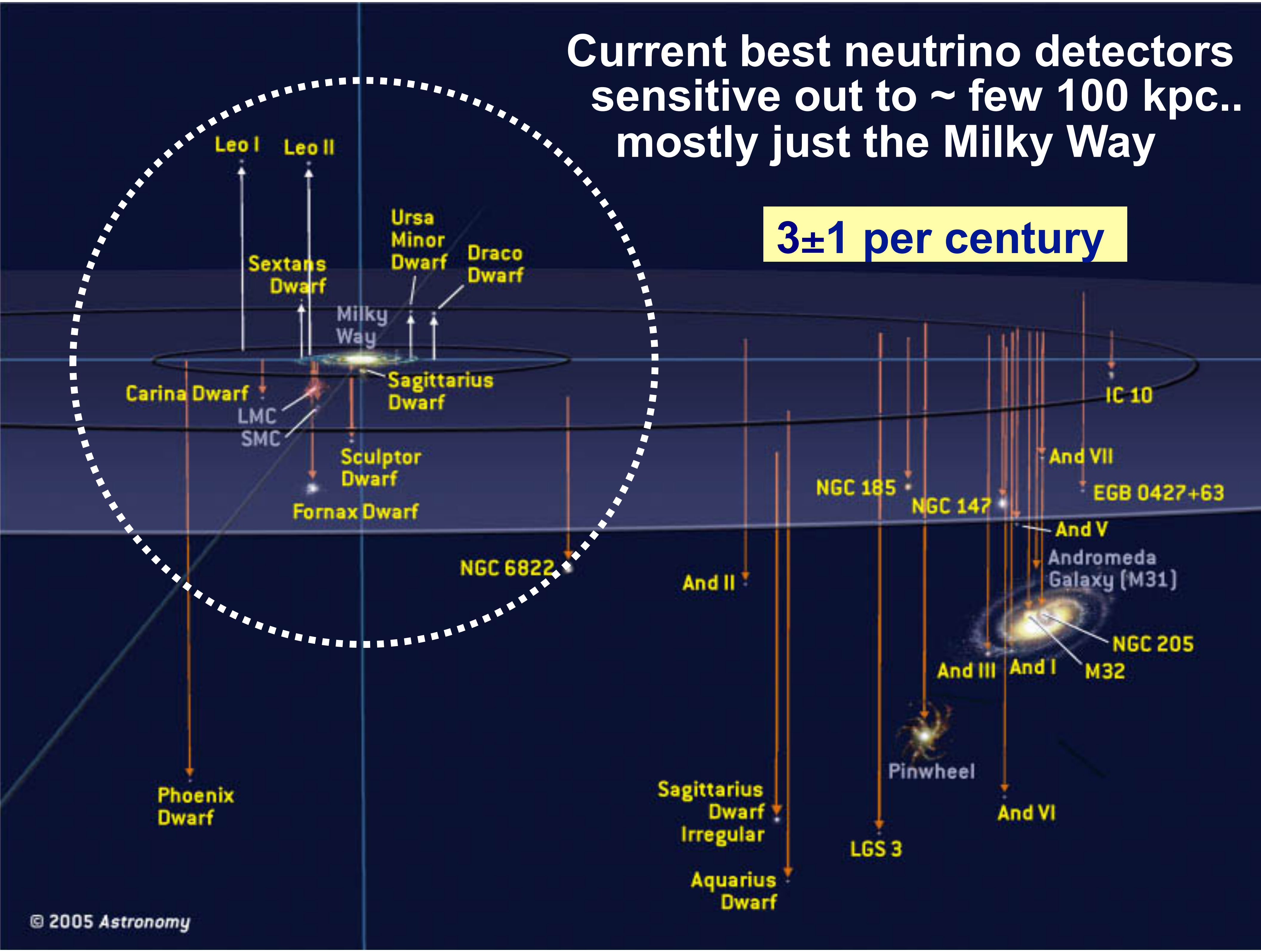


$\bar{\nu}_e$

Confirmed baseline model... but still many questions

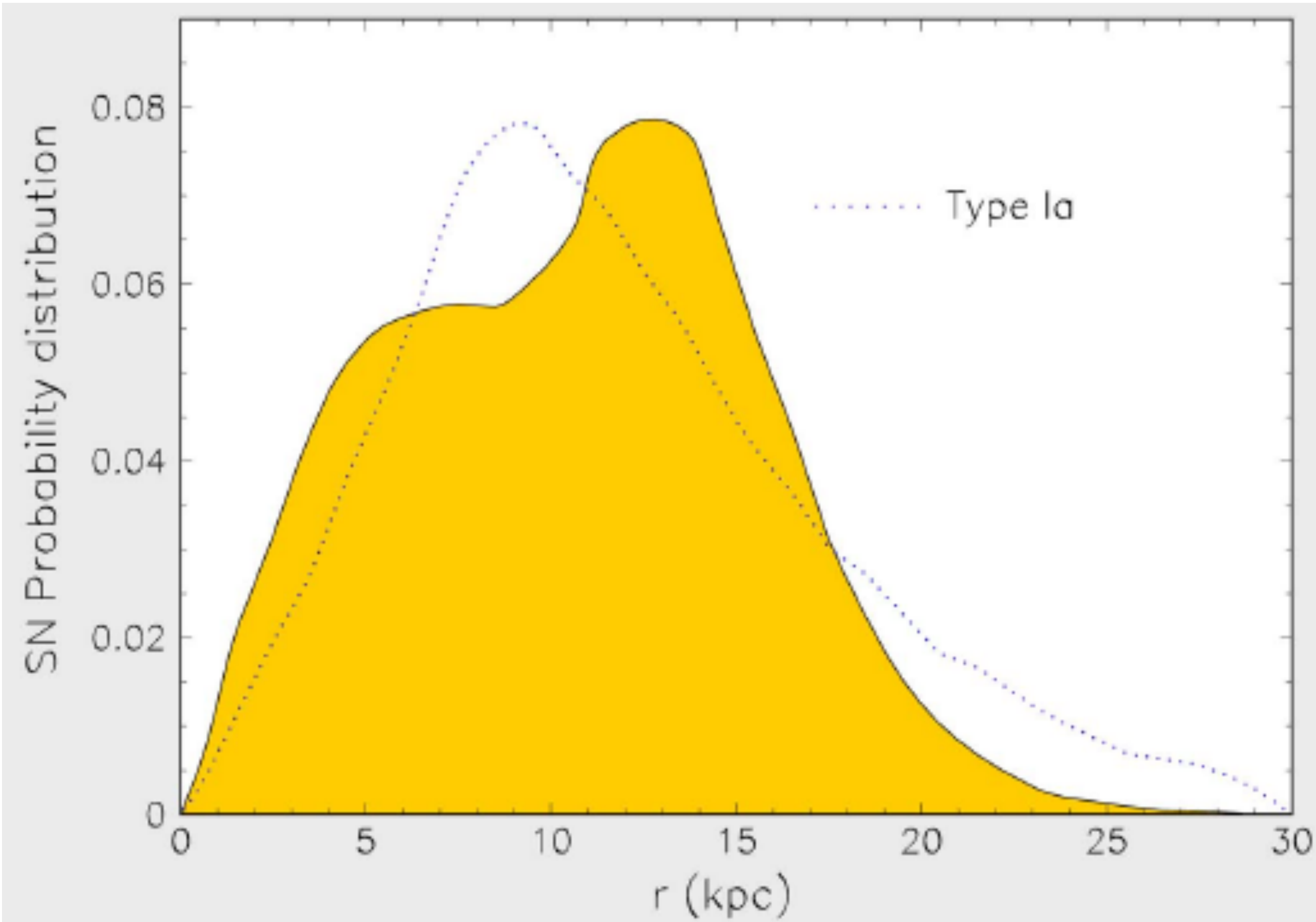
Current best neutrino detectors sensitive out to ~ few 100 kpc.. mostly just the Milky Way

3±1 per century



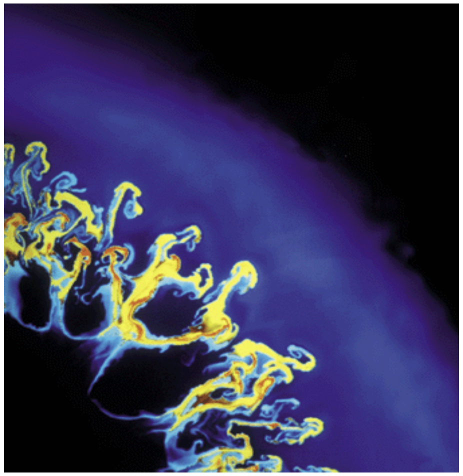
Typical distance from us: ~10-15 kpc

(10 kpc is "standard distance")



Mirizzi, Raffelt and Serpico , astro-ph/0604300

What We Can Learn

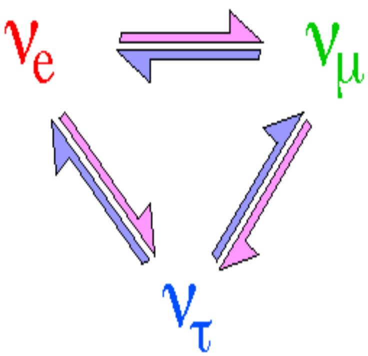


CORE COLLAPSE PHYSICS

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

from flavor, energy, time structure of burst

NEUTRINO/OTHER PARTICLE PHYSICS



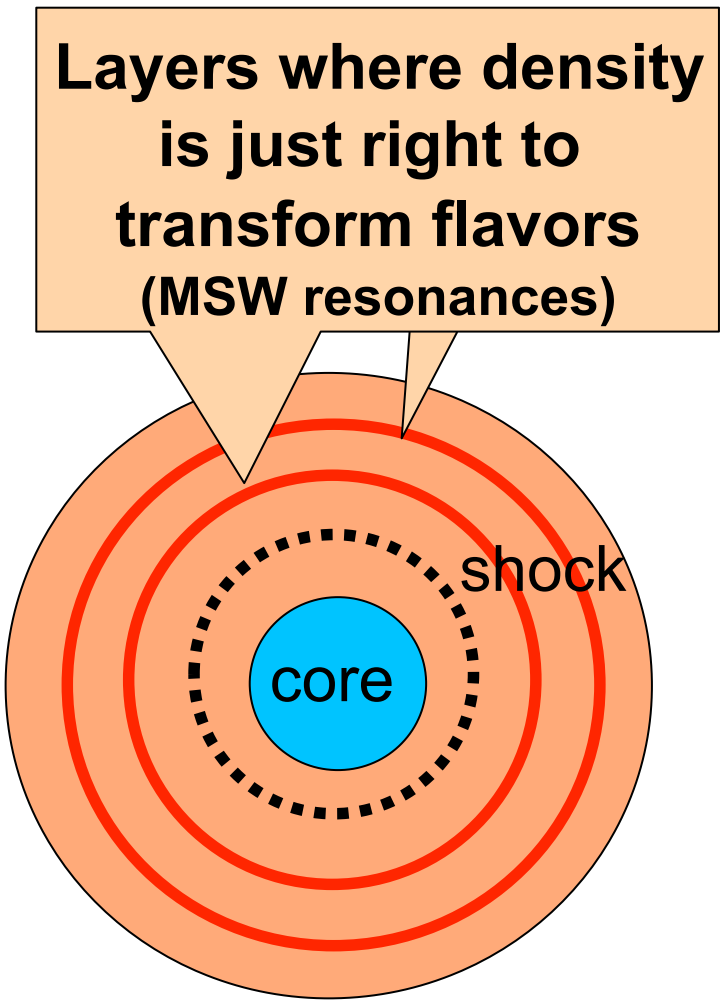
- ν absolute mass (not competitive)
- ν mixing from spectra: flavor conversion in SN/Earth
- other ν properties: sterile ν's, magnetic moment,...
- axions, extra dimensions, FCNC, ...

+ EARLY ALERT

Getting at neutrino oscillation parameters, e.g. sign(Δm^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

- $\nu-\nu$ interactions
- nonlinear effects
- 'multi-angle' effects

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

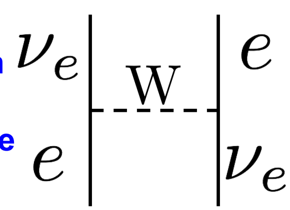
In the proto-neutron star the neutrino density is so high that *neutrino-neutrino interactions* matter

From G. Fuller

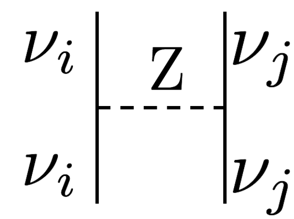
$$\psi_{\nu,i} = \begin{bmatrix} \text{amplitude to be } \nu_e \\ \text{amplitude to be } \nu_{\mu,\tau} \end{bmatrix}$$

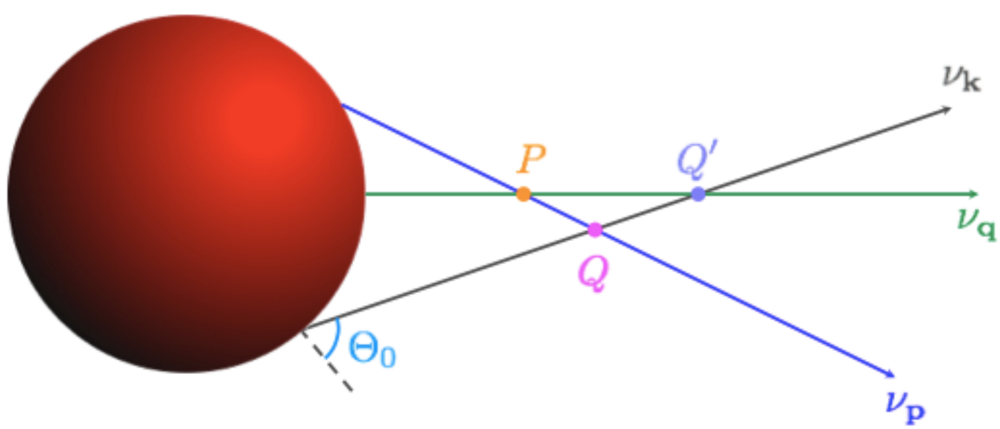
$$i \frac{\partial}{\partial t} \psi_{\nu,i} = \left(\mathcal{H}_{\mathrm{vac},i} + \mathcal{H}_{\mathrm{e},i} + \mathcal{H}_{\nu\nu,i} \right) \psi_{\nu,i}$$

neutrino-electron charged current forward exchange scattering



neutrino-neutrino neutral current forward scattering





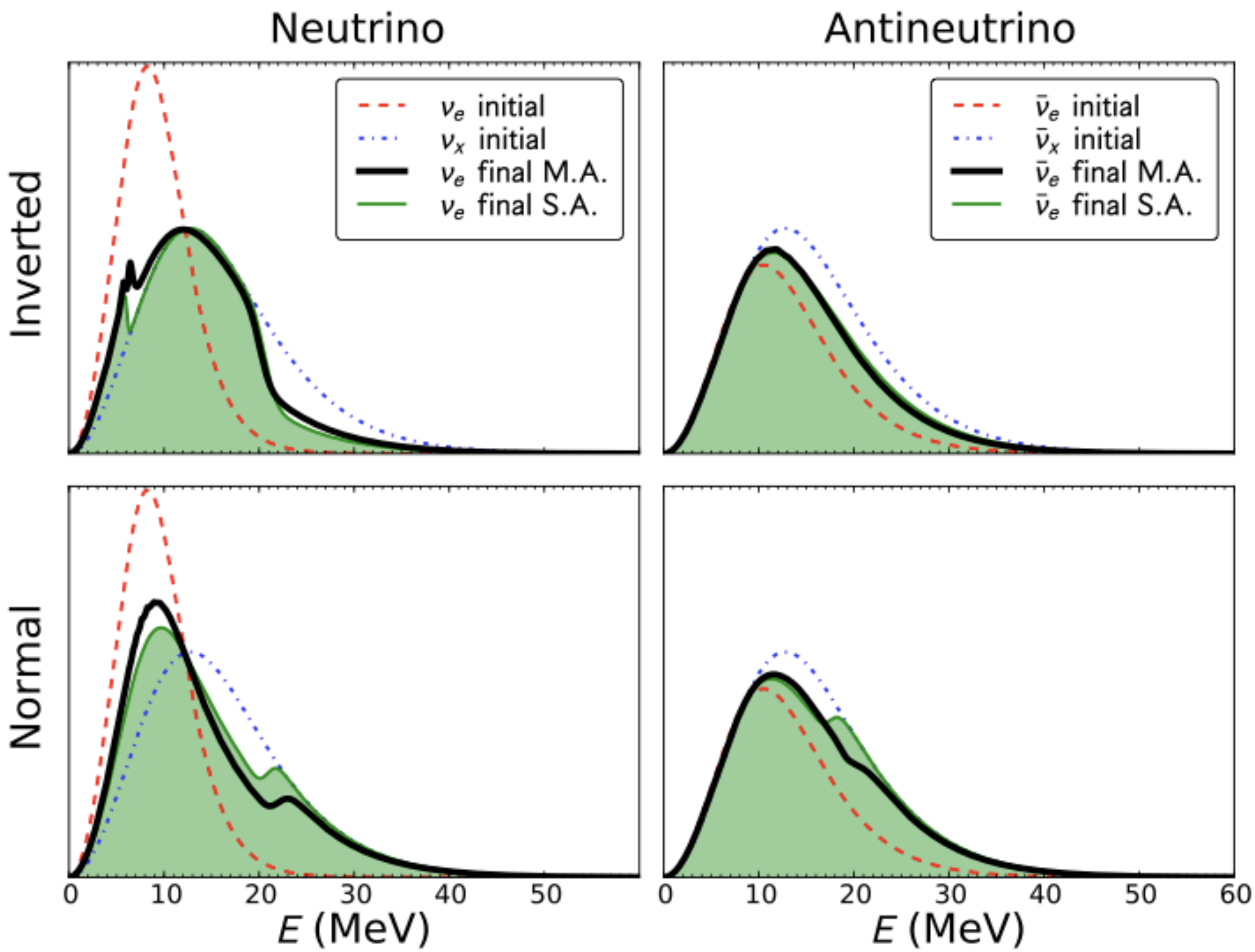
Must solve many *millions* of coupled, nonlinear partial differential equations!!

Anisotropic, nonlinear quantum coupling of all neutrino flavor evolution histories:

"collective effects"

"The physics is addictive" -- G. Raffelt

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



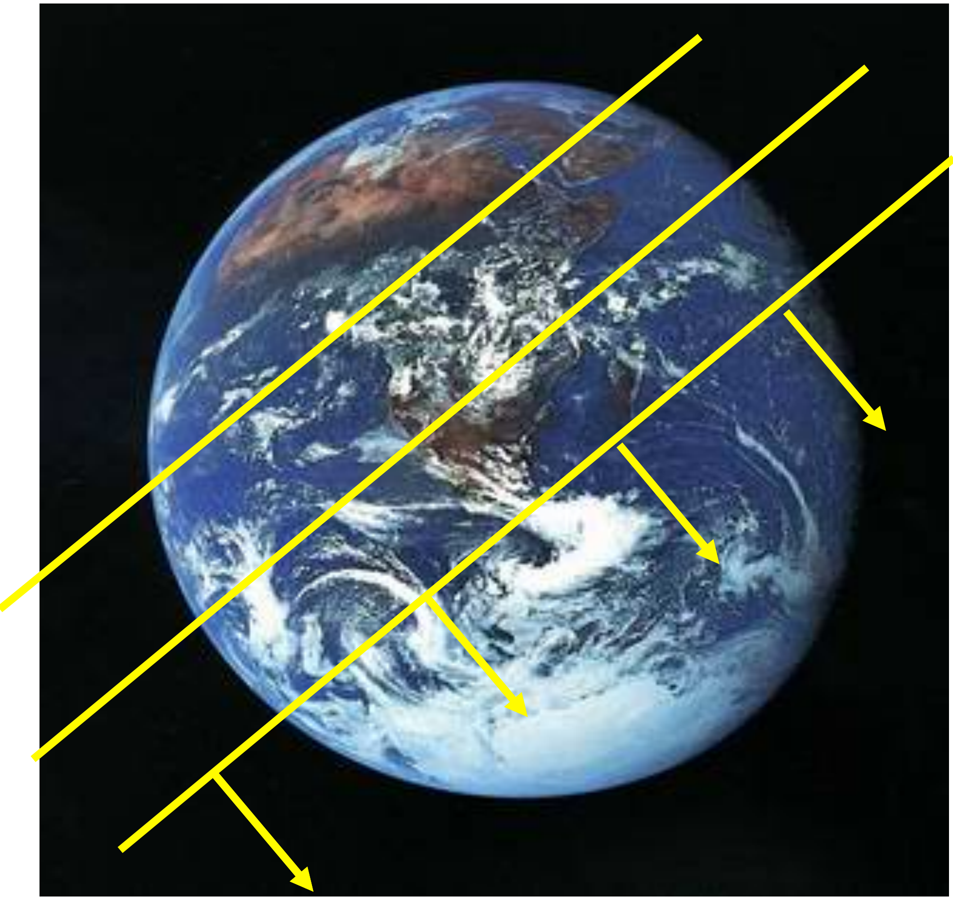
***Distinctive spectral swap features depend on neutrino mass hierarchy*, for neutrinos vs antineutrinos**

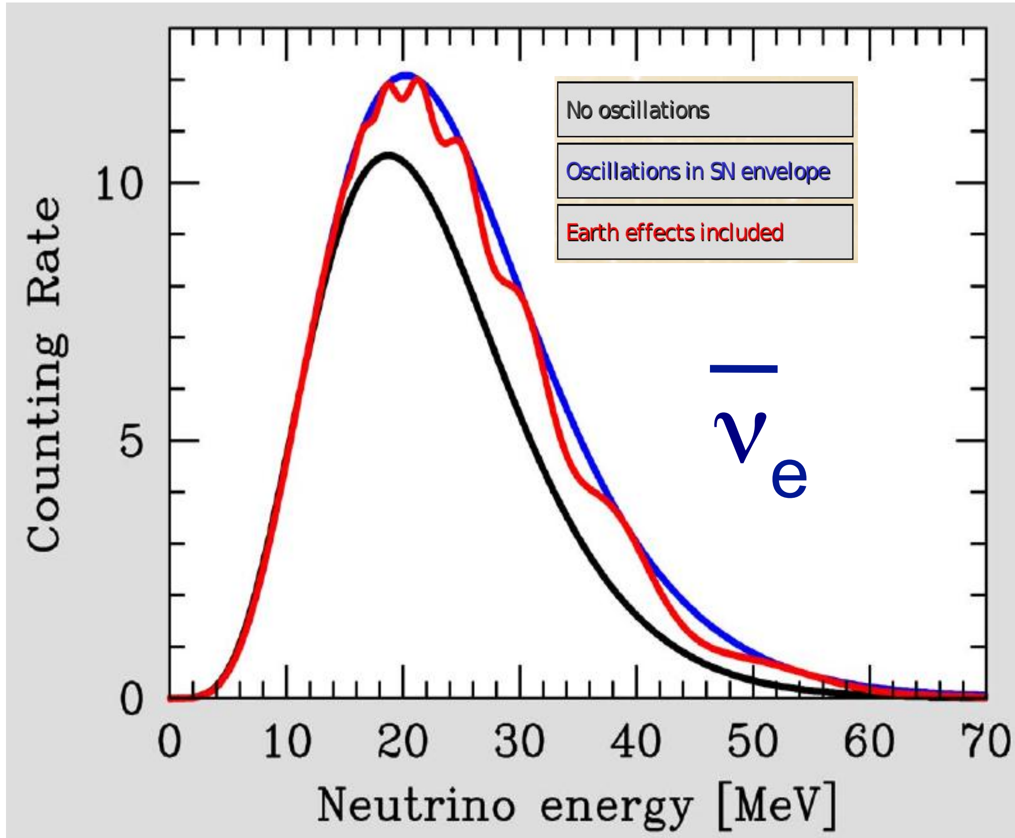
Experimentally, can we tell the difference?

Another possibility:

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

Kachelreiss, Raffelt et al.





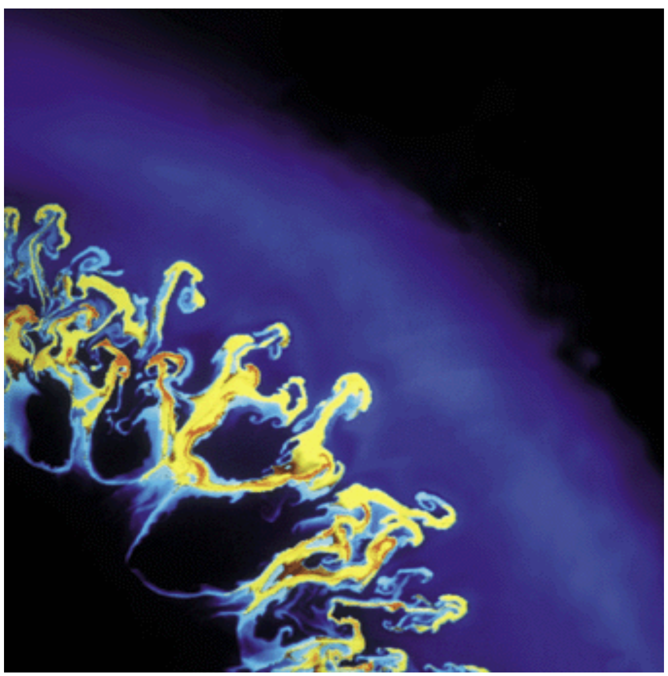
Compare fluxes of different flavors a different locations; or, look for spectral distortions in a single detector

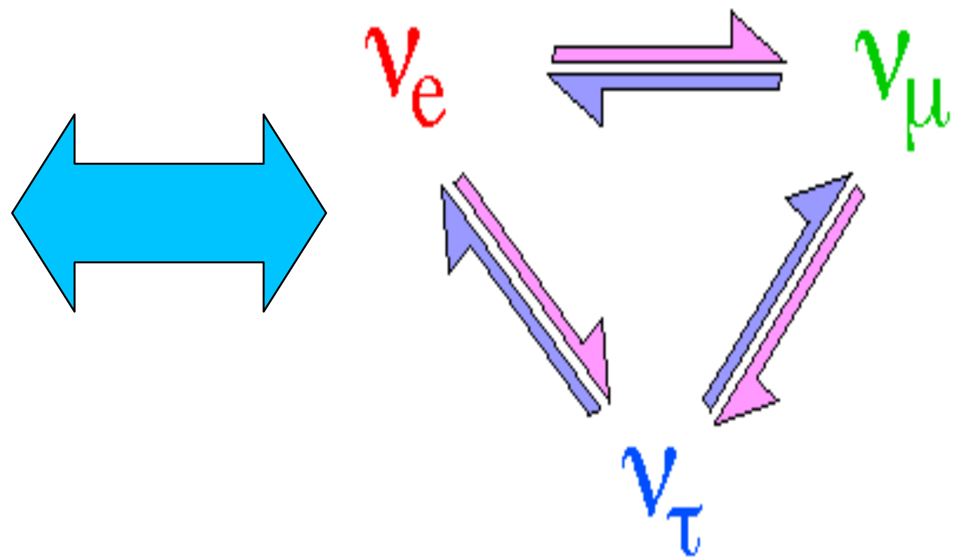
My message here:

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!





What do we want in a SN ν detector?

- Need ~ 1kton for ~ few 100 interactions for burst at the Galactic center (8.5 kpc away)

- Must have bg rate << signal rate in ~10 sec burst (typically easy for underground detectors, even thinkable at the surface)

Also want:
- Timing
- Energy resolution
- Pointing
- Flavor sensitivity

Sensitivity to different flavors *and ability to tag interactions* is key!

ν_e vs $\bar{\nu}_e$ vs ν_x

What do we want in a SN ν detector?

- Need ~ 1kton for ~ few 100 interactions for burst at the Galactic center (8.5 kpc away)

- Must have bg rate << signal rate in ~10 sec burst (typically easy for underground detectors, even thinkable at the surface)

Also want:

- Timing
- Energy resolution
- Pointing
- Flavor sensitivity

Require NC sensitivity for $\nu_{\mu,\tau}$, since SN ν energies below CC threshold

Sensitivity to different flavors *and ability to tag interactions* is key!

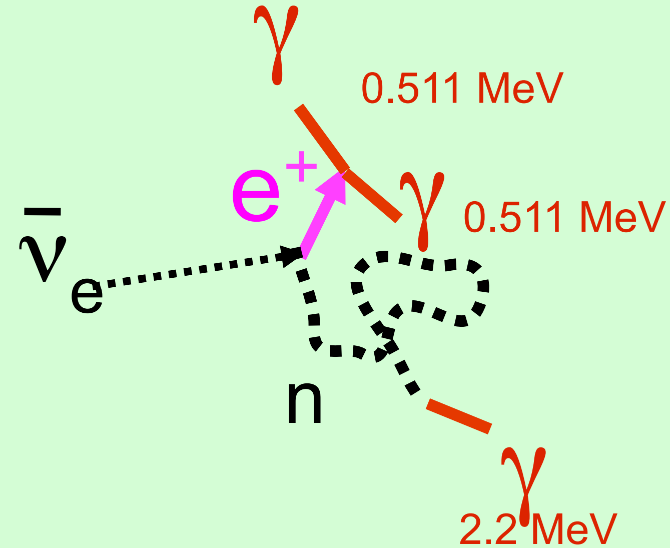
ν_e vs $\bar{\nu}_e$ vs ν_x

Neutrino interactions in the few-tens-of-MeV range

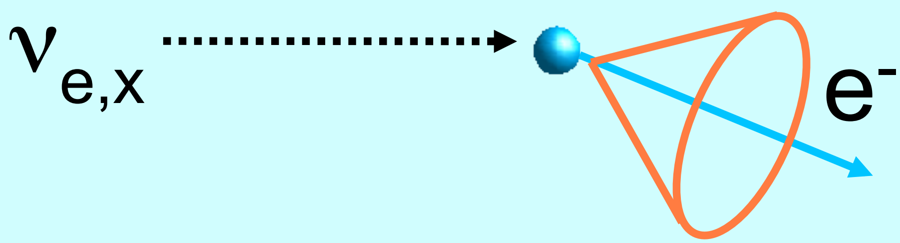
Inverse Beta Decay (CC)

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

In any detector with lots of free protons (e.g. water, scint) this dominates



Elastic scattering on atomic electrons



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

(useful for pointing)

CC and NC interactions on nuclei

$$\nu_e + (N,Z) \rightarrow (N-1, Z+1) + e^-$$

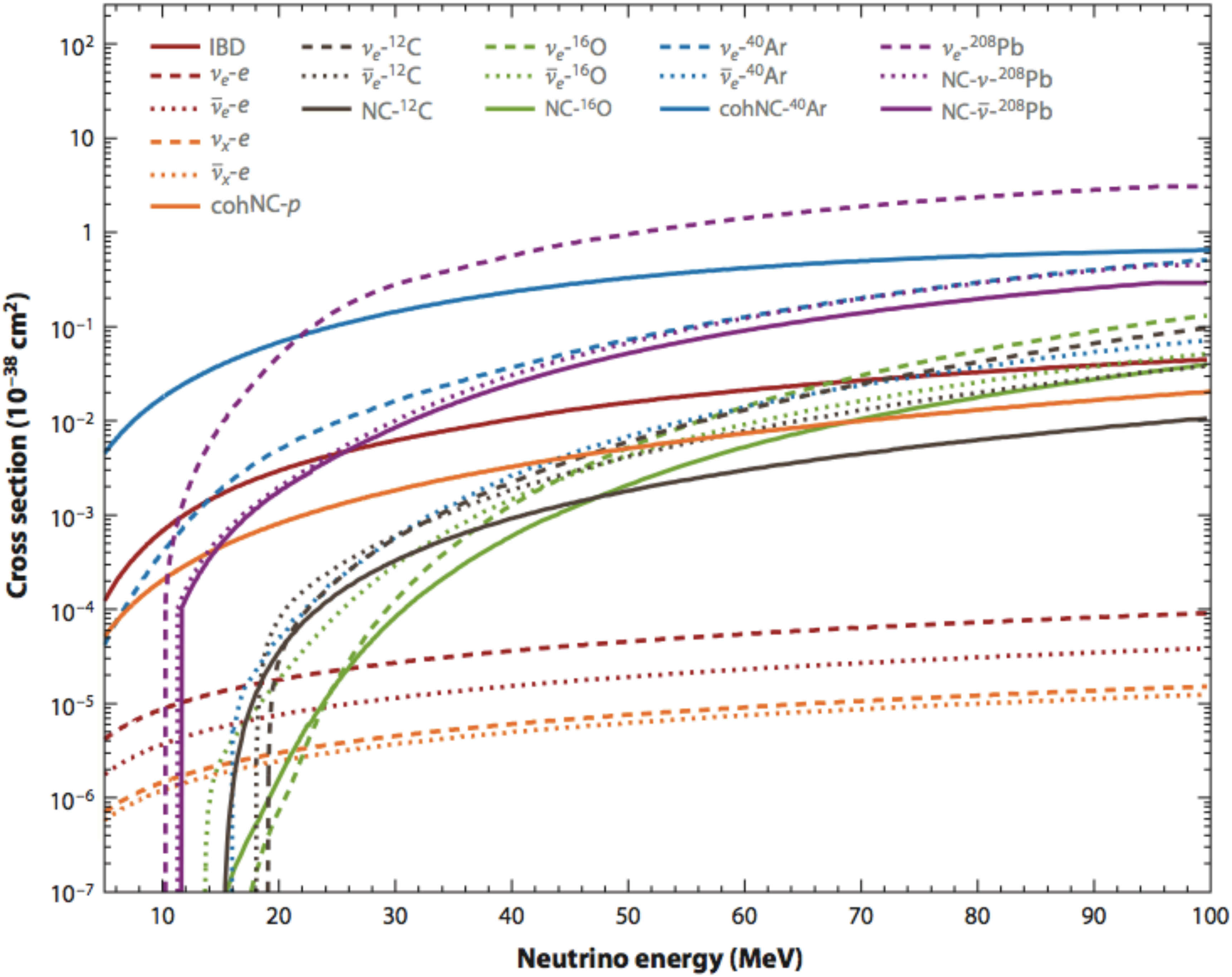
$$\bar{\nu}_e + (N, Z) \rightarrow (N+1, Z-1) + e^+$$

$$\nu_x + (A,Z) \rightarrow (A-1,Z) + n + \nu_x$$

$$\nu_x + (A,Z) \rightarrow (A,Z)^* + \nu_x$$

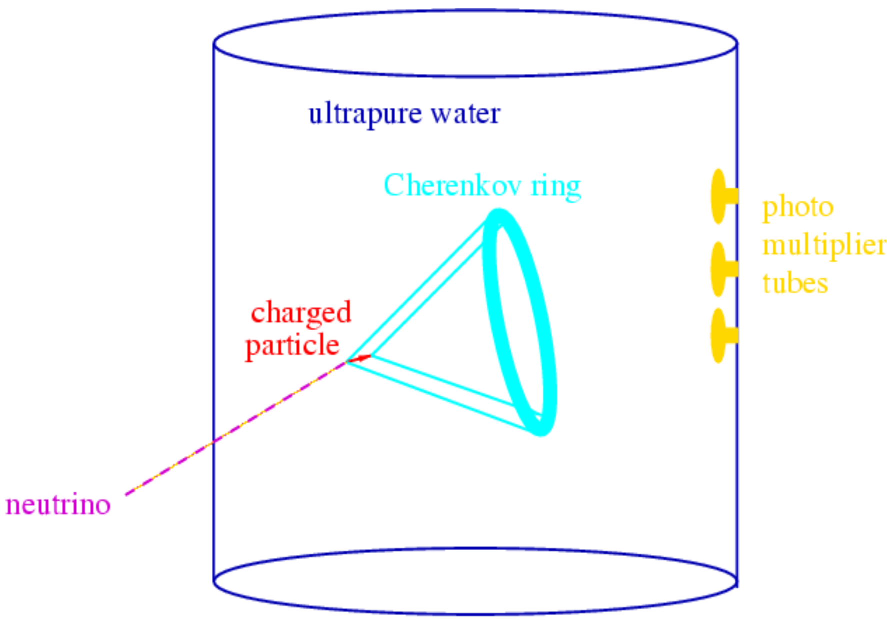
$$\hookrightarrow (A,Z) + \gamma$$

+ NC coherent scattering



IBD
ν_e-e
$\bar{\nu}_e$-e
ν_x-e
$\bar{\nu}_x$-e
cohNC-p
ν_e-^{12}C
$\bar{\nu}_e$-^{12}C
NC-^{12}C
ν_e-^{16}O
$\bar{\nu}_e$-^{16}O
NC-^{16}O
ν_e-^{40}Ar
$\bar{\nu}_e$-^{40}Ar
cohNC-^{40}Ar
ν_e-^{208}Pb
NC-ν-^{208}Pb
NC-$\bar{\nu}$-^{208}Pb
Cross section (10^{-38} cm^2)
Neutrino energy (MeV)

Water Cherenkov detectors



- few 100 events/kton

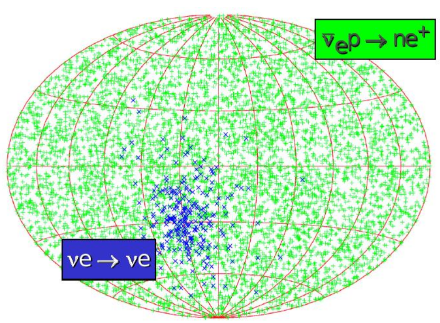
- typical energy threshold
  ~ several MeV makes
  2.2 MeV neutron tag difficult
  (unless Gd added)

Inverse Beta Decay (CC)

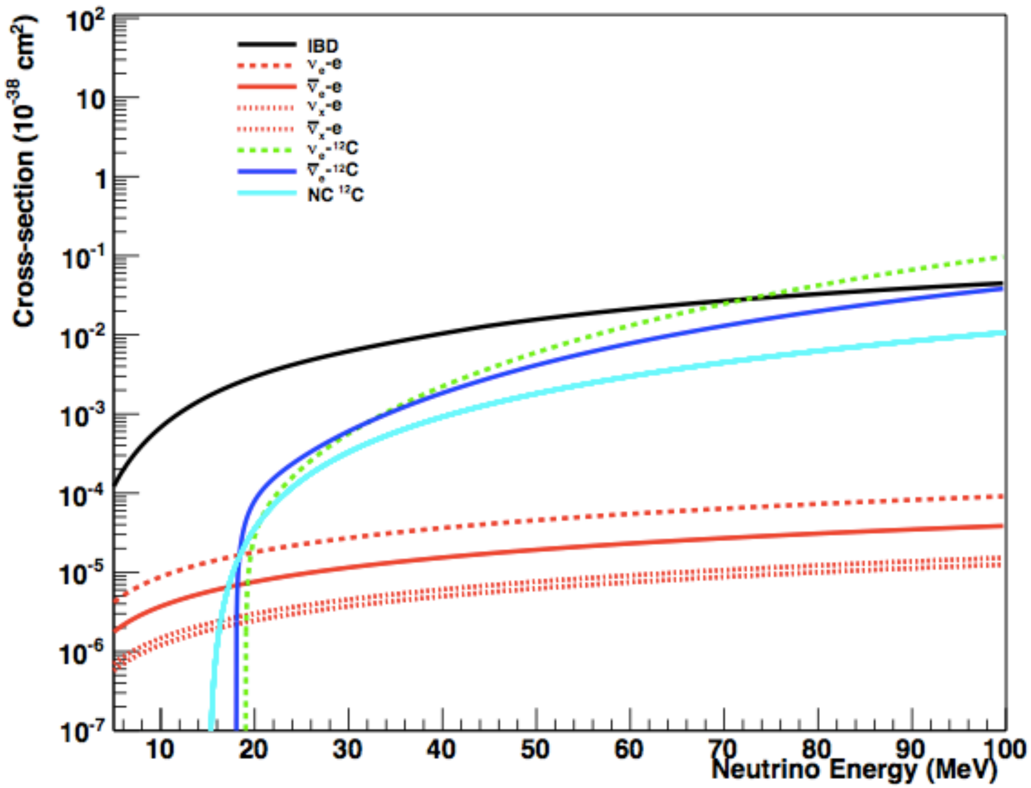
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

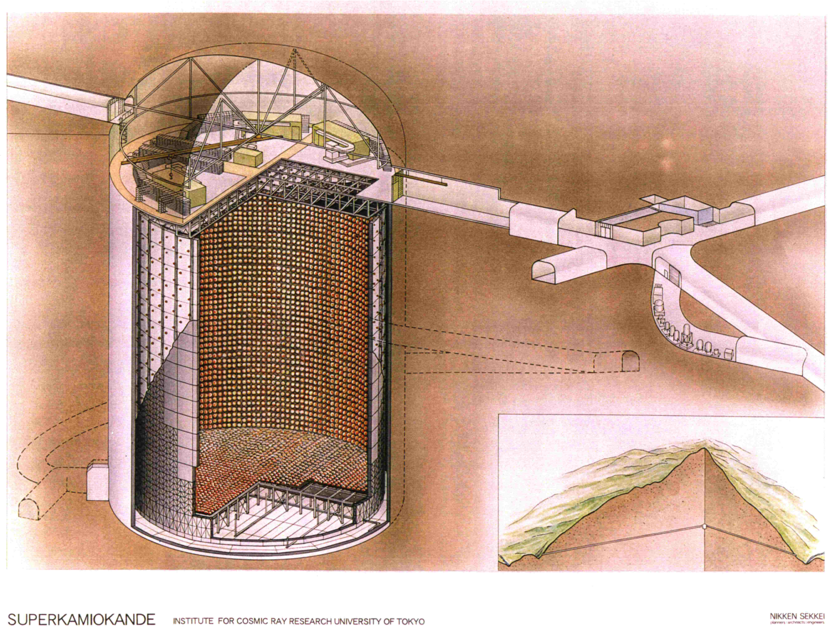
dominates

E_{thr}=1.8 MeV



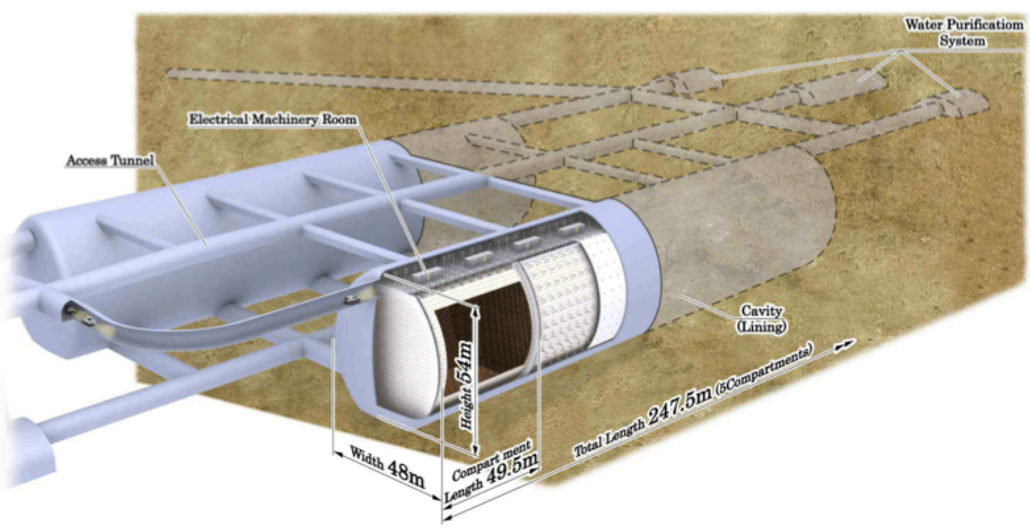
Some pointing from ES





Super-Kamiokande

Mozumi, Japan
22.5 kton fiducial volume
~5-10K events (mostly anti-nue)

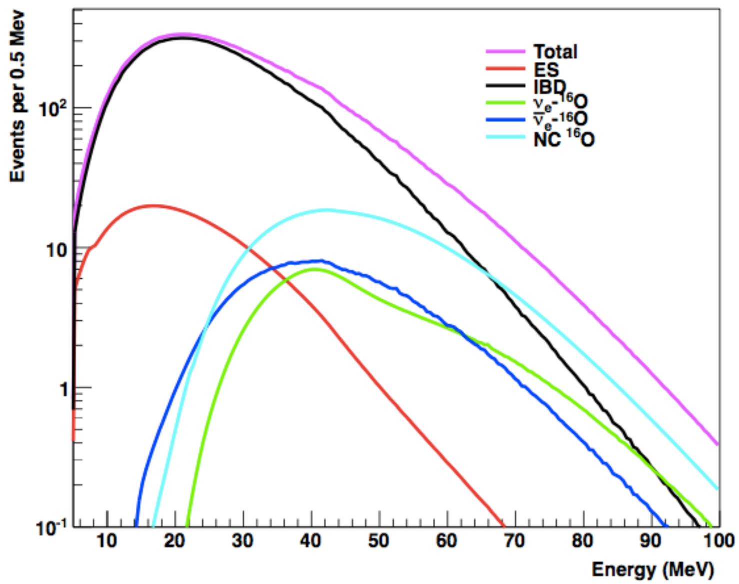


Hyper-Kamiokande

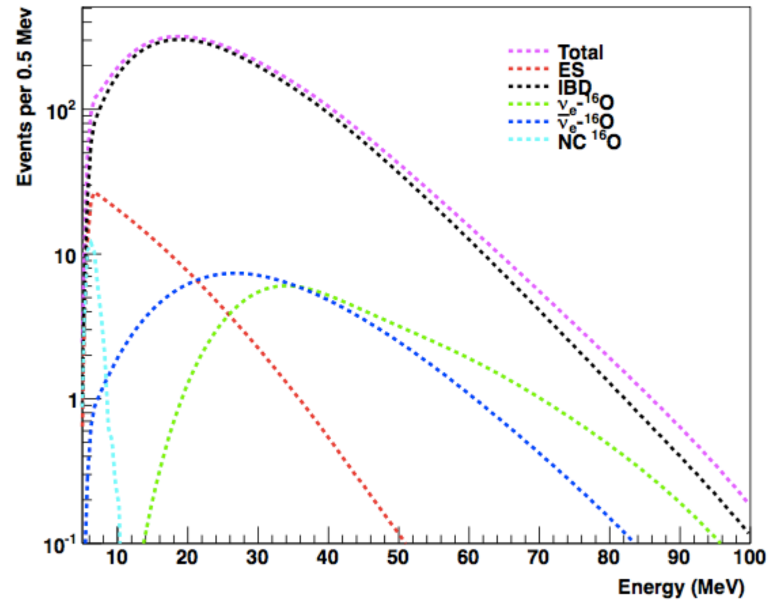
560 kton fiducial volume
Design & site-selection underway
~half photocoverage, but still good efficiency for SN

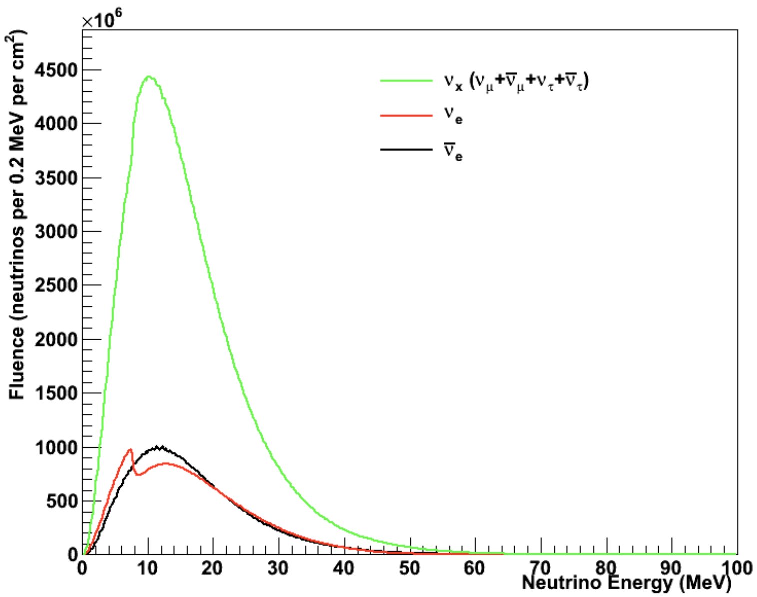
Signal in a water Cherenkov detector

Interactions, as a function of neutrino energy



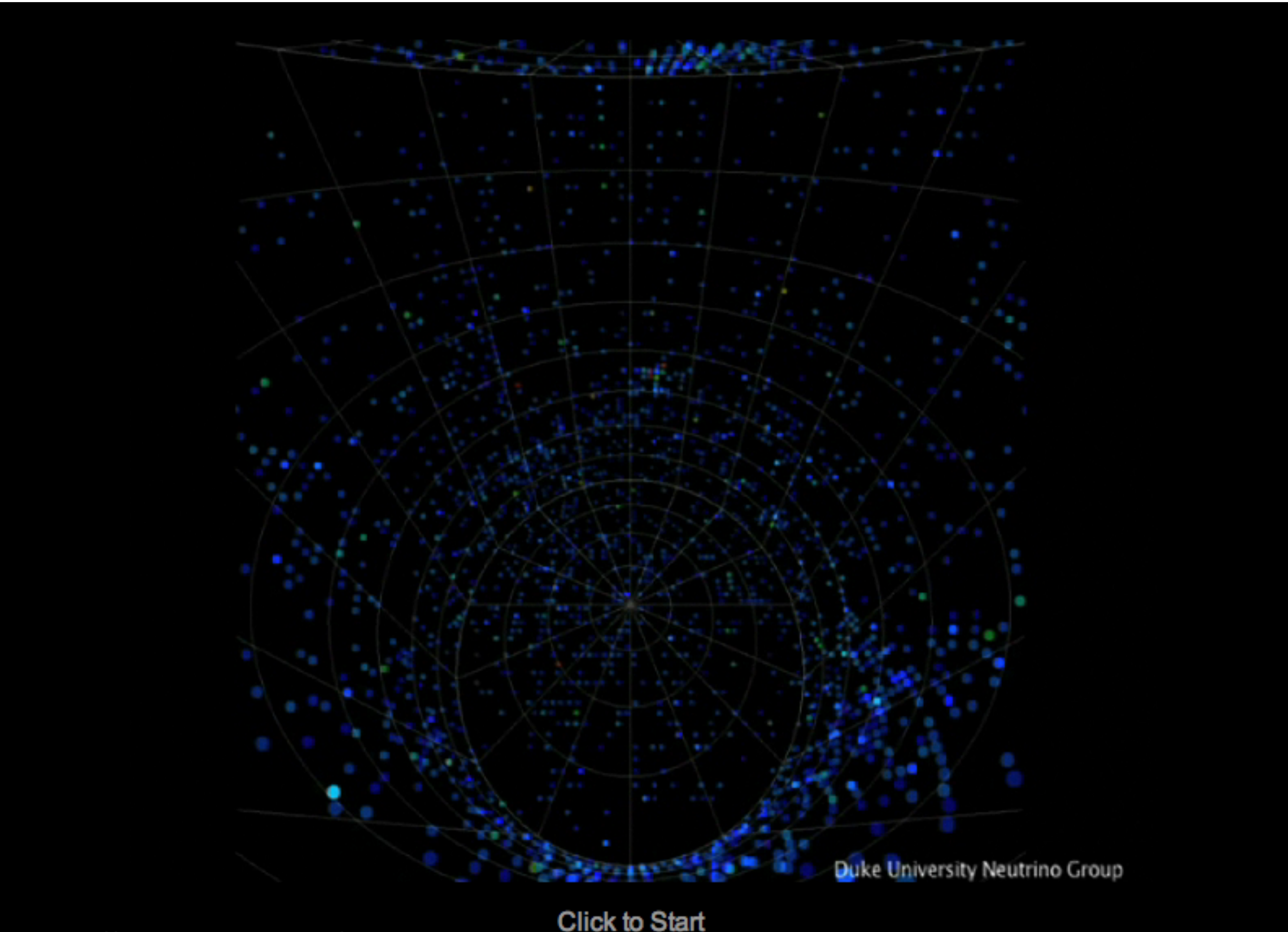
Events seen, as a function of observed energy





Channel	No of events (observed), GVKM 10 kpc, 100 kton	No. of events (observed), Livermore
IBD	16210	27116
ES	534	868
Nue-O16	378	88
Nuebar-O16	490	700
NC- O16	124	513
Total	17738	29284

Notes:
- **IBD overwhelmingly dominant**
- **NC component weak**
- **low energy features smeared out in ES**
- **large model variation in rate**



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

Possible enhancement:

use gadolinium to capture neutrons for tag of $\bar{\nu}_e$

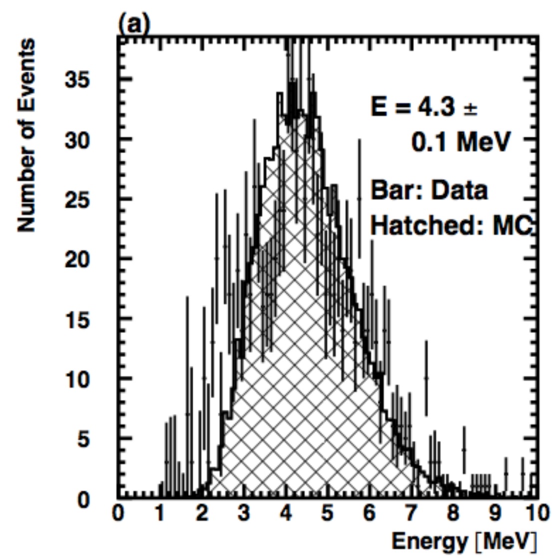
$$\bar{\nu}_e + p \longrightarrow e^+ + n$$

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

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

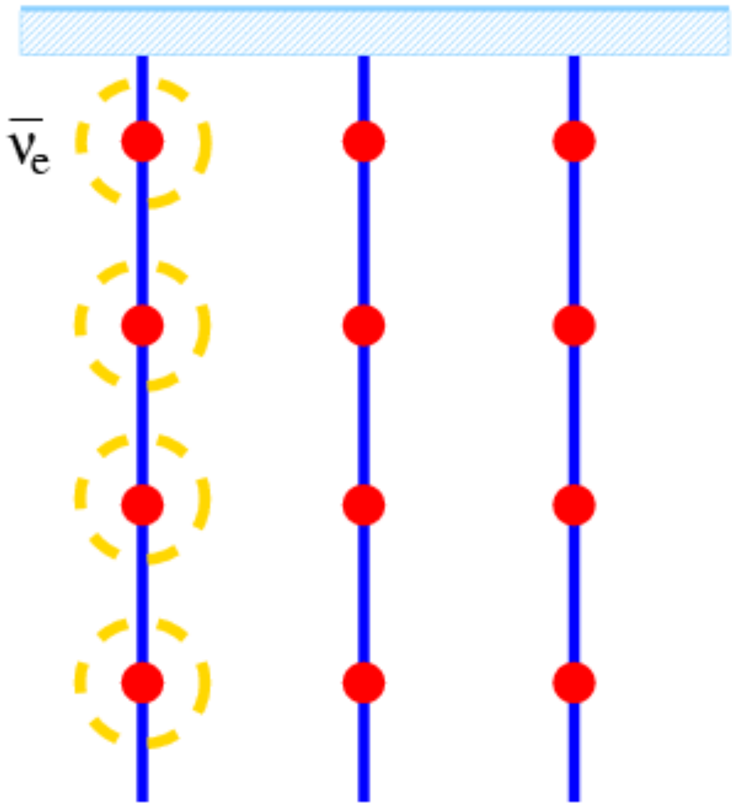
Previously used in small scintillator detectors; may be possible for large water detectors with Gd compounds in solution

Beacom & Vagins, hep-ph/0309300
H. Watanabe et al., Astropart. Phys. 31, 320-328 (2009), arXiv:0811.0735



About 4 MeV visible energy per capture;
~67% efficiency in SK
➔ *need good photocoverage*

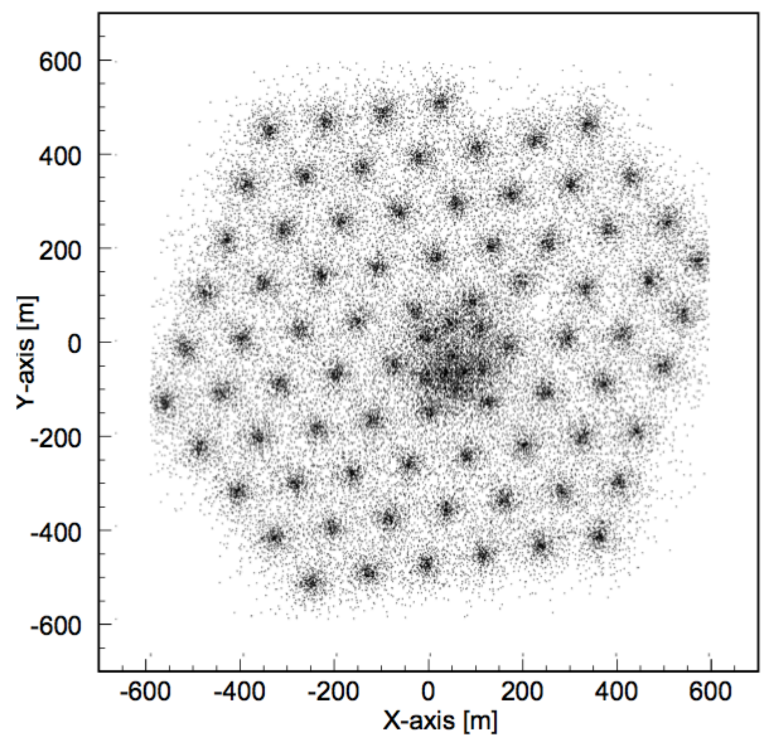
Long string water Cherenkov detectors



~kilometer long strings of PMTs in very clear water or ice

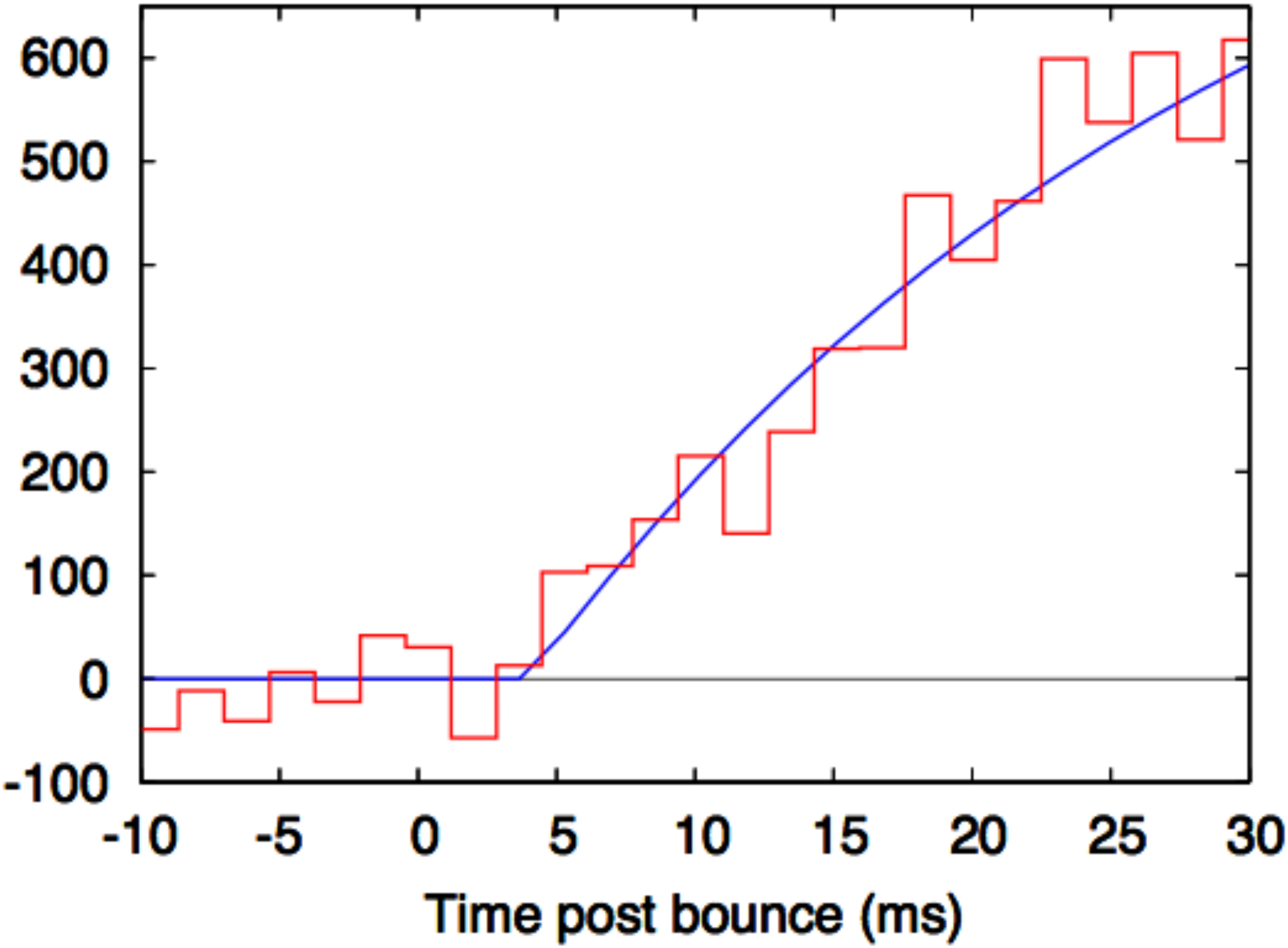
Nominally multi-GeV energy threshold... but, may see burst of low energy $\bar{\nu}_e$'s as *coincident increase in single PMT count rates* (M_{eff}~ 0.7 kton/PMT)

cannot tag flavor, or other interaction info, but gives overall rate and time structure



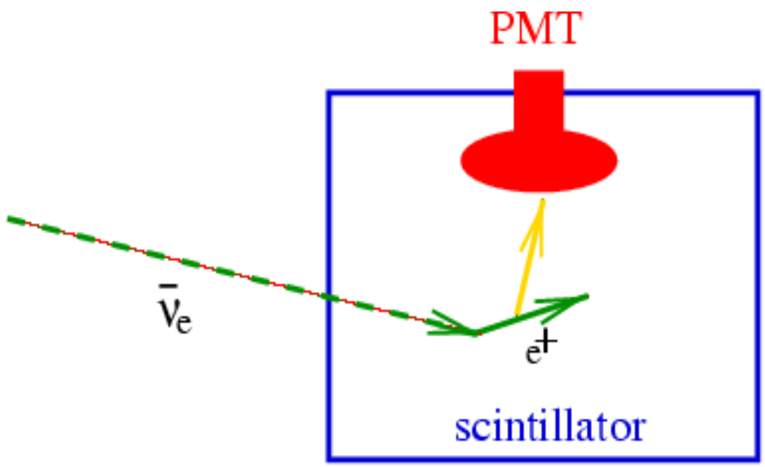
IceCube at the South Pole, Antares (+ PINGU...)

Halzen & Raffelt, arXiv:0908.2317



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

Scintillation detectors

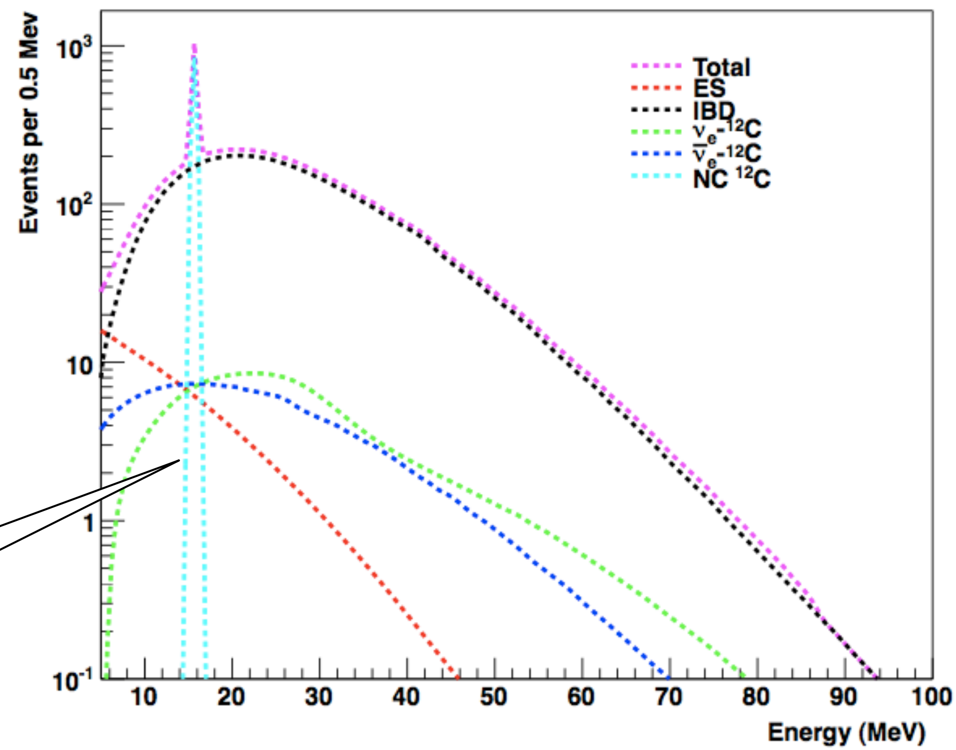


Liquid scintillator C_nH_{2n} volume surrounded by photomultipliers

LVD, KamLAND, Borexino, SNO+, (MiniBooNE)
+Double Chooz, Daya Bay and RENO

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

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

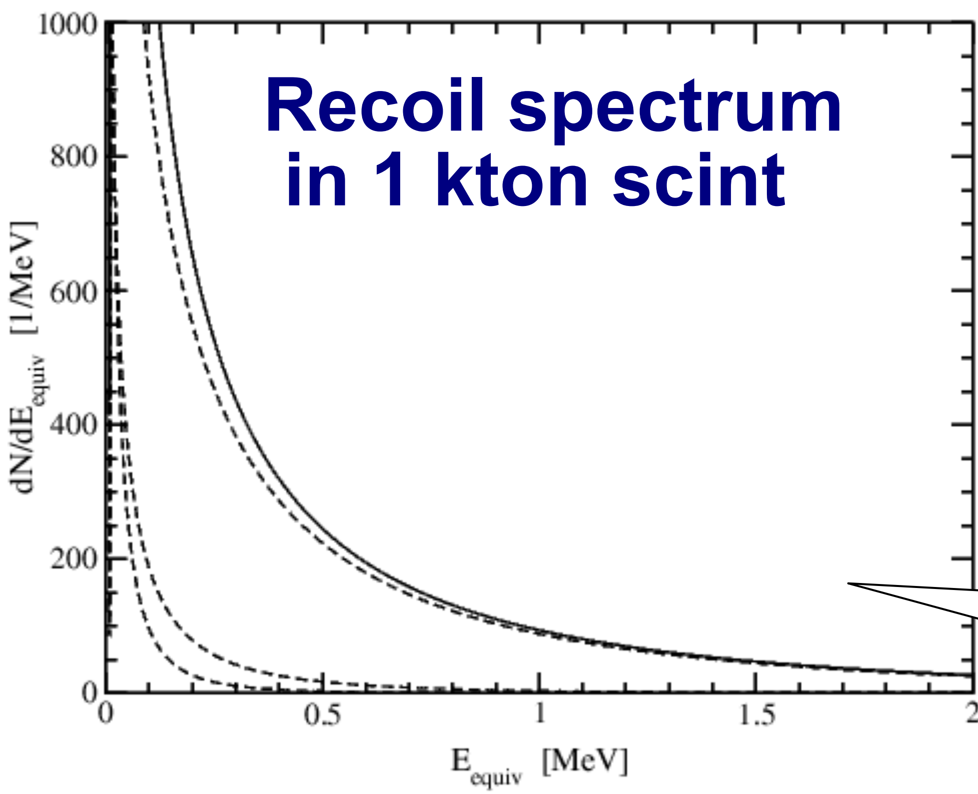


50 kt @ 10 kpc

NC neutrino-proton elastic scattering

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

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



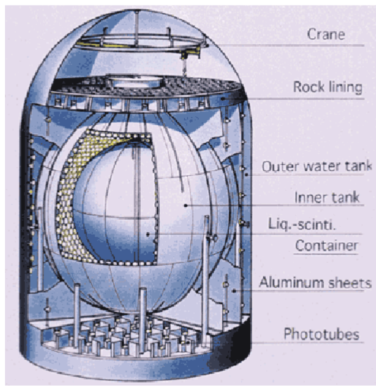
Expect ~few 100 events/kton for 8.5 kpc SN

Neutrino spectral information from recoil energies

J. Beacom et al., hep-ph/0205220

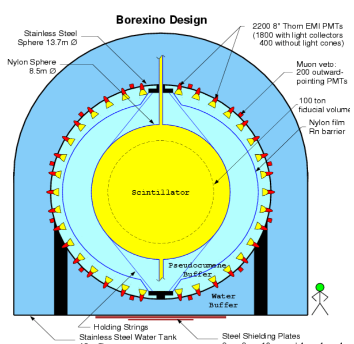
Current and near-future scintillator detectors

KamLAND
(Japan)
1 kton

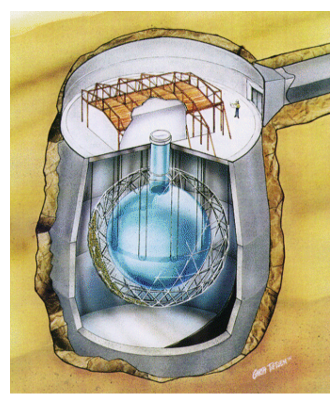


LVD
(Italy)
1 kton

Borexino
(Italy)
0.33 kton

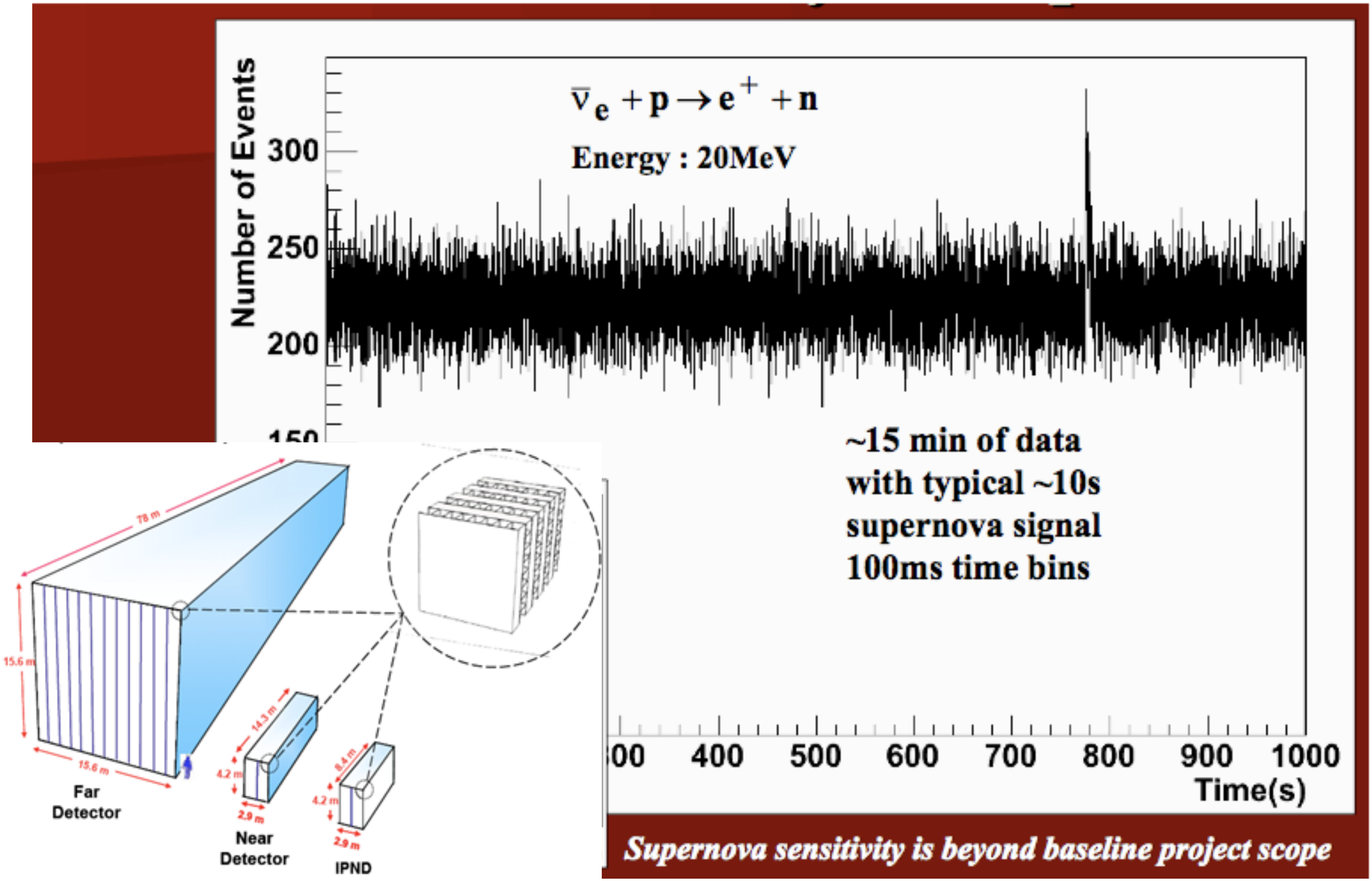


SNO+
(Canada)
1 kton



NOνA: long baseline oscillation experiment (Ash River, MN)
15 kton scintillator, near surface

K. Arms, CIPANP '09



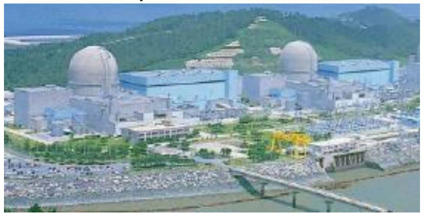
Although on the surface, reactor experiments w/ Gd-doped scintillator will record events

Detector	Type	Location	Mass (ton)	Events @ 10 kpc
Double Chooz	Scintillator	France	20	**7**
RENO	Scintillator	South Korea	30	**11**
Daya Bay	Scintillator	China	160	**58**

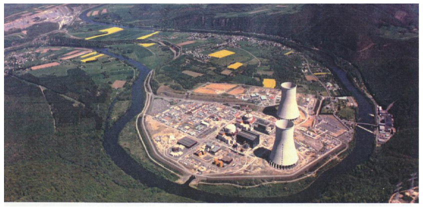
Although signal numbers are small, for low bg rates and good tagging, there will be good S/B

Also: coincidence between multiple detectors will help for a SN trigger

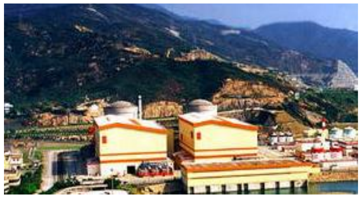
RENO, South Korea



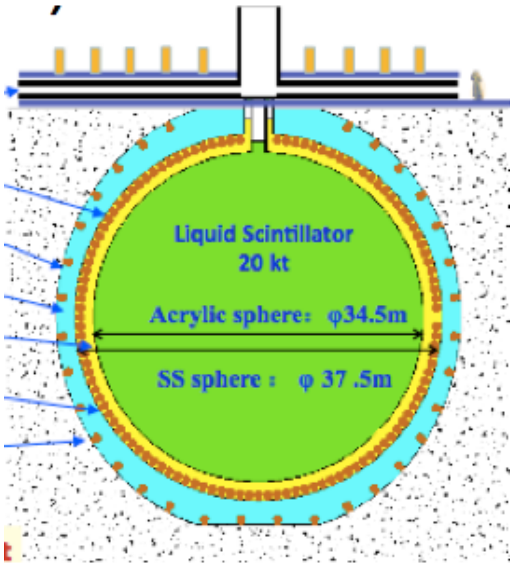
Double CHOOZ, France

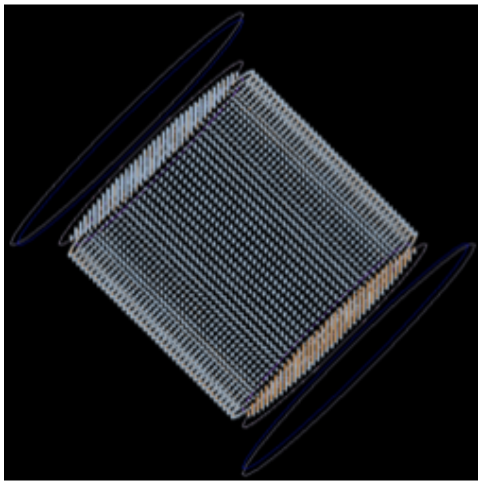


Daya Bay, China



Next-generation detectors





JUNO
(China)
20 kton

RENO-50
(S. Korea)
18 kton

LENA
(Finland)
50 kton

For most existing (and planned) large detectors, inverse beta decay dominates, (and is potentially taggable) so primary sensitivity is to $\bar{\nu}_e$

CC and NC interactions on nuclei play a role, too

(cross-sections smaller for bound nucleons)

$\nu_e + n \rightarrow p + e^-$: $\nu_e + (N,Z) \rightarrow (N-1, Z+1) + e^-$

$\bar{\nu}_e + p \rightarrow n + e^+$: $\bar{\nu}_e + (N, Z) \rightarrow (N+1, Z-1) + e^+$

$\nu_x + (A,Z) \rightarrow (A-1,Z) + n + \nu_x$

$\nu_x + (A,Z) \rightarrow (A,Z)^* + \nu_x$

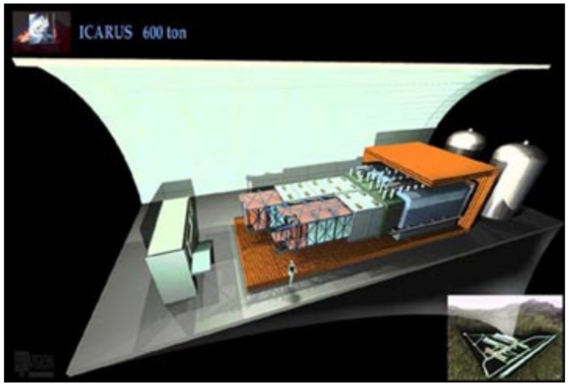
$\hookrightarrow (A,Z) + \gamma$

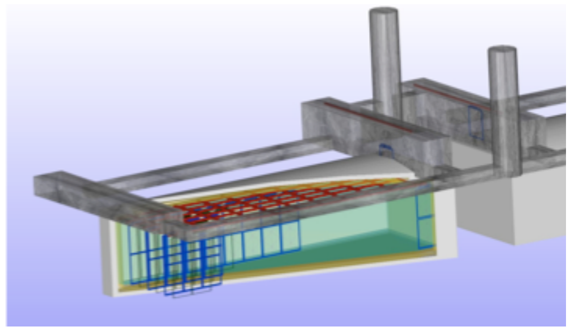
Rates and observables depend on specific nucleus: need measurements!

Observables for tagging
- charged lepton $e^{+/-}$
- possibly ejected nucleons
- possibly de-excitation γ's

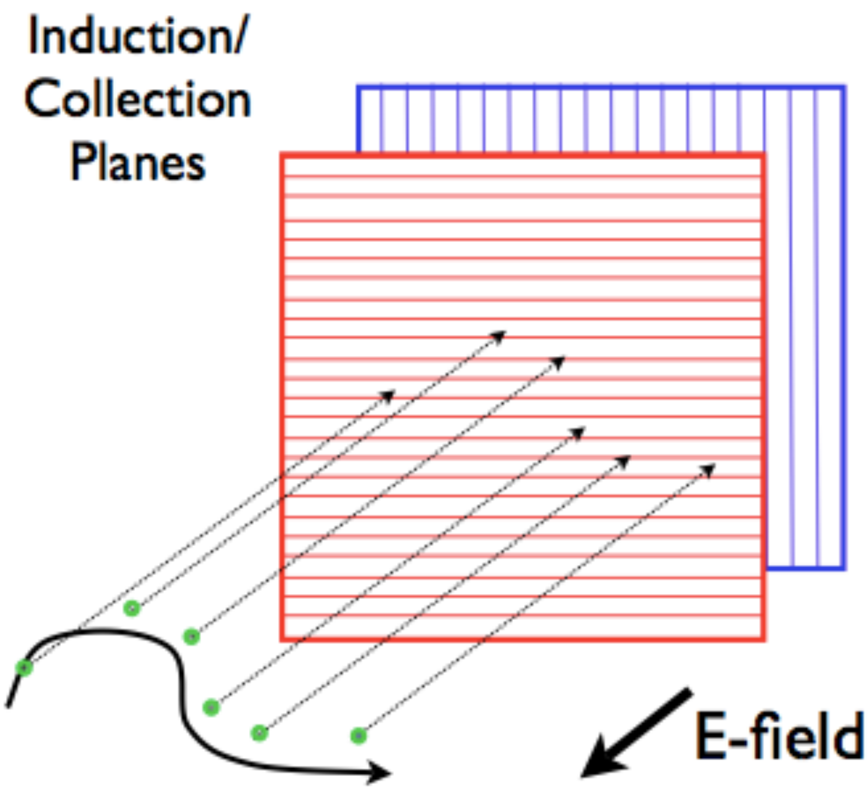
Liquid argon time projection chambers

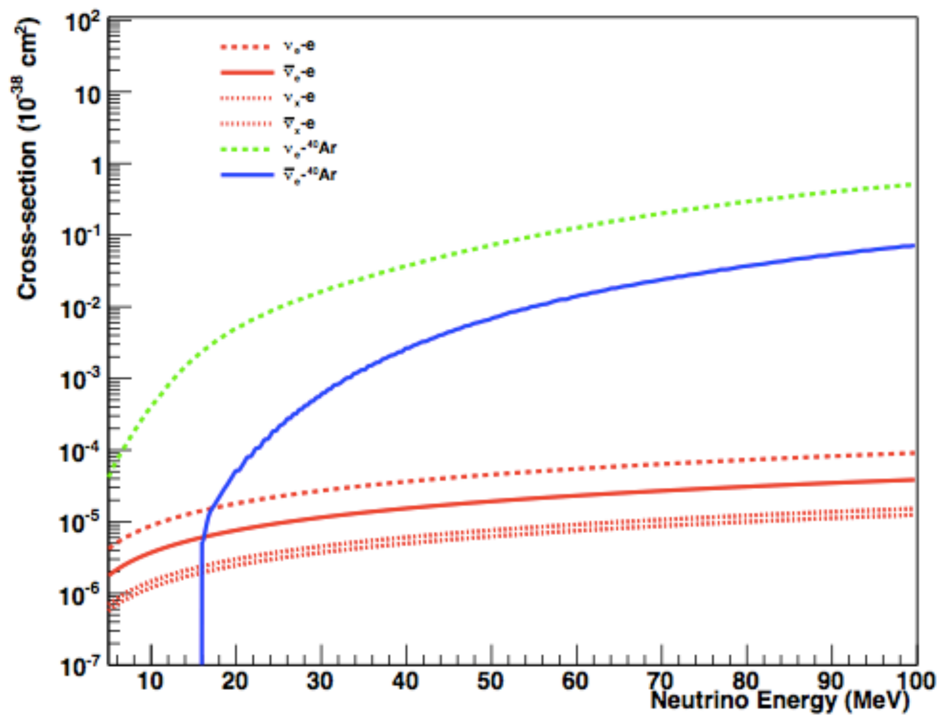
e.g. Icarus, LBNE LAr, MicroBooNE





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





Low energy neutrino interactions in argon

Charged-current absorption

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

Dominant

$$\bar{\nu}_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*$$

Neutral-current excitation

$$\nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*$$

Insufficient info in literature; ignoring for now

Elastic scattering

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

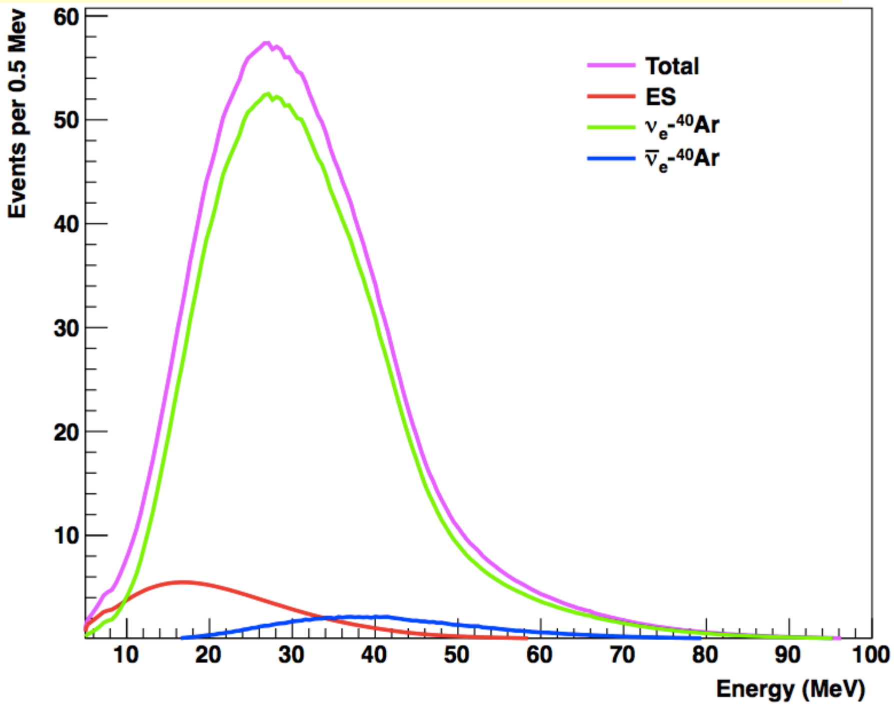
Can use for pointing

- In principle can tag modes with
- deexcitation gammas (or lack thereof)...

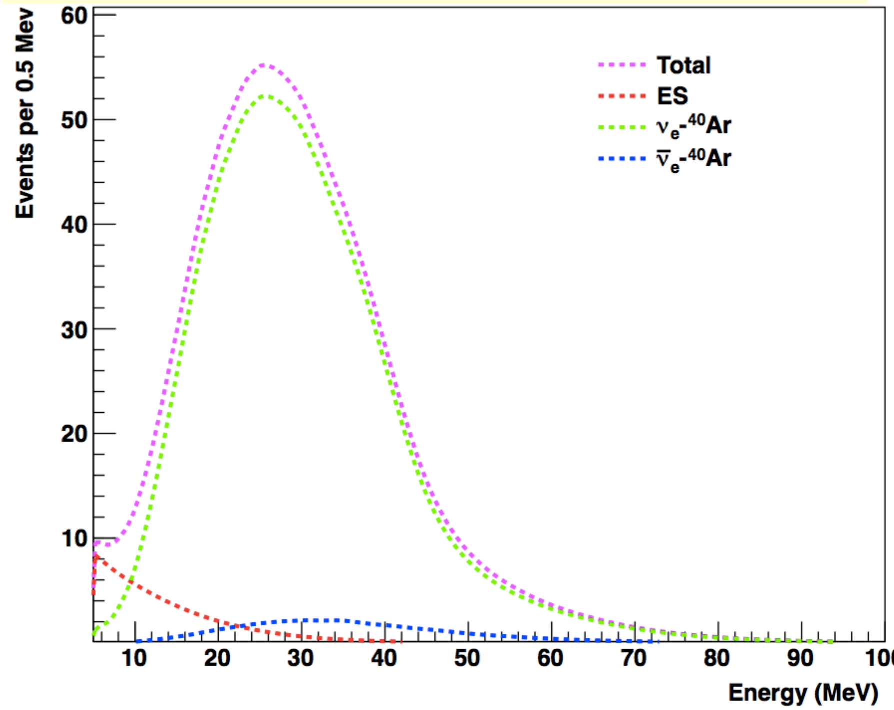
Expected signal in LAr

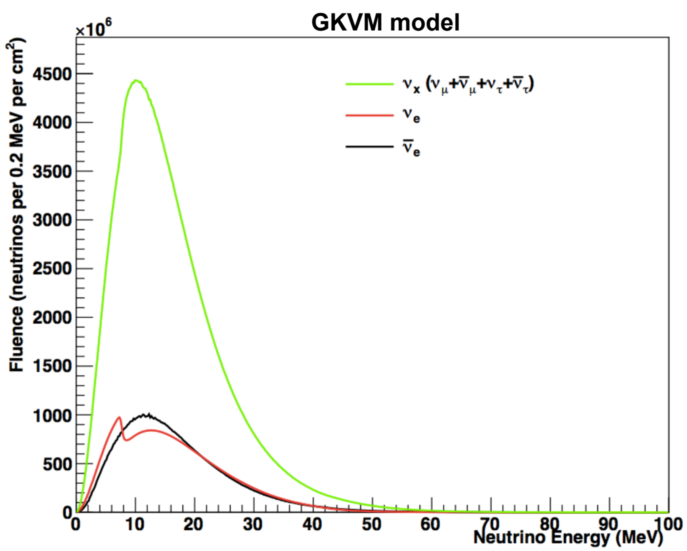
SN @ 10 kpc

Interactions, as a function of neutrino energy



Events seen, as a function of observed energy





Channel	No of events (observed), GKVM, 34 kton	No. of events (observed), Livermore
Nue-Ar40	2848	2308
Nuebar-Ar40	134	194
ES	178	296
Total	**3160**	**2798**

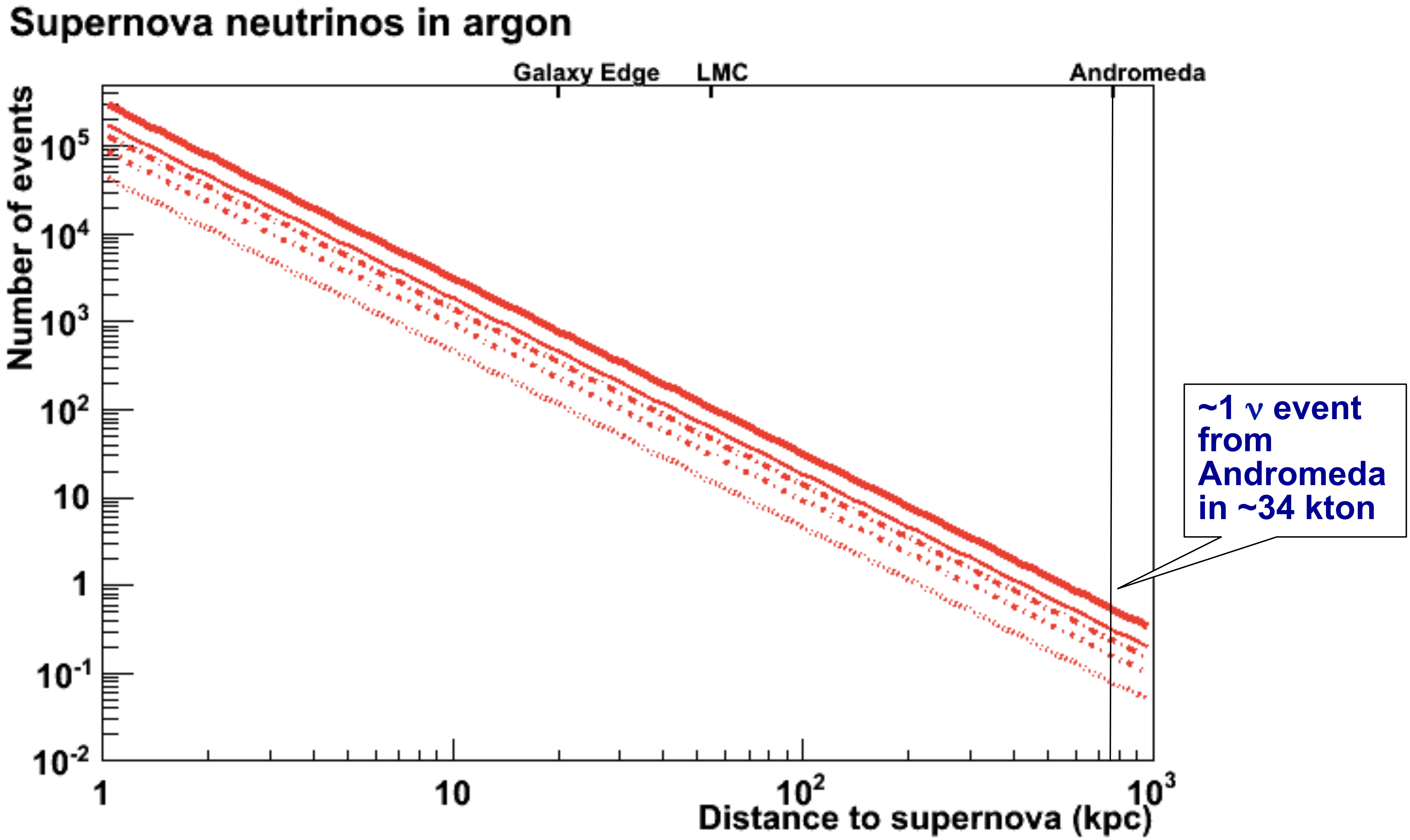
Dominated by ν_e

Long-Baseline Neutrino Experiment

Long-Baseline Neutrino Experiment

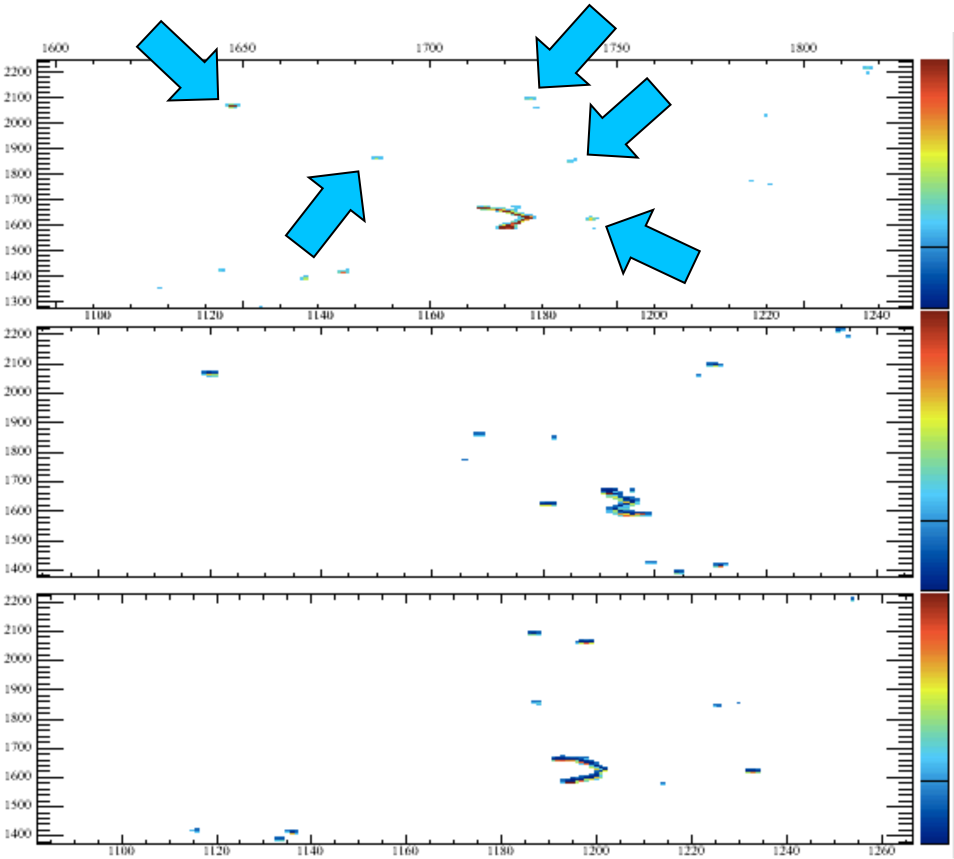
34 kton LArTPC in SD @ 4850 ft
1300 km baseline
New 700 kW beam
(CD1 for 10kt on the surface)

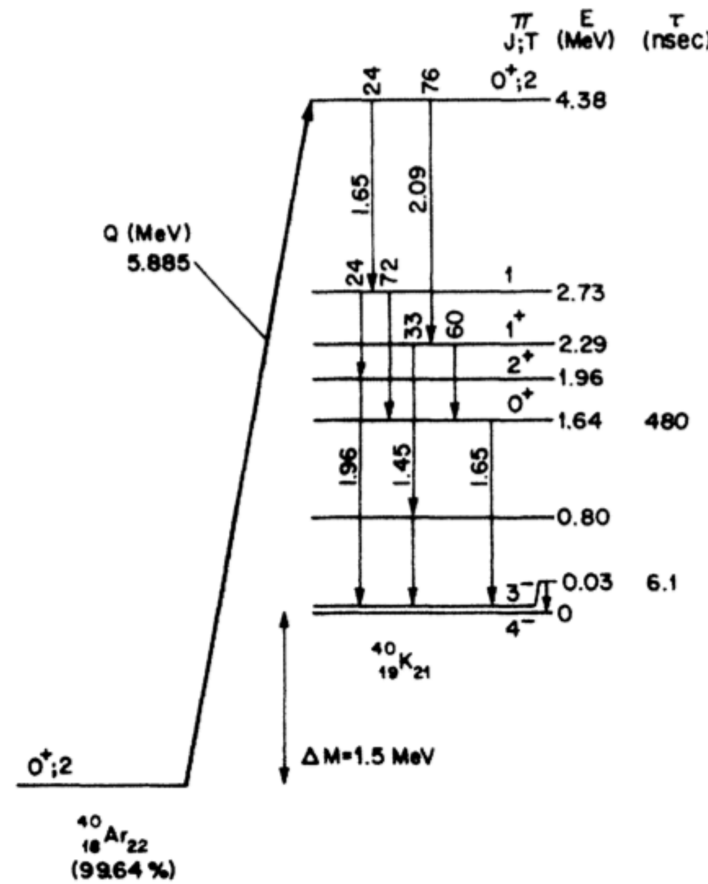
Signal rates vs distance for LBNE configurations



5, 10, 15, 20, 34 kton

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





20 MeV ν_e , 14.1 MeV e^-, Raghavan model gammas
MicroBooNE geometry, fixed position (0,0,0)

HALO at SNOLab

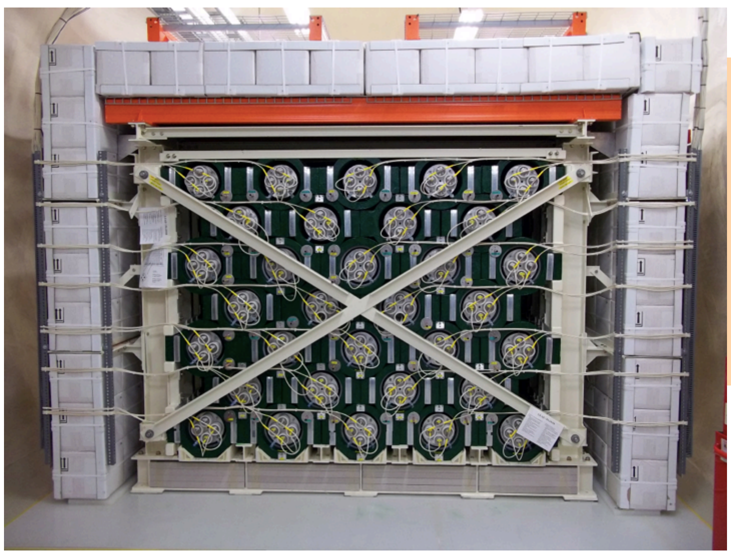
$\nu_e + {}^{208}Pb \rightarrow {}^{208}Bi^* + e^-$ CC

↘ 1n, 2n emission

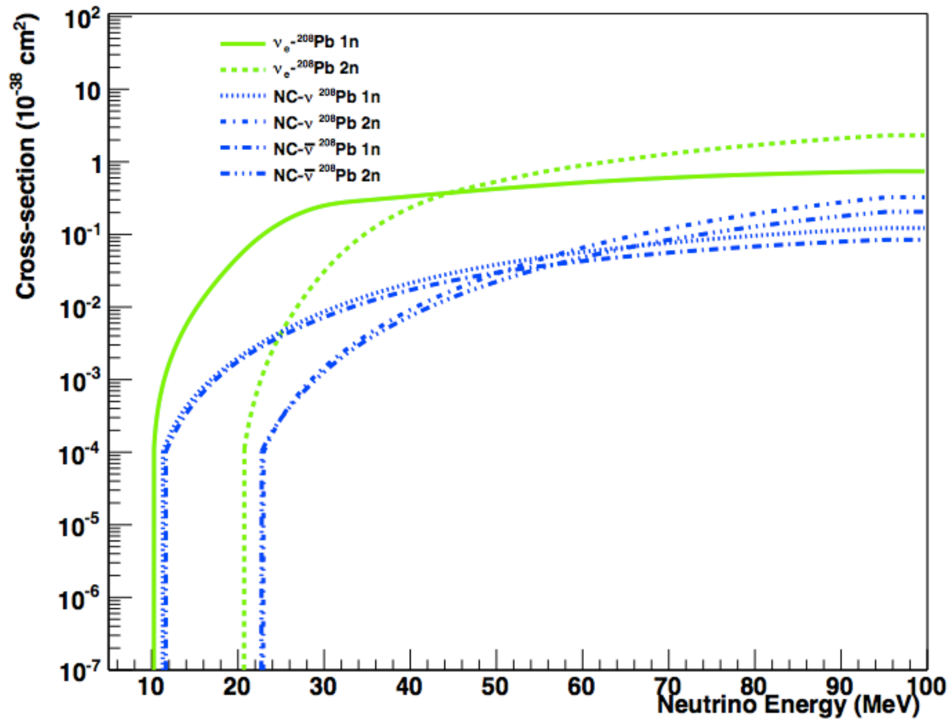
$\nu_x + {}^{208}Pb \rightarrow {}^{208}Pb^* + \nu_x$ NC

↘ 1n, 2n, γ emission

Relative 1n/2n rates sharply dependent on ν energy
$\Rightarrow$ spectral sensitivity
(oscillation sensitivity)



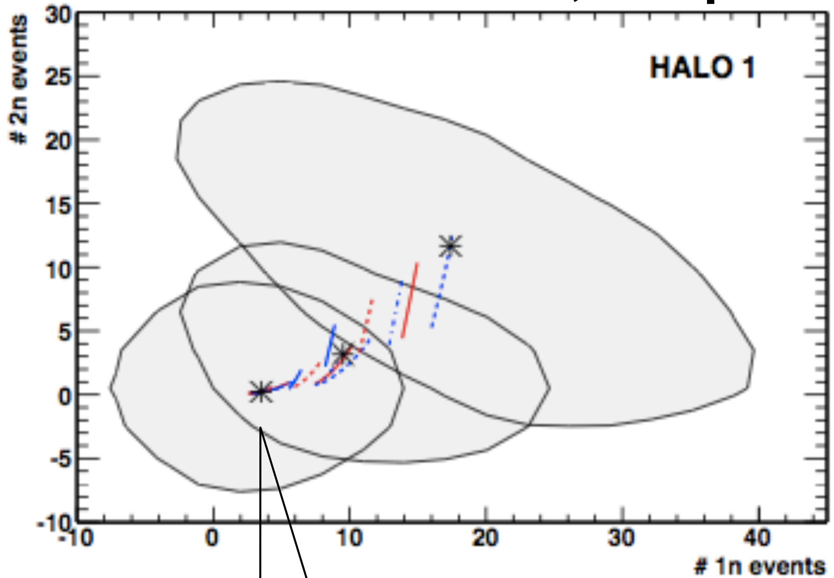
HALO operational as of May 2012!



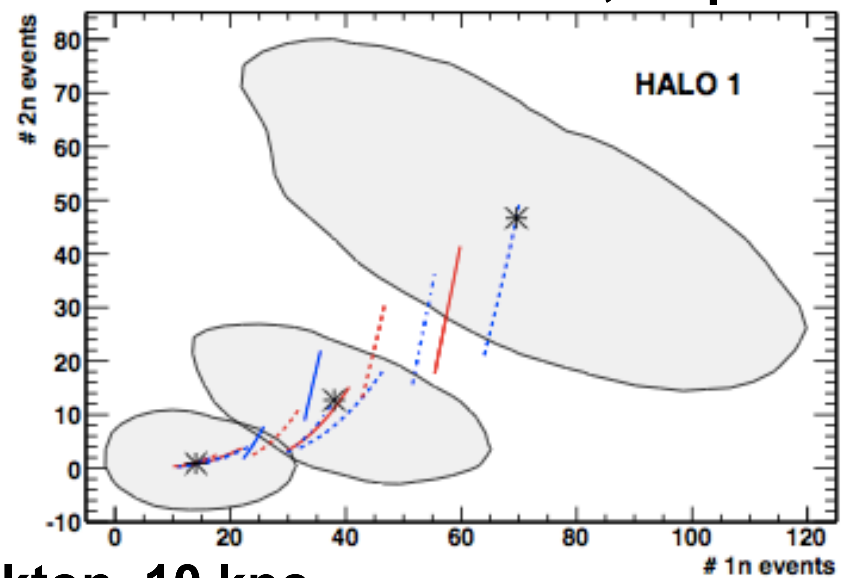
SNO ^3He counters + 79 tons of Pb: ~1-40 events @ 10 kpc

HALO sensitivity

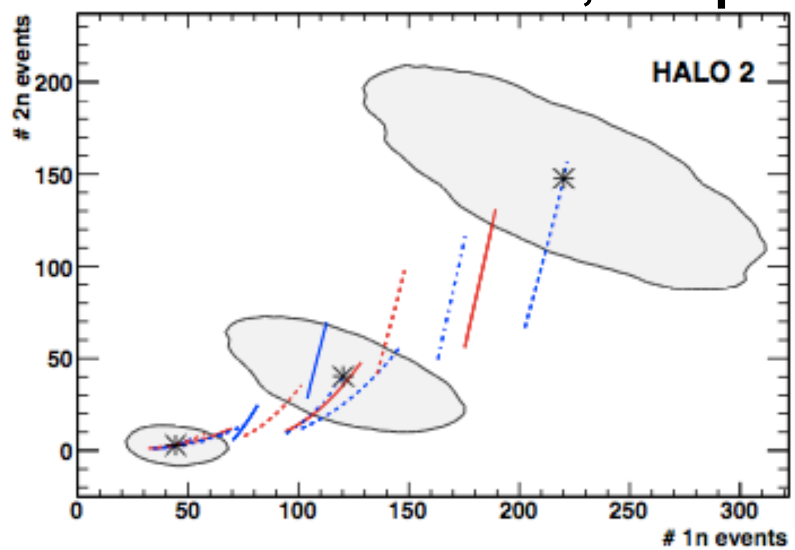
79 tons, 10 kpc



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

Neutrino-nucleus NC elastic scattering in ultra-low energy detectors

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

C. Horowitz et al., astro-ph/0302071

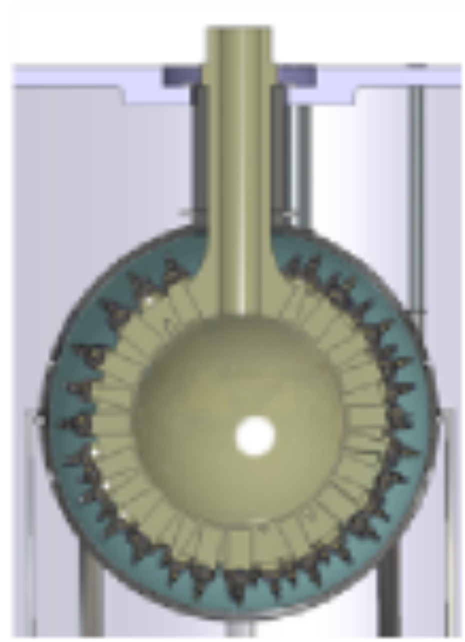
High x-scn but *very* low recoil energy (10's of keV)

$\Rightarrow$ possibly observable in solar pp/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: $\bar{\nu}_e + p \rightarrow e^+ + n$

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

KS, arXiv:1205.6003

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

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
$\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + {}^{12}\mathrm{N}^{(*)}$	C, N, G	3/9
$\bar{\nu}_e + {}^{12}\mathrm{C} \rightarrow e^+ + {}^{12}\mathrm{B}^{(*)}$	C, N, G, A	6/8
$\nu_x + {}^{12}\mathrm{C} \rightarrow \nu_x + {}^{12}\mathrm{C}^*$	G, N	68/25
$\nu_e + {}^{16}\mathrm{O} \rightarrow e^- + {}^{16}\mathrm{F}^{(*)}$	C, N, G	1/4
$\bar{\nu}_e + {}^{16}\mathrm{O} \rightarrow e^+ + {}^{16}\mathrm{N}^{(*)}$	C, N, G	7/5
$\nu_x + {}^{16}\mathrm{O} \rightarrow \nu_x + {}^{16}\mathrm{O}^*$	G, N	50/12
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	C, G	67/83
$\bar{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	C, A, G	5/4
$\nu_e + {}^{208}\mathrm{Pb} \rightarrow e^- + {}^{208}\mathrm{Bi}^*$	N	144/228
$\nu_x + {}^{208}\mathrm{Pb} \rightarrow \nu_x + {}^{208}\mathrm{Pb}^*$	N	150/55
$\nu_x + A \rightarrow \nu_x + A$	C	9,408/4,974

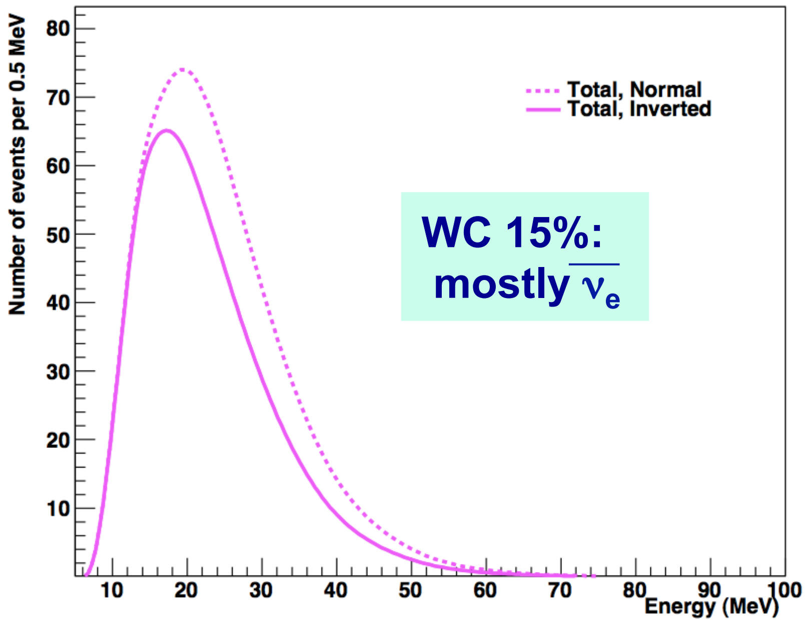
(Livermore/GKVM)

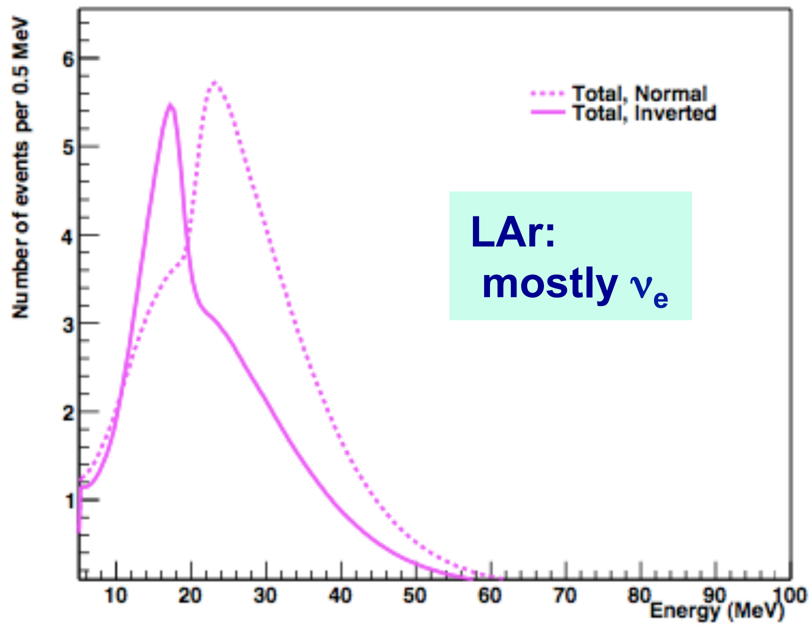
C: energy loss of a charged particle
N: neutrons
A: annihilation gammas
G: de-excitation gammas

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 is good...

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

Comments on extracting information from the supernova signal:

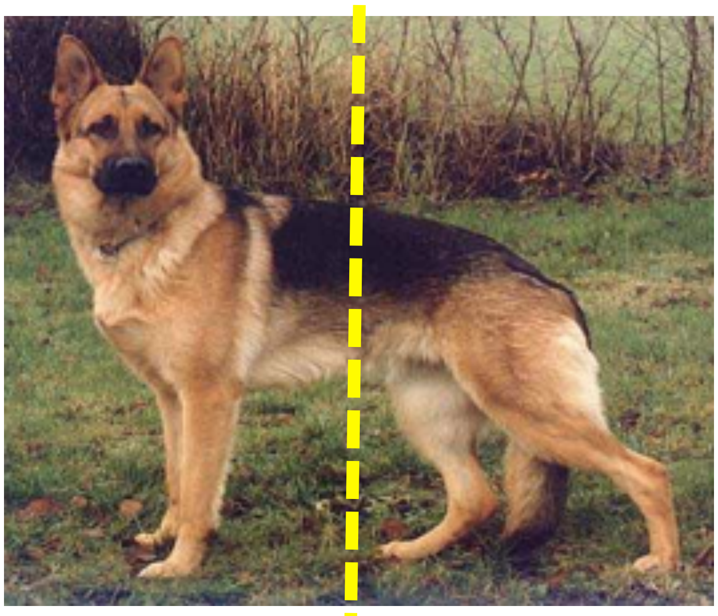
The signatures of physics and astrophysics are `rich': many complex features in energy spectrum, flavor and time evolution depending on progenitor, SN type, oscillation parameters, model assumptions...

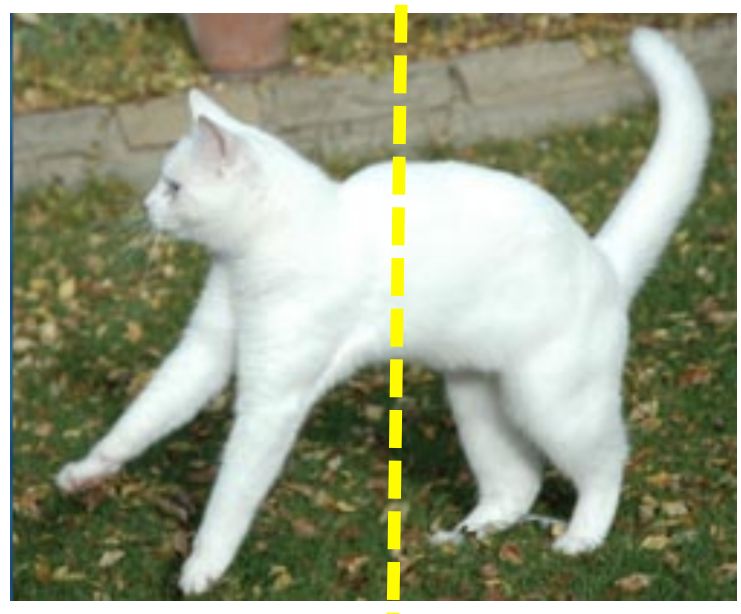
... models aren't identical, and individual SN explosions may also vary but there *are* generic features of e.g. mass hierarchy

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

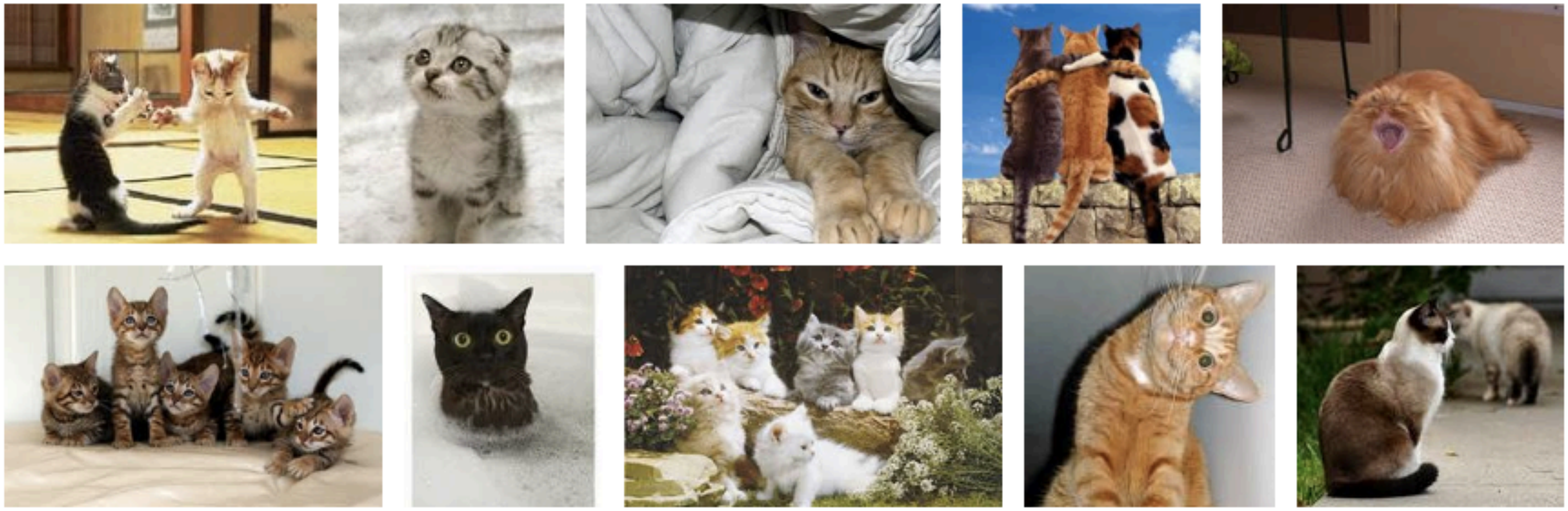
If your algorithm works, that's a good sign, and you get a reasonable suggestion about whether the front or the back picture is more useful, but:

- 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...



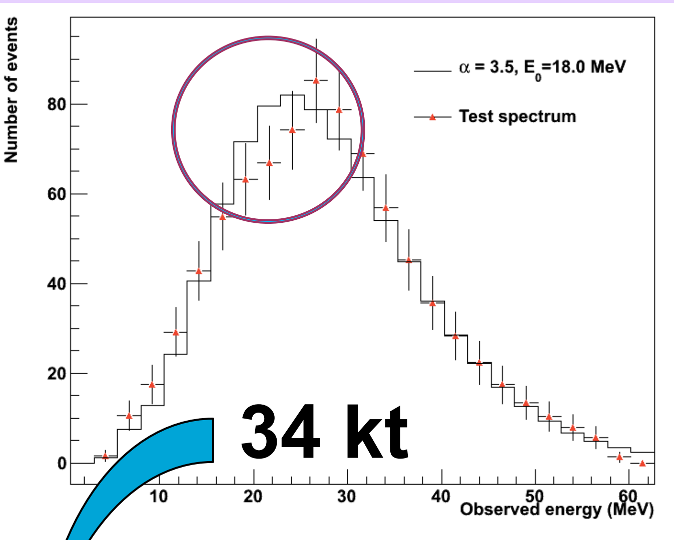
A wide sampling of models is needed

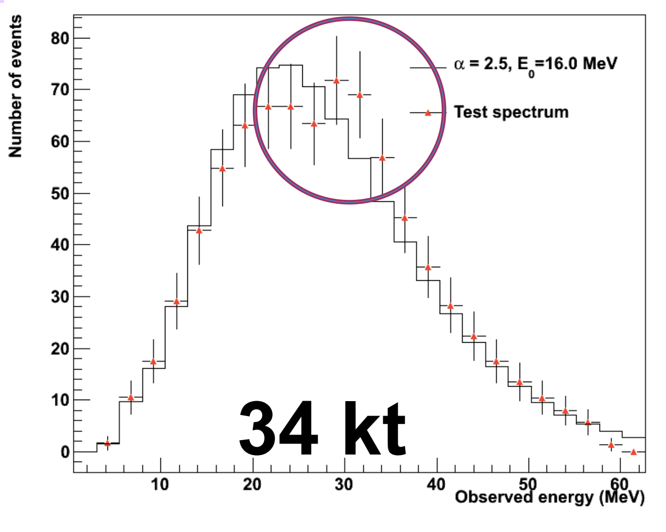
Hierarchy signature in SN shock w/LAr

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

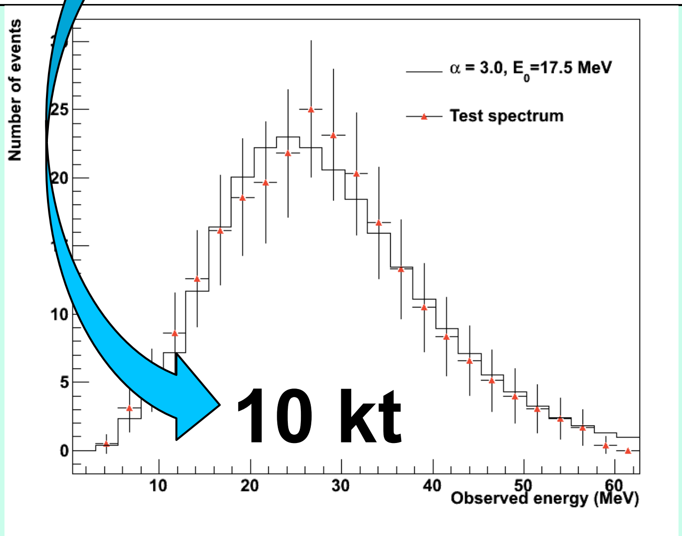
Preliminary: work in progress

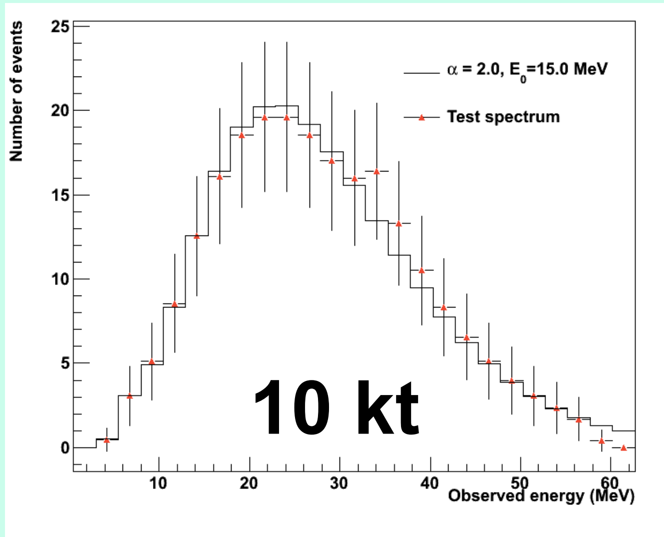
10 kpc spectra from A. Friedland/JJ Cherry/H. Duan smeared w/ SNOwGLoBES response
Based on Keil, Raffelt, Janka spectra, astro-ph/0208035, w/ collective oscillations + shock
Black line: best fit to pinched thermal spectrum





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



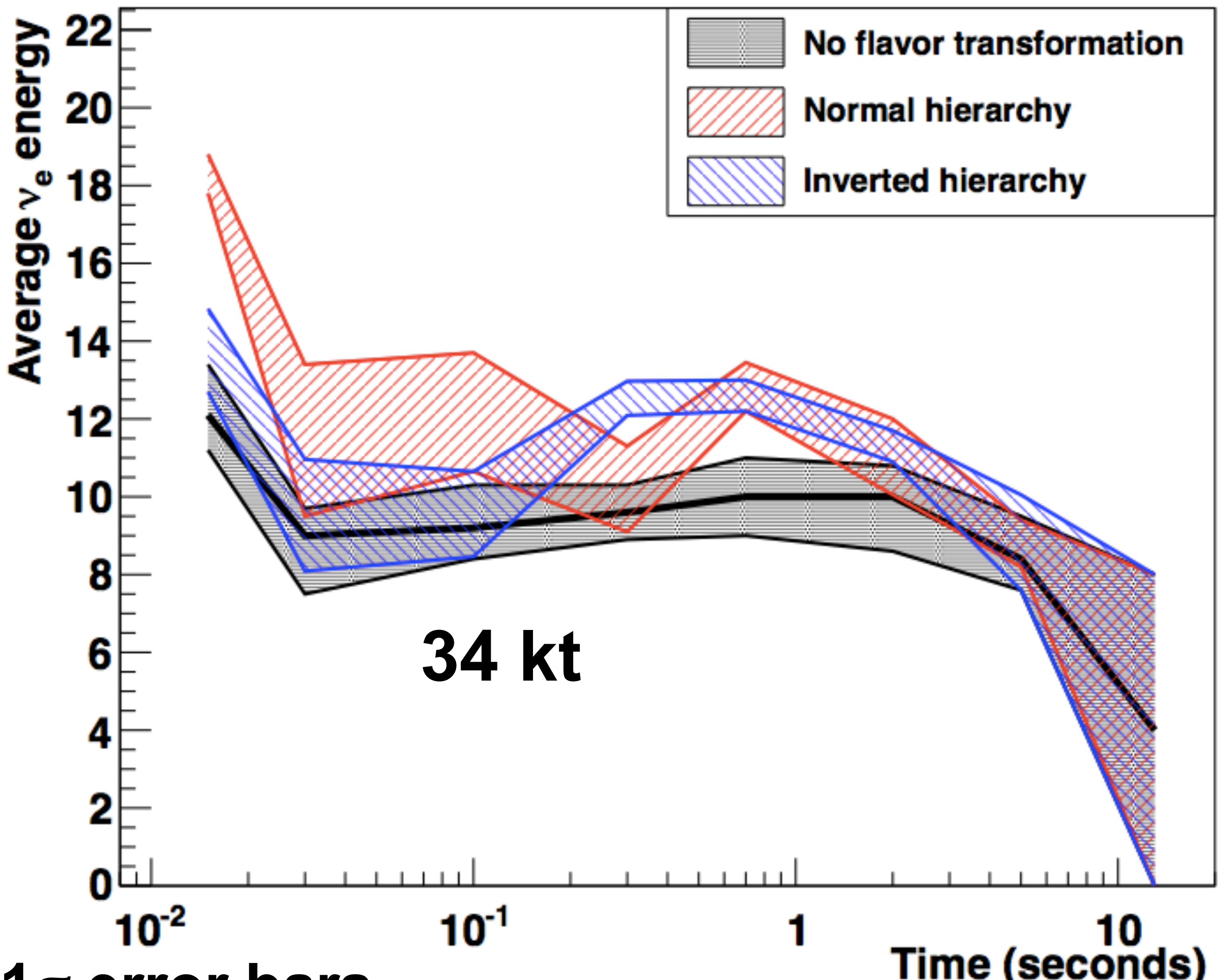


Features become difficult to see for 10 kt stats @ 10 kpc

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

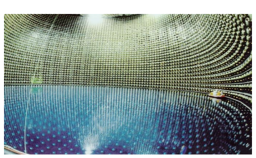
Solid line: original <E_ν>

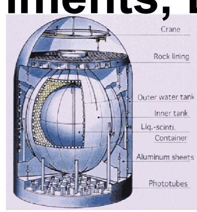
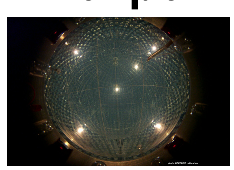
Preliminary: work in progress

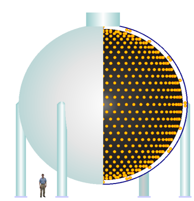
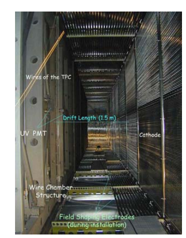
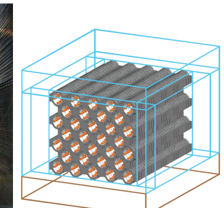
Current & near-future supernova neutrino detectors

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
Icarus	Liquid argon	Italy	0.6	(60)	(Recently finished)
NOvA	Scintillator	USA	15	3000	Under construction
SNO+	Scintillator	Canada	1	300	Under construction
MicroBooNE	Liquid argon	USA	0.17	17	Under construction

plus reactor experiments, DM experiments...



Primary sensitivity is to electron antineutrinos via inverse beta decay $\bar{\nu}_e + p \longrightarrow e^+ + n$

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
Icarus	Liquid argon	Italy	0.6	(60)	(Recently finished)
NOνA	Scintillator	USA	15	3000	Turning on
SNO+	Scintillator	Canada	1	300	Under construction
MicroBooNE	Liquid argon	USA	0.17	17	Under construction
LBNE LAr	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	
LENA	Scintillator	Europe	50	15,000	Proposed

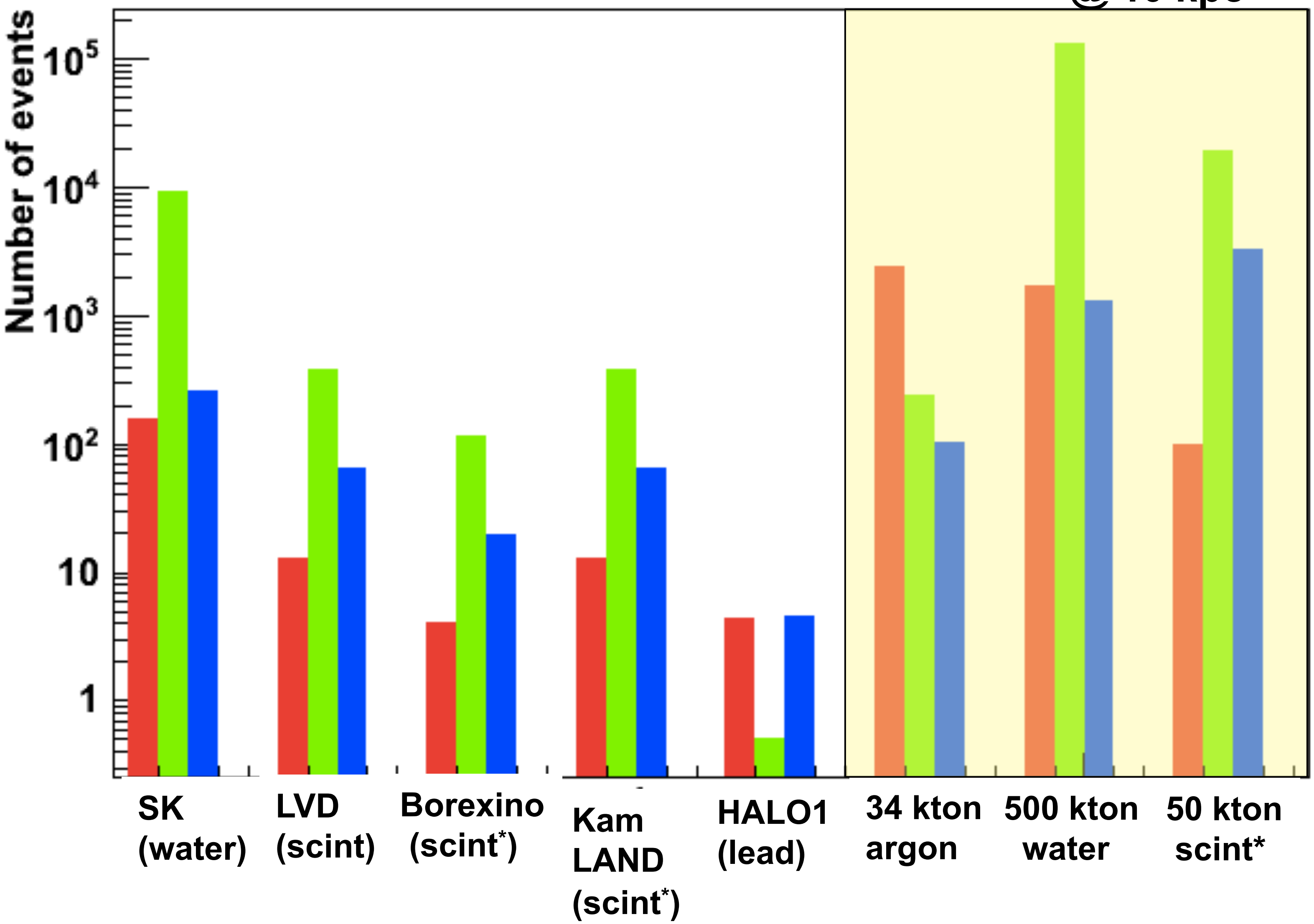
plus reactor experiments, DM experiments...

World SN flavor sensitivity

for largest detectors of each class

Electron neutrino
Electron antineutrino
Muon and tau neutrino and antineutrino

Livermore model
@ 10 kpc

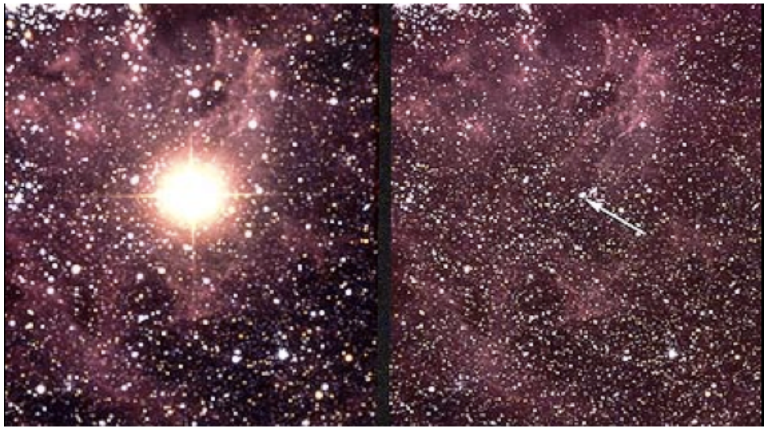


* plus NC ν-p scattering

An **EARLY ALERT** for astronomers

~hours of warning,

dependent on stellar envelope



Observations of light curve turn-on very rare for extragalactic SNae

Early light actually probably not that helpful for SN explosion theory (ν's are)

BUT:
- environment near progenitor probed by initial stages
- UV/ soft x-ray flash at shock breakout predicted

⇒ *info about progenitor* from spectroscopy

⇒ mass density profile for ν oscillation understanding

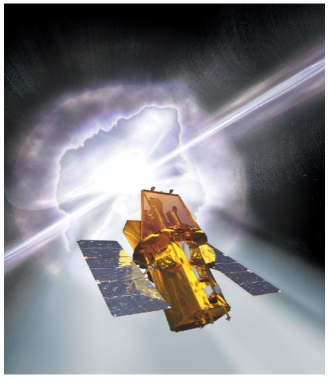
Plus: possible unknown early effects!

Any information saved, in any channel, may be valuable

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

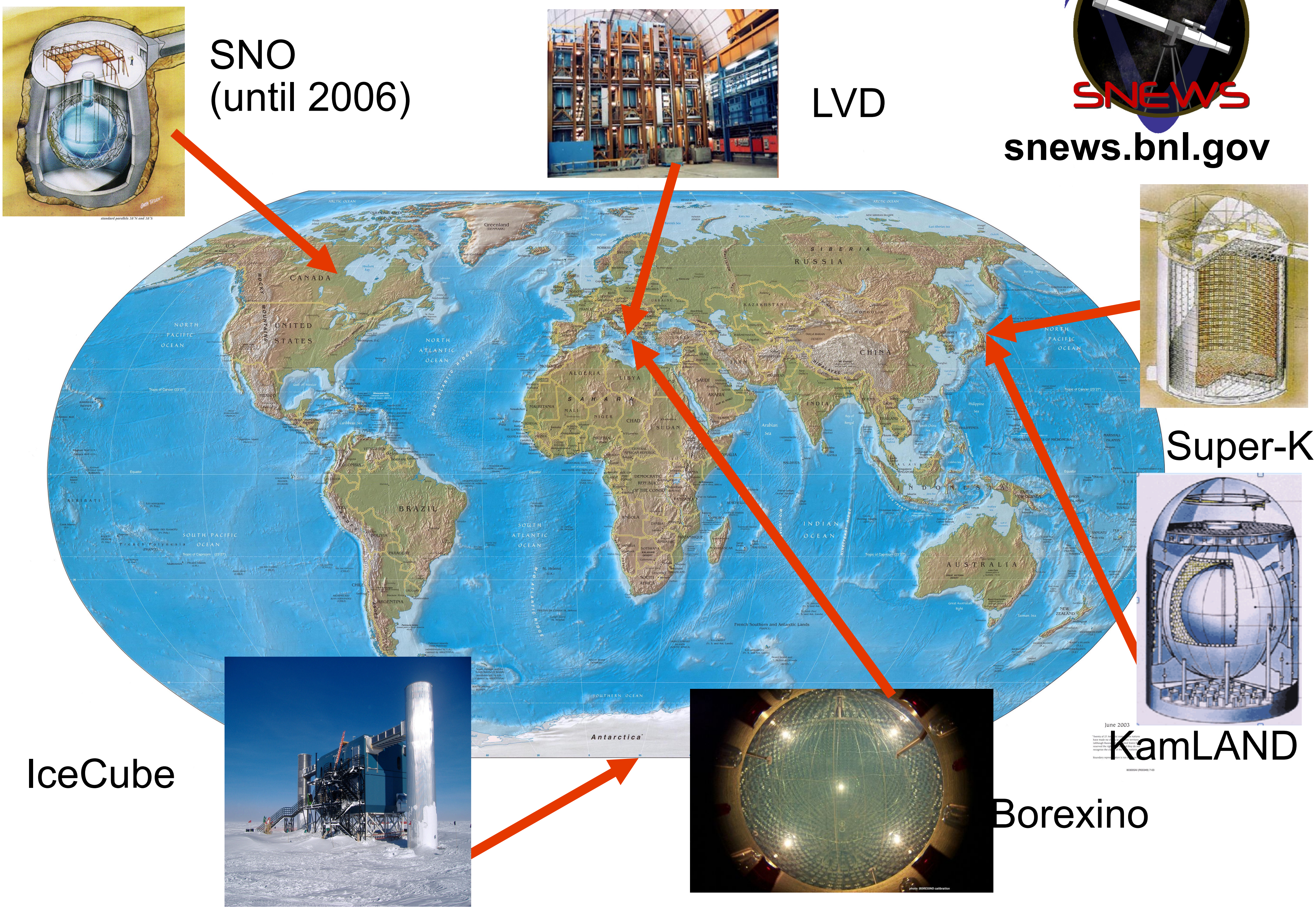
Combining information with other detectors sensitive to SNae is important! (alert & later)

gravitational waves



multiwavelength astronomy

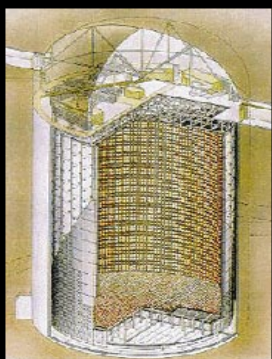
SNEWS: SuperNova Early Warning System



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

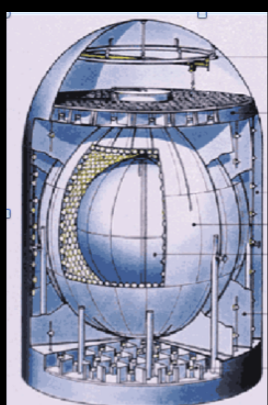


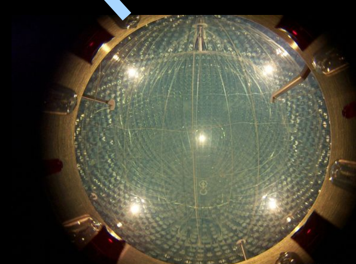
experiment
UT time
significance

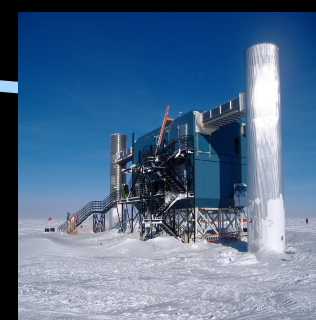
Coincidence Server at BNL

10 second coincidence by UT time stamp

alert to astronomers





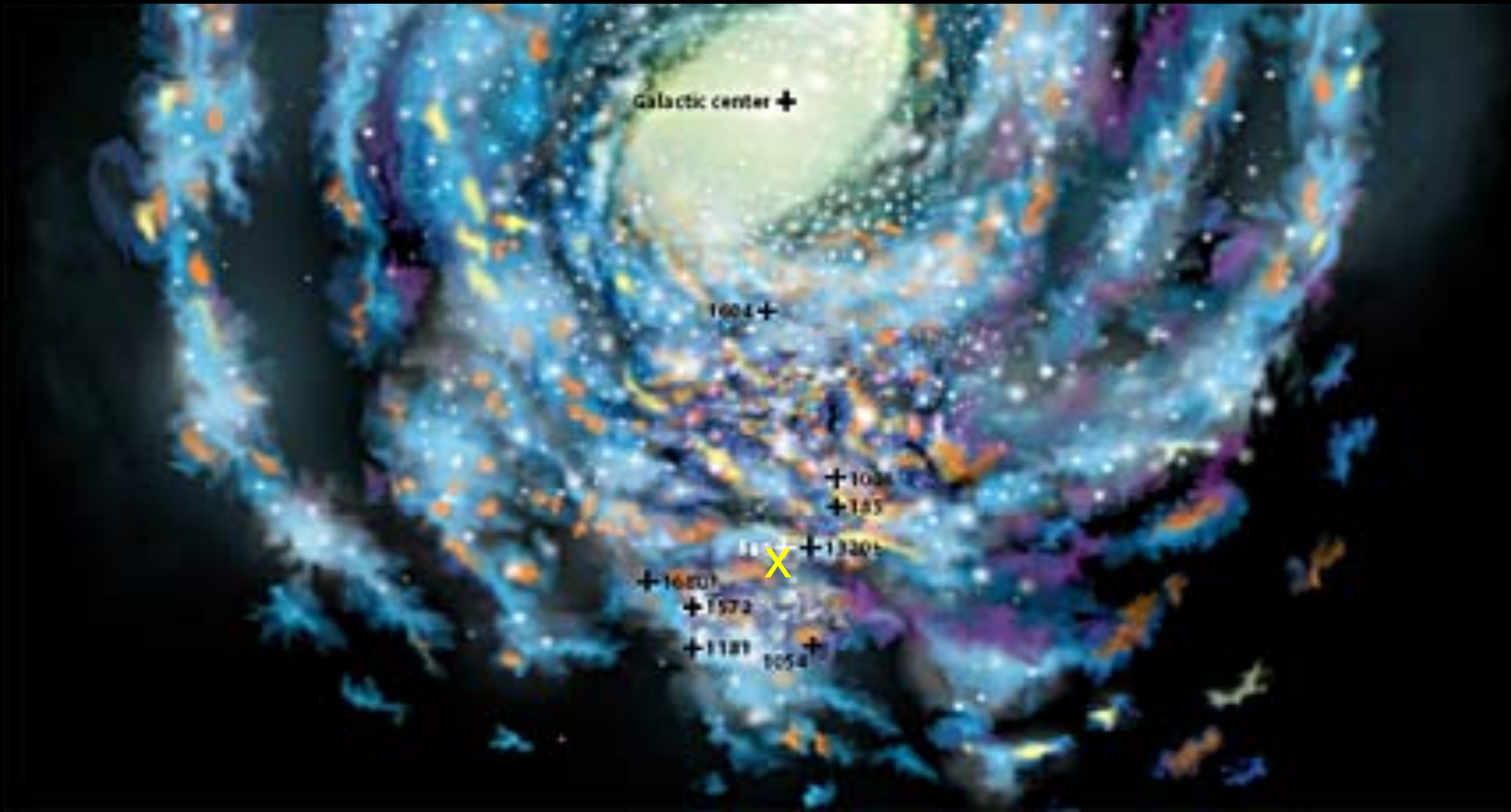


- Running smoothly for more than 10 years, automated since 2005
- Amateur astronomer connection

Possibly 1/6 will stand out obviously...

Historical Supernovae:

(Sky&Telescope)



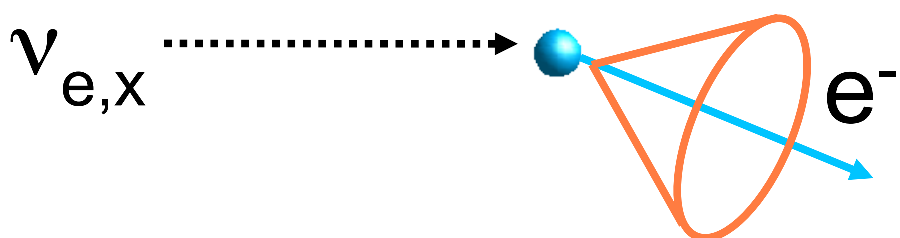
Also, fireworks may be intrinsically dim

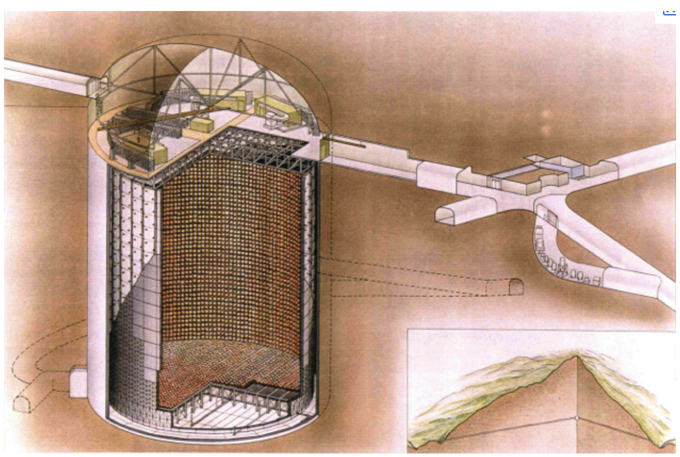
POINTING to the supernova with future detectors

(should be prompt if possible)

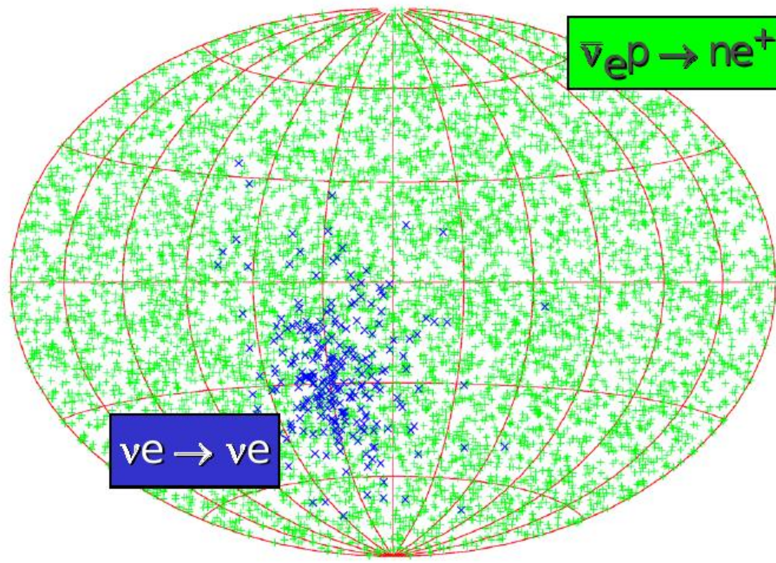
Elastic scattering off electrons is the best bet

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





In water Cherenkov few % of total rate



G. Raffelt

Super-K: ~8° pointing

Other possibilities:
- time triangulation
- matter oscillation pattern
- inv. βdk e^+n separation
- ~TeV neutrinos (delayed)

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

Tomas et al.,hep-ph/0307050

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, for megadetectors

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

Extras/backups

SN ν spectrum parameterizations: "pinched thermal" is decent description

Fermi-Dirac (T, η, Φ)

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

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

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

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

preferred by Garching SN modelers

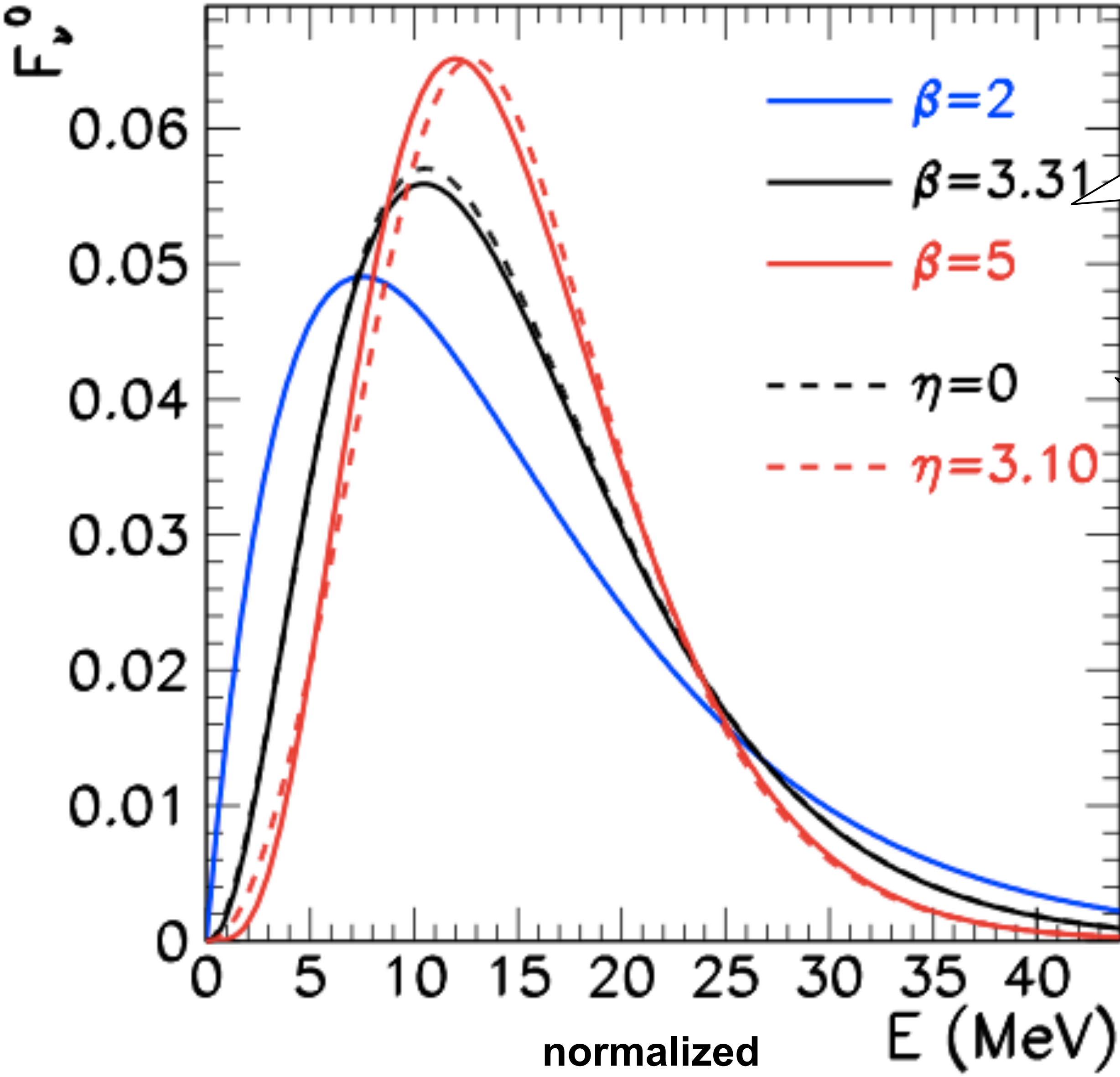
$$F^0_{\nu_\alpha}(E) = \frac{\Phi_{\nu_\alpha}}{\langle E_{\nu_\alpha} \rangle} \frac{\beta_{\nu_\alpha}^{\beta_{\nu_\alpha}}}{\Gamma(\beta_{\nu_\alpha})} \left(\frac{E}{\langle E_{\nu_\alpha} \rangle} \right)^{\beta_{\nu_\alpha} - 1} \exp\left(-\beta_{\nu_\alpha} \frac{E}{\langle E_{\nu_\alpha} \rangle}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

see e.g. arXiv:0802.1489

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

$$E^{\rm tot}_{\nu_\alpha} = \Phi_{\nu_\alpha} \langle E_{\nu_\alpha} \rangle$$

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



"Pinching" controlled by β for Garching

"Pinching" controlled by η for FD

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

normalized
$\langle E\rangle = 15$ MeV

arXiv:0802.1489

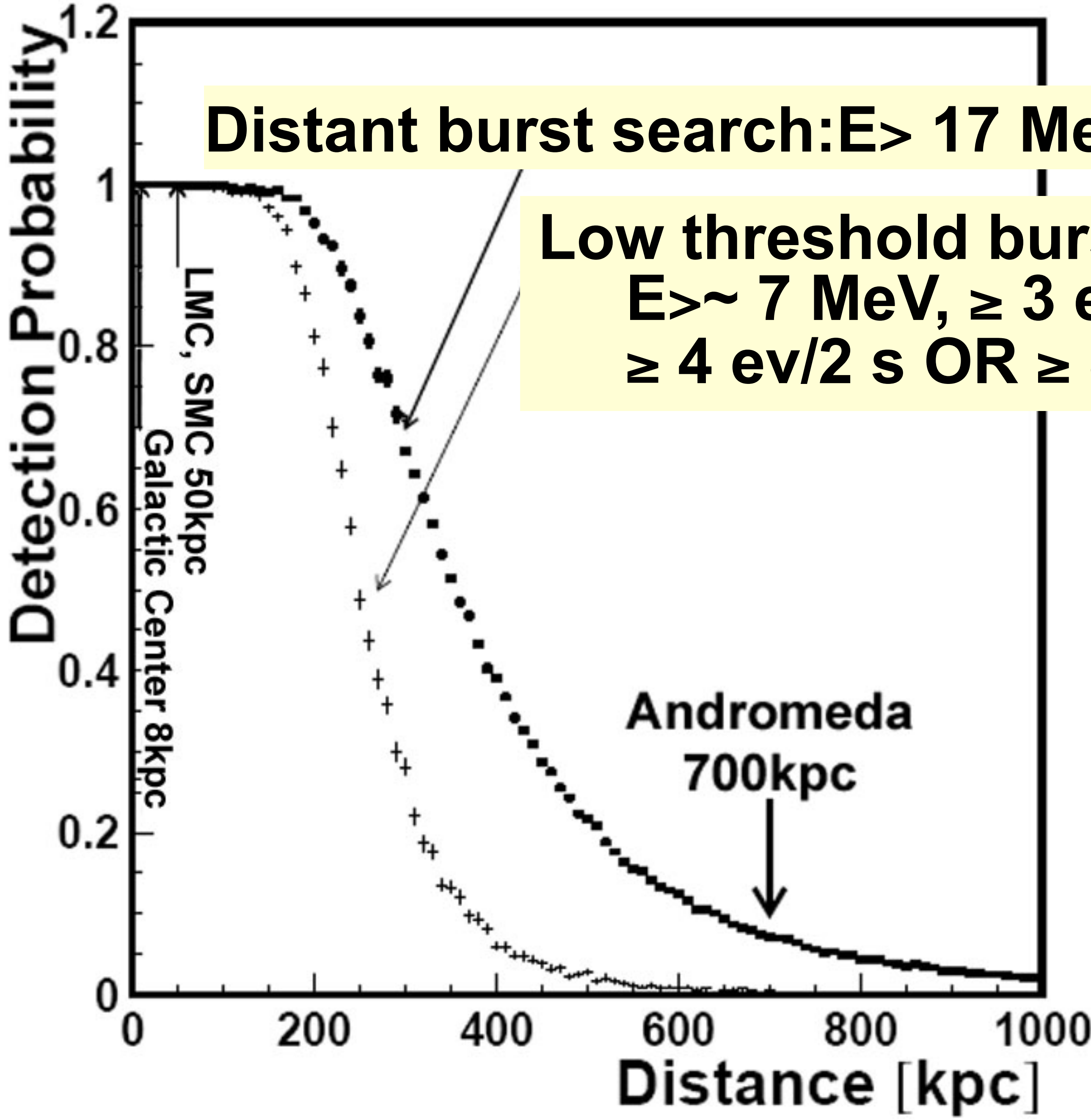
Interaction rates in a detector material

Flux — Cross section — Number of targets

$$R = \Phi \, \sigma \, N_t$$

$$\propto \text{detector mass}, 1/D^2$$

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

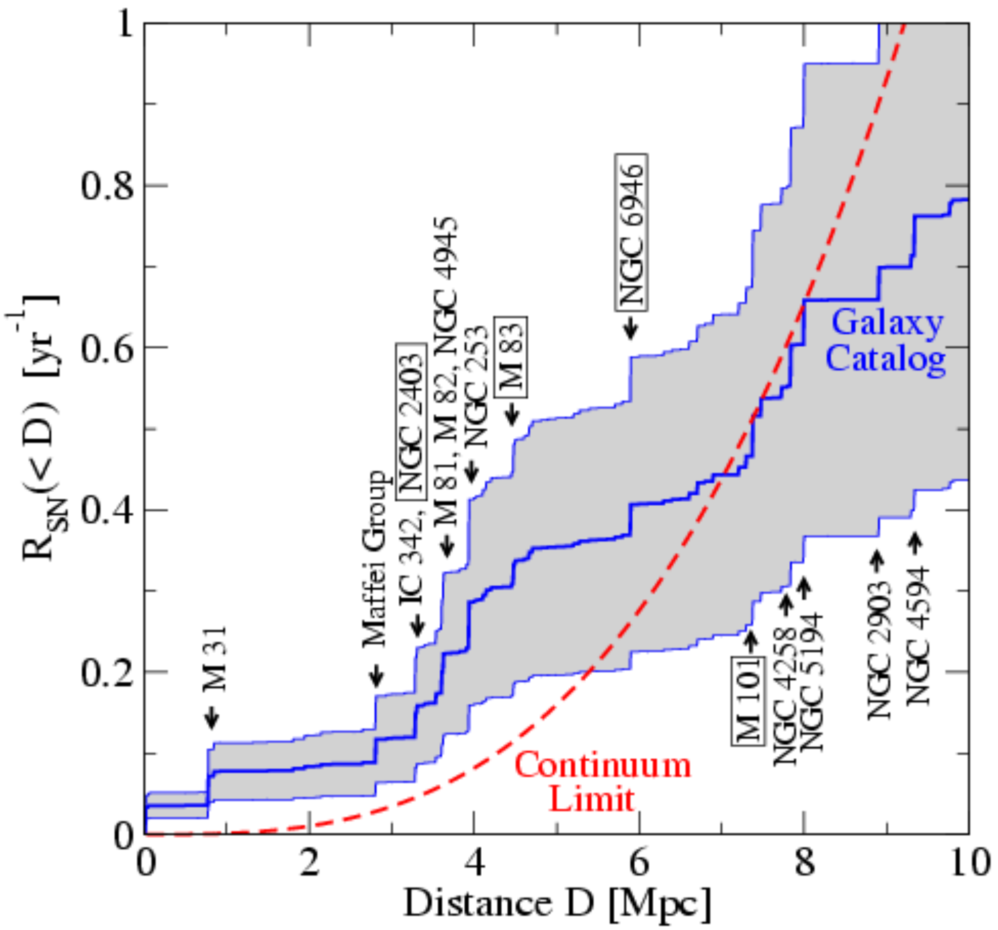


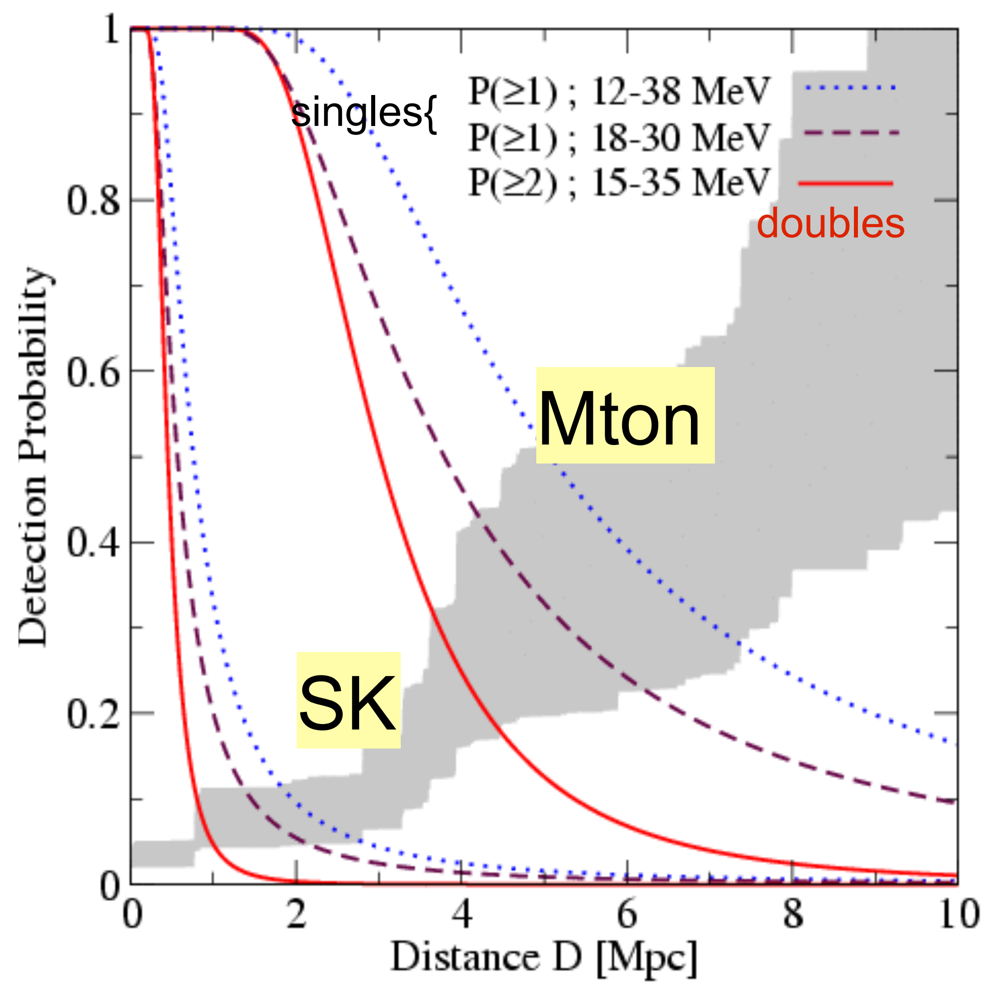
For "untriggered" distant search, it's all about the background...

Ikeda et al., arXiv:0706.2283

Looking beyond: number of sources α D^3

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



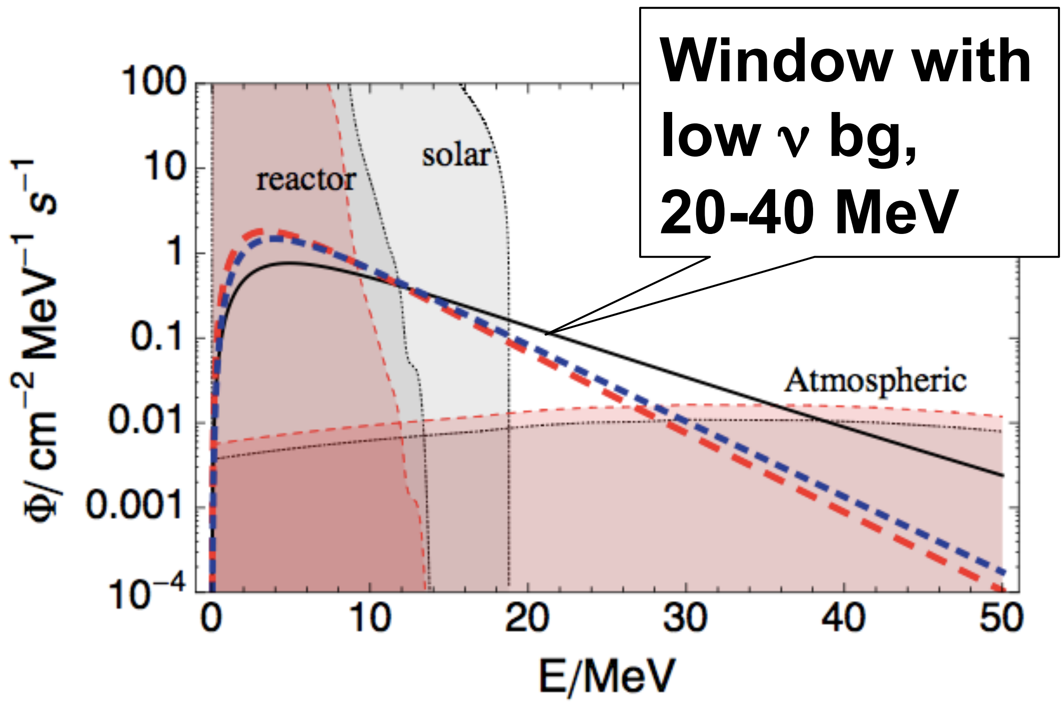


With Mton scale detector, probability of detecting 1-2 events reasonably close to ~1 at distances where rate is <~1/year

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

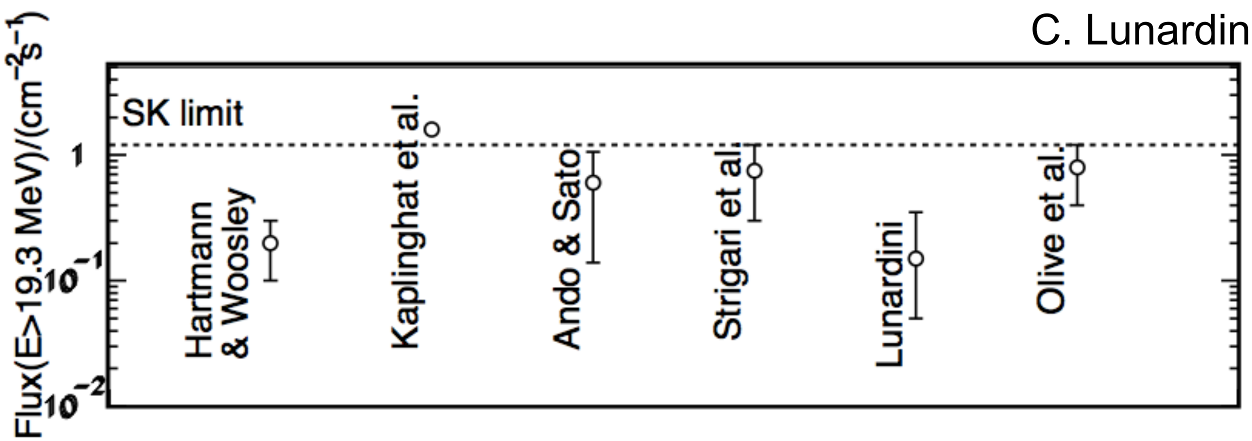
And going even farther out: we are awash in a sea of *'relic'* or diffuse SN ν's (DSNB), from ancient SNae

Learn about average supernova properties over cosmic history



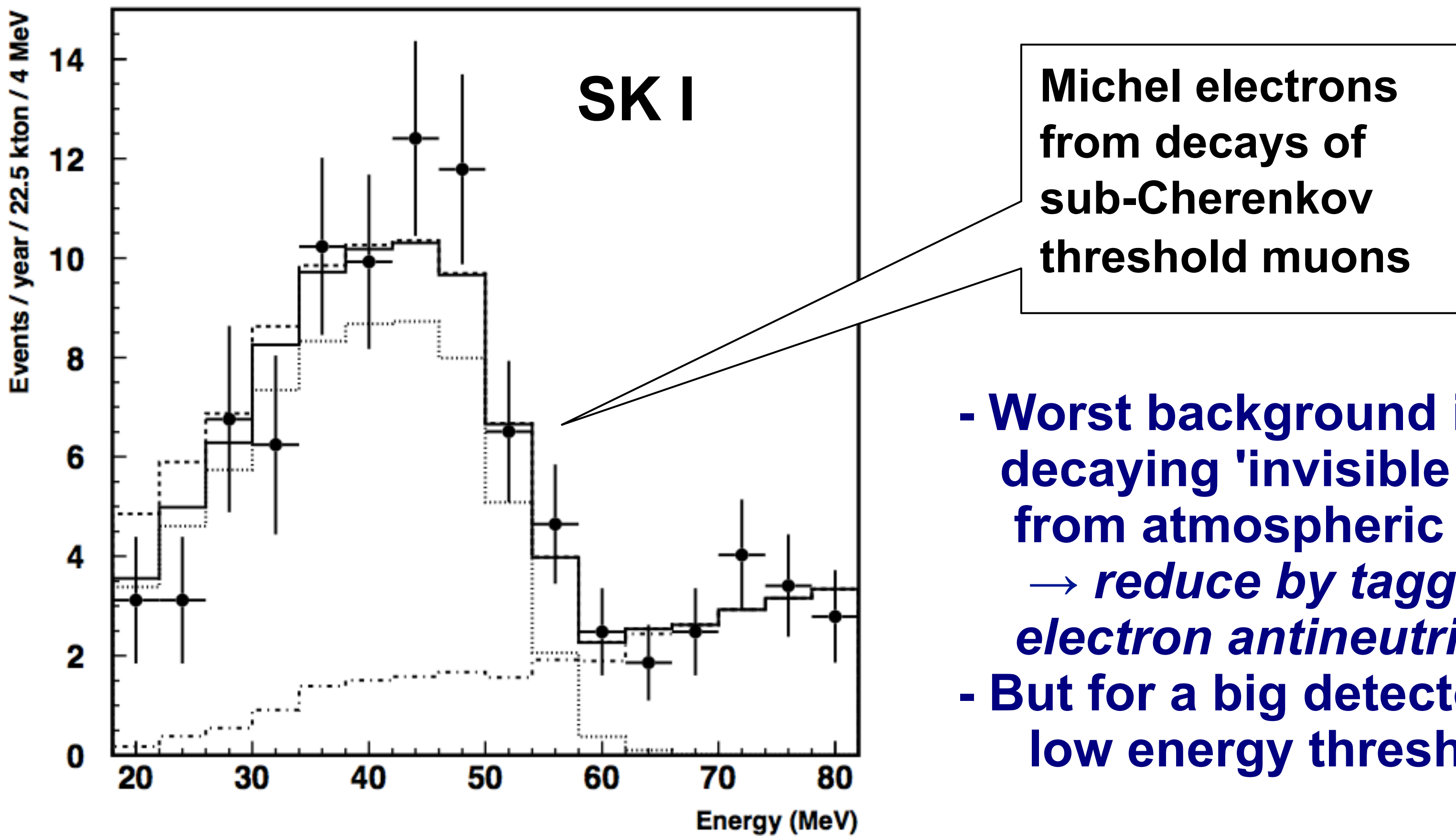
Difficulty is tagging for decent signal/bg (no burst, 2 ν coincidences optical SNae...)

C. Lunardini



~few events per year in SK

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



- **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	Galactic SN
	~300 events/kt/30 year
~0.1 event/kt/year	~10 events/kt/yr
more background	less background
low rate of return, but a sure thing	risky in the short term, but you win in the very long term

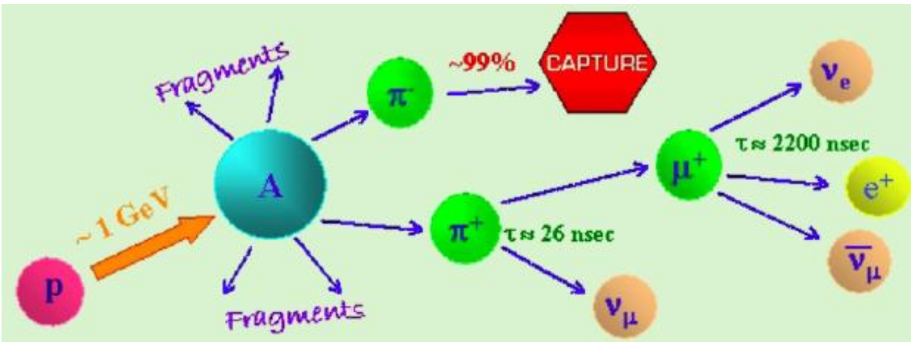
bonds vs stocks...

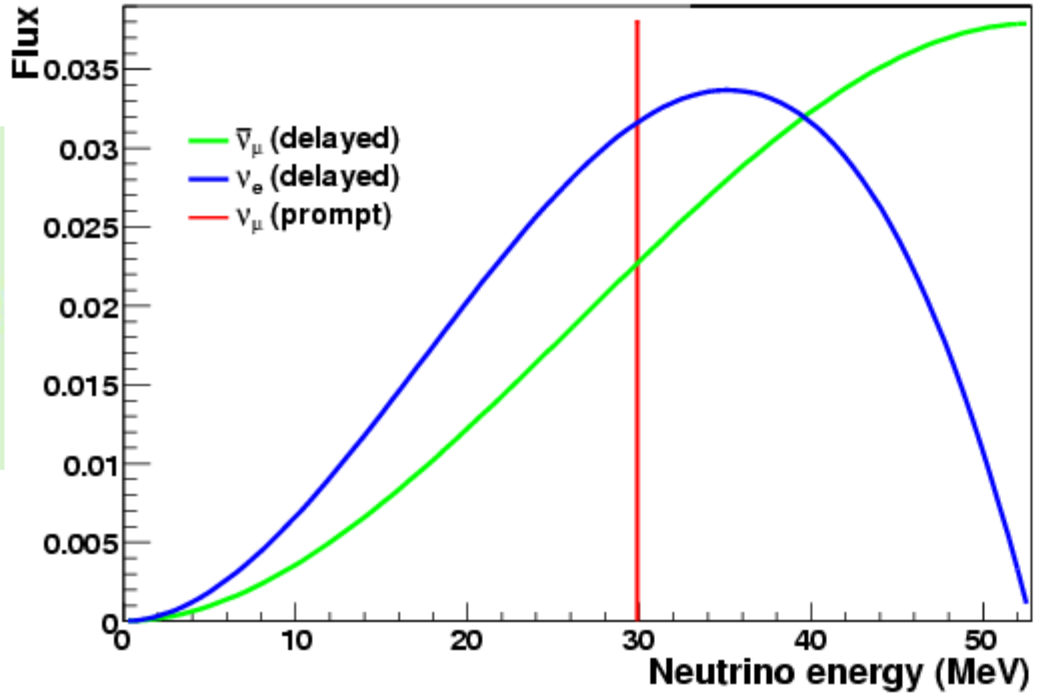
(Of course if you build a big detector and run it a long time, you may get both! Diversify!)

Measuring Supernova-Relevent Neutrino-Nucleus Cross-Sections at a Stopped-Pion Source

Expected DAR neutrino spectrum

F. Avignone and Y. Efremenko, J. Phys. G: 29 (2003) 2615-2628





$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

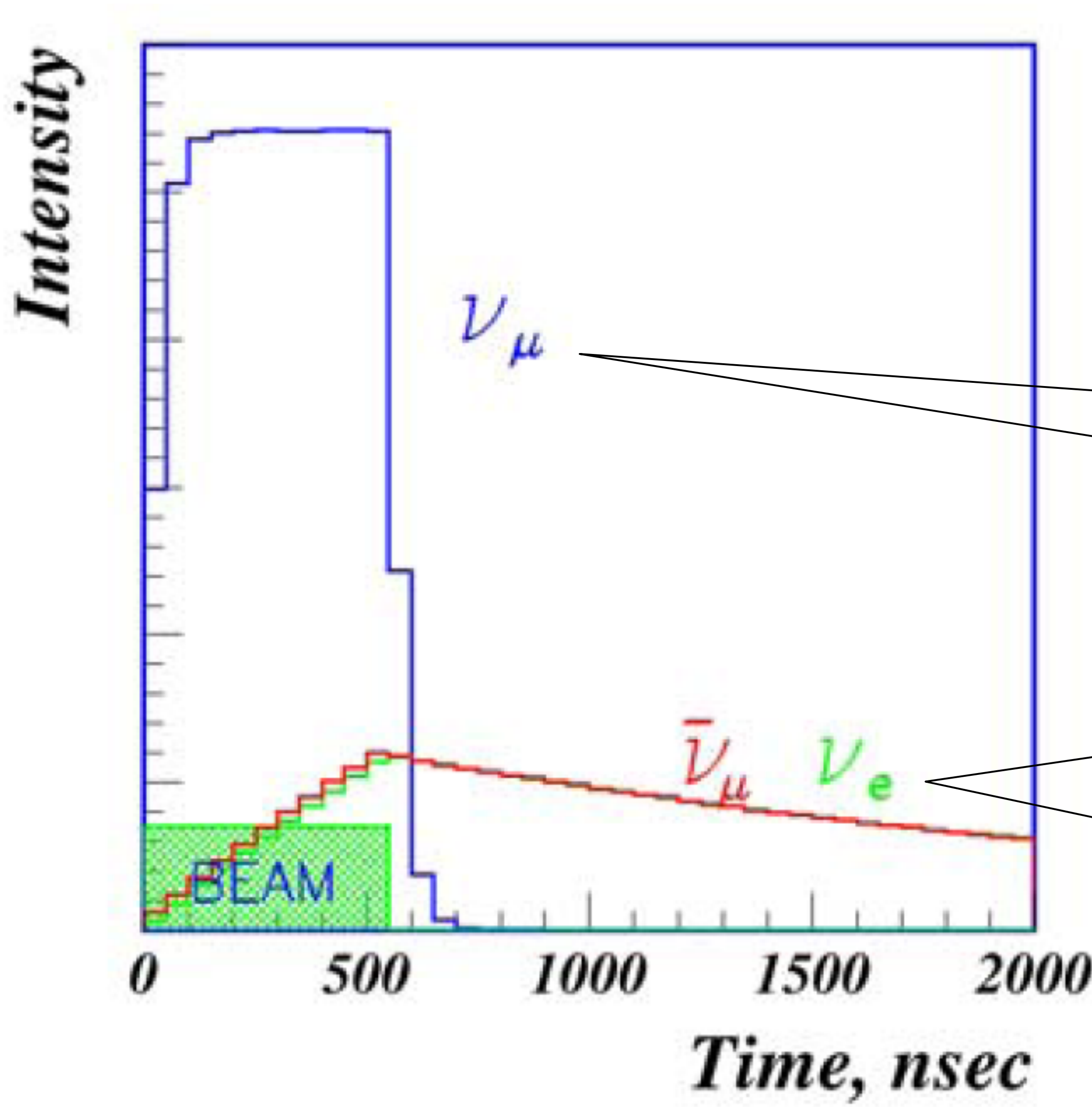
2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

3-body decay: range of energies between 0 and $m_\mu/2$
DELAYED (2.2 μs)

Neutrino flux: few times 10^7 /s/cm^2 at 20 m ~0.13 per flavor per proton

Time structure of the source



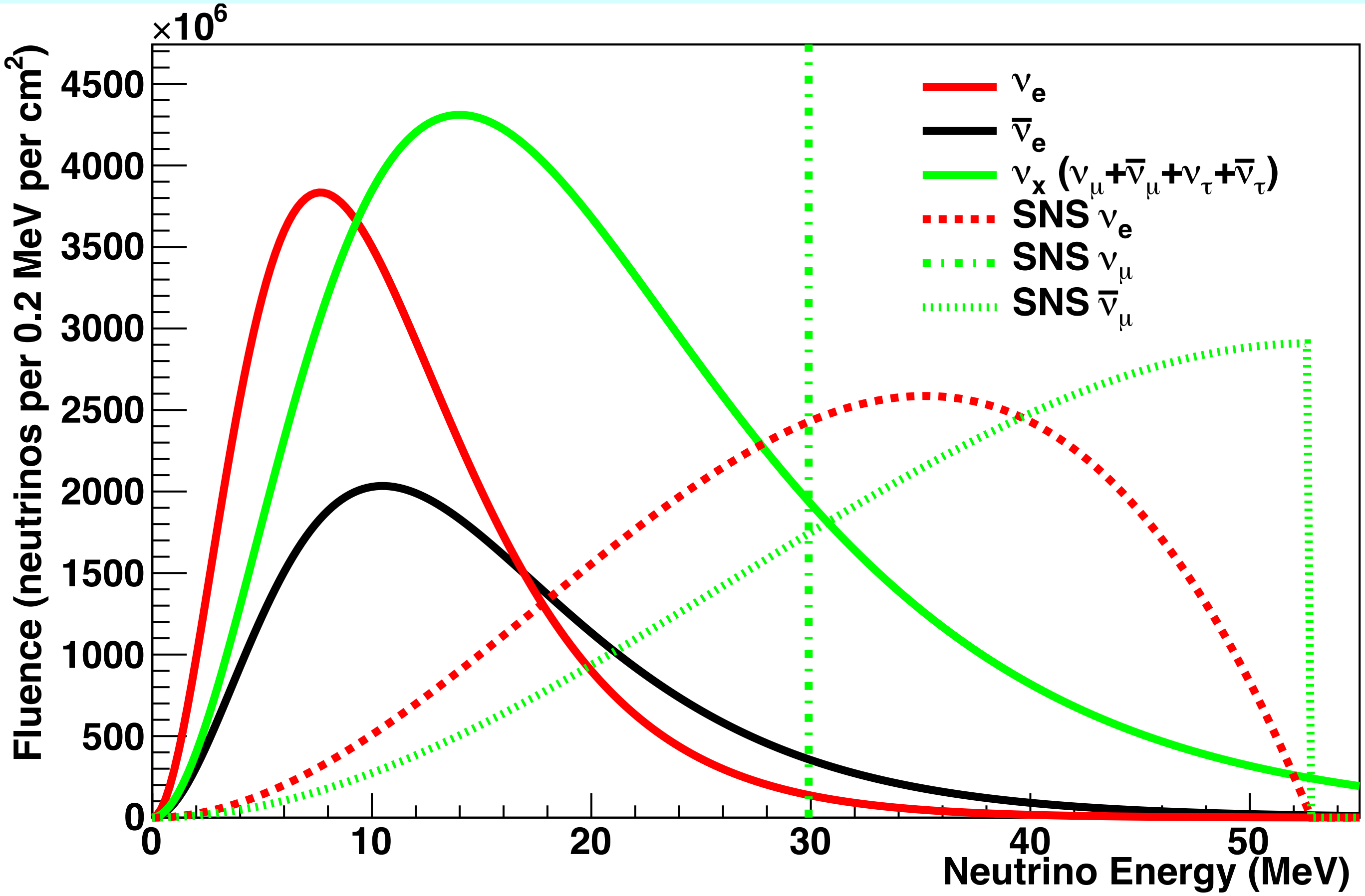
60 Hz *pulsed* source

in time with beam

delayed on μ decay timescale (2.2 μs)

Background rejection factor ~few x 10^{-4}

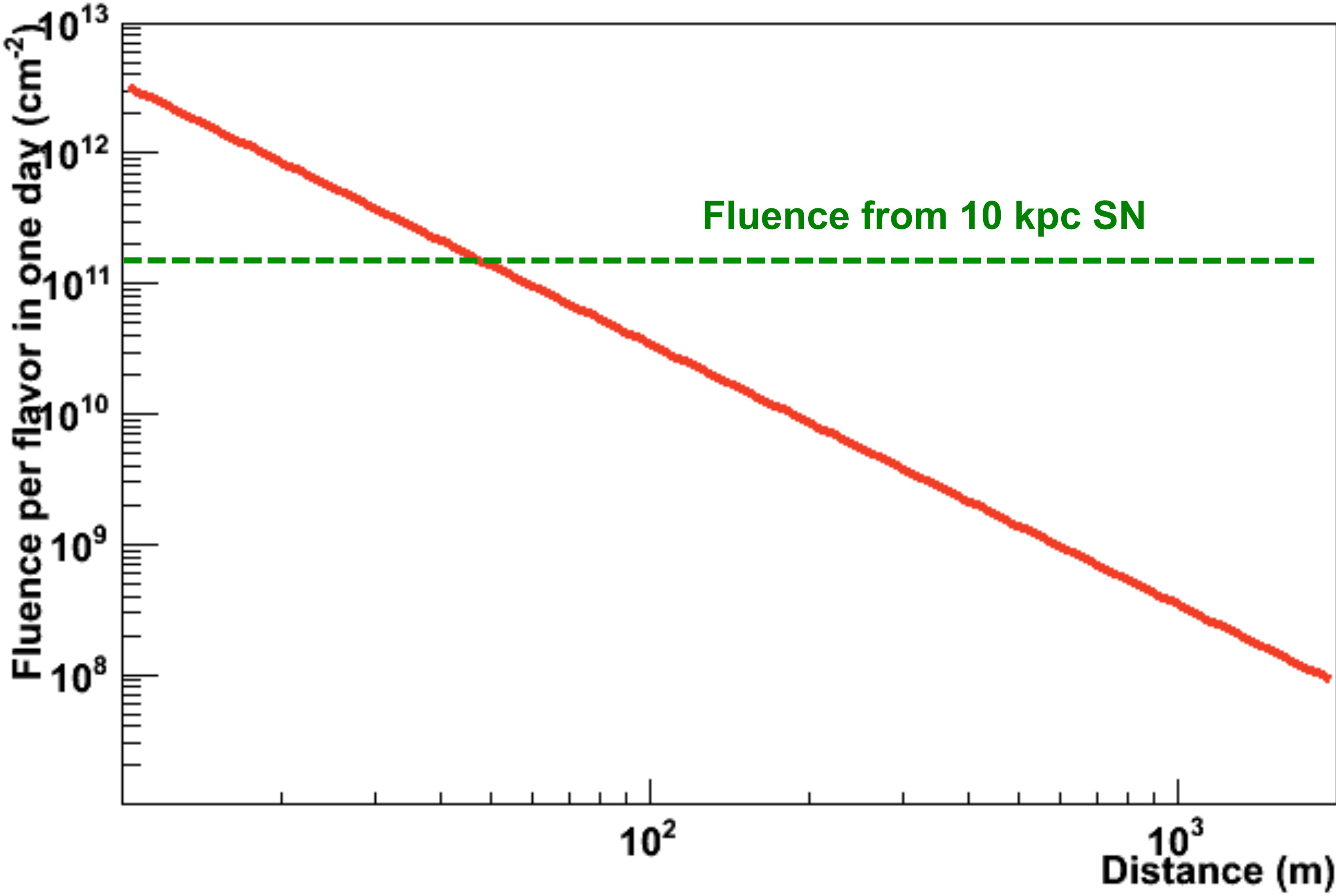
Supernova neutrino spectrum overlaps very nicely with stopped π neutrino spectrum



Study CC and NC interactions with various nuclei, in few to 10's of MeV range

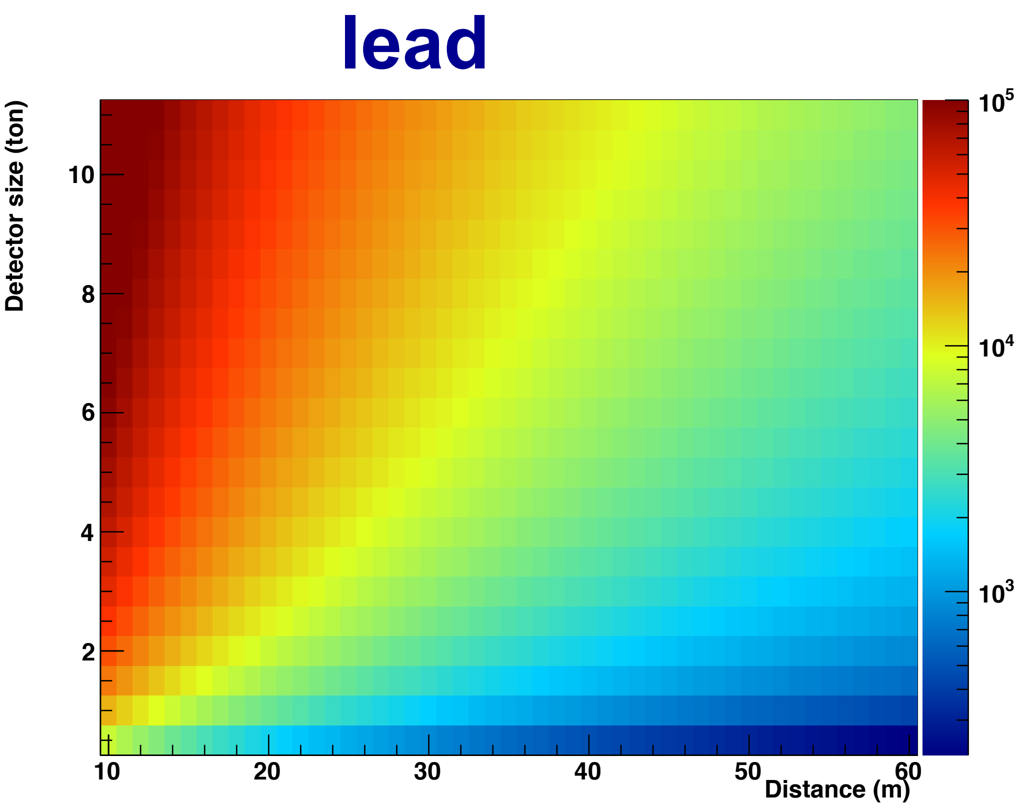
1. Understanding of *core-collapse SN processes*, nucleosynthesis
2. Understanding of *SN ν detection* processes

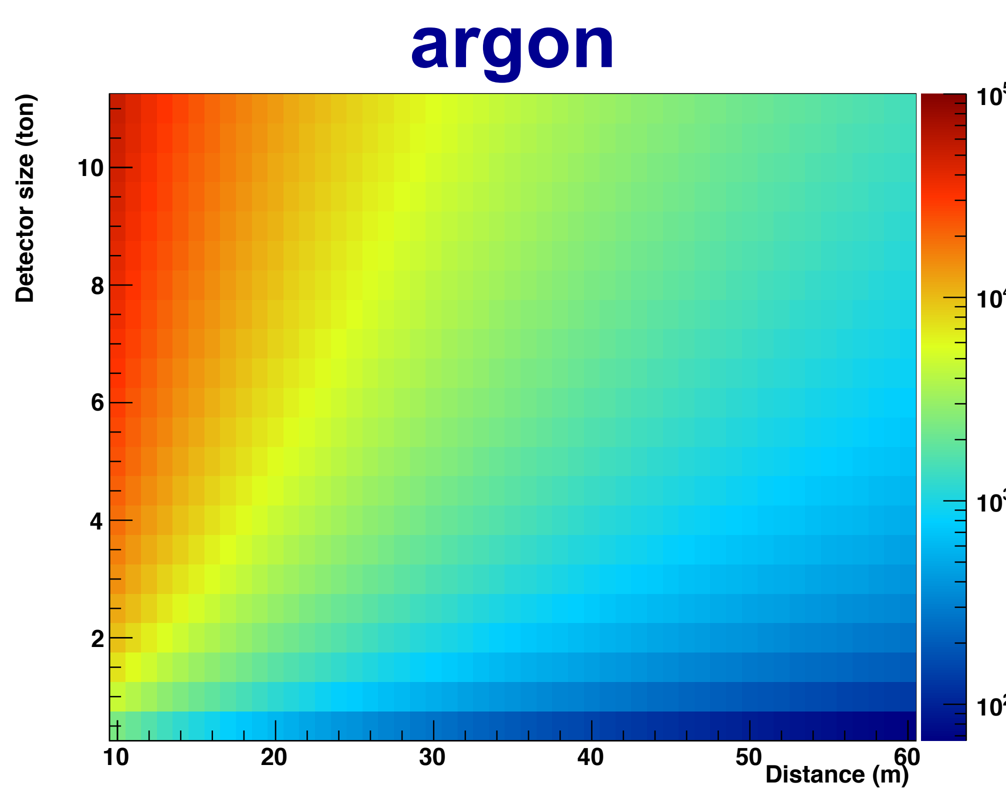
Fluence at ~50 m from the stopped pion source amounts to ~ a supernova a day!



Total events per year at the SNS as a function of distance and mass

just scaling as α 1/R^2, α M



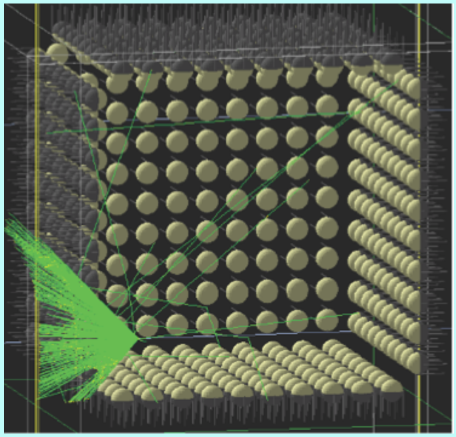


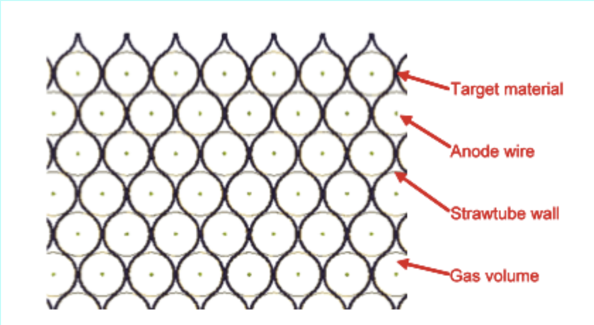
~10^3 events per few tons at 30 m

Possible Experiments for CC/NC Measurements

NuSNS:
interchangeable targets

- homogeneous detector for transparent liquids
- foils + strawtubes for metallic targets





Small LAr TPC

ArgoNeut?
LBNE prototype?

Small lead + n detector

HALO-inspired