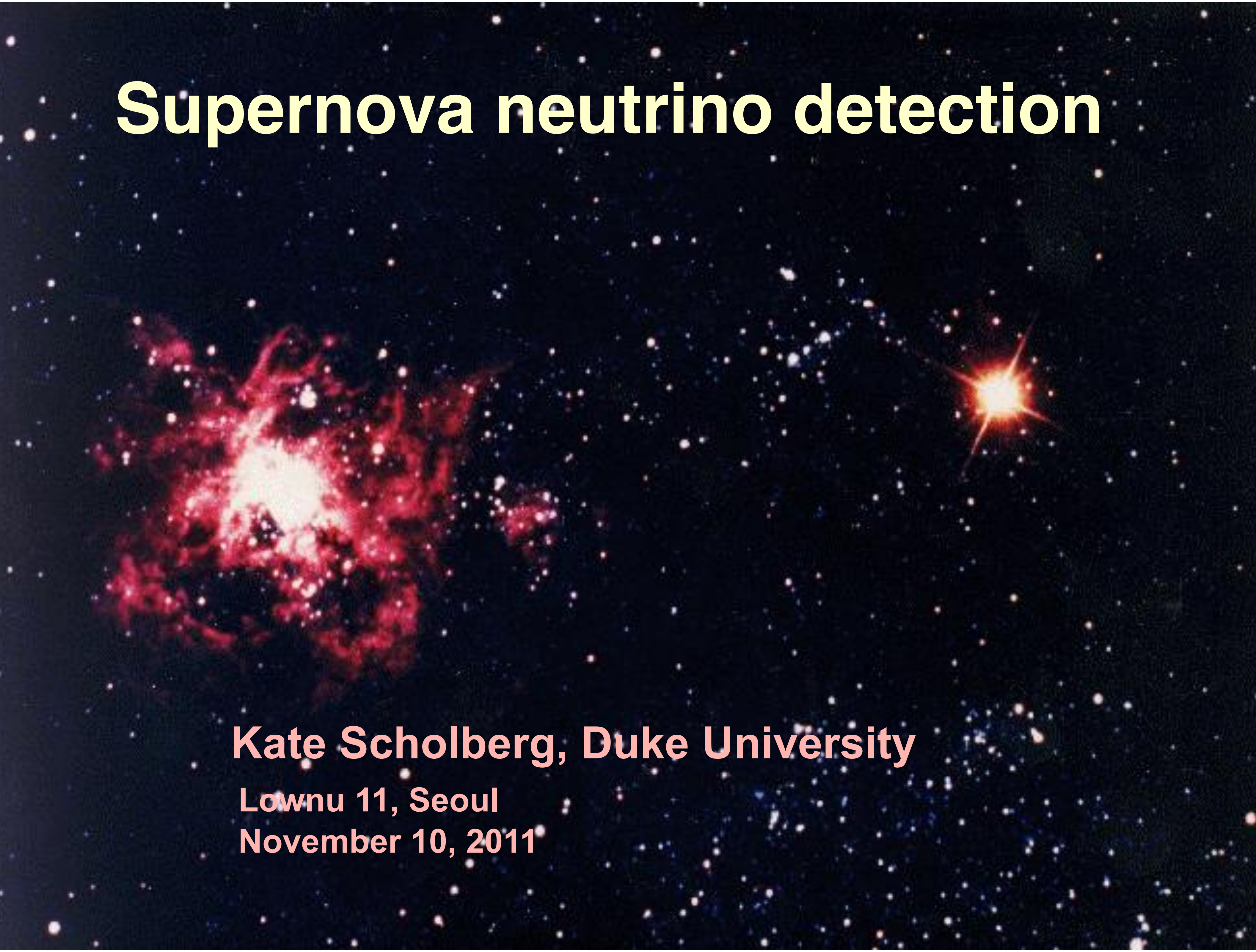


Supernova neutrino detection

Kate Scholberg, Duke University

Lownu 11, Seoul
November 10, 2011

OUTLINE

Neutrinos from supernovae

  What can be learned

Supernova neutrino detection

Current and near future detectors

Future detection: LBNE example

Summary

Neutrinos from core collapse

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

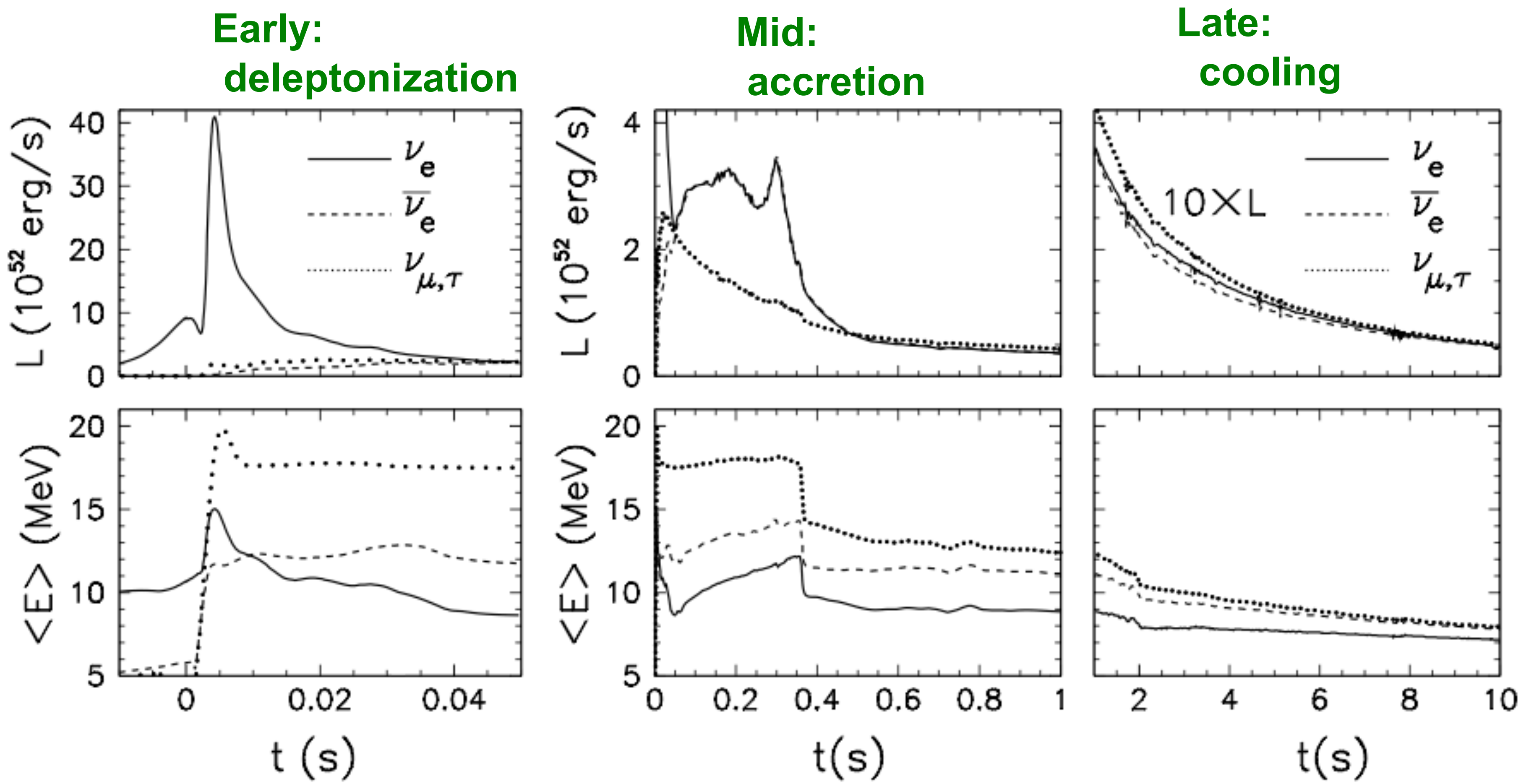
(Energy *can* escape via ν's)

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

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

Expected neutrino luminosity and average energy vs time

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



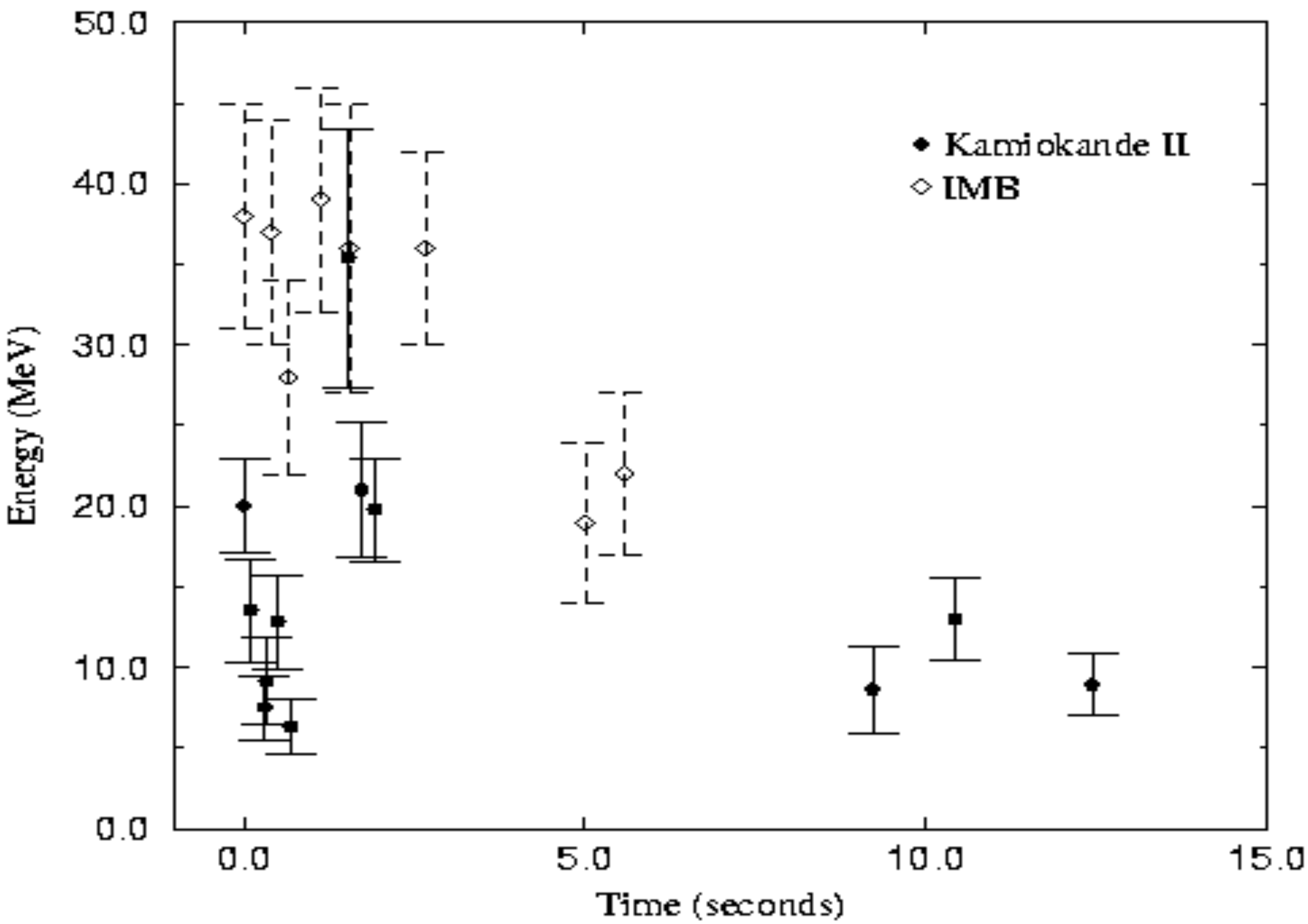
Generic feature:
(may or may not be robust)

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

SN1987A in LMC

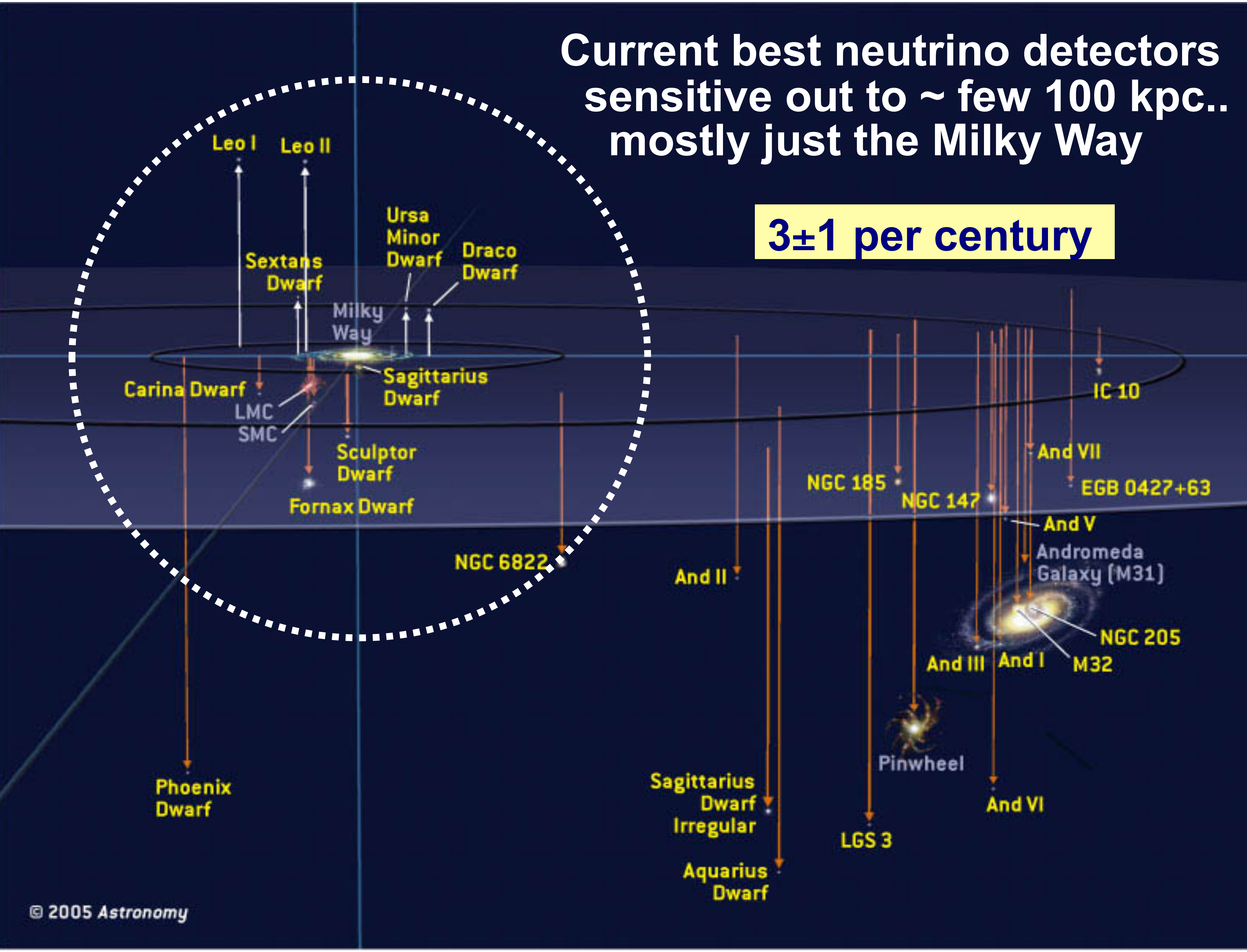
at 55 kpc
ν's seen ~2.5 hours before first light

Water Cherenkov:	IMB	E_{th}~ 29 MeV, 6 kton	8 events
	Kam II	E_{th}~ 8.5 MeV, 2.4 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??

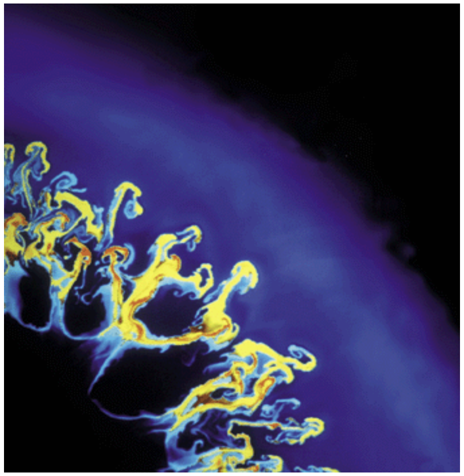


$\bar{\nu}_e$

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

What We Can Learn

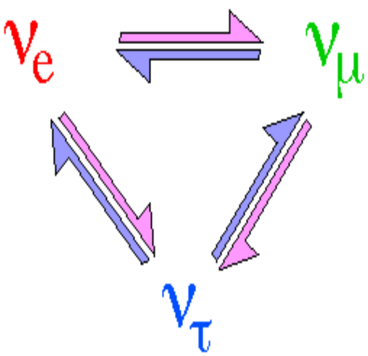


CORE COLLAPSE PHYSICS

- 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
  (' θ_{13} the lucky and patient way')
- other ν properties: sterile ν's, magnetic moment,...
- axions, extra dimensions, FCNC, ...

+ EARLY ALERT

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

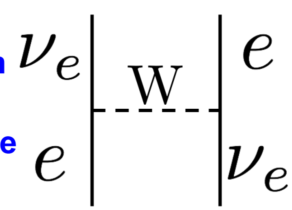
In the proto-neutron star the neutrino density is so high that *neutrino-neutrino interactions* matter

From G. Fuller

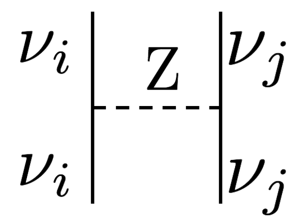
$$\psi_{\nu,i} = \begin{bmatrix} \text{amplitude to be } \nu_{\mathrm{e}} \\ \text{amplitude to be } \nu_{\mu,\tau} \end{bmatrix}$$

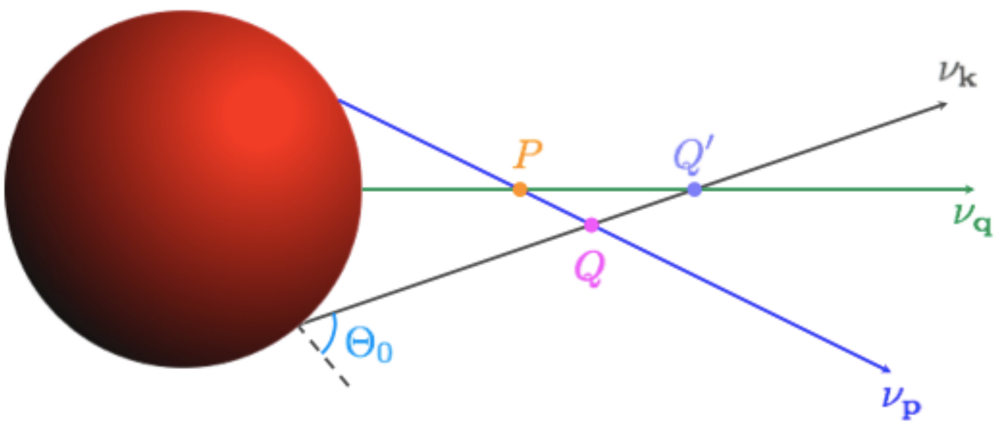
$$i\,\frac{\partial}{\partial t}\psi_{\nu,i} = \left(\mathcal{H}_{\mathrm{vac},i} + \mathcal{H}_{\mathrm{e},i} + \mathcal{H}_{\nu\nu,i}\right)\psi_{\nu,i}$$

neutrino-electron charged current forward exchange scattering



neutrino-neutrino neutral current forward scattering





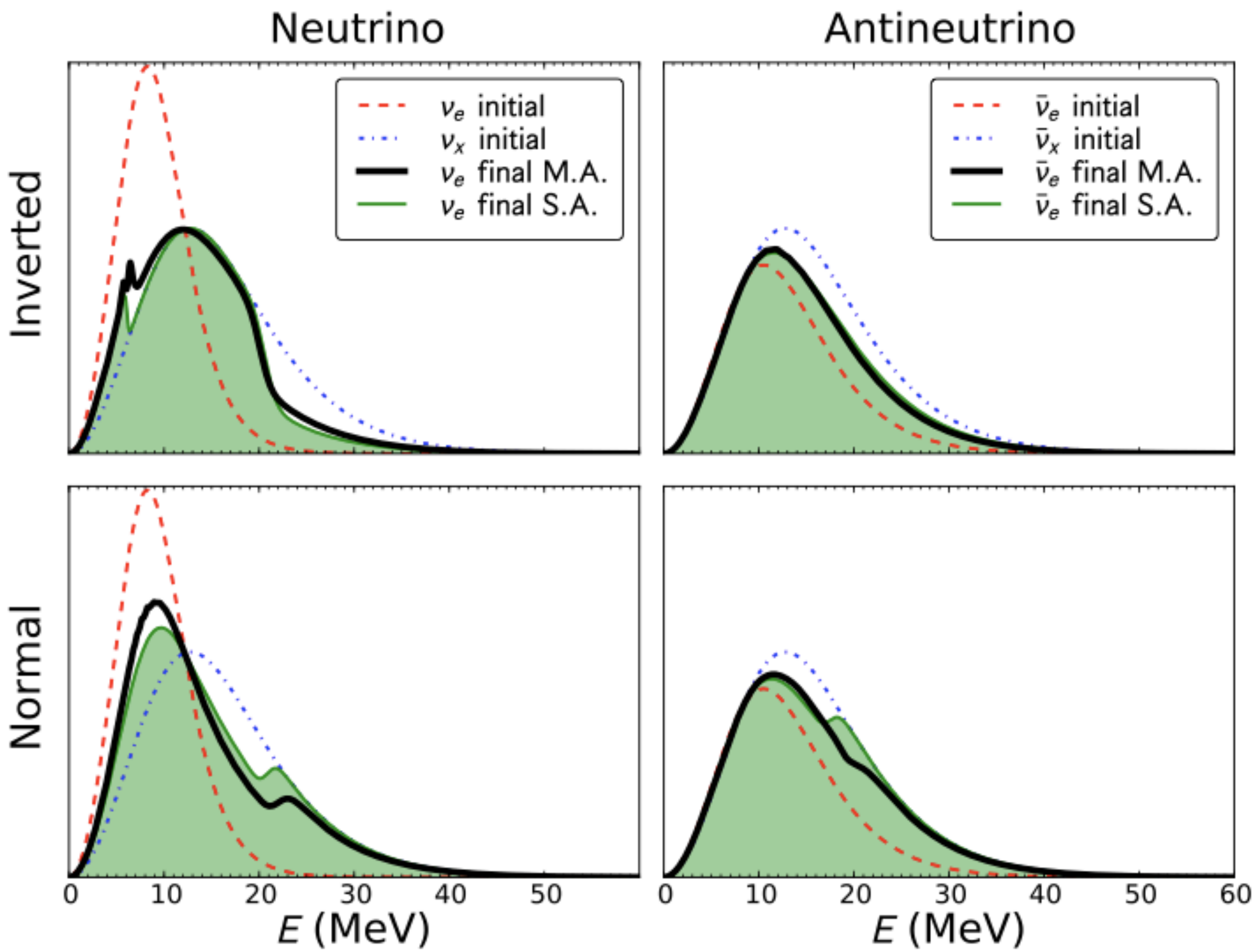
Must solve many *millions* of coupled, nonlinear partial differential equations!!

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



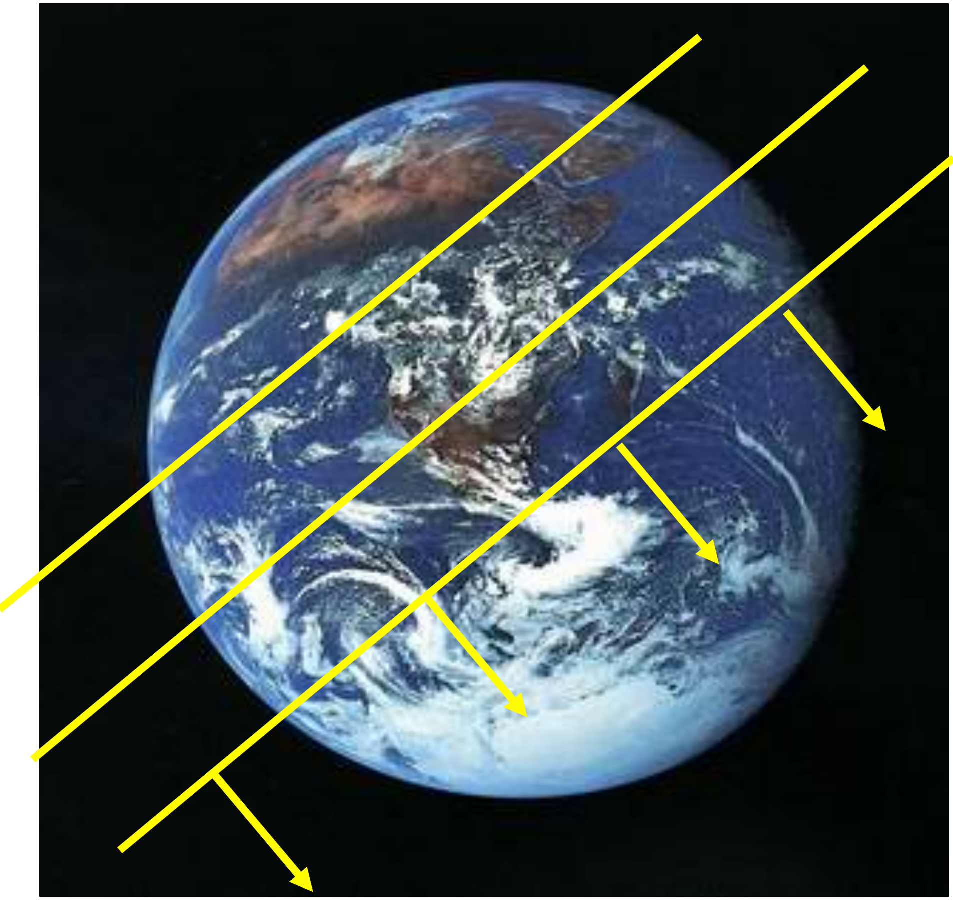
***Distinctive spectral swap features depend on neutrino mass hierarchy*, for neutrinos vs antineutrinos**

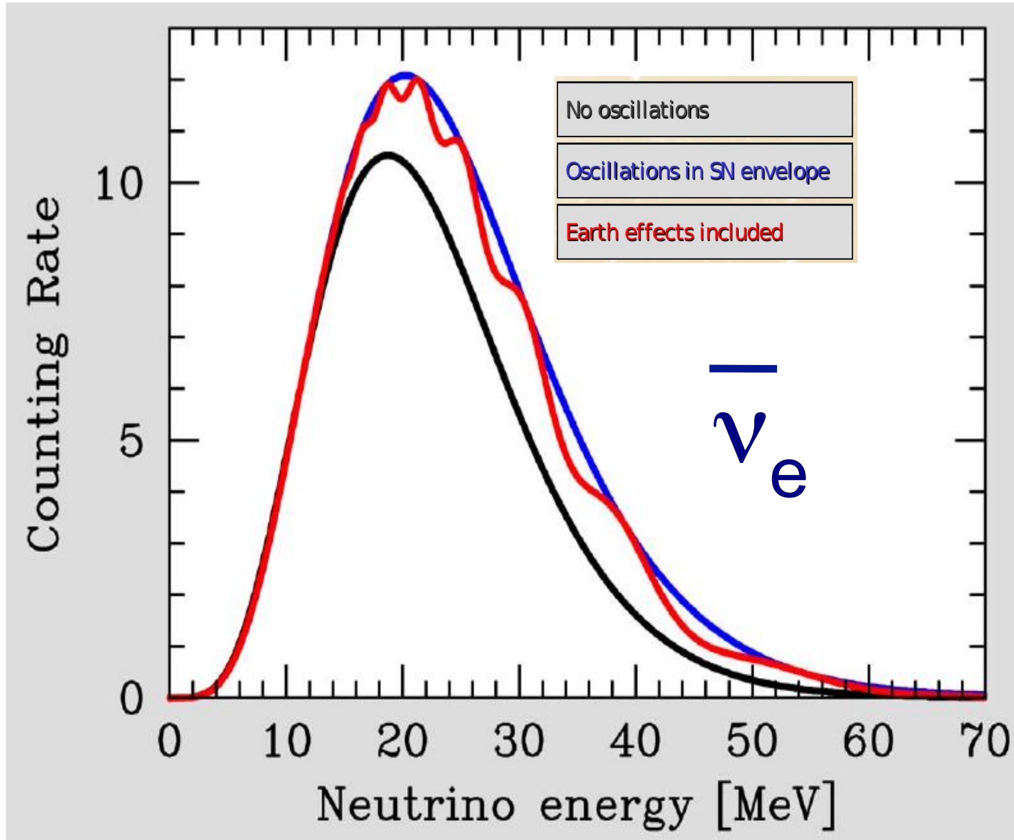
Experimentally, can we tell the difference?

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

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 << 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!

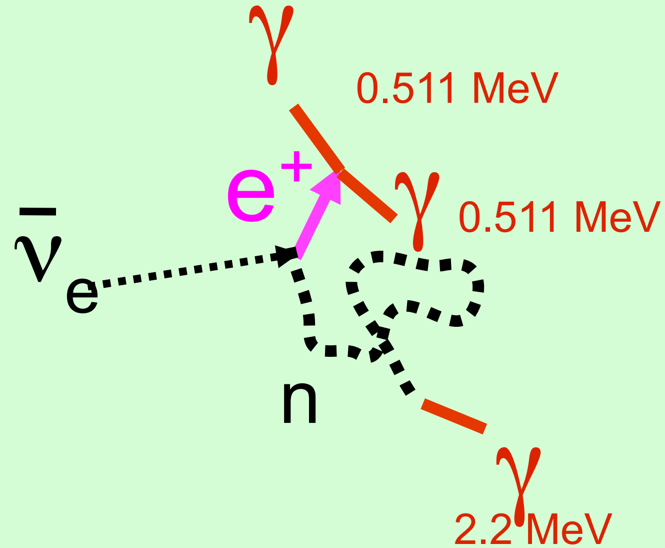
ν_e vs $\bar{\nu}_e$ vs ν_x

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

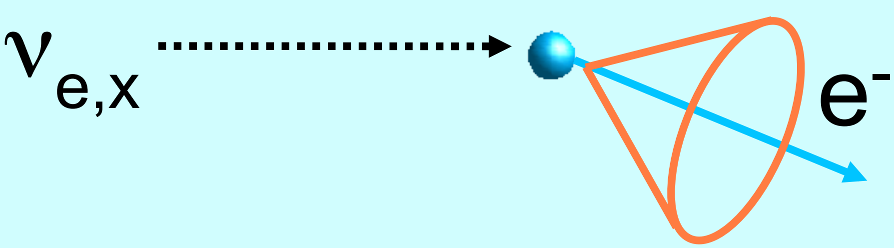
Inverse Beta Decay (CC)

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

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

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

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

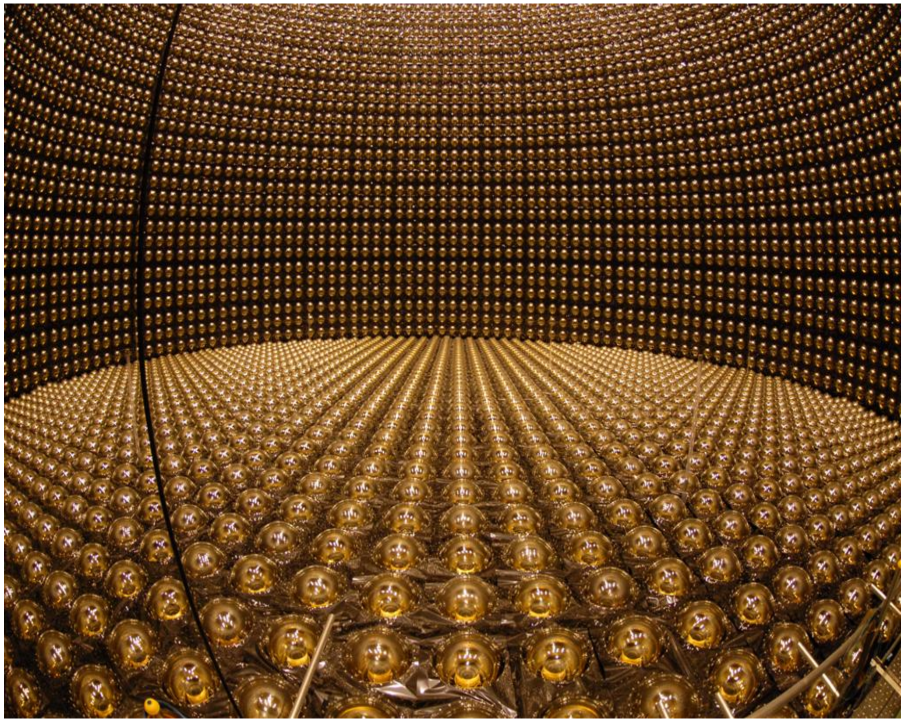
$$\nu_x + (A,Z) \rightarrow (A-1,Z) + n + \nu_x$$

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

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

+ NC coherent scattering

Water Cherenkov detectors



- few 100 events/kton

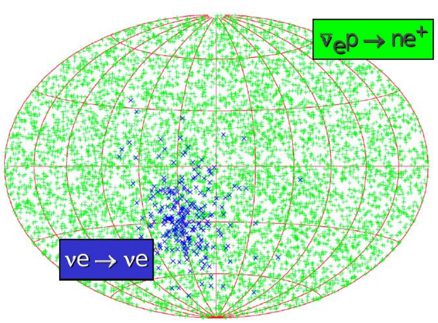
- typical energy threshold
  ~ several MeV makes
  2.2 MeV neutron tag difficult
  (unless Gd added)

Inverse Beta Decay (CC)

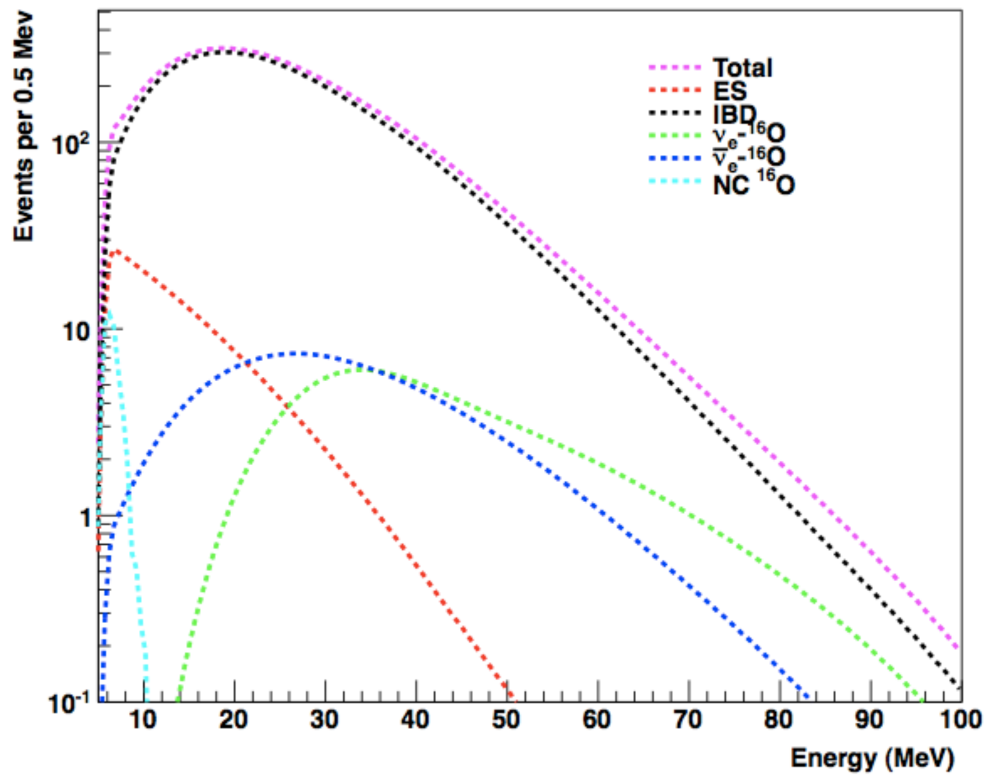
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

dominates

E_{thr}=1.8 MeV

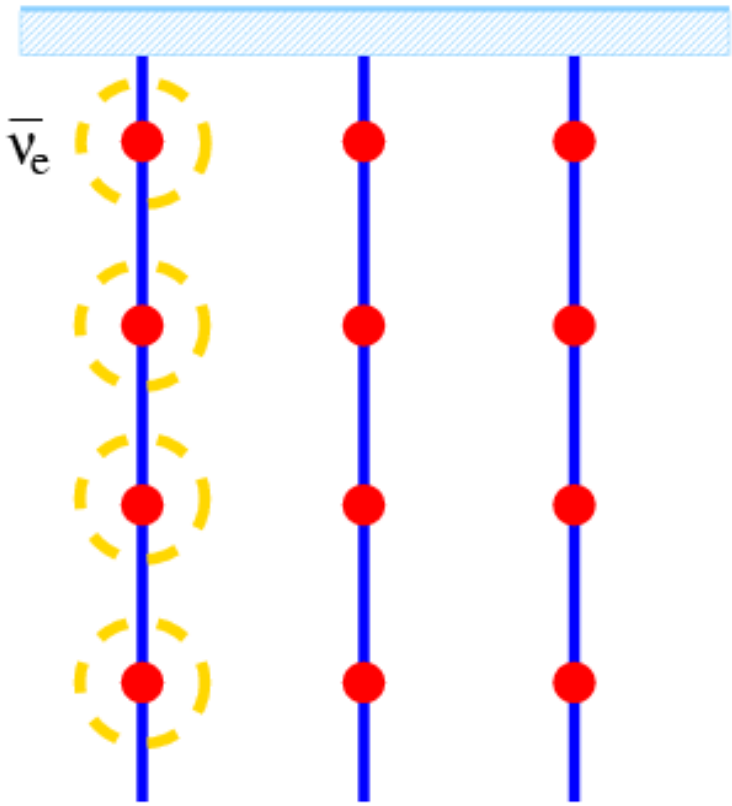


Some pointing from ES



100 kt @ 10 kpc

Long string water Cherenkov detectors

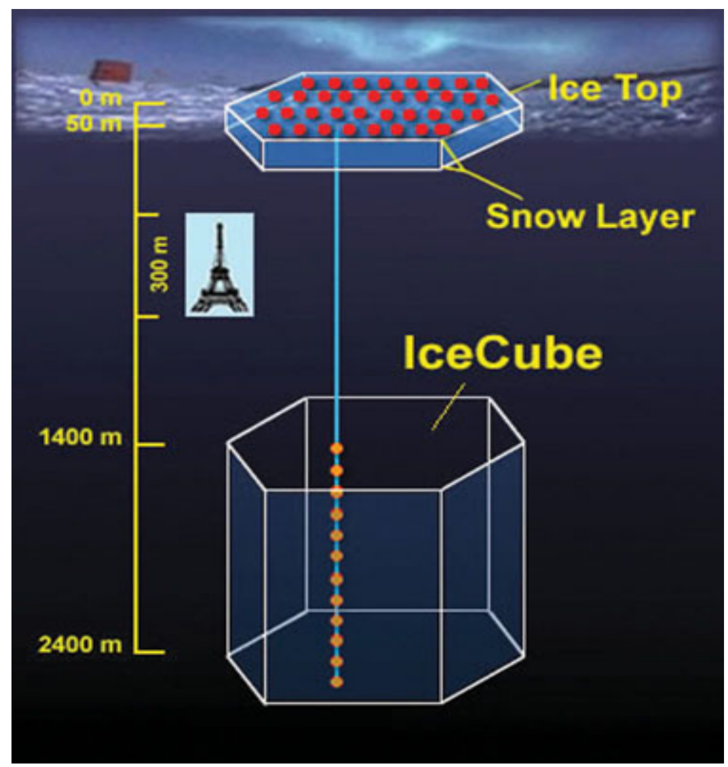


~kilometer long strings of PMTs in very clear water or ice

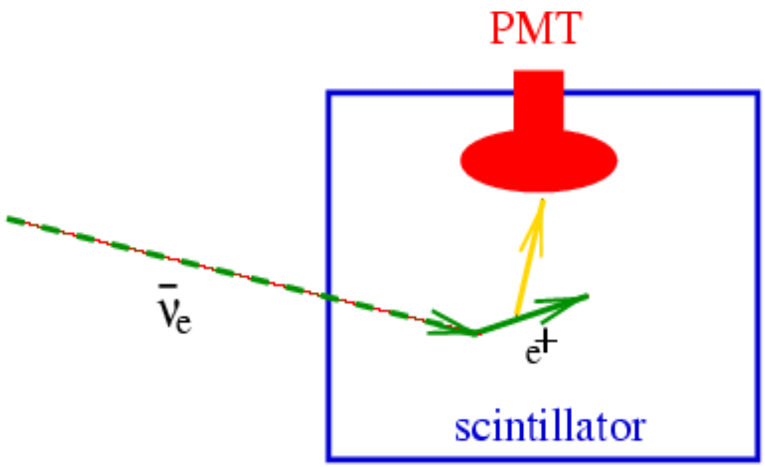
Nominally multi-GeV energy threshold... but, may see burst of low energy $\bar{\nu}_e$'s as *coincident increase in single PMT count rates* (M_{eff}~ 0.7 kton/PMT)

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

IceCube at the South Pole, Antares



Scintillation detectors



Liquid scintillator C_nH_{2n} volume surrounded by photomultipliers

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

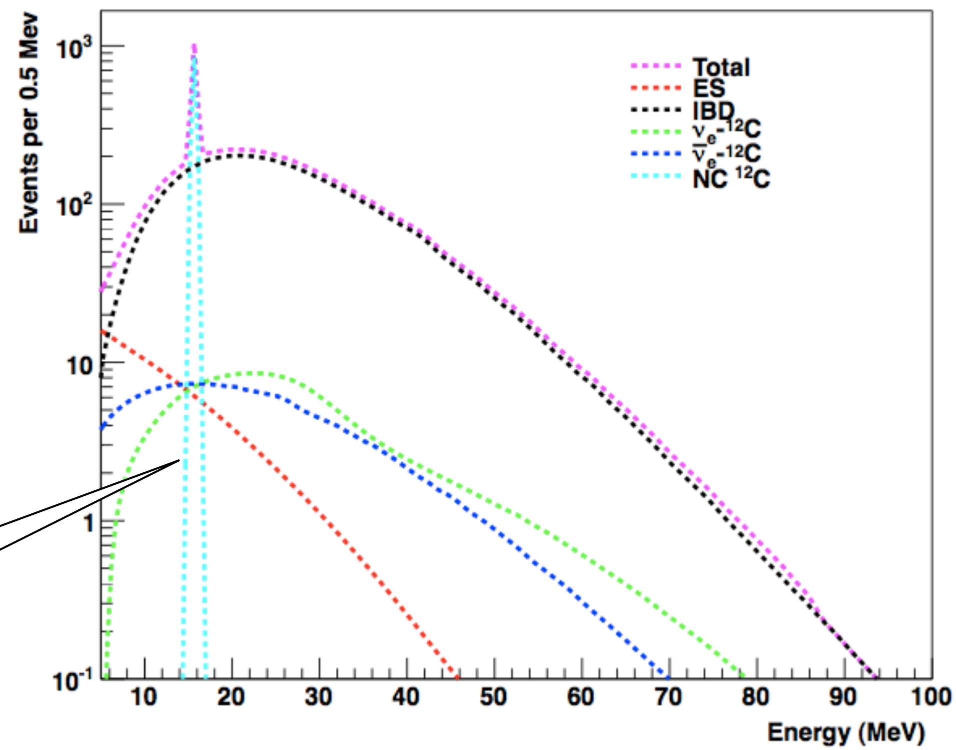
- few 100 events/kton

- 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

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

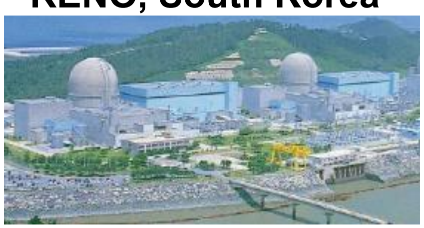
Detector	Type	Location	Mass (ton)	Events @ 10 kpc*
Double Chooz	Scintillator	France	20	**7**
RENO	Scintillator	South Korea	30	**11**
Daya Bay	Scintillator	China	160	**58**

*** plus coherent ν-p scatters**

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

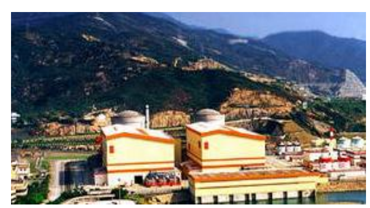
Also: coincidence between multiple detectors will help for a SN trigger

RENO, South Korea



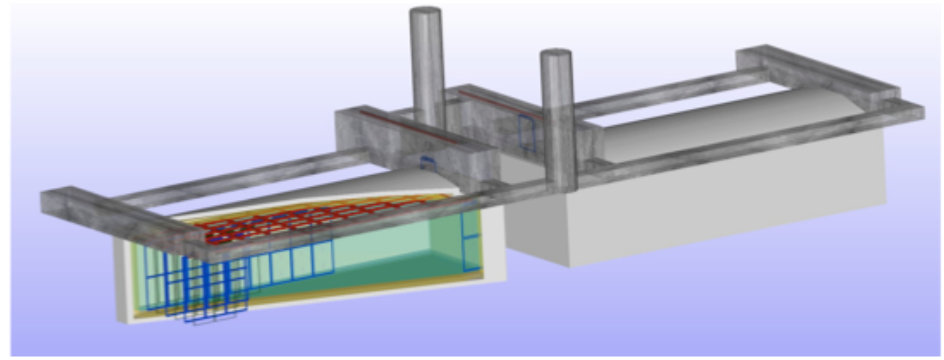
Double CHOOZ, France

Daya Bay, China



Liquid argon time projection chambers

e.g. Icarus, LBNE LAr



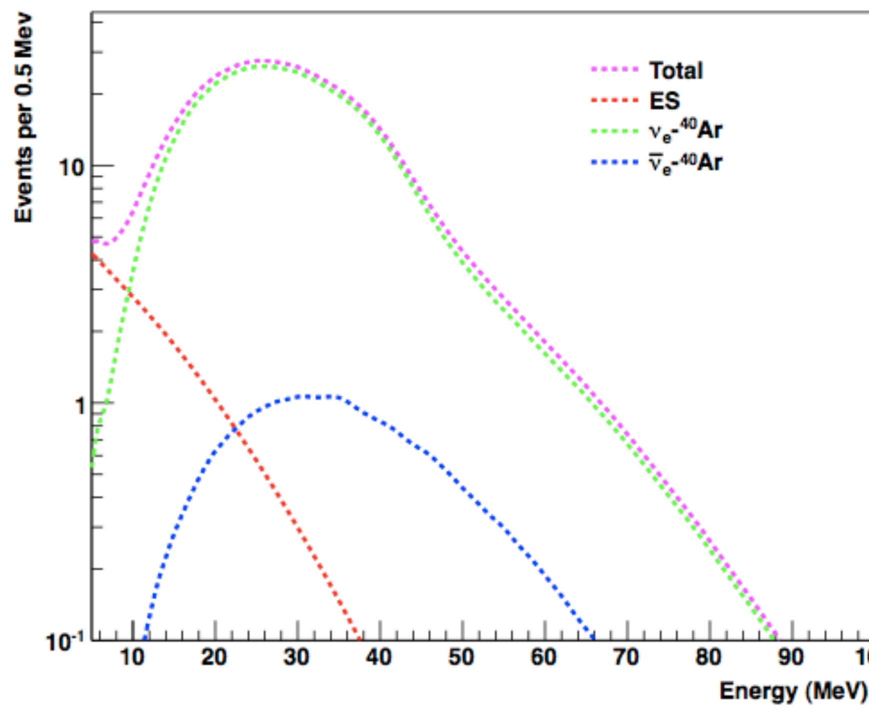
CC $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$

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

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

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

- **Tag modes with gamma spectrum (or lack thereof)**
- **Excellent electron neutrino sensitivity**



17 kt @ 10 kpc

HALO at SNOLab

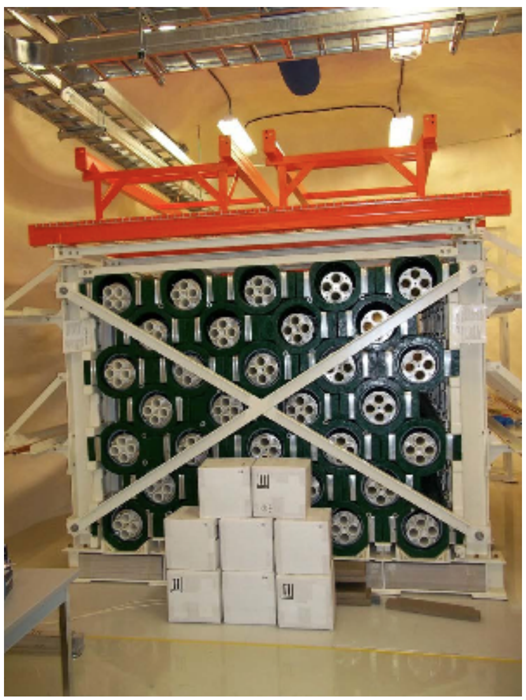
$\nu_e + {}^{208}Pb \rightarrow {}^{208}Bi^* + e^-$ CC

1n, 2n emission

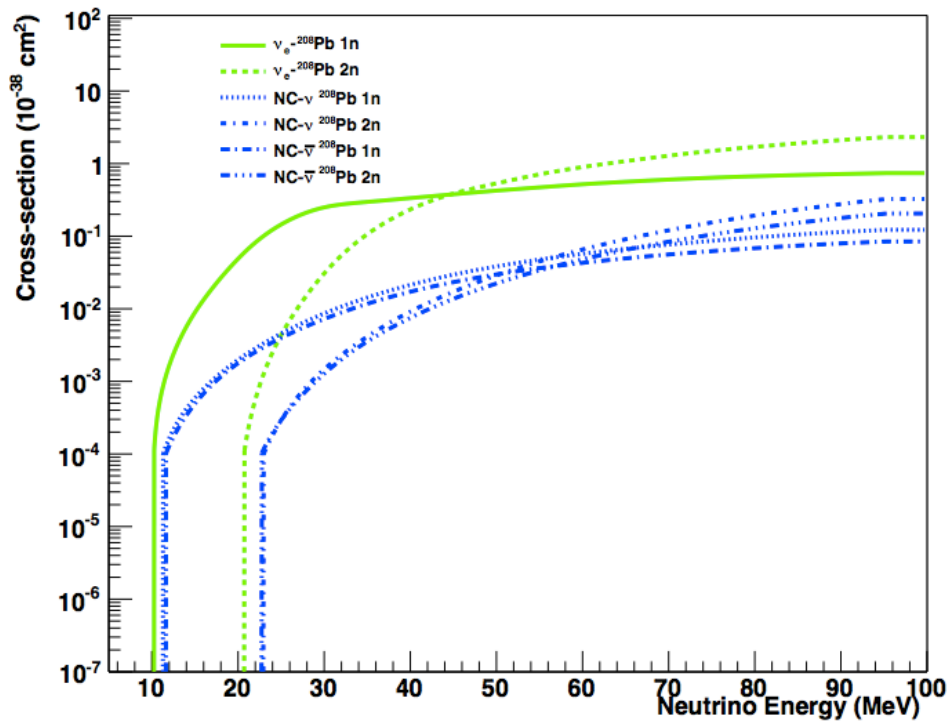
$\nu_x + {}^{208}Pb \rightarrow {}^{208}Pb^* + \nu_x$ NC

1n, 2n, γ emission

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



HALO will be operational by ~end 2011

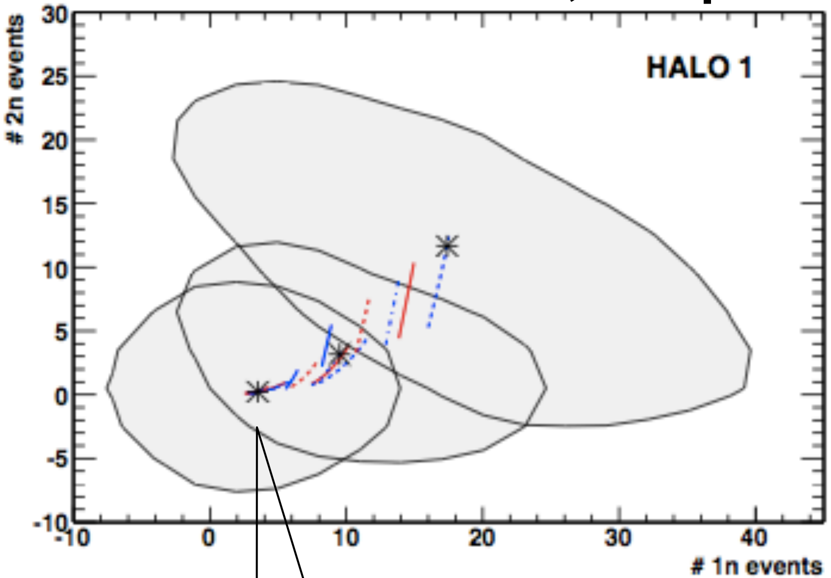


SNO ^{3}He counters + 79 tons of Pb: ~85 events @ 10 kpc

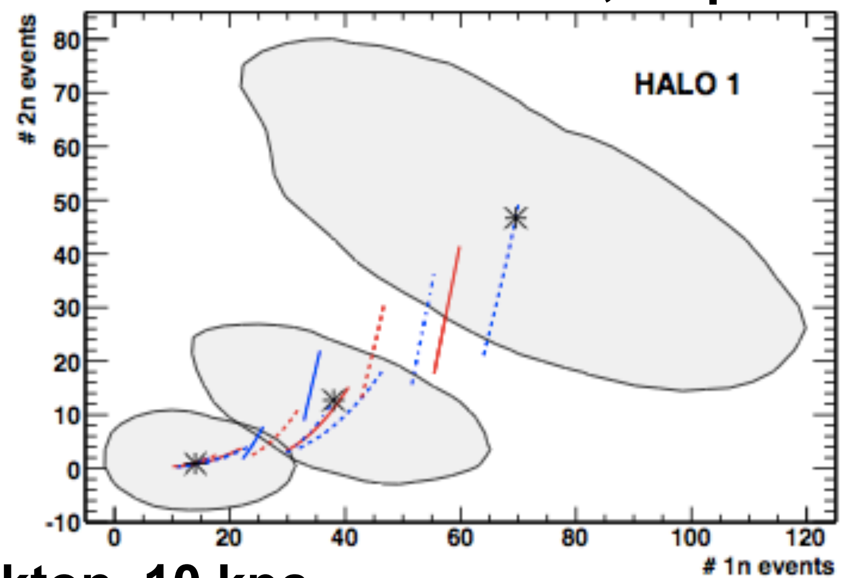
NEW

HALO sensitivity

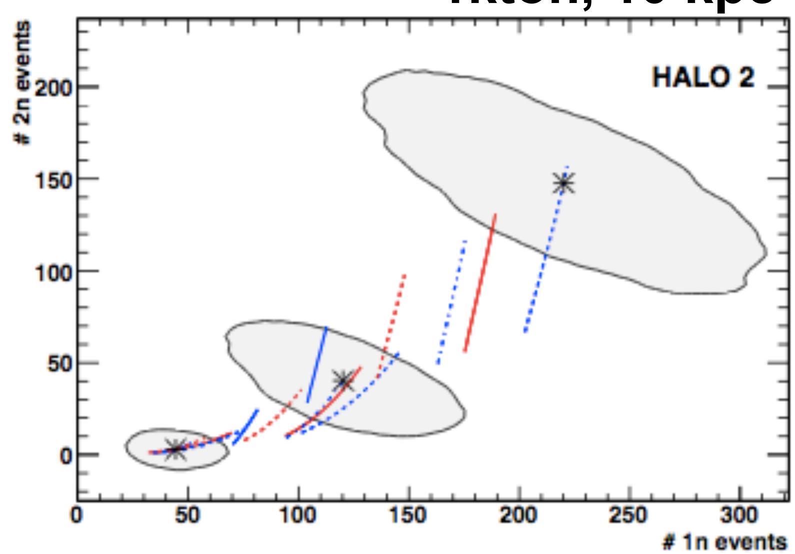
79 tons, 10 kpc



79 tons, 5 kpc



1kton, 10 kpc



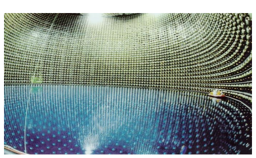
Note that measuring few events will give significant information

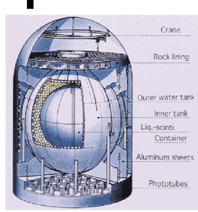
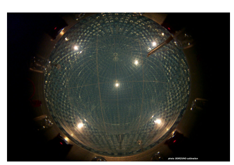
- Curves represent predictions for a range of models with different fluxes and oscillation parameters, from Vaananen & Volpe arXiv:1105.6225
- Shaded regions enclose 90% of HALO inferred values, for simulated neutron detection efficiencies

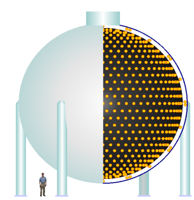
Current & near-feature supernova neutrino detectors

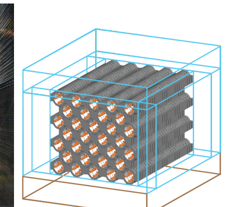
Detector	Type	Location	Mass (kton)	Events @ 10 kpc	Status
Super-K	Water	Japan	32	8000	Running (SK IV)
LVD	Scintillator	Italy	1	300	Running
KamLAND	Scintillator	Japan	1	300	Running
Borexino	Scintillator	Italy	0.3	100	Running
IceCube	Long string	South Pole	(600)	(10^6)	Running
Baksan	Scintillator	Russia	0.33	50	Running
Mini-BOONE	Scintillator	USA	0.7	200	Running
Icarus	Liquid argon	Italy	0.6	60	Running
HALO	Lead	Canada	0.079	20	Under construction
NOνA	Scintillator	USA	15	3000	Construction started
SNO+	Scintillator	Canada	1	300	Under construction

plus reactor experiments, DM experiments…



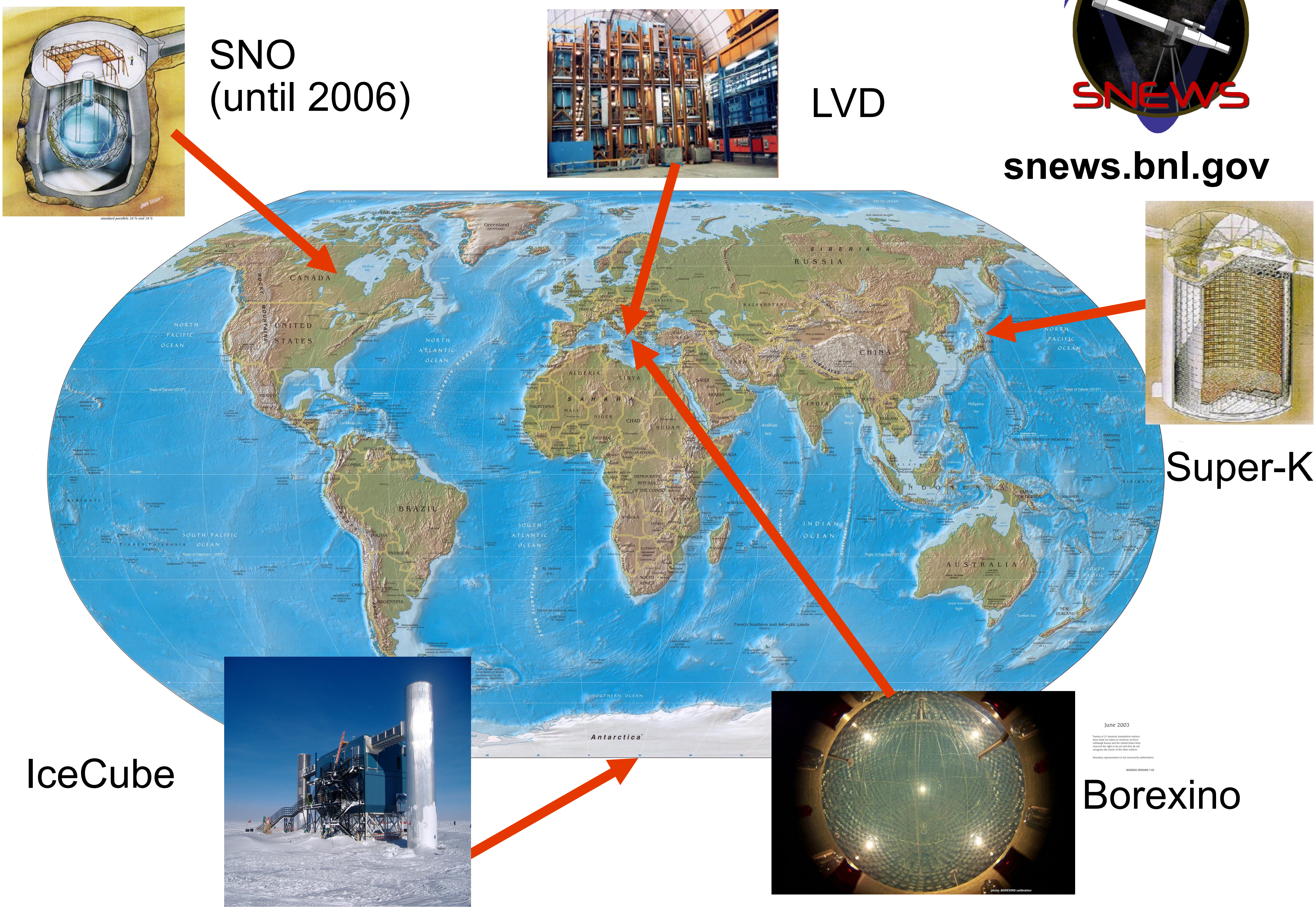





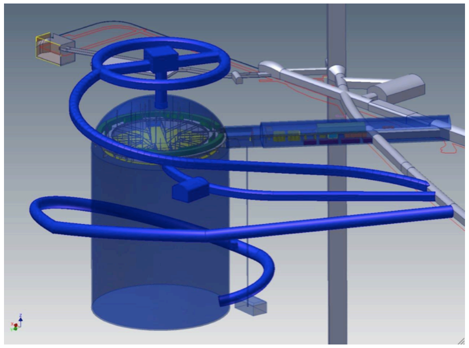
Primary sensitivity is to electron antineutrinos via inverse beta decay $\bar{\nu}_e + p \longrightarrow e^+ + n$

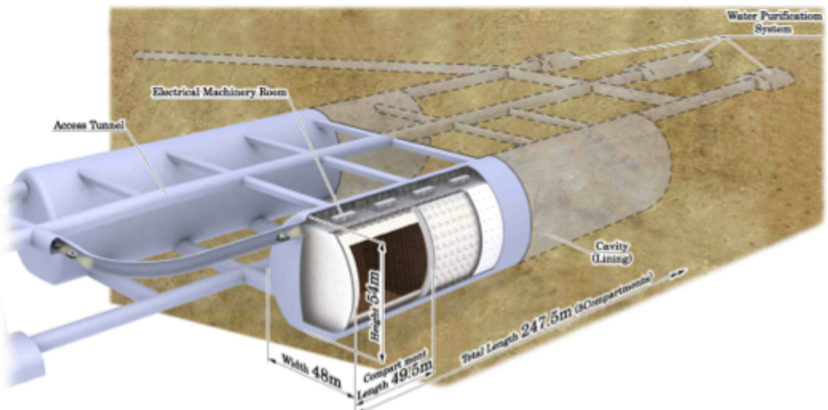
SNEWS: SuperNova Early Warning System



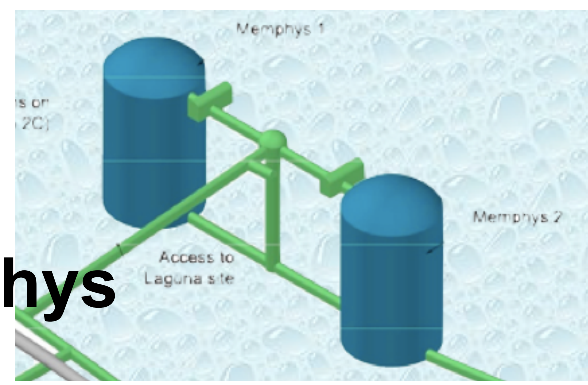
Next generation mega-detectors (10-20 years)

LBNE WCh



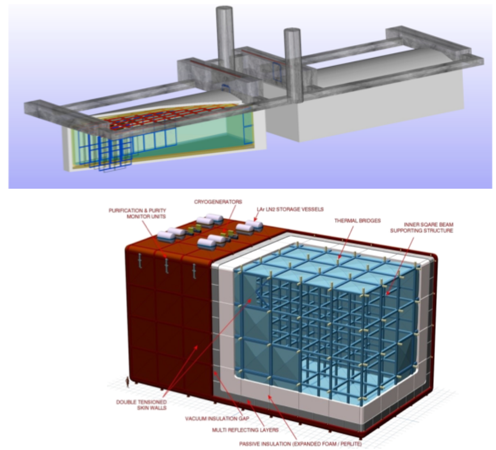


Hyper-K

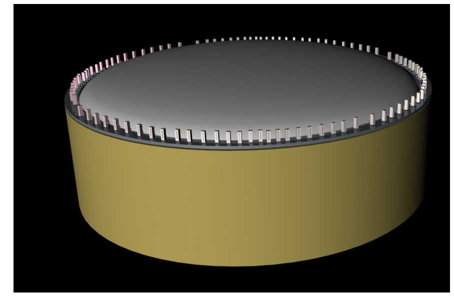


Memphys

Megaton-scale water detector concepts



5-100 kton-scale liquid argon concepts



LBNE LAr

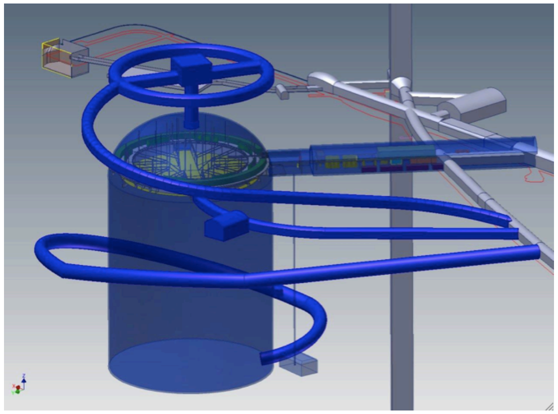
GLACIER

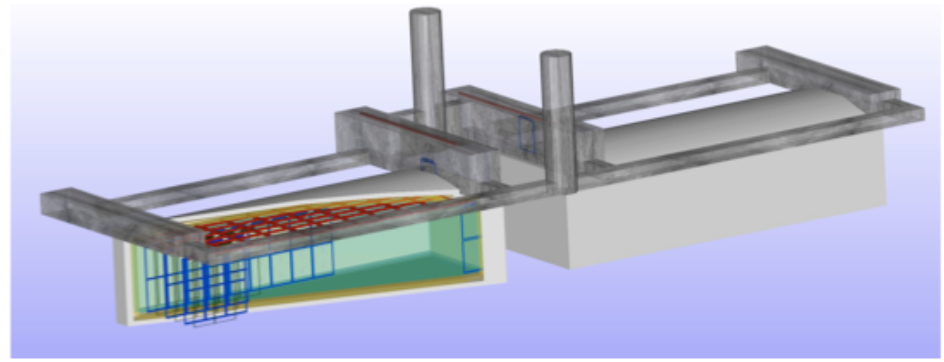
10-100 kton-scale scintillator detector concepts

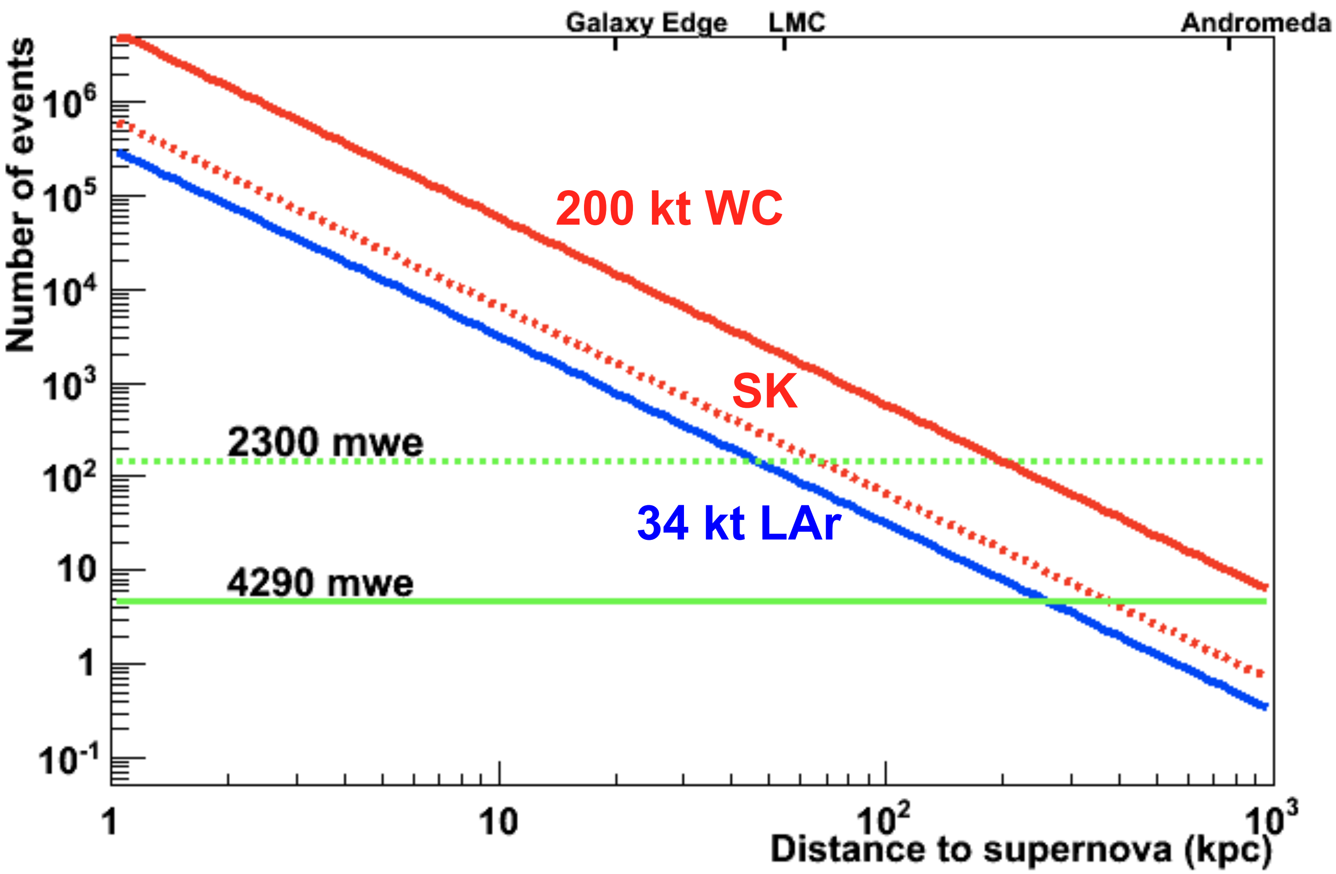
LENA

Zoom in on LBNE: Long Baseline Neutrino Experiment

'Day job': going after θ_{13}, hierarchy, δ, via long baseline beam







Also will have excellent supernova sensitivity!

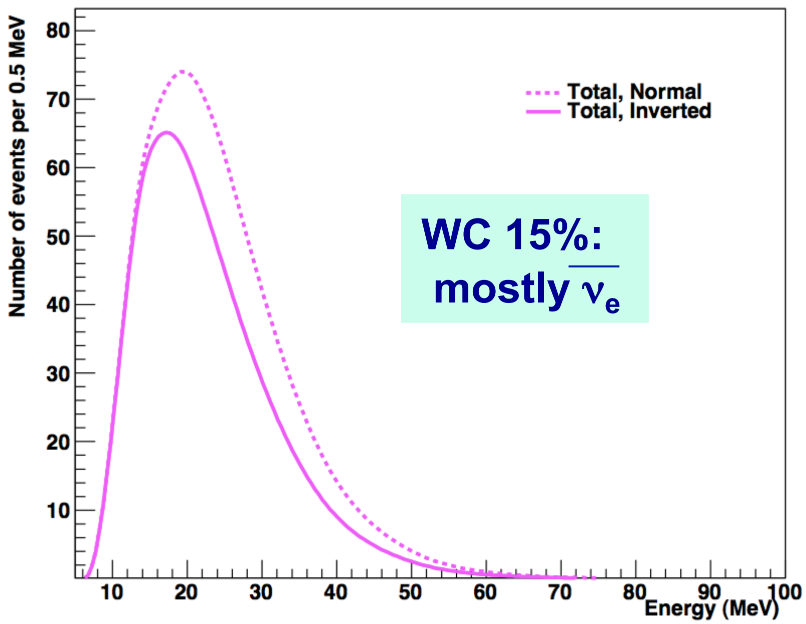
Under consideration:

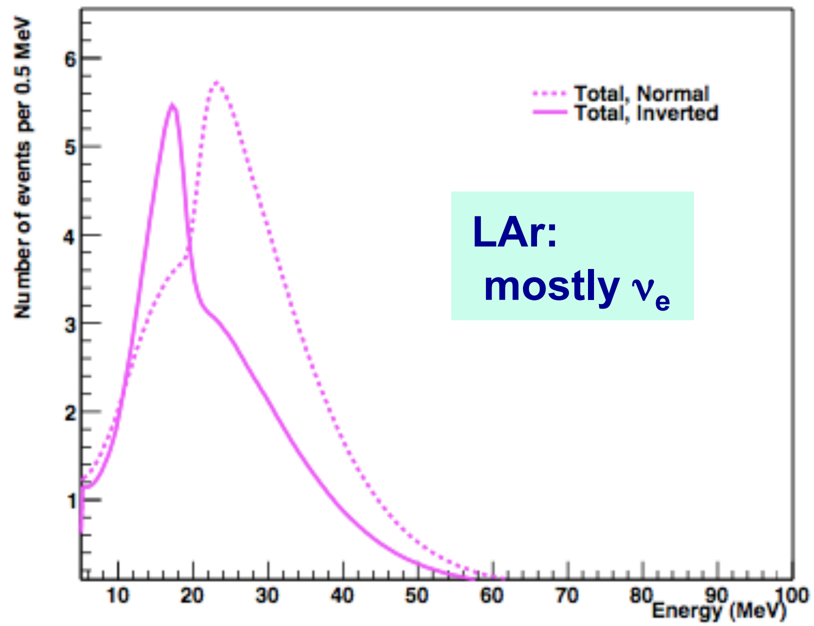
- 150-200 kt WCh
- 2 x 17 kt LAr TPC

Observability of oscillation features: 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... systematic surveys underway

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

Summary of supernova neutrino detectors

Galactic sensitivity

Extragalactic

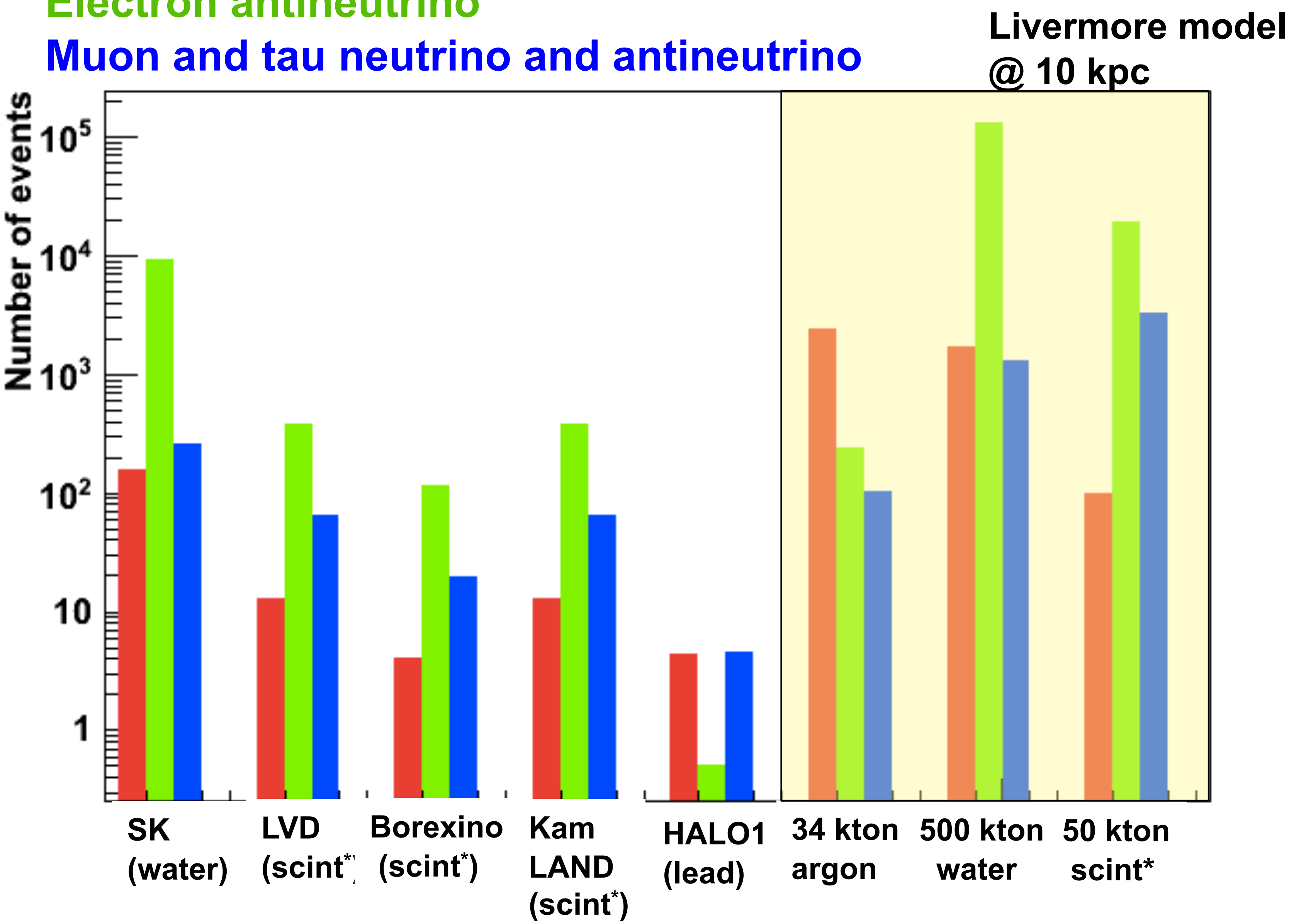
Detector	Type	Location	Mass (kton)	Events @ 8 kpc	Status
Super-K	Water	Japan	32	8000	Running (SK IV)
LVD	Scintillator	Italy	1	300	Running
KamLAND	Scintillator	Japan	1	300	Running
Borexino	Scintillator	Italy	0.3	100	Running
IceCube	Long string	South Pole	(600)	(10^6)	Running
Baksan	Scintillator	Russia	0.33	50	Running
Mini-BOONE	Scintillator	USA	0.7	200	Running
Icarus	Liquid argon	Italy	0.6	60	Running
HALO	Lead	Canada	0.079	20	Under construction
NOνA	Scintillator	USA	15	3000	Construction started
SNO+	Scintillator	Canada	1	300	Under construction
LBNE LAr	Liquid argon	USA	34	3000	Proposed
LBNE WC	Water	USA	200	44,000	Proposed
MEMPHYS	Water	Europe	440	88,000	Proposed
Hyper-K	Water	Japan	540	110,000	Proposed
LENA	Scintillator	Europe	50	15,000	Proposed
GLACIER	Liquid argon	Europe	100	9000	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



* plus NC ν-p scattering

Summary

Current 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

Near future

- more flavor sensitivity (e.g. HALO)

Farther future:

- extragalactic reach
- huge statistics, richer flavor sensitivity
- excellent oscillation sensitivity

SNOwGLoBES
(SuperNova Observatories with GLoBES)

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A. Beck, F. Beroz, R. Carr, KS, W. Johnson, A. Moss, D. Reitzner, D. Webber, R. Wendell

A. Dighe, H. Duan, A. Friedland, J. Kneller

- Computes interaction rates and detector spectra for given GLoBES-formatted flux file
- Work initiated in context of recent physics study for LBNE
- Public release envisioned (< 1 month)

Dependencies: GLoBES, GLoBES' dependencies, Perl
(uses GLoBES event rate engine only, not oscillation part)

`www.mpi-hd.mpg.de/personalhomes/globes`

Will be released under GPL

To evaluate sensitivity to different features of flux/physics, we need to fold

$$\text{flux} \otimes \text{xscn} \otimes \text{detector response}$$

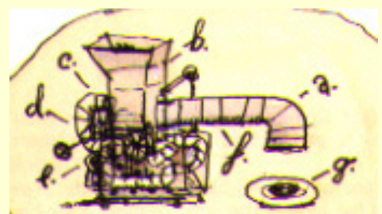
flux differential spectra w/physics

cross- sections for relevant channels

smearing matrix for given detector config: includes both interaction product distributions and detector response

post-smearing efficiency

SNOw GLoBES



interaction rates, as a function of neutrino energy

‘smeared’ rates as a function of detected energy

evaluate physics sensitivity

SNOwGLoBES package contents

- driving script
- data files:
  - cross-section files for O, Ar, C, Pb (+...)
  - smearing and efficiency files for several detector configurations (100kt, scint, LAr, HALO)
  - example flux file(s)
- example plotting scripts
- documentation w/refs

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- Smearing and efficiency files provided are based on:
  - published information (resolutions etc.), reasonable assumptions
  - for LBNE configurations: simulation output
- Users (typically) would provide their own fluxes
- Users could use the packaged detector smearing datafiles, or provide their own
- Please email me if you are interested in testing it