Supernova Neutrino Detection:
Water Cherenkov Detectors

Matthew Malek

7th April 2022

IoP HEPP / APP Topical Workshop:

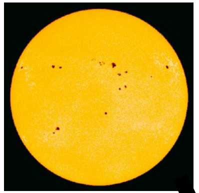
Supernova Neutrinos in the Multimessenger Era

Outline

- Introduction to supernova neutrinos
- A brief history of supernova neutrino detection
- Interactions in water Cherenkov detectors
- The next galactic supernova burst
- Supernova relic neutrinos
- Complementarity with other detection media

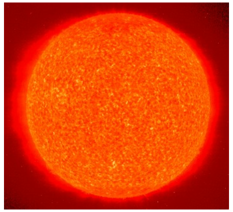
Introduction: Progenitors

Main Sequence



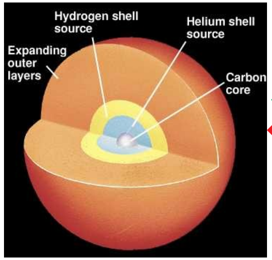
H core

Red Giant



He core + H shell

Supergiant

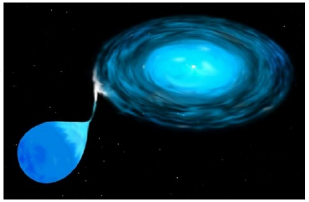


C & O core
He & H shells

$m > 8\ M_\odot$?

YES

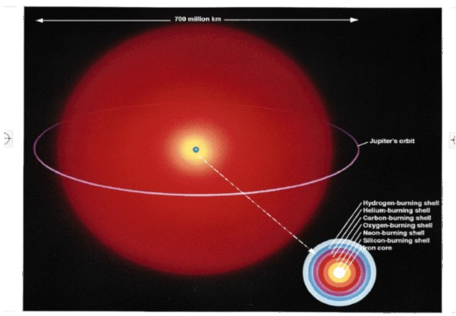
Accreting White Dwarf



→ **Carbon deflagration supernova “Type Ia”**

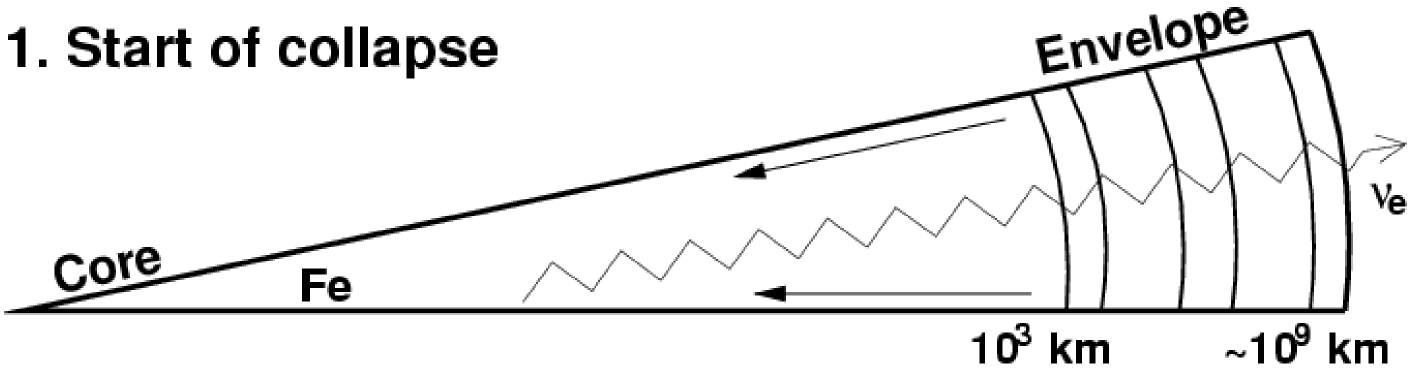
NO

“Onion” Shells
(H,He,C,O,Ne,Si,Fe)



→ **Core Collapse!**

Introduction: Core Collapse

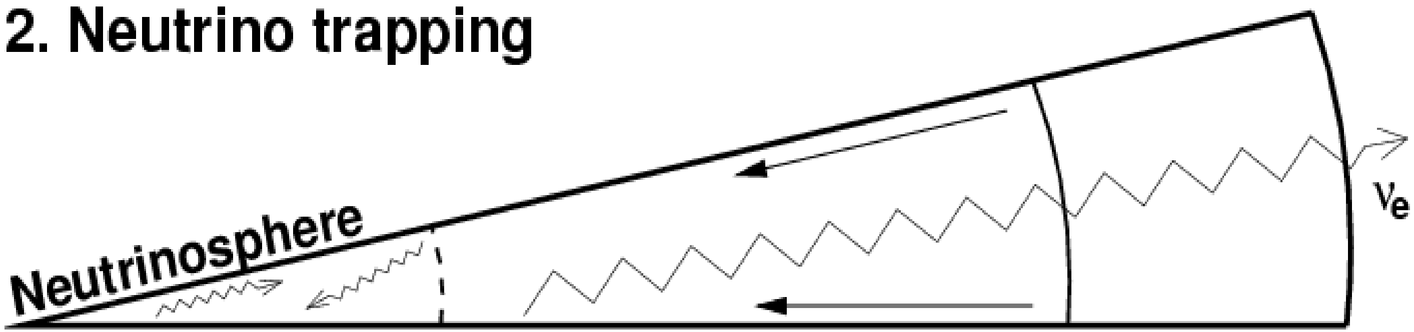


- Electrons captured on nuclei produce ν_e via:

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

- Mean free path of neutrinos > core size
- Neutrinos escape promptly

Introduction: Core Collapse

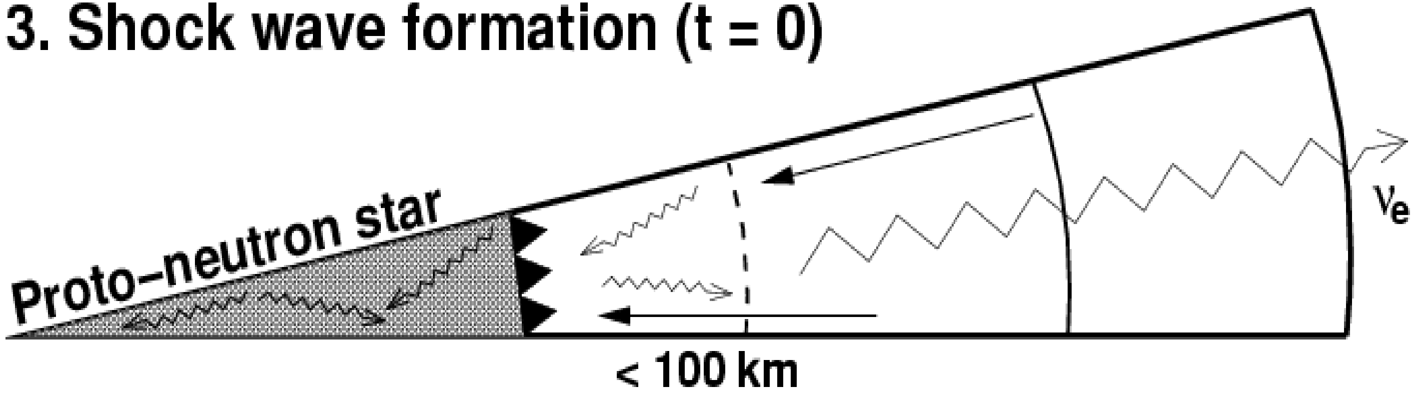


- Core density increases as collapse continues
- Mean free path of ν shrinks w/ increasing density

- Neutrinos trapped by scattering off nuclei:

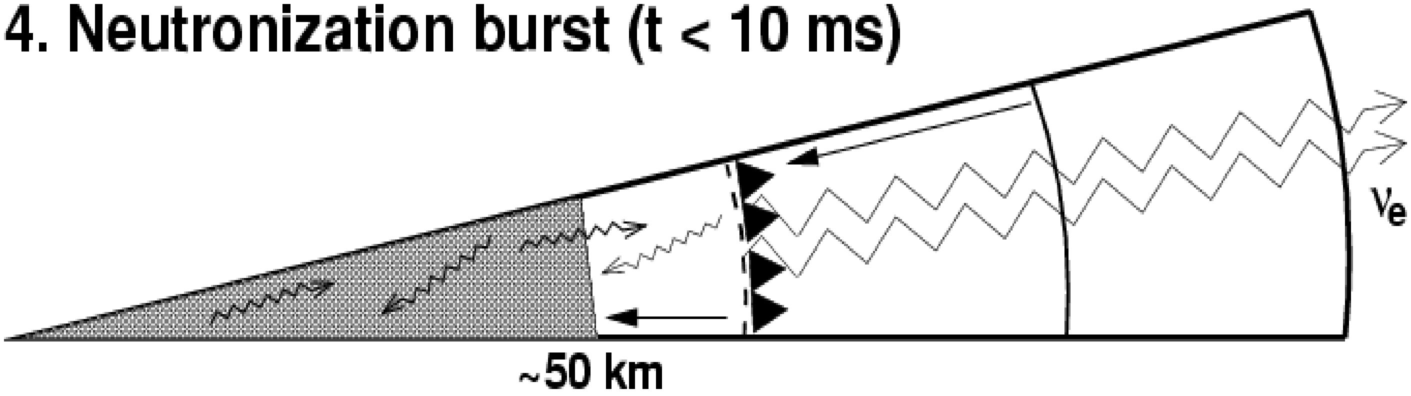
$$\nu + A(N,Z) \rightarrow \nu + A(N,Z)$$

Introduction: Core Collapse



- Inner core reaches nuclear densities
- Neutron degeneracy halts gravitation attraction
- Inner core rebounds, causing shock wave
- Shock wave propagates through infalling outer core
- Larger ν-sphere; νs still emitted from outer core

Introduction: Core Collapse

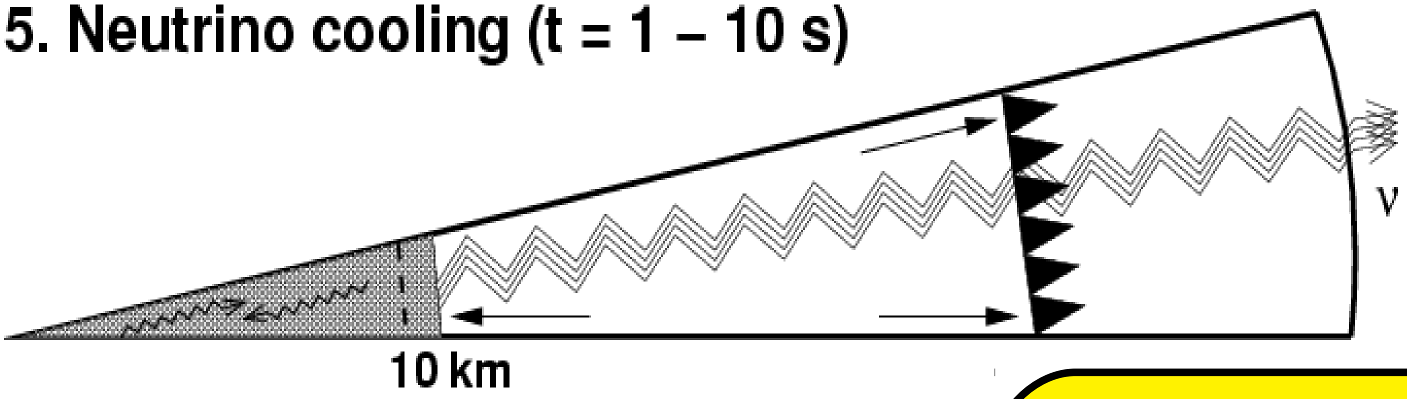


- Shock slows infalling matter and separates nucleons
- Shock loses energy (8 MeV) per dissociated nucleon
- Electrons captured on dis. protons produce ν_e via:

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

- Liquid argon detectors particularly sensitive to this signal!

Introduction: Core Collapse



- E_{grav} → E_{therm}, about 10^{46} Joules
- T ≈ 40 MeV ≈ 500,000,000,000 K
- Cooling via ν emission
  - All six types of neutrinos emitted
- Neutron star (or black hole) left behind

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

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

$e^- + e^+ \rightarrow \nu + \bar{\nu}$

$e^\pm + N \rightarrow e^\pm + N + \nu + \bar{\nu}$

$N + N \rightarrow N + N + \nu + \bar{\nu}$

$\gamma\ (+ e^\pm) \rightarrow \nu + \bar{\nu}$

Core Collapse Summary

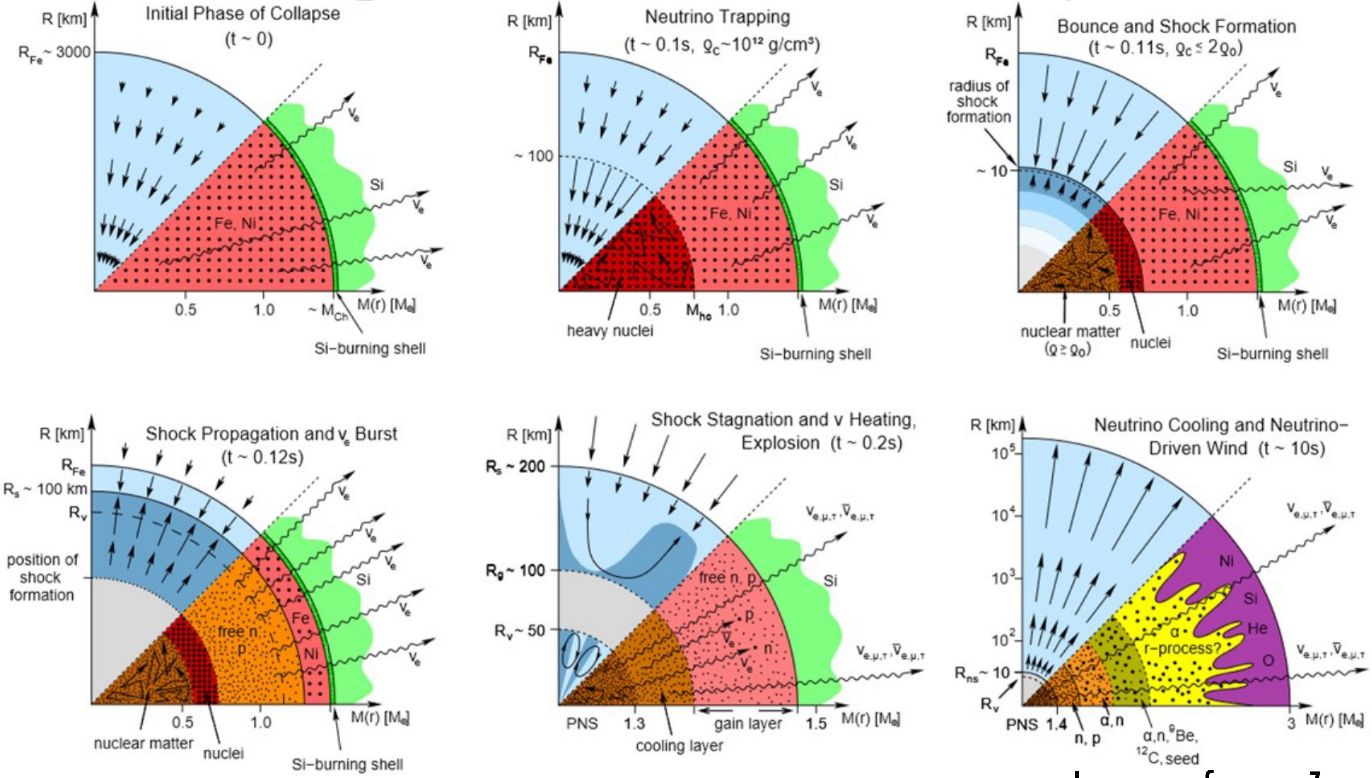
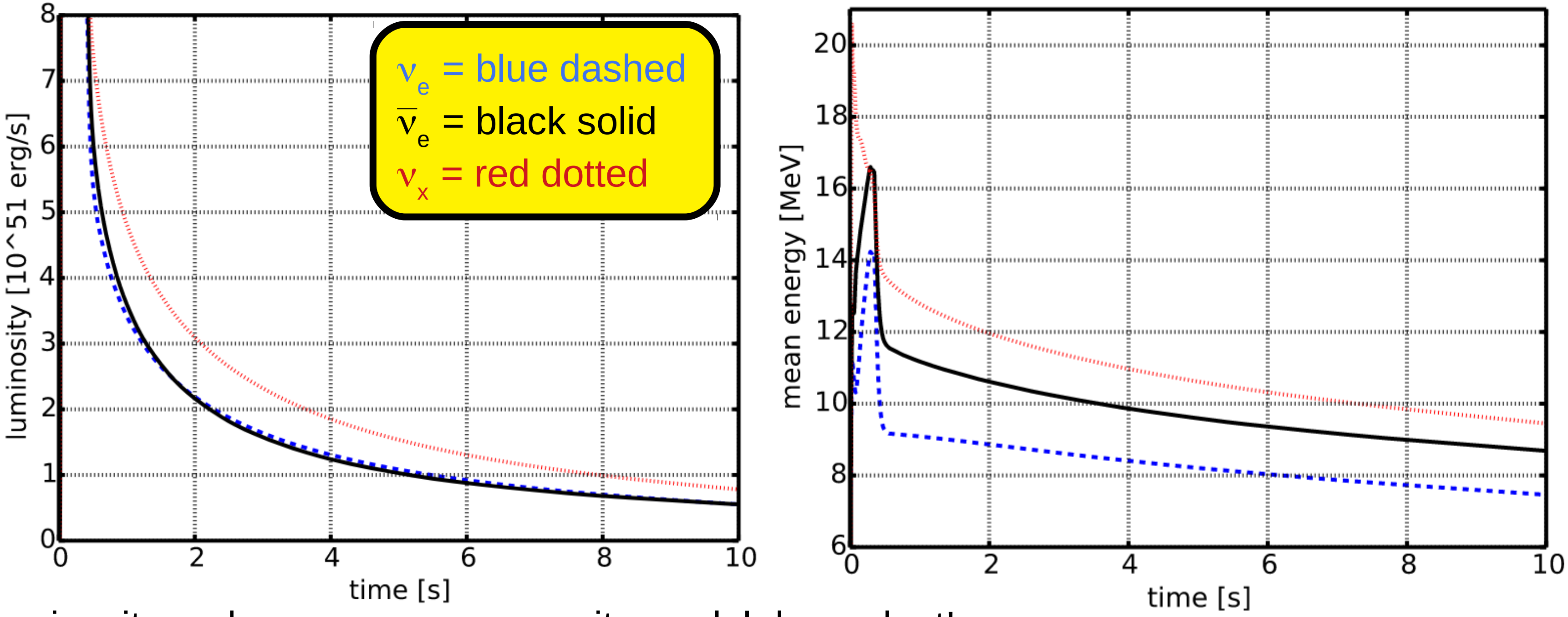


Image from *Janka, H.Th. et al*
Theory of core-collapse supernovae
Phys. Rep. 442, pp 38 – 74 (2007).

Luminosity & Mean Energy



Luminosity and mean energy are quite model dependent!

Figures shown here represent Nakazato *et al* model (*Astrophys. J. Suppl.* **205** (2013)) for a progenitor of 20 solar masses

Multimessenger: ν and γ

Neutrinos (ν)

- 99% of the energy from a core-collapse supernova is released as neutrinos
- ν emitted during SN, giving unique insight into the process of a supernova & neutron star formation
- ν carry information direct from core; no scattering!
- ν are not obscured by interstellar media in the galactic plane

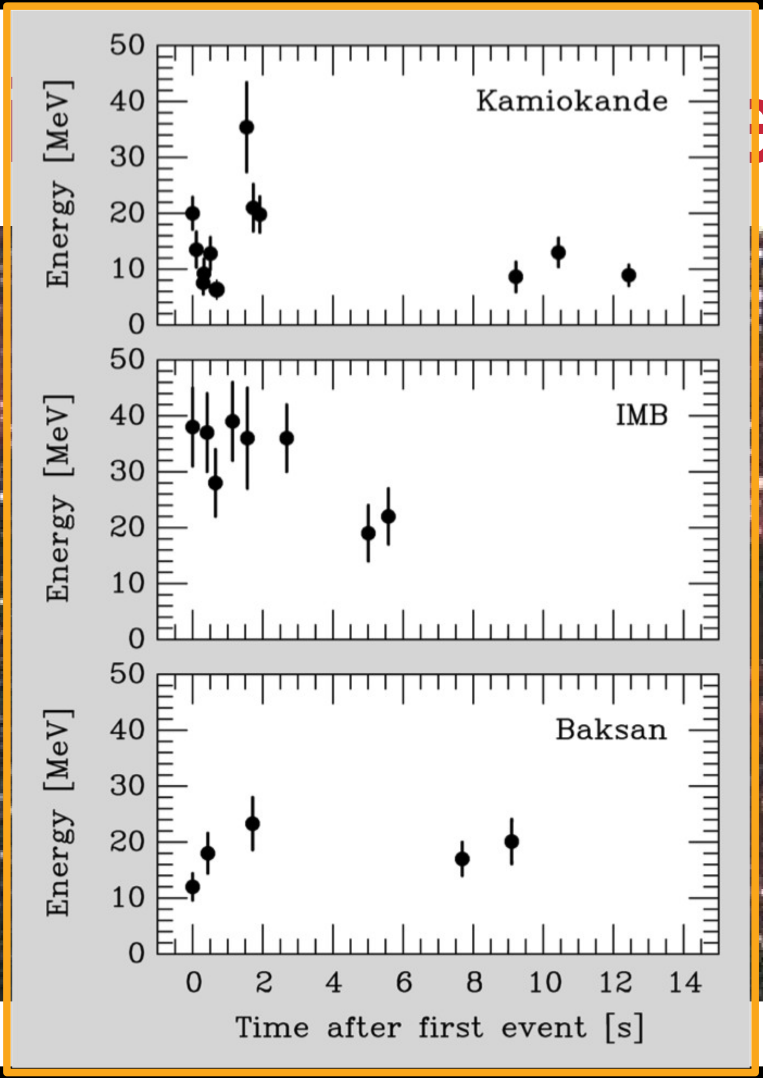
Photons (γ)

- Photons are much easier to detect than neutrinos!
- Photons are emitted hours later, largely from decay of radioactive elements produced in the supernova's shock wave, providing information from after the core-collapse

History of Supernova ν Detection

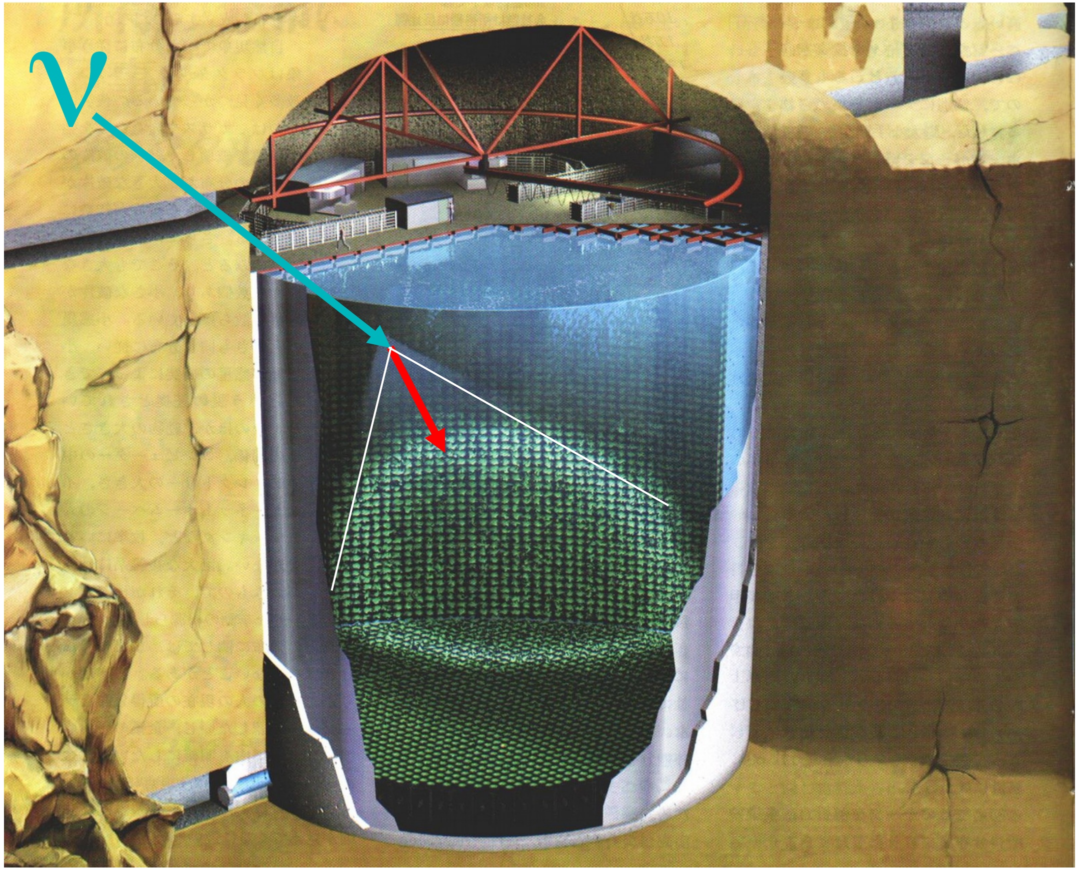
- To date, only supernova ν burst came from Sanduleak 69 202 in Large Magellanic Cloud (~51.4 kpc distance)
- Observed on 24th Feb 1987, this is – of course – the famous supernova 1987A
- 24 (or 25) supernova neutrinos seen in three neutrino telescopes:
  - 11 (or 12) at Kamiokande [Japan]
  - 8 at Irvine-Michigan-Brookhaven (IMB) [USA]
  - 5 at the Baksan Observatory [USSR]
- Both Kamiokande and IMB are water Cherenkov detectors

H ernova ν Detection



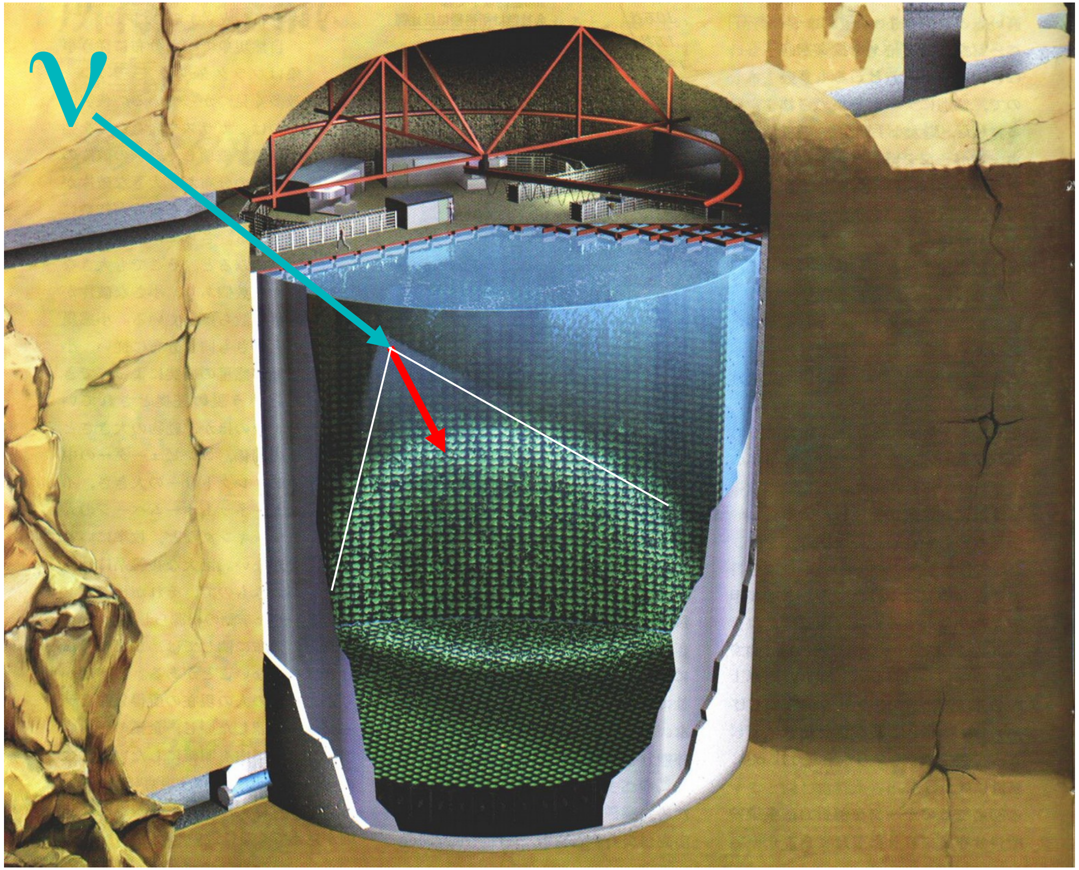
- To date, only supernova ν burst came from Sanduleak 69 202 in Large Magellanic Cloud (~51.4 kpc distance)
- Observed on 24th Feb 1987, this is – of course – the famous supernova 1987A
- 24 (or 25) supernova neutrinos seen in three neutrino telescopes:
  - 11 (or 12) at Kamiokande [Japan]
  - 8 at Irvine-Michigan-Brookhaven (IMB) [USA]
  - 5 at the Baksan Observatory [USSR]
- Both Kamiokande and IMB are water Cherenkov detectors

Water Cherenkov Detectors

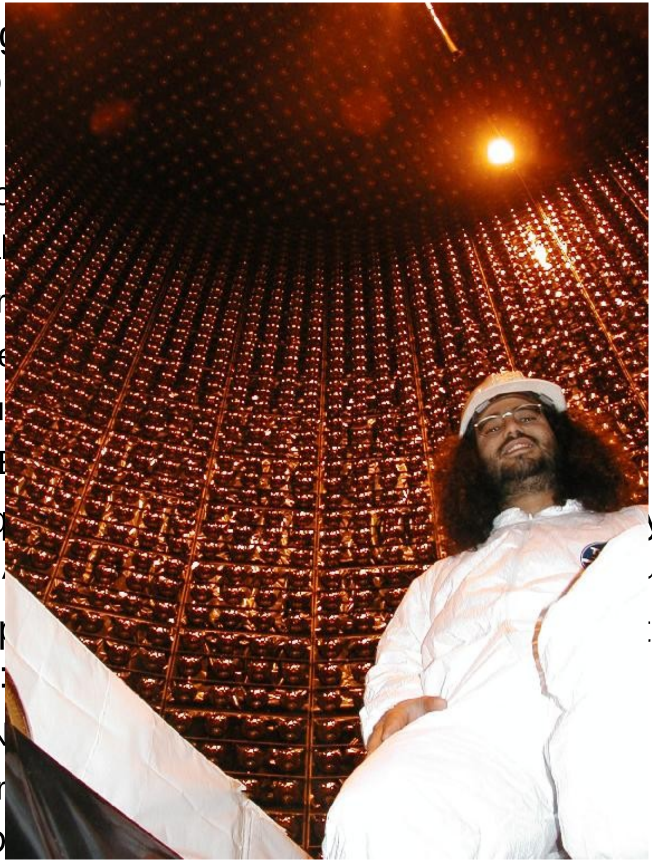


- Running or previous water Cherenkov neutrino detectors include:
  - IMB
  - Kamiokande
  - Baikal
  - Super-Kamiokande
  - Antares
  - IceCube
  - ANNIE
- Technique also used for observing gamma rays (*e.g.*, HAWC) and cosmic rays (*e.g.*, Pierre Auger)
- Future planned water Cherenkov neutrino detectors include:
  - KM3Net
  - IceCube Gen2
  - Hyper-Kamiokande
  - IWCD

Water Cherenkov Detectors



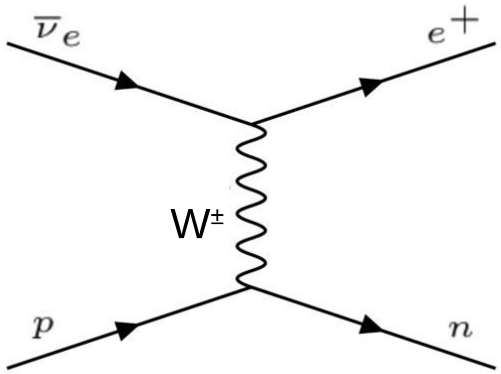
- Running o
  detecto
  - IMB
  - Kamic
  - Baikal
  - Super
  - Antare
  - IceCu
  - ANNI
- Technic ys
  (*e.g.*, H uger)
- Future ectors
  include:
  - KM3N
  - Hyper
  - IWCD

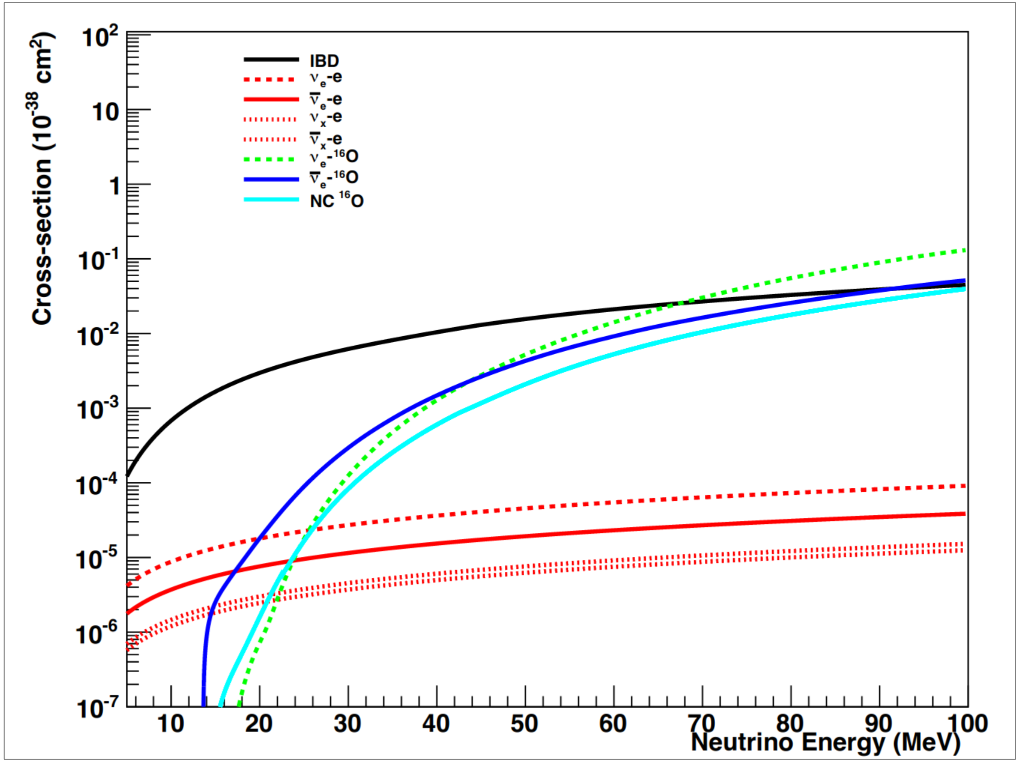


Supernova Neutrino Interactions

in a water Cherenkov detector

- Dominant cross-section is inverse beta decay (IBD)
  - $\overline{\nu}_e + p \rightarrow e^+ + n$



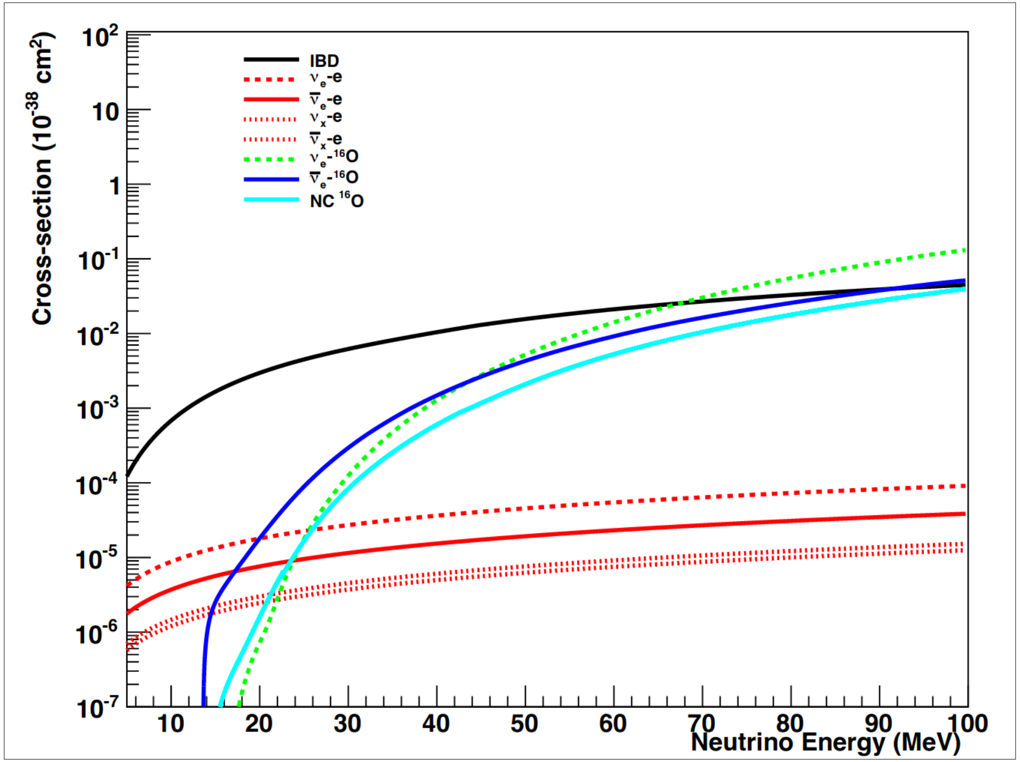


- Comprises ~90% of events seen in a water Cherenkov detector
- Positron emission is (roughly) non-directional

Supernova Neutrino Interactions

in a water Cherenkov detector

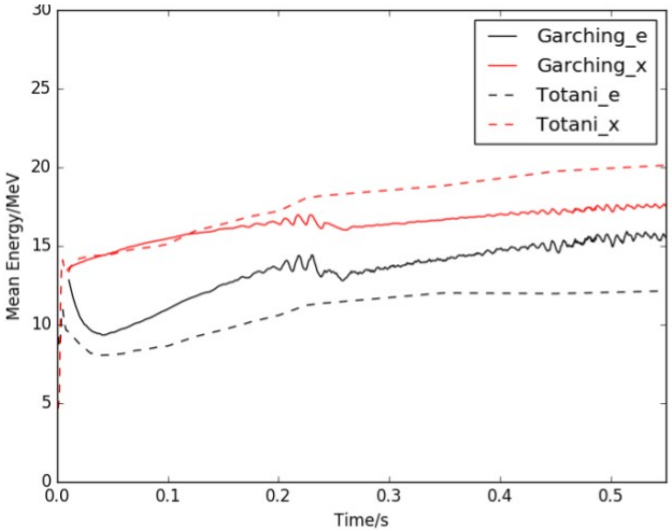
- Dominant cross-section is inverse beta decay (IBD):
    - $\bar{\nu}_e + p \rightarrow e^+ + n$
- Sub-dominant interaction is elastic scattering:
    - $\nu + e \rightarrow \nu + e$
  - Preserves direction information
- Other modes are highly model dependent, due to threshold effects:
    - $\nu_e + {}^{16}O \rightarrow e + {}^{16}F$ (E_{thresh} = 15 MeV)

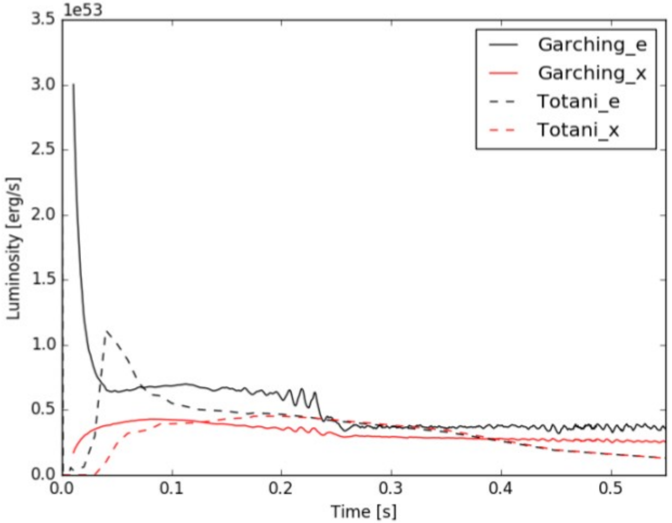


Supernova Neutrino Interactions

in a water Cherenkov detector

- Most charged-current ^{16}O events originate from ν_x that undergo MSW oscillation within the supernova
  - $\nu_e + {}^{16}O \rightarrow e + {}^{16}F$ (E_{thresh} = 15 MeV)





	Totani 1998	Garching 2014
No Oscillation	80	115
Normal	4100	224

Supernova Neutrino Results

since 1987

SEARCH FOR SUPERNOVA NEUTRINO BURSTS AT SUPER-KAMIOKANDE

The Super-Kamiokande Collaboration

Astrophys.J.669:519-524,2007

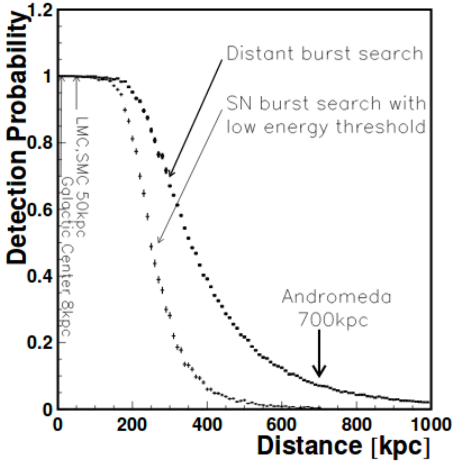


FIG. 6.— The probability of detecting supernovae assuming a specific supernova model at SK. Full (100%) detection probability is retained out to around 100 kpc.

Concise summary of results:

No burst

See upcoming talk by Jost Migenda on preparations to do model discrimination when the next burst arrives

Supernova Relic Neutrinos

sometimes known as “diffuse supernova neutrino background”

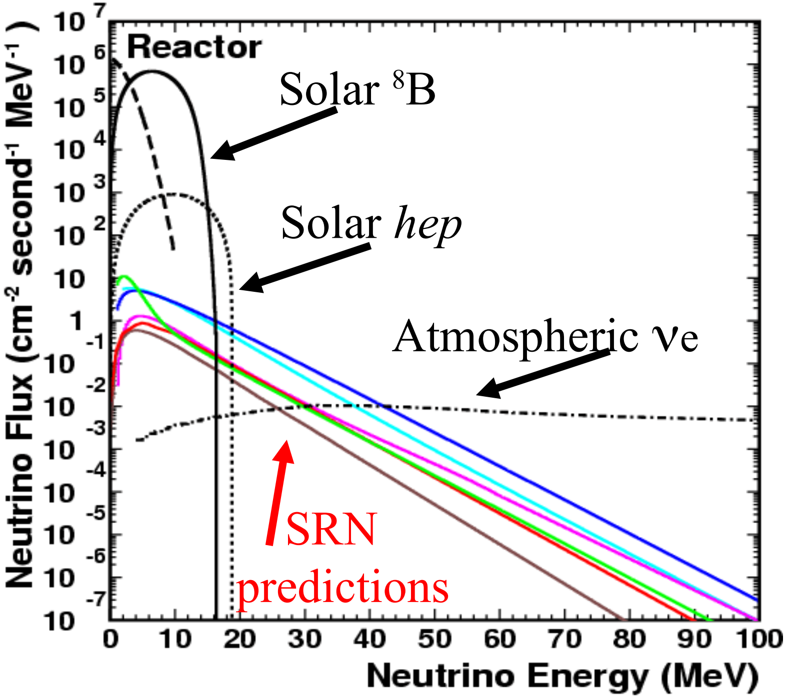
- SRN should be an isotropic signal composed of ν from **all** previous core-collapse supernovae

- Predictions obtained by taking ν spectrum from single SN and redshifting according to SN rate

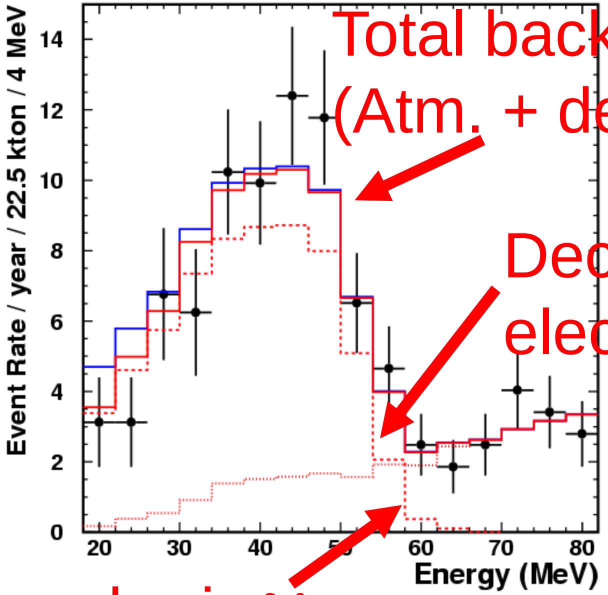
- Natural energy window to search

- Massive stars that die in core-collapse burn through fuel quickly and have relatively short lives

- Thus, SN rate is a good tracker of star formation rate!



Supernova Relic Neutrino Searches

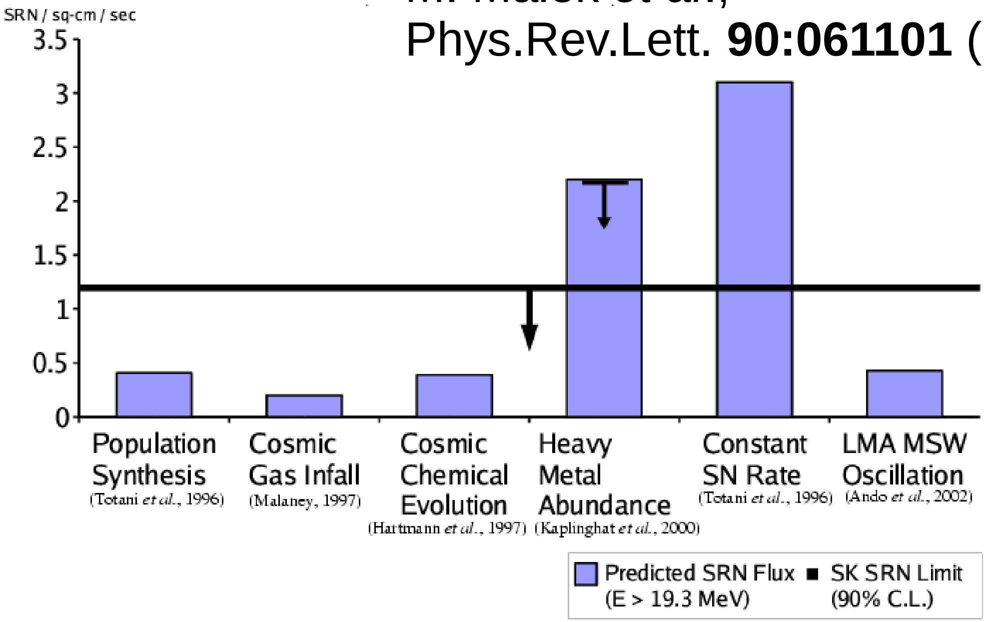


Total background (Atm. + decay e)

Decay electrons

Atmospheric ν_e

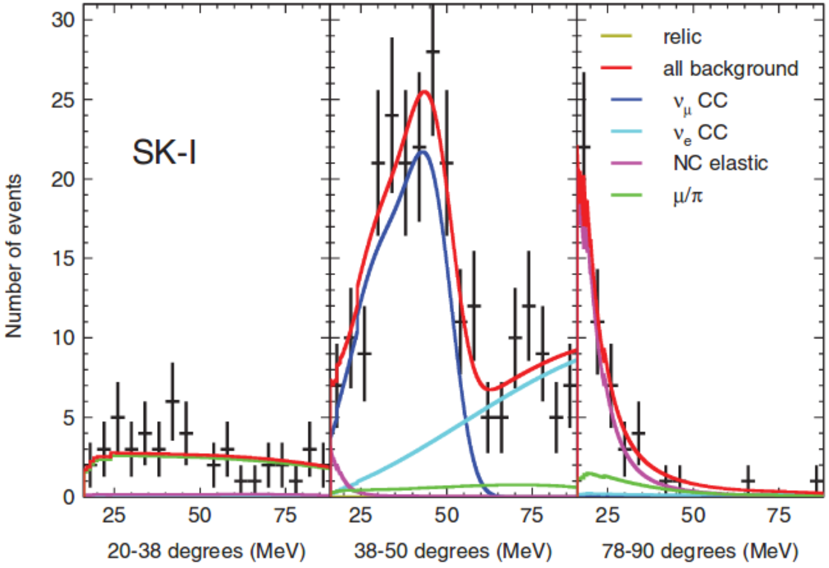
M. Malek *et al.*,
Phys.Rev.Lett. **90:061101** (2003)



- First “modern” search performed at Super-K nearly 20 years ago
- Irreducible backgrounds prevented discovery
- May be possible to overcome by taking advantage of IBD structure

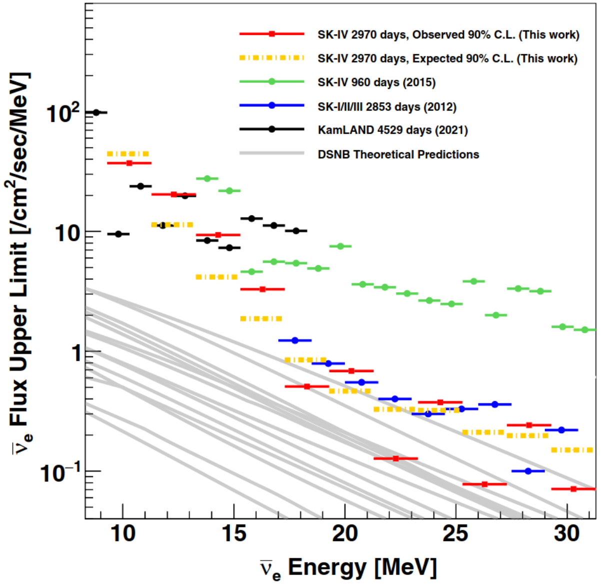
Supernova Relic Neutrino Searches

- IBD events produce positron <u>and</u> neutron
- In 2008, Super-K upgraded its electronics to see the 2.2 MeV gamma released when neutron captures on free proton (hydrogen)



PHYSICAL REVIEW D **85,** 052007 (2012)

Supernova relic neutrino search at super-Kamiokande

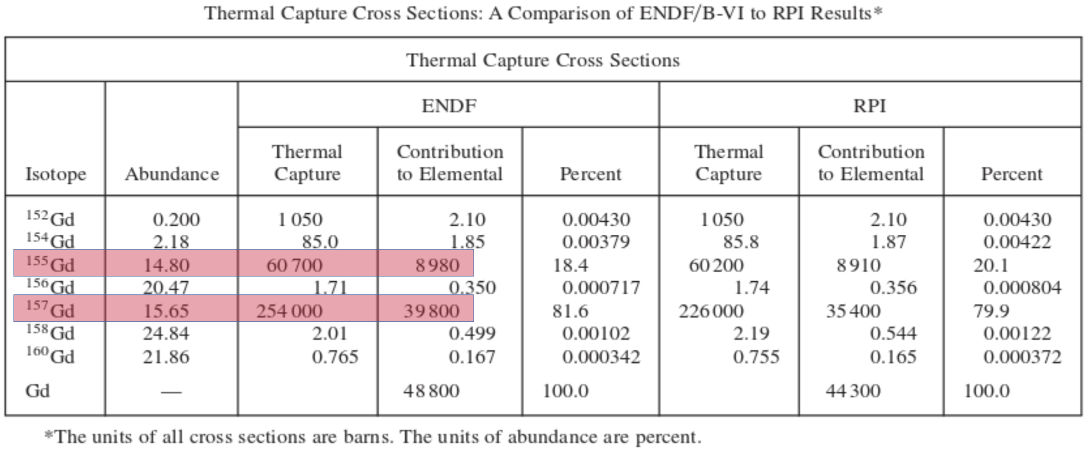


Diffuse supernova neutrino background search at Super-Kamiokande

K. Abe *et al.* (Super-Kamiokande Collaboration)
Phys. Rev. D **104**, 122002 – Published 10 December 2021

Future SRN Searches

- Super-Kamiokande has been upgraded to include gadolinium:

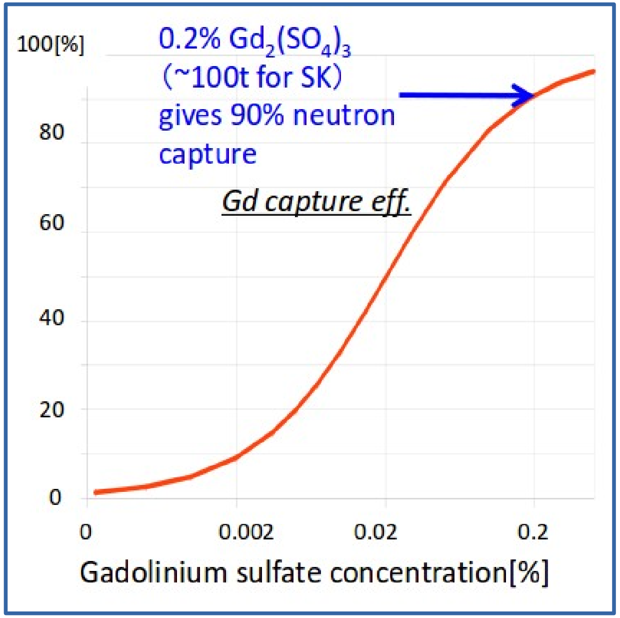


Thermal Capture Cross Sections: A Comparison of ENDF/B-VI to RPI Results*

Isotope	Abundance	ENDF Thermal Capture	ENDF Contribution to Elemental	ENDF Percent	RPI Thermal Capture	RPI Contribution to Elemental	RPI Percent
^{152}Gd	0.200	1 050	2.10	0.00430	1 050	2.10	0.00430
^{154}Gd	2.18	85.0	1.85	0.00379	85.8	1.87	0.00422
^{155}Gd	14.80	60 700	8 980	18.4	60 200	8 910	20.1
^{156}Gd	20.47	1.71	0.350	0.000717	1.74	0.356	0.000804
^{157}Gd	15.65	254 000	39 800	81.6	226 000	35 400	79.9
^{158}Gd	24.84	2.01	0.499	0.00102	2.19	0.544	0.00122
^{160}Gd	21.86	0.765	0.167	0.000342	0.755	0.165	0.000372
Gd	—		48 800	100.0		44 300	100.0

*The units of all cross sections are barns. The units of abundance are percent.

G. Leinweber *et al*., Nucl.Sci.Eng. **154:261** (2006)



0.2% $Gd_2(SO_4)_3$ (~100t for SK) gives 90% neutron capture

Gd capture eff.

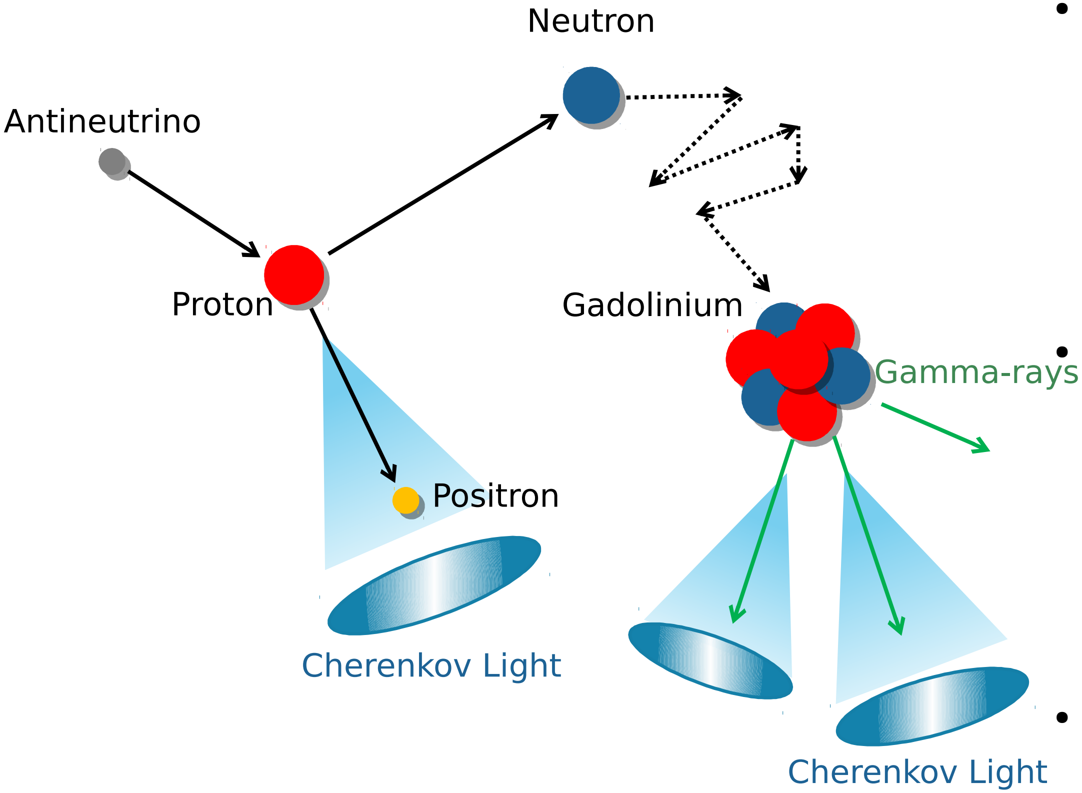
Cross-section for neutron capture is:

  - ~49,000 barns for natural Gd
  - 0.3 barns for H

0.1% Gd concentration results in ~90% of neutrons capturing on Gd

Future SRN Searches

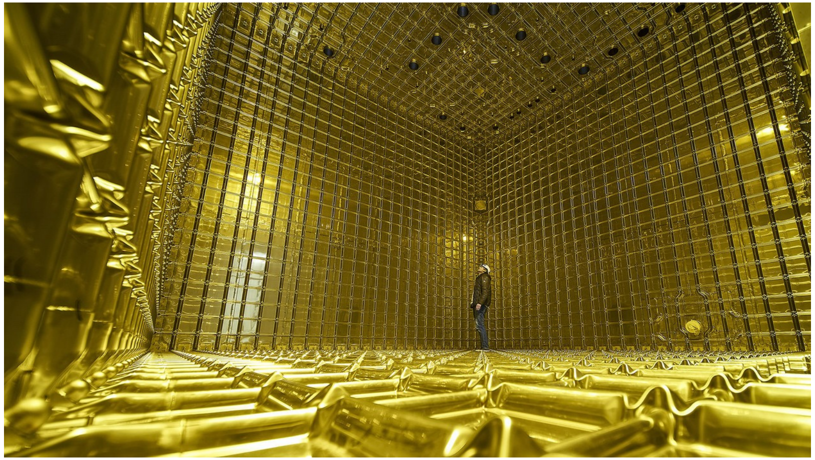
- Super-Kamiokande has been upgraded to include gadolinium:



- In ordinary water, neutron thermalizes, then is captured on a free proton
  - Capture time is ~200 μsec
  - 2.2 MeV gamma emitted
  - Detection efficiency @ SK is ~20%
- When n captured on water with 0.1% Gd:
  - Capture time ~30 μsec
  - ~8 MeV gamma cascade
  - 4 - 5 MeV visible energy
  - > 70% detection efficiency
- See upcoming talk by Liz Kneale on coincidence reconstruction in Gd-loaded water Cherenkov

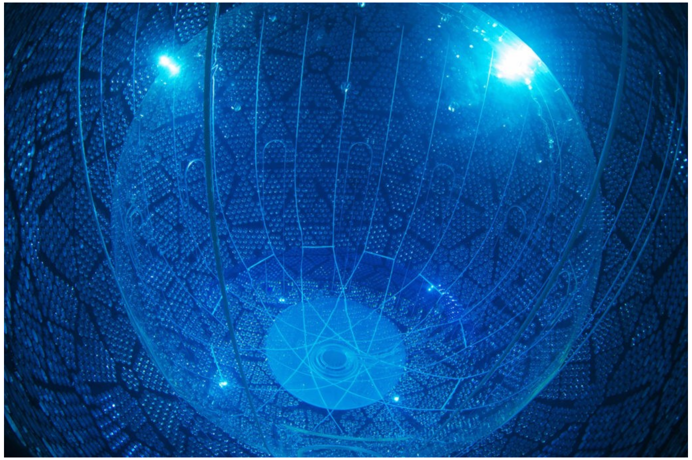
Other Detection Media

- Water Cherenkov detectors have the advantage of being able to build very large with cheap material
- Other detector media have complementary capabilities



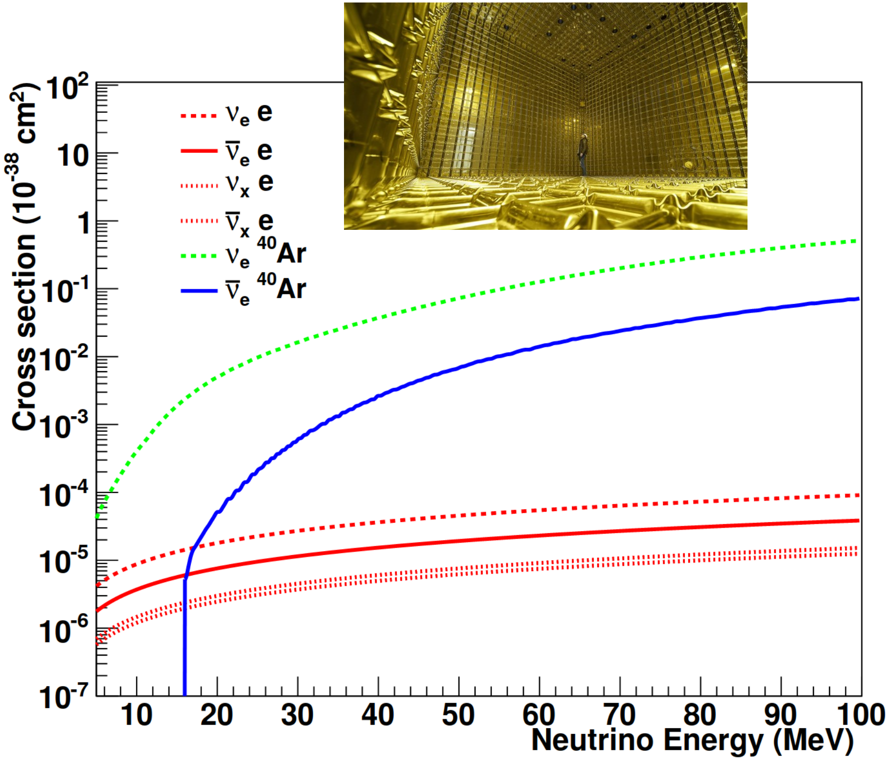
Liquid argon is sensitive to the ν_e signal from the neutronisation burst via:

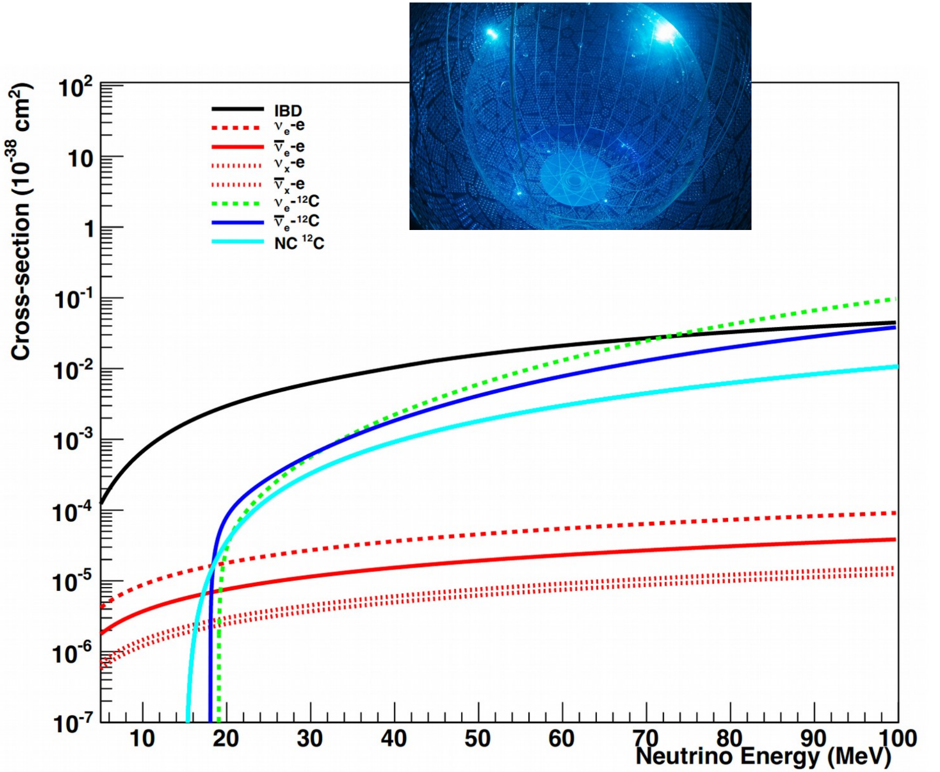
$\nu_e + {}^{40}Ar \rightarrow e + {}^{40}K^*$



Liquid scintillator has lower energy thresholds and better energy resolution

Other Detection Media





See upcoming talk from Sammy Valder on supernova neutrino studies in liquid argon (DUNE) and liquid scintillator (SNO+)

Summary

- Supernova neutrinos give us a unique handle to understand the core-collapse mechanism.
- Waiting > 35 years for next supernova neutrino burst, but we have not been idle! New detectors and analysis techniques make us well prepared for when those neutrinos arrive.
- With the new addition of gadolinium, Super-Kamiokande is well-positioned to make first discovery of supernova relic neutrinos.
- Water Cherenkov detectors are a well-established tool for supernova neutrino detection.
- New (and larger) water Cherenkov detectors will be coming online in the near future, such as KM3Net and Hyper-Kamiokande.
- Neutrino detectors with different targets, such as liquid argon & liquid scintillator, have complementary advantages.
- In the multimessenger era, we are starting to explore synergies with gravitational wave detectors, etc.
- Exciting times ahead… now we just need a nearby star to explode!

Thank you for listening!