52nd Cracow School on Theoretical Physics
Zakopane, Tatra Mountains, Poland, 19–27 May 2012

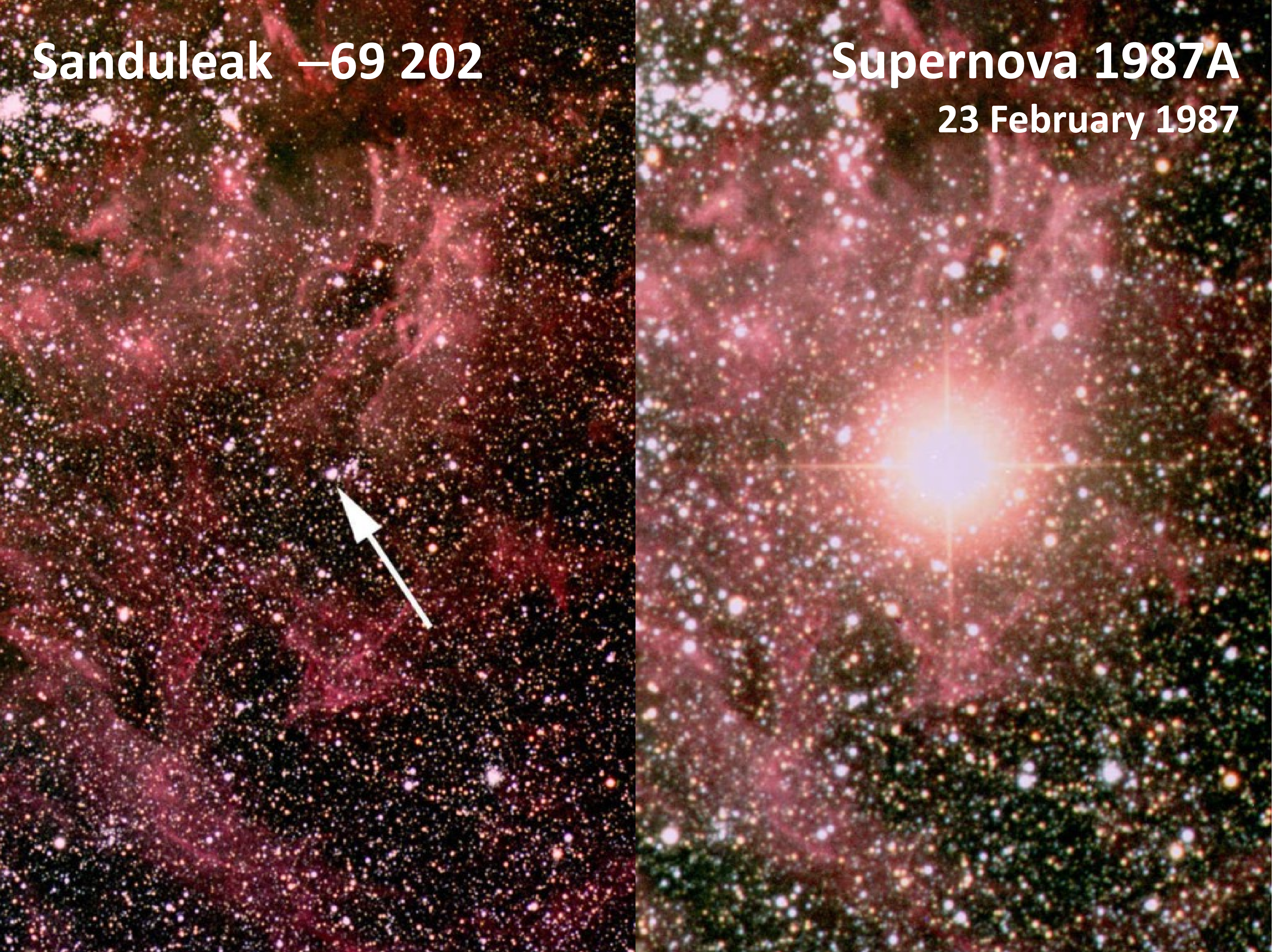
Supernova Neutrinos

Georg G. Raffelt
Max-Planck-Institut für Physik, München, Germany

Sanduleak –69 202

Tarantula Nebula

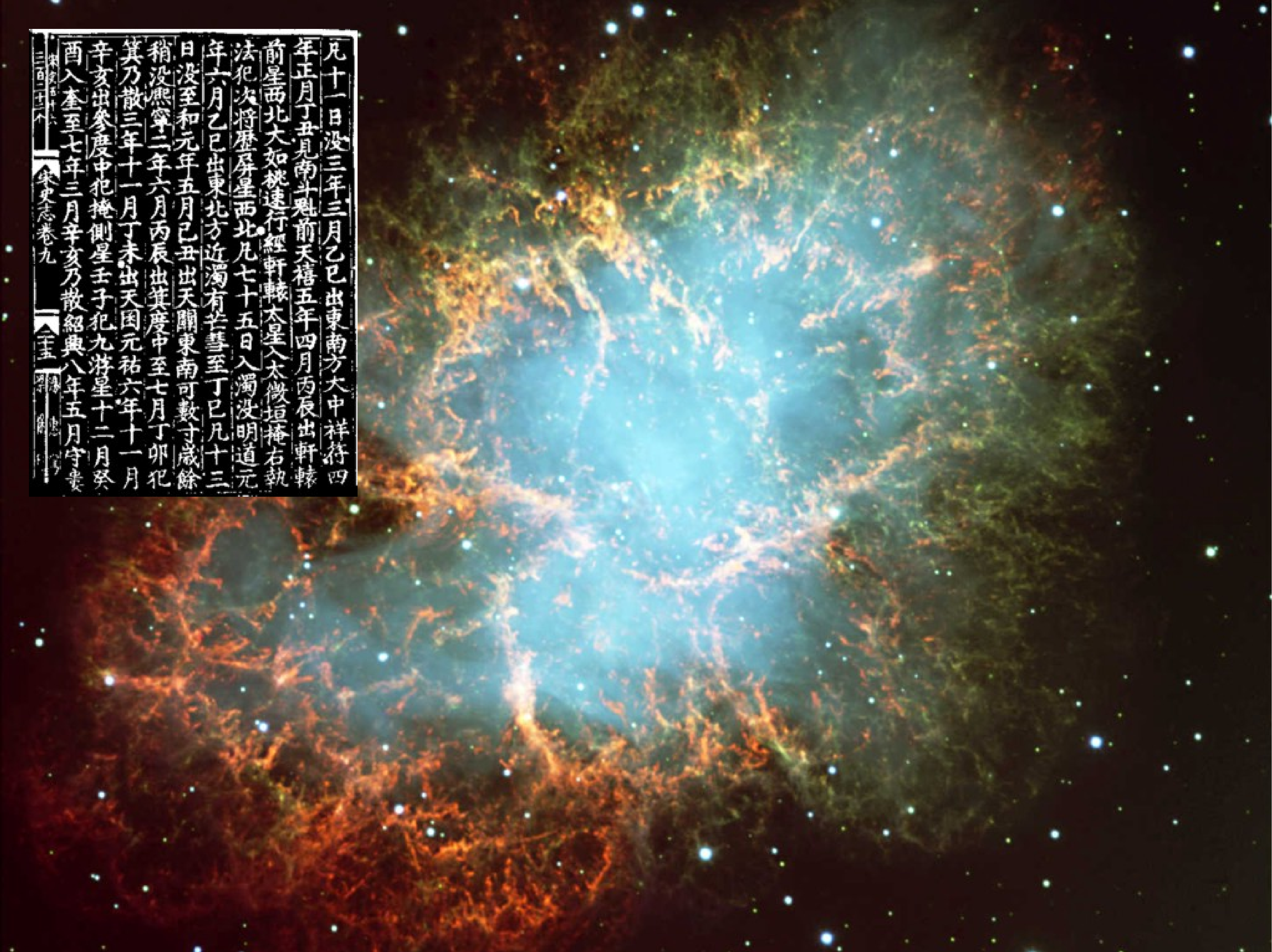
Large Magellanic Cloud
Distance 50 kpc
(160.000 light years)



Sanduleak –69 202

Supernova 1987A

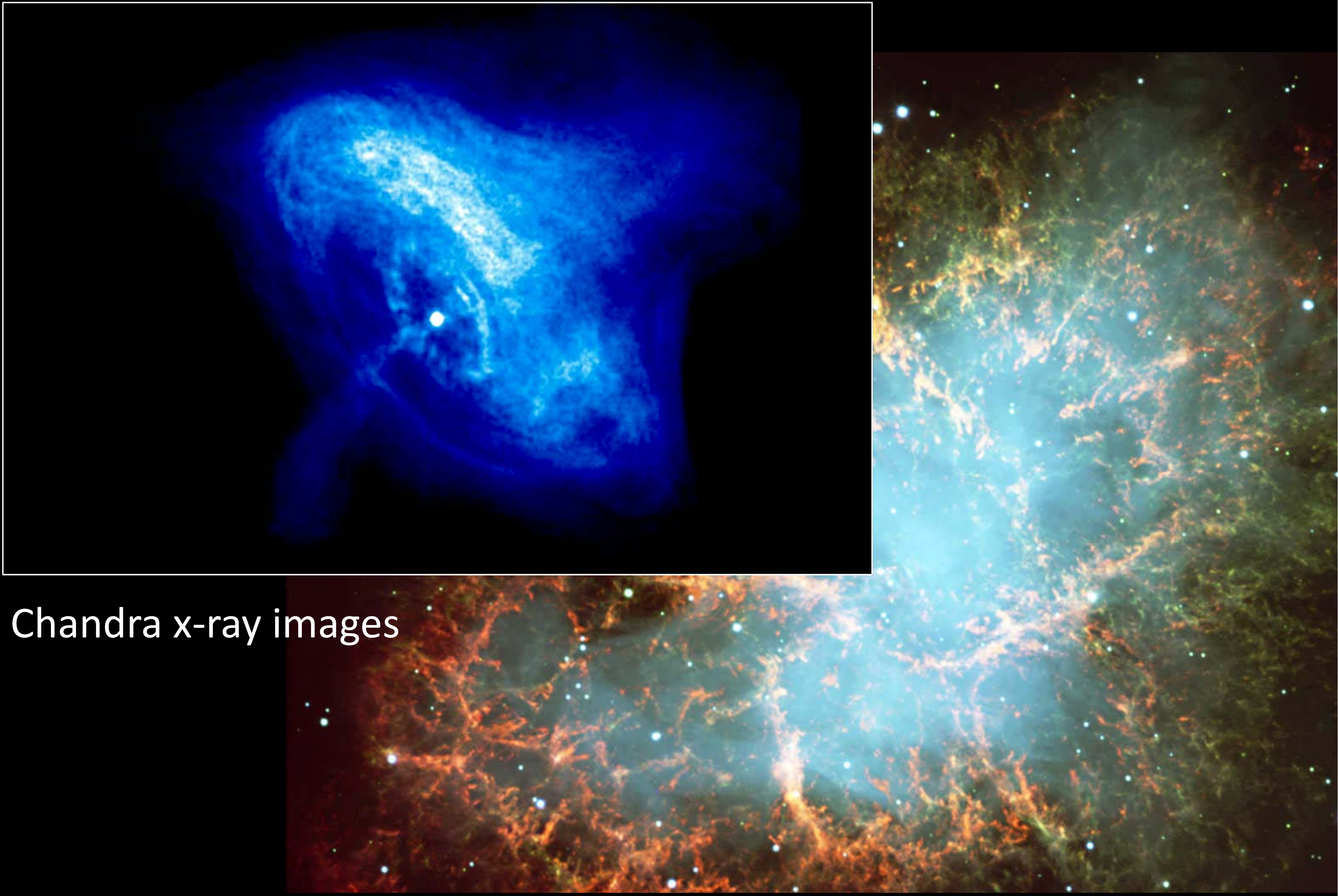
23 February 1987



凡十一日沒三年三月乙巳出東南方大中祥符四年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅前星西北大如桃速行經軒轅太星入太微垣掩右執法犯次將歷屛星西北凡七十五日入濁沒明道元年六月乙巳出東北方近濁有芒彗至丁巳凡十三日沒至和元年五月己丑出天關東南可數寸歲餘稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯箕乃散三年十一月丁未出天囷元祐六年十一月辛亥出參度中犯掩側星壬子犯九游星十二月癸酉入奎至七年三月辛亥乃散紹興八年五月守婁

宋史志卷九

The Crab Pulsar



Chandra x-ray images

Walter Baade (1893–1960)

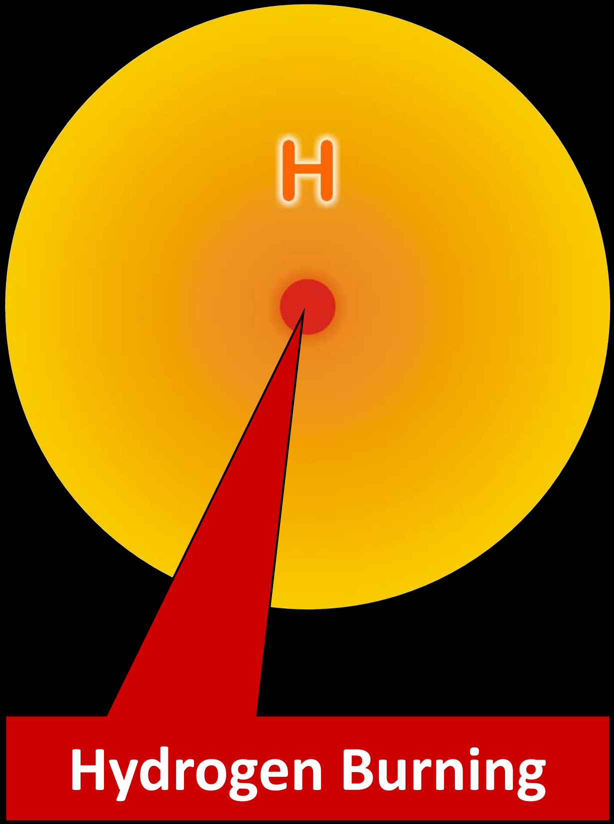
Fritz Zwicky (1898–1974)

Baade and Zwicky were the first to speculate about a connection between supernova explosions and neutron-star formation

[Phys. Rev. 45 (1934) 138]

Stellar Collapse and Supernova Explosion

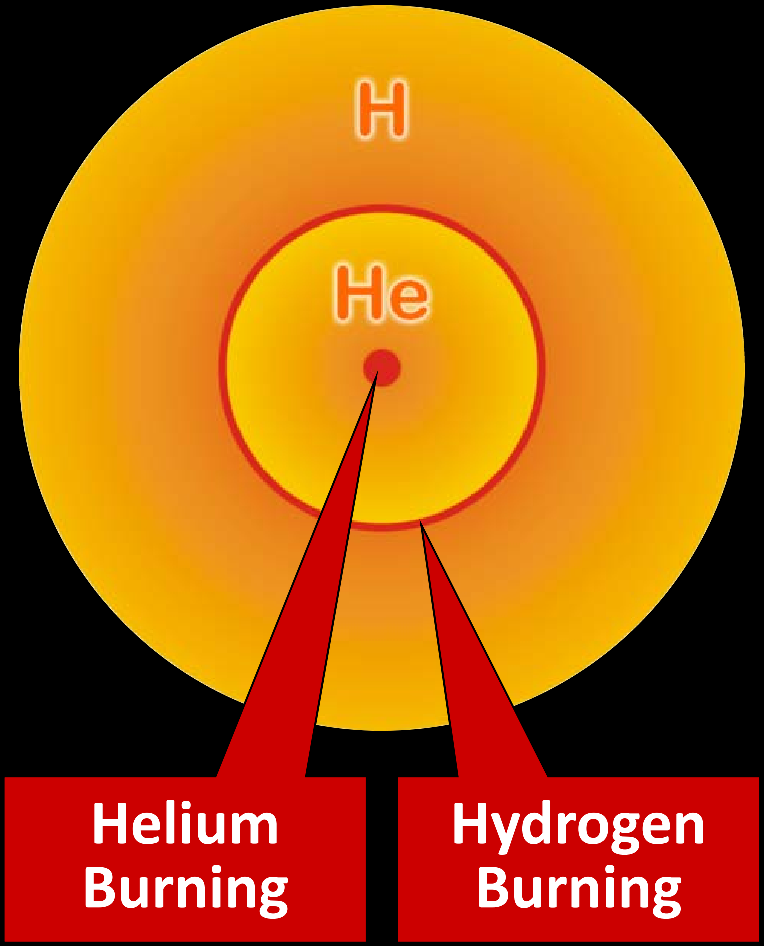
Main-sequence star



H

Hydrogen Burning

Helium-burning star



H

He

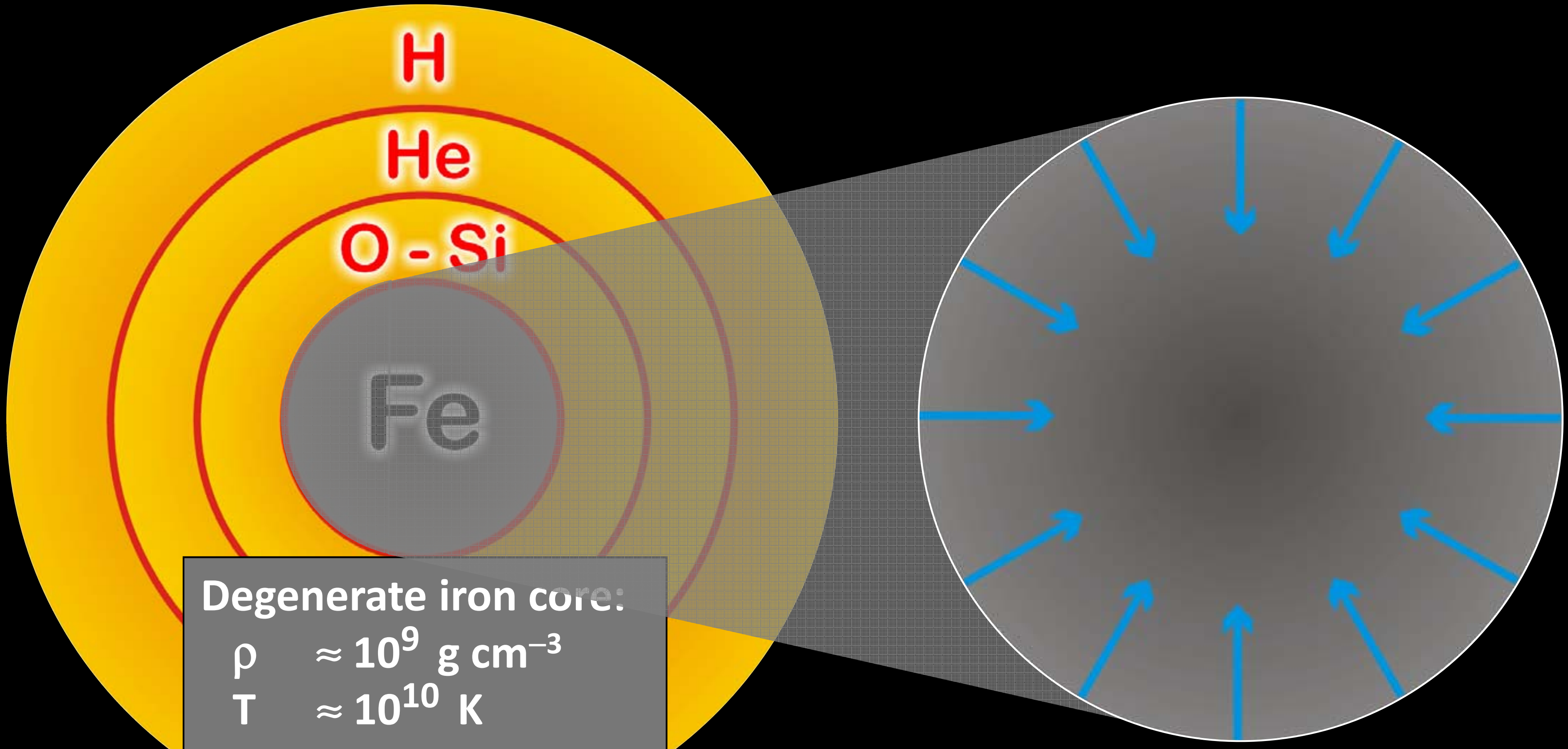
Helium Burning

Hydrogen Burning

Stellar Collapse and Supernova Explosion

Onion structure

Collapse (implosion)



Degenerate iron core:

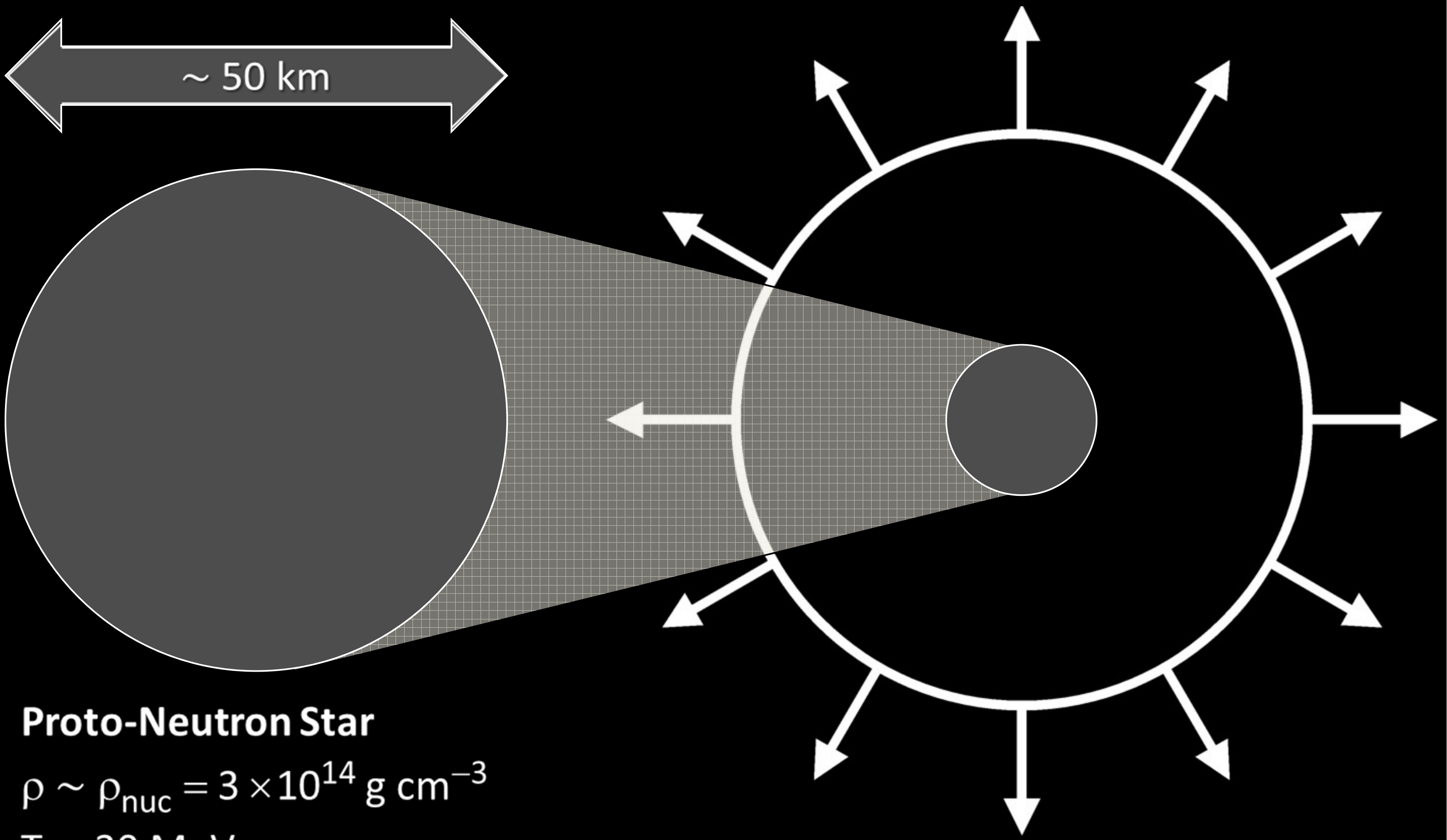
$\rho \approx 10^9\ \mathrm{g\ cm^{-3}}$

$T \approx 10^{10}\ \mathrm{K}$

$M_{Fe} \approx 1.5\ M_{sun}$

$R_{Fe} \approx 8000\ \mathrm{km}$

Stellar Collapse and Supernova Explosion



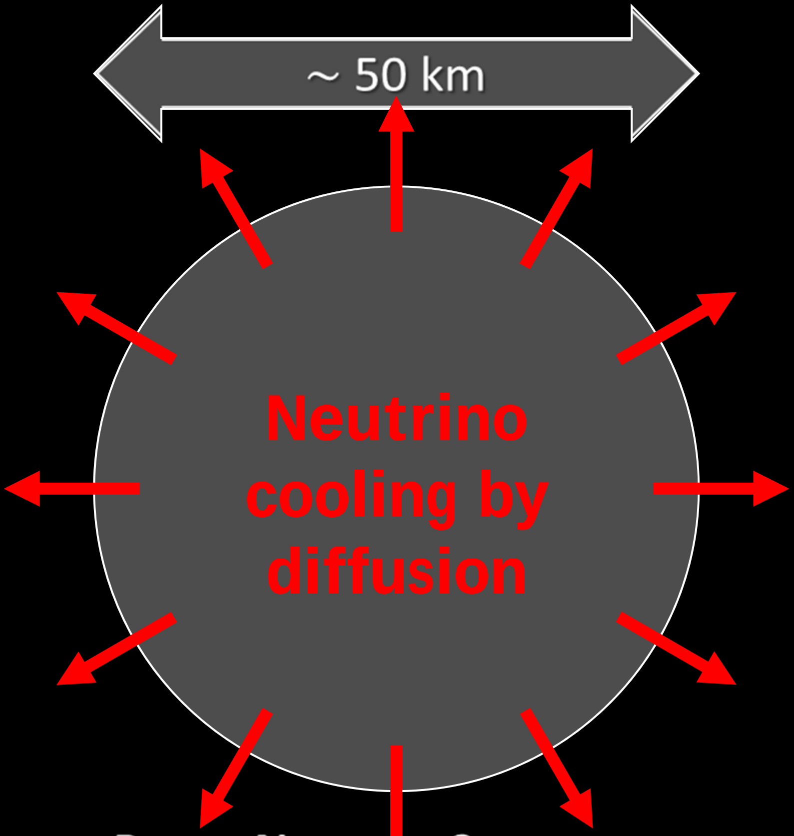
Proto-Neutron Star

$\rho \sim \rho_{\mathrm{nuc}} = 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$

$T \sim 30\ \mathrm{MeV}$

Stellar Collapse and Supernova Explosion

Newborn Neutron Star



Proto-Neutron Star

$\rho \sim \rho_{\mathrm{nuc}} = 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$

$T \sim 30\ \mathrm{MeV}$

Gravitational binding energy

$$E_b \approx 3 \times 10^{53}\ \mathrm{erg} \approx 17\%\ M_{\mathrm{SUN}}\, c^2$$

This shows up as

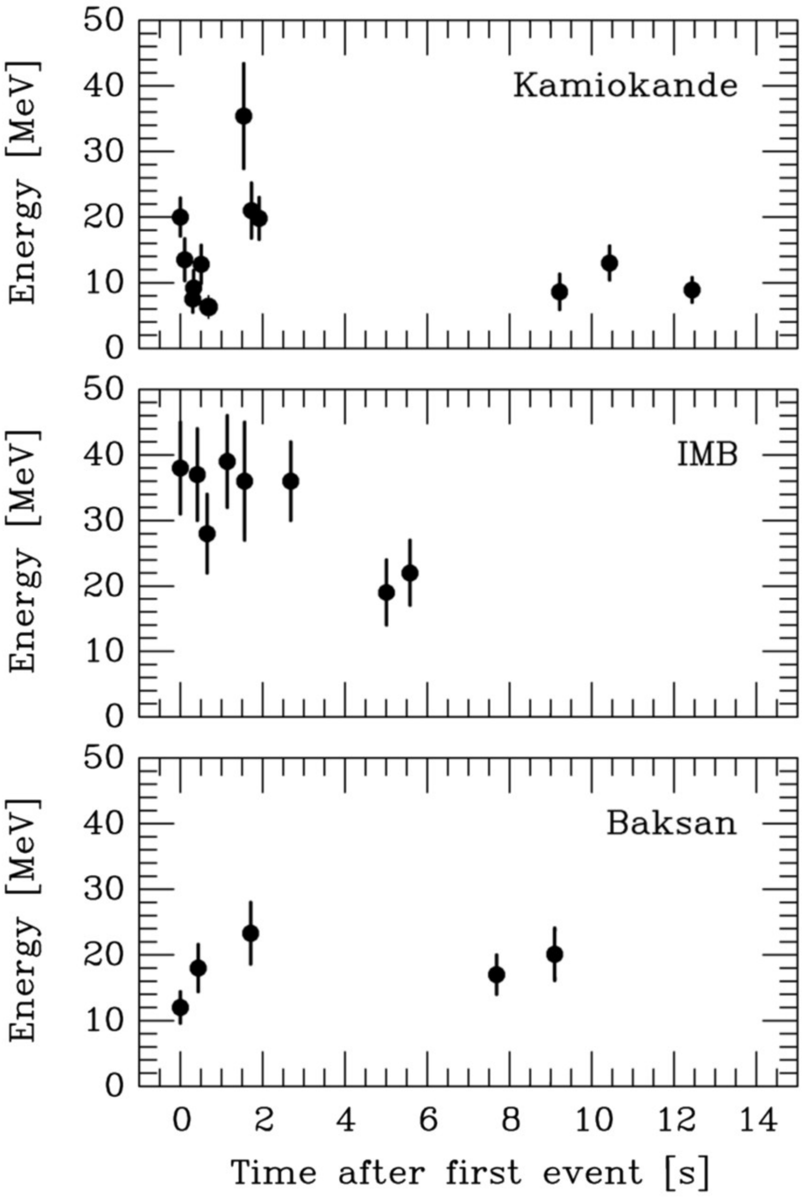
99%	Neutrinos
1%	Kinetic energy of explosion
0.01%	Photons, outshine host galaxy

Neutrino luminosity

$$L_\nu \sim 3 \times 10^{53}\ \mathrm{erg} / 3\ \mathrm{sec}$$
$$\sim 3 \times 10^{19}\ L_{\mathrm{SUN}}$$

While it lasts, outshines the entire visible universe

Neutrino Signal of Supernova 1987A



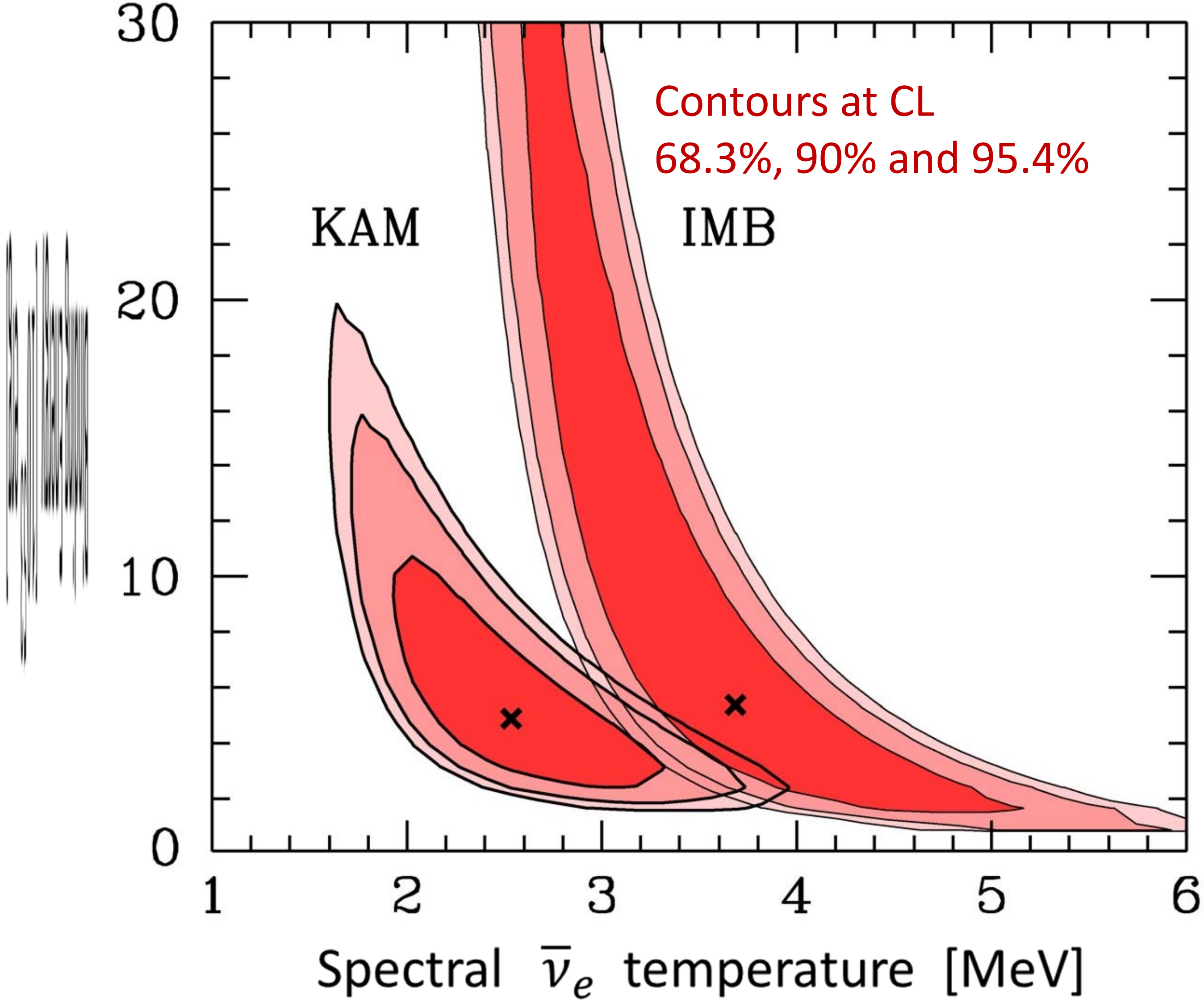
Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ±1 min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty ±50 ms

Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster ~ 0.7/day
Clock uncertainty +2/–54 s

Within clock uncertainties,
all signals are contemporaneous

Interpreting SN 1987A Neutrinos



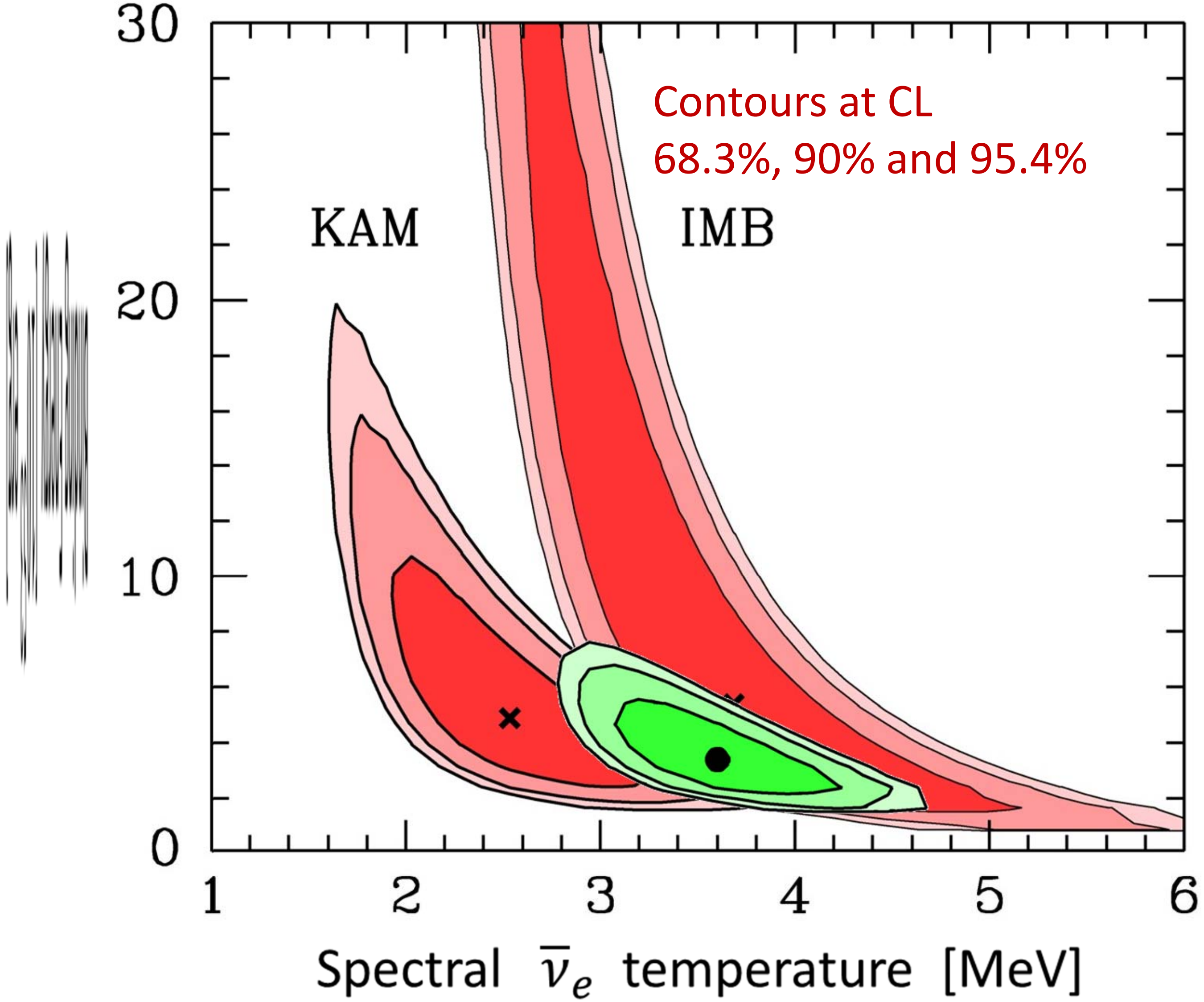
Contours at CL
68.3%, 90% and 95.4%

Assume

- Thermal spectra
- Equipartition of energy between $\nu_e, \overline{\nu}_e, \nu_\mu, \overline{\nu}_\mu, \nu_\tau$ and $\overline{\nu}_\tau$

Jegerlehner,
Neubig & Raffelt,
PRD 54 (1996) 1194

Interpreting SN 1987A Neutrinos

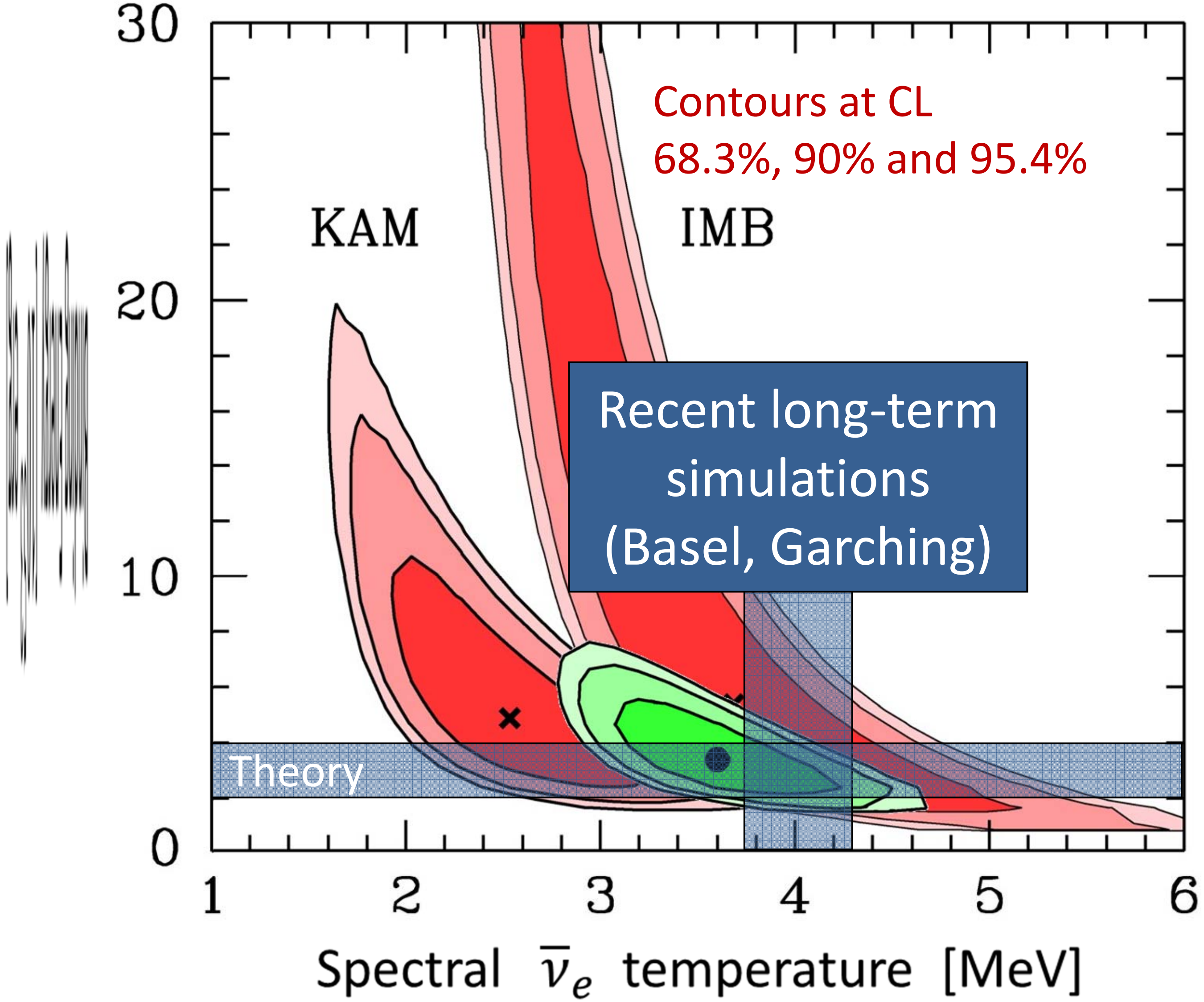


Contours at CL
68.3%, 90% and 95.4%

Assume
- Thermal spectra
- Equipartition of energy between ν_e, $\overline{\nu}_e$, ν_μ, $\overline{\nu}_\mu$, ν_τ and $\overline{\nu}_\tau$

Jegerlehner,
Neubig & Raffelt,
PRD 54 (1996) 1194

Interpreting SN 1987A Neutrinos



Contours at CL
68.3%, 90% and 95.4%

Recent long-term simulations (Basel, Garching)

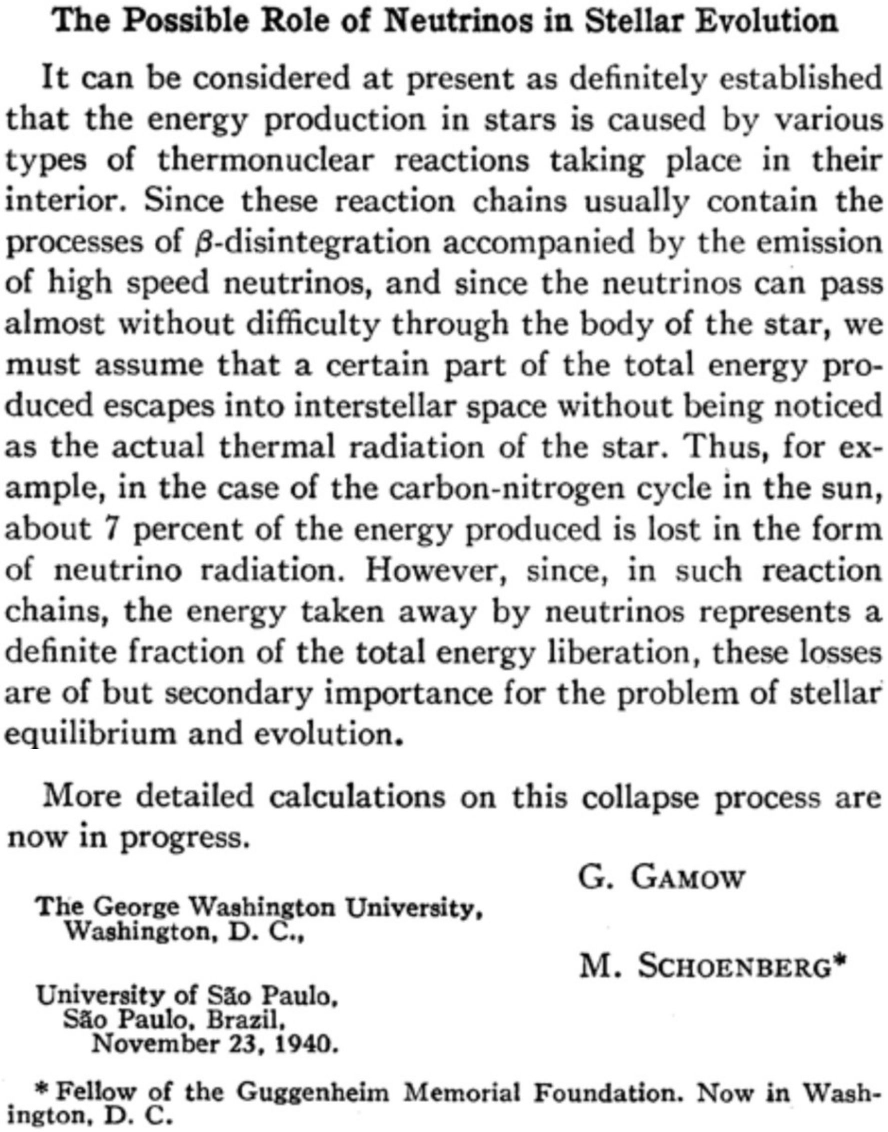
Theory

Assume

- Thermal spectra
- Equipartition of energy between $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau$ and $\bar{\nu}_\tau$

Jegerlehner,
Neubig & Raffelt,
PRD 54 (1996) 1194

Predicting Neutrinos from Core Collapse



The Possible Role of Neutrinos in Stellar Evolution

It can be considered at present as definitely established that the energy production in stars is caused by various types of thermonuclear reactions taking place in their interior. Since these reaction chains usually contain the processes of β-disintegration accompanied by the emission of high speed neutrinos, and since the neutrinos can pass almost without difficulty through the body of the star, we must assume that a certain part of the total energy produced escapes into interstellar space without being noticed as the actual thermal radiation of the star. Thus, for example, in the case of the carbon-nitrogen cycle in the sun, about 7 percent of the energy produced is lost in the form of neutrino radiation. However, since, in such reaction chains, the energy taken away by neutrinos represents a definite fraction of the total energy liberation, these losses are of but secondary importance for the problem of stellar equilibrium and evolution.

More detailed calculations on this collapse process are now in progress.

G. Gamow

The George Washington University,
Washington, D. C.,

M. Schoenberg*

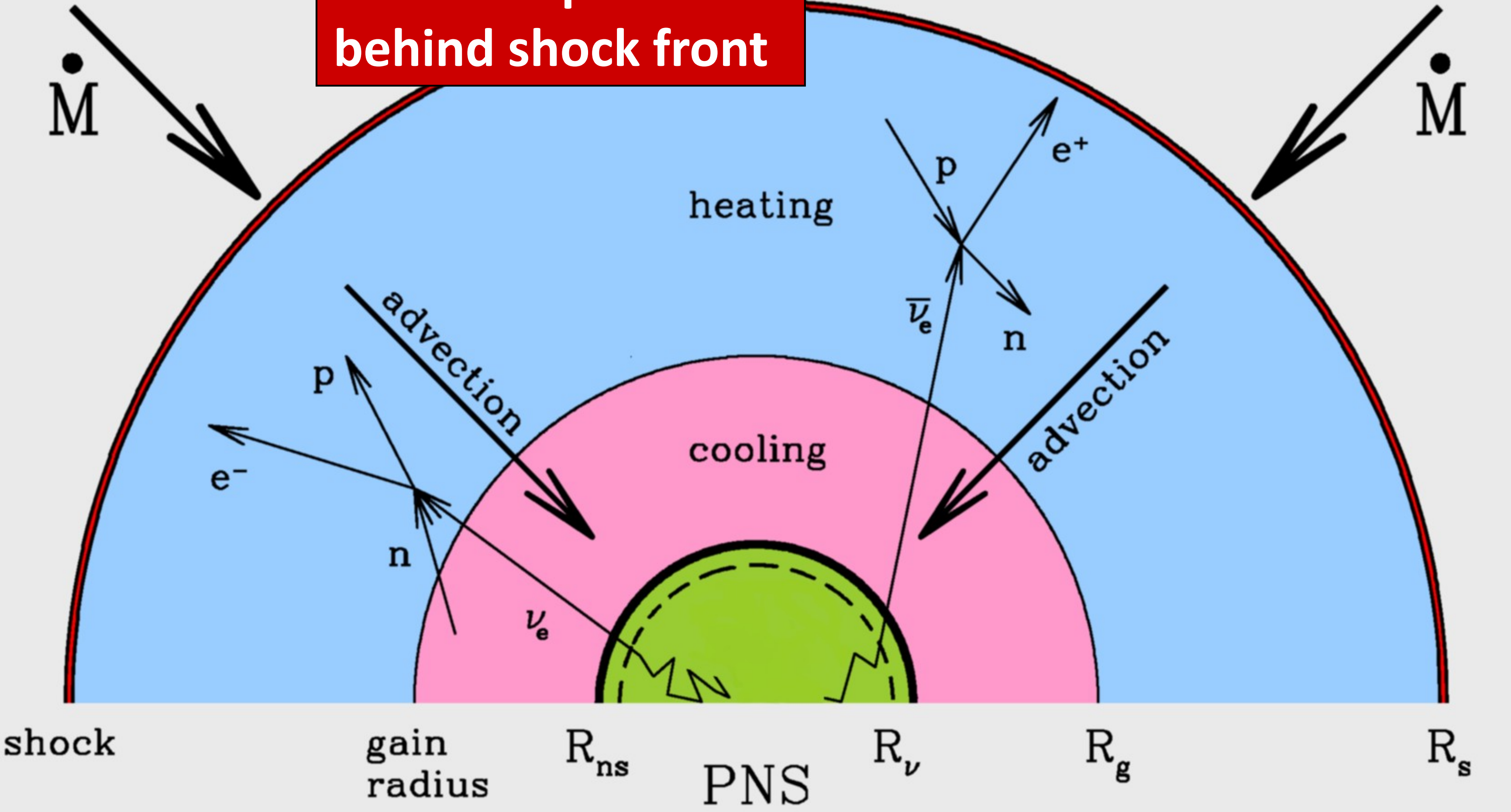
University of São Paulo,
São Paulo, Brazil,
November 23, 1940.

---

* Fellow of the Guggenheim Memorial Foundation. Now in Washington, D. C.

Phys. Rev. 58:1117 (1940)

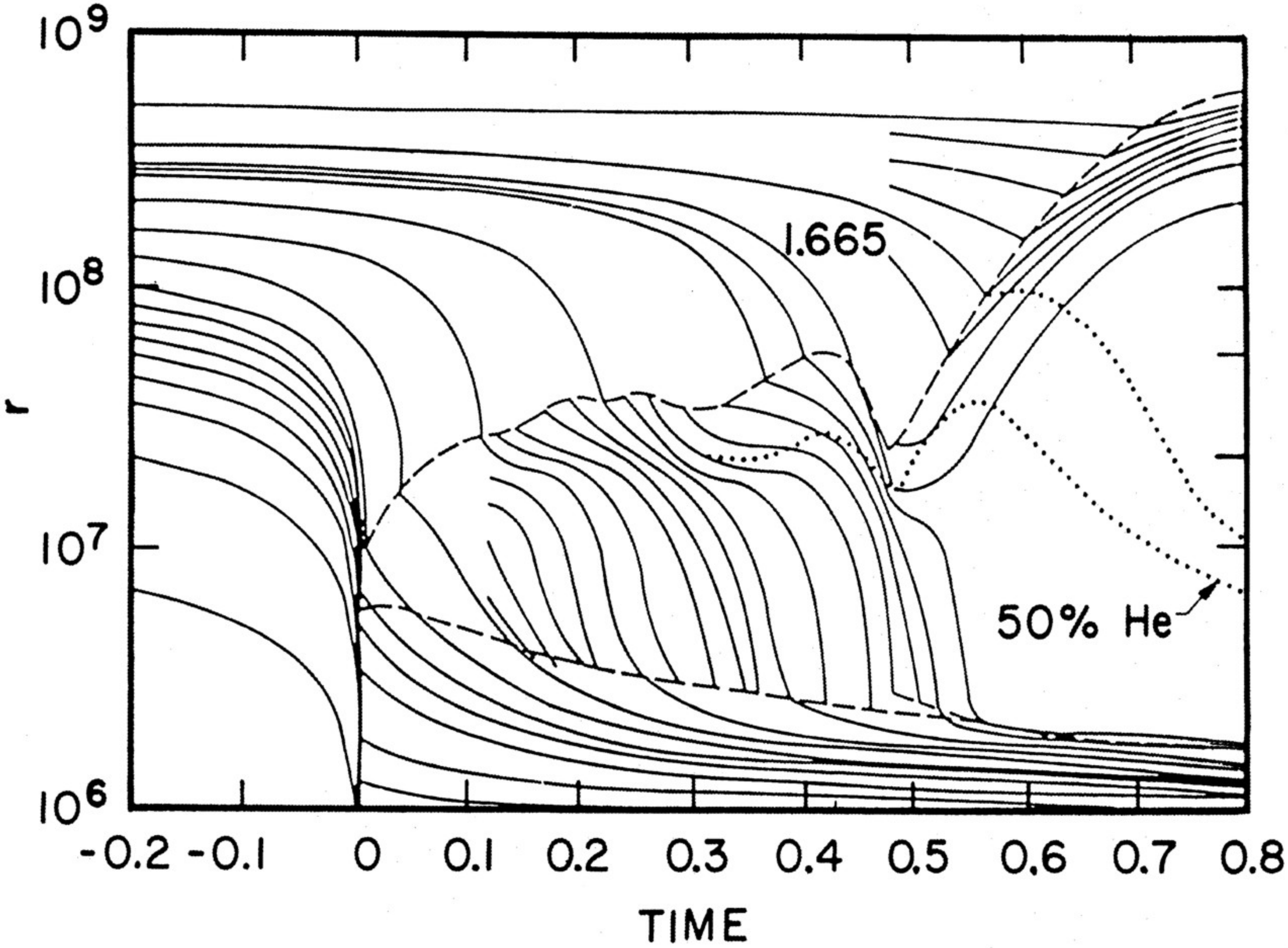
Neutrinos Rejuvenating Stalled Shock



Neutrino heating increases pressure behind shock front

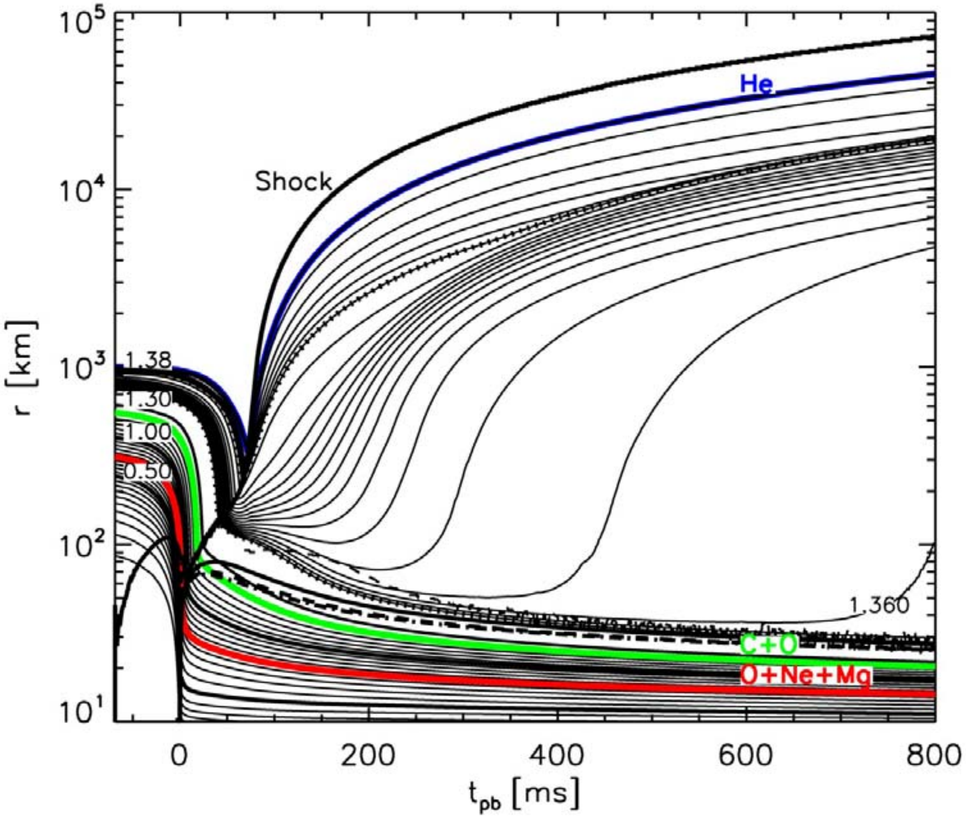
Picture adapted from Janka, astro-ph/0008432

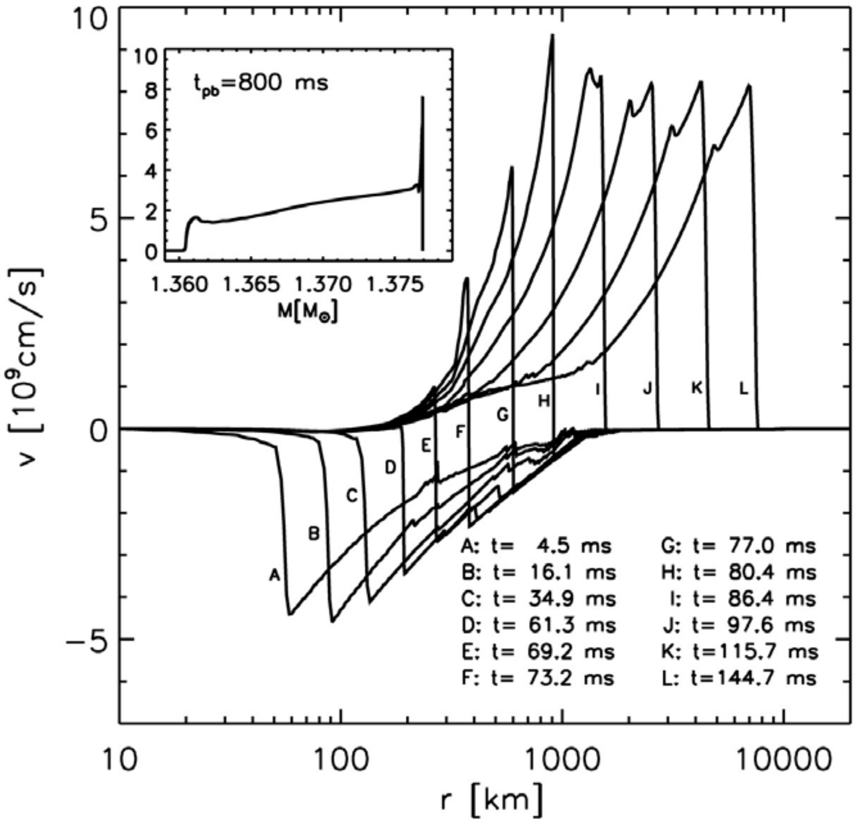
Delayed Explosion



Wilson, Proc. Univ. Illinois Meeting on Num. Astrophys. (1982)
Bethe & Wilson, ApJ 295 (1985) 14

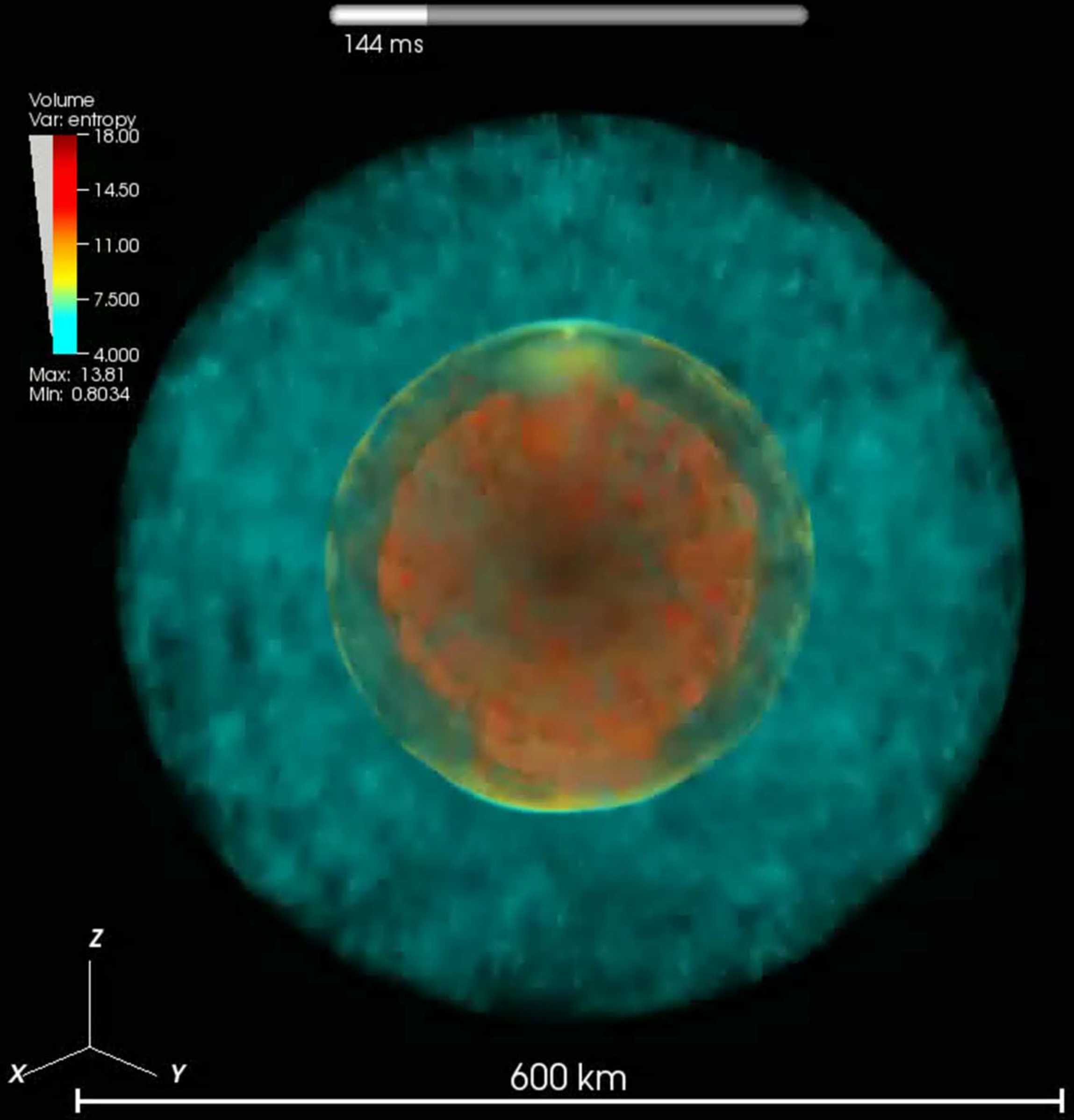
Exploding Models (8–10 Solar Masses)



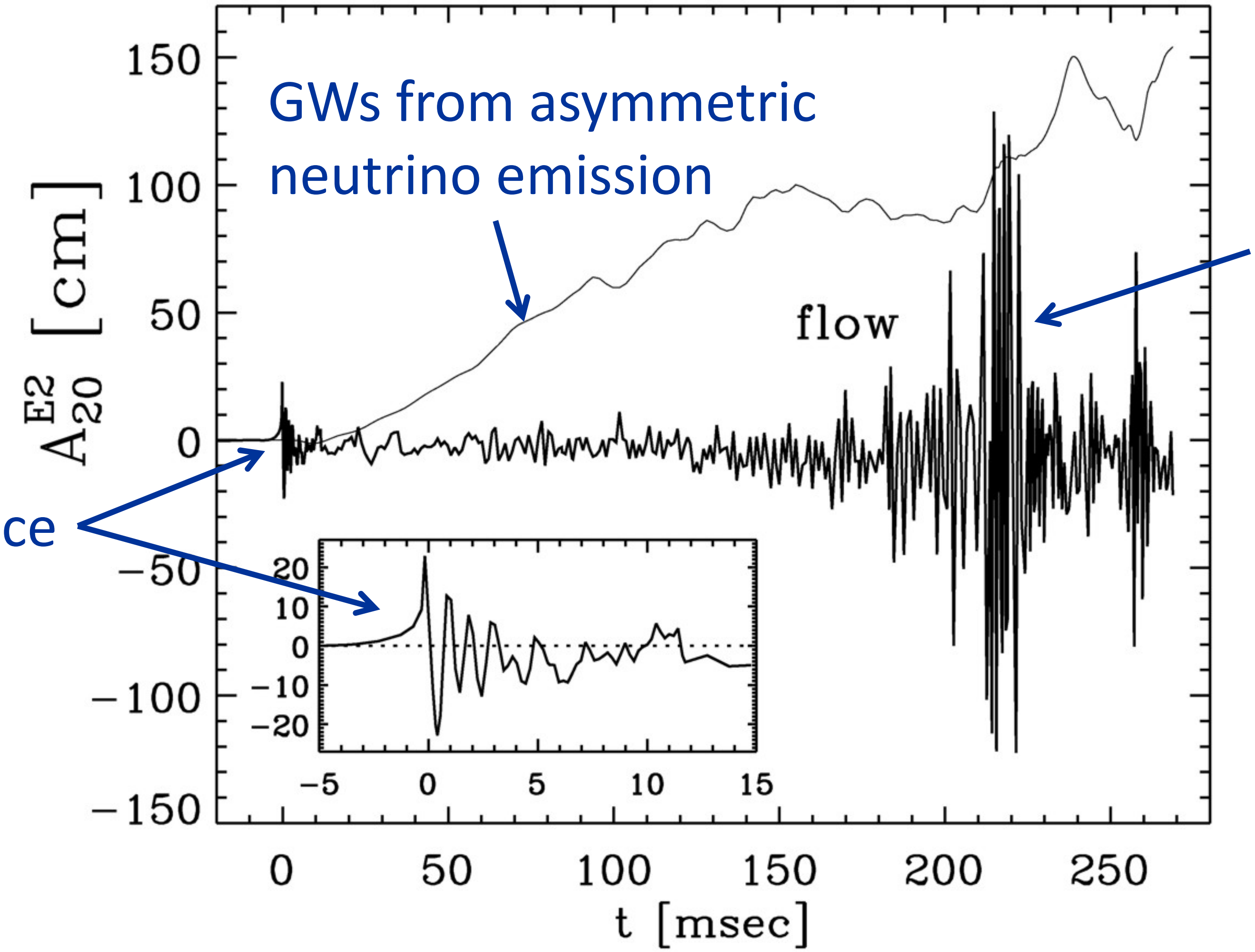


Kitaura, Janka & Hillebrandt: “Explosions of O-Ne-Mg cores, the Crab supernova, and subluminous type II-P supernovae”, astro-ph/0512065

3D Simulation (Garching group)



Gravitational Waves from Core-Collapse Supernovae



GWs from asymmetric neutrino emission

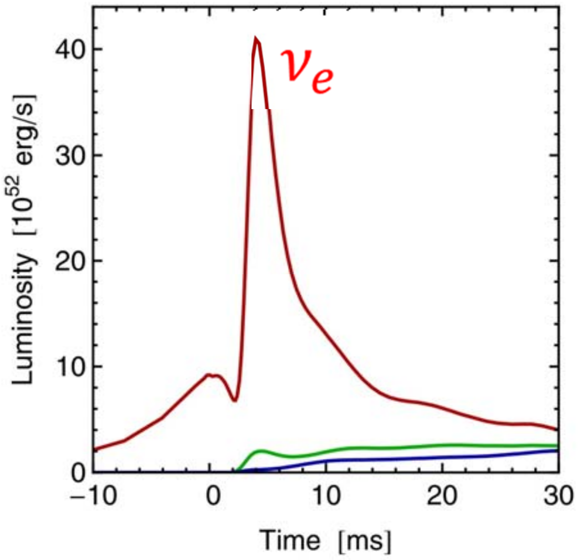
GWs from convective mass flows

Bounce

Müller, Rampp, Buras, Janka, & Shoemaker, astro-ph/0309833
“Towards gravitational wave signals from realistic core collapse supernova models”

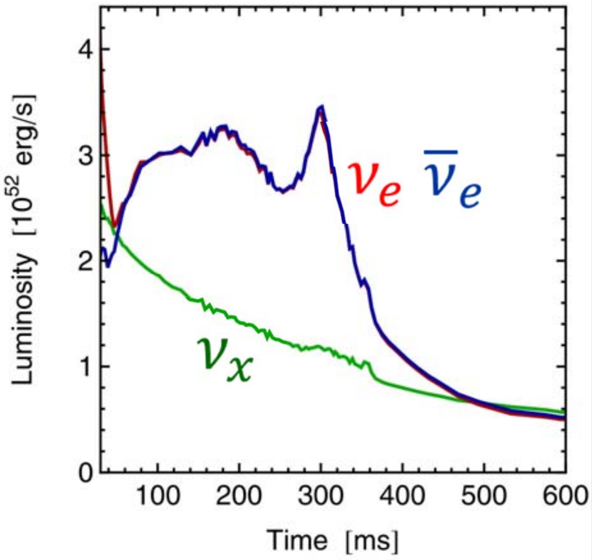
Three Phases of Neutrino Emission

Prompt ν_e burst



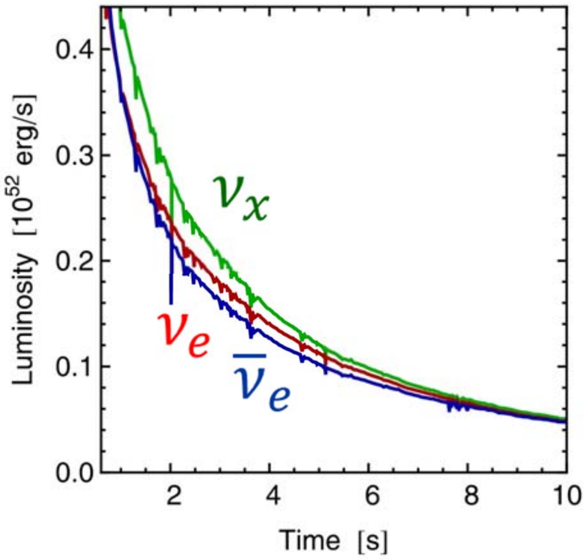
- Shock breakout
- De-leptonization of outer core layers

Accretion



- Shock stalls ~ 150 km
- Neutrinos powered by infalling matter

Cooling



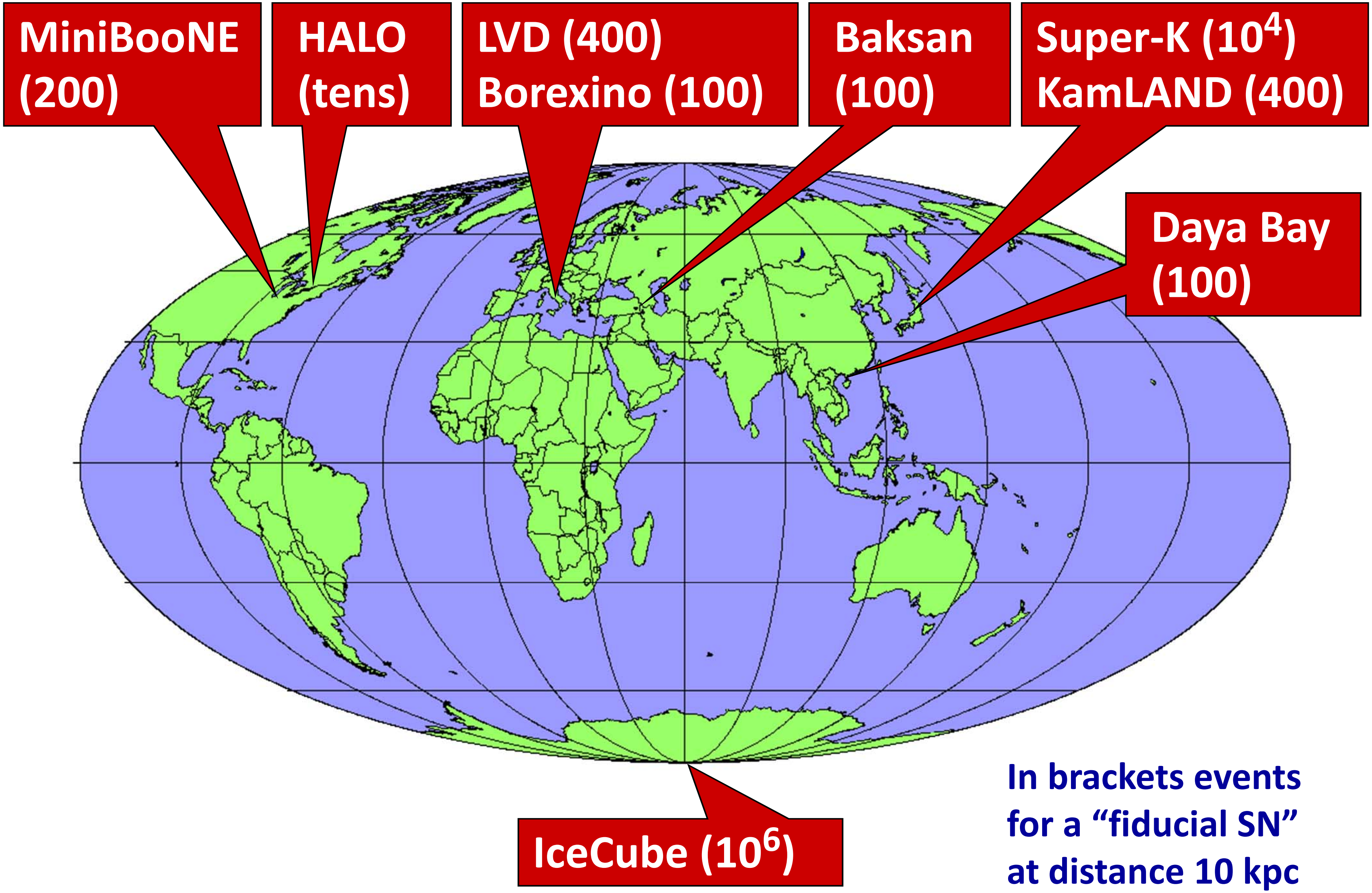
Cooling on neutrino diffusion time scale

- Spherically symmetric model (10.8 $M_\odot$) with Boltzmann neutrino transport
- Explosion manually triggered by enhanced CC interaction rate

Fischer et al. (Basel group), A&A 517:A80, 2010 [arxiv:0908.1871]

Neutrinos from Next Nearby SN

Operational Detectors for Supernova Neutrinos



MiniBooNE (200)

HALO (tens)

LVD (400)
Borexino (100)

Baksan (100)

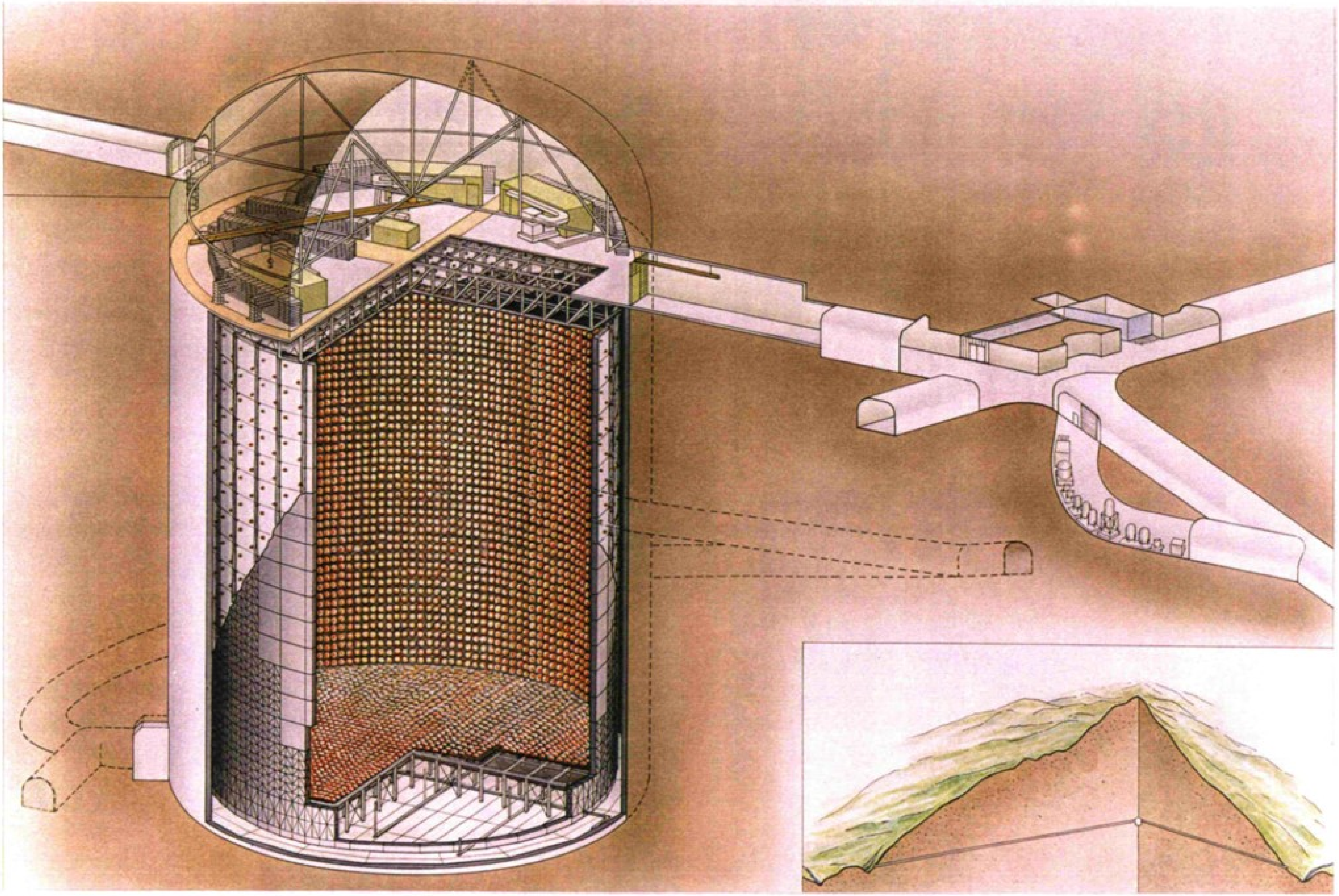
Super-K (10^4)
KamLAND (400)

Daya Bay (100)

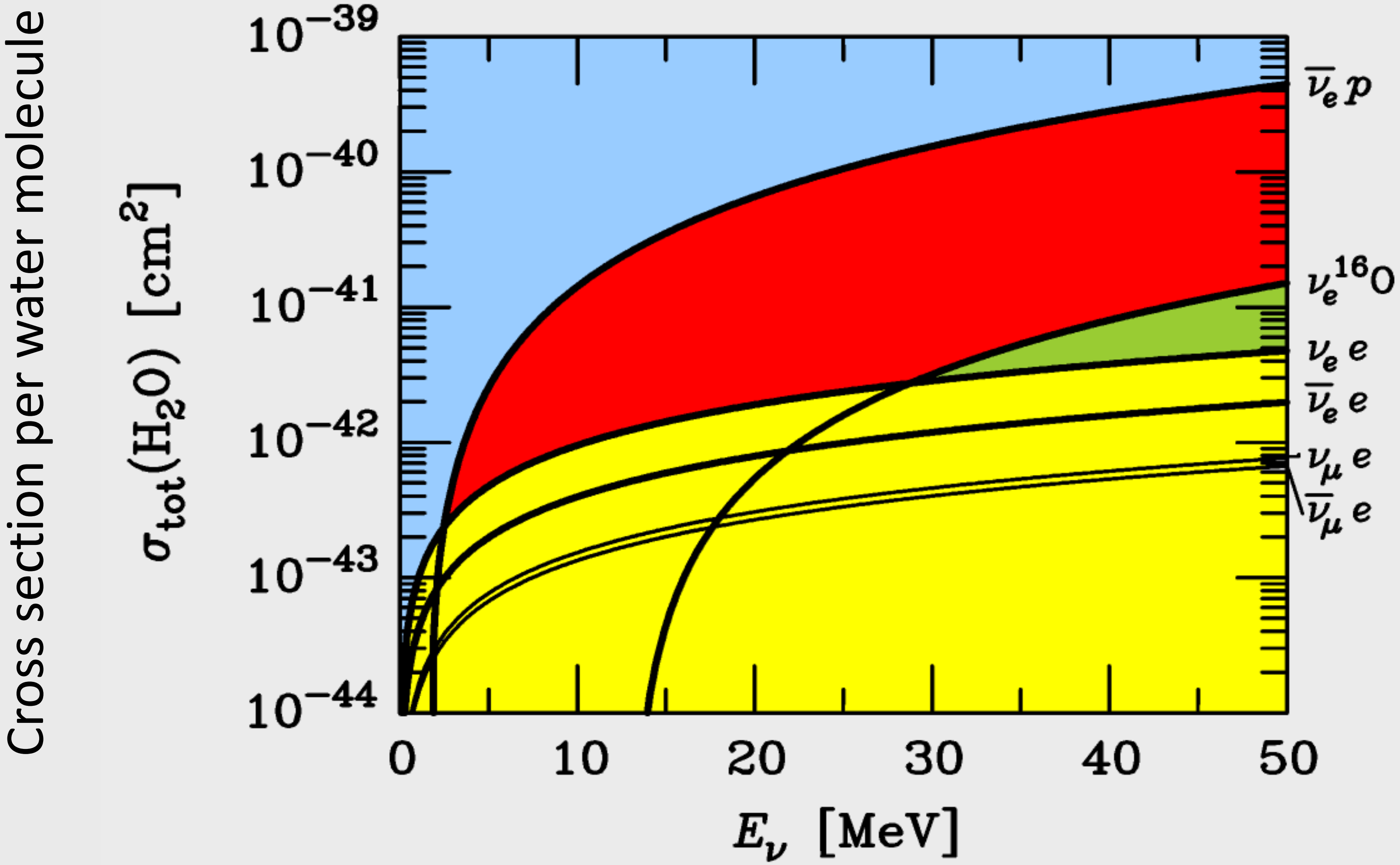
IceCube (10^6)

In brackets events for a “fiducial SN” at distance 10 kpc

Super-Kamiokande Neutrino Detector



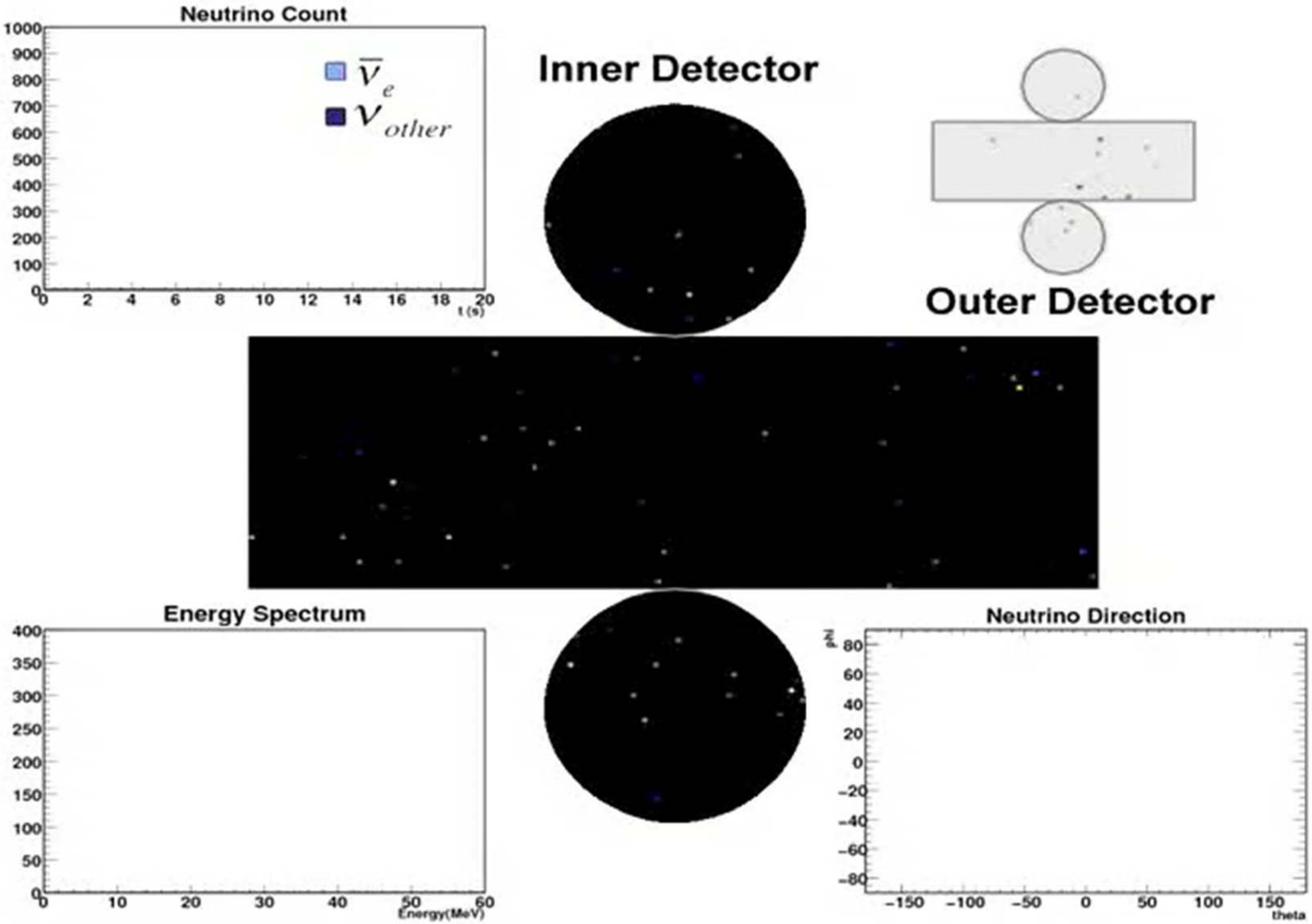
Neutrino Cross Section in a Water Target



$\overline{\nu}_e + p \to n + e^+$ dominates for SN neutrinos

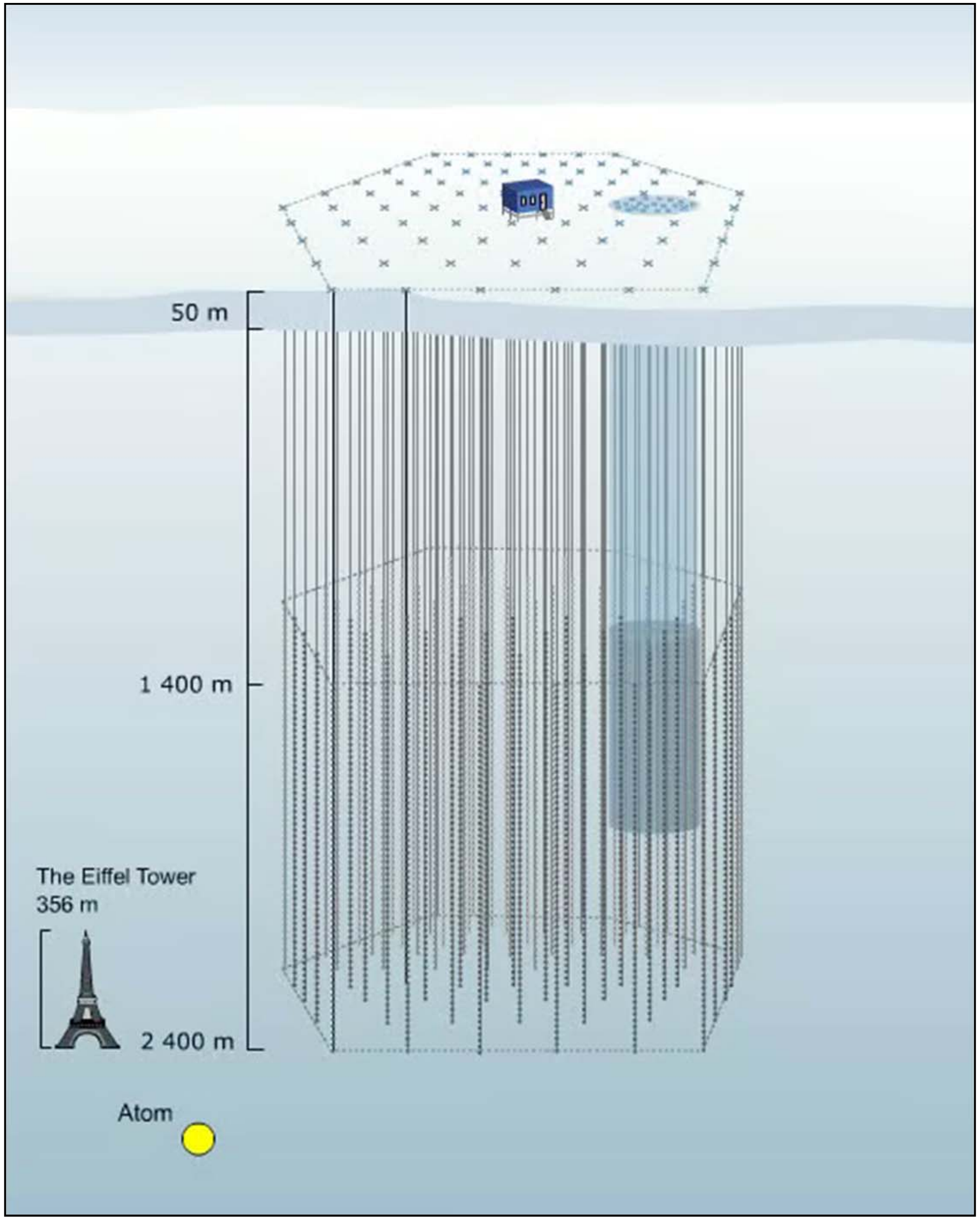
$\nu_e + e \to e + \nu_e$ dominates for solar neutrinos

Simulated Supernova Burst in Super-Kamiokande

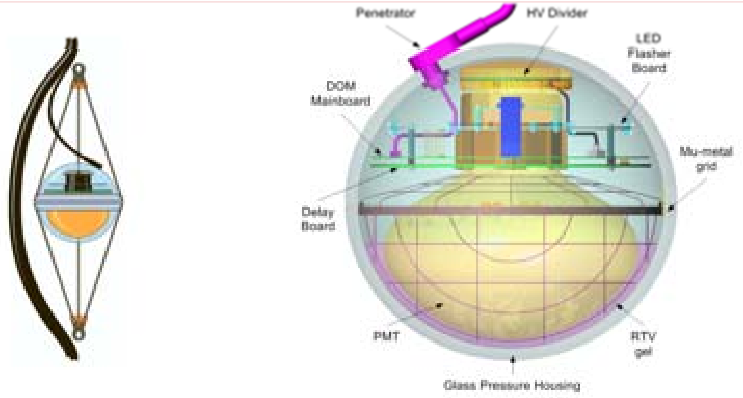


Movie by C. Little, including work by S. Farrell & B. Reed,
(Kate Scholberg's group at Duke University)
http://snews.bnl.gov/snmovie.html

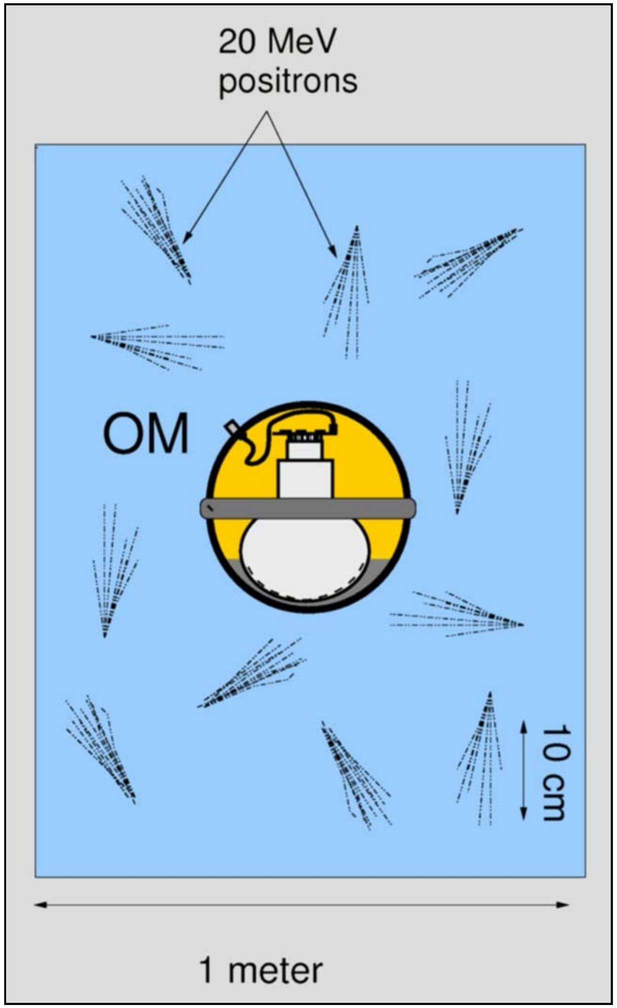
IceCube Neutrino Telescope at the South Pole



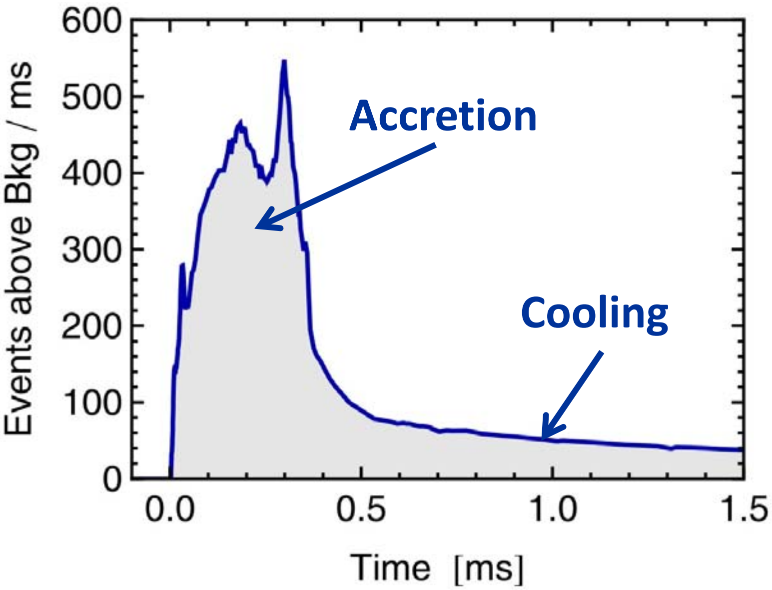
Instrumentation of 1 km^3 antarctic ice with ~ 5000 photo multipliers completed December 2010



IceCube as a Supernova Neutrino Detector



- Each optical module (OM) picks up Cherenkov light from its neighborhood
- ~ 300 Cherenkov photons per OM from SN at 10 kpc
- Bkgd rate in one OM < 300 Hz
- SN appears as “correlated noise” in ~ 5000 OMs

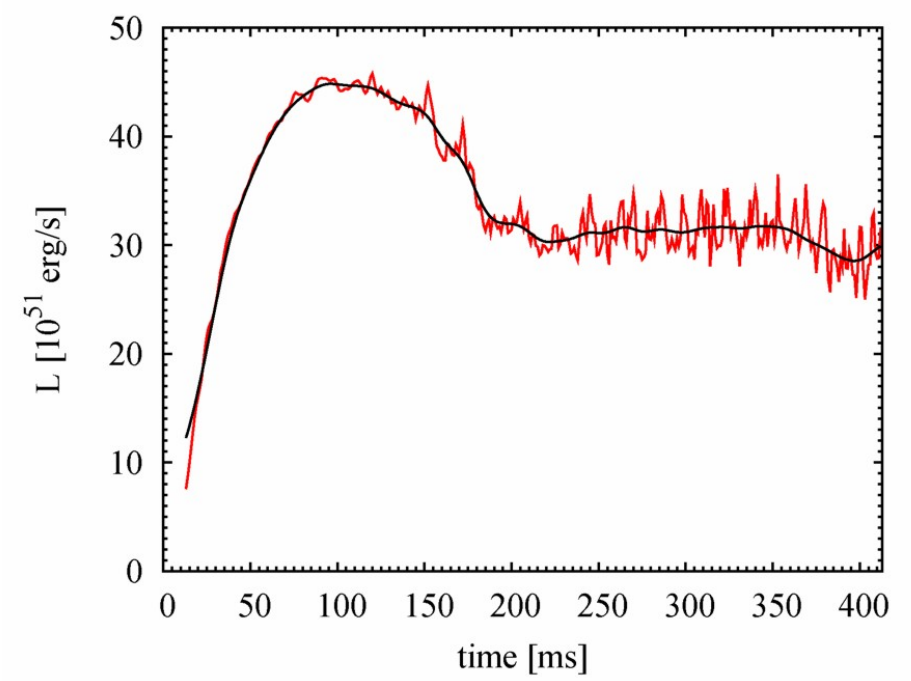


SN signal at 10 kpc
10.8 M_{sun} simulation
of Basel group
[arXiv:0908.1871]

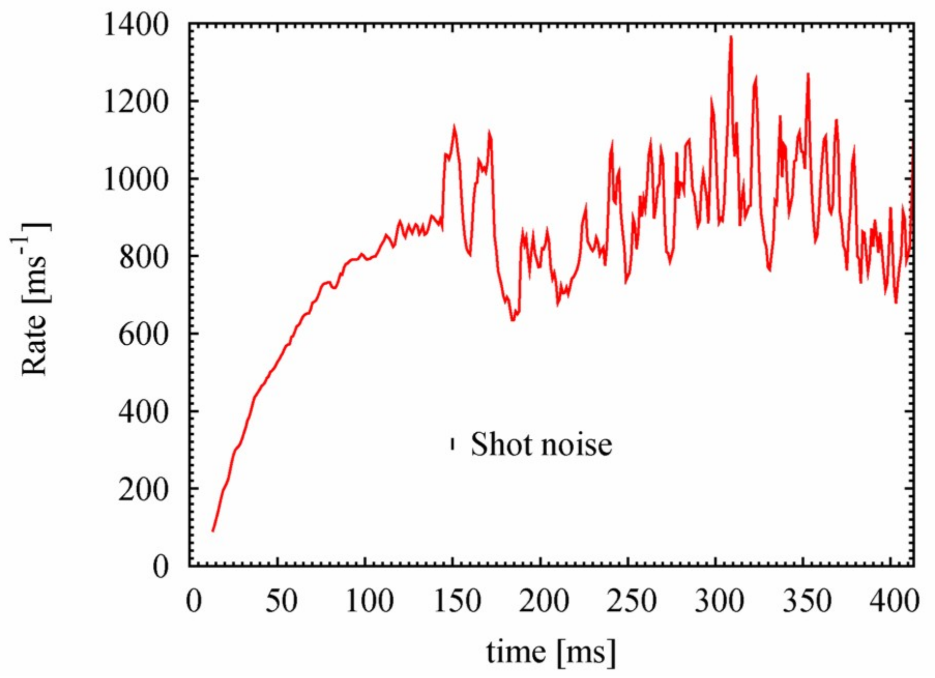
Pryor, Roos & Webster (ApJ 329:355, 1988), Halzen, Jacobsen & Zas (astro-ph/9512080)

Variability seen in Neutrinos

Luminosity



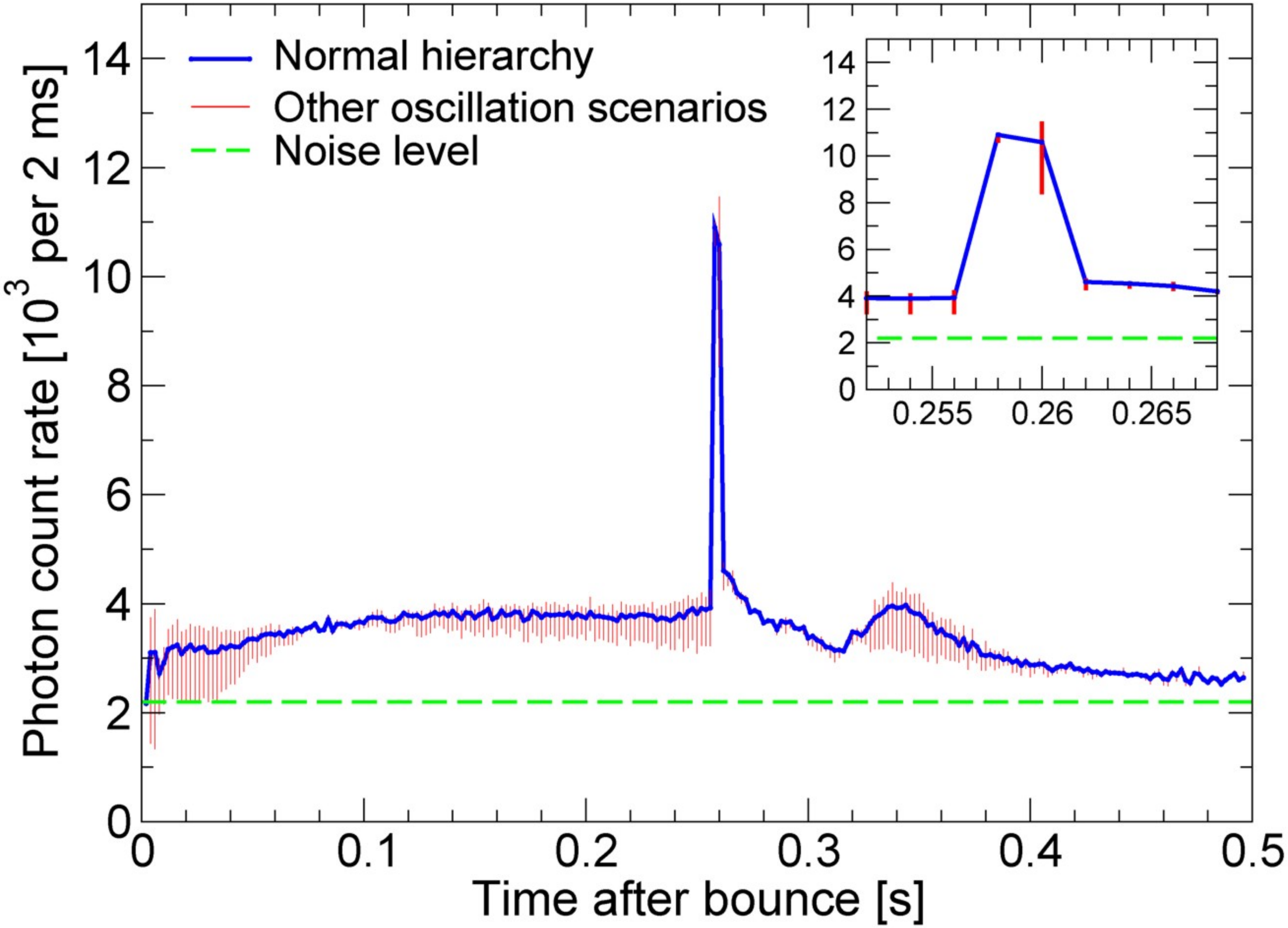
Detection rate in IceCube



Smaller in realistic 3D models

Lund, Marek, Lunardini, Janka & Raffelt, arXiv:1006.1889
Using 2-D model of Marek, Janka & Müller, arXiv:0808.4136

Quark-Matter Phase Transition Signature in IceCube

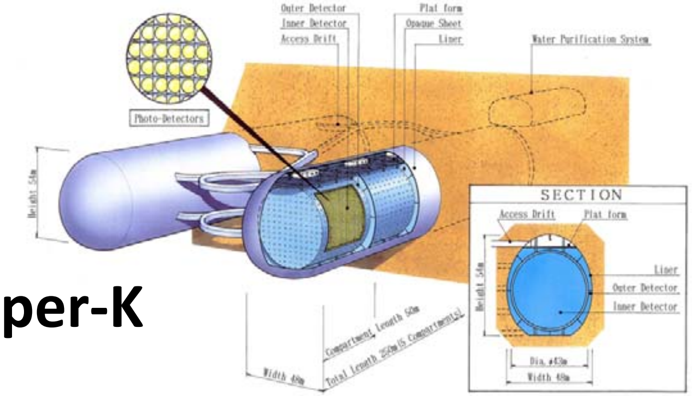


Dasgupta, Fischer, Horiuchi, Liebendörfer, Mirizzi, Sagert & Schaffner-Bielich
arXiv:0912.2568

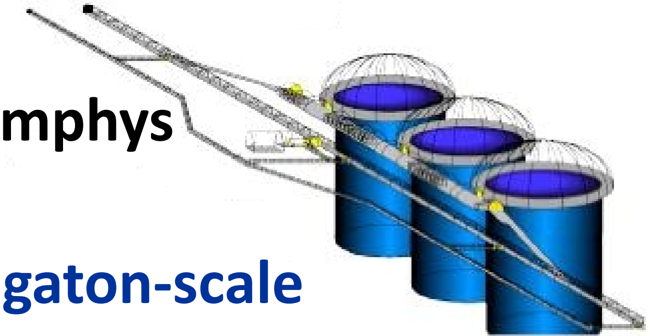
Next Generation Large-Scale Detector Concepts

DUSEL
LBNE

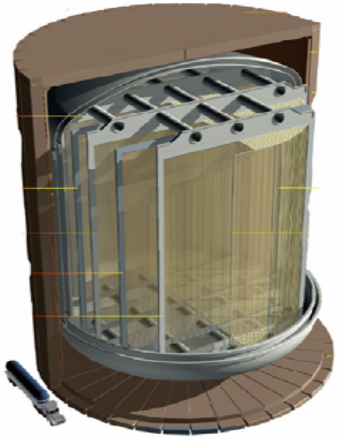
Hyper-K



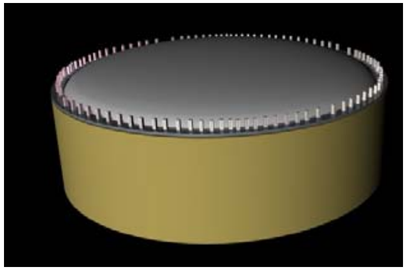
Memphys

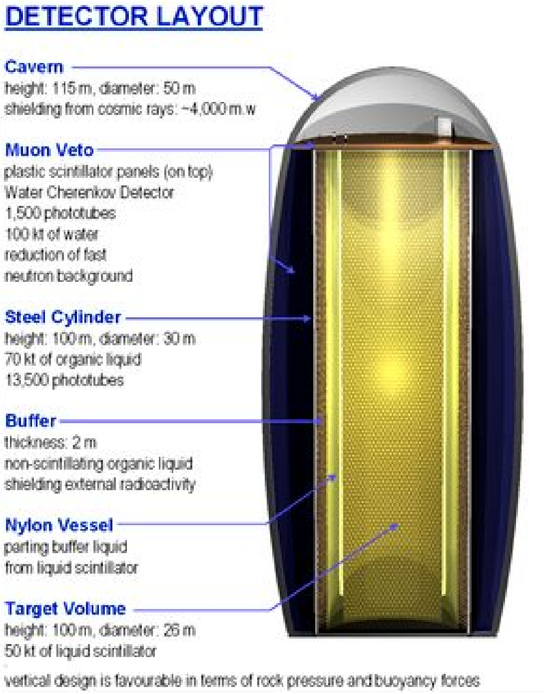


Megaton-scale water Cherenkov



5-100 kton liquid Argon





DETECTOR LAYOUT

Cavern
height: 115 m, diameter: 50 m
shielding from cosmic rays: ~4,000 m.w

Muon Veto
plastic scintillator panels (on top)
Water Cherenkov Detector
1,500 phototubes
100 kt of water
reduction of fast
neutron background

Steel Cylinder
height: 100 m, diameter: 30 m
70 kt of organic liquid
13,500 phototubes

Buffer
thickness: 2 m
non-scintillating organic liquid
shielding external radioactivity

Nylon Vessel
parting buffer liquid
from liquid scintillator

Target Volume
height: 100 m, diameter: 26 m
50 kt of liquid scintillator

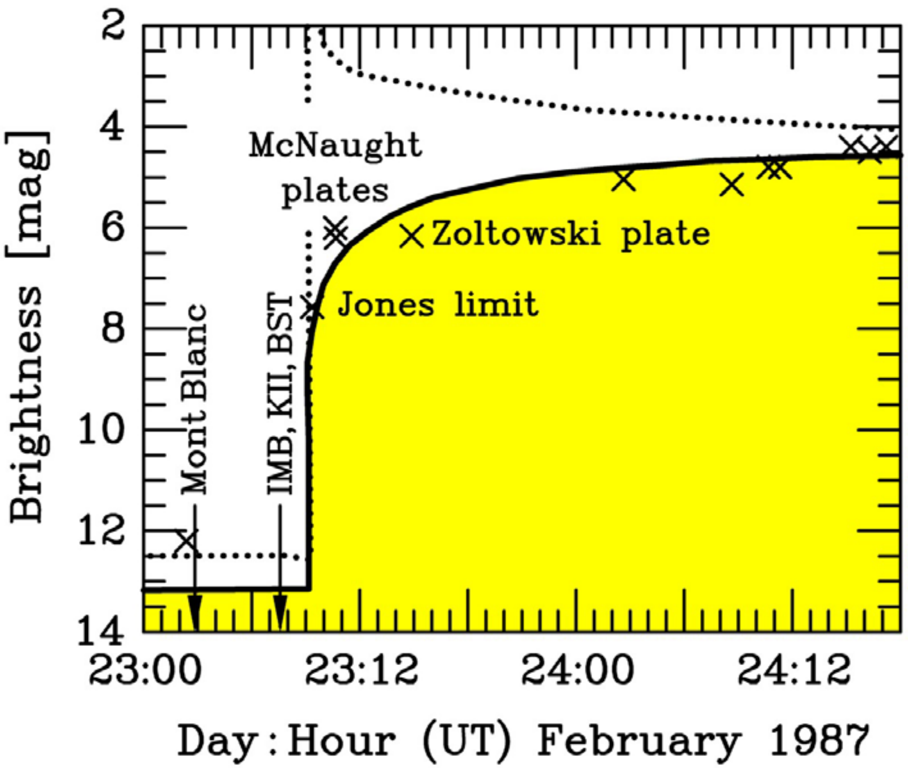
vertical design is favourable in terms of rock pressure and buoyancy forces

100 kton scale scintillator

LENA
HanoHano

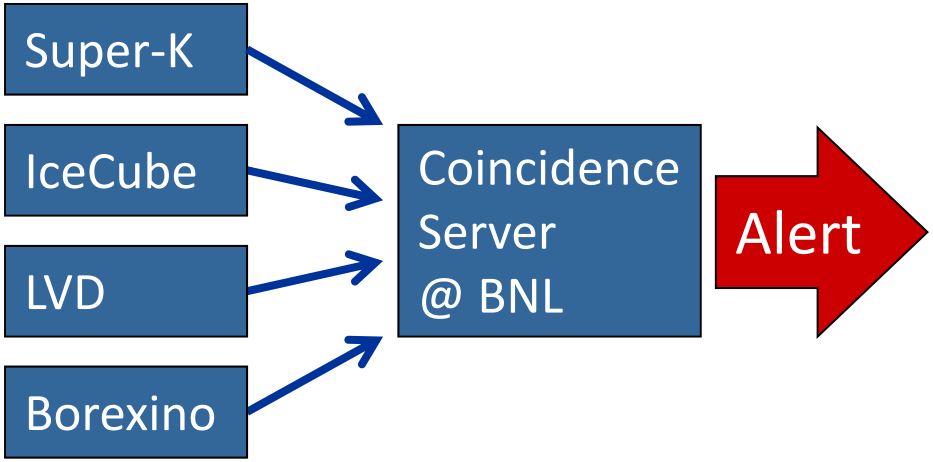
SuperNova Early Warning System (SNEWS)

Early light curve of SN 1987A



http://snews.bnl.gov

- Neutrinos arrive several hours before photons
- Can alert astronomers several hours in advance



Super-K

IceCube

LVD

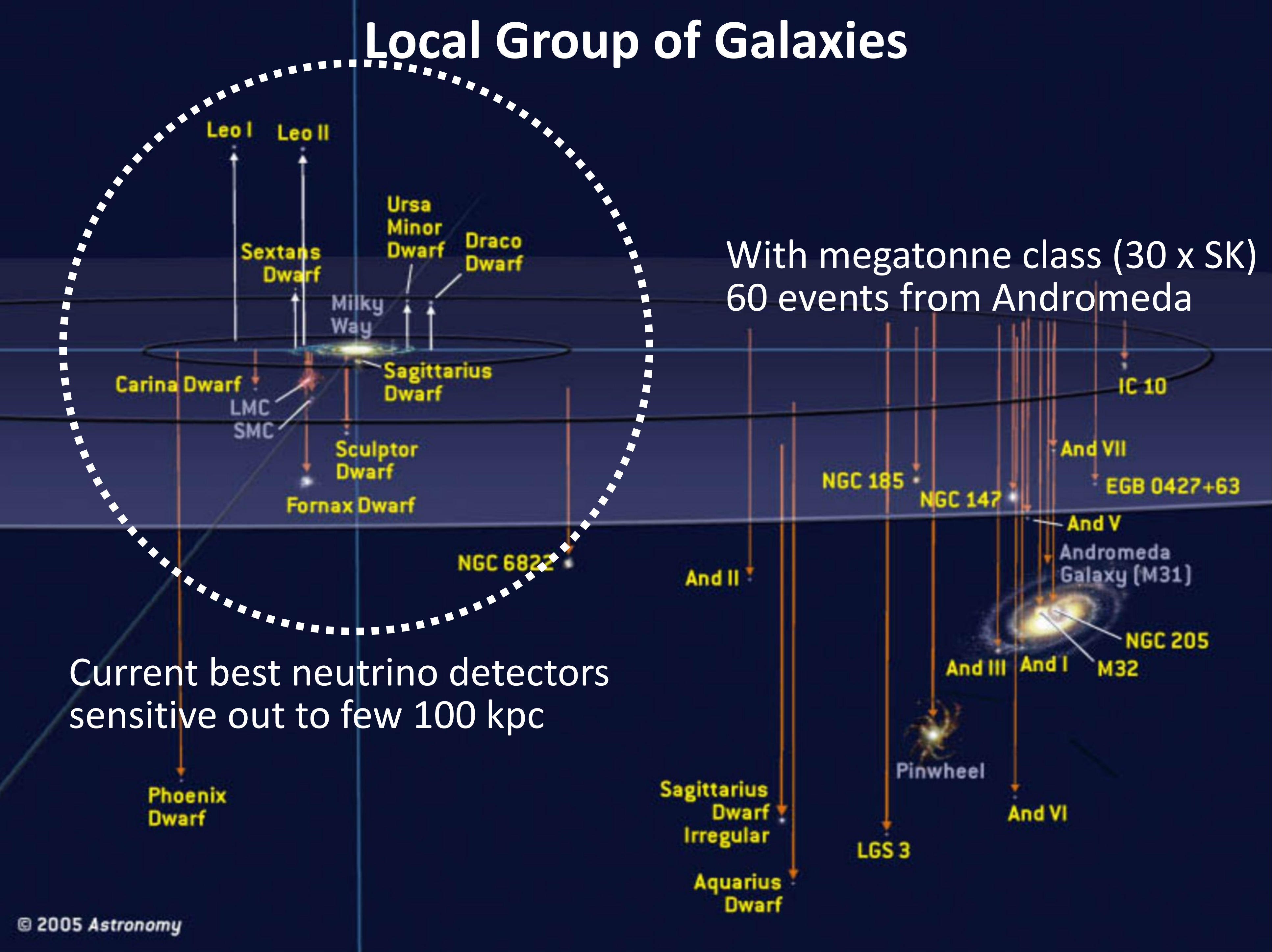
Borexino

Coincidence Server @ BNL

Alert

Supernova Rate

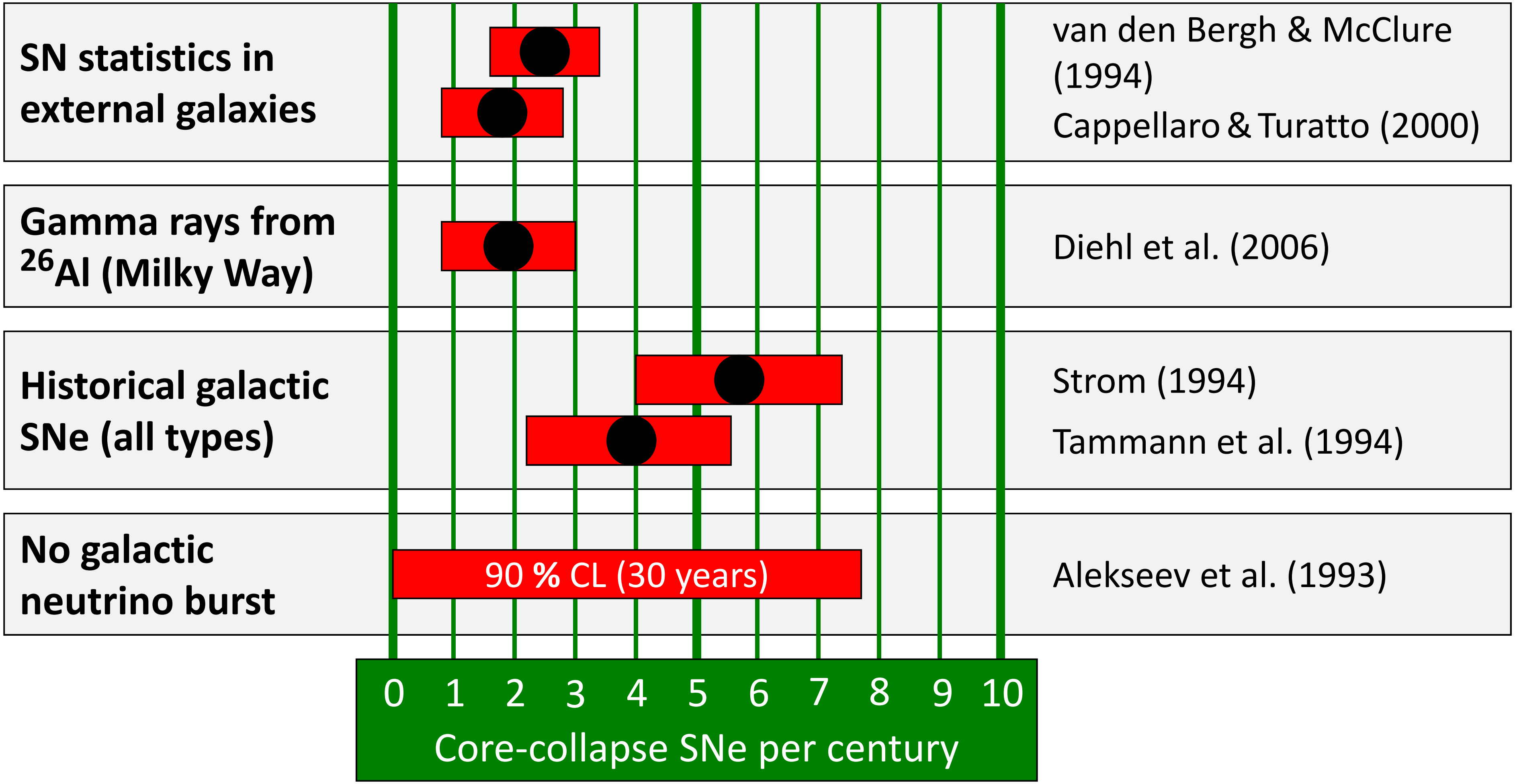
Local Group of Galaxies



With megatonne class (30 x SK)
60 events from Andromeda

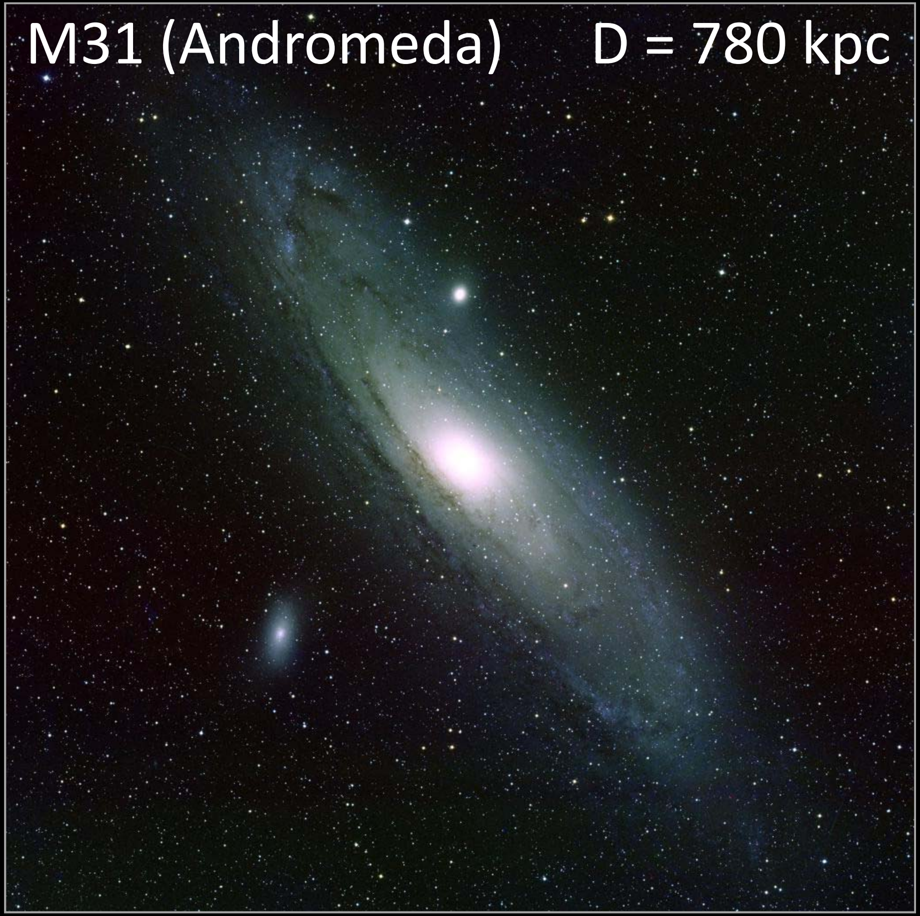
Current best neutrino detectors
sensitive out to few 100 kpc

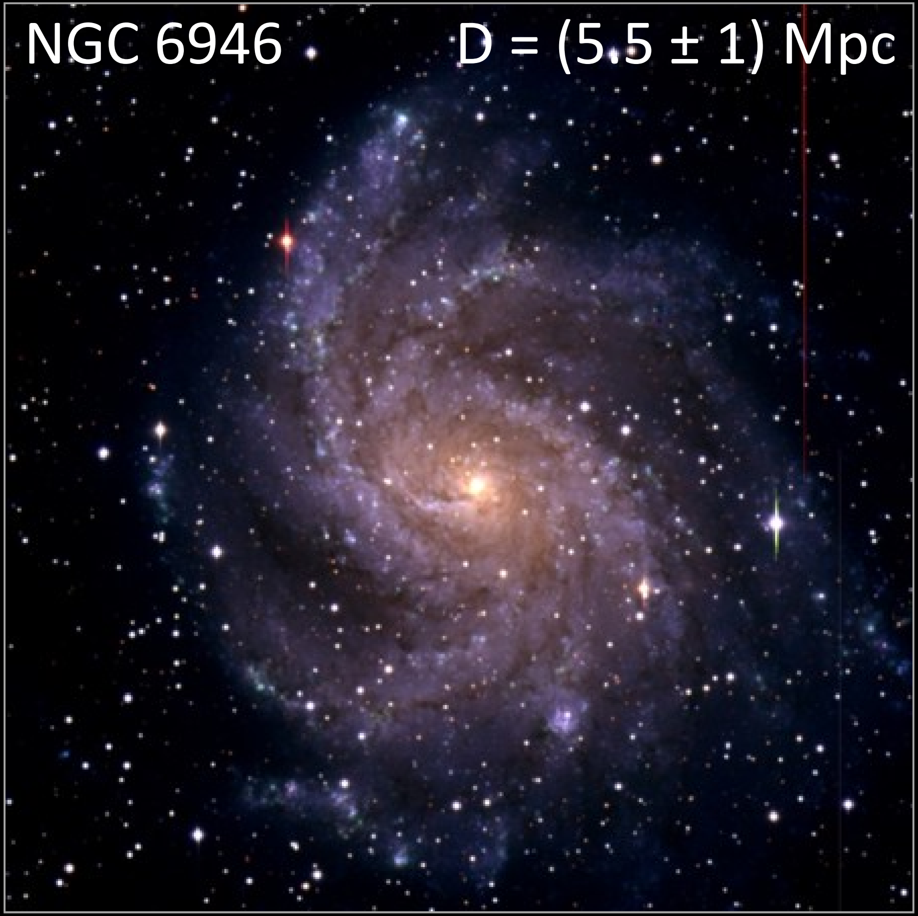
Core-Collapse SN Rate in the Milky Way



References: van den Bergh & McClure, ApJ 425 (1994) 205. Cappellaro & Turatto, astro-ph/0012455. Diehl et al., Nature 439 (2006) 45. Strom, Astron. Astrophys. 288 (1994) L1. Tammann et al., ApJ 92 (1994) 487. Alekseev et al., JETP 77 (1993) 339 and my update.

High and Low Supernova Rates in Nearby Galaxies

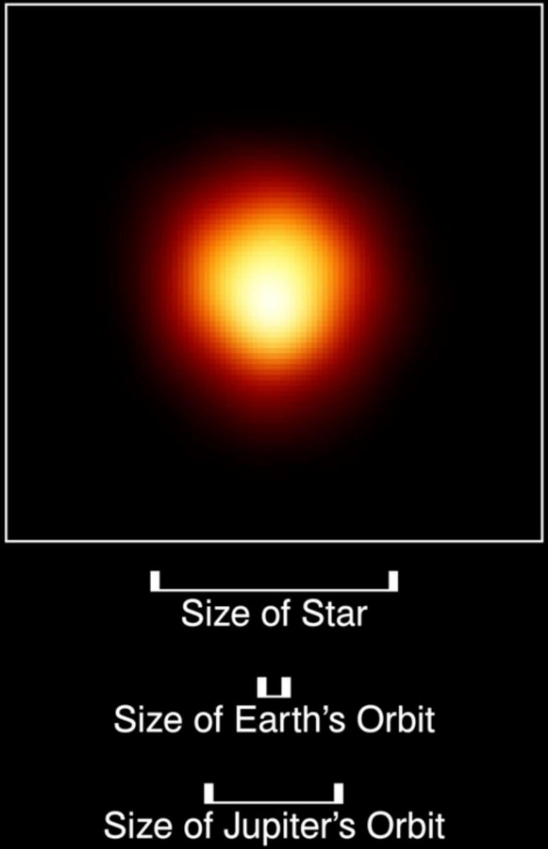




Last Observed Supernova: 1885A

Observed Supernovae:
1917A, 1939C, 1948B, 1968D, 1969P,
1980K, 2002hh, 2004et, 2008S

The Red Supergiant Betelgeuse (Alpha Orionis)



First resolved image of a star other than Sun

Distance (Hipparcos)
130 pc (425 lyr)

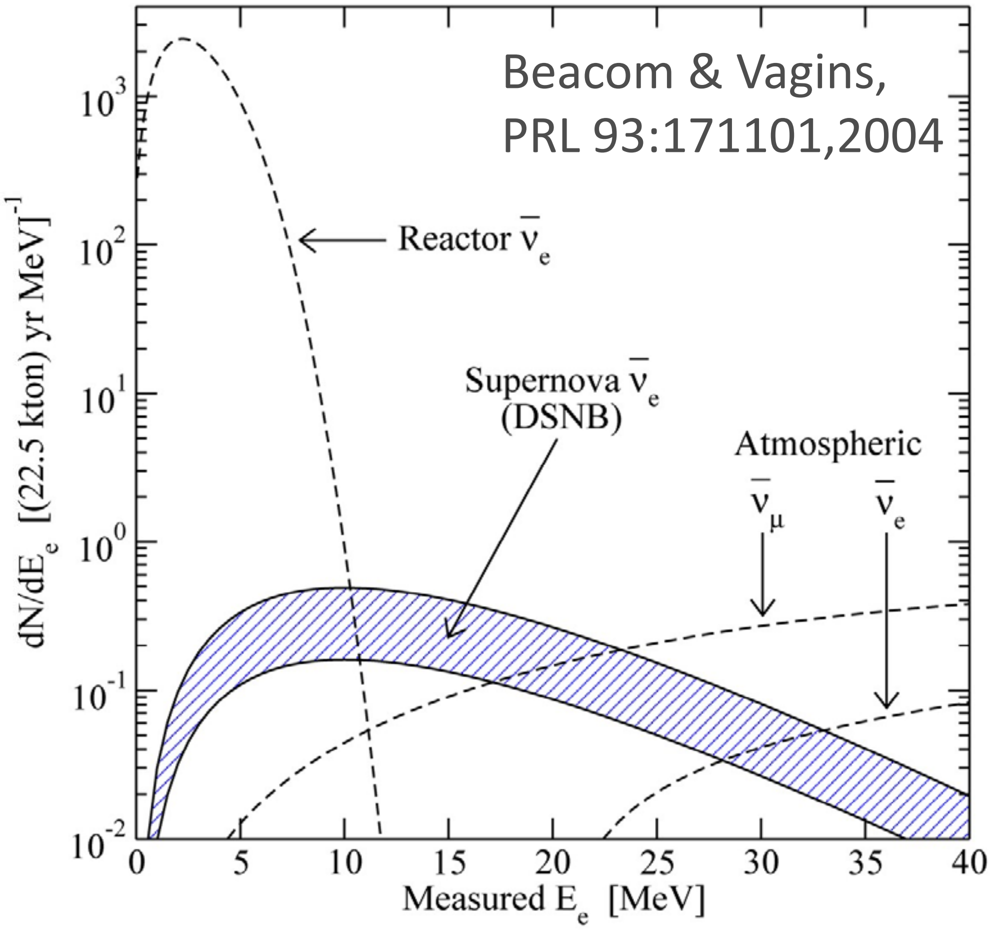
If Betelgeuse goes Supernova:

- 6×10^7 neutrino events in Super-Kamiokande
- 2.4×10^3 neutrons /day from Si burning phase (few days warning!), need neutron tagging [Odrzywolek, Misiaszek & Kutschera, astro-ph/0311012]

Diffuse SN Neutrino Background

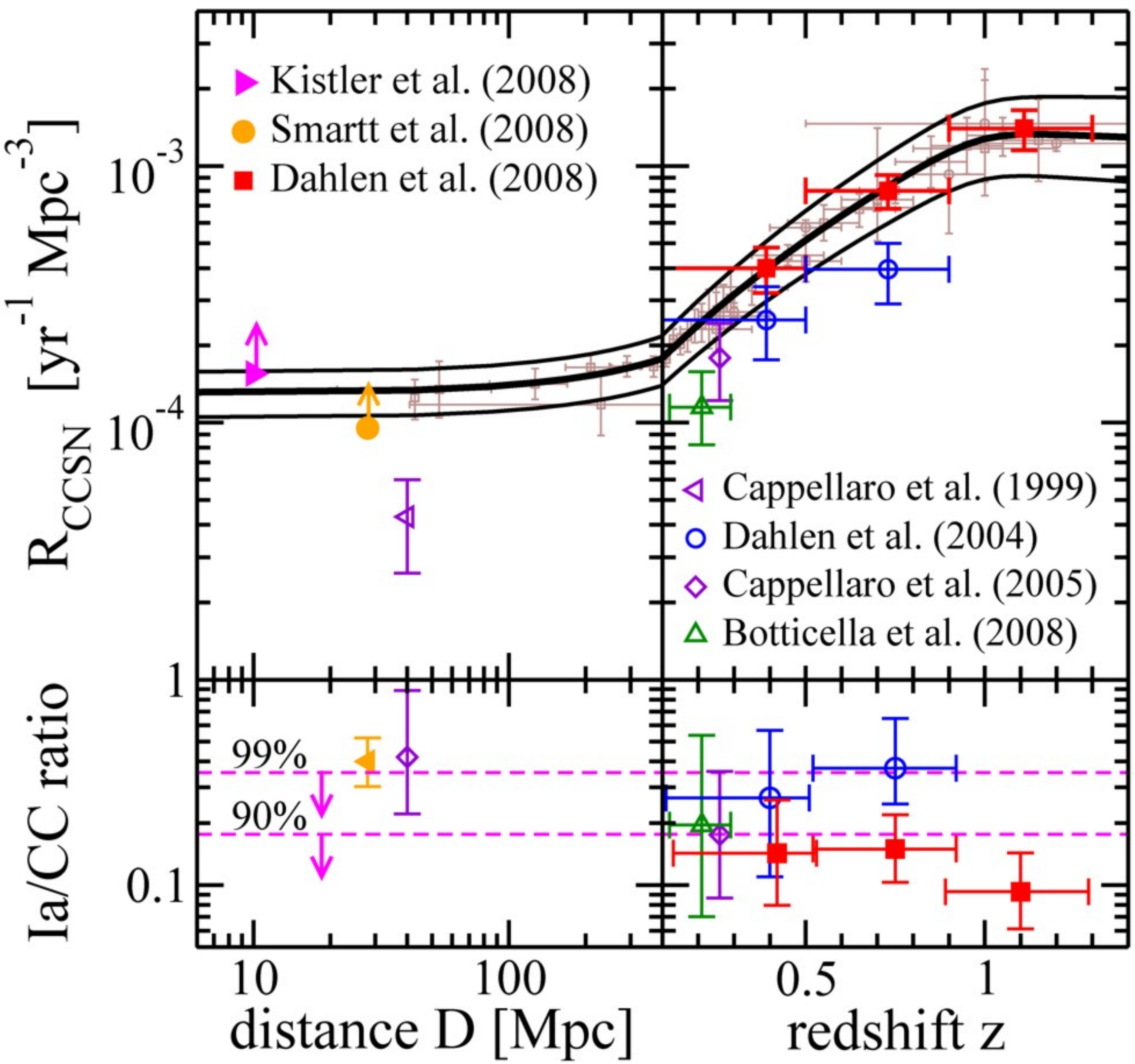
Diffuse Supernova Neutrino Background (DSNB)

- Approx. 10 core collapses/sec in the visible universe
- Emitted ν energy density
  $\sim$ extra galactic background light
  $\sim$ 10% of CMB density
- Detectable $\overline{\nu}_e$ flux at Earth
  $\sim 10\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
  mostly from redshift $z \sim 1$
- Confirm star-formation rate
- Nu emission from average core collapse & black-hole formation
- Pushing frontiers of neutrino astronomy to cosmic distances!



Window of opportunity between reactor $\overline{\nu}_e$ and atmospheric ν bkg

Redshift Dependence of Cosmic Supernova Rate



Core-collapse rate depending on redshift

Relative rate of type Ia

Horiuchi, Beacom & Dwek, arXiv:0812.3157v3

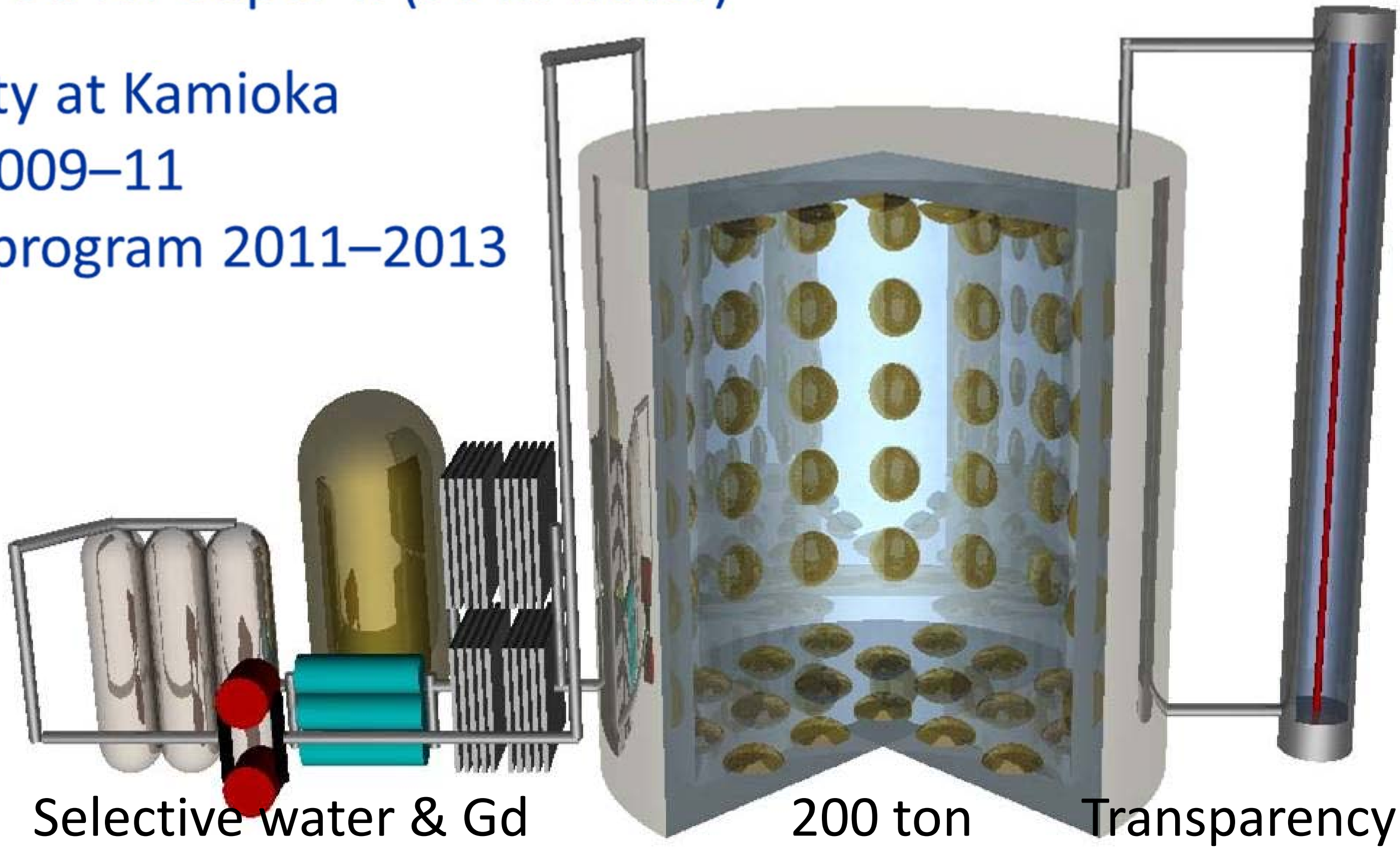
Neutron Tagging in Super-K with Gadolinium

Background suppression: Neutron tagging in $\overline{\nu}_e + p \rightarrow n + e^+$

- Scintillator detectors: Low threshold for γ(2.2 MeV)
- Water Cherenkov: Dissolve Gd as neutron trap (8 MeV γ cascade)
- Need 100 tons Gd for Super-K (50 kt water)

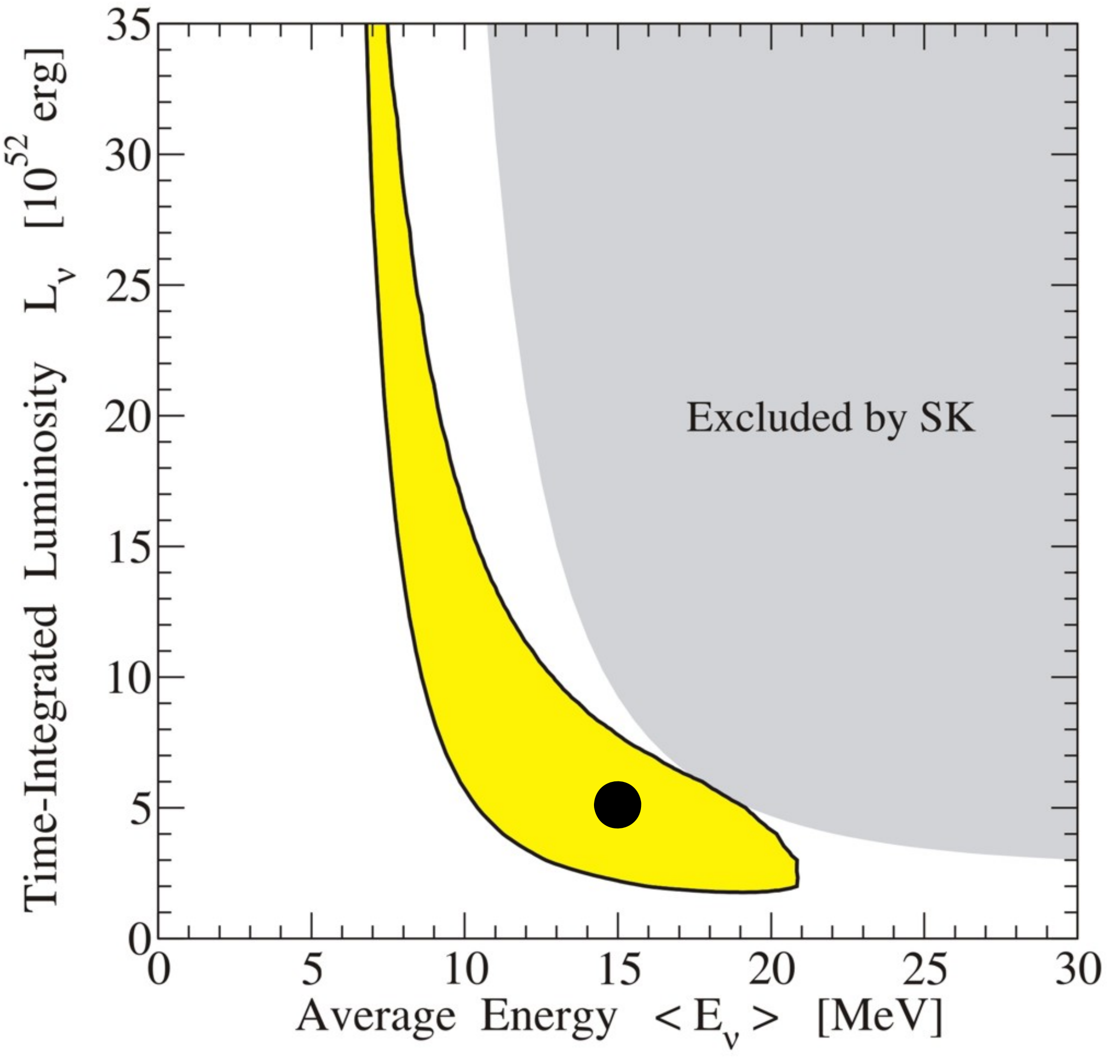
EGADS test facility at Kamioka

- Construction 2009–11
- Experimental program 2011–2013



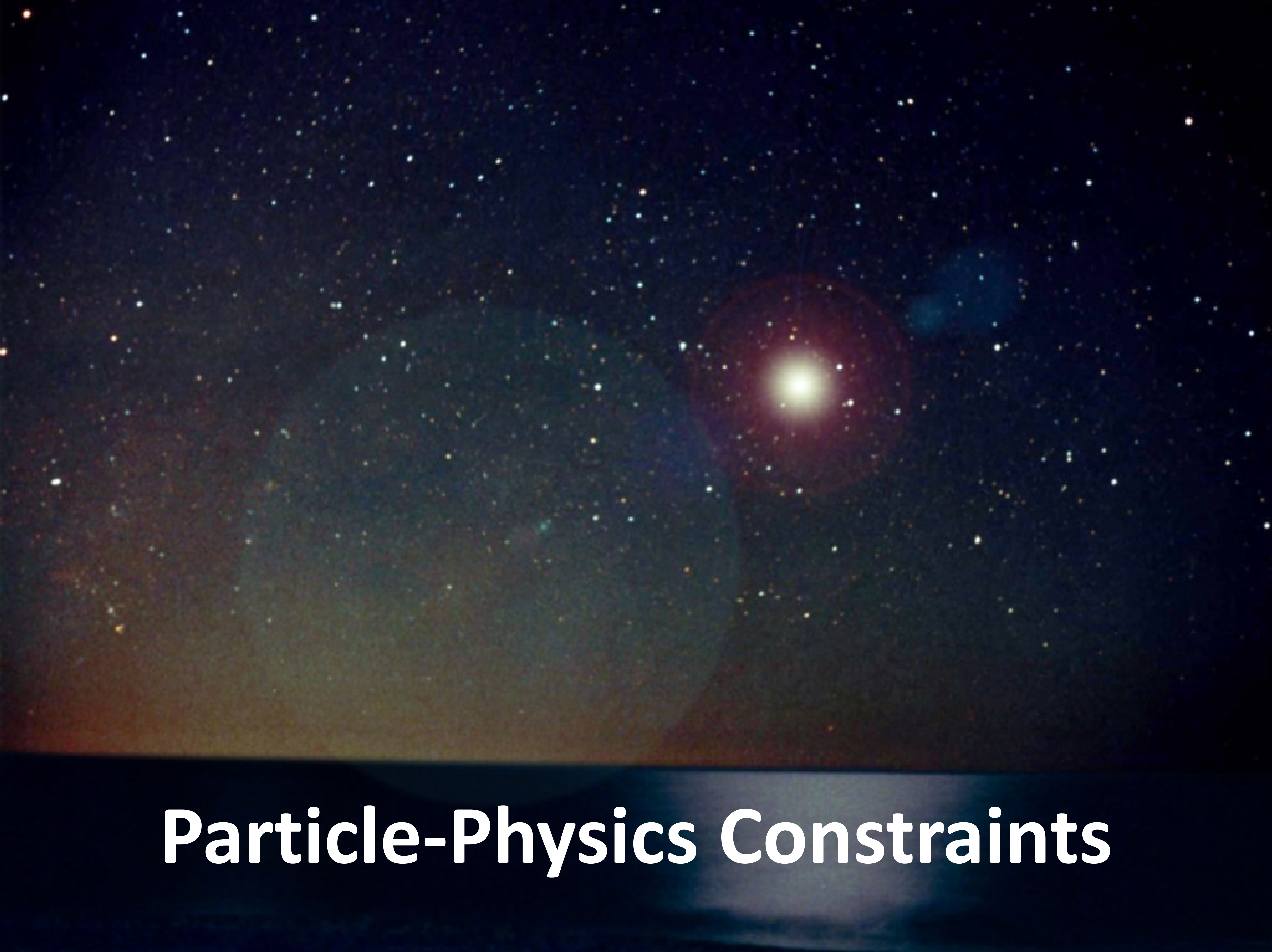
Mark Vagins
Neutrino 2010

Average spectral properties from DSNB



90% CL sensitivity to average SN spectrum from DSNB after 5 years of Gd enhanced Super-K

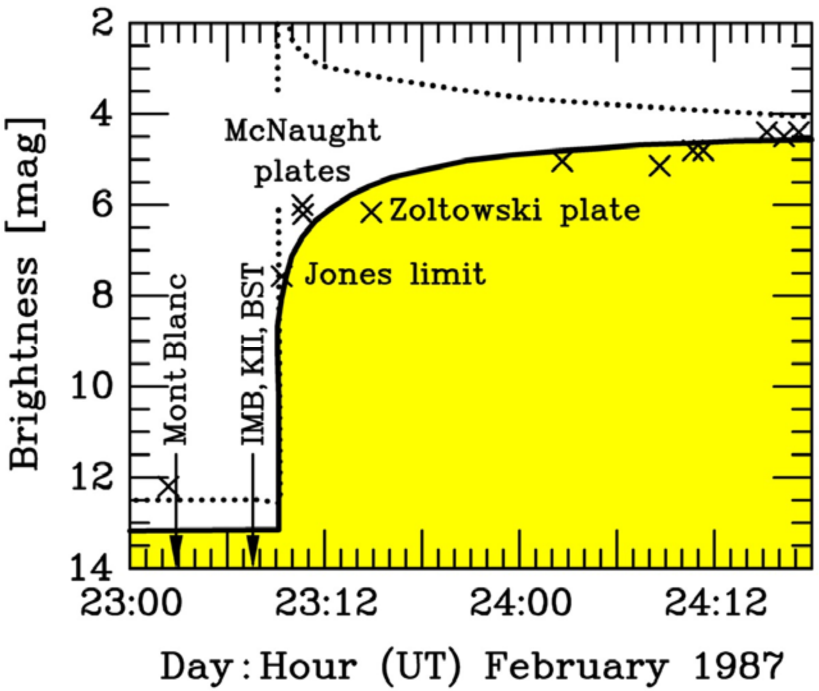
Adapted from Yüksel, Ando & Beacom, astro-ph/0509297



Particle-Physics Constraints

Do Neutrinos Gravitate?

Early light curve of SN 1987A



- Neutrinos arrived several hours before photons as expected
- Transit time for ν and γ same (160.000 yr) within a few hours

Shapiro time delay for particles moving in a gravitational potential

$$\Delta t = -2 \int_A^B dt\, \Phi[r(t)]$$

For trip from LMC to us, depending on galactic model,

$$\Delta t \approx 1\text{–}5 \text{ months}$$

Neutrinos and photons respond to gravity the same to within

$$1\text{–}4 \times 10^{-3}$$

Longo, PRL 60:173, 1988

Krauss & Tremaine, PRL 60:176, 1988

Millisecond Bounce Time Reconstruction

Super-Kamiokande

- Emission model adapted to measured SN 1987A data
- “Pessimistic distance” 20 kpc
- Determine bounce time to a few tens of milliseconds

Pagliaroli, Vissani, Coccia & Fulgione
arXiv:0903.1191

IceCube

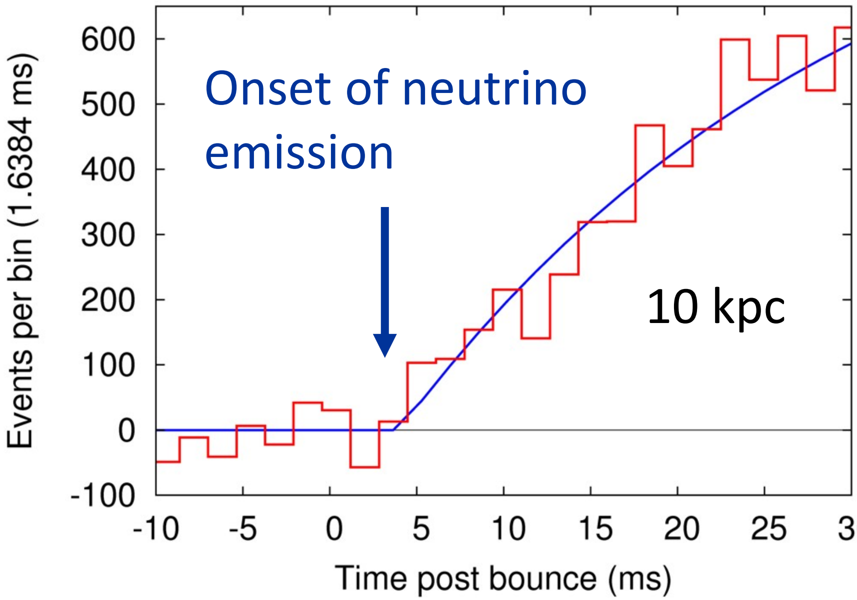


FIG. 1: Typical Monte Carlo realization (red histogram) and reconstructed fit (blue line) for the benchmark case discussed in the text for a SN at 10 kpc.

Halzen & Raffelt, arXiv:0908.2317

Neutrino Limits by Intrinsic Signal Dispersion

Time of flight delay by neutrino mass

G. Zatsepin, JETP Lett. 8:205, 1968

$$\Delta t = 2.57\mathrm{s}\,\frac{D}{50\ \mathrm{kpc}}\left(\frac{10\ \mathrm{MeV}}{E_\nu}\right)^2\left(\frac{m_\nu}{10\ \mathrm{eV}}\right)^2$$

SN 1987A signal duration implies

$$m_{\nu_e} \lesssim 20\ \mathrm{eV}$$

Loredo & Lamb
Ann N.Y. Acad. Sci. 571 (1989) 601
find 23 eV (95% CL limit) from detailed maximum-likelihood analysis

- At the time of SN 1987A competitive with tritium end-point
- Today $\mathrm{m}_\nu < 2.2\ \mathrm{eV}$ from tritium
- Cosmological limit today $m_\nu \lesssim 0.2\ \mathrm{eV}$

“Milli charged” neutrinos

Path bent by galactic magnetic field, inducing a time delay

$$\frac{\Delta t}{t} = \frac{e_\nu^2 (B_\perp d_B)^2}{6E_\nu^2} < 3\times 10^{-12}$$

SN 1987A signal duration implies

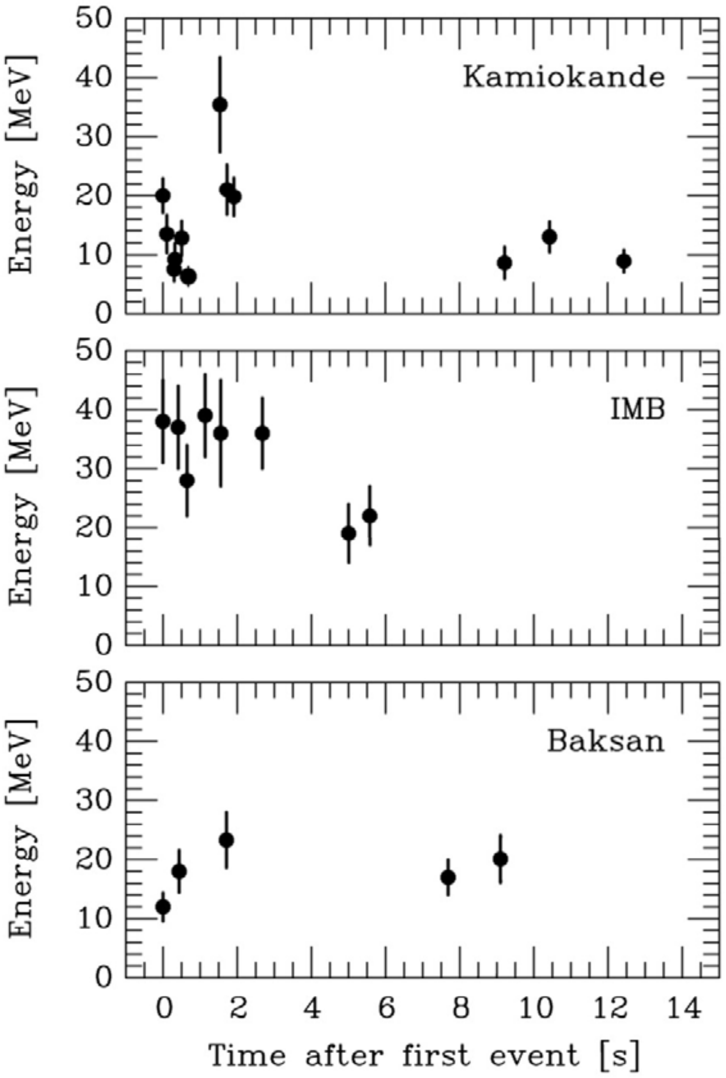
$$\frac{e_\nu}{e} < 3\times 10^{-17}\ \frac{1\mu G}{B_\perp}\ \frac{1\ \mathrm{kpc}}{d_B}$$

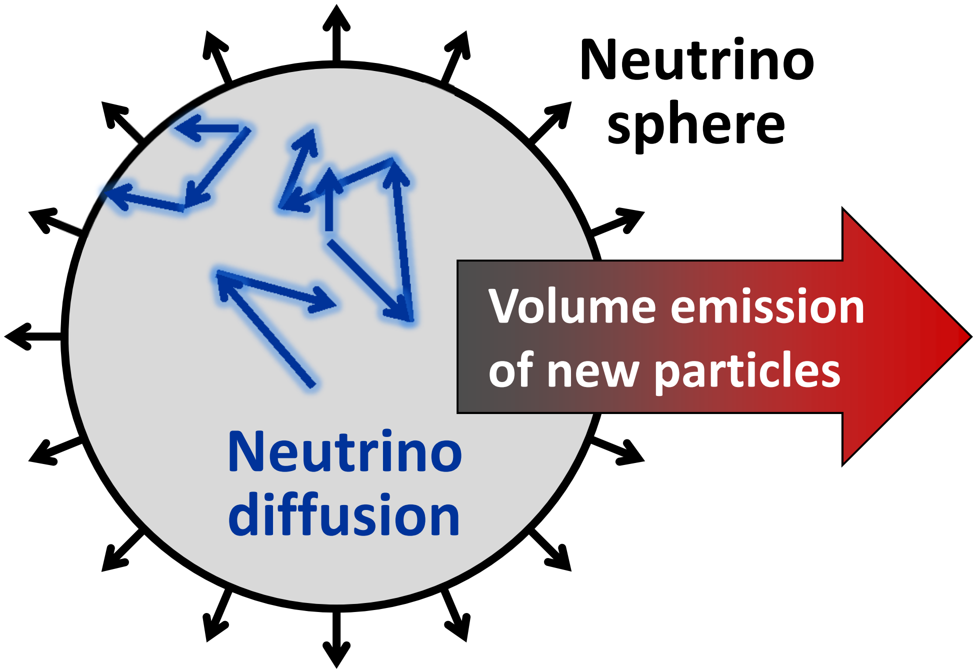
- Barbiellini & Cocconi, Nature 329 (1987) 21
- Bahcall, Neutrino Astrophysics (1989)

Assuming charge conservation in neutron decay yields a more restrictive limit of about 3×10^{-21} e

Supernova 1987A Energy-Loss Argument

SN 1987A neutrino signal





Neutrino sphere

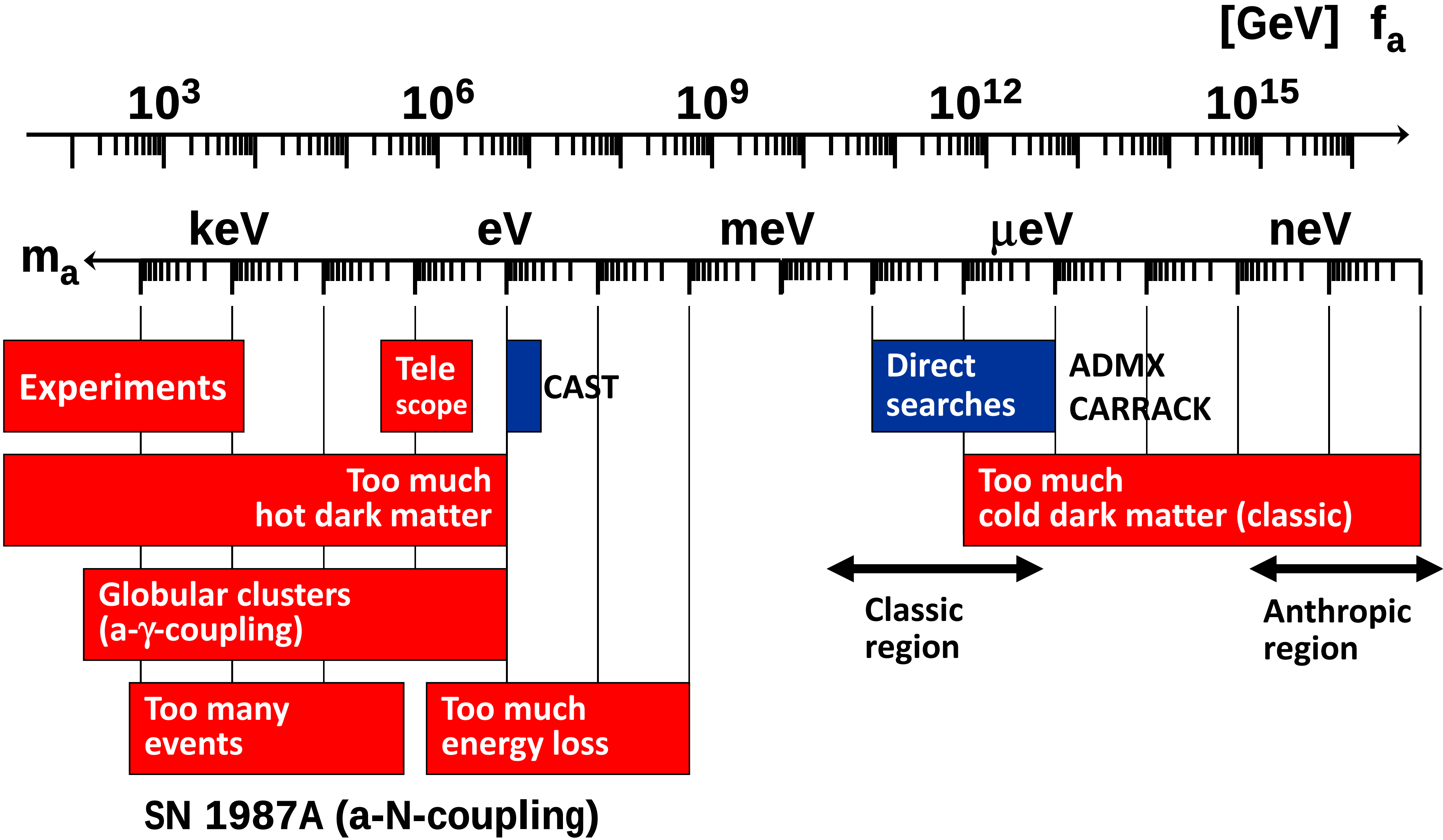
Volume emission of new particles

Neutrino diffusion

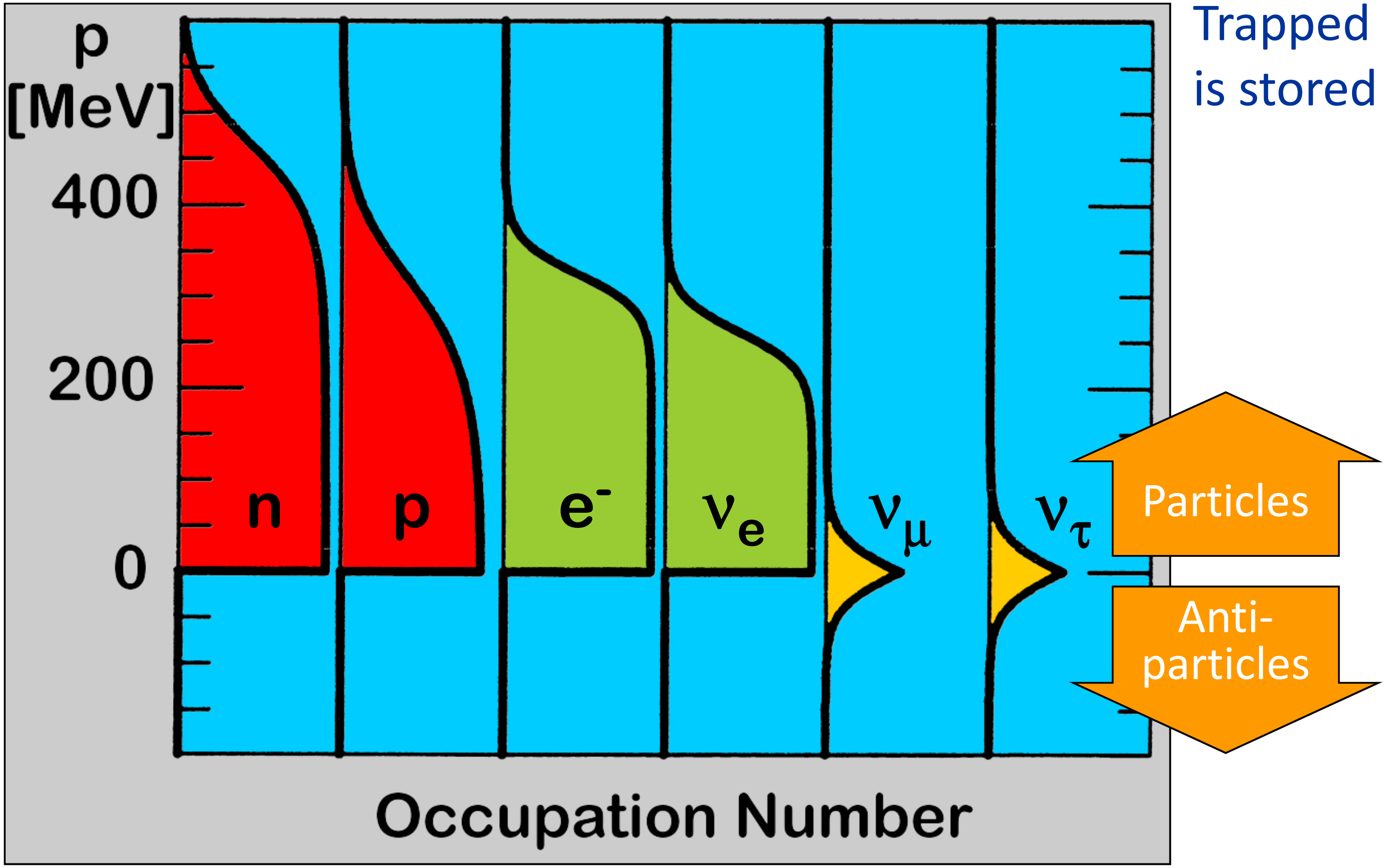
Emission of very weakly interacting particles would "steal" energy from the neutrino burst and shorten it. (Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

Late-time signal most sensitive observable

Axion Bounds



Degenerate Fermi Seas in a Supernova Core

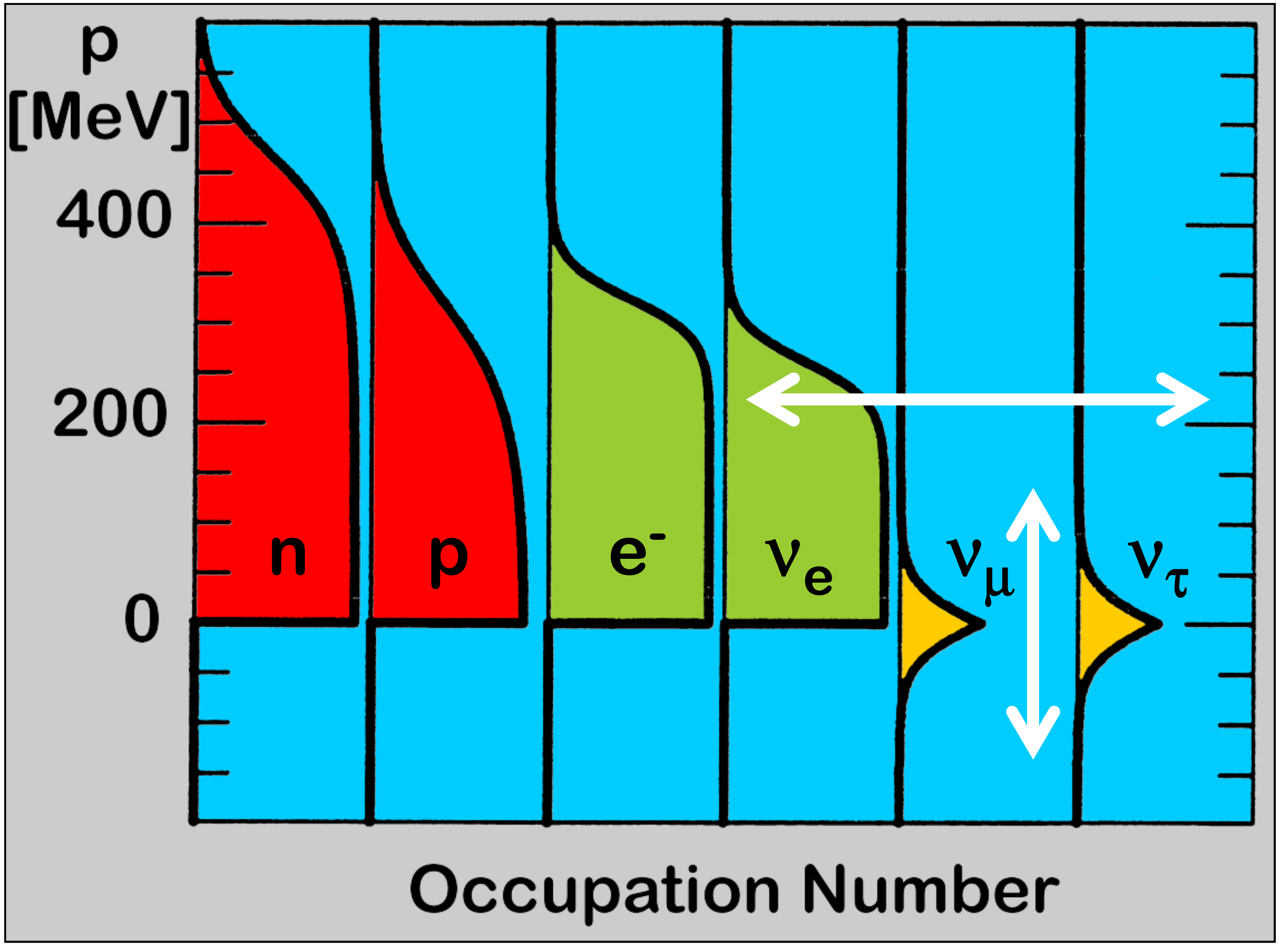


Trapped lepton number is stored in e^- and ν_e

In true thermal equilibrium with flavor mixing, only one chemical potential for charged leptons and one for neutrinos.

No chemical potential for Majorana neutrinos (lepton number violation)

Degenerate Fermi Seas in a Supernova Core



Equilibration by flavor lepton number violation, but flavor oscillations ineffective (matter effect)

Non-standard interactions could be effective, most sensitive environment

Consequences in core collapse should be studied numerically

Equilibration by lepton number violation, but Majorana masses too small

R-parity violating SUSY interactions?
TeV-scale bi-leptons?

Eur. Phys. J. C (2010) 67: 213–227
DOI 10.1140/epjc/s10052-010-1291-9

THE EUROPEAN
PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

TeV-scale bileptons, see-saw type II and lepton flavor violation in core-collapse supernova

Oleg Lychkovskiy[1,a], **Sergei Blinnikov**[1,2], **Mikhail Vysotsky**[1]

[1]Institute for Theoretical and Experimental Physics, B. Cheremushkinskaya 25, 117218 Moscow, Russia
[2]IPMU, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, 277-8568, Japan

Received: 7 January 2010 / Published online: 31 March 2010

Abstract Electrons and electron neutrinos in the inner core of the core-collapse supernova are highly degenerate and therefore numerous during a few seconds of explosion. In contrast, leptons of other flavors are non-degenerate and therefore relatively scarce. This is due to lepton flavor conservation. If this conservation law is broken by some non-standard interactions, ν_e are converted to ν_μ, ν_τ, and e are converted to μ. This affects the supernova dynamics and the supernova neutrino signal. We consider lepton flavor violating interactions mediated by scalar bileptons, i.e. heavy scalars with lepton number 2. It is shown that in case of TeV-mass bileptons the electron Fermi gas is equilibrated with non-electron species inside the inner supernova core at a time scale ∼(1–100) ms. In particular, a scalar triplet which generates neutrino masses through the see-saw type II mechanism is considered. It is found that the supernova core is sensitive to yet unprobed values of masses and couplings of the triplet.

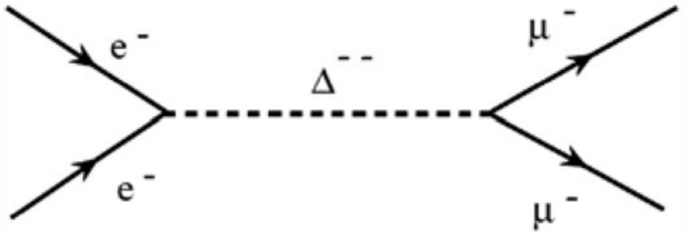
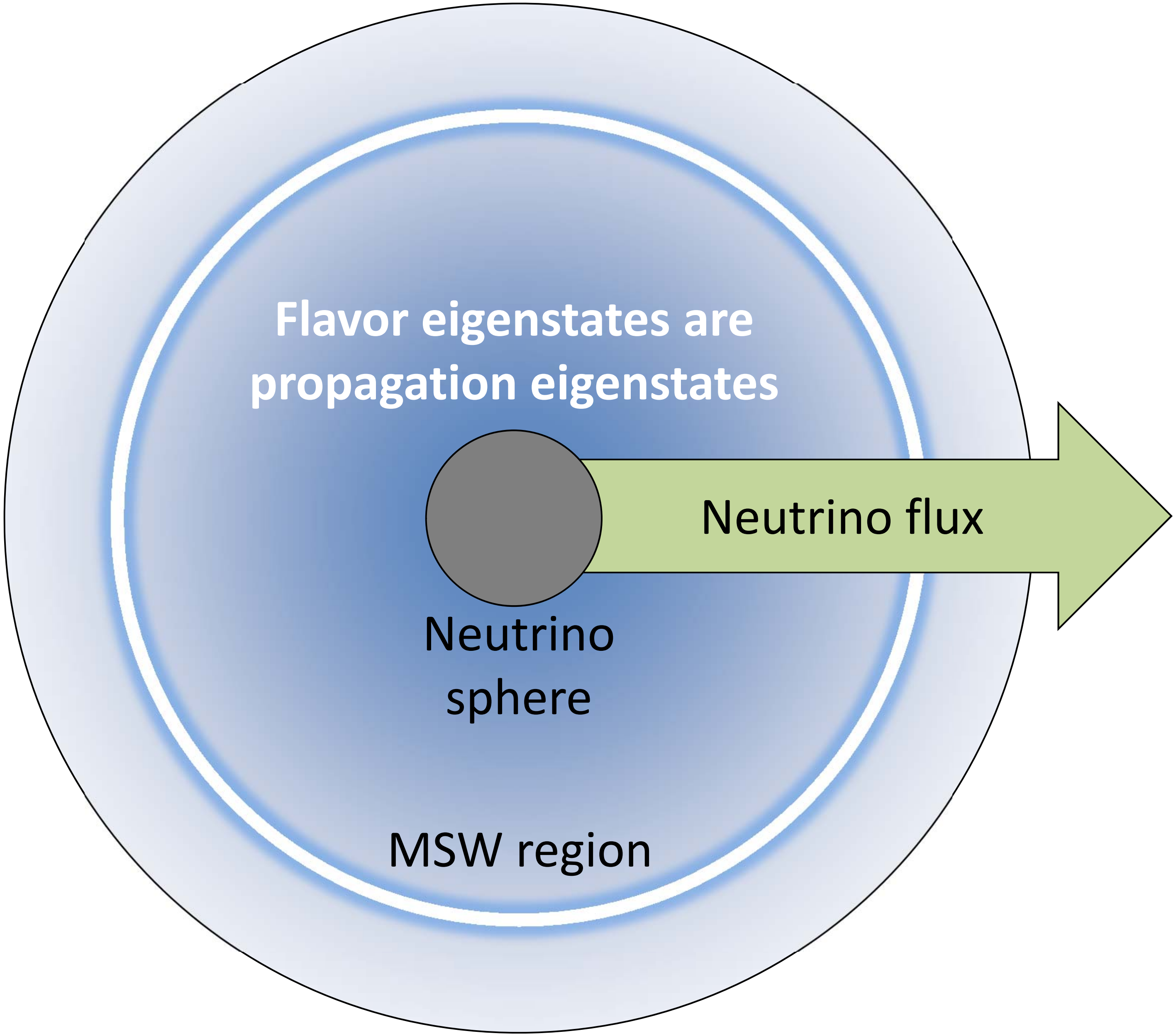


Fig. 1 $ee \to \mu\mu$ LFV transition mediated by the doubly charged bilepton Δ^{--}

Neutrino Flavor Oscillations

Flavor Oscillations in Core-Collapse Supernovae



Flavor eigenstates are propagation eigenstates

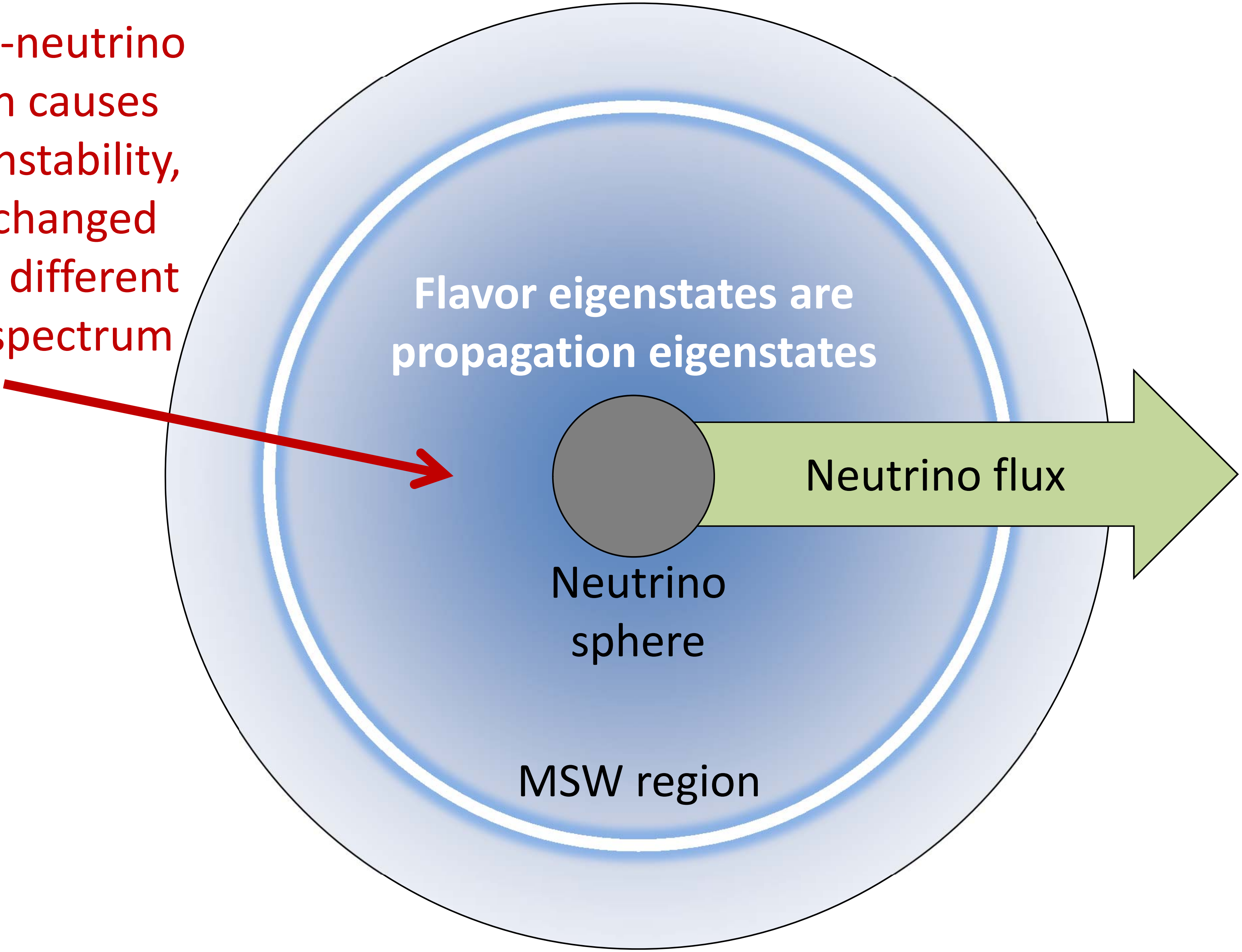
Neutrino flux

Neutrino sphere

MSW region

Flavor Oscillations in Core-Collapse Supernovae

Neutrino-neutrino refraction causes a flavor instability, flavor exchanged between different parts of spectrum



More tomorrow …