Physics Opportunities with Supernova Neutrinos

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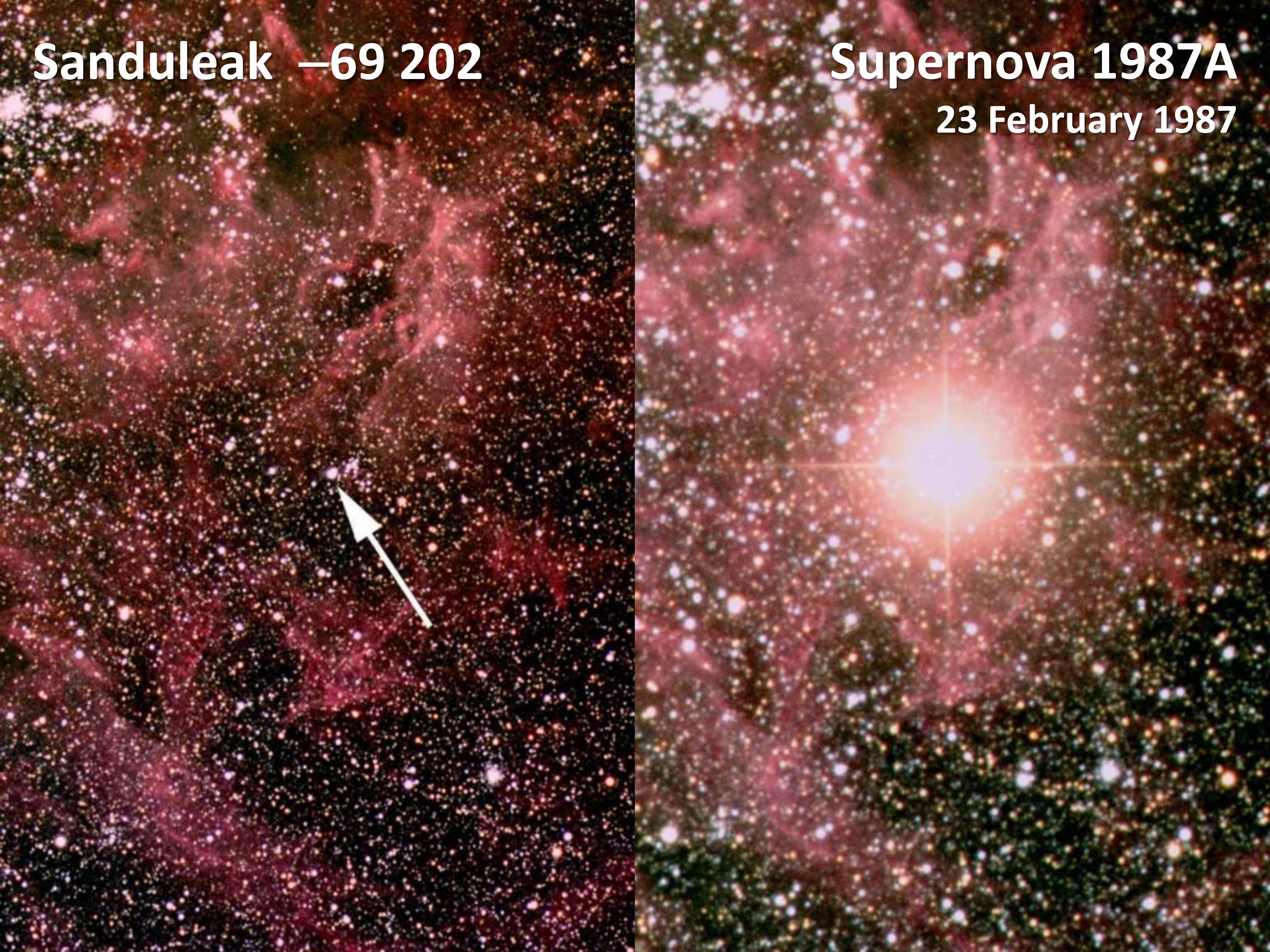
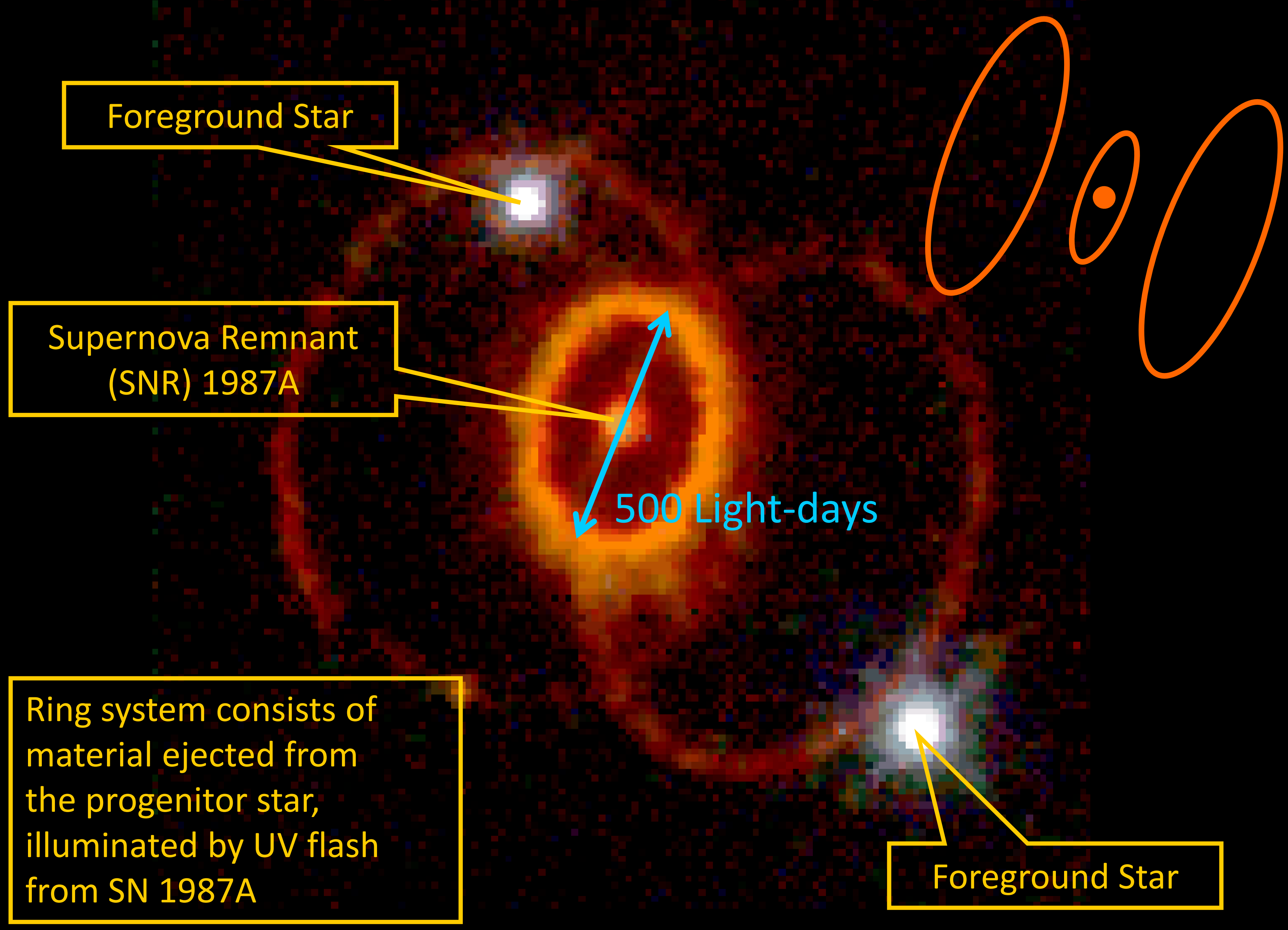
Sanduleak –69 202


Tarantula Nebula

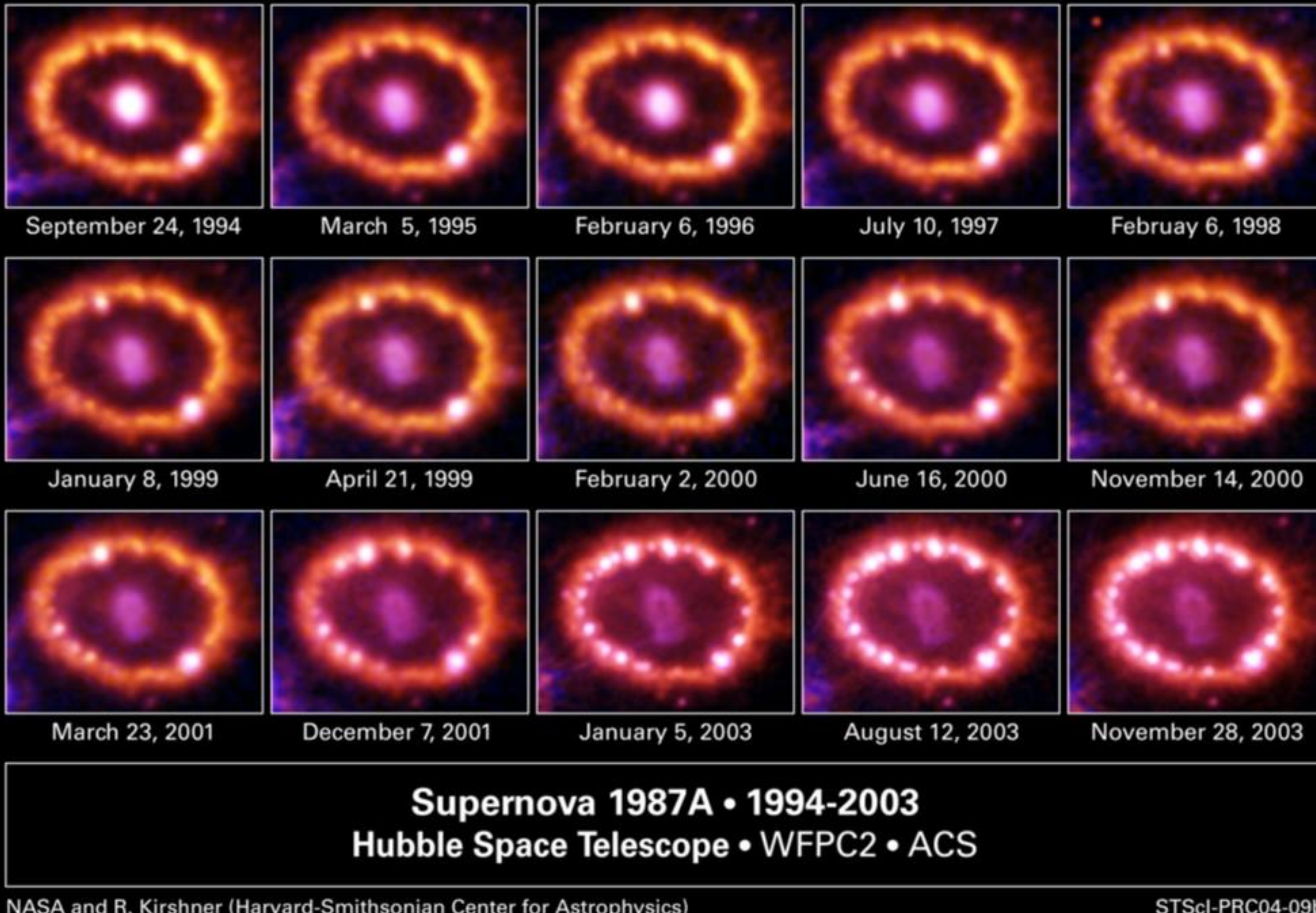

Large Magellanic Cloud
Distance 50 kpc
(160.000 light years)


Sanduleak –69 202
Supernova 1987A
23 February 1987

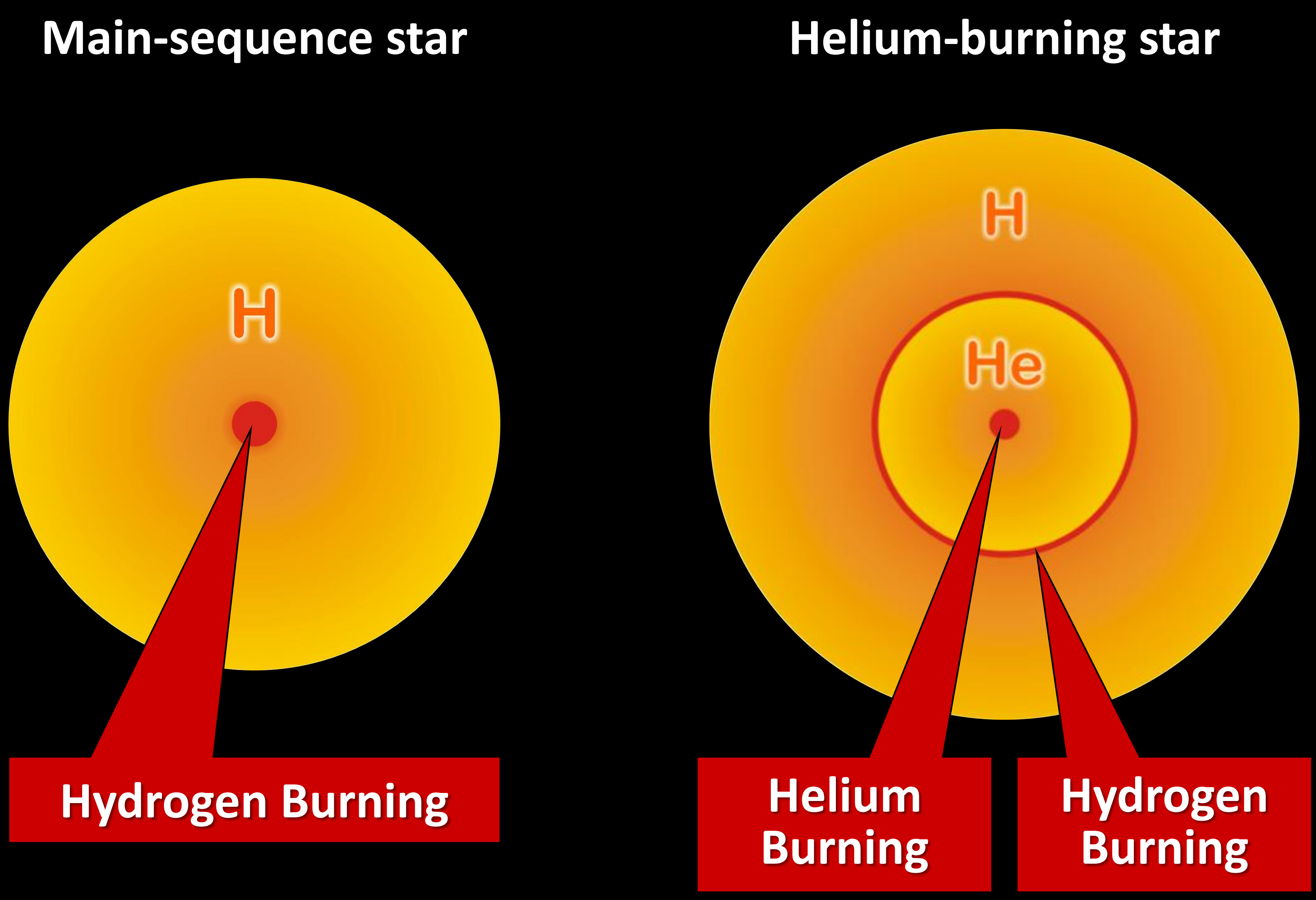
SN 1987A Rings (Hubble Space Telescope 4/1994)



SN 1987A Explosion Hits Inner Ring

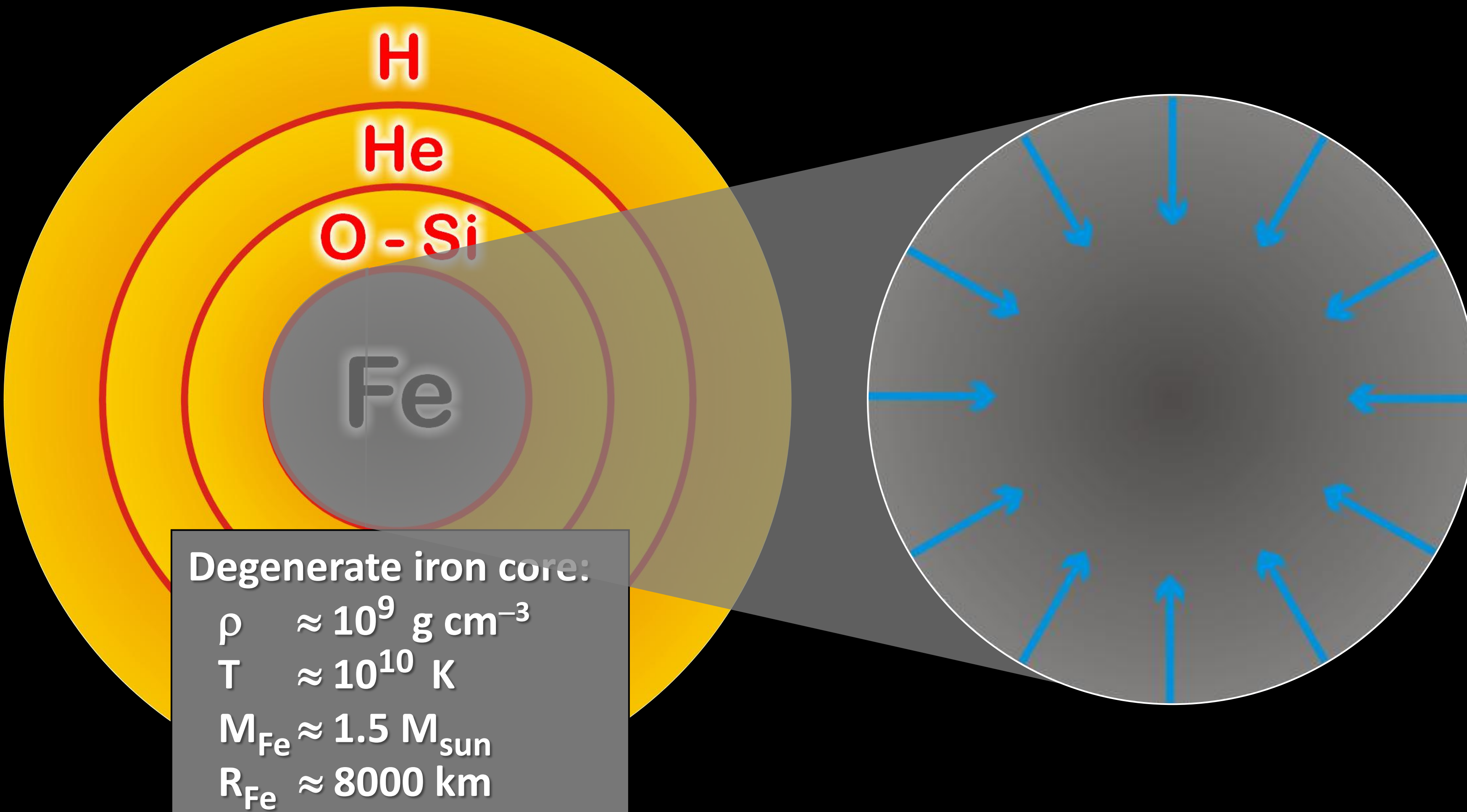


Stellar Collapse and Supernova Explosion



Stellar Collapse and Supernova Explosion

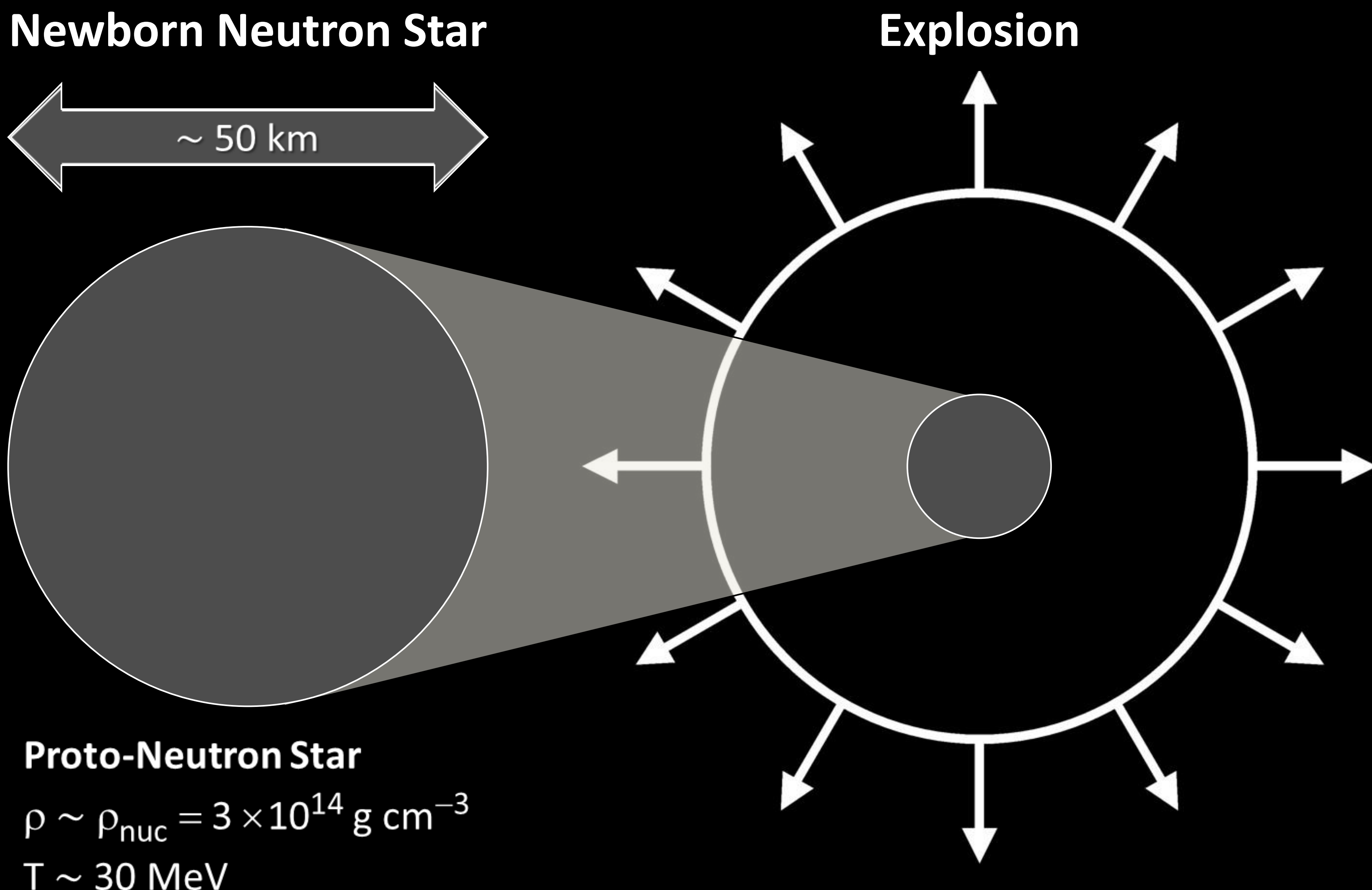
Onion structure | **Collapse (implosion)**



Degenerate iron core:

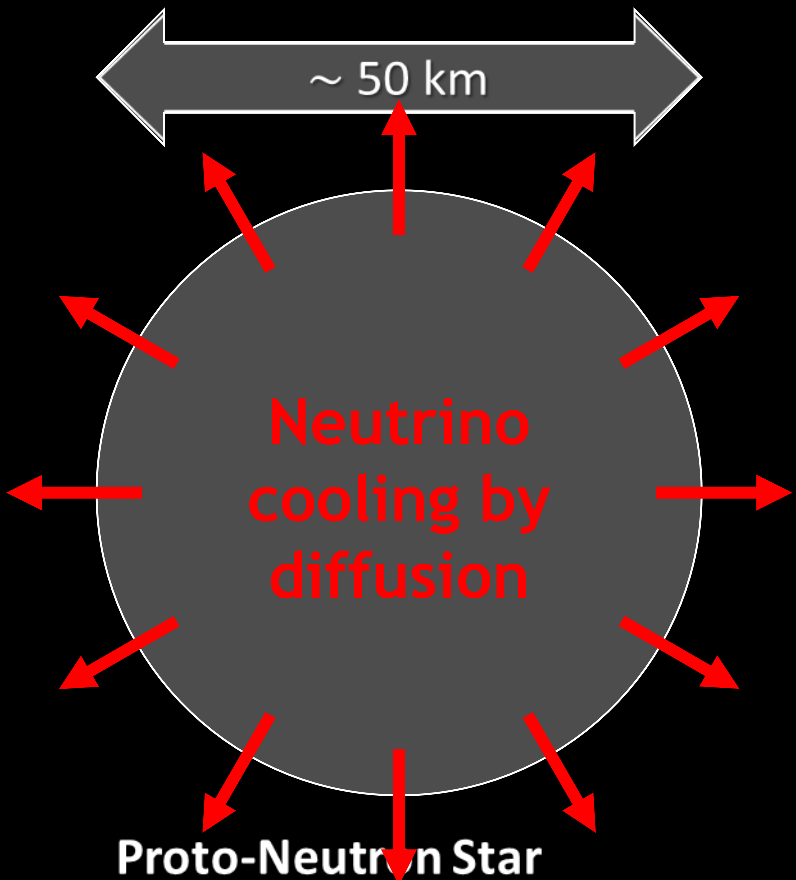
- $\rho \approx 10^9\ \mathrm{g\ cm^{-3}}$
- $T \approx 10^{10}\ \mathrm{K}$
- $M_{Fe} \approx 1.5\ M_{sun}$
- $R_{Fe} \approx 8000\ \mathrm{km}$

Stellar Collapse and Supernova Explosion



Stellar Collapse and Supernova Explosion

Newborn Neutron Star



Proto-Neutron Star

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

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

Gravitational binding energy

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

This shows up as

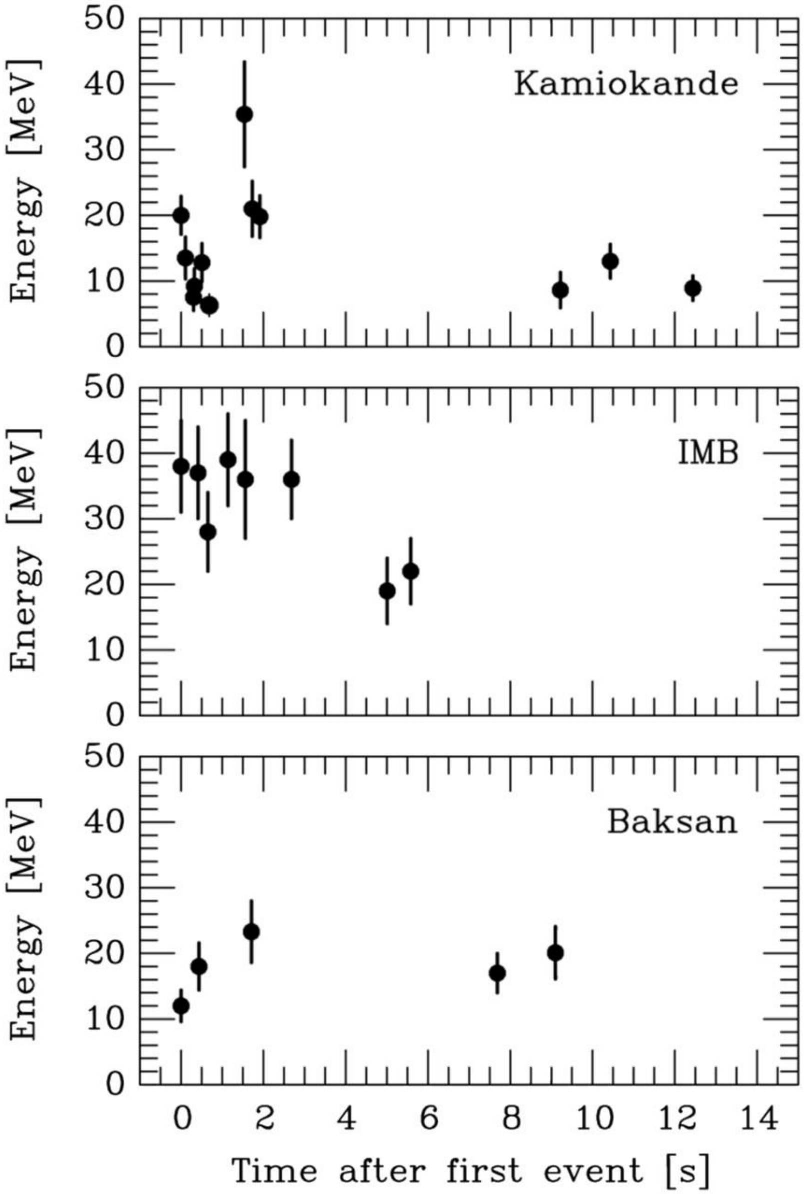
- 99% Neutrinos
- 1% Kinetic energy of explosion
- 0.01% Photons, outshine host galaxy

Neutrino luminosity

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

While it lasts, outshines the entire visible universe

Neutrino Signal of Supernova 1987A



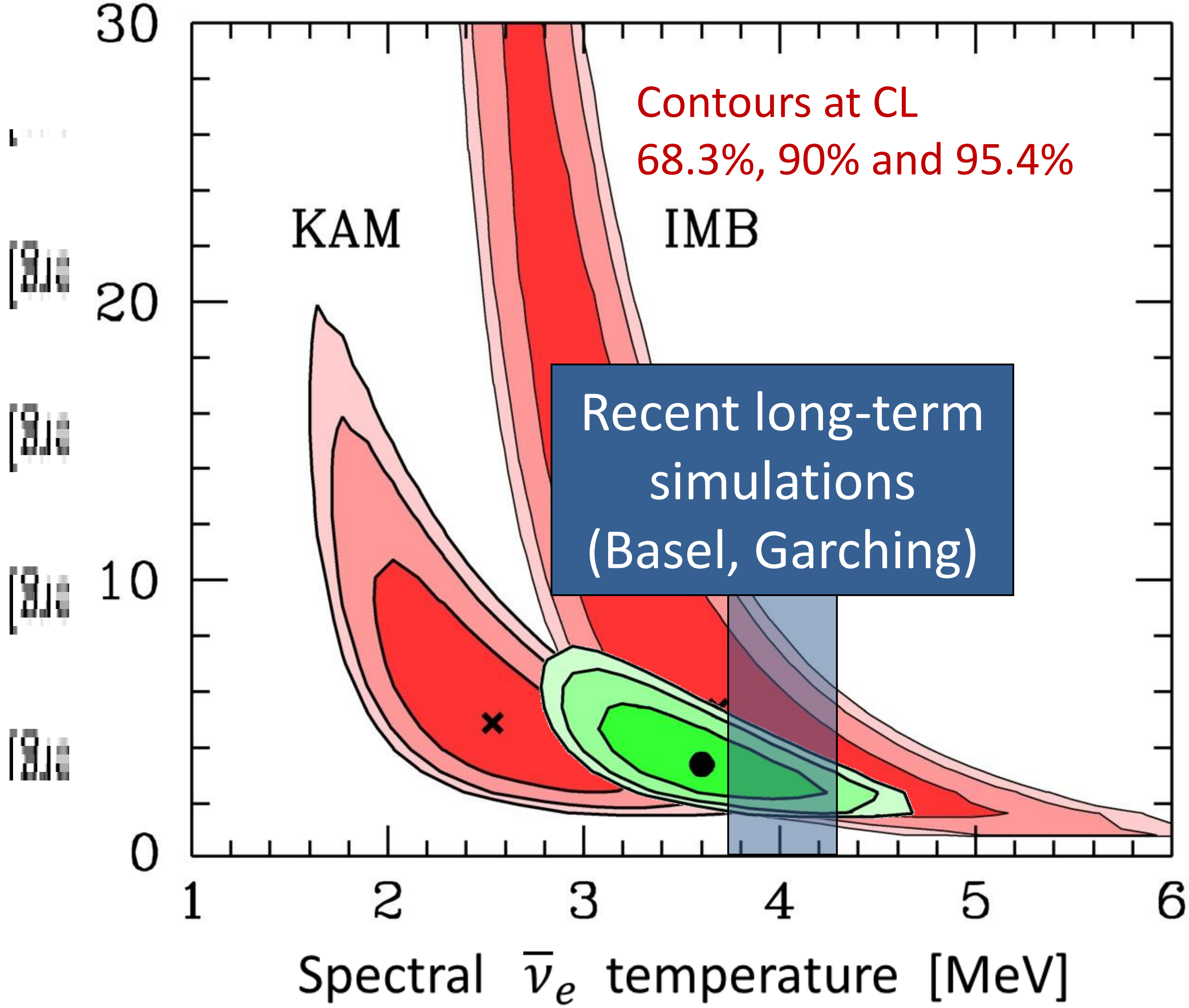
Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty $\pm$1 min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty $\pm$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



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

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.

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

M. SCHOENBERG*

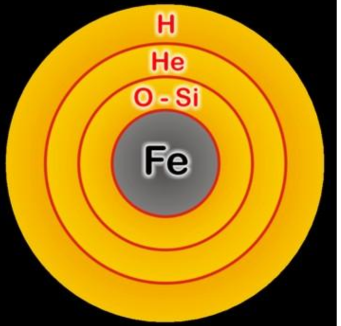
University of São Paulo,
São Paulo, Brazil,
November 23, 1940.

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

Phys. Rev. 58:1117 (1940)

Thermonuclear vs. Core-Collapse Supernovae

Thermo-nuclear (Type Ia)	Core collapse (Type II, Ib/c)
• Carbon-oxygen white dwarf (remnant of low-mass star) • Accretes matter from companion	• Degenerate iron core of evolved massive star • Accretes matter by nuclear burning at its surface



Chandrasekhar limit is reached — $M_{Ch} \approx 1.5\, M_{sun}\, (2Y_e)^2$

COLLAPSE SETS IN

Nuclear burning of C and O ignites → Nuclear deflagration ("Fusion bomb" triggered by collapse)	Collapse to nuclear density Bounce & shock Implosion → Explosion
Powered by nuclear binding energy	Powered by gravity
Gain of nuclear binding energy 1 MeV per nucleon	Gain of gravitational binding energy 100 MeV per nucleon 99% into neutrinos

Comparable "visible" energy release of $\sim 3 \times 10^{51}$ erg

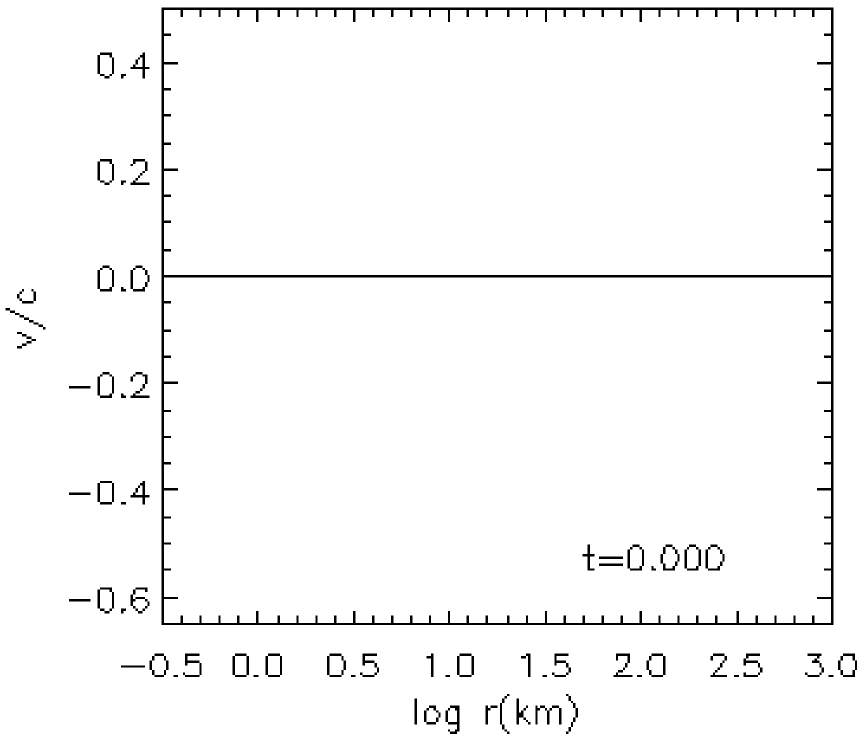
Spectral Classification of Supernovae

Spectral Type	Ia	Ib	Ic	II
Spectrum	No Hydrogen			Hydrogen
	Silicon	No Silicon		
		Helium	No Helium	
Physical Mechanism	Nuclear explosion of low-mass star	Core collapse of evolved massive star (may have lost its hydrogen or even helium envelope during red-giant evolution)		
Light Curve	Reproducible	Large variations		
Neutrinos	Insignificant	$\sim 100 \times$ Visible energy		
Compact Remnant	None	Neutron star (typically appears as pulsar) Sometimes black hole ?		
Rate / h^2 SNu	0.36 ± 0.11	0.14 ± 0.07		0.71 ± 0.34
Observed	Total $\sim$ 5600 as of 2011 (Asiago SN Catalogue)			

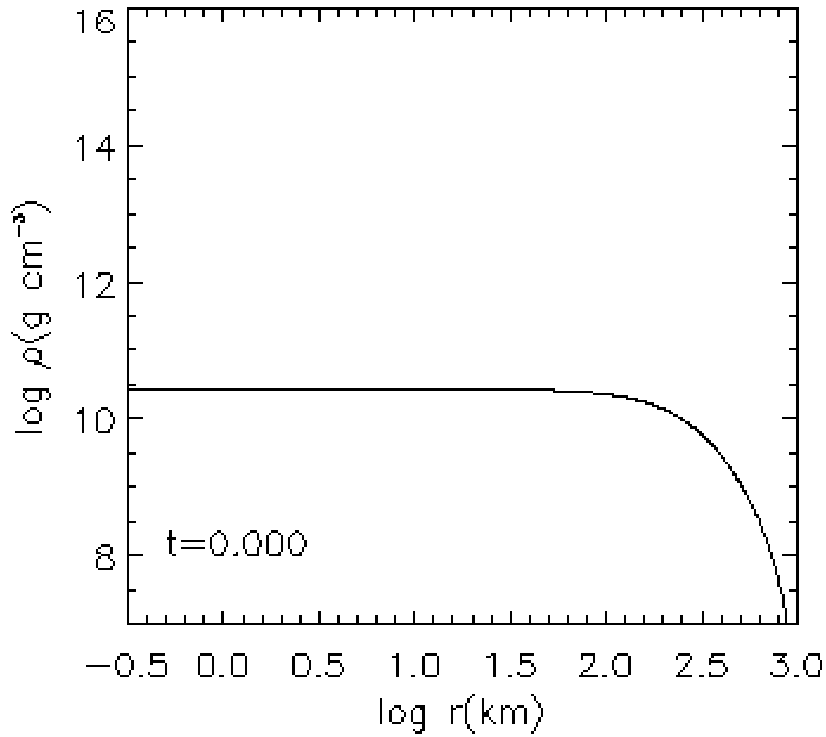
Explosion Mechanism

Collapse and Prompt Explosion

Velocity



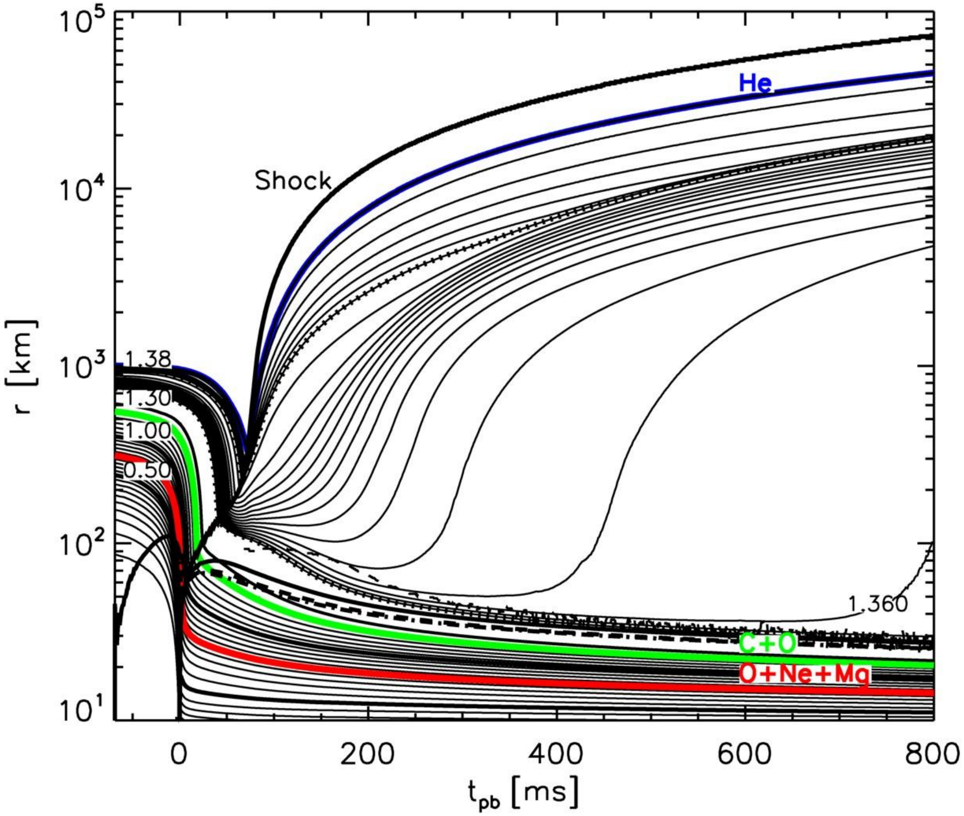
Density

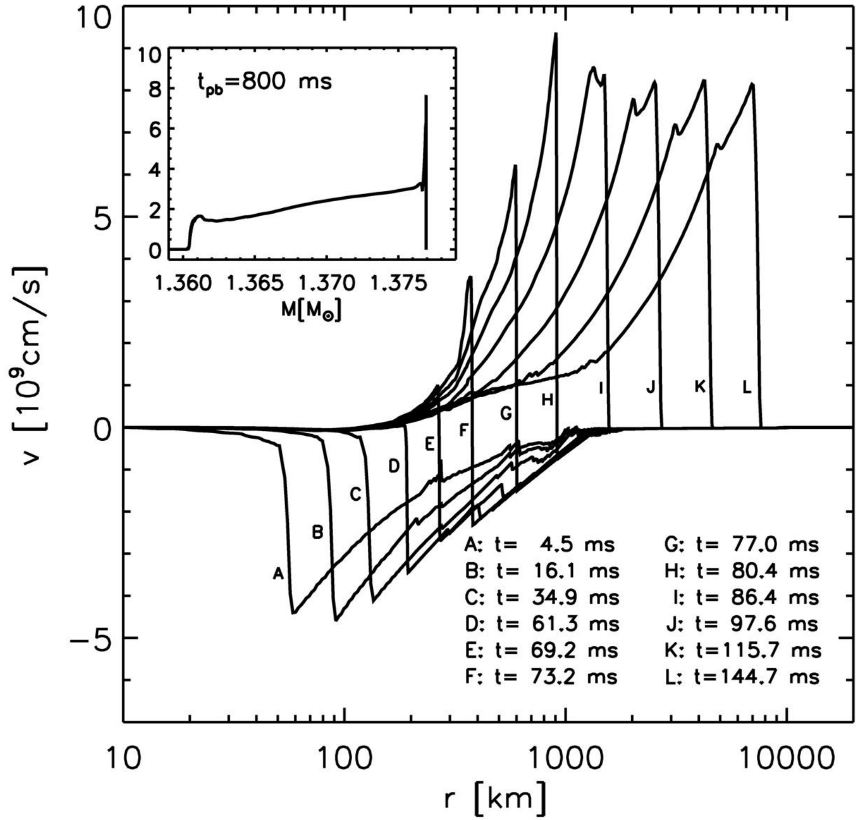


Movies by J.A.Font, Numerical Hydrodynamics in General Relativity
http://www.livingreviews.org

Supernova explosion is primarily a hydrodynamical phenomenon

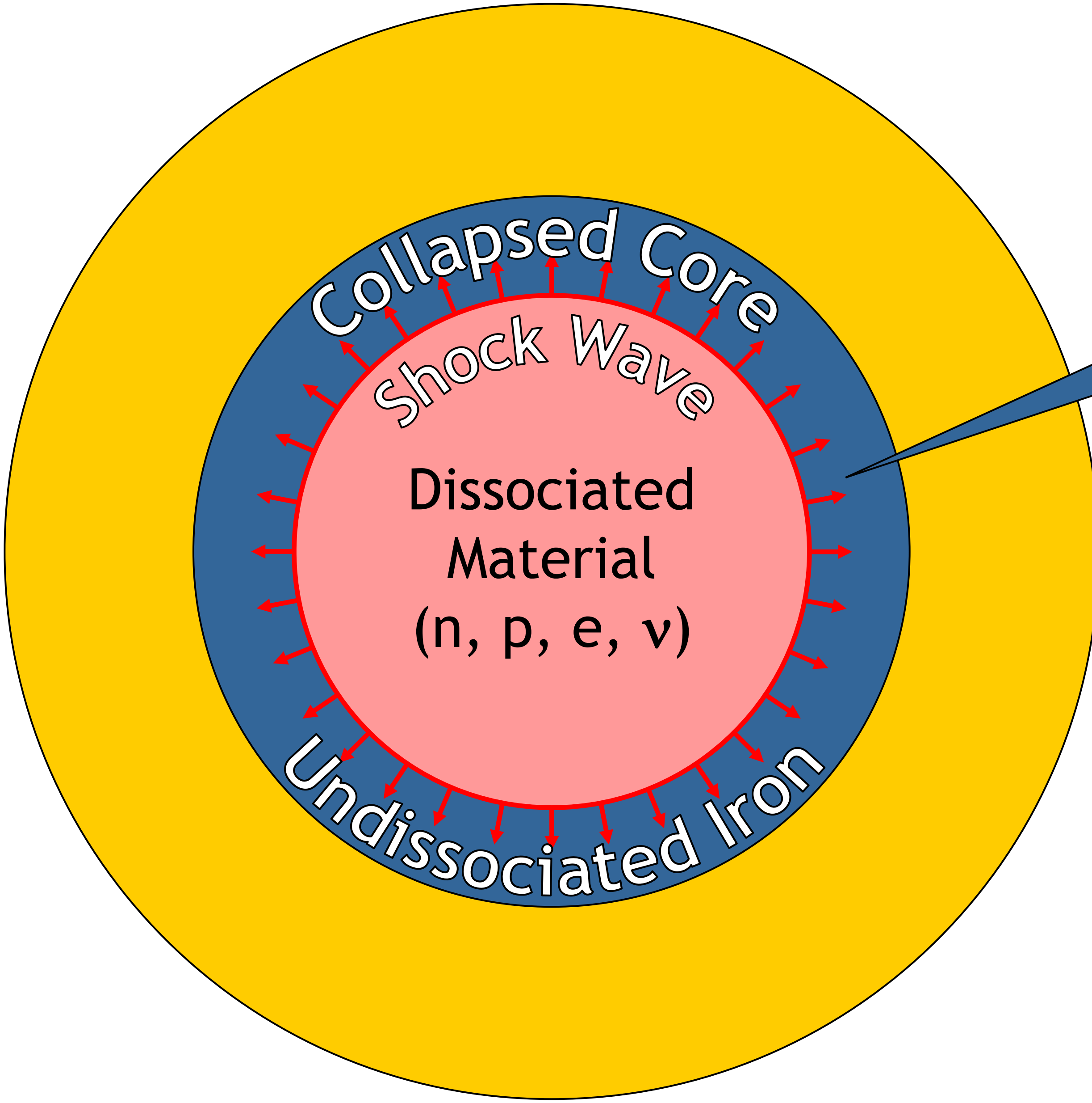
Exploding Models (8–10 Solar Masses) with O-Ne-Mg-Cores





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

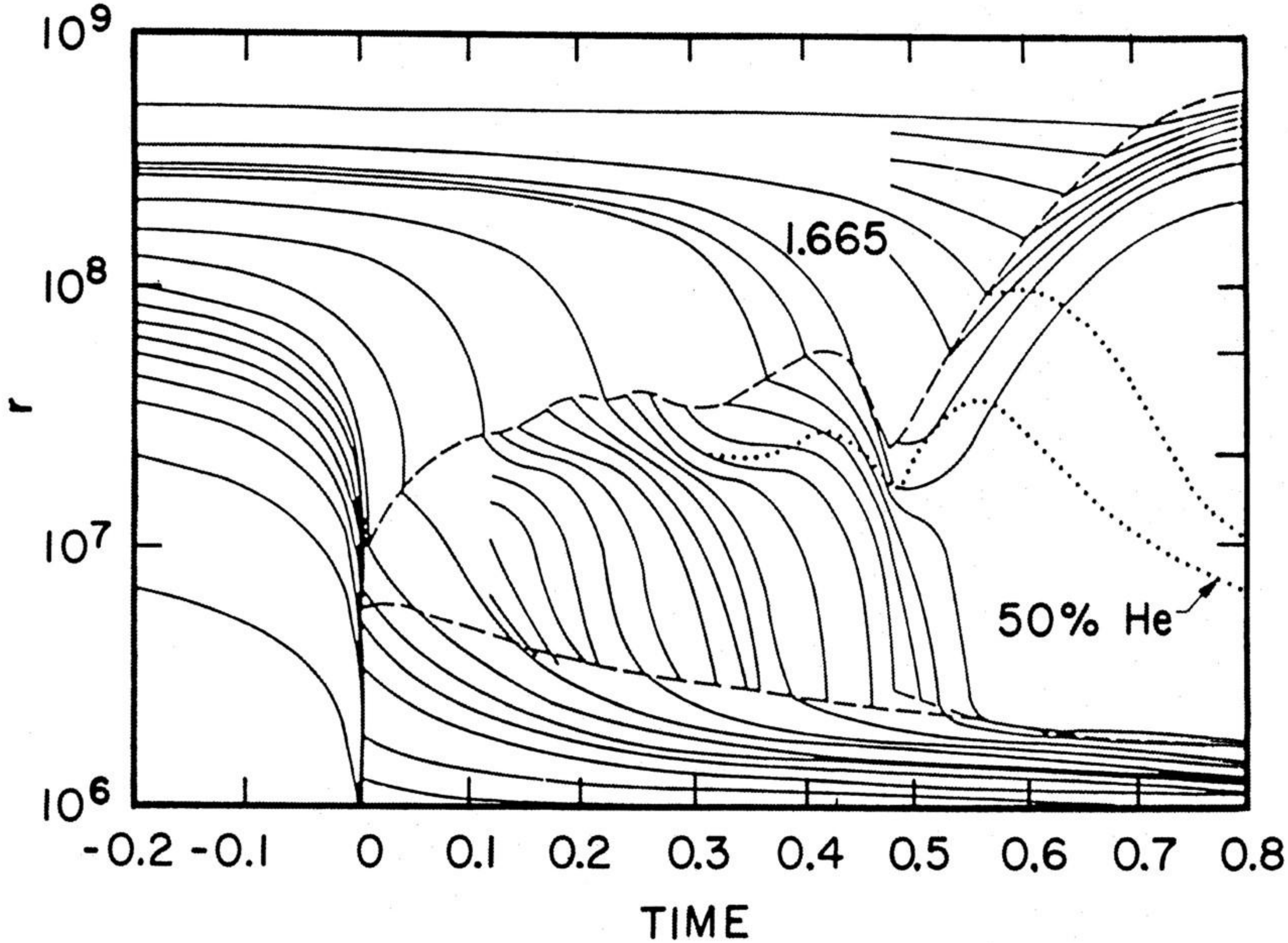
Why No Prompt Explosion?



- 0.1 M_{sun} of iron has a nuclear binding energy $\approx 1.7 \times 10^{51}$ erg
- Comparable to explosion energy

- **Shock wave forms within the iron core**
- **Dissipates its energy by dissociating the remaining layer of iron**

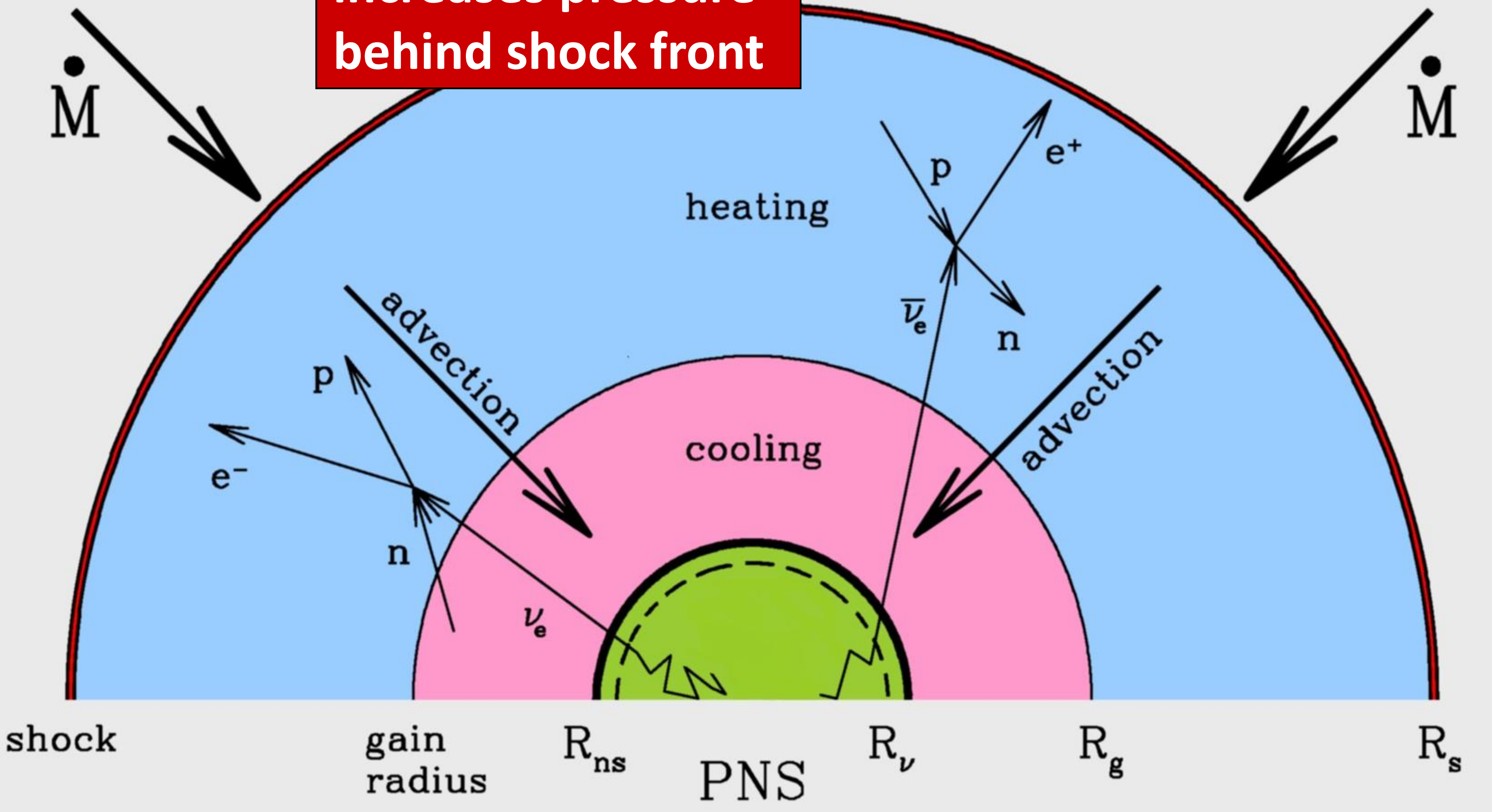
Delayed Explosion



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

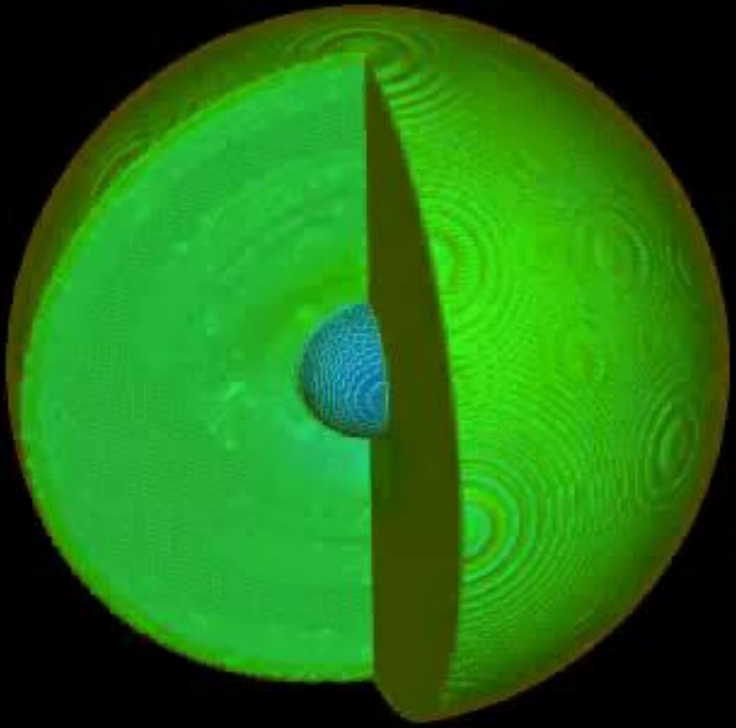
Neutrinos to the Rescue

Neutrino heating increases pressure behind shock front



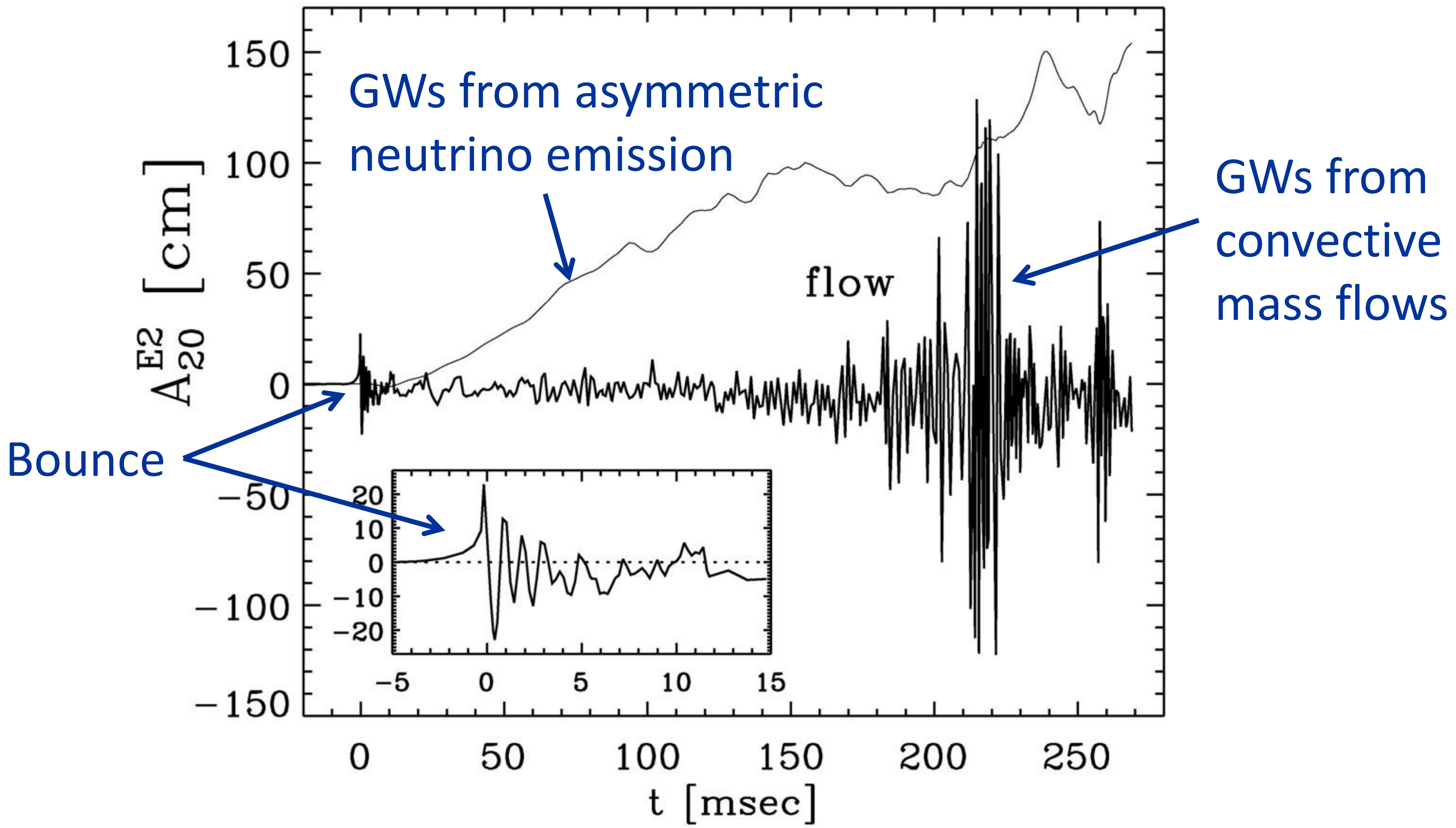
Picture adapted from Janka, astro-ph/0008432

Standing Accretion Shock Instability



Mezzacappa et al., http://www.phy.ornl.gov/tsi/pages/simulations.html

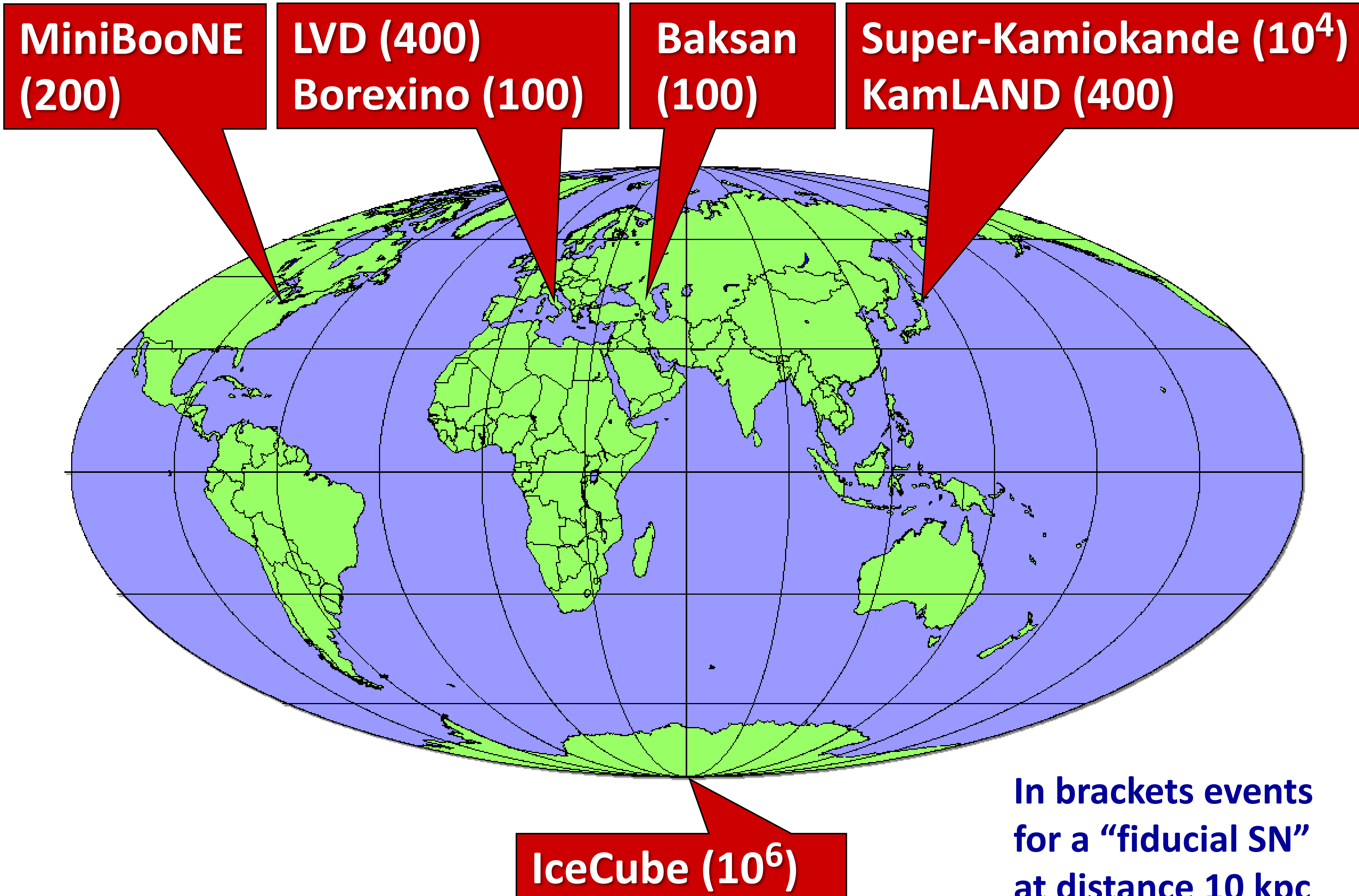
Gravitational Waves from Core-Collapse Supernovae



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

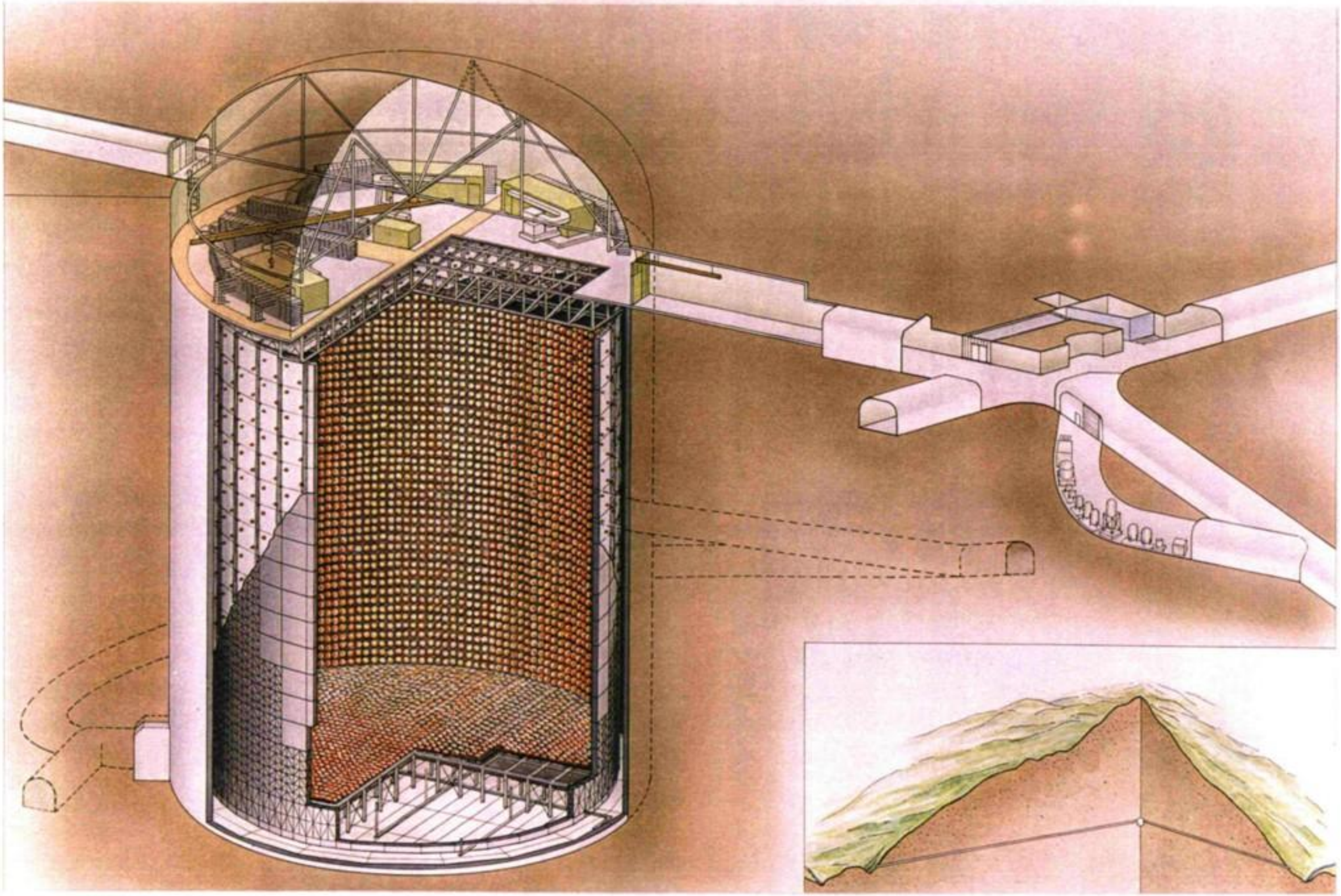
Neutrinos from Next Nearby SN

Operational Detectors for Supernova Neutrinos

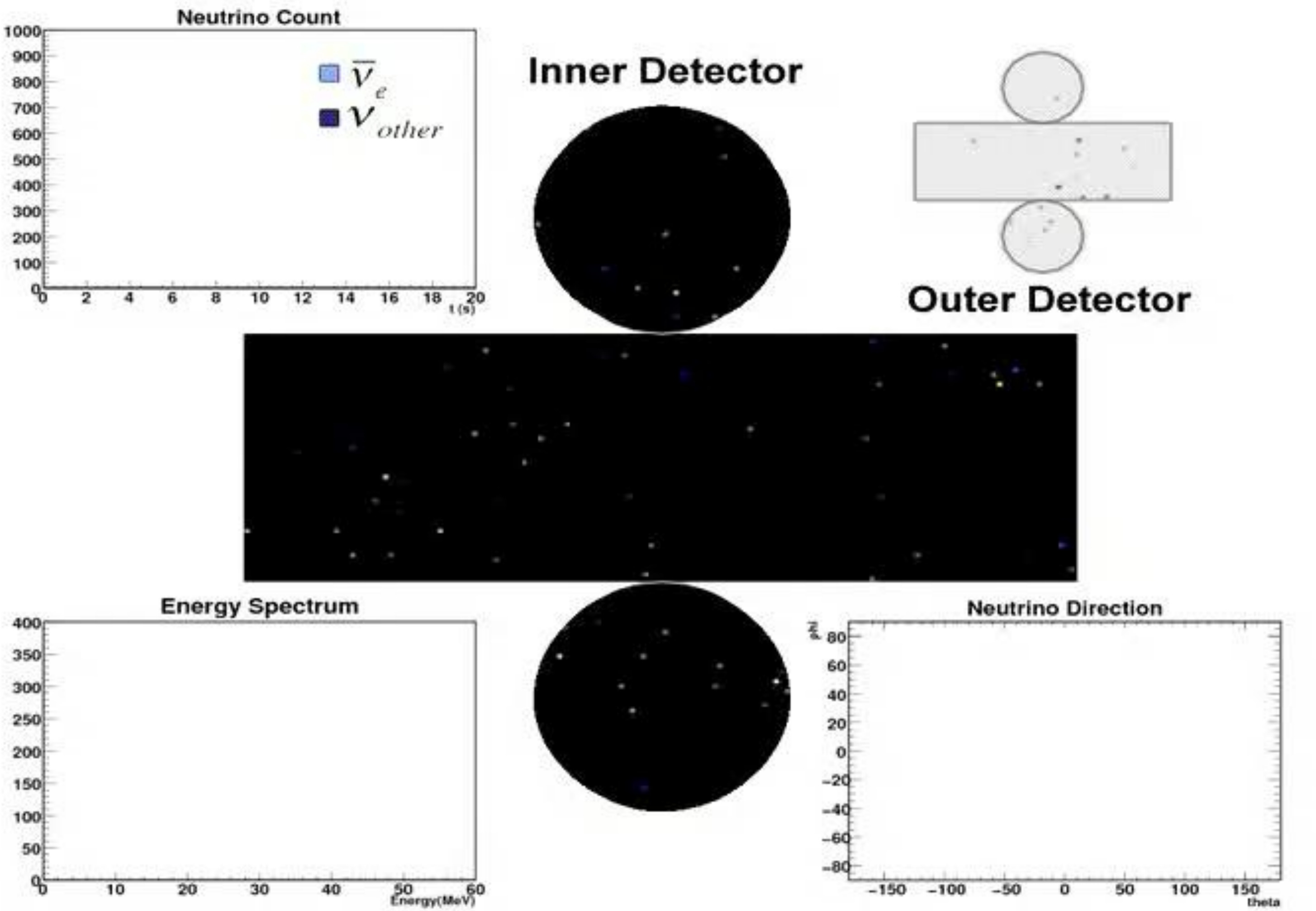


In brackets events for a “fiducial SN” at distance 10 kpc

Super-Kamiokande Neutrino Detector

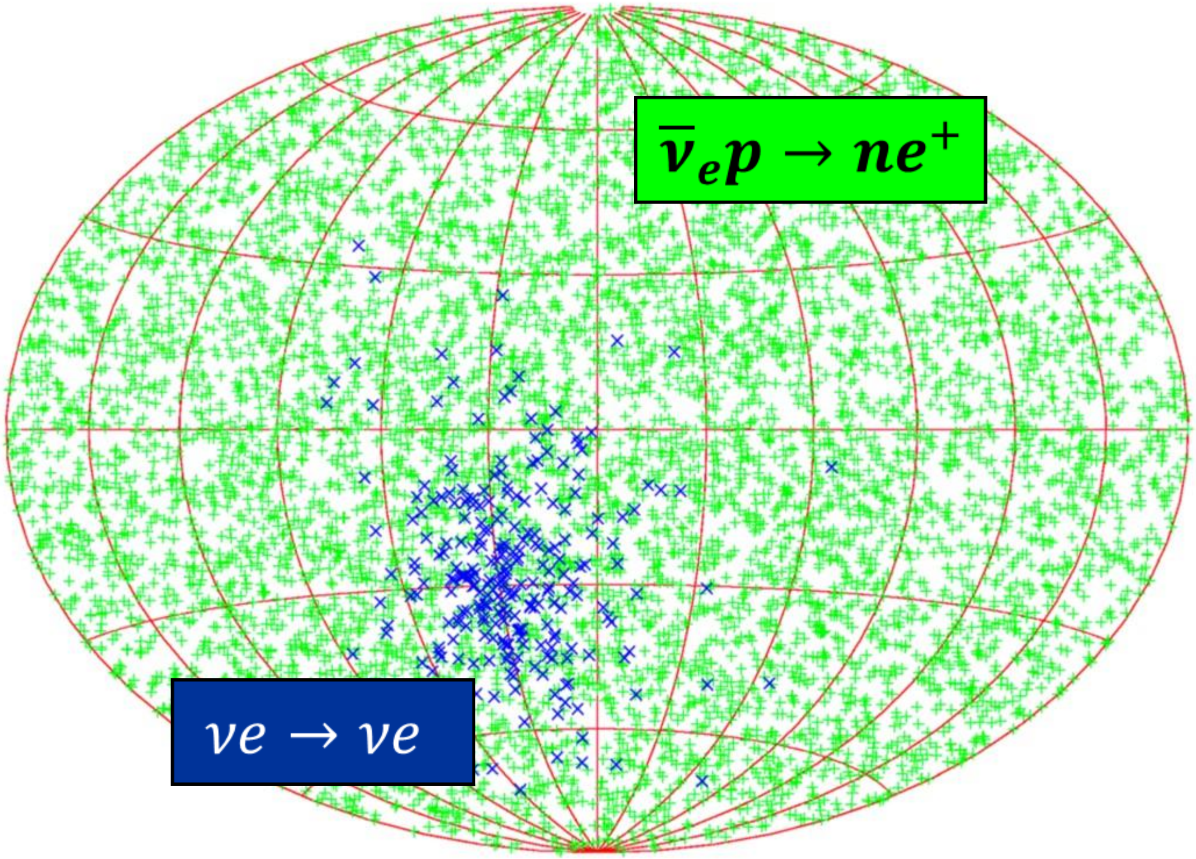


Simulated Supernova Burst in Super-Kamiokande



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

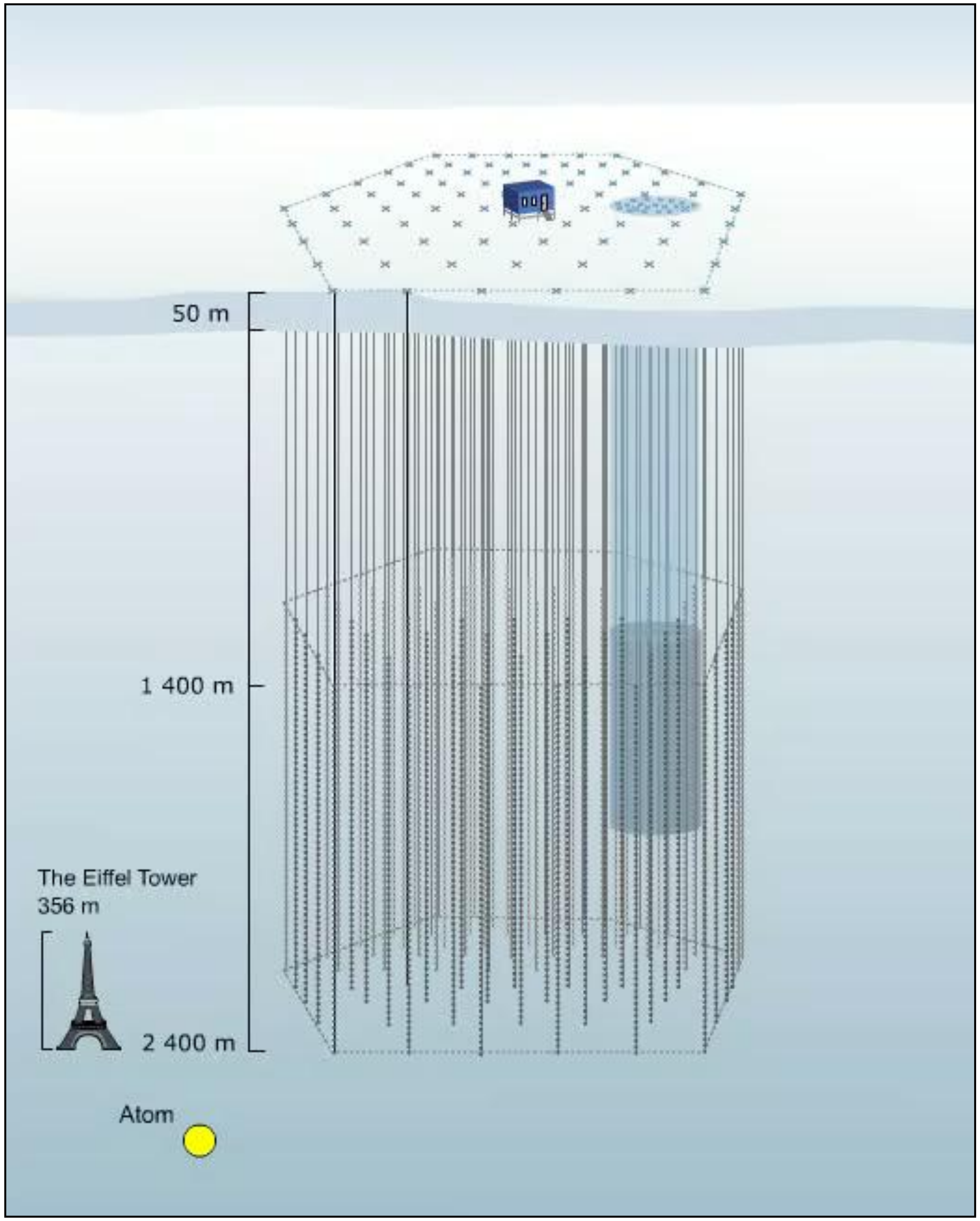
Supernova Pointing with Neutrinos



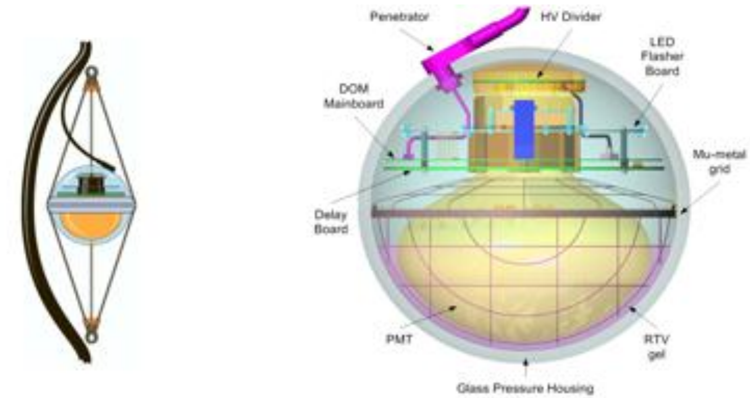
Neutron tagging efficiency		
None	90 %	
7.8°	3.2°	SK
1.4°	0.6°	SK × 30
95% CL half-cone opening angle		

- Beacom & Vogel: Can a supernova be located by its neutrinos? [astro-ph/9811350]
- Tomàs, Semikoz, Raffelt, Kachelriess & Dighe: Supernova pointing with low- and high-energy neutrino detectors [hep-ph/0307050]

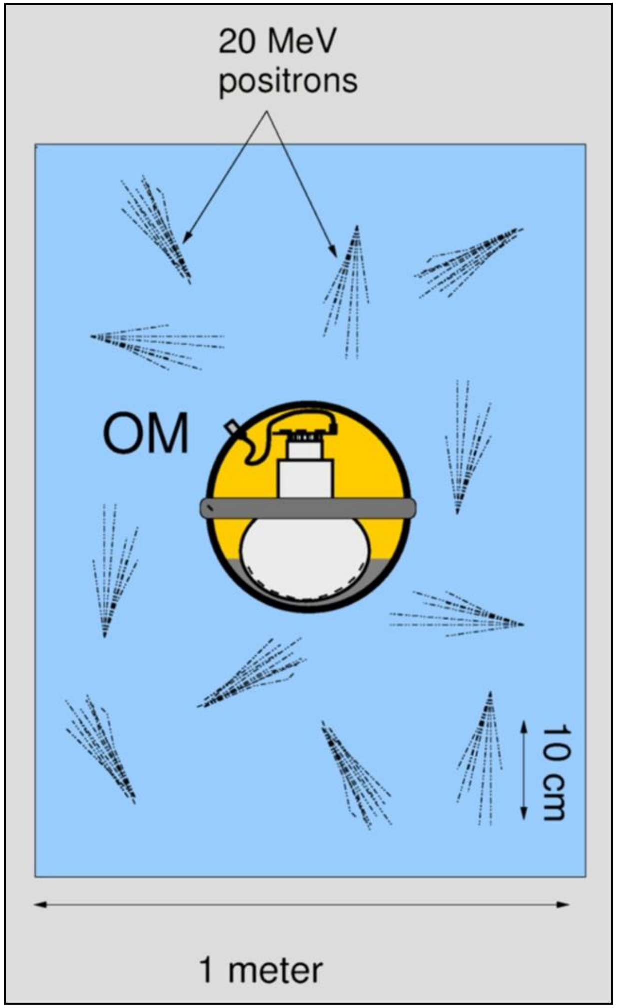
IceCube Neutrino Telescope at the South Pole



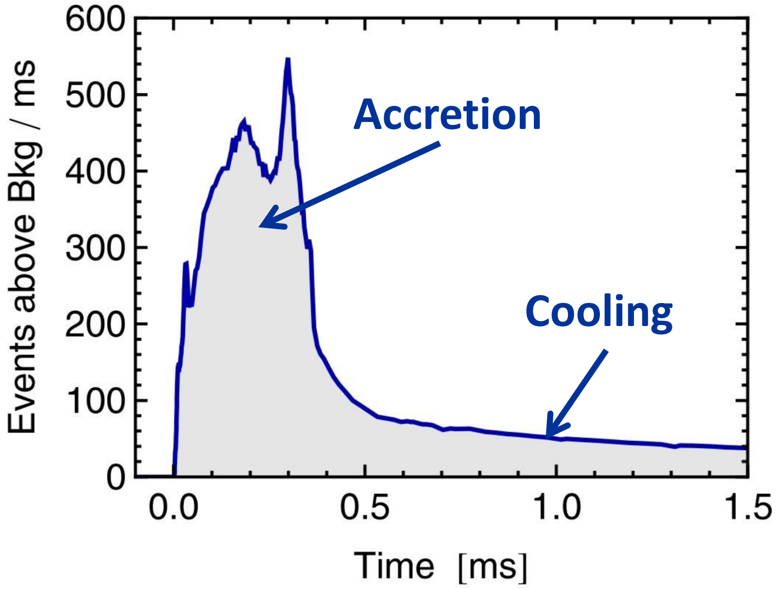
Instrumentation of 1 km^3 antarctic ice with ~ 5000 photo multipliers completed December 2010



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

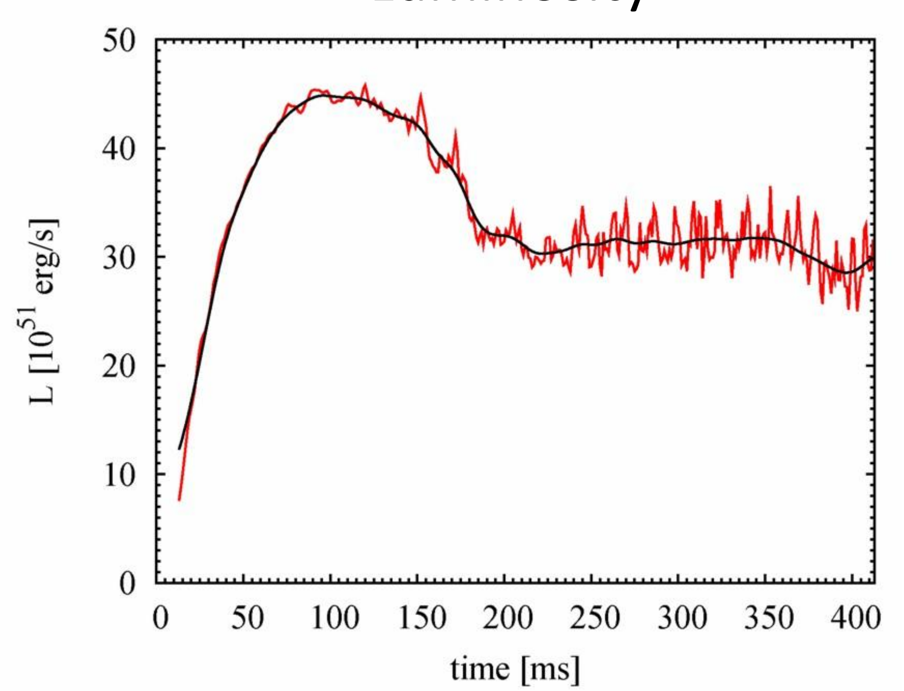


SN signal at 10 kpc
10.8 M_{sun} simulation of Basel group
[arXiv:0908.1871]

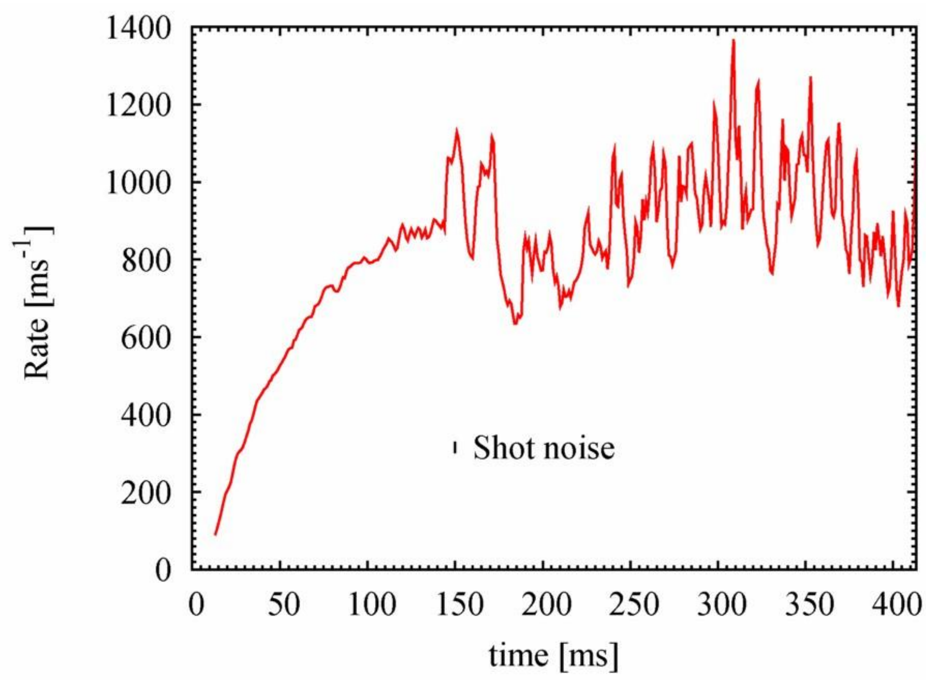
Pryor, Roos & Webster (ApJ 329:355, 1988), Halzen, Jacobsen & Zas (astro-ph/9512080)

Variability seen in Neutrinos

Luminosity



Detection rate in IceCube



Could be smaller in realistic 3D models

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

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

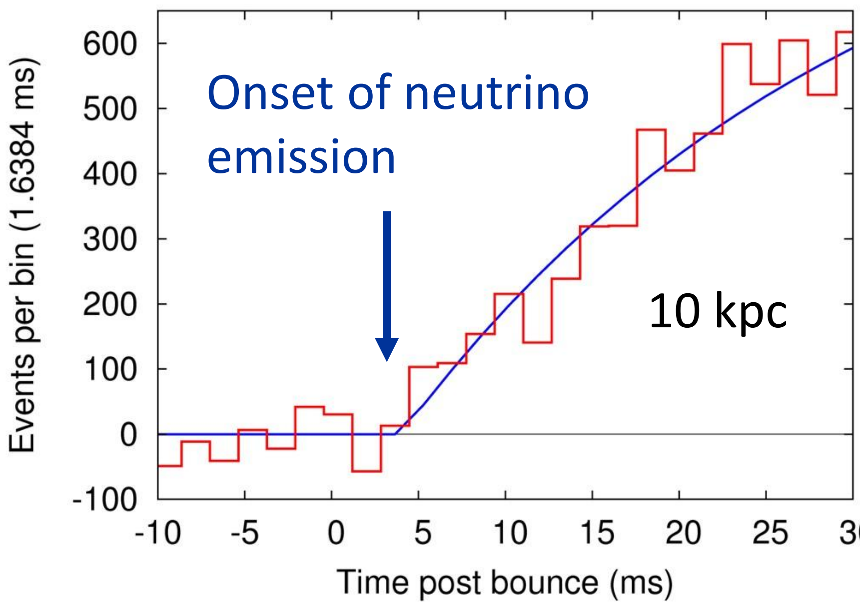
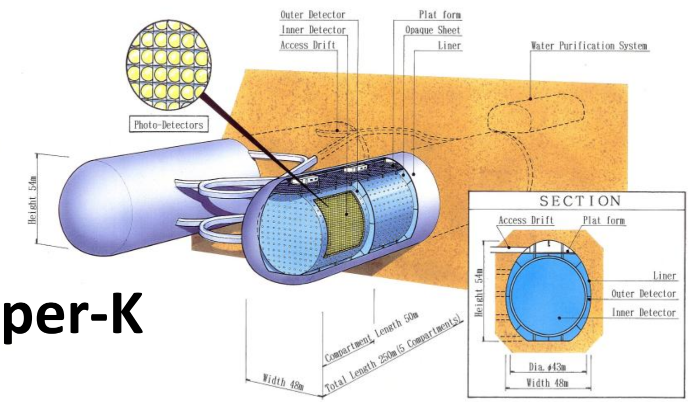


FIG. 1: Typical Monte Carlo realization (red histogram) and reconstructed fit (blue line) for the benchmark case discussed in the text for a SN at 10 kpc.

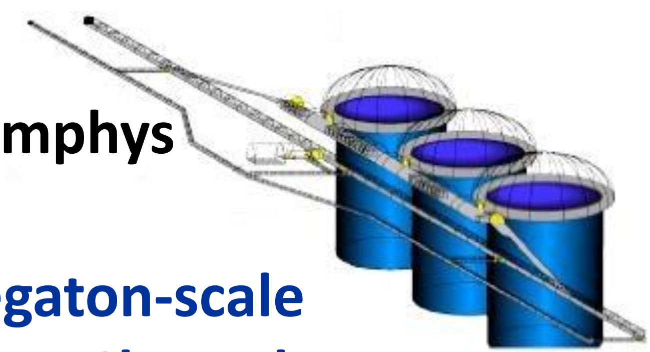
Halzen & Raffelt, arXiv:0908.2317

Next Generation Large-Scale Detector Concepts

DUSEL
LBNE



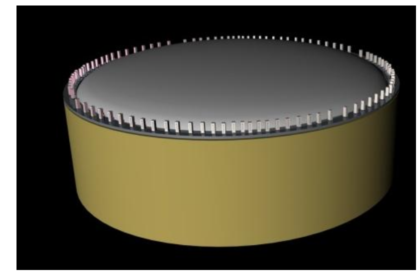
Hyper-K

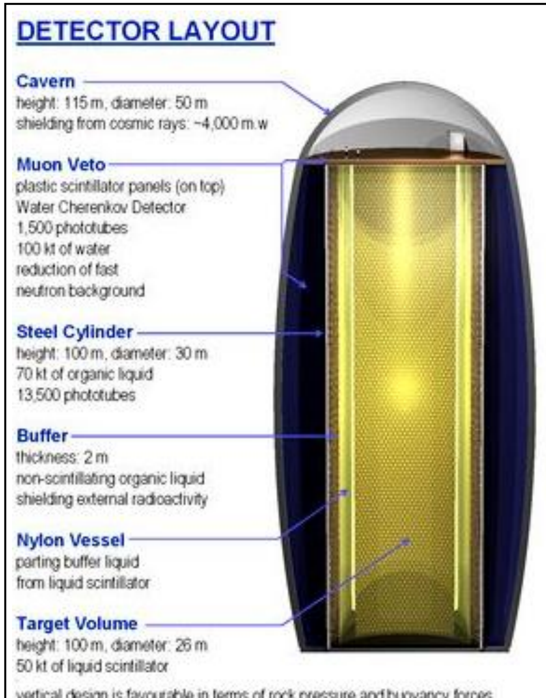


Memphys

Megaton-scale water Cherenkov

5-100 kton liquid Argon



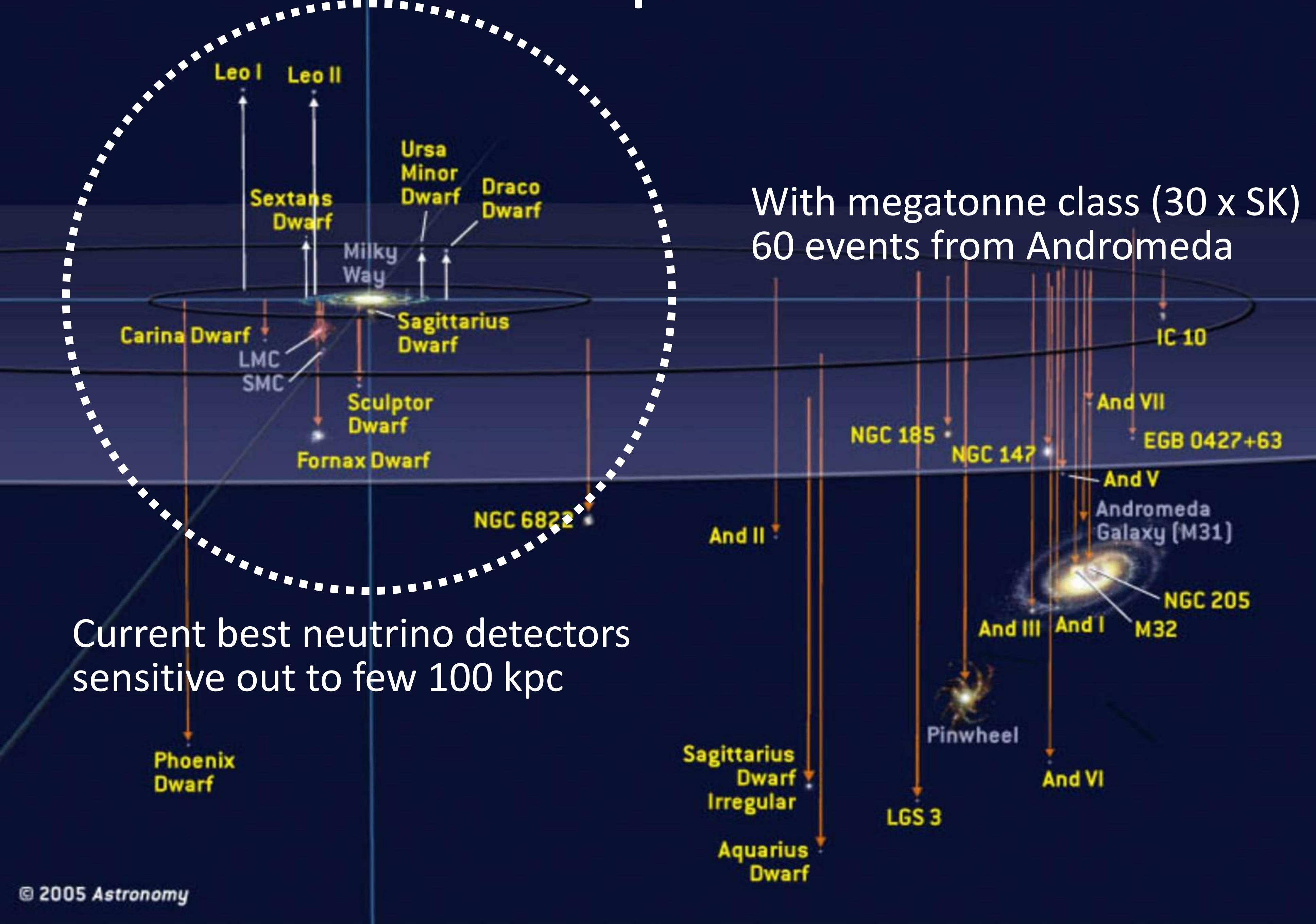


100 kton scale scintillator

LENA
HanoHano

Supernova Rate

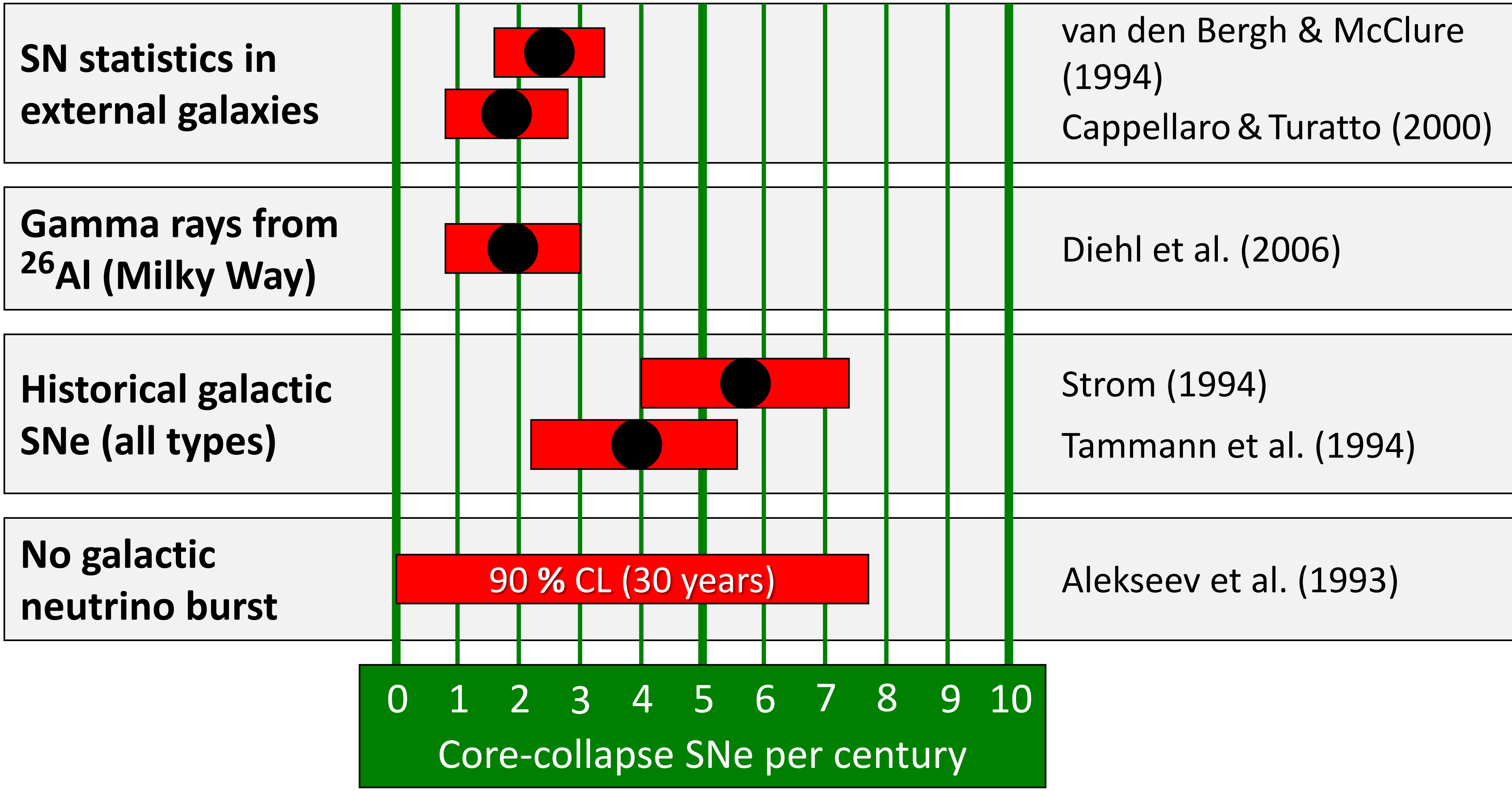
Local Group of Galaxies



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

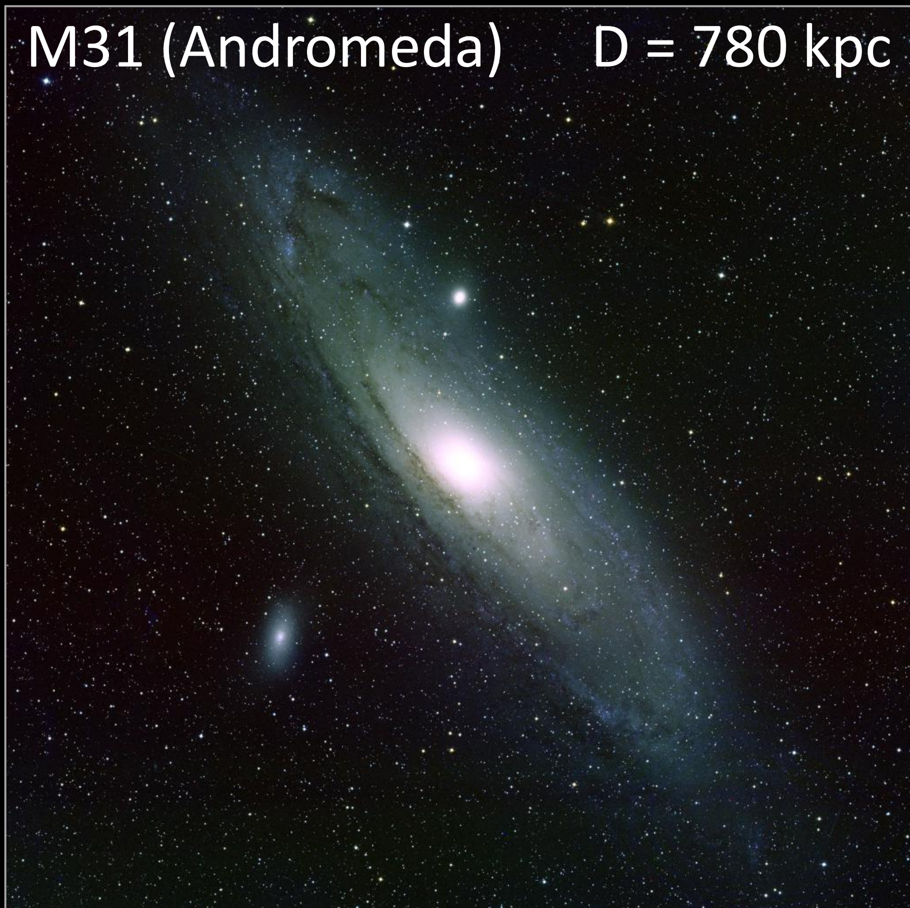
Current best neutrino detectors
sensitive out to few 100 kpc

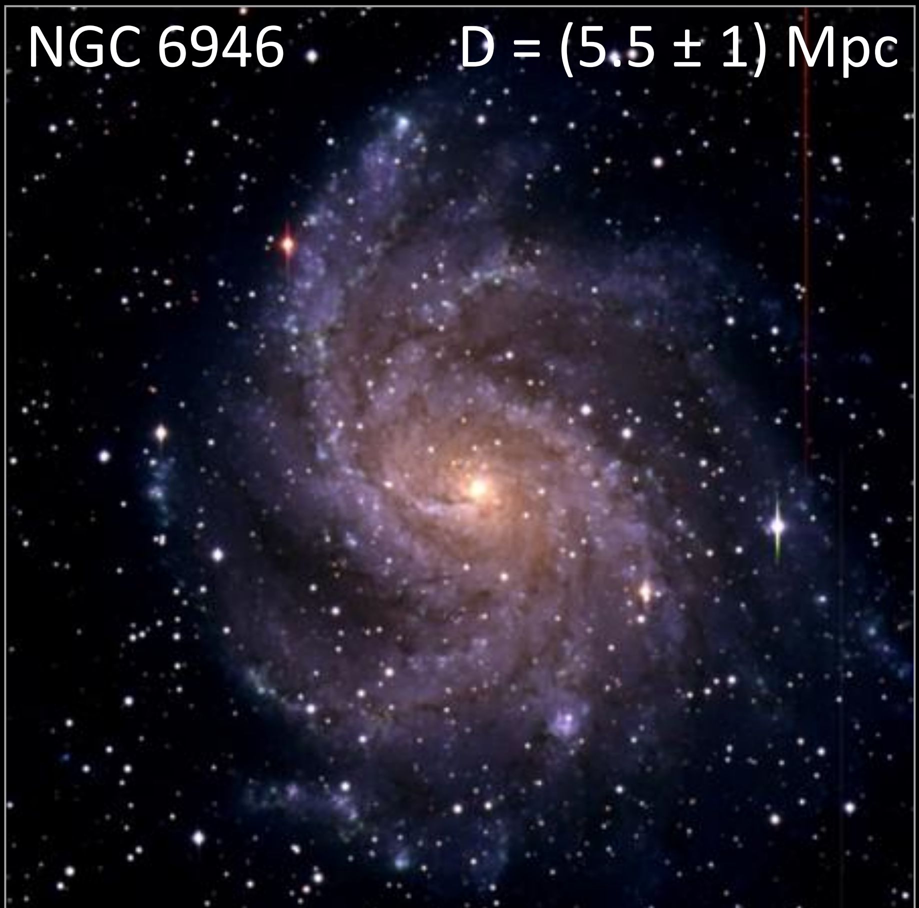
Core-Collapse SN Rate in the Milky Way



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

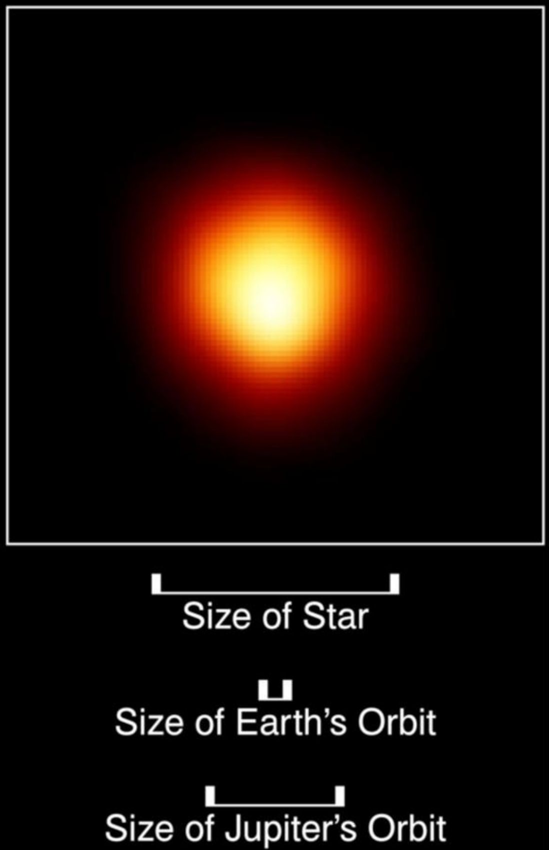


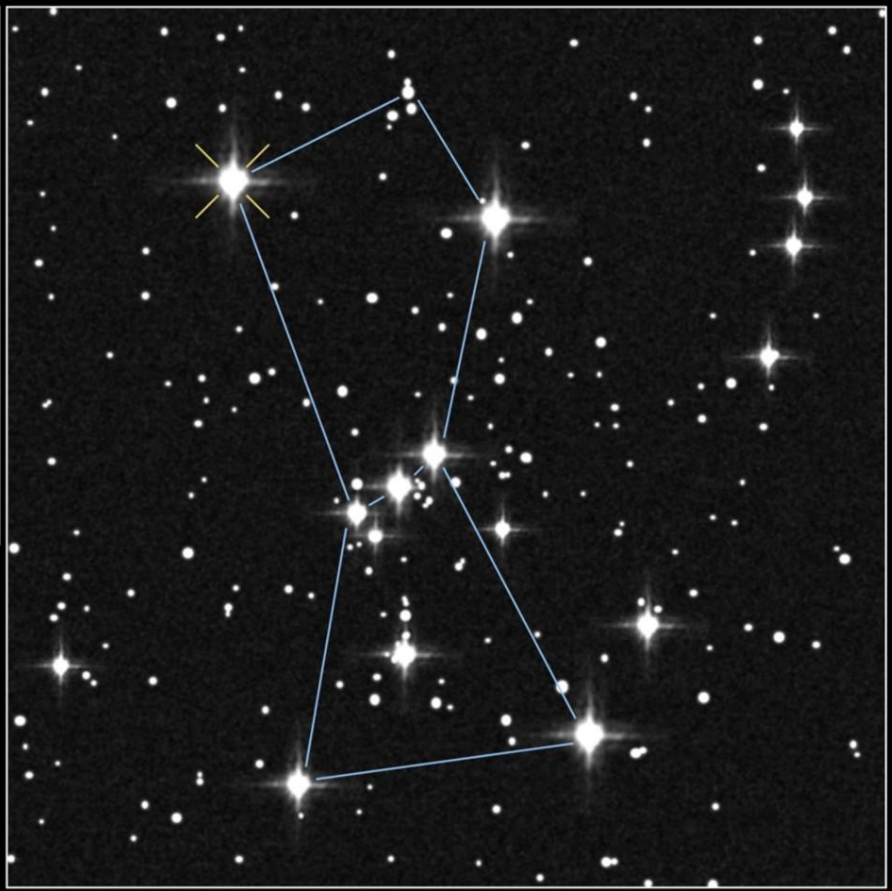


Last Observed Supernova: 1885A

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

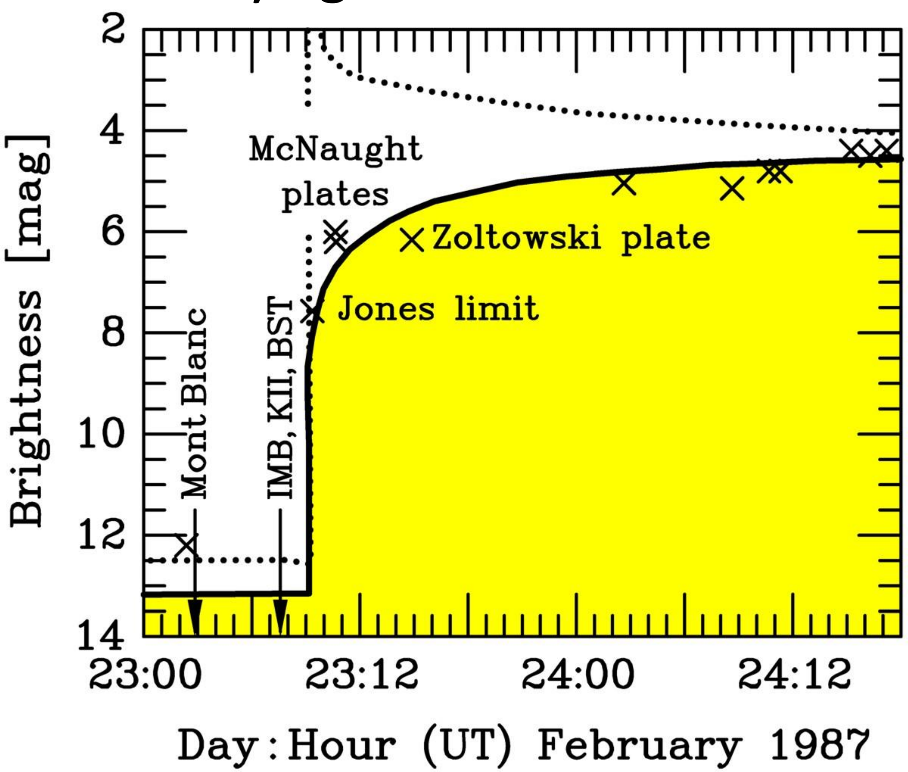
Distance (Hipparcos) 130 pc (425 lyr)

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]

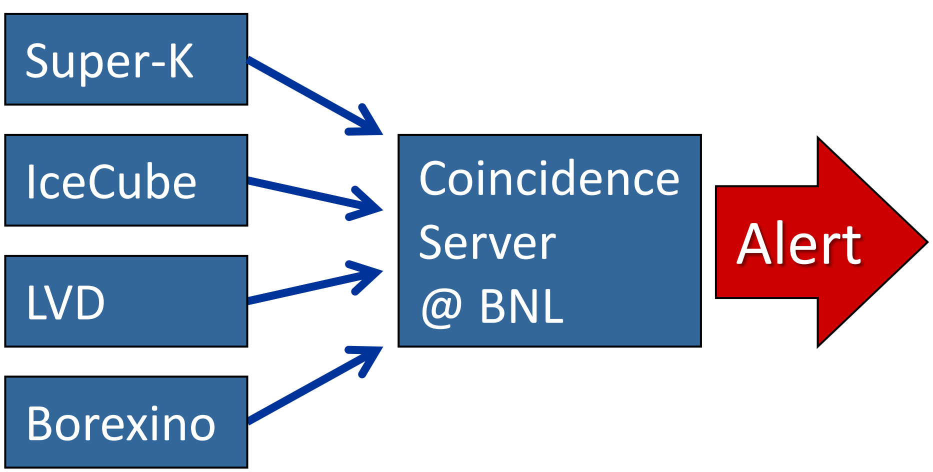
SuperNova Early Warning System (SNEWS)

Early light curve of SN 1987A



http://snews.bnl.gov

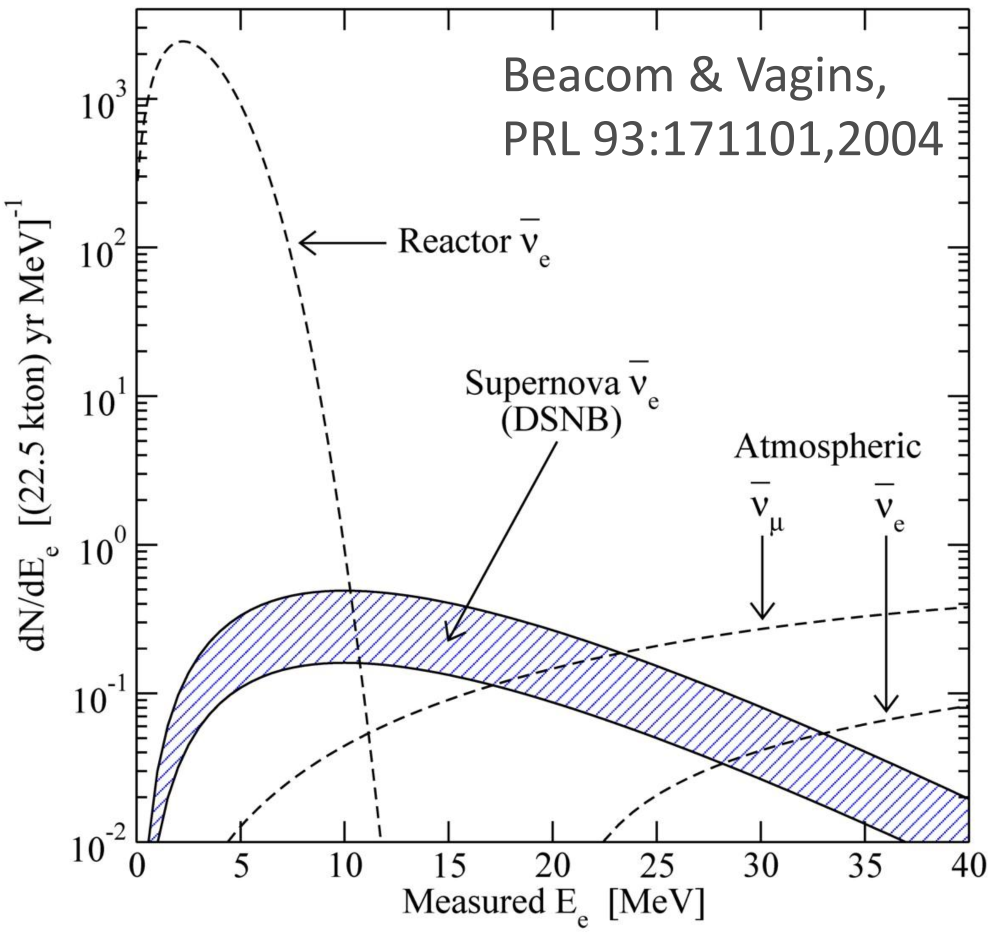
- Neutrinos arrive several hours before photons
- Can alert astronomers several hours in advance



Diffuse SN Neutrino Background

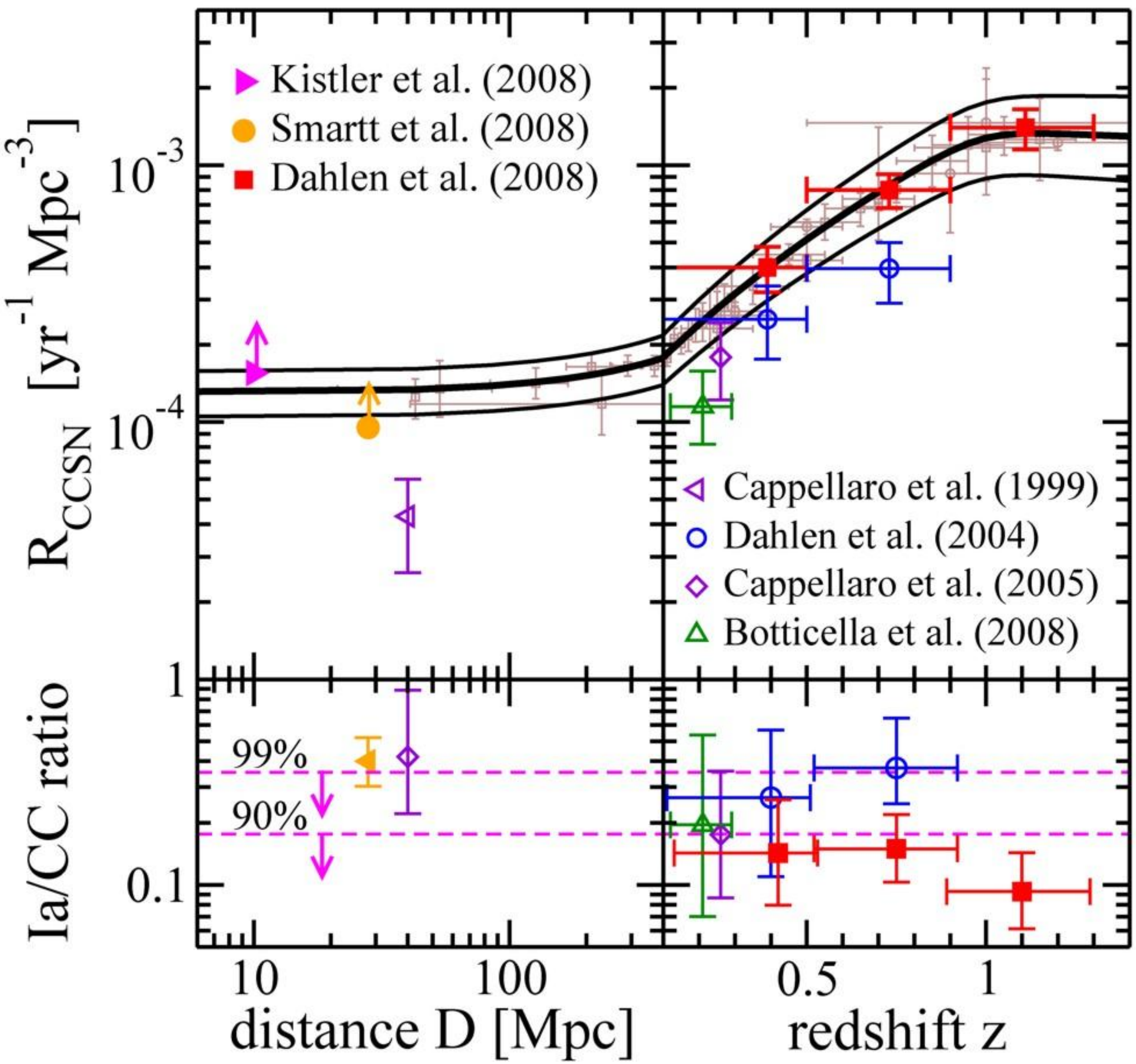
Diffuse Supernova Neutrino Background (DSNB)

- Approx. 10 core collapses/sec in the visible universe
- Emitted ν energy density
  ~ extra galactic background light
  ~ 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

Realistic DSNB Estimate

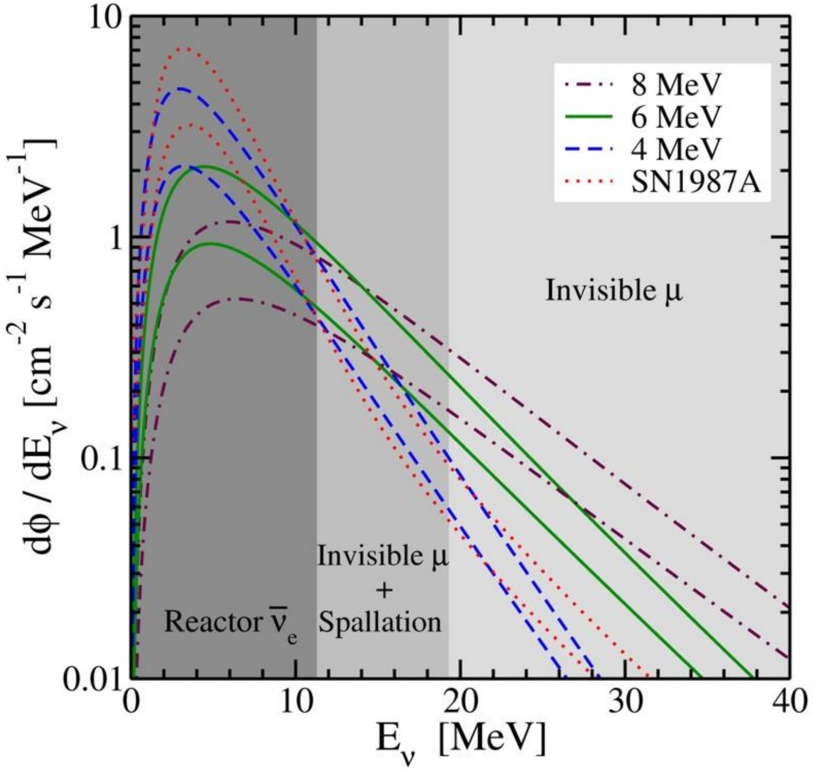


FIG. 4: DSNB flux spectrum for emitted neutrino spectra as labeled. For each spectrum, two curves are plotted representing the full range of uncertainties due to astrophysical inputs (the fiducial prediction lies in between). The shadings indicate backgrounds, with origins as labeled. Decays of invisible muons and spallation products would be reduced in a gadolinium-enhanced SK, opening the energy region 10 MeV and above to a rate-limited DSNB search; see Fig. 5.

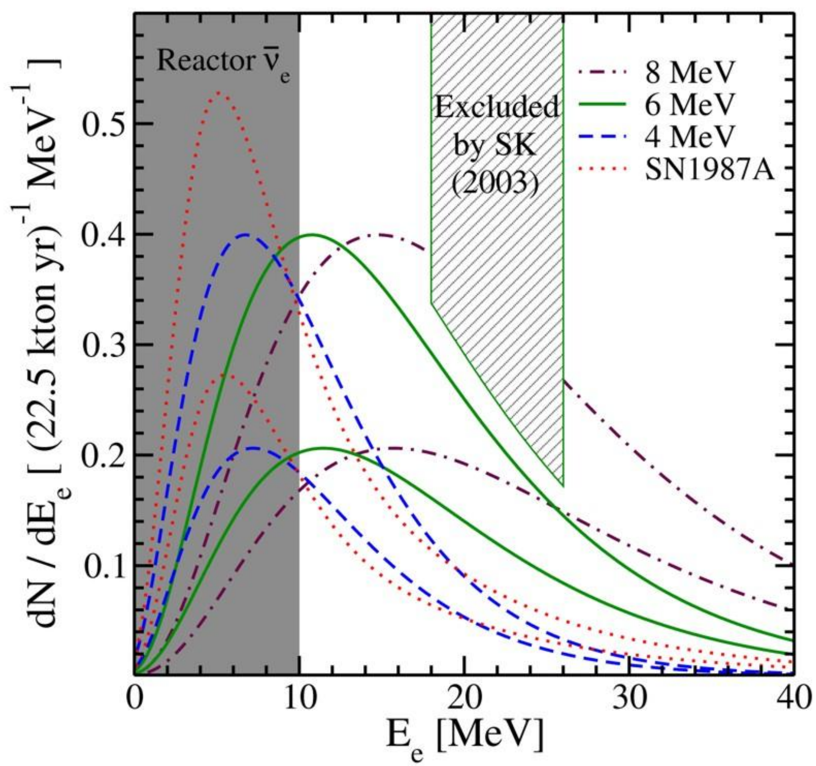


FIG. 5: DSNB event rates at SK (flux spectra weighted with the detection cross section) against positron energy. Note the linear axis. We hatch in the 2003 upper limit by the Super-Kamiokande Collaboration, < 2 events $(22.5 \text{ kton yr})^{-1}$ in the energy range 18–26 MeV. The limit applies to all spectra (see text). In a gadolinium-enhanced SK, decays of invisible muon and spallation products would be reduced, opening up the energy range $\gtrsim 10$ MeV for DSNB search (unshaded region).

Horiuchi, Beacom & Dwek, arXiv:0812.3157v3

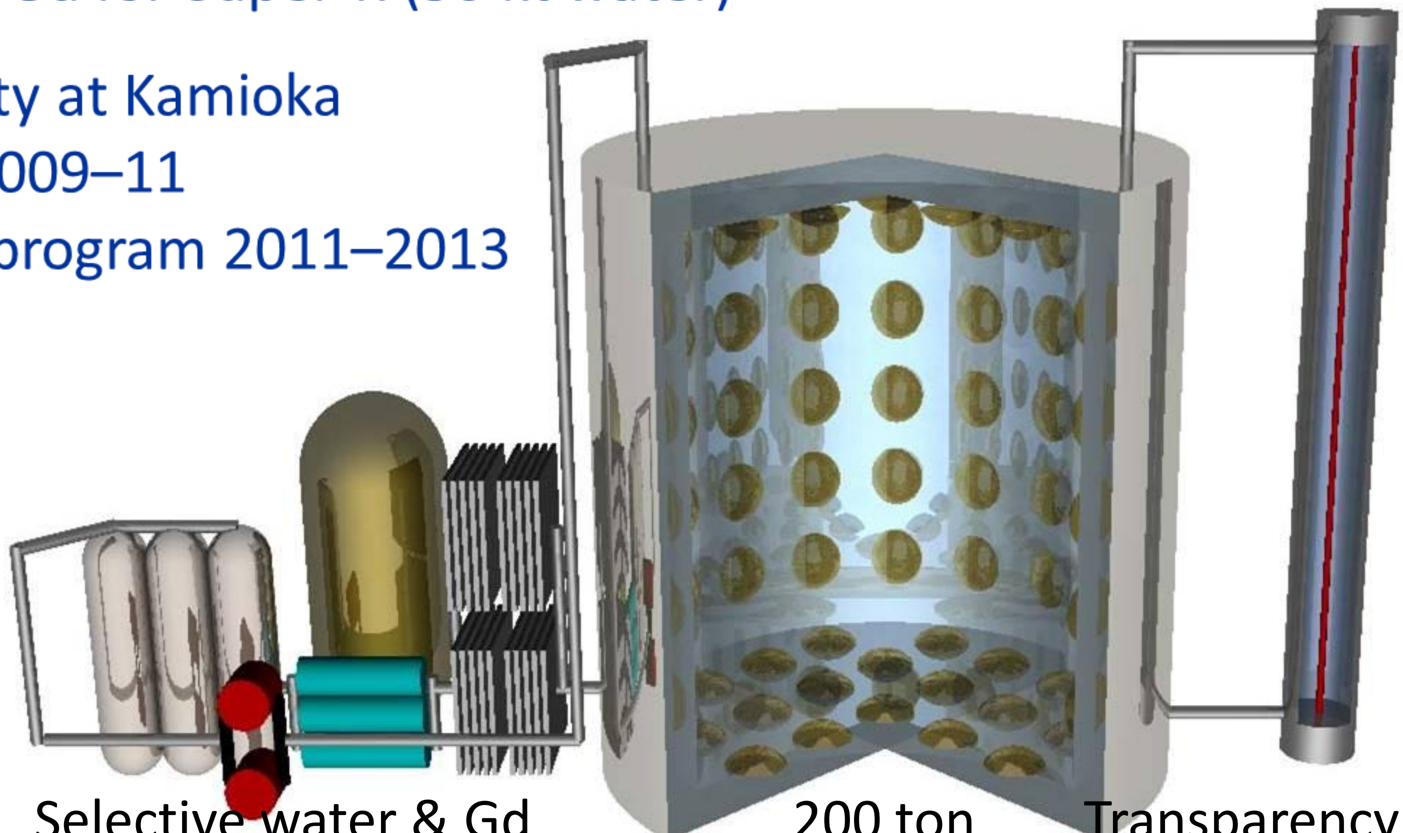
Neutron Tagging in Super-K with Gadolinium

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

- 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

Selective water & Gd filtration system

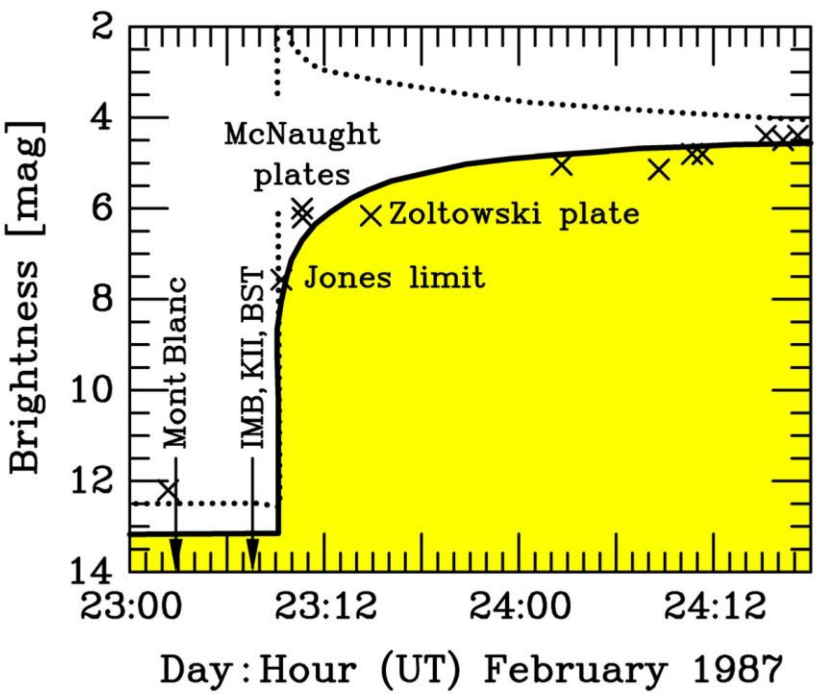
200 ton water tank

Transparency measurement

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

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 $m_\nu < 2.2$ eV from tritium
- Cosmological limit today $m_\nu \lesssim 0.2$ 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

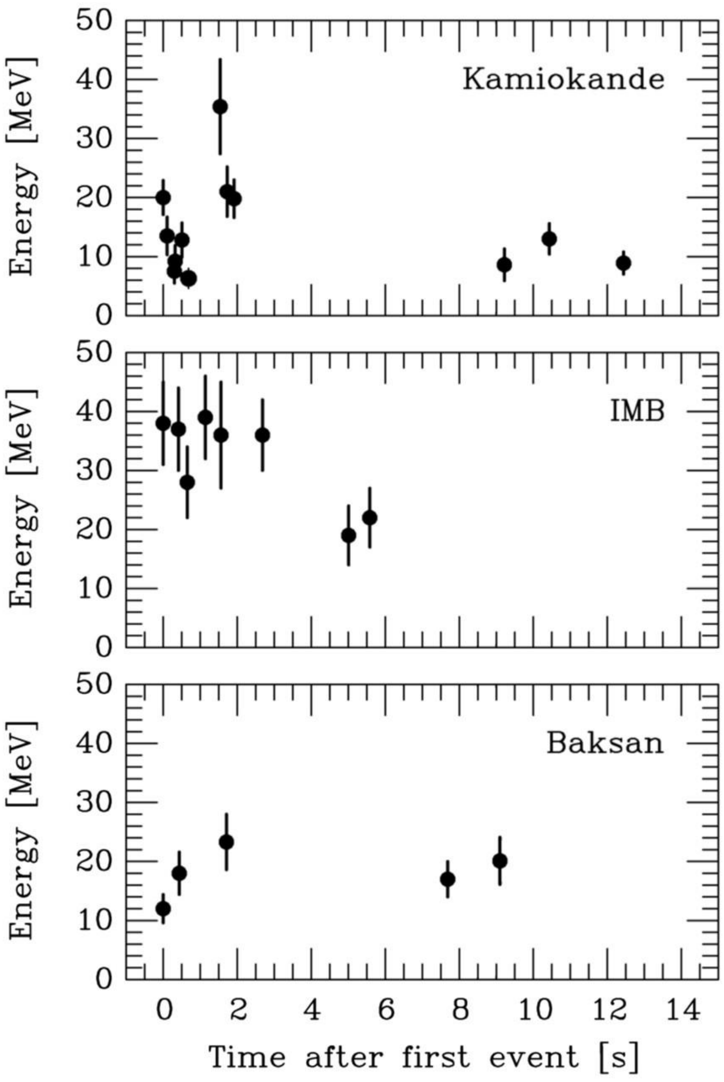
$$\frac{e_\nu}{e} < 3\times 10^{-17}\ \frac{1\mu G}{B_\perp}\ \frac{1\ \mathrm{kpc}}{d_B}$$

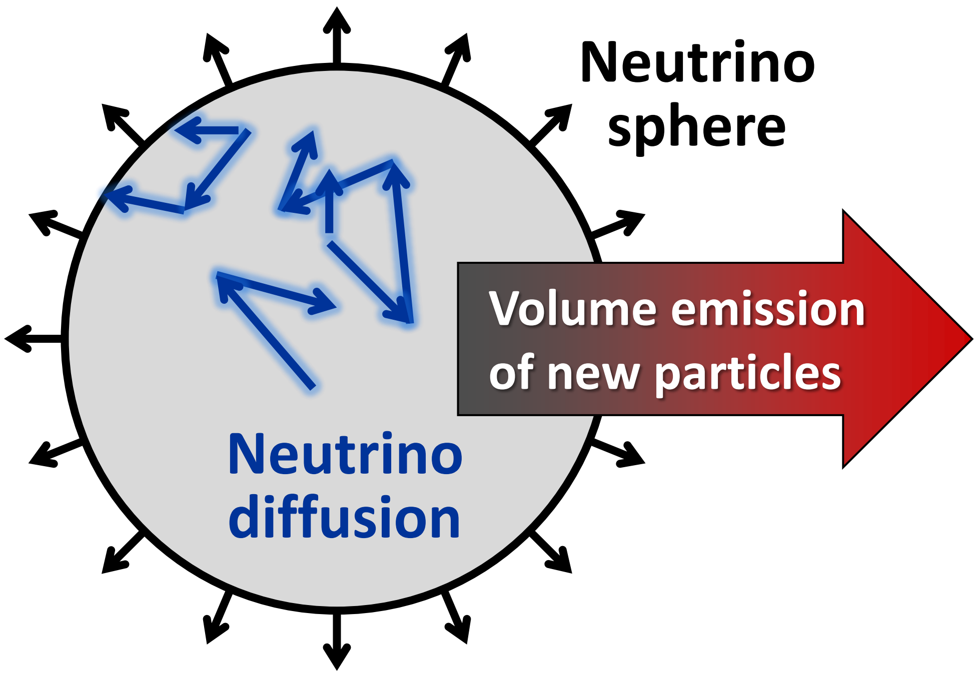
- Barbiellini & Cocconi, Nature 329 (1987) 21
- Bahcall, Neutrino Astrophysics (1989)

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

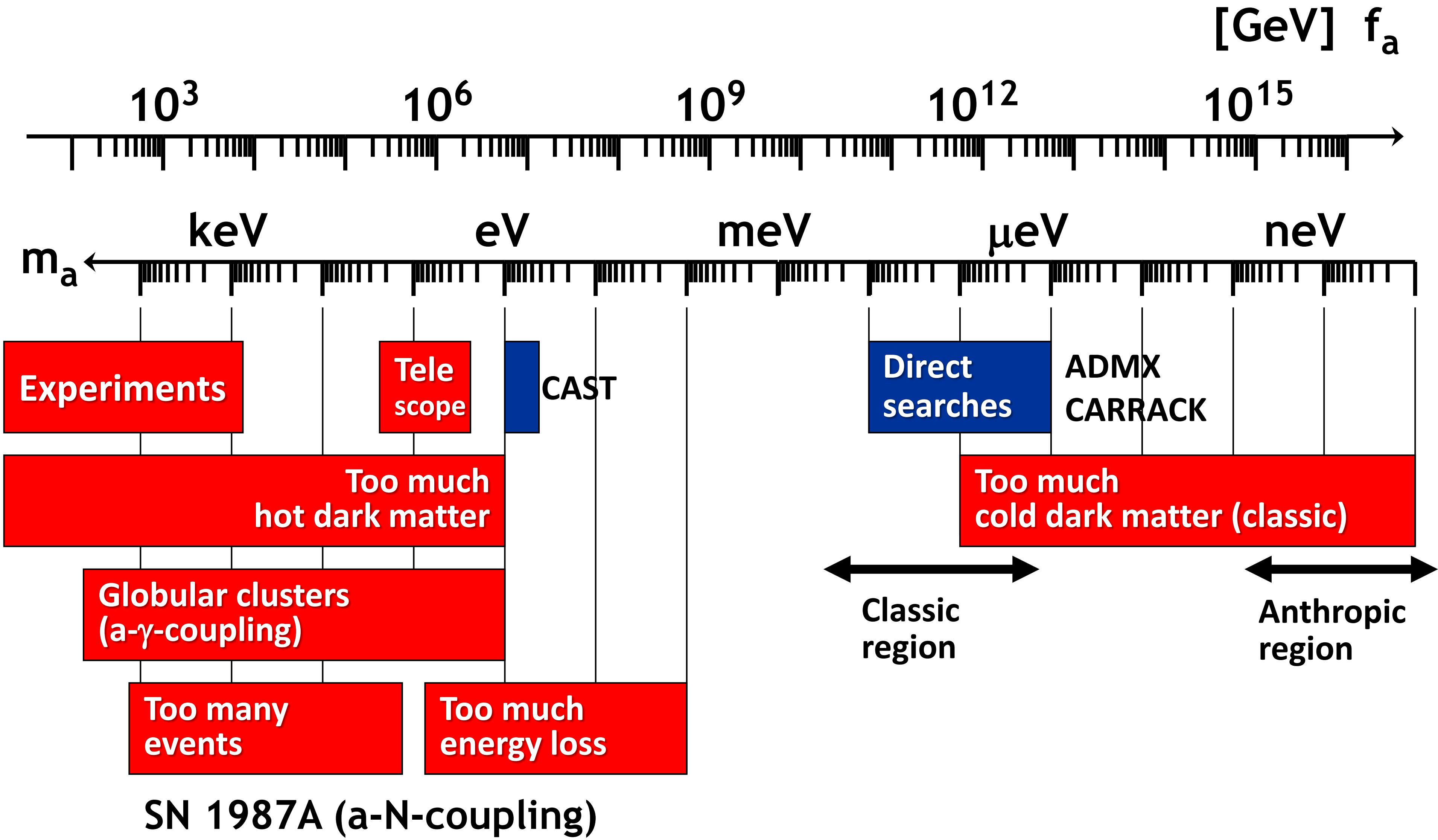




Emission of very weakly interacting particles would "steal" energy from the neutrino burst and shorten it.
(Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

Late-time signal most sensitive observable

Axion Bounds



Neutrino Diffusion in a Supernova Core

Main neutrino reactions	Electron flavor $\nu_e + n \to p + e^-$ $\bar{\nu}_e + p \to n + e^+$ All flavors $\nu + N \to N + \nu$
Neutral-current scattering cross section	$\sigma_{\nu N} = \frac{C_V^2 + 3C_A^2}{\pi} G_{\rm F}^2 E_\nu^2 \approx 2 \times 10^{-40} {\rm cm}^2 \left(\frac{E_\nu}{100\ {\rm MeV}}\right)^2$
Nucleon density	$n_B = \frac{\rho_{\rm nuc}}{m_N} \approx 1.8 \times 10^{38}\ {\rm cm}^{-3}$
Scattering rate	$\Gamma = \sigma n_B \approx 1.1 \times 10^9\ {\rm s}^{-1} \left(\frac{E_\nu}{100\ {\rm MeV}}\right)^2$
Mean free path	$\lambda = \frac{1}{\sigma n_B} \approx 28\ {\rm cm} \left(\frac{100\ {\rm MeV}}{E_\nu}\right)^2$
Diffusion time	$t_{\rm diff} \approx \frac{R^2}{\lambda} \approx 1.2\ {\rm sec} \left(\frac{R}{10\ {\rm km}}\right)^2 \left(\frac{{\rm E}_\nu}{100\ {\rm MeV}}\right)^2$

Sterile Neutrino Emission from a SN Core

- Assume sterile neutrino mixed with ν_e, small mixing angle Θ
- Due to matter effect, oscillation length < mean free path (mfp), (weak damping limit)

$$\ell_{\rm osc} \ll \lambda_{\rm s} = \Gamma_s^{-1}$$

- ν_e appears as ν_s on average with probability

$$\langle p_{\nu_e\to\nu_s}\rangle = \frac{1}{2}\sin^2 2\Theta$$

- Typical ν_e interaction rate in SN core (inverse mfp)

$$\Gamma_e \sim 10^{10}\ {\rm s}^{-1}$$

- Production rate (inverse mfp) relative to that of ν_e

$$\Gamma_s = \frac{1}{2}\sin^2(2\Theta)\,\Gamma_e \sim \frac{1}{2}\sin^2(2\Theta)\times 10^{10}\ {\rm s}^{-1}$$

- Avoiding fast energy loss of SN 1987A

$$\Gamma_s < 1\ {\rm s}^{-1}$$

- Constrain mixing angle for masses $\gtrsim$ 30 keV (matter effect irrelevant)

$$\sin^2(2\Theta) \lesssim 2\times 10^{-10}$$

Sterile Neutrino Limits

INERT NEUTRINOS IN SUPERNOVAE

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Received 22 November 1990

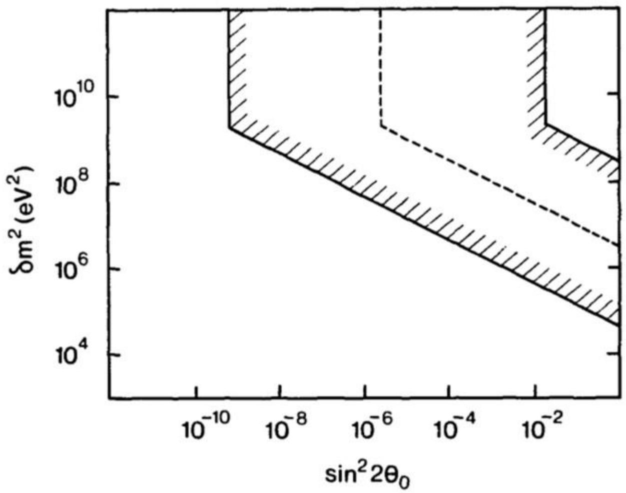


Fig. 1. Constraints from the supernova SN1987A for the squared mass difference δm^2 and the mixing angle θ_0 of the electron neutrino and an inert neutrino. The shaded region is forbidden by the observations. The dashed line shows the trapping condition (15).

See also:

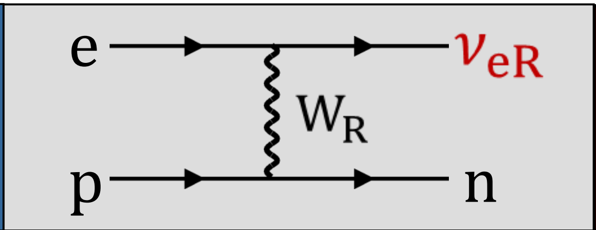
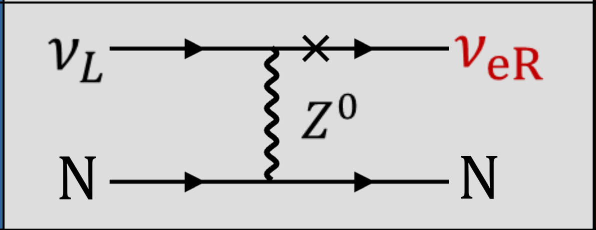
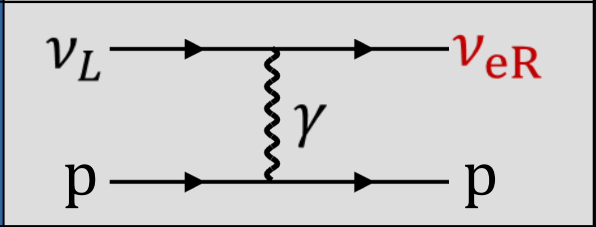
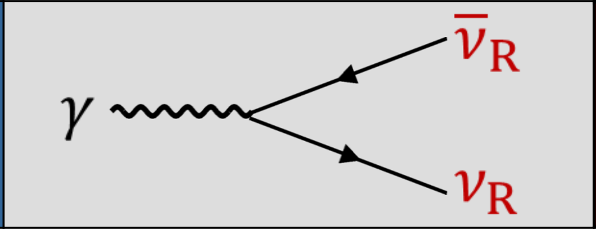
Maalampi & Peltoniemi:
Effects of the 17-keV neutrino in supernovae
PLB 269:357,1991

Raffelt & Zhou
arXiv:1102.5124

Hidaka & Fuller:
Dark matter sterile neutrinos in stellar collapse: alteration of energy/lepton number transport and a mechanism for supernova explosion enhancement
PRD 74:125015,2006

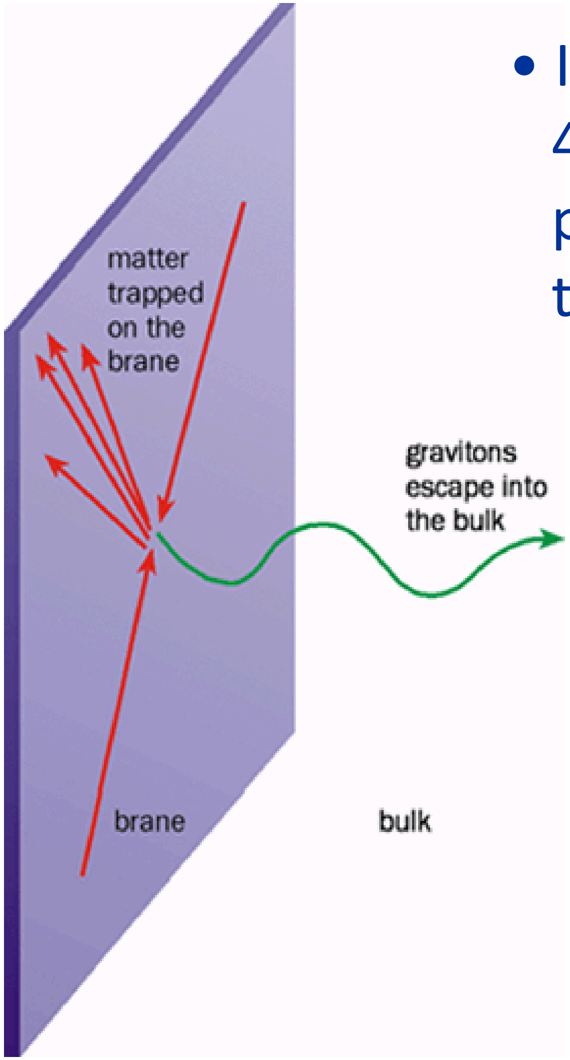
Dirac Neutrino Constraints by SN 1987A

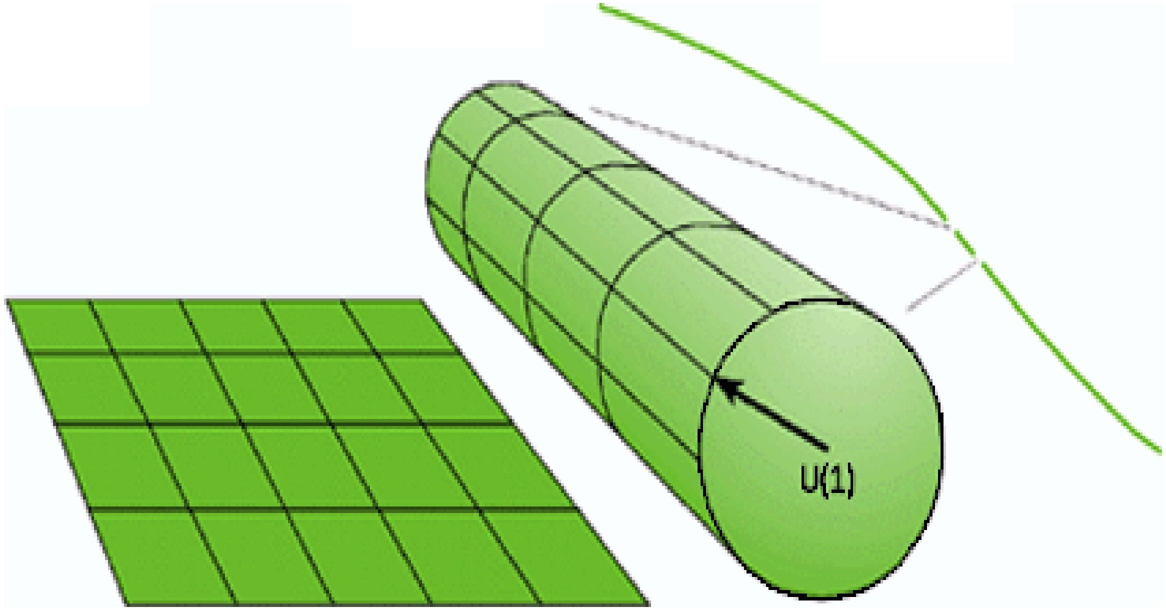
- **If neutrinos are Dirac particles, right-handed states exist that are "sterile" (non-interacting)**
- **Couplings are constrained by SN 1987A energy-loss**

Right-handed currents		$G_R \lesssim 10^{-5} G_F$
Dirac mass		$m_D \lesssim 30\ \mathrm{keV}$
Dipole moments		$\mu_\nu \lesssim 10^{-12} \mu_B$
Milli charge		$e_\nu \lesssim 10^{-9} e$

Large Extra Dimensions

- Fundamentally, space-time can have more than 4 dimensions (e.g. 10 or 11 in string theories)
- If standard model fields are confined to 4D brane in (4+n) D space-time, and only gravity propagates in the (4+n) D bulk, the compactification scale could be macroscopic





Supernova 1987A Limit on Large Extra Dimensions

Cullen & Perelstein, hep-ph/9904422, Hanhart et al., nucl-th/0007016

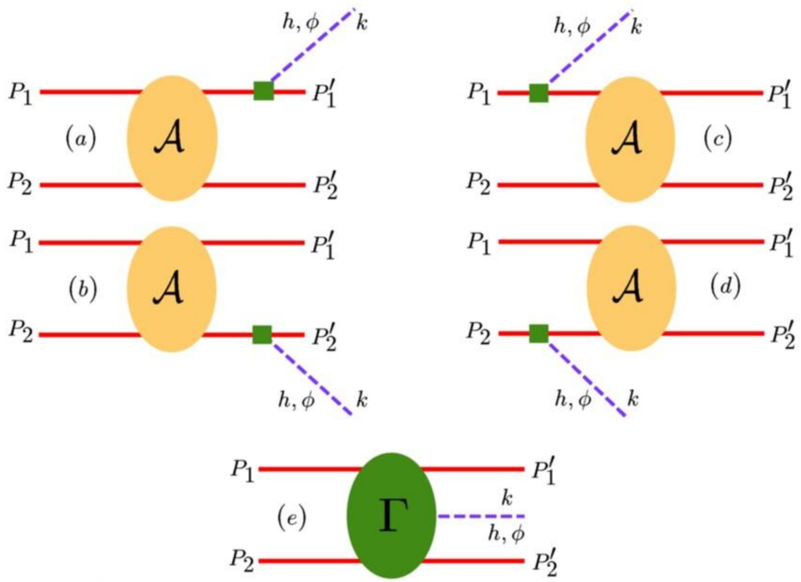


FIG. 1. *The leading diagrams contributing to processes $NN \to NNh$ and $NN \to NN\phi$. Nucleons are denoted by solid lines and the KK-modes h or ϕ are denoted by dashed lines. Solid squares denote an insertion of the single-nucleon energy-momentum tensor, while solid ovals containing $\mathcal{A}$ denote an insertion of the full NN scattering amplitude. The solid oval containing Γ denotes the non-pole vertex required for the sum of diagrams to satisfy $\partial_\mu M^{\mu\nu} = 0$.*

SN core emits large flux of KK gravity modes by nucleon-nucleon bremsstrahlung

$$\text{Rate} \propto M_{\text{Pl}}^{-2}$$

Large multiplicity of modes

$$RT \sim 10^{11}$$

for R ~ 1 mm, T ~ 30 MeV

$$\text{Rate} \propto \frac{(RT)^n}{M_{\text{Pl}}^2} \propto \frac{T^n}{M_{\text{Pl}}^{2+n}}$$

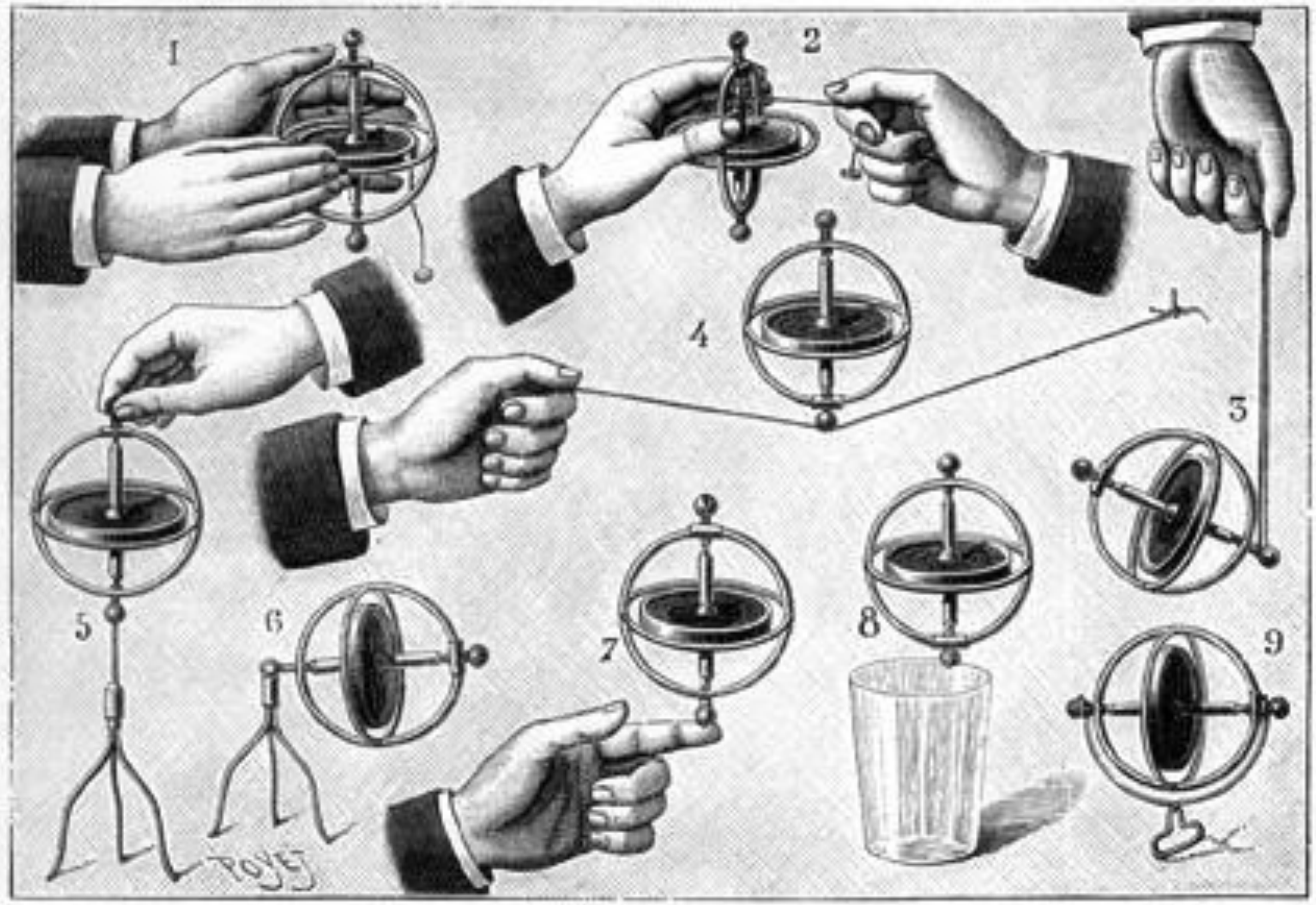
SN 1987A energy-loss argument:

R < 1 mm, M > 9 TeV (n = 2)

R < 1 nm, M > 0.7 TeV (n = 3)

- Originally the most restrictive limit on such theories, except for cosmological arguments.
- Other restrictive limits from neutron stars.

Collective Neutrino Oscillations



3rd Schrödinger Lecture
Thursday 19 May 2011