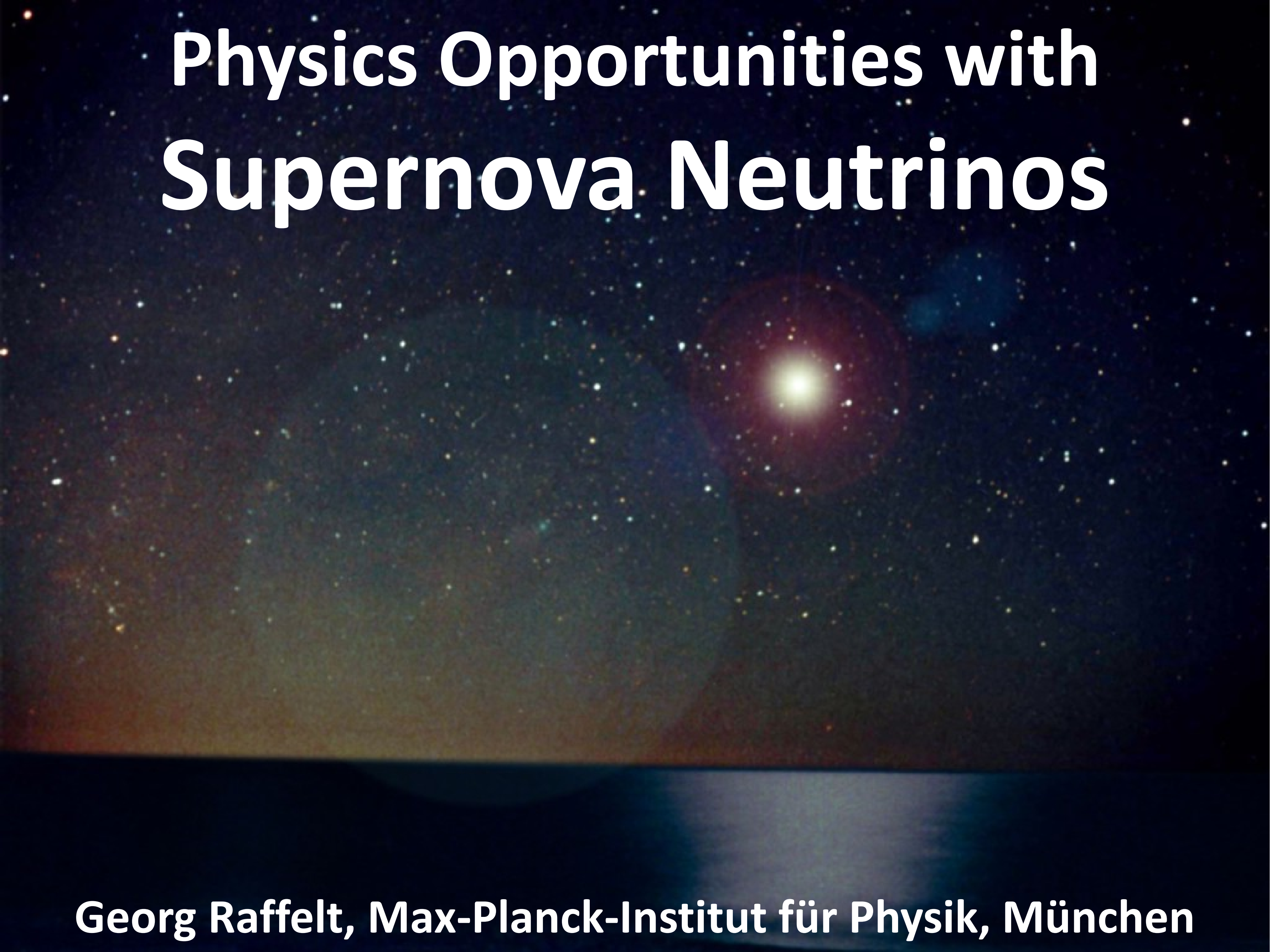
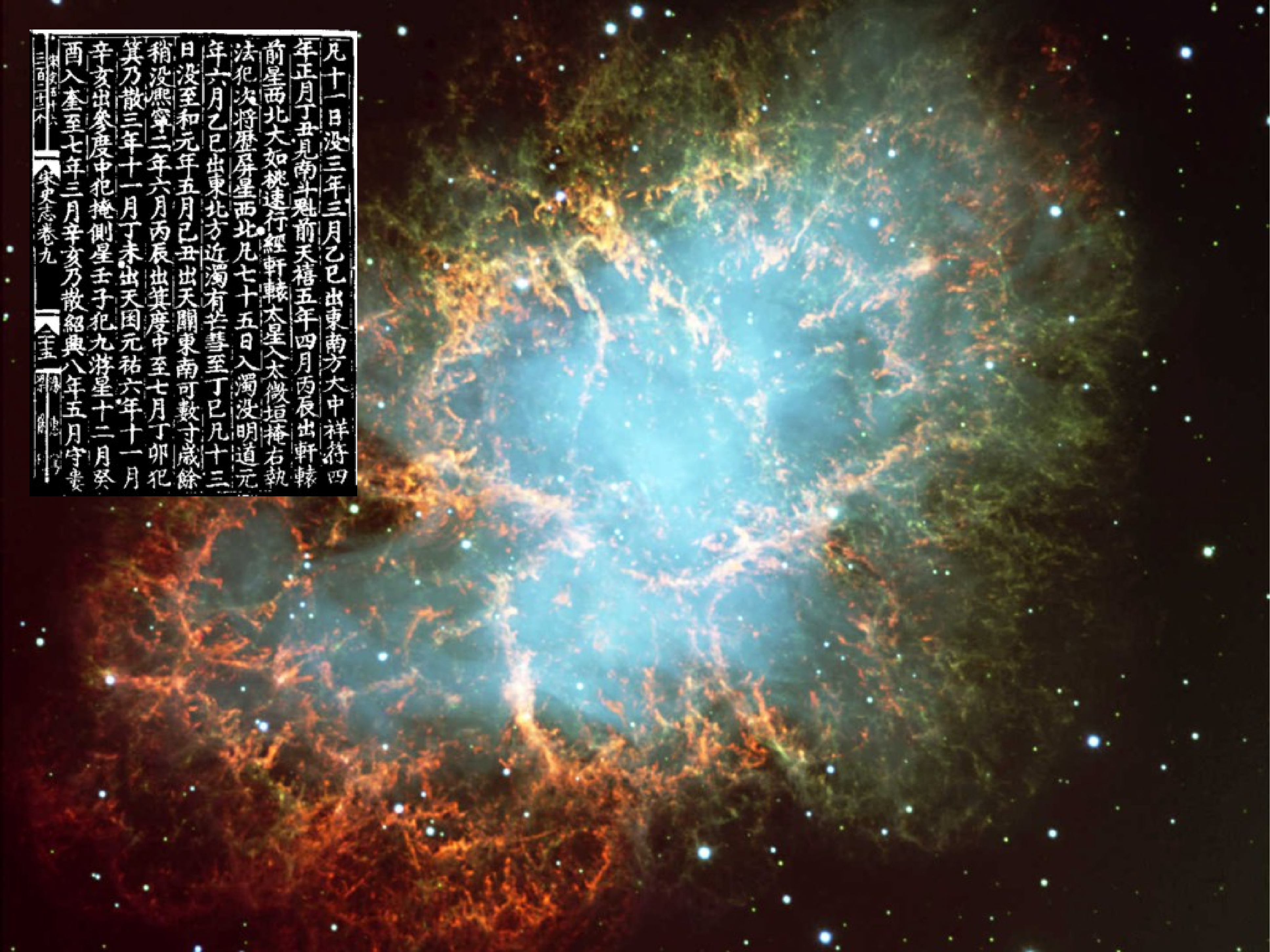
Physics Opportunities with Supernova Neutrinos



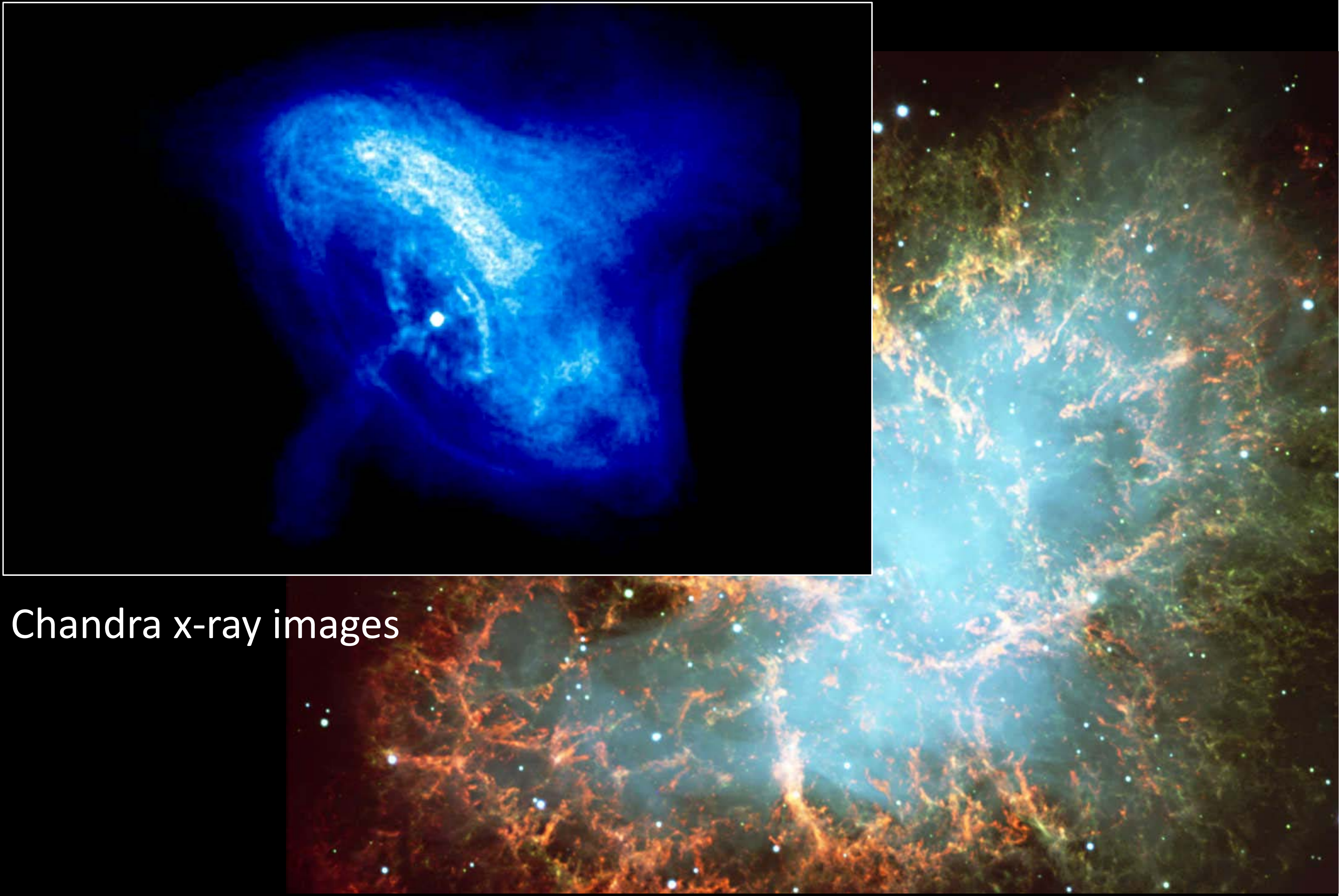
Georg Raffelt, Max-Planck-Institut für Physik, München



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大星入太微垣掩右執法犯次將歷屏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

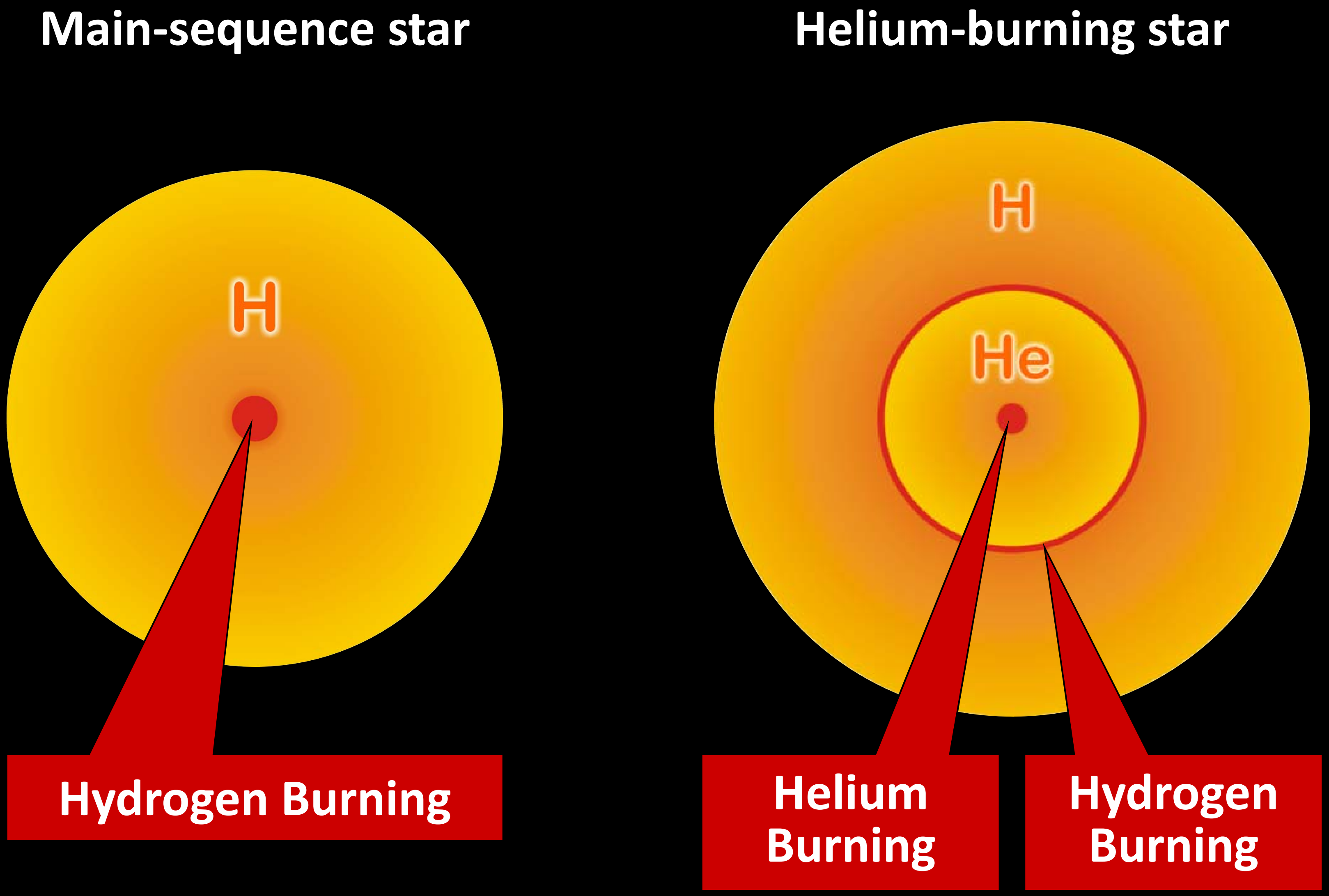
Walter Baade (1893–1960)

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]

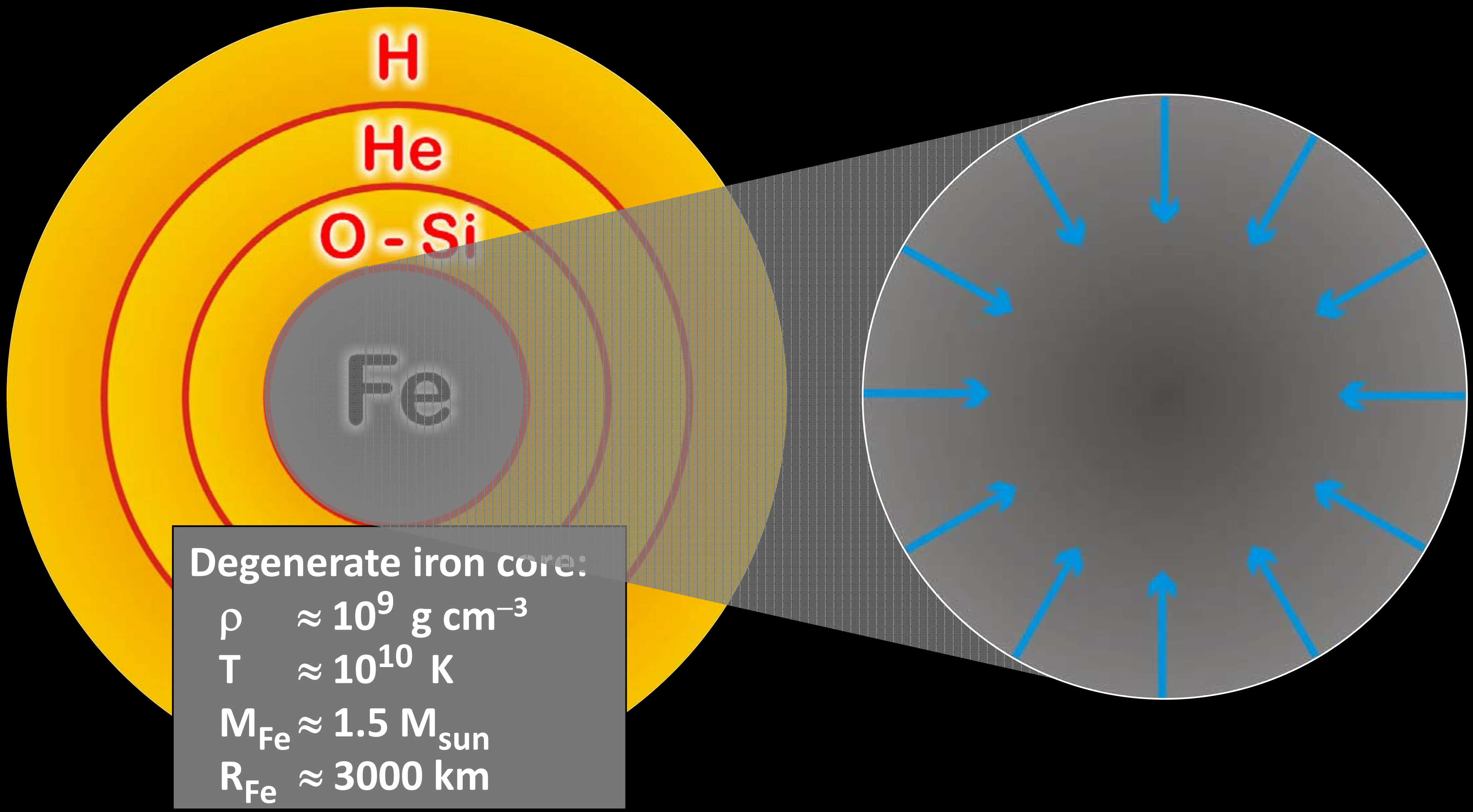
Stellar Collapse and Supernova Explosion



Stellar Collapse and Supernova Explosion

Onion structure

Collapse (implosion)



Degenerate iron core:

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

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

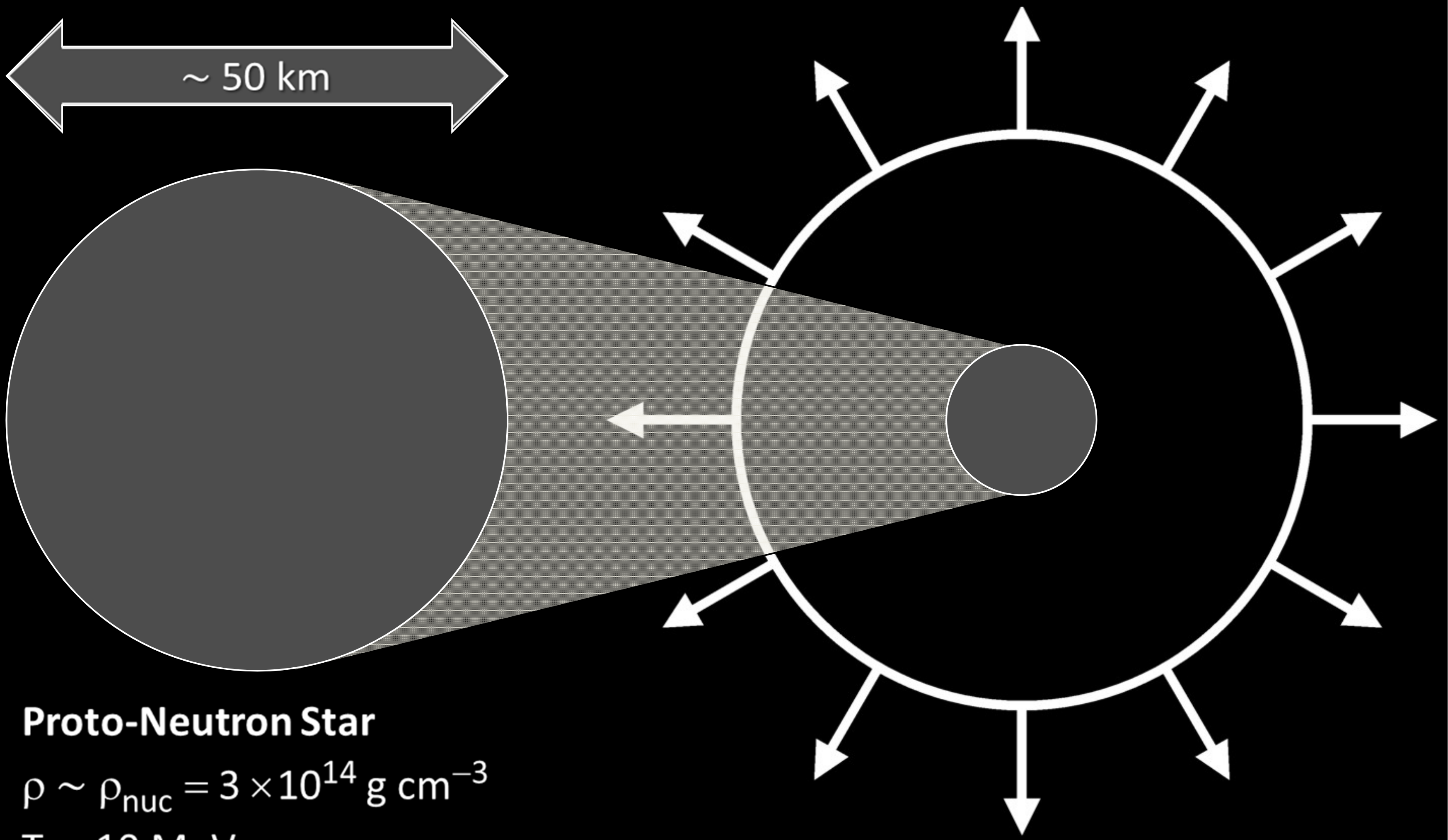
$M_{\mathrm{Fe}} \approx 1.5\ M_{\mathrm{sun}}$

$R_{\mathrm{Fe}} \approx 3000\ \mathrm{km}$

Stellar Collapse and Supernova Explosion

Newborn Neutron Star

Explosion



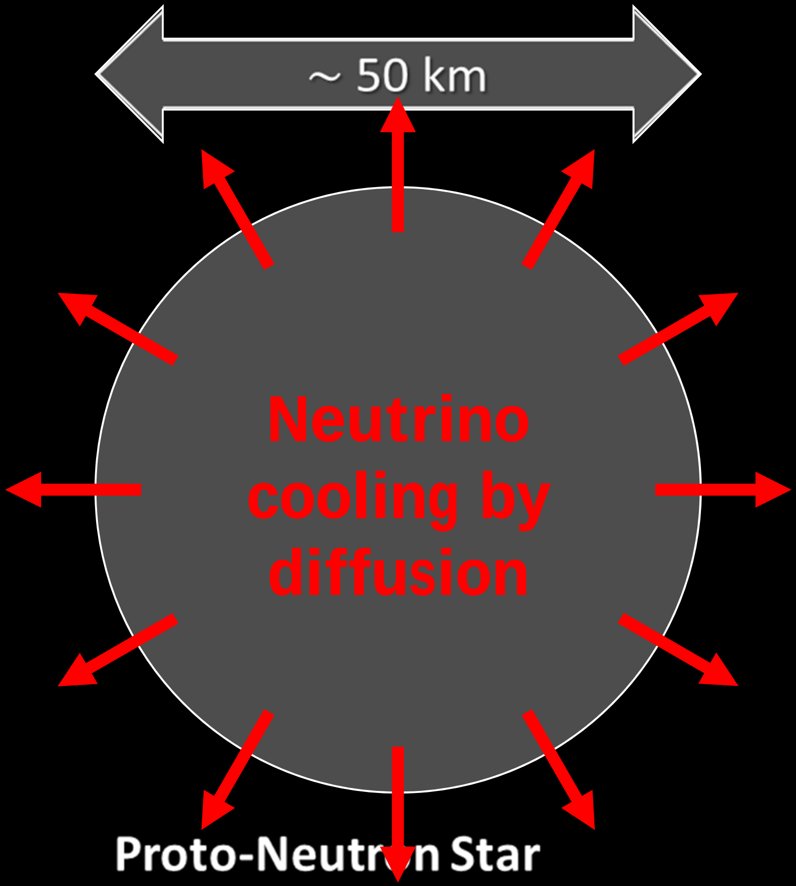
Proto-Neutron Star

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

$T \sim 10\ {\rm MeV}$

Stellar Collapse and Supernova Explosion

Newborn Neutron Star



Proto-Neutron Star

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

$T \sim 10\ \mathrm{MeV}$

Gravitational binding energy

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

This shows up as

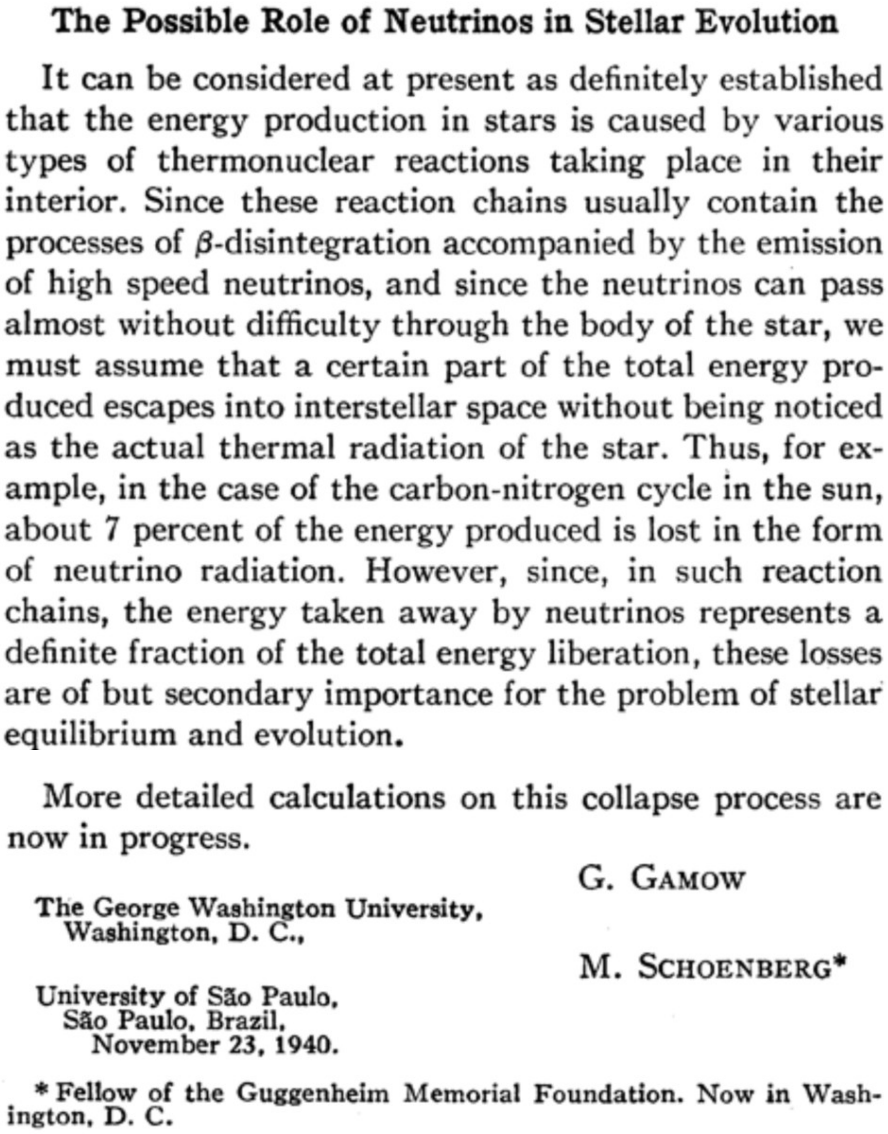
99%	Neutrinos
1%	Kinetic energy of explosion
0.01%	Photons, outshine host galaxy

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

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.

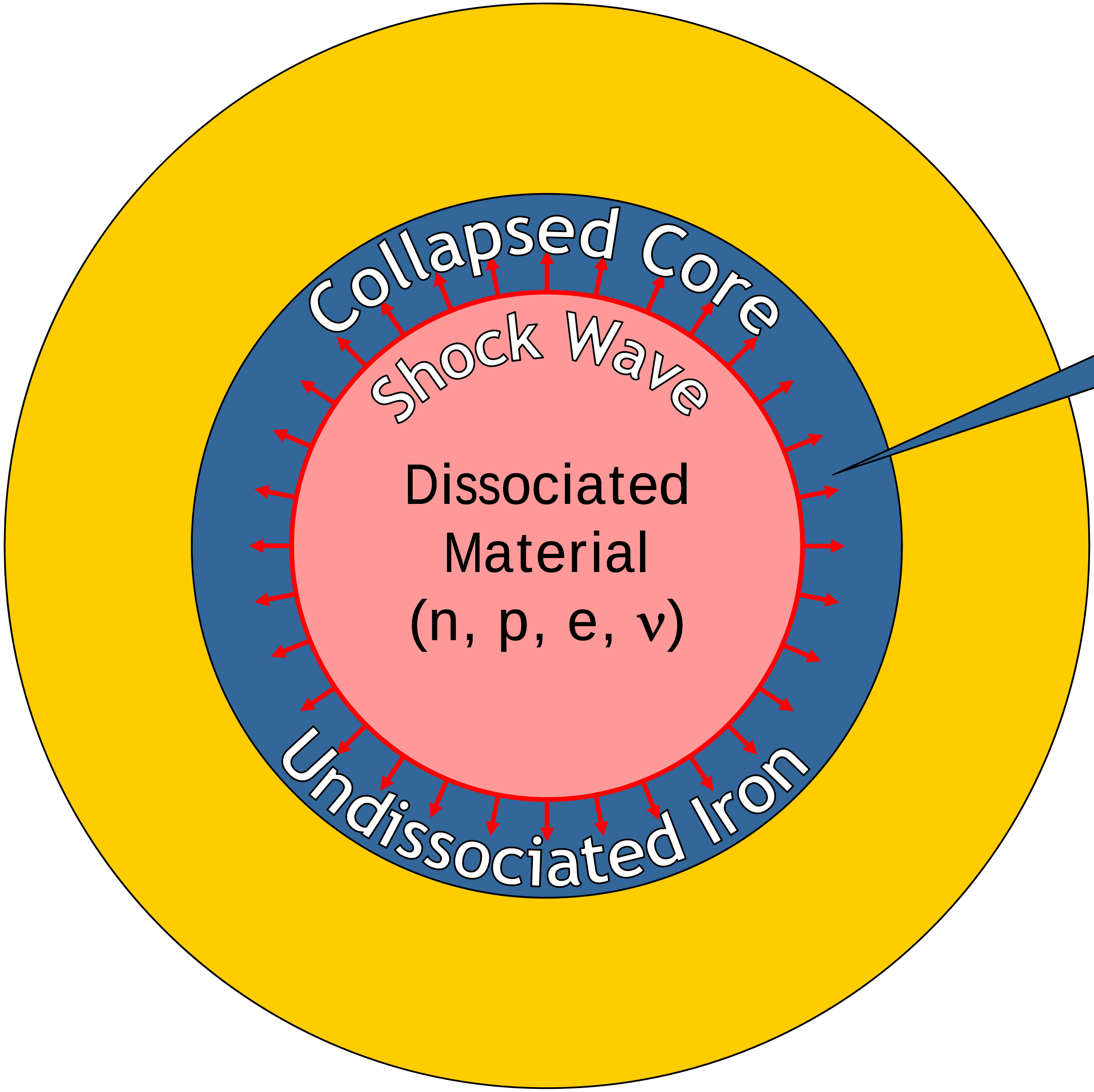
* Fellow of the Guggenheim Memorial Foundation. Now in Washington, D. C.

Phys. Rev. 58:1117 (1940)

George Gamow
(1904 – 1968)

Explosion Mechanism

Why No Prompt Explosion?



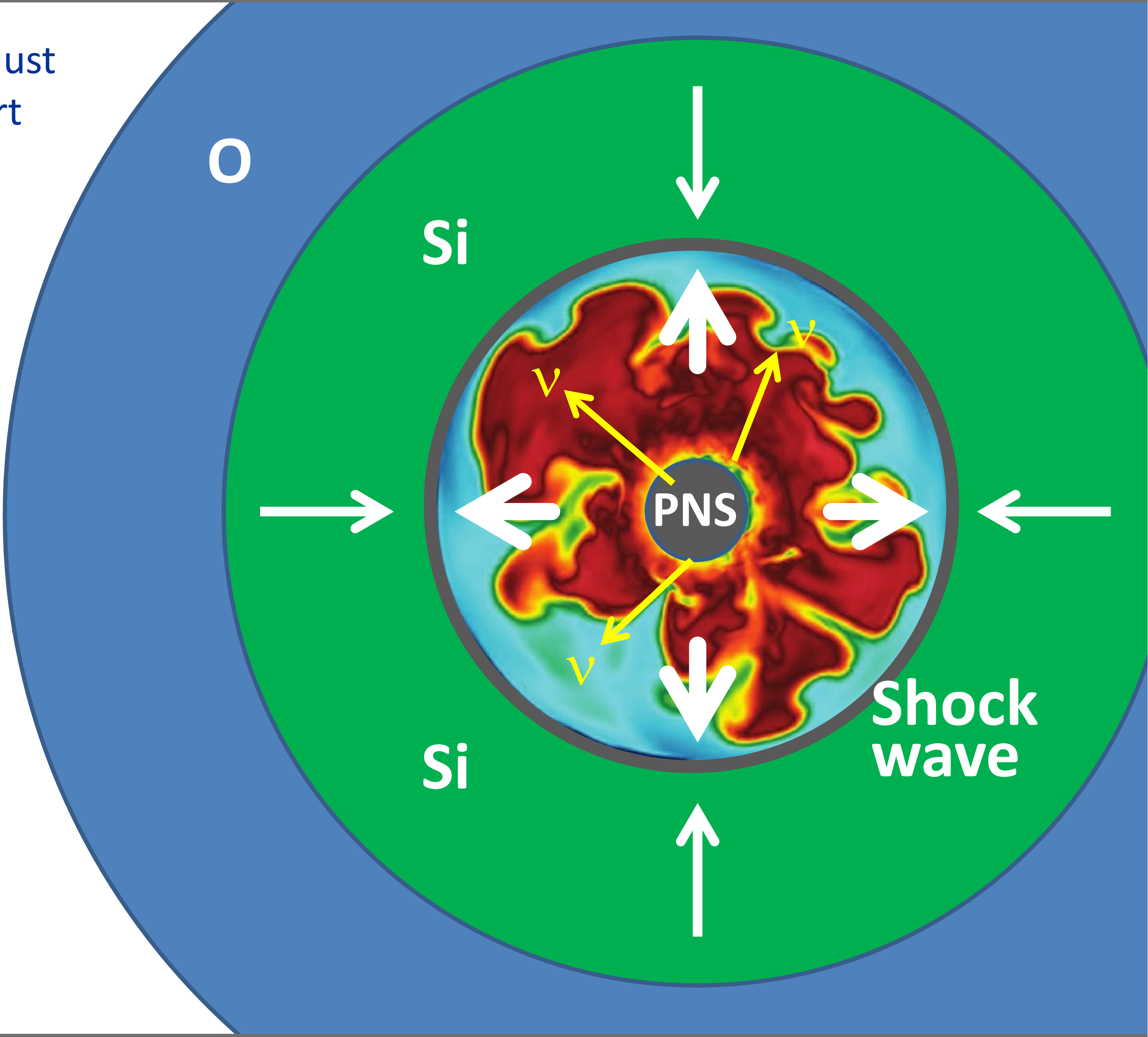
- $0.1\,M_{sun}$ of iron has a nuclear binding energy $\approx 1.7 \times 10^{51}$ erg
- Comparable to explosion energy

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

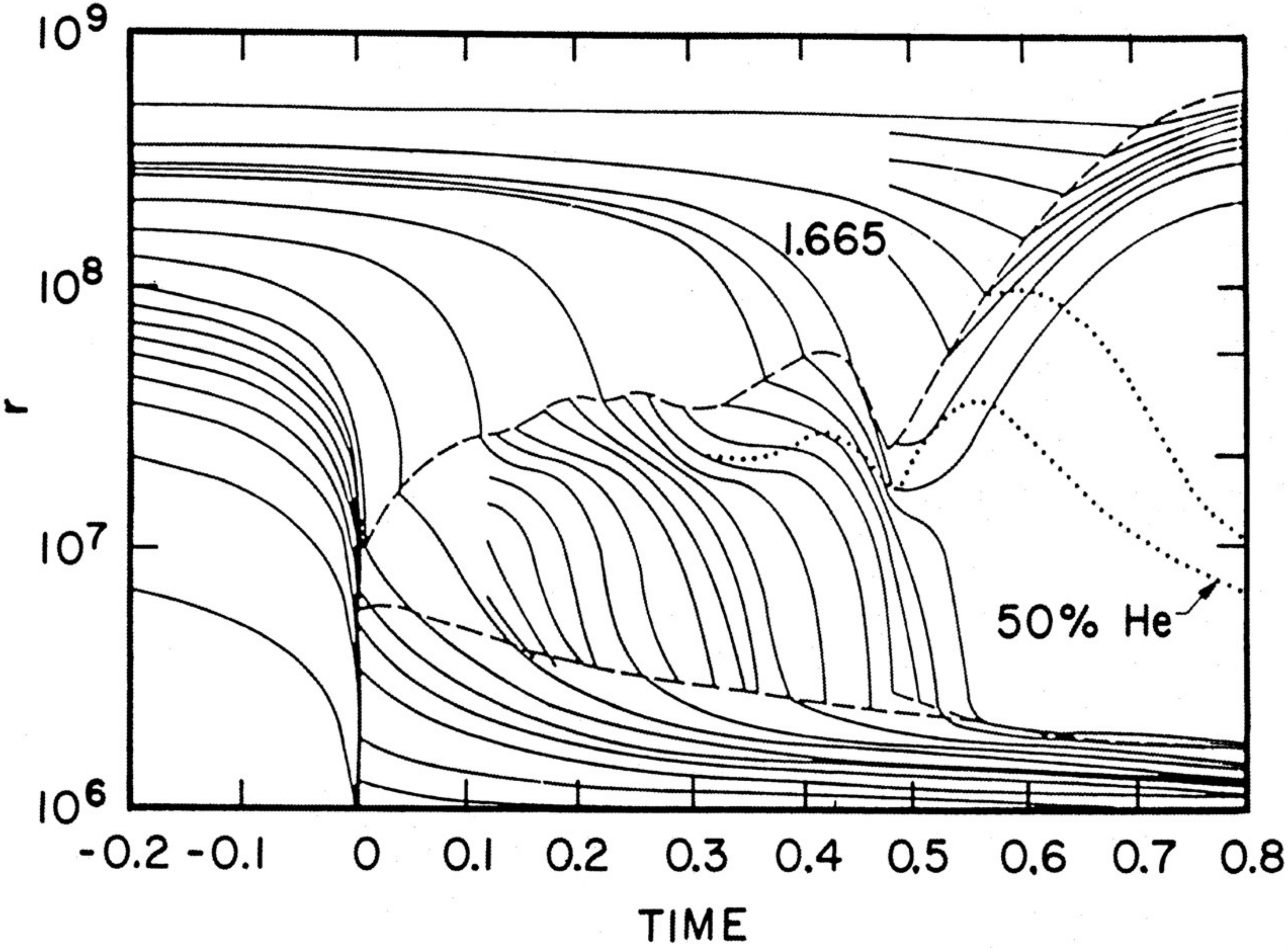
Shock Revival by Neutrinos

Stalled shock wave must receive energy to start re-expansion against ram pressure of infalling stellar core

Shock can receive fresh energy from neutrinos!



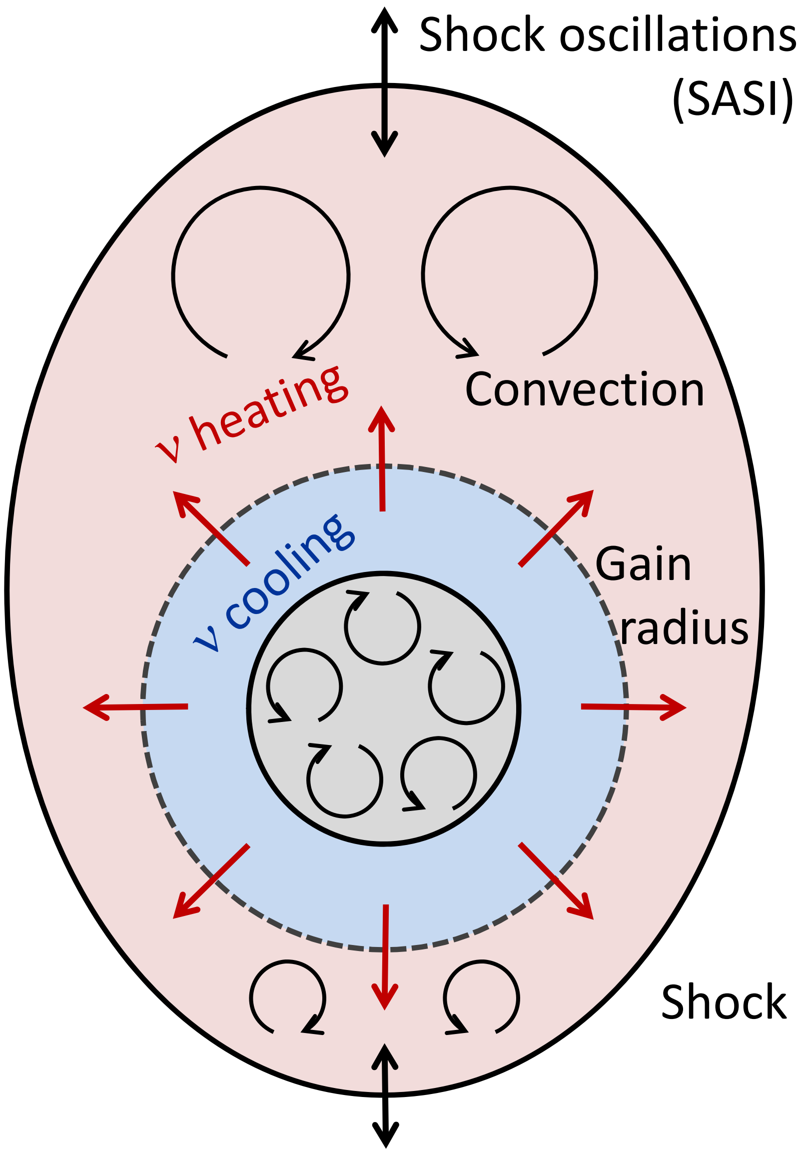
Delayed (Neutrino-Driven) Explosion



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

Neutrino-Driven Mechanism – Modern Version

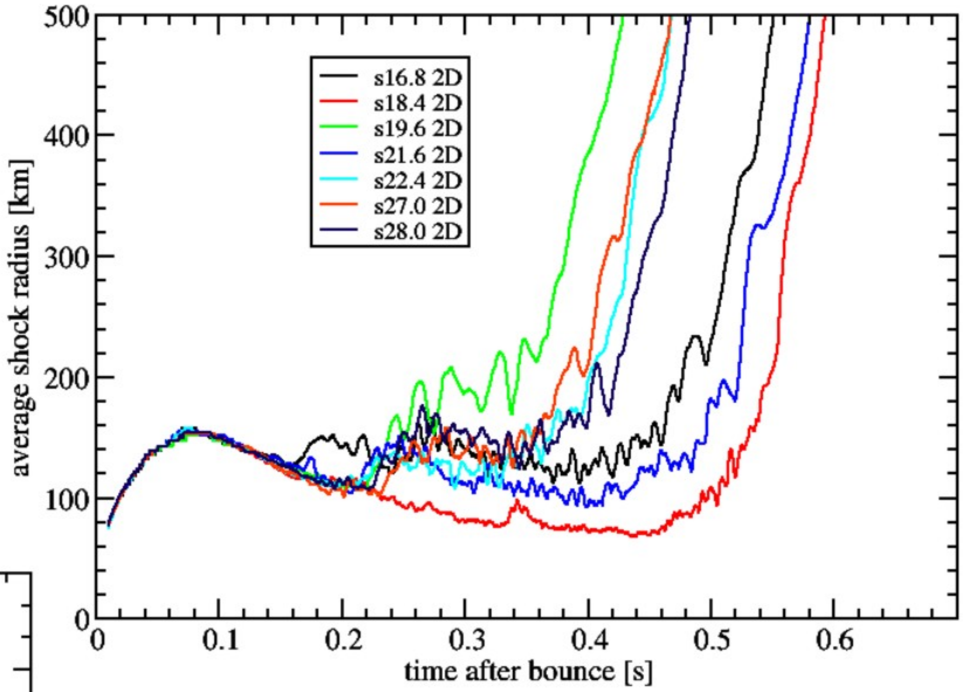
- Stalled accretion shock pushed out to ~150 km as matter piles up on the PNS
- Heating (gain) region develops within some tens of ms after bounce
- Convective overturn & shock oscillations (SASI) enhance efficiency of ν-heating, finally revives shock
- Successful explosions in 1D and 2D for different progenitor masses (e.g. Garching group)
- Details important (treatment of GR, ν interaction rates, etc.)
- Role of 3D not yet clear, first self-consistent studies being performed



Adapted from B. Müller

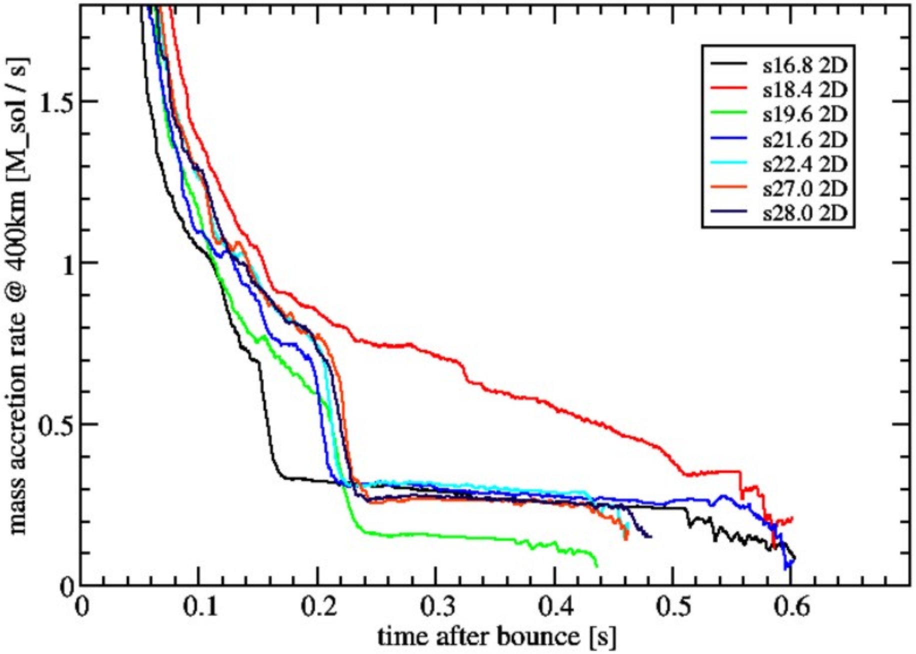
Growing Set of 2D Exploding Models

Florian Hanke, PhD Project
MPA, Garching, 2013



Average shock radius

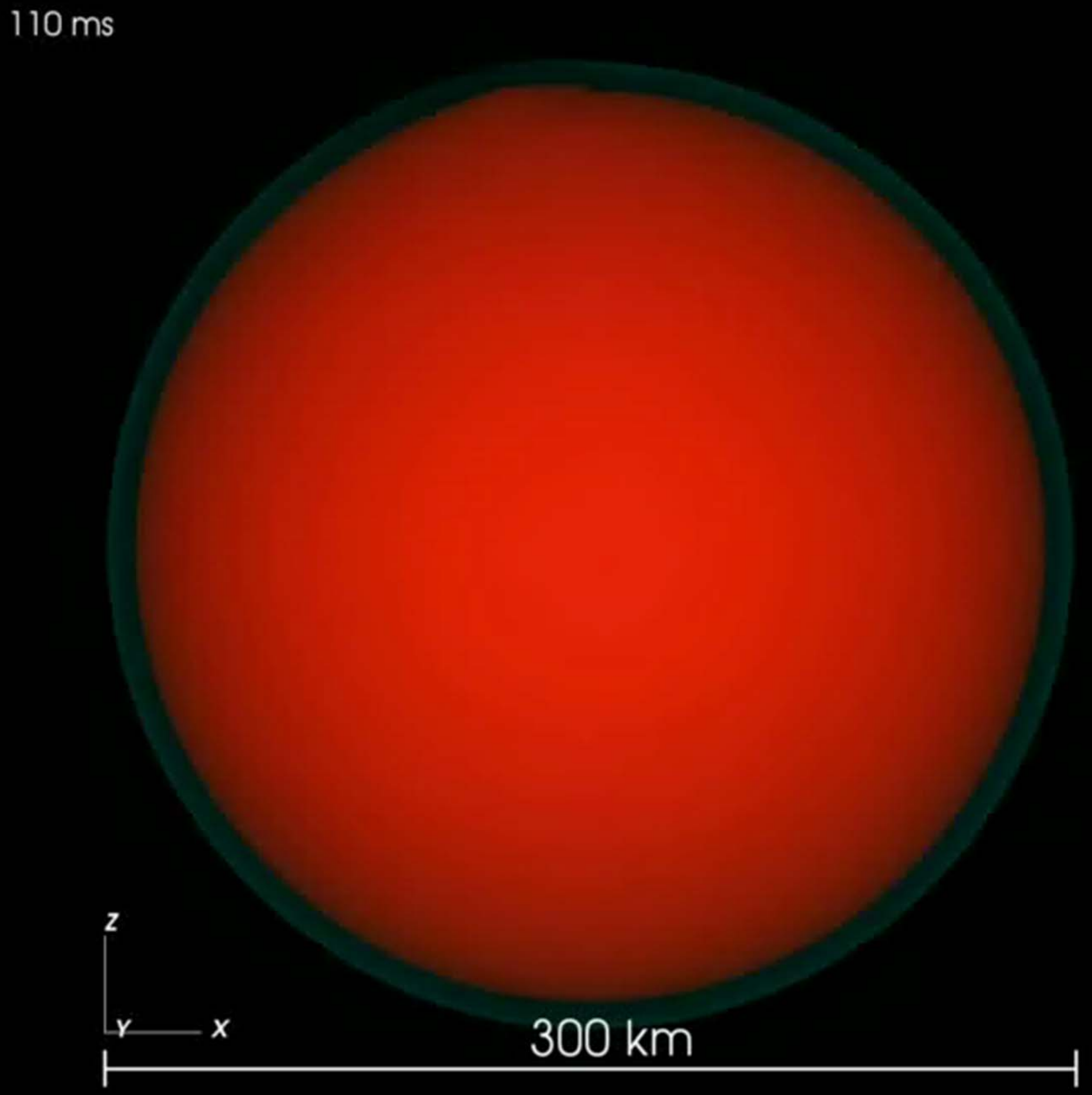
Mass accretion rate



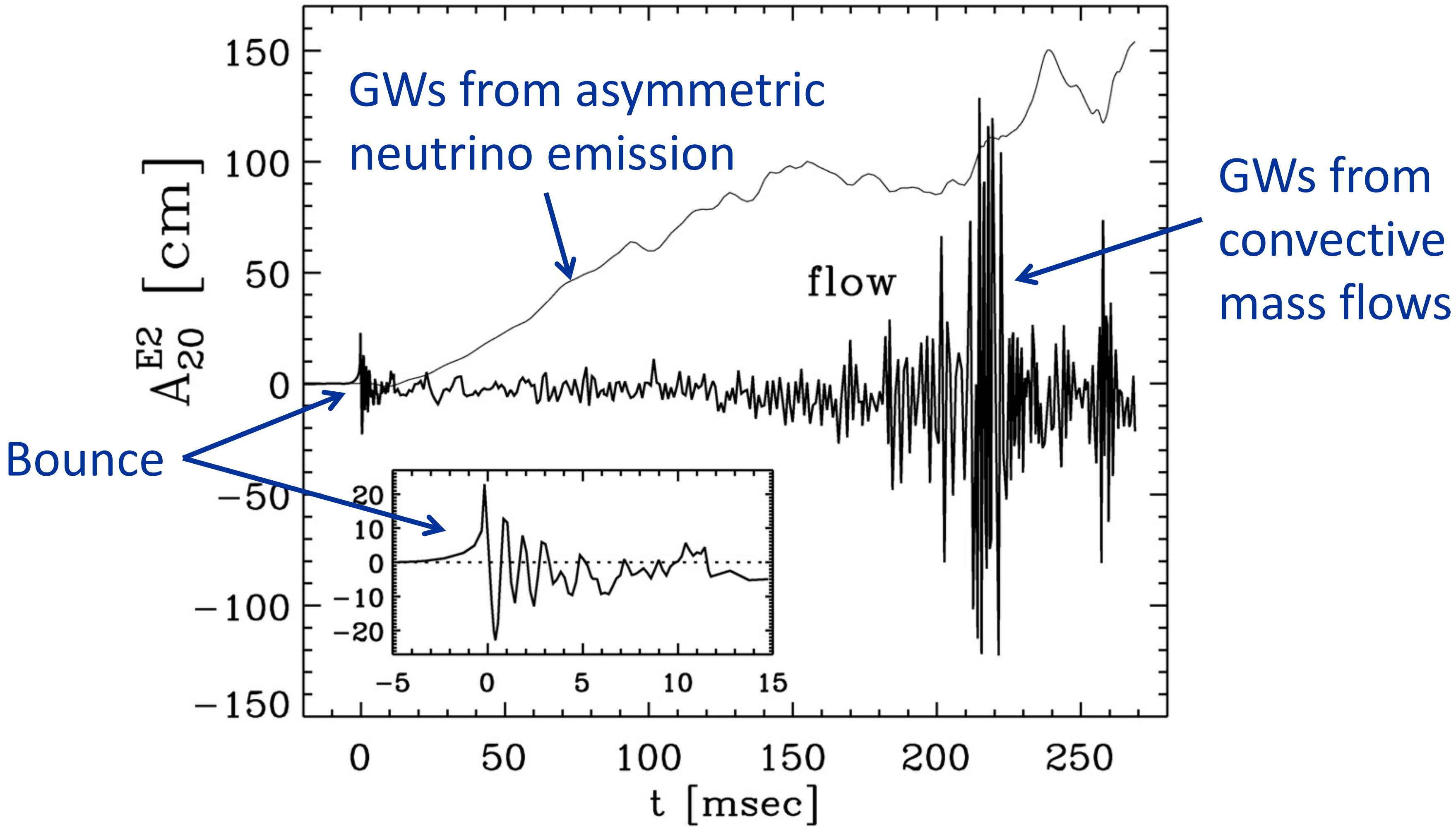
Progenitor models:
Woosley et al. RMP (2002)

Slide from Thomas Janka at Fifty-One Ergs, NC State University, Raleigh, North Carolina, 13–17 May 2013

First Realistic 3D Simulation (27 $M_\odot$ Garching Group)



Gravitational Waves from Core-Collapse Supernovae



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

Summary Explosion Mechanism

- Standard paradigm for many years:
  Neutrino-driven explosion (delayed explosion, Wilson mechanism)

- Numerical explosions ok for small-mass progenitors in 1D
  (spherical symmetry)

- Numerical explosions ok for broad mass range in 2D
  (axial symmetry)

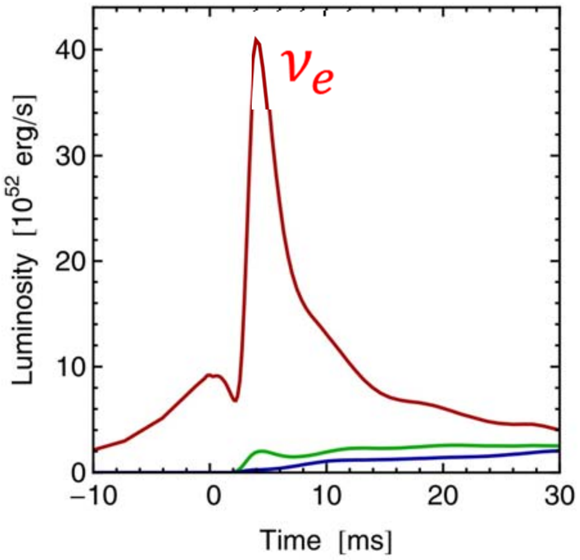
- 3D studies only beginning – no clear picture yet
  Better resolution needed?

- Strong progenitor dependence? 3D progenitor models needed?

Neutrino Signal

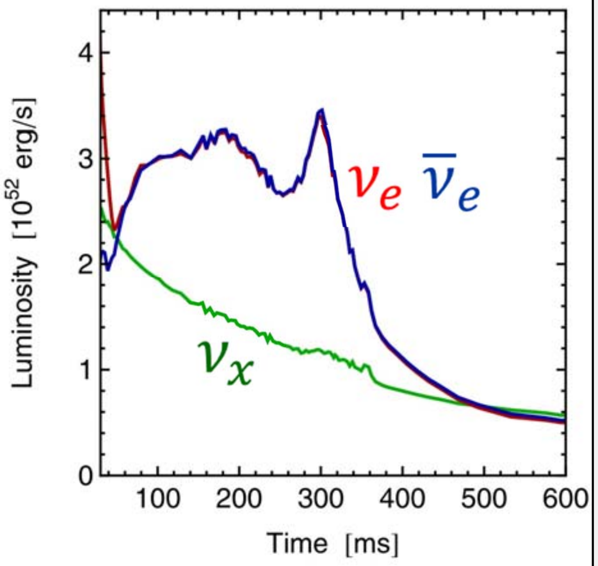
Three Phases of Neutrino Emission

Prompt ν_e burst



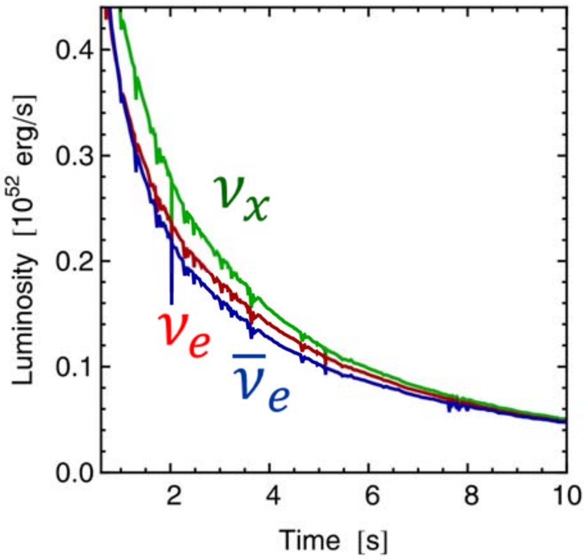
- Shock breakout
- De-leptonization of outer core layers

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]

Sanduleak –69 202

Tarantula Nebula

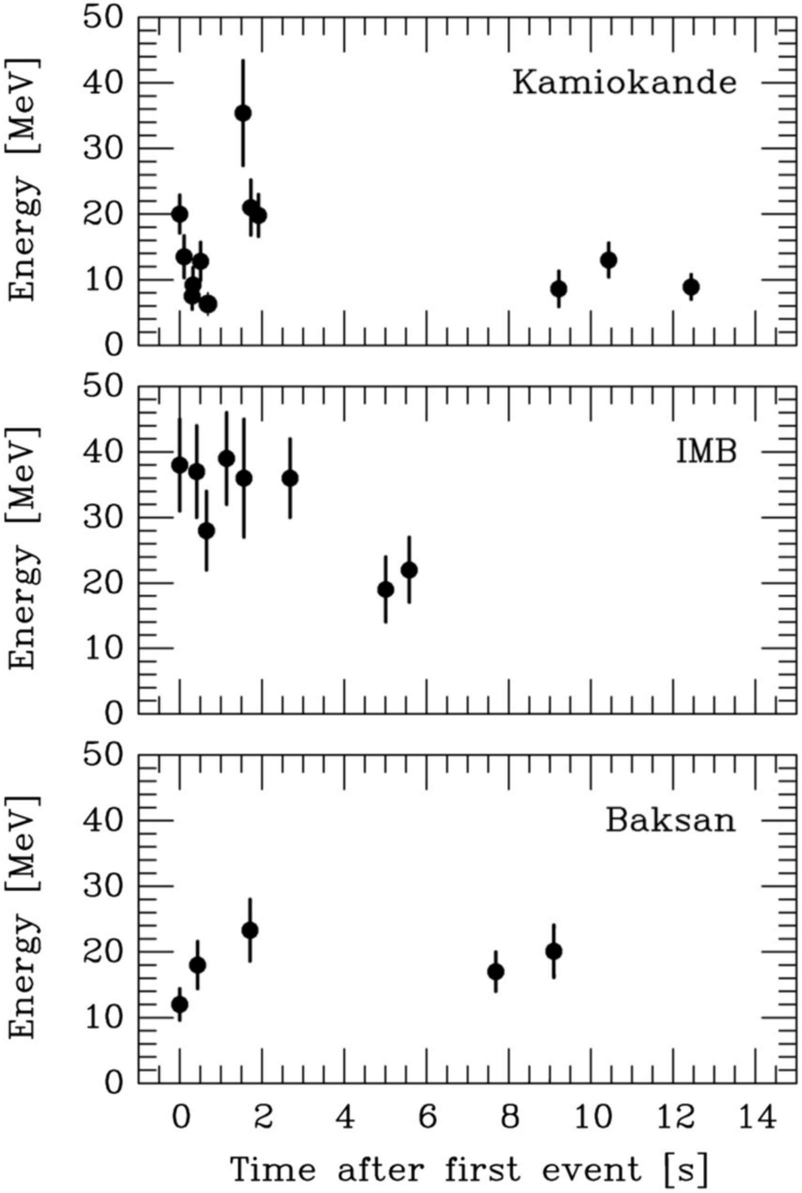
Large Magellanic Cloud
Distance 50 kpc
(160.000 light years)

Sanduleak –69 202

Supernova 1987A

23 February 1987

Neutrino Signal of Supernova 1987A



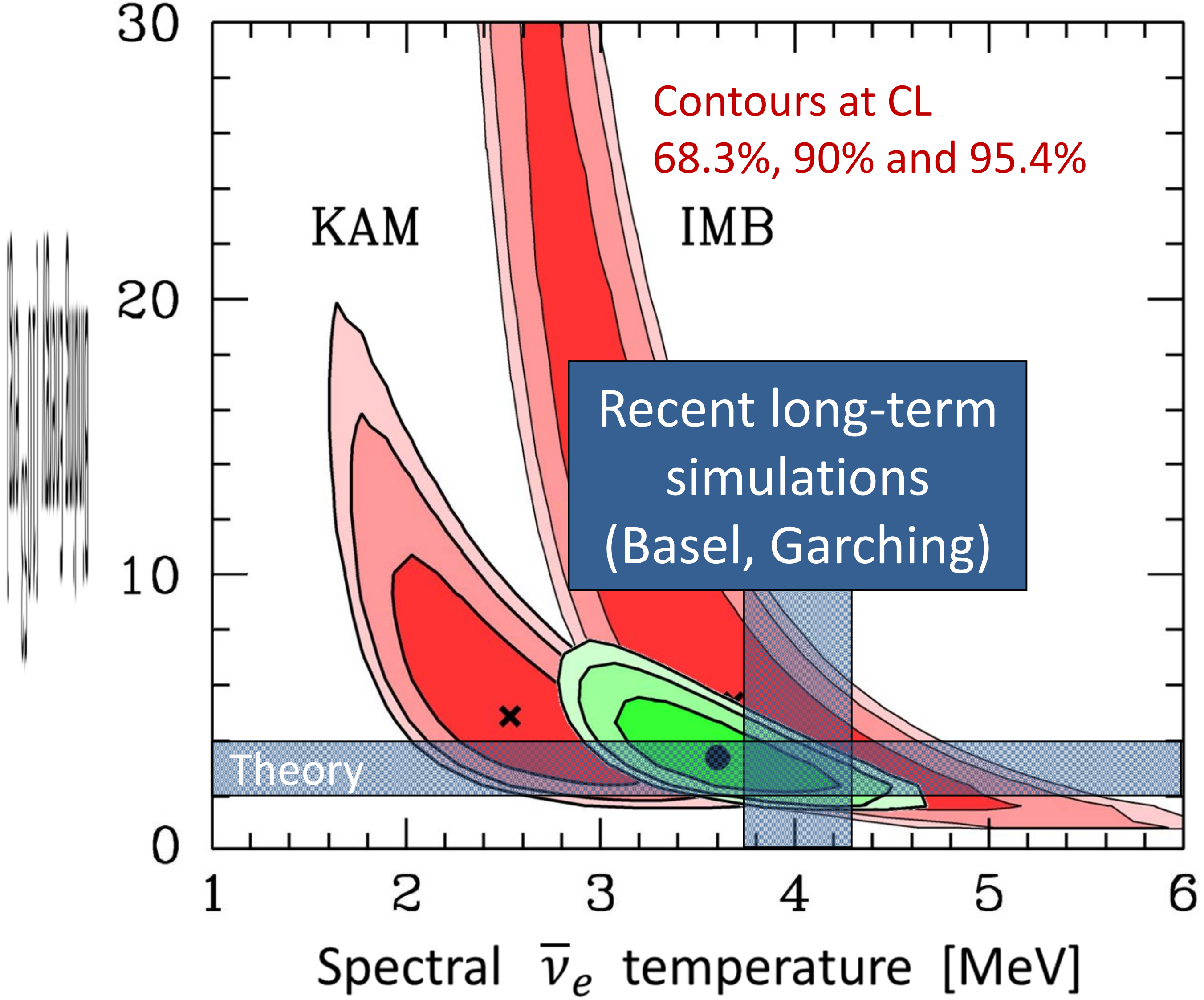
Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ±1 min

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%

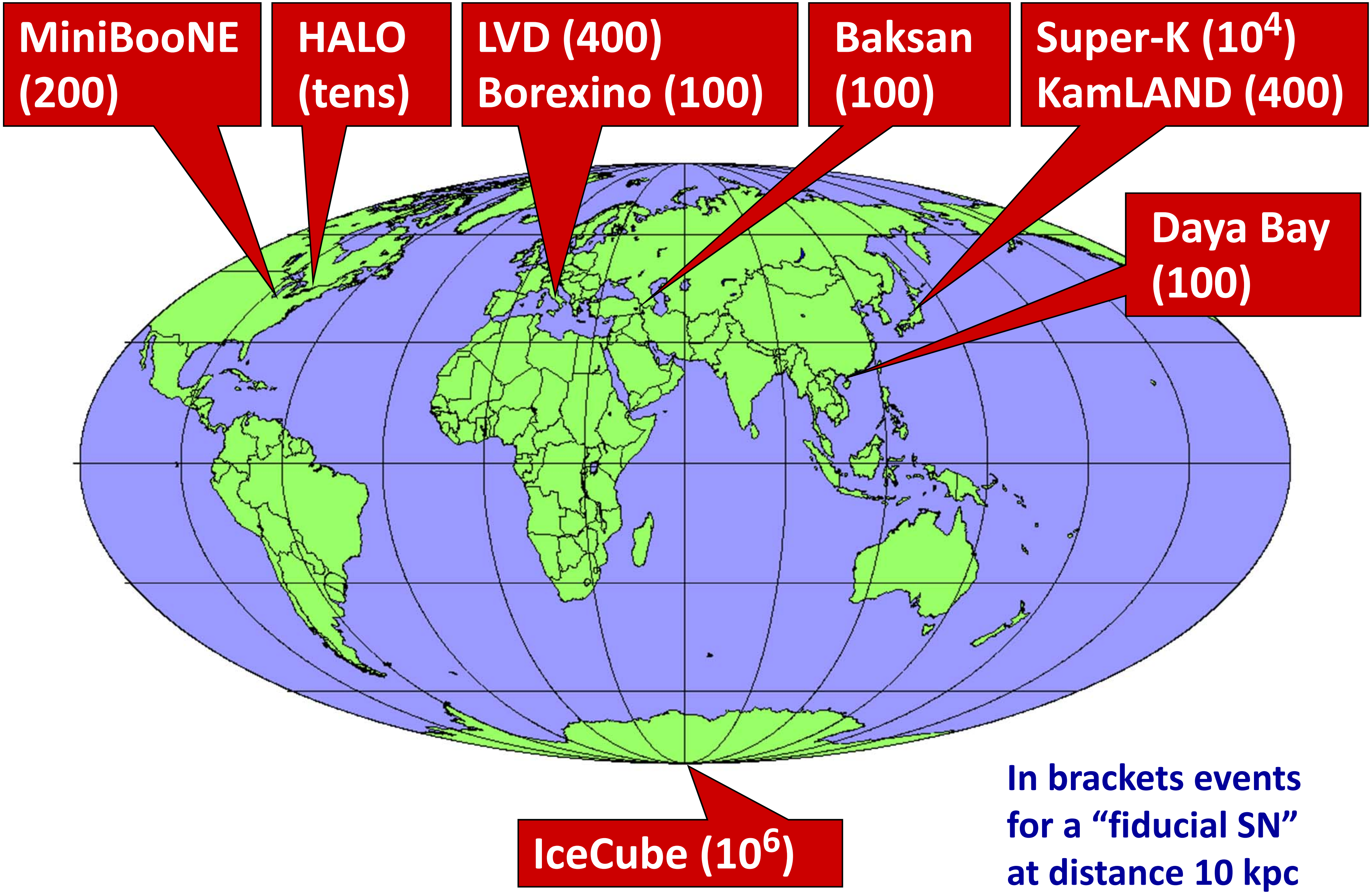
Recent long-term simulations (Basel, Garching)

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

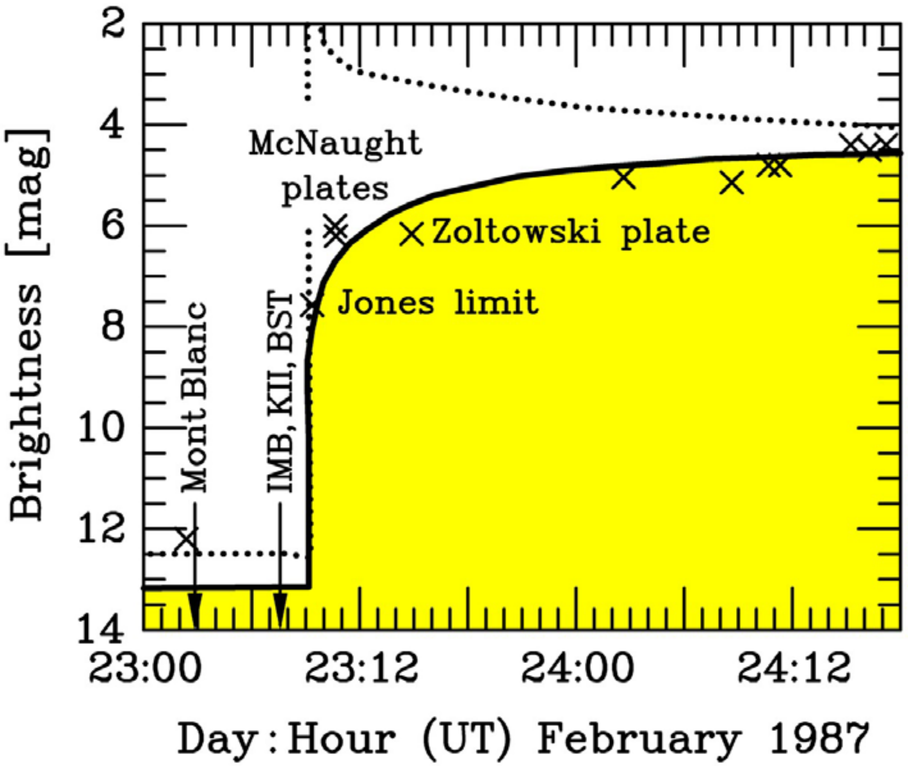
Operational Detectors for Supernova Neutrinos



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

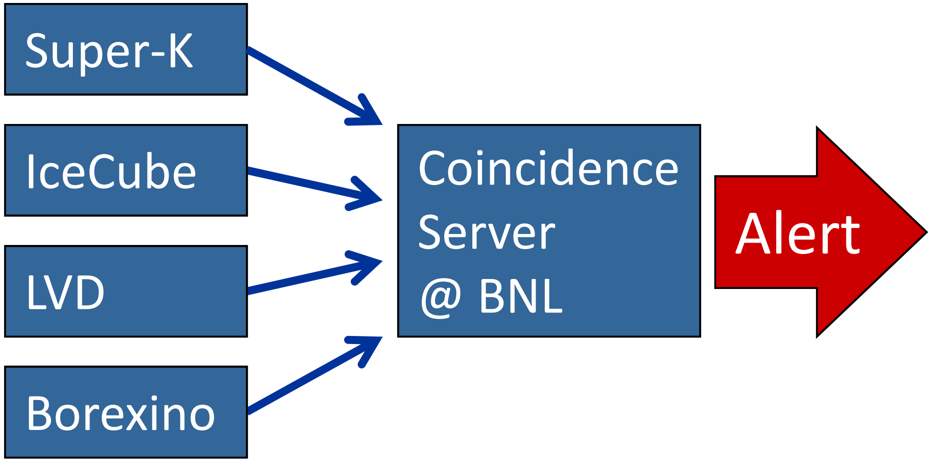
SuperNova Early Warning System (SNEWS)

Early light curve of SN 1987A



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

http://snews.bnl.gov



Super-K

IceCube

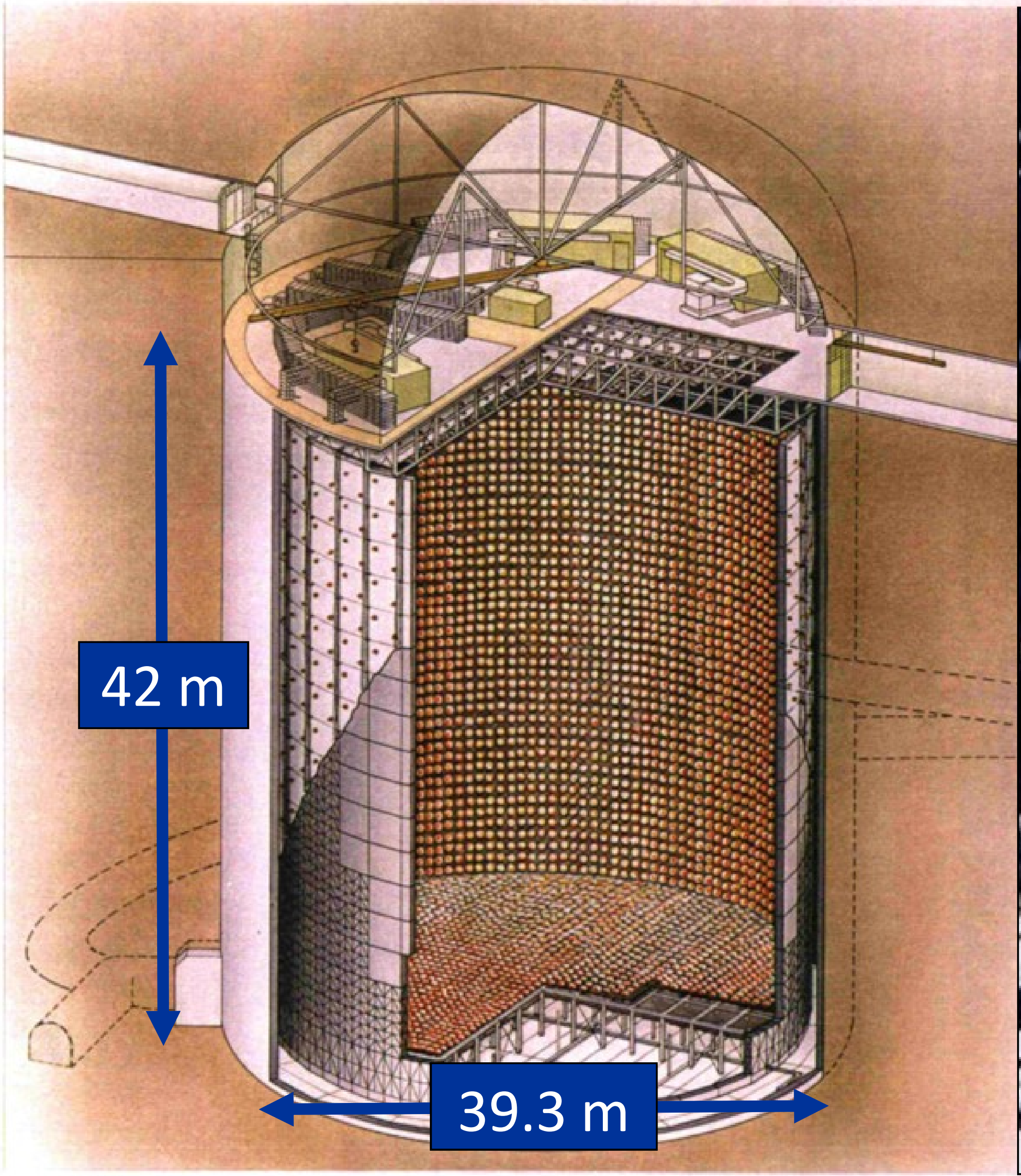
LVD

Borexino

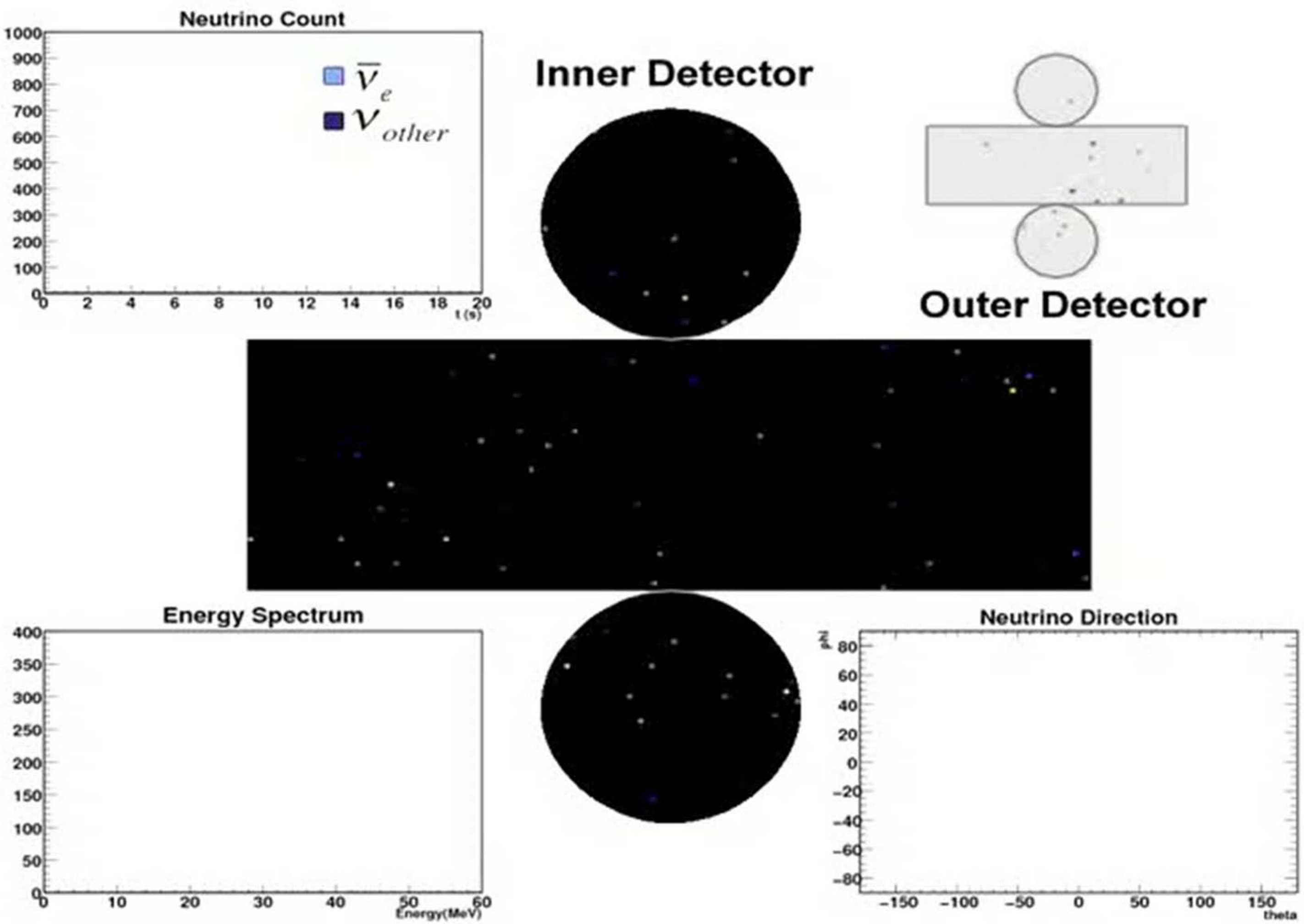
Coincidence Server @ BNL

Alert

Super-Kamiokande Neutrino Detector (Since 1996)

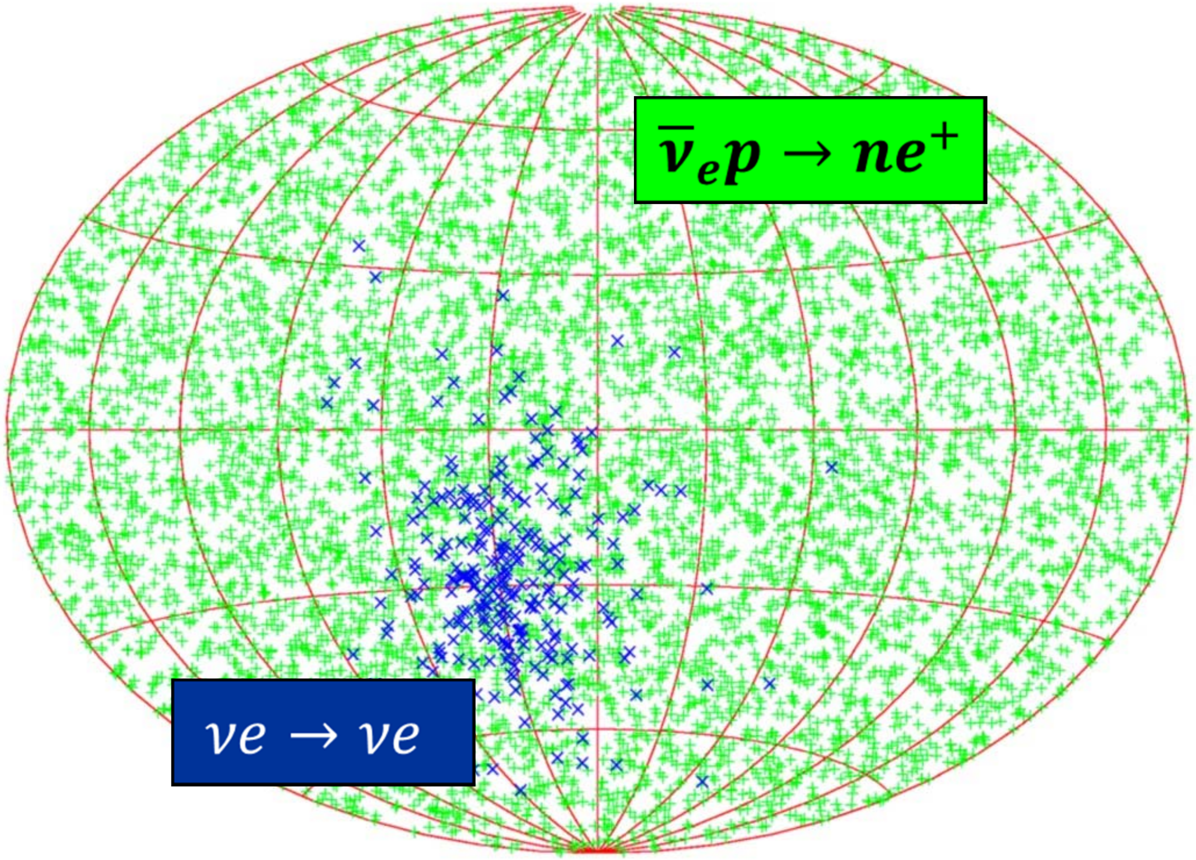


Simulated Supernova Burst in Super-Kamiokande



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

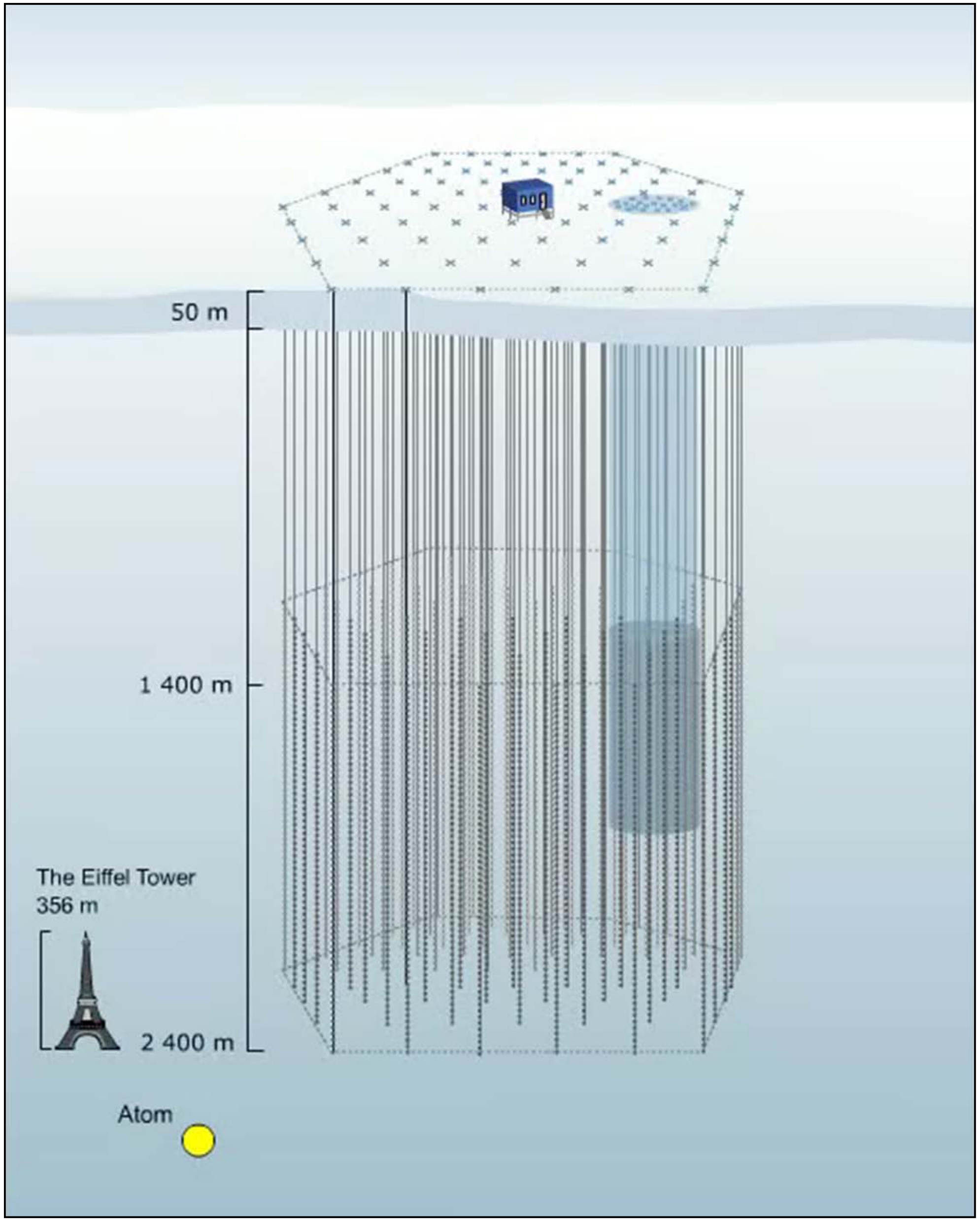
Supernova Pointing with Neutrinos



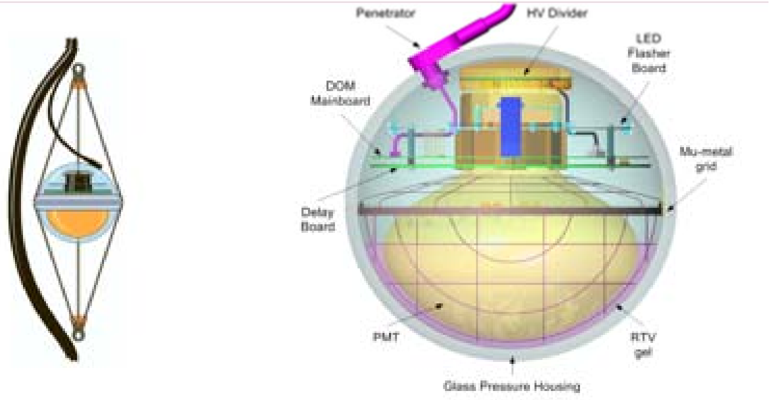
Neutron tagging efficiency		
None	90 %	
7.8°	3.2°	SK
1.4°	0.6°	SK × 30
95% CL half-cone opening angle		

- 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]

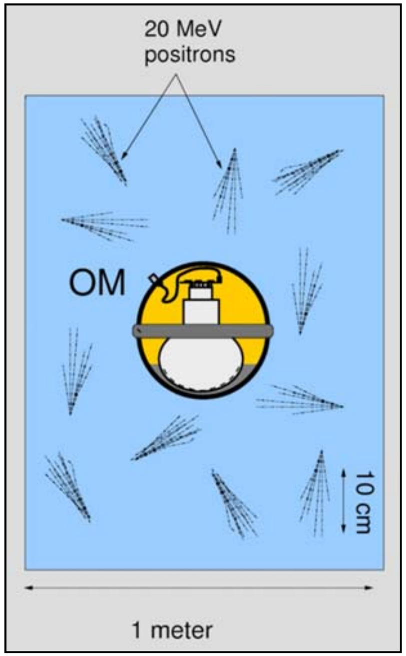
IceCube Neutrino Telescope at the South Pole

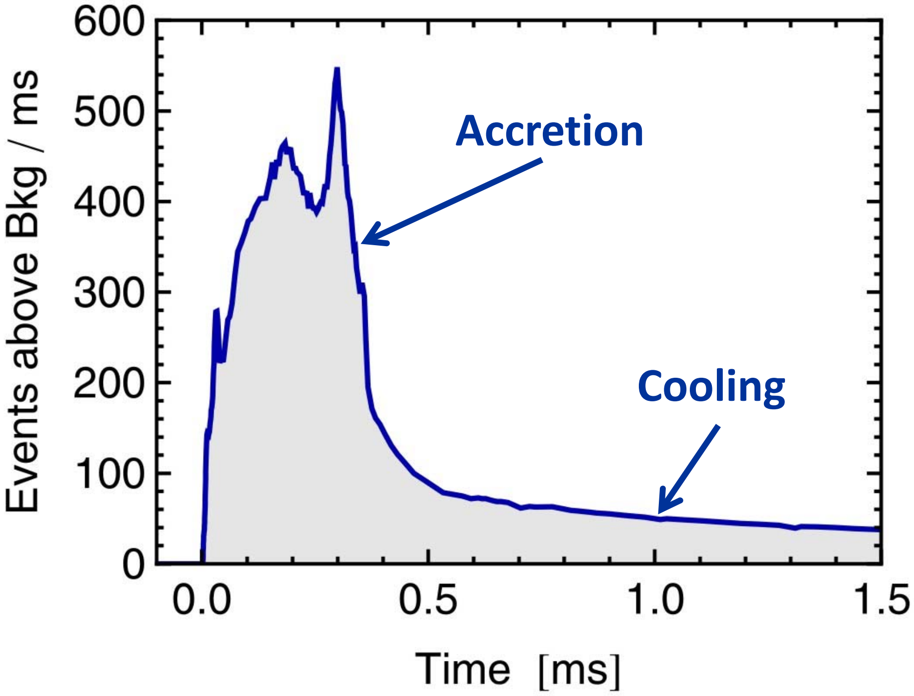


Instrumentation of 1 km^3 antarctic ice with ~ 5000 photo multipliers completed December 2010



IceCube as a Supernova Neutrino Detector



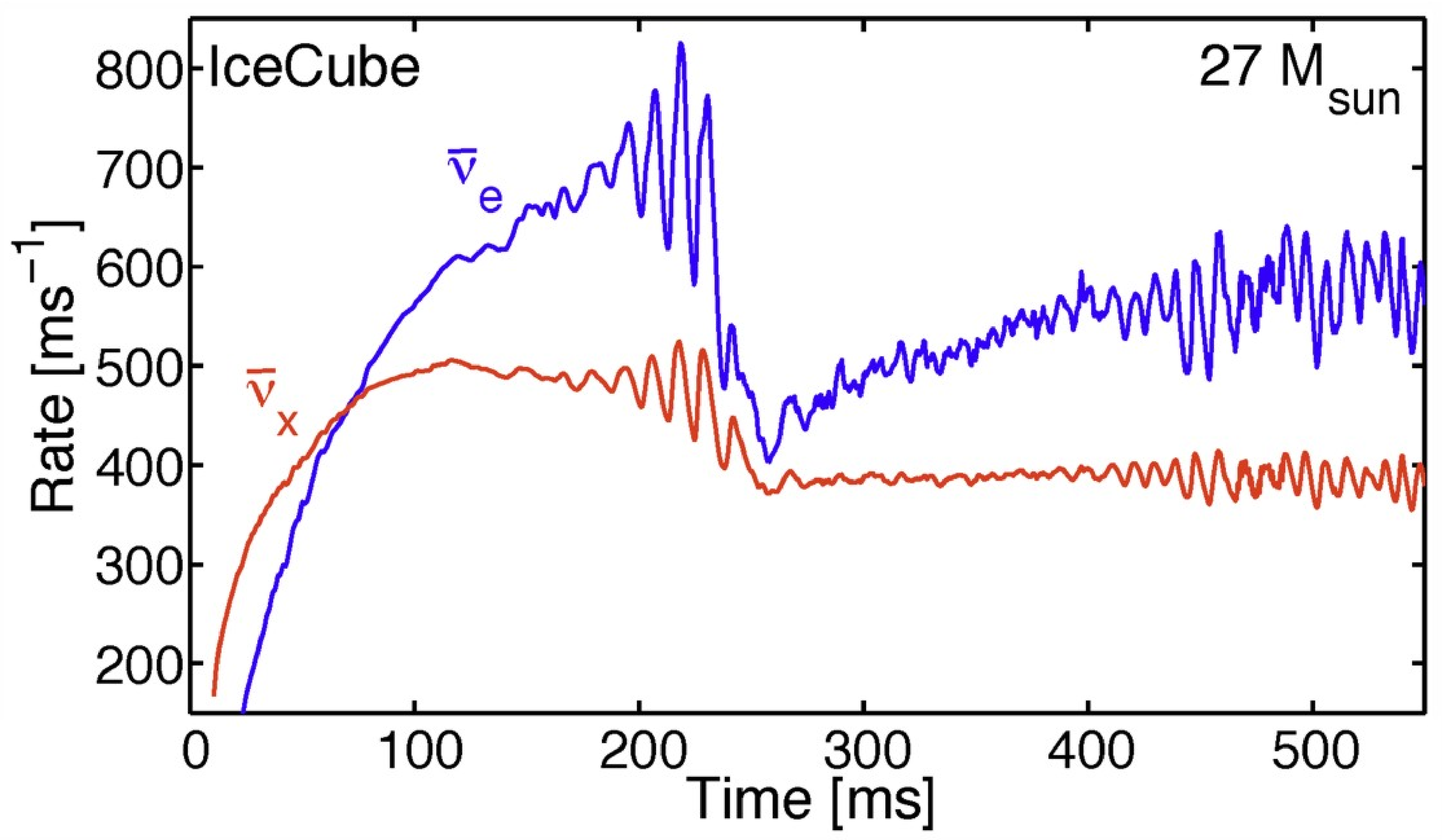


SN signal at 10 kpc
10.8 M_{sun} simulation
of Basel group
[arXiv:0908.1871]

- 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
- Significant energy information from time-correlated hits

Pryor, Roos & Webster, ApJ 329:355, 1988. Halzen, Jacobsen & Zas, astro-ph/9512080. Demirörs, Ribordy & Salathe, arXiv:1106.1937.

Variability seen in Neutrinos (3D Model)

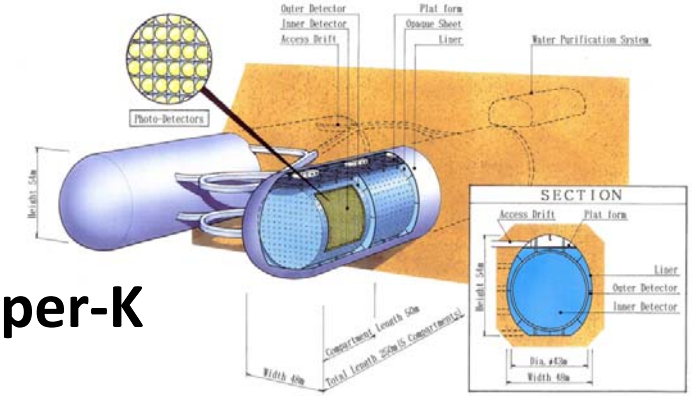


Tamborra, Hanke, Müller, Janka & Raffelt, arXiv:1307.7936
See also Lund, Marek, Lunardini, Janka & Raffelt, arXiv:1006.1889

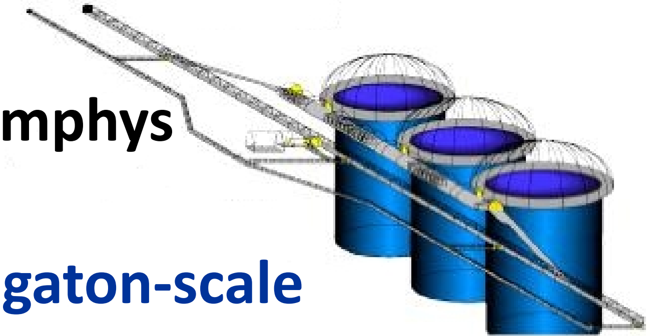
Next Generation Large-Scale Detector Concepts

DUSEL
LBNE

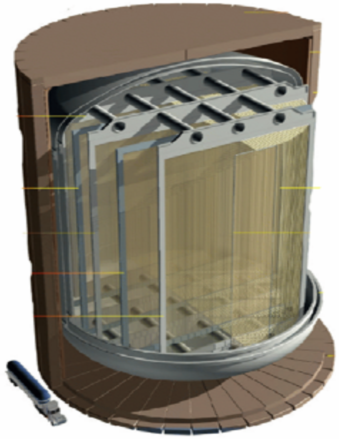
Hyper-K



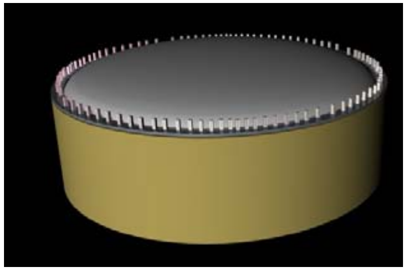
Memphys

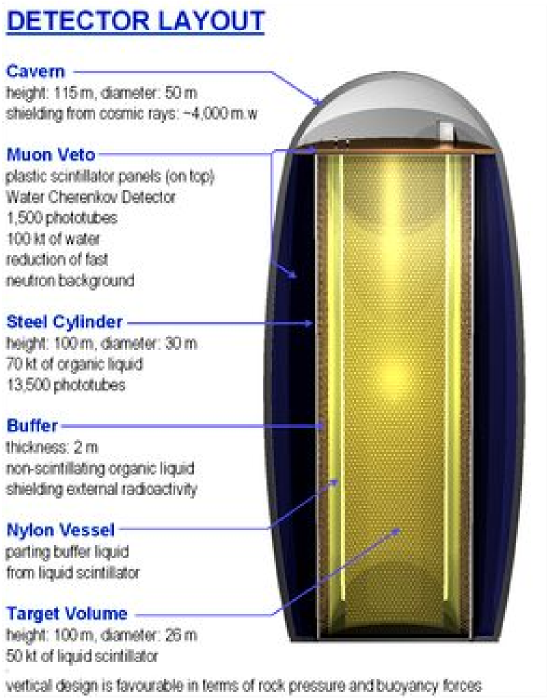


Megaton-scale water Cherenkov



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

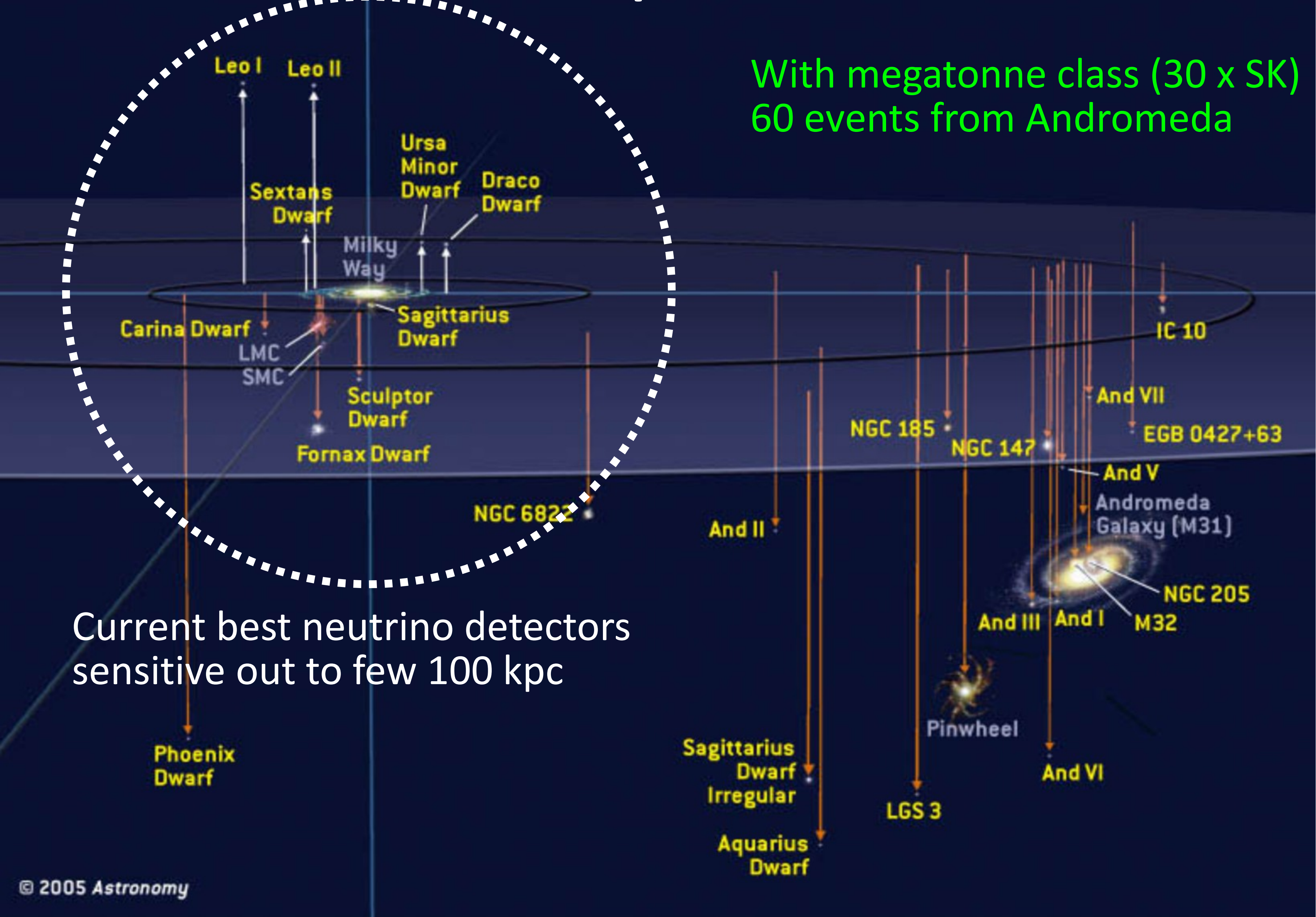
LENA
HanoHano
Juno

Supernova Rate

Local Group of Galaxies

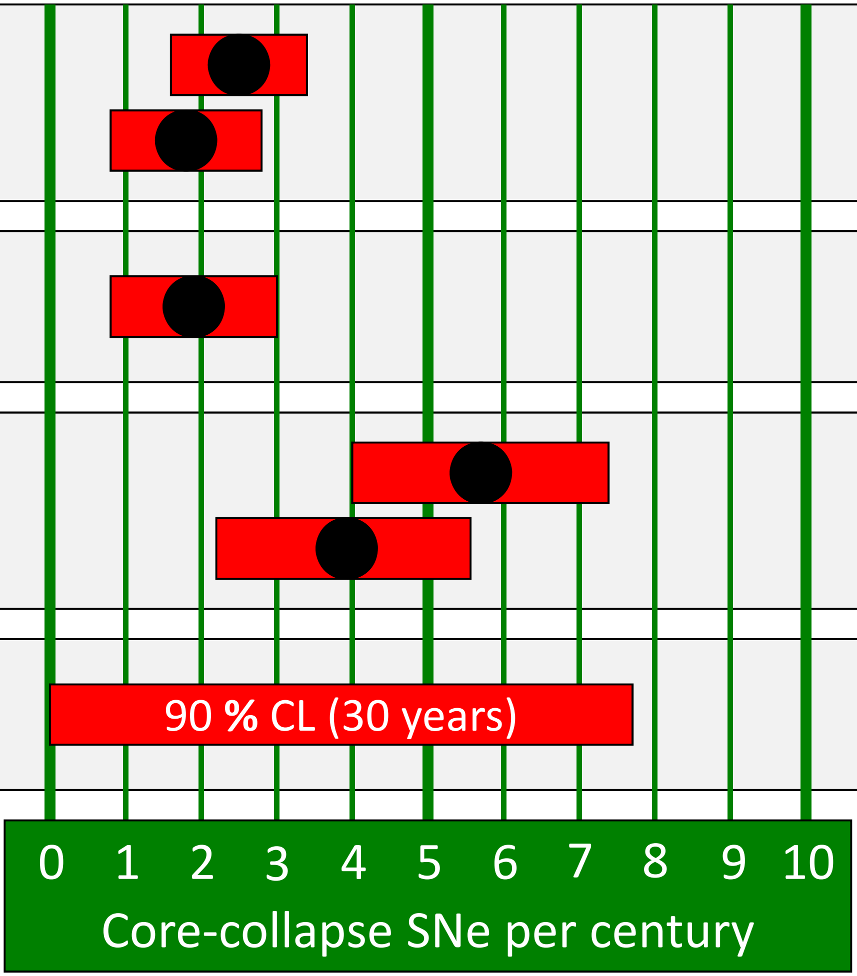
With megatonne class (30 x SK)
60 events from Andromeda

Current best neutrino detectors
sensitive out to few 100 kpc



© 2005 Astronomy

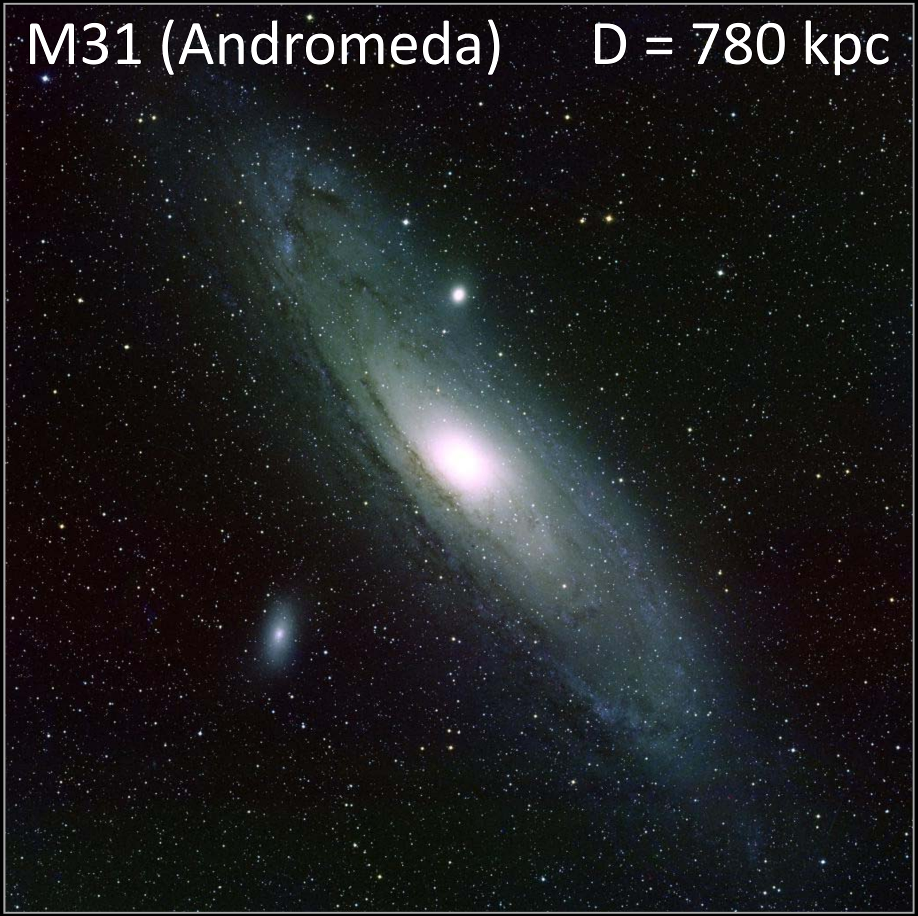
Core-Collapse SN Rate in the Milky Way

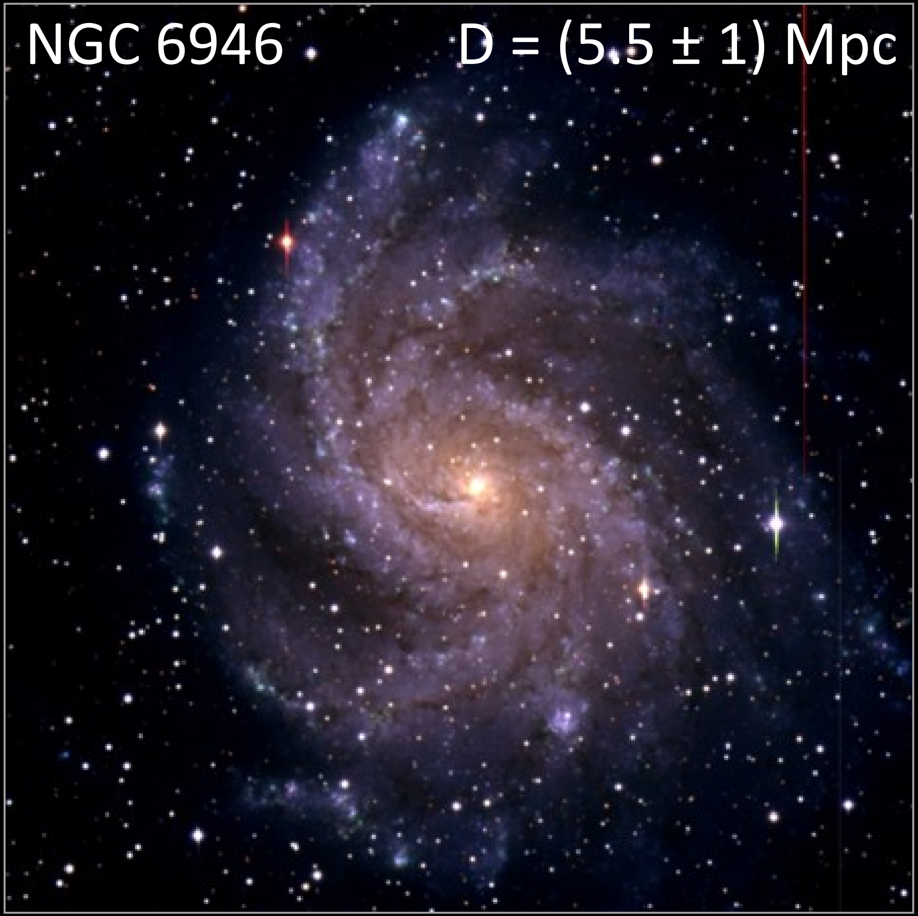


SN statistics in external galaxies	van den Bergh & McClure (1994) Cappellaro & Turatto (2000)
Gamma rays from ^{26}Al (Milky Way)	Diehl et al. (2006)
Historical galactic SNe (all types)	Strom (1994) Tammann et al. (1994)
No galactic neutrino burst	Alekseev et al. (1993)

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

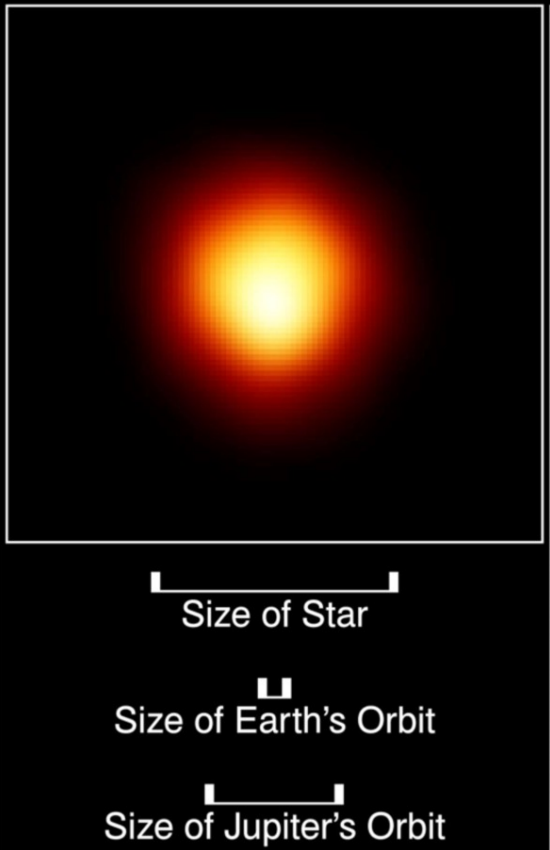




Last observed supernova: 1885A

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)

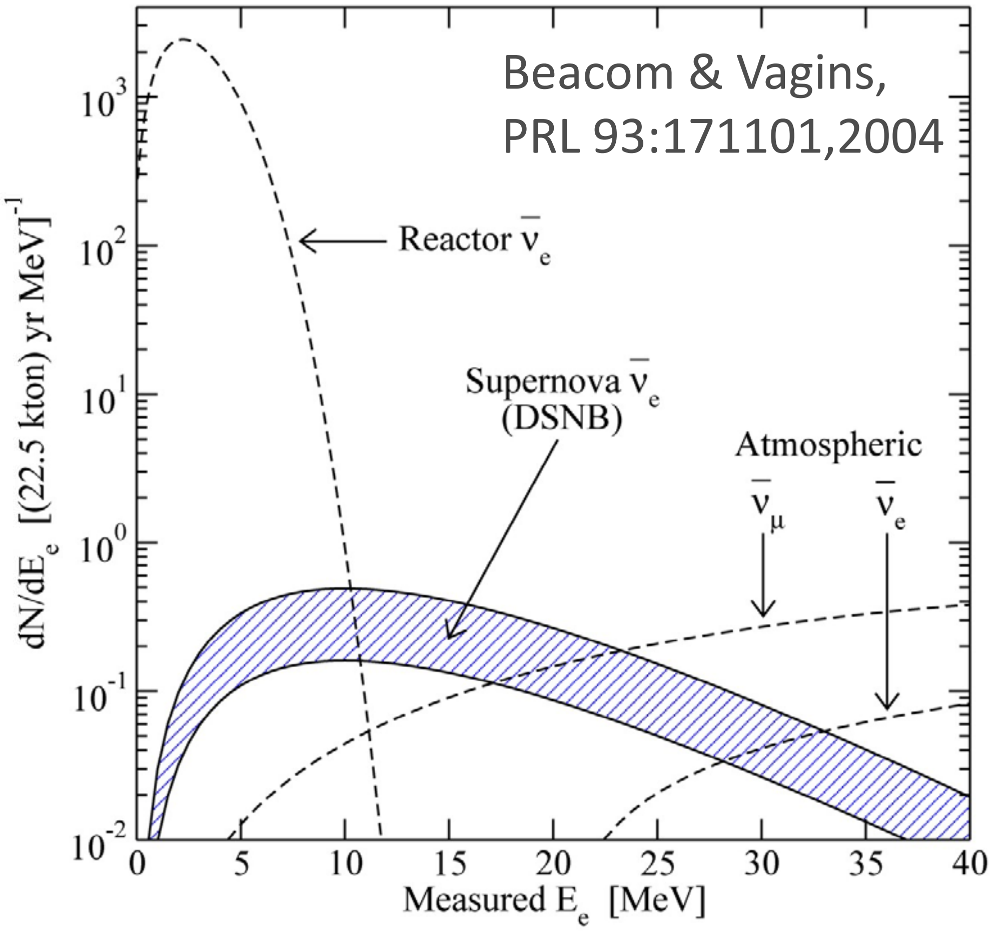
If Betelgeuse goes Supernova:

- 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

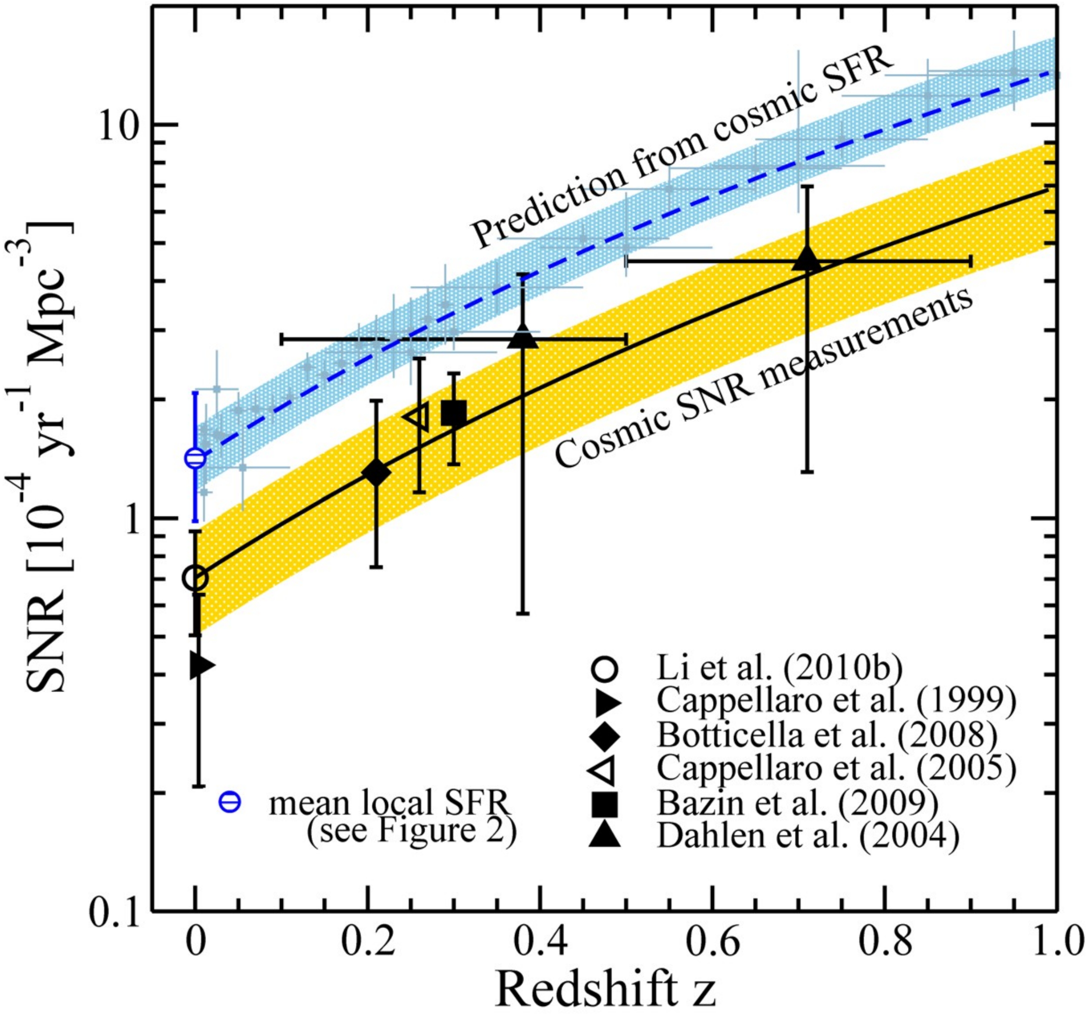
Diffuse Supernova Neutrino Background (DSNB)

- A few 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

Supernova vs. Star Formation Rate in the Universe



Measured SN rate about half the prediction from star formation rate

Many “dark SNe” ?

Horiuchi, Beacom, Kochanek, Prieto, Stanek & Thompson
arXiv:1102.1977

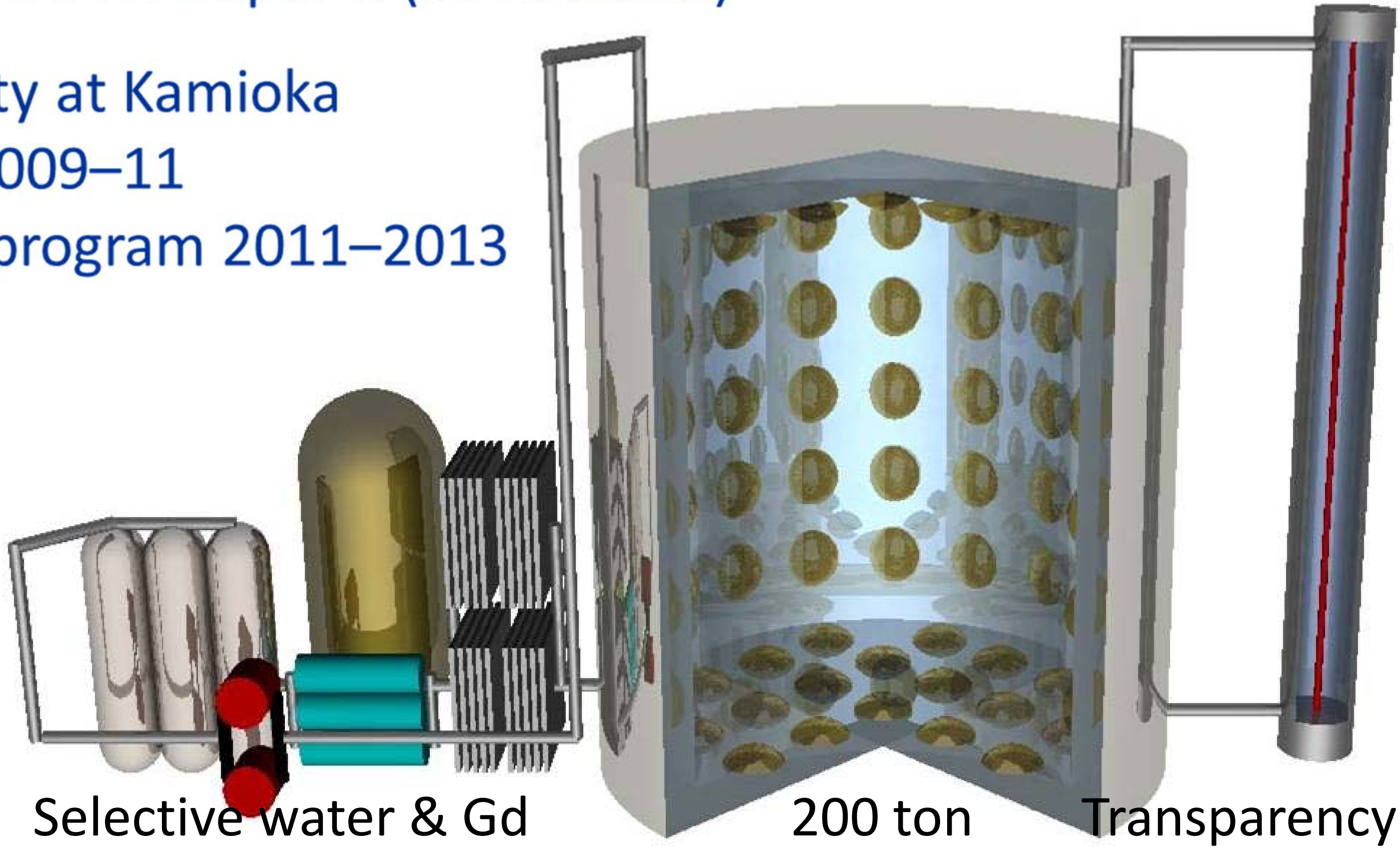
Neutron Tagging in Super-K with Gadolinium

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

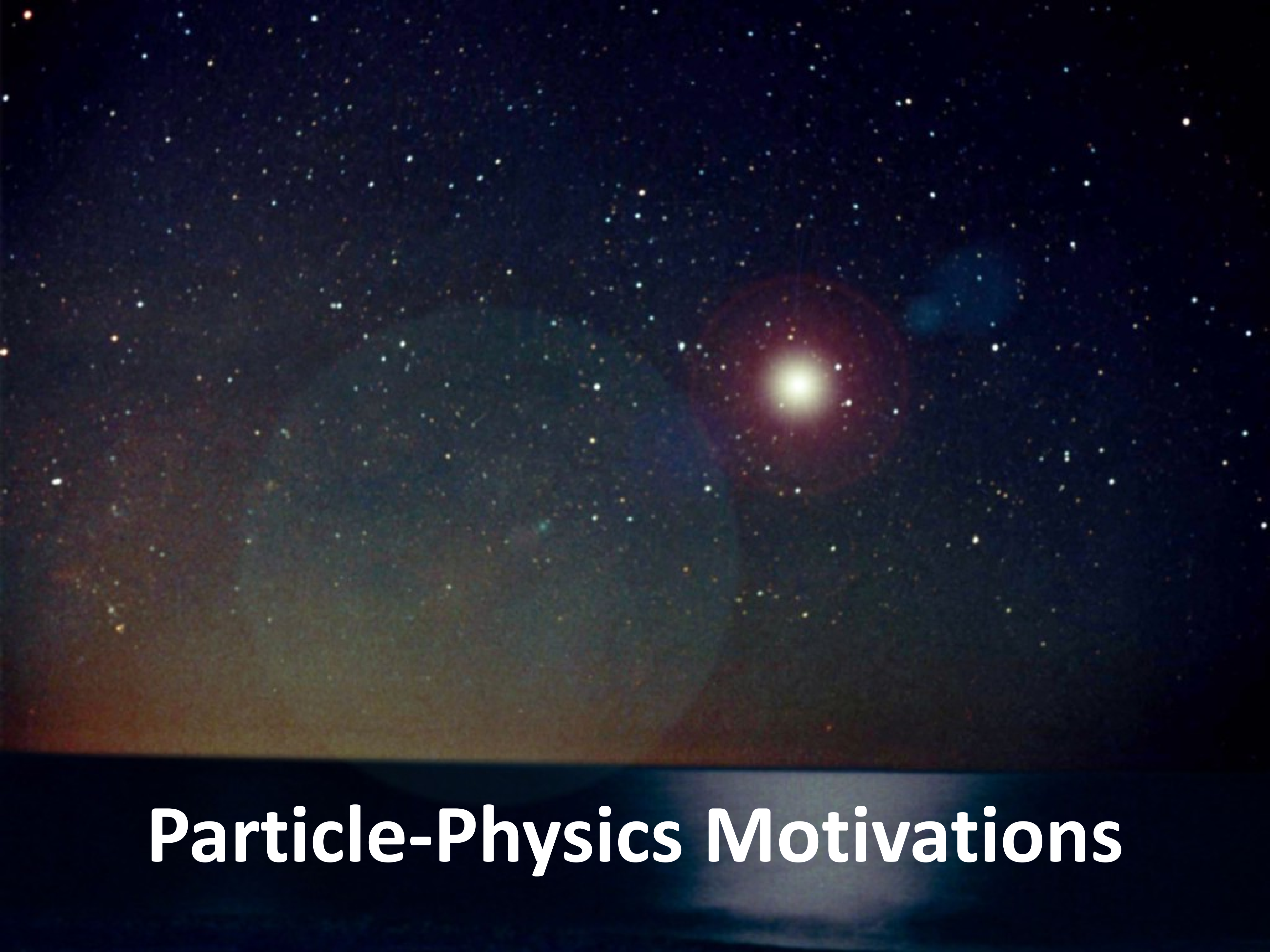


Mark Vagins
Neutrino 2010

Selective water & Gd
filtration system

200 ton
water tank

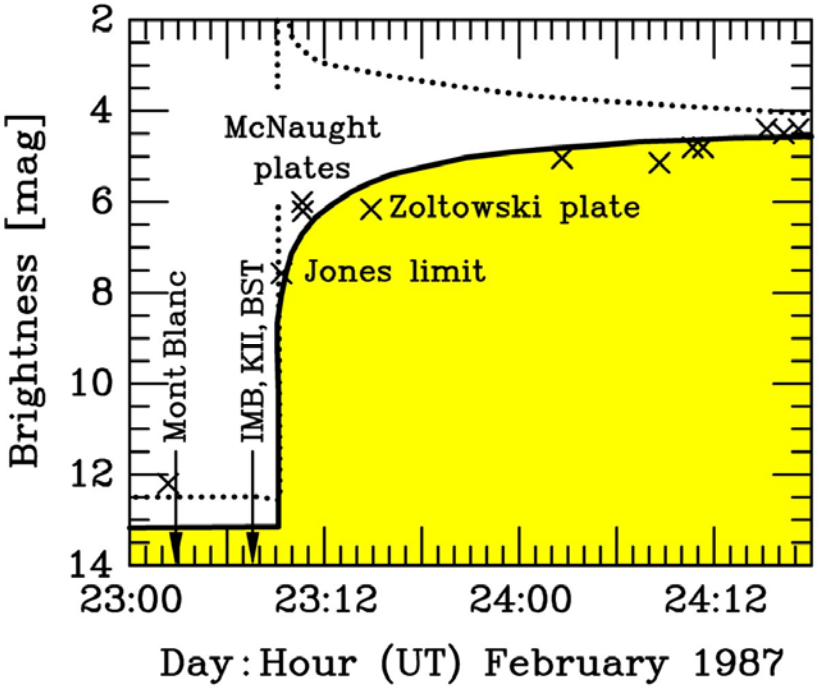
Transparency
measurement



Particle-Physics Motivations

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

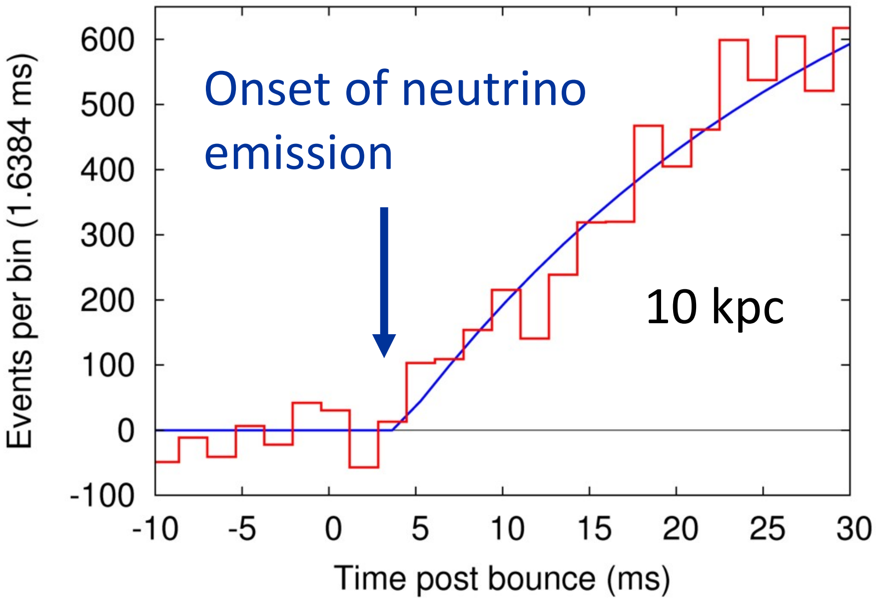
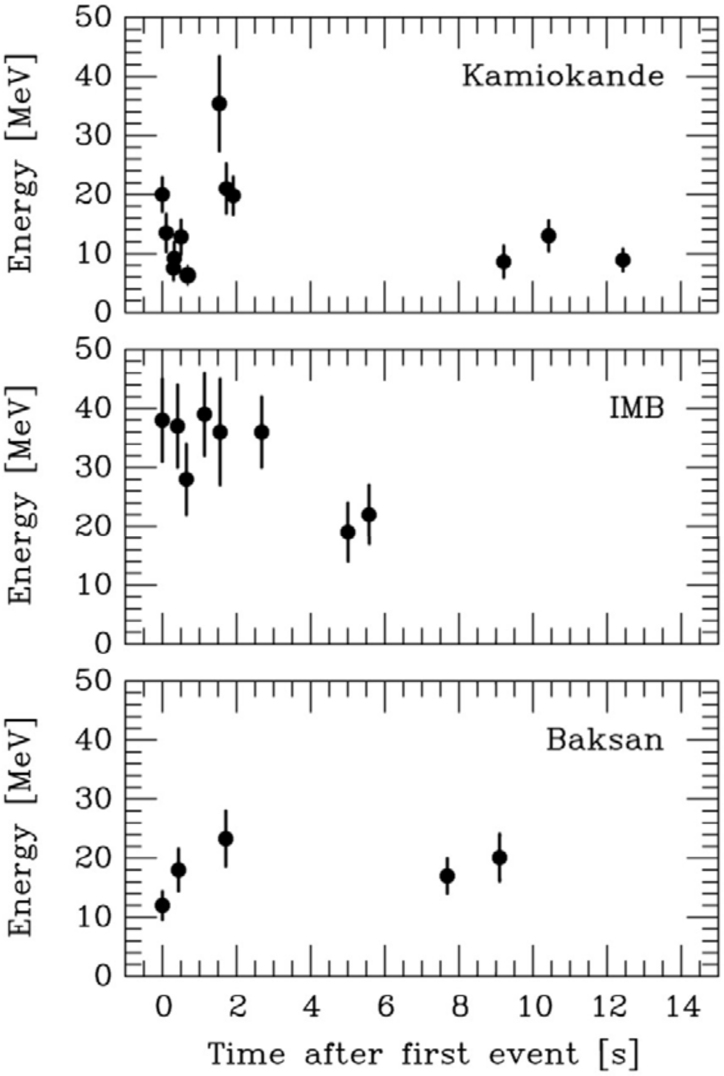


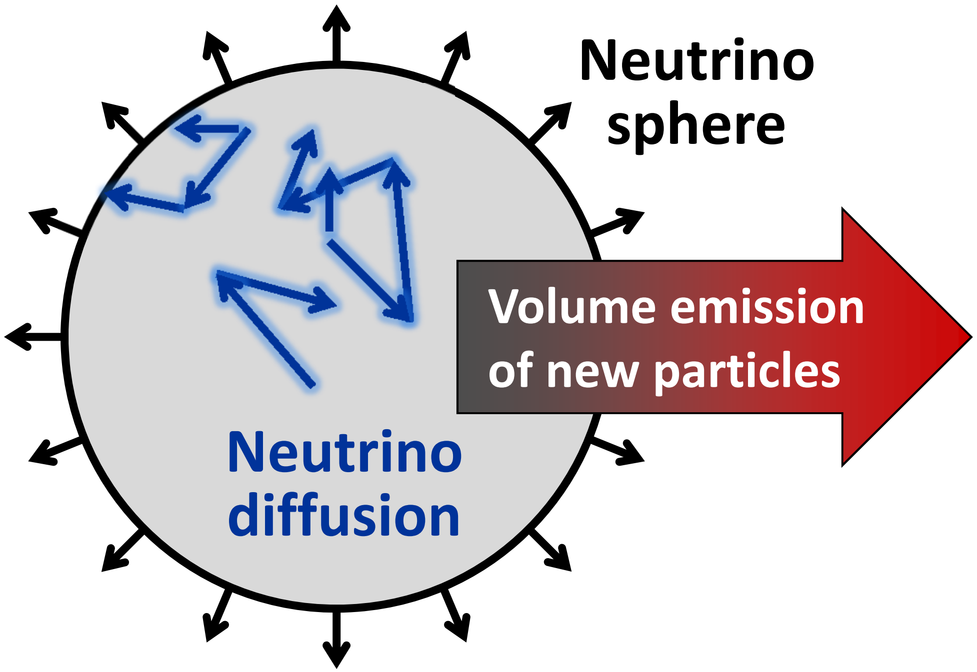
FIG. 1: Typical Monte Carlo realization (red histogram) and reconstructed fit (blue line) for the benchmark case discussed in the text for a SN at 10 kpc.

Halzen & Raffelt, arXiv:0908.2317

Supernova 1987A Energy-Loss Argument

SN 1987A neutrino signal





Volume emission of new particles

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.
Good mesurement of cooling time important!

Neutrino Flavor Oscillations

Neutrino Flavor Oscillations

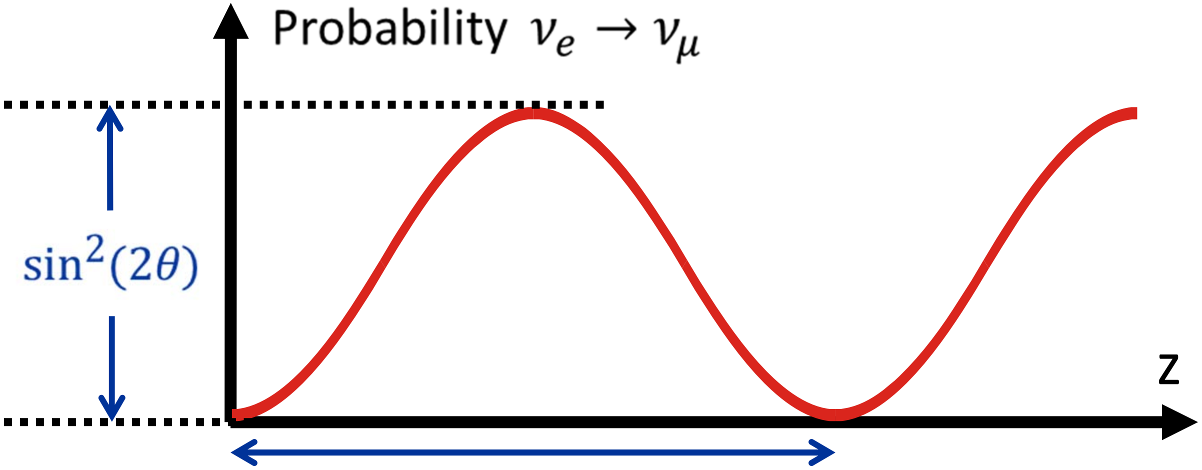
Two-flavor mixing $\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$

Bruno Pontecorvo
(1913–1993)
Invented nu oscillations

Each mass eigenstate propagates as e^{ipz}

with $p = \sqrt{E^2 - m^2} \approx E - m^2/2E$

Phase difference $\frac{\delta m^2}{2E} z$ implies flavor oscillations

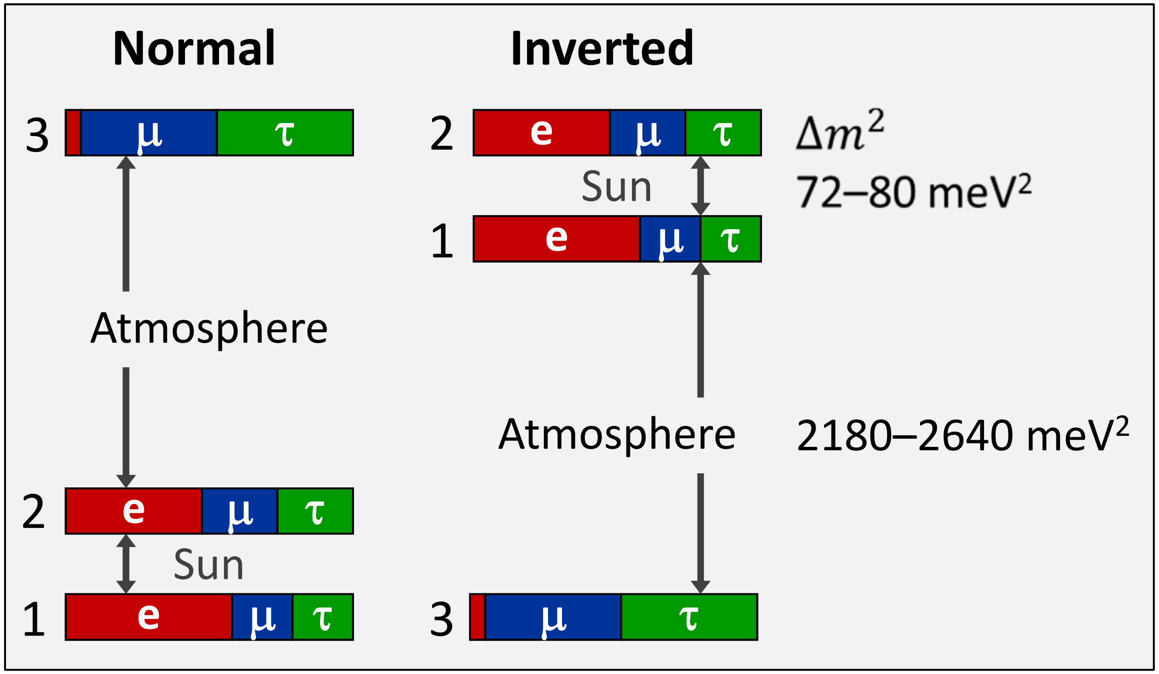


Oscillation Length $\frac{4\pi E}{\delta m^2} = 2.5\ \mathrm{m}\ \frac{E}{\mathrm{MeV}} \left(\frac{\mathrm{eV}}{\delta m}\right)^2$

Three-Flavor Neutrino Parameters

Three mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$ (Euler angles for 3D rotation), $c_{ij} = \cos\theta_{ij}$, a CP-violating “Dirac phase” δ, and two “Majorana phases” α_2 and α_3

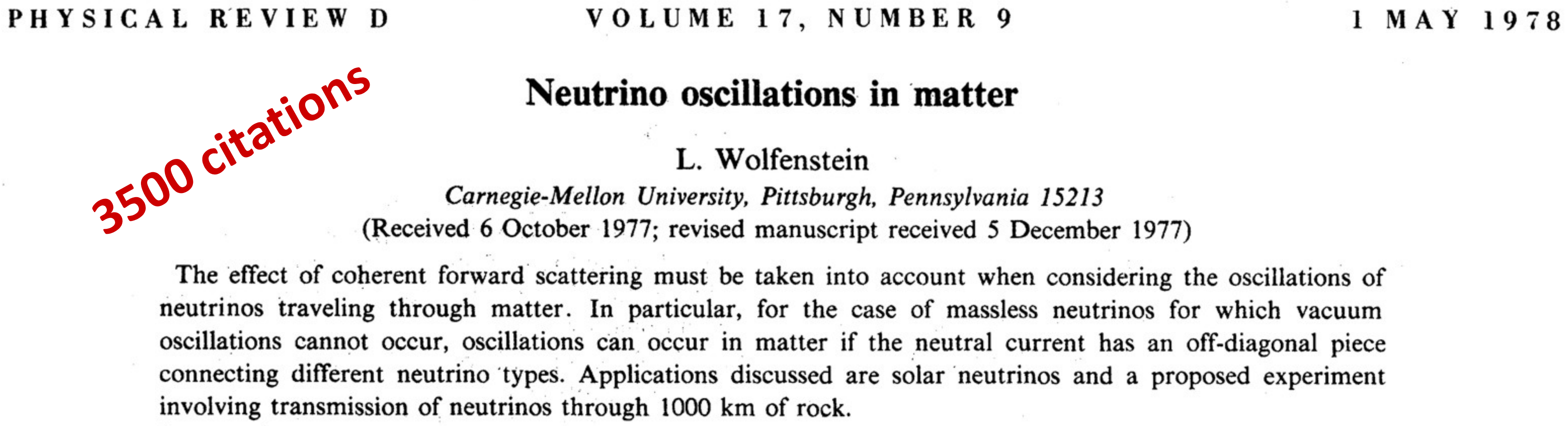
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1&0&0\\ 0&c_{23}&s_{23}\\ 0&-s_{23}&c_{23}\end{pmatrix}}_{\substack{39^\circ<\theta_{23}<53^\circ\\ \text{Atmospheric/LBL-Beams}}} \underbrace{\begin{pmatrix}c_{13}&0&e^{-i\delta}s_{13}\\ 0&1&0\\ -e^{i\delta}s_{13}&0&c_{13}\end{pmatrix}}_{\substack{7^\circ<\theta_{13}<11^\circ\\ \text{Reactor}}} \underbrace{\begin{pmatrix}c_{12}&s_{12}&0\\ -s_{12}&c_{12}&0\\ 0&0&1\end{pmatrix}}_{\substack{33^\circ<\theta_{12}<37^\circ\\ \text{Solar/KamLAND}}} \underbrace{\begin{pmatrix}1&0&0\\ 0&e^{i\frac{\alpha_2}{2}}&0\\ 0&0&e^{i\frac{\alpha_3}{2}}\end{pmatrix}}_{\substack{\text{Relevant for}\\ 0\nu2\beta\text{ decay}}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



Tasks and Open Questions

- Precision for all angles
- CP-violating phase δ ?
- Mass ordering ?
  (normal vs inverted)
- Absolute masses ?
  (hierarchical vs degenerate)
- Dirac or Majorana ?

3500 citations



PHYSICAL REVIEW D VOLUME 17, NUMBER 9 1 MAY 1978

Neutrino oscillations in matter

L. Wolfenstein
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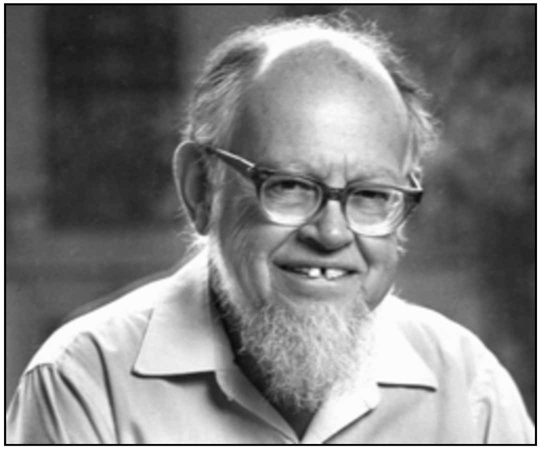
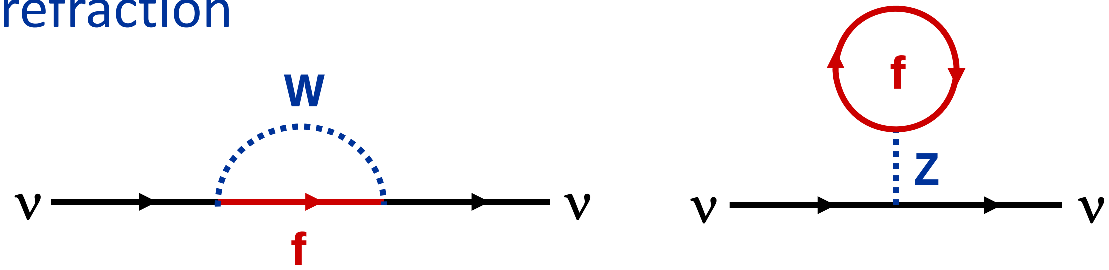
(Received 6 October 1977; revised manuscript received 5 December 1977)

The effect of coherent forward scattering must be taken into account when considering the oscillations of neutrinos traveling through matter. In particular, for the case of massless neutrinos for which vacuum oscillations cannot occur, oscillations can occur in matter if the neutral current has an off-diagonal piece connecting different neutrino types. Applications discussed are solar neutrinos and a proposed experiment involving transmission of neutrinos through 1000 km of rock.



Lincoln Wolfenstein

Neutrinos in a medium suffer flavor-dependent refraction

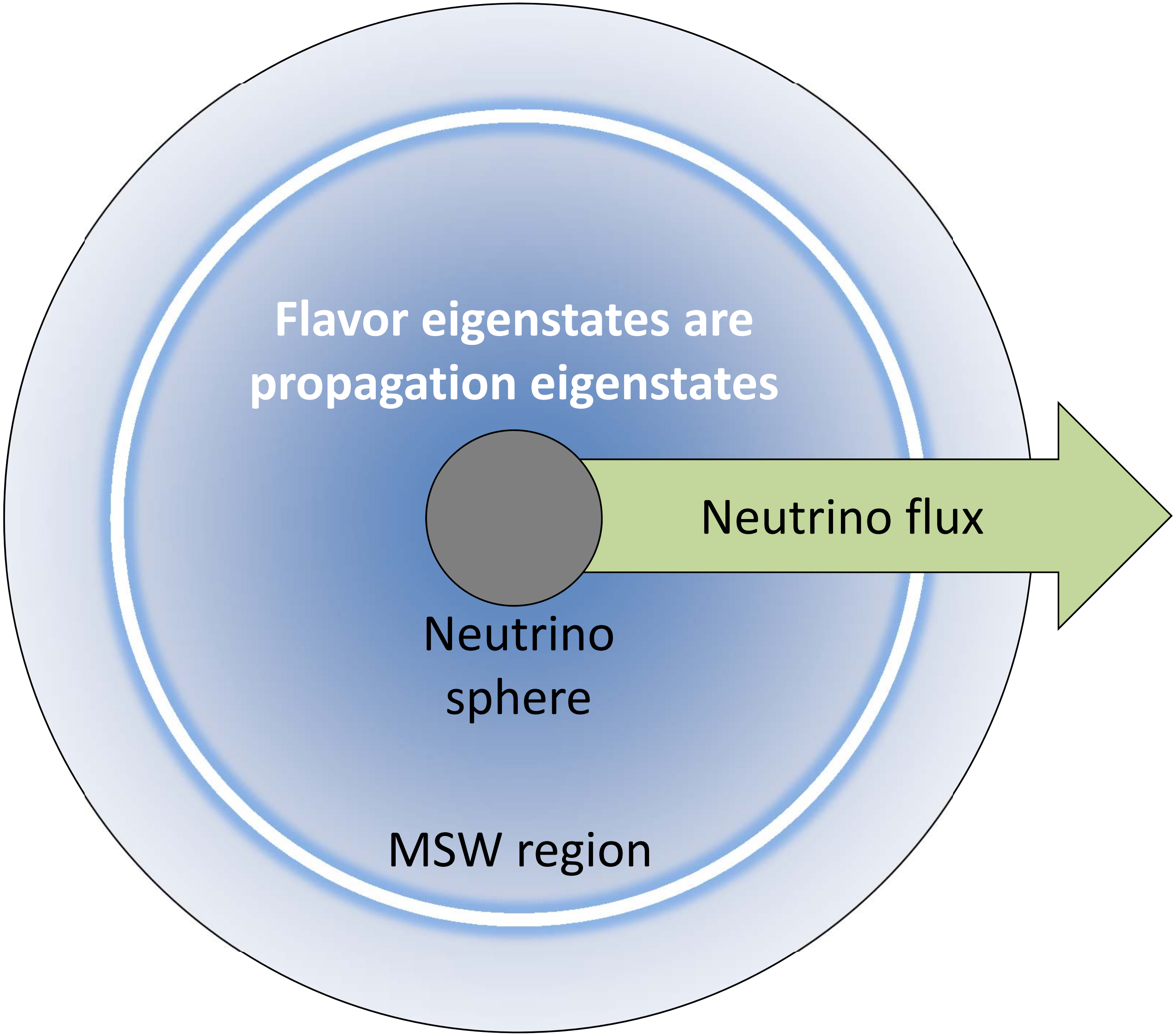


$$V_{\mathrm{weak}} = \sqrt{2}G_{\mathrm{F}} \times \begin{cases} N_{\mathrm{e}} - N_{\mathrm{n}}/2 & \text{for } \nu_{\mathrm{e}} \\ -N_{\mathrm{n}}/2 & \text{for } \nu_{\mu} \end{cases}$$

Typical density of Earth: 5 g/cm^3

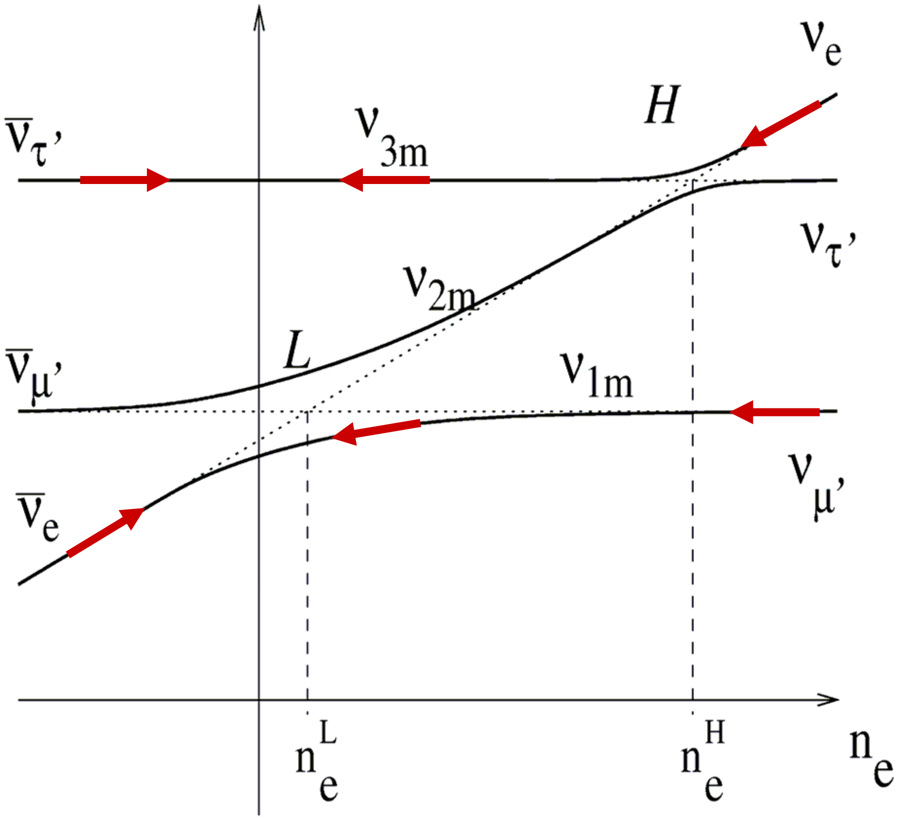
$$\Delta V_{\mathrm{weak}} \approx 2 \times 10^{-13}\ \mathrm{eV} = 0.2\ \mathrm{peV}$$

Flavor Oscillations in Core-Collapse Supernovae



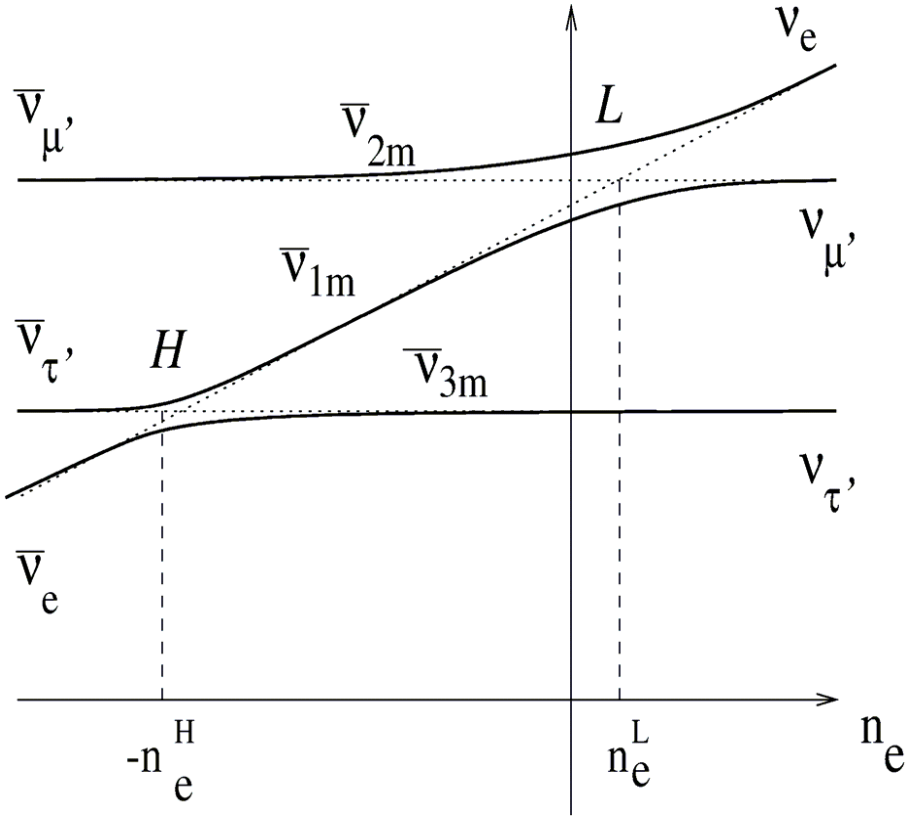
Three-Flavor Eigenvalue Diagram

Normal mass ordering (NH)



Vacuum

Inverted mass ordering (IH)



Vacuum

Dighe & Smirnov, Identifying the neutrino mass spectrum from a supernova neutrino burst, astro-ph/9907423

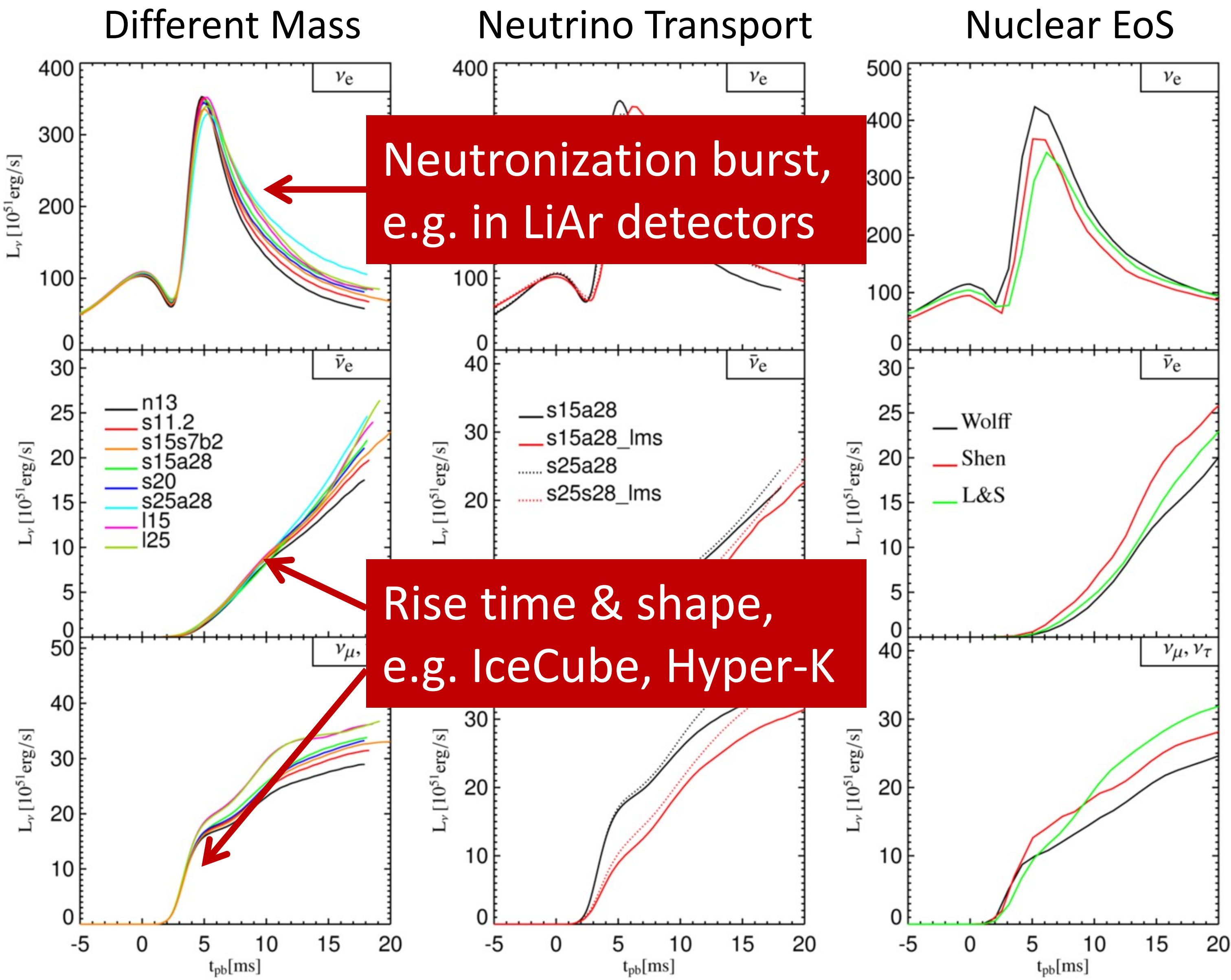
SN Flavor Oscillations and Mass Hierarchy

- Mixing angle Θ_{13} has been measured to be “large”
- MSW conversion in SN envelope adiabatic
- Assume that collective flavor oscillations are not important

	Mass ordering	
	Normal (NH)	Inverted (IH)
ν_e survival prob.	0	$\sin^2\theta_{12} \approx 0.3$
$\overline{\nu}_e$ survival prob.	$\cos^2\theta_{12} \approx 0.7$	0
$\overline{\nu}_e$ Earth effects	Yes	No

- When are collective oscillations important?
- How to detect signatures of hierarchy?

Neutronization Burst as a Standard Candle



Different Mass

Neutrino Transport

Nuclear EoS

Neutronization burst, e.g. in LiAr detectors

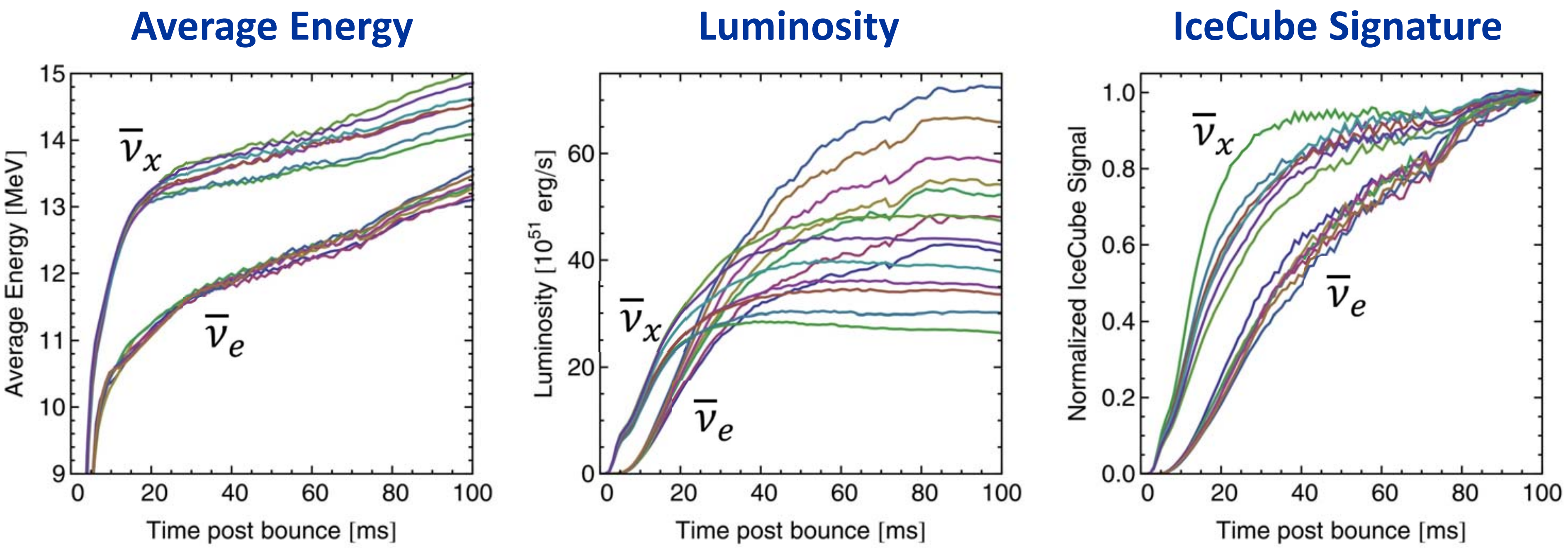
Rise time & shape, e.g. IceCube, Hyper-K

If mixing scenario is known, can determine SN distance (better than 5-10%)

Kachelriess, Tomàs, Buras, Janka, Marek & Rampp, astro-ph/0412082

Early Phase Signal in Anti-Neutrino Sector

Garching Models with M = 12–40 $M_\odot$



Average Energy

Luminosity

IceCube Signature

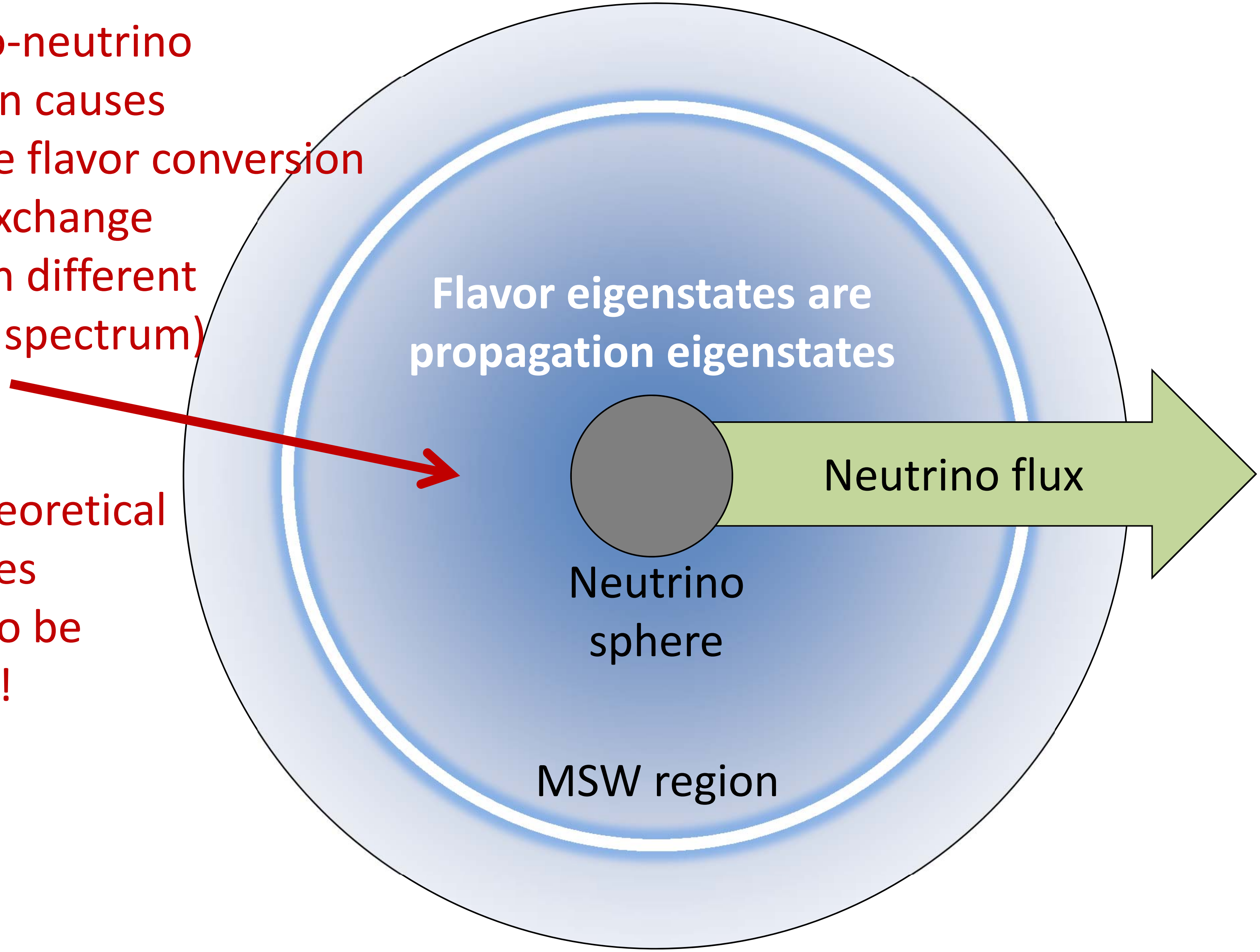
- In principle very sensitive to hierarchy, notably IceCube
- "Standard candle" to be confirmed beyond Garching models

Abbasi et al. (IceCube Collaboration) A&A 535 (2011) A109
Serpico, Chakraborty, Fischer, Hüdepohl, Janka & Mirizzi, arXiv:1111.4483

Neutrino Flavor Conversion

Neutrino-neutrino refraction causes collective flavor conversion (flavor exchange between different parts of spectrum)

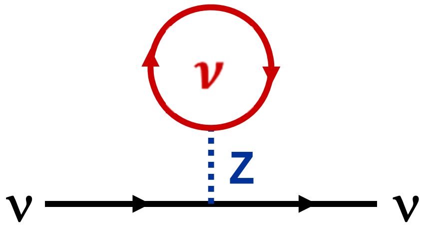
Many theoretical challenges remain to be resolved!



Flavor-Off-Diagonal Refractive Index

2-flavor neutrino evolution as an effective 2-level problem

$$\mathrm{i}\frac{\partial}{\partial t}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = H\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$



Effective mixing Hamiltonian

$$H = \frac{M^2}{2E} + \sqrt{2}G_\mathrm{F}\begin{pmatrix} N_e - \frac{N_n}{2} & 0 \\ 0 & -\frac{N_n}{2}\end{pmatrix} + \sqrt{2}G_\mathrm{F}\begin{pmatrix} N_{\nu_e} & N_{\langle\nu_e|\nu_\mu\rangle} \\ N_{\langle\nu_\mu|\nu_e\rangle} & N_{\nu_\mu}\end{pmatrix}$$

Mass term in flavor basis: causes vacuum oscillations

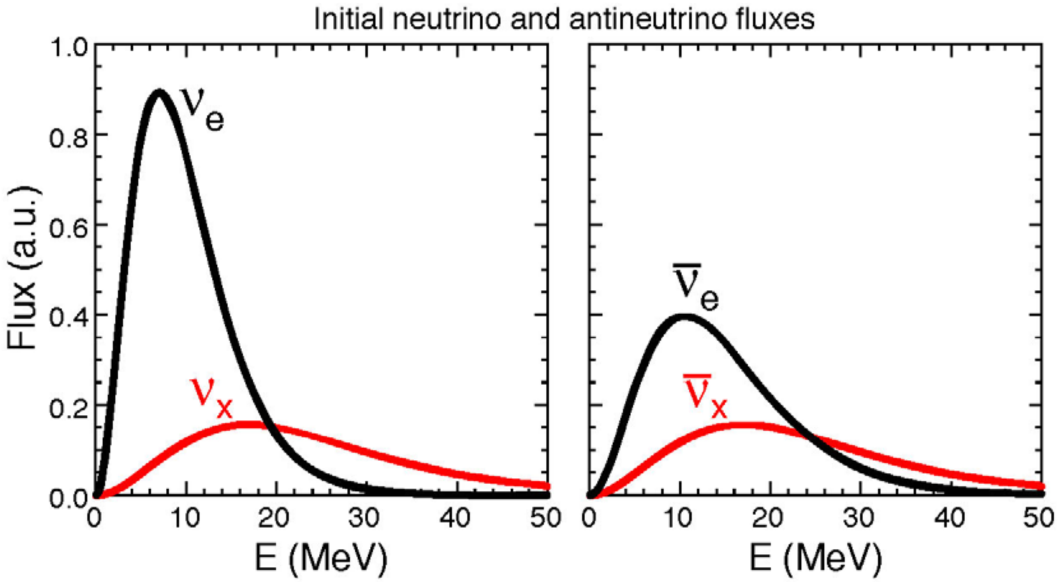
Wolfenstein’s weak potential, causes MSW “resonant” conversion together with vacuum term

Flavor-off-diagonal potential, caused by flavor oscillations. (J.Pantaleone, PLB 287:128,1992)

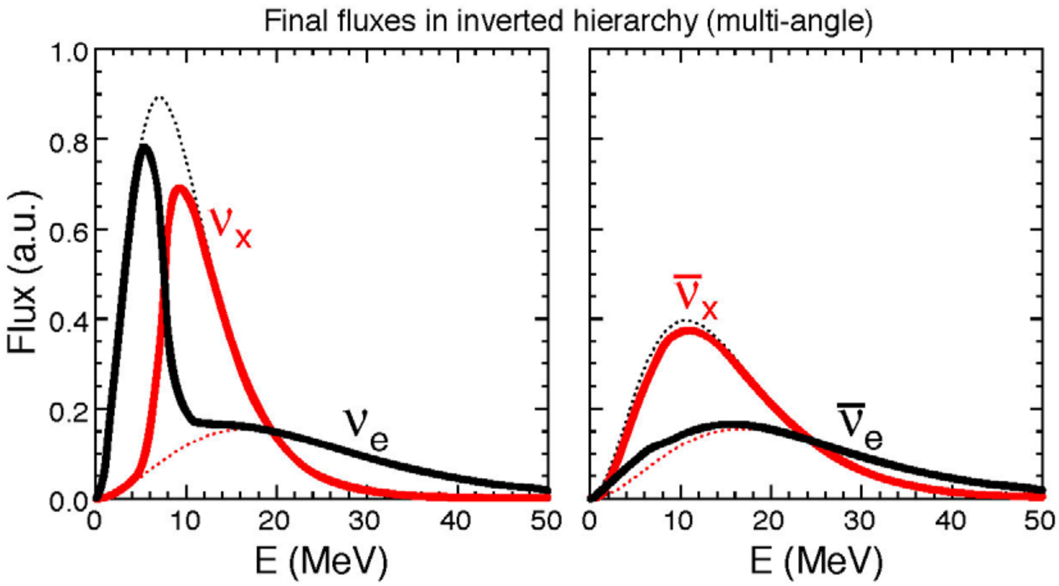
Flavor oscillations feed back on the Hamiltonian: Nonlinear effects!

Spectral Split

Initial fluxes at neutrino sphere



After collective transformation



Figures from

Fogli, Lisi, Marrone & Mirizzi, arXiv:0707.1998

Explanations in

Raffelt & Smirnov arXiv:0705.1830 and 0709.4641

Duan, Fuller, Carlson & Qian arXiv:0706.4293 and 0707.0290

Collective Supernova Nu Oscillations since 2006

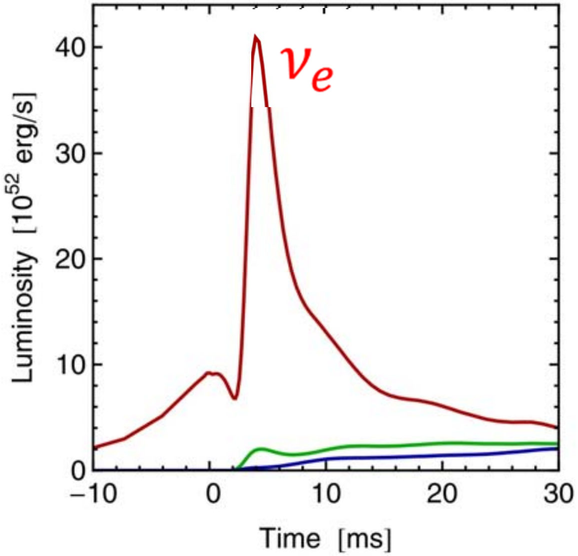
Two seminal papers in 2006 triggered a torrent of activities

Duan, Fuller, Qian, astro-ph/0511275, Duan et al. astro-ph/0606616

Balantekin, Gava & Volpe [0710.3112]. Balantekin & Pehlivan [astro-ph/0607527]. Blennow, Mirizzi & Serpico [0810.2297]. Cherry, Fuller, Carlson, Duan & Qian [1006.2175, 1108.4064]. Cherry, Wu, Fuller, Carlson, Duan & Qian [1109.5195]. Cherry, Carlson, Friedland, Fuller & Vlasenko [1203.1607]. Chakraborty, Choubey, Dasgupta & Kar [0805.3131]. Chakraborty, Fischer, Mirizzi, Saviano, Tomàs [1104.4031, 1105.1130]. Choubey, Dasgupta, Dighe & Mirizzi [1008.0308]. Dasgupta & Dighe [0712.3798]. Dasgupta, Dighe & Mirizzi [0802.1481]. Dasgupta, Dighe, Raffelt & Smirnov [0904.3542]. Dasgupta, Dighe, Mirizzi & Raffelt [0801.1660, 0805.3300]. Dasgupta, Mirizzi, Tamborra & Tomàs [1002.2943]. Dasgupta, Raffelt & Tamborra [1001.5396]. Dasgupta, O'Connor & Ott [1106.1167]. Duan [1309.7377]. Duan, Fuller, Carlson & Qian [astro-ph/0608050, 0703776, 0707.0290, 0710.1271]. Duan, Fuller & Qian [0706.4293, 0801.1363, 0808.2046, 1001.2799]. Duan, Fuller & Carlson [0803.3650]. Duan & Kneller [0904.0974]. Duan & Friedland [1006.2359]. Duan, Friedland, McLaughlin & Surman [1012.0532]. Esteban-Pretel, Mirizzi, Pastor, Tomàs, Raffelt, Serpico & Sigl [0807.0659]. Esteban-Pretel, Pastor, Tomàs, Raffelt & Sigl [0706.2498, 0712.1137]. Fogli, Lisi, Marrone & Mirizzi [0707.1998]. Fogli, Lisi, Marrone & Tamborra [0812.3031]. Friedland [1001.0996]. Gava & Jean-Louis [0907.3947]. Gava & Volpe [0807.3418]. Galais, Kneller & Volpe [1102.1471]. Galais & Volpe [1103.5302]. Gava, Kneller, Volpe & McLaughlin [0902.0317]. Hannestad, Raffelt, Sigl & Wong [astro-ph/0608695]. Wei Liao [0904.0075, 0904.2855]. Lunardini, Müller & Janka [0712.3000]. Mirizzi [1308.5255, 1308.1402]. Mirizzi, Pozzorini, Raffelt & Serpico [0907.3674]. Mirizzi & Serpico [1111.4483]. Mirizzi & Tomàs [1012.1339]. Pehlivan, Balantekin, Kajino & Yoshida [1105.1182]. Pejcha, Dasgupta & Thompson [1106.5718]. Raffelt [0810.1407, 1103.2891]. Raffelt, Sarikas & Seixas [1305.7140]. Raffelt & Seixas [1307.7625]. Raffelt & Sigl [hep-ph/0701182]. Raffelt & Smirnov [0705.1830, 0709.4641]. Raffelt & Tamborra [1006.0002]. Sawyer [hep-ph/0408265, 0503013, 0803.4319, 1011.4585]. Sarikas, Raffelt, Hüdepohl & Janka [1109.3601]. Sarikas, Tamborra, Raffelt, Hüdepohl & Janka [1204.0971]. Saviano, Chakraborty, Fischer, Mirizzi [1203.1484]. Väänänen & Volpe [1306.6372]. Volpe, Väänänen & Espinoza [1302.2374]. Vlasenko, Fuller Cirigliano [1309.2628]. Wu & Qian [1105.2068].

Three Phases – Three Opportunities

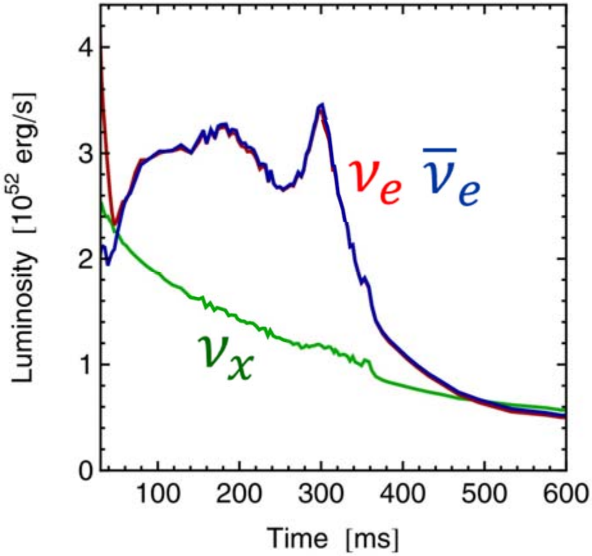
Prompt ν_e burst



Standard Candle (?)

- SN theory
- Distance
- Flavor conversions
- Multi-messenger time of flight

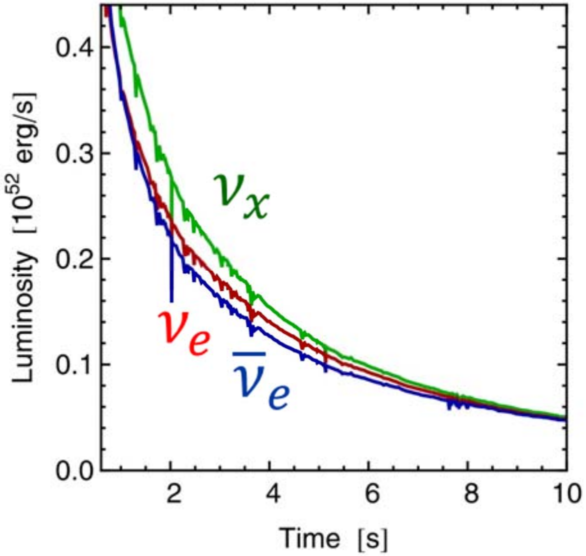
Accretion



Strong variations (progenitor, 3D effects, black hole formation, …)

- Testing astrophysics of core collapse
- Flavor conversions strong impact on signal

Cooling



EoS & mass dependence

- Testing Nuclear Physics
- Nucleosynthesis in neutrino-driven wind
- Particle bounds from cooling speed (axions …)

Neutrinos from next nearby supernova:
A once-in-a-lifetime opportunity – don’t miss it!