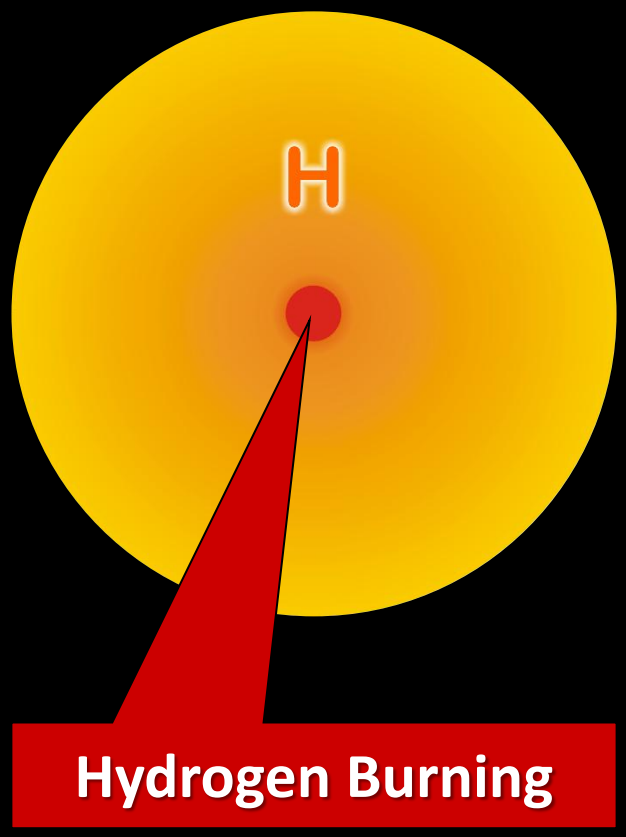
Georg Raffelt, Max-Planck-Institut für Physik, München

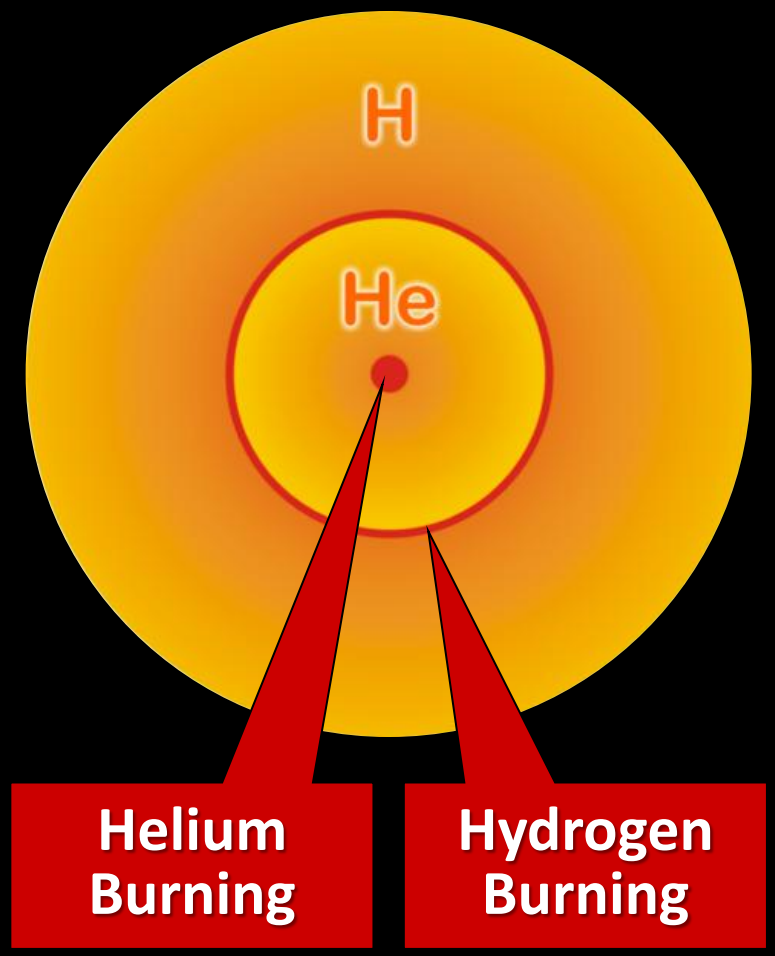
Physics Opportunities with Supernova Neutrinos

Stellar Collapse and Supernova Explosion

Main-sequence star

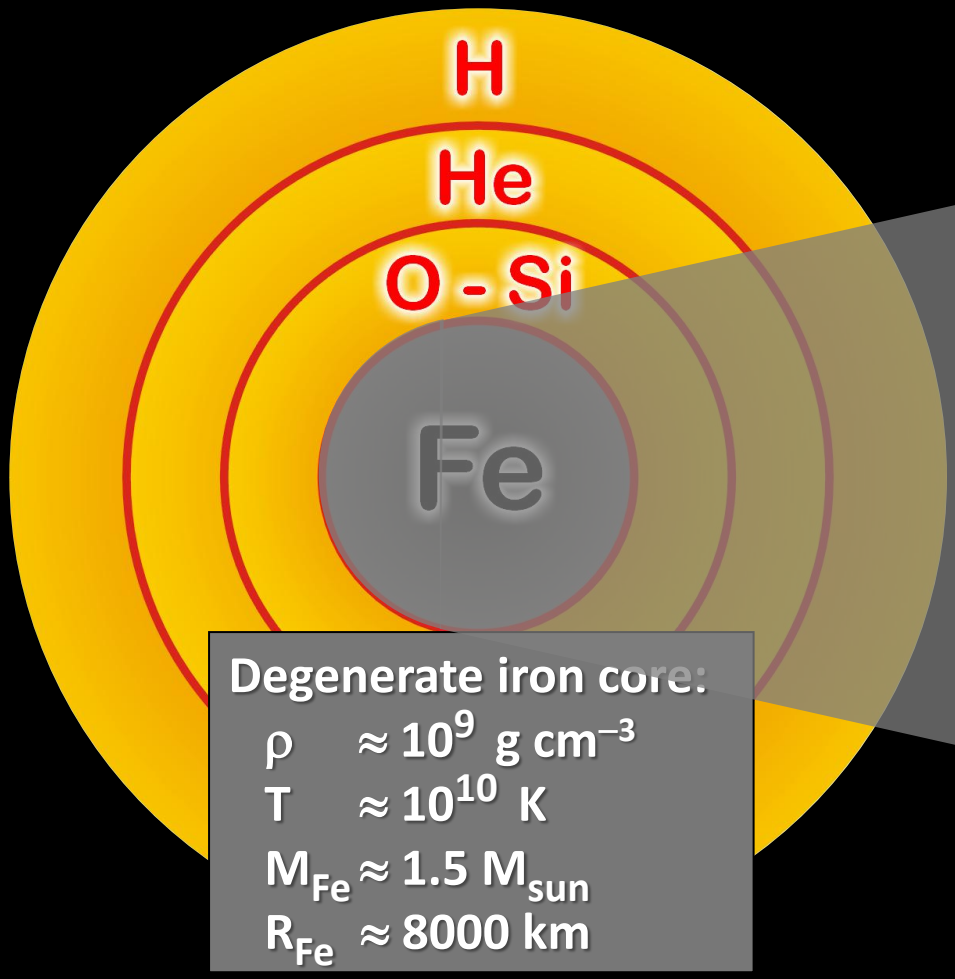


Helium-burning star



Stellar Collapse and Supernova Explosion

Onion structure



Degenerate iron core:

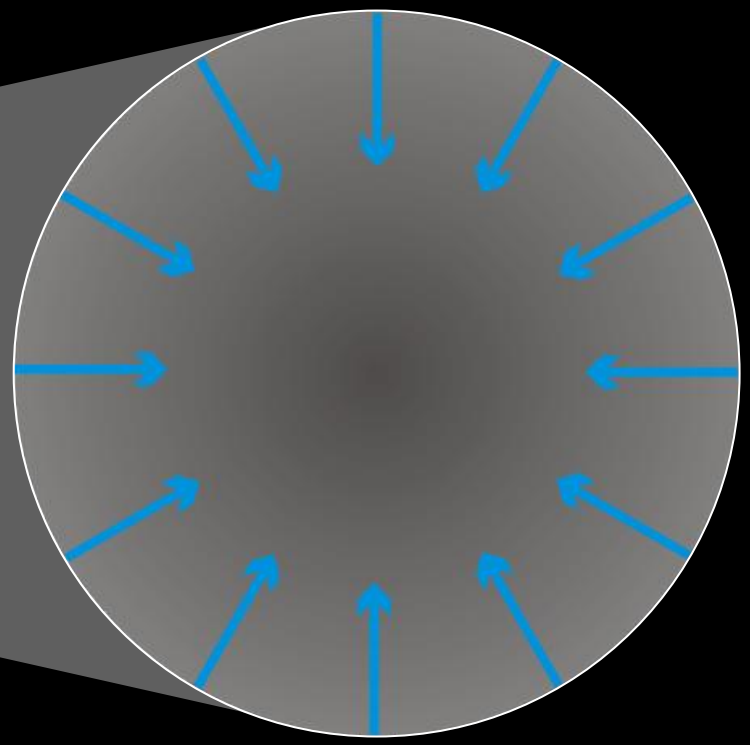
$\rho \approx 10^9$ g cm^{-3}

$T \approx 10^{10}$ K

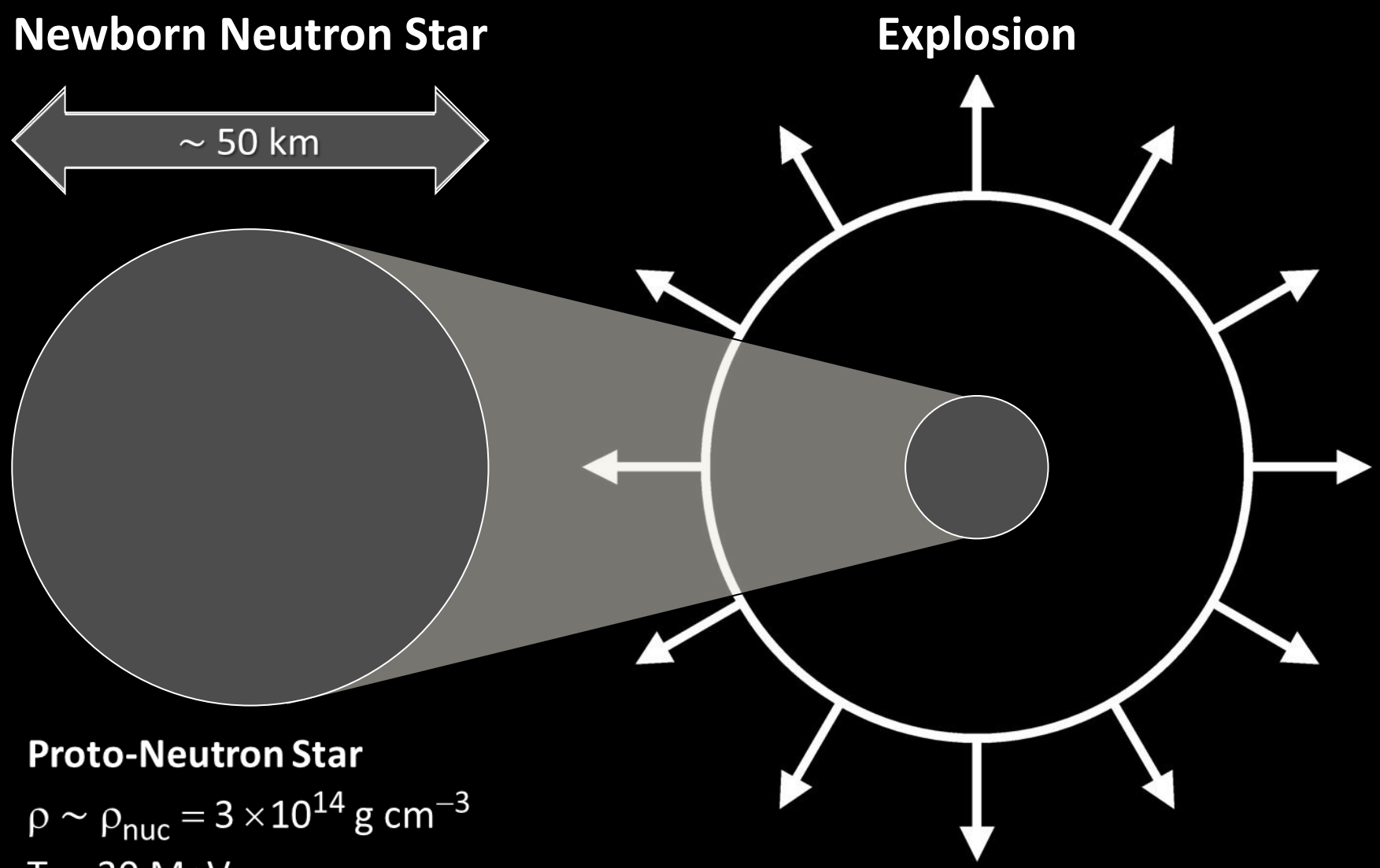
$M_{Fe} \approx 1.5\ M_{sun}$

$R_{Fe} \approx 8000$ km

Collapse (implosion)



Stellar Collapse and Supernova Explosion



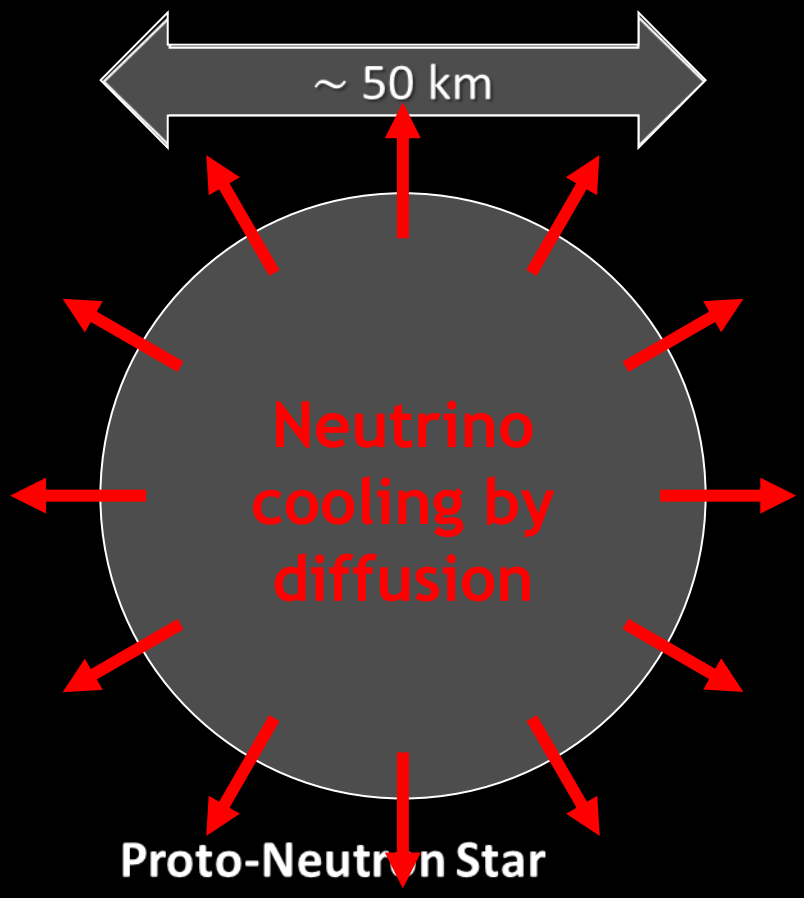
Proto-Neutron Star

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

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

Stellar Collapse and Supernova Explosion

Newborn Neutron Star



Proto-Neutron Star

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

T ~ 30 MeV

Gravitational binding energy

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

This shows up as

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

Neutrino luminosity

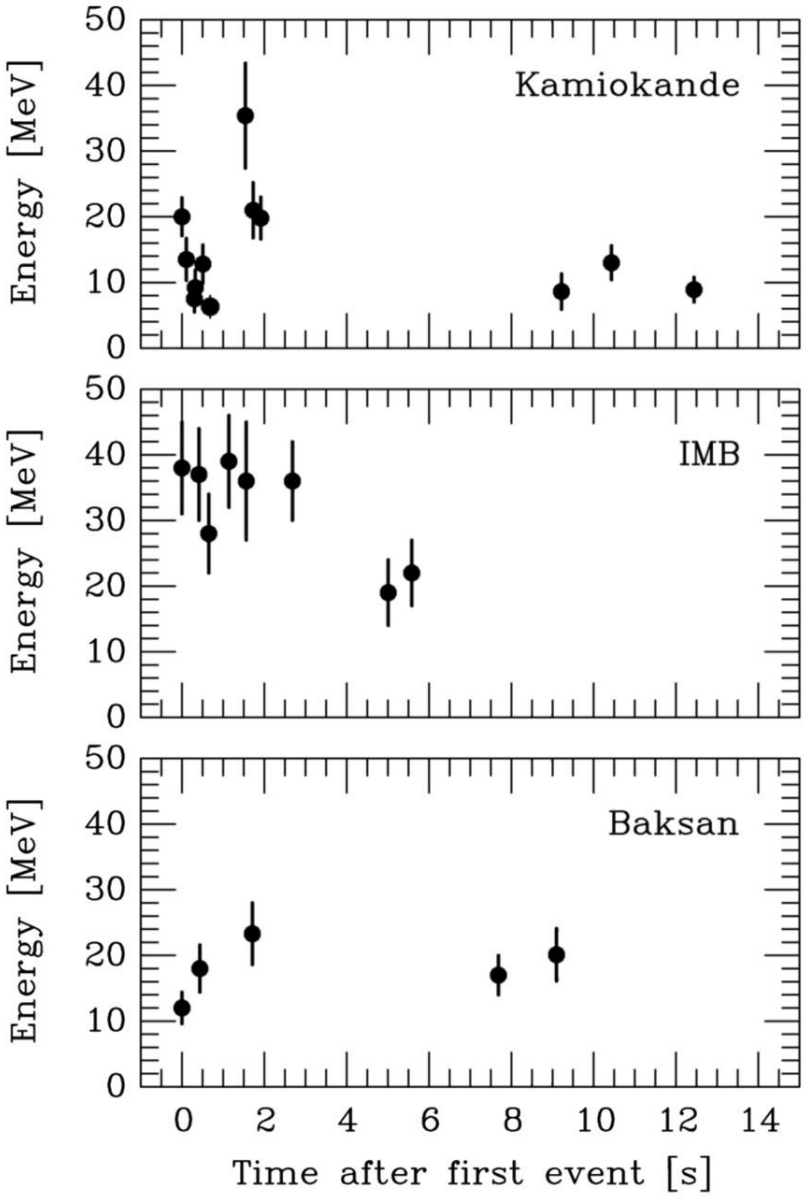
$$L_\nu \sim 3 \times 10^{53} \text{ erg} / 3 \text{ sec}$$
$$\sim 3 \times 10^{19} \, L_{SUN}$$

While it lasts, outshines the entire visible universe

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

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.,

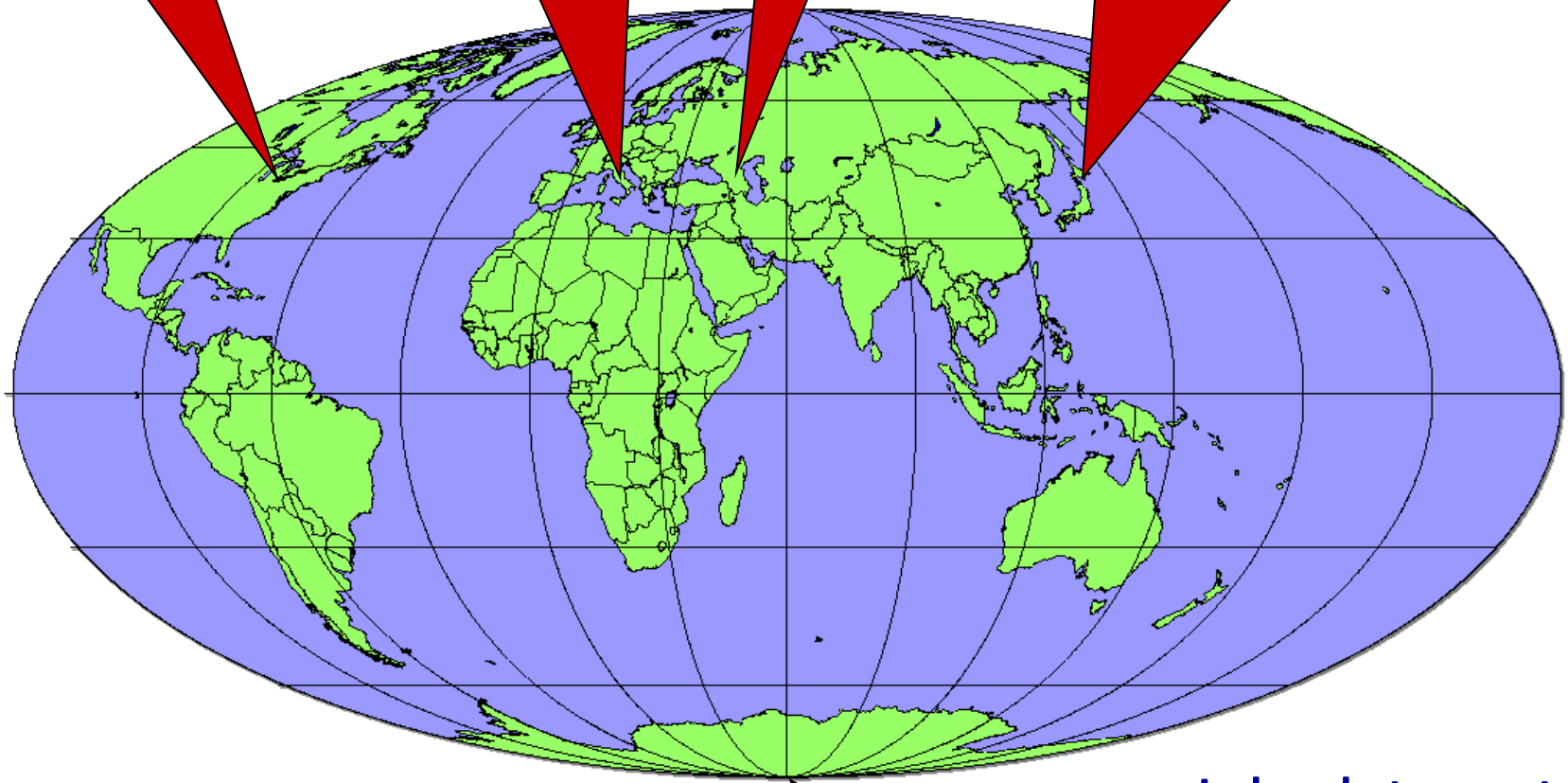
M. Schoenberg*

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

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

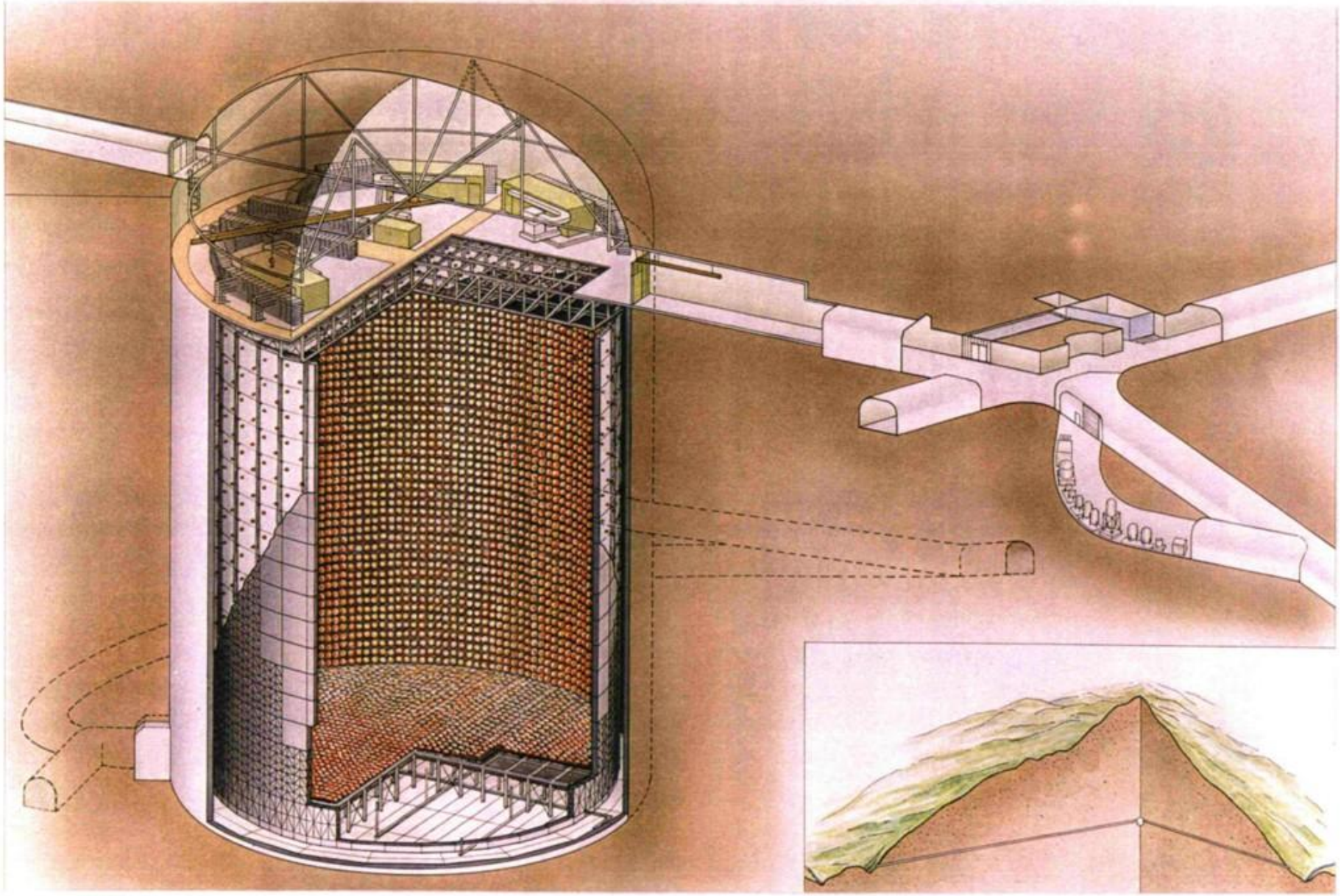
Phys. Rev. 58:1117 (1940)

Operational Detectors for Supernova Neutrinos

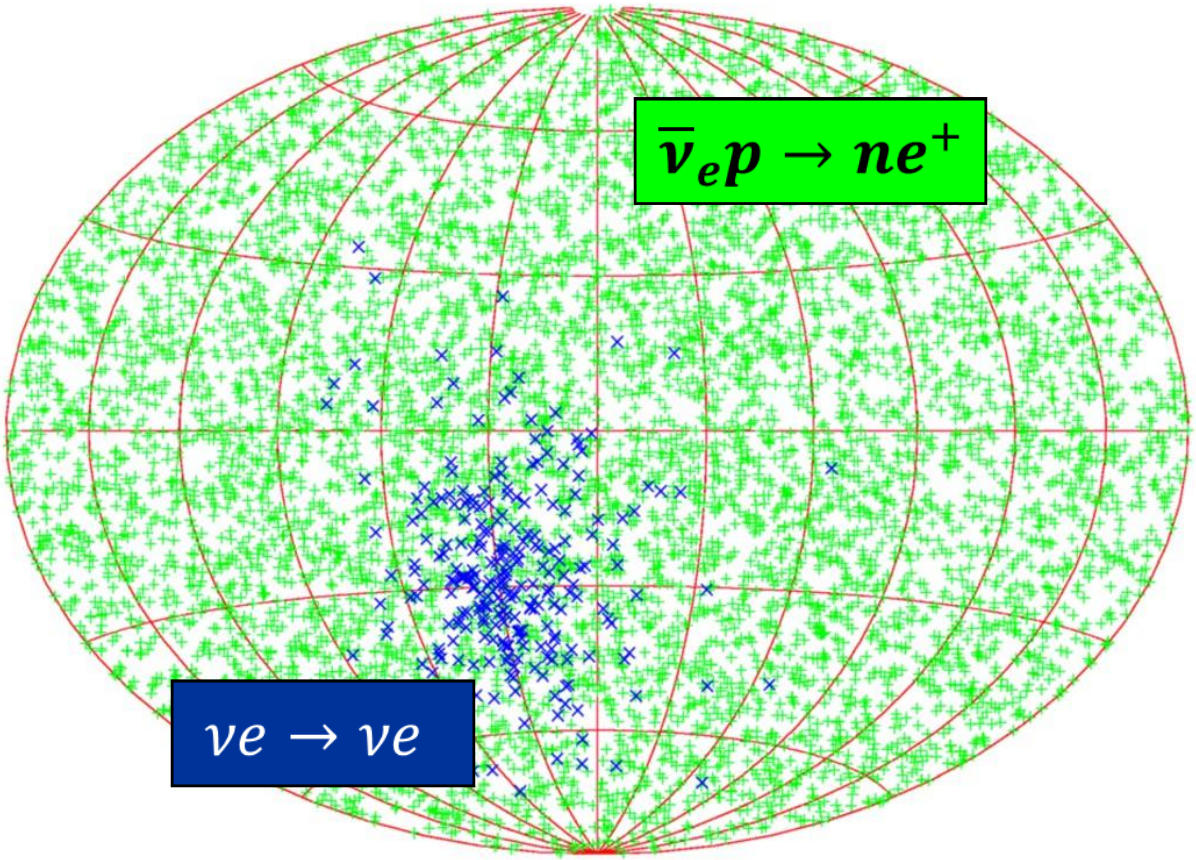


In brackets events for a "fiducial SN" at distance 10 kpc

Super-Kamiokande Neutrino Detector



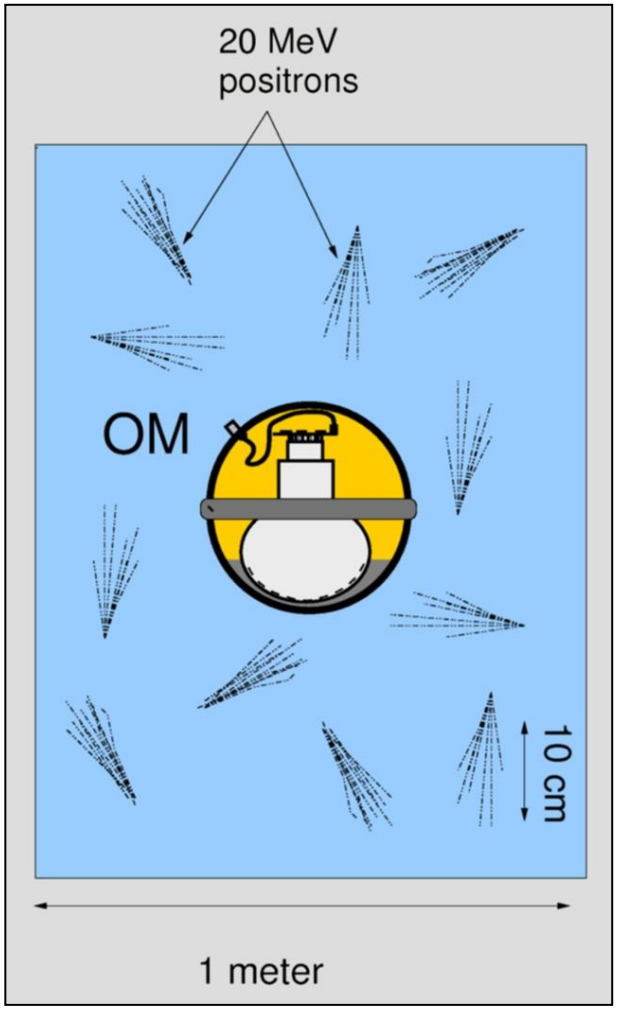
Supernova Pointing with Neutrinos



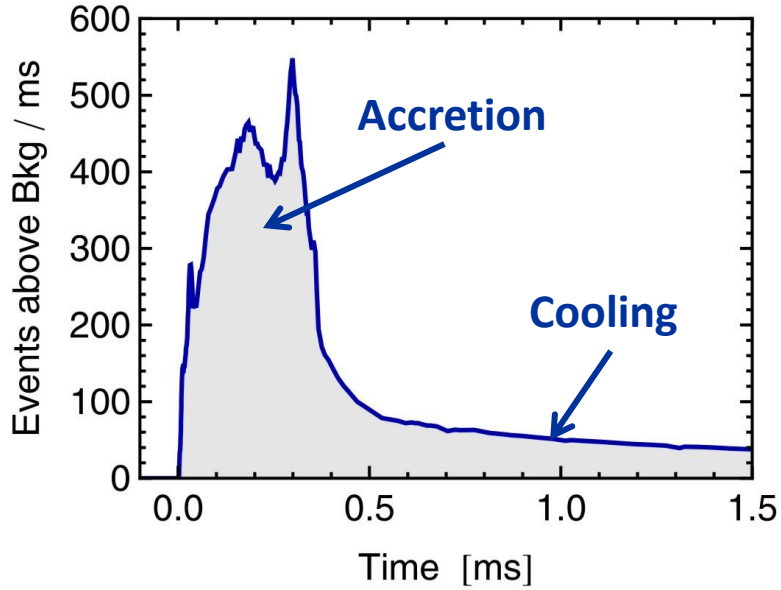
Neutron tagging efficiency		
None	90 %	
7.8°	3.2°	SK
1.4°	0.6°	SK × 30
95% CL half-cone opening angle		

- 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 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

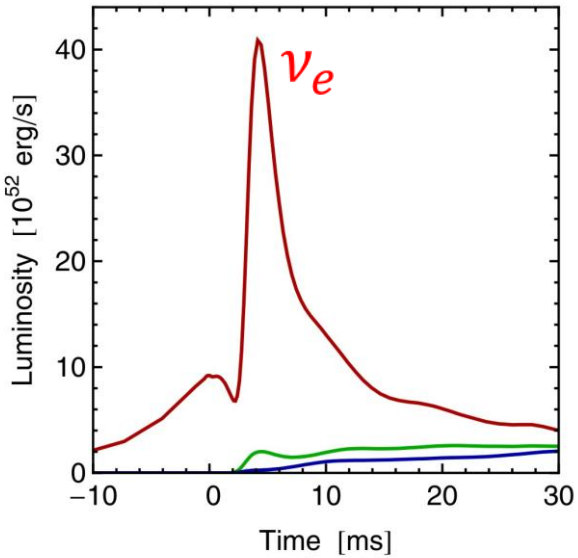


SN signal at 10 kpc
10.8 M_{sun} simulation
of Basel group
[arXiv:0908.1871]

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

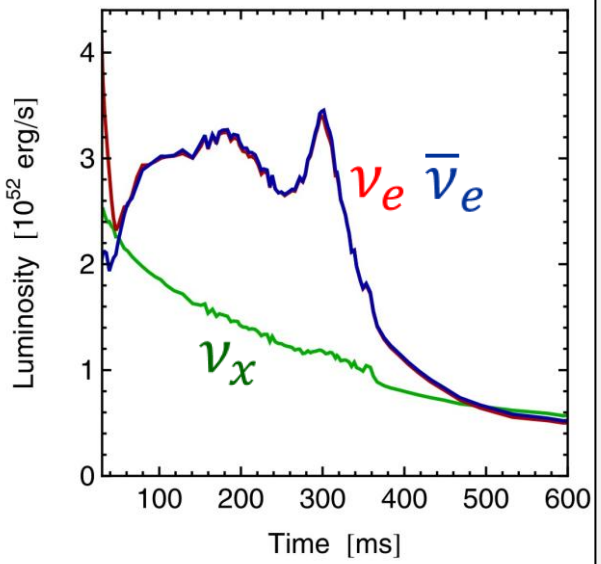
Three Phases of Neutrino Emission

Prompt ν_e burst



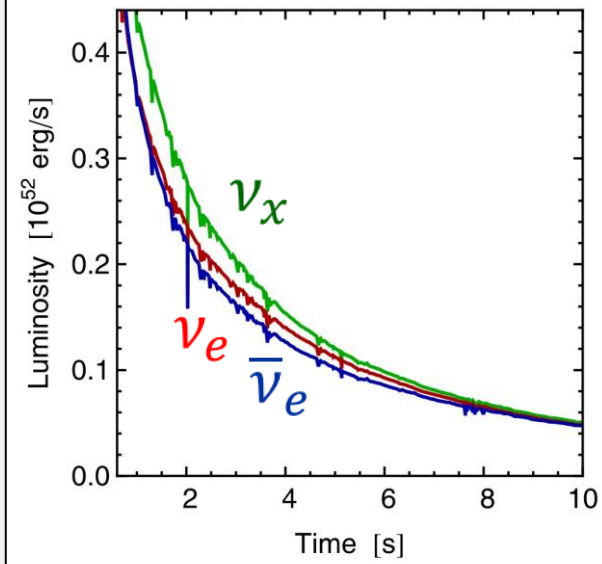
- Shock breakout
- De-leptonization of outer core layers

Accretion



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

Cooling

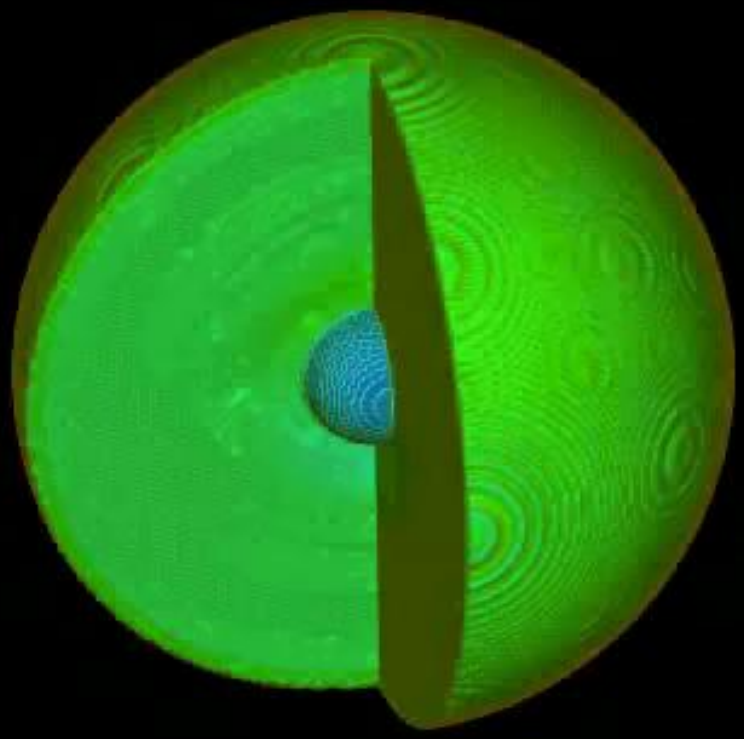


Cooling on neutrino diffusion time scale

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

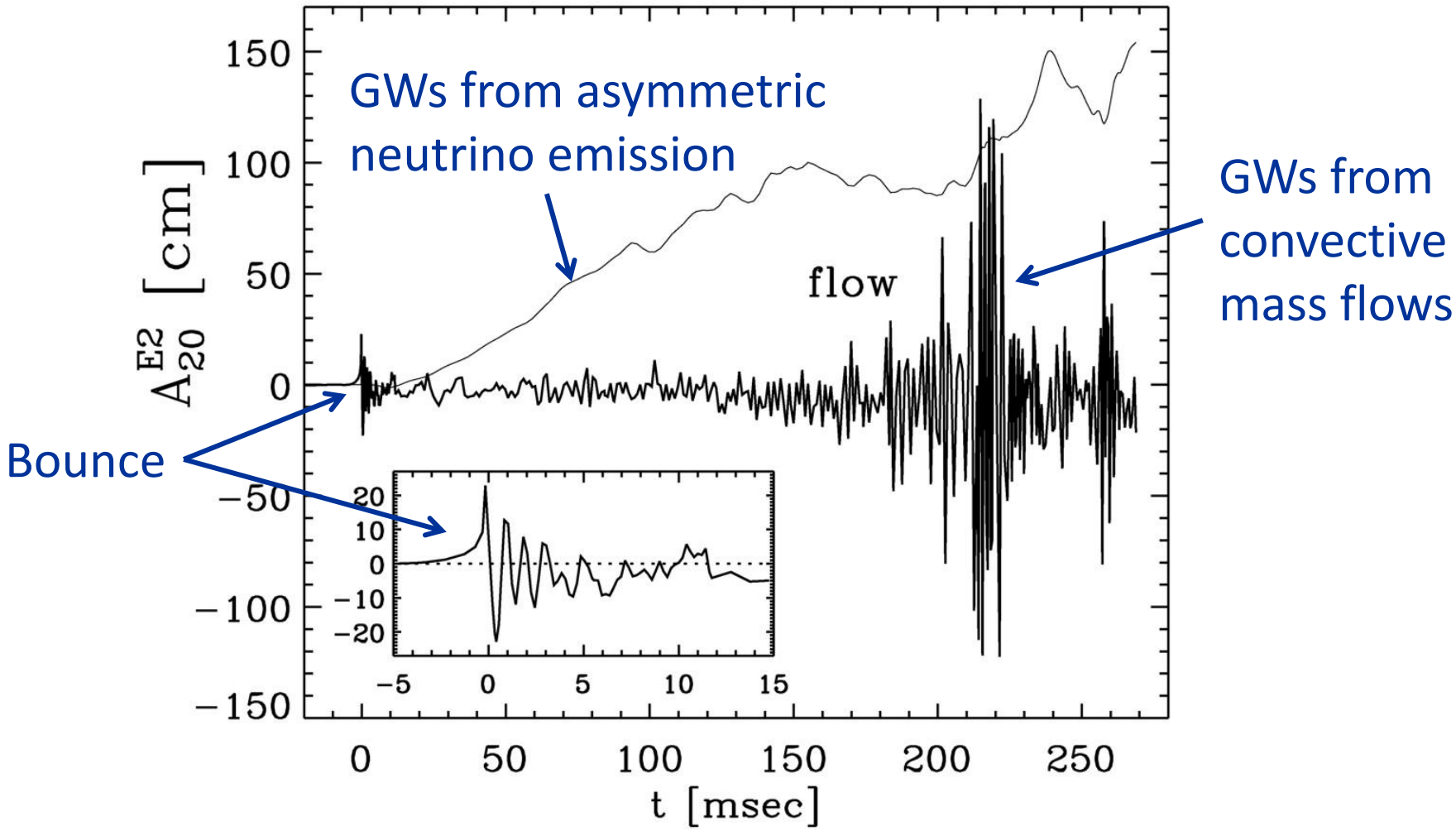
Fischer et al. (Basel group), A&A 517:A80, 2010 [arxiv:0908.1871]

Standing Accretion Shock Instability



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

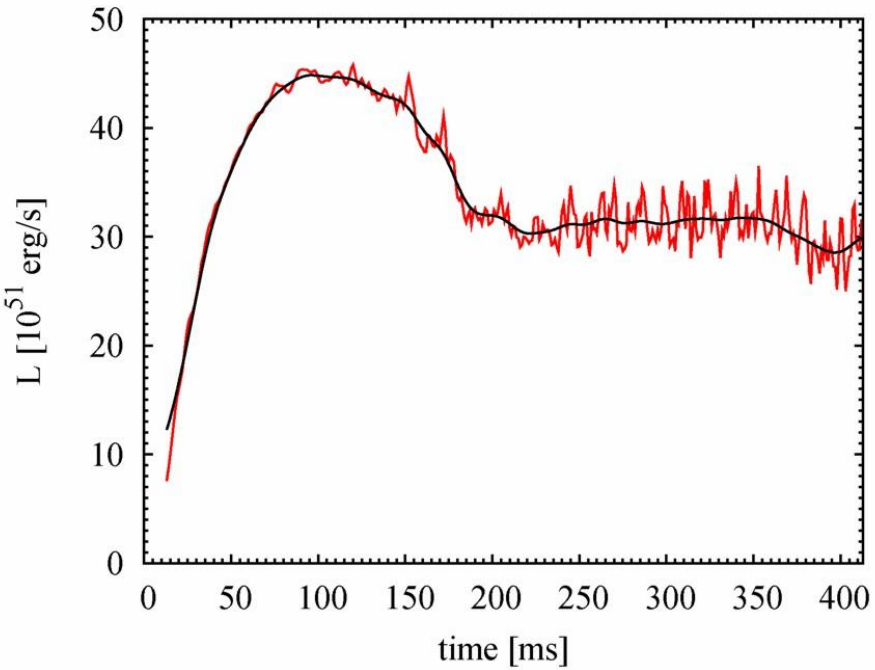
Gravitational Waves from Core-Collapse Supernovae



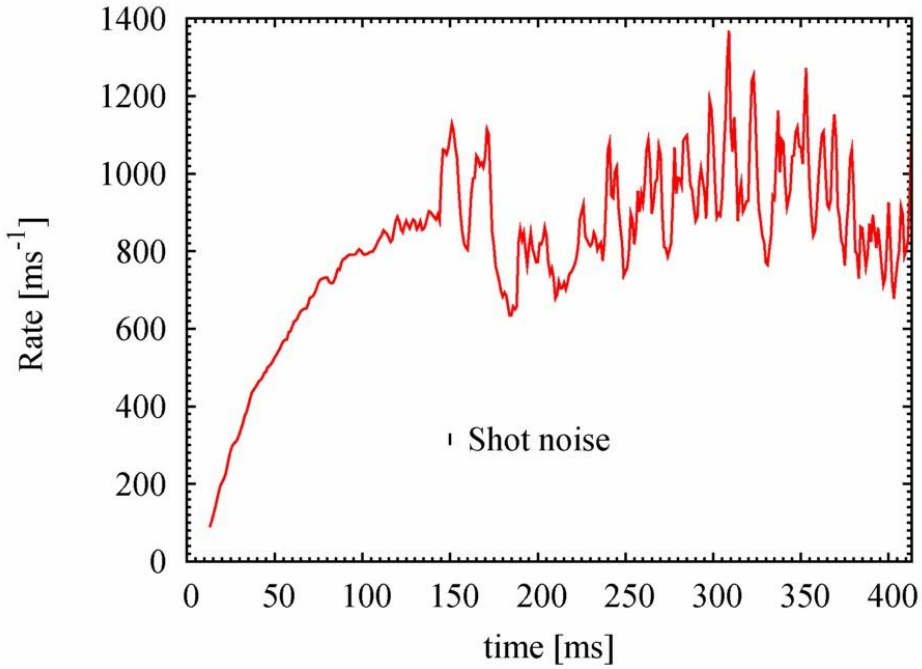
Müller, Rampp, Buras, Janka, & Shoemaker, astro-ph/0309833
"Towards gravitational wave signals from realistic core collapse supernova models"

Variability Seen in Neutrinos

Luminosity



Detection rate in IceCube



Probably 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

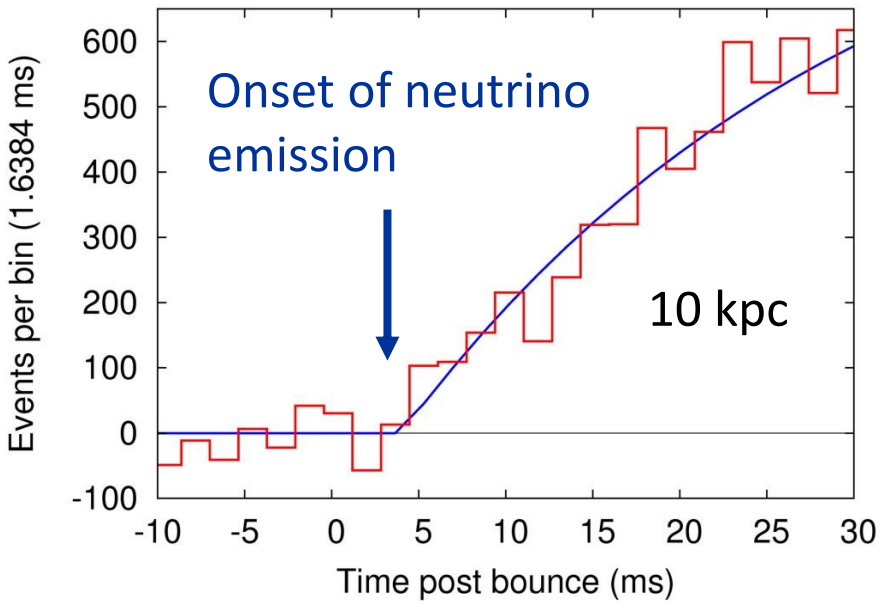
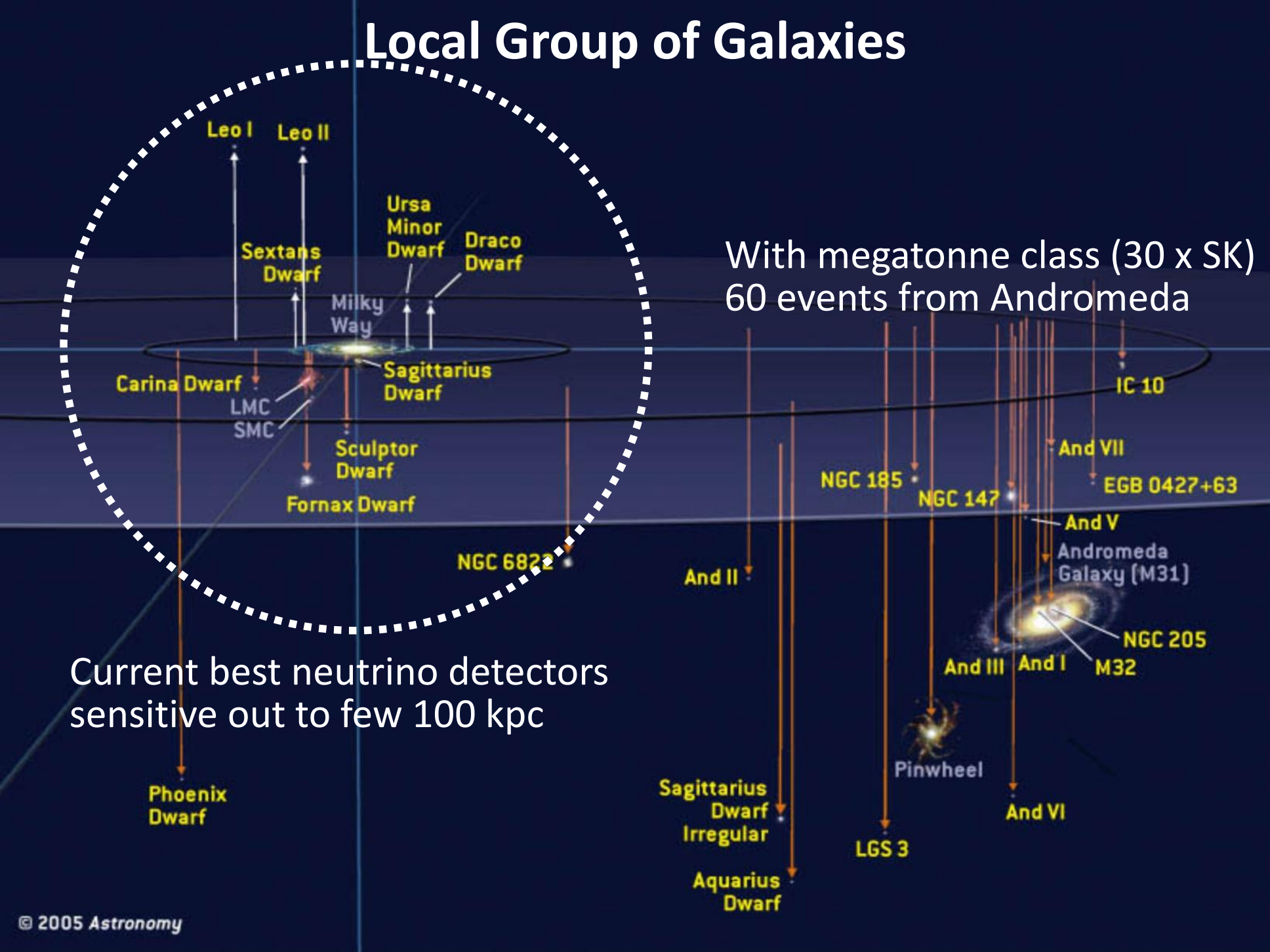


FIG. 1: Typical Monte Carlo realization (red histogram) and reconstructed fit (blue line) for the benchmark case discussed in the text for a SN at 10 kpc.

Halzen & Raffelt, arXiv:0908.2317

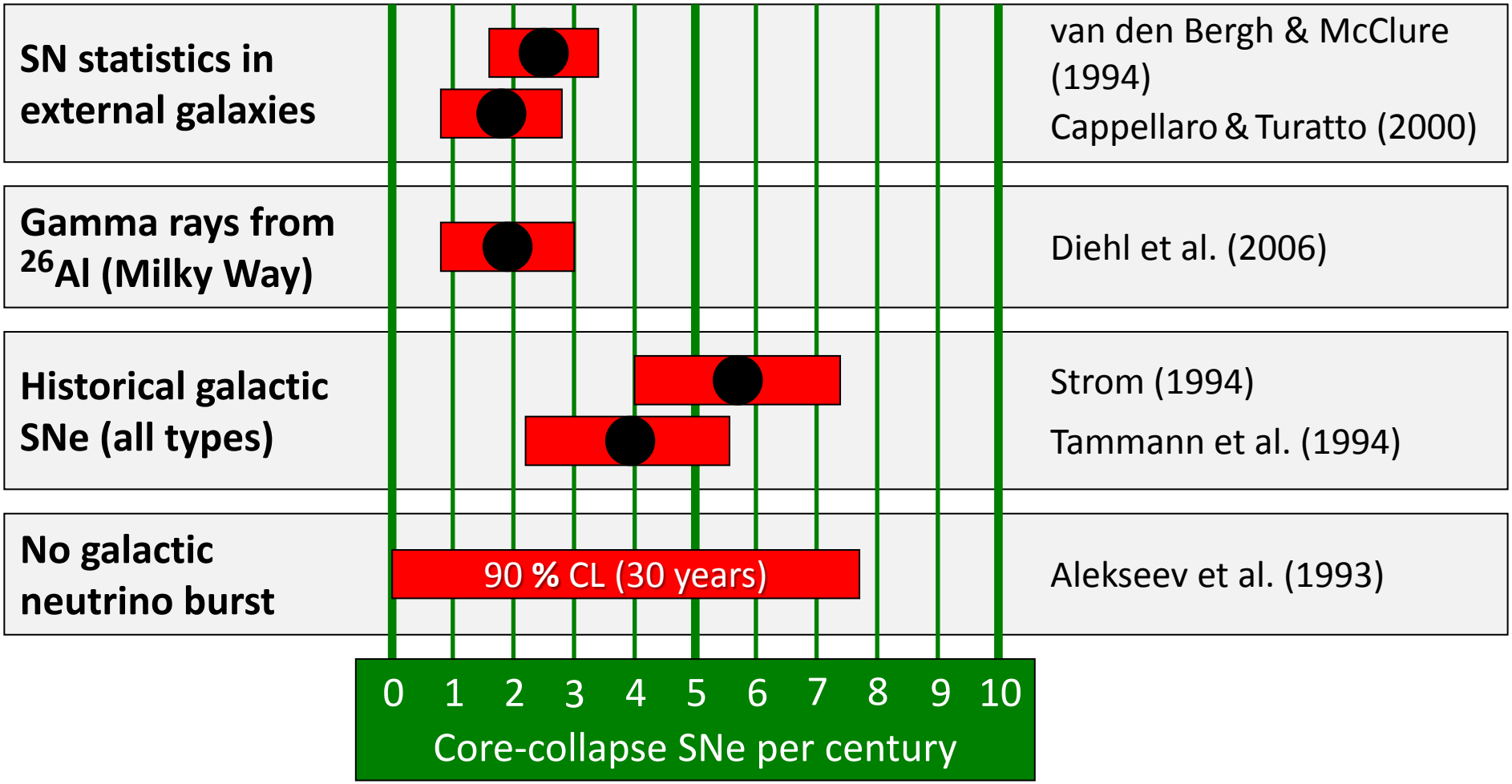
Local Group of Galaxies



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

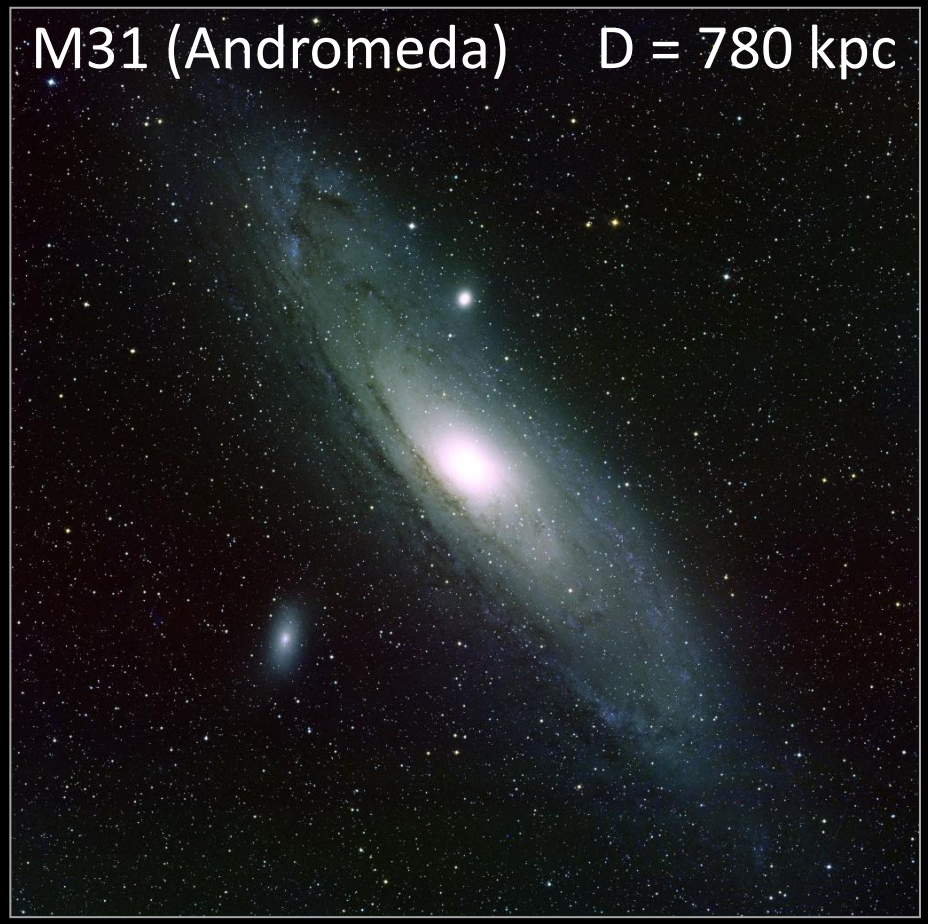
Current best neutrino detectors
sensitive out to few 100 kpc

Core-Collapse SN Rate in the Milky Way

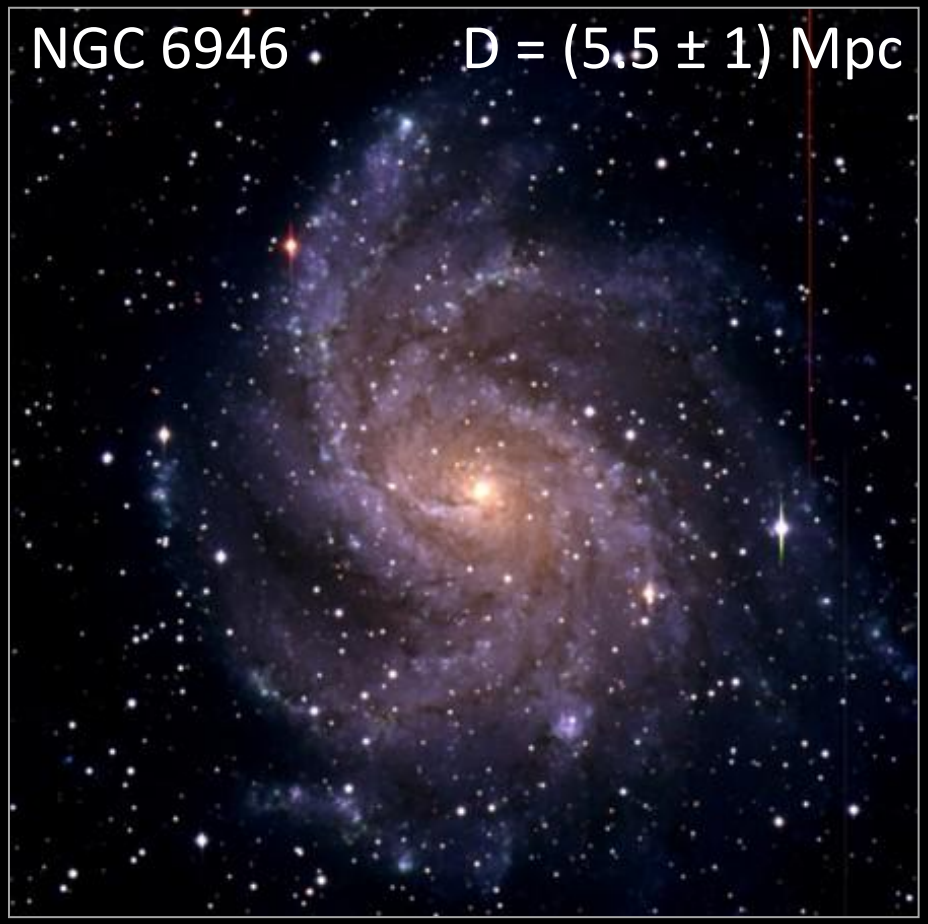


References: van den Bergh & McClure, ApJ 425 (1994) 205. Cappellaro & Turatto, astro-ph/0012455. Diehl et al., Nature 439 (2006) 45. Strom, Astron. Astrophys. 288 (1994) L1. Tammann et al., ApJ 92 (1994) 487. Alekseev et al., JETP 77 (1993) 339 and my update.

High and Low Supernova Rates in Nearby Galaxies

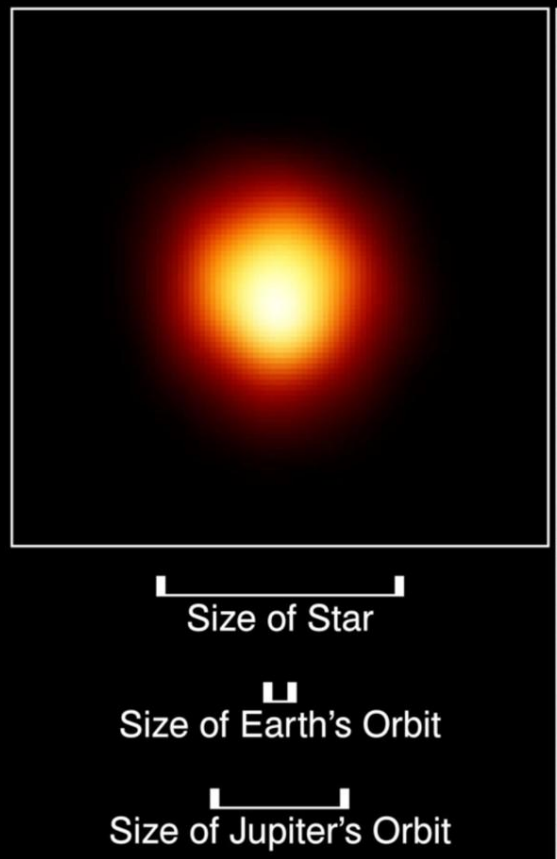


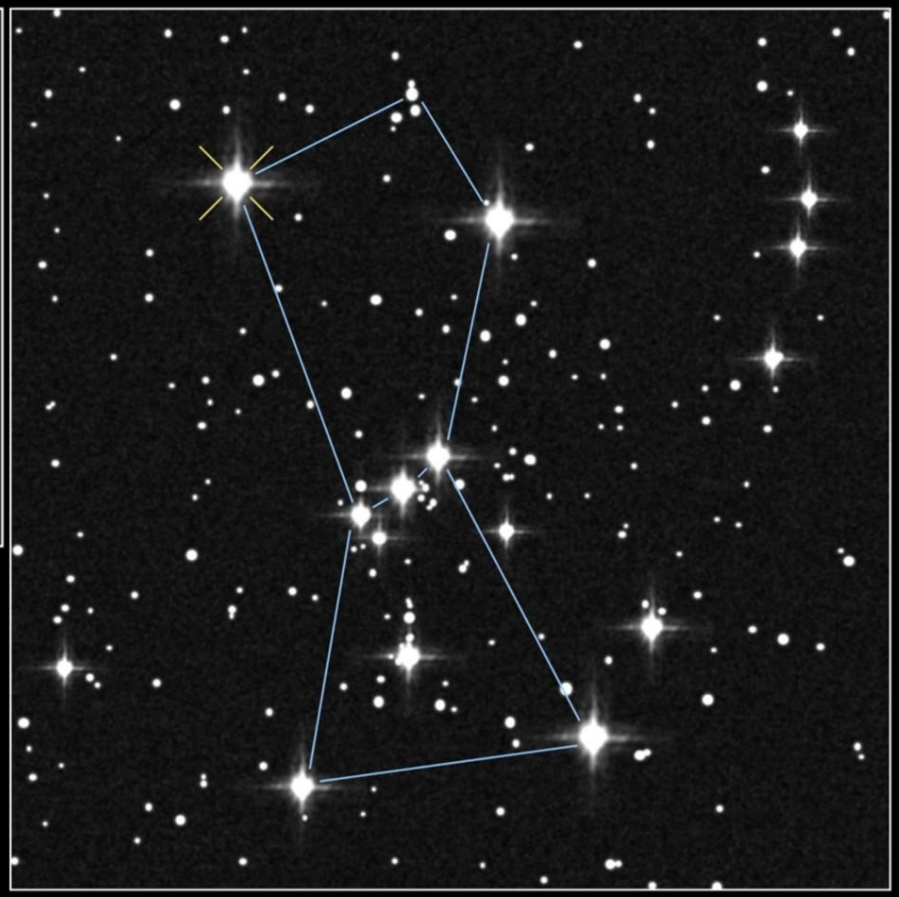
Last Observed Supernova: 1885A



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

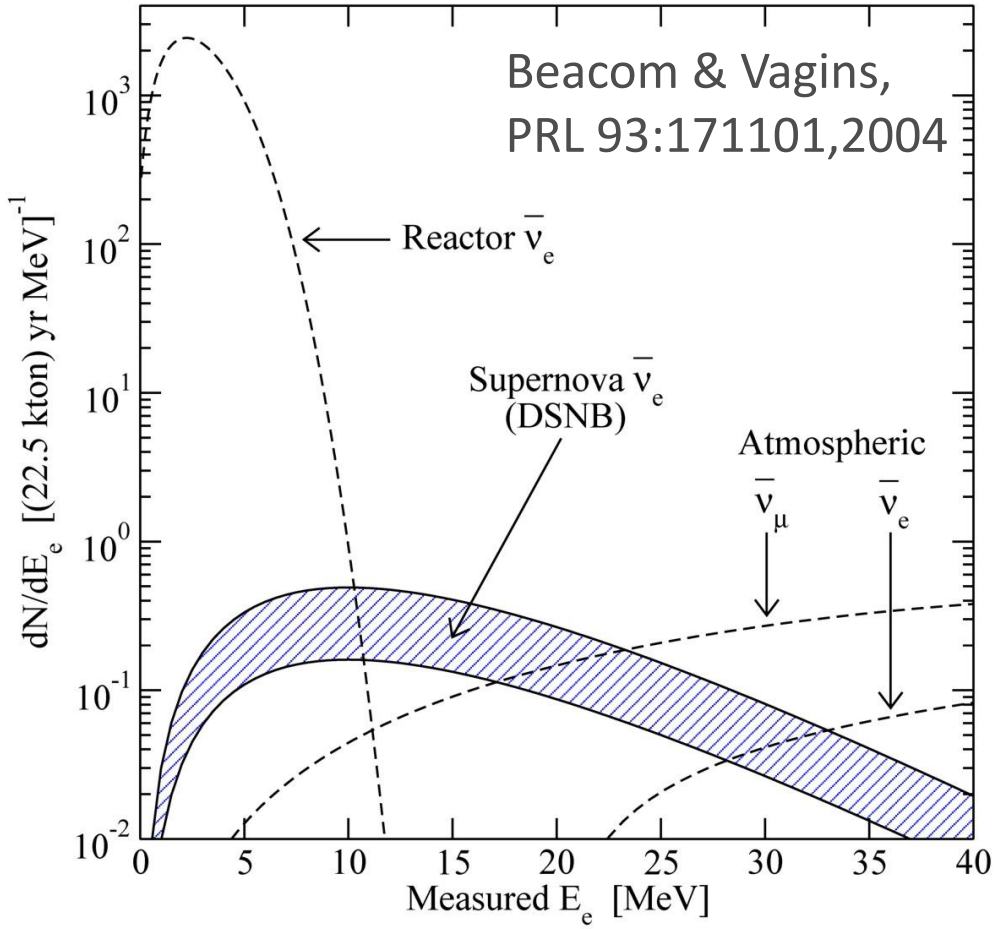
Distance (Hipparcos) 130 pc (425 lyr)

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 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 $\bar{\nu}_e$ 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 $\bar{\nu}_e$ and atmospheric ν bkg

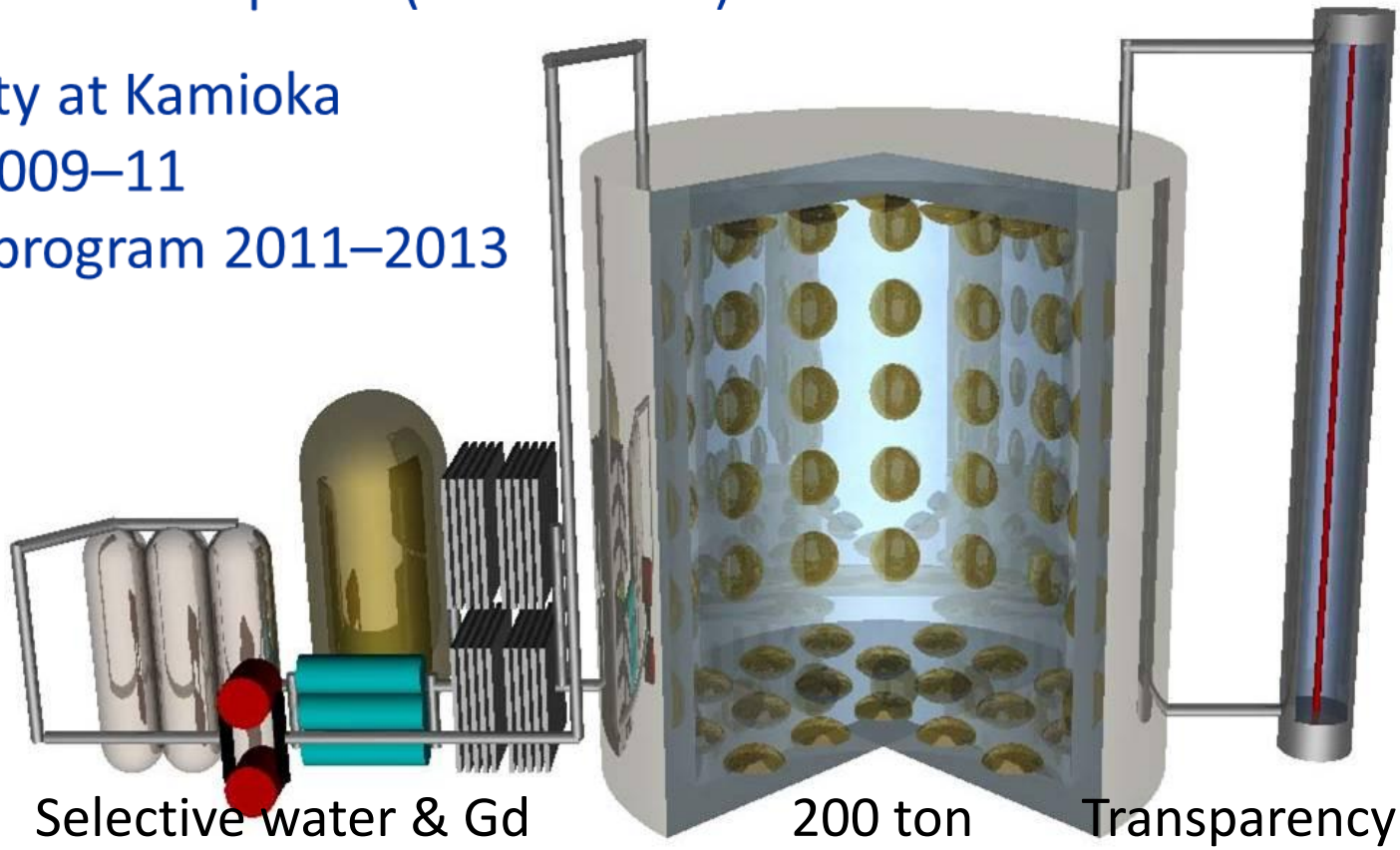
Neutron Tagging in Super-K with Gadolinium

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

- 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

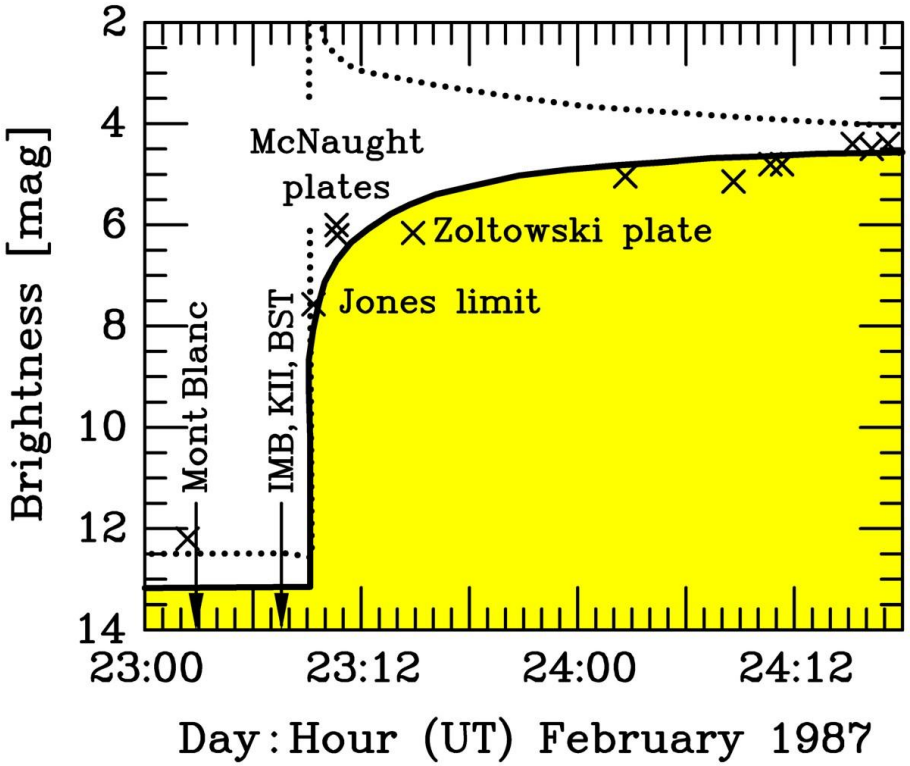
Selective water & Gd filtration system

200 ton water tank

Transparency measurement

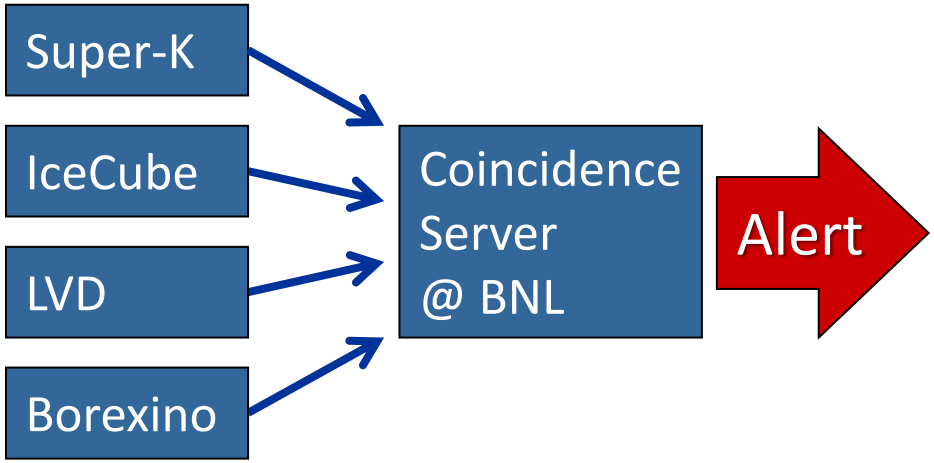
SuperNova Early Warning System (SNEWS)

Early light curve of SN 1987A



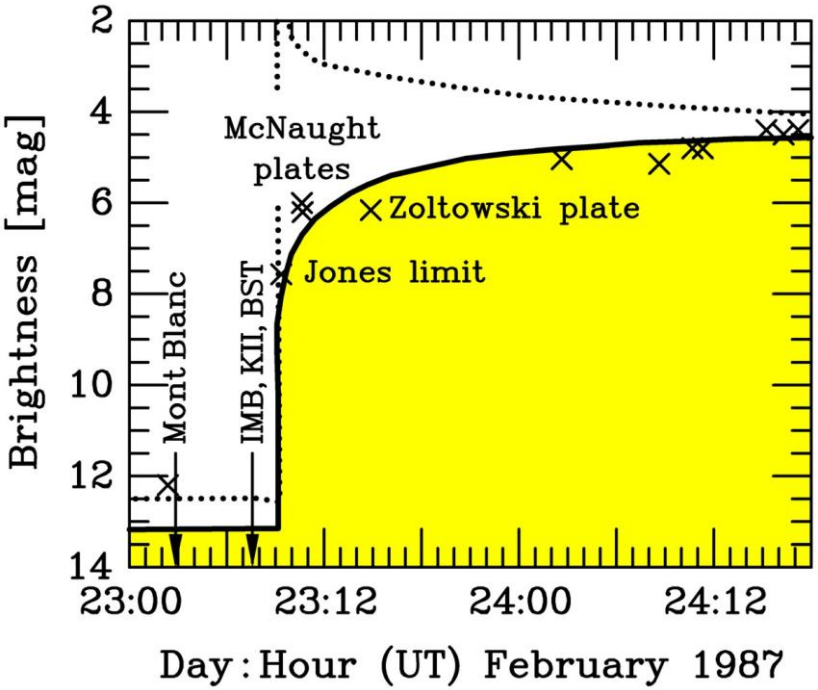
http://snews.bnl.gov

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



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,

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

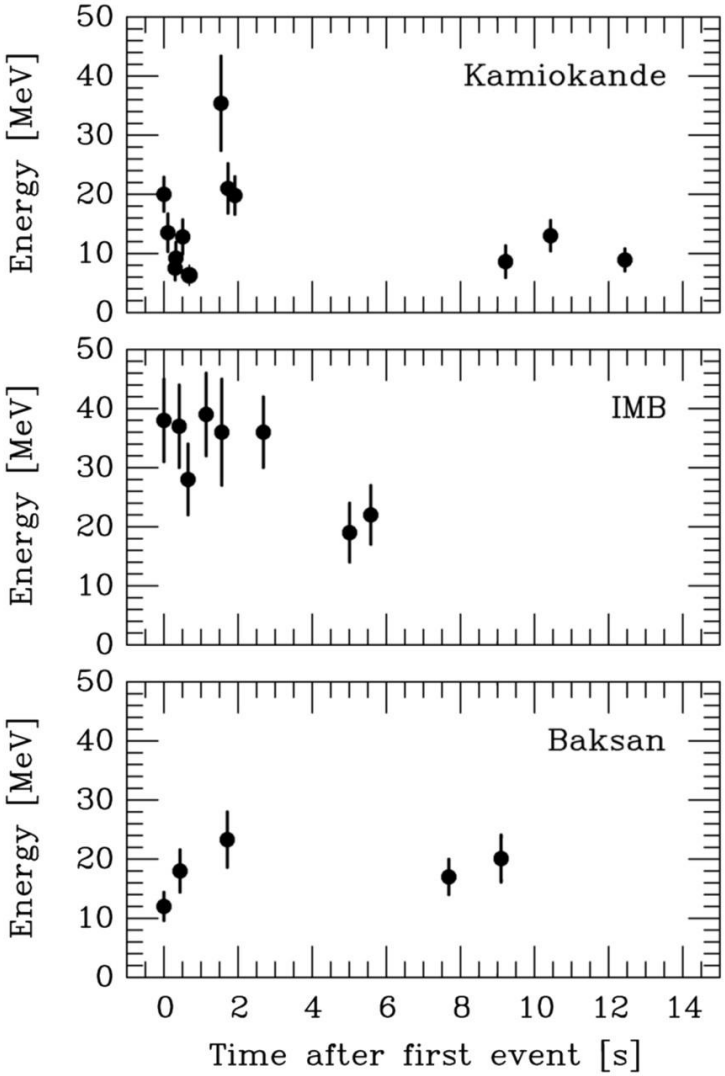
Neutrinos and photons respond to gravity the same to within

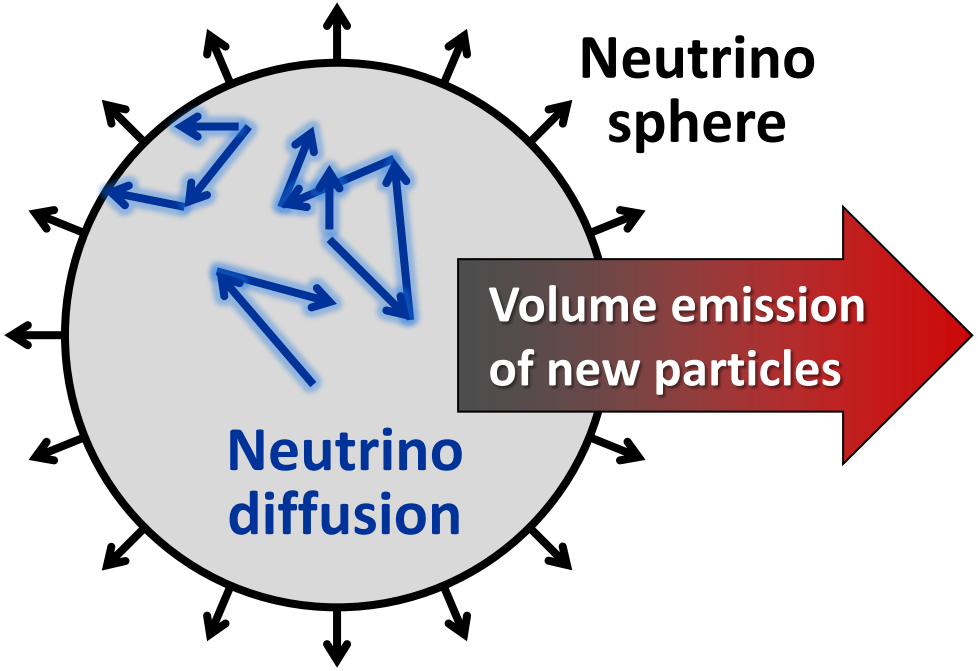
$$1\text{–}4 \times 10^{-3}$$

Longo, PRL 60:173, 1988
Krauss & Tremaine, PRL 60:176, 1988

Supernova 1987A Energy-Loss Argument

SN 1987A neutrino signal

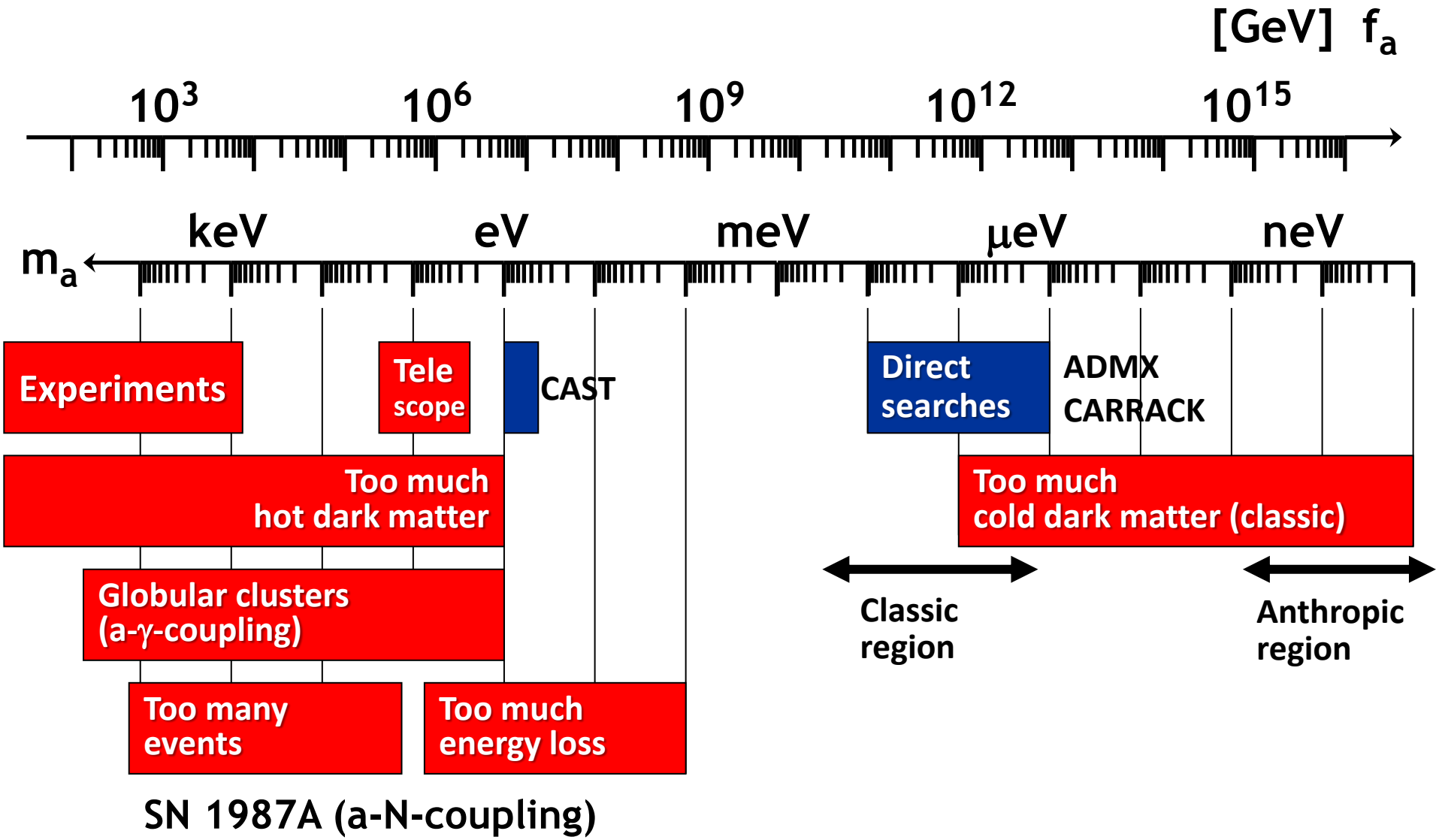




Emission of very weakly interacting particles would "steal" energy from the neutrino burst and shorten it.
(Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

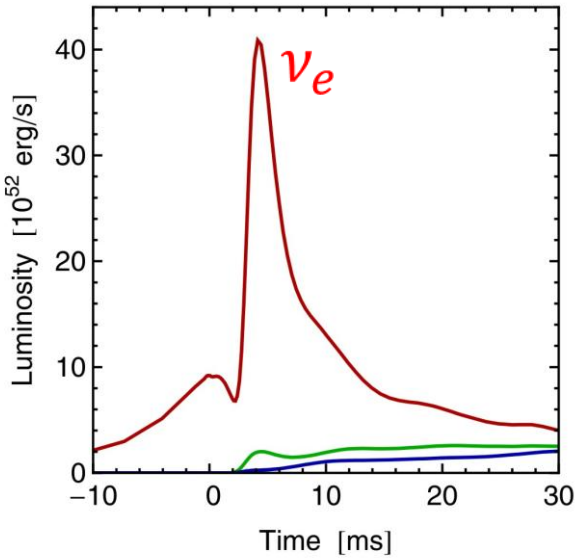
Late-time signal most sensitive observable

Axion Bounds



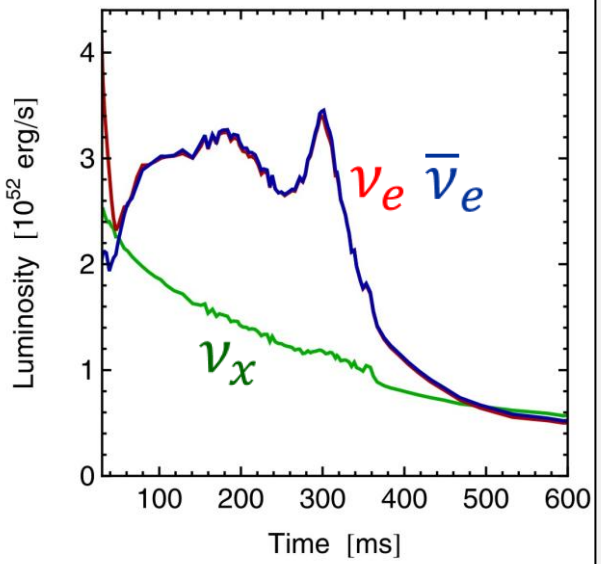
Three Phases of Neutrino Emission

Prompt ν_e burst



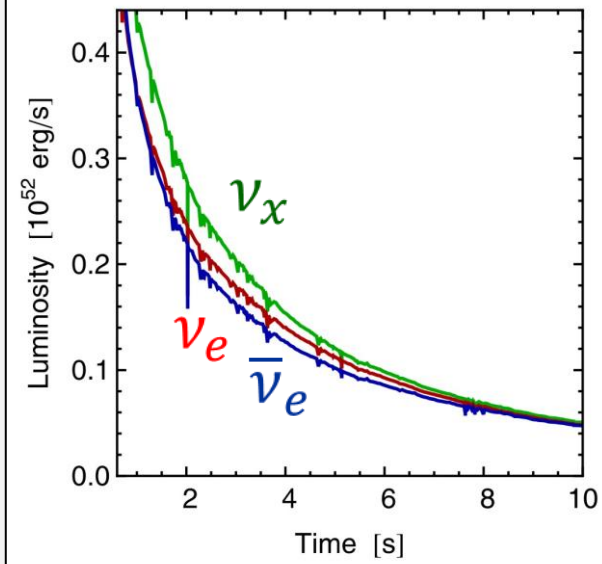
- Shock breakout
- De-leptonization of outer core layers

Accretion



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

Cooling

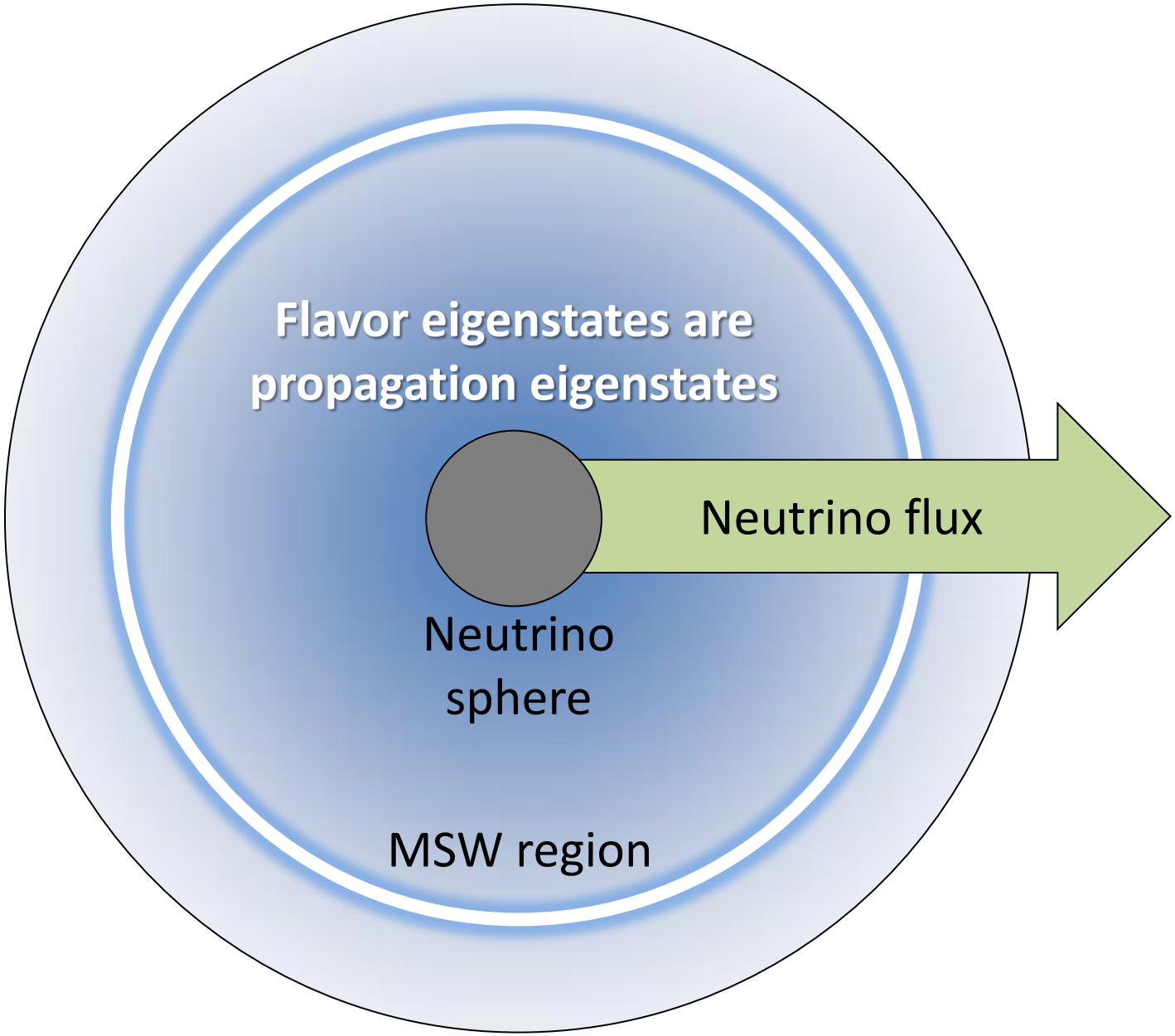


Cooling on neutrino diffusion time scale

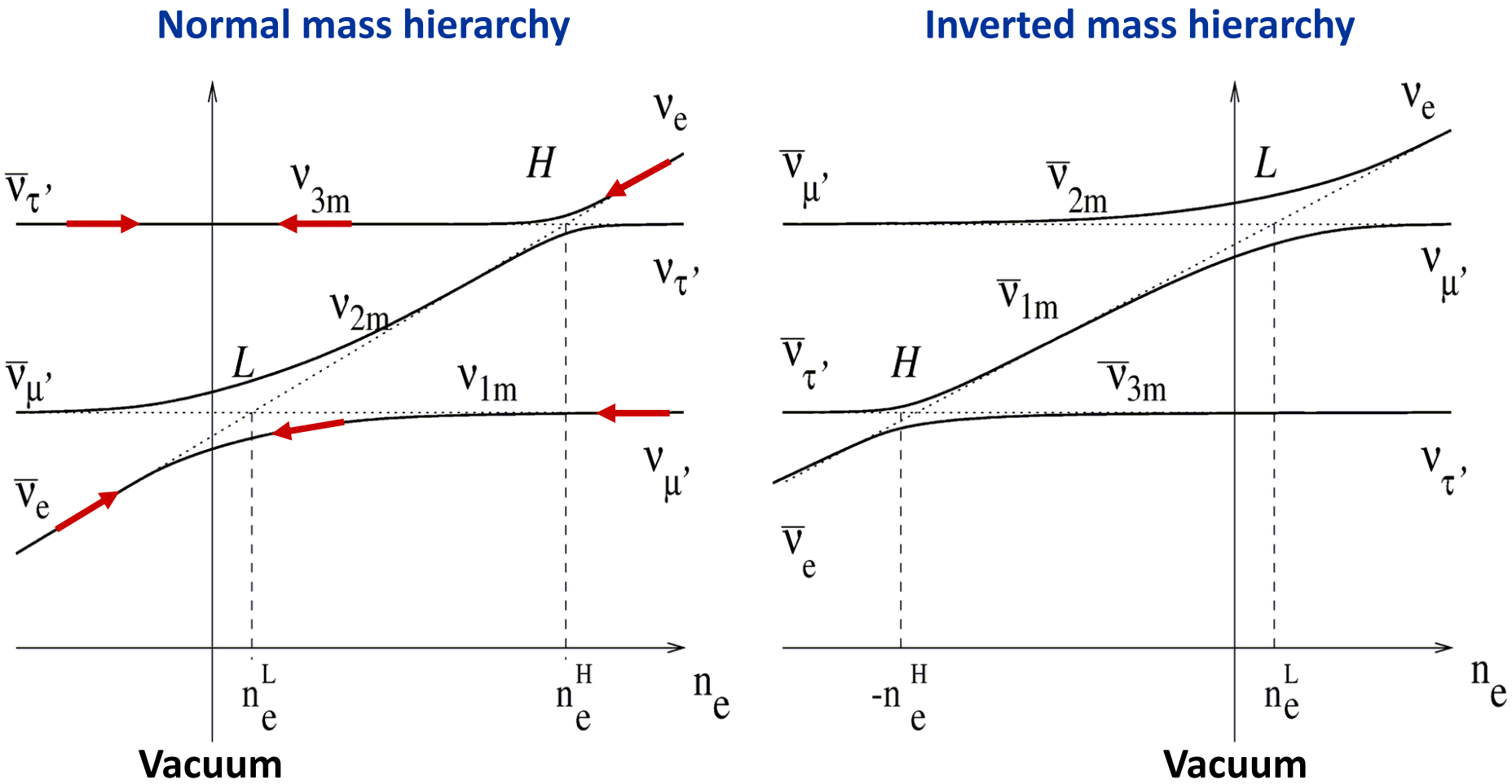
- Spherically symmetric model (10.8 $M_\odot$) with Boltzmann neutrino transport
- Explosion manually triggered by enhanced CC interaction rate

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

Flavor Oscillations in Core-Collapse Supernovae



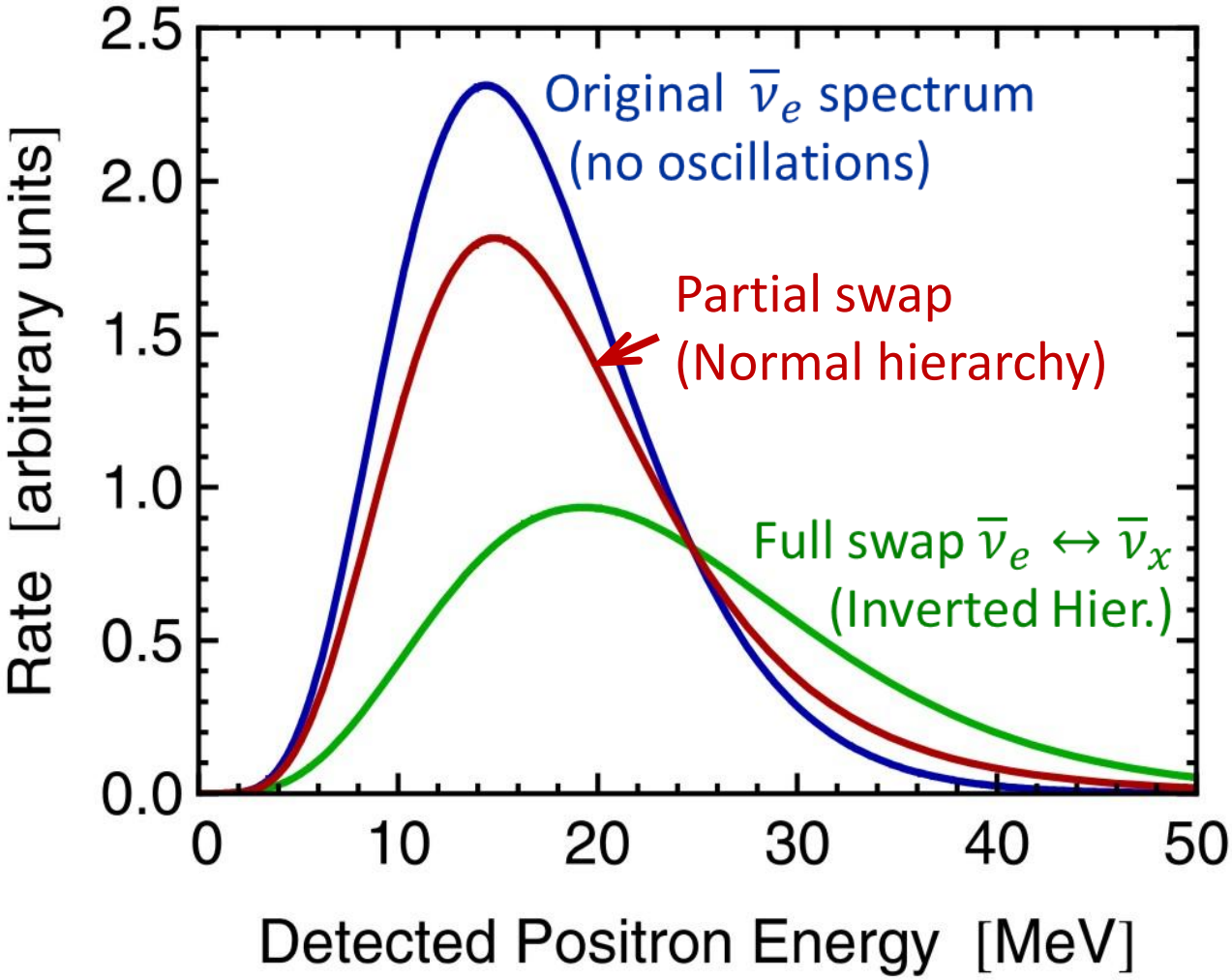
Level-Crossing Diagram in a Supernova Envelope



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

Stanislaw Mikheev († 23 April 2011)

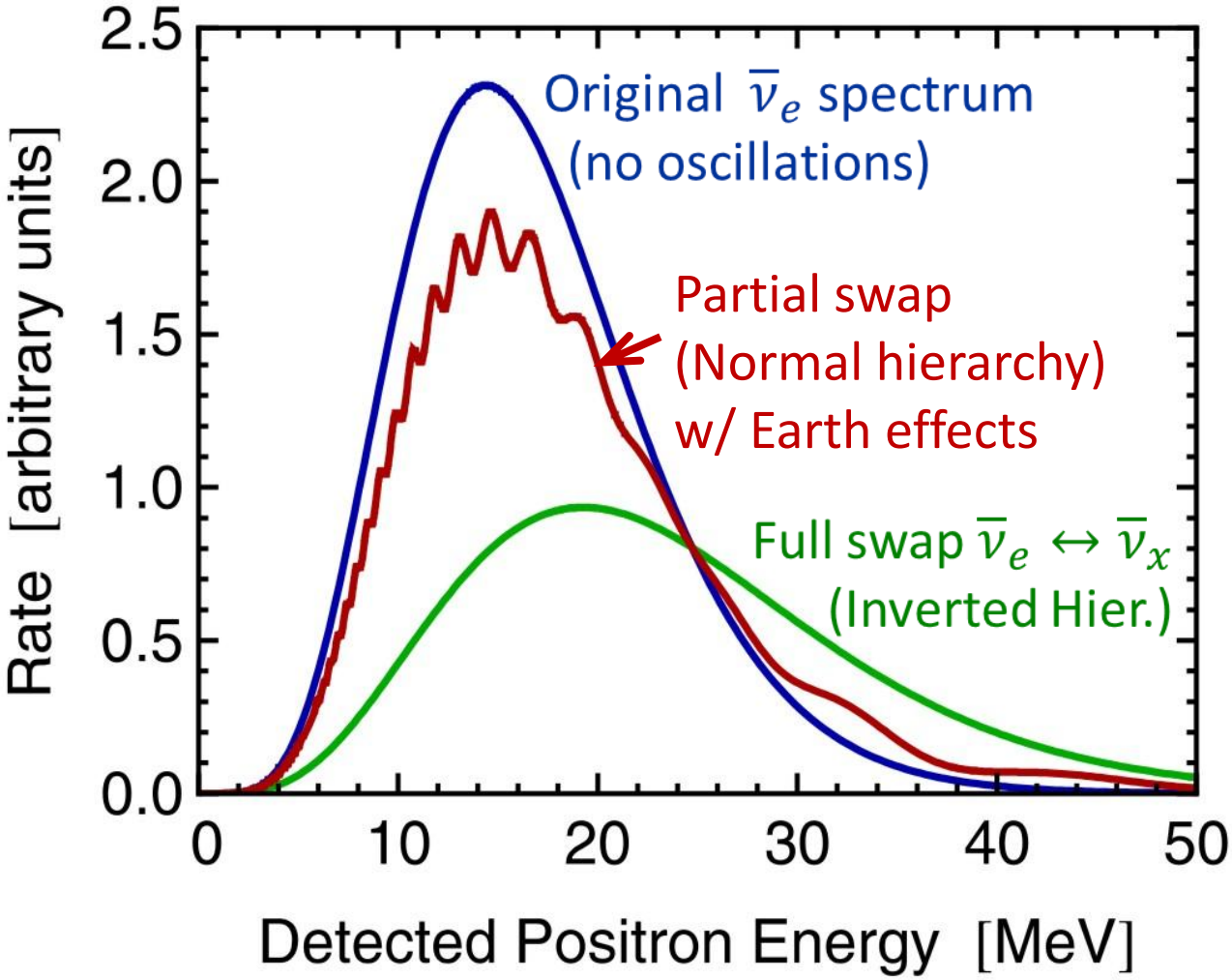
Oscillation of Supernova Anti-Neutrinos



Basel accretion phase model ($10.8\ M_\odot$)

Detection spectrum by $\overline{\nu}_e + p \rightarrow n + e^+$ (water Cherenkov or scintillator detectors)

Oscillation of Supernova Anti-Neutrinos



Basel accretion phase model ($10.8\ M_\odot$)

Detection spectrum by $\overline{\nu}_e + p \rightarrow n + e^+$ (water Cherenkov or scintillator detectors)

8000 km path length in Earth assumed

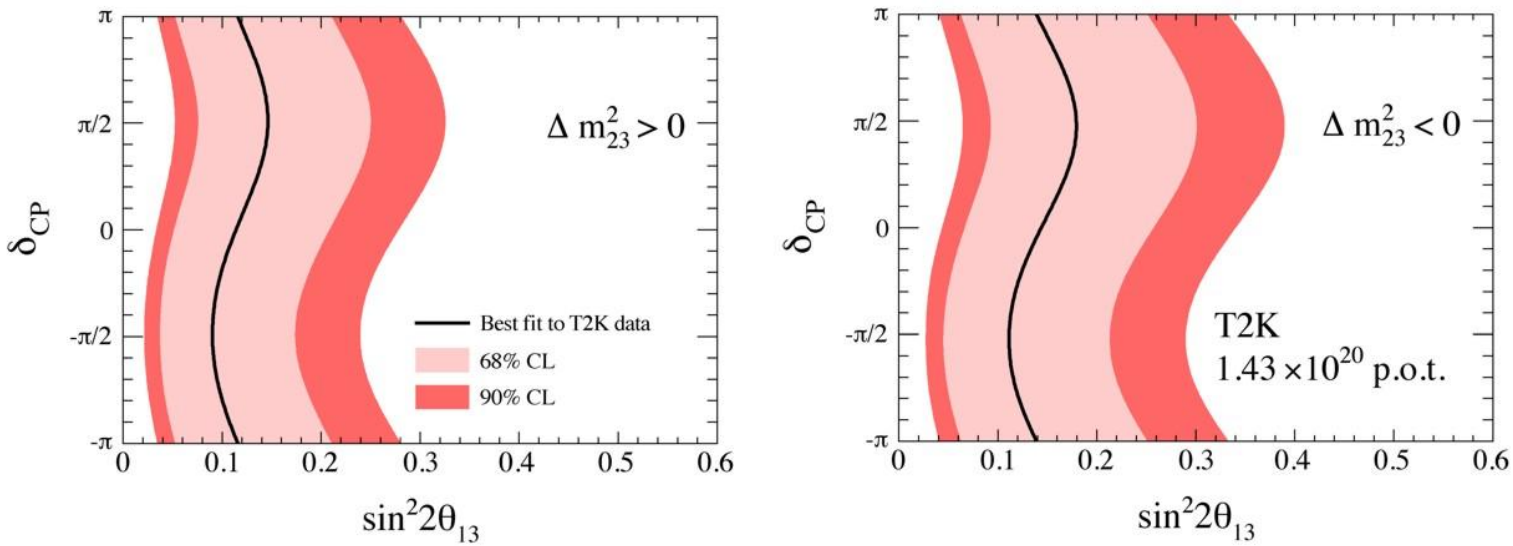
Detecting Earth effects requires good energy resolution
(Large scintillator detector, e.g. LENA, or megaton water Cherenkov)

Signature of Flavor Oscillations (Accretion Phase)

	1-3-mixing scenarios		
	A	B	C
Mass ordering	Normal (NH)	Inverted (IH)	Any (NH/IH)
$\sin^2 2\theta_{13}$	$\gtrsim 10^{-3}$		$\lesssim 10^{-5}$
MSW conversion	adiabatic		non-adiabatic
ν_e survival prob.	0	$\sin^2\theta_{12} \approx 0.3$	$\sin^2\theta_{12} \approx 0.3$
$\bar{\nu}_e$ survival prob.	$\cos^2\theta_{12} \approx 0.7$	0	$\cos^2\theta_{12} \approx 0.7$
$\bar{\nu}_e$ Earth effects	Yes	No	Yes
	May distinguish mass ordering		

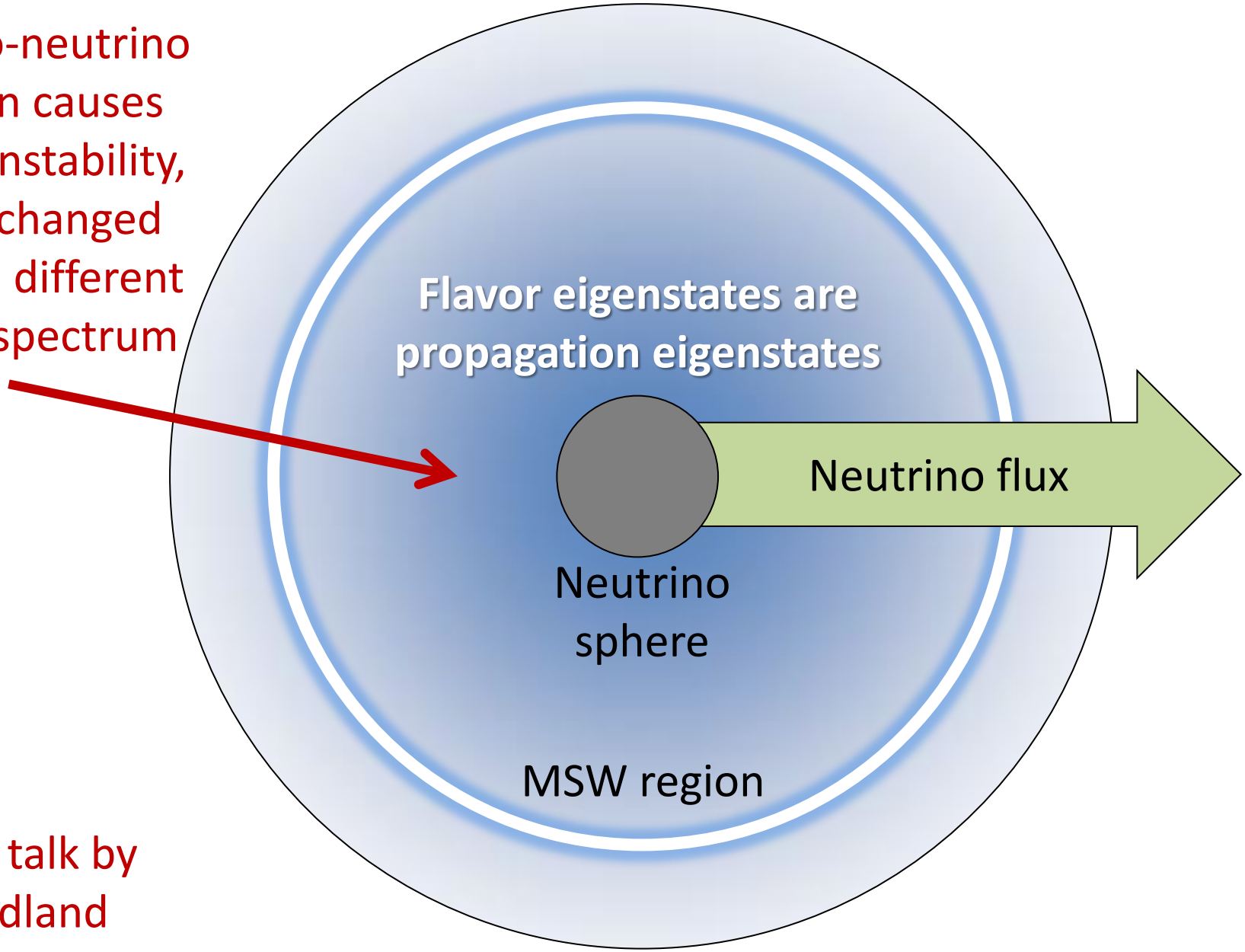
Assuming collective effects are not important during accretion phase (Chakraborty et al., arXiv:1105.1130)

Theta-13 discovered at T2K?



Flavor Oscillations in Core-Collapse Supernovae

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

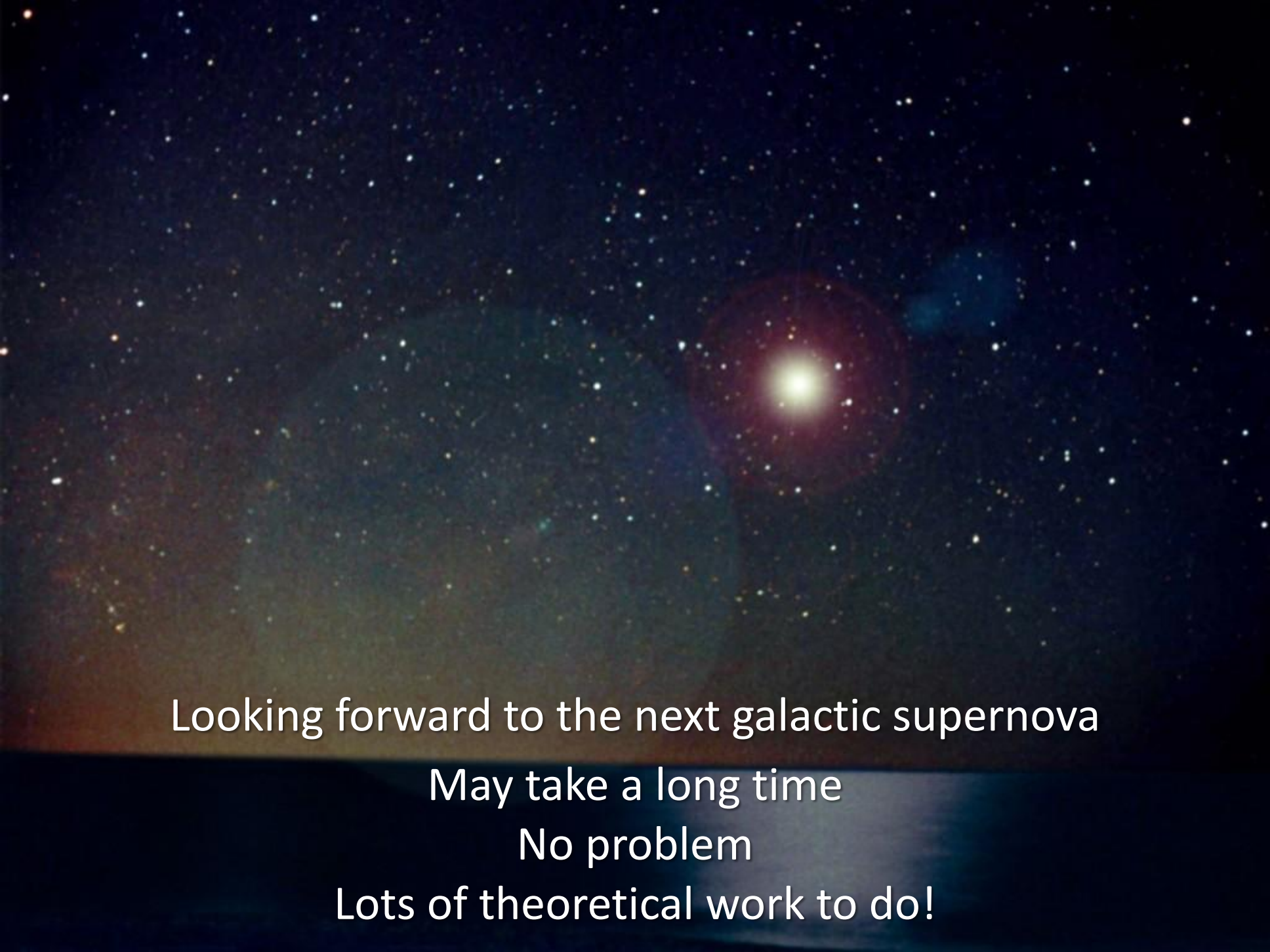


See next talk by Alex Friedland

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, arXiv:0710.3112. Balantekin & Pehlivan, astro-ph/0607527. Blennow, Mirizzi & Serpico, arXiv:0810.2297. Cherry, Fuller, Carlson, Duan & Qian, arXiv:1006.2175. Chakraborty, Choubey, Dasgupta & Kar, arXiv:0805.3131. Chakraborty, Fischer, Mirizzi, Saviano, Tomàs, arXiv:1104.4031, 1105.1130. Choubey, Dasgupta, Dighe & Mirizzi, arXiv:1008.0308. Dasgupta & Dighe, arXiv:0712.3798. Dasgupta, Dighe & Mirizzi, arXiv:0802.1481. Dasgupta, Dighe, Mirizzi & Raffelt, arXiv:0801.1660, 0805.3300. Dasgupta, Mirizzi, Tamborra & Tomàs, arXiv:1002.2943. Dasgupta, Dighe, Raffelt & Smirnov, 0904.3542. Dasgupta, Raffelt, Tamborra, arXiv:1001.5396. Duan, Fuller, Carlson & Qian, astro-ph/0608050, 0703776, arXiv:0707.0290, 0710.1271. Duan, Fuller & Qian, arXiv:0706.4293, 0801.1363, 0808.2046, 1001.2799. Duan, Fuller & Carlson, arXiv:0803.3650. Duan & Kneller, arXiv:0904.0974. Duan & Friedland, arXiv:1006.2359. Duan, Friedland, McLaughlin & Surman, arXiv:1012.0532. Esteban-Pretel, Pastor, Tomàs, Raffelt & Sigl, arXiv:0706.2498, 0712.1137. Esteban-Pretel, Mirizzi, Pastor, Tomàs, Raffelt, Serpico & Sigl, arXiv:0807.0659. Fogli, Lisi, Marrone & Mirizzi, arXiv:0707.1998. Fogli, Lisi, Marrone & Tamborra, arXiv:0812.3031. Friedland, arXiv:1001.0996. Gava & Jean-Louis, arXiv:0907.3947. Gava & Volpe, arXiv:0807.3418. Galais, Kneller & Volpe, arXiv:1102.1471. Galais & Volpe, arXiv:1103.5302. Gava, Kneller, Volpe & McLaughlin, arXiv:0902.0317. Hannestad, Raffelt, Sigl & Wong, astro-ph/0608695. Wei Liao, arXiv:0904.0075, 0904.2855. Lunardini, Müller & Janka, arXiv:0712.3000. Mirizzi, Pozzorini, Raffelt & Serpico, arXiv:0907.3674. Mirizzi & Tomàs, arXiv:1012.1339. Pehlivan, Balantekin, Kajino, Yoshida, arXiv:1105.1182. Raffelt, arXiv:0810.1407, 1103.2891. Raffelt & Tamborra, arXiv:1006.0002. Raffelt & Sigl, hep-ph/0701182. Raffelt & Smirnov, arXiv:0705.1830, 0709.4641. Sawyer, hep-ph/0408265, 0503013, arXiv:0803.4319, 1011.4585. Wu & Qian, arXiv:1105.2068.



Looking forward to the next galactic supernova

May take a long time

No problem

Lots of theoretical work to do!