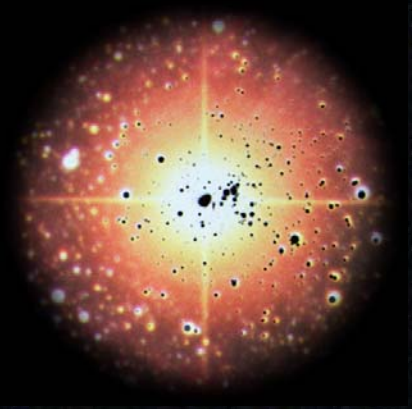
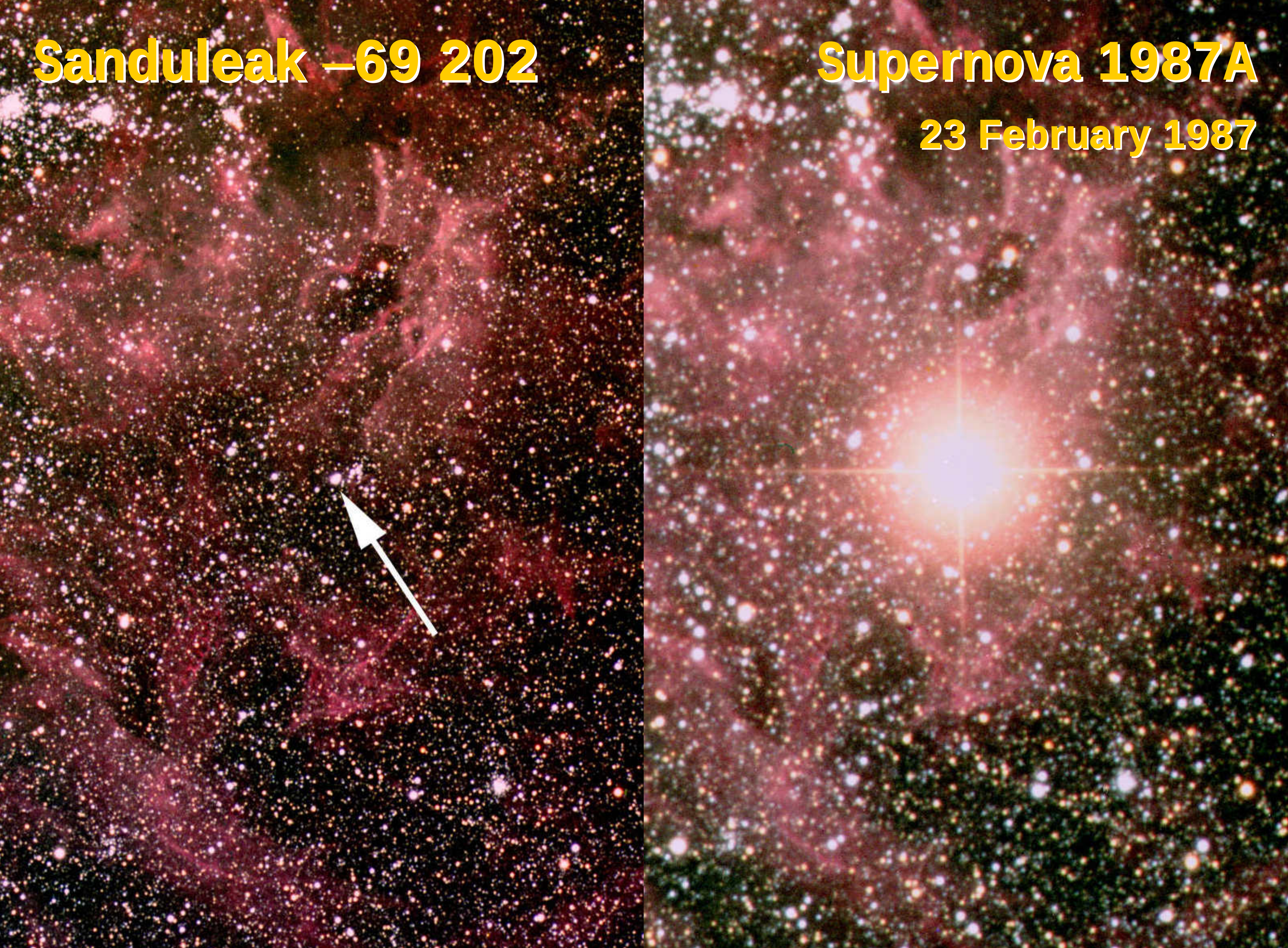


Supernova Neutrinos

LAUNCH, 21-23 March 2007, MPIK Heidelberg

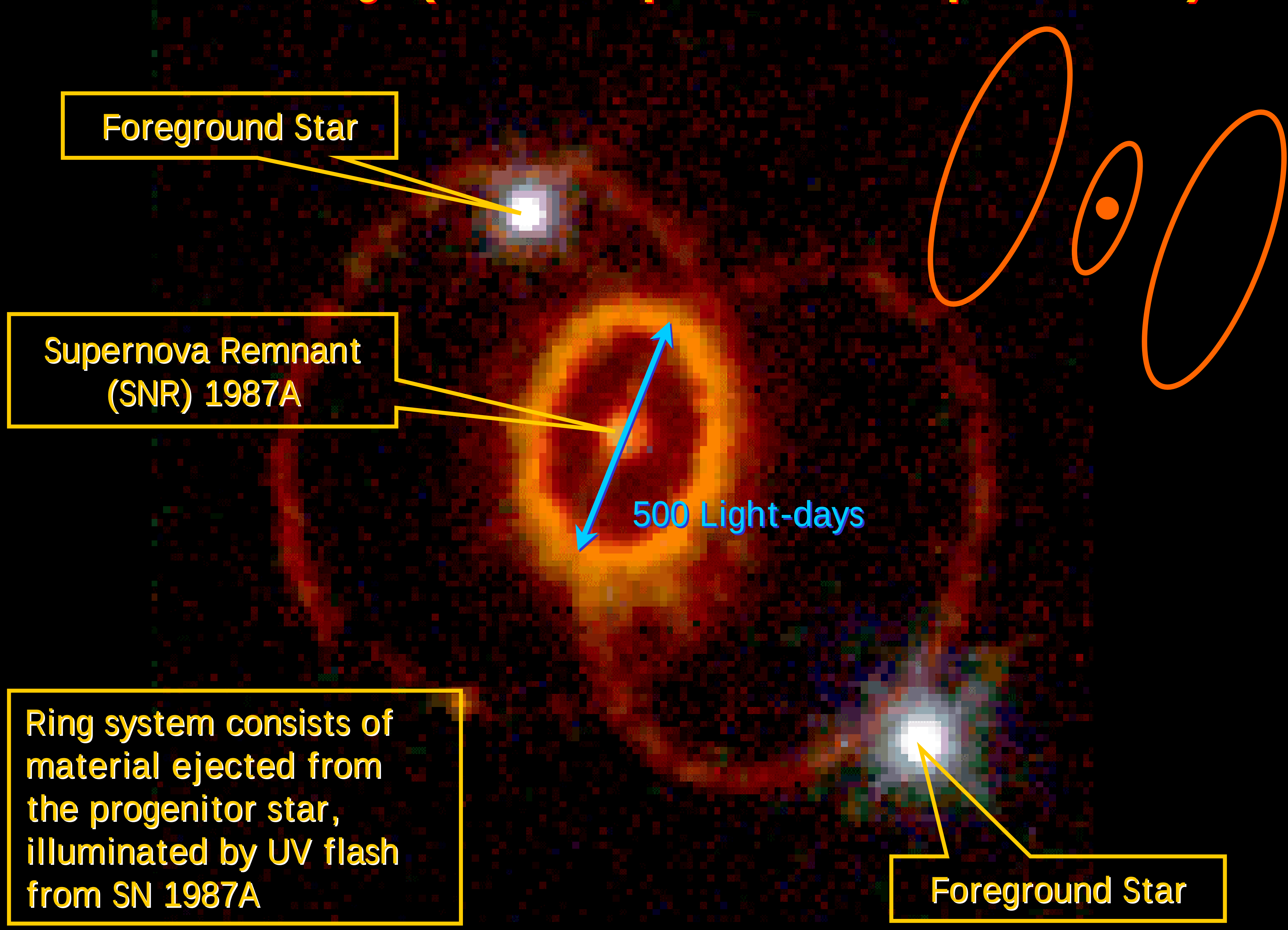
Georg G. Raffelt
Max-Planck-Institut für Physik, München, Germany

Sanduleak –69 202


Sanduleak –69 202
Supernova 1987A
23 February 1987

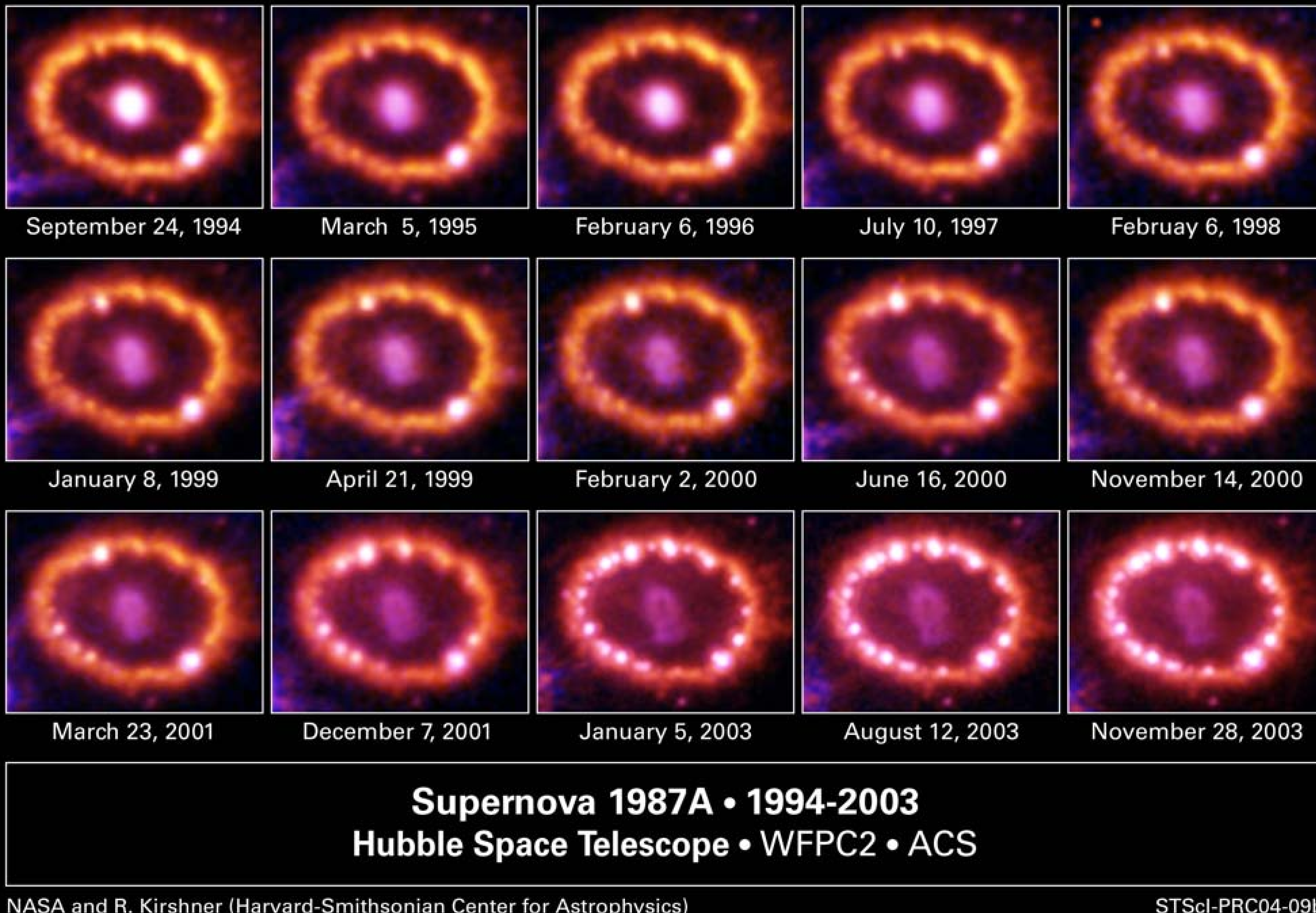
SN 1987A Rings (Hubble Space Telescope 4/1994)

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

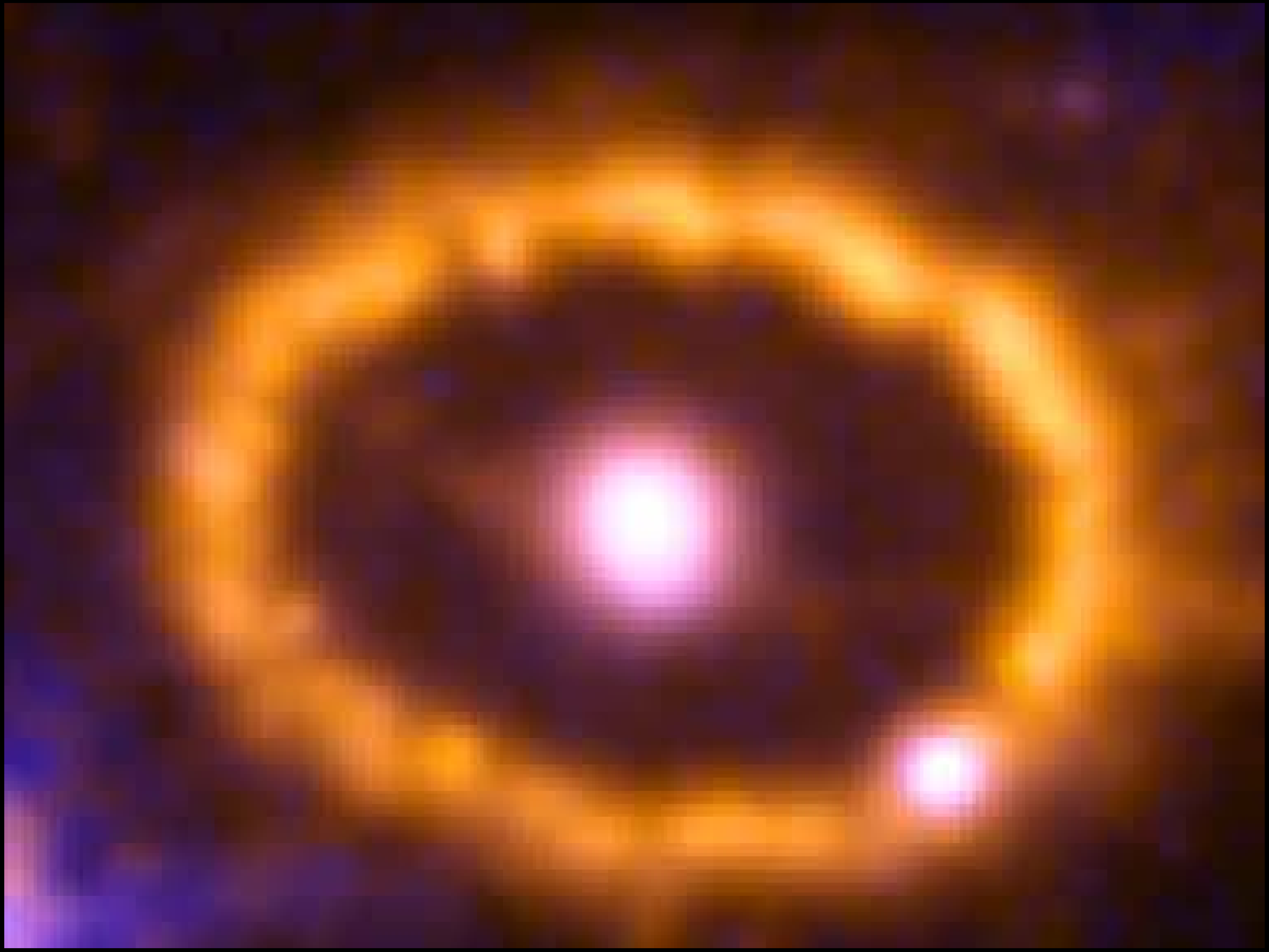


Georg Raffelt, Max-Planck-Institut für Physik, München, Germany

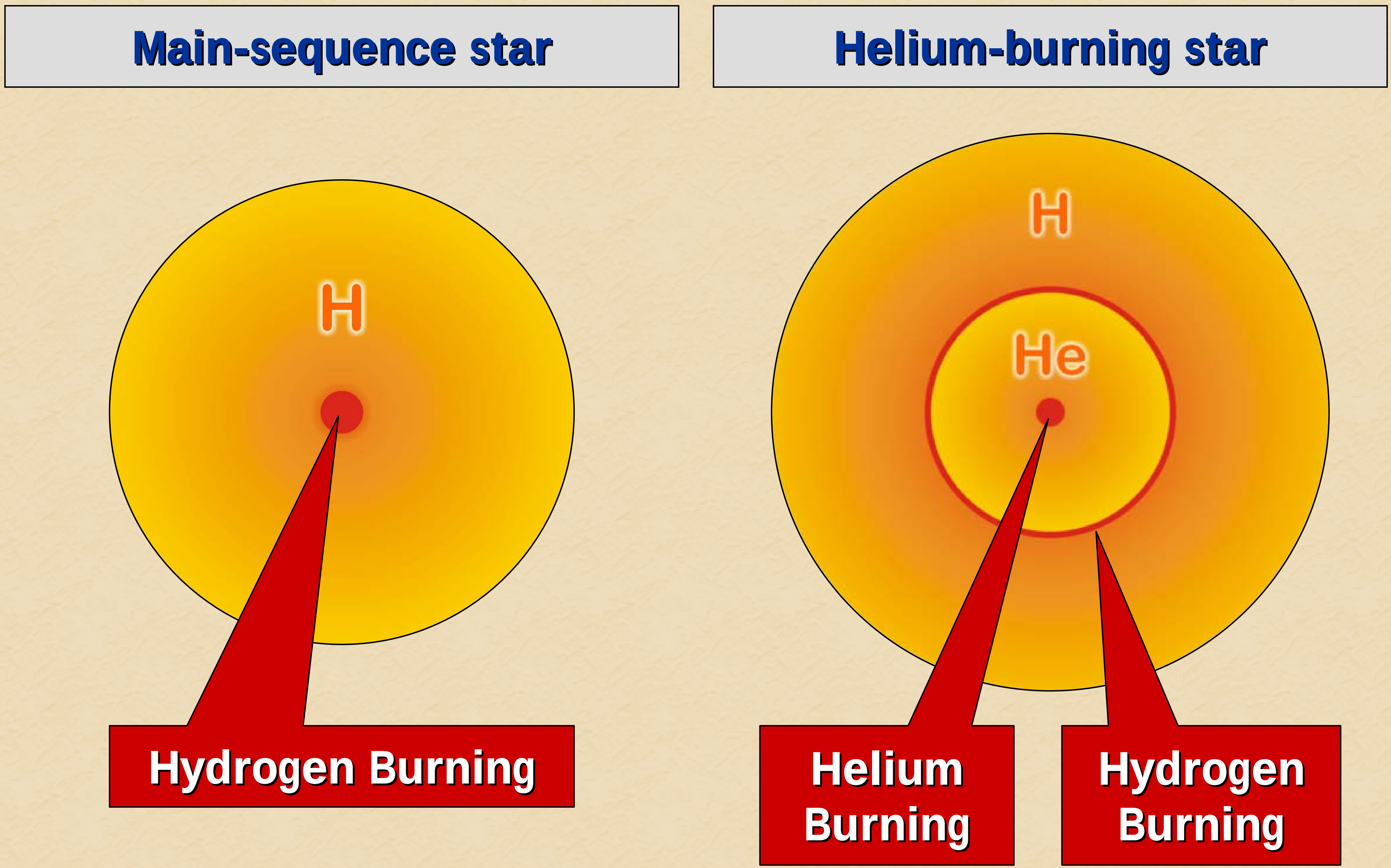
SN 1987A - Explosion Hits Inner Ring



SN 1987A - Explosion Hits Inner Ring

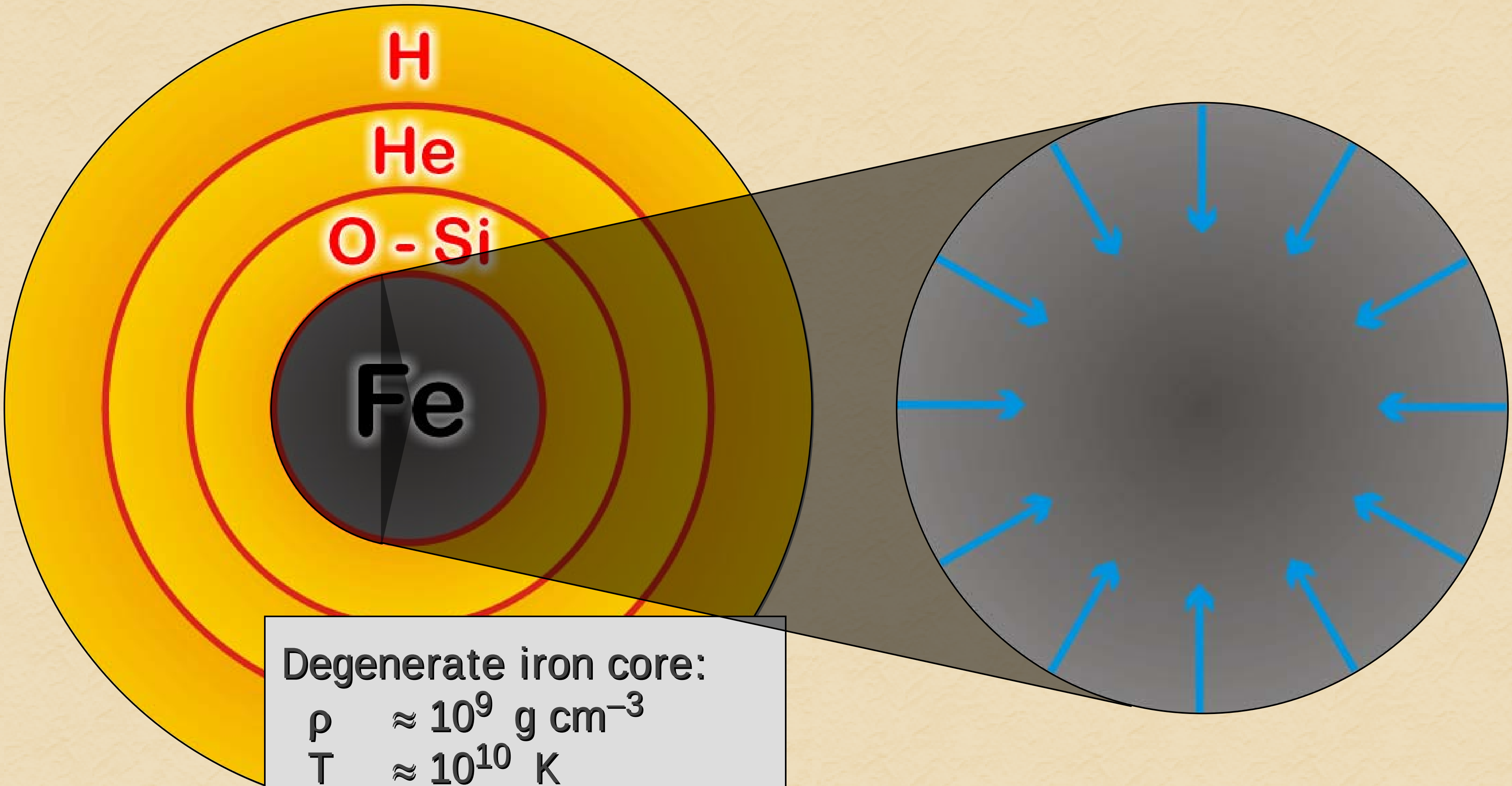


Stellar Collapse and Supernova Explosion



Stellar Collapse and Supernova Explosion

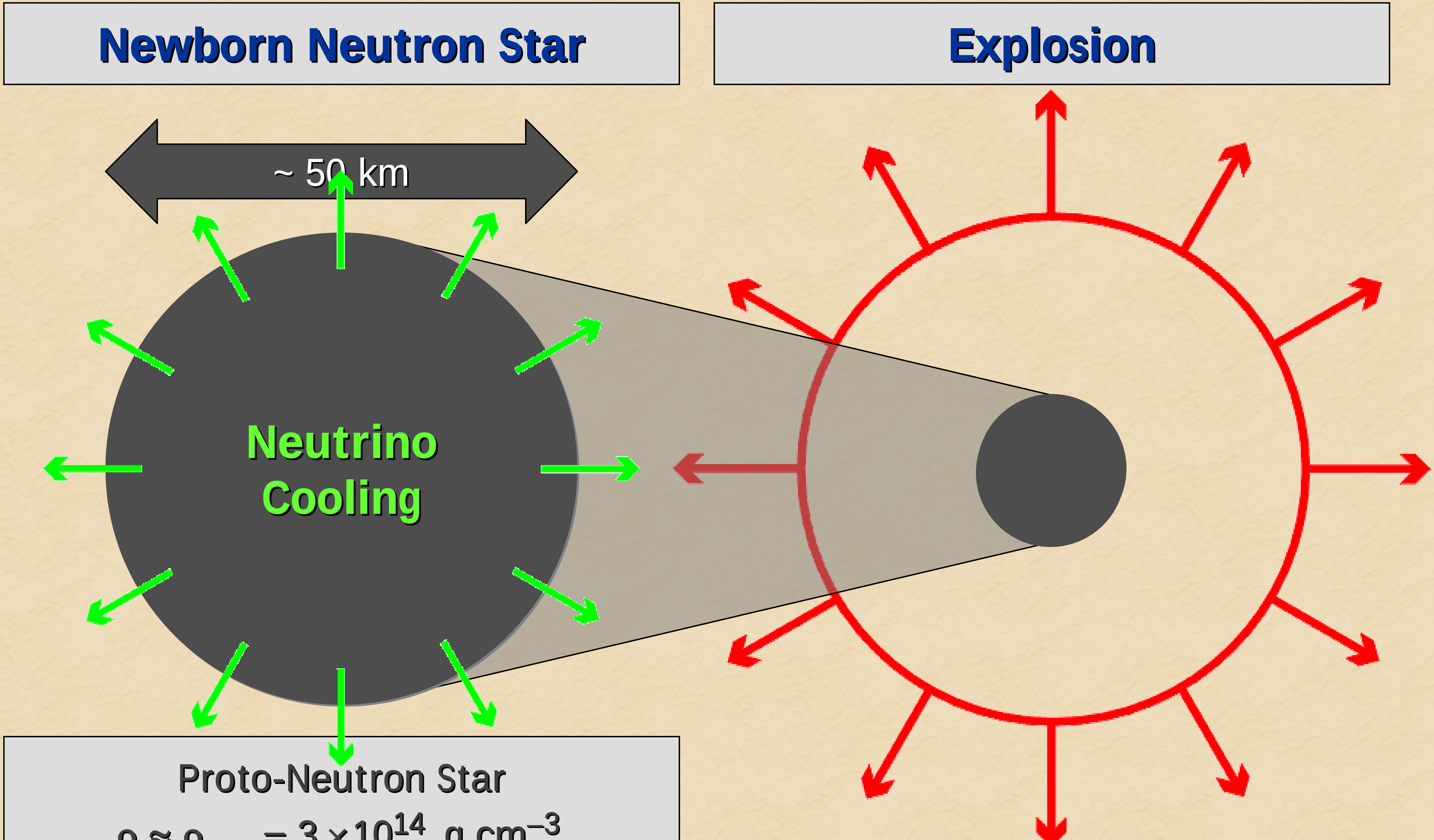
Onion structure | **Collapse (implosion)**



Degenerate iron core:

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

Stellar Collapse and Supernova Explosion



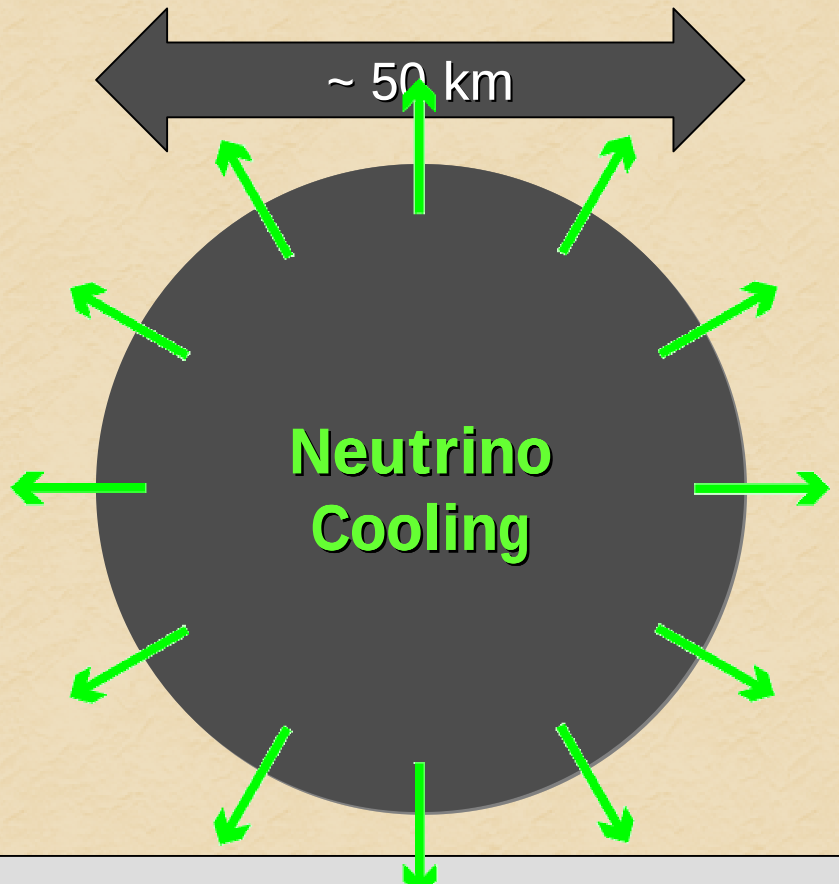
Proto-Neutron Star

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

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

Stellar Collapse and Supernova Explosion

Newborn Neutron Star



Proto-Neutron Star

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

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

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 (1% of this into cosmic rays)
- 0.01% Photons, outshine host galaxy

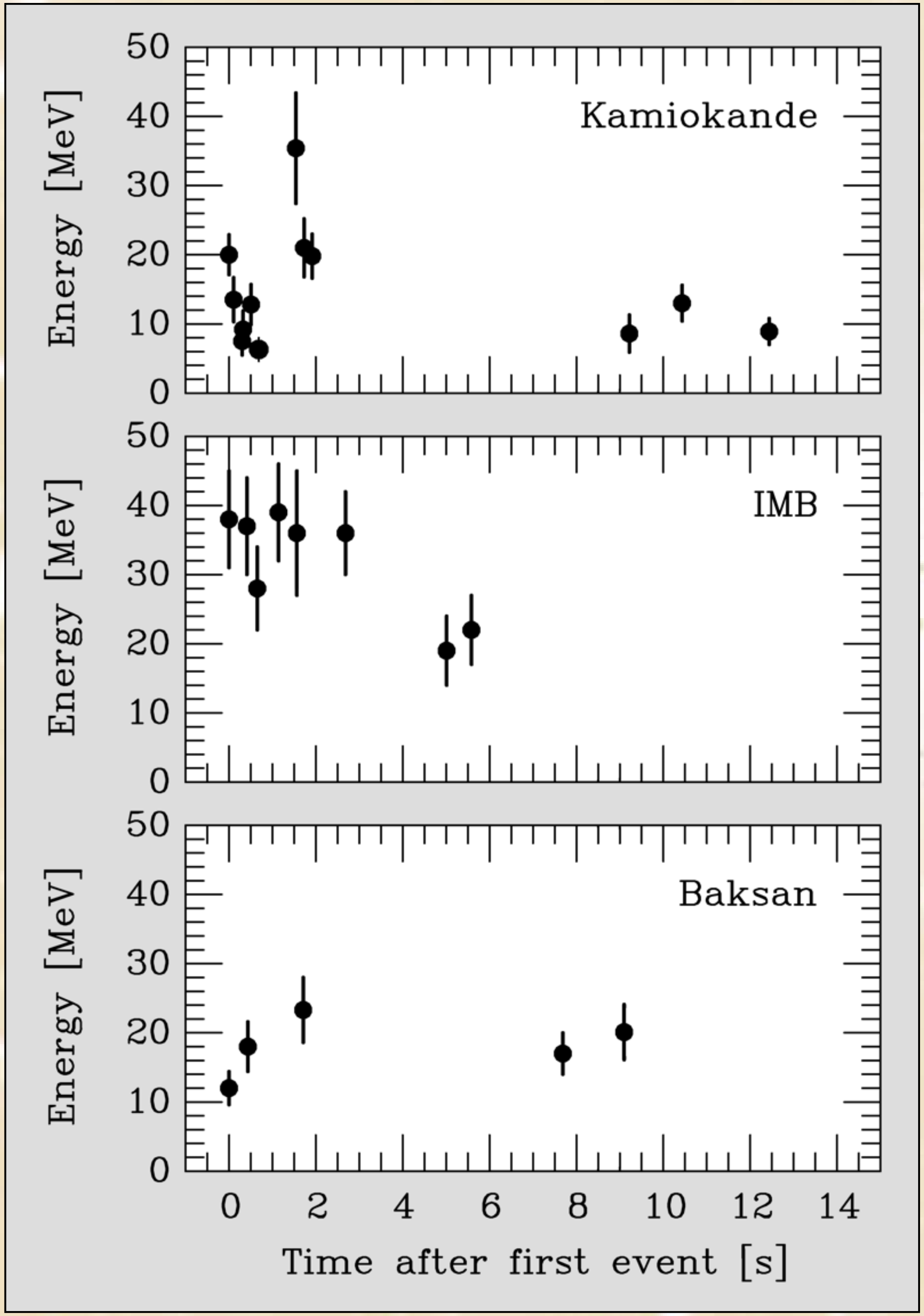
Neutrino luminosity

$L_\nu \approx 3 \times 10^{53}\ \mathrm{erg} / 3\ \mathrm{sec}$

$\approx 3 \times 10^{19}\ L_{SUN}$

While it lasts, outshines the entire visible universe

Neutrino Signal of Supernova 1987A



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

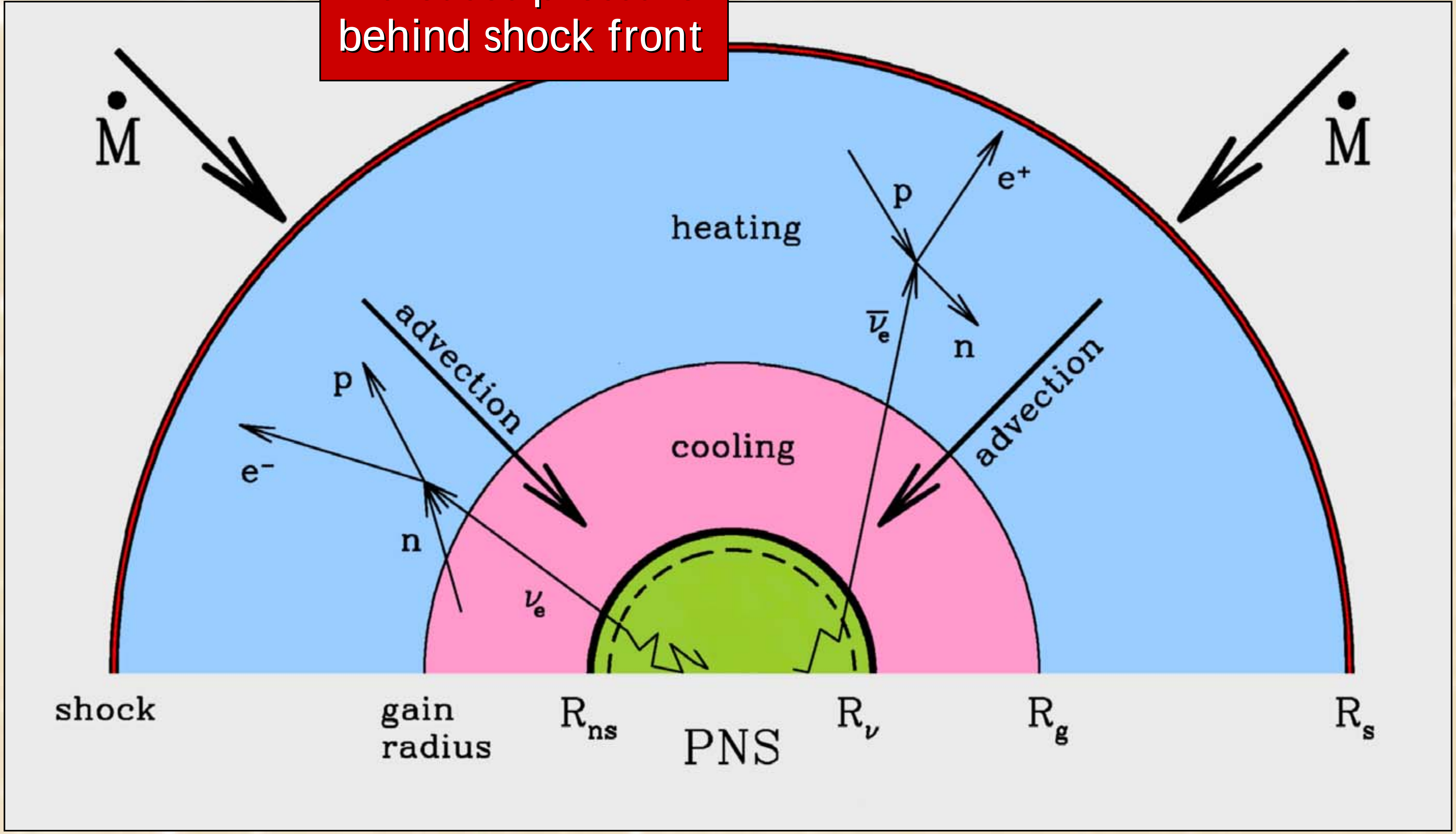
Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty ±50 ms

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

Within clock uncertainties, signals are contemporaneous

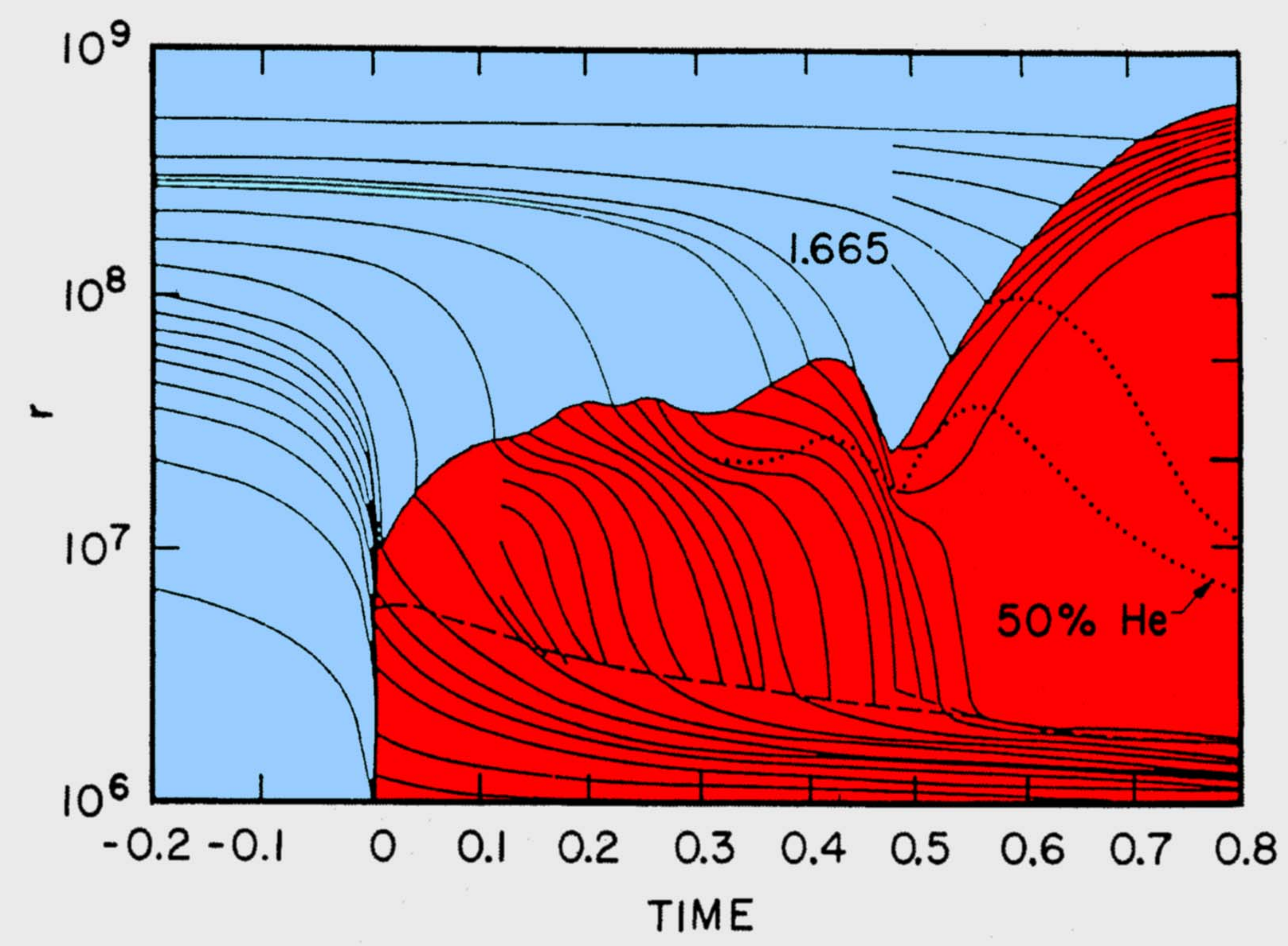
Neutrino-Driven Delayed Explosion

Neutrino heating increases pressure behind shock front



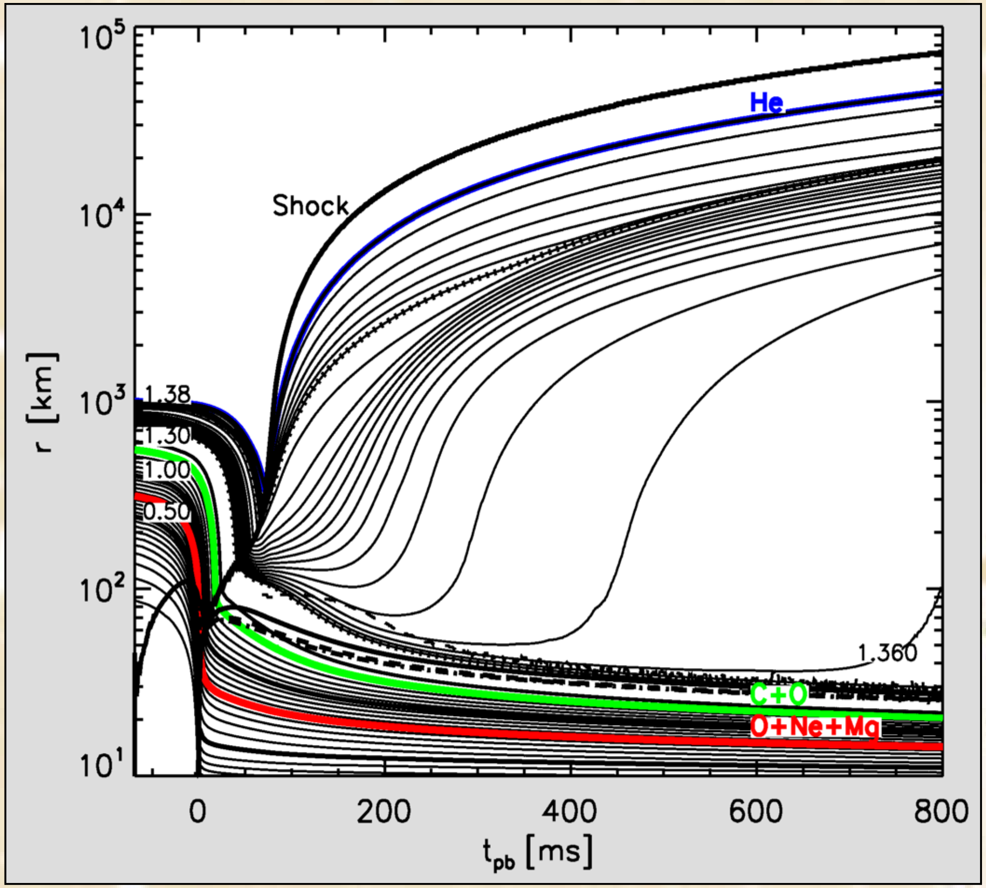
Picture adapted from Janka, astro-ph/0008432

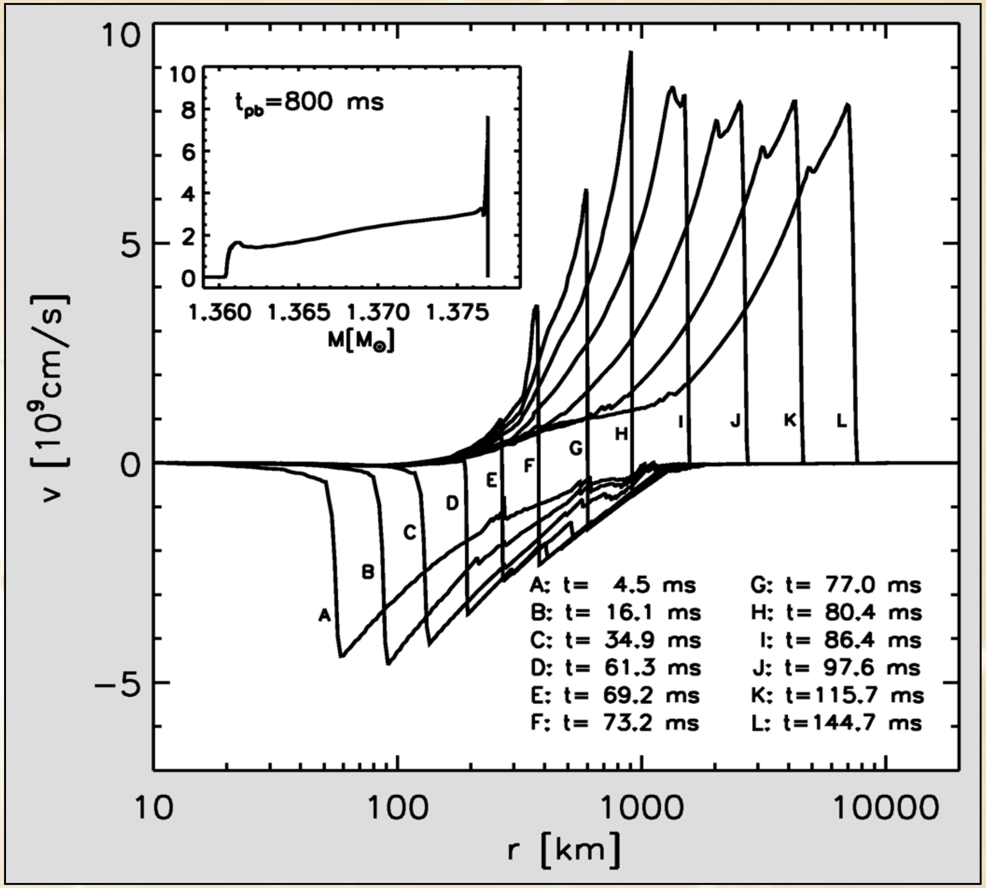
Delayed Explosion



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

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

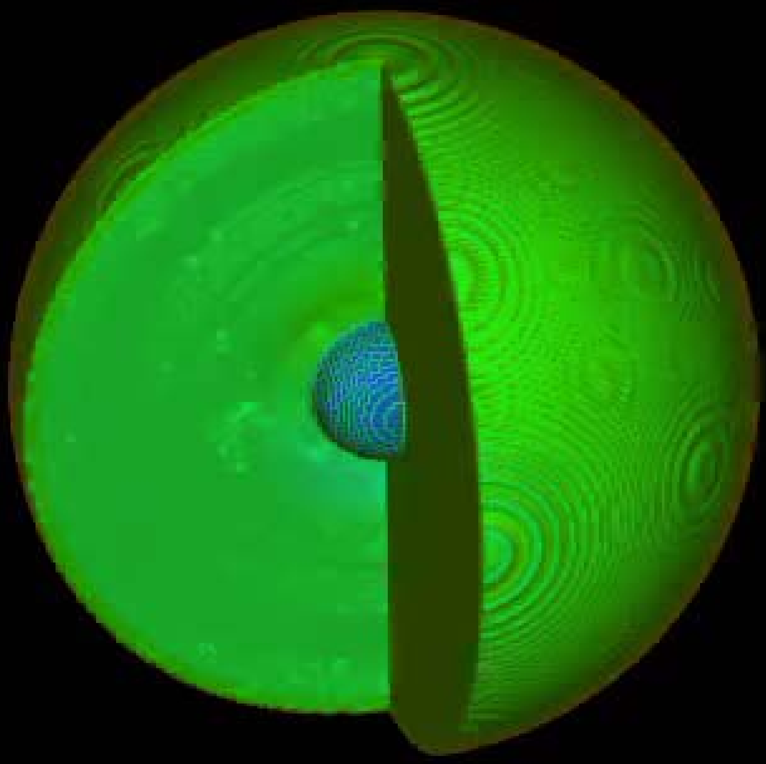




Kitaura, Janka & Hillebrandt: "Explosions of O-Ne-Mg cores, the Crab supernova, and subluminous type II-P supernovae", astro-ph/0512065

Standing Accretion Shock Instability (SASI)

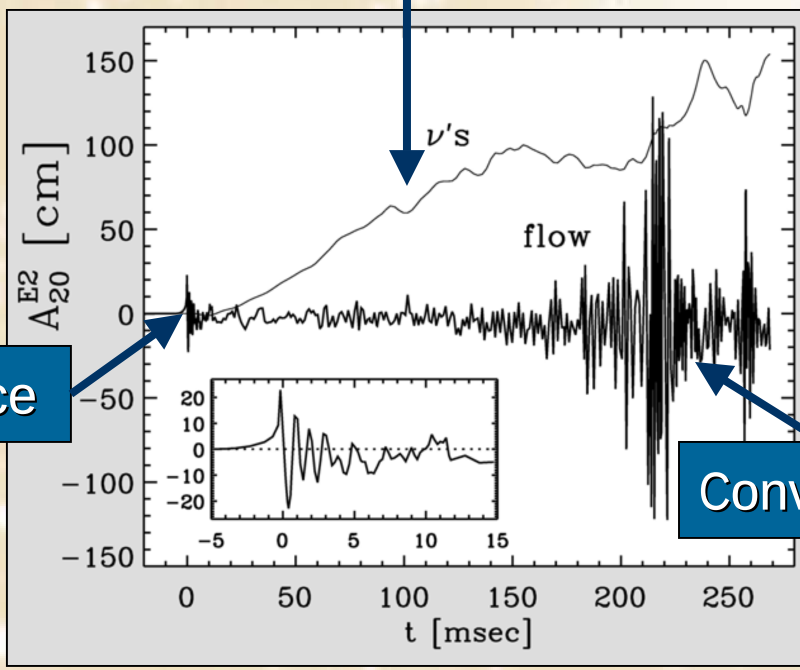
Mezzacappa et al., http://www.phy.ornl.gov/tsi/pages/simulations.html



Gravitational Waves from Core-Collapse Supernovae

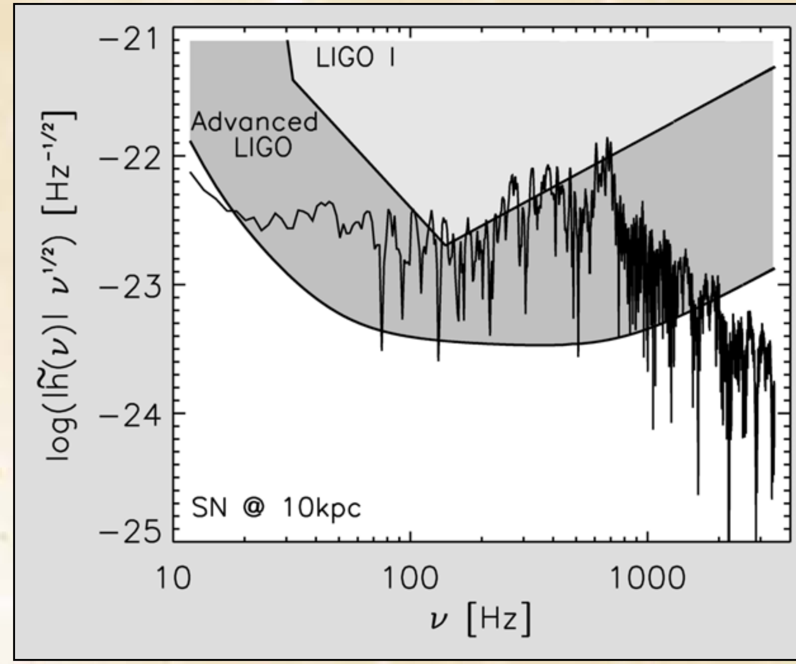
Müller, Rampp, Buras, Janka, & Shoemaker, "Towards gravitational wave signals from realistic core collapse supernova models," astro-ph/0309833

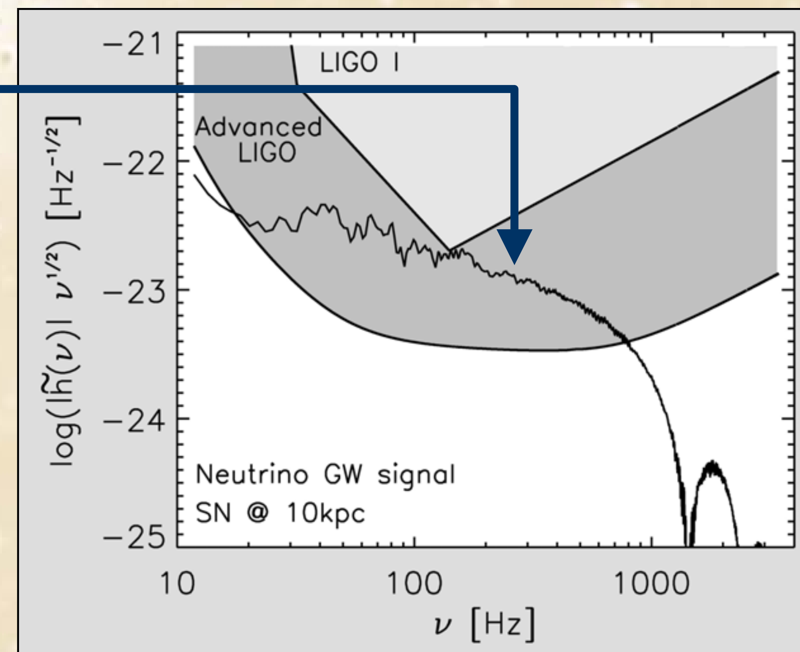
Asymmetric neutrino emission



Bounce

Convection

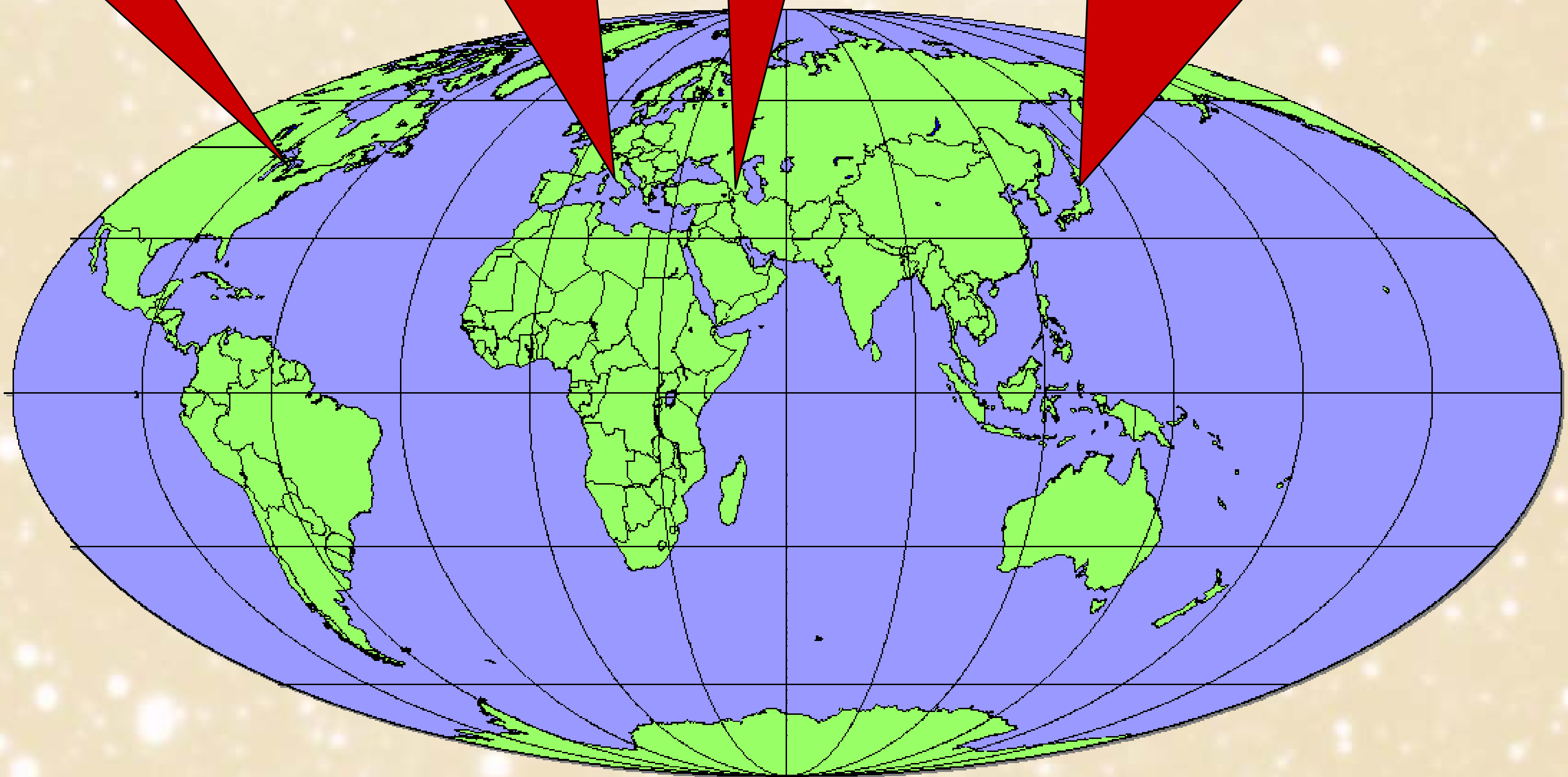




The gravitational-wave signal from convection is a generic and dominating feature

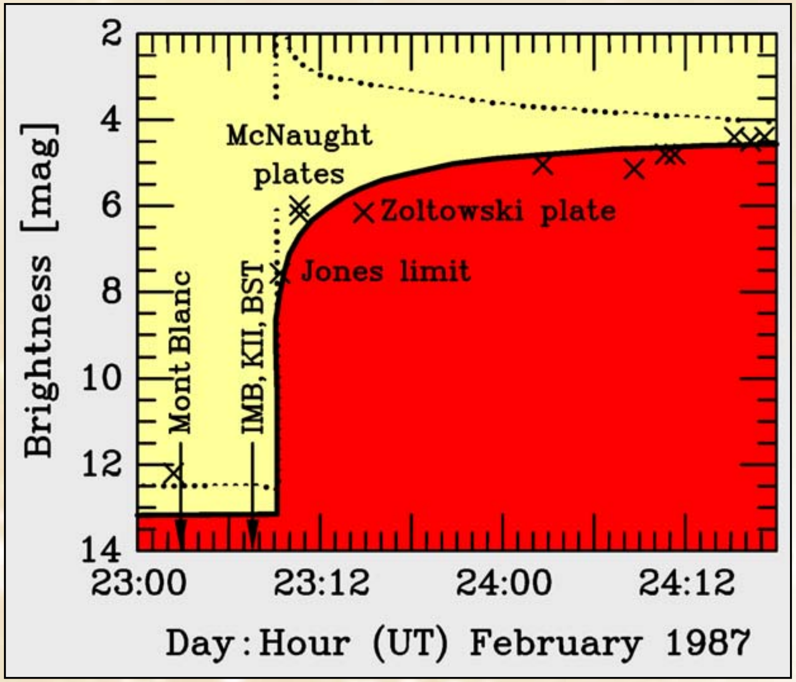
Future Supernova Neutrino Observations

Large Detectors for Supernova Neutrinos



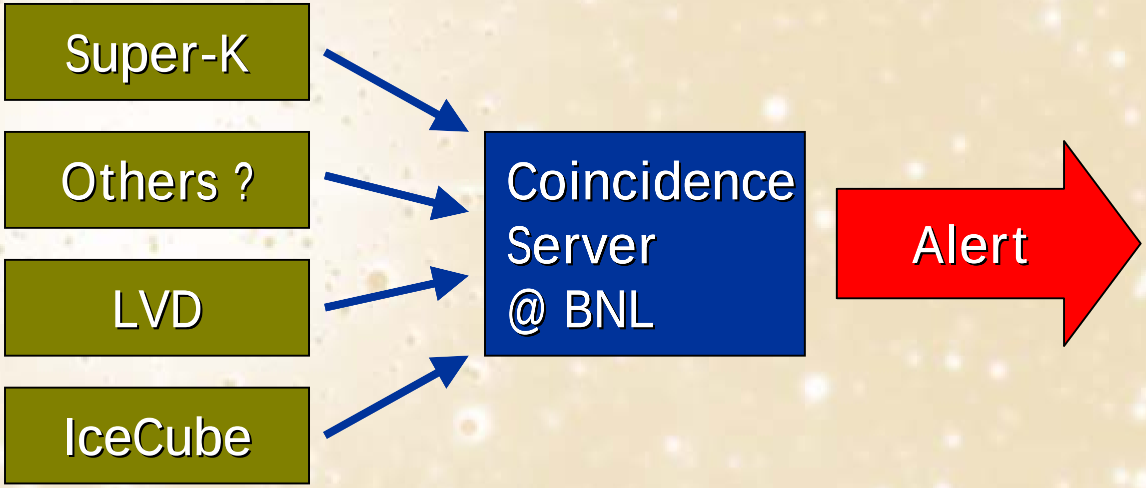
In brackets events for a “fiducial SN” at a distance 10 kpc

SuperNova Early Warning System (SNEWS)



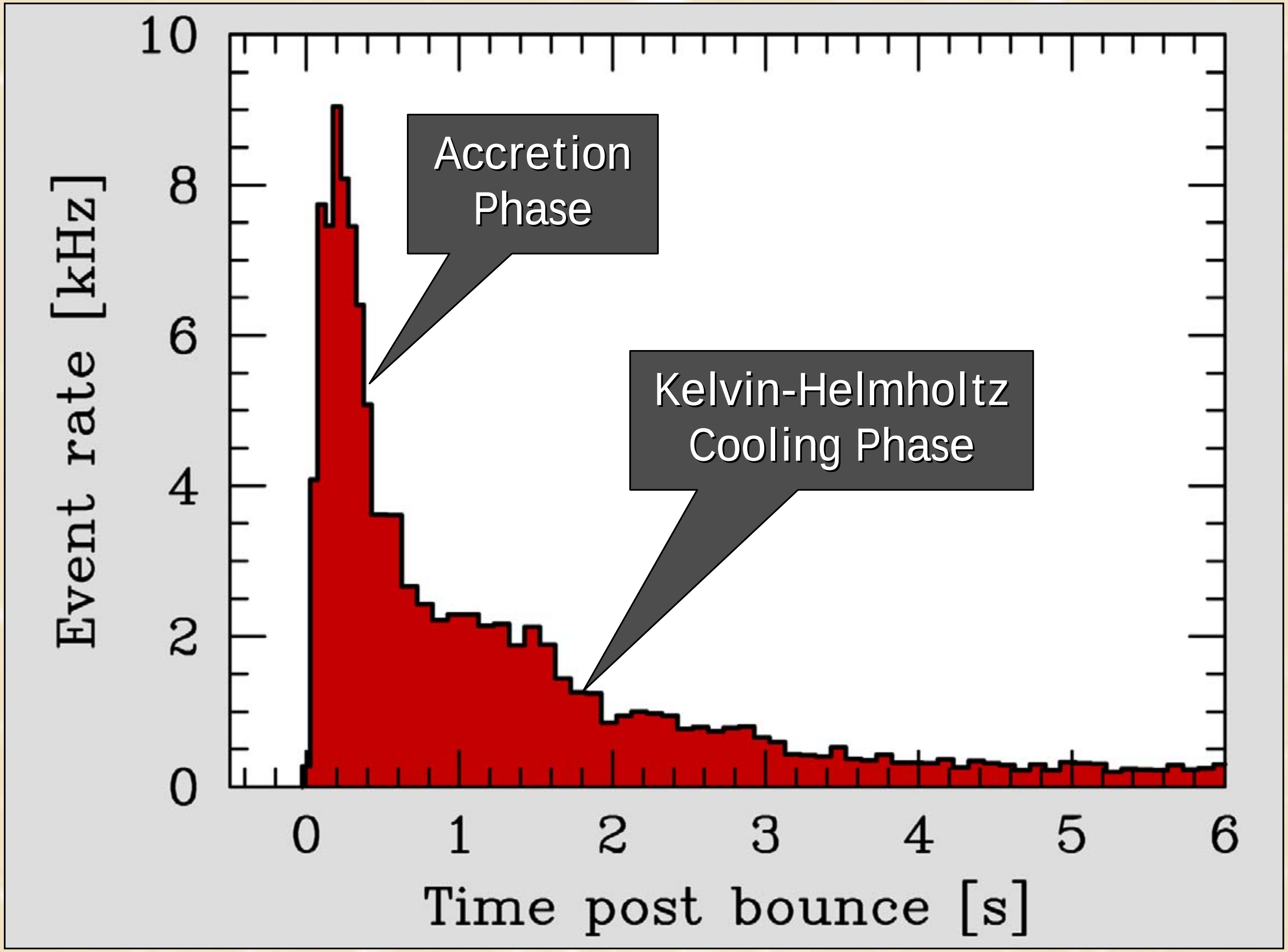
Supernova 1987A
Early Light Curve

Neutrino observation can alert astronomers several hours in advance to a supernova.
To avoid false alarms, require alarm from at least two experiments.



http://snews.bnl.gov
astro-ph/0406214

Simulated Supernova Signal at Super-Kamiokande

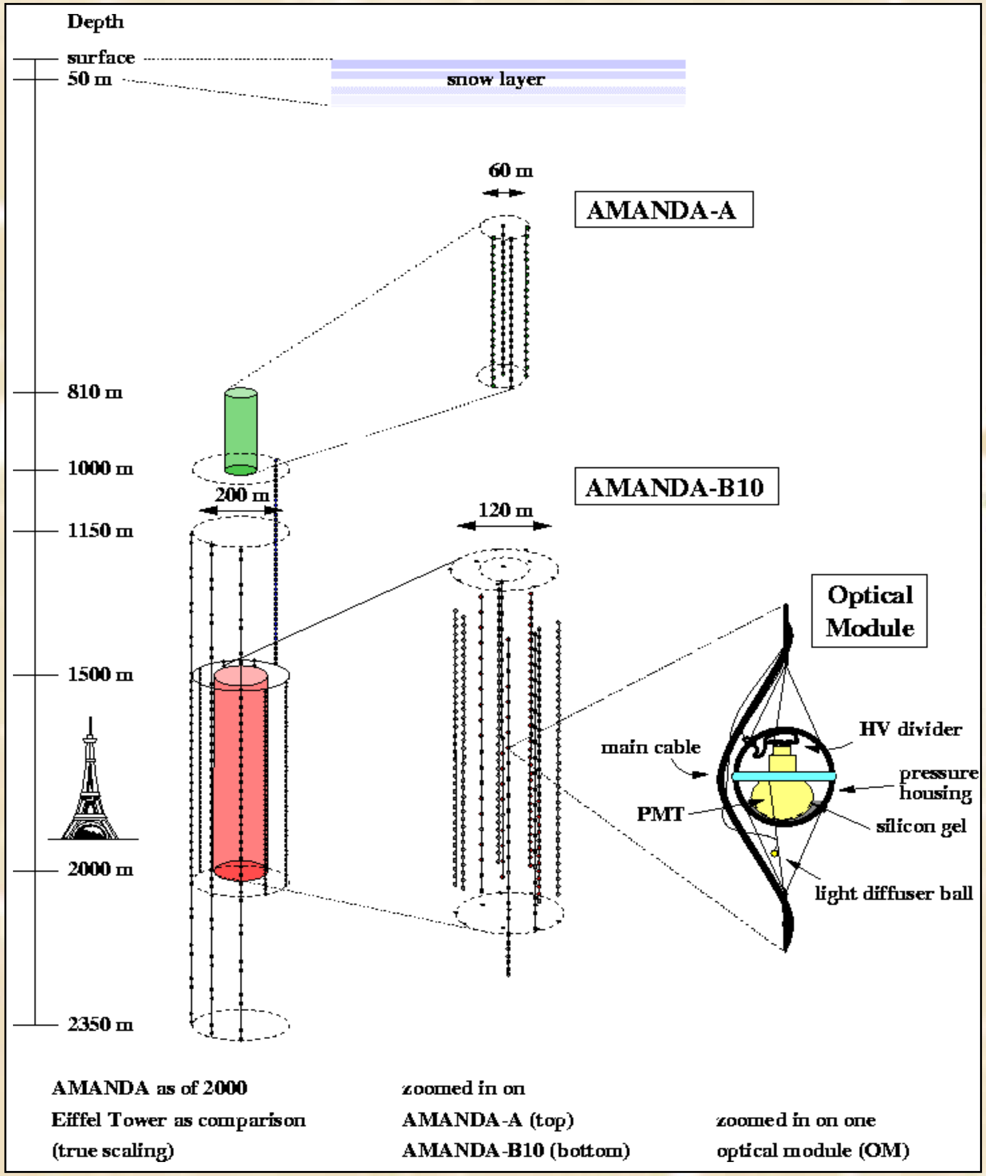


Simulation for Super-Kamiokande SN signal at 10 kpc, based on a numerical Livermore model

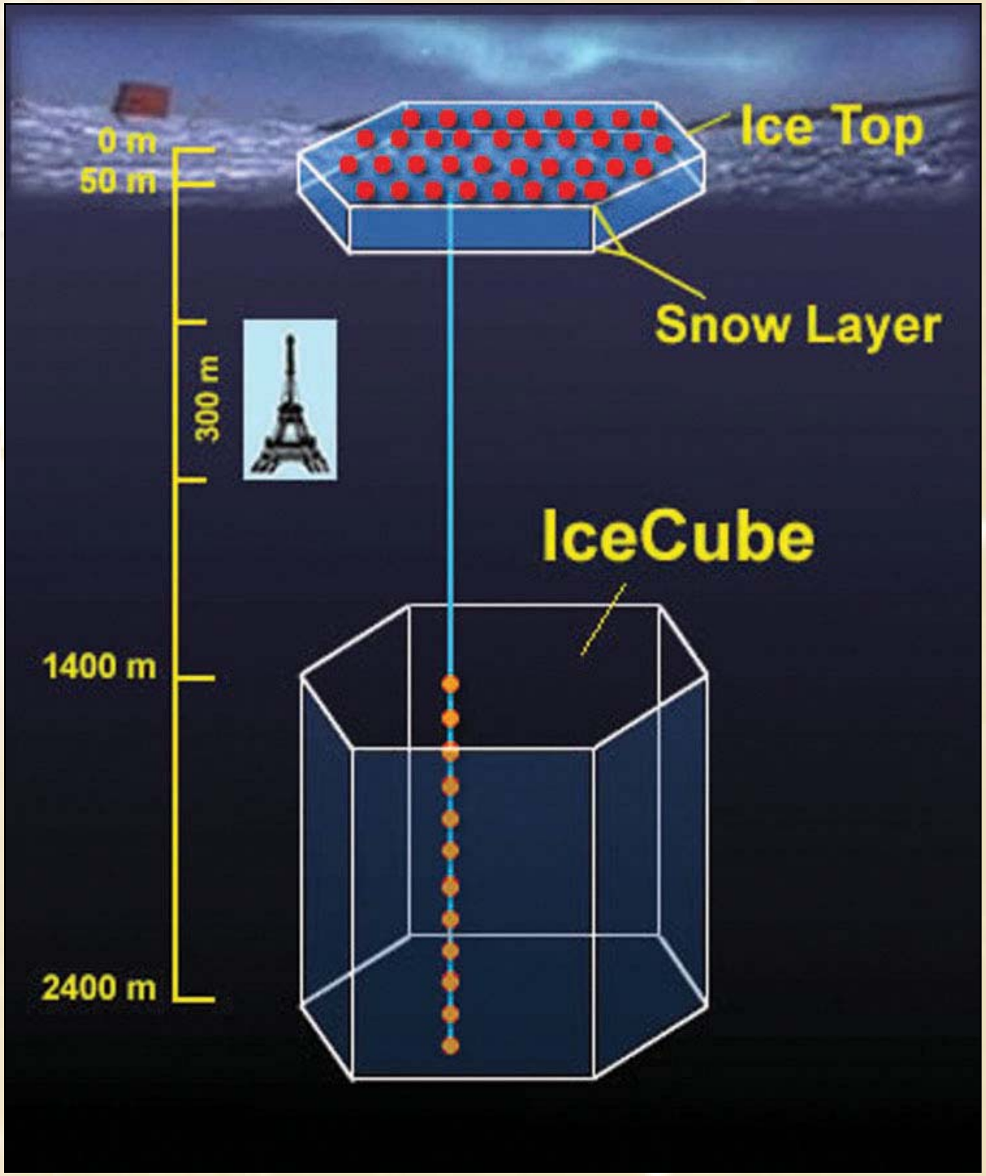
[Totani, Sato, Dalhed & Wilson, ApJ 496 (1998) 216]

Southpole Ice-Cherenkov Neutrino Detectors

AMANDA II (0.1 km^3, 800 PMTs)



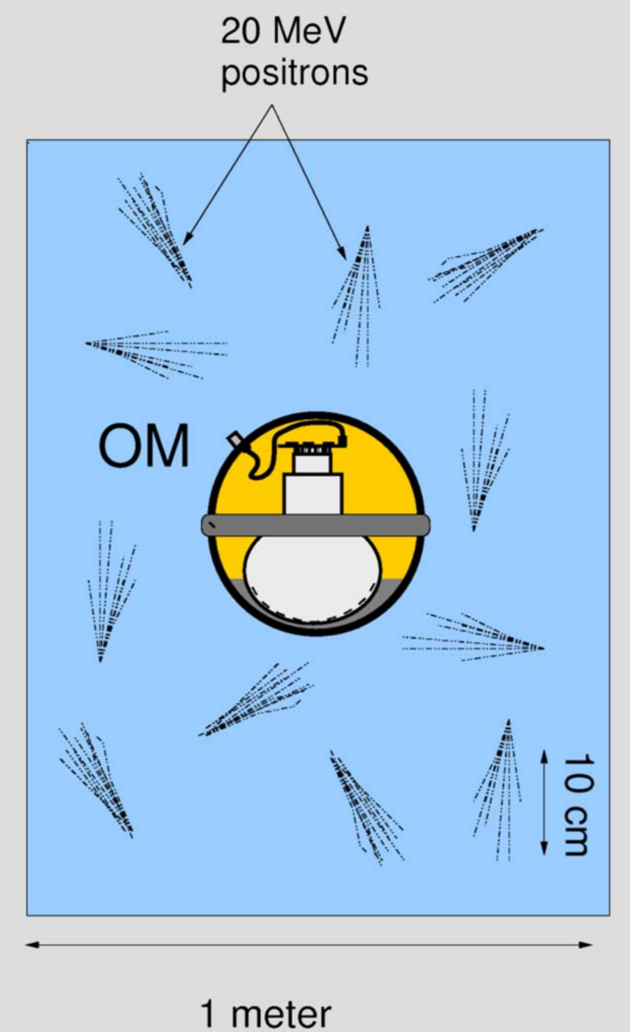
Future IceCube (1 km^3, 4800 PMTs)

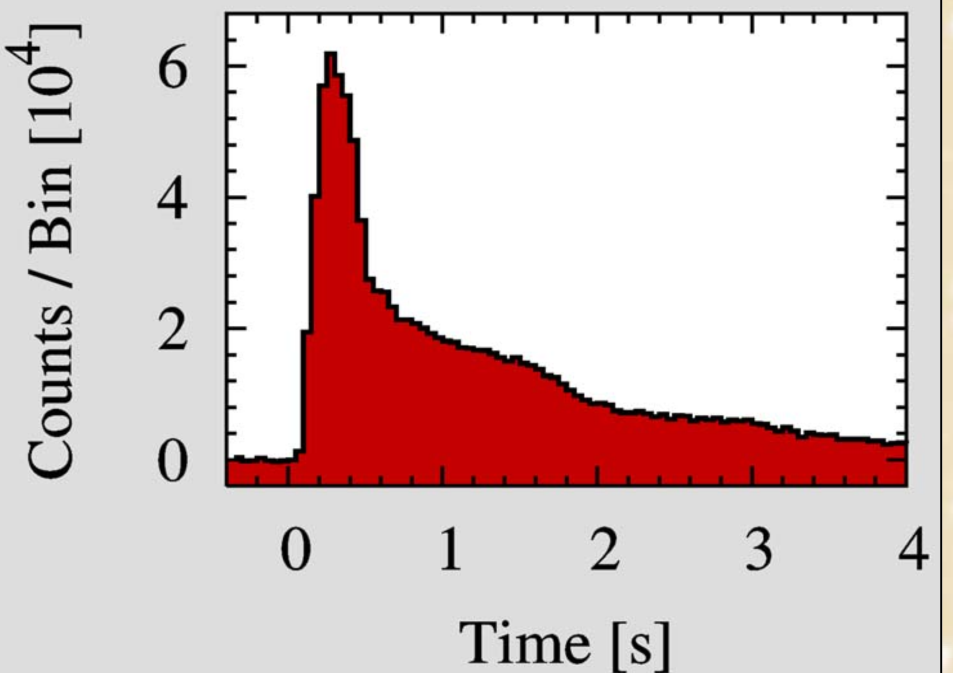


IceCube as a Supernova Neutrino Detector

Each optical module (OM) picks up Cherenkov light from its neighborhood. SN appears as “correlated noise”.

- About 300 Cherenkov photons per OM from a SN at 10 kpc
- Noise per OM < 260 Hz
- Total of 4800 OMs in IceCube





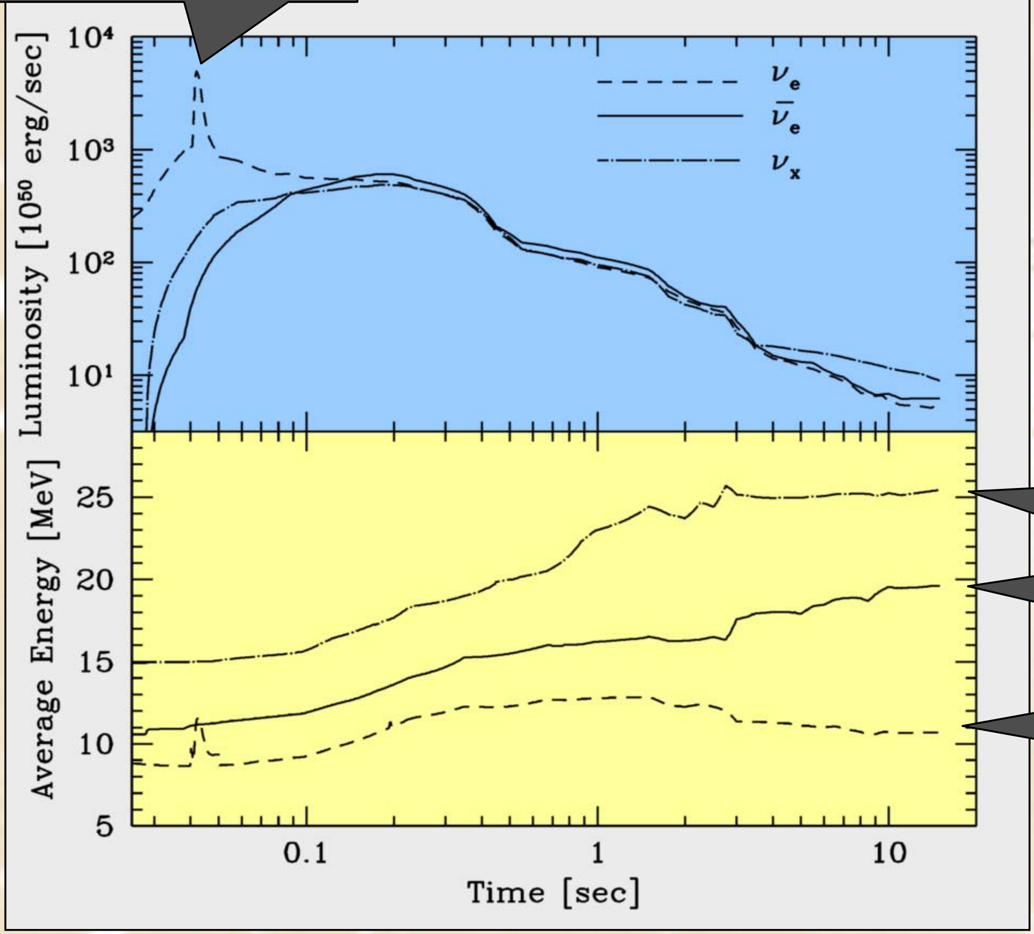
IceCube SN signal at 10 kpc, based on a numerical Livermore model [Dighe, Keil & Raffelt, hep-ph/0303210]

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


Supernova
Neutrino Oscillations

Flavor-Dependent Fluxes and Spectra

Prompt ν_e deleptonization burst



ν_x

$\bar{\nu}_e$

ν_e

Livermore numerical model
ApJ 496 (1998) 216

Broad characteristics

- Duration a few seconds
- $\langle E_\nu \rangle \sim$ 10–20 MeV
- $\langle E_\nu \rangle$ increases with time
- Hierarchy of energies

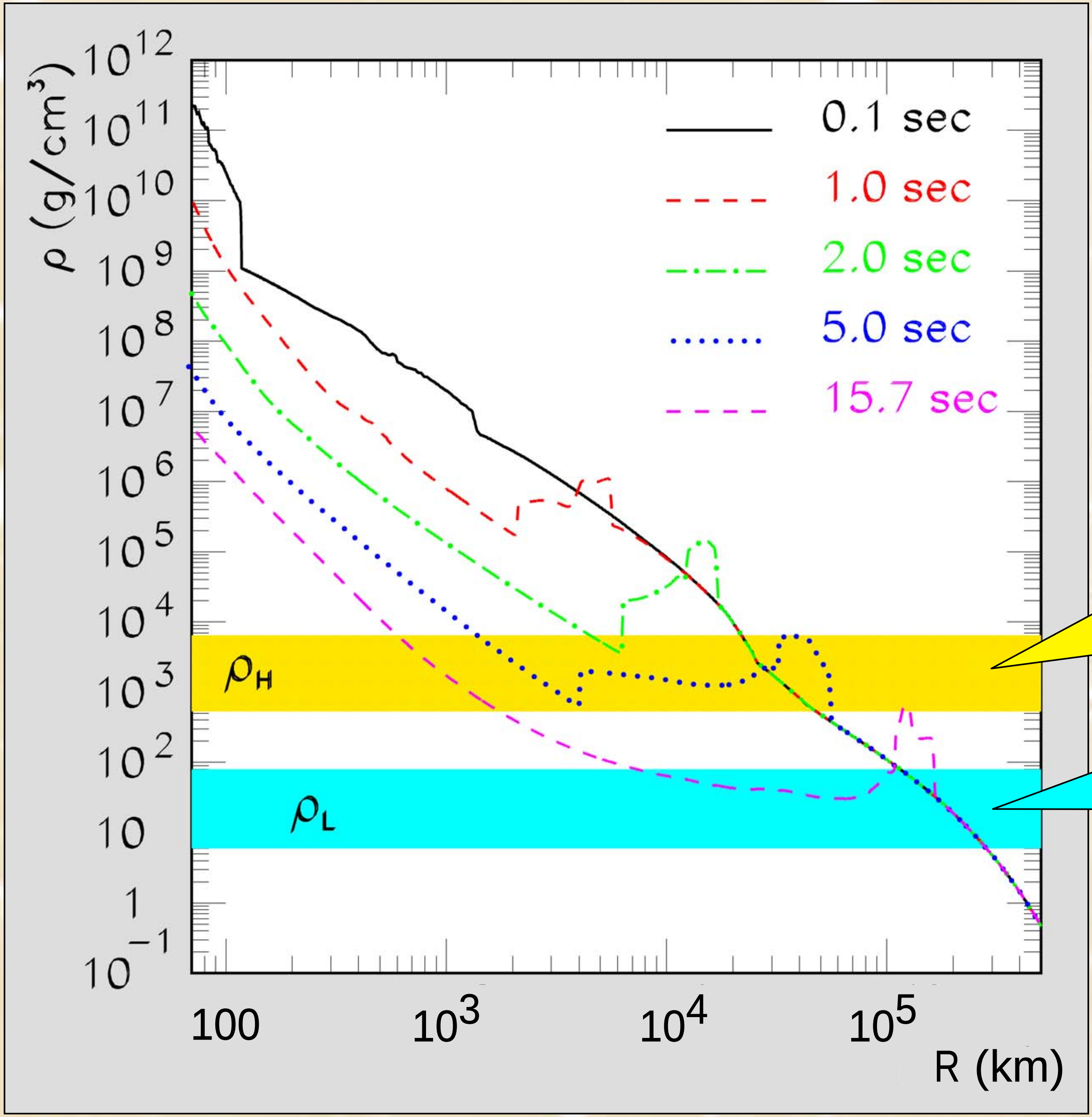
$$\left\langle E_{\nu_e} \right\rangle < \left\langle E_{\bar{\nu}_e} \right\rangle < \left\langle E_{\nu_x} \right\rangle$$

- Approximate equipartition of energy between flavors

However, in traditional simulations transport of ν_μ and ν_τ schematic

- Incomplete microphysics
- Crude numerics to couple neutrino transport with hydro code

H- and L-Resonance for MSW Oscillations



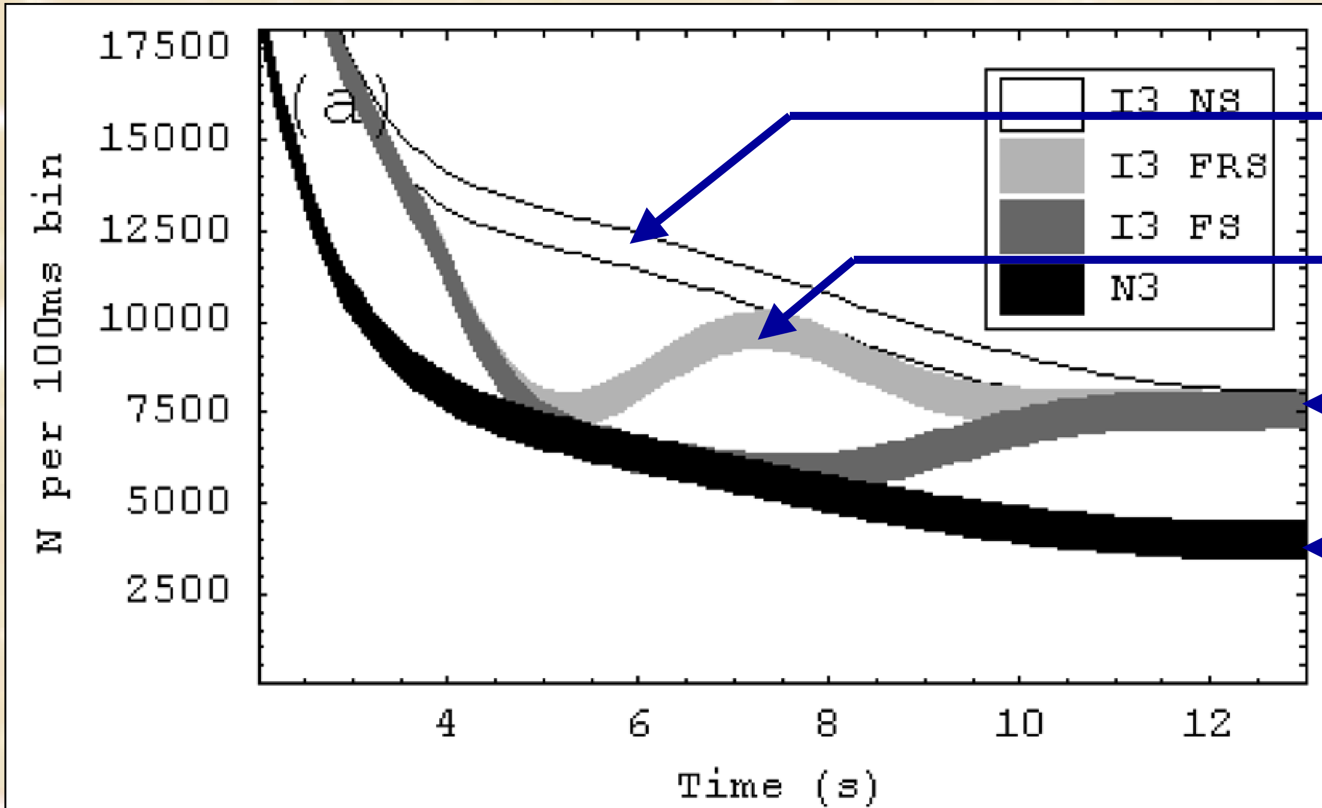
R. Tomàs, M. Kachelriess, G. Raffelt, A. Dighe, H.-T. Janka & L. Scheck: Neutrino signatures of supernova forward and reverse shock propagation [astro-ph/0407132]

Resonance density for Δm^2_{atm}

Resonance density for Δm^2_{sol}

Shock-Wave Propagation in IceCube

$$\frac{\text{Flux}(\bar{\nu}_e)}{\text{Flux}(\bar{\nu}_x)} = 0.8, \qquad \langle E_{\bar{\nu}_e} \rangle = 15\,\text{MeV}, \qquad \langle E_{\bar{\nu}_x} \rangle = 18\,\text{MeV}$$



Inverted Hierarchy
No shockwave

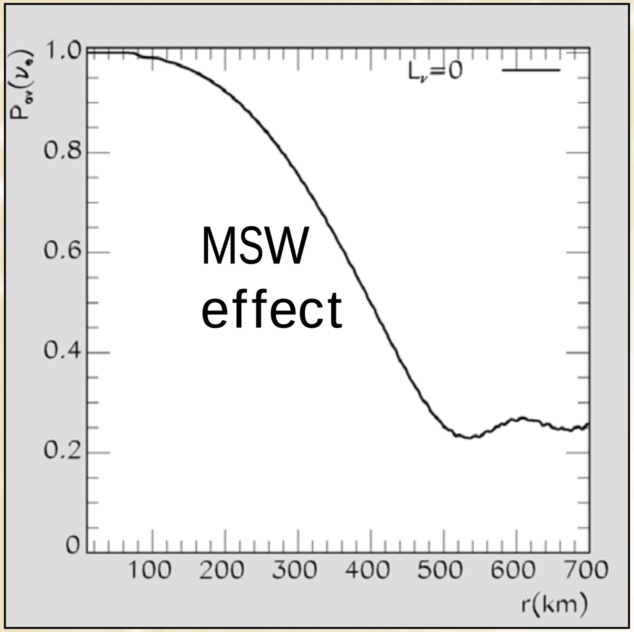
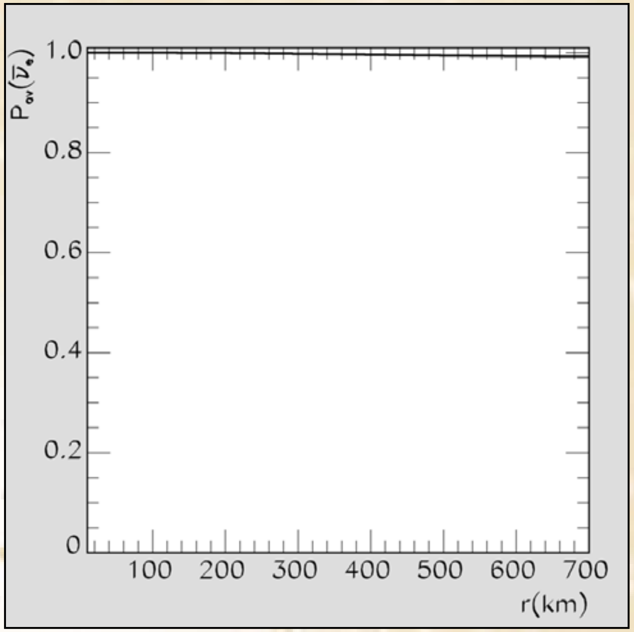
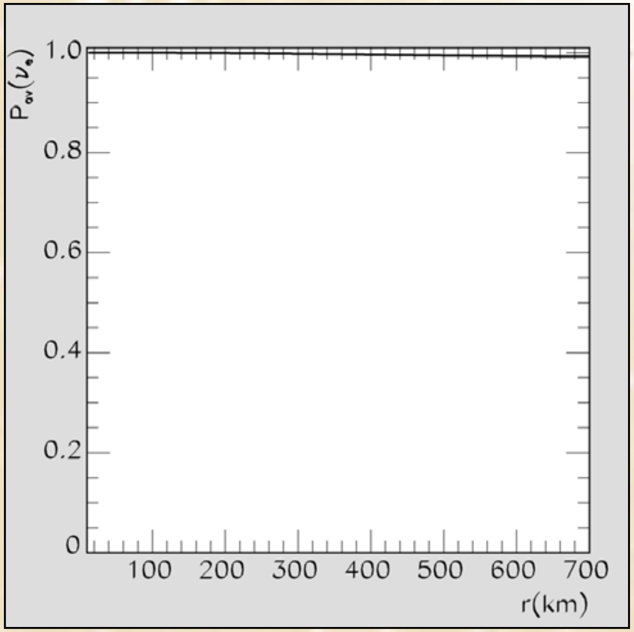
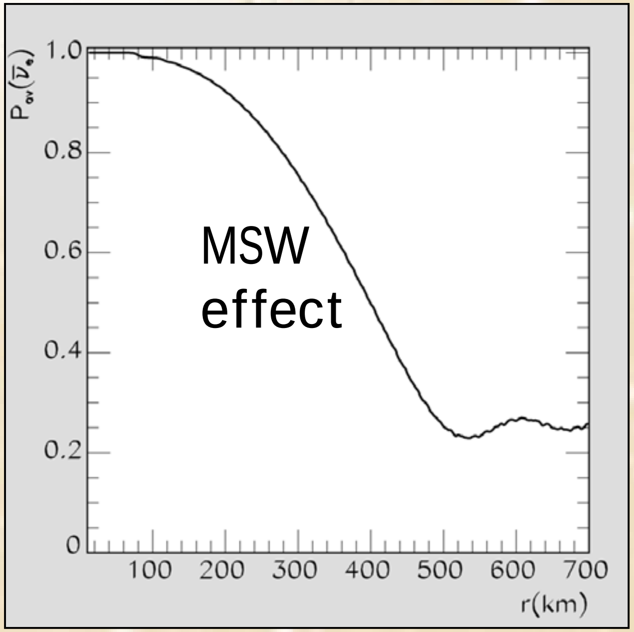
Inverted Hierarchy
Forward & reverse shock

Inverted Hierarchy
Forward shock

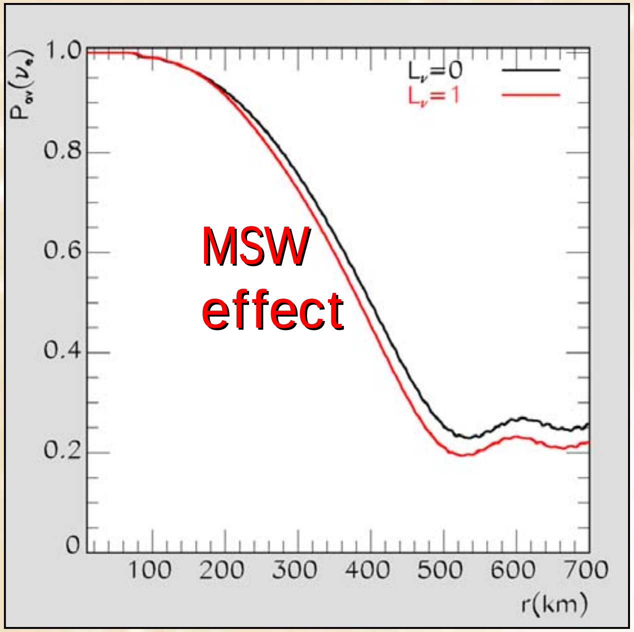
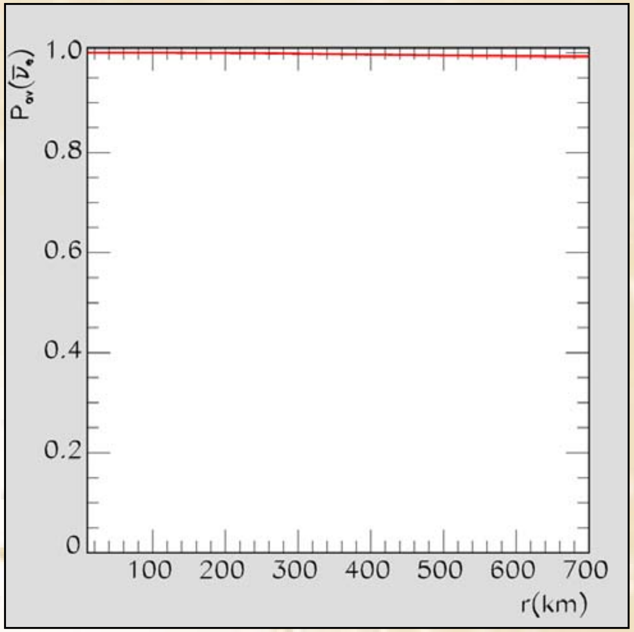
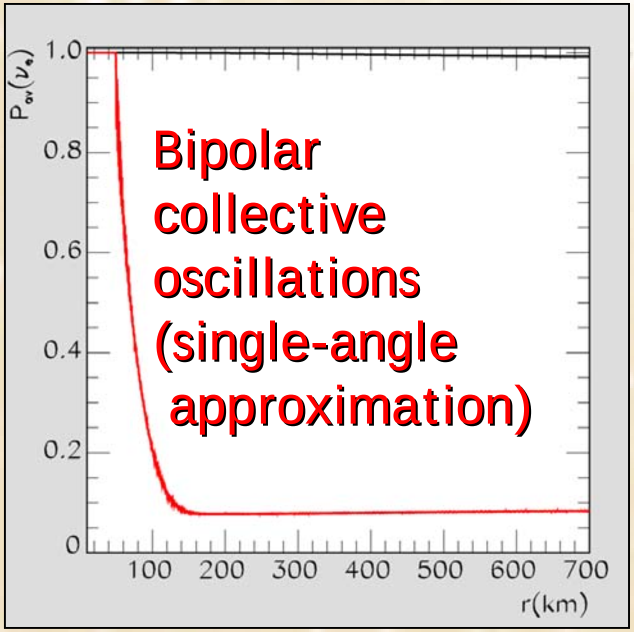
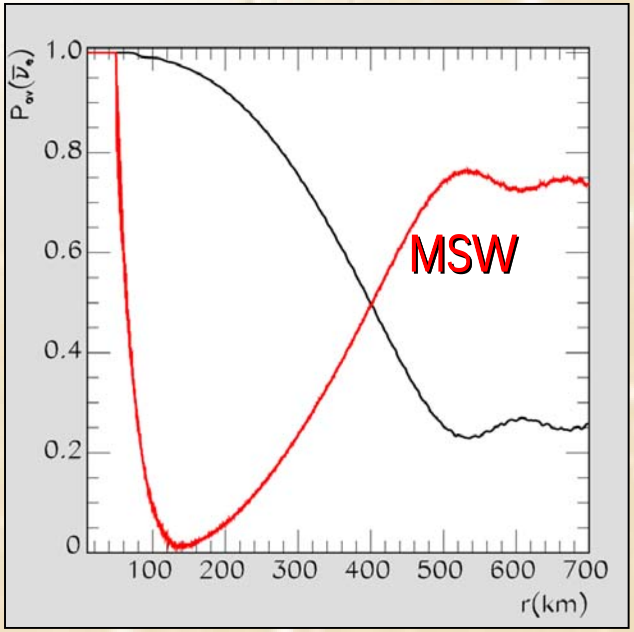
Normal Hierarchy

Choubey, Harries & Ross, "Probing neutrino oscillations from supernovae shock waves via the IceCube detector", astro-ph/0604300

Self-Induced Flavor Oscillations of SN Neutrinos

	Survival probability ν_e	Survival probability $\bar{\nu}_e$	
Normal Hierarchy atm Δm^2 Θ_{13} close to Chooz limit			No nu-nu effect
Inverted Hierarchy			No nu-nu effect

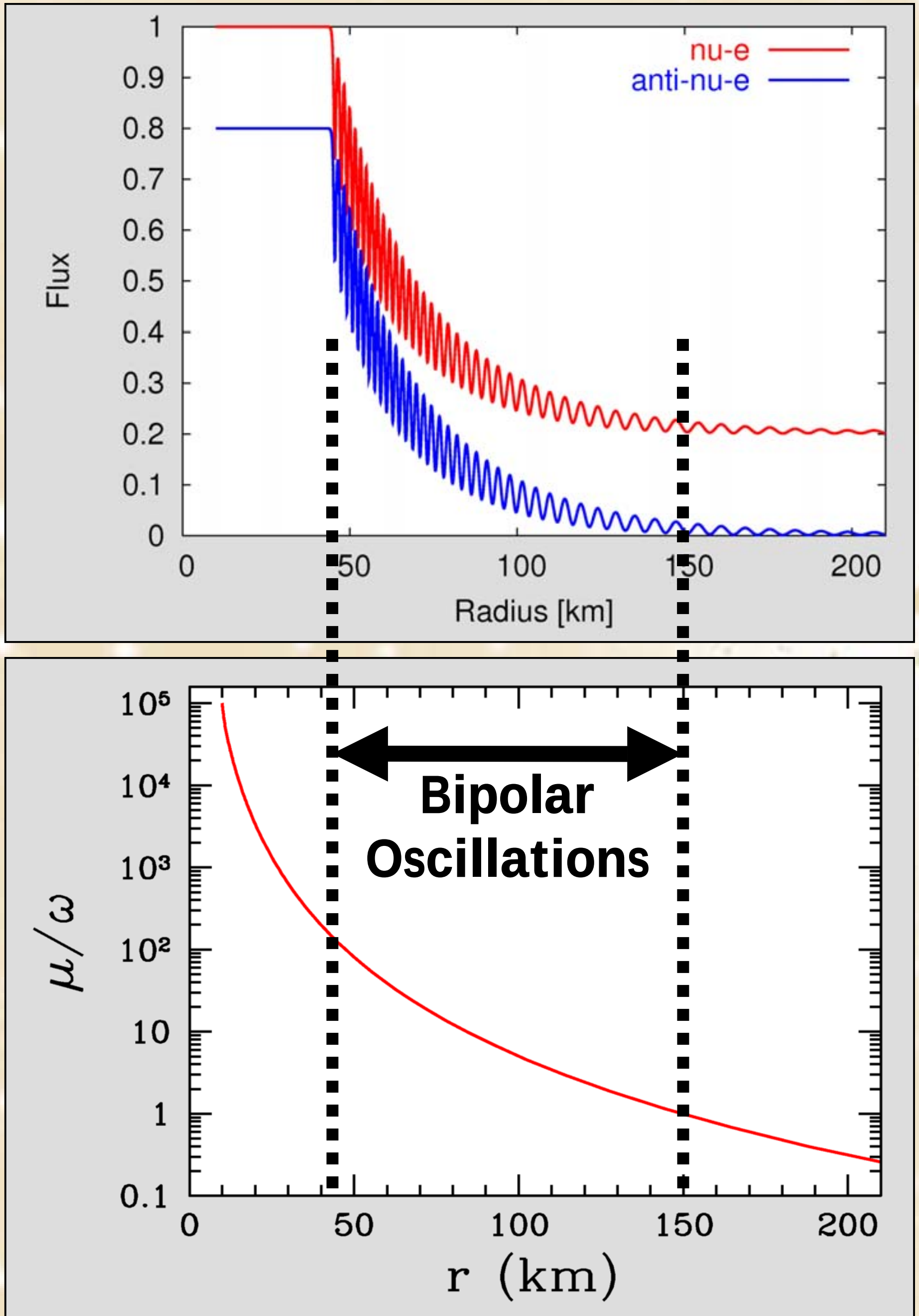
Self-Induced Flavor Oscillations of SN Neutrinos

	Survival probability ν_e	Survival probability $\bar{\nu}_e$	
Normal Hierarchy atm Δm^2 Θ_{13} close to Chooz limit			Realistic nu-nu effect No nu-nu effect
Inverted Hierarchy			Realistic nu-nu effect No nu-nu effect

Types of Neutrino Oscillation Phenomena

	Ordinary Flavor Oscillations	Collective Pair Oscillations
What oscillates?	Flavor: $\nu_e \to \nu_\mu$, $\bar\nu_e \to \bar\nu_\mu$	Pairs: $\nu_e \bar\nu_e \to \nu_\mu \bar\nu_\mu$ (flavor lepton number is conserved in the mass basis)
Frequency in vacuum	$\omega = \frac{\Delta m^2}{2E}$	$\kappa = \sqrt{\omega\mu}$ with $\mu = \sqrt{2}\, G_F n_\nu$
Role of mixing angle	Determines oscillation amplitude	Almost no dependence
Role of matter	• Modifies mixing angle and oscillation length • Can lead to resonance (MSW)	Almost no effect
Role of dense neutrinos $\mu > \omega$	Synchronization of ordinary flavor oscillations	Is a prerequisite for any collective phenomena

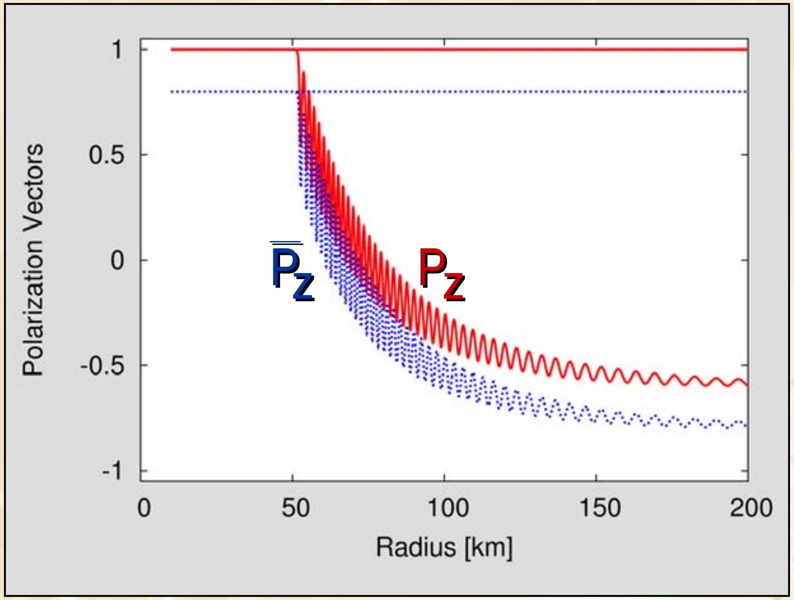
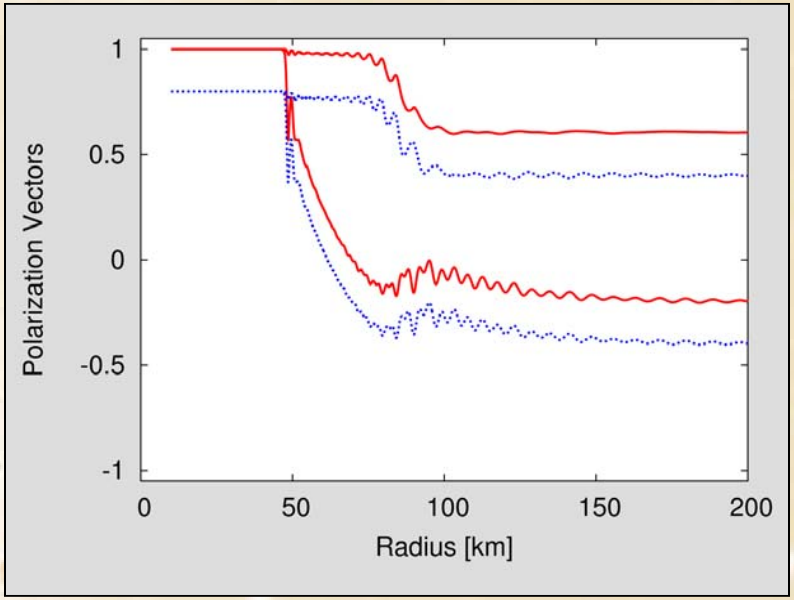
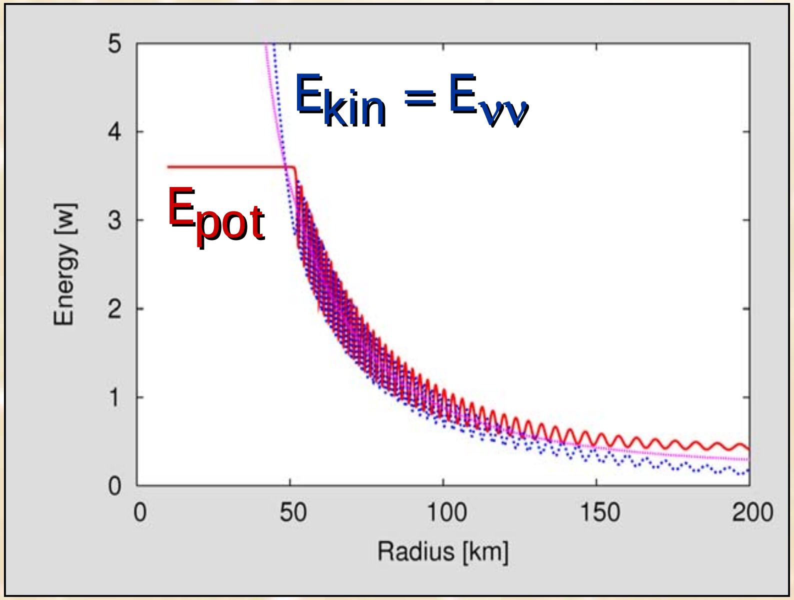
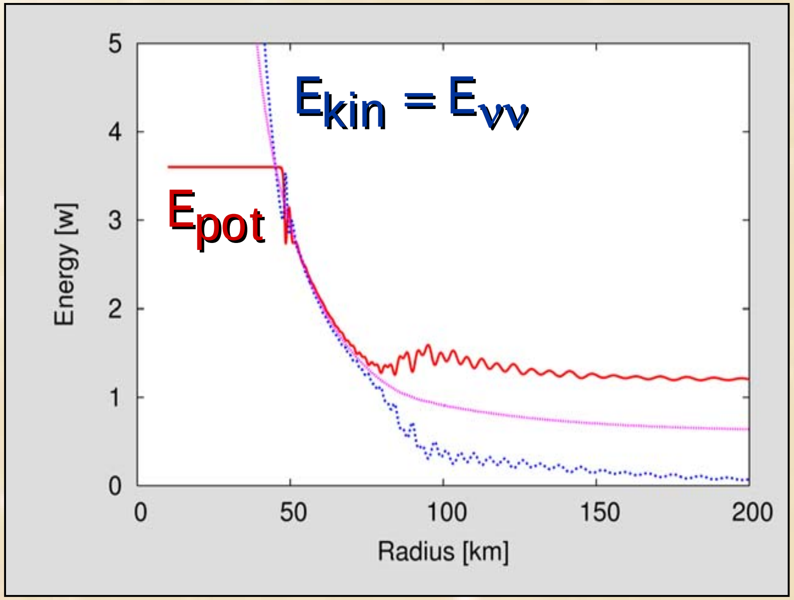
Toy Supernova in "Single-Angle" Approximation



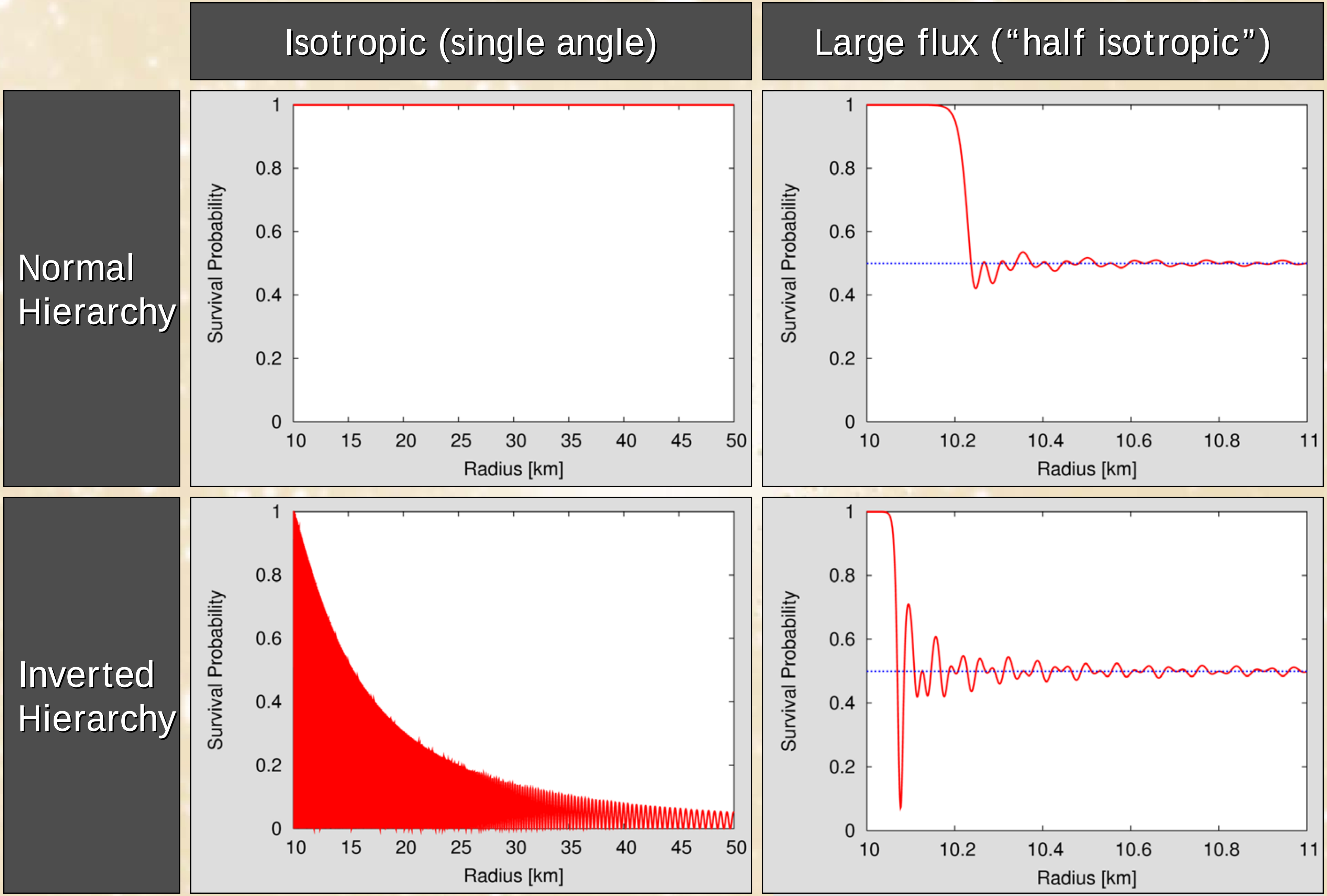
- Assume 80% anti-neutrinos
- Vacuum oscillation frequency $\omega = 0.3\ \mathrm{km}^{-1}$
- Neutrino-neutrino interaction energy at nu sphere (r = 10 km) $\mu = 0.3\times10^5\ \mathrm{km}^{-1}$
- Falls off approximately as r^{-4} (geometric flux dilution and nus become more co-linear)

Decline of oscillation amplitude explained in pendulum analogy by inreasing moment of inertia (Hannestad, Raffelt, Sigl & Wong astro-ph/0608695)

Inverted Hierarchy - Asymmetric Case ($\alpha = 0.8$)

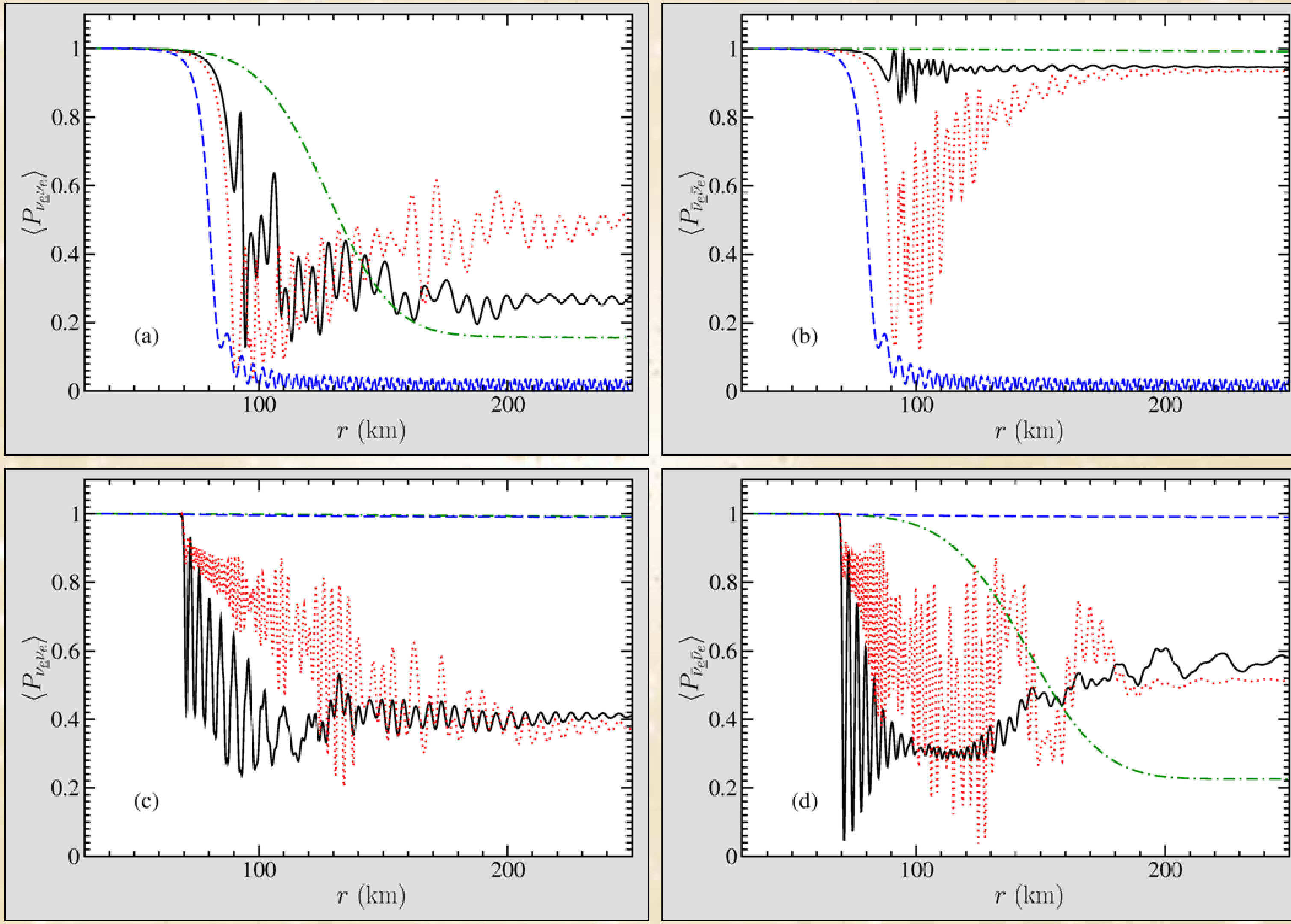
	Single angle	Multi angle
Polarization vectors • Length • z-component		
Energy components		

Kinematical Decoherence - Symmetric Case



Nonlinear Neutrino Conversion in Supernovae

	Survival probability ν_e	Survival probability $\bar{\nu}_e$
Normal Hierarchy atm Δm^2 Θ_{13} close to Chooz limit	(a)	(b)
Inverted Hierarchy	(c)	(d)



Duan, Fuller, Carlson, Qian: "Simulation of Coherent Non-Linear Neutrino Flavor Transformation in the Supernova Environment. 1. Correlated Neutrino Trajectories", astro-ph/0606616. See also: astro-ph/0608050

Different Oscillation Modes in Supernovae

$\mu_{\nu_\mu} = \mu_{\nu_\tau} = 0$
$\mu_{\nu_e} \approx 100$ MeV
$n_{\nu_e} \gg n_{\nu_\mu} = n_{\nu_\tau}$
$n_{\bar\nu_e} \ll n_{\bar\nu_\mu} = n_{\bar\nu_\tau}$

Fluxes
$F_{\nu_\mu} = F_{\bar\nu_\mu} = F_{\nu_\tau} = F_{\bar\nu_\tau}$
$F_{\nu_e} > F_{\nu_\mu}$, $F_{\bar\nu_e} > F_{\bar\nu_\mu}$

H-Resonance (atm)

L-Resonance (sol)

R [km]: 0, ~15, ~80, ~200, $\sim 10^4$, $\sim 10^5$

Center

Neutrino sphere

Free streaming

Matter effect important
Usually suppresses mixing angle

MSW

MSW

Neutrino-neutrino
collective effects strong

Synchronised oscillations

Little effect because of matter-suppressed mixing angle

Collective pair conversion
$F_{\nu_e} \to F_{\nu_\mu}$, $F_{\bar\nu_e} \to F_{\bar\nu_\mu}$

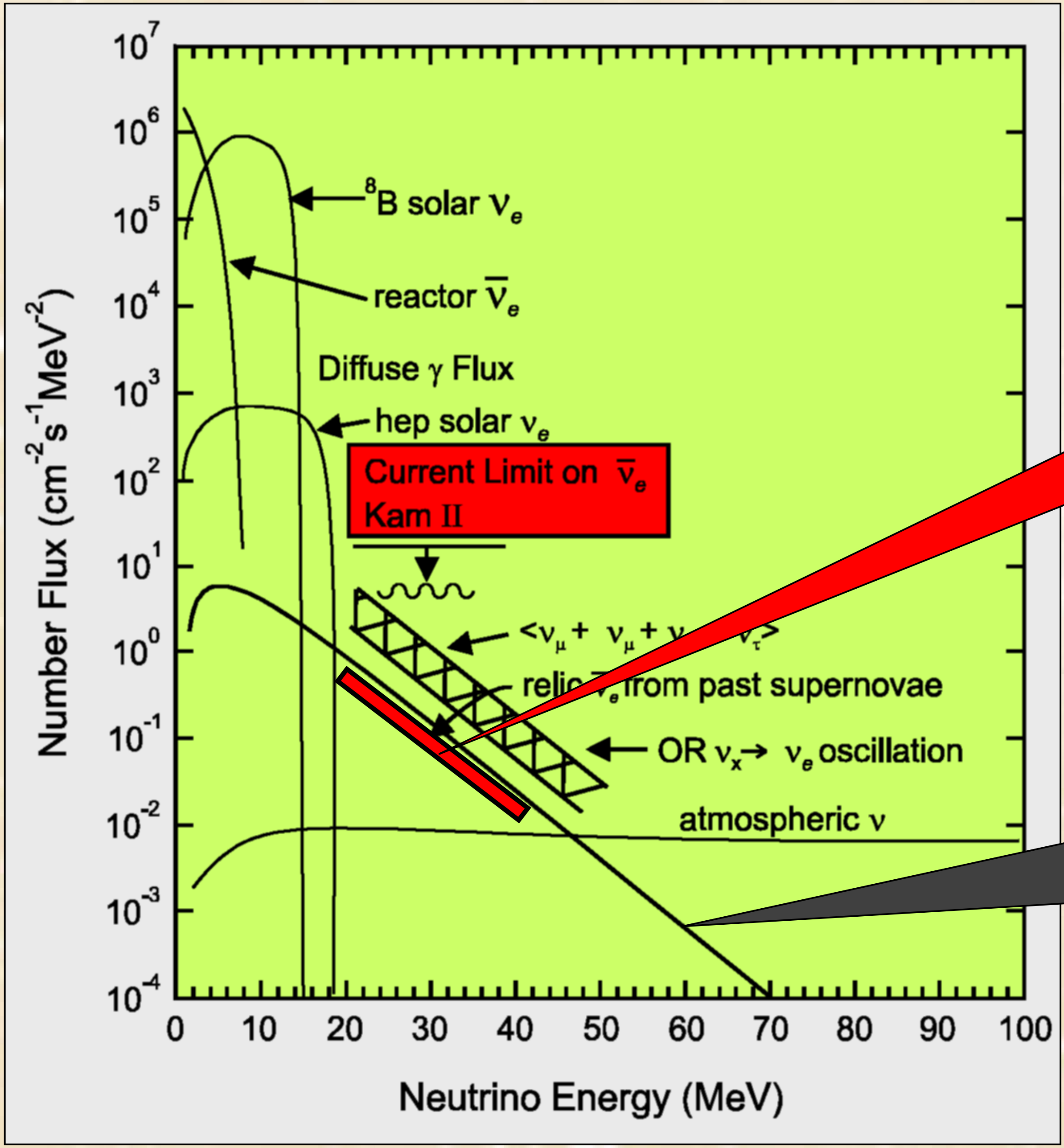
Importance of bipolar oscillations in this SN region first noted by Duan, Fuller & Qian astro-ph/0511275

Papers on collective neutrino oscillations

1992 Flavor off-diagonal refractive index	Pantaleone, PLB 287(1992) 128
1992-1998 Numerical & analytic studies, but not much impact (nobody really understood)	Samuel, Kostolecký & Pantaleone in various combinations: PLB 315:46 & 318:127 (1993), 385:159 (1996) PRD 48:1462 (1993), 49:1740 (1994), 52:621 & 3184 (1995), 53:5382 (1996), 58:073002 (1998)
2001-2002 Flavor equilibration of cosmological neutrinos with chemical potential before BBN epoch	Pastor, Raffelt & Semikoz, hep-ph/0109035 Lunardini & Smirnov, hep-ph/0012056 Dolgov et al., hep-ph/0201287 Wong, hep-ph/0203180 Abazajian, Beacom & Bell, astro-ph/0203442
1994-2004 SN neutrino oscillations and r-process nucleosynthesis (everybody missed the main point)	Pantaleone, astro-ph/9405008 Qian & Fuller, astro-ph/9406073 Sigl, astro-ph/9410094 Pastor & Raffelt, astro-ph/0207281 Balantekin & Yüksel, astro-ph/0411159
2006-2007 "Bipolar" oscillations crucial for SN neutrinos	Duan, Fuller & Qian, astro-ph/0511275 Duan, Fuller, Carlson & Qian, astro-ph/0606616 Hannestad, Raffelt, Sigl & Wong, astro-ph/0608695 Raffelt & Sigl, hep-ph/0701182


Cosmic Diffuse Supernova
Neutrino Background (DSNB)

Experimental Limits on Relic Supernova Neutrinos



Super-K upper limit
29 cm^{-2} s^{-1} for
Kaplinghat et al. spectrum
[hep-ex/0209028]

Upper-limit flux of
Kaplinghat et al.,
astro-ph/9912391
Integrated 54 cm^{-2} s^{-1}

Cline, astro-ph/0103138

Improved Sensitivity with Neutron Tagging

Beacom & Vagins, hep-ph/0309300
[Phys. Rev. Lett., 93 (2004) 171101]

Detection of DSNB limited by
- Solar neutrinos for $E_\nu \lesssim 18$ MeV
- Sub-Cherenkov muons from atm nus
  $\mu \to e + \nu_e + \overline{\nu}_\mu$
- Solution: neutron tagging from
  $\overline{\nu}_e + p \to e^+ + n$
- 2.2 MeV gamma from $n + p \to d$
  invisible in water Cherenkov detector

Add gadolinium to Super-Kamiokande
- Efficient neutron capture on Gd
- 8 MeV gamma cascade easily visible
- 0.1% (100 tons of Gd Cl_3)
  achieves $>$ 90% tagging efficiency
- Diffuse SN nu background (DSNB):
  a few events per year in Super-K
  with no background at all

Status of R & D (04/2006)
[Mark Vagins, private communication]

Nov 05: Gd Cl_3 added to K2K test tank
(kiloton or KT detector)
- Gd Cl_3 is easy to dissolve
- Gd Cl_3 does not significantly affect
  the light collection
- Choice of detector materials critical
  (old rust in KT with Gd Cl_3 badly
  affected transparency)
- The 20 inch Super-K PMT's operate
  well in conductive water
- Gd filtration works as designed at
  3.6 tons/h, can easily be scaled up

- Looks promising for Super-K,
  conceivable within next few years
- Capital cost negligible for future
  megatonne-class detectors

DSNB Measurement with Neutron Tagging

Beacom & Vagins, hep-ph/0309300
[Phys. Rev. Lett., 93:171101, 2004]

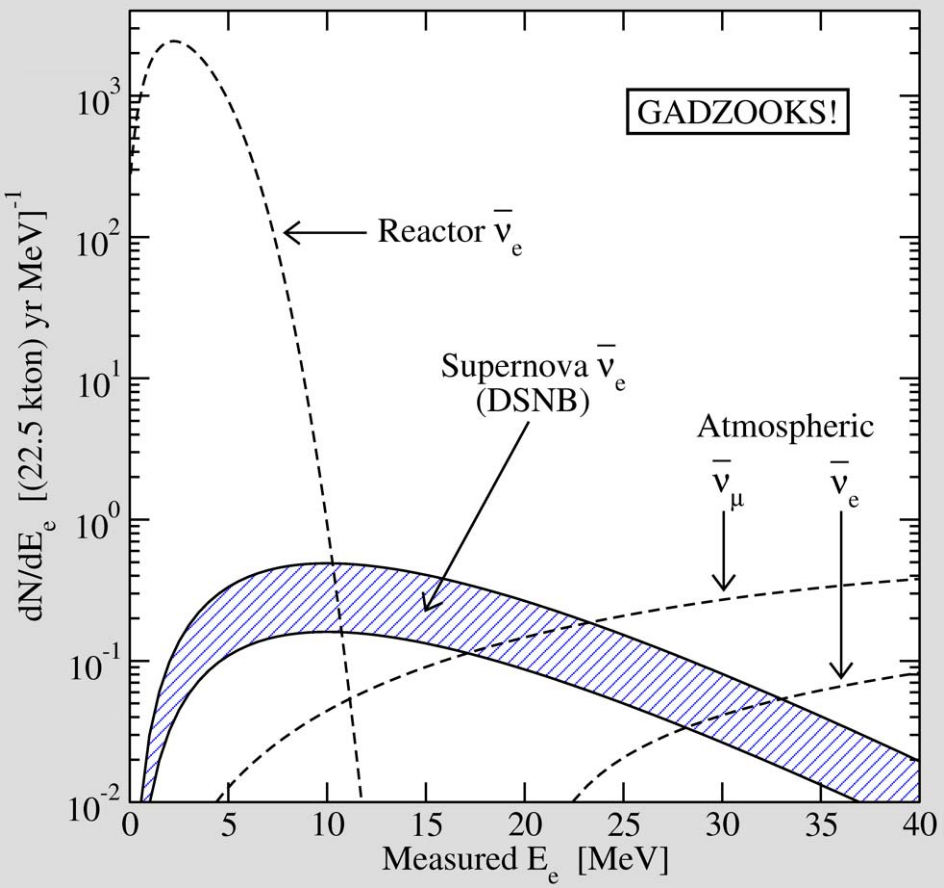


FIG. 1: Spectra of low-energy $\bar{\nu}_e + p \rightarrow e^+ + n$ coincidence events and the sub-Čerenkov muon background. We assume full efficiencies, and include energy resolution and neutrino oscillations. Singles rates (not shown) are efficiently suppressed.

Future large-scale scintillator detectors (e.g. LENA with 50 kt)

- Inverse beta decay reaction tagged
- Location with smaller reactor flux (e.g. Pyhäsalmi in Finland) could allow for lower threshold

Pushing the boundaries of neutrino astronomy to cosmological distances

Looking forward to the next galactic supernova

http://antwrp.gsfc.nasa.gov/apod/ap060430.html