Neutrinos

in Astrophysics and Cosmology

Supernova Neutrinos

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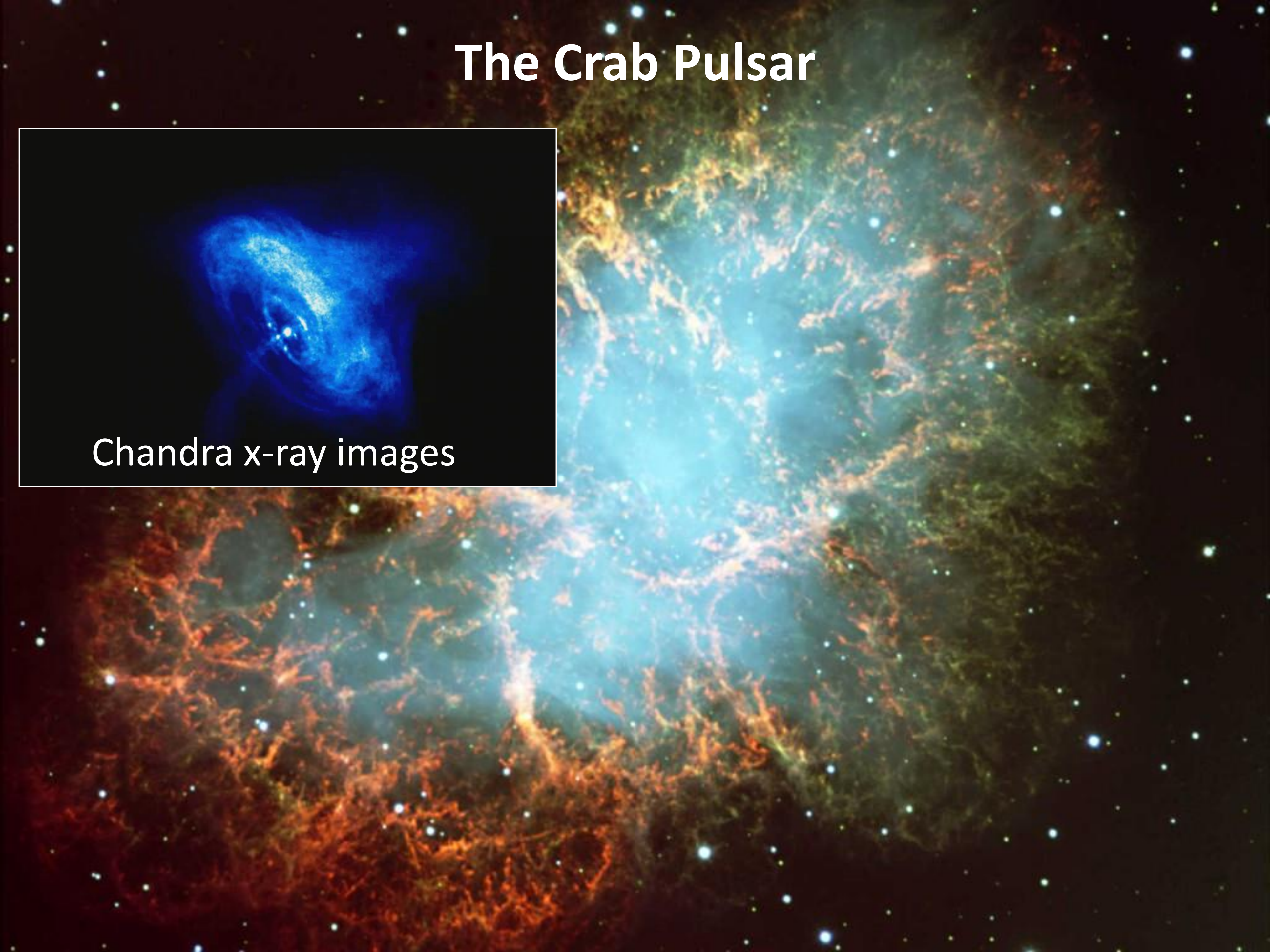
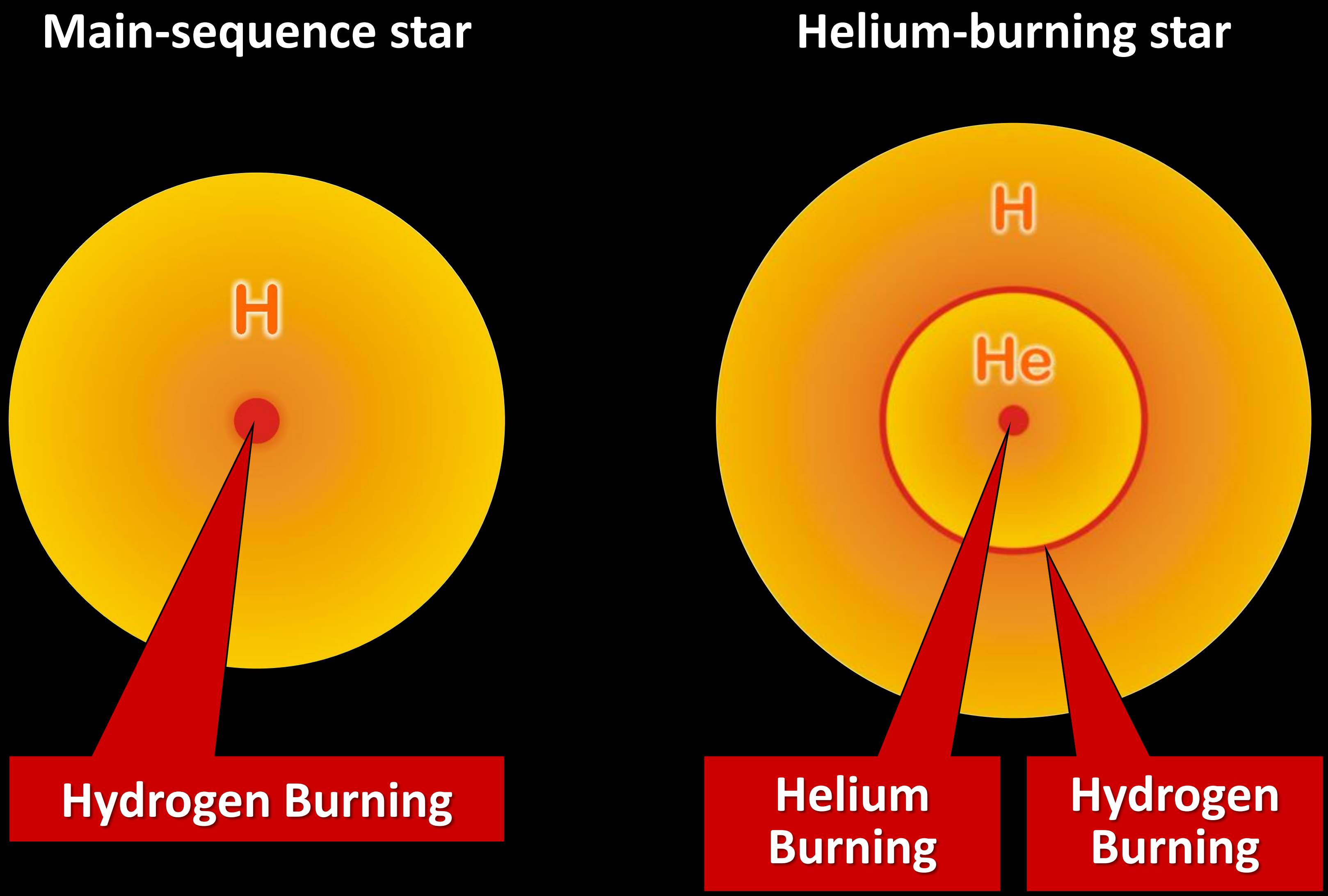
凡十一日沒三年三月乙巳出東南方大中祥符四
年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅
前星西北大如桃速行經軒轅太星入太微垣掩右執
法犯次將歷屛星西北凡七十五日入濁沒明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日沒至和元年五月己丑出天關東南可數寸歲餘
稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九游星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁

The Crab Pulsar



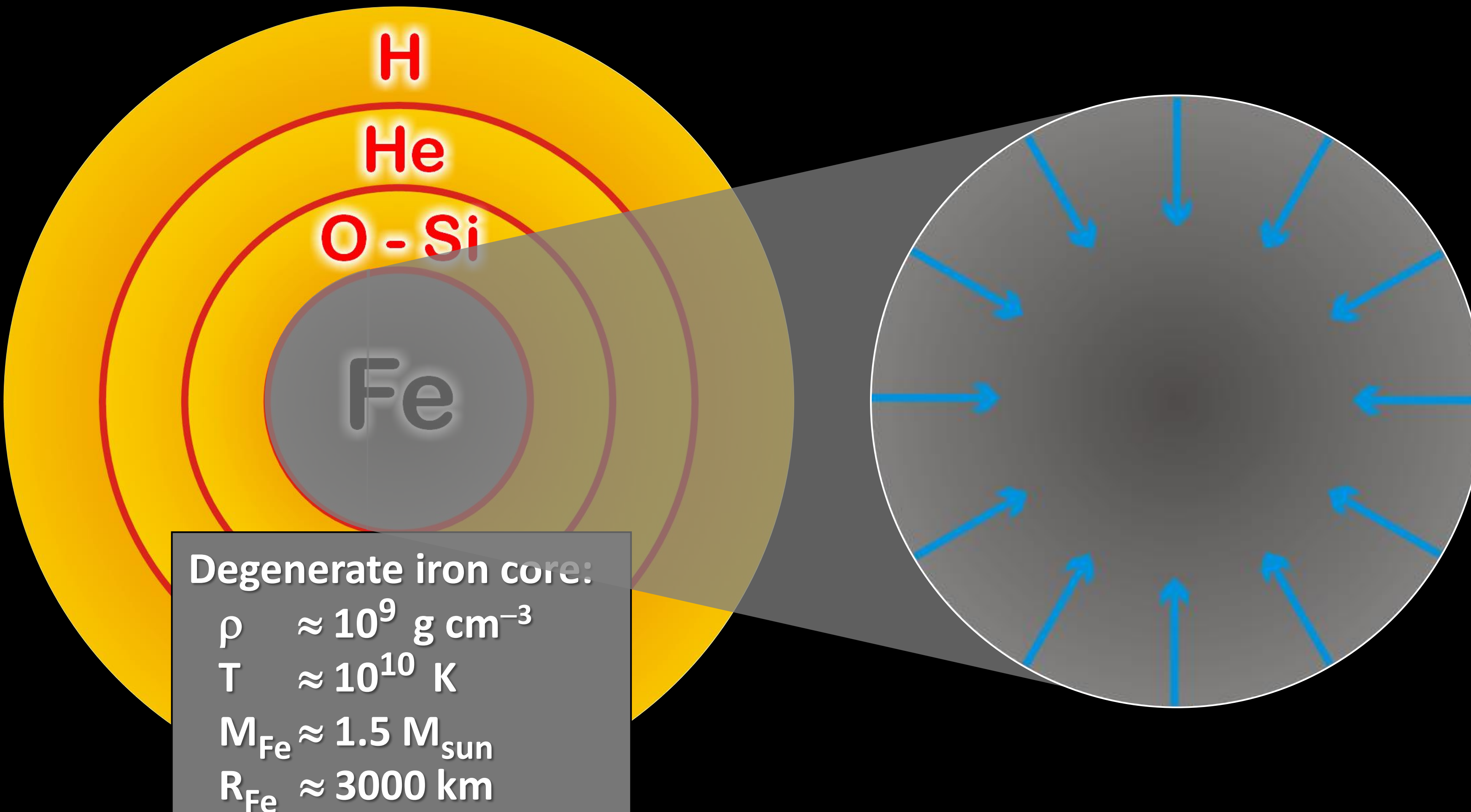
Chandra x-ray images

Stellar Collapse and Supernova Explosion



Stellar Collapse and Supernova Explosion

Onion structure | **Collapse (implosion)**



Degenerate iron core:

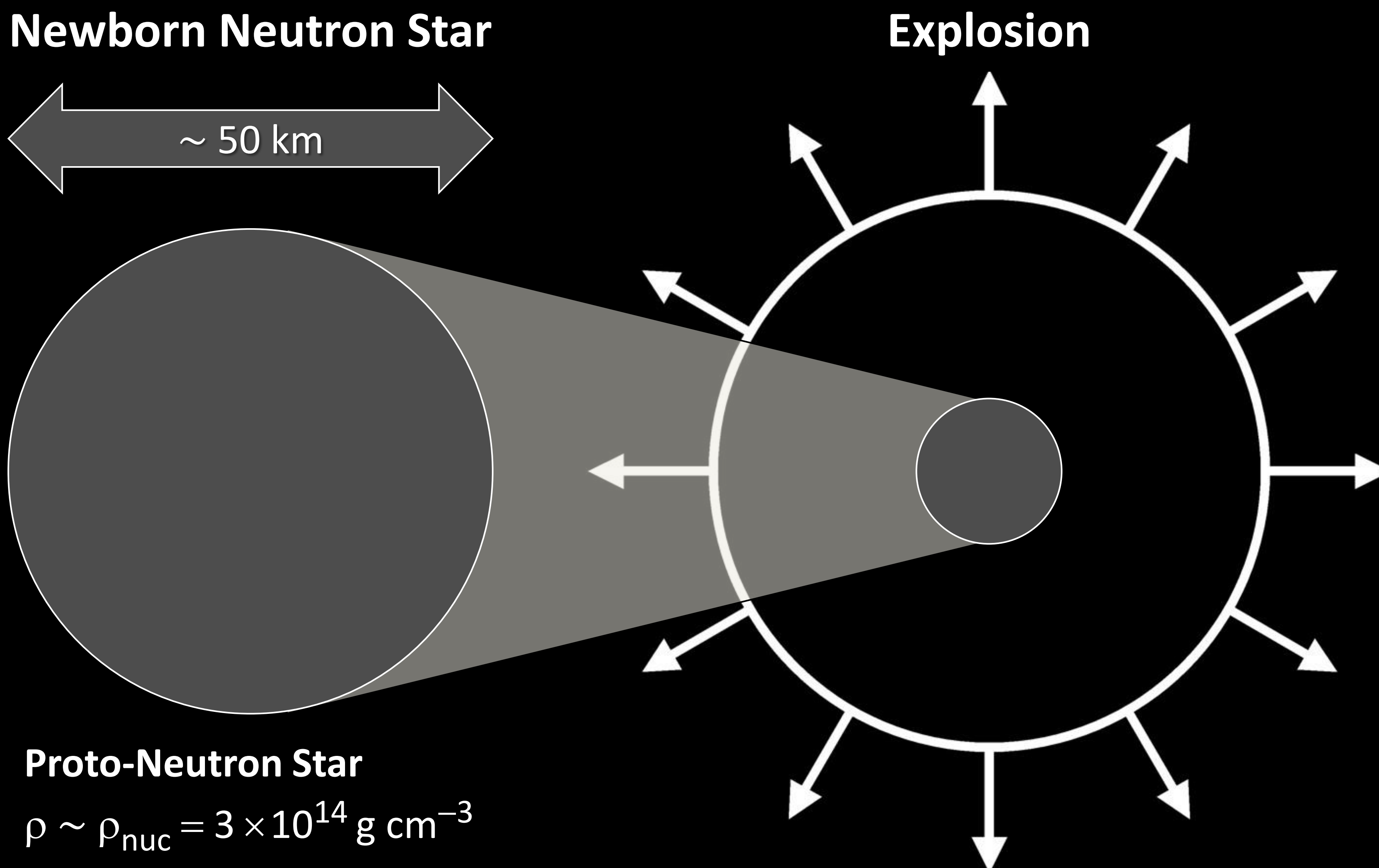
$\rho \approx 10^{9}$ g cm^{-3}

$T \approx 10^{10}$ K

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

$R_{Fe} \approx 3000$ km

Stellar Collapse and Supernova Explosion



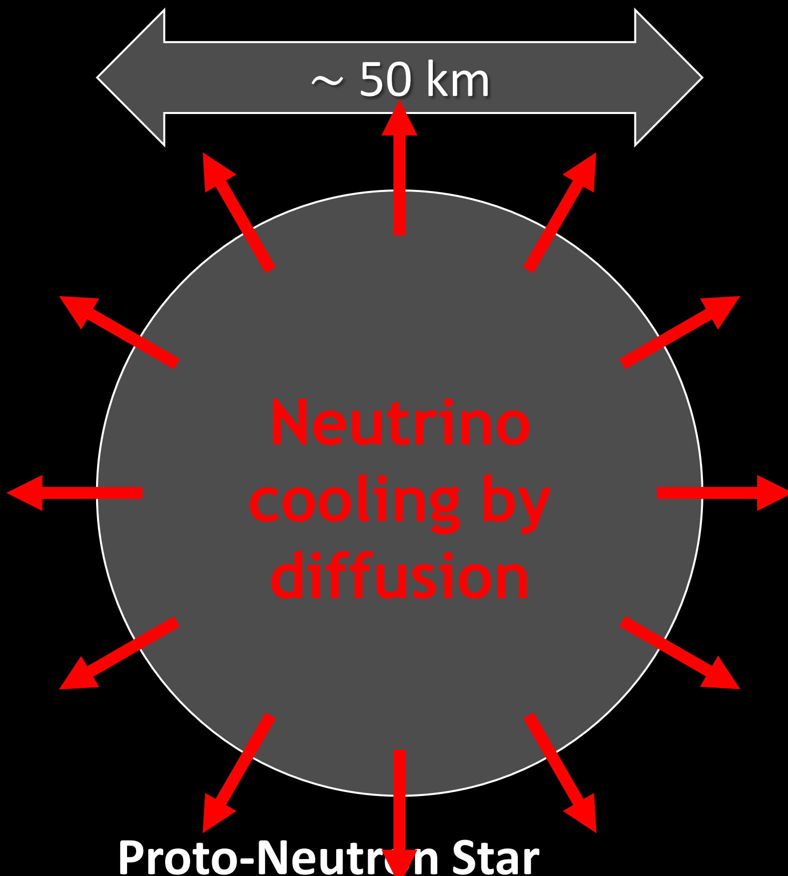
Proto-Neutron Star

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

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

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

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	$\sigma_{\nu N} = \frac{C_V^2 + 3C_A^2}{\pi} G_F^2 E_\nu^2 \approx 2 \times 10^{-40}\,\mathrm{cm}^2 \left(\frac{E_\nu}{100\ \mathrm{MeV}}\right)^2$
Nucleon density	$n_B = \frac{\rho_{\rm nuc}}{m_N} \approx 1.8 \times 10^{38}\ \mathrm{cm}^{-3}$
Scattering rate	$\Gamma = \sigma n_B \approx 1.1 \times 10^9\ \mathrm{s}^{-1} \left(\frac{E_\nu}{100\ \mathrm{MeV}}\right)^2$
Mean free path	$\lambda = \frac{1}{\sigma n_B} \approx 28\ \mathrm{cm} \left(\frac{100\ \mathrm{MeV}}{E_\nu}\right)^2$
Diffusion time	$t_{\rm diff} \approx \frac{R^2}{\lambda} \approx 1.2\ \mathrm{sec} \left(\frac{R}{10\ \mathrm{km}}\right)^2 \left(\frac{\mathrm{E}_\nu}{100\ \mathrm{MeV}}\right)^2$

What Determines the Neutrino Energies?

Hydrostatic equilibrium (virial equilibrium)

$$-\frac{1}{2}\langle\Phi_{\rm grav}\rangle = \langle E_{\rm kin}\rangle = \frac{3}{2}k_{\rm B}T$$

Assume SN core is homogeneous sphere with

$$M = 1.5\,M_\odot,\quad \rho = \rho_{\rm nuc} = 3\times10^{14}\,{\rm g/cm^3},\quad R = 13.4\,{\rm km}$$

Gravitational potential of nucleon at center

$$\Phi_{\rm grav} = -\frac{3}{2}\,\frac{\rm G_N M_{core} m_p}{\rm R} \sim -\,234\ {\rm MeV}$$

For non-interacting and non-degenerate nucleons implies

$$T \sim 80\ {\rm MeV}$$

More realistic, nuclear equation-of-state dependent values

$$T \sim 20\text{–}40\ {\rm MeV}$$

Energy sale in the multi-10 MeV range set by gravitational potential

Supernovas the Power Supply for Cosmic Rays?

Required power supply $L_{CR} = V_D \, r_{CR}/t_{res}$

$\approx 5 \times 10^{40}$ erg/s $\approx 10^{7} \, L_{Sun}$

Disk volume $V_D = \pi R^2 d \approx \pi \, (15 \text{ kpc})^2 \; 200 \text{ pc}$

$\approx 4 \times 10^{66} \text{ cm}^3$

Energy density in CRs $r_{CR} \approx 1 \text{ eV} / \text{cm}^3$

Residence time in galaxy $t_{res} \approx 6 \times 10^{6}$ yrs

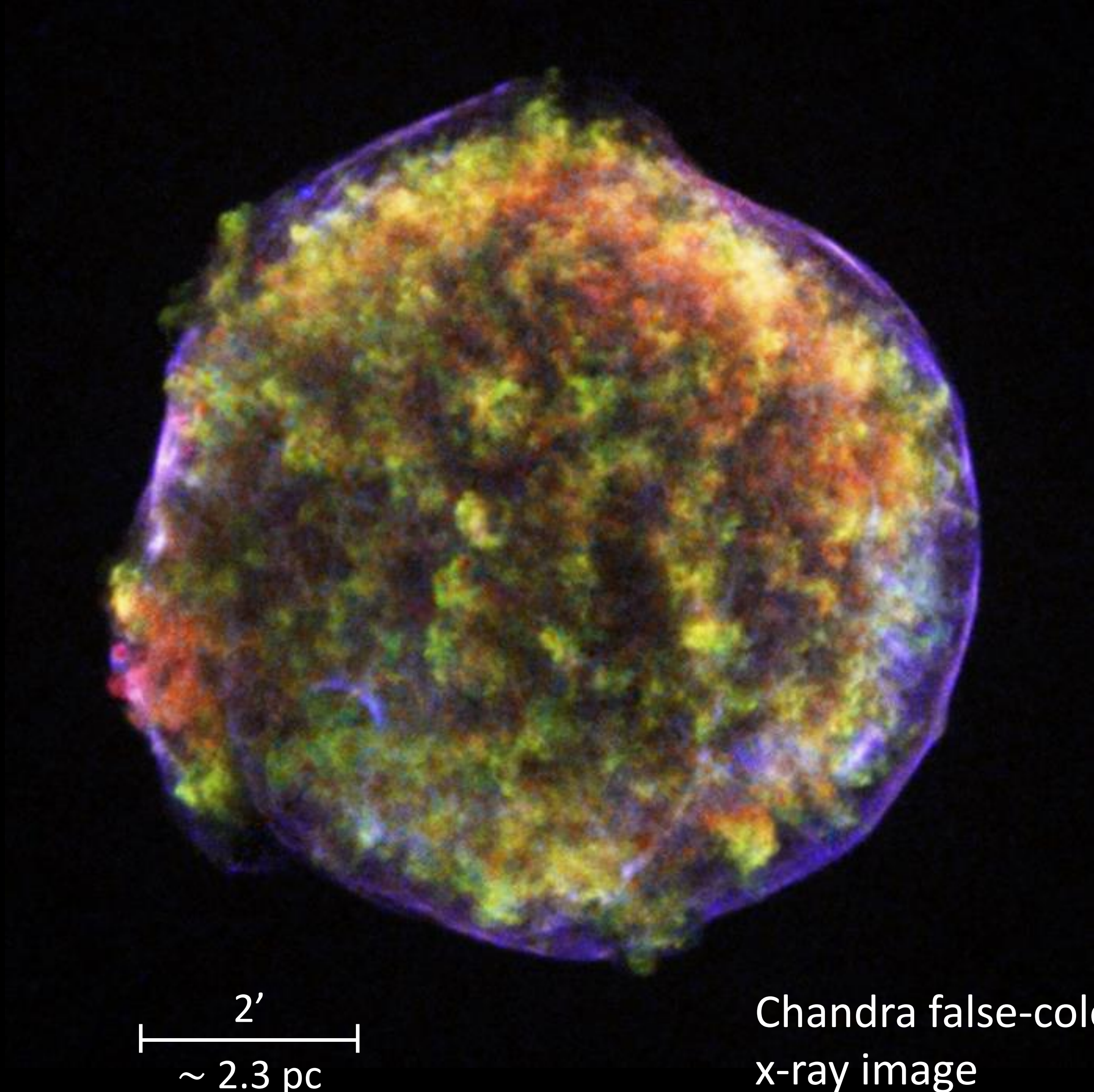
Suggestive of supernovae:

- One SN explosion deposits ~ 3×10^{51} erg in kinetic energy of ejecta into the interstellar medium (ISM)
- Rate approx. 1 SN / 30 years / galaxy

Total average energy deposition: $L_{SN} \approx 3 \times 10^{42}$ erg/s $\approx 50 \, L_{CR}$

Efficiency of a few percent required

Tycho's Supernova (1572) Remnant



Chandra false-color x-ray image

Thermonuclear vs. Core-Collapse Supernovae

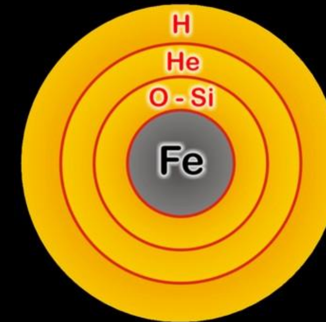
Thermo-nuclear (Type Ia)	Core collapse (Type II, Ib/c)

Thermo-nuclear (Type Ia)

- Carbon-oxygen white dwarf (remnant of low-mass star)
- Accretes matter from companion

Core collapse (Type II, Ib/c)

- 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

Thermo-nuclear	Core collapse
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

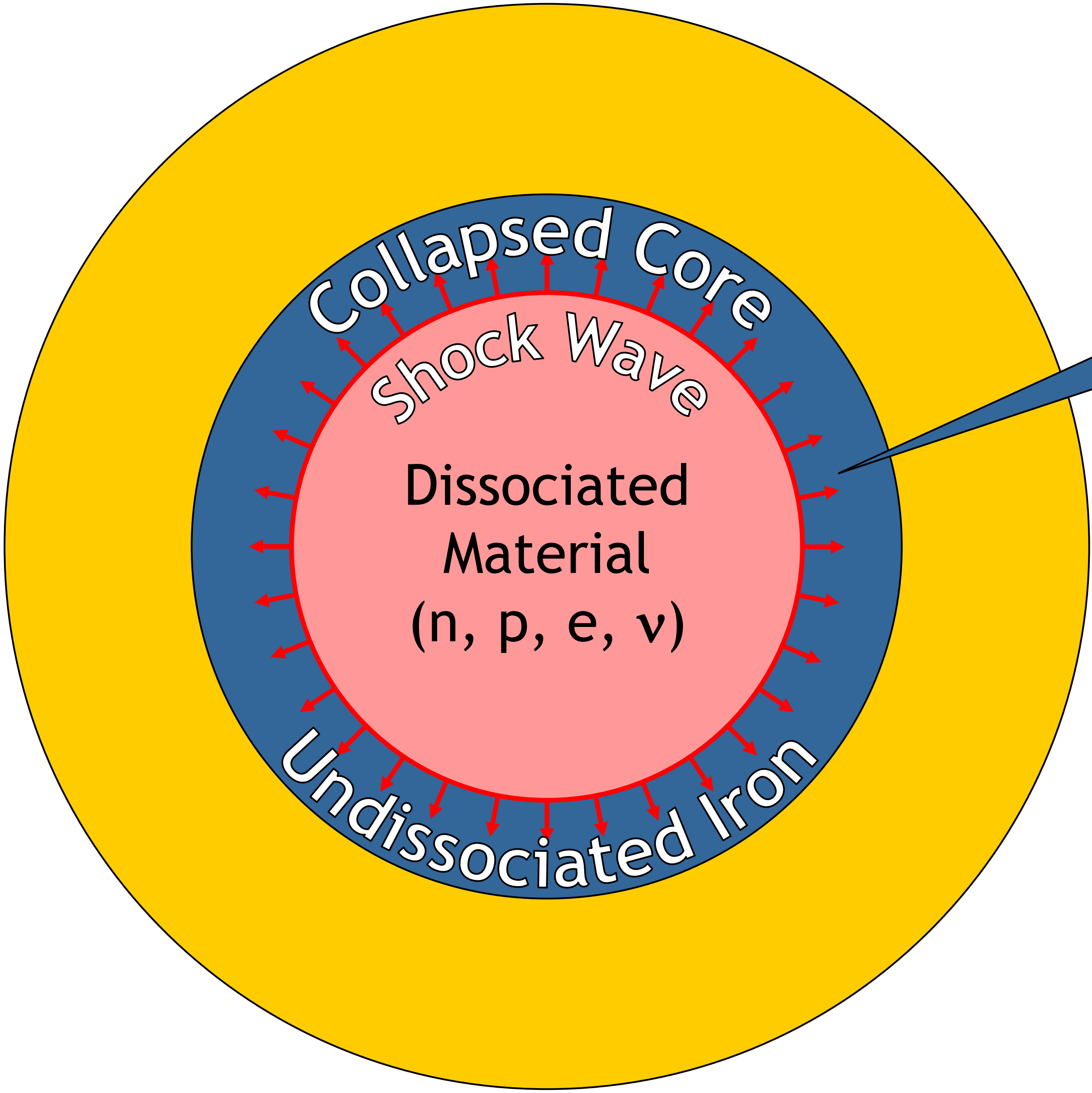
Comparable "visible" energy release of $\sim 3 \times 10^{51}$ erg

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 $\sim$ 6400 as of 2014 (Asiago SN Catalogue)			

Explosion Mechanism

Why No Prompt Explosion?



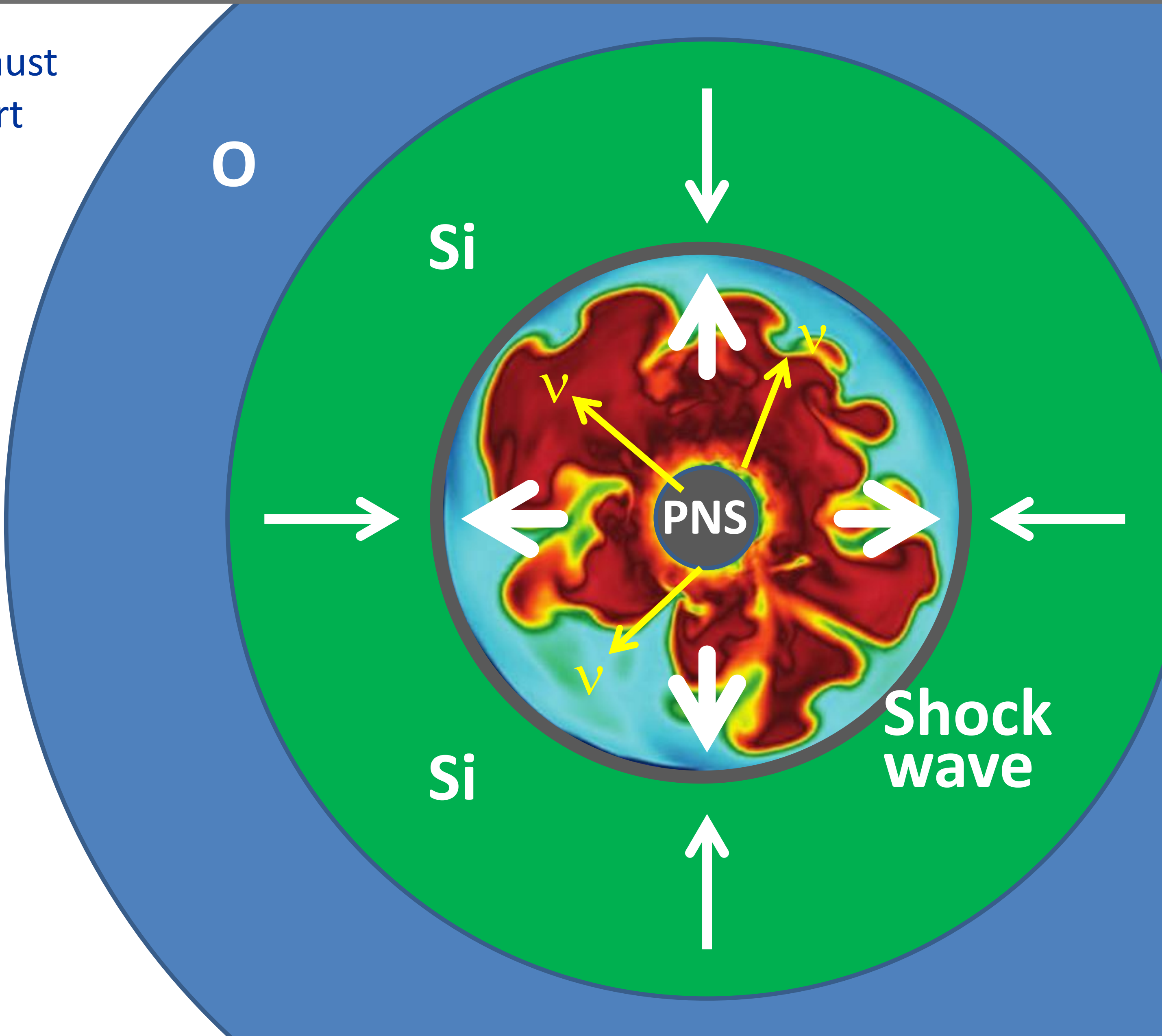
- $0.1\,M_{sun}$ of iron has a nuclear binding energy $\approx 1.7 \times 10^{51}$ erg
- Comparable to explosion energy

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

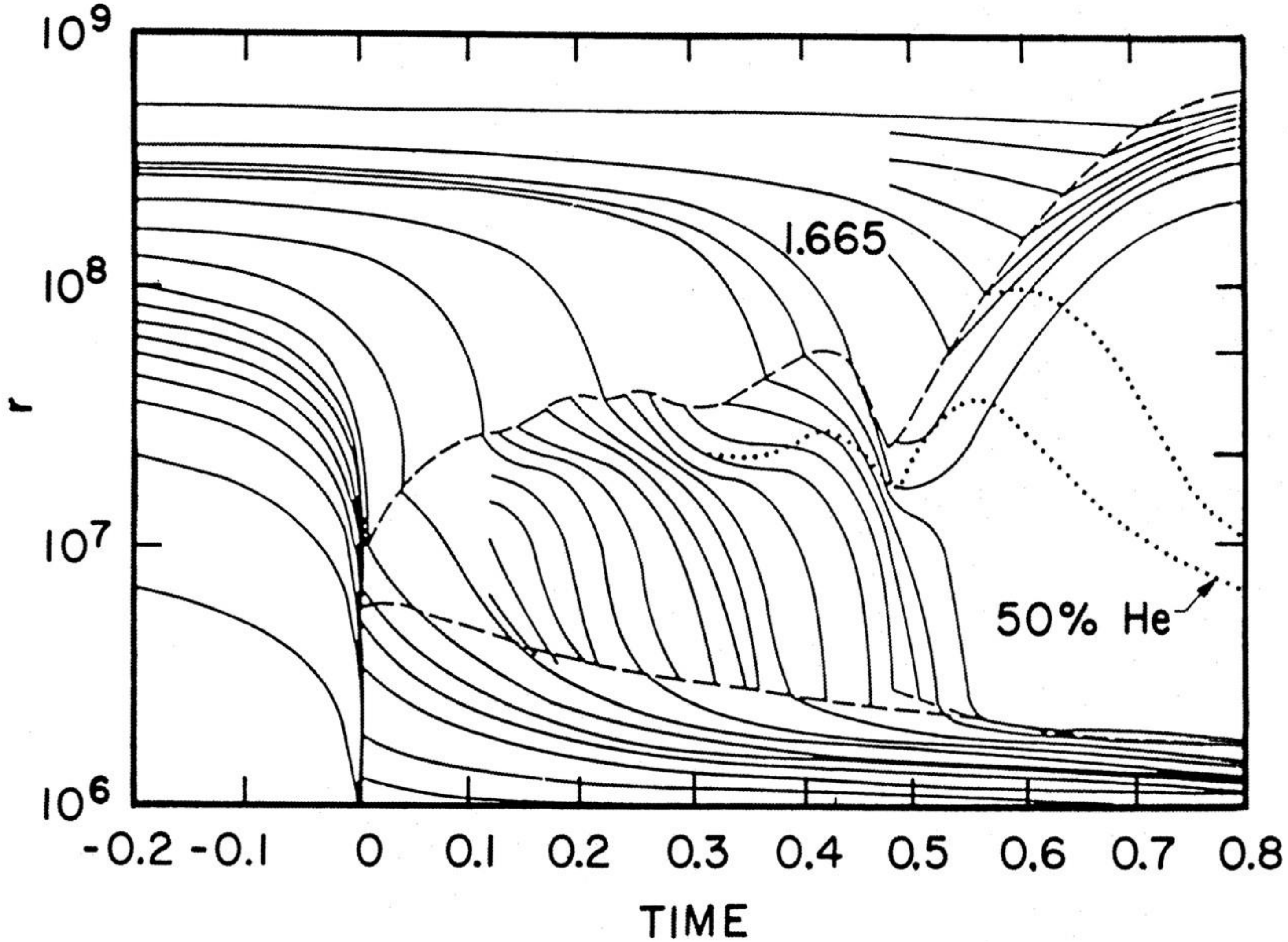
Shock Revival by Neutrinos

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

Shock can receive fresh energy from neutrinos!



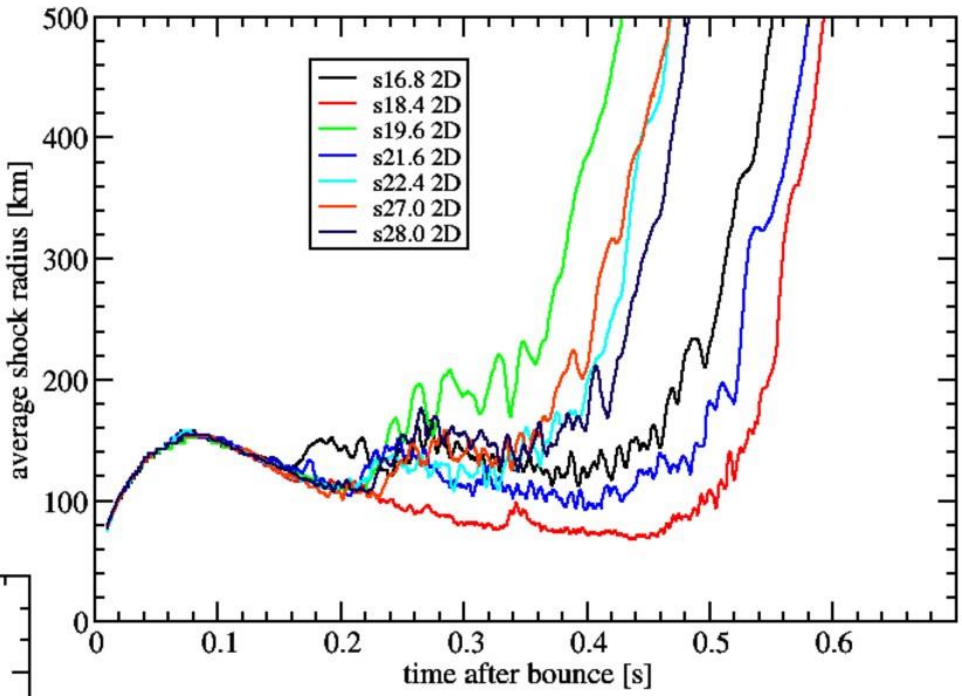
Delayed (Neutrino-Driven) Explosion



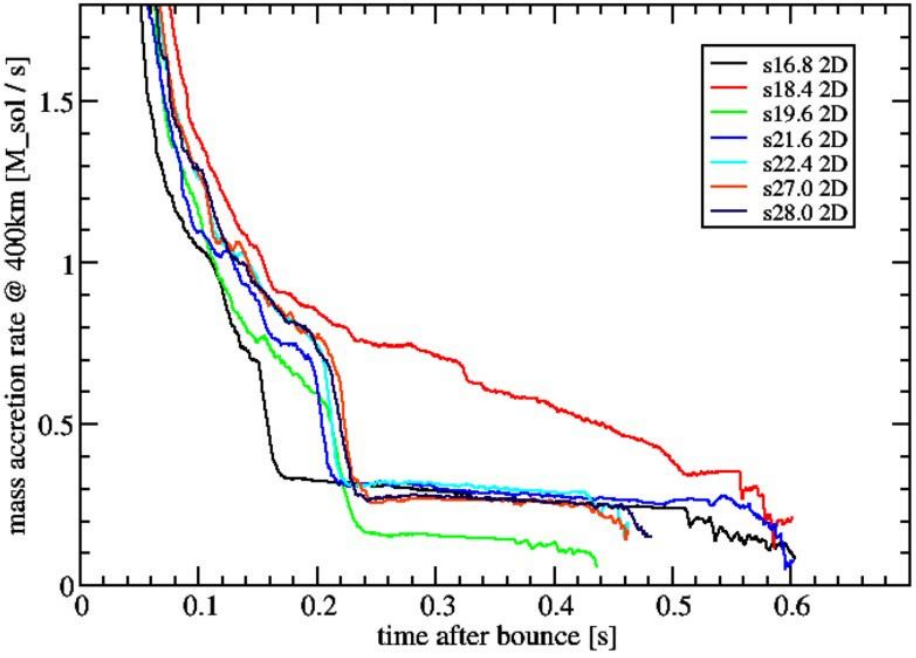
Wilson, Proc. Univ. Illinois Meeting on Num. Astrophys. (1982)
Bethe & Wilson, ApJ 295 (1985) 14

Growing Set of 2D Exploding Models

Florian Hanke, PhD Project
MPA, Garching, 2013



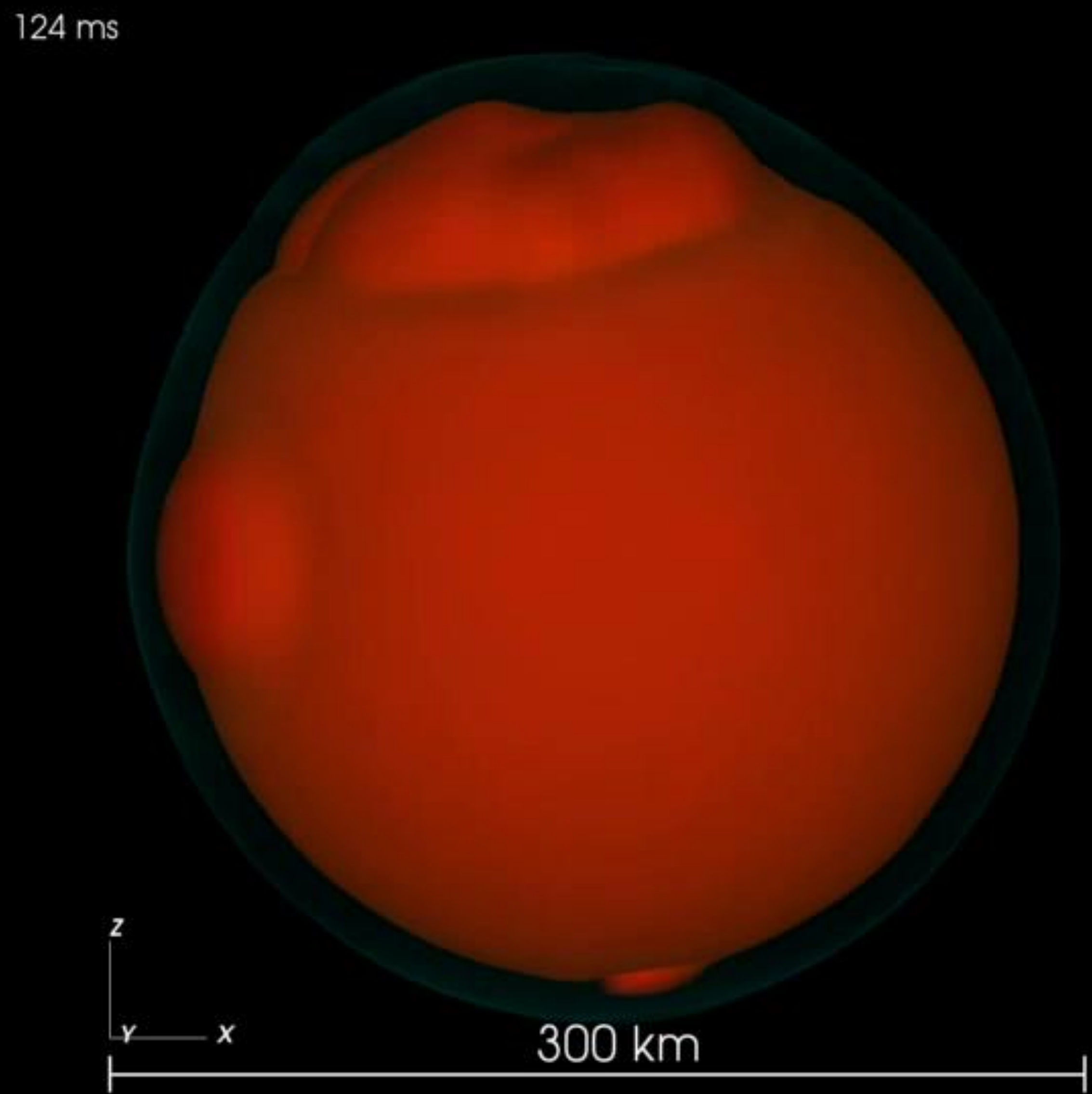
Mass accretion rate



Average shock radius

Progenitor models:
Woosley et al. RMP (2002)

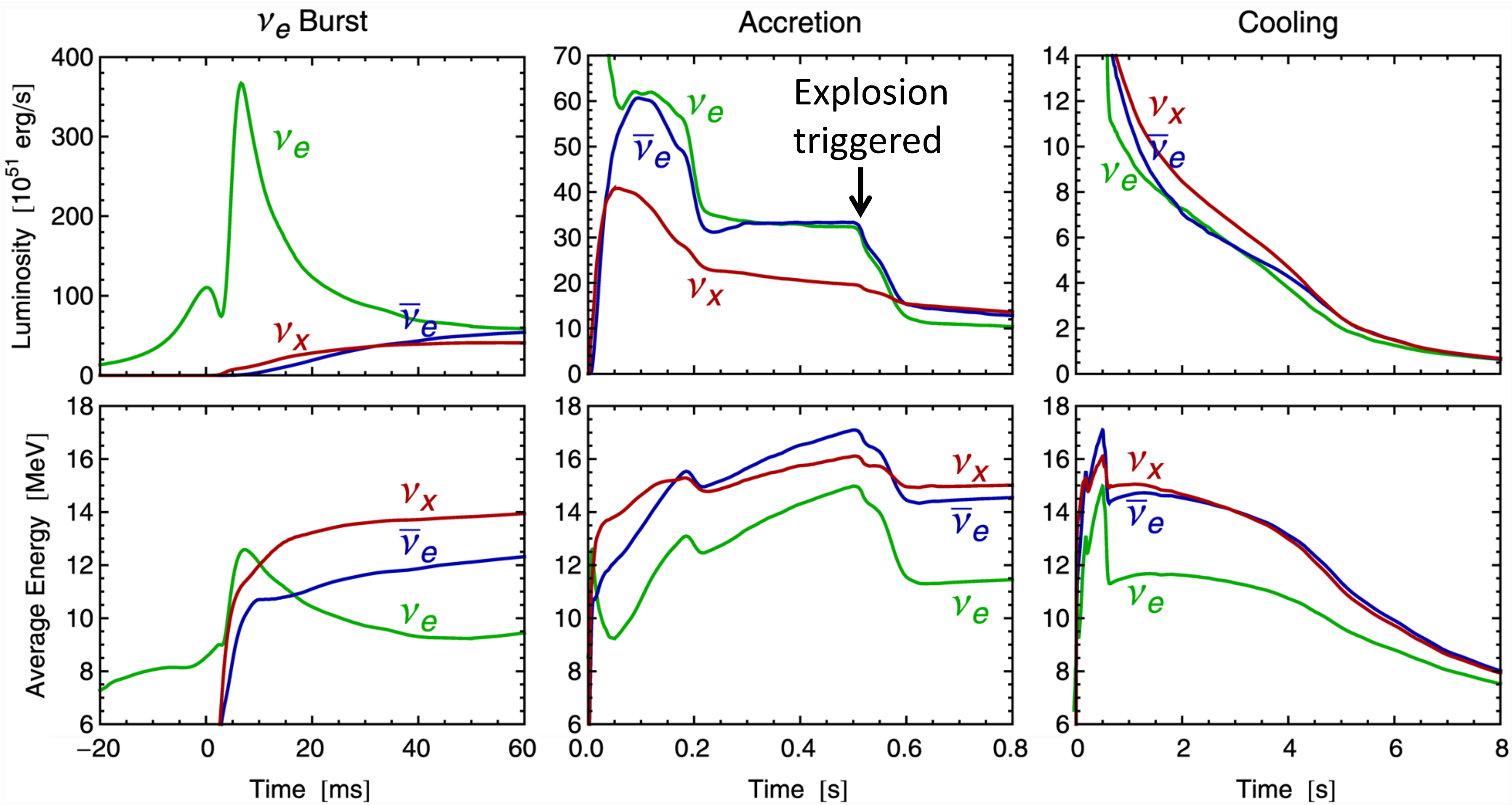
First Realistic 3D Simulation (27 $M_\odot$ Garching Group)



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 spatial resolution needed?
- Strong progenitor dependence? 3D progenitor models needed?

Three Phases of Neutrino Emission



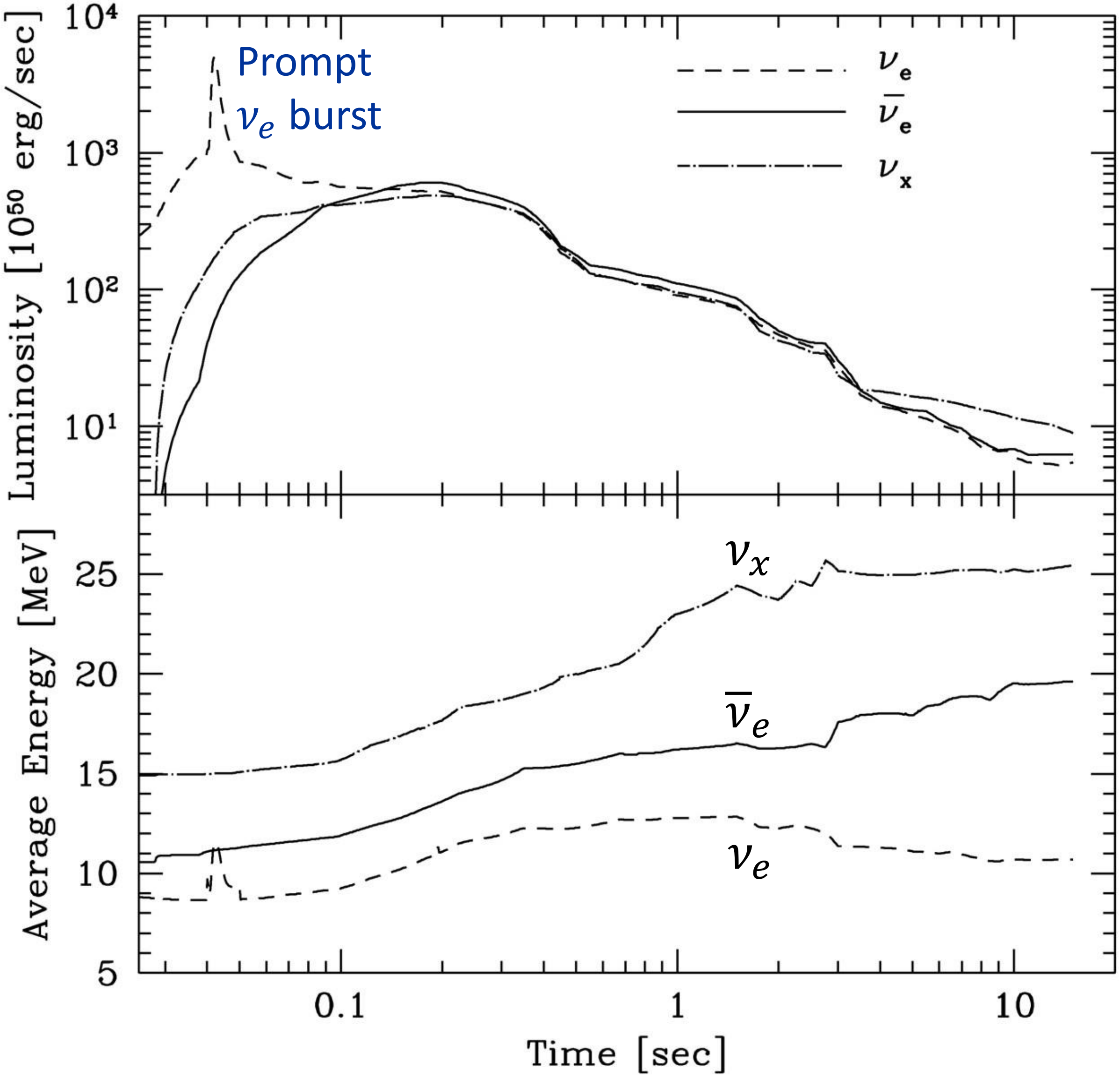
- Shock breakout
- De-leptonization of outer core layers

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

Cooling on neutrino diffusion time scale

Spherically symmetric Garching model (25 $M_\odot$) with Boltzmann neutrino transport

Livermore Fluxes and Spectra



Schematic transport of ν_μ and ν_τ

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

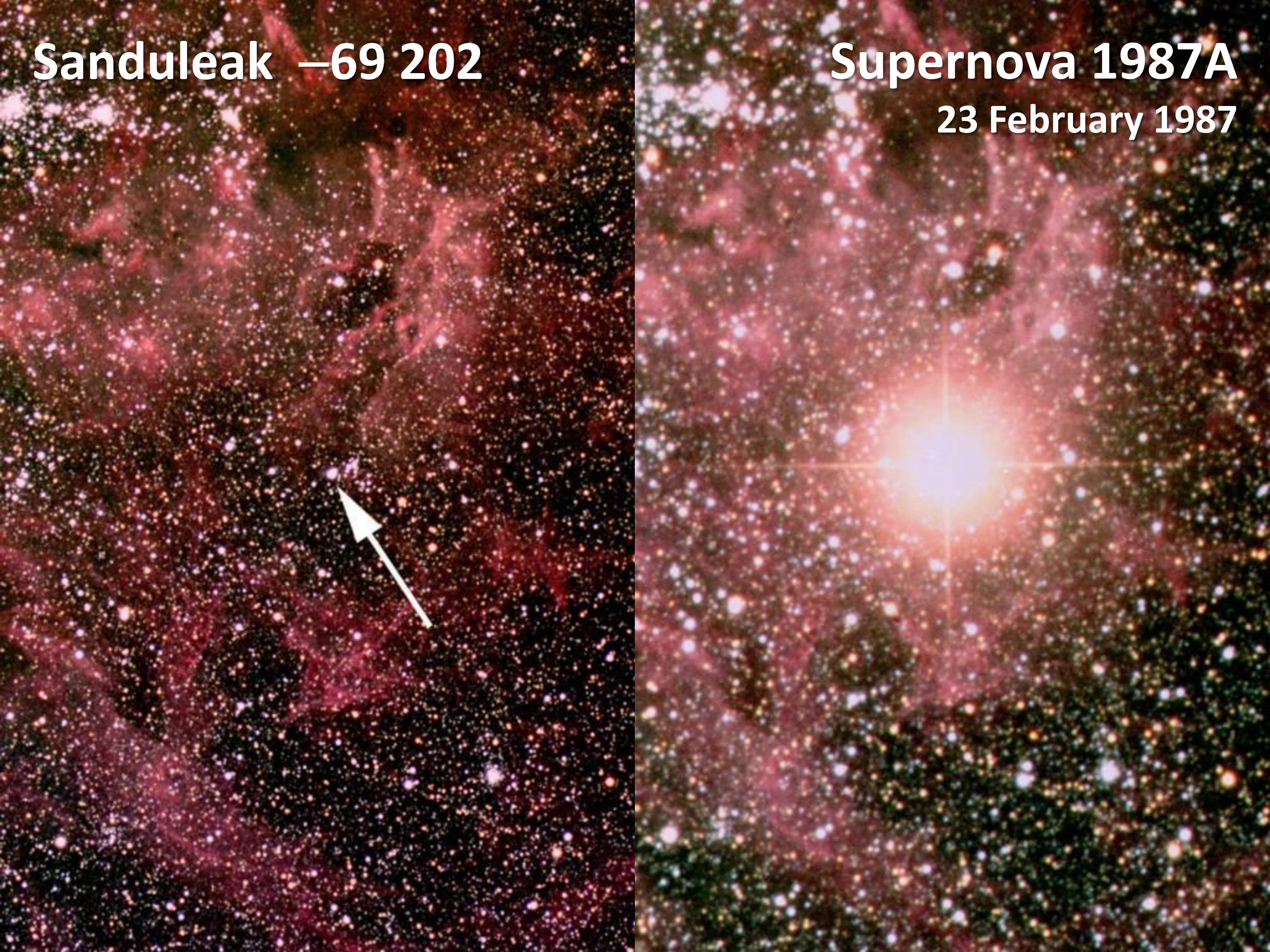
Livermore numerical model
ApJ 496 (1998) 216

Neutrinos from Supernova 1987A

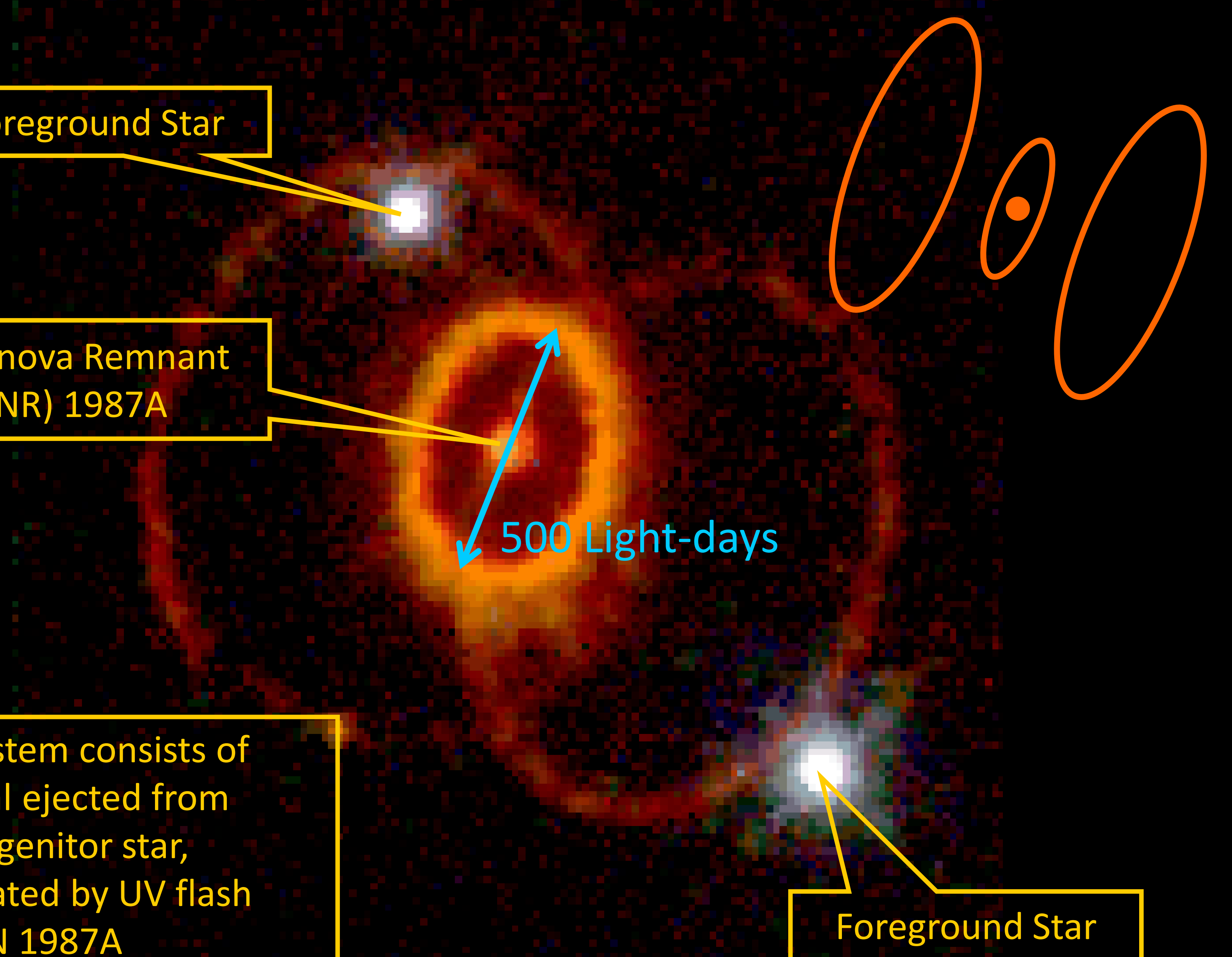

Sanduleak –69 202


Tarantula Nebula


Large Magellanic Cloud
Distance 50 kpc
(160.000 light years)

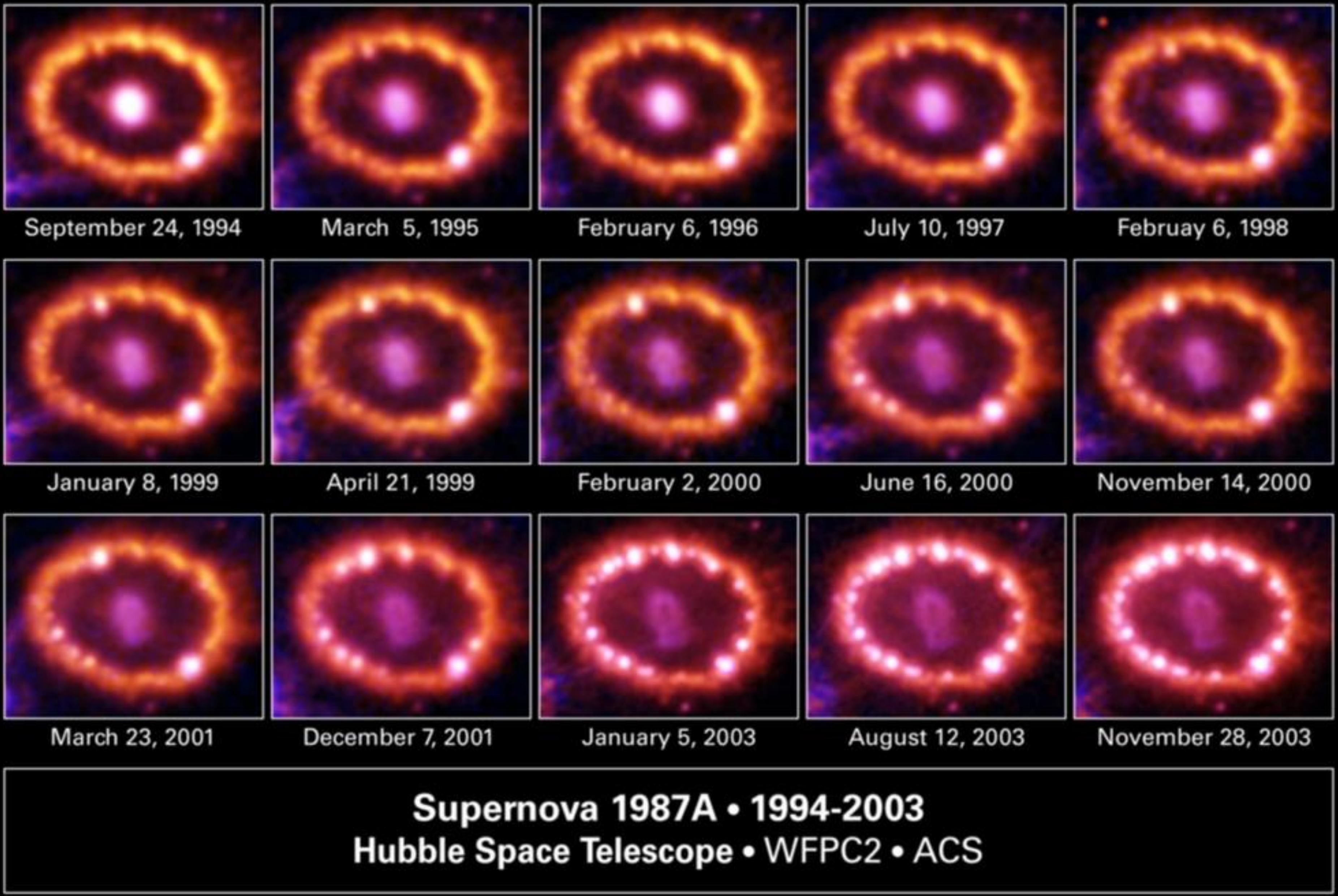

Sanduleak –69 202
Supernova 1987A
23 February 1987

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



Ring system consists of material ejected from the progenitor star, illuminated by UV flash from SN 1987A

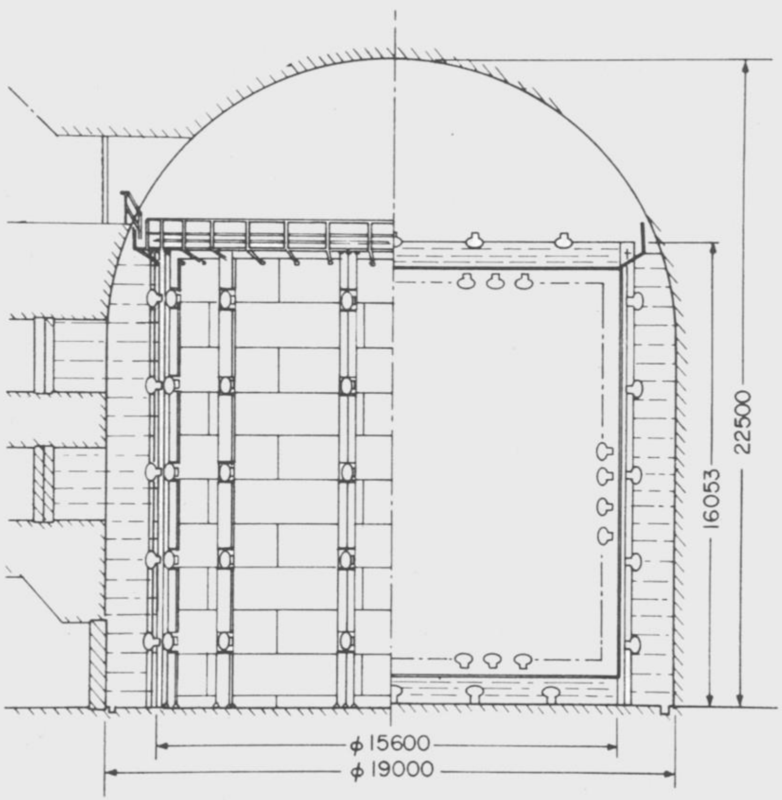
SN 1987A Explosion Hits Inner Ring

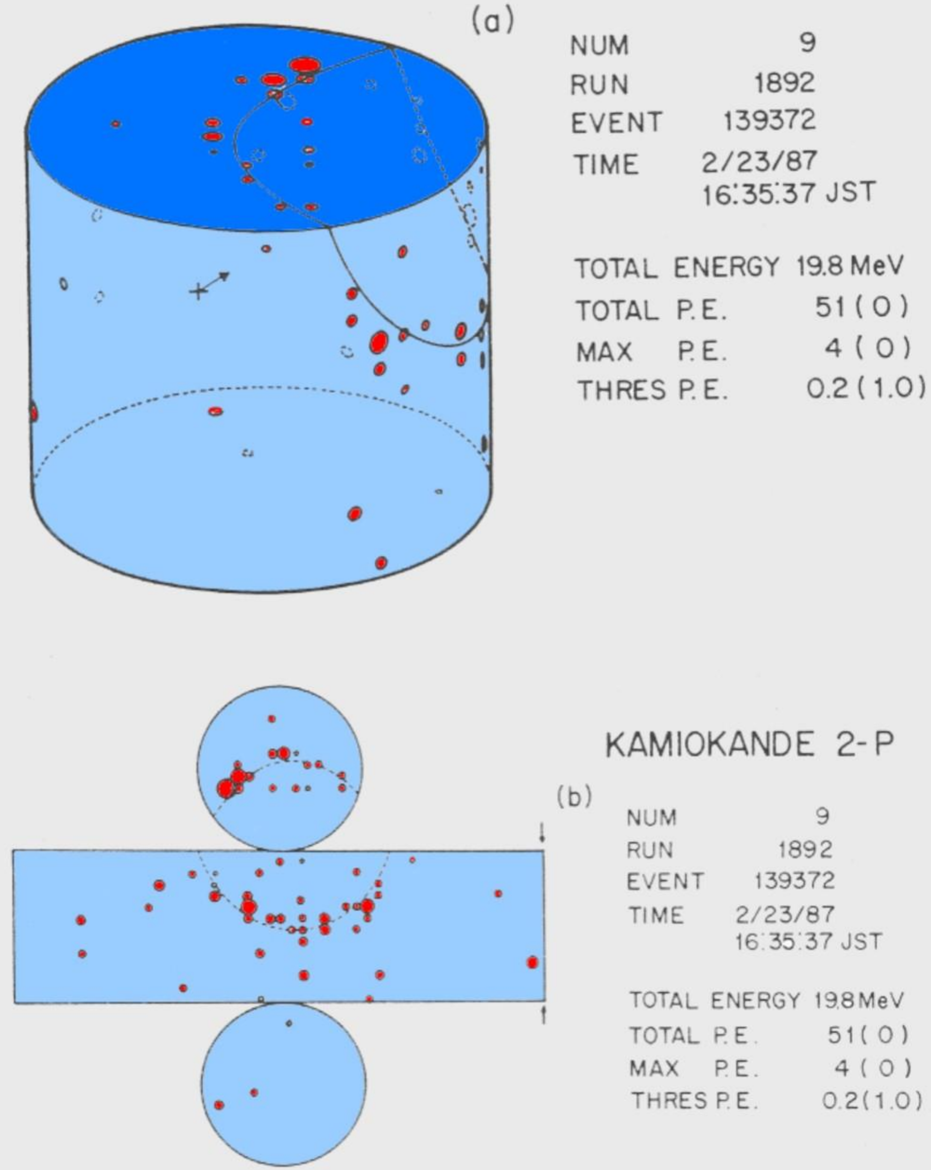


NASA and R. Kirshner (Harvard-Smithsonian Center for Astrophysics) STScI-PRC04-09b

SN 1987A Event No.9 in Kamiokande

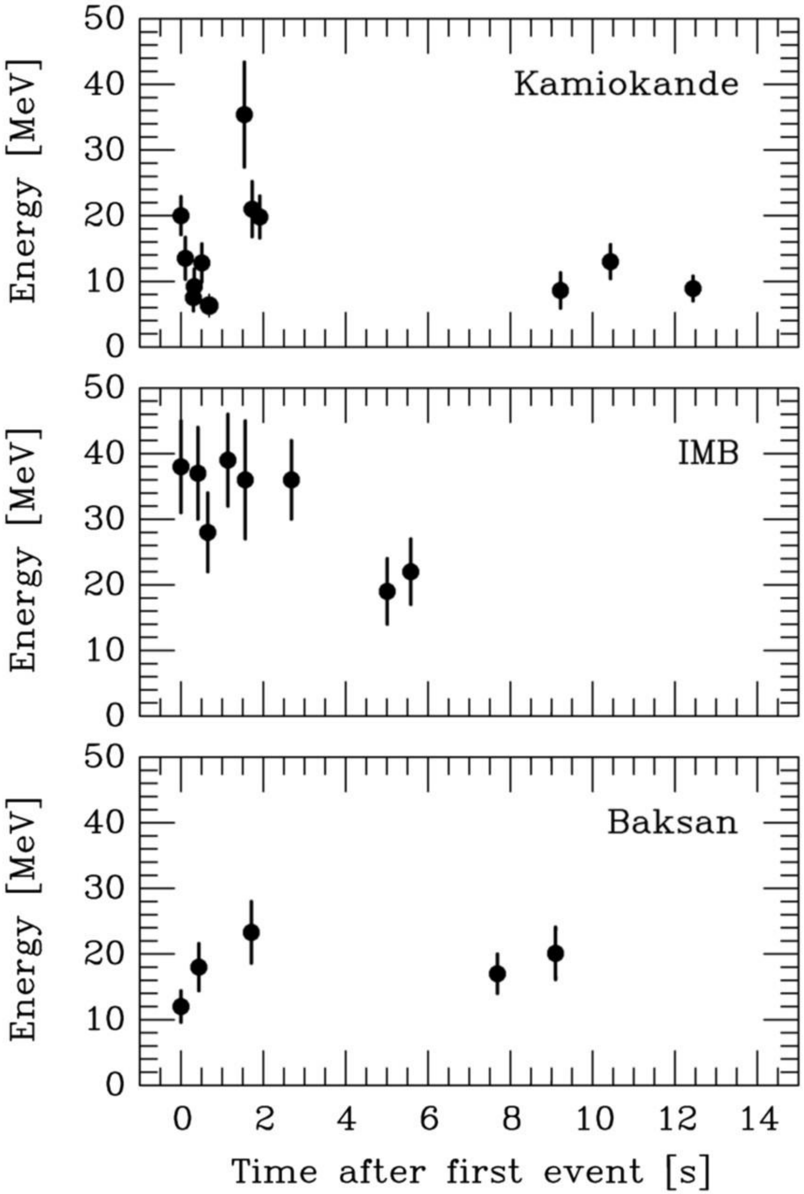
Kamiokande Detector





Hirata et al., PRD 38 (1988) 448

Neutrino Signal of Supernova 1987A



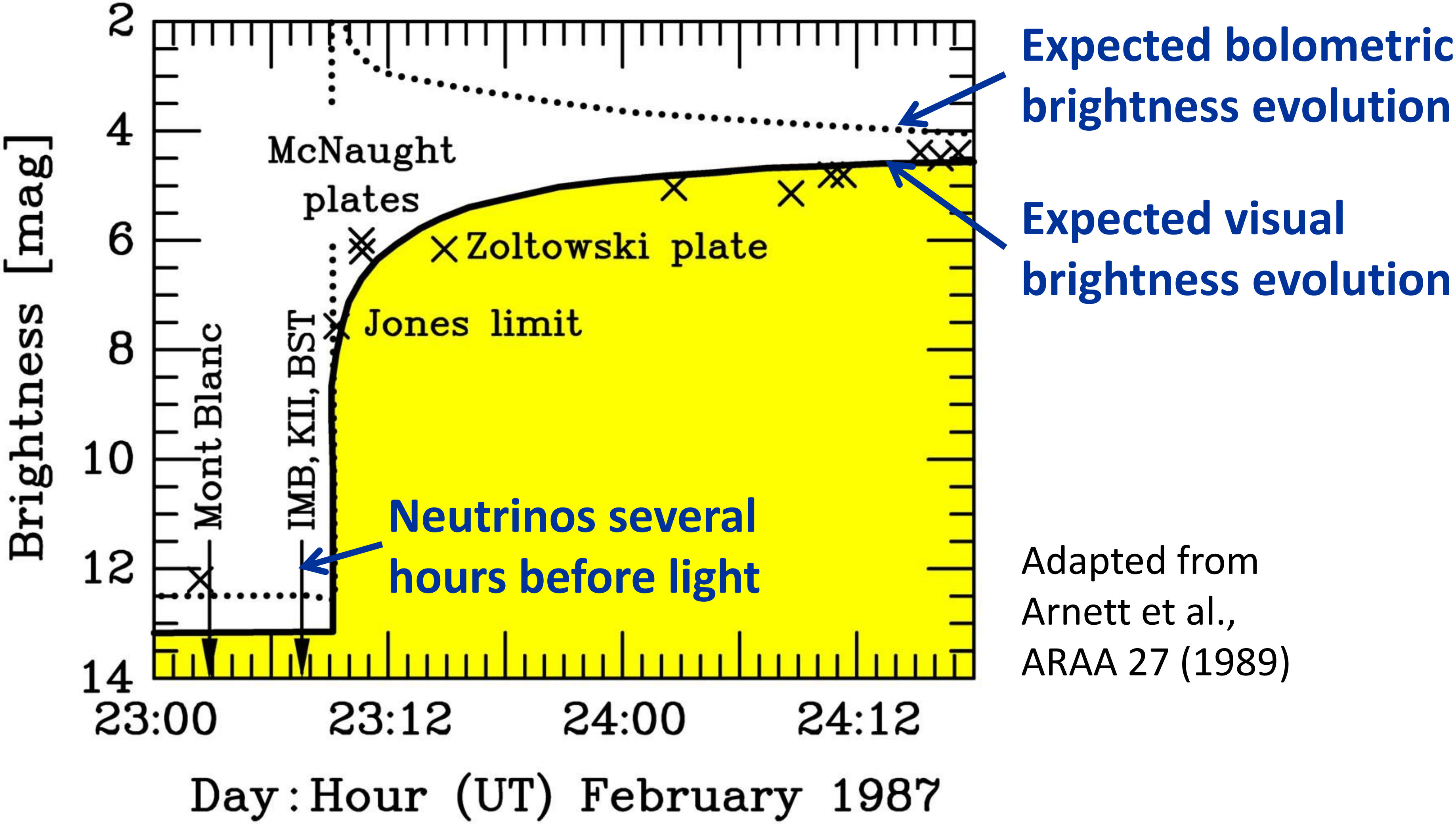
Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty $\pm$1 min

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

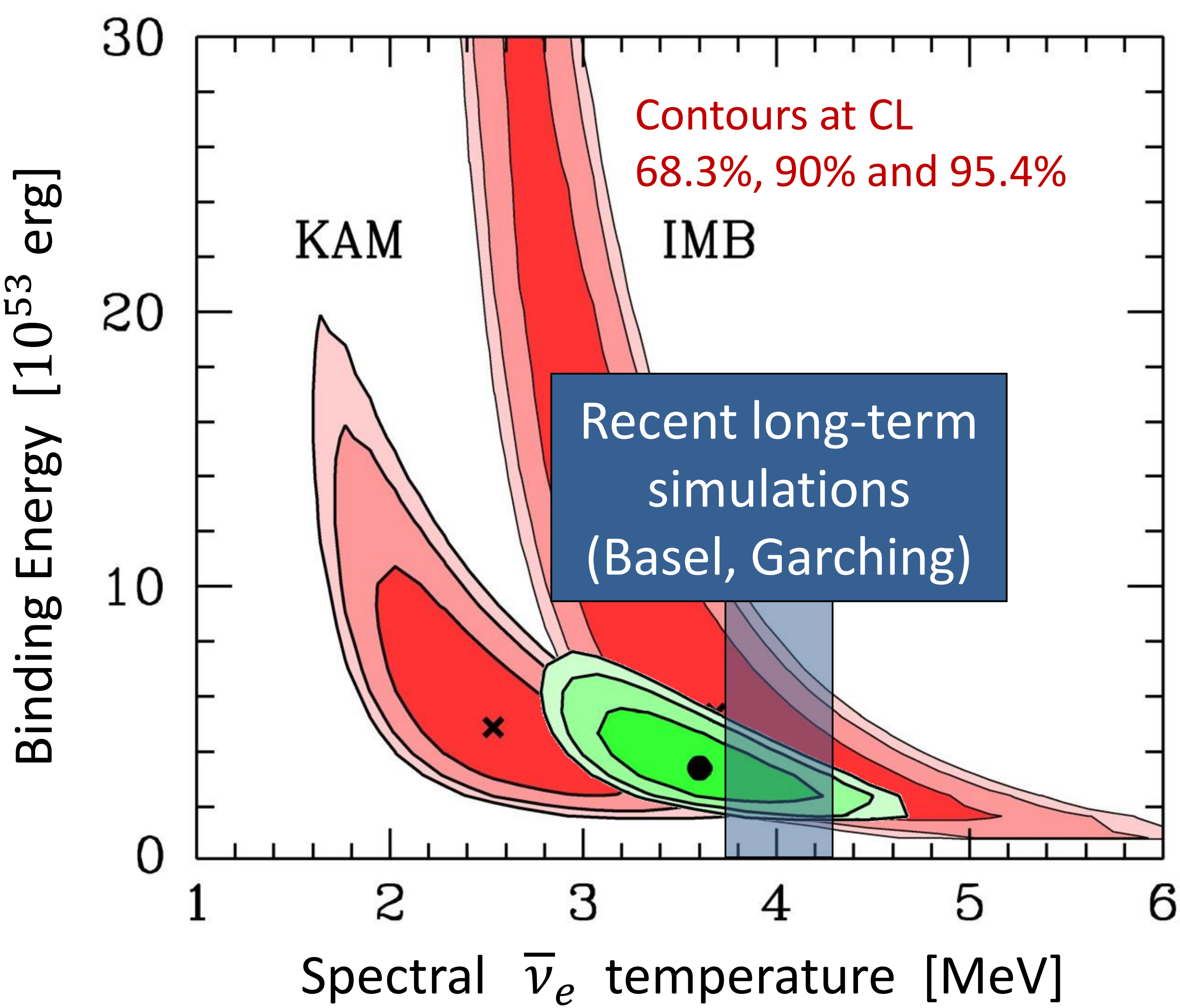
Within clock uncertainties,
all signals are contemporaneous

Early Lightcurve of SN 1987A



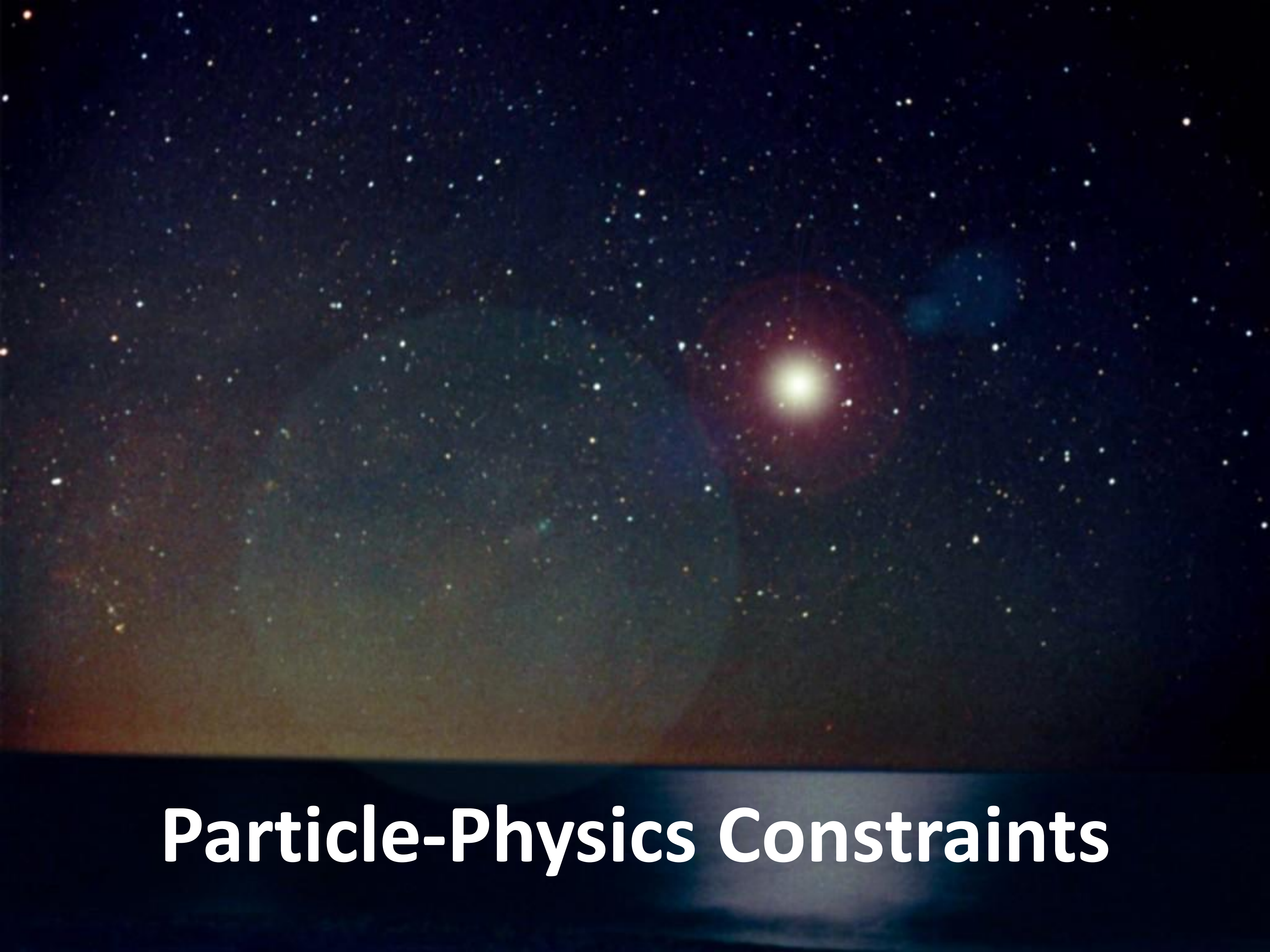
Adapted from Arnett et al., ARAA 27 (1989)

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



Particle-Physics Constraints

Neutrino Limits by Intrinsic Signal Dispersion

Time of flight delay by neutrino mass

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

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

SN 1987A signal duration implies

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

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

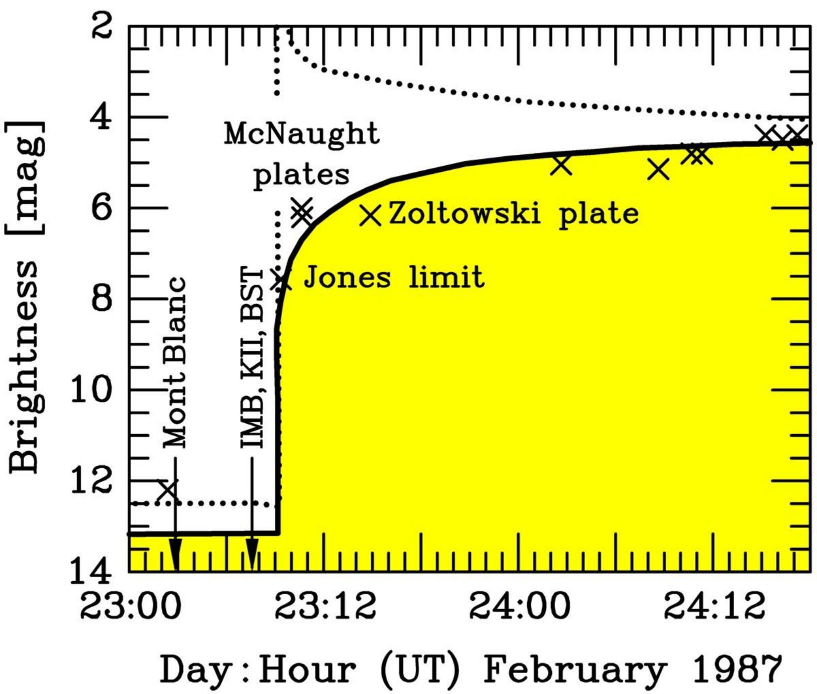
$$\frac{e_\nu}{e} < 3\times 10^{-17}\ \frac{1\mu G}{B_\perp}\ \frac{1\text{ kpc}}{d_B}$$

- 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

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,

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

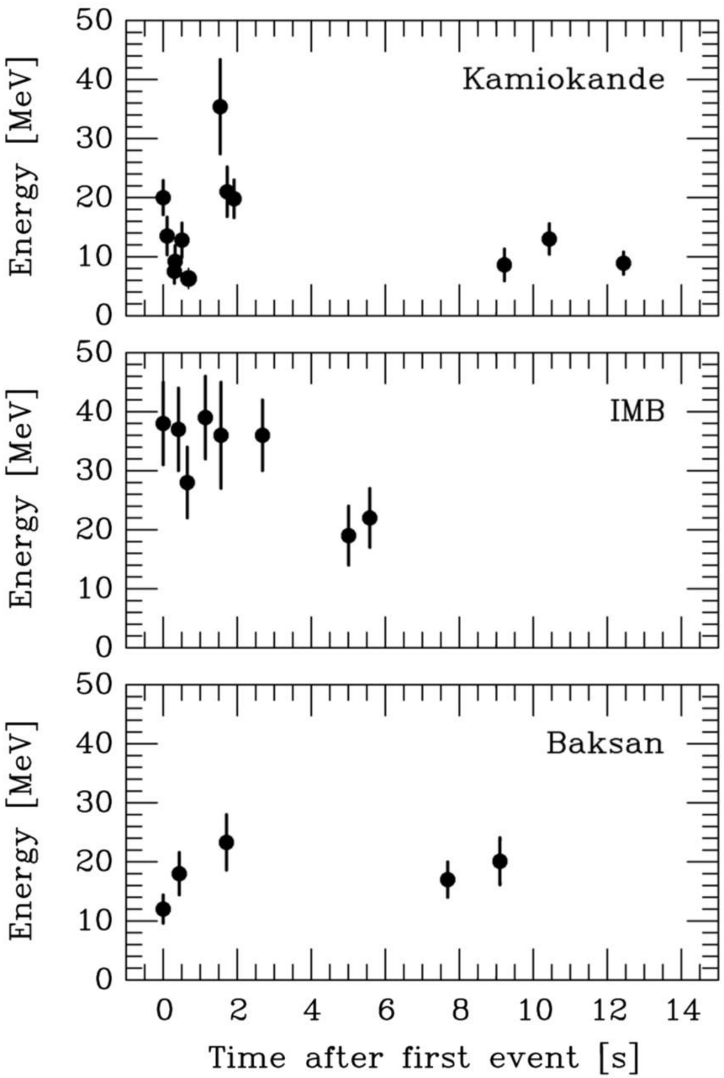
Neutrinos and photons respond to gravity the same to within

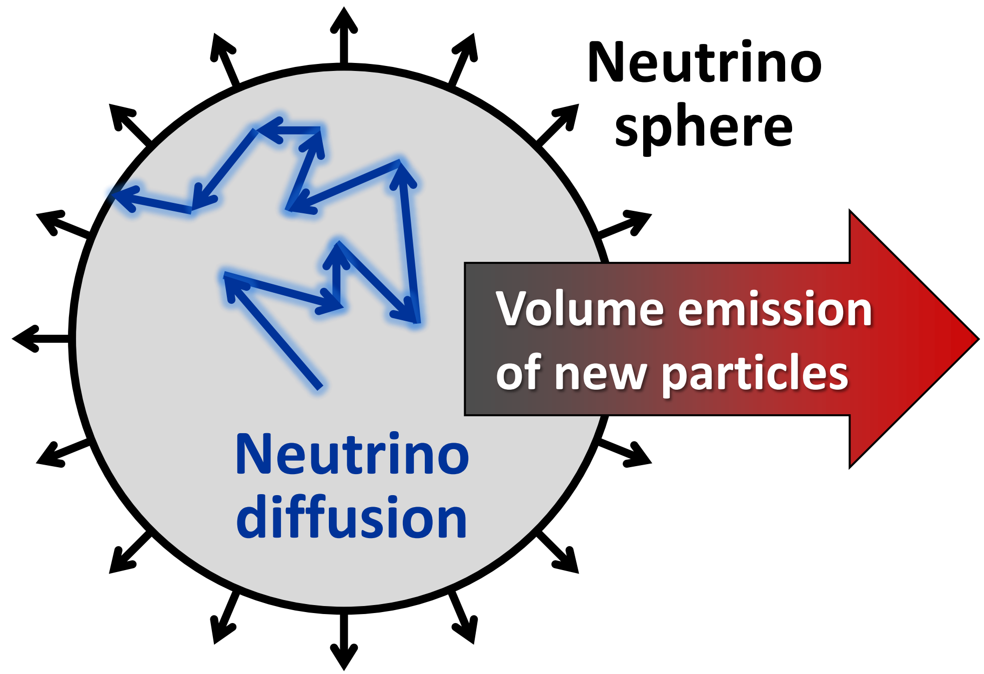
$$1\text{–}4 \times 10^{-3}$$

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

Supernova 1987A Energy-Loss Argument

SN 1987A neutrino signal

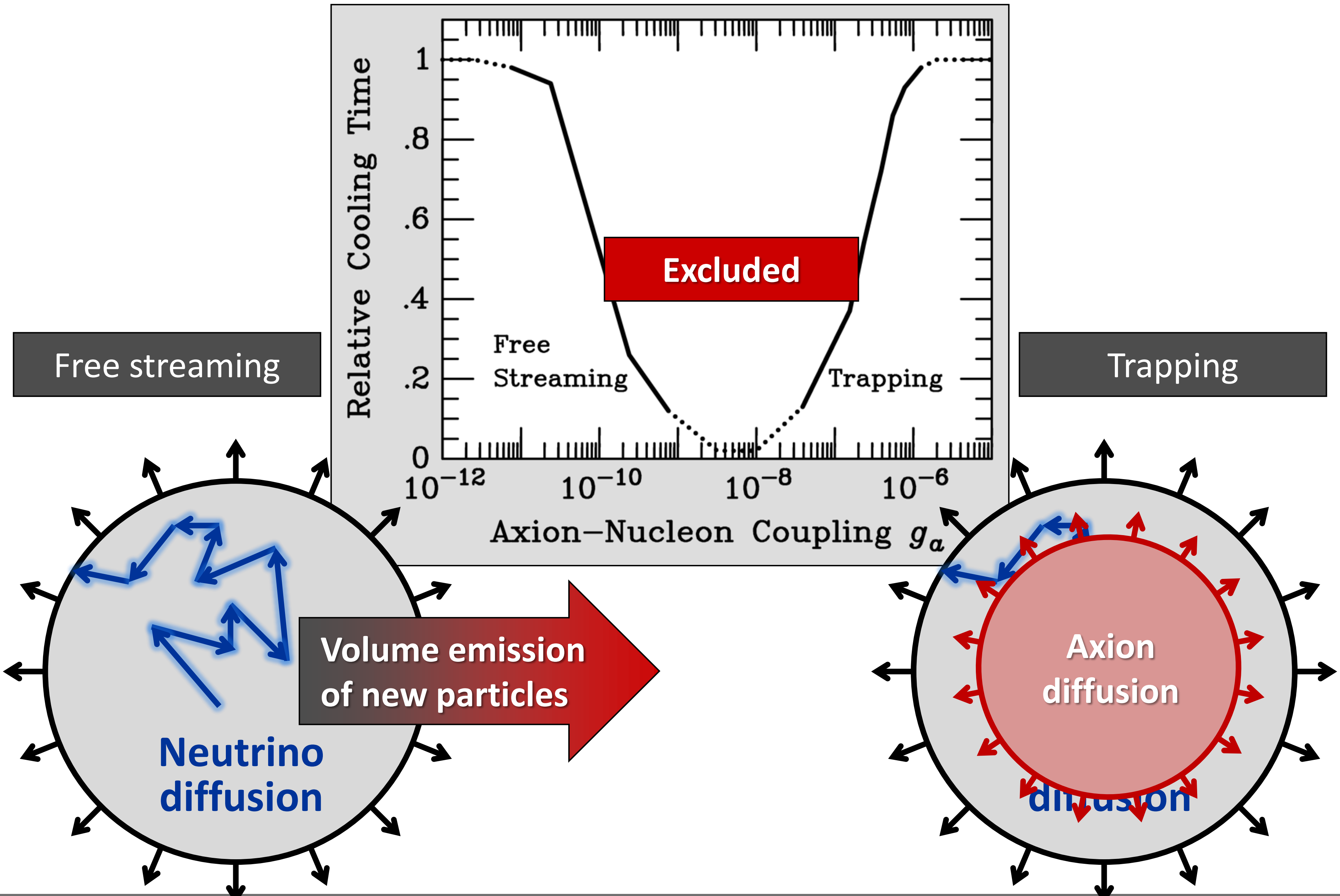




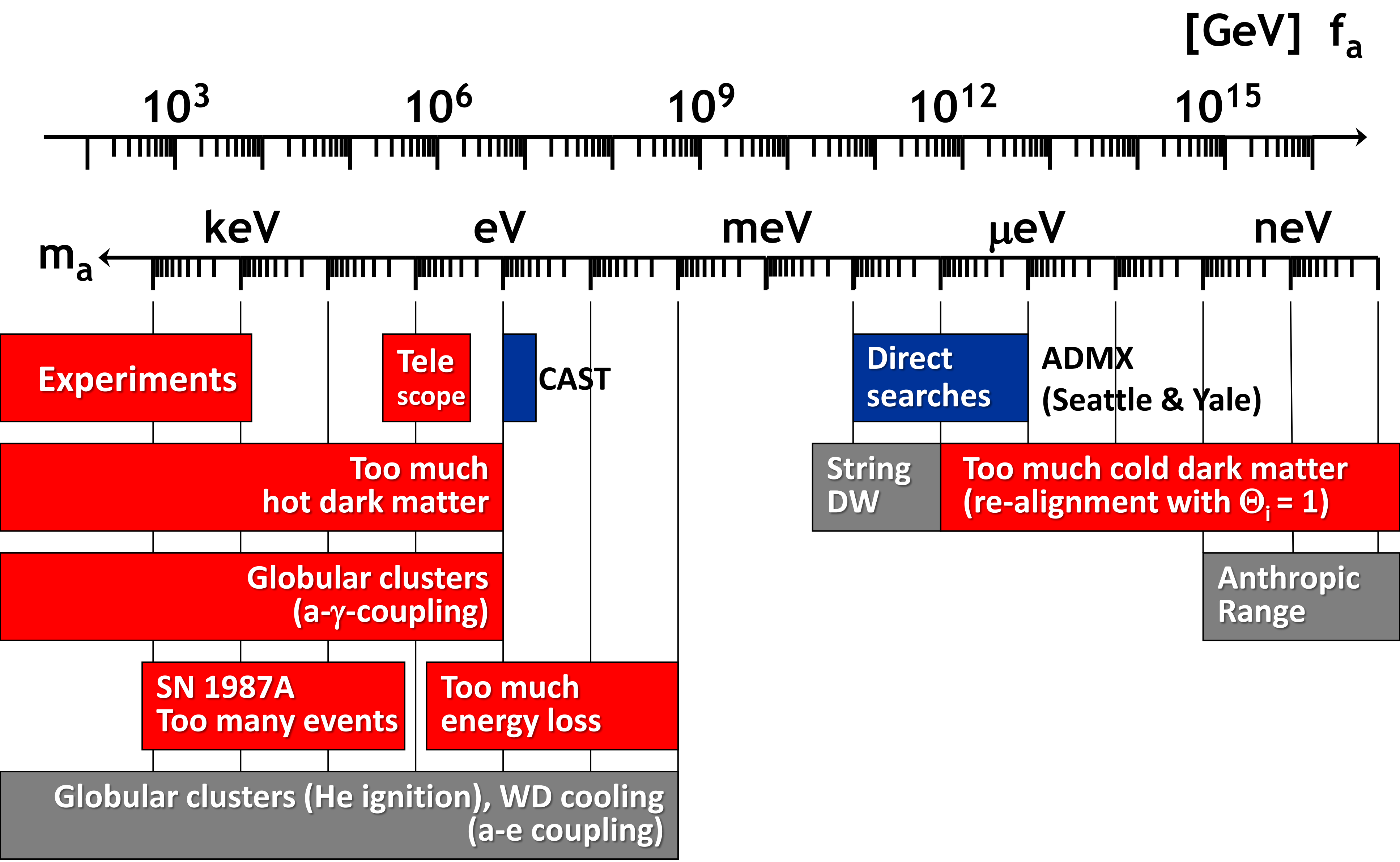
Emission of very weakly interacting particles would "steal" energy from the neutrino burst and shorten it.
(Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

Late-time signal most sensitive observable

SN 1987A Axion Limits

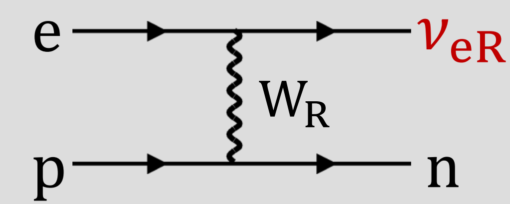
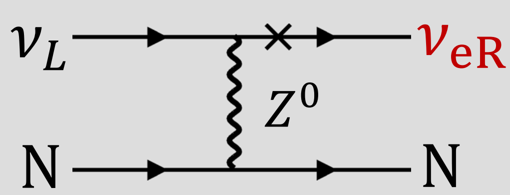
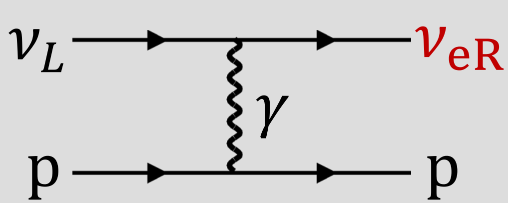
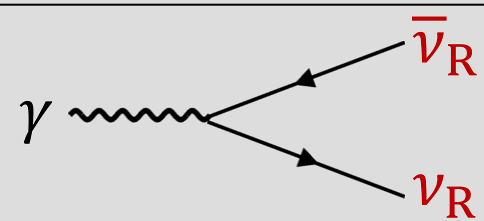


Axion Bounds and Searches



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		$G_\mathrm{R} \lesssim 10^{-5} G_\mathrm{F}$
Dirac mass		$m_\mathrm{D} \lesssim 30\ \mathrm{keV}$
Dipole moments		$\mu_\nu \lesssim 10^{-12} \mu_B$
Milli charge		$e_\nu \lesssim 10^{-9} e$

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)

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

Sterile Neutrino Limits

INERT NEUTRINOS IN SUPERNOVAE

K. KAINULAINEN*

NORDITA, Copenhagen Ø, Denmark

J. MAALAMPI**

Department of Theoretical Physics, University of Helsinki, Finland

J.T. PELTONIEMI***

Department of Theoretical Physics, University of Helsinki, Finland

Received 22 November 1990

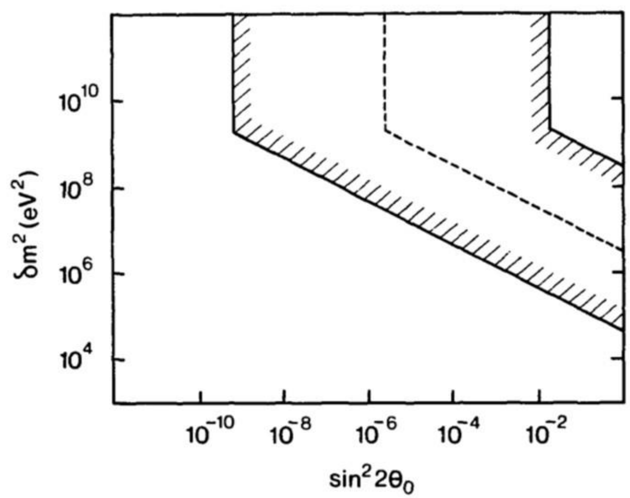


Fig. 1. Constraints from the supernova SN1987A for the squared mass difference δm^2 and the mixing angle θ_0 of the electron neutrino and an inert neutrino. The shaded region is forbidden by the observations. The dashed line shows the trapping condition (15).

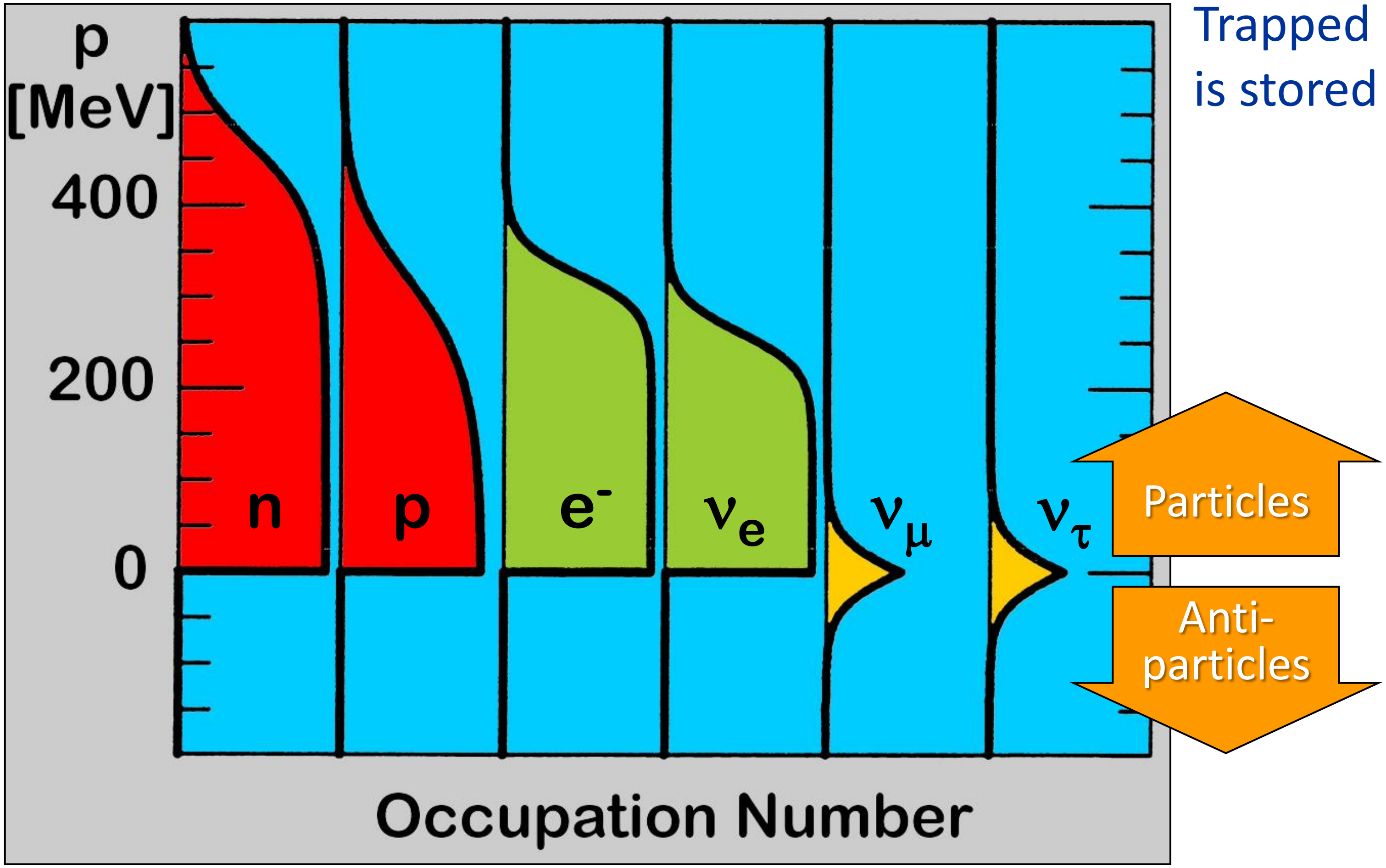
See also:

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

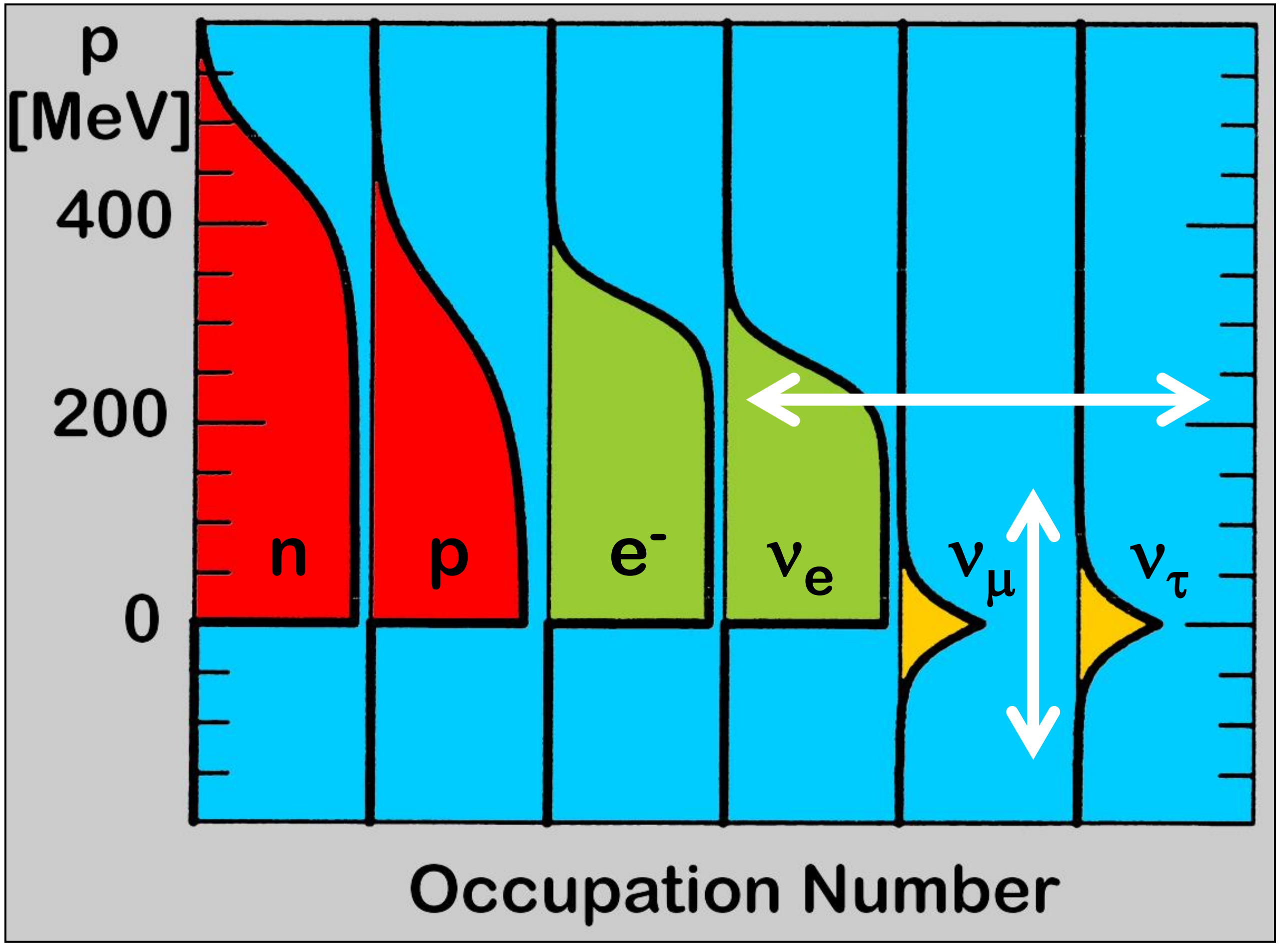
Degenerate Fermi Seas in a Supernova Core



Trapped lepton number is stored in e^- and ν_e

In true thermal equilibrium with flavor mixing, only one chemical potential for charged leptons and one for neutrinos.
No chemical potential for Majorana neutrinos (lepton number violation)

Degenerate Fermi Seas in a Supernova Core



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

Non-standard interactions could be effective, most sensitive environment

Consequences in core collapse should be studied numerically

Equilibration by lepton number violation, but Majorana masses too small

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

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

THE EUROPEAN
PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

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

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

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

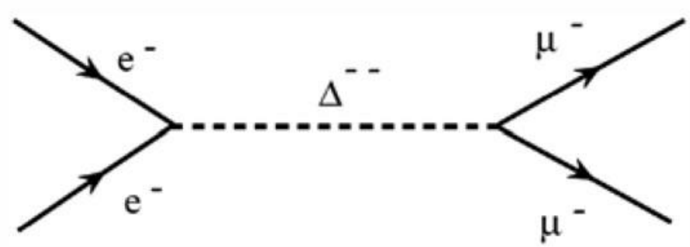
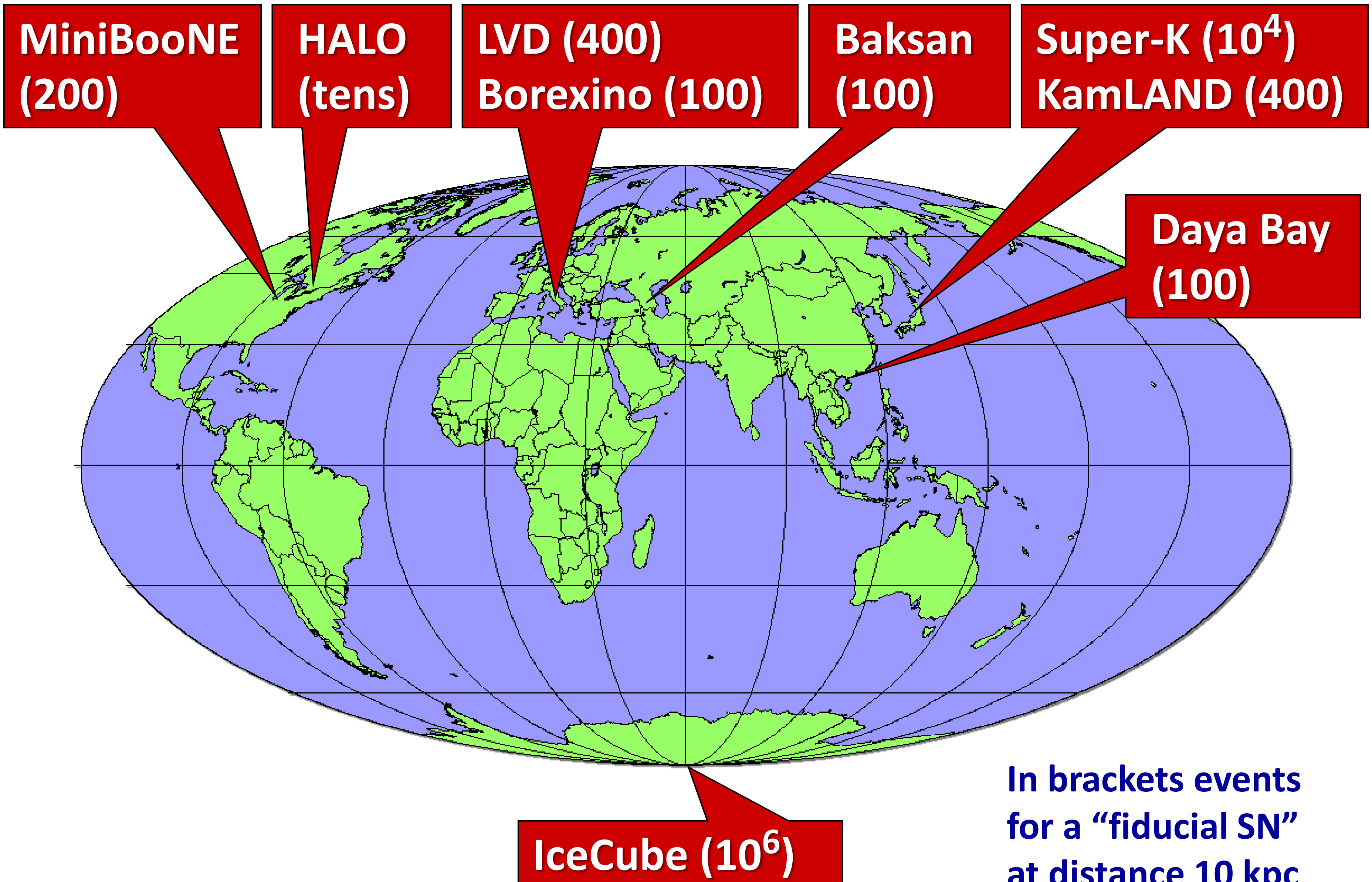


Fig. 1 $ee \to \mu\mu$ LFV transition mediated by the doubly charged bilepton Δ^{--}

Neutrinos from Next Nearby SN

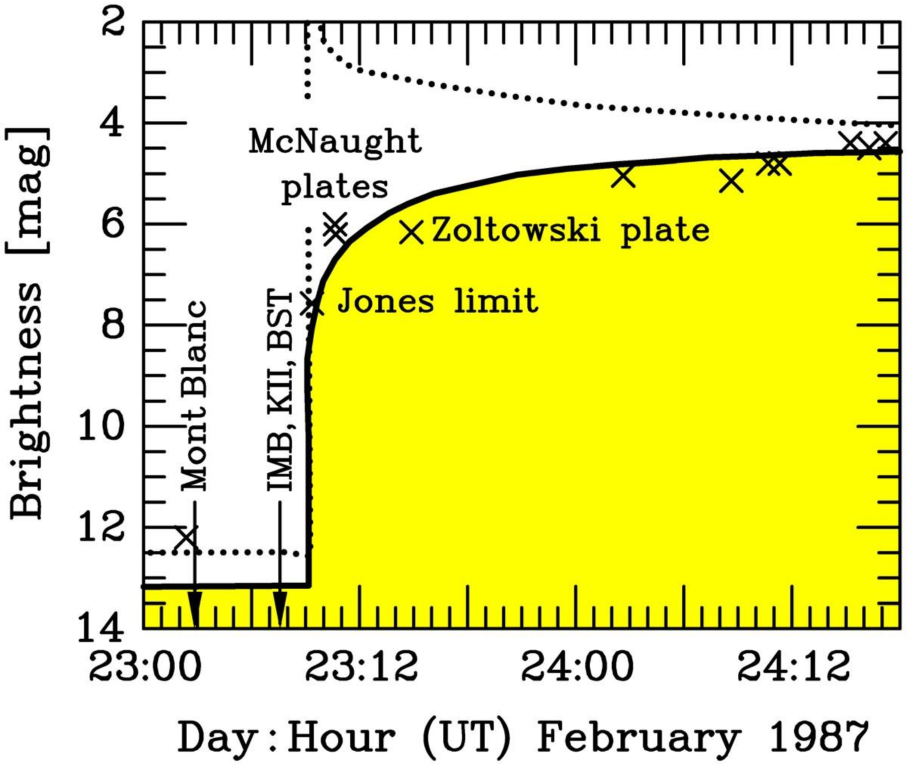
Operational Detectors for Supernova Neutrinos



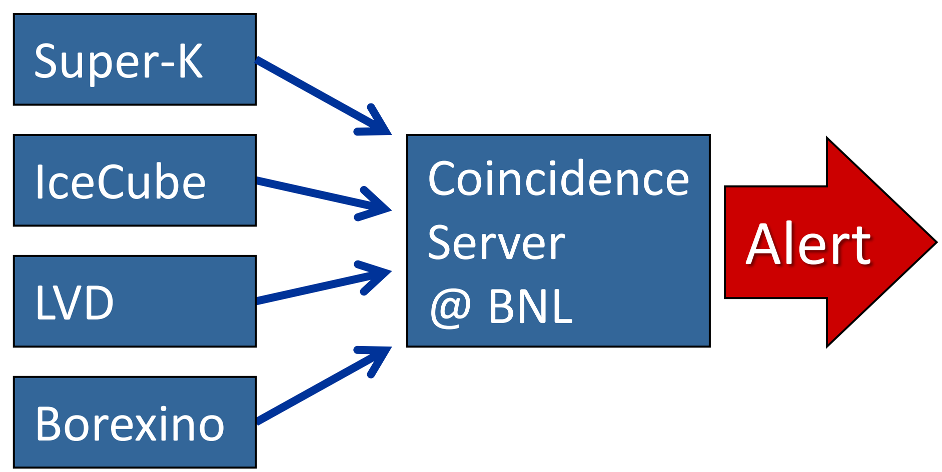
In brackets events for a “fiducial SN” at distance 10 kpc

SuperNova Early Warning System (SNEWS)

Early light curve of SN 1987A

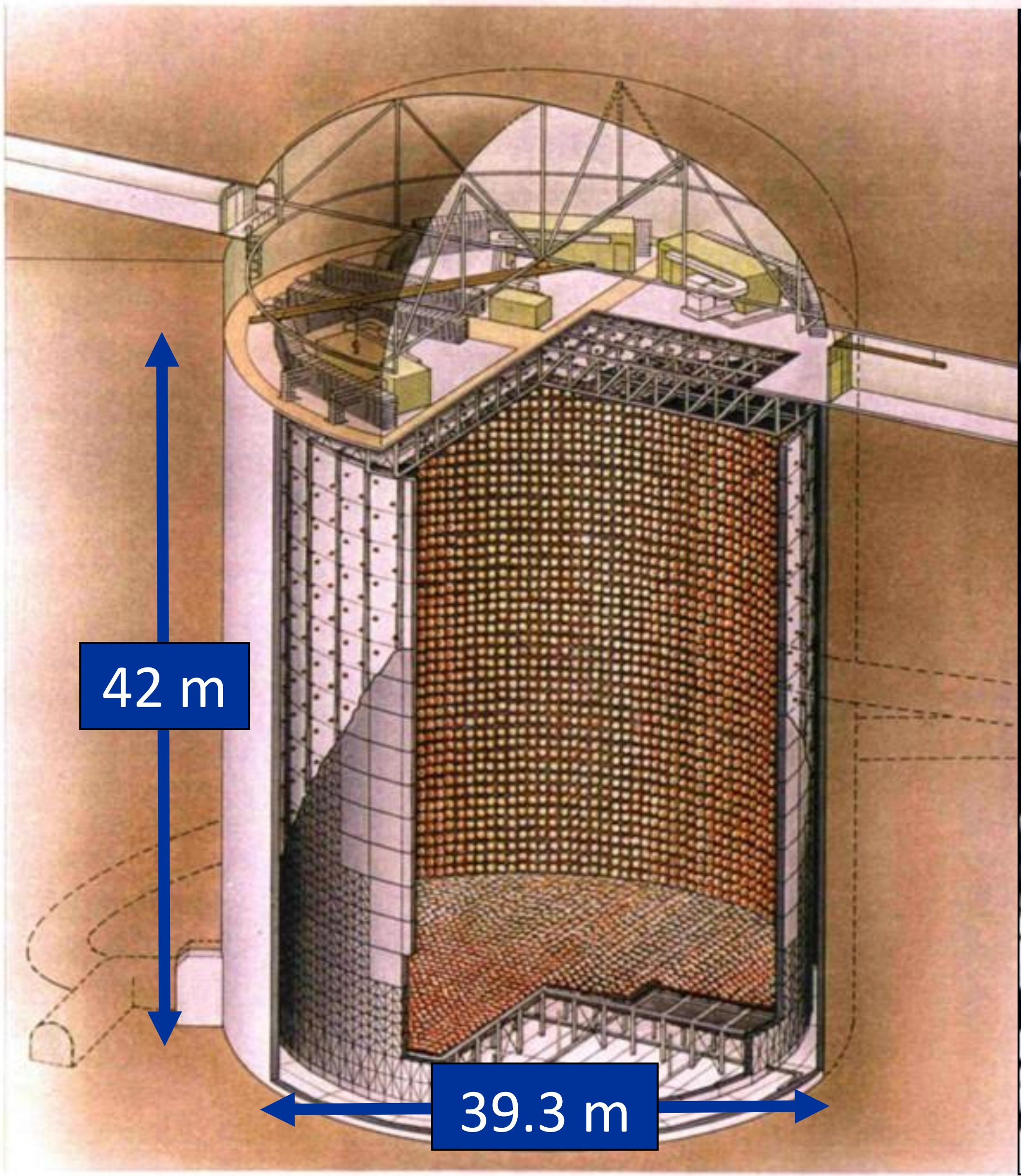


http://snews.bnl.gov

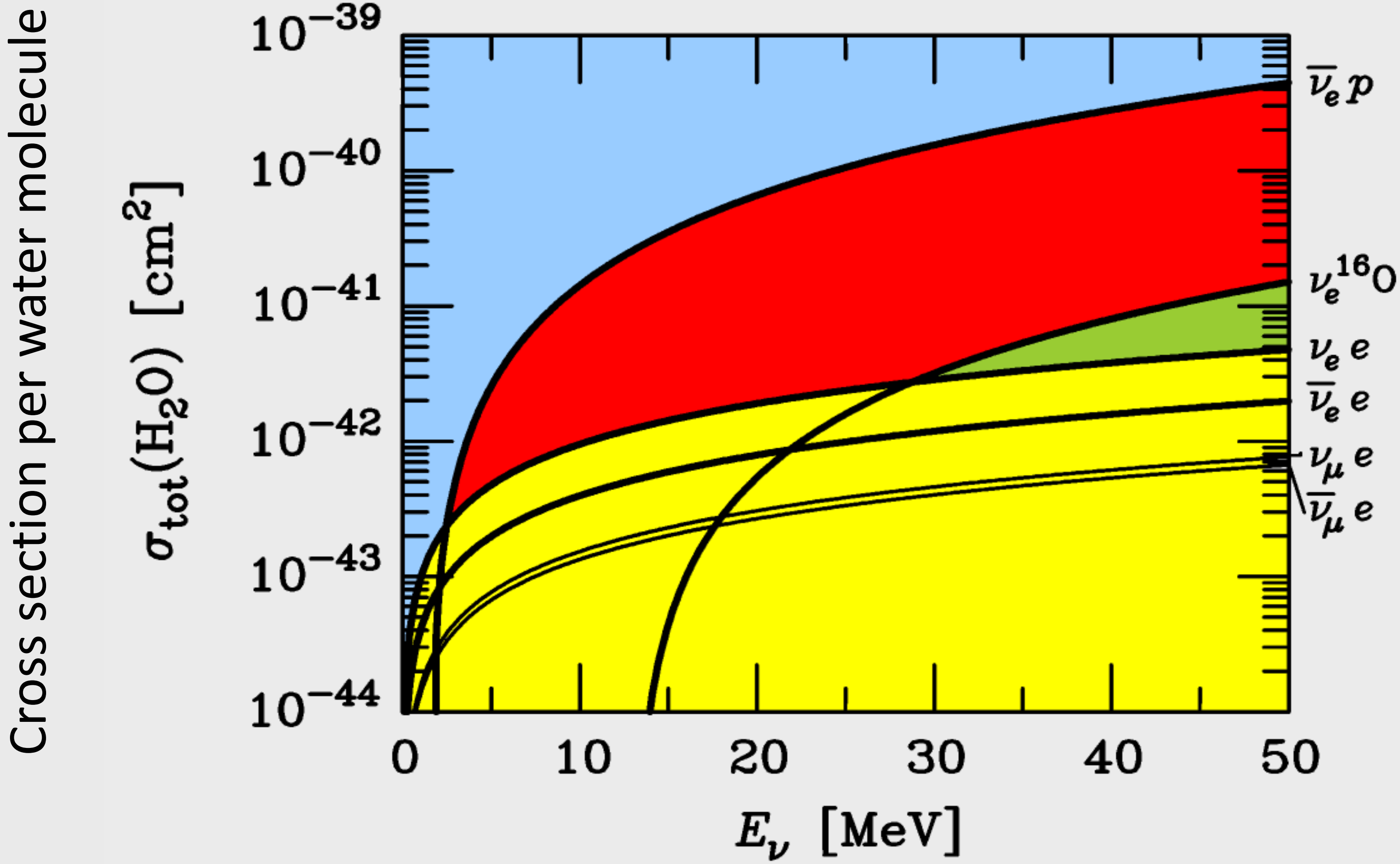


- Neutrinos arrive several hours before photons
- Can alert astronomers several hours in advance

Super-Kamiokande Neutrino Detector (Since 1996)



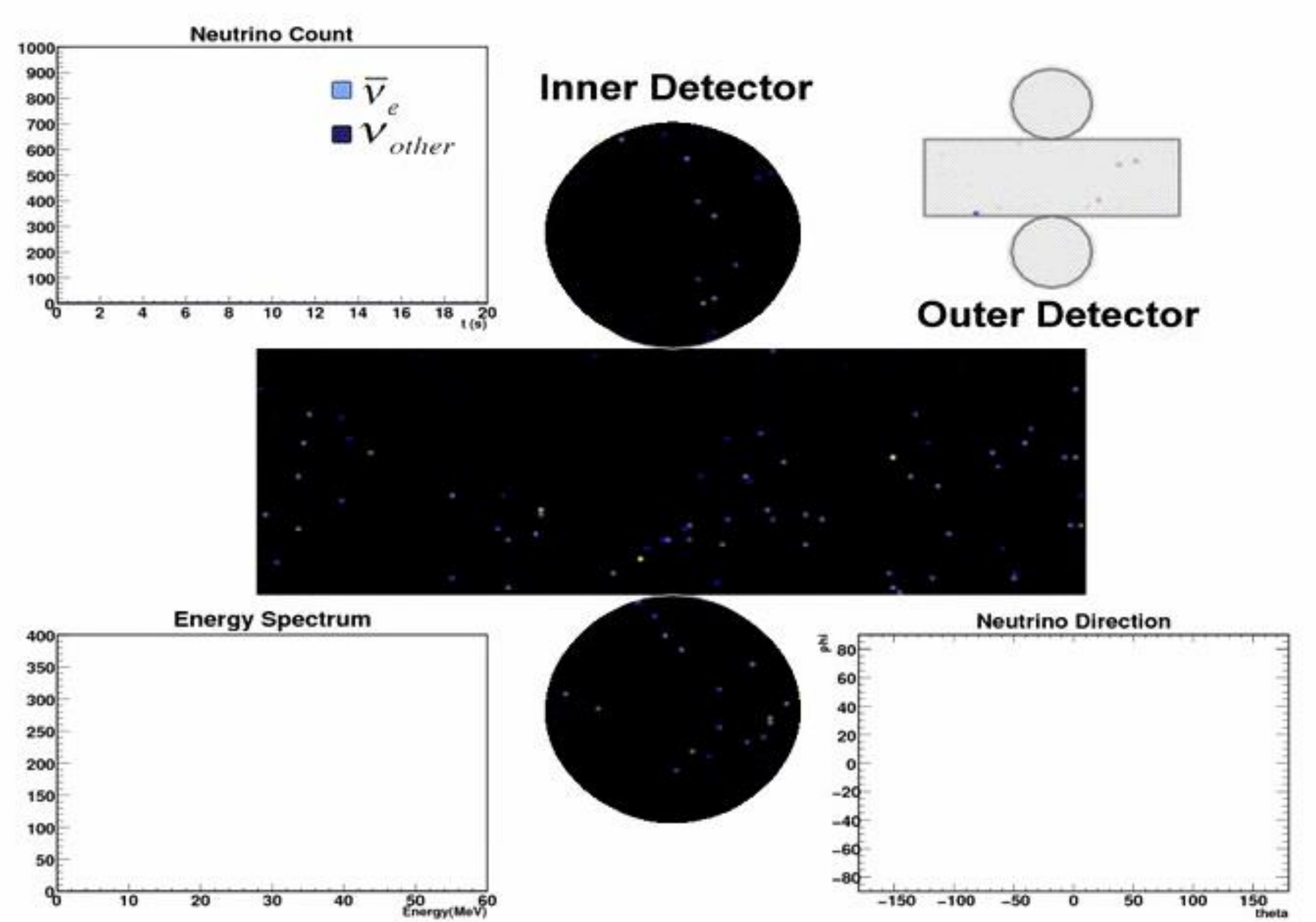
Neutrino Cross Section in a Water Target



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

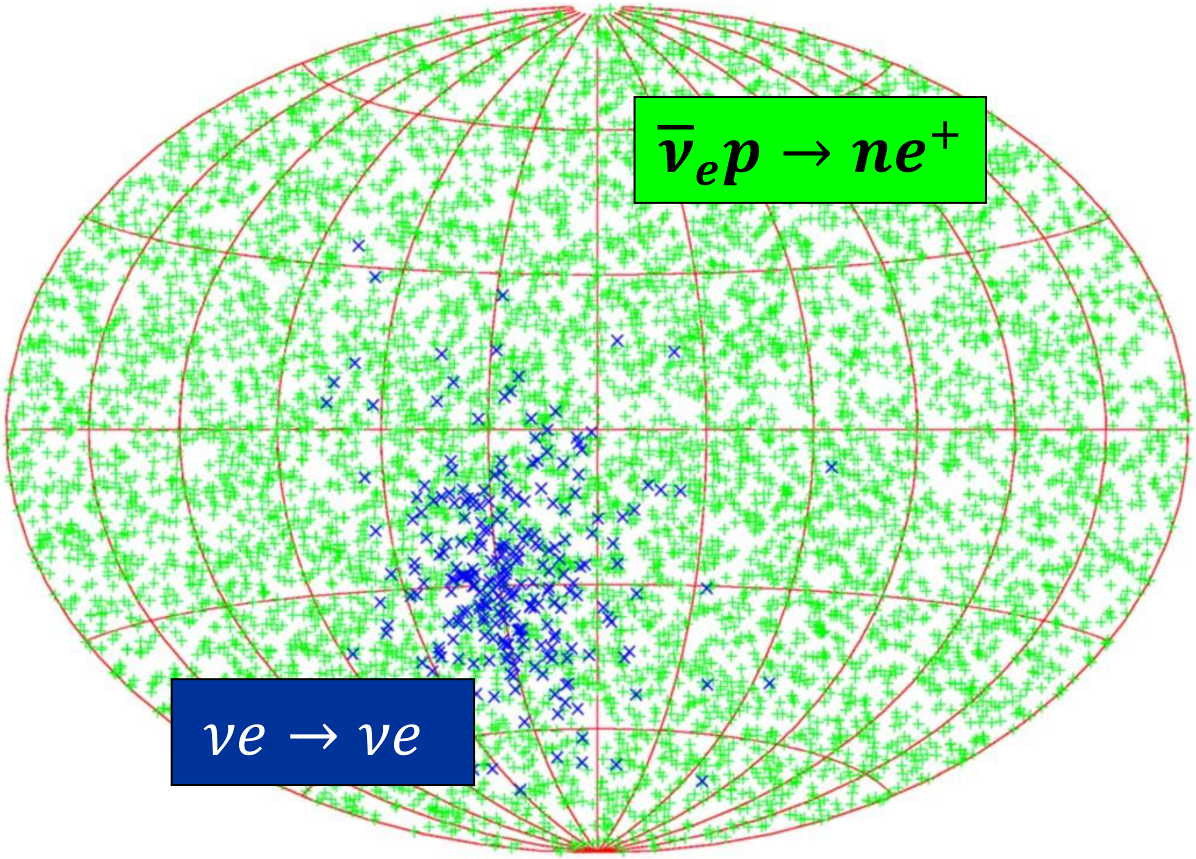
$\nu_e + e \to e + \nu_e$ dominates for solar neutrinos

Simulated Supernova Burst in Super-Kamiokande



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

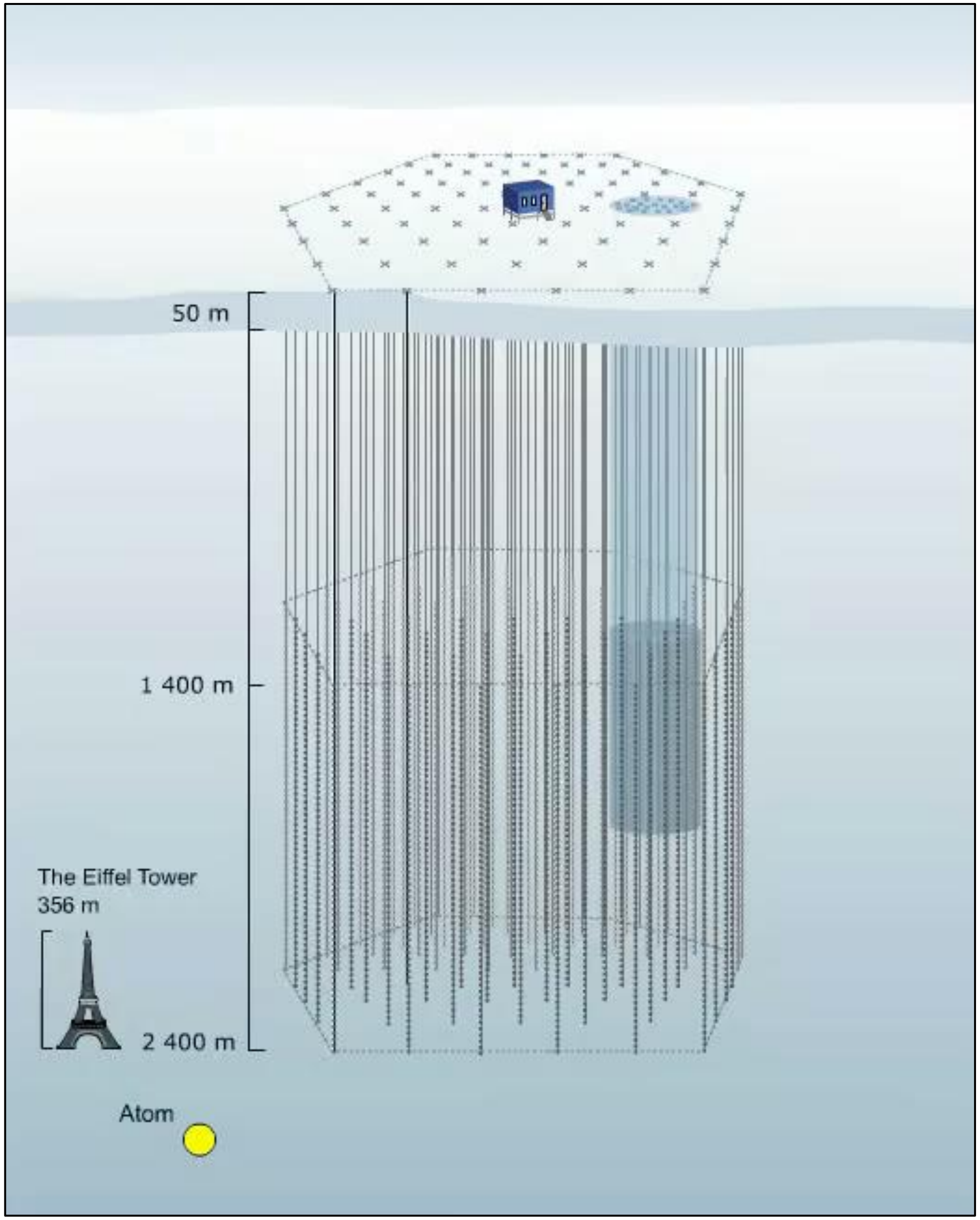
Supernova Pointing with Neutrinos



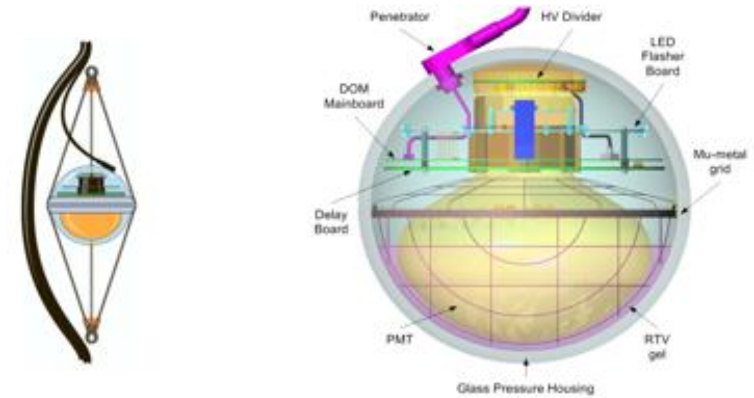
Neutron tagging efficiency		
None	90 %	
7.8°	3.2°	SK
1.4°	0.6°	SK × 30
95% CL half-cone opening angle		

- 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]

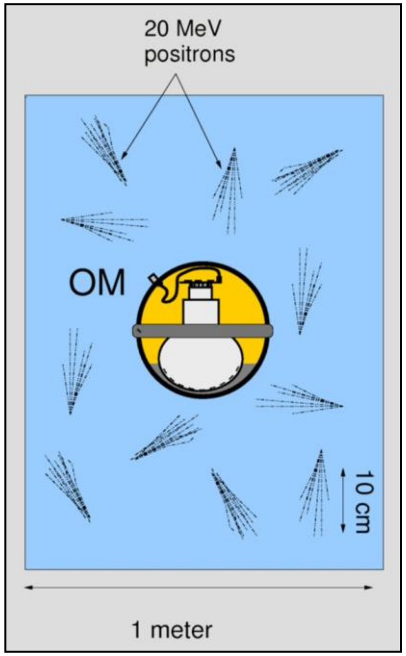
IceCube Neutrino Telescope at the South Pole

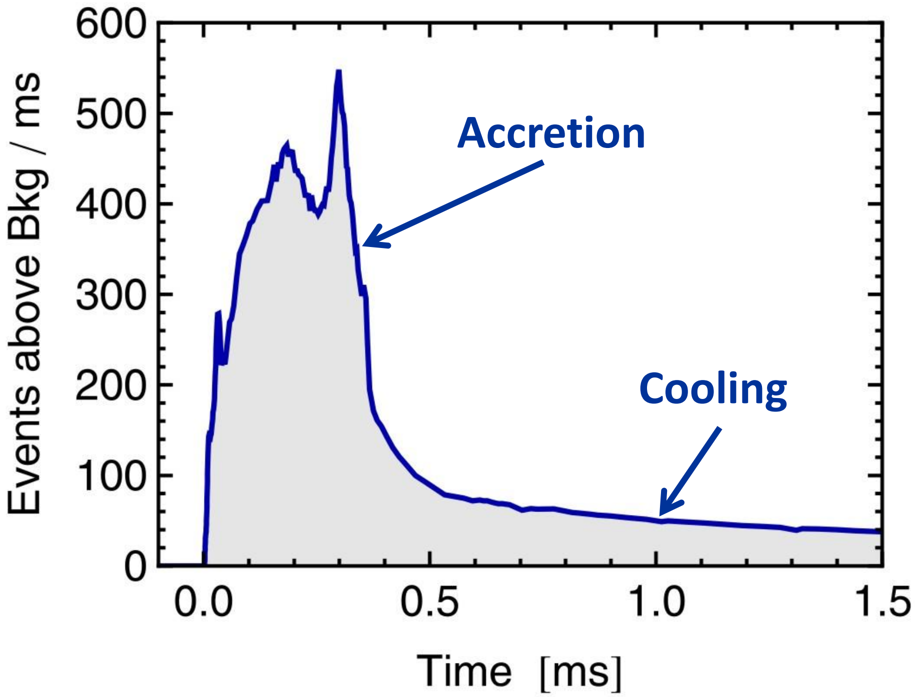


Instrumentation of 1 km^3 antarctic ice with ~ 5000 photo multipliers completed December 2010



IceCube as a Supernova Neutrino Detector



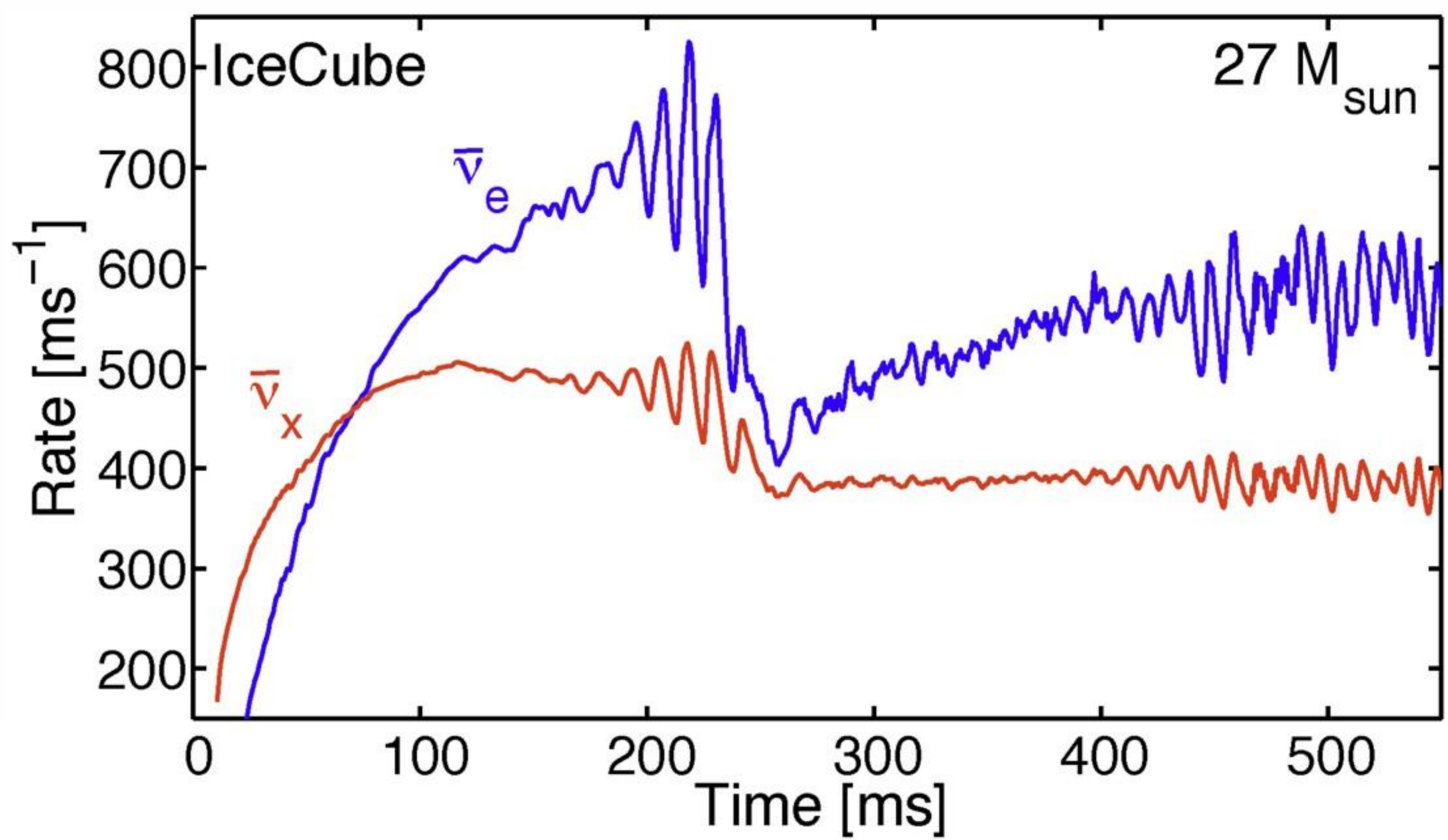


SN signal at 10 kpc
10.8 M_{sun} simulation of Basel group [arXiv:0908.1871]

- 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.

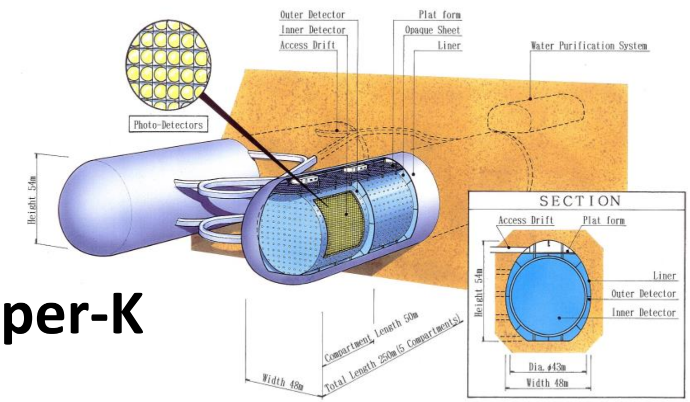
Variability seen in Neutrinos (3D Model)



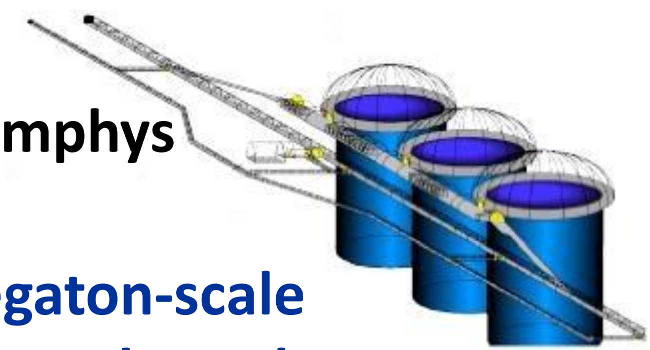
Tamborra, Hanke, Müller, Janka & Raffelt, arXiv:1307.7936
See also Lund, Marek, Lunardini, Janka & Raffelt, arXiv:1006.1889

Next Generation Large-Scale Detector Concepts

DUSEL
LBNE

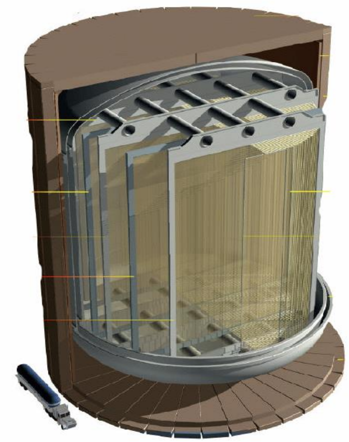


Hyper-K

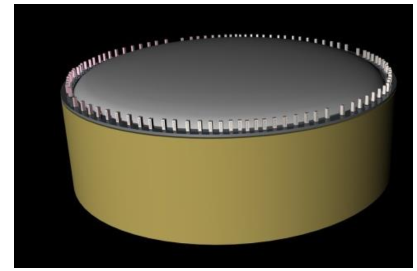


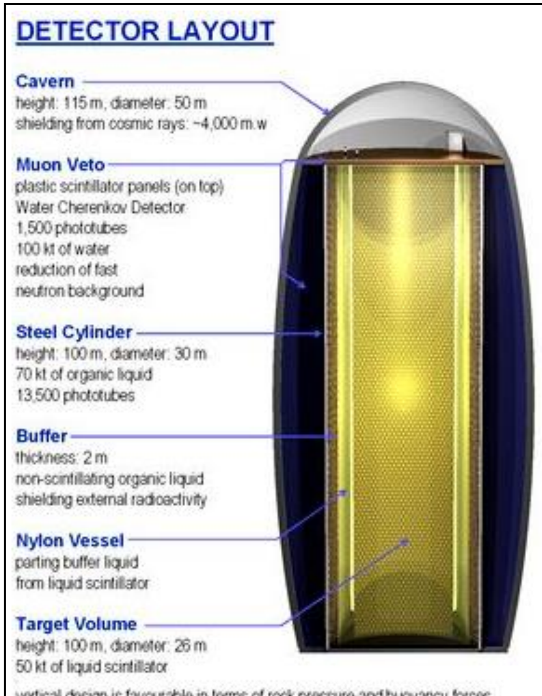
Memphys

Megaton-scale water Cherenkov



5-100 kton liquid Argon



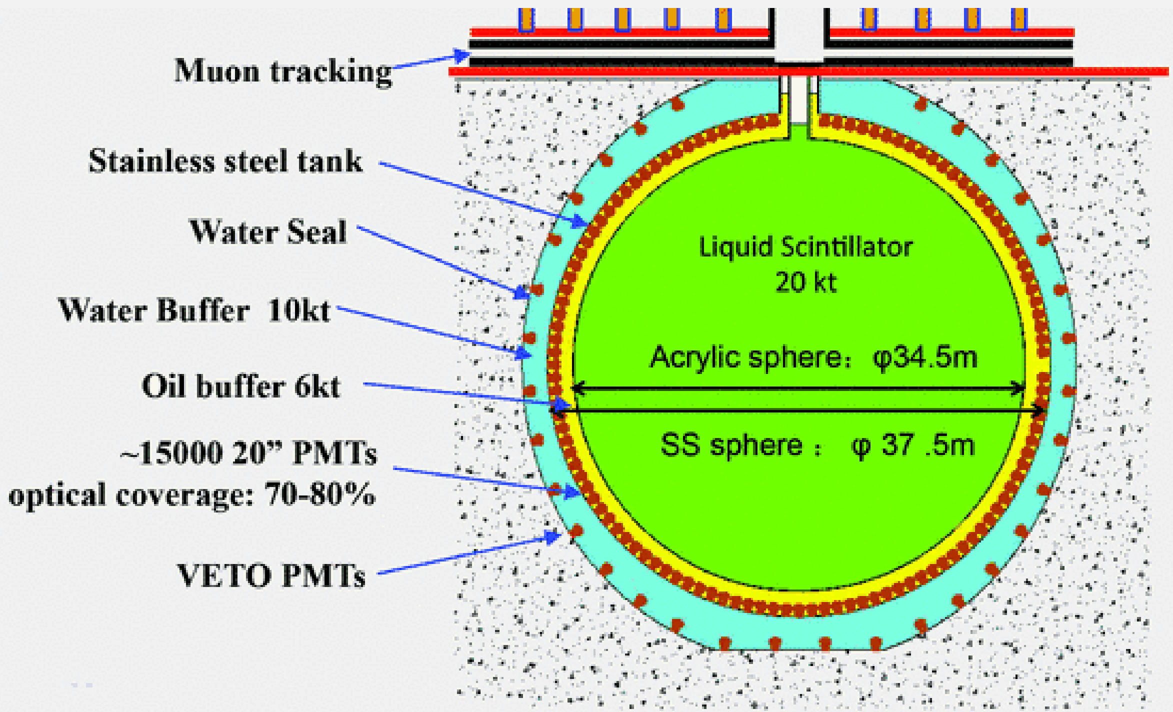


100 kton scale scintillator

LENA
HanoHano
Juno

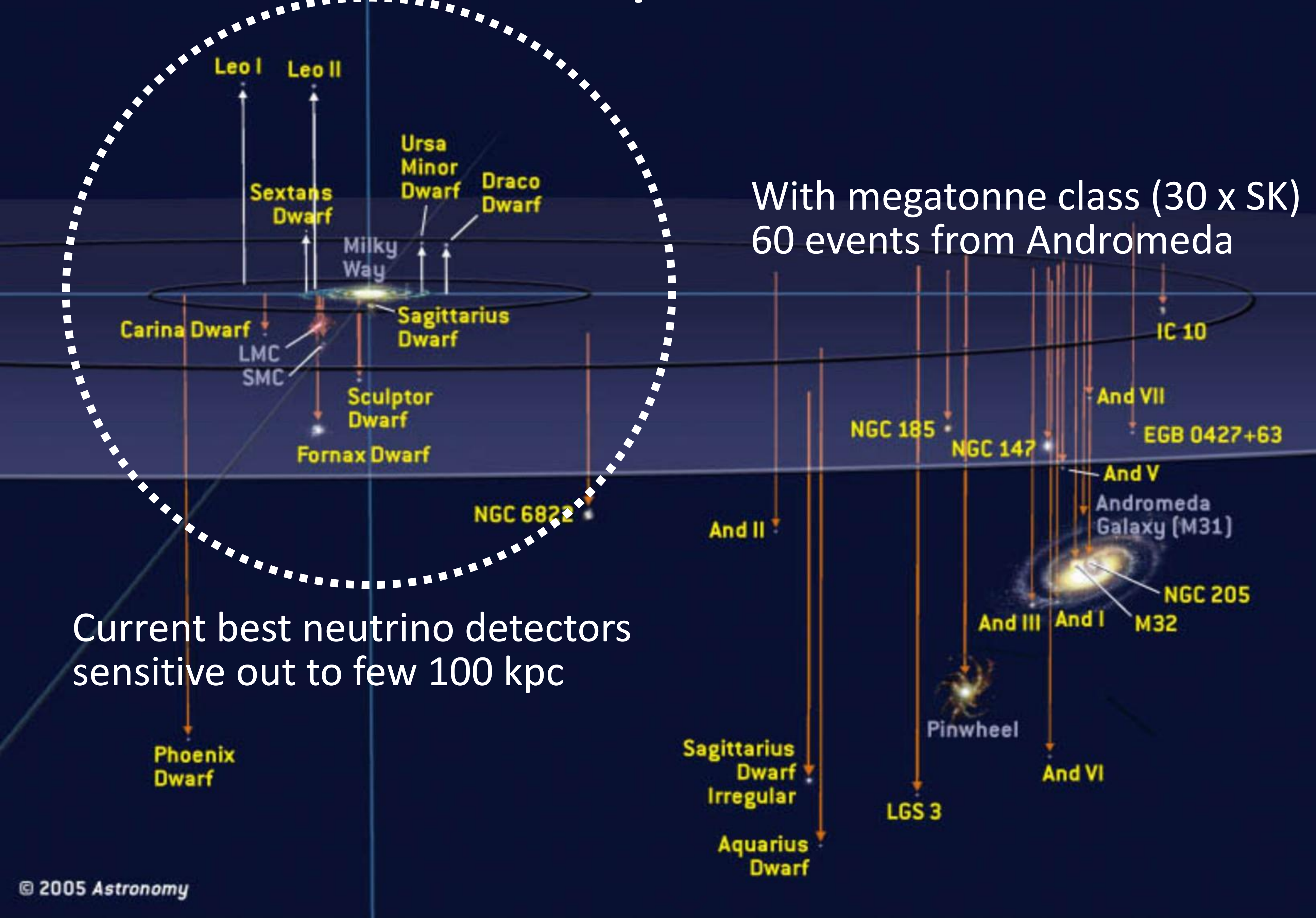
LENA: From Dream to Reality

JUNO (formerly Daya Bay II) Collaboration formed (2014)
20 kt scintillator detector
Hierarchy determination with reactor neutrinos
Excellent for low-energy neutrino astronomy



Supernova Rate

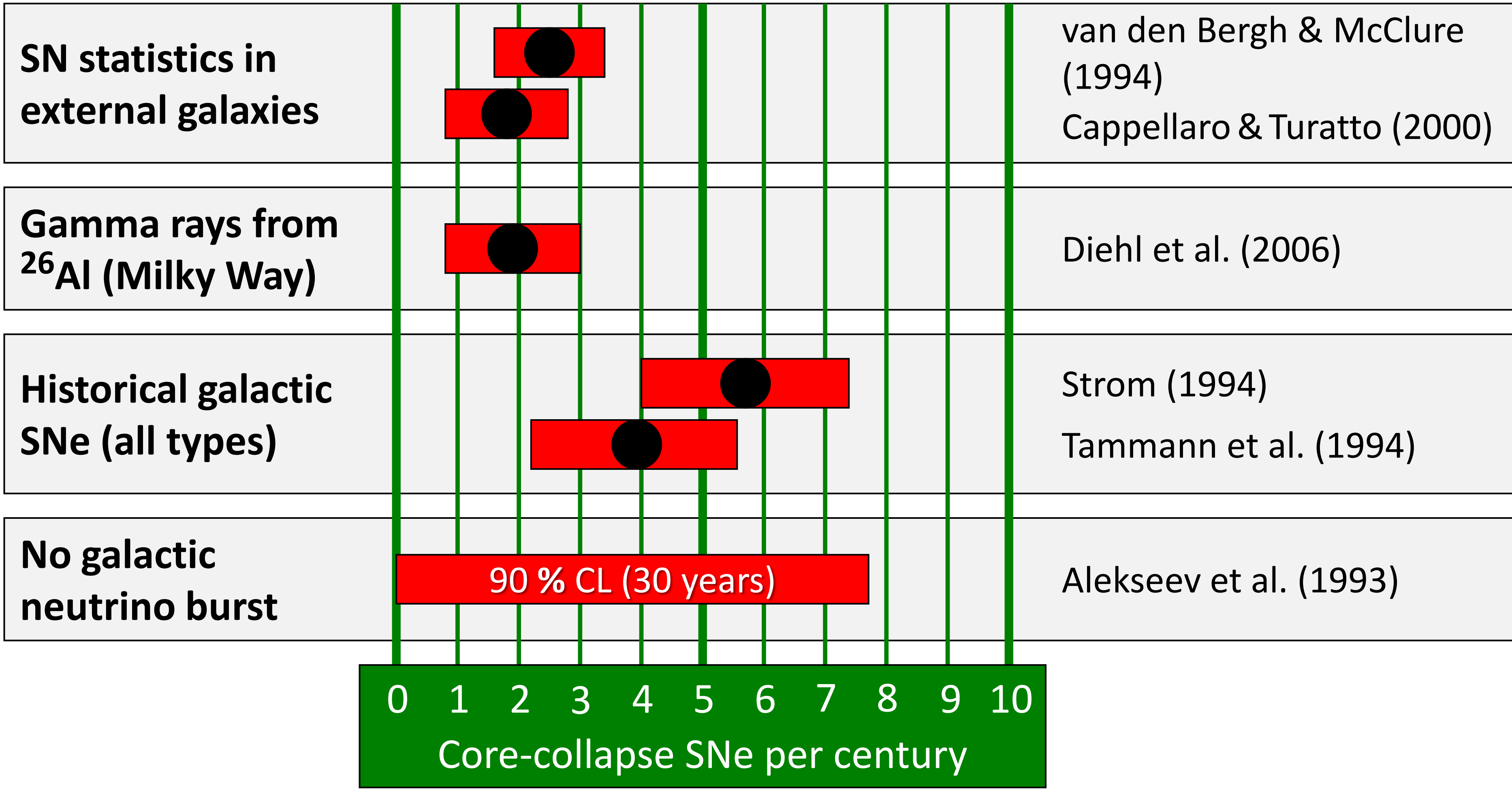
Local Group of Galaxies



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

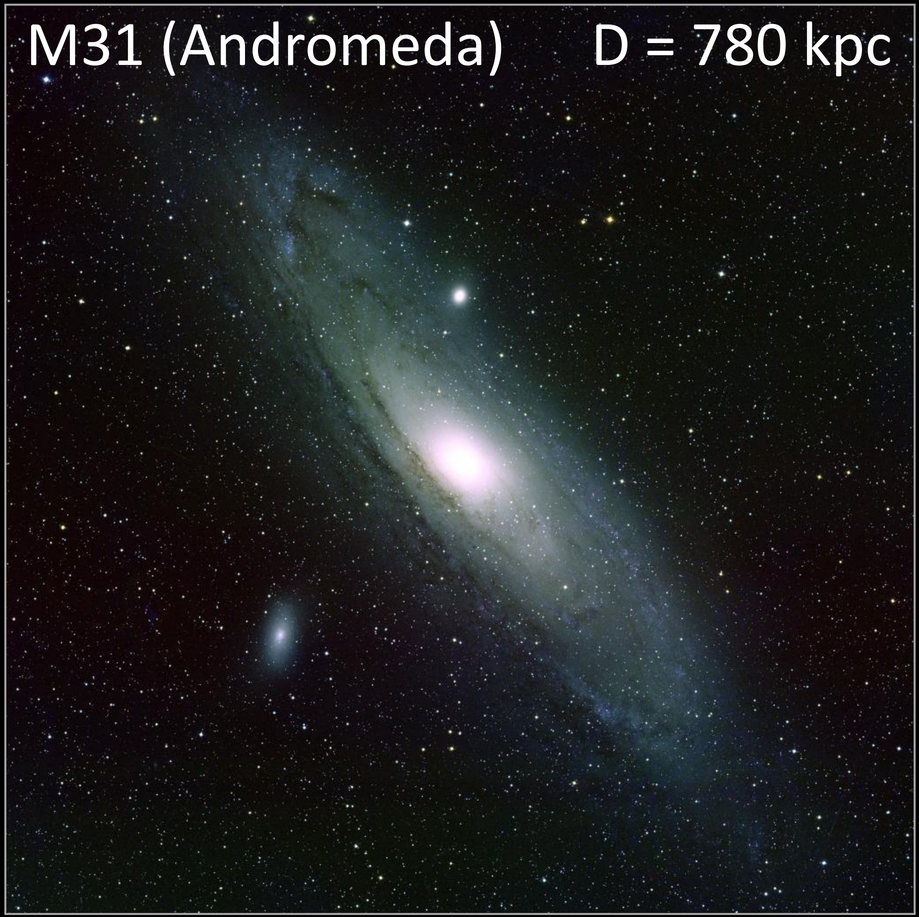
Current best neutrino detectors
sensitive out to few 100 kpc

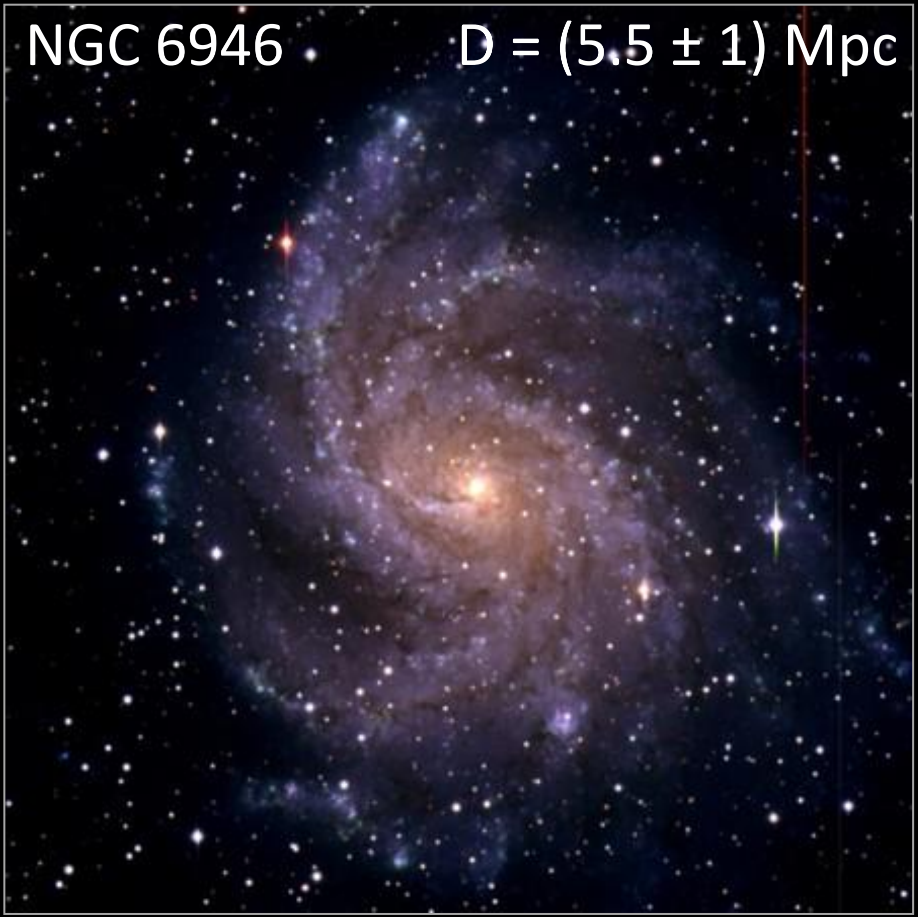
Core-Collapse SN Rate in the Milky Way



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

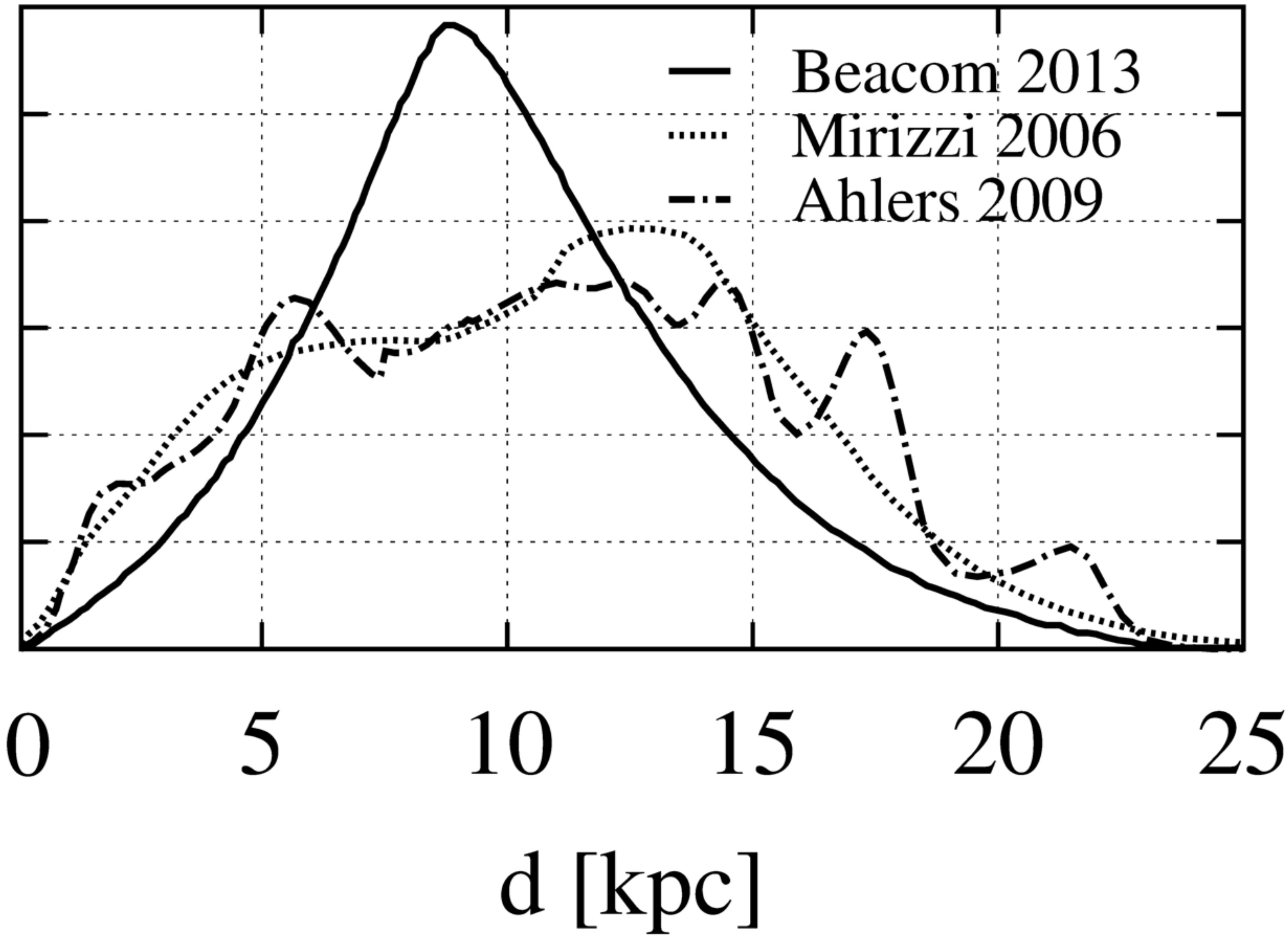




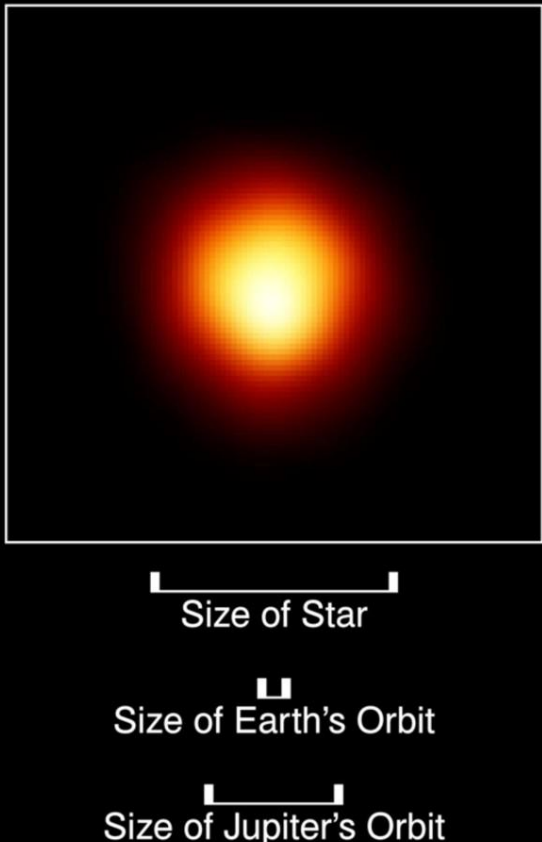
Last Observed Supernova: 1885A

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

Expected Galactic SN Distance Distribution



The Red Supergiant Betelgeuse (Alpha Orionis)



First resolved image of a star other than Sun

Distance (Hipparcos) 130 pc (425 lyr)

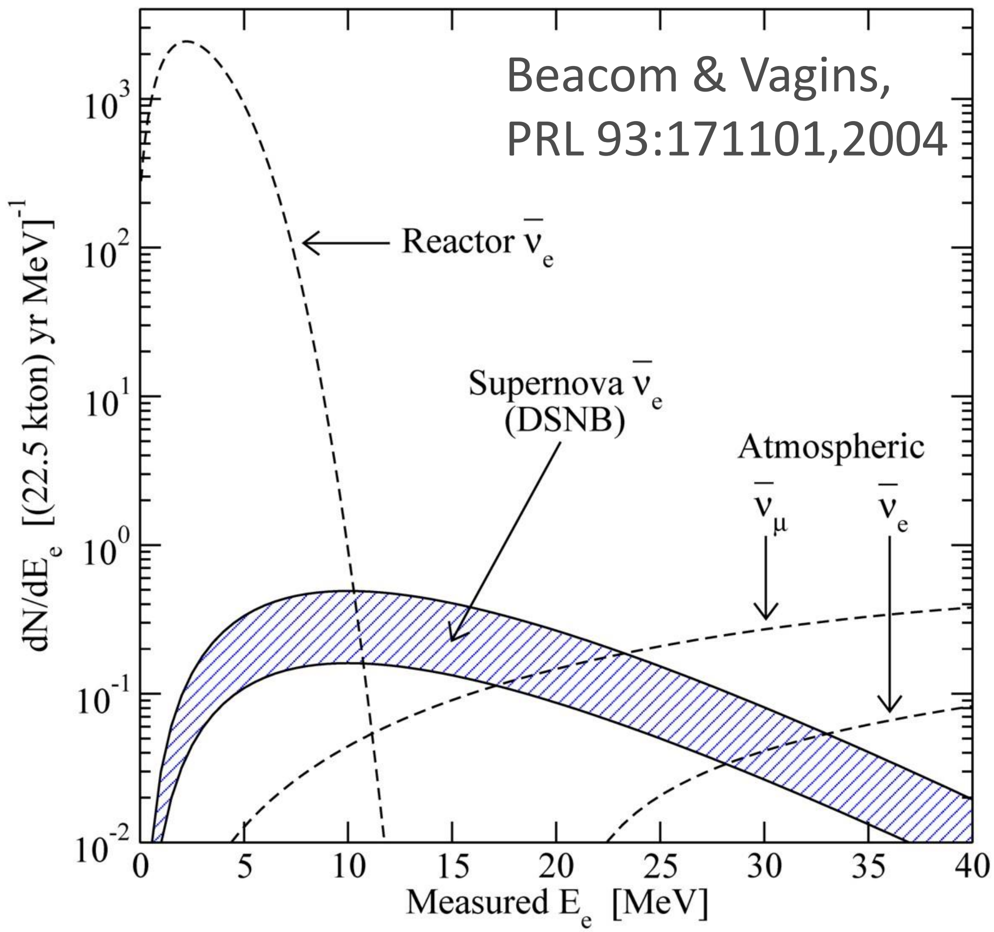
If Betelgeuse goes Supernova:

- 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

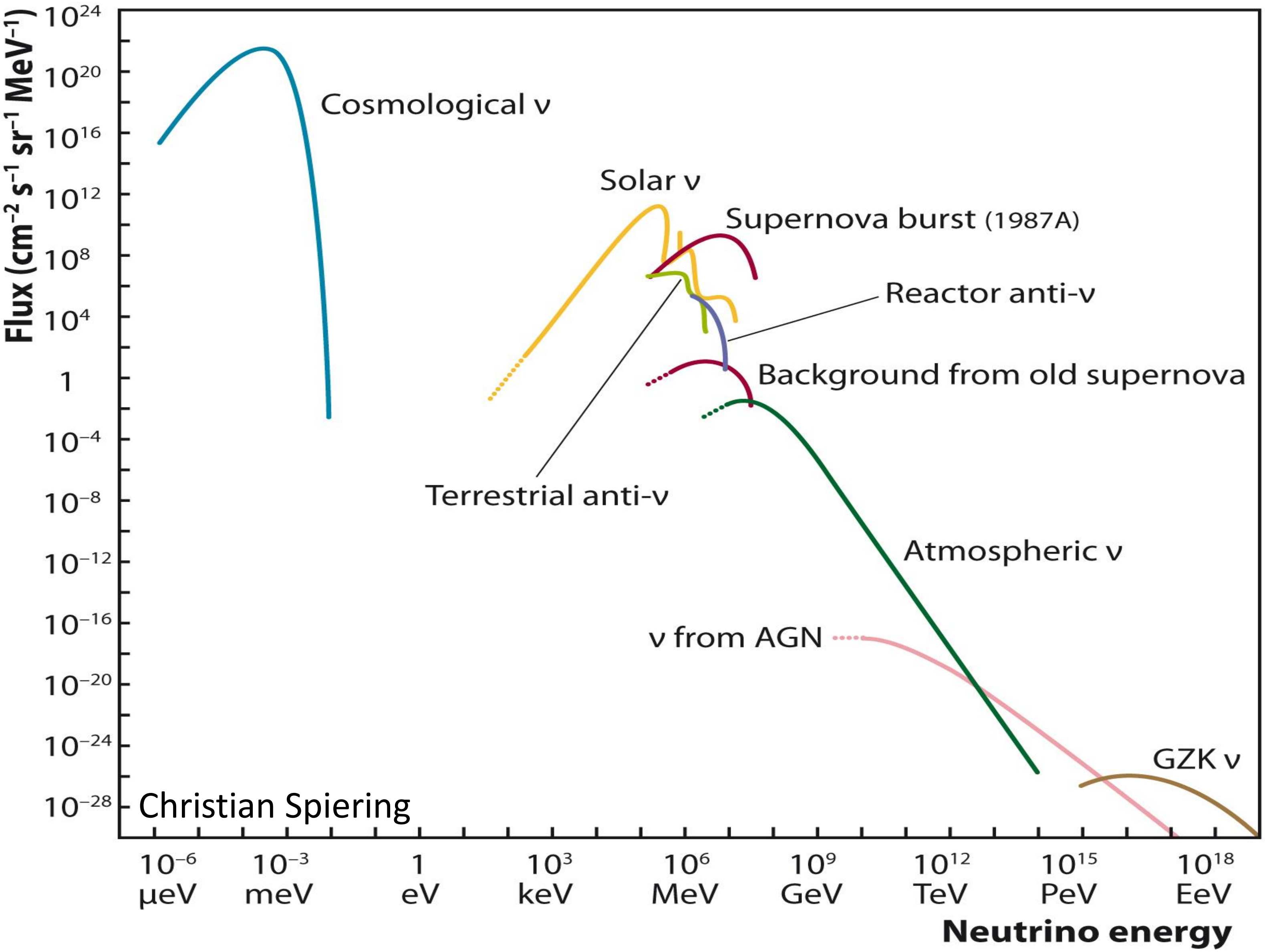
Diffuse Supernova Neutrino Background (DSNB)

- A few core collapses per second 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

Grand Unified Neutrino Spectrum



Realistic DSNB Estimate

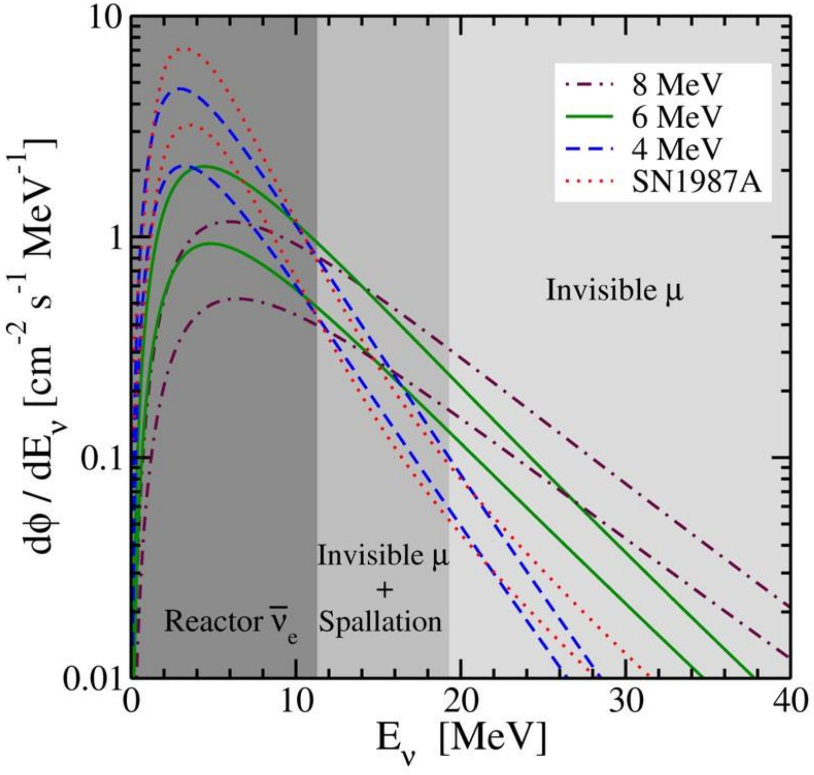


FIG. 4: DSNB flux spectrum for emitted neutrino spectra as labeled. For each spectrum, two curves are plotted representing the full range of uncertainties due to astrophysical inputs (the fiducial prediction lies in between). The shadings indicate backgrounds, with origins as labeled. Decays of invisible 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.

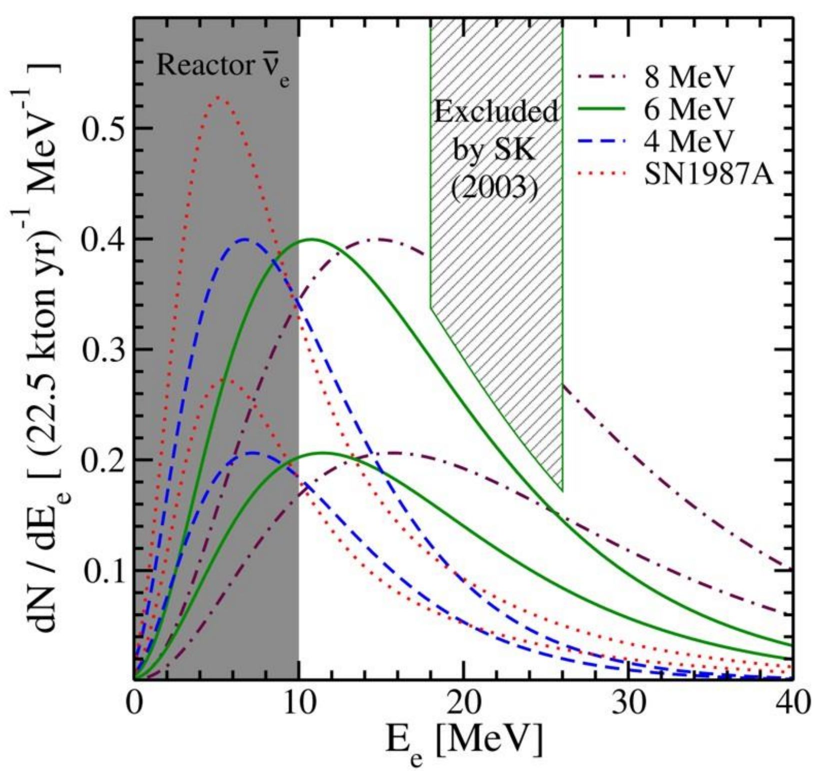


FIG. 5: DSNB event rates at SK (flux spectra weighted with the detection cross section) against positron energy. Note the linear axis. We hatch in the 2003 upper limit by the Super-Kamiokande Collaboration, < 2 events (22.5 kton yr)$^{-1}$ in the energy range 18–26 MeV. The limit applies to all spectra (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

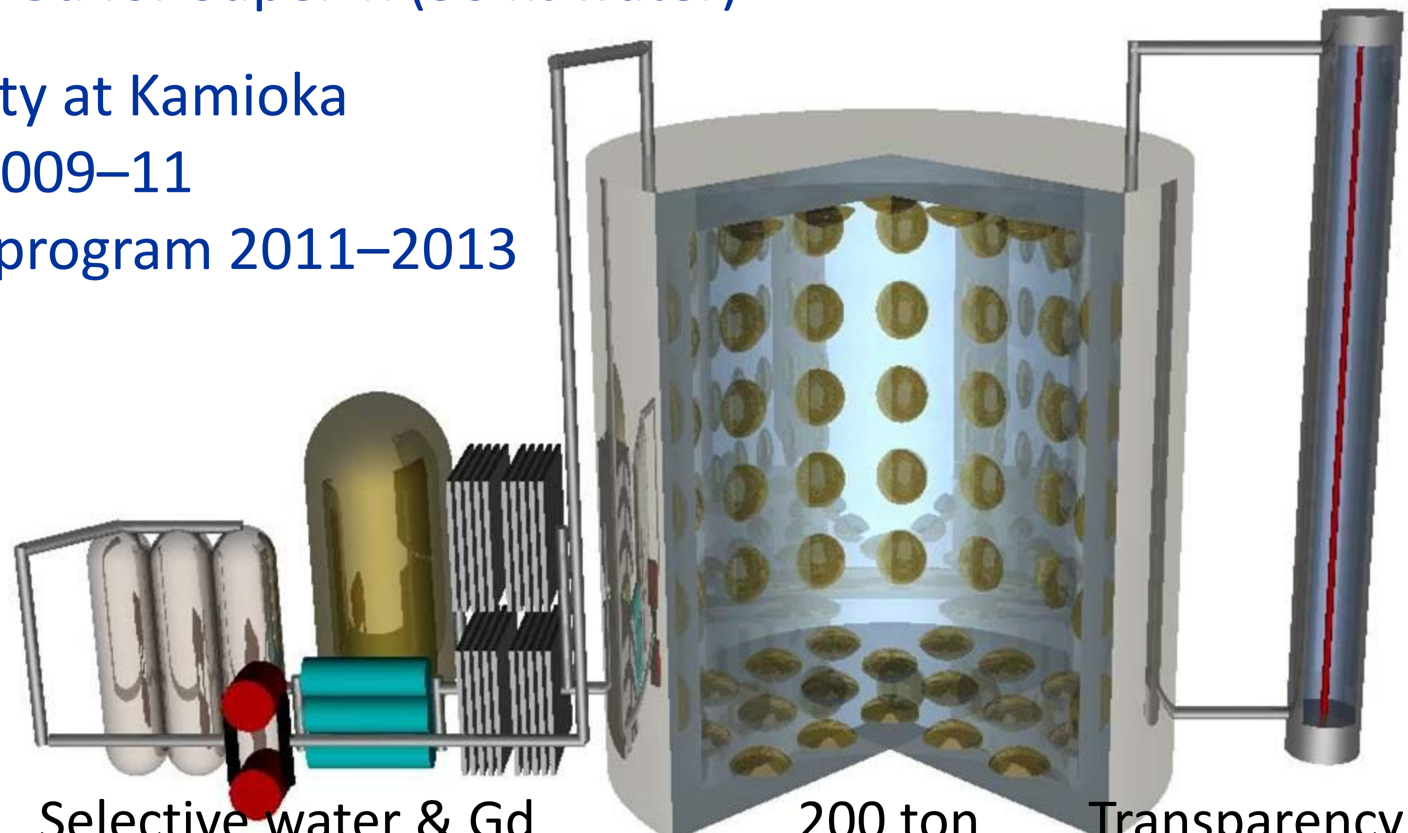
Neutron Tagging in Super-K with Gadolinium

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

- 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



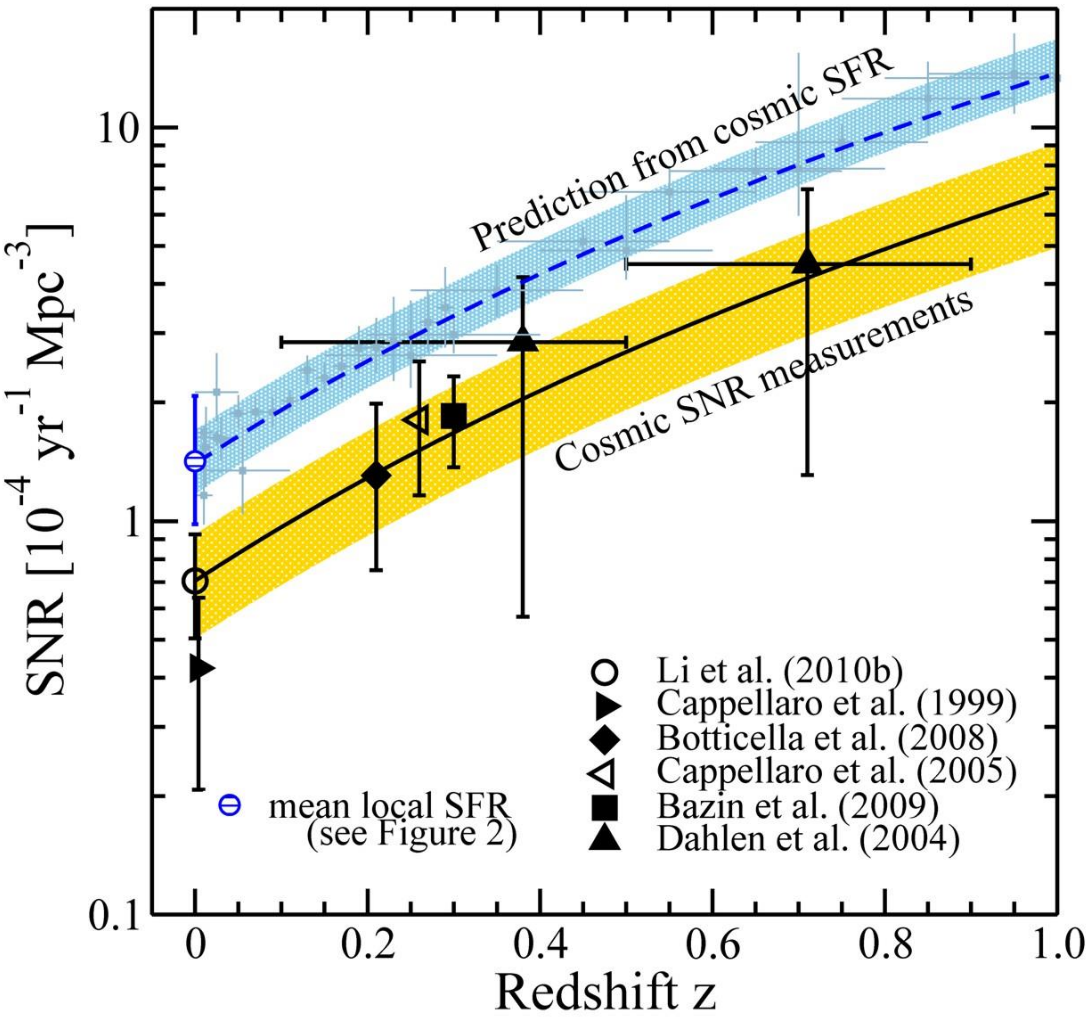
Mark Vagins
Neutrino 2010

Selective water & Gd filtration system

200 ton water tank

Transparency measurement

Supernova 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

Neutrino Flavor Conversion

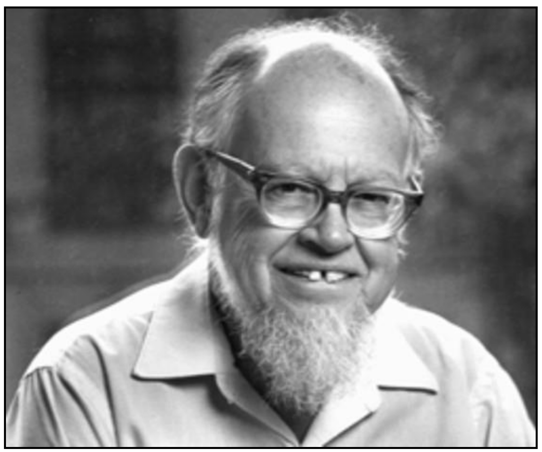
PHYSICAL REVIEW D VOLUME 17, NUMBER 9 1 MAY 1978

3700 citations

Neutrino oscillations in matter

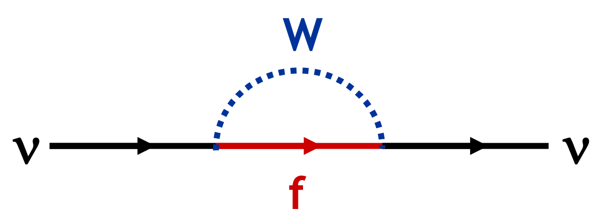
L. Wolfenstein
Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213
(Received 6 October 1977; revised manuscript received 5 December 1977)

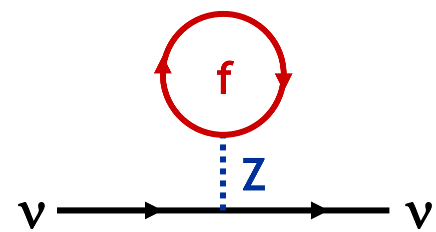
The effect of coherent forward scattering must be taken into account when considering the oscillations of neutrinos traveling through matter. In particular, for the case of massless neutrinos for which vacuum oscillations cannot occur, oscillations can occur in matter if the neutral current has an off-diagonal 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





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

Typical density of Earth: 5 g/cm^3

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

Suppression of Oscillations in Supernova Core

Effective mixing angle in matter

$$\tan 2\theta_{\mathrm{m}} = \frac{\sin 2\theta}{\cos 2\theta - N_e 2E\sqrt{2}G_{\mathrm{F}}/\Delta m^2}$$

Supernova core

$$\rho = 3 \times 10^{14}\ \mathrm{g\,cm^{-3}}$$
$$Y_e = 0.35$$
$$N_e = 6 \times 10^{37}\ \mathrm{cm^{-3}}$$
$$E \sim 100\ \mathrm{MeV}$$

Solar mixing

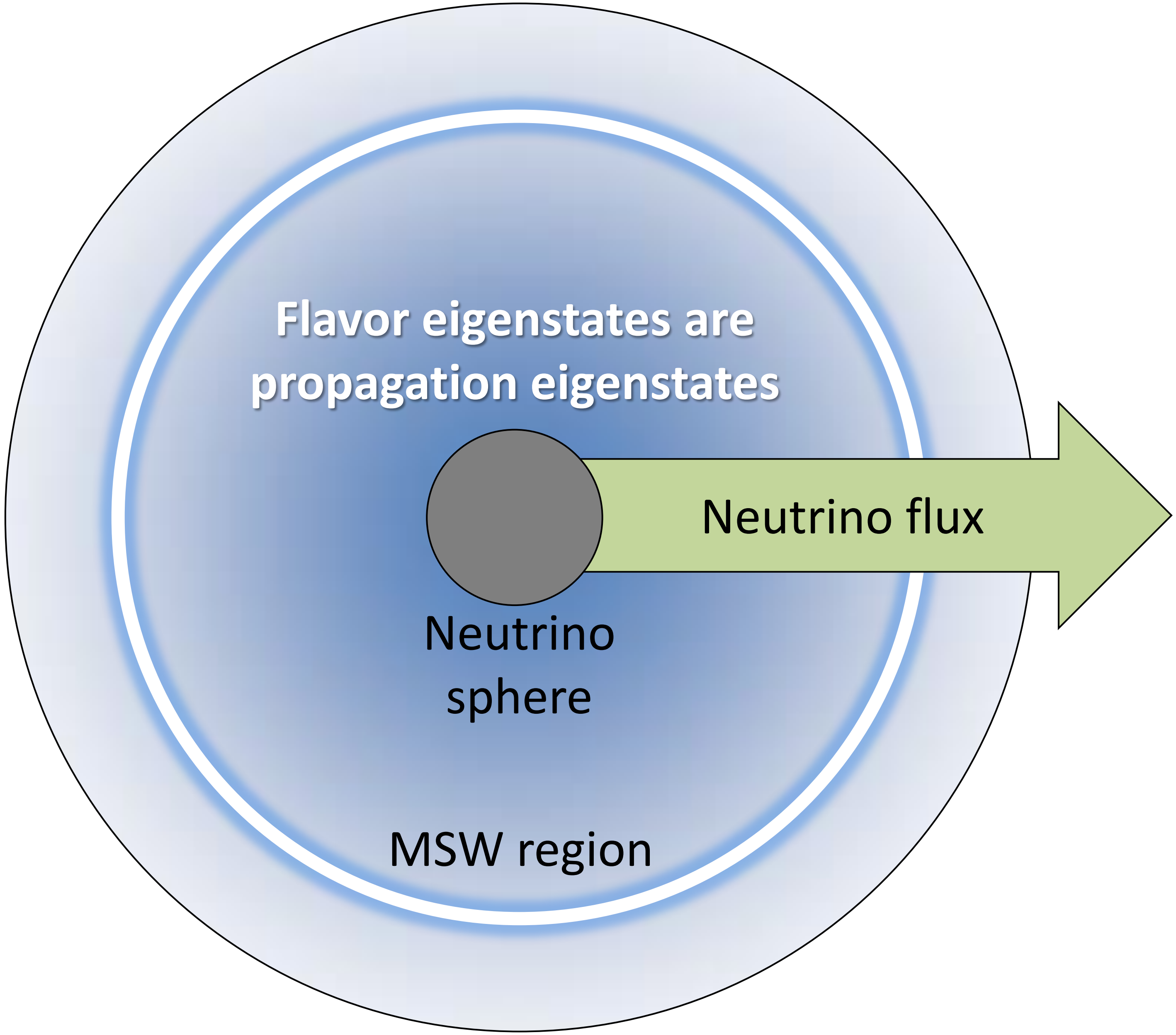
$$\Delta m^2 \sim 75\ \mathrm{meV}^2$$
$$\sin 2\theta \sim 0.94$$

Matter suppression effect

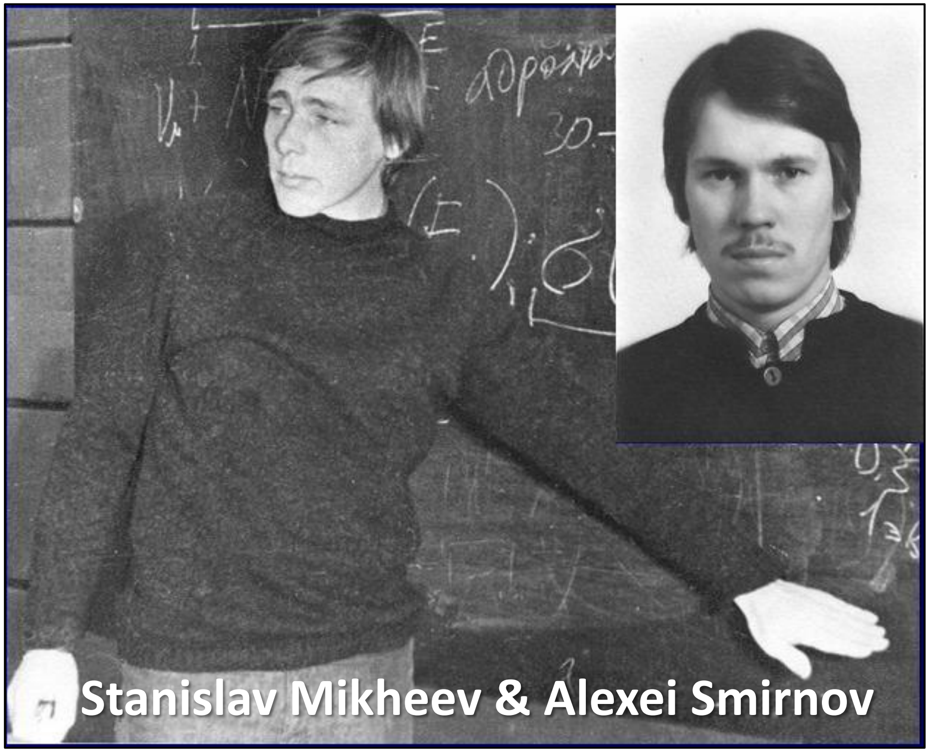
$$N_e 2E\sqrt{2}G_F/\Delta m^2 \sim 2 \times 10^{13}$$

- Inside a SN core, flavors are “de-mixed”
- Very small oscillation amplitude
- Trapped e-lepton number can only escape by diffusion

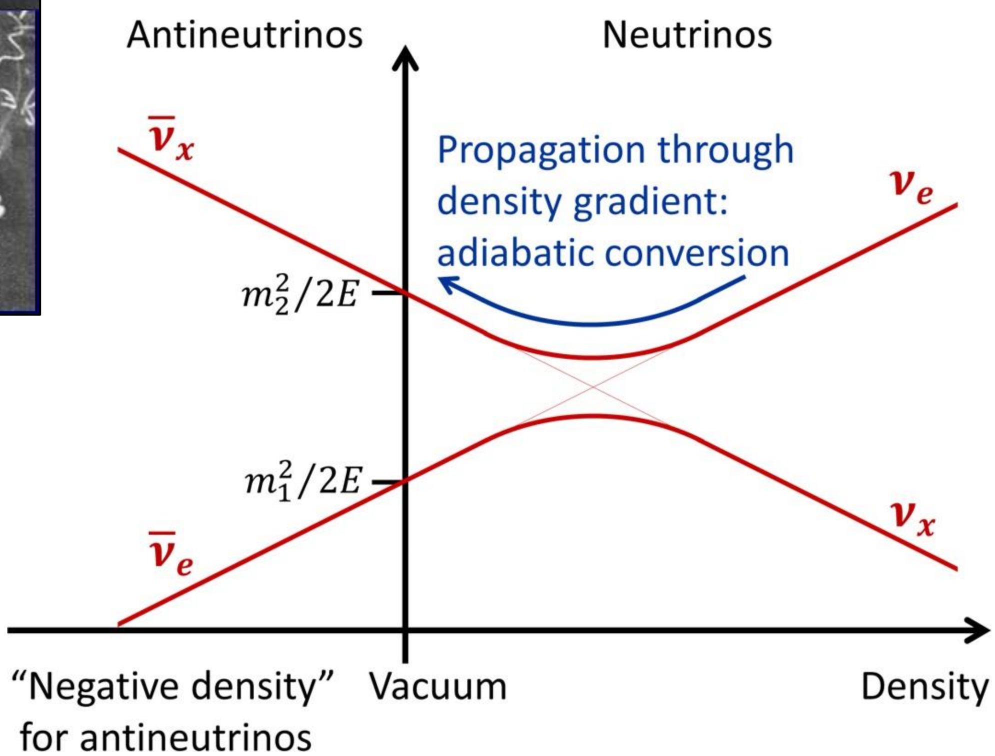
Flavor Oscillations in Core-Collapse Supernovae



Mikheev-Smirnov-Wolfenstein (MSW) effect

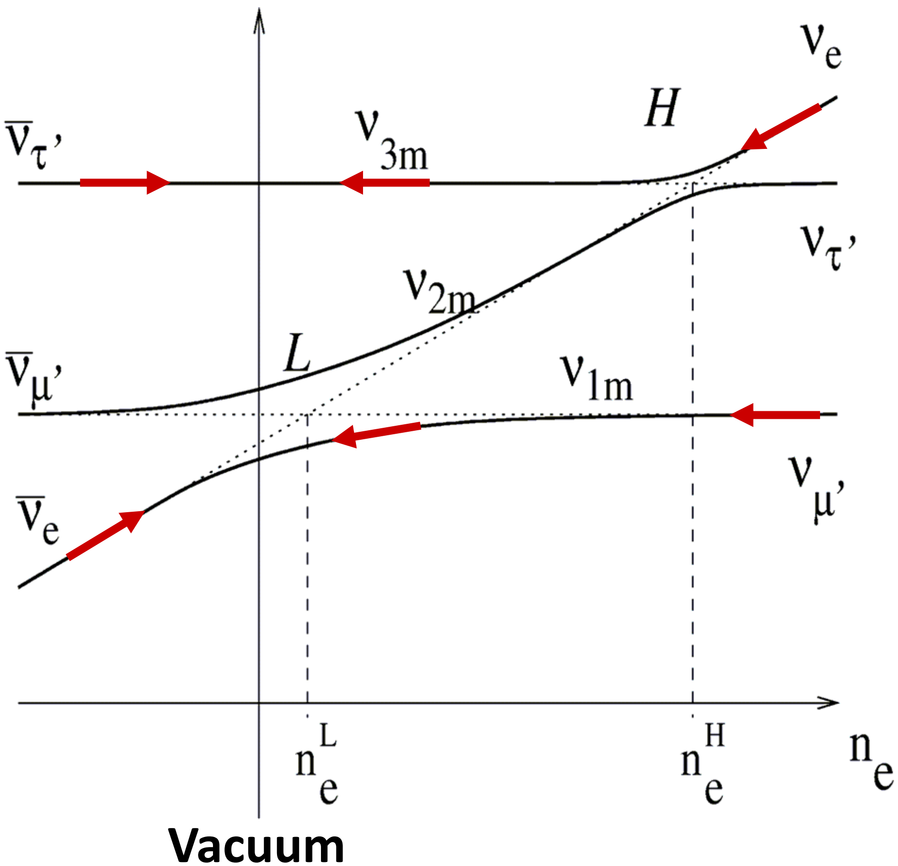


Eigenvalues of Hamiltonian for 2-flavor mixing

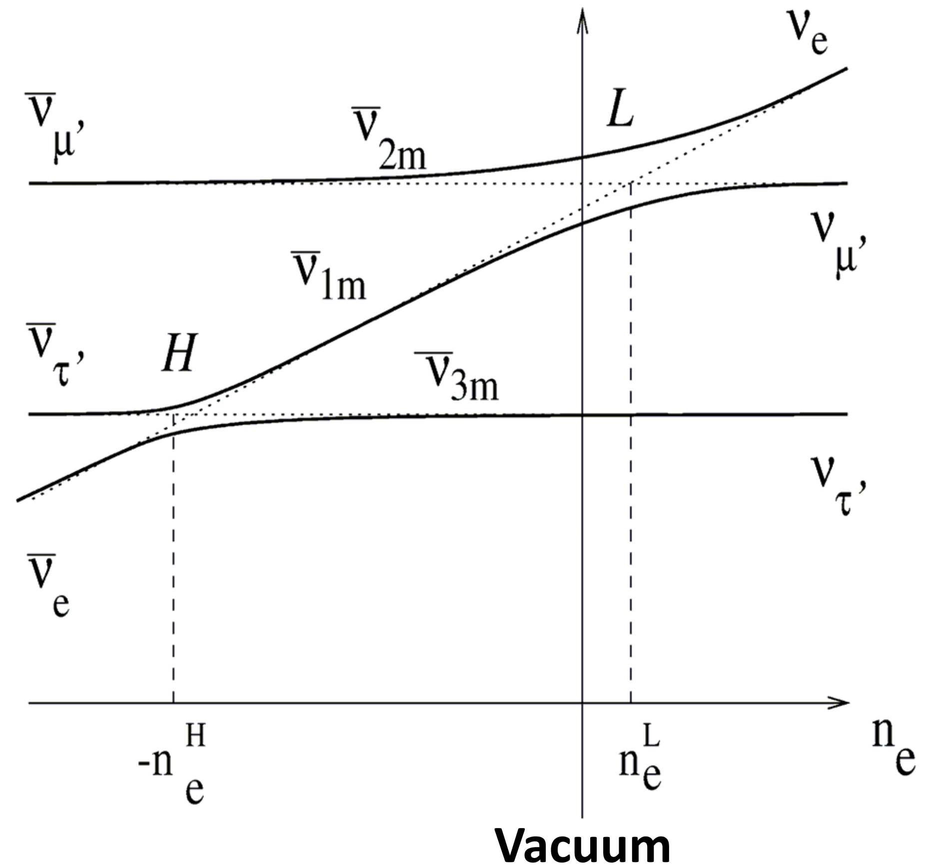


Three-Flavor Eigenvalue Diagram

Normal mass ordering (NH)



Inverted mass ordering (IH)



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

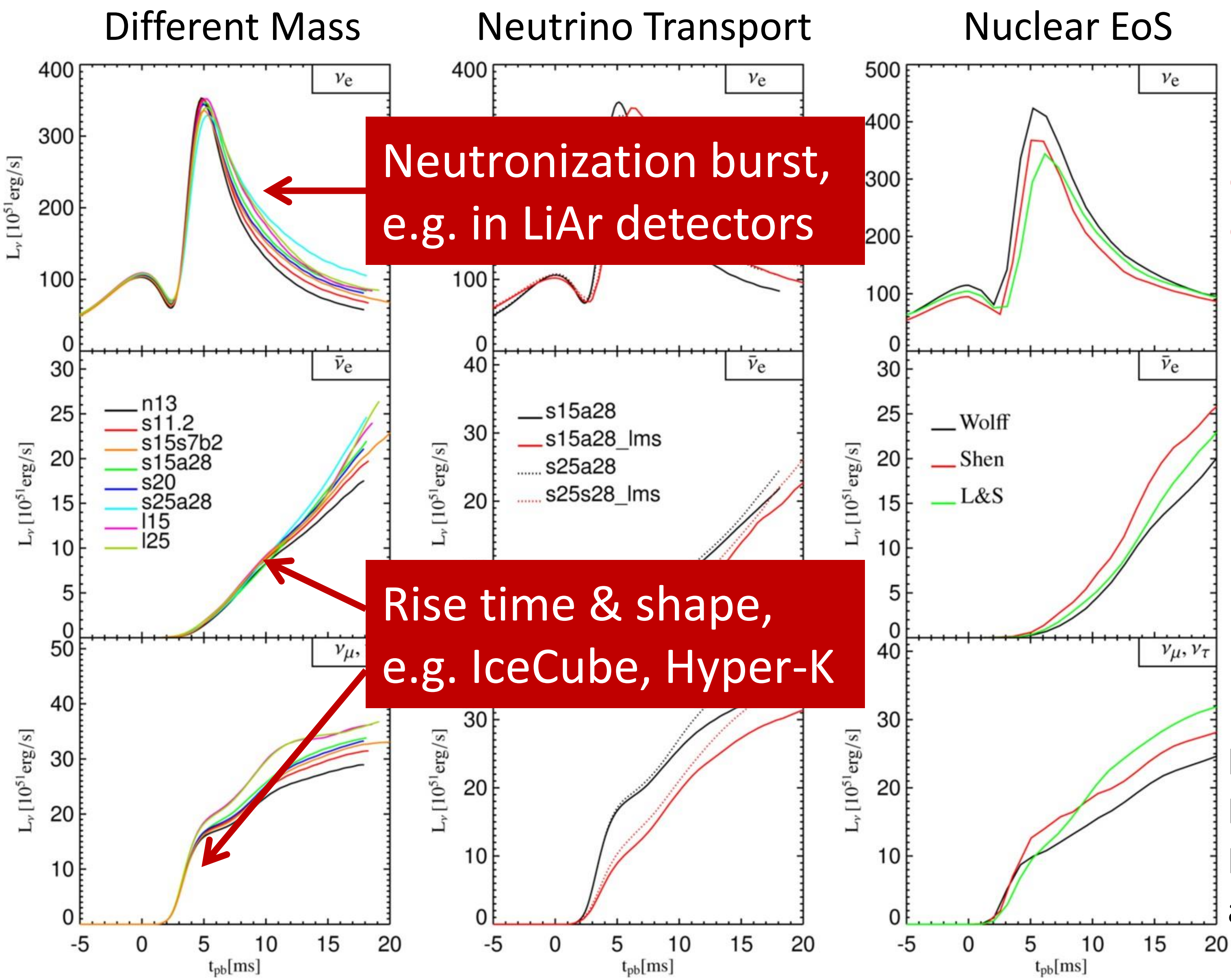
SN Flavor Oscillations and Mass Hierarchy

- 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



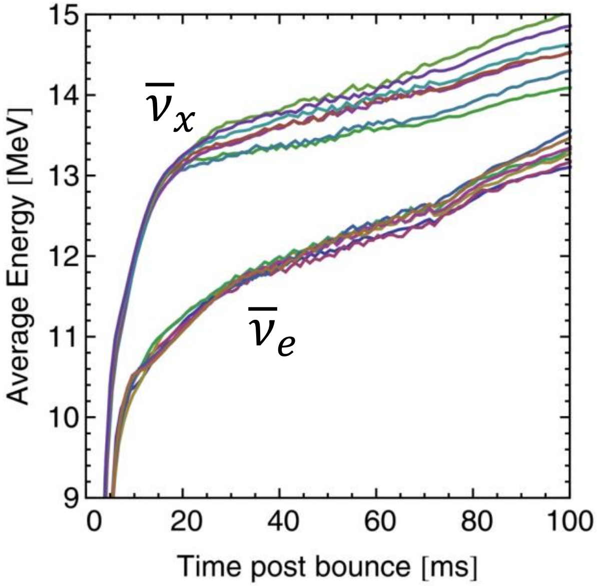
If mixing scenario is known, can determine SN distance (better than 5-10%)

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

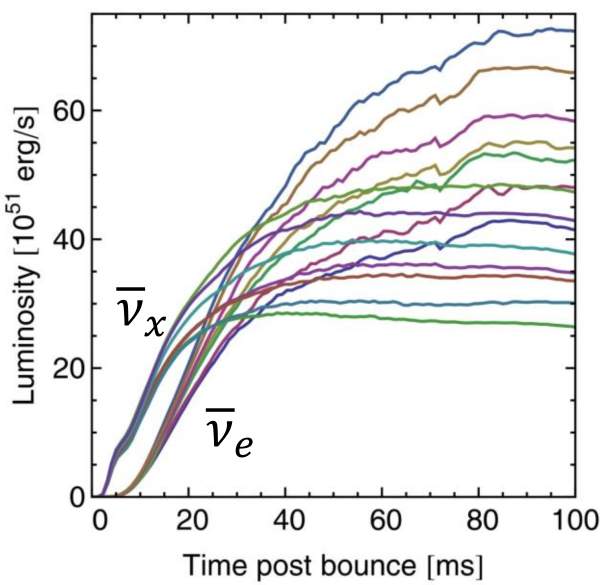
Early Phase Signal in Anti-Neutrino Sector

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

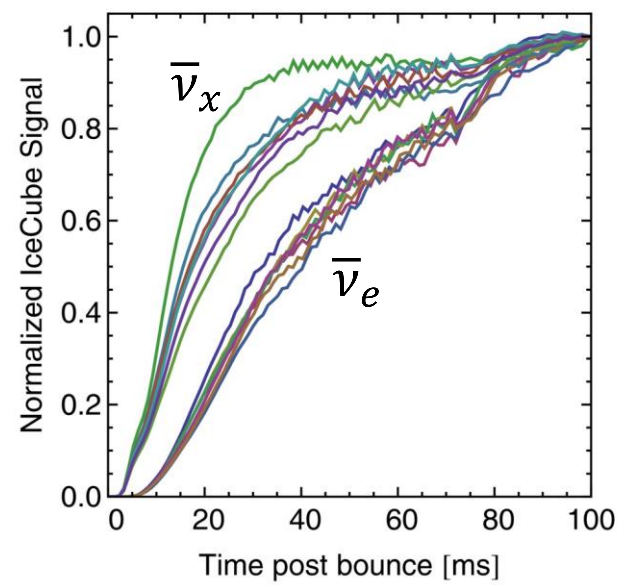
Average Energy



Luminosity



IceCube Signature

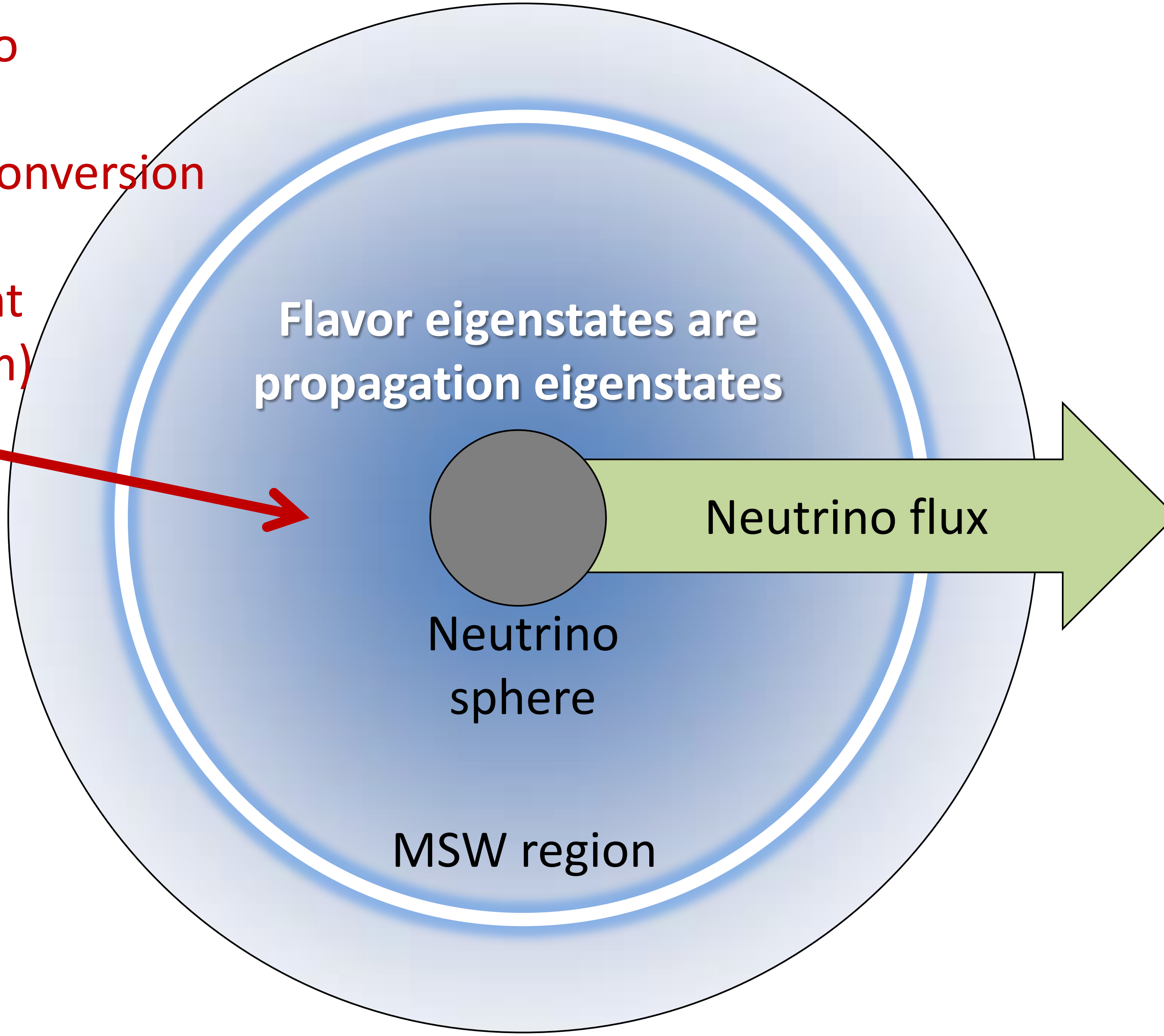


- In principle very sensitive to hierarchy, notably IceCube
- "Standard candle" to be confirmed beyond Garching models

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)

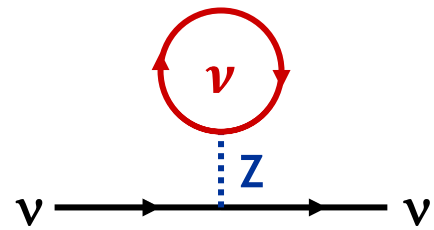


Many theoretical challenges remain to be resolved!

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!

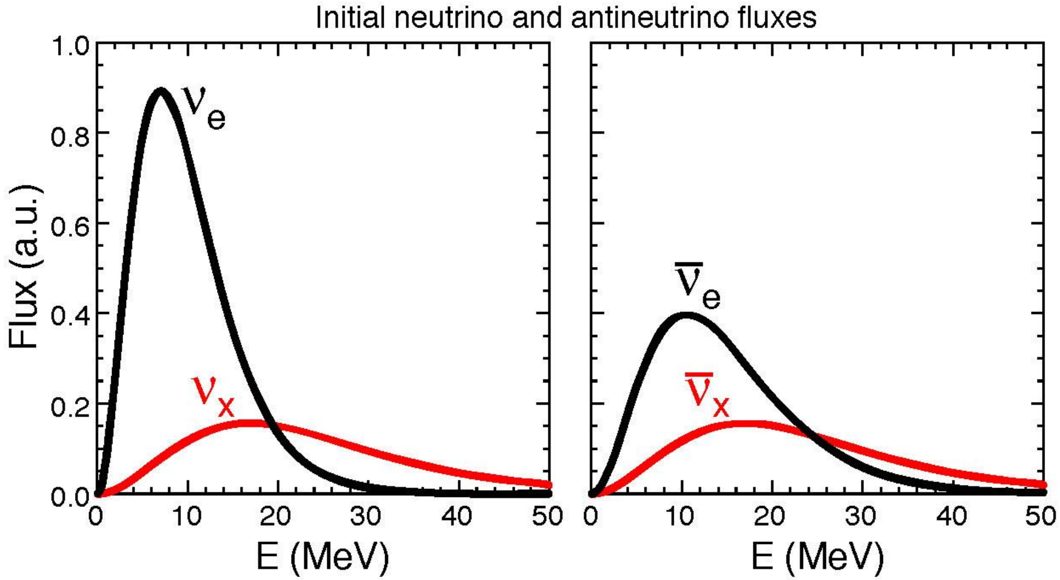
Collective Supernova Nu Oscillations since 2006

Two seminal papers in 2006 triggered a torrent of activities
Duan, Fuller, Qian, astro-ph/0511275, Duan et al. astro-ph/0606616

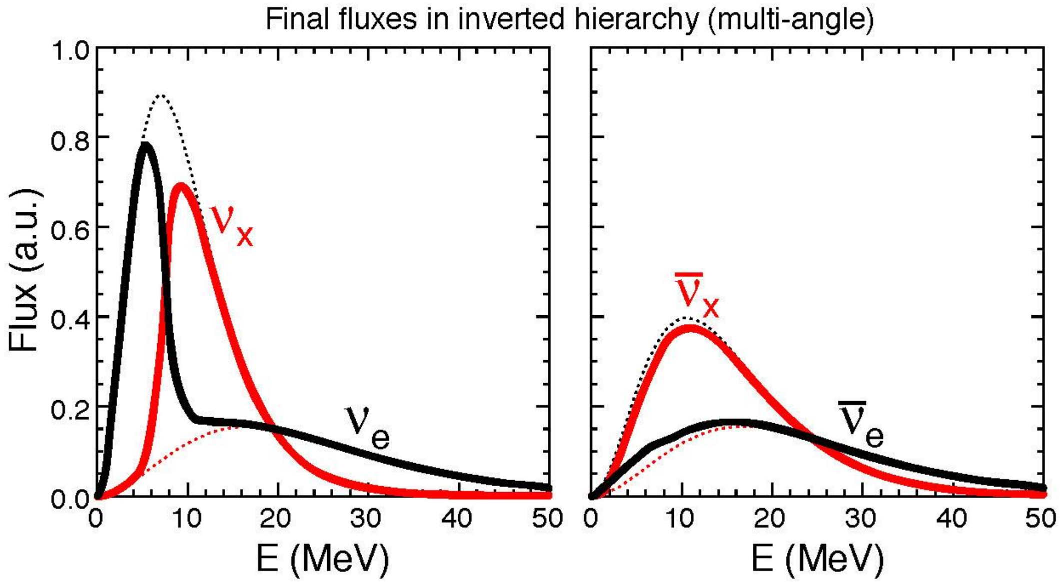
Balantekin, Gava & Volpe [0710.3112]. Balantekin & Pehlivan [astro-ph/0607527]. Blennow, Mirizzi & Serpico [0810.2297]. Cherry, Fuller, Carlson, Duan & Qian [1006.2175, 1108.4064]. Cherry, Wu, Fuller, Carlson, Duan & Qian [1109.5195]. Cherry, Carlson, Friedland, Fuller & Vlasenko [1203.1607]. Chakraborty, 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].

Spectral Split

Initial fluxes at neutrino sphere



After collective trans-formation



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

Multi-Angle Matter Effect

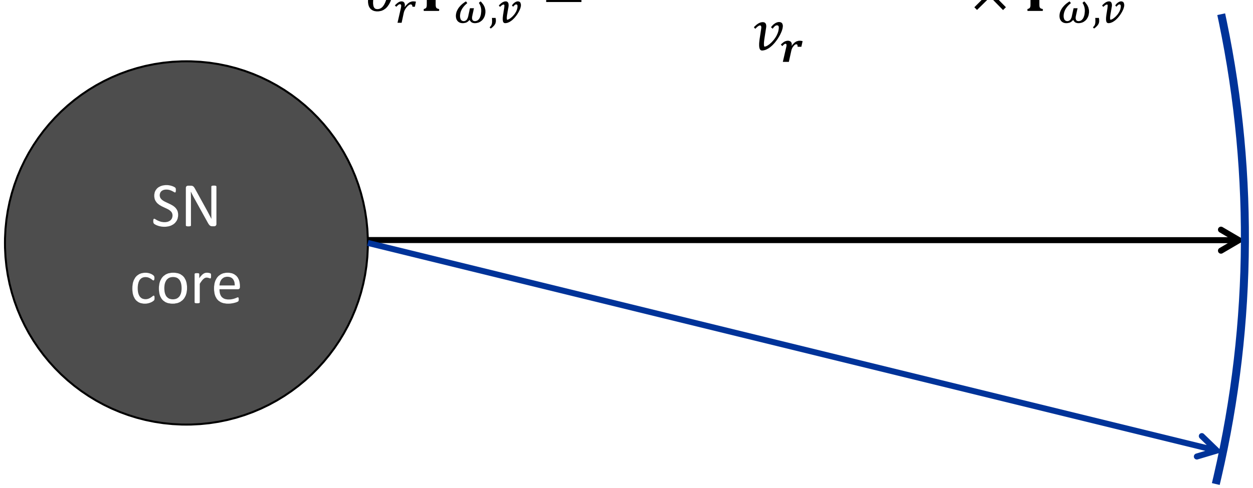
Liouville form of oscillation equation

$$\dot{\mathbf{P}}_{\omega,\mathbf{v}} + (\mathbf{v}\cdot\nabla_r)\,\mathbf{P}_{\omega,\mathbf{v}} = (\omega\mathbf{B} + \lambda\mathbf{L} + \mu\mathbf{P}) \times \mathbf{P}_{\omega,\mathbf{v}}$$

Drops out for stationary solutions

$\lambda = \sqrt{2}G_{\mathrm{F}}N_e$ $\quad\mu = \sqrt{2}G_{\mathrm{F}}N_\nu$

$$\partial_r \mathbf{P}_{\omega,v} = \frac{\omega\mathbf{B} + \lambda\mathbf{L} + \mu\mathbf{P}}{v_r} \times \mathbf{P}_{\omega,v}$$

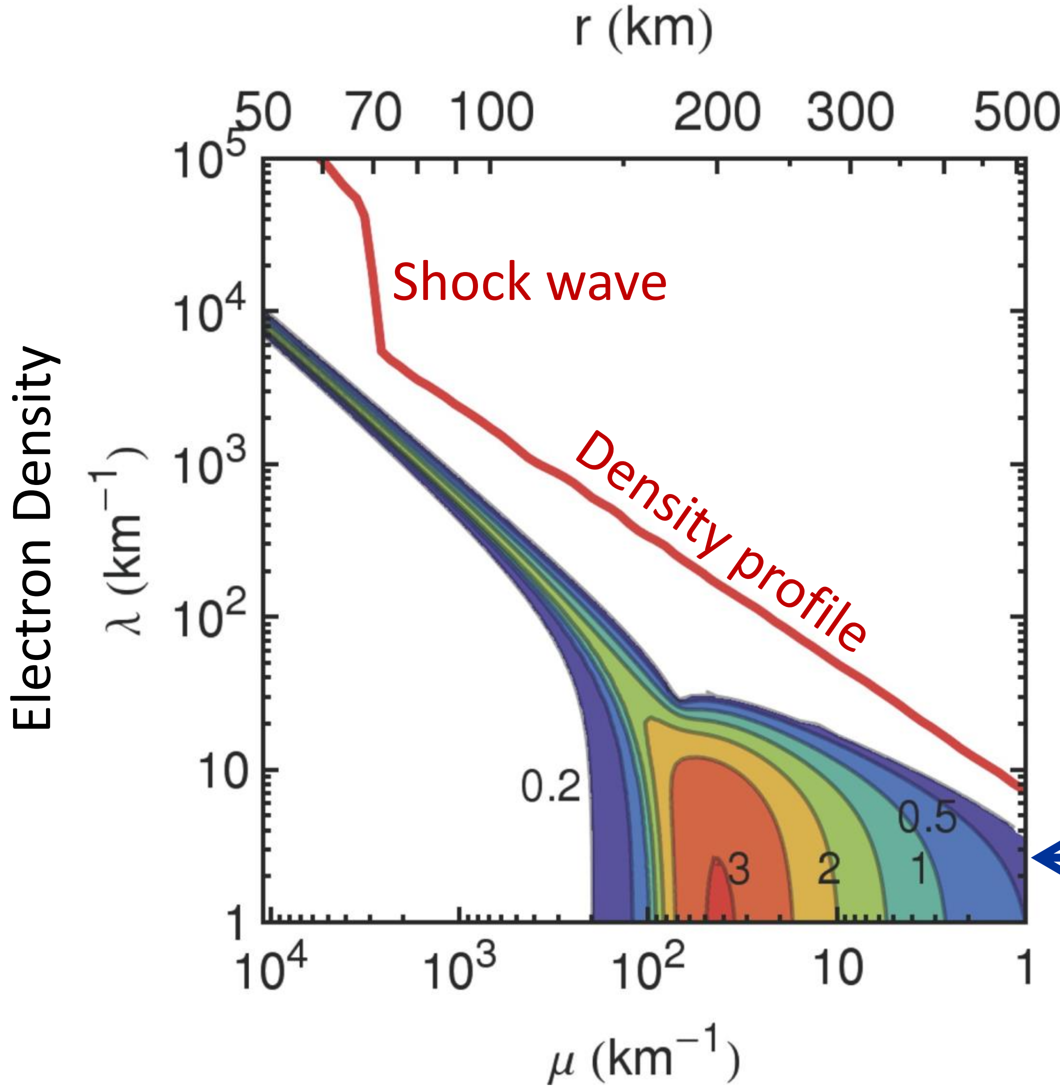


Longer path to same radial distance: Larger matter effect

Self-induced conversion suppressed for $N_e \gtrsim N_\nu$

Esteban-Pretel, Mirizzi, Pastor, Tomàs, Raffelt, Serpico & Sigl, arXiv:0807.0659

Multi-Angle Multi-Energy Stability Analysis

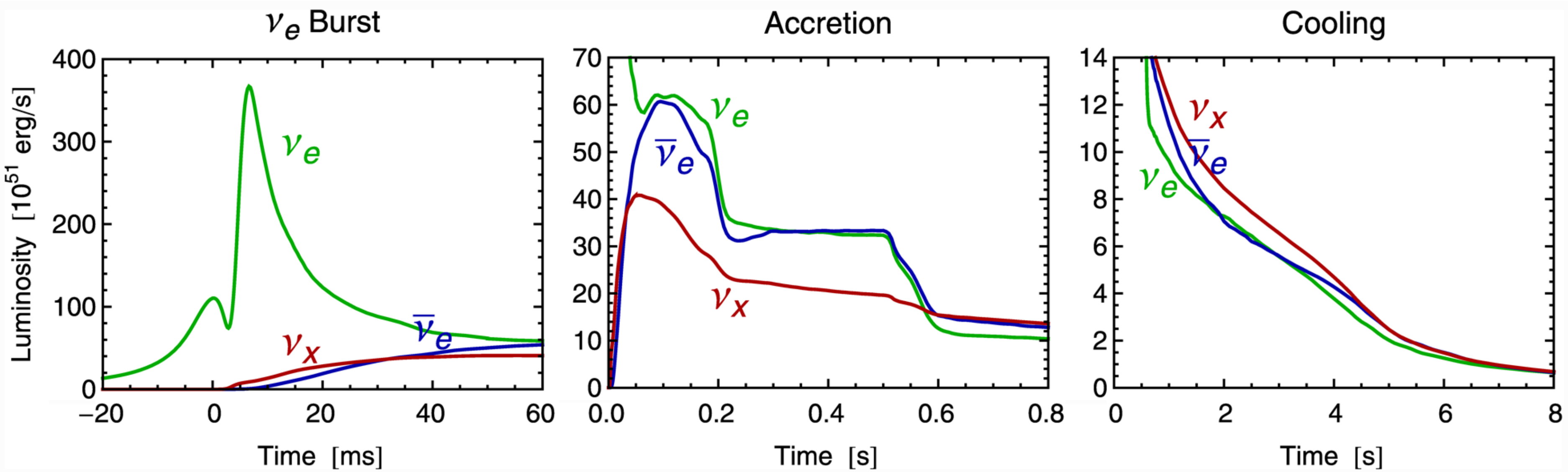


Tested 15 $M_\odot$ accretion-phase models (Garching) are stable against collective flavor conversion

Contours of growth rate κ [km^{-1}]

Sarikas, Raffelt, Hüdepohl & Janka, arXiv:1109.3601

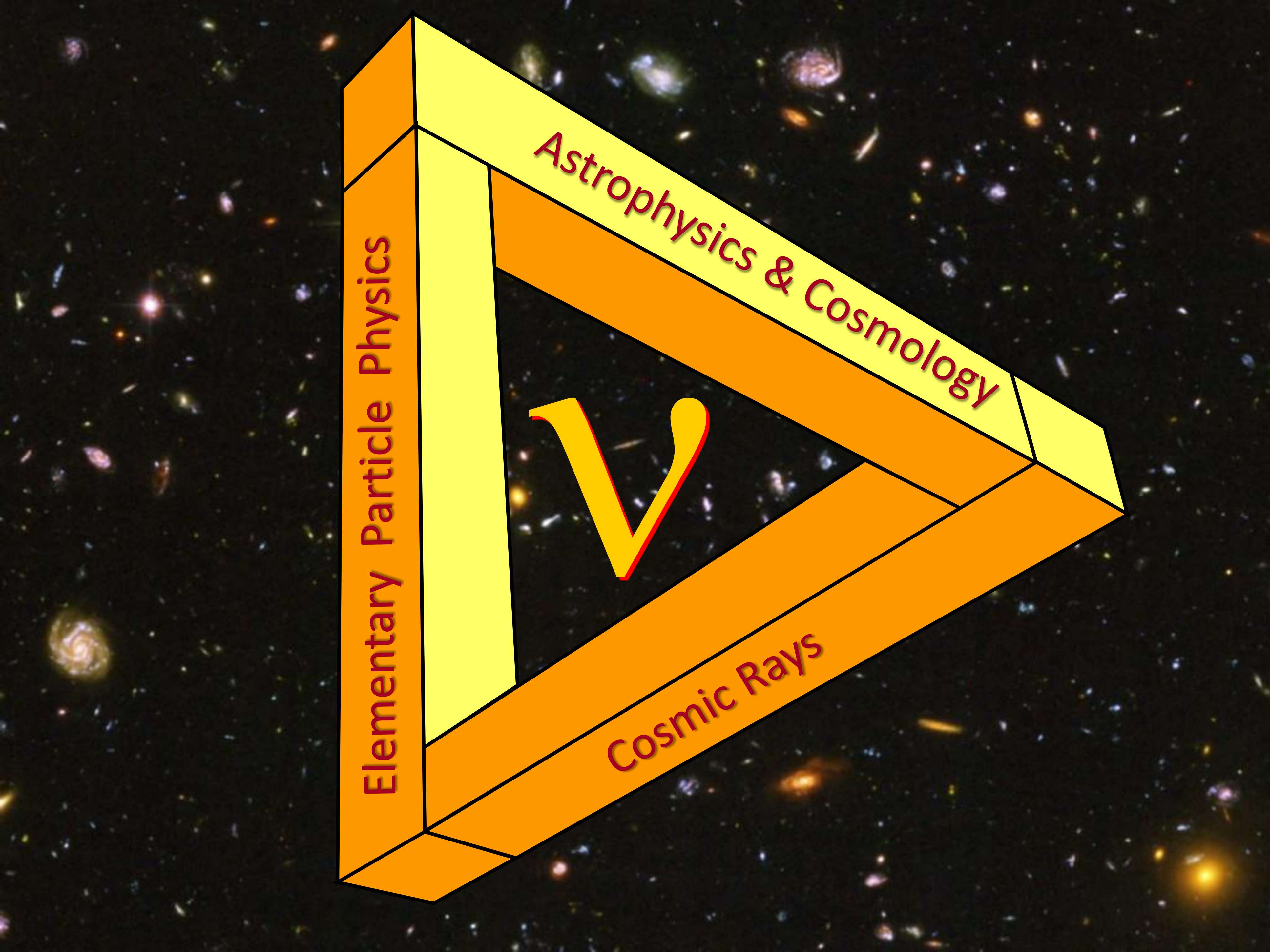
Three Phases – Three Opportunities



Standard Candle (?)
- SN theory
- Distance
- Flavor conversions
- Multi-messenger time of flight

Strong variations (progenitor, 3D effects, black hole formation, …)
- Testing astrophysics of core collapse
- Flavor conversion has strong impact on signal

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


Astrophysics & Cosmology
Elementary Particle Physics
Cosmic Rays
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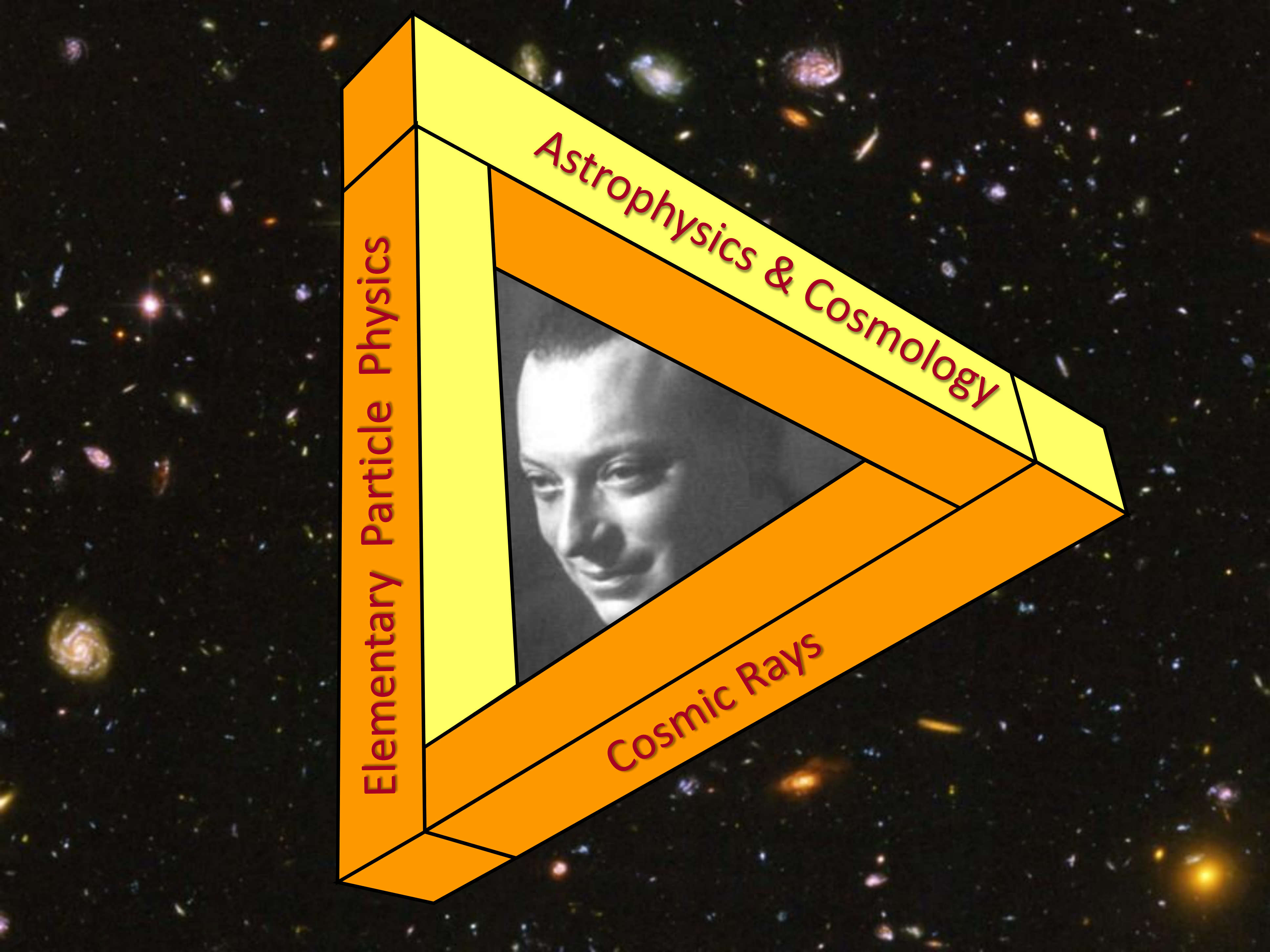

Astrophysics & Cosmology
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