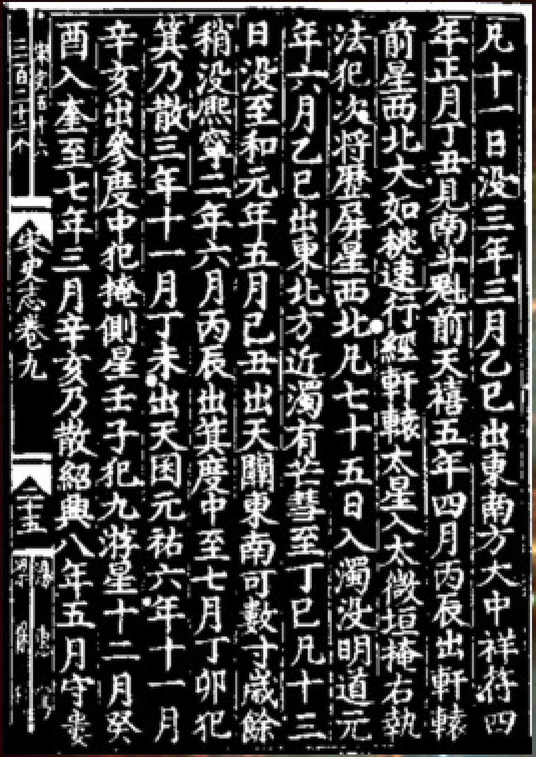
Neutrinos in Cosmology, Astro, Particle & Nuclear Physics

16–24 September 2009, Erice, Sicily



見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
法犯次將歷屏星西北凡七十五日入濁沒明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日沒至和元年五月己丑出天關東南可數寸歲餘
稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九游星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁

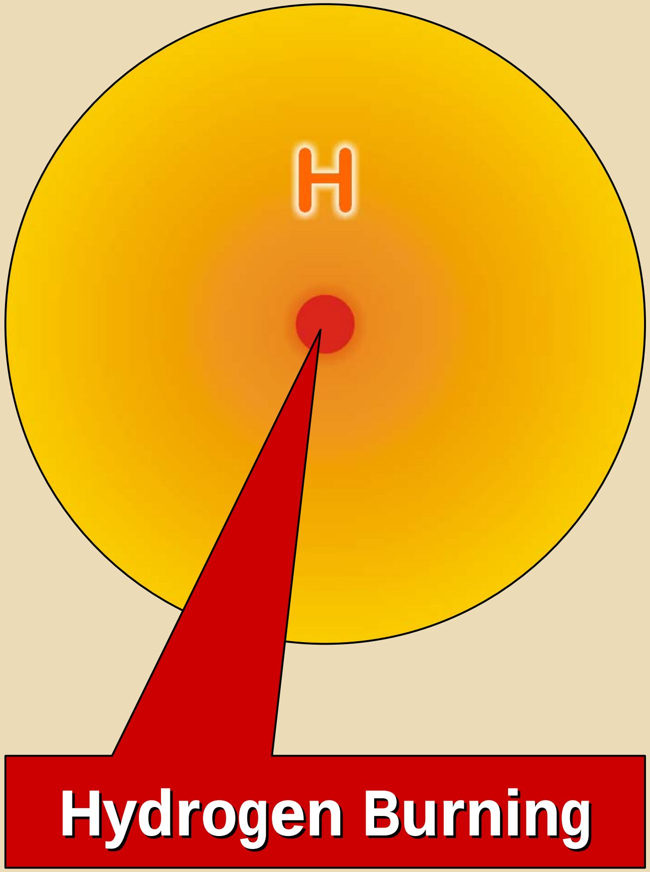
宋史志卷九

Physics Opportunities with
Supernova Neutrinos

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

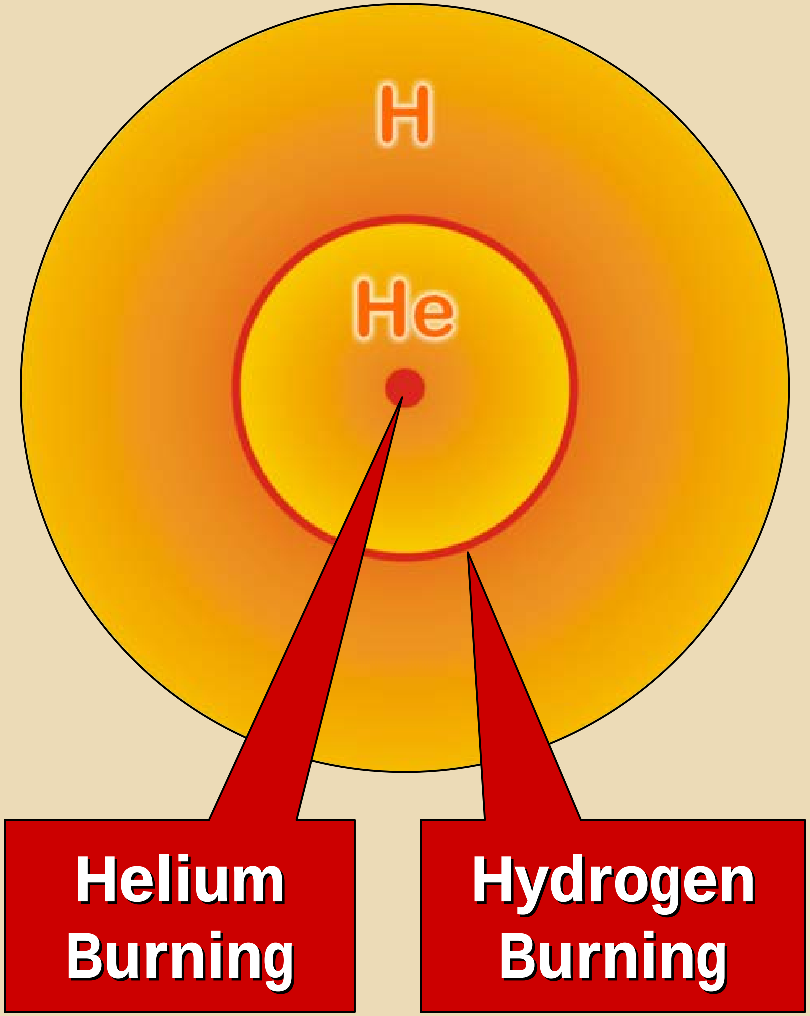
Stellar Collapse and Supernova Explosion

Main-sequence star



Hydrogen Burning

Helium-burning star



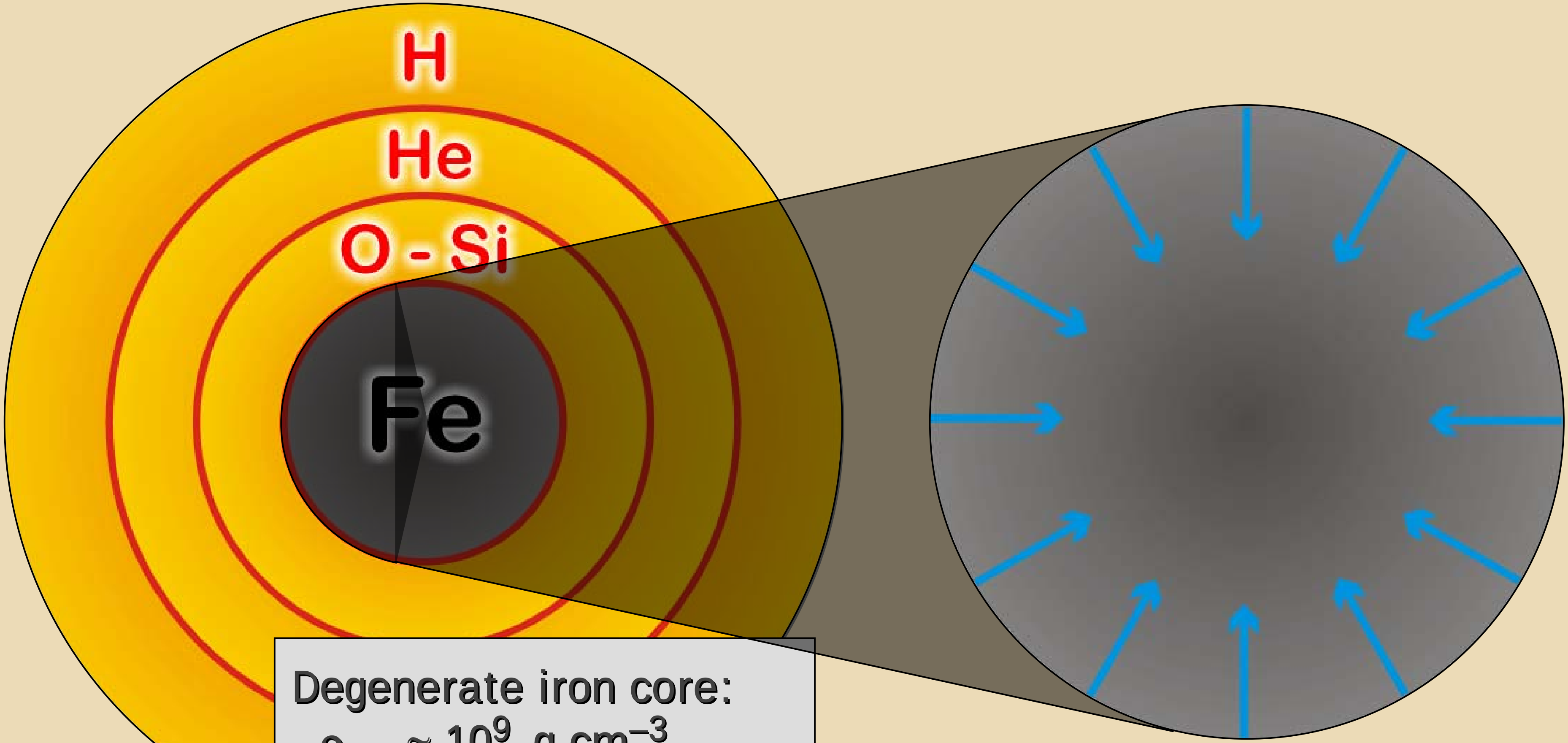
Helium Burning

Hydrogen Burning

Stellar Collapse and Supernova Explosion

Onion structure

Collapse (implosion)



Degenerate iron core:

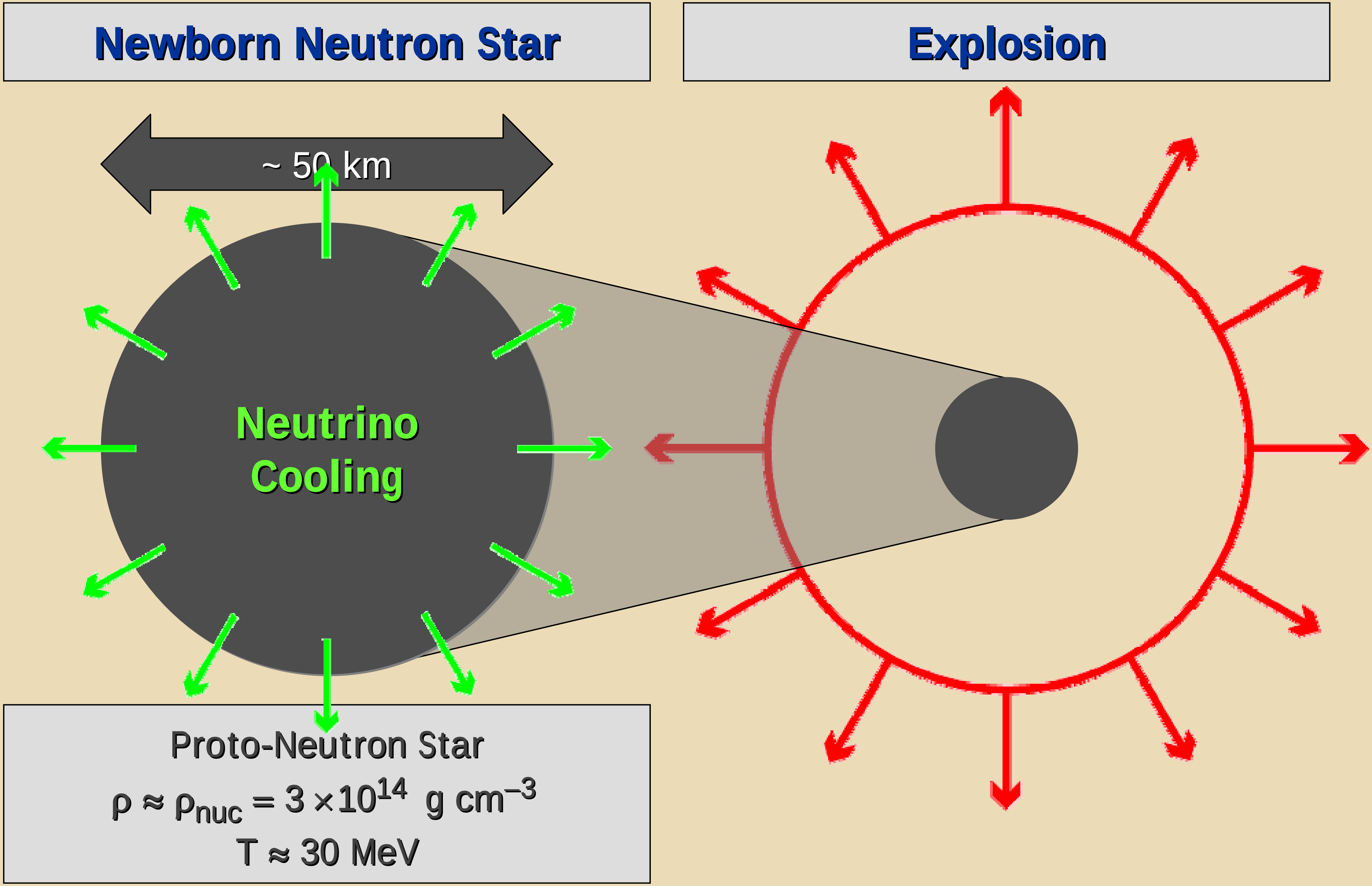
$\rho \approx 10^{9}$ g cm^{-3}

$T \approx 10^{10}$ K

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

$R_{Fe} \approx 8000$ km

Stellar Collapse and Supernova Explosion



Newborn Neutron Star

Explosion

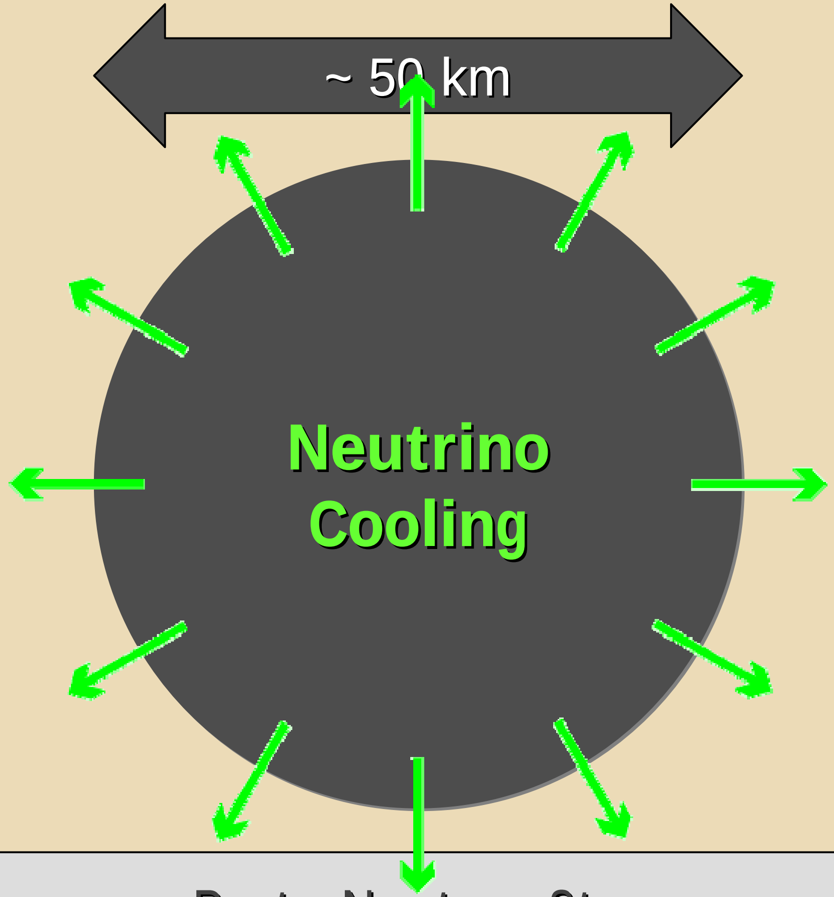
Proto-Neutron Star

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

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

Stellar Collapse and Supernova Explosion

Newborn Neutron Star



Proto-Neutron Star

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

$T \approx 30$ 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

Diffuse Supernova Neutrino Background (DSNB)

Supernova rate approximately

1 SN / 10^{10} $L_{\mathrm{Sun,B}}$ / 100 years

$L_{\mathrm{sun,B}} = 0.54\, L_{\mathrm{sun}} = 2 \times 10^{33}$ erg/s

$E_\nu \sim 3 \times 10^{53}$ erg per core-collapse

Core-collapse neutrino luminosity of typical galaxy comparable to photon luminosity (from nuclear burning)

Core-collapse rate somewhat larger in the past. Estimated present-day $\bar\nu_e$ flux ~ 10 $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

Pushing the boundaries of neutrino astronomy to cosmological distances

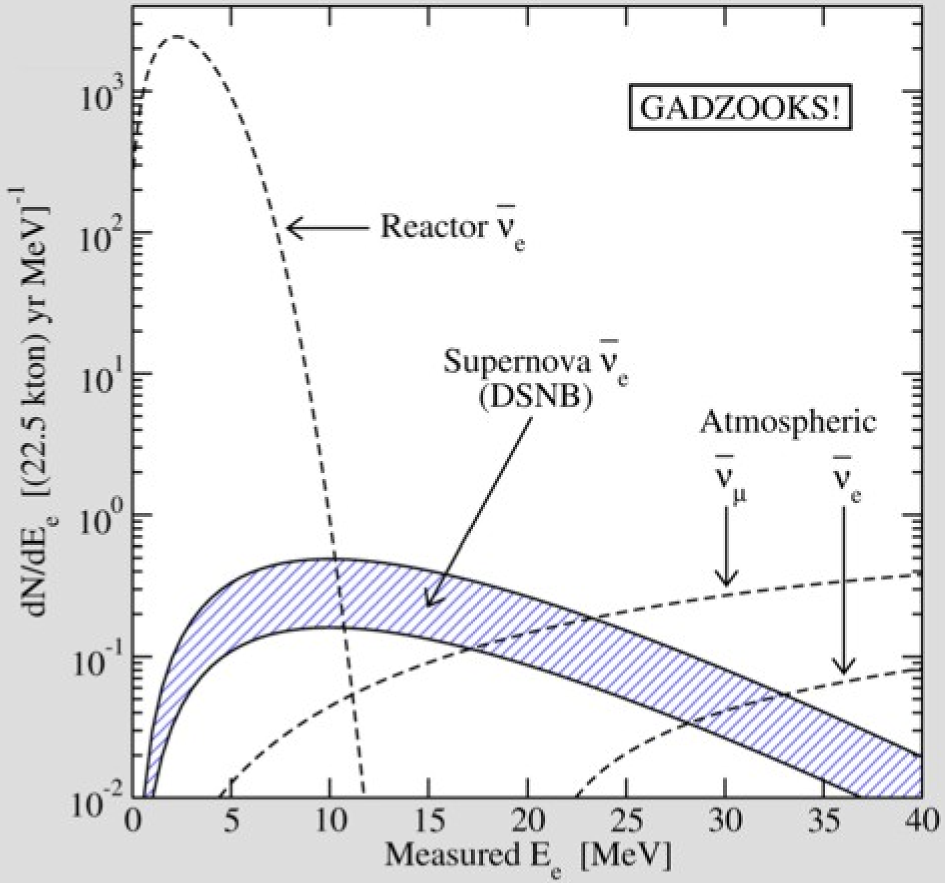


FIG. 1: Spectra of low-energy $\bar\nu_e + p \to e^+ + n$ coincidence events and the sub-Čerenkov muon background. We assume full efficiencies, and include energy resolution and neutrino oscillations. Singles rates (not shown) are efficiently suppressed.

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

Realistic DSNB Estimate

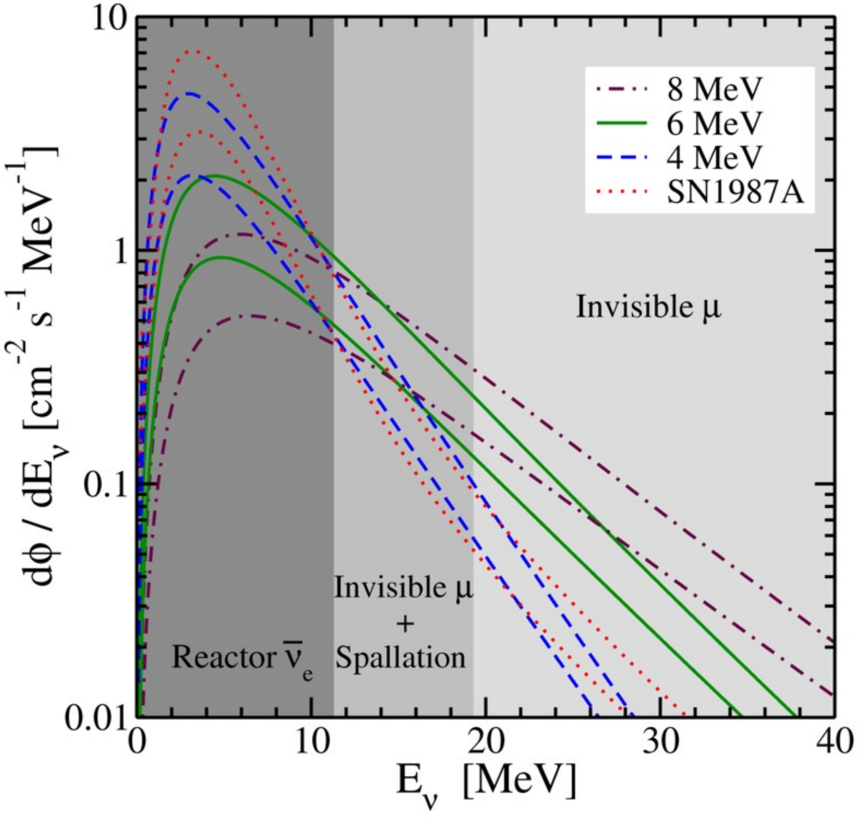


FIG. 4: DSNB flux spectrum for emitted neutrino spectra as labeled. For each spectrum, two curves are plotted representing the full range of uncertainties due to astrophysical inputs (the fiducial prediction lies in between). The shadings indicate backgrounds, with origins as labeled. Decays of invisible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

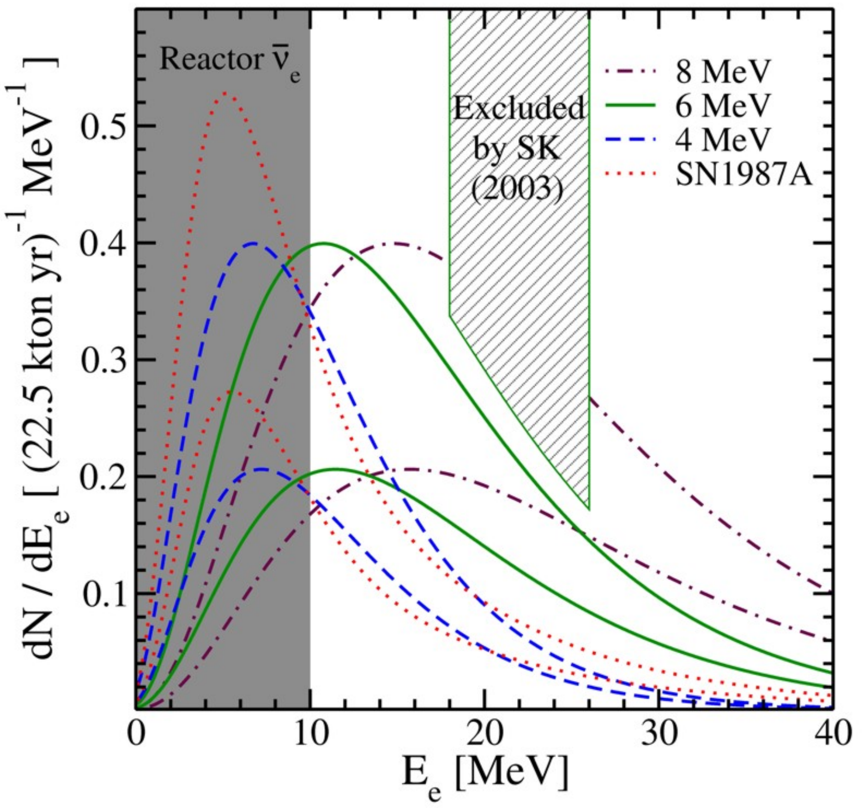


FIG. 5: DSNB event rates at SK (flux spectra weighted with the detection cross section) against positron energy. Note the linear axis. We hatch in the 2003 upper limit by the Super-Kamiokande Collaboration, < 2 events $(22.5 \text{ kton yr})^{-1}$ in the energy range 18–26 MeV. The limit applies to all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

Horiuchi, Beacom & Dwek, arXiv:0812.3157v3

Sanduleak –69 202

Tarantula Nebula

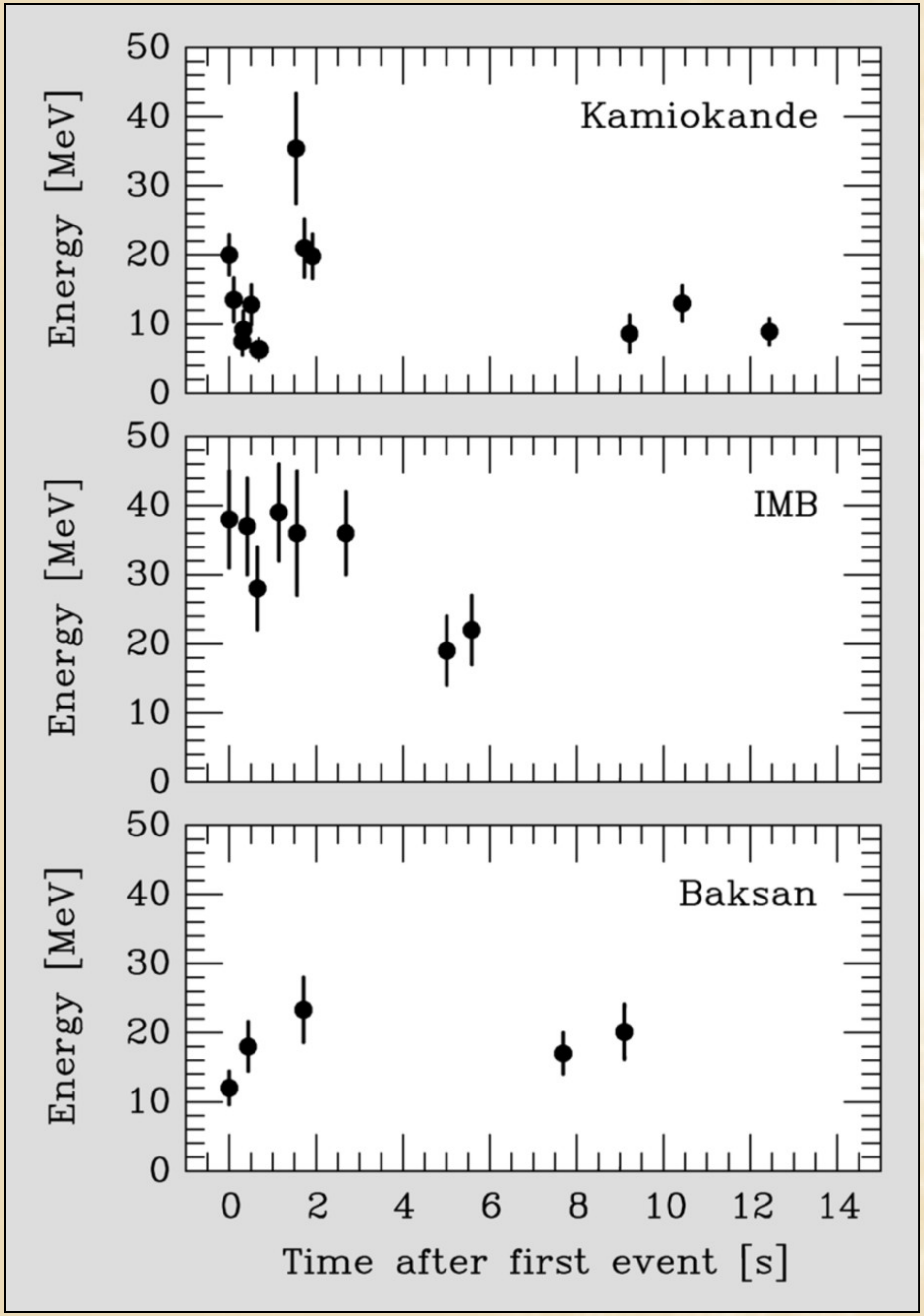
Large Magellanic Cloud
Distance 50 kpc
(160.000 light years)

Sanduleak –69 202

Supernova 1987A

23 February 1987

Neutrino Signal of Supernova 1987A



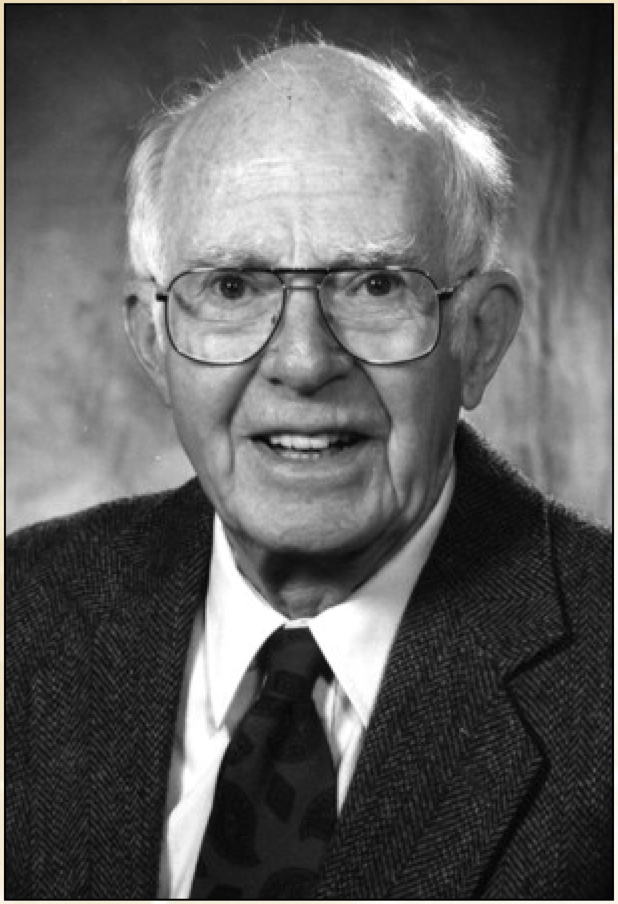
Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ±1 min

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

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

**Within clock uncertainties,
signals are contemporaneous**

2002 Physics Nobel Prize for Neutrino Astronomy

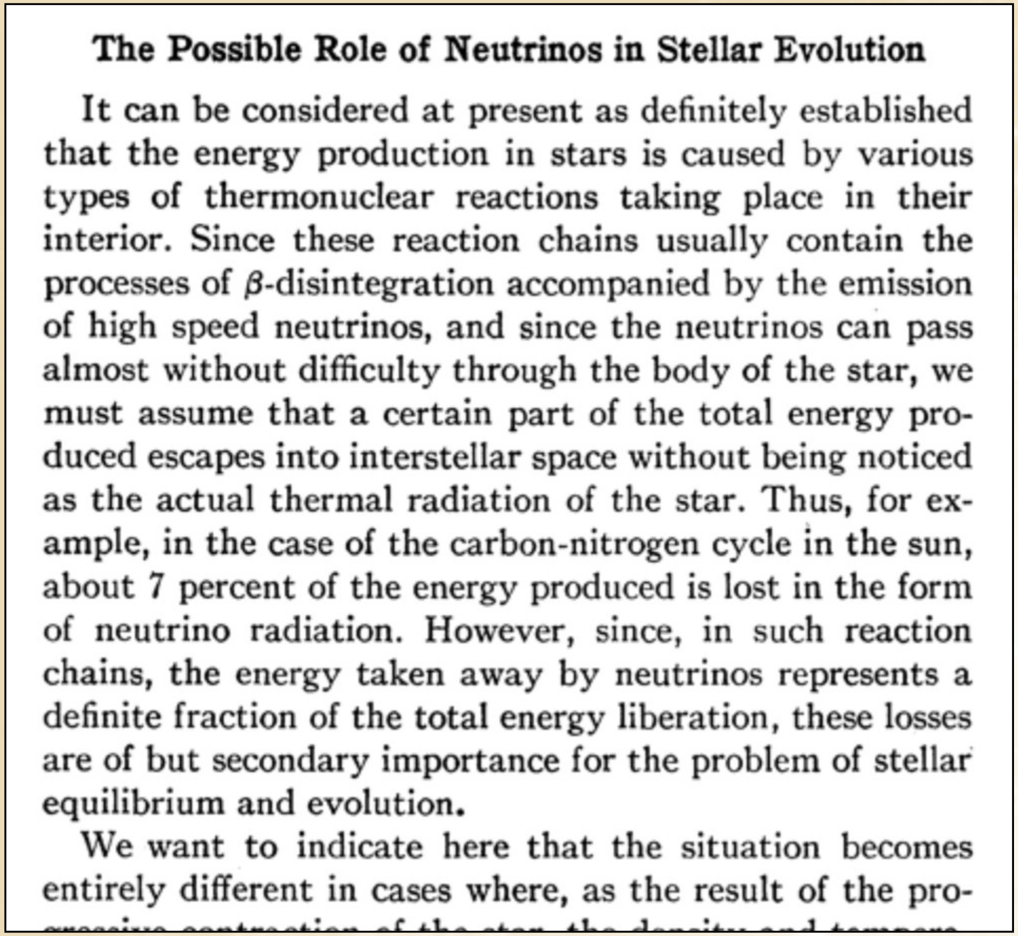


Ray Davis Jr.
(1914 – 2006)

Masatoshi Koshiba
(*1926)

“for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos”

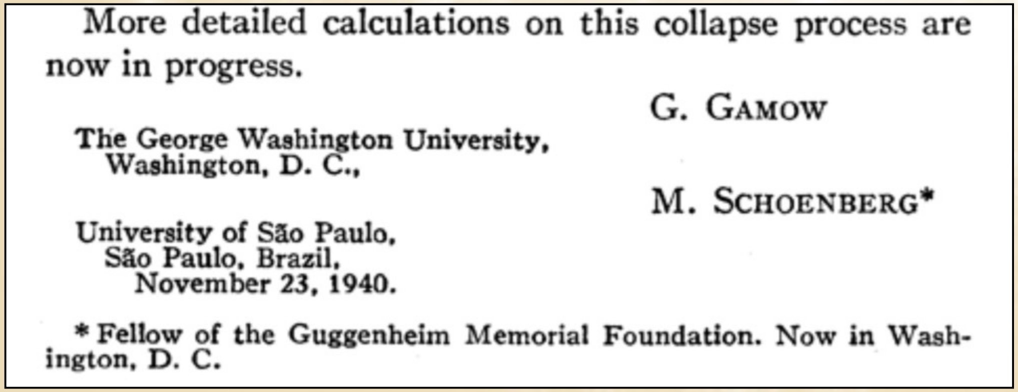
Gamow & Schoenberg, Phys. Rev. 58:1117 (1940)



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.

We want to indicate here that the situation becomes entirely different in cases where, as the result of the progressive contraction of the star, the density and tempera-



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.

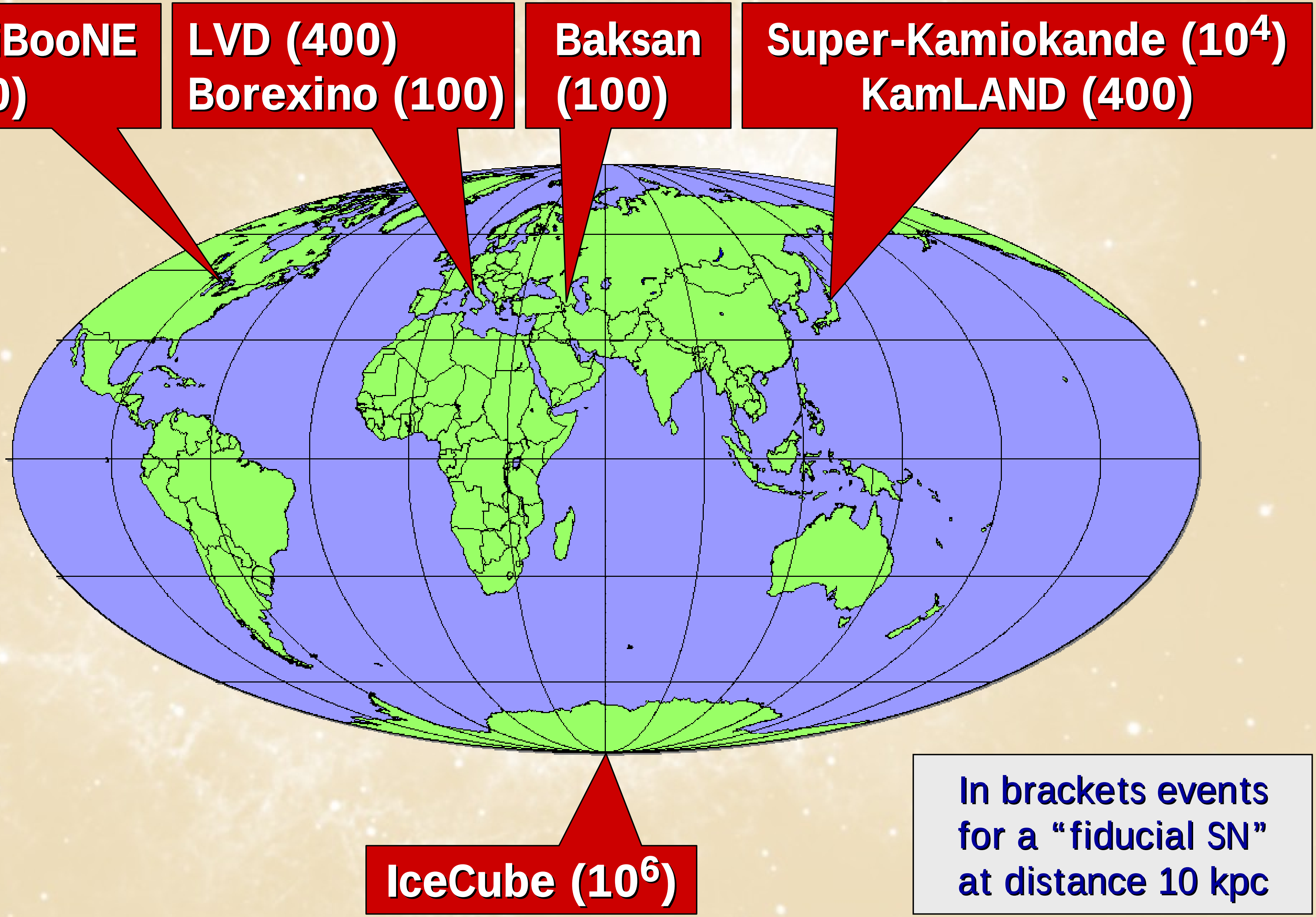
---

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

George Gamow

(1904 – 1968)

Large Detectors for Supernova Neutrinos



MiniBooNE (200)

LVD (400)
Borexino (100)

Baksan (100)

Super-Kamiokande (10^4)
KamLAND (400)

IceCube (10^6)

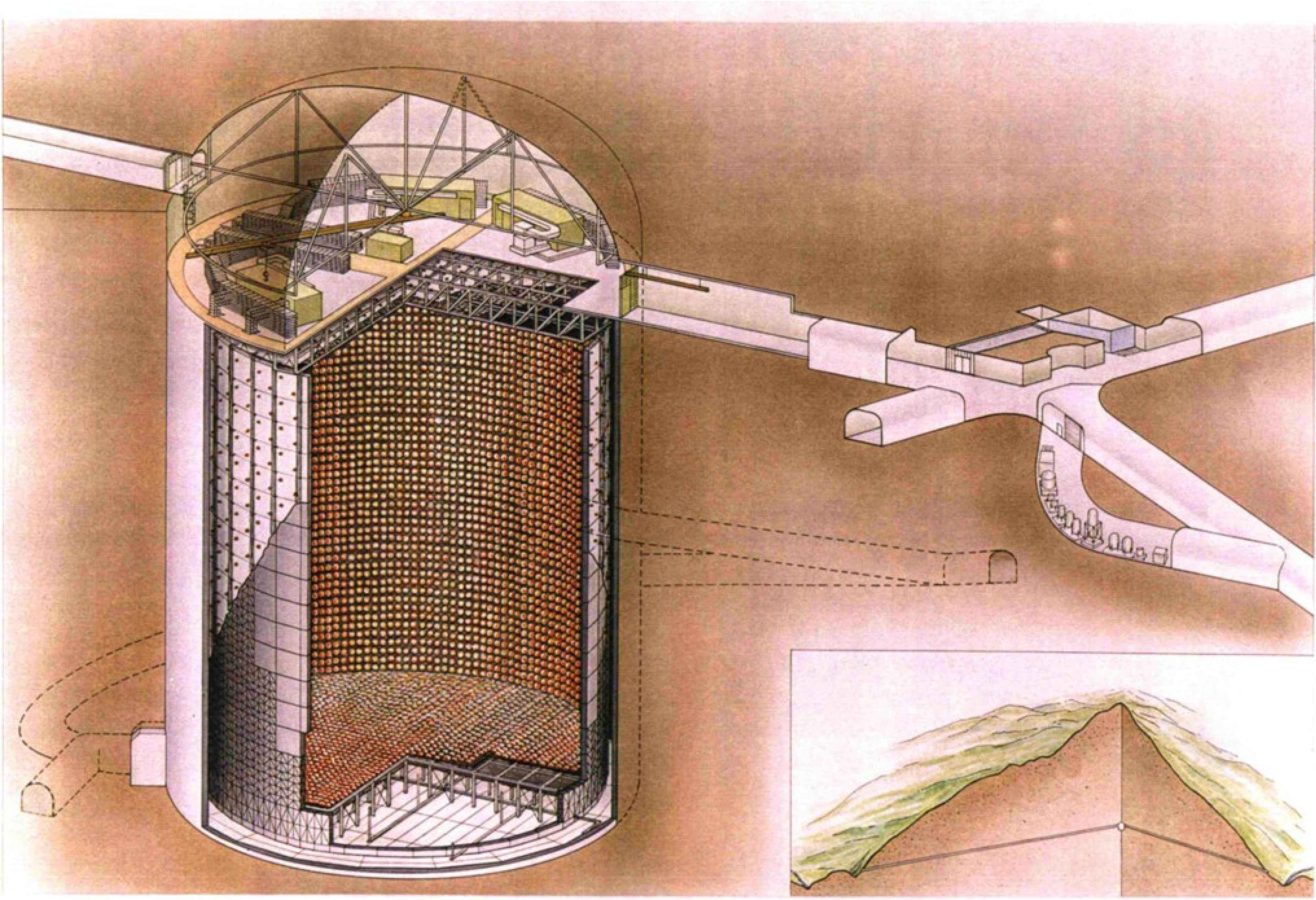
In brackets events
for a “fiducial SN”
at distance 10 kpc

Current and Near-Future SN Neutrino Detectors

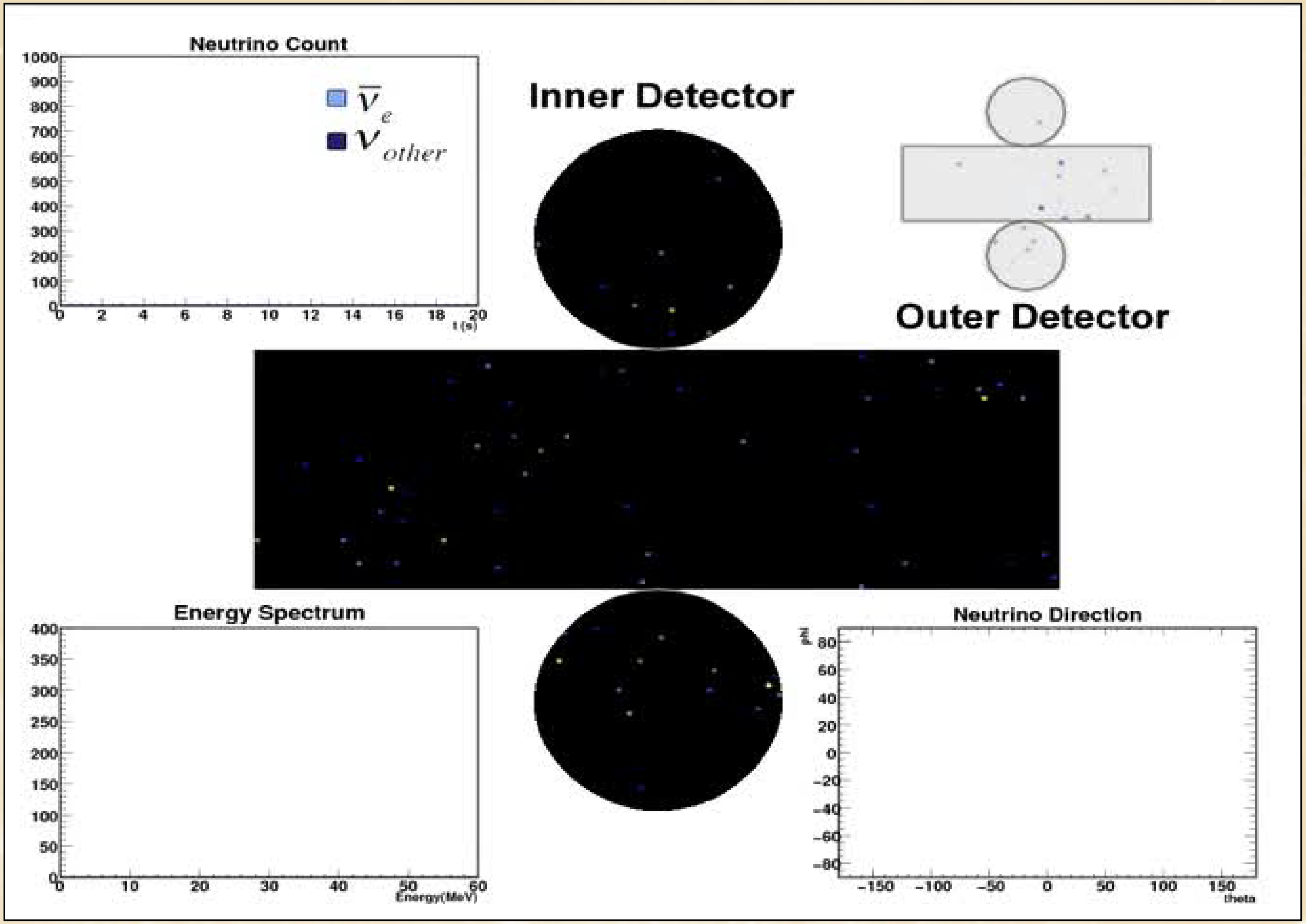
Detector	Type	Location	Mass (kton)	Events @ 8 kpc	Status
Super-K	Water	Japan	32	8000	Running (SK IV)
LVD	Scintillator	Italy	1	300	Running
KamLAND	Scintillator	Japan	1	300	Running
Borexino	Scintillator	Italy	0.3	100	Running
IceCube	Ice	South Pole	0.4/PMT	1 million	Running
Baksan	Scintillator	Russia	0.33	50	Running
Mini-BOONE	Scintillator	USA	0.7	200	Running
HALO	Lead	Canada	0.076	85	Under construction
Icarus	Liquid argon	Italy	0.6	230	Almost ready
NOνA	Scintillator	USA	15	3000	Construction started
SNO+	Scintillator	Canada	1	300	Funded

Adapted from Kate Scholberg, TAUP 2009

Super-Kamiokande Neutrino Detector

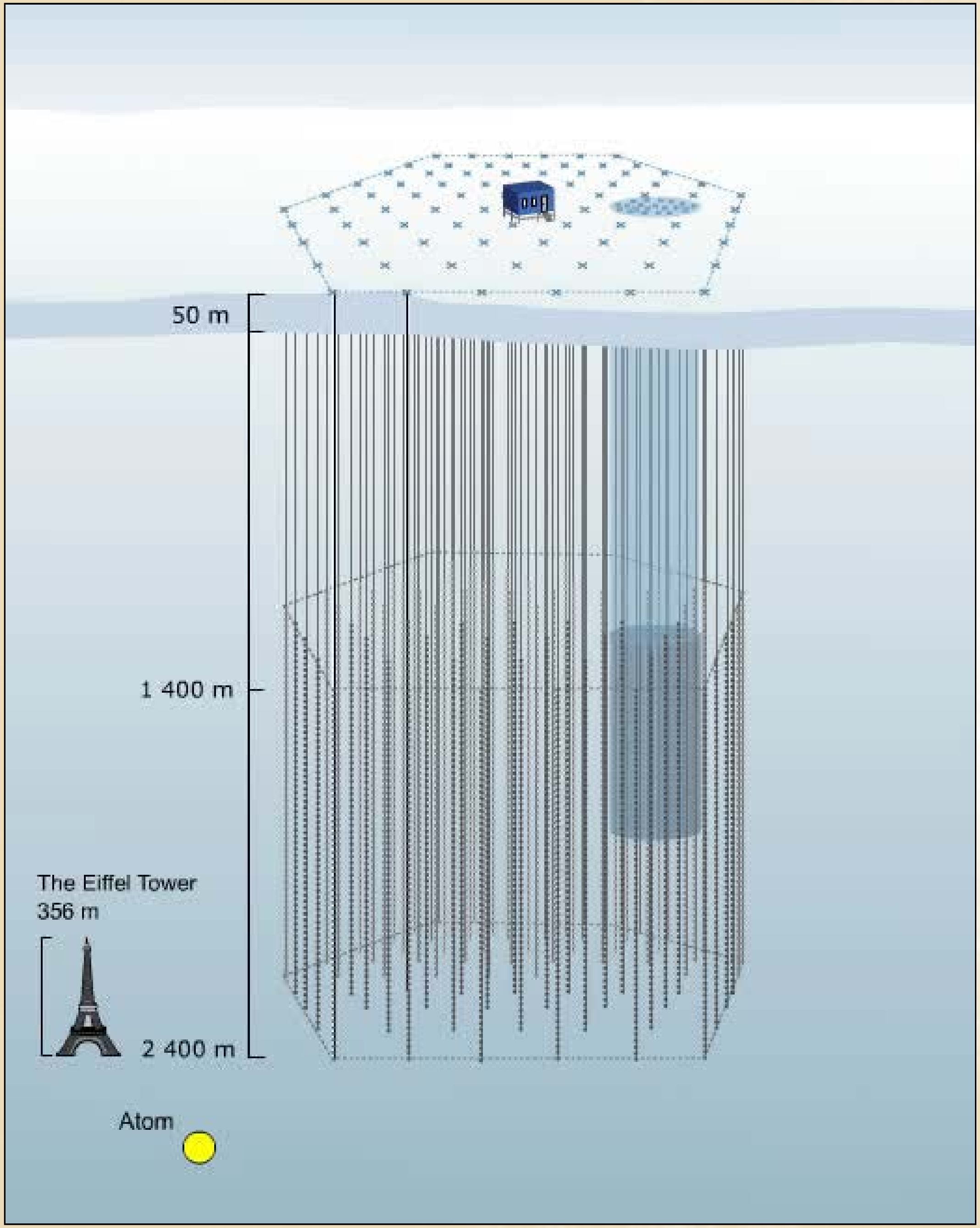


Simulated Supernova Burst in Super-Kamiokande

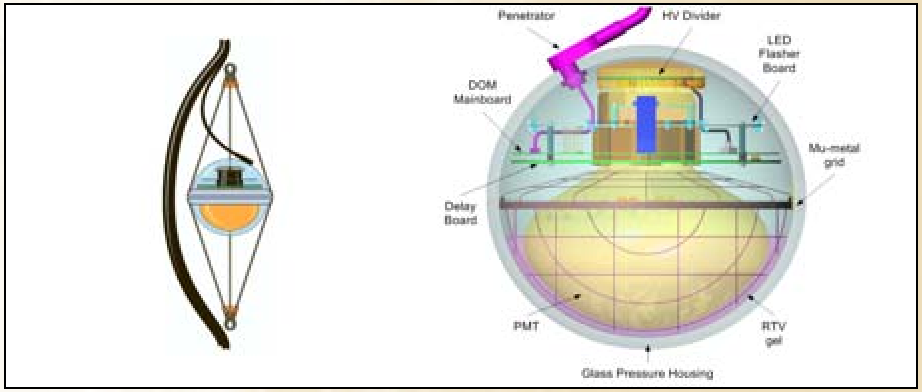


Movie by C. Little, including work by S. Farrell & B. Reed,
(Kate Scholberg’s group at Duke University)
http://snews.bnl.gov/snmovie.html

IceCube Neutrino Telescope at the South Pole



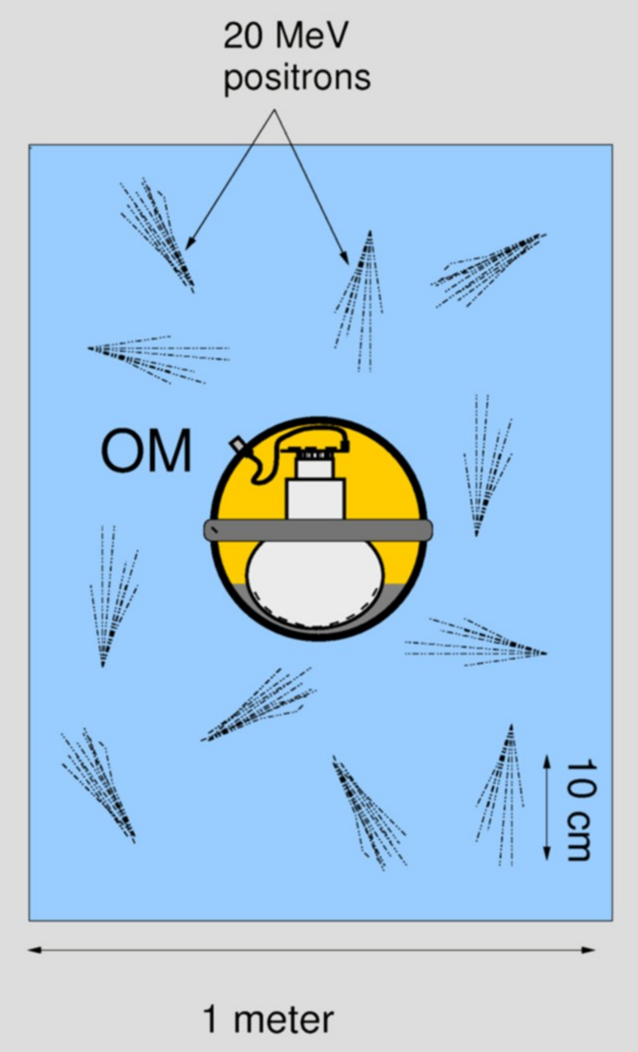
- 1 km^3 antarctic ice, instrumented with 4800 photomultipliers
- 59 of 80 strings installed (2009)
- Completion until 2011 foreseen

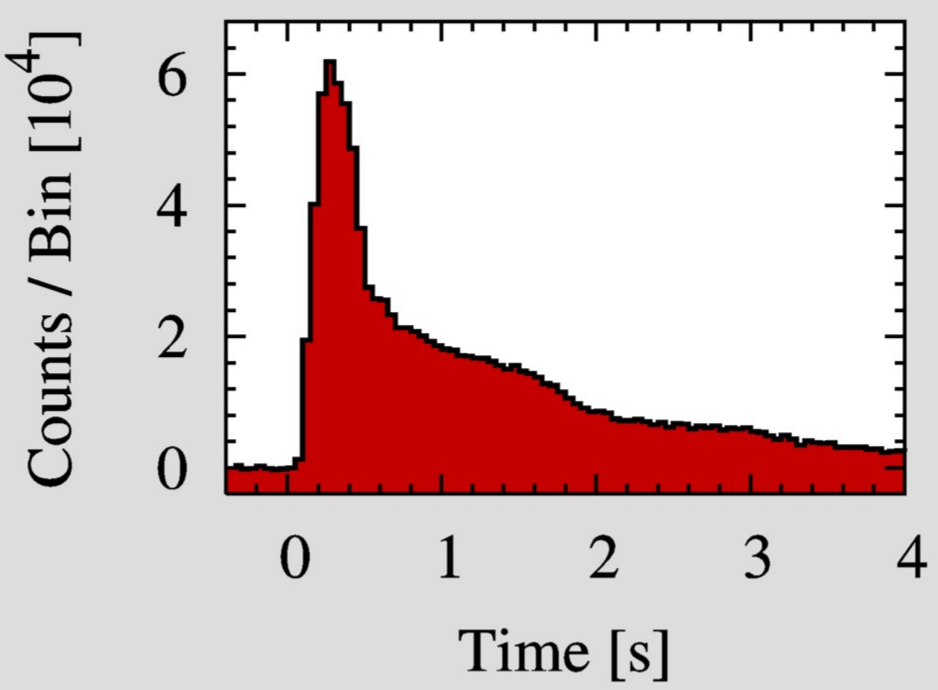


IceCube as a Supernova Neutrino Detector

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 ~280 Hz
- Total of 4800 OMs foreseen in IceCube

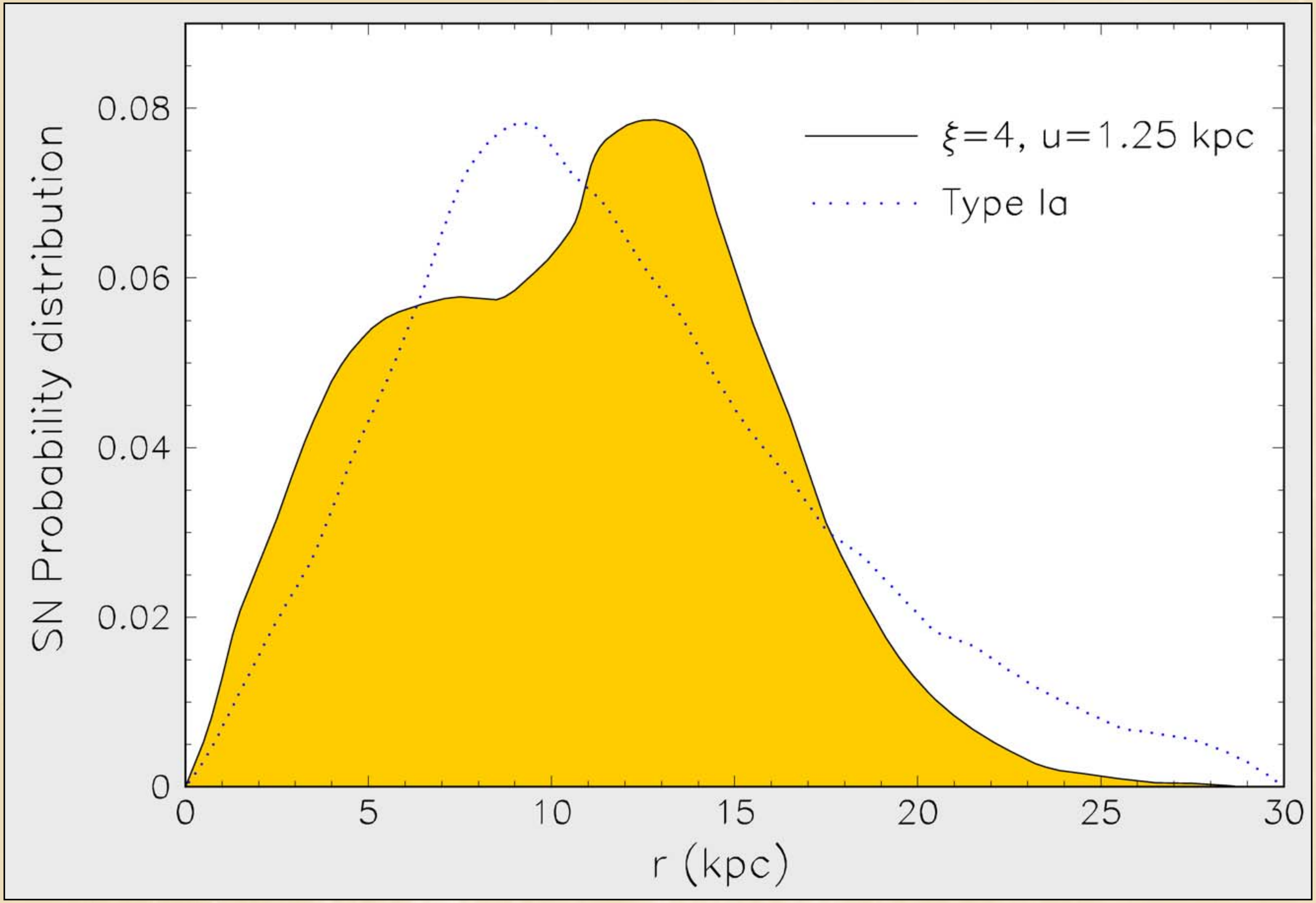




IceCube SN signal at 10 kpc, based on a numerical Livermore model [Dighe, Keil & Raffelt, hep-ph/0303210]

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

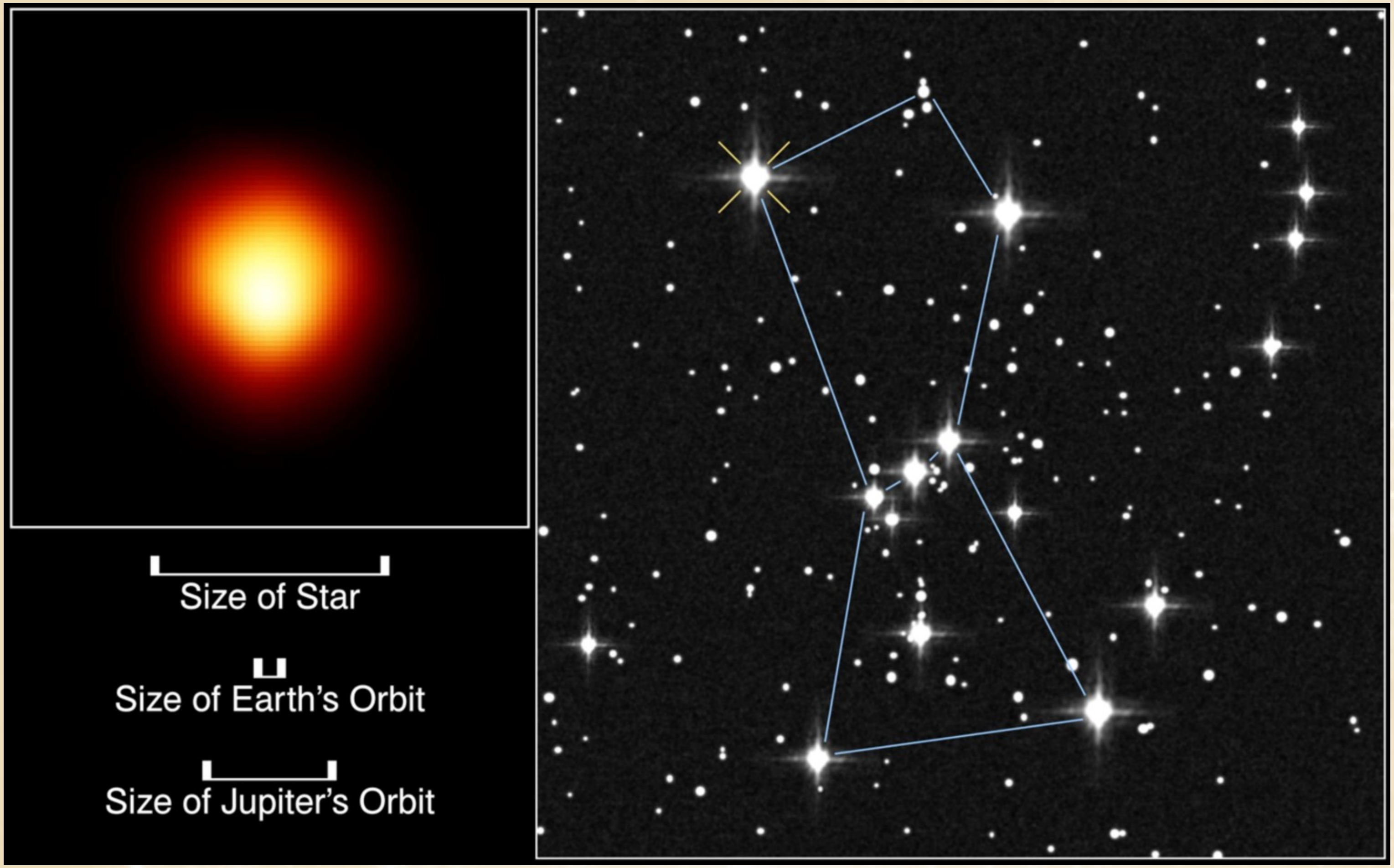
Galactic Supernova Distance Distribution



Mirizzi,
Raffelt,
Serpico,
astro-ph
0604300

Average distance 10.7 kpc, rms dispersion 4.9 kpc
(11.9 kpc and 6.0 kpc for SN Ia distribution)

The Red Supergiant Betelgeuse (Alpha Orionis)



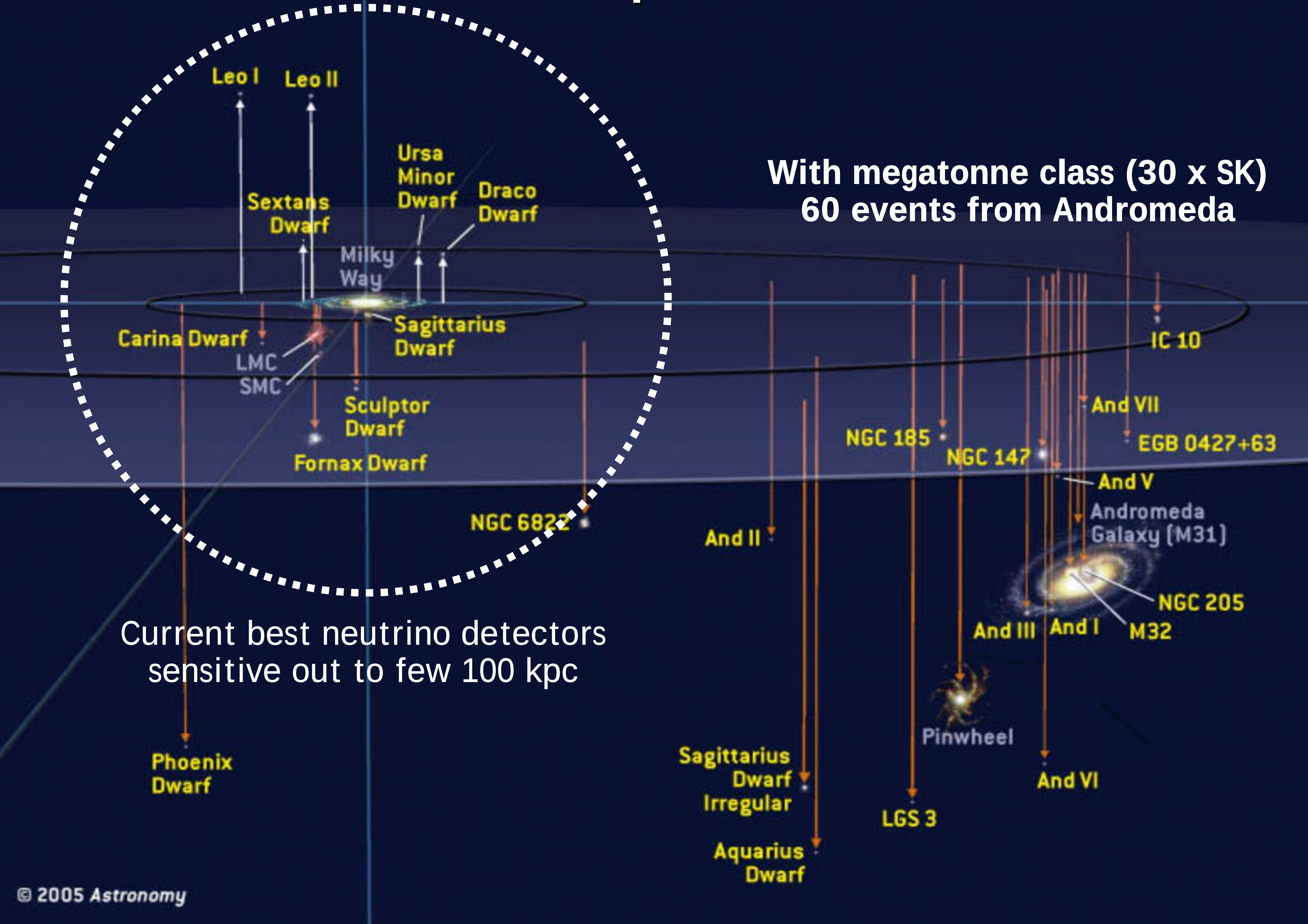
First resolved image of a star other than Sun

Distance (Hipparcos)
130 pc (425 lyr)

If Betelgeuse goes Supernova:

- 6×10^7 neutrino events in Super-Kamiokande
- 2.4×10^3 neutron events per day from Silicon-burning phase (few days warning!), need neutron tagging [Odrzywolek, Misiaszek & Kutschera, astro-ph/0311012]

Local Group of Galaxies



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

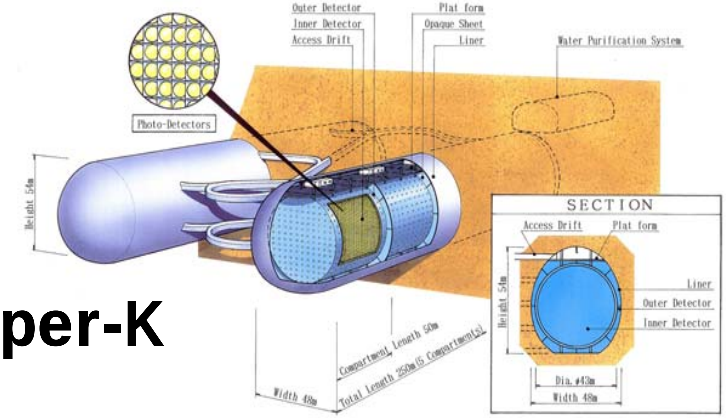
Current best neutrino detectors
sensitive out to few 100 kpc

© 2005 Astronomy

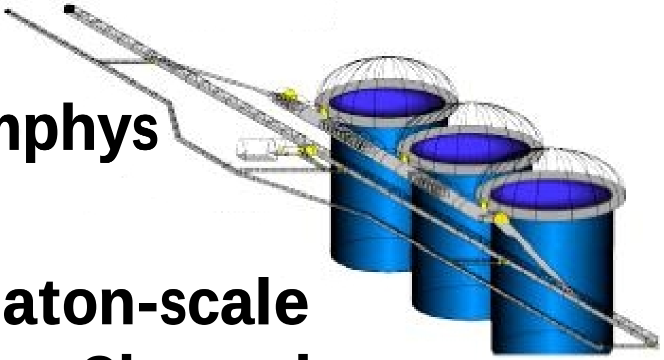
Next Generation Large-Scale Detector Concepts

DUSEL
LBNE

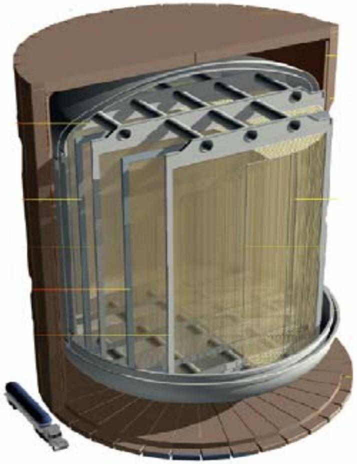
Hyper-K



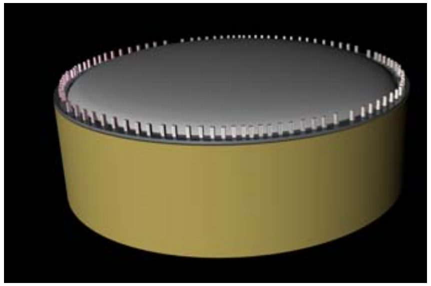
Memphys

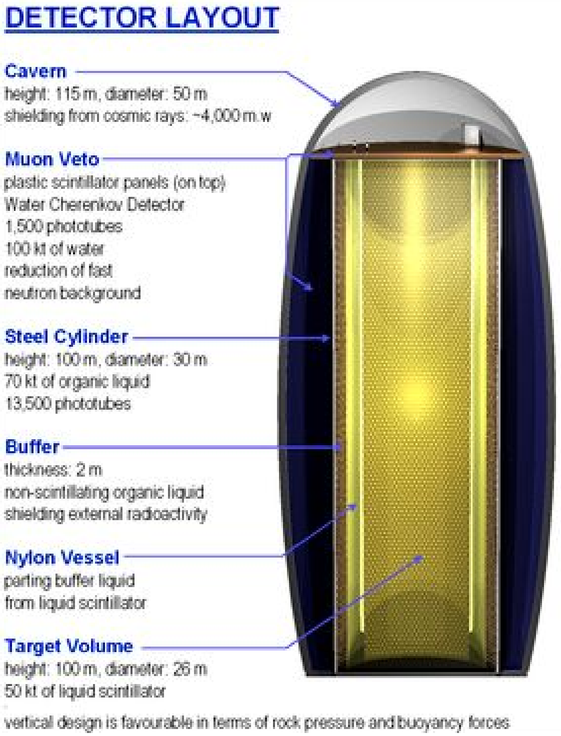


Megaton-scale water Cherenkov



5–100 kton liquid Argon





DETECTOR LAYOUT

Cavern
height: 115 m, diameter: 50 m
shielding from cosmic rays: ~4,000 m.w

Muon Veto
plastic scintillator panels (on top)
Water Cherenkov Detector
1,500 phototubes
100 kt of water
reduction of fast
neutron background

Steel Cylinder
height: 100 m, diameter: 30 m
70 kt of organic liquid
13,500 phototubes

Buffer
thickness: 2 m
non-scintillating organic liquid
shielding external radioactivity

Nylon Vessel
parting buffer liquid
from liquid scintillator

Target Volume
height: 100 m, diameter: 26 m
50 kt of liquid scintillator

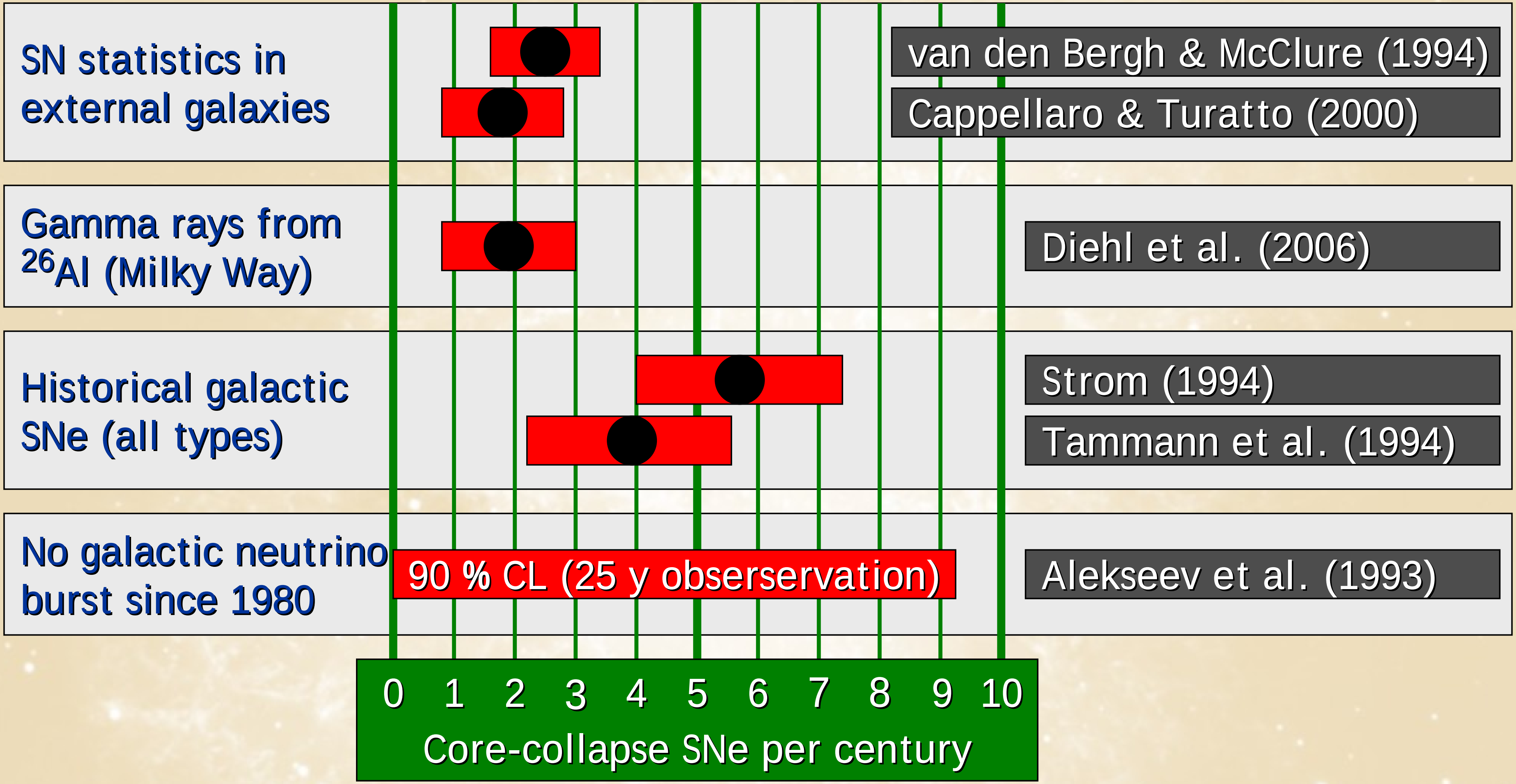
vertical design is favourable in terms of rock pressure and buoyancy forces

100 kton scale scintillator

LENA
HanoHano

Galactic Supernova Rate

Core-Collapse SN Rate in the Milky Way



SN statistics in external galaxies

van den Bergh & McClure (1994)

Cappellaro & Turatto (2000)

Gamma rays from ^{26}Al (Milky Way)

Diehl et al. (2006)

Historical galactic SNe (all types)

Strom (1994)

Tammann et al. (1994)

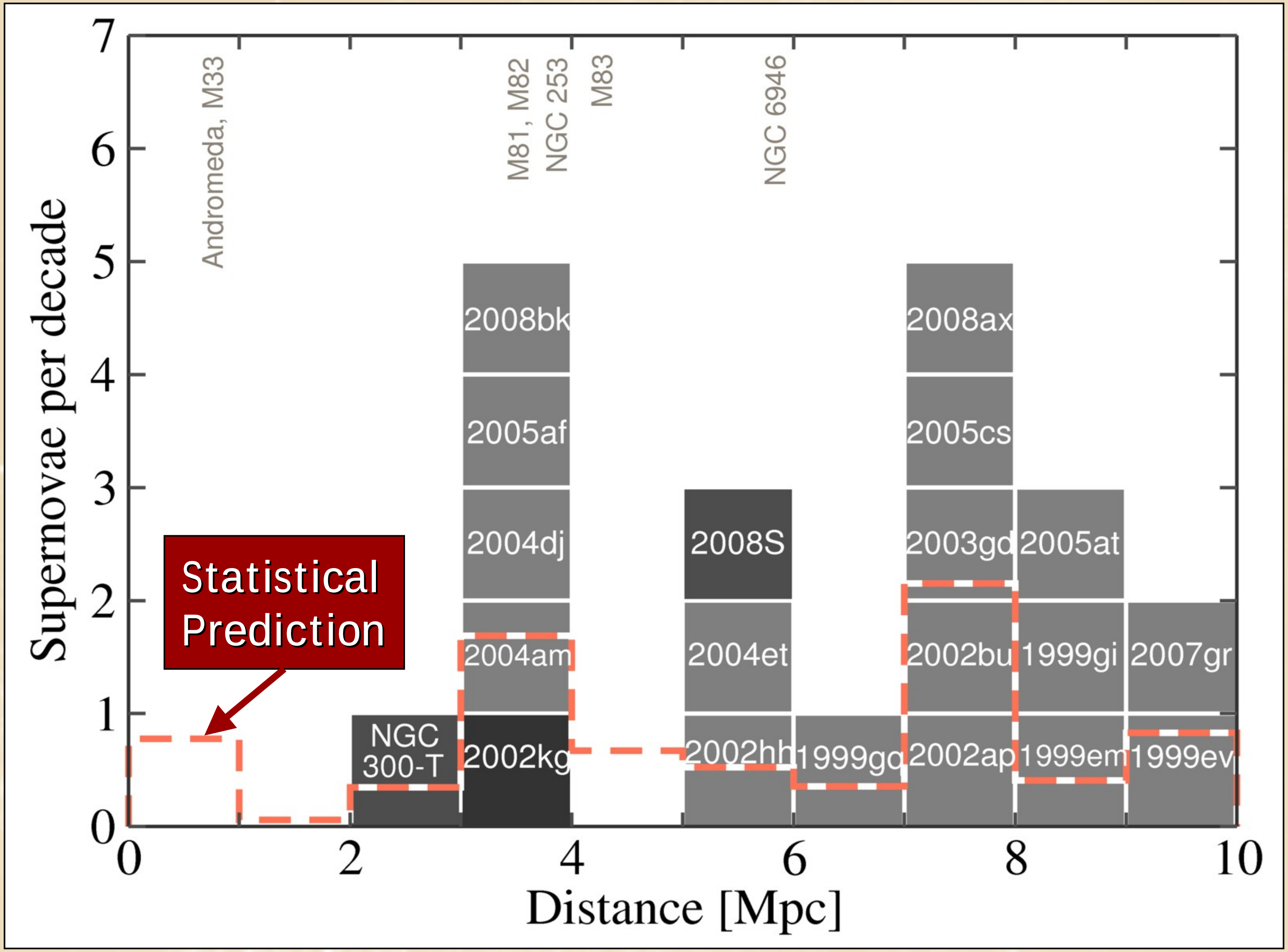
No galactic neutrino burst since 1980

90 % CL (25 y obserservation)

Alekseev et al. (1993)

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

Observed SNe in the Local Universe (Past Decade)

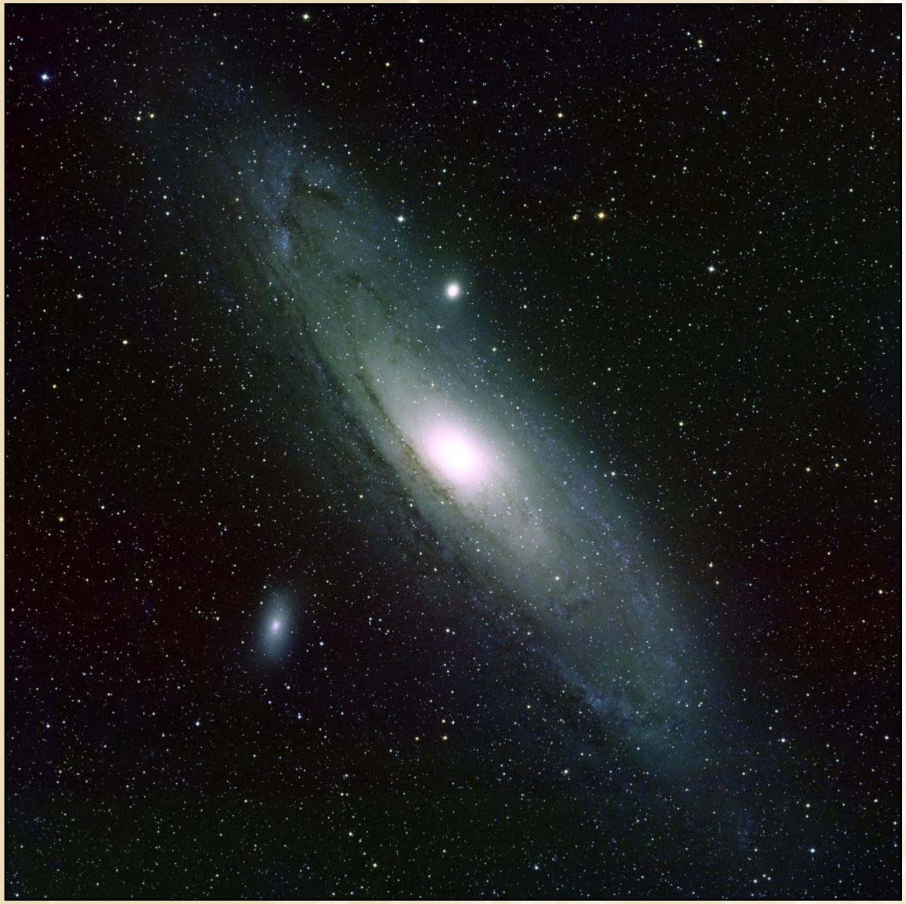


Statistical Prediction

Kistler, Yüksel, Ando, Beacom & Suzuki, arXiv:0810.1959

High and Low Supernova Rates in Nearby Galaxies

M31 (Andromeda)
D = 780 kpc



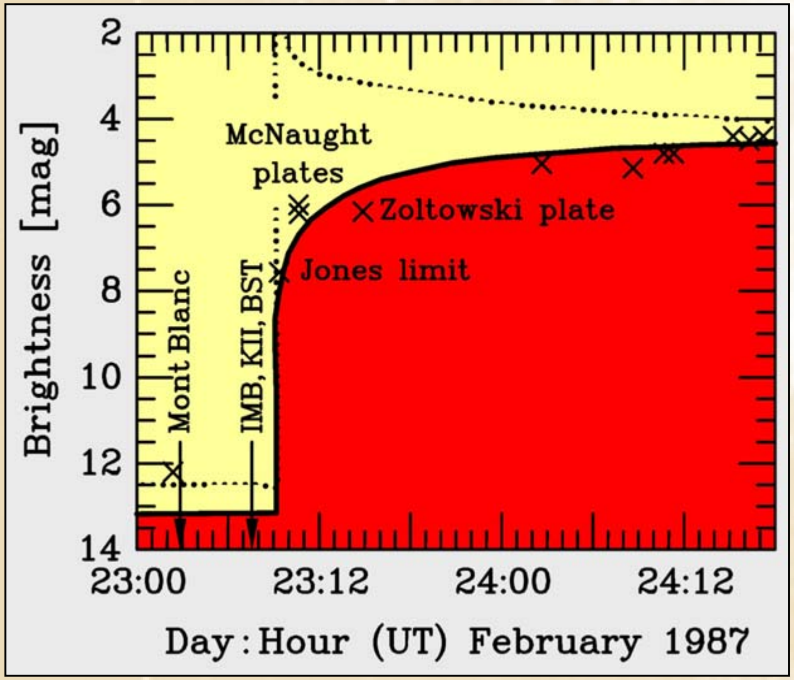
Last Observed Supernova: 1885A

NGC 6946
D = (5.5 ± 1) Mpc

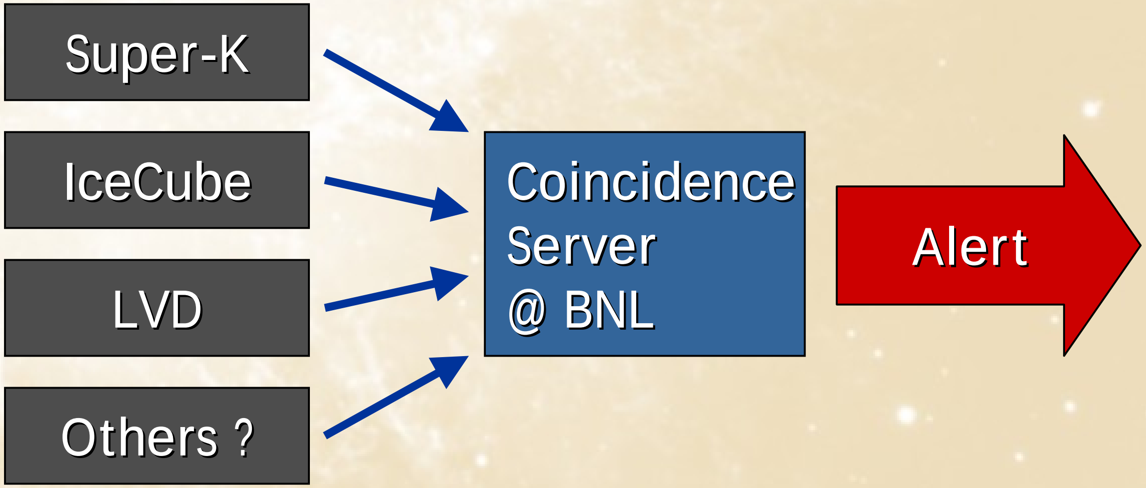
Observed Supernovae:
1917A, 1939C, 1948B, 1968D, 1969P,
1980K, 2002hh, 2004et, 2008S

SuperNova Early Warning System (SNEWS)

Supernova 1987A
Early Light Curve



http://snews.bnl.gov



Super-K

IceCube

LVD

Others ?

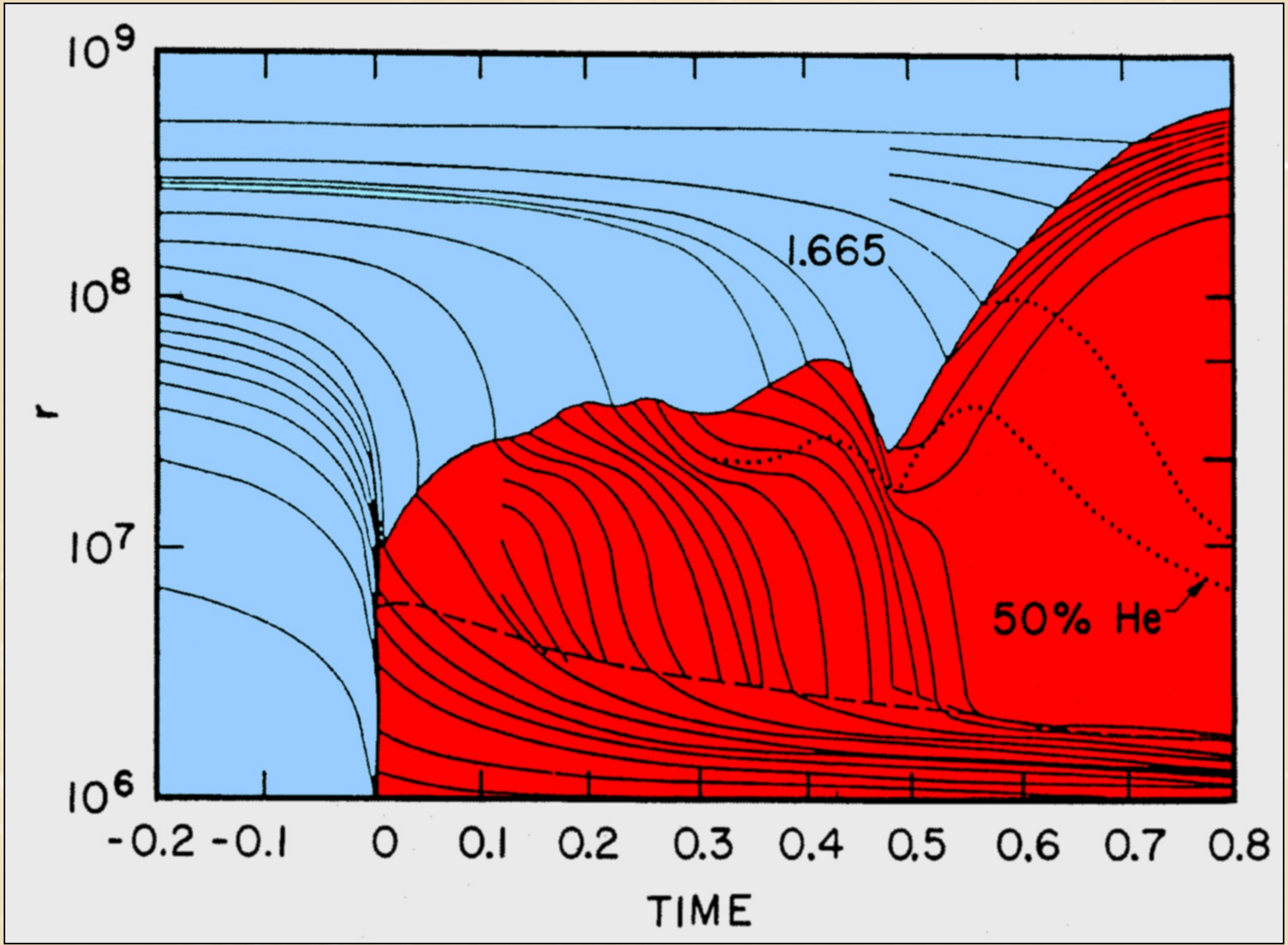
Coincidence
Server
@ BNL

Alert

Neutrino observation can alert astronomers several hours in advance to a supernova.

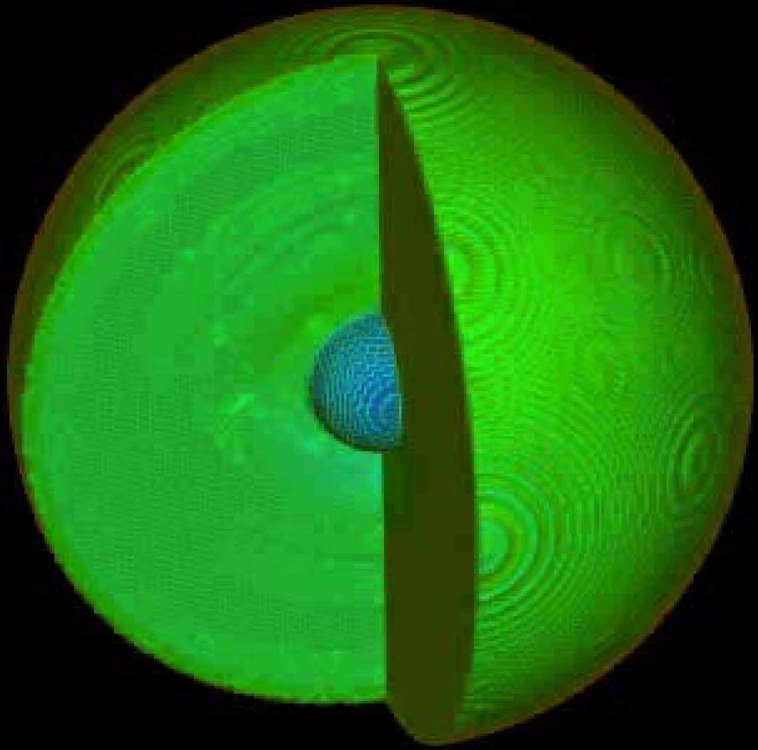
Probing Supernova Physics

Delayed Explosion



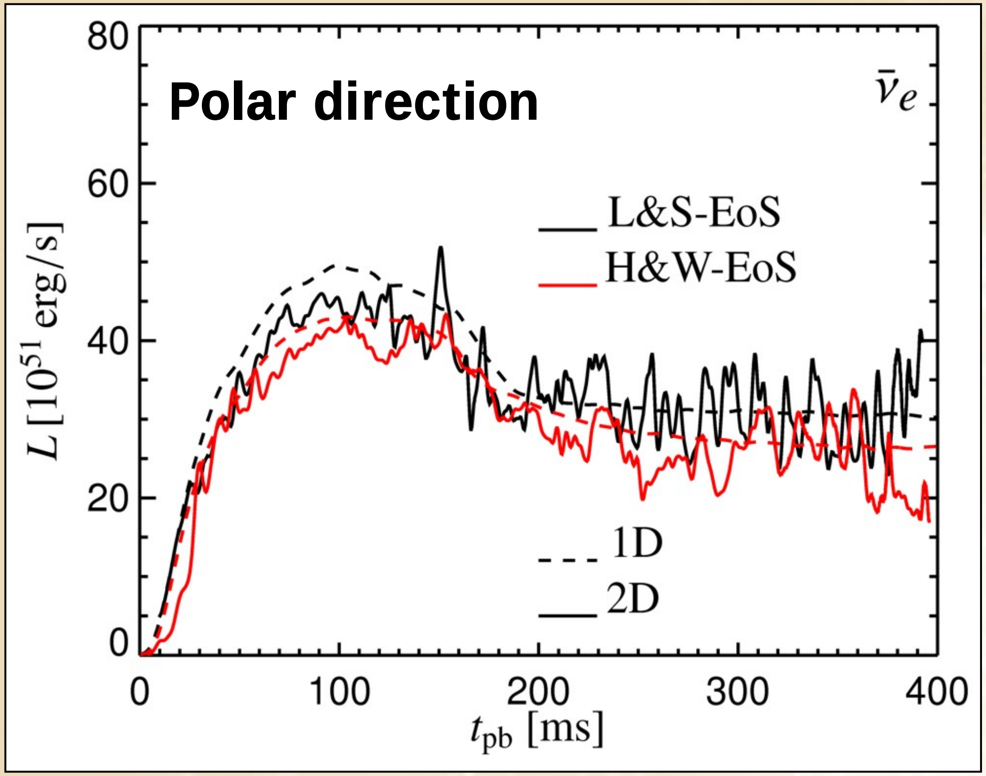
Wilson, Proc. Univ. Illinois Meeting on Num. Astrophys.(1982)
Bethe & Wilson, ApJ 295 (1985) 14

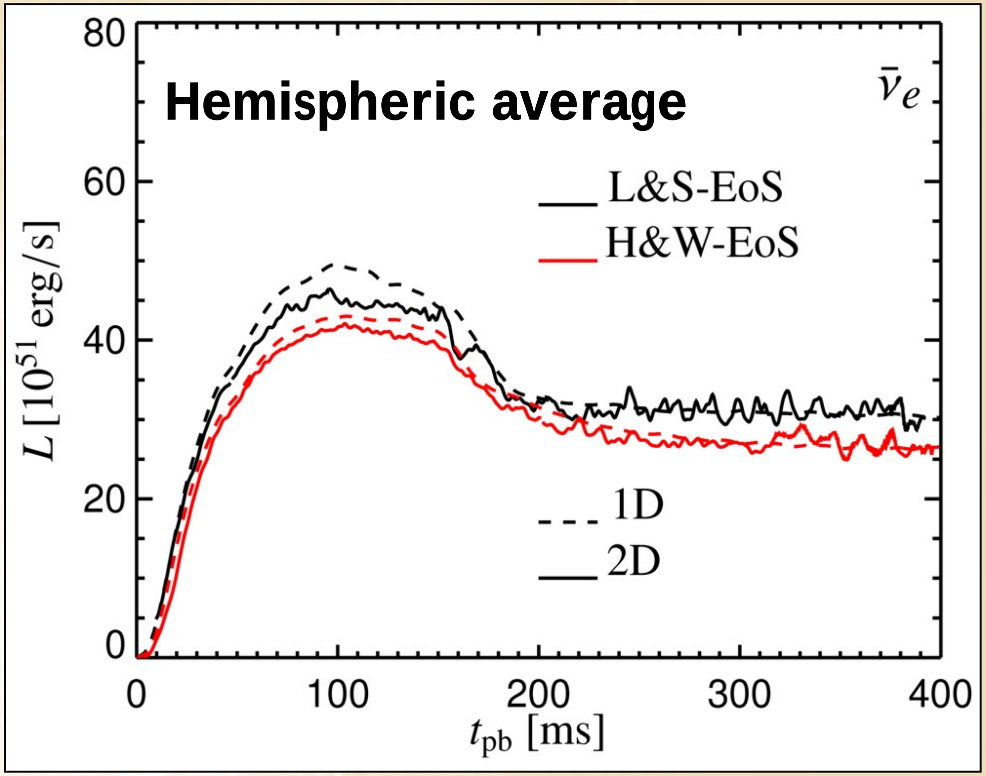
Standing Accretion Shock Instability (SASI)



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

Luminosity Variation Detectable in Neutrinos?





Neutrino events in 10 ms bins for SN (10 kpc) during accretion phase:

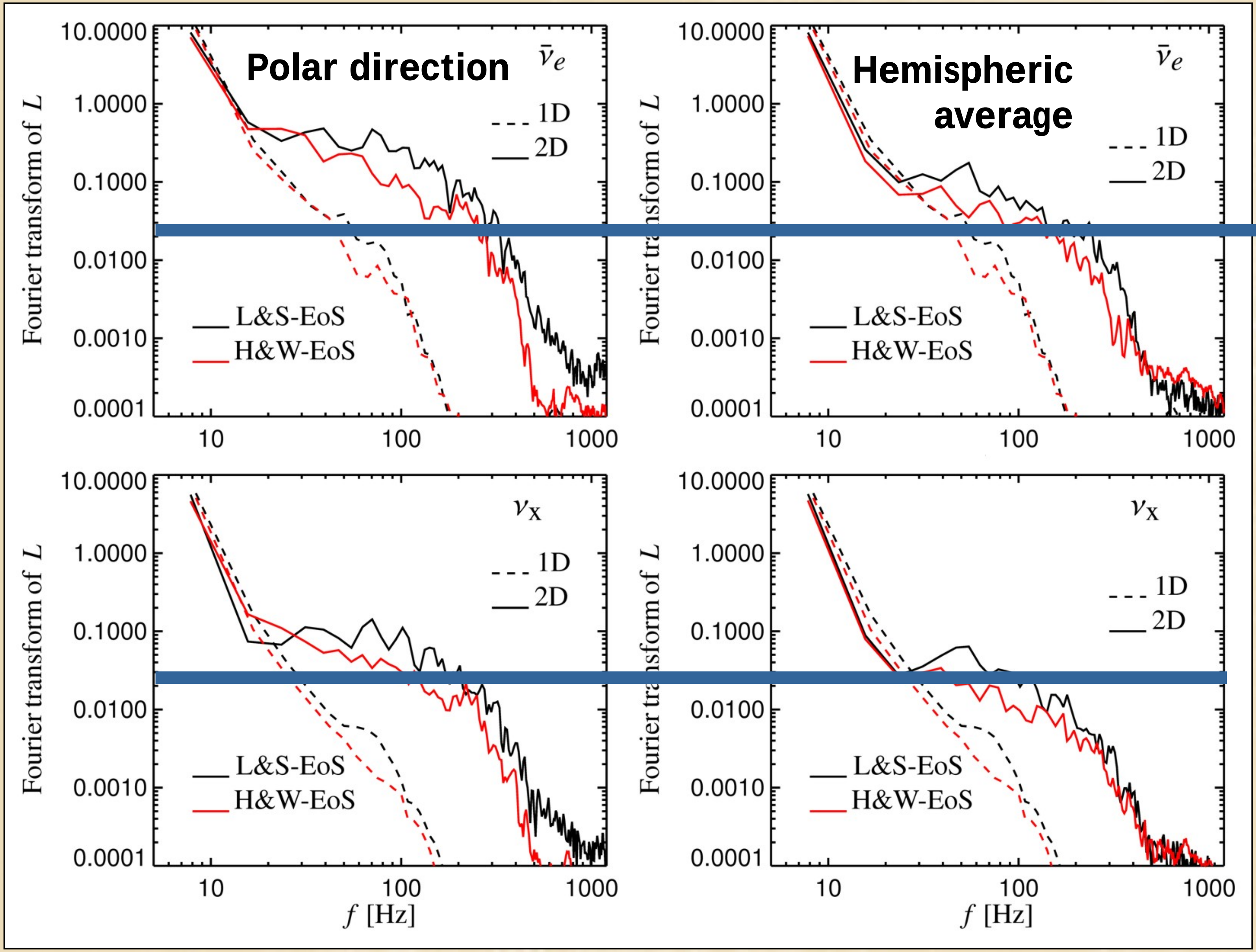
• Super-K	70	1σ ~ 10%
• 30 x Super-K	2×10^3	1σ ~ 2%
• IceCube	1×10^4	1σ ~ 1%

Detecting the spectrum of luminosity variations can

- Detect SASI instability in neutrinos
- Provide equation-of-state information

Marek, Janka & Müller, arXiv:0808.4136

Fourier Transform of Luminosity Variation



Approximate level of Poisson noise in IceCube for a SN at 10 kpc

Detectability to be studied in more detail (Lund, Marek, Lunardini, Janka, Raffelt, Work in progress)

Marek, Janka & Müller, arXiv:0808.4136

Neutrino Mass and Resolution of Time Variations

Signal dispersion for Next Nearby SN

$$\Delta t = 5.1\,\mathrm{ms}\left(\frac{D}{10\,\mathrm{kpc}}\right)\left(\frac{10\,\mathrm{MeV}}{E_\nu}\right)^2\left(\frac{m_\nu}{1\mathrm{eV}}\right)^2$$

- IceCube binning of data: 1.64 ms in each OM
- Laboratory neutrino mass limit: 2.2 eV
- Cosmological limit $\Sigma m_\nu < 0.6$ eV, so individual mass limit 0.2 eV
- KATRIN sensitivity roughly 0.2 eV

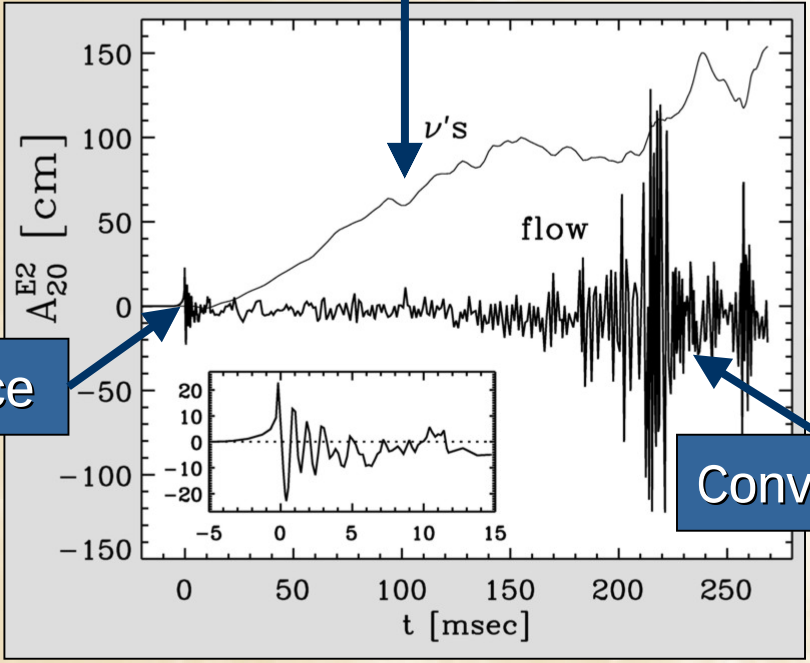
For SN signal interpretation of fast time variations, it is important to have the cosmological limit and future KATRIN measurement/limit

Supernova neutrino aficionados are new customers for KATRIN results!

Gravitational Waves from Core-Collapse Supernovae

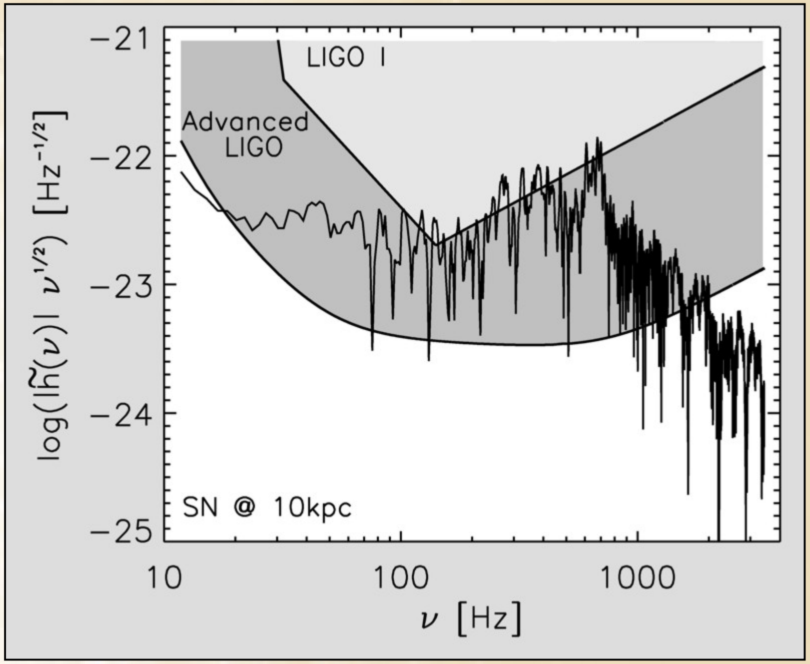
Müller, Rampp, Buras, Janka, & Shoemaker, "Towards gravitational wave signals from realistic core collapse supernova models," astro-ph/0309833

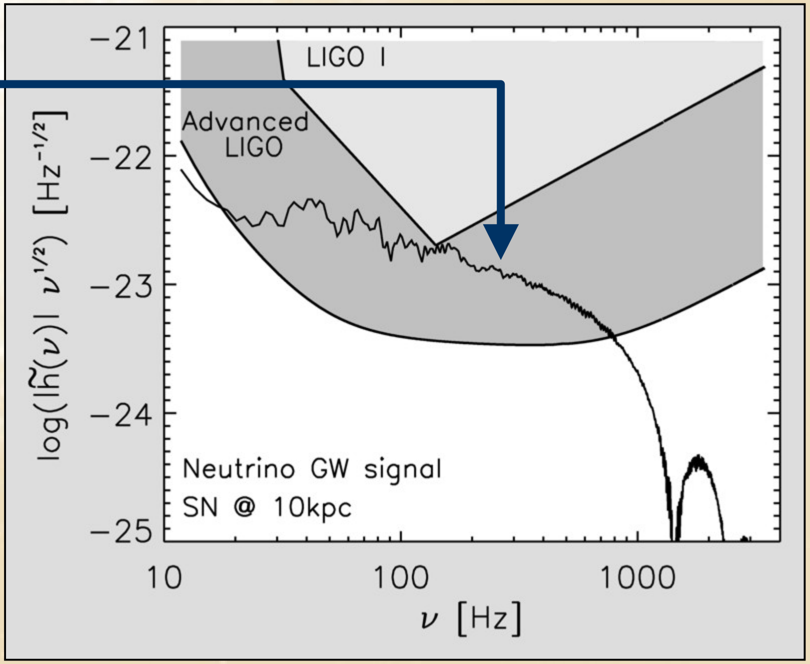
Asymmetric neutrino emission



Bounce

Convection

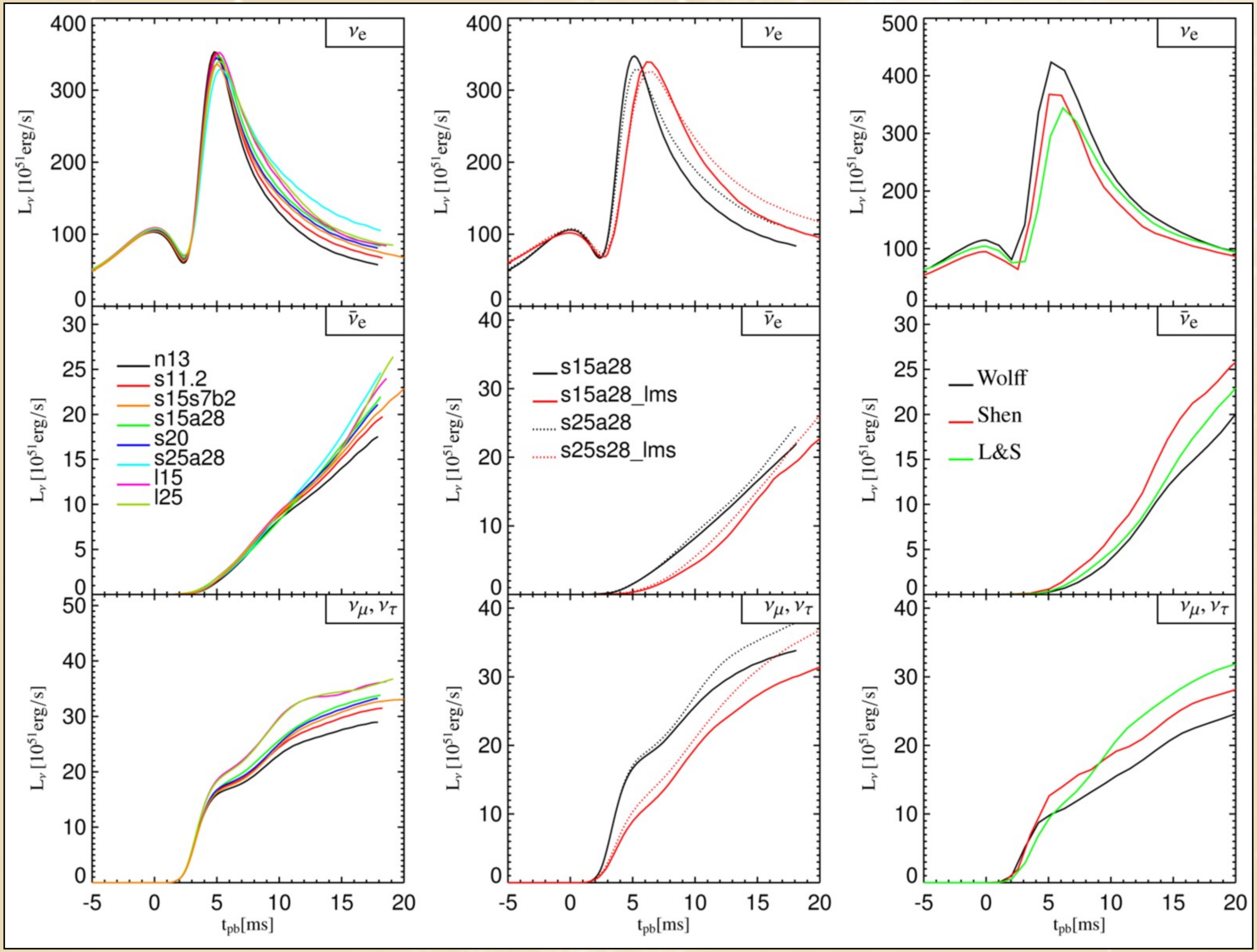




The gravitational-wave signal from convection is a generic and dominating feature

Neutrino Emission Around Bounce Time

Different Mass | **Neutrino Transport** | **Nuclear EoS**



Prompt Neutronization Burst

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

Millisecond Bounce Time Reconstruction

Super-Kamiokande

- Emission model adapted to measured SN 1987A data
- "Pessimistic distance" of 20 kpc
- Determine bounce time to within a few tens of milliseconds

Pagliaroli, Vissani, Coccia & Fulgione
arXiv:0903.1191

IceCube

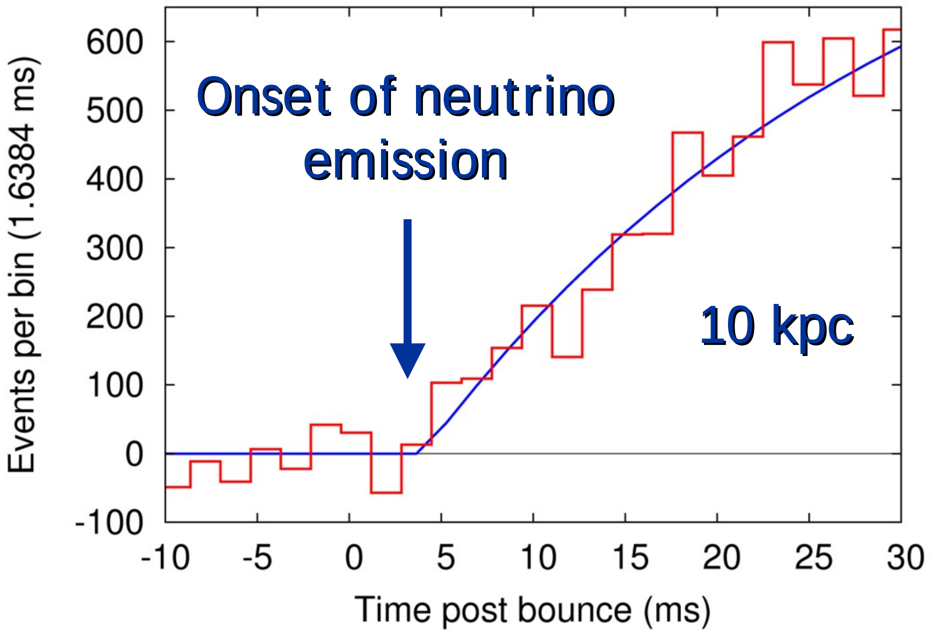


FIG. 1: Typical Monte Carlo realization (red histogram) and reconstructed fit (blue line) for the benchmark case discussed in the text for a SN at 10 kpc.

Halzen & Raffelt
arXiv:0908.2317

Do Neutrinos Gravitate?

Neutrinos arrive a few hours earlier than photons → Early warning (SNEWS)
SN 1987A: Transit time for photons and neutrinos equal to within ~ 3h

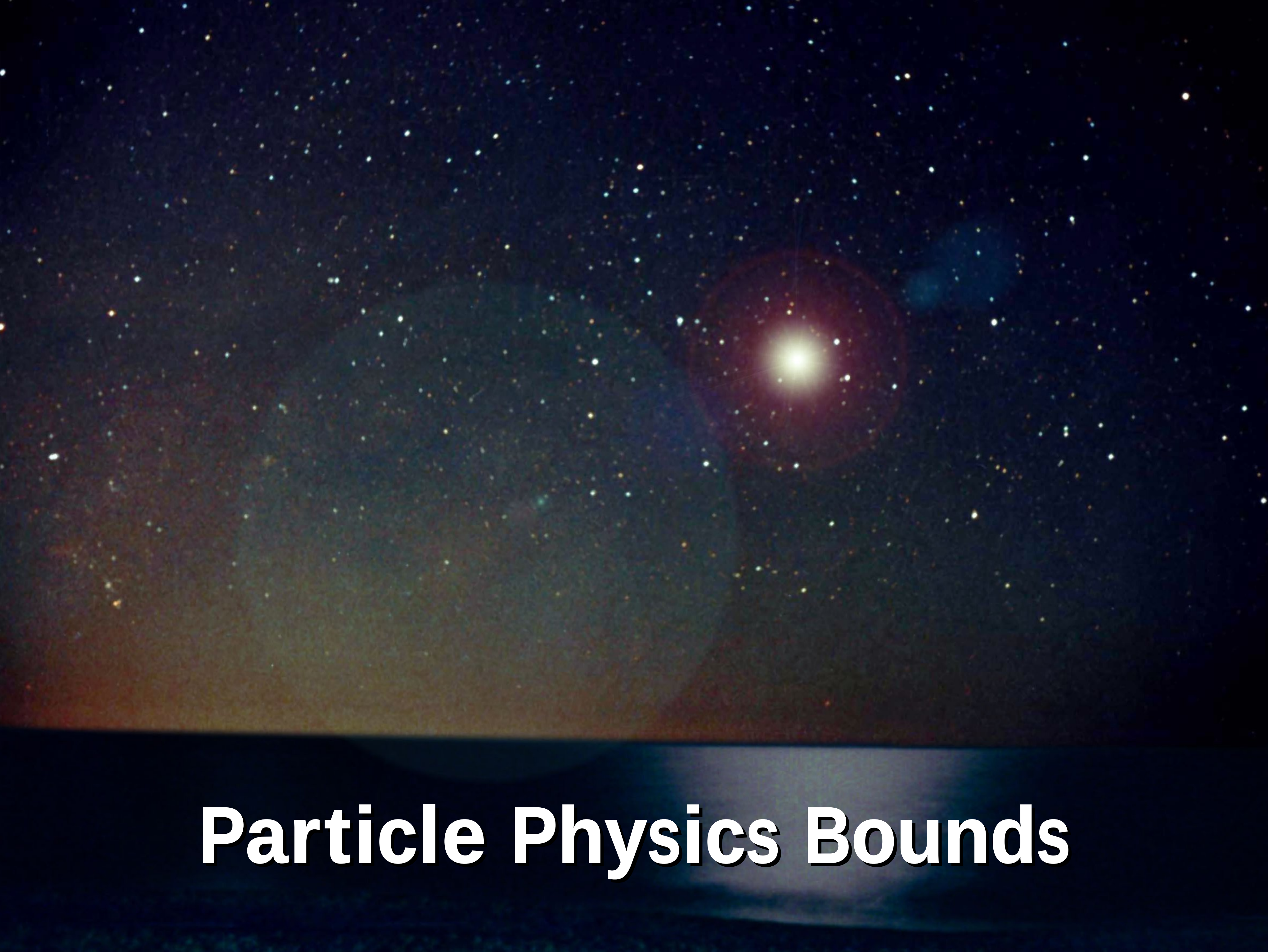
Shapiro time delay for particles moving in a gravitational potential

$$\Delta t_{\text{Shapiro}} = -2\int_A^B U[r(t)]\,dt \approx 1-5\ \text{months}$$

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

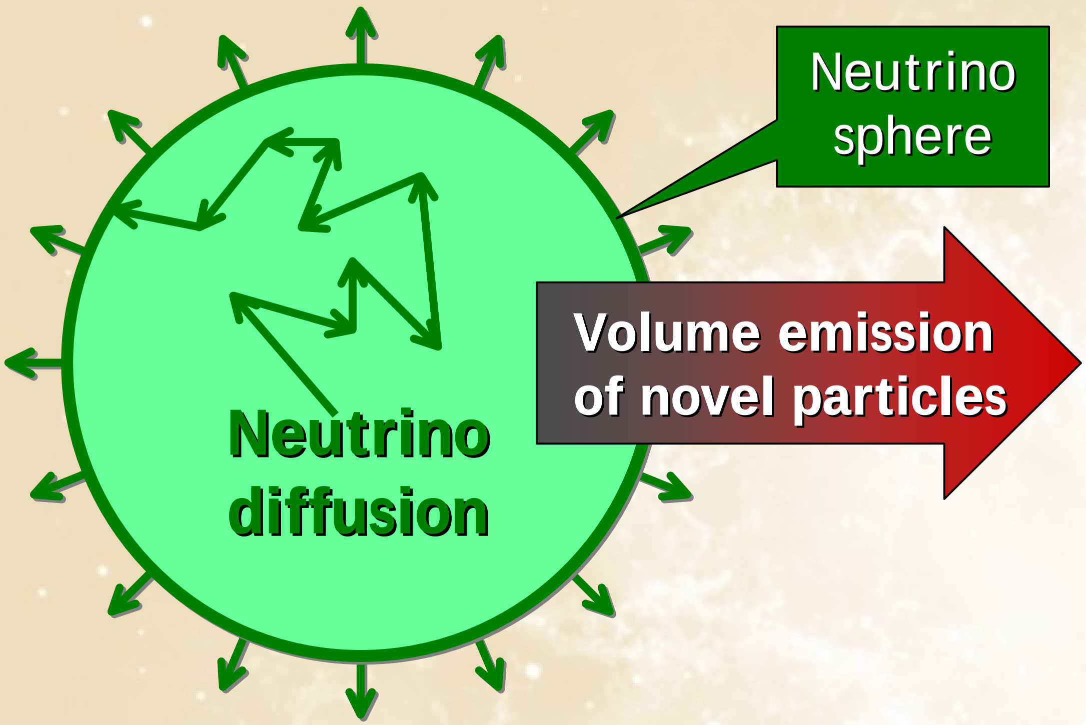
Equal within ~ 1 – 4 $\times 10^{-3}$

- Proves directly that neutrinos respond to gravity in the usual way because for photons gravitational lensing already proves this point
- Cosmological limits $\Delta N_\nu \lesssim 1$ much worse test of neutrino gravitation
- Provides limits on parameters of certain non-GR theories of gravitation



Particle Physics Bounds

The Energy-Loss Argument

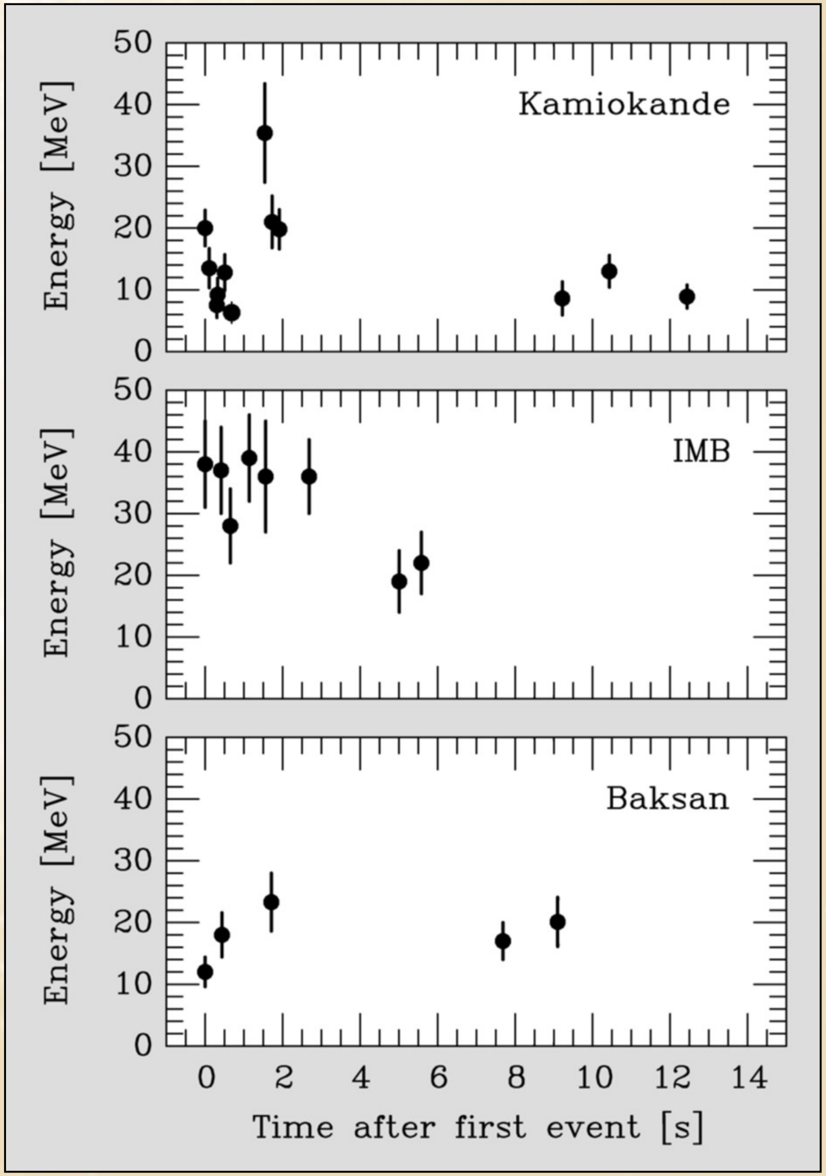


Neutrino sphere

Volume emission of novel particles

Neutrino diffusion

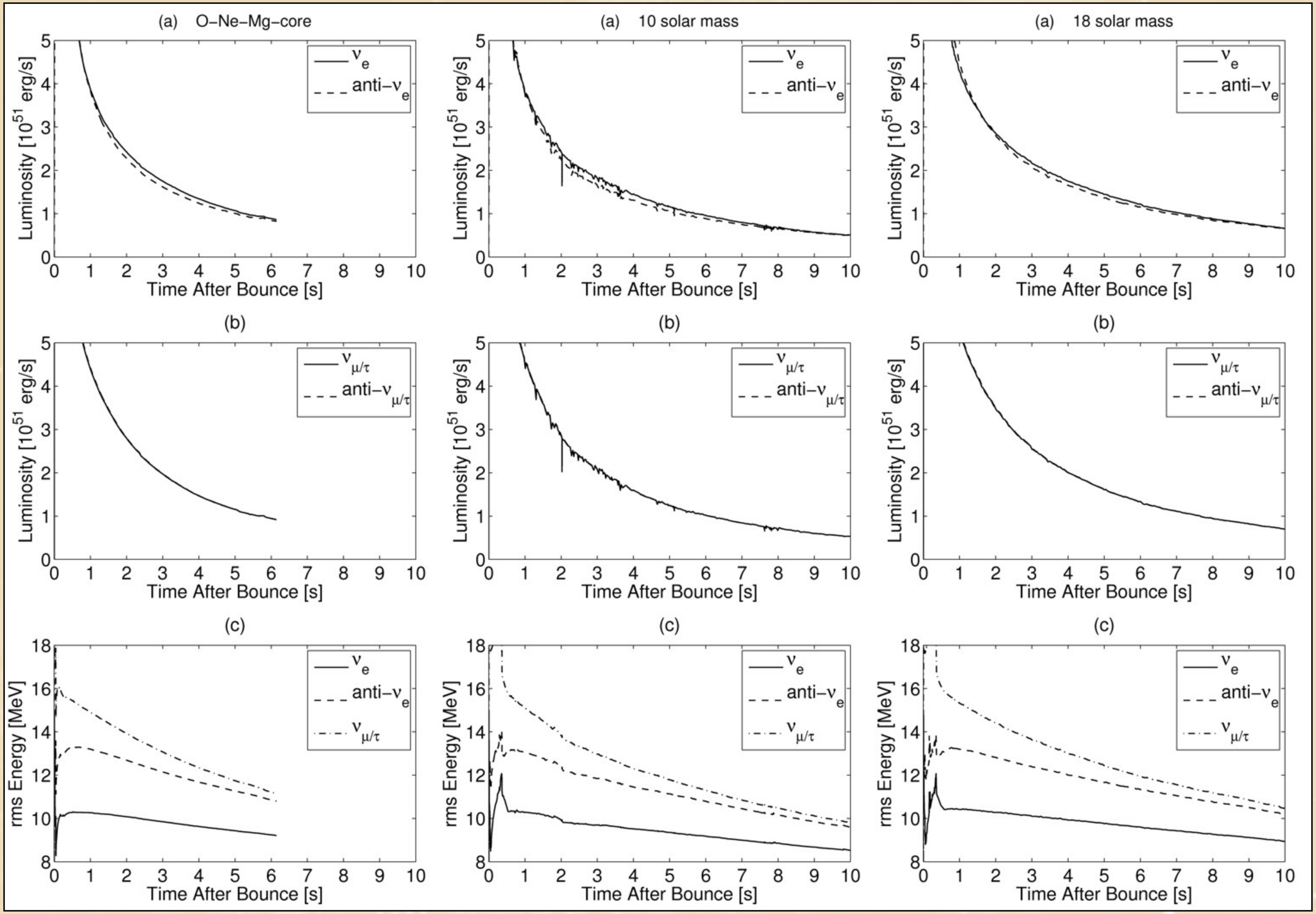
SN 1987A neutrino signal



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

New Long-Term Cooling Calculations

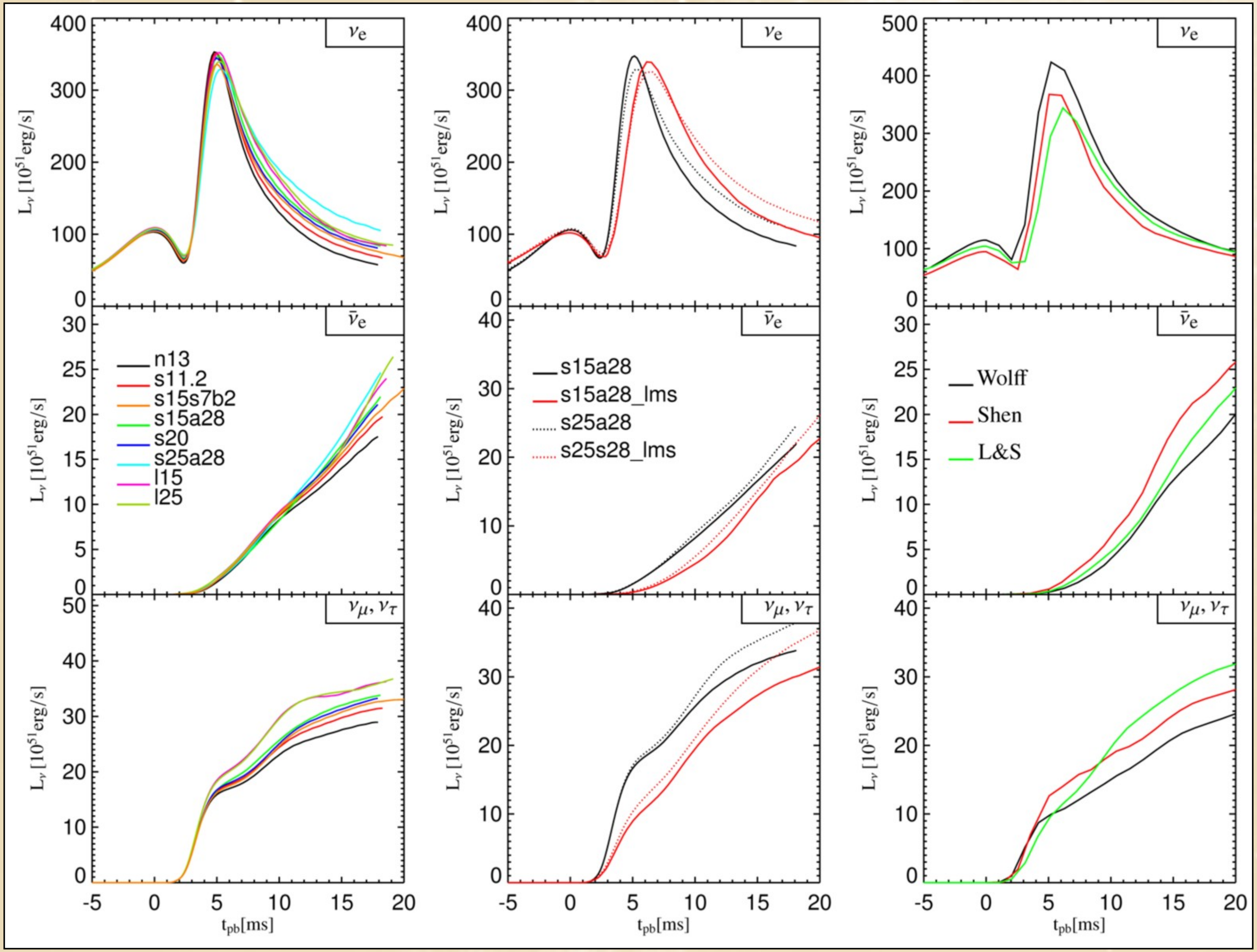


Fischer et al. (Basel Group), arXiv:0908.1871

Neutrino Flavor Oscillations

Neutrino Emission Around Bounce Time

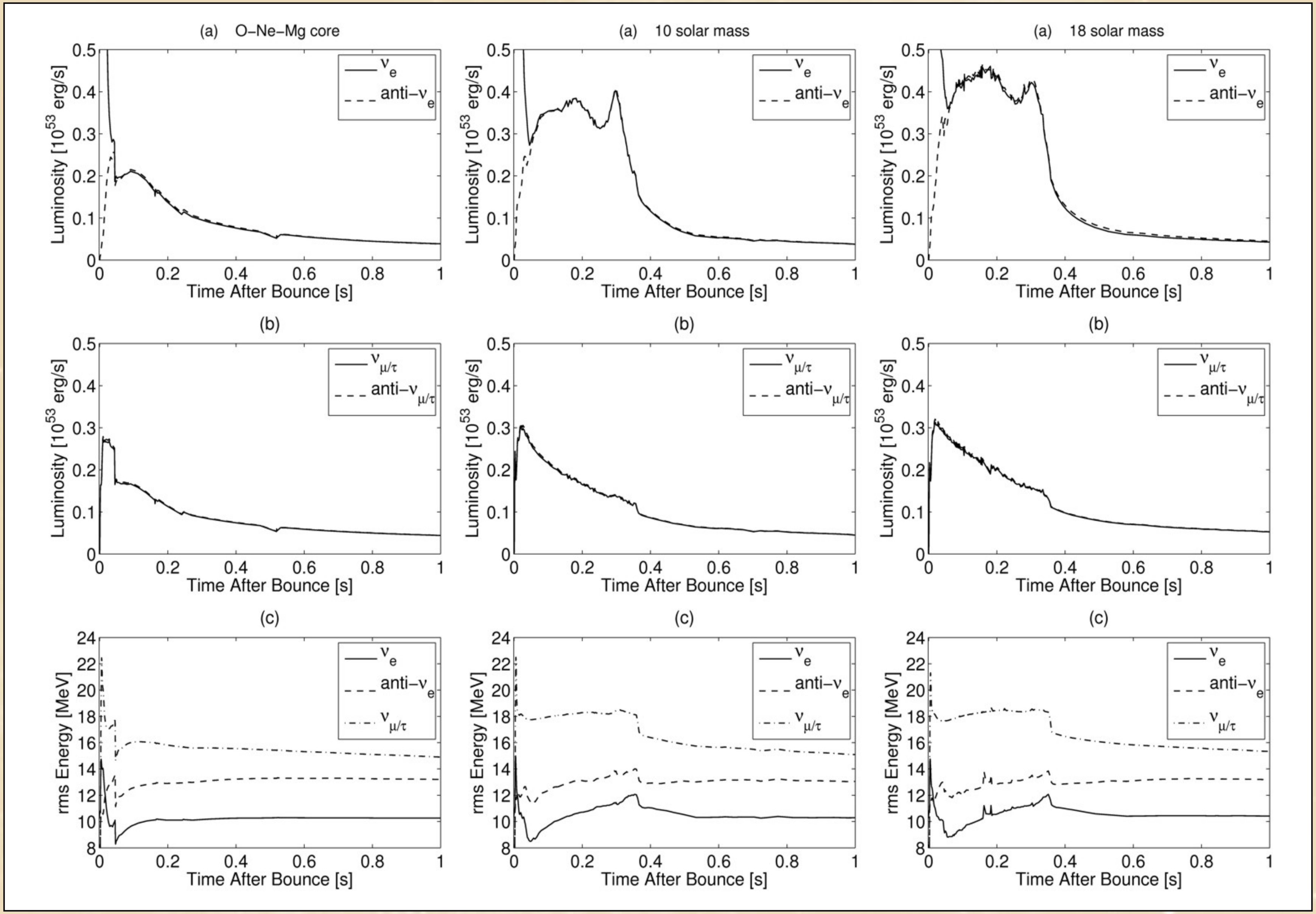
Different Mass | **Neutrino Transport** | **Nuclear EoS**



Prompt Neutronization Burst

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

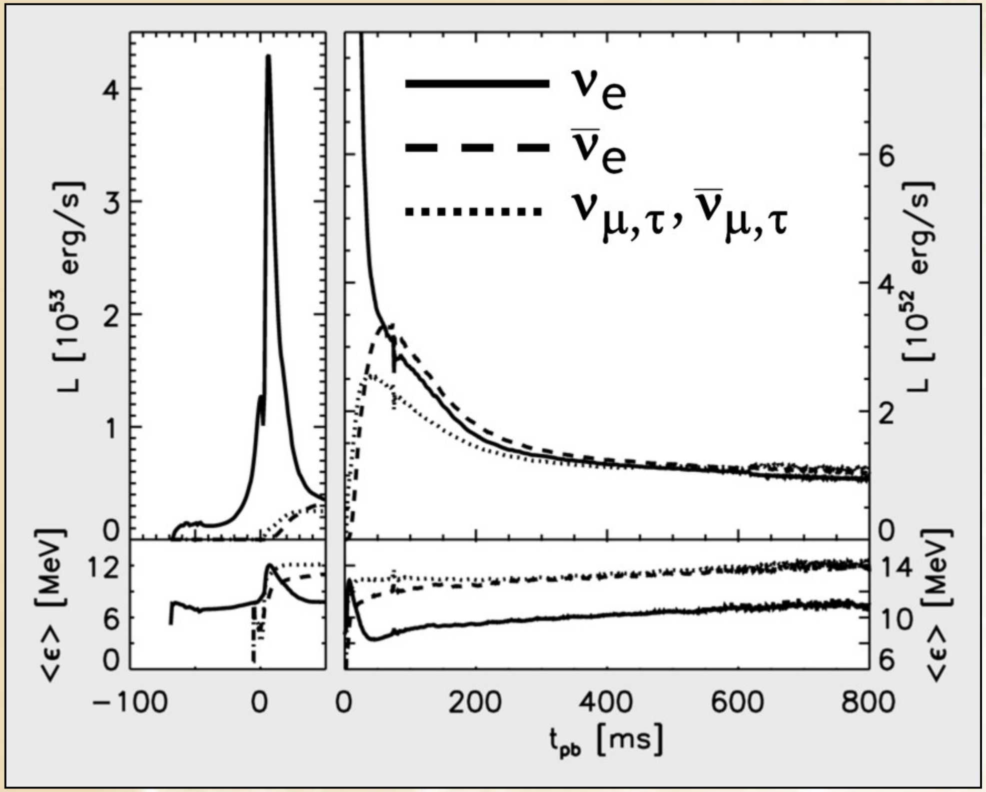
Flavor Dependence of Neutrino Emission



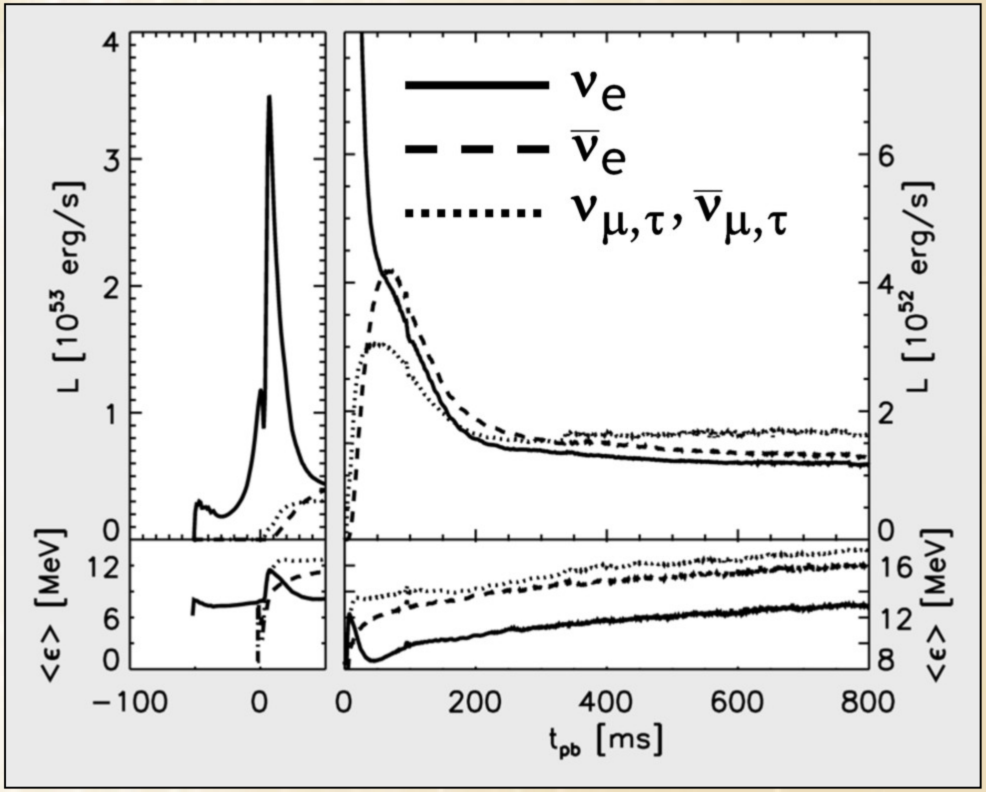
Fischer et al. (Basel Group), arXiv:0908.1871

Flavor-Dependent Neutrino Fluxes vs. Equation of State

Wolff & Hillebrandt nuclear EoS (stiff)



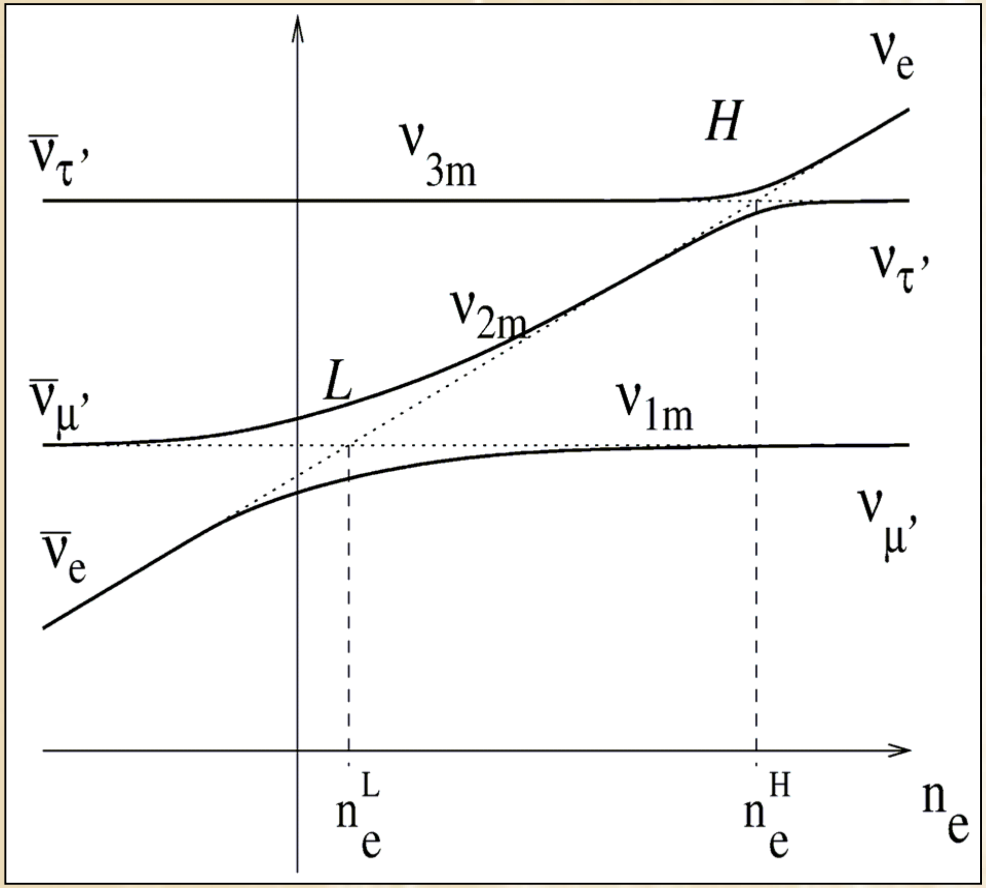
Lattimer & Swesty nuclear EoS (soft)



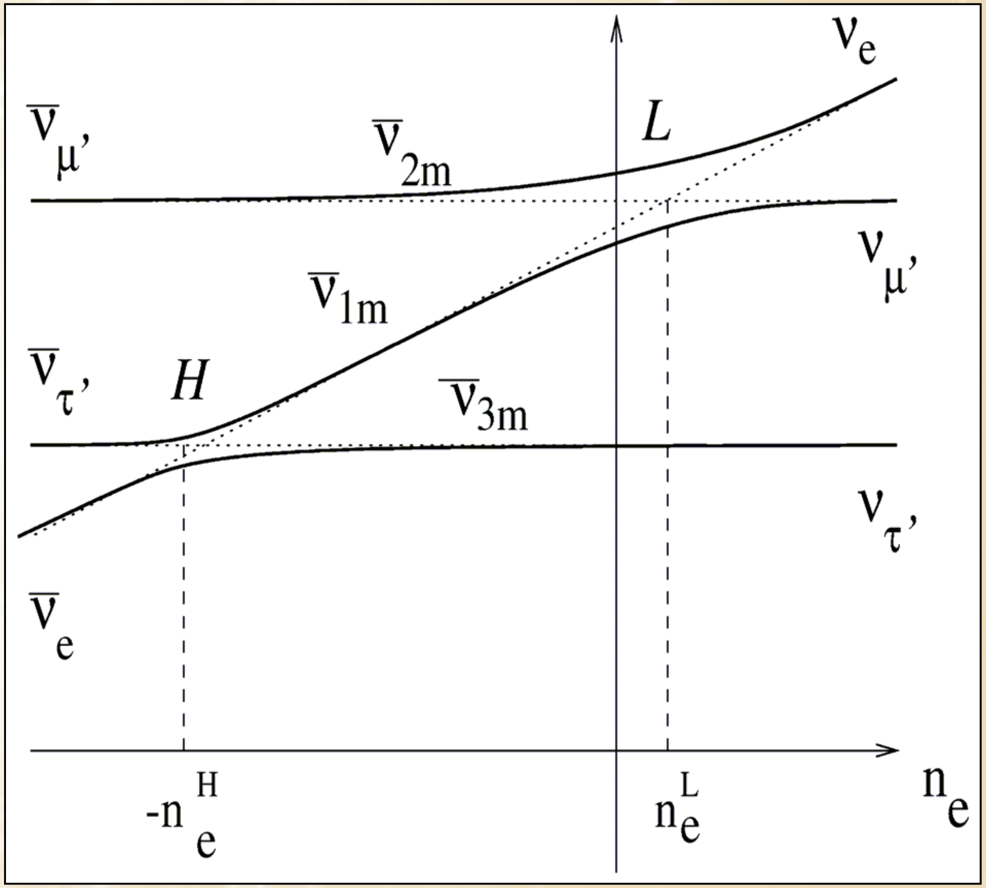
Kitaura, Janka & Hillebrandt, “Explosions of O-Ne-Mg cores, the Crab supernova, and subluminous Type II-P supernovae”, astro-ph/0512065

Level-Crossing Diagram in a SN Envelope

Normal mass hierarchy



Inverted mass hierarchy



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

Spectra Emerging from a Supernova

Primary fluxes

F_e^0 for ν_e

$F_{\bar{e}}^0$ for $\bar{\nu}_e$

F_x^0 for $\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$

After leaving the supernova envelope, the fluxes are partially swapped

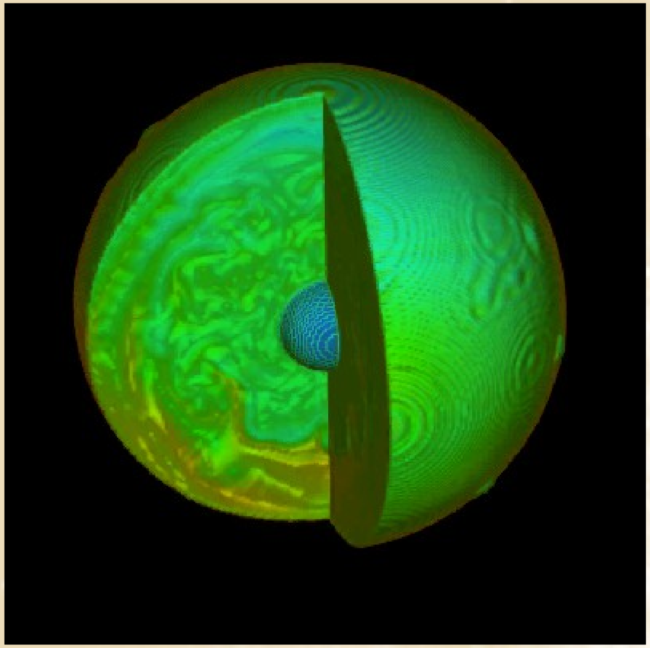
$$F_e^0 = p F_e^0 + (1-p) F_x^0$$

$$F_{\bar{e}}^0 = \bar{p} F_{\bar{e}}^0 + (1-\bar{p}) F_x^0$$

$$\frac{1}{4}\sum F_x = \frac{2+p+\bar{p}}{4} F_x^0 + \frac{1-p}{4} F_e^0 + \frac{1-\bar{p}}{4} F_{\bar{e}}^0$$

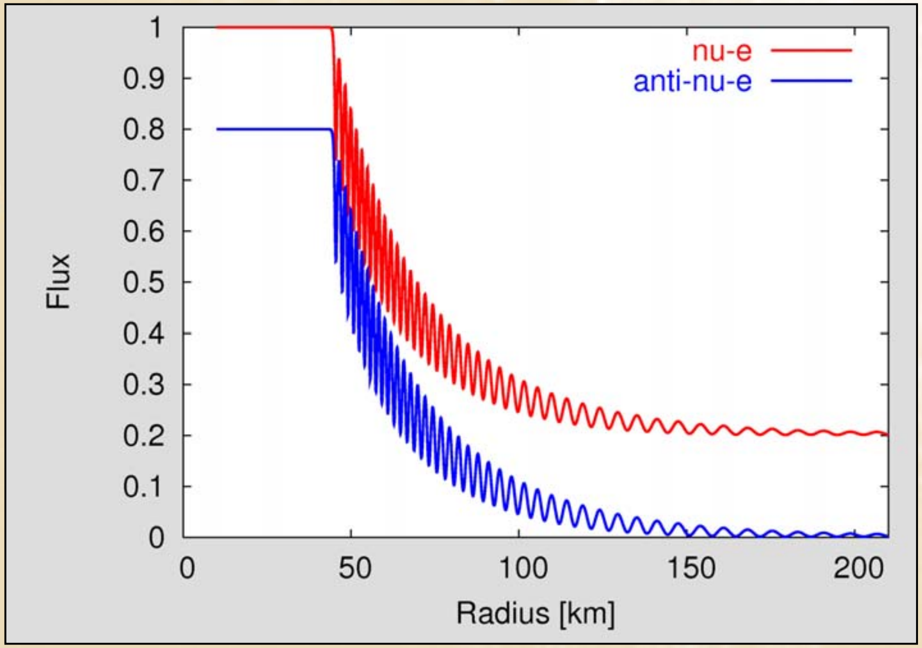
Case	Mass ordering	$\sin^2(2\Theta_{13})$	Survival probability	
			p (for ν_e)	$\bar{p}$ (for $\bar{\nu}_e$)
A	Normal	$\gtrsim 10^{-3}$	0	$\cos^2(\Theta_{12})$
B	Inverted		$\sin^2(\Theta_{12})$	0
C	Any	$\lesssim 10^{-5}$	$\sin^2(\Theta_{12})$	$\cos^2(\Theta_{12})$

Collective Effects in Neutrino Flavor Oscillations



Collapsed supernova core or accretion torus of merging neutron stars:

- Neutrino flux very dense: Up to 10^{35} cm^{-3}
- Neutrino-neutrino interaction energy much larger than vacuum oscillation frequency
- Large “matter effect” of neutrinos on each other
- Non-linear oscillation effects



- 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)

Collective SN Neutrino 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

Duan, Fuller, Carlson & Qian, astro-ph/0608050, 0703776, arXiv:0707.0290, 0710.1271. Duan, Fuller & Qian, arXiv:0706.4293, 0801.1363, 0808.2046. Duan, Fuller & Carlson, arXiv:0803.3650. Duan & Kneller, arXiv:0904.0974. Hannestad, Raffelt, Sigl & Wong, astro-ph/0608695. Balantekin & Pehlivan, astro-ph/0607527. Balantekin, Gava & Volpe, arXiv:0710.3112. Gava & Volpe, arXiv:0807.3418. Gava, Kneller, Volpe & McLaughlin, arXiv:0902.0317. Raffelt & Sigl, hep-ph/0701182. Raffelt & Smirnov, arXiv:0705.1830, 0709.4641. Esteban-Pretel, Pastor, Tomàs, Raffelt & Sigl, arXiv:0706.2498, 0712.1137. Esteban-Pretel, Mirizzi, Pastor, Tomàs, Raffelt, Serpico & Sigl, arXiv:0807.0659. Raffelt, arXiv:0810.1407. Fogli, Lisi, Marrone & Mirizzi, arXiv:0707.1998. Fogli, Lisi, Marrone & Tamborra, arXiv:0812.3031, 0907.5115. Lunardini, Müller & Janka, arXiv:0712.3000. Dasgupta & Dighe, arXiv:0712.3798. Dasgupta, Dighe & Mirizzi, arXiv:0802.1481. Dasgupta, Dighe, Mirizzi & Raffelt, arXiv:0801.1660, 0805.3300. Dasgupta, Dighe, Raffelt & Smirnov, arXiv:0904.3542. Sawyer, arXiv:0803.4319. Chakraborty, Choubey, Dasgupta & Kar, arXiv:0805.3131. Blennow, Mirizzi & Serpico, arXiv:0810.2297. Wei Liao, arXiv:0904.0075, 0904.2855.

General Equations of Motion

ν

$$i\partial_t \rho_{\vec{p}} = +\left[\frac{M^2}{2p}, \rho_{\vec{p}}\right] + \sqrt{2}G_F[L,\rho_{\vec{p}}] + \sqrt{2}G_F\int\frac{d^3\vec{q}}{(2\pi)^3}(1-\cos\theta_{\vec{p}\vec{q}})[(\rho_{\vec{q}}-\bar{\rho}_{\vec{q}}),\rho_{\vec{p}}]$$

$\bar{\nu}$

$$i\partial_t \bar{\rho}_{\vec{p}} = -\left[\frac{M^2}{2p}, \bar{\rho}_{\vec{p}}\right] + \sqrt{2}G_F[L,\bar{\rho}_{\vec{p}}] + \sqrt{2}G_F\int\frac{d^3\vec{q}}{(2\pi)^3}(1-\cos\theta_{\vec{p}\vec{q}})[(\rho_{\vec{q}}-\bar{\rho}_{\vec{q}}),\bar{\rho}_{\vec{p}}]$$

- Vacuum oscillations
  M is neutrino mass matrix
- Note opposite sign between
  neutrinos and antineutrinos

Usual matter effect with

$$L = \begin{pmatrix} n_e - n_{\bar{e}} & 0 & 0 \\ 0 & n_\mu - n_{\bar{\mu}} & 0 \\ 0 & 0 & n_\tau - n_{\bar{\tau}} \end{pmatrix}$$

Nonlinear nu-nu effects are important when nu-nu interaction energy exceeds typical vacuum oscillation frequency (Do not compare with matter effect!)

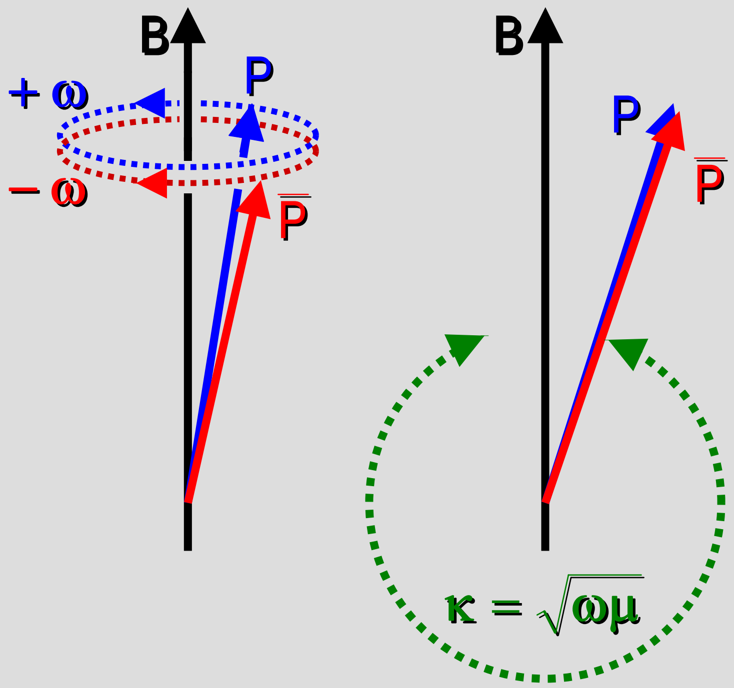
$$\omega_{\mathrm{osc}} = \frac{\Delta m^2}{2E} < \mu = \sqrt{2}\,G_F n_\nu \langle 1-\cos\theta\rangle$$

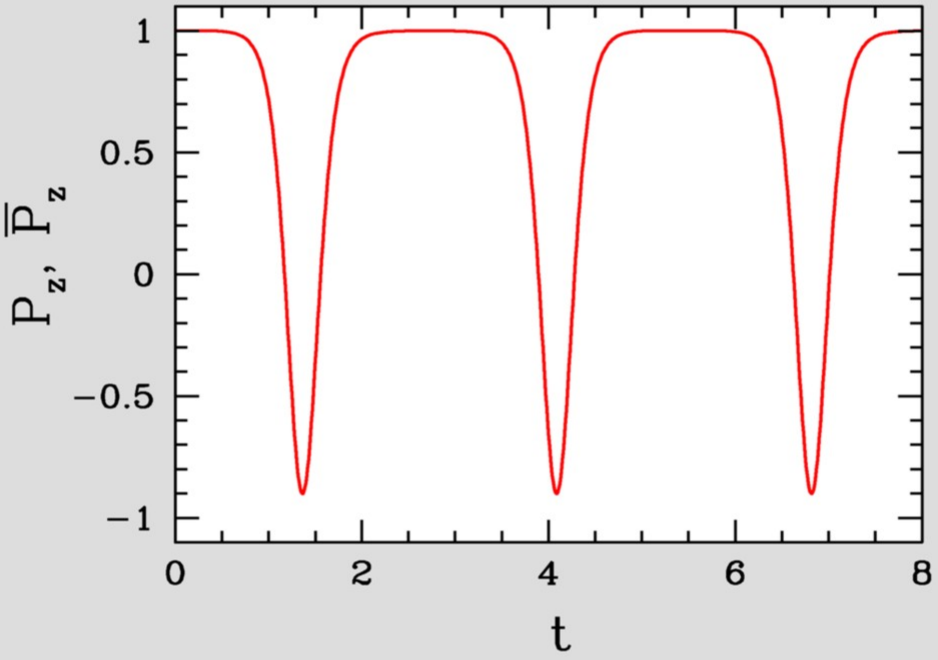
Oscillations of Neutrinos plus Antineutrinos in a Box

Equal ν_e and $\bar{\nu}_e$ densities, single energy E, with $\mu = \sqrt{2}\,G_F n_{\nu_e} \gg \omega = \frac{\Delta m^2}{2E}$

$$(\nu) \qquad \partial_t \mathbf{P} = +\omega \mathbf{B} \times \mathbf{P} + \mu (\mathbf{P} - \bar{\mathbf{P}}) \times \mathbf{P}$$

$$(\bar{\nu}) \qquad \partial_t \bar{\mathbf{P}} = \underbrace{-\omega \mathbf{B} \times \bar{\mathbf{P}}}_{\text{Opposite vacuum oscillations}} + \underbrace{\mu (\mathbf{P} - \bar{\mathbf{P}}) \times \bar{\mathbf{P}}}_{\text{Equal self terms}}$$

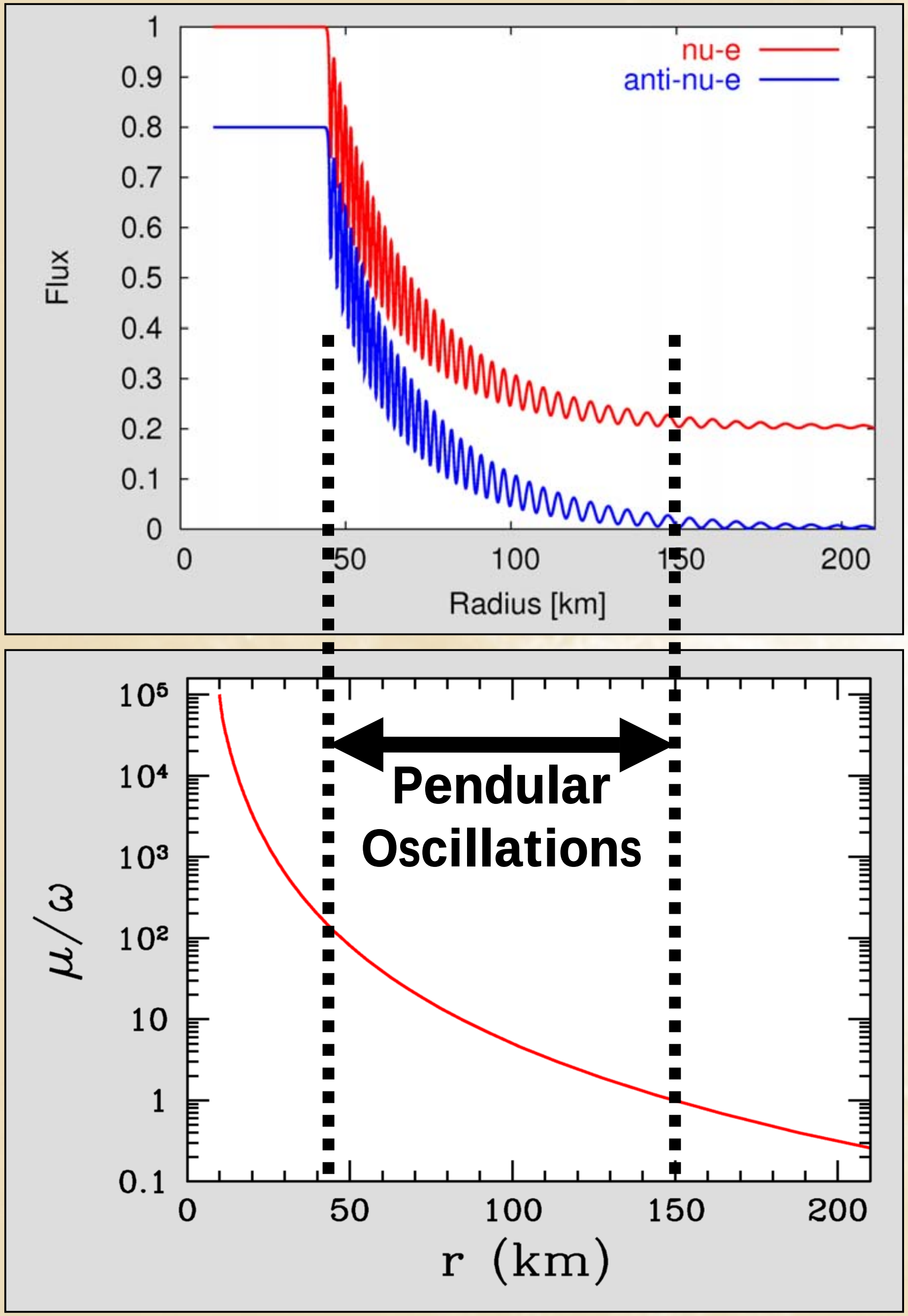




"Pendulum in flavor space"

- Inverted mass hierarchy
  → Inverted pendulum
  → Unstable even for small mixing angle
- Normal mass hierarchy
  → Small-amplitude oscillations

Flavor Conversion in Toy Supernova

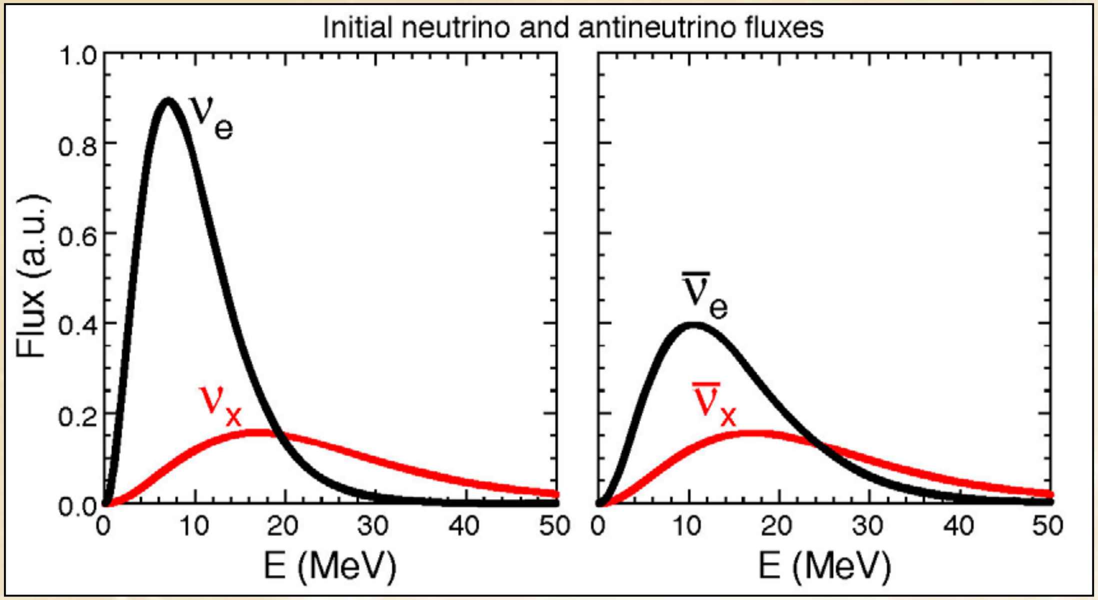


- Assume 80% anti-neutrinos
- Vacuum oscillation frequency $\omega = 0.3\ \mathrm{km}^{-1}$
- Neutrino-neutrino interaction energy at nu sphere (r = 10 km) $\mu = 0.3\times10^5\ \mathrm{km}^{-1}$
- Falls off approximately as r^{-4} (geometric flux dilution and nus become more co-linear)

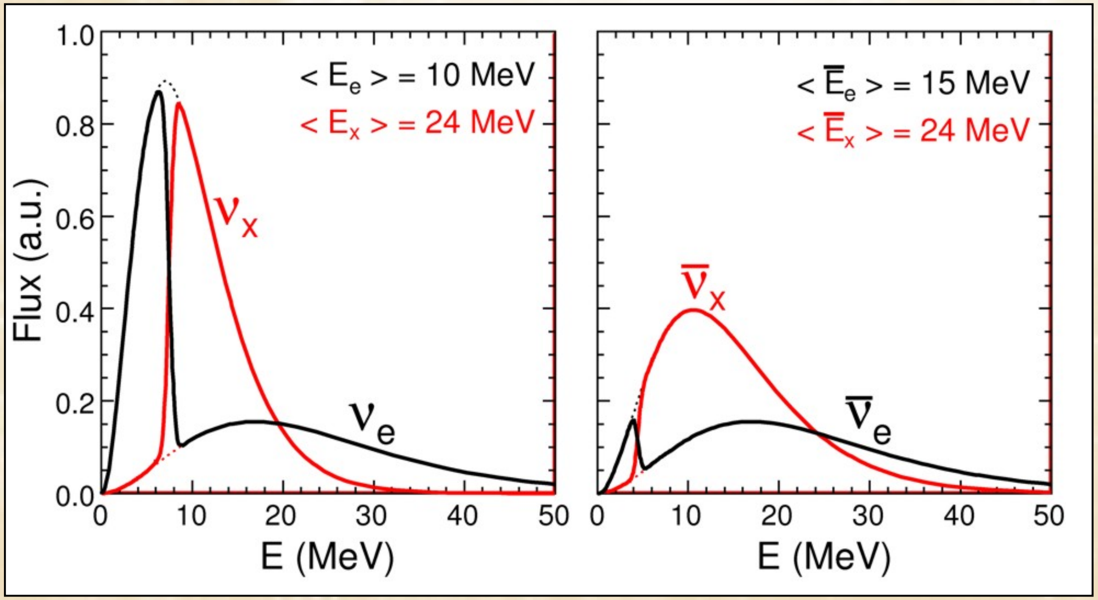
Decline of oscillation amplitude explained in pendulum analogy by inreasing moment of inertia (Hannestad, Raffelt, Sigl & Wong astro-ph/0608695)

Spectral Split for Accretion Phase Example

Initial fluxes at nu sphere



After collective trans-formation



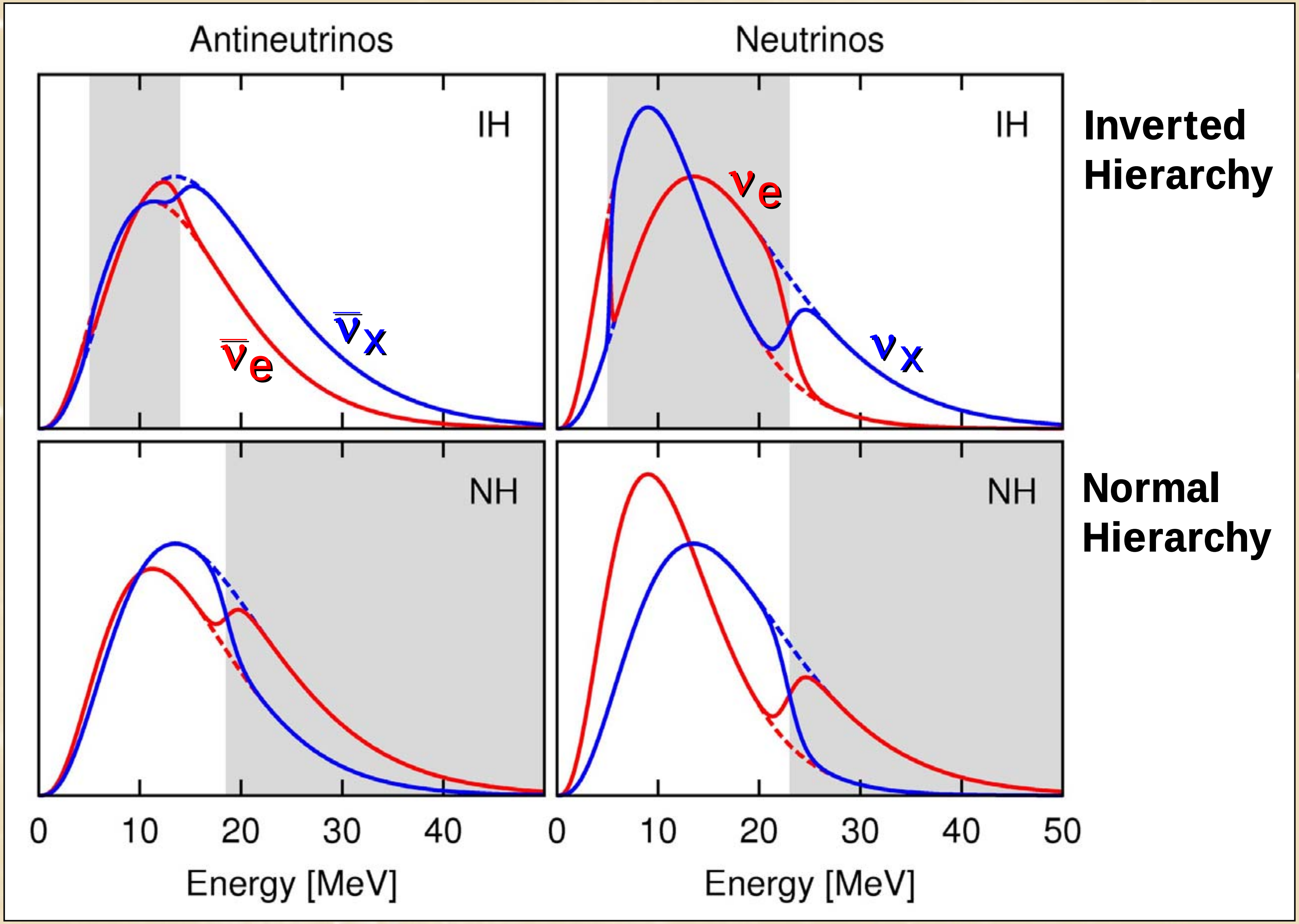
For explanation see

Raffelt & Smirnov
arXiv:0705.1830
0709.4641

Duan, Fuller,
Carlson & Qian
arXiv:0706.4293
0707.0290

Fogli et al., arXiv:0707.1998, 0808.0807

Multiple Spectral Splits (Cooling-Phase Example)

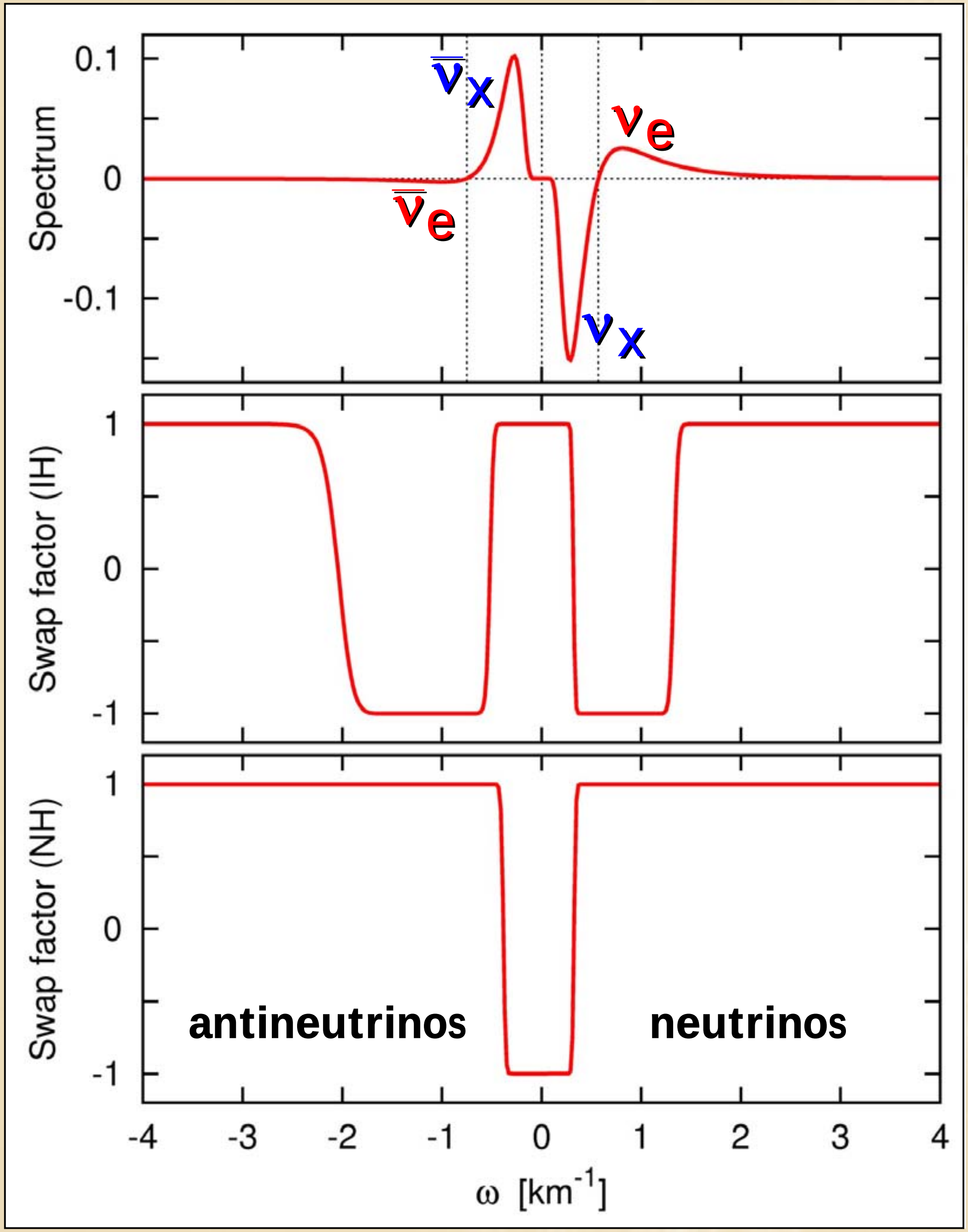


Inverted Hierarchy

Normal Hierarchy

Dasgupta, Dighe, Raffelt & Smirnov, arXiv:0904.3542

Multiple Spectral Splits in the ω Variable



Given is the flux spectrum f(E) for each flavor

Use $\omega = \Delta m^2/2E$ to label modes

Label anti-neutrinos with $-\omega$

Define "spectrum" as

$$g(\omega) \propto \begin{cases} f_{\nu_e}(E) - f_{\nu_x}(E) & \text{Neutrinos} \\ f_{\bar\nu_x}(E) - f_{\bar\nu_e}(E) & \text{Antineutrinos} \end{cases}$$

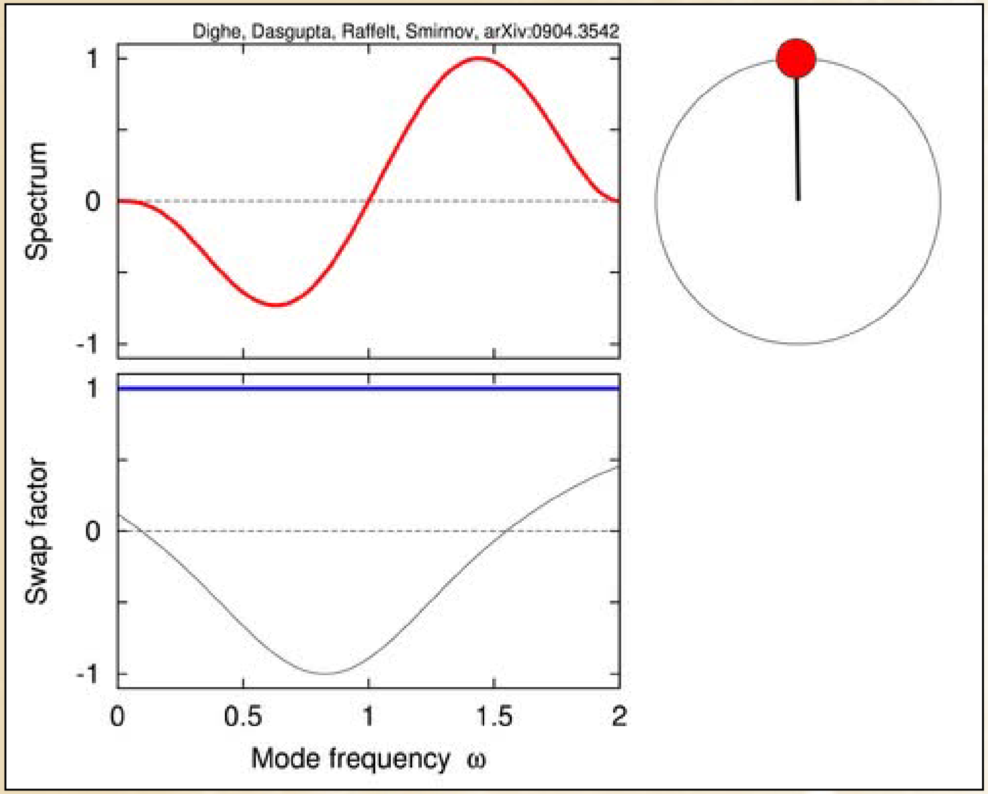
Swaps develop around every "positive" spectral crossing

Each swap flanked by two splits

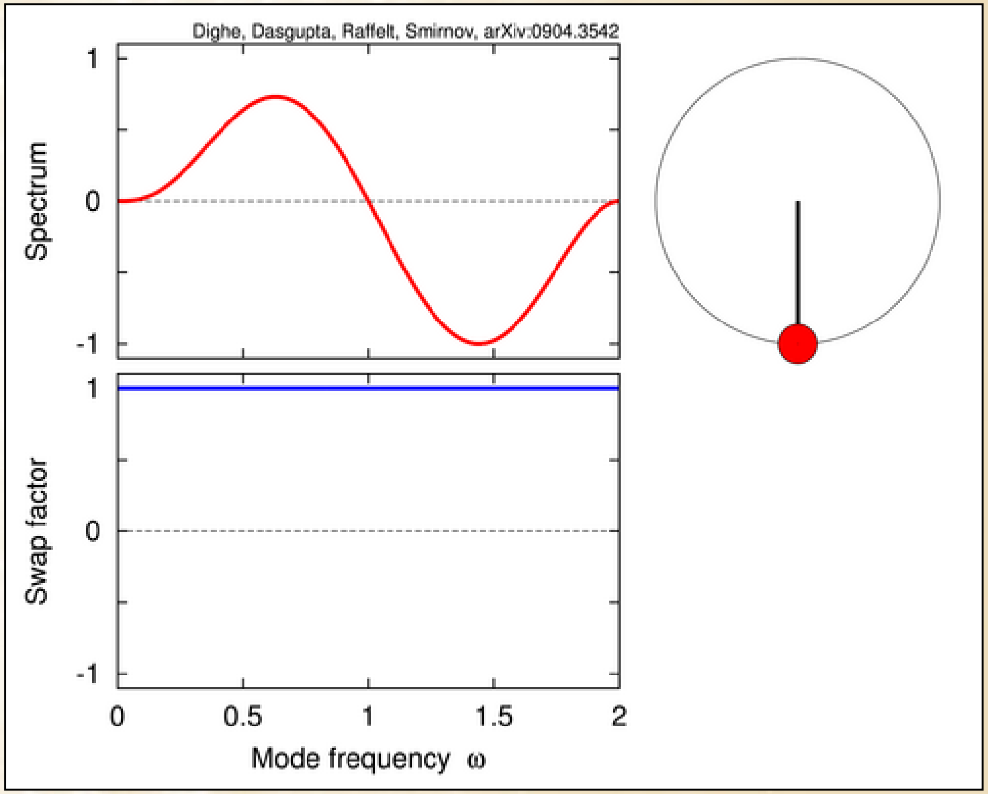
Dasgupta, Dighe, Raffelt & Smirnov, arXiv:0904.3542

Flavor Pendulum

Single “positive” crossing
(potential energy at a maximum)



Single “negative” crossing
(potential energy at a minimum)

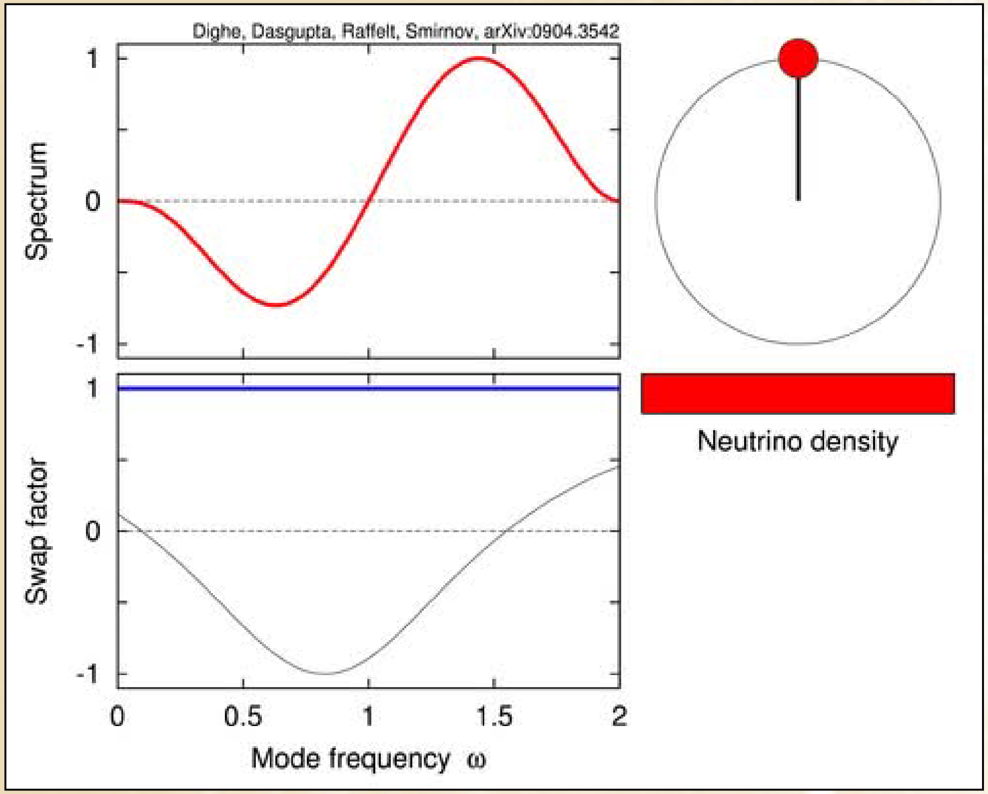


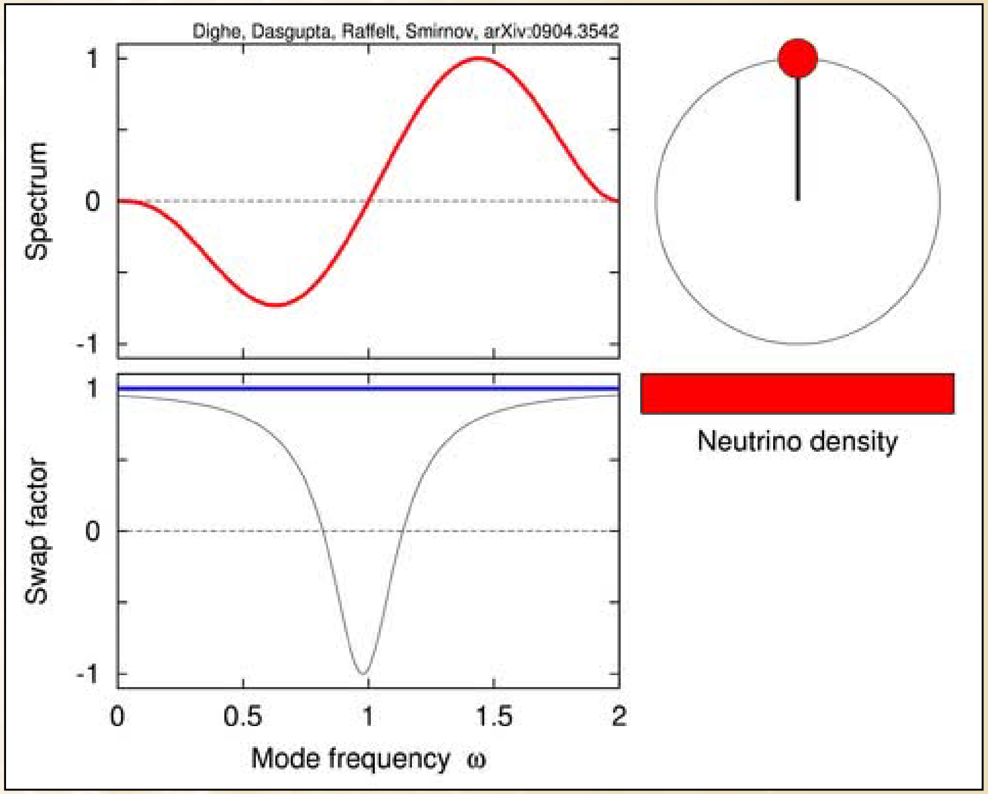
Dasgupta, Dighe, Raffelt & Smirnov, arXiv:0904.3542
For movies see http://www.mppmu.mpg.de/supernova/multisplits

Decreasing Neutrino Density

Certain initial neutrino density

Four times smaller
initial neutrino density

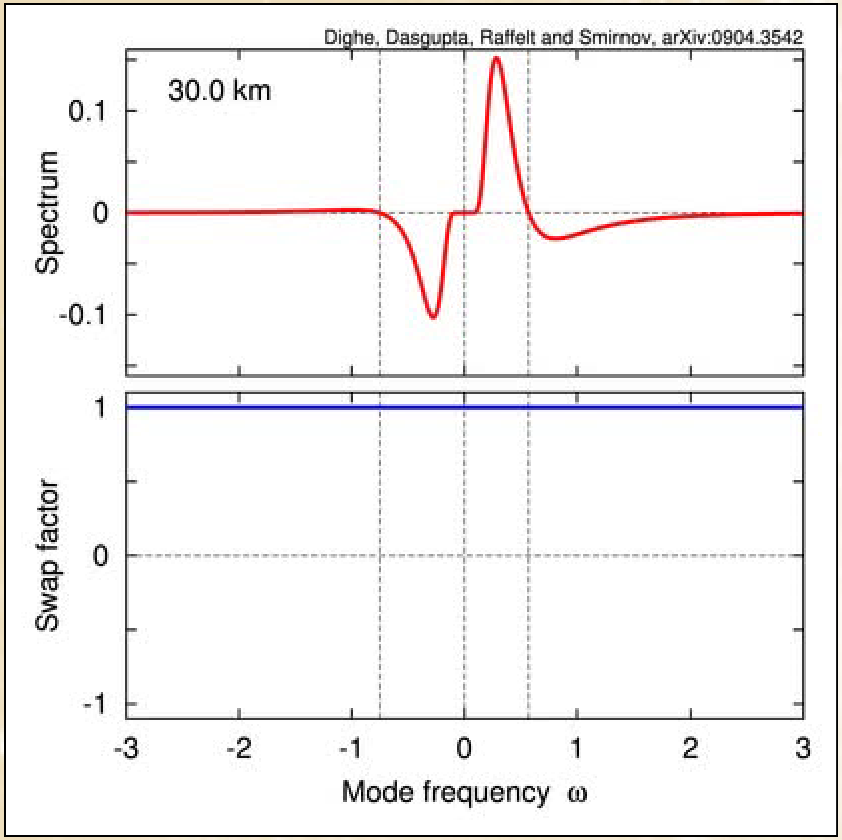




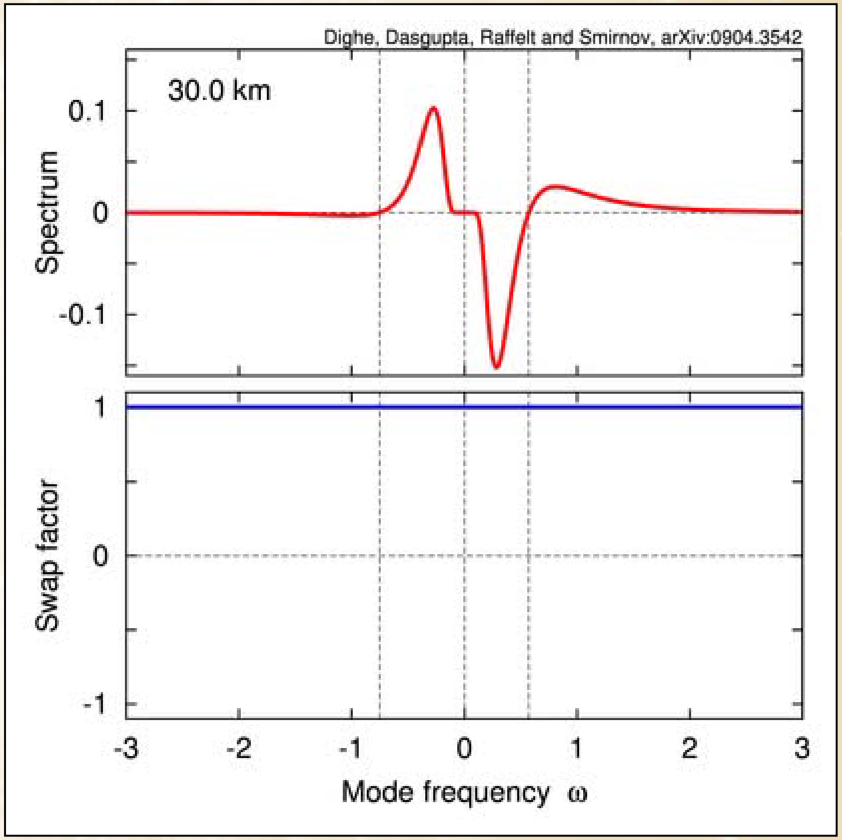
Dasgupta, Dighe, Raffelt & Smirnov, arXiv:0904.3542
For movies see http://www.mppmu.mpg.de/supernova/multisplits

Supernova Cooling-Phase Example

Normal Hierarchy

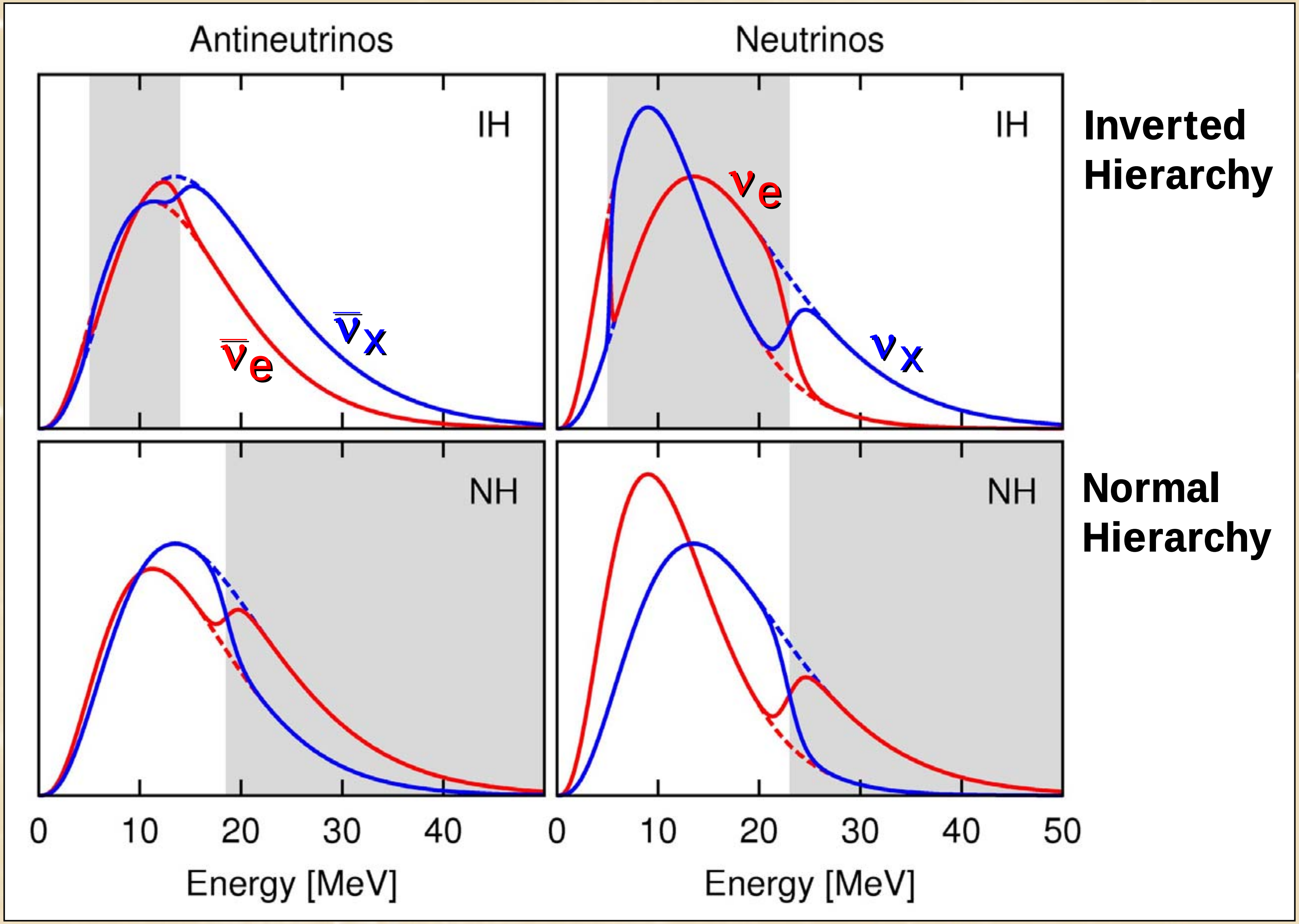


Inverted Hierarchy



Dasgupta, Dighe, Raffelt & Smirnov, arXiv:0904.3542
For movies see http://www.mppmu.mpg.de/supernova/multisplits

Multiple Spectral Splits (Cooling-Phase Example)



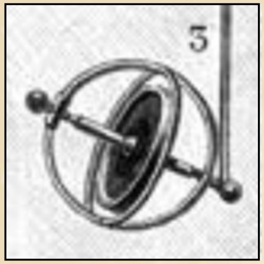
Inverted Hierarchy

Normal Hierarchy

Dasgupta, Dighe, Raffelt & Smirnov, arXiv:0904.3542

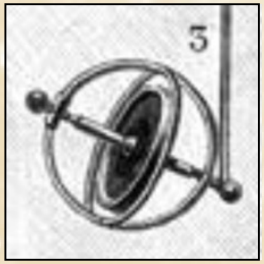
Questions and Opportunities

Self-induced collective oscillations occur even for very small 13-mixing (instability!)



Observation of spectral split or swap indication can provide signature for mass hierarchy and nontrivial neutrino propagation dynamics

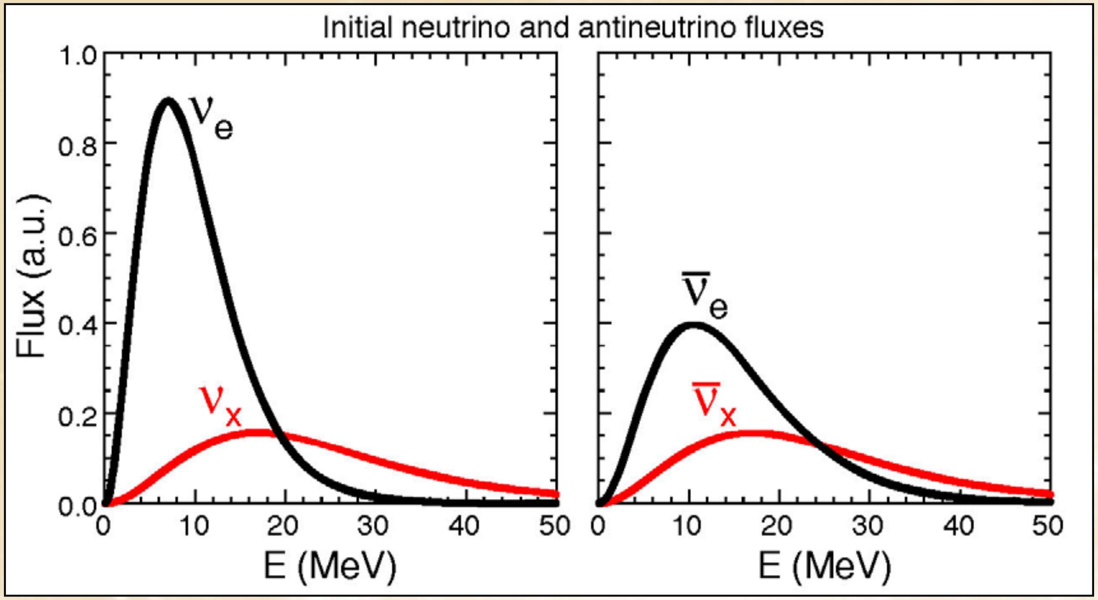
Do matter-density fluctuations have any realistic impact?



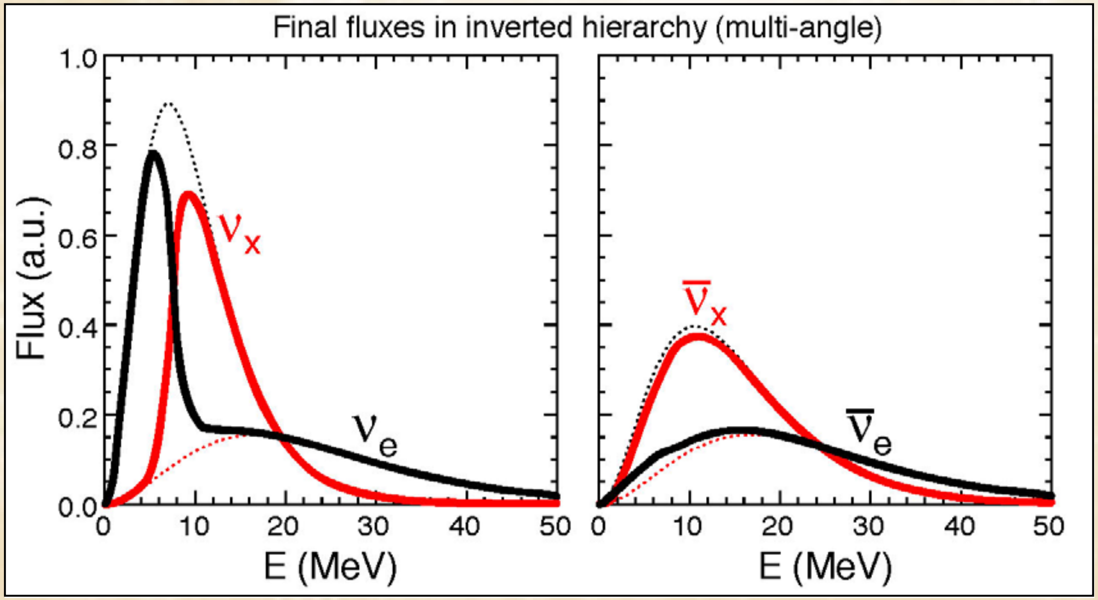
Theoretical understanding and role of "multi-angle effects" largely missing

Spectral Split (Accretion-Phase Example)

Initial fluxes at neutrino sphere



After collective trans-formation



For explanation see

Raffelt & Smirnov
arXiv:0705.1830
0709.4641

Duan, Fuller, Carlson & Qian
arXiv:0706.4293
0707.0290

Fogli, Lisi, Marrone & Mirizzi, arXiv:0707.1998

Distinguishing Mixing Scenarios

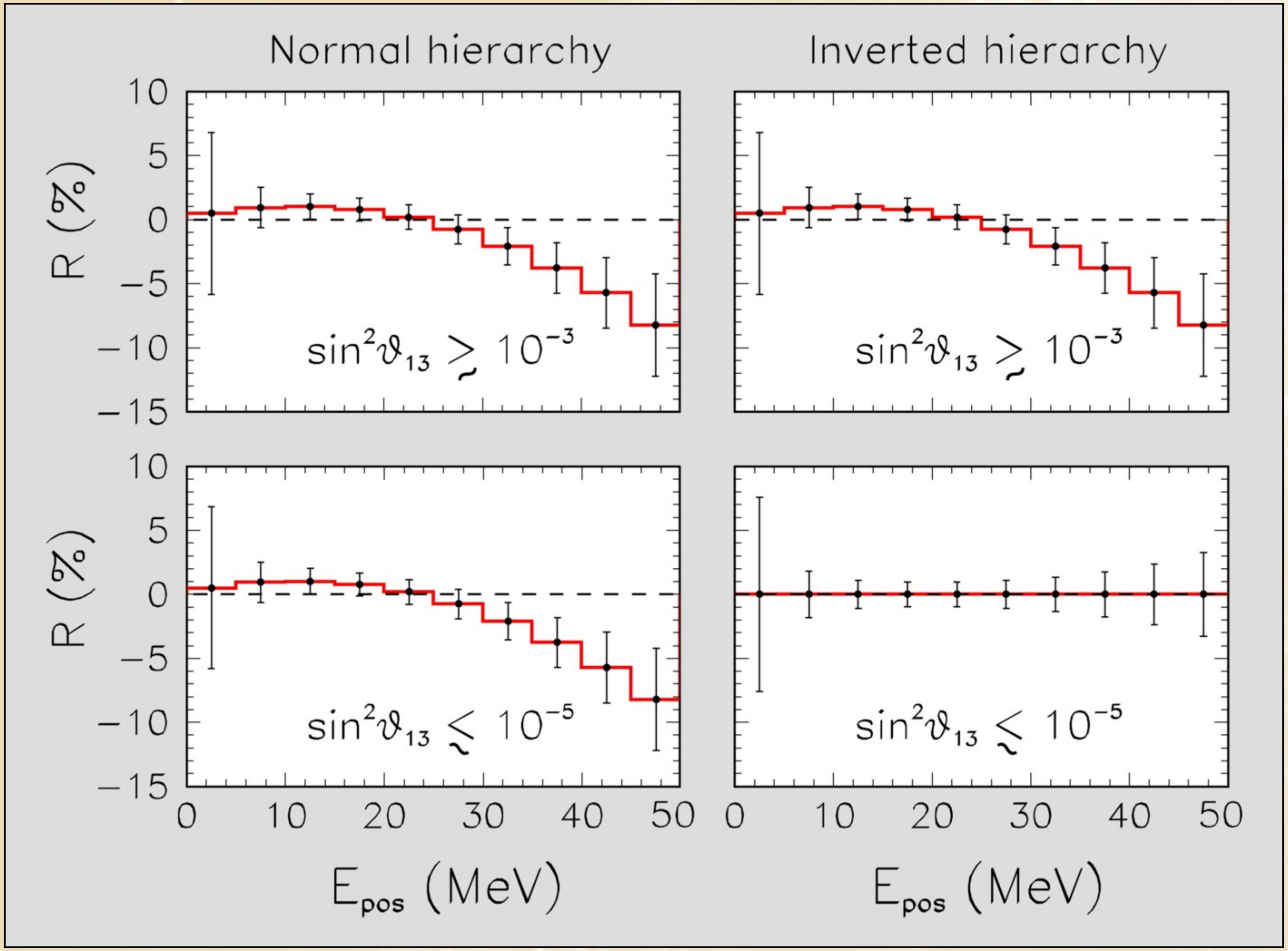
Hierarchy	$\sin^2\Theta_{13}$	Survival Probability			Earth effects
		ν_e		$\bar{\nu}_e$	
		$E < E_{split}$	$E > E_{split}$		
Normal	$\gtrsim 10^{-3}$	0	0	$\cos^2\Theta_{12}$	$\bar{\nu}_e$
Inverted		$\sin^2\Theta_{12}$			
Normal	$\lesssim 10^{-5}$		$\sin^2\Theta_{12}$		$\bar{\nu}_e$ ν_e
Inverted			0	0	–

- Assuming “standard” flux spectra leading to a single split
- Probably generic for accretion phase

Adapted from Dighe, arXiv:0809.2977

Mass Hierarchy at Extremely Small Theta-13

Using Earth matter effects to diagnose transformations



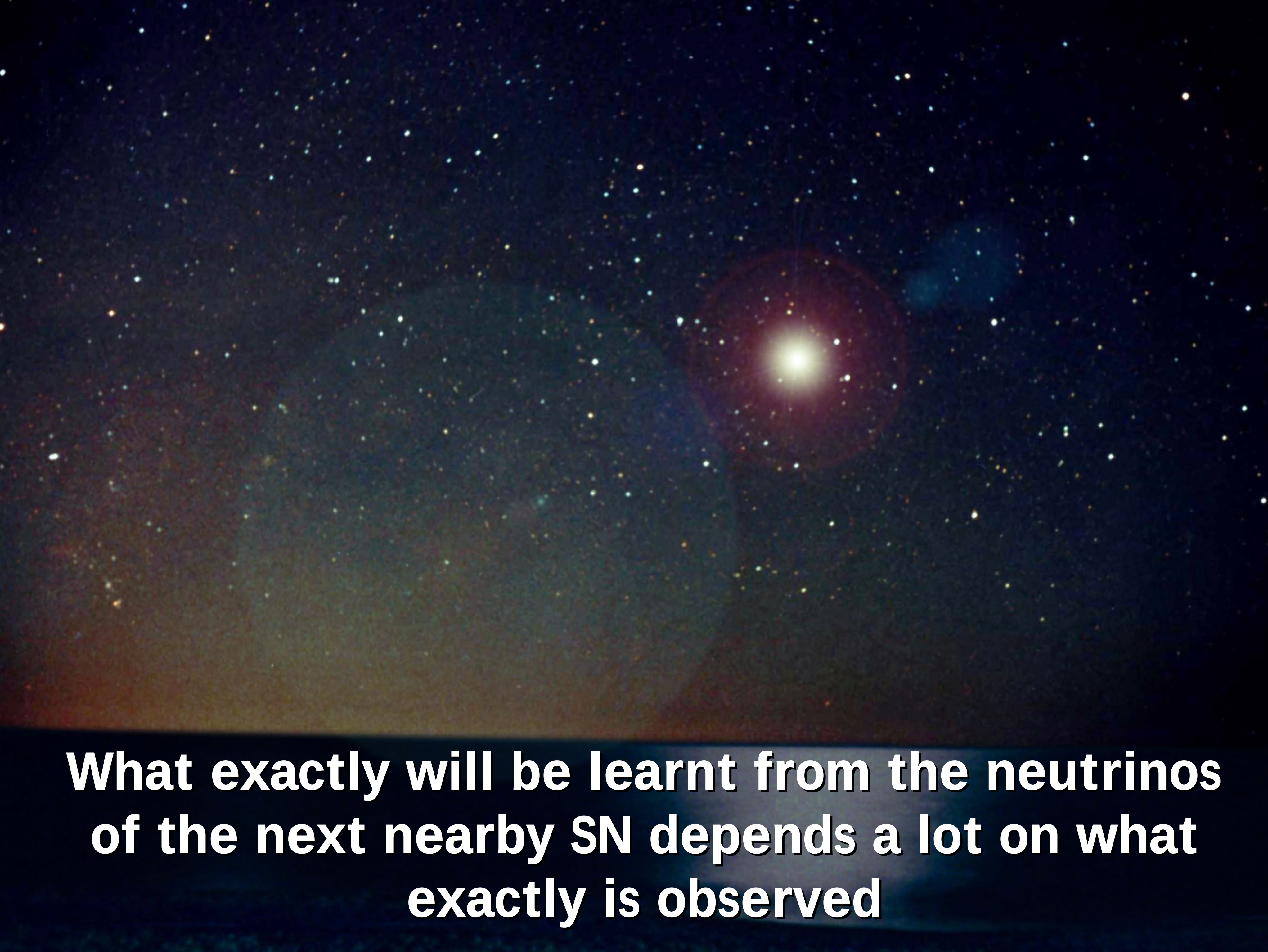
Ratio of spectra in two water Cherenkov detectors (0.4 Mton), one shadowed by the Earth, the other not

Dasgupta, Dighe & Mirizzi, arXiv:0802.1481

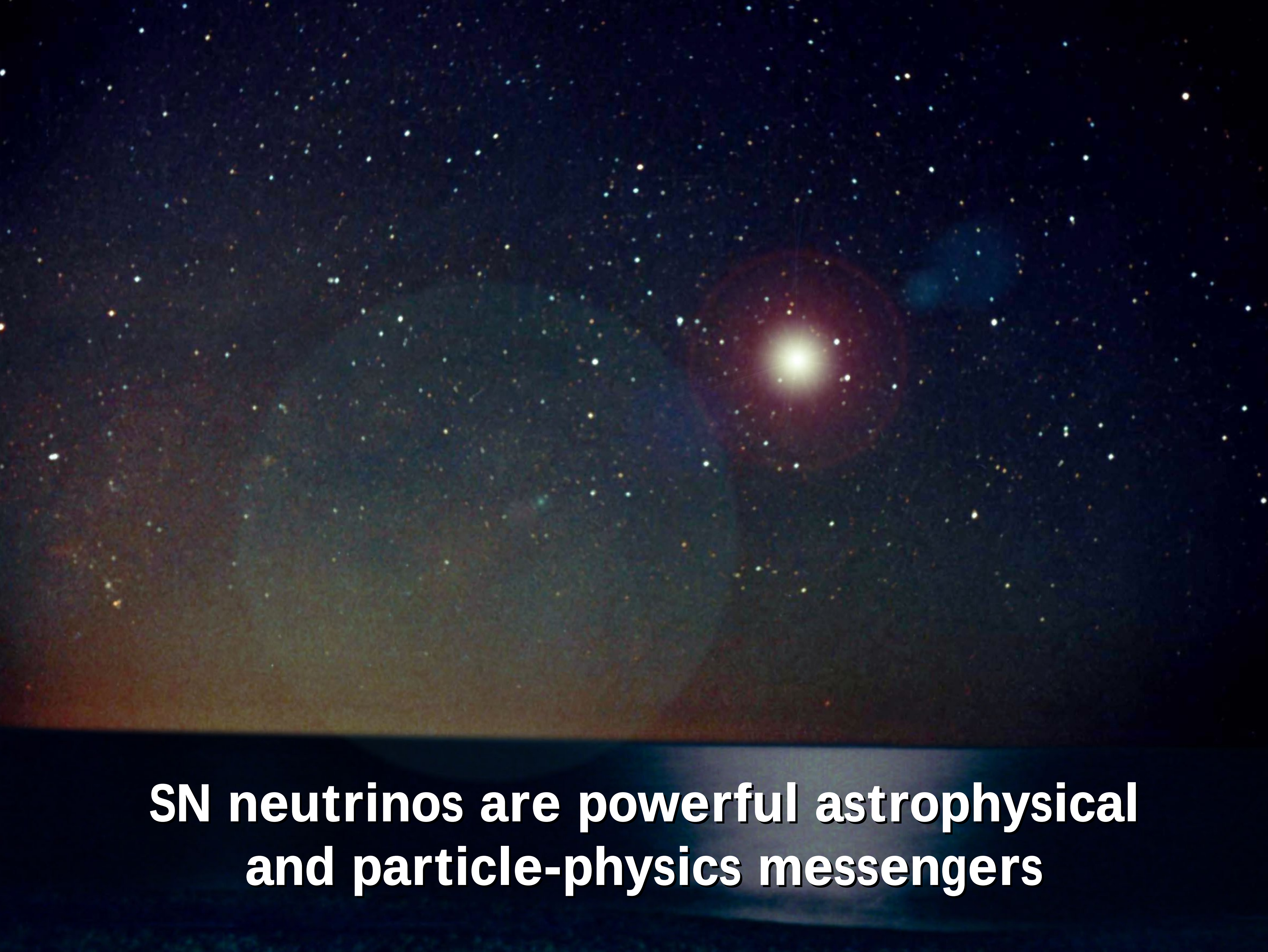
Diagnosing Collective Transformations

Assuming the mass ordering is measured to be inverted in the lab,
the presence or absence of Earth effects distinguishes between
the presence or not of collective transformations

		Collective Transformations			
		No		Yes	
Hierarchy	$\sin^2\Theta_{13}$	$\bar{\nu}_e$ survival probability	$\bar{\nu}_e$ Earth effects	$\bar{\nu}_e$ survival probability	$\bar{\nu}_e$ Earth effects
Normal	$\gtrsim 10^{-3}$	$\cos^2\Theta_{12}$	Yes	$\cos^2\Theta_{12}$	Yes
Inverted		0	No		
Normal	$\lesssim 10^{-5}$	$\cos^2\Theta_{12}$	Yes		
Inverted				0	No



What exactly will be learnt from the neutrinos of the next nearby SN depends a lot on what exactly is observed



SN neutrinos are powerful astrophysical
and particle-physics messengers