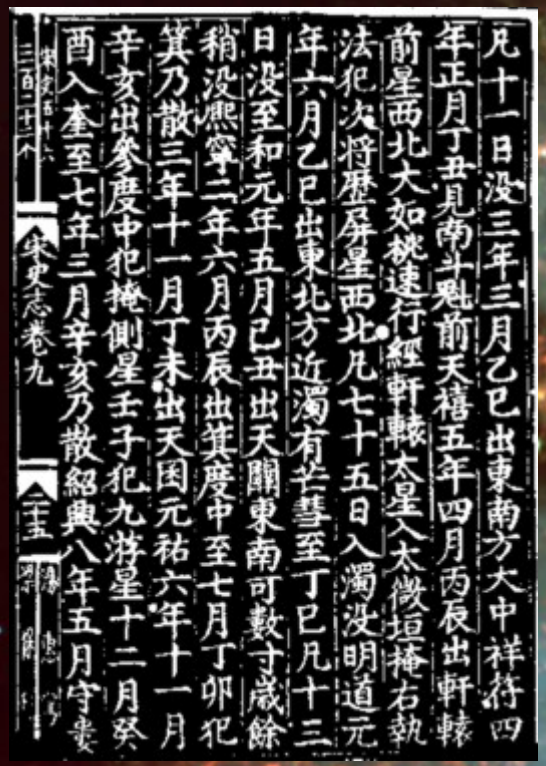
Tea-Colloquium MPI Kernphysik, 9 July 2009
and TR27 Meeting “Neutrinos and Beyond”

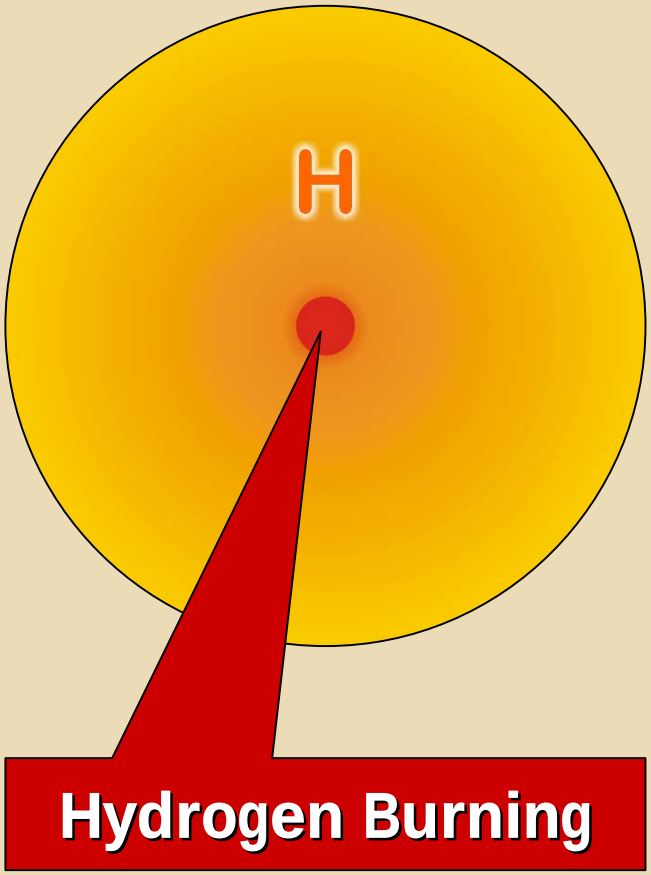

凡十一日没三年三月乙巳出東南方大中祥符四
年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅
前星西北大如桃速行經軒轅太星入太微垣掩右執
法犯次將歷屏星西北凡七十五日入濁没明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日没至和元年五月己丑出天關東南可數寸歲餘
稍没熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九游星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁
宋史志卷九

Supernova Neutrinos

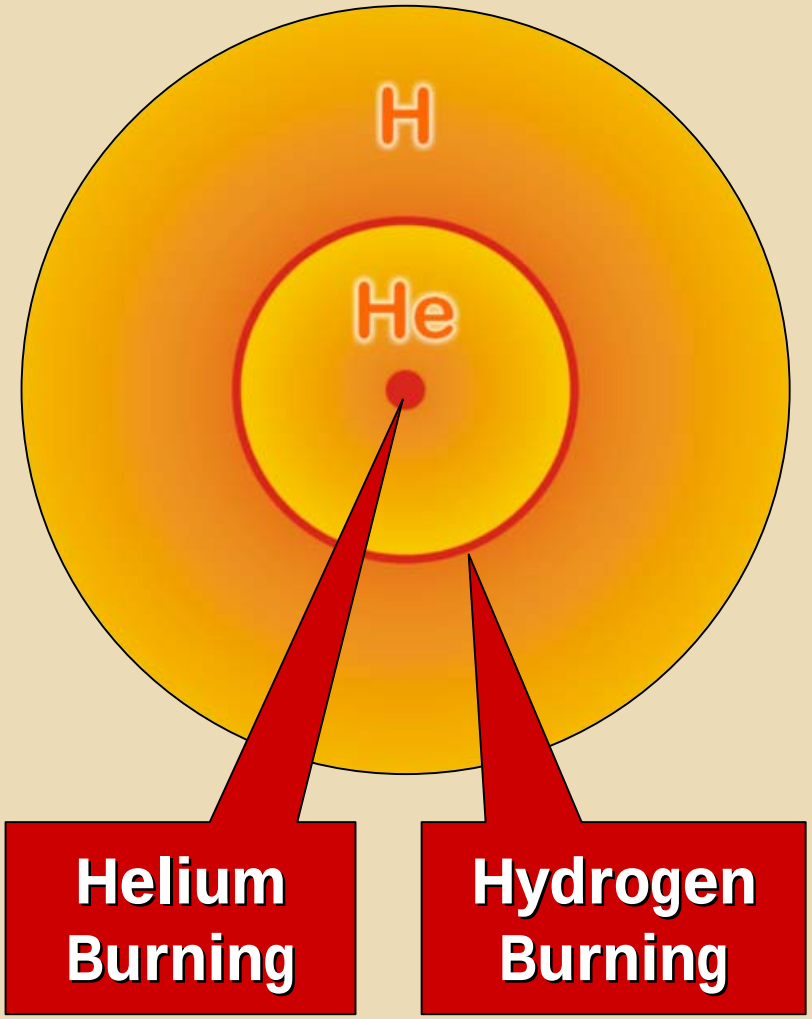
Georg Raffelt, Max-Planck-Institut für Physik, München

Stellar Collapse and Supernova Explosion

Main-sequence star



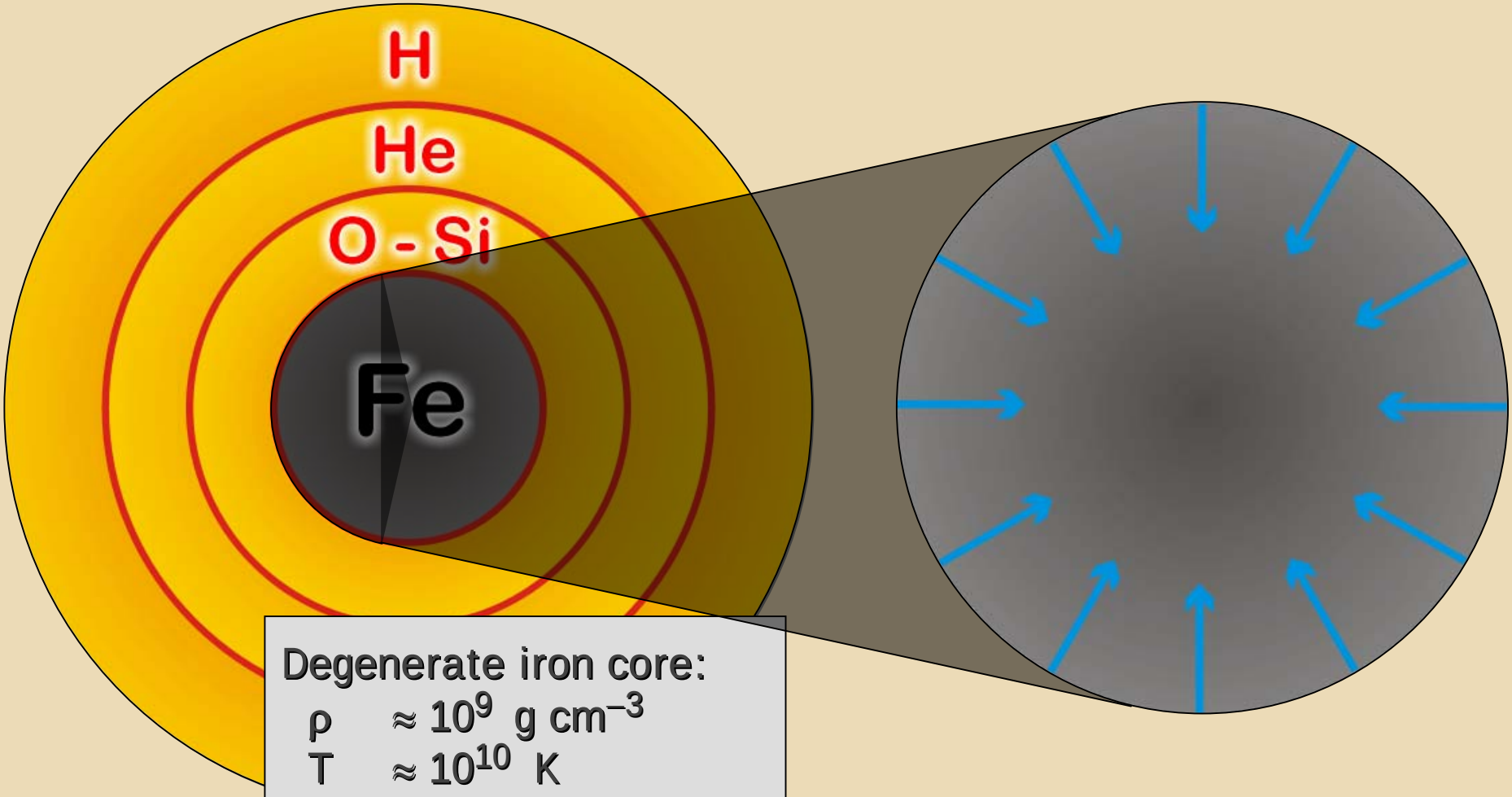
Helium-burning star



Stellar Collapse and Supernova Explosion

Onion structure

Collapse (implosion)



Degenerate iron core:

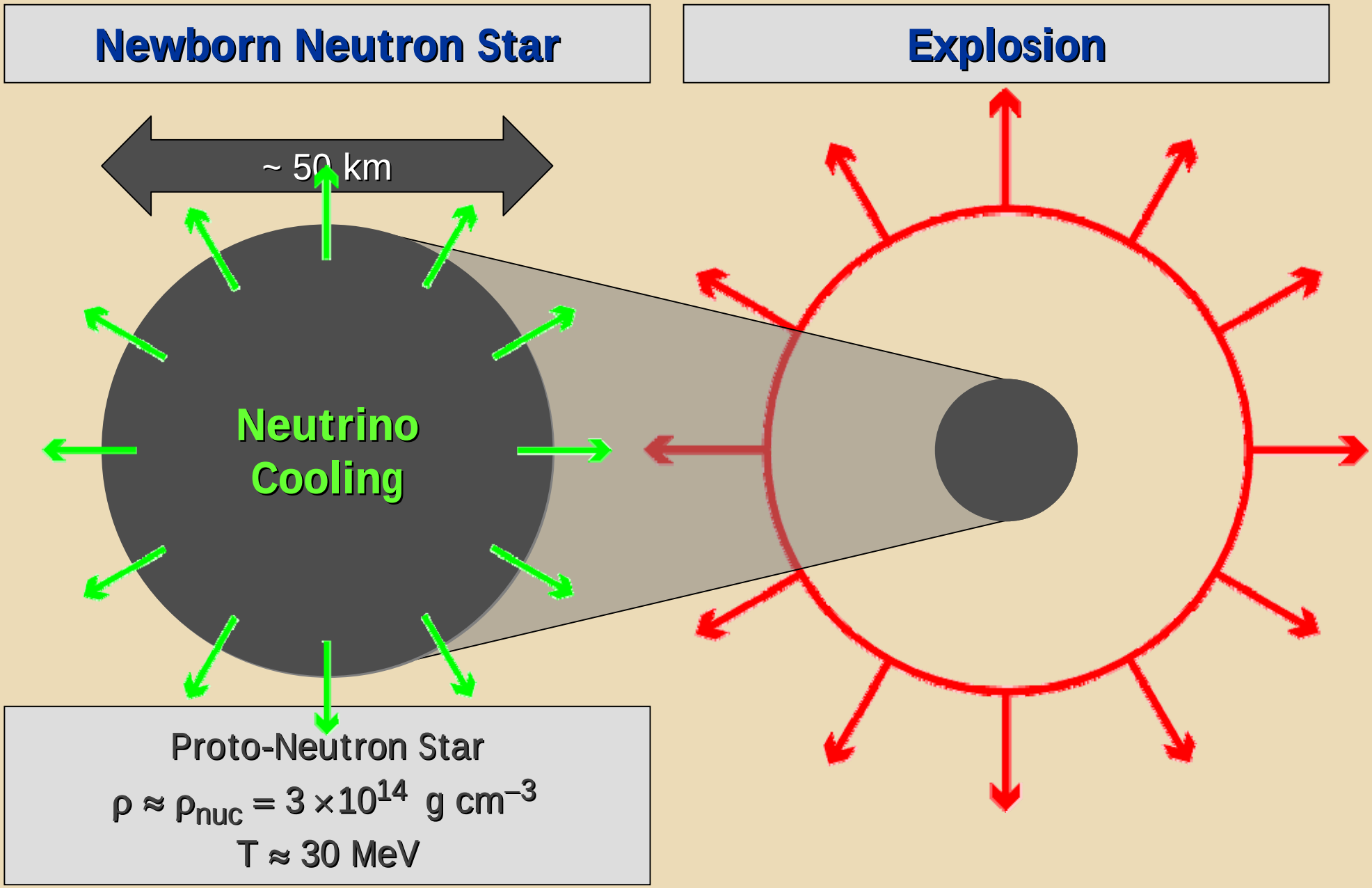
$\rho \approx 10^9$ g cm^{-3}

$T \approx 10^{10}$ K

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

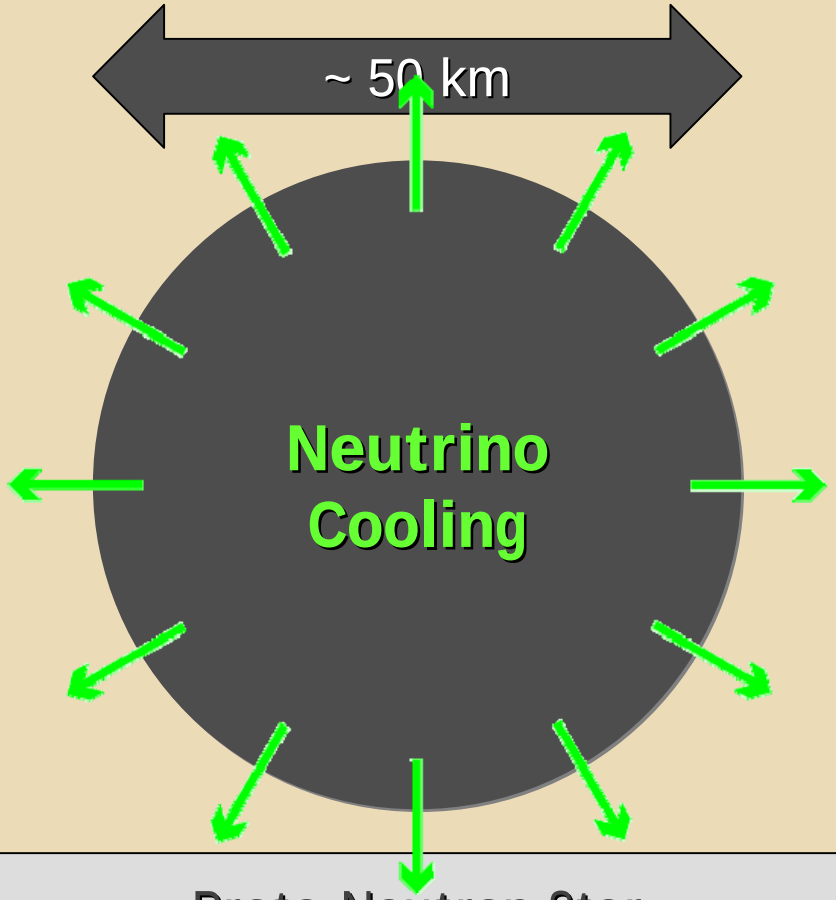
$R_{Fe} \approx 8000$ km

Stellar Collapse and Supernova Explosion



Stellar Collapse and Supernova Explosion

Newborn Neutron Star



Proto-Neutron Star

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

T ≈ 30 MeV

Gravitational binding energy

$E_b \approx 3 \times 10^{53}$ 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

$L_\nu \approx 3 \times 10^{53}$ erg / 3 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} $L_{Sun,B}$ / 100 years

$L_{sun,B} = 0.54\ L_{sun} = 2 \times 10^{33}$ 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 cm^{-1} s^{-1}

Pushing the boundaries of neutrino astronomy to cosmological distances

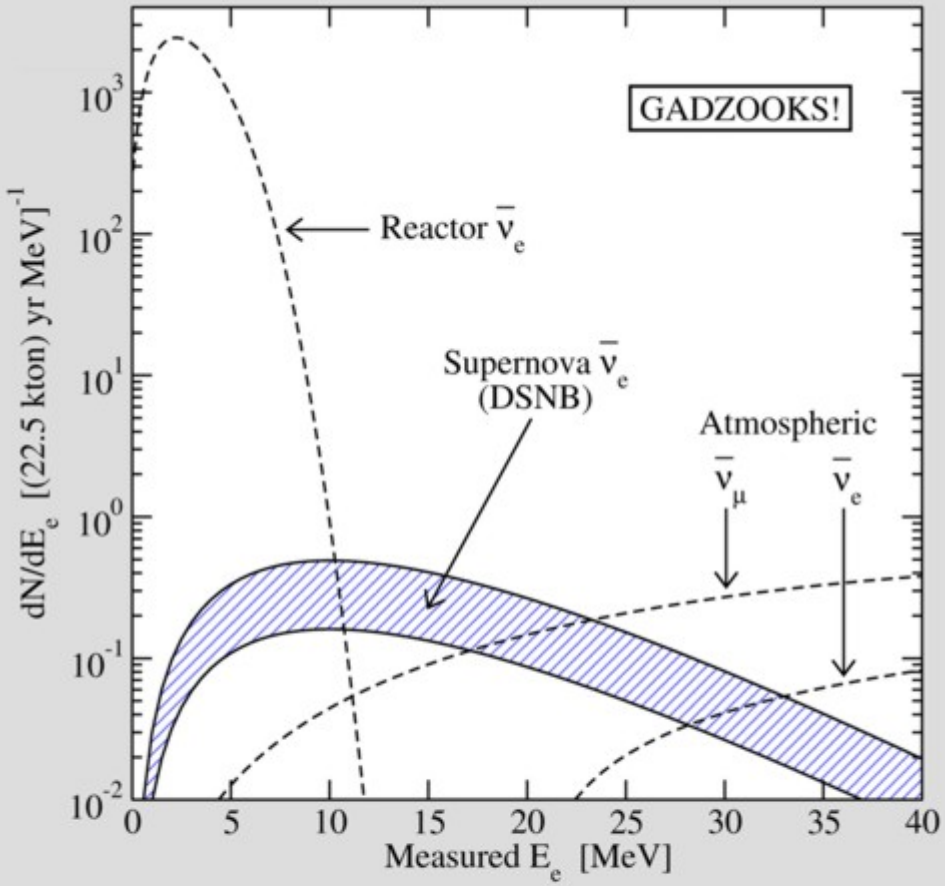


FIG. 1: Spectra of low-energy $\bar{\nu}_e + p \rightarrow e^+ + n$ coincidence events and the sub-Čerenkov muon background. We assume full efficiencies, and include energy resolution and neutrino oscillations. Singles rates (not shown) are efficiently suppressed.

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

Realistic DSNB Estimate

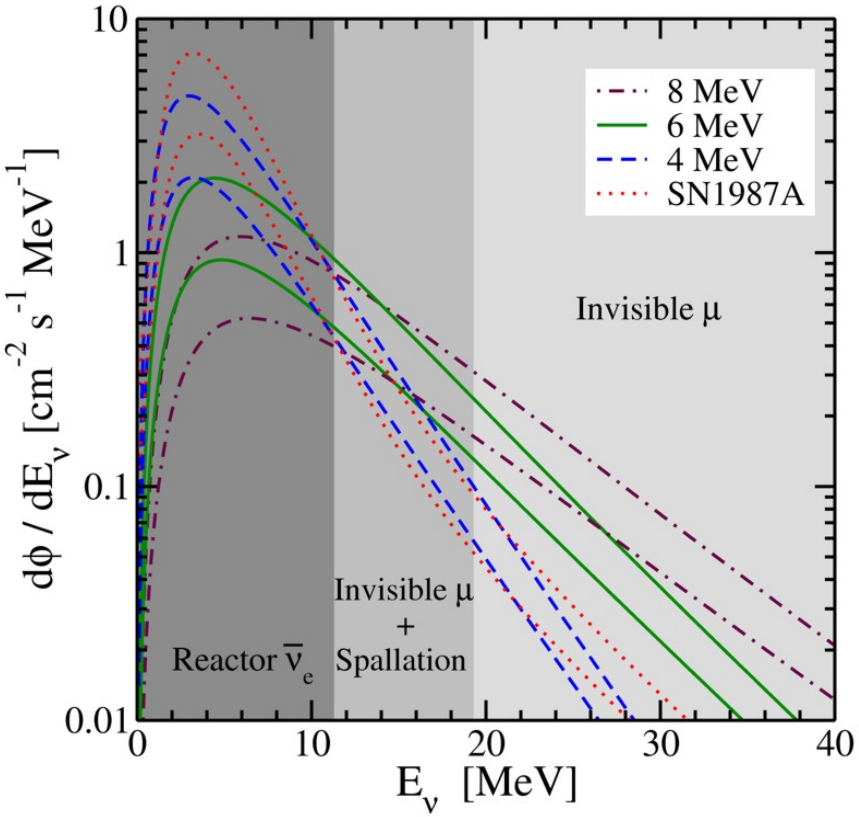


FIG. 4: DSNB flux spectrum for emitted neutrino spectra as labeled. For each spectrum, two curves are plotted representing the full range of uncertainties due to astrophysical inputs (the fiducial prediction lies in between). The shadings indicate backgrounds, with origins as labeled. Decays of invisible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

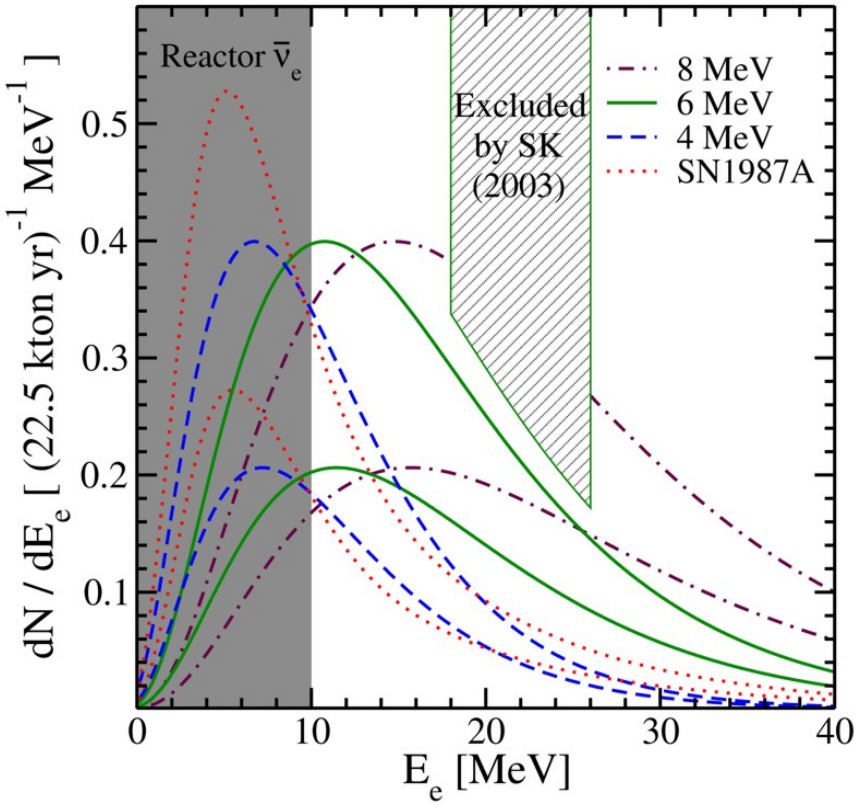


FIG. 5: DSNB event rates at SK (flux spectra weighted with the detection cross section) against positron energy. Note the linear axis. We hatch in the 2003 upper limit by the Super-Kamiokande Collaboration, < 2 events $(22.5 \text{ kton yr})^{-1}$ in the energy range 18–26 MeV. The limit applies to all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

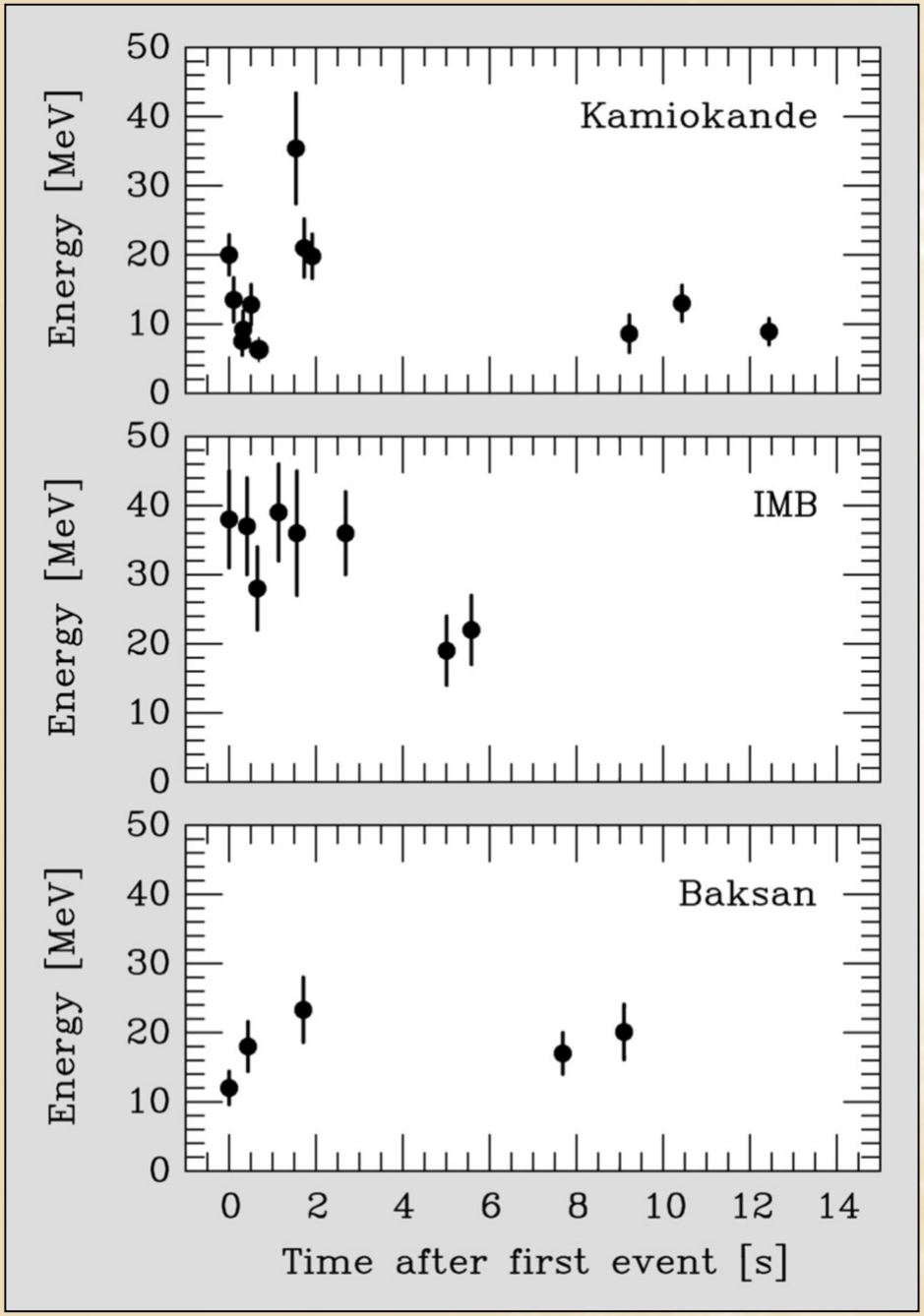

Tarantula Nebula


Large Magellanic Cloud
Distance 50 kpc
(160.000 light years)


Sanduleak –69 202


Supernova 1987A
23 February 1987

Neutrino Signal of Supernova 1987A



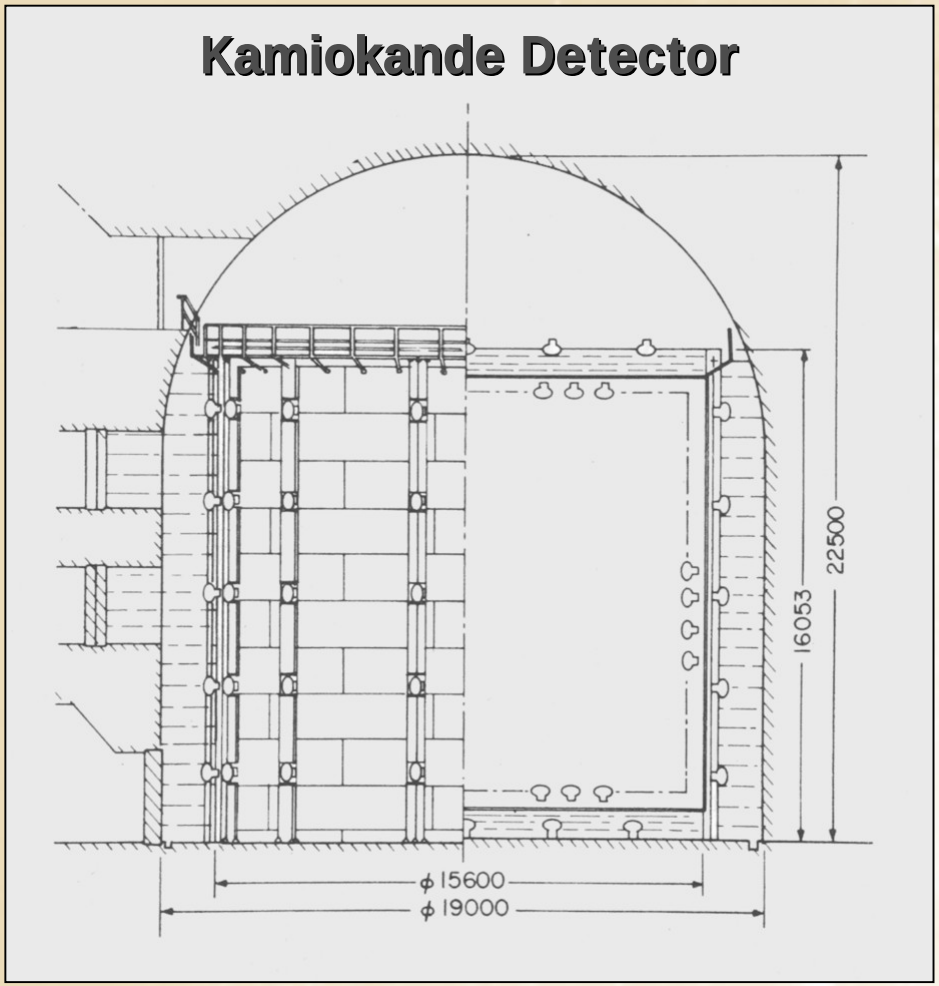
Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ±1 min

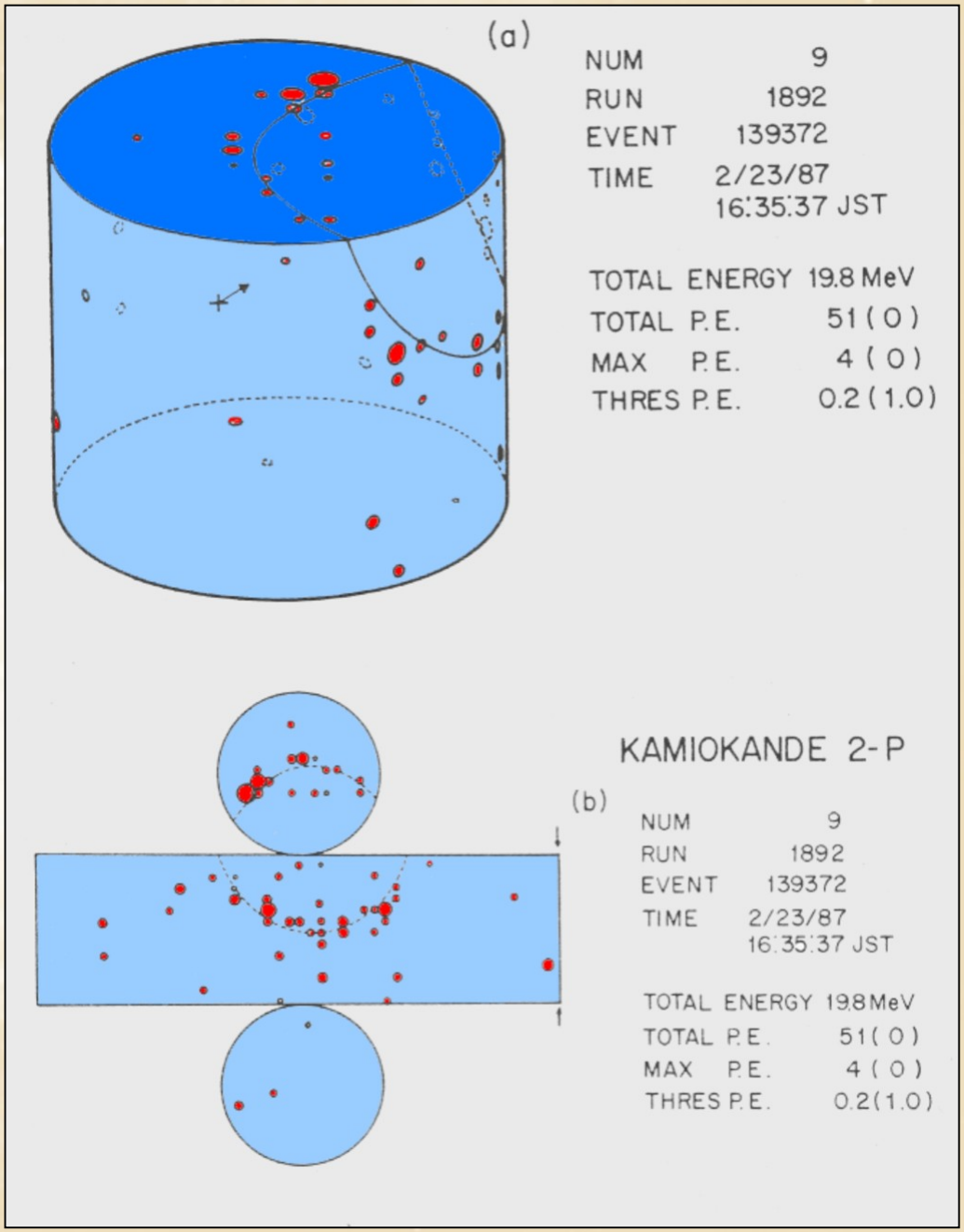
Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty ±50 ms

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

Within clock uncertainties, signals are contemporaneous

SN 1987A Event No.9 in Kamiokande

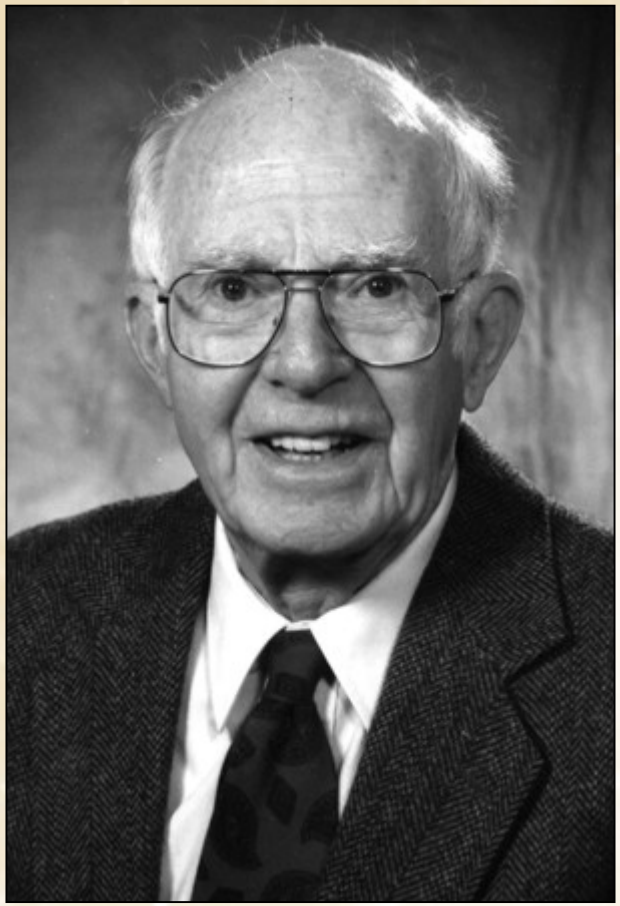




$$\bar{\nu}_e + p \rightarrow n + e^+ \Rightarrow \text{Cherenkov Light}$$

Hirata et al., PRD 38 (1988) 448

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 pro-

More detailed calculations on this collapse process are now in progress.

G. Gamow

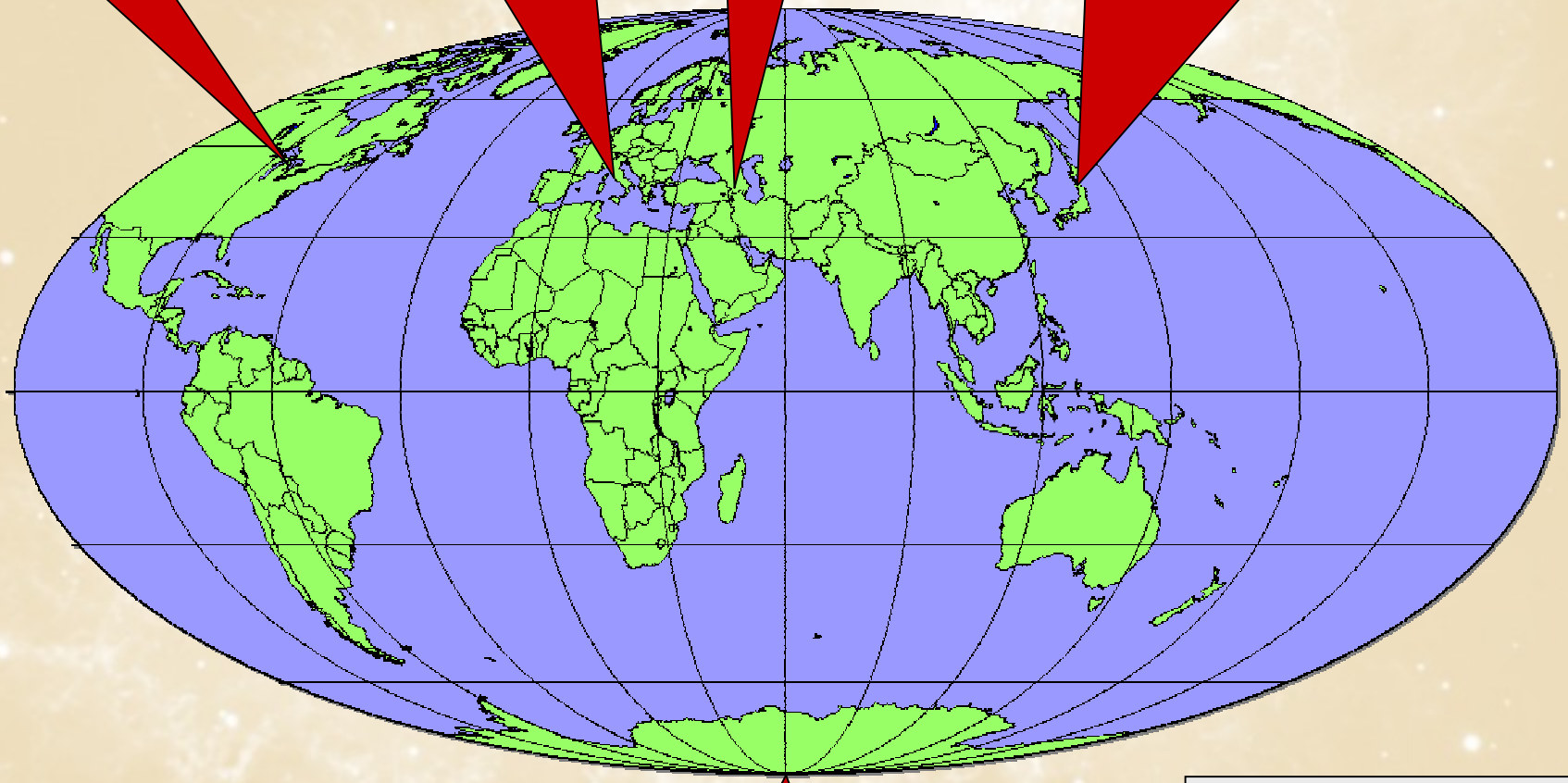
The George Washington University,
Washington, D. C.,

M. Schoenberg*

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

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

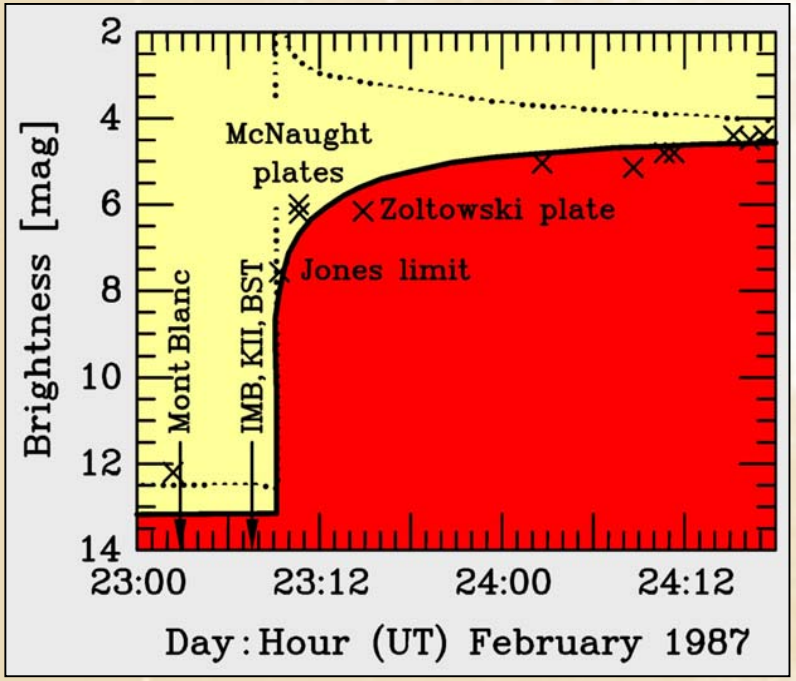
Large Detectors for Supernova Neutrinos



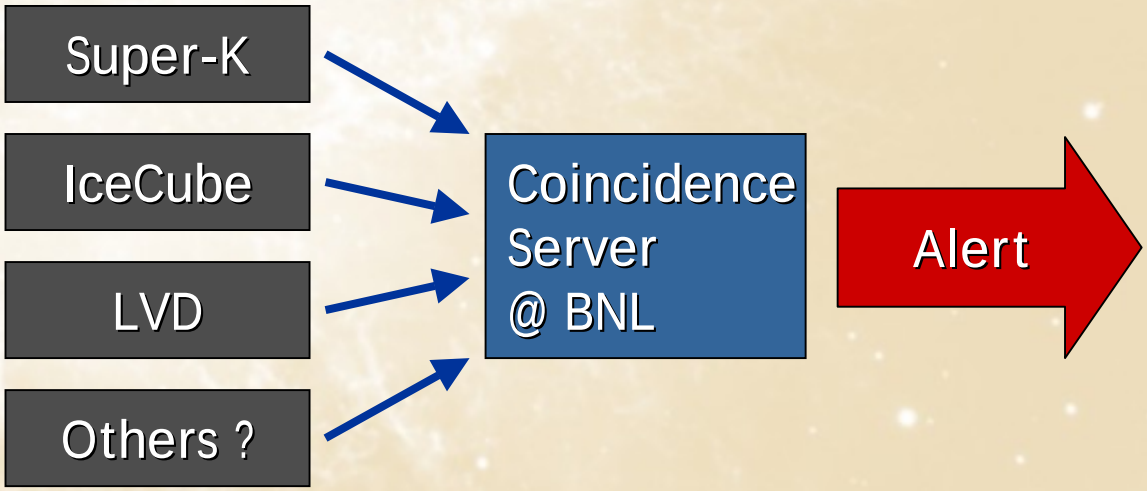
In brackets events for a "fiducial SN" at distance 10 kpc

SuperNova Early Warning System (SNEWS)

Supernova 1987A
Early Light Curve

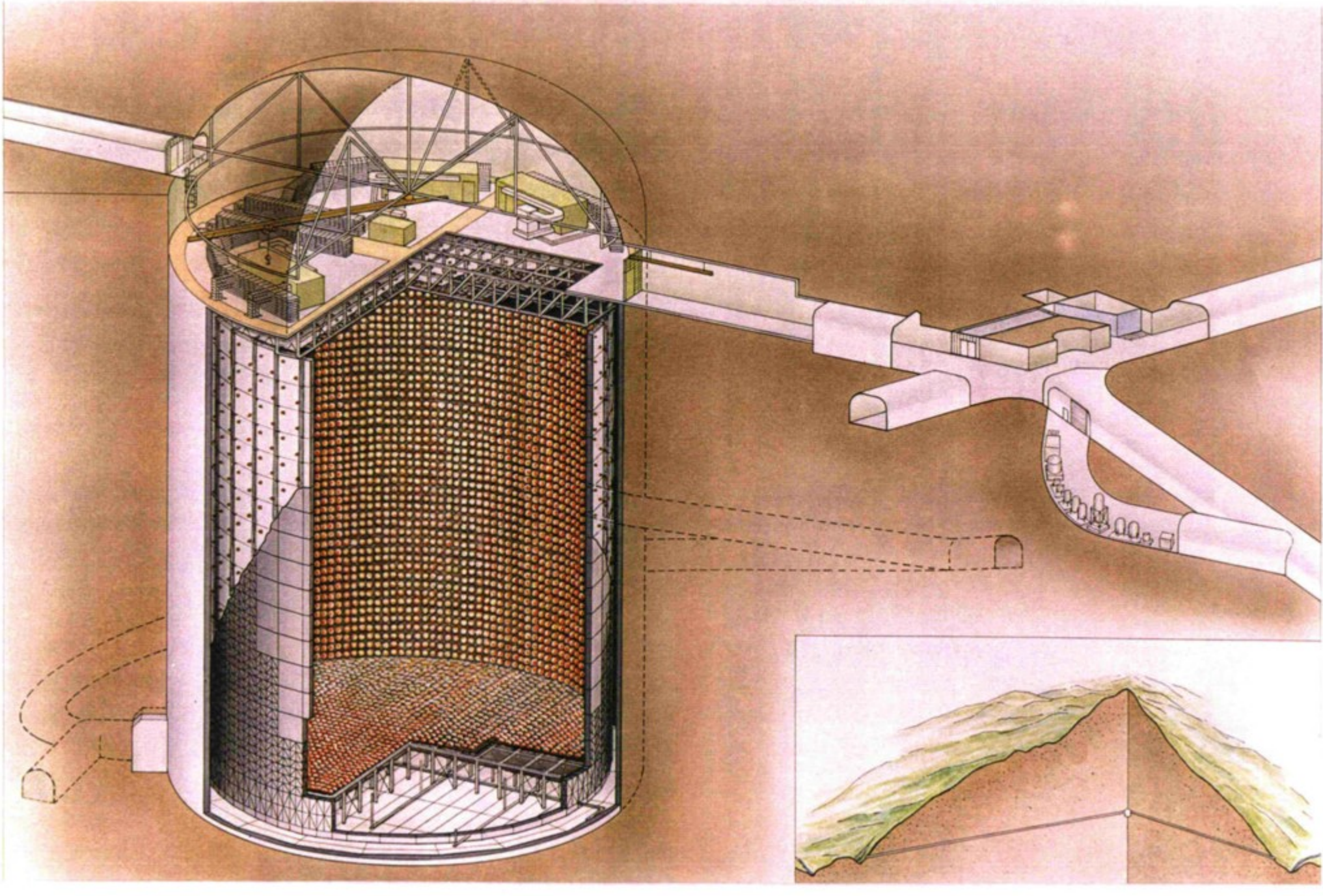


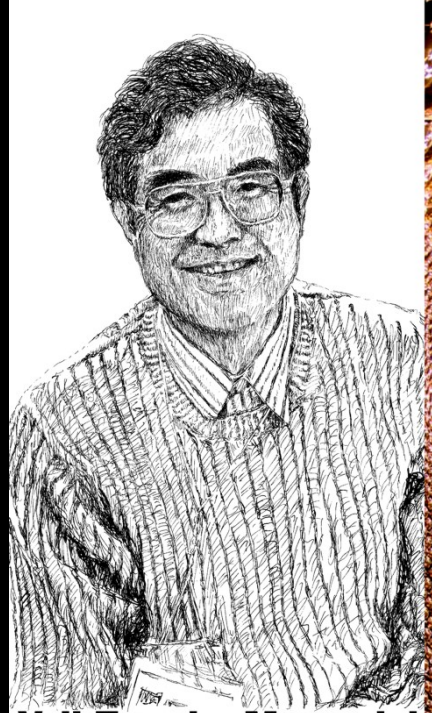
http://snews.bnl.gov

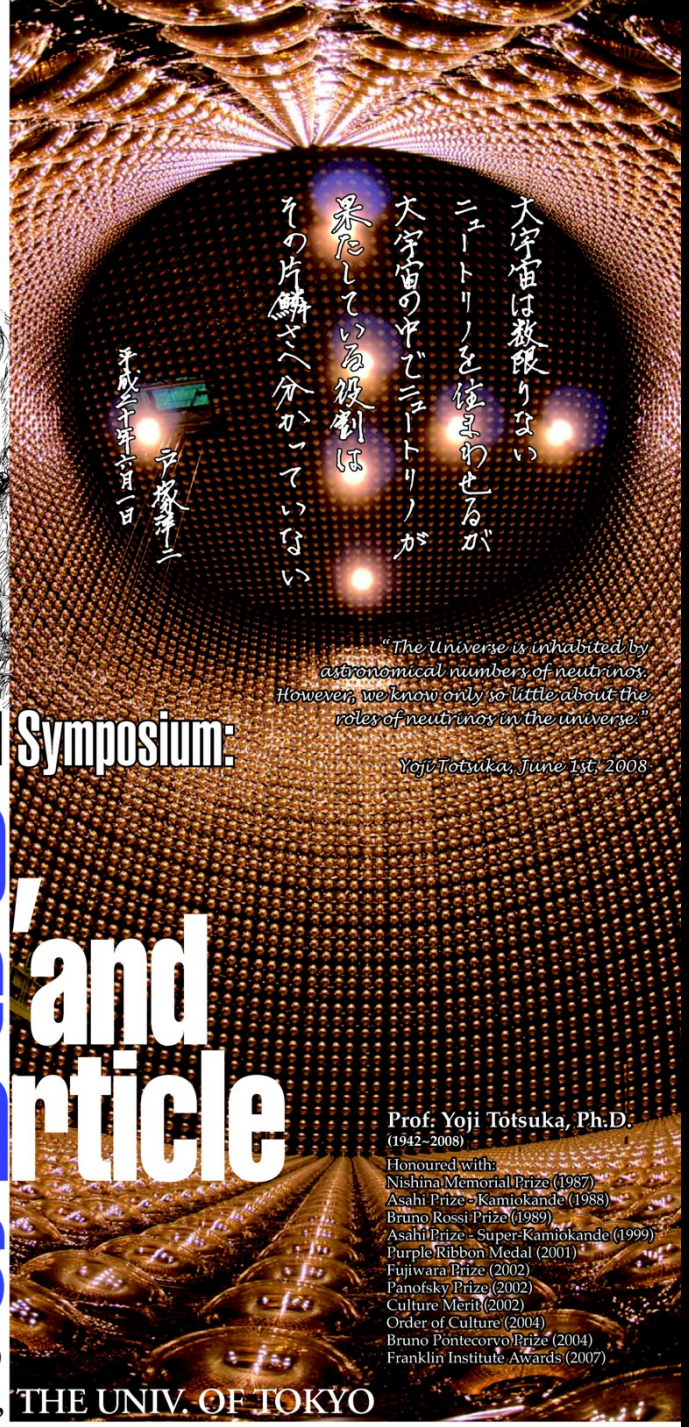


Neutrino observation can alert astronomers several hours in advance to a supernova.

Super-Kamiokande Neutrino Detector







Yoji Totsuka Memorial Symposium:

Neutrino, Particle and Astroparticle Physics

Prof. Yoji Totsuka, Ph.D.
(1942~2008)

Honoured with:
- Nishina Memorial Prize (1987)
- Asahi Prize - Kamiokande (1988)
- Bruno Rossi Prize (1989)
- Asahi Prize - Super-Kamiokande (1999)
- Purple Ribbon Medal (2001)
- Fujiwara Prize (2002)
- Panofsky Prize (2002)
- Culture Merit (2002)
- Order of Culture (2004)
- Bruno Pontecorvo Prize (2004)
- Franklin Institute Awards (2007)

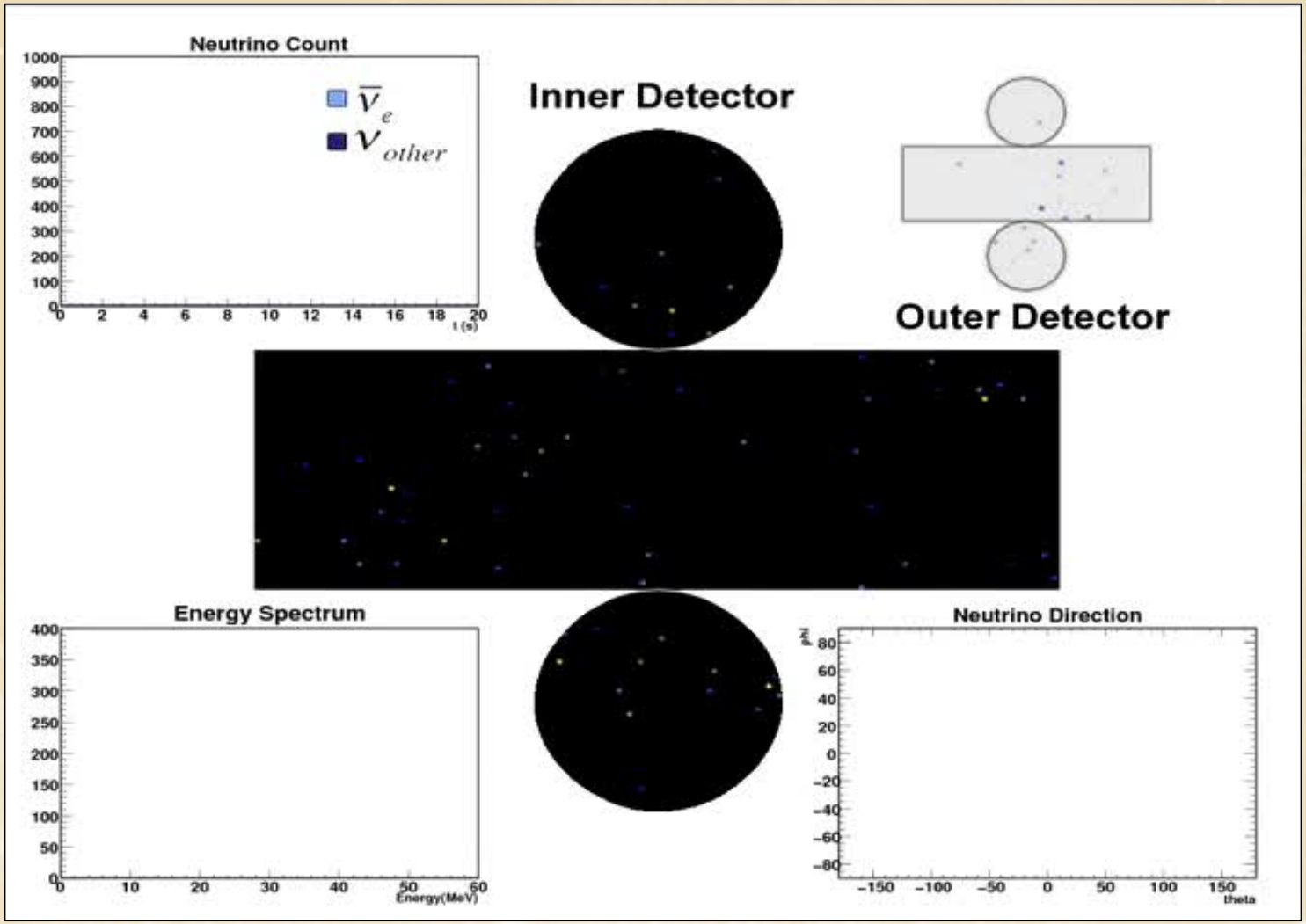
JUNE 9TH (TUE), 2009
YASUDA-AUDITORIUM, THE UNIV. OF TOKYO

HOSTED BY 東京大学 THE UNIVERSITY OF TOKYO ICRR

JOINTLY ORGANIZED BY ICEPP JPS

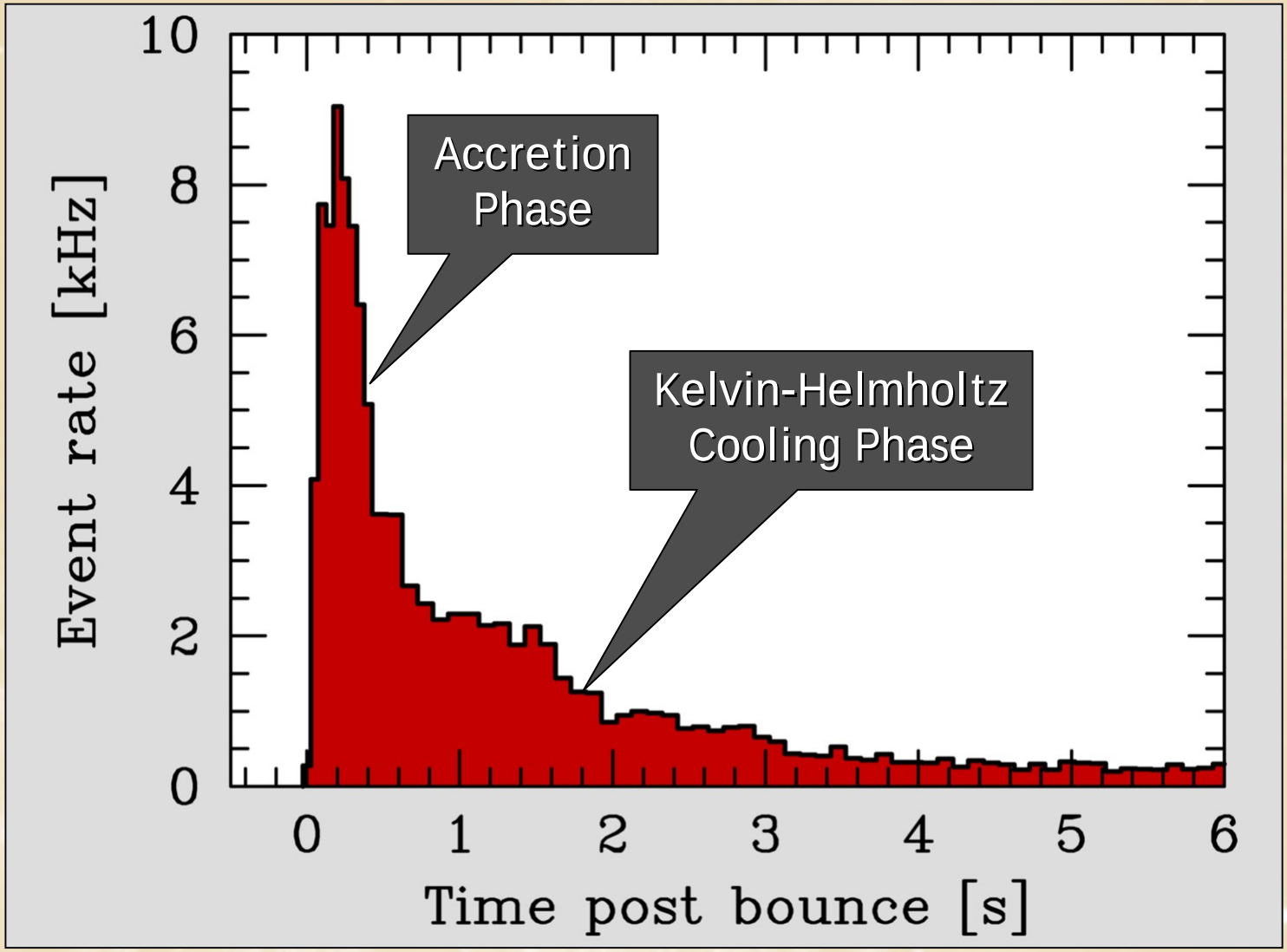
http://www.icrr.u-tokyo.ac.jp/tribute_yoji_totsuka

Simulated Supernova Burst in Super-Kamiokande



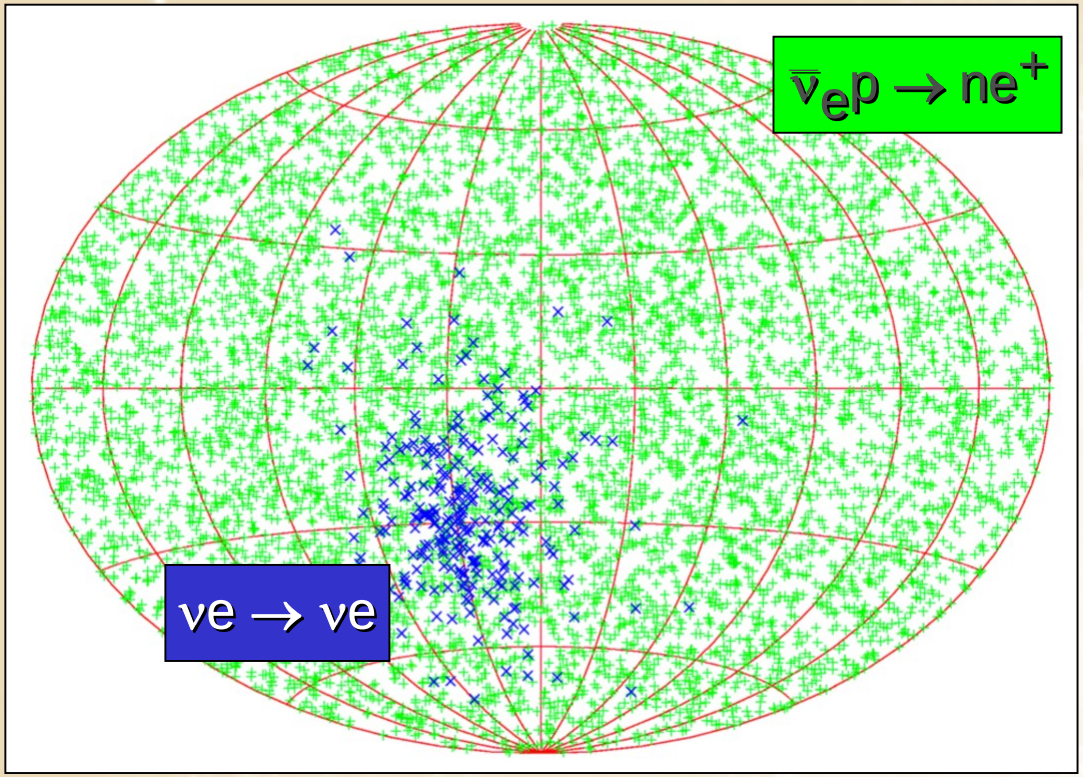
Movie by C. Little, including work by S. Farrell & B. Reed,
(Kate Scholberg's group at Duke University)
http://snews.bnl.gov/snmovie.html

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]

Supernova Pointing with Neutrinos

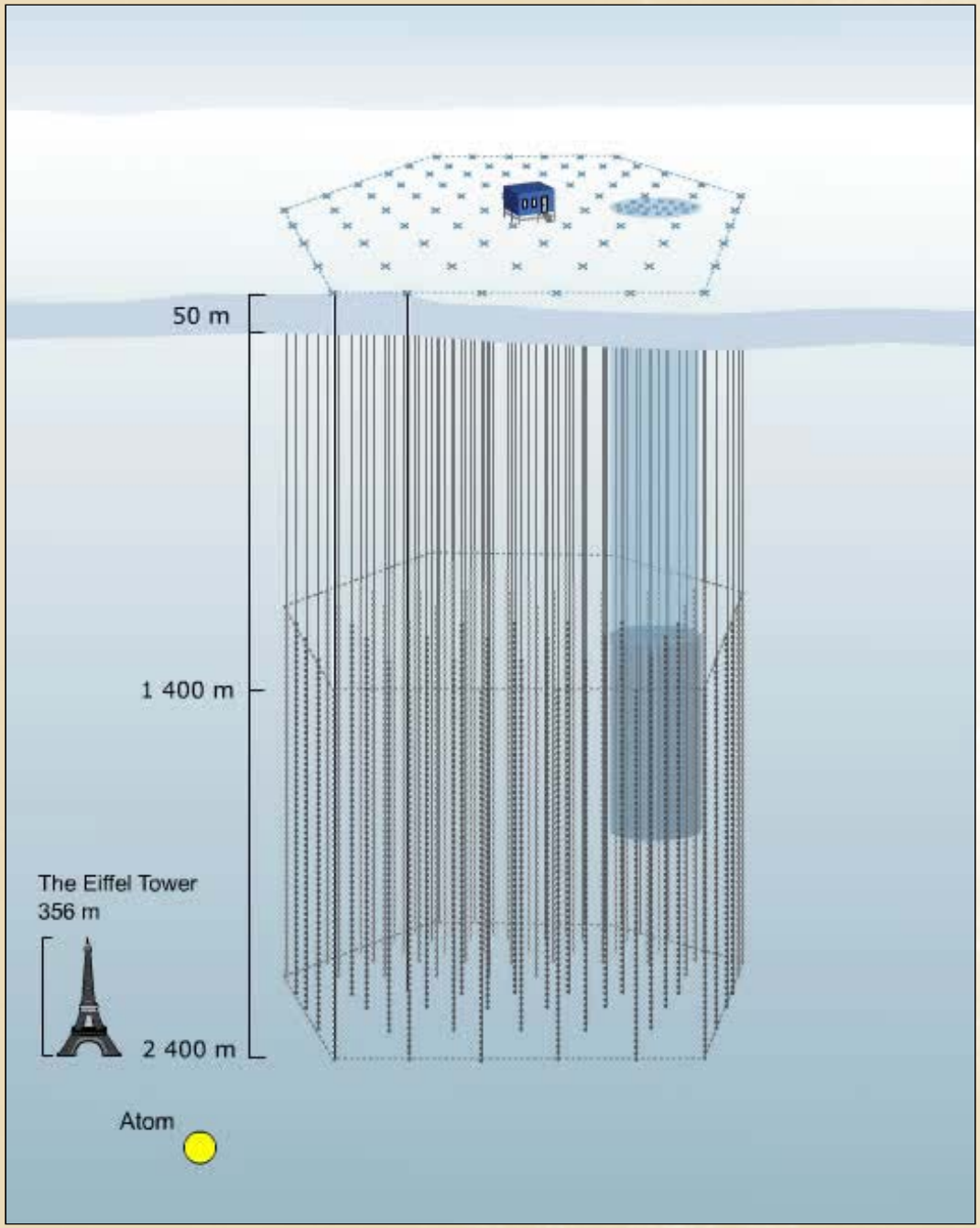


95% CL half-cone opening angle

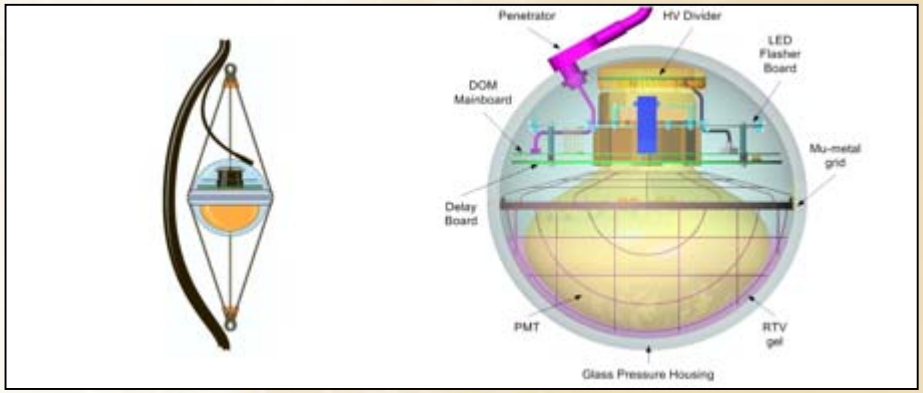
	Neutron tagging efficiency	
	None	90 %
SK	7.8º	3.2º
SK × 30	1.4º	0.6º

- 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



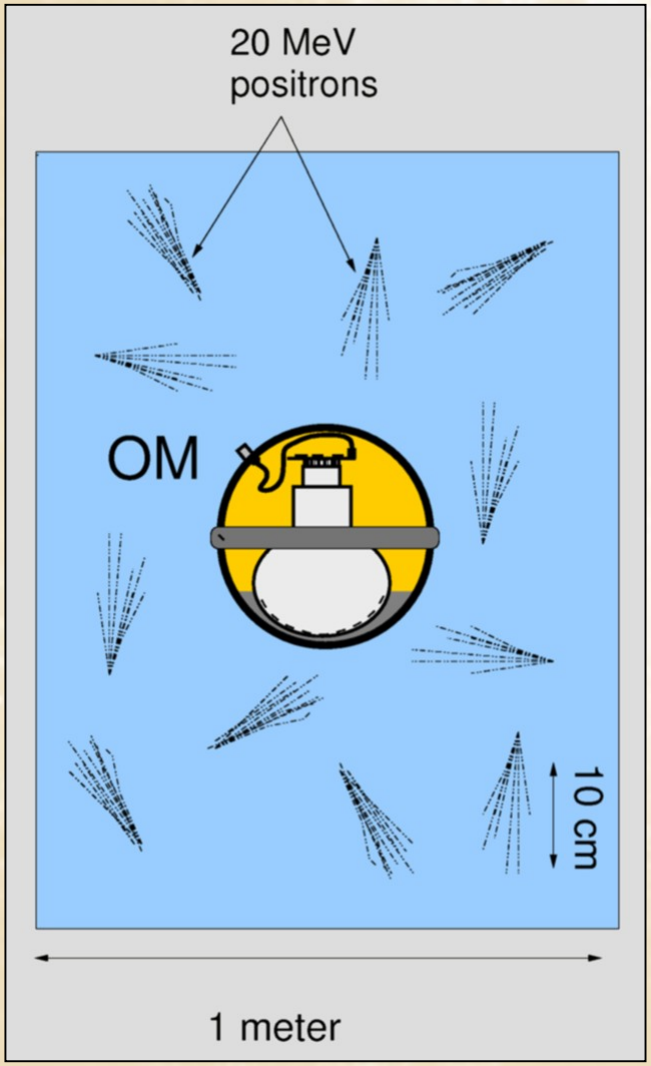
- 1 km^3 antarctic ice, instrumented with 4800 photomultipliers
- 59 of 80 strings installed (2009)
- Completion until 2011 foreseen

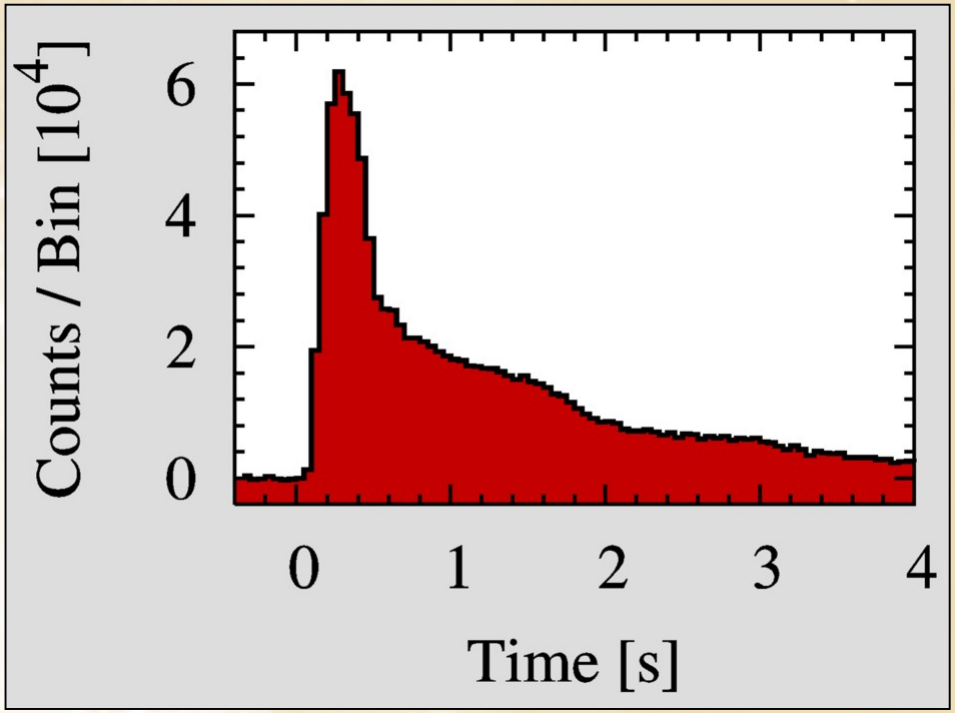


IceCube as a Supernova Neutrino Detector

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 < 300 Hz
- Total of 4800 OMs foreseen in IceCube

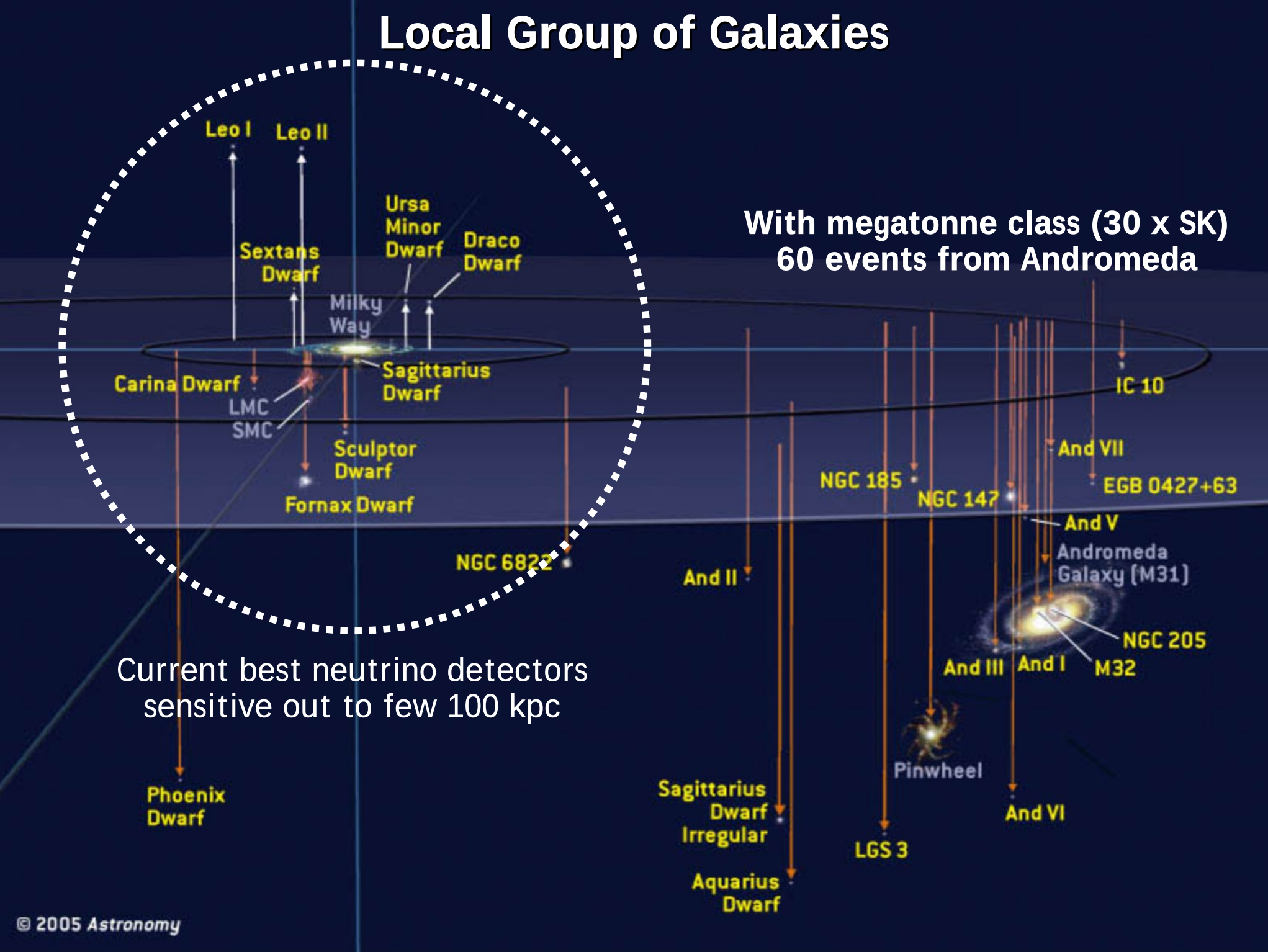




IceCube SN signal at 10 kpc, based on a numerical Livermore model
[Dighe, Keil & Raffelt, hep-ph/0303210]

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

Local Group of Galaxies



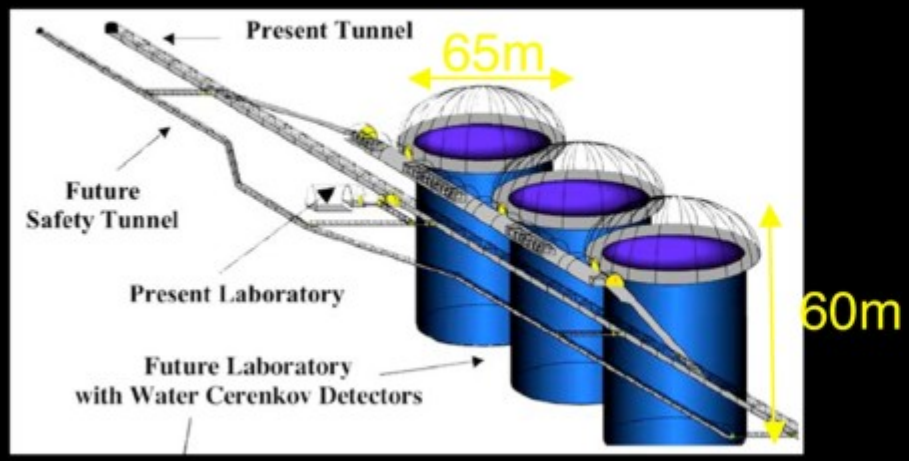
With megatonne class (30 x SK)
60 events from Andromeda

Current best neutrino detectors sensitive out to few 100 kpc

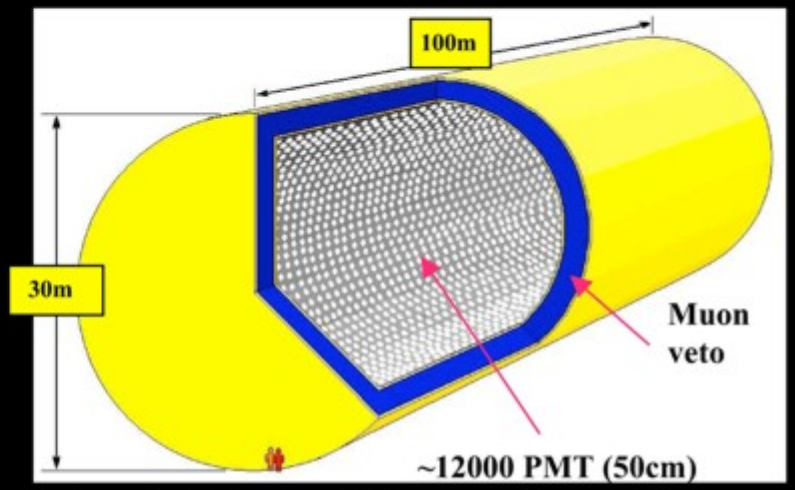
LAGUNA - Ongoing European (FP7) Design Study

Large Apparati for Grand Unification and Neutrino Astrophysics
(see also arXiv:0705.0116)

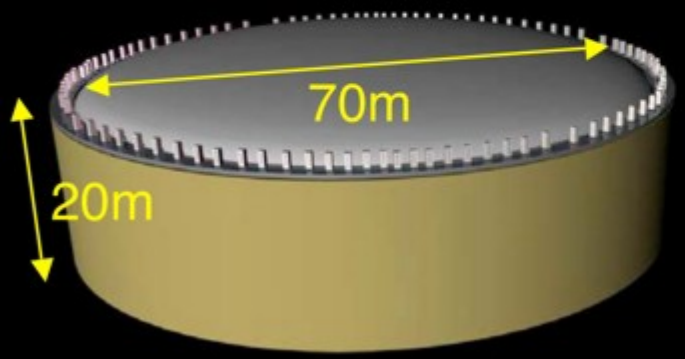
- Three types of large multi-purpose underground detectors with astrophysical program



Water Cherenkov (≈0.5 → 1 Mton)
MEMPHYS

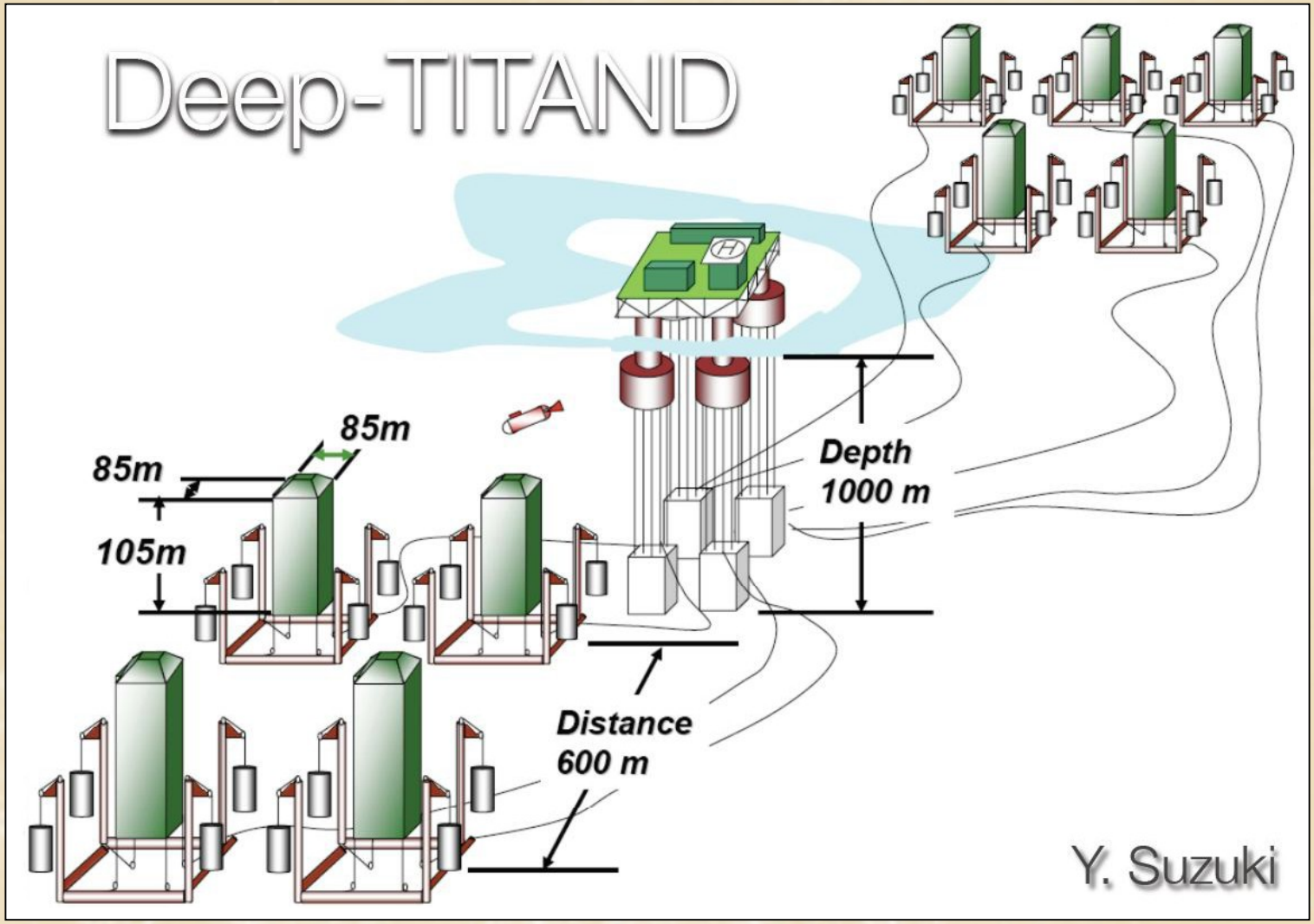


Liquid Scintillator (→ 50 kton)
LENA



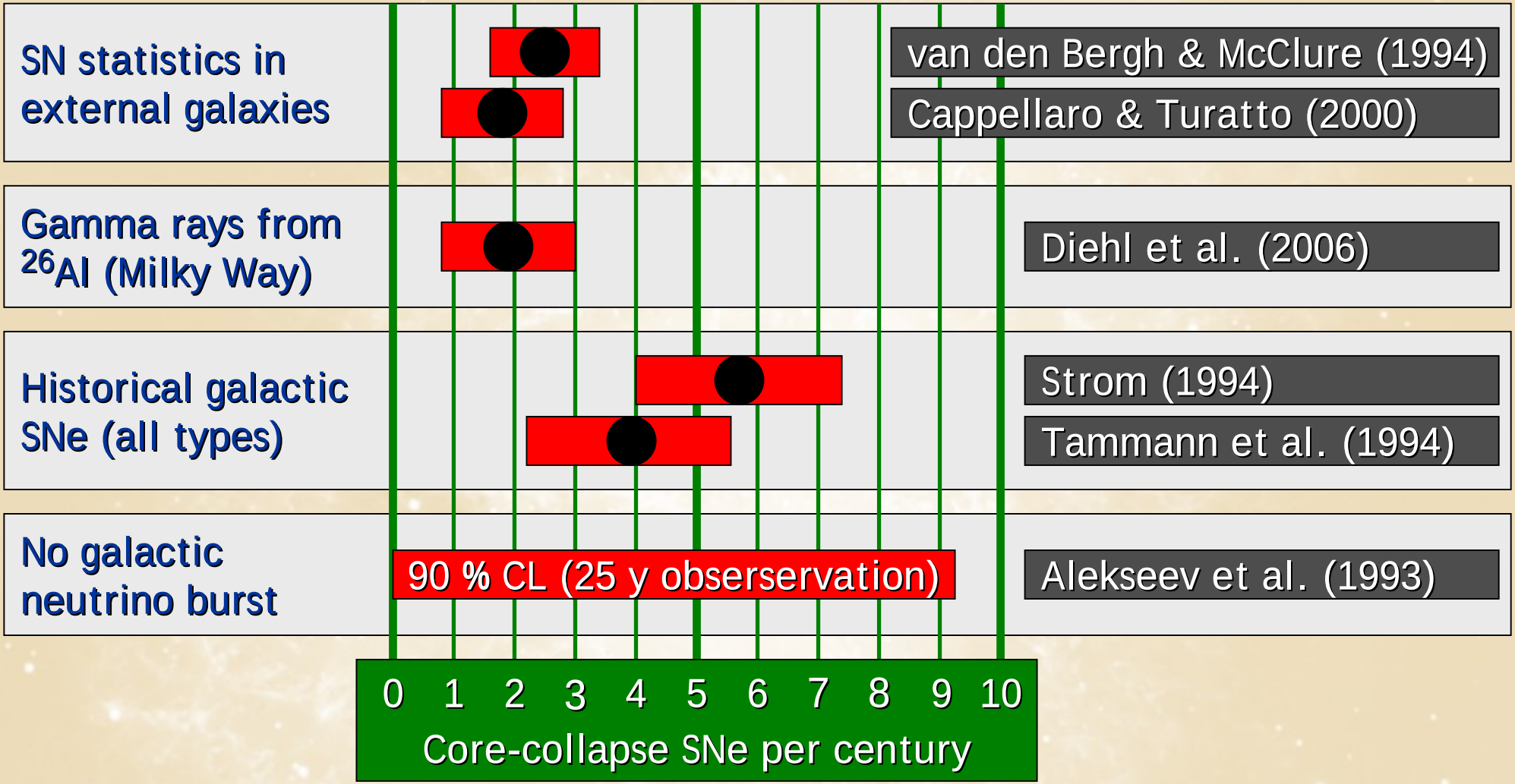
Liquid Argon (≈10→100 kton)
GLACIER

Reaching Beyond the Milky Way: Five-Megaton Detector



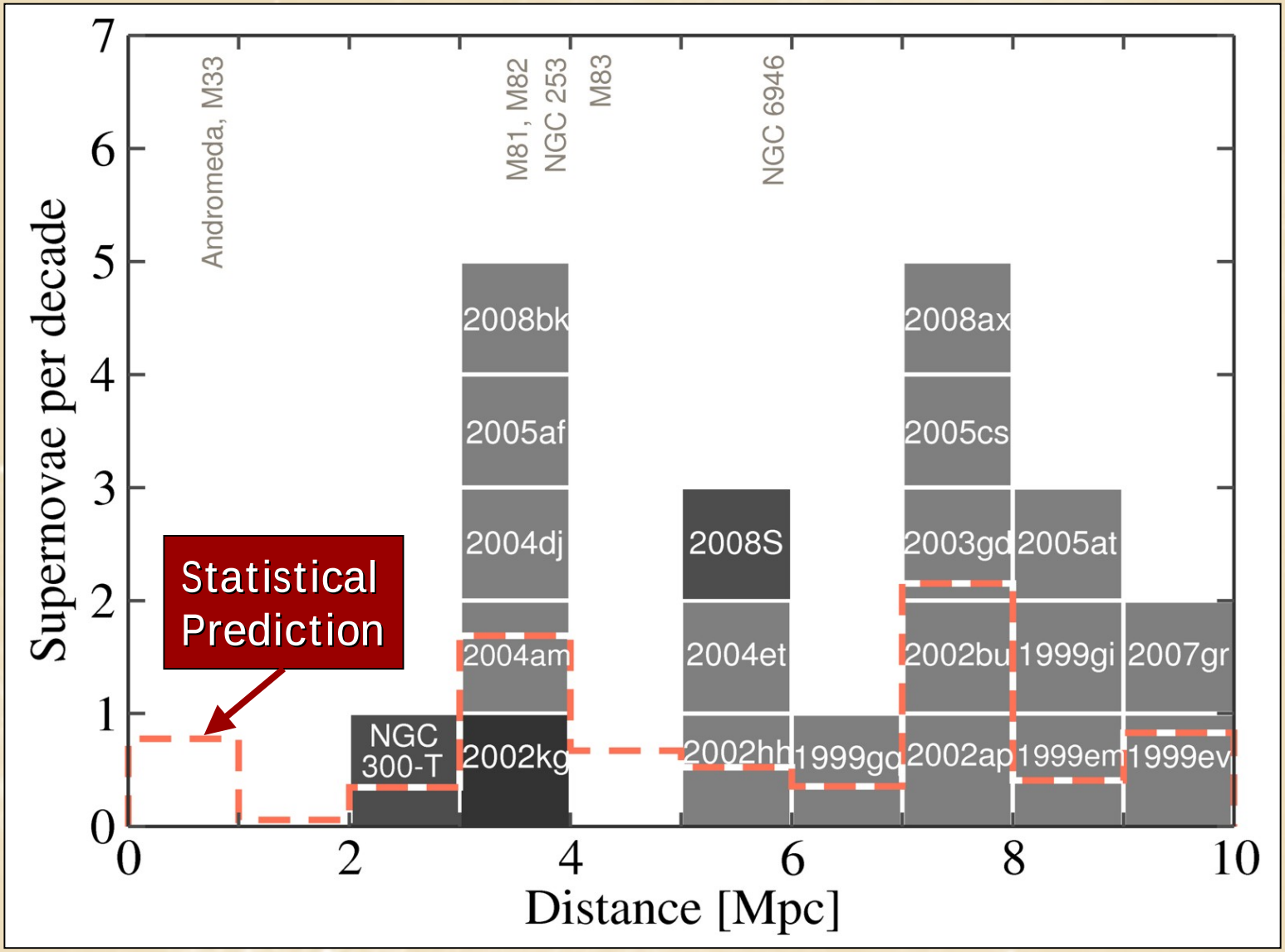
Modular 5-Mt underwater detector
for proton decay, long-baseline oscillation experiments,
atmospheric neutrinos, and low-energy burst detection

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.

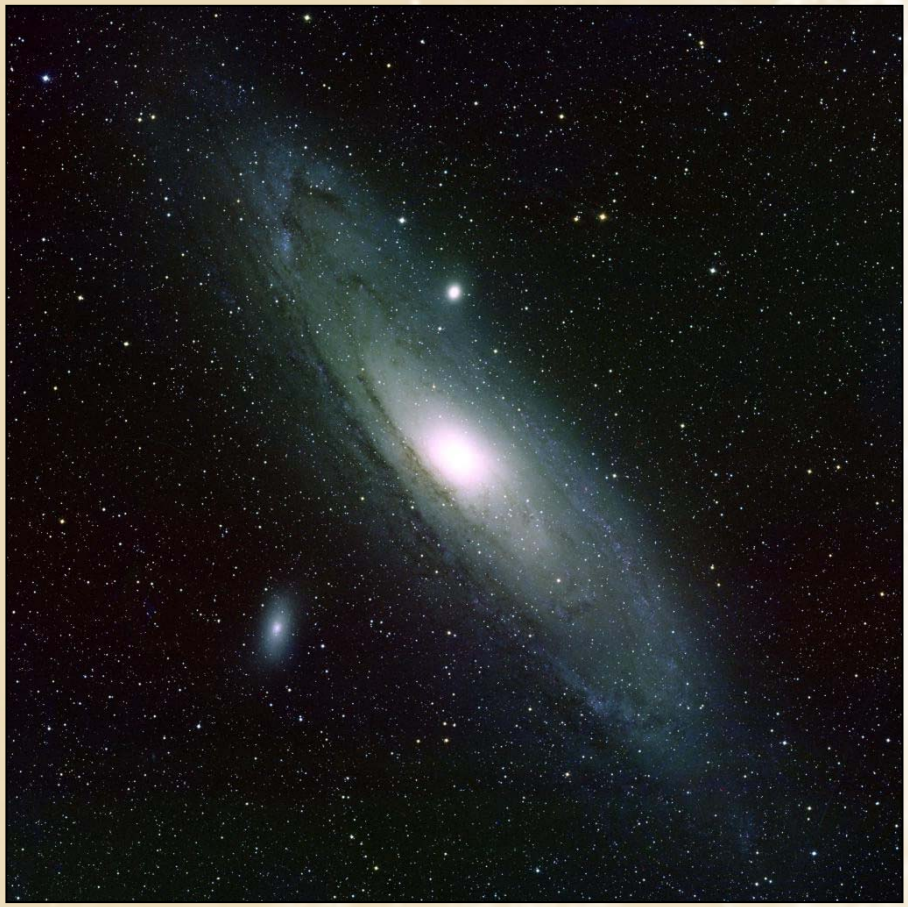
Supernova Rate in the Local Universe (Past Decade)



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

High and Low Supernova Rates in Nearby Galaxies

M31 (Andromeda)
D = 780 kpc

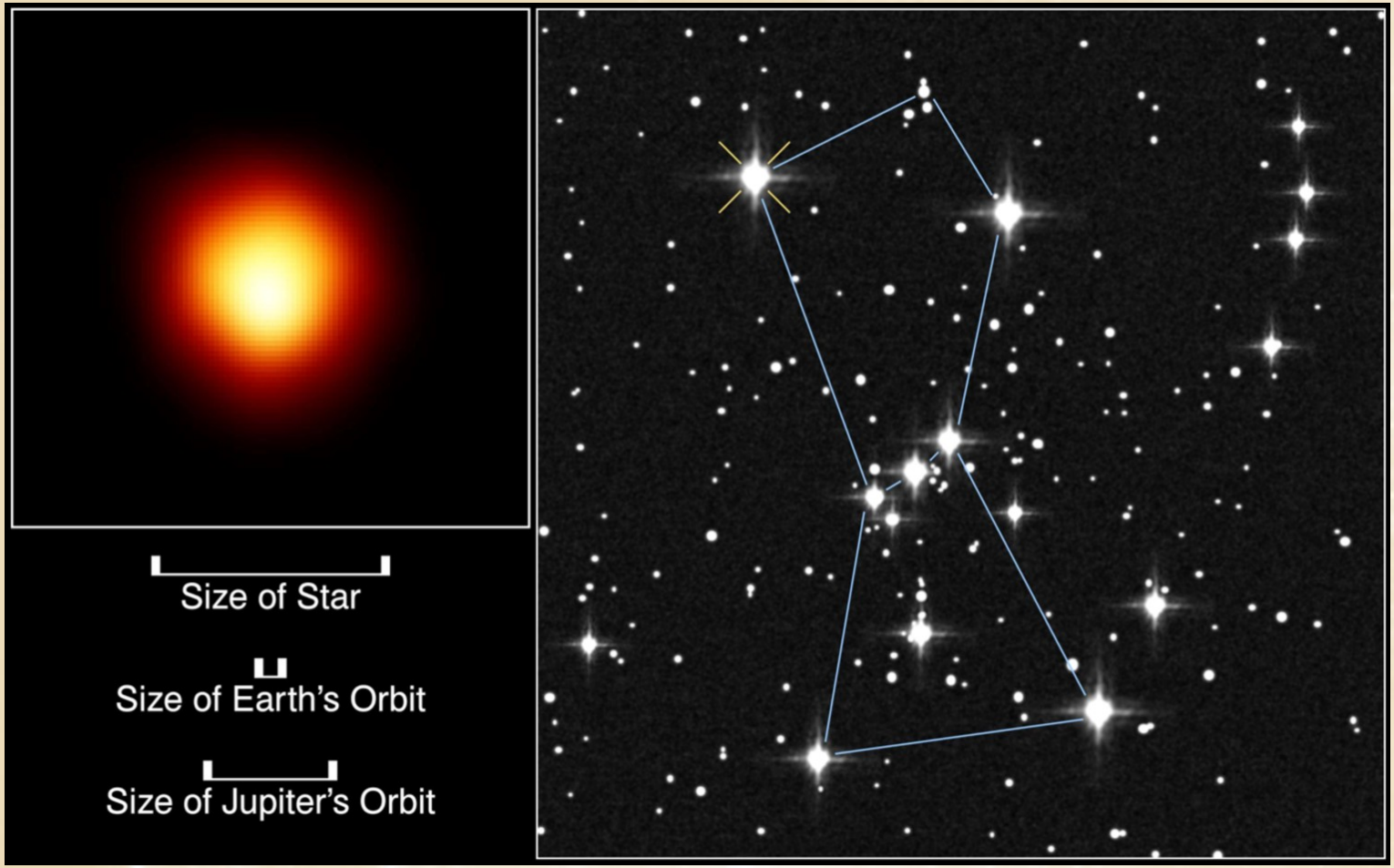


Last Observed Supernova: 1885A

NGC 6946
D = (5.5 ± 1) Mpc

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

The Red Supergiant Betelgeuse (Alpha Orionis)

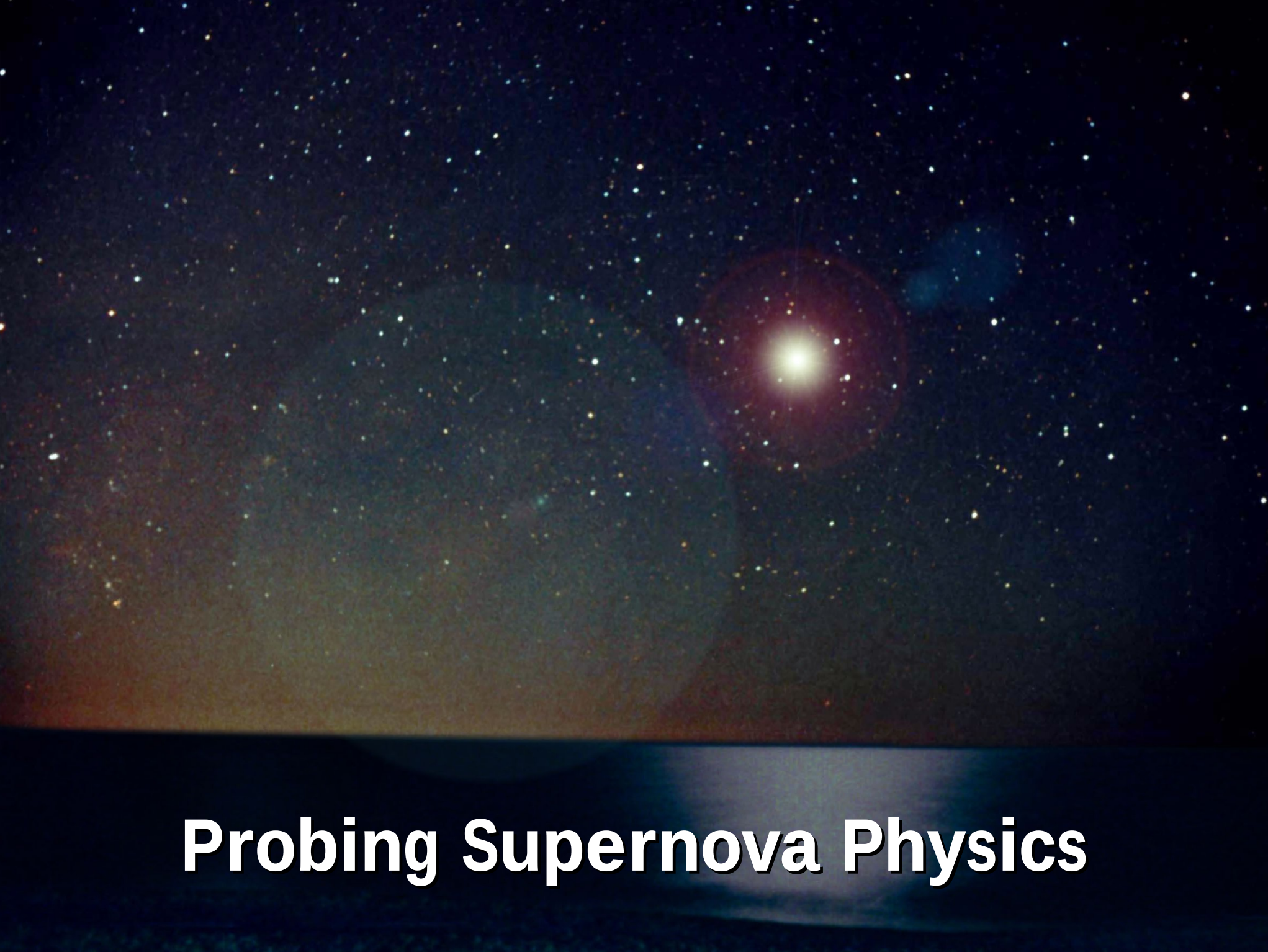


First resolved image of a star other than Sun

Distance (Hipparcos) 130 pc (425 lyr)

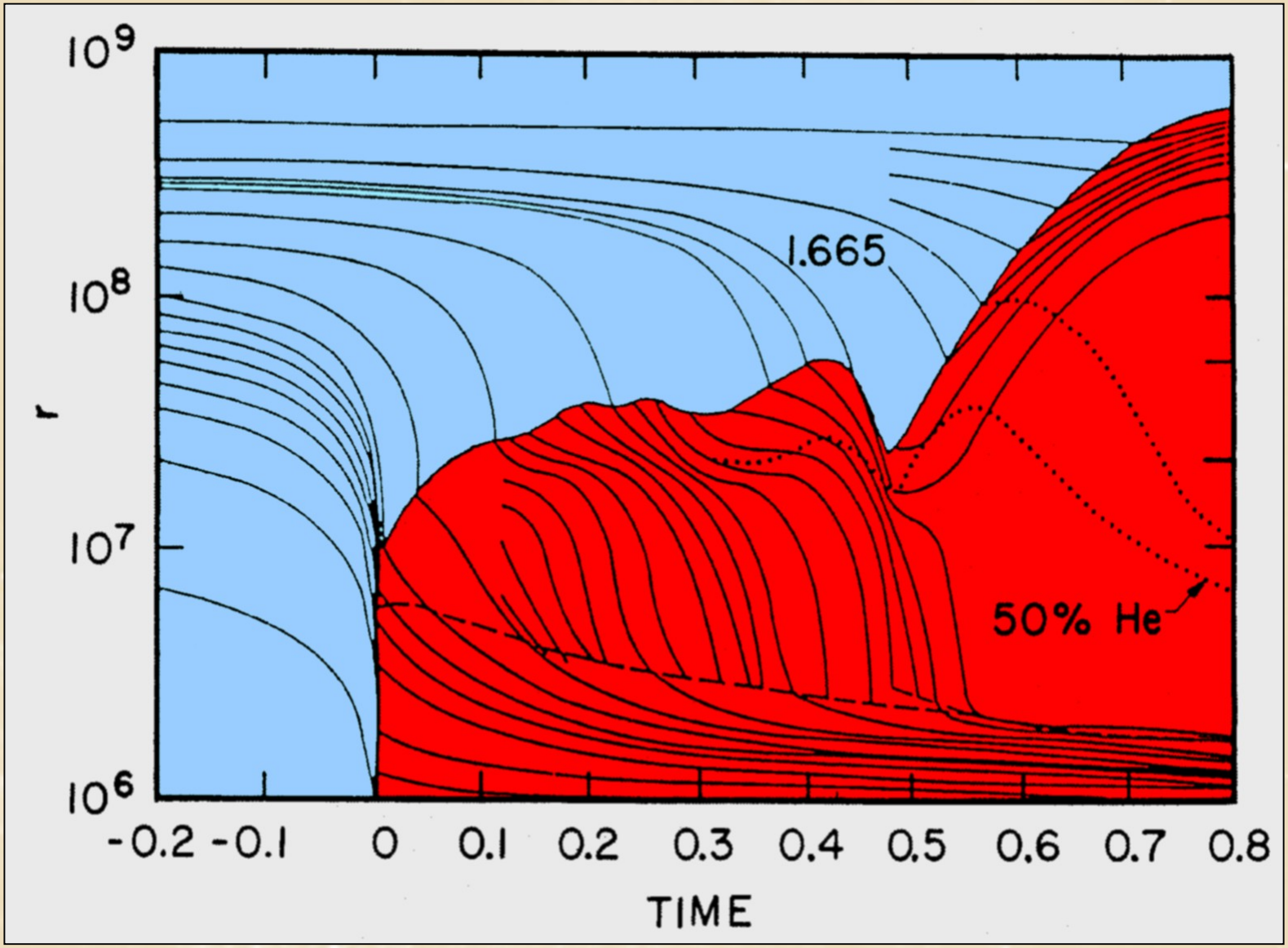
If Betelgeuse goes Supernova:

- 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]



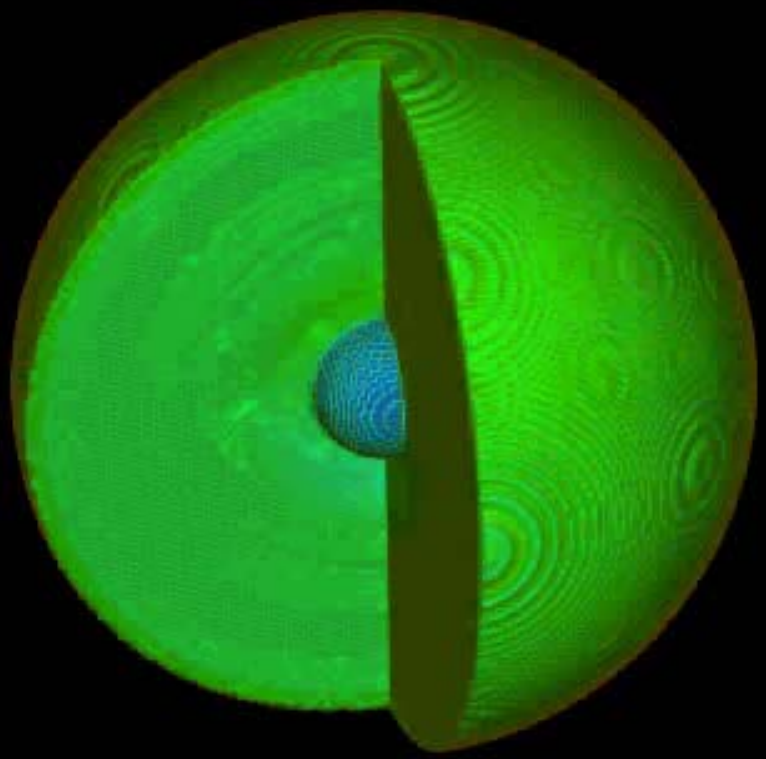
Probing Supernova Physics

Delayed Explosion



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

Standing Accretion Shock Instability (SASI)

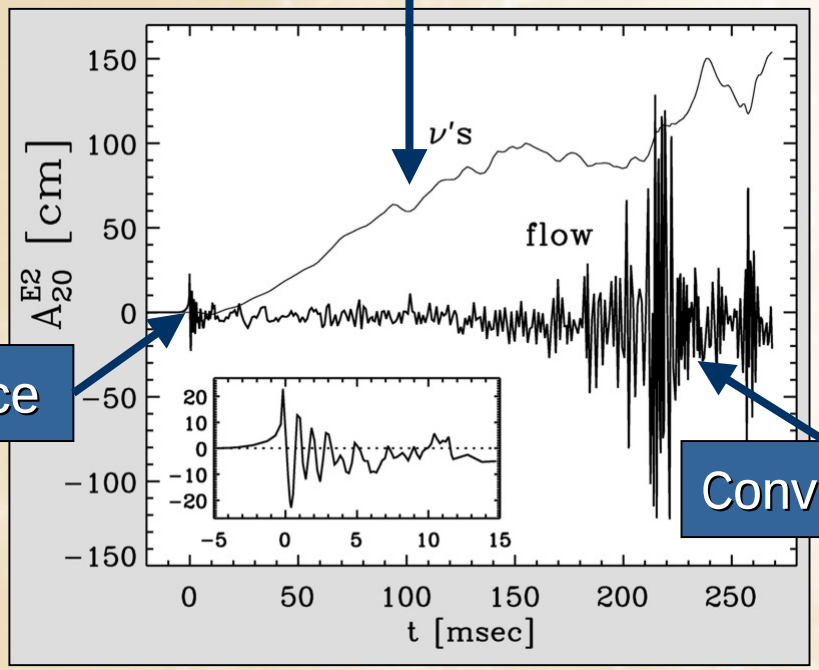


Mezzacappa et al., http://www.phy.ornl.gov/tsi/pages/simulations.html

Gravitational Waves from Core-Collapse Supernovae

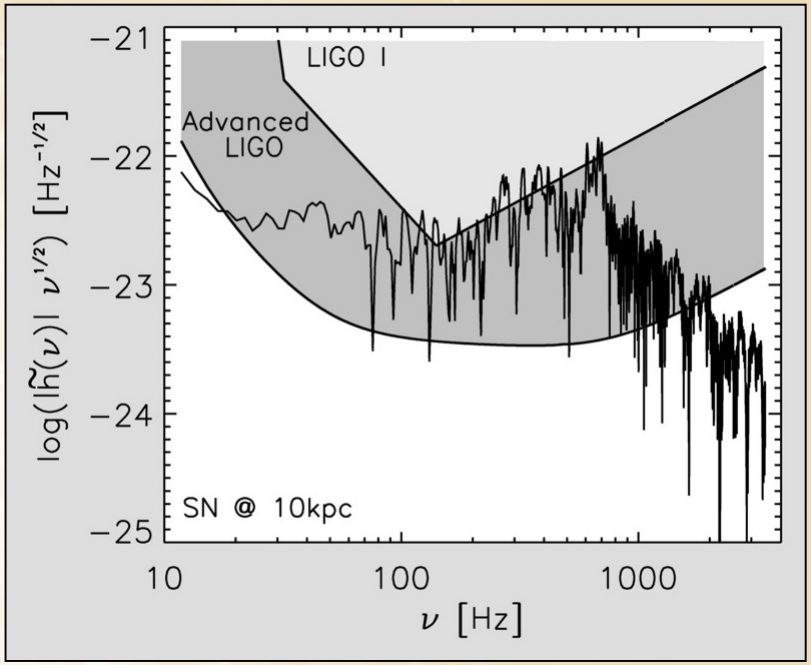
Müller, Rampp, Buras, Janka, & Shoemaker, "Towards gravitational wave signals from realistic core collapse supernova models," astro-ph/0309833

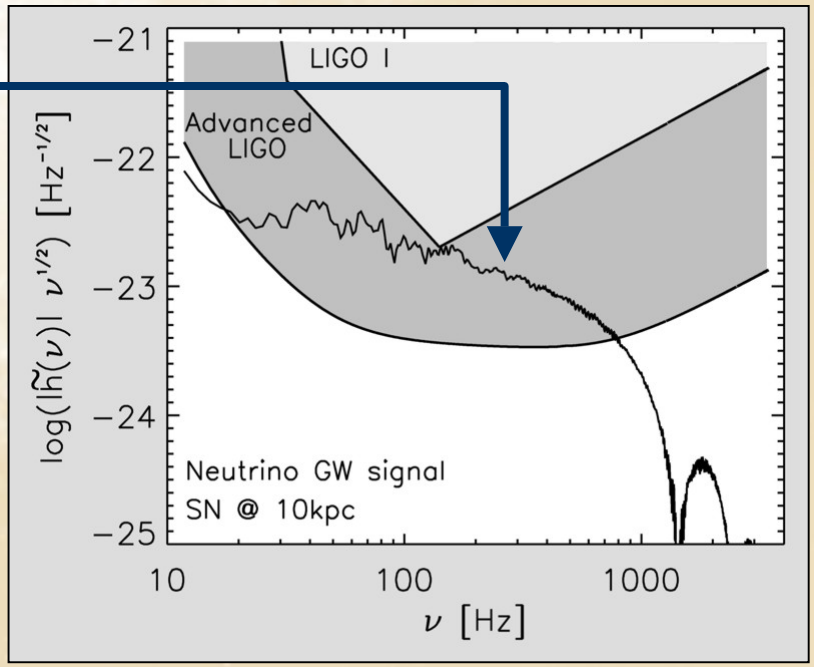
Asymmetric neutrino emission



Bounce

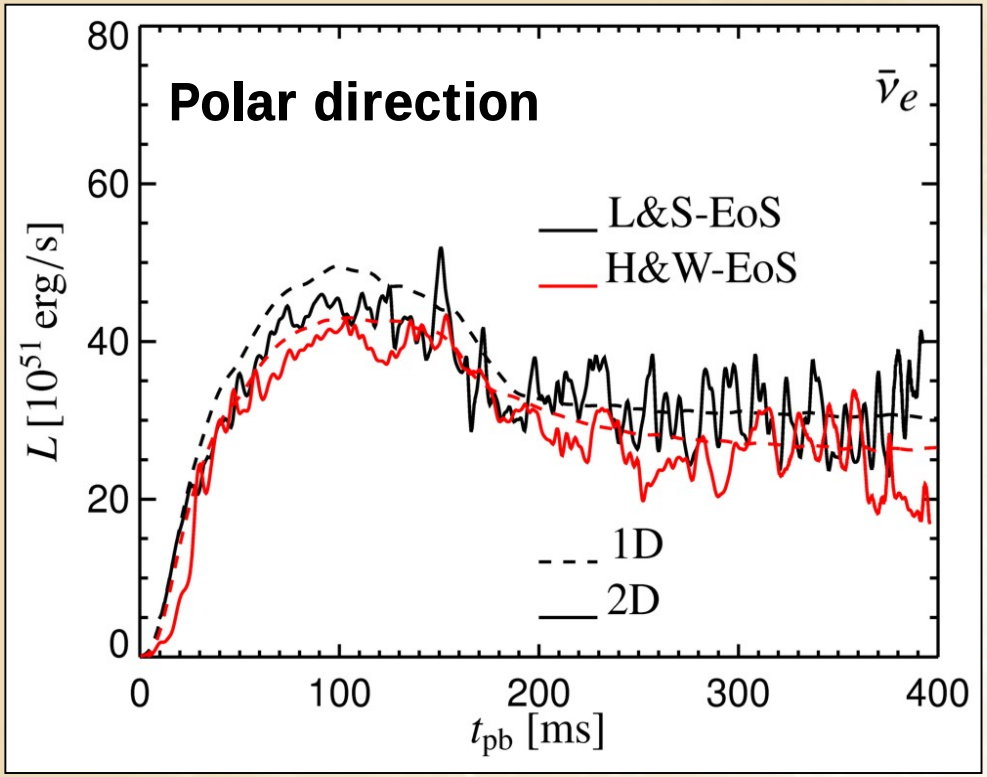
Convection

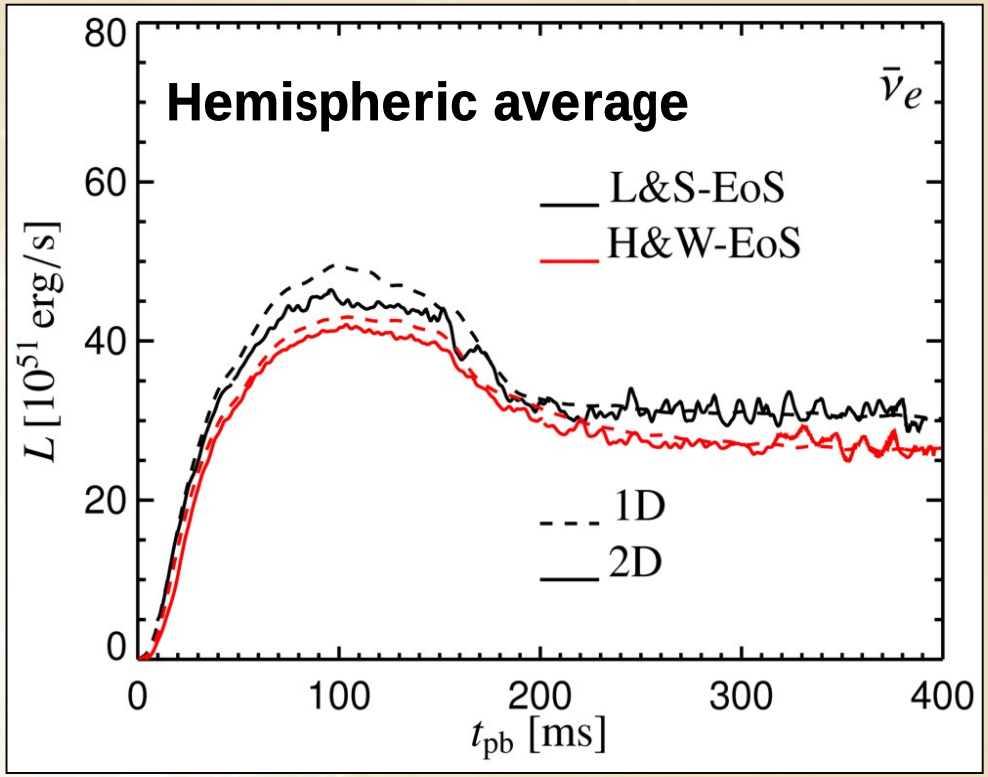




The gravitational-wave signal from convection is a generic and dominating feature

Luminosity Variation Detectable in Neutrinos?





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

• Super-K	70	$1\sigma \sim 10\%$
• 30 x Super-K	2×10^3	$1\sigma \sim 2\%$
• IceCube	1×10^4	$1\sigma \sim 1\%$

Detecting the spectrum of luminosity variations can

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

Marek, Janka & Müller, arXiv:0808.4136

Neutrino Limits by Intrinsic Signal Dispersion

Time of flight delay by neutrino mass
(G. Zatsepin, JETP Lett. 8:205, 1968)

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

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

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

For "milli charged" neutrinos, path bent by galactic magnetic field, inducing a time delay

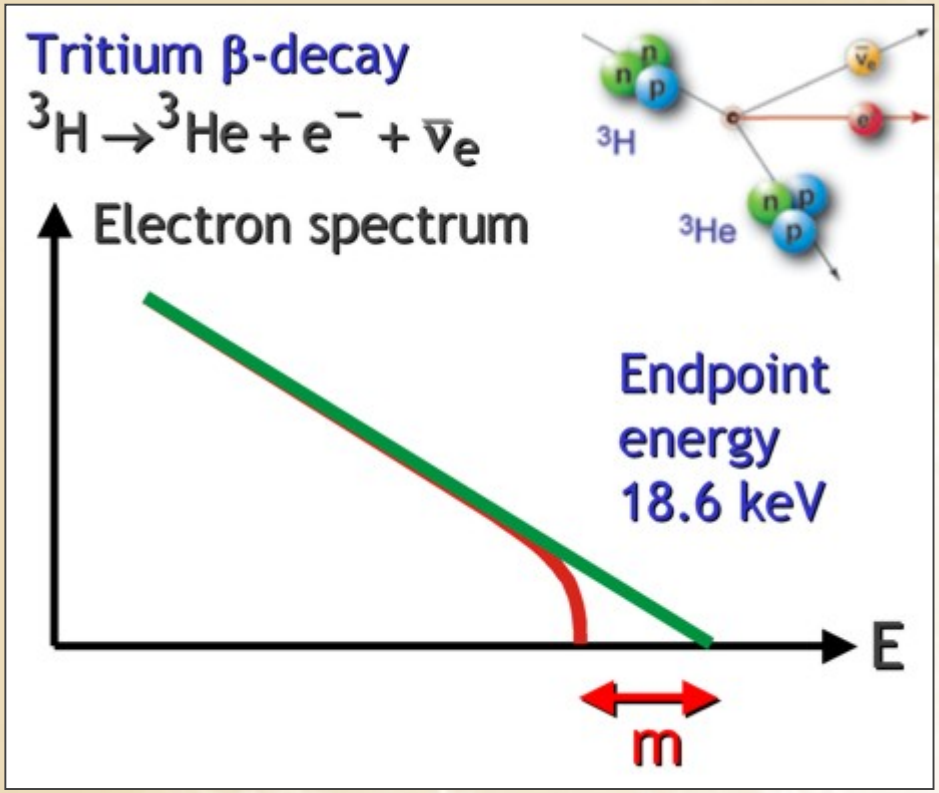
$$\frac{\Delta t}{t} = \frac{e_\nu^2 (B_\perp d_B)^2}{6E_\nu^2} < 3\times10^{-12}$$

$$\frac{e_\nu}{e} < 3\times10^{-17}\left(\frac{1\,\mu\mathrm{G}}{B_\perp}\right)\left(\frac{1\,\mathrm{kpc}}{d_B}\right)$$

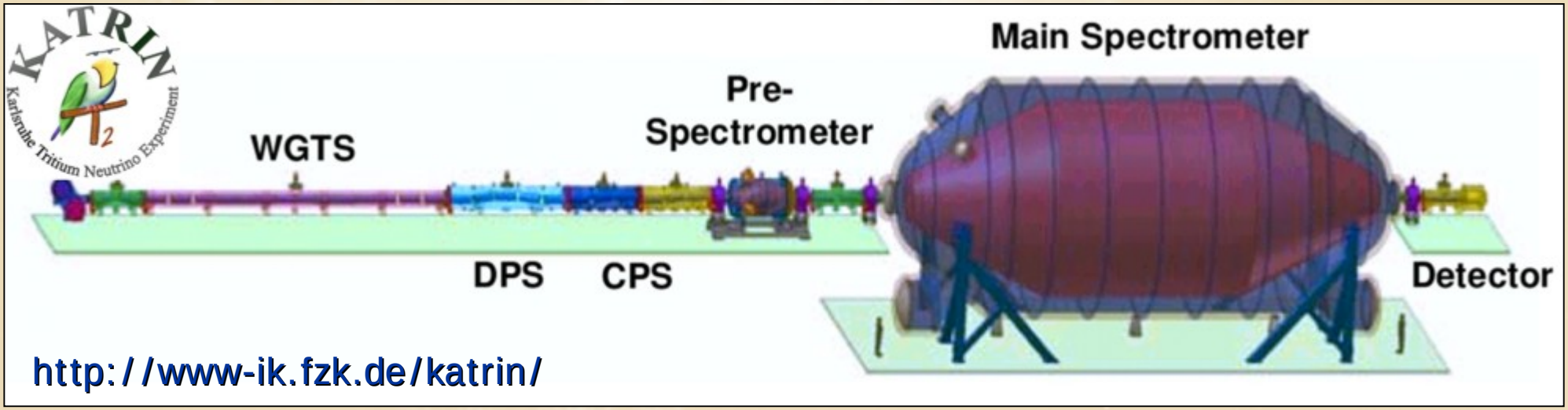
- Barbiellini & Cocconi, Nature 329 (1987) 21
- Bahcall, Neutrino Astrophysics (1989)

Assuming charge conservation in neutron decay yields a more restrictive limit of about 3×10^{-21} e

“Weighing” Neutrinos with KATRIN



- Sensitive to common mass scale m for all flavors because of small mass differences from oscillations
- Best limit from Mainz and Troitsk
  m < 2.2 eV (95% CL)
- KATRIN can reach 0.2 eV
- Under construction
- Data taking foreseen to begin in 2009



http://www-ik.fzk.de/katrin/

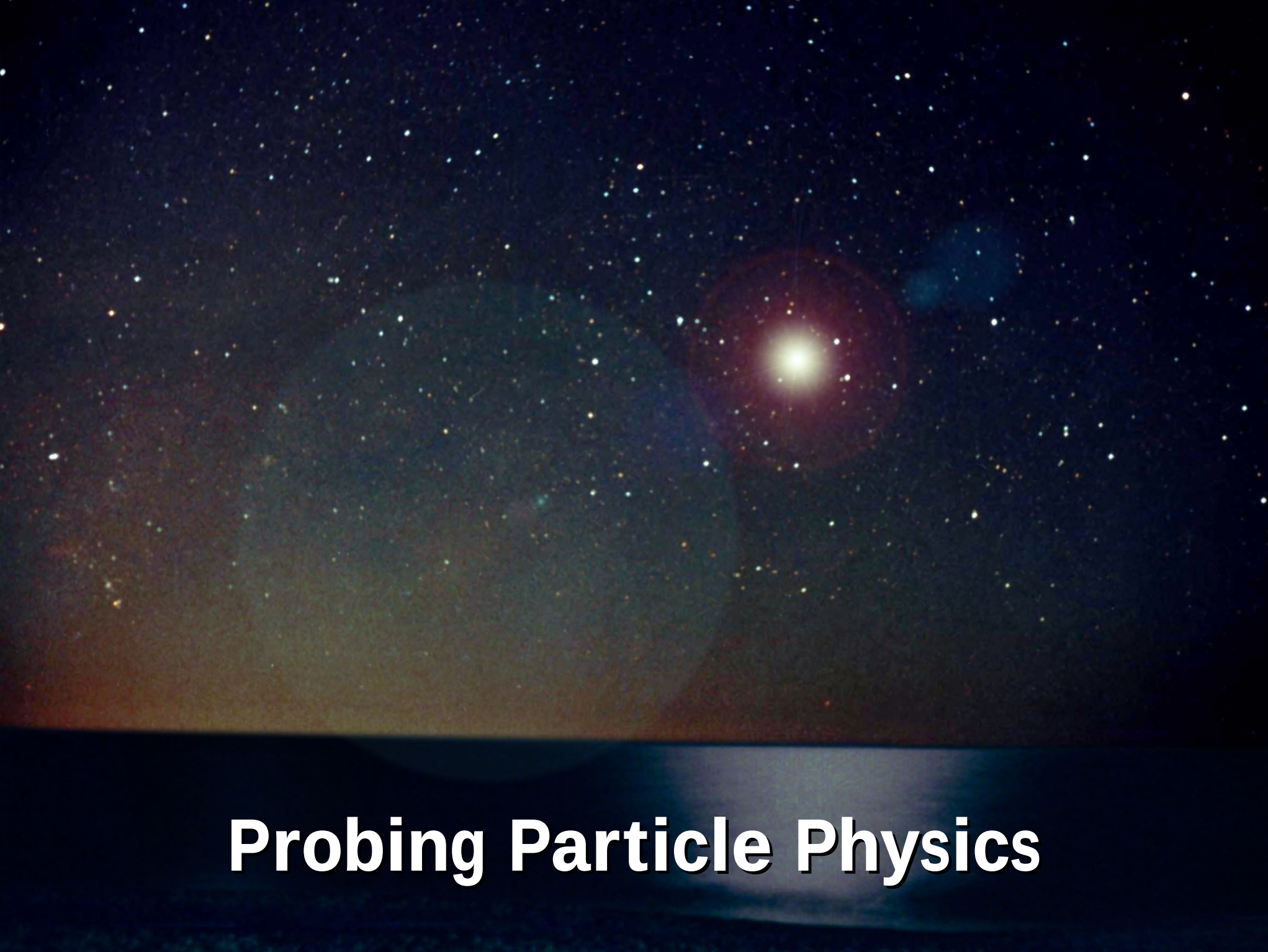
Neutrino Mass and Resolution of Time Variations

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!



Probing Particle Physics

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

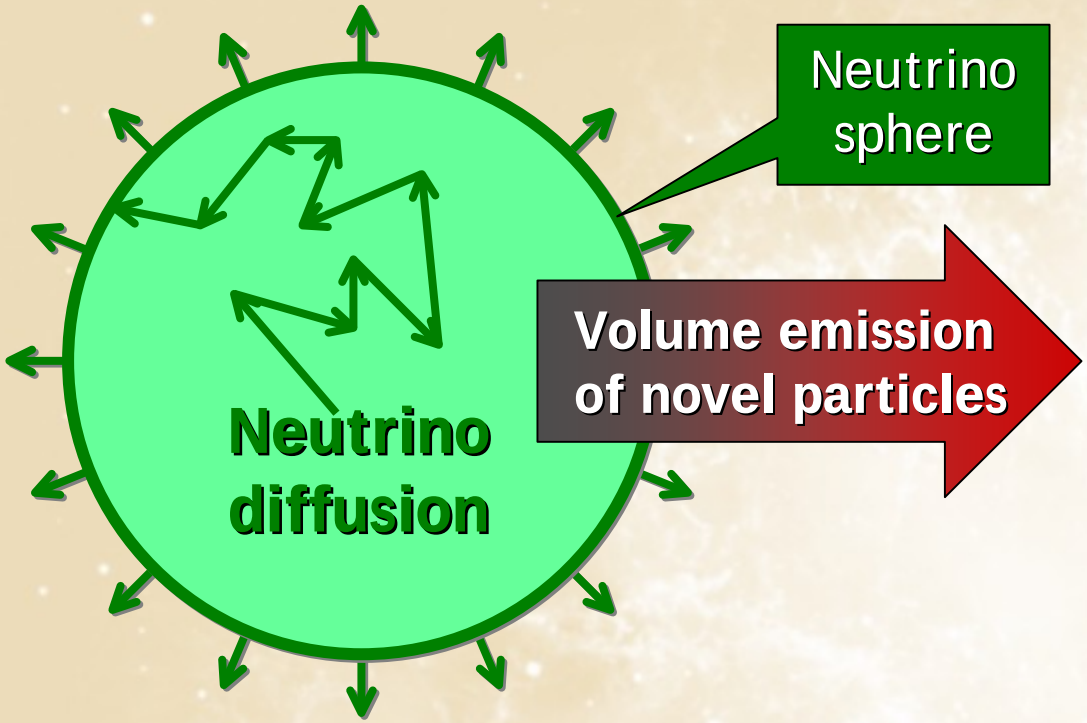
$$\Delta t_{Shapiro} = -2\int_A^B U[r(t)]\,dt \approx 1-5 \text{ months}$$

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

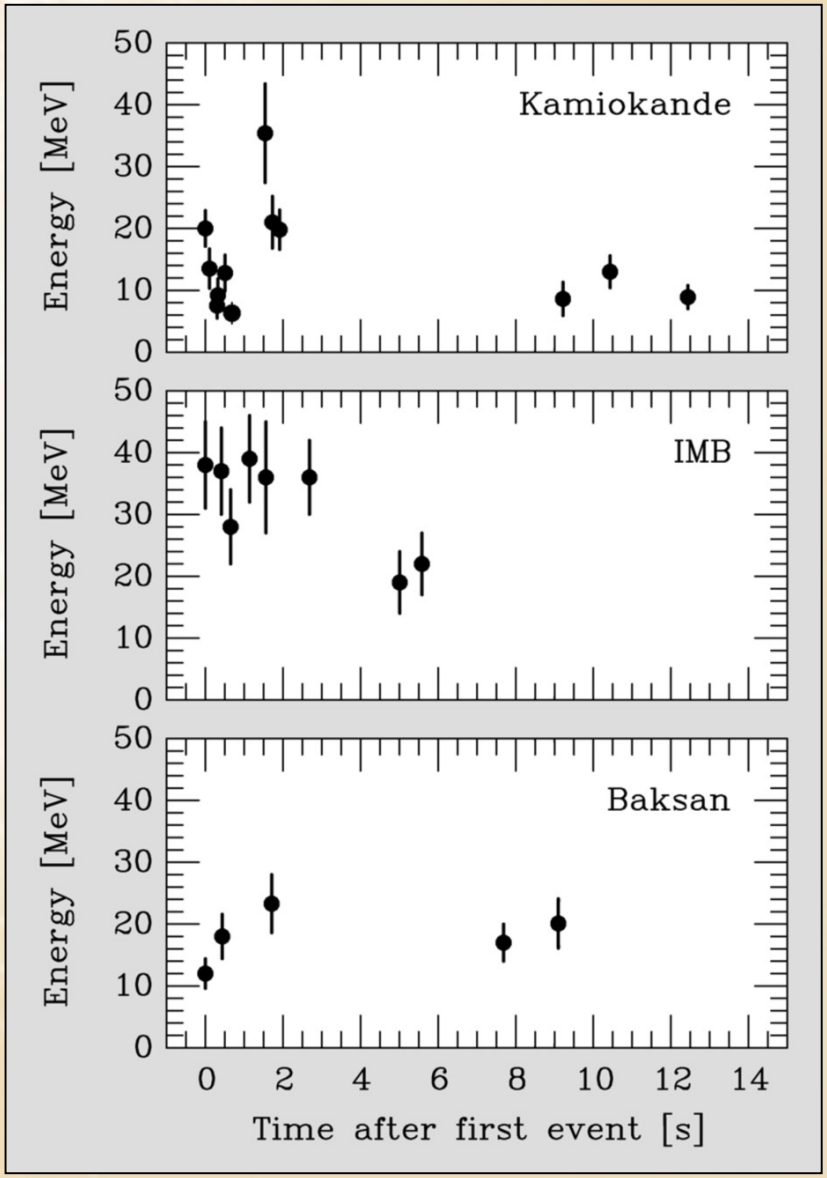
The Energy-Loss Argument



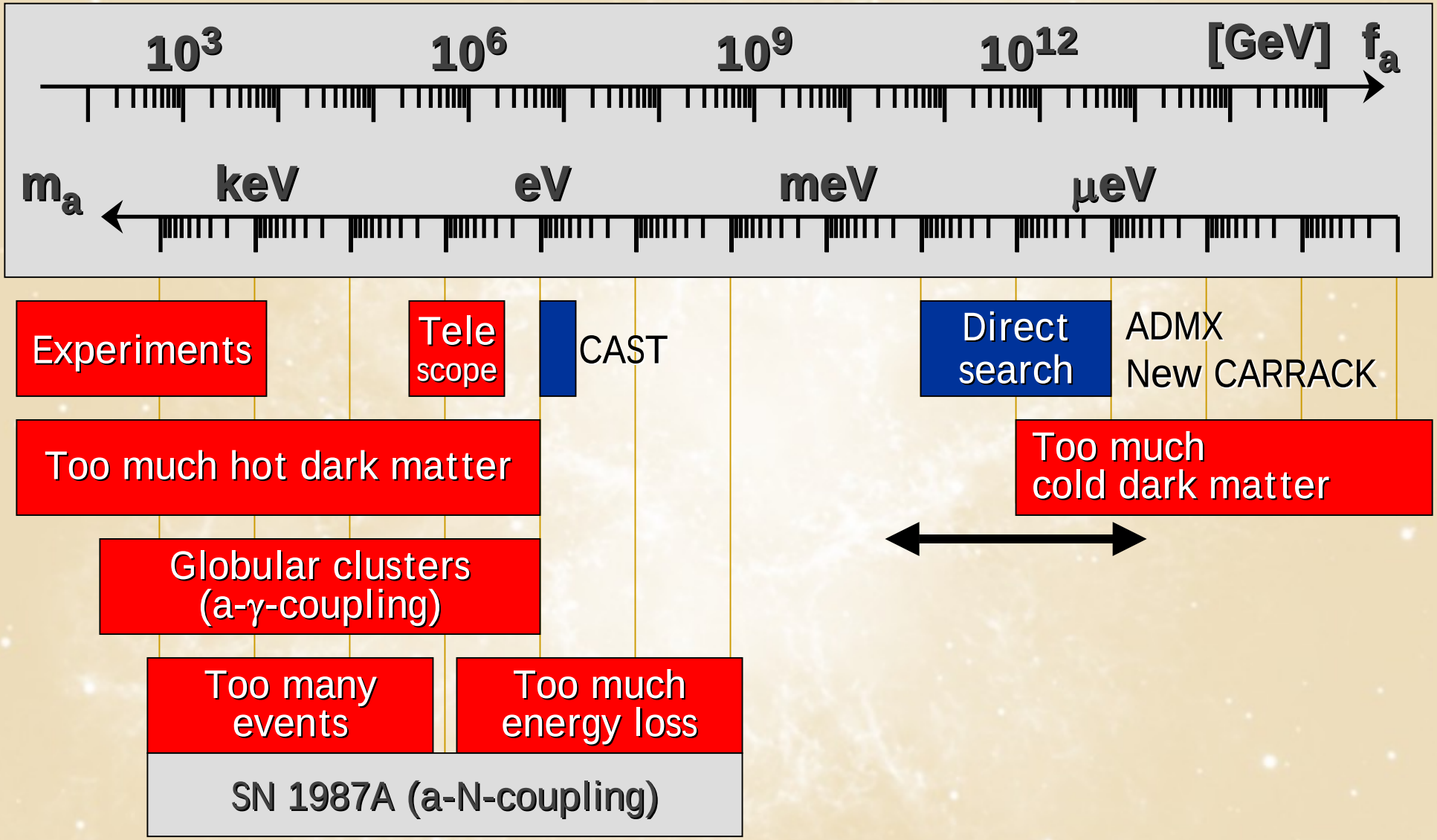
Emission of very weakly interacting particles would "steal" energy from the neutrino burst and shorten it.
(Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

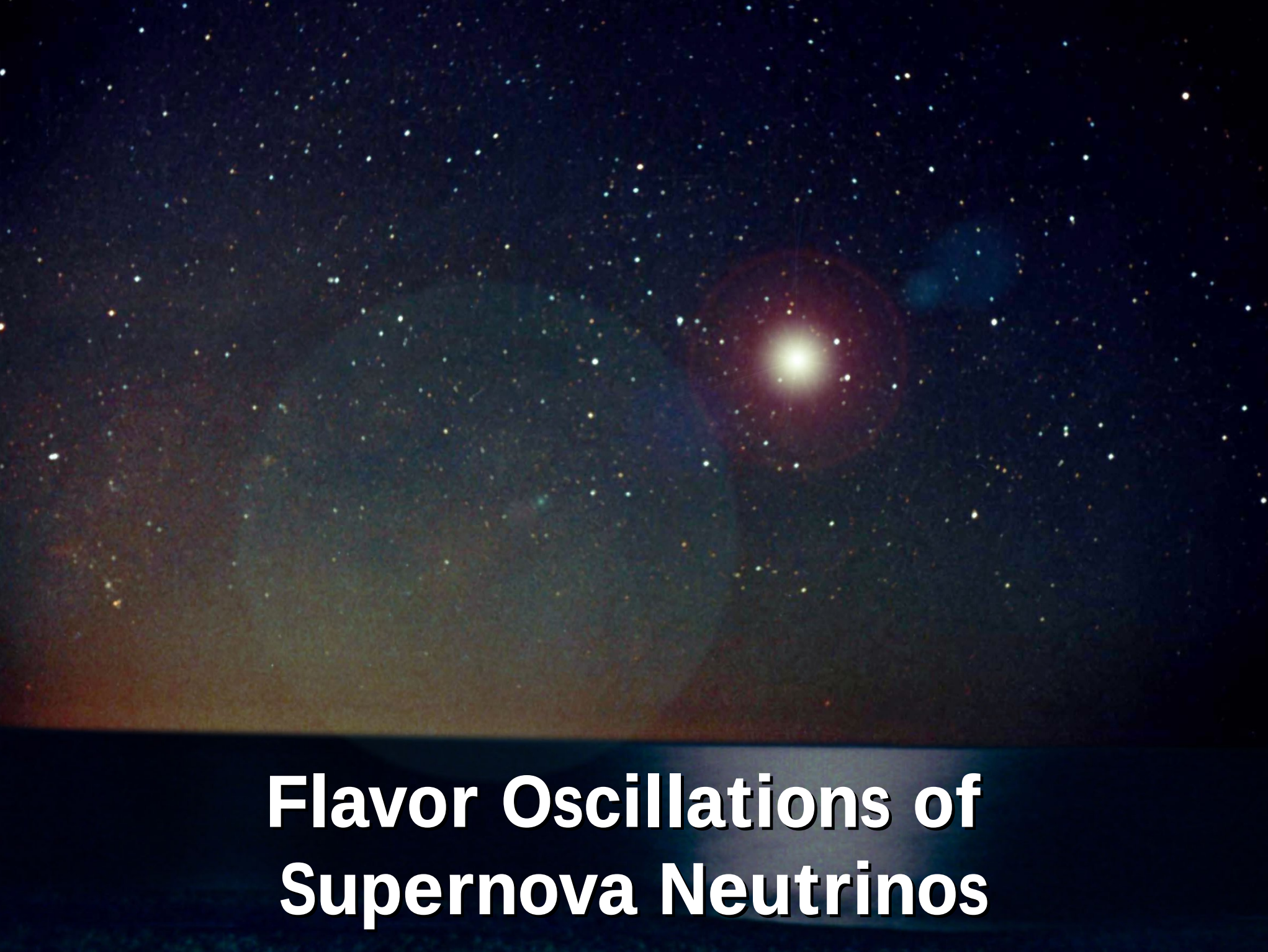
Late-time signal most sensitive observable

SN 1987A neutrino signal



Axion Bounds





Flavor Oscillations of Supernova Neutrinos

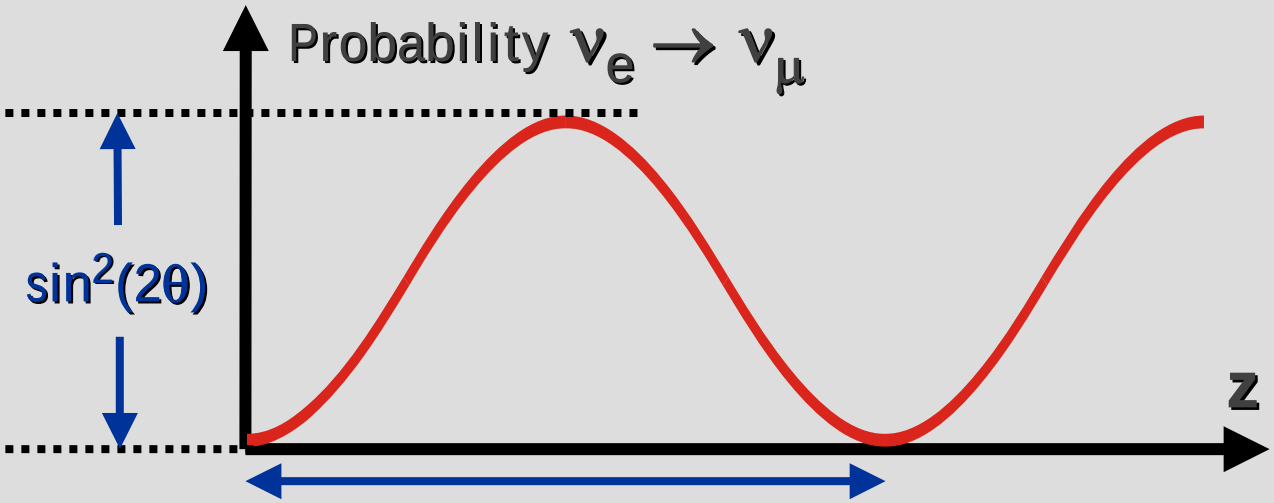
Neutrino Flavor Oscillations

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

Each mass eigenstate propagates as e^{ipz}

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

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



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

Bruno Pontecorvo
(1913 – 1993)
Invented nu oscillations

Three-Flavor Neutrino Parameters

Atmospheric/K2K	CHOOZ	Solar/KamLAND	2σ ranges
$37^\circ < \theta_{23} < 54^\circ$	$\theta_{13} < 11^\circ$	$30^\circ < \theta_{12} < 36^\circ$	hep-ph/0405172

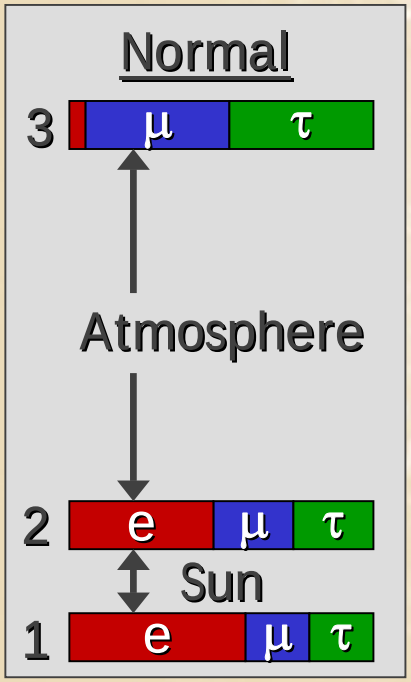
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & e^{-i\delta} s_{13} \\ & 1 & \\ -e^{i\delta} s_{13} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

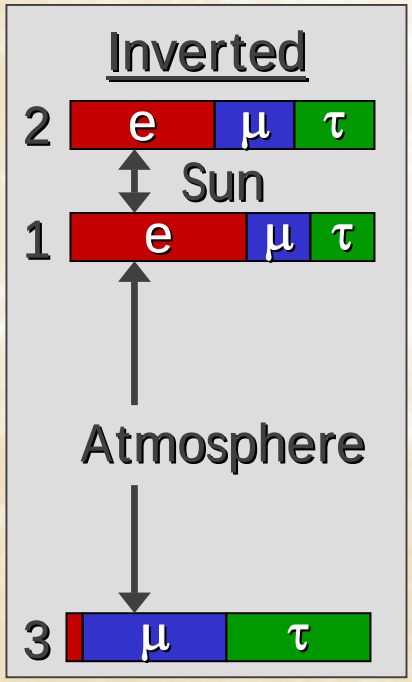
$c_{12} = \cos\theta_{12}$ etc., δ CP-violating phase

Solar 75–92

Atmospheric 1400–3000

$\Delta m^2 / \mathrm{meV}^2$

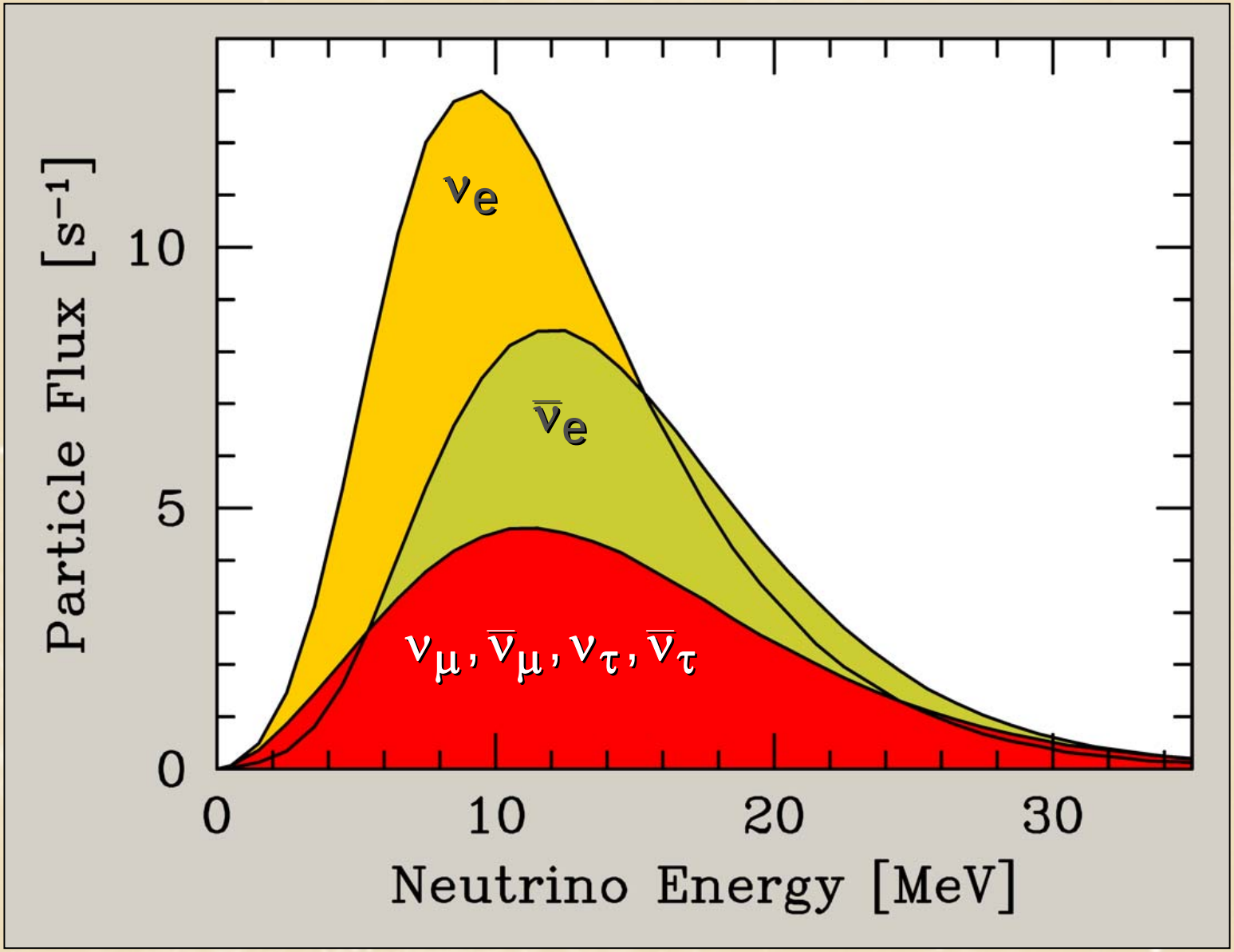




Tasks and Open Questions

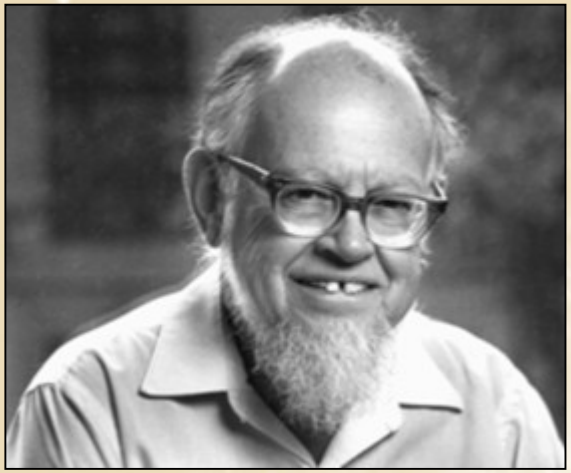
- Precision for θ_{12} and θ_{23}
- How large is θ_{13}?
- CP-violating phase δ?
- Mass ordering? (normal vs inverted)
- Absolute masses? (hierarchical vs degenerate)
- Dirac or Majorana?

Flavor-Dependent Fluxes in an Accretion-Phase Model



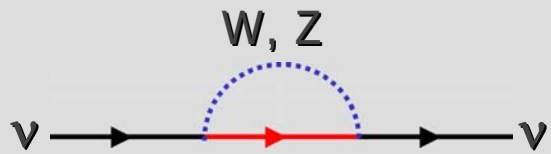
Keil, Raffelt & Janka, ApJ (2003) [astro-ph/0208035]

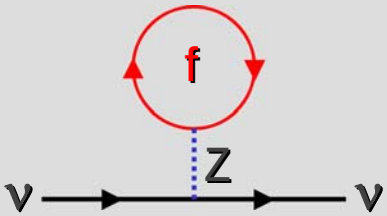
Neutrino Oscillations in Matter



Lincoln Wolfenstein

Neutrinos in a medium suffer flavor-dependent refraction (PRD 17:2369, 1978)



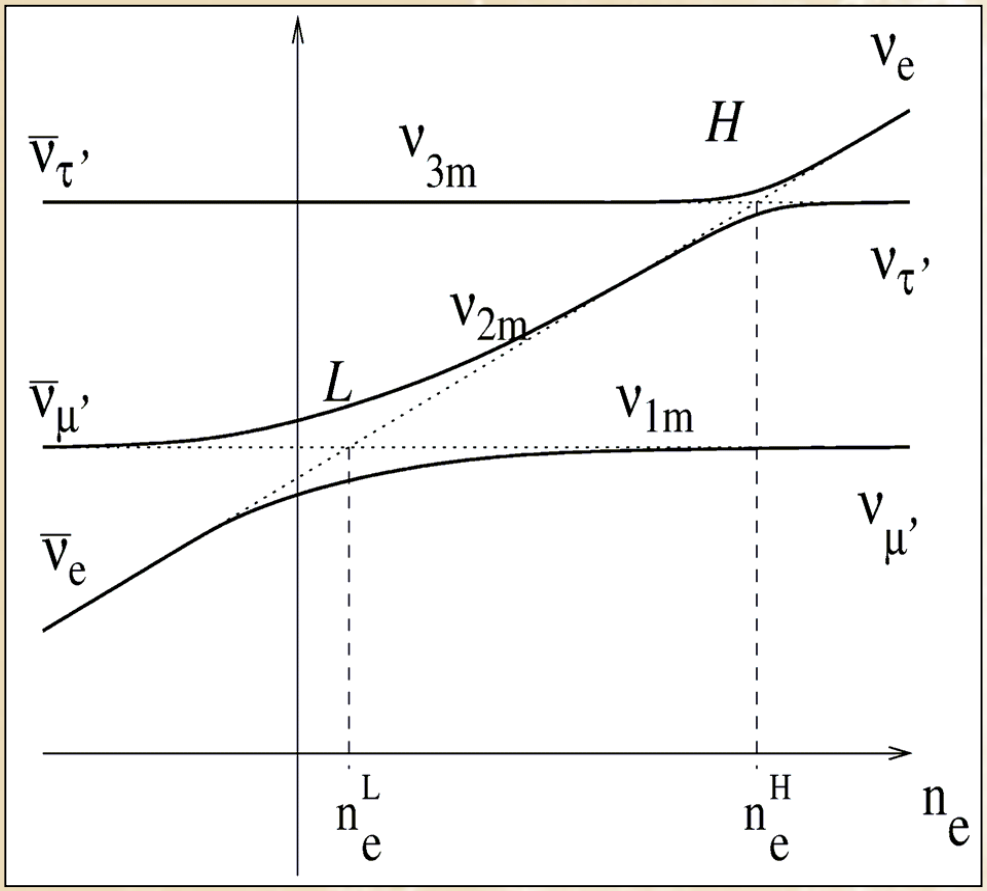


$$i\frac{\partial}{\partial z}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}=\left[\frac{M^2}{2E}+\sqrt{2}G_F\begin{pmatrix}n_e-\frac{1}{2}n_n & 0\\ 0 & -\frac{1}{2}n_n\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

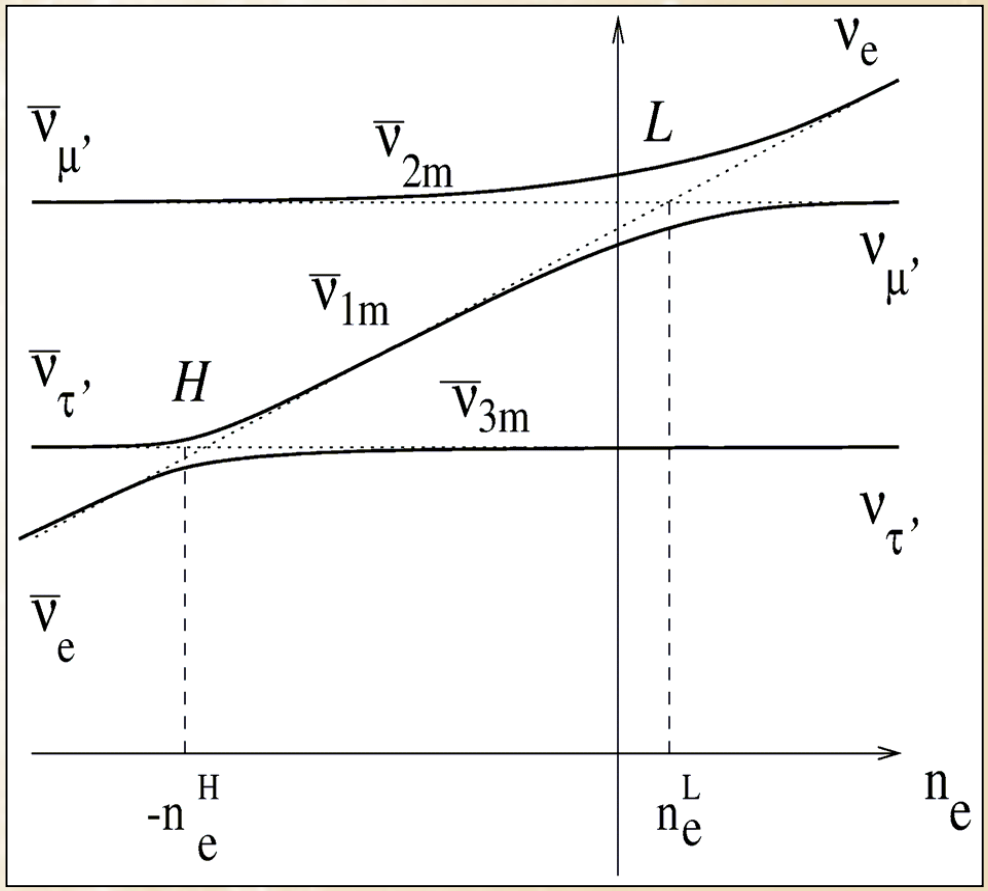
- "Level crossing" possible in a medium with a gradient (MSW effect)
  - For solar nus large flavor conversion anyway due to large mixing
  - Still important for 13-oscillations in supernova envelope
- Breaks degeneracy between Θ and $\pi/2-\Theta$ (dark vs light side)
  - 12 mass ordering for solar nus established
  - 13 mass ordering (normal vs inverted) at future LBL or SN
- Discriminates against sterile nus in atmospheric oscillations
- CP asymmetry in LBL, to be distinguished from intrinsic CP violation
- Prevents flavor conversion in a SN core and within shock wave
- Strongly affects sterile nu production in SN or early universe

Level-Crossing Diagram in a SN Envelope

Normal mass hierarchy



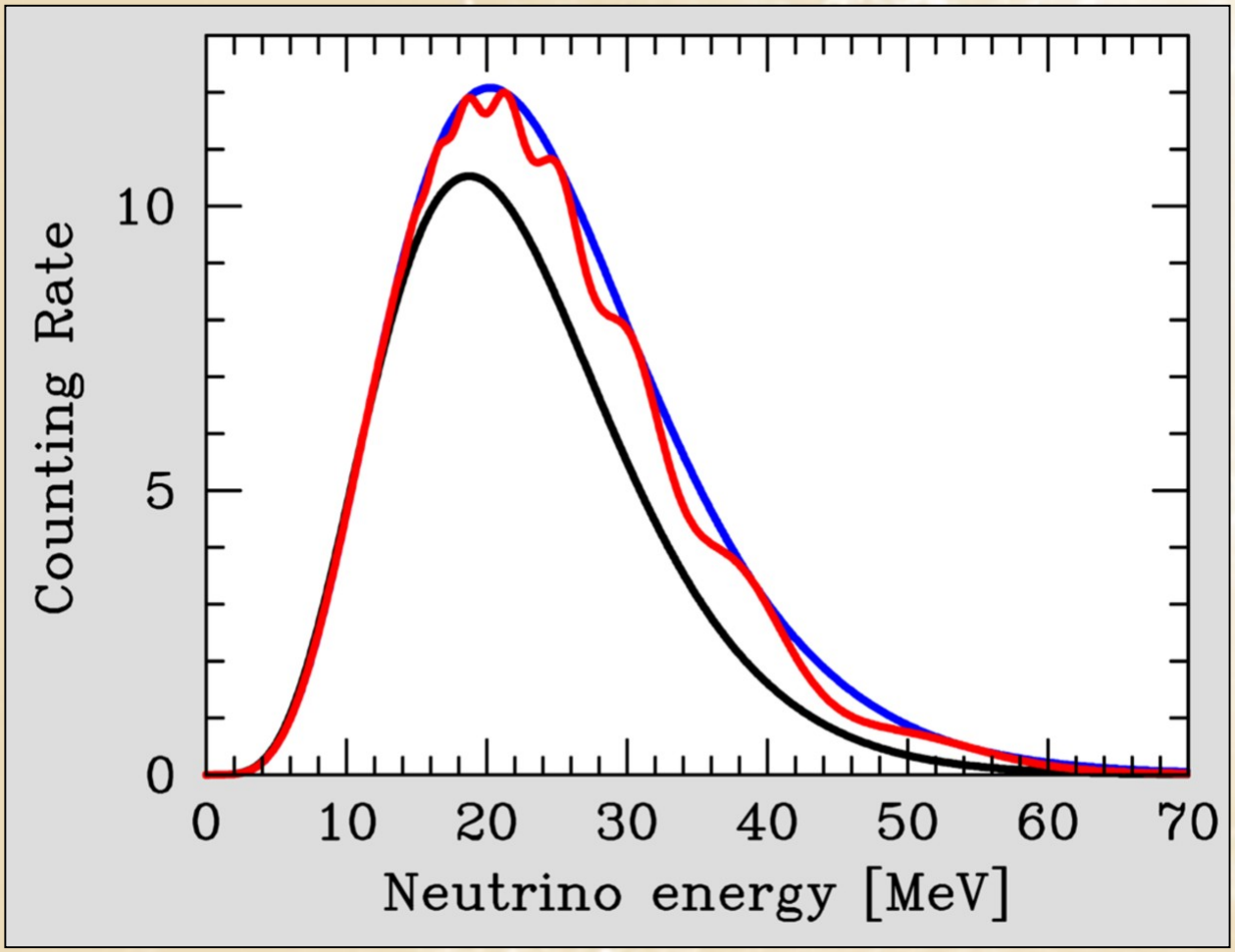
Inverted mass hierarchy



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

Oscillation of Supernova Anti-Neutrinos

Measured $\bar{\nu}_e$ spectrum at a detector like Super-Kamiokande



Assumed flux parameters

Flux ratio $\bar{\nu}_e : \bar{\nu}_\mu = 0.8 : 1$

$\langle E(\bar{\nu}_e) \rangle = 15\,\text{MeV}$

$\langle E(\bar{\nu}_x) \rangle = 18\,\text{MeV}$

Mixing parameters

$\Delta m^2_{sun} = 60\,\text{meV}^2$

$\sin^2(2\theta) = 0.9$

No oscillations

Oscillations in SN envelope

Earth effects included

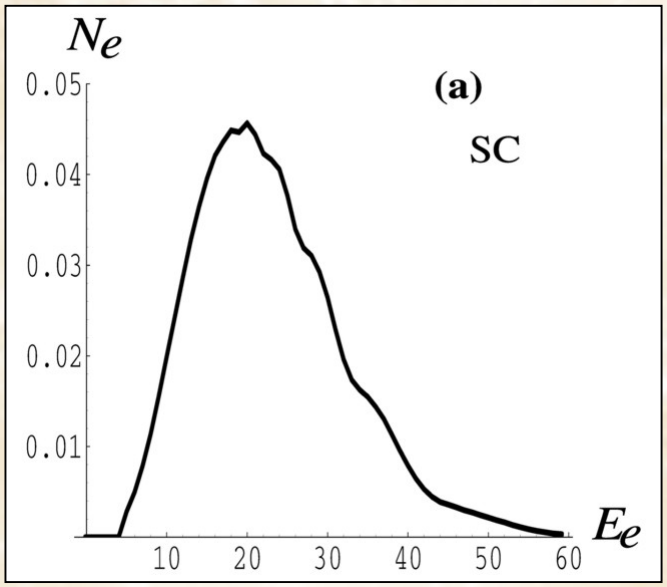
Π(Dighe, Kachelriess, Keil, Raffelt, Semikoz, Tomàs), hep-ph/0303210, hep-ph/0304150, hep-ph/0307050, hep-ph/0311172

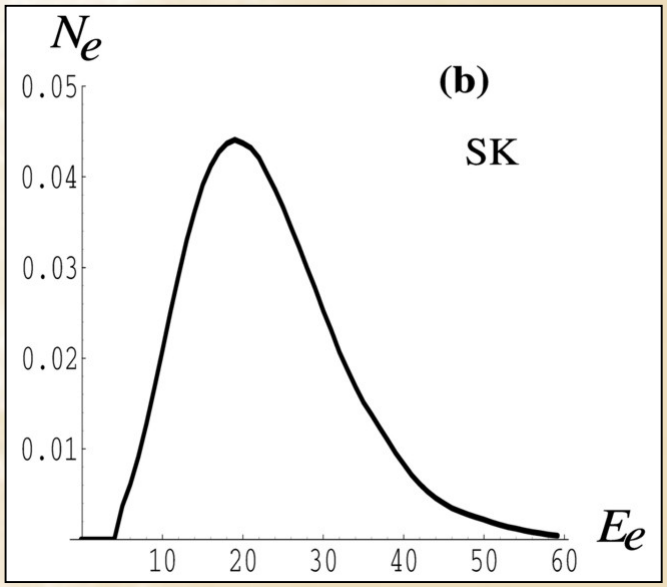
Model-Independent Strategies for Observing Earth Effects

One detector observes SN shadowed by Earth

Case 1:
- Another detector observes SN directly
- Identify Earth effects by comparing signals

Case2: Identify "wiggles" in signal of single detector
Problem: Smearing by limited energy resolution





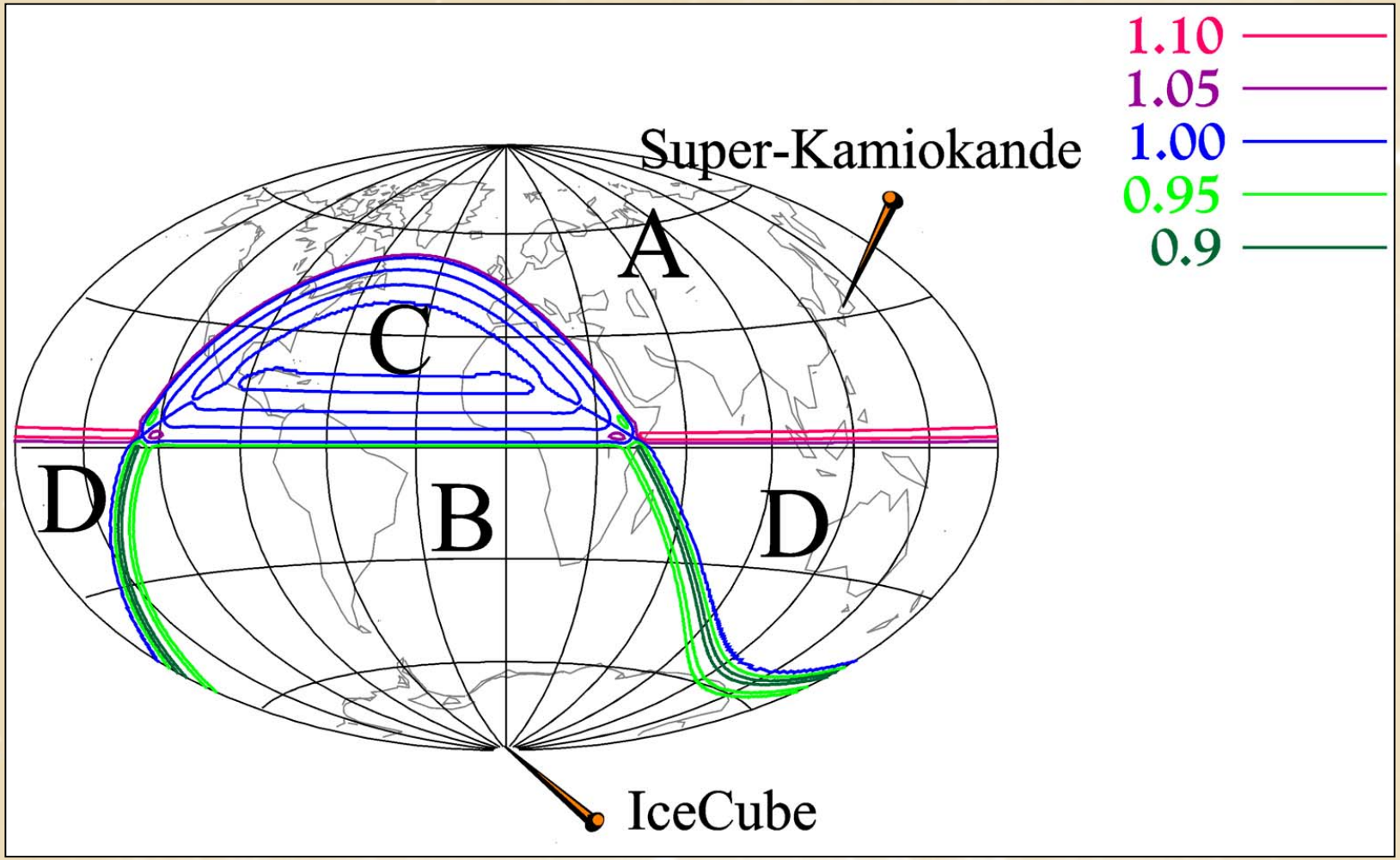
If 13-mixing angle is known to be "large", e.g. from Double Chooz, observed "wiggles" in energy spectrum signify normal mass hierarchy

Scintillator detector
~ 2000 events
may be enough

Water Cherenkov
Need megaton detector
with ~ 10^5 events

Dighe, Keil & Raffelt, "Identifying Earth matter effects on supernova neutrinos at a single detector" [hep-ph/0304150]

Two-Detector Sky Coverage with Super-K & IceCube

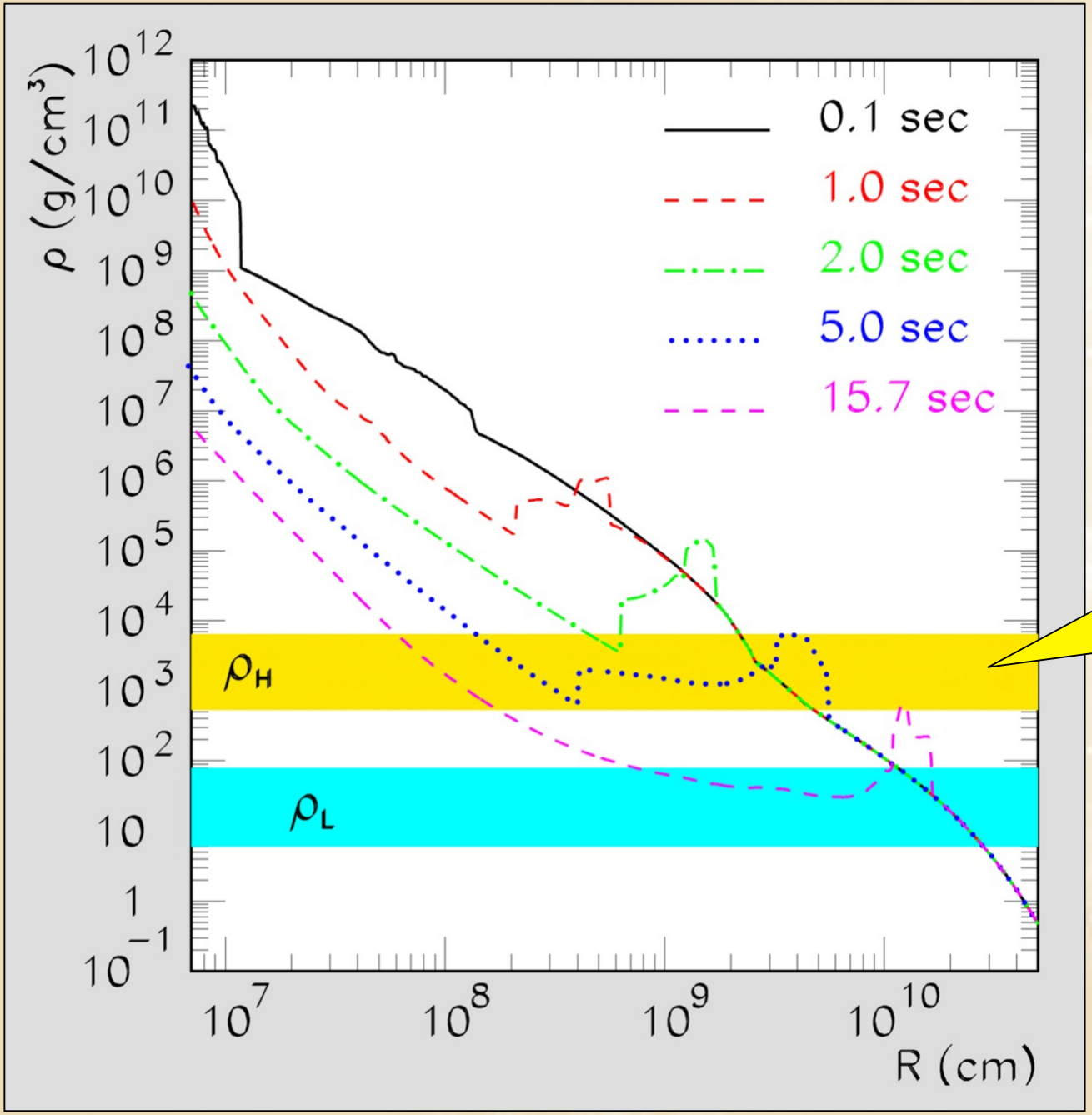


Dighe, Keil, Raffelt hep-ph/0303210

Earth effects appear in

	IceCube	A	35%	Suitable for two-detector method
Super-K		B	35%	
Super-K	IceCube	C	15%	Approx. same signal in both detectors
		D	15%	

Supernova Shock Propagation and Neutrino Oscillations



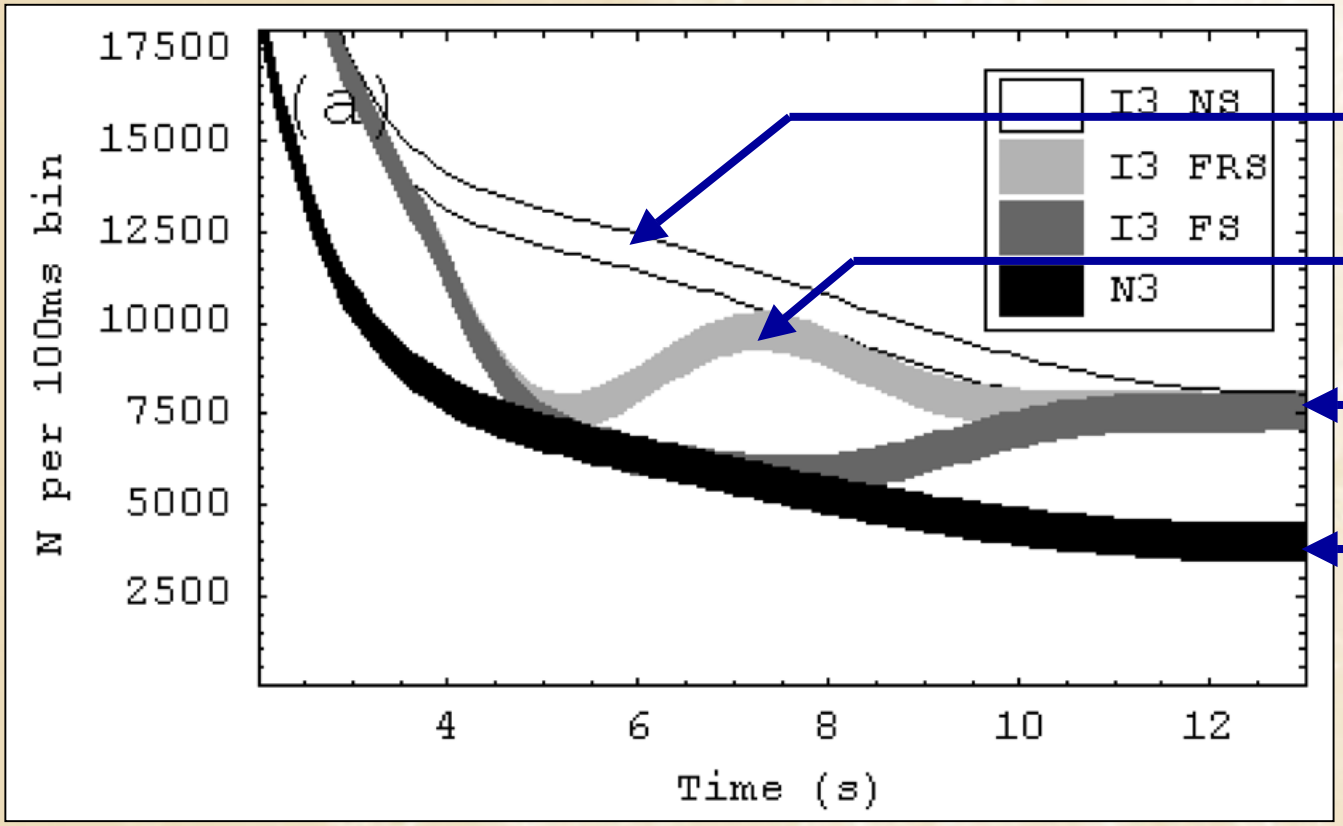
Schirato & Fuller: Connection between supernova shocks, flavor transformation, and the neutrino signal [astro-ph/0205390]

Resonance density for Δm^2_{atm}

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]

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

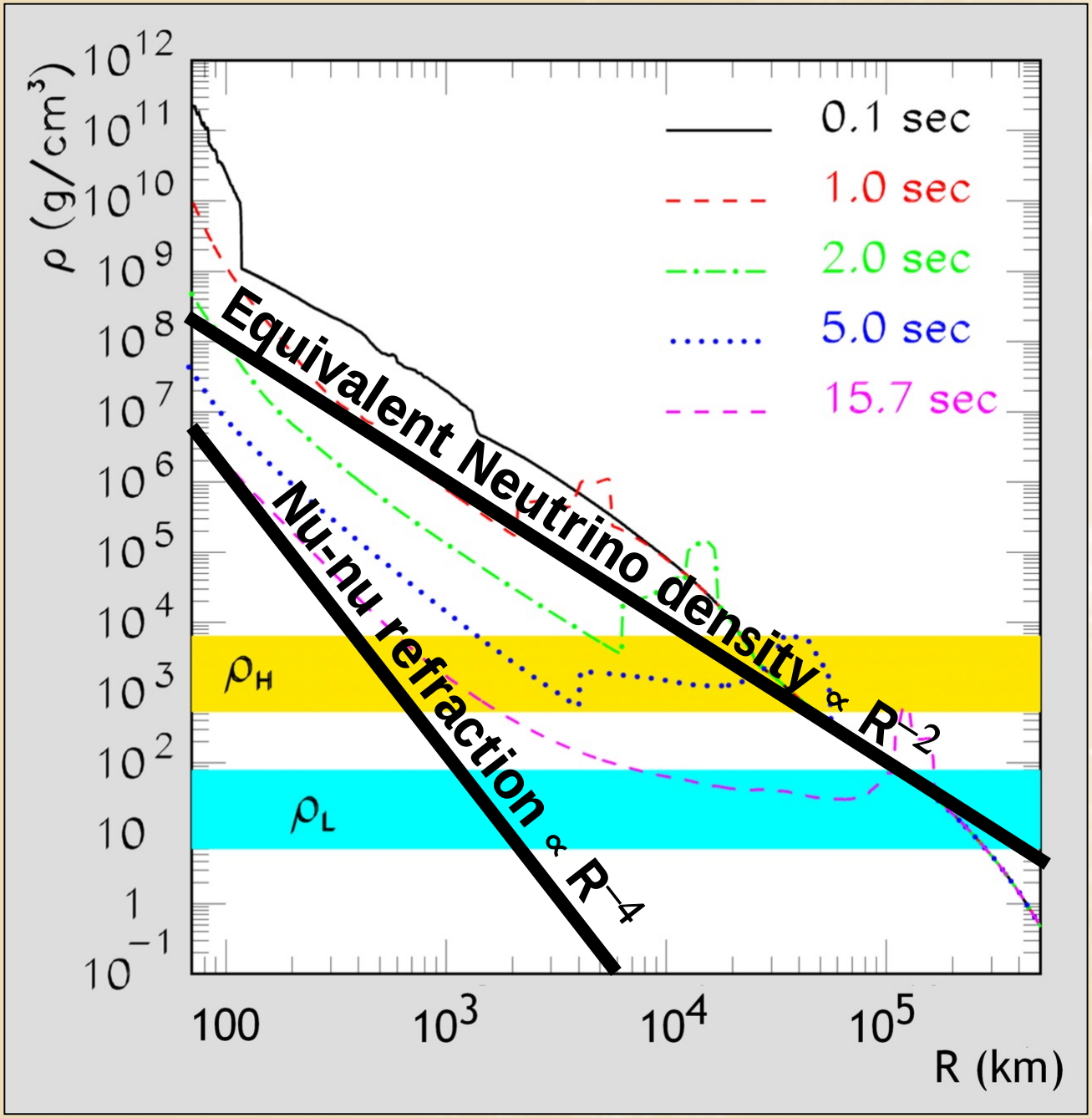
Inverted Hierarchy
Forward & reverse shock

Inverted Hierarchy
Forward shock

Normal Hierarchy

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

Neutrino Density Streaming off a Supernova Core



Typical luminosity in one neutrino species

$$L_\nu = 3\times 10^{52}\,\frac{\text{erg}}{\text{s}}$$

Corresponds to a neutrino number density of

$$n_\nu = 3\times 10^{35}\,\text{cm}^{-3}\left(\frac{\text{km}}{R}\right)^2$$

Current-current structure of weak interaction causes suppression of effective potential for collinear-moving particles

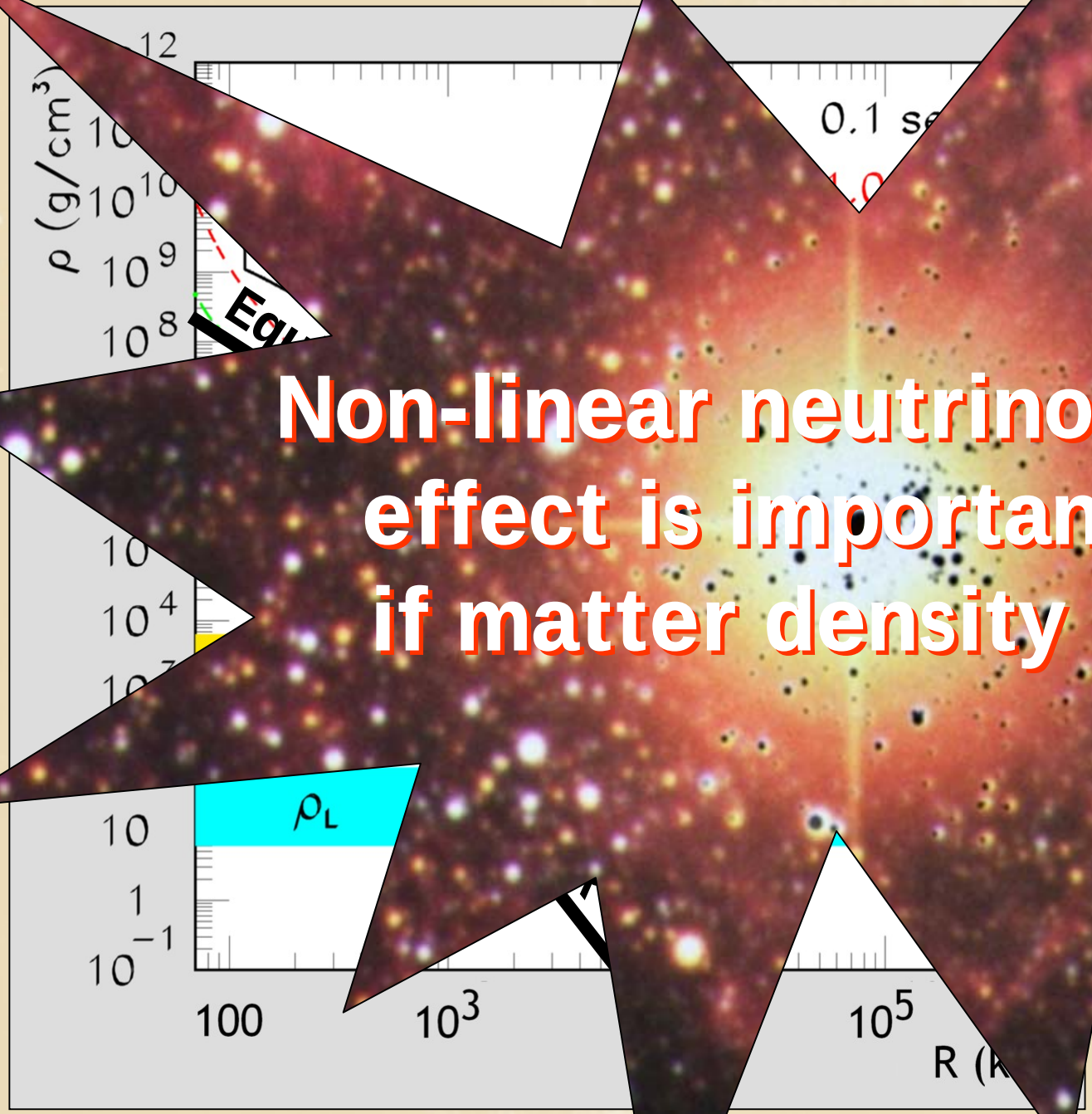
$$V_{weak} \propto G_F(1-\cos\theta)$$

Nu-nu refractive effect decreases as

$$V_{\nu\nu} \propto R^{-4}$$

Appears to be negligible

Neutrino Density Streaming off a Supernova Core



ypical luminosity in one
eutrino species

o a neutrino
sity of

ucture
ion

ving particles

(1 – cos θ)

Nu-ne e effect
decrease

$V_{\nu\nu} \propto R^{-4}$

Appears to be negligible

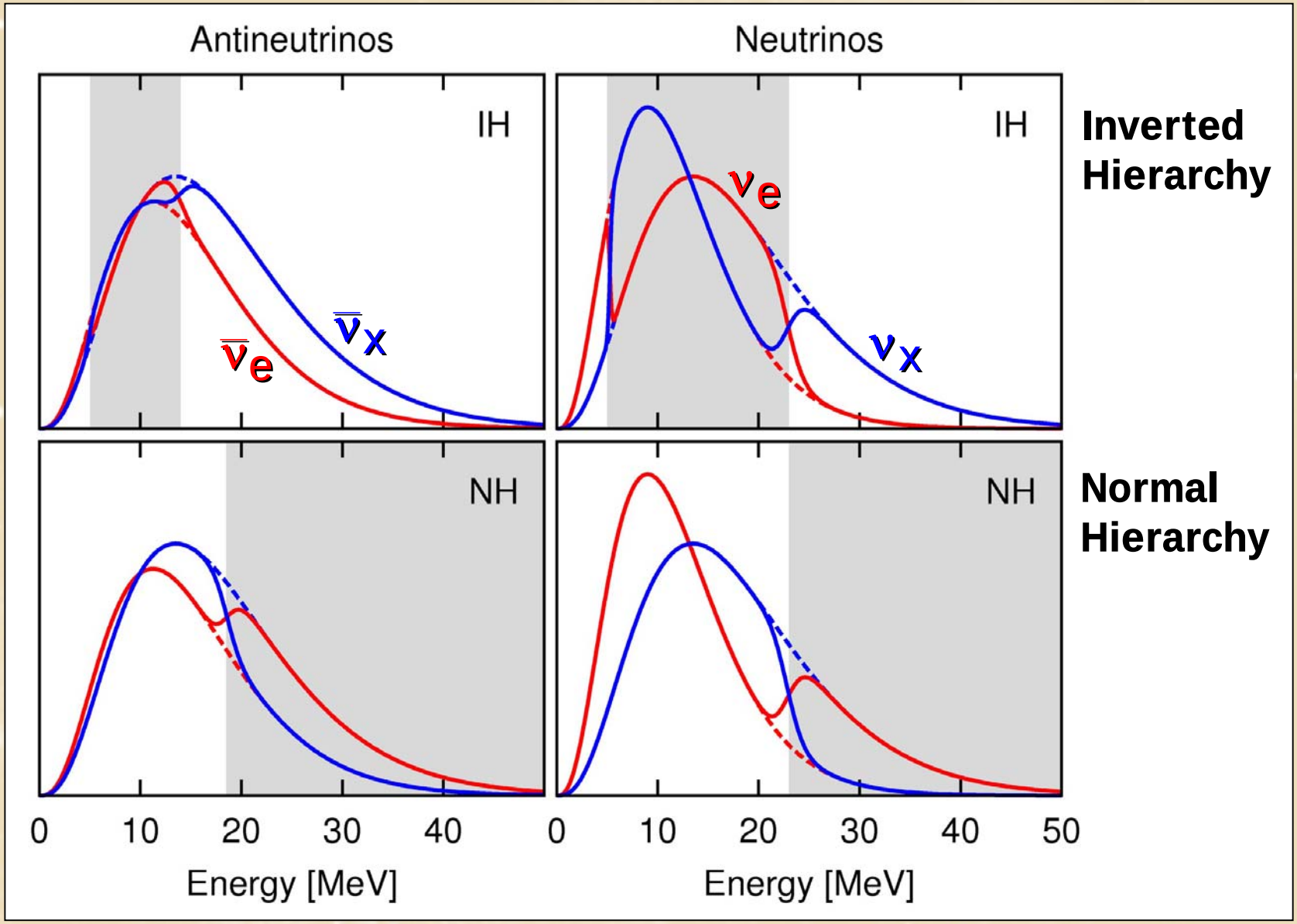
Non-linear neutrino-neutrino effect is important, even if matter density is large

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

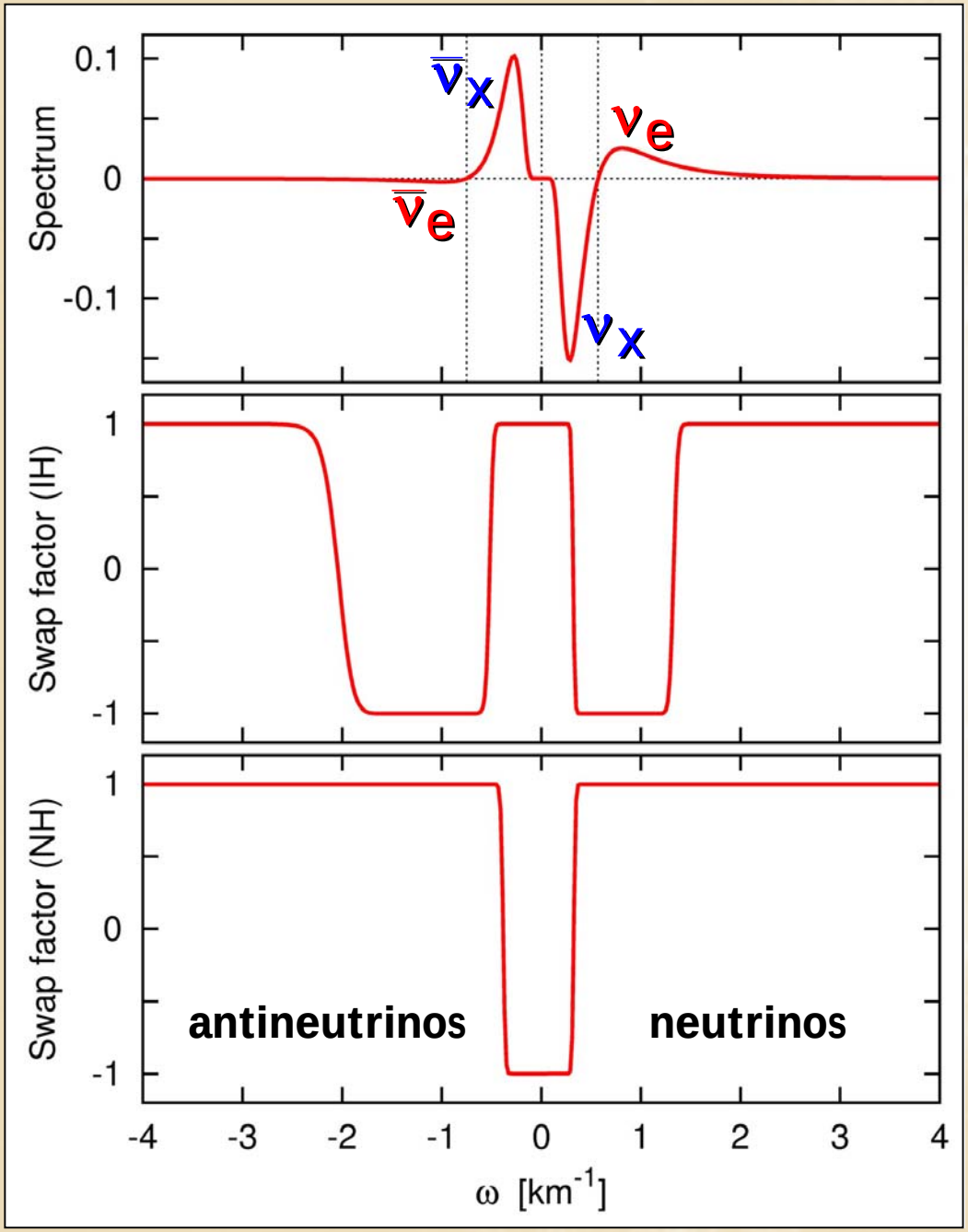
Duan, Fuller, Carlson & Qian, astro-ph/0608050, 0703776, arXiv:0707.0290, 0710.1271. Duan, Fuller & Qian, arXiv:0706.4293, 0801.1363, 0808.2046. Duan, Fuller & Carlson, arXiv:0803.3650. Duan & Kneller, arXiv:0904.0974. Hannestad, Raffelt, Sigl & Wong, astro-ph/0608695. Balantekin & Pehlivan, astro-ph/0607527. 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. 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.

Multiple Spectral Splits (Cooling-Phase Example)



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

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

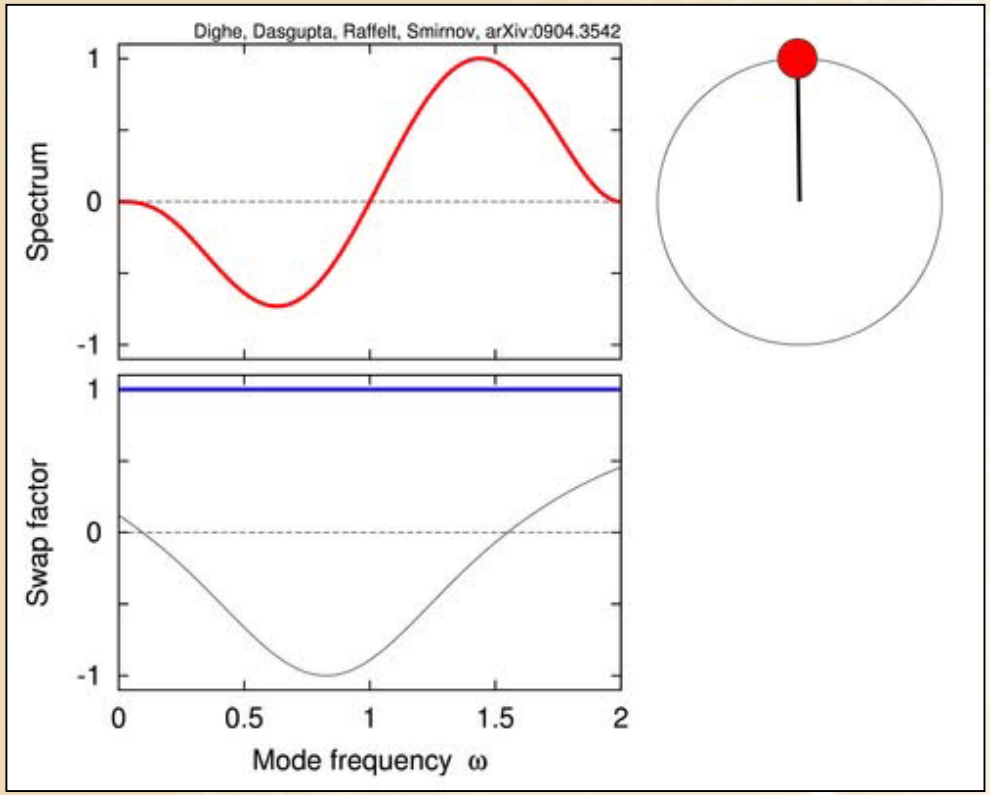
Swaps develop around every "positive" spectral crossing

Each swap flanked by two splits

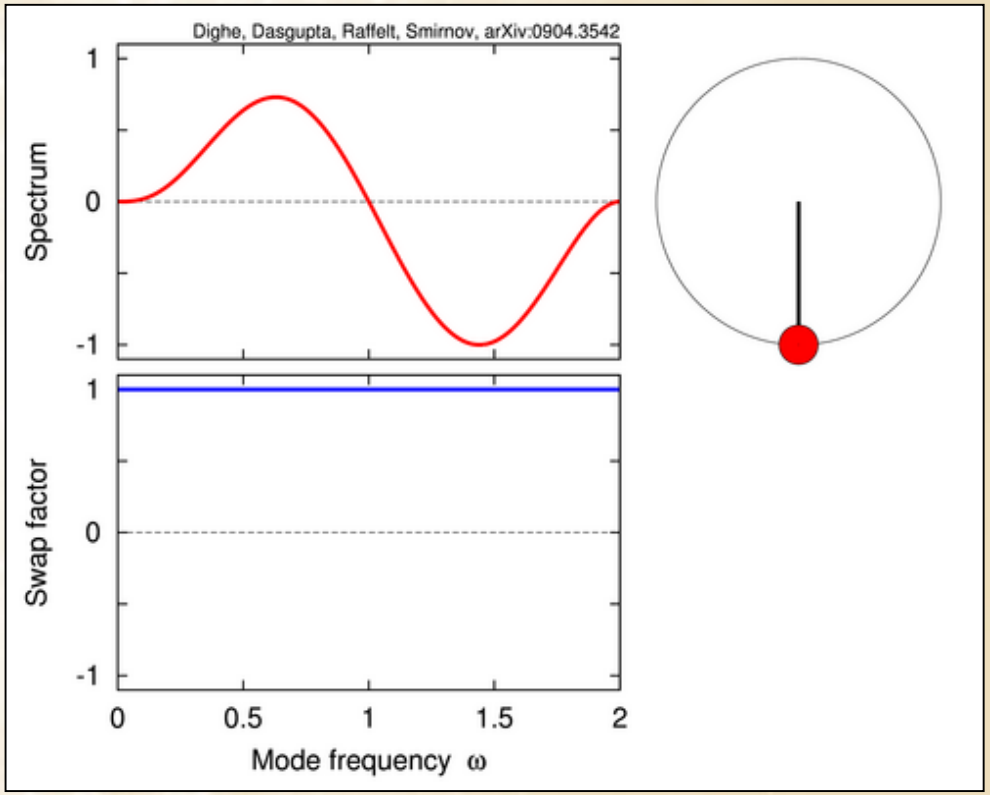
Dasgupta, Dighe, Raffelt & Smirnov, arXiv:0904.3542

Flavor Pendulum

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



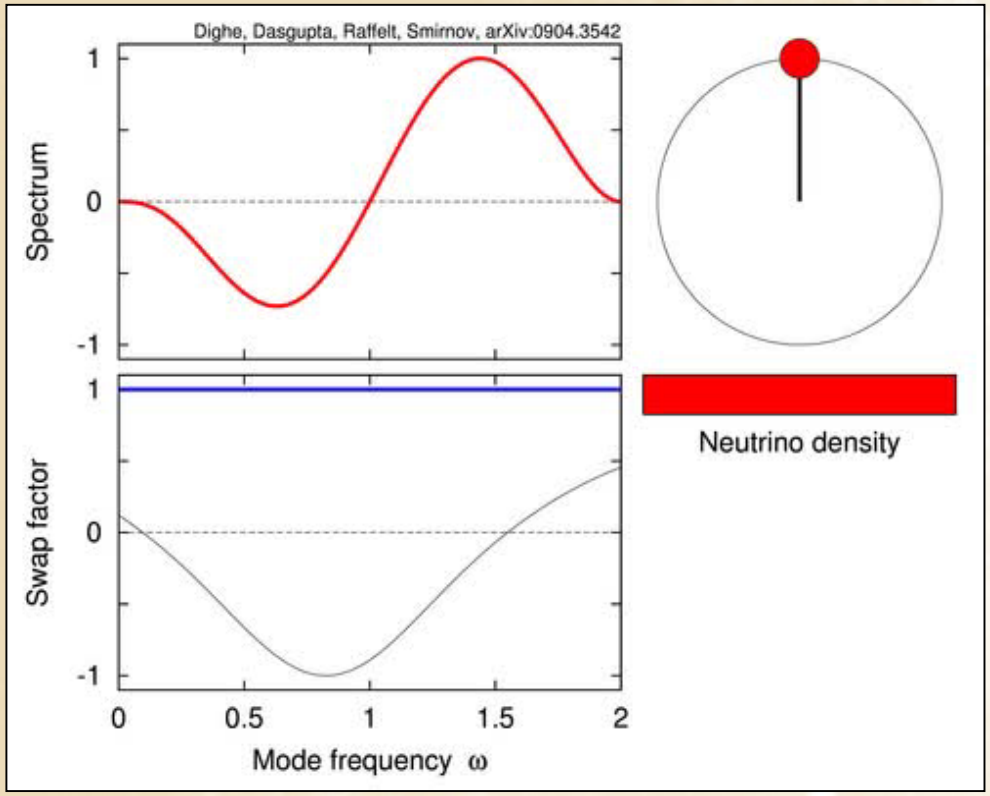
Single “negative” crossing
(potential energy at a minimum)



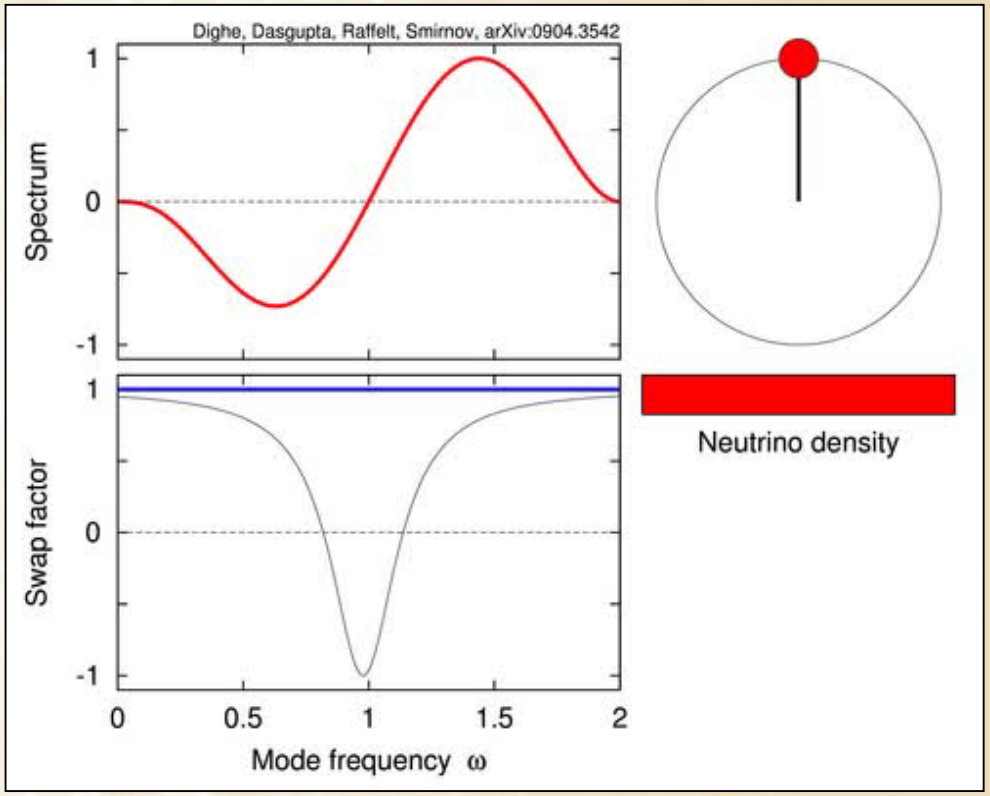
Dasgupta, Dighe, Raffelt & Smirnov, arXiv:0904.3542
For movies see http://www.mppmu.mpg.de/supernova/multisplits

Decreasing Neutrino Density

Certain initial neutrino density



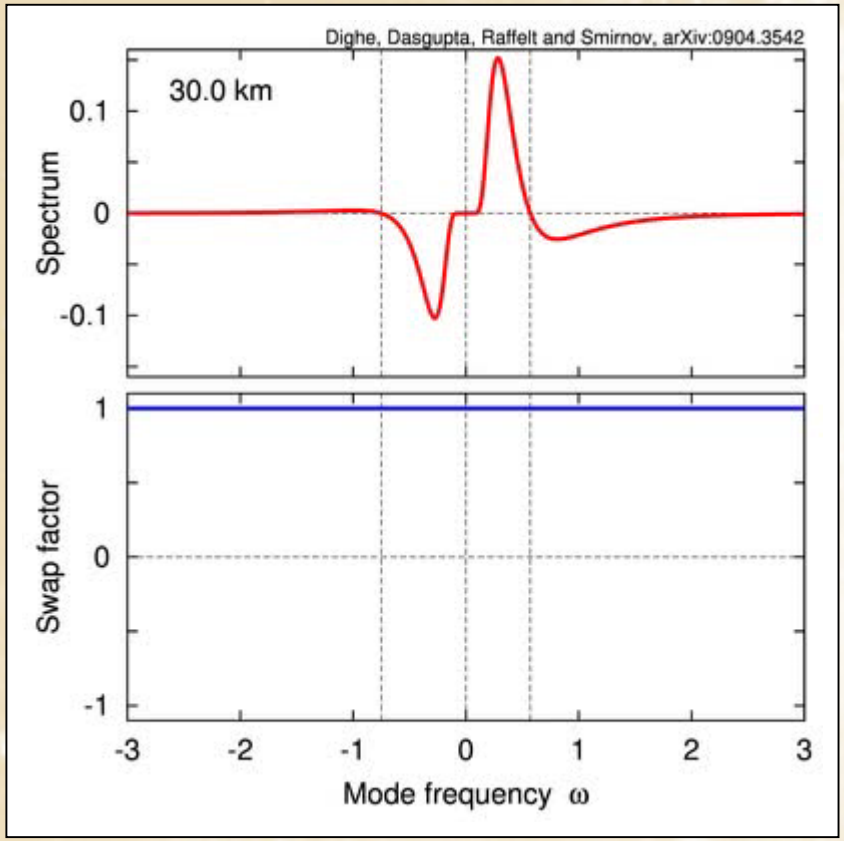
Four times smaller initial neutrino density



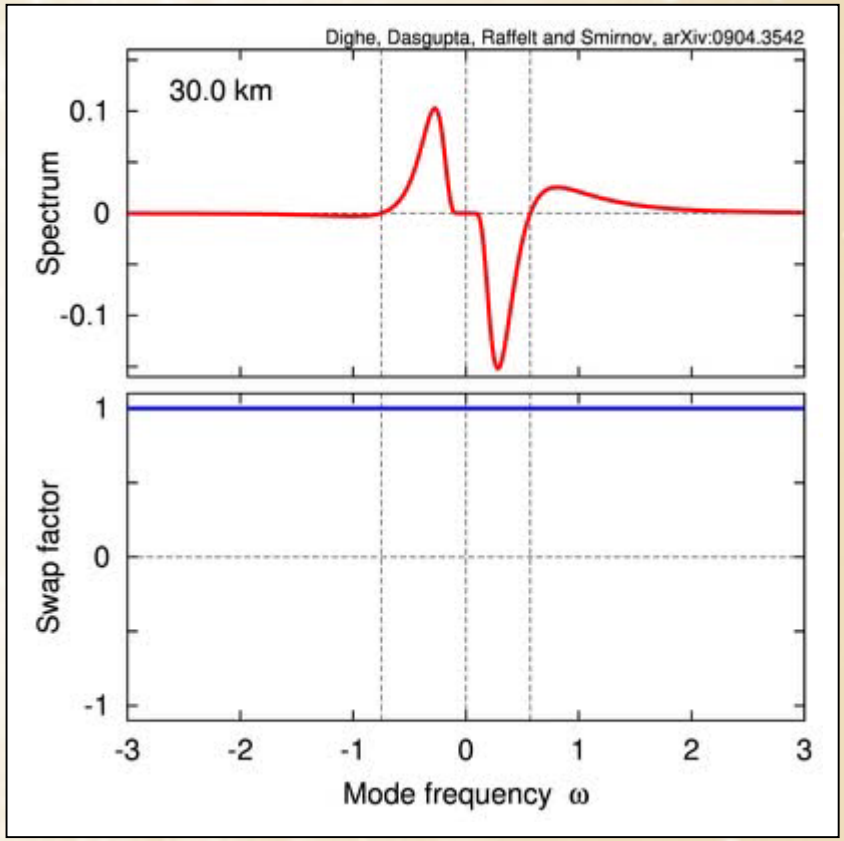
Dasgupta, Dighe, Raffelt & Smirnov, arXiv:0904.3542
For movies see http://www.mppmu.mpg.de/supernova/multisplits

Supernova Cooling-Phase Example

Normal Hierarchy

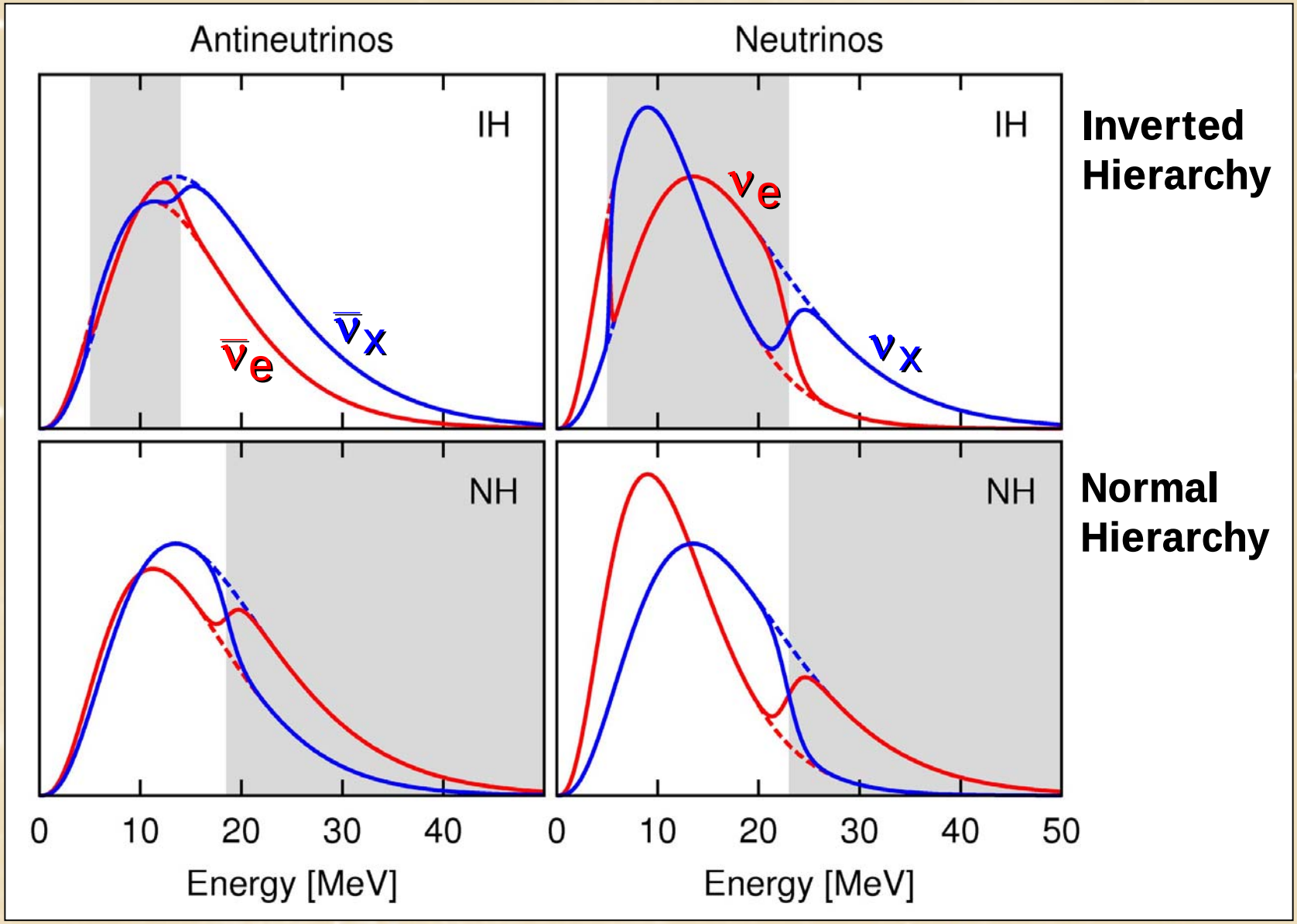


Inverted Hierarchy



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

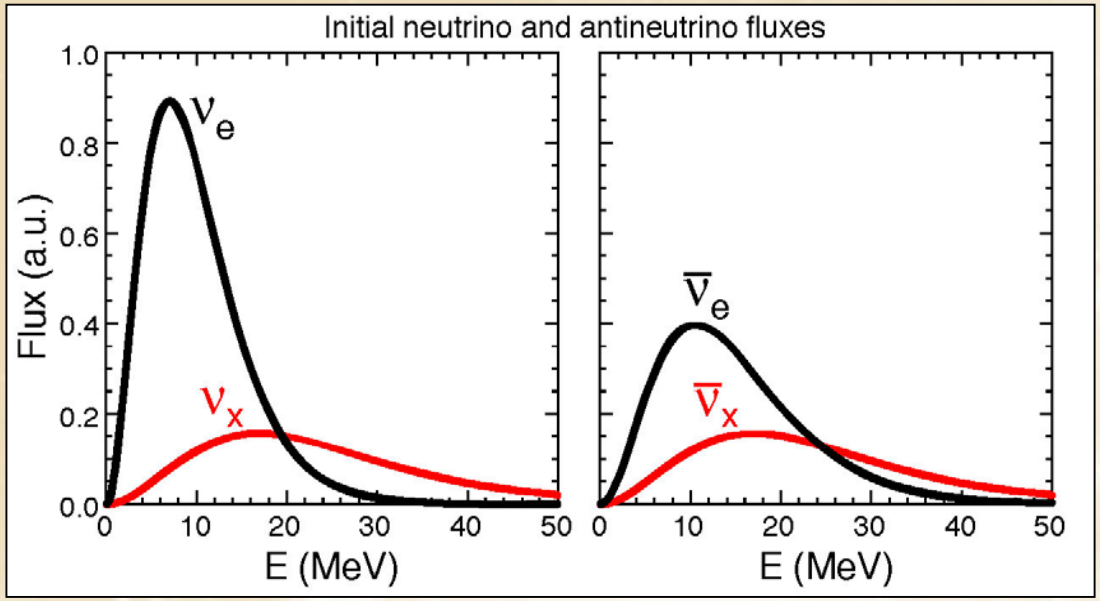
Multiple Spectral Splits (Cooling-Phase Example)



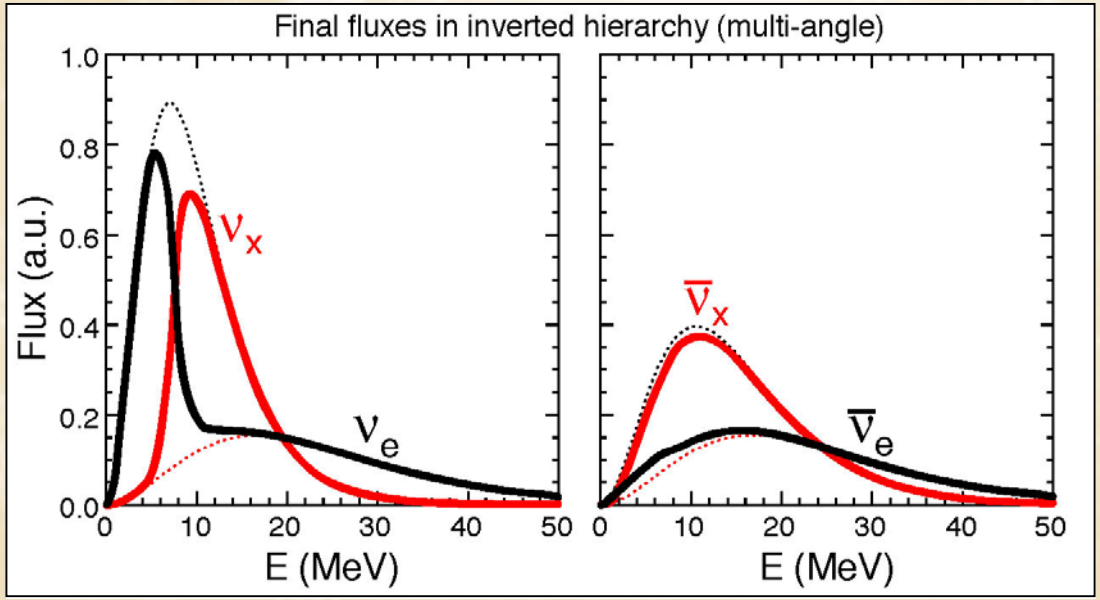
Dasgupta, Dighe, Raffelt & Smirnov, arXiv:0904.3542

Spectral Split for Accretion Phase Example

Initial fluxes at nu sphere



After collective trans-formation



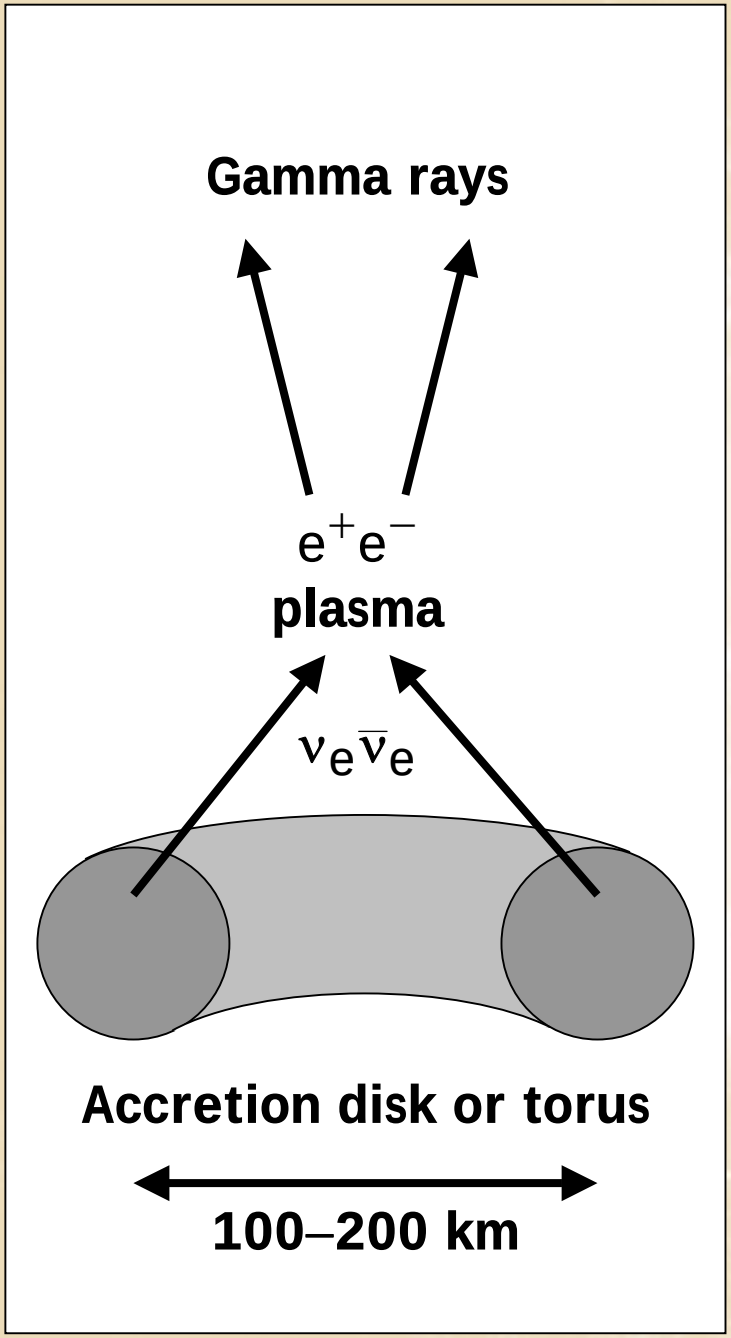
For explanation see

Raffelt & Smirnov
arXiv:0705.1830
0709.4641

Duan, Fuller, Carlson & Qian
arXiv:0706.4293
0707.0290

Fogli, Lisi, Marrone & Mirizzi, arXiv:0707.1998

Coalescing Neutron Stars and Short Gamma-Ray Bursts



- Annihilation rate strongly suppressed if $\nu_e\bar{\nu}_e$ pairs transform to $\nu_x\bar{\nu}_x$ pairs
- Collective effects important?

Density of torus relatively small:

- ν_μ and ν_τ not efficiently produced
- Large $\nu_e\bar{\nu}_e$ pair abundance

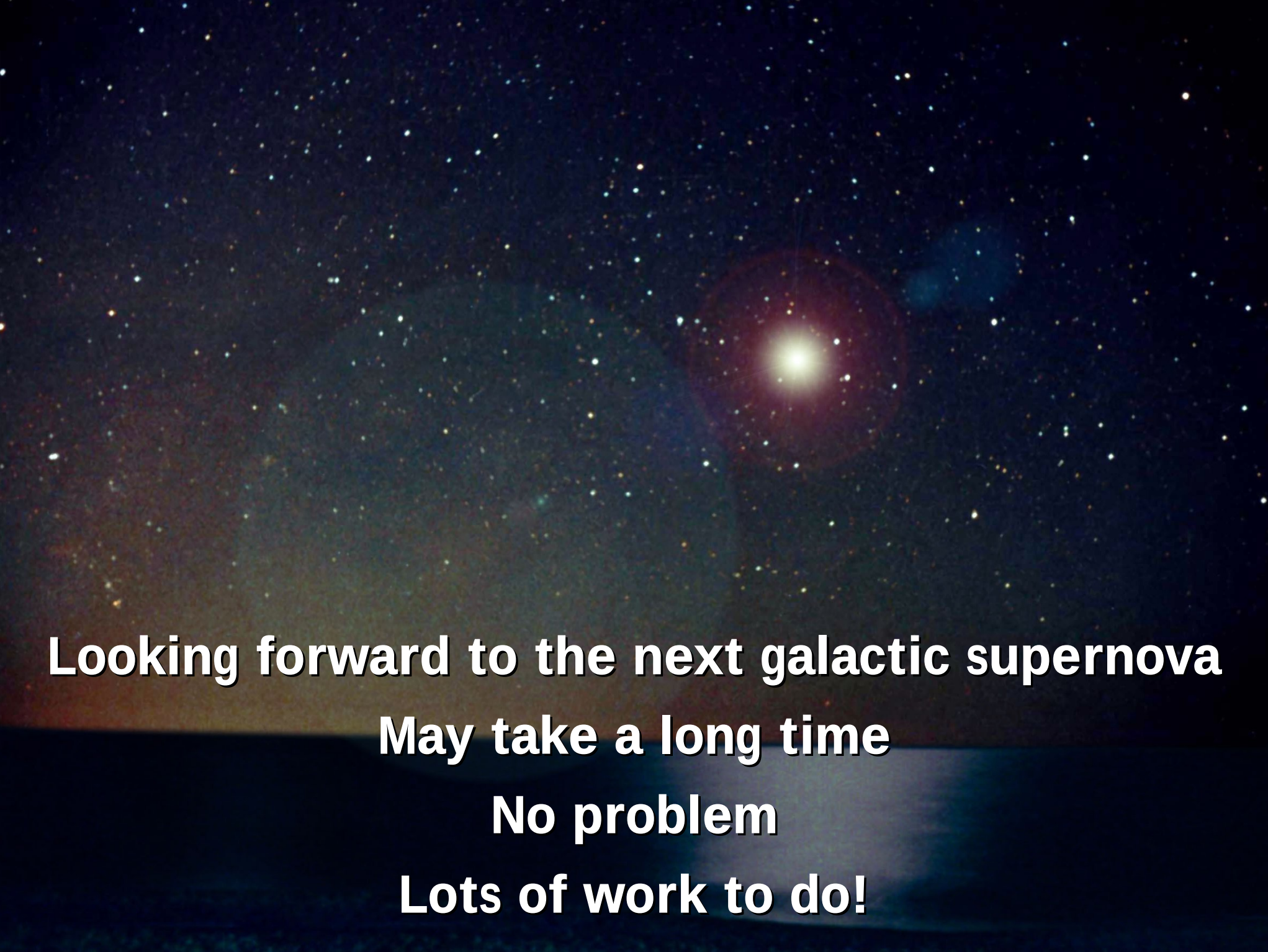
Questions and Opportunities

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



Looking forward to the next galactic supernova

May take a long time

No problem

Lots of work to do!