Neutrino 2006, 13-19 June 2006, Santa Fe, USA

Supernova Neutrino Observations: What Could We Learn?

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

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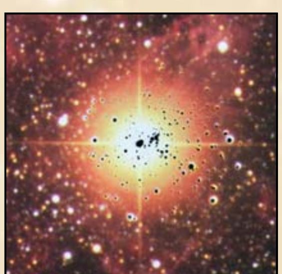
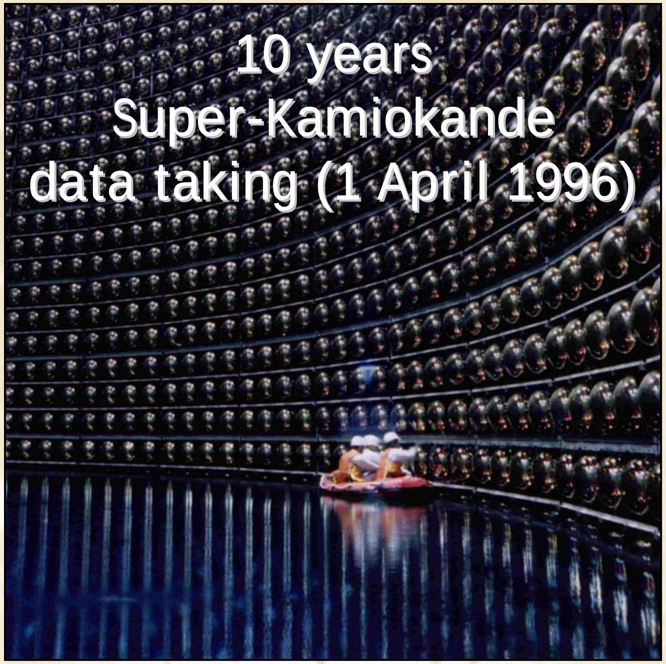
Some particle-physics lessons from SN 1987A and possible improvements



Oscillations of supernova neutrinos

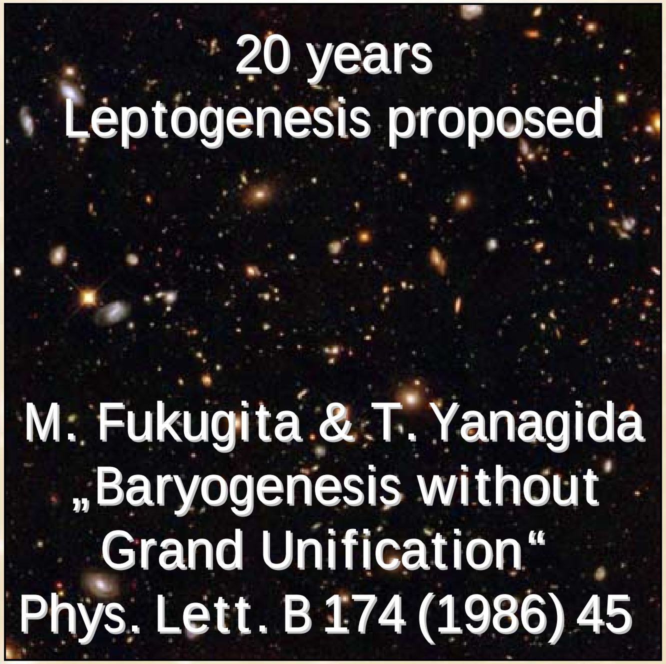
Selected Anniversaries at Neutrino 2006 (± 1 year)

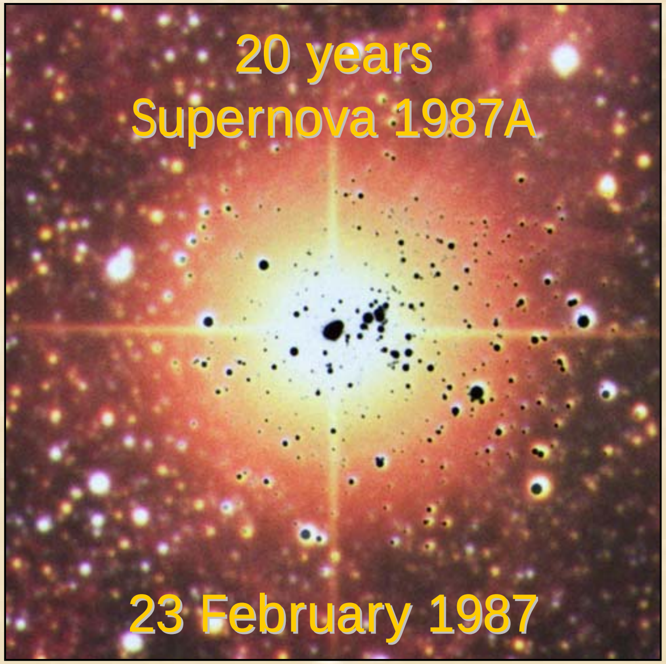
50 years
Neutrino Discovery



1000 years
Supernova 1006 (30 April)

75 years
Neutrino Proposed



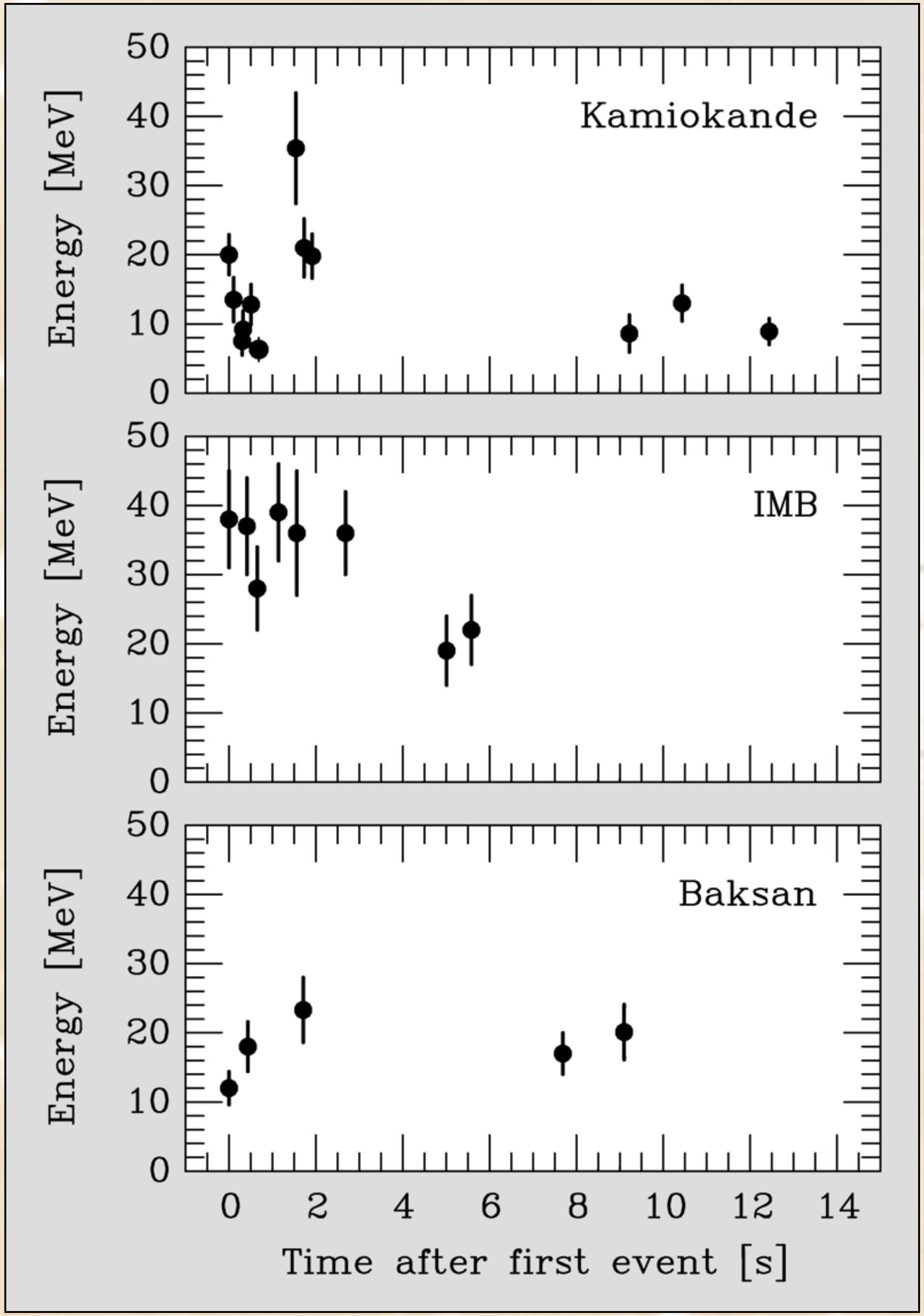


Sanduleak –69 202


Sanduleak –69 202


Supernova 1987A
23 February 1987

Neutrino Signal of Supernova 1987A



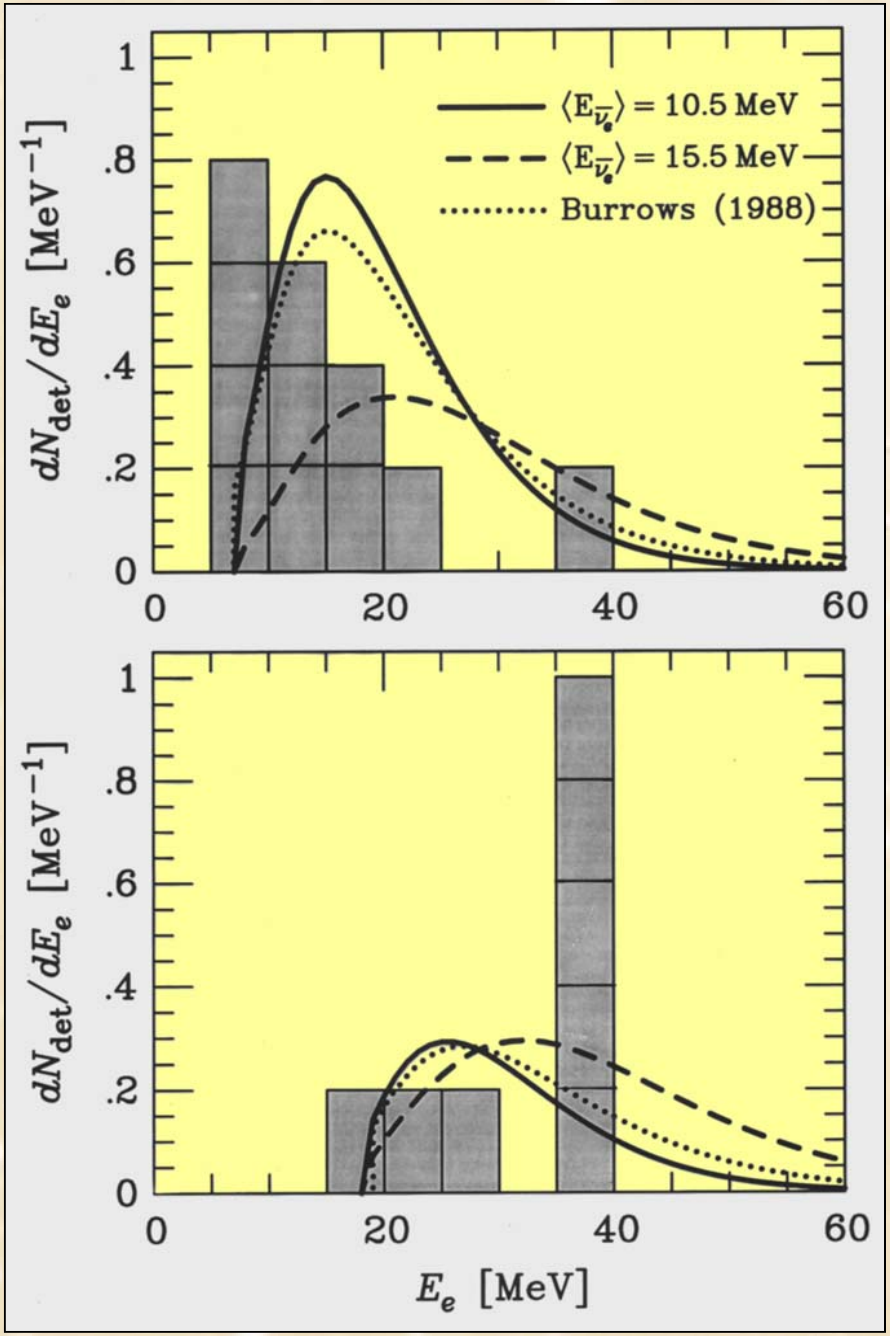
Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ±1 min

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

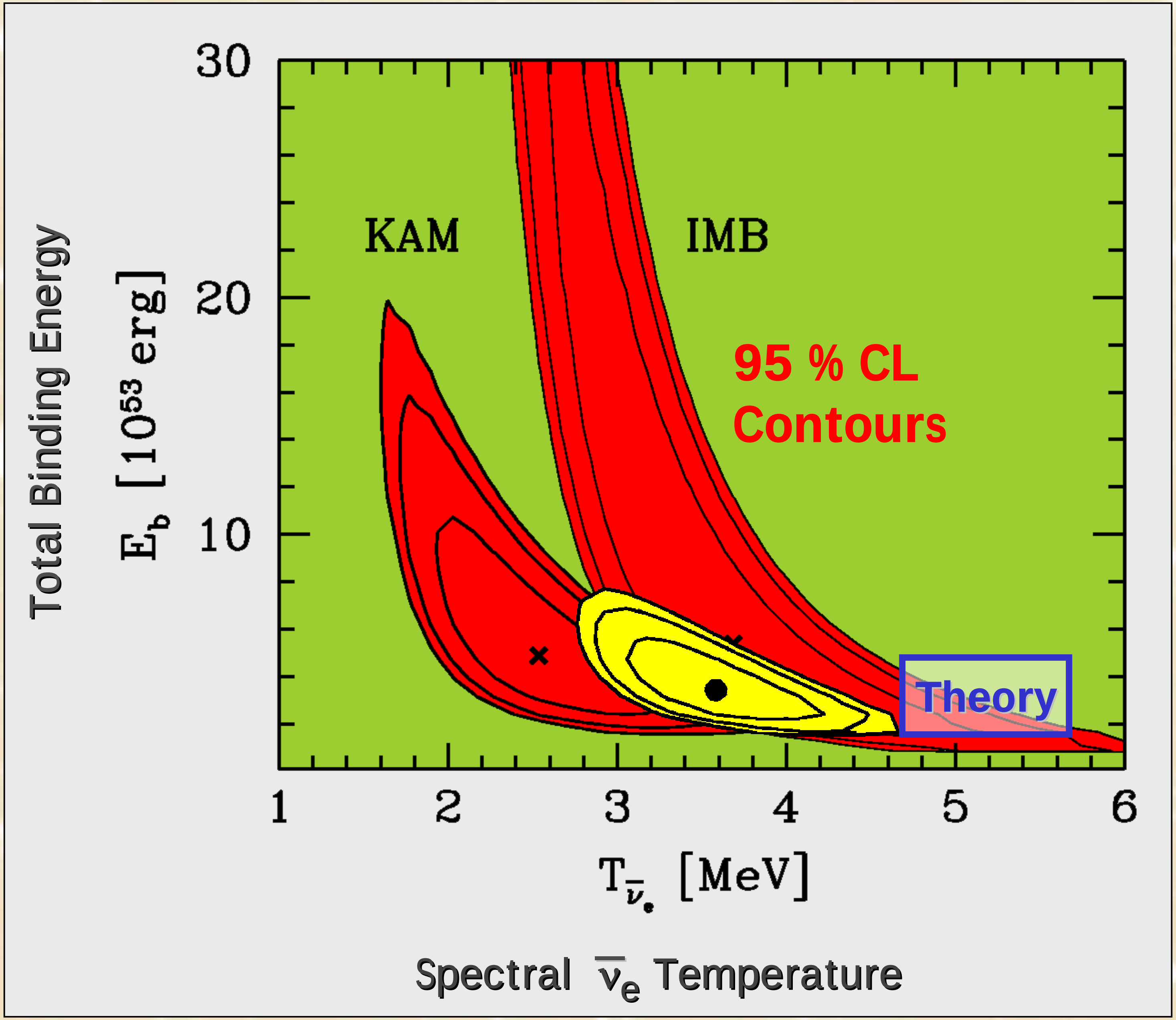
Energy Distribution of SN 1987A Neutrinos



Kamiokande II

IMB

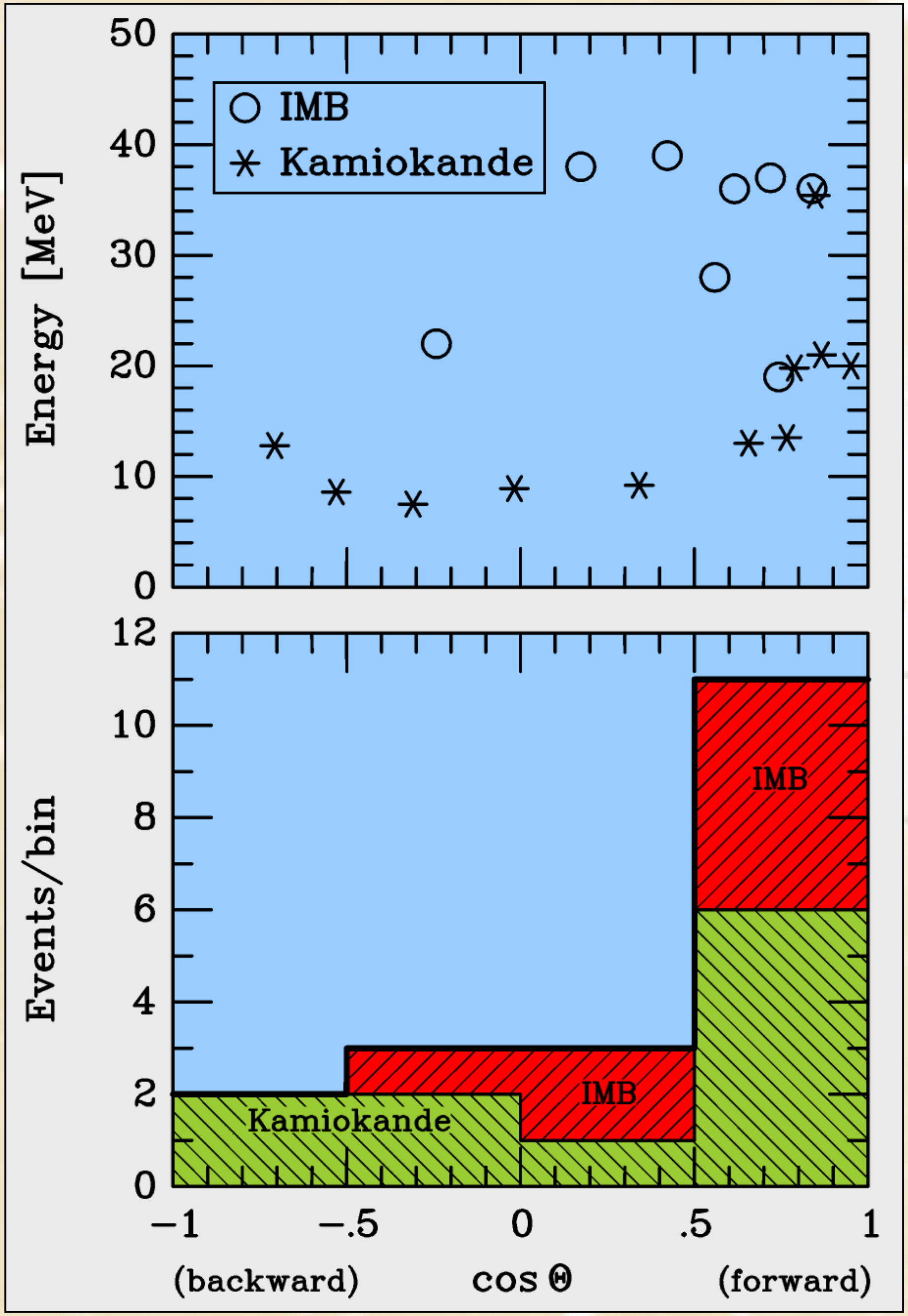
Interpreting SN 1987A Neutrinos



Jegerlehner, Neubig & Raffelt, PRD 54 (1996) 1194

Assume thermal spectra and equipartition of energy between the six degrees of freedom ν_e, ν_μ, ν_τ and their antiparticles

Angular Distribution of SN 1987A Neutrinos



Main detection reaction

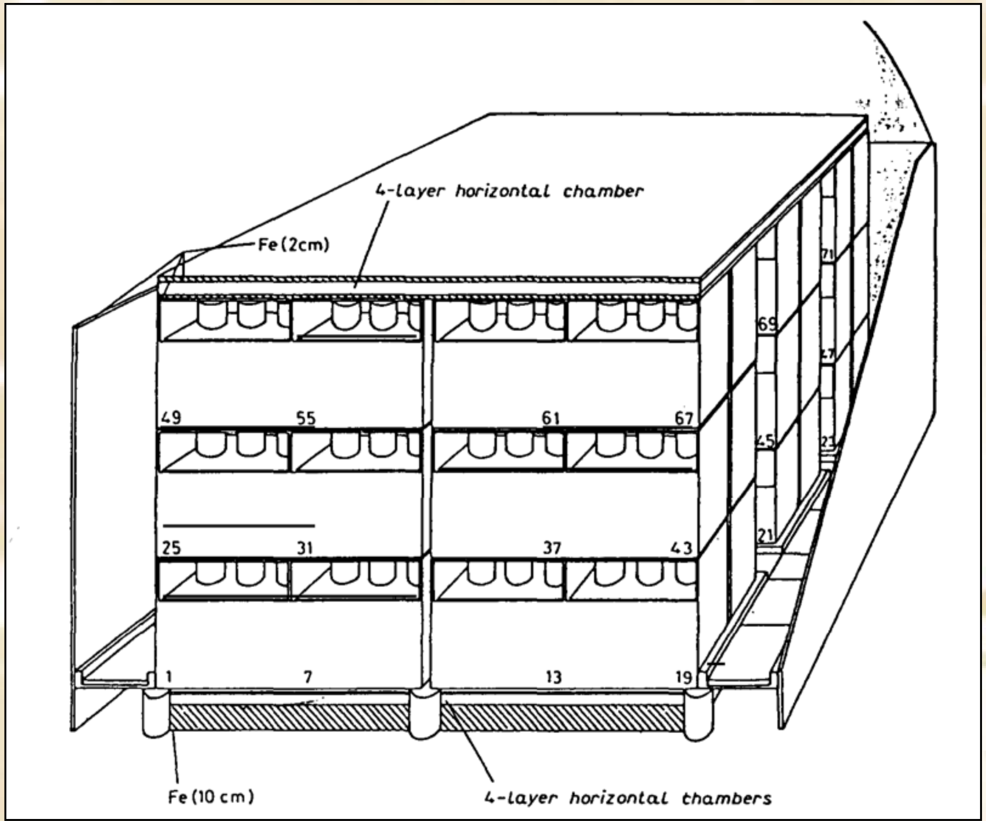
$$\bar{\nu}_e + p \rightarrow n + e^+$$

is essentially isotropic for the relevant energies.

Expect only a fraction of an event from forward-peaked reaction

$$\nu + e^- \rightarrow e^- + \nu$$

SN 1987A Signal in LSD (Mont Blanc)?



- Observed a 5-event cluster 4.72 hours before IMB/Kam-II
- Triggered automatic SN alert
- Statistical fluctuation very unlikely
- No significant signal in IMB/Kam-II at LSD time
- No significant LSD signal at IMB time

LSD (Liquid Scintillator Detector)
in the Mont Blanc Tunnel
(Oct. 1984 - March 1999)
Supernova monitor for our galaxy
90 tons scintillator
200 tons iron (support structure)

- Interpretation as "double bang": Huge ν_e flux (~ 40 MeV) at LSD time
- LSD signal caused by interactions in iron of support structure
- Second bang ordinary multi-flavor signal

(Imshennik & Ryazhskaya, "A rotating collapsar and possible interpretation of the LSD neutrino signal from SN 1987A", astro-ph/0401613)

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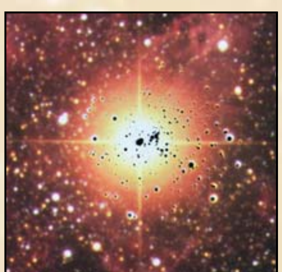
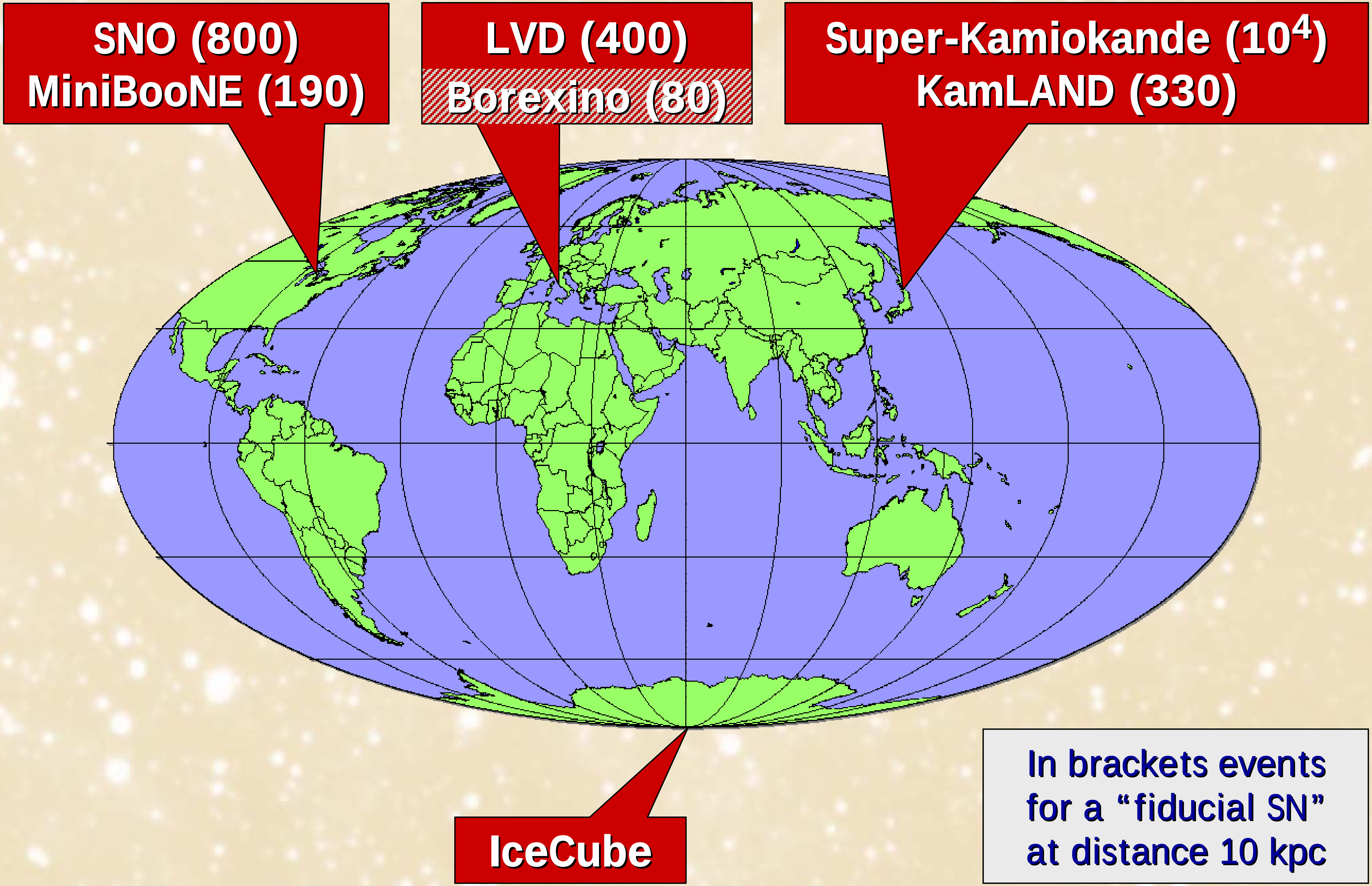


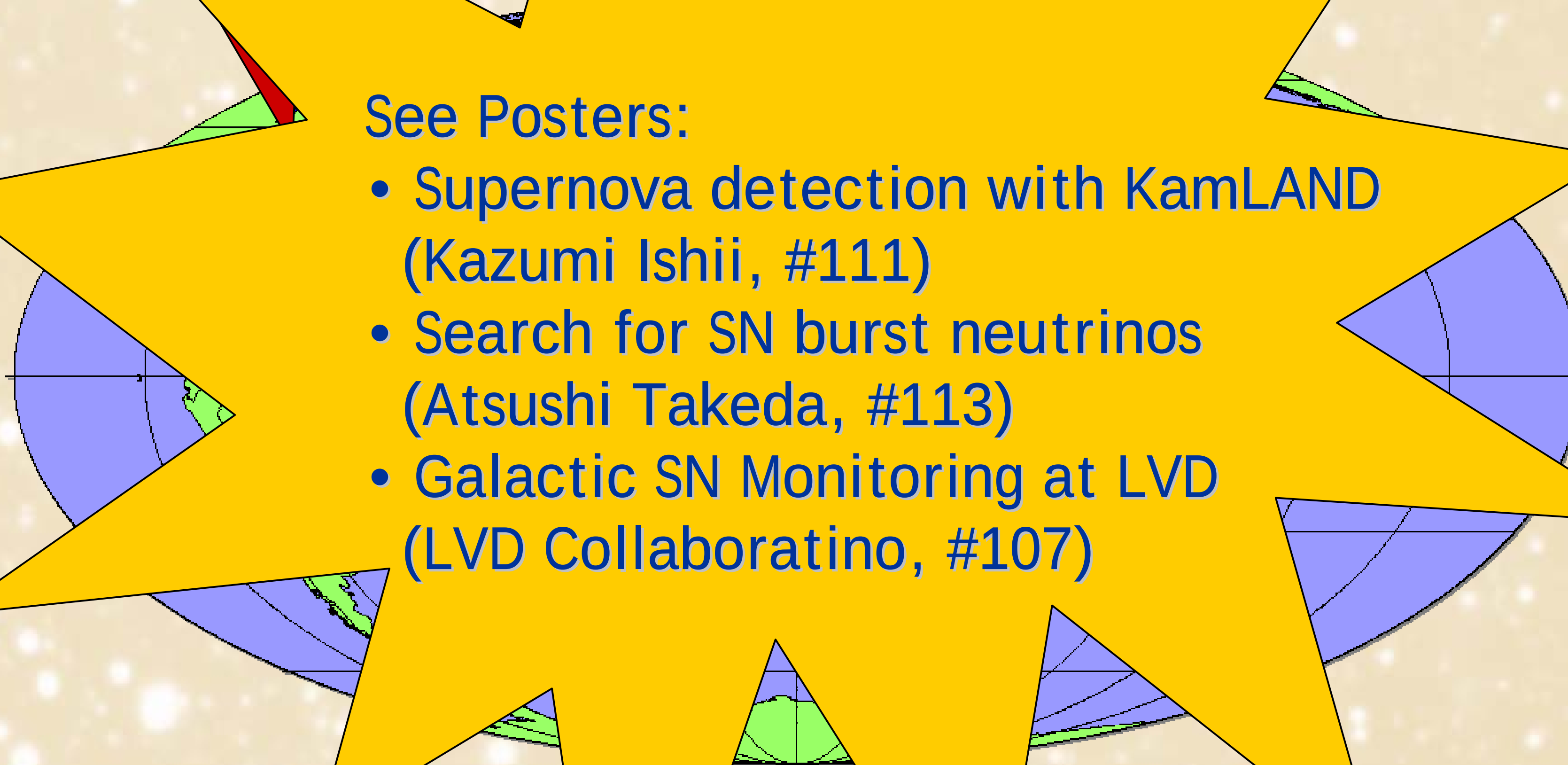
Oscillations of supernova neutrinos

Large Detectors for Supernova Neutrinos



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

Large Detectors for Supern a Neutrinos

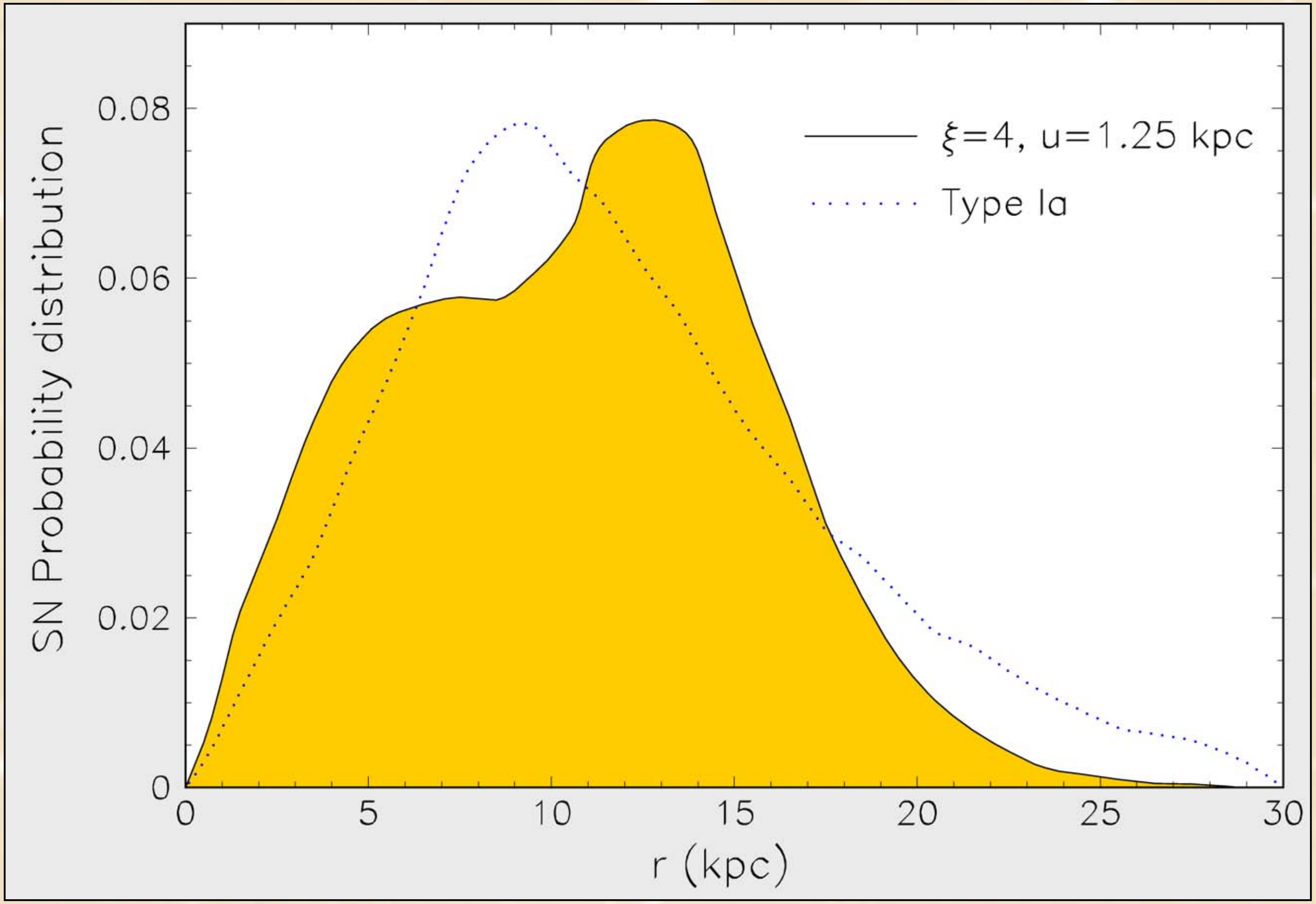


See Posters:

- Supernova detection with KamLAND (Kazumi Ishii, #111)
- Search for SN burst neutrinos (Atsushi Takeda, #113)
- Galactic SN Monitoring at LVD (LVD Collaboratino, #107)

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

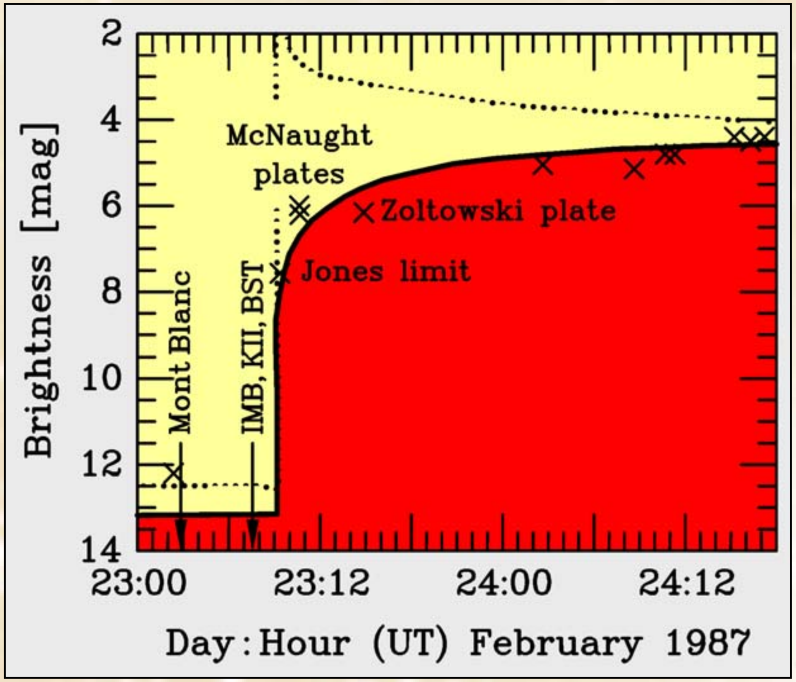
Supernova Distance Distribution



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

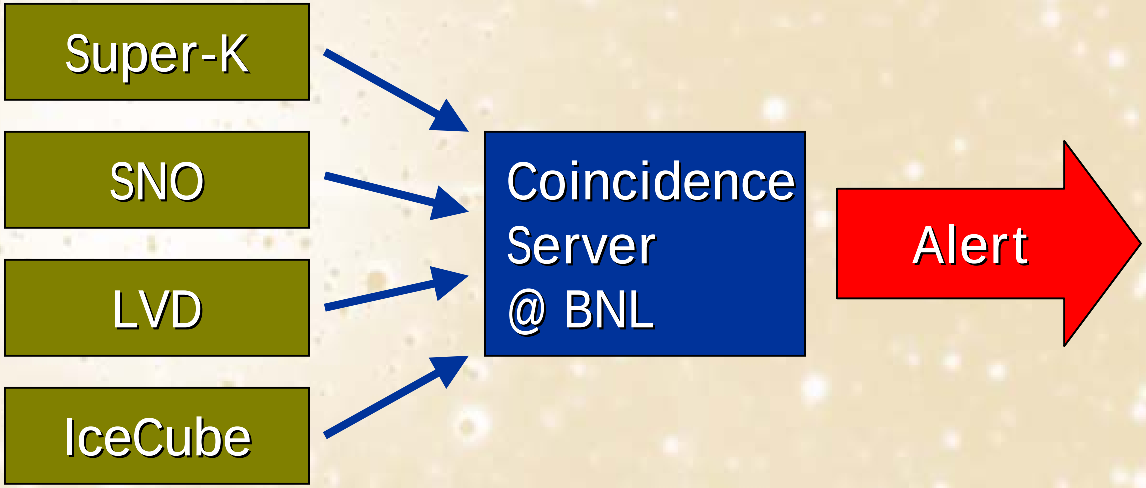
Mirizzi, Raffelt & Serpico, "Earth matter effects in supernova neutrinos: Optimal detector locations", astro-ph/0604300

SuperNova Early Warning System (SNEWS)



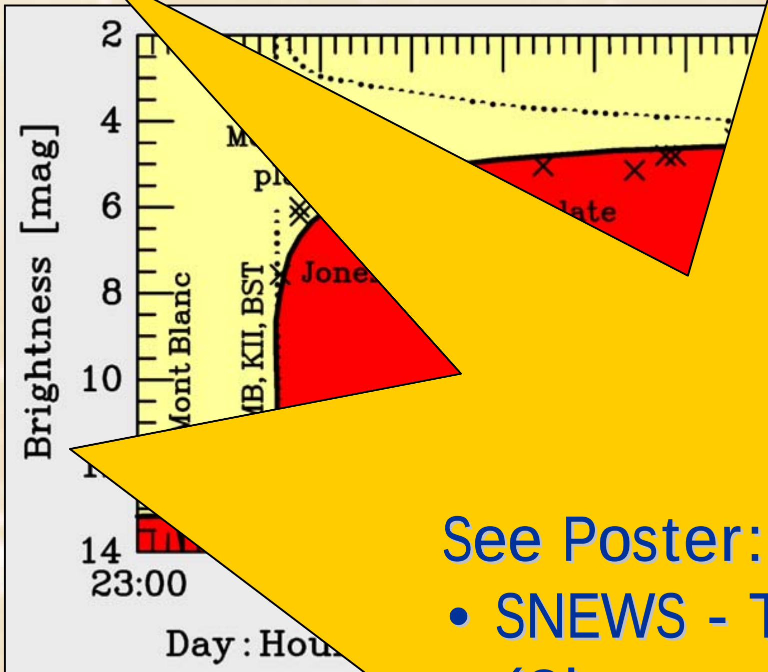
Supernova 1987A
Early Light Curve

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



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

SuperNova Early Warning System (SNEWS)



Neutrino ob ion can alert astronomers
everal h dvance to a supernova.
voi rms, r alarm from at

Sup

See Poster:

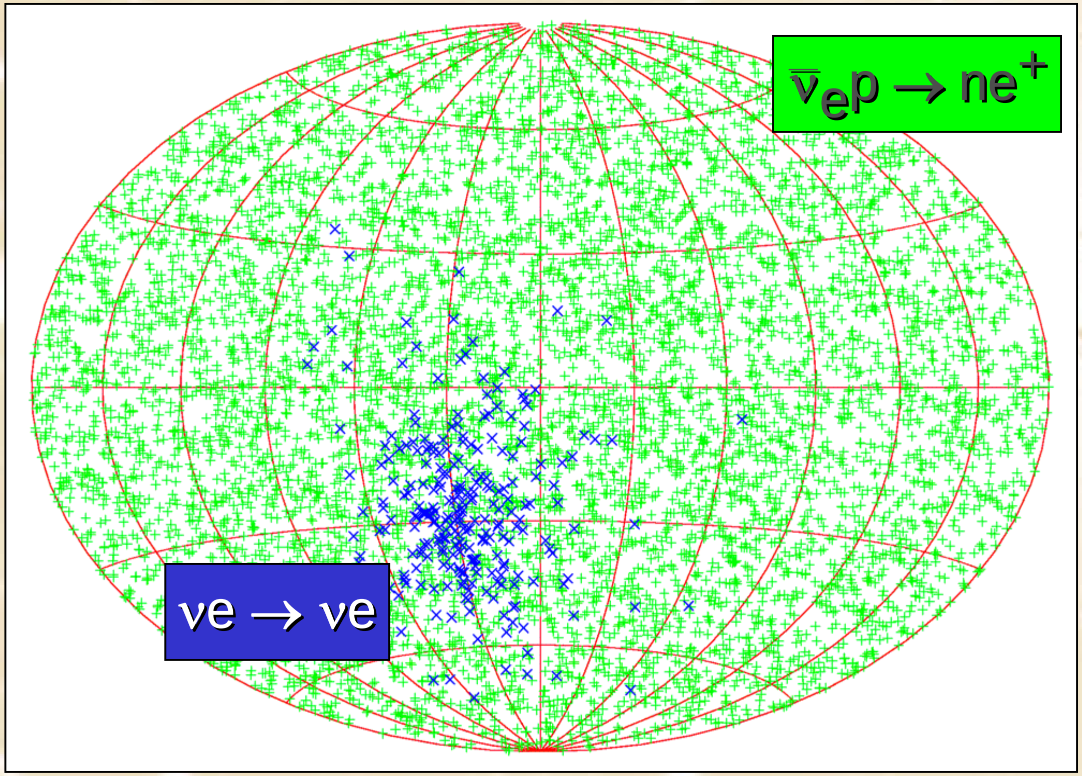
- SNEWS - The SN Early Warning System (Clarence J. Virtue, #115)

Alert

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

Supernova Pointing with Neutrinos

- 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]

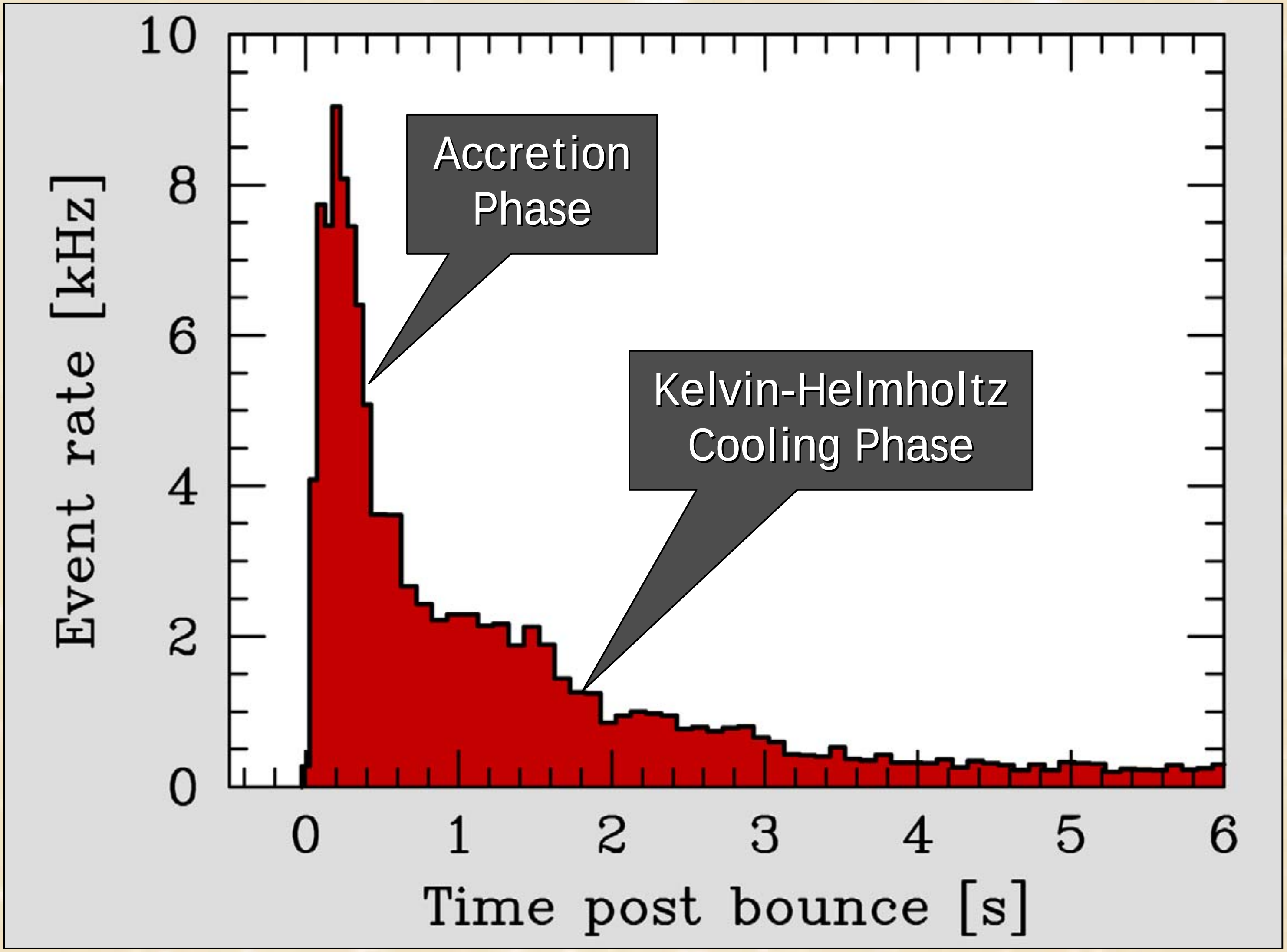


95% CL half-cone opening angle

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

Neutron tagging in a large water Cherenkov detector by gadolinium loading is investigated within Super-K Collaboration, R&D apparently going well (GADZOOKS!, for original idea see Beacom and Vagins, hep-ph/0309300)

Simulated Supernova Signal at Super-Kamiokande



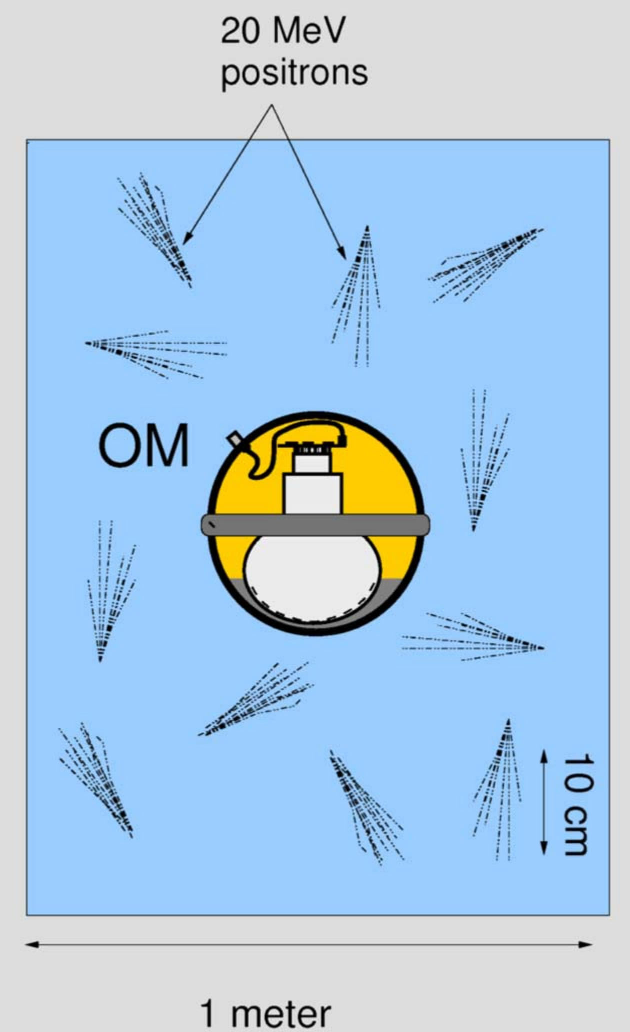
Simulation for Super-Kamiokande SN signal at 10 kpc, based on a numerical Livermore model

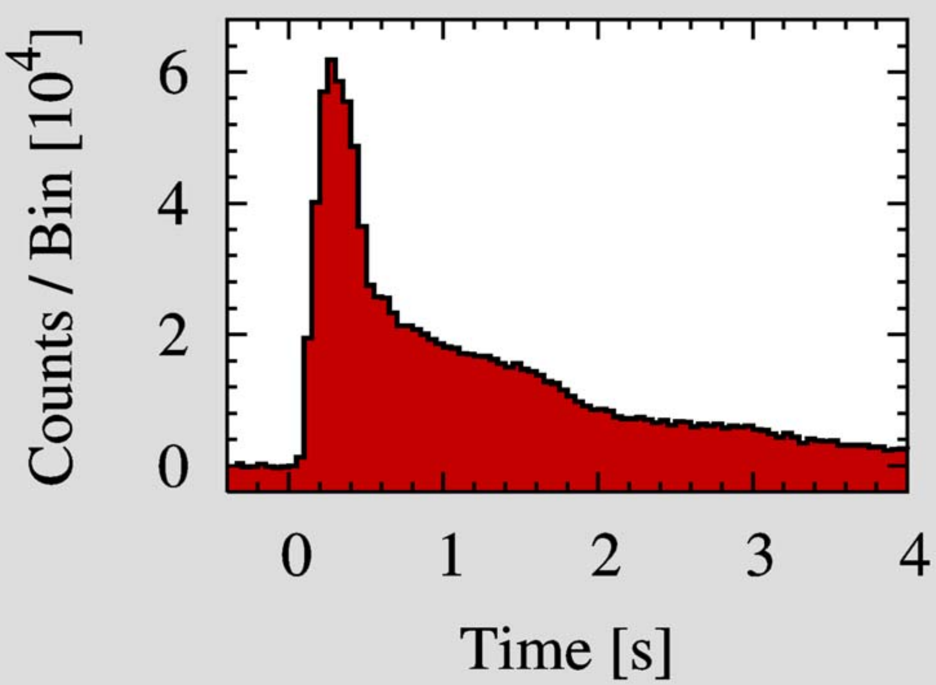
[Totani, Sato, Dalhed & Wilson, ApJ 496 (1998) 216]

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 < 500 Hz
- Total of 4800 OMs in IceCube

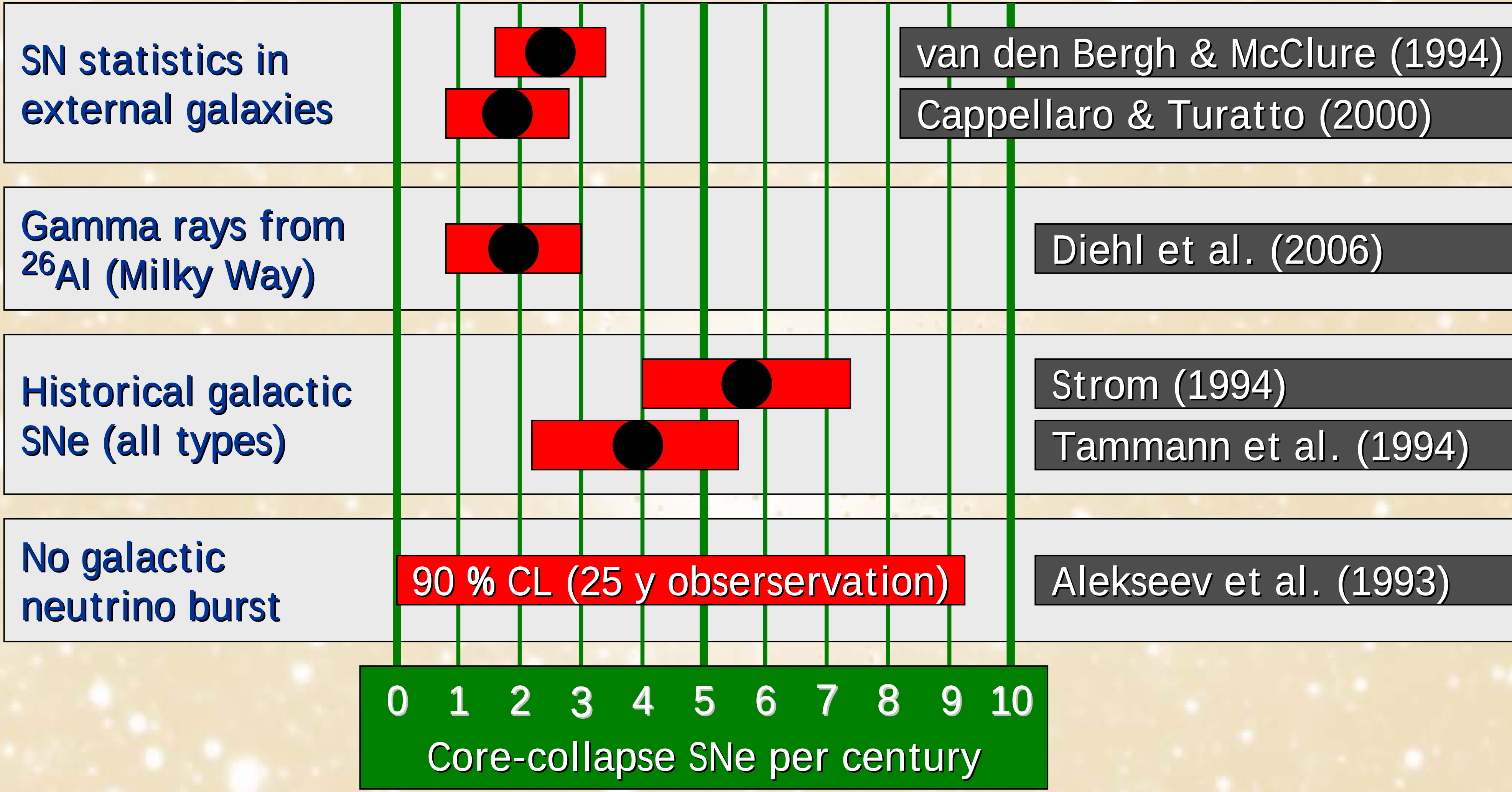




IceCube SN signal at 10 kpc, based on a numerical Livermore model [Dighe, Keil & Raffelt, hep-ph/0303210]

Method first proposed by Halzen, Jacobsen & Zas astro-ph/9512080

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.

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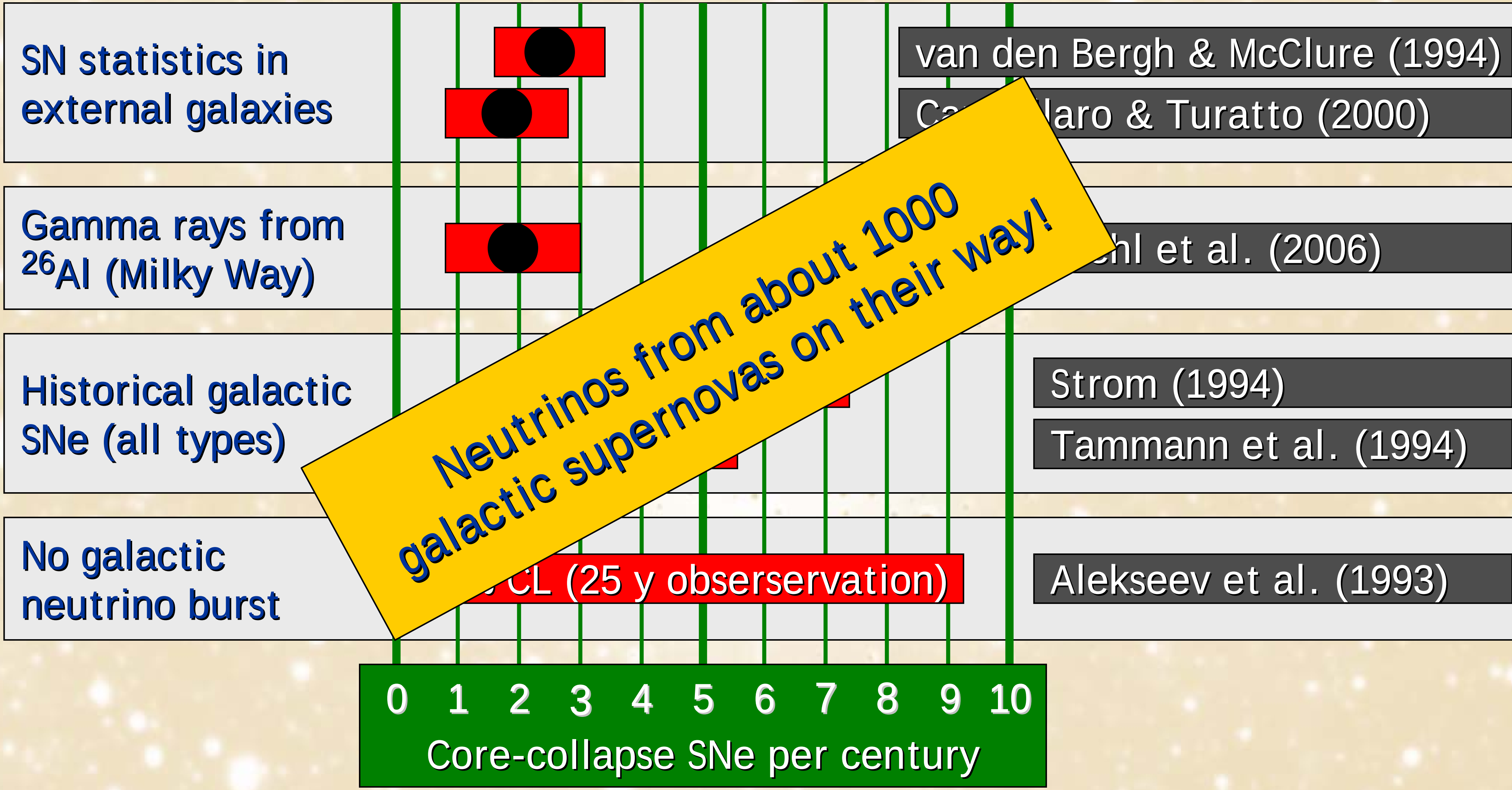
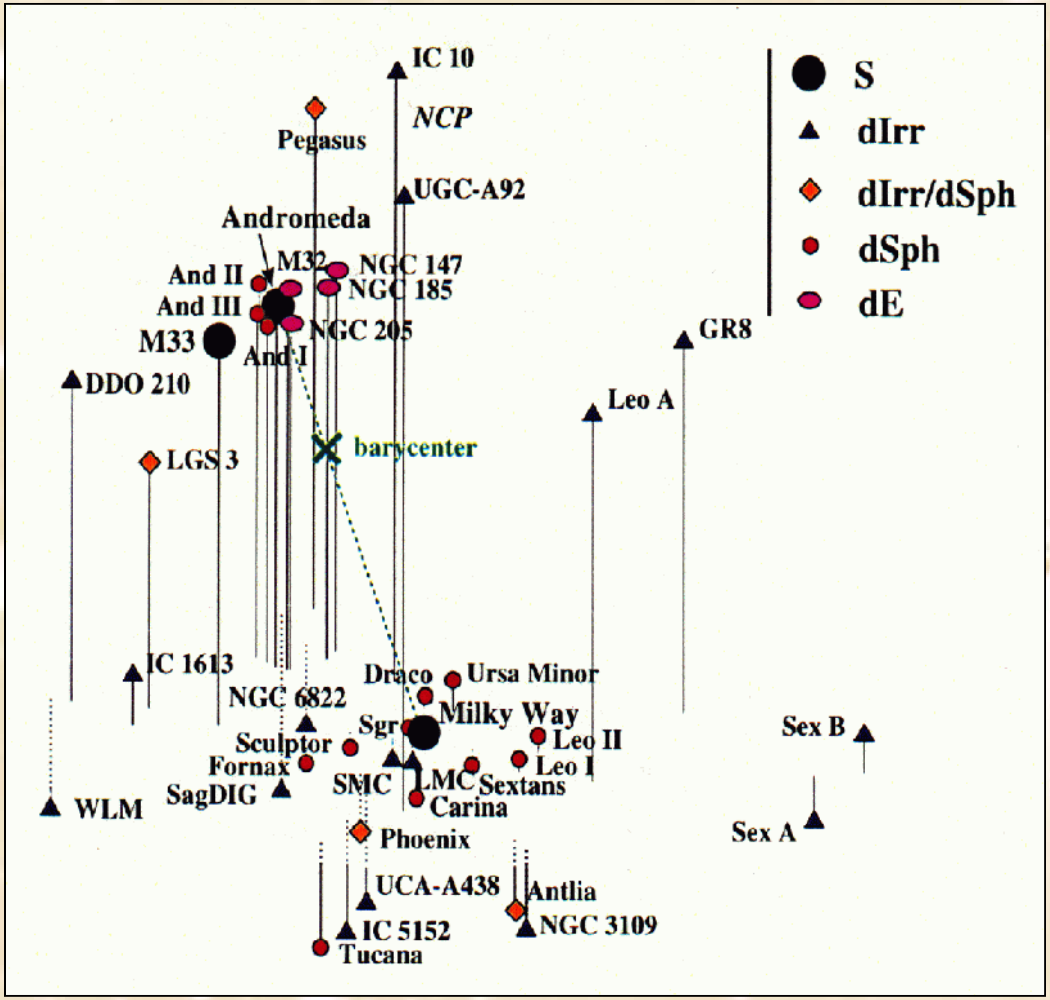
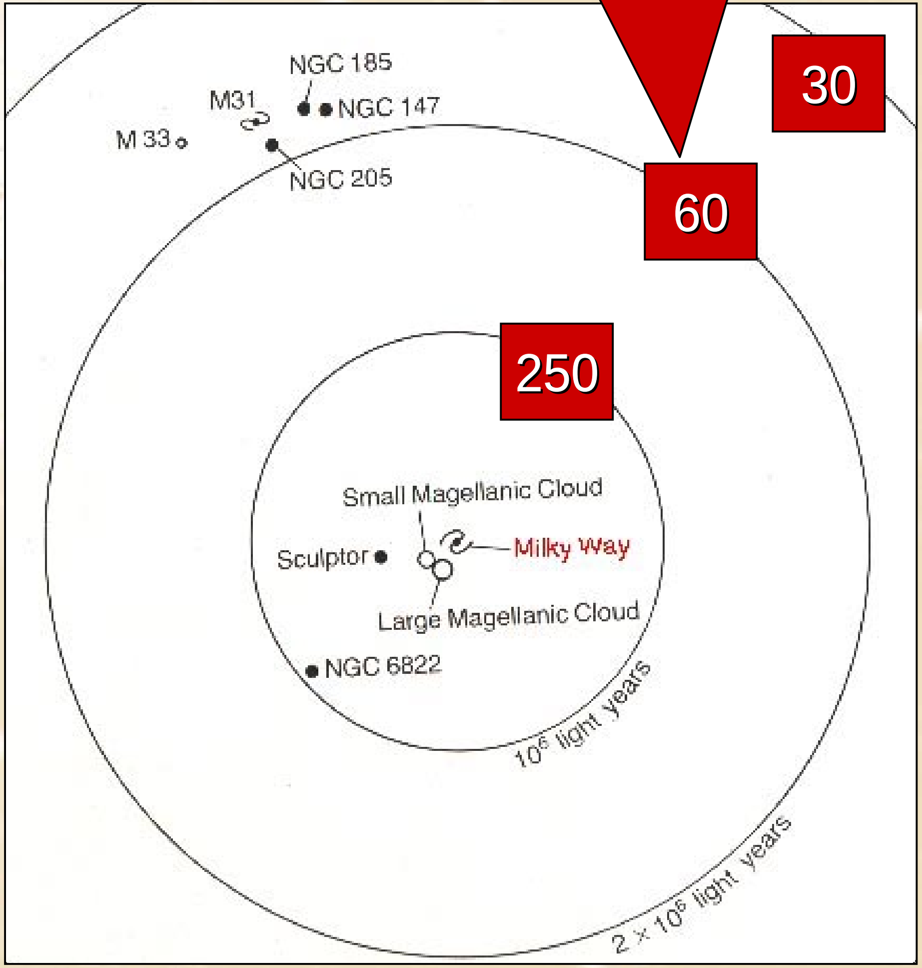


References: van den Bergh & McClure, ApJ 425 (1994) 205. Cappellaro & Turatto, astro-ph/0012455. Diehl et al., Nature 439 (2006) 45. Strom, Astron. Astrophys. 288 (1994) L1. Tammann et al., ApJ 92 (1994) 487. Alekseev et al., JETP 77 (1993) 339 and my update.

Local Group of Galaxies



Events in a detector with
30 x Super-K fiducial volume,
(Hyper-K, MEMPHYS, UNO, ...)



Nearby Galaxies with Many Observed Supernovae

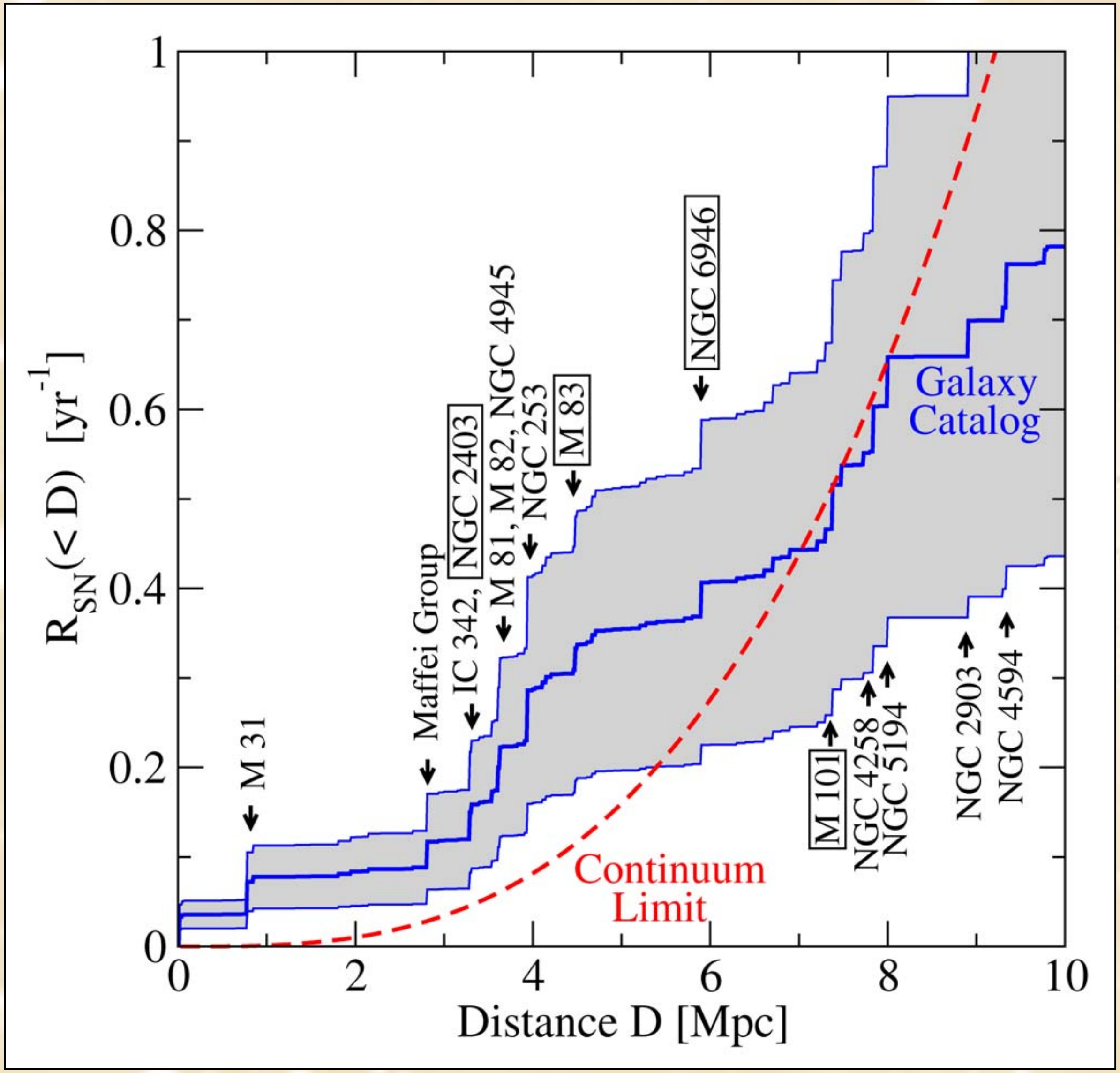
M83 (NGC 5236, Southern Pinwheel)
D = 4.5 Mpc

Observed Supernovae:
1923A, 1945B, 1950B,
1957D, 1968L, 1983N

NGC 6946
D = (5.5 ± 1) Mpc

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

Supernova Rate in Nearby Galaxies



Expected rates and their uncertainties based on galaxy types and sizes, scaled with SN statistics derived from external galaxies

However, observed SNe in this volume in recent years about 3 times the expected rate (9 within 10 Mpc with 2.8 expected, 4 within 4 Mpc with 1.0 expected)

Ando, Beacom & Yüksel, “Detection of neutrinos from supernovae in nearby galaxies”, astro-ph/0503321

Cosmic Diffuse Supernova Neutrino Background (DSNB)

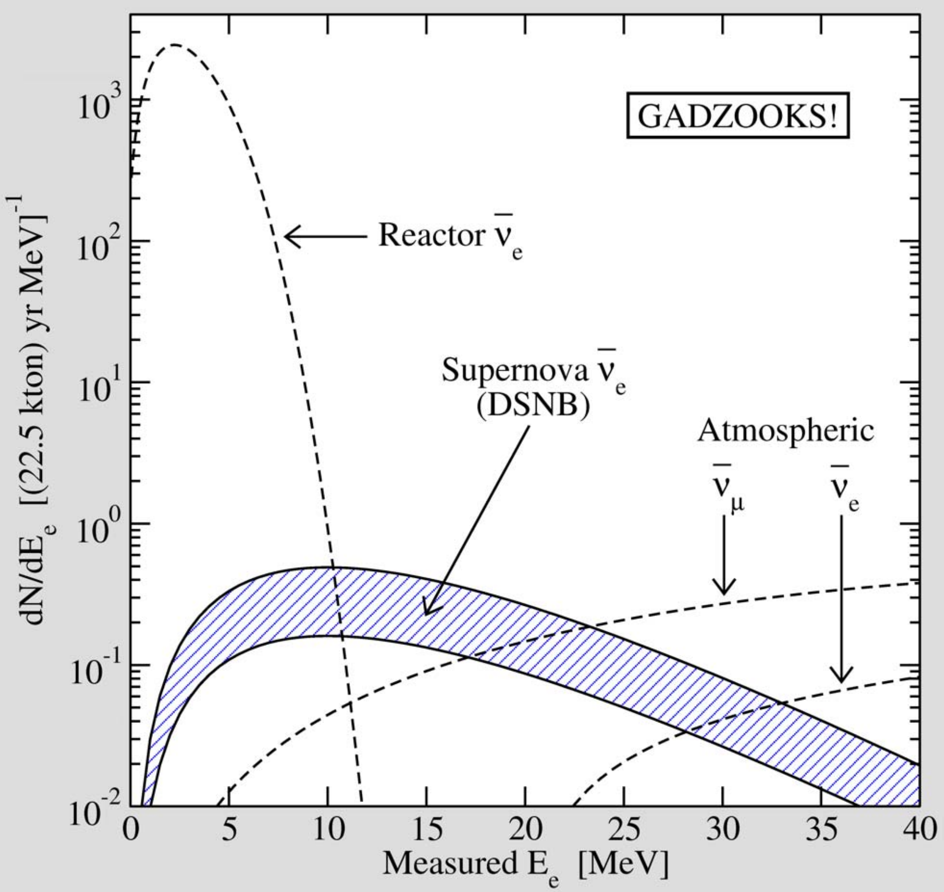


FIG. 1: Spectra of low-energy $\bar{\nu}_e + p \to e^+ + n$ coincidence events and the sub-Čerenkov muon background. We assume full efficiencies, and include energy resolution and neutrino oscillations. Singles rates (not shown) are efficiently suppressed.

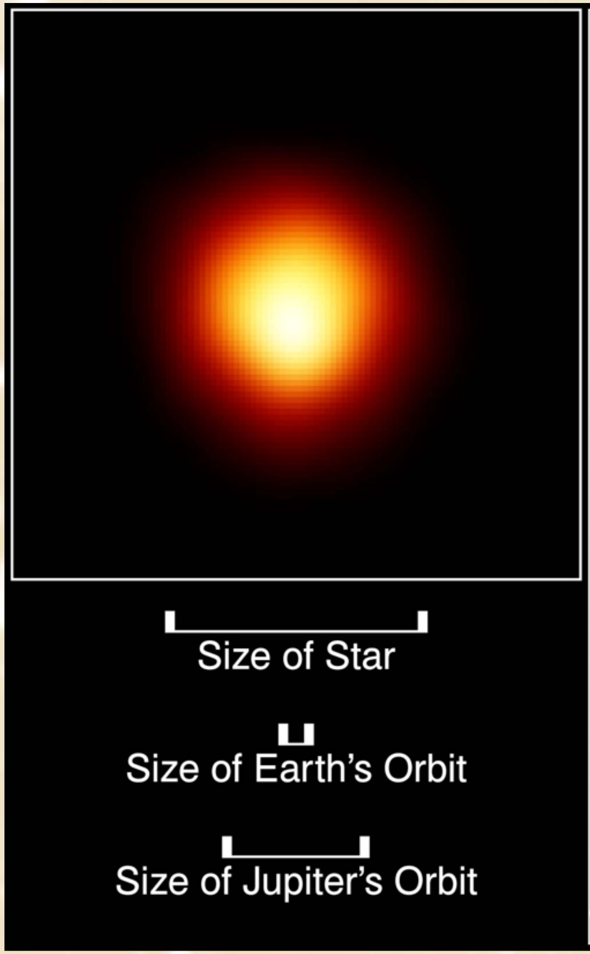
- About 1 SN per sec in the visible universe
- Diffuse SN neutrino background (DSNB) from all past SNe

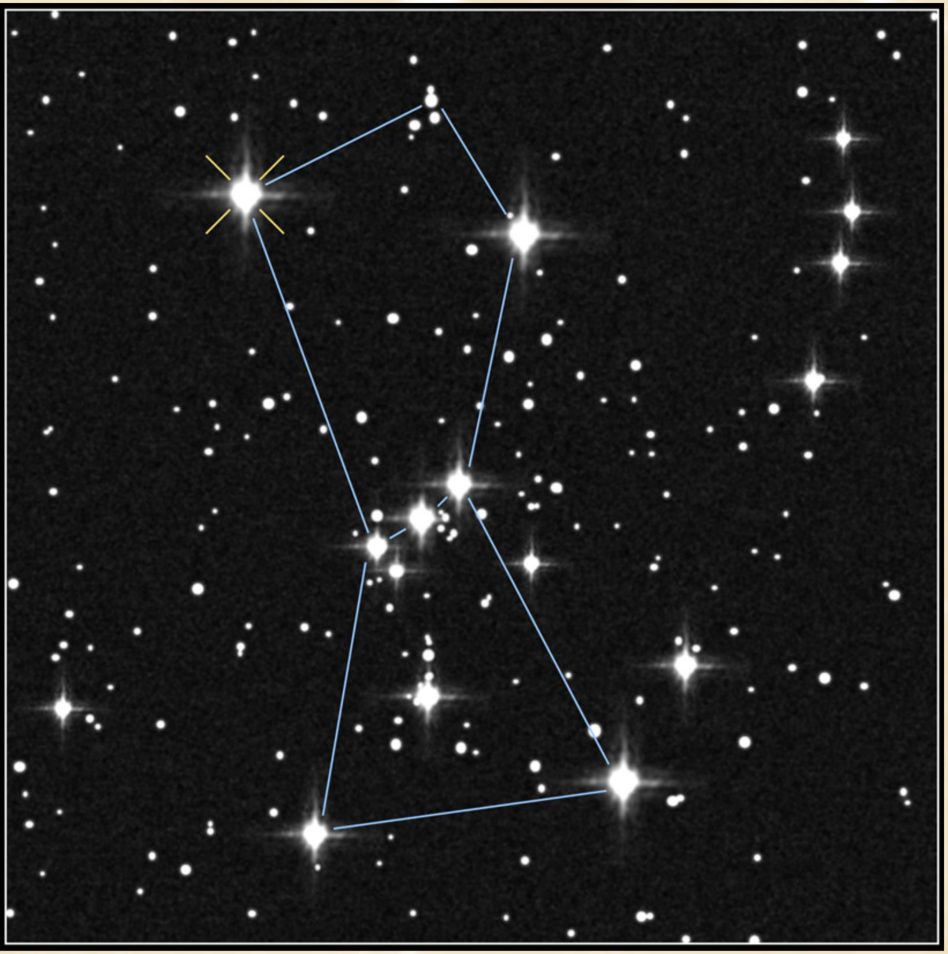
  few $\bar{\nu}_e$ cm^{-2}s^{-1}
- Can be measured even in Super-K sized detector (few events/year)
- Need neutron tagging
  - Gadolinium loading of SK
  - Large scintillator detector (LENA project, 50 kt)

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

Pushing the boundaries of neutrino astronomy to cosmological distances

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]

The Red Supergiant Betelgeuse (Alpha Orionis)

First resolved image of a star other than Sun

Distance (Hipparcos) 130 pc (425 lyr)

See Poster:
- Thermal neutrinos from pre-SN (Andrzej Odrzywolek, #117)

If Betelgeuse goes Su... a:
- 6×10^7 neutrino ev... in Sup... iokan...
- 2.4×10^3 neutron events per d... om Silico... ning phase (few days warning!), need ne... n tagging [Odrzywolek, Misiaszek & Kut... era, astro-ph/0311012]

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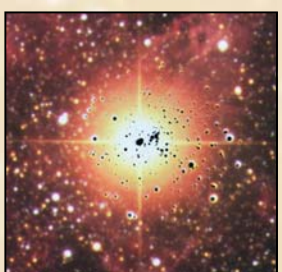


Oscillations of supernova neutrinos

Dispersion between Neutrinos and Photons

Transit time for photons and neutrinos are equal to within ~ 3h

Total transit time ~ 5×10^{12} sec
→ Equal for photons and neutrinos
within ~ 2×10^{-9}

(Longo 1987, Stodolsky 1988)

$$\left|\frac{c_\nu - c_\gamma}{c_\nu + c_\gamma}\right| < 10^{-9}$$

Shapiro time delay for particles moving through a gravitational potential

$$\Delta t_{\rm Shapiro} = -2\int_A^B U[r(t)]\,dt \approx 2-6\times 10^6 \text{ sec}$$

(Krauss & Tremaine 1988)

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

- Proves directly that neutrinos respond to gravity in the standard way
- Provides limits on parameters of certain non-GR theories of gravitation
- Could be extended to neutrinos vs. anti-neutrinos or different flavors from signal of a future galactic SN

Neutrino Limits by Intrinsic Signal Dispersion

Time of flight delay by neutrino mass

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

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

- Detailed maximum-likelihood analysis yields similar limit
- At the time of SN 1987A competitive with tritium end-point limits, today $m_{\nu_e} < 2.2$ eV
- Cosmological limit today $m_\nu \lesssim 0.2$ eV

Next galactic SN observation:
Time-of-flight dispersion not important for signal interpretation

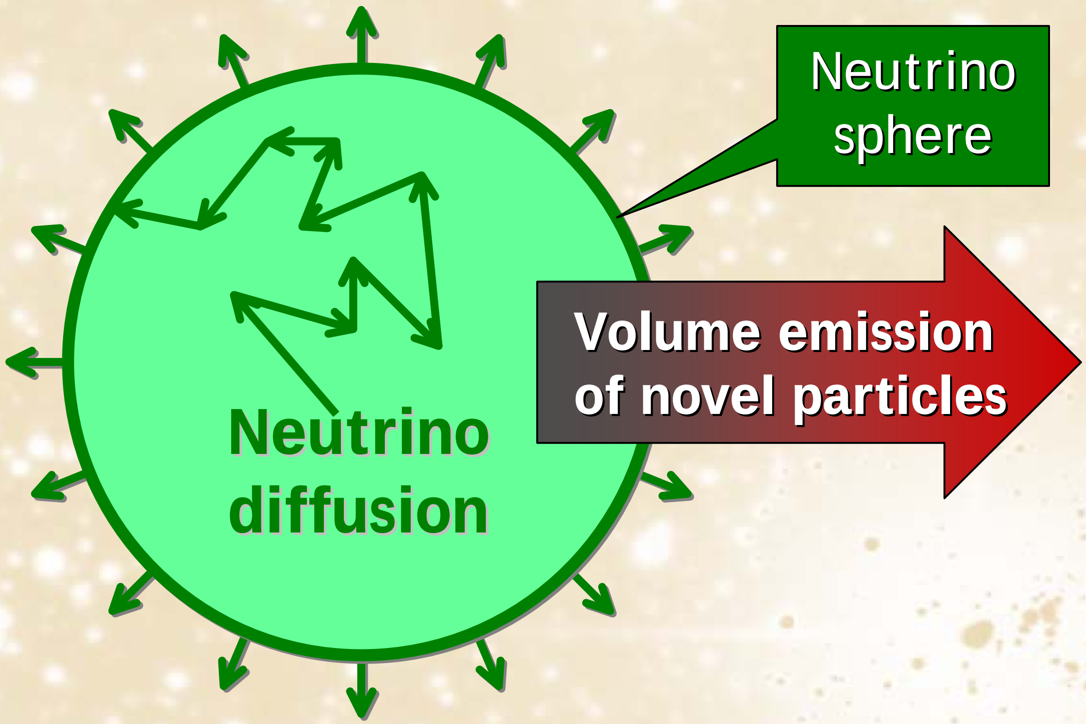
For "milli charged" neutrinos, path bent by galactic magnetic field, inducing a time delay

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

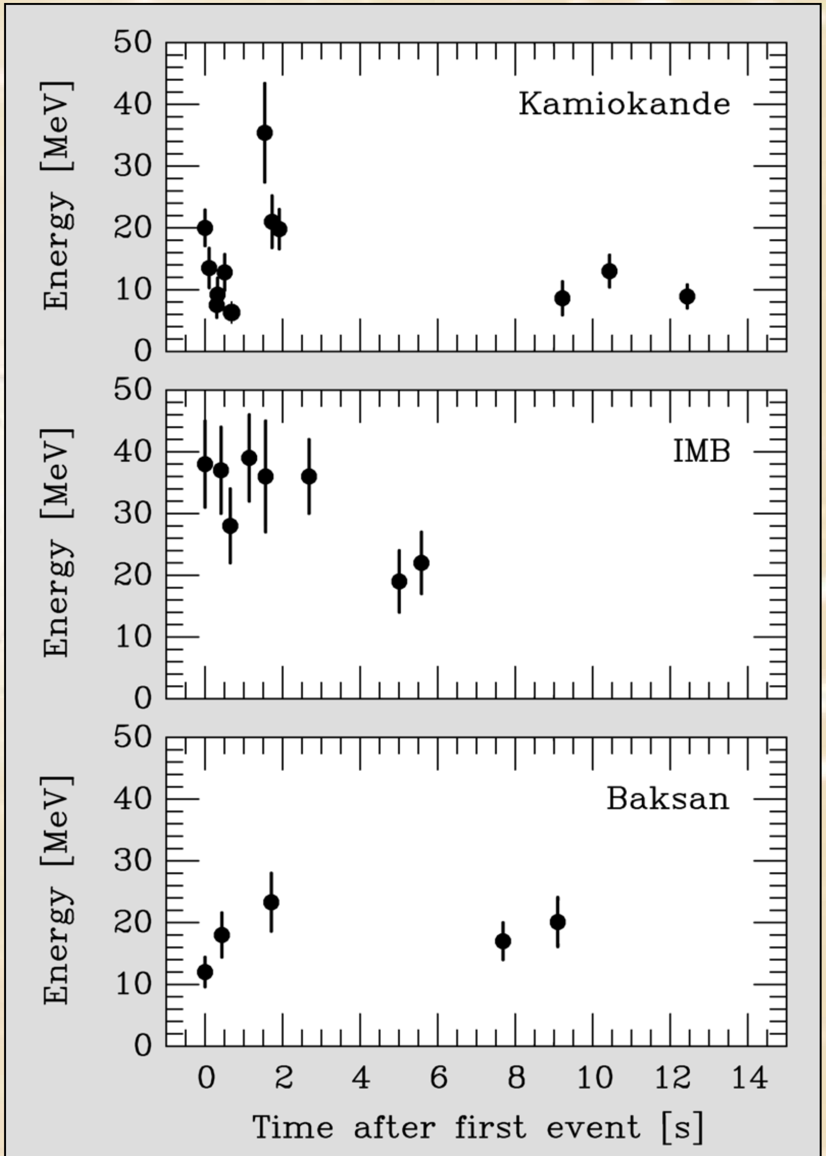
$$\frac{e_\nu}{e} < 3\times10^{-17}\left(\frac{1\,\mu\mathrm{G}}{B_\perp}\right)\left(\frac{1\,\mathrm{kpc}}{d_B}\right)$$

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

The Energy-Loss Argument



SN 1987A neutrino signal

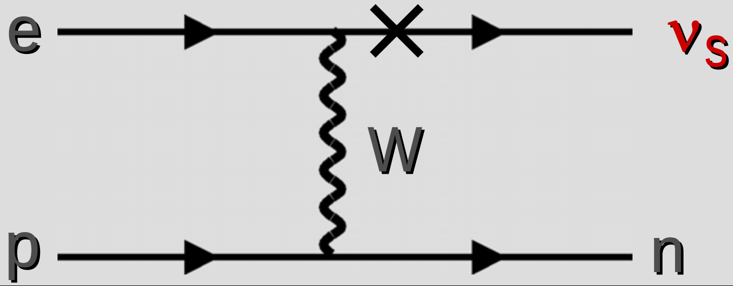


Emission of very weakly interacting particles would "steal" energy from the neutrino burst and shorten it.
(Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

Late-time signal most sensitive observable

Sterile Neutrinos

Active-sterile mixing



Electron neutrino appears as sterile neutrino in ½ $\sin^2(2\Theta_{es})$ of all cases

$$\Gamma_s \approx \frac{1}{2}\sin^2(2\Theta_{es})\,\Gamma_L$$

Average scattering rate in SN core involving ordinary left-handed neutrinos

$$\Gamma_L \approx 10^{10}\,s^{-1}$$

To avoid complete energy loss in ~ 1 s

$$\frac{1}{2}\sin^2(2\Theta_{es})\,10^{10}\,s^{-1} < 1\,s^{-1}$$

$\sin^2(2\Theta_{es}) \lesssim 3 \times 10^{-10}$

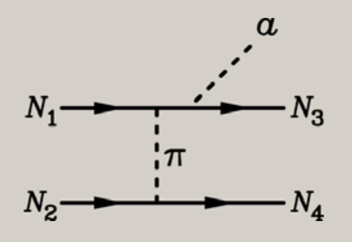
(for $m_s \gtrsim 100$ keV)

Axion Emission Processes in Stars

Nucleons

$$\frac{C_N}{2f_a}\overline{\Psi}_N\gamma_\mu\gamma_5\Psi_N\,\partial^\mu a$$

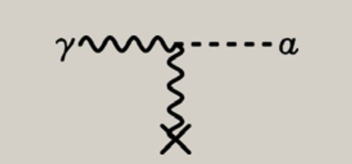
Nucleon Bremsstrahlung



Photons

$$\frac{C_e}{2f_a}\overline{\Psi}_e\gamma_\mu\gamma_5\Psi_e\,\partial^\mu a$$

Primakoff

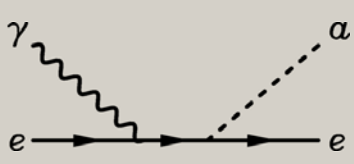


Electrons

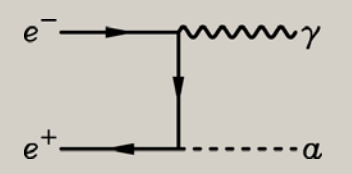
$$C_\gamma\,\frac{\alpha}{2\pi f_a}\,\frac{1}{4}F_{\mu\nu}\tilde{F}^{\mu\nu}a$$

$$= -C_\gamma\,\frac{\alpha}{2\pi f_a}\,\vec{E}\cdot\vec{B}\,a$$

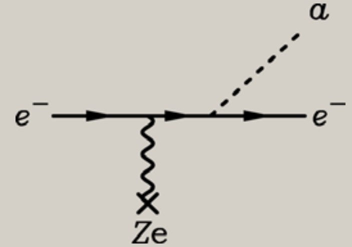
Compton



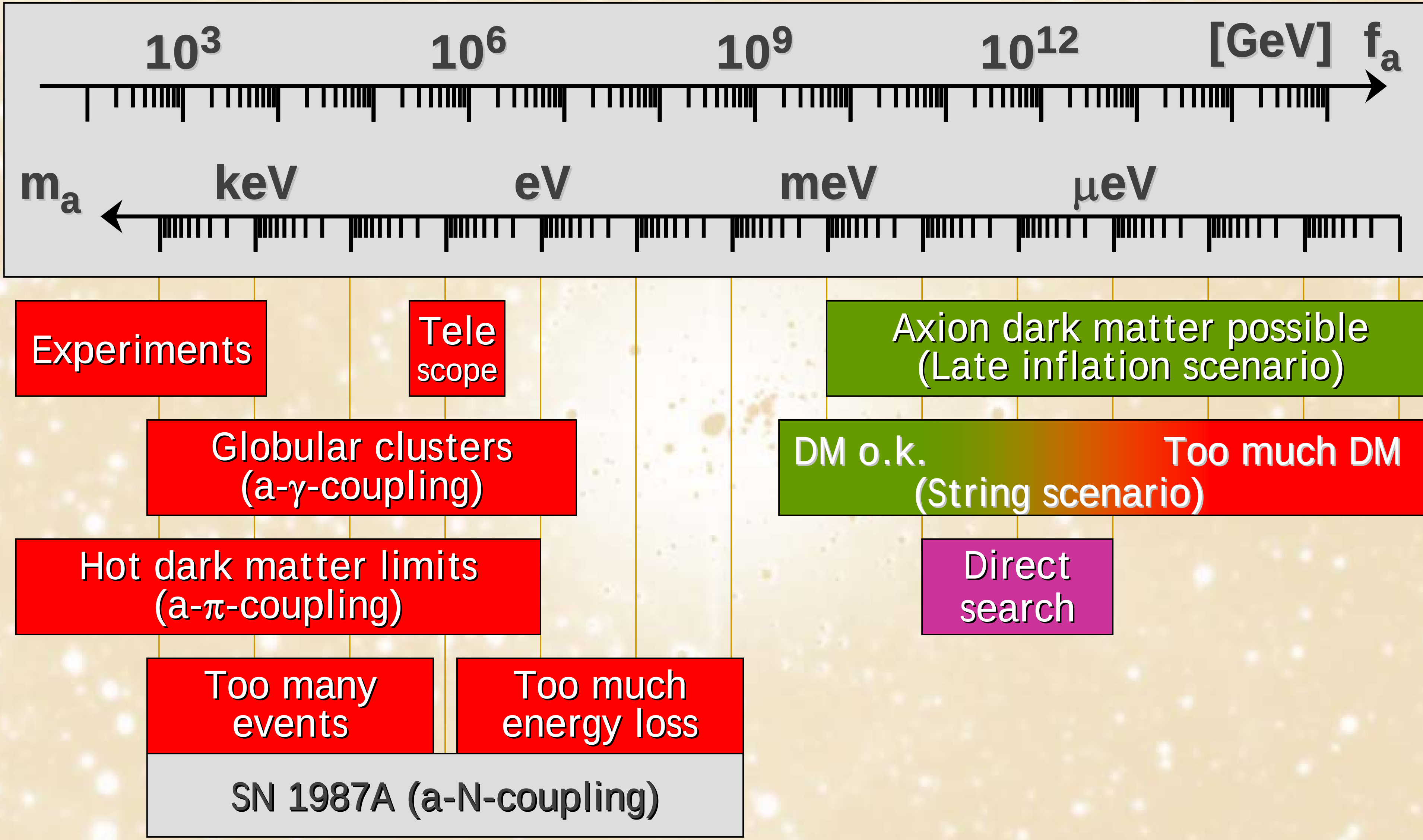
Pair Annihilation



Electromagnetic Bremsstrahlung



Astrophysical Axion Bounds



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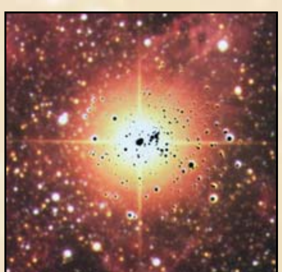
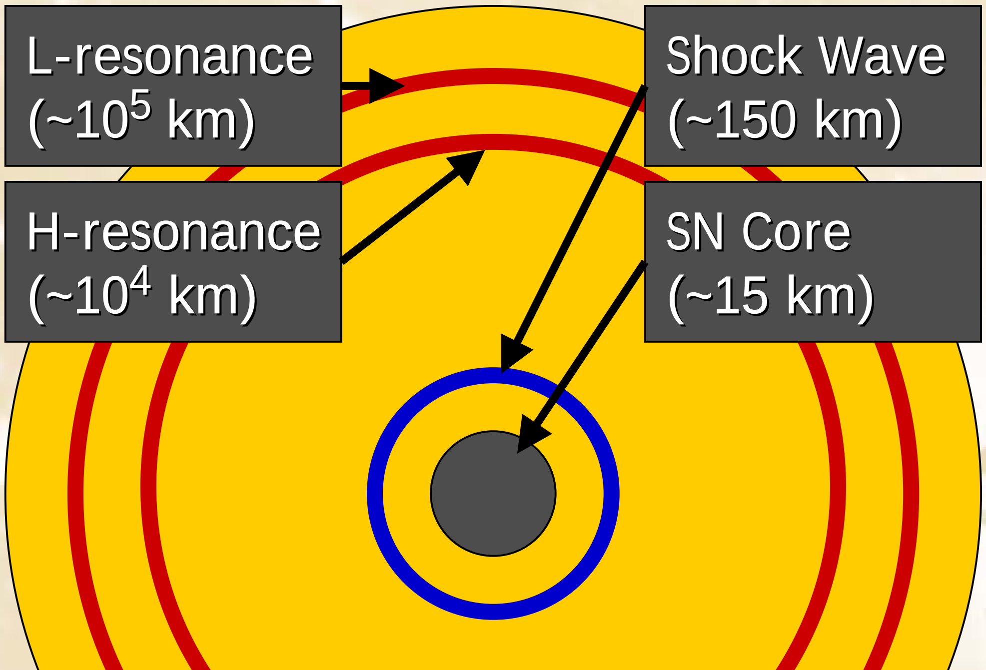


Oscillations of supernova neutrinos

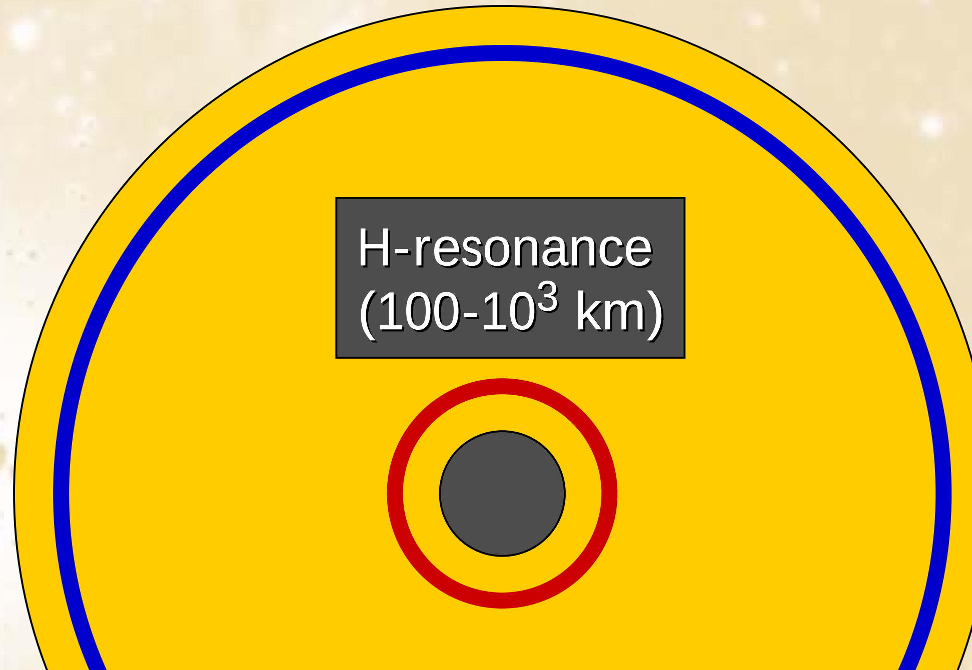
Flavor Oscillations of Supernova Neutrinos

Shortly after collapse



- Flavor conversion suppressed in core and near shockwave by large matter effects
- Flavor oscillations only important for freely streaming neutrinos at large r

Late time (few sec after bounce)

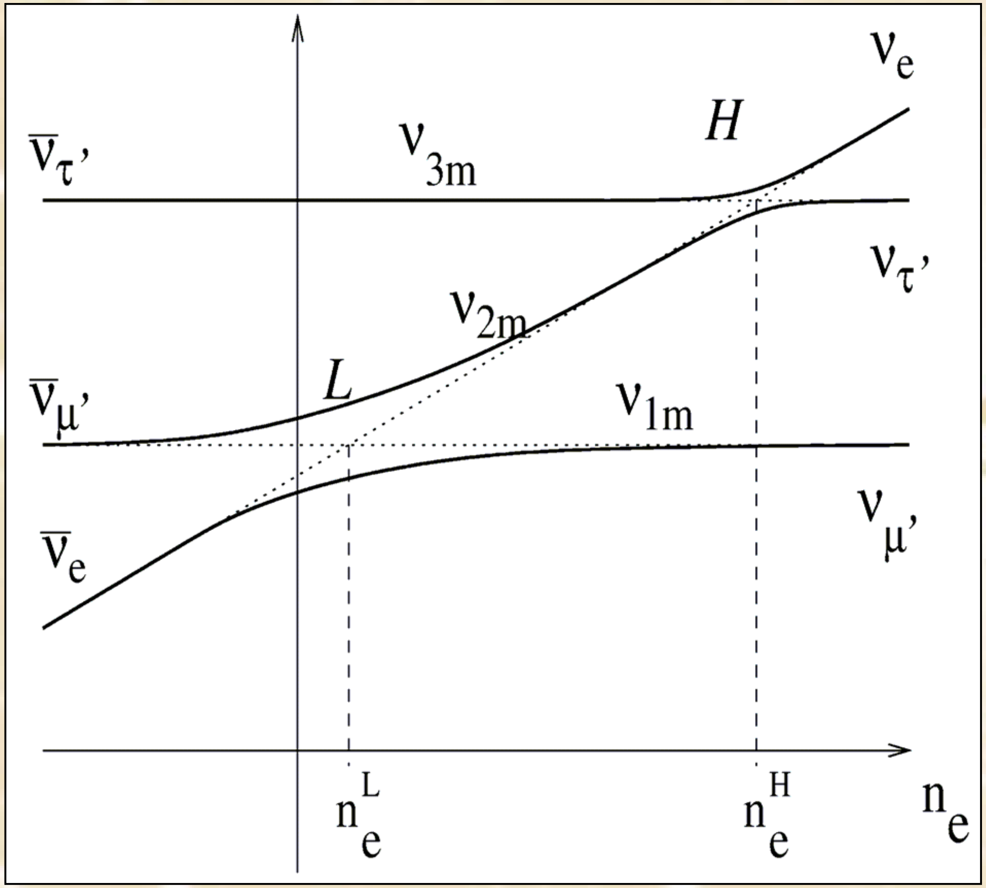


Flavor conversion can be important for r-process nucleosynthesis in hot bubble region
[Qian, Fuller & Woosley, PRL 71 (1993) 1965]

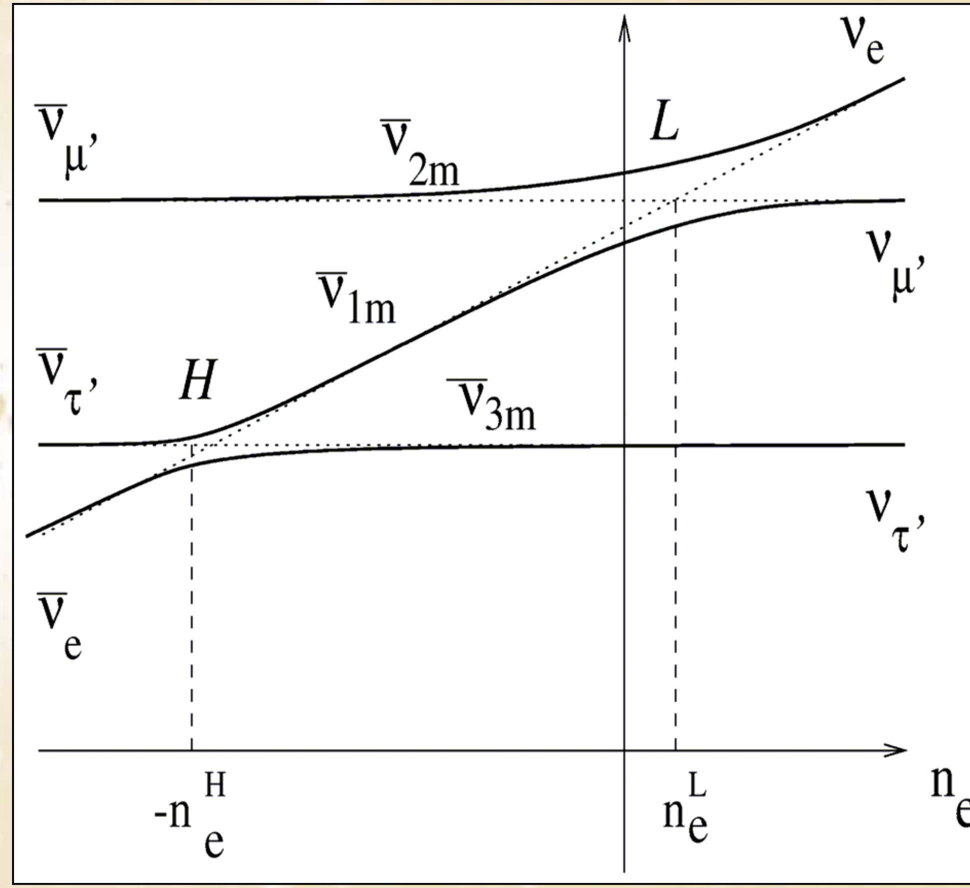
Collective effects from nu-nu interaction important in hot bubble region
[Pastor & Raffelt, astro-ph/0207281, Balantekin & Yüksel, astro-ph/0411159, Duan, Fuller, Carlson & Qian, 2006, forthcoming paper]

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, hep-ph/9907423

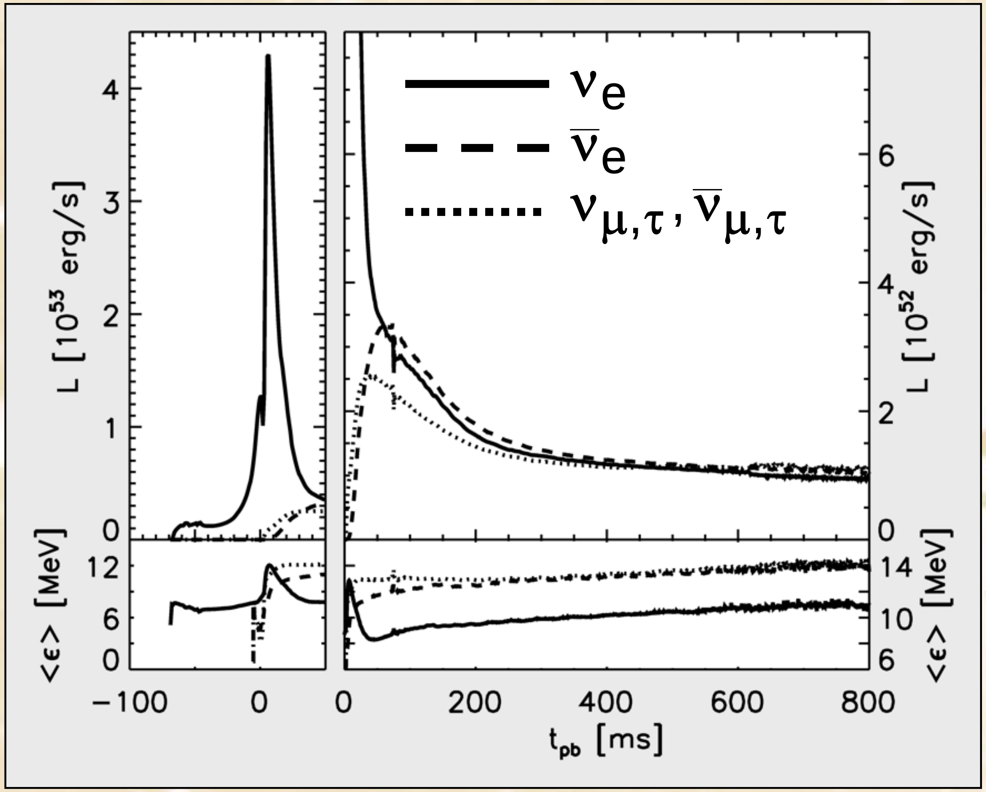
Spectra Emerging from Supernovae

Primary fluxes	F^0_e for ν_e $F^0_{\bar{e}}$ for $\bar{\nu}_e$ F^0_x for $\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$
After leaving the supernova envelope, the fluxes are partially swapped	$F^0_e = p F^0_e + (1-p) F^0_x$ $F^0_{\bar{e}} = \bar{p} F^0_{\bar{e}} + (1-\bar{p}) F^0_x$ $\frac{1}{4}\sum F_x = \frac{2+p+\bar{p}}{4} F^0_x + \frac{1-p}{4} F^0_e + \frac{1-\bar{p}}{4} F^0_{\bar{e}}$

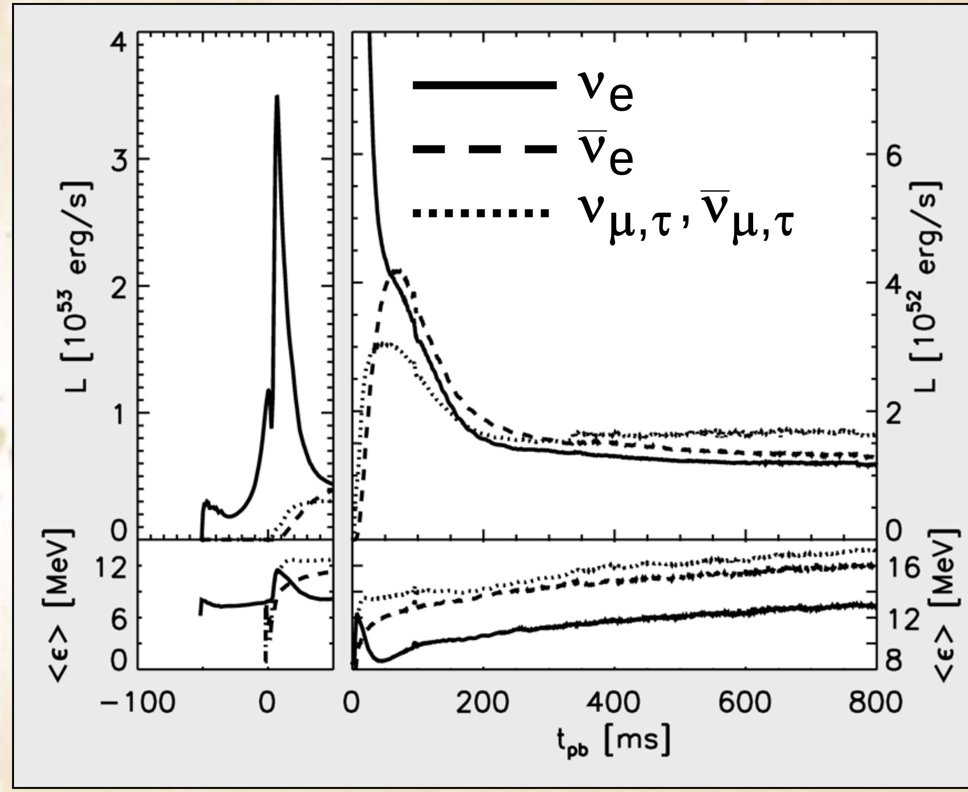
Case	Mass ordering	$\sin^2(2\Theta_{13})$	Survival probability	
			p (for ν_e)	$\bar{p}$ (for $\bar{\nu}_e$)
A	Normal	$\gtrsim 10^{-3}$	0	$\cos^2(\Theta_{12}) \approx 0.7$
B	Inverted	$\gtrsim 10^{-3}$	$\sin^2(\Theta_{12}) \approx 0.3$	0
C	Any	$\lesssim 10^{-5}$	$\sin^2(\Theta_{12}) \approx 0.3$	$\cos^2(\Theta_{12}) \approx 0.7$

Flavor-Dependent Neutrino Fluxes vs. Equation of State

Wolff & Hillebrandt nuclear EoS (stiff)



Lattimer & Swesty nuclear EoS (soft)

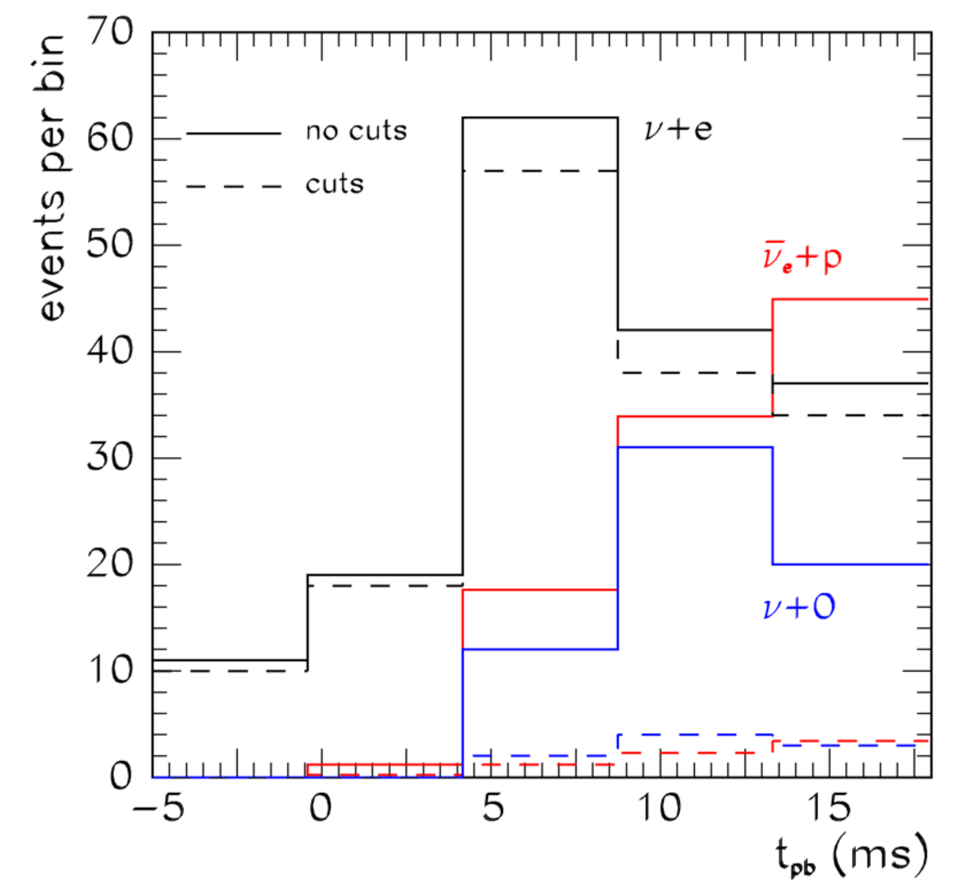


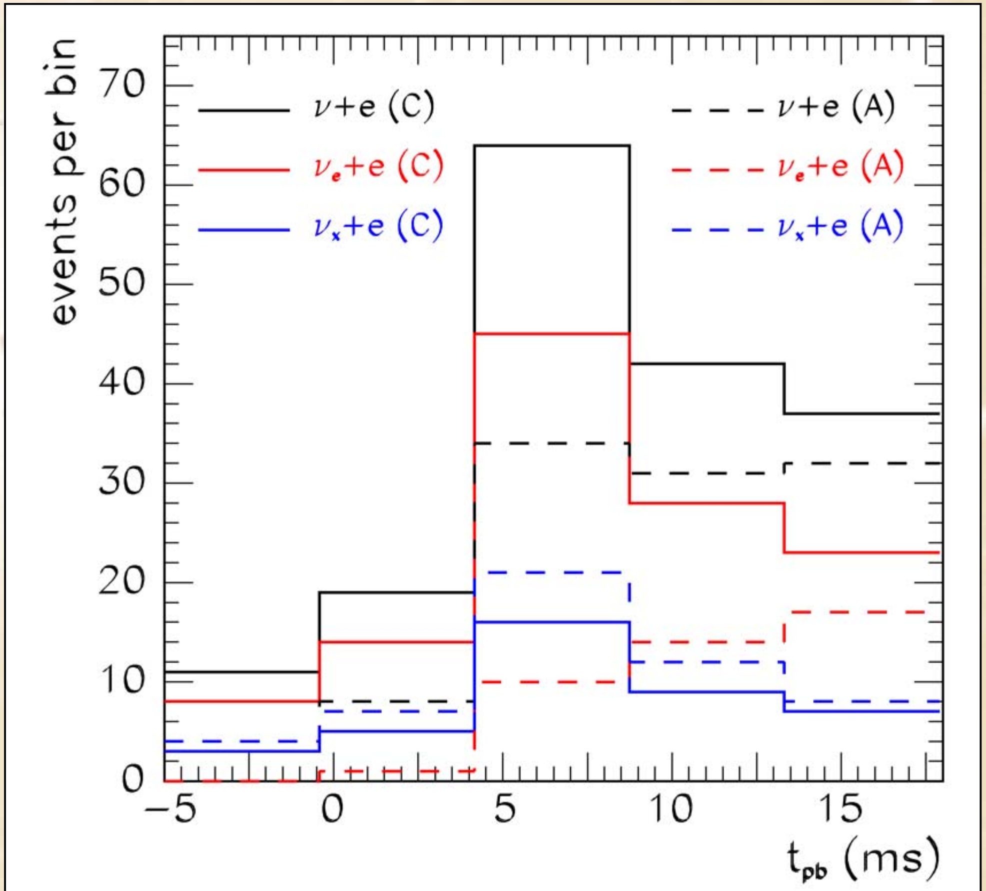
Kitaura, Janka & Hillebrandt, “Explosions of O-Ne-Mg cores, the Crab supernova, and subluminous Type II-P supernovae”, astro-ph/0512065

Neutronization Burst in a Mt Detector w/ Neutron Tagging

After angular cuts, almost background-free neutronization burst from ν-e-scattering

Neutrino oscillations cause a significantly different time profile (absolute flux depends on distance)

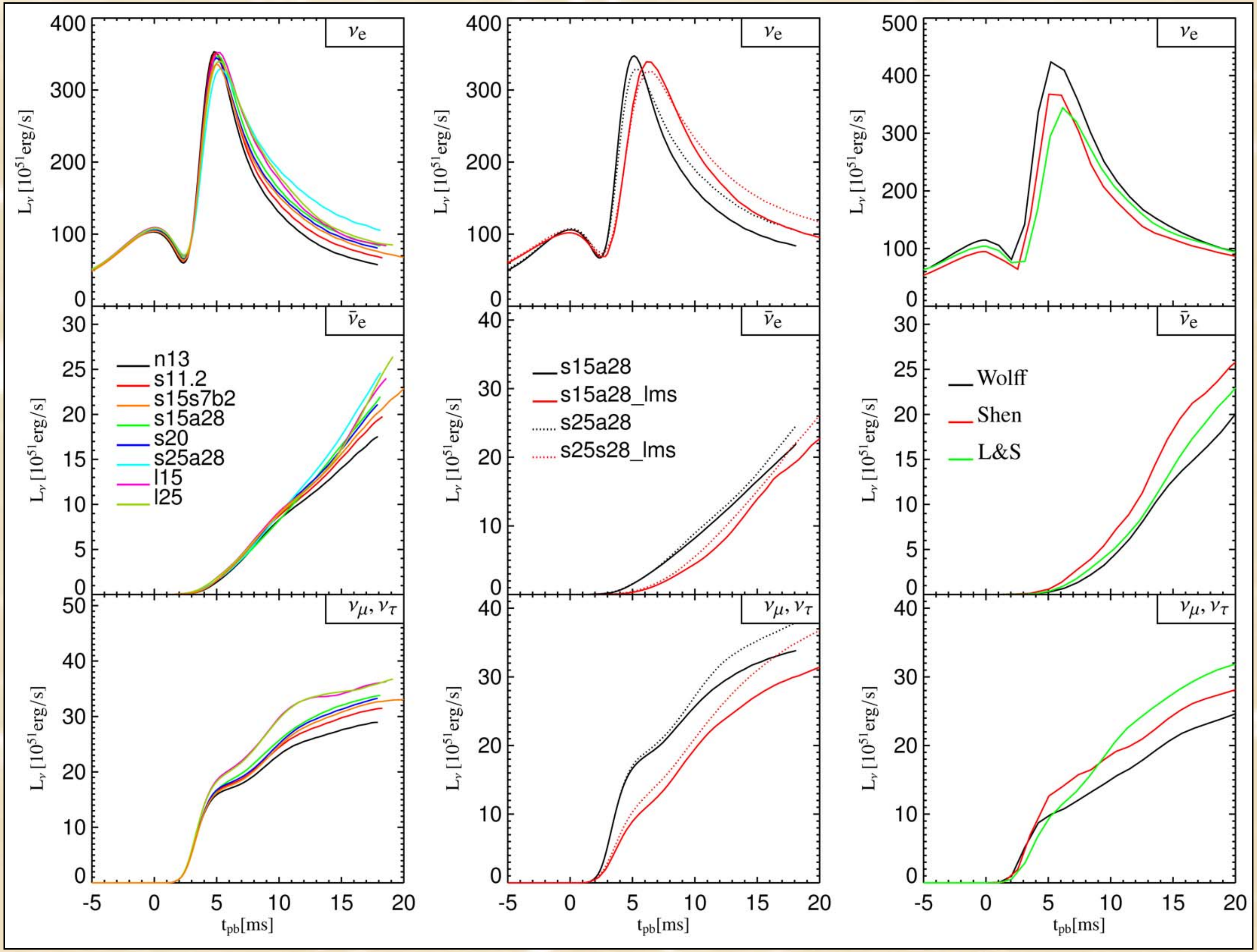




Kachelriess, Tomàs, Buras, Janka, Marek & Rampp, astro-ph/0412082

Neutronization Burst as a Standard Candle

Different Mass	Neutrino Transport	Nuclear EoS

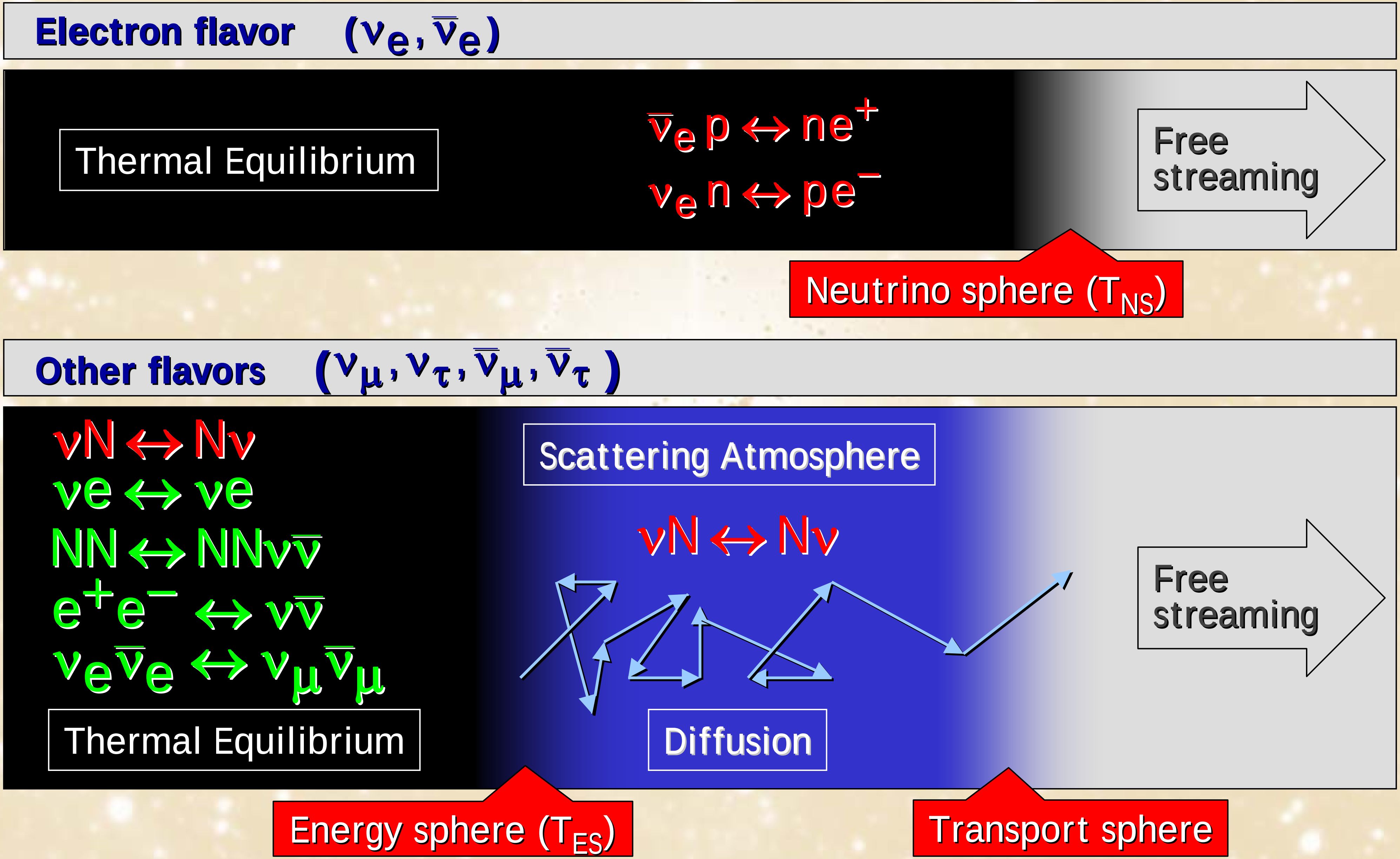


If mixing scenario is known, perhaps best method to determine SN distance, especially if obscured

(better than 5-10%)

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

Supernova Neutrino Spectra Formation



Raffelt (astro-ph/0105250), Keil, Raffelt & Janka (astro-ph/0208035)

Supernova Neutrino Spectra Formation

Electron flavor $(\nu_e, \bar{\nu}_e)$

Thermal Equilibrium

$\bar{\nu}_e p \leftrightarrow n e^+$

$\nu_e n \leftrightarrow p e^-$

$T_{flux} \sim T_{NS}$

Neutrino sphere (T_{NS})

Other flavors $(\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau)$

$\nu N \leftrightarrow N \nu$

$\nu e \leftrightarrow \nu e$

$NN \leftrightarrow NN \nu \bar{\nu}$

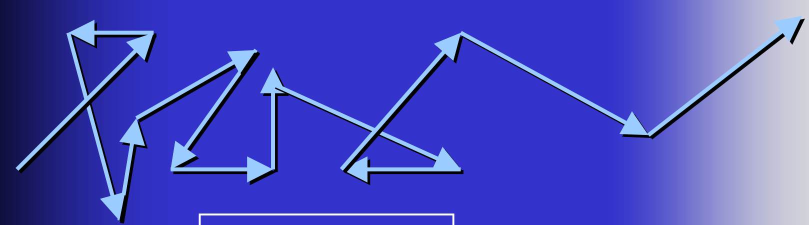
$e^+ e^- \leftrightarrow \nu \bar{\nu}$

$\nu_e \bar{\nu}_e \leftrightarrow \nu_\mu \bar{\nu}_\mu$

Thermal Equilibrium

Scattering Atmosphere

$\nu N \leftrightarrow N \nu$



Diffusion

$T_{flux} \sim 0.6 T_{ES}$

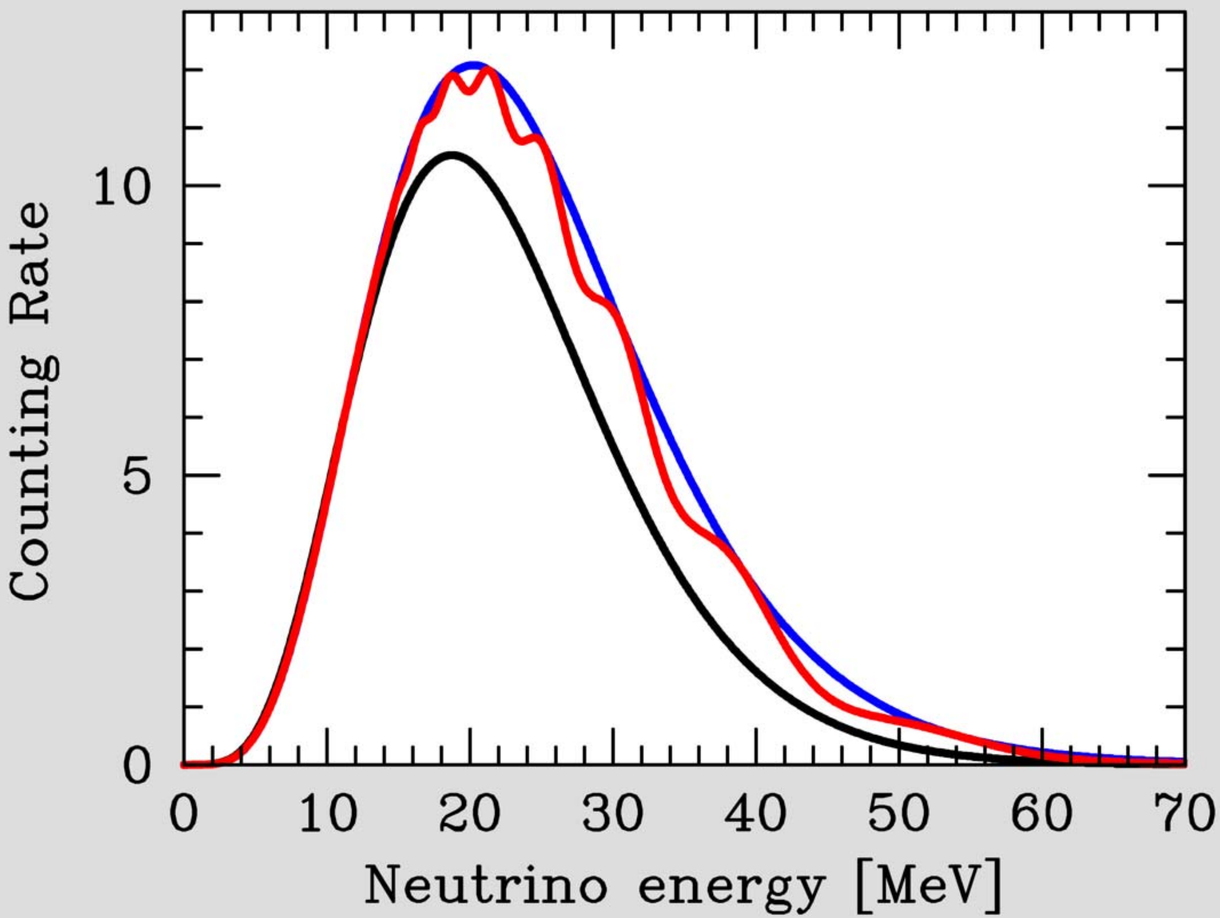
Energy sphere (T_{ES})

Transport sphere

Raffelt (astro-ph/0105250), Keil, Raffelt & Janka (astro-ph/0208035)

Oscillation of Supernova Anti-Neutrinos

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



Assumed flux parameters

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

$\langle E(\overline{\nu}_e) \rangle = 15\,\mathrm{MeV}$

$\langle E(\overline{\nu}_x) \rangle = 18\,\mathrm{MeV}$

Mixing parameters

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

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

No oscillations

Oscillations in SN envelope

Earth effects included

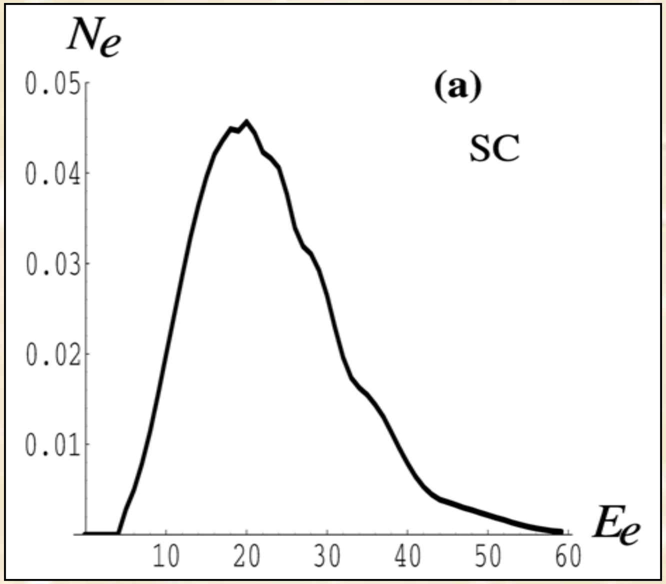
Π(Dighe, Kachelriess, Keil, Raffelt, Semikoz, Tomàs),
hep-ph/0303210, hep-ph/0304150, hep-ph/0307050, hep-ph/0311172

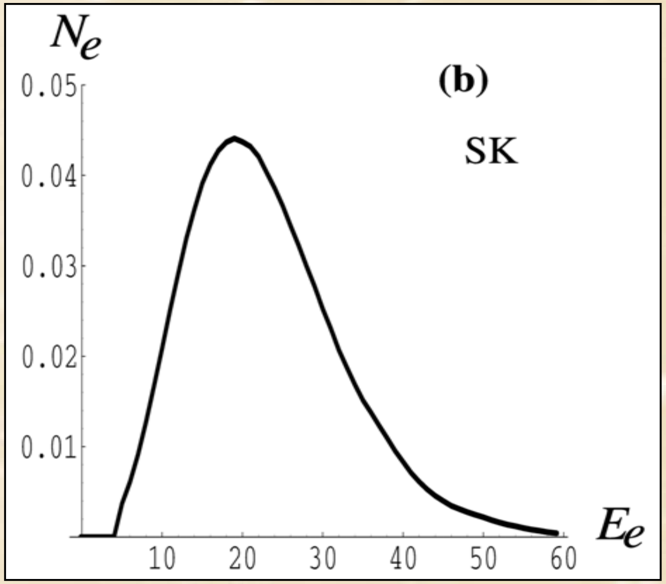
Model-Independent Strategies for Observing Earth Effects

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





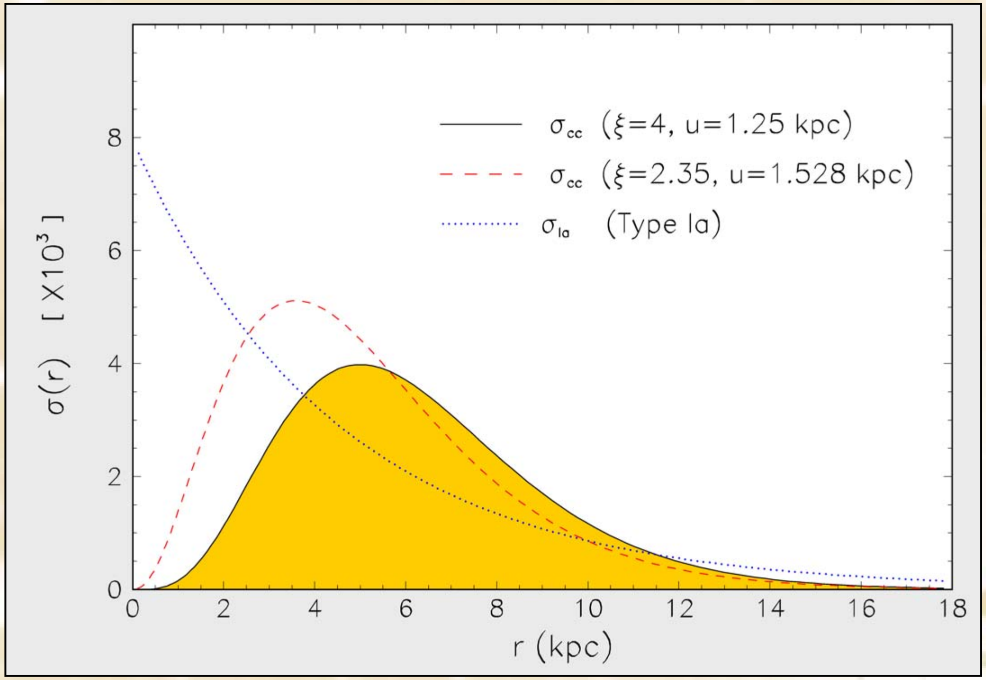
Scintillator detector
~ 2000 events
may be enough

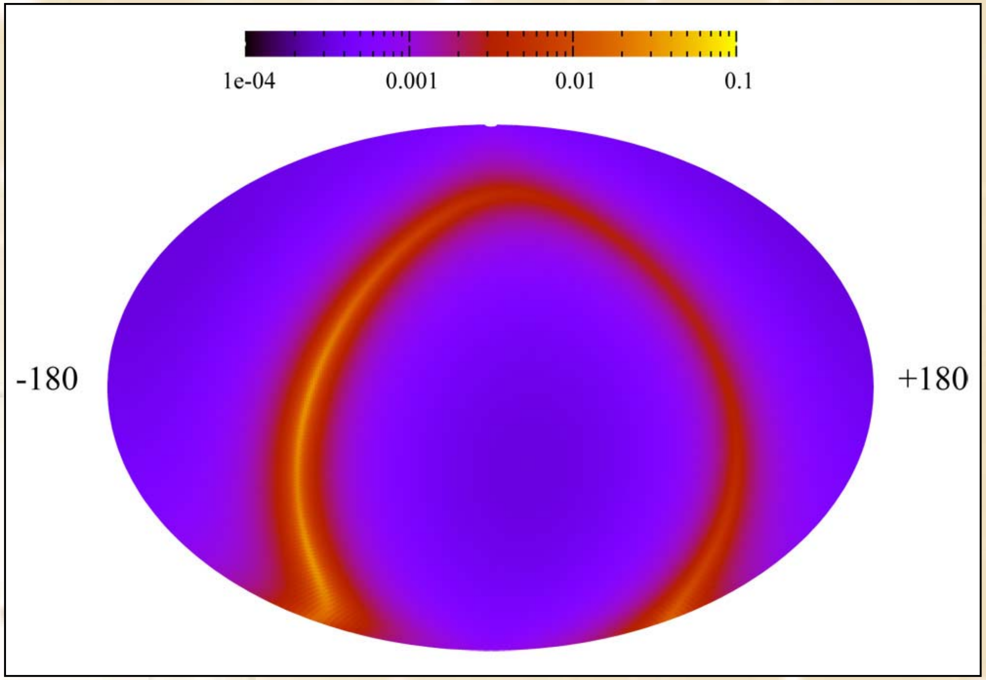
Water Cherenkov
Need megaton detector
with ~ 10^5 events

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

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

Galactic Distribution of Core-Collapse Supernovae





"Surface density" depleted near center (from pulsar distribution and other indicators)

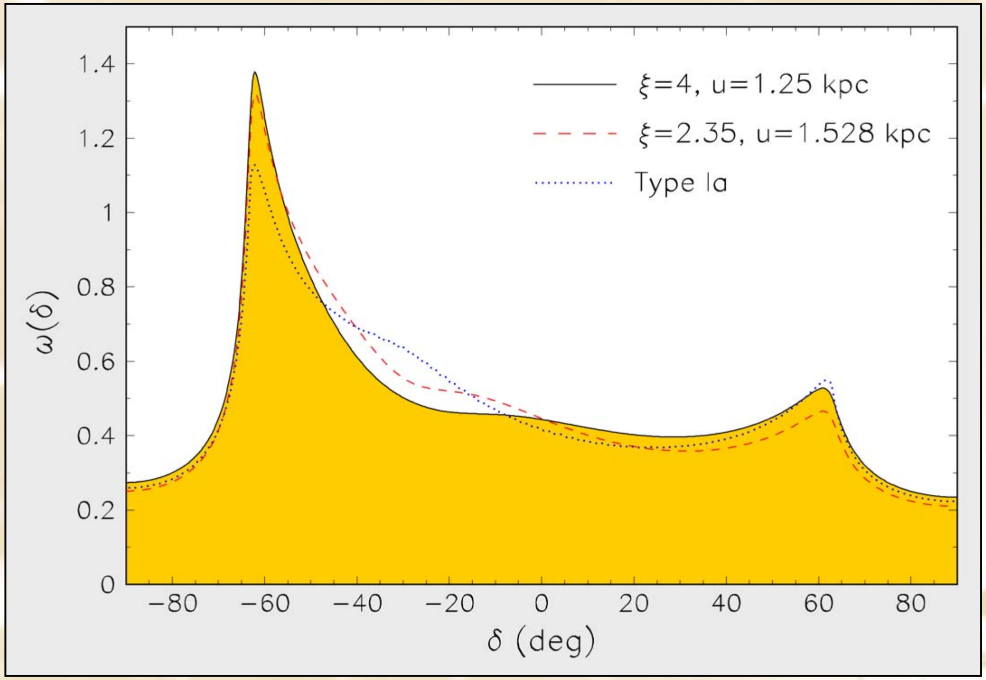
$$\sigma \propto r^{\xi} \exp\left(-\frac{r}{u}\right)$$

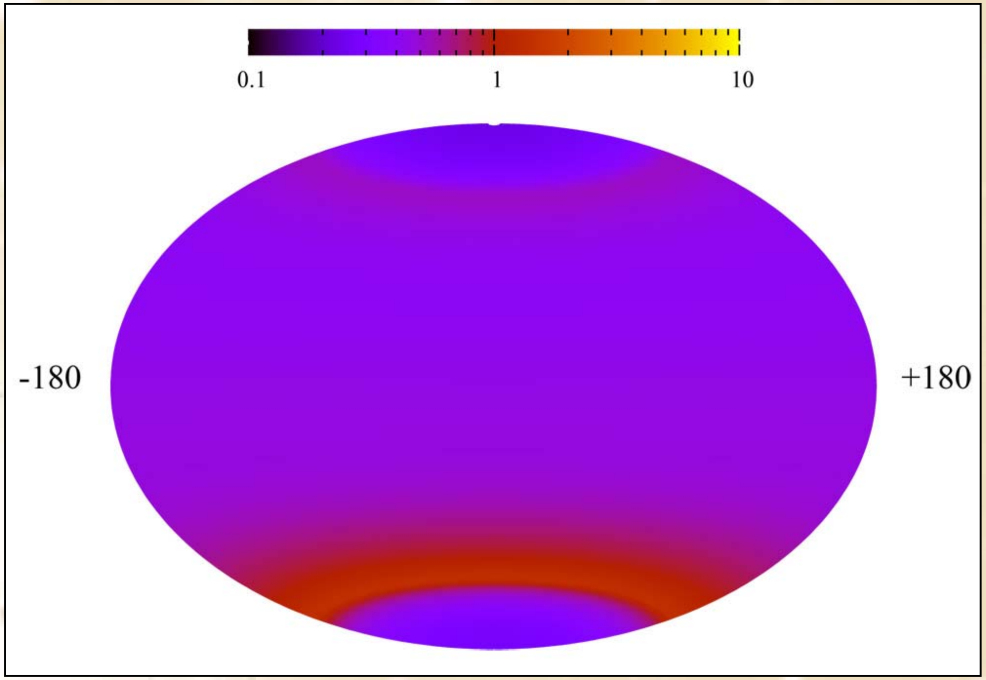
Assumed vertical distribution in the galactic disk

$$R(z) \propto 0.79 \exp\left[-\left(\frac{z}{212\ \text{pc}}\right)^2\right] + 0.21 \exp\left[-\left(\frac{z}{636\ \text{pc}}\right)^2\right]$$

Mirizzi, Raffelt & Serpico, "Earth matter effects in supernova neutrinos: Optimal detector locations", astro-ph/0604300

Average over Right Ascension (Earth Rotation)

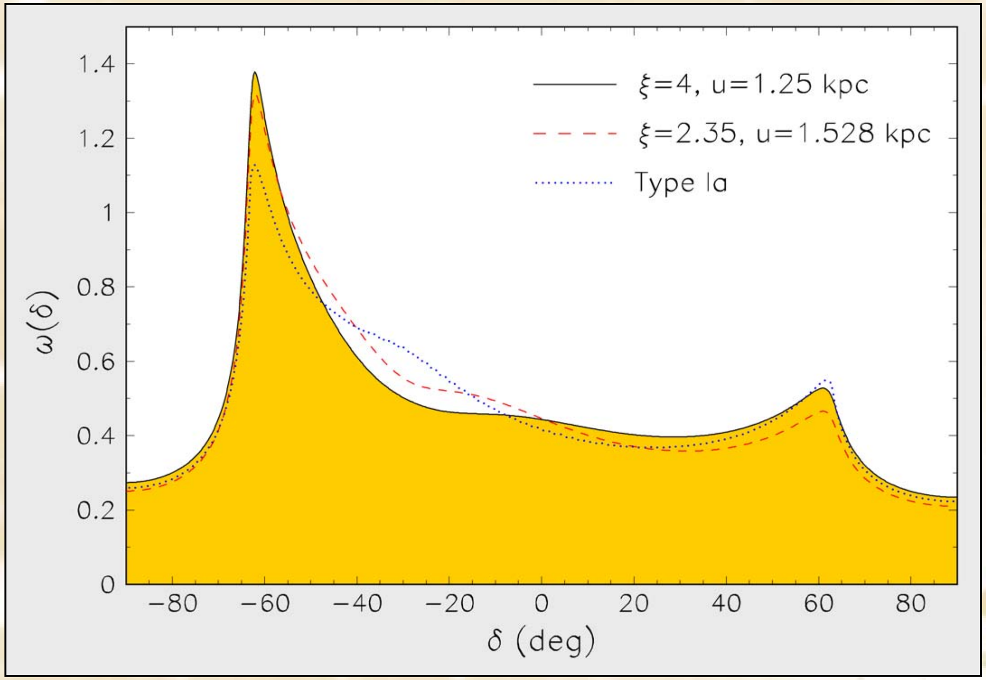


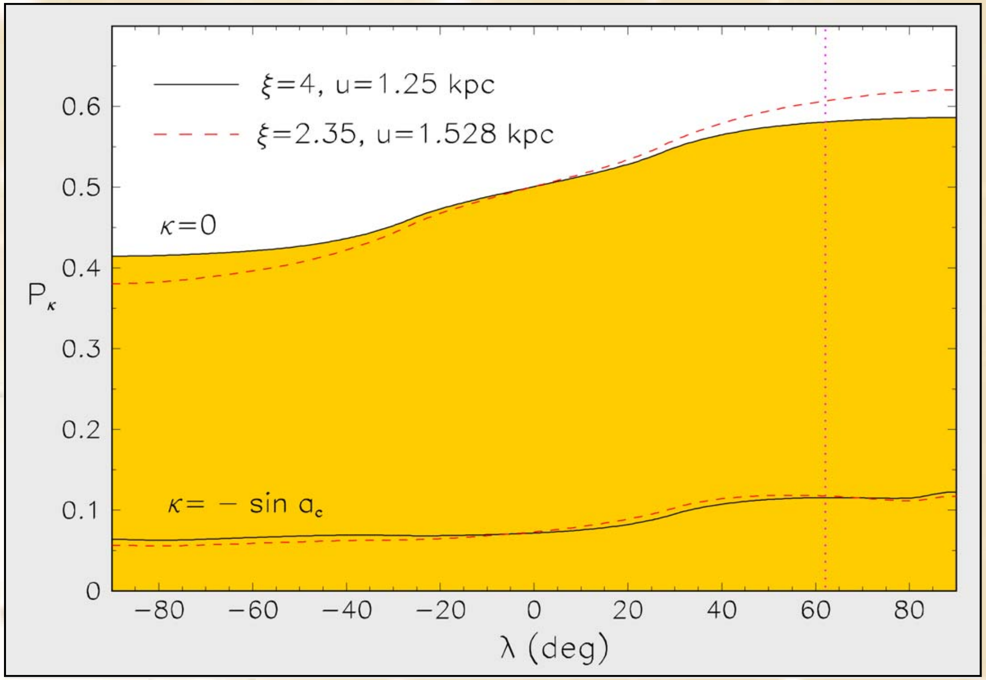


Dependence on geographic latitude quite robust relative to details of assumed galactic distribution

Mirizzi, Raffelt & Serpico, "Earth matter effects in supernova neutrinos: Optimal detector locations", astro-ph/0604300

Average over Right Ascension (Earth Rotation)





Dependence on geographic latitude quite robust relative to details of assumed galactic distribution

Probability of Earth and core shadowing as a function of geographic latitude

Mirizzi, Raffelt & Serpico, "Earth matter effects in supernova neutrinos: Optimal detector locations", astro-ph/0604300

Mirizzi, Raffelt & Serpico
astro-ph/0604300

| Home | One detector | Two detectors |

SUPERNOVA NEUTRINOS
EARTH SHADOWING PROBABILITY

(one detector)

Latitude (deg): 64
Longitude (deg): 26

- (•) Earth (Re = 6371 km) crossing , L (km): 0.0
- ( ) Core (Rc = 3486 km) crossing , L (km): 10665.35
- ( ) Minimal path length L (km): 0

Execute

SHADOWING PROBABILITY:

0.581

| Home | One detector | Two detectors |

SUPERNOVA NEUTRINOS
EARTH SHADOWING PROBABILITY

(two detectors)

Latitude 1 (deg): 64
Longitude 1 (deg): 26
Latitude 2 (deg): 18
Longitude 2 (deg): 156

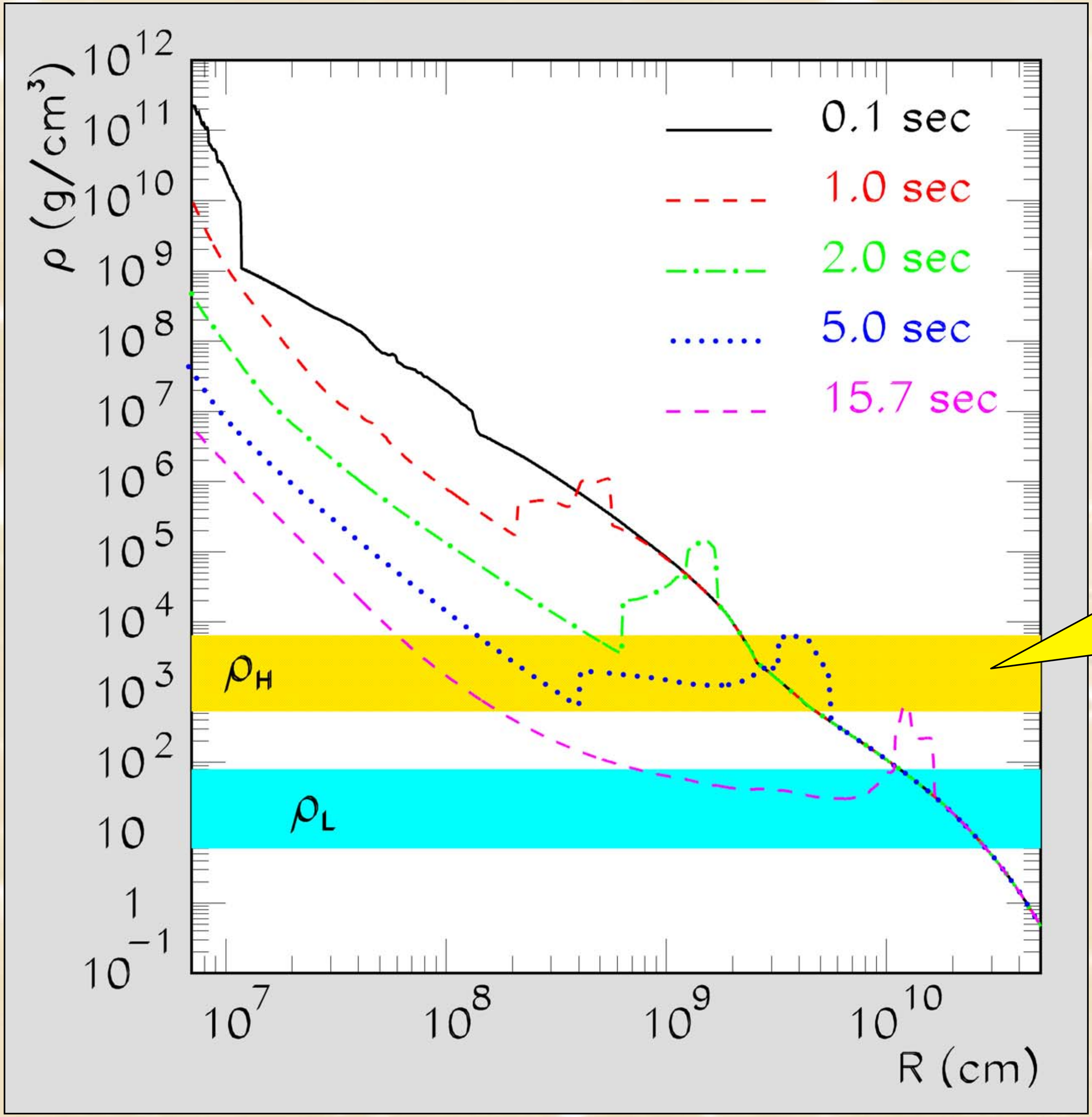
- (•) Earth crossing , L (km): 0.0
- ( ) Core crossing , L (km): 10665.35
- ( ) Minimal path length L (km): 0

Execute

SHADOWING PROBABILITY:

P(1, not 2):	0.270
P(not 1, 2):	0.214
P(1 and 2):	0.311
P(1 or 2, or both):	0.795
P(1 or 2, not both):	0.484
P(not 1, not 2):	0.206

Supernova Shock Propagation and Neutrino Oscillations

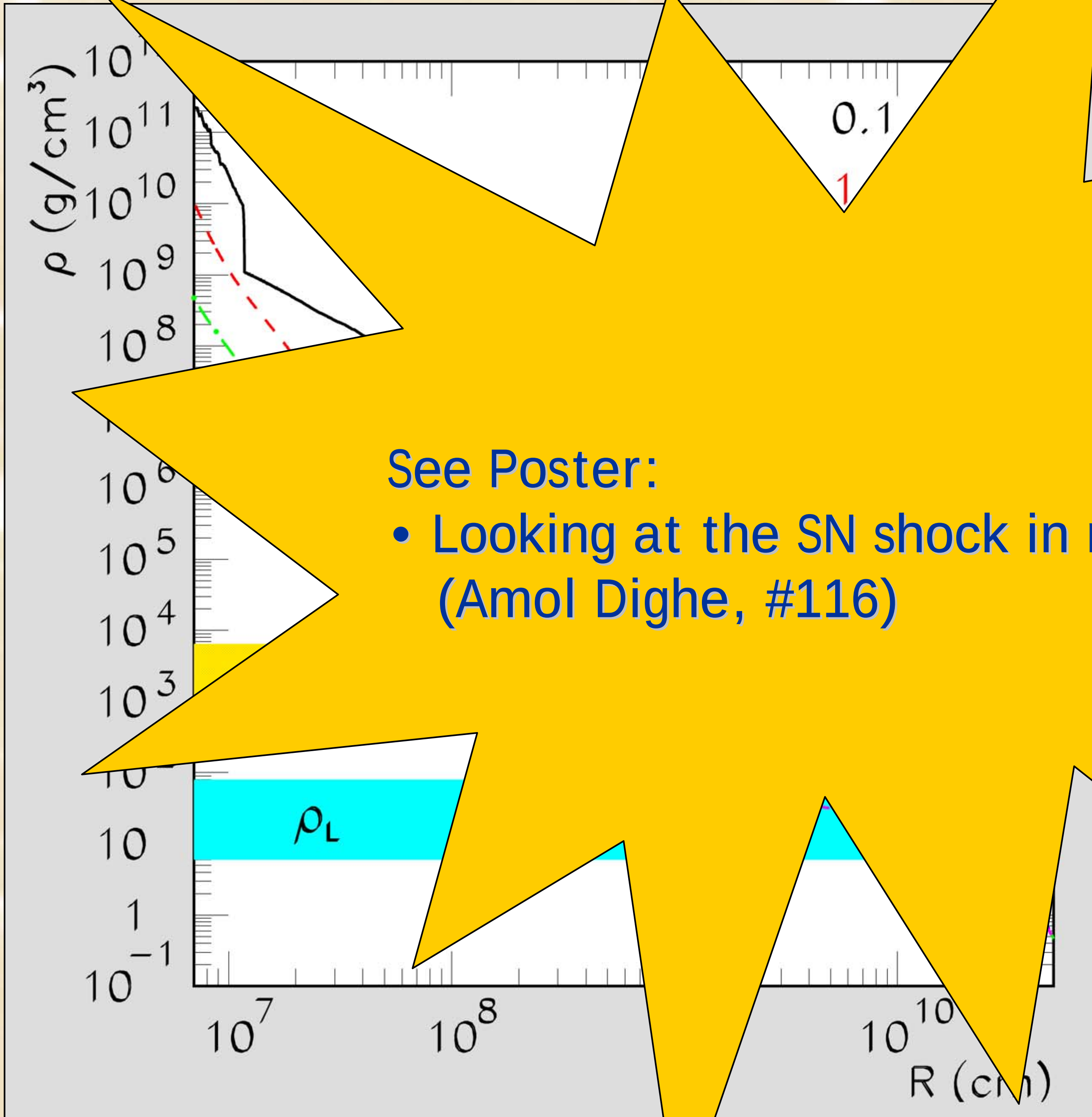


Schirato & Fuller: Connection between supernova shocks, flavor transformation, and the neutrino signal [astro-ph/0205390]

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]

Supernova Shock Propagation and Neutrino Oscillations

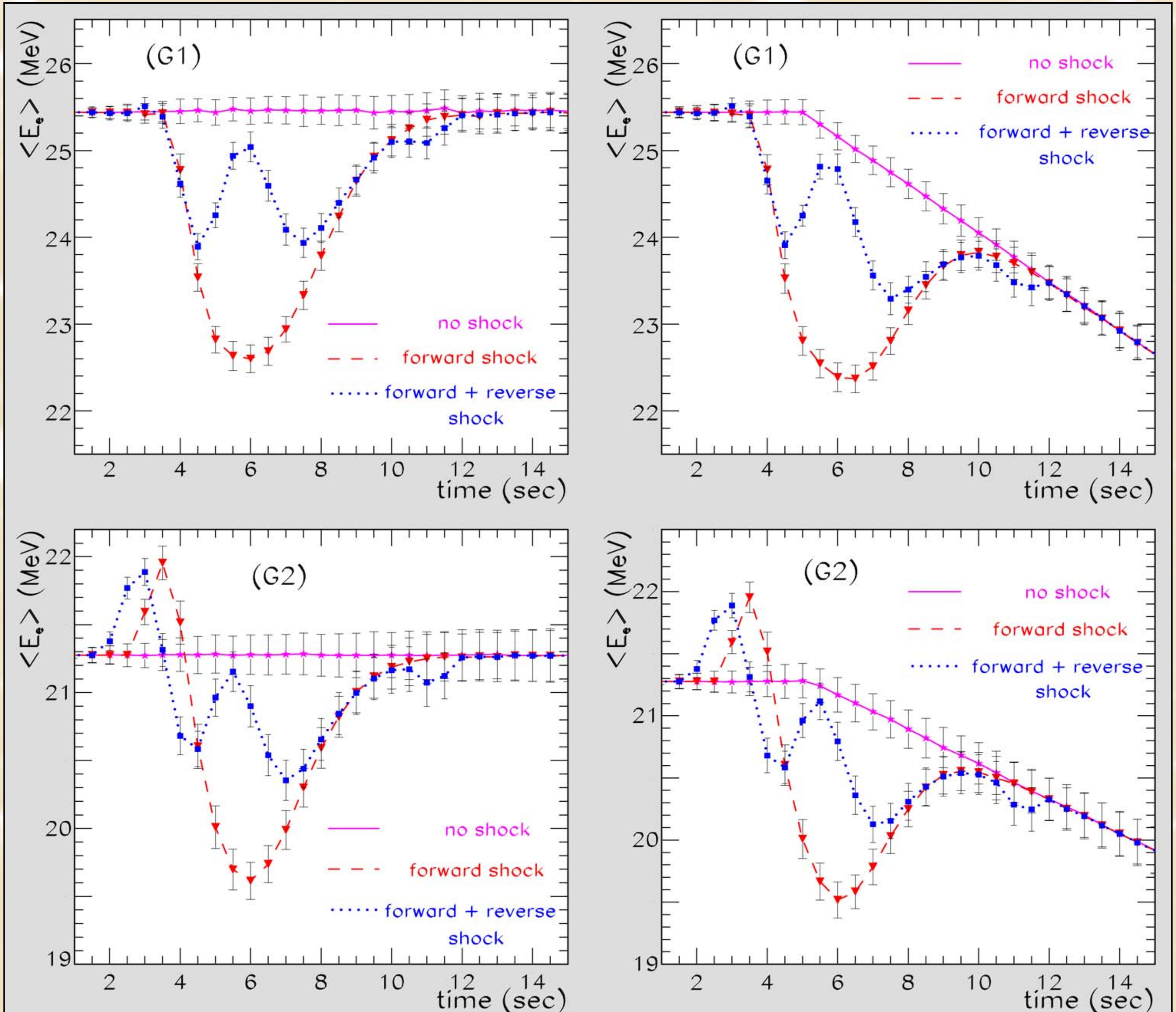


See Poster:
- Looking at the SN shock in neutrinos (Amol Dighe, #116)

Schirato & Fuller:
Connection between
supern... shocks,
...ansformation,
...e neutrino signal
...ph/0205390]

...às, M. Kachelriess,
...lt, A. Dighe,
H.-... ka & L. Scheck:
Neutri... ignatures of
supernova forward and
reverse shock propagation
[astro-ph/0407132]

Megatonne Cherenkov Detector (Inverted Hierarchy)



$$\frac{\text{Flux}(\bar{\nu}_e)}{\text{Flux}(\bar{\nu}_x)} = 0.8$$

$E_0(\bar{\nu}_e) = 15\,\text{MeV}$

$E_0(\bar{\nu}_x) = 18\,\text{MeV}$

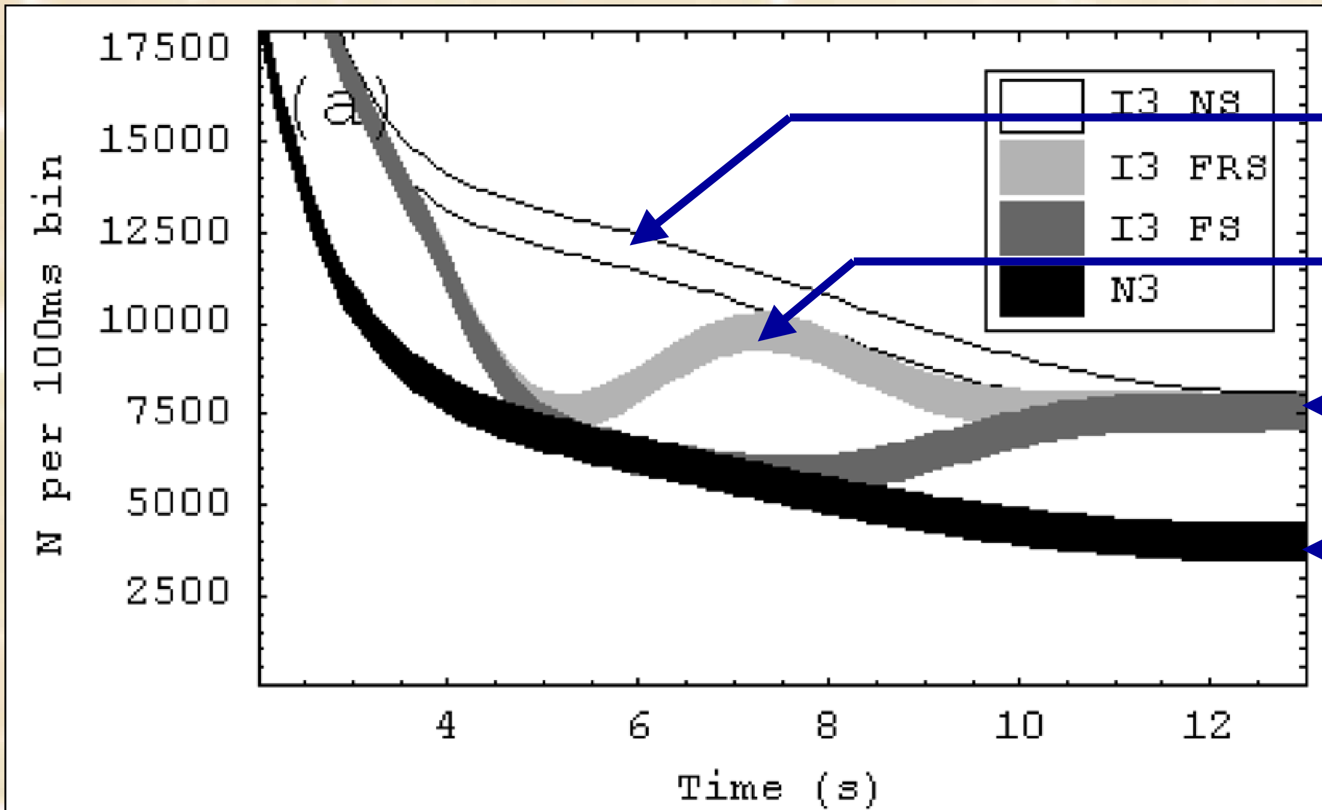
$$\frac{\text{Flux}(\bar{\nu}_e)}{\text{Flux}(\bar{\nu}_x)} = 0.5$$

$E_0(\bar{\nu}_e) = 15\,\text{MeV}$

$E_0(\bar{\nu}_x) = 15\,\text{MeV}$

Shock-Wave Propagation in IceCube

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



Inverted Hierarchy
No shockwave

Inverted Hierarchy
Forward & reverse shock

Inverted Hierarchy
Forward shock

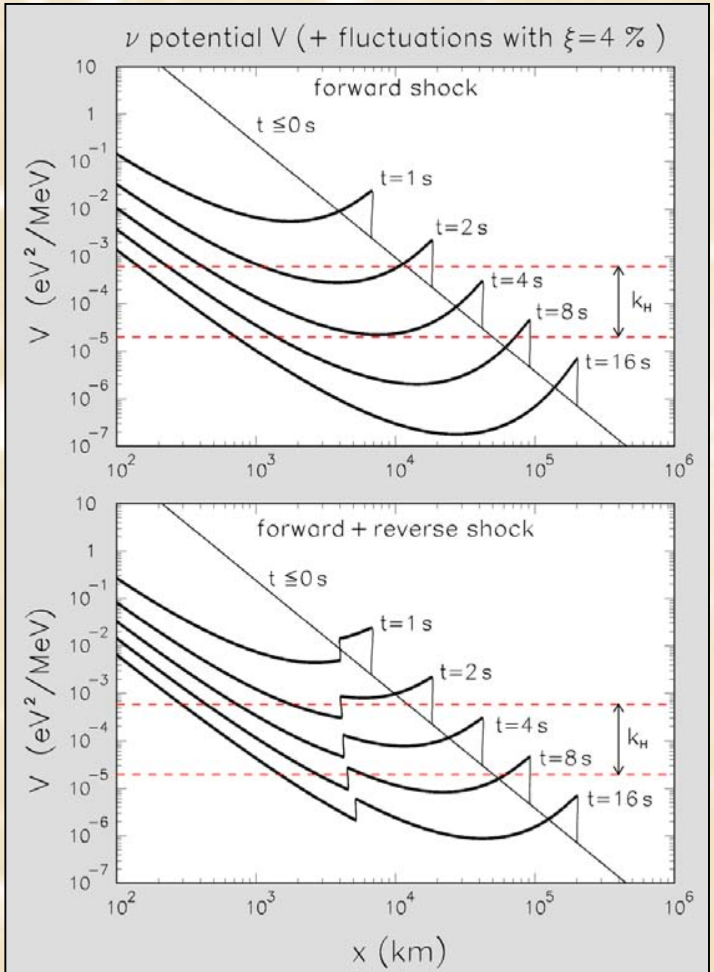
Normal Hierarchy

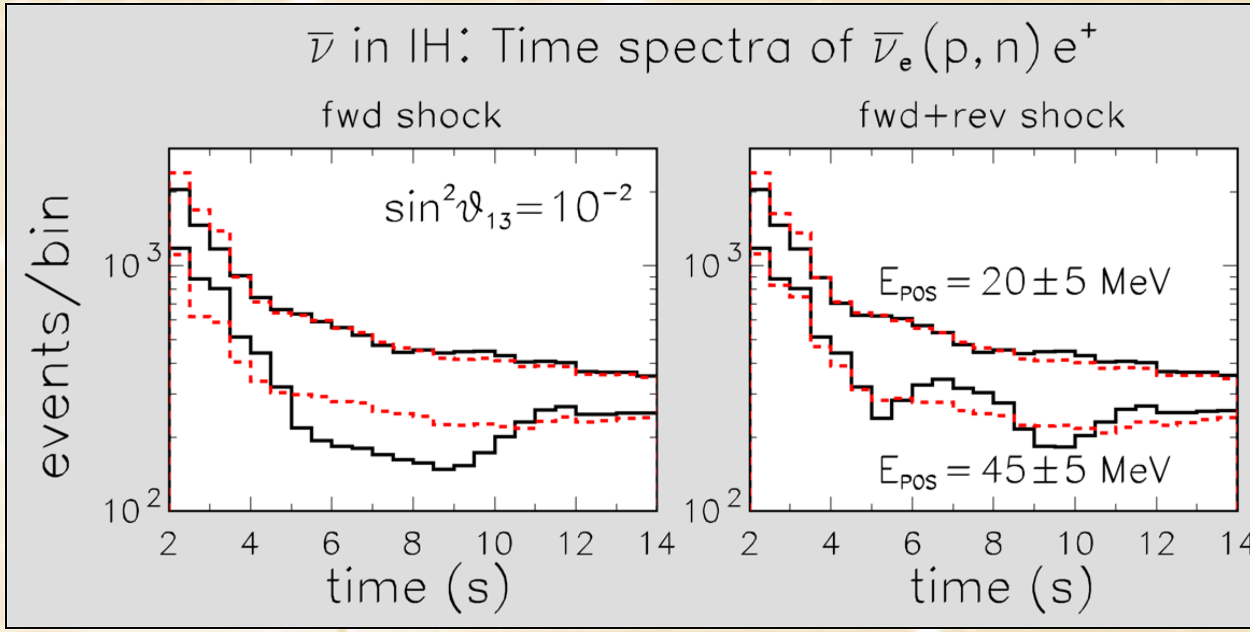
Choubey, Harries & Ross, “Probing neutrino oscillations from supernovae shock waves via the IceCube detector”, astro-ph/0604300

Stochastic Density Fluctuations

Schematic time-dependent shock-wave profile

Events in a 0.4 Mt water Cherenkov detector
Black: no noise. Red: with noise.





Assume δ-correlated noise, length-scale of order the oscillation length (10 km), amplitude 4% (line-width on plot)

Fogli, Lisi, Mirizzi & Montanino, “Damping of supernova neutrino transitions in stochastic shock-wave density profiles”, hep-ph/0603033

So what could we learn?

Depends on which detectors will be running, what they will see, and what else will be known at that time, e.g. about neutrino mixing parameters.

Even small-statistics signal (e.g. SN at Andromeda distance with a Mt detector) useful to determine spectra and duration better than SN 1987A (especially useful for particle-physics limits and for prediction of diffuse SN neutrino background)

High-statistics observation from galactic SN:

- Early warning, direction and distance
- Follow in detail stellar collapse, test SN theory
- May observe new features (e.g. collapse to black hole)

Neutrino oscillations:

- May observe evidence for flavor oscillations and determine mass hierarchy and/or magnitude of Theta-13
- May observe shock-wave propagation effects

Probably requires new detectors, e.g. Mton water Cherenkov (Hyper-K, MEMPHYS, UNO), neutron tagging (GADZOOKS!) large scintillator detectors (LENA), large nu-e detector (liquid argon TPC). In Europe: LAGUNA R&D initiative forming

Supernova 1054 Petrograph

Possible SN 1054 Petrograph by the Anasazi people
(Chaco Canyon, New Mexico)