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Supernovae as Multiflavor Neutrino Sources

Georg G. Raffelt

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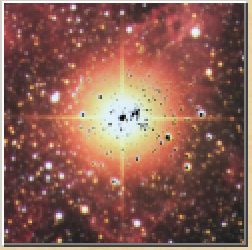
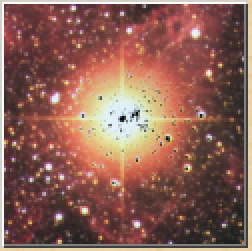
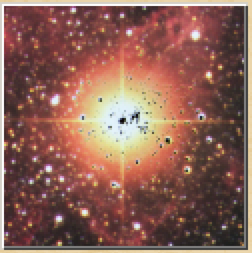
Supernovae as Multiflavor Neutrino Sources



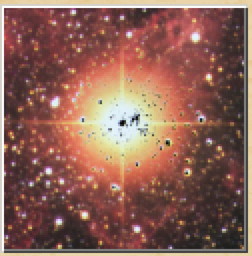
Physical mechanism
of core-collapse supernovae



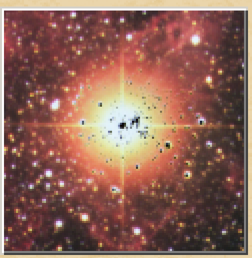
Supernova neutrino detection



Flavor-dependent fluxes and spectra



Earth effect in SN neutrinos
and normal vs. inverted mass hierarchy

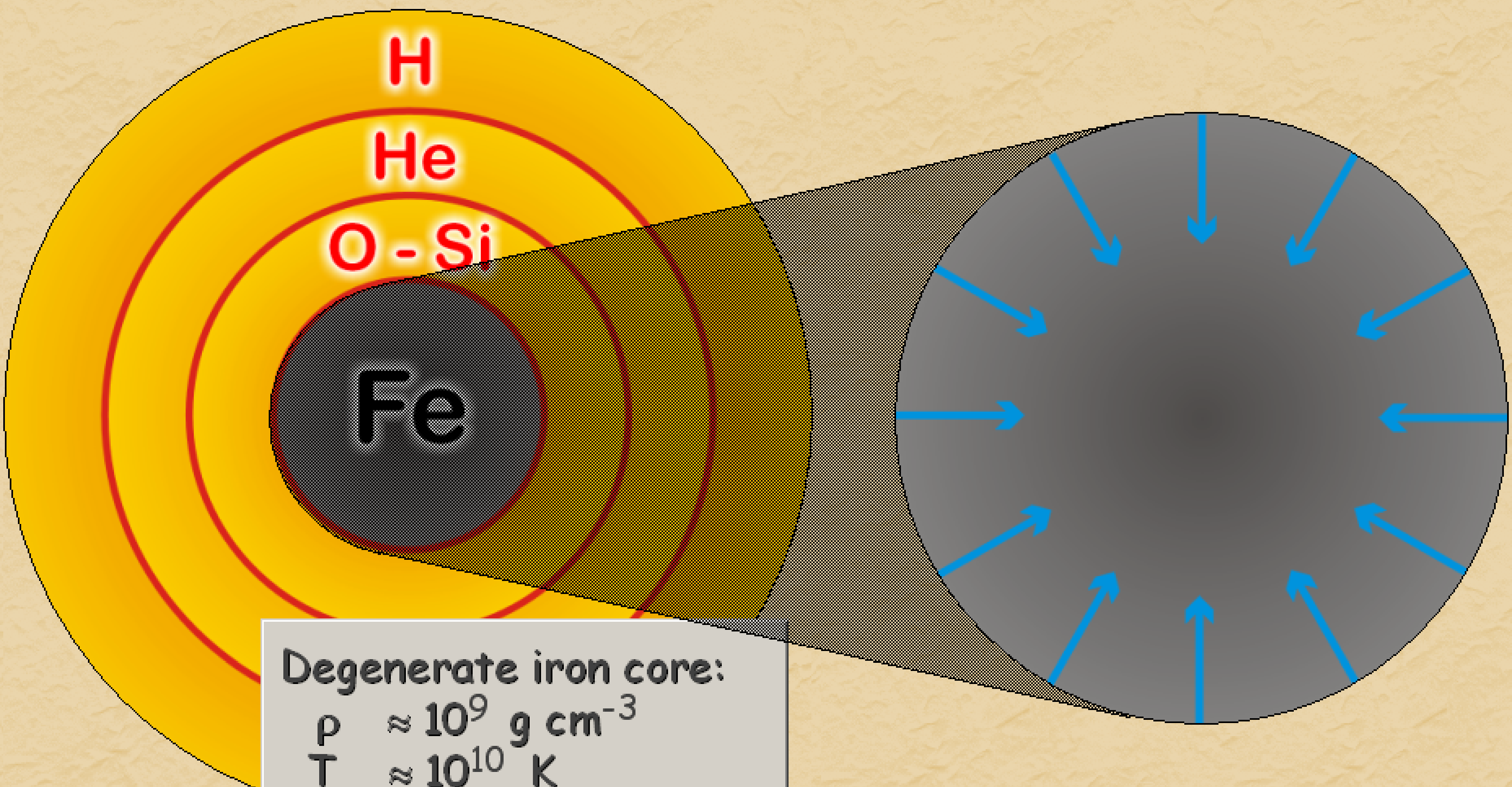


Diffuse flux from all cosmic supernovae

Stellar Collapse and Supernova Explosion

Onion Structure

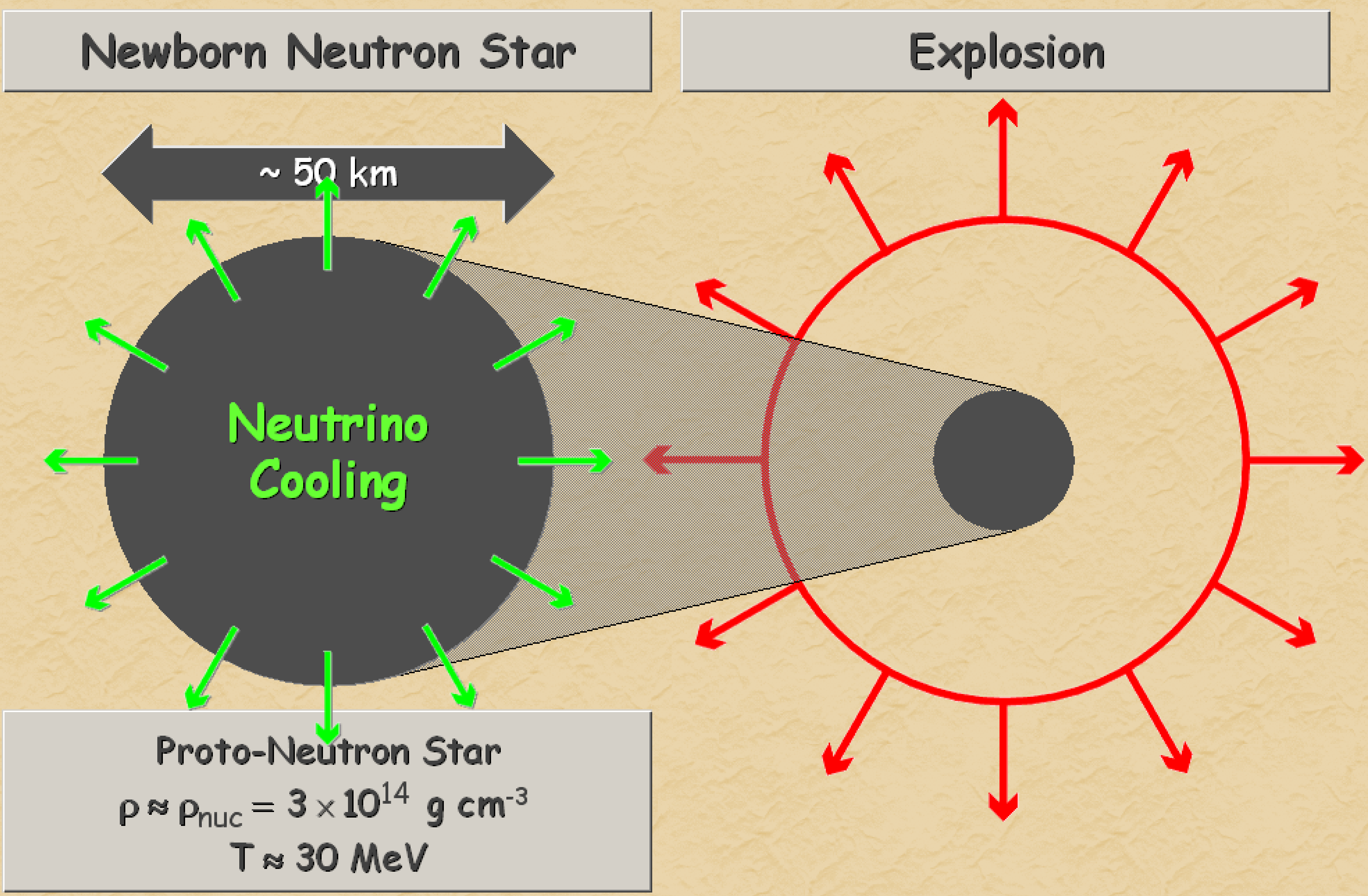
Collapse (Implosion)



Degenerate iron core:

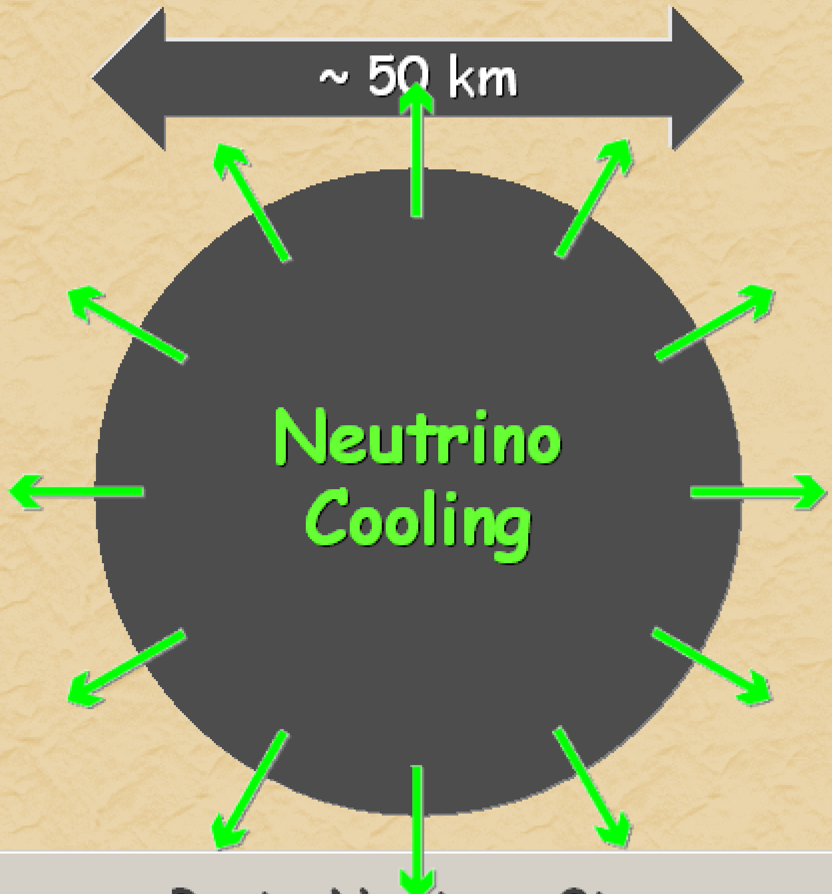
$\rho \approx 10^{9}$ g cm^{-3}
$T \approx 10^{10}$ K
$M_{Fe} \approx 1.5\ M_{sun}$
$R_{Fe} \approx 8000$ km

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}

$T \approx 30$ 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

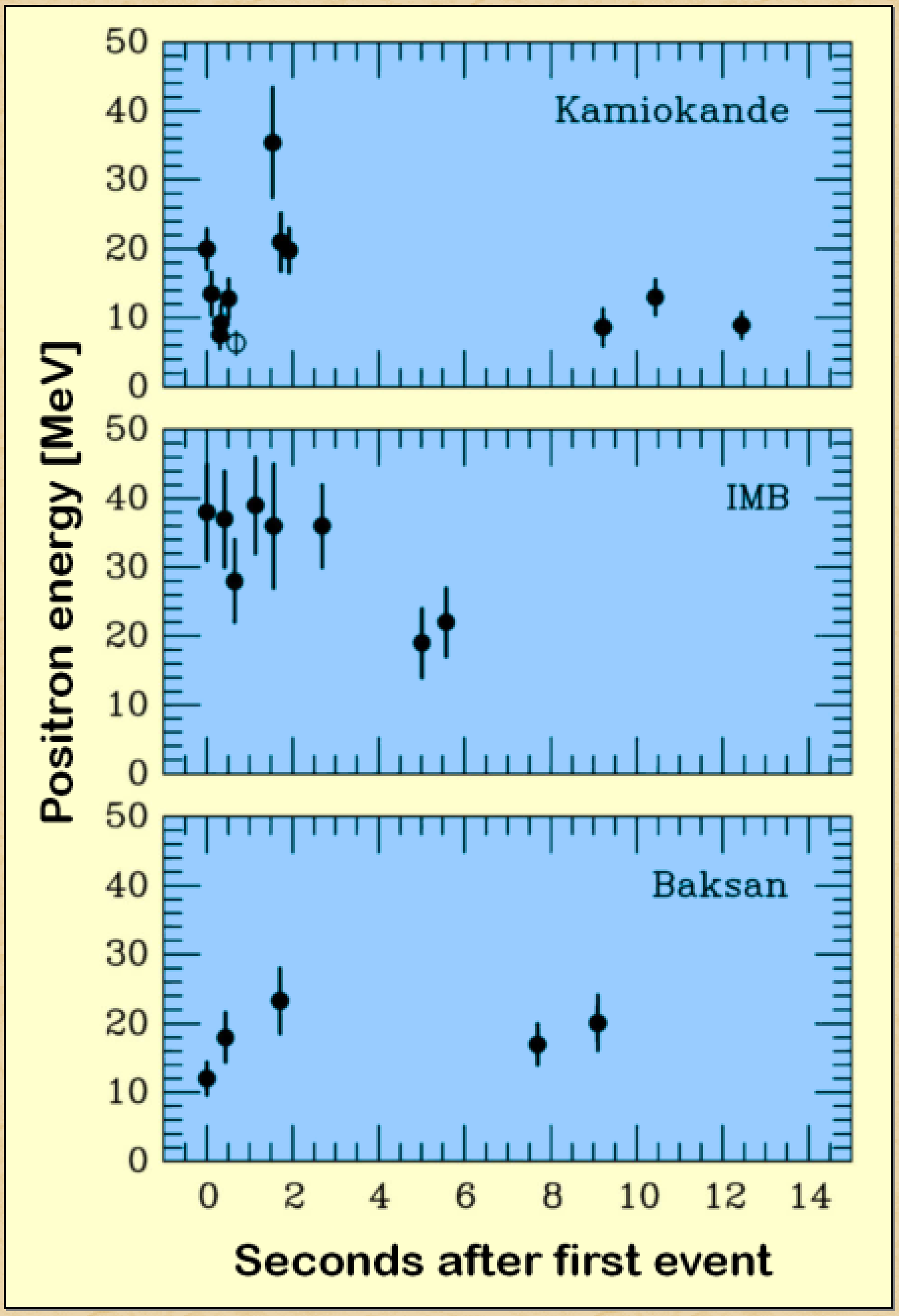
Neutrino luminosity

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

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

While it lasts, outshines the entire visible universe

Neutrino Signal of Supernova 1987A



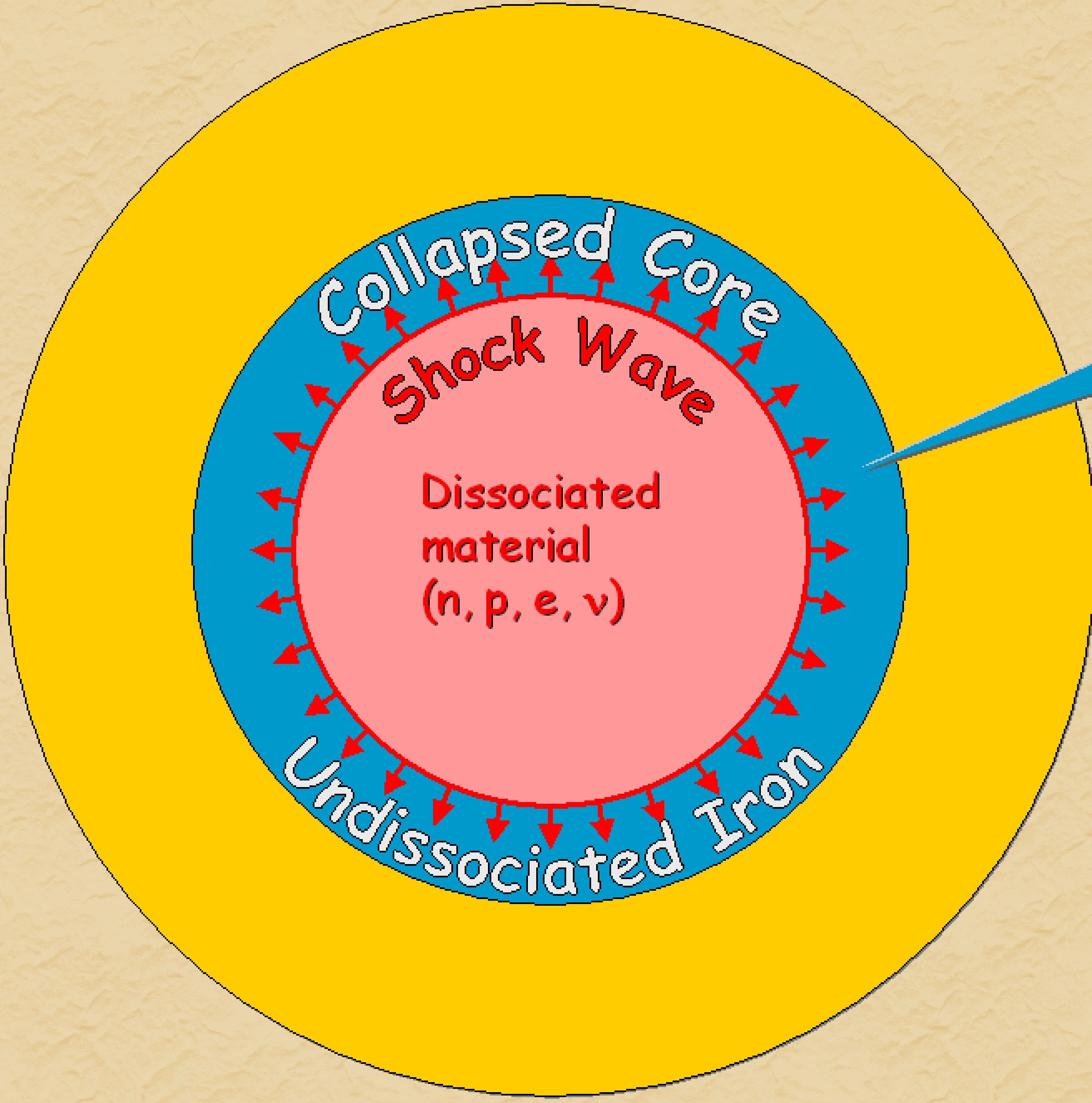
Kamiokande (Japan)
Water Cherenkov detector
Clock uncertainty ±1 min

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

Baksan Scintillator Telescope
(Soviet Union)
Clock uncertainty +2/-54 s

Within clock uncertainties, signals are contemporaneous

Why No Prompt Explosion?

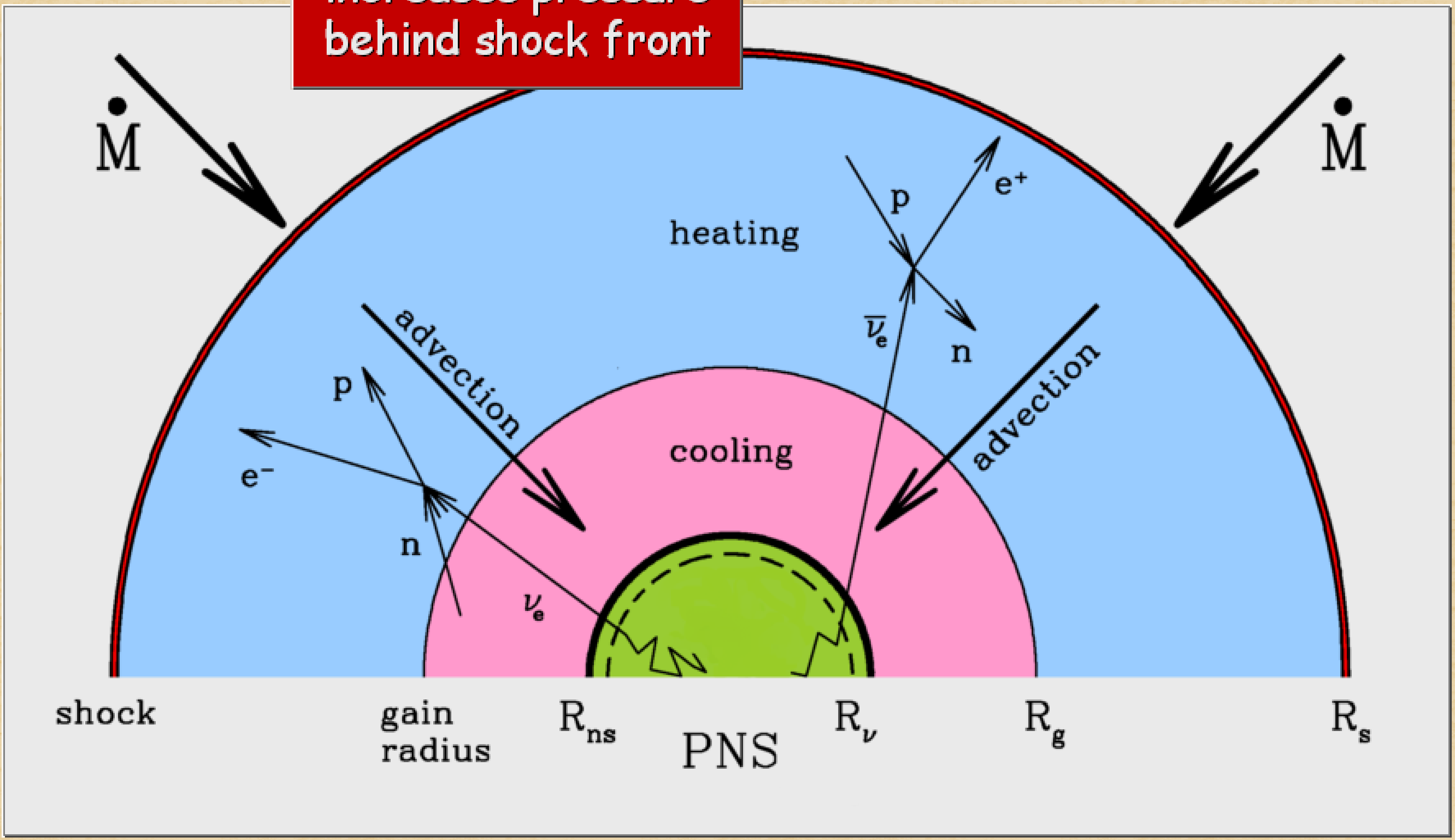


- 0.1 M_{sun} Fe has nuclear binding energy $\approx 1.7 \times 10^{51}$ erg
- Comparable to explosion energy

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

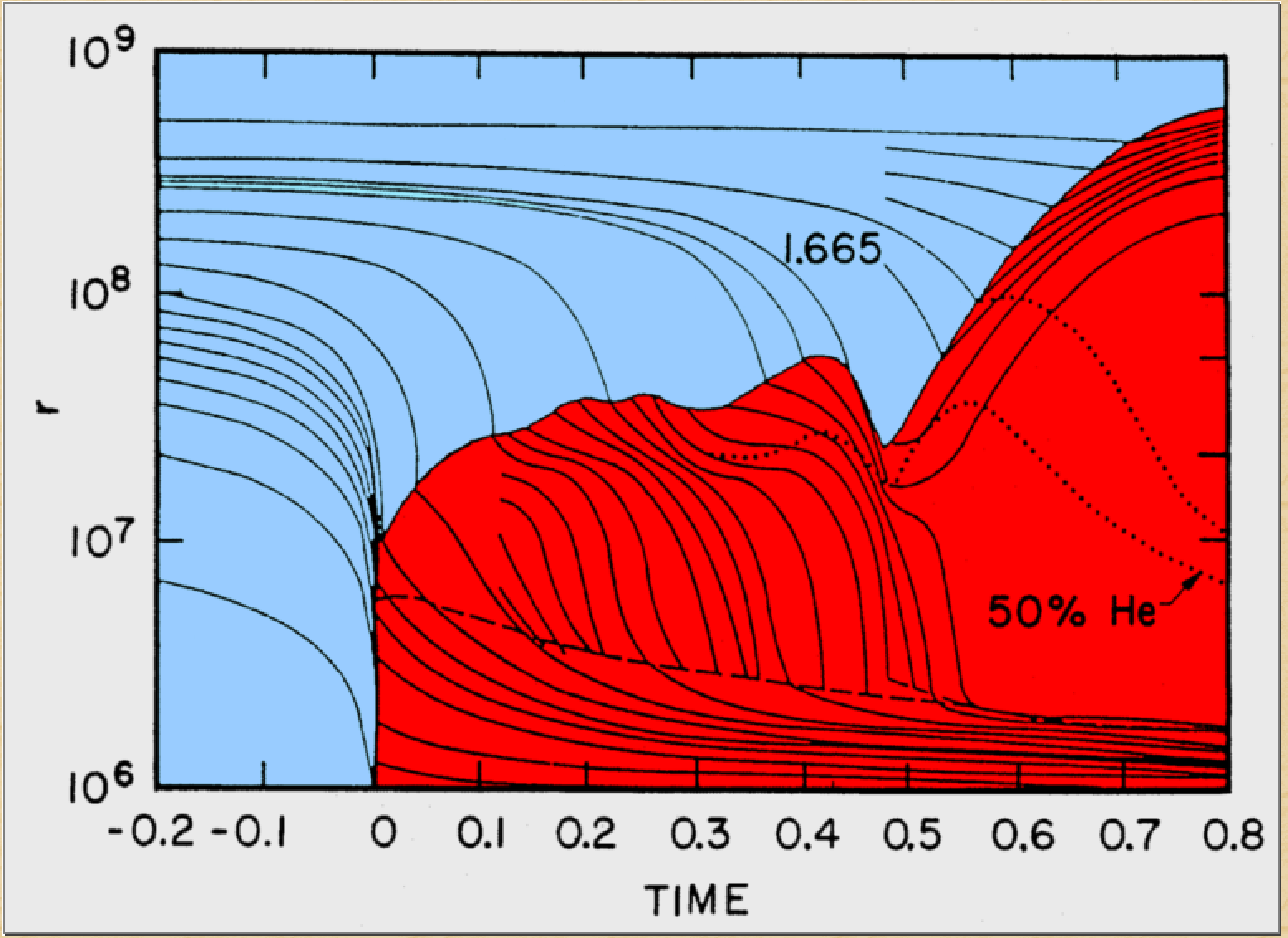
Neutrinos to the Rescue

Neutrino heating increases pressure behind shock front



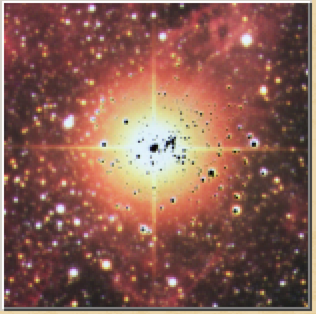
Picture adapted from Janka, astro-ph/0008432

Revival of a Stalled Supernova Shock by Neutrino Heating

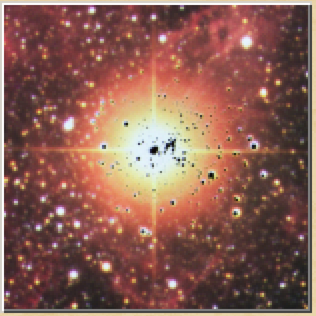


Wilson, Proc. Univ. Illinois Meeting on Numerical Astrophysics (1982)
Bethe & Wilson, ApJ 295 (1985) 14

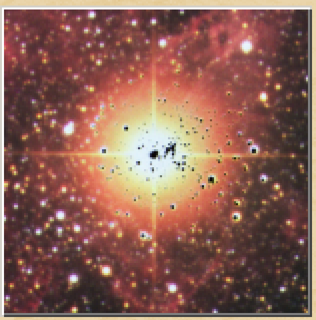
Theoretical Status of Supernova Explosions



- Spherically symmetric models do not explode, even with state-of-the-art Boltzmann solvers for neutrino transport
- Delayed explosion scenario requires enhanced neutrino luminosity at early times (~ factor 2)



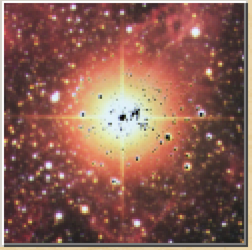
- Convection between proto neutron star (PNS) and shock wave and perhaps within PNS helps
- But 2-D simulations self-consistently coupled with state-of-the-art neutrino transport do not explode either



- New physical ingredients required?
- Explosion a magneto-hydrodynamical effect? (Strong B-fields and fast rotation possible)
- Nuclear equation of state very different?

Buras, Rampp, Janka & Kifonidis (MPA Garching),
Improved Models of Stellar Core Collapse and Still no Explosions:
What is Missing?
[astro-ph/0303171, to be published in Phys. Rev. Letters]

Supernovae as Multiflavor Neutrino Sources



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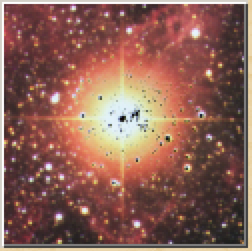
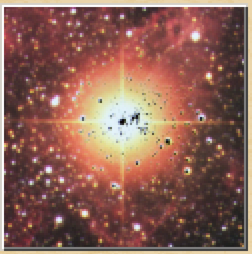
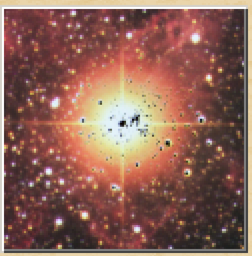


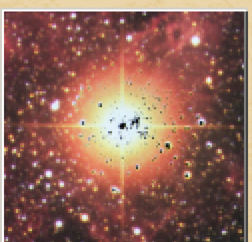
Supernova neutrino detection



Flavor-dependent fluxes and spectra

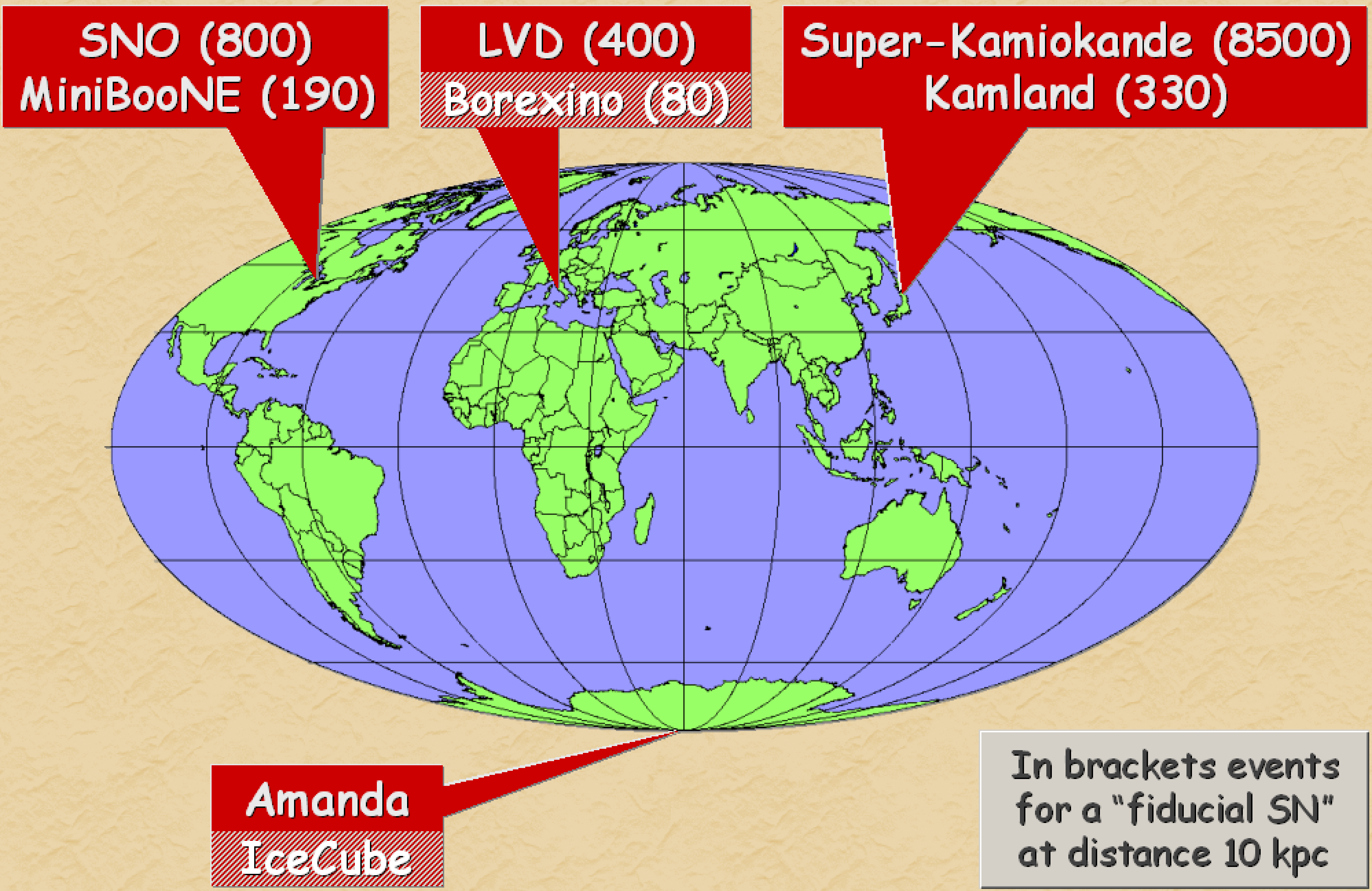


Earth effect in SN neutrinos
and normal vs. inverted mass hierarchy



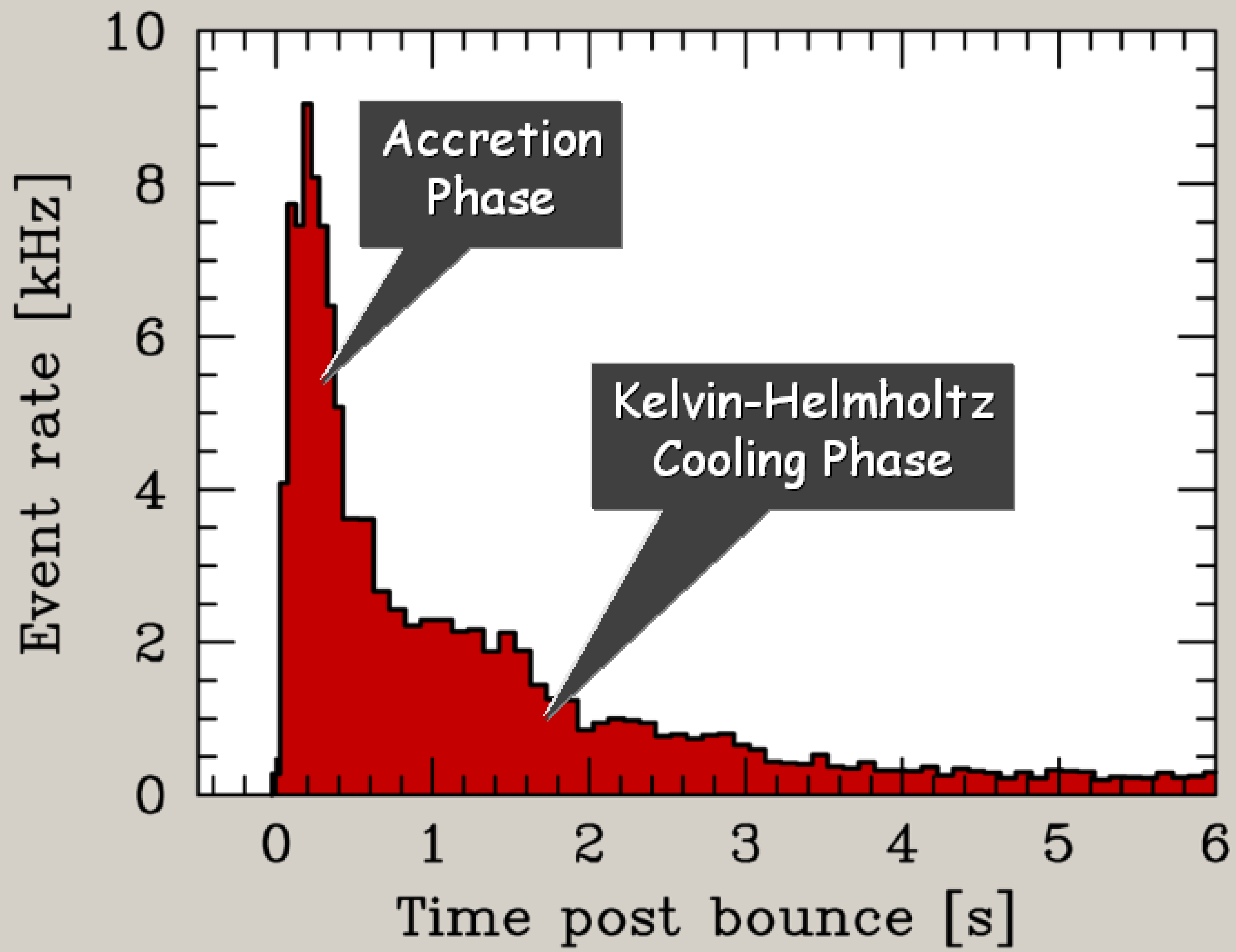
Diffuse flux from all cosmic supernovae

Large Detectors for SN Neutrinos



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

Simulated Supernova Signal at Super-Kamiokande

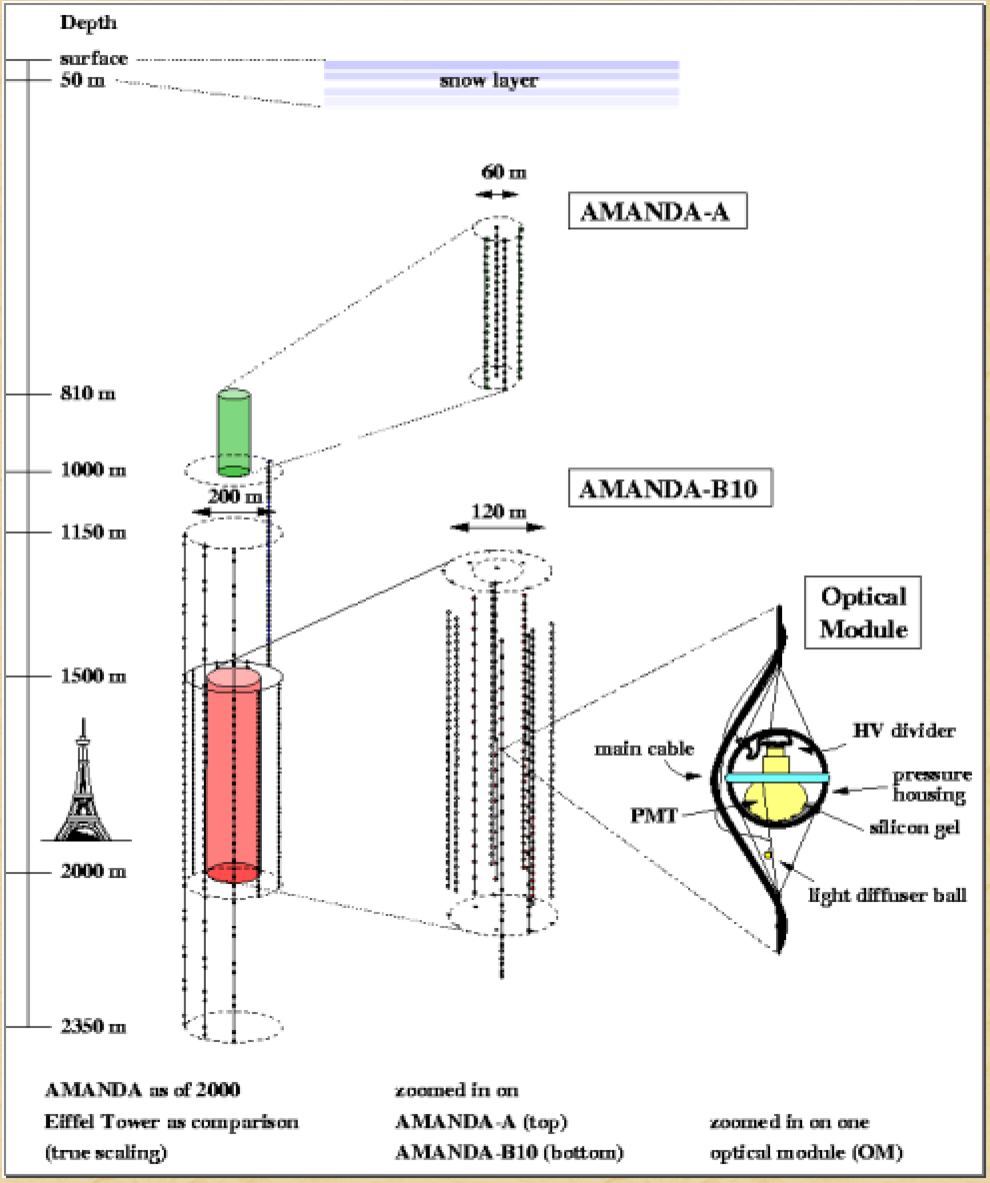


Simulation for Super-Kamiokande SN signal at 10 kpc, based on a numerical Livermore model

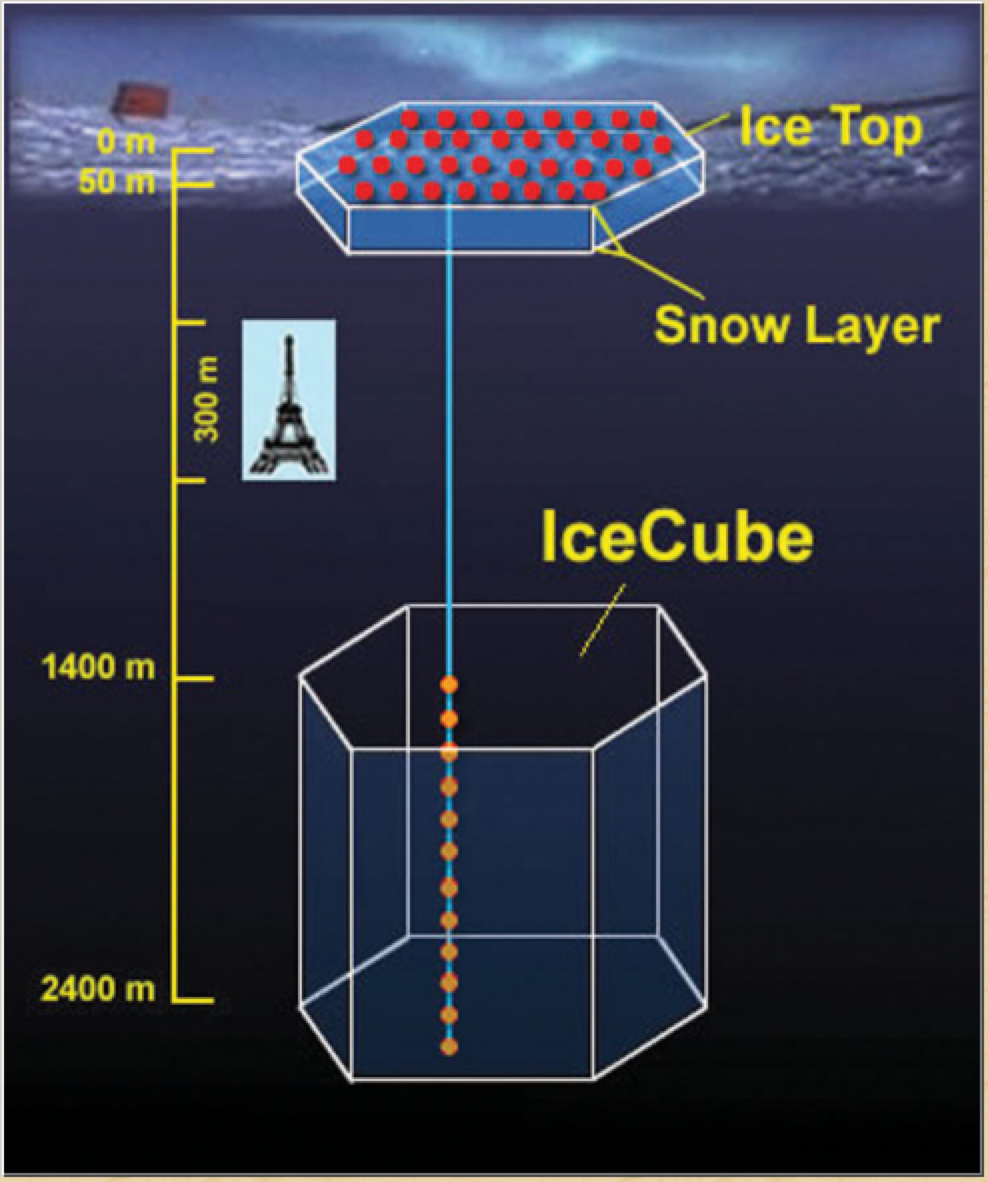
[Totani, Sato, Dalhed & Wilson, ApJ 496 (1998) 216]

Southpole Ice-Cherenkov Neutrino Detectors

AMANDA II (0.1 km^3, 800 PMTs)



Future IceCube (1 km^3, 4800 PMTs)

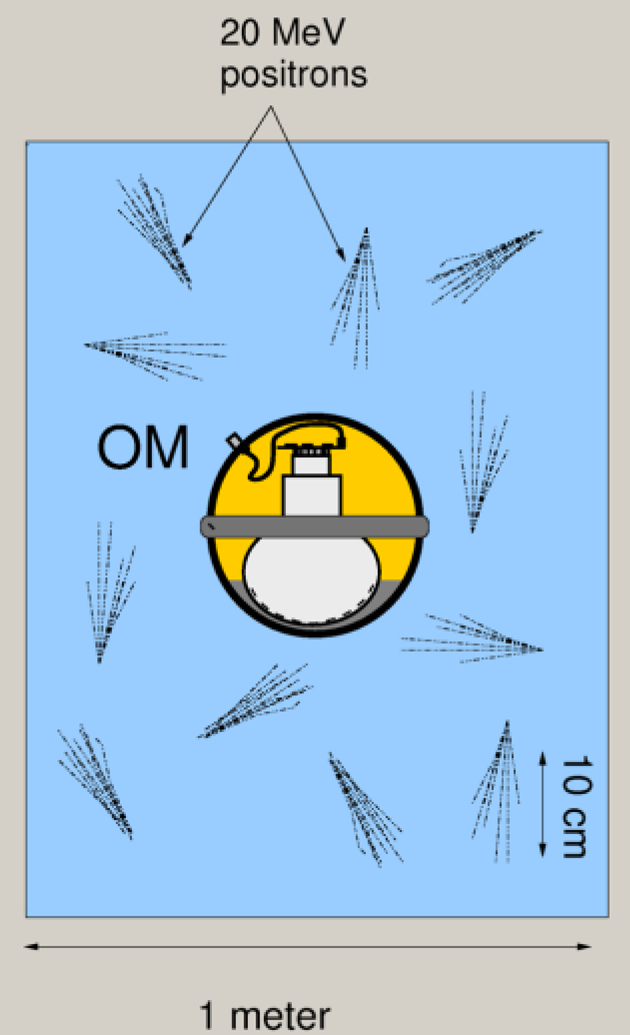


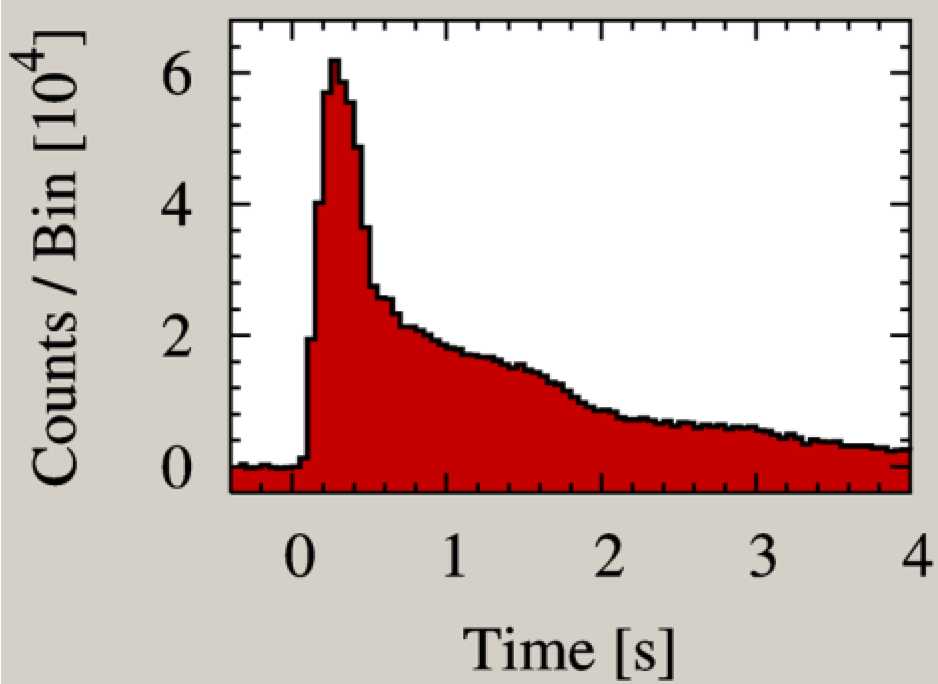
IceCube as a Supernova Neutrino Detector

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

~ 300 Cherenkov photons per OM from SN at 10 kpc

Noise per OM < 500 Hz

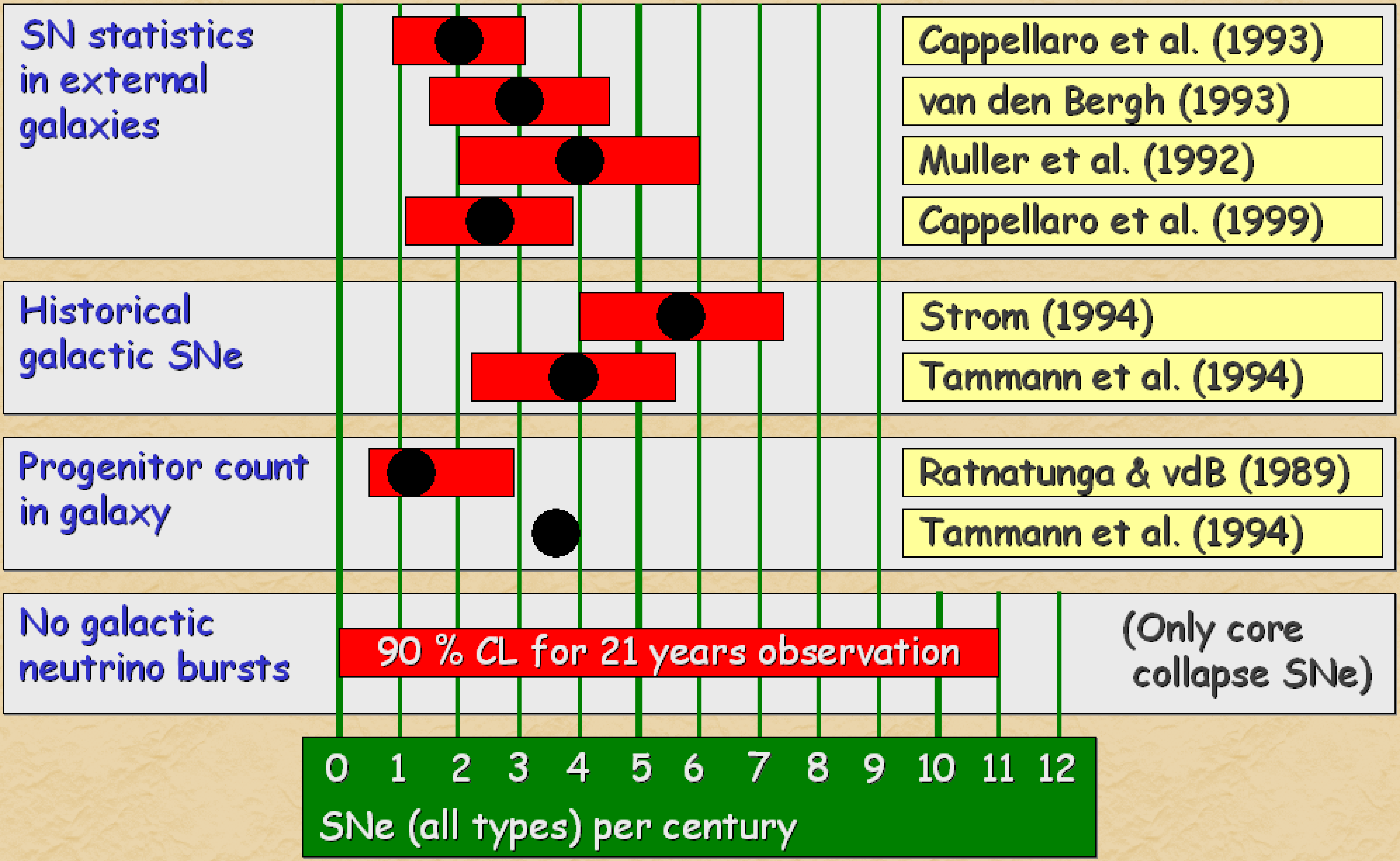




IceCube SN signal at 10 kpc, based on a numerical Livermore model

[Dighe, Keil & Raffelt, hep-ph/0303210]

Estimates of the Galactic SN Rate



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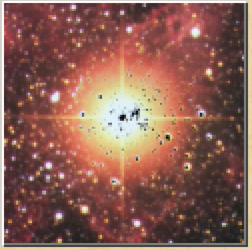

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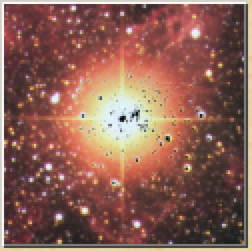

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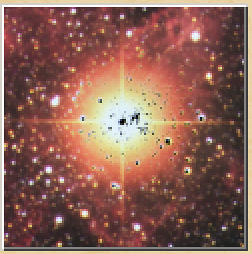
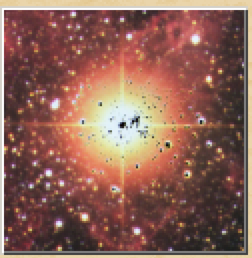


Flavor-dependent fluxes and spectra



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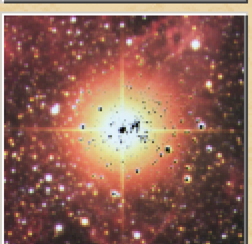
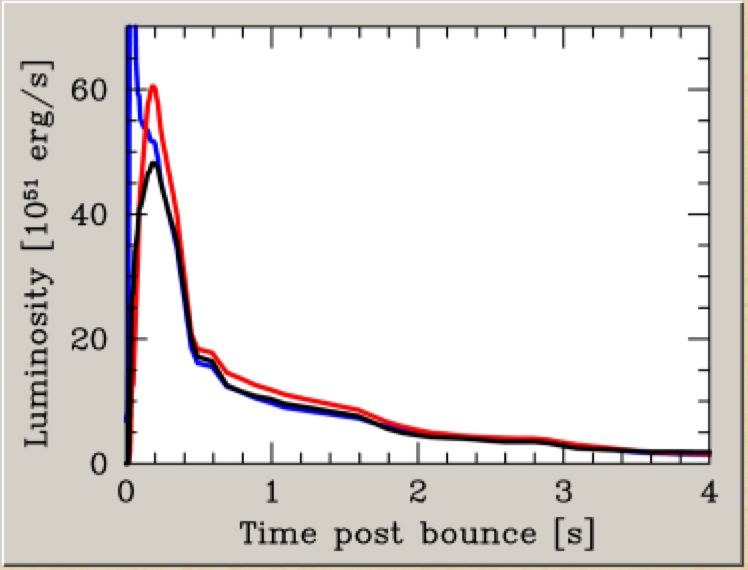
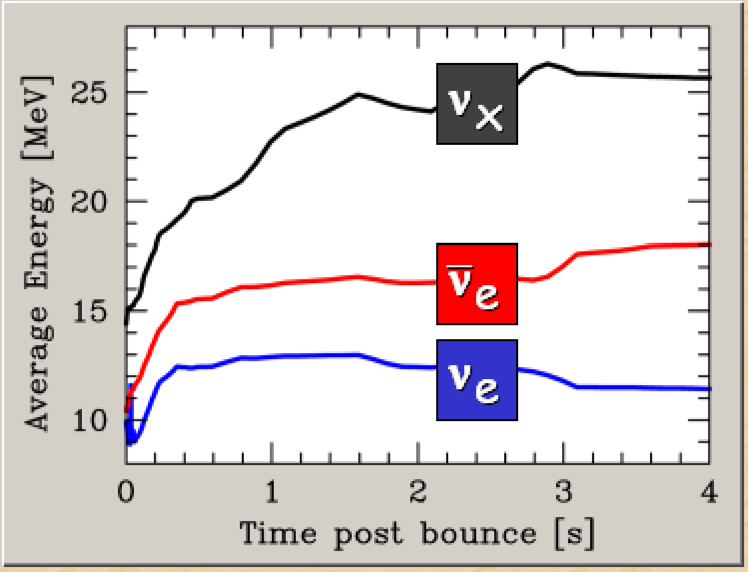


Diffuse flux from all cosmic supernovae

Flavor-Dependent Fluxes and Spectra

Livermore num. simulation
[ApJ 496 (1998) 216]





From these and similar studies the "standard" assumptions are

- Almost exact equipartition of energy among flavors
- Pronounced hierarchy of average energies

However, in traditional simulations the transport of ν_x (ν_μ and ν_τ) is rather schematic

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

Neutrino Spectra Formation

G.Raffelt
astro-ph/0105250

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

Thermal Equilibrium

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

$\nu_e\, n \leftrightarrow p\, e^-$

Free streaming

Neutrino sphere (T_{NS})

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

$\nu N \leftrightarrow N \nu$

$\nu e \leftrightarrow \nu e$

$N N \leftrightarrow N N \nu \bar{\nu}$

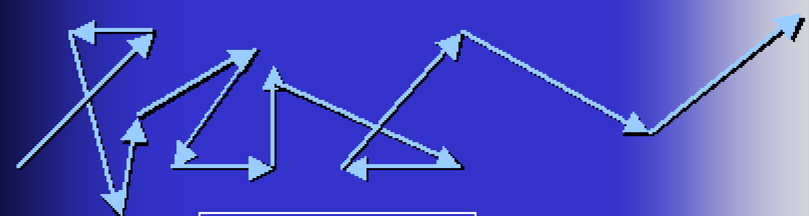
$e^+ e^- \leftrightarrow \nu \bar{\nu}$

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

Thermal Equilibrium

Scattering Atmosphere

$\nu N \leftrightarrow N \nu$



Diffusion

Free streaming

Energy sphere (T_{ES})

Transport sphere

Neutrino Spectra Formation

G.Raffelt
astro-ph/0105250

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

$\nu N \leftrightarrow N \nu$

$\nu e \leftrightarrow \nu e$

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

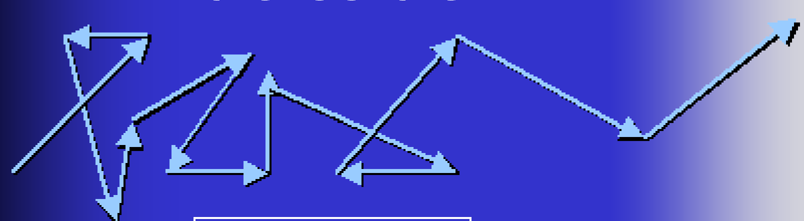
$e^+ e^- \leftrightarrow \nu \bar{\nu}$

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

Thermal Equilibrium

Scattering Atmosphere

$\nu N \leftrightarrow N \nu$



Diffusion

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

Energy sphere (T_{ES})

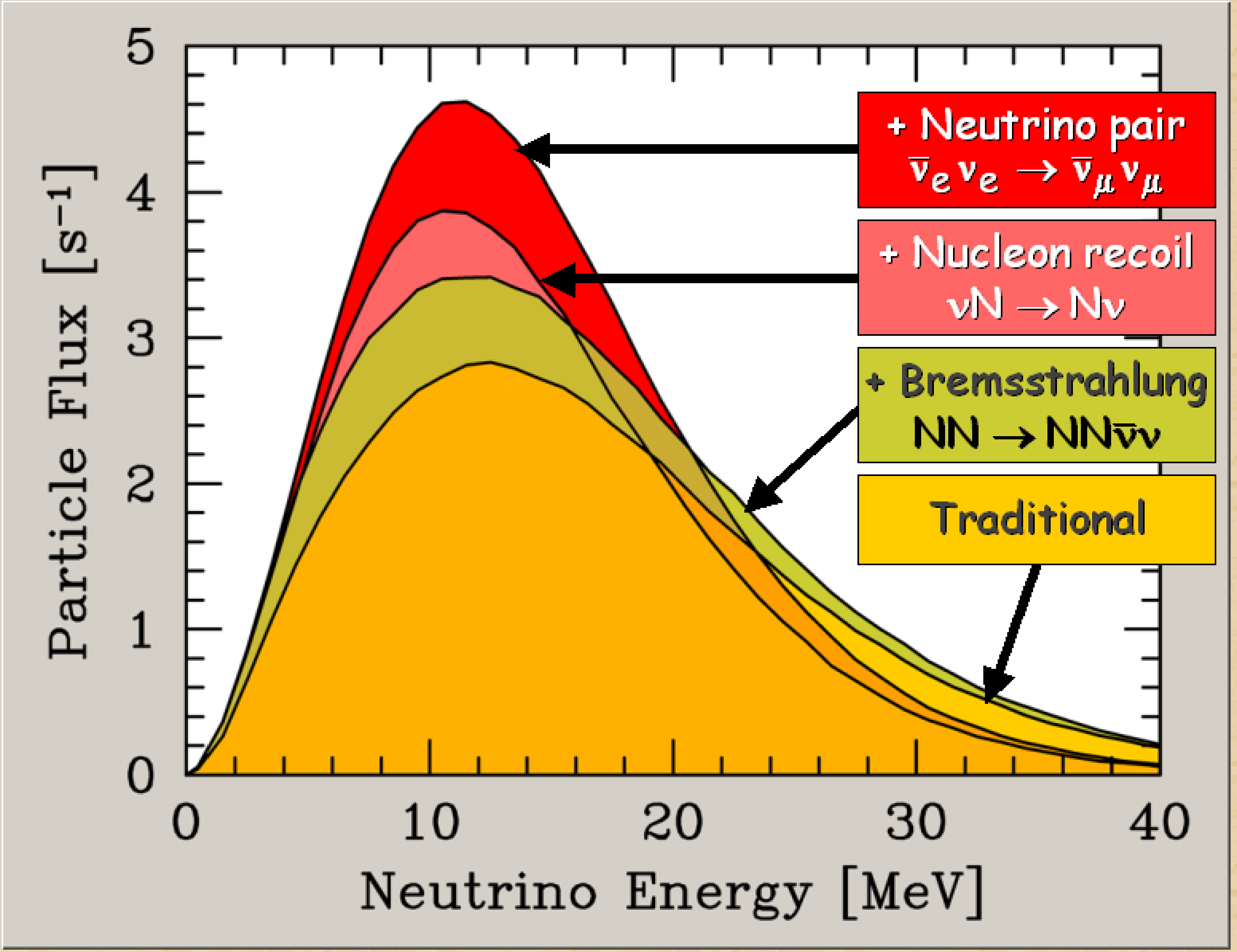
Transport sphere

Microphysics for Mu- and Tau-Neutrino Transport

	Traditional treatment	Dominant processes
Main opacity	$\nu + N \to N + \nu$	$\nu + N \to N + \nu$
Energy exchange	$\nu + e \to e + \nu$	$\nu + e \to e + \nu$ Recoil $\nu + N \to N + \nu$ [2,6,7]
Pair production	$e^+ + e^- \to \bar{\nu} + \nu$	$N + N \to N + N + \bar{\nu} + \nu$ [1-4] $\bar{\nu}_e + \nu_e \to \bar{\nu} + \nu$ [6,7]

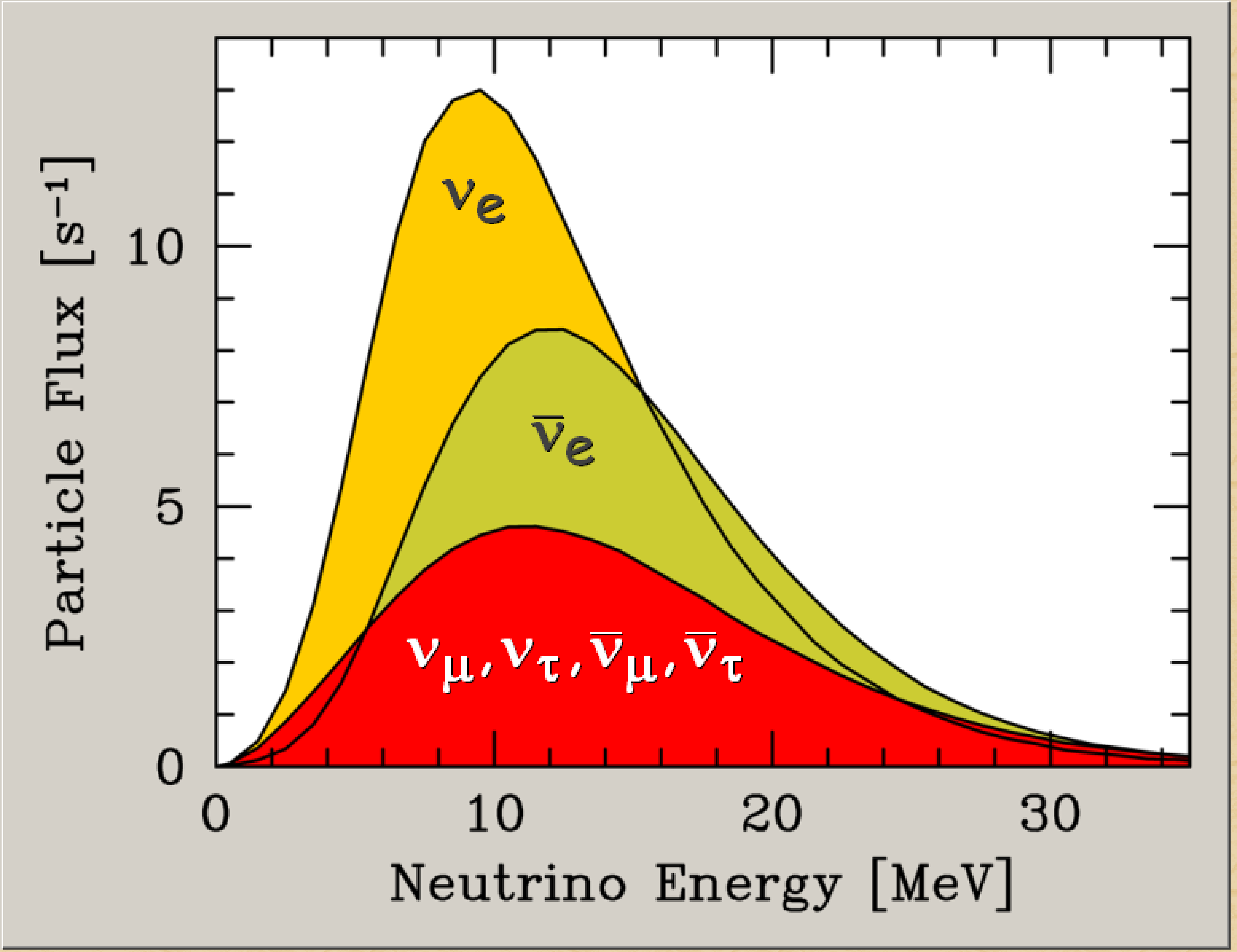
[1] Suzuki, Num. Astrophys. Japan 2 (1991) 267
[2] Janka, W.Keil, Raffelt & Seckel, PRL 76 (1996) 2621 [astro-ph/9507023]
[3] Hannestad & Raffelt, ApJ 507 (1998) 339 [astro-ph/9711132]
[4] Thompson, Burrows & Horvath, PRC 62 (2000) 035802 [astro-ph/0003054]
[6] Raffelt, ApJ 561 (2001) 890 [astro-ph/0105250]
[6] Buras, Janka, M.Keil, Raffelt & Rampp, ApJ (2003) [astro-ph/0205006]
[7] M.Keil, Raffelt & Janka, ApJ submitted (2003) [astro-ph/0208035]

Flux and Spectra Modification by New Processes



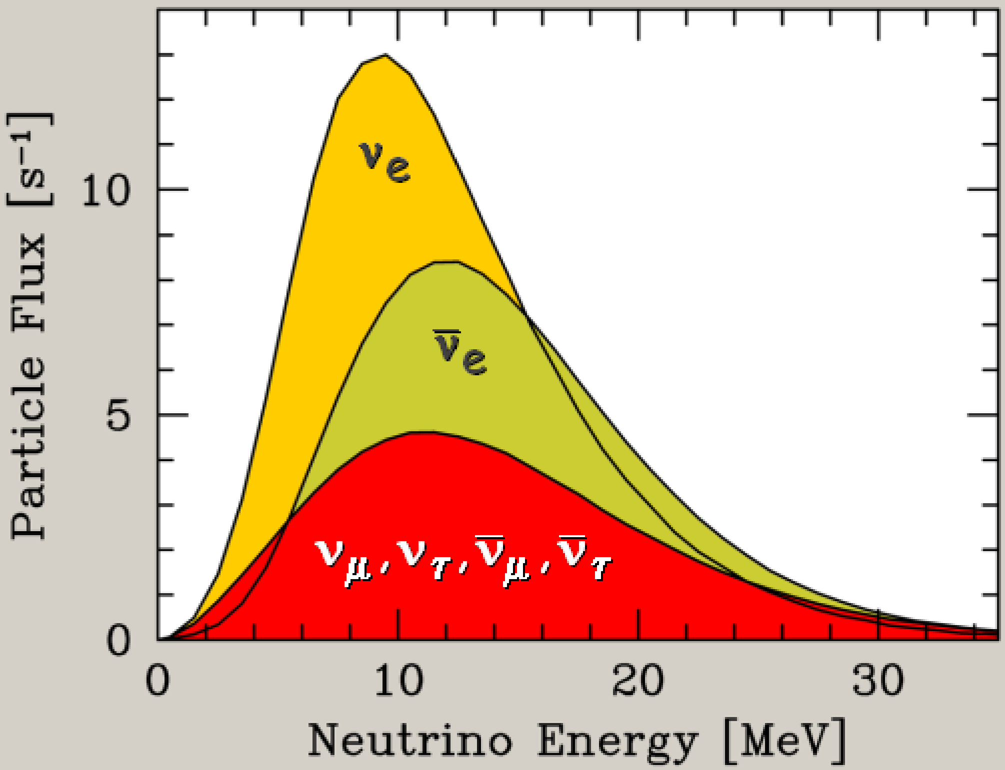
Keil, Raffelt & Janka, ApJ (2003) [astro-ph/0208035]

Flavor-Dependent Fluxes in an Accretion-Phase Model



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

What Are The Spectral Flux Characteristics?



The spectra are crudely thermal, but how to characterize in detail?

Commonly used global parameters

- Total luminosity L_ν
- Average energy $\langle E \rangle$
- General energy moments $\langle E^n \rangle$
- "RMS energy" $E_{rms} = \sqrt{\frac{\langle E^3 \rangle}{\langle E \rangle}}$

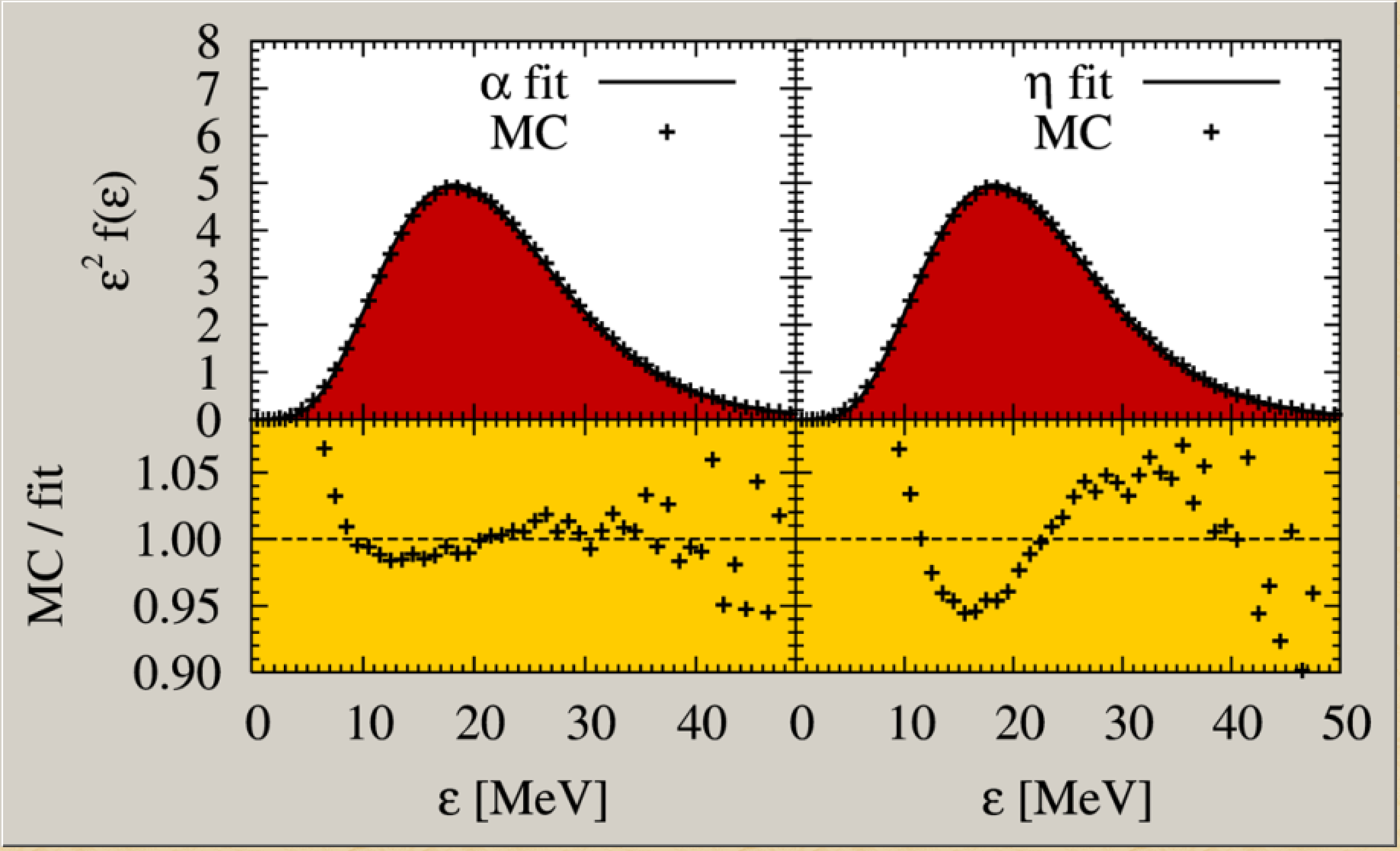
Two-parameter fits (Normalization is third parameter)	Thermal spectrum, i.e. Fermi-Dirac shape (η fit)	$F(E) \propto \frac{E^2}{1+e^{-\eta+E/T}}$
	Quasi power law (α fit)	$F(E) \propto E^\alpha \exp\left[-(\alpha+1)\frac{E}{\bar{E}}\right]$

How Good are the Two-Parameter Global Fits?

$$F(E) \propto E^{\alpha} \exp\left[-(\alpha+1)\frac{E}{\overline{E}}\right]$$

$$F(E) \propto \frac{E^2}{1+e^{-\eta+E/T}}$$

Keil, Raffelt & Janka, astro-ph/0208035



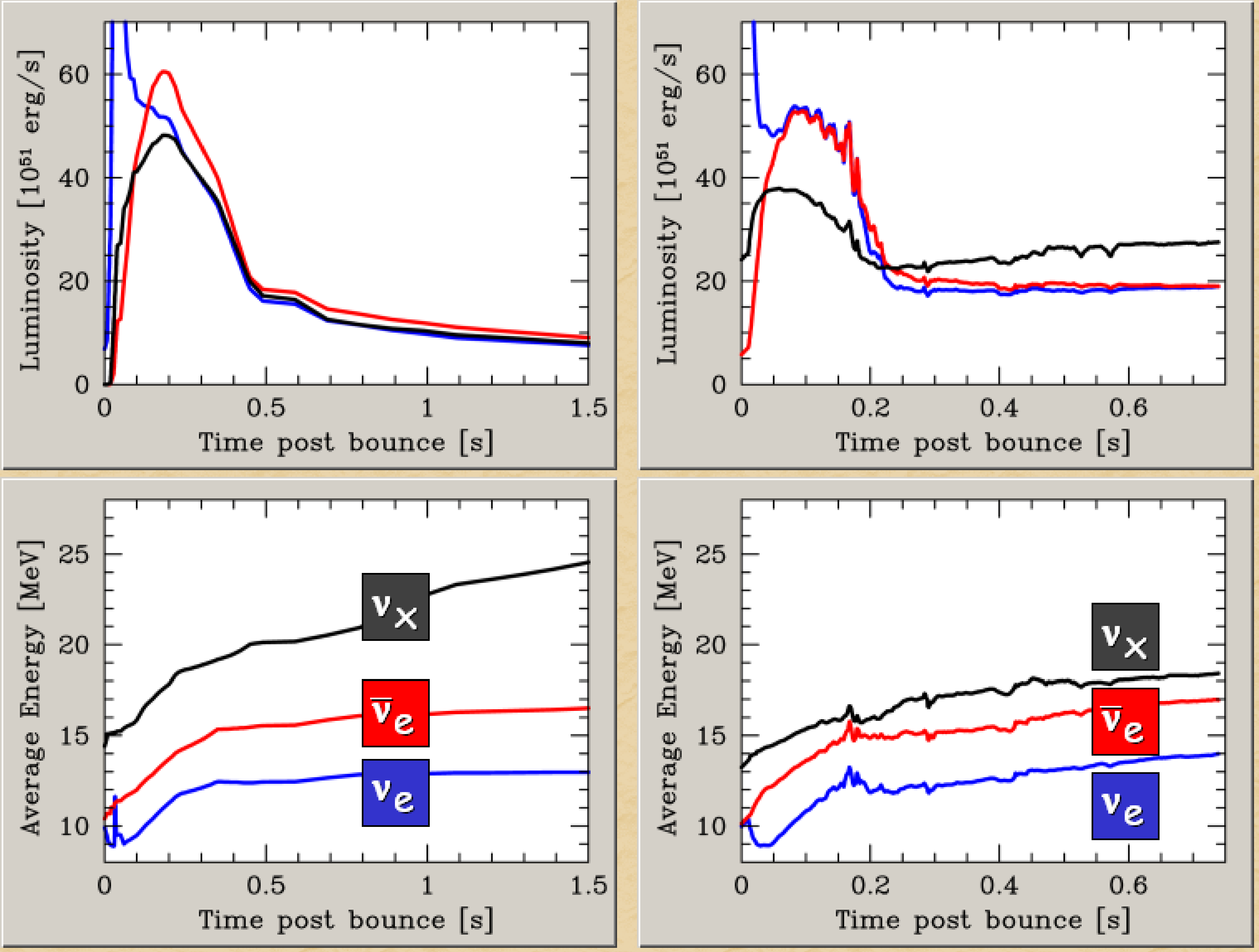
Monte Carlo Study of Fluxes and Spectra

Model	Luminosities			⟨E⟩			Alpha			Eta		
	ν_e	$\bar\nu_e$	ν_x	ν_e	$\bar\nu_e$	ν_x	ν_e	$\bar\nu_e$	ν_x	ν_e	$\bar\nu_e$	ν_x
Accretion I	1.01	1	0.56	0.84	1	1.02	2.9	3.8	2.7	1.4	2.7	1.2
Accretion II	1.01	1	0.38	0.84	1	1.02	3.4	4.2	2.5	2.1	3.2	0.8
Power Law I	0.66	1	0.63	0.76	1	1.14	3.7	4.5	3.3	2.7	3.7	2.2
Power Law II	2.09	1	1.99	0.75	1	1.14	3.7	4.1	3.0	2.9	3.1	1.5

Accretion I	Self-consistent accretion-phase model from Oakridge group
Accretion II	Self-consistent accretion-phase model from Garching group
Power Law I	Power law: $\rho \propto r^{-5}$, $T \propto r^{-1}$, $Y_e = 0.3$
Power Law II	Power law: $\rho \propto r^{-10}$, $T \propto r^{-2}$, $Y_e = 0.2$

Fluxes and Spectra from Numerical Simulations

Livermore (traditional) [ApJ 496 (1998) 216]	Garching (new microphyiscs) [astro-ph/0303226]



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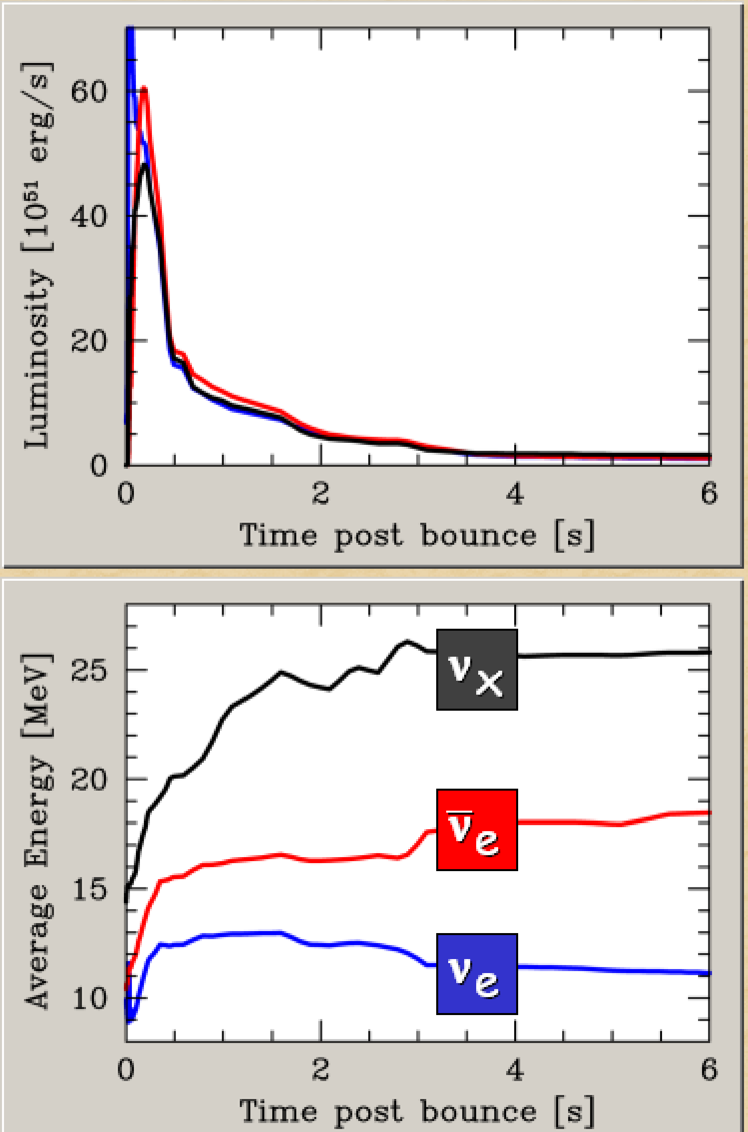

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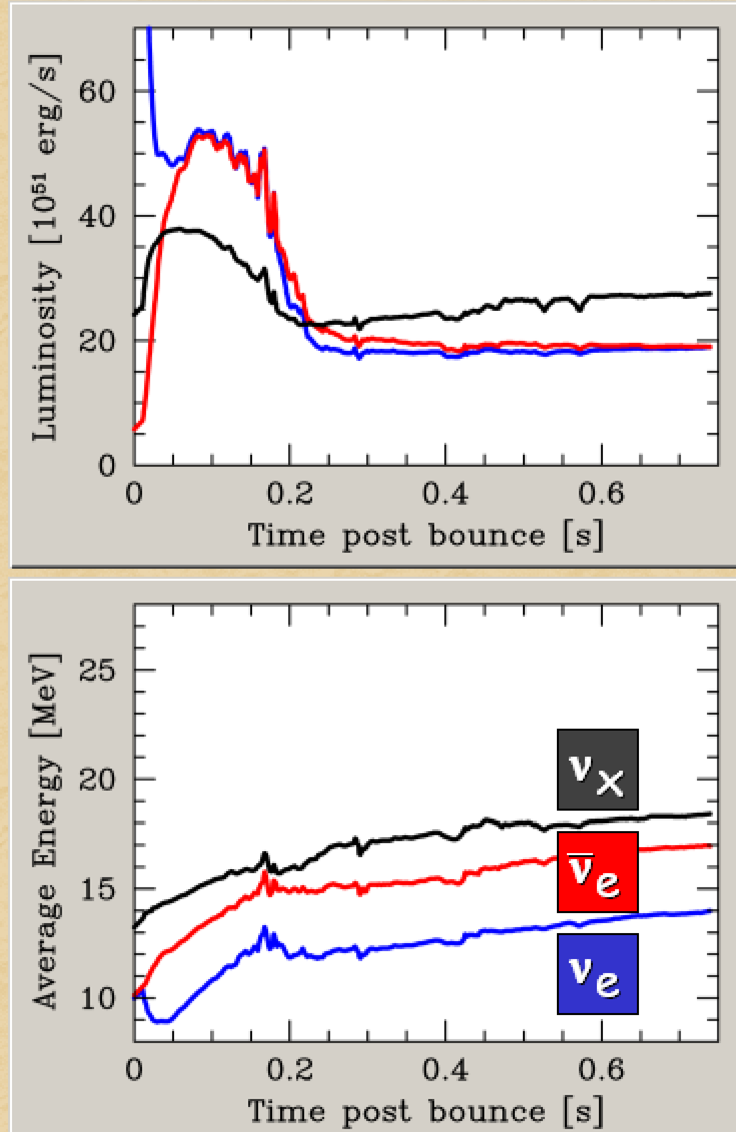

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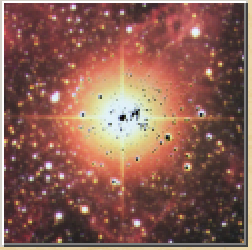

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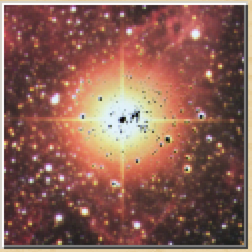

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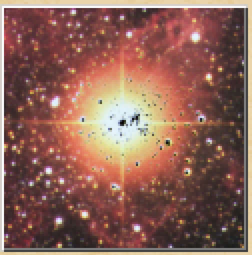

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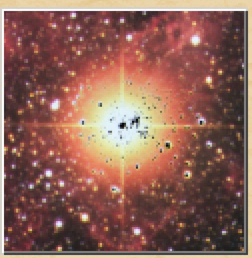
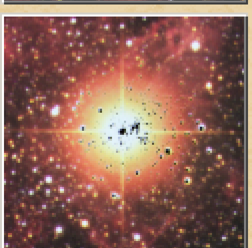


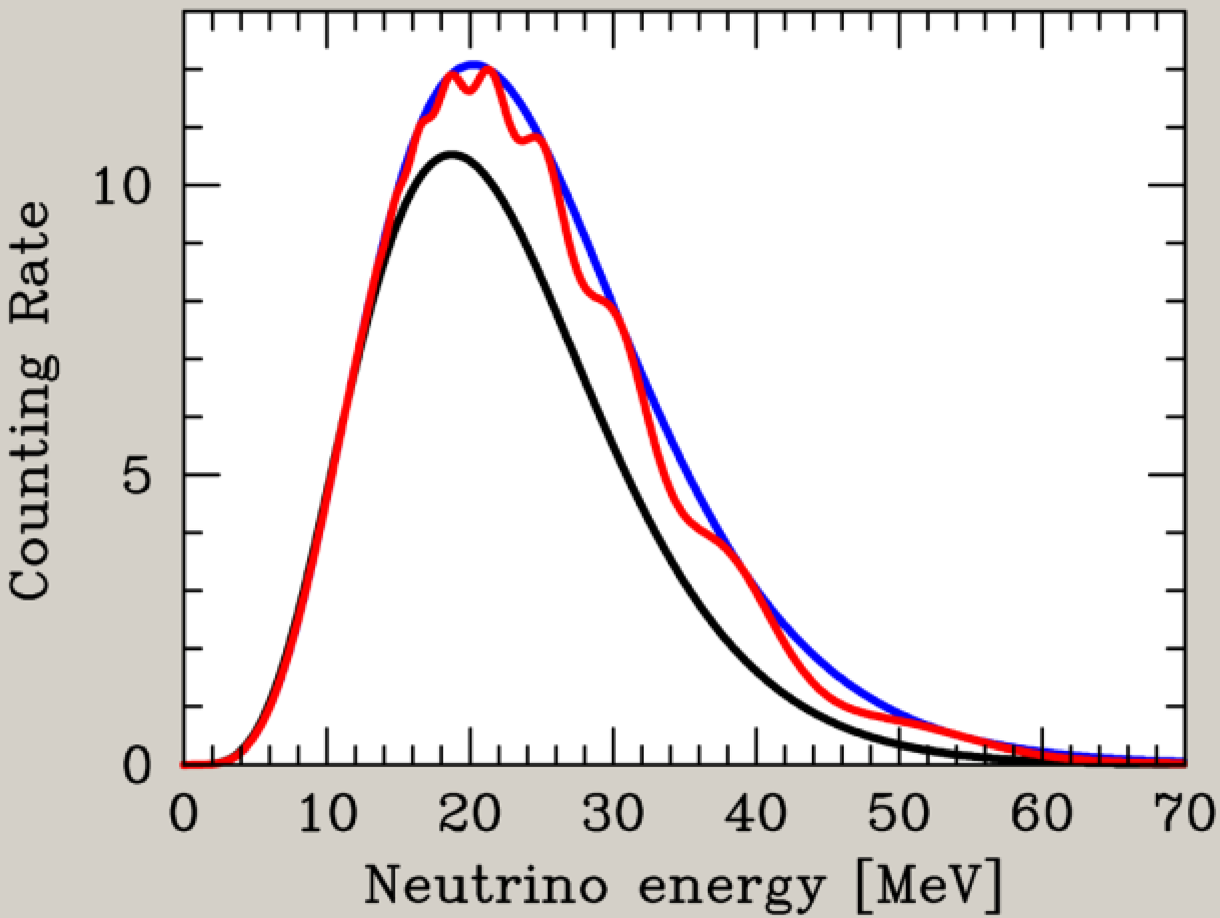
Earth effect in SN neutrinos
and normal vs. inverted mass hierarchy



Diffuse flux from all cosmic supernovae

Oscillation of Supernova Anti-Neutrinos

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



Assumed flux parameters:

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

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

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

Mixing parameters:

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

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

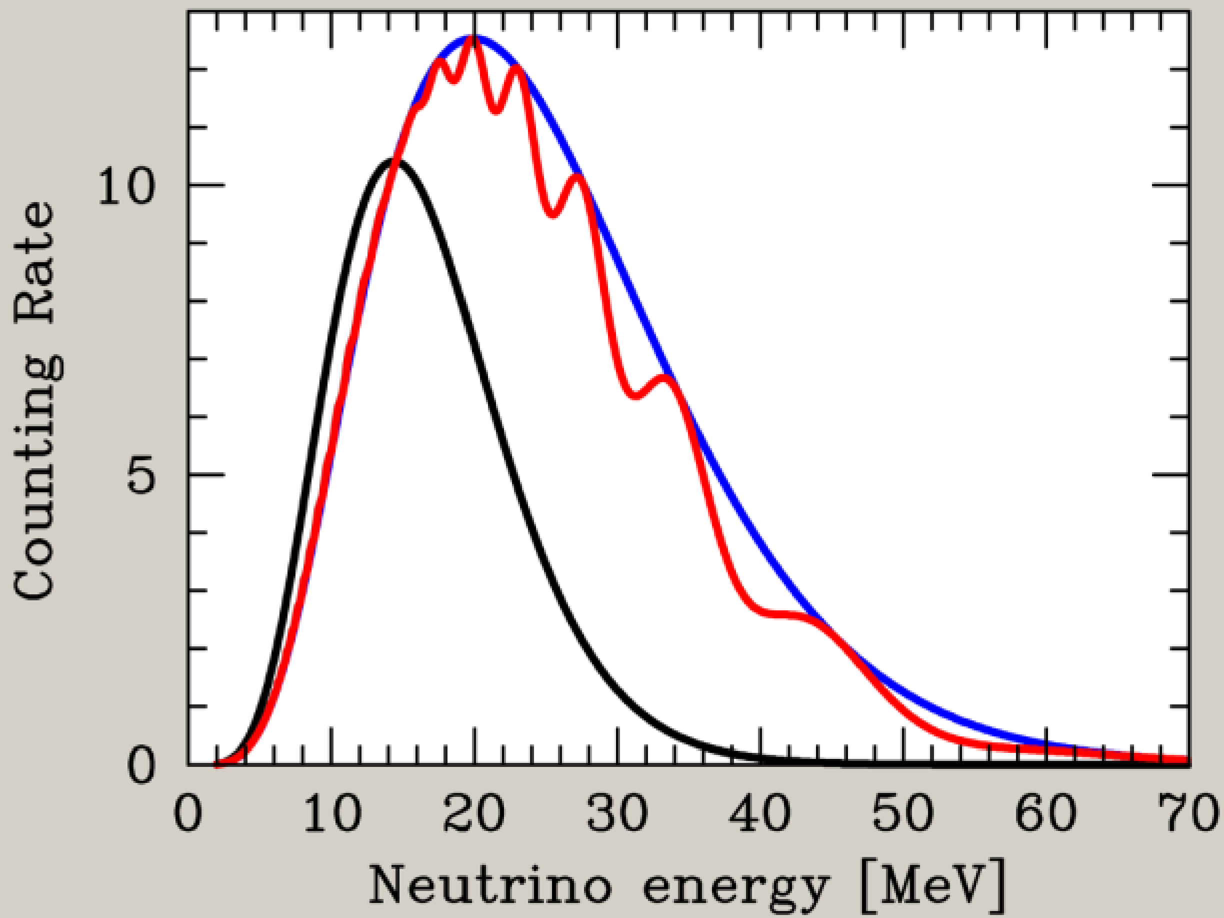
No oscillations

Oscillations in SN envelope

Earth effects included

Oscillation of Supernova Neutrinos

Measured ν_e spectrum at a detector like SNO, considering only CC reactions



Assumed flux parameters:

Flux ratio $\nu_e : \nu_x = 0.9 : 1$

$\langle E(\nu_e) \rangle = 12\,\mathrm{MeV}$

$\langle E(\nu_x) \rangle = 18\,\mathrm{MeV}$

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

Implications of Observing Earth Effects

	normal hierarchy	inverted hierarchy	
Supernova nus: Earth effects appear in channels	$\bar{\nu}_e$	ν_e	$\sin^2(\theta_{13}) > 10^{-3}$
	ν_e and $\bar{\nu}_e$	ν_e and $\bar{\nu}_e$	$\sin^2(\theta_{13}) < 10^{-3}$

One plausible scenario

$\sin^2(\theta_{13}) > 10^{-3}$ established e.g. by long-baseline reactor expt.	Earth effects observed in $\bar{\nu}_e$ channel ?	Yes: Normal hierarchy
		No: Inverted hierarchy or SN source spectra "anomalous"

Positively observing Earth effects in SN neutrinos gives us unique information about neutrino parameters

Not observing the effects in a SN signal is ambiguous: Can always be blamed on SN source spectra

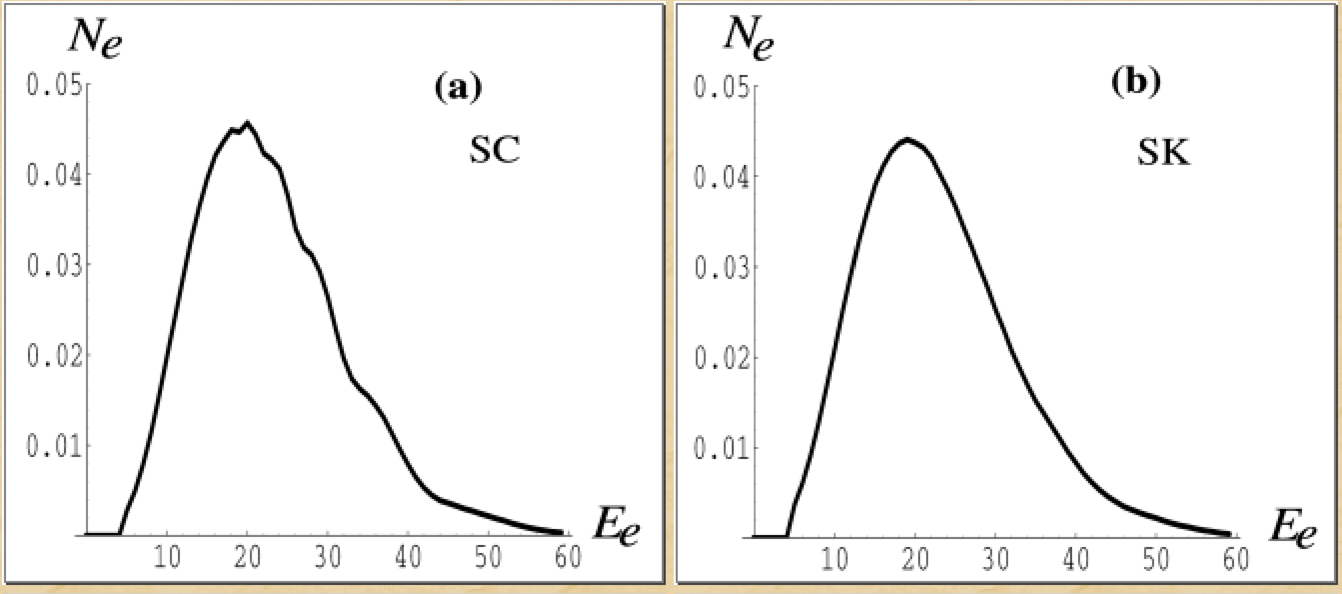
Robust Strategies for Observing Earth Effects

One detector observes SN shadowed by Earth

Another detector observes SN directly

Identify Earth effects by comparing signals

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

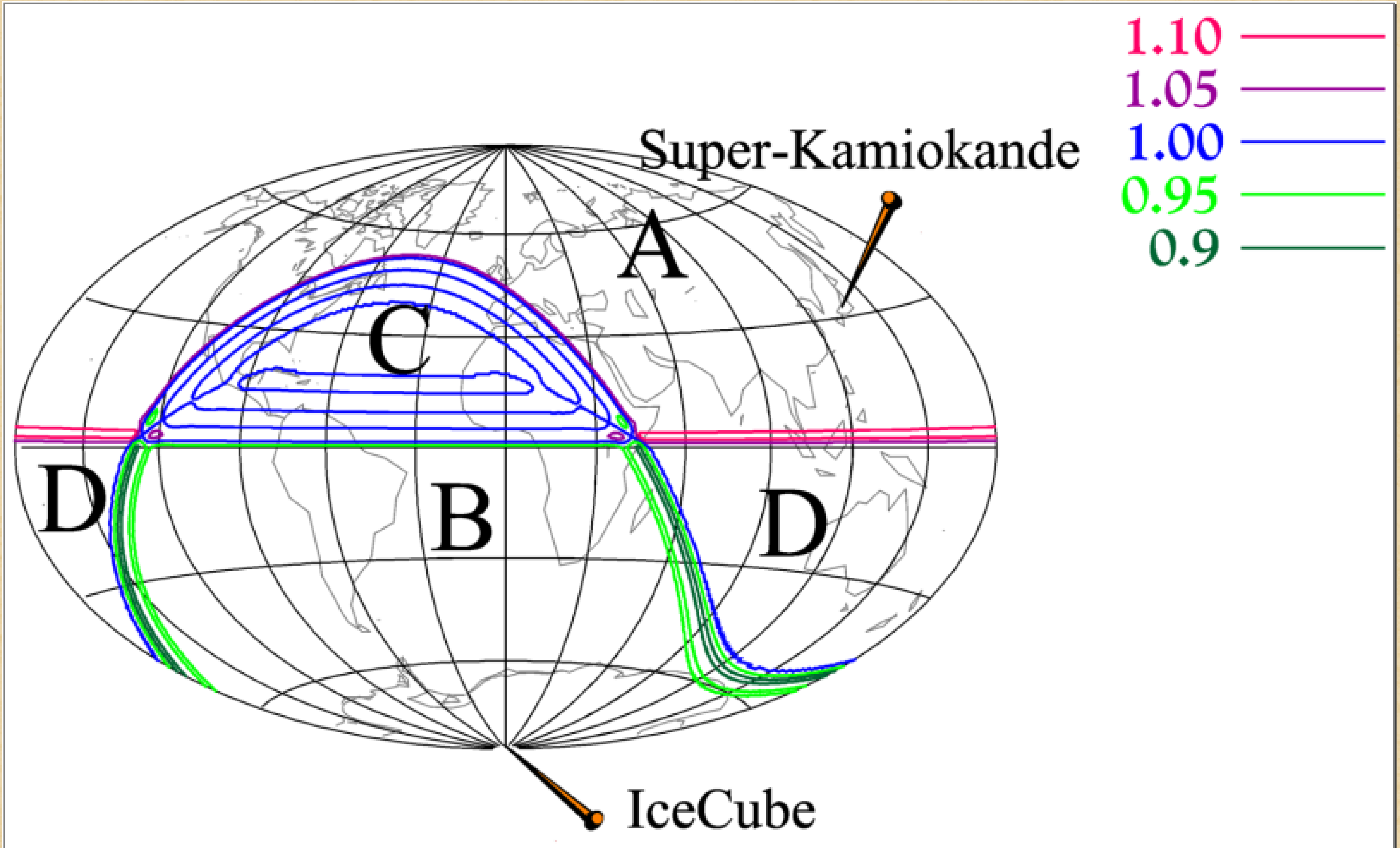


Scintillation detector
~ 2000 events
may be enough

Water Cherenkov:
Need Hyper-Kamiokande
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

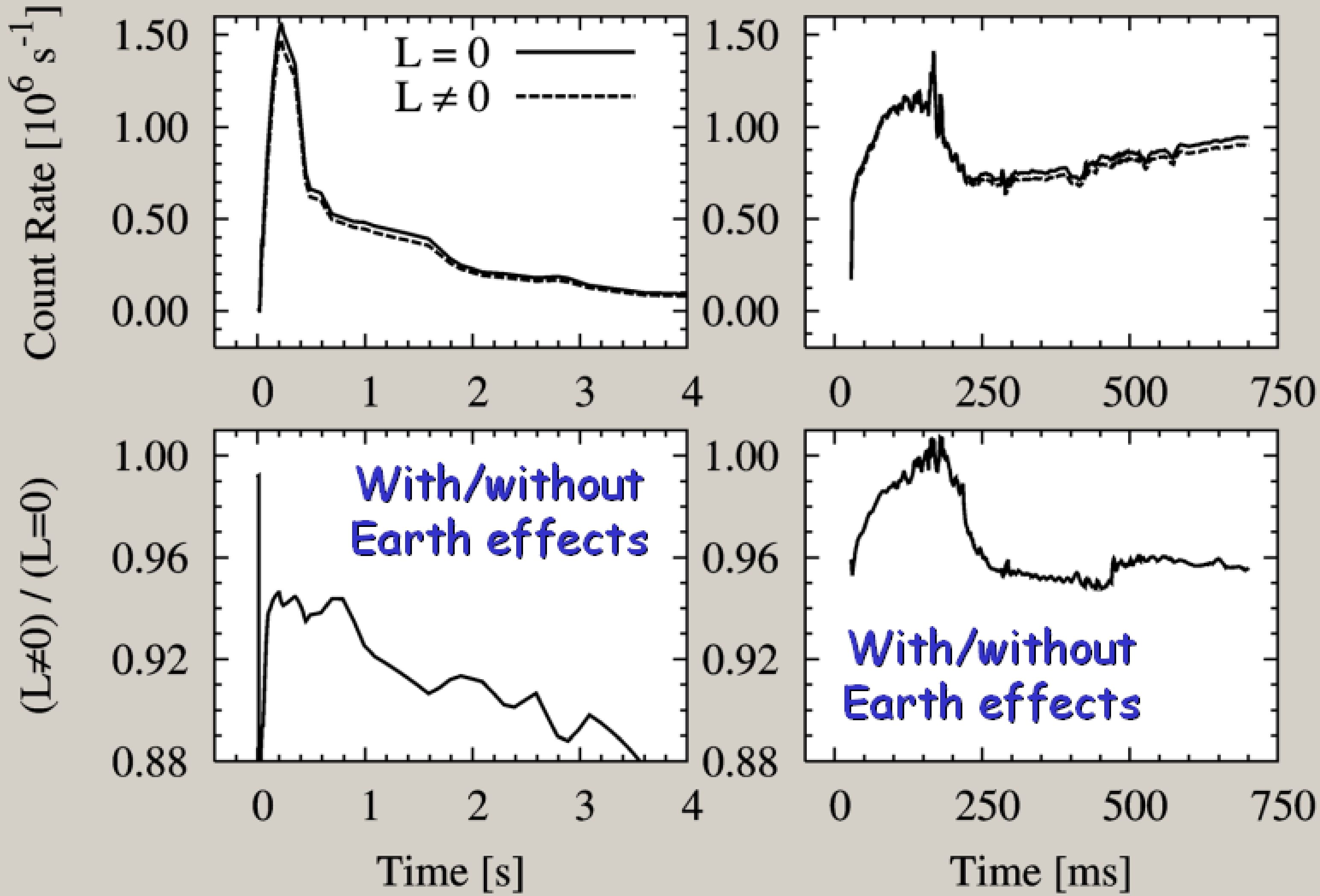


Dighe, Keil, Raffelt hep-ph/0303210

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%	

Observing the Earth Effects in IceCube

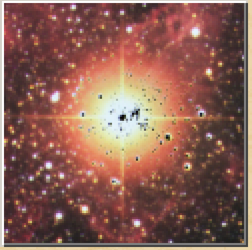
Livermore simulation | Garching simulation



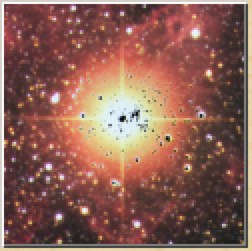
Dighe, Keil, Raffelt hep-ph/0303210

Statistical IceCube signal precision < 1%

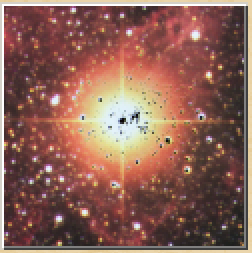
Supernovae as Multiflavor Neutrino Sources



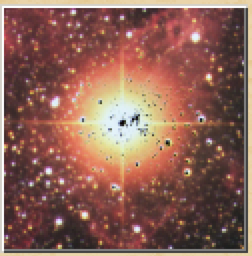
Physical mechanism
of core-collapse supernovae



Supernova neutrino detection



Flavor-dependent fluxes and spectra



Earth effect in SN neutrinos
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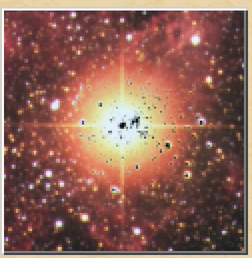
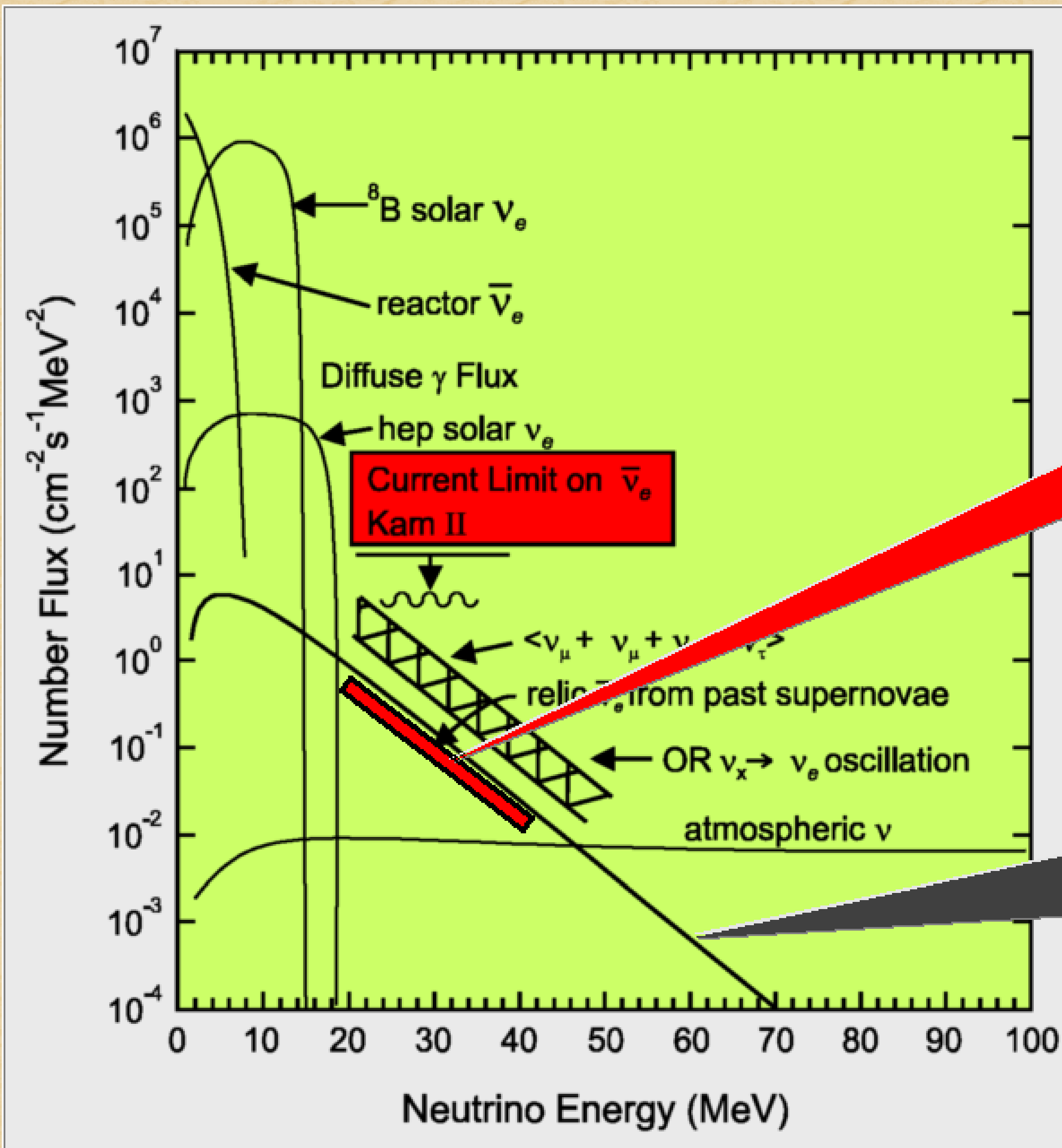


Diffuse flux from all cosmic supernovae

Experimental Limits on Relic SN Neutrinos



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

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

Cline, astro-ph/0103138

Improved Sensitivity with Neutron Tagging

M.Vagins, Talk at NOON 2003, http://www-sk.icrr.u-tokyo.ac.jp/noon2003/

Super-Kamiokande limited by
- Solar neutrinos for E_ν < 18-19 MeV
- Sub-Cherenkov muons from atm nus
  $\mu \to e + \nu_e + \bar{\nu}_\mu$

Solution:
Neutron tagging $\bar{\nu}_e + p \to e^+ + n$

Water: Neutron capture on protons
2.2 MeV gammas, invisible in SK

Add gadolinium to SK:
- Efficient neutron capture
- 8 MeV gamma cascade, easily visible
- 0.1 % (100 tons of Gd Cl_3) achieves > 90% tagging efficiency

SN relic nus: A few events per year in SK with no background at all

A Modest Proposal

Pouring a bunch of stuff into Super–K is a big step, and not to be done lightly, no matter how promising things may look initially.

Here's what comes next:

1) Spend the next year or so exploring the chemistry, stability, and optical properties of $GdCl_3$ in detail.
2) Understand any changes needed in the SK water system and Monte Carlo the modified detector's response using what's learned above as input.
3) Build a small test tank (one supermodule) with exactly the same materials as in SK. Put in PMT's, cables, water, and $GdCl_3$ and let it sit for two years. Check for $GdCl_3$-induced damage.
4) If everything looks good, in the last month(s) of SK–II put in 9 tons of $GdCl_3$ to make sure we really understand our backgrounds. Look for reactor antineutrinos!

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Onward, Ever Onward

Finally, if every test *still* looks good, mix 100 tons of $GdCl_3$ into SK–III and prepare for the bright new days of supernova and reactor neutrino data ahead!