NOON 2003, 10-14 Feb 2003, Ishikawa Kousei Nenkin Kaikan, Kanazawa, Japan

Supernova Neutrinos

Flavor-Dependent Fluxes and Spectra

Georg G. Raffelt

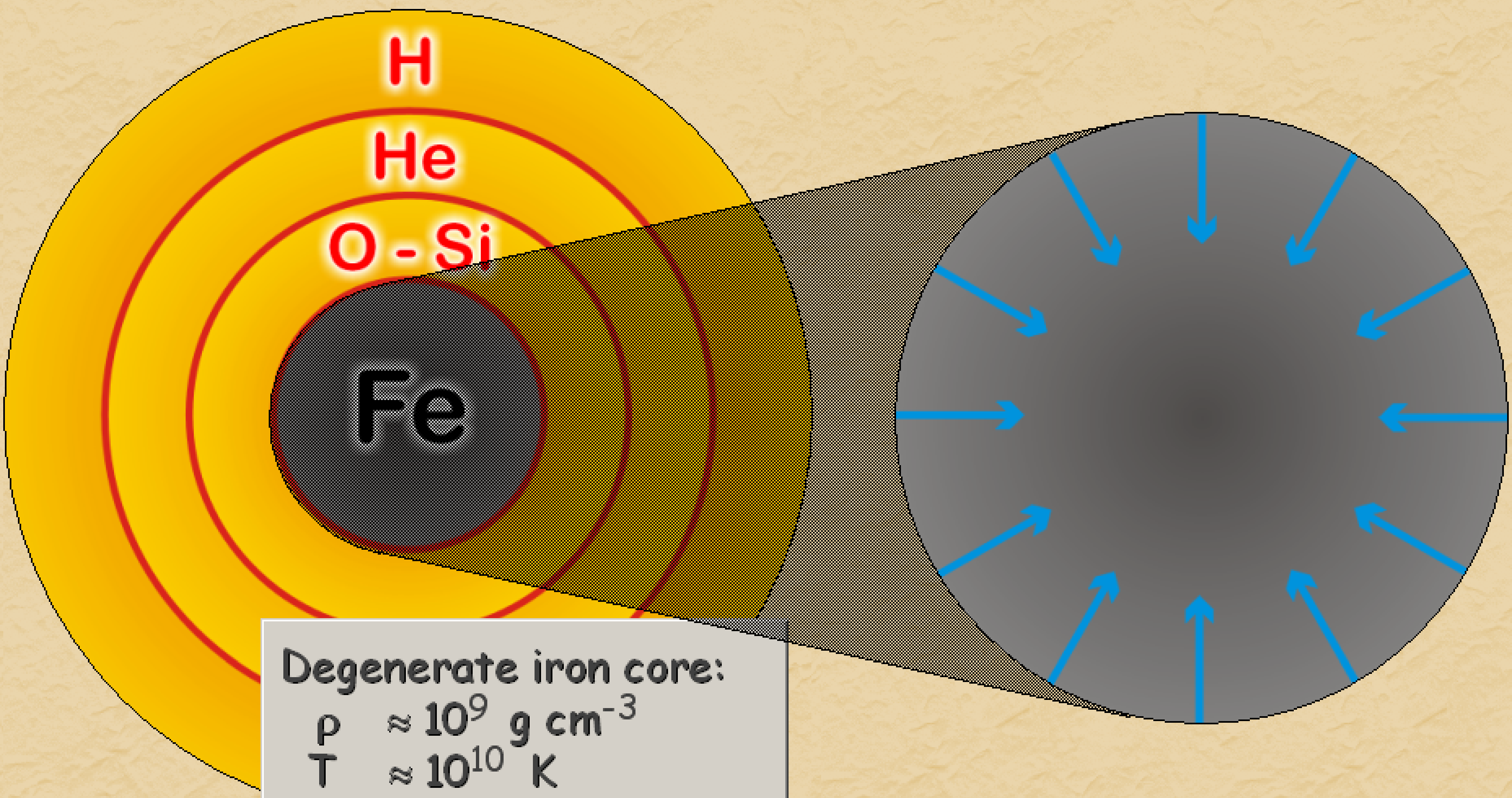
Max-Planck-Institut für Physik, München, Germany

(Based on work with M.Keil, R.Buras & H.-T.Janka)

Stellar Collapse and Supernova Explosion

Onion Structure

Collapse (Implosion)



Degenerate iron core:

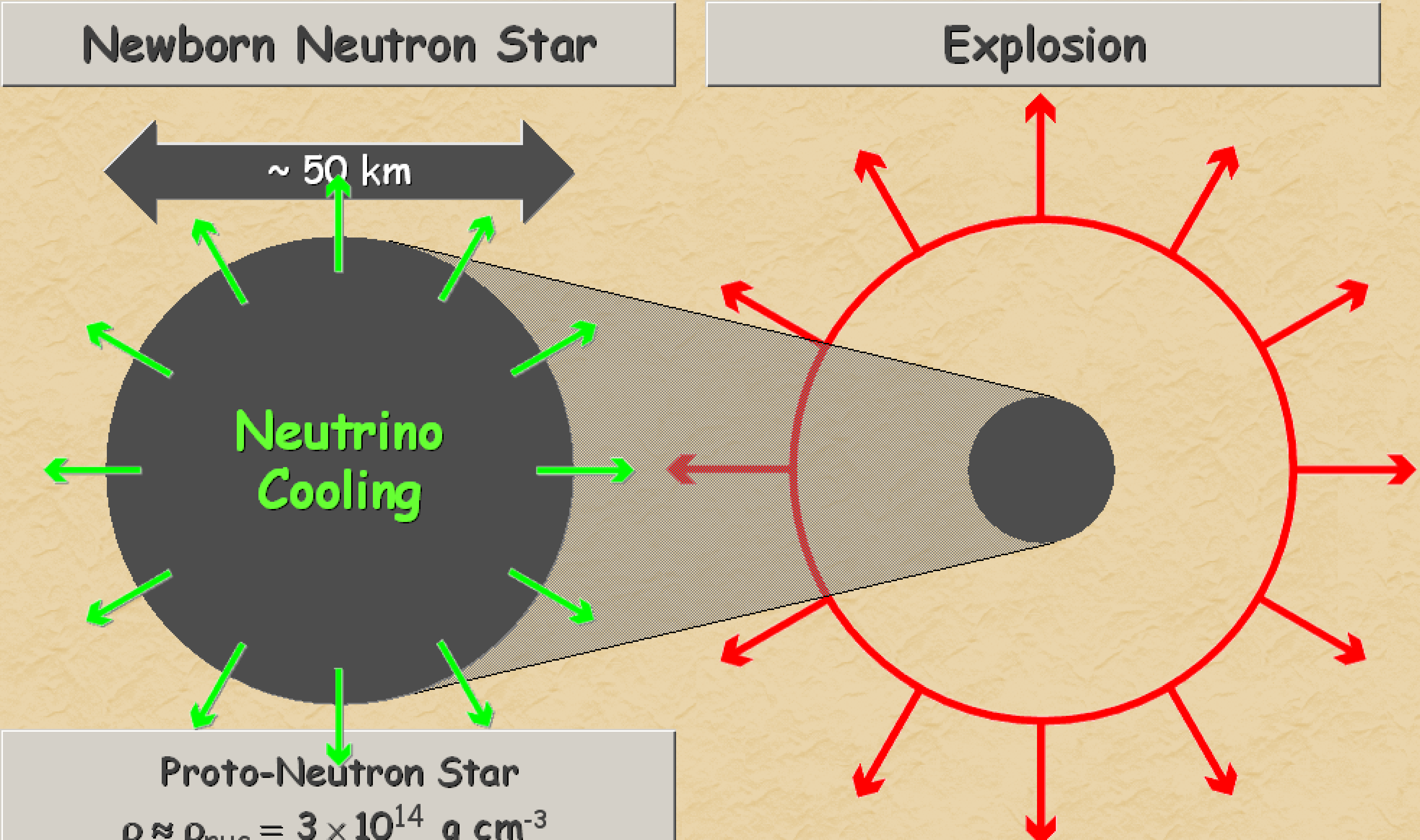
$\rho \approx 10^{9}$ g cm^{-3}

$T \approx 10^{10}$ K

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

$R_{Fe} \approx 8000$ km

Stellar Collapse and Supernova Explosion



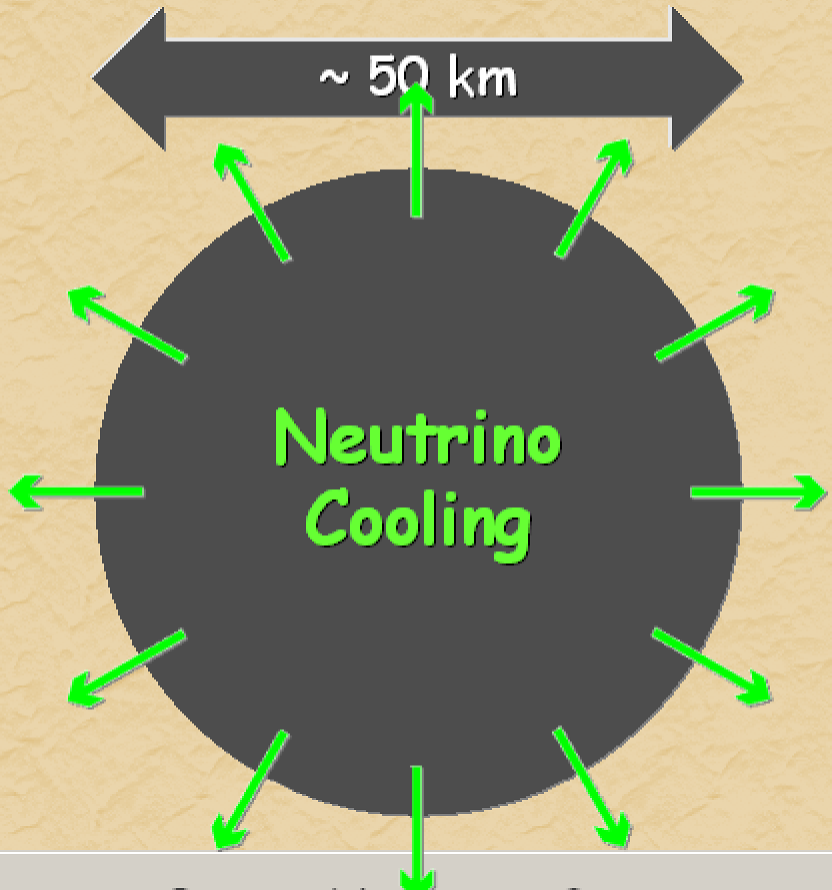
Proto-Neutron Star

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

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

Stellar Collapse and Supernova Explosion

Newborn Neutron Star



Proto-Neutron Star

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

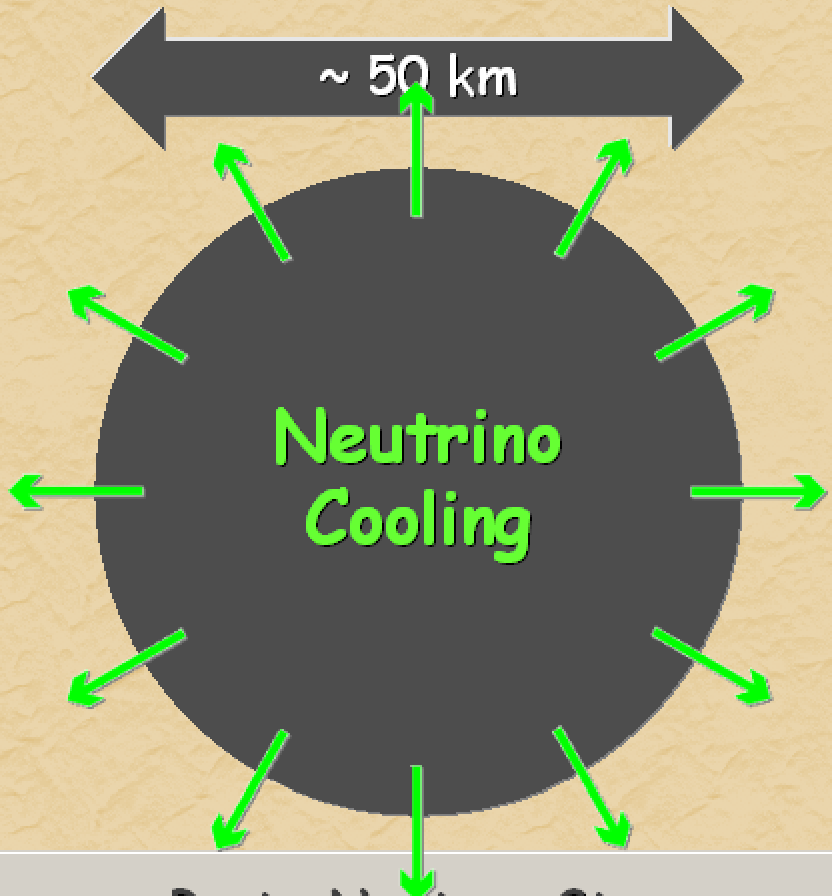
$L_\nu \approx 3 \times 10^{53}$ erg / 3 sec

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

While it lasts, outshines the entire visible universe

Stellar Collapse and Supernova Explosion

Newborn Neutron Star



Proto-Neutron Star

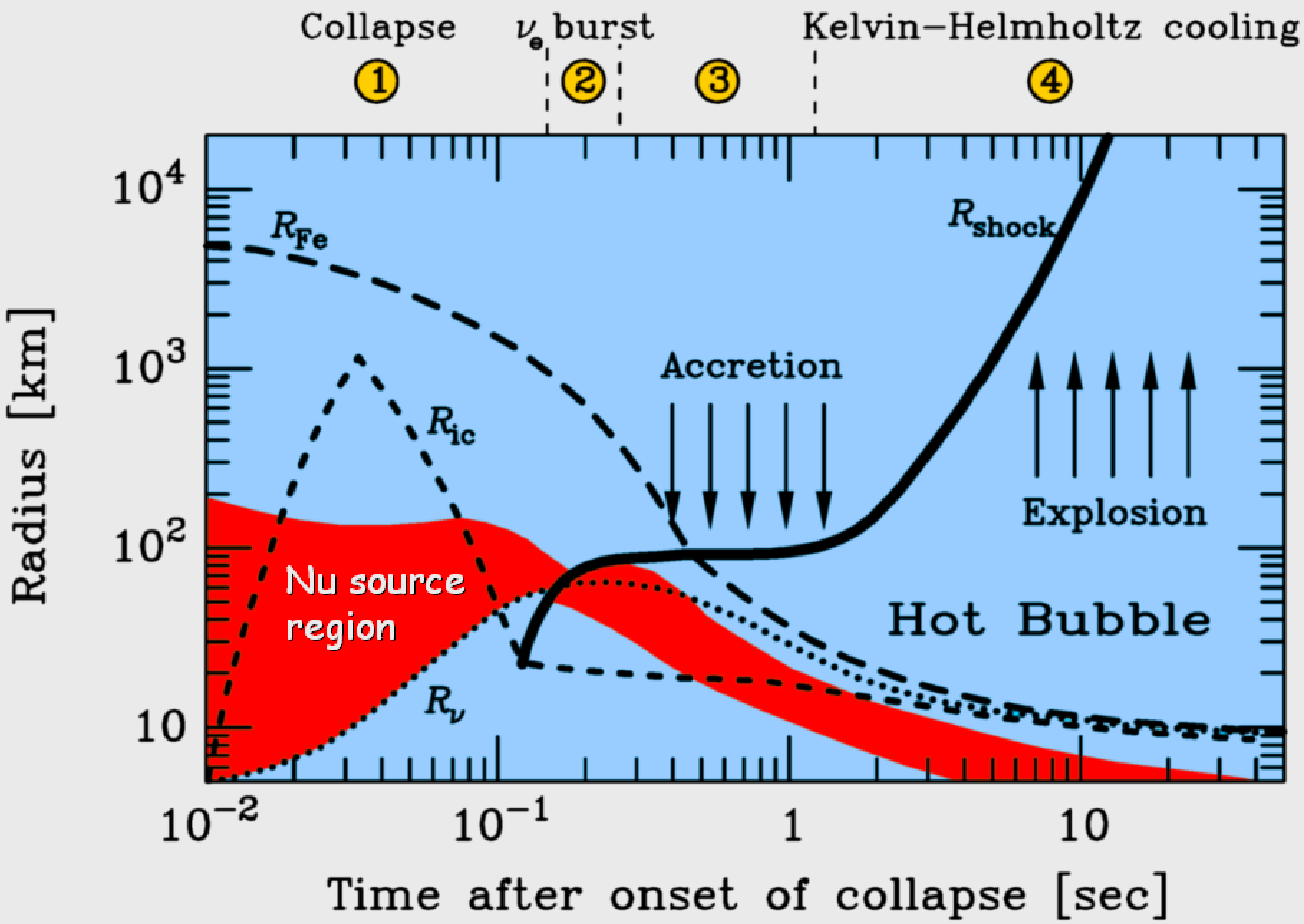
$\rho \approx \rho_{nuc} = 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$

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

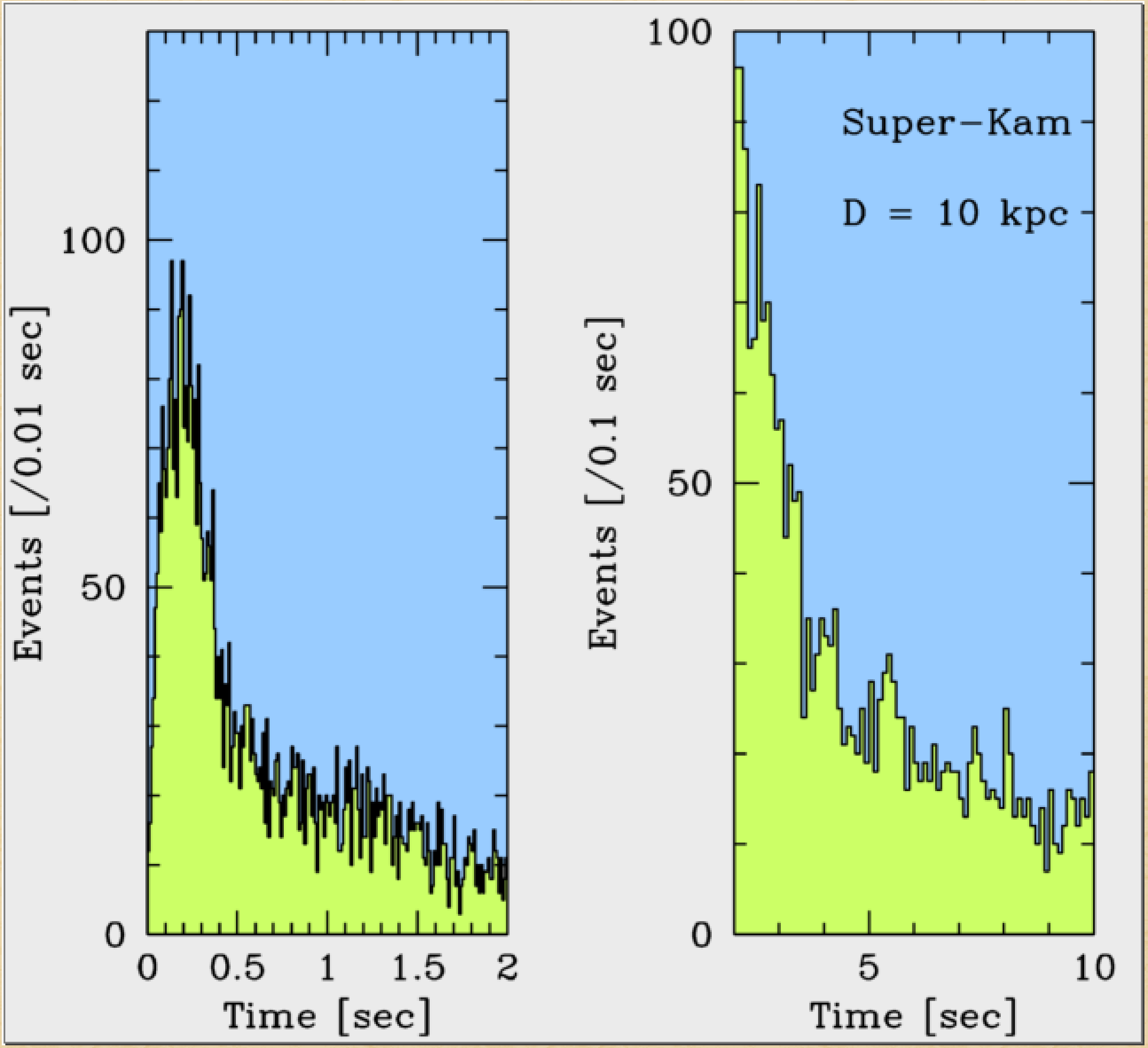
Neutrino Trapping

- Neutron star so hot and dense that neutrinos are trapped
- Cooling time scale governed by diffusion time scale
- Neutrinos of all flavors emitted from neutron-star surface
- Essentially a blackbody source for all neutrino flavors
- Oscillation physics: Subtle flavor-dependent spectrum and flux differences important

Supernova Collapse and Explosion



Simulated Supernova Signal in Super-Kamiokande



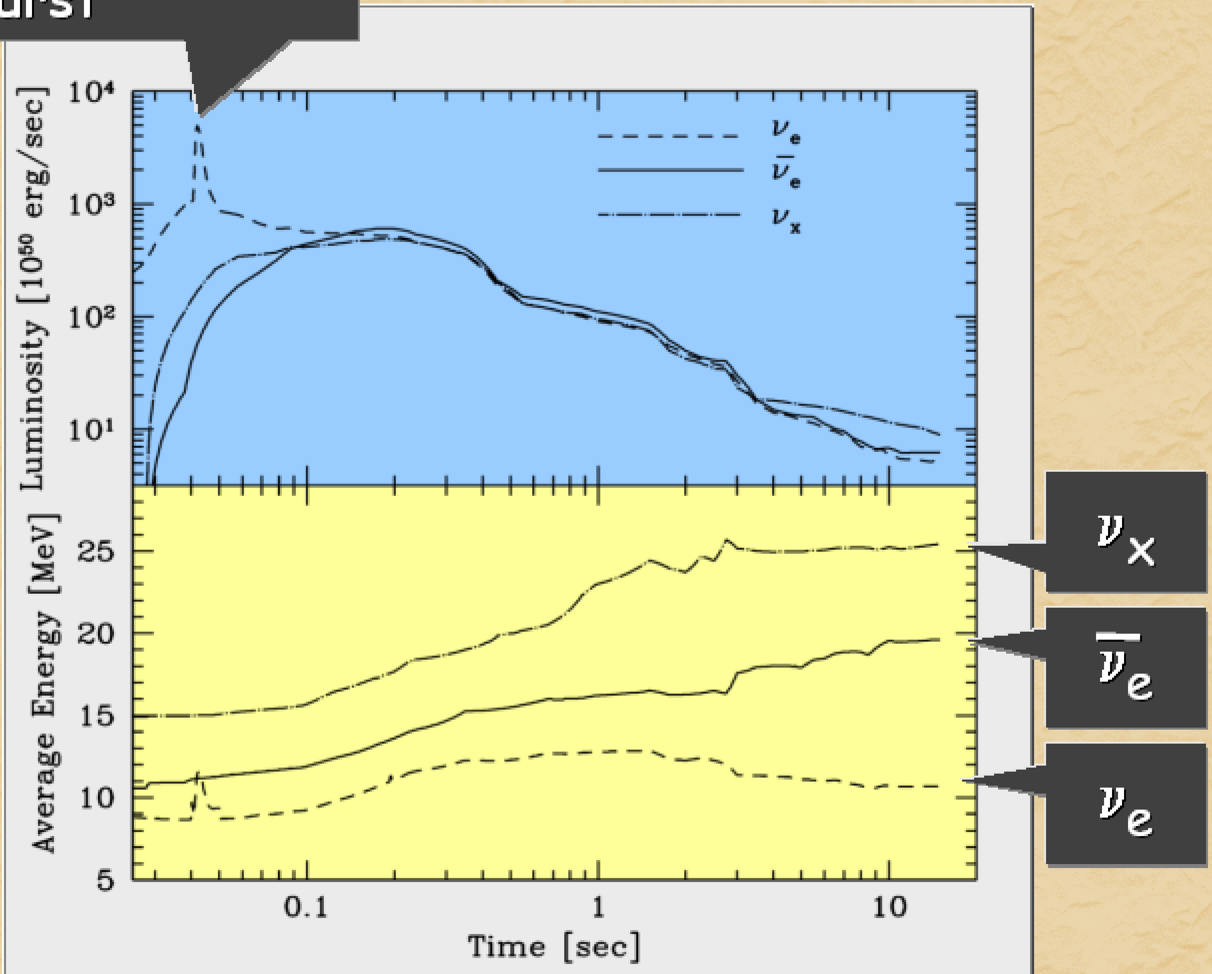
Totani, Sato, Dalhed & Wilson, ApJ 496 (1998) 216

Total of about 8300 events for t < 18 s

Monte-Carlo simulation for Super-Kamiokande signal of SN at 10 kpc, based on a numerical Livermore model

Flavor-Dependent Fluxes and Spectra

Prompt ν_e deleptonization burst



Livermore numerical model
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 transport of ν_μ and ν_τ 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 $(\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau)$

$\nu N \leftrightarrow N \nu$

$\nu e \leftrightarrow \nu e$

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

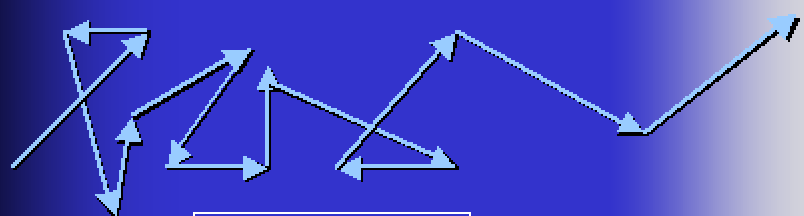
$e^+e^- \leftrightarrow \nu\bar{\nu}$

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

Thermal Equilibrium

Scattering Atmosphere

$\nu N \leftrightarrow N \nu$



Diffusion

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

$\nu N \leftrightarrow N \nu$

$\nu e \leftrightarrow \nu e$

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

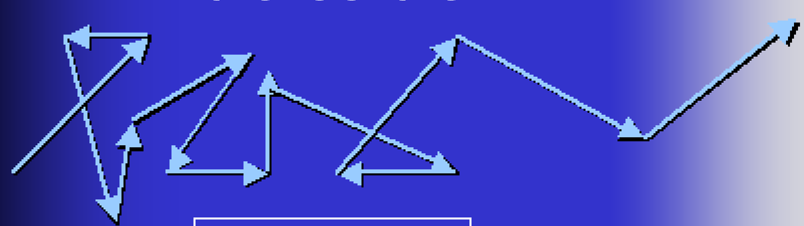
$e^+ e^- \leftrightarrow \nu \bar{\nu}$

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

Thermal Equilibrium

Scattering Atmosphere

$\nu N \leftrightarrow N \nu$



Diffusion

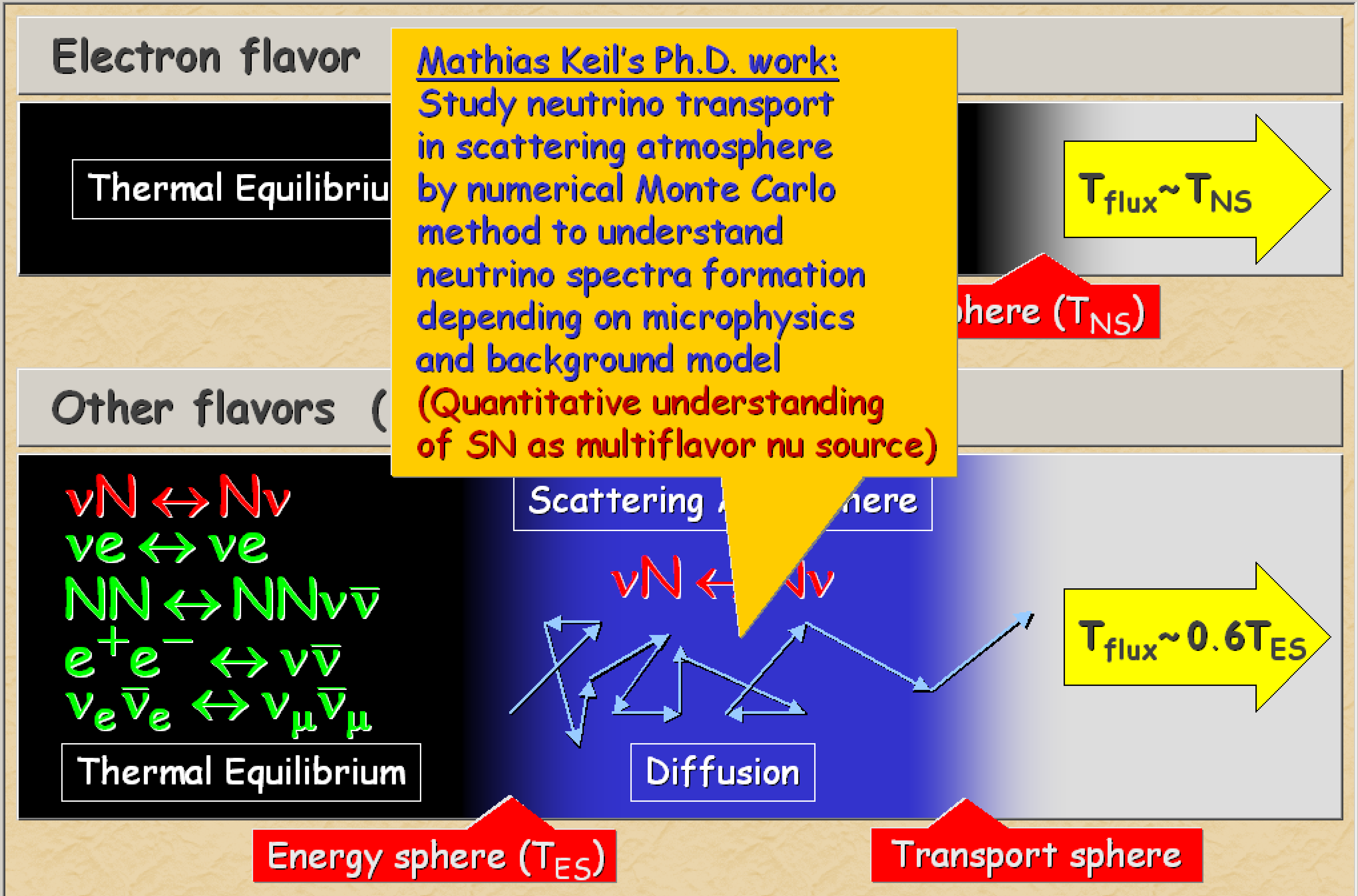
$T_{flux} \sim 0.6 T_{ES}$

Energy sphere (T_{ES})

Transport sphere

Neutrino Spectra Formation

G.Raffelt
astro-ph/0105250

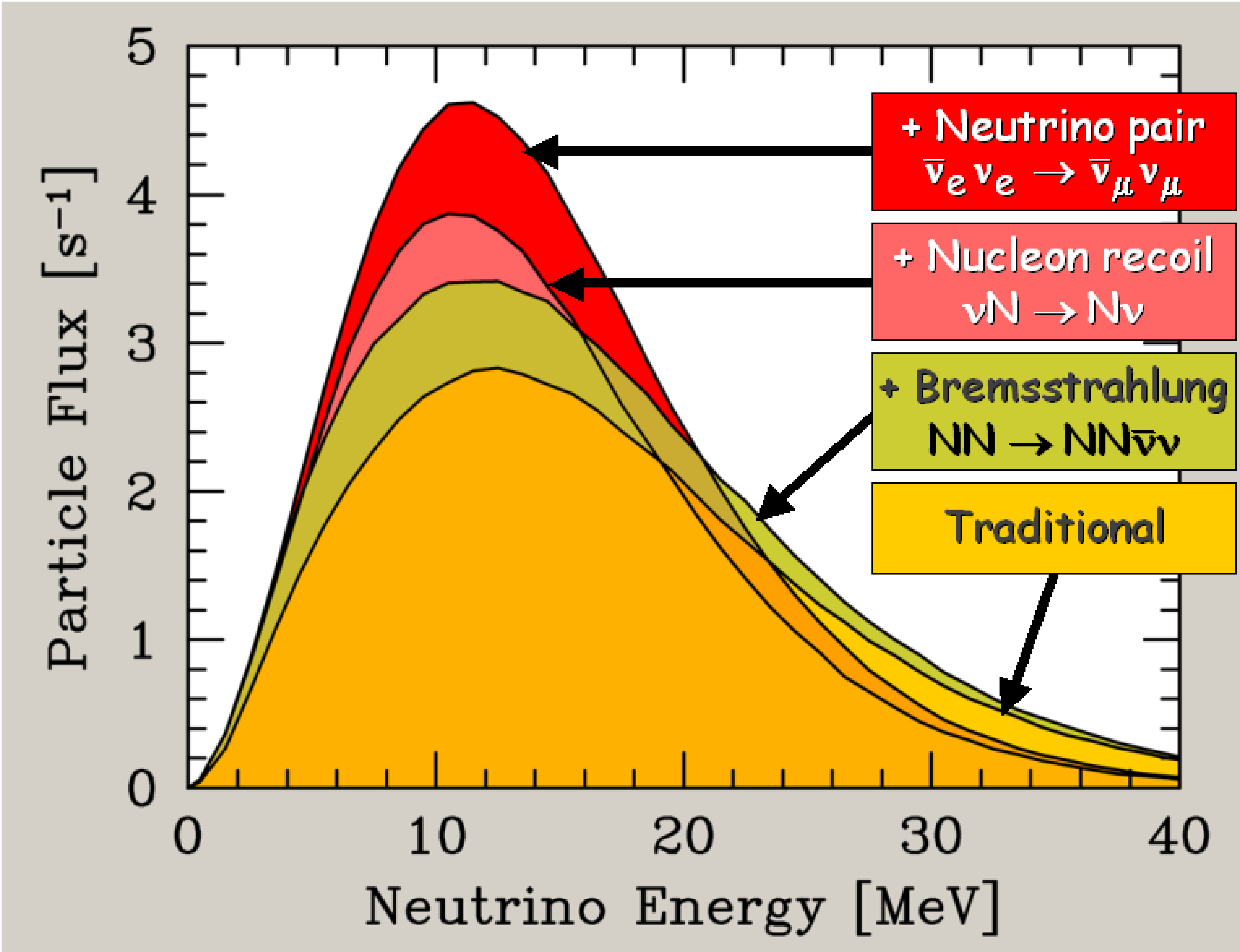


Microphysics for Mu- and Tau-Neutrino Transport

	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]

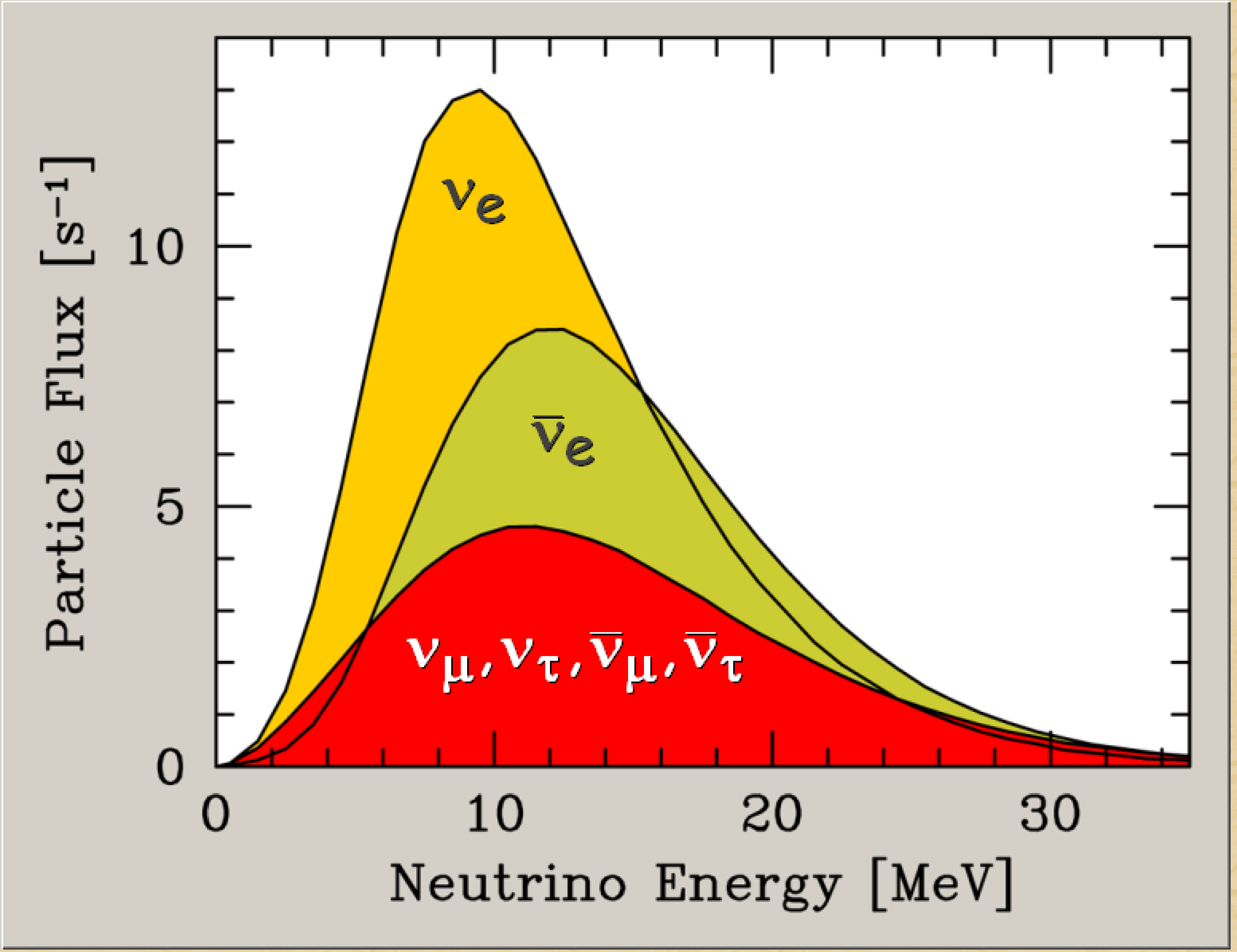
[1] Suzuki, Num. Astrophys. Japan 2 (1991) 267
[2] Janka, W.Keil, Raffelt & Seckel, PRL 76 (1996) 2621 [astro-ph/9507023]
[3] Hannestad & Raffelt, ApJ 507 (1998) 339 [astro-ph/9711132]
[4] Thompson, Burrows & Horvath, PRC 62 (2000) 035802 [astro-ph/0003054]
[6] Raffelt, ApJ 561 (2001) 890 [astro-ph/0105250]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



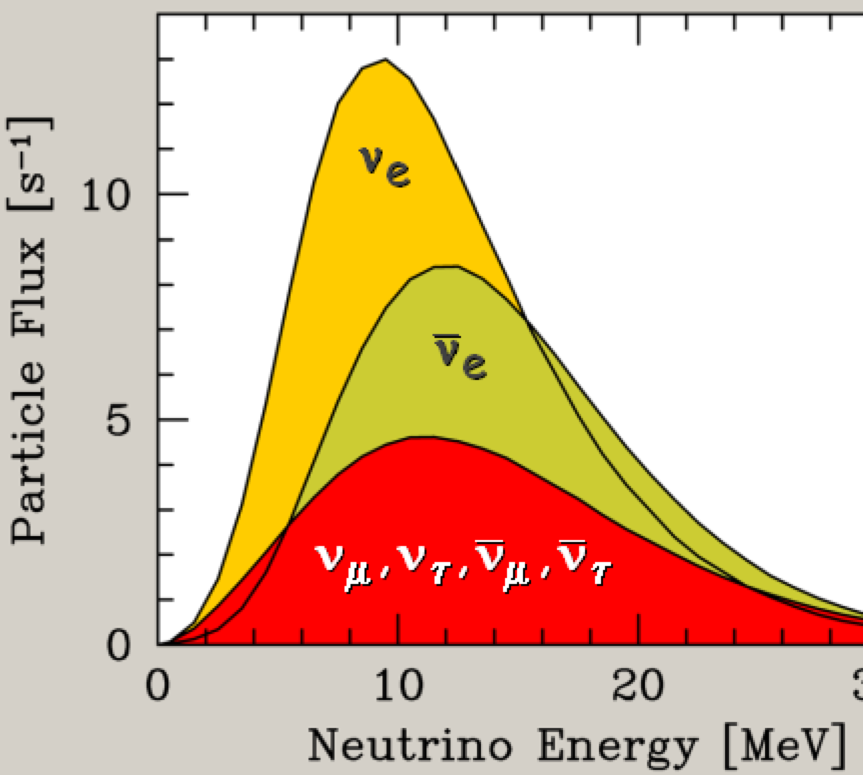
Keil, Raffelt & Janka, ApJ (2003) [astro-ph/0208035]

Flavor-Dependent Fluxes in One Specific 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

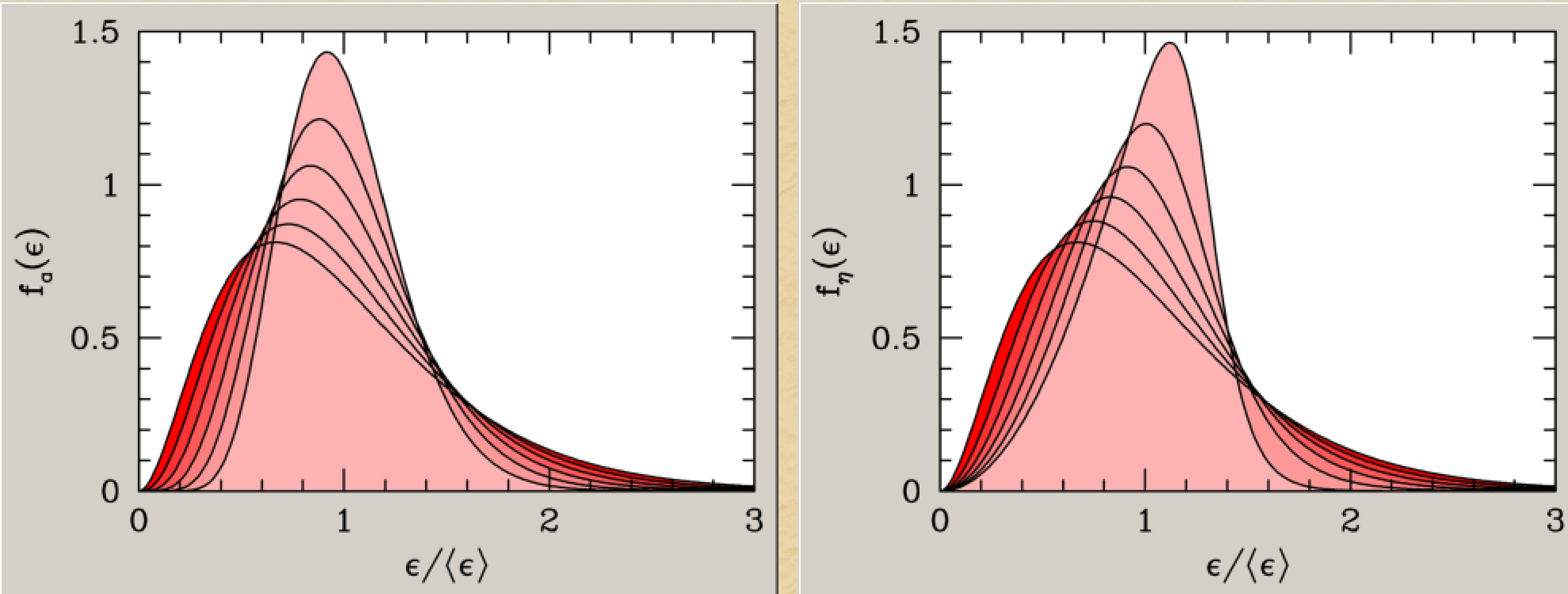
- Total luminosity L_ν
- Average energy $\langle E \rangle$
- General energy moments $\langle E^n \rangle$
- "RMS energy" $E_{rms} = \sqrt{\frac{\langle E^3 \rangle}{\langle E \rangle}}$

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

Alpha vs. Eta Fit

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

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



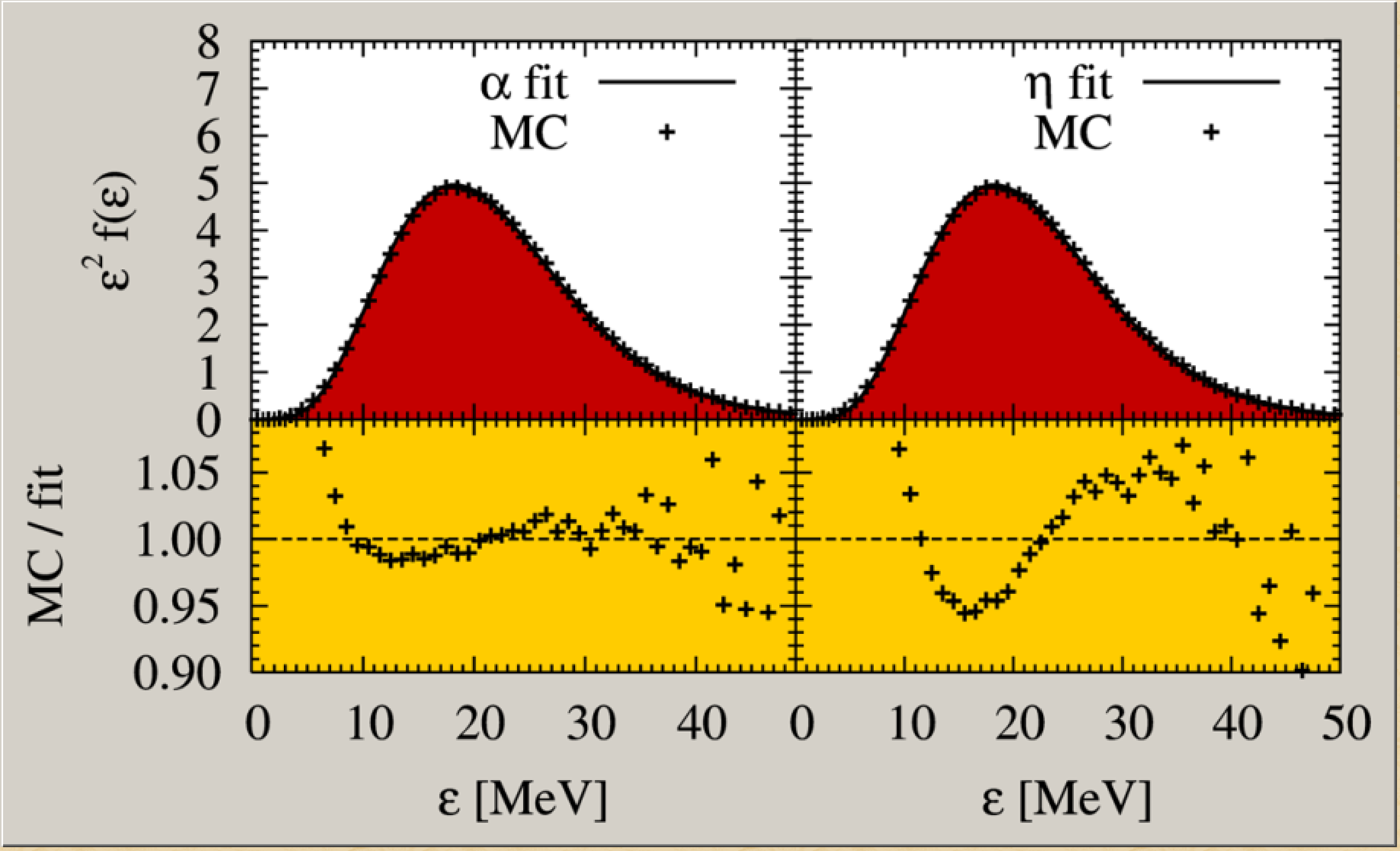
Starting with $F(E) \propto E^2 \exp\left(-3\frac{E}{\overline{E}}\right)$ the width is reduced in 10% steps

How Good are the Two-Parameter Global Fits?

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

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

Keil, Raffelt & Janka, astro-ph/0208035

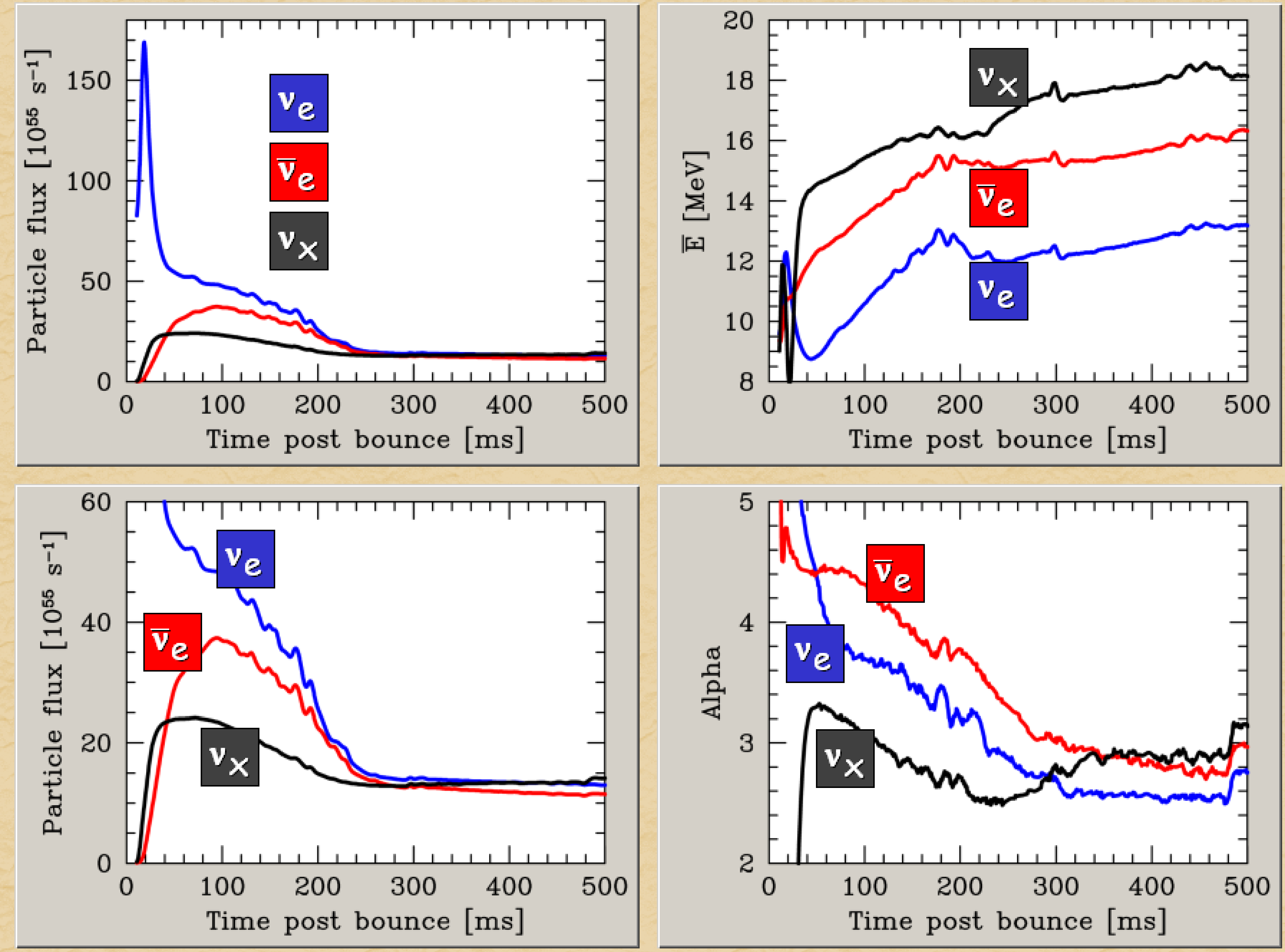


Monte Carlo Study of Fluxes and Spectra

Model	Luminosities			$\langle E \rangle$			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: $\rho \propto r^{-10}$, $T \propto r^{-2}$, $Y_e = 0.2$

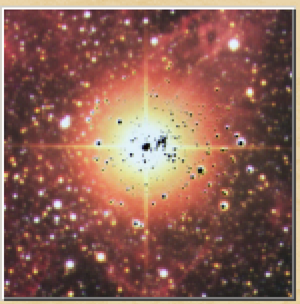
Garching 3-D Simulation with Boltzmann-Solver



Summary

A variety of processes are important for ν_μ and ν_τ spectra formation that are not included in traditional simulations, i.e. nucleon recoil in $\nu N \to N\nu$, bremsstrahlung $NN \to NN\bar{\nu}\nu$, and $\bar{\nu}_e \nu_e \to \bar{\nu}_\mu \nu_\mu$

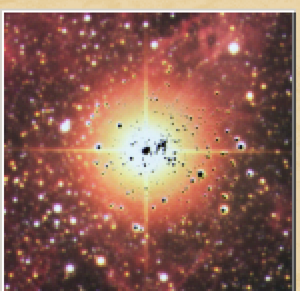
- Monte Carlo spectra are well fit by "power law" $F(E) \propto E^\alpha \exp\left[-(\alpha+1)E/\bar{E}\right]$
- Three parameters enough to characterize the fluxes: Luminosity L_ν, average energy $\bar{E}$, and "power-law index" α



Flavor-dependent luminosities not generally equal
During accretion-dominated phase we find

$$\langle L(\nu_e)\rangle : \langle L(\bar{\nu}_e)\rangle : \langle L(\nu_{\mu,\tau}, \bar{\nu}_{\mu,\tau})\rangle \approx 1:1:0.5$$

but can become similar or even cross over during cooling phase



No strong hierarchy of average energies

$$\langle E(\nu_e)\rangle : \langle E(\bar{\nu}_e)\rangle : \langle E(\nu_{\mu,\tau}, \bar{\nu}_{\mu,\tau})\rangle \approx 0.8:1:1-1.15$$

But "hierarchy" of spectral pinching, at least during early phase

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