Flavor-dependent SN neutrino spectra and fluxes

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JIGSAW 10, 22–26 Feb 2010, TIFR, Mumbai, India

Based on some very old and some very new papers

G. G. Raffelt
Mu- and tau-neutrino spectra formation in supernovae
Astrophys. J. 561, 890 (2001) [astro-ph/0105250]

M. T. Keil, G. G. Raffelt & H.-T. Janka
Monte Carlo study of supernova neutrino spectra formation
Astrophys. J. 590, 971 (2003) [astro-ph/0208035]

T. Fischer, S. C. Whitehouse, A. Mezzacappa, F. K. Thielemann & M. Liebendörfer ("Basel Group")
Protoneutron star evolution and the neutrino driven wind in general relativistic neutrino radiation hydrodynamics simulations
arXiv:0908.1871

L. Hüdepohl, B. Müller, H.-T. Janka, A. Marek & G. G. Raffelt ("Garching Group")
Neutrino signal of electron-capture supernovae from core collapse to cooling,
arXiv:0912.0260

What and Why?

Existing and upcoming large-scale detectors for low-E neutrinos are looking for

Diffuse SN neutrino background (DSNB)	Next nearby supernova (NNSN)
• Assured signal, but few events • How much realistic information? (Star formation rate already well known?)	• May be a long wait • Large statistics • Detailed SN dynamics • Fast time variations • Neutrino flavor conversions
• Need neutrino flux and spectrum of an “average SN” • Typical average energy most crucial for counting rate	• Next nearby SN need not be “typical”, but a lot of detail can be diagnosed in neutrinos • For flavor oscillations significant differences between flavor spectra required

Like to predict absolute energy scale and flavor dependence

Diffuse Supernova Neutrino Background (DSNB)

Supernova rate approximately

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

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

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

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

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

Pushing the boundaries of neutrino astronomy to cosmological distances

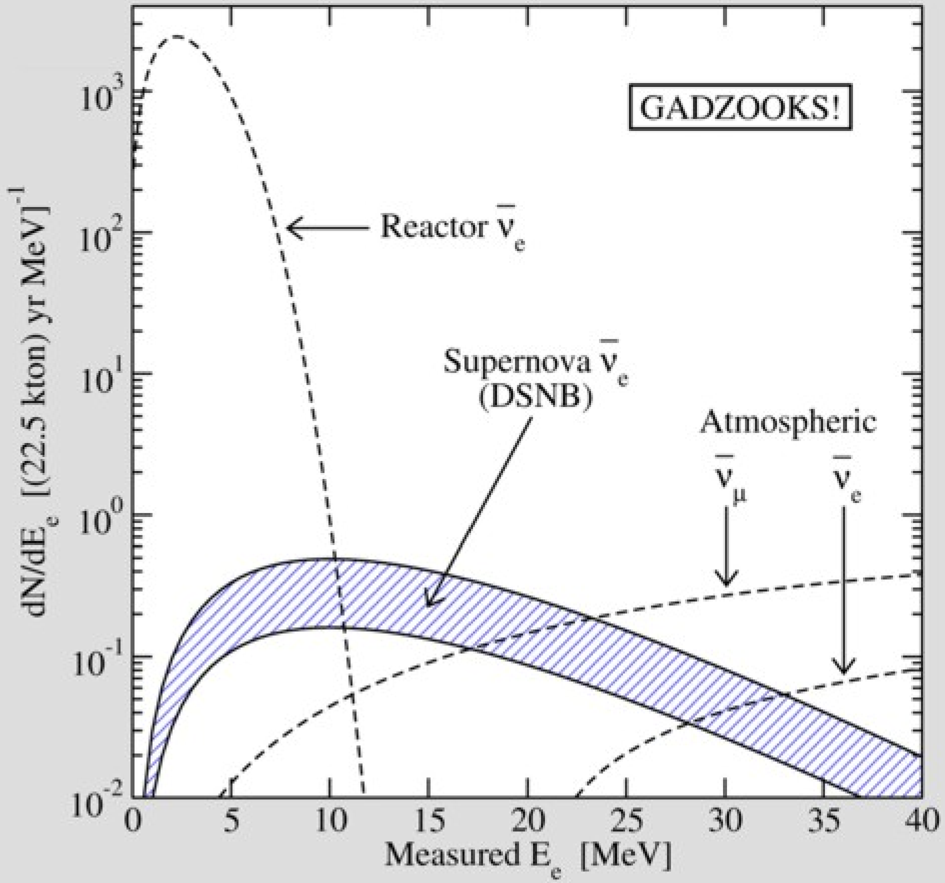


FIG. 1: Spectra of low-energy $\bar{\nu}_e + p \to e^+ + n$ coincidence events and the sub-Čerenkov muon background. We assume full efficiencies, and include energy resolution and neutrino oscillations. Singles rates (not shown) are efficiently suppressed.

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

Realistic DSNB Estimate

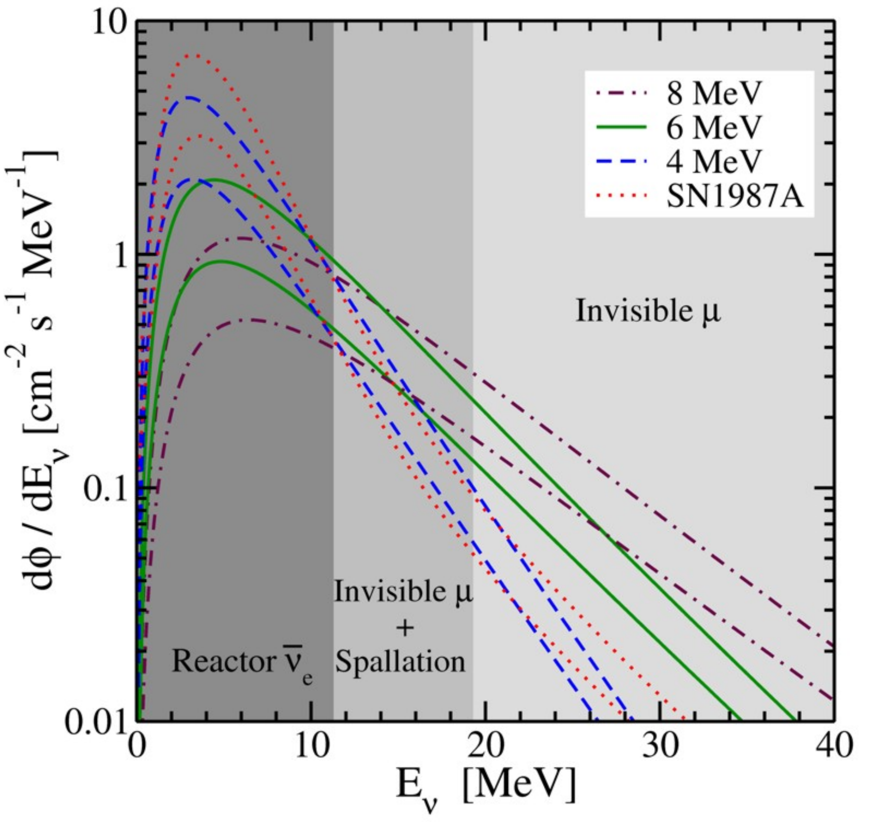


FIG. 4: DSNB flux spectrum for emitted neutrino spectra as labeled. For each spectrum, two curves are plotted representing the full range of uncertainties due to astrophysical inputs (the fiducial prediction lies in between). The shadings indicate backgrounds, with origins as labeled. Decays of invisible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

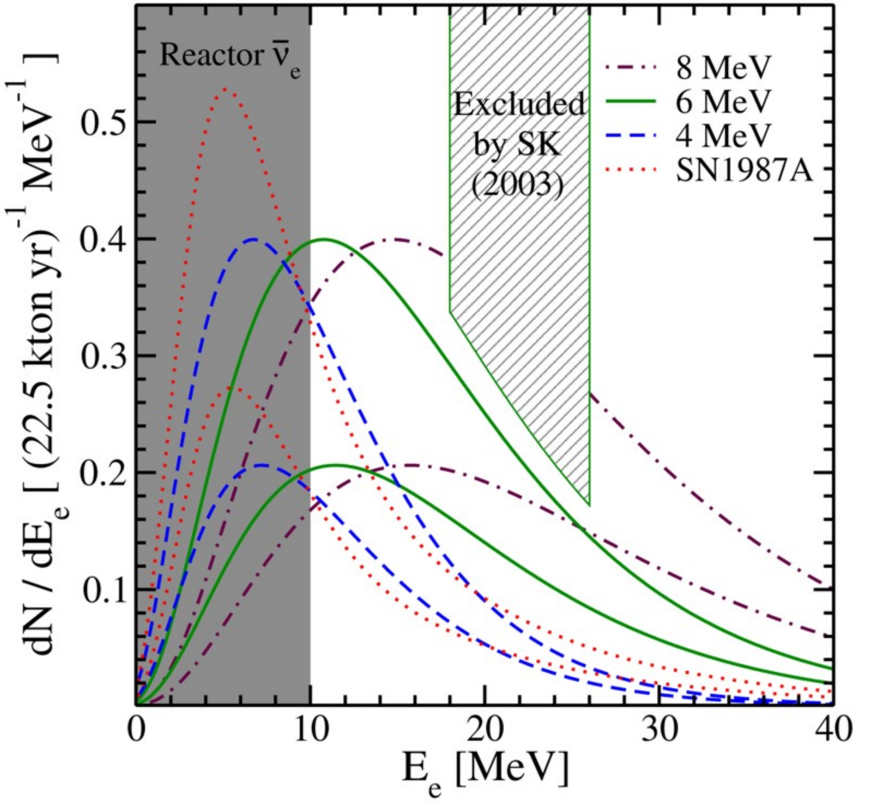
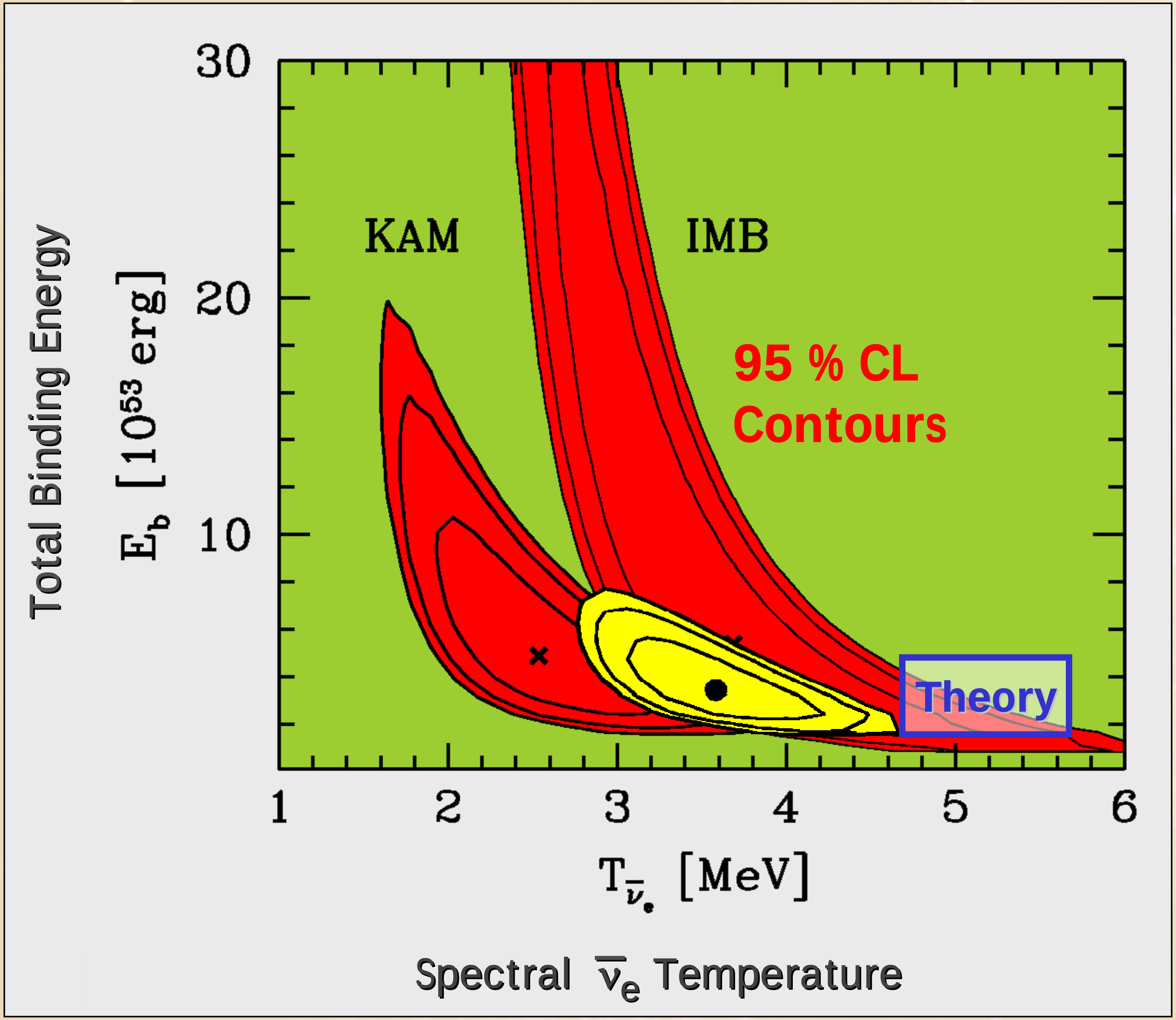


FIG. 5: DSNB event rates at SK (flux spectra weighted with the detection cross section) against positron energy. Note the linear axis. We hatch in the 2003 upper limit by the Super-Kamiokande Collaboration, < 2 events $(22.5 \text{ kton yr})^{-1}$ in the energy range 18–26 MeV. The limit applies to all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

Horiuchi, Beacom & Dwek, arXiv:0812.3157v3

Interpreting SN 1987A Neutrinos



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

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

Literature Scan of Flavor-Dependent Neutrino Spectra

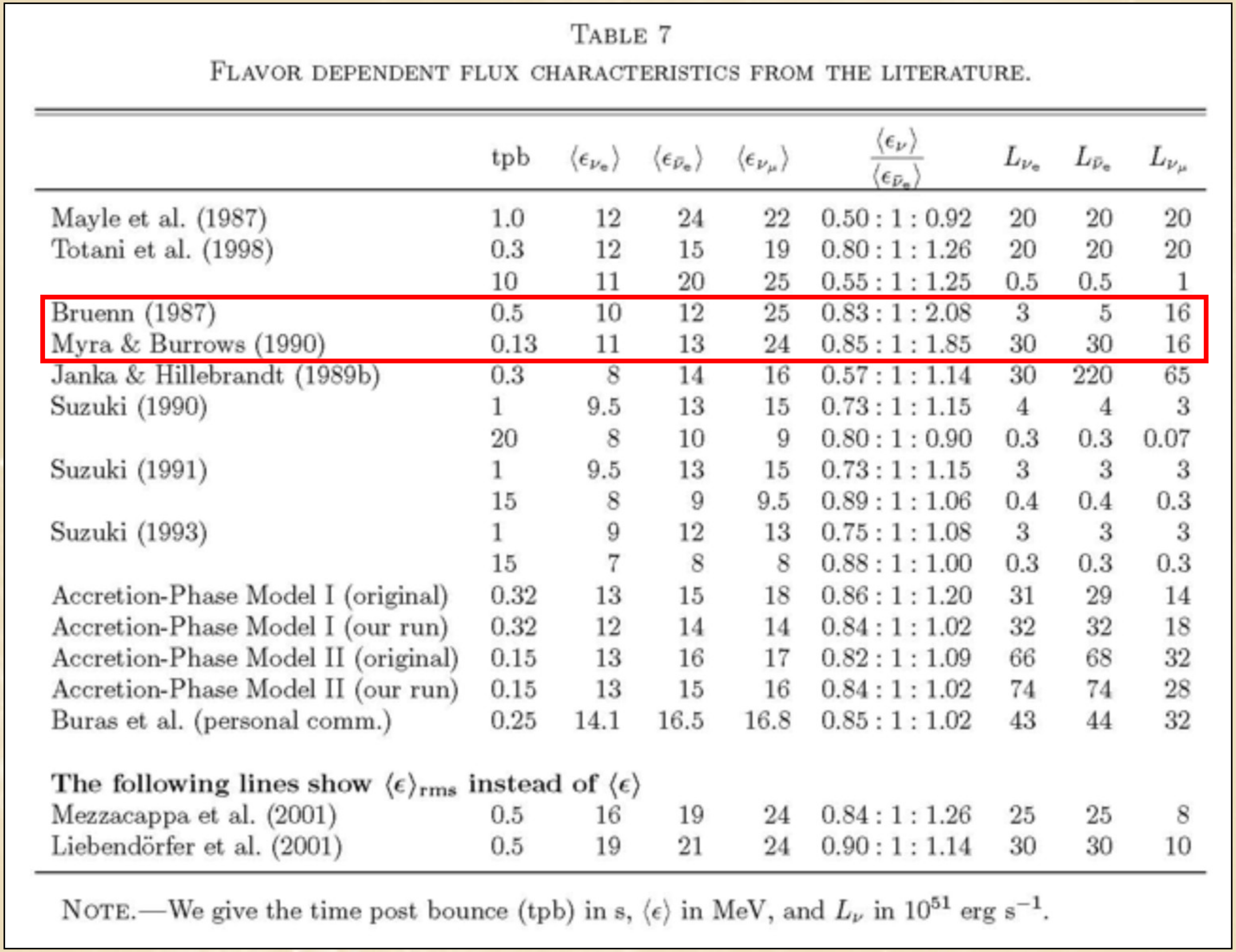


TABLE 7

FLAVOR DEPENDENT FLUX CHARACTERISTICS FROM THE LITERATURE.

	tpb	$\langle\epsilon_{\nu_e}\rangle$	$\langle\epsilon_{\bar\nu_e}\rangle$	$\langle\epsilon_{\nu_\mu}\rangle$	$\frac{\langle\epsilon_\nu\rangle}{\langle\epsilon_{\bar\nu_e}\rangle}$	L_{ν_e}	$L_{\bar\nu_e}$	L_{ν_μ}
Mayle et al. (1987)	1.0	12	24	22	0.50 : 1 : 0.92	20	20	20
Totani et al. (1998)	0.3	12	15	19	0.80 : 1 : 1.26	20	20	20
	10	11	20	25	0.55 : 1 : 1.25	0.5	0.5	1
Bruenn (1987)	0.5	10	12	25	0.83 : 1 : 2.08	3	5	16
Myra & Burrows (1990)	0.13	11	13	24	0.85 : 1 : 1.85	30	30	16
Janka & Hillebrandt (1989b)	0.3	8	14	16	0.57 : 1 : 1.14	30	220	65
Suzuki (1990)	1	9.5	13	15	0.73 : 1 : 1.15	4	4	3
	20	8	10	9	0.80 : 1 : 0.90	0.3	0.3	0.07
Suzuki (1991)	1	9.5	13	15	0.73 : 1 : 1.15	3	3	3
	15	8	9	9.5	0.89 : 1 : 1.06	0.4	0.4	0.3
Suzuki (1993)	1	9	12	13	0.75 : 1 : 1.08	3	3	3
	15	7	8	8	0.88 : 1 : 1.00	0.3	0.3	0.3
Accretion-Phase Model I (original)	0.32	13	15	18	0.86 : 1 : 1.20	31	29	14
Accretion-Phase Model I (our run)	0.32	12	14	14	0.84 : 1 : 1.02	32	32	18
Accretion-Phase Model II (original)	0.15	13	16	17	0.82 : 1 : 1.09	66	68	32
Accretion-Phase Model II (our run)	0.15	13	15	16	0.84 : 1 : 1.02	74	74	28
Buras et al. (personal comm.)	0.25	14.1	16.5	16.8	0.85 : 1 : 1.02	43	44	32
The following lines show $\langle\epsilon\rangle_{\rm rms}$ instead of $\langle\epsilon\rangle$								
Mezzacappa et al. (2001)	0.5	16	19	24	0.84 : 1 : 1.26	25	25	8
Liebendörfer et al. (2001)	0.5	19	21	24	0.90 : 1 : 1.14	30	30	10

NOTE.—We give the time post bounce (tpb) in s, $\langle\epsilon\rangle$ in MeV, and L_ν in 10^{51} erg s^{-1}.

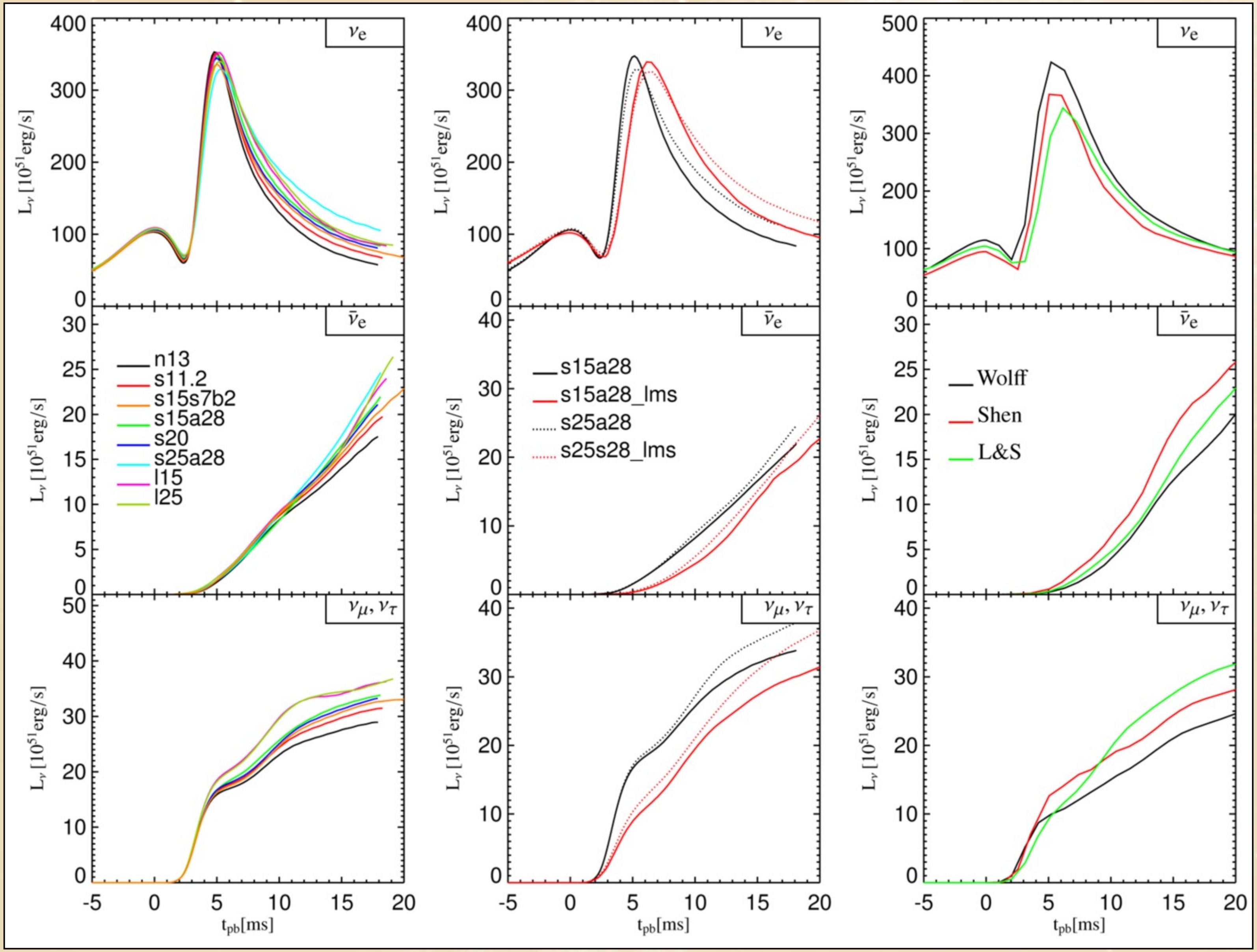
Keil, Janka & Raffelt, astro-ph/0208035

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

Millisecond Bounce Time Reconstruction

Super-Kamiokande

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

Pagliaroli, Vissani, Coccia & Fulgione
arXiv:0903.1191

IceCube

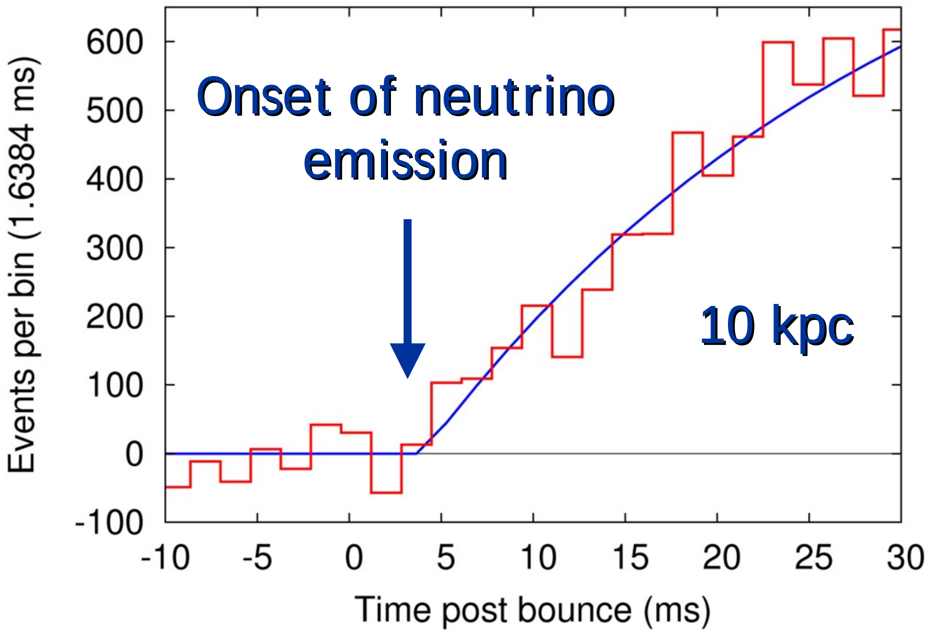
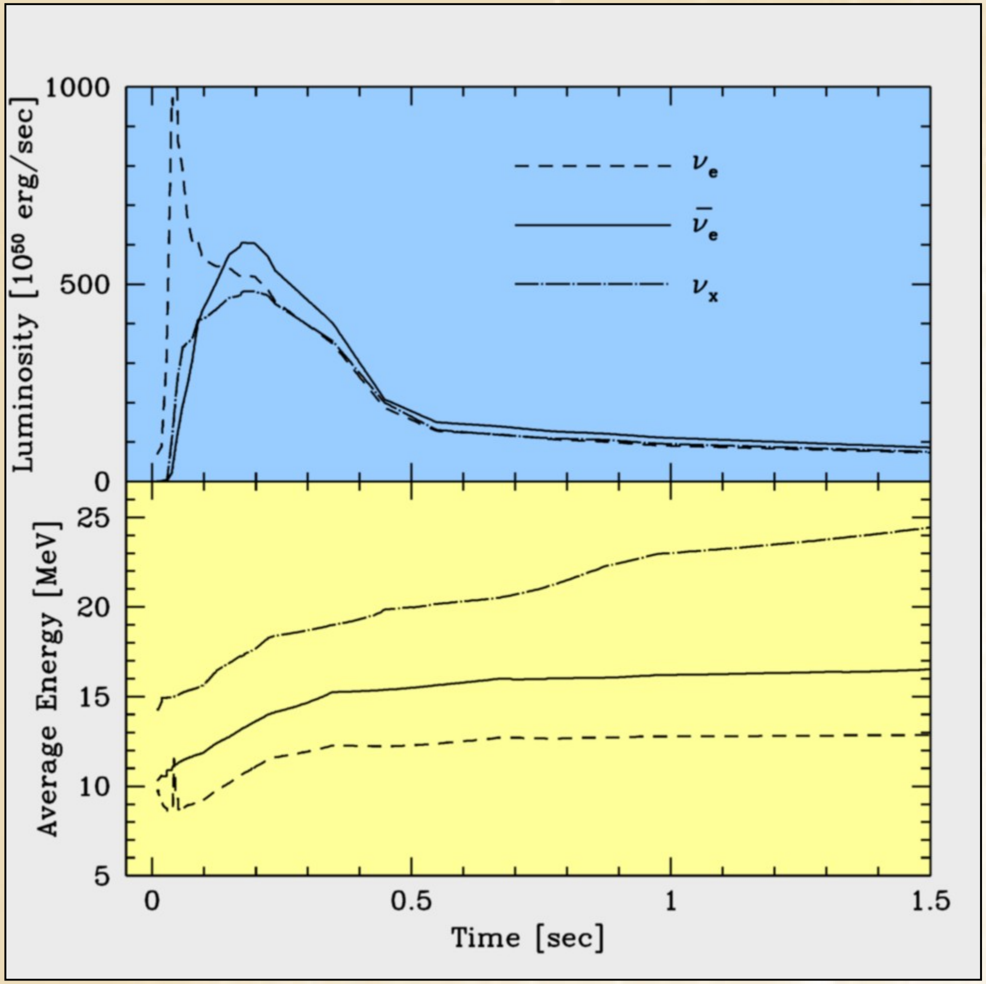
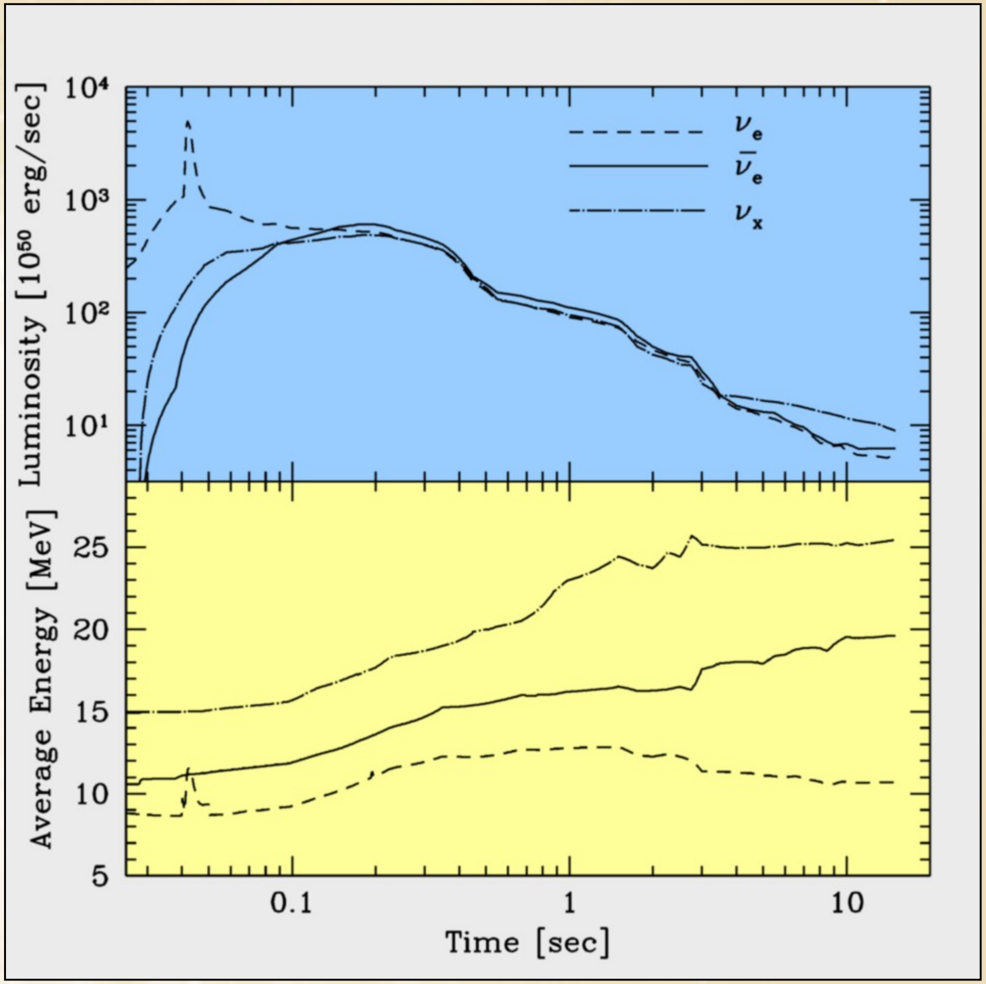


FIG. 1: Typical Monte Carlo realization (red histogram) and reconstructed fit (blue line) for the benchmark case discussed in the text for a SN at 10 kpc.

Halzen & Raffelt
arXiv:0908.2317

Numerical Neutrino Signal (Livermore)





Linear Time & Luminosity Scale

Logarithmic Time & Luminosity

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

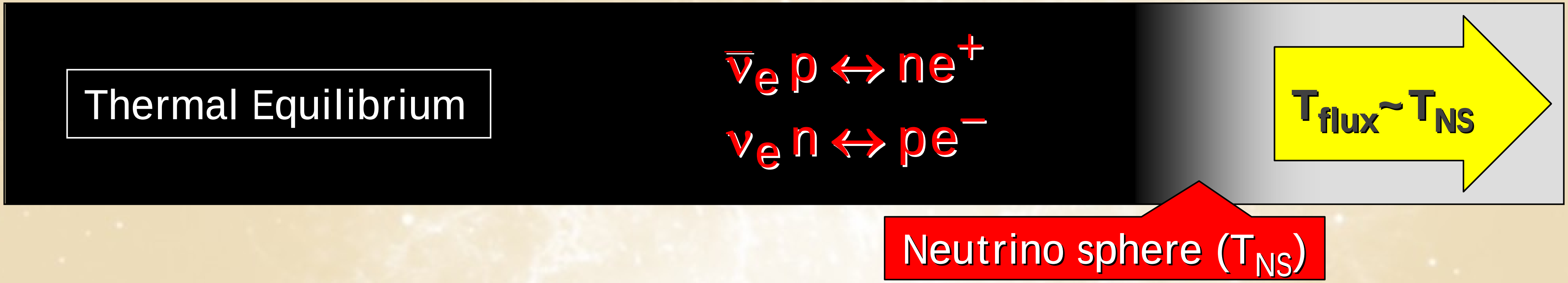
Microphysics for Mu- and Tau-Neutrino Transport

	Traditional treatment	Dominant processes
Main opacity	$\nu + N \rightarrow N + \nu$	$\nu + N \rightarrow N + \nu$
Energy exchange	$\nu + e \rightarrow e + \nu$	$\nu + e \rightarrow e + \nu$ Recoil $\nu + N \rightarrow N + \nu$ [2,6,7]
Pair production	$e^+ + e^- \rightarrow \bar{\nu} + \nu$	$N + N \rightarrow N + N + \bar{\nu} + \nu$ [1-4] $\bar{\nu}_e + \nu_e \rightarrow \bar{\nu} + \nu$ [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 (2003) [astro-ph/0208035]

Supernova Neutrino Spectra Formation

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



Thermal Equilibrium

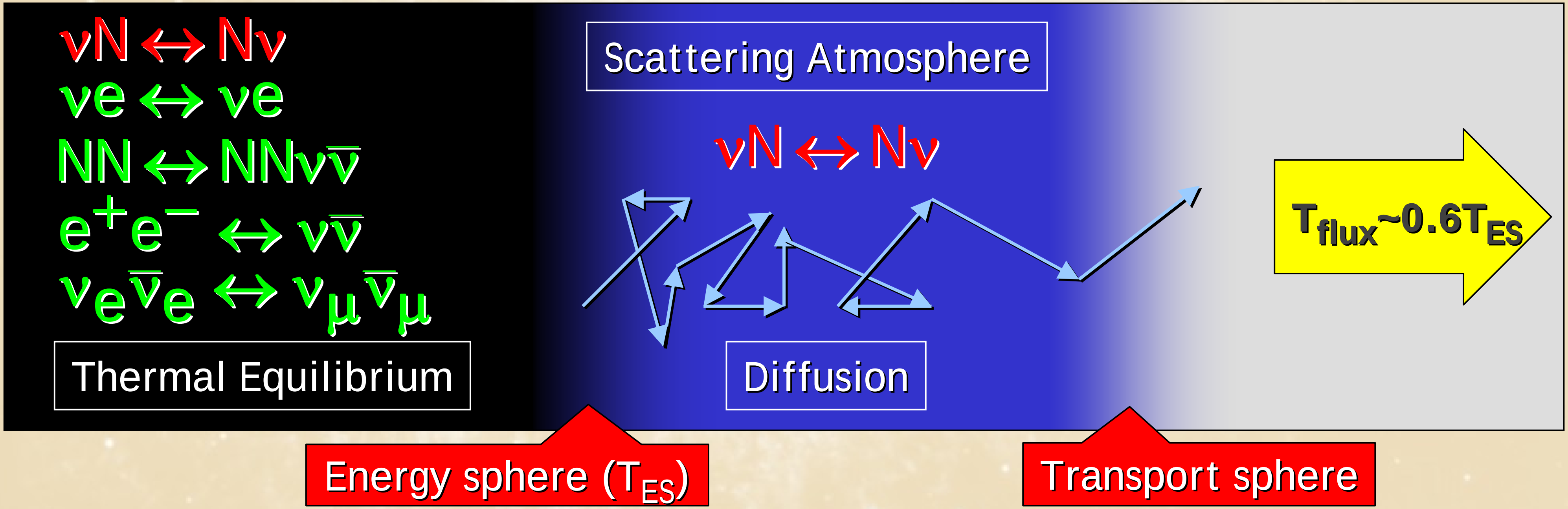
$\bar{\nu}_e\, p \leftrightarrow n e^+$

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

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

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

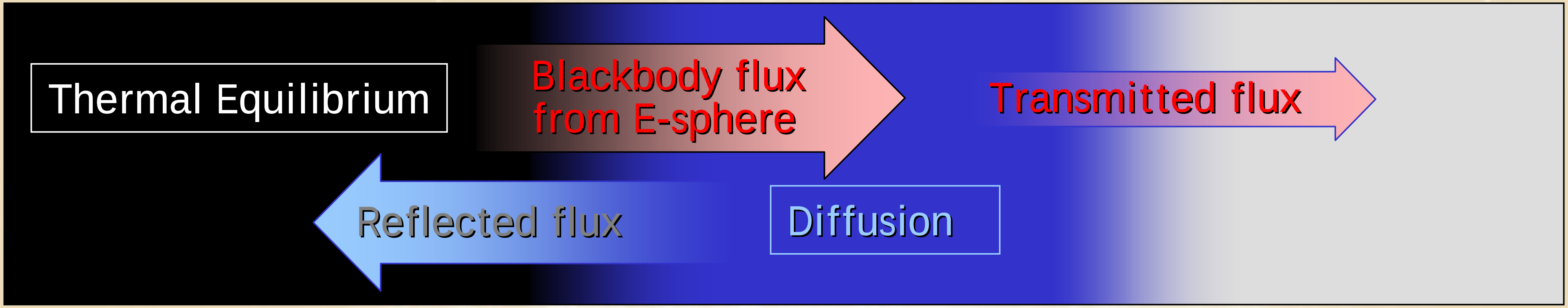
$T_{\text{flux}} \sim 0.6 T_{\text{ES}}$

Energy sphere (T_{ES})

Transport sphere

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

Scattering Atmosphere as a “Low-Pass Filter”



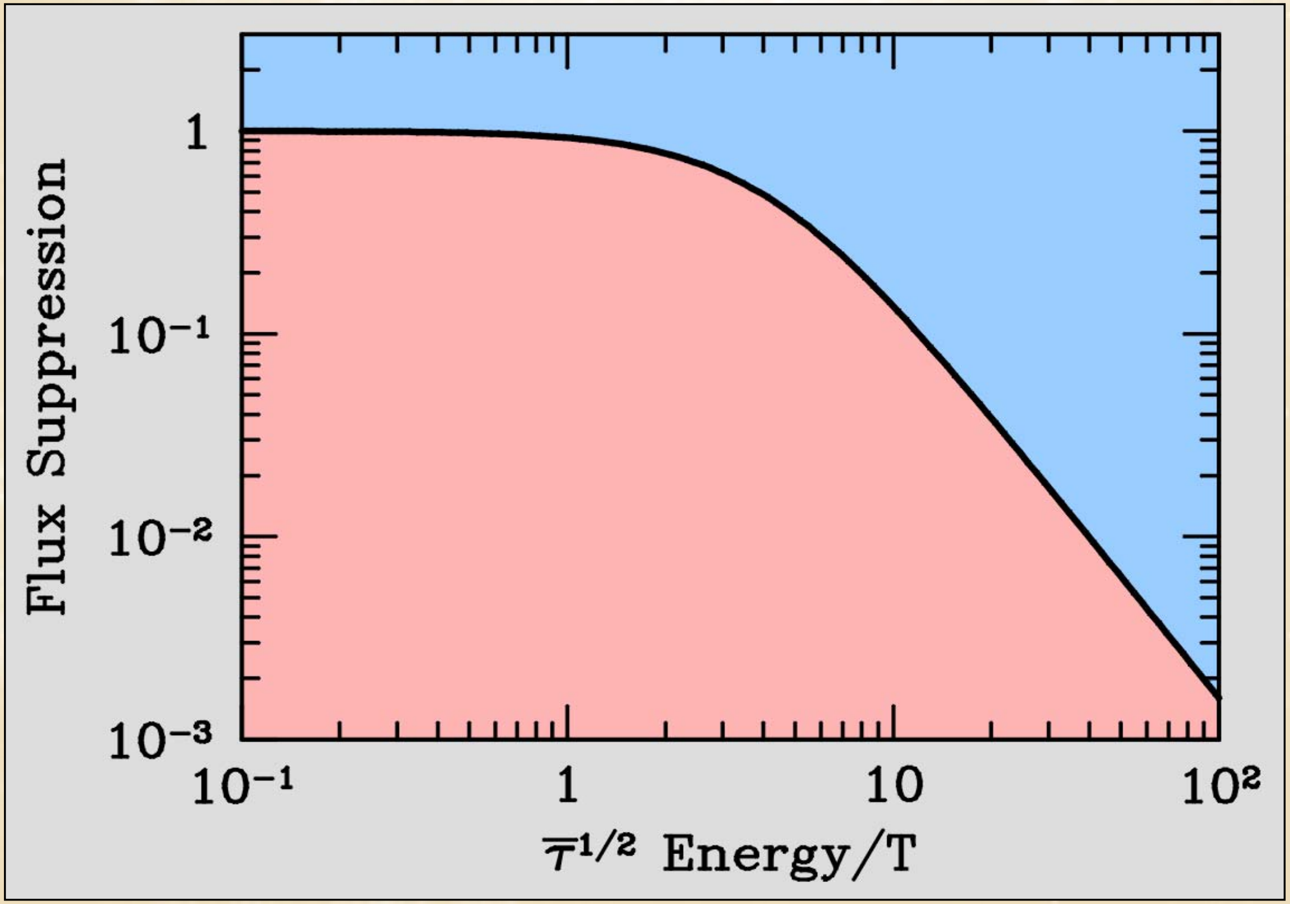
Thermal Equilibrium

Blackbody flux from E-sphere

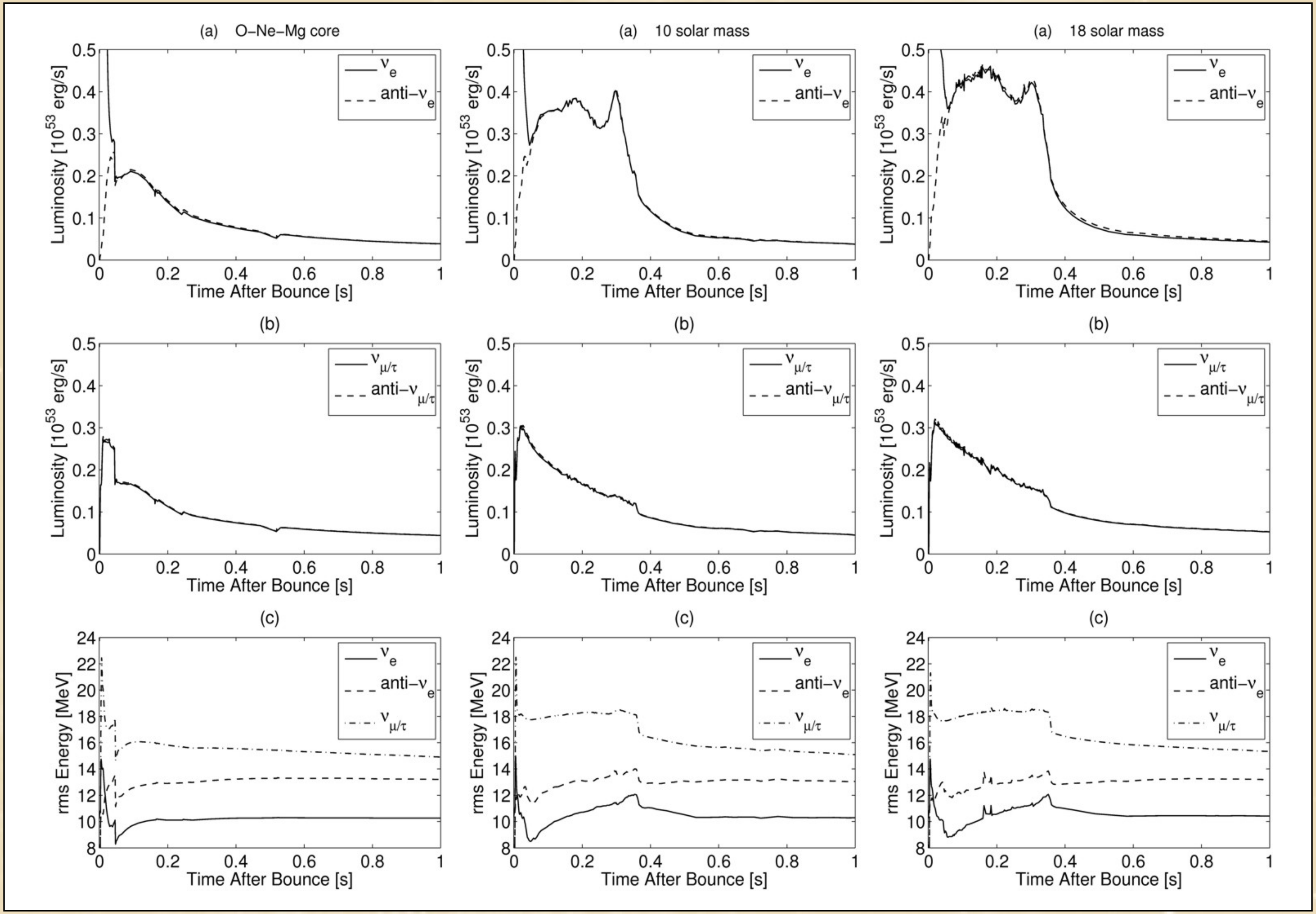
Transmitted flux

Reflected flux

Diffusion



Flavor Dependence of Neutrino Emission (Basel Group)



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

Spectral Flux Characteristics

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

Energy moments

(besides total luminosity L_ν)

Average energy $\langle E \rangle$

Spectral temperature $T = \langle E \rangle / 3$ (Maxwell Boltzmann)

General energy moments $\langle E^n \rangle$

(Two moments required to determine parameters for two-parameter fits, in addition to normalization)

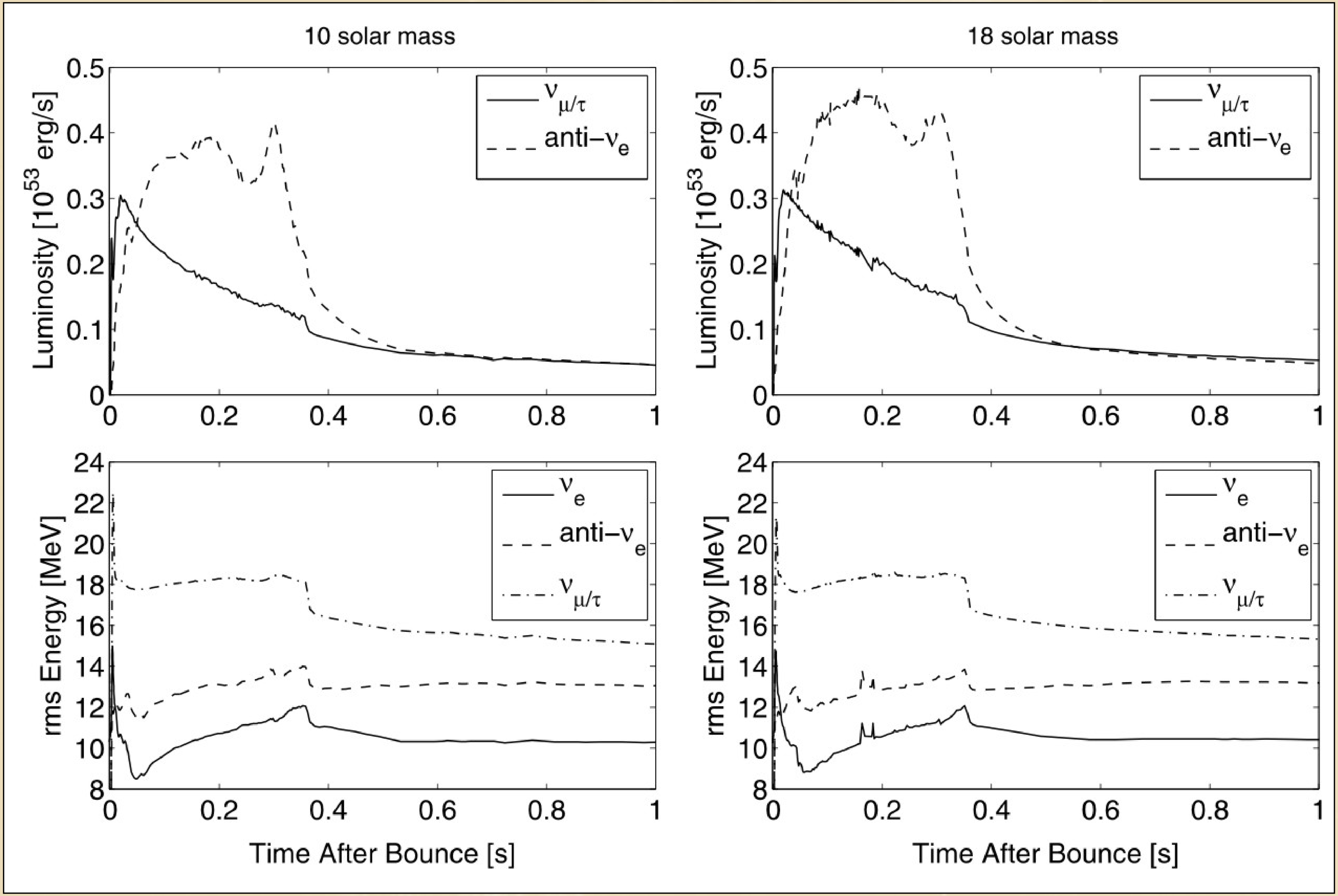
RMS energy (Basel and perhaps others)

$$E_{\rm rms} = \langle E^2 \rangle^{1/2} \approx 1.15\,\langle E \rangle$$ (Maxwell Boltzmann)

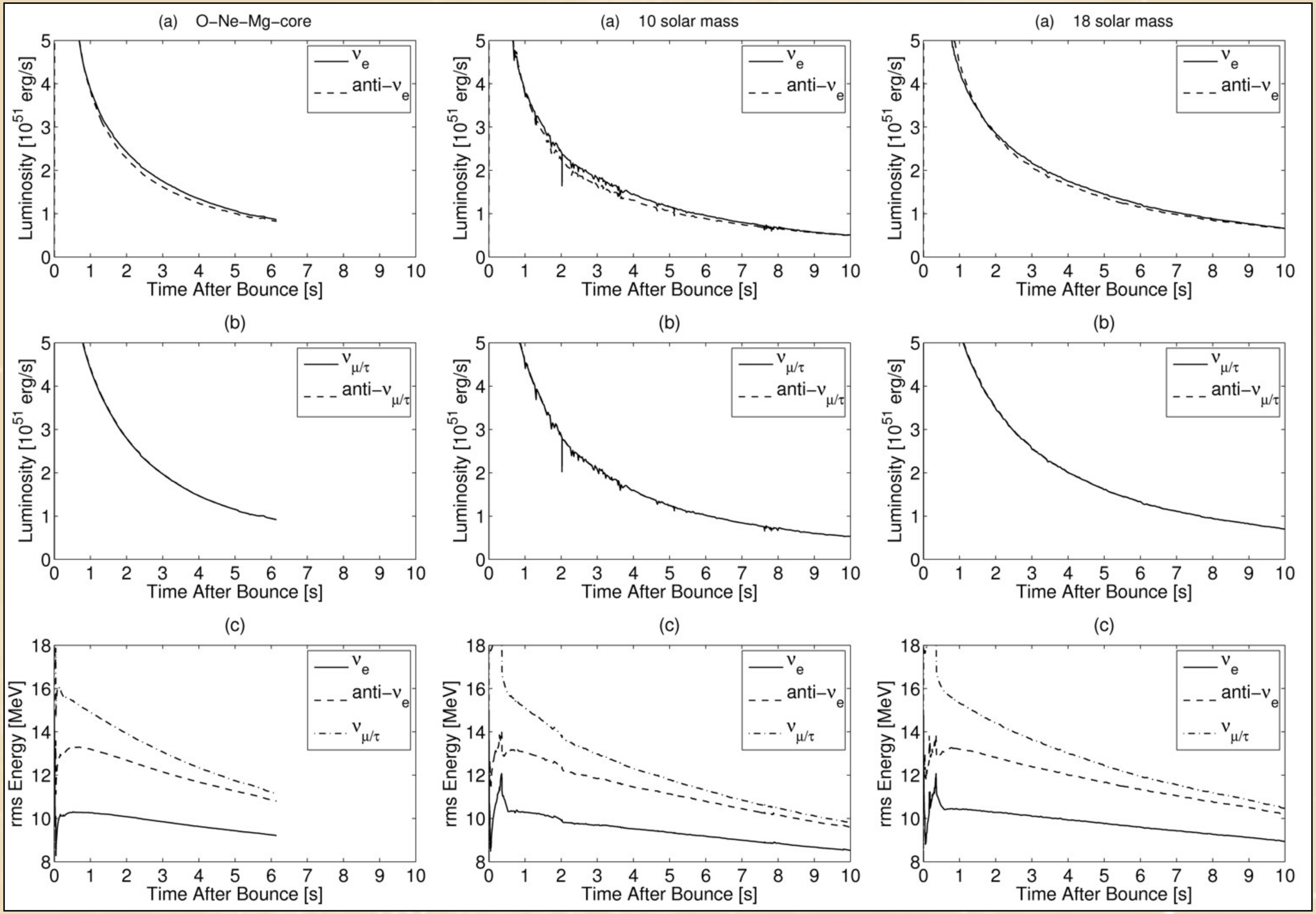
RMS energy (Garching)

$$E_{\rm rms} = \left(\langle E^3 \rangle \,/\, \langle E \rangle \right)^{1/2} \approx 1.49\,\langle E \rangle$$ (Maxwell Boltzmann)

Accretion Phase Results (Basel)

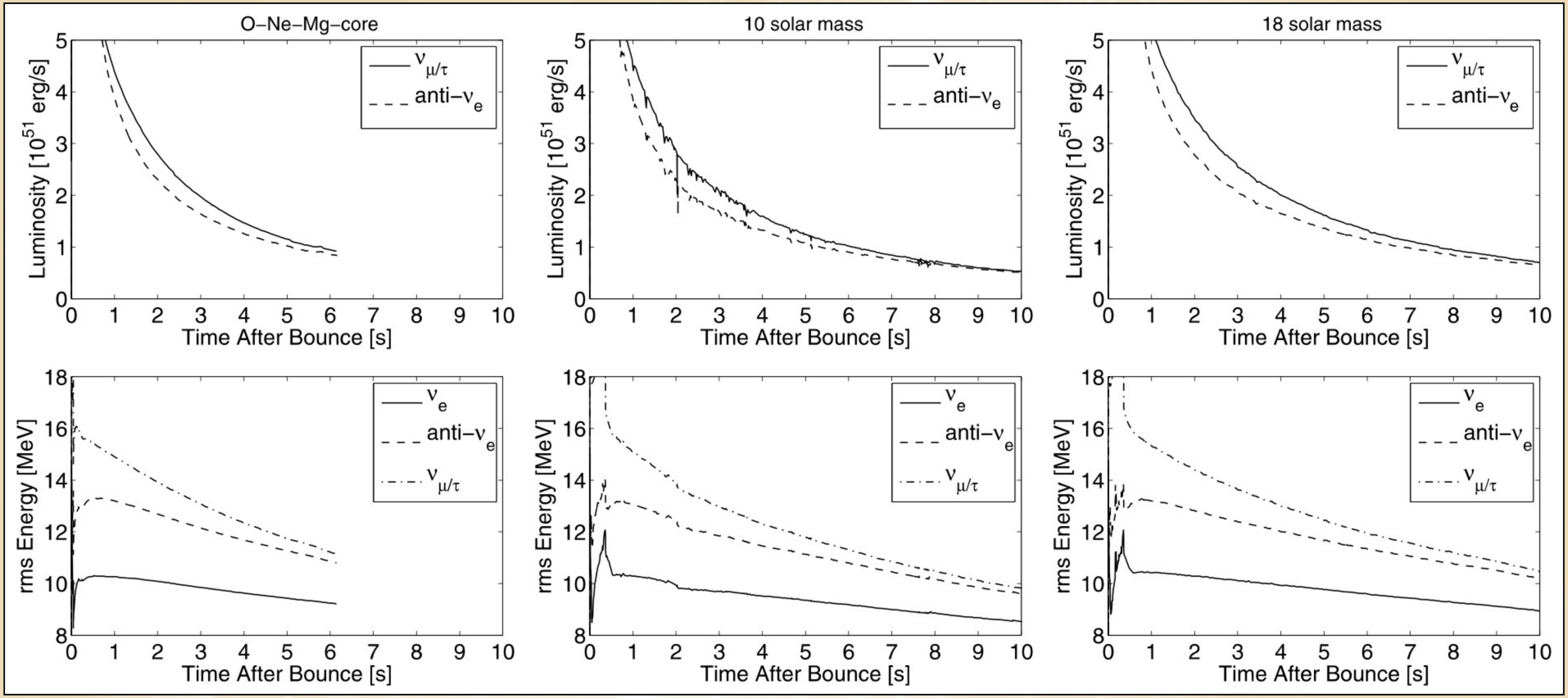


New Long-Term Cooling Calculations (Basel Group)



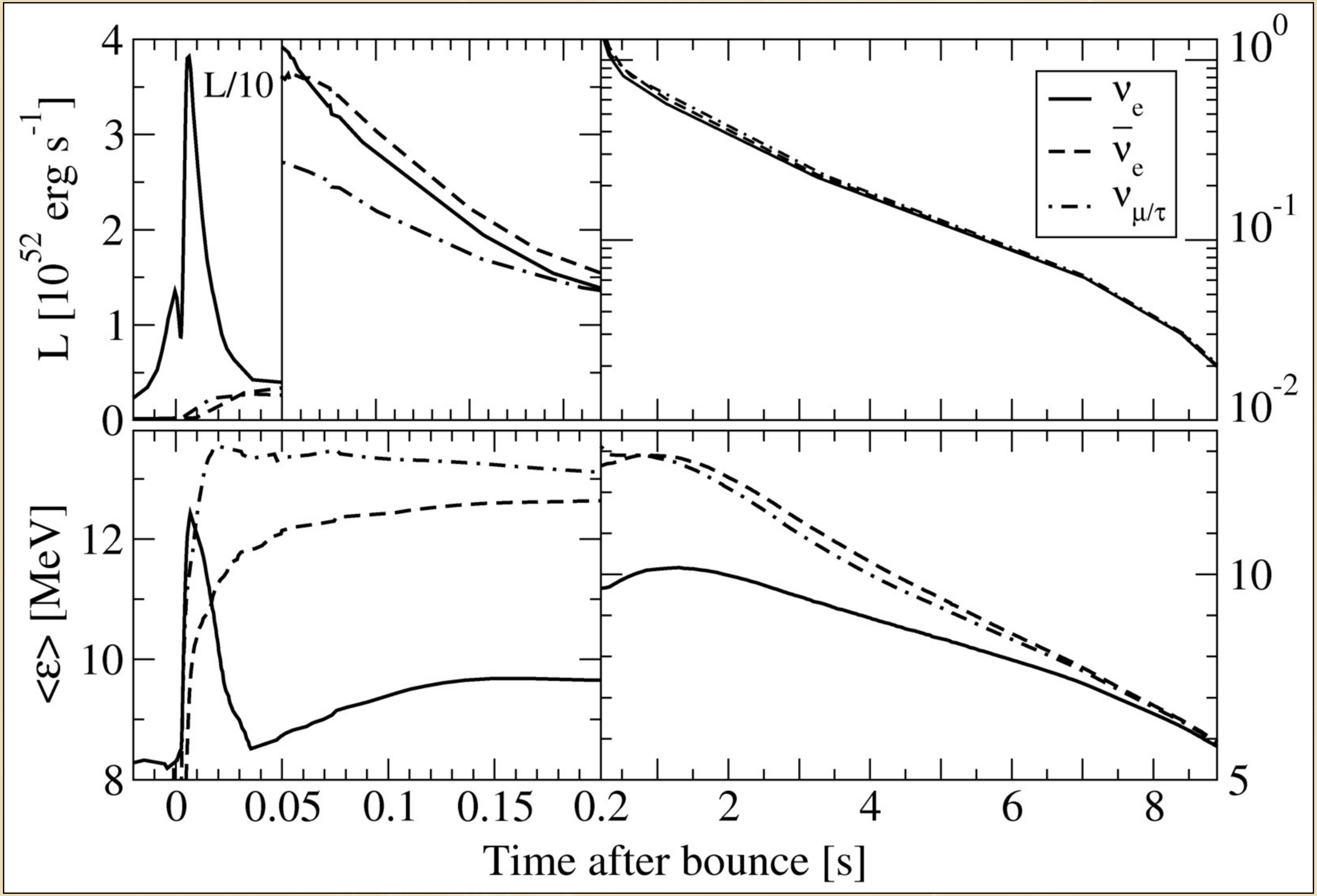
Fischer et al. (Basel Group), arXiv:0908.1871

New Long-Term Cooling Calculations (Basel Group)

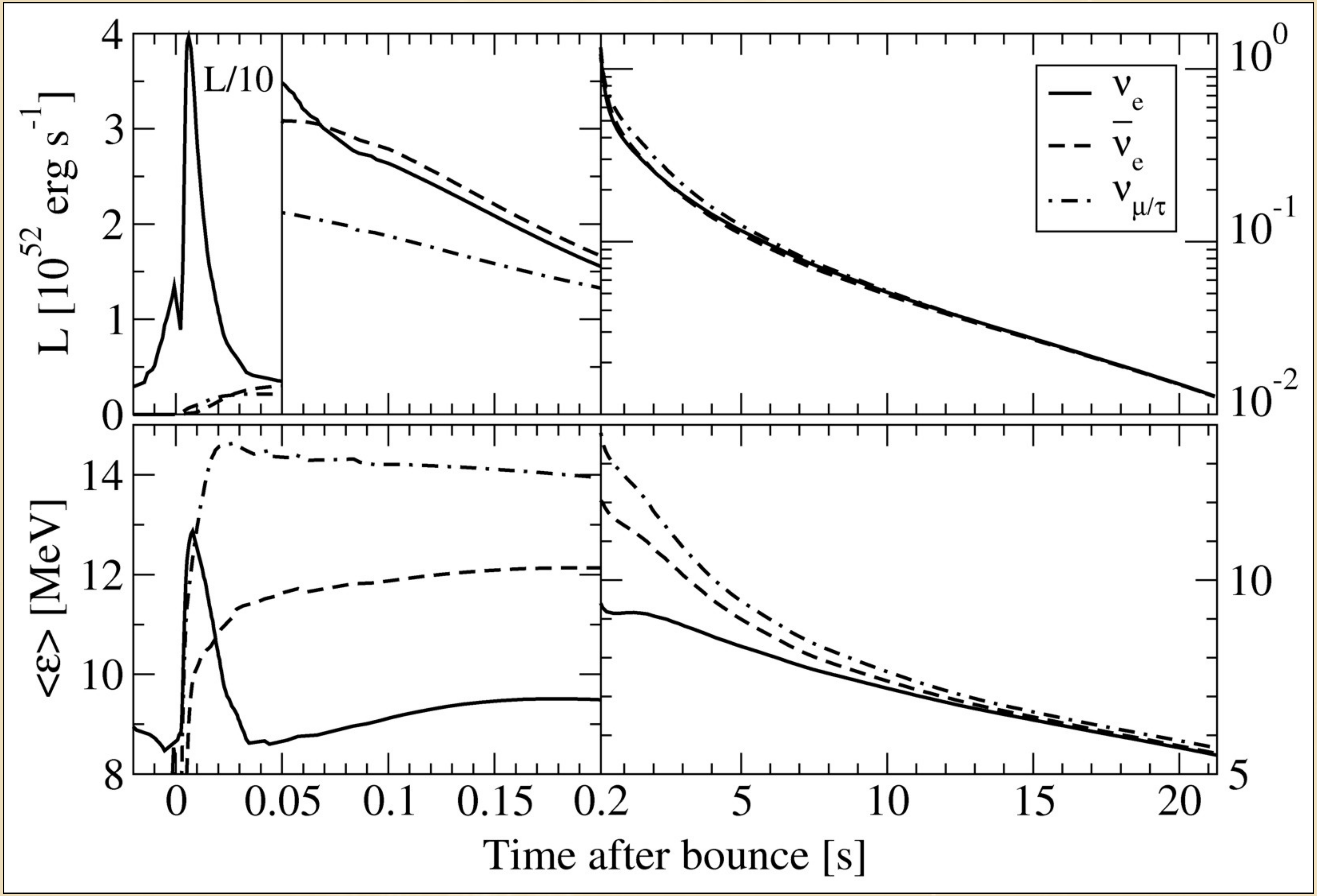


Fischer et al. (Basel Group), arXiv:0908.1871

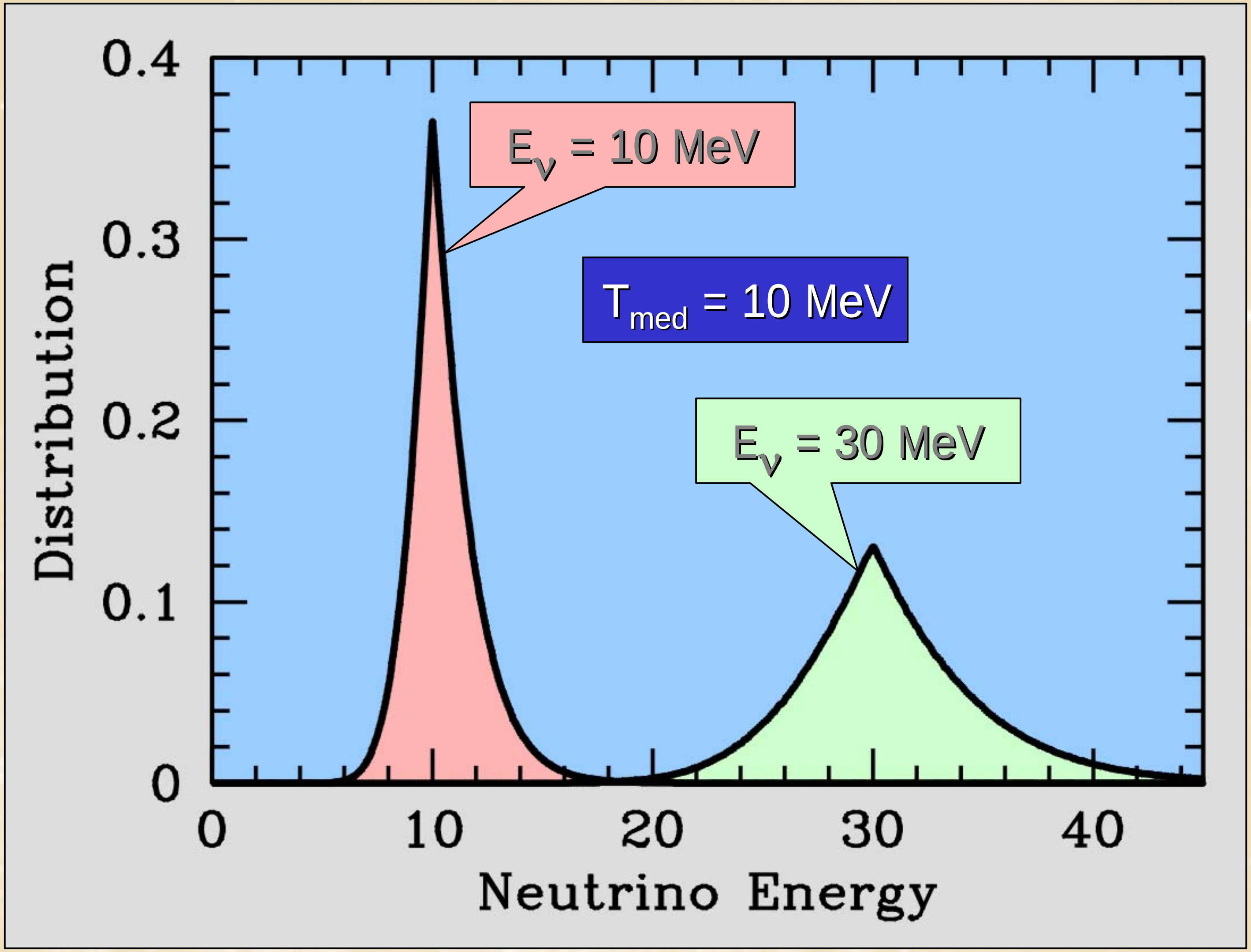
Garching EC-SN (Full Set of Opacities)



Garching EC-SN (Reduced Set of Opacities)

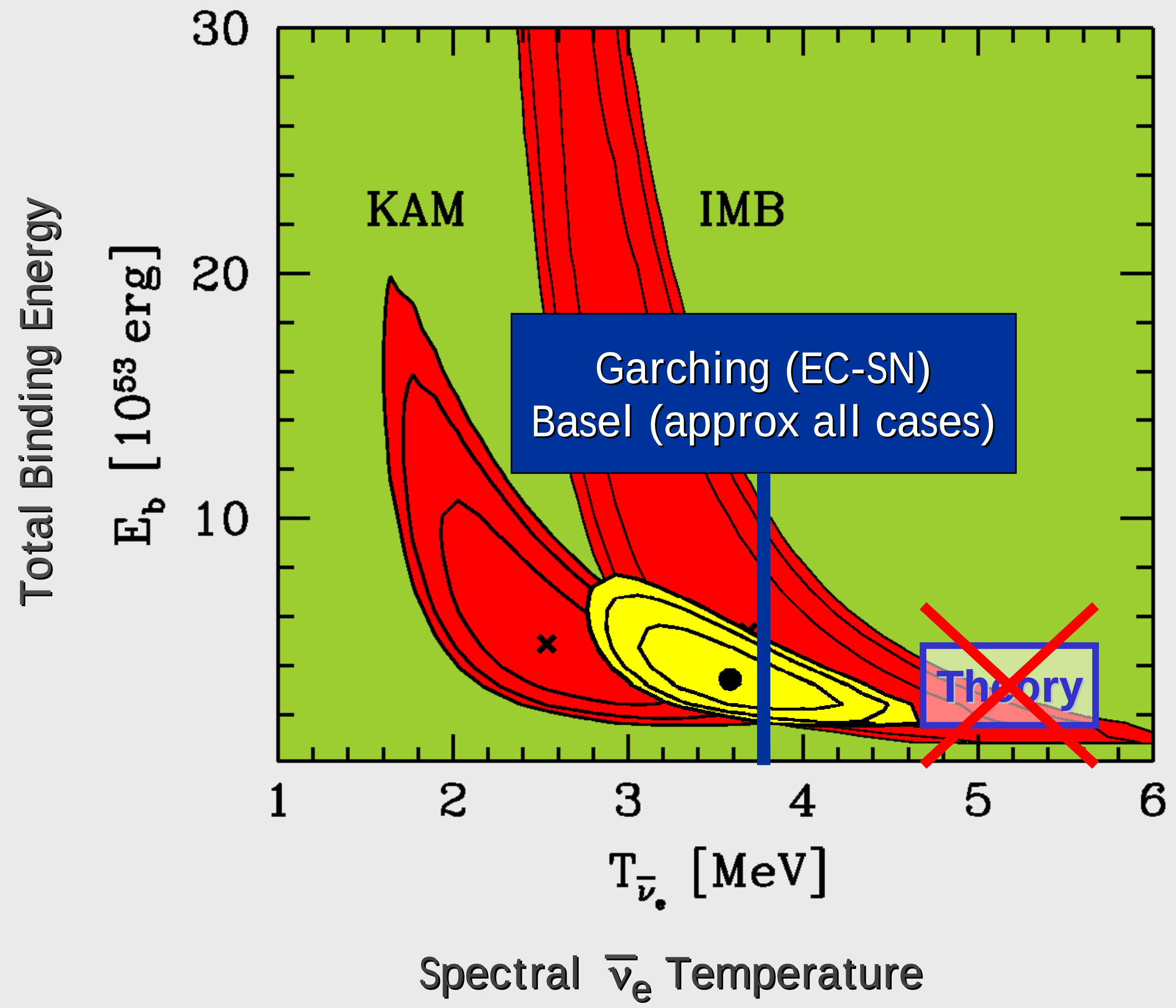


Energy Transfer by Nucleon Recoils



Energy transfer in νN collisions not insignificant
Typically lowers T_{flux} by 10–15%

Interpreting SN 1987A Neutrinos



Garching (EC-SN)
Basel (approx all cases)

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

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

Conclusions

Long term SN simulations in 1-D from collapse to cooling have become possible, using a full Boltzmann solver for neutrino transport (very recent results by Basel and Garching groups).

Based on Shen’s relatively stiff EoS, $\langle E(\bar{\nu}_e)\rangle \sim 11-12\ \mathrm{MeV}$ of integrated signal, similar for all progenitor masses (Basel), agreeing reasonably well with SN 1987A.
Probably not very different for other EoS (Garching forthcoming).

If there is a well developed accretion phase, flavor-dependent spectral and flux differences large
→ Best bet for observing flavor oscillation effects
with anti-neutrino detectors

During cooling phase, good luminosity equipartition (~10%) and hardly any spectral differences in anti-neutrino sector.