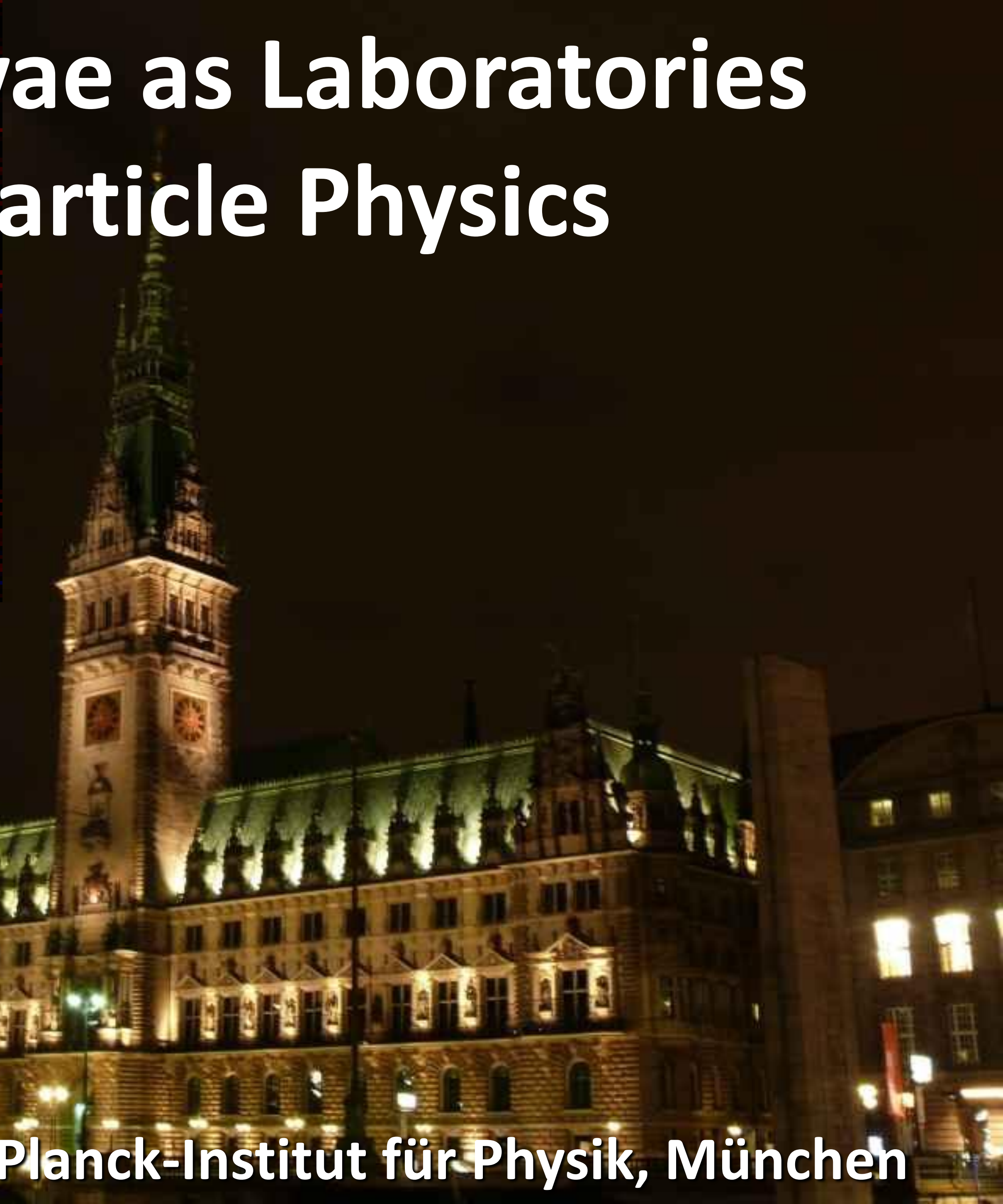
Supernovae as Laboratories for Particle Physics



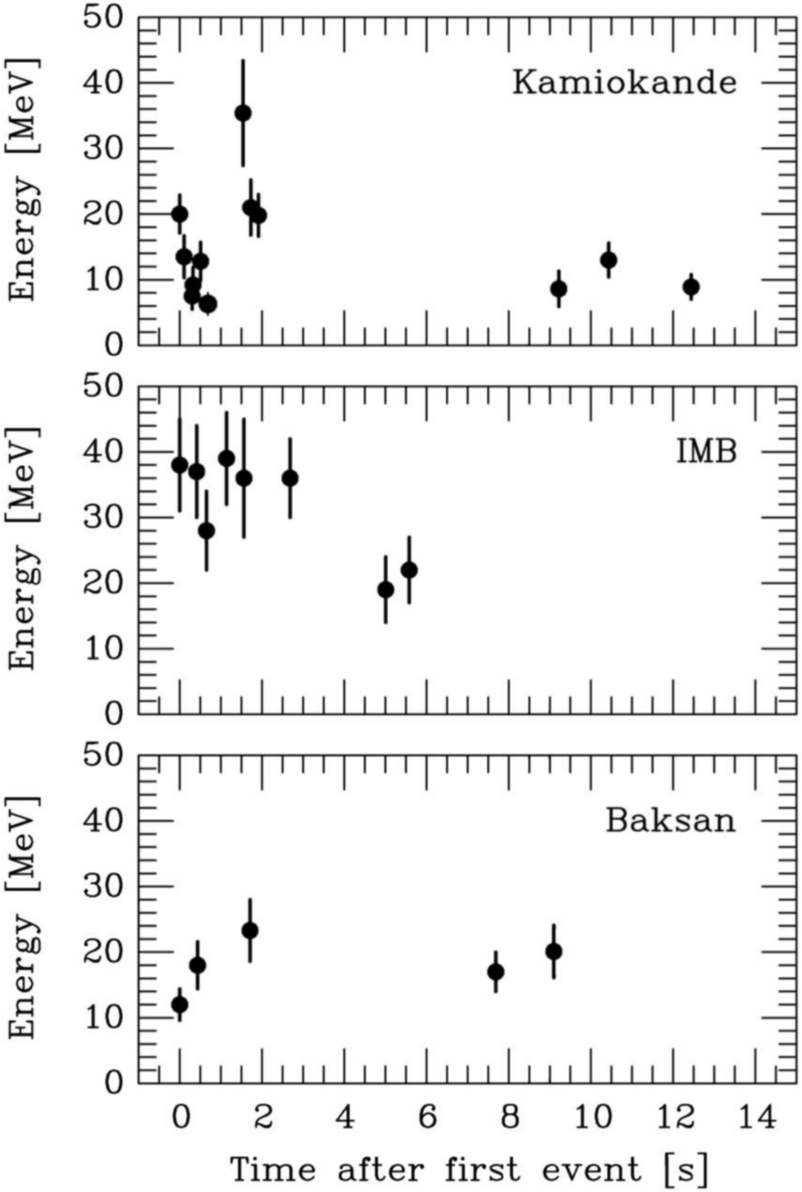
Georg Raffelt, Max-Planck-Institut für Physik, München

Sanduleak –69 202

Supernova 1987A

23 February 1987

Neutrino Signal of Supernova 1987A



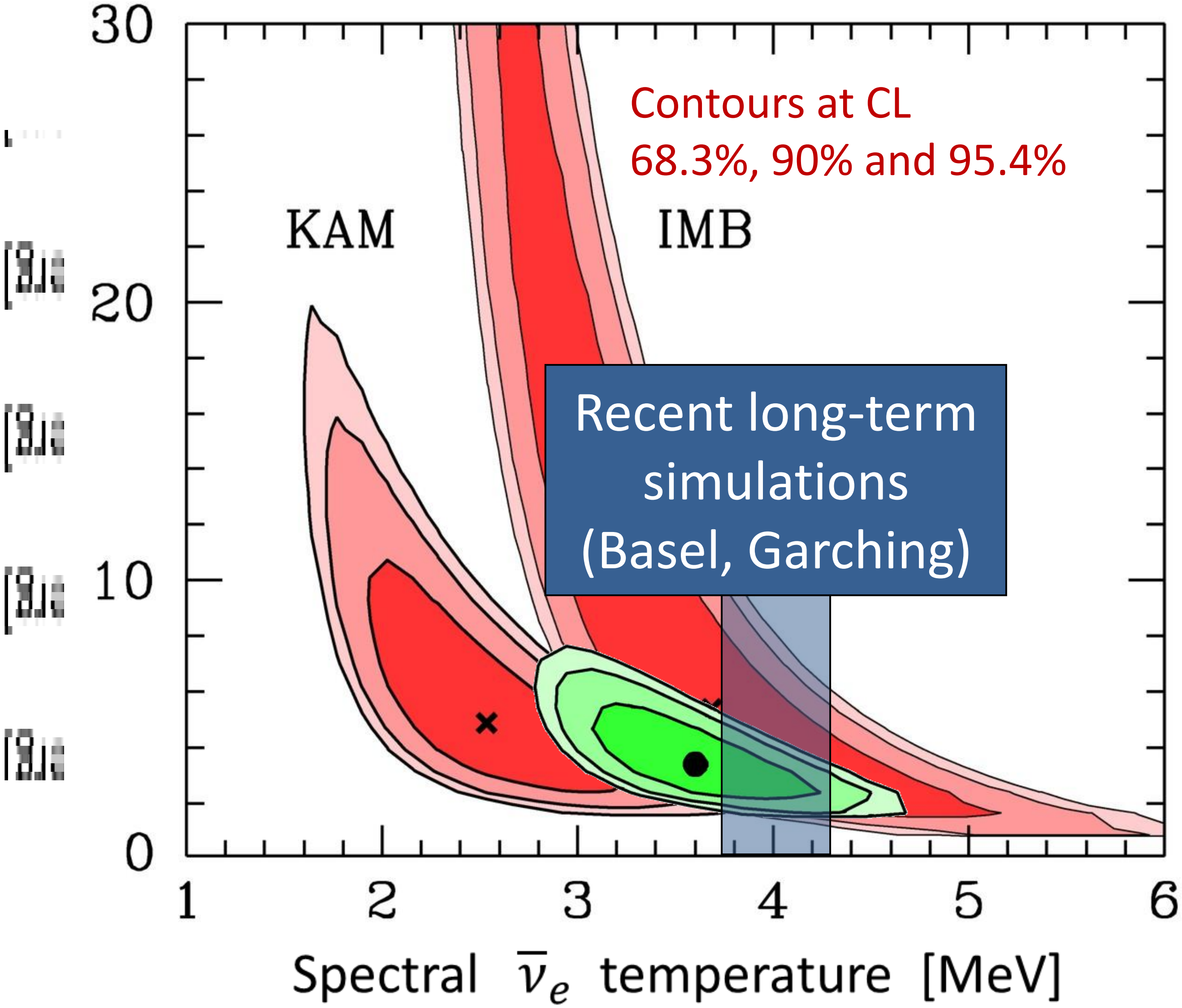
Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ±1 min

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,
all signals are contemporaneous**

Interpreting SN 1987A Neutrinos



Contours at CL
68.3%, 90% and 95.4%

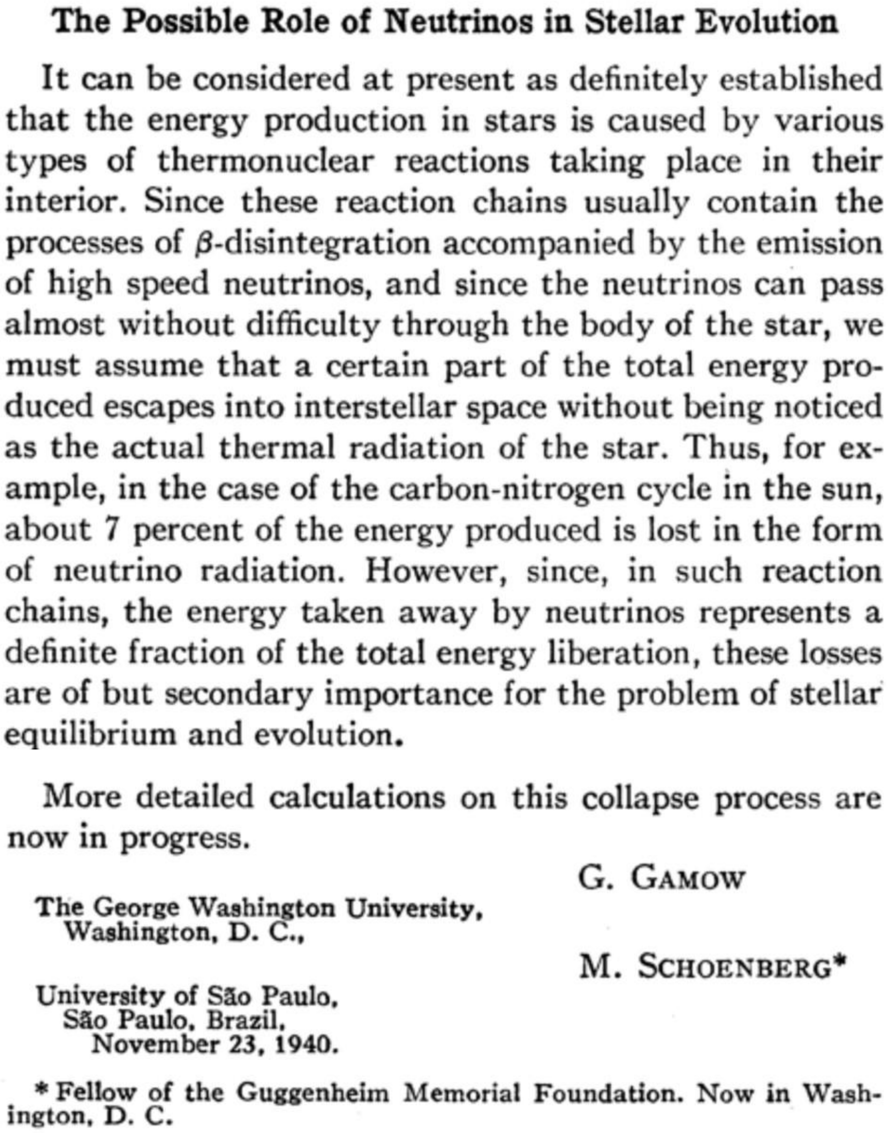
Recent long-term simulations (Basel, Garching)

Assume

- Thermal spectra
- Equipartition of energy between $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau$ and $\bar{\nu}_\tau$

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

Predicting Neutrinos from Core Collapse



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.

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.

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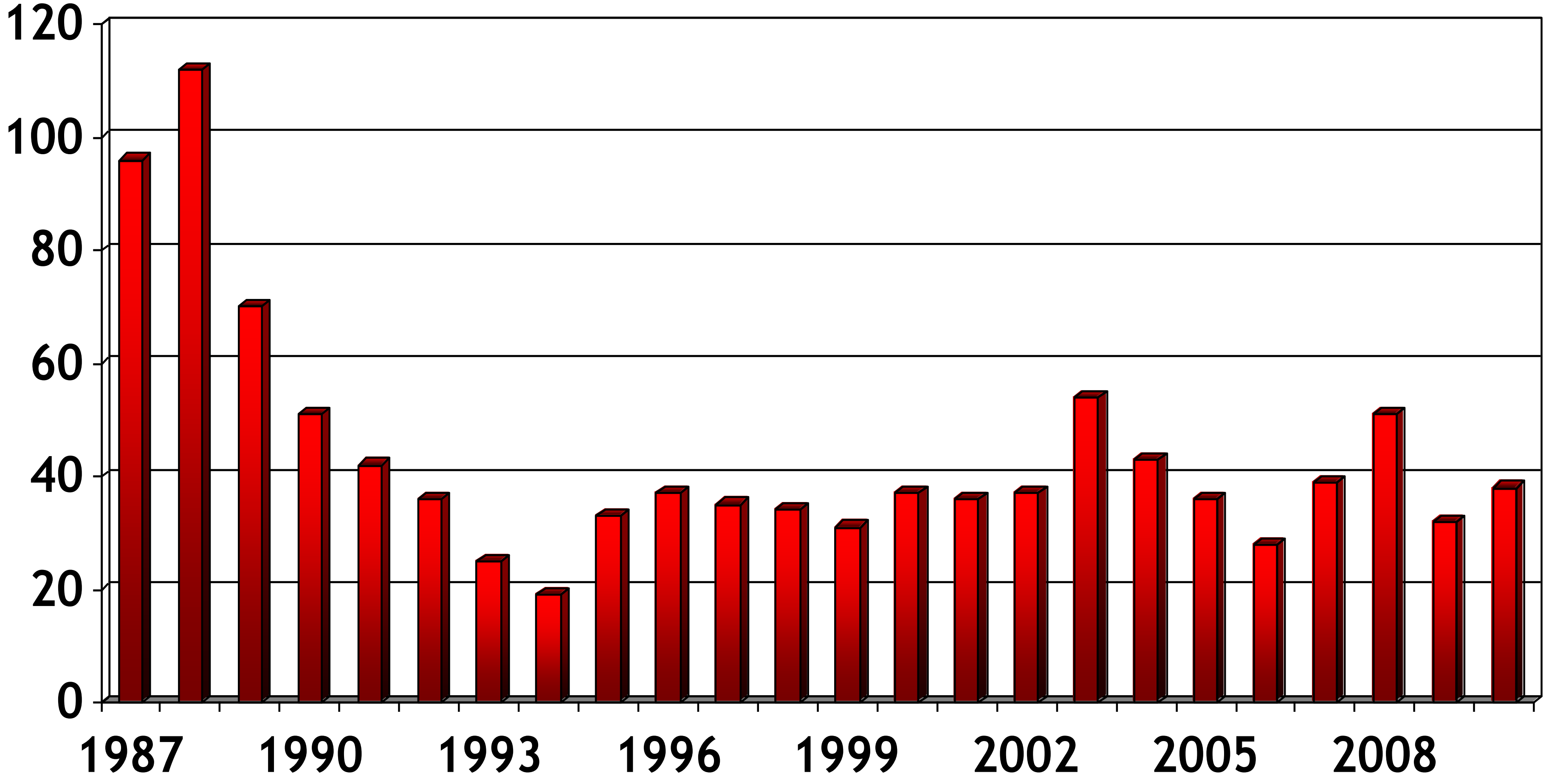
* Fellow of the Guggenheim Memorial Foundation. Now in Washington, D. C.

Phys. Rev. 58:1117 (1940)

SN 1987A Burst of Papers



Annual citations in SPIRES of the papers reporting the KII, IMB & BST neutrino observations (total of 1053 citations 1987-2010)

Signal Dispersion

Neutrino Limits by Intrinsic Signal Dispersion

Time of flight delay by neutrino mass

G. Zatsepin, JETP Lett. 8:205, 1968

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

SN 1987A signal duration implies

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

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 $\mathrm{m}_\nu < 2.2$ eV from tritium
- Cosmological limit today $m_\nu \lesssim 0.2$ eV

“Milli charged” neutrinos

Path bent by galactic magnetic field, inducing a time delay

$$\frac{\Delta t}{t} = \frac{e_\nu^2 (B_\perp d_B)^2}{6E_\nu^2} < 3 \times 10^{-12}$$

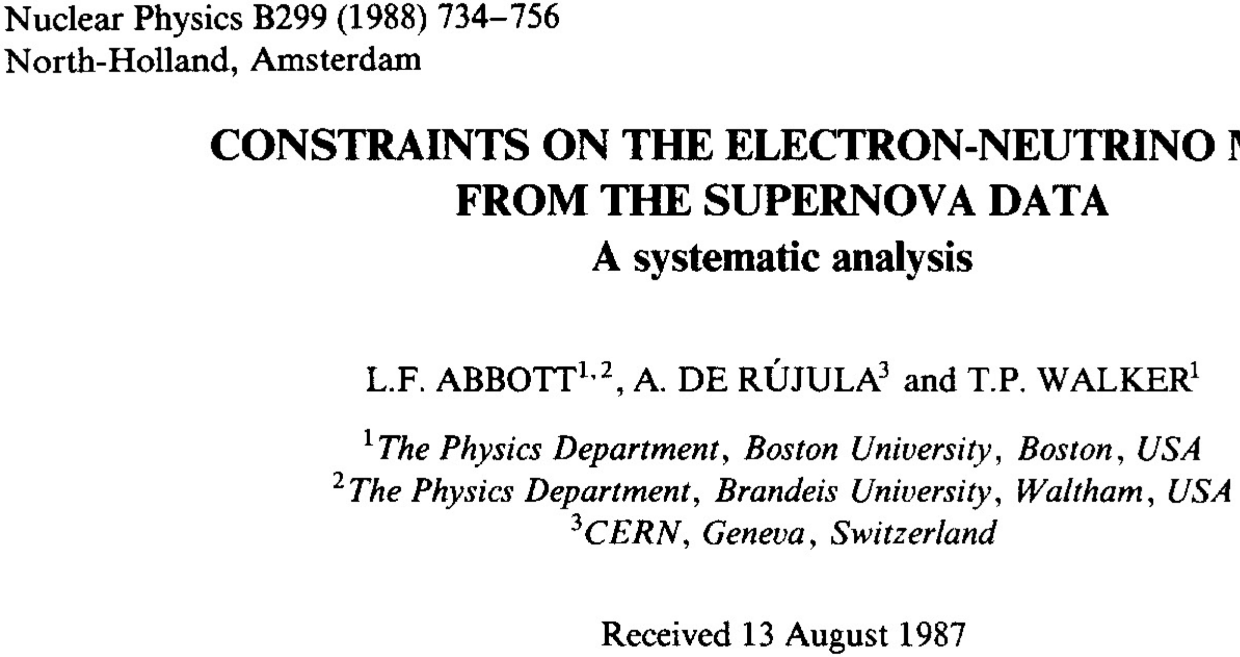
SN 1987A signal duration implies

$$\frac{e_\nu}{e} < 3 \times 10^{-17}\,\frac{1\mu G}{B_\perp}\,\frac{1\text{ kpc}}{d_B}$$

- 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

Some Papers on SN 1987A Neutrino Mass Limits



Nuclear Physics B299 (1988) 734–756
North-Holland, Amsterdam

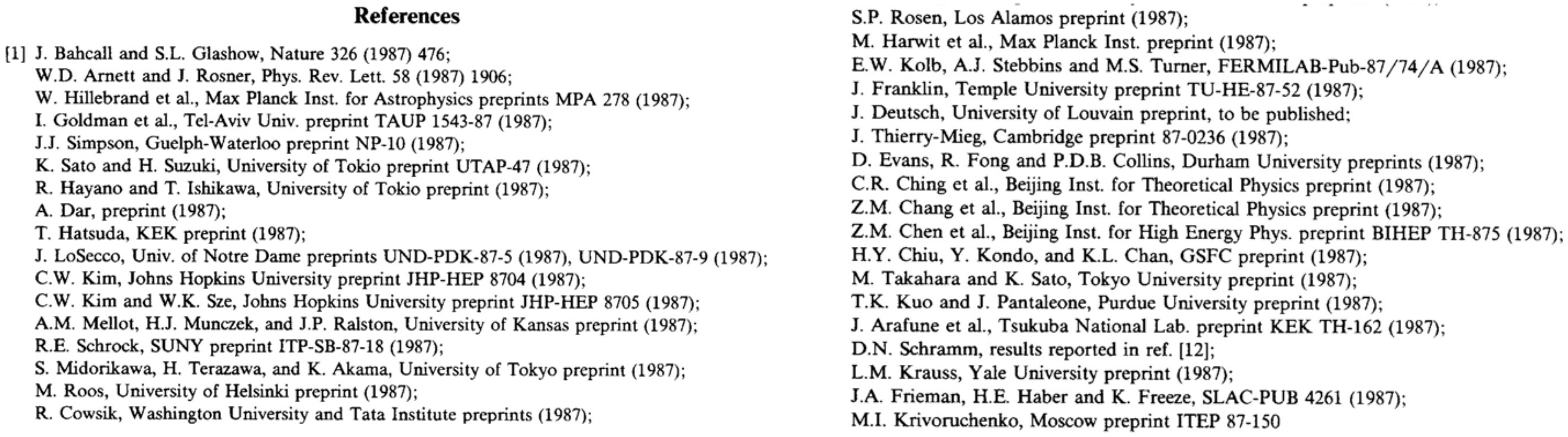
CONSTRAINTS ON THE ELECTRON-NEUTRINO MASS FROM THE SUPERNOVA DATA

A systematic analysis

L.F. ABBOTT[1,2], A. DE RÚJULA[3] and T.P. WALKER[1]

[1] *The Physics Department, Boston University, Boston, USA*
[2] *The Physics Department, Brandeis University, Waltham, USA*
[3] *CERN, Geneva, Switzerland*

Received 13 August 1987



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I. Goldman et al., Tel-Aviv Univ. preprint TAUP 1543-87 (1987);
J.J. Simpson, Guelph-Waterloo preprint NP-10 (1987);
K. Sato and H. Suzuki, University of Tokio preprint UTAP-47 (1987);
R. Hayano and T. Ishikawa, University of Tokio preprint (1987);
A. Dar, preprint (1987);
T. Hatsuda, KEK preprint (1987);
J. LoSecco, Univ. of Notre Dame preprints UND-PDK-87-5 (1987), UND-PDK-87-9 (1987);
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R.E. Schrock, SUNY preprint ITP-SB-87-18 (1987);
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C.R. Ching et al., Beijing Inst. for Theoretical Physics preprint (1987);
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M. Takahara and K. Sato, Tokyo University preprint (1987);
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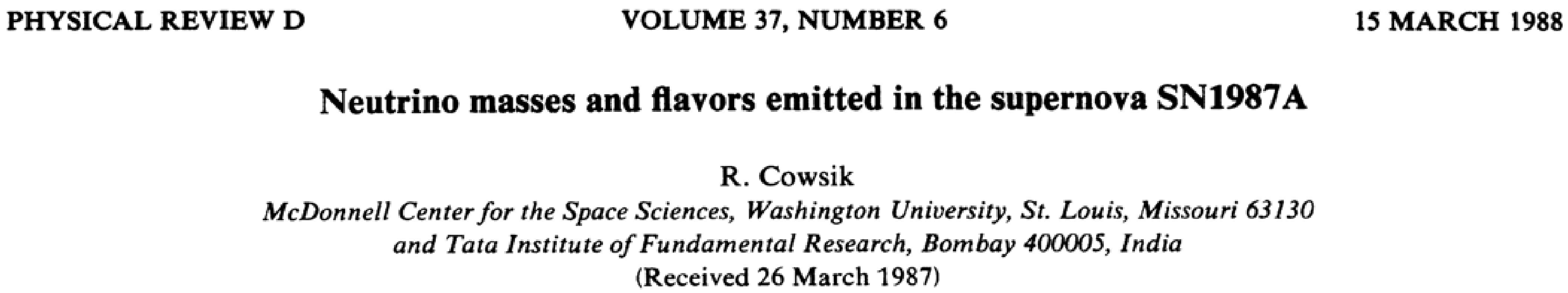
M.I. Krivoruchenko, Moscow preprint ITEP 87-150

Evidence for Cosmologically Interesting Masses?



PHYSICAL REVIEW D **VOLUME 37, NUMBER 6** **15 MARCH 1988**

Neutrino masses and flavors emitted in the supernova SN1987A

R. Cowsik
McDonnell Center for the Space Sciences, Washington University, St. Louis, Missouri 63130
and Tata Institute of Fundamental Research, Bombay 400005, India

(Received 26 March 1987)

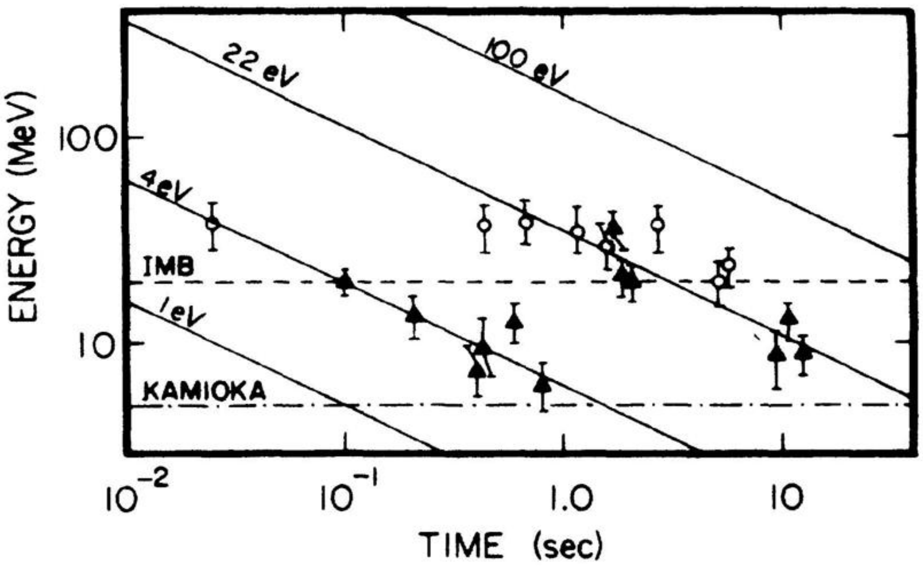


FIG. 1. The arrival time of the events is plotted against the observed energy for the Kamioka (triangles) and the IMB (circles) events. Lines of constant mass [Eq. (1)] are labeled.

If all neutrinos left the SN at the same time, evidence for the two mass values 4 and 22 eV

Neutrino Mass Sensitivity by Signal Dispersion

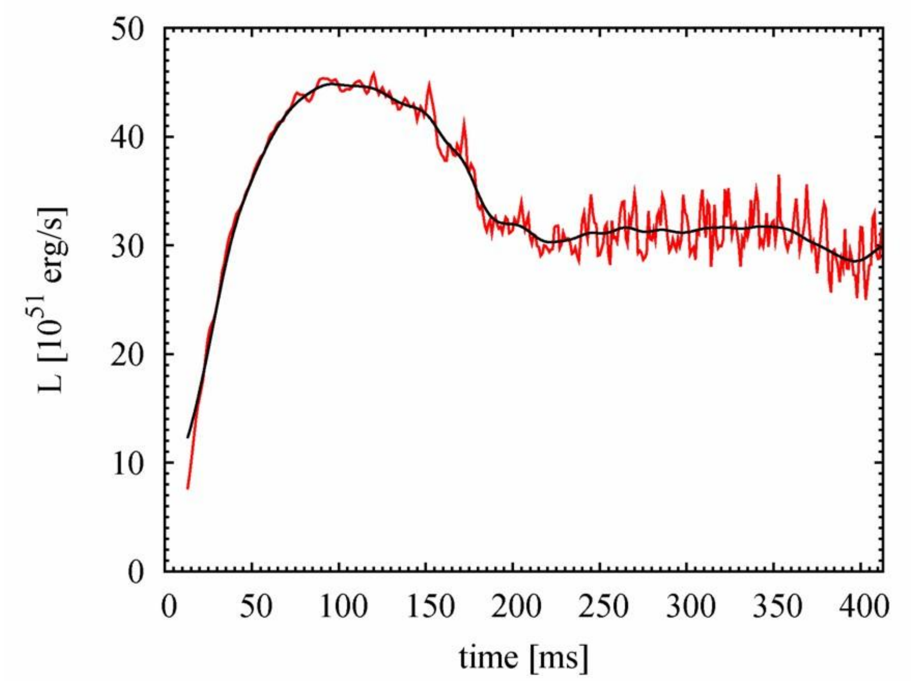
Time of flight delay of massive neutrinos

$$\Delta t = 5.1\ \mathrm{ms}\left(\frac{D}{10\ \mathrm{kpc}}\right)\left(\frac{10\ \mathrm{MeV}}{E_\nu}\right)^2\left(\frac{m_\nu}{1\ \mathrm{eV}}\right)^2$$

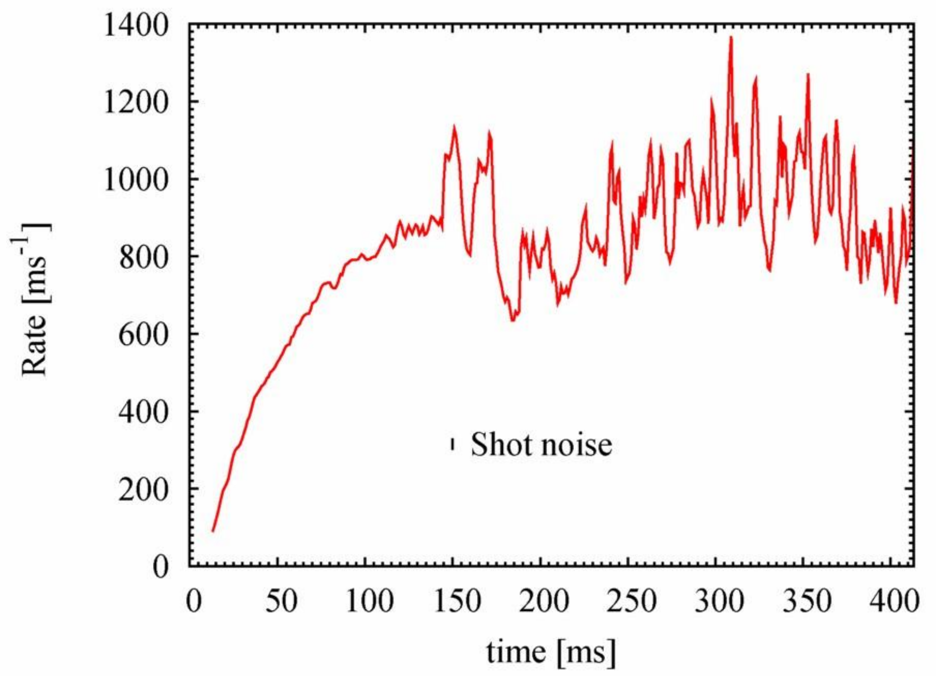
SN 1987A (50 kpc)	$E \approx 20$ MeV, $\Delta t \approx 10$ s Simple estimate or detailed maximum likelihood analysis give similar results	$m_\nu \lesssim 20$ eV
Future Galactic SN at 10 kpc (Super-K)	Rise-time of signal ~ 10 ms (Totani, PRL 80:2040, 1998)	$m_\nu \sim 3$ eV
	Full signal (Nardi & Zuluaga, NPB 731:140, 2005)	$m_\nu \sim 1$ eV
With late black-hole formation	Cutoff “infinitely” fast (Beacom et al., PRD 63:073011, 2001)	$m_\nu \sim 2$ eV
Future SN in Andromeda (Megatonne)	$D \approx 750$ kpc, $\Delta t \approx 10$ s few tens of events	$m_\nu \sim 1–2$ eV

Variability seen in Neutrinos

Luminosity



Detection rate in IceCube

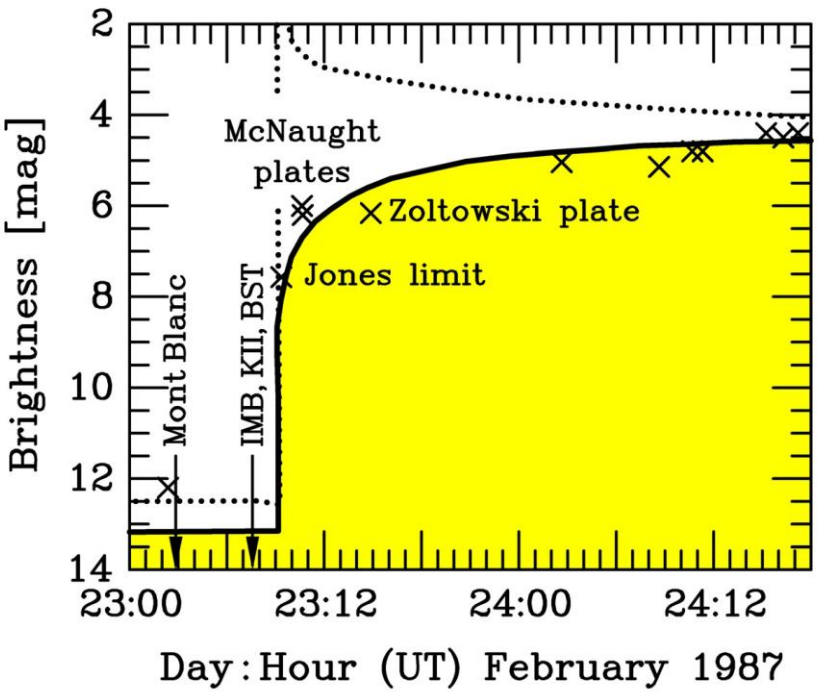


Smaller in realistic 3D models

Lund, Marek, Lunardini, Janka & Raffelt, arXiv:1006.1889
Using 2-D model of Marek, Janka & Müller, arXiv:0808.4136

Do Neutrinos Gravitate?

Early light curve of SN 1987A



- Neutrinos arrived several hours before photons as expected
- Transit time for ν and γ same (160.000 yr) within a few hours

Shapiro time delay for particles moving in a gravitational potential

$$\Delta t = -2 \int_A^B dt\, \Phi[r(t)]$$

For trip from LMC to us, depending on galactic model,

$$\Delta t \approx 1\text{–}5 \text{ months}$$

Neutrinos and photons respond to gravity the same to within

$$1\text{–}4 \times 10^{-3}$$

Longo, PRL 60:173, 1988
Krauss & Tremaine, PRL 60:176, 1988

Millisecond Bounce Time Reconstruction

Super-Kamiokande

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

Pagliaroli, Vissani, Coccia & Fulgione
arXiv:0903.1191

IceCube

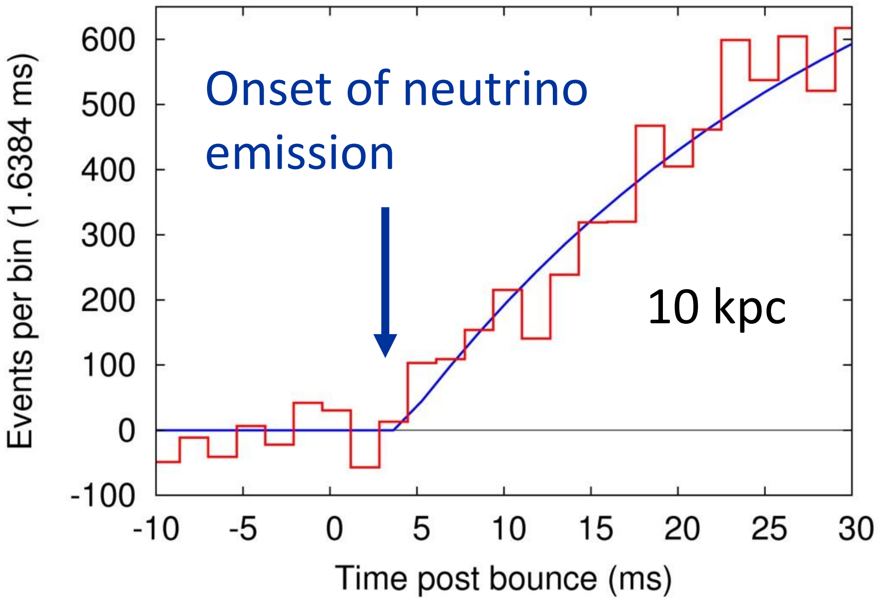


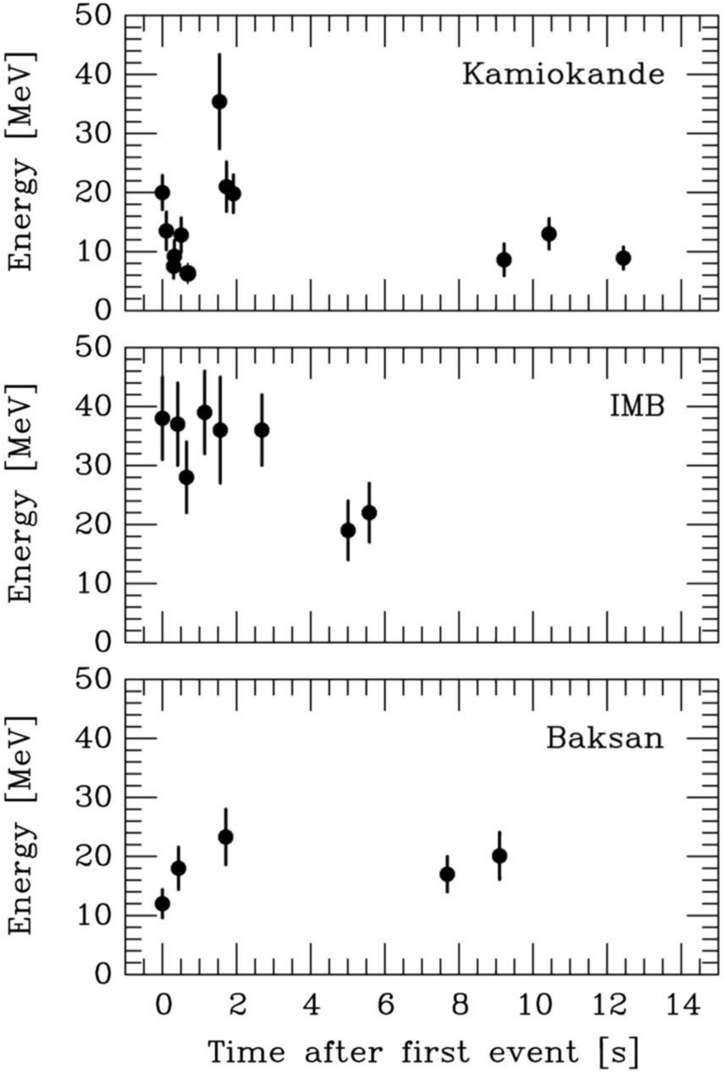
FIG. 1: Typical Monte Carlo realization (red histogram) and reconstructed fit (blue line) for the benchmark case discussed in the text for a SN at 10 kpc.

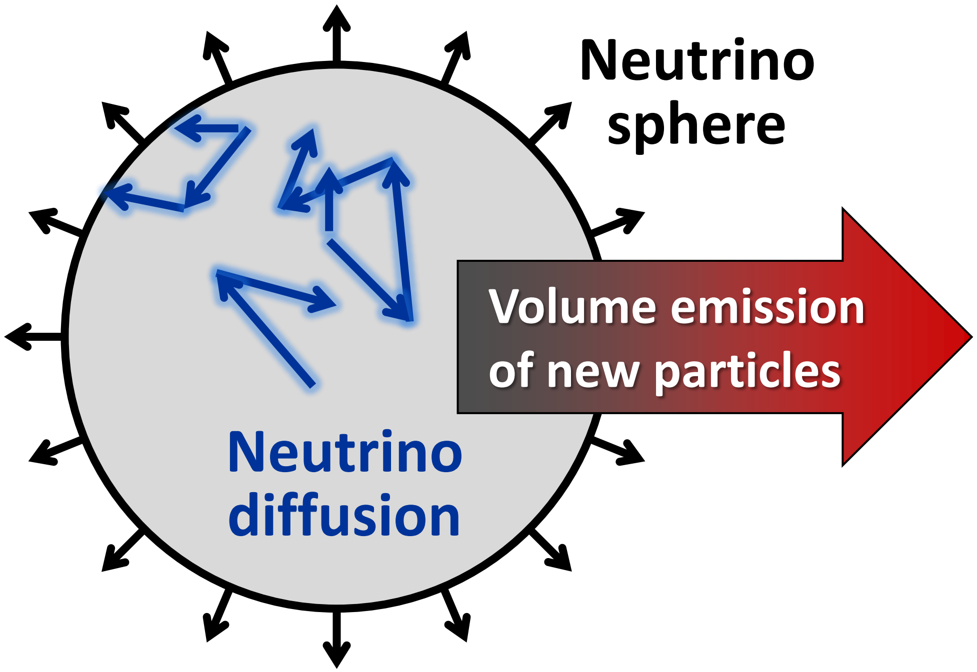
Halzen & Raffelt, arXiv:0908.2317

Energy-Loss Argument

Supernova 1987A Energy-Loss Argument

SN 1987A neutrino signal





Neutrino sphere

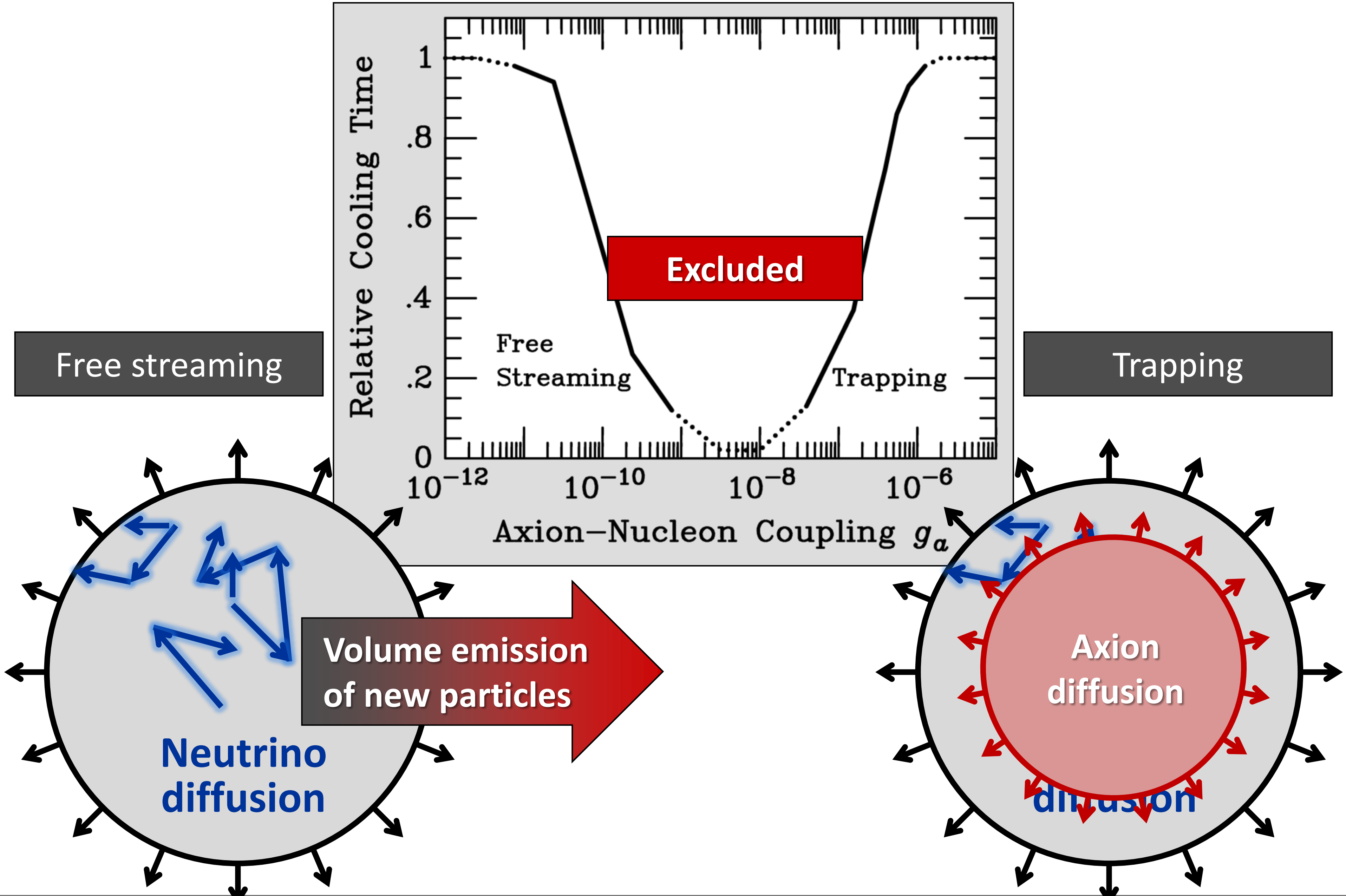
Volume emission of new particles

Neutrino diffusion

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 Axion Limits



Excluded

Free streaming

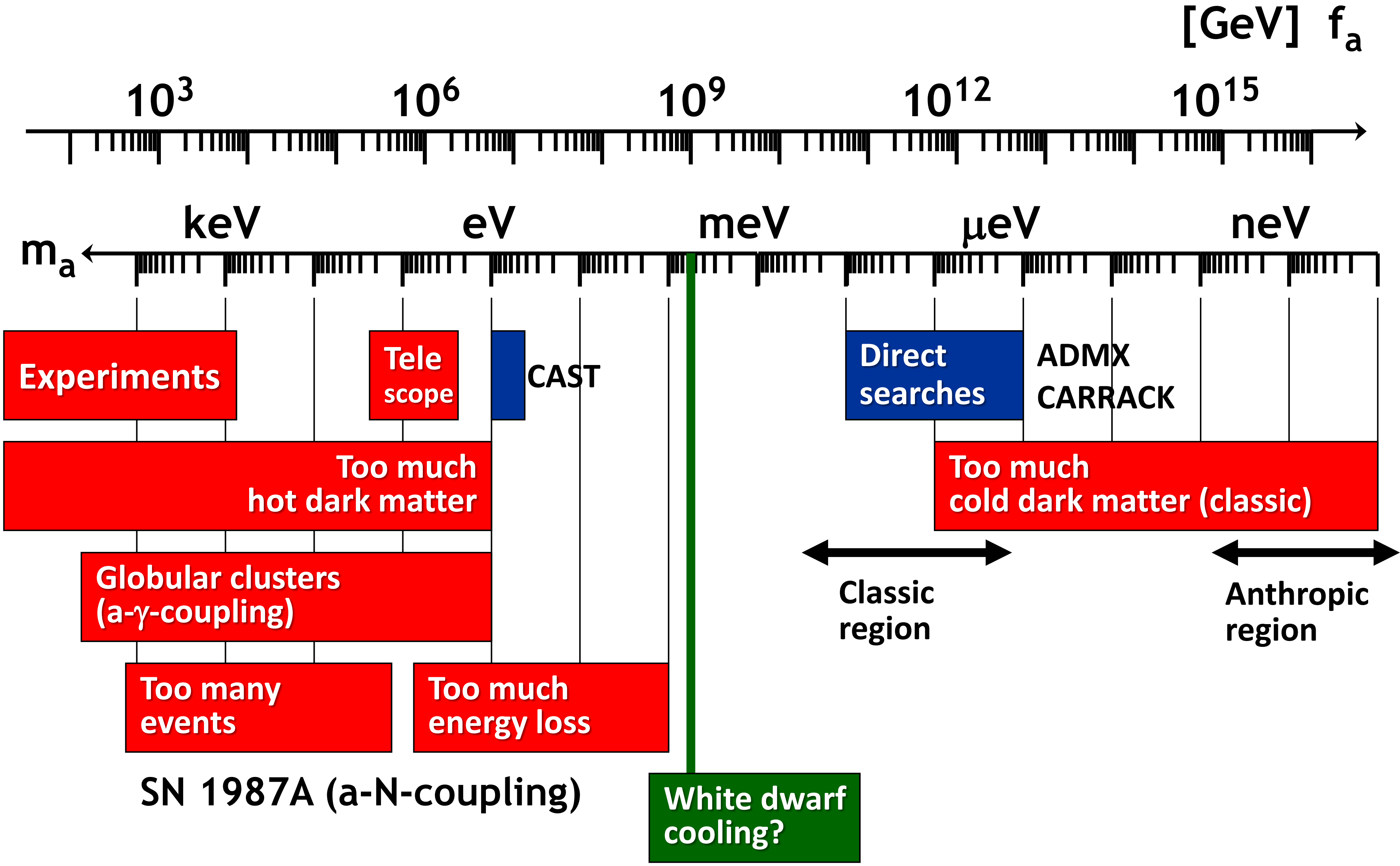
Trapping

Volume emission of new particles

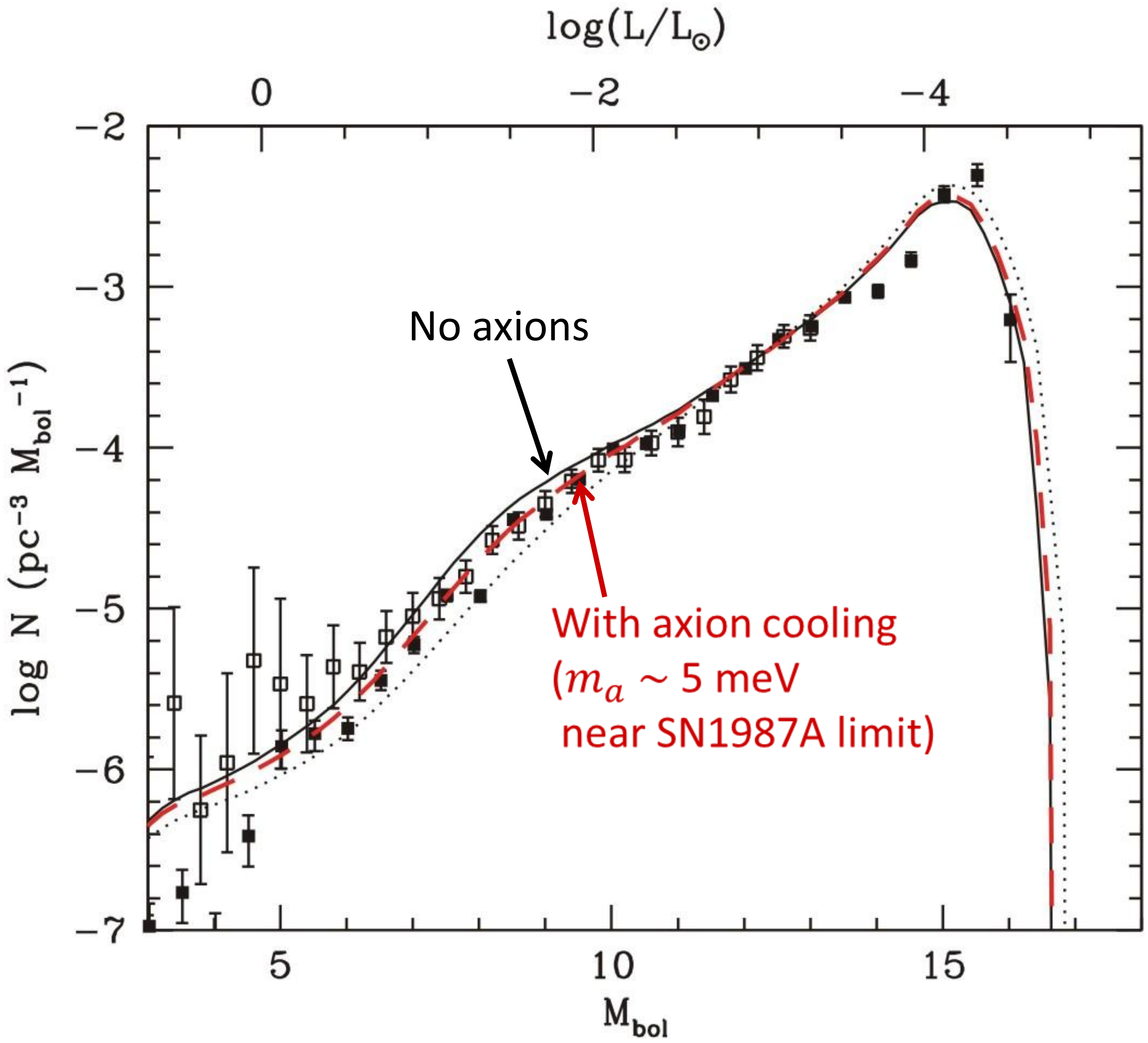
Neutrino diffusion

Axion diffusion

Axion Bounds



Do White Dwarfs Need Axion Cooling?



No axions

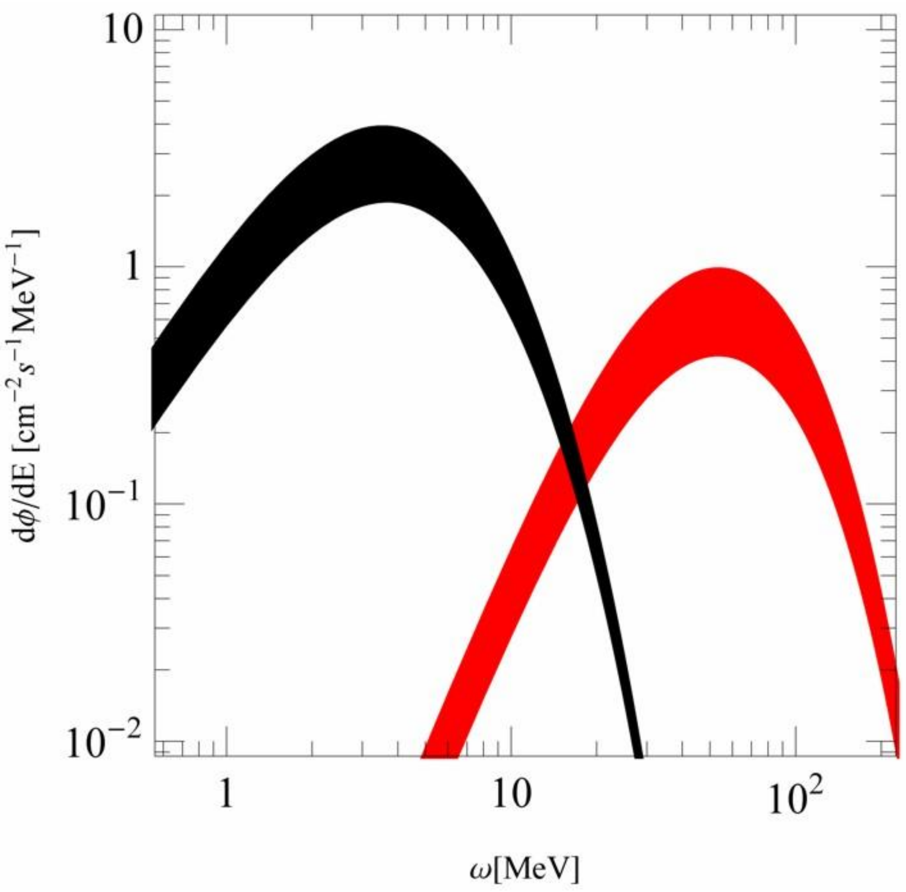
With axion cooling ($m_a \sim 5$ meV near SN1987A limit)

White dwarf luminosity function (number of WDs per brightness interval)

Isern, Catalán, García-Berro & Torres arXiv:0812.3043

Diffuse Supernova Axion Background (DSAB)

- Neutrinos from all core-collapse SNe comparable to photons from all stars
- Diffuse Supernova Neutrino Background (DSNB) similar energy density as extra-galactic background light (EBL), approx 10% of CMB energy density
- DSNB probably next astro neutrinos to be measured



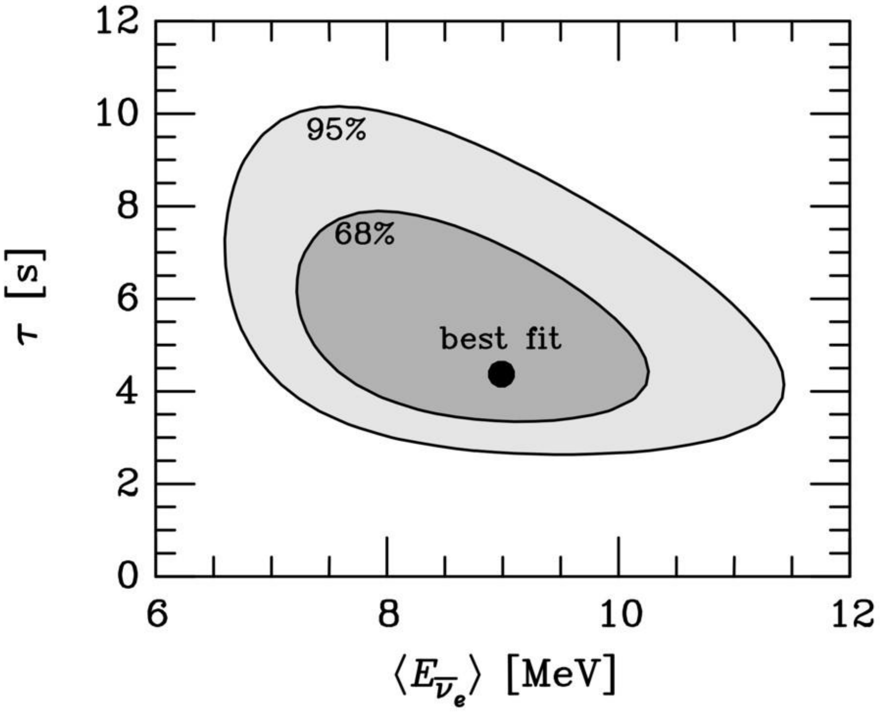
- Axions with $m_a \sim 10$ meV near SN 1987A energy-loss limit
- Provide DSAB with compable energy density as DSNB and EBL
- No obvious detection channel

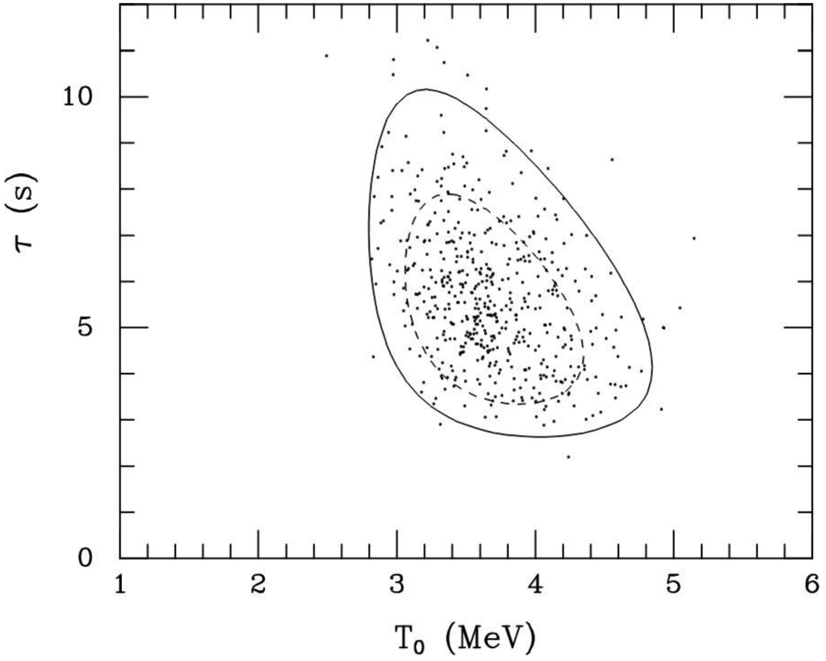
Raffelt, Redondo & Viaux
work in progress (2011)

Cooling Time Scale

Exponential cooling model: $T = T_0\, e^{-t/4\tau}$, constant radius, $L = L_0\, e^{-t/\tau}$

Fit parameters are T_0, τ, radius, 3 offset times for KII, IMB & BST detectors

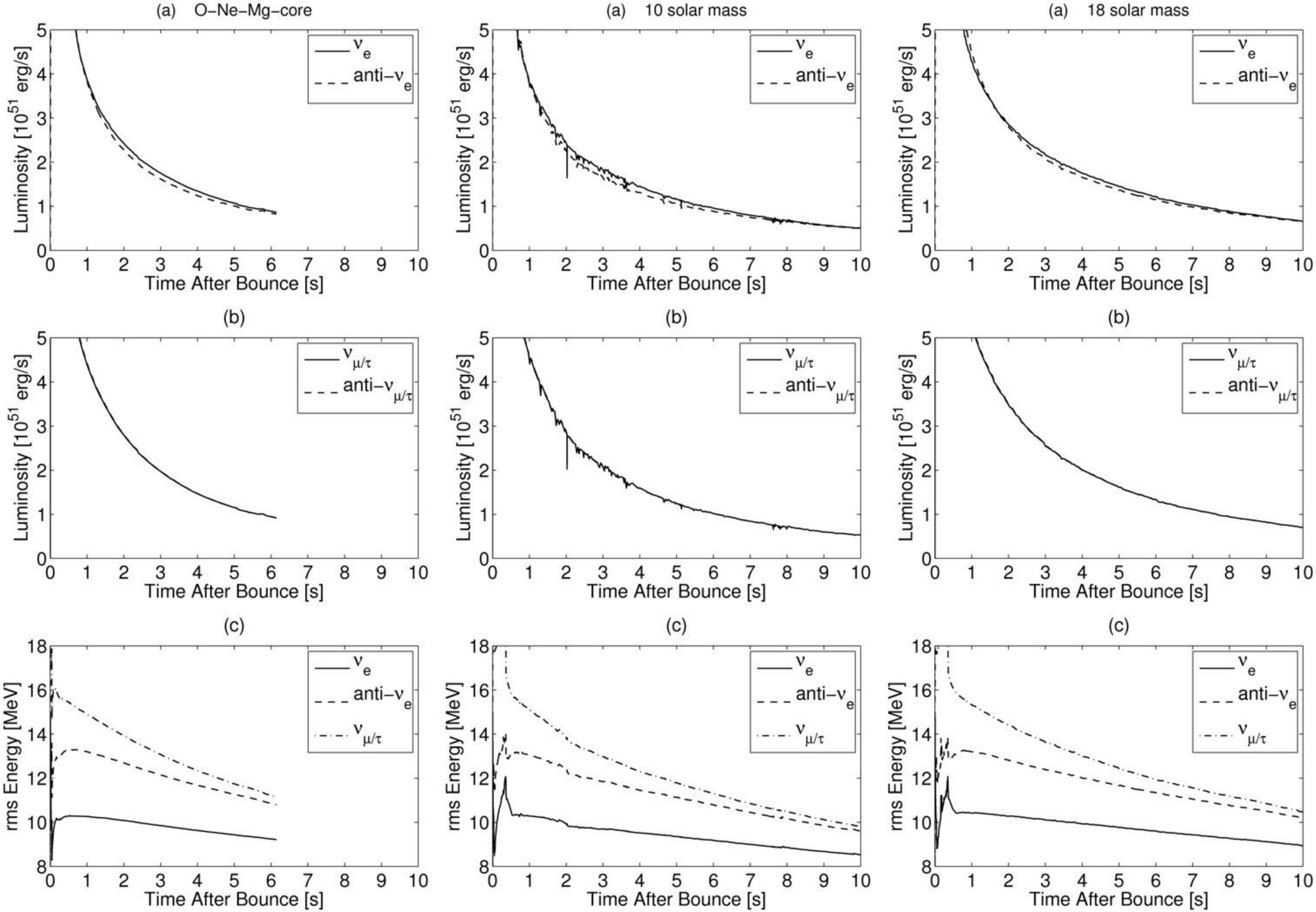




Loredo and Lamb
Unpublished preprint 1995

Loredo and Lamb, Bayesian analysis
astro-ph/0107260

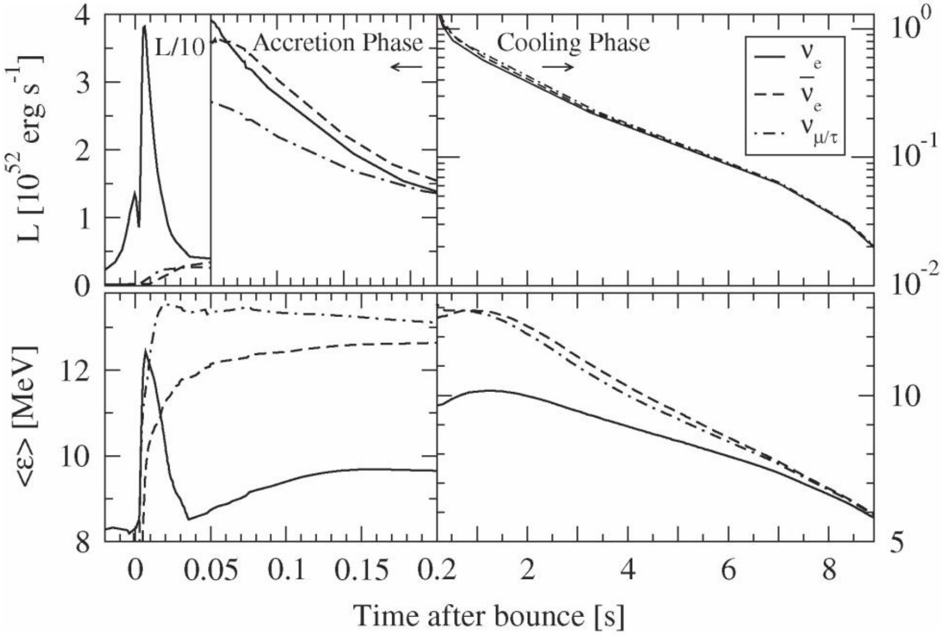
Long-Term Cooling Calculations (Basel 2009)

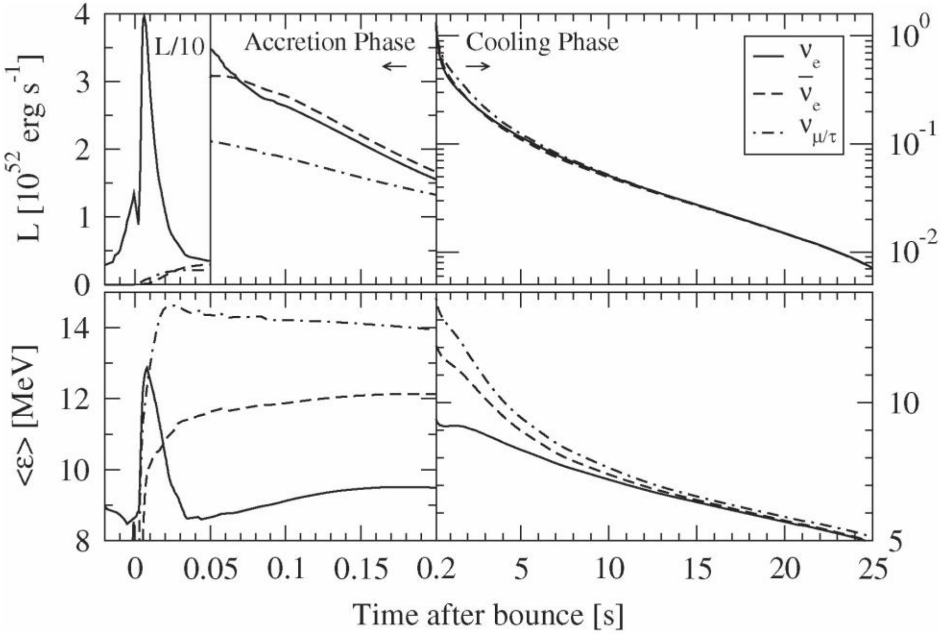


Long-Term Cooling of EC SN (Garching 2009)

Neutrino opacities with strong NN correlations and nucleon recoil in neutrino-nucleon scattering.
Exponential cooling with $\tau = 2.6\ \mathrm{s}$
Barely allowed by SN 1987A

Neutrino opacities without these effects (~ Basel case?)
Much longer cooling times





L. Hüdepohl et al. (Garching Group), arXiv:0912.0260

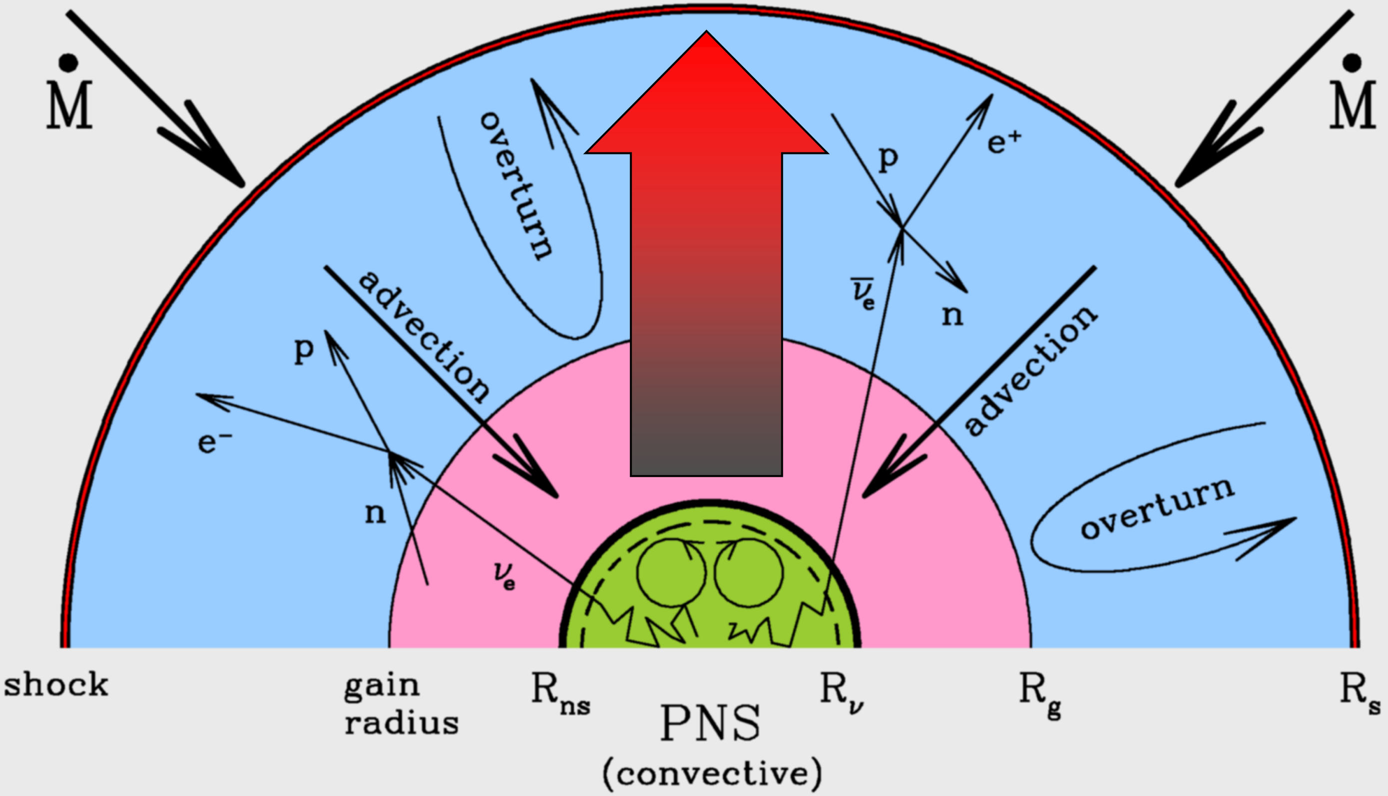
Next Steps

Possibility for long-term cooling calculations suggests that one should

- Study cooling behavior for a range of EoS, progenitor masses and opacity assumptions
- Impact of PNS convection?
- Compare with SN 1987A neutrino signal
- Include generic energy loss by new channel

Energy Transfer to Gain Region

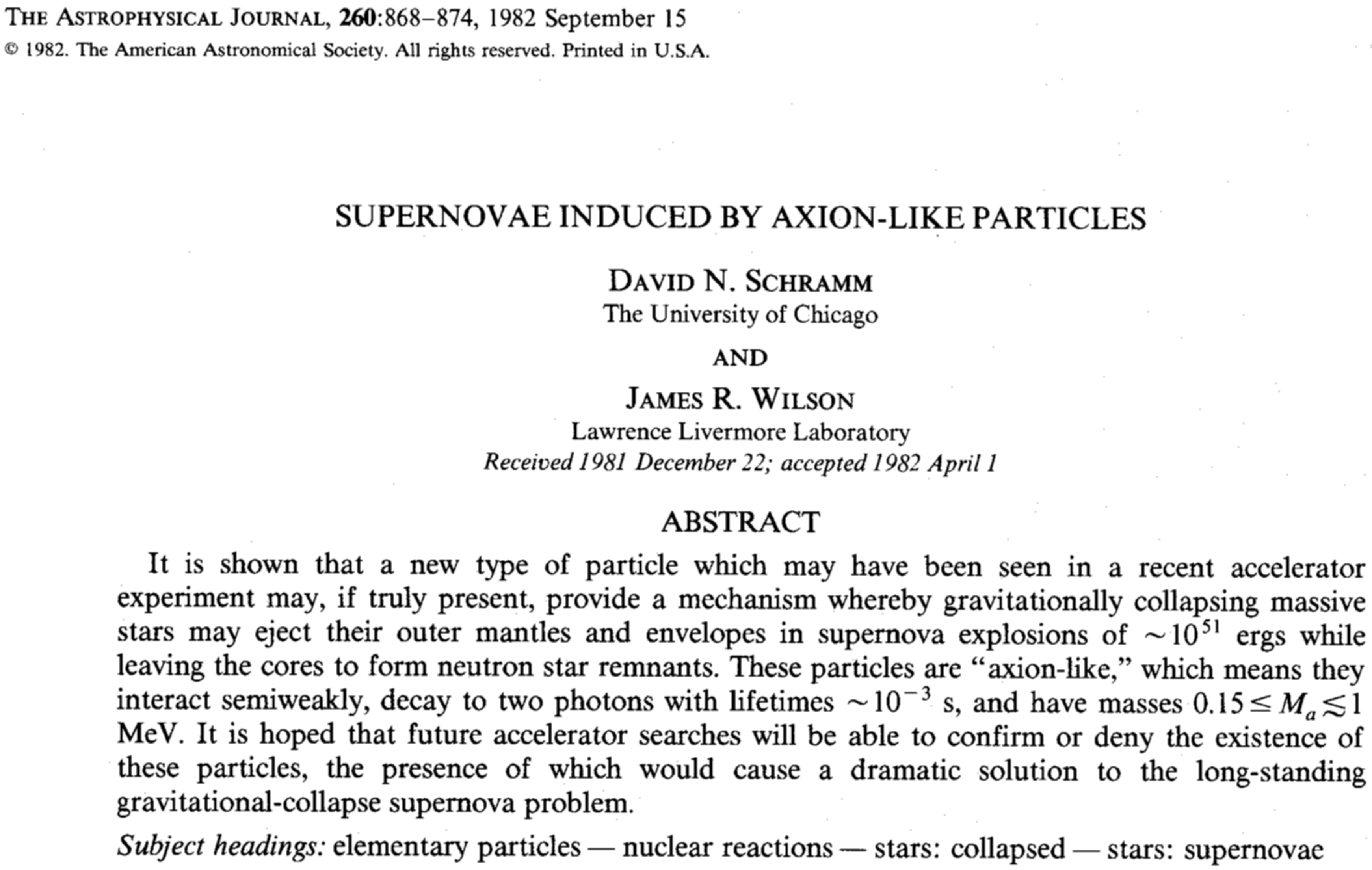
Novel Forms of Energy Transfer?



New particles or neutrinos with novel properties could provide a channel of energy transfer from proto neutron star to shock wave

Must not transfer too much energy: Limits on decaying neutrinos [Falk & Schramm, PLB 79 (1978) 511]

Shock Revival by Novel Particles?



THE ASTROPHYSICAL JOURNAL, **260**:868–874, 1982 September 15

SUPERNOVAE INDUCED BY AXION-LIKE PARTICLES

DAVID N. SCHRAMM
The University of Chicago
AND
JAMES R. WILSON
Lawrence Livermore Laboratory

Received 1981 December 22; accepted 1982 April 1

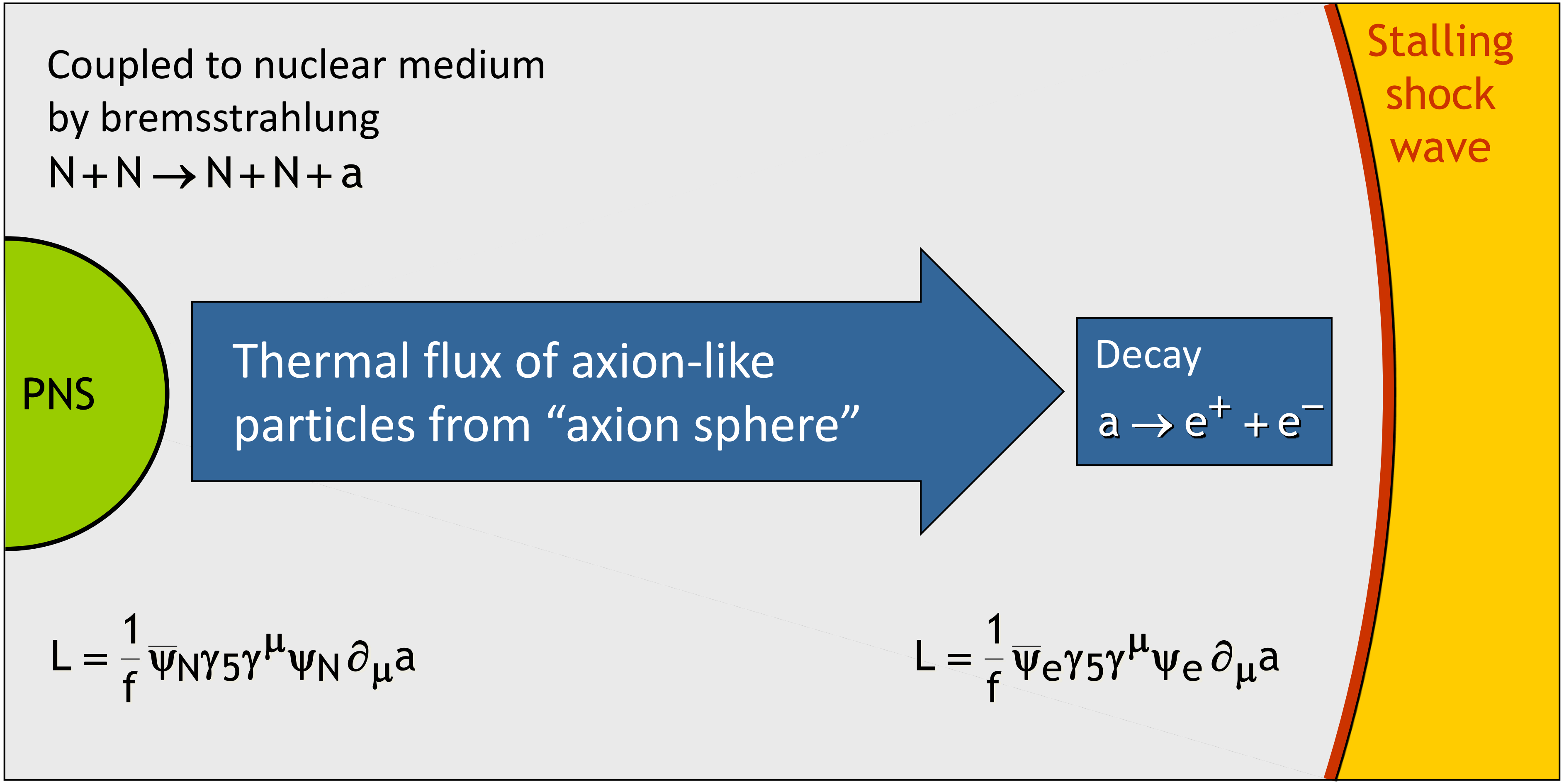
ABSTRACT

It is shown that a new type of particle which may have been seen in a recent accelerator experiment may, if truly present, provide a mechanism whereby gravitationally collapsing massive stars may eject their outer mantles and envelopes in supernova explosions of $\sim 10^{51}$ ergs while leaving the cores to form neutron star remnants. These particles are "axion-like," which means they interact semiweakly, decay to two photons with lifetimes $\sim 10^{-3}$ s, and have masses $0.15 \leq M_a \lesssim 1$ MeV. It is hoped that future accelerator searches will be able to confirm or deny the existence of these particles, the presence of which would cause a dramatic solution to the long-standing gravitational-collapse supernova problem.

Subject headings: elementary particles — nuclear reactions — stars: collapsed — stars: supernovae

Viable Scenario with Axion-Like Particles

Berezhiani & Drago, PLB 473 (2000) 281



Coupled to nuclear medium
by bremsstrahlung
$N+N \rightarrow N+N+a$

PNS

Thermal flux of axion-like particles from “axion sphere”

Decay
$a \rightarrow e^{+} + e^{-}$

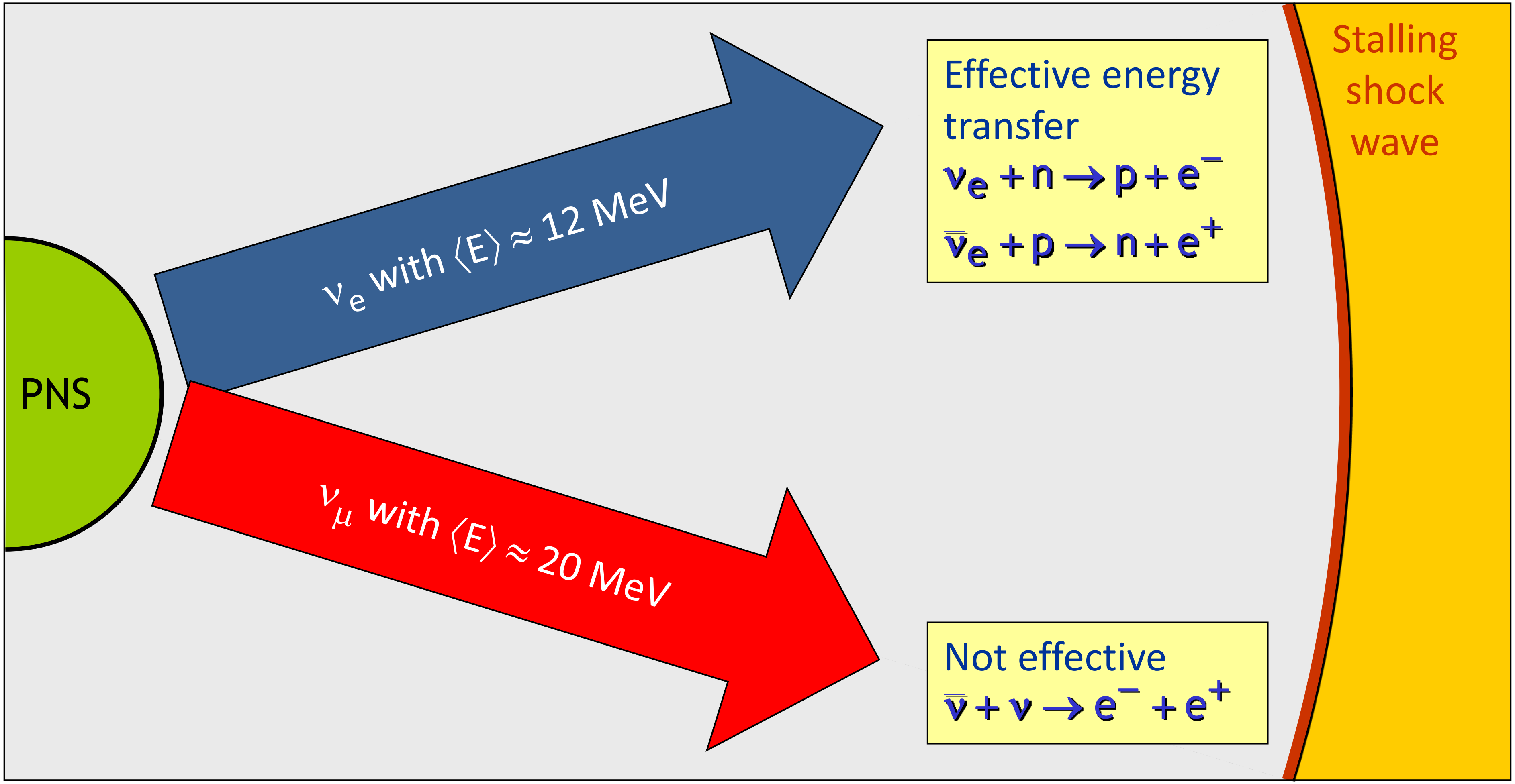
Stalling
shock
wave

$$L = \frac{1}{f}\,\overline{\psi}_N \gamma_5 \gamma^{\mu} \psi_N\, \partial_{\mu} a$$

$$L = \frac{1}{f}\,\overline{\psi}_e \gamma_5 \gamma^{\mu} \psi_e\, \partial_{\mu} a$$

Apparently consistent with f = few 10^5 GeV and m = few MeV
Not excluded by other arguments, but also not independently motivated

Swapping Neutrino Spectra by Oscillations



Effective energy transfer

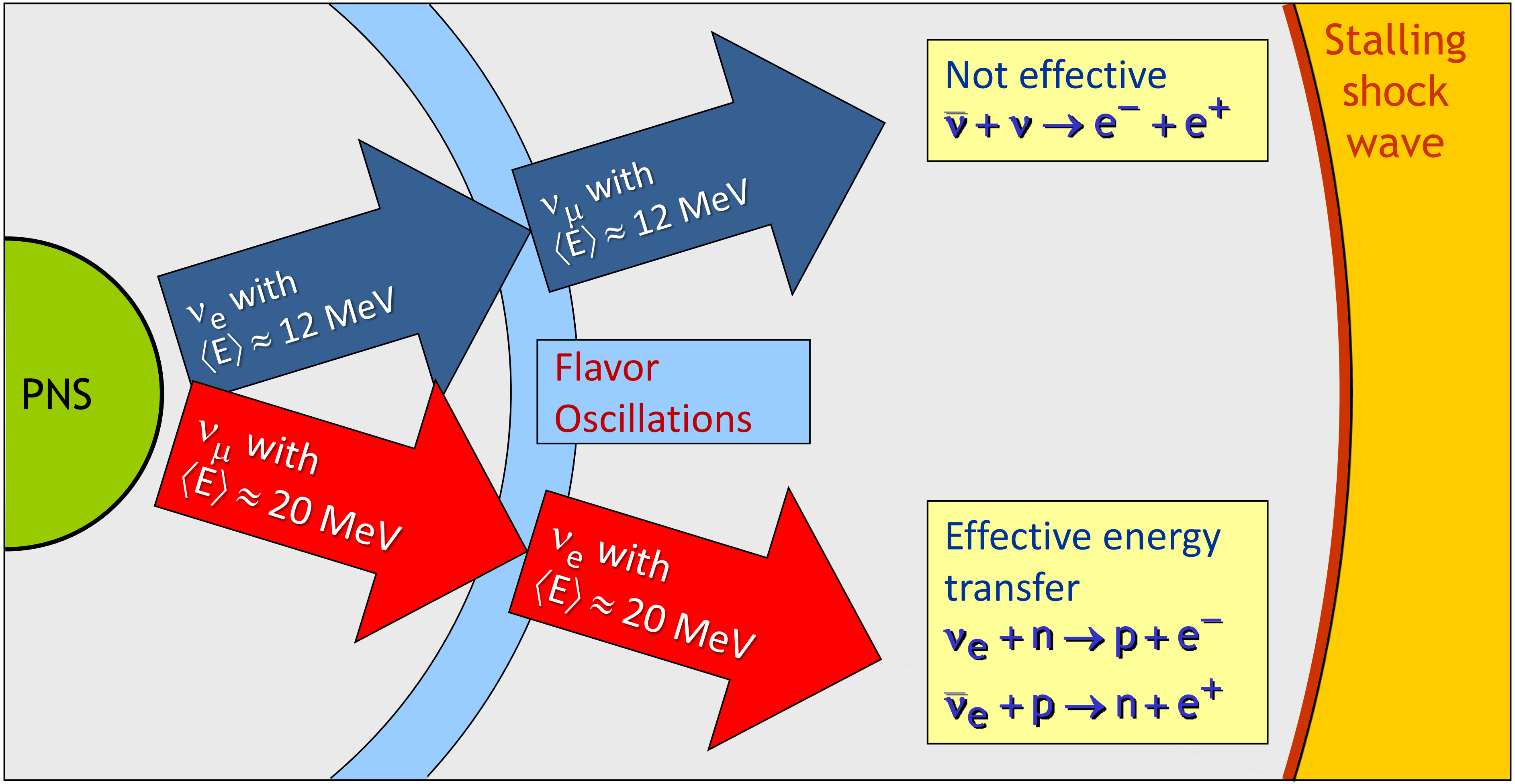
$\nu_e + n \to p + e^-$

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

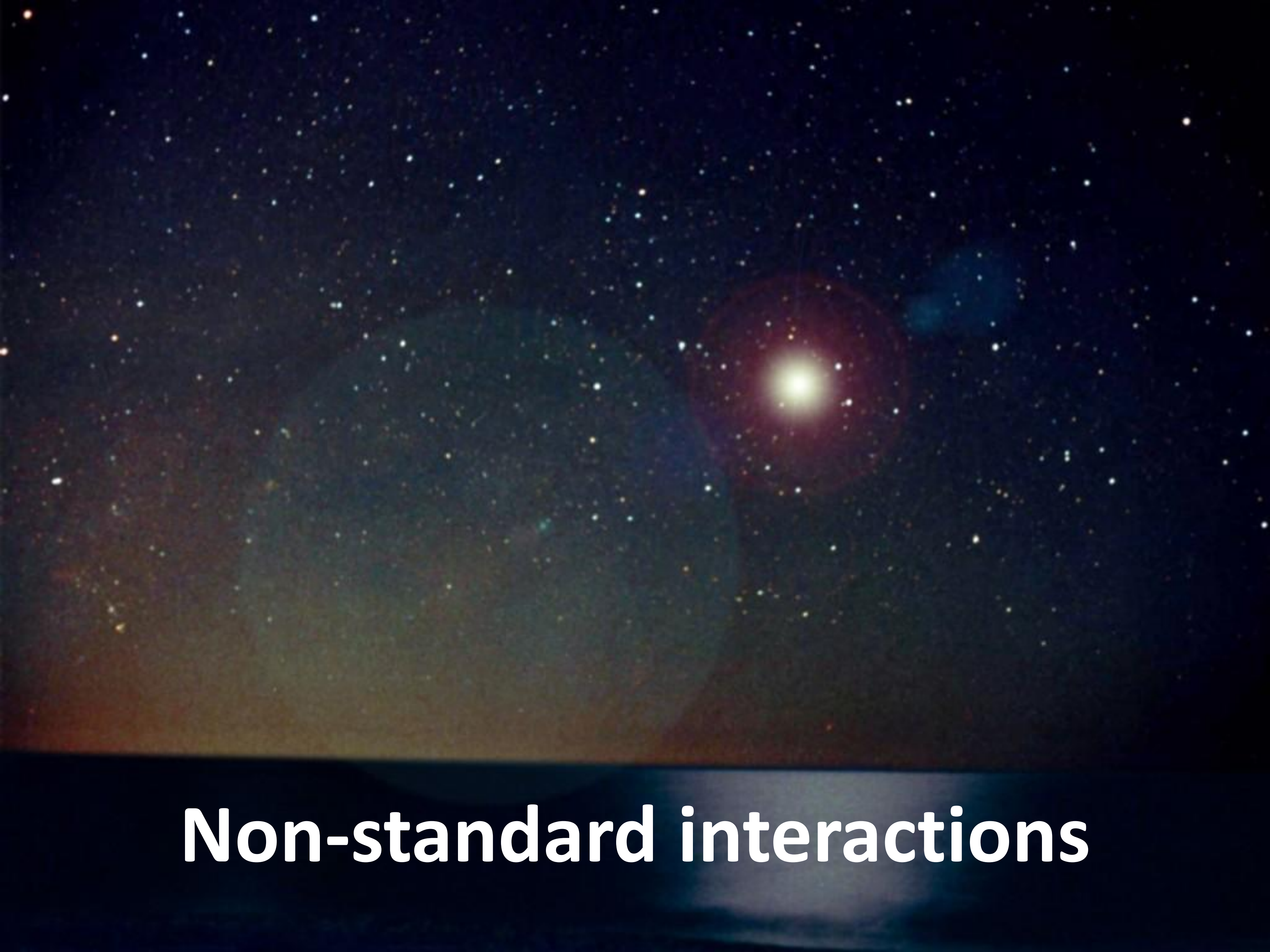
Not effective

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

Swapping Neutrino Spectra by Oscillations

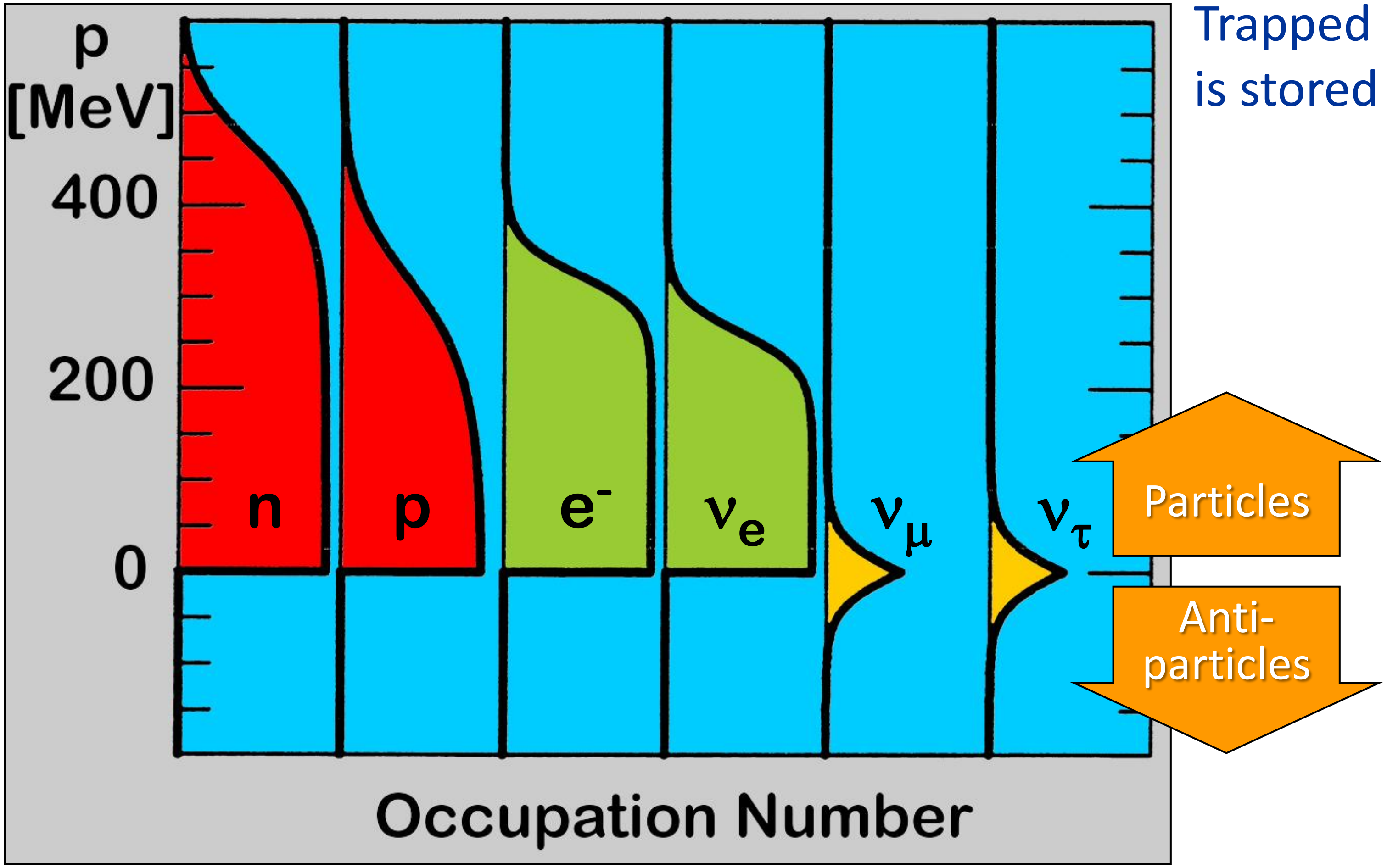


Swapping neutrino spectra by flavor oscillations enhances the rate of energy transfer to stalling shock wave [Fuller et al., ApJ 389 (1992) 517]



Non-standard interactions

Degenerate Fermi Seas in a Supernova Core

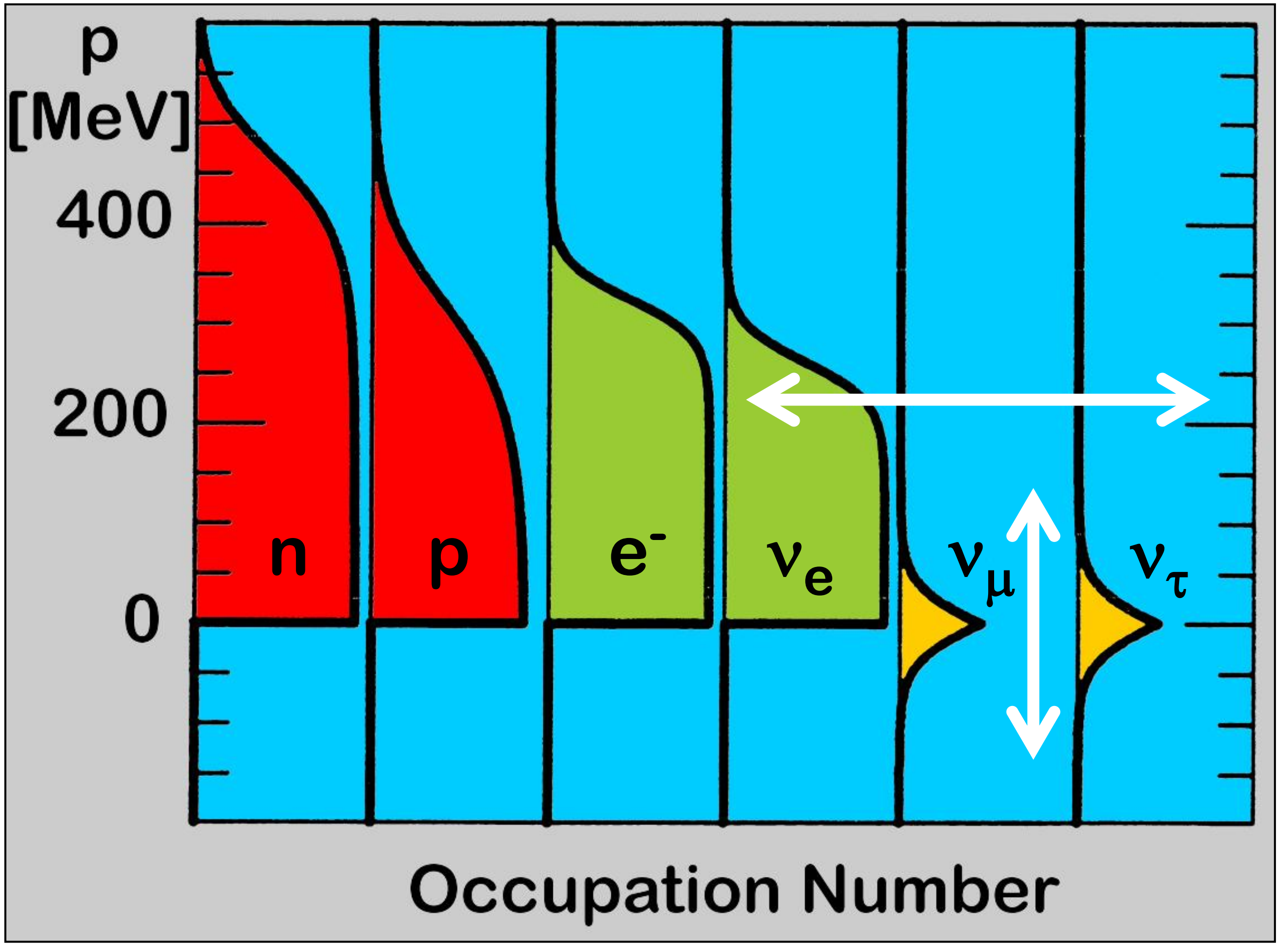


Trapped lepton number is stored in e^- and ν_e

In true thermal equilibrium with flavor mixing, only one chemical potential for charged leptons and one for neutrinos.

No chemical potential for Majorana neutrinos (lepton number violation)

Degenerate Fermi Seas in a Supernova Core



Equilibration by flavor lepton number violation, but flavor oscillations ineffective (matter effect)

Non-standard interactions could be effective, most sensitive environment

Consequences in core collapse should be studied numerically

Equilibration by lepton number violation, but Majorana masses too small

R-parity violating SUSY interactions?
TeV-scale bi-leptons?

Eur. Phys. J. C (2010) 67: 213–227
DOI 10.1140/epjc/s10052-010-1291-9

THE EUROPEAN
PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

TeV-scale bileptons, see-saw type II and lepton flavor violation in core-collapse supernova

Oleg Lychkovskiy[1,a], **Sergei Blinnikov**[1,2], **Mikhail Vysotsky**[1]

[1]Institute for Theoretical and Experimental Physics, B. Cheremushkinskaya 25, 117218 Moscow, Russia
[2]IPMU, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, 277-8568, Japan

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Abstract Electrons and electron neutrinos in the inner core of the core-collapse supernova are highly degenerate and therefore numerous during a few seconds of explosion. In contrast, leptons of other flavors are non-degenerate and therefore relatively scarce. This is due to lepton flavor conservation. If this conservation law is broken by some non-standard interactions, ν_e are converted to ν_μ, ν_τ, and e are converted to μ. This affects the supernova dynamics and the supernova neutrino signal. We consider lepton flavor violating interactions mediated by scalar bileptons, i.e. heavy scalars with lepton number 2. It is shown that in case of TeV-mass bileptons the electron Fermi gas is equilibrated with non-electron species inside the inner supernova core at a time scale ∼(1–100) ms. In particular, a scalar triplet which generates neutrino masses through the see-saw type II mechanism is considered. It is found that the supernova core is sensitive to yet unprobed values of masses and couplings of the triplet.

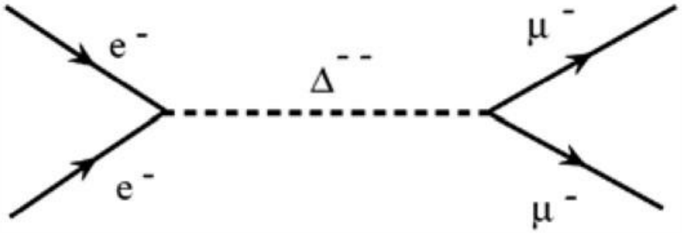
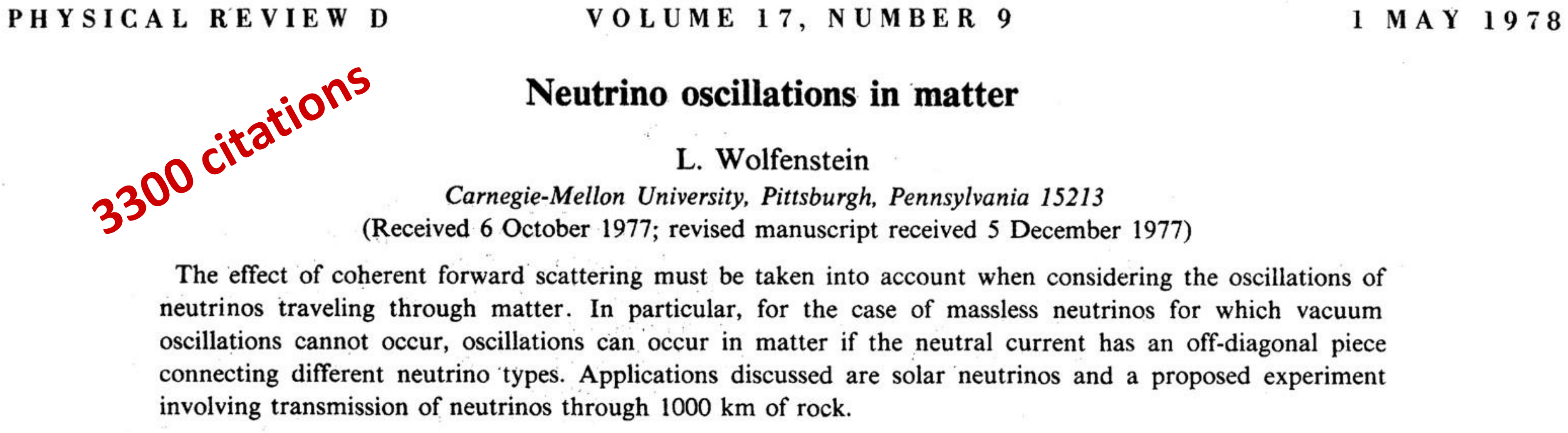


Fig. 1 $ee \rightarrow \mu\mu$ LFV transition mediated by the doubly charged bilepton Δ^{--}

Flavor oscillations



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3300 citations

Neutrino oscillations in matter

L. Wolfenstein
Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213
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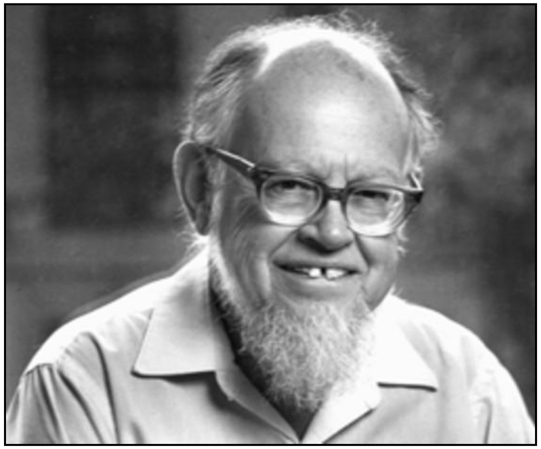
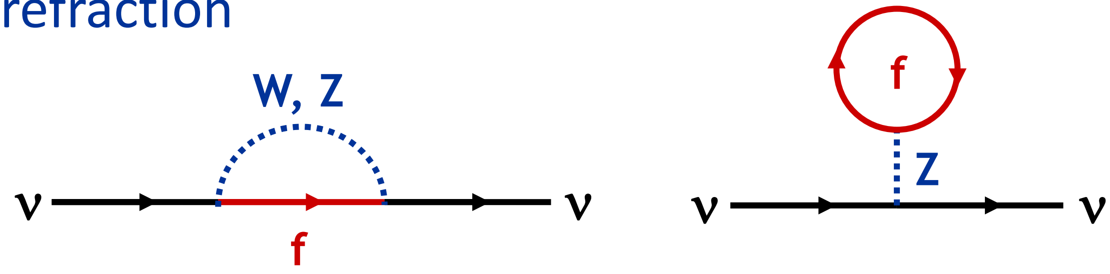
The effect of coherent forward scattering must be taken into account when considering the oscillations of neutrinos traveling through matter. In particular, for the case of massless neutrinos for which vacuum oscillations cannot occur, oscillations can occur in matter if the neutral current has an off-diagonal piece connecting different neutrino types. Applications discussed are solar neutrinos and a proposed experiment involving transmission of neutrinos through 1000 km of rock.



Lincoln Wolfenstein

Neutrinos in a medium suffer flavor-dependent refraction



$$V_{\mathrm{weak}} = \sqrt{2}G_{\mathrm{F}} \times \begin{cases} N_{\mathrm{e}} - N_{\mathrm{n}}/2 & \text{for } \nu_{\mathrm{e}} \\ -N_{\mathrm{n}}/2 & \text{for } \nu_{\mu} \end{cases}$$

Typical density of Earth: 5 g/cm^3

$$\Delta V_{\mathrm{weak}} \approx 2 \times 10^{-13}\ \mathrm{eV} = 0.2\ \mathrm{peV}$$

Suppression of Oscillations in Supernova Core

Effective mixing angle in matter

$$\tan 2\theta_{\mathrm{m}} = \frac{\sin 2\theta}{\cos 2\theta - N_e 2E\sqrt{2}G_{\mathrm{F}}/\Delta m^2}$$

Supernova core

$$\rho = 3\times 10^{14}\ \mathrm{g\,cm^{-3}}$$
$$Y_e = 0.35$$
$$N_e = 6\times 10^{37}\ \mathrm{cm^{-3}}$$
$$E \sim 100\ \mathrm{MeV}$$

Solar mixing

$$\Delta m^2 \sim 75\ \mathrm{meV}^2$$
$$\sin 2\theta \sim 0.94$$

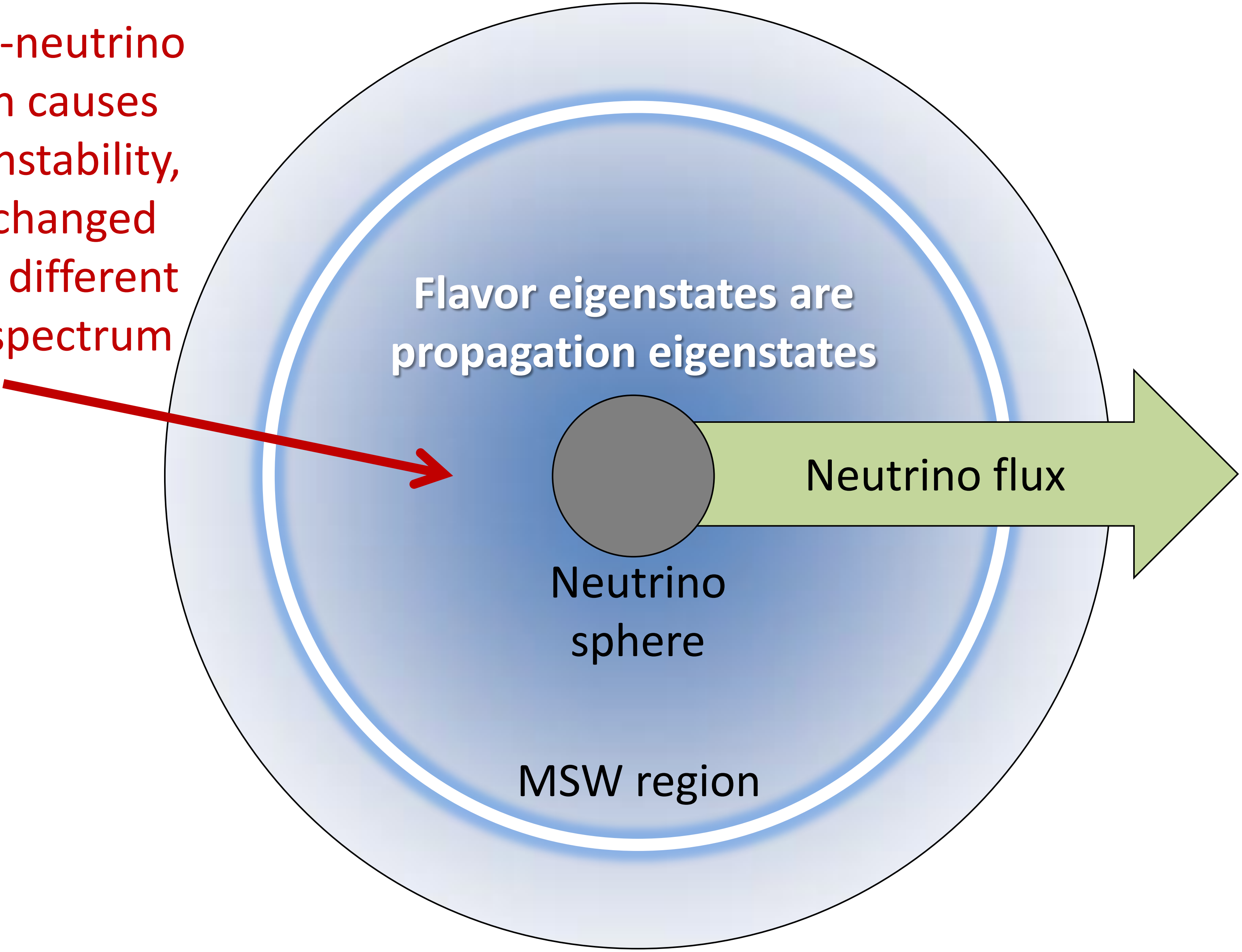
Matter suppression effect

$$N_e 2E\sqrt{2}G_F/\Delta m^2 \sim 2\times 10^{13}$$

- Inside a SN core, flavors are “de-mixed”
- Very small oscillation amplitude
- Trapped e-lepton number can only escape by diffusion

Flavor Oscillations in Core-Collapse Supernovae

Neutrino-neutrino refraction causes a flavor instability, flavor exchanged between different parts of spectrum



Flavor eigenstates are propagation eigenstates

Neutrino flux

Neutrino sphere

MSW region

Collective Supernova Nu Oscillations since 2006

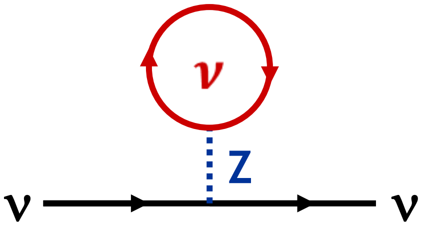
Two seminal papers in 2006 triggered a torrent of activities
Duan, Fuller, Qian, astro-ph/0511275, Duan et al. astro-ph/0606616

Balantekin, Gava & Volpe, arXiv:0710.3112. Balantekin & Pehlivan, astro-ph/0607527. Blennow, Mirizzi & Serpico, arXiv:0810.2297. Cherry, Fuller, Carlson, Duan & Qian, arXiv:1006.2175. Chakraborty, Choubey, Dasgupta & Kar, arXiv:0805.3131. Chakraborty, Fischer, Mirizzi, Saviano, Tomàs, arXiv:1104.4031, 1105.1130. Choubey, Dasgupta, Dighe & Mirizzi, arXiv:1008.0308. Dasgupta & Dighe, arXiv:0712.3798. Dasgupta, Dighe & Mirizzi, arXiv:0802.1481. Dasgupta, Dighe, Mirizzi & Raffelt, arXiv:0801.1660, 0805.3300. Dasgupta, Mirizzi, Tamborra & Tomàs, arXiv:1002.2943. Dasgupta, Dighe, Raffelt & Smirnov, 0904.3542. Dasgupta, Raffelt, Tamborra, arXiv:1001.5396. Duan, Fuller, Carlson & Qian, astro-ph/0608050, 0703776, arXiv:0707.0290, 0710.1271. Duan, Fuller & Qian, arXiv:0706.4293, 0801.1363, 0808.2046, 1001.2799. Duan, Fuller & Carlson, arXiv:0803.3650. Duan & Kneller, arXiv:0904.0974. Duan & Friedland, arXiv:1006.2359. Duan, Friedland, McLaughlin & Surman, arXiv:1012.0532. Esteban-Pretel, Pastor, Tomàs, Raffelt & Sigl, arXiv:0706.2498, 0712.1137. Esteban-Pretel, Mirizzi, Pastor, Tomàs, Raffelt, Serpico & Sigl, arXiv:0807.0659. Fogli, Lisi, Marrone & Mirizzi, arXiv:0707.1998. Fogli, Lisi, Marrone & Tamborra, arXiv:0812.3031. Friedland, arXiv:1001.0996. Gava & Jean-Louis, arXiv:0907.3947. Gava & Volpe, arXiv:0807.3418. Galais, Kneller & Volpe, arXiv:1102.1471. Galais & Volpe, arXiv:1103.5302. Gava, Kneller, Volpe & McLaughlin, arXiv:0902.0317. Hannestad, Raffelt, Sigl & Wong, astro-ph/0608695. Wei Liao, arXiv:0904.0075, 0904.2855. Lunardini, Müller & Janka, arXiv:0712.3000. Mirizzi, Pozzorini, Raffelt & Serpico, arXiv:0907.3674. Mirizzi & Tomàs, arXiv:1012.1339. Pehlivan, Balantekin, Kajino, Yoshida, arXiv:1105.1182. Raffelt, arXiv:0810.1407, 1103.2891. Raffelt & Tamborra, arXiv:1006.0002. Raffelt & Sigl, hep-ph/0701182. Raffelt & Smirnov, arXiv:0705.1830, 0709.4641. Sawyer, hep-ph/0408265, 0503013, arXiv:0803.4319, 1011.4585. Wu & Qian, arXiv:1105.2068.

Flavor-Off-Diagonal Refractive Index

2-flavor neutrino evolution as an effective 2-level problem

$$\mathrm{i}\frac{\partial}{\partial t}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = H\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$



Effective mixing Hamiltonian

$$H = \frac{M^2}{2E} + \sqrt{2}G_\mathrm{F}\begin{pmatrix} N_e - \frac{N_n}{2} & 0 \\ 0 & -\frac{N_n}{2}\end{pmatrix} + \sqrt{2}G_\mathrm{F}\begin{pmatrix} N_{\nu_e} & N_{\langle\nu_e|\nu_\mu\rangle} \\ N_{\langle\nu_\mu|\nu_e\rangle} & N_{\nu_\mu}\end{pmatrix}$$

Mass term in flavor basis: causes vacuum oscillations

Wolfenstein's weak potential, causes MSW "resonant" conversion together with vacuum term

Flavor-off-diagonal potential, caused by flavor oscillations. (J.Pantaleone, PLB 287:128,1992)

Flavor oscillations feed back on the Hamiltonian: Nonlinear effects!

Fermi-Dirac Spectrum

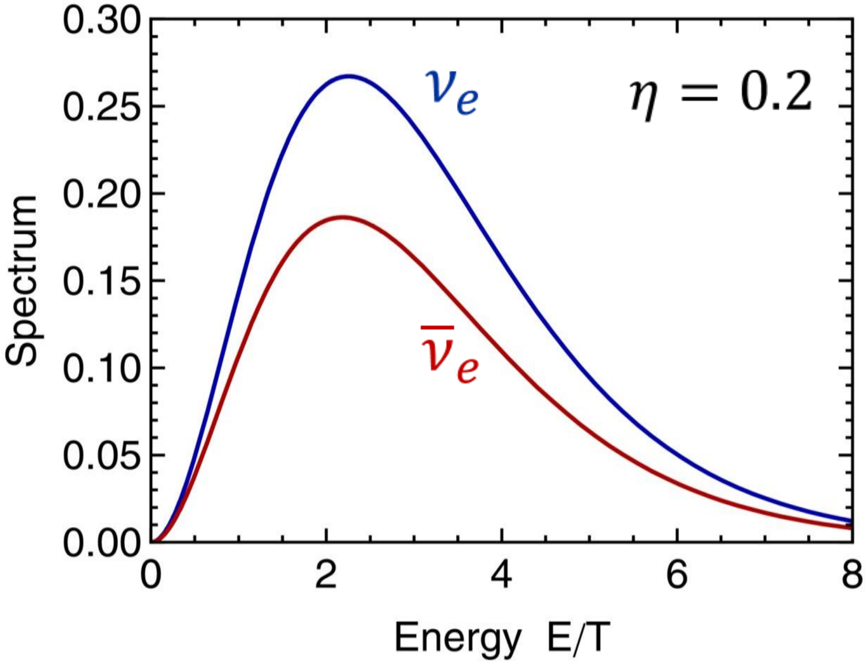
Fermi-Dirac energy spectrum

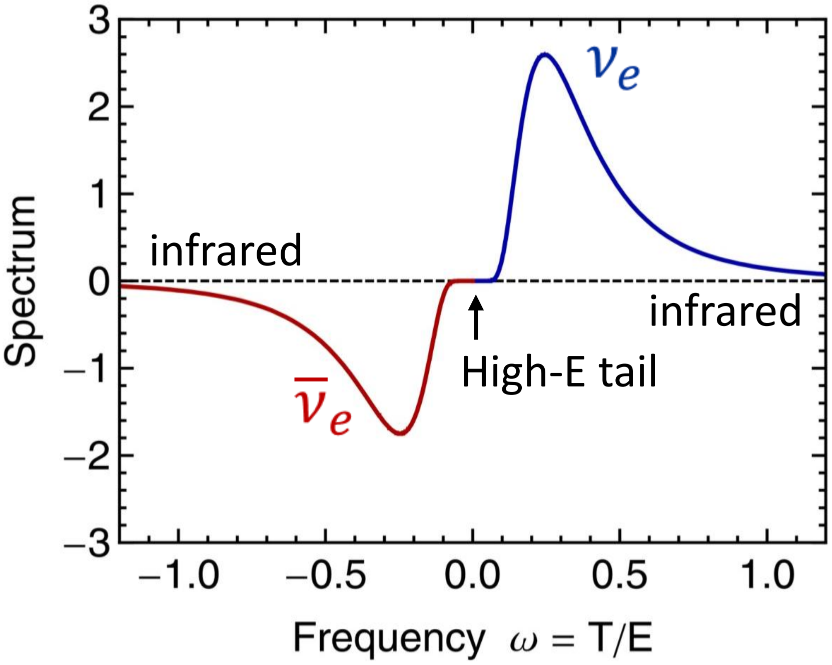
$$\frac{dN}{dE} \propto \frac{E^2}{e^{E/T-\eta}+1}$$

η degeneracy parameter, $-\eta$ for $\overline{\nu}$

Same spectrum in terms of $\omega = T/E$

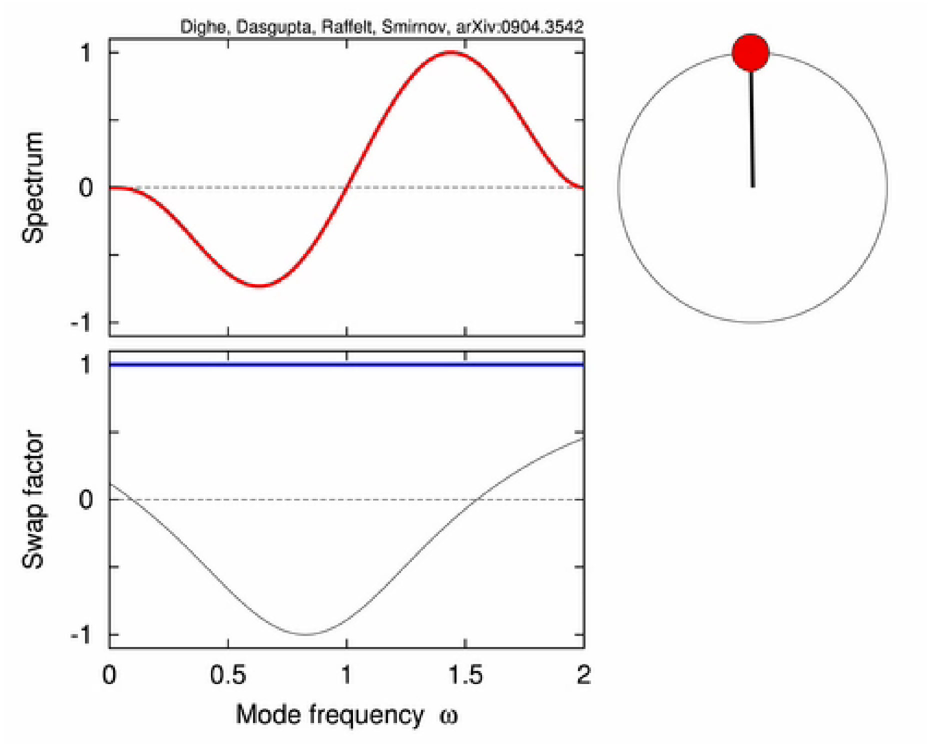
- Antineutrinos $E \to -E$
- and dN/dE negative
  (flavor isospin convention)
  $\omega > 0$: $\nu_e = \uparrow$ and $\nu_\mu = \downarrow$
  $\omega < 0$: $\overline{\nu}_e = \downarrow$ and $\overline{\nu}_\mu = \uparrow$





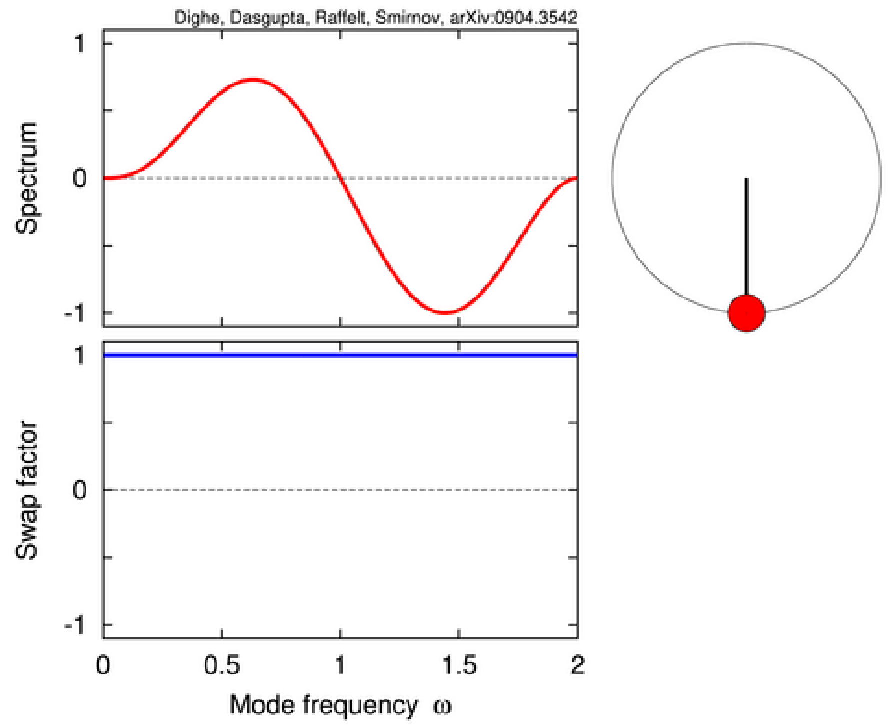
Flavor Pendulum

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



Dighe, Dasgupta, Raffelt, Smirnov, arXiv:0904.3542

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



Dighe, Dasgupta, Raffelt, Smirnov, arXiv:0904.3542

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

General Stability Condition

Spin-precession equations of motion for modes with $\omega = \Delta m^2/2E$

$$\dot{\mathbf{P}}_\omega = \omega \mathbf{B} \times \mathbf{P}_\omega + \mu \mathbf{P} \times \mathbf{P}_\omega$$

Small-amplitude expansion: x-y-component described as complex number S (off-diagnonal ρ element), linearized EoMs

$$-\mathrm{i}\dot{S}_\omega = \omega S_\omega - \mu \int d\omega'\, g_{\omega'} S_{\omega'}$$

Fourier transform $S_\omega = Q_\omega e^{i\Omega t}$, with $\Omega = \gamma + i\kappa$ a complex frequency

$$(\omega - \Omega) Q_\omega = \mu \int d\omega'\, g_{\omega'} S_{\omega'}$$

Eigenfunction is $Q_\omega \propto (\omega - \Omega)^{-1}$ and eigenvalue $\Omega = \gamma + i\kappa$ is solution of

$$\mu^{-1} = \int d\omega \frac{g_\omega}{\omega - \Omega}$$

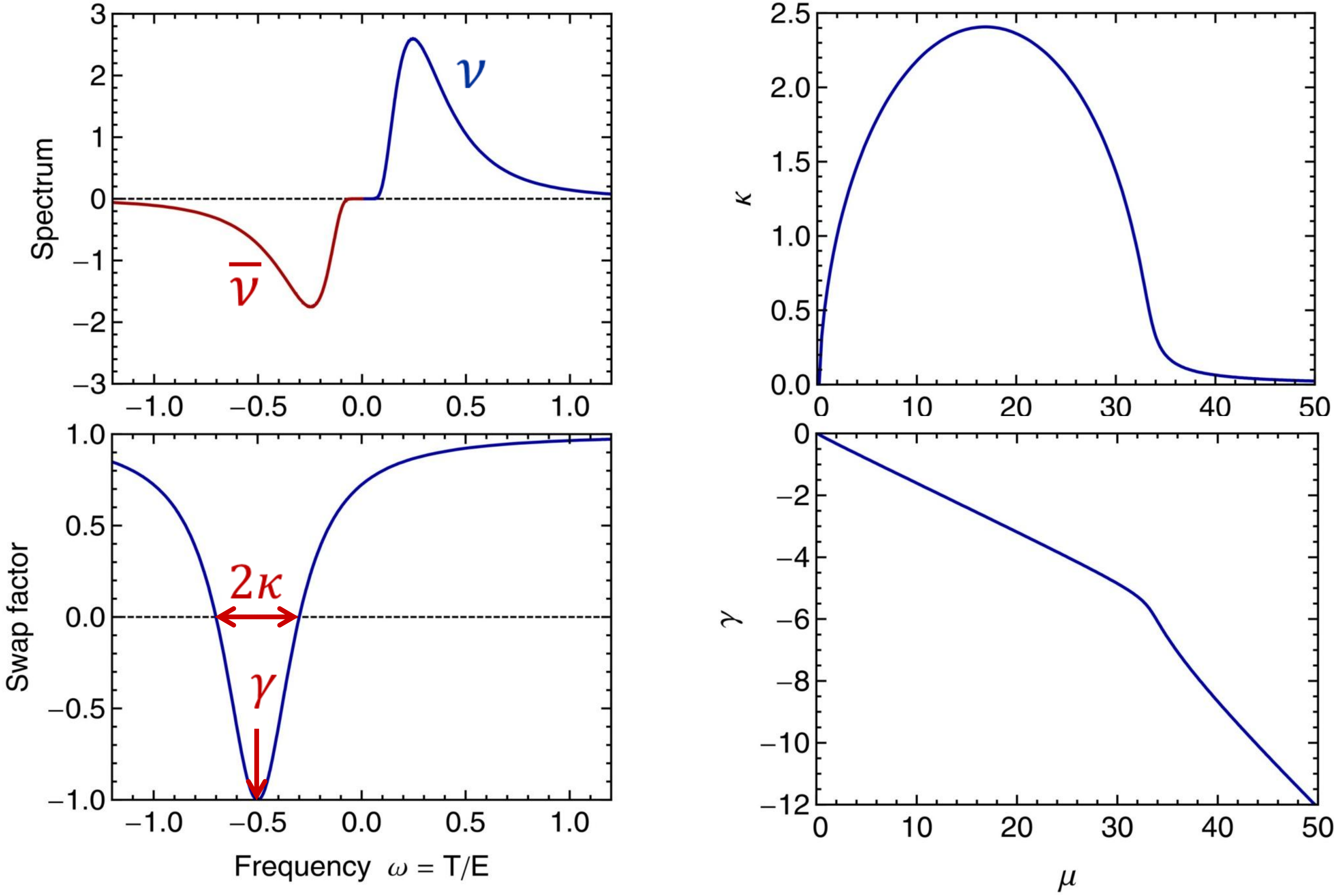
Instability occurs for

$$\kappa = \operatorname{Im} \Omega \neq 0$$

Exponential run-away solutions become pendulum for large amplitude.

Banerjee, Dighe & Raffelt, arXiv:1107.2308

Stability of Fermi-Dirac Spectrum



Banerjee, Dighe & Raffelt, arXiv:1107.2308

MPP-2011-81, TIFR/TH/11-30

Linearized flavor-stability analysis of dense neutrino streams

Arka Banerjee,[1] Amol Dighe,[1] and Georg Raffelt[2]
[1] *Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400005, India*
[2] *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 München, Germany*

(Dated: July 13, 2011)

Neutrino-neutrino interactions in dense neutrino streams, like those emitted by a core-collapse supernova, can lead to self-induced neutrino flavor conversions. While this is a nonlinear phenomenon, the onset of these conversions can be examined through a standard stability analysis of the linearized equations of motion. The problem is reduced to a linear eigenvalue equation that involves the neutrino density, energy spectrum, angular distribution, and matter density. In the single-angle case, we reproduce previous results and use them to identify two generic instabilities: The system is stable above a cutoff density ("cutoff mode"), or can approach an asymptotic instability for increasing density ("saturation mode"). We analyze multi-angle effects on these generic types of instabilities and find that even the saturation mode is suppressed at large densities. For both types of modes, a given multi-angle spectrum typically is unstable when the neutrino and electron densities are comparable, but stable when the neutrino density is much smaller or much larger than the electron density. The role of an instability in the SN context depends on the available growth time and on the range of affected modes. At large matter density, most modes are off-resonance even when the system is unstable.

PACS numbers: 14.60.Pq, 97.60.Bw

I. INTRODUCTION

Neutrino flavor oscillations in a supernova (SN) are strongly suppressed by matter effects [1] until the neutrinos pass through the usual MSW region [2–5] far out in the envelope of the collapsing star. However, neutrino-neutrino interactions [6, 7], through a flavor off-diagonal refractive index, can trigger self-induced flavor conversions [8–13]. This collective effect tends to occur between the neutrino sphere and the MSW region and can lead to strongly modified neutrino spectra, showing features such as spectral swaps and splits [14–19]; for a review see dynamics. Recent studies dedicated to the SN accretion phase, under simplifying assumptions, once more confirm this picture [24, 25].

However, what is missing is a systematic approach to decide, without solving the equations of motion, if self-induced flavor conversions occur for given neutrino spectra (flavor-dependent energy and angular distribution), overall neutrino density, and matter density. Formal stability criteria exist only in the "single-angle approximation" where it is assumed that all neutrinos feel the same neutrino-neutrino refractive effect. In this case the analytic pendulum solution has been found and its existence

Summary

Neutrino signal duration provides most useful particle-physics information
- New long-term simulations with non-standard cooling would be welcome
- Neutrino signal of next nearby SN makes this argument much more precise
- Theoretical uncertainties of emission rates (dense medium) remain large

Impact of non-standard neutrino interactions on hydrodynamics should be studied
- Flavor lepton number violation (leading to flavor conversion at high density)
- Lepton number violation (leading to internal deleptonization)

Collective flavor oscillations remain to be investigated
- Flavor instabilities where and when?
  → Systematic linear stability analysis (Ray Sawyer's talk)
- Which impact?

Ordinary MSW conversion (Amol Dighe's talk)
- What can we learn about neutrino mixing parameters from next SN?