Liquid Scintillator Detectors and Sensitivity to Diffuse Supernova Neutrino Background

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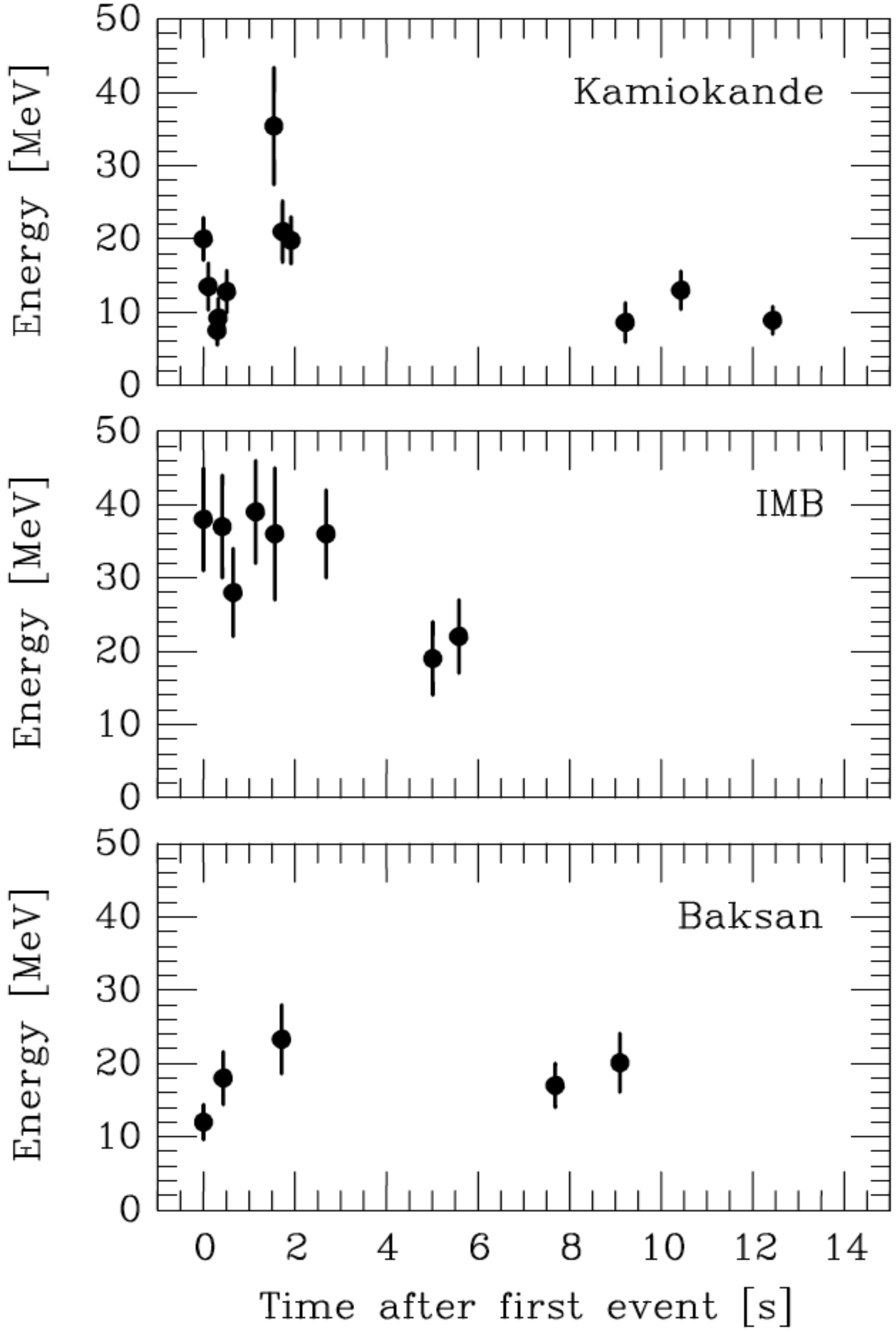
SN1987A and Core Collapse Supernova

Neutrinos from SN1987A



- Neutrinos from SN1987A in LMC at ~ 50 kpc at three independent detectors
- neutrino transport in supernova matter
- neutrino emission phase and corresponding neutrino effects
- neutrino properties during different phases

Estimation of Total Energy from Kamiokande II

from M. Nakahata, Observation of SN1987A at Kamiokande

Mean neutrino energy

$$\frac{\int_{thr.}^{\infty} E_\nu \phi(E_\nu)\sigma(E_\nu)\varepsilon(E_\nu)\, dE_\nu}{\int_{thr.}^{\infty} \phi(E_\nu)\sigma(E_\nu)\varepsilon(E_\nu)\, dE_\nu} = \sim 16.7\ \text{MeV}$$

thr.=8.9MeV

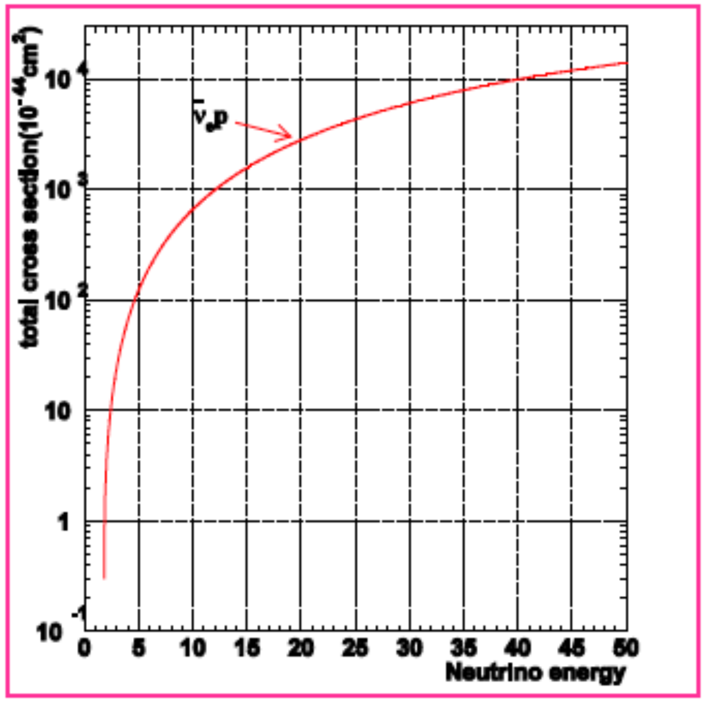
$\phi(E_\nu)$: neutrino flux without chemical potential (kT~2.7 MeV)

$$F \times \frac{\alpha E_\nu^2}{\exp(E_\nu/kT)+1}$$

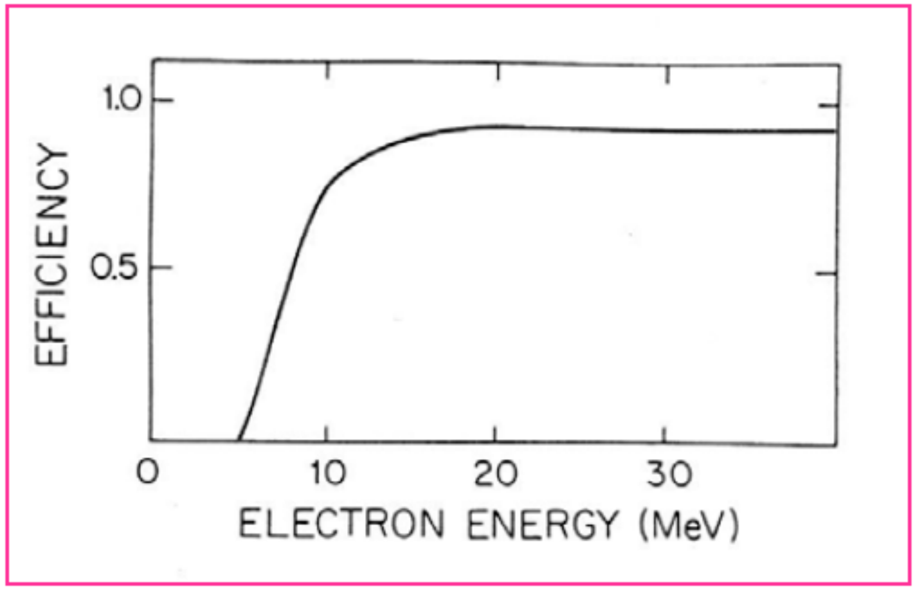
$$\int \frac{E_\nu^2}{\exp(E_\nu/kT)+1} = 1/\alpha$$

$$\frac{\int_0^{\infty} E_\nu \phi(E_\nu) dE_\nu}{\int_0^{\infty} \phi(E_\nu) dE_\nu} = \sim 8.6\text{MeV}$$

σ : cross section



ε : detection efficiency at Kamiokande



Estimation of Total Energy from Kamiokande II (continued)

Number of events

$$\int_{\mathrm{thr.}}^{\infty} \phi(E_\nu)\sigma(E_\nu)N_p\varepsilon(E_\nu)\, dE_\nu = 11 \text{ events}$$

$\boxed{\text{thr.=8.9MeV}}$

$$\phi(E_\nu) : \quad F \times \frac{\alpha E_\nu^2}{\exp(E_\nu/kT)+1}$$

$$\int \frac{E_\nu^2}{\exp(E_\nu/kT)+1} = 1/\alpha$$

N_p : number of protons

Total flux of anti electron neutrinos at the Earth = ~1.8×10^{10}/ cm^2/burst

Number of anti electron neutrino produced = ~$6x10^{57}$

Energy release by anti electron neutrinos = ~$6x10^{52}$ erg

for all neutrinos by x6 = ~$5x10^{53}$ erg

Estimation of Total Energy from Kamiokande II (continued)

- **For core collapse supernova, the huge gravitational binding energy of neutron star is carried away by neutrinos : with Newtonian gravity**

$$E_{\mathrm{b}} \sim E_{\mathrm{g}} \approx \frac{3}{5}\frac{GM_{\mathrm{ns}}^2}{R_{\mathrm{ns}}} \approx 3.6\times 10^{53}\left(\frac{M_{\mathrm{ns}}}{1.5\,M_{\odot}}\right)^{2}\left(\frac{R_{\mathrm{ns}}}{10\,\mathrm{km}}\right)^{-1}\ \mathrm{erg}\,.$$

- **From the detection of anti electron neutrinos from SN1987A, the core collapse scenario of massive star is consistent with the data.**

The Lives of the Stars

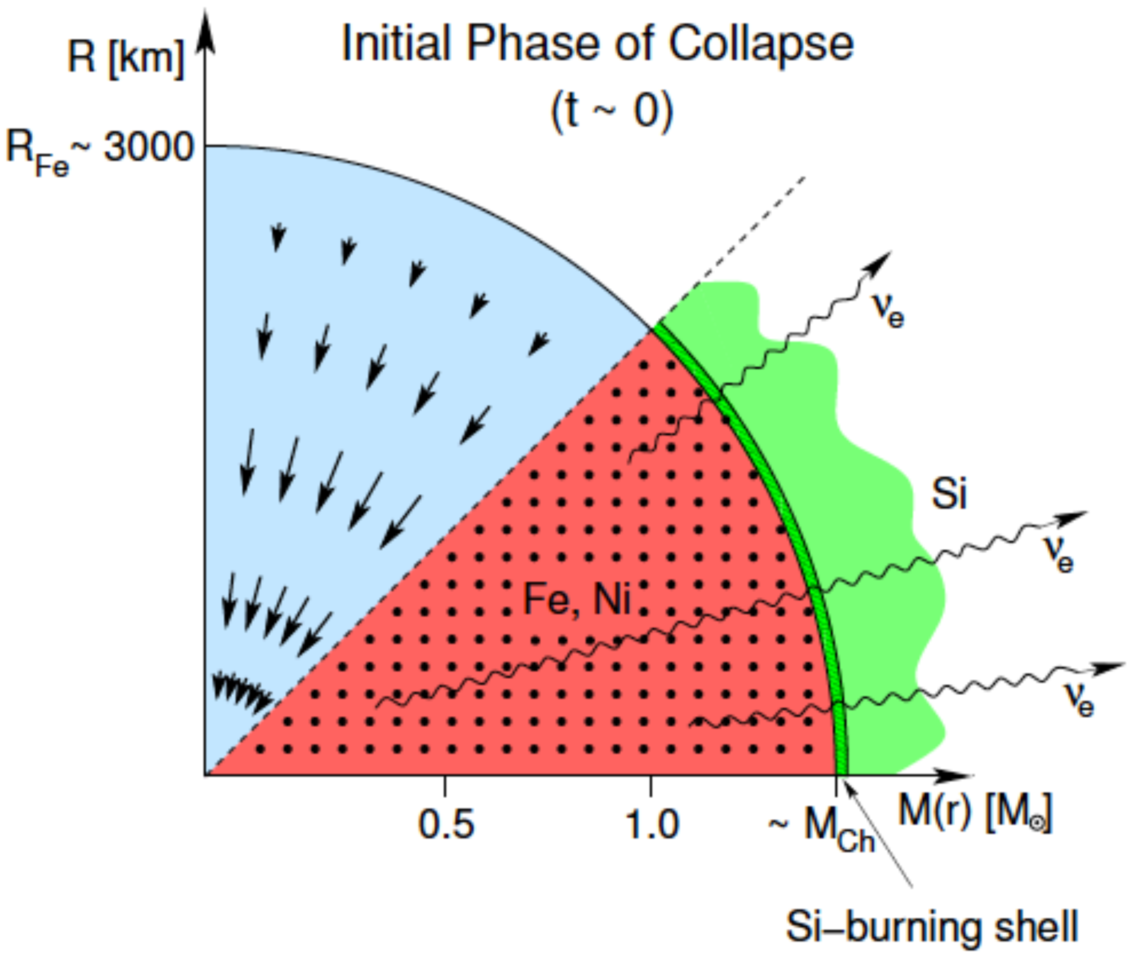
- **The mass of a star almost entirely determines its structure and ultimate fate.**
  ➪ Born to be massive star, it shines brightly but has short life-time.
  ➪ The stars that have smaller mass than a part of Sun's have longer life-time than the age of the Universe.

- **None of the first degree stars shining brightly today were born when dinosaurs walked on the Earth 100M years ago.**

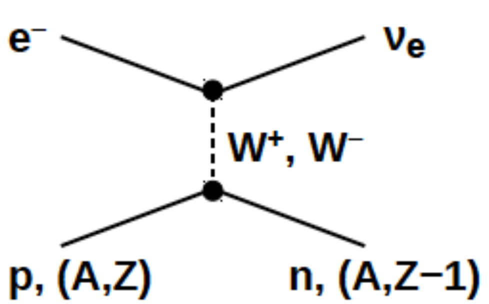
- **The massive stars within $8M_\odot \leq M \leq 40M_\odot$ will burn its core to iron; a core has no further source of energy.**
  ➪ gravitational infalling

A Scenario of the Neutrinos Emission from Supernova

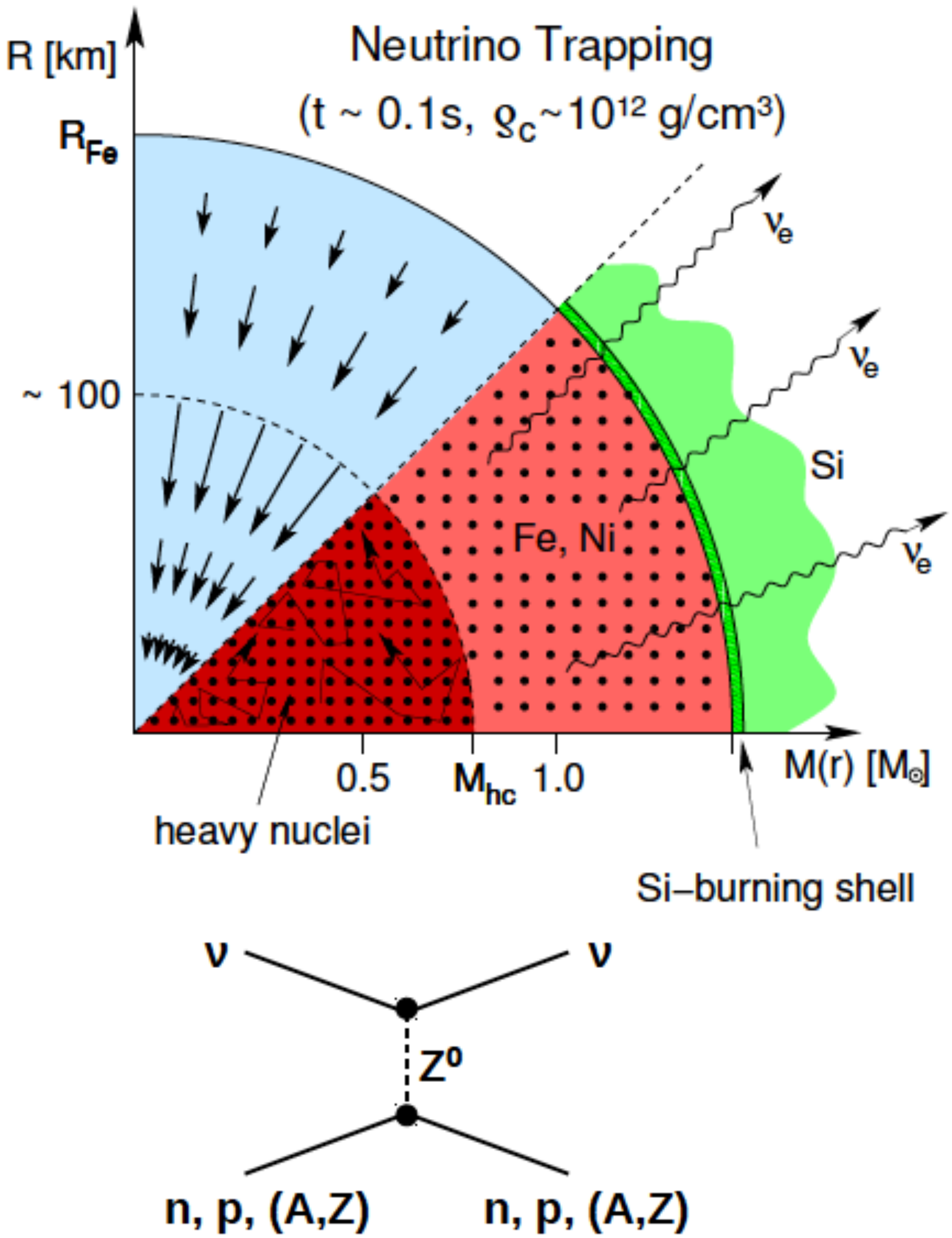
Onset of Stellar Core



- Slow construction of the growing and aging iron core
- When its central temperature approaches 1 MeV, thermal gammas become energetic to disintegrate the iron-group nuclei to alpha and free nucleon.
- With high Fermi energy of the degenerate electron, electron captures on nuclei become possible.

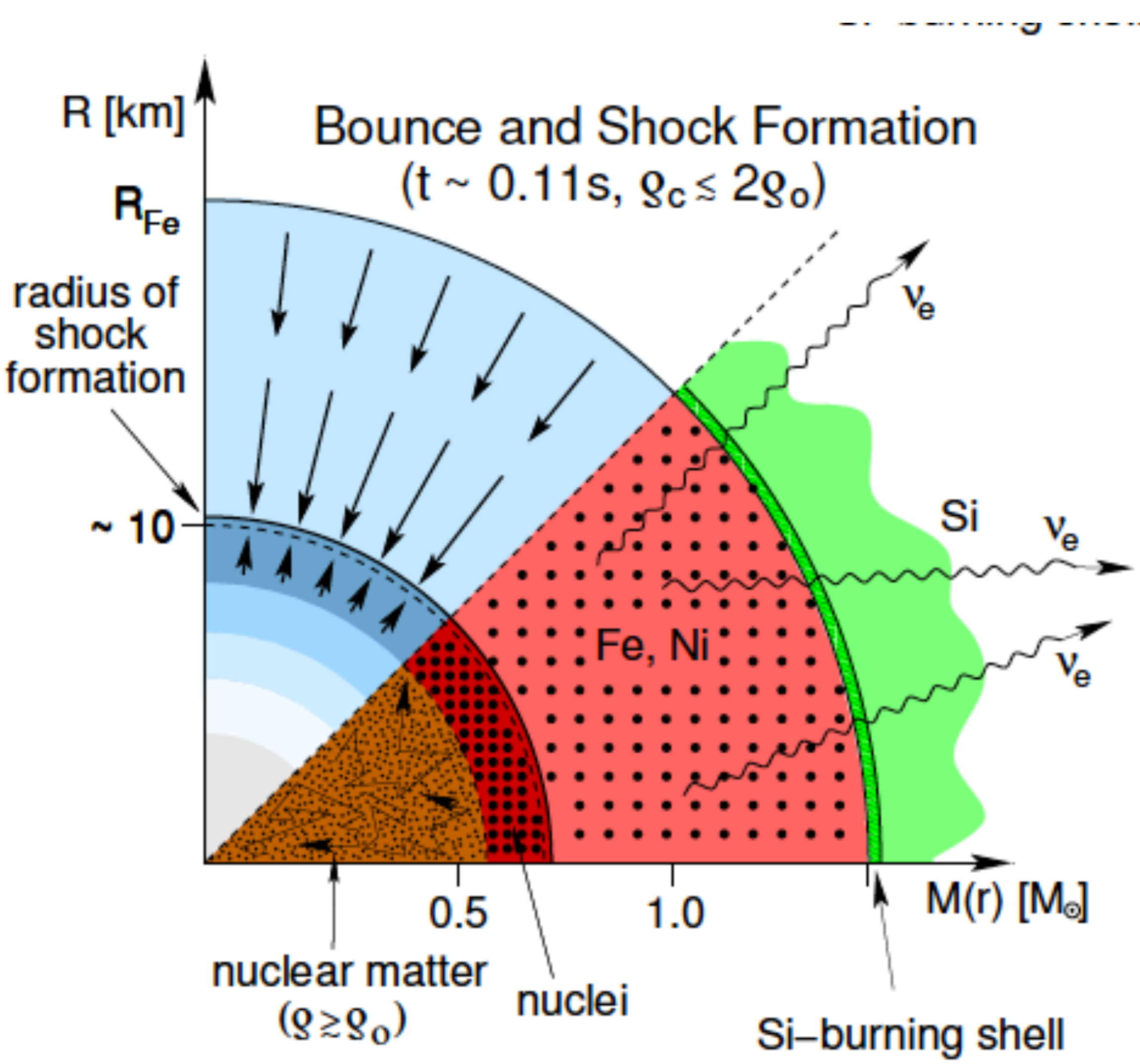


Neutrino Trapping



- When core density exceeds a few times 10^{11}g/cm^3, neutrinos become trapped on the core.
- The electron neutrino produced by ongoing electron capture on free protons are swept inward with the infalling matter.
- Neutrino trapping is mainly a consequence of neutral current scattering of low energy neutrinos on heavy nuclei, coherent scattering.
- As electrons continue to be converted to electron neutrino, the dynamical collapse has nearly free-fall velocity up to ~30% of speed of light.

Core Bounce and Shock Formation

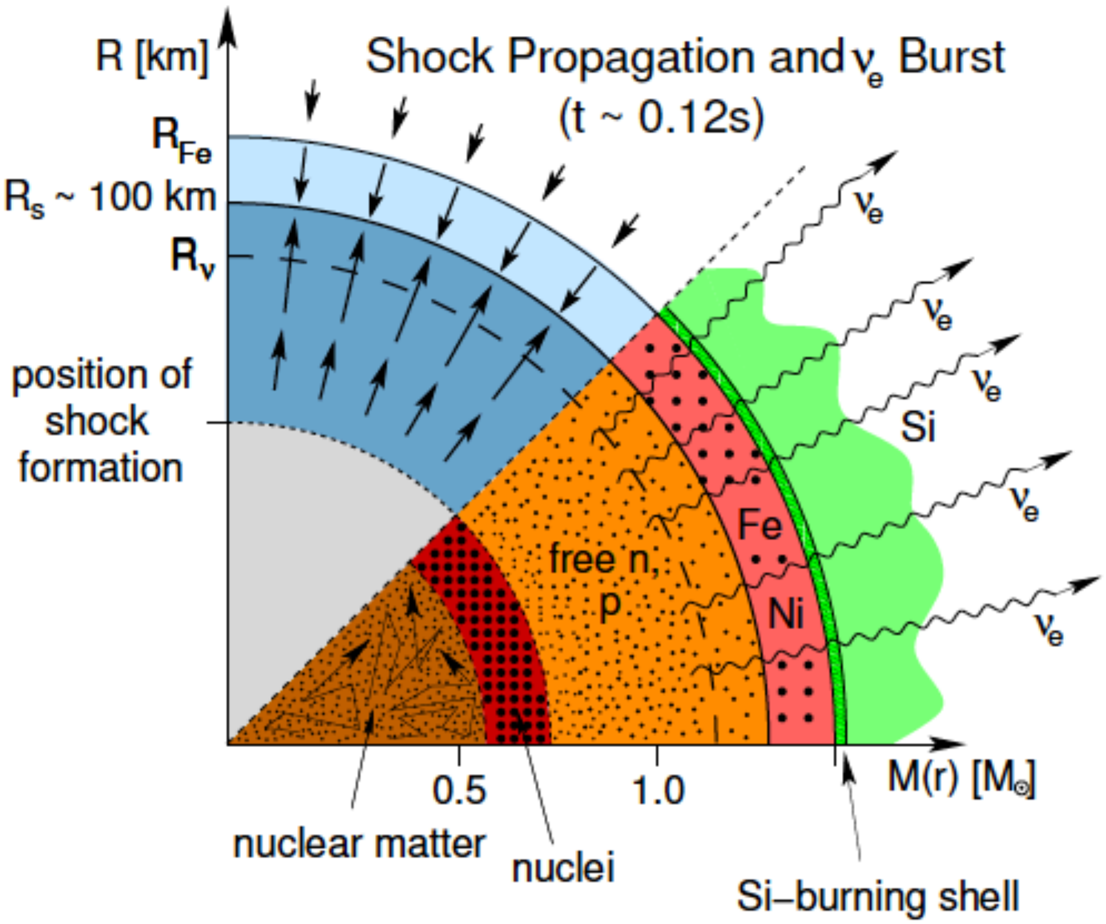


- Within some time after trapping, the center reaches nuclear matter density, $\rho \sim 10^{12} g/cm^3$ having incompressibility.

$$t_{ff} \sim 1/\sqrt{G\rho} \sim 4 \times 10^{-3}\text{s}$$

- Incompressibility due to repulsive force between the nucleons provides resistance against further collapse, and the collapse of the inner core comes to an abrupt halt.
  ->shock formation

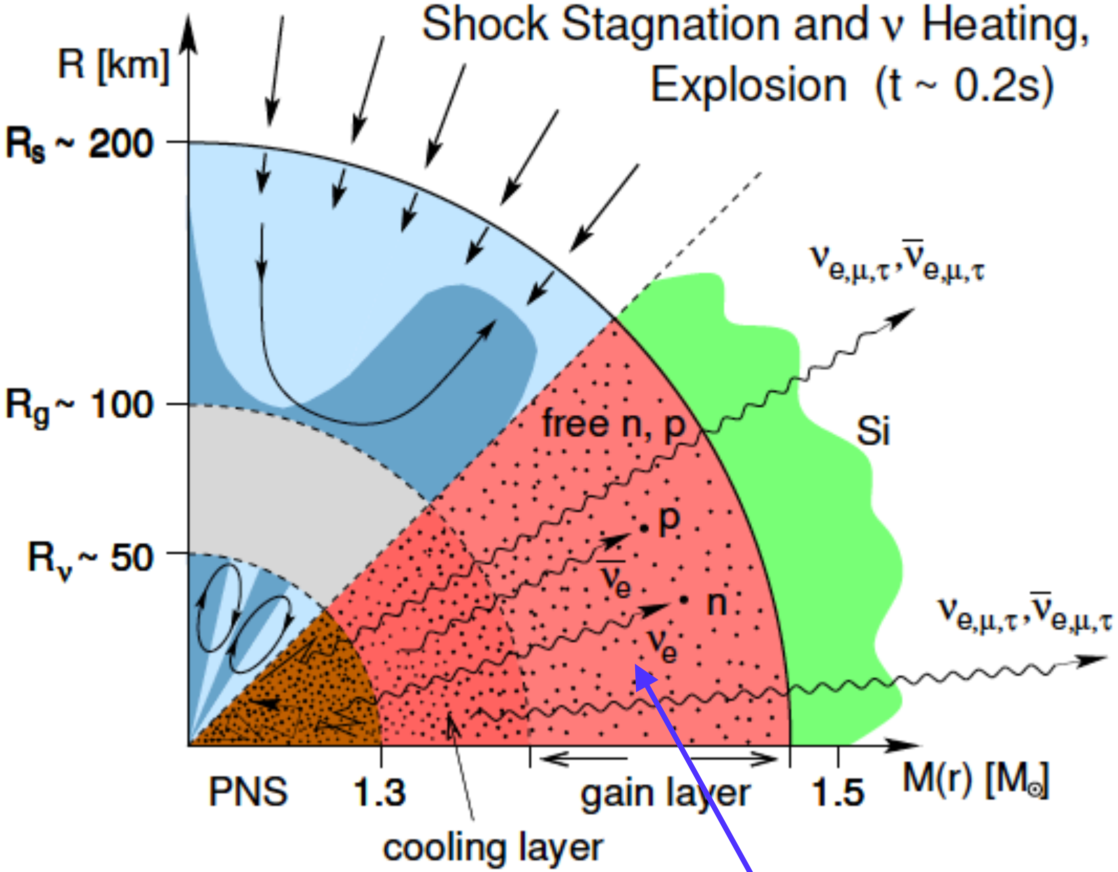
Shock Propagation and ν_e Burst at Shock Breakout



- Electron neutrinos are produced in huge numbers by electron capture on free protons behind the outward moving shock front.

- When dense post shock matter reaches sufficient low densities for electron neutrino, a luminous flash of electron neutrinos is emitted, the breakout burst.
  -> lead dramatic loss of electron-lepton number
  -> appearance of large amount concentration of positrons
  -> With positrons and neutrons becoming more and more abundant, positron captures on neutrons accomplish the emission of anti electron neutrinos
  -> electron-positron pair production become efficient and start to create heavy lepton neutrinos and antineutrinos

Shock Stagnation and Revival by Neutrino Heating



$$\nu_e + n \longrightarrow p + e^-$$
$$\bar{\nu}_e + p \longrightarrow n + e^+ .$$

- The kinetic energy of preshock matter is dissipated into thermal energy which lead to heavy nucleus disintegration to free nucleons.
- This energy drains and the energy losses by the electron neutrino burst reduce the post shock pressure and weaken the expansion of the bounce shock.
  ->shock stagnation
  ->need a mechanism to revive the stalled shock
- Energy transfer by the intense neutrino flux radiated from the newly born neutron star deposit fresh energy behind the shock electron and anti electron neutrinos on free nucleon. -> shock revival

Neutrino Transportation

- **Neutrino transport in supernova cores is described by the Boltzmann transport equation,**

neutrino phase-space distribution function

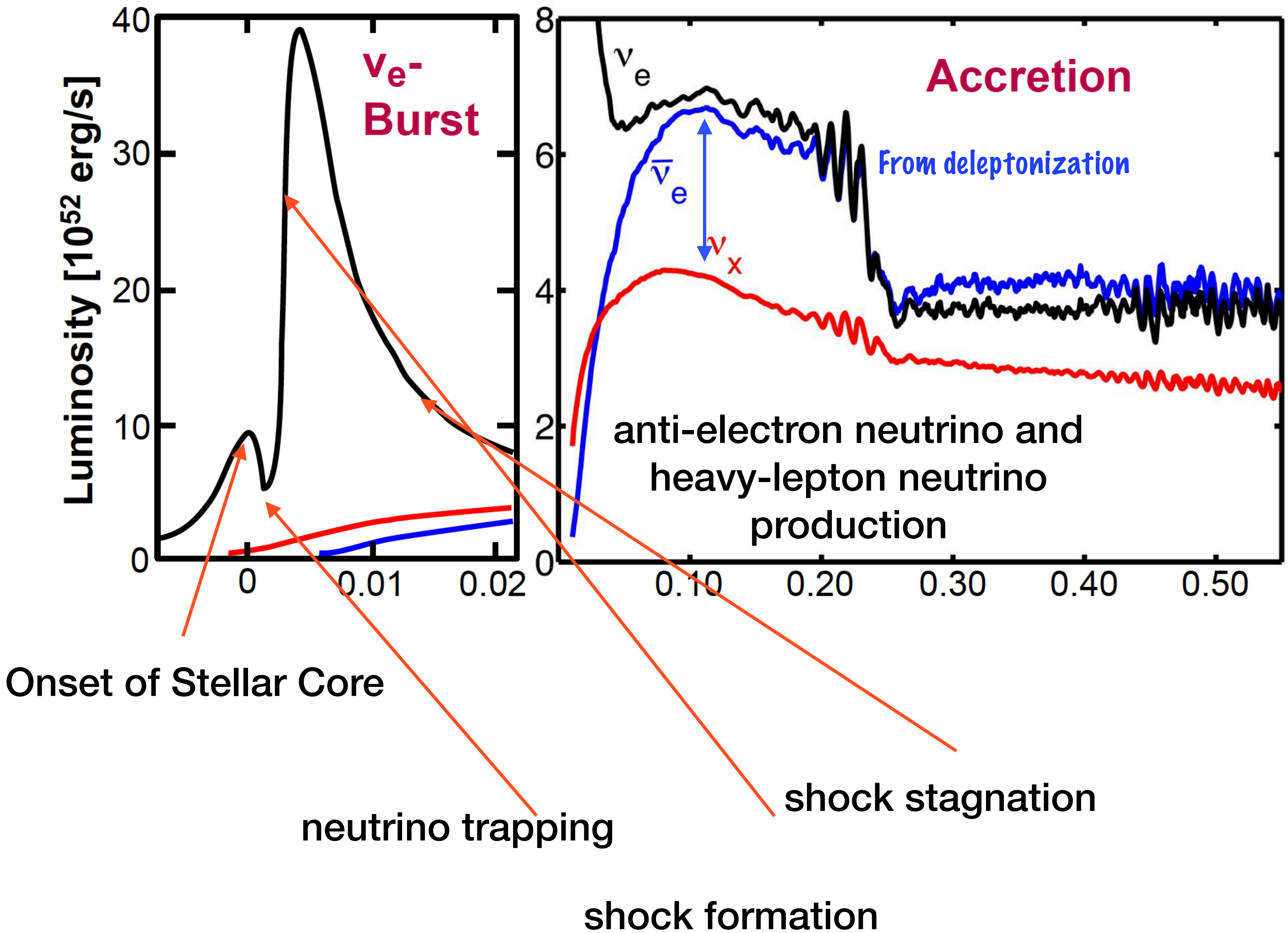
$$\frac{\mathrm{D}\mathscr{F}(\boldsymbol{r},\boldsymbol{q},t)}{\mathrm{D}t} = \frac{\partial\mathscr{F}}{\partial t} + \frac{\partial\boldsymbol{r}}{\partial t}\nabla_{\boldsymbol{r}}\mathscr{F} + \frac{\partial\boldsymbol{q}}{\partial t}\nabla_{\boldsymbol{q}}\mathscr{F} = \mathscr{C}(\mathscr{F})$$

collision integral that contains all rates of neutrino-processes

- **Since the solution of the time-dependent Boltzmann equation in three spatial dimensions with its full energy-momentum dependence is not feasible on current computing technologies, a variety of different approximations are applied.**

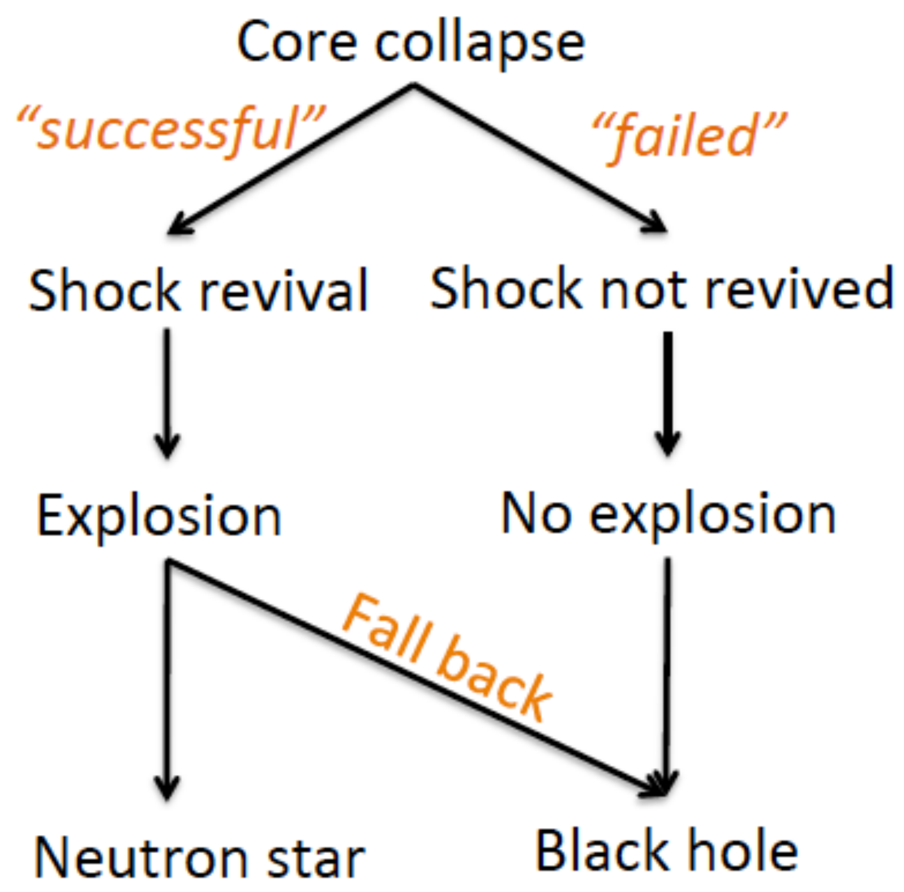
  ➪ **Many assumptions and approximations are there ; model-dependent neutrino transport : Garching Model**

Neutrino Emission Properties



Collapse to Black Hole

- **Even core collapse might fail to make an optical explosion, but can generate copious neutrinos.**
  - ➪ **chance to study evolution of the neutron star to the black hole**

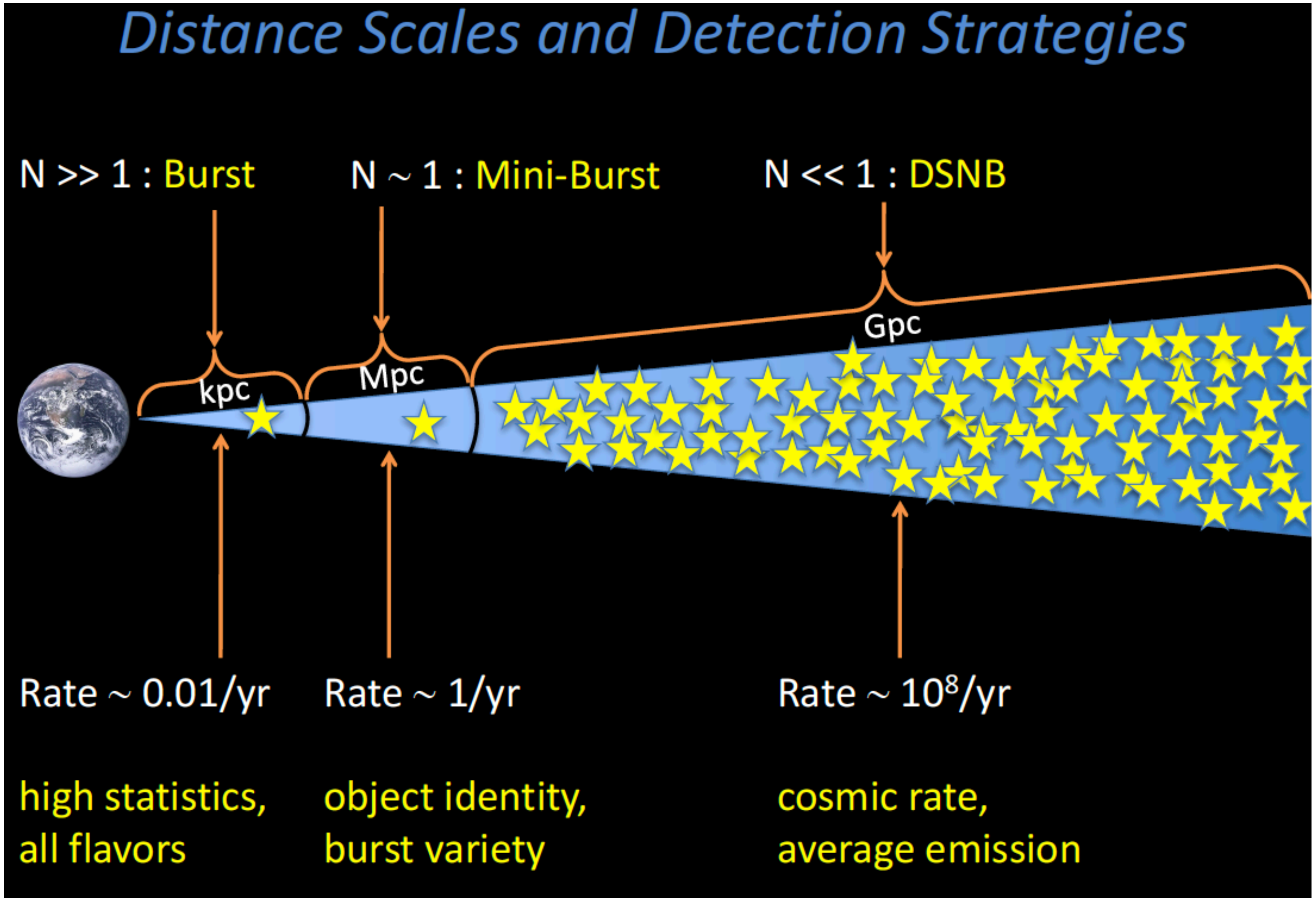


Liebendoerfer et al 2004, Fischer et al 2009, Sumiyoshi et al 06, 07, 08, 09, Nakazato et al 2008, 2010, O'Connor & Ott 2011, ...

Flux Calculation of Diffuse Supernovae Neutrino Background

What is DSNB ?

- The Diffuse Supernova Neutrino Background (DSNB) is the flux of neutrinos and antineutrinos emitted by all core-collapse supernovae in the causally-reachable universe.
  - ➯ isotropic and time-independent in feasible observations



from J. Beacom's slide, "Future Prospects for Supernova Neutrinos", 2017

- **Understanding supernovae is crucial to astrophysics and physics.**
  - ➪ history of stellar birth and death
  - ➪ the production of chemical elements, neutron stars and black holes, cosmic rays, and gravitational waves
- **We cannot understand supernovae without detecting neutrinos.**
  - ➪ the total energy in photons is much less than that in neutrinos
- **Detecting bursts of neutrinos from nearby supernovae is difficult.**
  - ➪ a few burst per century in the Milky Way
- **The DSNB is a guaranteed steady source of supernova neutrinos.**
  - ➪new probes of supernova neutrino emission and the cosmic core-collapse rate.

DSNB Flux Density

S. Ando, K. Sato, and T. Totani, Astrophys. J., 18, 307, (2013)

- **DSNB flux density**

$$\frac{dF_\nu}{dq} = \frac{c}{H_0}\int_0^{z_{max}} R_{SN}\frac{dN_\nu((1+z)q)}{dq}\frac{dz}{\sqrt{(1+\Omega_m z)(1+z)^2 - \Omega_\lambda(2z+z^2)}}$$

supernova rate

neutrino flux density from a supernova

- **The supernova rate : to be proportional to SFR**
  - ➪ SFR : star formation rate
  - ➪ since the lifetime of progenitors of core-collapse supernovae is much shorter than the cosmological time scale.

- **Used five SFRs per comoving volume**
  - ➪ three theoretical SFR
  - ➪ two SFR from the observational fit

First three models are based on the Einstein-de Sitter Universe

$$R_{SF1}(z) = 0.3h_{65}\frac{e^{3.4z}}{e^{3.8z}+45}M_{\odot}\ \mathrm{yr}^{-1}\ \mathrm{Mpc}^{-3}$$

P. Madau, L. Pozzetti, Mon. Not. R. Astron. Soc. 312 (2000) L9

$$R_{SF2}(z) = 0.15h_{65}\frac{e^{3.4z}}{e^{3.4z}+22}M_{\odot}\ \mathrm{yr}^{-1}\ \mathrm{Mpc}^{-3}$$

C.C. Steidel, K.L. Adelberger, M. Giavalisco, M. Dickinson, M. Pettini, Astrophys. J. 519 (1999) 1

$$R_{SF3}(z) = 0.2h_{65}\frac{e^{3.05z}}{e^{2.93z}+15}M_{\odot}\ \mathrm{yr}^{-1}\ \mathrm{Mpc}^{-3}$$

C. Porciani, P. Madau, Astrophys. J. 548 (2001) 522

$$R_{SF}(z) = h_{65}\frac{\sqrt{(1+\Omega_m z)(1+z^2)-\Omega_\lambda(2z+z^2)}}{(1+z)^{3/2}}R_{SF}(z;1,0,1)$$

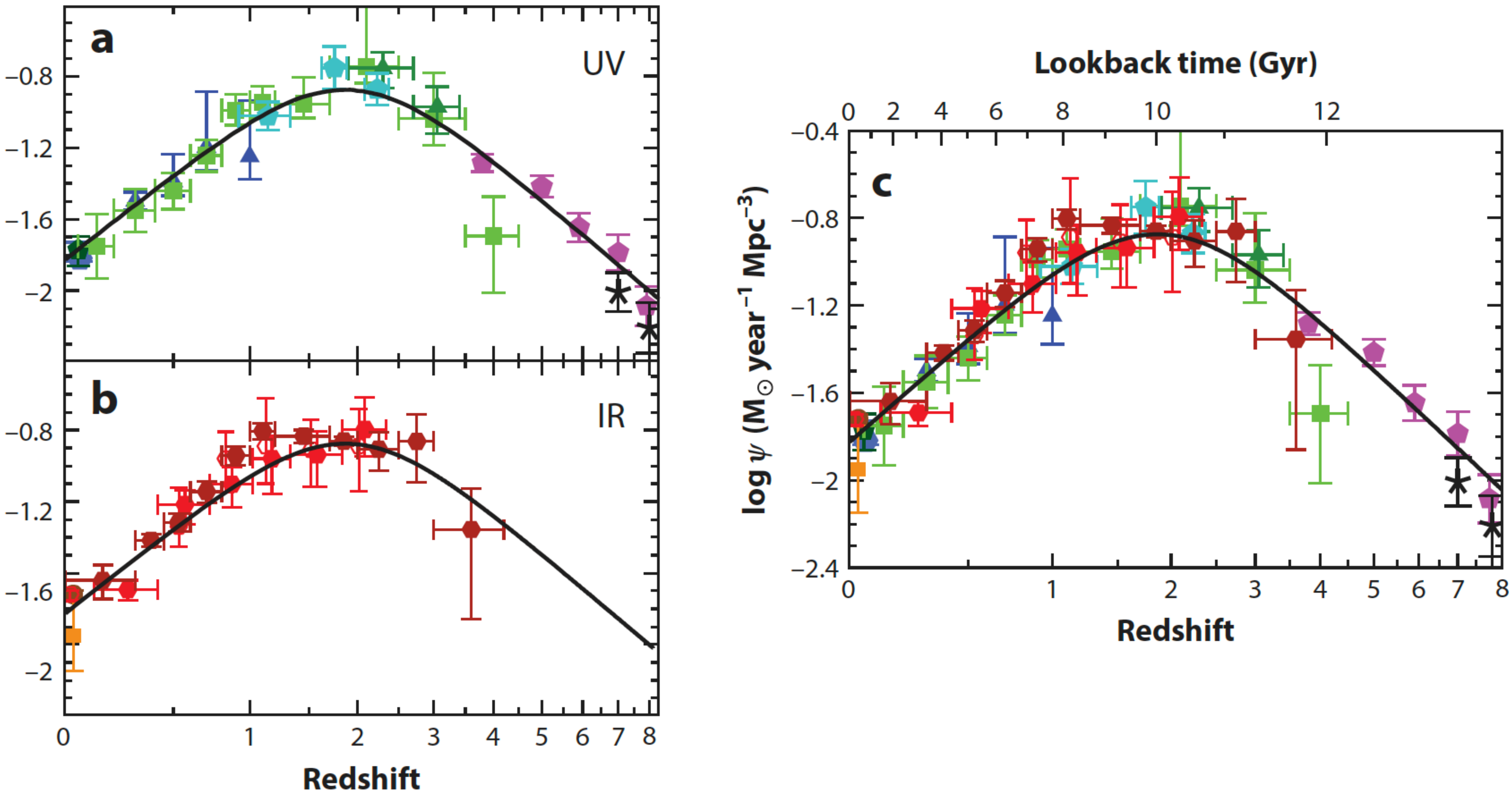
$$\Omega_m = 0.3 \quad \Omega_\lambda = 0.7$$

$$R_{CC} = R_{SN}\times\frac{\int_{8M_\odot}^{125M_\odot}\phi(m)dm}{\int_{0.001M_\odot}^{125M_\odot}m\phi(m)dm} \equiv R_{SN}\times k_{CC} = 0.0122R_{SN}$$

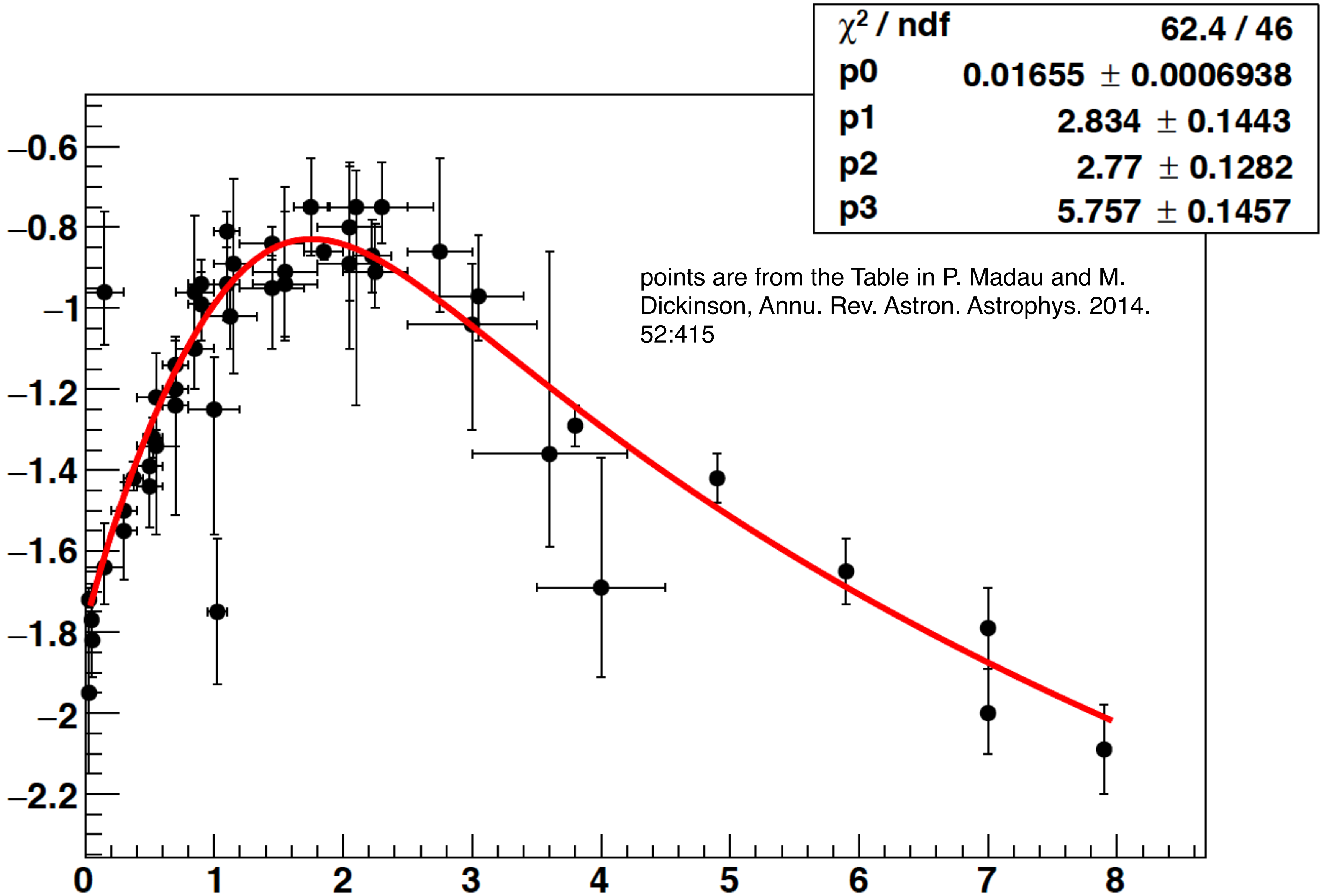
$\phi(m)$: Salpeter IMF(initial mass function)

$$R_{SN4} \longrightarrow \Psi(z) = 0.015 \frac{(1+z)^{2.7}}{1+\left(\frac{1+z}{2.9}\right)^{5.6}} \ M_\odot \ \mathrm{yr}^{-1} \ \mathrm{Mpc}^{-3} \quad (0 < z \leq 4)$$

P. Madau and M. Dickinson, Annu. Rev. Astron. Astrophys. 2014. 52:415

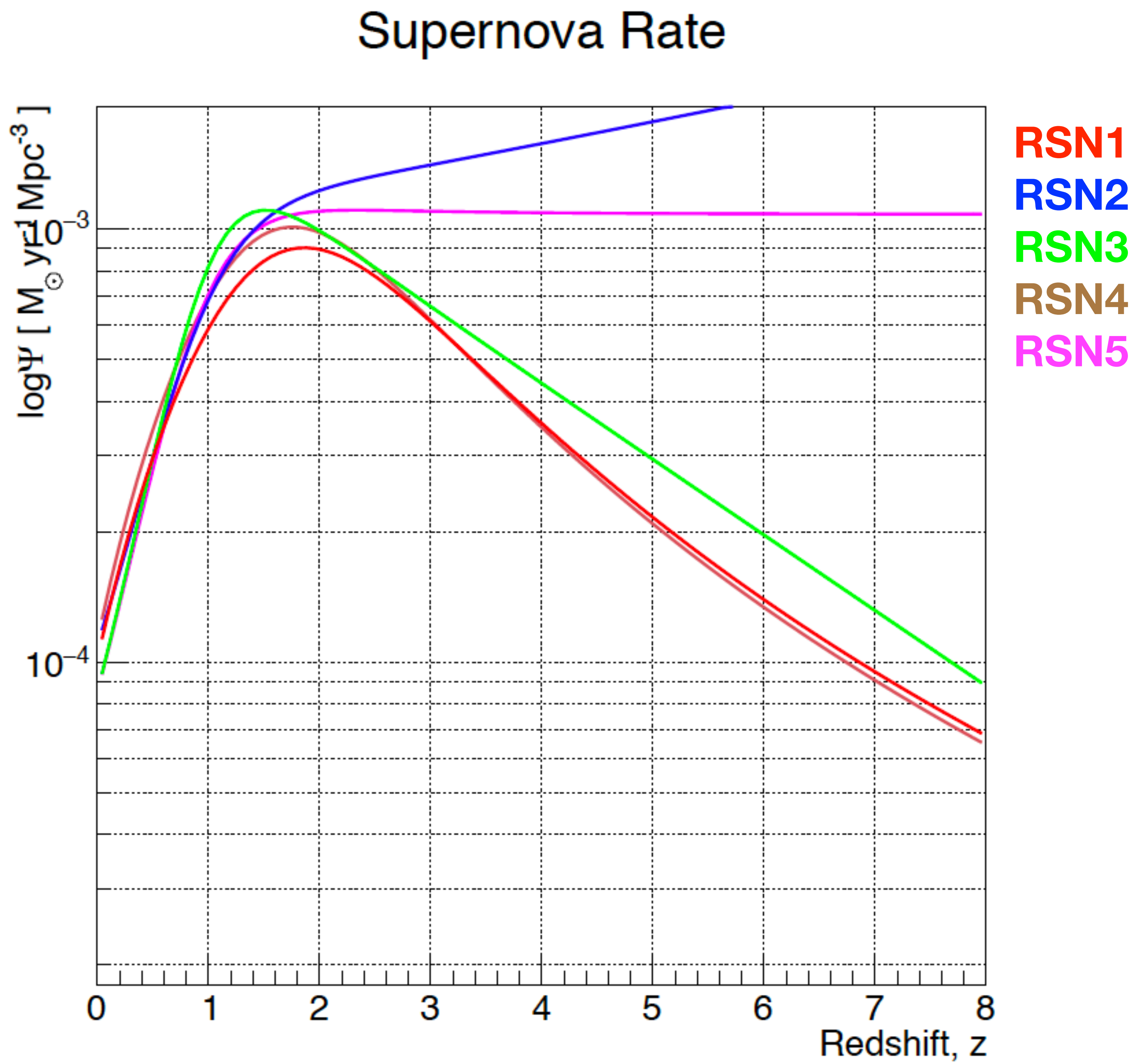


$R_{SN5} \longrightarrow \quad \Psi(z) = p_0 \frac{(1+z)^{p_1}}{1+(\frac{1+z}{p_2})^{p3}} M_\odot \ \mathrm{yr}^{-1} \ \mathrm{Mpc}^{-3}$

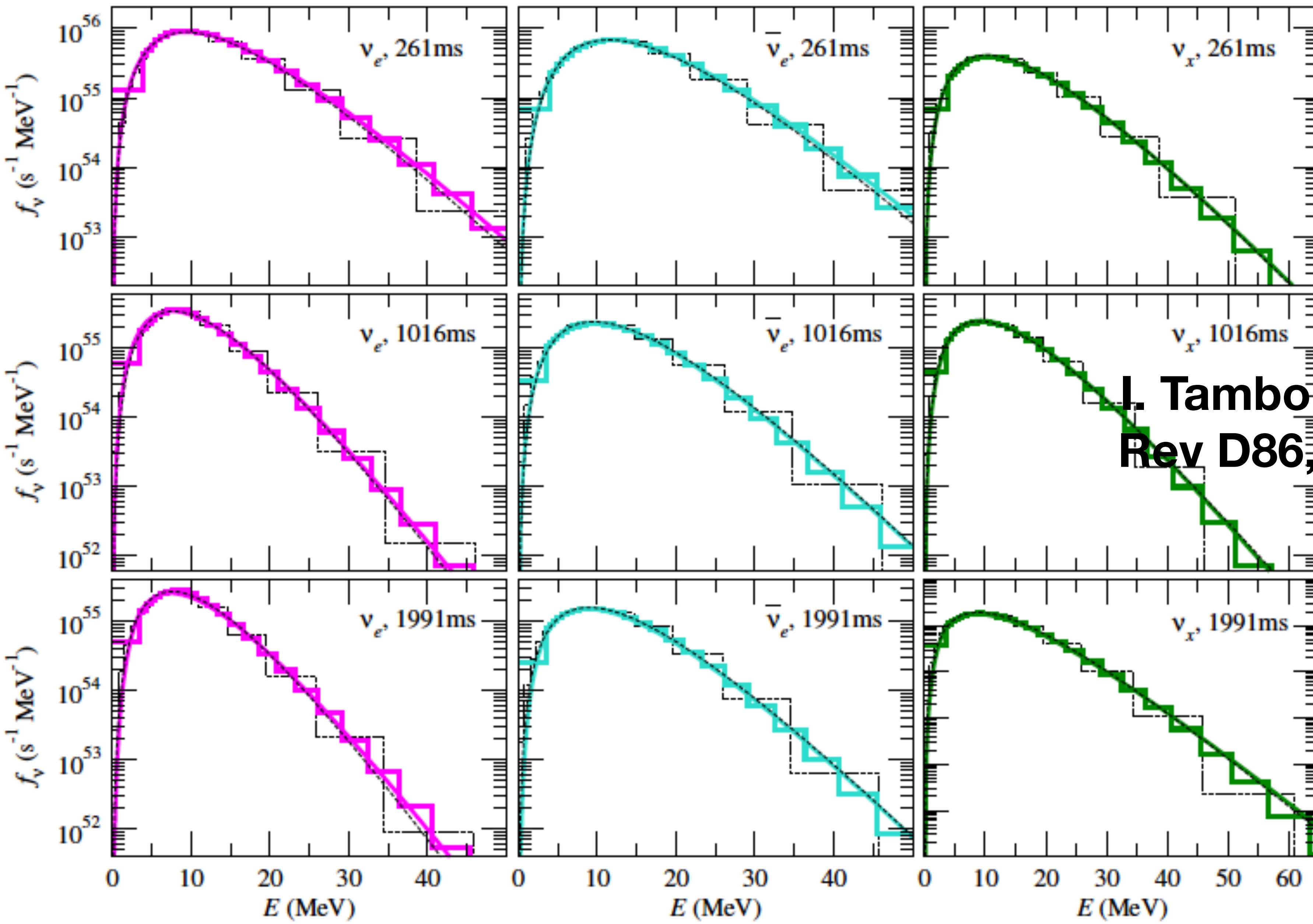


$$R_{CC} = \Psi(z) \times \frac{\int_{m_{min}}^{m_{max}} \phi(m)dm}{\int_{m_{min}}^{m_{max}} m\phi(m)dm} \equiv \Psi(z) \times k_{CC}$$

Supernova Rates from Various Functions



Spectral Shape



I. Tamborra et al., Phys. Rev D86, 125031, (2012)

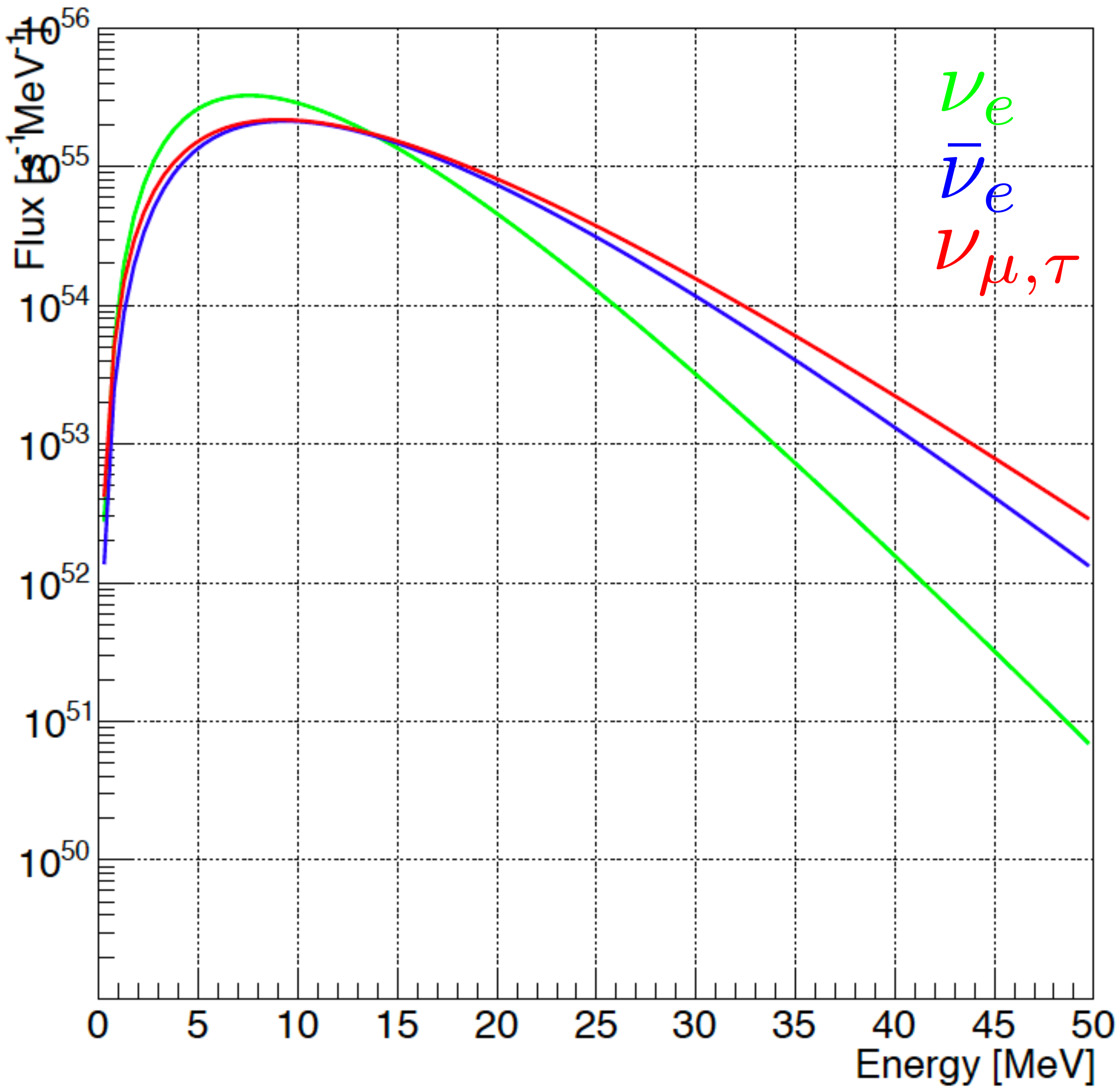
Fig. 9 Spectra for electron neutrinos (ν_e; *left column*), electron antineutrinos ($\bar{\nu}_e$; *middle column*), and heavy-lepton neutrinos (ν_x, *right column*) during the accretion phase (261 ms after core bounce, *top row*) and for two times during the proto-neutron star cooling phase (1016 ms, *middle row*; 1991 ms, *bottom row*). The step functions are results of numerical simulations with lower (thin dashed) and higher (thick, colored) resolution. The continuous curves are quasi-thermal fits according to Eq. (33) for the lower resolution (thin dashed lines) and higher resolution (thick solid lines) cases. All α values for the fit functions are in the interval $2.3 \leq \alpha \leq 3.3$. (Figure taken from Tamborra et al, 2012)

Neutrinos Flux with Oscillation

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = P(\bar{\nu}_e \to \bar{\nu}_\mu) = \frac{1}{2}(\sin^2\theta_{12} + \cos^4\theta_{13}\sin^2\theta_{13})$$

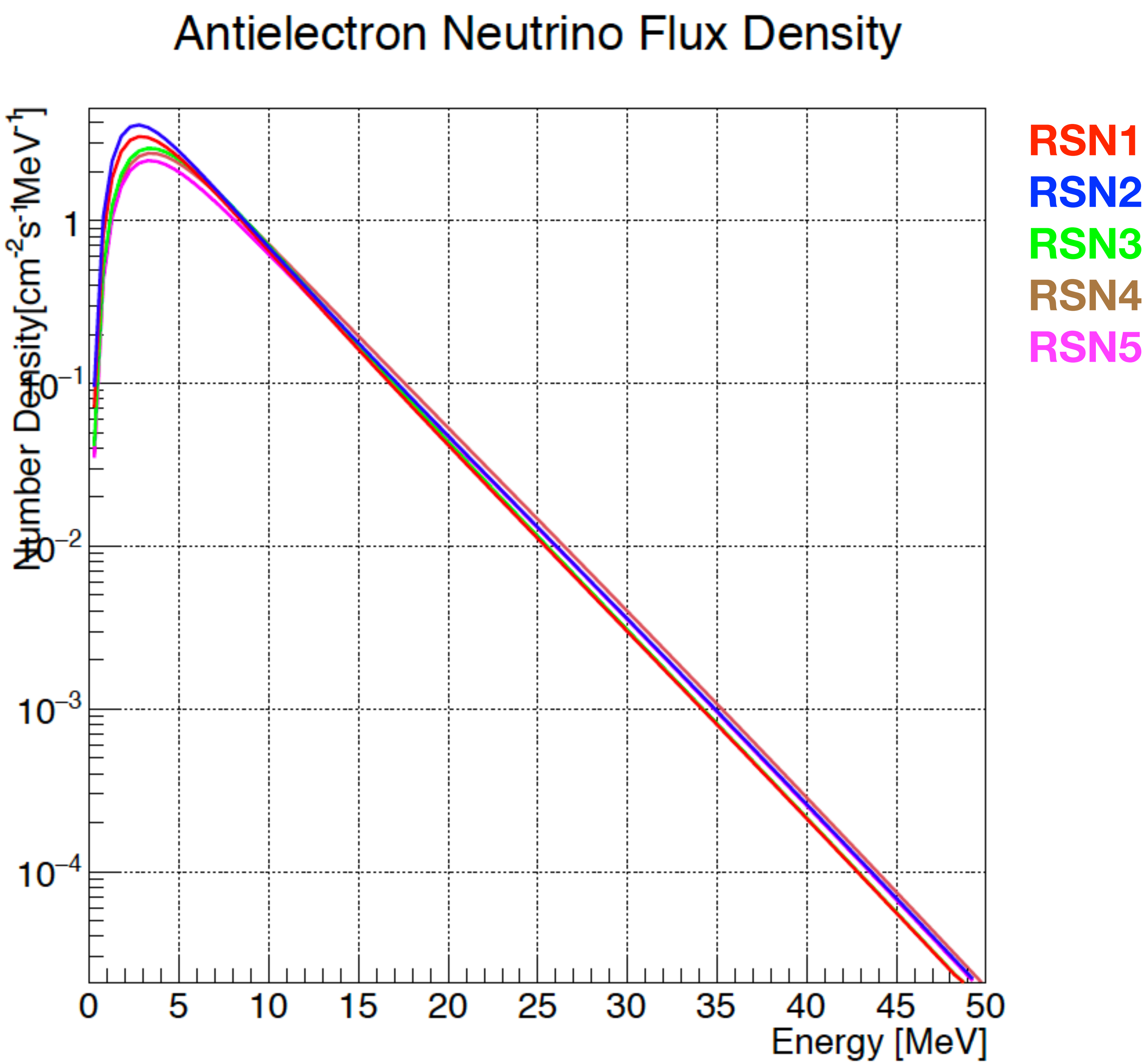
$$F_{\bar{\nu}_e} = \{(1 - P(\bar{\nu}_e \to \bar{\nu}_\mu)\}F^0_{\bar{\nu}_e} + P(\bar{\nu}_\mu \to \bar{\nu}_e)F^0_{\bar{\nu}_\mu}$$

Flux Density

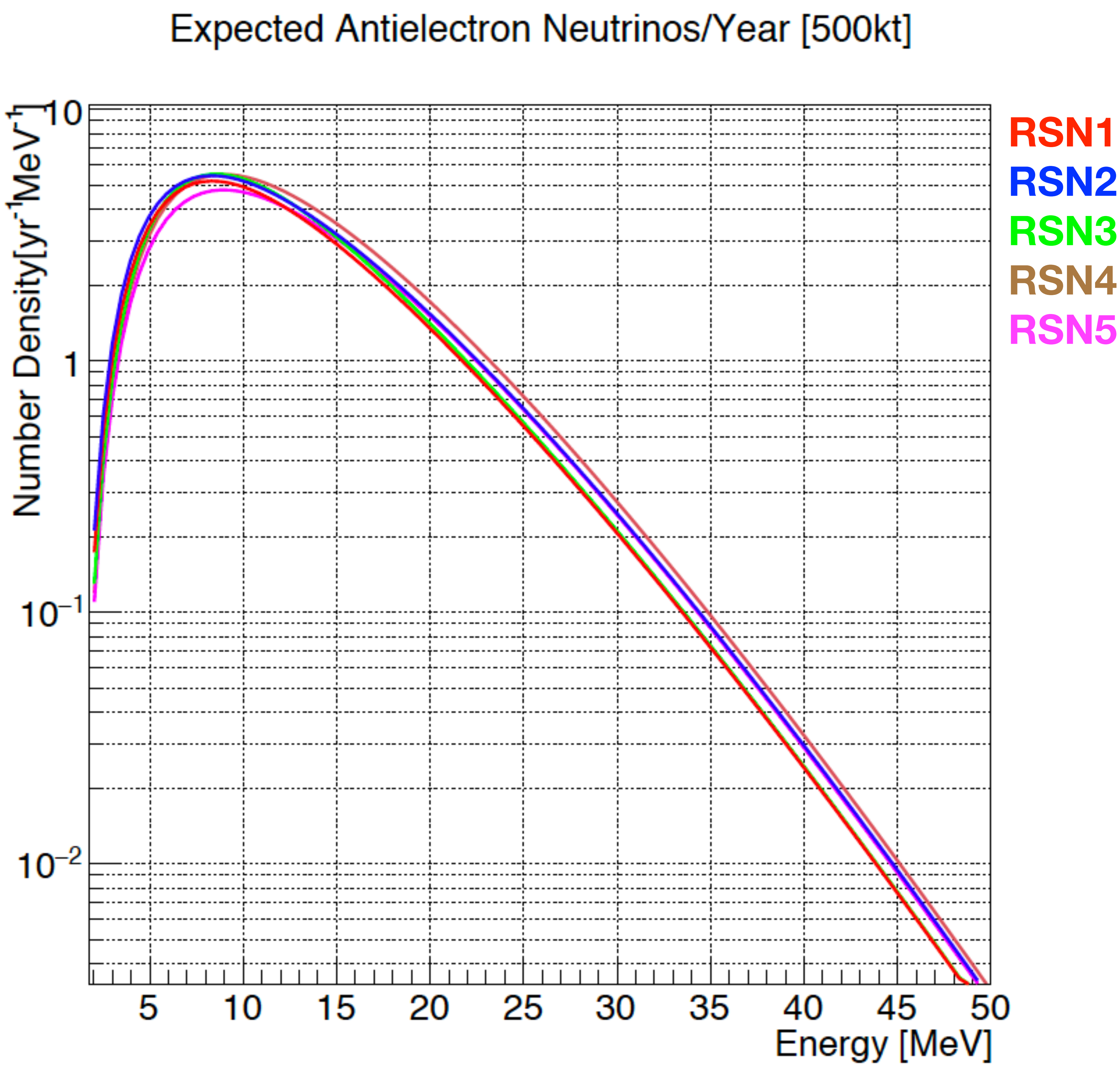


- **If the fluxes from anti-muon and anti-electron neutrinos have same order, the oscillation effect is negligible.**
- **Oscillation effect : E>~30 MeV.**

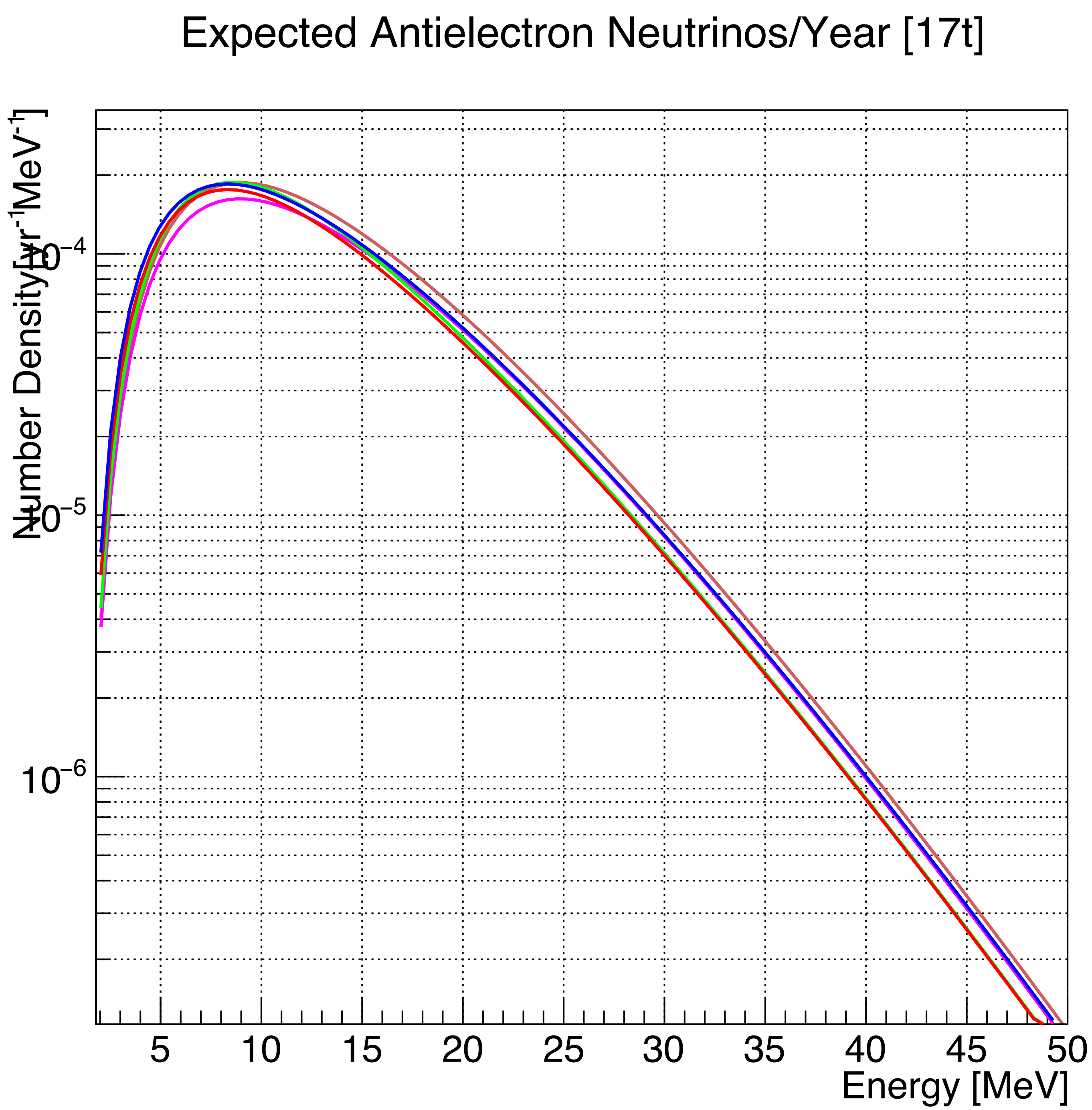
Antielectron Neutrino Number Density



Expected Antielectron Neutrinos/yr at 500kt Neutrino Detector



Expected Antielectron Neutrinos/yr at JSNS2



RSN1
RSN2
RSN3
RSN4
RSN5

SNF	events/yr [10<E<=30]
SN1	0.00131
SN2	0.00123
SN3	0.00135
SN4	0.00148
SN5	0.00129

- **We need ~800 yrs to detect DSNB.**
  - ➪ **hopeless for DSNB**
  - ➪ **but, what if Galaxy Core-Collapse SN?**

Possible candidate?

It has following parameters.

$$M \approx 11.6^{+5.0}_{-3.9}\ M_{\odot}$$

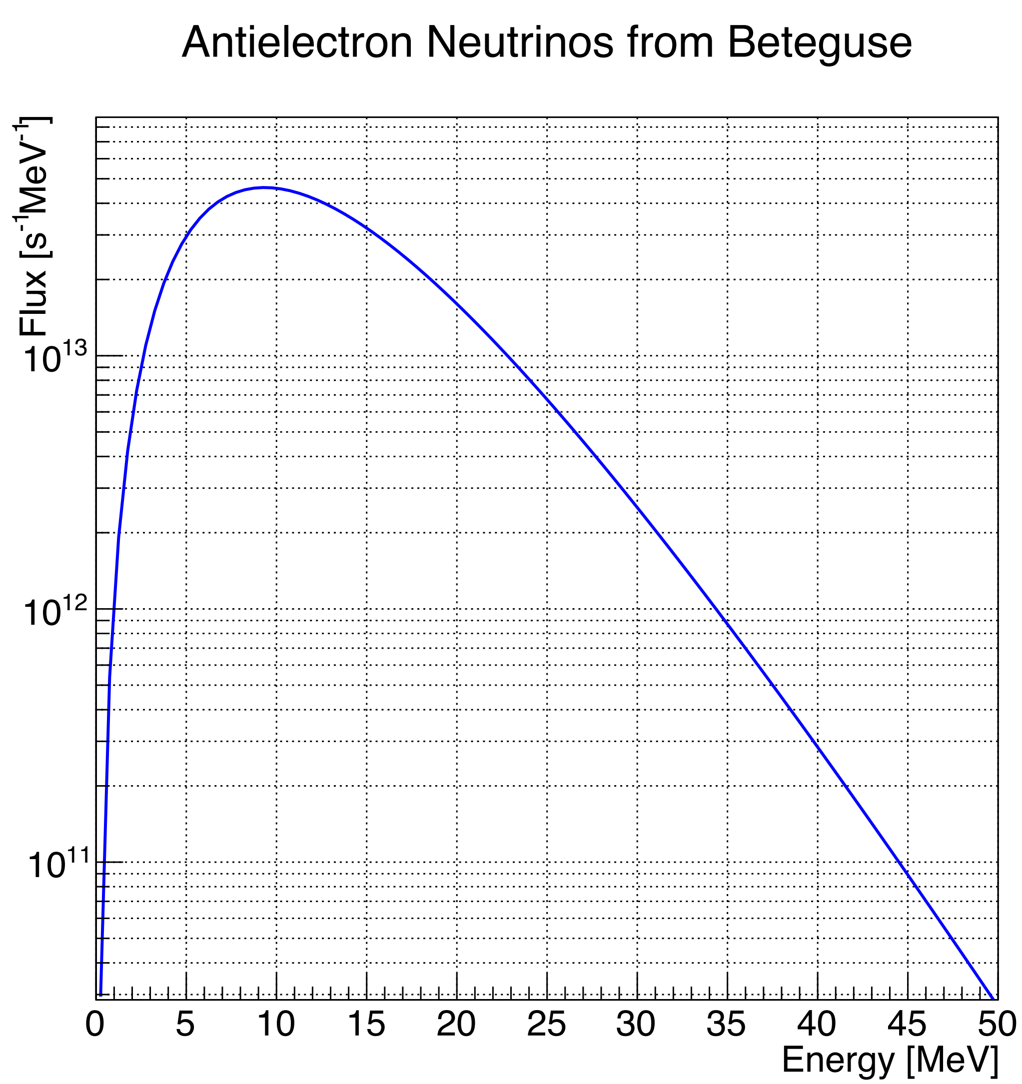
$$R \approx 887 \pm 203\ M_{\odot}$$

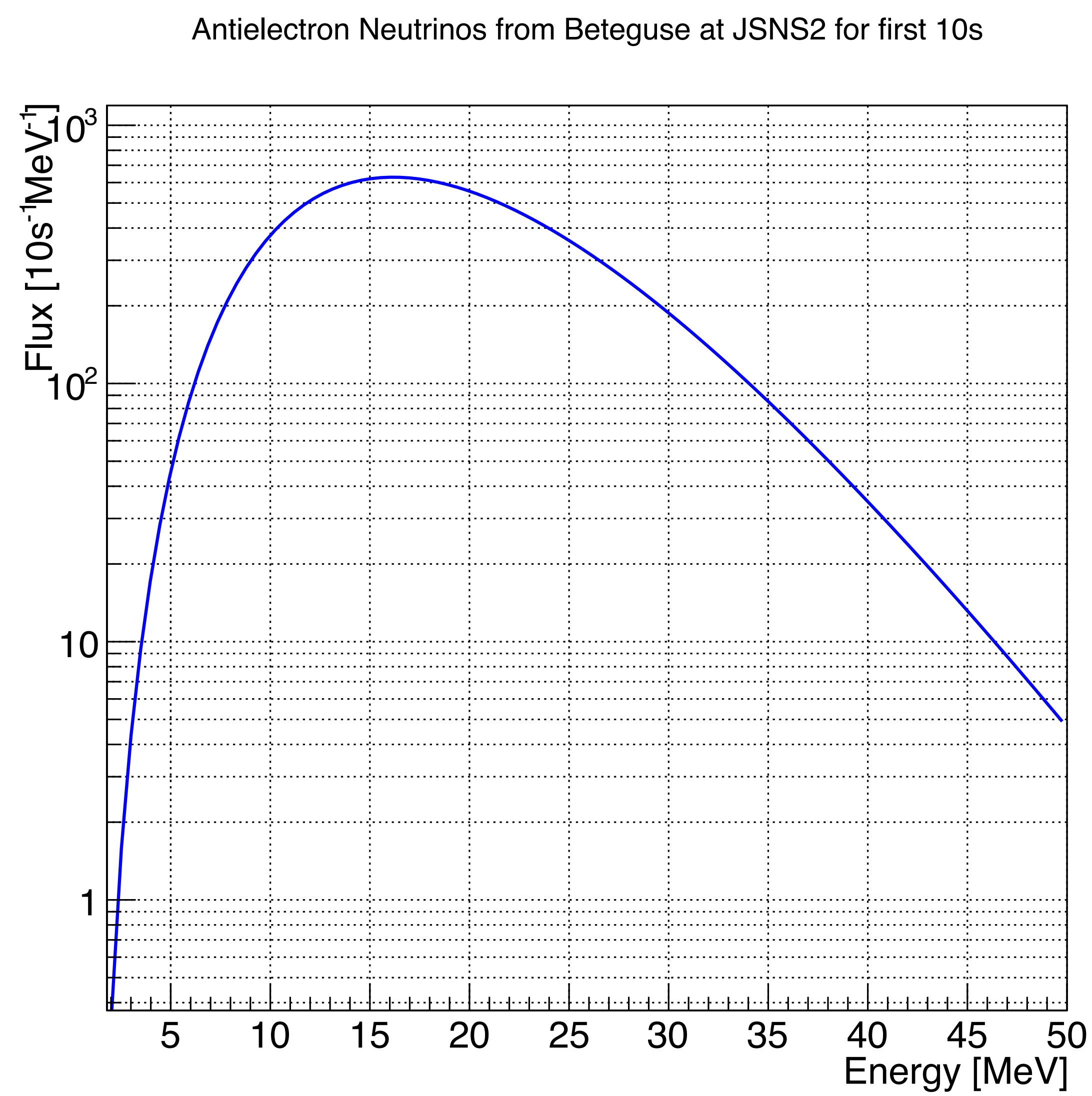
$$Age \approx 8.0 - 8.5 \times 10^{6}\ \mathrm{yr}$$

$$Distance \approx 197 \pm 45\ \mathrm{pc}$$

If Betelgeuse explodes, we will obtain a lots of neutrino data but people lose his memory about the night sky.

Antielectron Neutrinos from Betelguse at JSNS2 for first 10s





- **Number of expected anti-electron neutrinos from Betelguse at JSNS2 for first 10s (10<E<=40 MeV) : 1.0x10^4 x ~0.12 (trigger time efficiency) = ~1,200 neutrinos**
- **Sufficient to study core-collapse supernova evolution**

Summary

- **JSNS2 having 17t Gd-LS target has no ability to detect DSNB.**

  ➩ ~1.2×10^{-3} events expected per a year
- **Neutrino burst from a nearby core collapse supernova such as Betelgeuse in Milky Way could be detected using JSNS2 detector to study the evolution of the star.**

  ➩ 1,200 events expected for first 10s (with ~0.12 trigger efficiency)

  ➩ sufficient amount of data to look into anti-electron neutrino spectrum which can reveal properties of neutrino transport stage : deeper understanding of the death of very massive mass stars