Strong magnetic field impacts on the neutrino transport in Core-Collapse Supernovae

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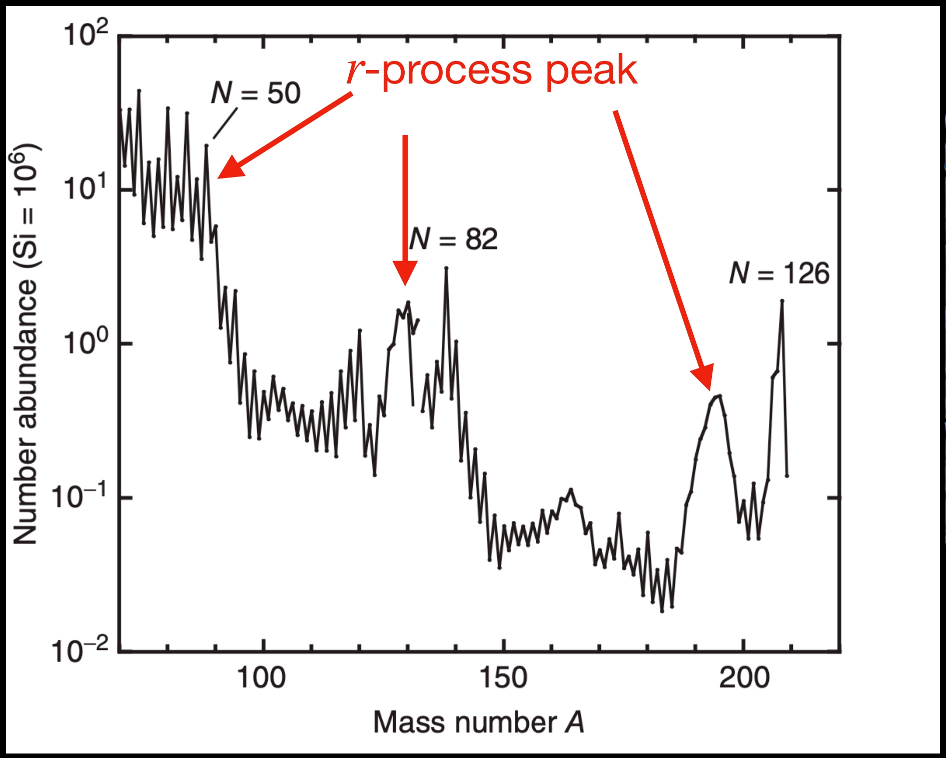
OMEG17, Chengdu,11th Sep

Motivation

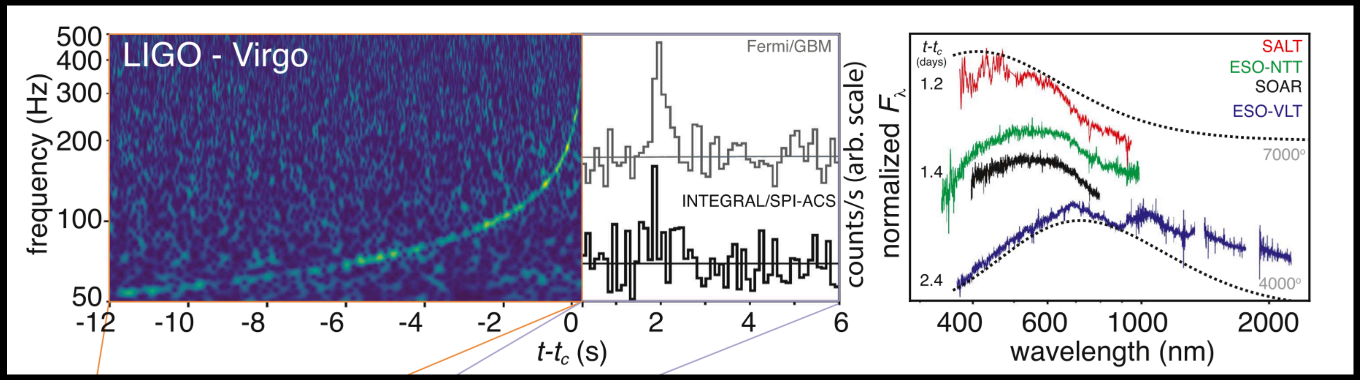


- Main sites of r-process nucleosynthesis

- Binary neutron star merger

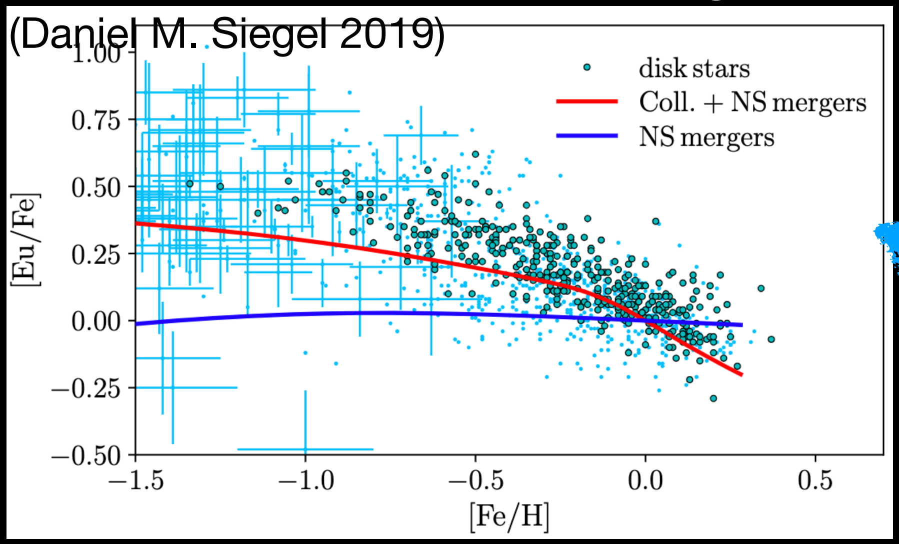
- Supernovae

GW detection + GRB observation



(Abbott et al 2017)

Evolution of Eu versus iron at high metallicity (Daniel M. Siegel 2019)

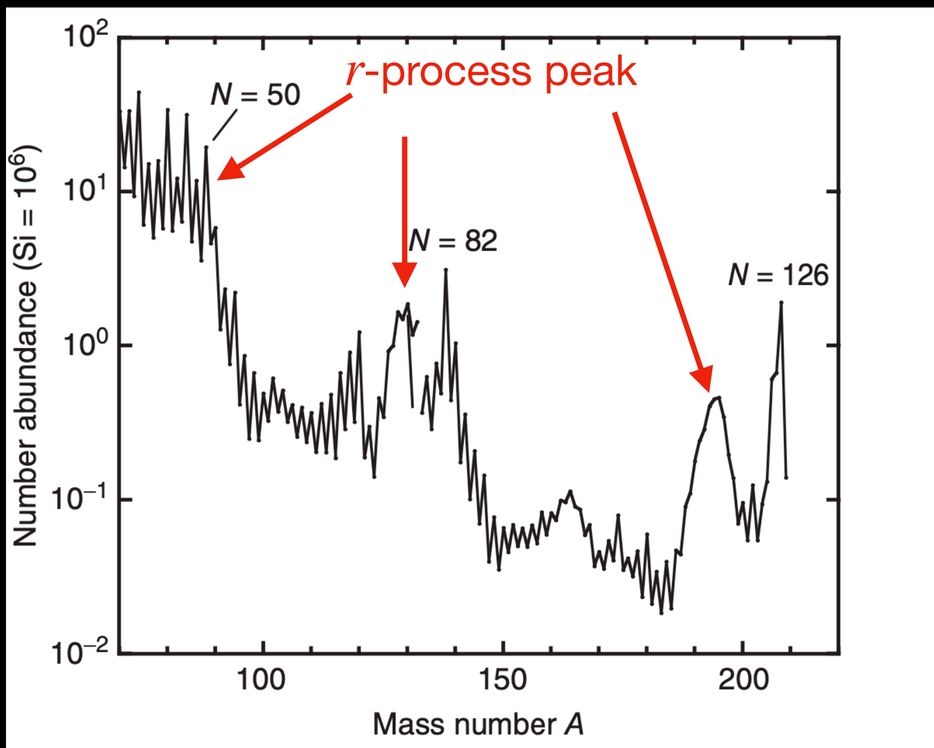


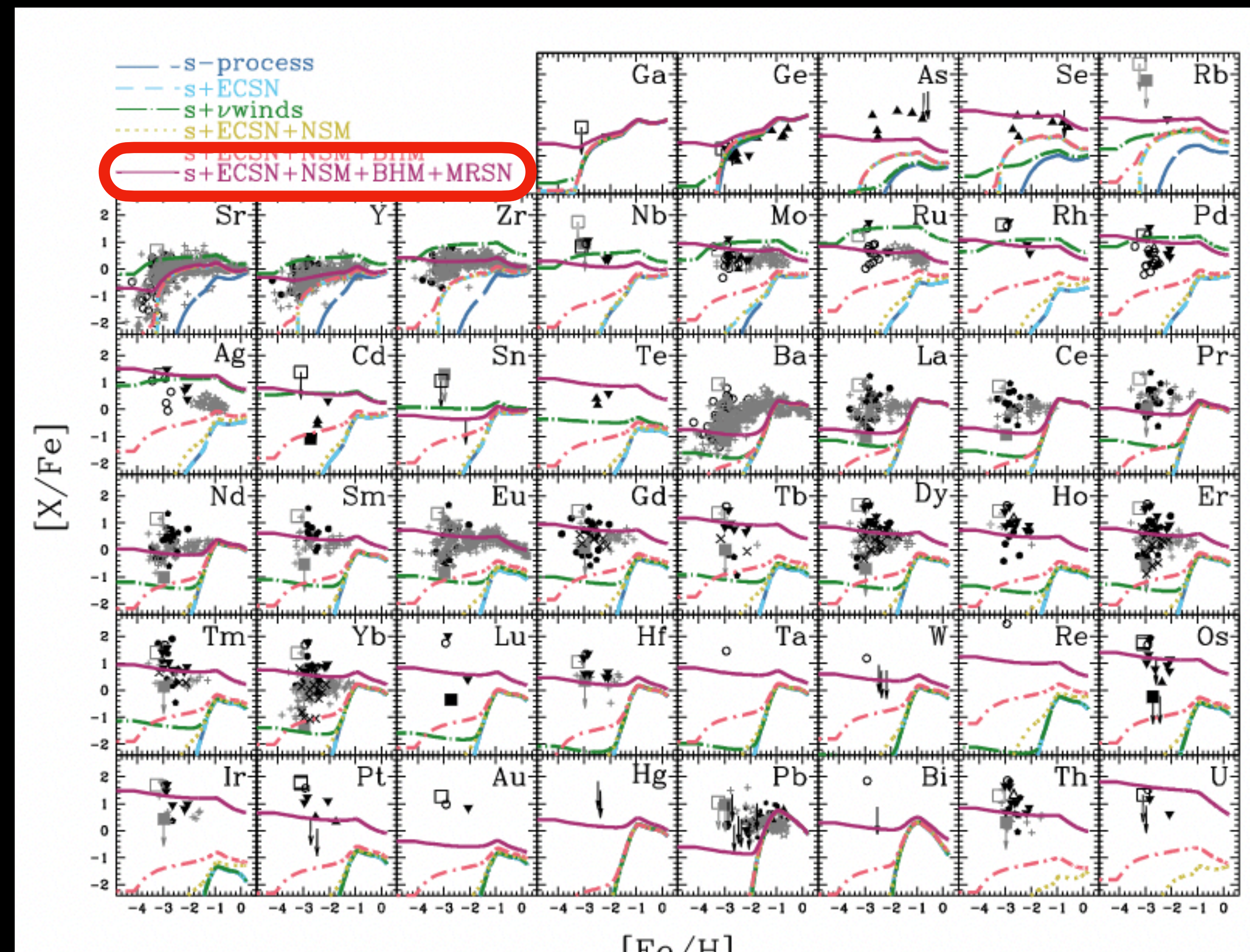
- Apply the kilonova parameters from GW170817

- Merger-only r-process enrichment is not sufficient to reproduce Eu abundance

- The major enrichment sites are believed still Supernovae

Motivation

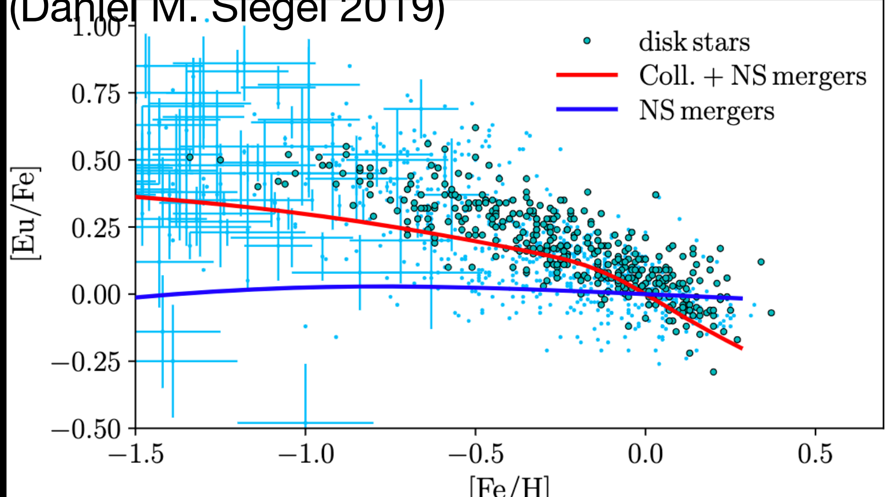




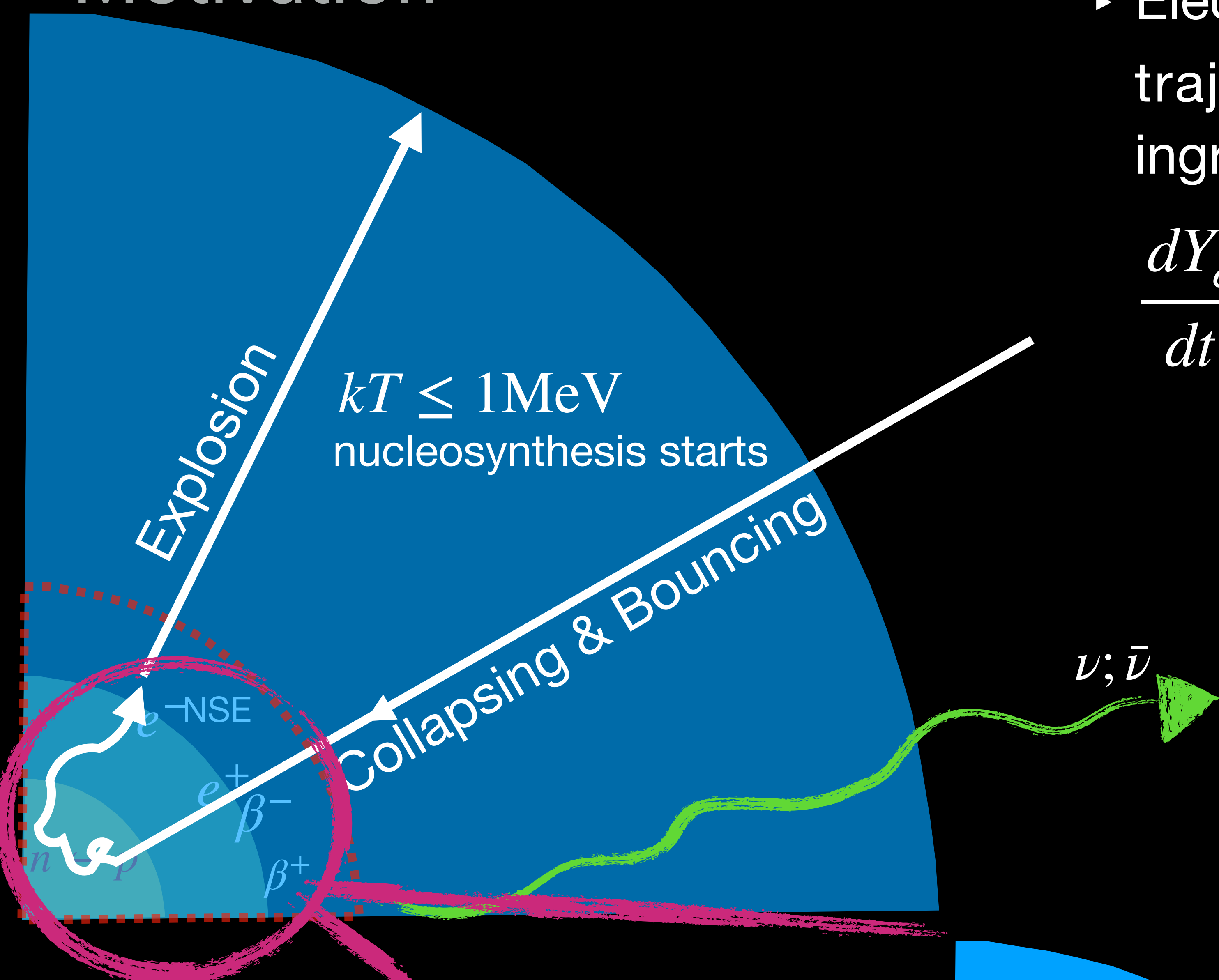
Kobayashi 2020

Evolution of Eu versus iron at high metallicity

(Daniel M. Siegel 2019)

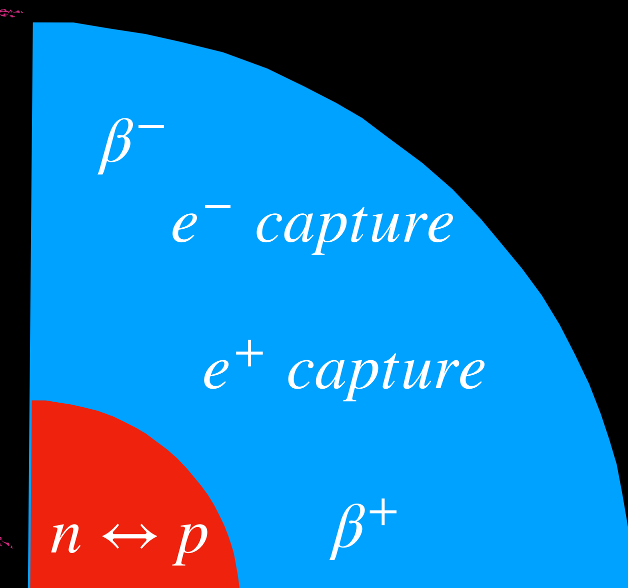


Motivation



- Electron fraction Y_e evolves along with the trajectory. $Y_e(T, \rho, Y_e)$ describes the ingredient for r-process nucleosynthesis

$$\frac{dY_e}{dt} = -(\lambda_{pe^-} + \lambda_{p\bar{\nu}_e})X_p + (\lambda_{ne^+} + \lambda_{n\nu_e})X_n + \sum_h \left(\frac{X_h}{A_h}\right)(\lambda_{h\nu_e} + \lambda_{he^+} - \lambda_{h\bar{\nu}_e} - \lambda_{he^-})$$



- β decay and $e^\pm$ capture: determining the abundance flow and the isotopic ratio
- $n \leftrightarrow p$: determines electron fraction Y_e, which further affect the neutron-richness.

Magnetic field in SNe could be $10^{14\sim16}$ G, strongly influence the electron motion as well as weak interactions

Magnetic Field Impact on Weak Interactions

Magnetic Field Impact on Weak Interactions

- Electron capture rate with magnetic field

$$\Gamma^B_{pe^-\to n\nu_e} = \sum_{n=0}^{\infty} (2-\delta_{n0}) \cdot \int_0^{\infty} \sigma(E_\nu, B)\, dp_z\ f_{FD}(\epsilon; \mu, T_\gamma) g(E_\nu; \mu_\nu, T_\nu)$$

$$E_e^2 = p_z^2 + m_e^2 + 2eBn$$

$(c = \hbar = 1)$

Phase space:

$$\sum_{n=0}^{\infty} (2-\delta_{n0}) \frac{dp_z}{2\pi} \frac{eB}{2\pi} f_{FD}(E_B, T)$$

$\Phi(E)$

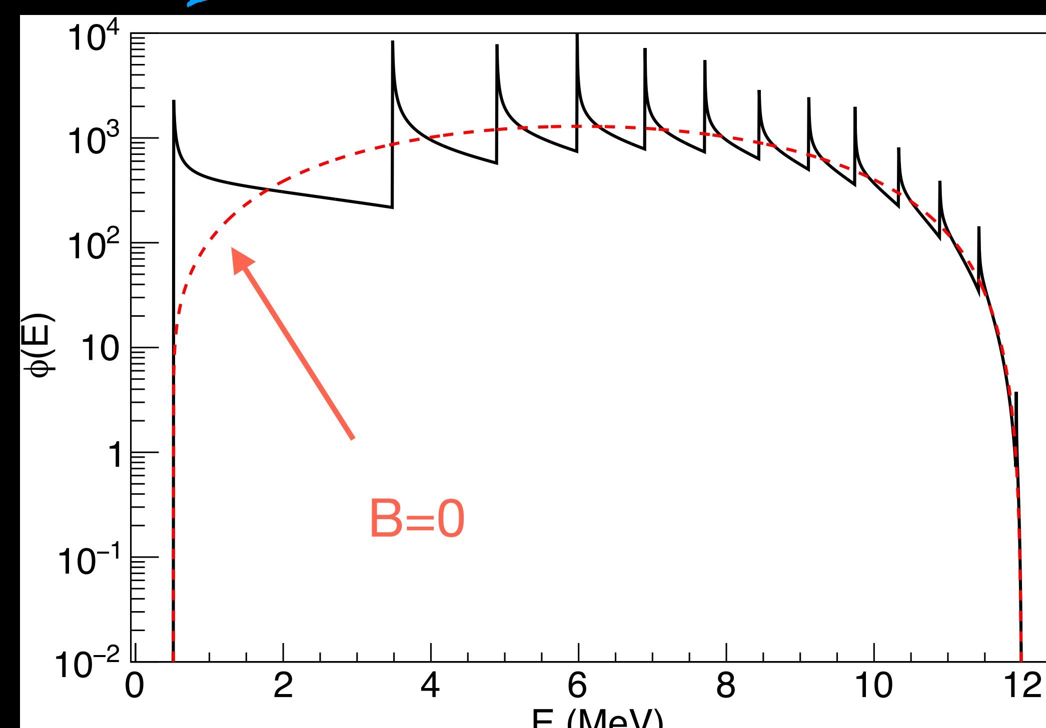
Cross section of neutrino interaction

$$\sigma_{\nu N}(B) = \sigma_B^1 \left[1 + 2\chi \frac{(f \pm g)g}{f^2 + 3g^2} \cos\Theta_\nu\right] + \sigma_B^2 \left[\frac{f^2 - g^2}{f^2 + 3g^2} \cos\Theta_\nu + 2\chi \frac{(f \mp g)g}{f^2 + 3g^2}\right]$$

$$\sigma_B^1 = \frac{G_F^2 \cos^2\theta_C}{2\pi} (f^2 + 3g^2) eB \sum_{n=0}^{n_{max}} \frac{g_n E_e}{\sqrt{E_e^2 - m_e^2 - 2neB}}$$

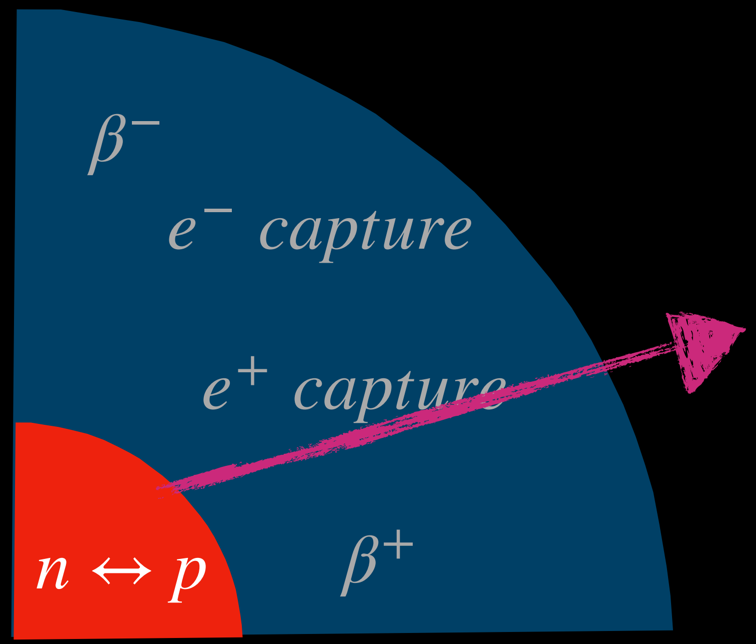
$$\sigma_B^2 = \frac{G_F^2 \cos^2\theta_C}{2\pi} (f^2 + 3g^2) eB \frac{E_e}{\sqrt{E_e^2 - m_e^2}},$$

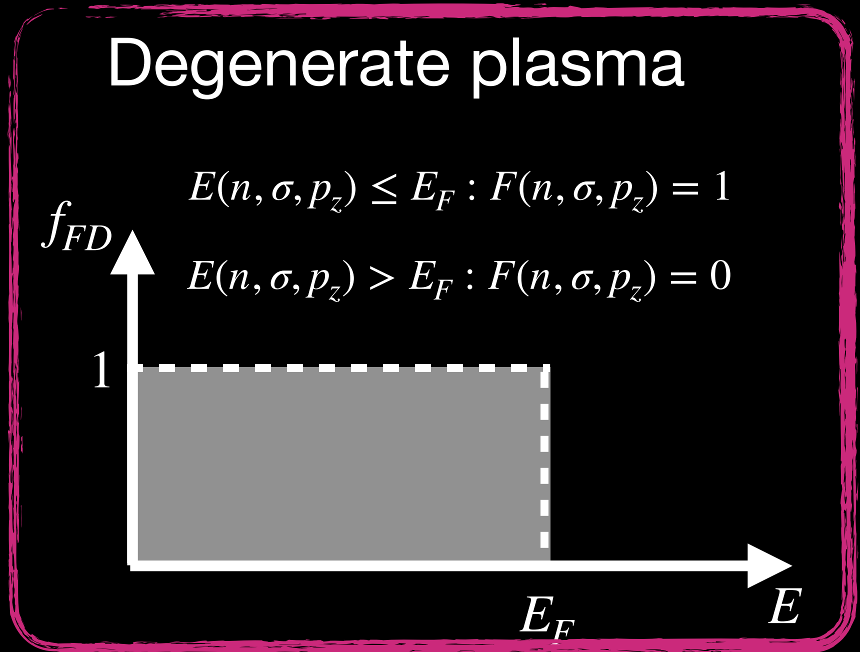
Duan&Qian 2005



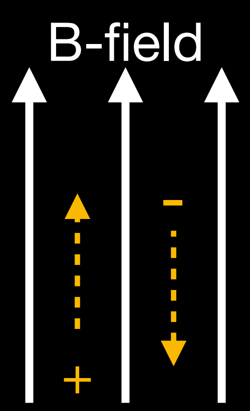
Famiano et al, ApJ 898, 163

Magnetic Field Impact on Weak Interactions





- Fermi energy within magnetic filed

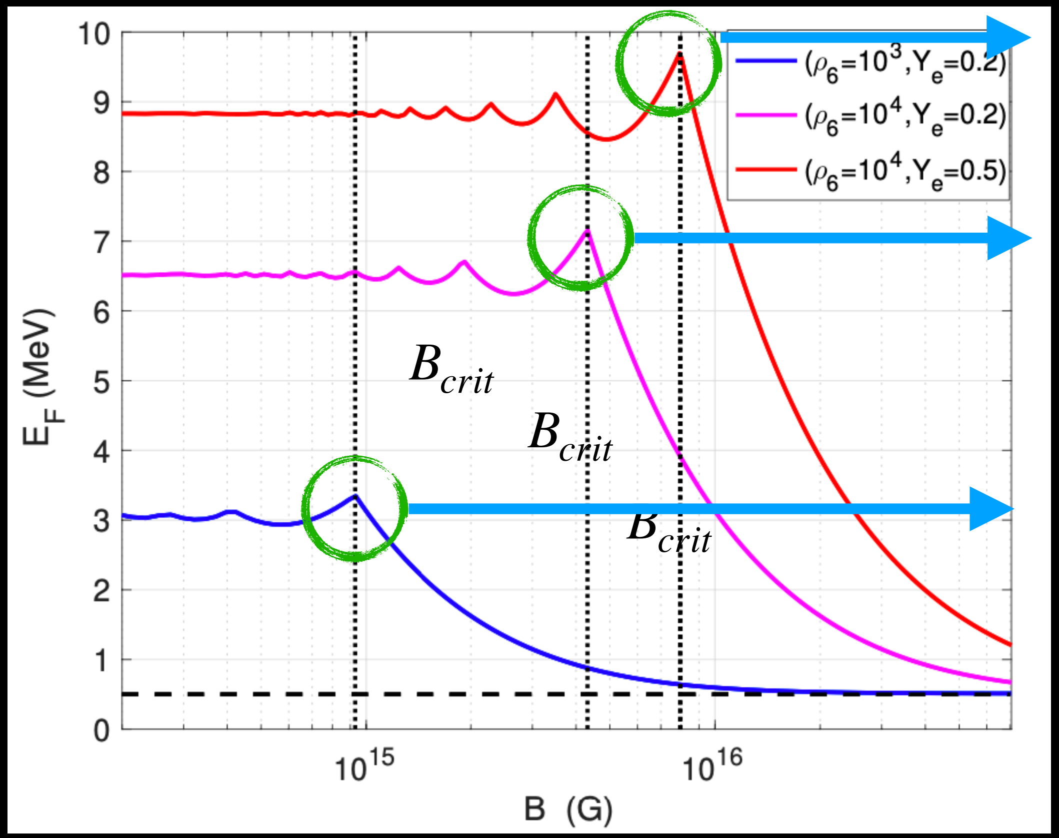


Total number of electrons

= Summation of electrons on all levels

$$\rho Y_e = \frac{N_+}{V} + \frac{N_-}{V}$$

E_F as a function of B-field strength



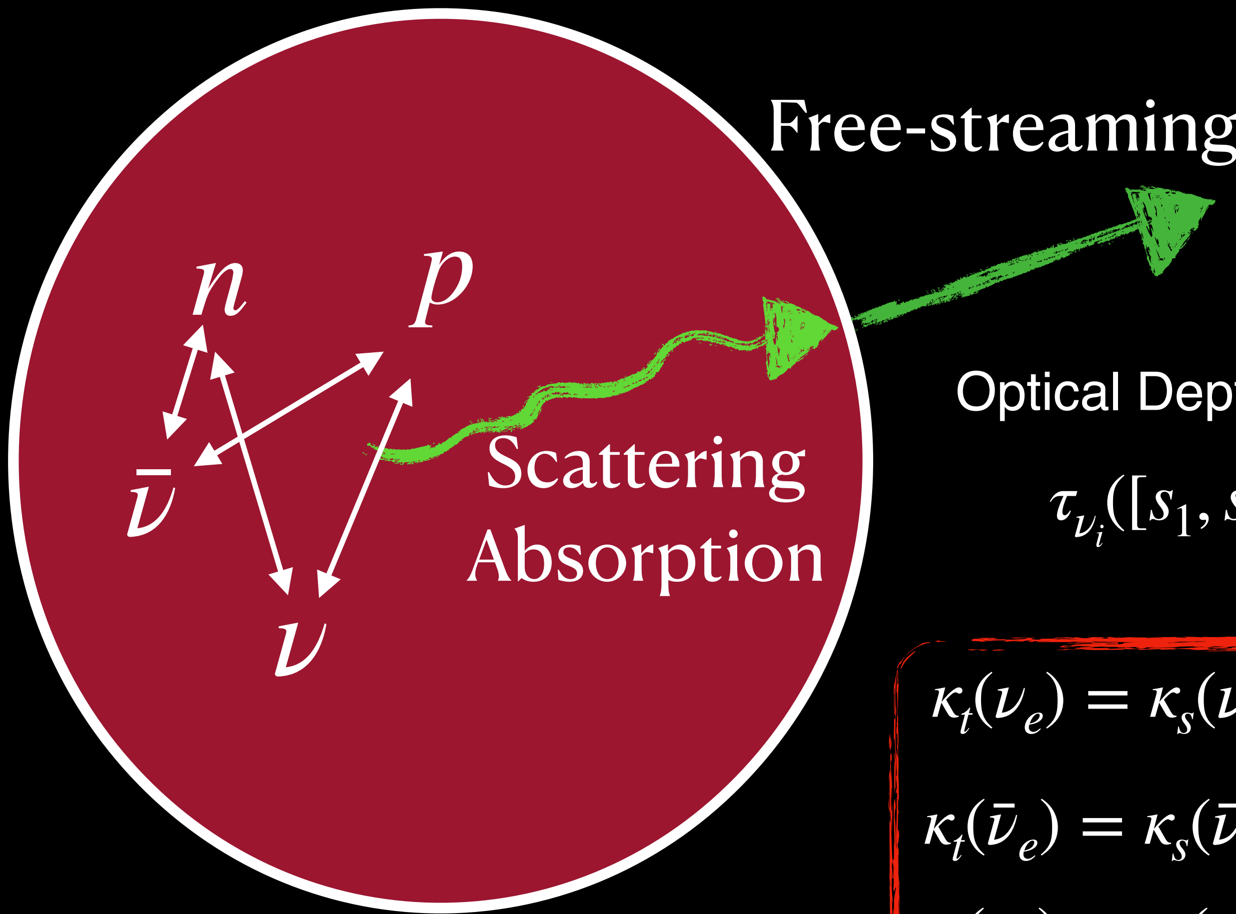
$(\rho_6 = \rho/10^6)$

$(B_{crit} = \frac{\pi}{e}[2\pi(\rho Y_e)^2]^{1/3})$

- $B > B_{crit}$, only lowest Landau level occupied, E_F decreases monotonically as a function of B
- The new Landau level leads to a peak of E_F, results in a wiggle shape

Neutrino transport in Core-Collapse Supernovae

Neutrino transport inside the $\nu-$sphere (Leakage Scheme)



- Definition of $\nu - sphere$

$$\tau = \int_{R_\nu}^{\infty} dr \kappa_t(r) = \frac{2}{3}$$

Opacity

Optical Depth along the path [s1, s2]:

$$\tau_{\nu_i}([s_1, s_2]) = \int_{s_1}^{s_2} ds \kappa_{\nu_i}(s)$$

$$\kappa_t(\nu_e) = \kappa_s(\nu_e n) + \kappa_s(\nu_e p) + \kappa_a(\nu_e n)$$

$$\kappa_t(\bar{\nu}_e) = \kappa_s(\bar{\nu}_e n) + \kappa_s(\bar{\nu}_e p) + \kappa_a(\bar{\nu}_e p)$$

$$\kappa_t(\nu_x) = \kappa_s(\nu_x n) + \kappa_s(\nu_x p)$$

s: scattering on n&p,
a: absorption on n/p

change with B-field

M. Ruffert, H.-Th. Janka, and G. Schafer (1995)
S. Rosswog and M. Liebendorfer (2003)
A. Perego, R. M. Cabezon, and R. Käppeli (2016)

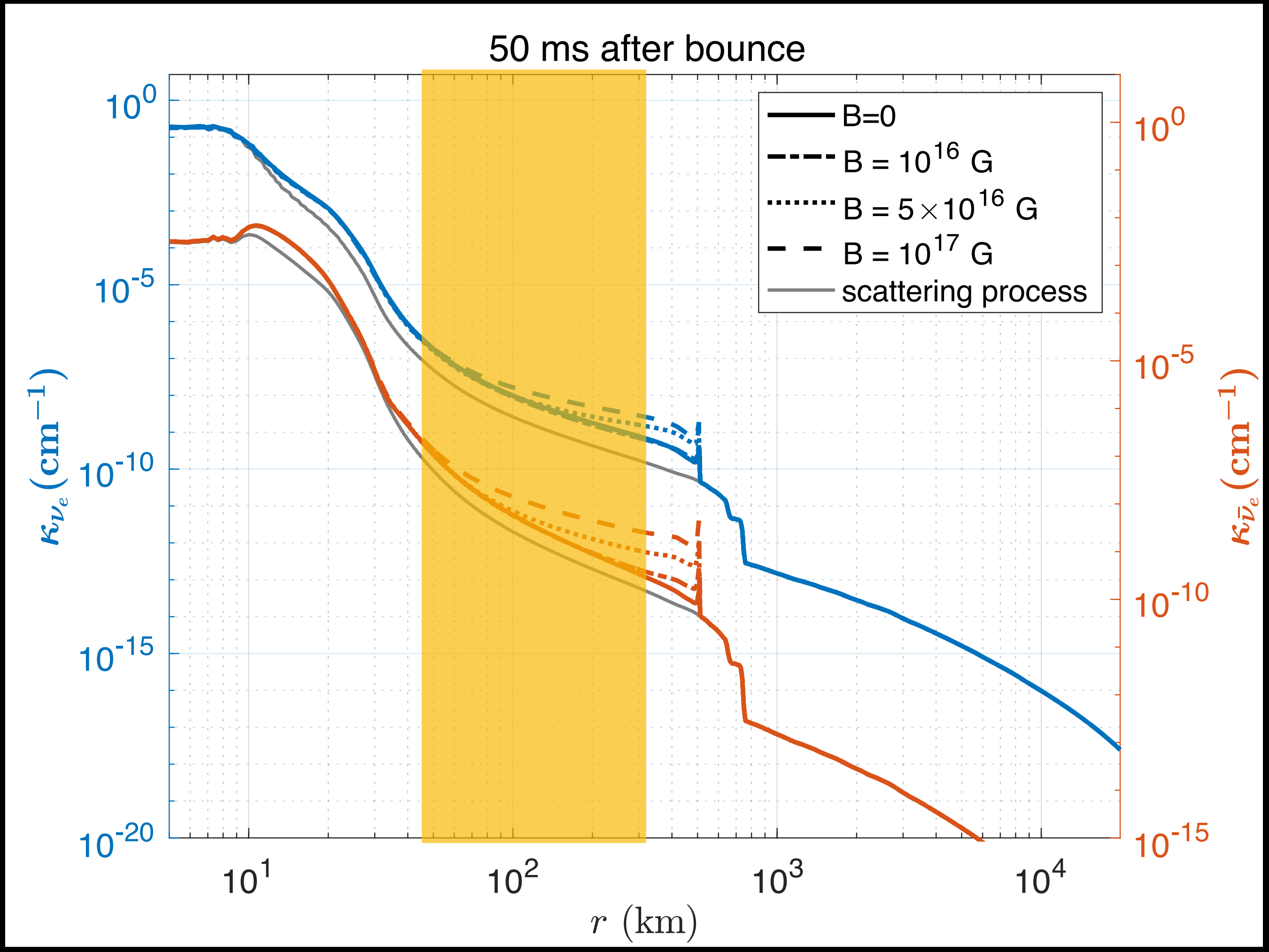
$$\kappa_a^B(\nu_e n) = A\rho Y_{np}\left(\frac{1}{m_e c^2}\right)^2 \frac{\int_0^\infty \sigma_{\nu N}(E_e, B) E_\nu^4 f_{FD}(E_\nu, \mu_\nu; T_\nu)}{\int_0^\infty E_\nu^2 f_{FD}(E_\nu, \mu_\nu; T_\nu)} \left[1 - \frac{1}{\exp(F_5(\eta_{\nu_e})/F_4(\eta_{\nu_e}) - \eta_e)}\right]$$

Neutrino transport inside the $\nu-$sphere

GR1D: 1D Core-Collapse SNe code O'Connor & Ott375 2010; O'Connor 2015

EoS: Lattimer & Swesty LS180 (1991) Progenitor: 9.6 M⊙ massive star (Heger)

▸ $\nu(\bar{\nu})$ Opacities



Y. Luo et al submitted

- No significant change @High density&temperature region (B is not strong to make $e^{\pm}$ confine on LLL)

- Quantized phase space of $e^{\pm}$

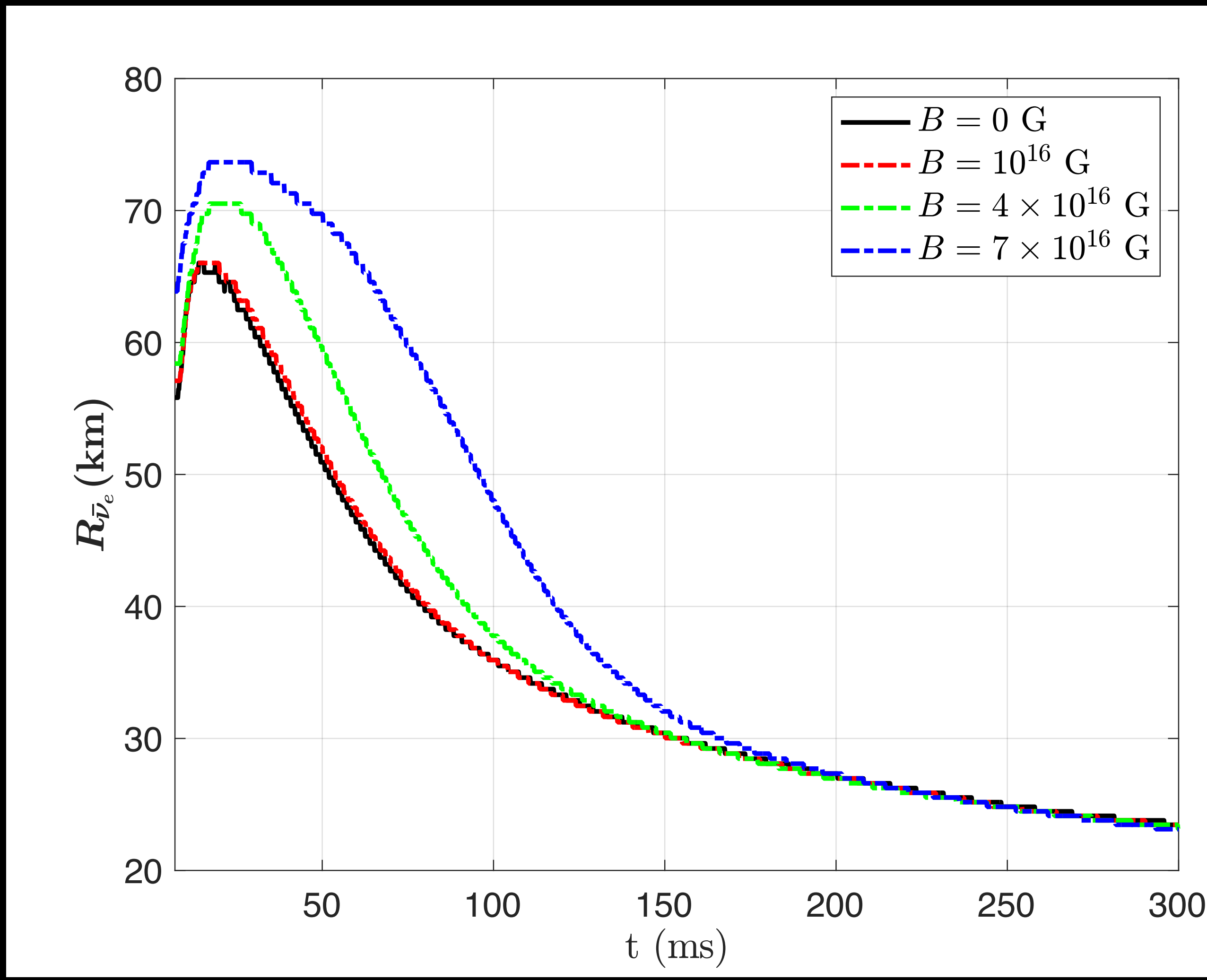
⟶ Enhancement of the number density

⟶ Enhancement of the interaction rate

Neutrino transport inside the $\nu-$sphere

▸ $\nu(\bar{\nu})$ Spheres evolution

Y. Luo et al submitted



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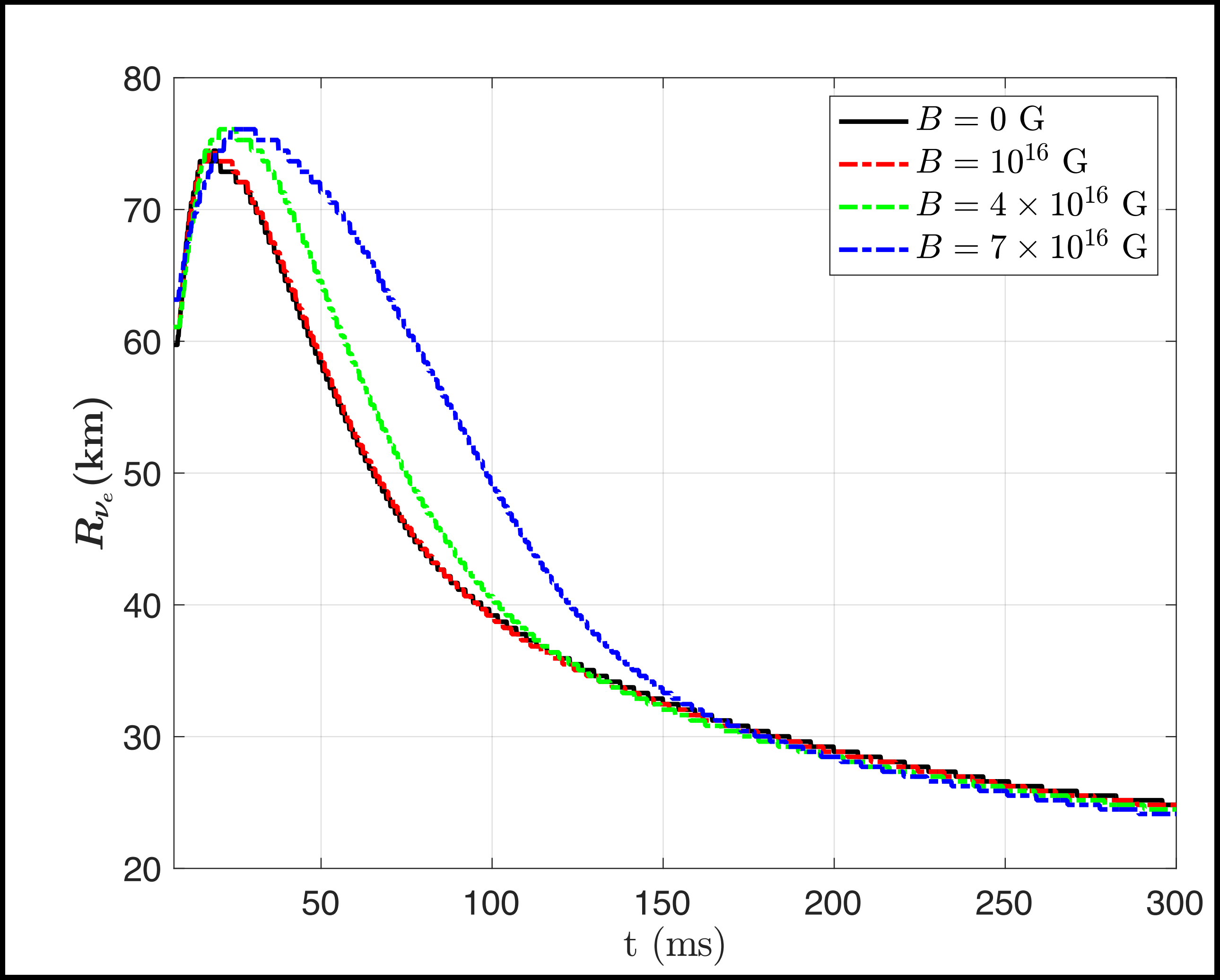
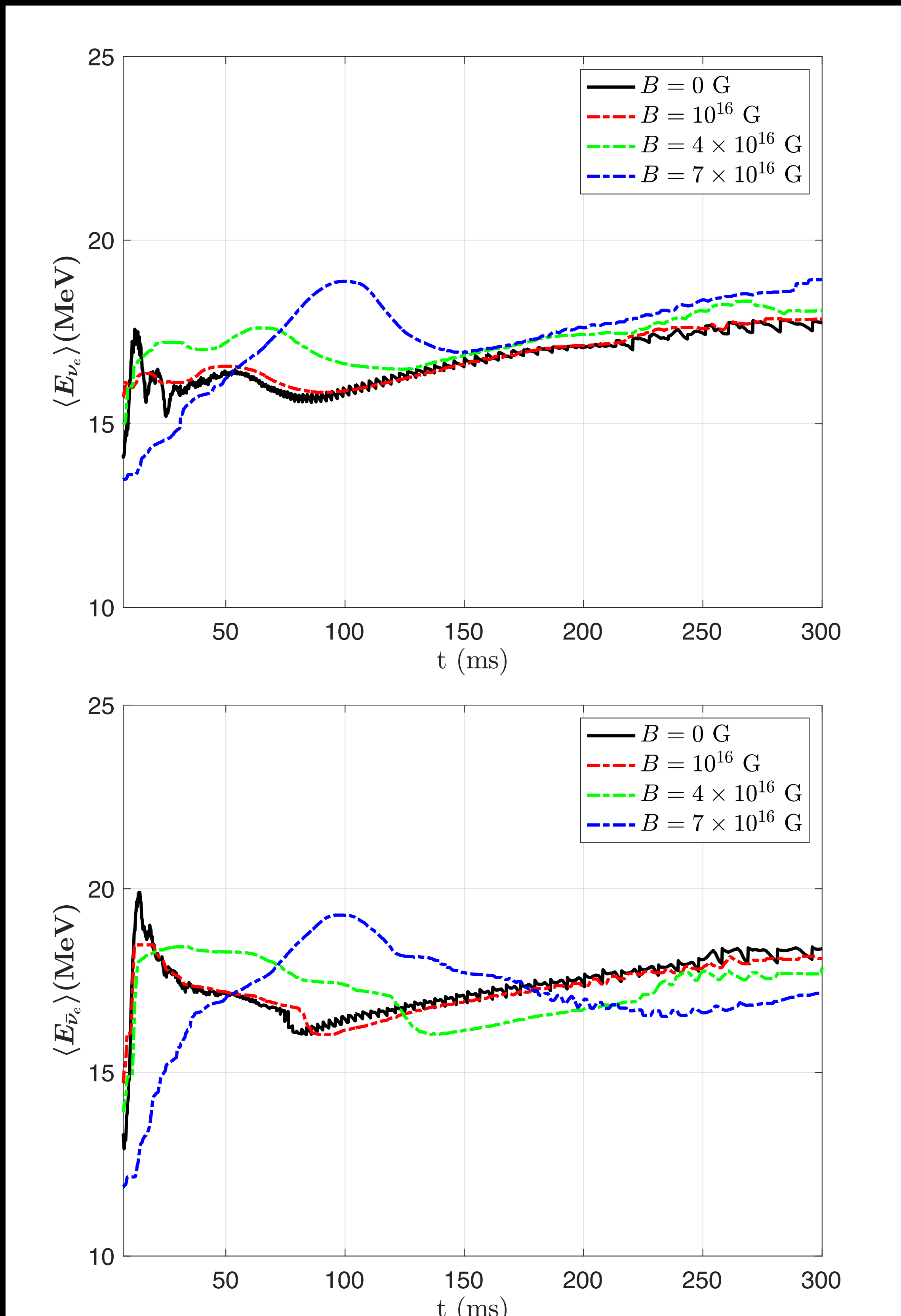


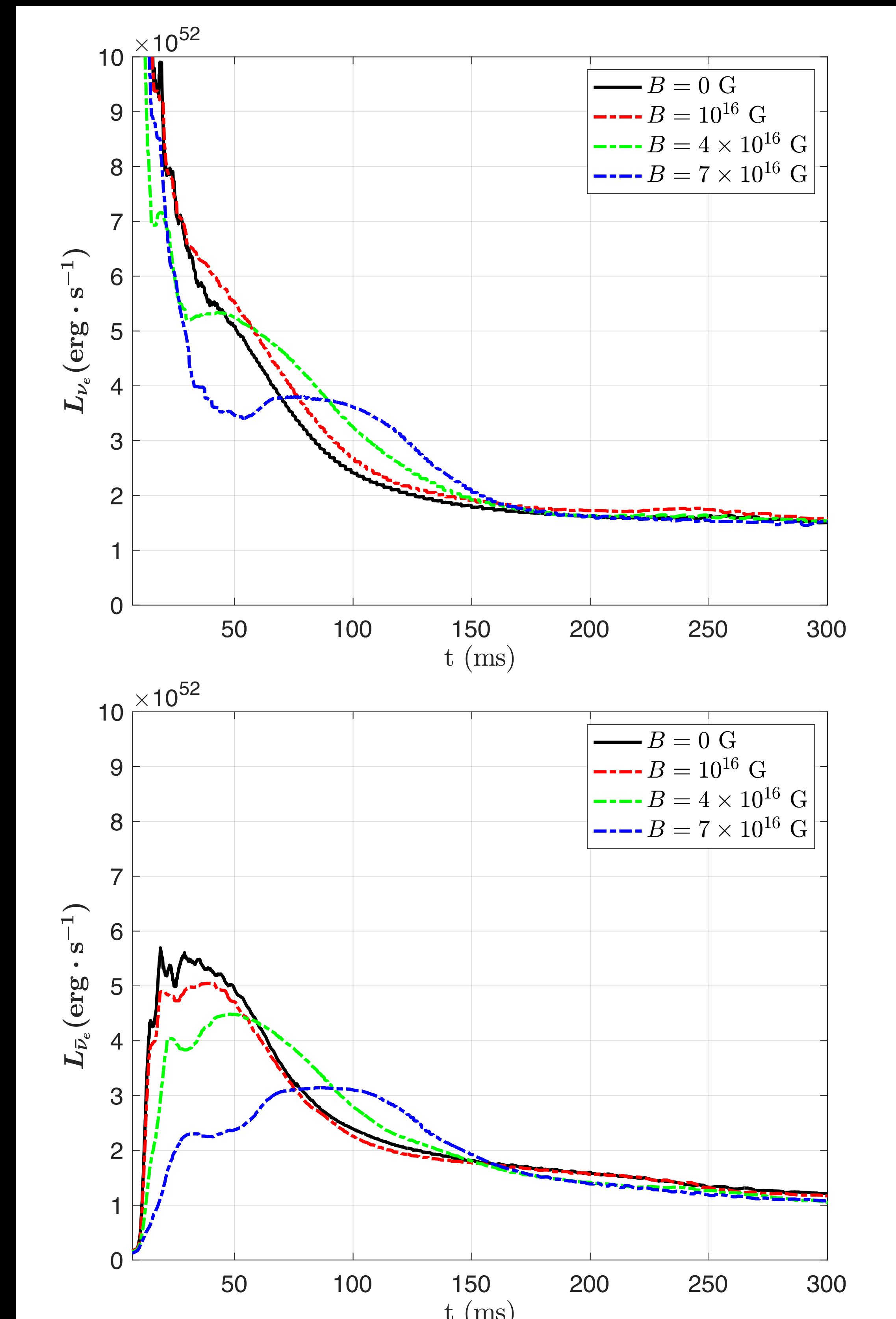
- The leakage scheme with B-field is modified in GR1D
- B-field is set as a const, but with $r_{\text{cut}} = 100$ km
- Enhanced $\nu(\bar{\nu})$ spheres after bounce until 150 ms
- Enhanced opacities directly enlarge $\nu(\bar{\nu})$ spheres
- $\bar{\nu}$-sphere is more sensitive

Neutrino transport inside the $\nu-$sphere

▸ $\nu(\bar{\nu})$ Mean energy

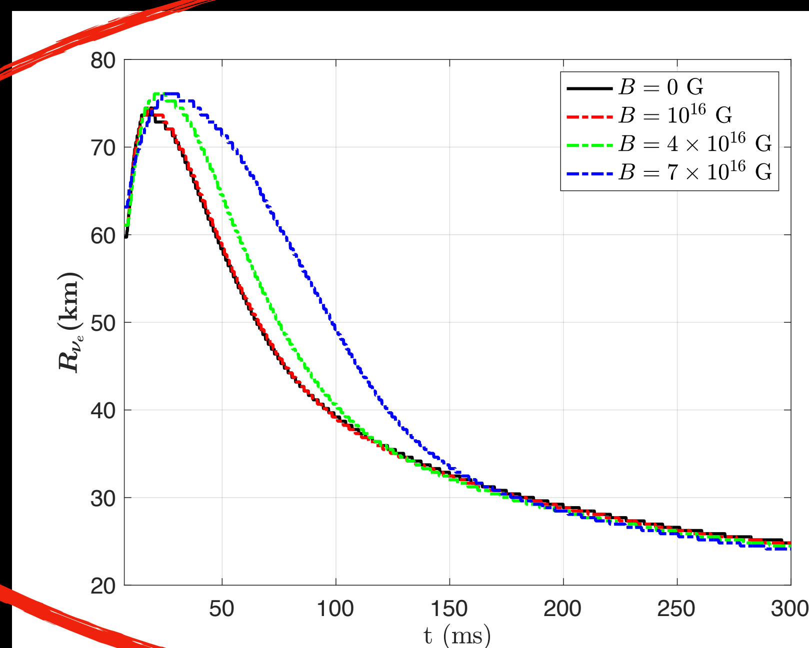


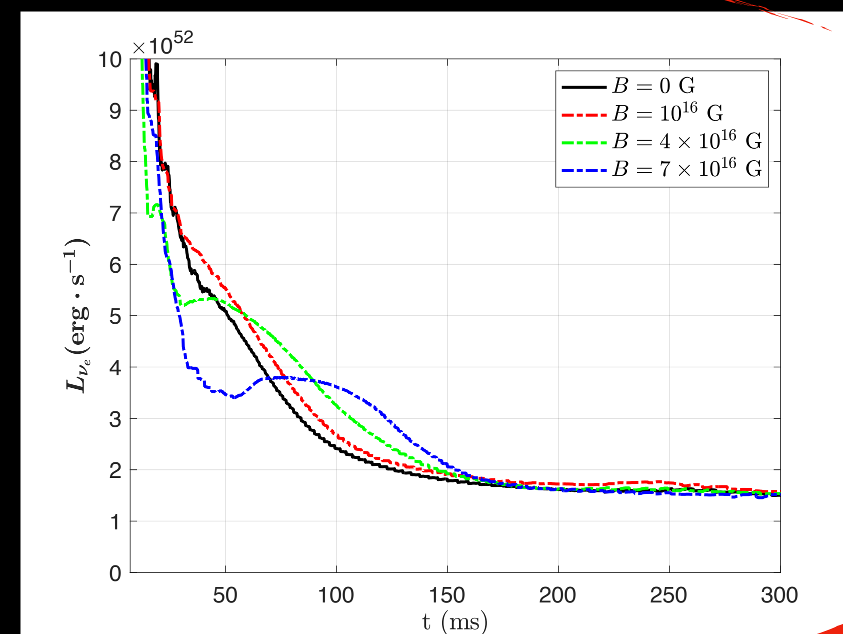
▸ $\nu(\bar{\nu})$ Luminosity

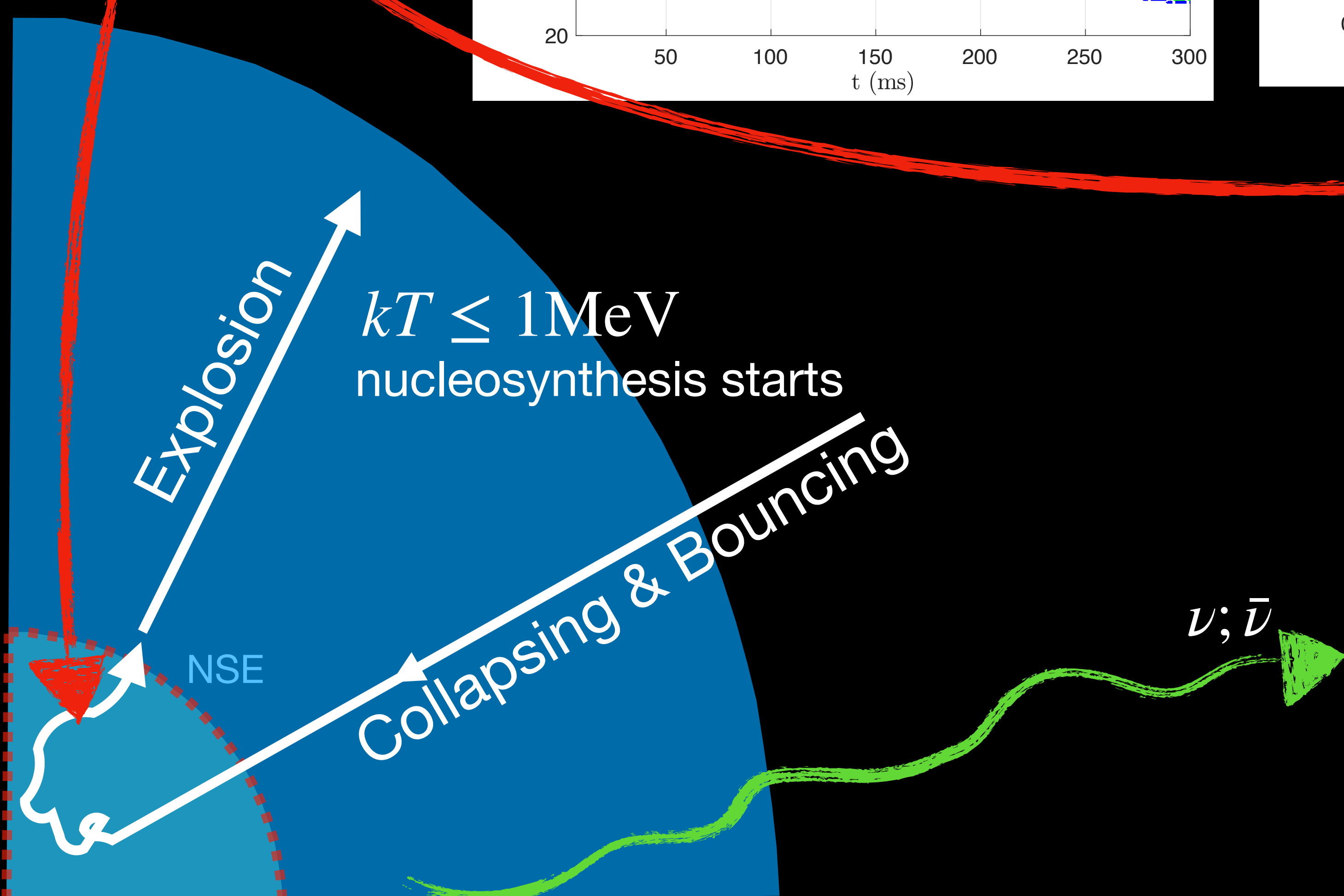


Conclusion

- Inside the ν-sphere, anti-neutrinos are more sensitive to B-field, $\nu(\bar{\nu})$-spheres are enlarged by B-field while luminosities are suppressed due to less energy release rate.







$$\frac{d\phi_{\nu_e}}{dE_{\nu_e}} = \frac{L_{\nu_e}}{8\pi^2 R_\nu^2} \frac{E_{\nu_e}^2}{exp(E_{\nu_e}/T_{\nu_e}) + 1}$$