

# GW170817

## Binary neutron star merger

A LIGO / Virgo gravitational wave detection with associated electromagnetic events observed by over 70 observatories.



Distance  
130 million light years

Discovered  
17 August 2017

Type  
Neutron star merger

12:41:04 UTC



gravitational  
waves detected



+2 seconds

$\gamma$ -ray burst  
detected

+10 hours 52 min

bright source of light  
detected in NGC4993

**“kilonova”**



+11 hours 36 min: infrared emission

+15 hours: ultra-violet emission

+ 9 days: X-ray emission



+ 16 days

radio emission detected

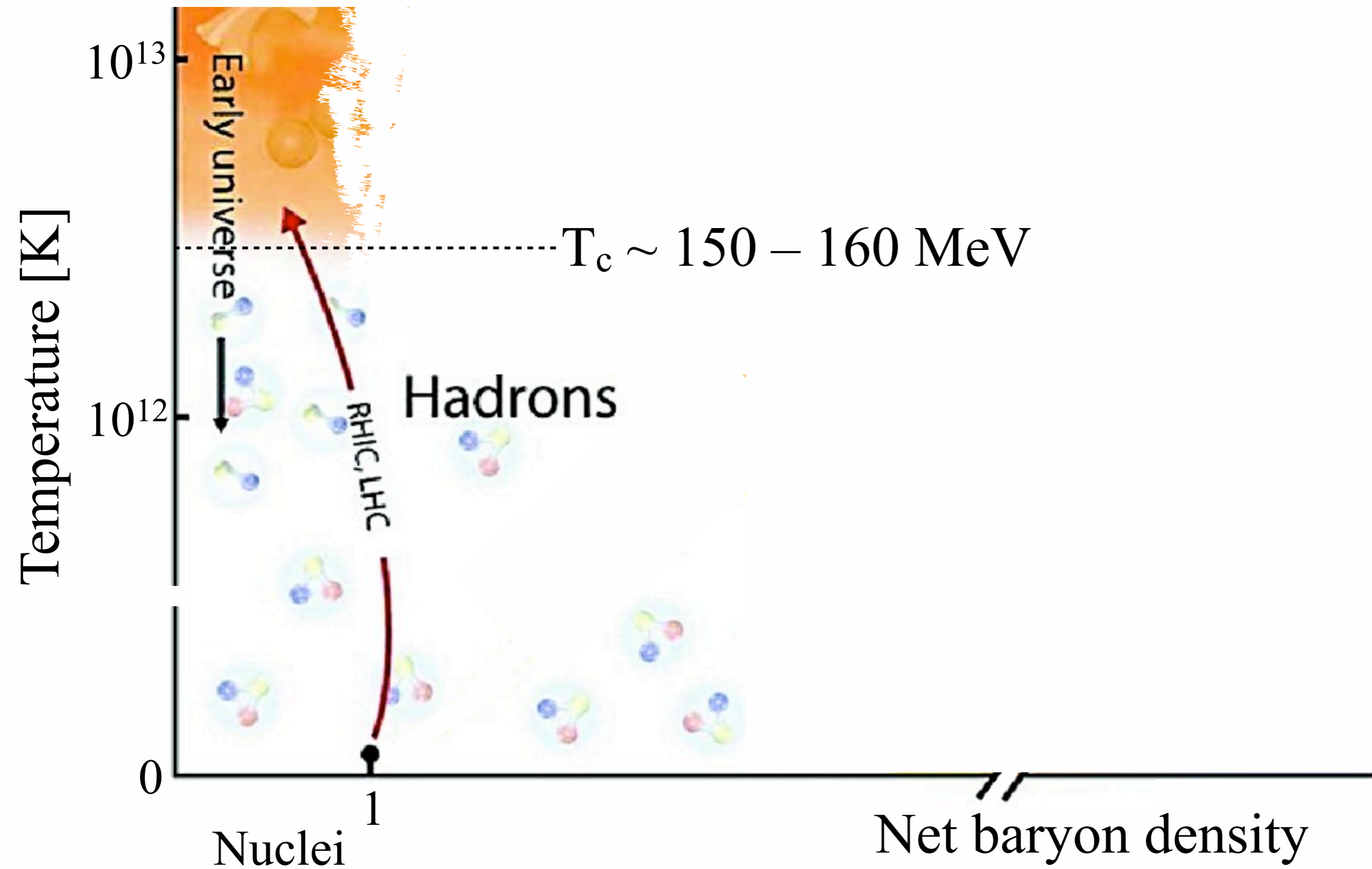


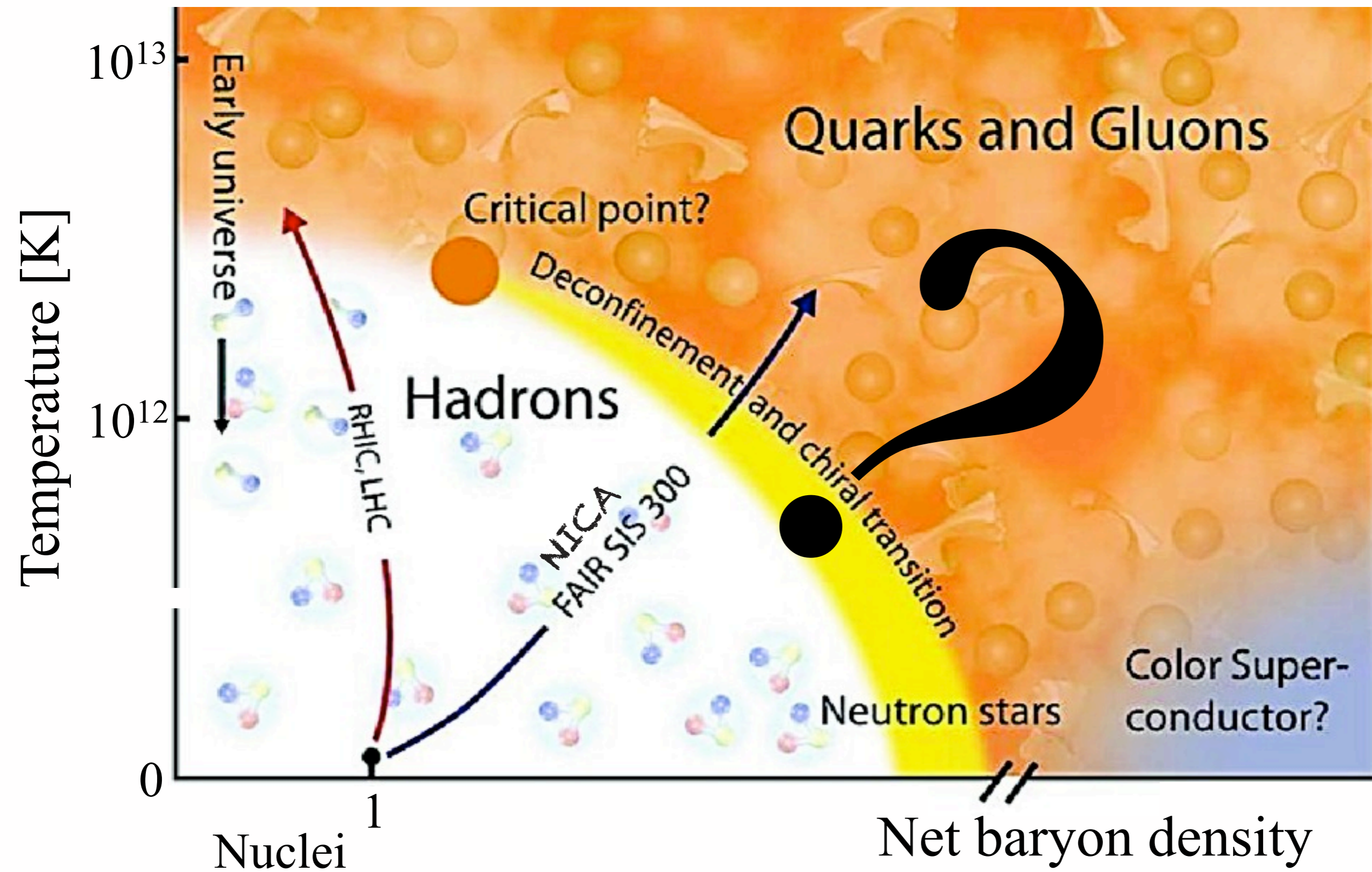
Accurate prediction of **observable** signal(s)

Relation to microscopic models of strongly-  
interacting matter

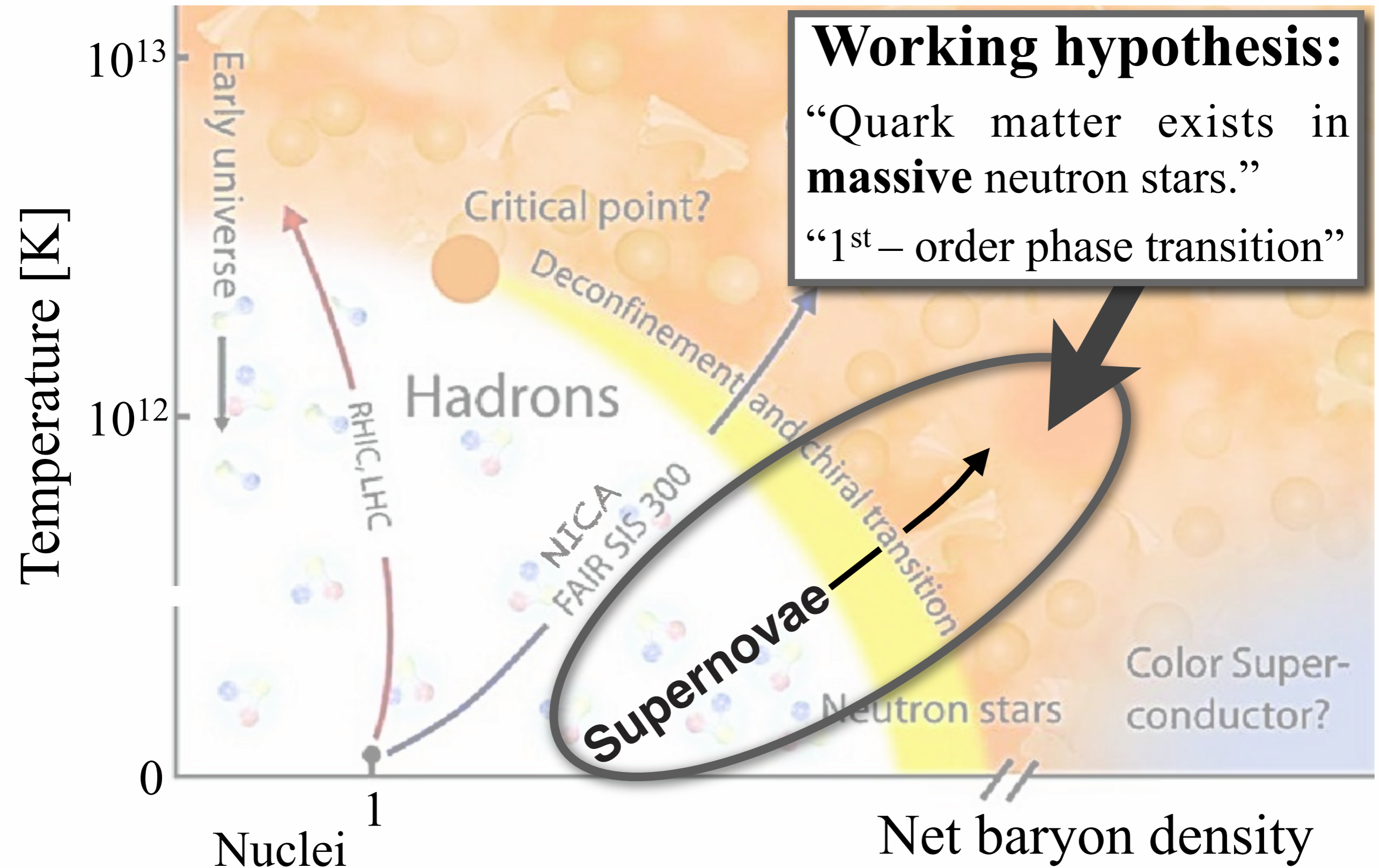
Astrophysics probes  
phase of hot and dense  
matter ?

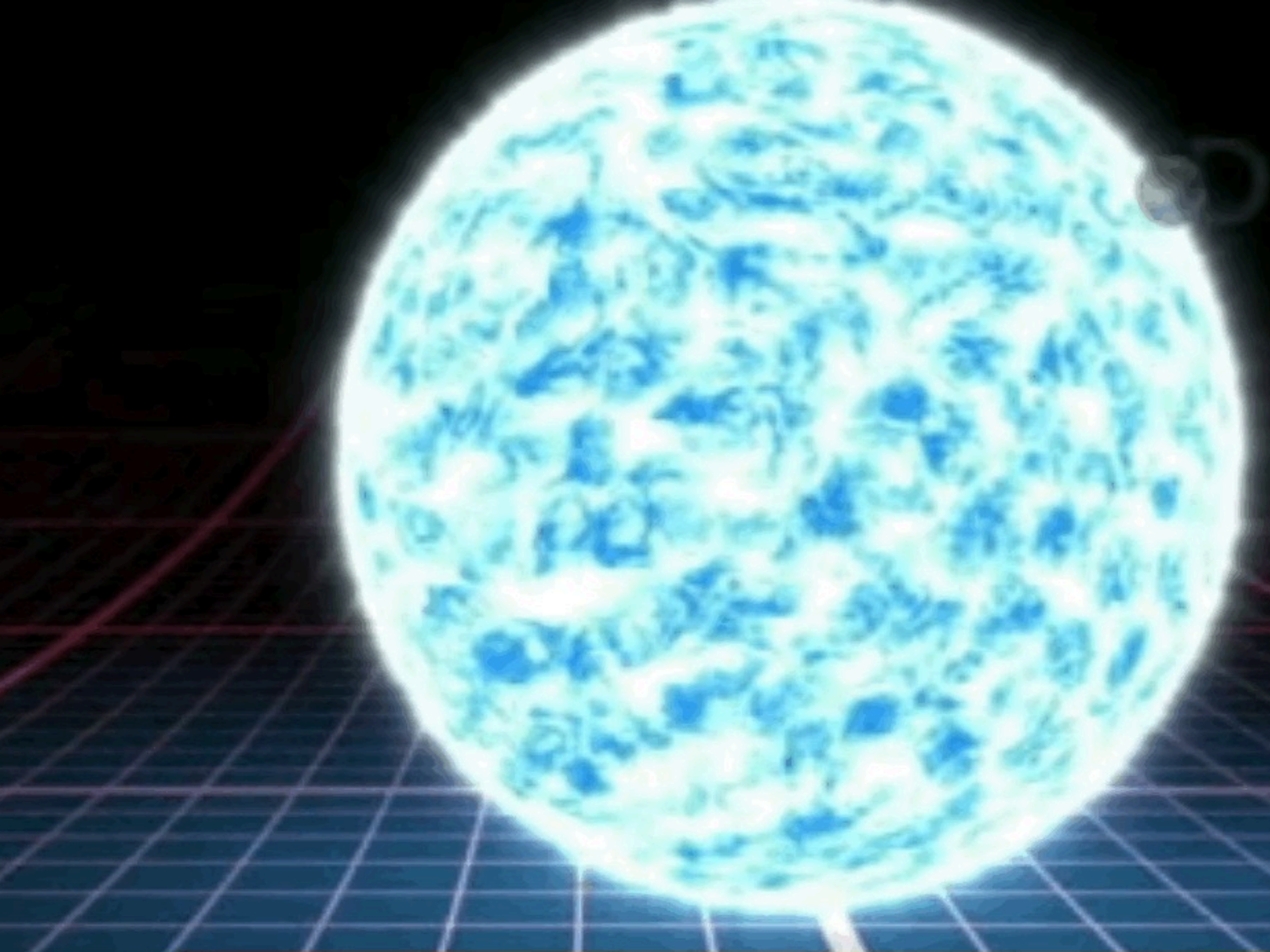




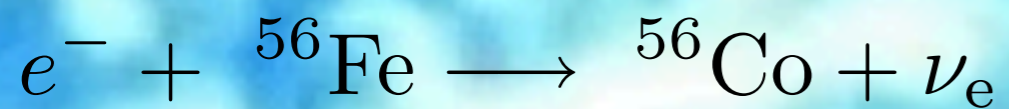
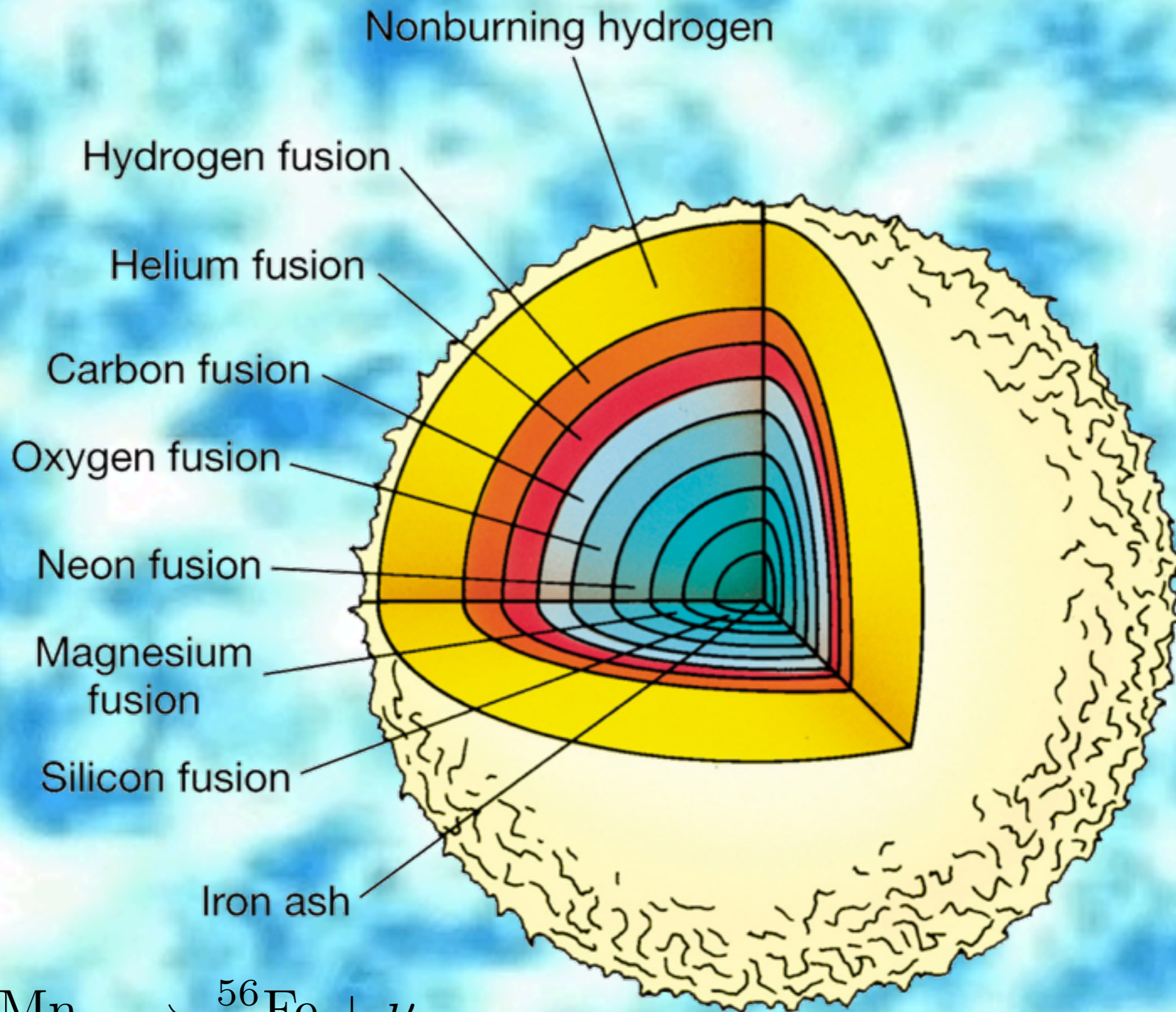


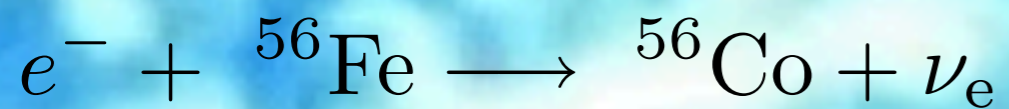
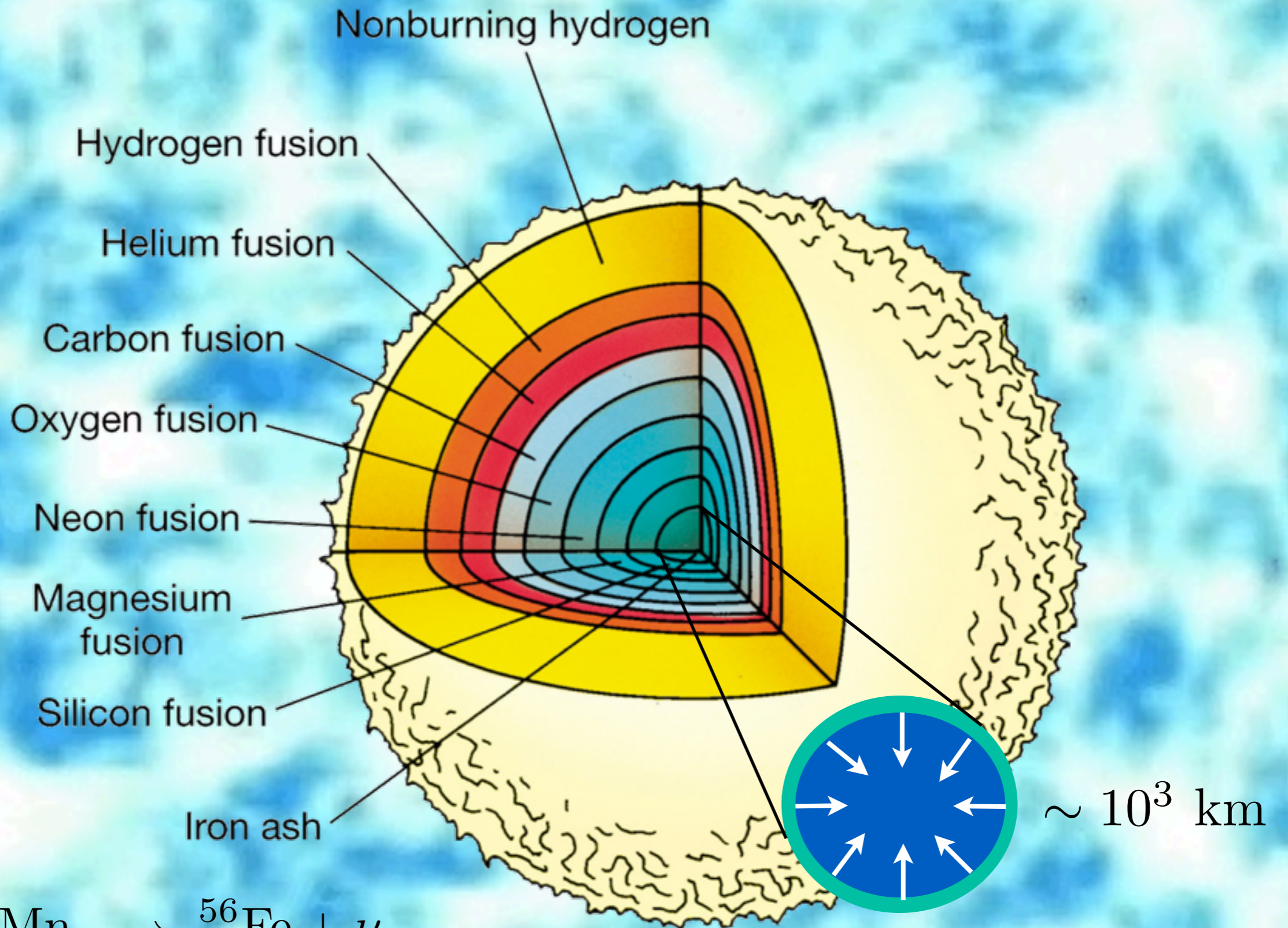
# Inaccessible in heavy-ion collisions







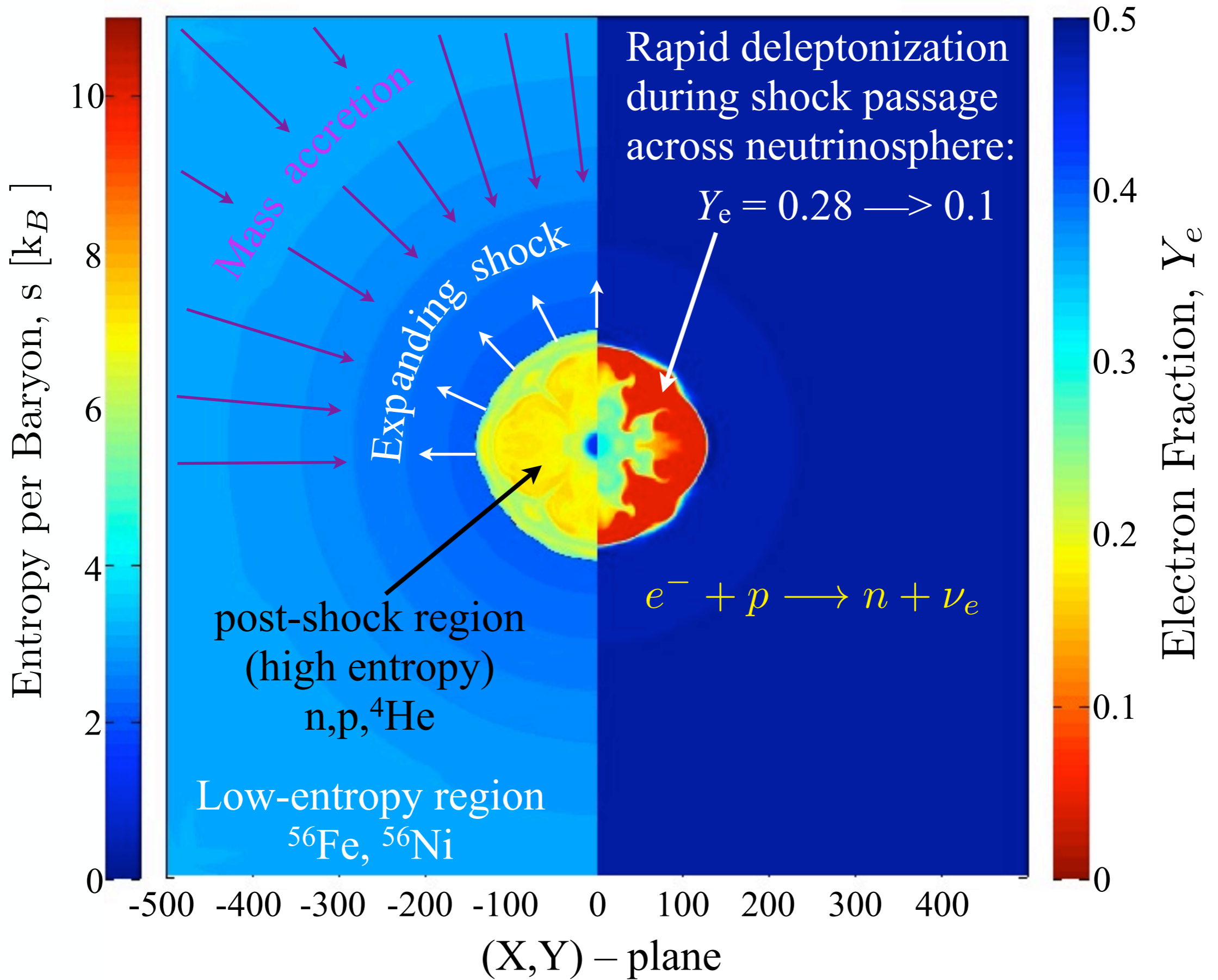




### Iron core collapse

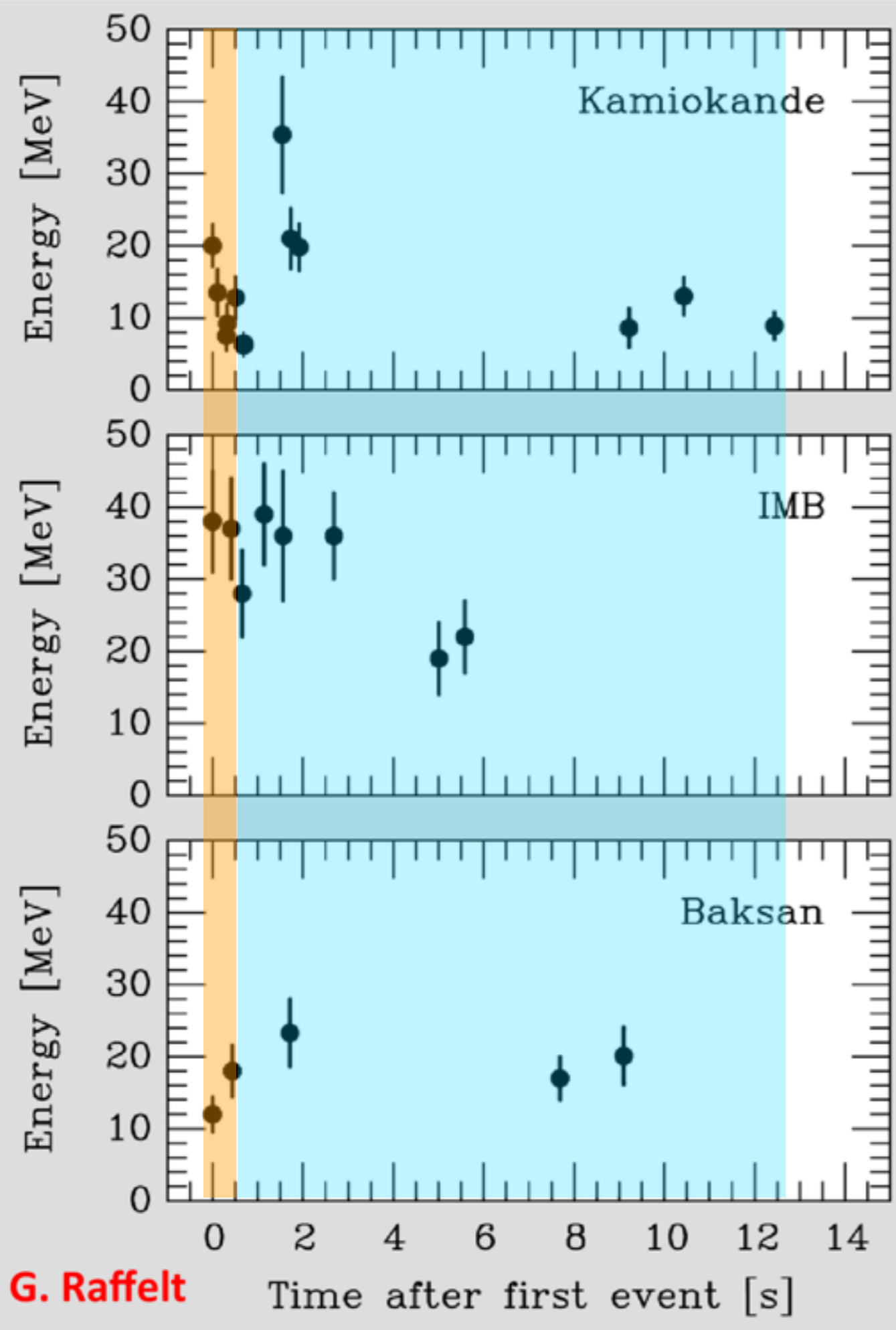
$$E_{\text{gain}} \simeq 3 - 6 \times 10^{53} \text{ erg}$$

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



*V*

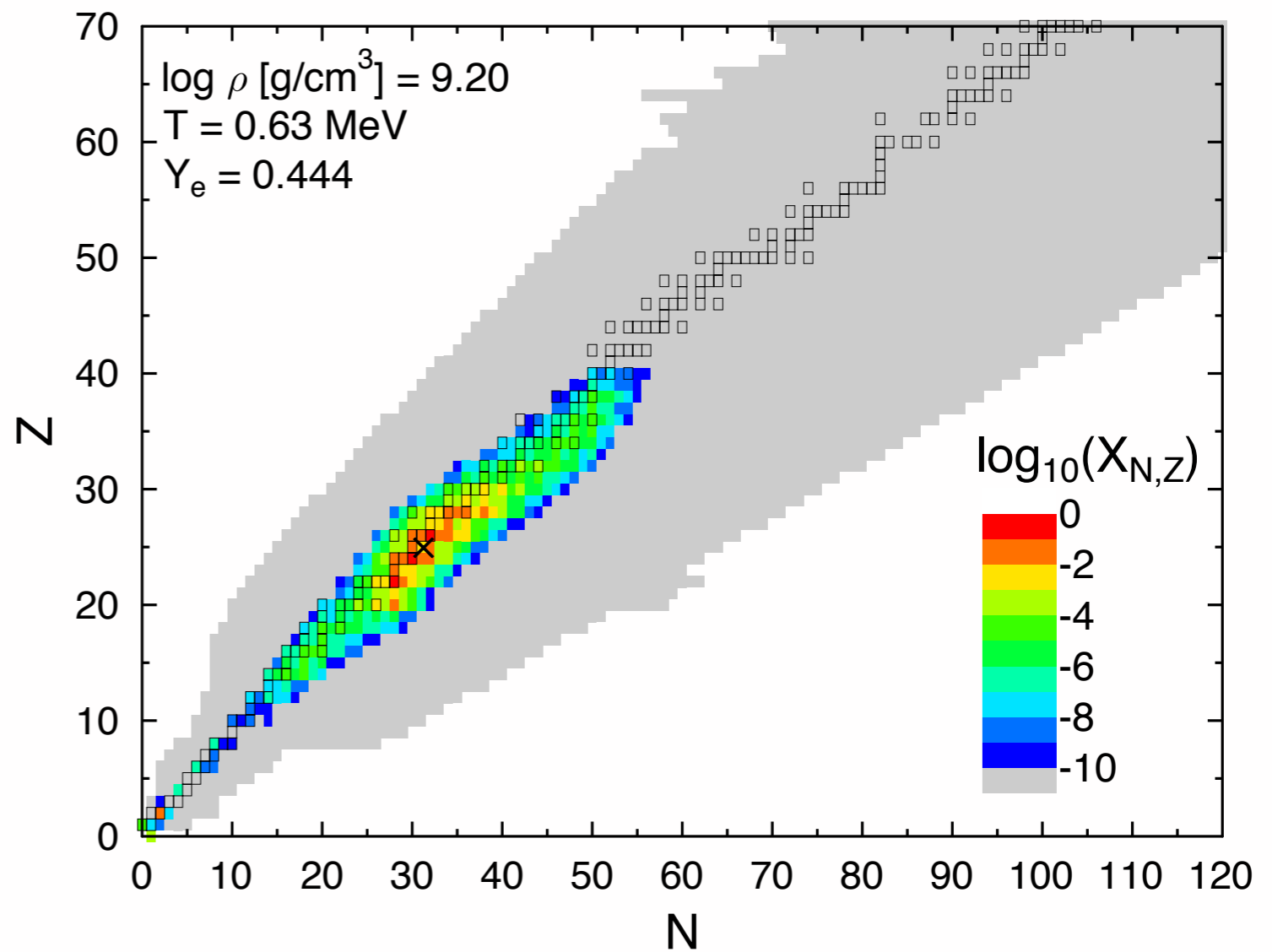
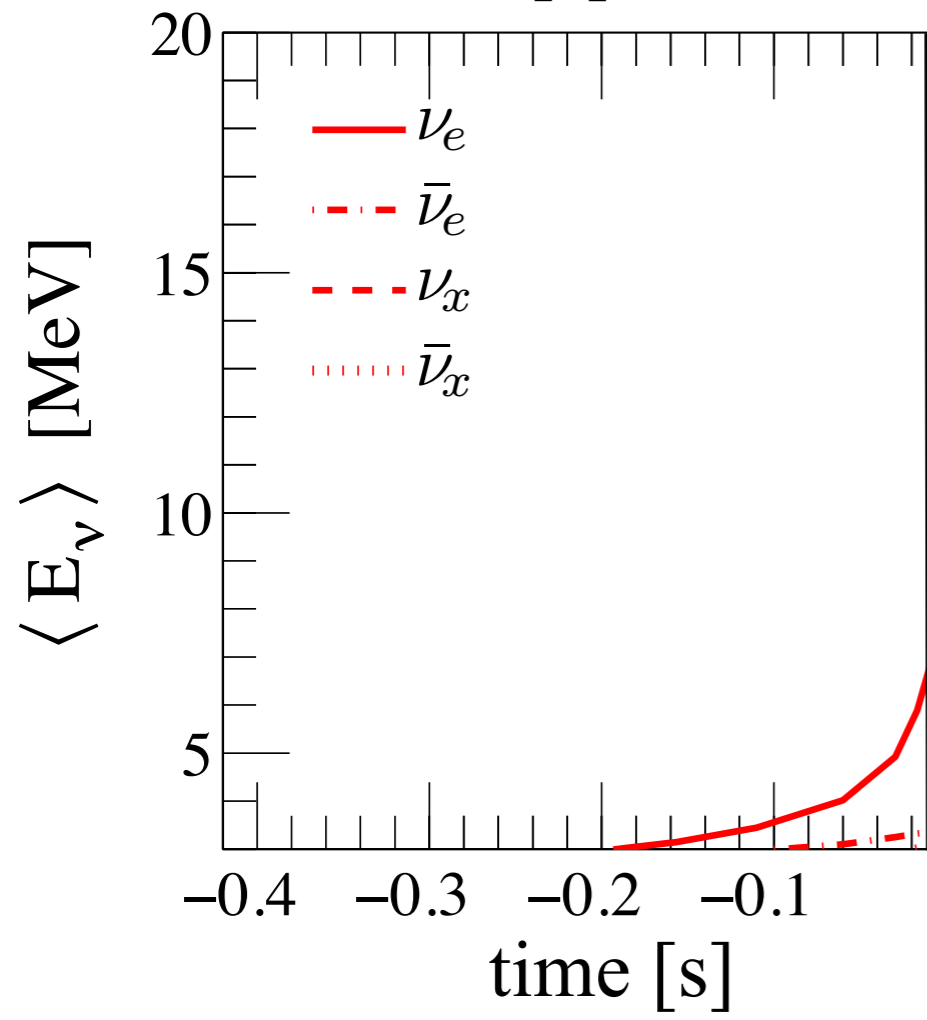
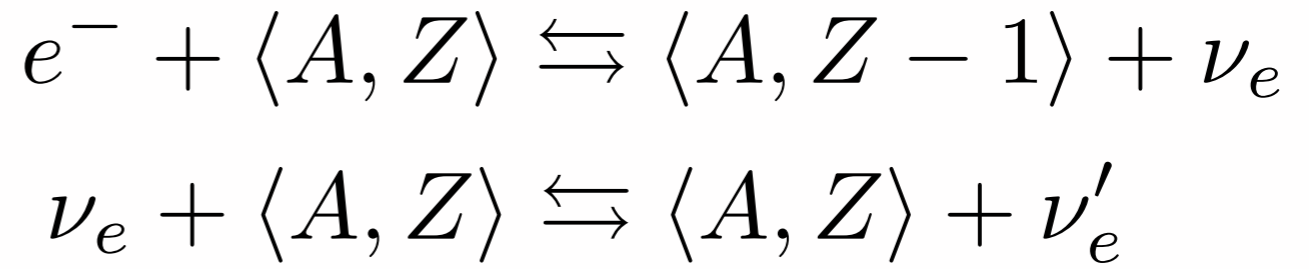
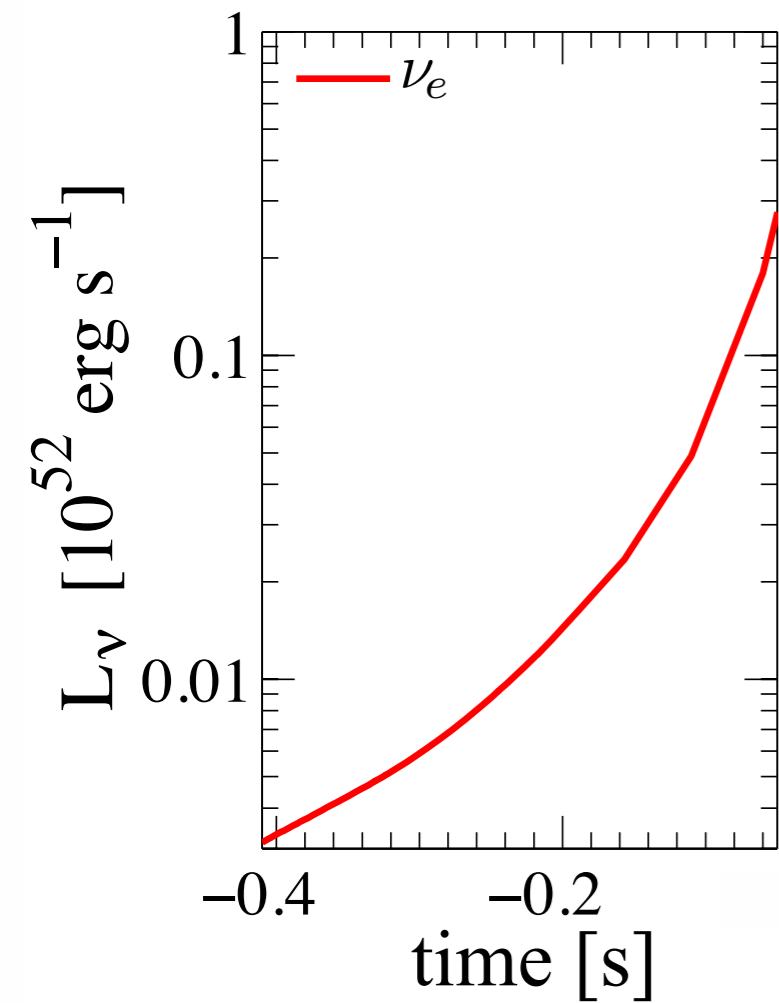


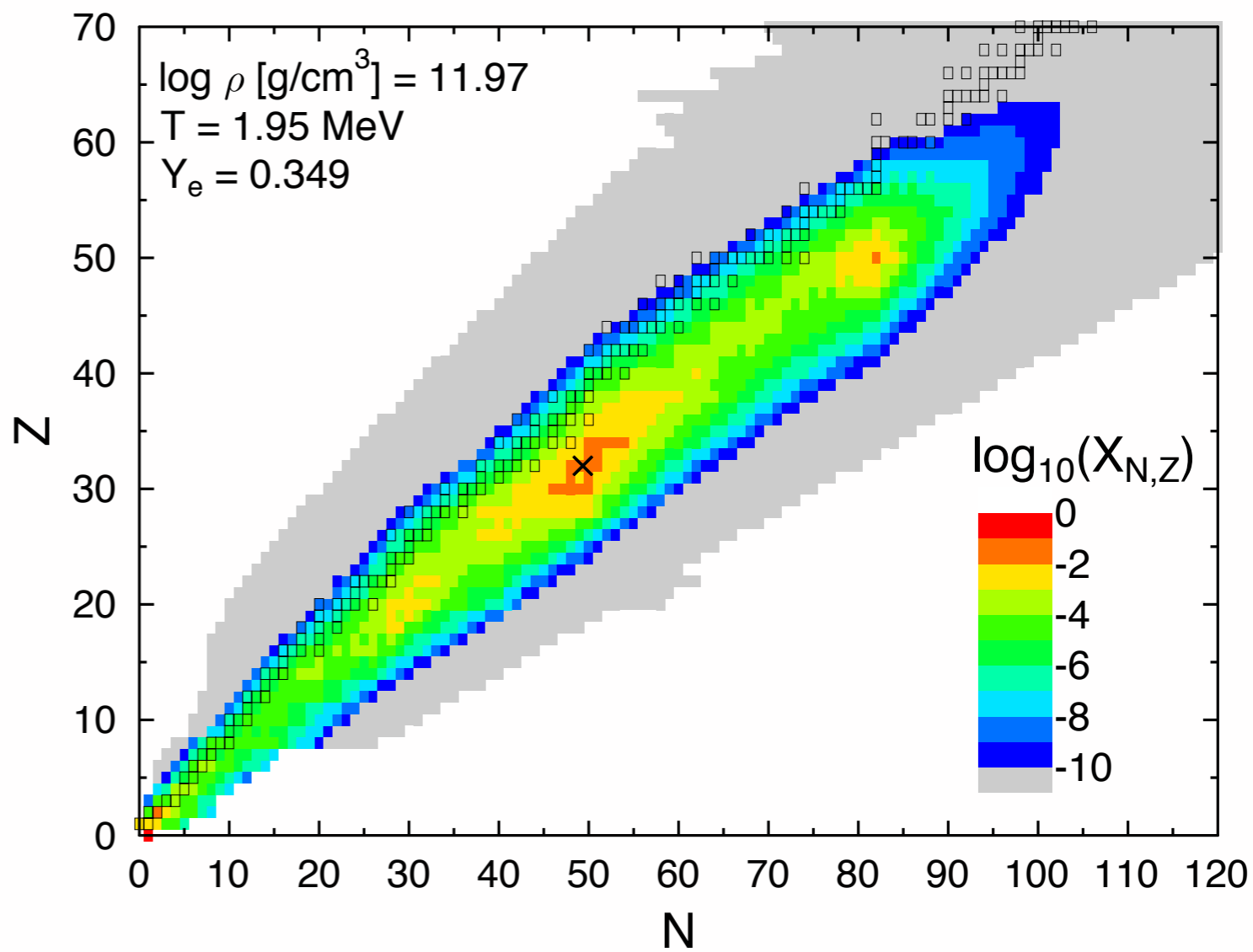
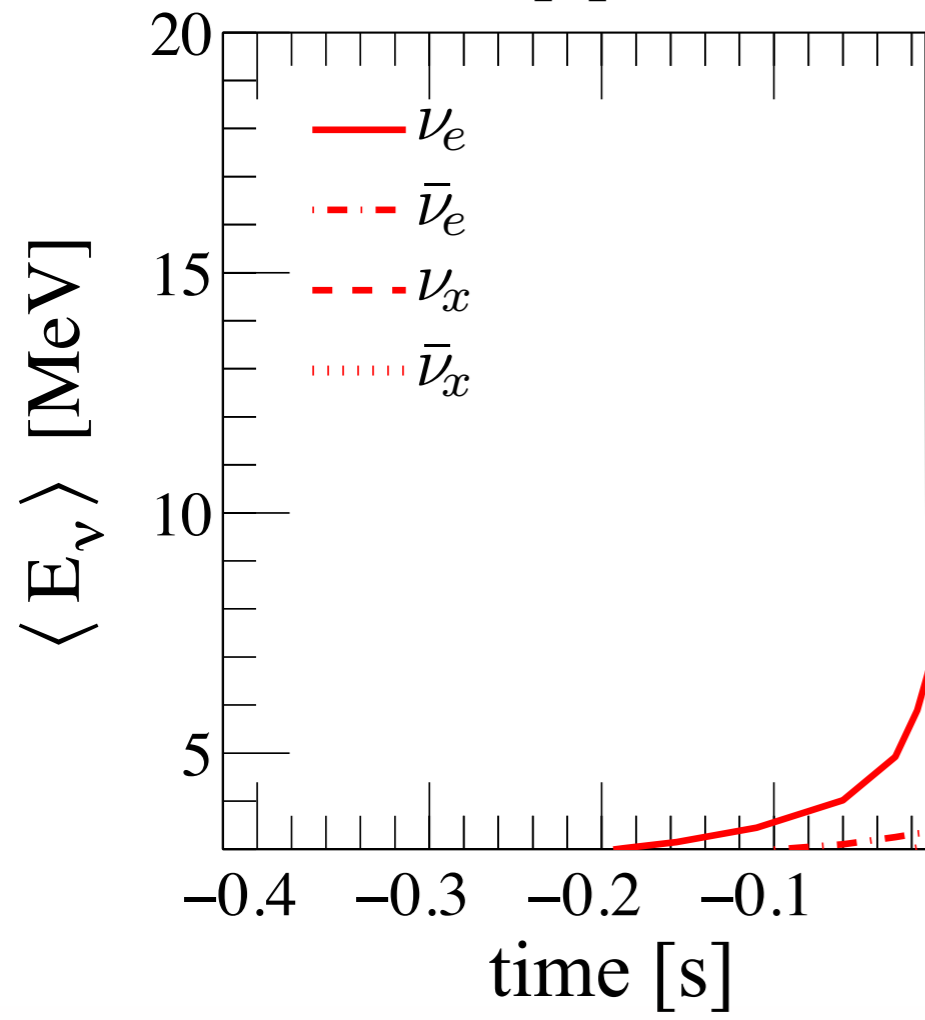
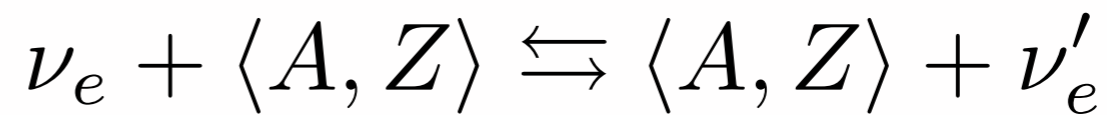
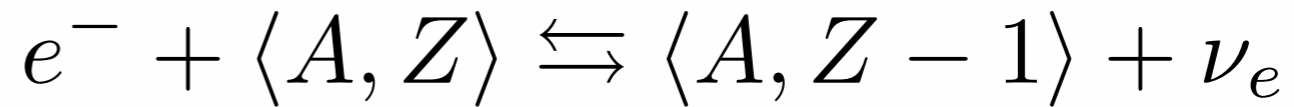
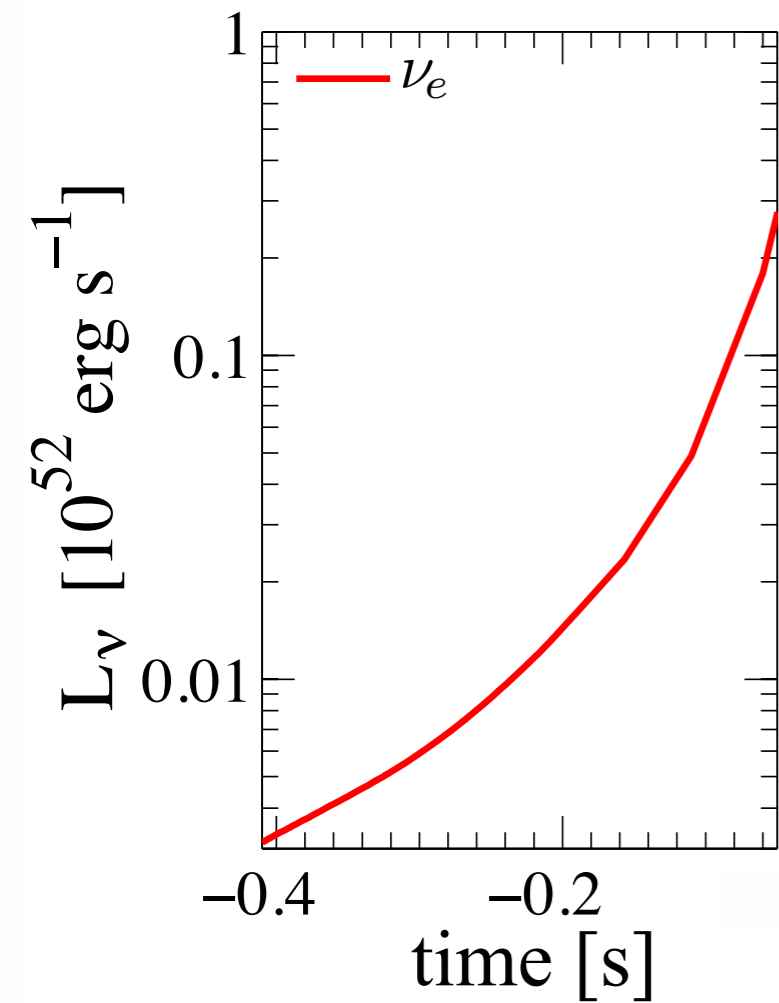


**G. Raffelt**

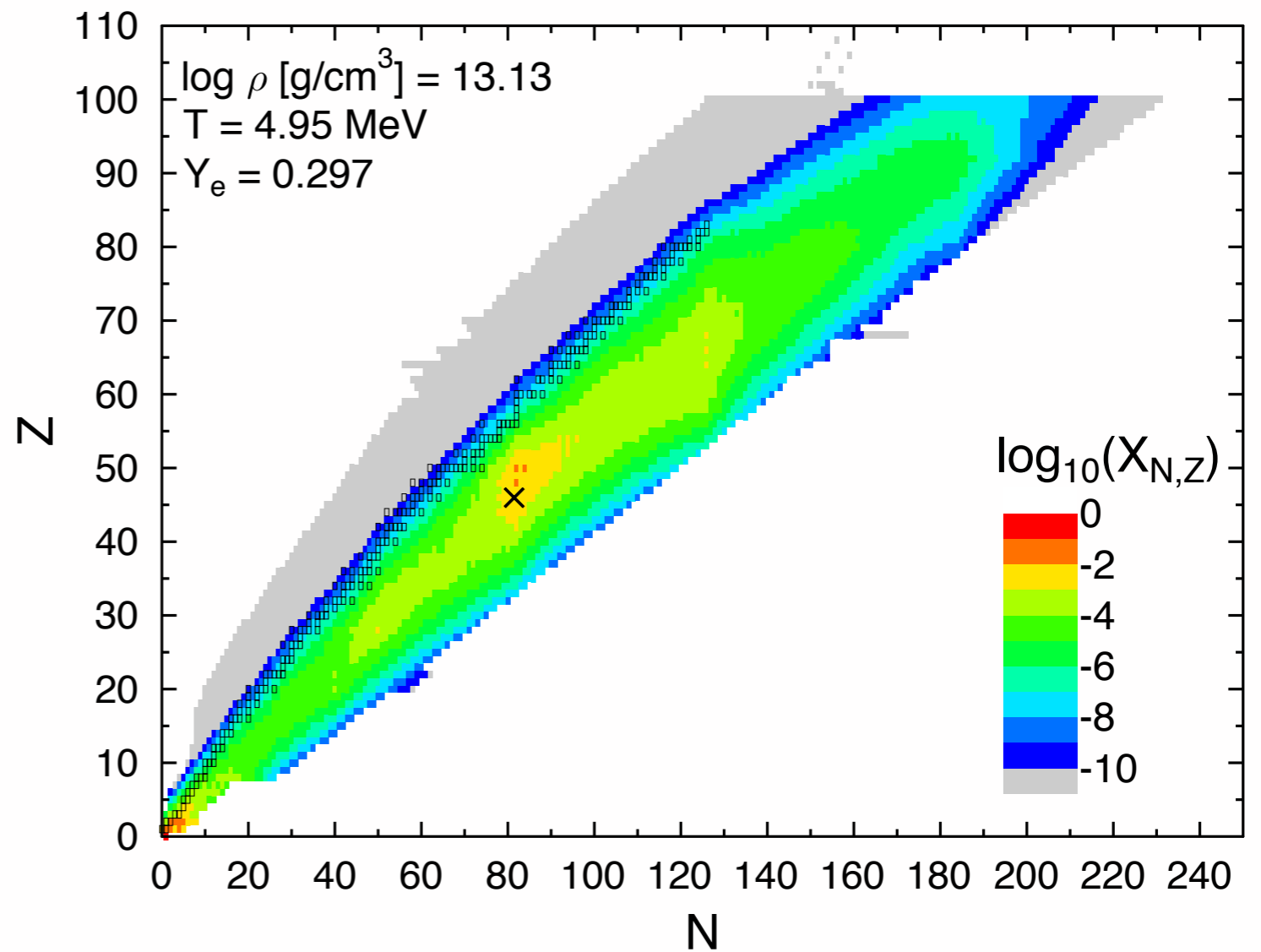
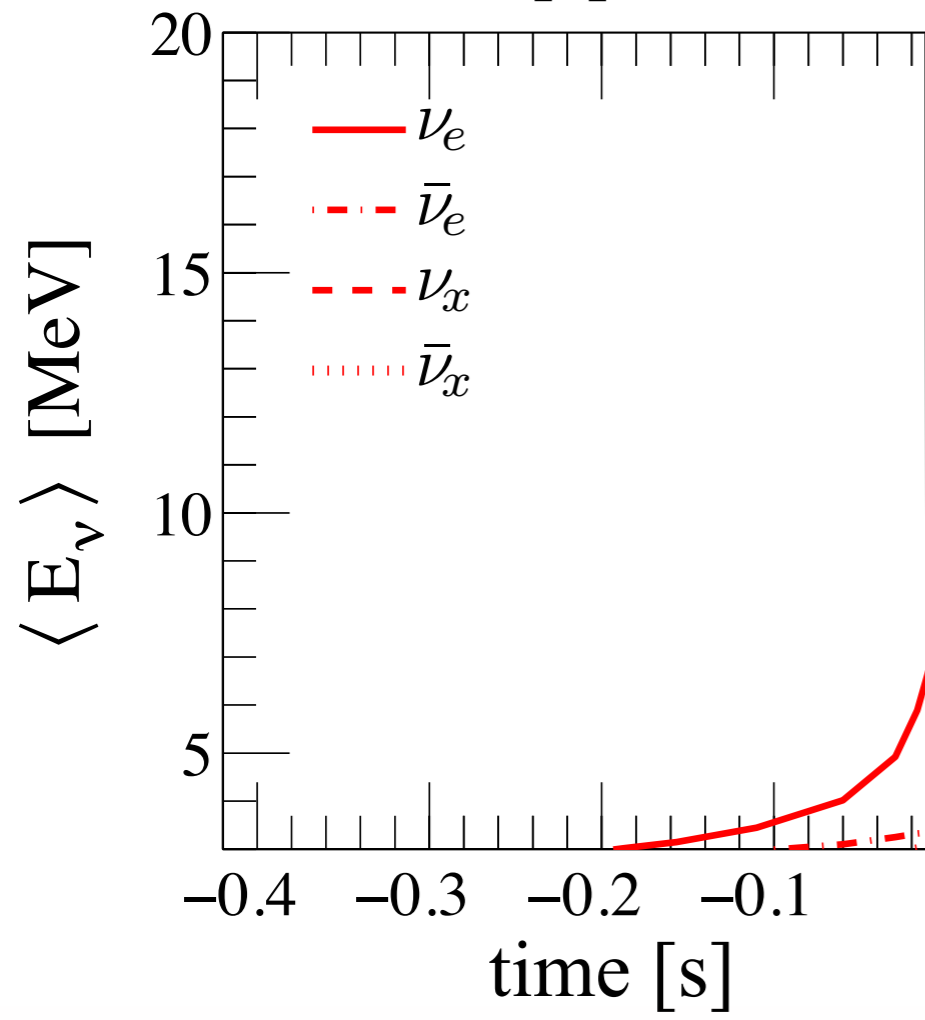
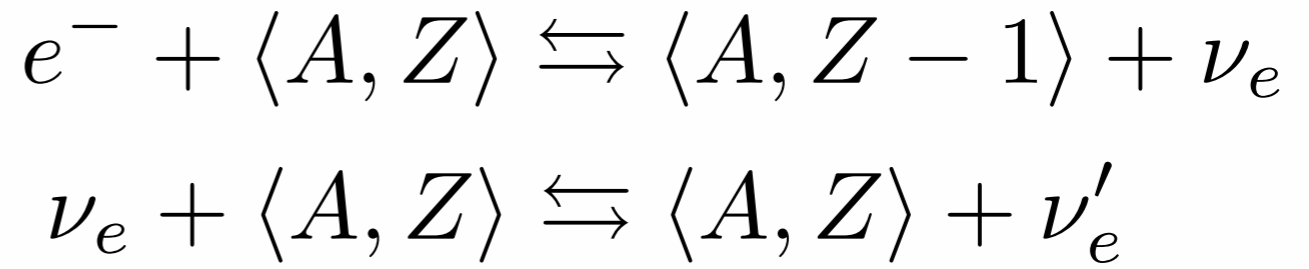
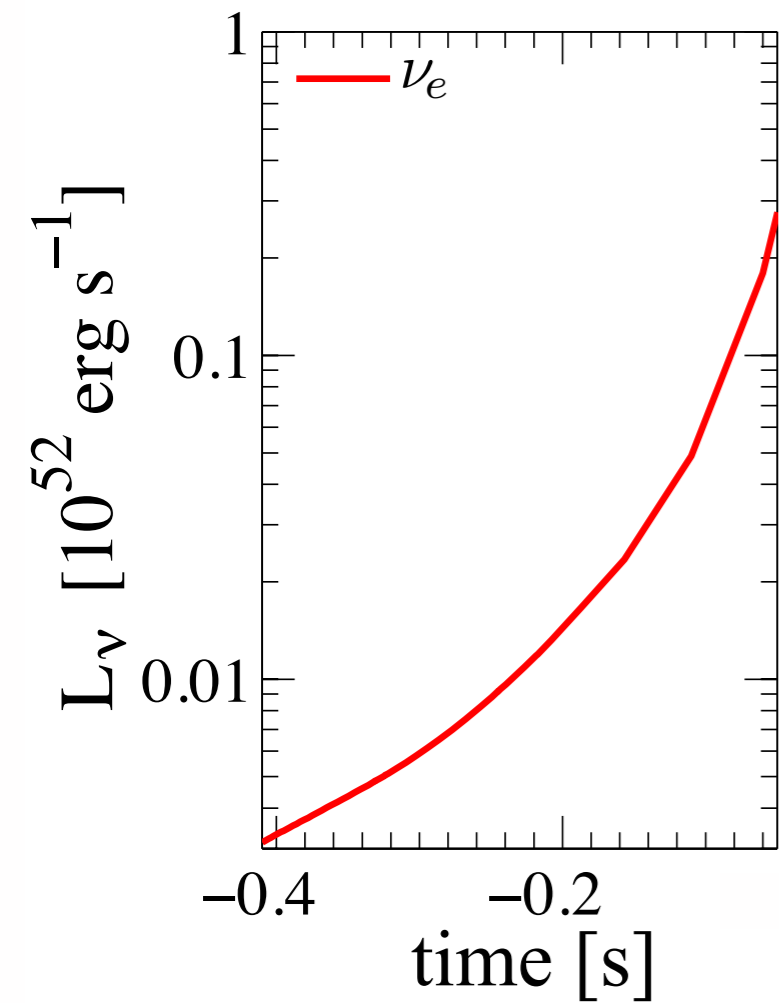
$$\dot{\epsilon} \approx 3 - 6 \times 10^{53} \text{ erg}$$

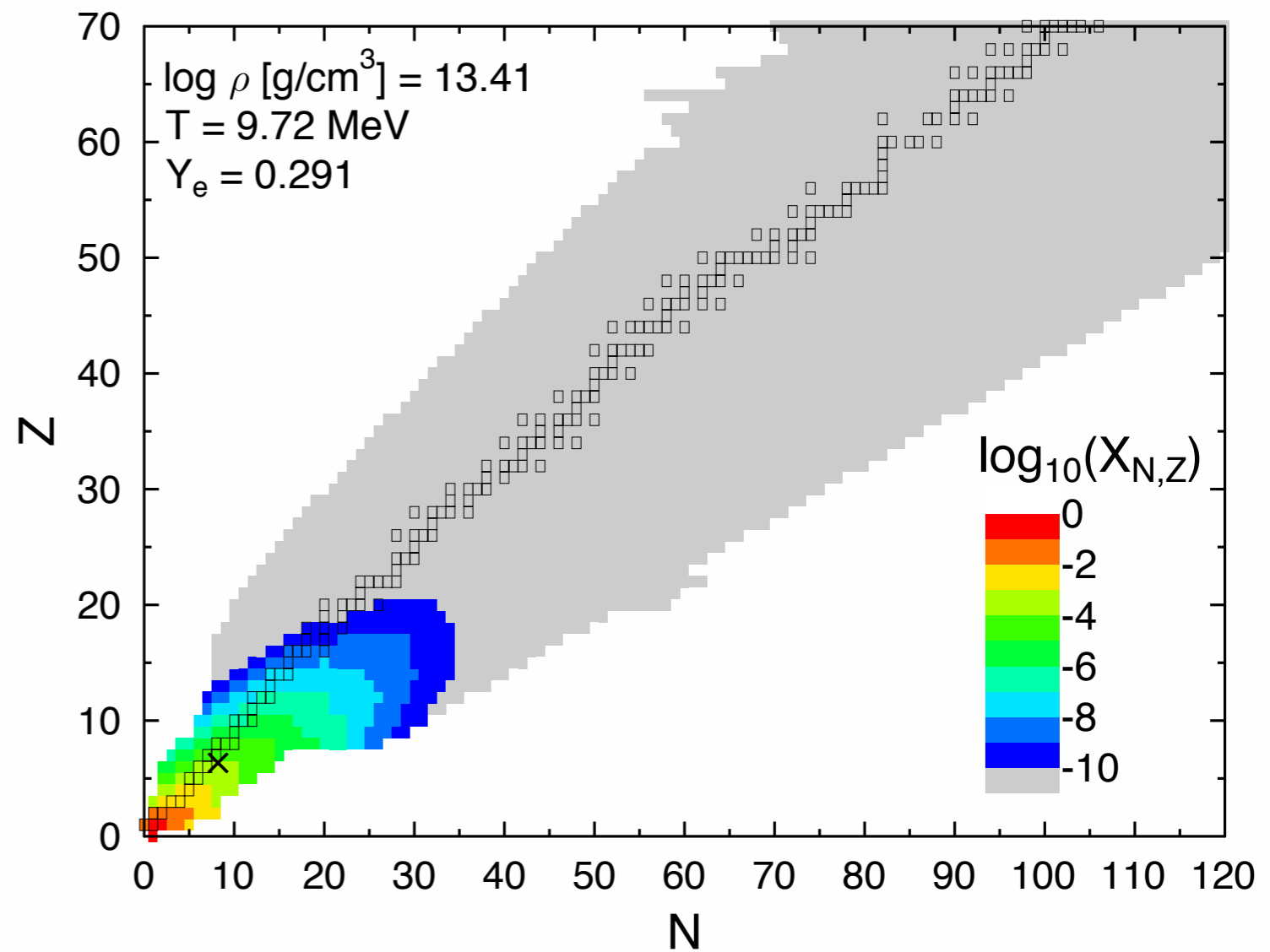
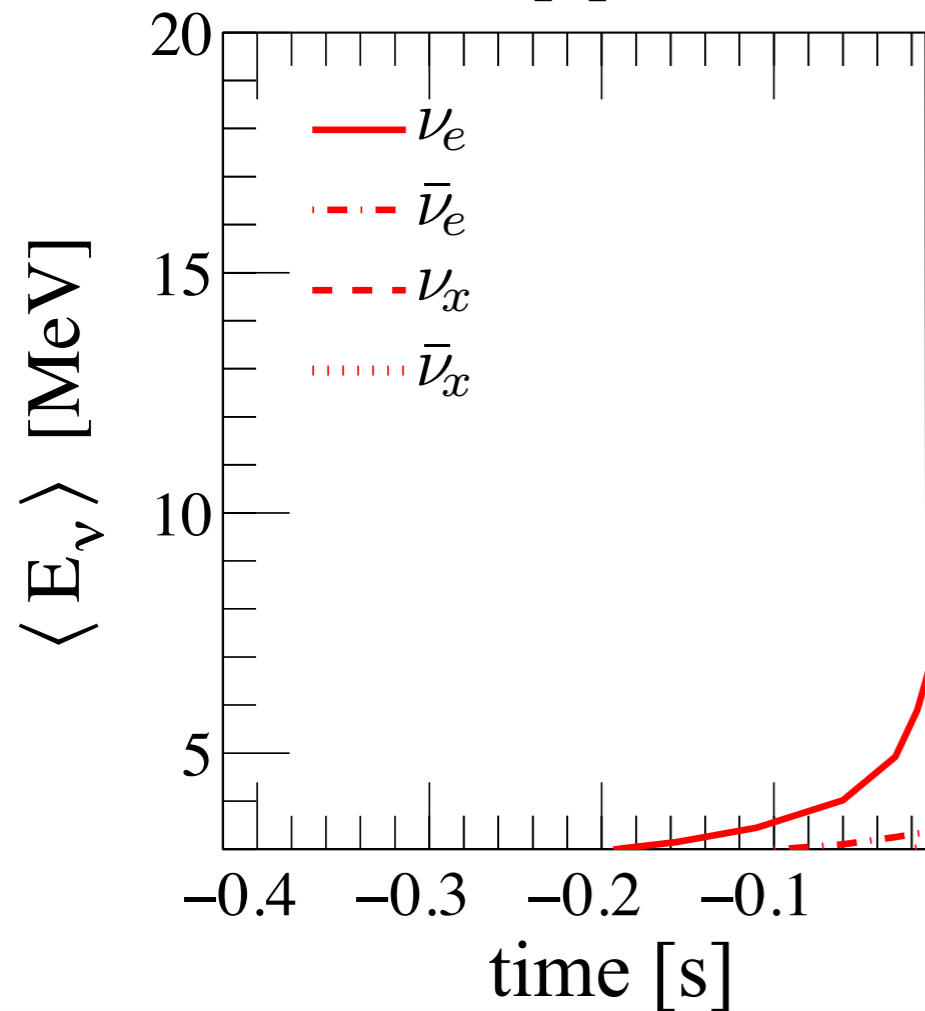
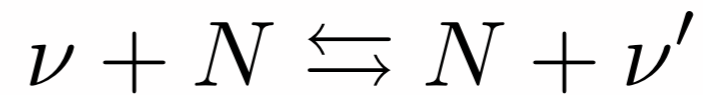
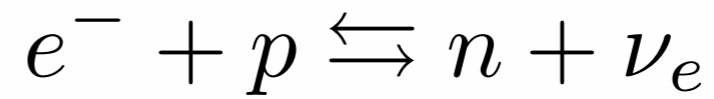
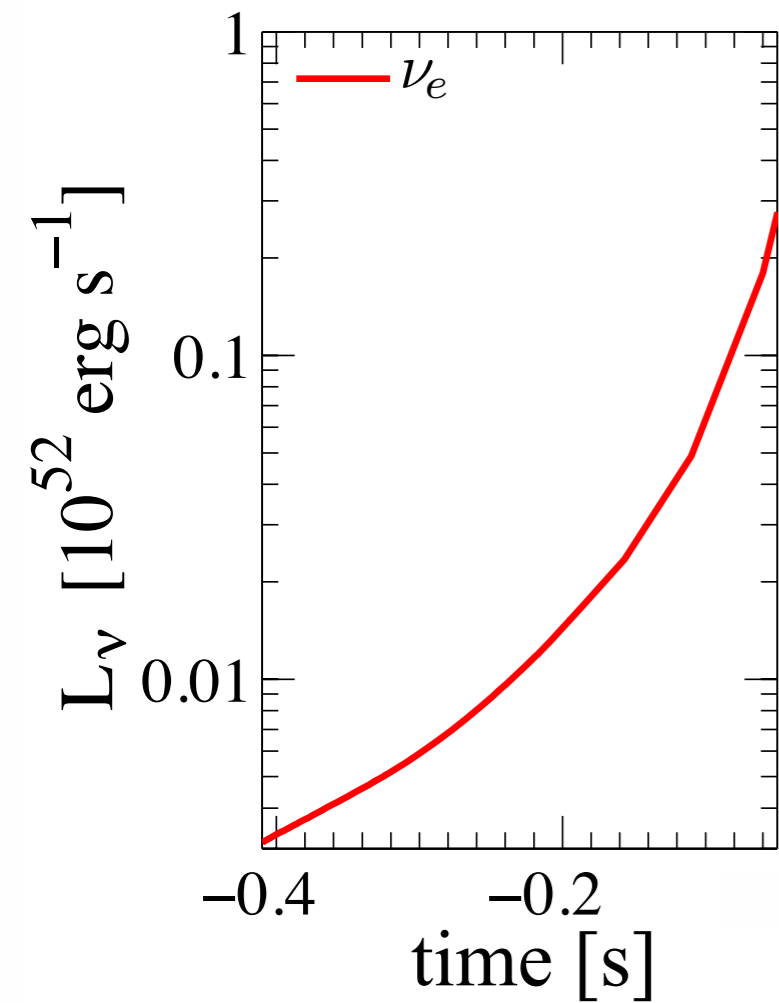
$$\propto 0.17 - 0.34 M_{\odot}$$

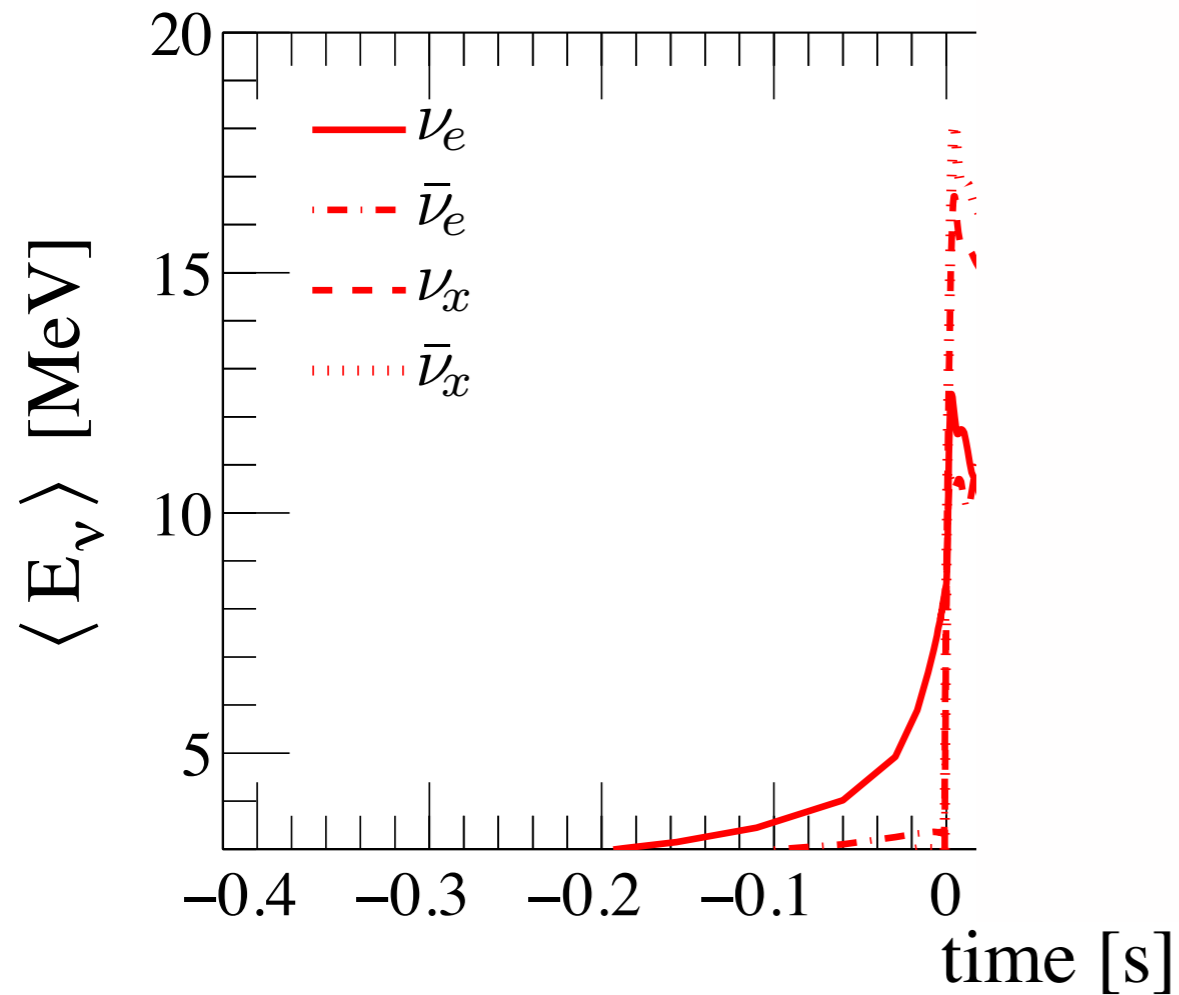
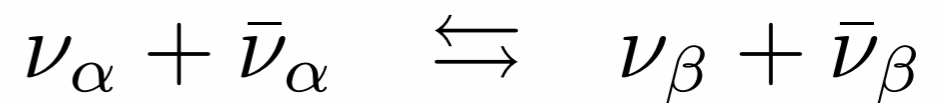
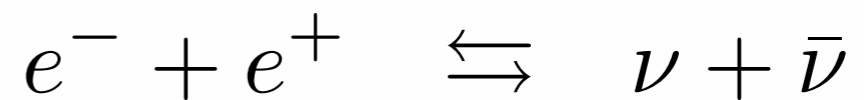
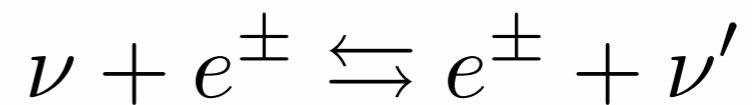
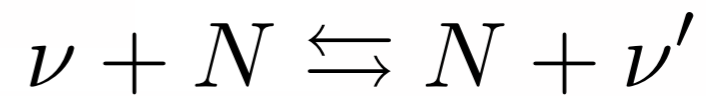
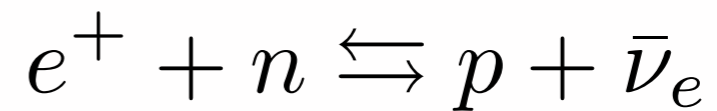
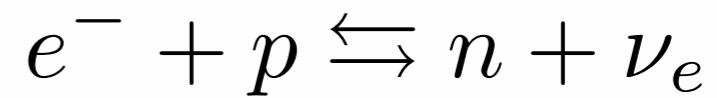
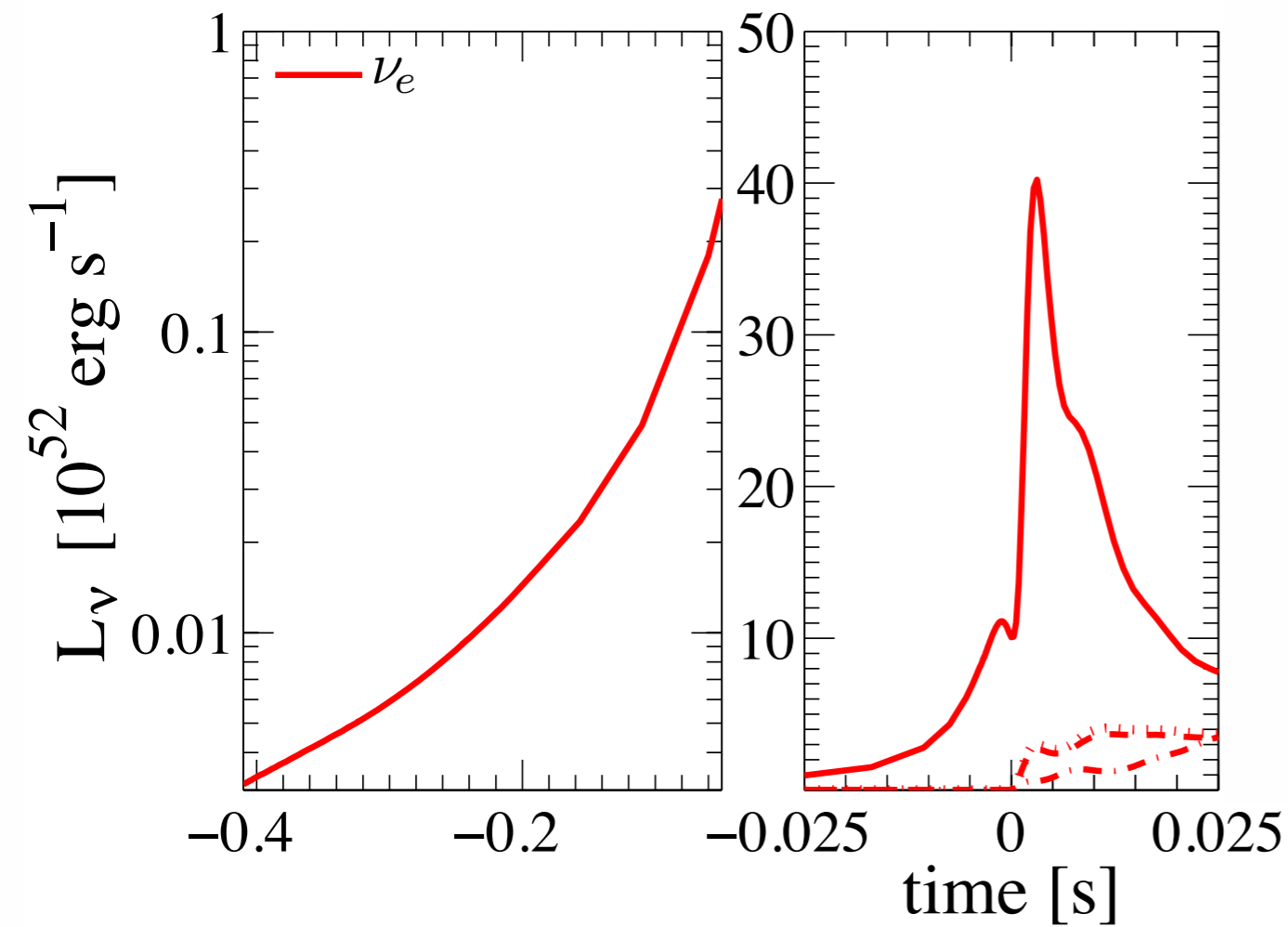


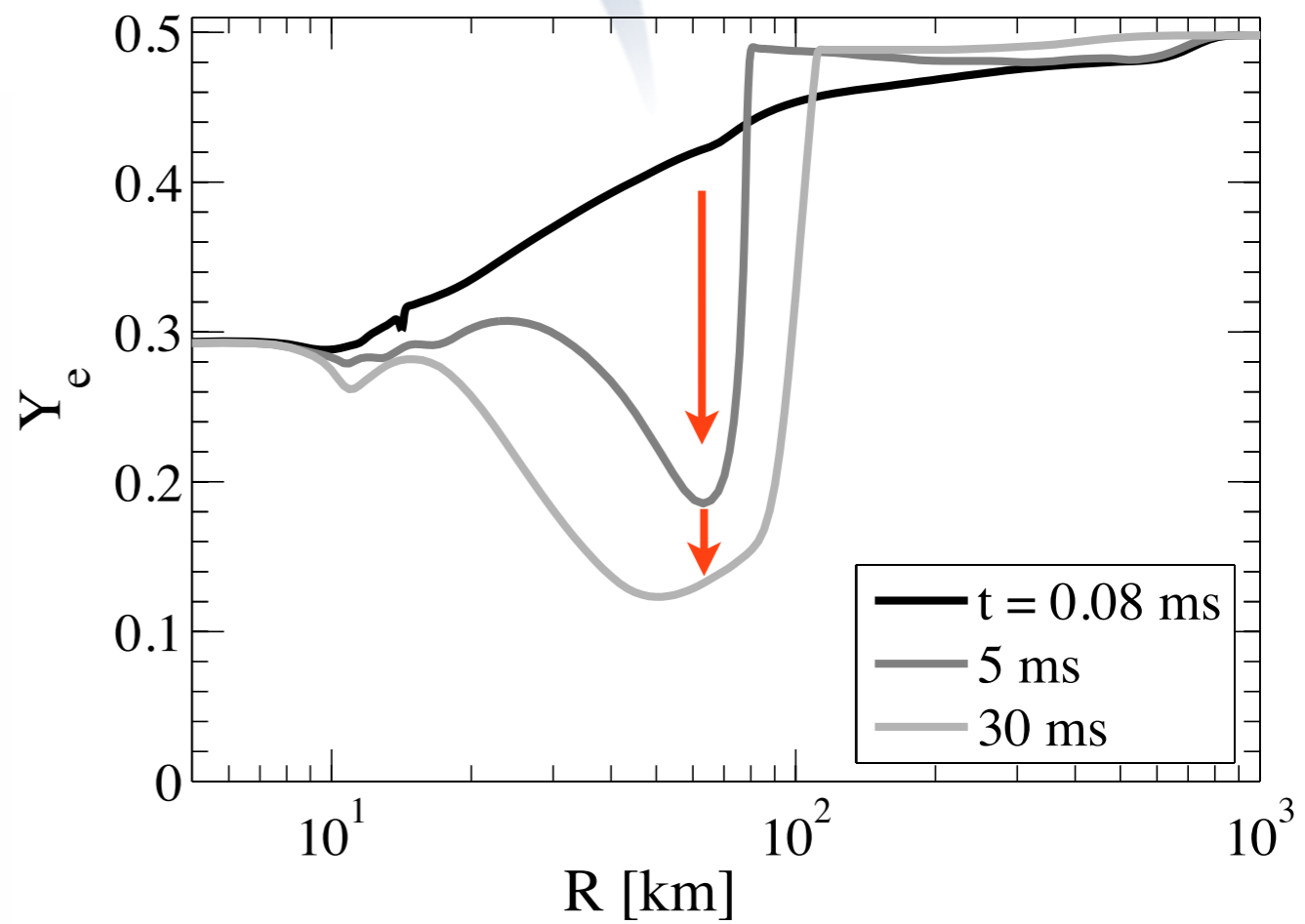
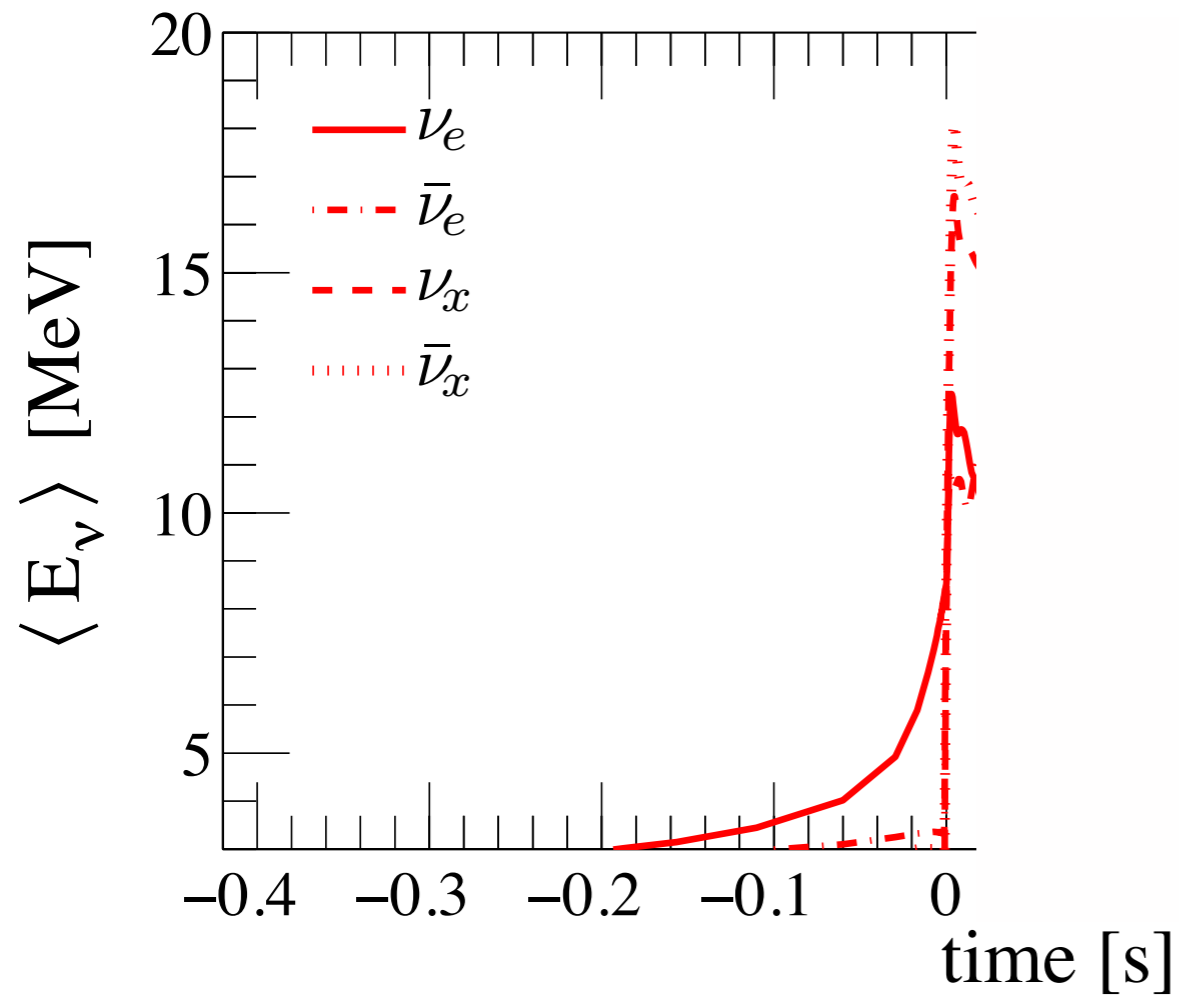
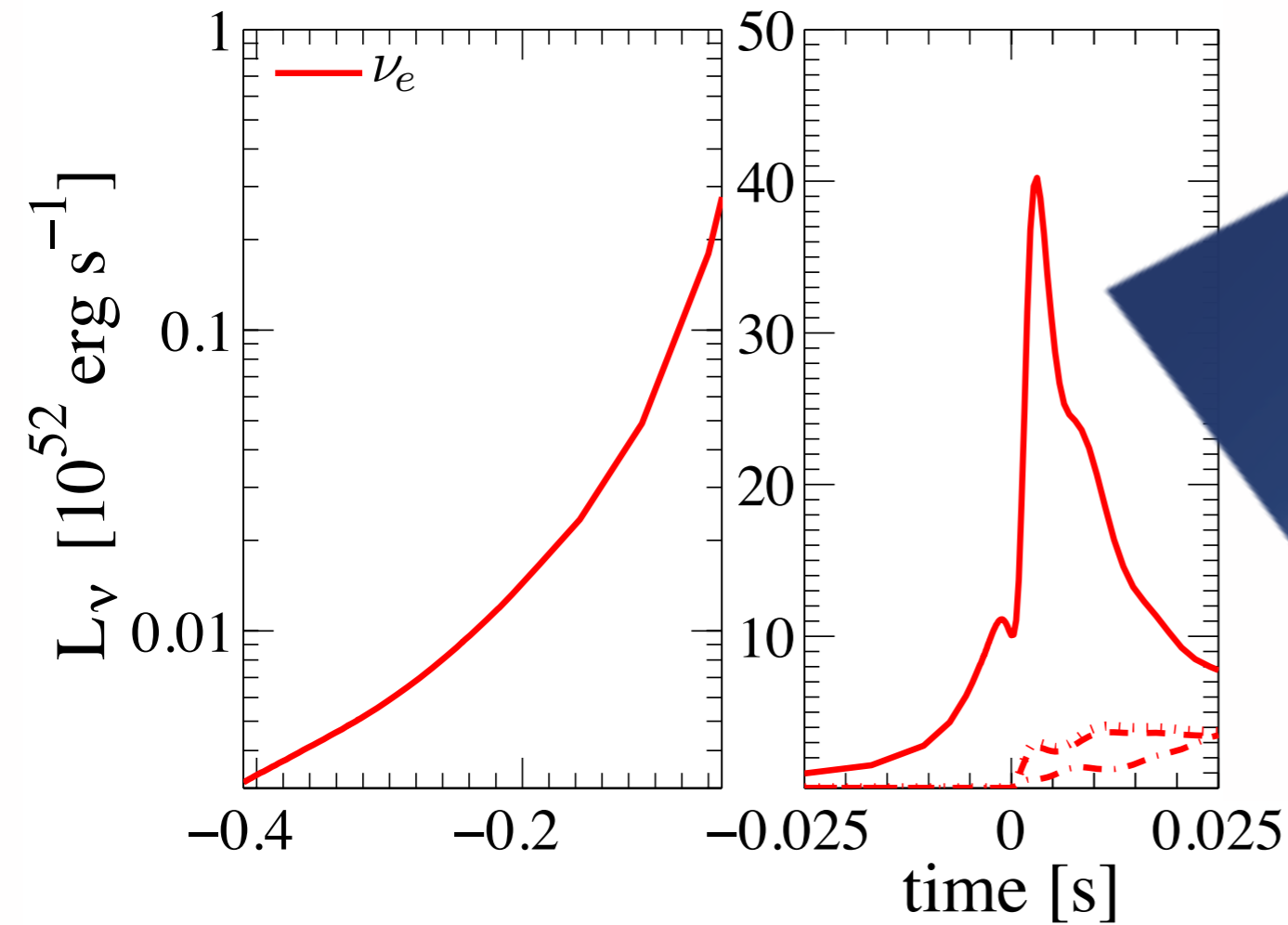


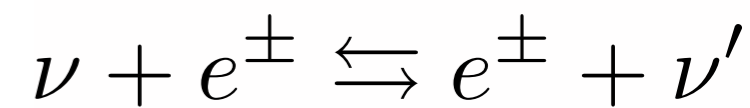
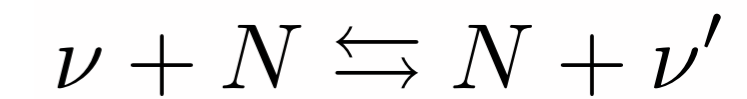
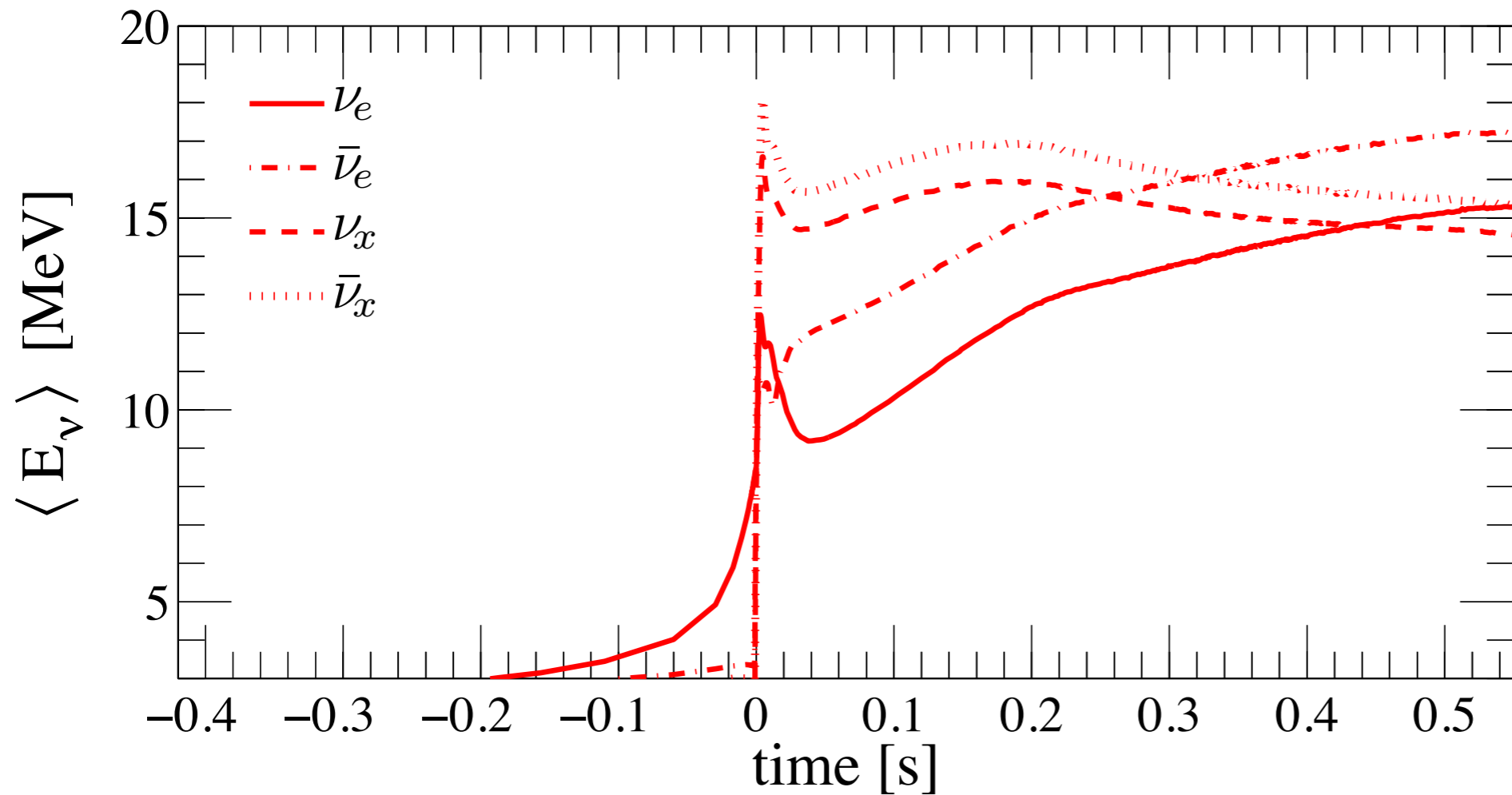
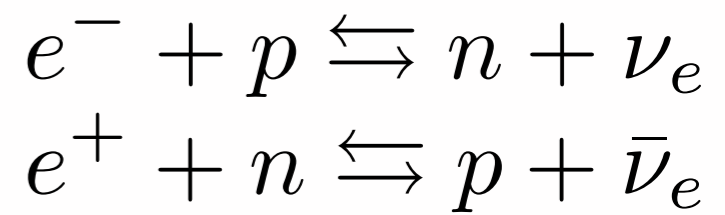
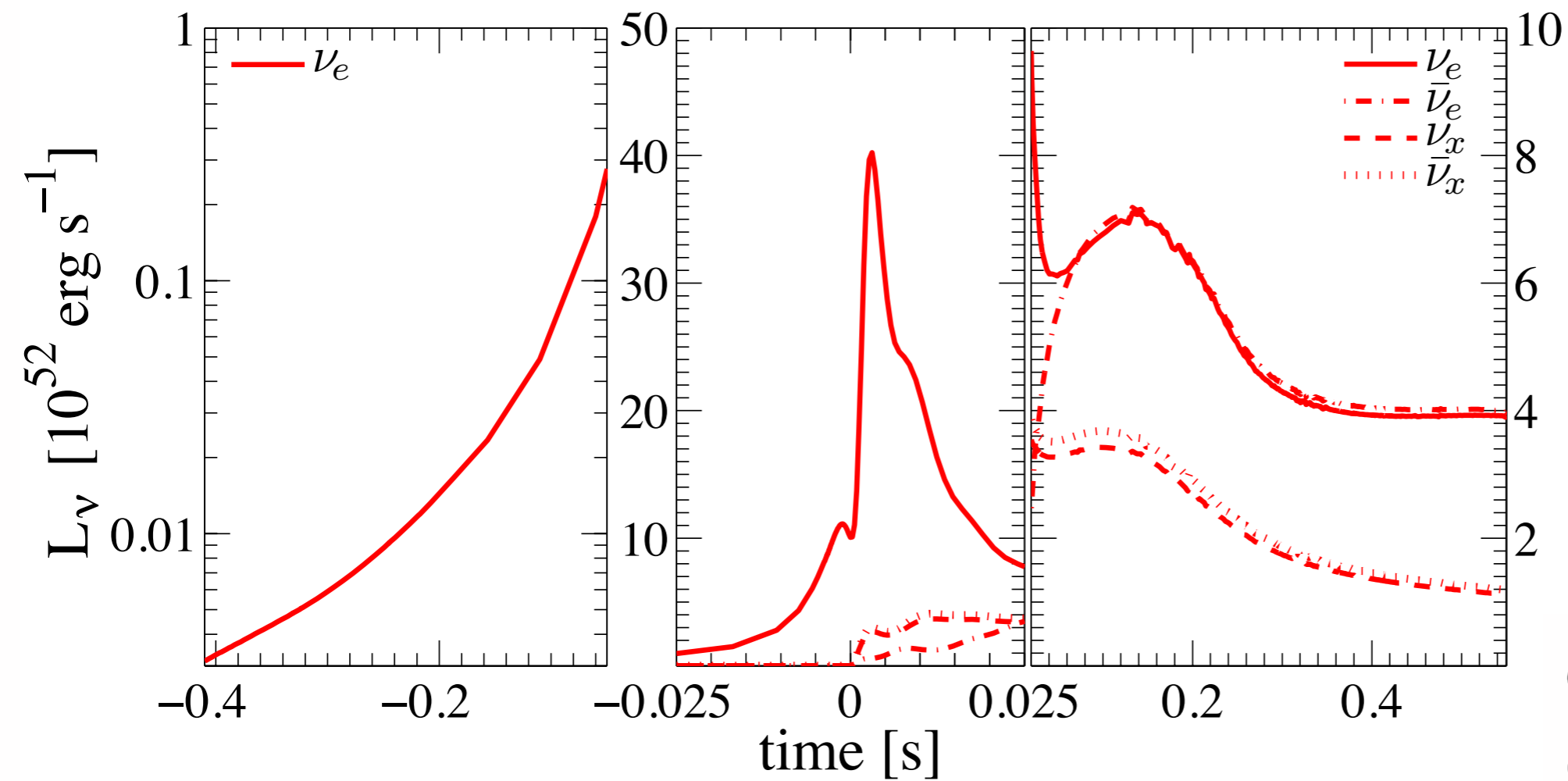




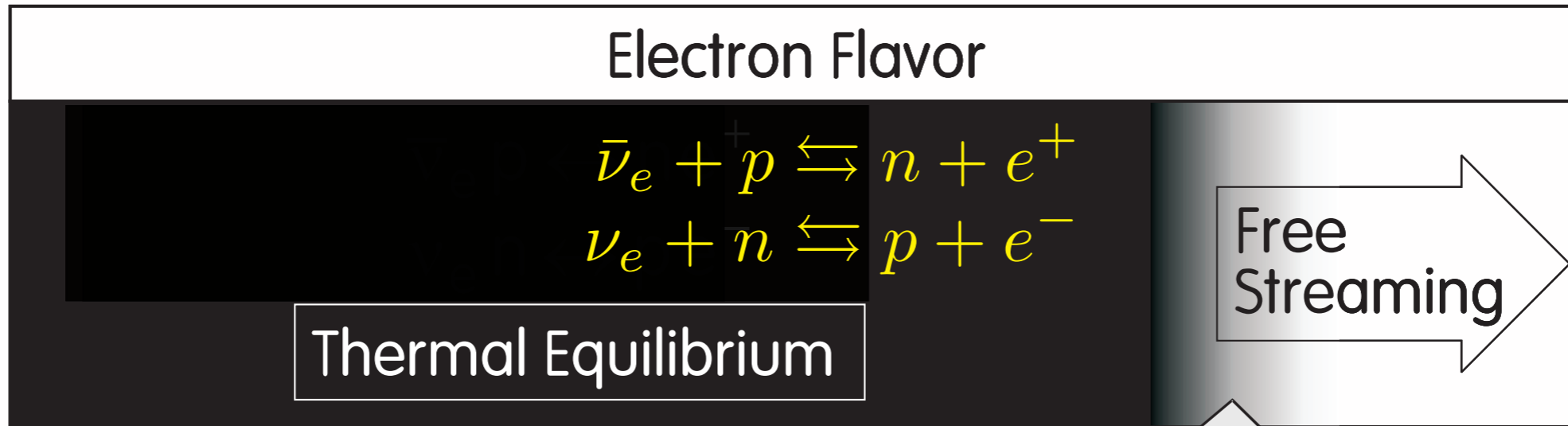






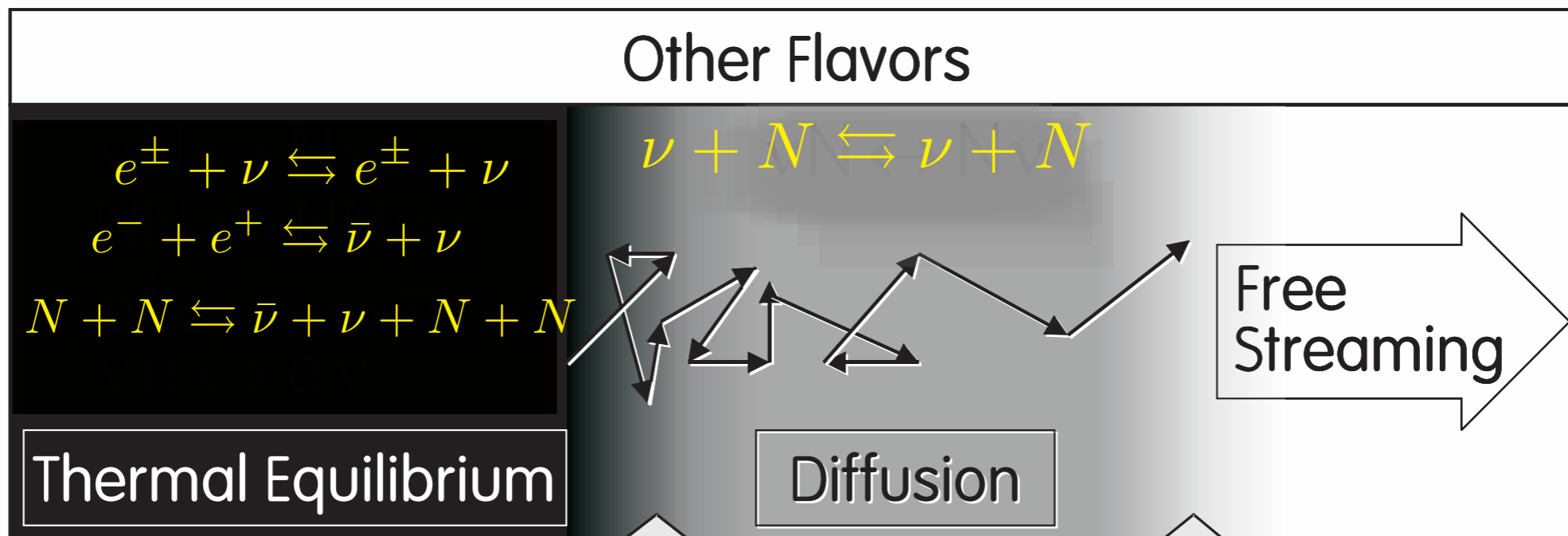


High density



Neutrino Sphere

Low density



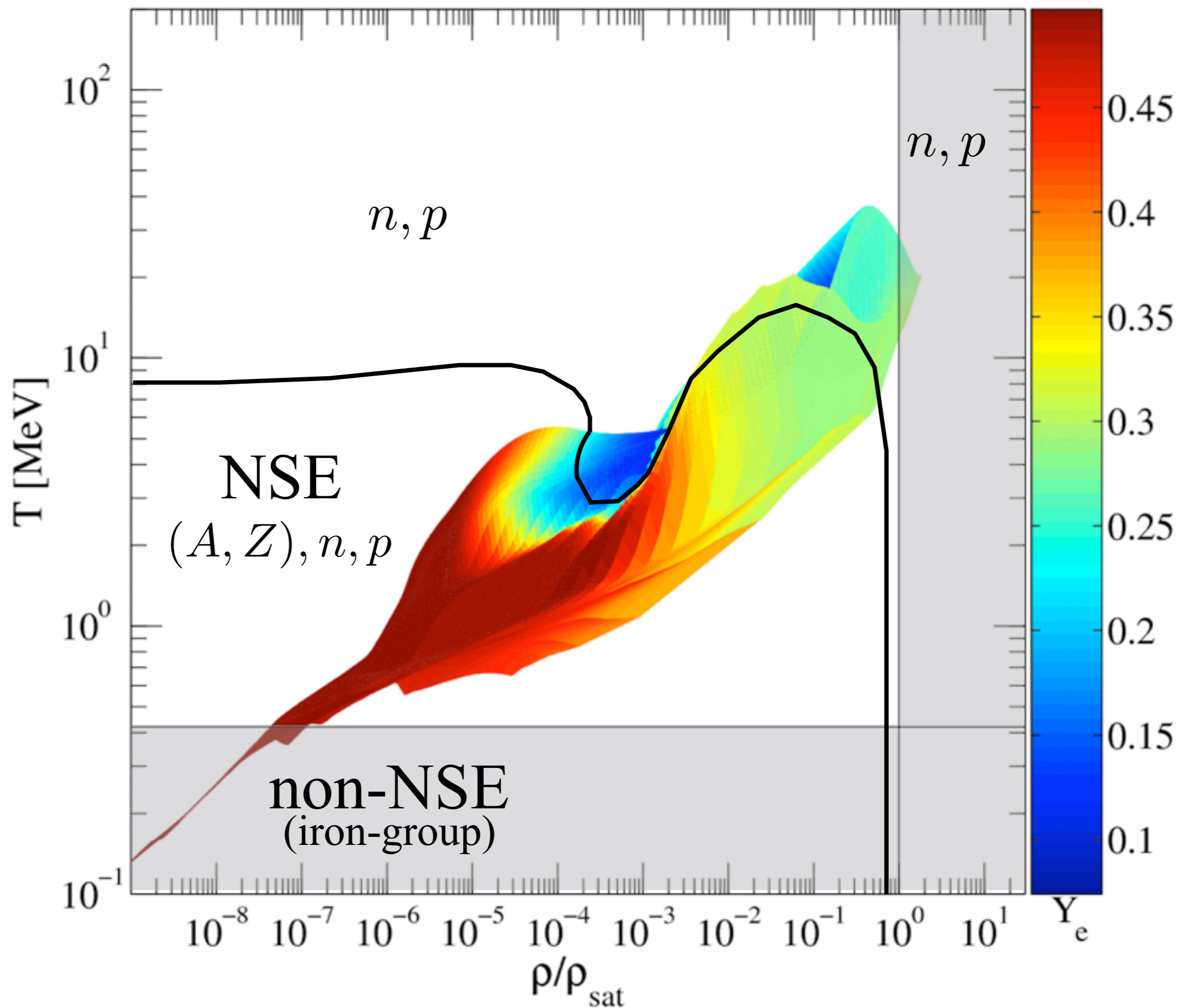
Energy Sphere (ES)

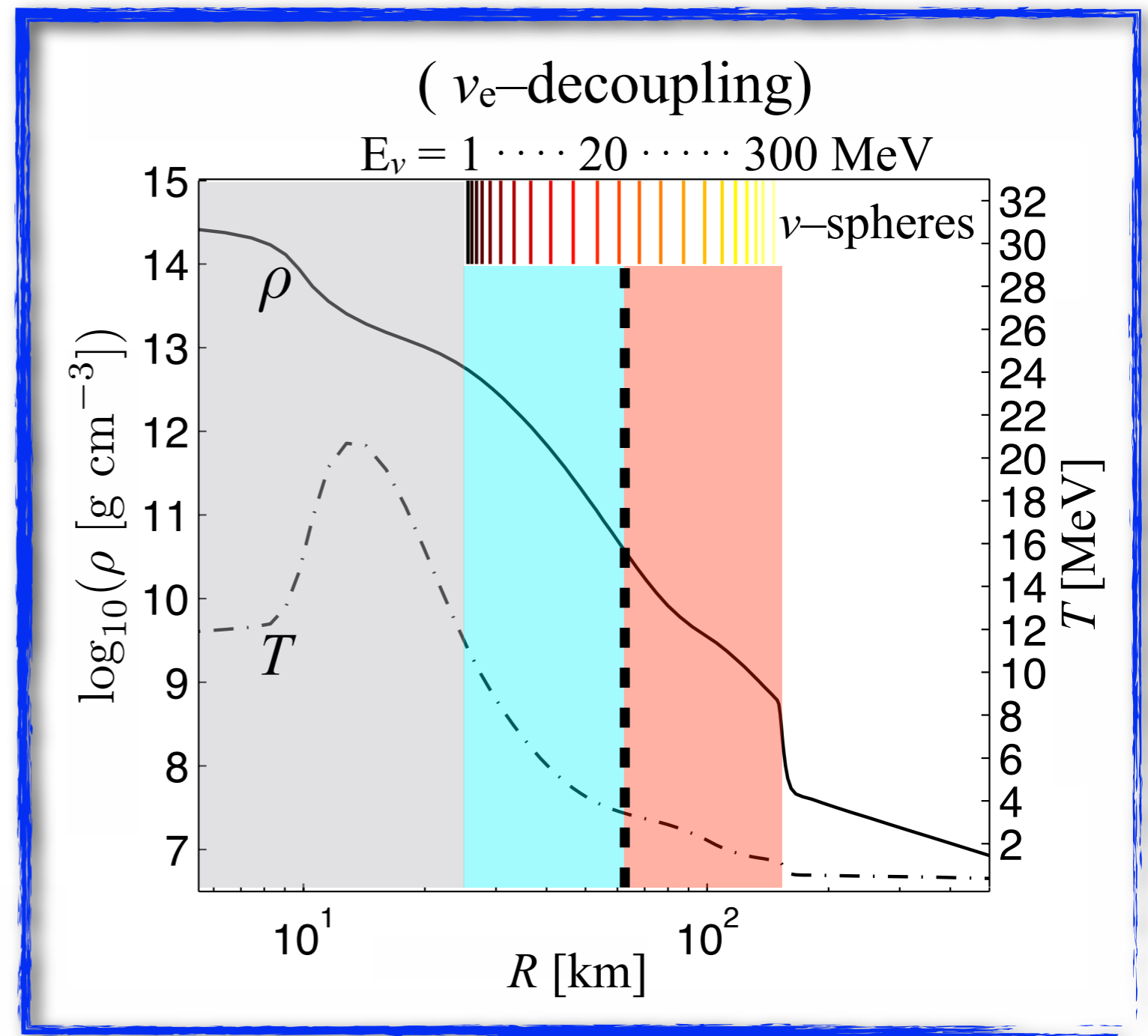
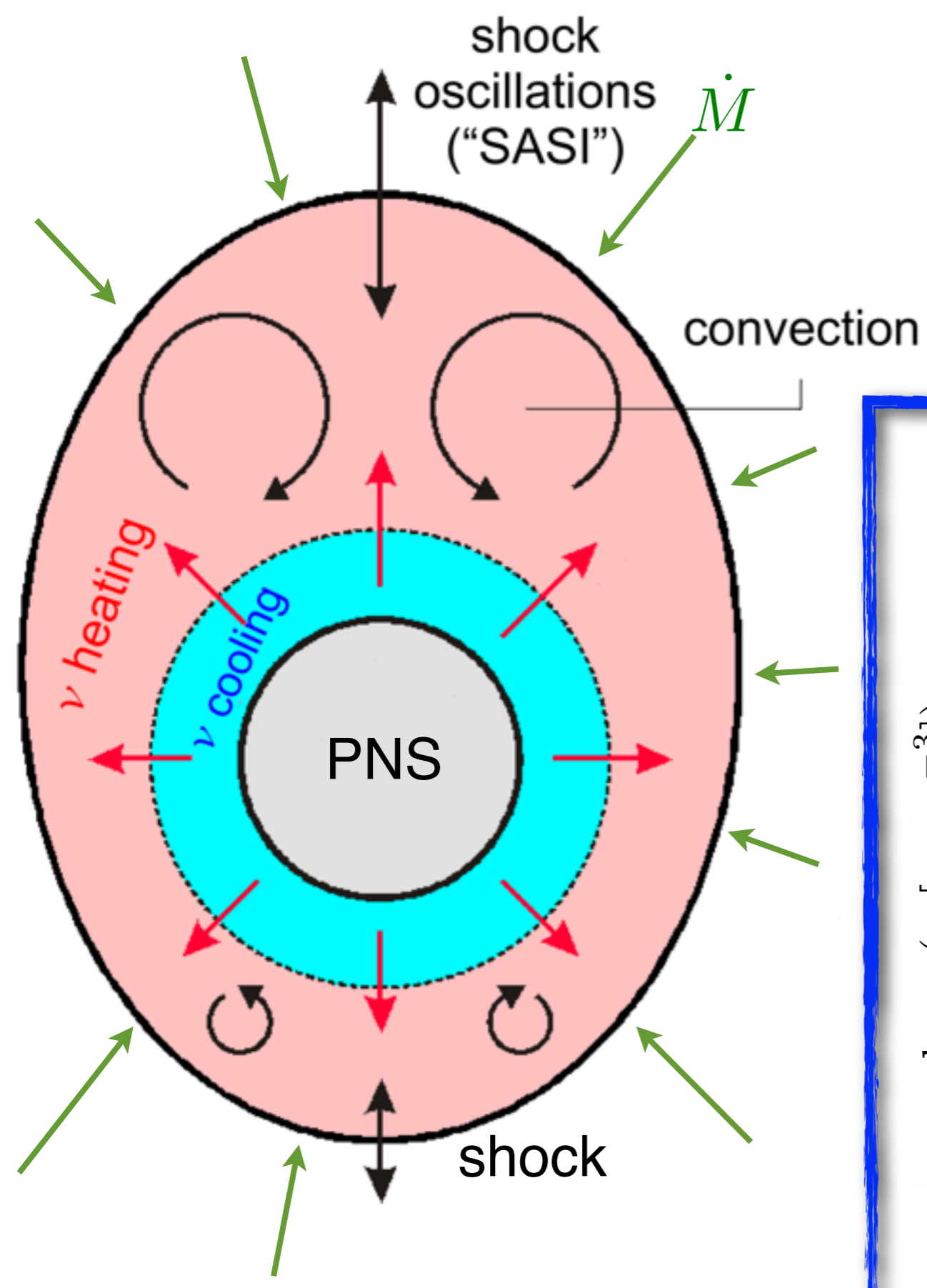
Transport Sphere

sphere of last energy exchange

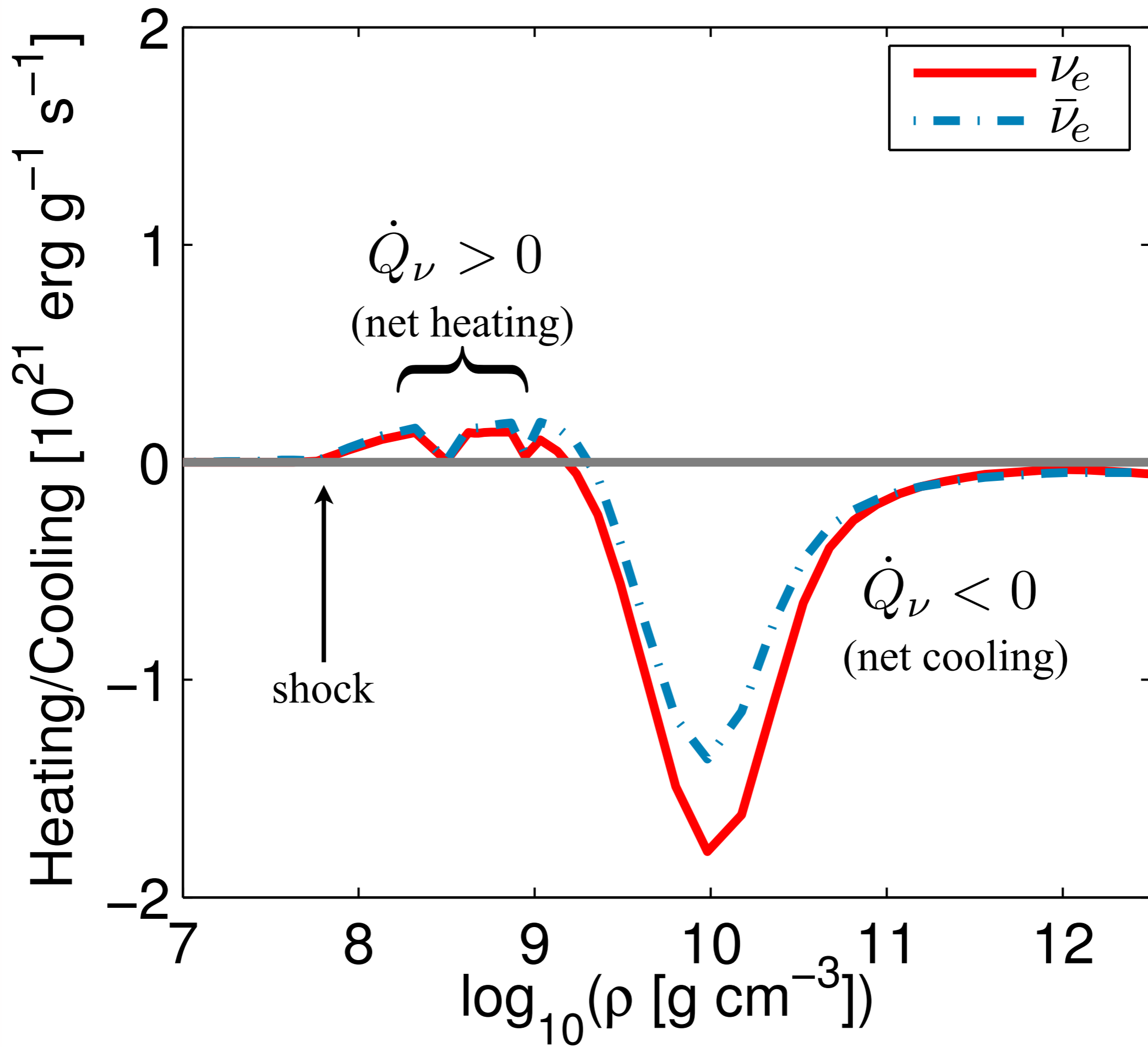
sphere of last elastic scattering

0.50165 s after bounce



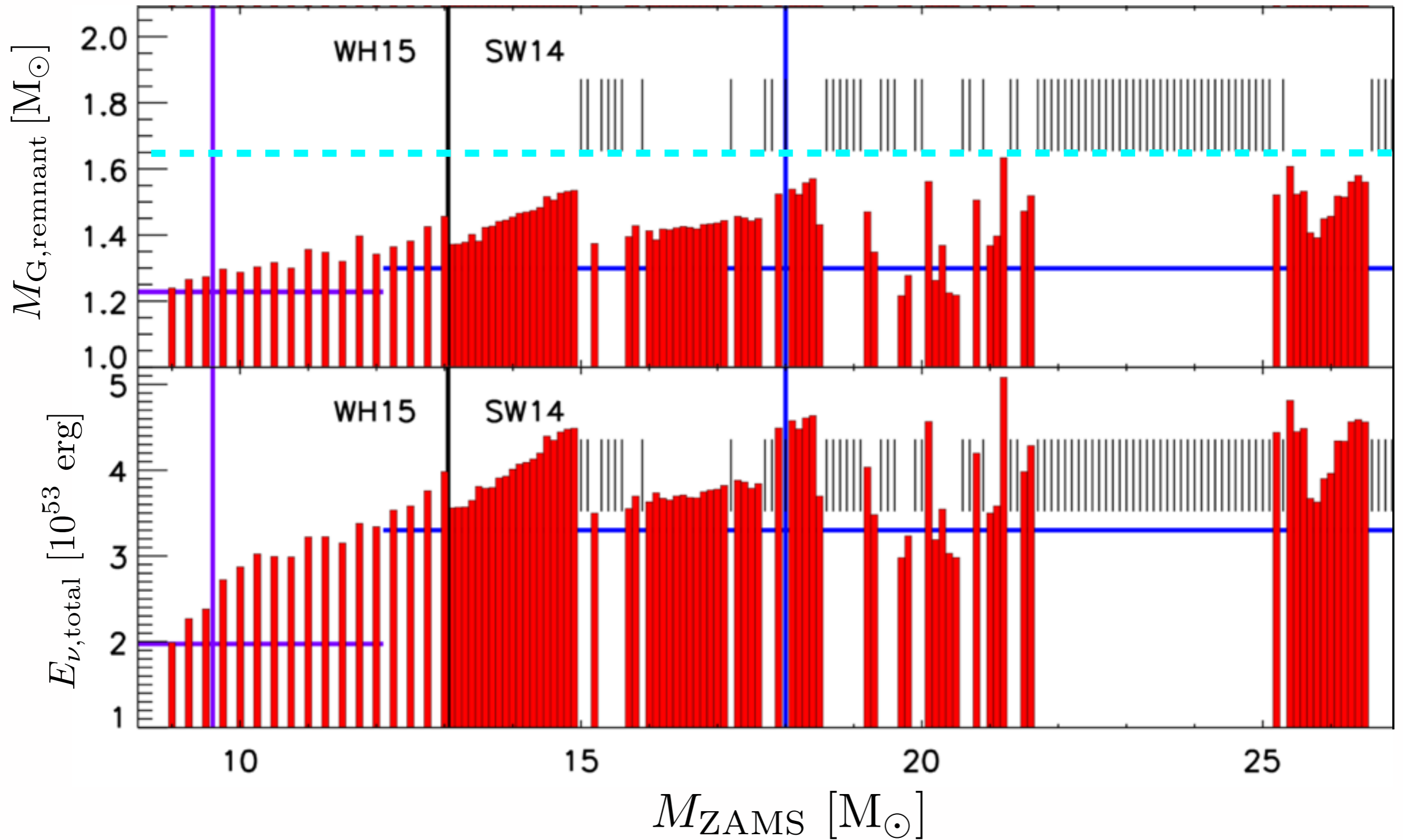


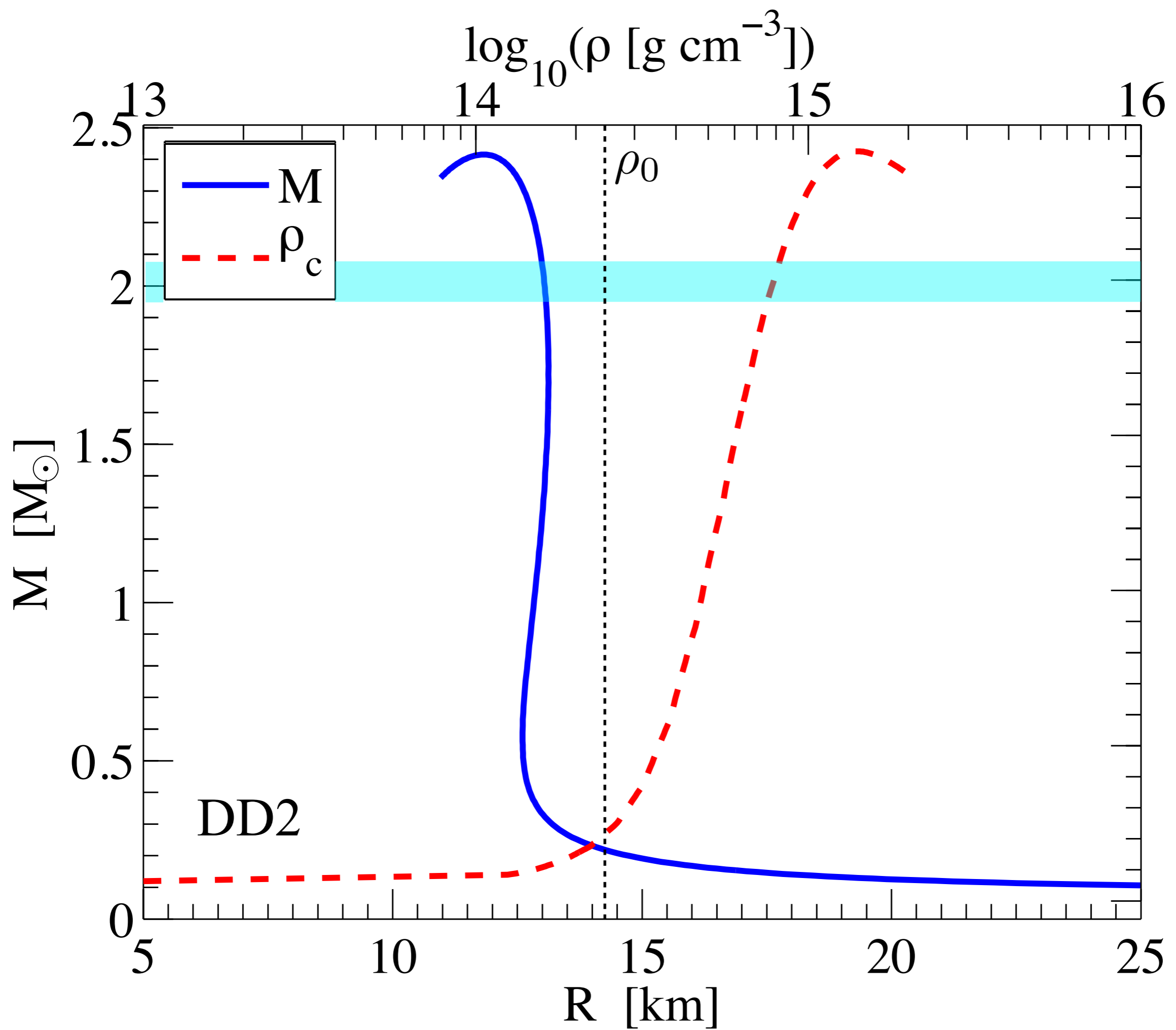


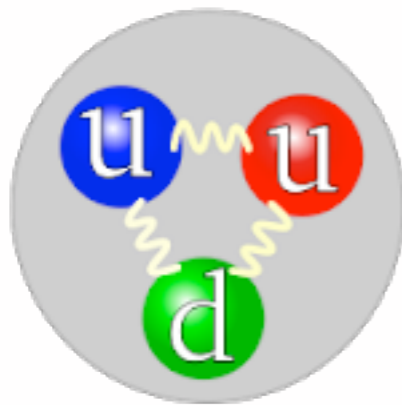
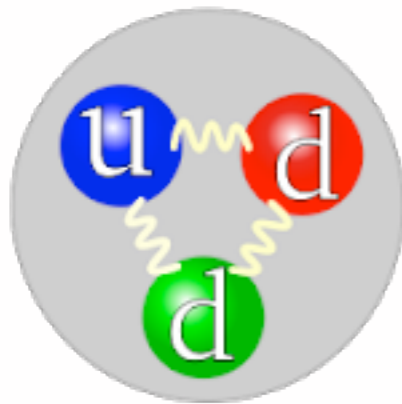


PSR J0348+0432:  $2.01 \pm 0.04 M_{\odot}$

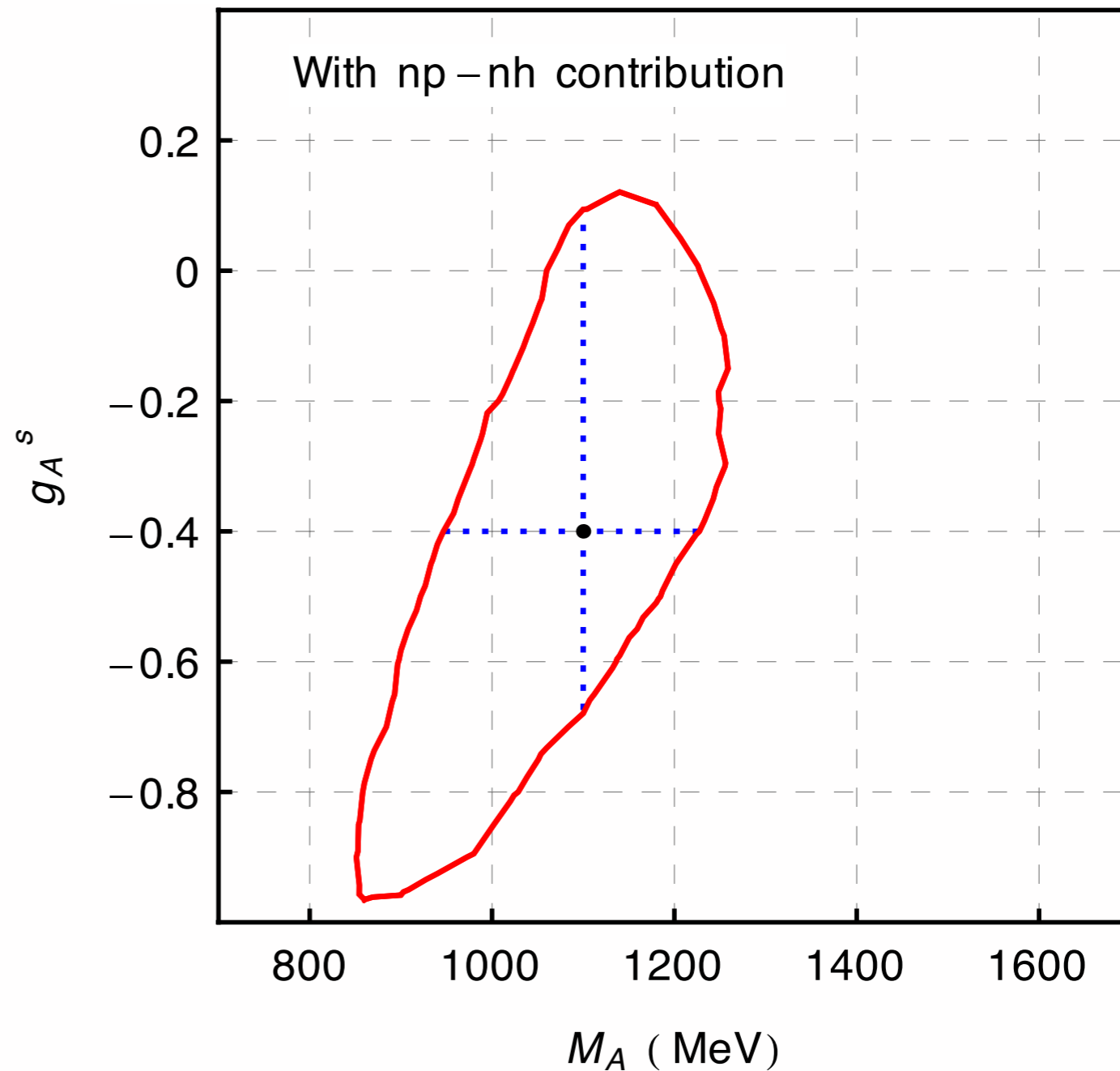
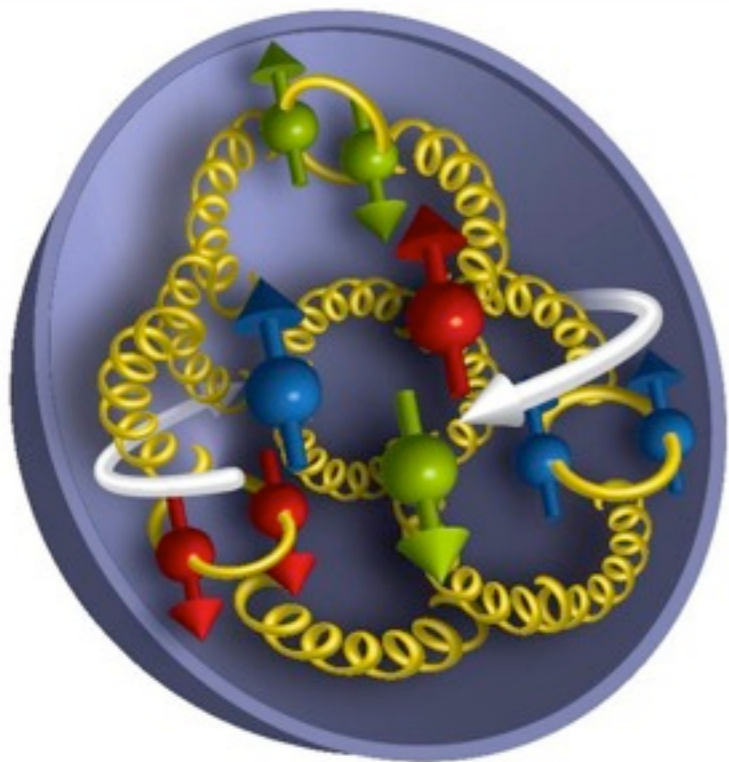
$M_{G,\text{remnant}} < 1.65 M_{\odot}$







mass	2.4 MeV/c <sup>2</sup>	1.27 GeV/c <sup>2</sup>	171.2 GeV/c <sup>2</sup>	0
charge	2/3	2/3	2/3	0
spin	1/2	1/2	1/2	1
name	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>γ</b> photon
Quarks	4.8 MeV/c <sup>2</sup>	104 MeV/c <sup>2</sup>	4.2 GeV/c <sup>2</sup>	0
	-1/3	-1/3	-1/3	0
	1/2	1/2	1/2	1
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>g</b> gluon
Leptons	<2.2 eV/c <sup>2</sup>	<0.17 MeV/c <sup>2</sup>	<15.5 MeV/c <sup>2</sup>	91.2 GeV/c <sup>2</sup>
	0	0	0	0
	1/2	1/2	1/2	1
	<b>ν<sub>e</sub></b> electron neutrino	<b>ν<sub>μ</sub></b> muon neutrino	<b>ν<sub>τ</sub></b> tau neutrino	<b>Z<sup>0</sup></b> Z boson
	0.511 MeV/c <sup>2</sup>	105.7 MeV/c <sup>2</sup>	1.777 GeV/c <sup>2</sup>	80.4 GeV/c <sup>2</sup>
	-1	-1	-1	±1
	1/2	1/2	1/2	1
	<b>e</b> electron	<b>μ</b> muon	<b>τ</b> tau	<b>W<sup>±</sup></b> W boson
				Gauge bosons

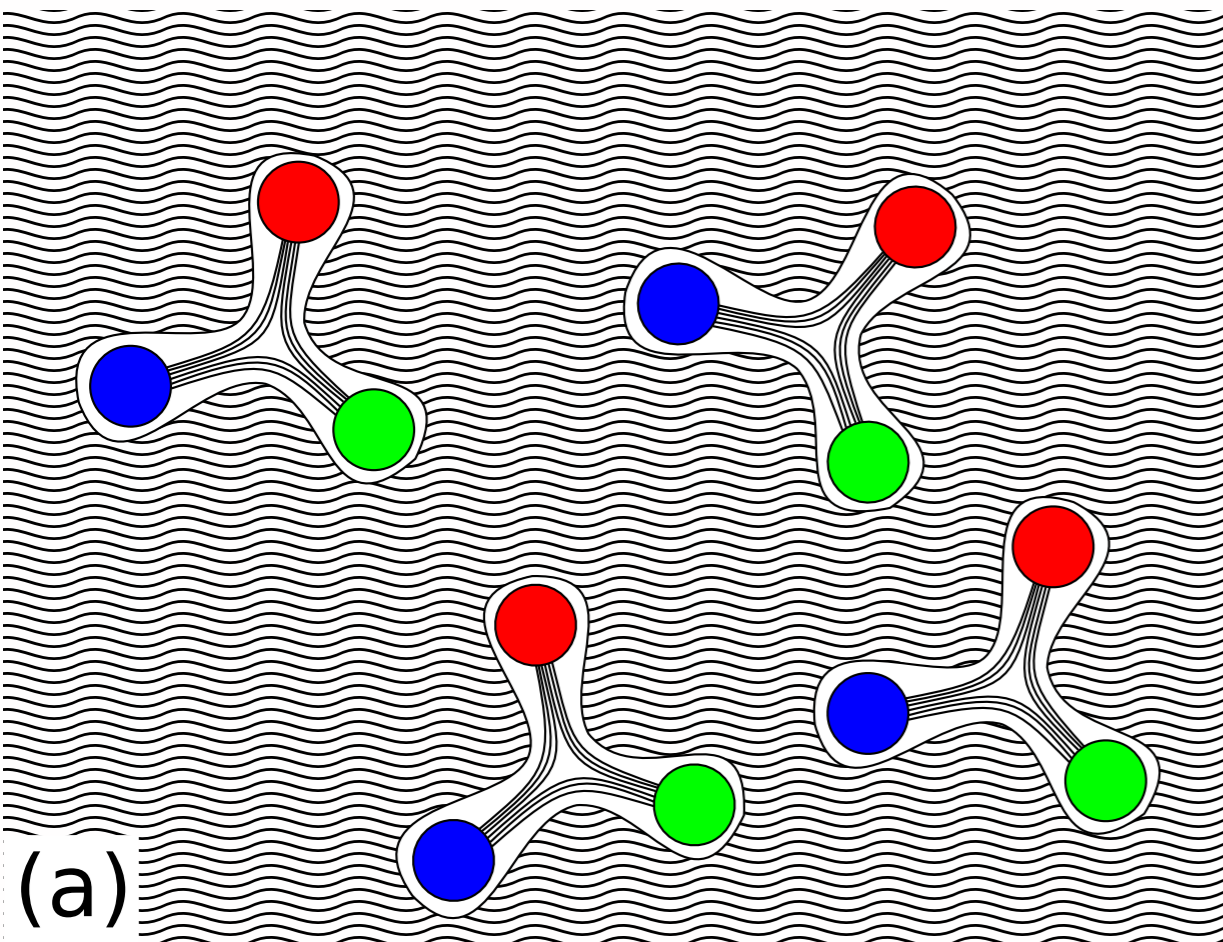


$$\frac{d\sigma}{d\Omega} \propto E^2 \left\{ g_V^2 (1 + \cos \theta) S_V + g_A^2 (3 - \cos \theta) S_A \right\}$$

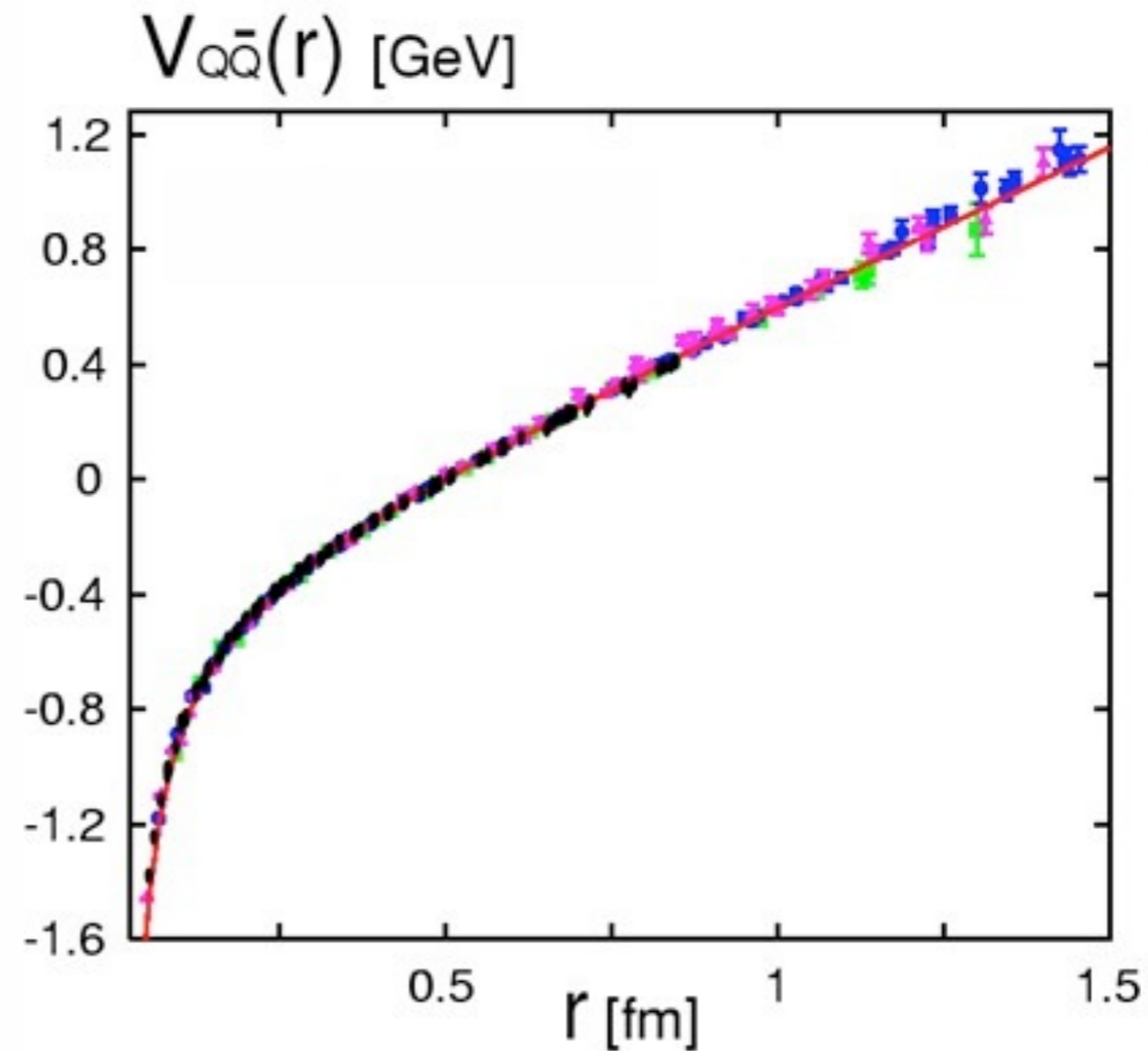
$$g_A \longrightarrow g_A + g_s$$

$$(g_A = 1.27, \quad g_s = -0.4_{-0.3}^{+0.5})$$

vacuum



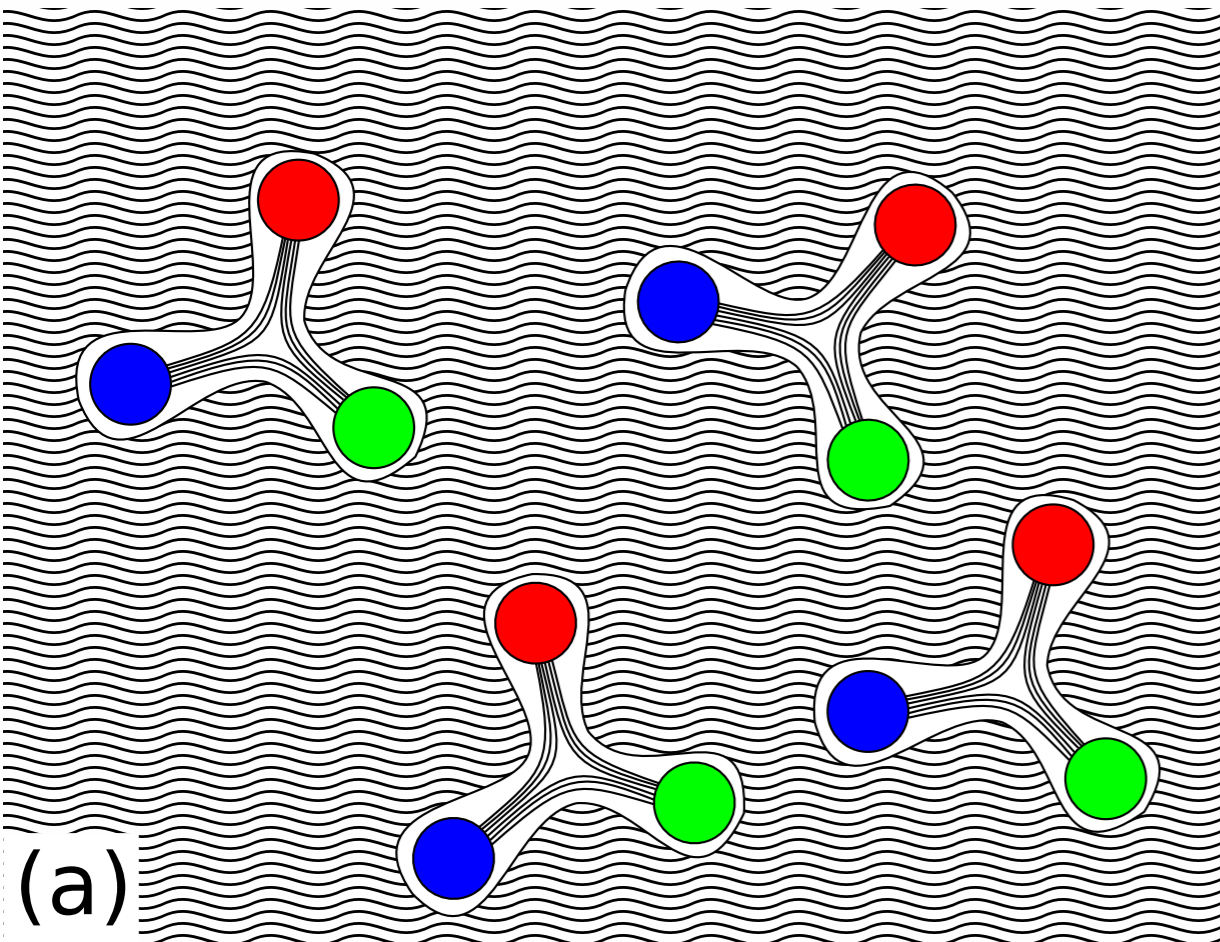
$$D = D_0$$



$$V_{Q\bar{Q}}(r) \propto D_0 r - \frac{A}{r}$$

$$D_0 = 1 \text{ GeV fm}^{-1}$$

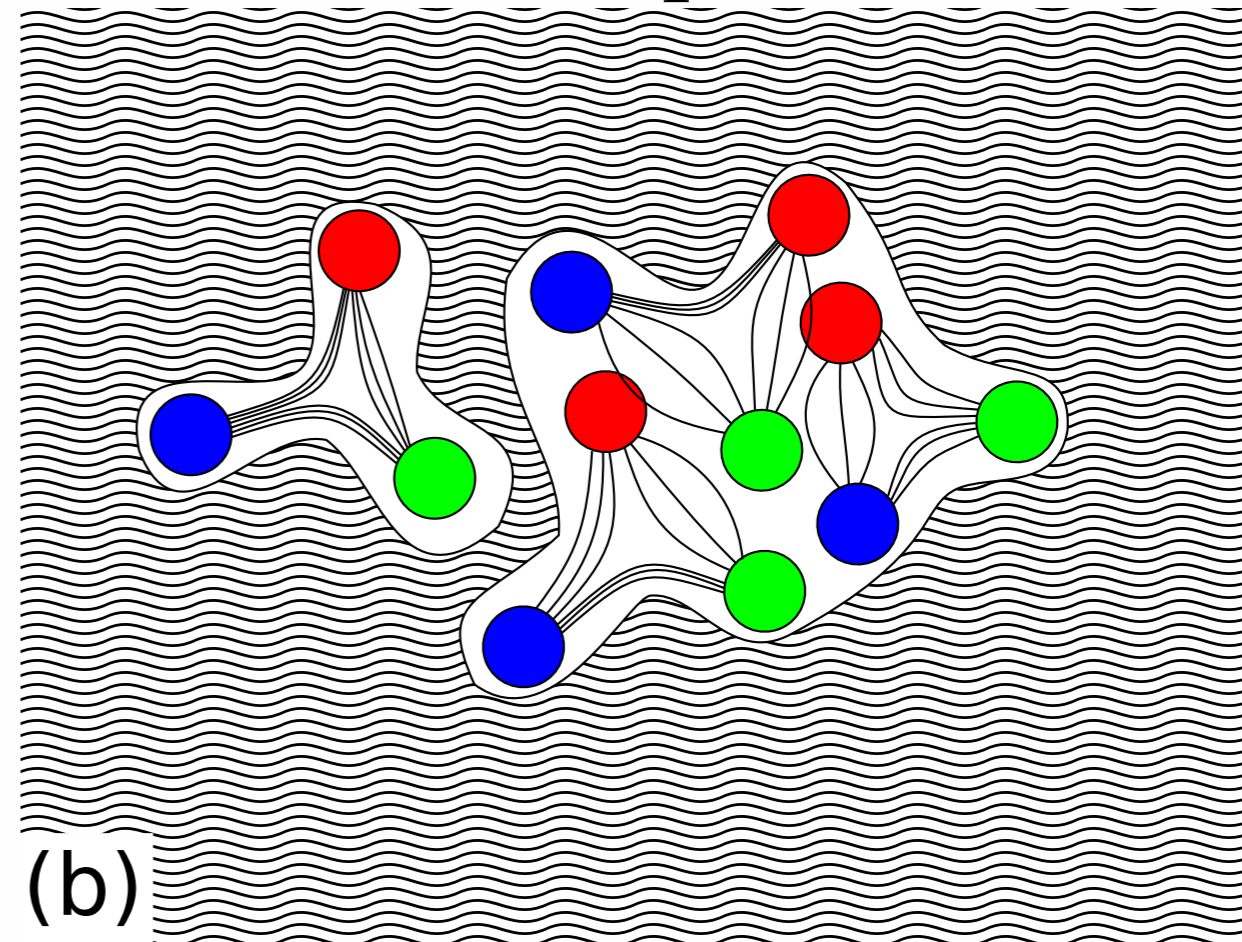
vacuum



$$D = D_0$$

(a)

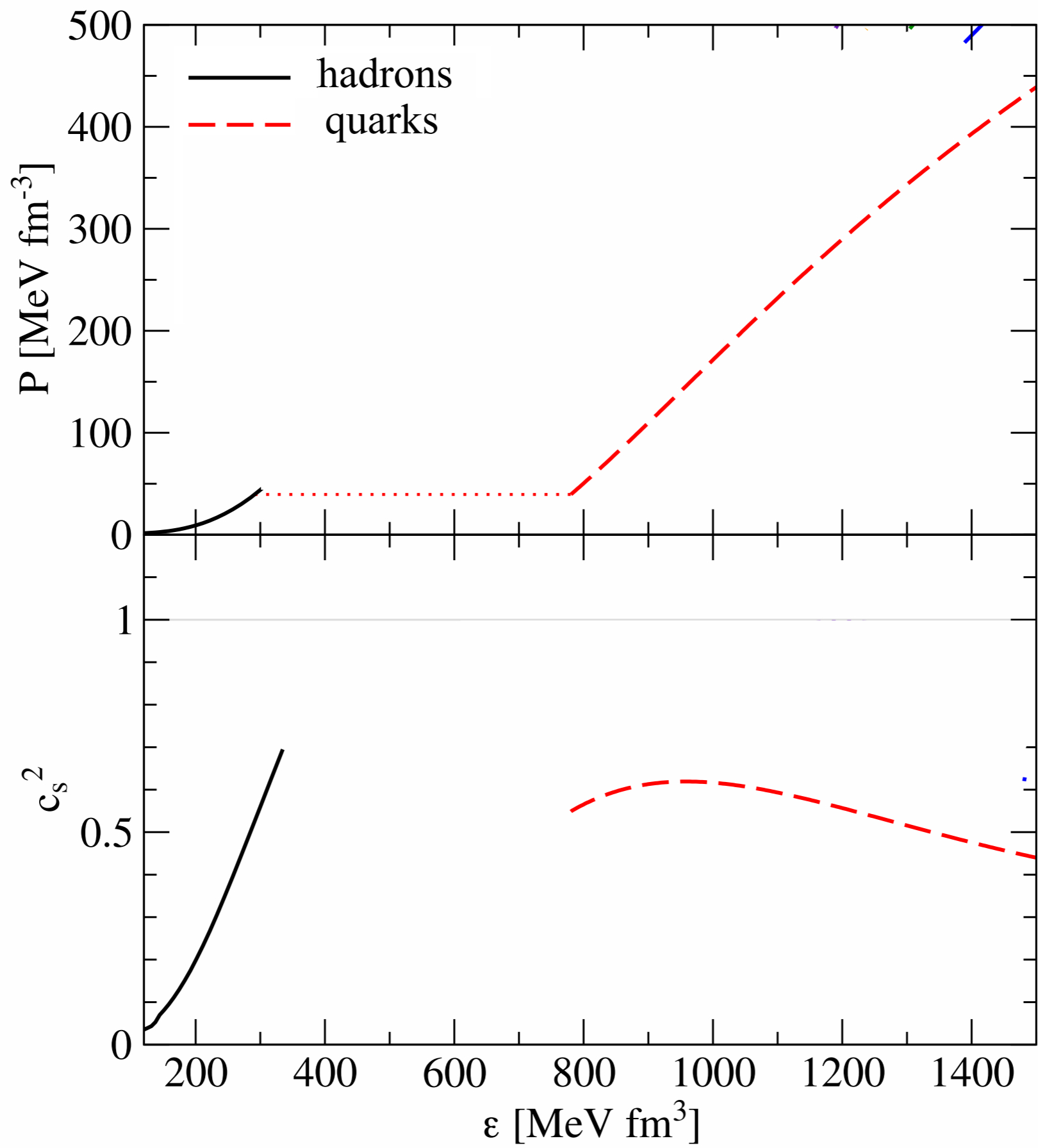
medium dependence



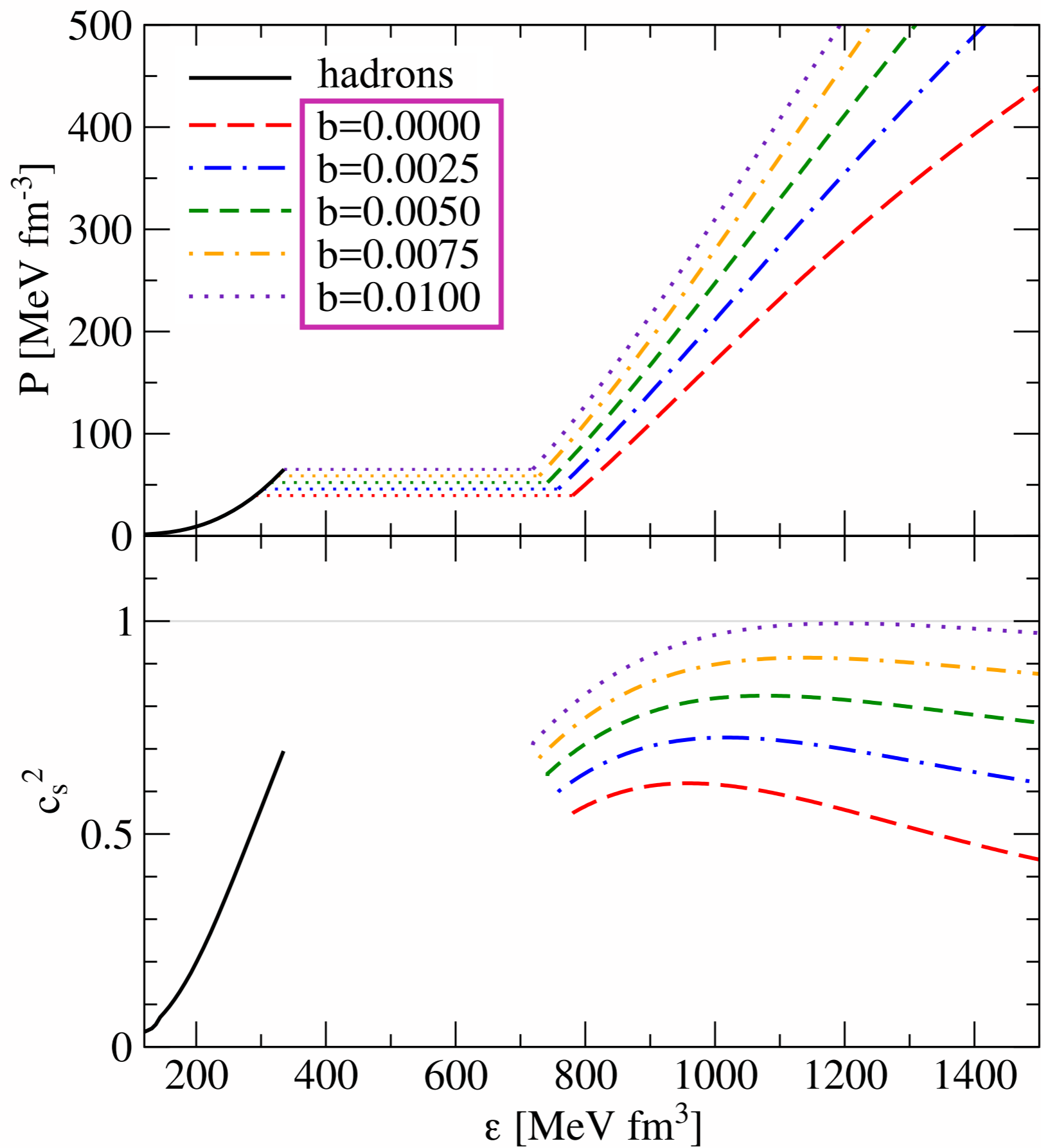
$$D(\rho) = D_0 \Phi(\rho)$$

$$\Phi(\rho) = \exp \left\{ -\alpha (\rho - \rho_0)^2 \right\}$$

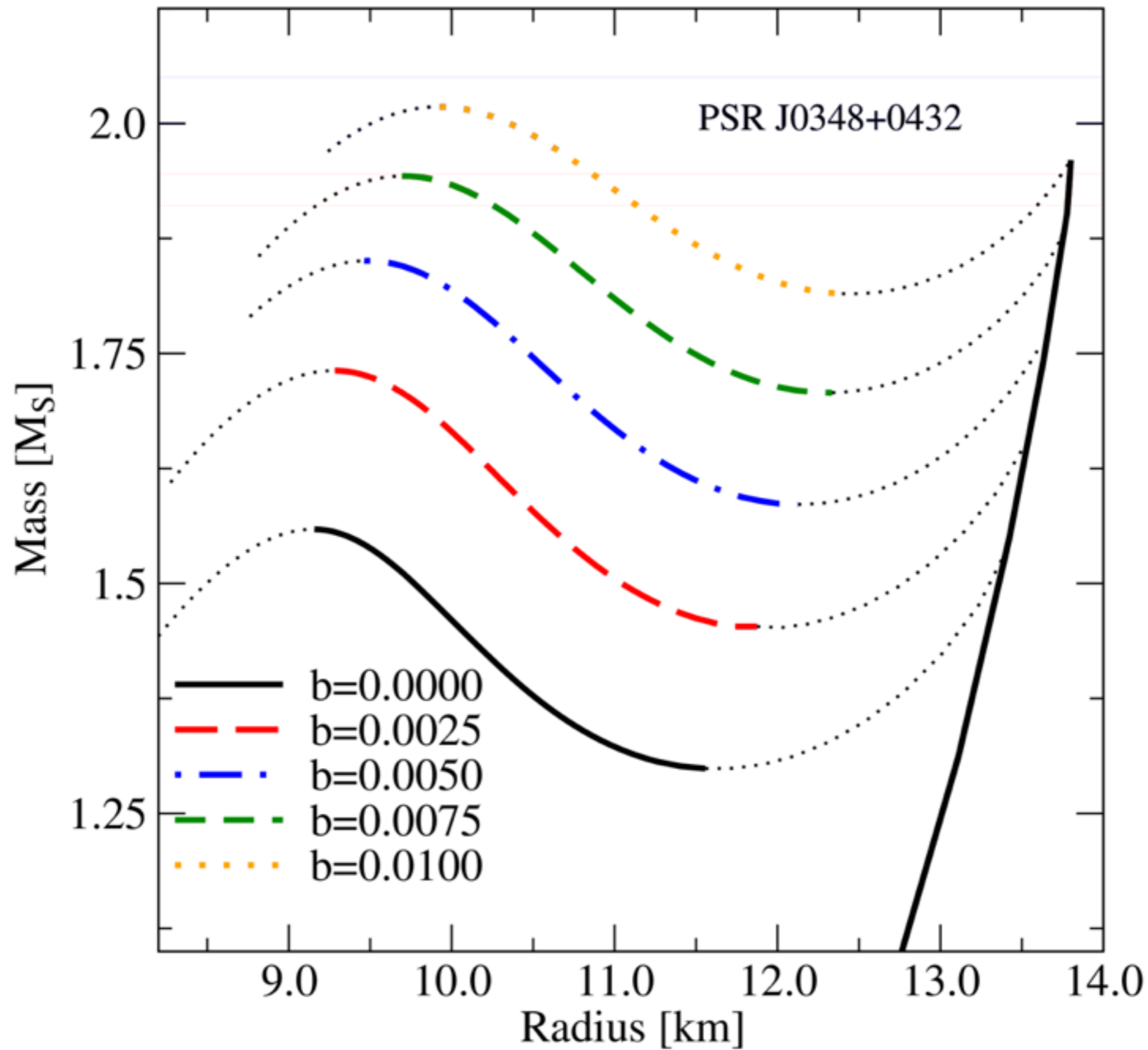
(b)



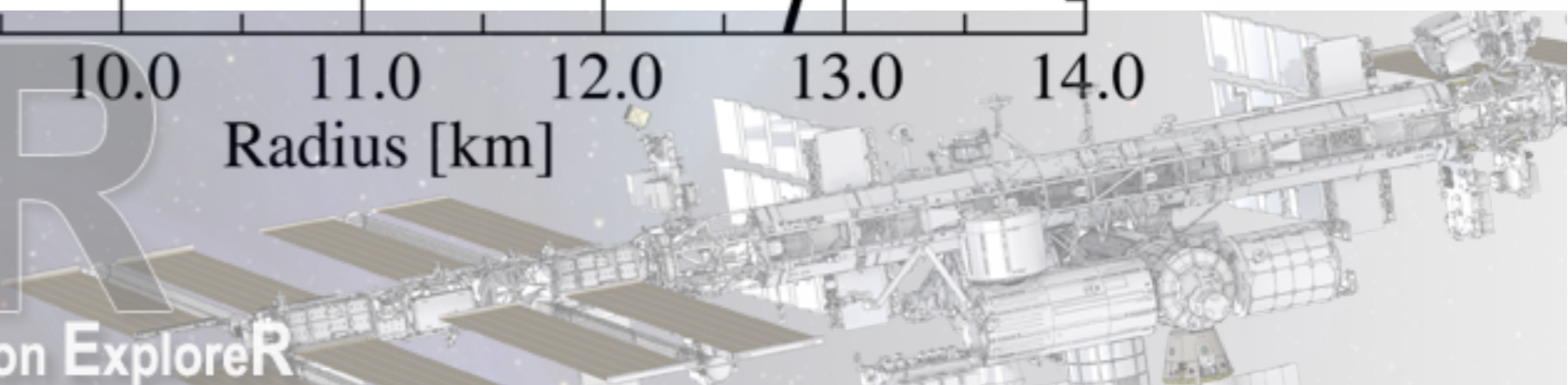
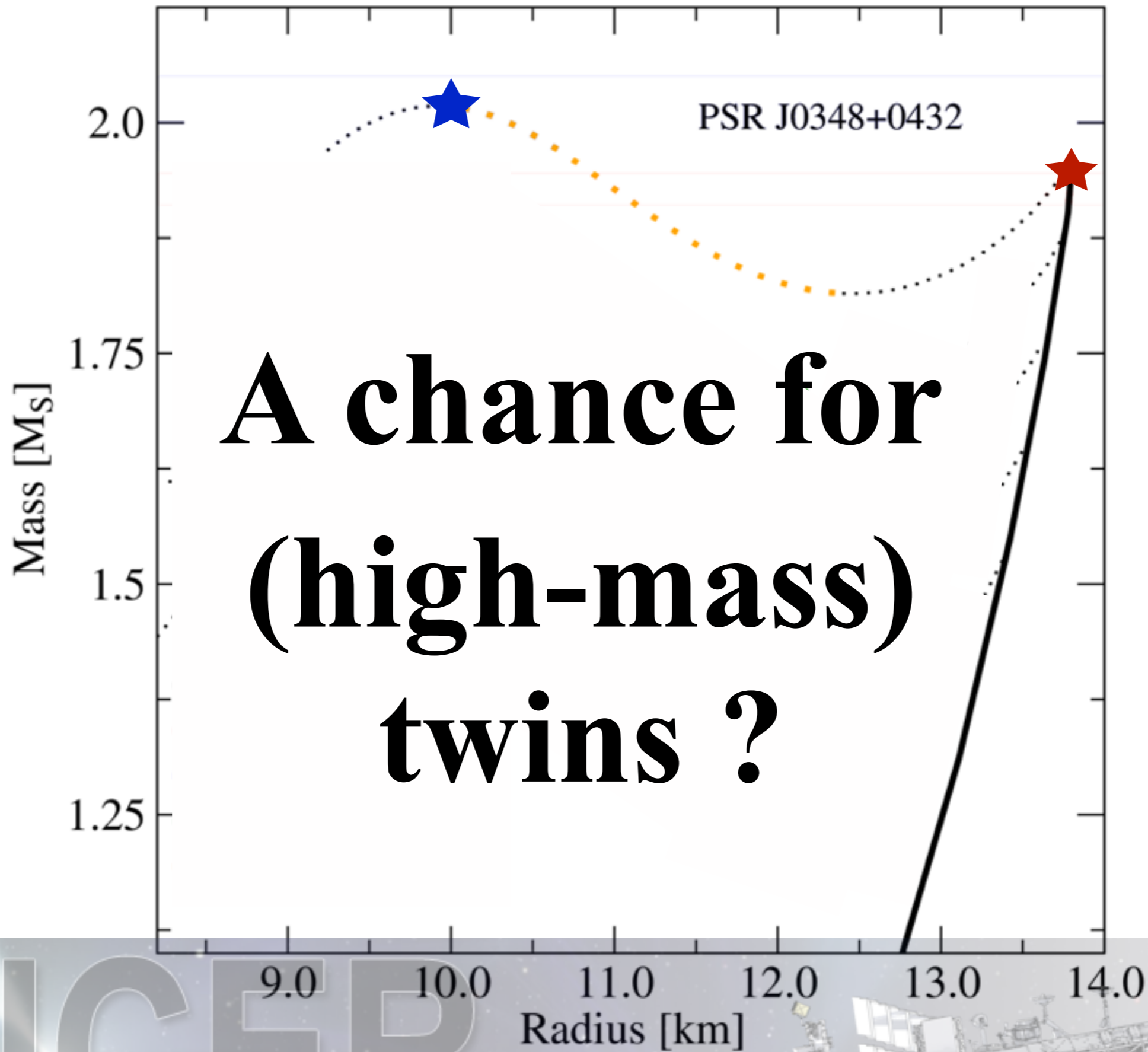


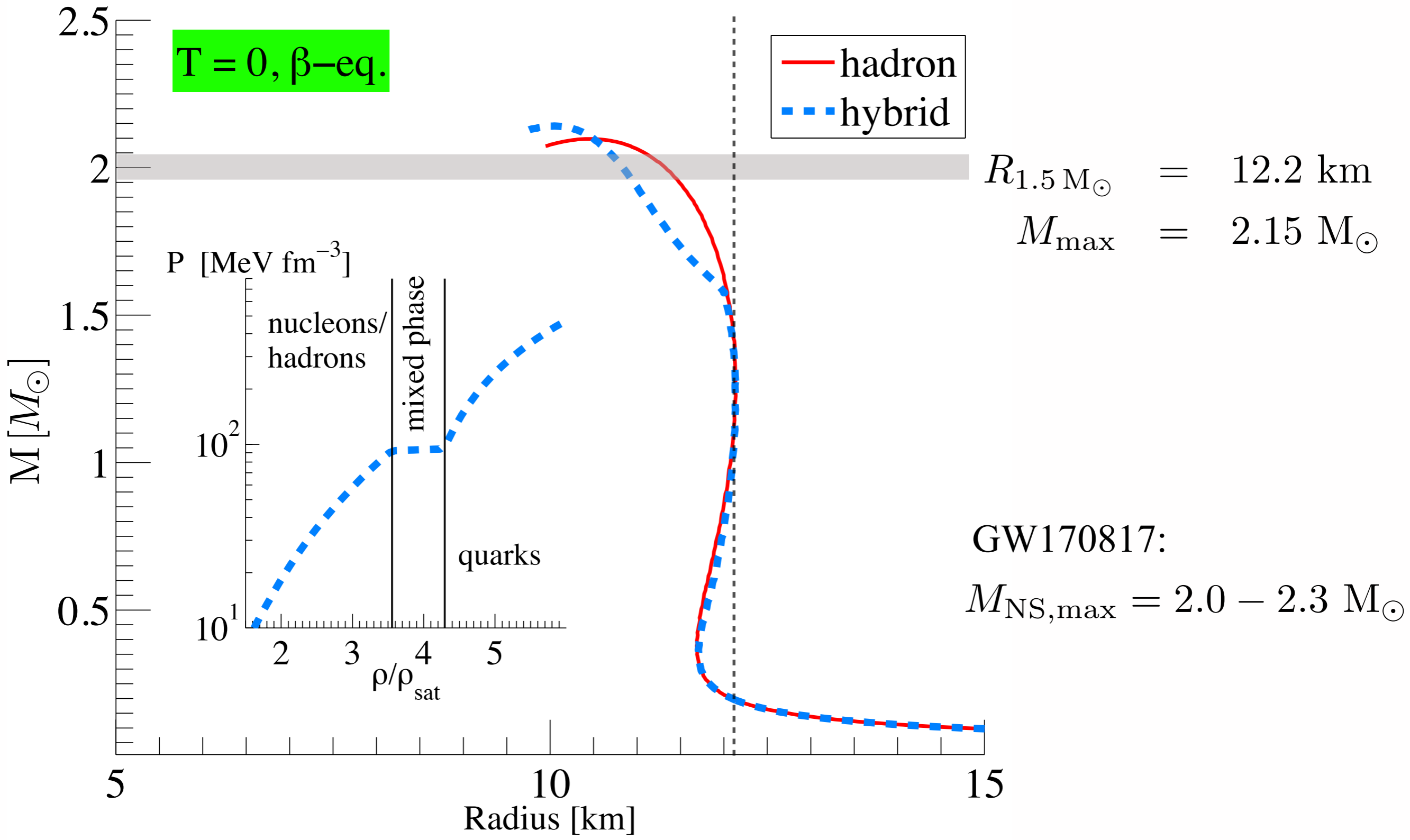


repulsive vector interaction:  $\mu^* = \mu - a\rho - \mathcal{O}(\rho^3)$

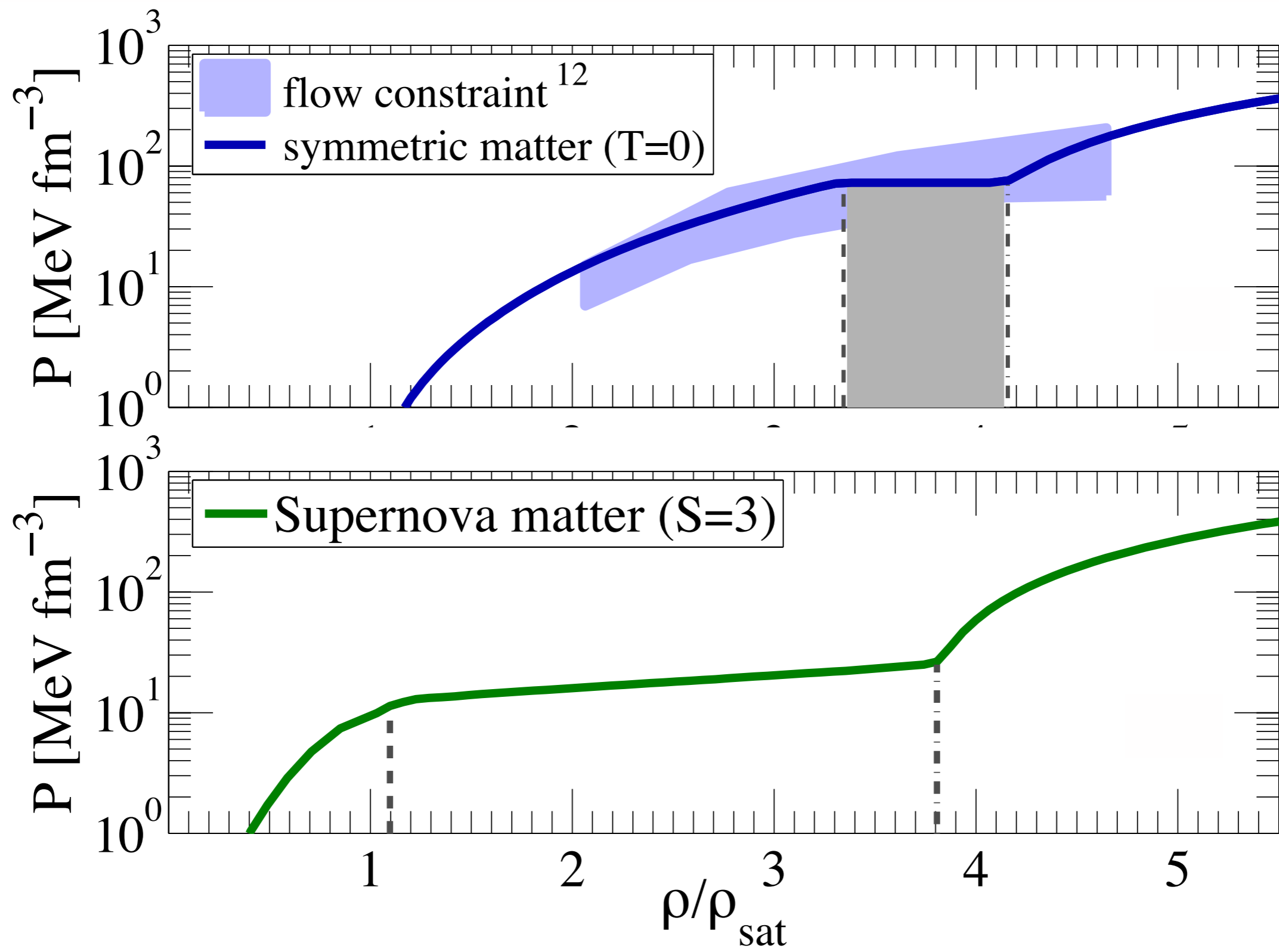


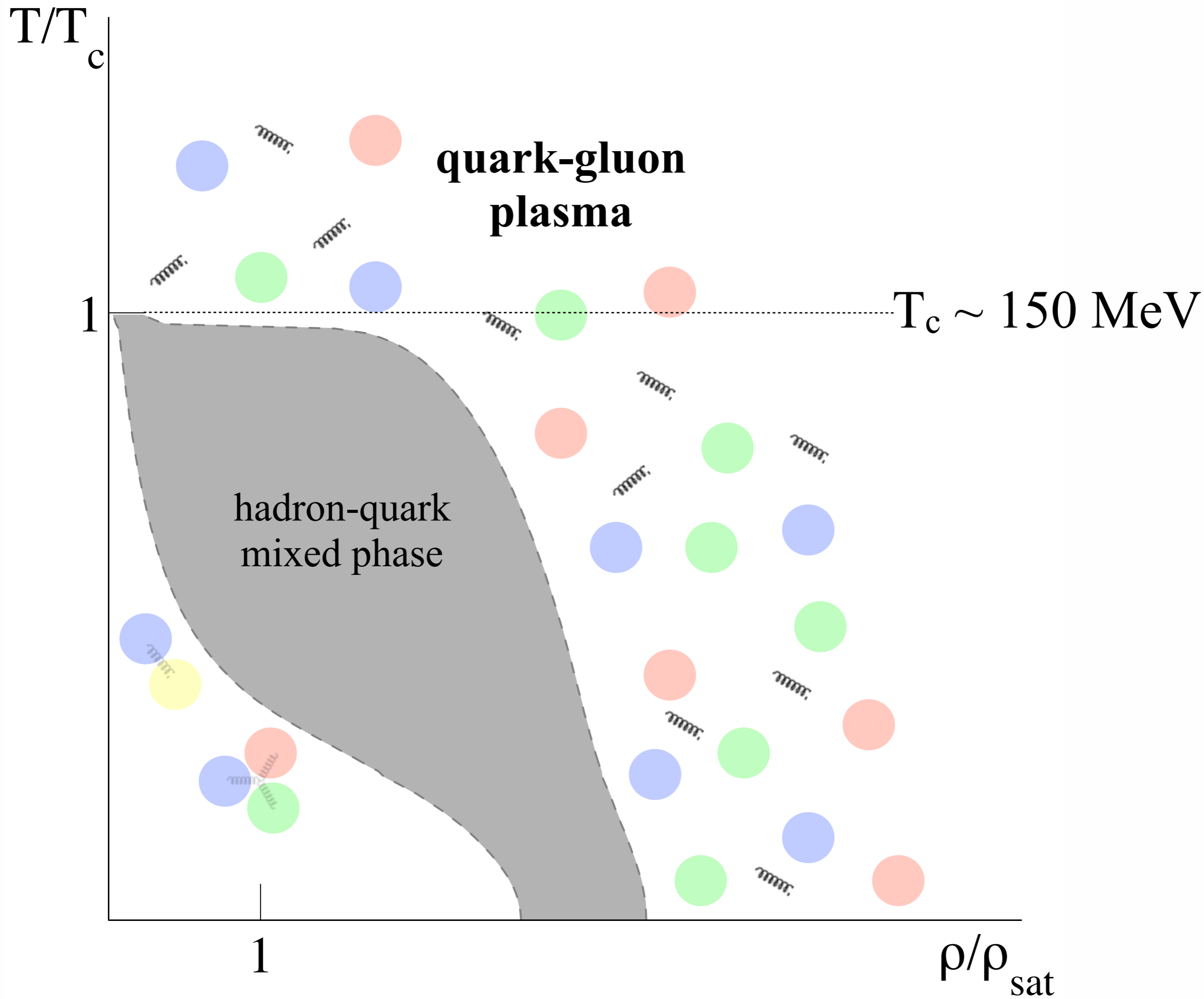
repulsive vector interaction:  $\mu^* = \mu - a\rho - \mathcal{O}(\rho^3)$

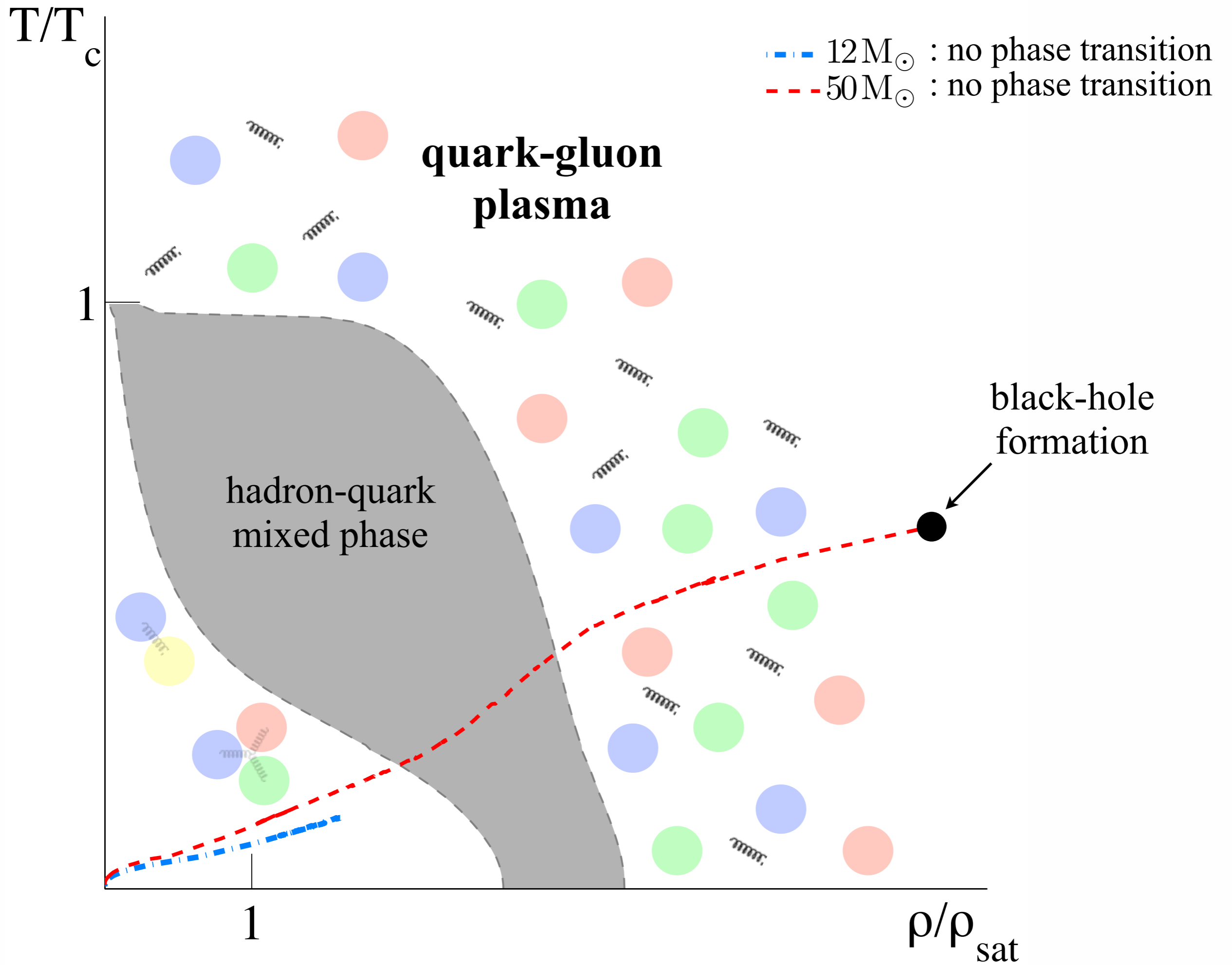


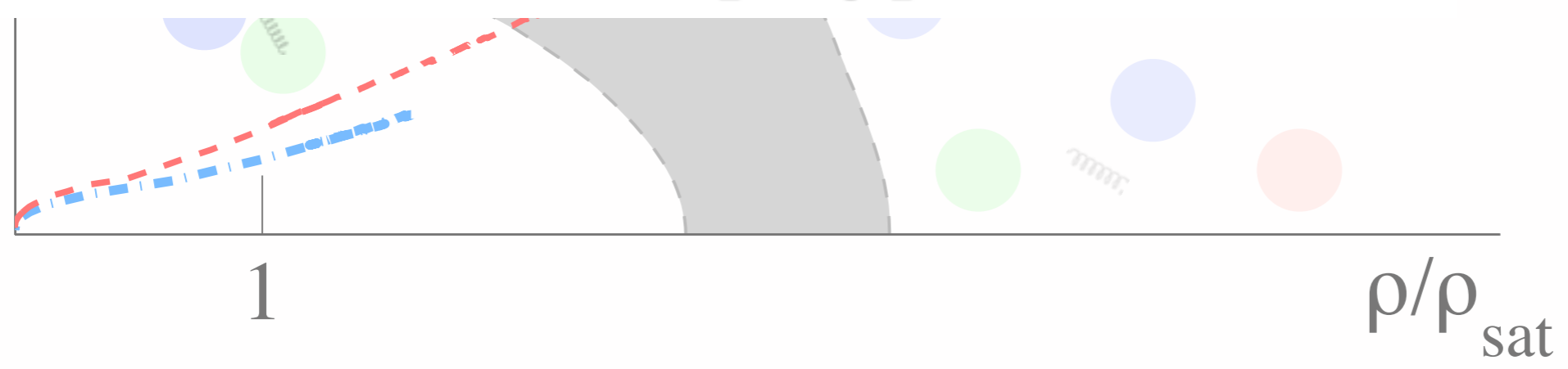
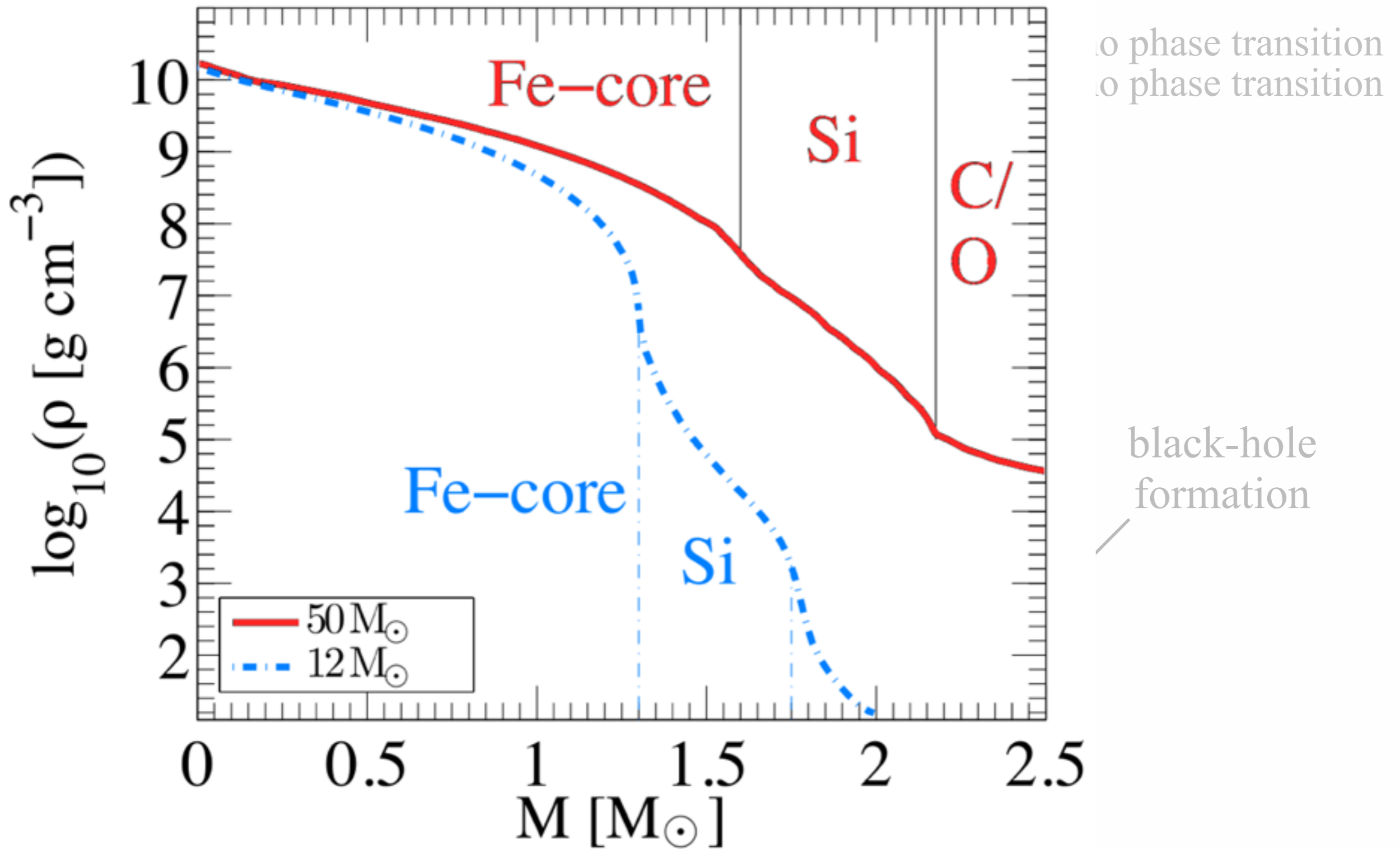


Margalit & Metzger (2017) ApJ 850, L19  
 Shibata et al., (2017) PRD 96, 123012  
 Rezzolla et al., (2018) ApJ 852, L25  
 Ruiz et al., (2018) PRD 97

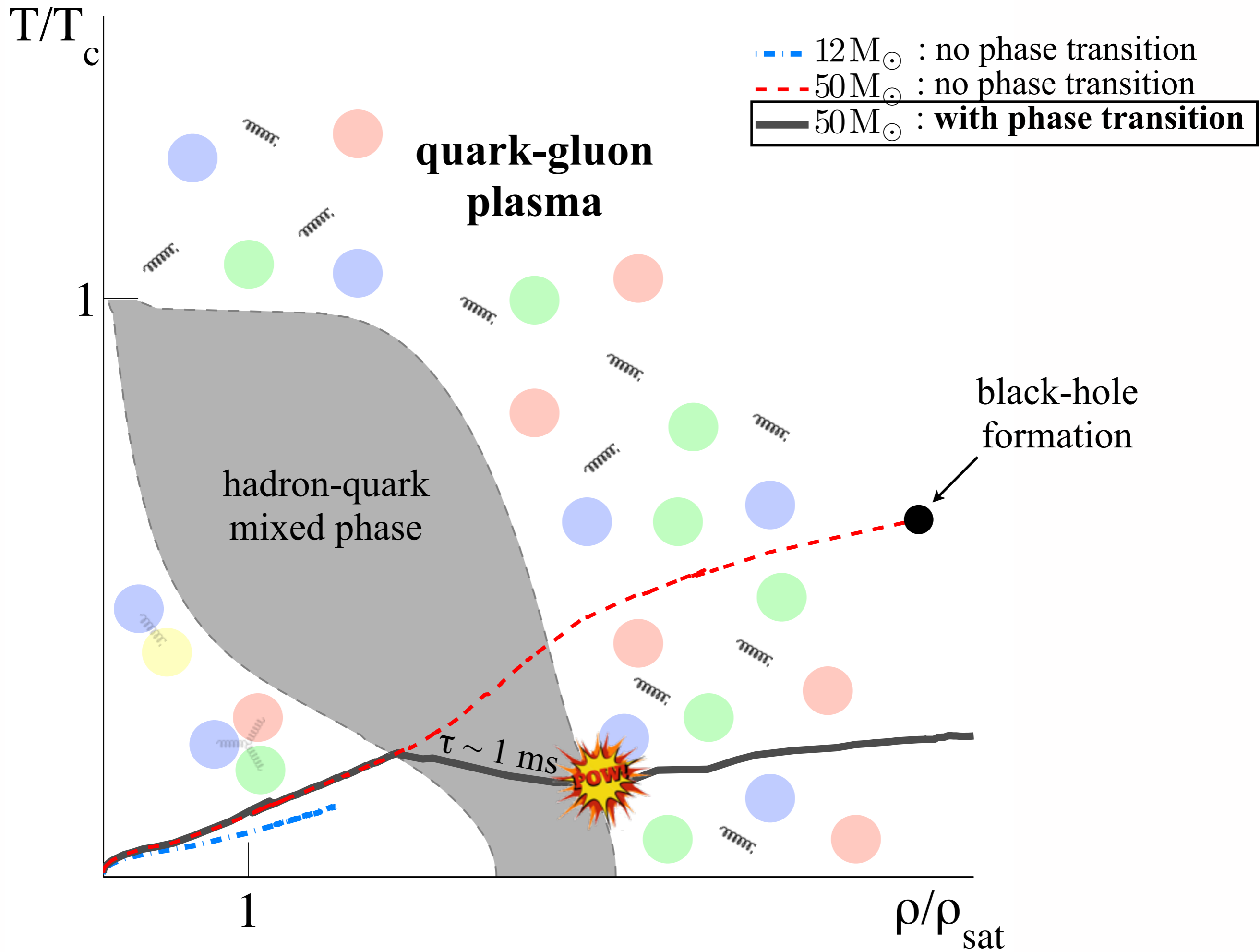


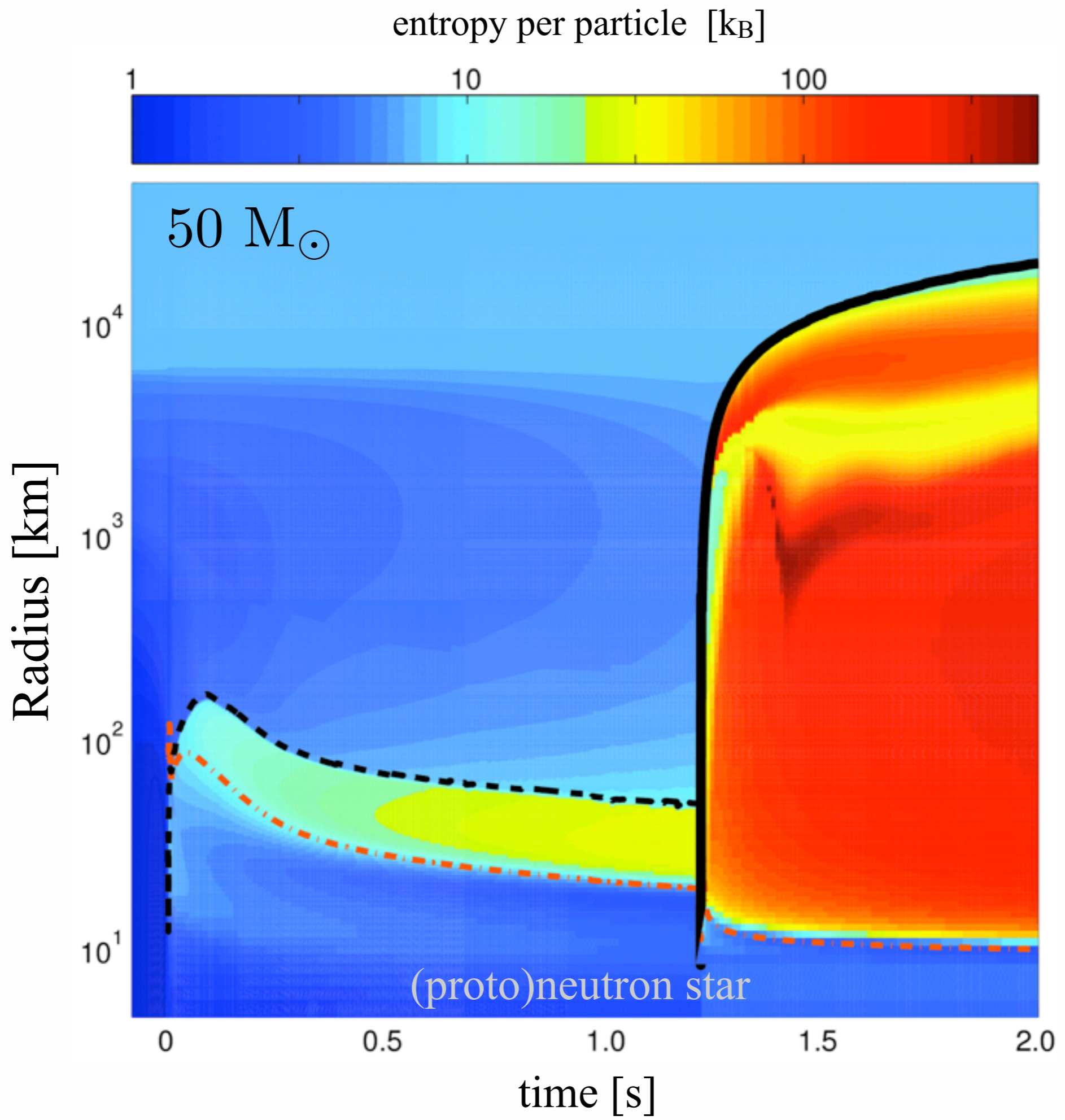




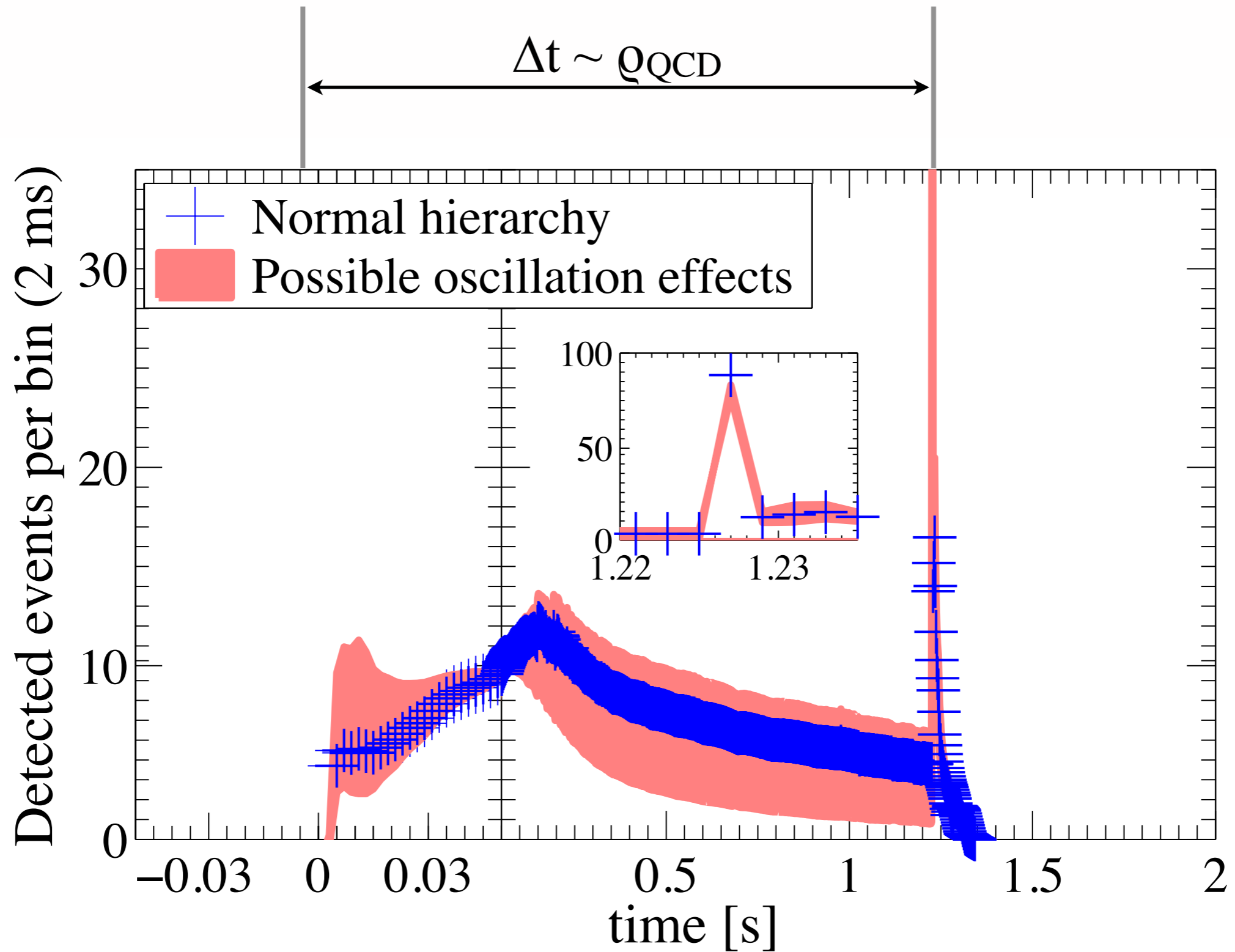






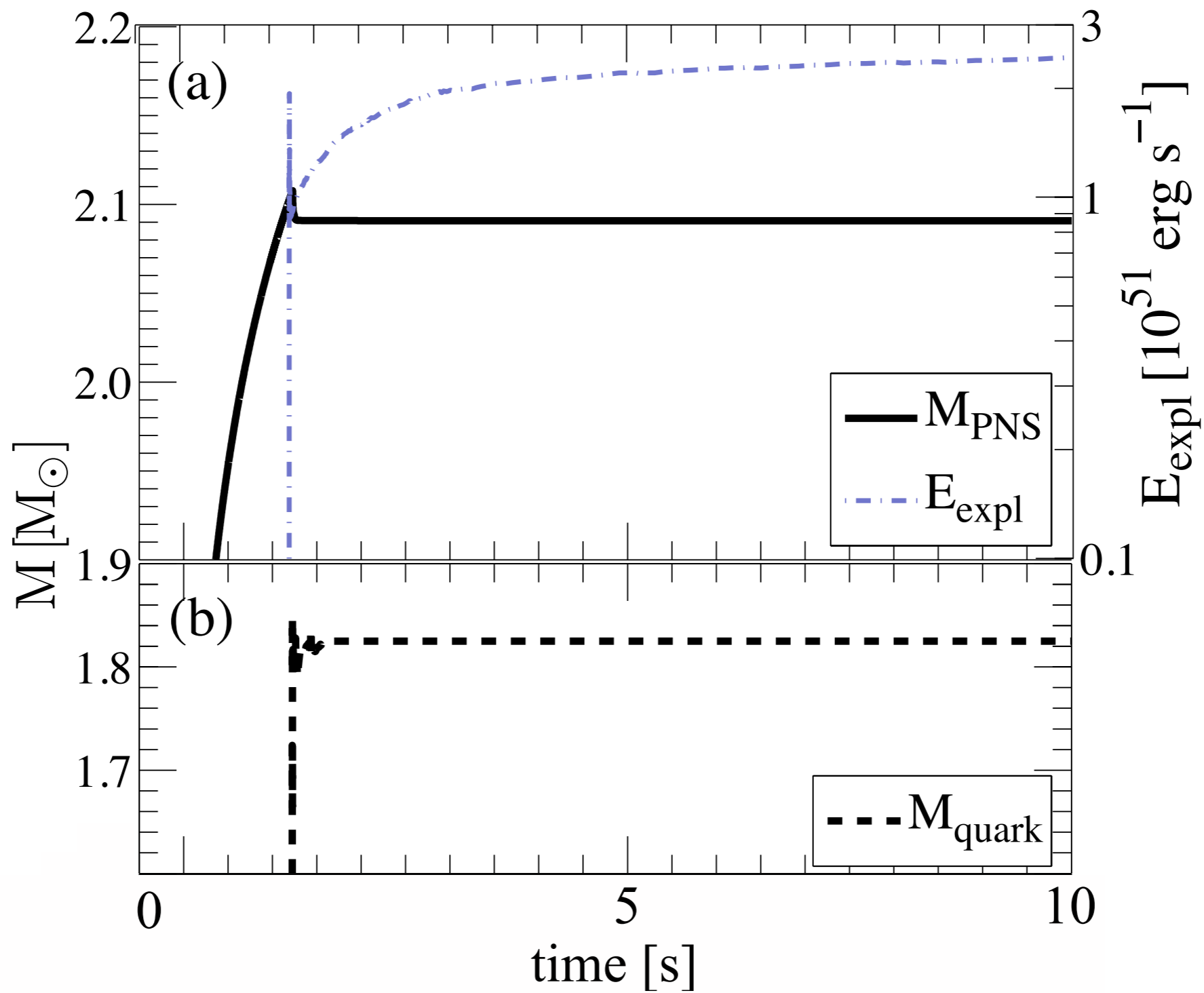


# $\nu$ – signal @ Super-Kamiokande ( $d \sim 10$ kpc)



$$E_{\text{expl}} = 3 \times 10^{51} \text{ erg s}^{-1}$$

$$M_{\text{NS}} \simeq 2 M_{\odot}$$

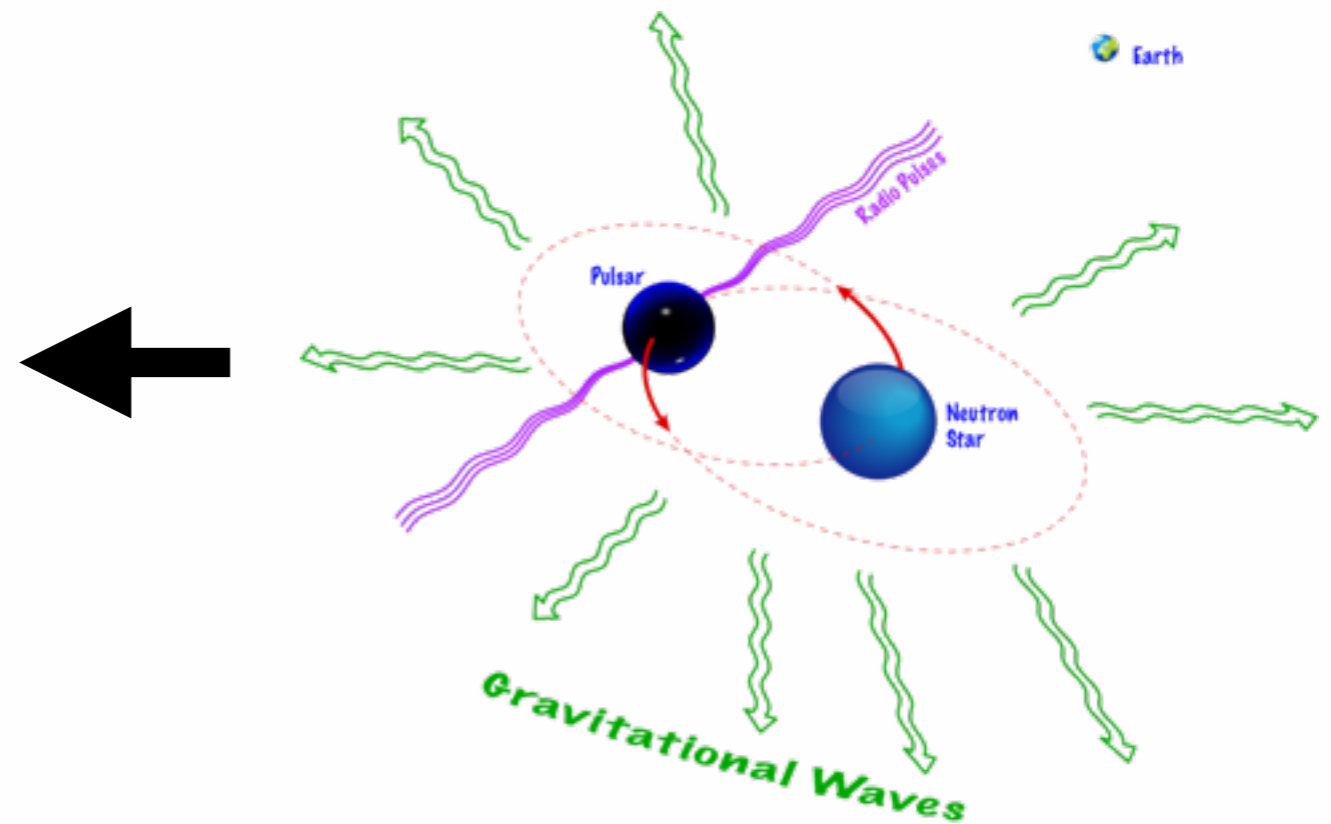
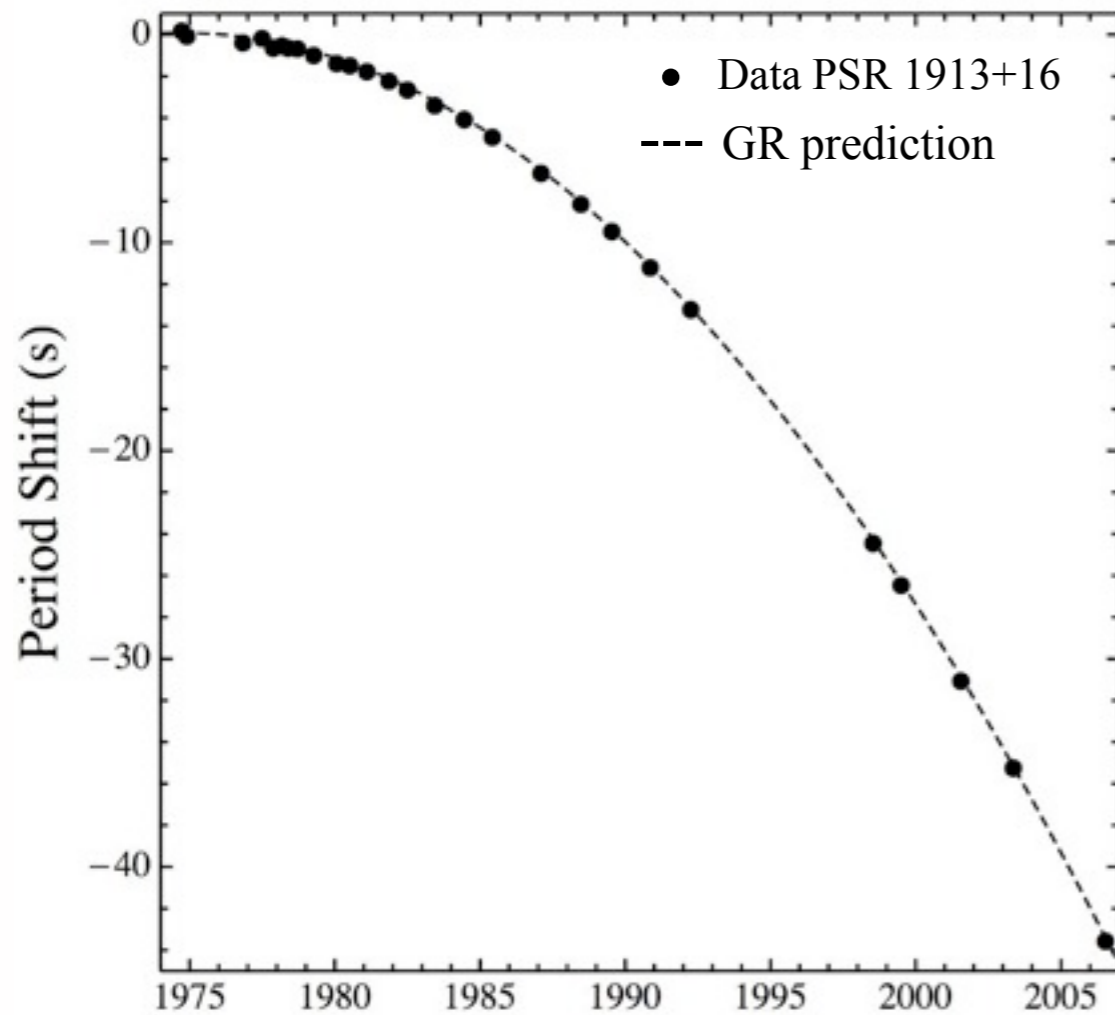


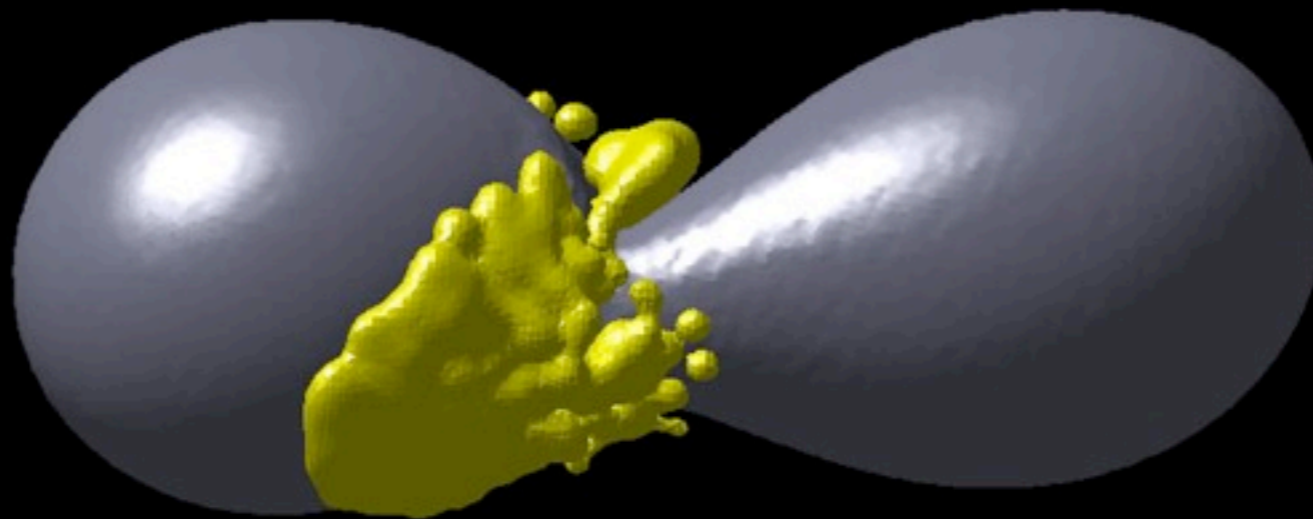


## The Nobel Prize in Physics 1993

Russell A. Hulse, Joseph H. Taylor Jr.

*"for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation"*

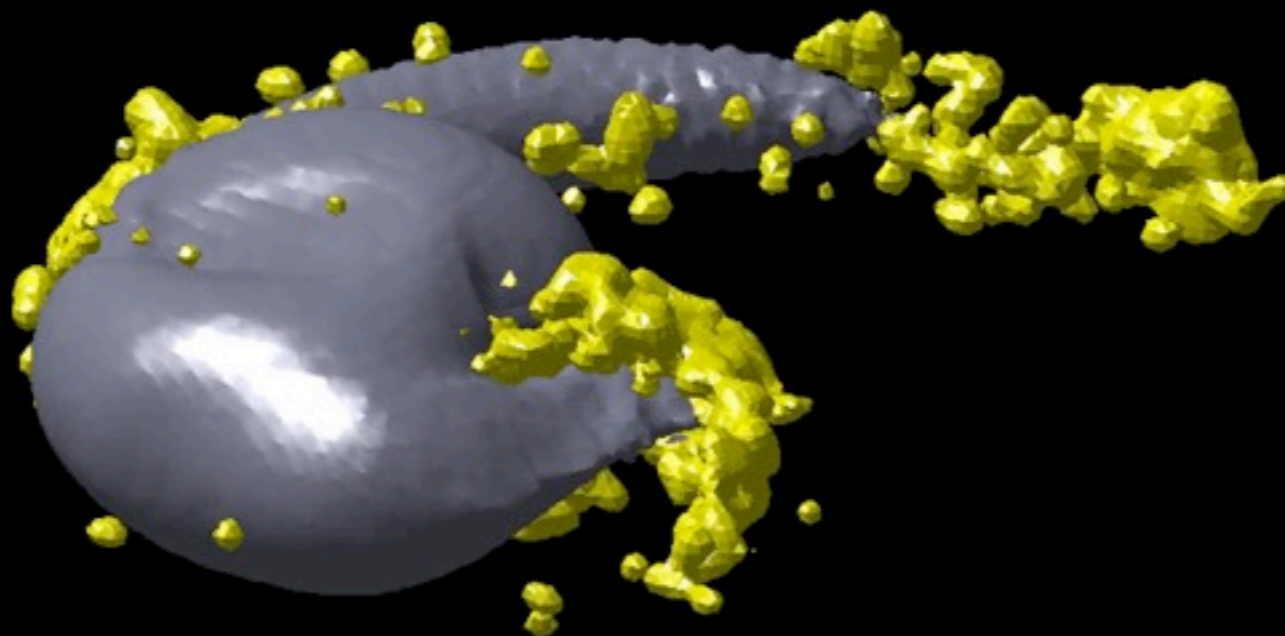




Goriely et al.,(2011) ApJ 738, L32  
Bauswein & Janka (2010) PRD 82, 084043  
Baiotti et al.,(2008) PRD 78, 084033  
Freiburghaus et al.,(1999) ApJ 525, L121  
Lattimer et al.,(1974) ApJ 192, L145

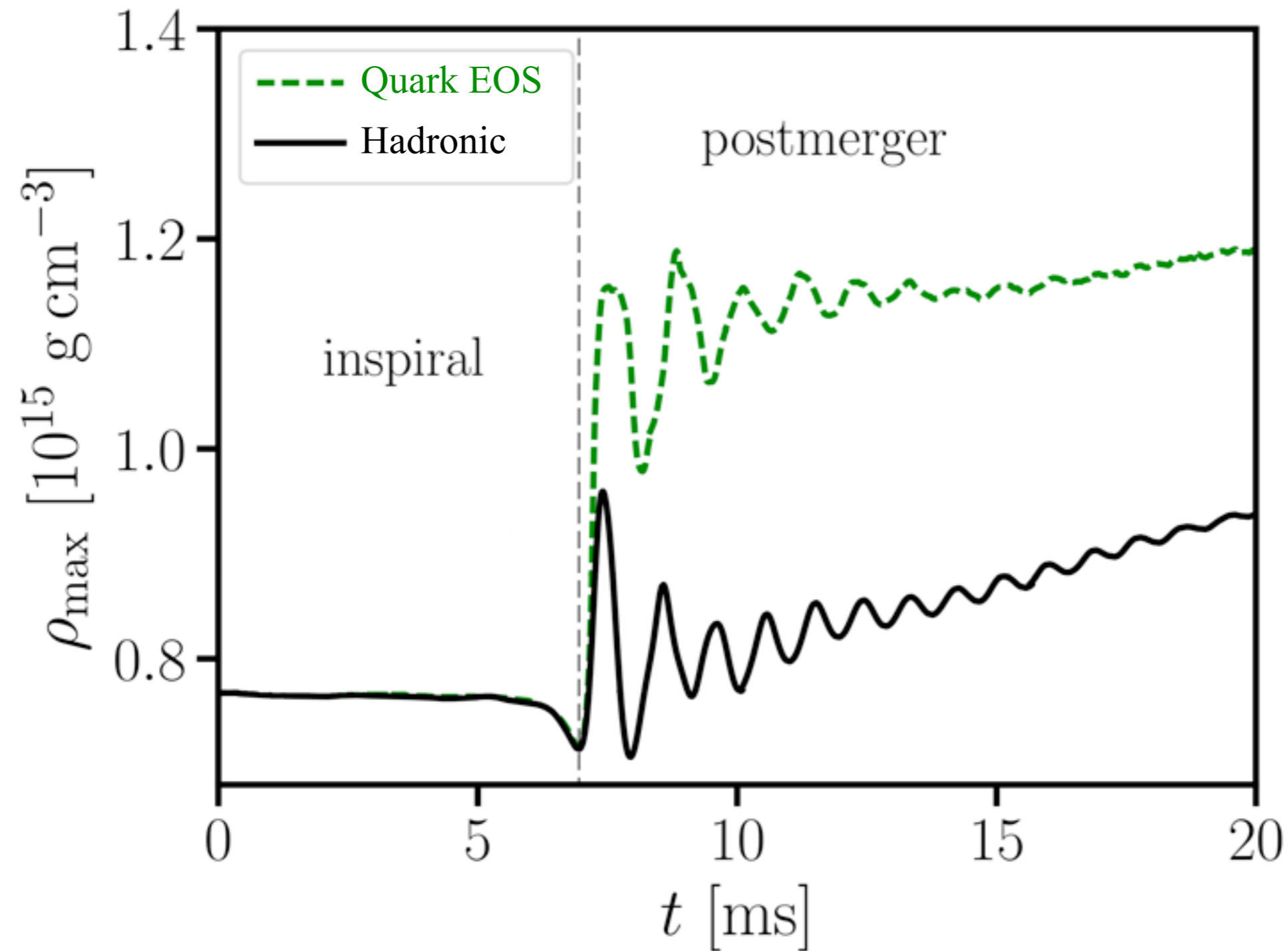
Rezzolla et al,(2016) PRD 93, 124051  
Goriely et al.,(2015) MNRAS 452, 894  
Bauswein et al.,(2015) PRC 92, 055805  
Eichler et al.,(2015) ApJ 808, 13  
Perego et al.,(2014) MNRAS 443, 3134  
Korobkin et al.,(2012) MNRAS 426, 1940

1<sup>st</sup> binary neutron star merger  
detection: **GW170817**



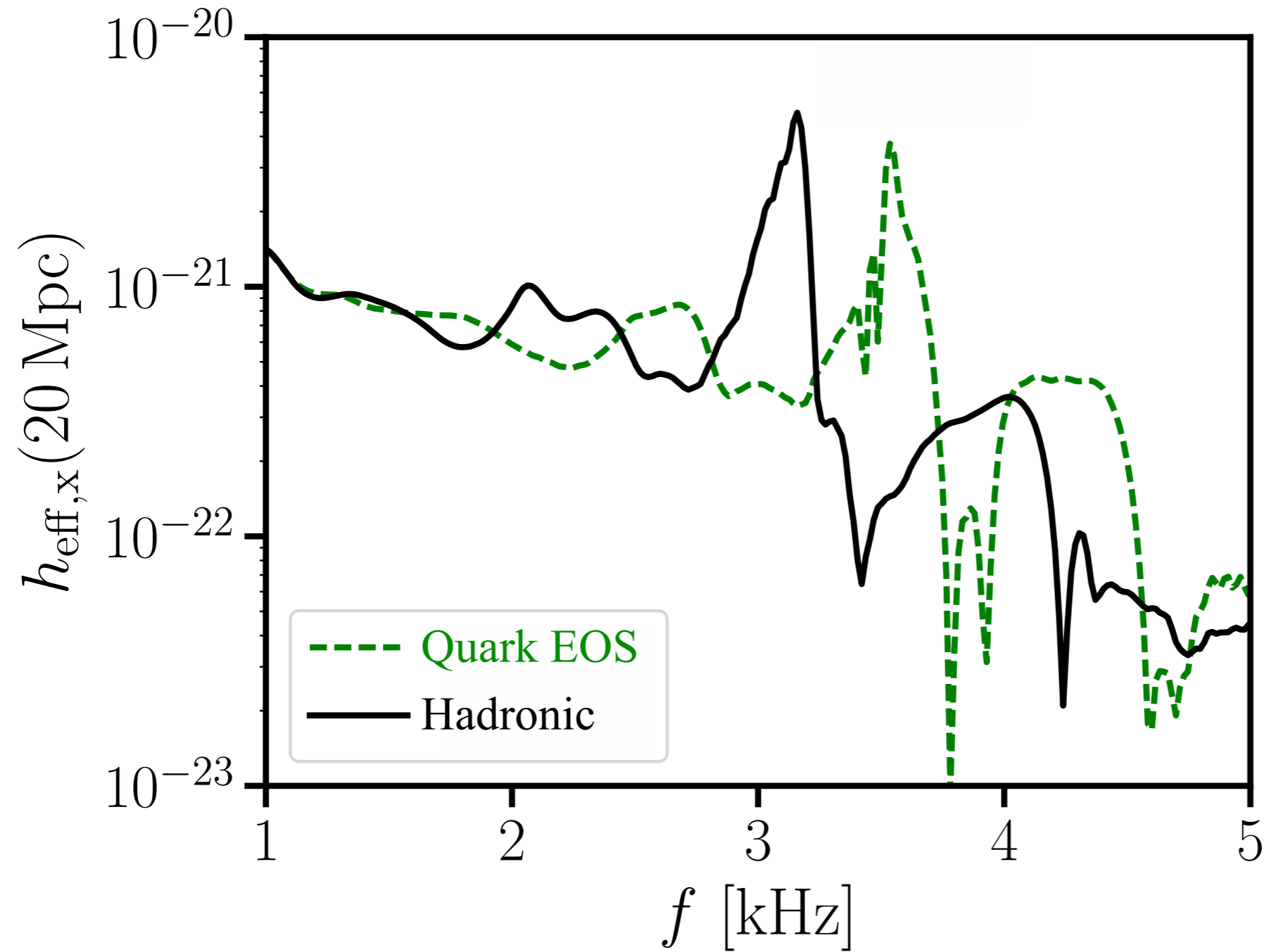
# Binary neutron star merger : $1.35 - 1.35 M_{\odot}$ (GW170817)

1<sup>st</sup>-order phase transition



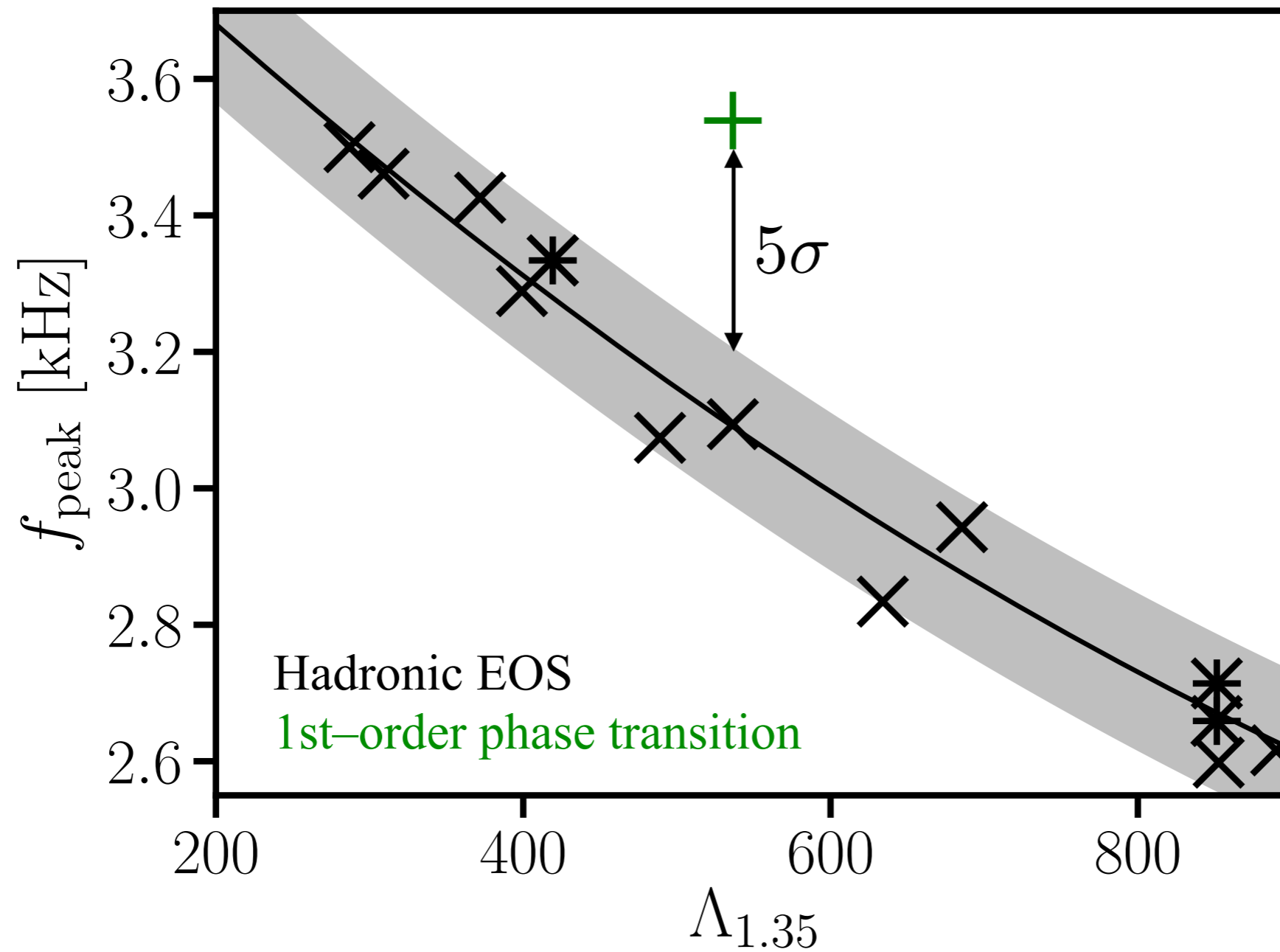
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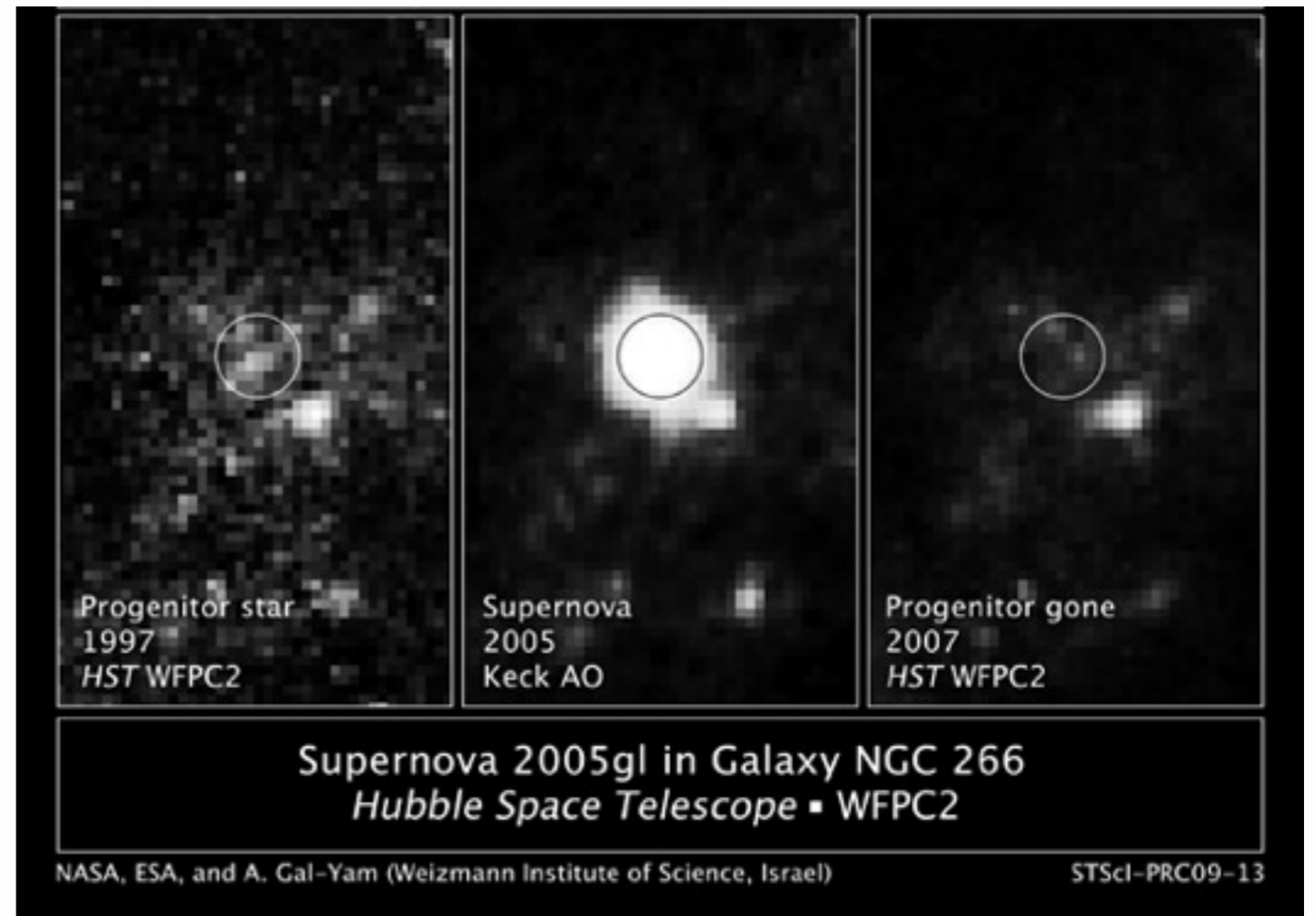


$$f_{\text{peak}} \neq (6.486 \times 10^{-7} \Lambda^2 - 2.231 \times 10^{-3} \Lambda + 4.1) \text{ Hz}$$



# Novel road to explosions of *very* massive stars $\gtrsim 40 - 50 M_{\odot}$

“The progenitor was so bright that it probably belonged to a class of stars called Luminous Blue Variables (LBVs)”

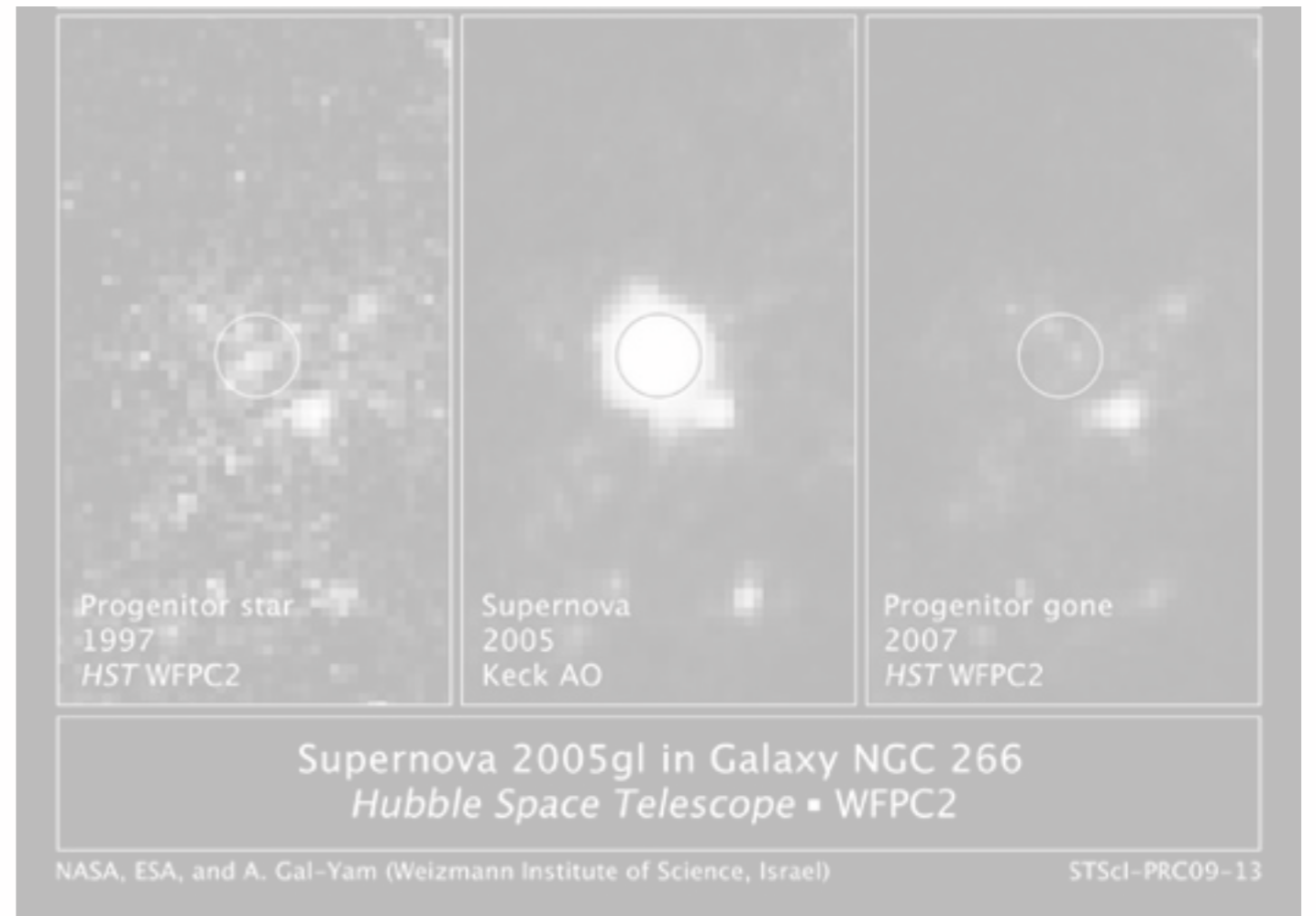


**Remnants: massive neutron stars  $\sim 2 M_{\odot}$**

**Additional neutrino burst**

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Additional neutrino burst

**GW-signal from neutron-star mergers**

# Wroclaw Supernova Project

Thanks for your attention

**In collaboration with:**

A. Bauswein	T. Klähn
N.-U. F. Bastian	K. Kotake
P. Balatkin	E. Sorokina
S. Blinnikov	S. Typel
D. Blaschke	M. R. Wu
M. Cierniak	