# Neutrino and GW signals from QCD driven massive star explosions (and their rotational effects)

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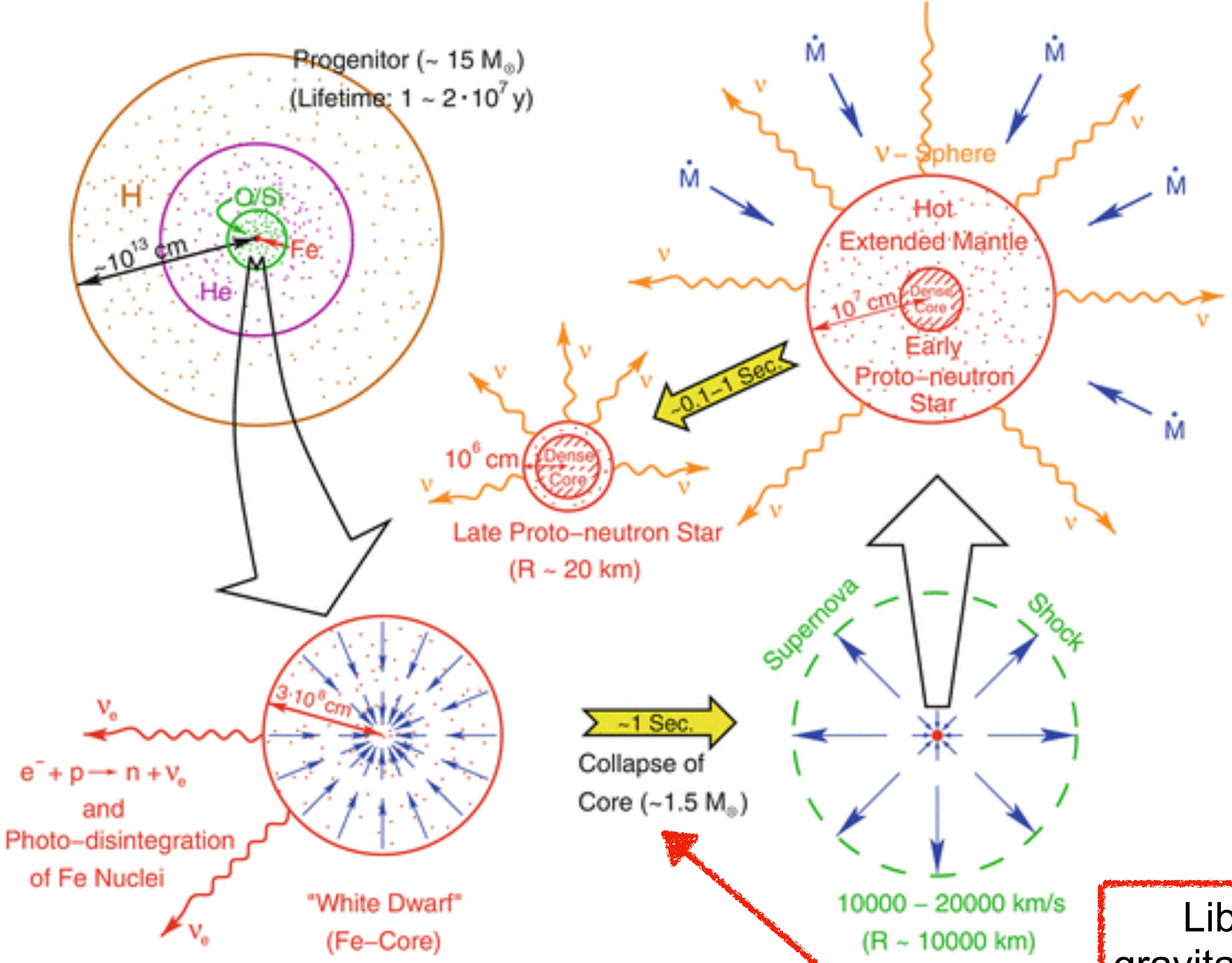
SN Workshop, 05/08/2022, Wroclaw

# The fate of massive stars (>~10$M_{sun}$)



Liberation of gravitational binding energy of ~$10^{53}$ erg

Burrows AS (1990b) Neutrinos from supernovae.
In: Petschek AG (ed) Supernovae. Springer, New York, pp 143–181

Why are SNe important?

## **They are the source/origin of:**

### **Neutrinos**

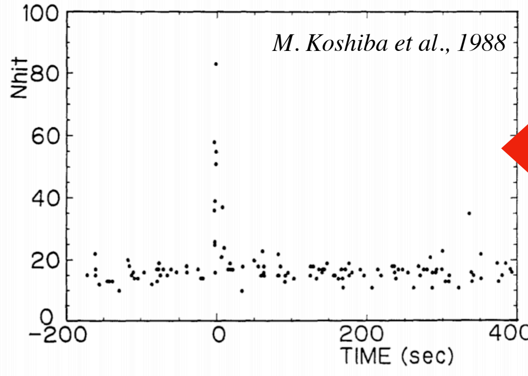
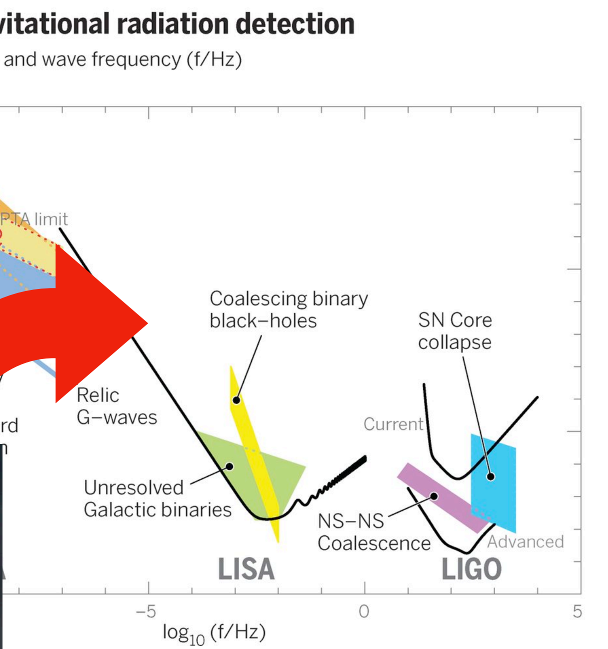
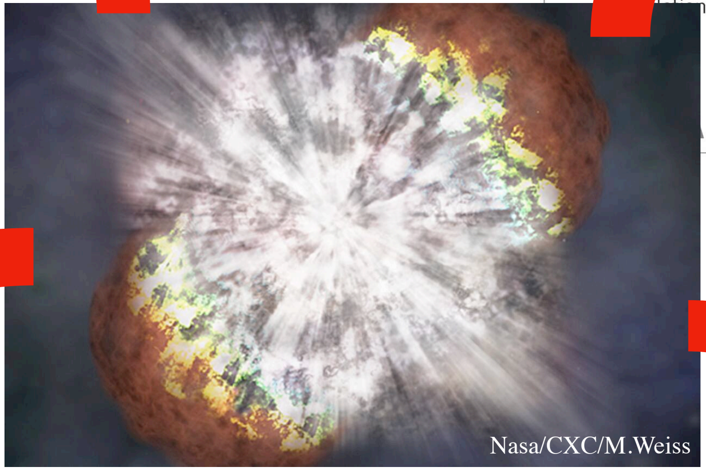


Fig. 2a : The supernova signal of the KAMIOKANDE-II experiment. It is a part of the laser printer output of the low energy raw data.Nhit is the number of hit photomultipliers.

### **GWs**

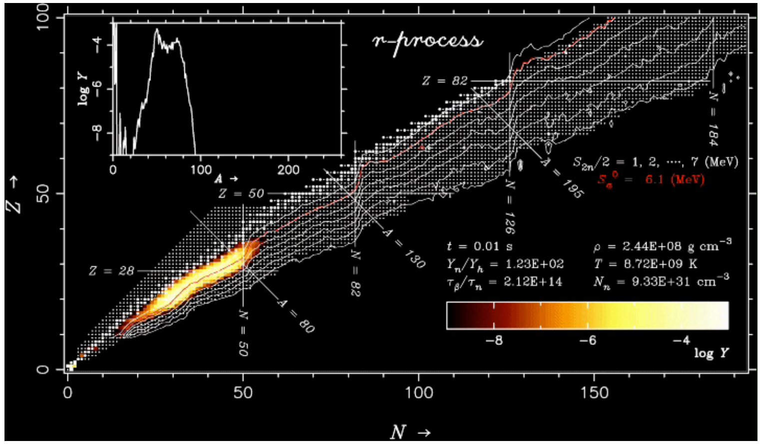


R. N. Manchester, The Twelfth Marcel Grossmann Meeting on General Relativity (2012)



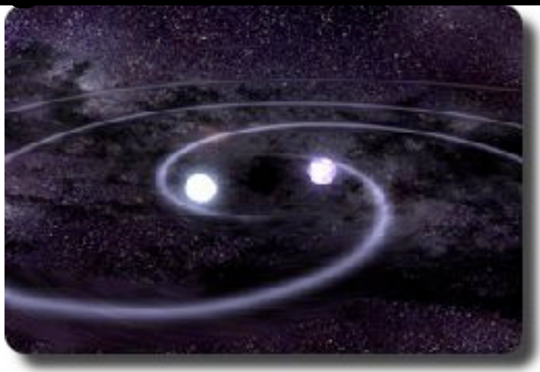
Nasa/CXC/M.Weiss

### **Heavy elements**



Wanajo+,'04

### **NSs, BHs, magnetars, exotic stars,...**



NASA / Dana Berry, Sky Works Digital

Our understanding of underlying SN explosion physics and of the formation channel to various compact stars has been remaining patchy in these several decades.

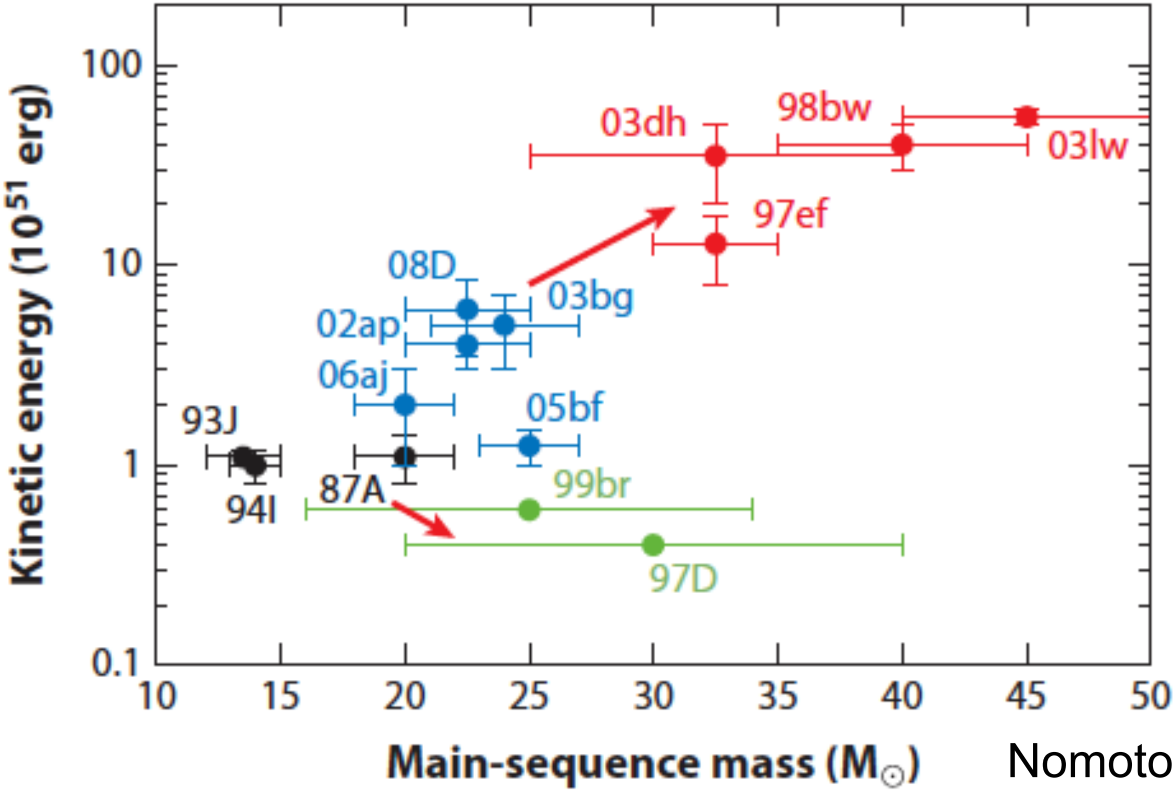
In SN physics, all the four fundamental forces play substantial roles.

- GR governs the overall dynamics.
- The nuclear force (i.e. strong force) determines structure of compact stars.
- SN explosion is driven by the neutrino heating (weak force).
- Or sometimes by magnetic fields (electromagnetic force).

**SN theory is one of the most challenging subjects in astrophysics!**

And numerical simulation is the most powerful tool to model such complex systems.

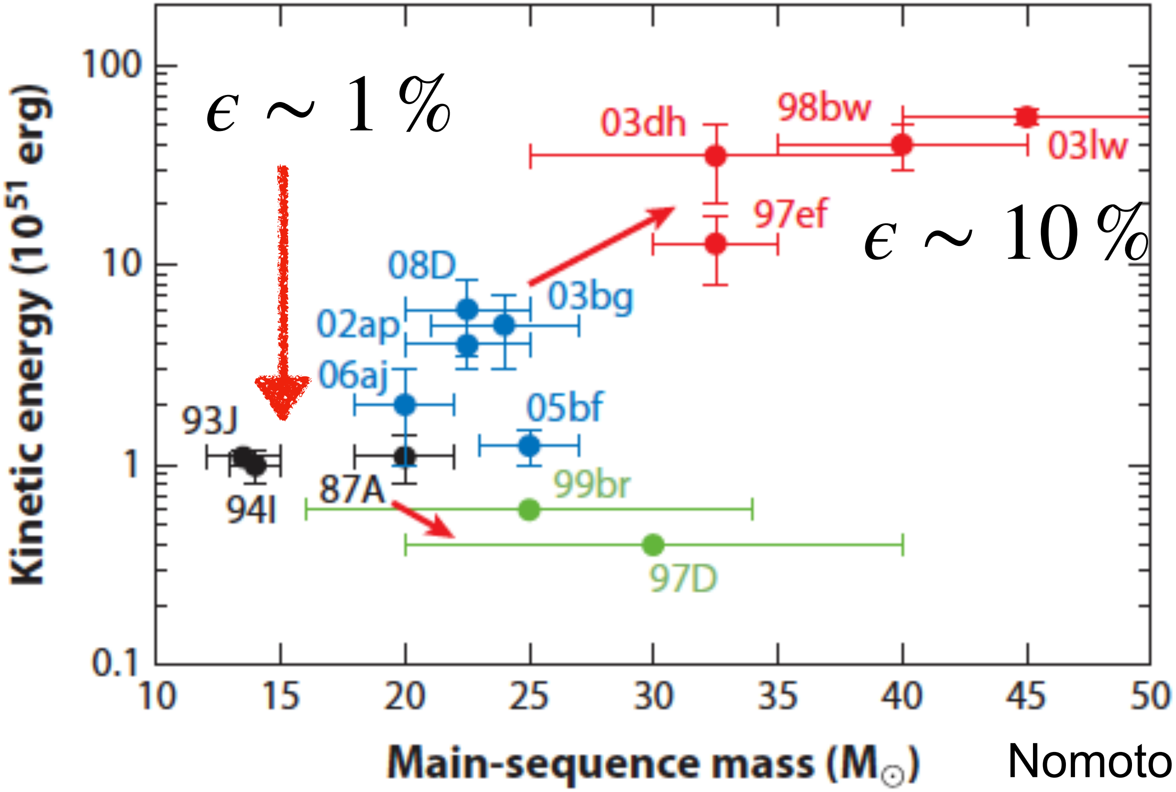
# The fundamental question: What mechanisms drive SNe?



Nomoto+, ’13

Even in this narrow mass range (10~45 $M_{sun}$, thus $U_{grv}$ could vary only several times), the explosion energies show a large difference $E_{exp}$~$10^{51-52}$ ergs.

# The fundamental question: What mechanisms drive SNe?



Nomoto+, ’13

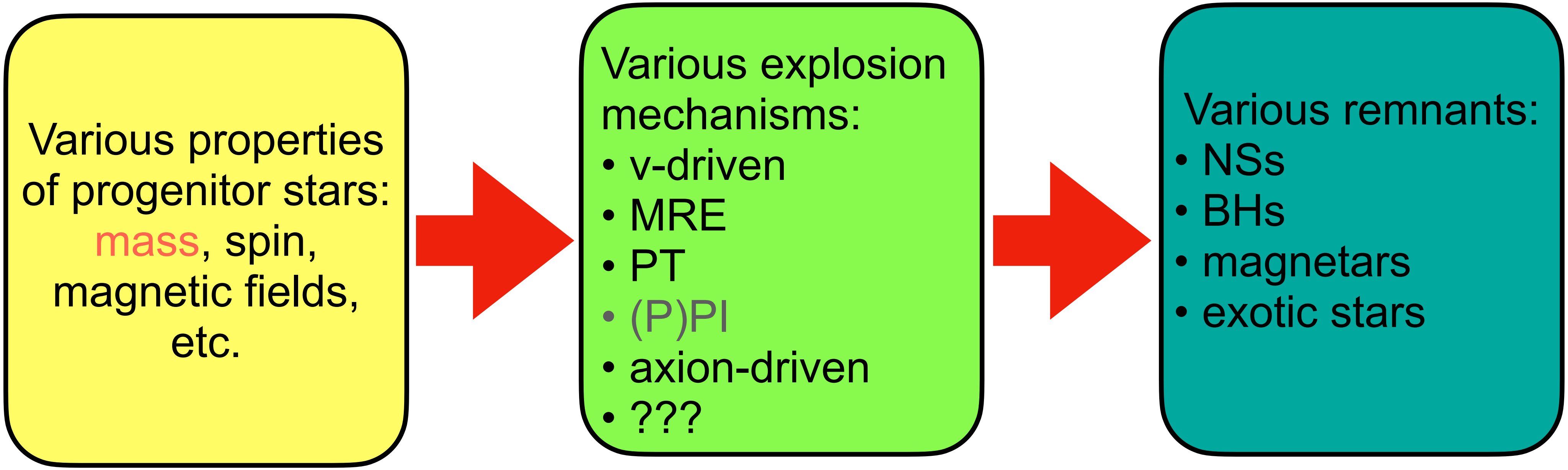
$$\epsilon = \frac{E_{\rm exp}}{U_{\rm grv}}$$

Even in this narrow mass range (10~45 $M_{\rm sun}$, thus $U_{\rm grv}$ could vary only several times), the explosion energies show a large difference $E_{\rm exp}$~$10^{51\text{-}52}$ ergs.

It is very unlikely that only one explosion mechanism explains all observed SNe.

# Possible SN explosion mechanisms

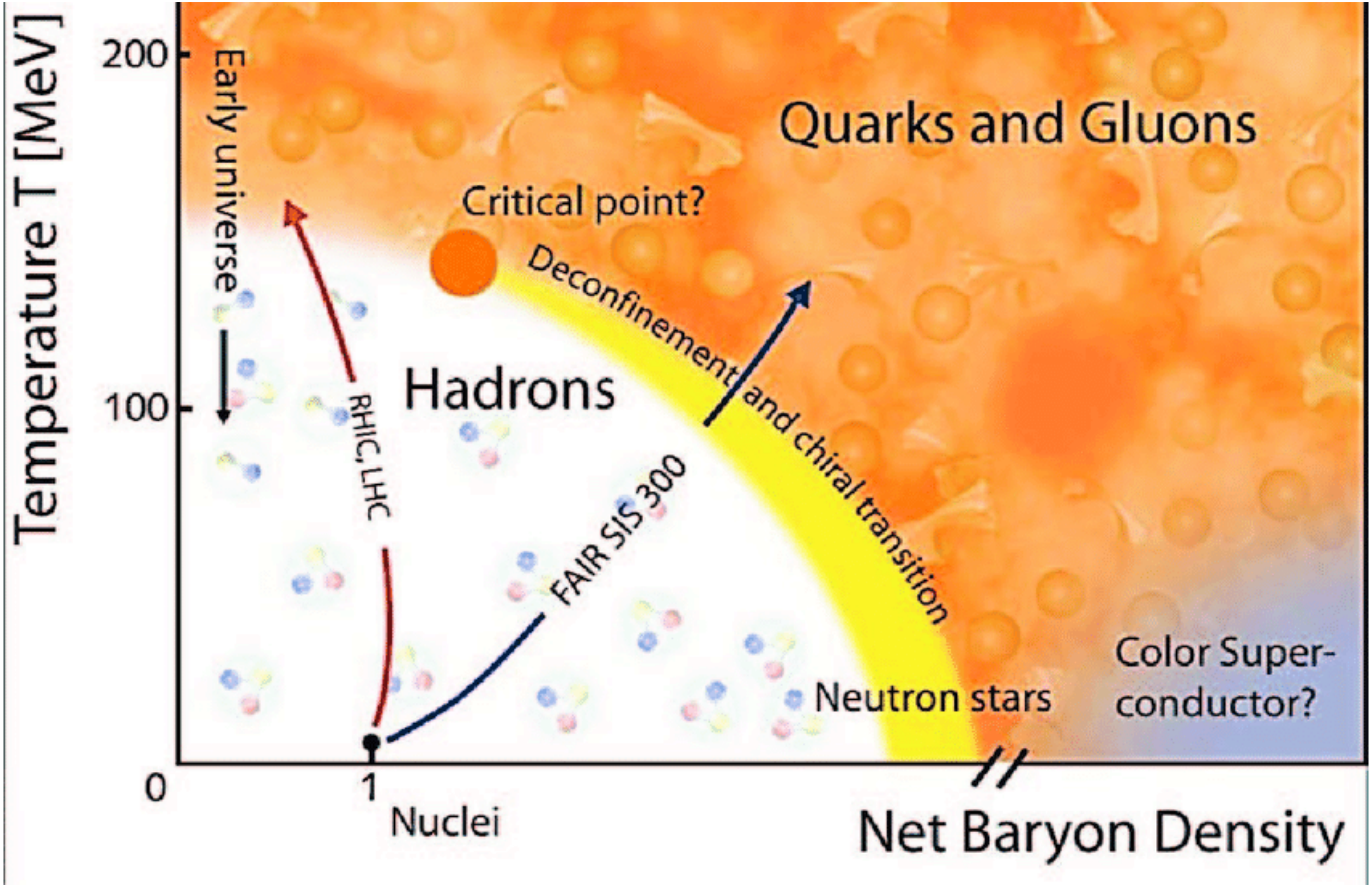
1. Neutrino driven explosion (ν-driven)
2. Magneto rotational explosion (MRE)
3. (Pulsational) pair instability ((P)PI)
4. Other mechanisms
   (e.g. phase transition from hadronic to quark matters (PT))



Various properties of progenitor stars: mass, spin, magnetic fields, etc.

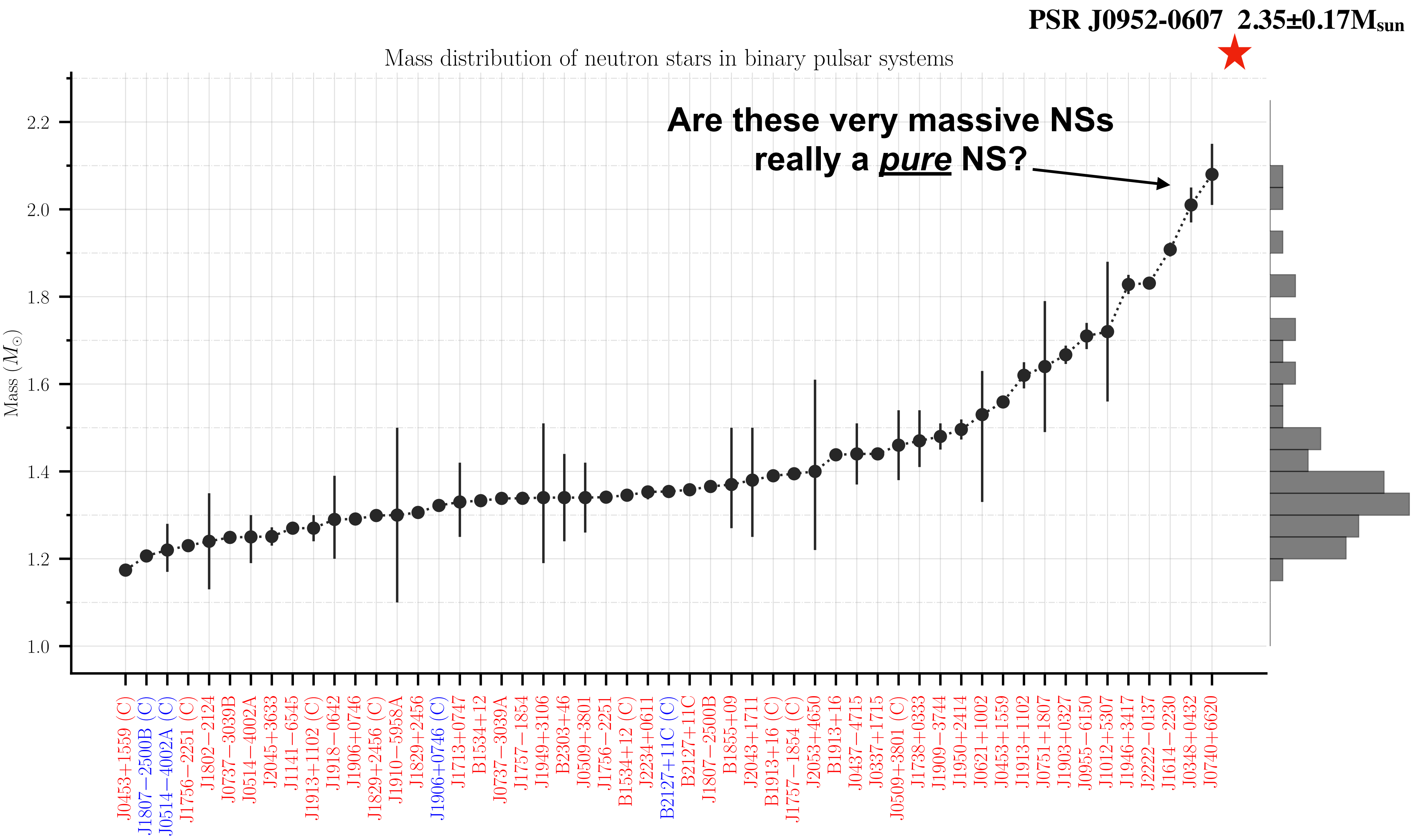
Various explosion mechanisms:
- ν-driven
- MRE
- PT
- (P)PI
- axion-driven
- ???

Various remnants:
- NSs
- BHs
- magnetars
- exotic stars


Temperature T [MeV]
200
100
0
1
Nuclei
Net Baryon Density
Early universe
RHIC, LHC
FAIR SIS 300
Hadrons
Critical point?
Quarks and Gluons
Deconfinement and chiral transition
Neutron stars
Color Super-
conductor?

Bicudo+, 2011

# Theoretical support of the existence of QSs

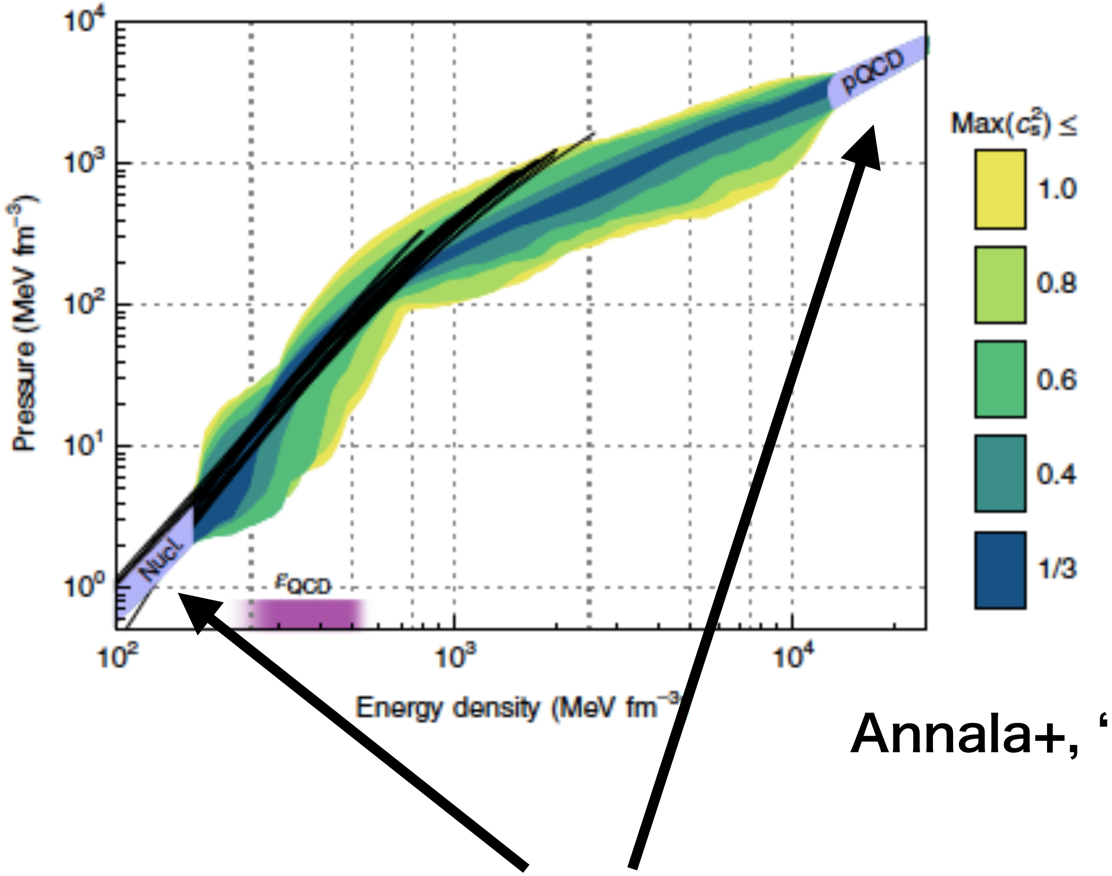


**PSR J0952-0607  2.35±0.17$M_{sun}$**

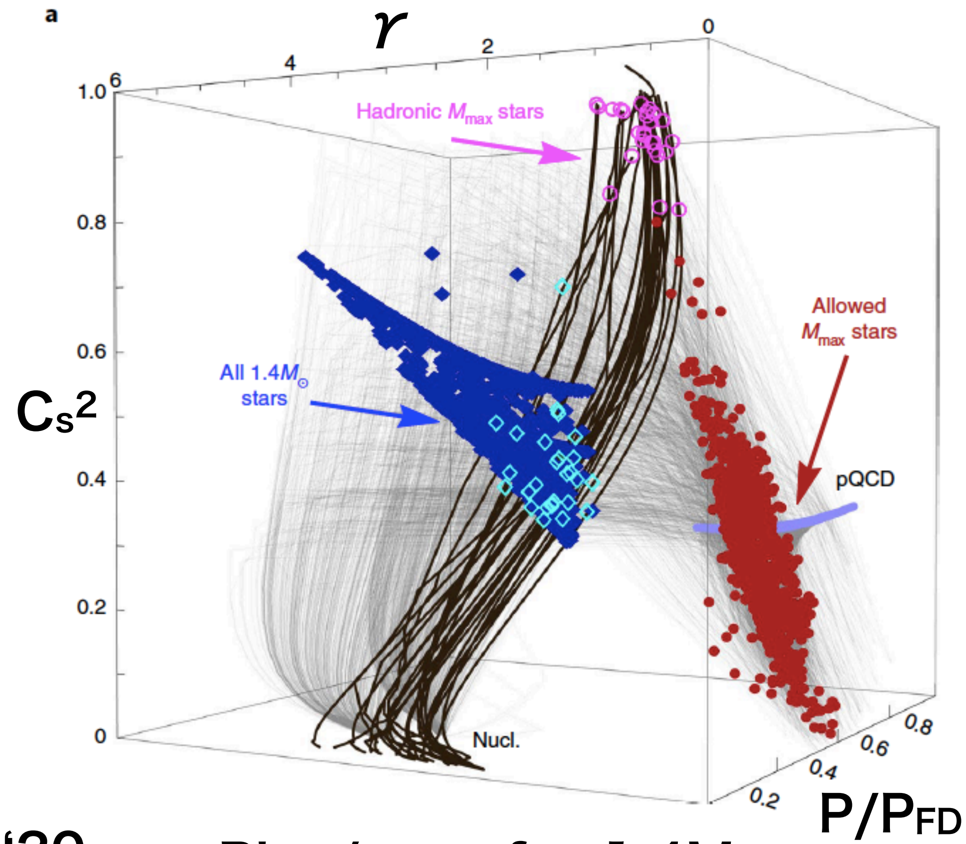
**Are these very massive NSs really a *pure* NS?**

https://www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html

# Theoretical support of the existence of QSs



Annala+, '20



Blue/cyan for 1.4$M_{sun}$

Red/magenta for $M_{maximum}$

These two limits
(nuclear and pQCD regions)
are relatively well understood.

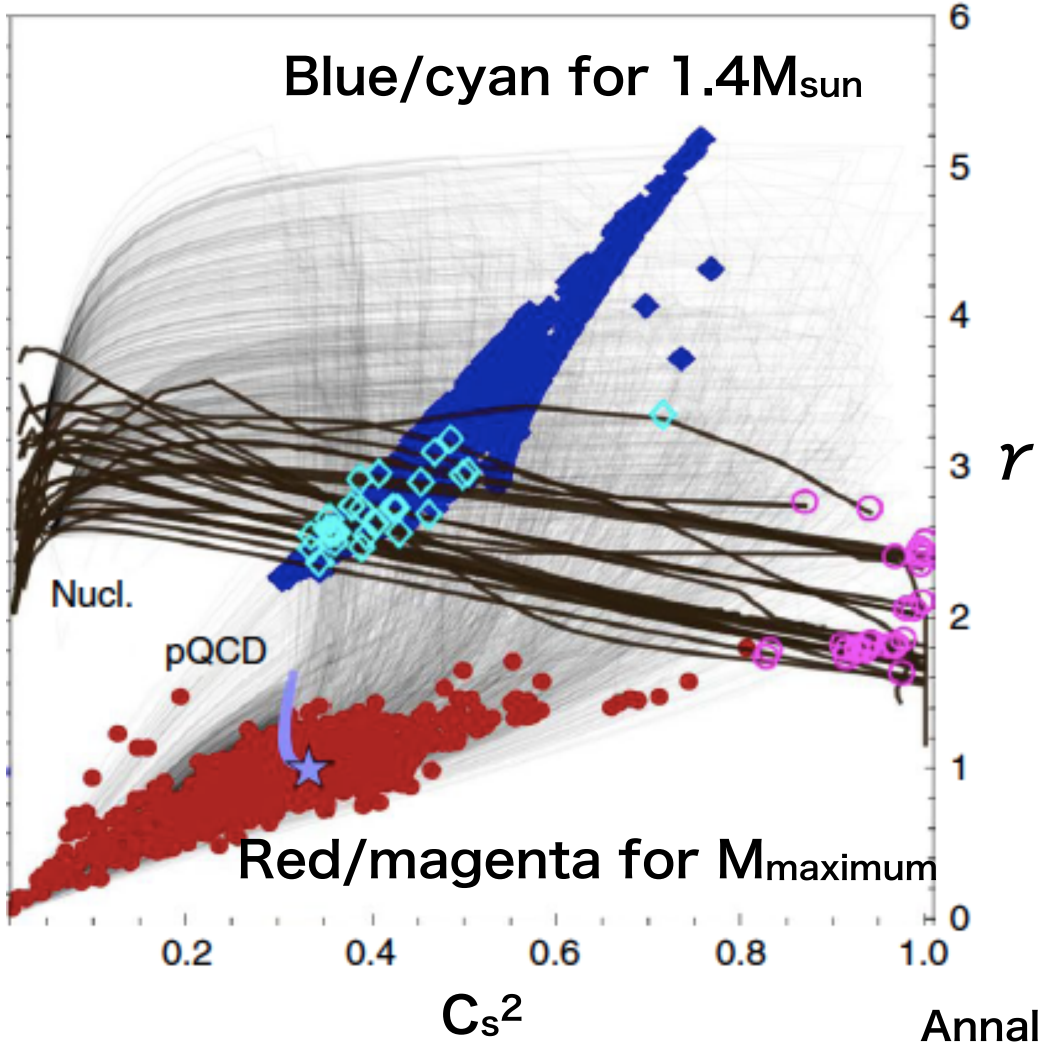
Constraints:

✓From causality, Cs<=1

✓Asymptotically, $C_s^2$<1/3 in QCD region

✓ and $C_s^2$<<1 in the lower limit

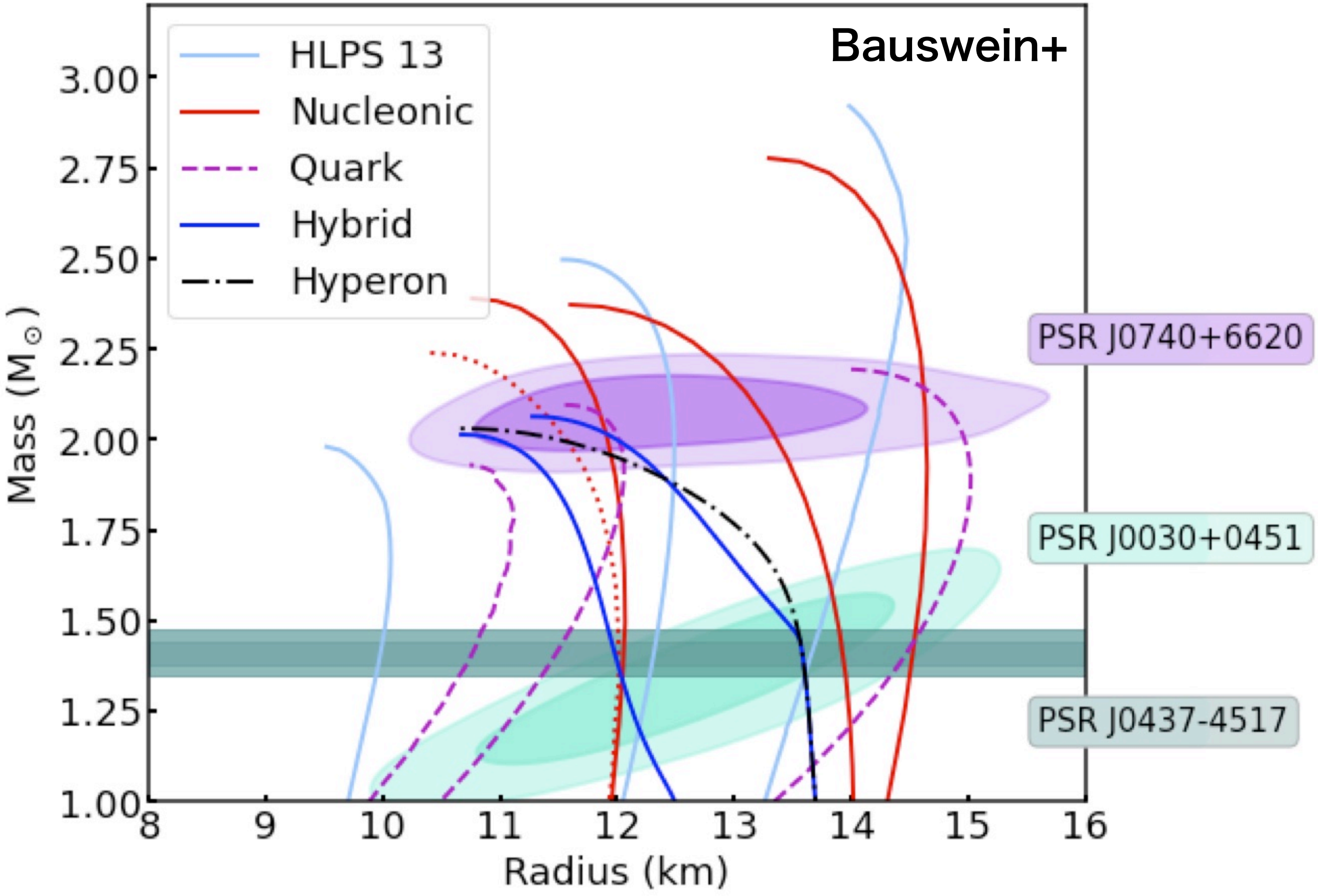
# Theoretical support of the existence of QSs



Annala+, ‘20

Very massive NSs (≳2Msun) are likely
to be composed of not only normal hadronic matters,
but some exotic nuclei.

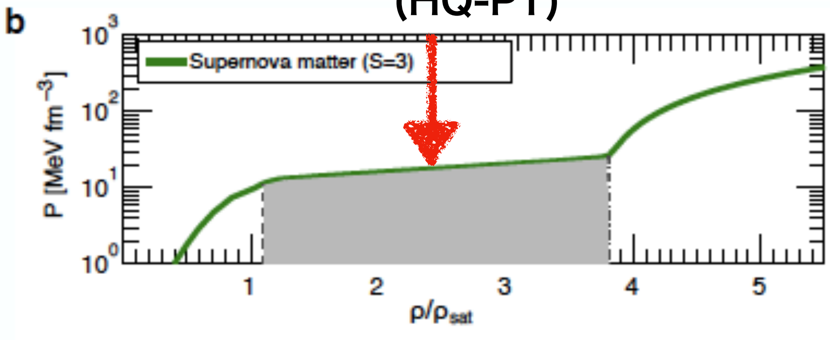
# Theoretical support of the existence of QSs

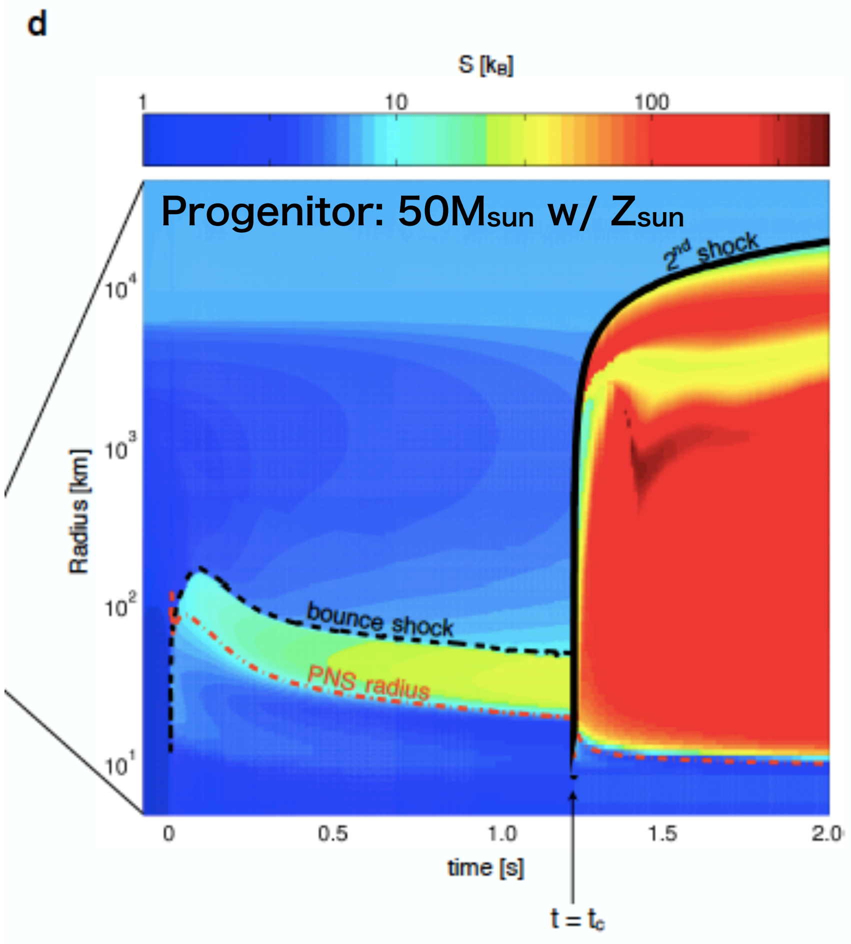


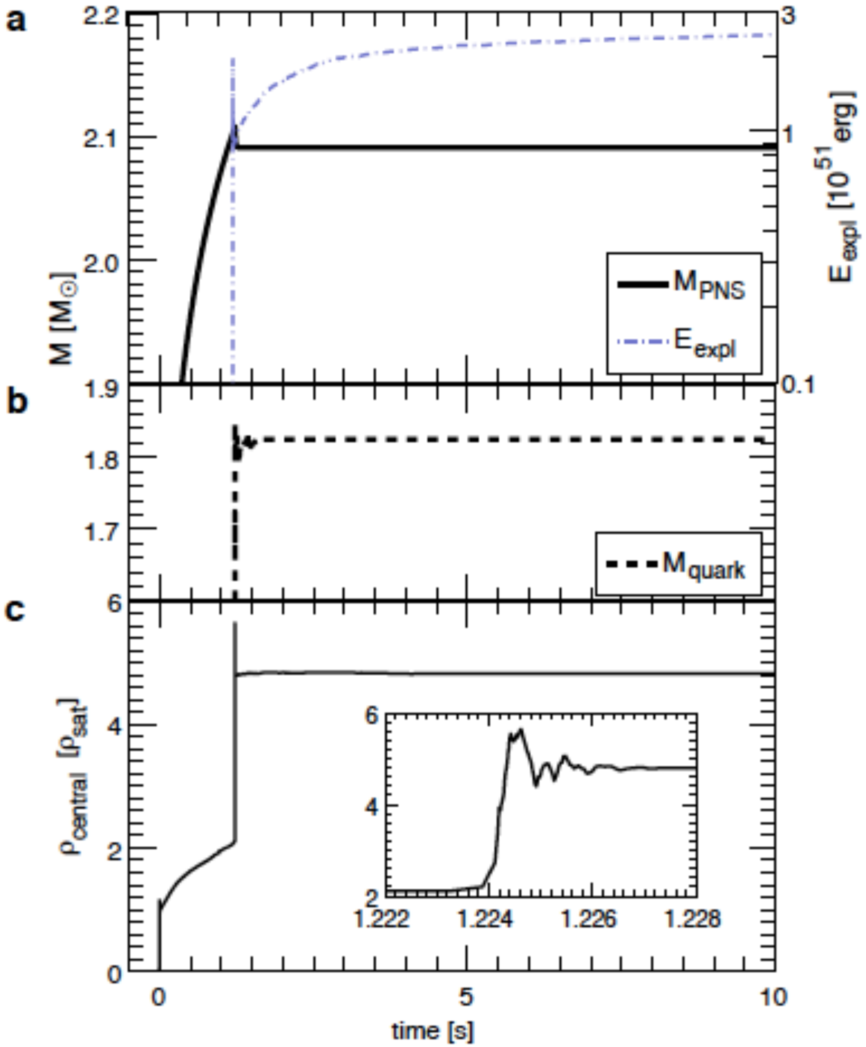
MR of QS (and hybrid, hyperon star) is within the error band of observations.

# Collapse of PNSs and formation of QSs.

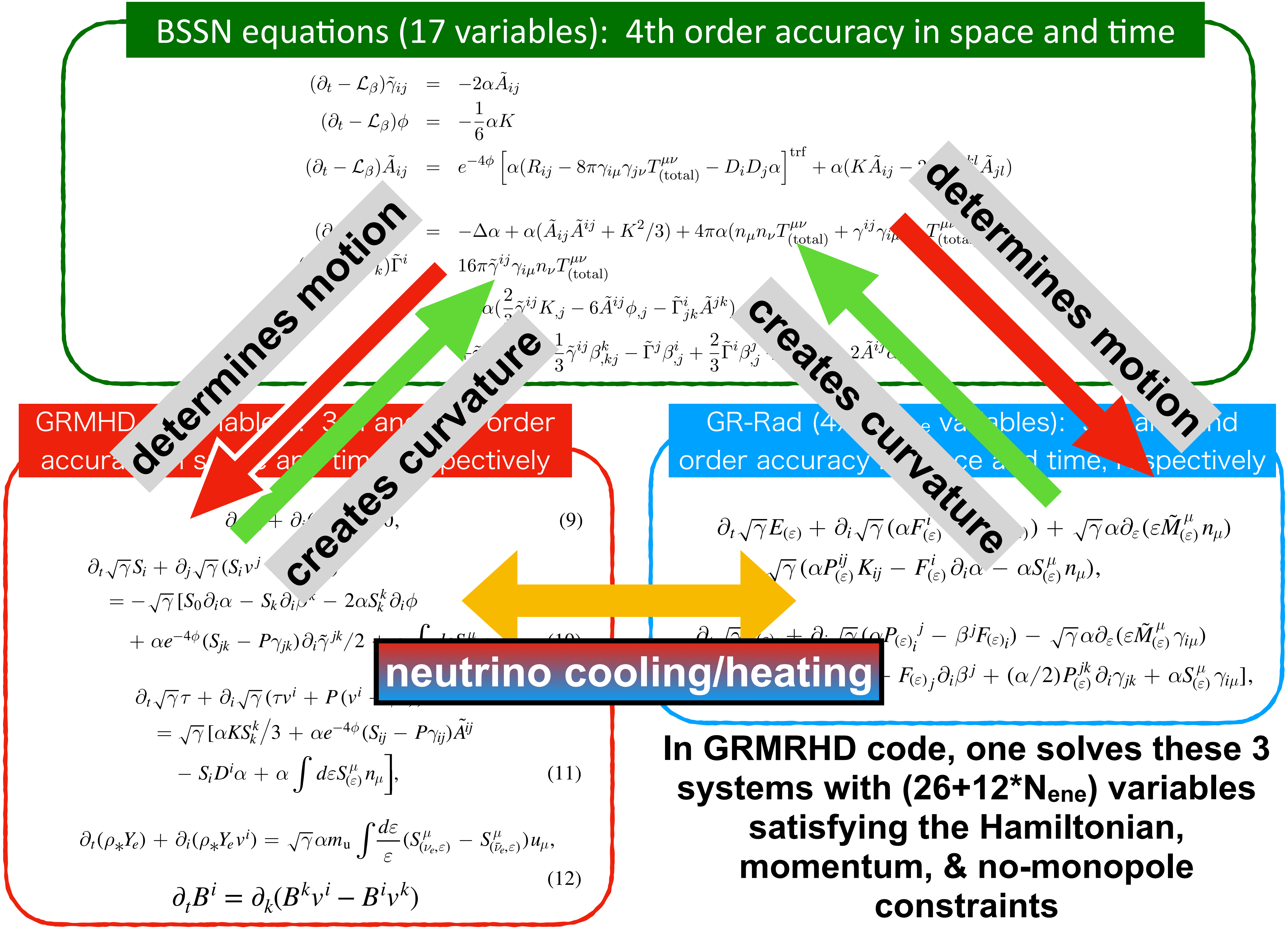
Hadron-Quark phase transition (HQ-PT)




Progenitor: $50M_{sun}$ w/ $Z_{sun}$



Fischer+,'17



BSSN equations (17 variables): 4th order accuracy in space and time

$$(\partial_t - \mathcal{L}_\beta)\tilde{\gamma}_{ij} = -2\alpha\tilde{A}_{ij}$$

$$(\partial_t - \mathcal{L}_\beta)\phi = -\frac{1}{6}\alpha K$$

$$(\partial_t - \mathcal{L}_\beta)\tilde{A}_{ij} = e^{-4\phi}\left[\alpha(R_{ij} - 8\pi\gamma_{i\mu}\gamma_{j\nu}T^{\mu\nu}_{(\mathrm{total})}) - D_iD_j\alpha\right]^{\mathrm{trf}} + \alpha(K\tilde{A}_{ij} - 2 \; {}^{kl}\tilde{A}_{jl})$$

$$(\partial \quad = -\Delta\alpha + \alpha(\tilde{A}_{ij}\tilde{A}^{ij} + K^2/3) + 4\pi\alpha(n_\mu n_\nu T^{\mu\nu}_{(\mathrm{total})} + \gamma^{ij}\gamma_{i\mu} \quad T^{\mu\nu}_{(\mathrm{tota}}$$

$$_k)\tilde{\Gamma}^i \quad 16\pi\tilde{\gamma}^{ij}\gamma_{i\mu}n_\nu T^{\mu\nu}_{(\mathrm{total})}$$

$$\alpha(\frac{2}{3}\tilde{\gamma}^{ij}K_{,j} - 6\tilde{A}^{ij}\phi_{,j} - \tilde{\Gamma}^i_{jk}\tilde{A}^{jk})$$

$$\frac{1}{3}\tilde{\gamma}^{ij}\beta^k_{,kj} - \tilde{\Gamma}^j\beta^i_{,j} + \frac{2}{3}\tilde{\Gamma}^i\beta^j_{,j} \quad 2\tilde{A}^{ij}\alpha$$

determines motion

creates curvature

GRMHD lable 3 an order
accura s an tim pectively

$$\partial \quad + \partial_i( \quad 0, \qquad (9)$$

$$\partial_t\sqrt{\gamma}S_i + \partial_j\sqrt{\gamma}(S_iv^j$$

$$= -\sqrt{\gamma}[S_0\partial_i\alpha - S_k\partial_i\beta^k - 2\alpha S^k_k\partial_i\phi$$

$$+ \alpha e^{-4\phi}(S_{jk} - P\gamma_{jk})\partial_i\tilde{\gamma}^{jk}/2 + \quad \int d\varepsilon S^\mu \qquad (10)$$

$$\partial_t\sqrt{\gamma}\tau + \partial_i\sqrt{\gamma}(\tau v^i + P(v^i$$

$$= \sqrt{\gamma}[\alpha KS^k_k/3 + \alpha e^{-4\phi}(S_{ij} - P\gamma_{ij})\tilde{A}^{ij}$$

$$- S_iD^i\alpha + \alpha\int d\varepsilon S^\mu_{(\varepsilon)}n_\mu\Big], \qquad (11)$$

$$\partial_t(\rho_*Y_e) + \partial_i(\rho_*Y_ev^i) = \sqrt{\gamma}\alpha m_{\mathrm{u}}\int\frac{d\varepsilon}{\varepsilon}(S^\mu_{(\nu_e,\varepsilon)} - S^\mu_{(\bar{\nu}_e,\varepsilon)})u_\mu, \qquad (12)$$

$$\partial_tB^i = \partial_k(B^kv^i - B^iv^k)$$

creates curvature

determines motion

GR-Rad (4 e va ables): ar nd
order accuracy ce a d time, spectively

$$\partial_t\sqrt{\gamma}E_{(\varepsilon)} + \partial_i\sqrt{\gamma}(\alpha F^i_{(\varepsilon)} \quad )) + \sqrt{\gamma}\alpha\partial_\varepsilon(\varepsilon\tilde{M}^\mu_{(\varepsilon)}n_\mu)$$

$$\sqrt{\gamma}(\alpha P^{ij}_{(\varepsilon)}K_{ij} - F^i_{(\varepsilon)}\partial_i\alpha - \alpha S^\mu_{(\varepsilon)}n_\mu),$$

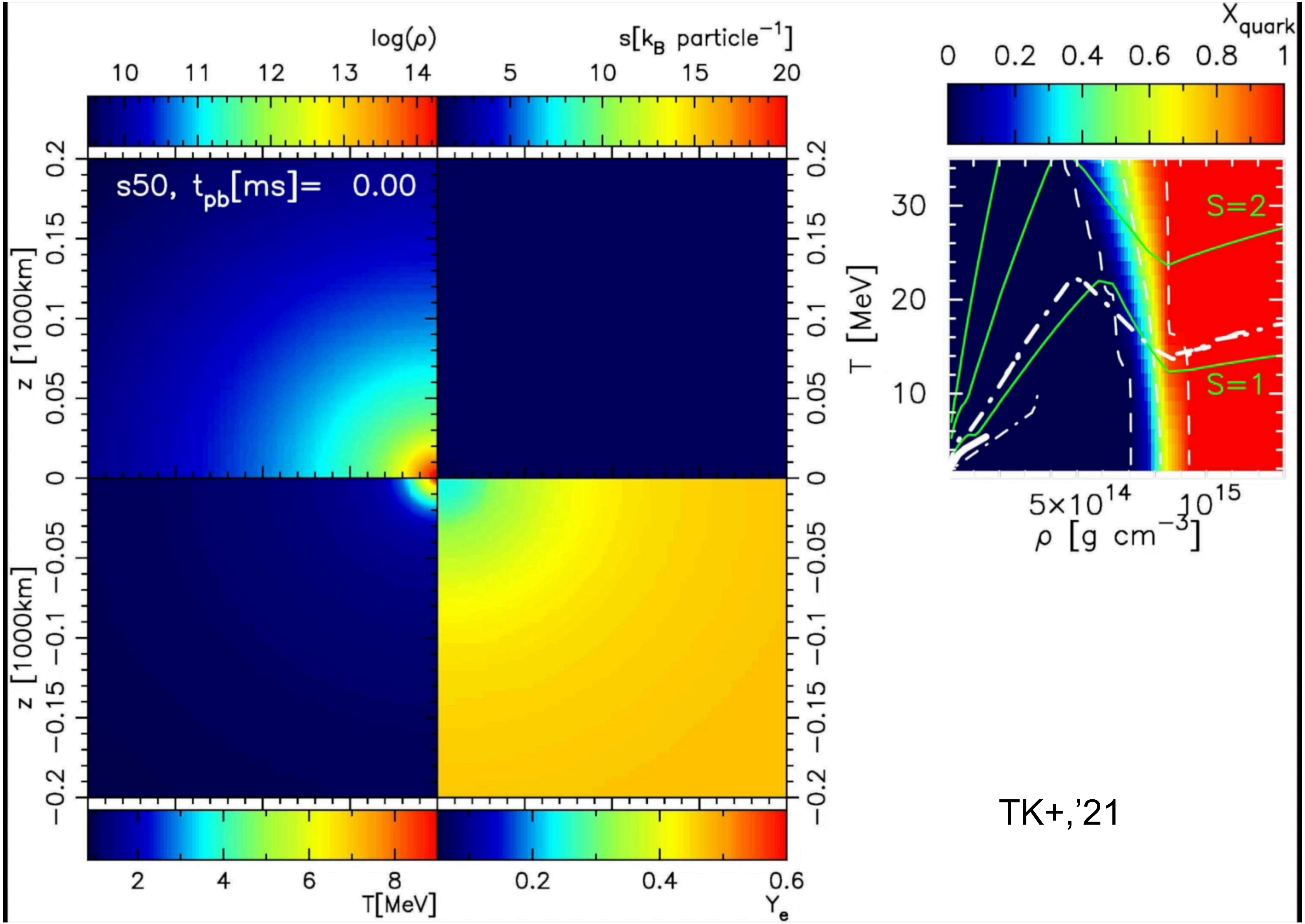
$$\partial_t \quad + \partial_i \quad (\alpha P_{(\varepsilon)}{}_i{}^j - \beta^jF_{(\varepsilon)}{}_i) - \sqrt{\gamma}\alpha\partial_\varepsilon(\varepsilon\tilde{M}^\mu_{(\varepsilon)}\gamma_{i\mu})$$

$$F_{(\varepsilon)}{}_j\partial_i\beta^j + (\alpha/2)P^{jk}_{(\varepsilon)}\partial_i\gamma_{jk} + \alpha S^\mu_{(\varepsilon)}\gamma_{i\mu}],$$

neutrino cooling/heating

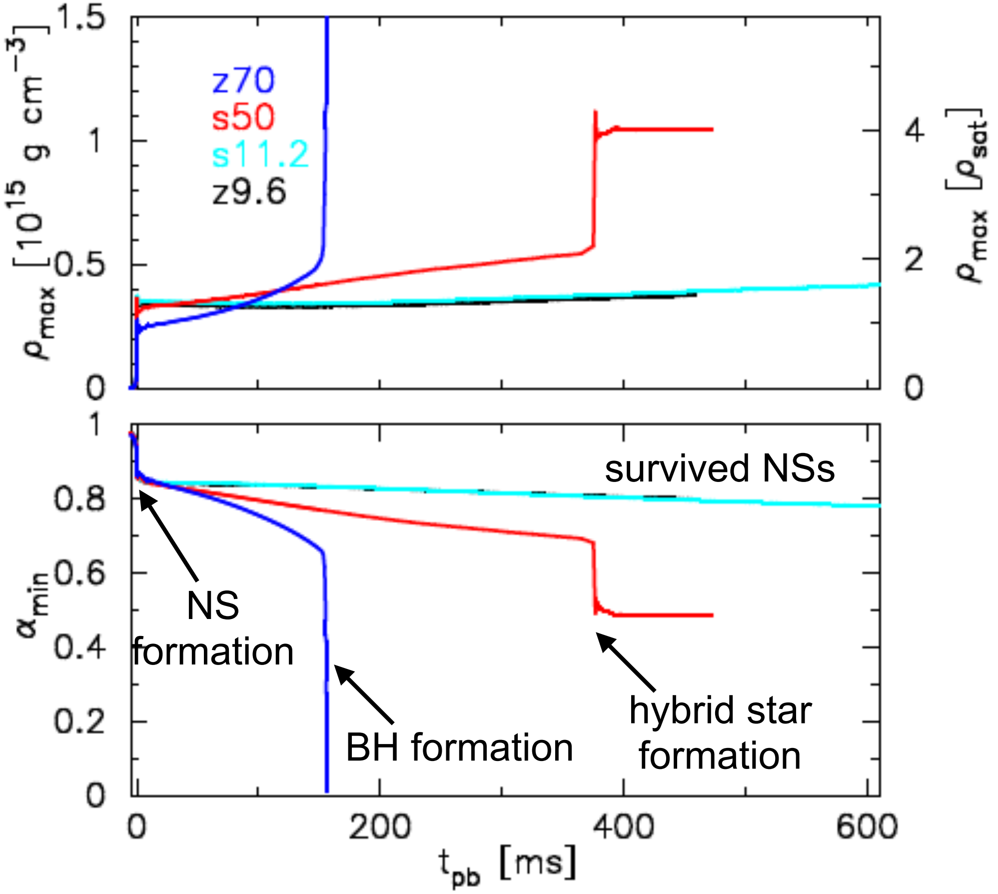
**In GRMRHD code, one solves these 3 systems with (26+12*N$_{\mathrm{ene}}$) variables satisfying the Hamiltonian, momentum, & no-monopole constraints**

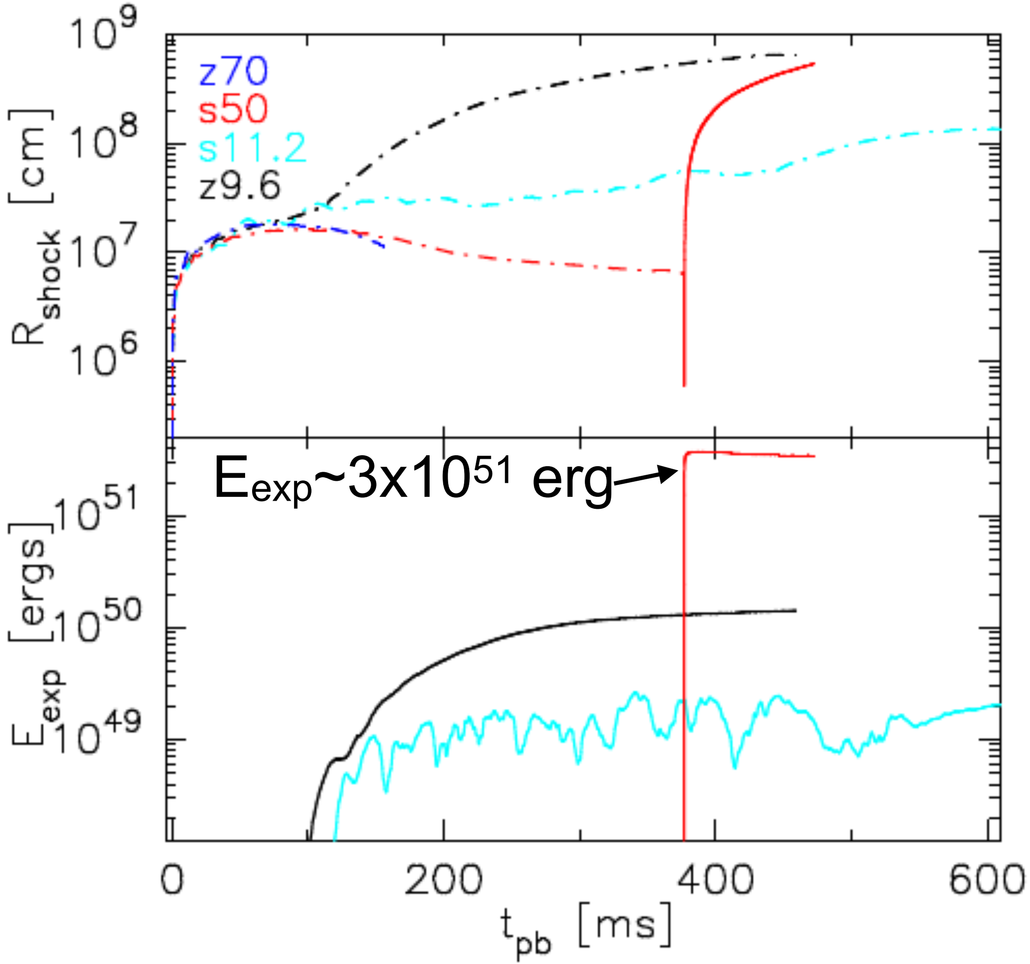
# New explosion mechanism: the PT from hadronic to quark matters



TK+,’21

# Various post (1st-)bounce evolutions

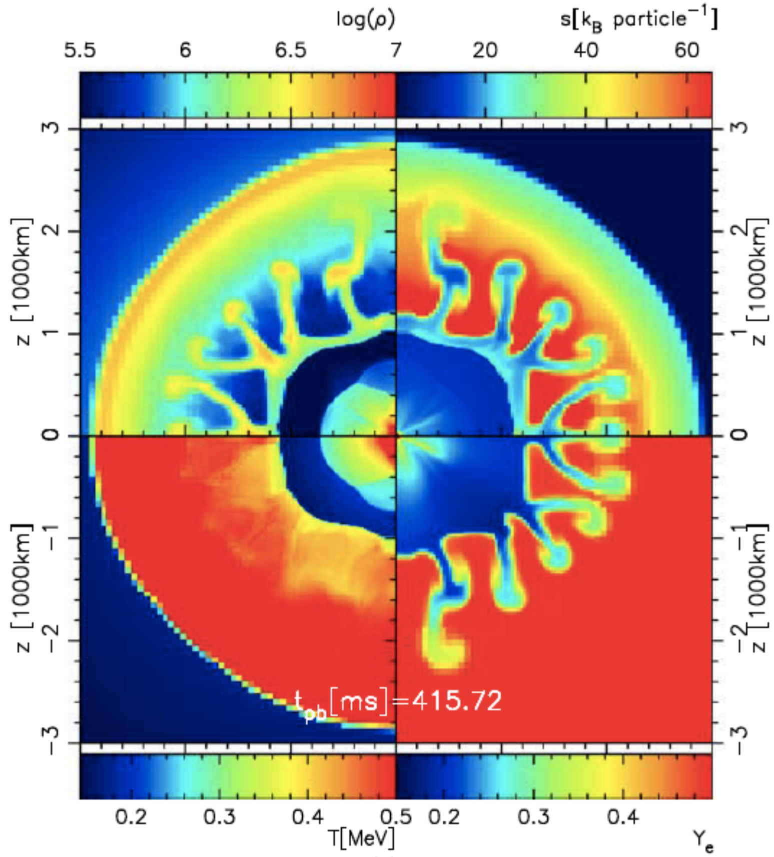




TK+,'21

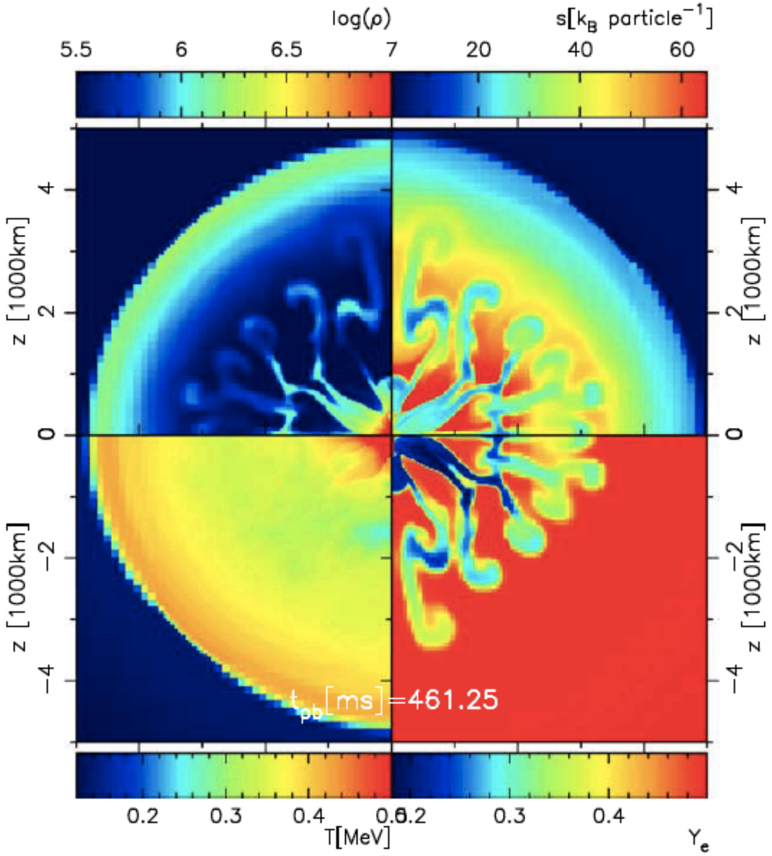
We have exhibited the first self-consistent full GR (2D-)simulations of various compact star formations.

# Strong aspherical explosion!



(c)

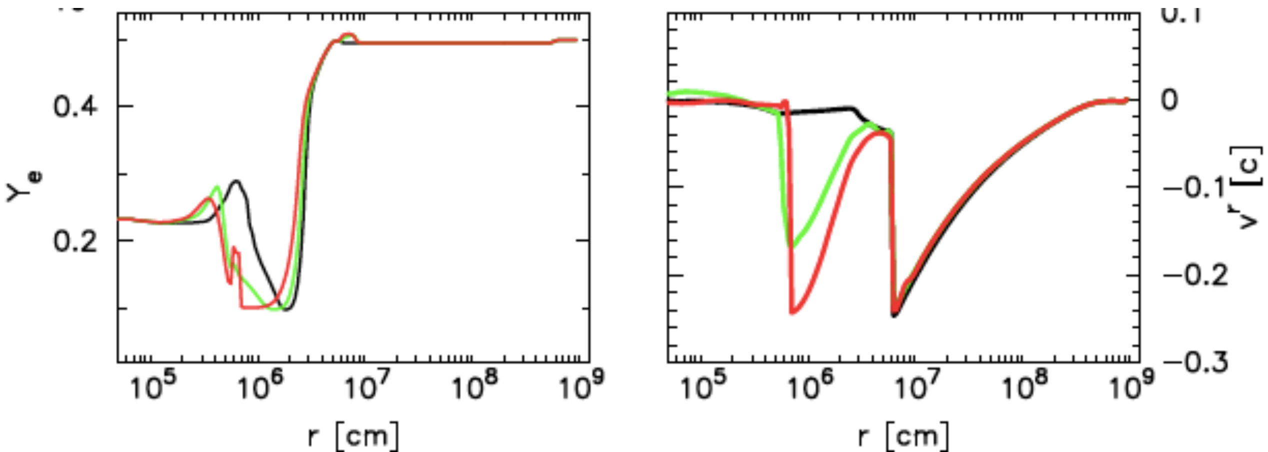
~30ms after the PT



(d)

~80ms after the PT

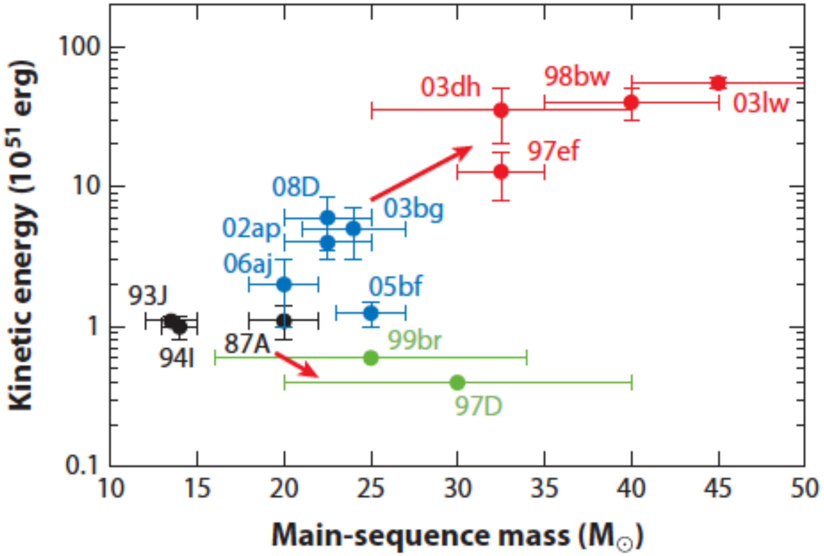
Strong Rayleigh-Taylor mixing ejects low-Ye materials (Ye~0.2-0.3)!



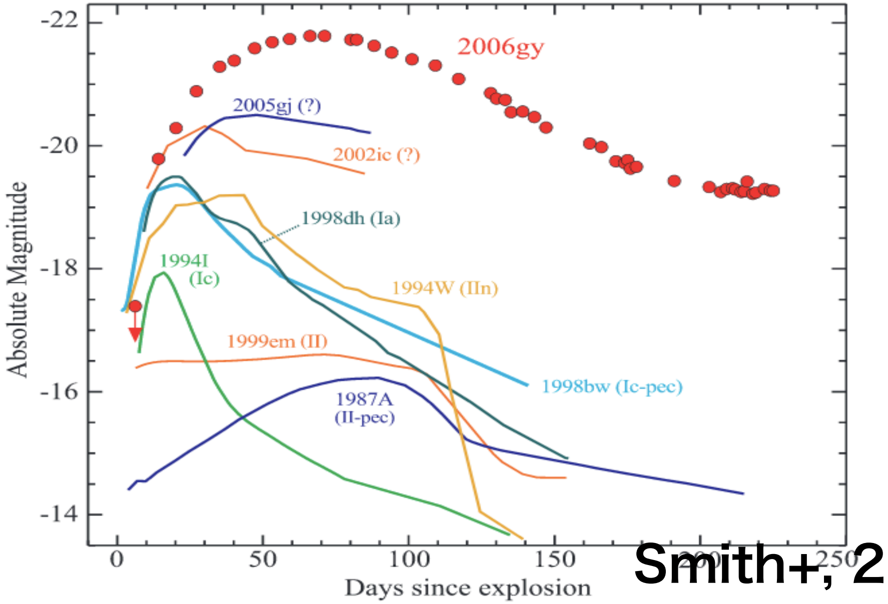
# Why do we need to bring up the PT mechanism?

✳Massive NSs (>2M$_{sun}$) cannot be explained solely by hadronic matters, but rather by, e.g., a hybrid constituent of hadronic and exotic matters (Annala+,’20).

✳One of plausible mechanisms to explain super-luminous SNe (SLSNe).
- SLSNe, such as SN2006gy, can be well modeled by slightly larger explosion energy than normal type IIp SNe, a few times 10$^{51}$ erg, and a dense CSM, with which the explosion collides (Smith+,’09, Moriya+,’13).
- From our simulations, it is likely that only massive stars with intermediate masses (~40-50M$_{sun}$) encounter the PT.
- From stellar evolution theory, these intermediate mass stars with Z$_{sun}$ may suffer heavy mass loss (Umeda&Nomoto,’08), producing dense CSM.



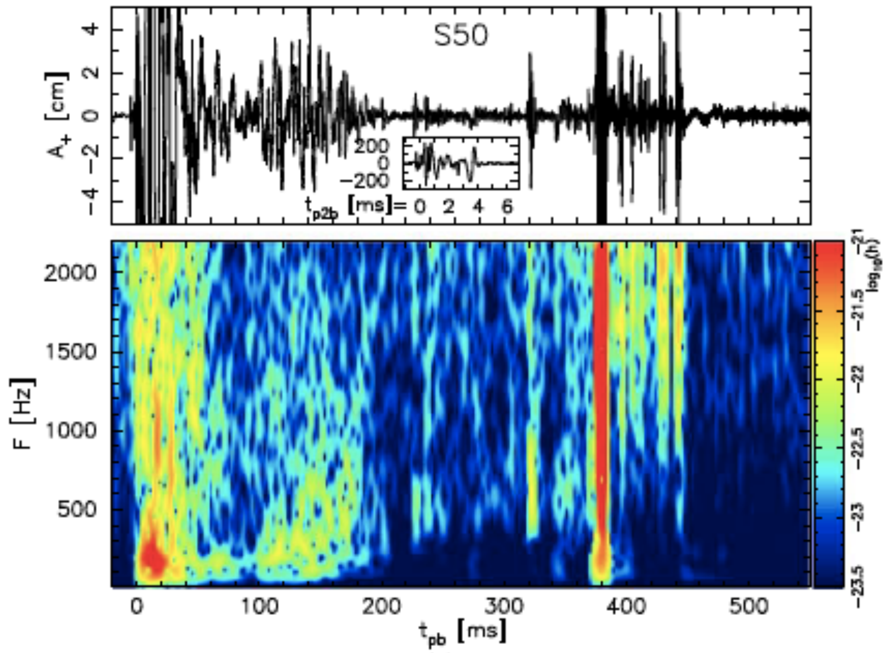
Nomoto+, ’13



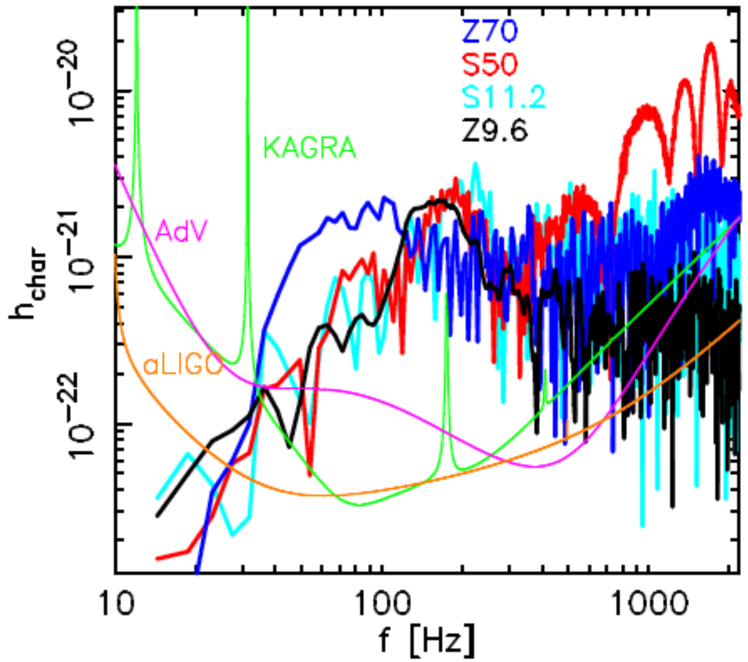
Smith+, 2007

# Their multi-messenger signals

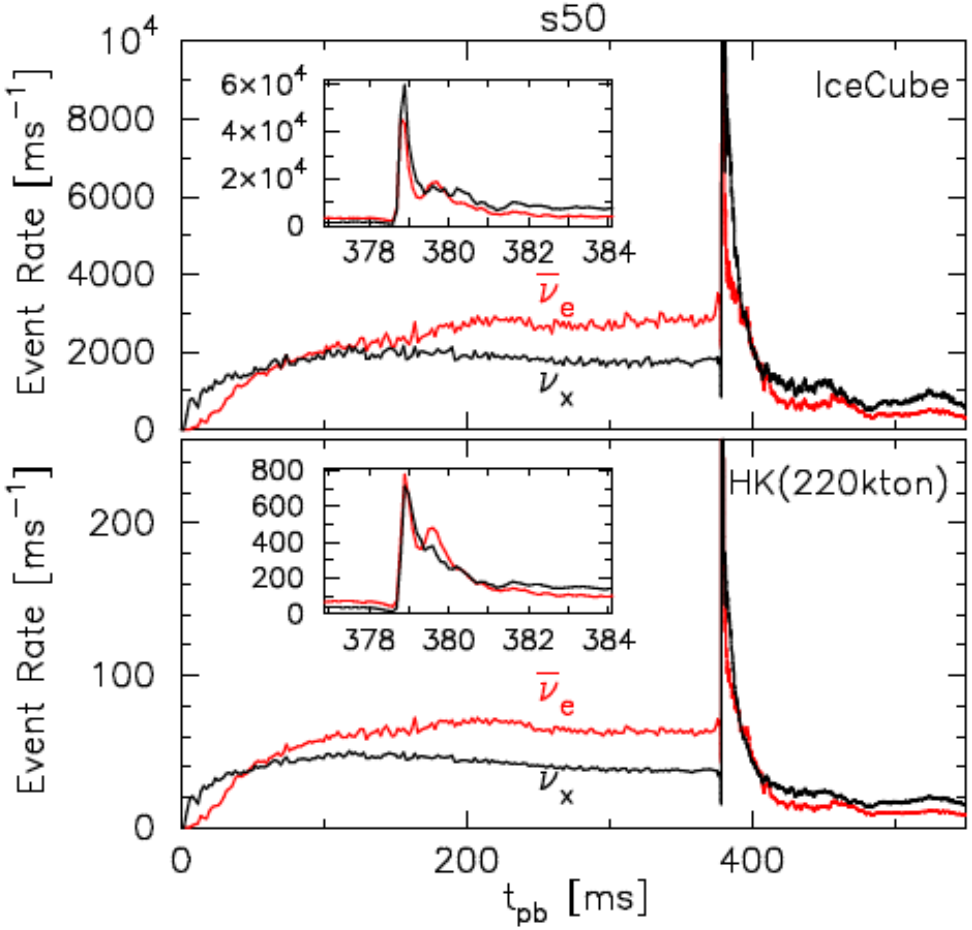
GW



(c)



Neutrino signals

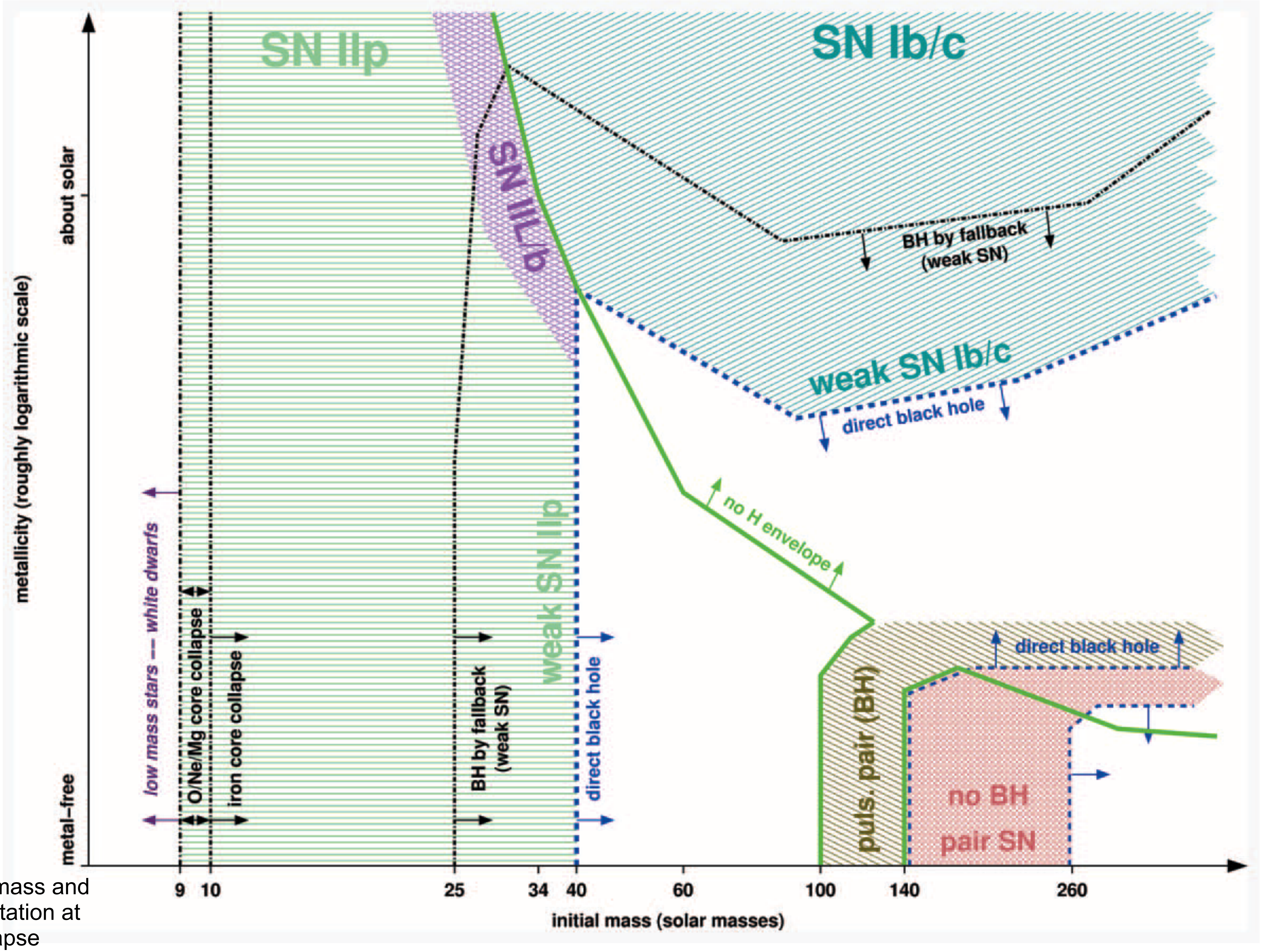


D=10kpc

TK+,’21

# Progenitor mass dependence

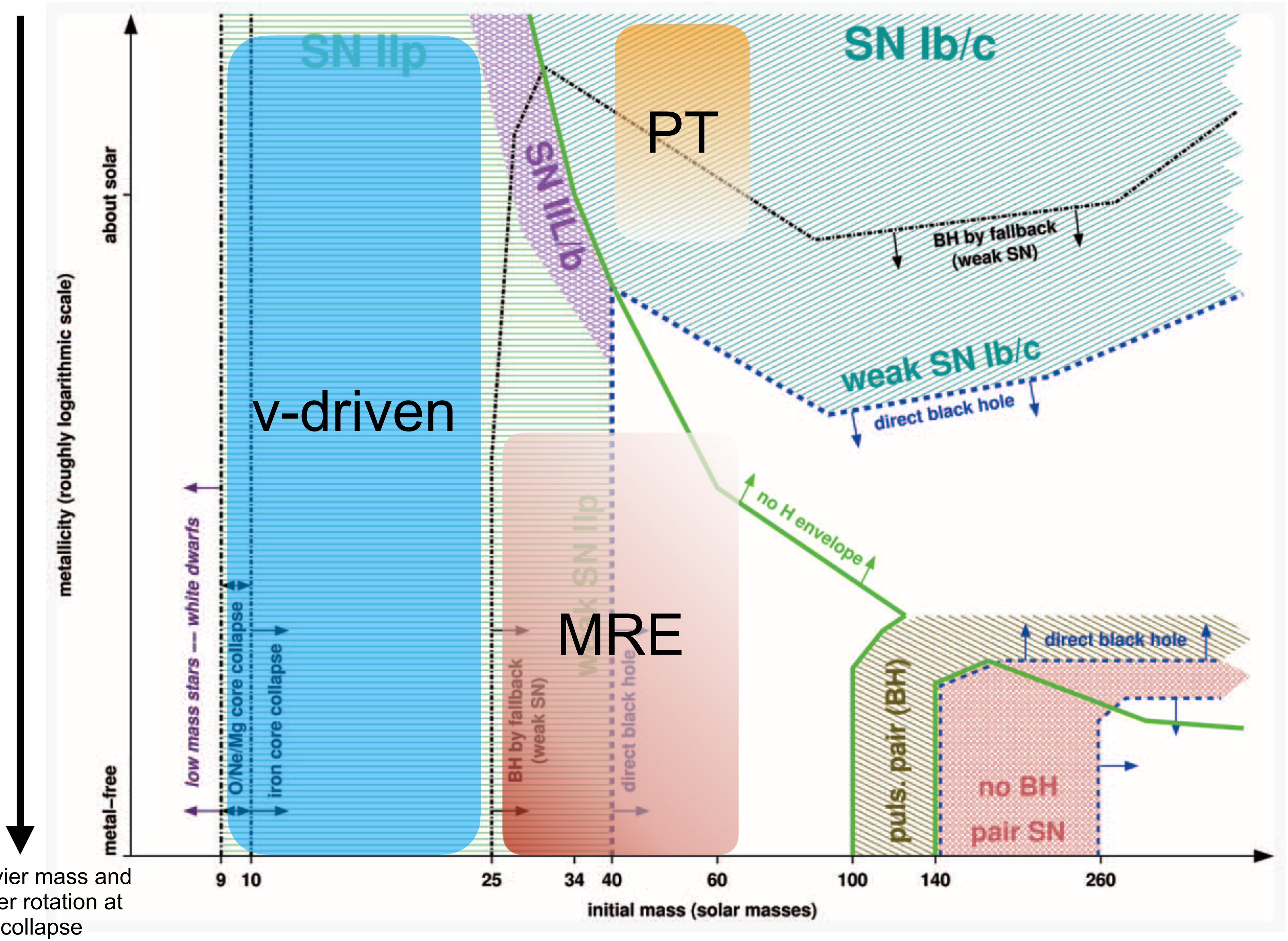
Heger+,2003



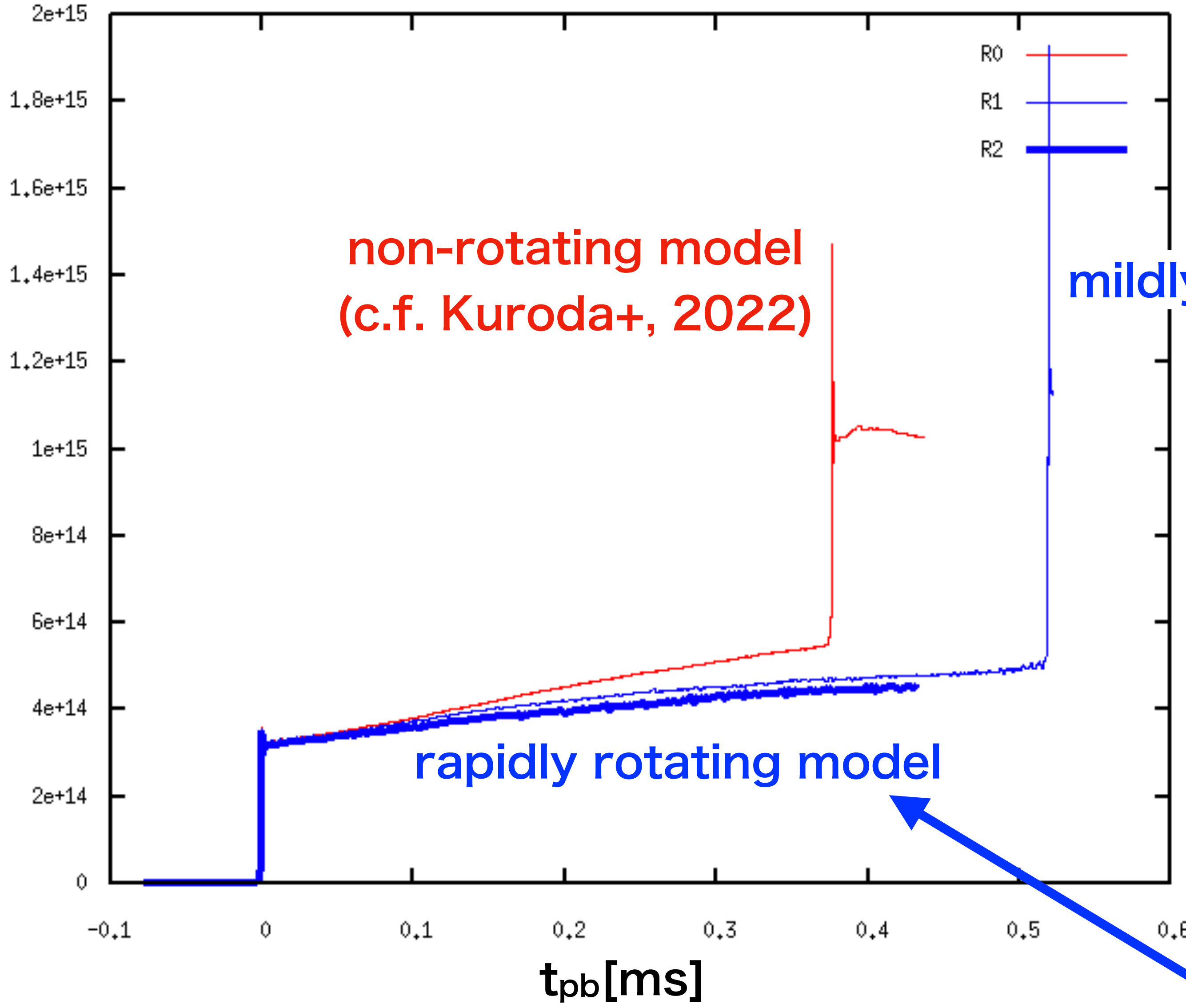
Heavier mass and faster rotation at collapse

# Progenitor mass dependence

Heger+,2003



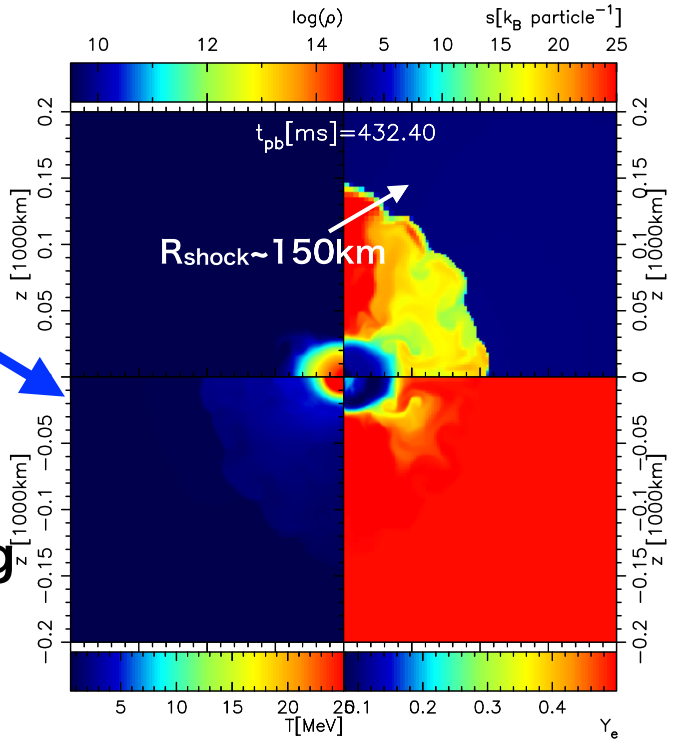
Heavier mass and faster rotation at collapse



non-rotating model
(c.f. Kuroda+, 2022)

mildly rotating model

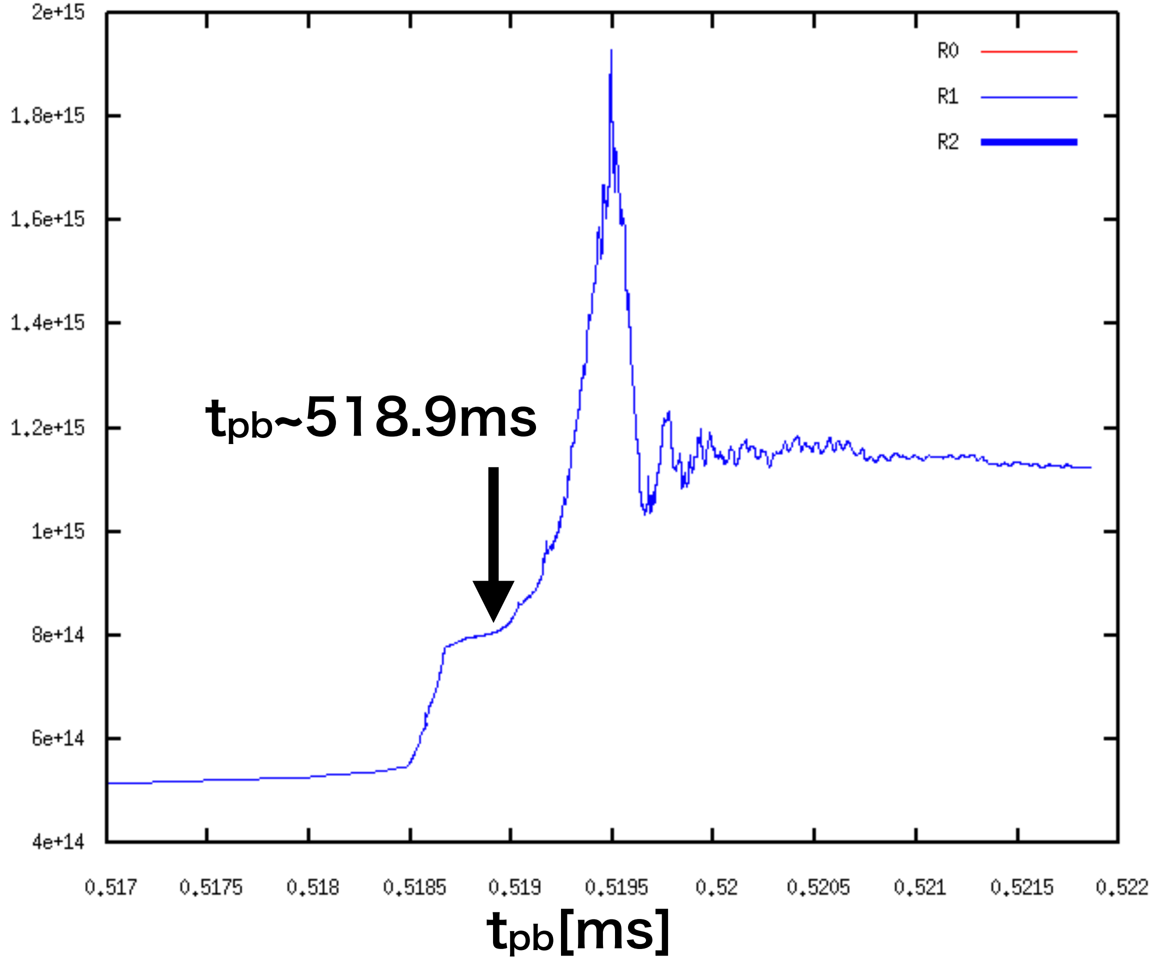
rapidly rotating model



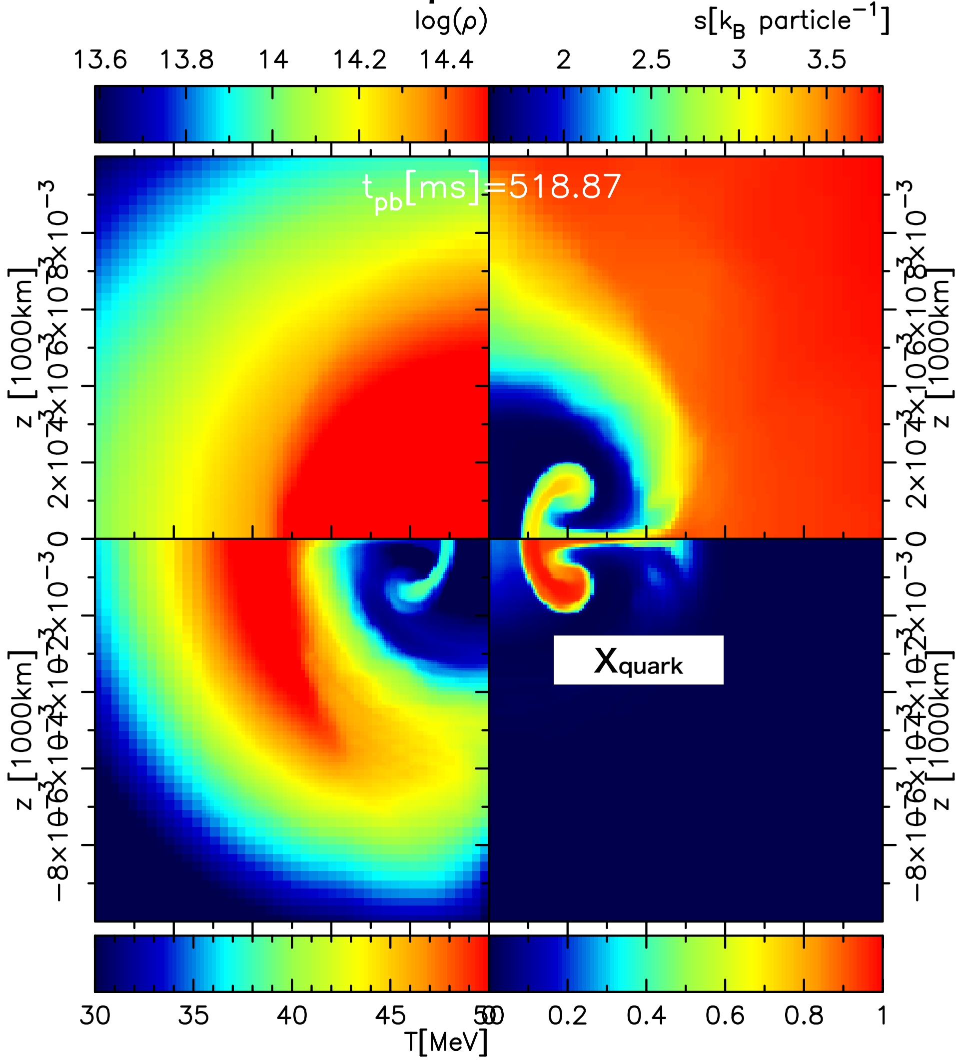
$R_{shock}$~150km

The rapidly rotating model seems to be already entering the neutrino-driven explosion phase.

# Offset hadron-quark phase transition (PT) in mildly rotating model, unlike our previous non-rotating model!



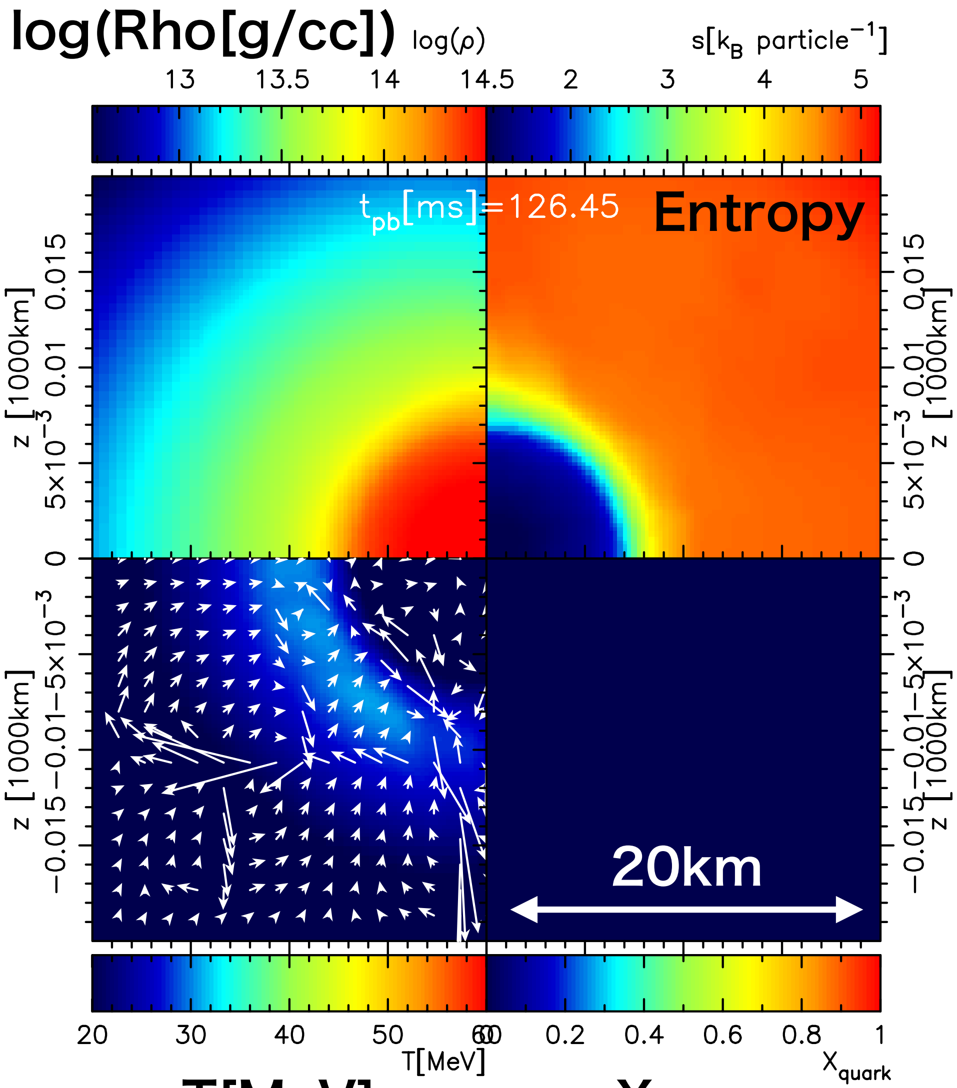
## @$t_{pb}$~518.9ms



### Why offset?

- Due to the meridional circulation, a hot disk is formed.
- The phase transition occurs first in that hot disk region.
- and then the “quark-torus” accretes onto the center.

# Evolution of the PNS and HQ-PT



**log(Rho[g/cc])**

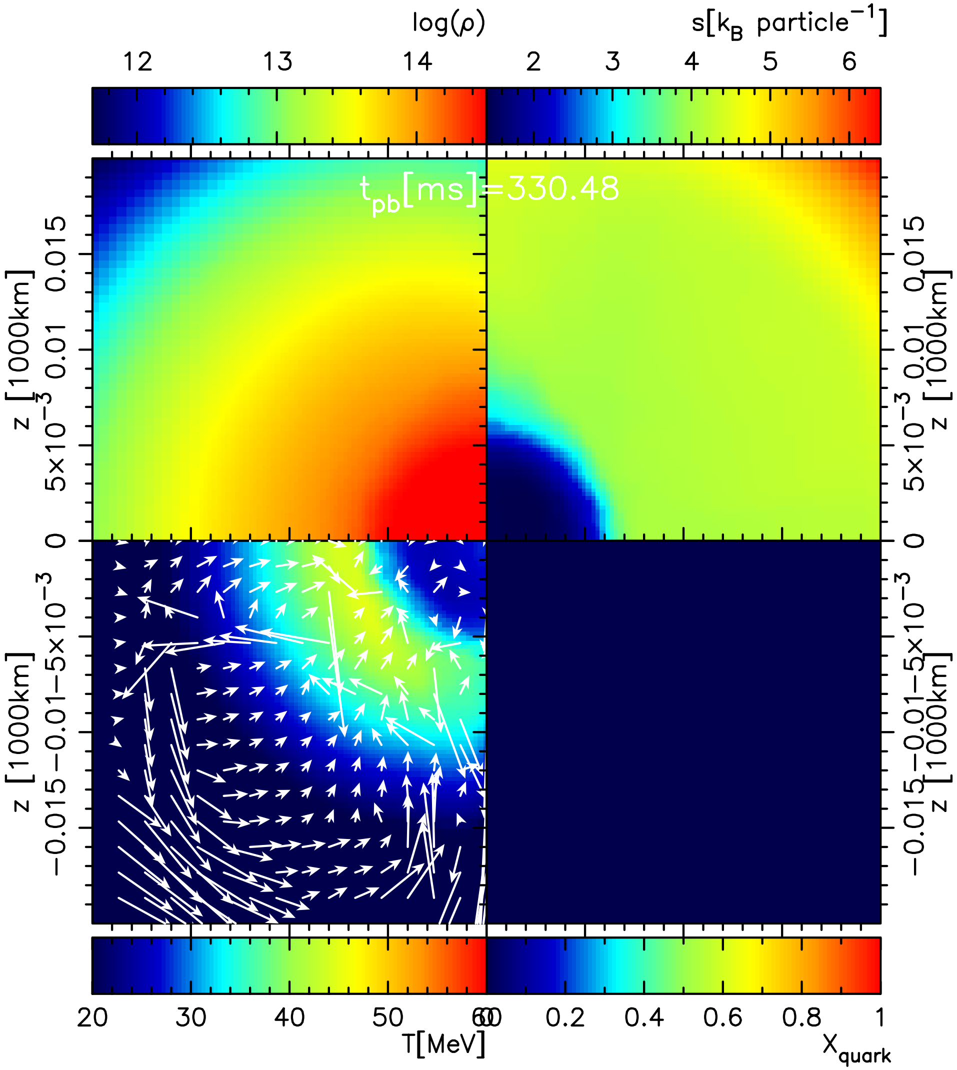
**Entropy**

**20km**

**T[MeV]**

**$X_{quark}$**

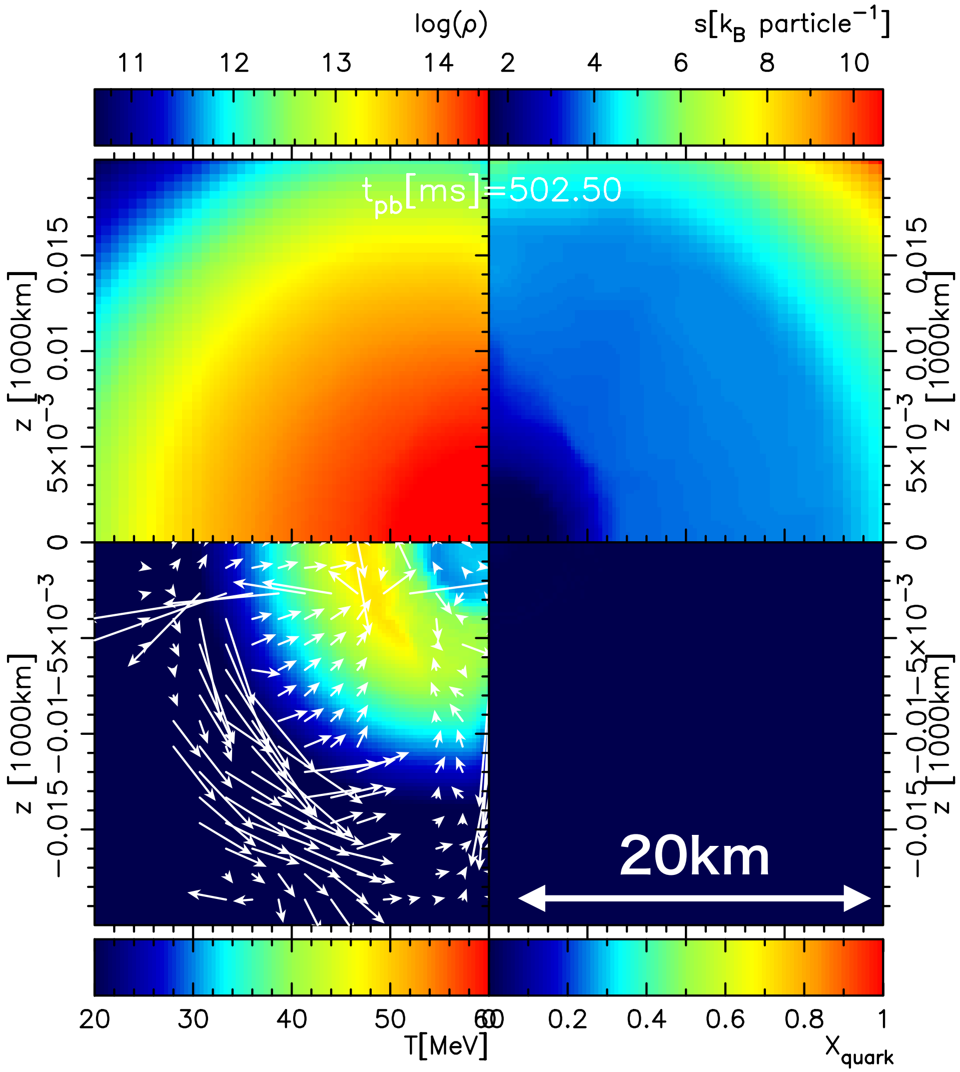
**$T_{pb}$=126[ms]**



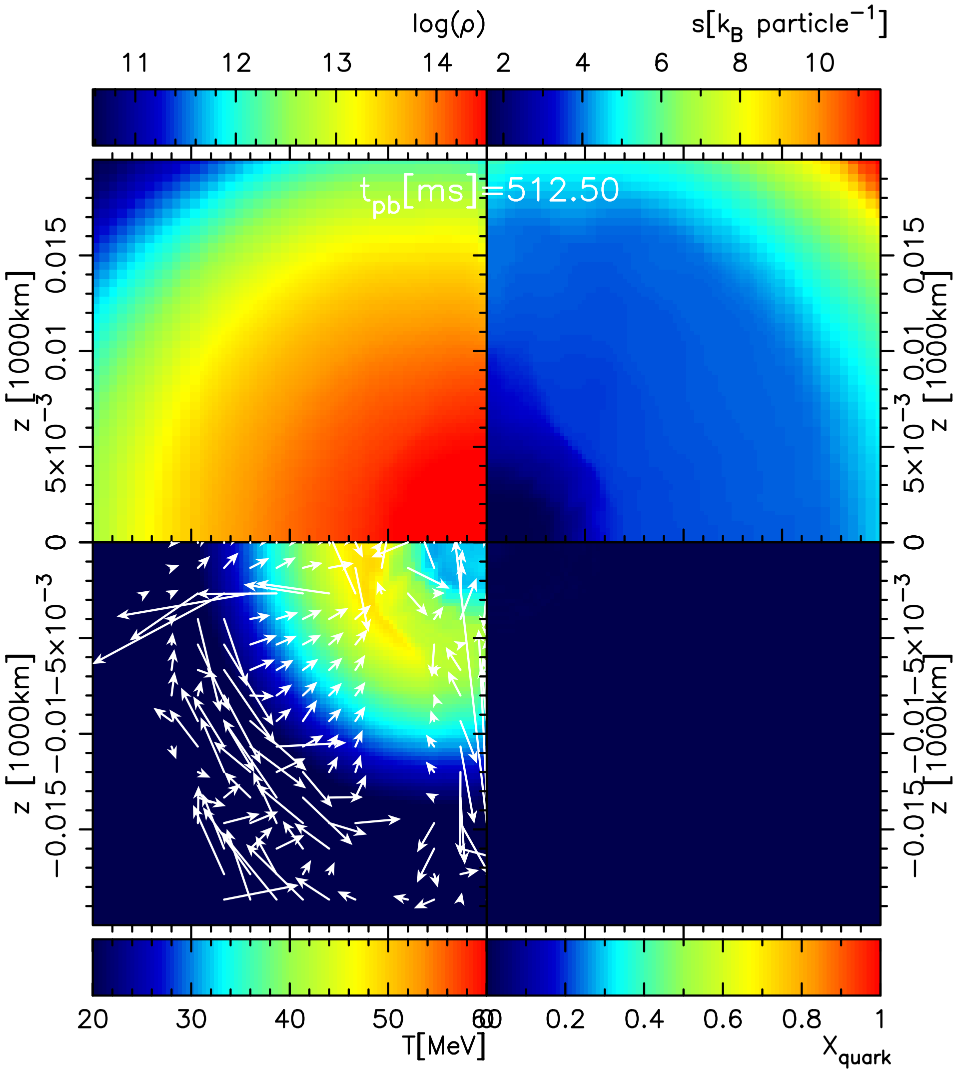
**$T_{pb}$=330[ms]**

**$T_{PT}$~519[ms]**

# Evolution of the PNS and HQ-PT



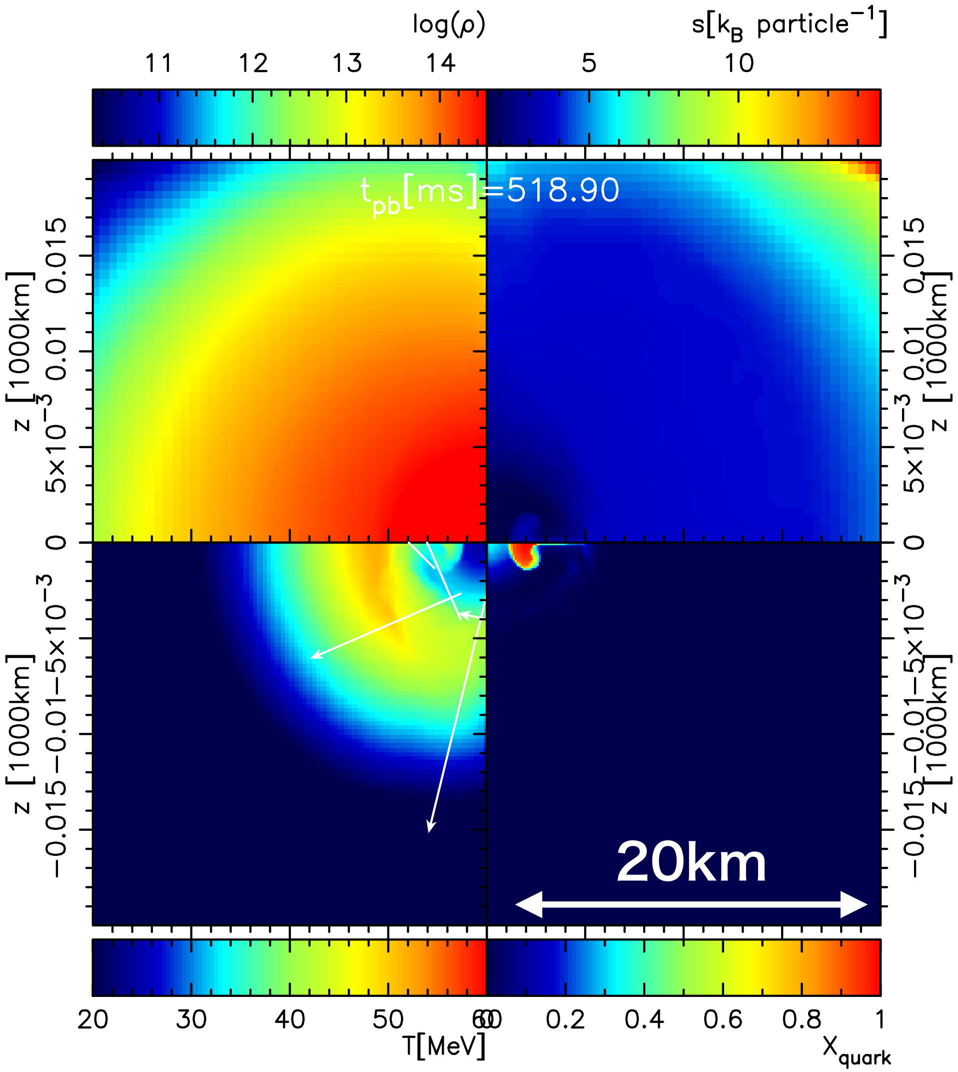
$T_{pb}$=502[ms]



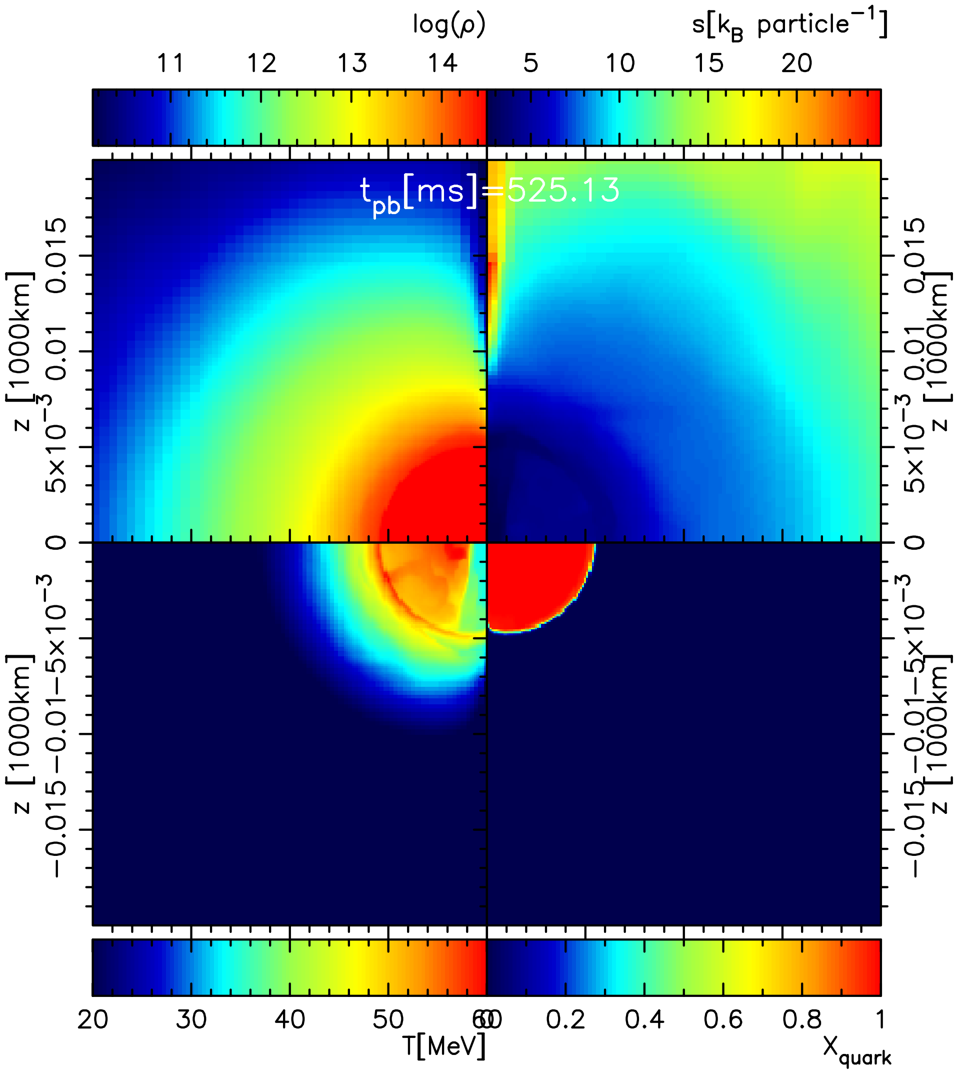
$T_{pb}$=512[ms]

$T_{PT}$~519[ms]

# Evolution of the PNS and HQ-PT



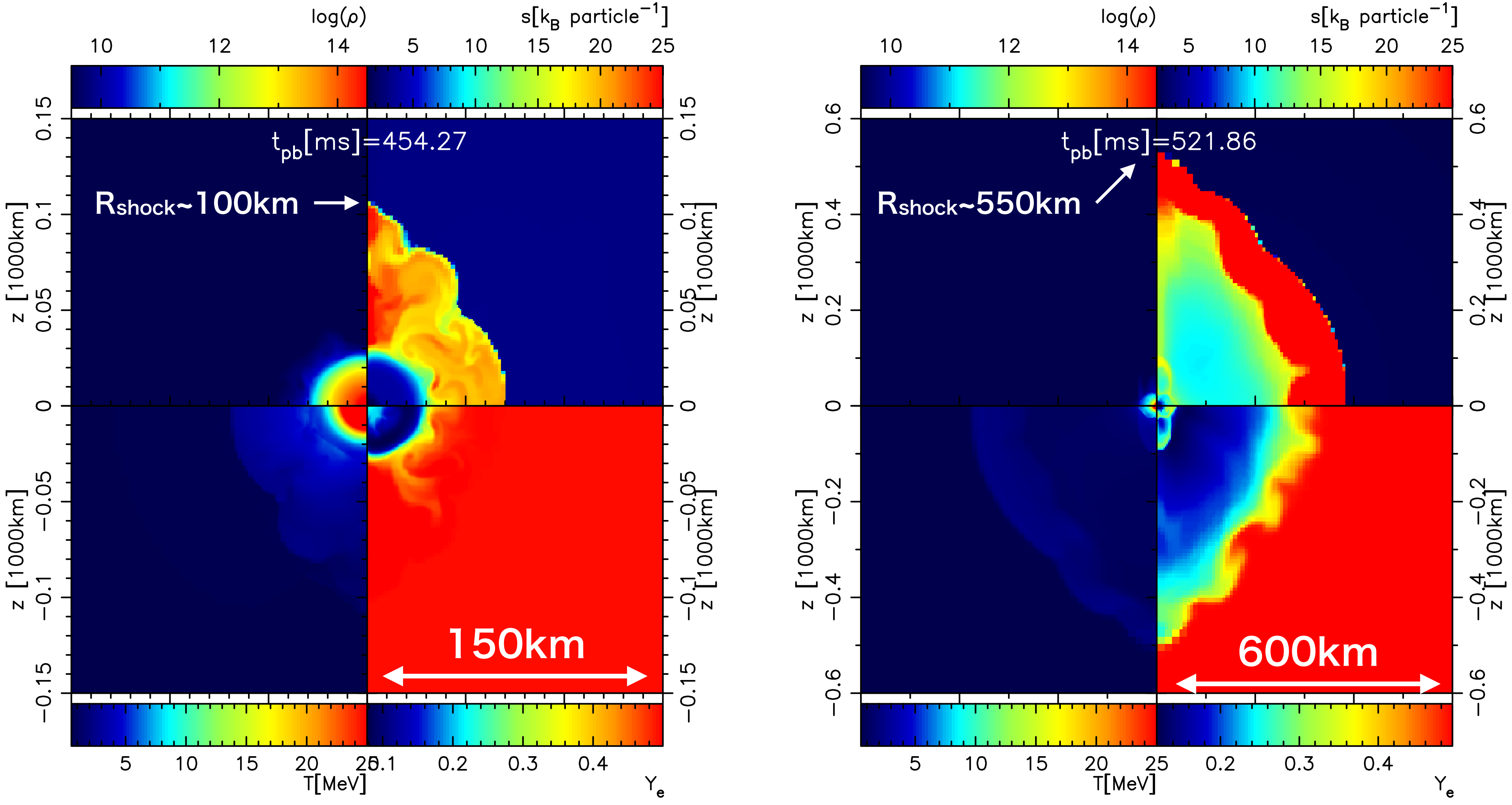
**$T_{pb}$=518.9[ms]**



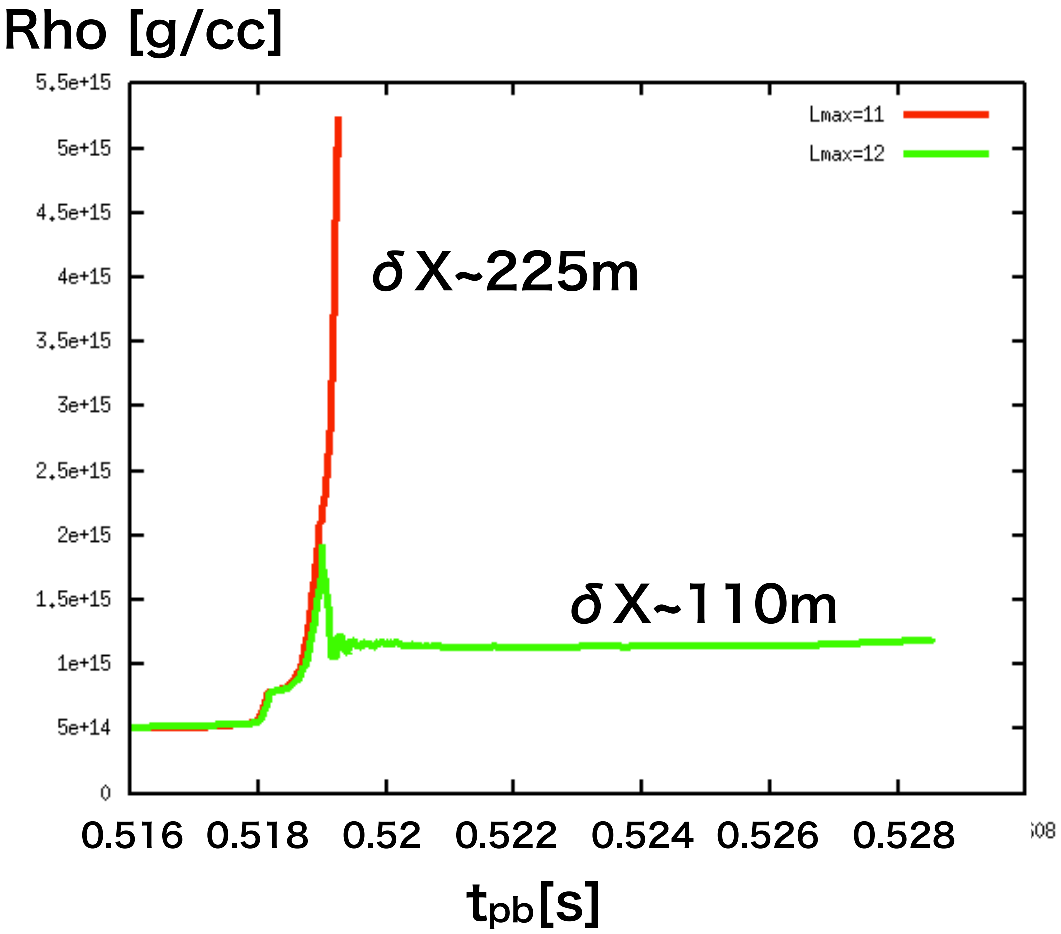
**$T_{pb}$=525[ms]**

**$T_{PT}$~519[ms]**

# Strong explosion driven by the HQ-PT.

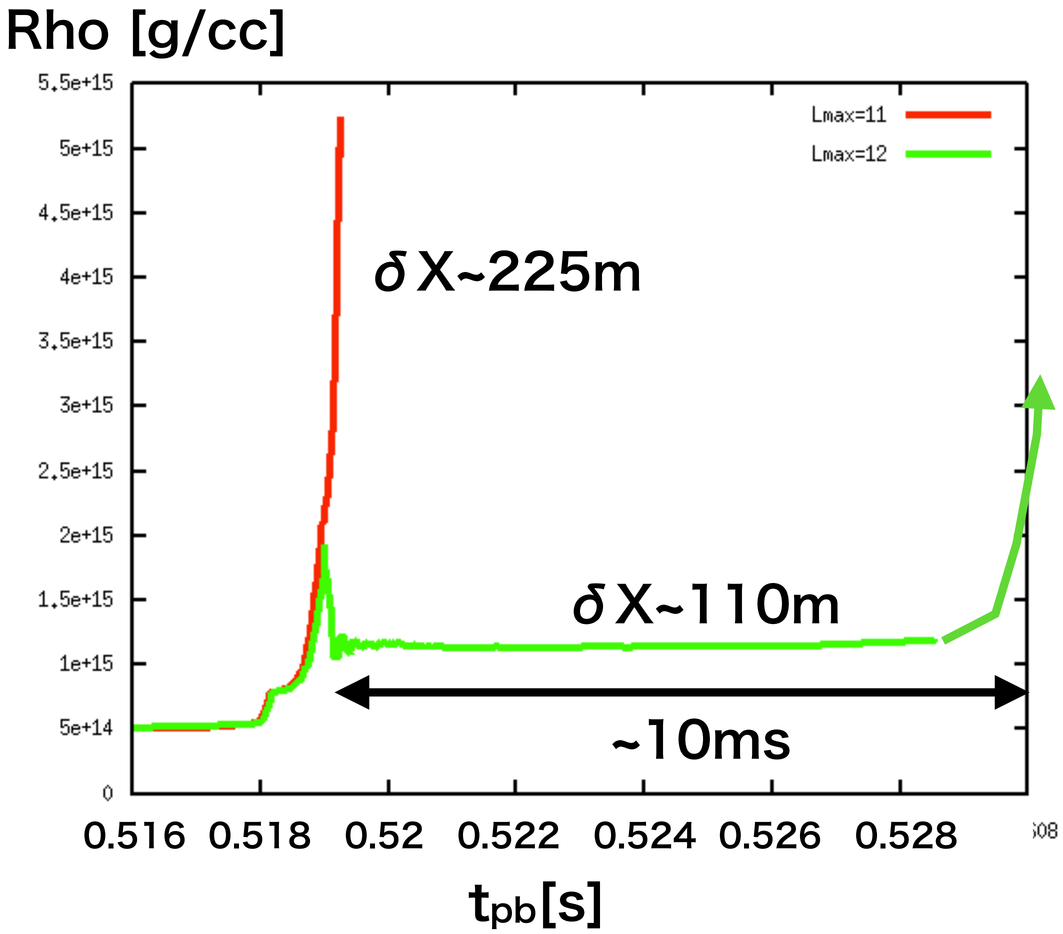


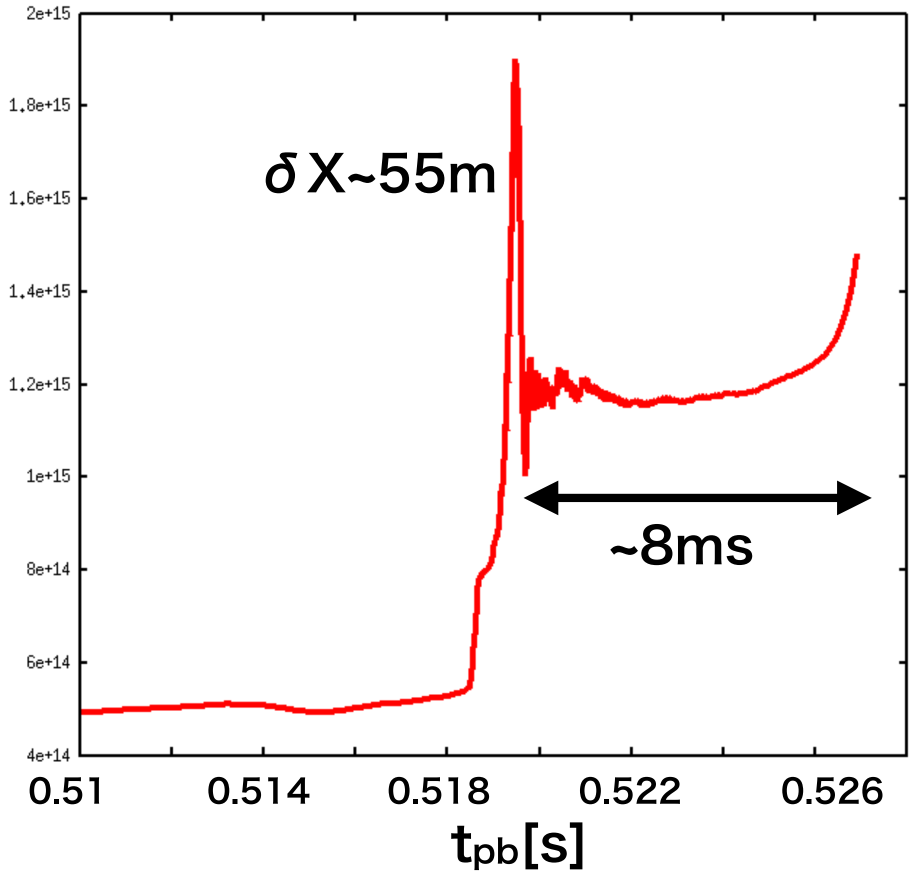
# Short-lived QS



- too coarse resolution (δx=225m) ——> (artificial) BH formation at the 2nd collapse
- finer resolution (δx=110m) ——> 2nd bounce and QS formation take place

# Short-lived QS





- too coarse resolution (δx=225m) ——> (artificial) BH formation at the 2nd collapse
- finer resolution (δx<110m) ——> 2nd bounce and QS formation take place,
  but soon after that the QS collapses.

# Why does the newly born QS immediately dies in a rotating case, while not in a non-rotating case?

I explored two possible scenarios:

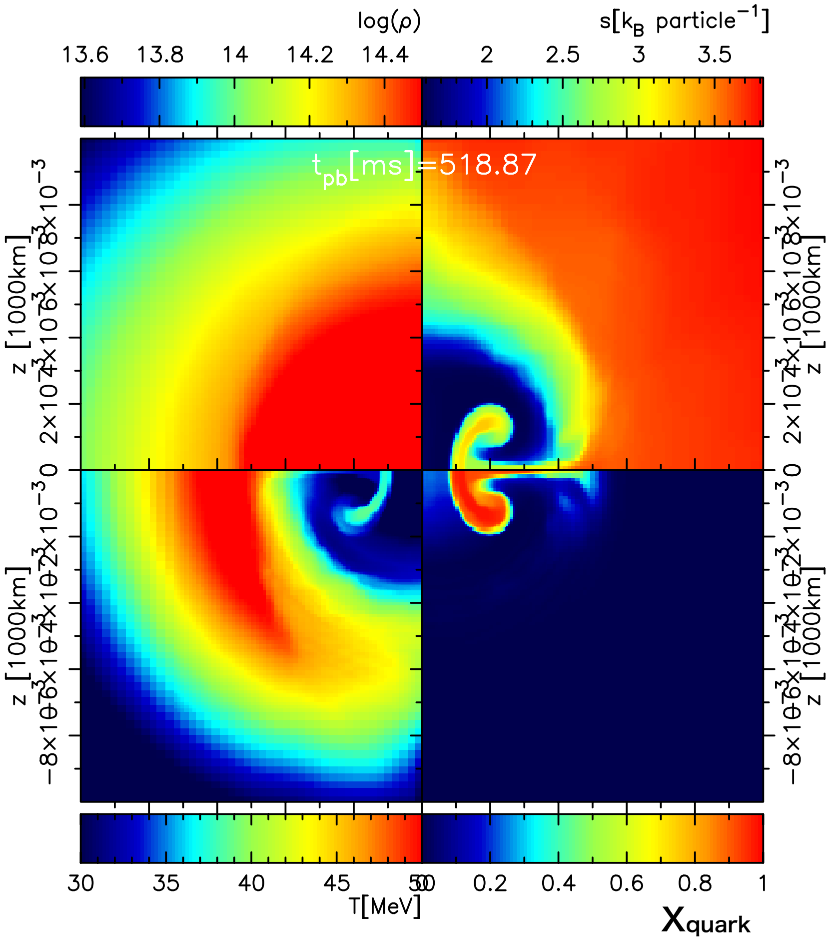
## 1. Due to GR instability?

GR instability: When the mass M is contracted within $R_c$, the dynamical instability sets in.

$$R_c = \frac{K}{\gamma - \frac{4}{3}} \frac{2GM}{c^2}$$

Chandrasekhar,'64

## 2.Due to the peculiar offset-PT?



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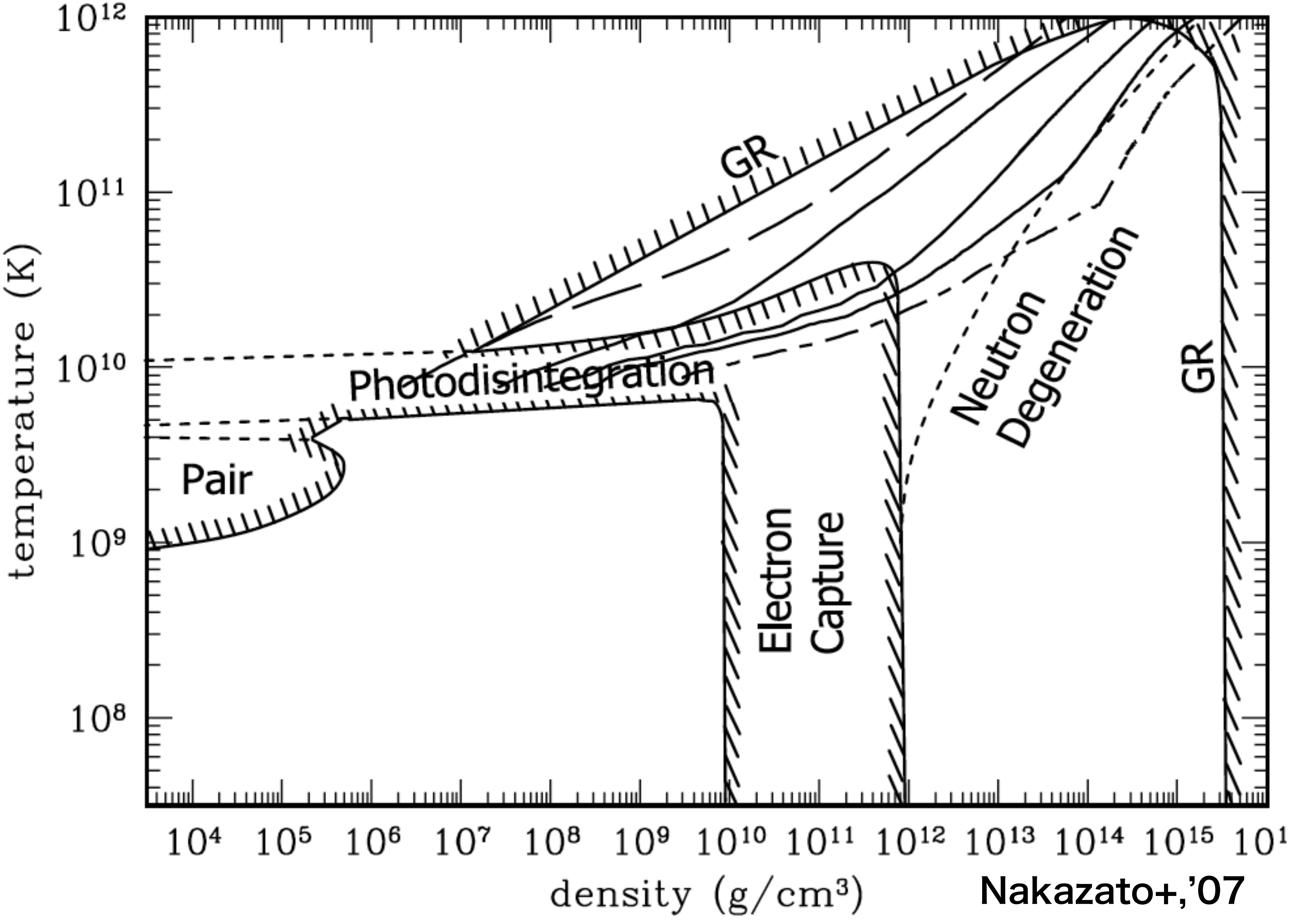
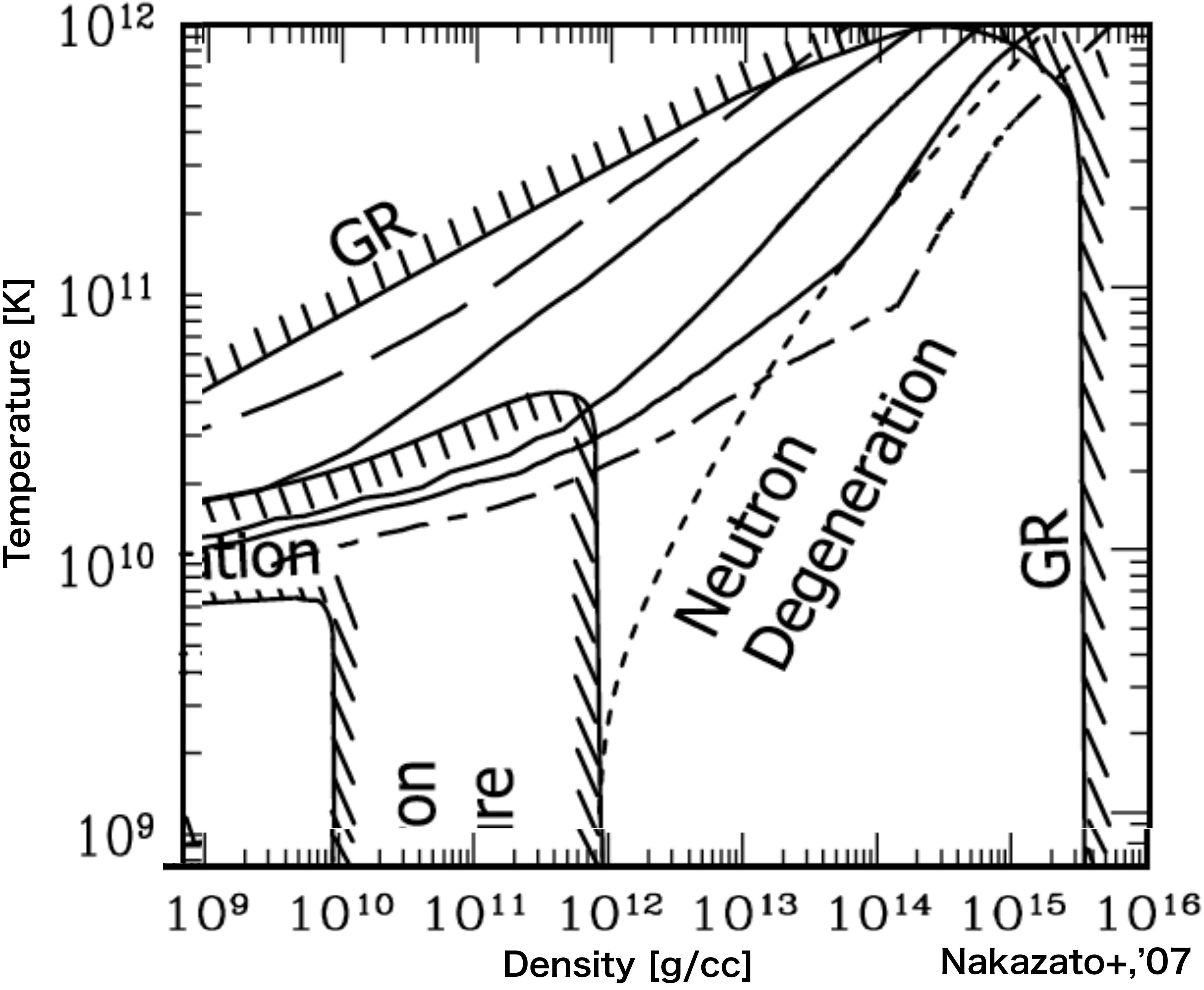


Nakazato+,'07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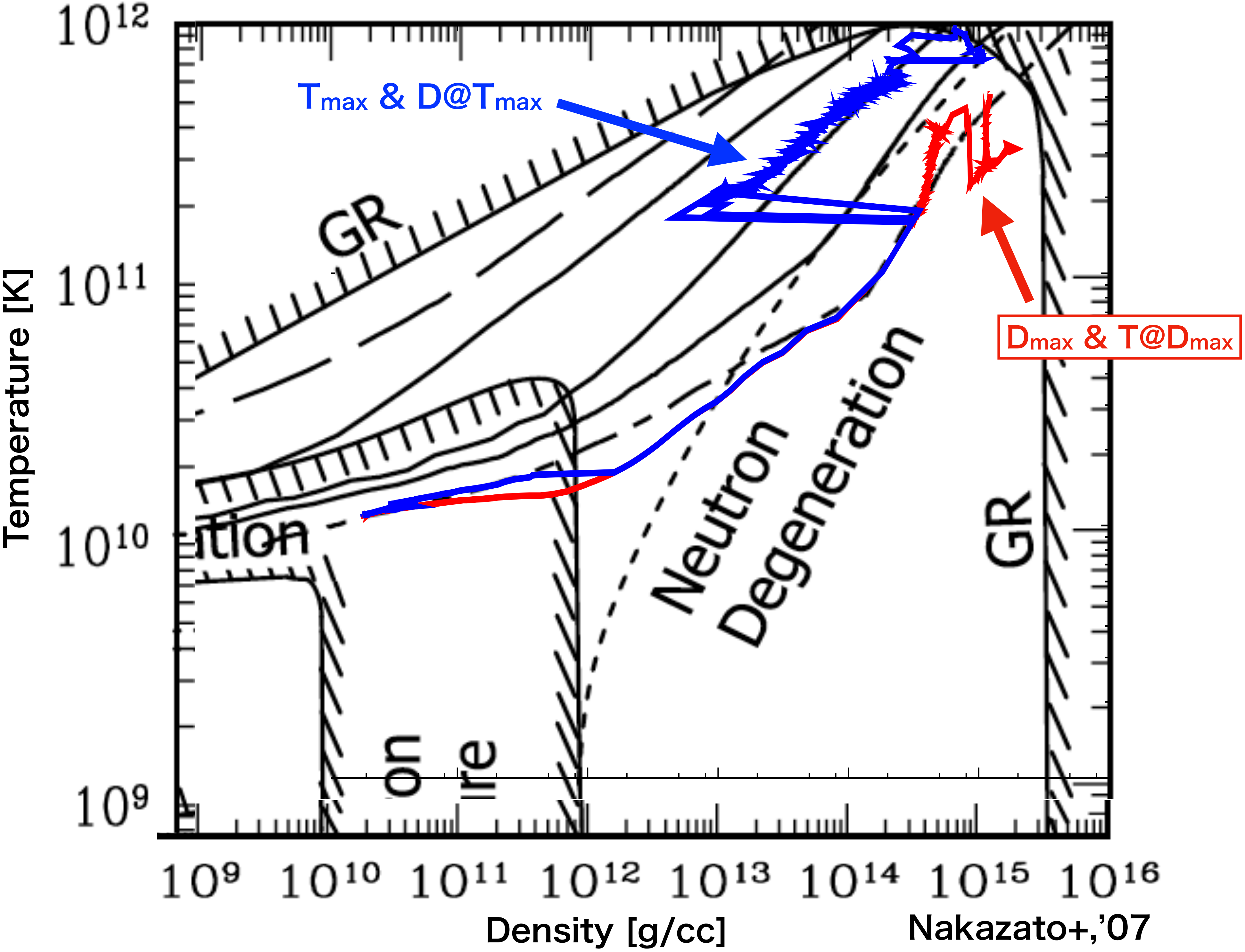
Density [g/cc]

Nakazato+,’07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Density [g/cc]
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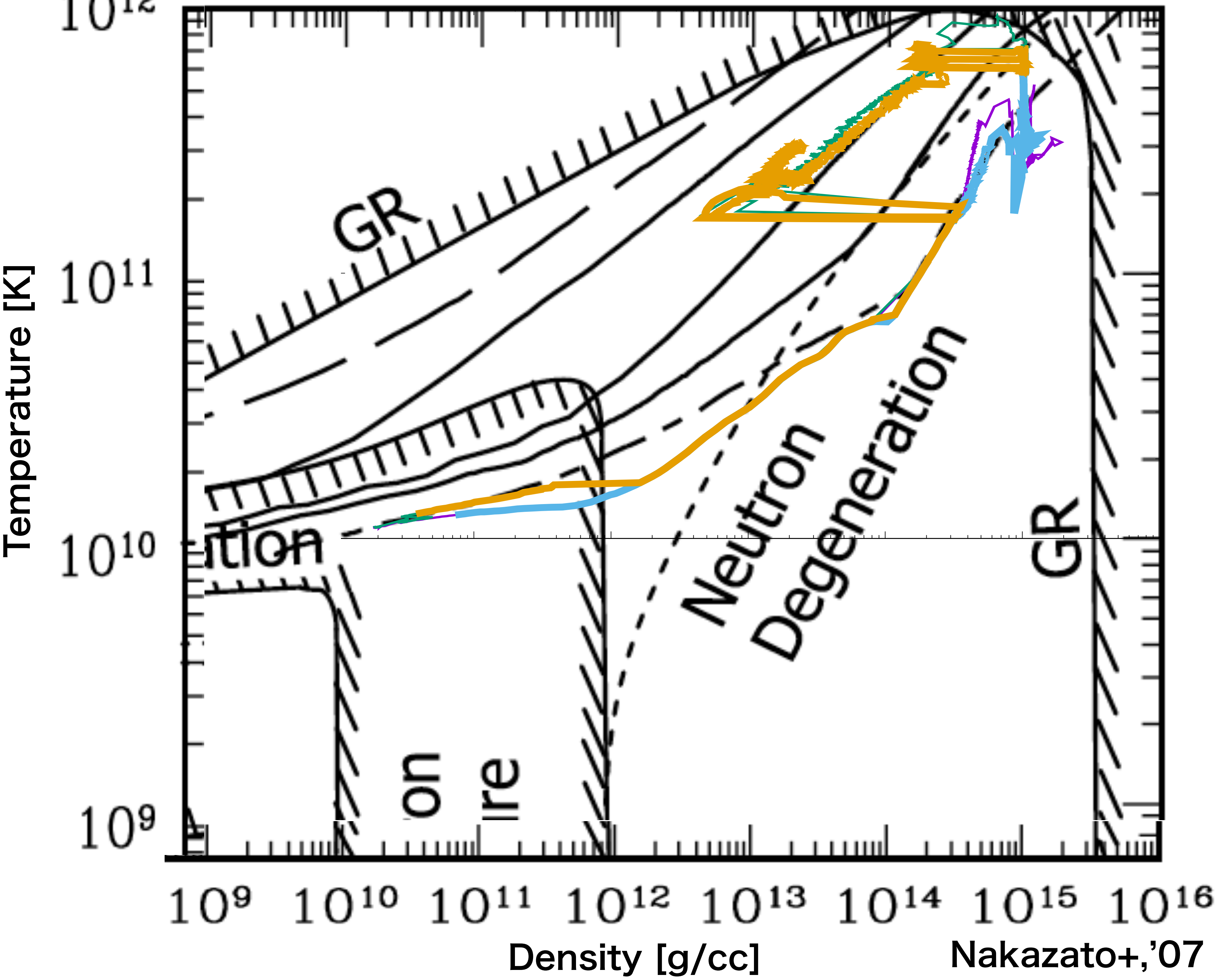
10^14
10^15
10^16

Nakazato+,'07

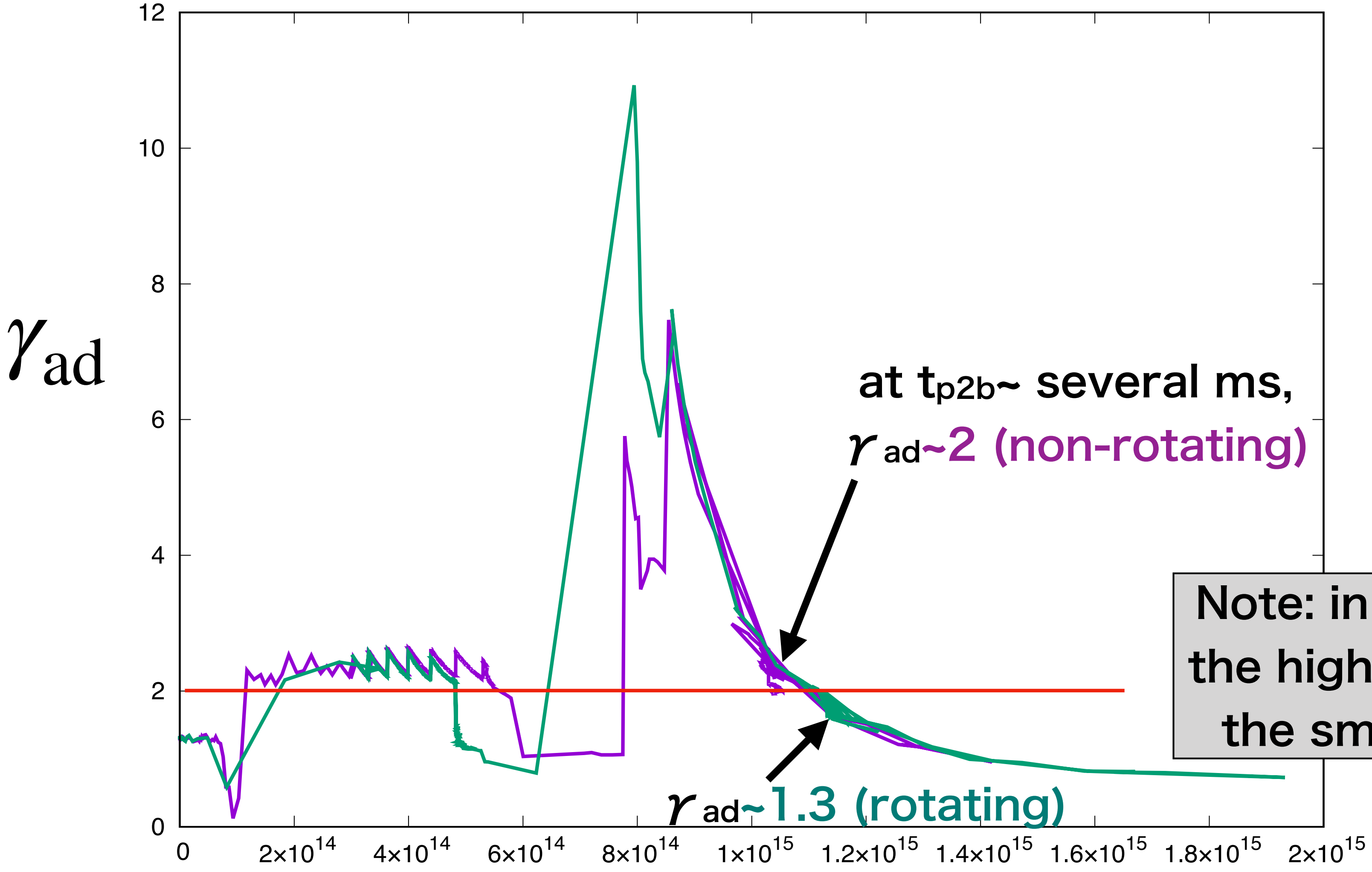
Thick lines=> non-rotating



Nakazato+,’07

1.GR instability

## 2.Due to the peculiar offset-HQ-PT?



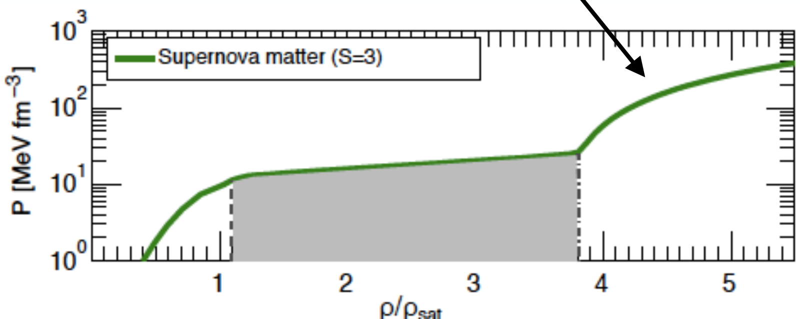
$D_{max}$ [g/cc]

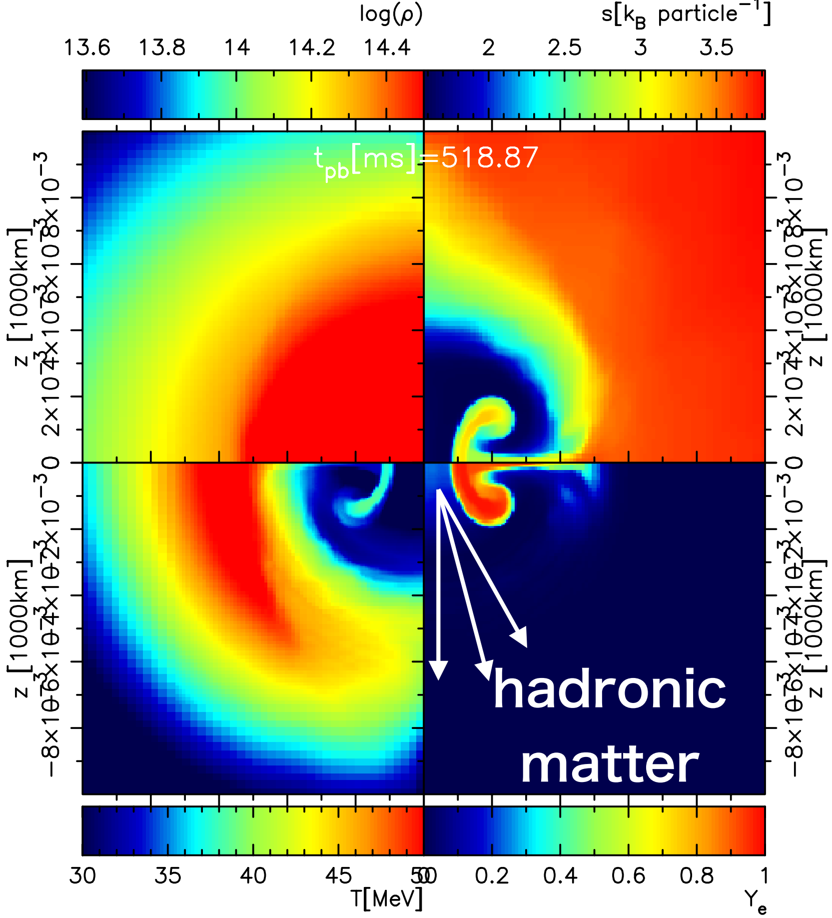
at $t_{p2b}$~ several ms,

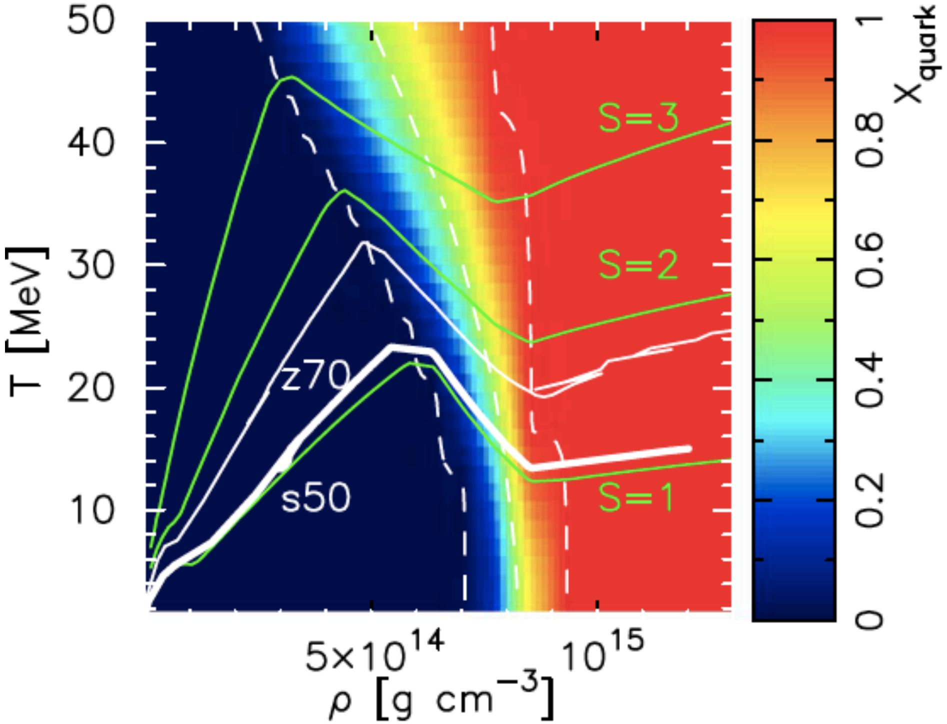
$\gamma_{ad}$~2 (non-rotating)

$\gamma_{ad}$~1.3 (rotating)

Note: in the QCD region, the higher the density is, the smaller the $\gamma_{ad}$ is.







When the quark torus accretes on the centre:

1a. the $\gamma$ inside the quark torus is not so high (as it is a hot torus) and, thus, a stronger overshooting

1b. extremely rapid rotation ($\Omega \sim 10^4$ rad/s) supports the 2nd bounce

After the ring down,

2. $D_{max}$ is slightly larger in rotating model (~10% compared to non-rot.)
3. The $\gamma_{ad}$ of quark core becomes smaller (this time ~1.3).

- **We showed the first self-consistent formation process of NSs, BHs, and hybrid-stars.**
- **If the explosion is triggered by the QCD phase transition, the strong Rayleigh-Taylor instability may develop and transport low-Ye material outward.**
- **Strong GWs and neutrino signals would be detectable as observable signatures of the QCD phase transition in CCSNe.**

Future plans:

1. Slowly rotating models, that experience the PT at center.
2. Beyond the BH formation!!