Hybrid star phenomenology from the properties of the special point

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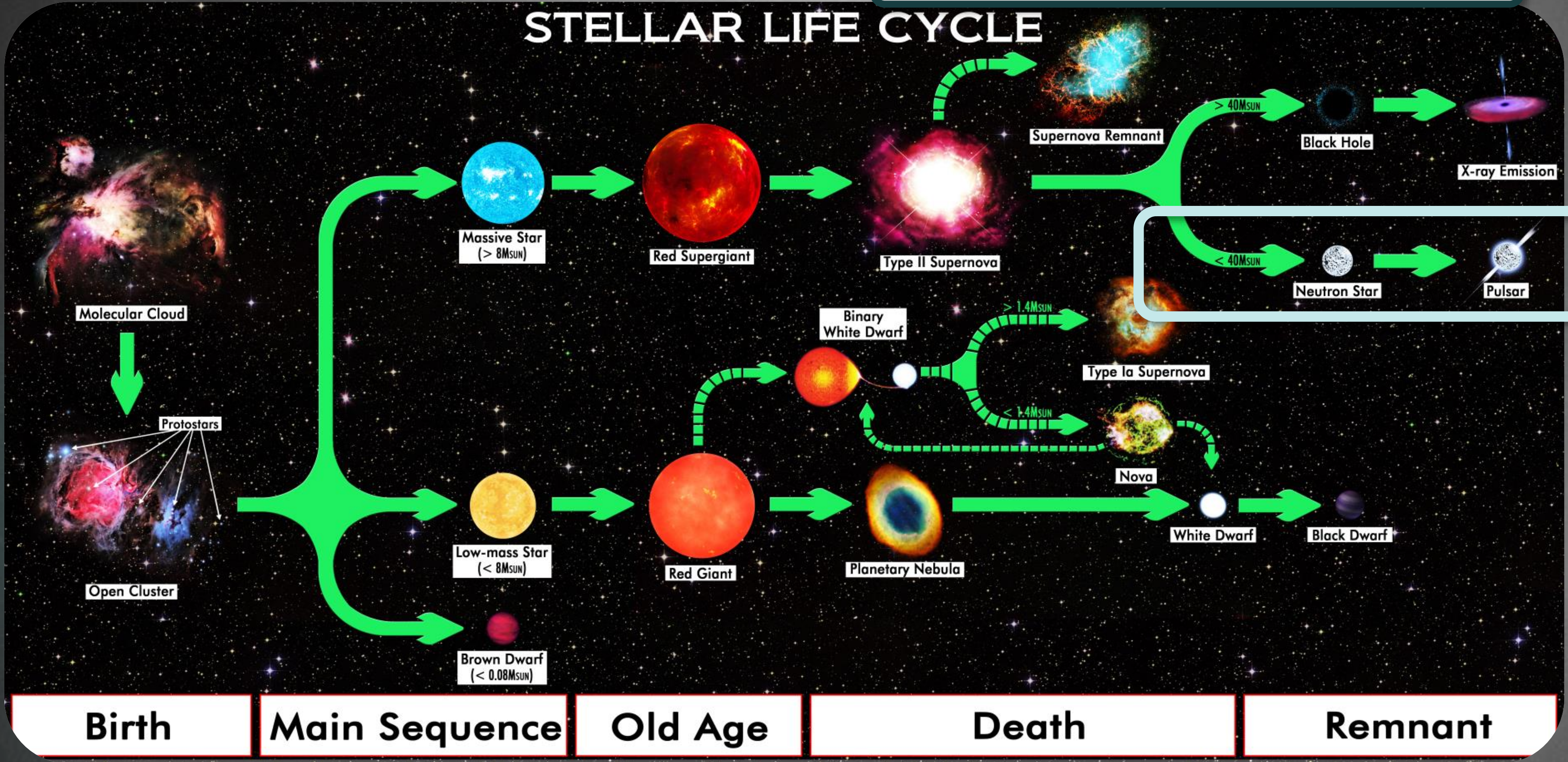
Outline

- ❑ Compact Stars ⟺ Phase transitions
- ❑ Construction of NS ⟺ Tools on the way
- ❑ Properties of M-R curves ⟺ The Special Point
- ❑ Conclusion

Compact stars

Evolution depending on mass



stars with

$$\approx 8 - 20 M_{\odot}$$

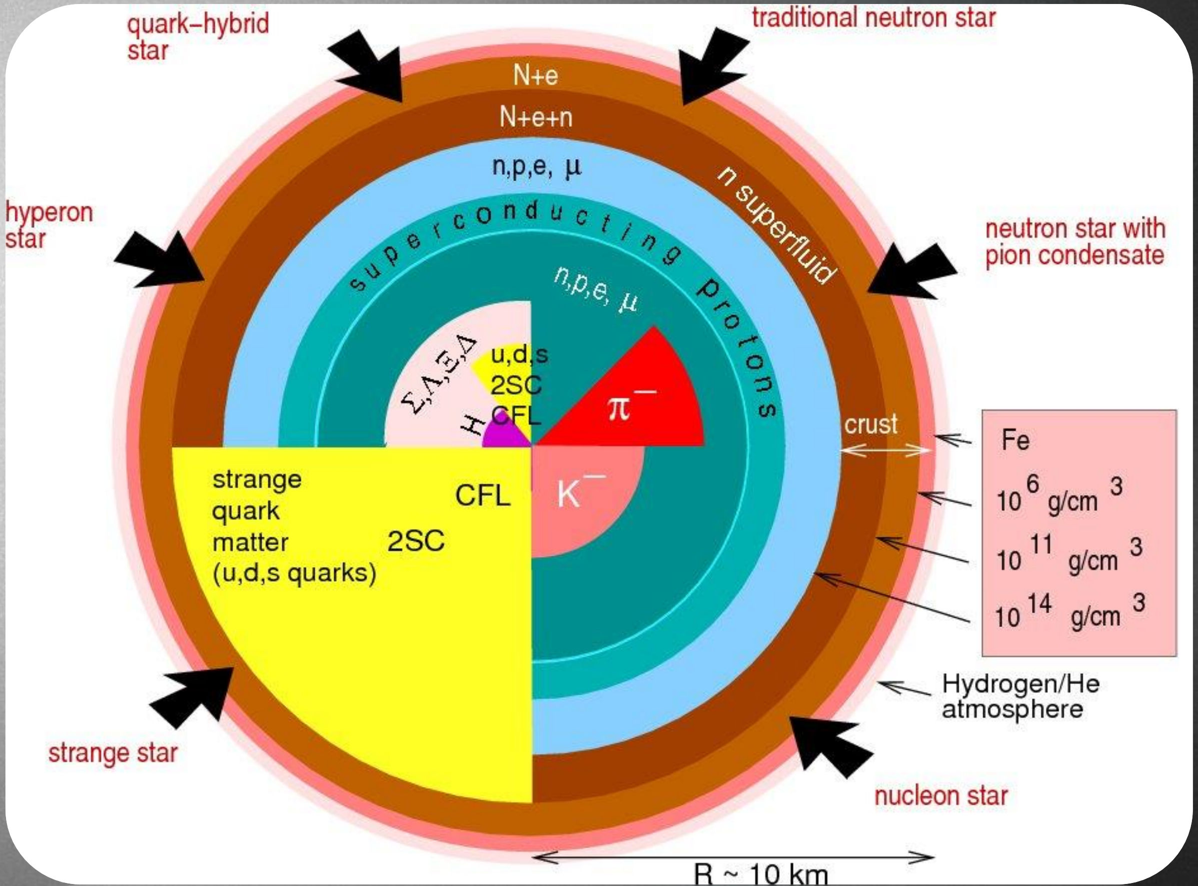
Size comparison: Manhattan - NS

characteristic properties

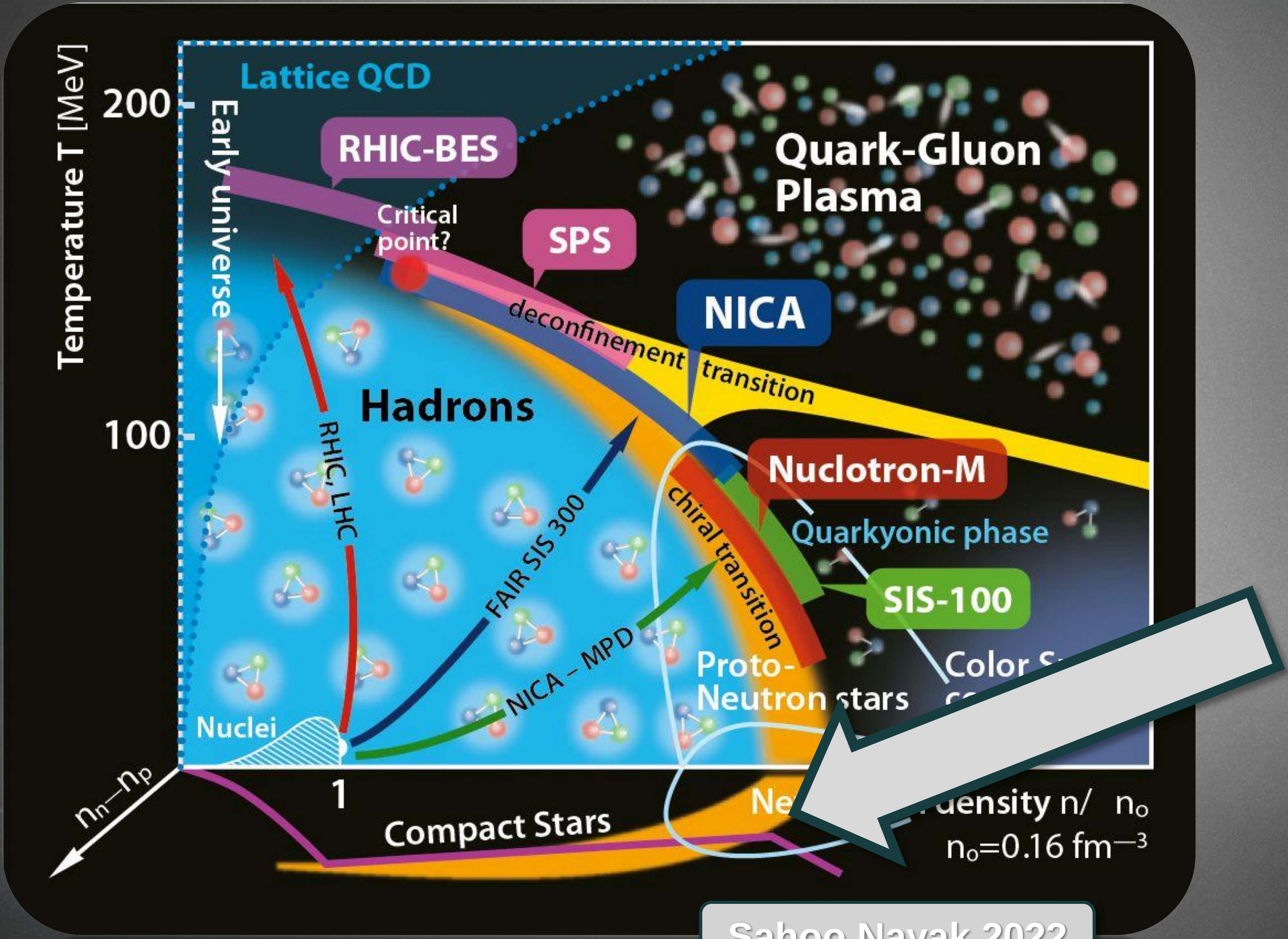
	Neutron star	White dwarf	Sun
$M_{max}(M_{\odot})$	2	1.44	1
R (km)	11-12	10^4	$7 \cdot 10^5$
n_c (g/cm^3)	$10^{14} - 10^{15}$	10^7	10^2
rotation speed (s)	$10^{-3} - 1$	100	$2 \cdot 10^6$
B (G)	$10^8 - 10^{16}$	100	1
T (K)	$10^6 - 10^{11}$	10^3	10^5

Possible composition of NSs

- ❑ **different possibilities (more or less in agreement with measurements)**
- ❑ **our work: First order phase transition to Quark Gluon Plasma (QGP)**
- ❑ **in general: → NSs → chance to probe QCD phase diagram**



QCD Phase Diagram



Sahoo,Nayak 2022

Construction of a hybrid NS

including ABPR parametrization

What is needed to obtain a possible NS configuration?

Tolmann-Oppenheimer-Volkoff Equations

(spherical symmetric and gravitational equilibrated objects)

$$\frac{dp}{dr} = -(\varepsilon + p)\frac{m+4\pi r^3}{r^2-2rm}$$

$$\frac{dm}{dr} = 4\pi r^2 \varepsilon$$

static

EoS $p(\varepsilon)$ **needs to be provided** → **hybrid EoS**

Model dependent choice:

→ First order phase transition between hadronic phase and Quark Gluon Plasma (QGP)

Hadronic phase:

- ❑ DD2npY-T model
- ❑ including protons, neutrons and hyperonic degrees of freedom

Quark matter phase:

- ❑ confining relativistic density functional approach
- ❑ encoded in underlying Lagrangian

Blaschke, Ivanytskyi (2022)

Relativistic density functional for quark EoS

$$\mathcal{L} = \bar{q}(i\partial\!\!\!/ - \hat{m})q + \mathcal{L}_{PS} + \mathcal{L}_V + \mathcal{L}_D$$

- **Pseudoscalar interaction ⇒ chiral dynamics**

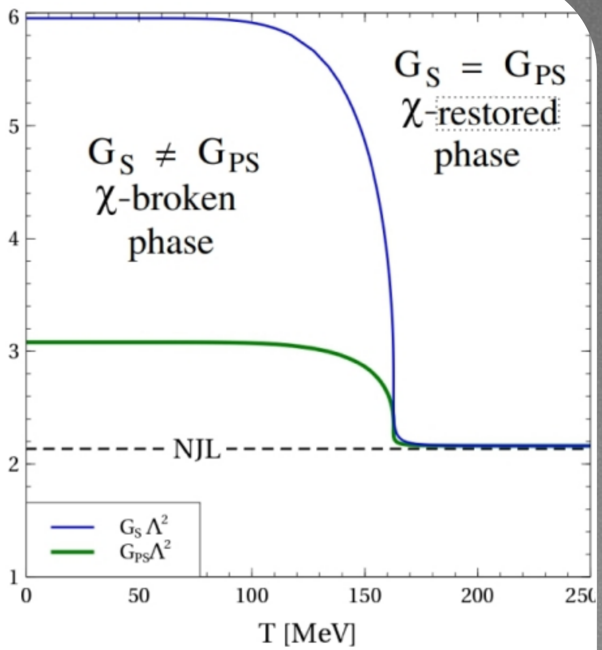
$$\mathcal{L}_{PS} = G_0 \left[(1+\alpha)\langle\bar{q}q\rangle_0^2 - (\bar{q}q)^2 - (\bar{q}i\vec{\tau}\gamma_5 q)^2\right]^{\frac{1}{3}}$$

- **Vector interaction ⇒ repulsion**

$$\mathcal{L}_V = -G_V(\bar{q}\gamma_\mu q)^2$$

- **Diquark pairing ⇒ color superconductivity**

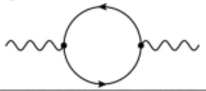
$$\mathcal{L}_D = G_D \sum_{A=2,5,7} (\bar{q}i\gamma_5\tau_2\lambda_A q^c)(\bar{q}^c i\gamma_5\tau_2\lambda_A q)$$



Details in:

Ivanytskyi, Blaschke, PRD (2022)

Ivanytskyi, Blaschke, Particles (2022)

- **Comparison to NJL model**
  - medium dependent scalar G_S and pseudoscalar G_{PS} couplings
  - high vacuum quark mass ⇒ phenomenological confinement
  - quark correlations ⇒ mesons: $\pi,\ \sigma\ =$ 

Summary

Chiral NJL-type model

- ❑ scalar and pseudoscalar coupling fixed by lightest mesons
- ❑ dimensionless couplings η_V, η_D left

Tedious calculations ahead…

ABPR parametrization

$$p = \frac{3A_4\mu^4}{4\pi^2} + \frac{3\Delta^2\mu^2}{\pi^2} - B$$

- extention of the bag pressure model accounting for the perturbative QCD correction to pressure and effects of quark pairing

M. Alford, M. Braby, M. W. Paris, and S. Reddy, Astrophys. J. 629, 969 (2005), arXiv:nucl-th/0411016

Fitting

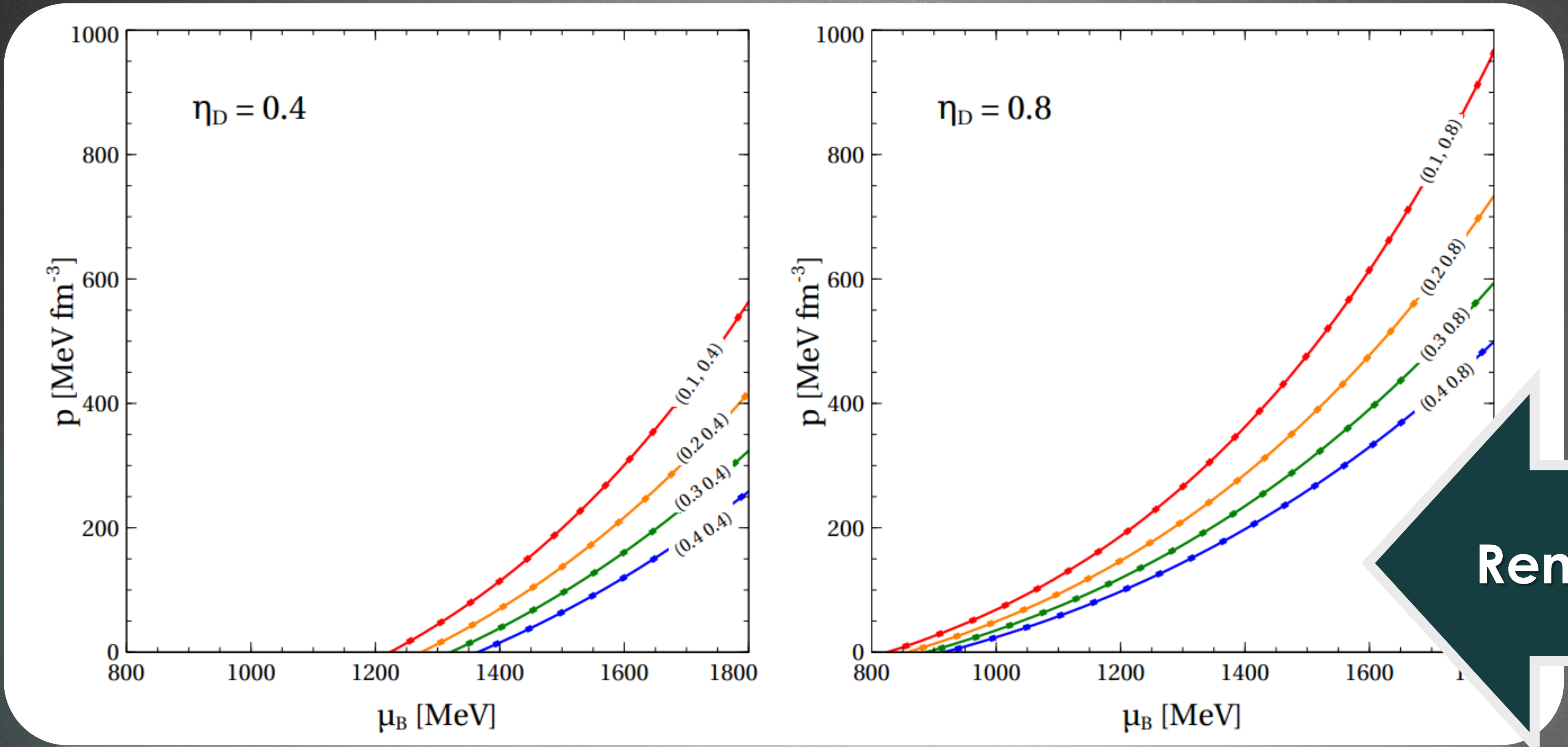
$$A_4 = a_1 + b_1\eta_V + c_1\eta_V^2 + (d_1 + \frac{e_1}{\eta_V})\eta_D,$$

$$\Delta = (a_2 + b_2\eta_V + c_2\eta_V^2)\sqrt{d_2 + e_2\eta_V + \eta_D},$$

$$B = a_3 + b_3\eta_V + c_3\eta_V^2 + d_3\eta_D + e_3\eta_D^2$$

i	units	a_i	b_i	c_i	d_i	e_i
1		0.757	-1.955	1.799	-0.063	0.046
2	[MeV]	300.7	8.534	-308.2	-0.235	1.458
3	[MeV/fm^3]	72.018	170.8	-241.0	512.7	-626.6

Comparison

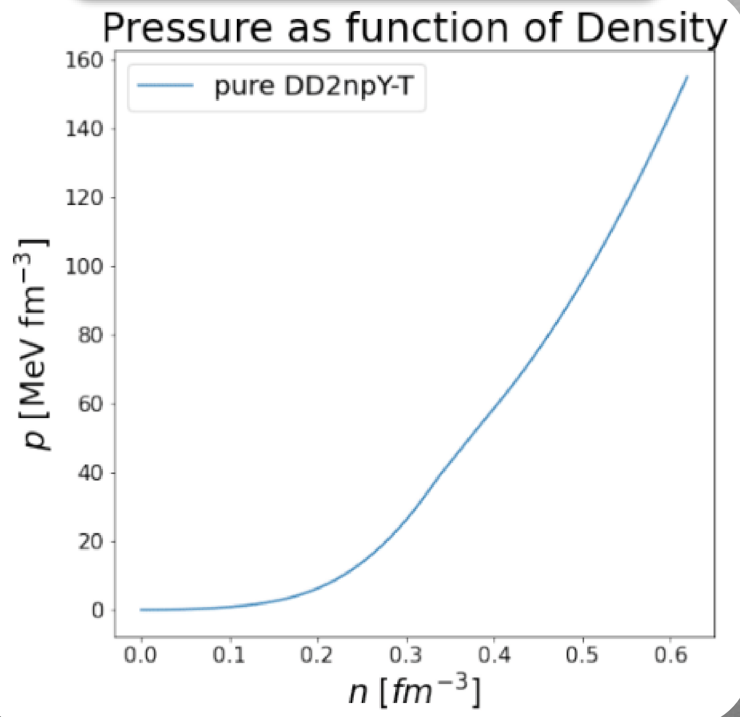


Remarkble tool!

❑ remarkable agreement between RDF approach (solid lines) and the ABPR parametrization (dots) !

Maxwell construction

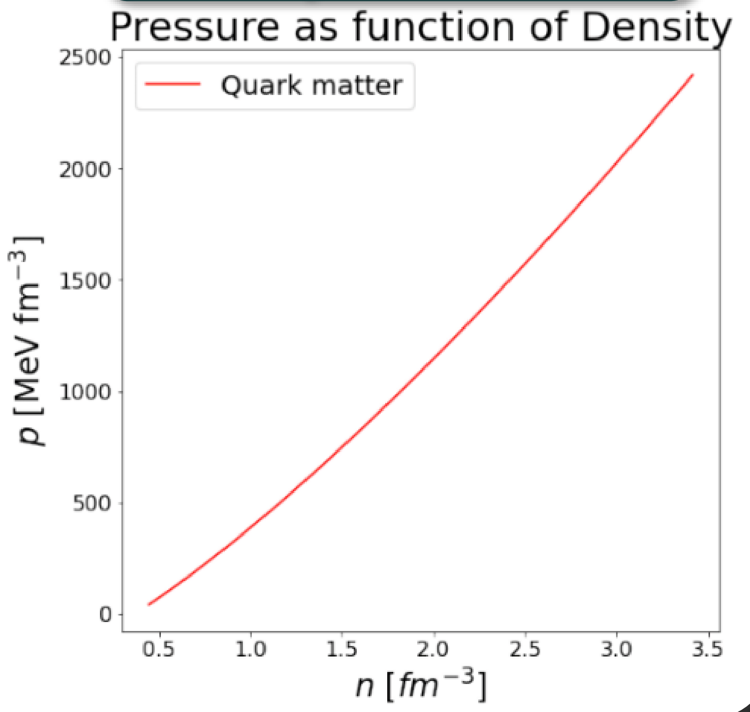
Hadronic phase:



look for intersection of $p(\mu)$ curves

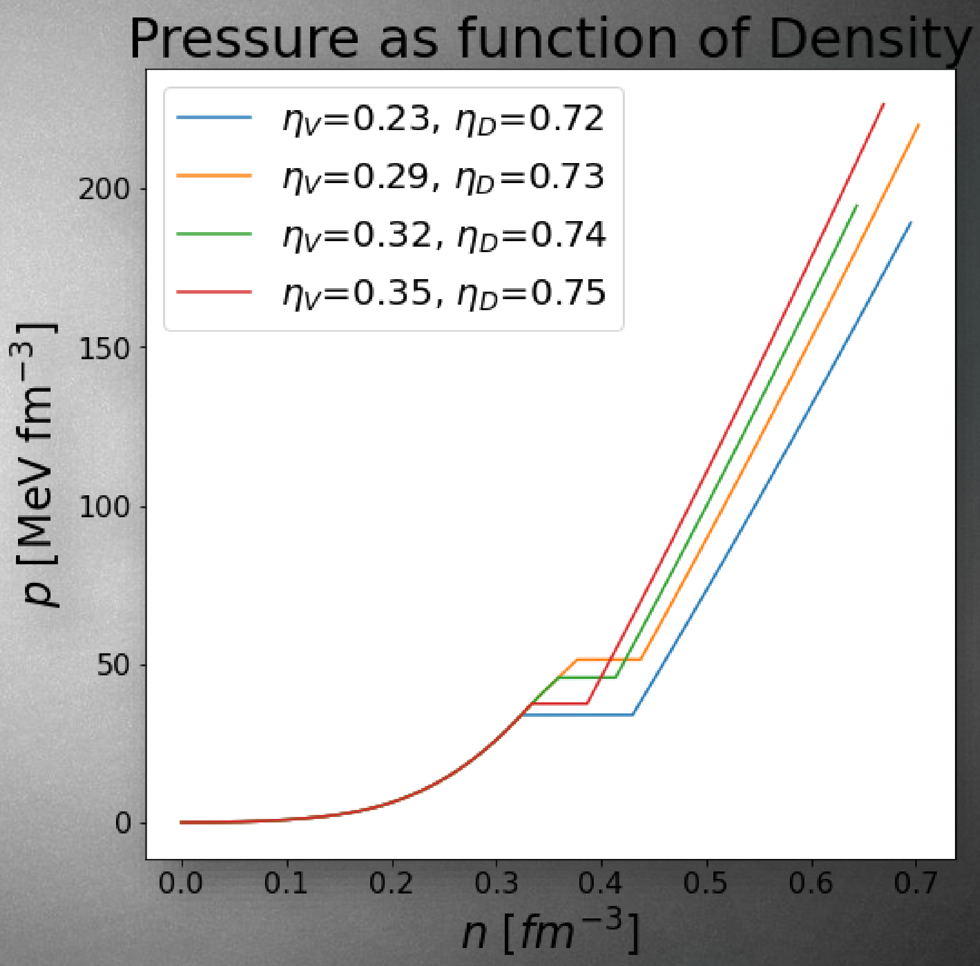
$$p_{Hadron}(\mu_c) = p_{Quark}(\mu_c) \Rightarrow \mu_c$$

Quark matter phase:

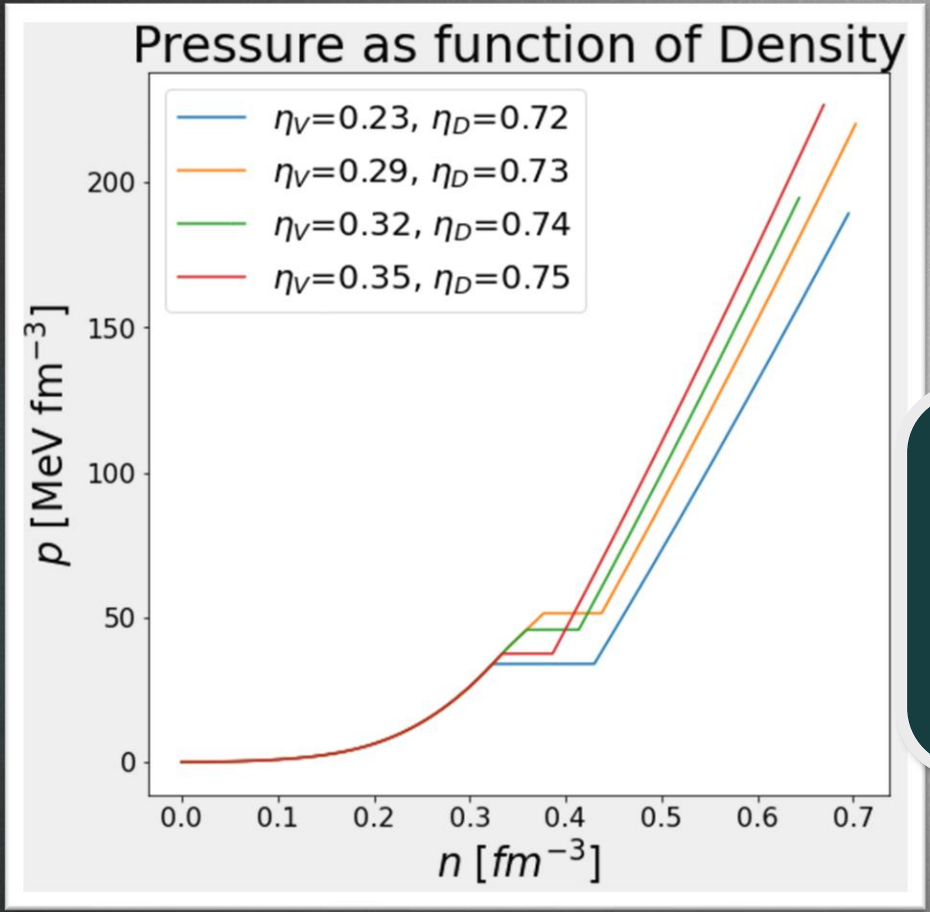


Resulting curves

- ❑ hybrid EoS
- ❑ typical plateau of first order phase transition
- ❑ But: inside star, no shell of mixed phase → narrow



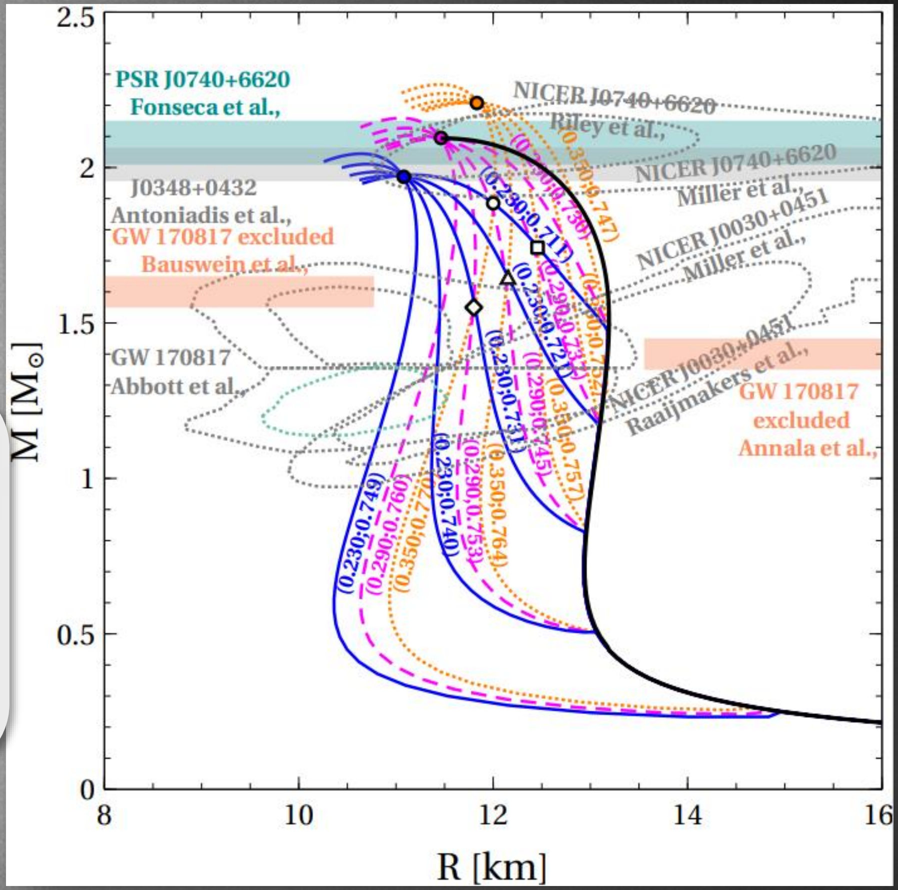
From EoS to M-R curves



TOV

$$\frac{dp}{dr} = -(\varepsilon + p)\frac{m+4\pi r^3}{r^2-2rm}$$

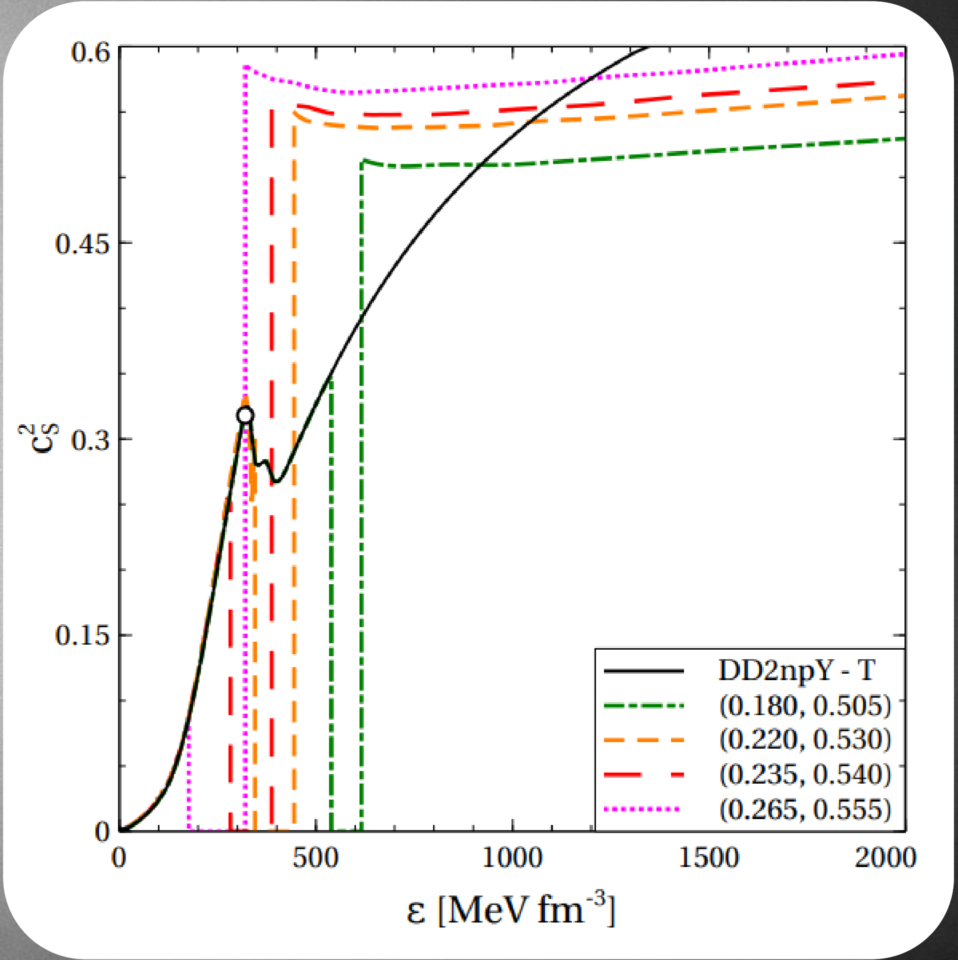
$$\frac{dm}{dr} = 4\pi r^2 \varepsilon$$



Often requested…

Speed of sound

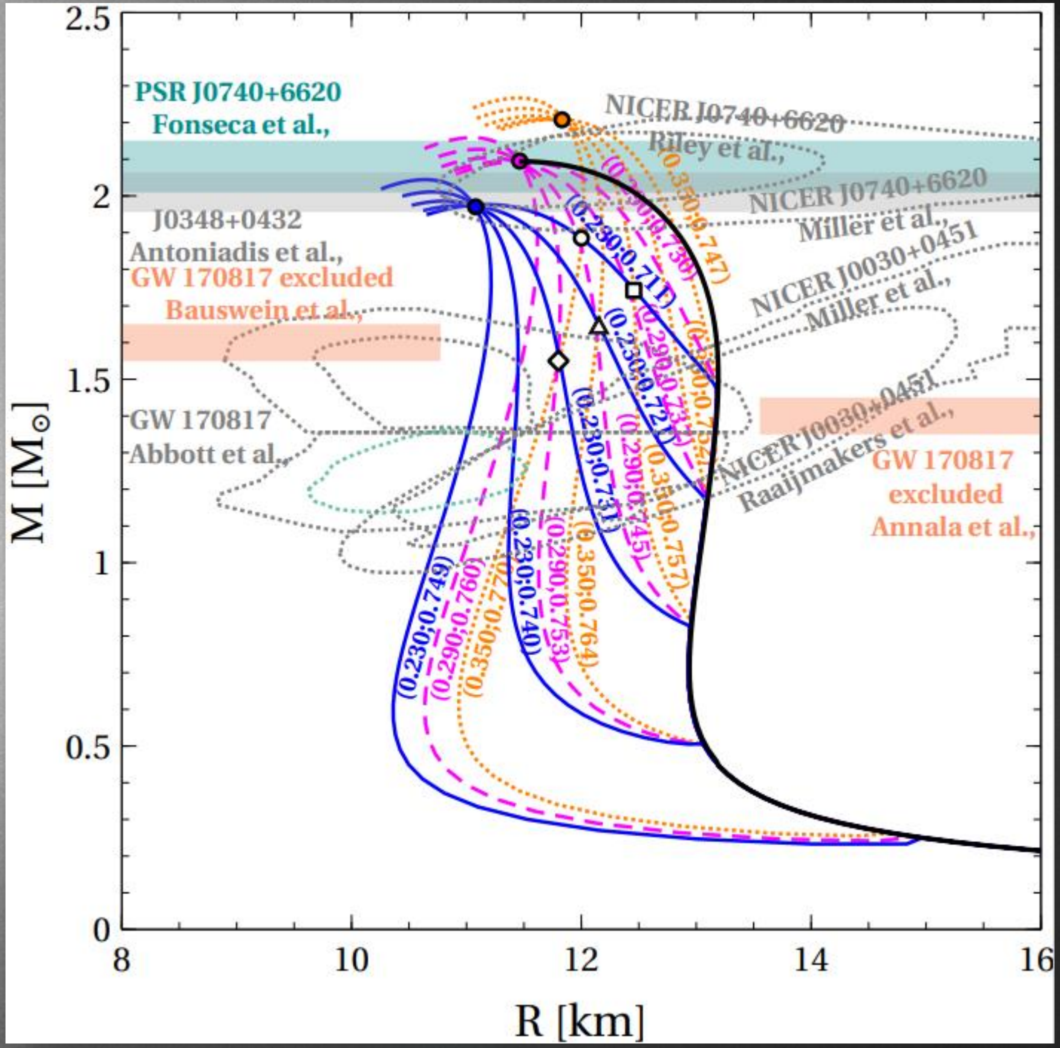
→ reaching conformal limit



Properties of M-R curves
… towards Special Points

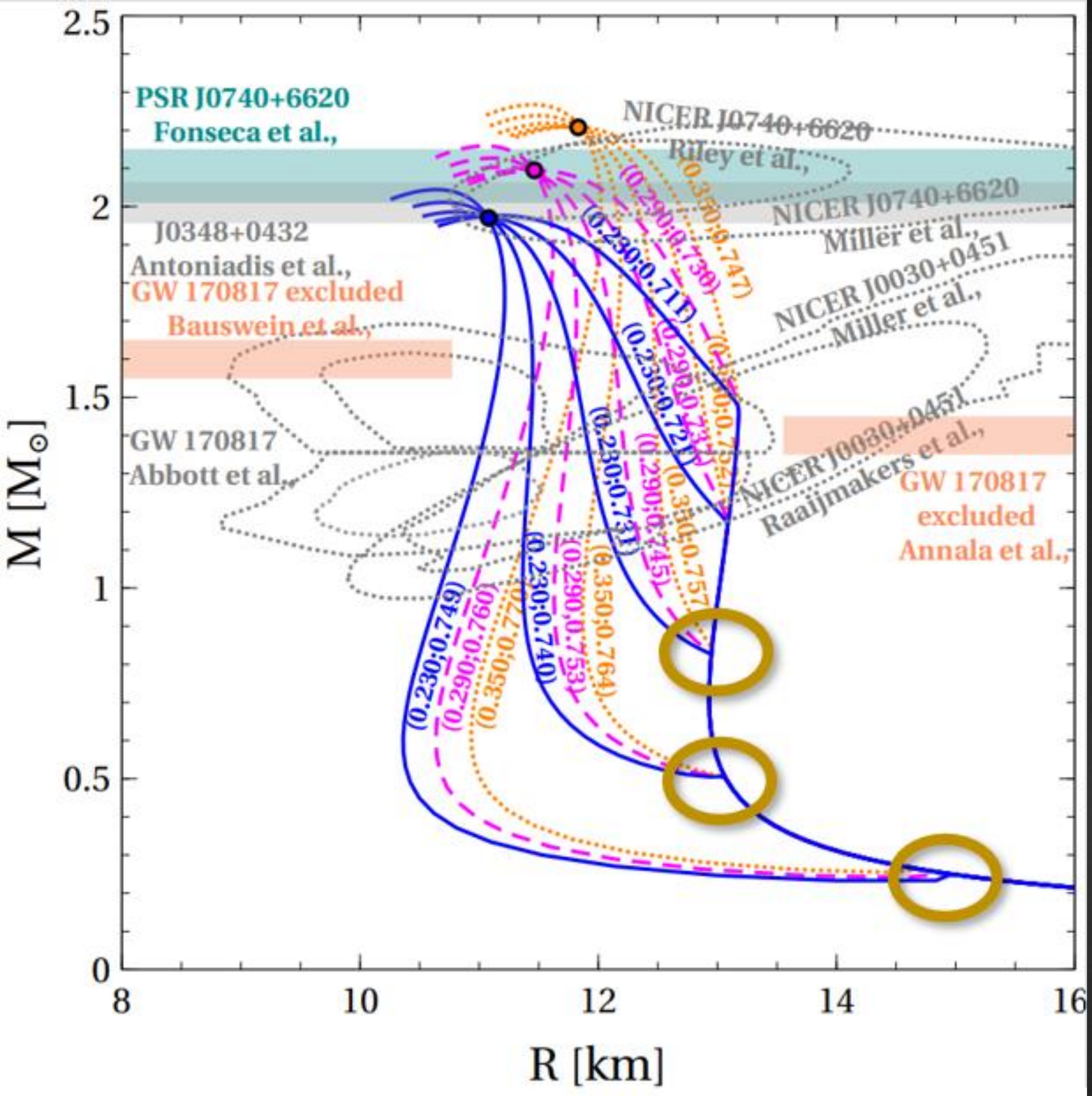
Preliminary comments

- each point is a NS configuration
- astrophysical constraints in the background
- plots for different combinations of η_V and η_D
- point of leaving the black curve
  → deconfinement phase transition



Deconfinement phase transition

- certain combination (η_V ,η_D) of give point of phase transition
- fixed η_V : smaller diquark coupling → later deconfinement
- larger η_D → earlier phase transition but greater maximum mass

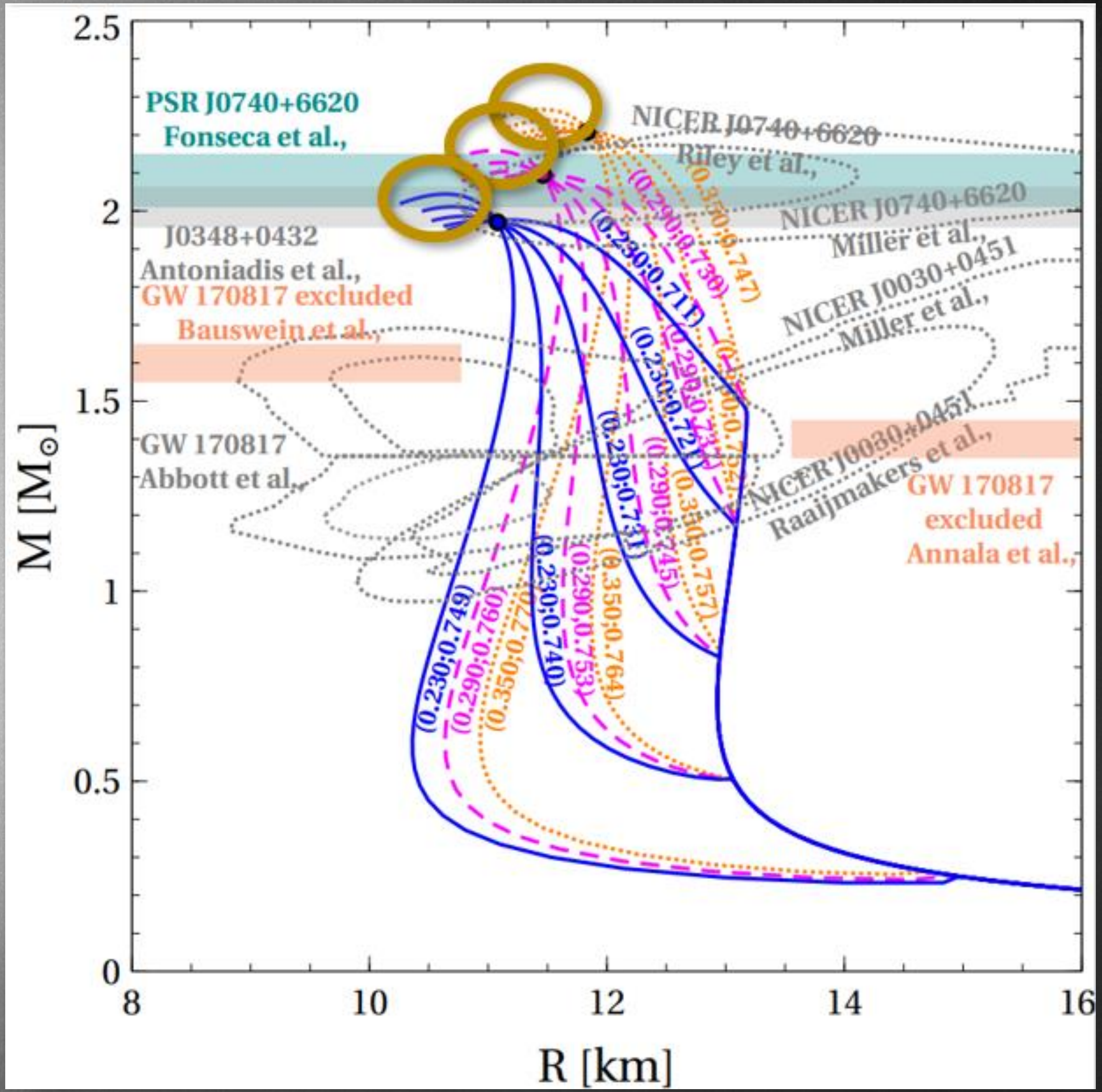


Maximum mass

- ❑ curves greater vector repulsion
  → higher maximum masses

- ❑ in general combination fixes
  maximum mass

- ❑ higher vector repulsion
  → stiffer EoS → higher masses



Special Points

Fitting parameters:

- ❑ relates observable quantities (M_{Max}, M_{Onset})

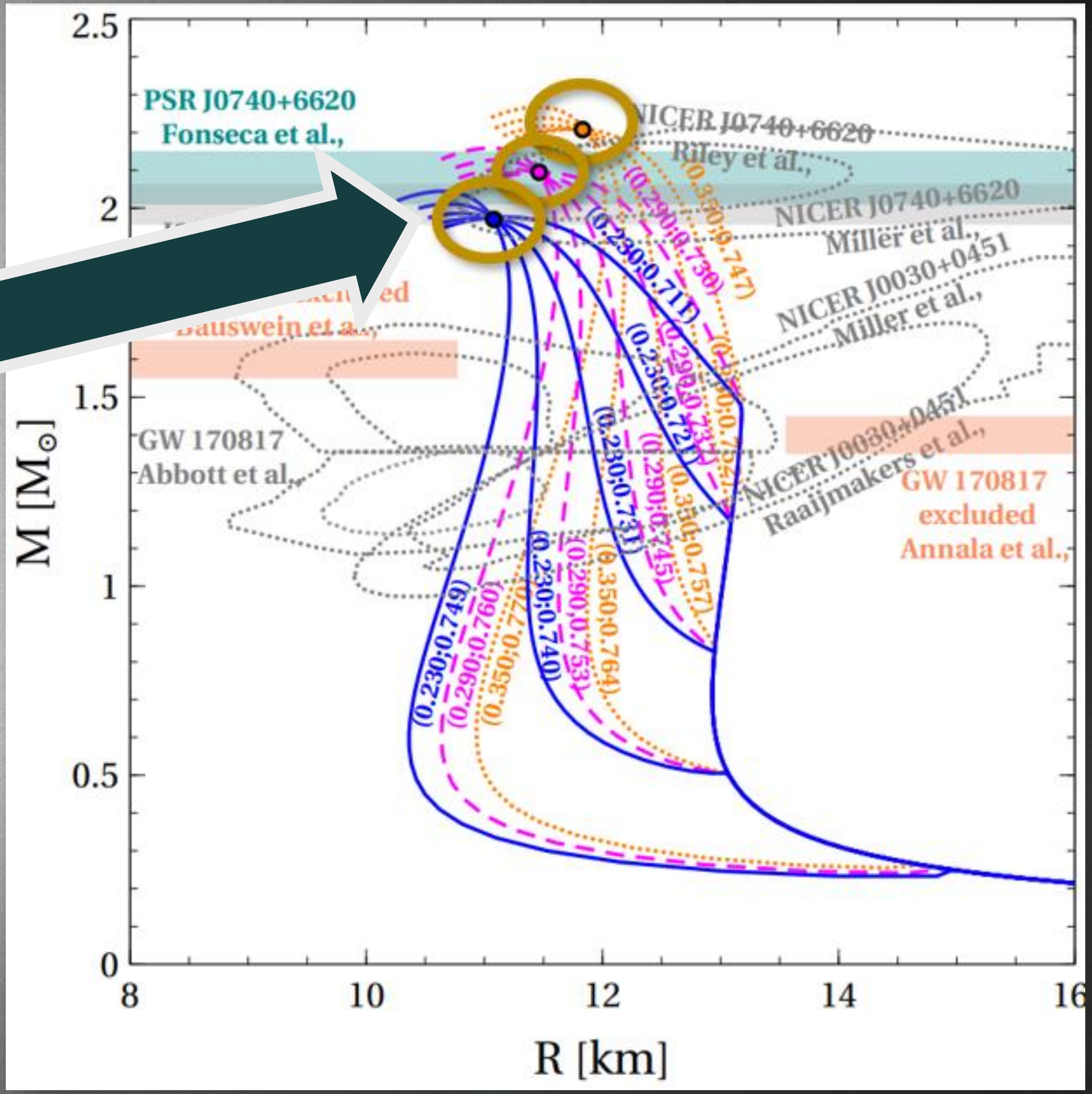
$$M^*_{onset} = 1.254 M_\odot,$$

$$\delta = k_\delta \eta_V + b_\delta,$$

$$k_\delta = -0.096\ \mathrm{M}_\odot^{-1} \qquad b_\delta = 0.093\ \mathrm{M}_\odot^{-1}$$

- ❑ empirical relation:

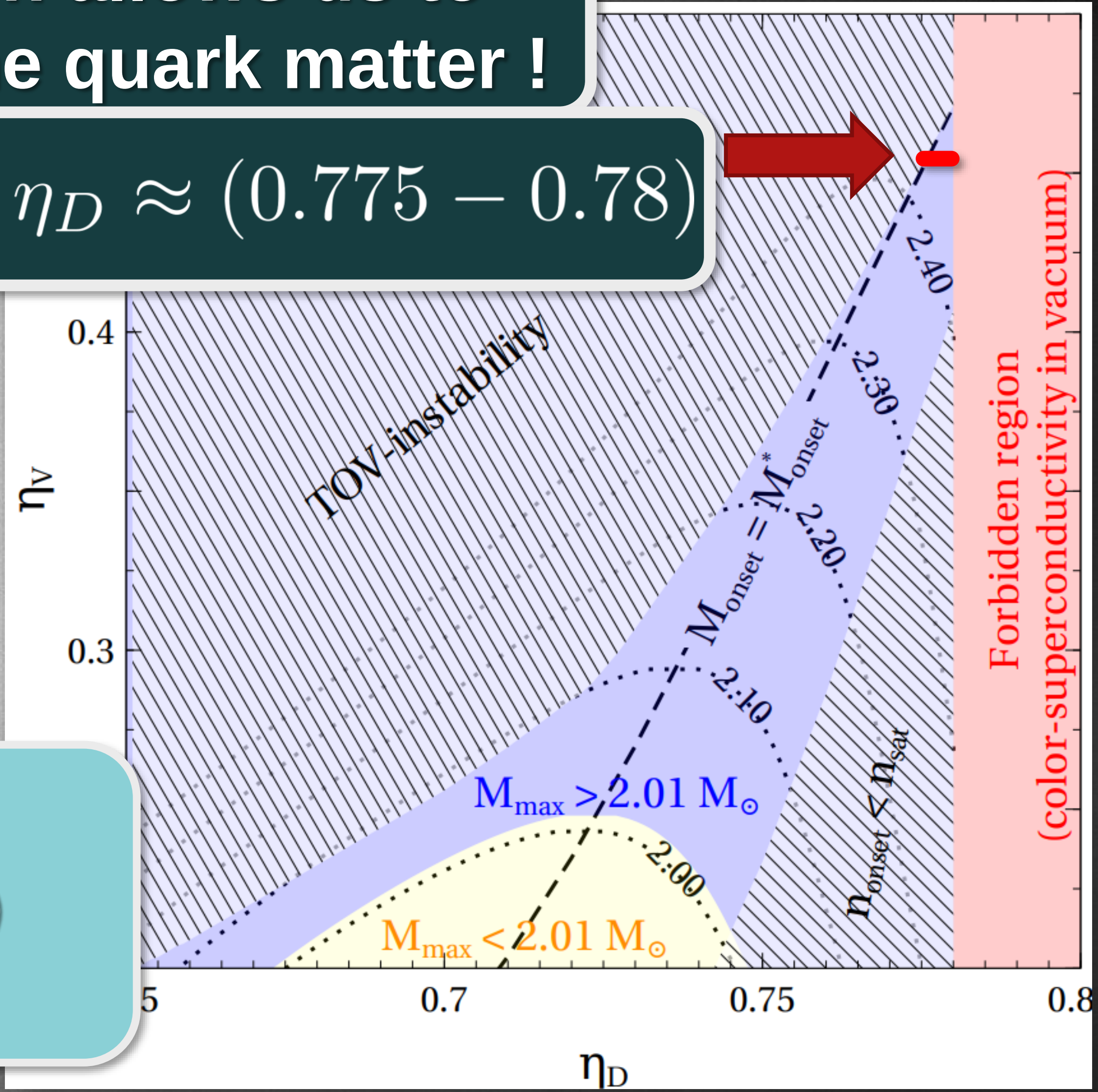
$$M_{Max} = M_{SP} + \delta |M^*_{onset} - M_{onset}|^2$$



Restricting couplings

This pretty accurate relation allows us to constrain the couplings of the quark matter !

$$\eta_D \approx (0.775 - 0.78)$$



Constraints

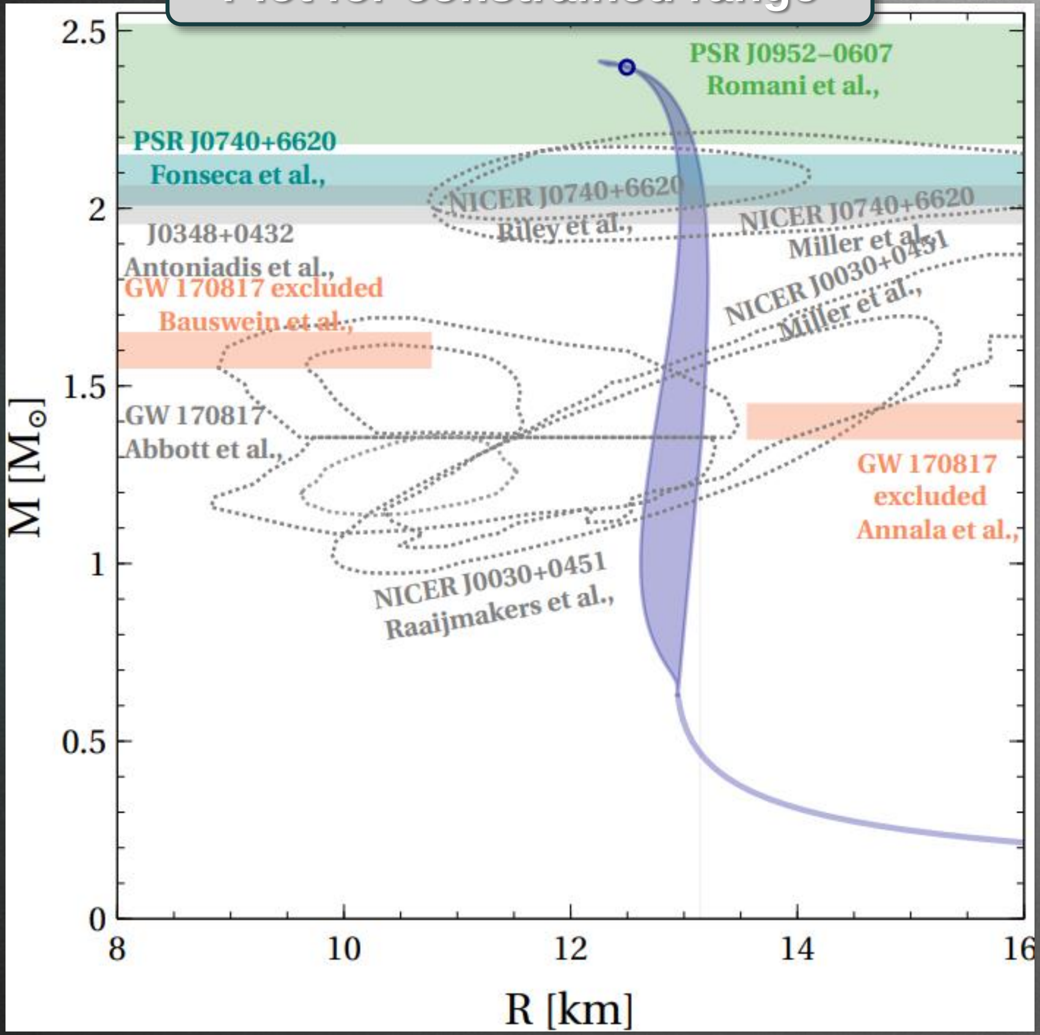
- TOV instability
- no phase transition before n_{sat}
- vacuum stable against color-superconductivity

→ further restriction:
→ fix η_V with vector meson mass (ω meson)

$$M_\omega = 782\text{MeV} \rightarrow \eta_V = 0.452$$

Implications

Plot for constrained range



- ❑ in good agreement with astrophysical constraints
- ❑ special point → blue dot
- ❑ in agreement with black widow pulsar → green bar

Conclusion

- phenomenological EoS → in agreement with astrophysical constraints (including deconfinement and color superconductivity)
- ABPR parametrization enables numerical advantages
- interesting behaviour: Variation of η_D while fixing η_V → family of hybrid EoS → M-R curves intersect in Special point
- microscopic parameters govern special point (independent of hadronic EoS, due to First Order Phase Transition)

Thank you for your attention

Conclusion

- emperical relation allows us to constrain the onset mass (phase transition) → contraints on couplings
- further constraints on η_V give small allowed range of M-R → massive NS in agreement with astrophyiscal constraints
- early deconfinement possible
- radial oscillations may give insights as well