Multimessenger constraints for ultra-dense matter

Tyler Gorda
IKP - TU Darmstadt,

NSs as multi-messenger laboratories for dense matter (online), 2021-06-16

Work in Collaboration with:

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V. Paschalidis, A. Vuorinen

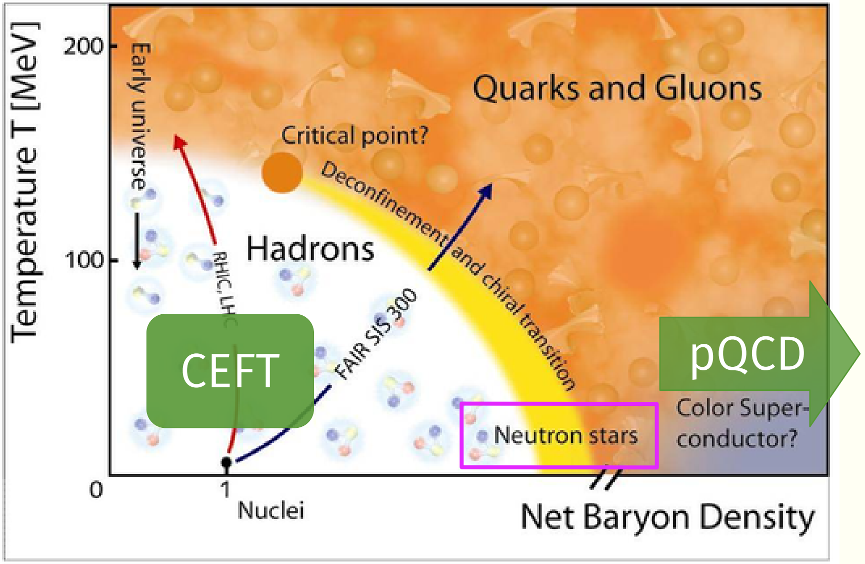
TECHNISCHE UNIVERSITÄT DARMSTADT

arXiv: 2105.05132

SFB 1245

Approach and motivation

- Extend NS EOS beyond controlled nuclear regime; use knowledge that QCD EOS goes to pQCD at high densities.



Compressed Baryonic Matter (CBM) experiment

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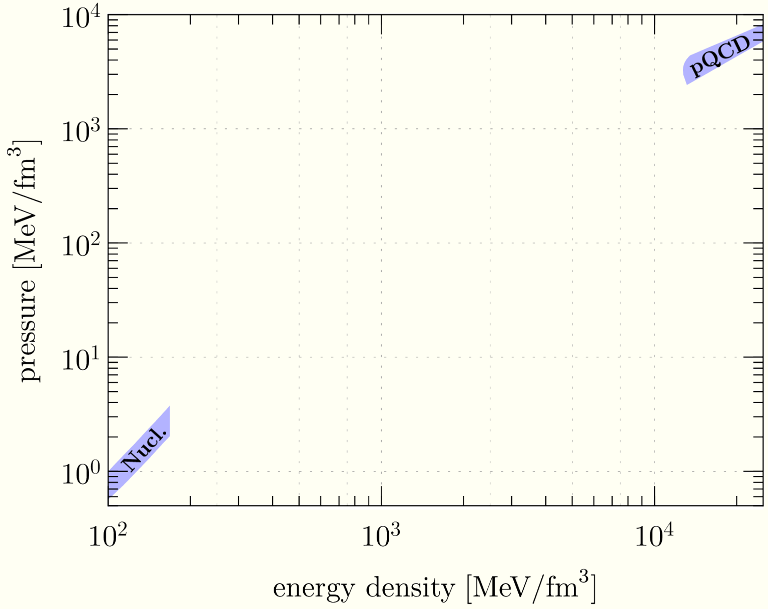

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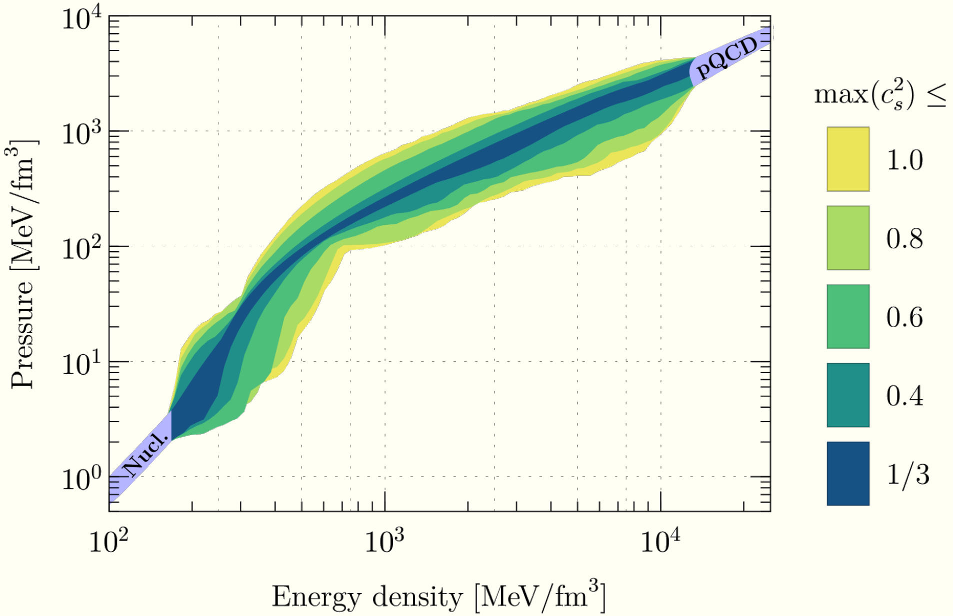
- Use ***parametrized-EOS ensemble approach*** to determine all allowed behaviors of the EOS between low and high density constraints. Want to be as conservative as possible!



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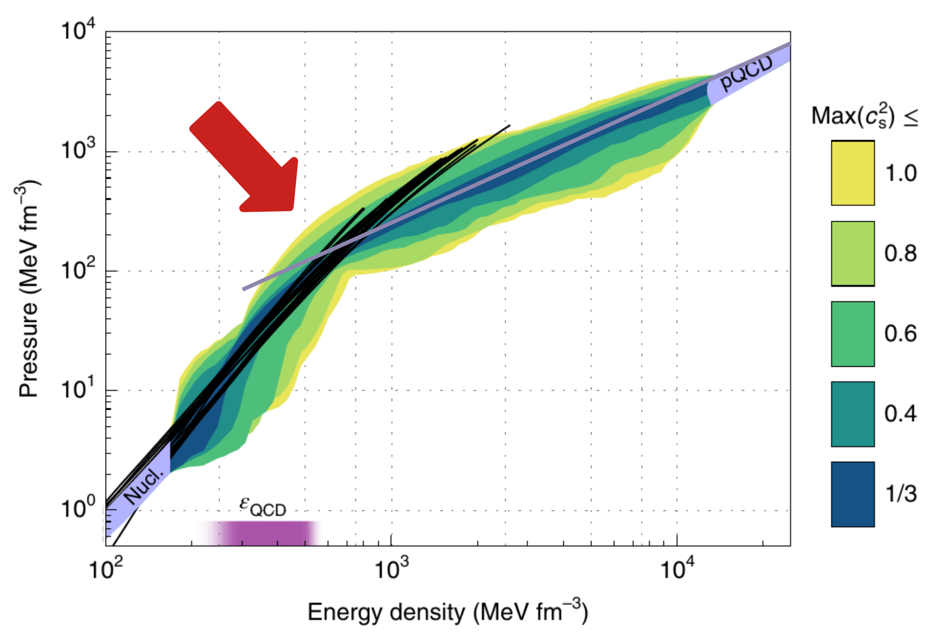
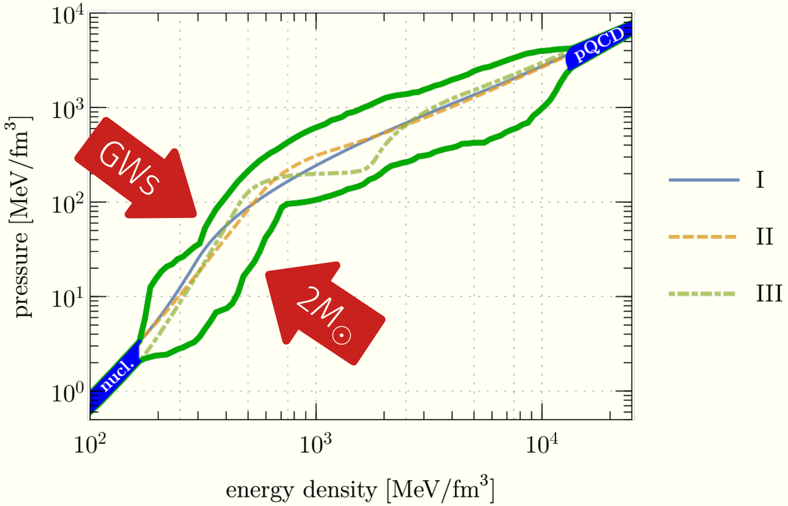
- Use ***parametrized-EOS ensemble approach*** to determine all allowed behaviors of the EOS between low and high density constraints. Want to be as conservative as possible!
- Has provided evidence for ***quark matter cores*** in massive NSs, identifying transition with softening of the EOS. Generic for EOSs with $\max(c_s^2) \leq 0.5$.
  Annala et al. Nature Phys. 2020



Motivation

- So far, have only used ***most robust*** constraints:
  - $M_{\mathrm{TOV}} \geq 2.0 M_{\odot}$
  - $\tilde{\Lambda} < 720$ for GW1701817
    $(q \in [0.73, 1], \mathcal{M}_{\mathrm{chirp}} = 1.186 M_{\odot})$



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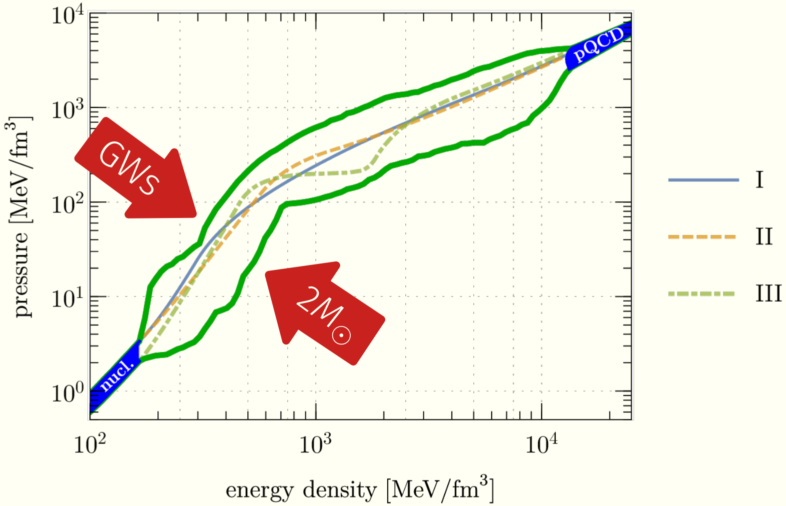
- *Other robust constraints that we can use?*



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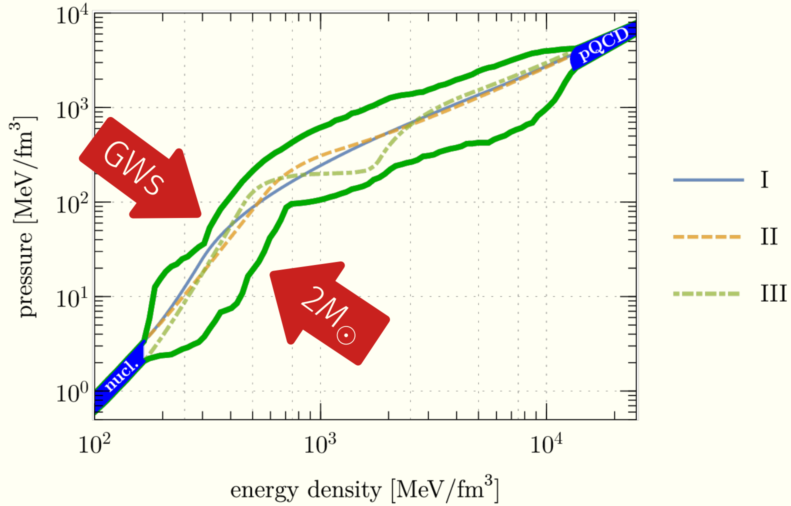

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  - $R(2.0M_\odot) \geq 11$ km, from measurement of PSR J0740+6620 by NICER+XMM

Also look at:
- GW190814
- future measurements

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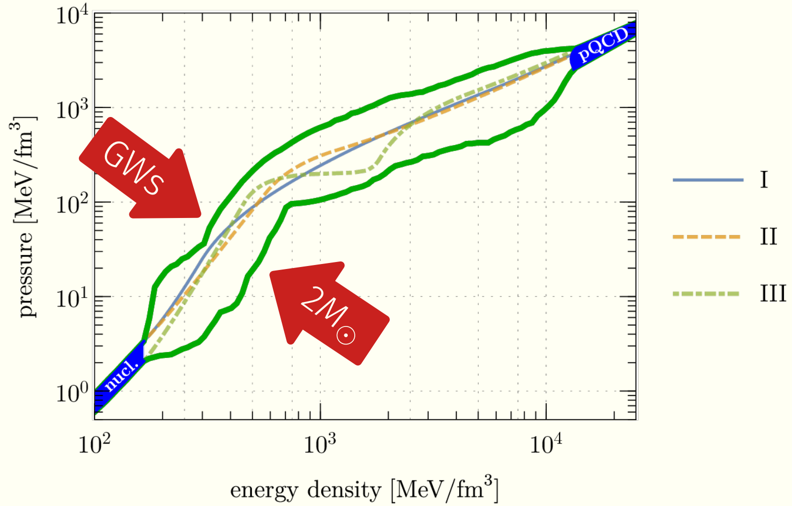

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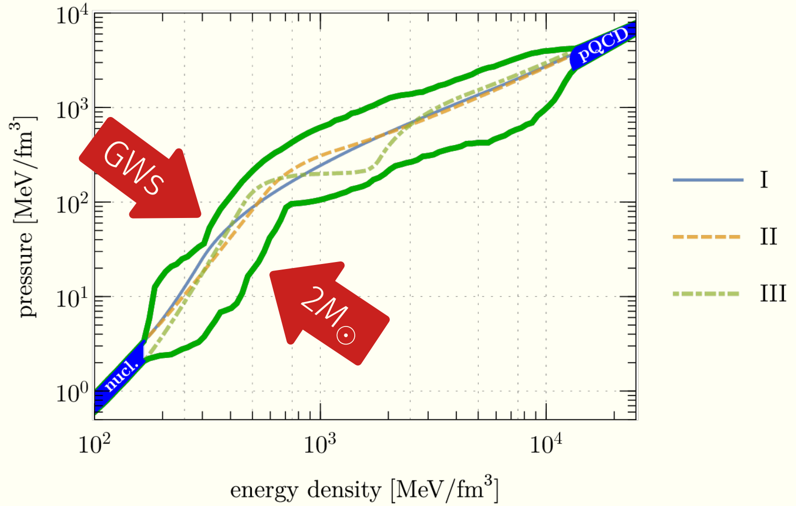

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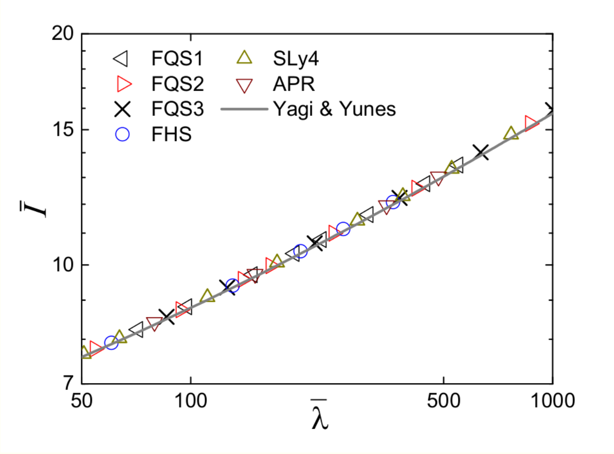
Less straightforward (esp. HMNS-hyp)

Straightforward

Methodology

- How to enforce BH-hyp or HMNS-hyp, ***without using quasi-universal relations?***
  - Additional input with unknown uncertainties for general EOS
  - Are known to be violated for EOSs with, e.g. 1st-order PTs Lau + Phys. Rev. D 95, (2017); Bandyopadhyay + Eur. Phys. J. A 54, (2018); Han and Steiner Phys. Rev. D 99, (2019); Bozzola + Eur. Phys. J. A 55, (2019)



Sample quasi-universal relation, Lau + Phys. Rev. D 95, (2017)

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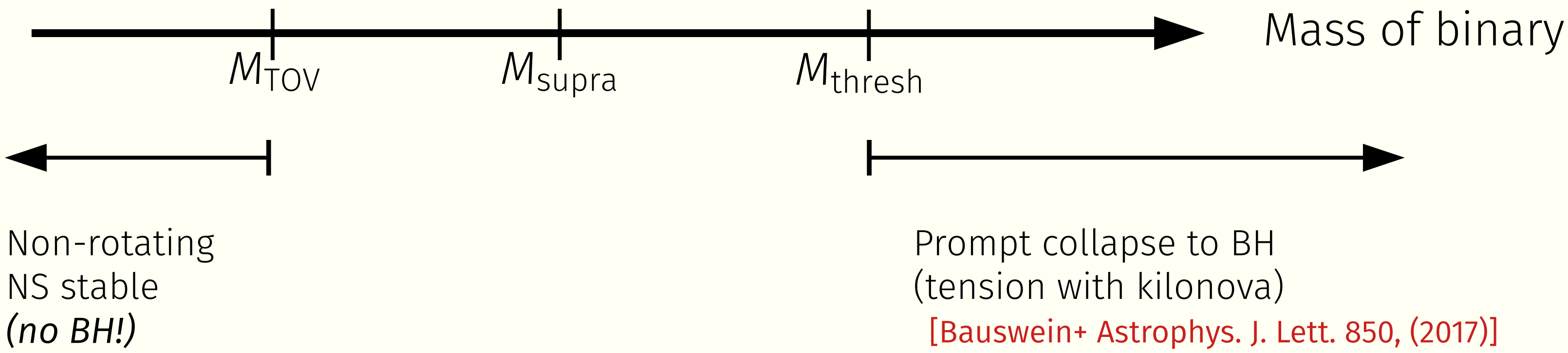

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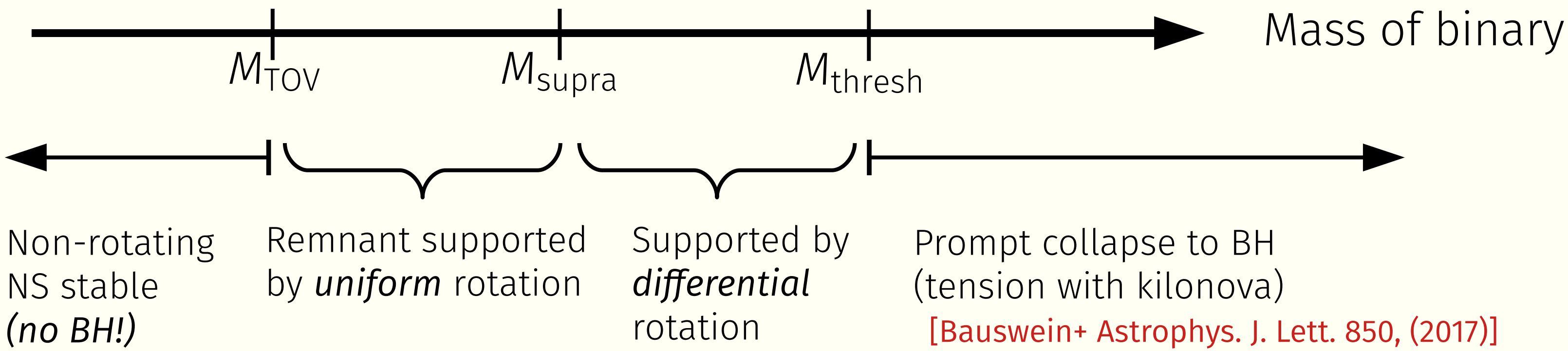

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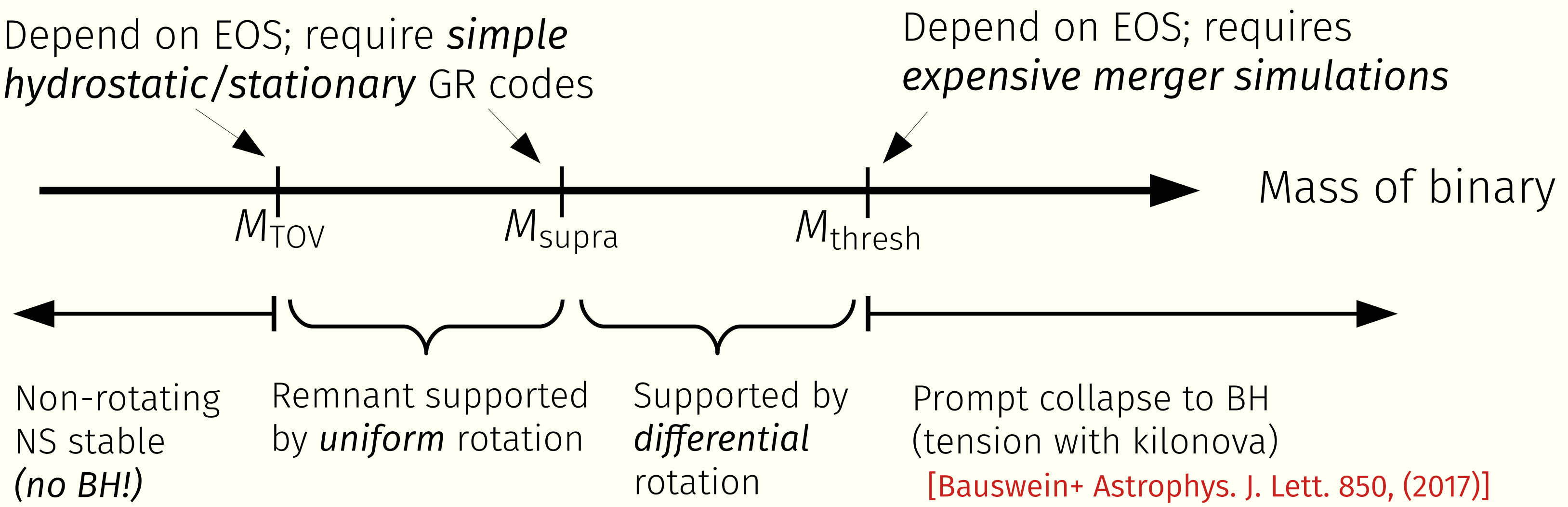

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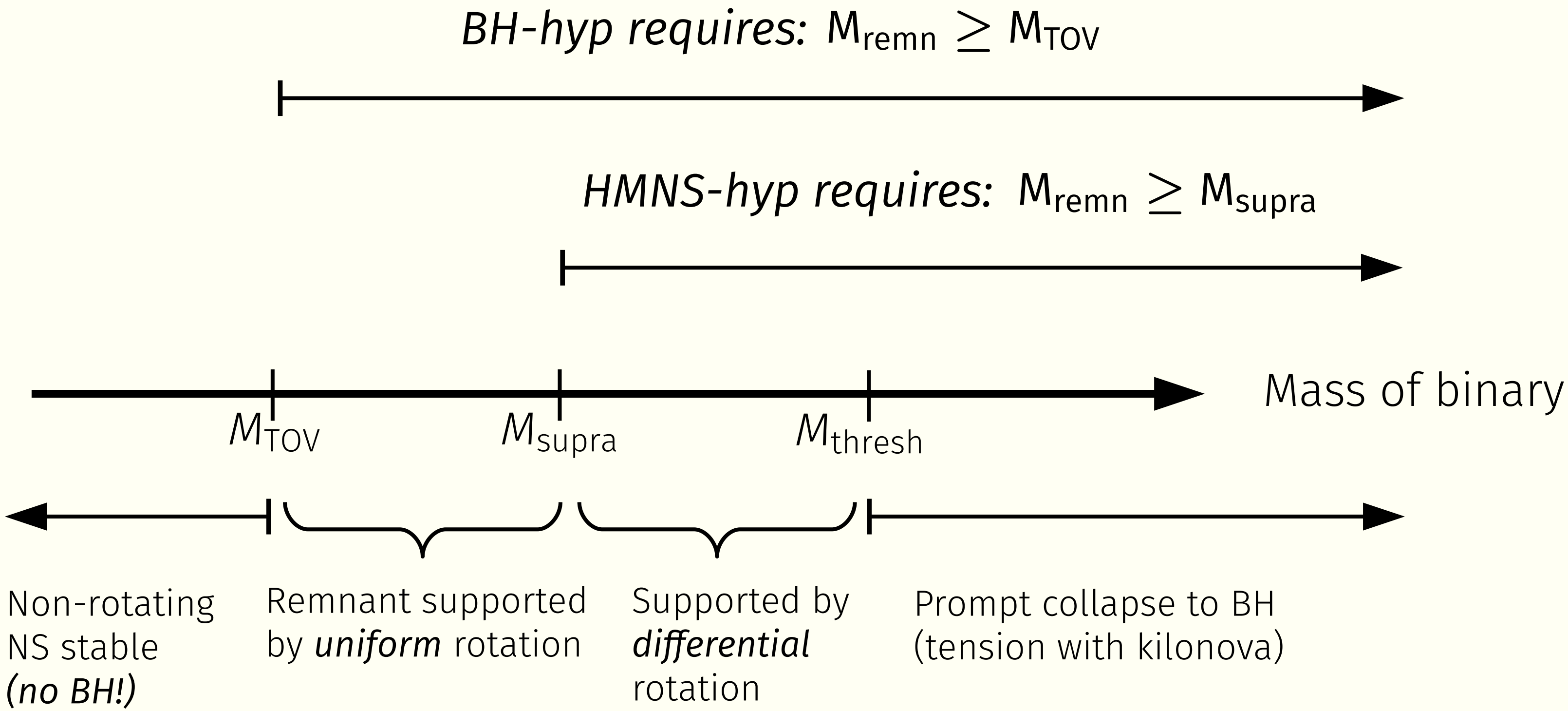

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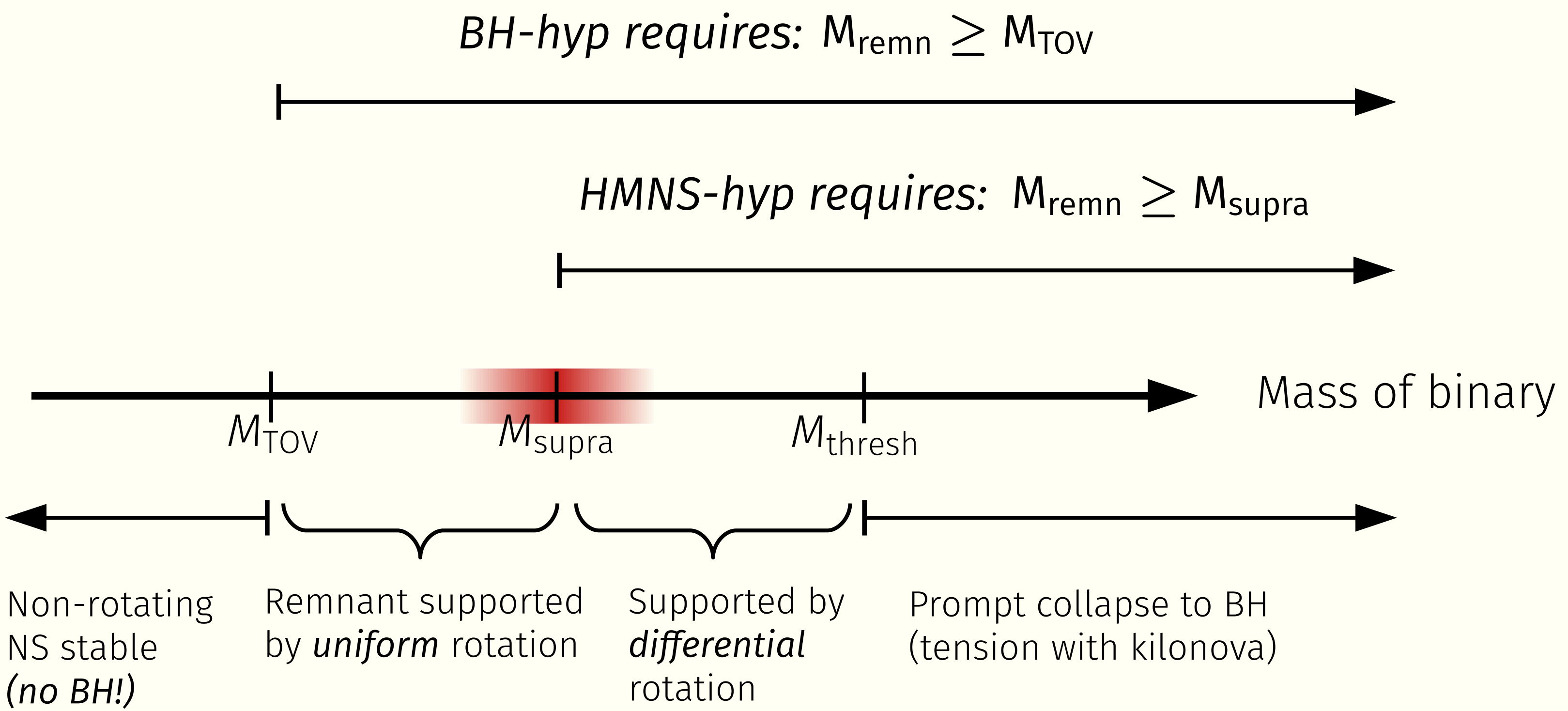

*kilonova and GRB suggest BH formed near M_{supra}

Margalit and Metzger, Astrophys. J. Lett. 850, (2017);
Rezzolla+ Astrophys. J. Lett. 852, (2018);
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Methodology

- Technical point: M not conserved, $M_{\mathrm{B}} = \bar{m} \cdot N_{\mathrm{B}}$ is!

$$M_{\mathrm{B,remn}} = M_{\mathrm{B},1} + M_{\mathrm{B},2} - M_{\mathrm{B,ejecta}}$$

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  1) $M_{\mathrm{B,remn}}(q) \geq M_{\mathrm{B,crit}}, \qquad M_{\mathrm{B,crit}} \in \{M_{\mathrm{B,TOV}}, M_{\mathrm{B,supra}}\}$
  2) $\tilde{\Lambda}(q) < 720$ (low-spin priors)

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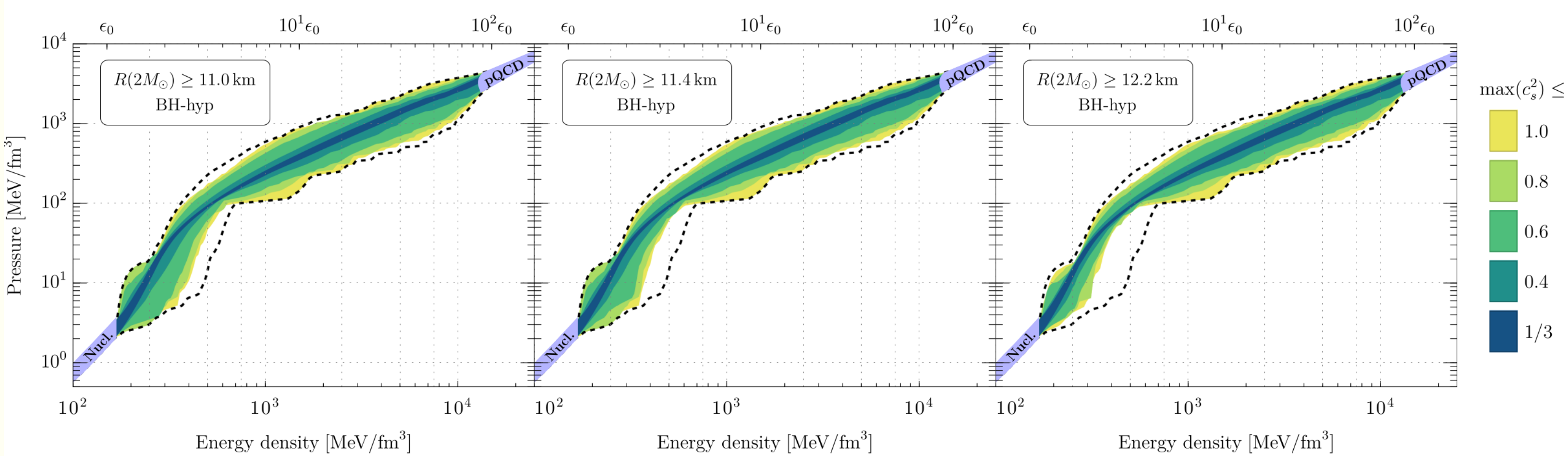
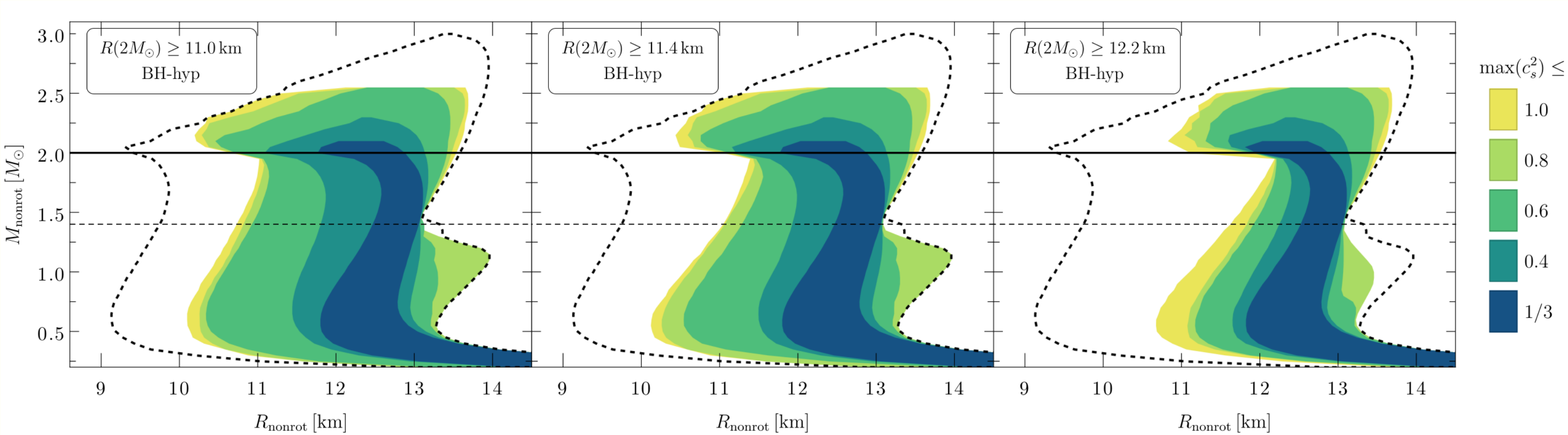
  2) $\tilde{\Lambda}(q) < 720$ (low-spin priors) *also look at high-spin priors

*additionally, implement $R(2M_\odot)$ lower bounds

Results

Results: BH-hyp + PSR J0740+6620 – most conservative





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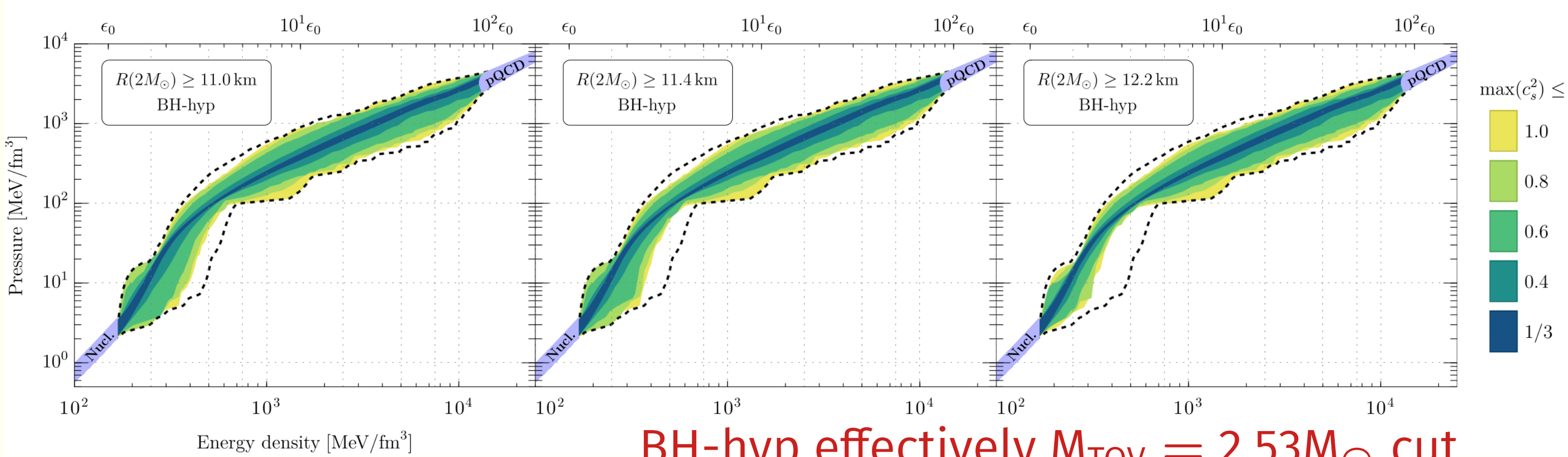
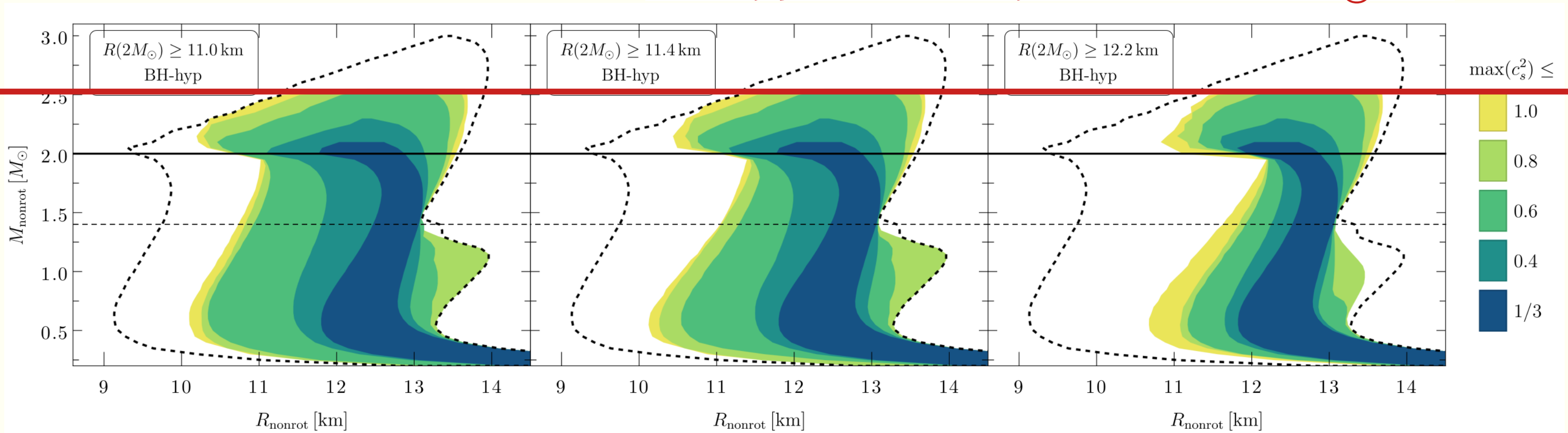


BH-hyp effectively $M_{TOV} = 2.53 M_\odot$ cut



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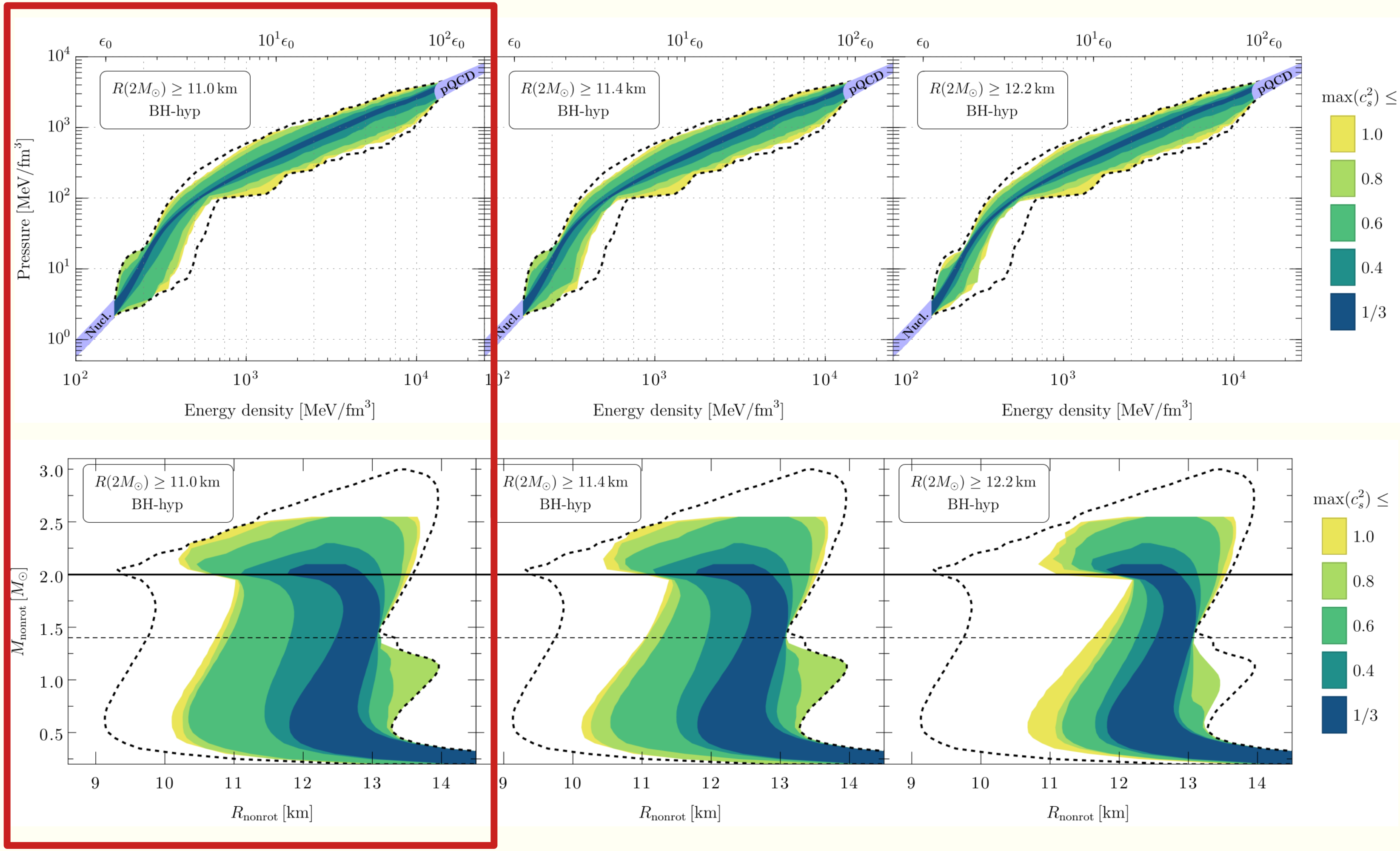
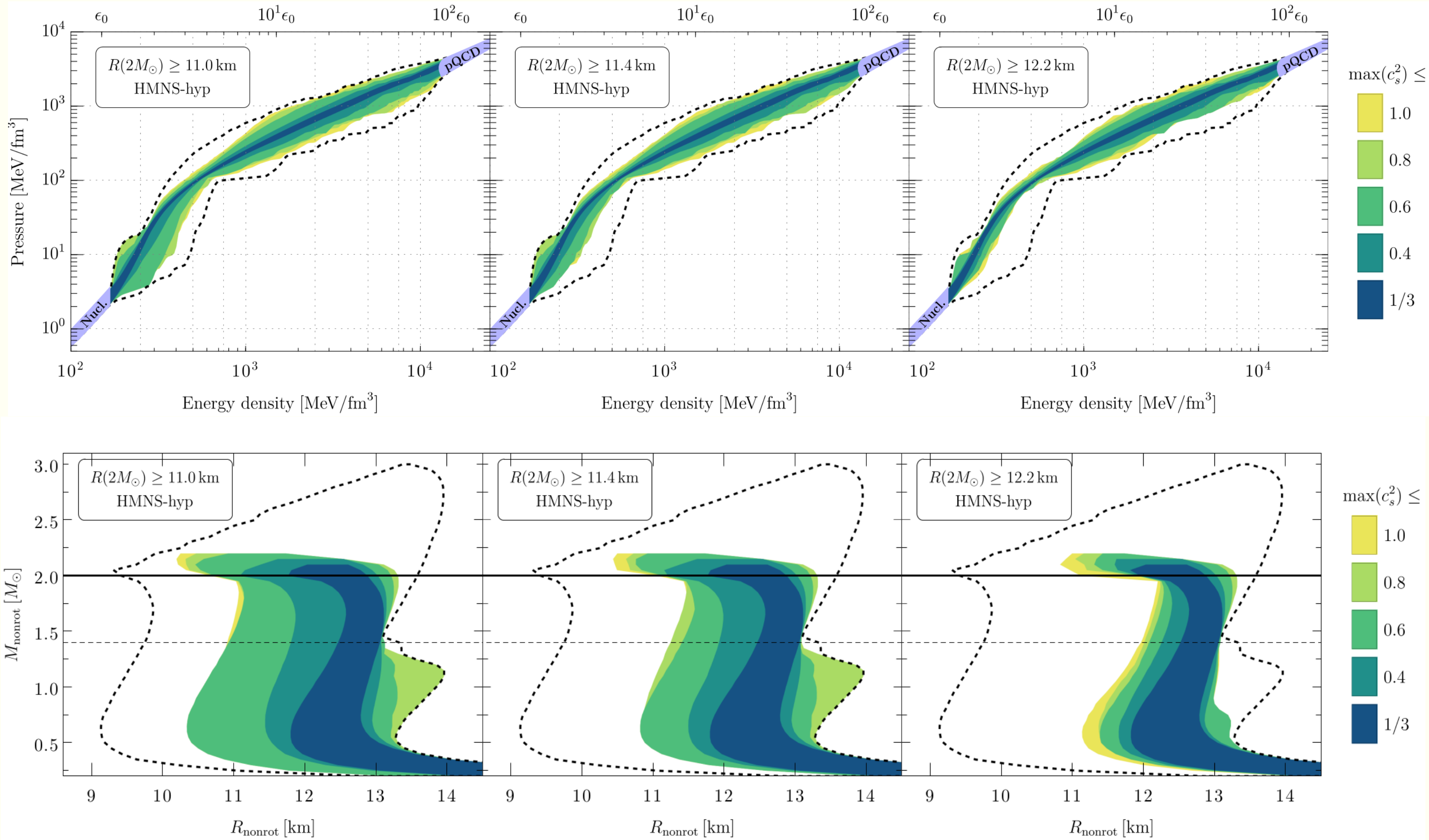
Main result



Results: HMNS-hyp + PSR J0740+6620 – more consistent with kilonova, GRB



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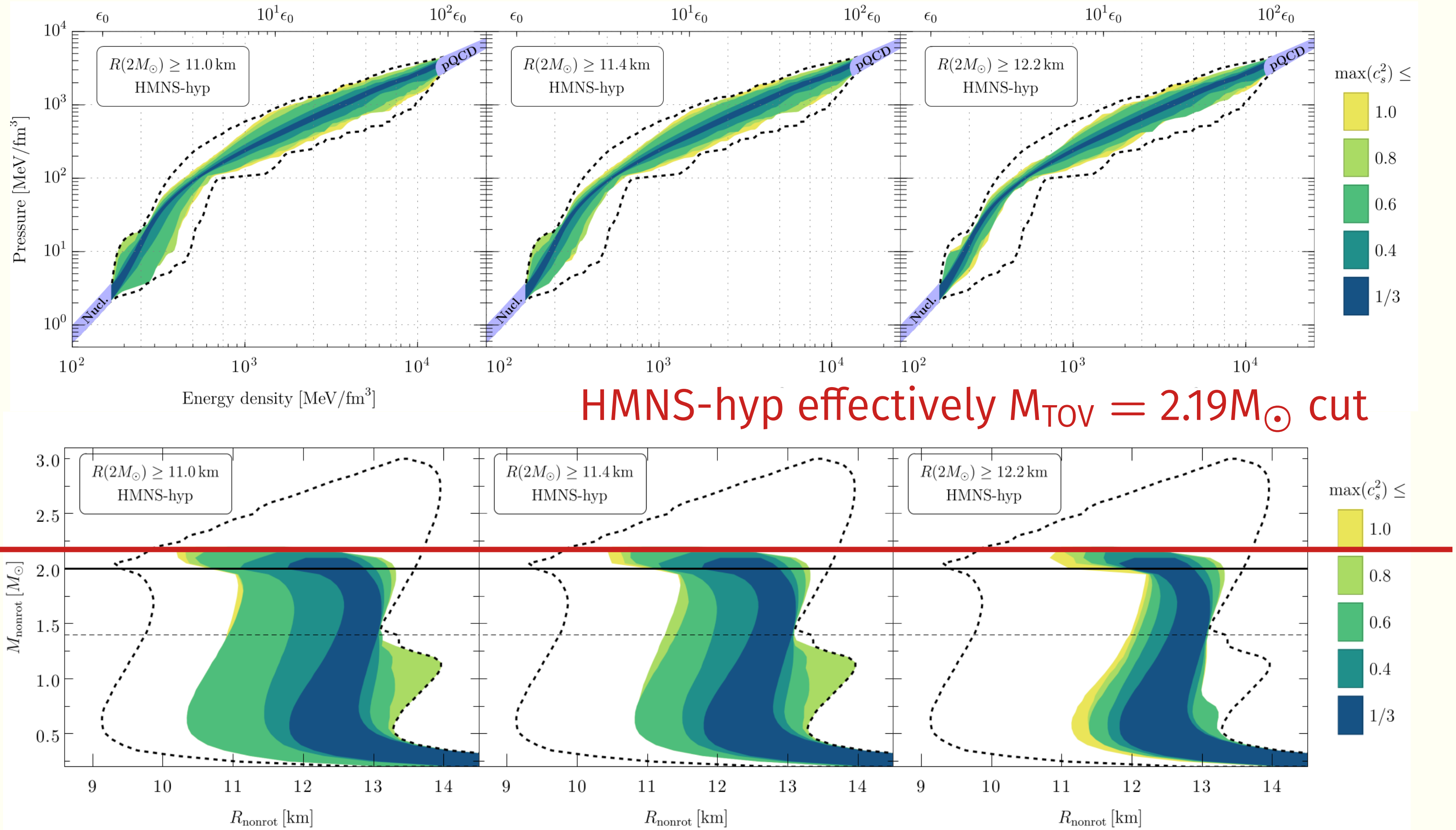

HMNS-hyp effectively $M_{TOV} = 2.19 M_\odot$ cut

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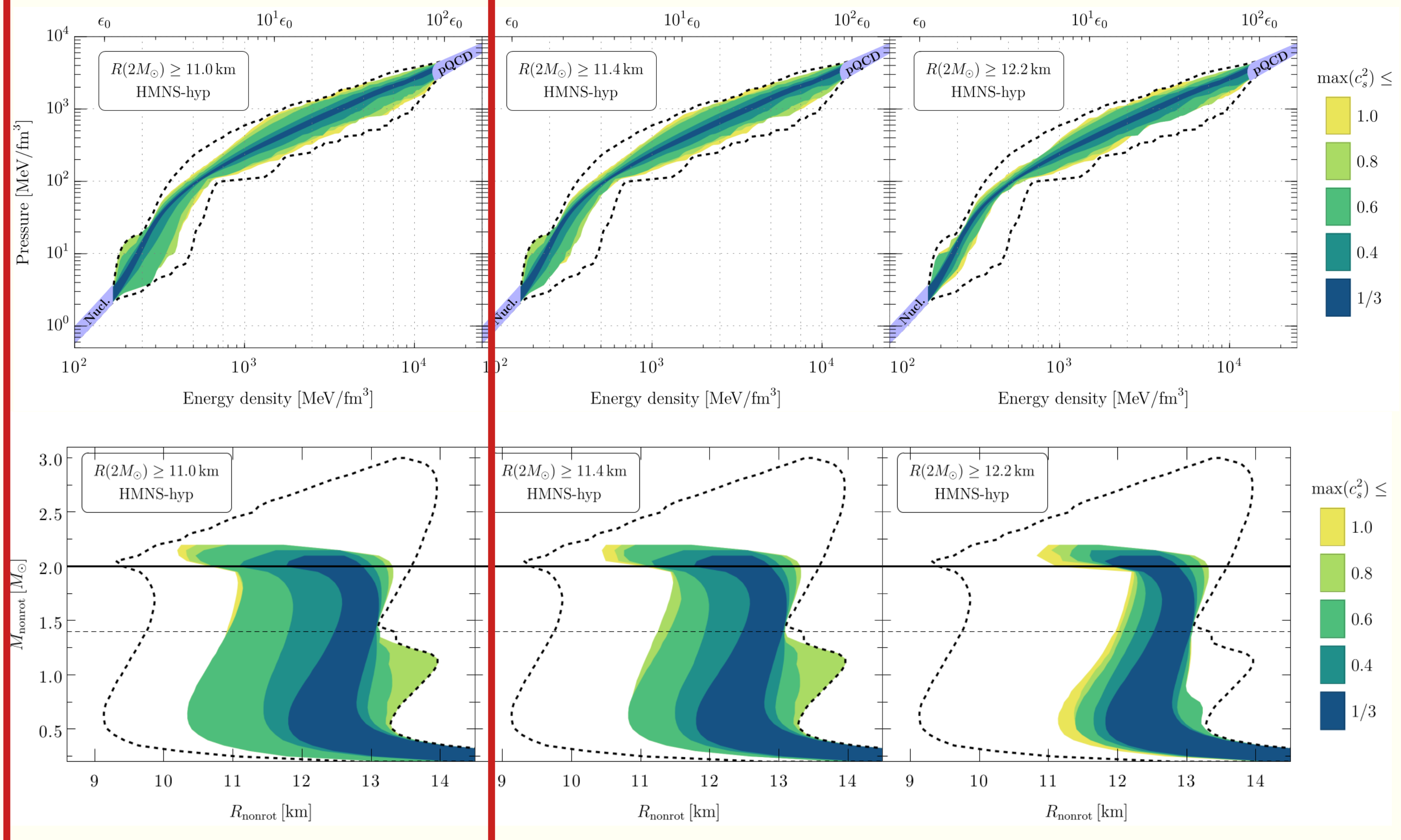
Most robust result consistent with kilonovae, GRB



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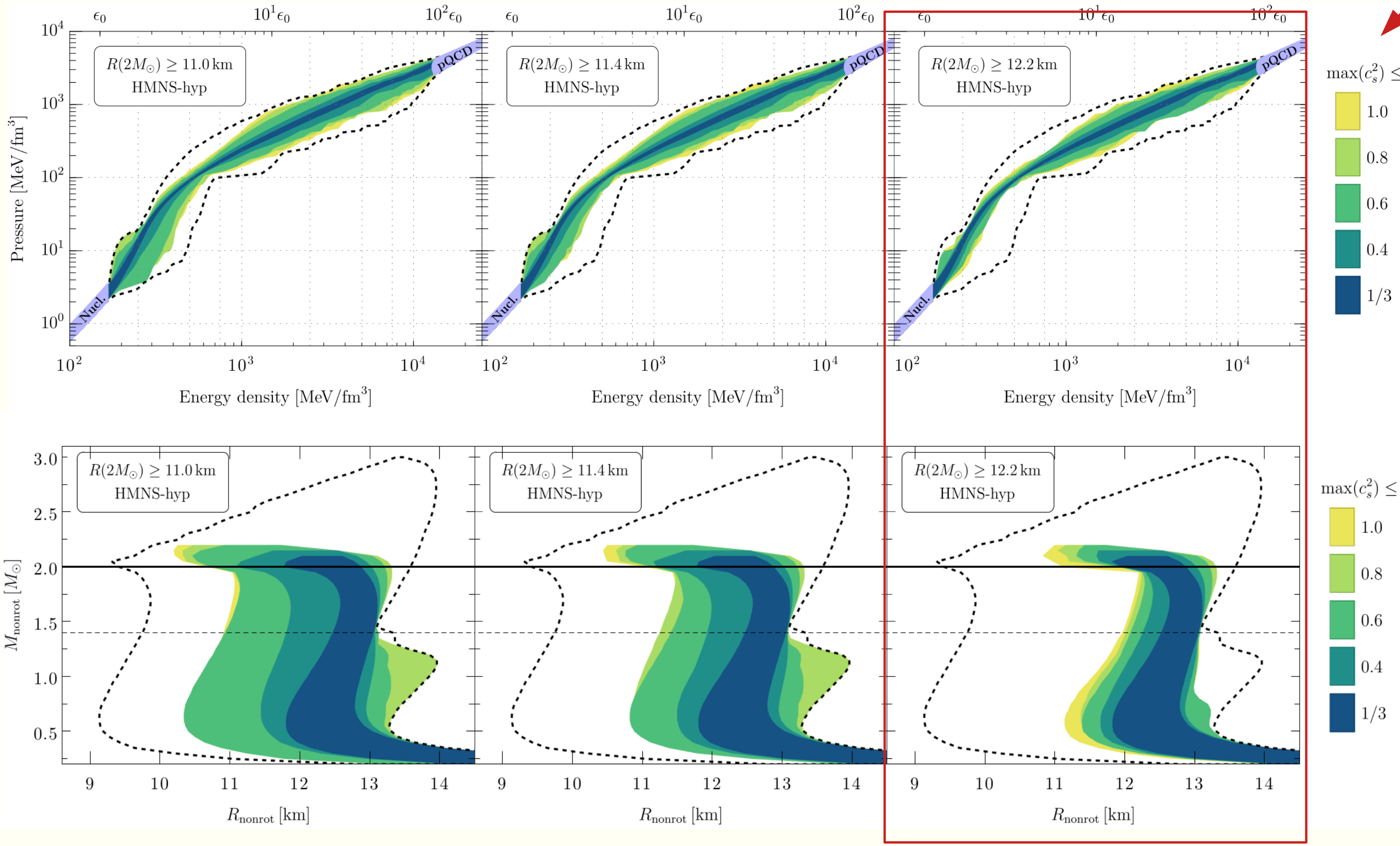
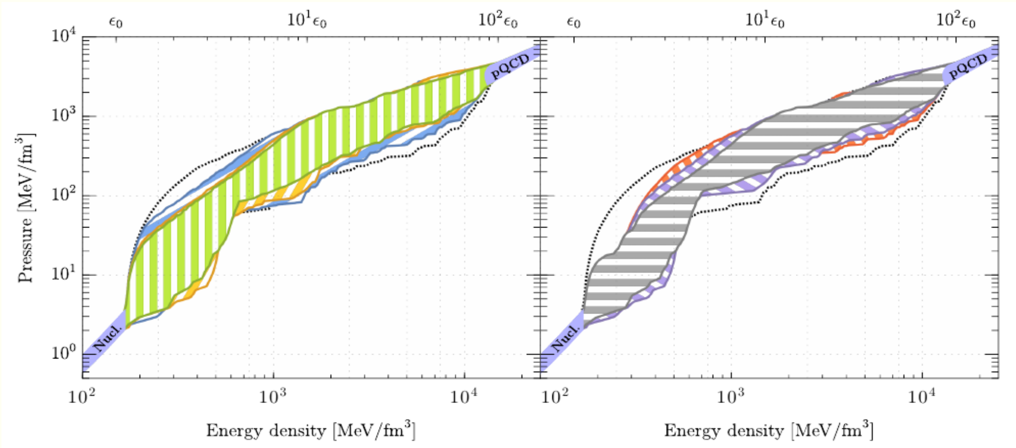
Even most restrictive consistent with with large QM cores!

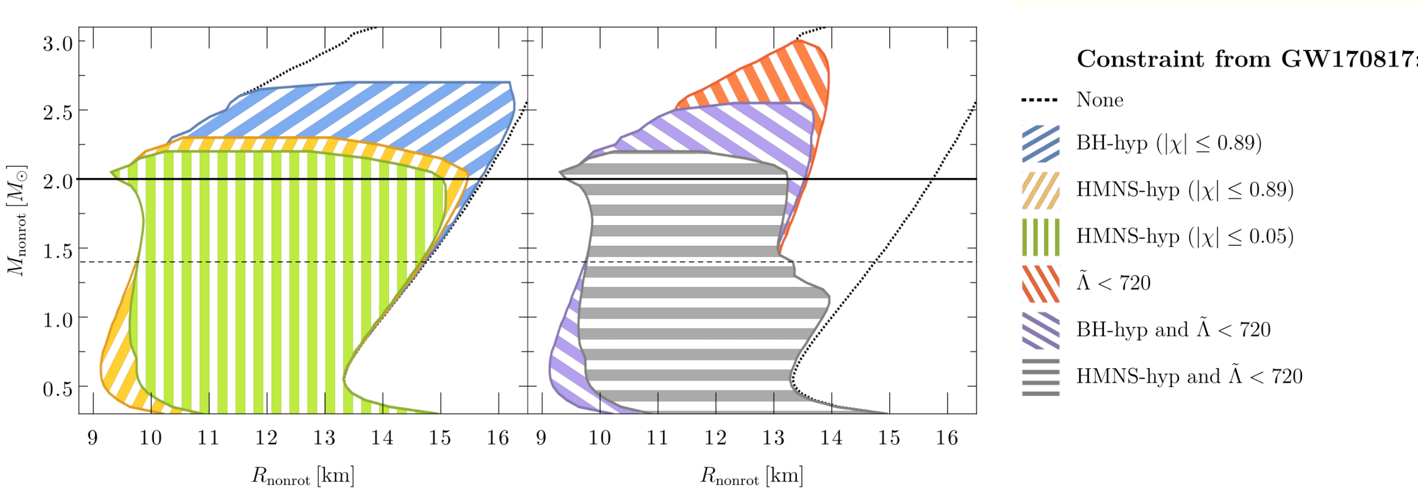
($\max(c_s^2) \lesssim 0.5 \implies$ *large QM cores*)



Results: different implementations of GW170817

Without $\tilde{\Lambda}$ With $\tilde{\Lambda}$





** approximately cuts on M_{TOV}, even in full analysis*

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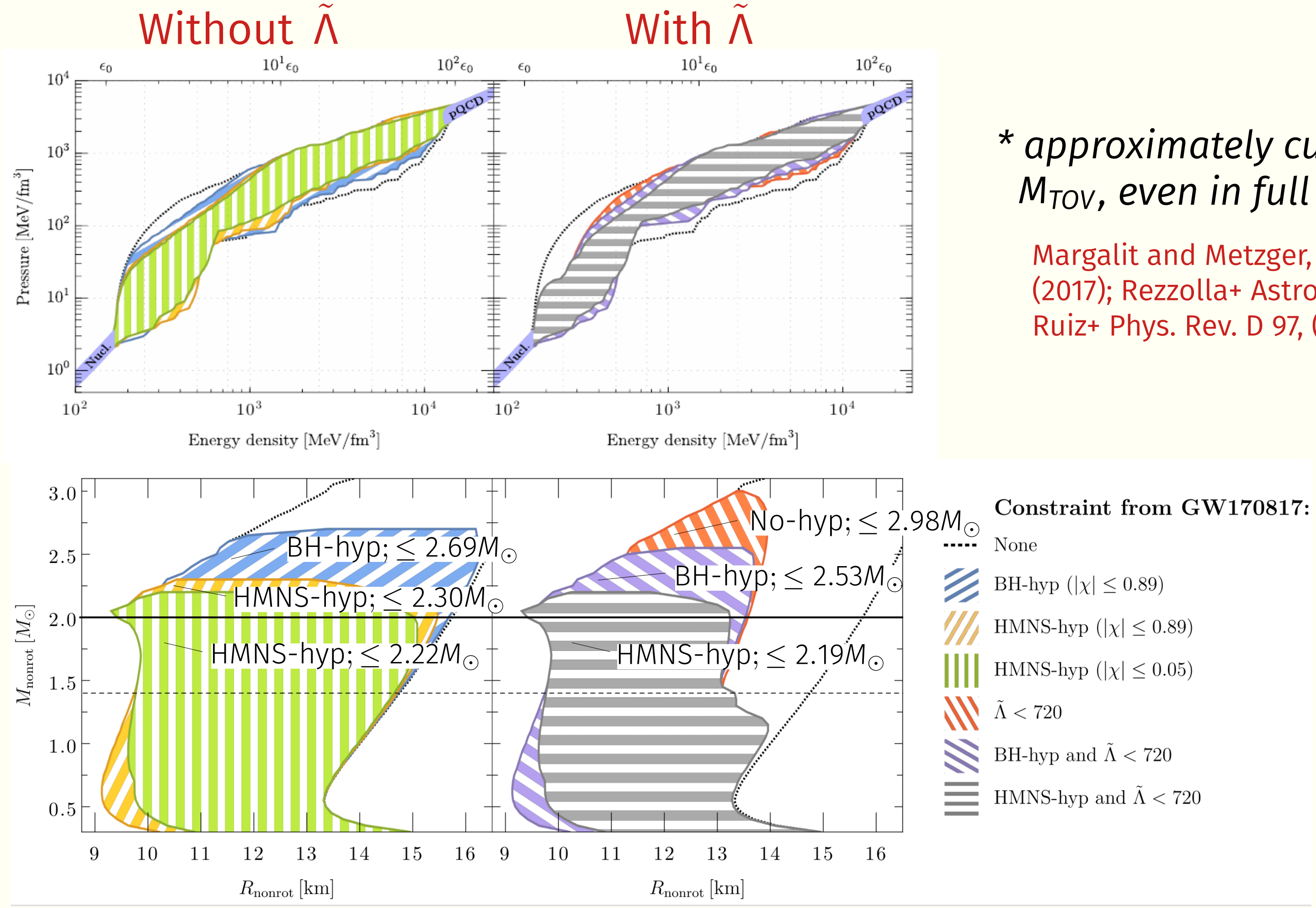

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Conclusions

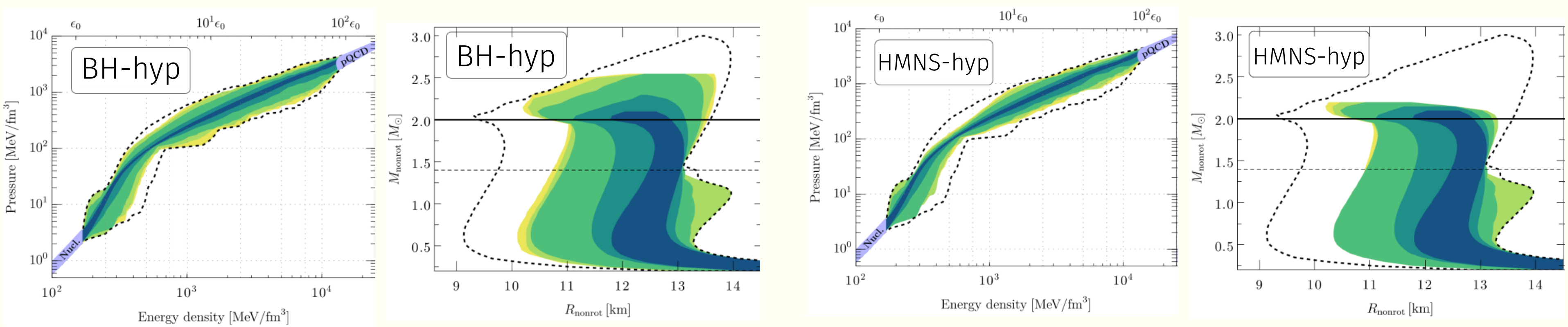
- New constraints on M_{TOV} within our ensemble framework :

$$\text{BH-hyp} \implies M_{\mathrm{TOV}} \leq 2.53 M_\odot \qquad \text{HMNS-hyp} \implies M_{\mathrm{TOV}} \leq 2.19 M_\odot$$

- **BH-hyp, HMNS-hyp, and $R(2.0M\odot) \geq 11.0, 11.4, 12.2$ km all compatible with QM cores in massive NSs**

- Discussion of GW190814, other future measurements in 2105.05132.

- Most robust regions [$R(2.0M_\odot) \geq 11$ km and BH-/HMNS-hyp]:



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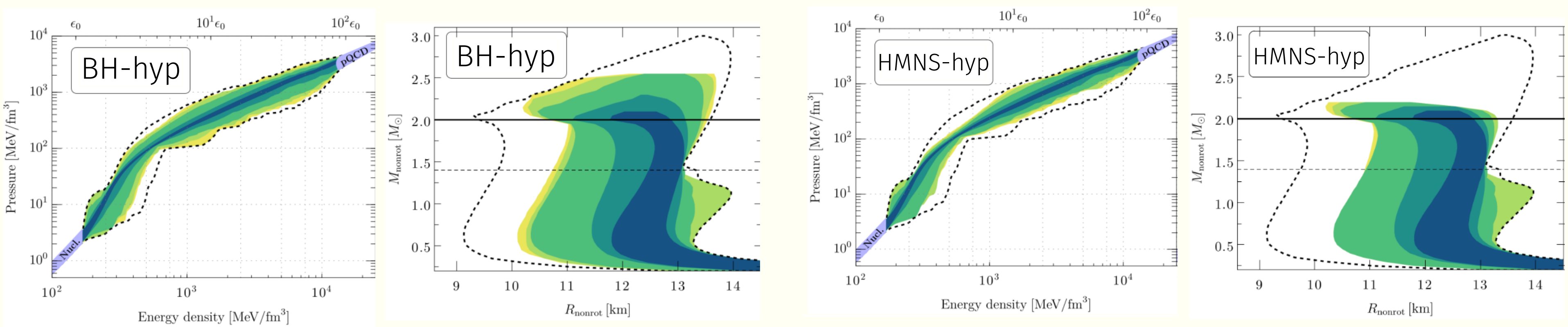
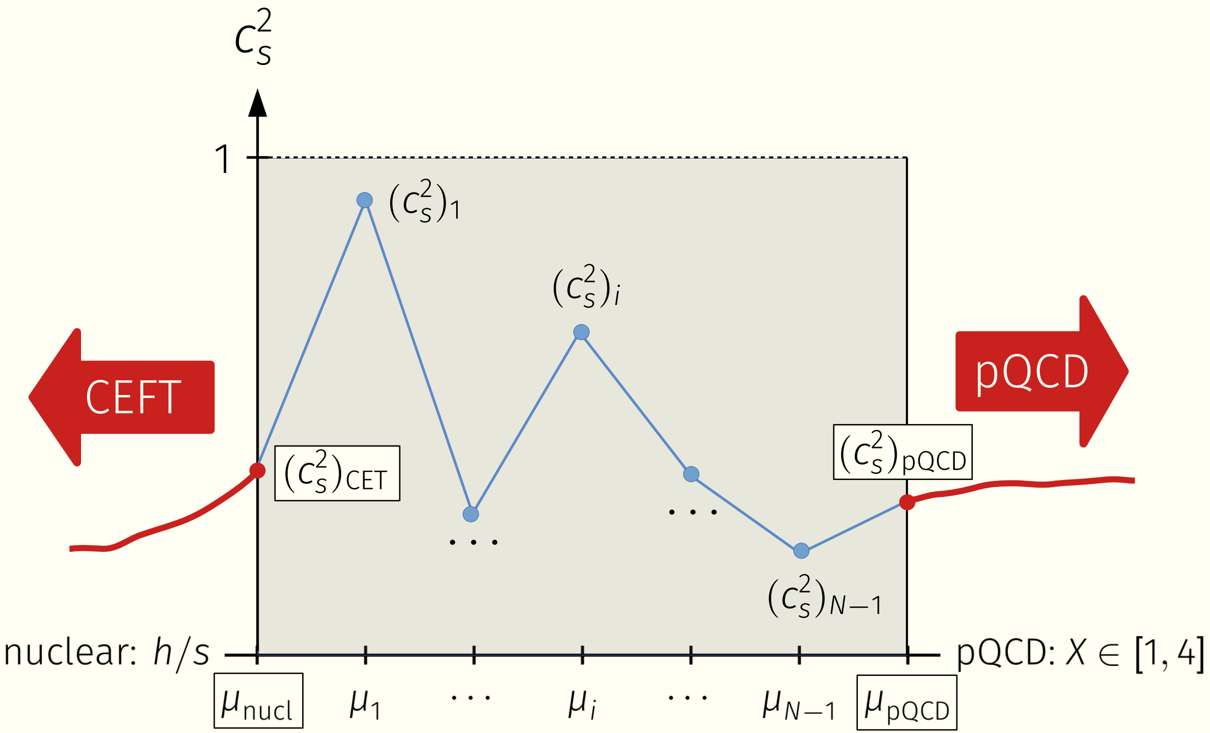


Thank you for your attention!

Details, additional results....

Quick detail of EOS interpolation



- $\{\mu_i, (c_s^2)_i\}_{i=1}^N$ random
- Connected piecewise linearly
- Enforce subluminalty, thermodynamic consistency:

  $\forall i : 0 < (c_s^2)_i < 1$

- No explicit phase trans., but don't restrict softness of EOS *(tantamount to 1st order PT)*

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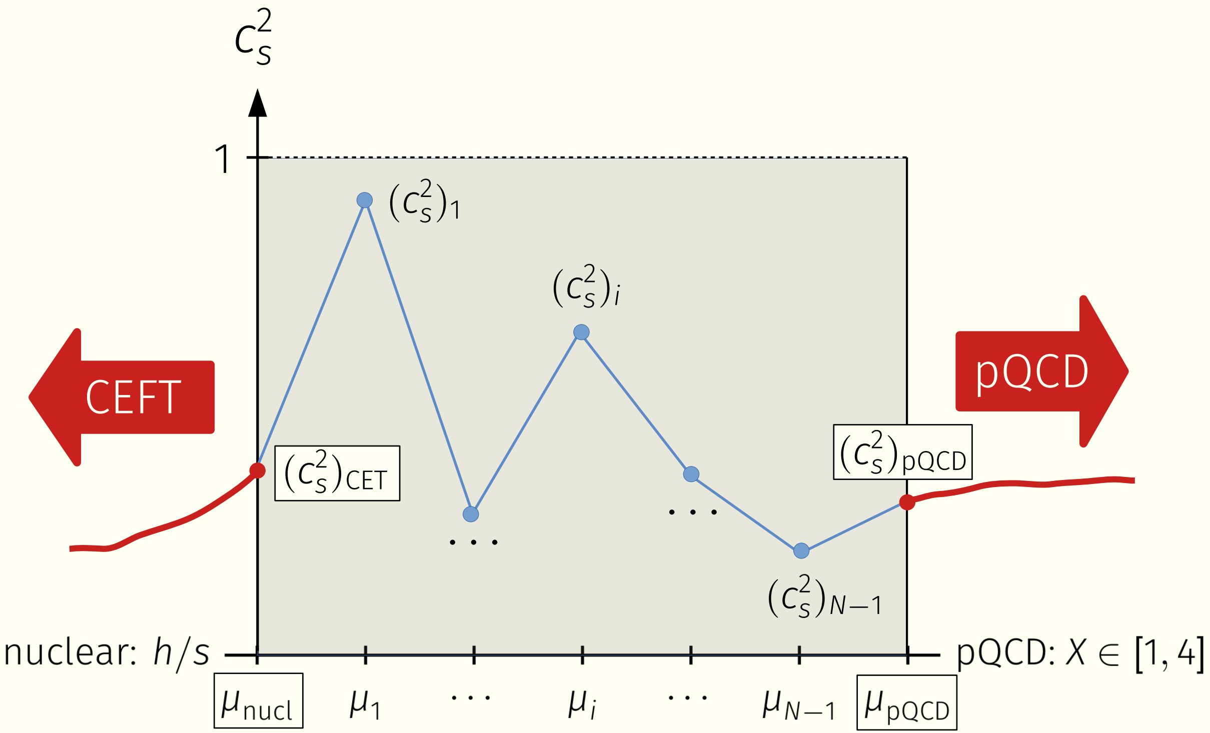
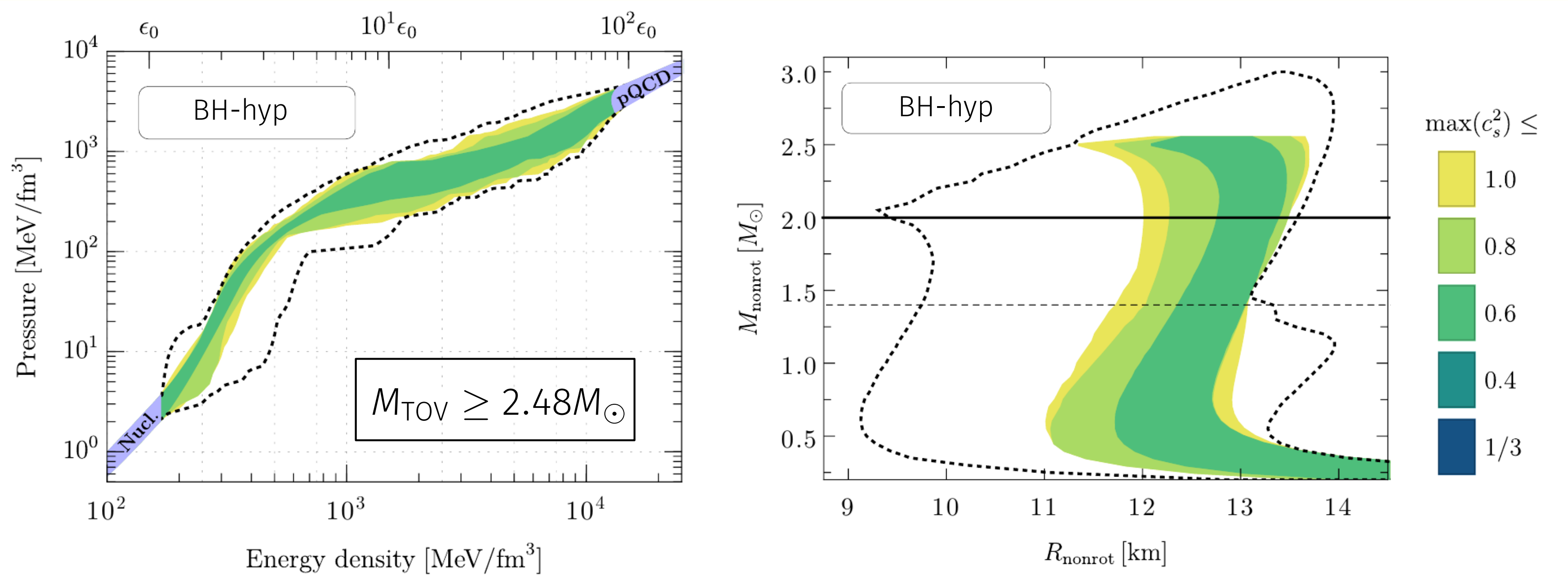


- Integrate twice to get other thermodynamic variables:

  1. $c_s^2(\mu) = \frac{n}{\mu}\left(\frac{dn}{d\mu}\right)^{-1}$
  2. $n = \frac{dp}{d\mu}$

GW190814 compatible with BH-hyp, but not HMNS-hyp...

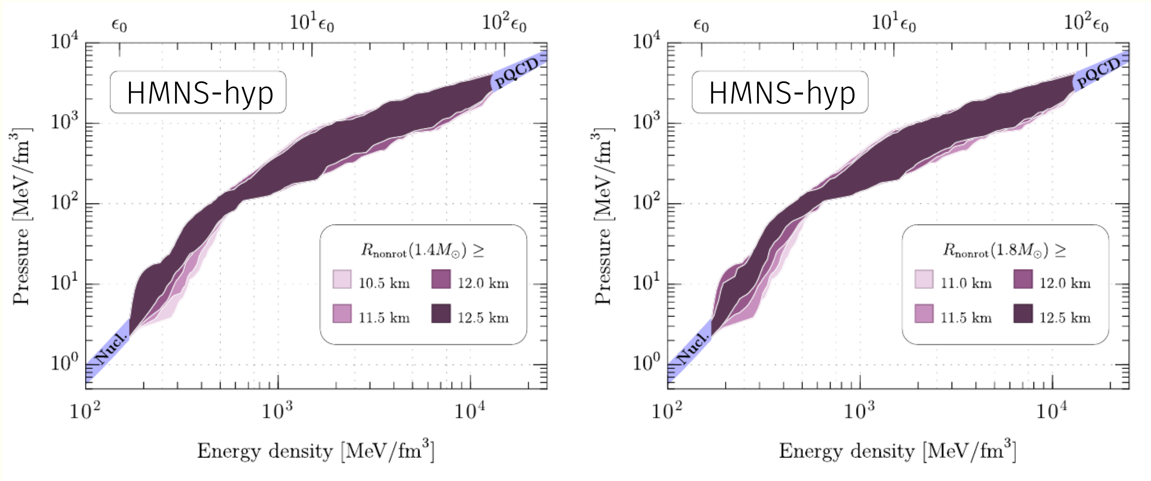


- Would imply $\max(c_s^2) \geq 0.51$...
- ...but hard to reconcile with multimessenger picture of GW170817
- Compatible with $R(2.0M_\odot) \geq 11$ km

Future measurements

Radii at different masses:

Weih+ Astrophys. J. 881, 73 (2019)



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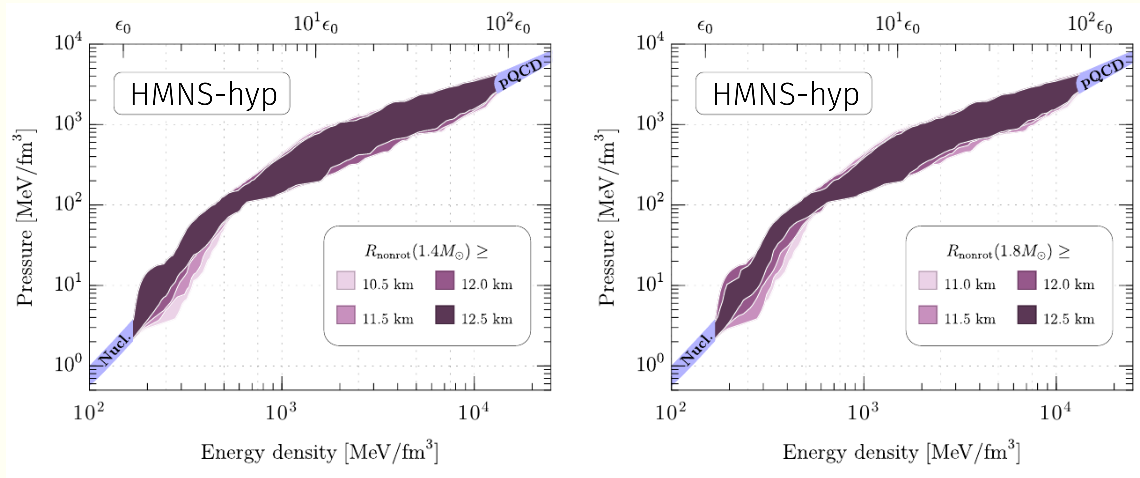

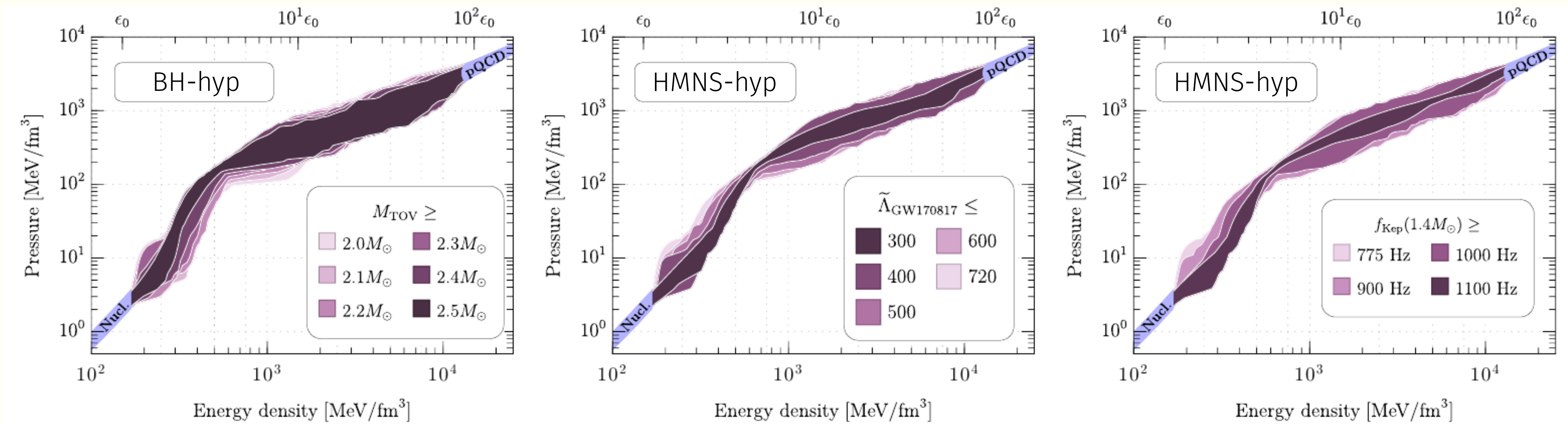

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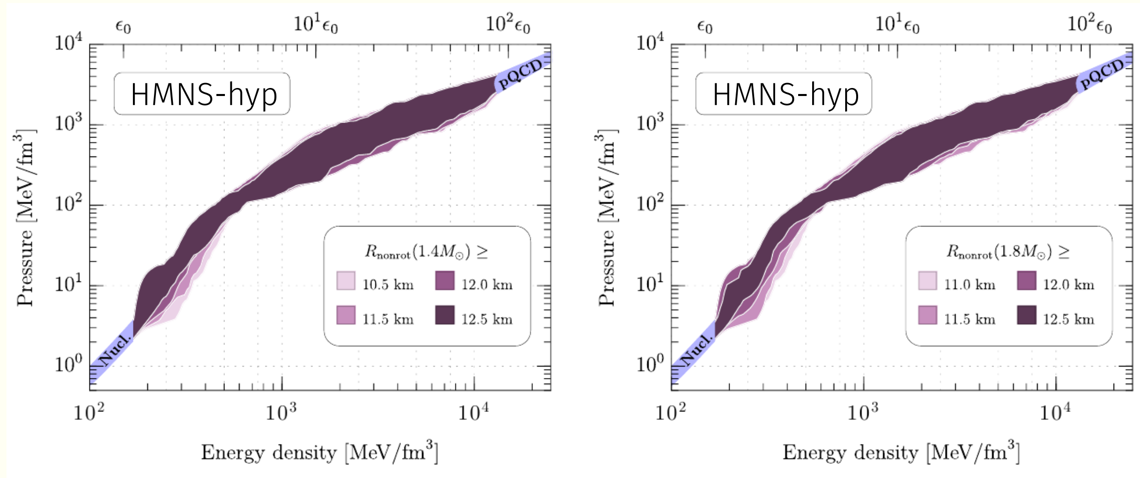

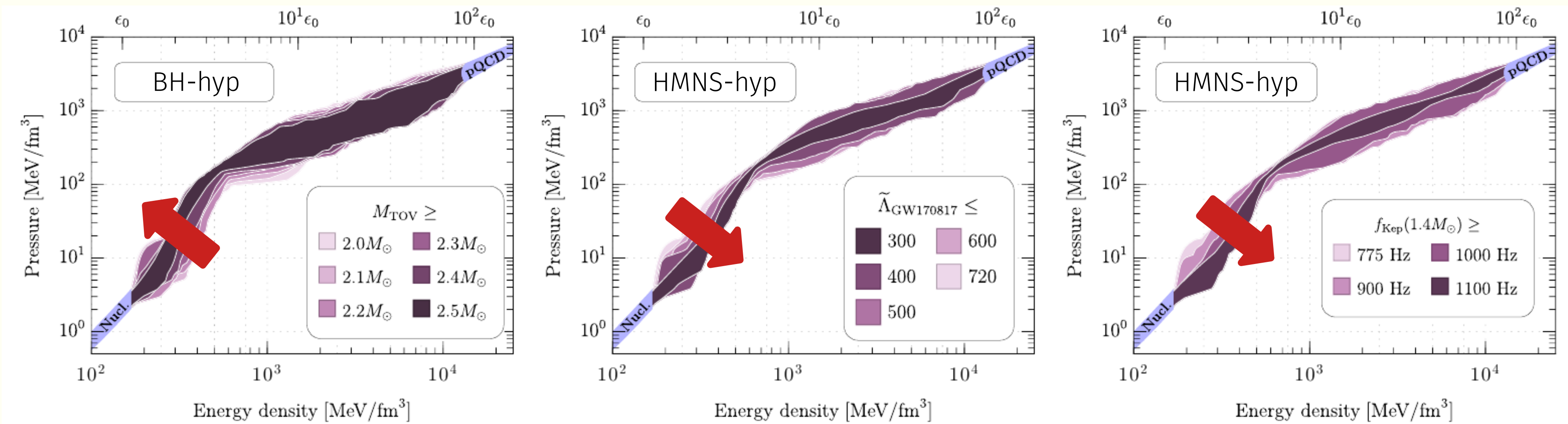

Numerical MR limits with various hypotheses

Assumptions		Resulting ensemble limits				
BH hypothesis	$R_{2.0,\mathrm{min}}$ (km)	$R_{1.4}$ (km)	$R_{1.6}$ (km)	$R_{1.8}$ (km)	$R_{2.0}$ (km)	M_{TOV} ($M_\odot$)
–	–	9.6–13.4	9.8–13.3	9.7–13.5	9.3–13.7	2.98
TOV	–	9.6–13.4	9.8–13.2	9.7–13.4	9.3–13.6	2.53
Supra	–	9.7–13.4	9.8–13.2	9.7–13.3	9.3–13.3	2.19
TOV	10.9	10.6–13.2	10.7–13.2	10.9–13.4	10.9–13.6	2.53
TOV	11.1	10.7–13.2	10.9–13.2	11.0–13.4	11.1–13.6	2.53
TOV	11.4	10.9–13.2	11.1–13.2	11.2–13.4	11.4–13.6	2.53
TOV	12.2	11.5–13.1	11.7–13.2	12.0–13.4	12.2–13.6	2.53
Supra	10.9	10.8–13.2	10.9–13.2	10.9–13.3	10.9–13.3	2.19
Supra	11.1	10.8–13.2	11.0–13.2	11.1–13.3	11.1–13.3	2.19
Supra	11.4	11.2–13.2	11.3–13.2	11.4–13.3	11.4–13.3	2.19
Supra	12.2	11.9–13.1	12.0–13.2	12.1–13.3	12.2–13.3	2.19