Combining Electromagnetic and Gravitational Wave Observations to Determine the Nature of Dense Matter

Andrew W. Steiner

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- You must have a prior distribution
- We are (still) in a data-starved regime
- There is no optimal prior, only better data sets

Even the conditional probability, which is formally separate from the prior, often contains assumptions which are arguably prior assumptions; Steiner (2018)

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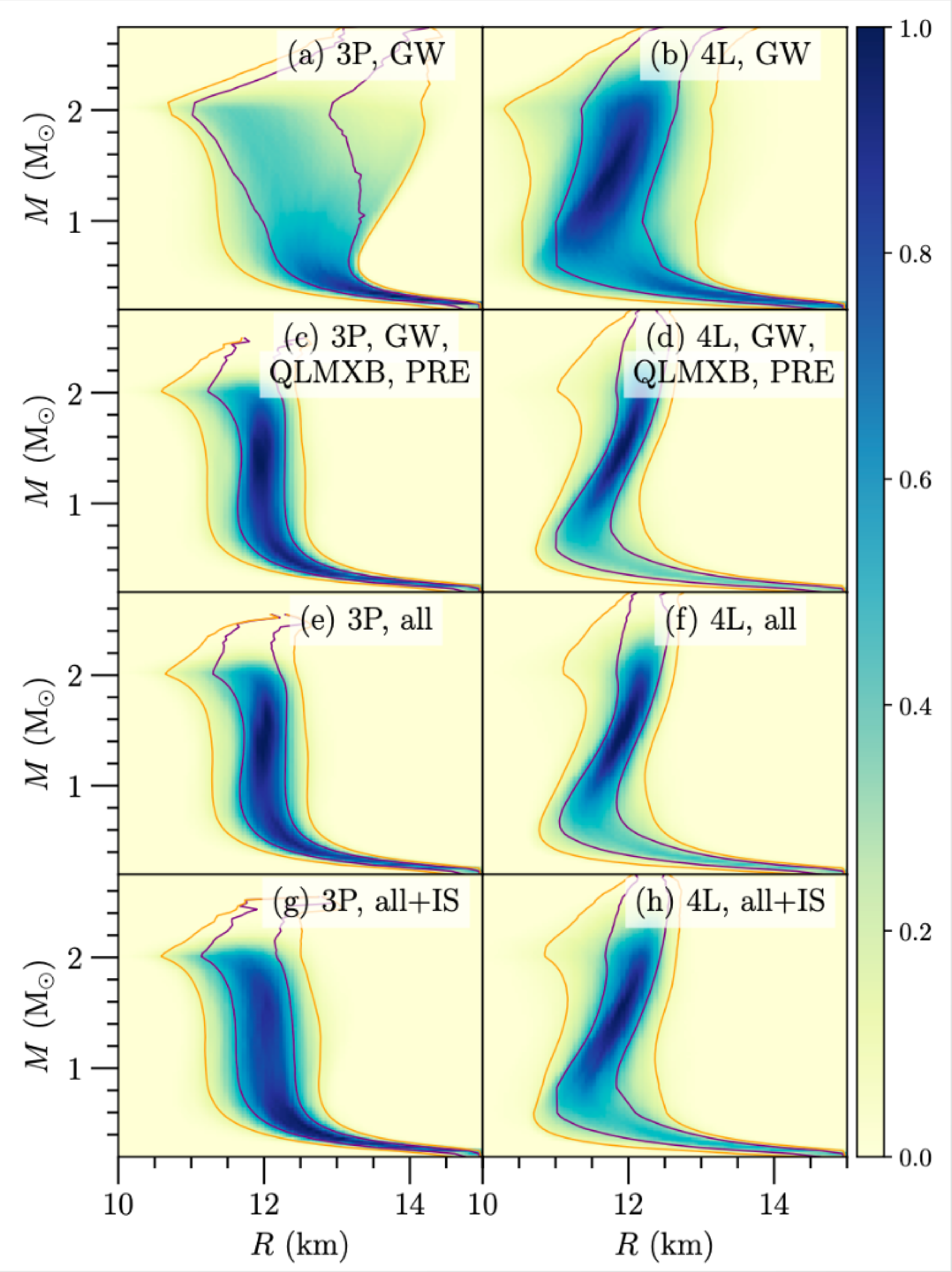
- Attempt to determine if EM observations contain systematic uncertainties which are unaccounted for

Mass-Radius Results



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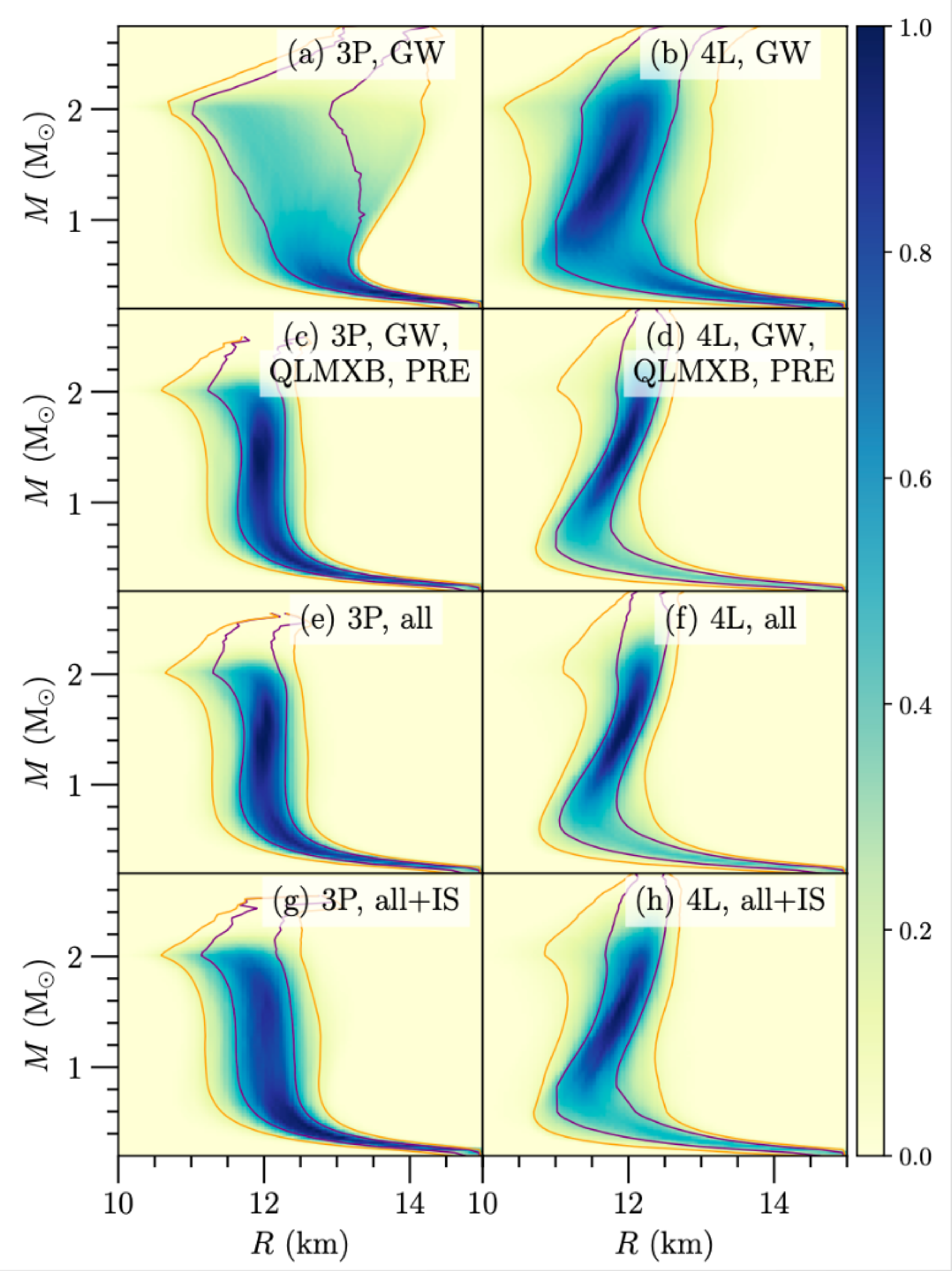

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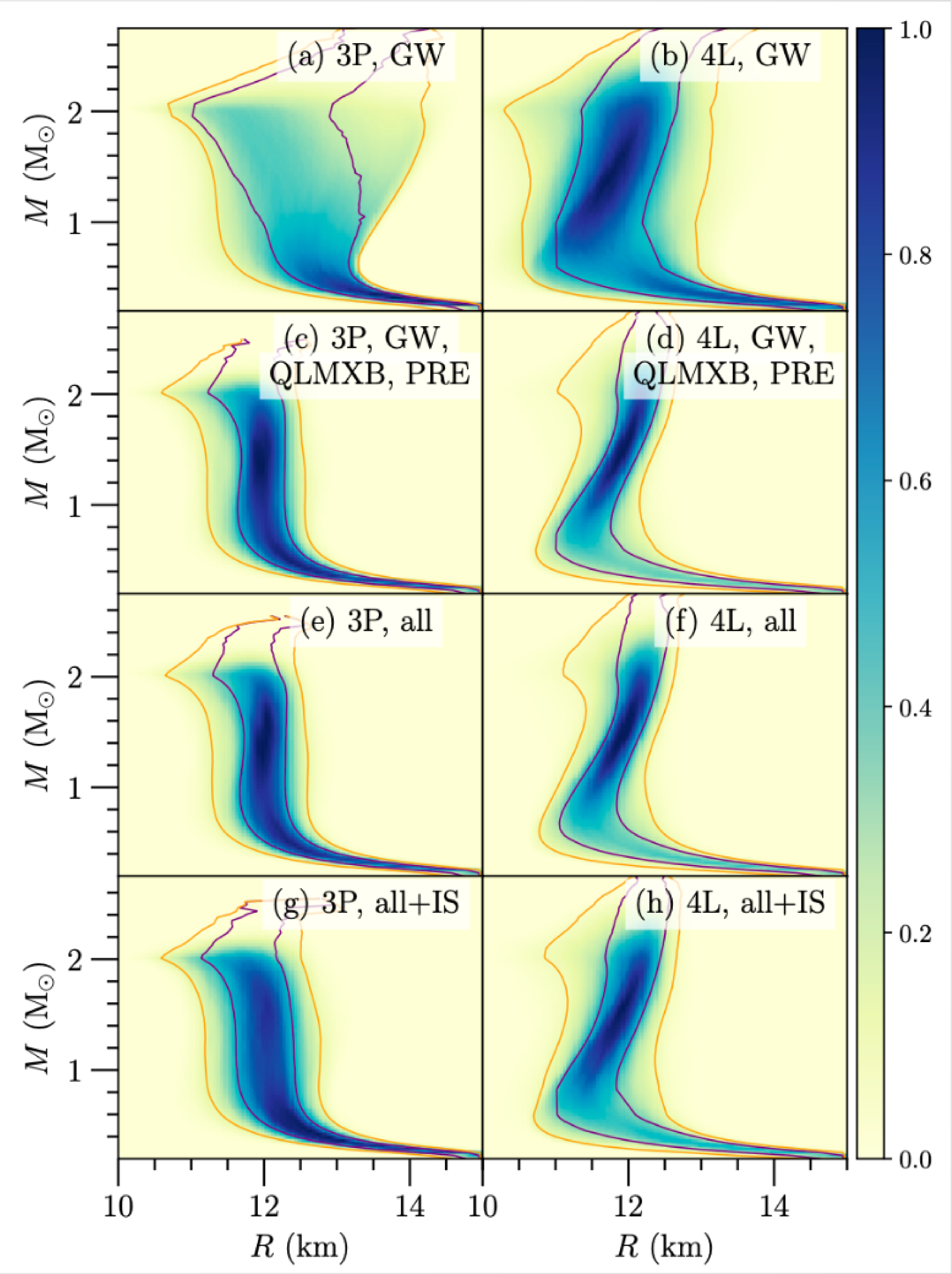

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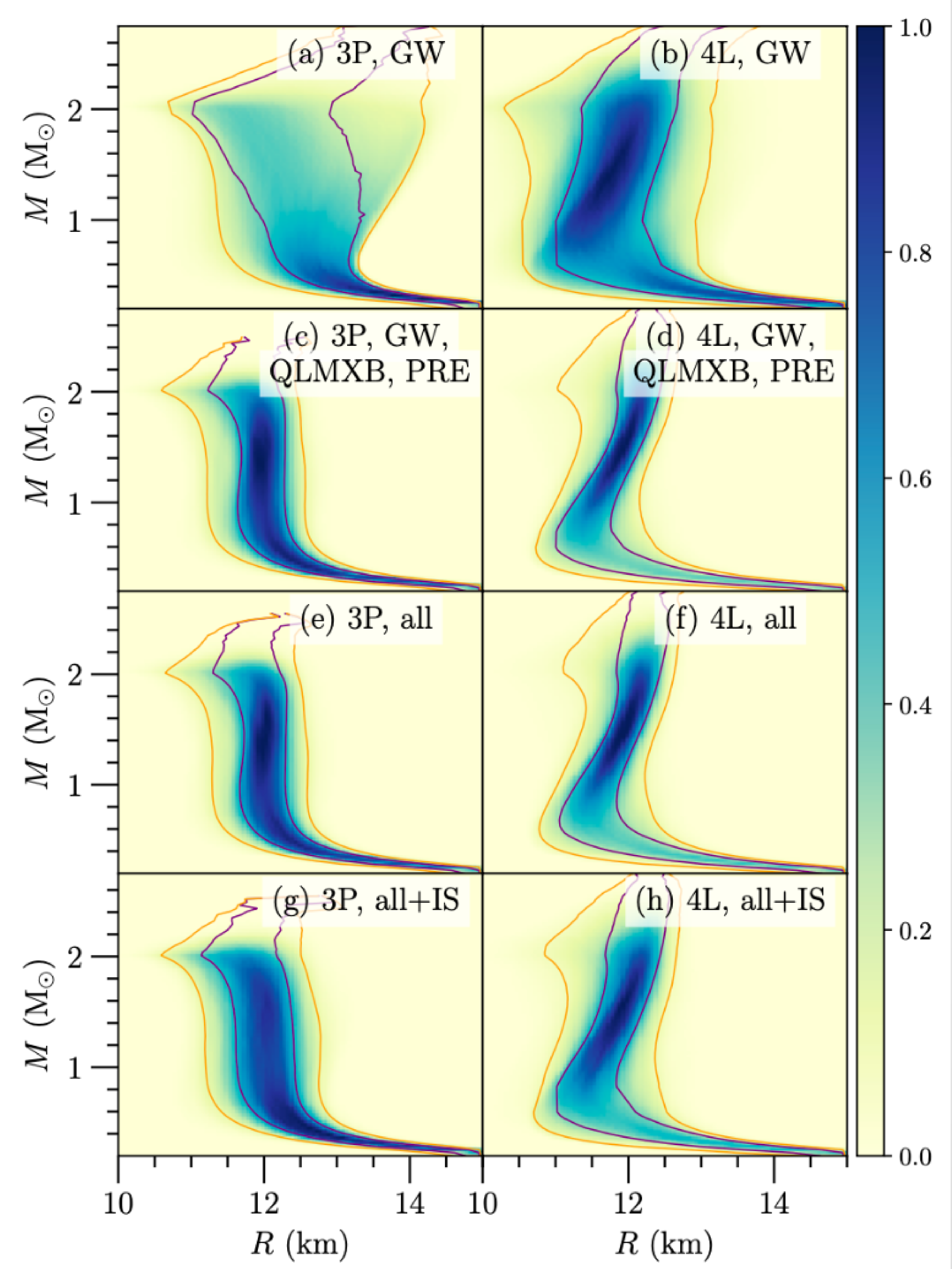

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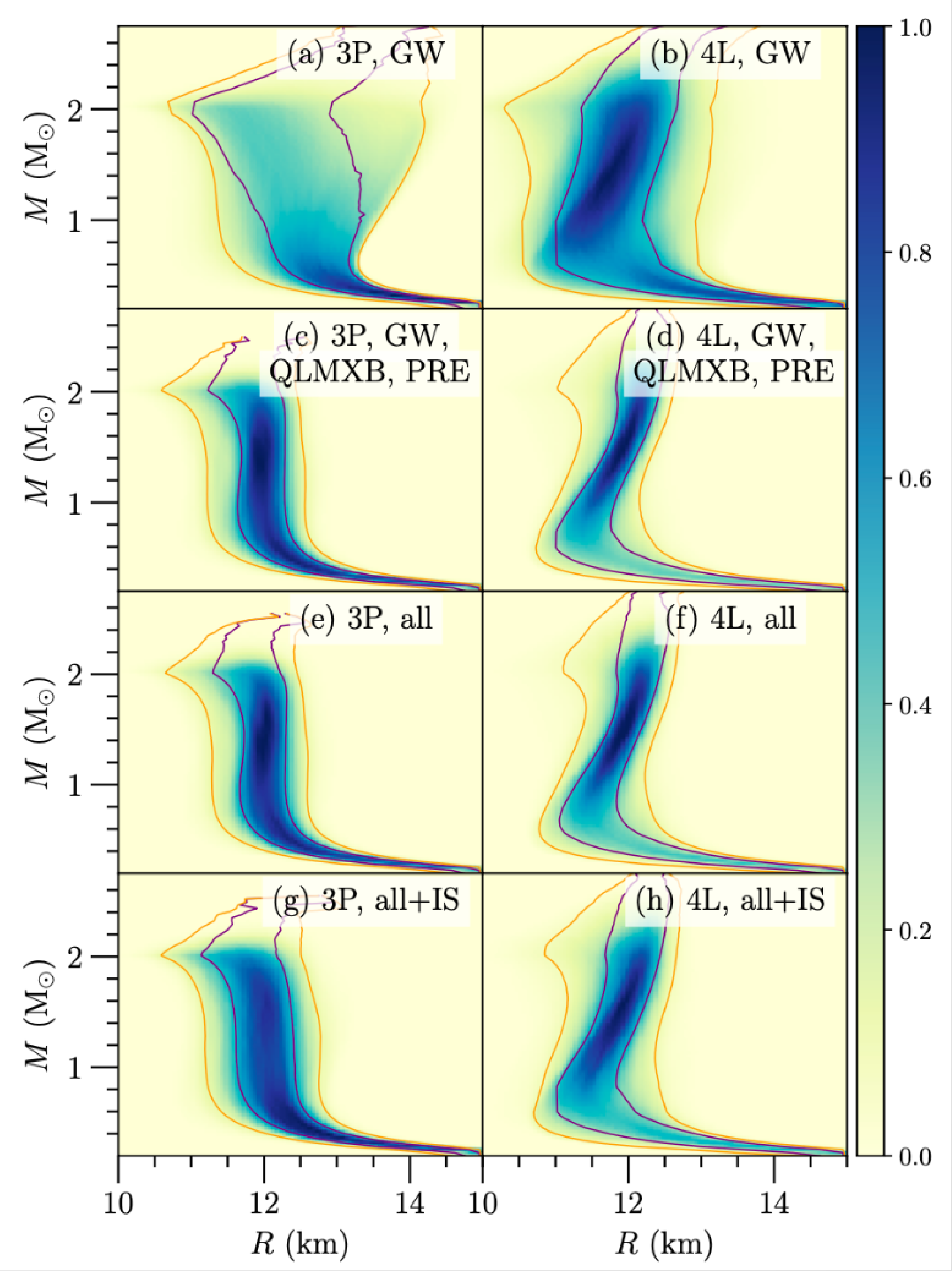
- ...but maximum mass posterior distribution varies significantly

This is why NICER results on J0740 are so important



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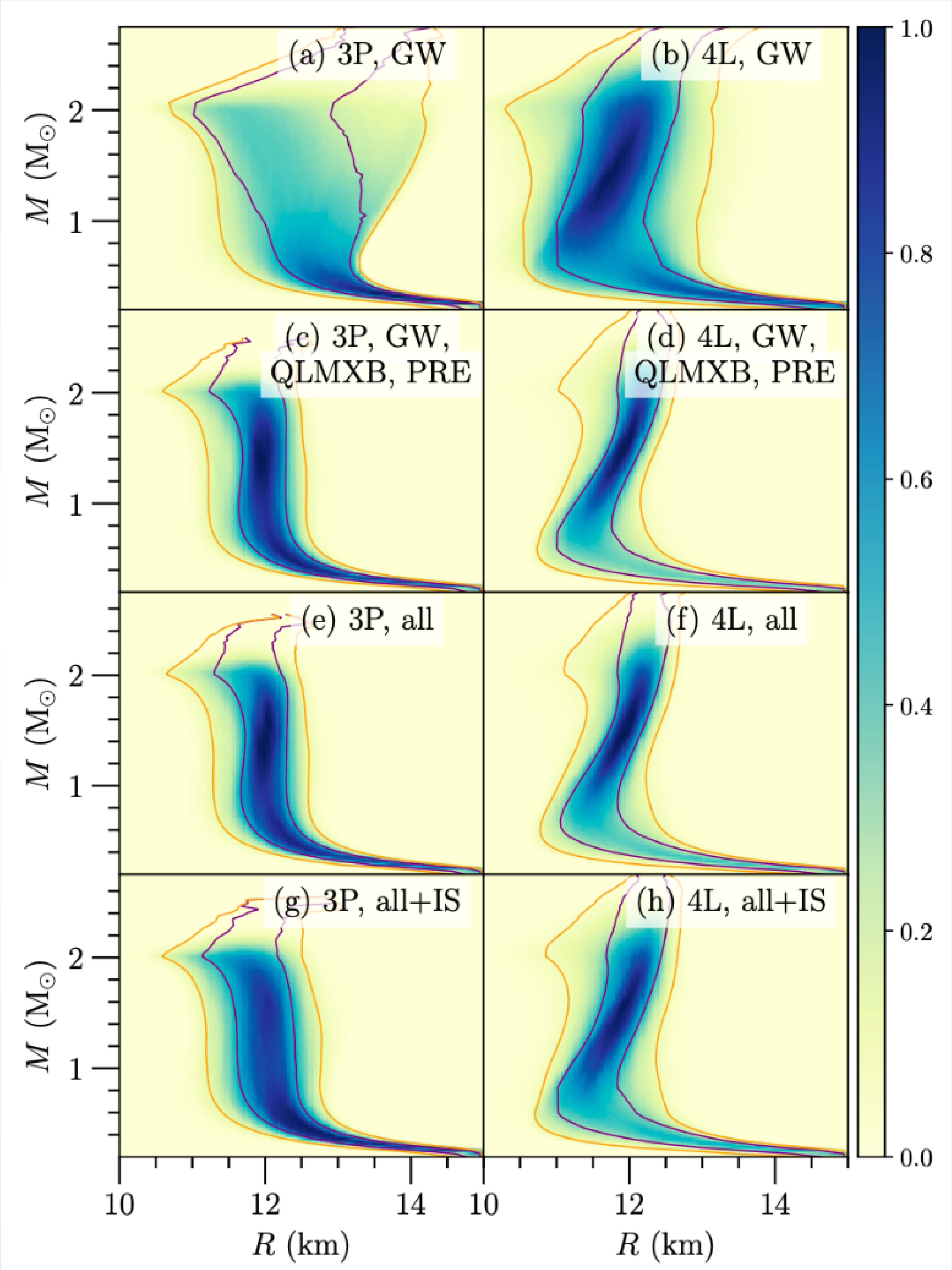
Assessing Systematics and J0030



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- Fold all EM observations with an independent uncertainty

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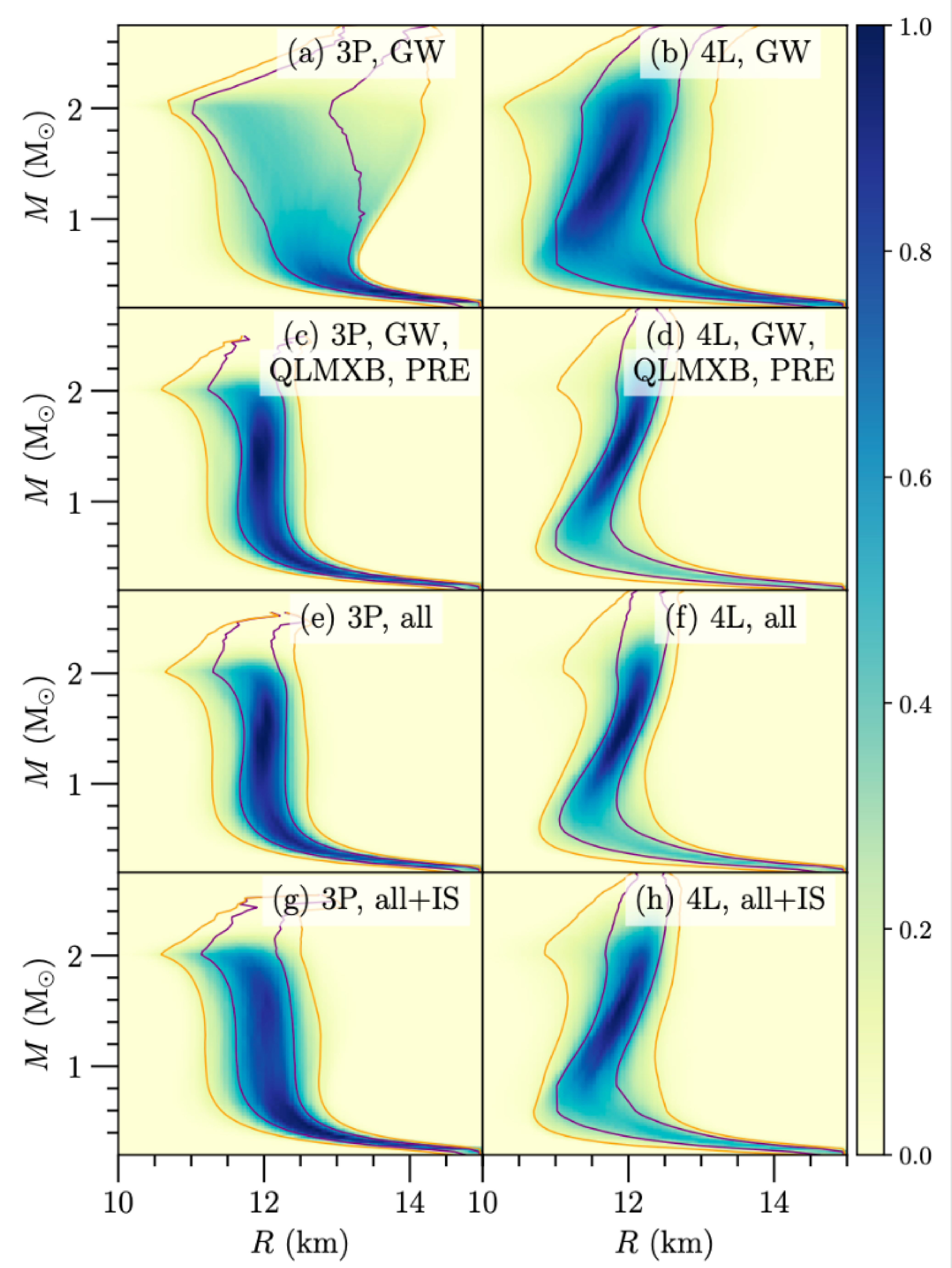

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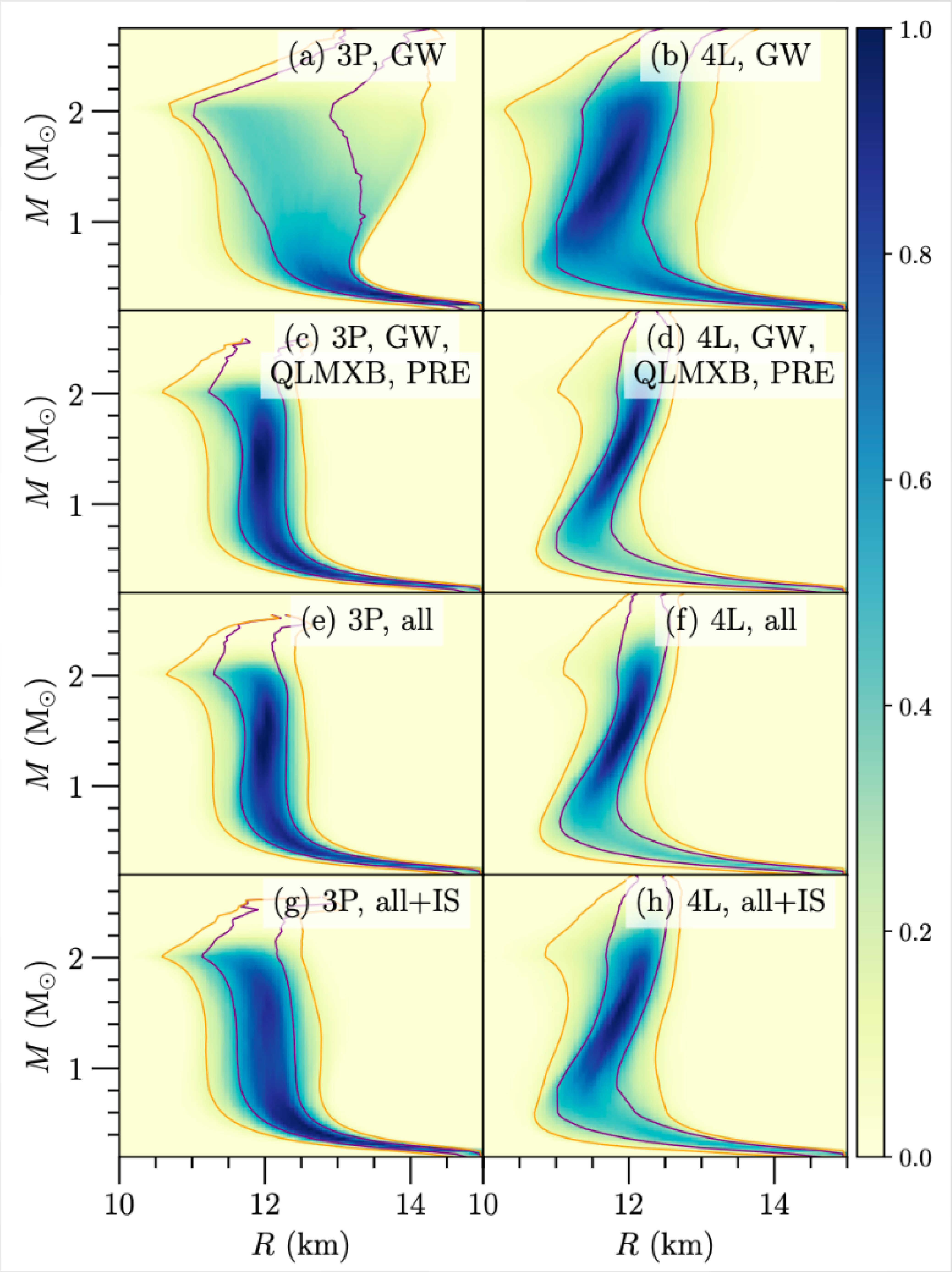

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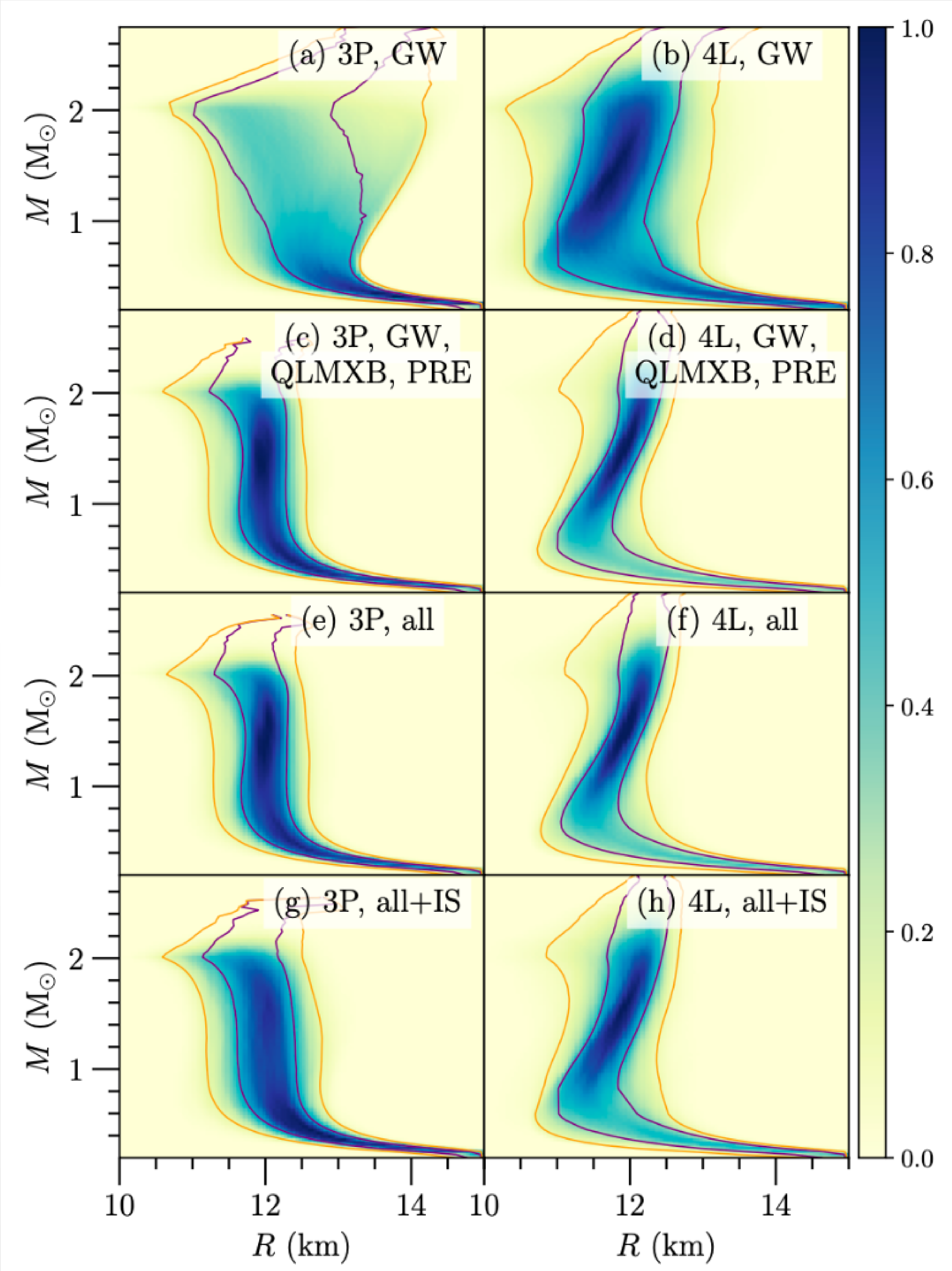
- NICER's constraint from J 0030 makes only small changes



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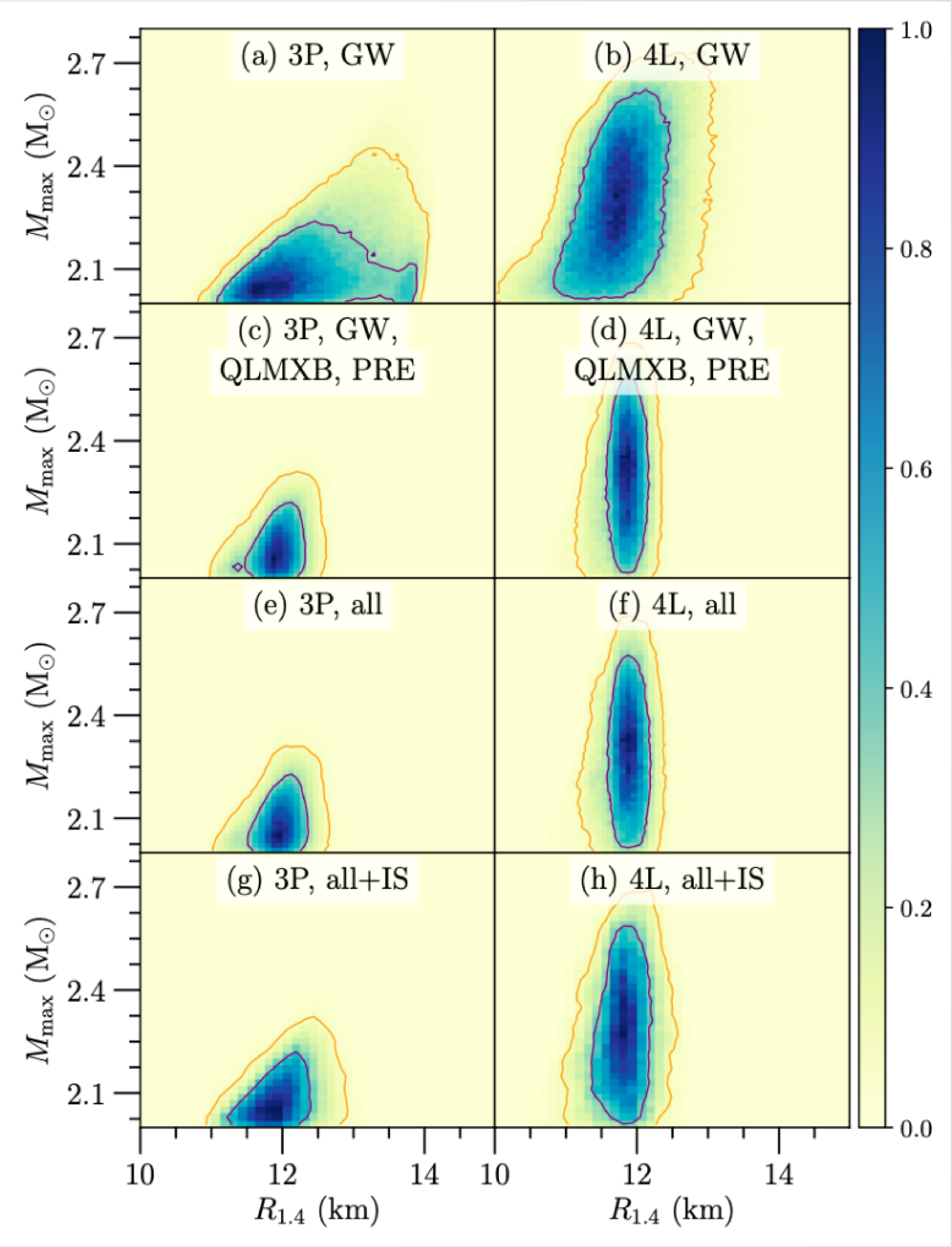

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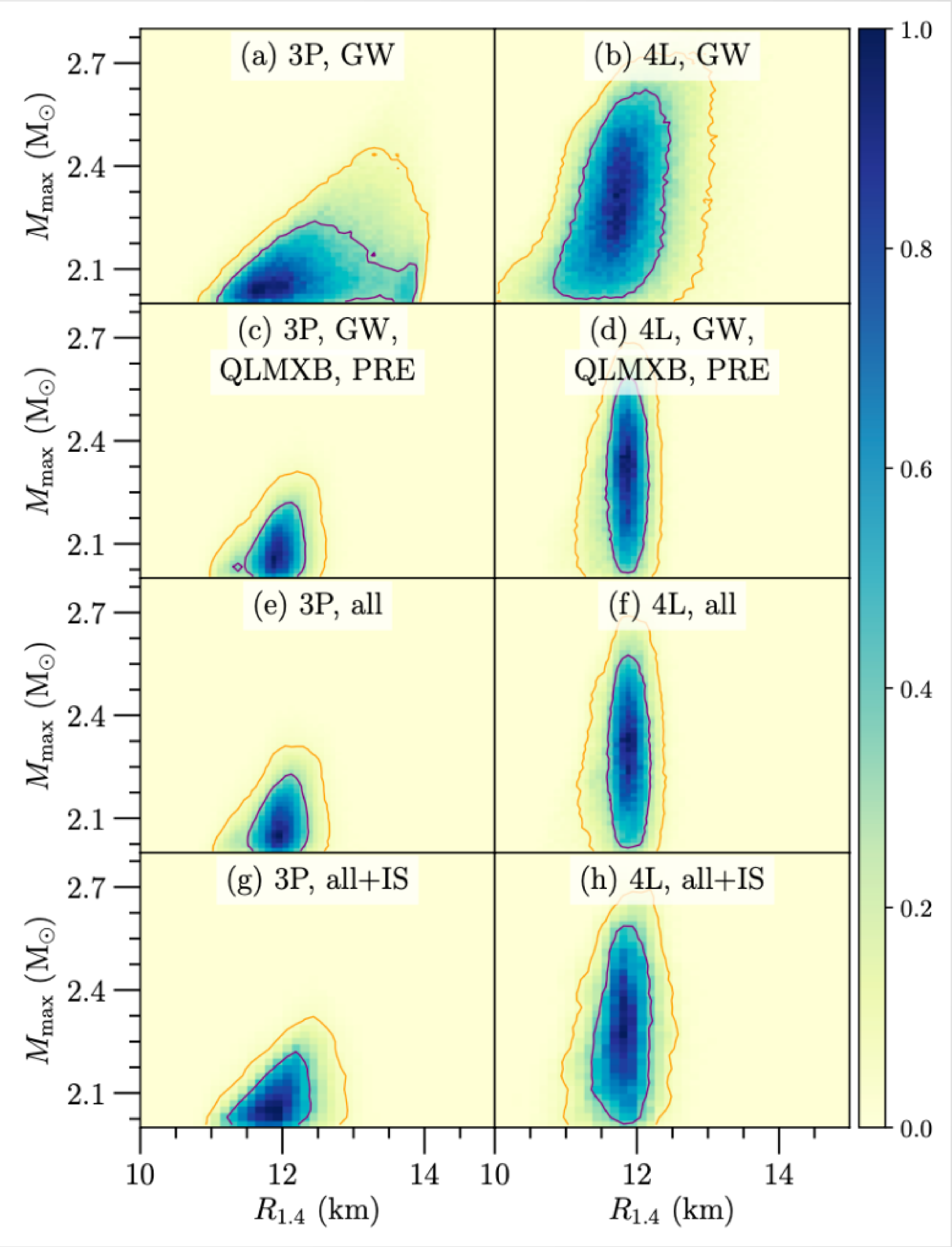

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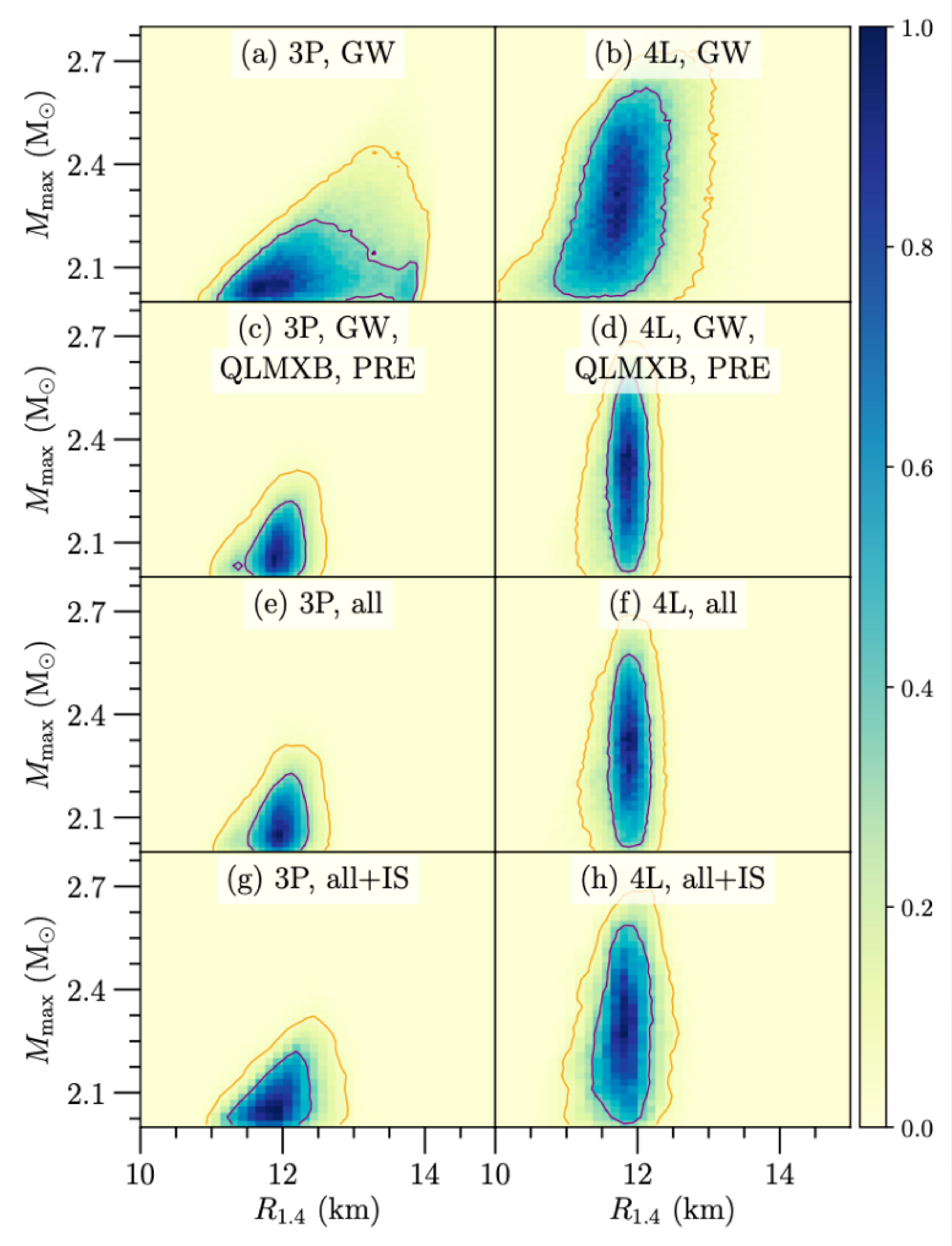

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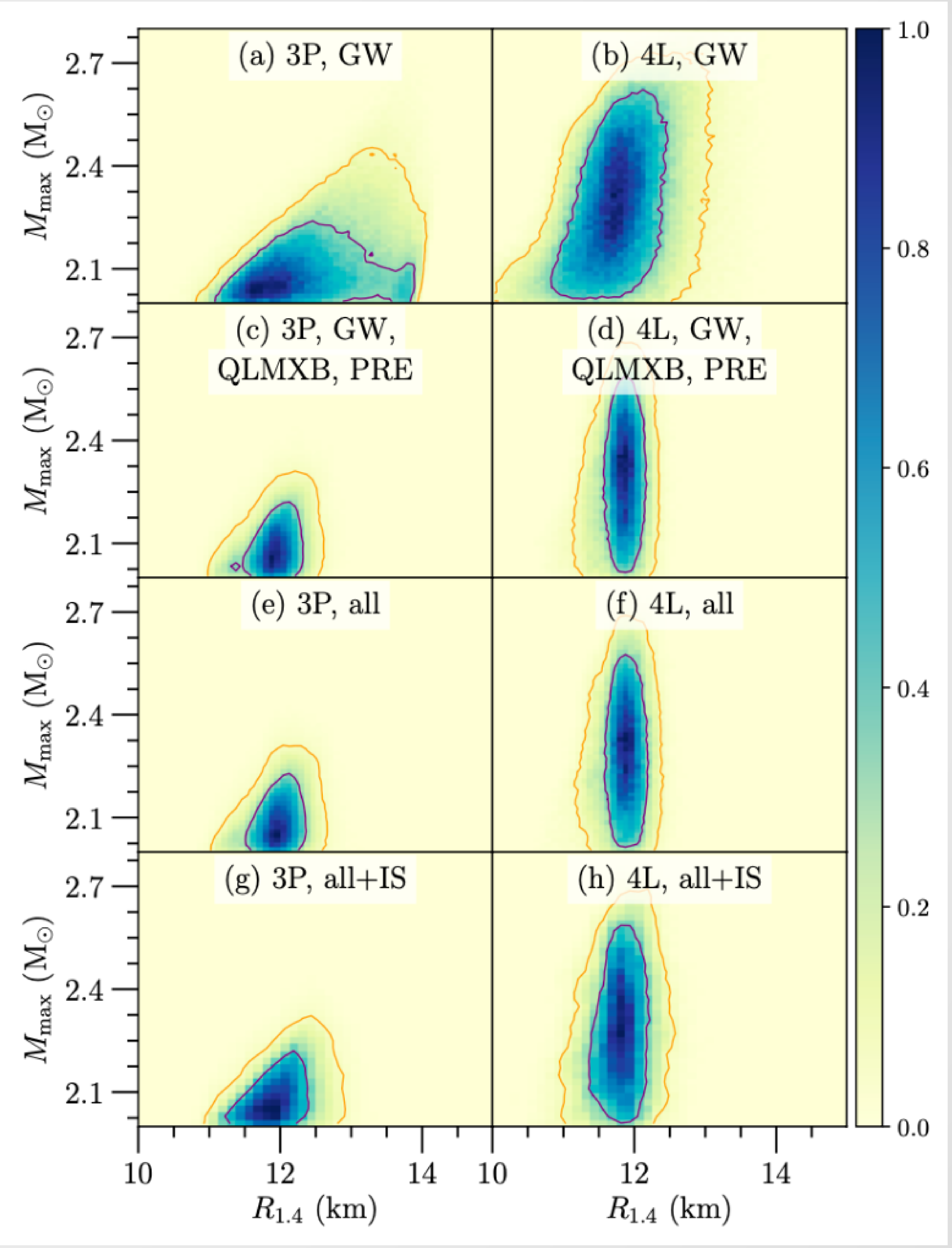

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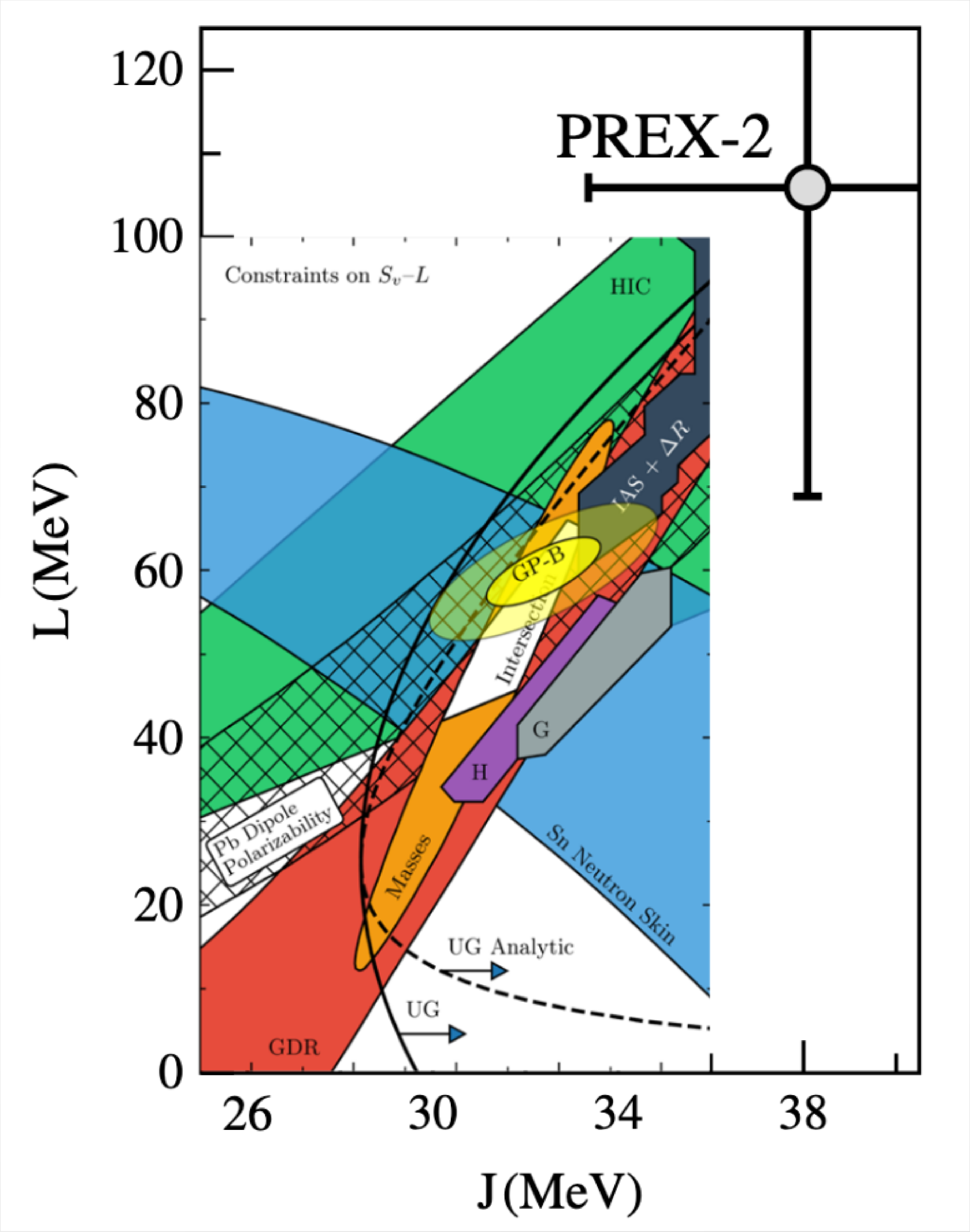

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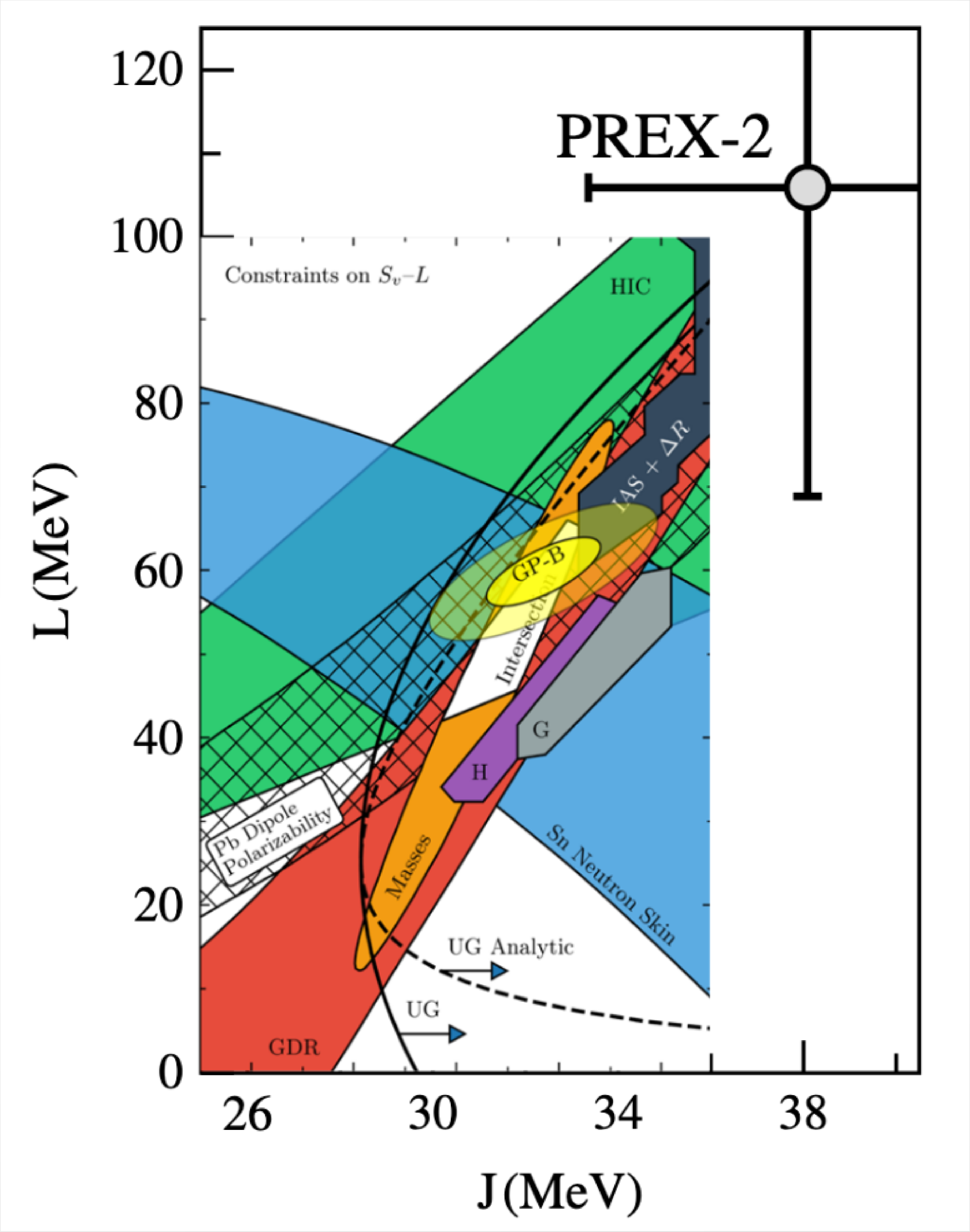

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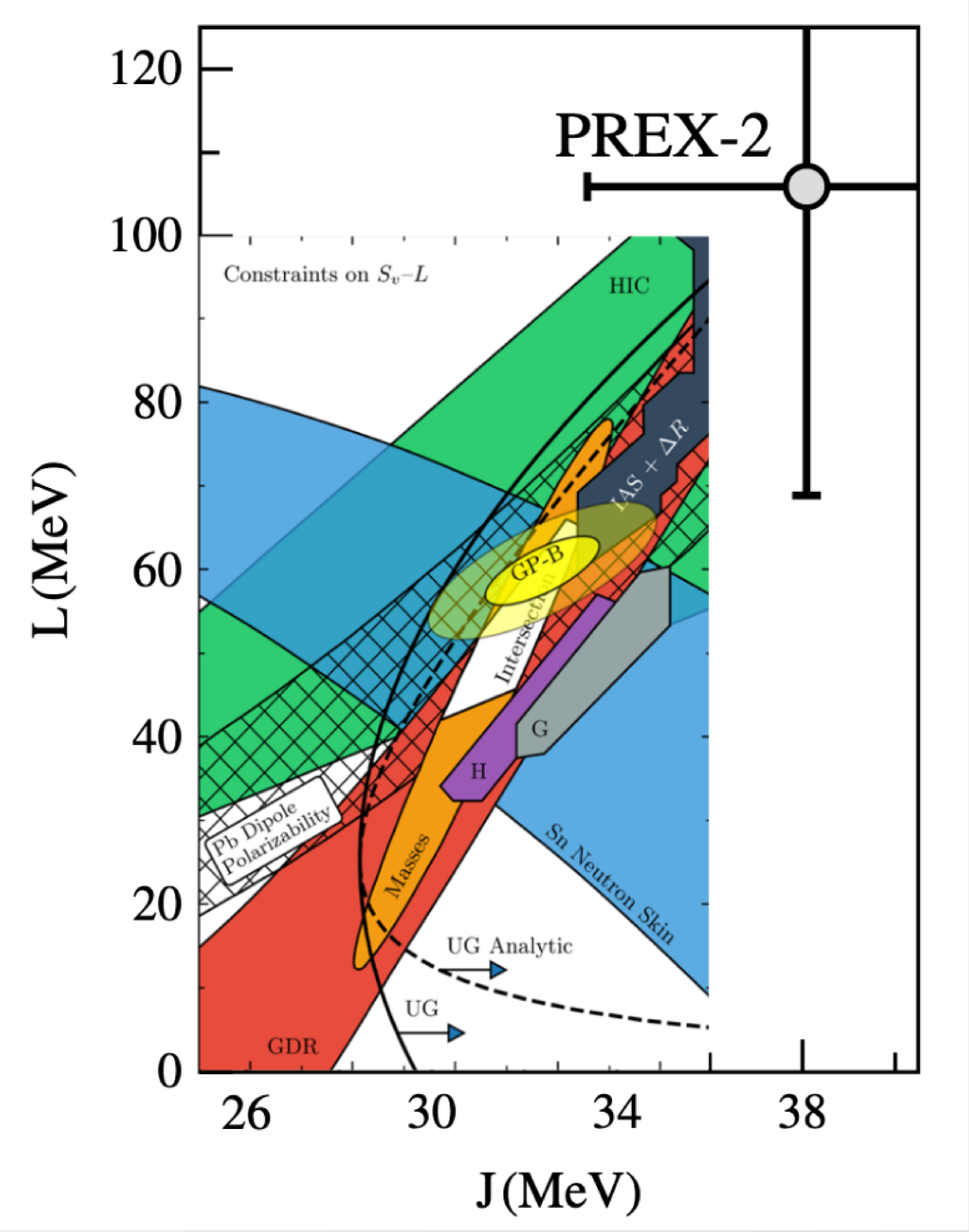

Reed et al. (2021)

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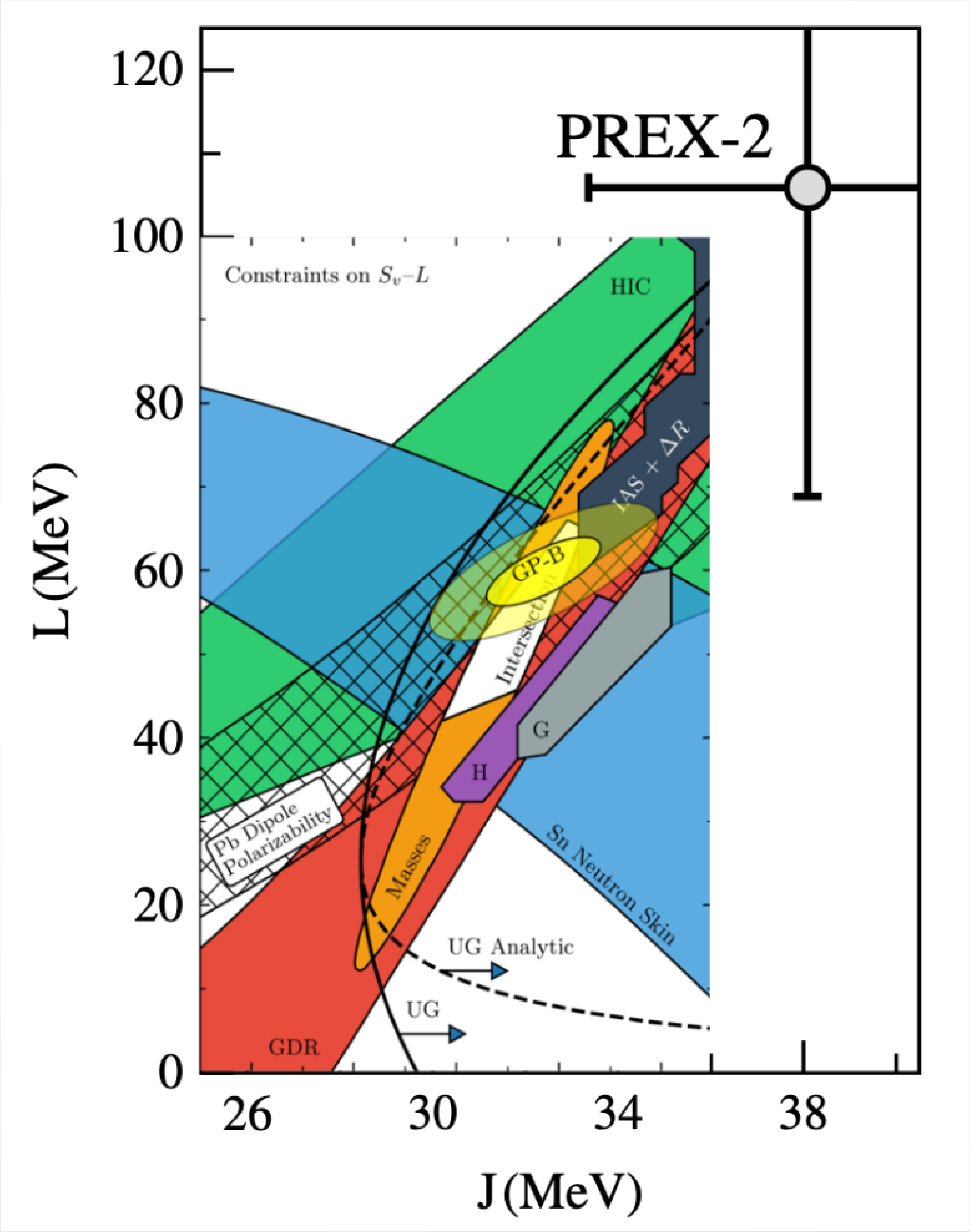

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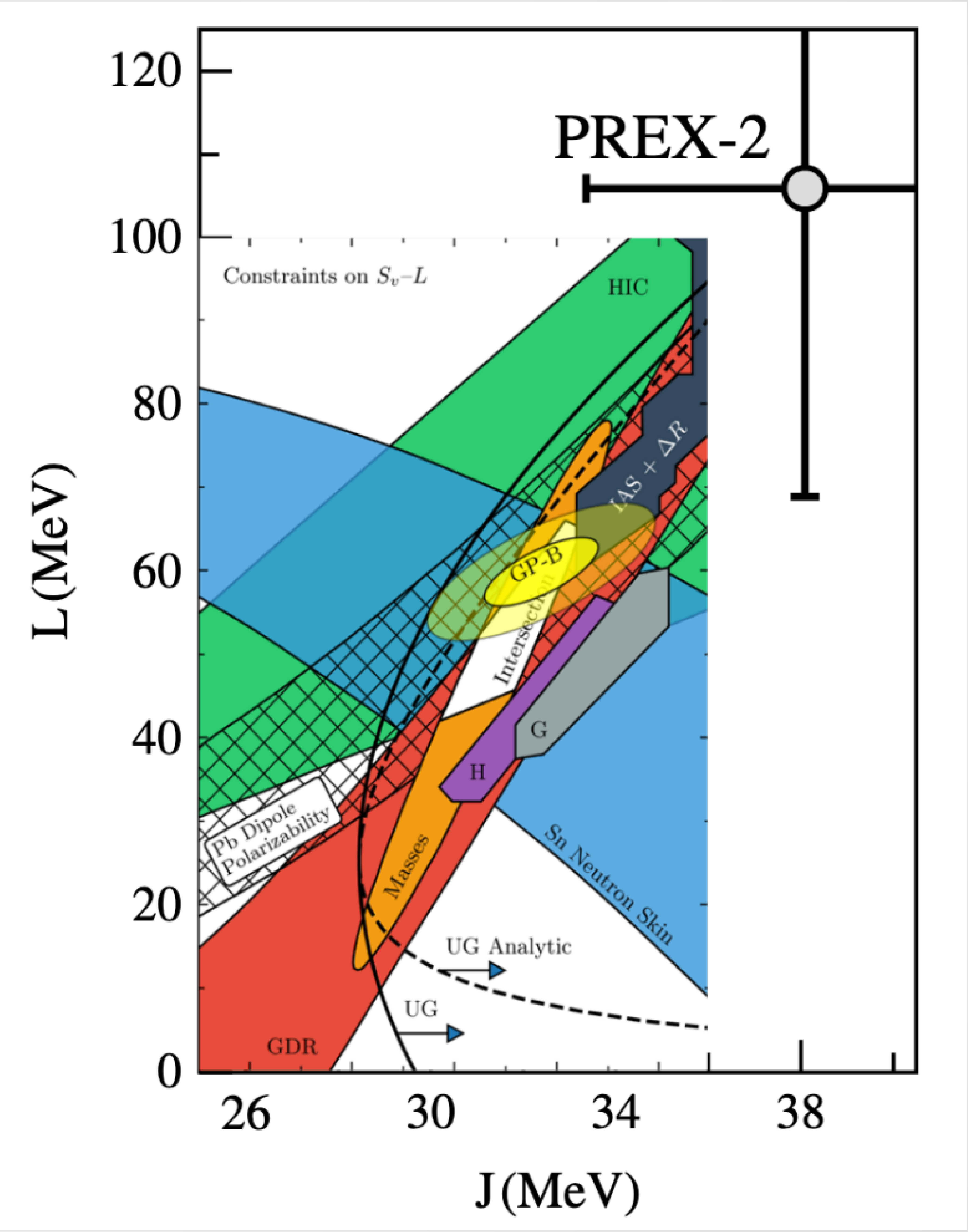

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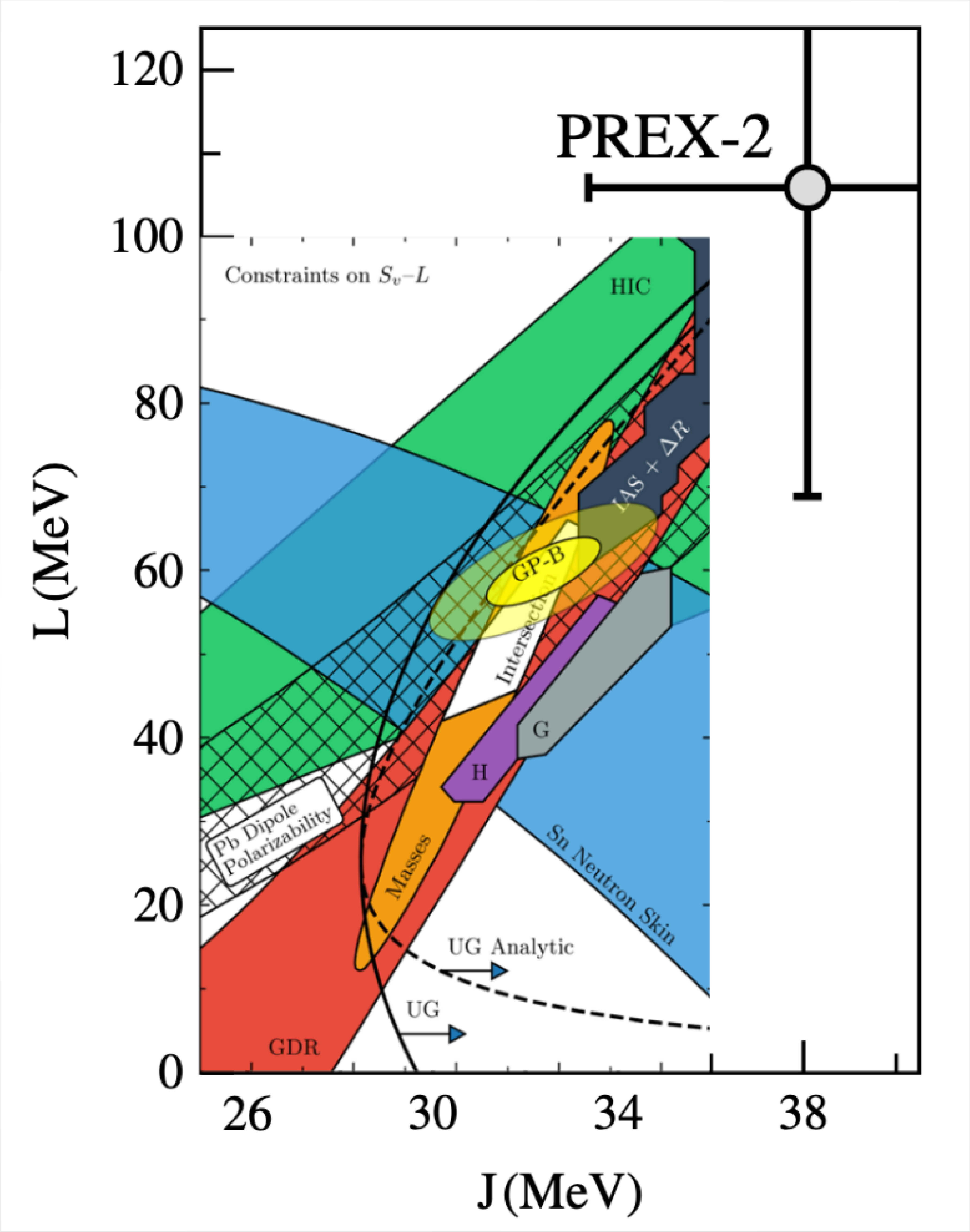

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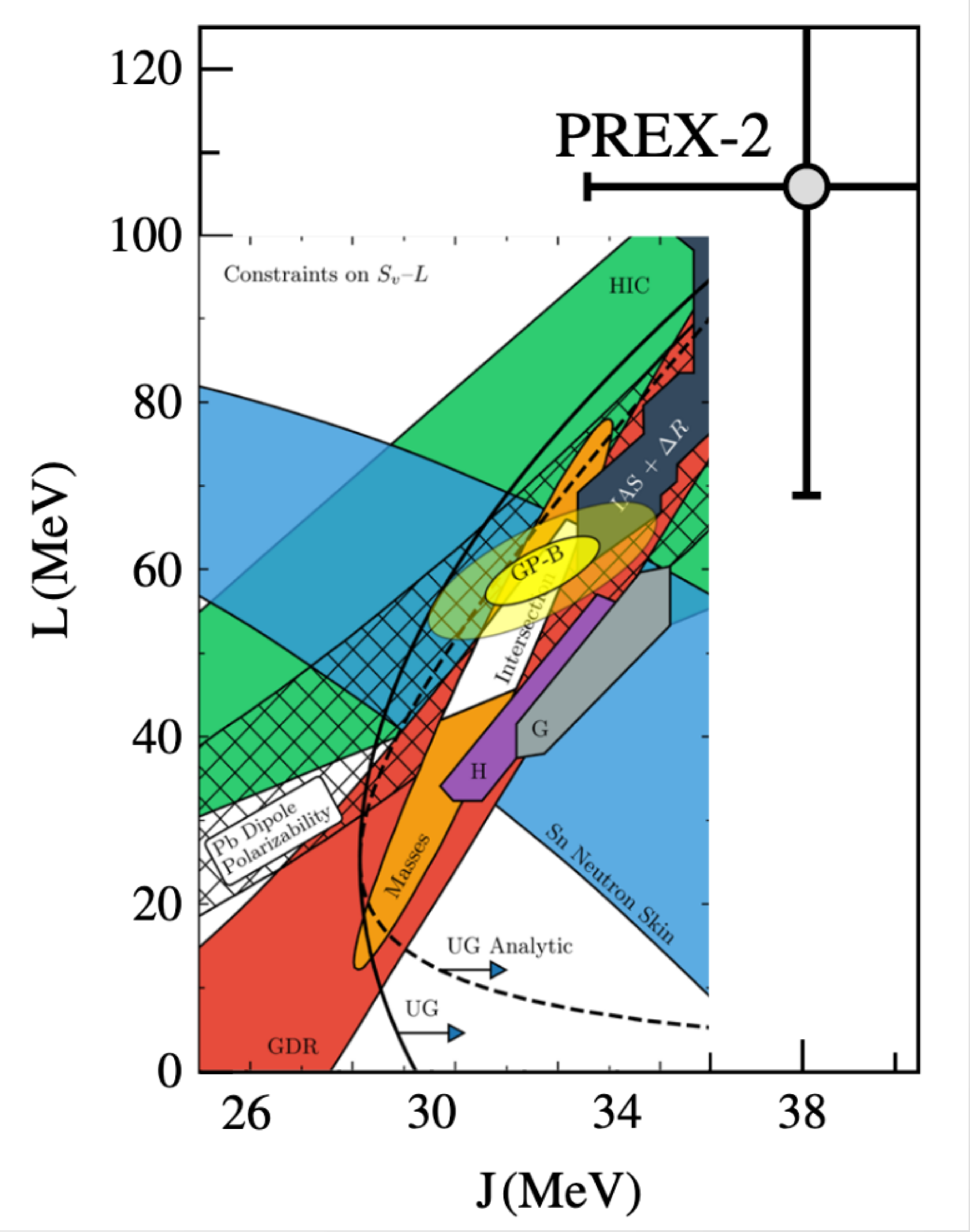
- A PREX II systematic, failure of correlation between form factor and L
- Or they're all right, and we're just a little bit unlucky
- Lots of current theory work, but the best way to resolve this is more data

It would be nice to put more NICERs on the ISS...



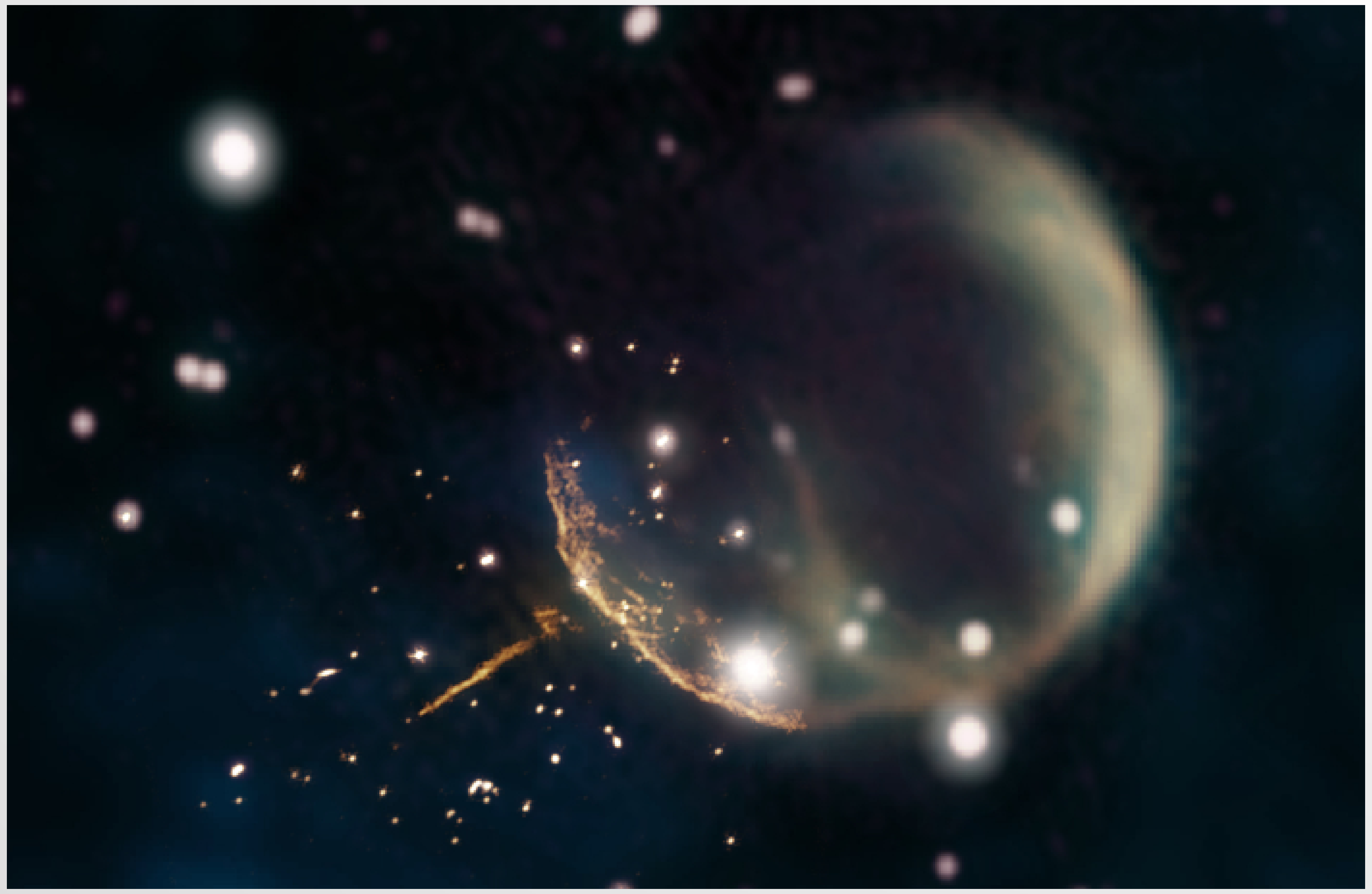
Reed et al. (2021)

Thermal Emission from Isolated Neutron Stars

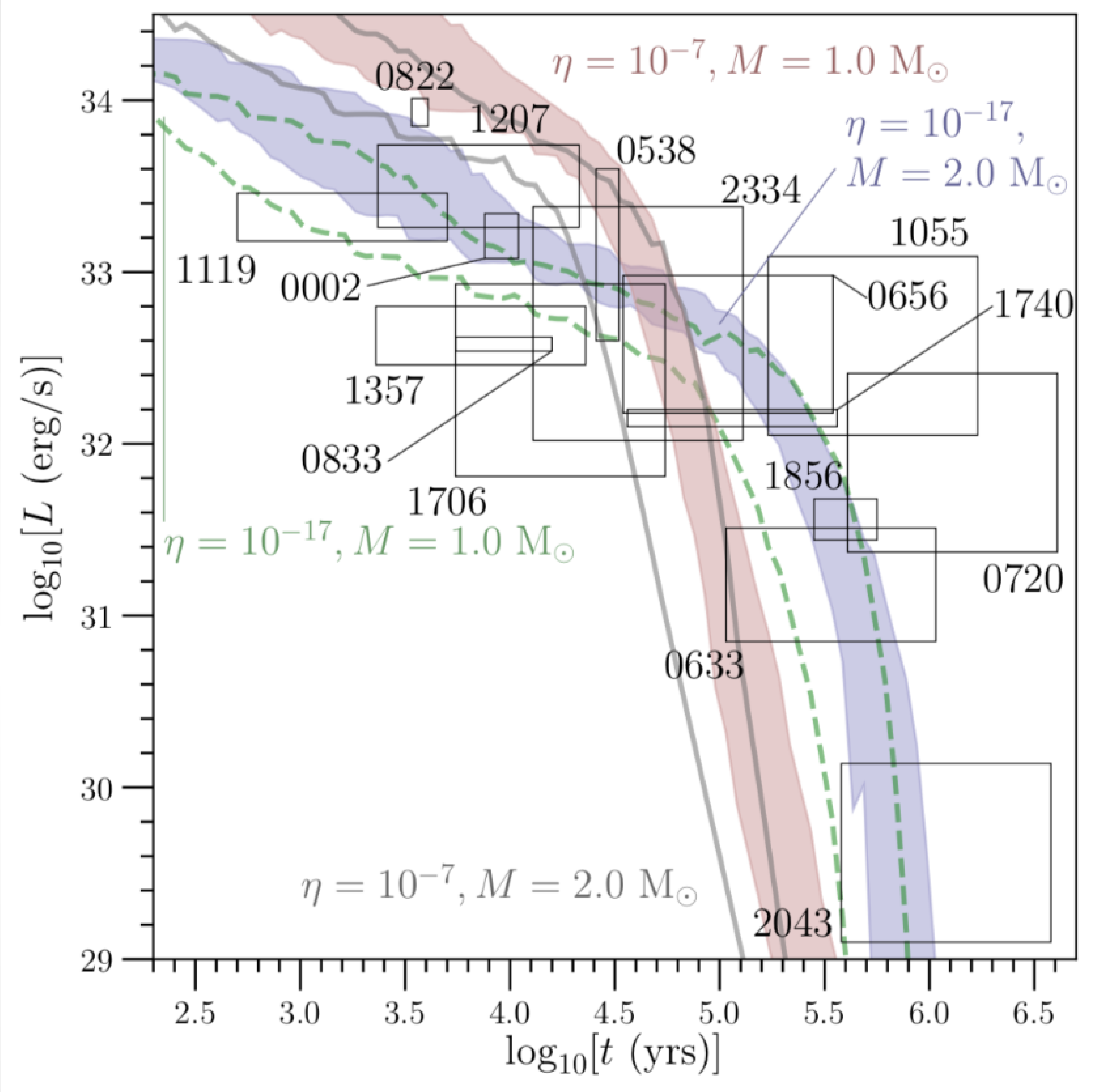
- After ~ 10 years, the neutron star is isothermal ⇒ one temperature = T

$$C_V \frac{dT}{dt} = L_\nu + L_\gamma$$

- Assume only neutrons and protons
- Age taken from, e.g., association with a supernova remnant



J0002-6246, i.e. the "cannonball pulsar"



Beloin et al. (2019)

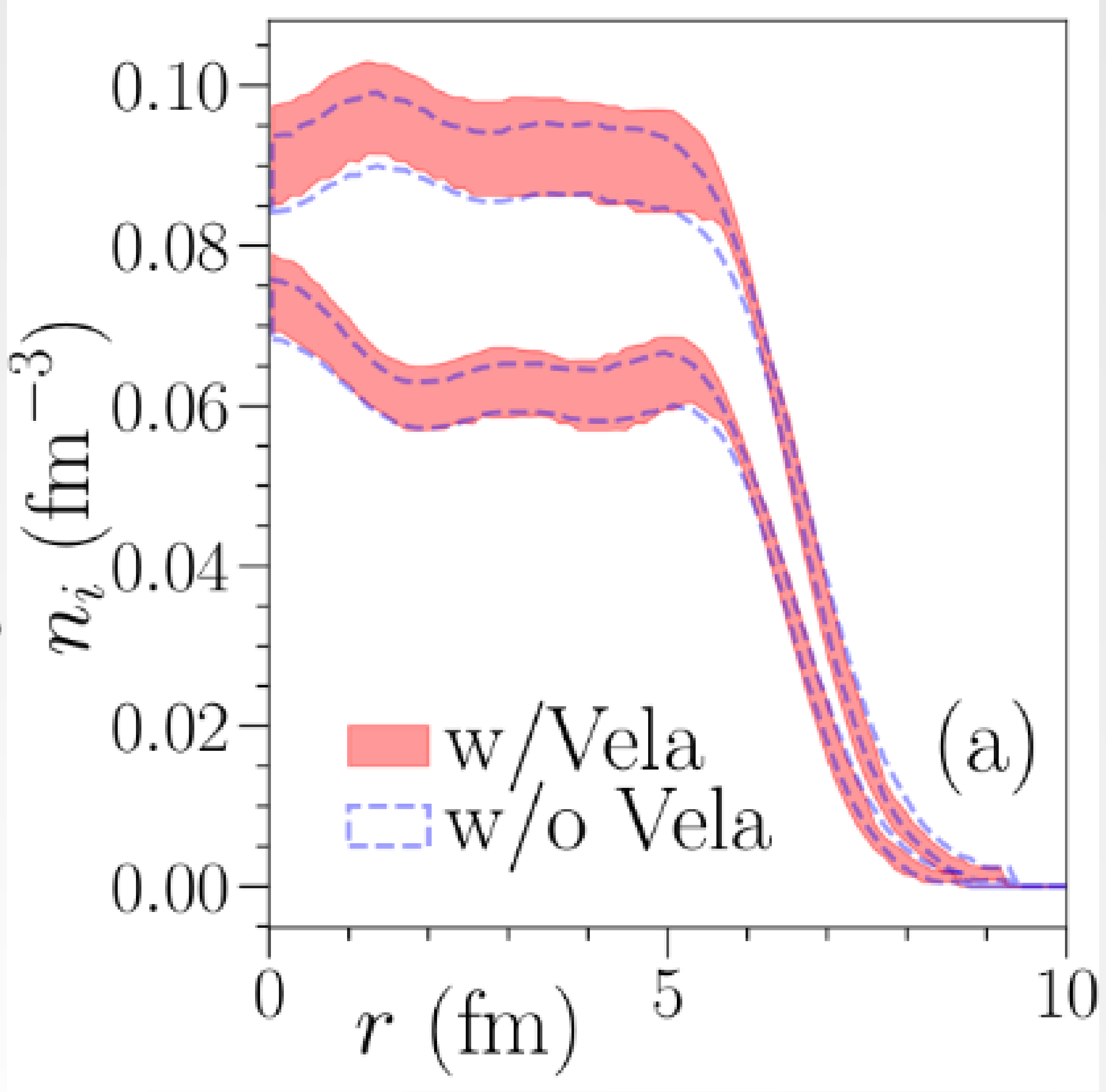
First Large-Scale Bayesian Inference for NSs

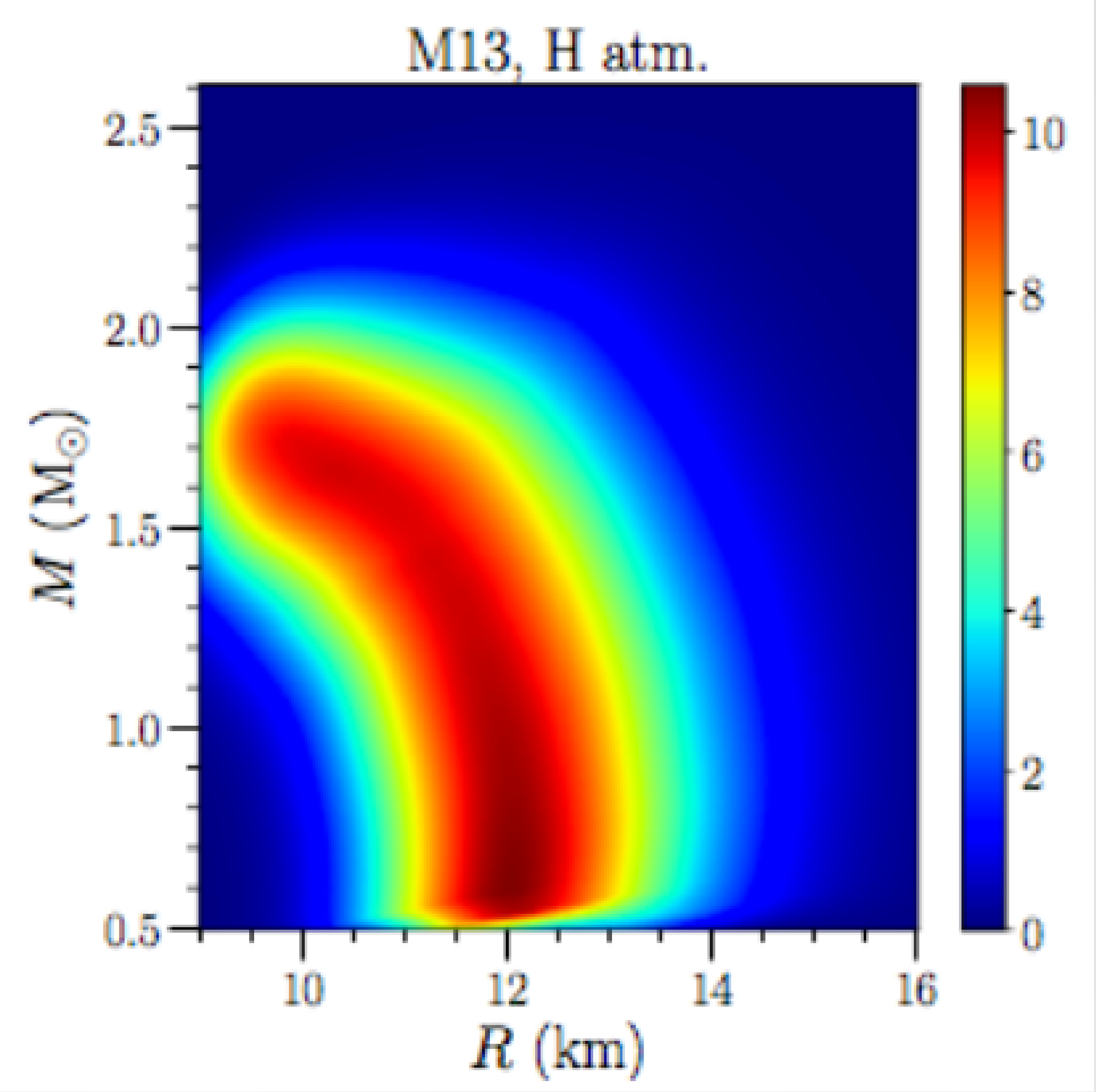
1. Include nuclear data (binding energies & charge radii of nuclei; Hartree approx.)

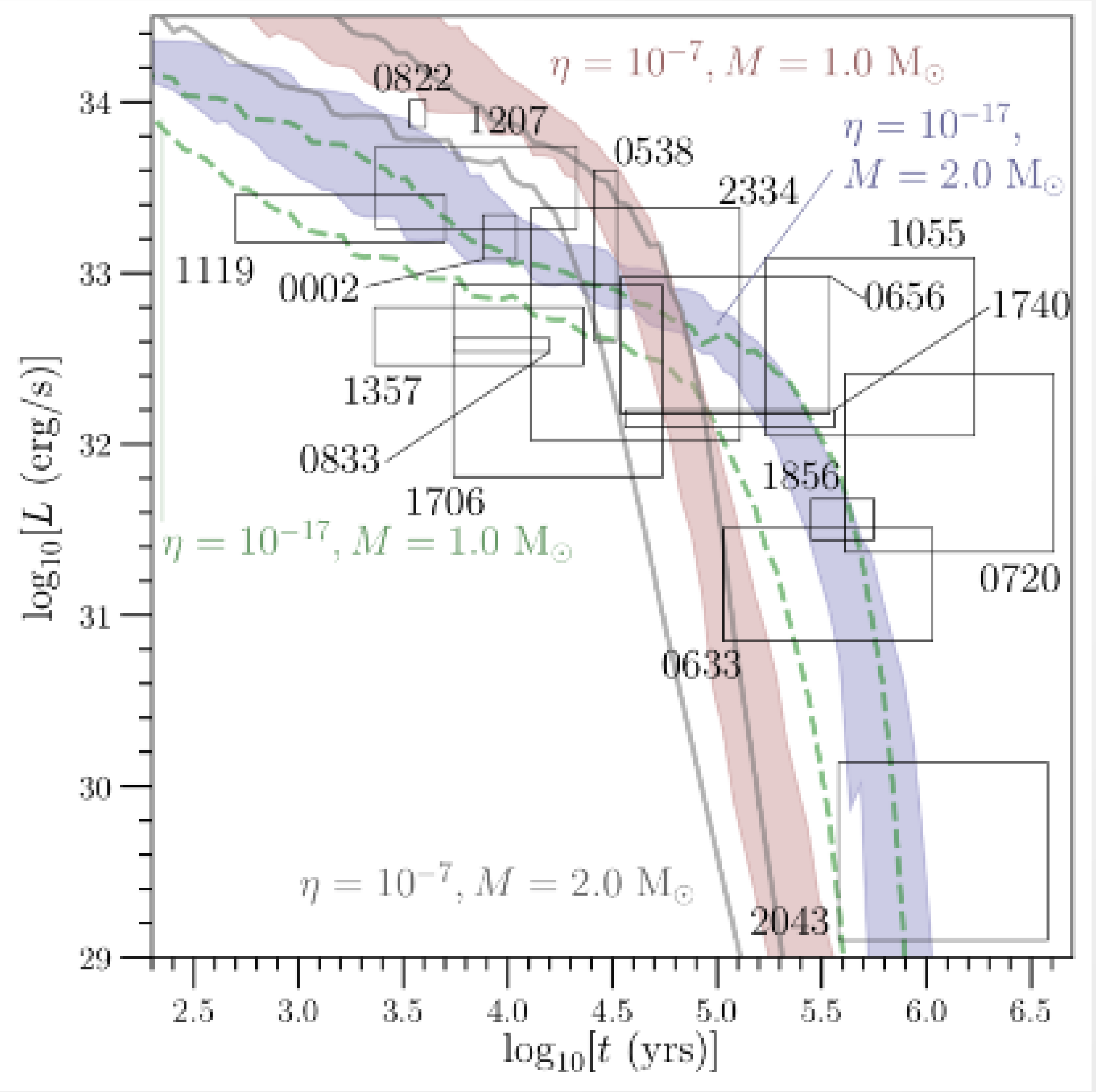
2. Neutron star mass and radius determinations from QLMXBs

3. Luminosity and age measurements of isolated neutron stars with $B < 10^{12}$ G

- Nuclear structure calculations
- Solution to TOV equations
- Simplified stellar evolution equations for neutron star cooling

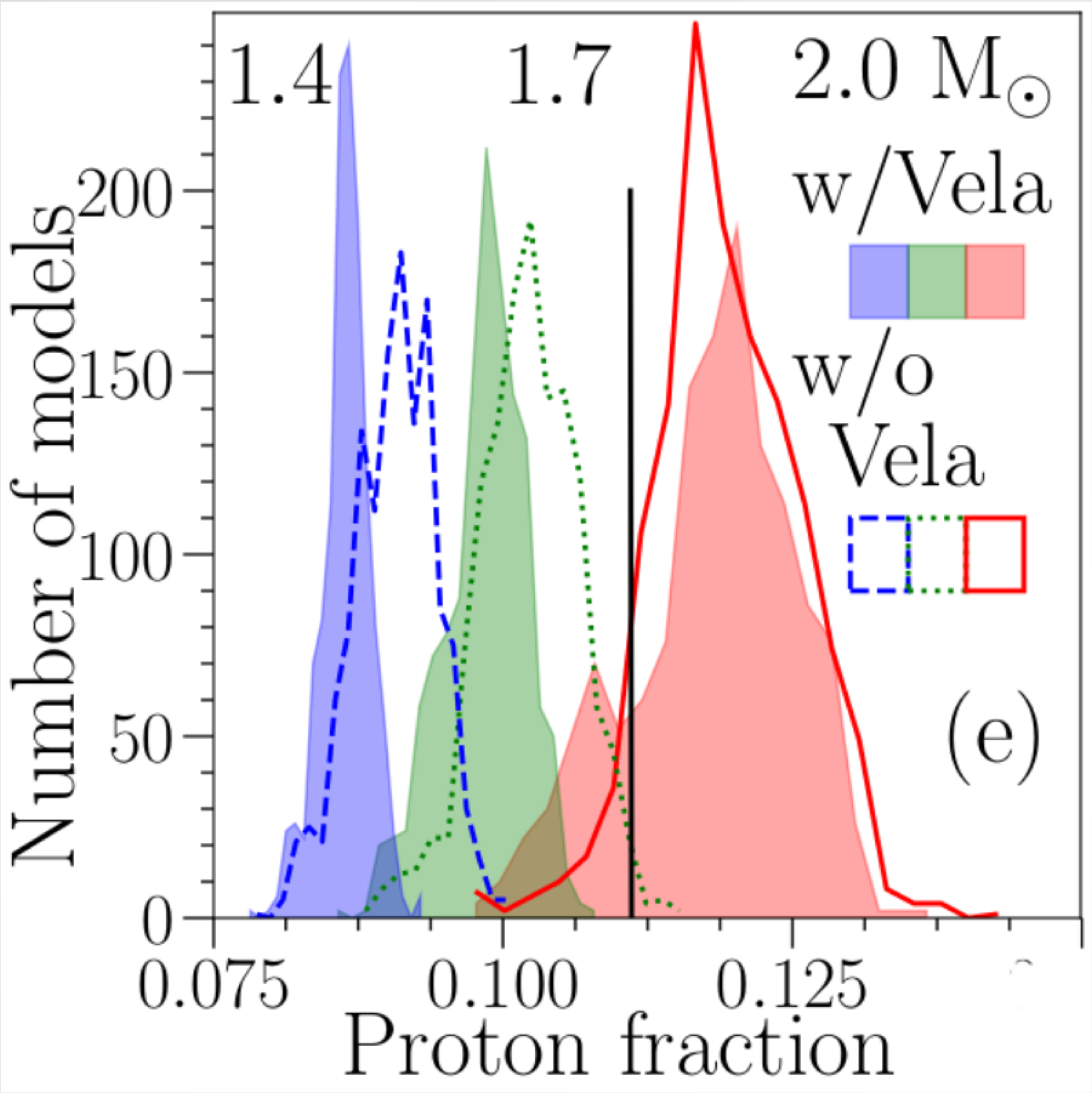






Beloin et al. (2019)

Now we have information on composition!



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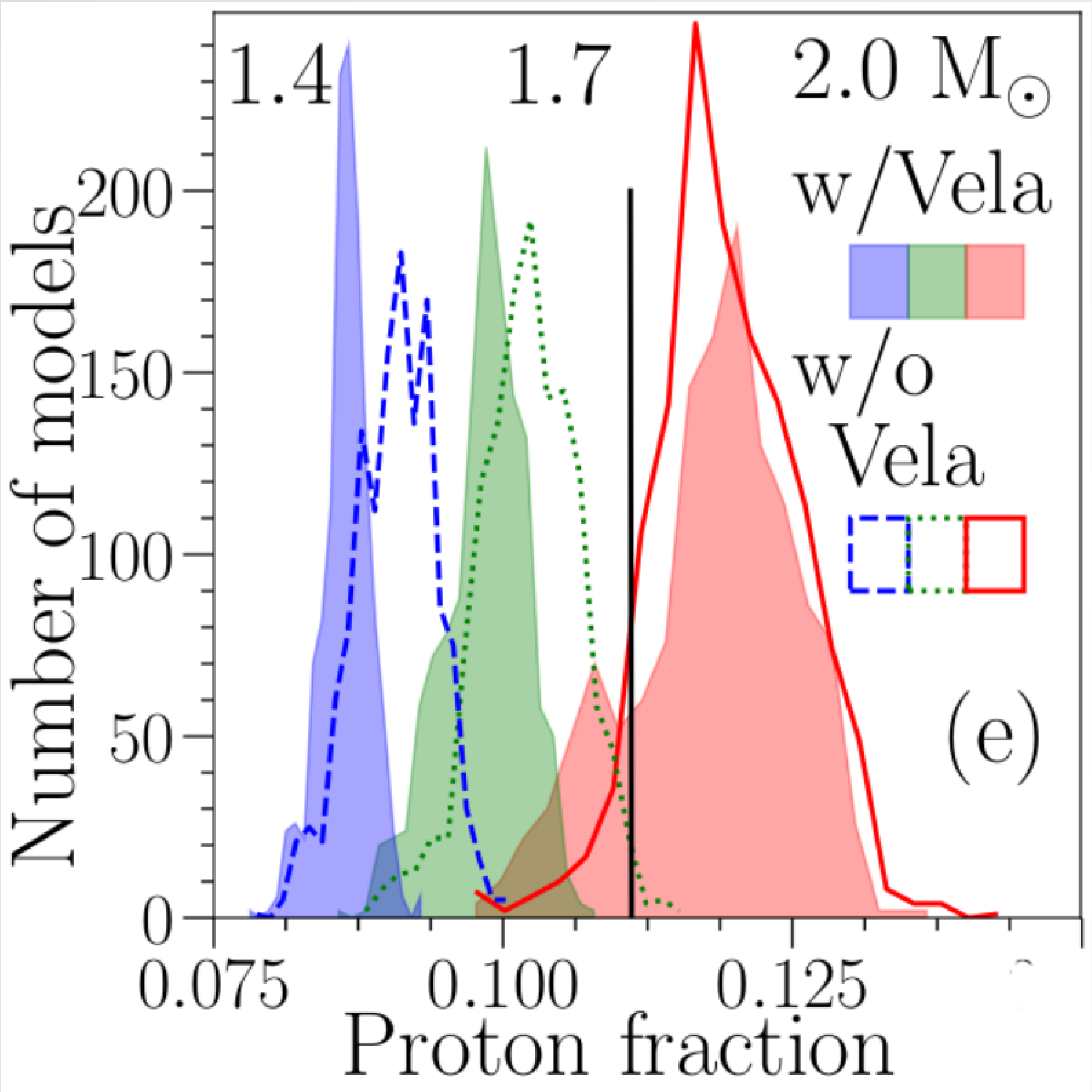

Beloin et al. (2019)

- Proton fraction is larger than 11% in the core of massive stars

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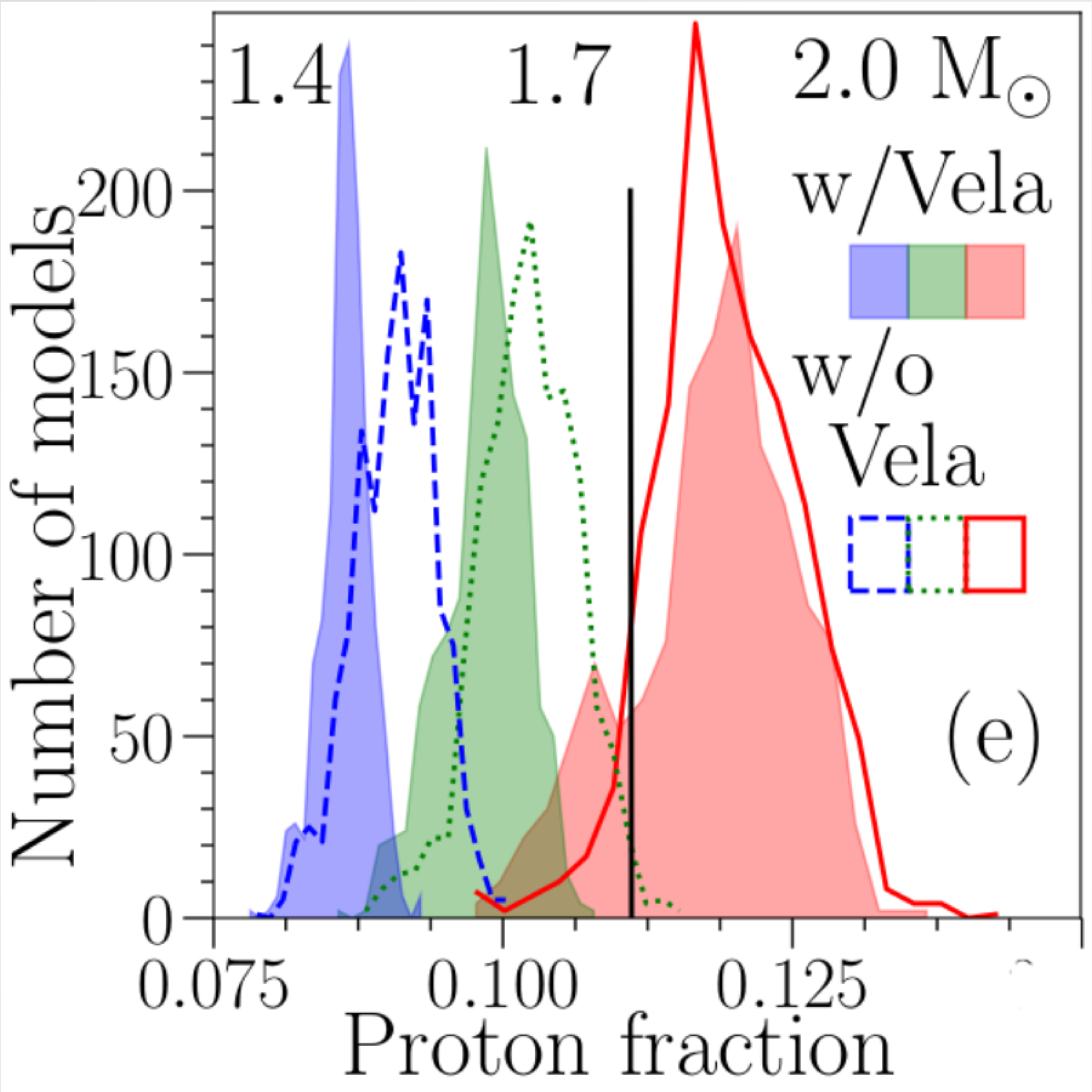

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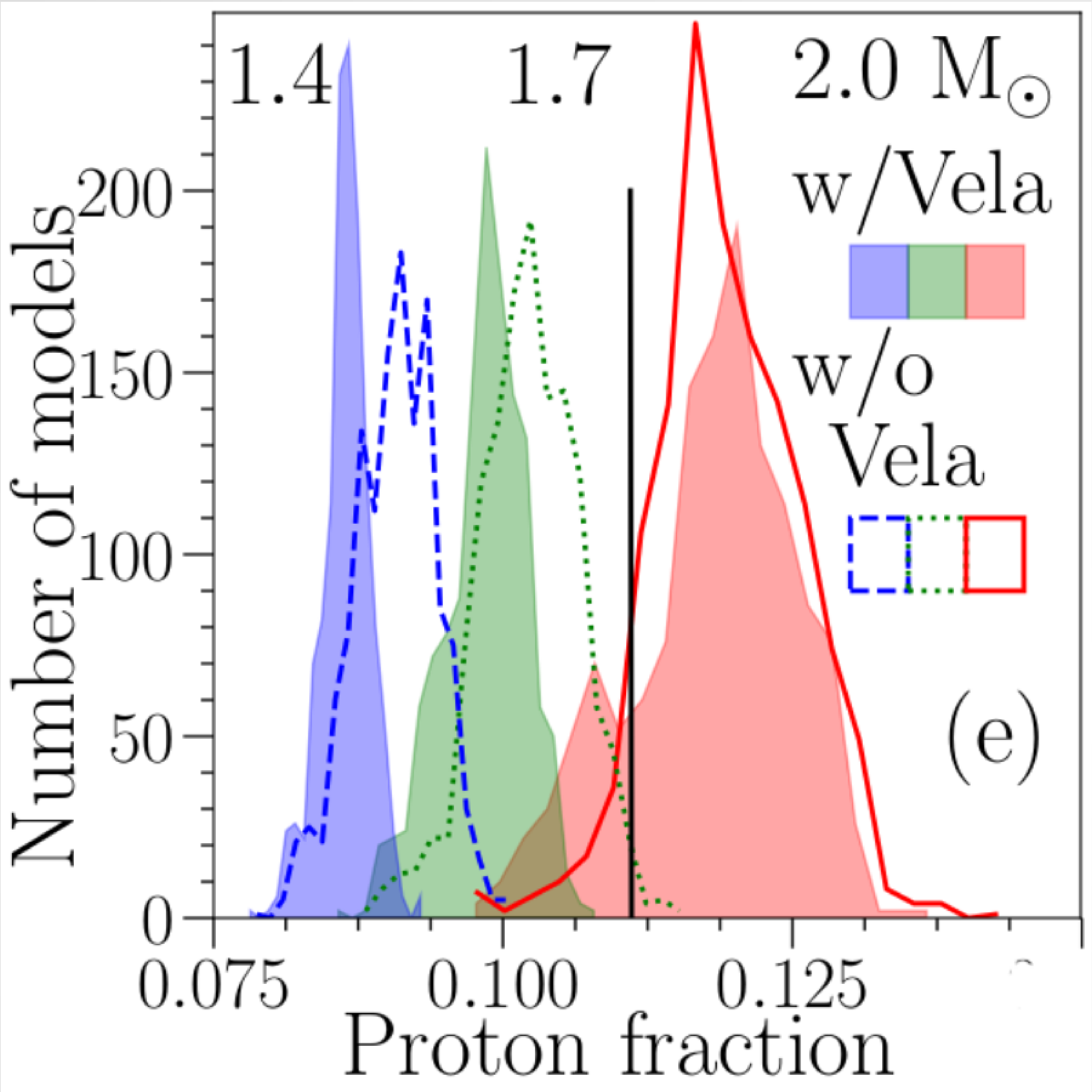

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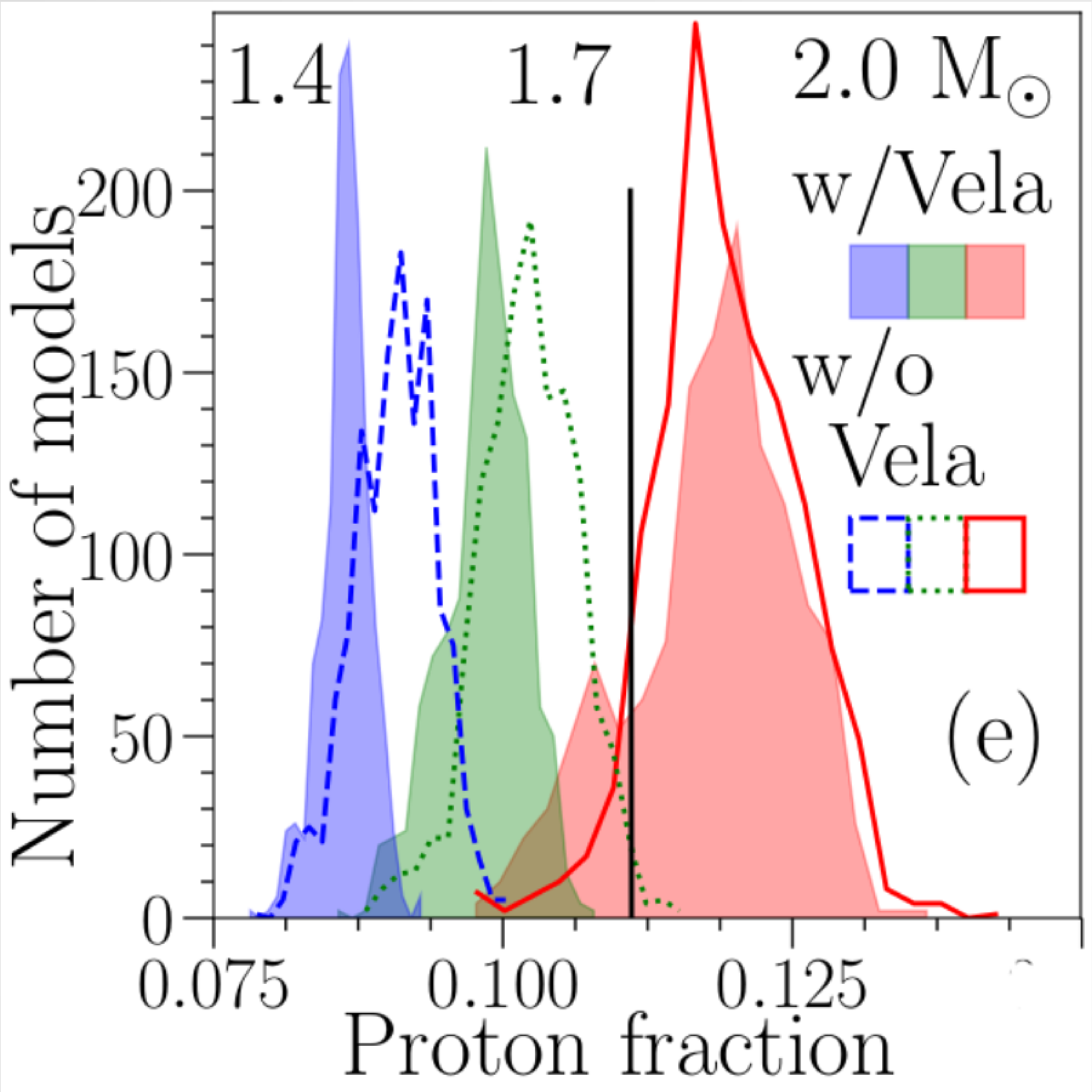

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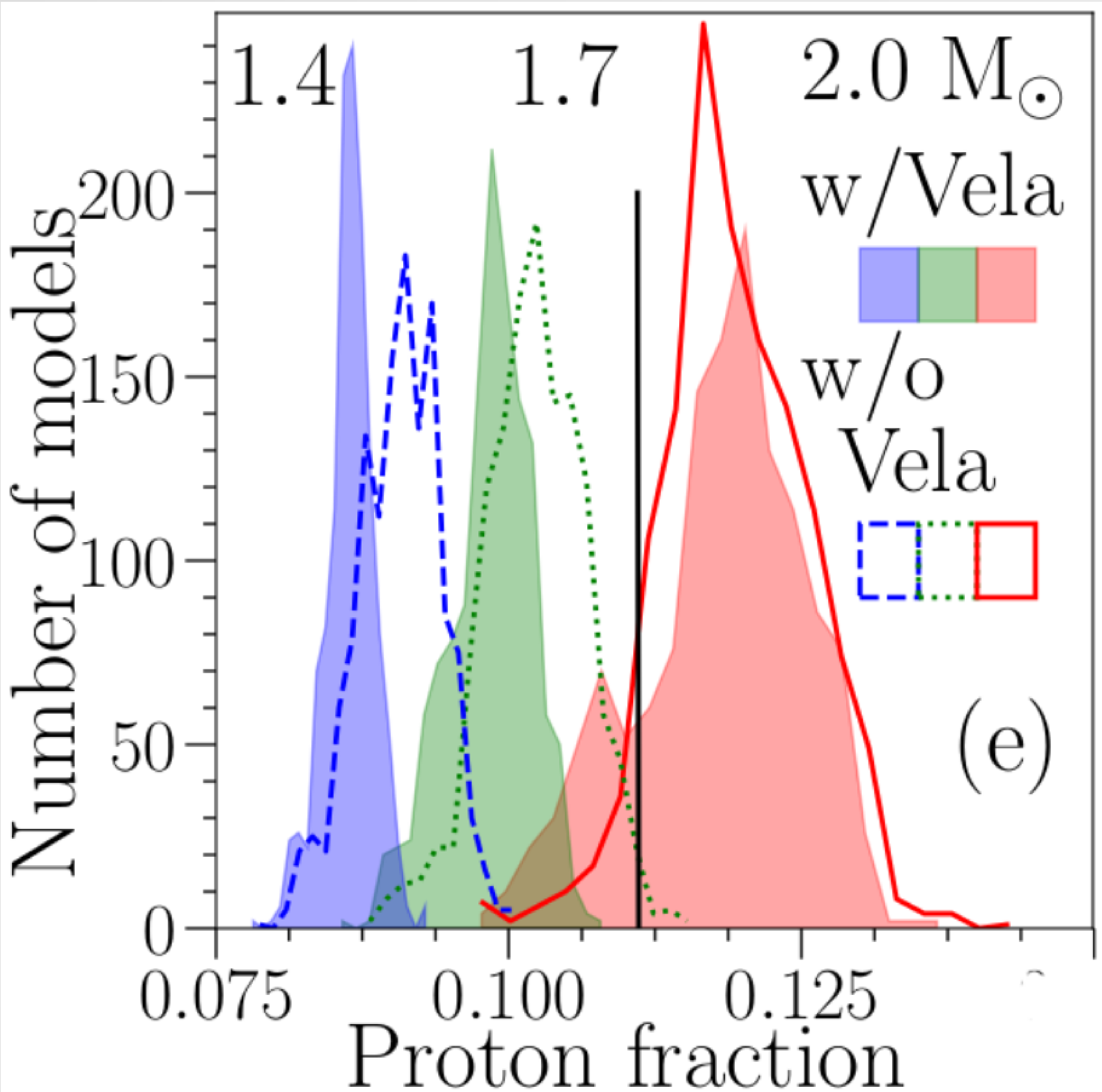

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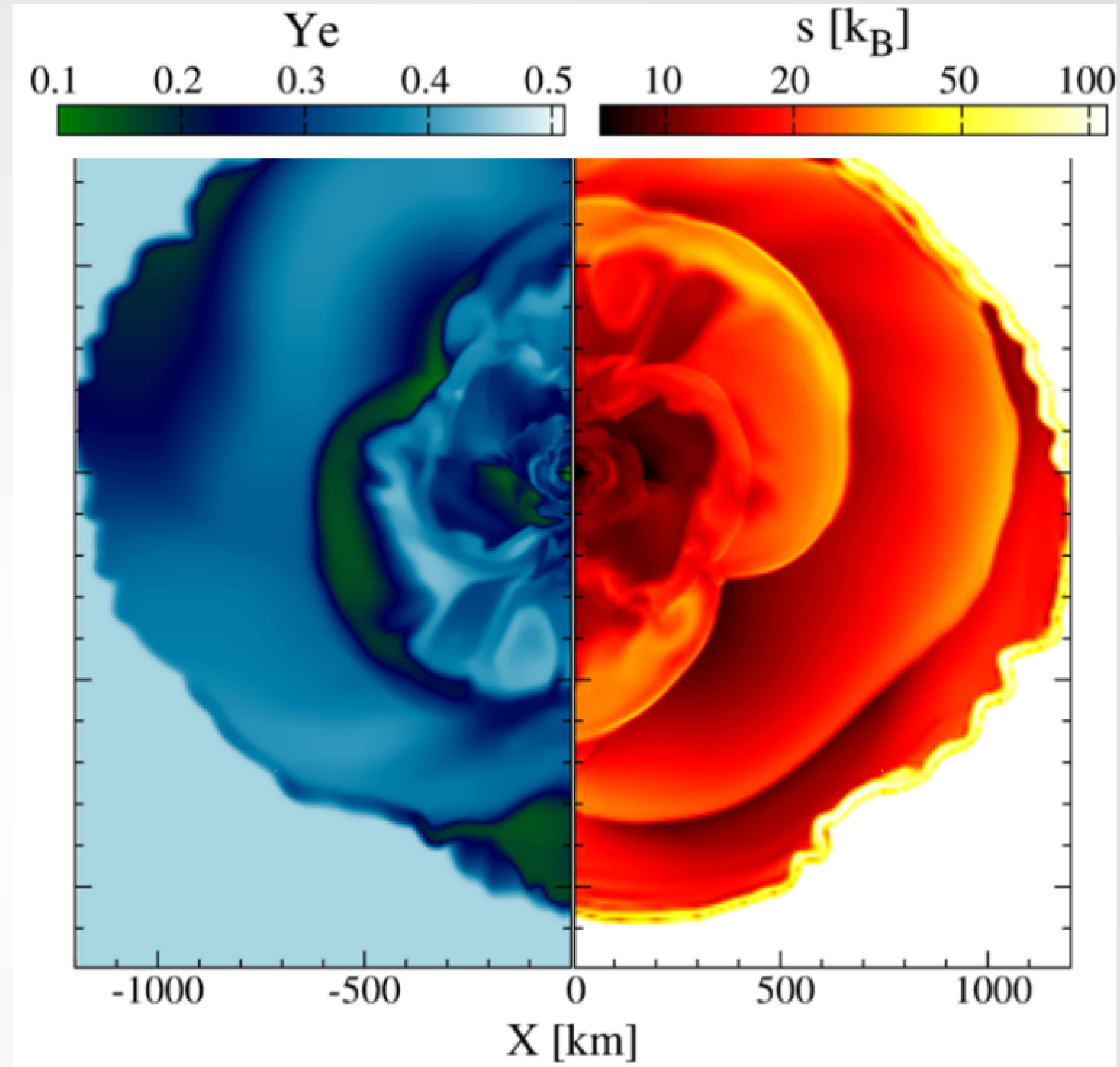
- More likely way out: make a superfluid
- Neutron triplet superfluidity pervades the star

Direct Relation to Neutron Star Mergers

- SFHo equation of state used in neutron star merger simulations
- Originally motivated by NS radius measurements
- R-process abundances are not strongly modified by equation of state changes
- However, amount of mass ejected significantly increased:
  SFHo: $> 1.0 \times 10^{-2}\ M_\odot$
  DD2: $< 2.1 \times 10^{-3}\ M_\odot$
  TM1: $< 1.2 \times 10^{-3}\ M_\odot$



Sekiguchi et al. (2015)

- Improves ability of mergers to produce r-process elements!

Summary

- EM observations and GW observations combined constrain the radius of a $M = 1.4\ \mathrm{M}_{\odot}$ neutron star — prior dependence is weak
- But, prior still matters for low and high masses
- EM and GW observations seem to agree, but interesting future with PREX II and NICER's observation of J0740
- Combined analysis with NS cooling constrains composition
- There are important connections between the EOS and NS mergers: maximum mass and amount of mass ejected
- Exciting news just around the corner...