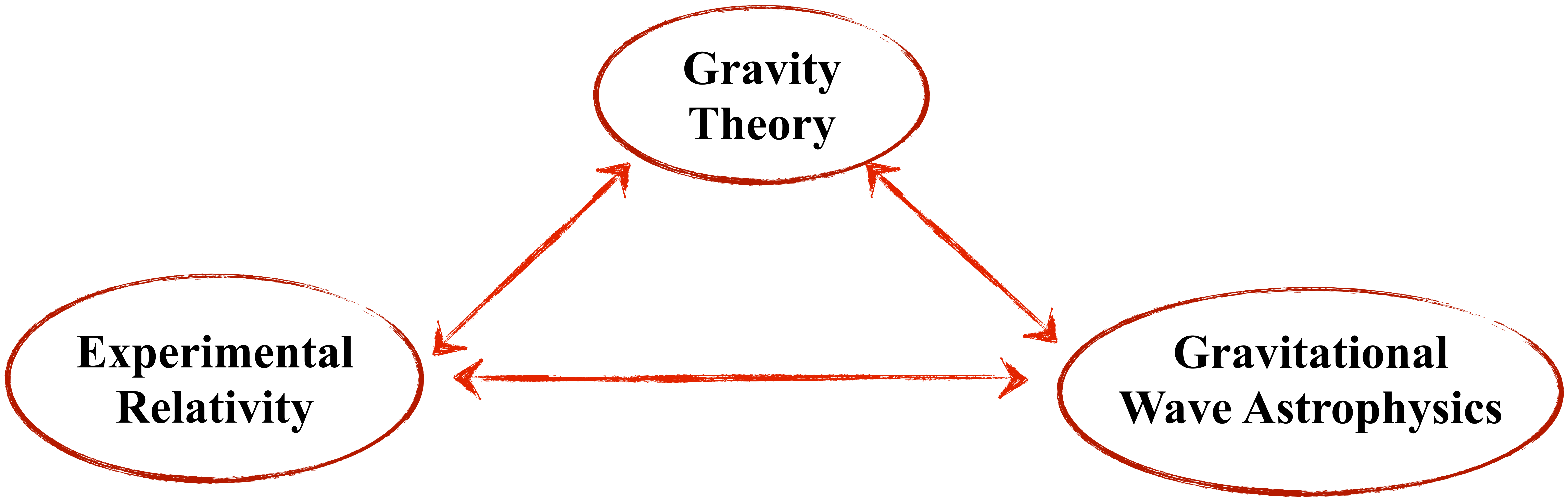
What can we learn from gravitational waves emitted by heavy neutron stars mergers?

Nicolas Yunes
Illinois Center for Advanced Studies of the UniverseUniversity of Illinois at Urbana-Champaign

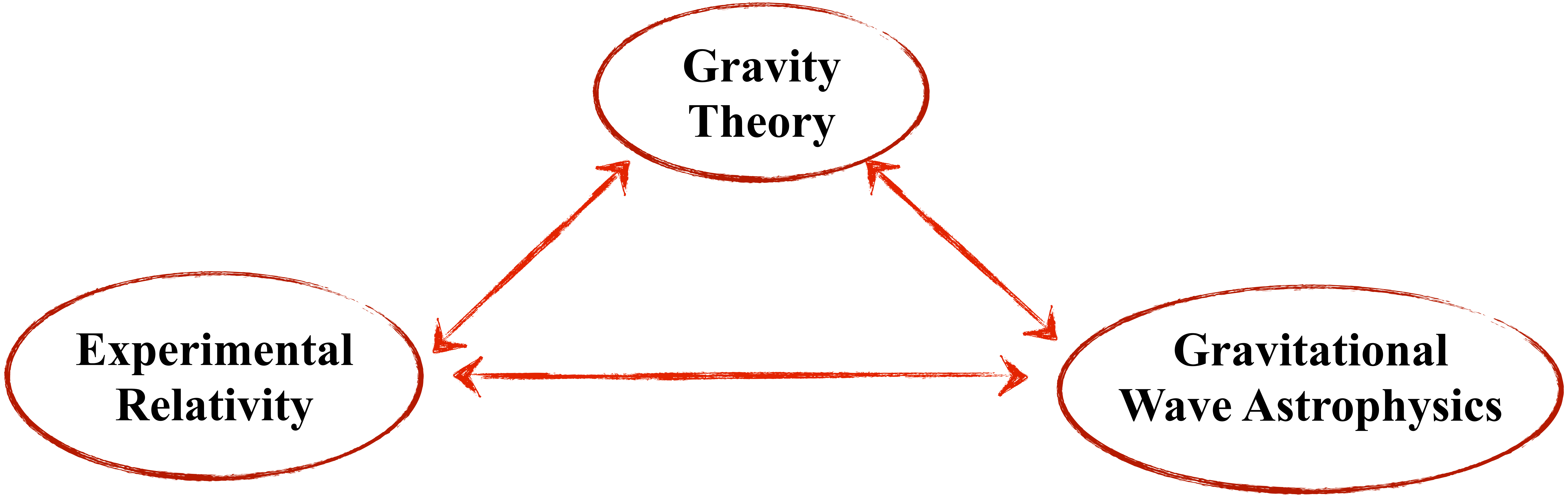
[in collaboration with **Hun Tan, Travis Dore**, Jaki Noronha-Hostler and Veronica Dexheimer]

DNP Workshop before April APS '21
April 14th, 2021

What is it that you do?



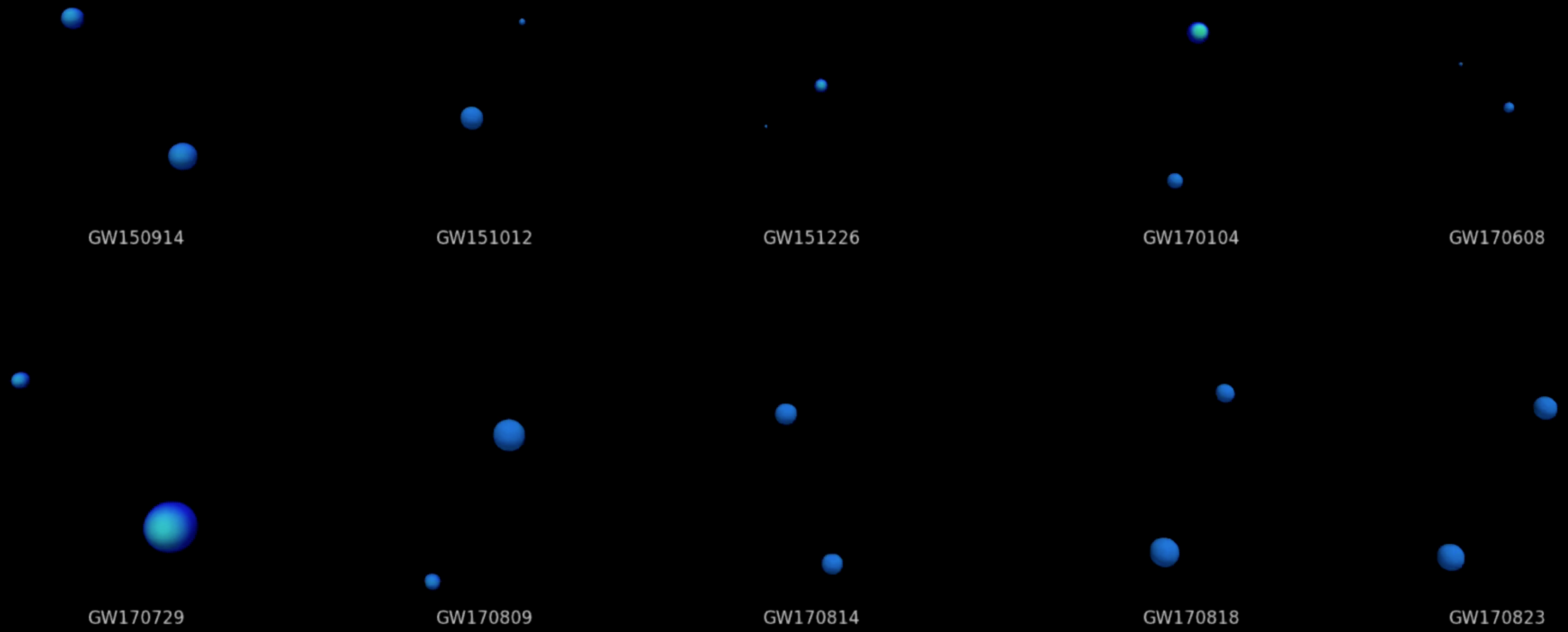
What is it that you do?



What can we learn about nuclear physics from the inspiral of heavy neutron stars?

A zoo of sources

Time: -0.63 seconds



[Credit: Teresita Ramirez / Geoffrey Lovelace / SXS Collaboration / LIGO Virgo Collaboration]

Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
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GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

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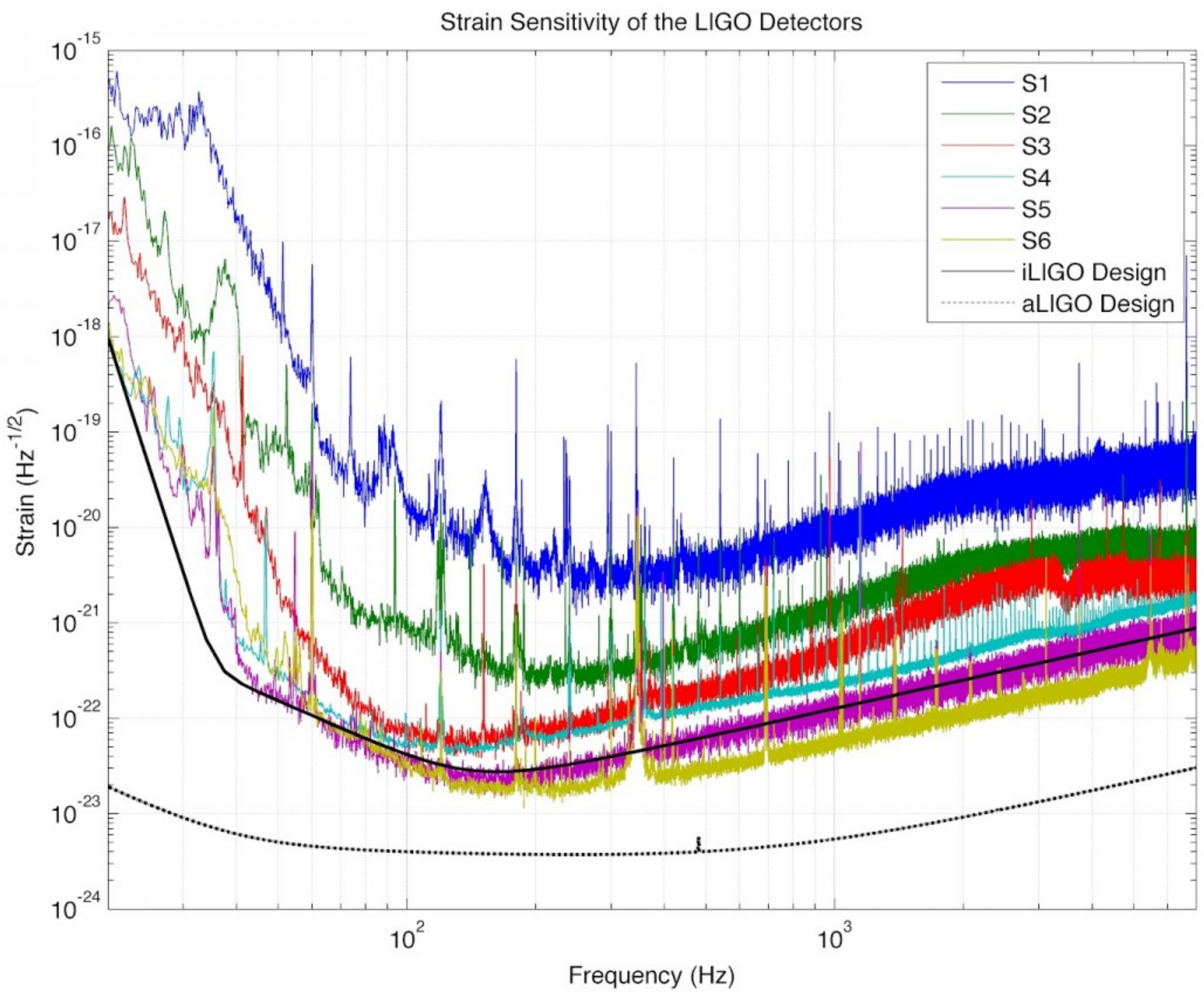
How do you extract information from gravitational



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Modelling 1. Create template “filters”

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Data Analysis

How do you extract information from gravitational

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Data Analysis 2. Cross-correlate filters & data

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$$\mathcal{L} = e^{-\frac{1}{2}(s-h\,|\,s-h)} = e^{4\Re\int\left[\tilde{s}^*(f)-\tilde{h}^*(f,\lambda^\mu)\right]\left[\tilde{s}(f)-\tilde{h}(f,\lambda^\mu)\right]\frac{df}{S_n(r)}}$$

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inner product ↗

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Likelihood function → inner product → Fourier transform →

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Fourier transform

detector noise (spectral noise density)

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Fourier transform → $\tilde{h}^*$

template param that characterize system → λ^μ

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How do you extract information from gravitational

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The waveform model is key to extract physics information from GW data through matched filtering

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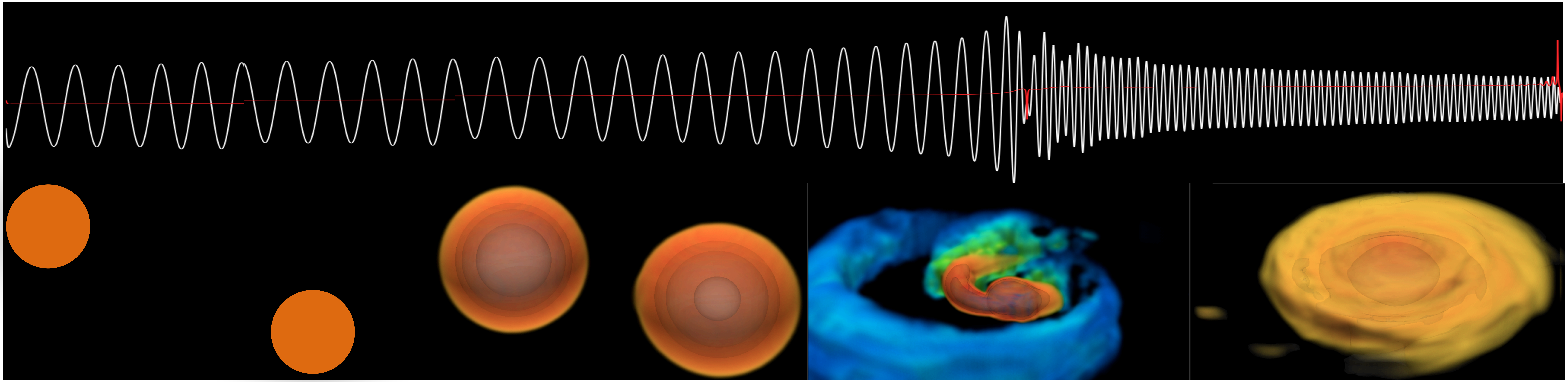

[see e.g. Blanchet, Liv. Rev. in Rel.,
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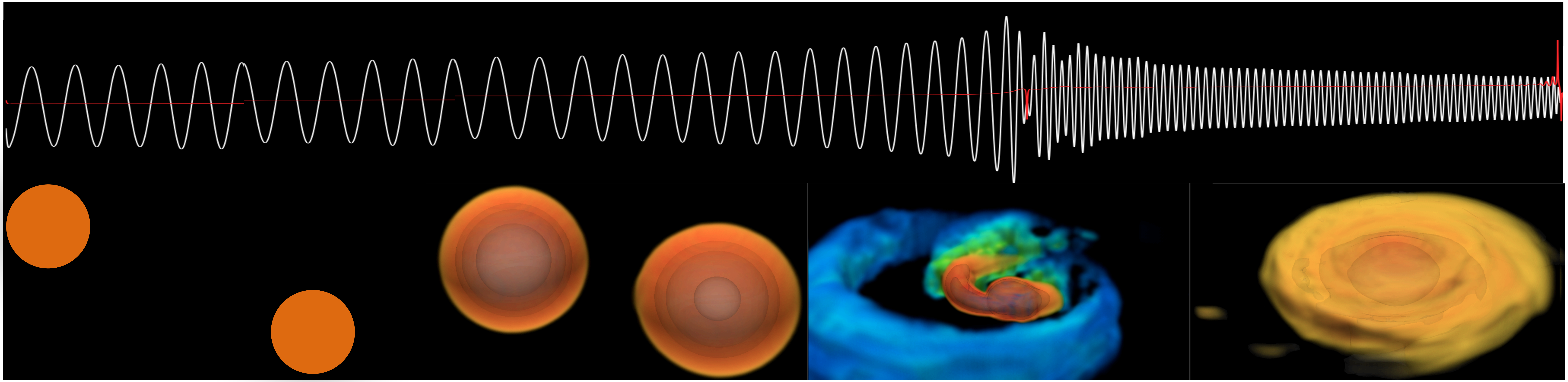

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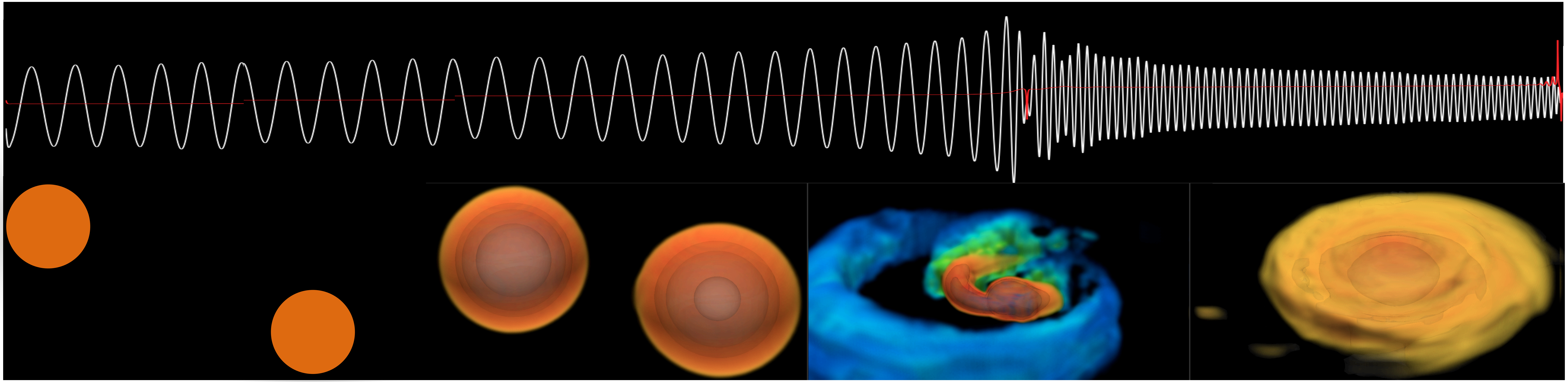

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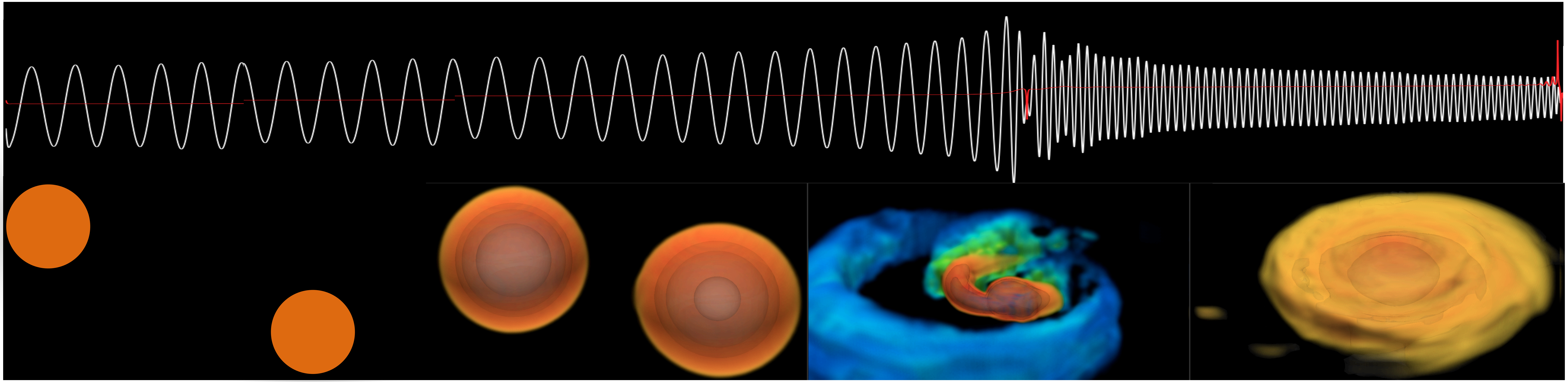

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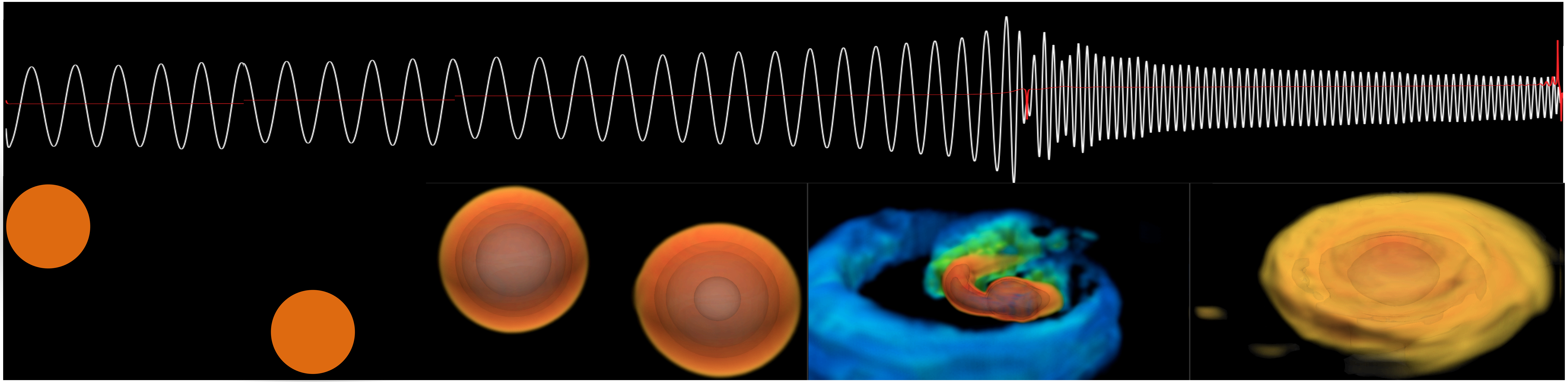

test-particles	tidal deformations	merger	post-merger
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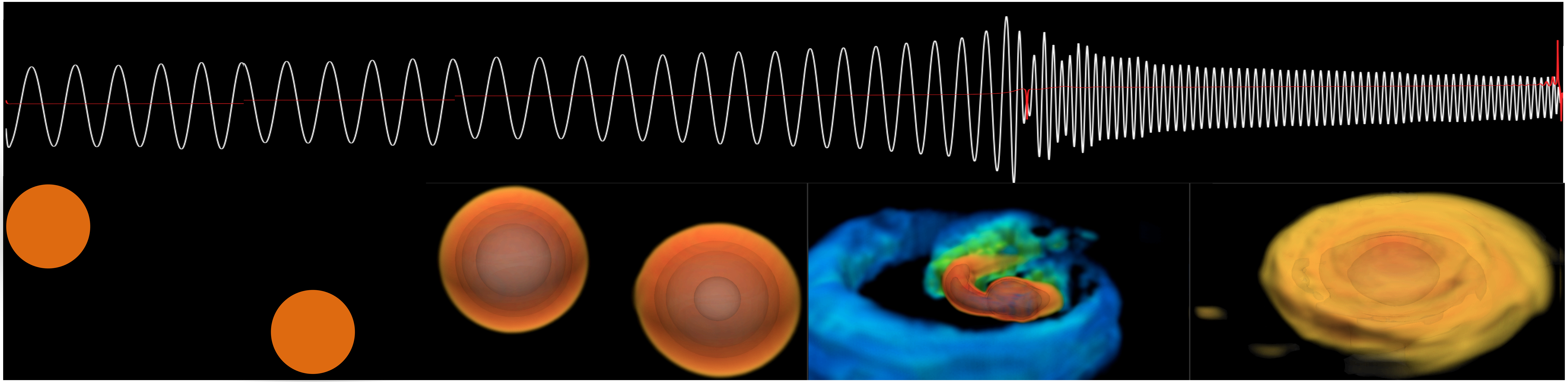

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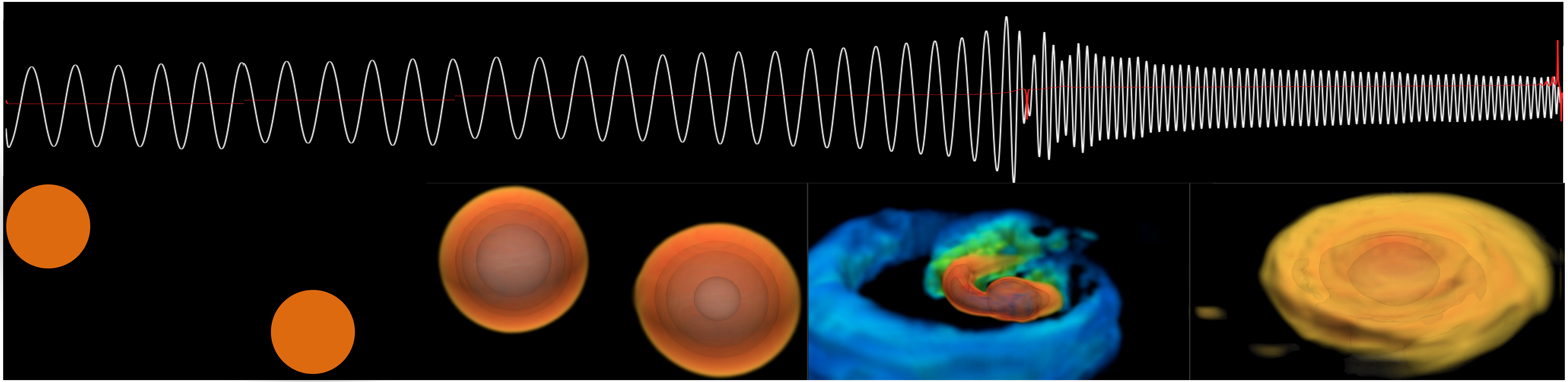

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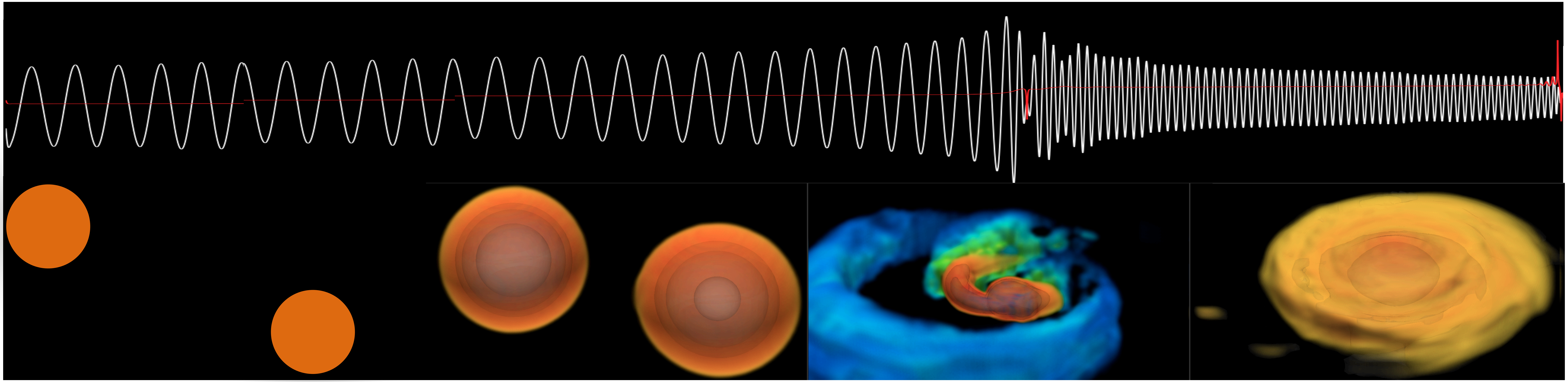

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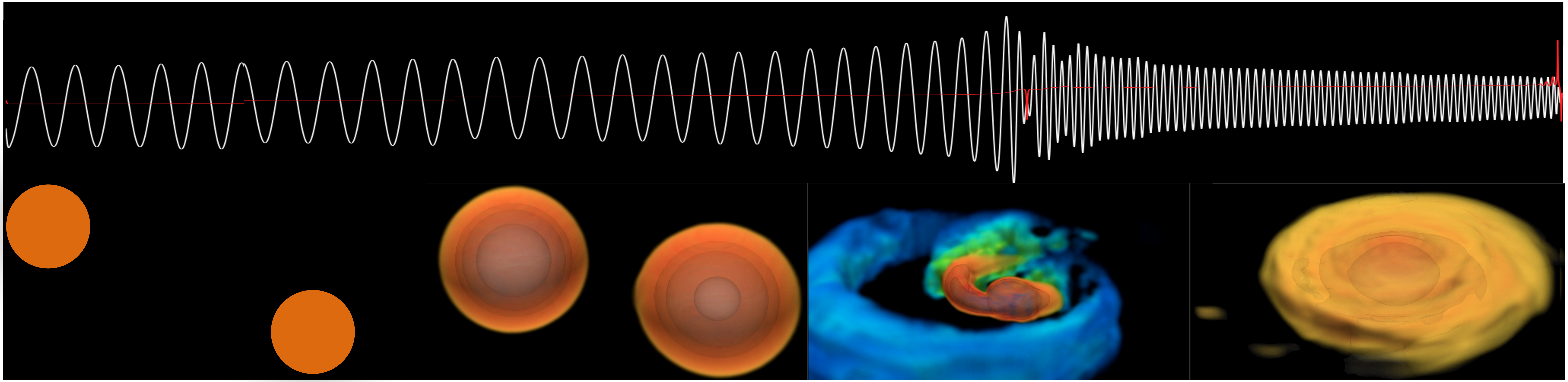

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Gravitational waves encode the tidal deformabilities

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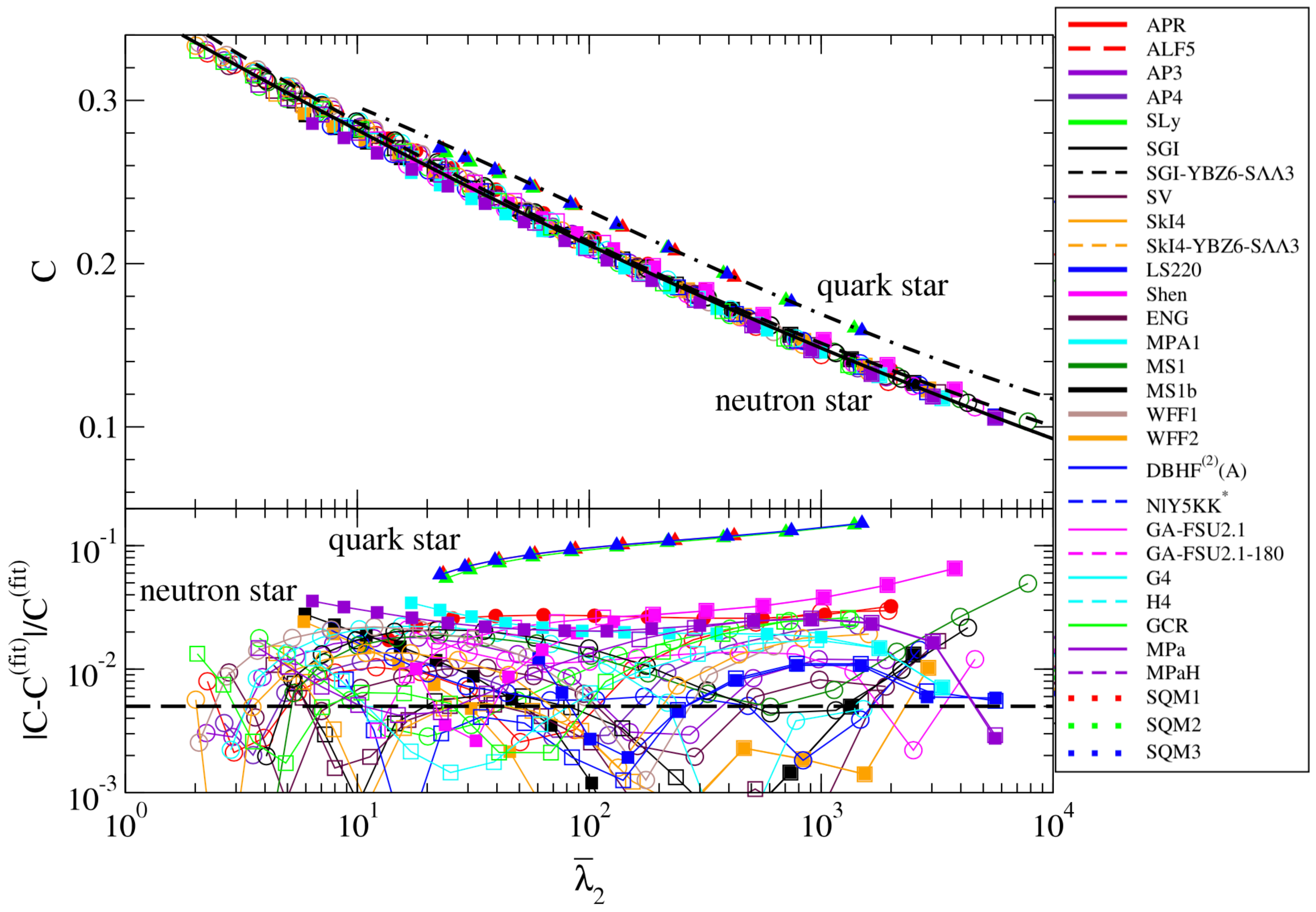
What's Love got to do with it*?

* "it" being nuclear physics.



[see e.g. Yagi & Yunes, Phys. Repts 681 (2017)]

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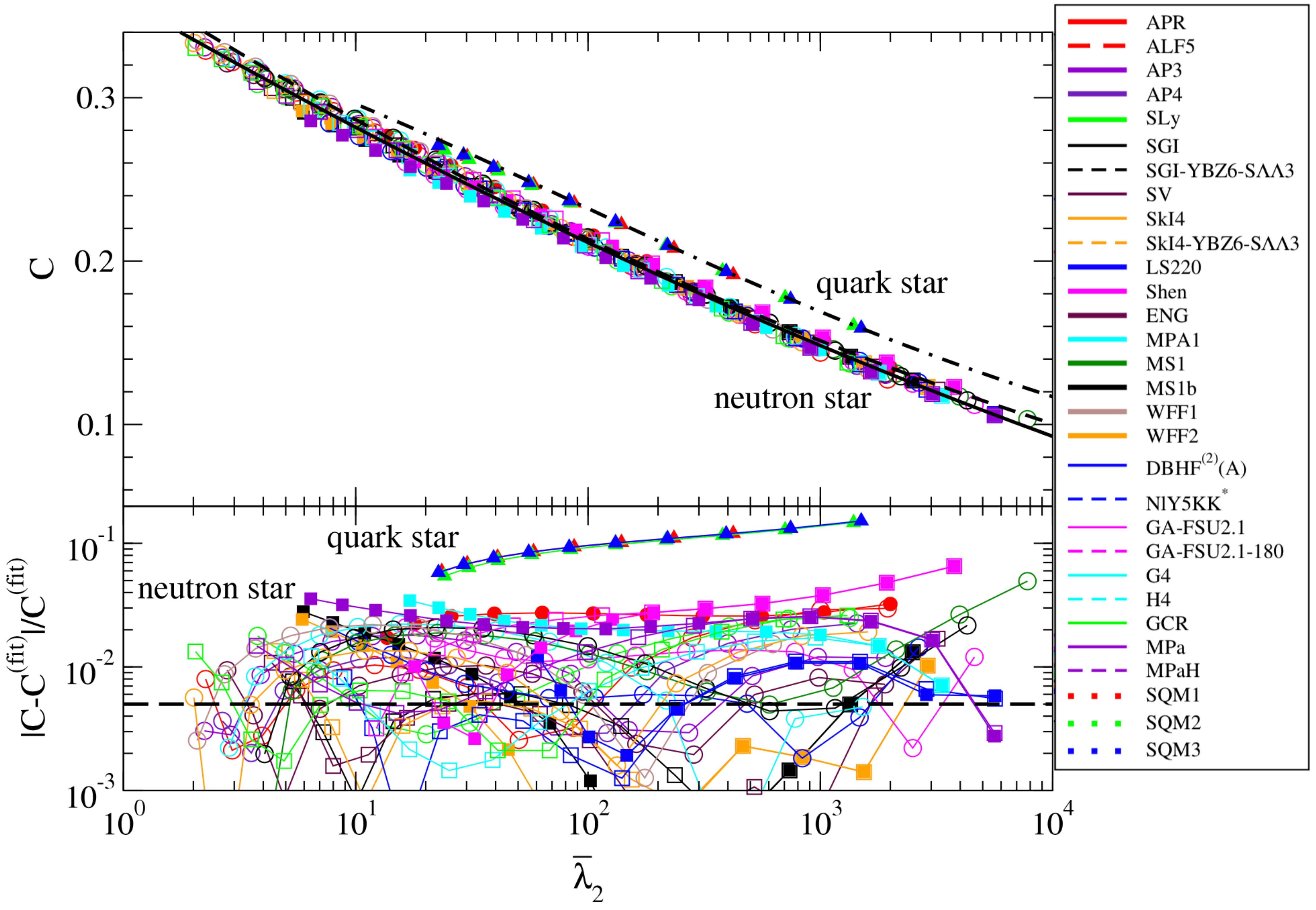

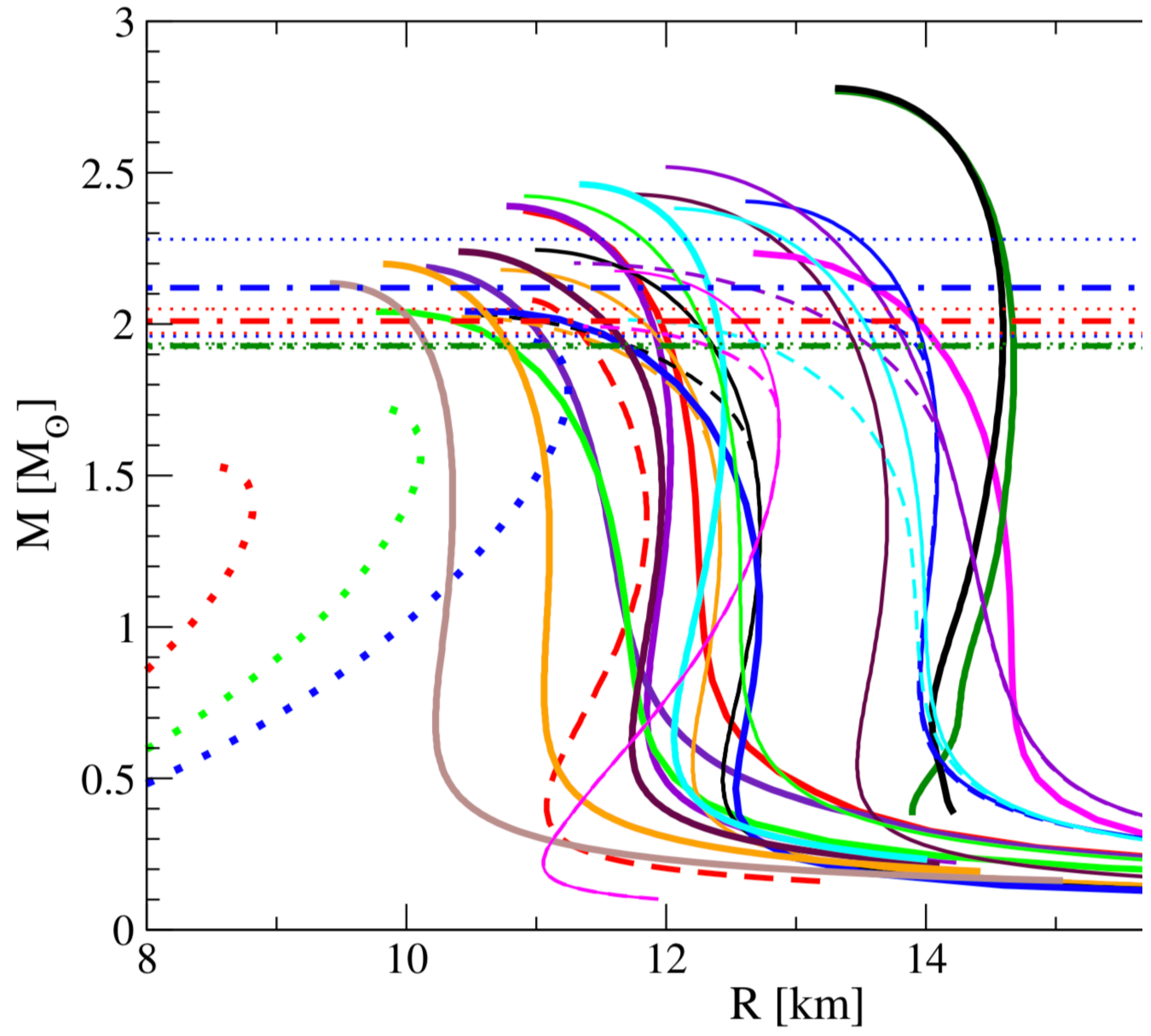

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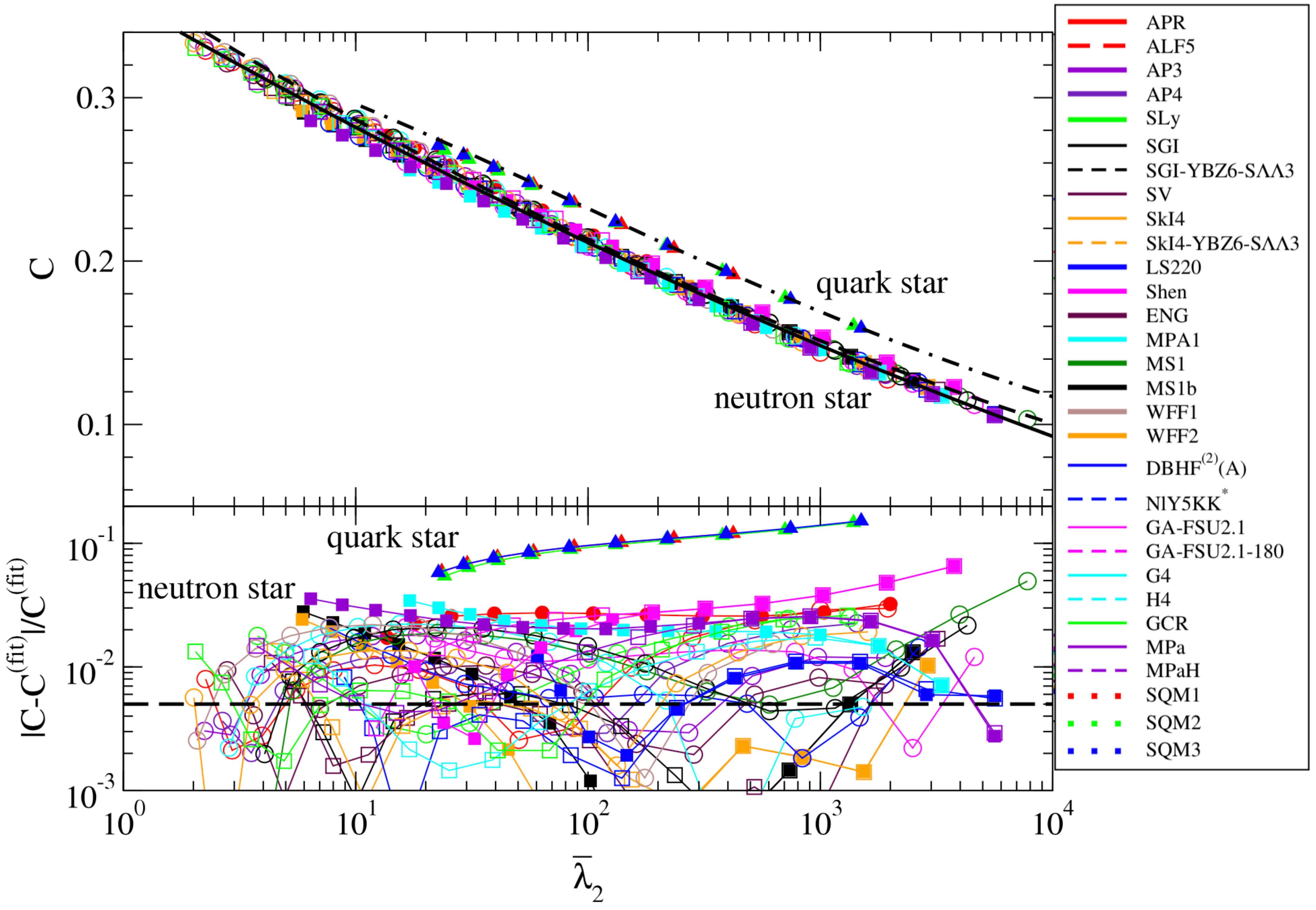

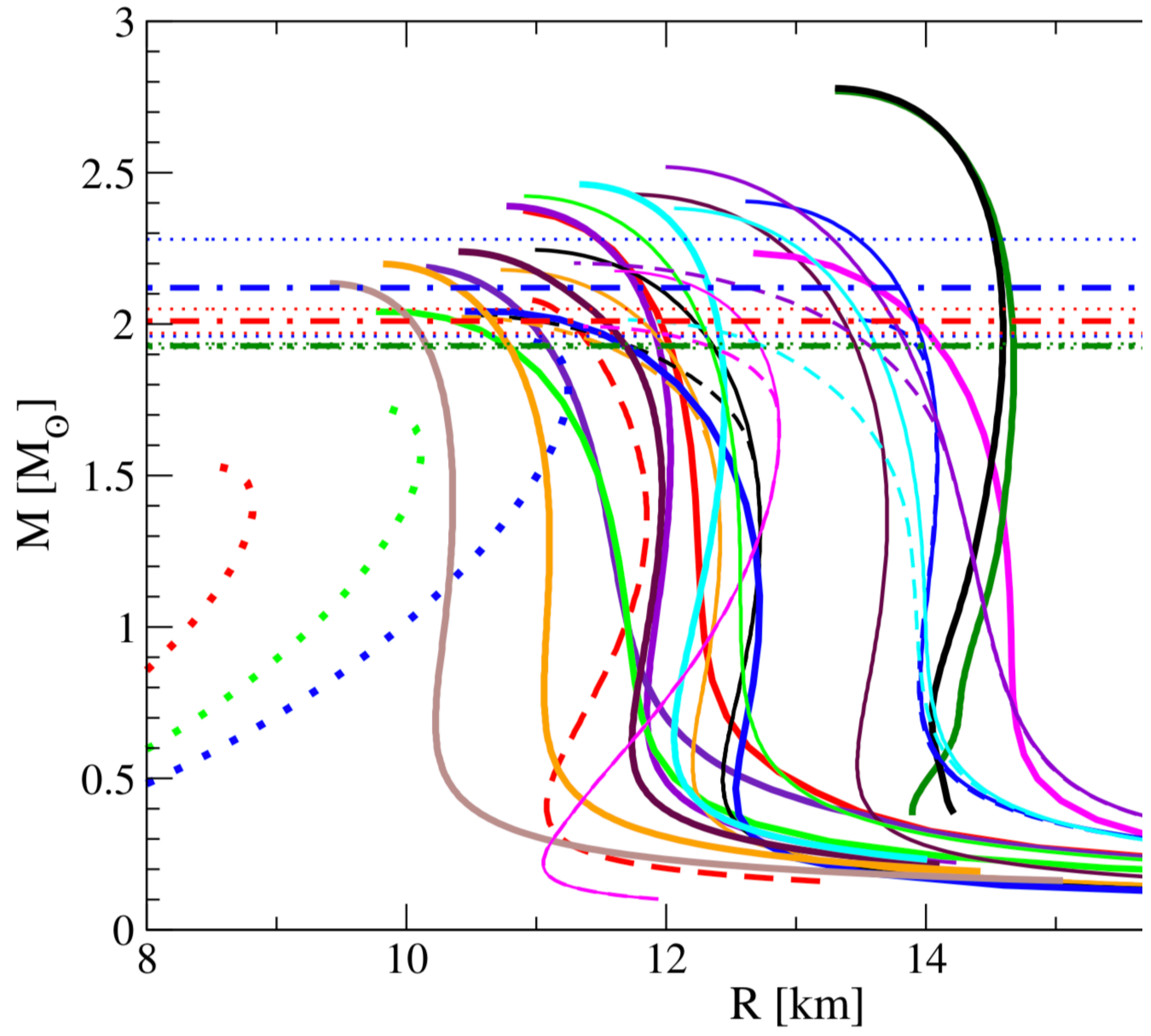

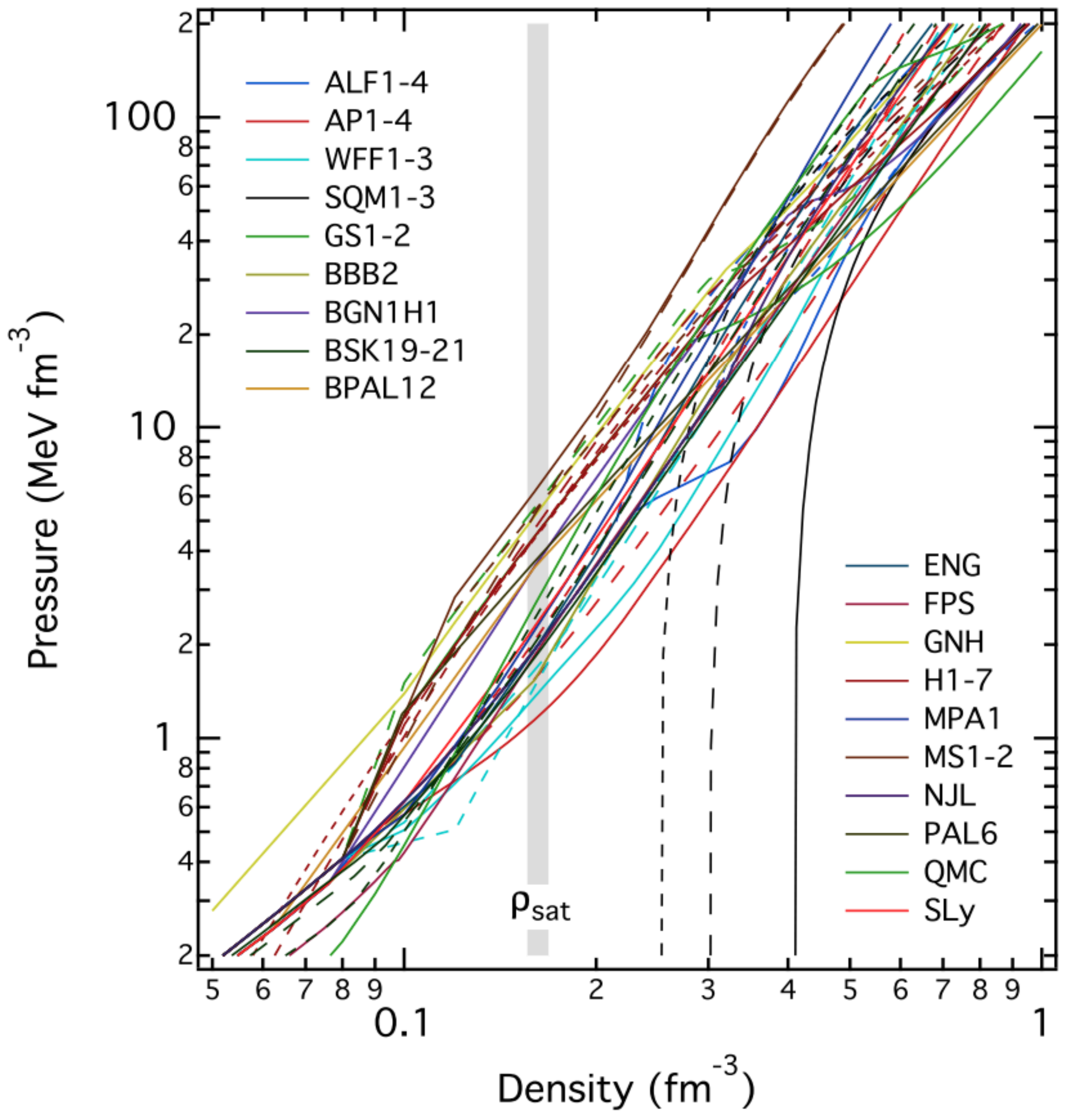

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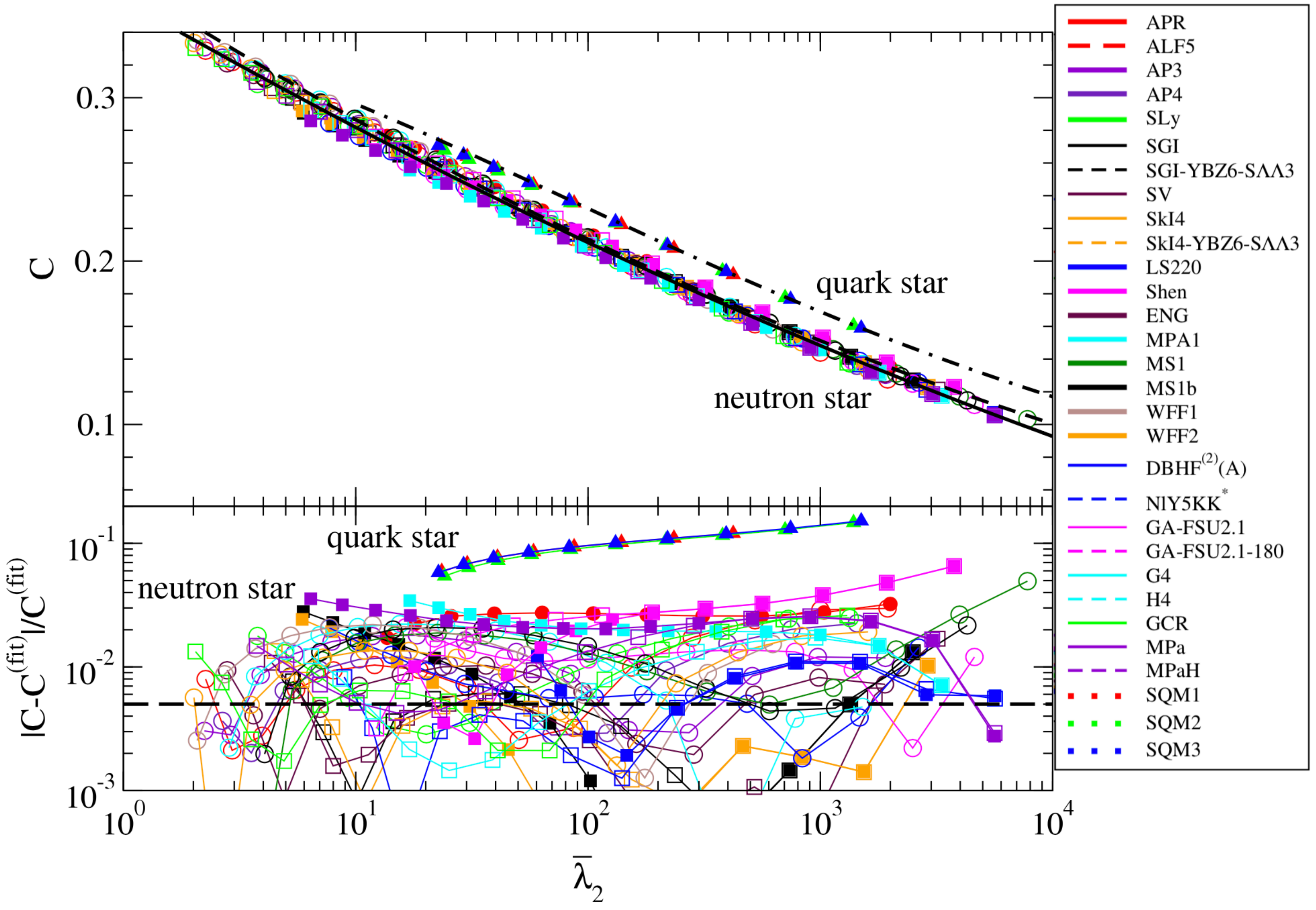
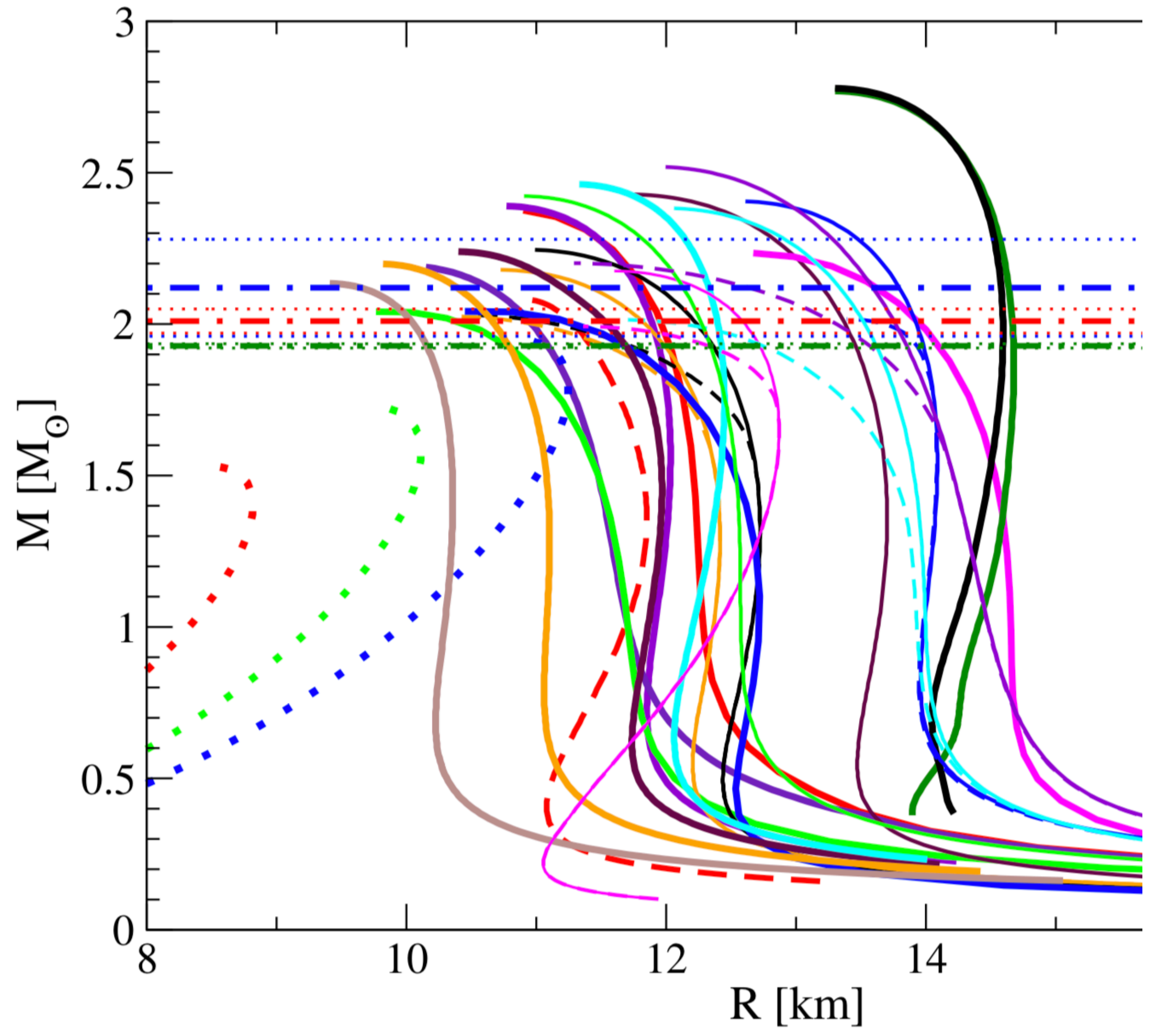
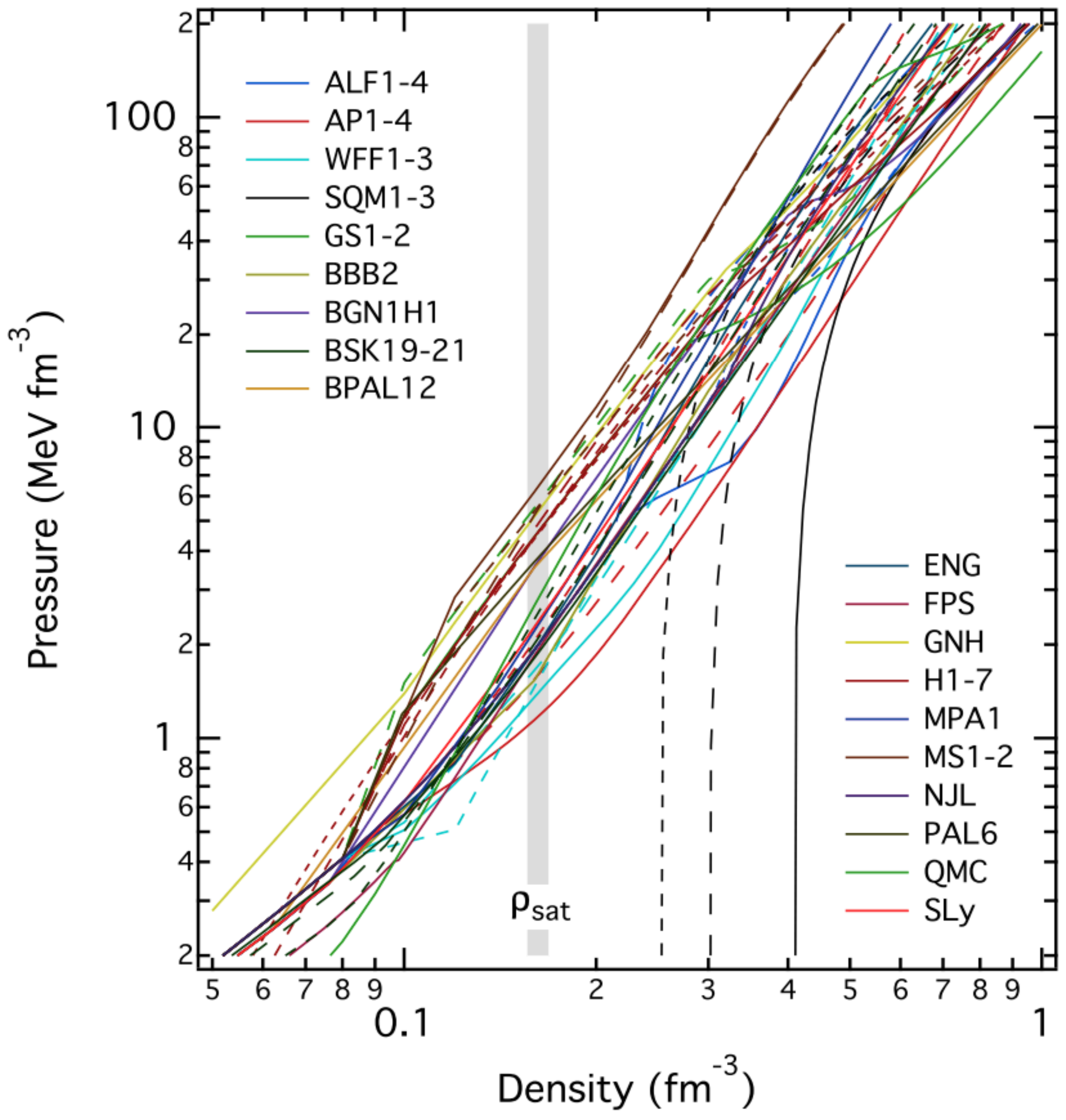


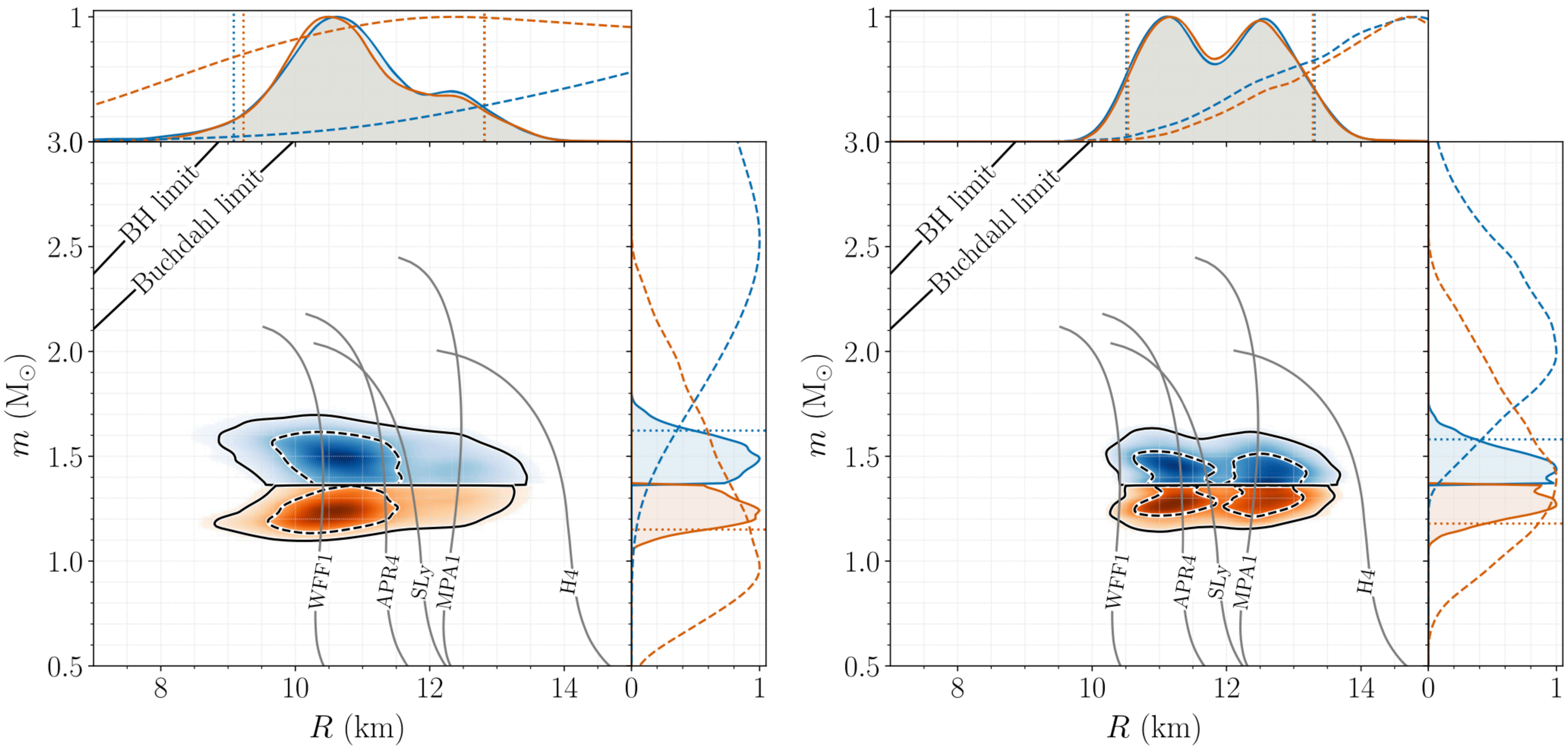




If you measure Love, you can
(i) infer the radius, and
(ii) you can let the data select between EoS models.

[see e.g. Yagi & Yunes, Phys. Repts 681 (2017)]

First GW measurements of Love (and Radius)



[LIGO, PRL 121 ('18)]

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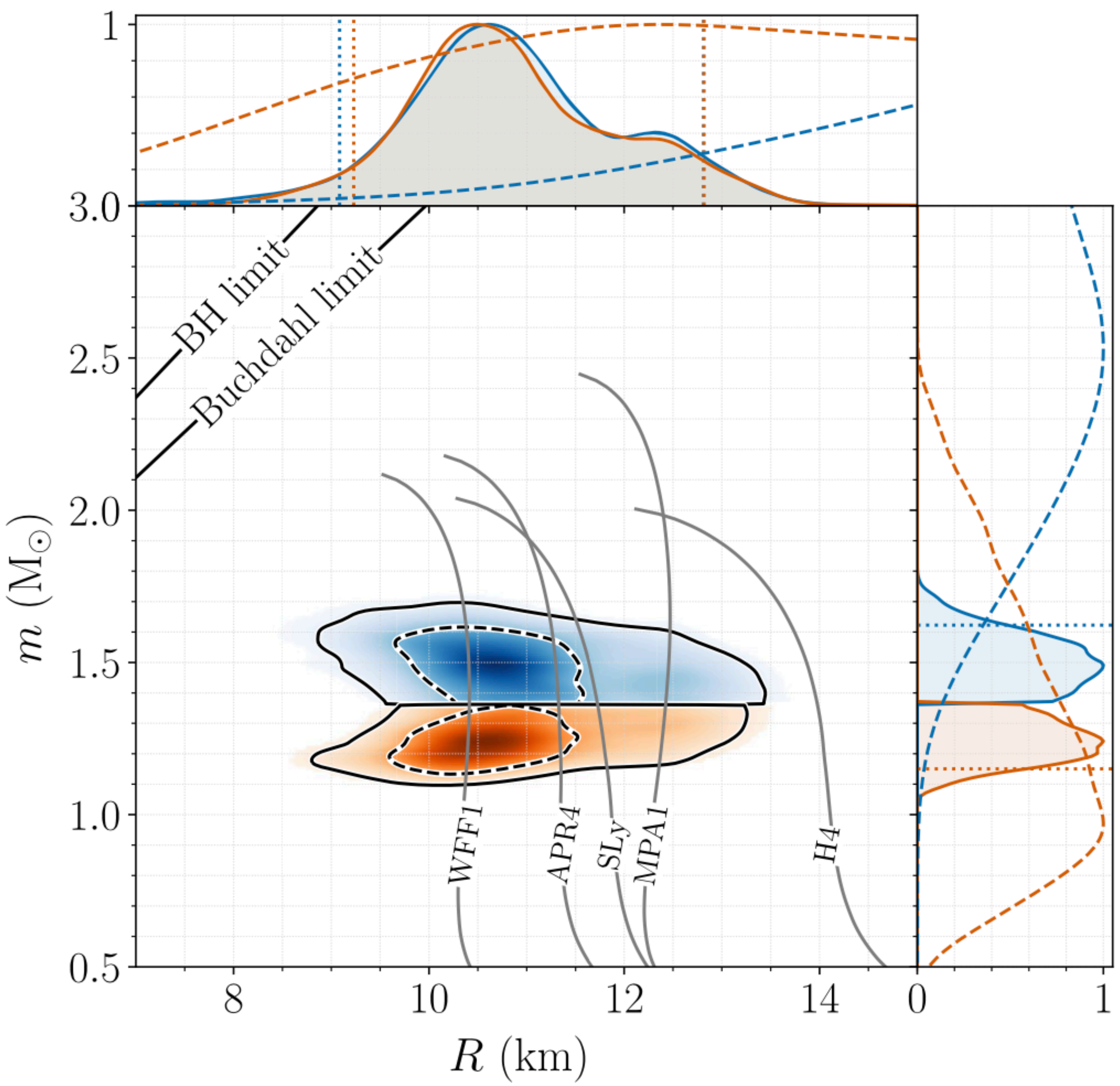
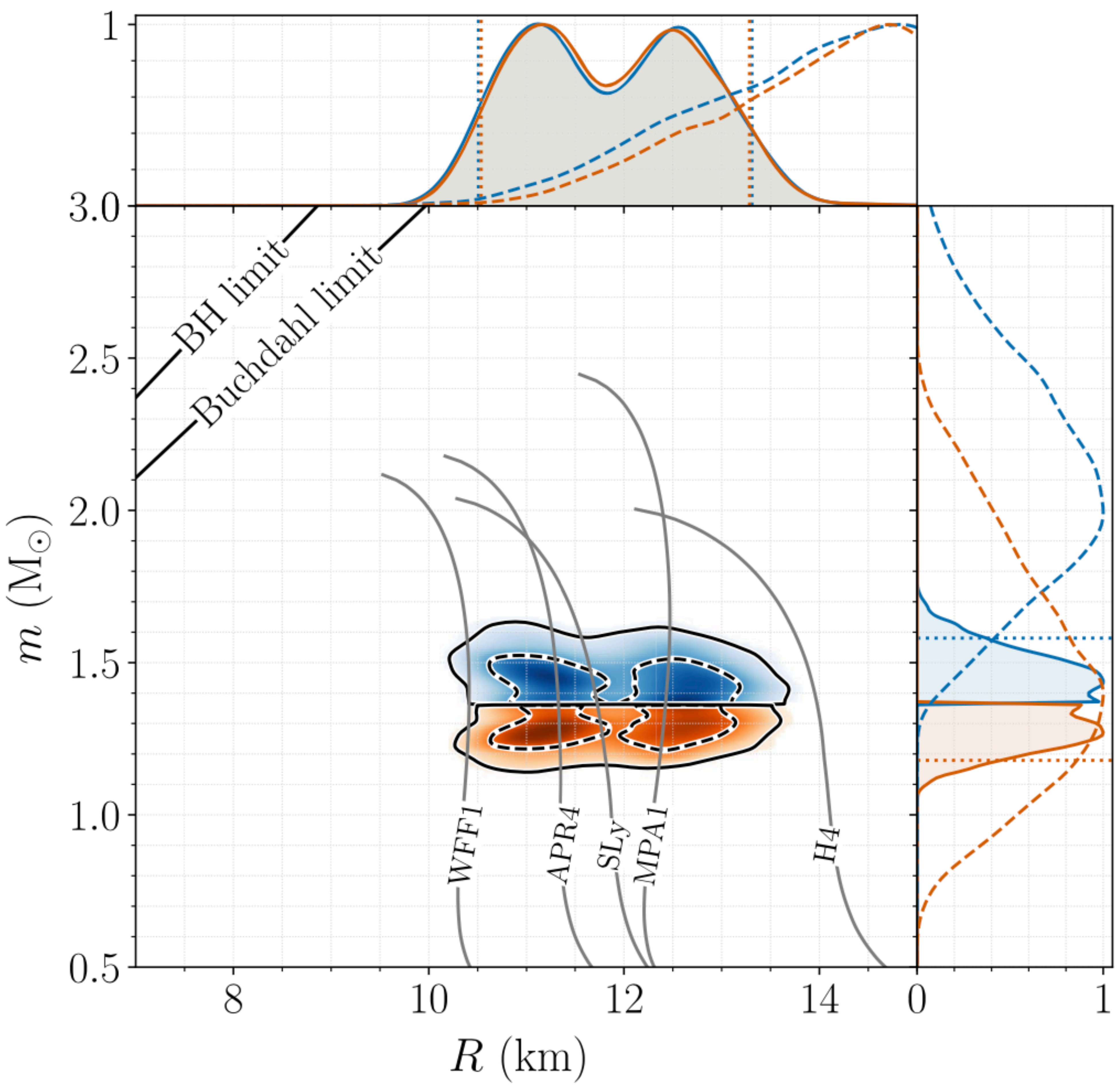


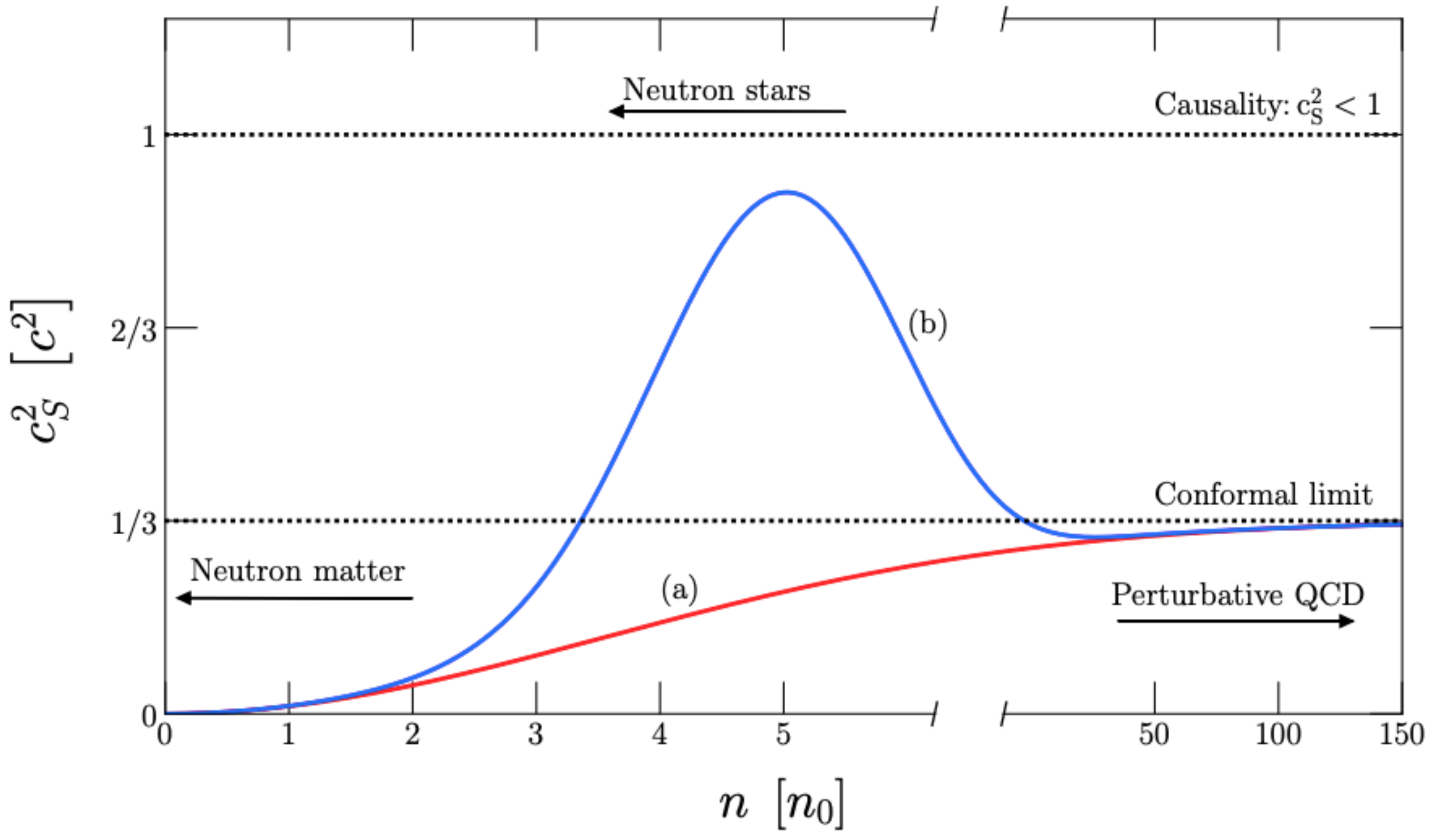


The GW170817 observation allowed for the first GW constraints on the Love number (and thus the radius)

[LIGO, PRL 121 ('18)]

What else can we learn about nuclear physics? Consider c_s^2…

Recent studies indicate a steep rise or bump



Bedaque & Steiner, PRL 114, '15; Alford et al, PRD92, '15,
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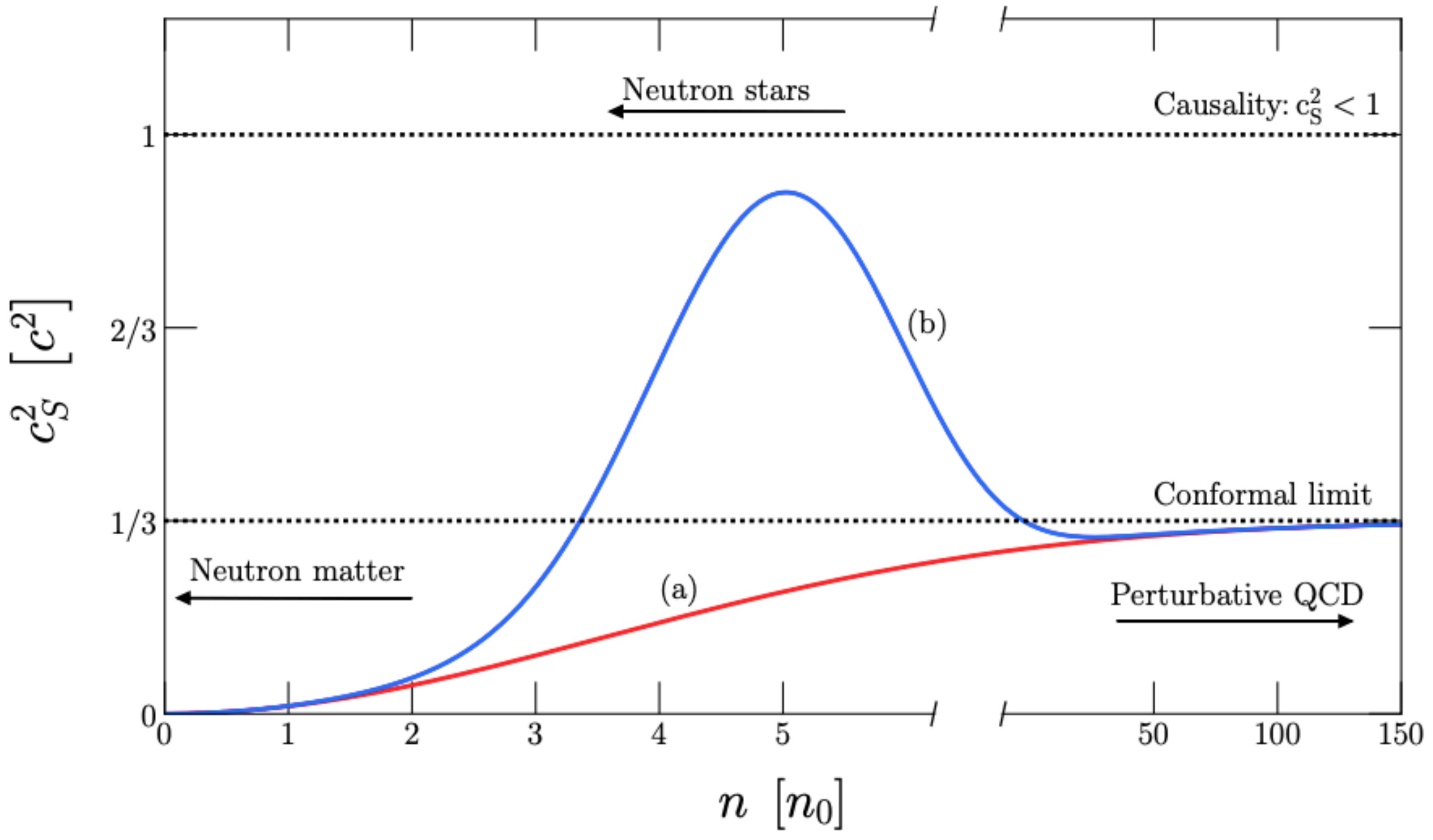

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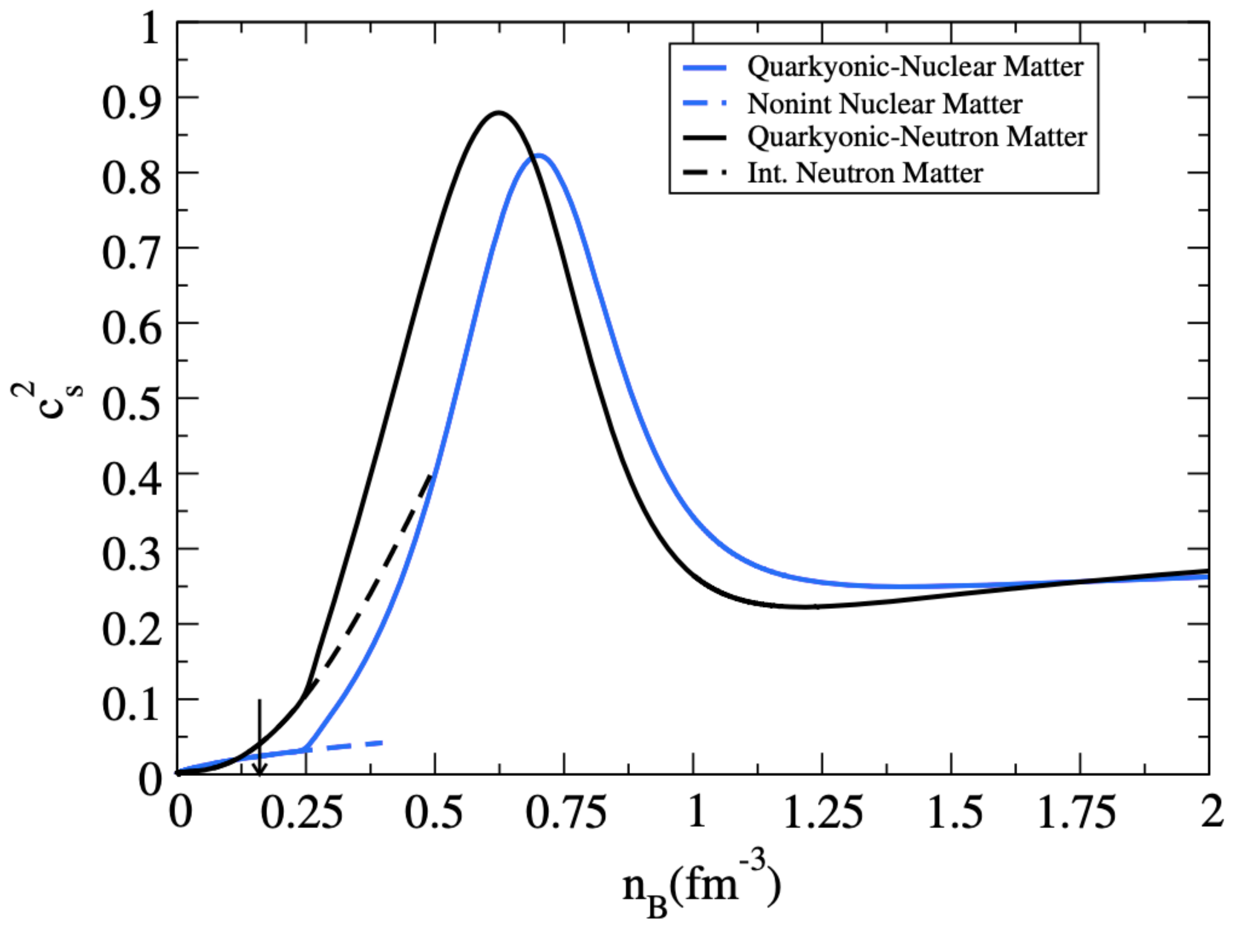
One physical mechanism: Quarkyonic Matter



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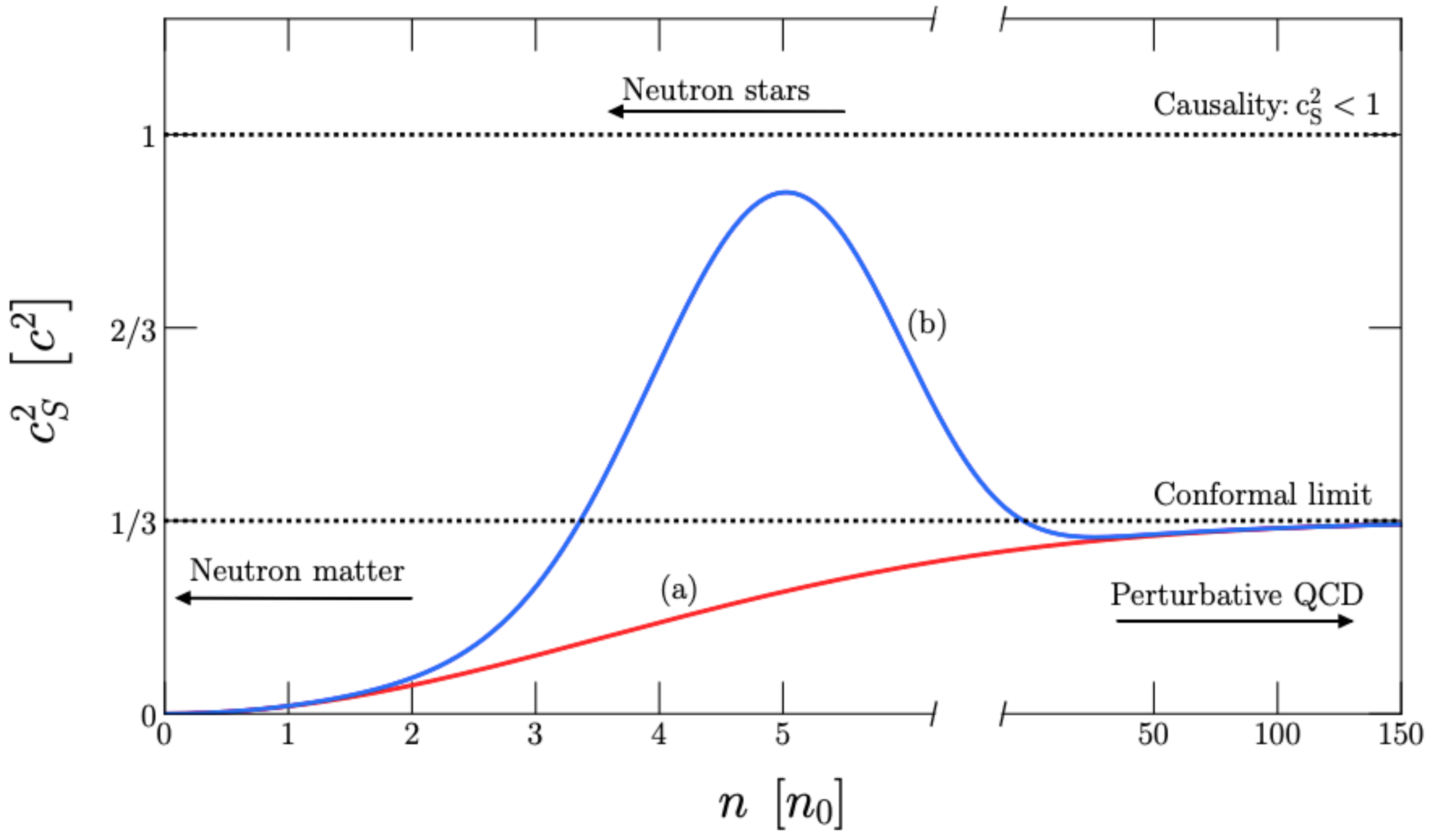

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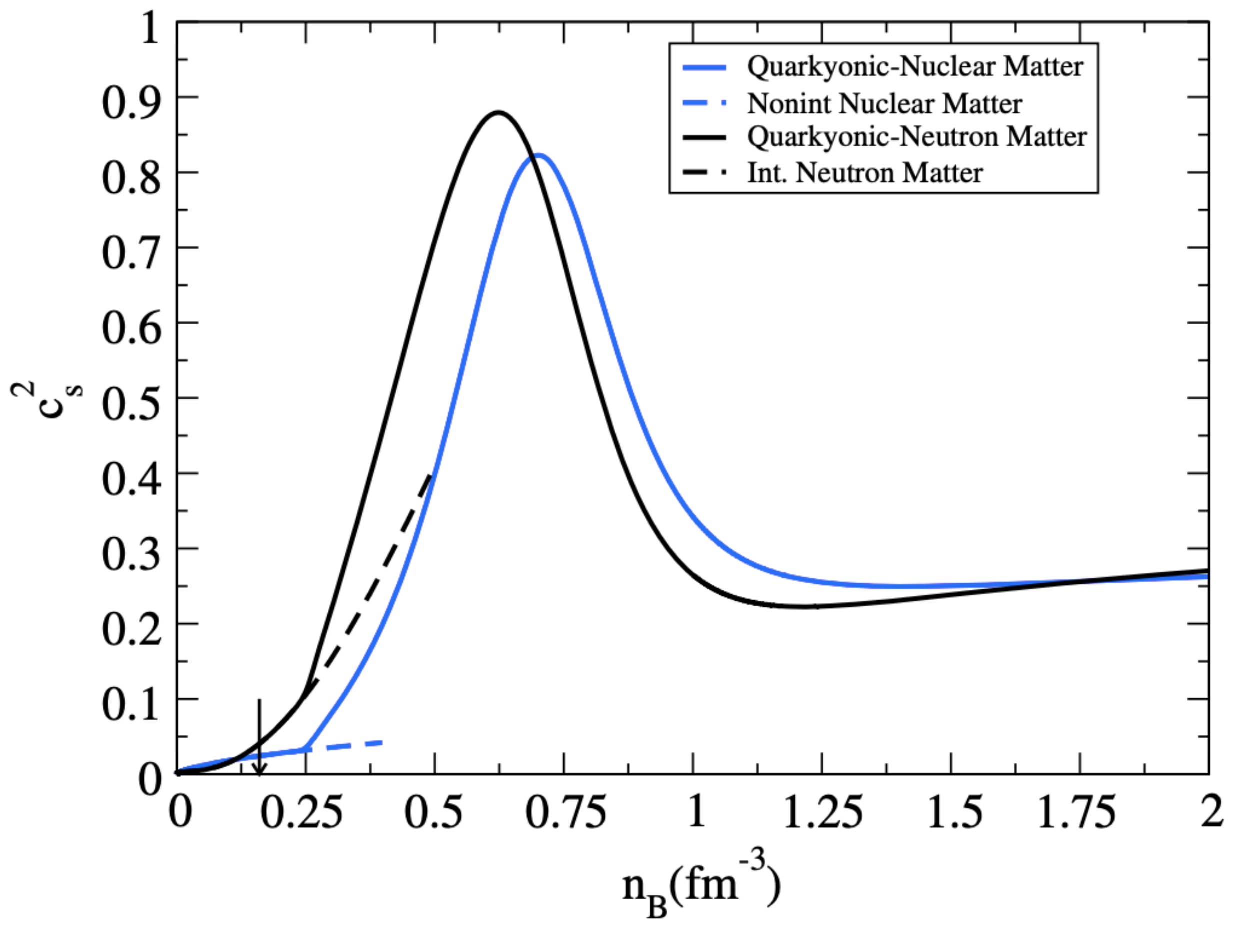

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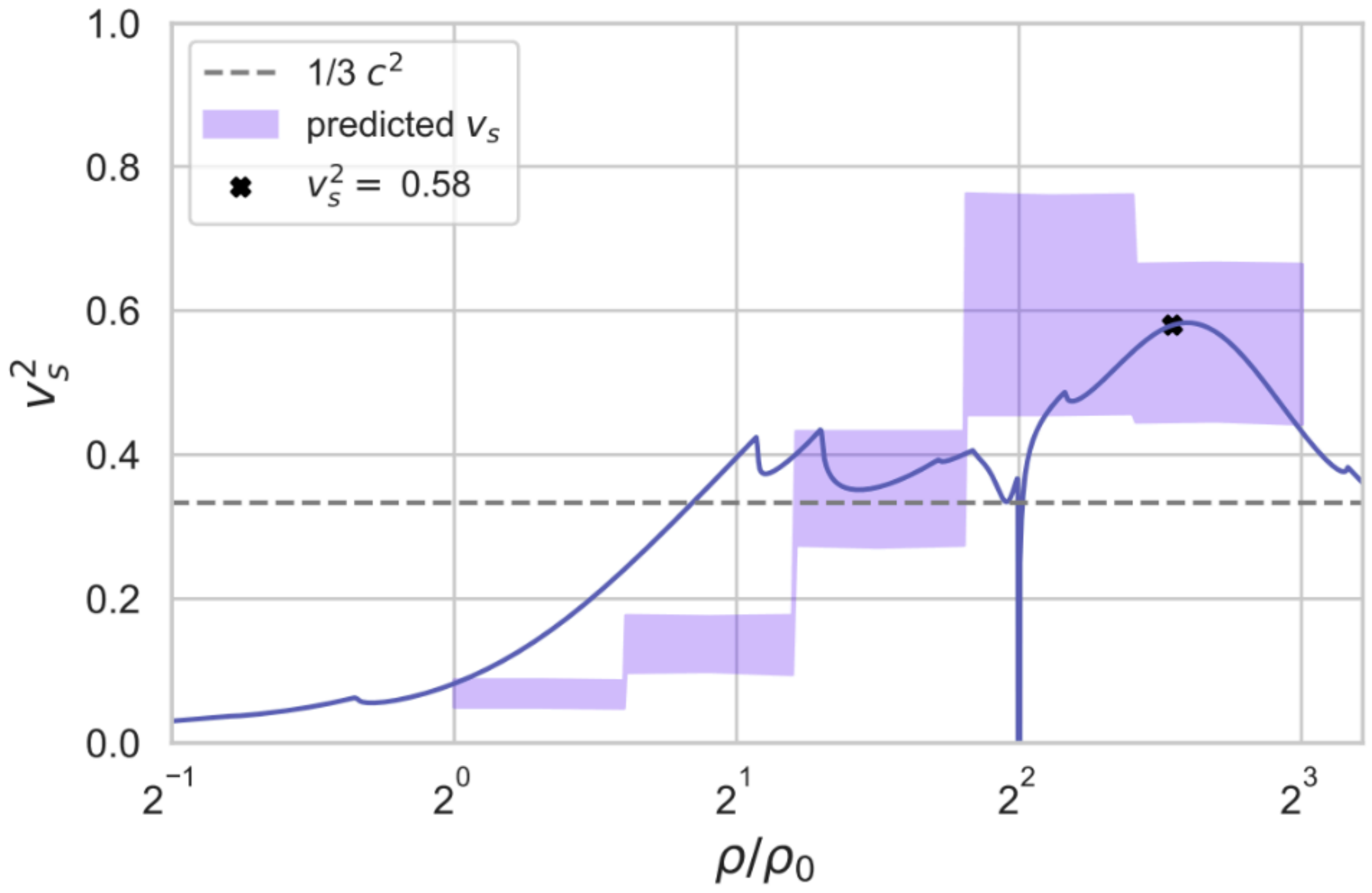
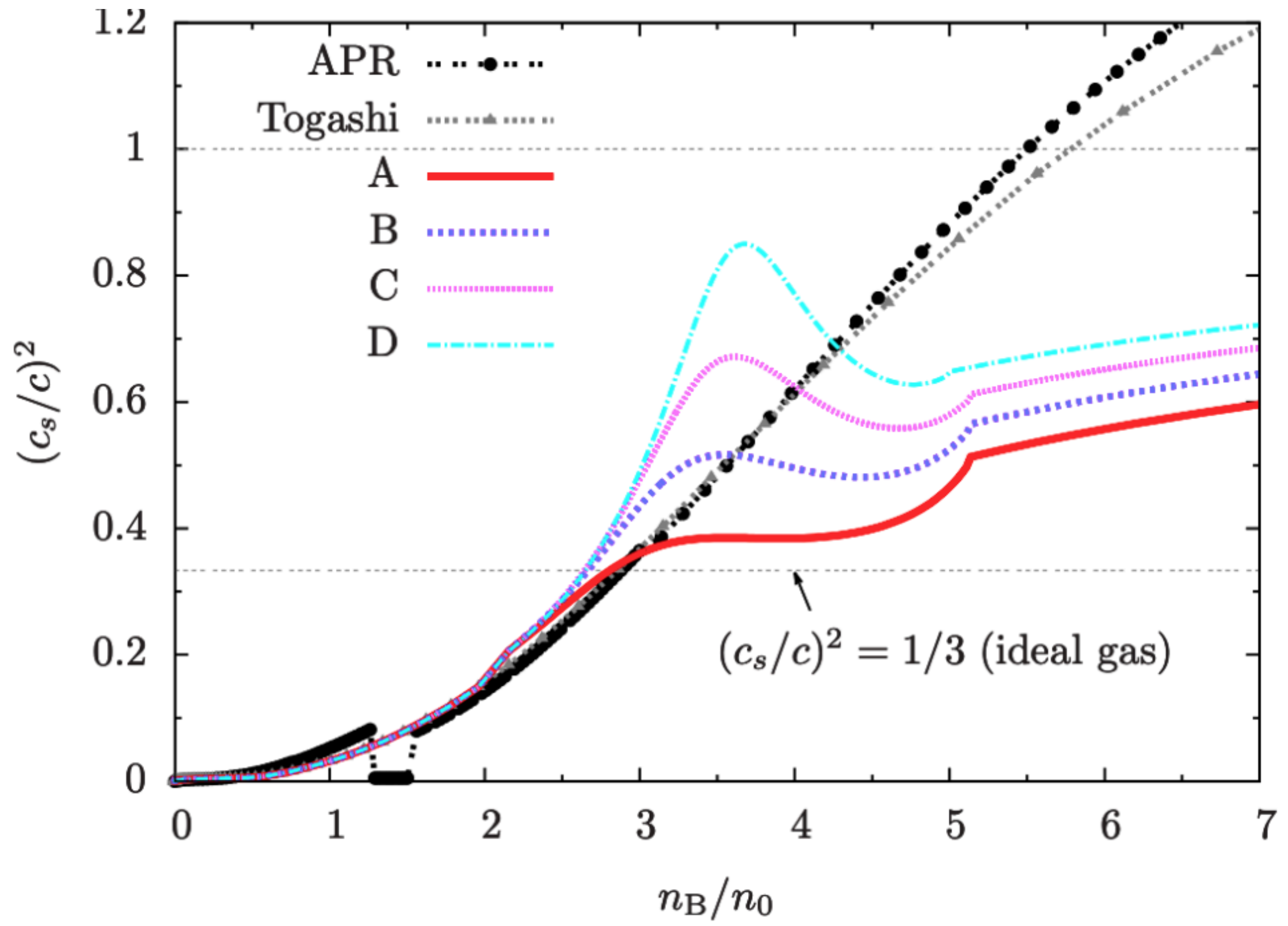
Other studies indicate sharp kinks



Chiral mean field model (hyperons and quarks)
Dexheimer & Schramm, PRC81, '10;
Jakobus, et al, 2004.07026

QHC19 (crossover to quarks)
Baym et al, ApJ 885, '19



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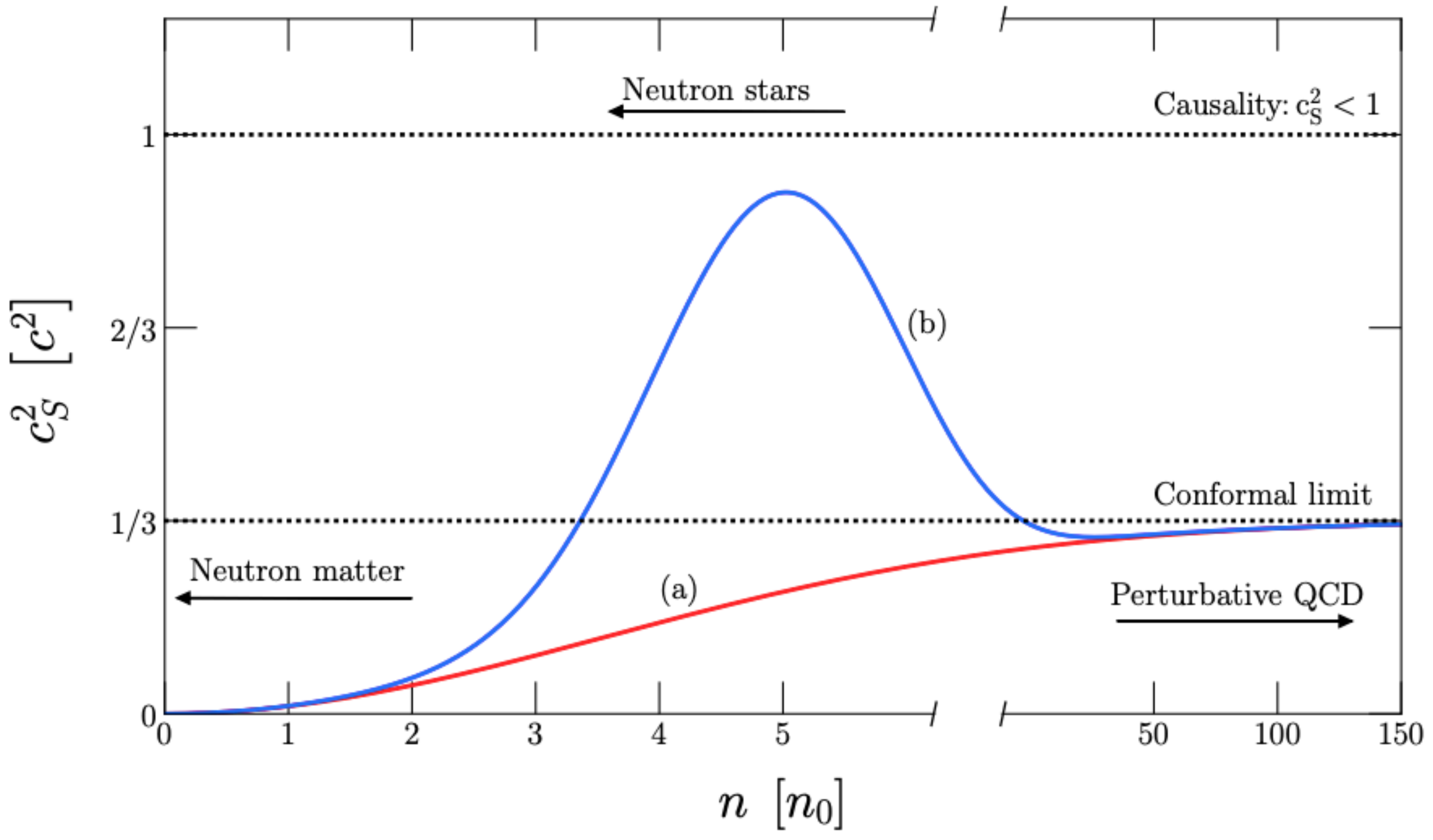

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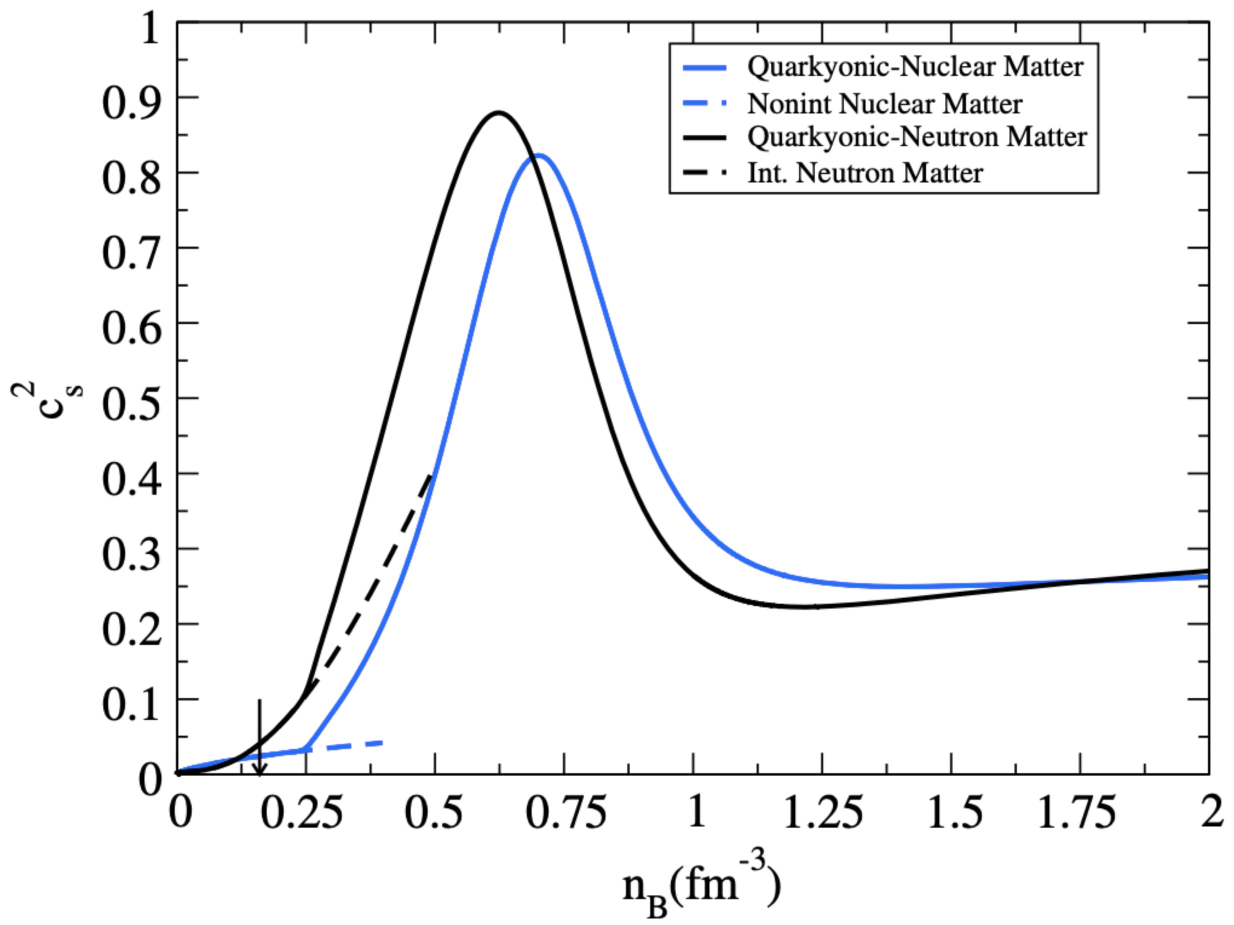

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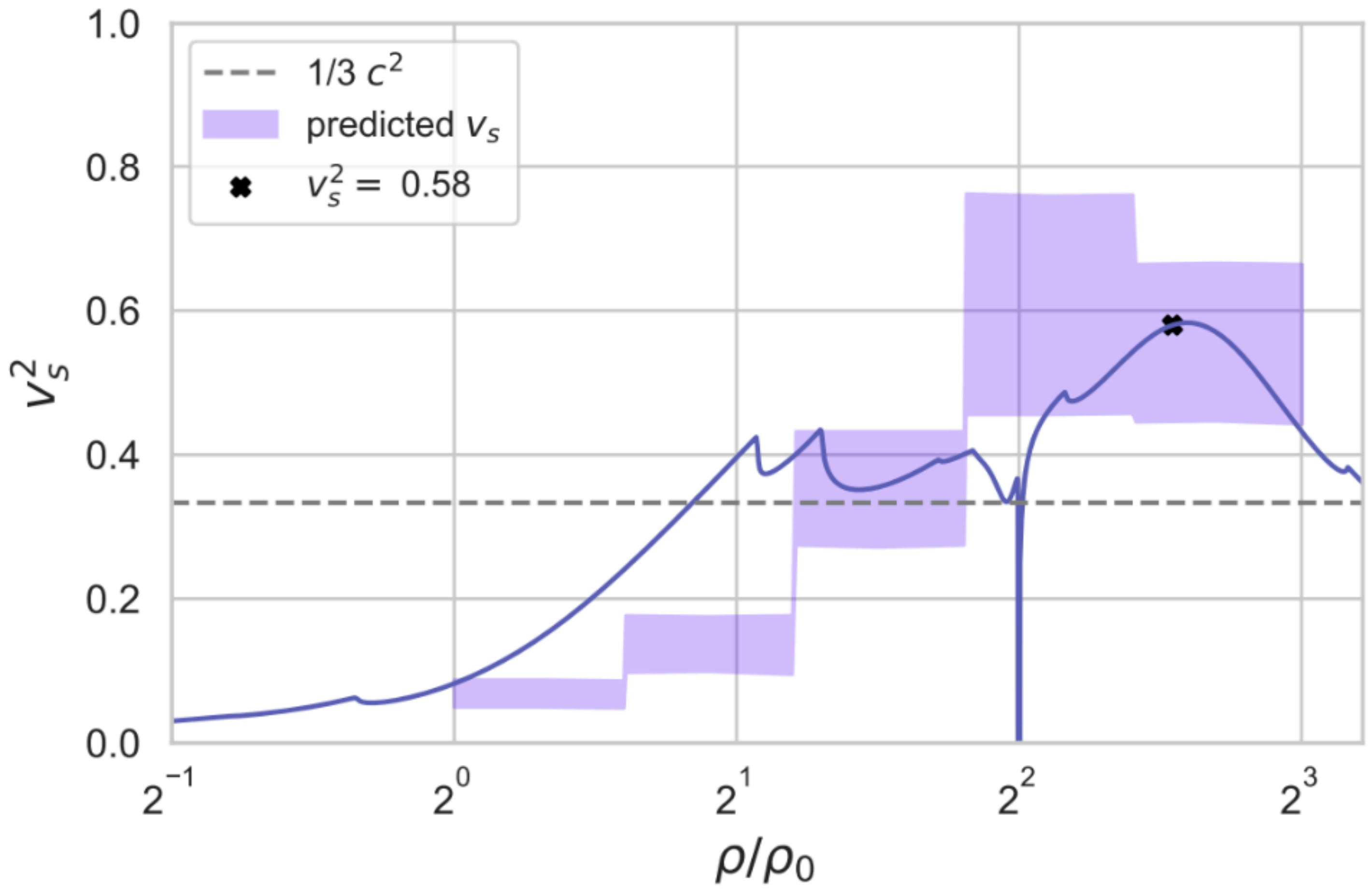

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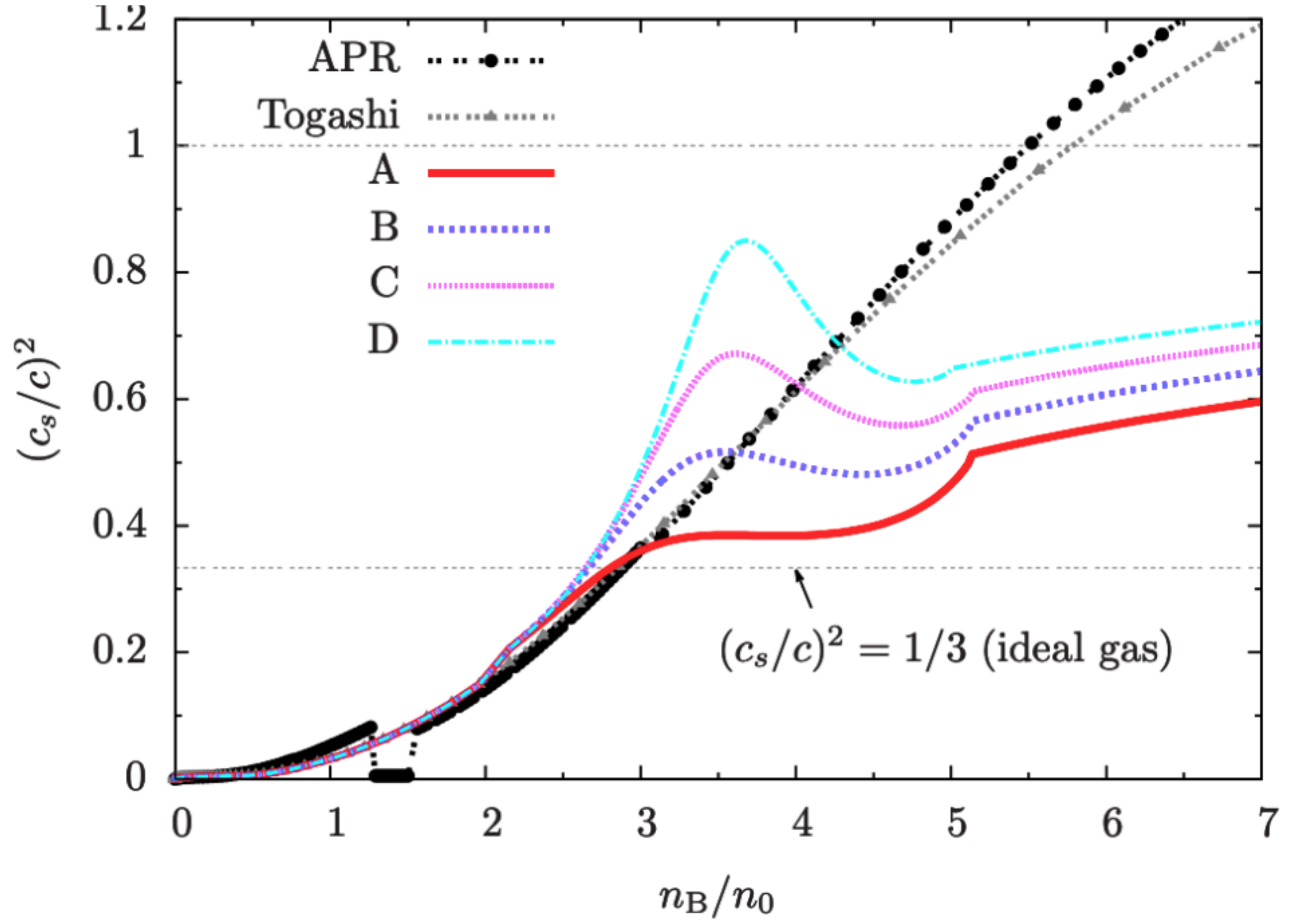
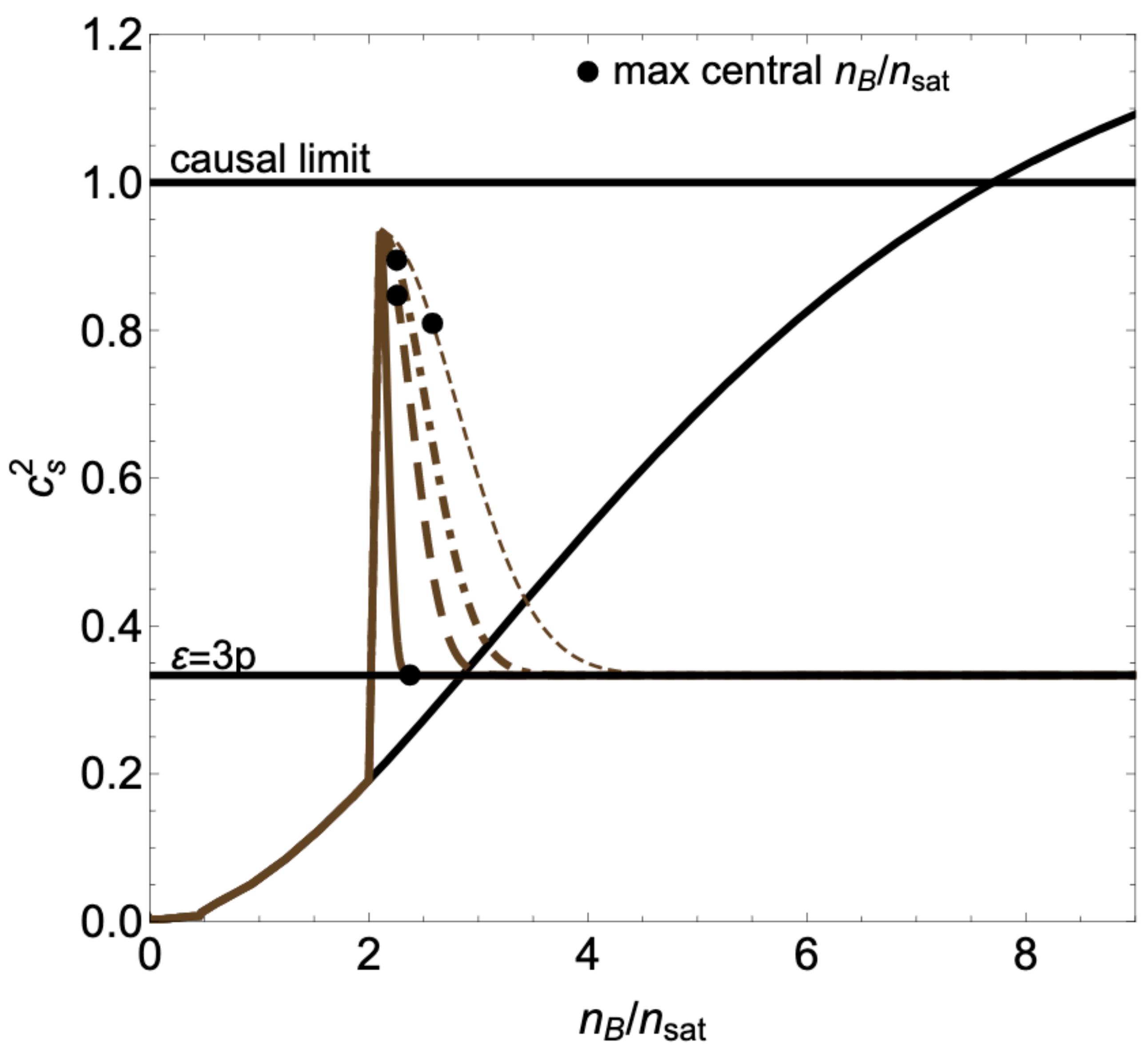


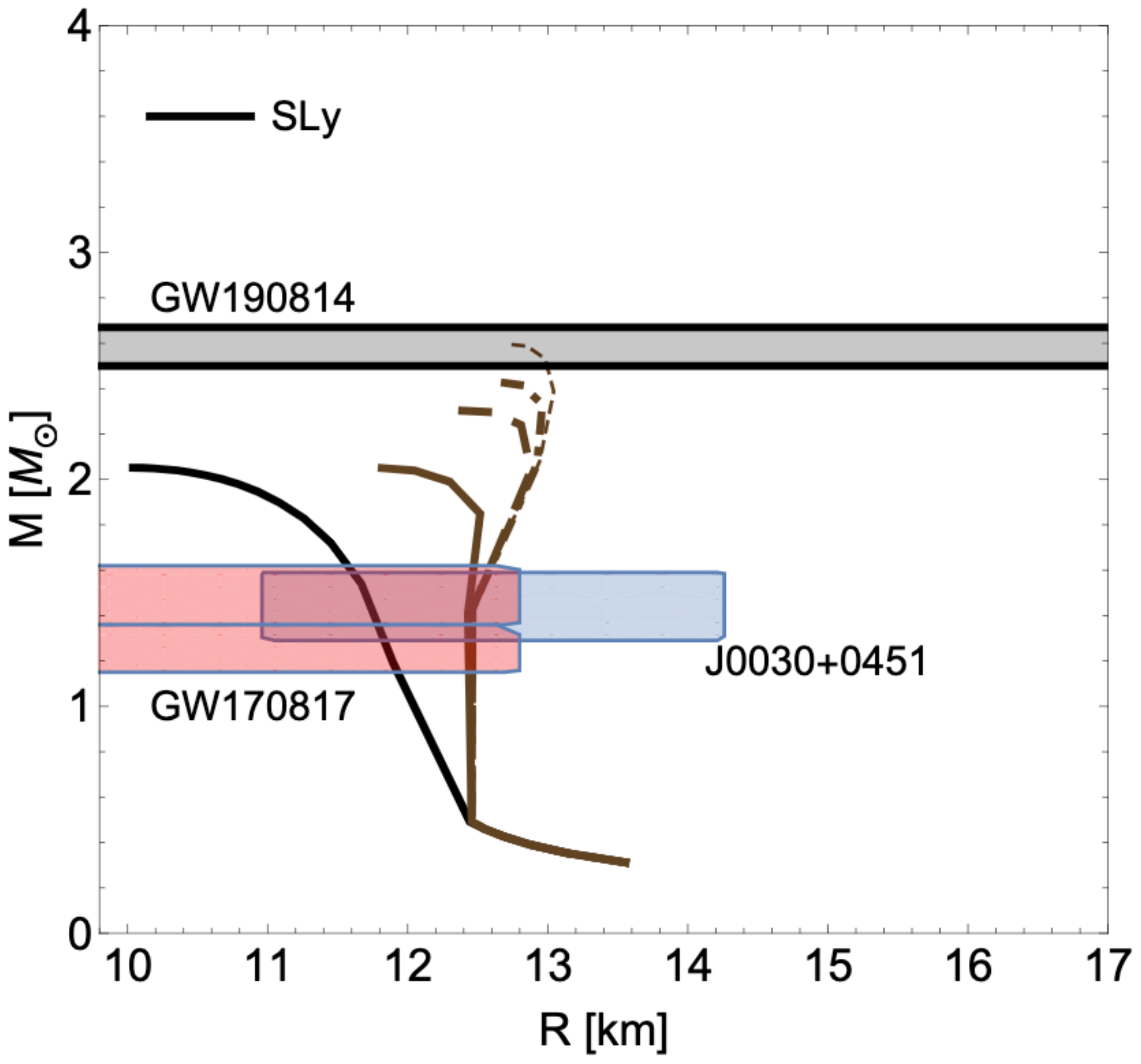
A kinky or bumpy speed of sound seems to be somewhat general in several nuclear physics models with quarks d.o.f.

Kinky and bumpy neutron stars

[**Tan**, Noronha-Hostler, Yunes, PRL 125, ’20;
+ in prep with Dexheimer, Dore]

Kinky and bumpy neutron stars





Holding the location of the bump constant, ↑ width ↑ $M_\odot$

[**Tan**, Noronha-Hostler, Yunes, PRL 125, ’20;
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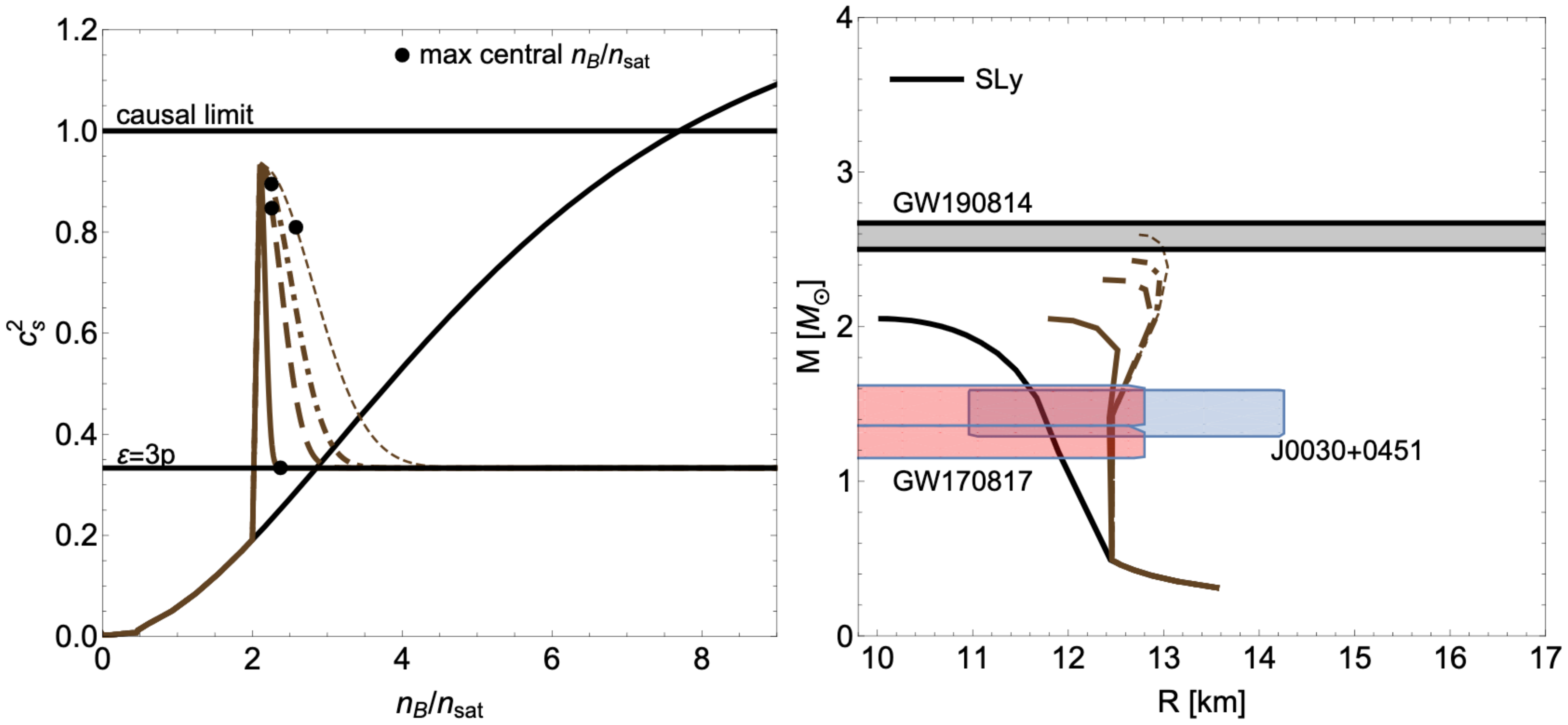

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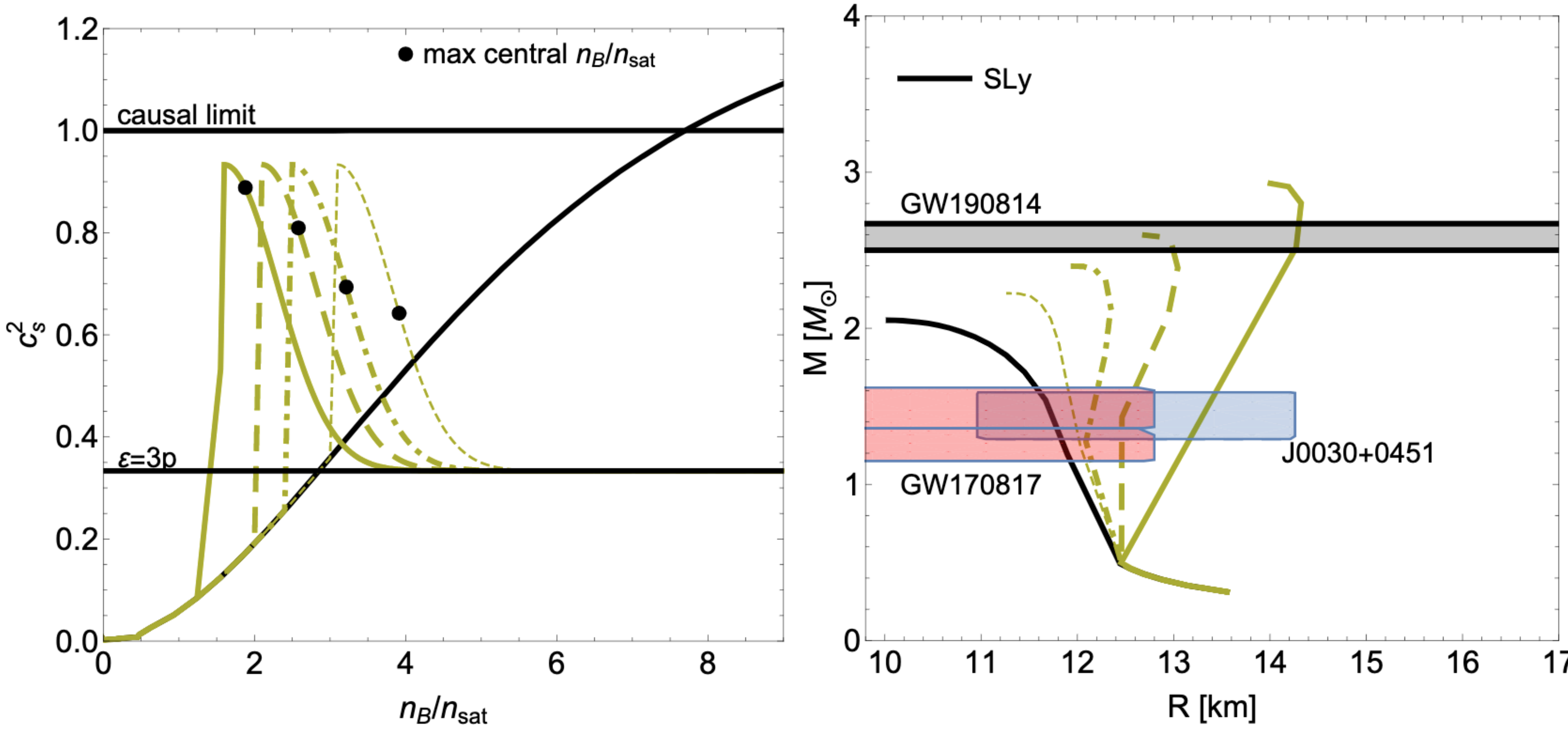
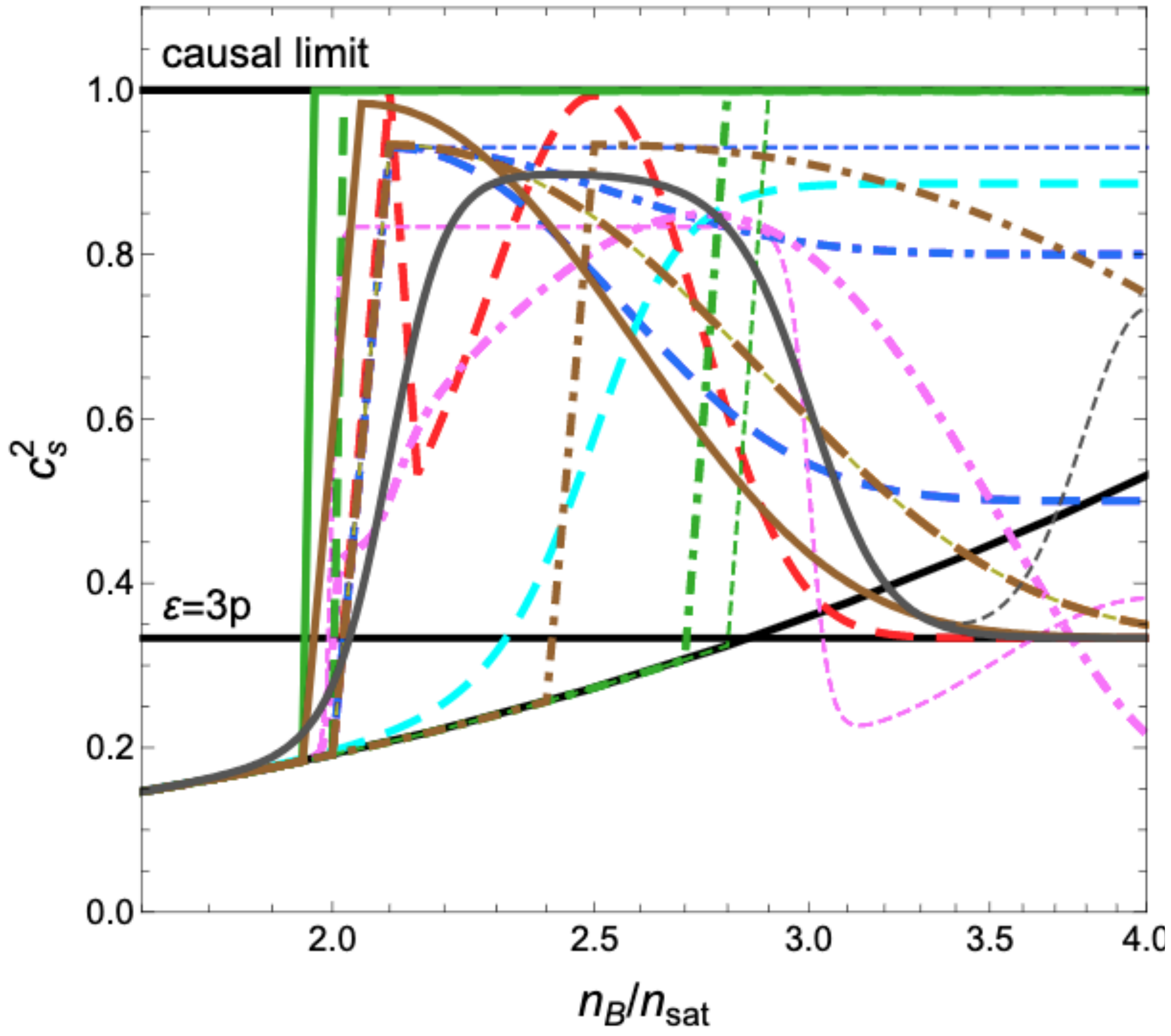
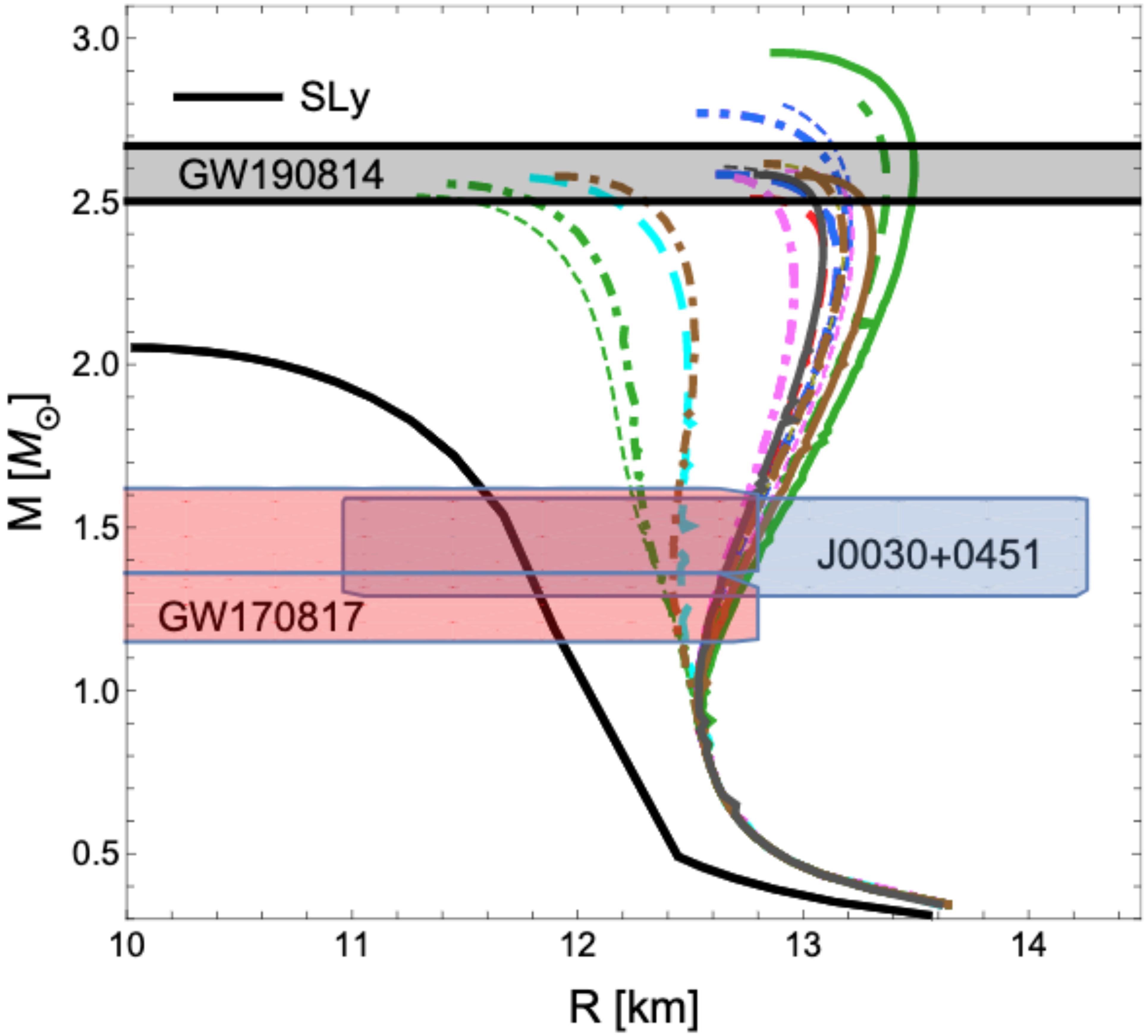


↑ n_B/n_{sat} for the rise, ↑ the radius (and max central density)

If GW190814 is a NS-BH merger, what does this say about c_s^2?

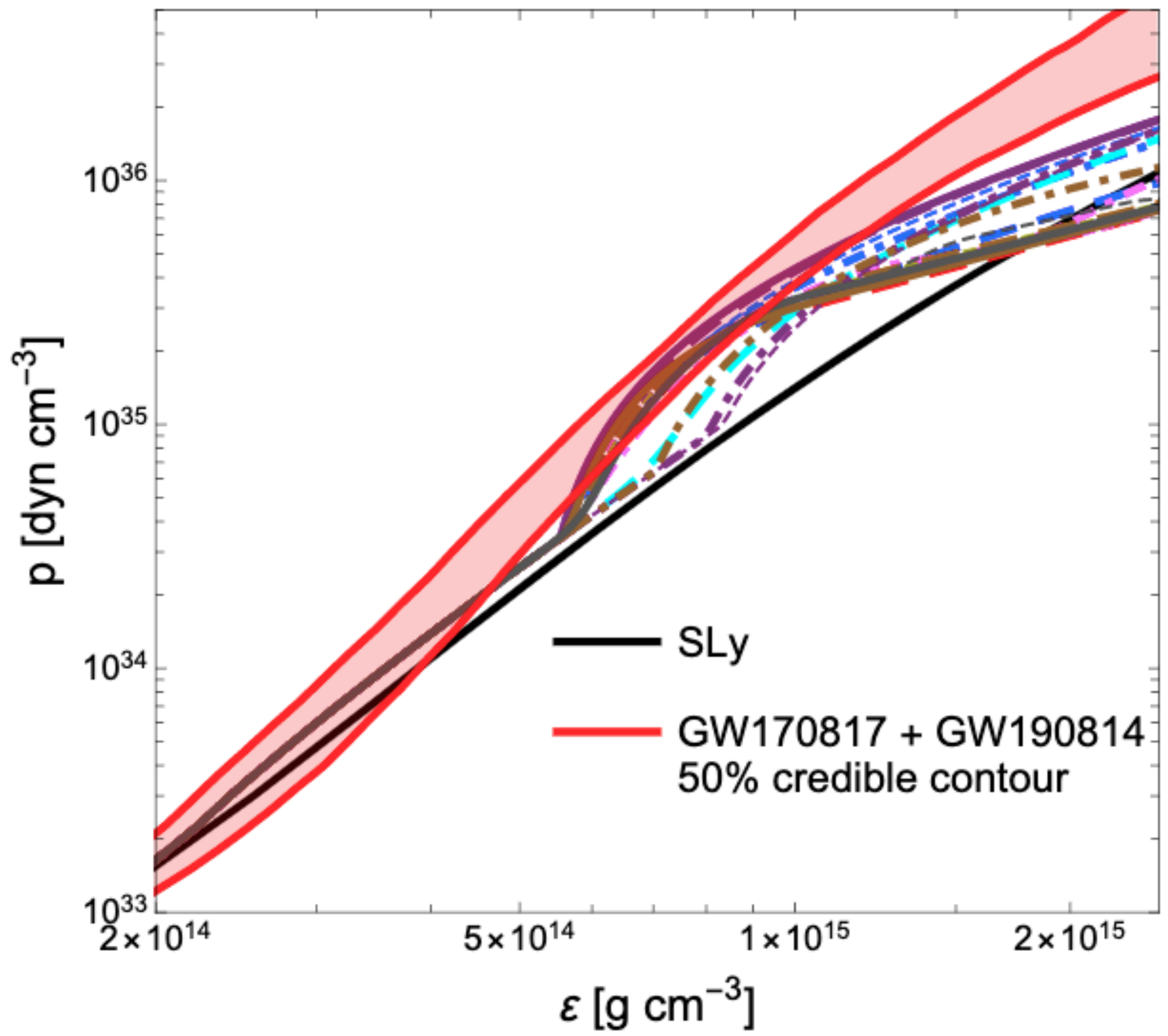


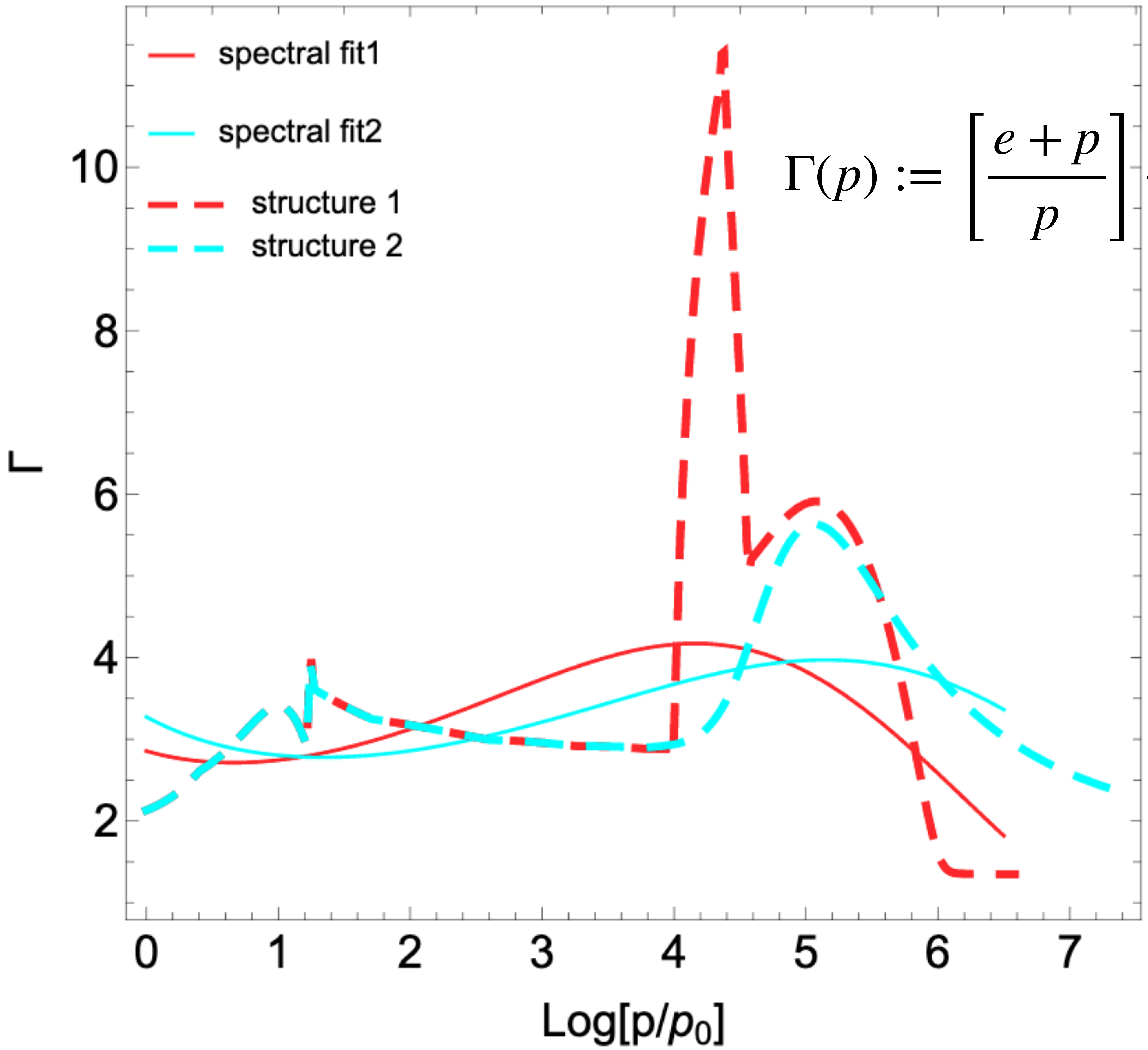


Large enough $M_\odot$ and match of R constraints requires step rise in c_s^2 between $n_B/n_{sat} \sim 2 - 3$

[**Tan**, Noronha-Hostler, Yunes, PRL 125, '20;
+ in prep with Dexheimer, Dore]

Isn't this in conflict with LIGO's observations?



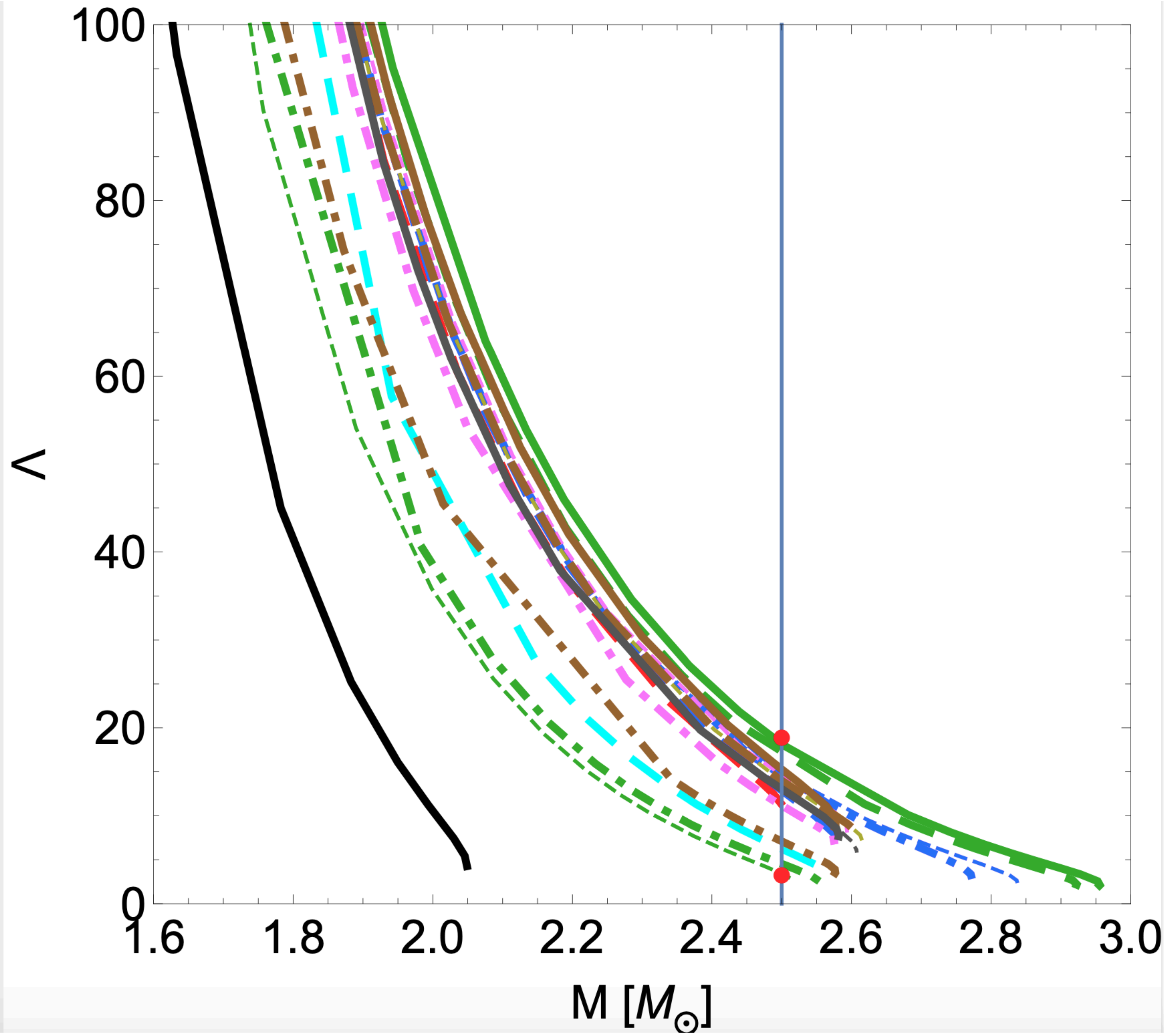


$$\Gamma(p) := \left[\frac{e+p}{p}\right]\frac{dp}{d\varepsilon} = \exp\left(\sum_i \gamma_k x^k\right)$$

[**Tan**, Noronha-Hostler, Yunes, PRL 125, '20;
+ in prep with Dexheimer, Dore]

The spectral representation cannot capture bumps/kinks/jumps in the EOS, can push the M-R curve out-of-bounds!

How can we be sure that it's a neutron star and not a black hole?



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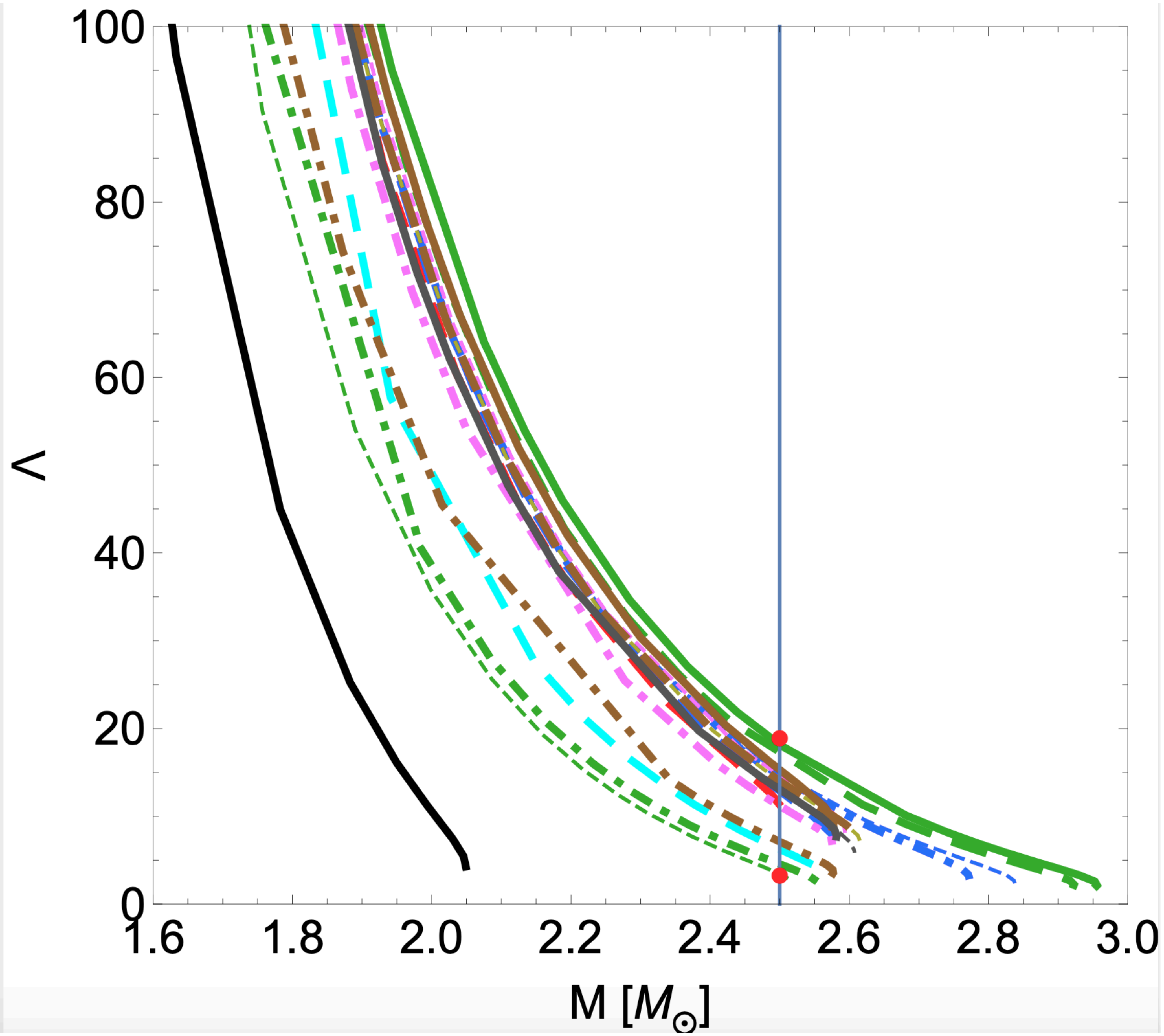

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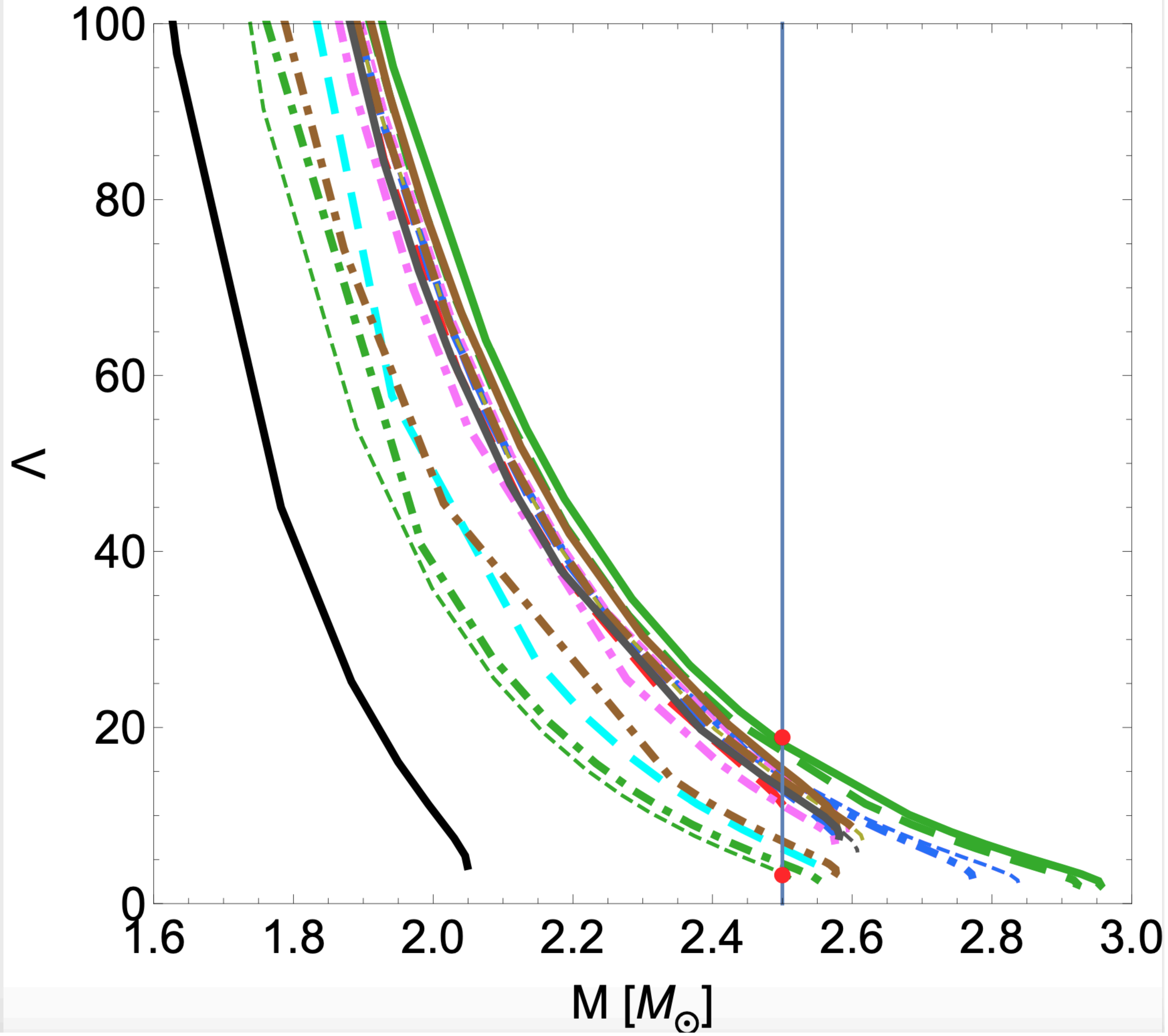

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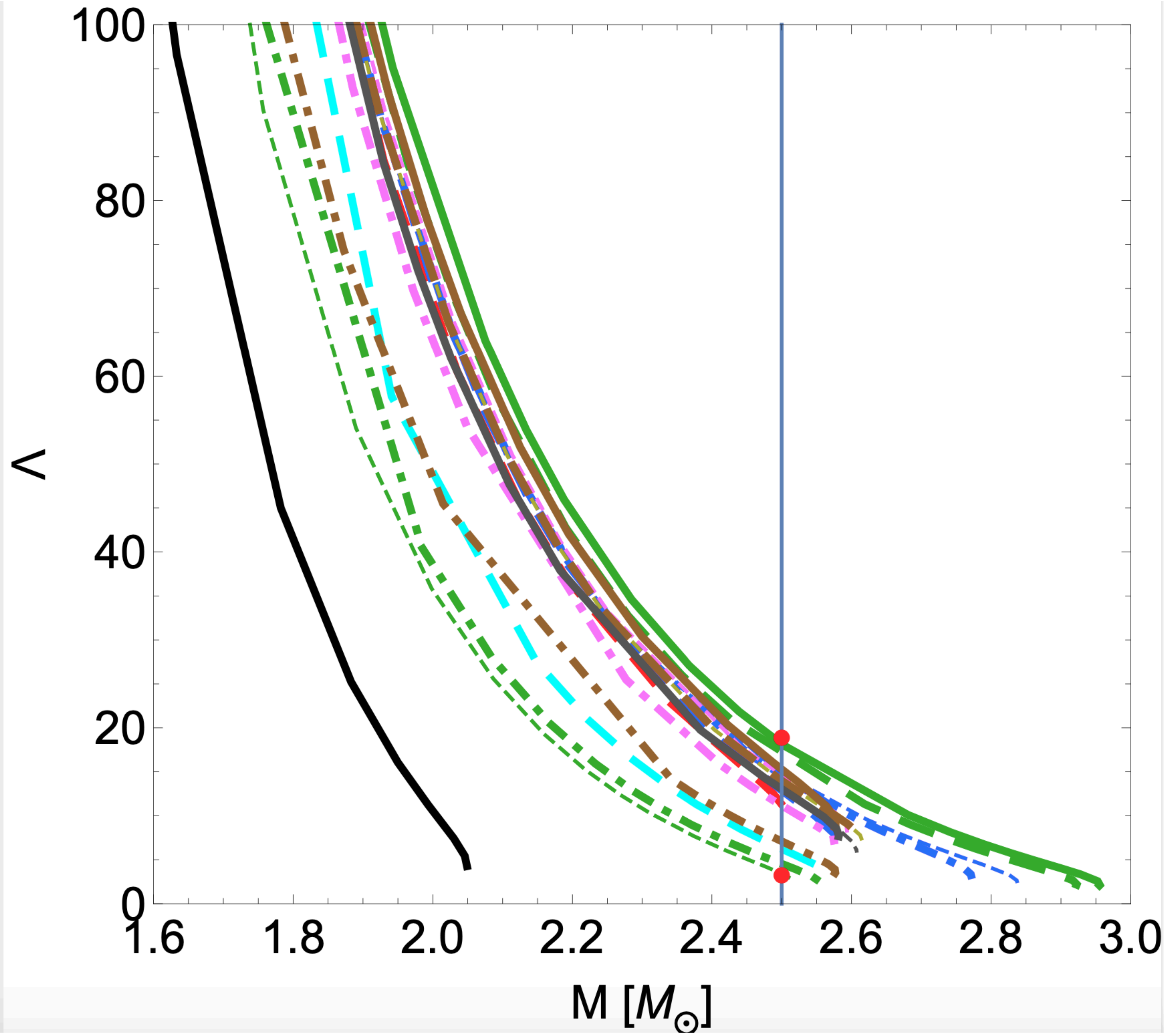

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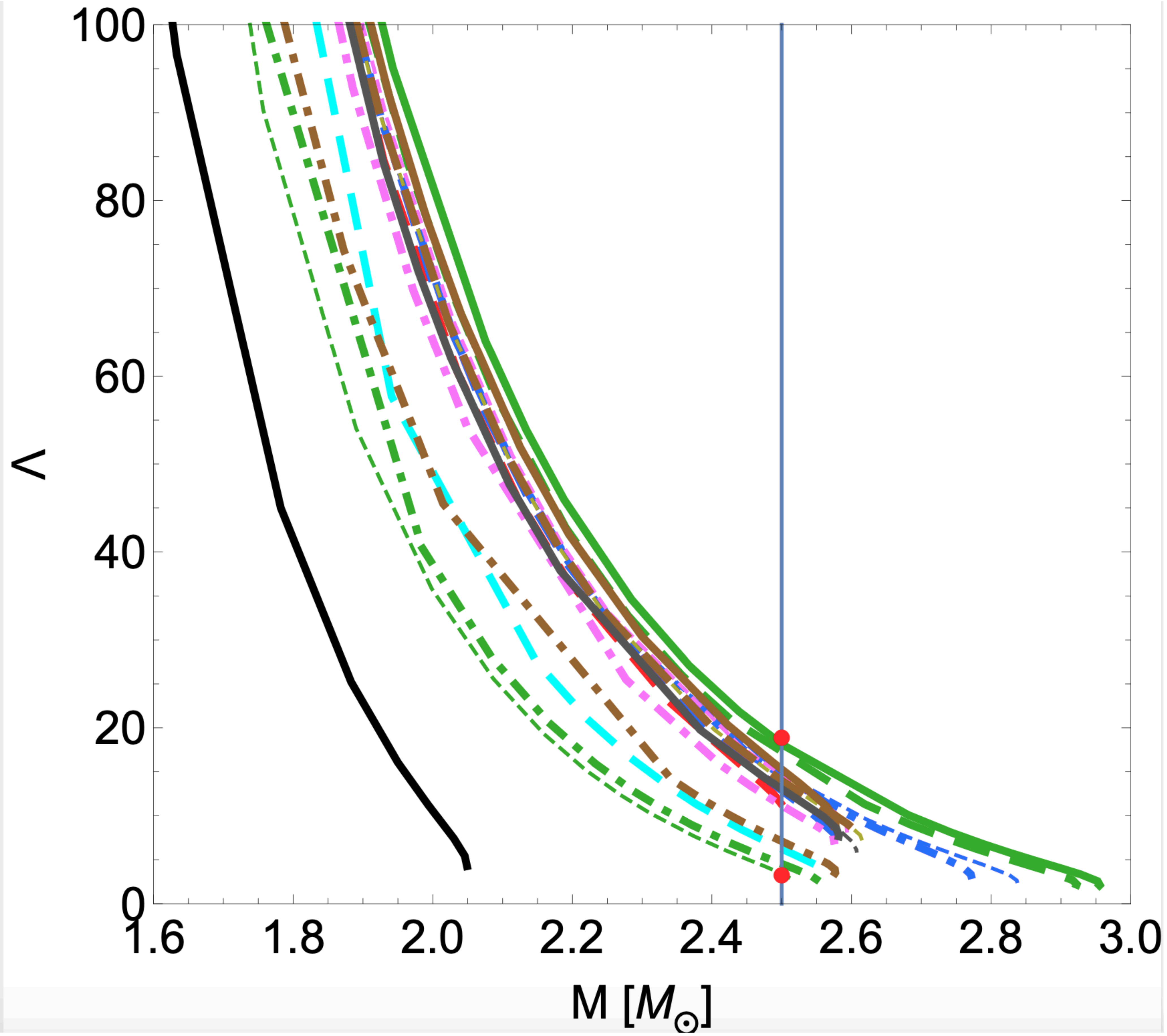

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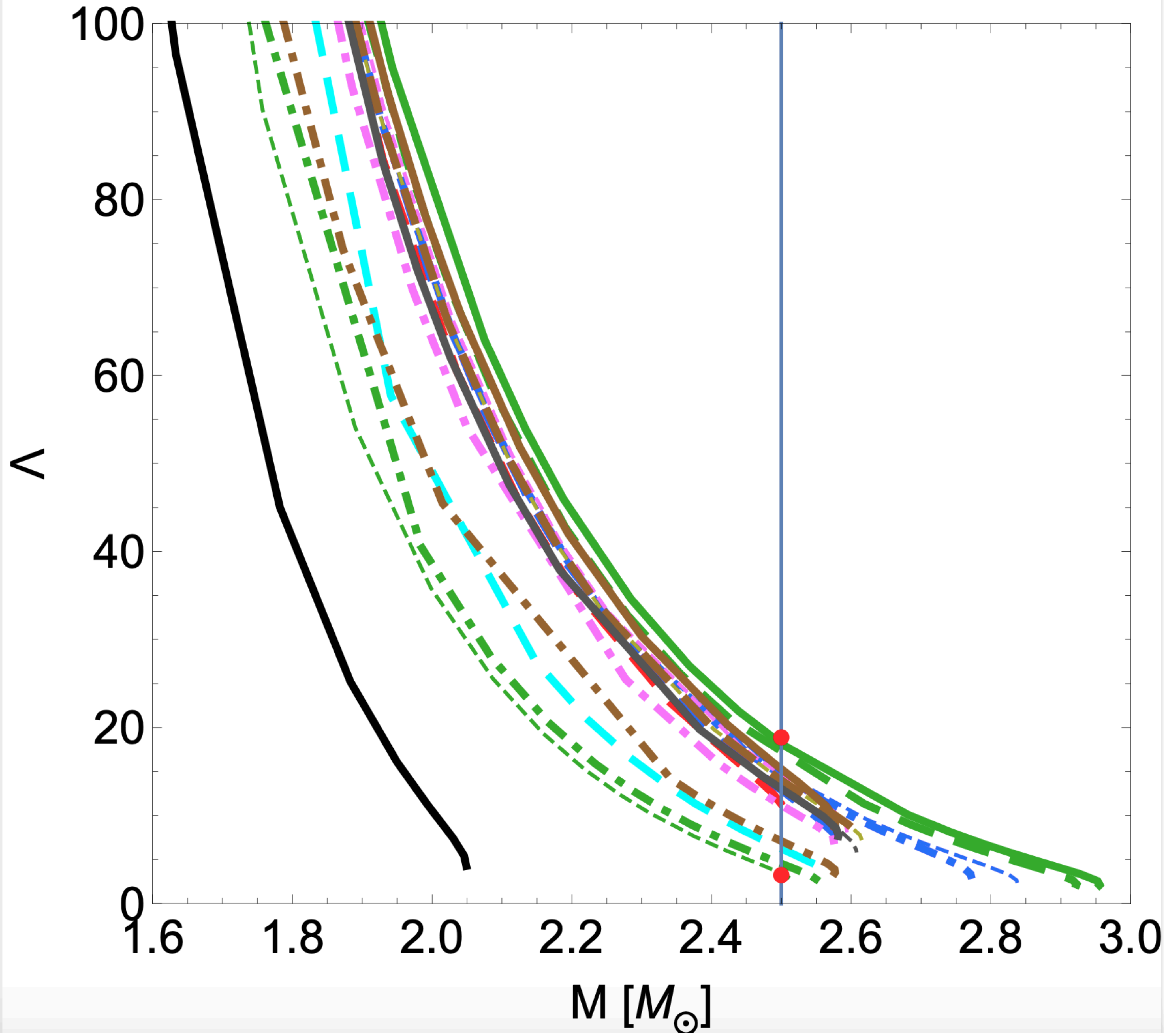

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Needs measurements of $\Lambda \sim$ 3-20, current detectors can measure $\Lambda \sim 100 - 400$

[**Tan**, Noronha-Hostler, Yunes, PRL 125, '20;
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Summary and Outlook

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"Assumptions are made and most assumptions are wrong."

Thank You

Why start with speed of sound: c_s^2?

Connection to the susceptibilities

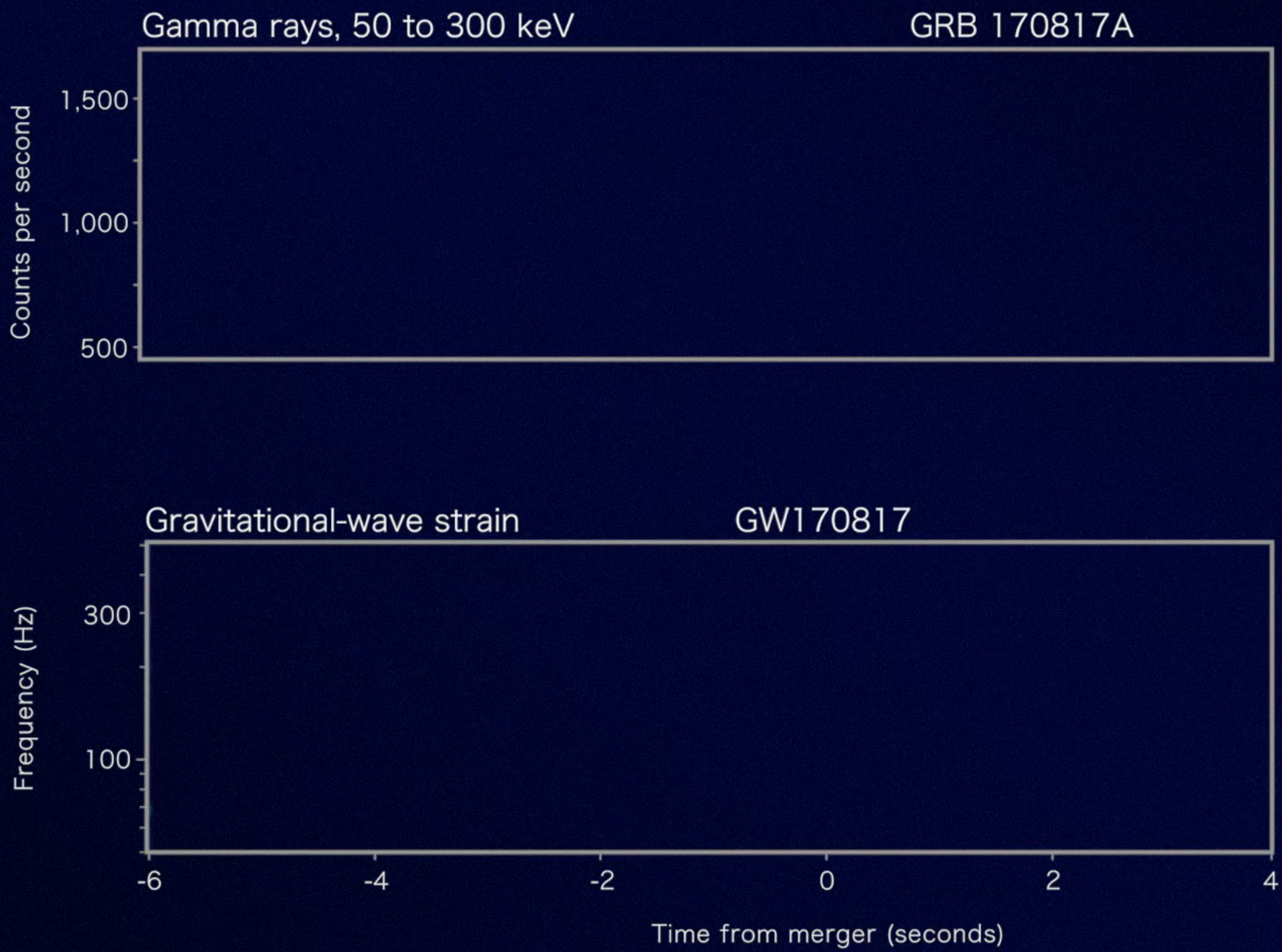
$$\chi_2 = \frac{d^2P}{d\mu_B^2} \text{ at T=0:}$$

$$c_s^2 = n_B/(\mu_B \chi_2)$$

McLerran & Reddy, Phys. Rev. Lett.122, 122701 (2019)

Fermi

LIGO


Gamma rays, 50 to 300 keV
GRB 170817A
Counts per second
1,500
1,000
500
Gravitational-wave strain
GW170817
Frequency (Hz)
300
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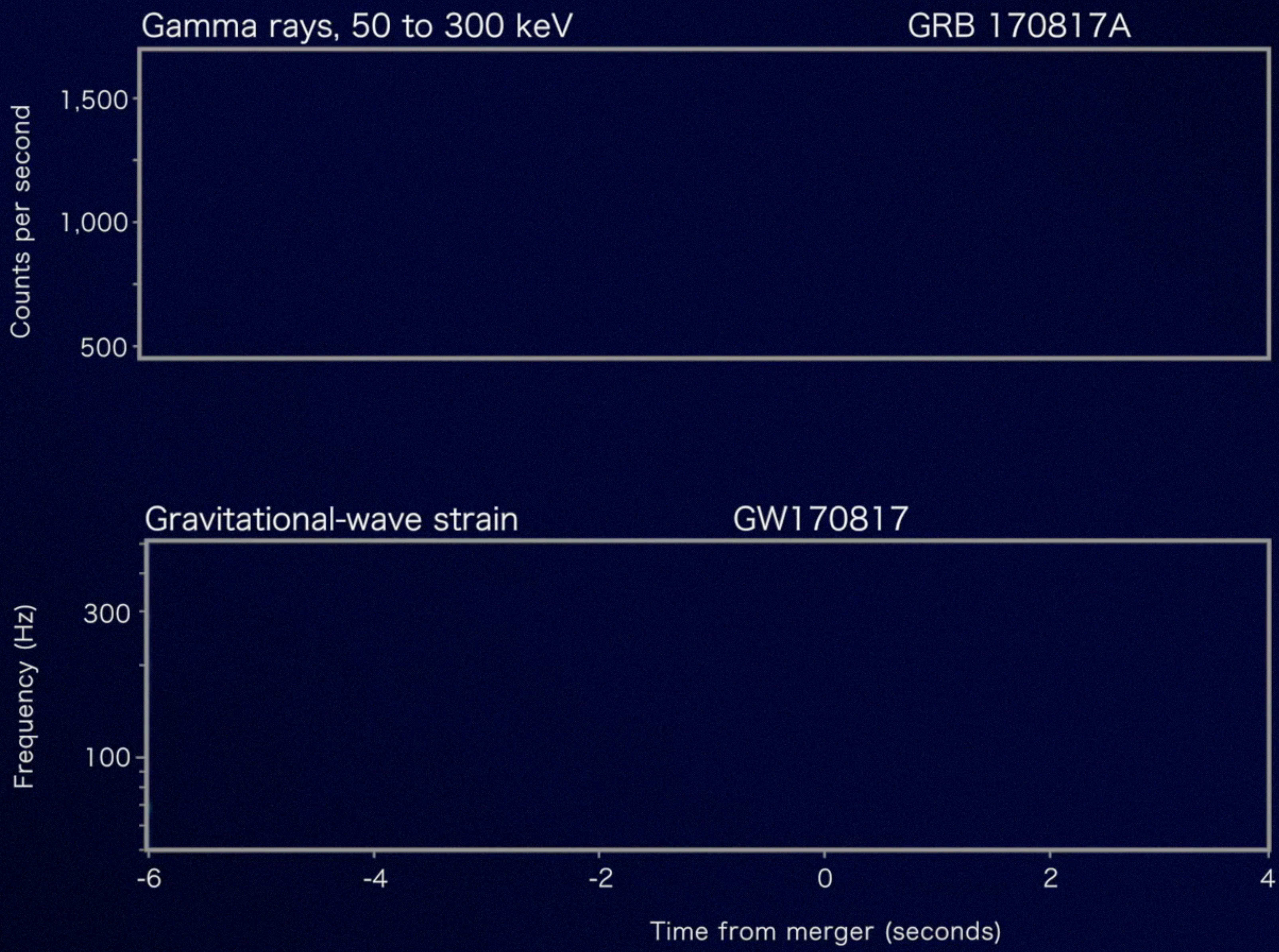
Time from merger (seconds)

Fermi



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LIGO

Binary Love to the rescue!

Tests of General Relativity

$$\tilde{h}(f) = \mathcal{A}(f) e^{i\psi_{\rm pp}(f) + i\psi_{\rm tidal}(f)}$$

$$\psi_{\rm tidal} = f(m_1, m_2)\, v(f)^5\, \Lambda$$

$$\Lambda = g(m_1, m_2)\lambda_1 + h(m_1, m_2)\lambda_2$$

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↓

If you have measured (m_1, λ_1) and (m_2, λ_2), then $\lambda_1 = \lambda_1(C_1)$ and $\lambda_2 = \lambda_2(C_2)$ relations give you (m_1, R_1) and (m_2, R_2) !

The baldness of compact objects

Tests of General Relativity

The baldness of compact objects

$\bar{I}$

$$\bar{I} = \frac{I}{M^3}$$

The baldness of compact objects

Tests of General Relativity

$\bar{I}$

$\bar{\lambda}$

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Tests of General Relativity

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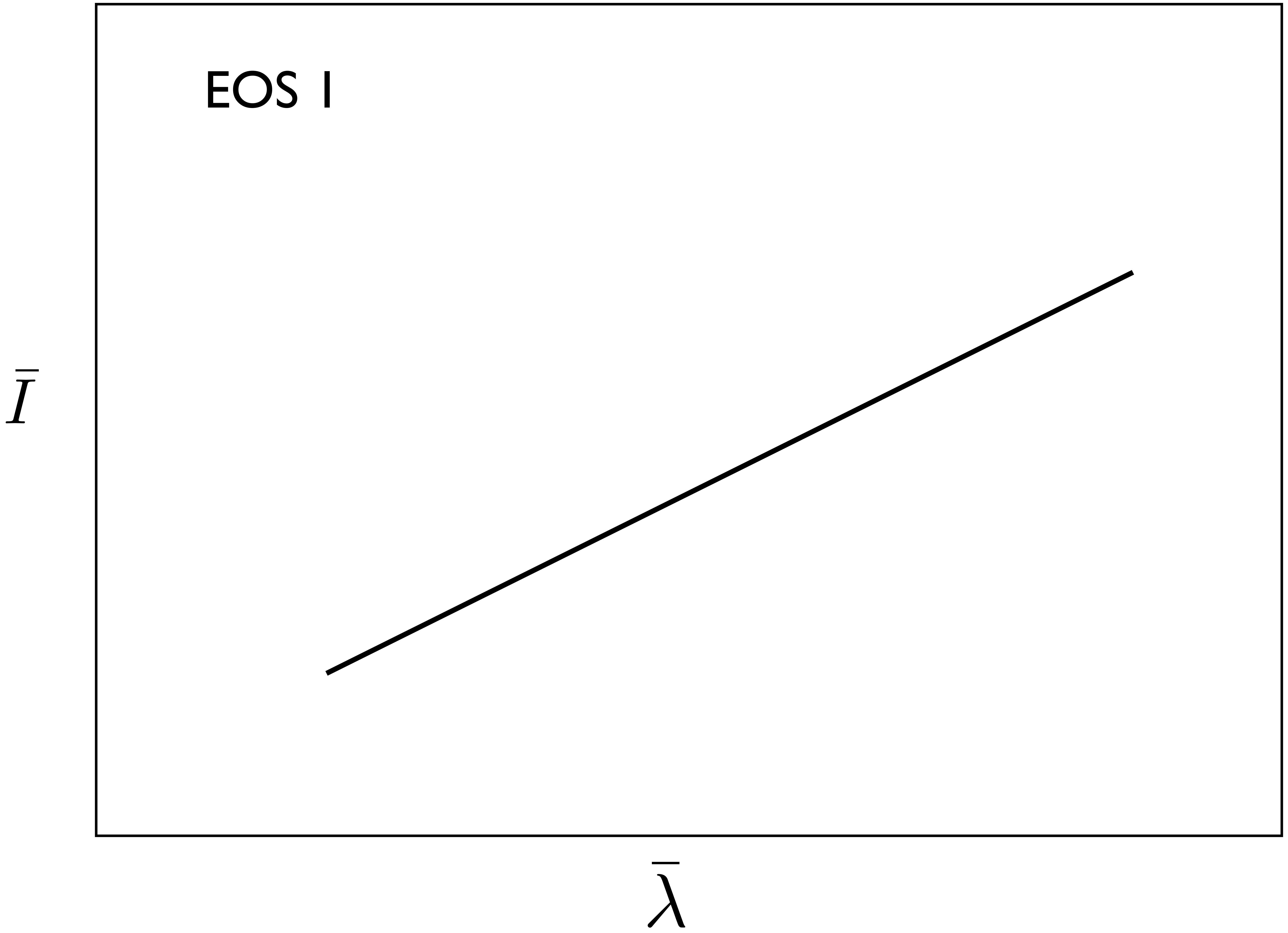

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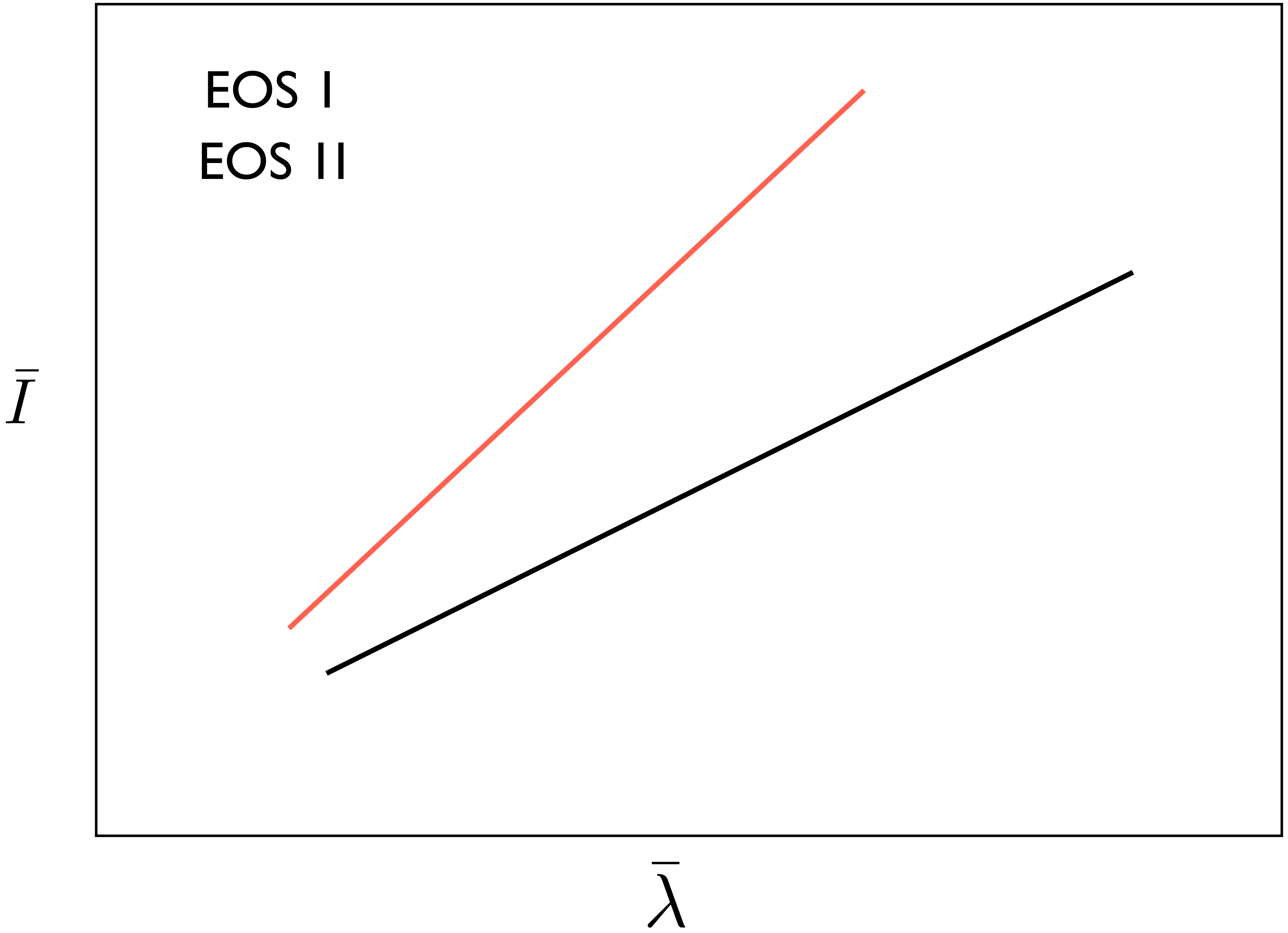

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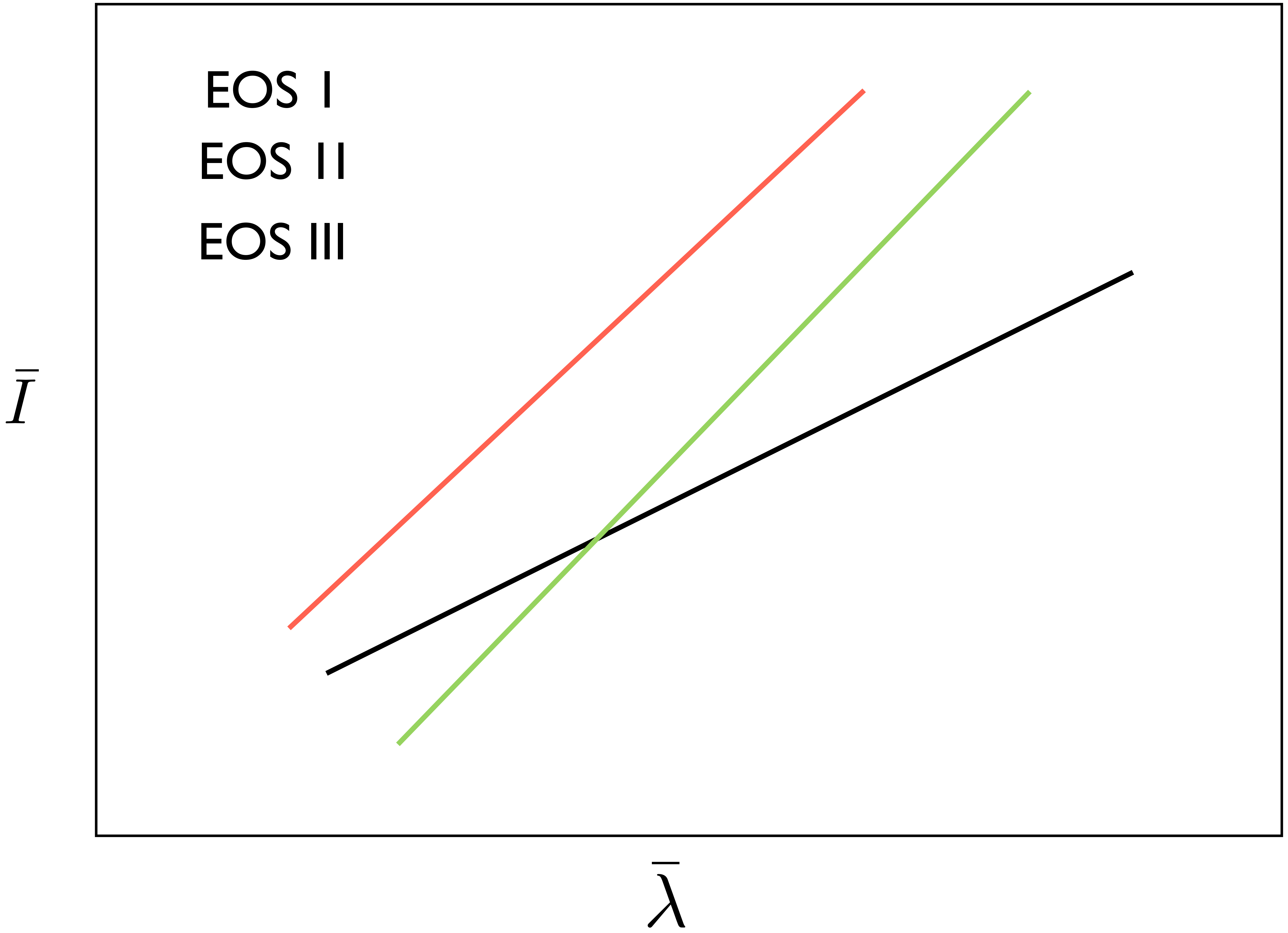

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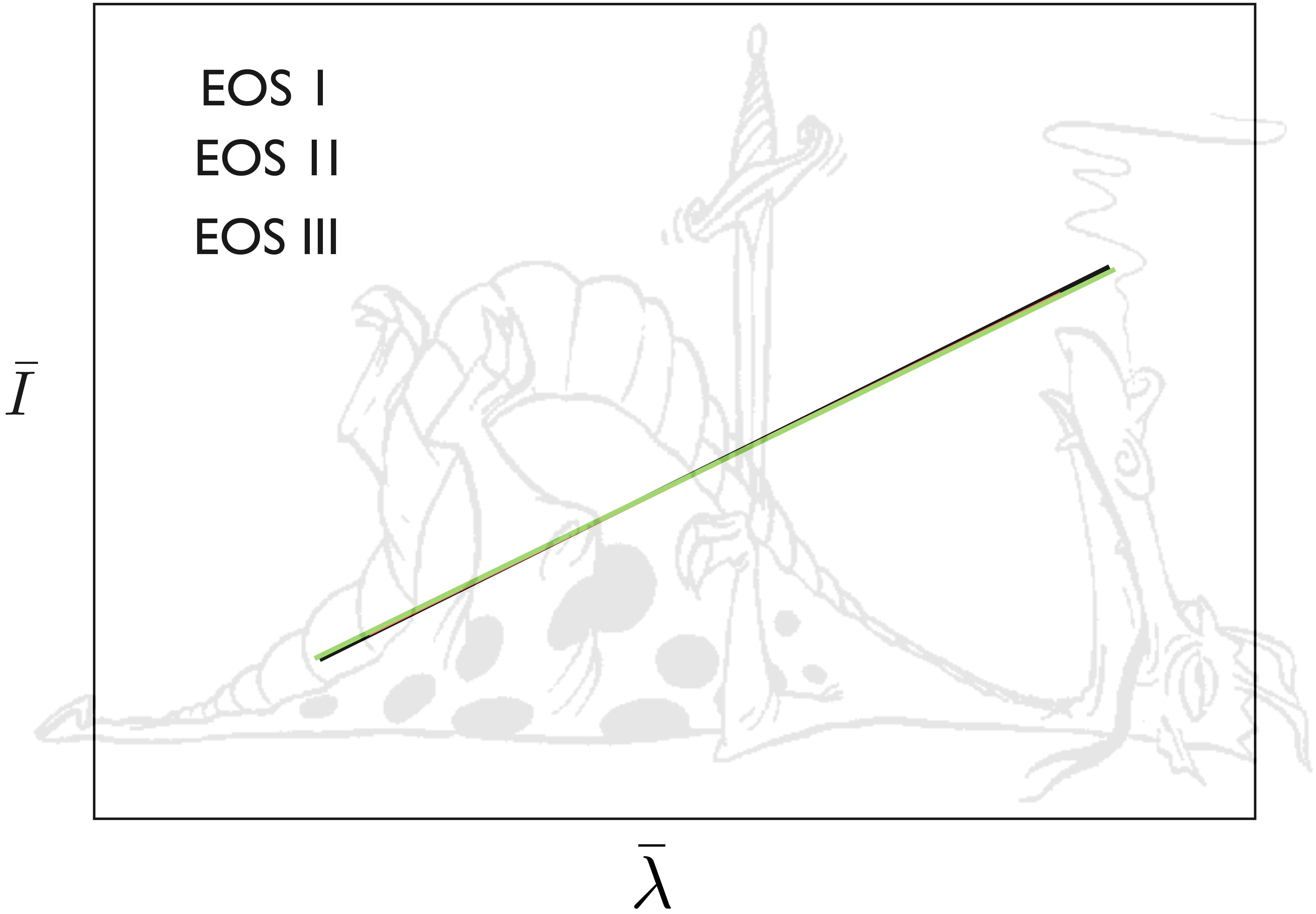

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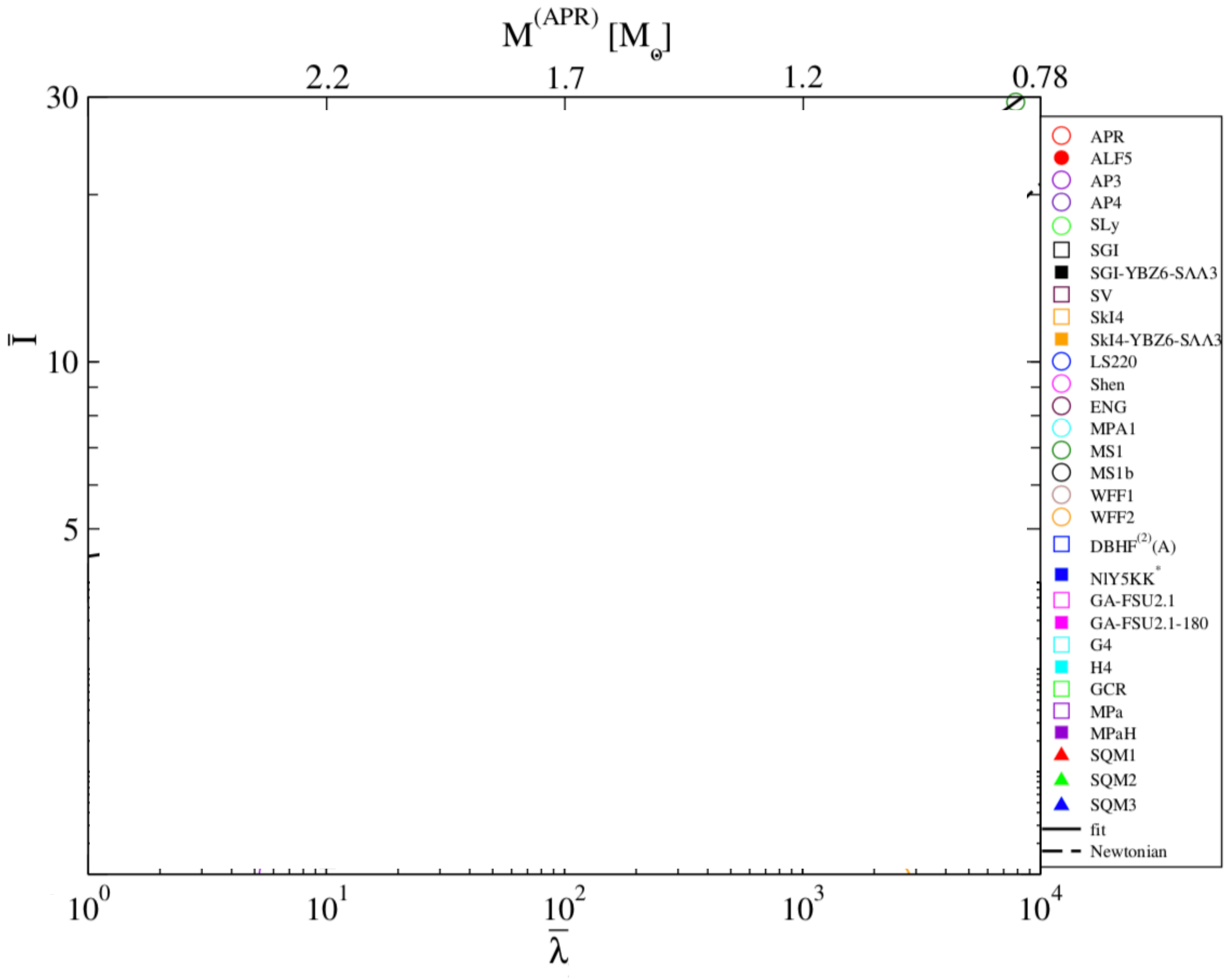
I-Love-Q relations



[Yagi & Yunes, Science 341 ('13), Yagi & Yunes, PRD 88 ('13)]

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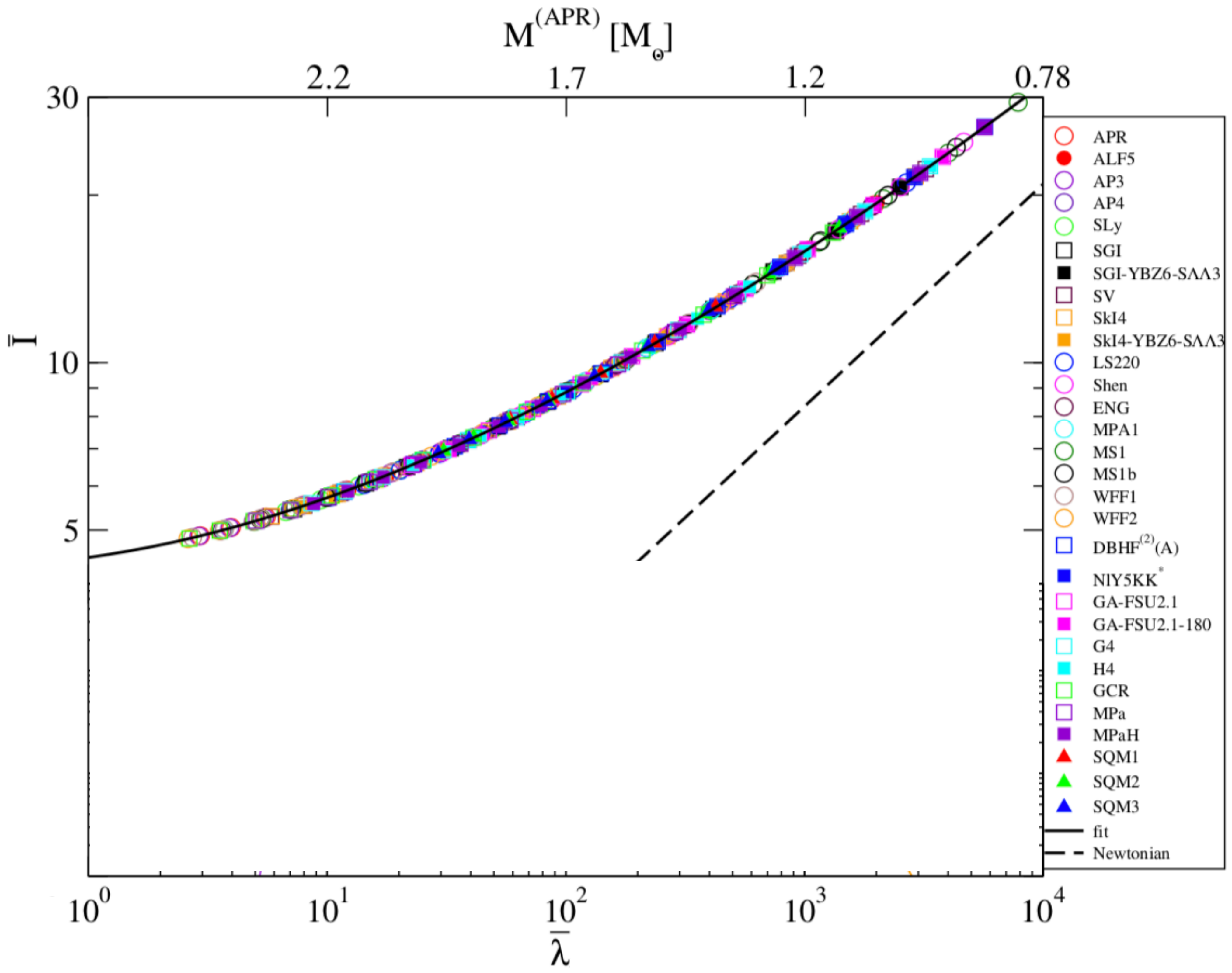

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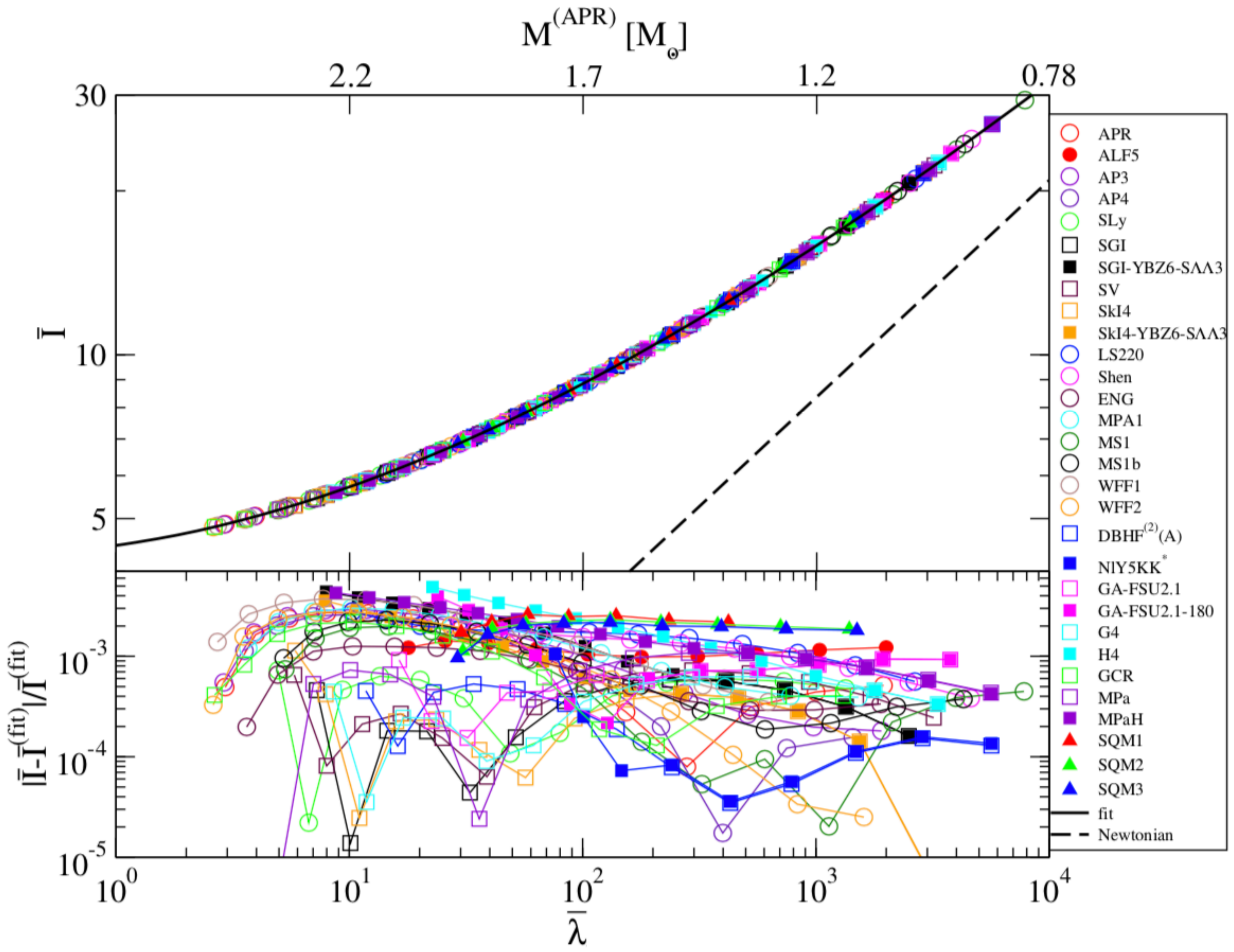

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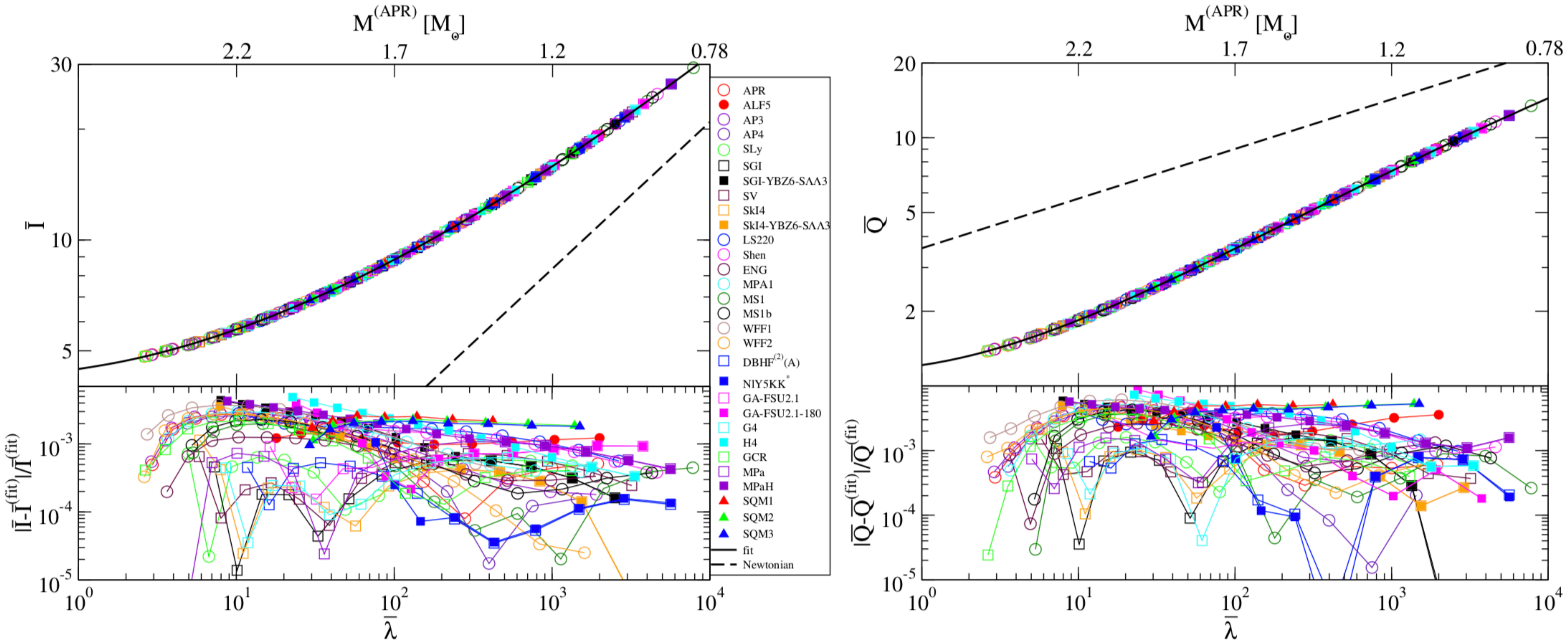

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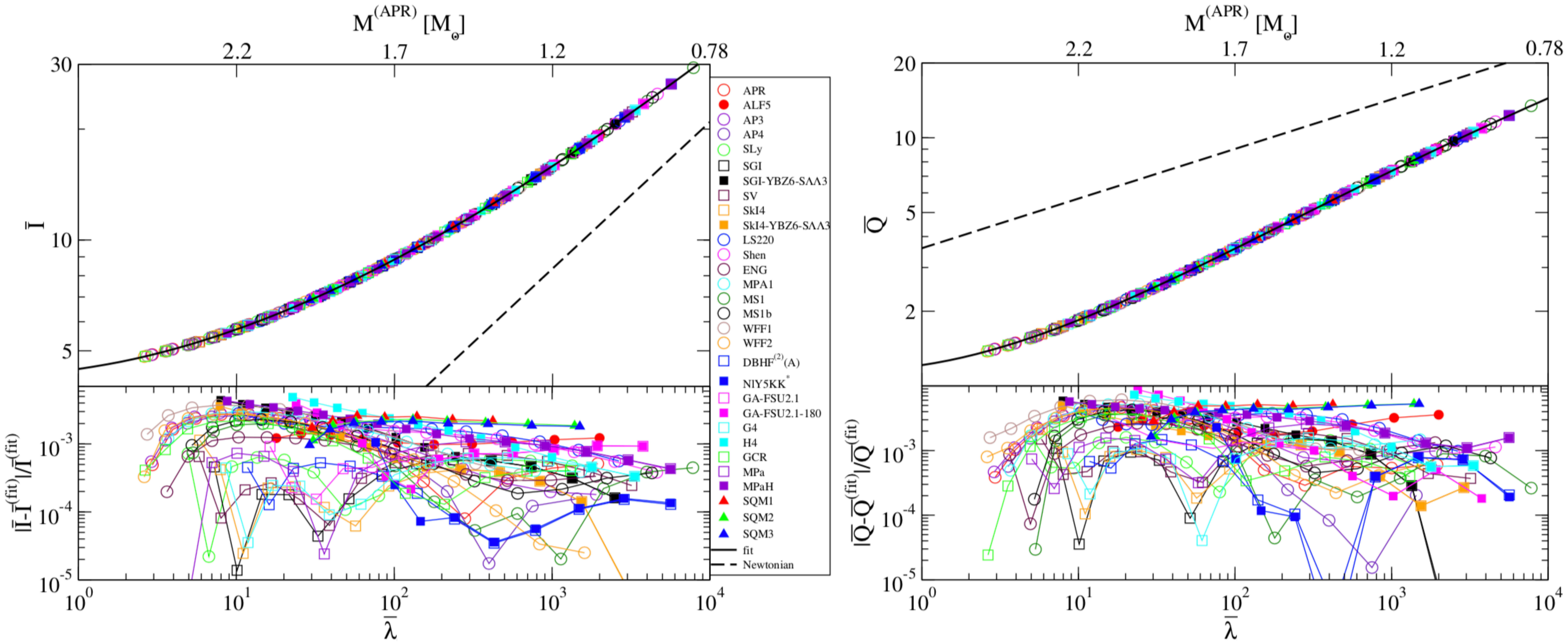
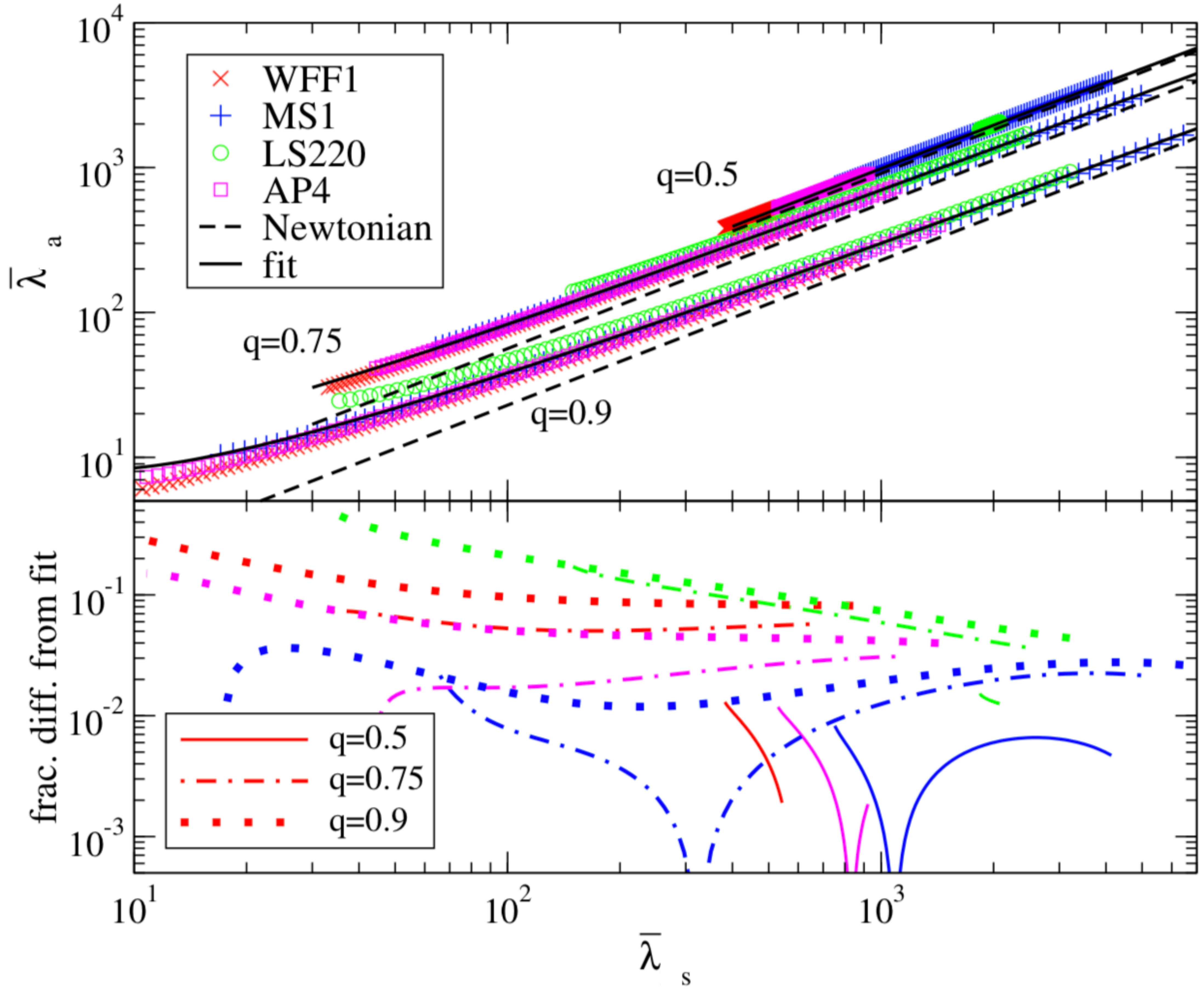


[Yagi & Yunes, Science 341 ('13), Yagi & Yunes, PRD 88 ('13)]

The moment of inertia, quadrupole moment and Love number satisfy (approx Universal), EoS-insensitive relations!

Binary Love relations

$$\bar{\lambda}_{s,a} = \frac{1}{2}\left(\bar{\lambda}_1 \pm \bar{\lambda}_2\right)$$



[Yagi & Yunes, CQG Letters 33 ('16)]

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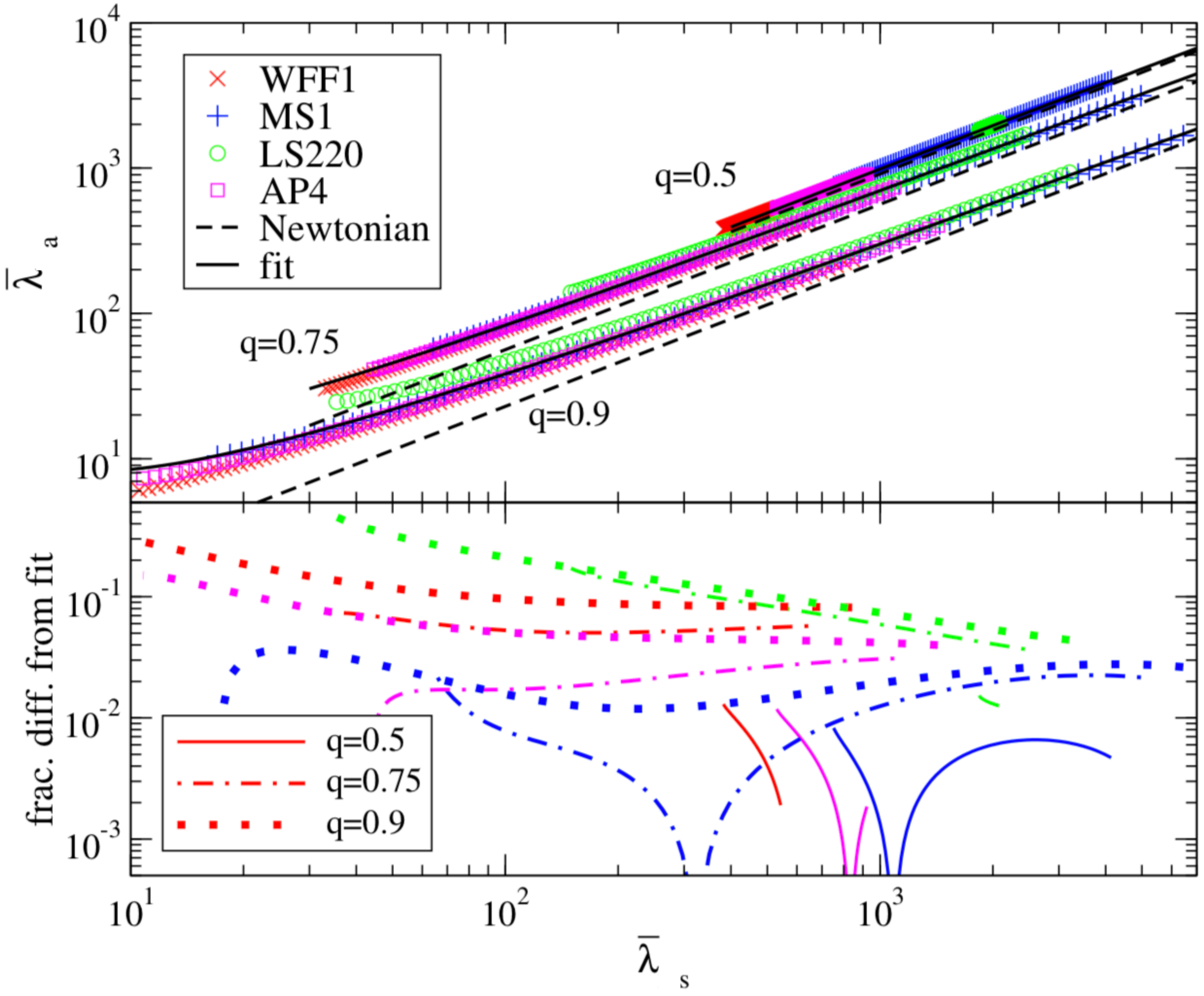

[Yagi & Yunes, CQG Letters 33 ('16)]

The tidal Love numbers satisfy (approx Universal), EoS-insensitive relations (that only depend on the mass ratio)!

Improvements in extraction of EoS

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Via stacking
(with aLIGO at design sensitivity, 2021-2023)

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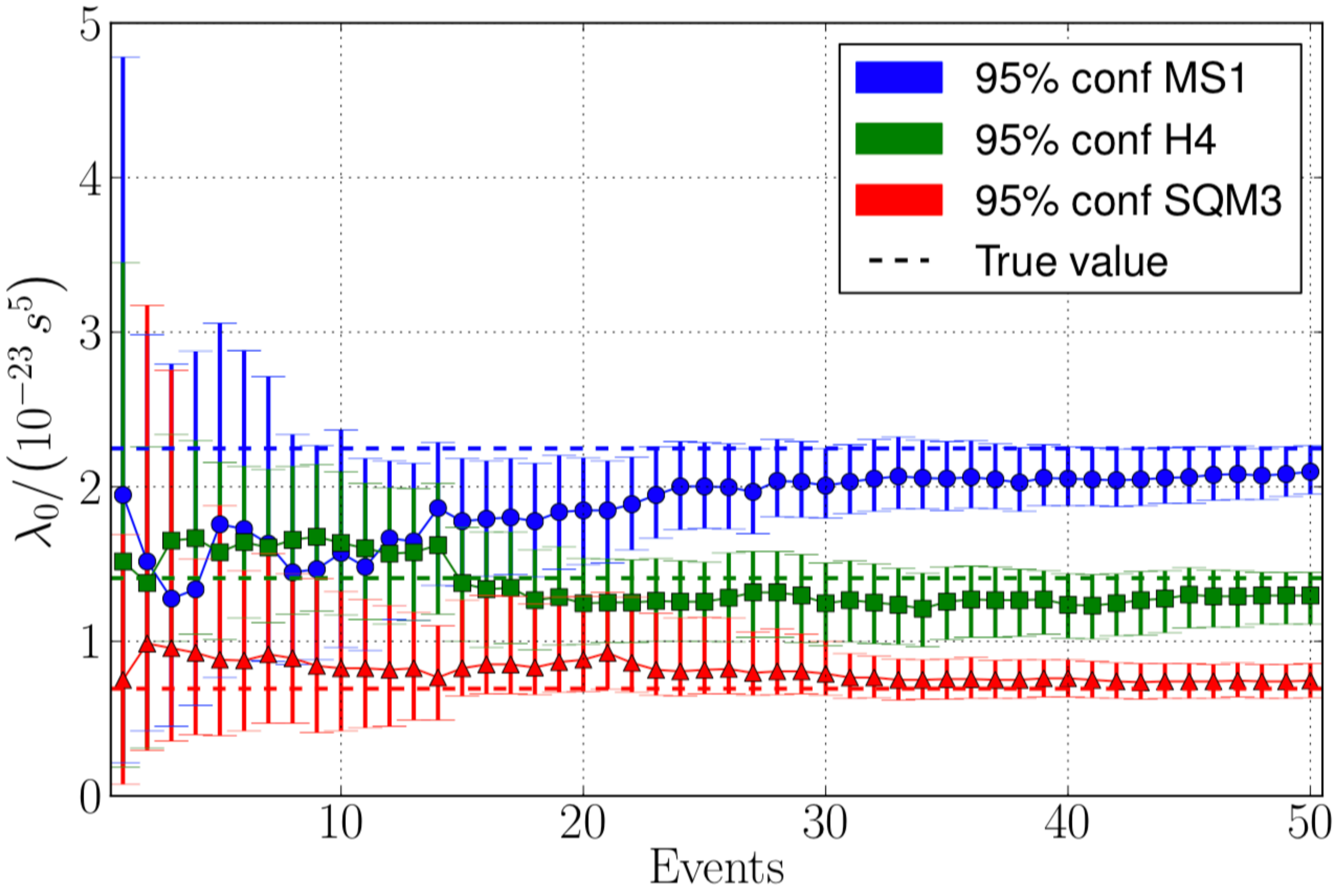

[Agathos et al, PRD 92 ('05)]

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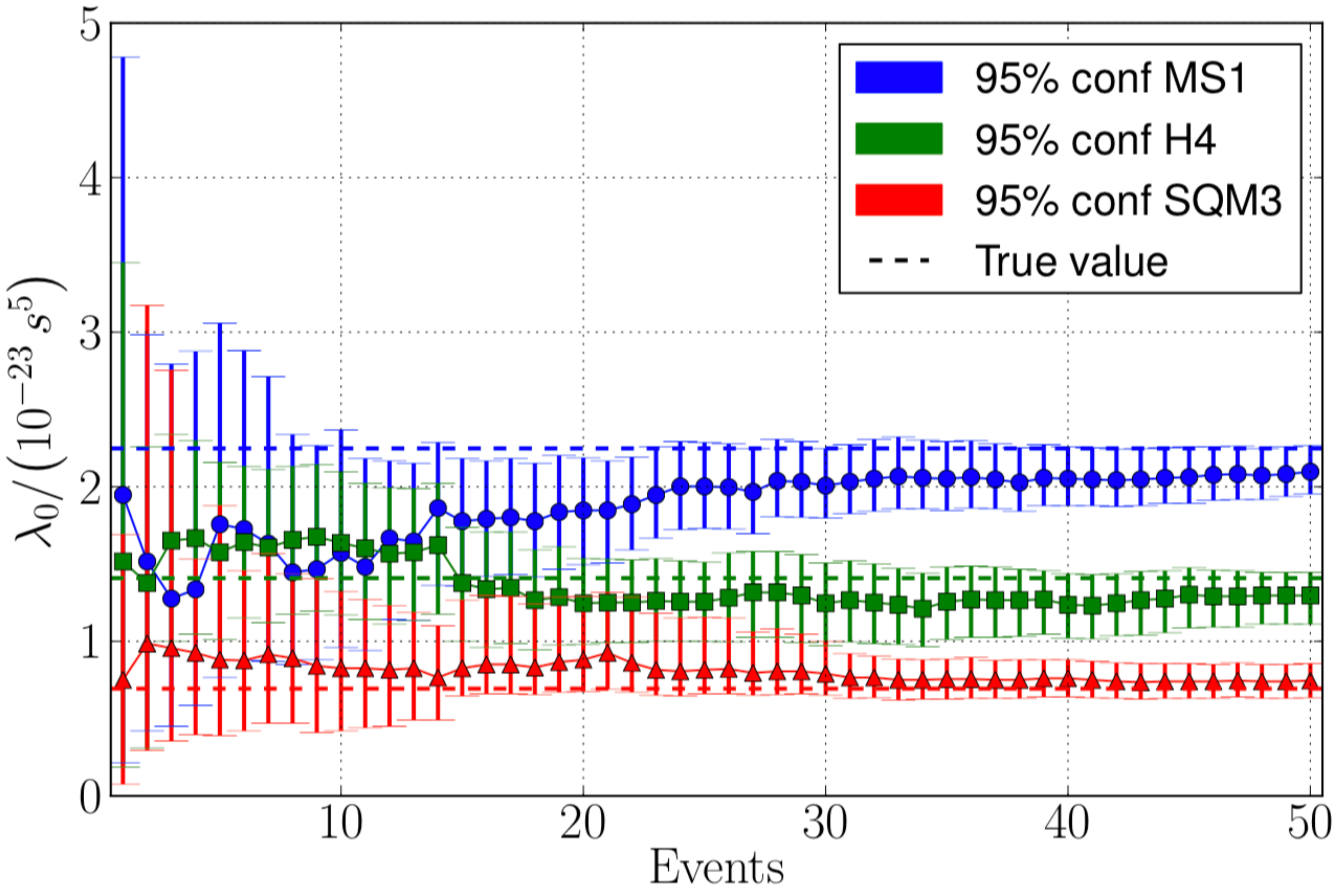
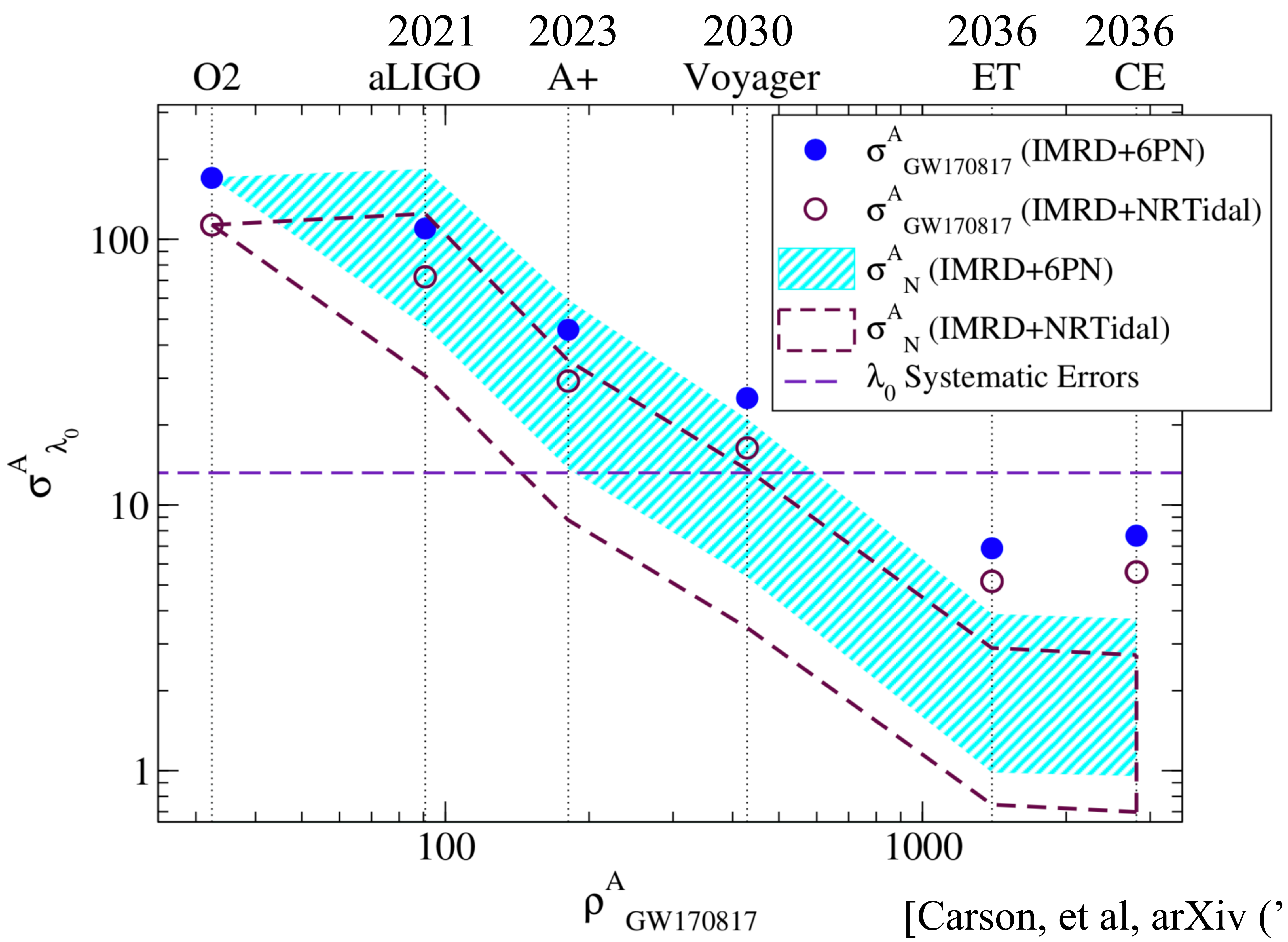


[Agathos et al, PRD 92 ('05)]

Single and future observations with 3G detectors
(λ_0=150, GW170817)



[Carson, et al, arXiv ('19)]

Beyond 2G detectors

2021 2025 2029 2033 2036

aLIGO
aVirgo
KAGRA

A+

LIGO-India

Voyager

improved quantum noise
improved thermal coating
increased range to 140% wrt aLIGO

silicon mirrors and suspensions
low temperature (120K)
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New physics

3G ground-based detectors

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