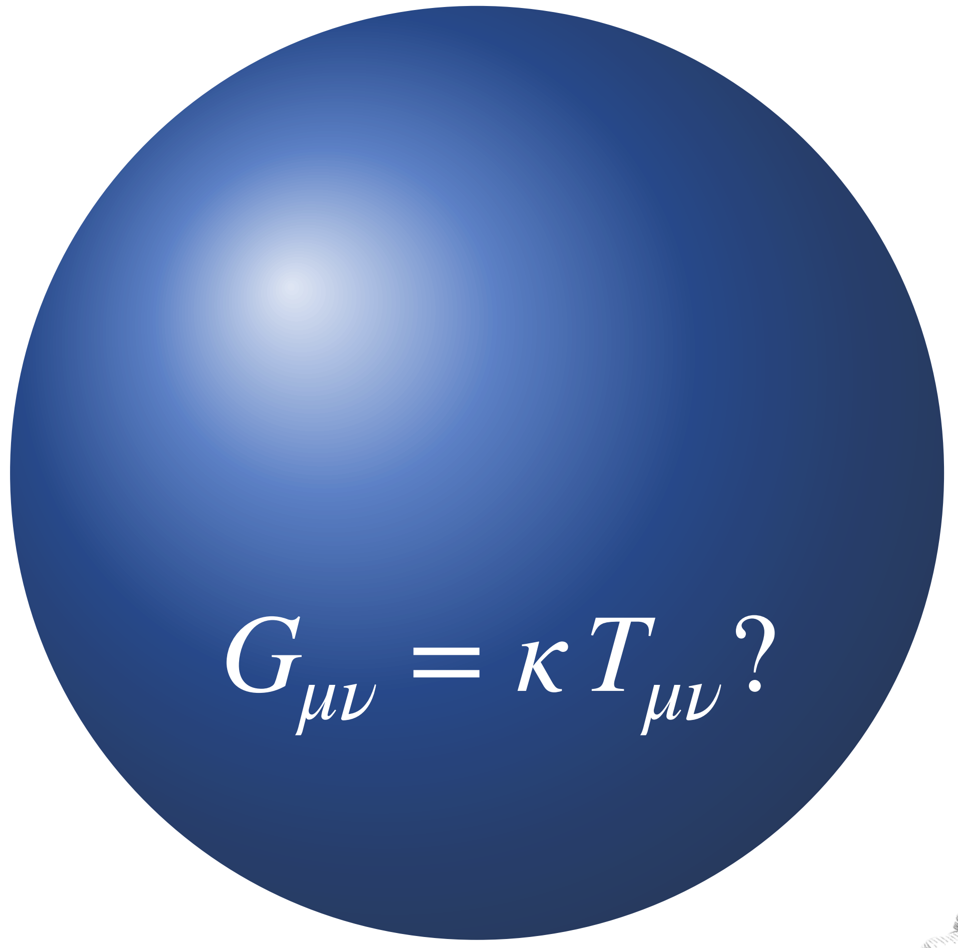
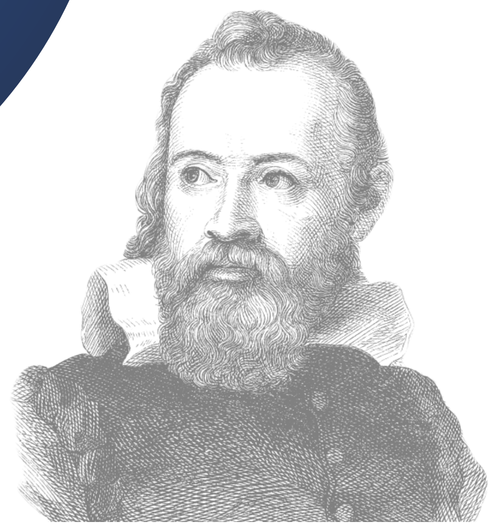
Testing strong-field gravity with multimessenger observations of neutron stars

based mostly on

HOS, A. Miguel Holgado, A. Cárdenas-Avendaño, and N. Yunes,
Phys. Rev. Lett. 126, 181101 (2021) [2004.01253]





Hector O. Silva
Max Planck Institute for Gravitational Physics
(Albert Einstein Institute), Potsdam, Germany

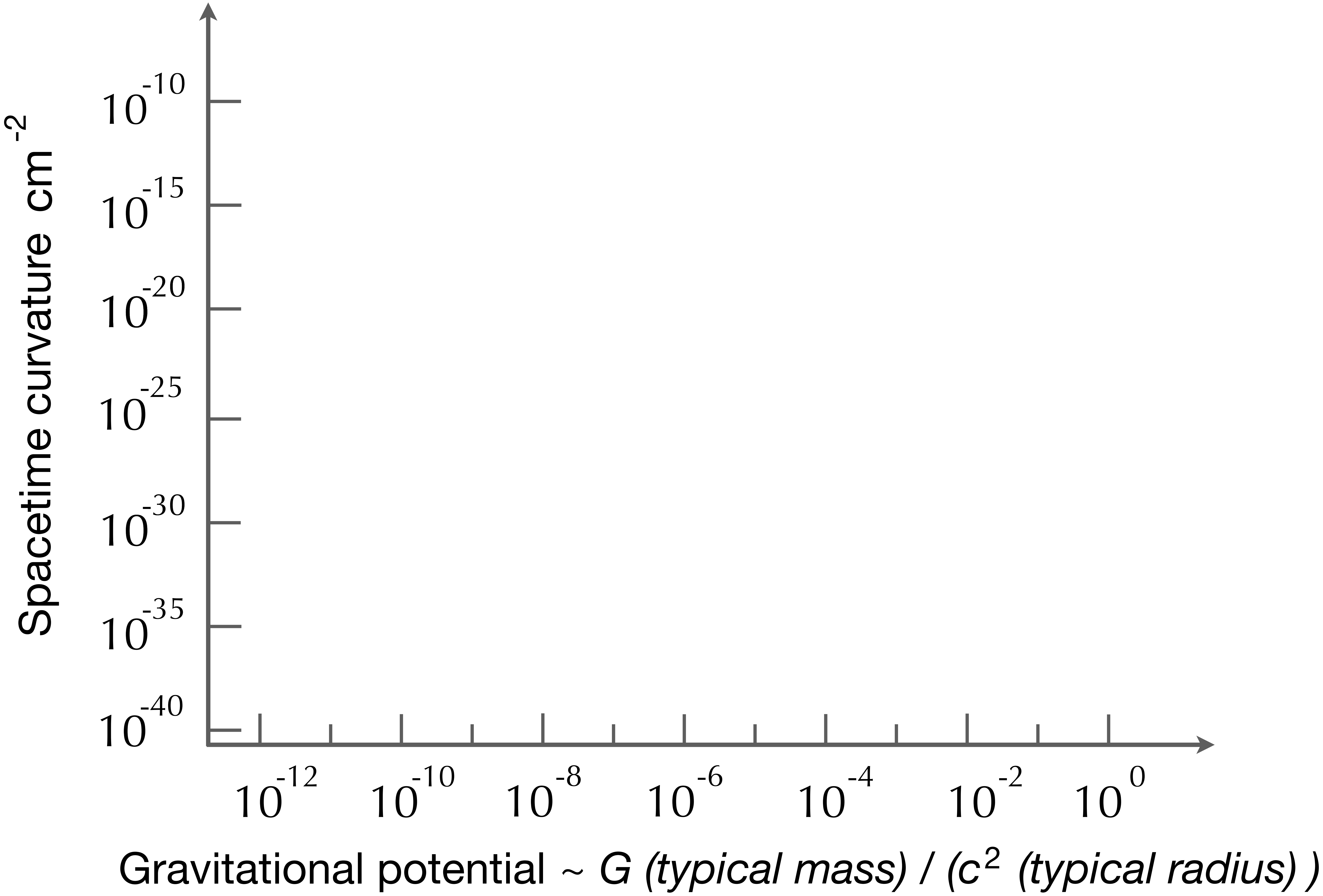
hector.silva@aei.mpg.de

https://www.phy.olemiss.edu/~hosilva

MAX-PLANCK-GESELLSCHAFT

Gravity Shape Pisa 2023
Università di Pisa, Italy
26.10.2023

The big picture



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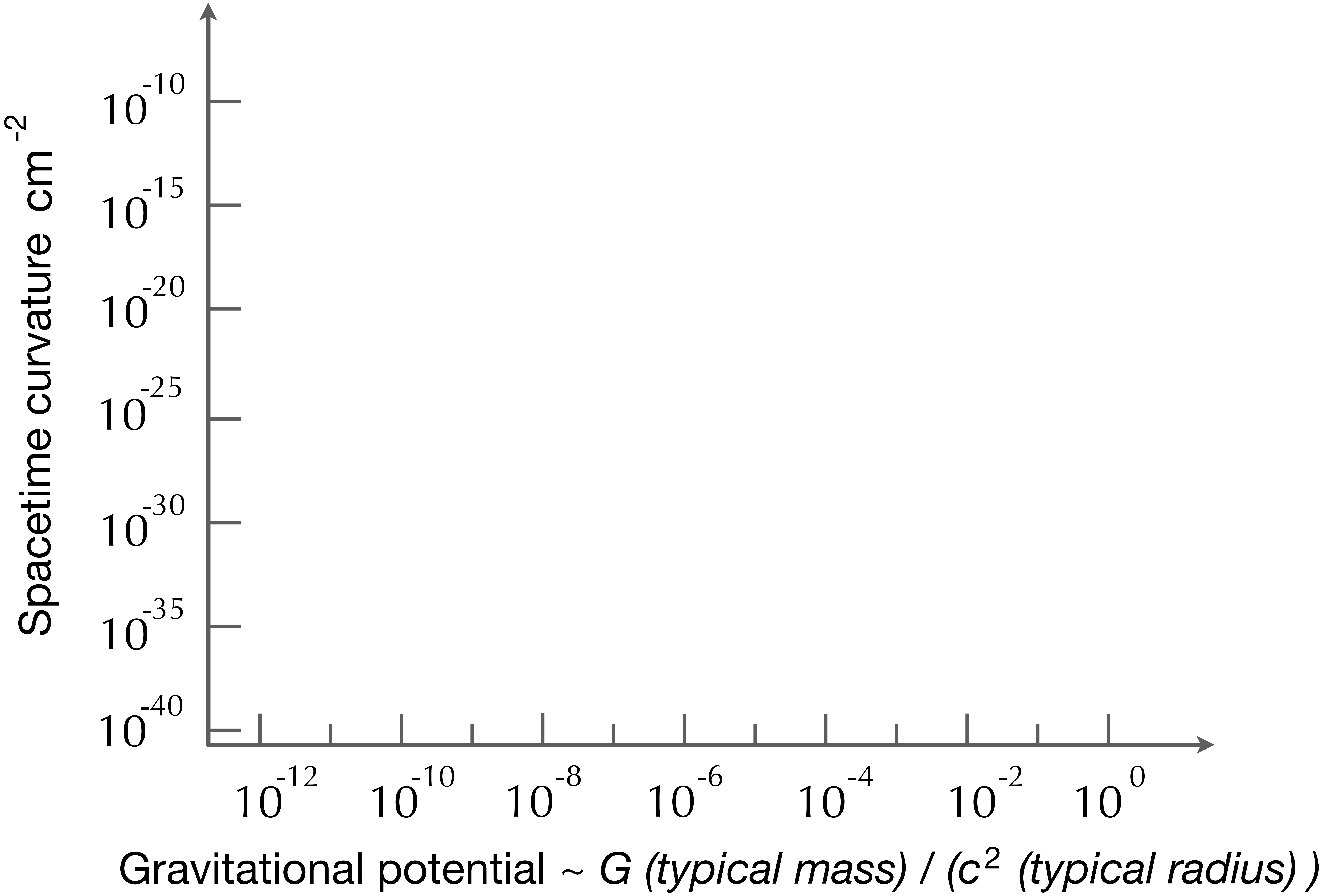

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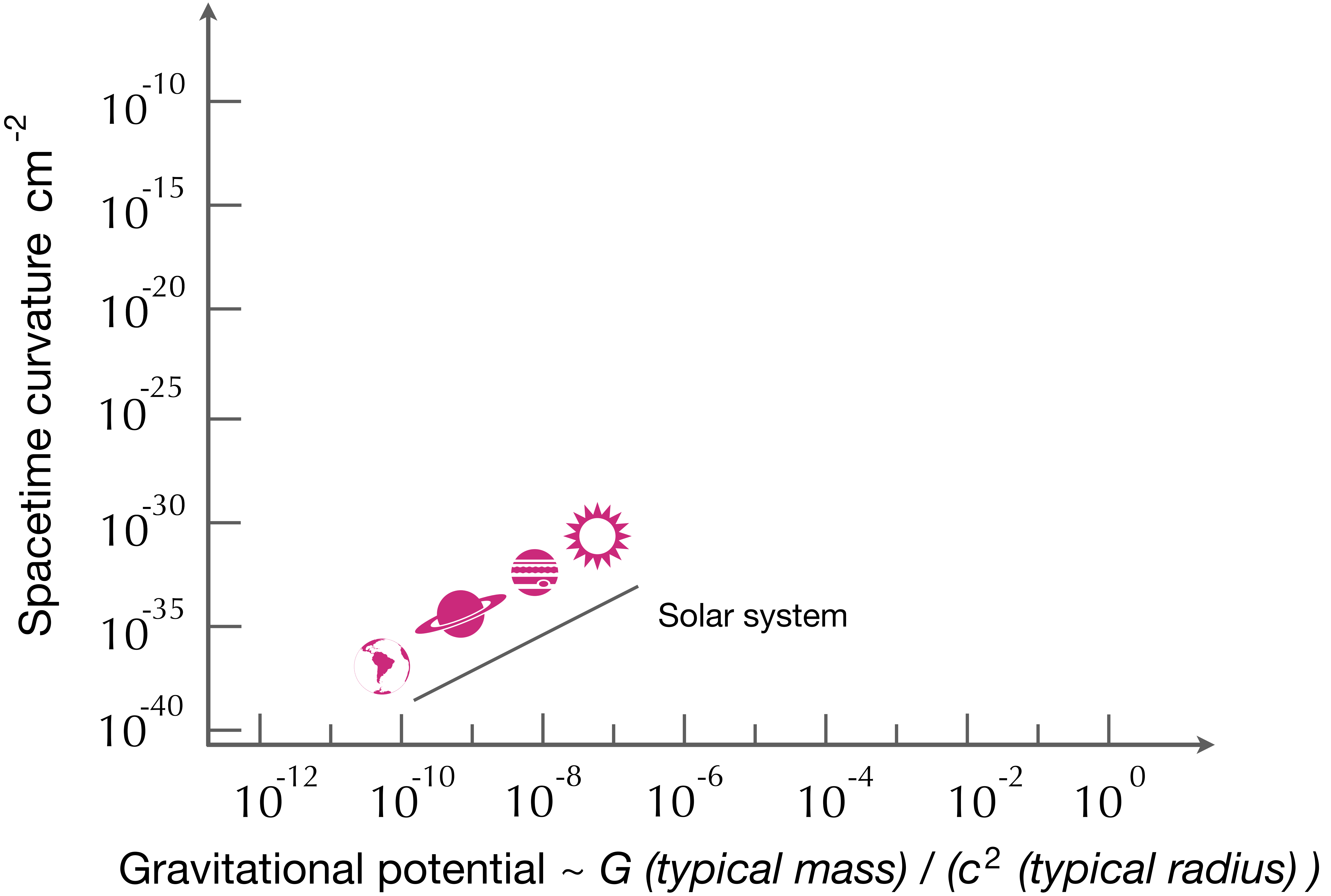

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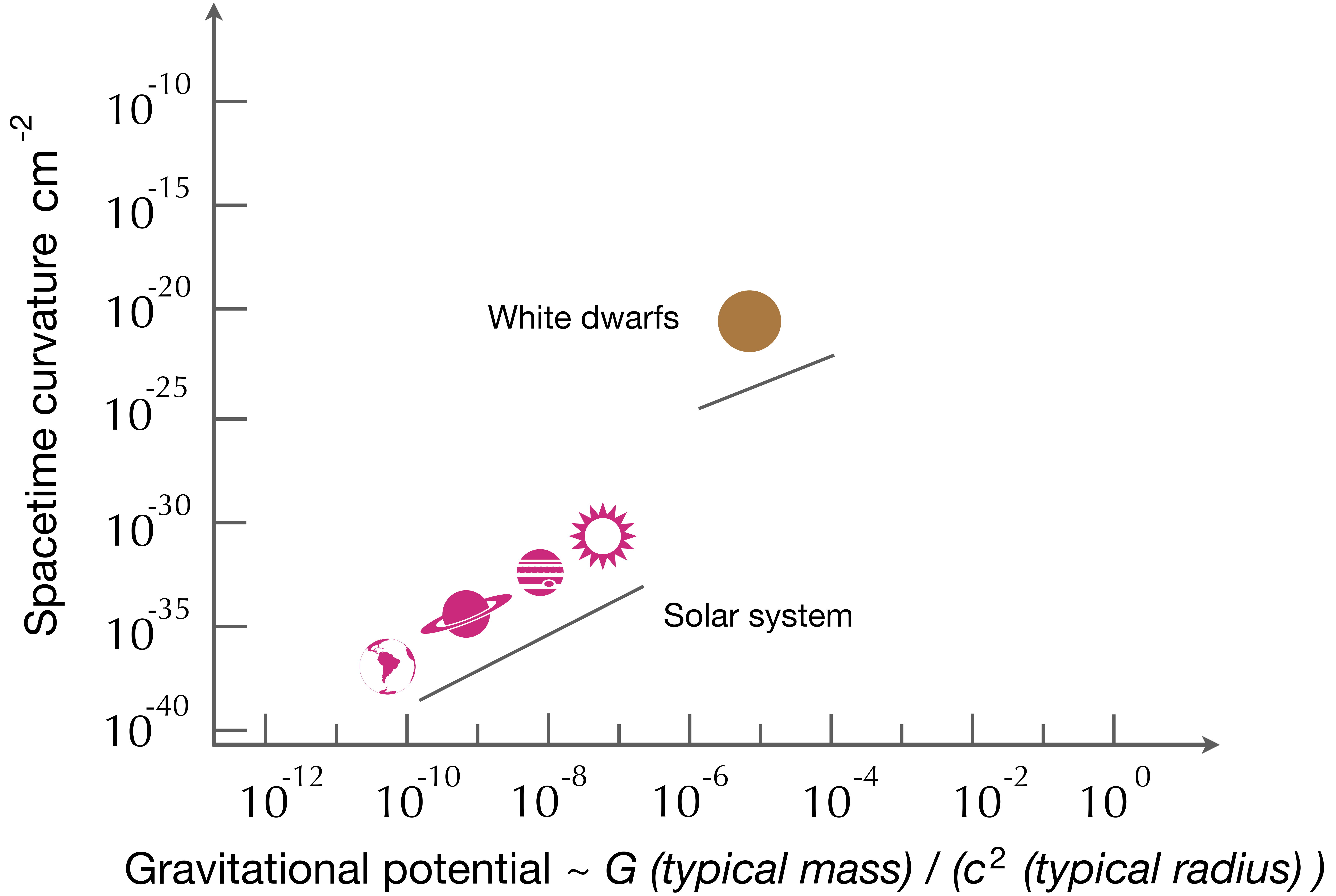

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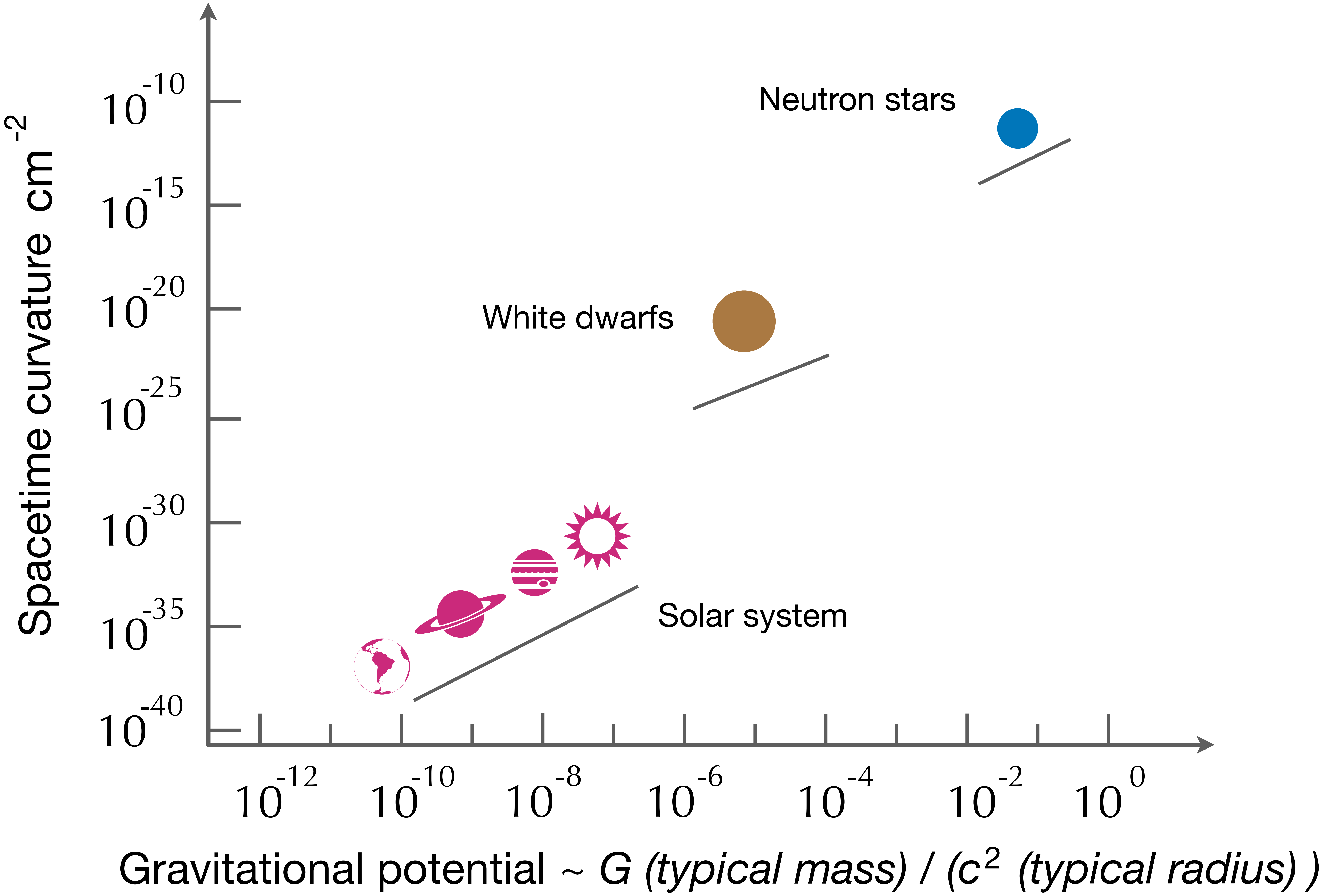

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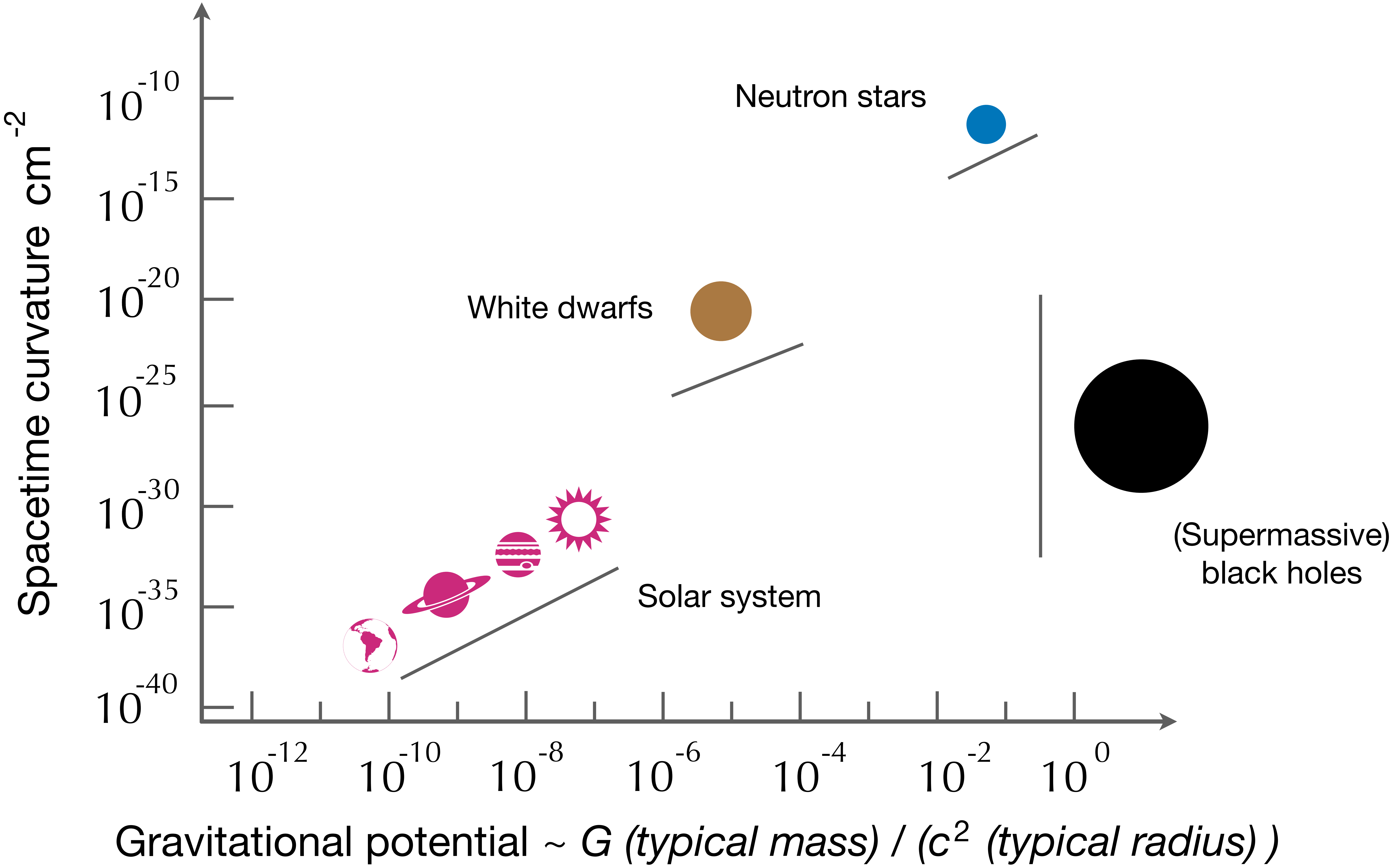

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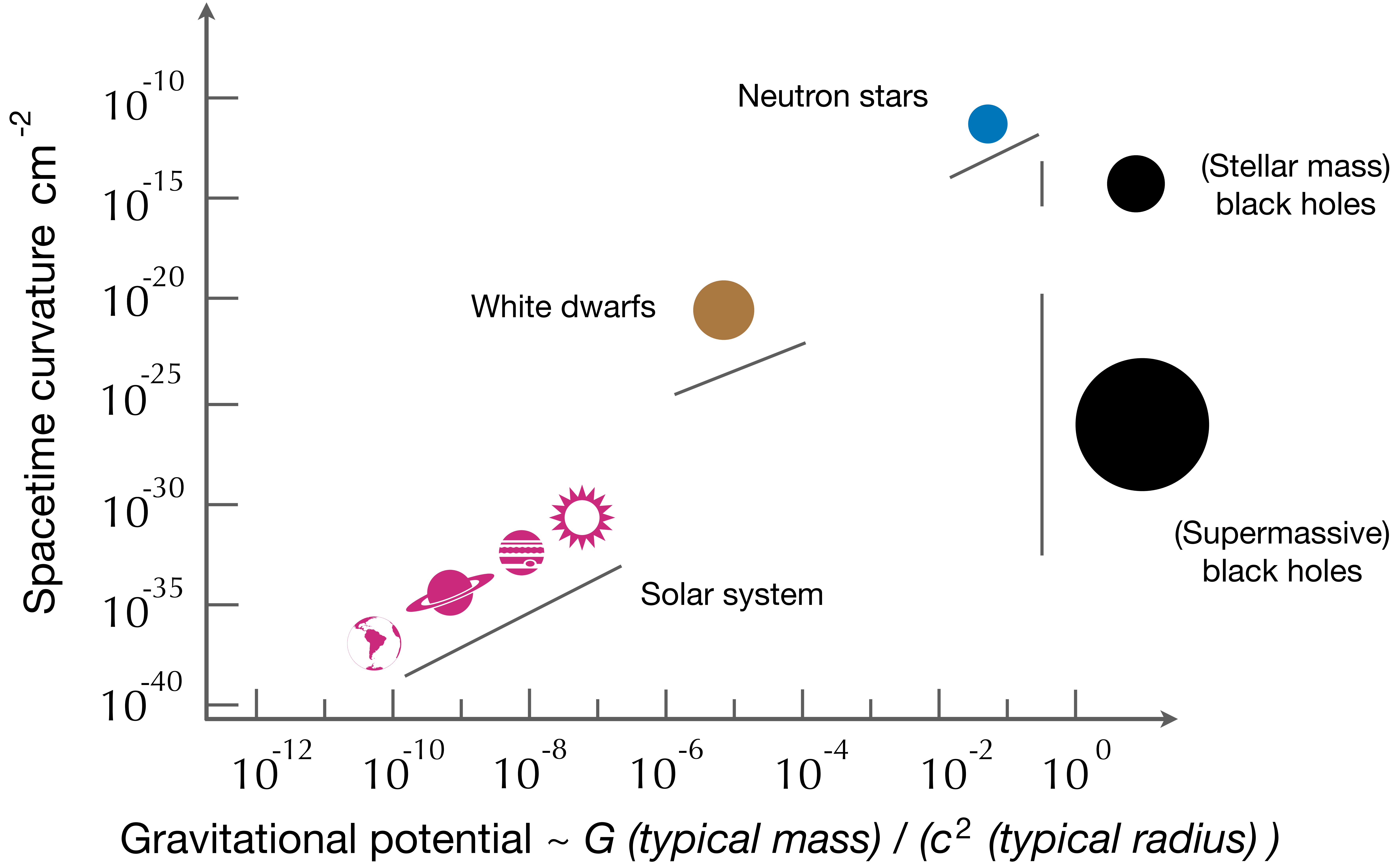

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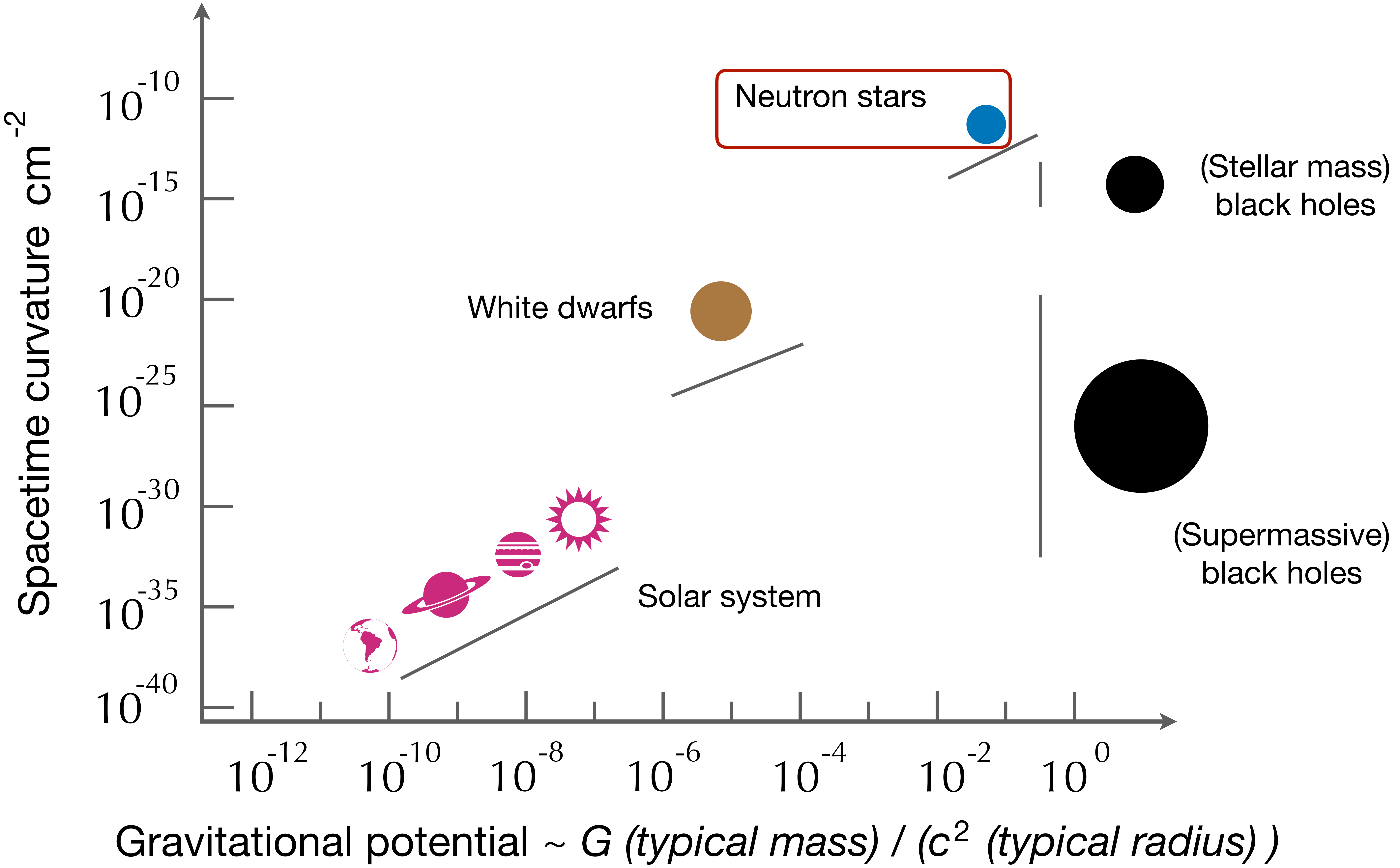
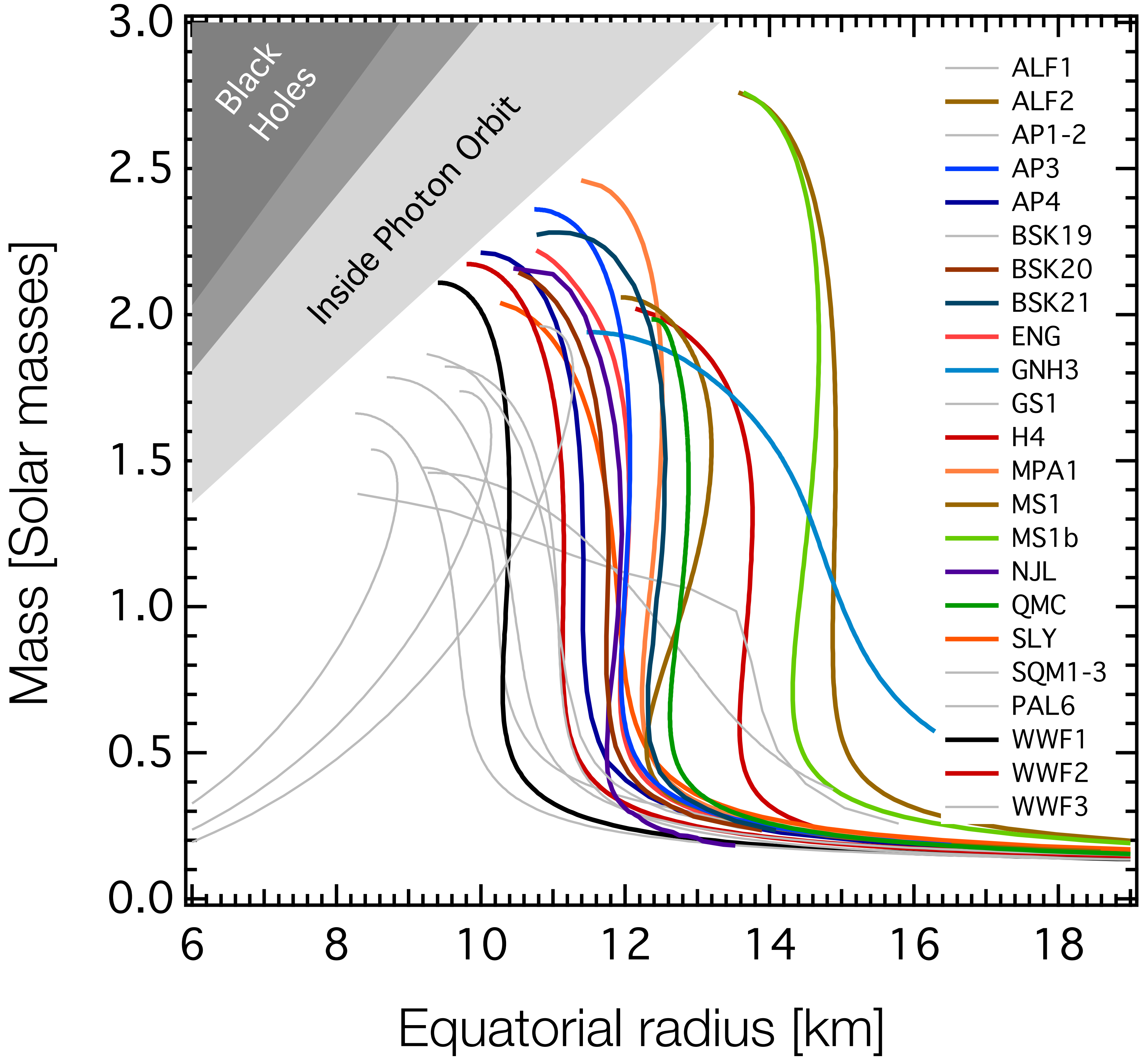


Extreme physics laboratories

Extreme physics laboratories

Gravity theory known, equation of state unknown



F. Özel and P. Freire, Ann. Rev. Astron. Astrophys. **54** (2016)

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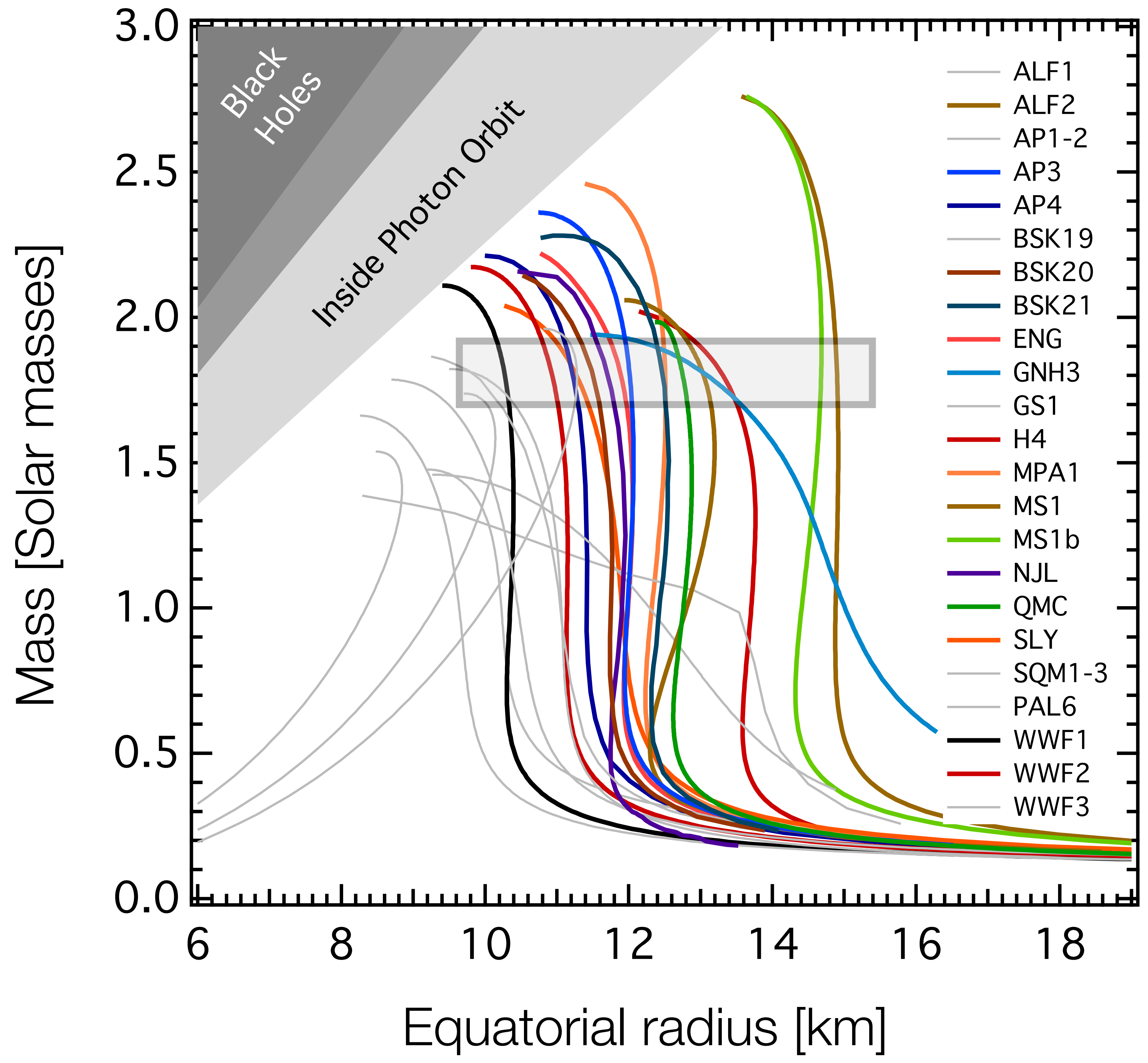

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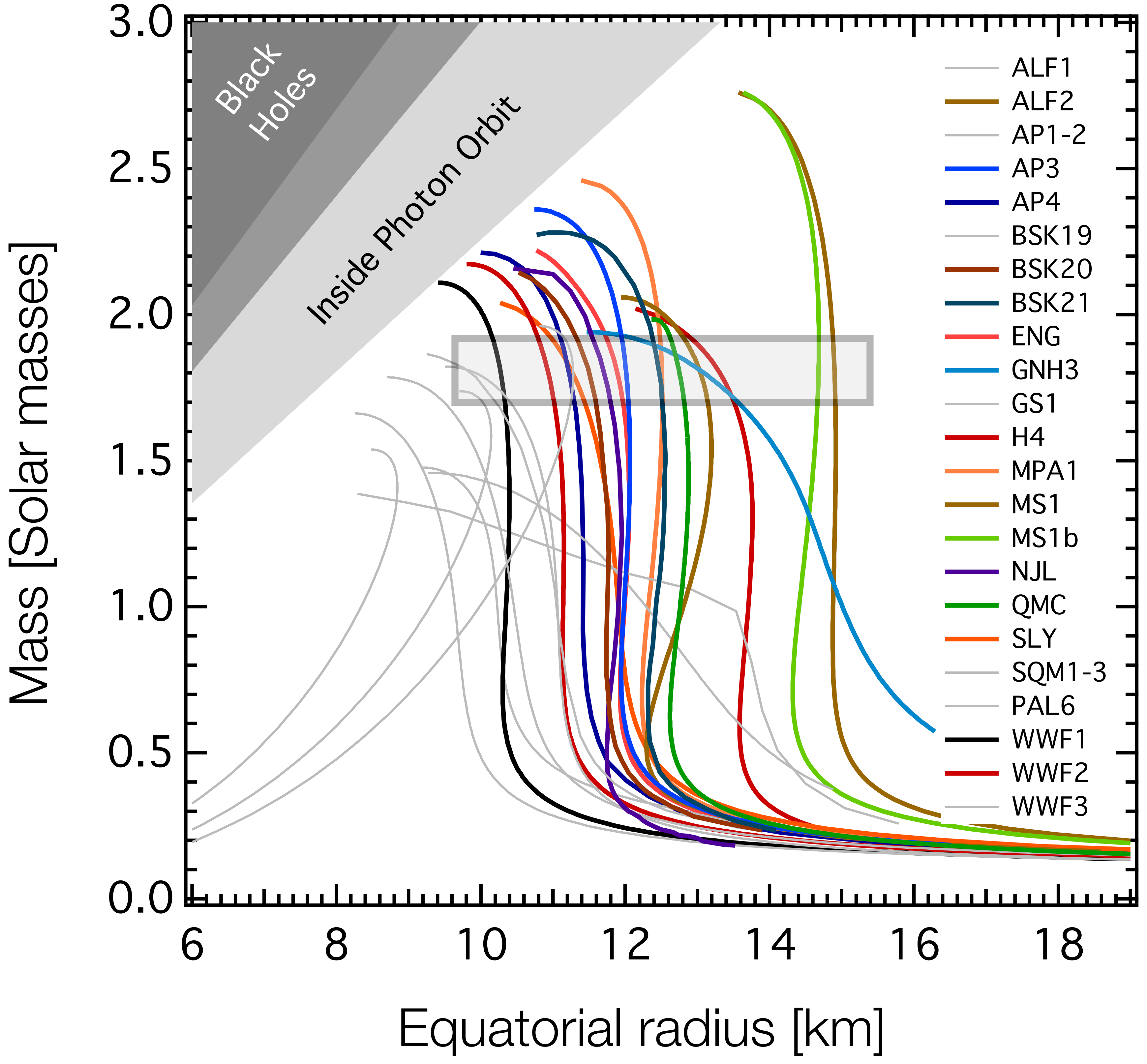

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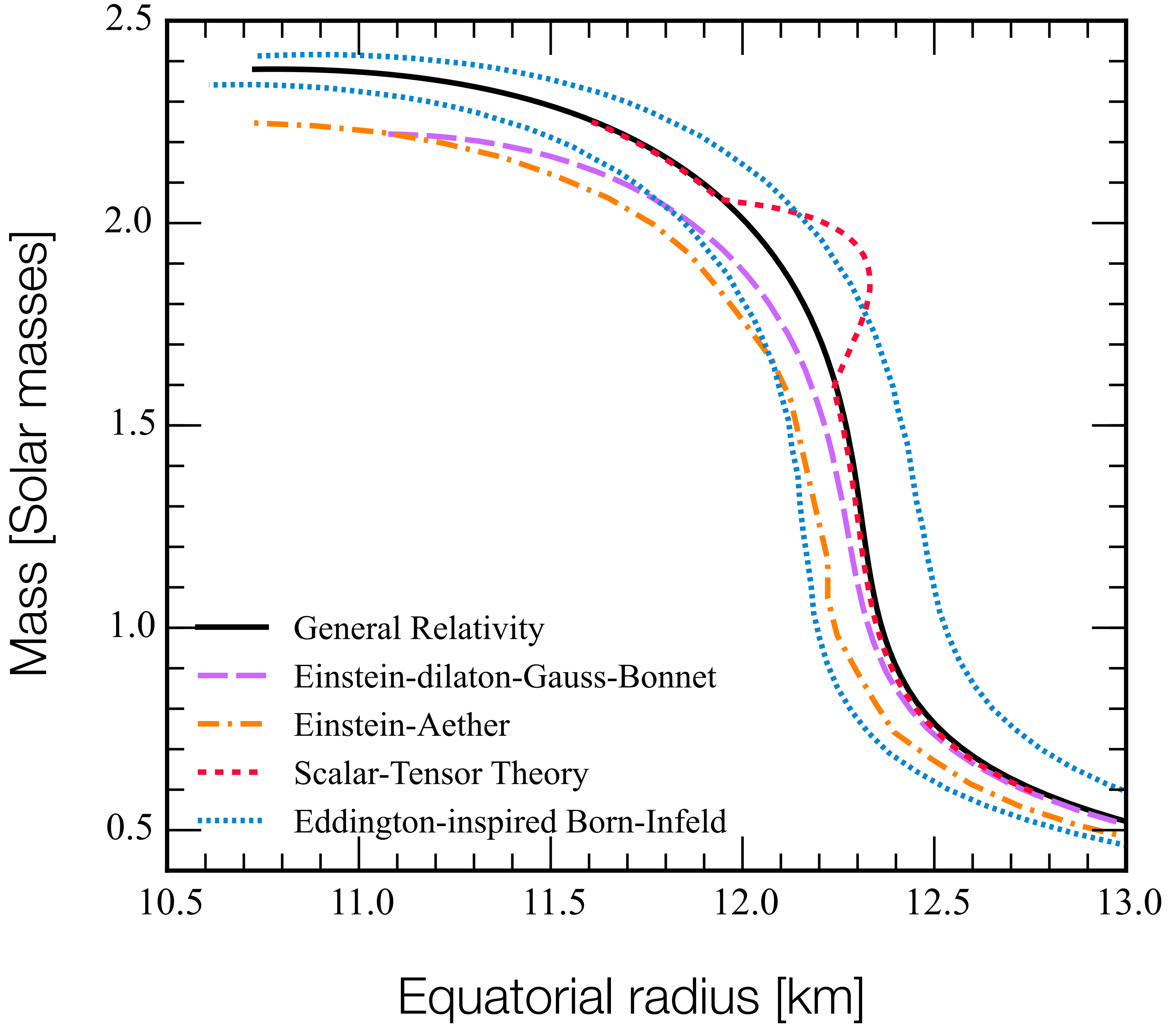


K. Glampedakis, G. Pappas, **HOS**, E. Berti, Phys. Rev. D, **92** 024056 (2015)

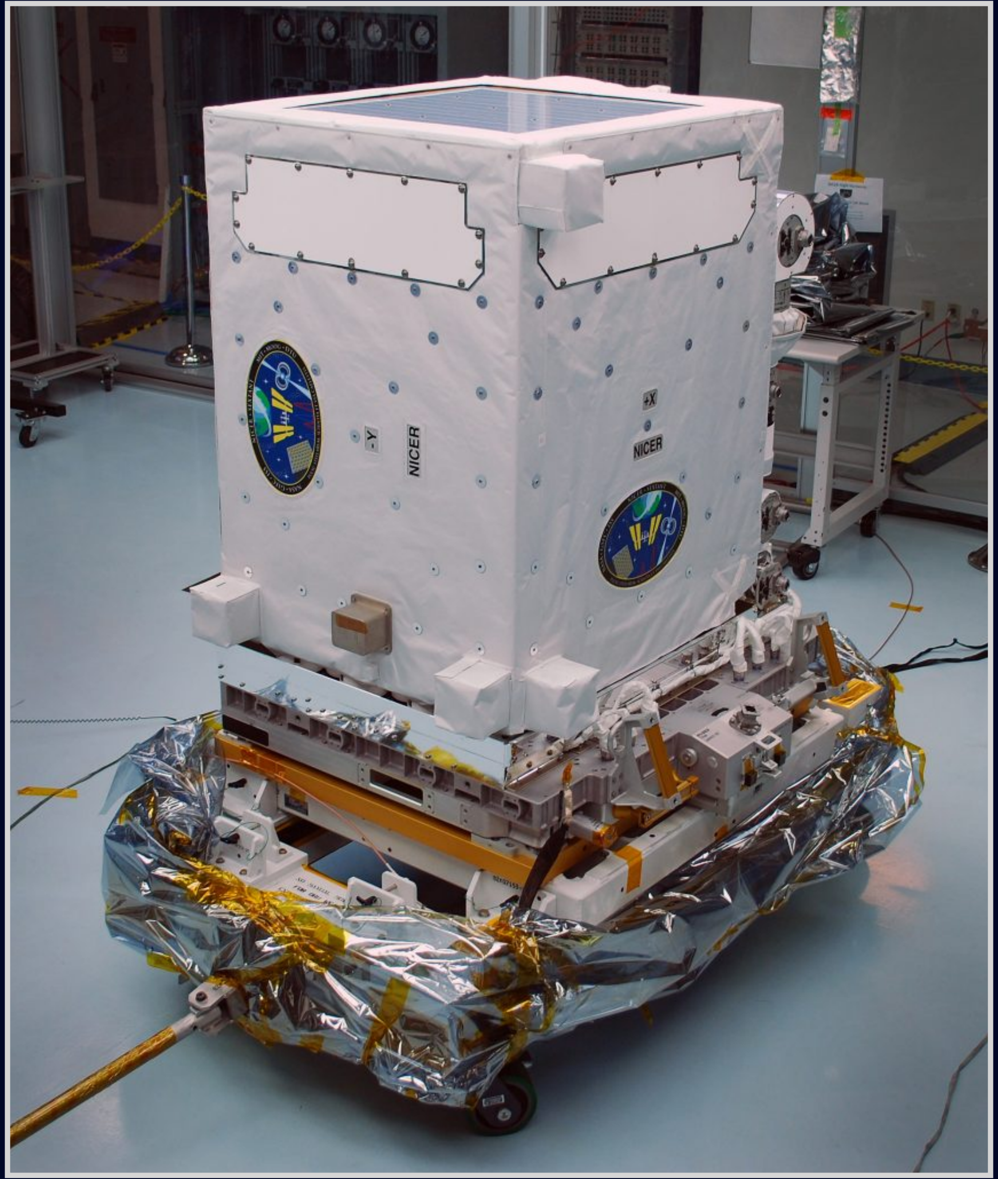
It is **very hard** to test gravity with **isolated** neutron stars.

Equation of state unknown. No effacement principle.

What can we do about this?

The Neutron Star Interior Composition Explorer

The Neutron Star Interior Composition Explorer



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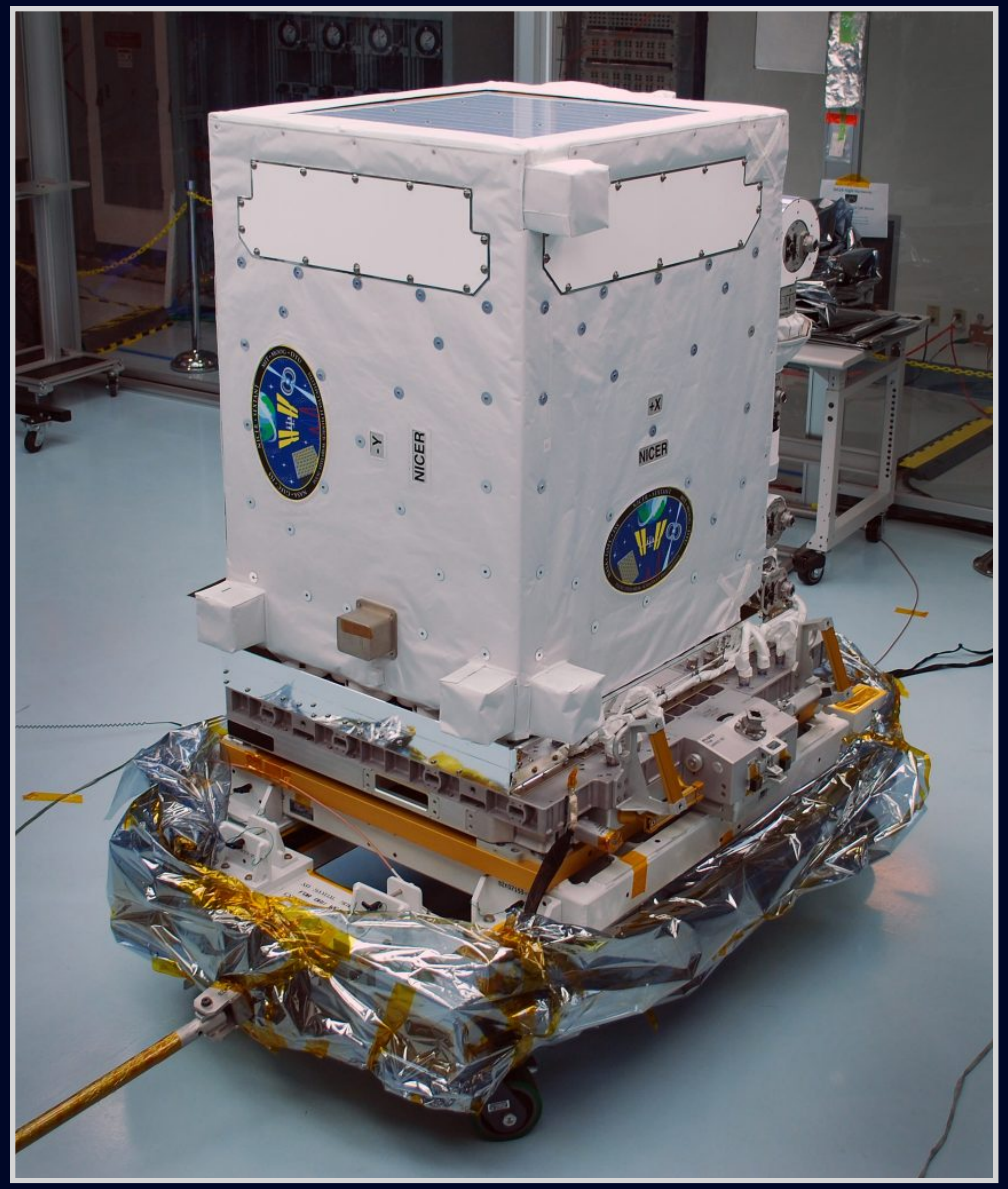

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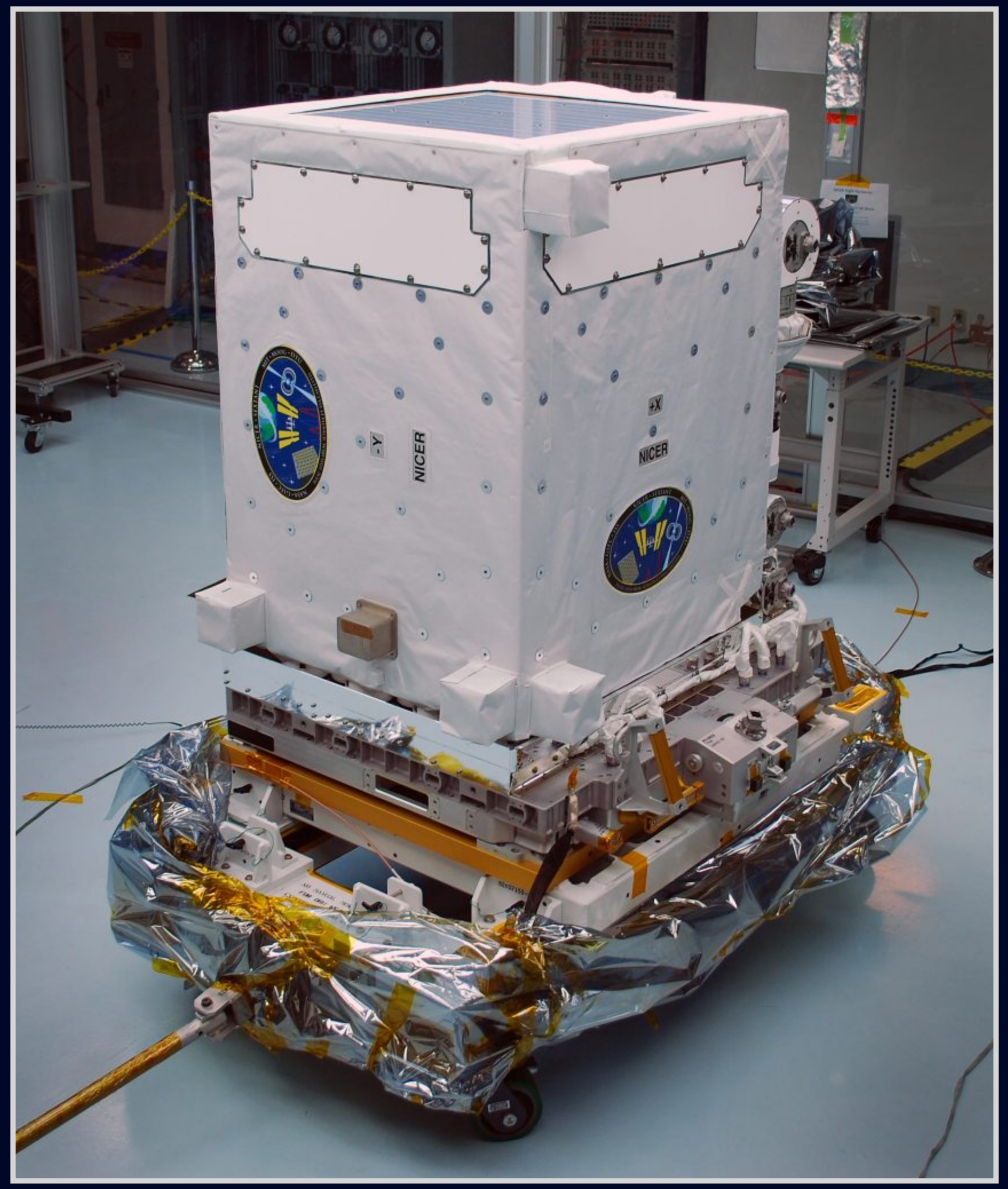

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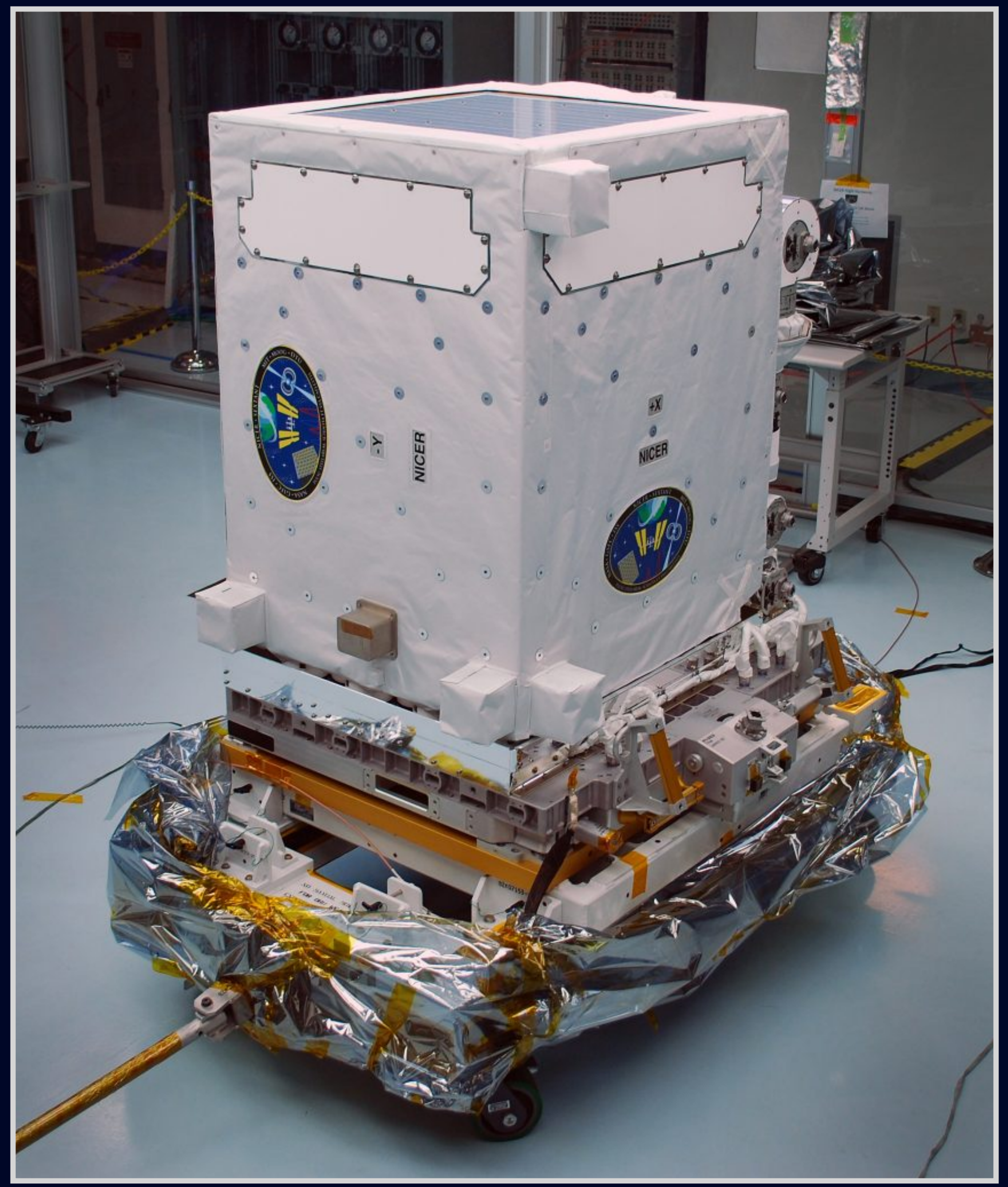
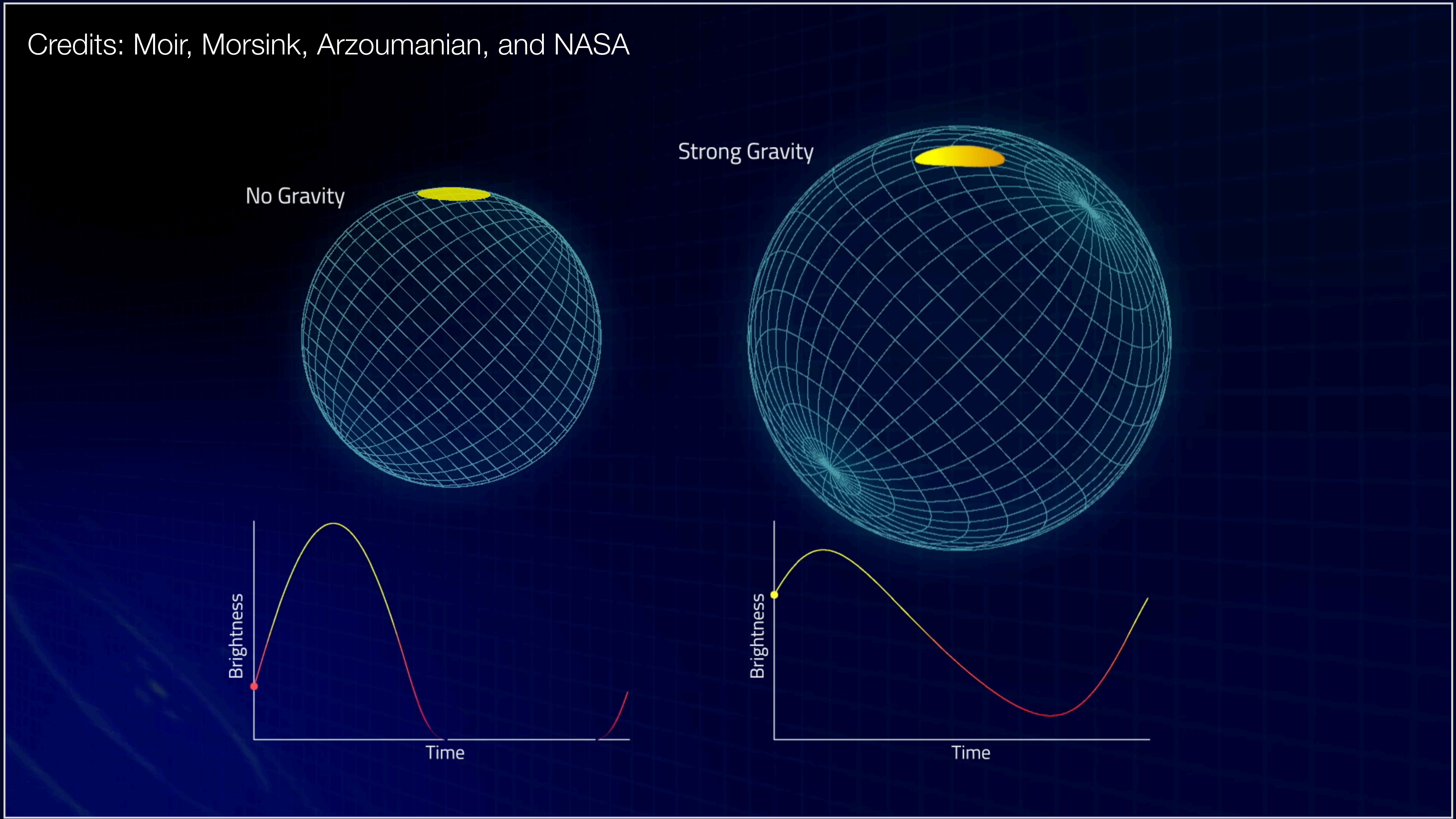
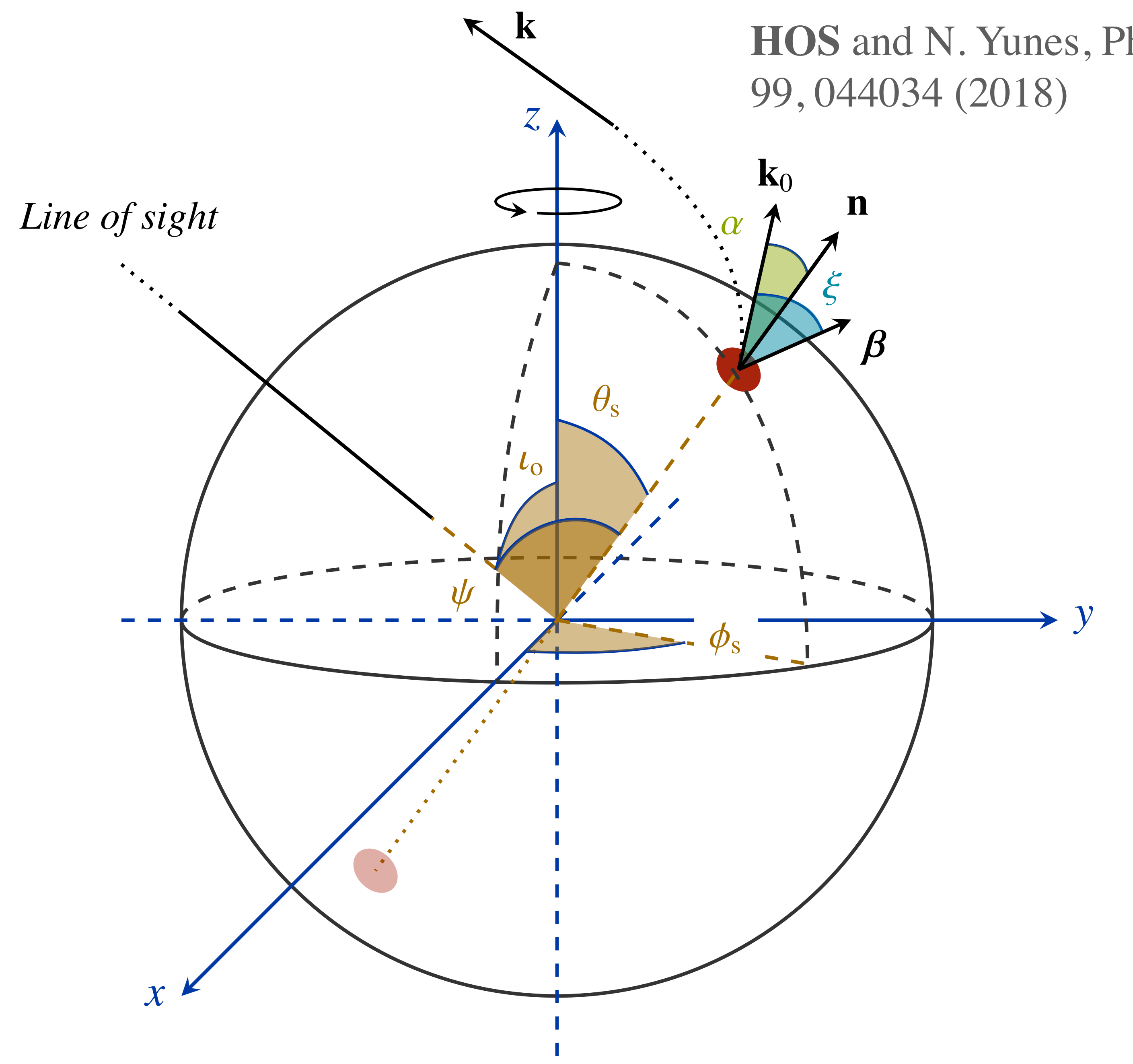


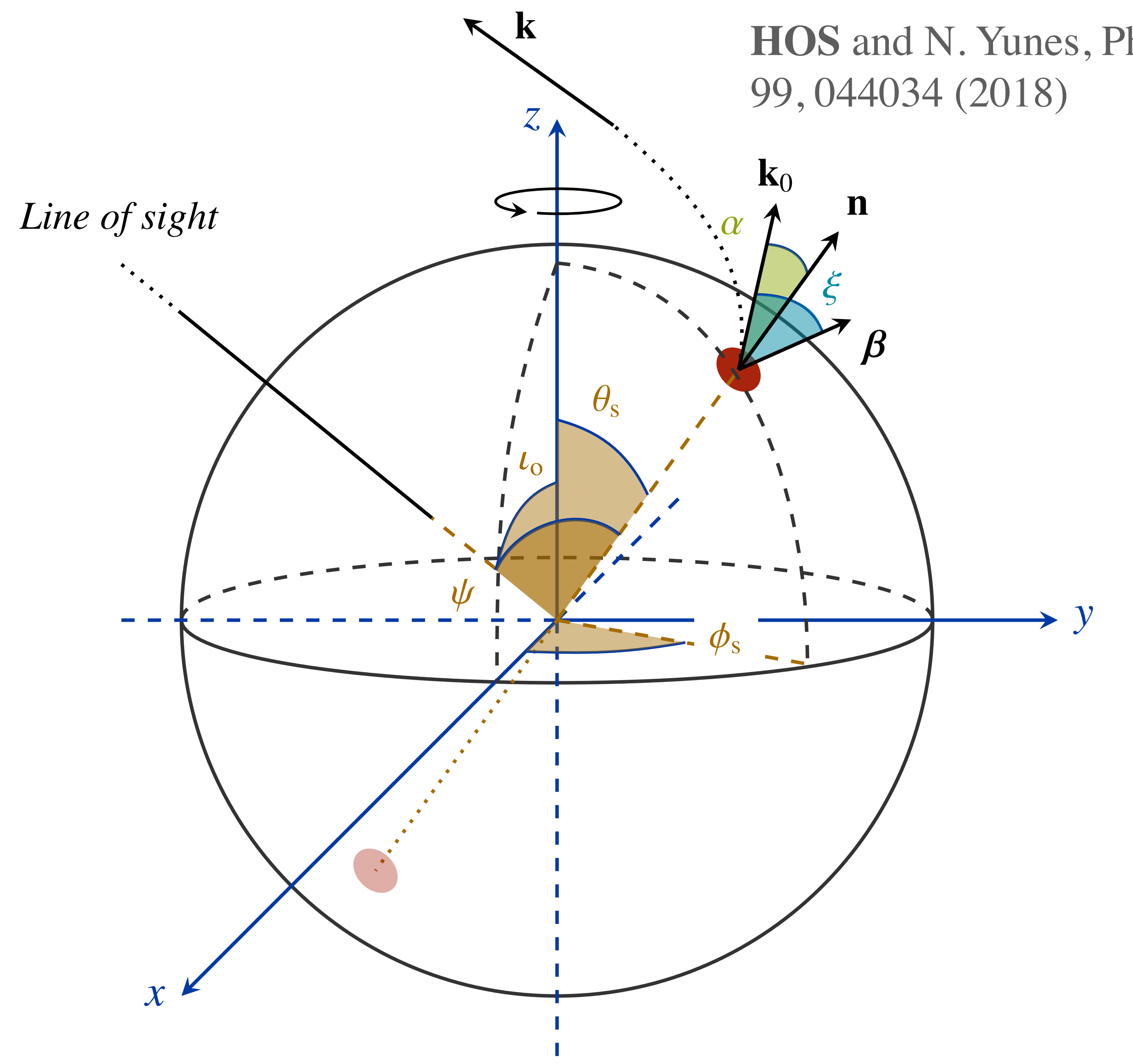


The anatomy of light

The anatomy of light



HOS and N. Yunes, Phys. Rev. D 99, 044034 (2018)



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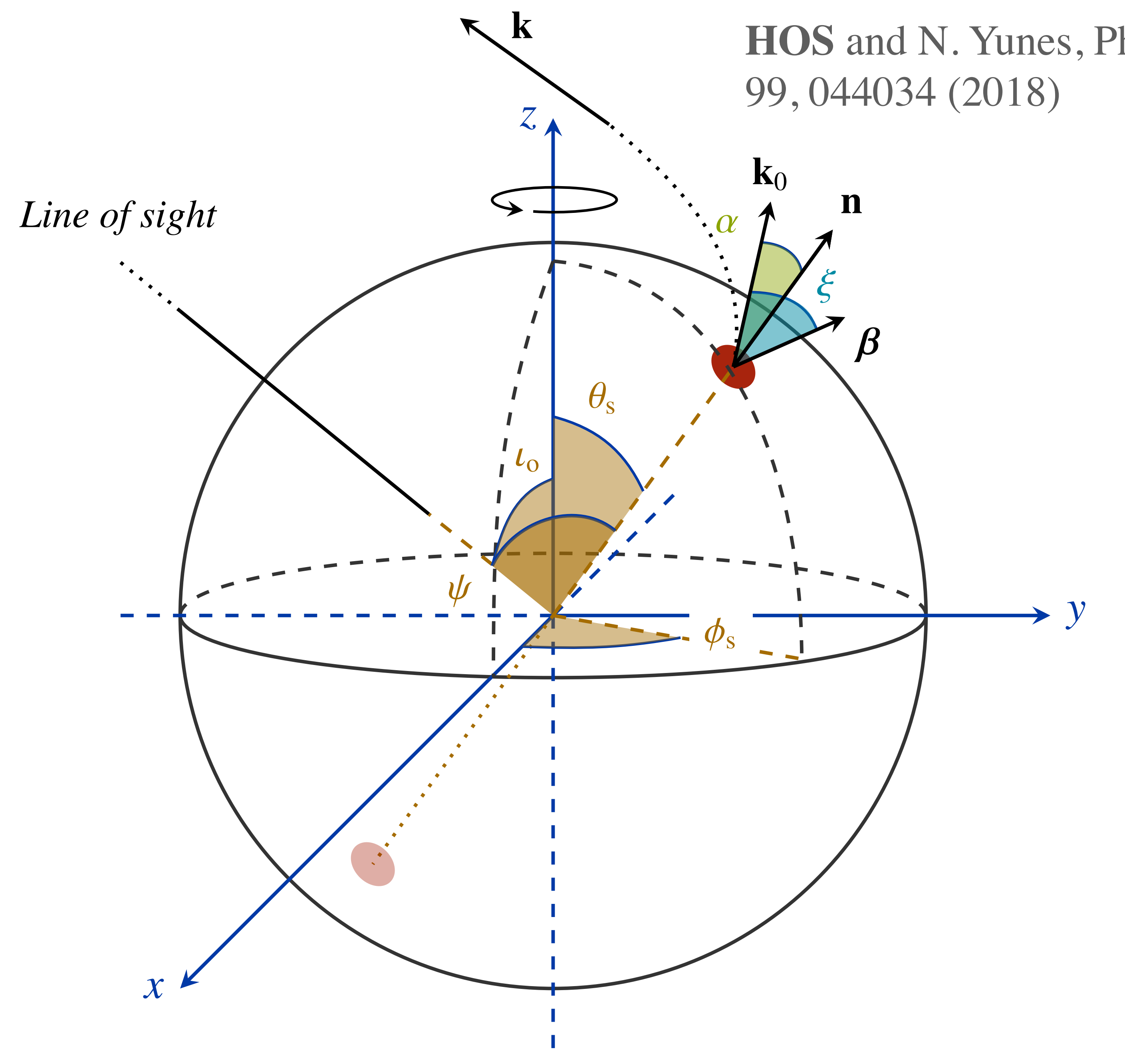
$R_{\mathrm{eq}} = 16\,\mathrm{km}$ $\quad \theta = 50^\circ$

The anatomy of light



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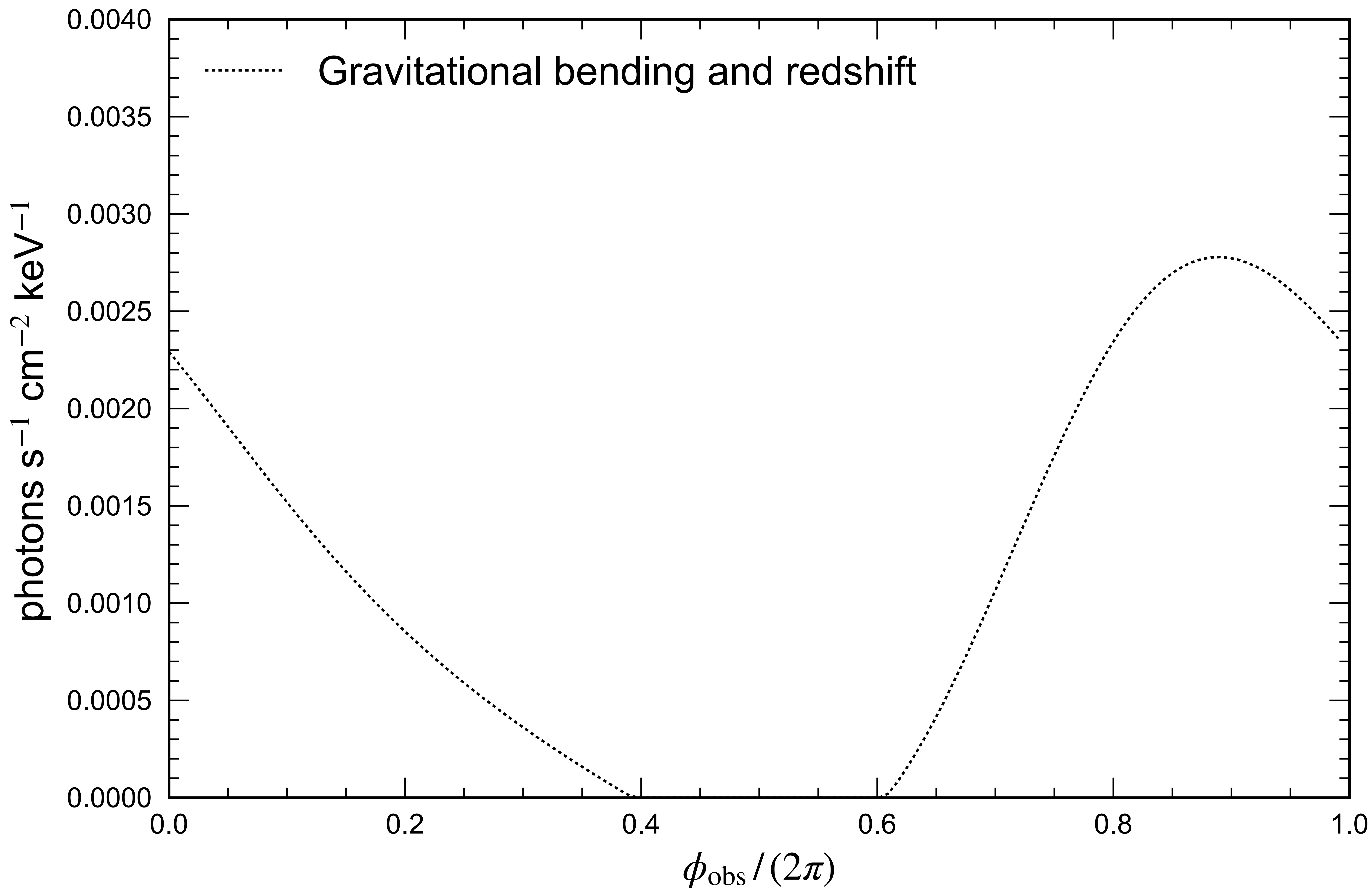

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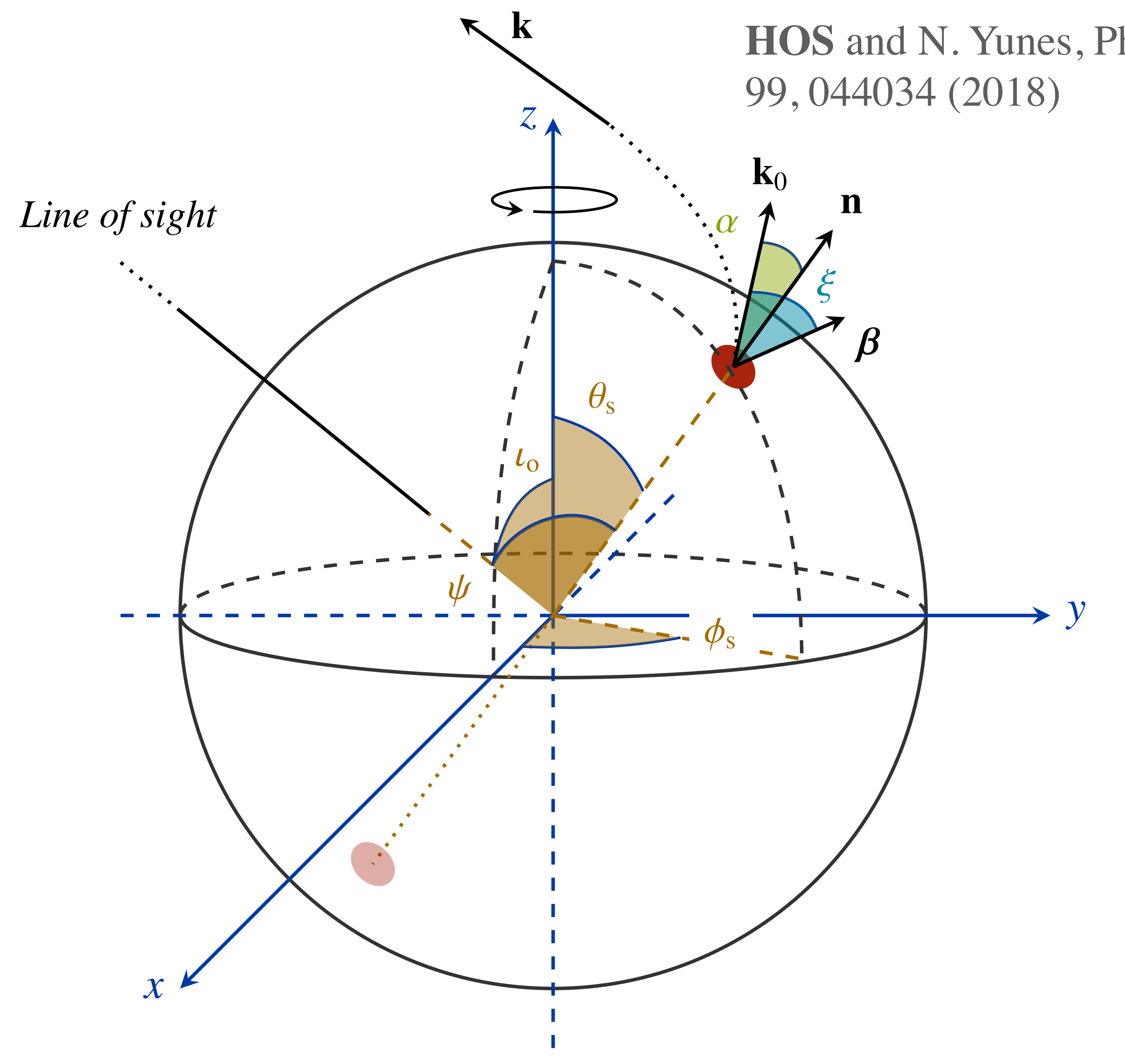

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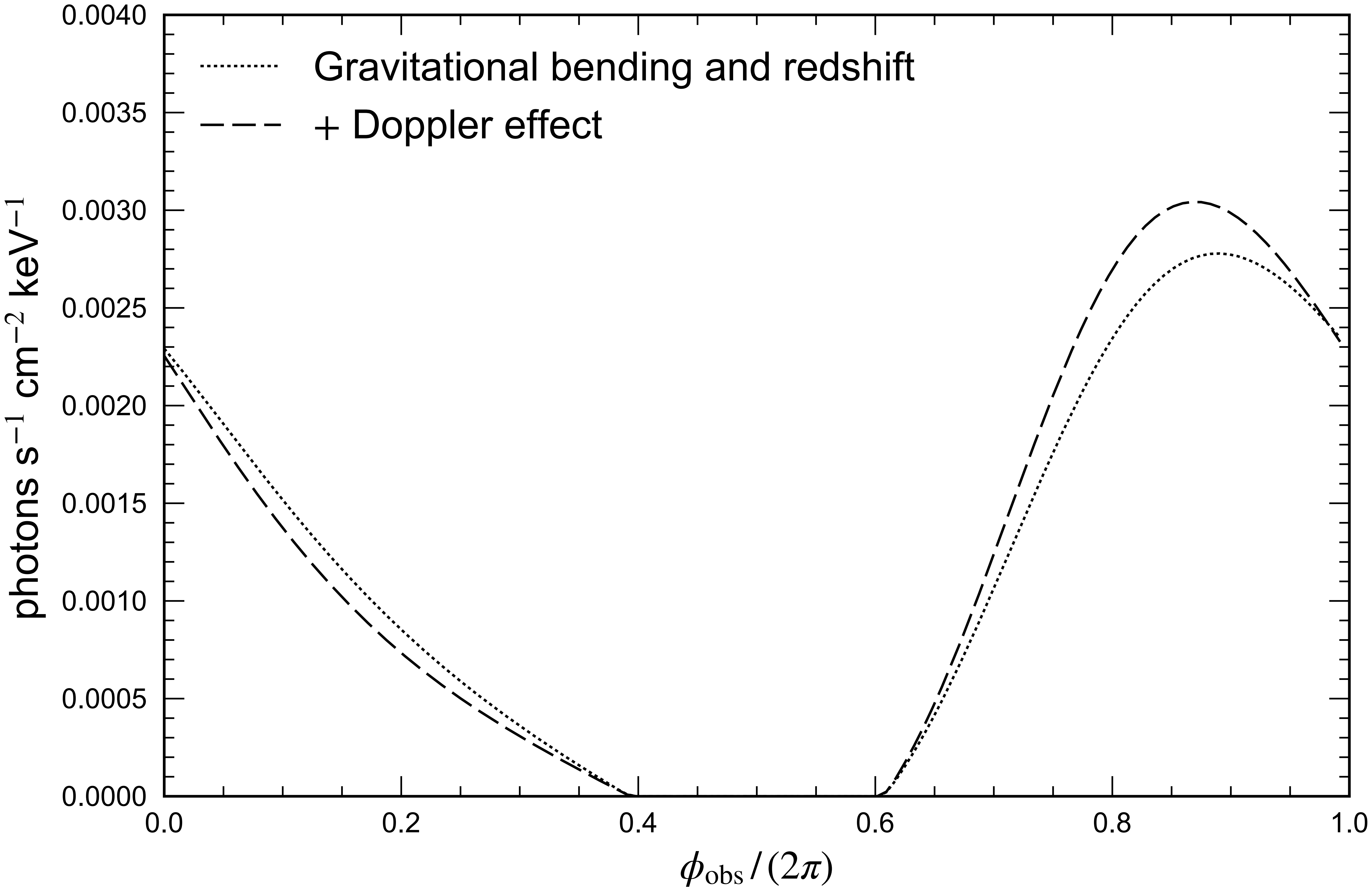

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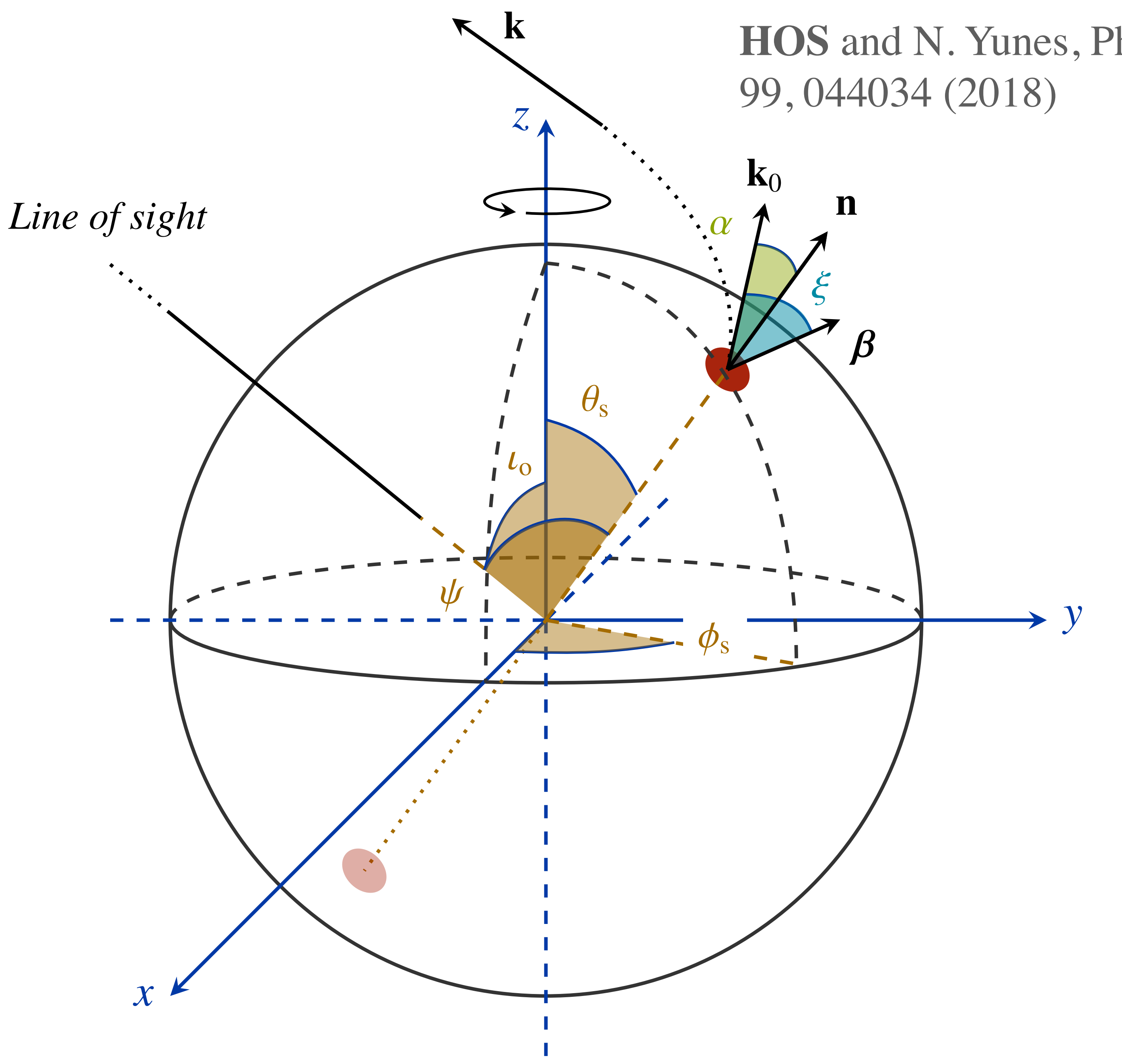

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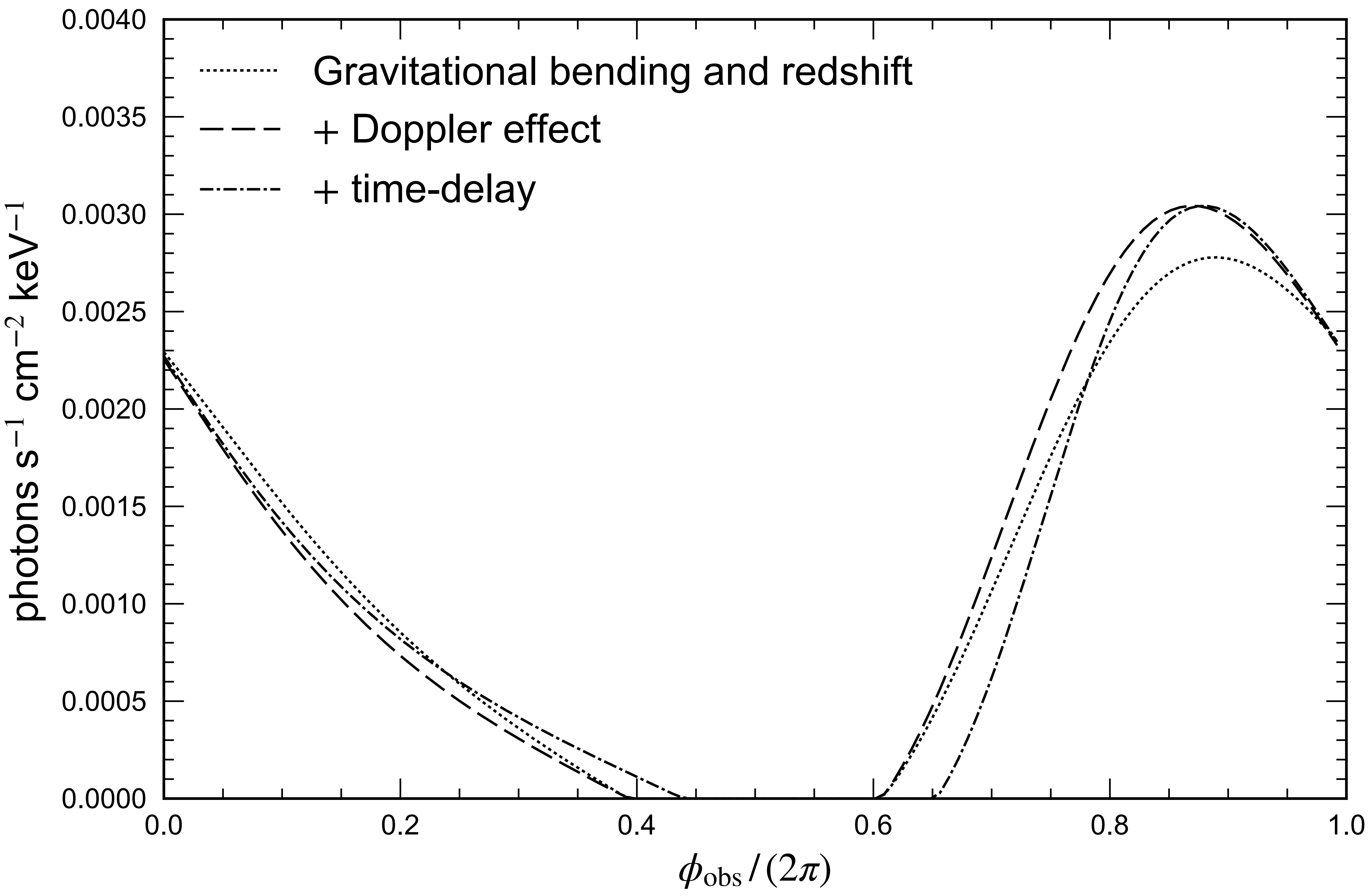

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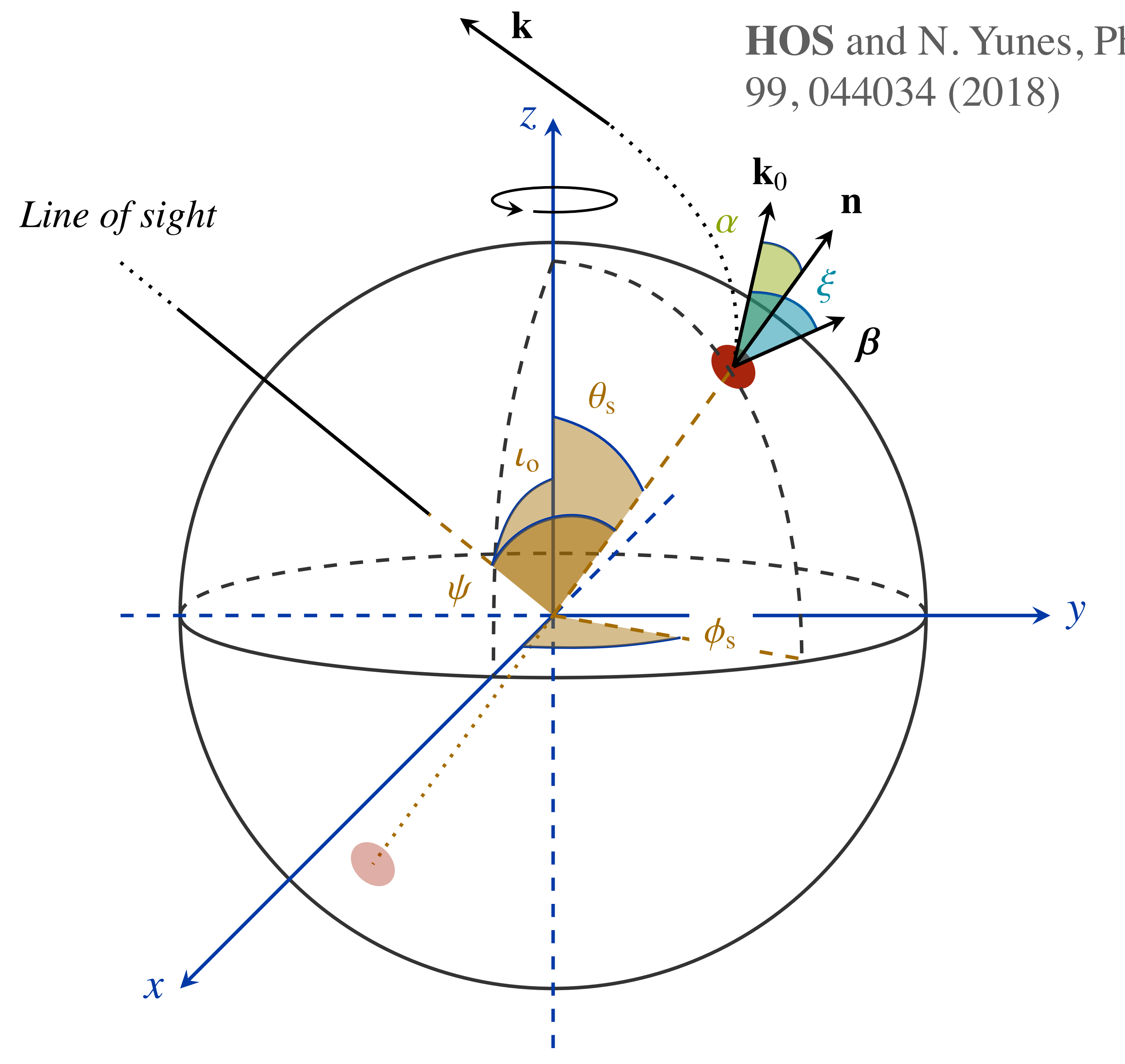

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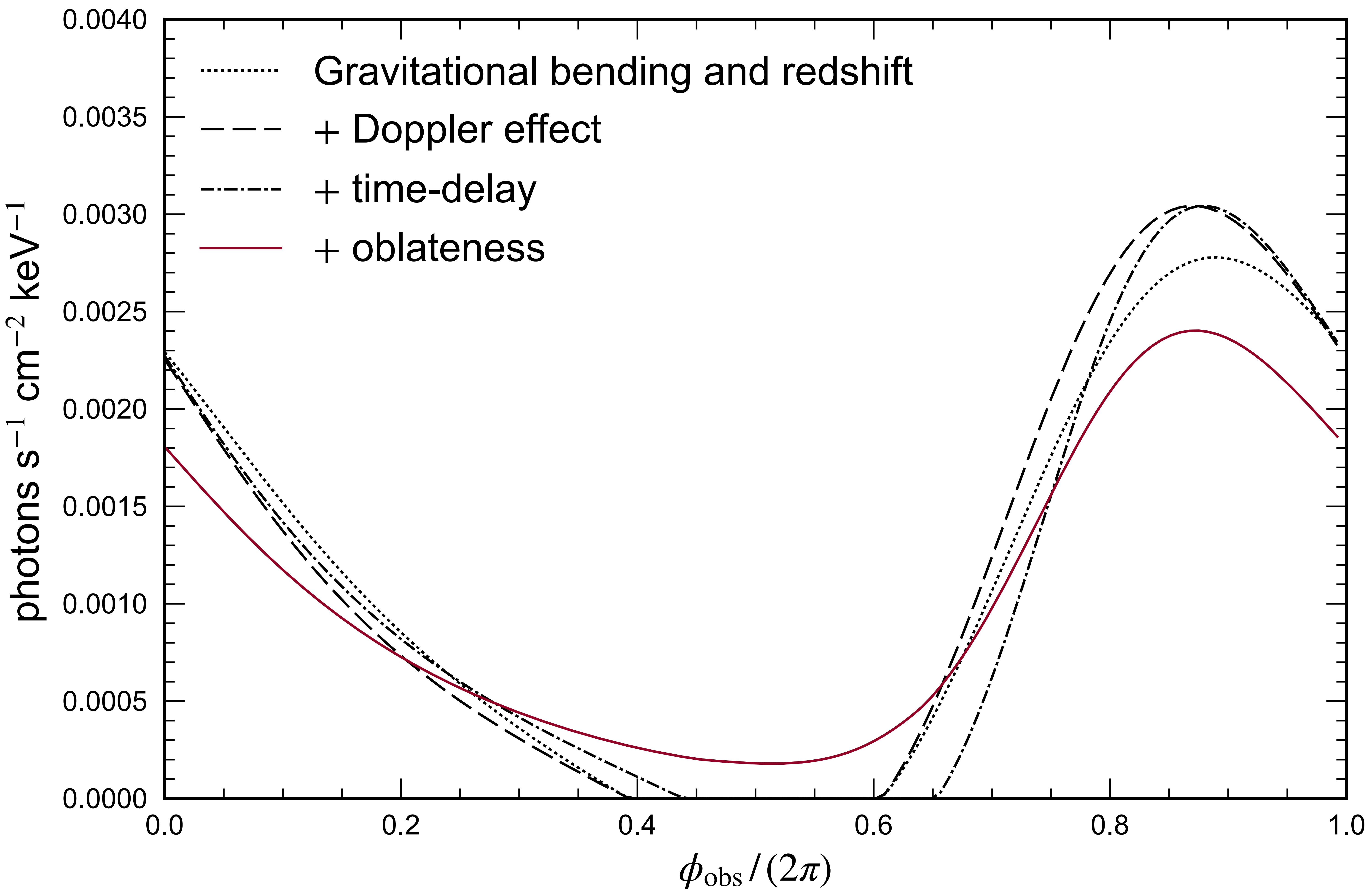

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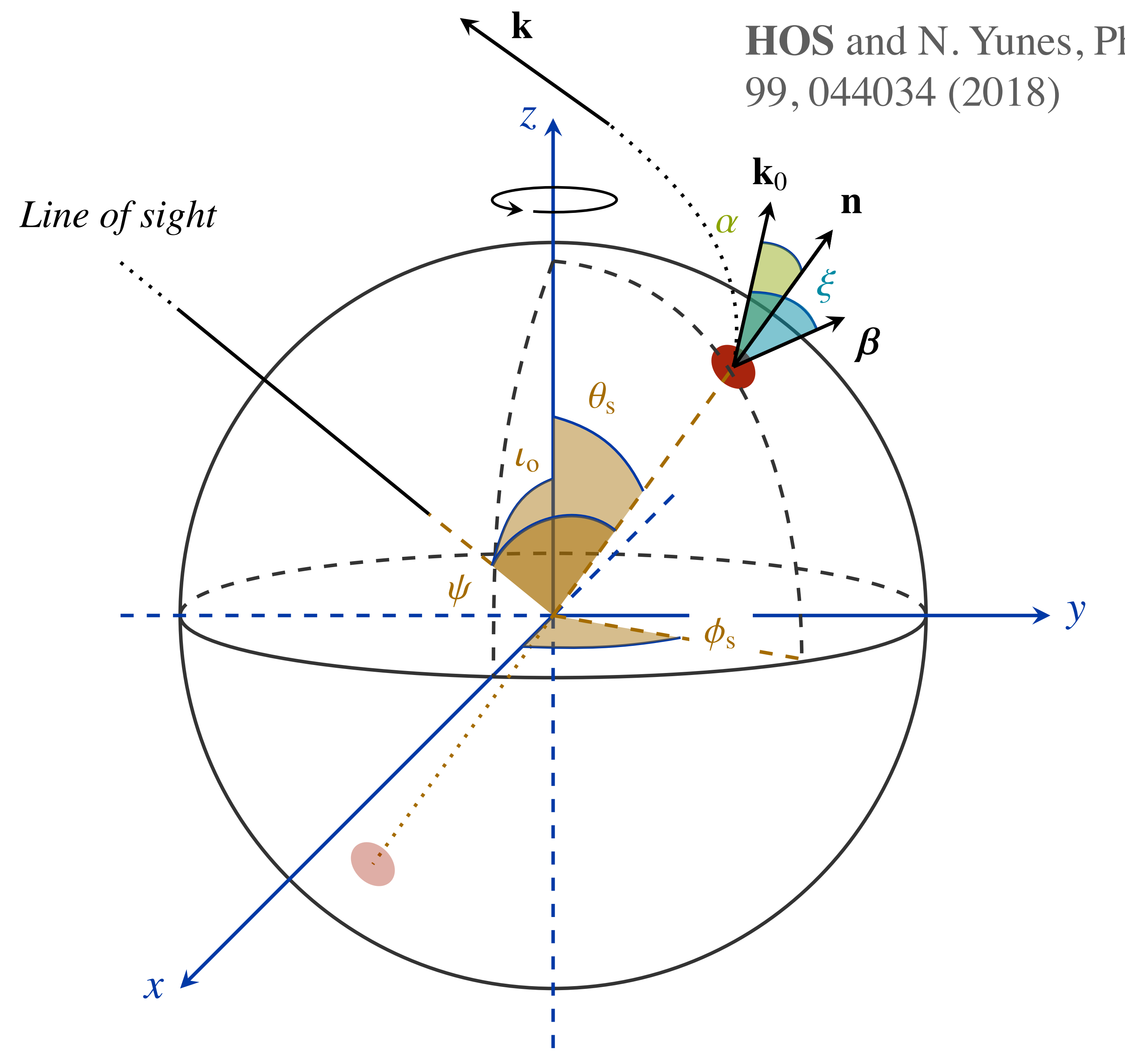

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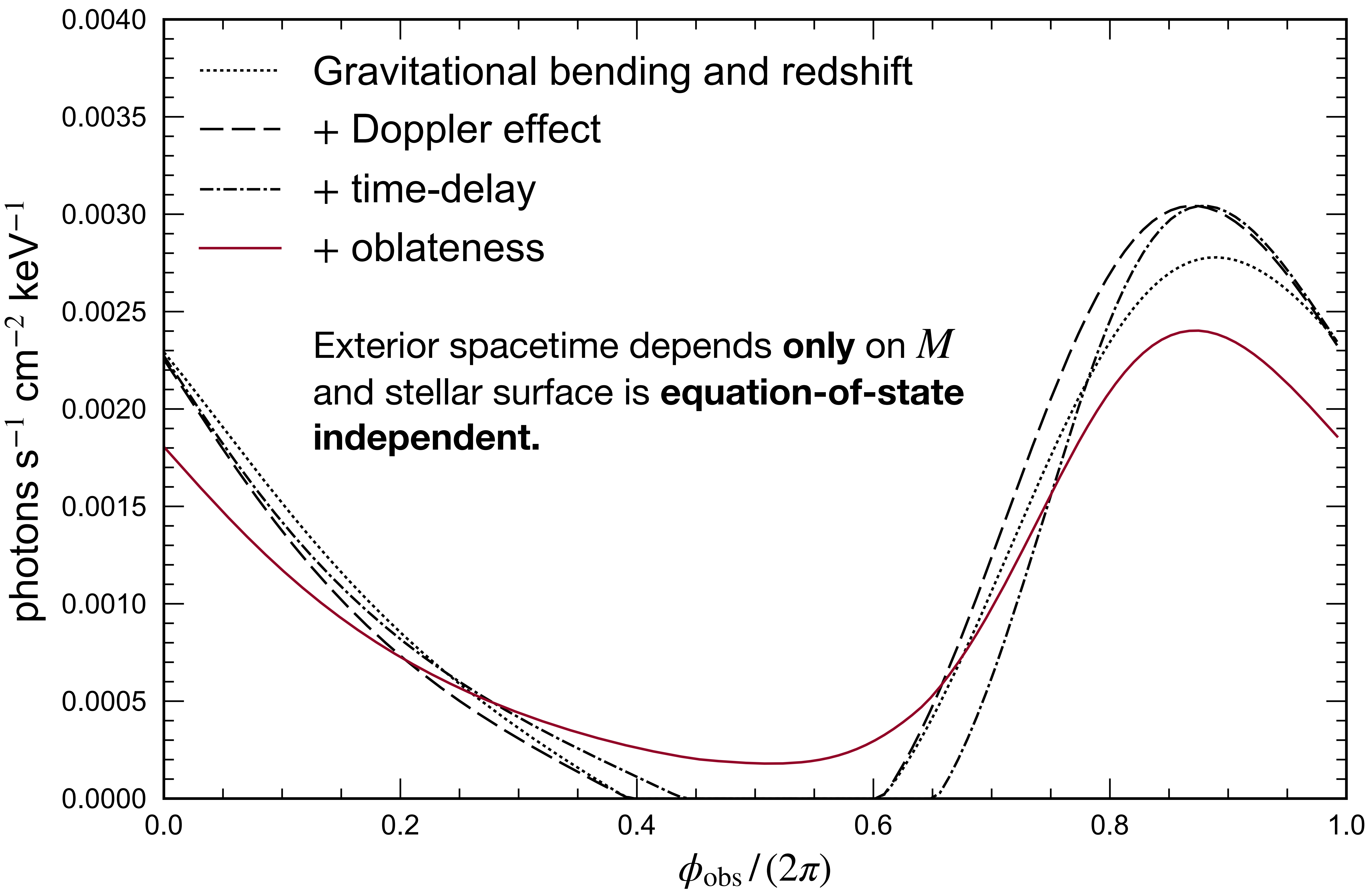

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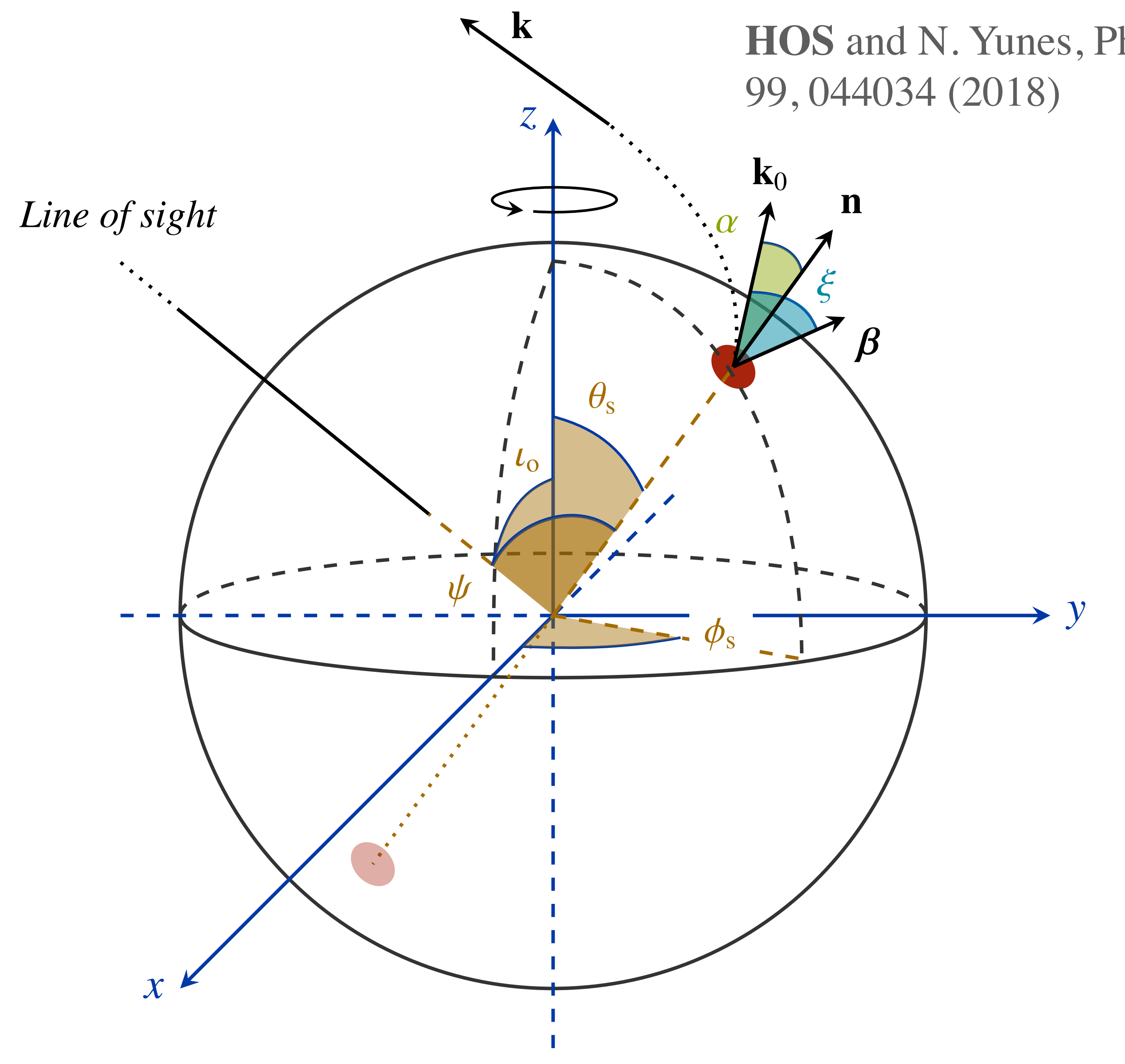

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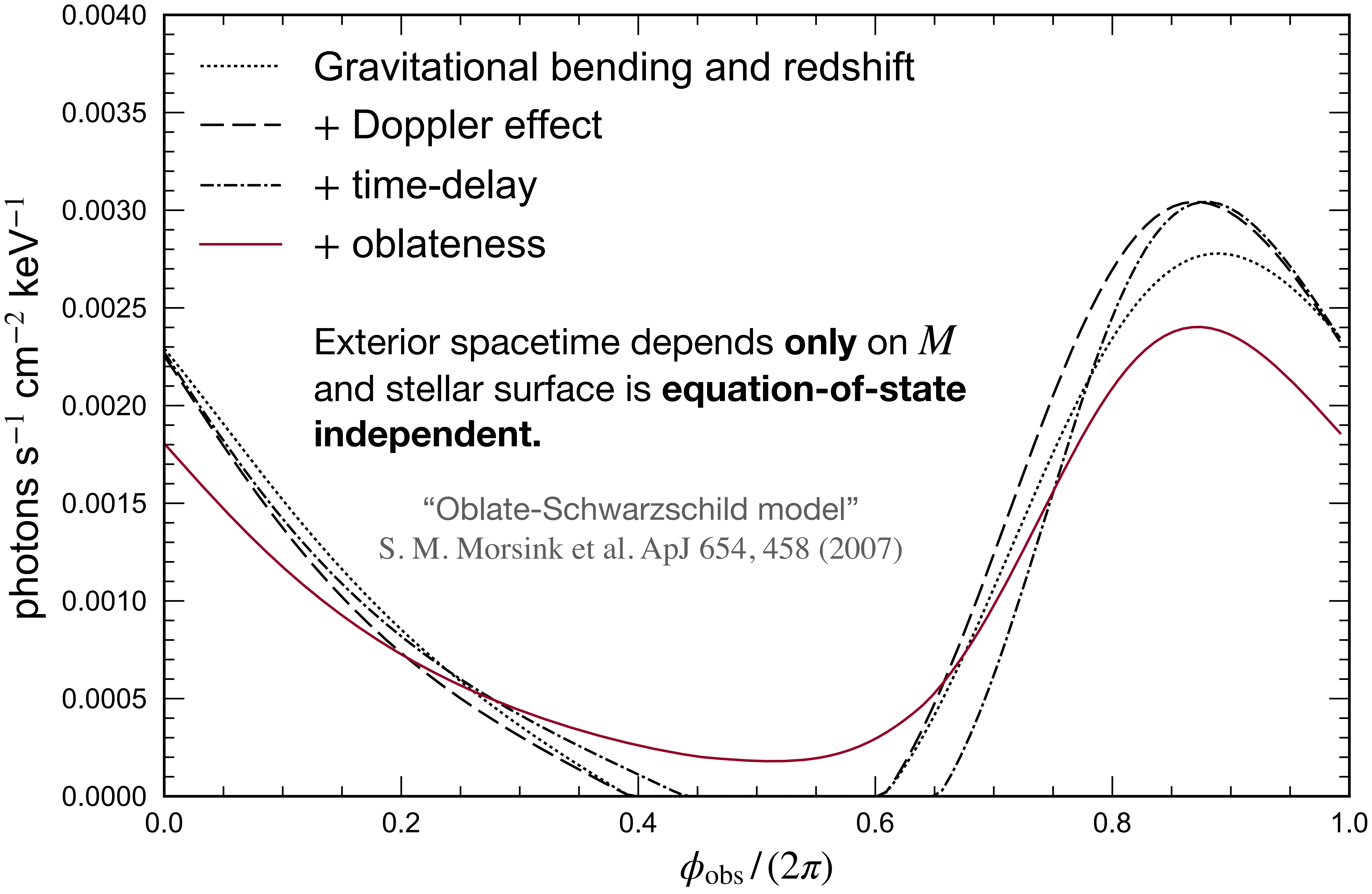

Exterior spacetime depends **only** on M and stellar surface is **equation-of-state independent.**

"Oblate-Schwarzschild model"
S. M. Morsink et al. ApJ 654, 458 (2007)

The case of PSR J0030+0451

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THE ASTROPHYSICAL JOURNAL LETTERS

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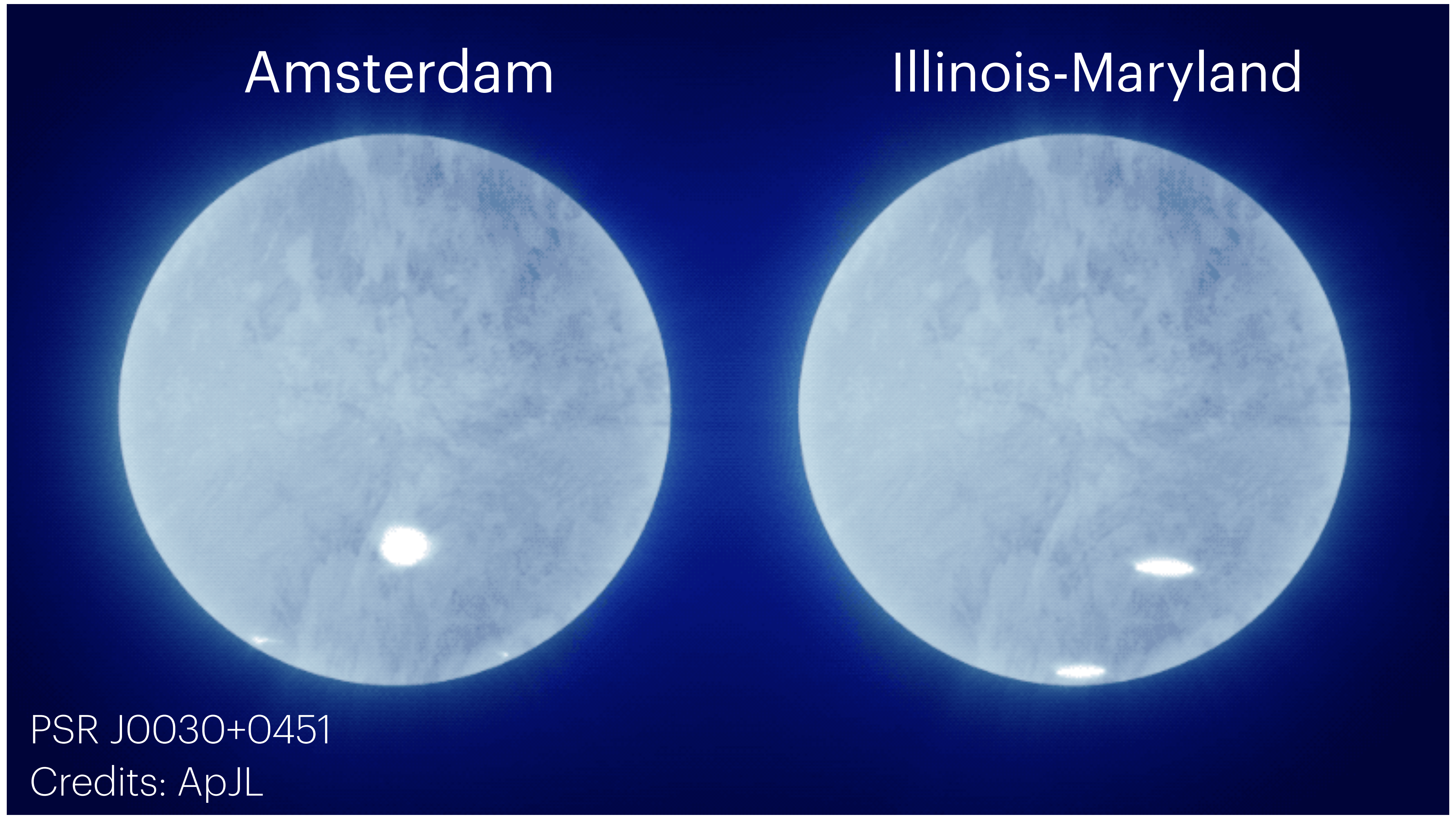

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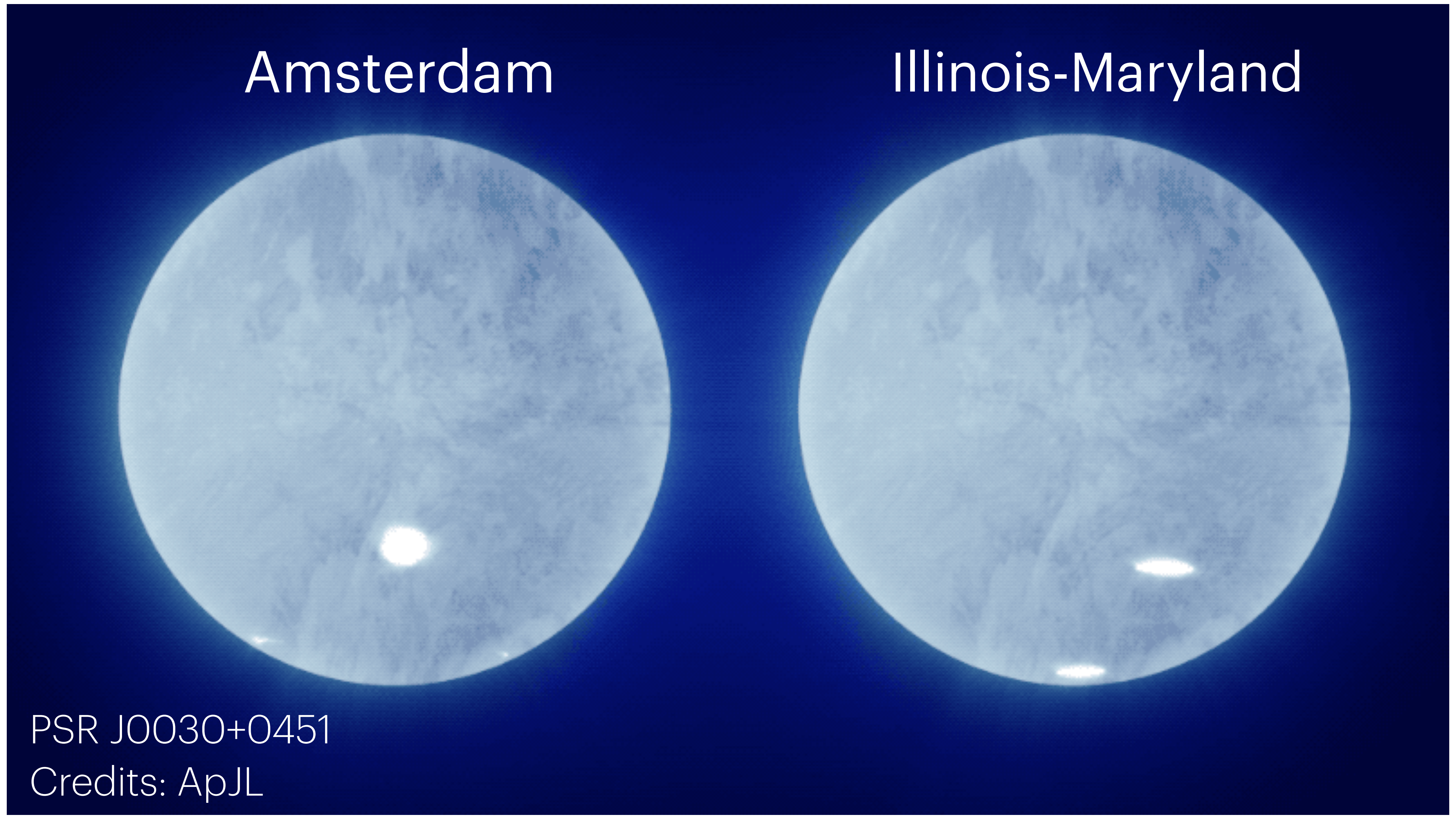

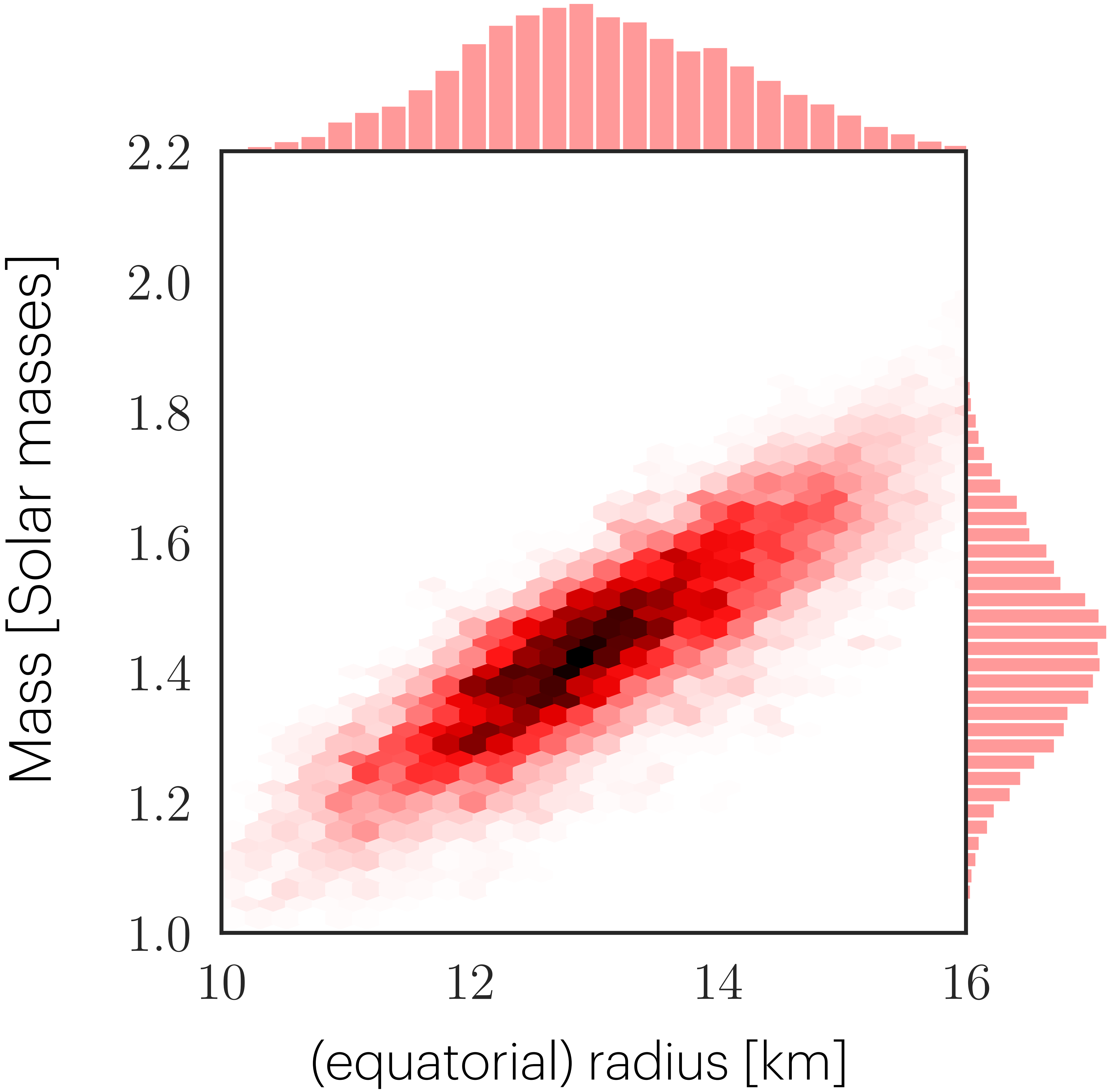

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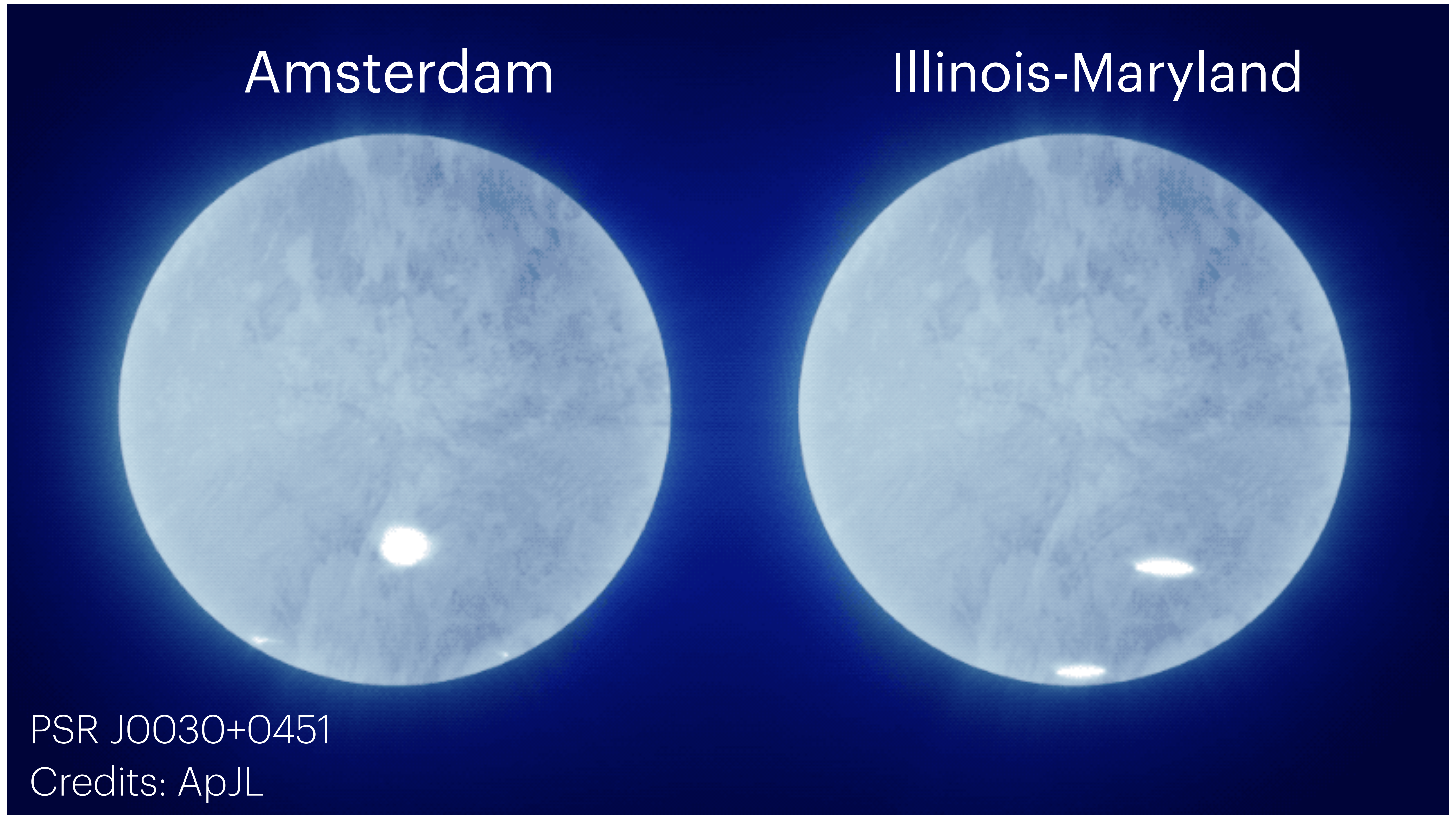

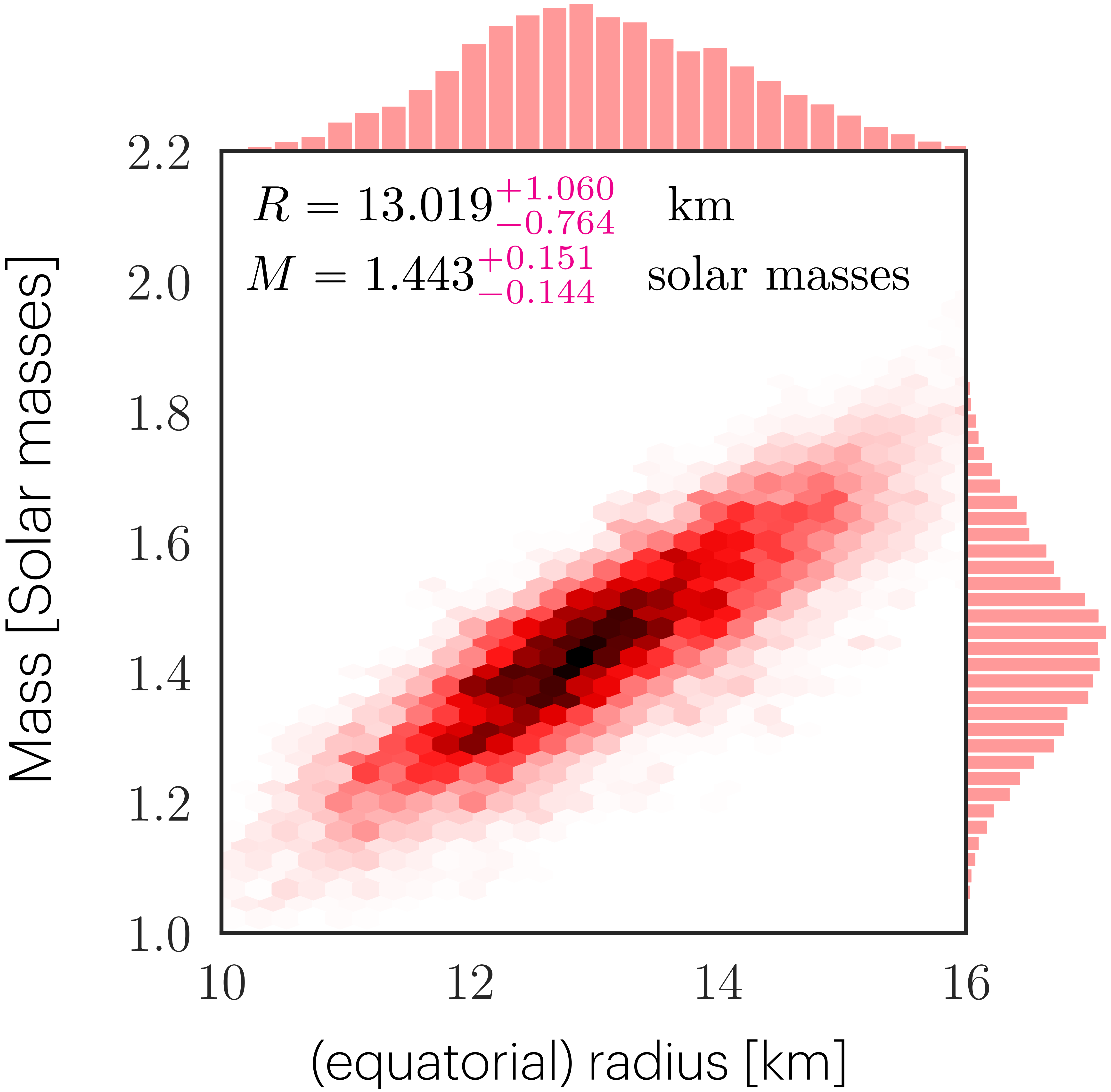

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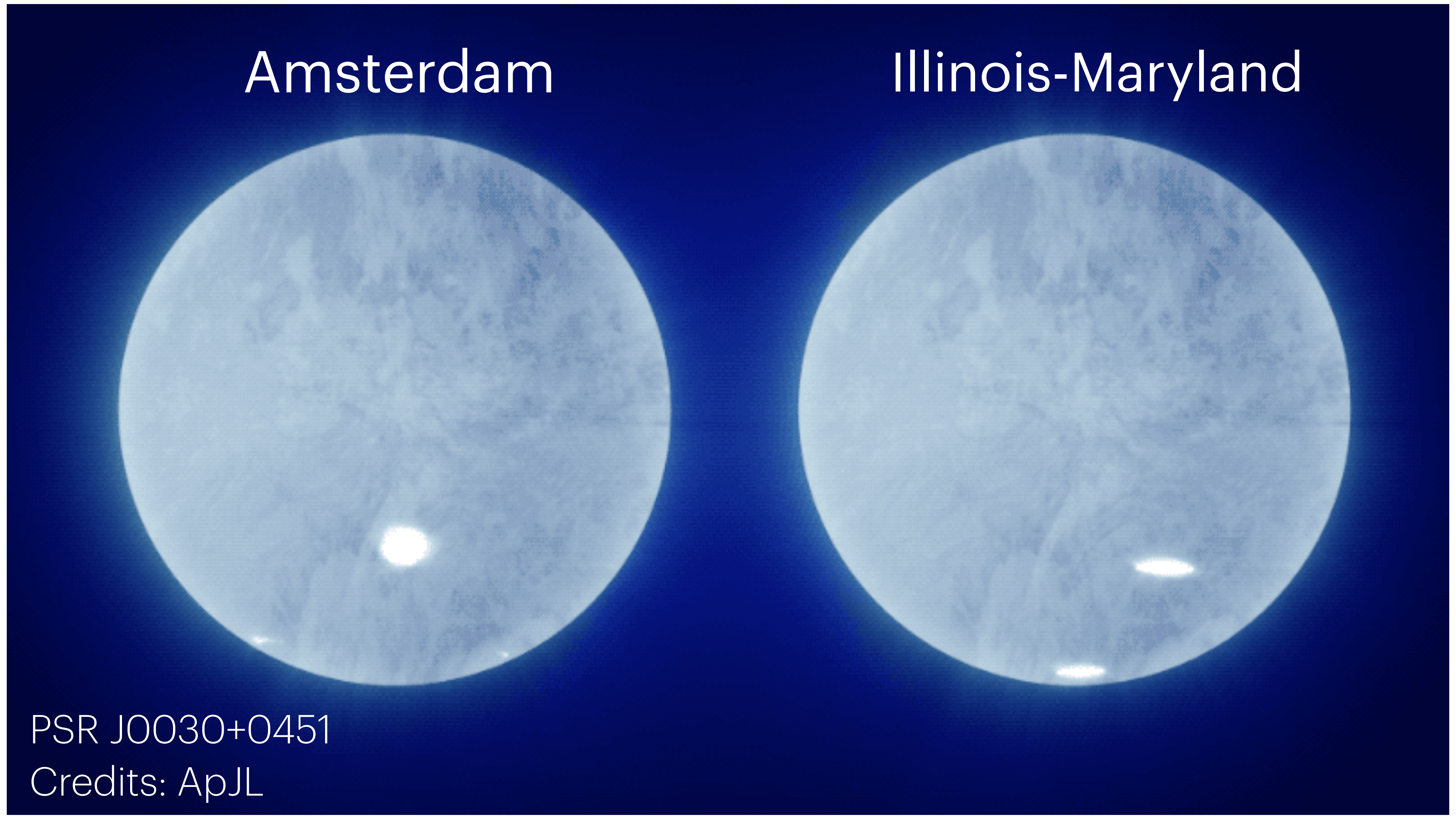
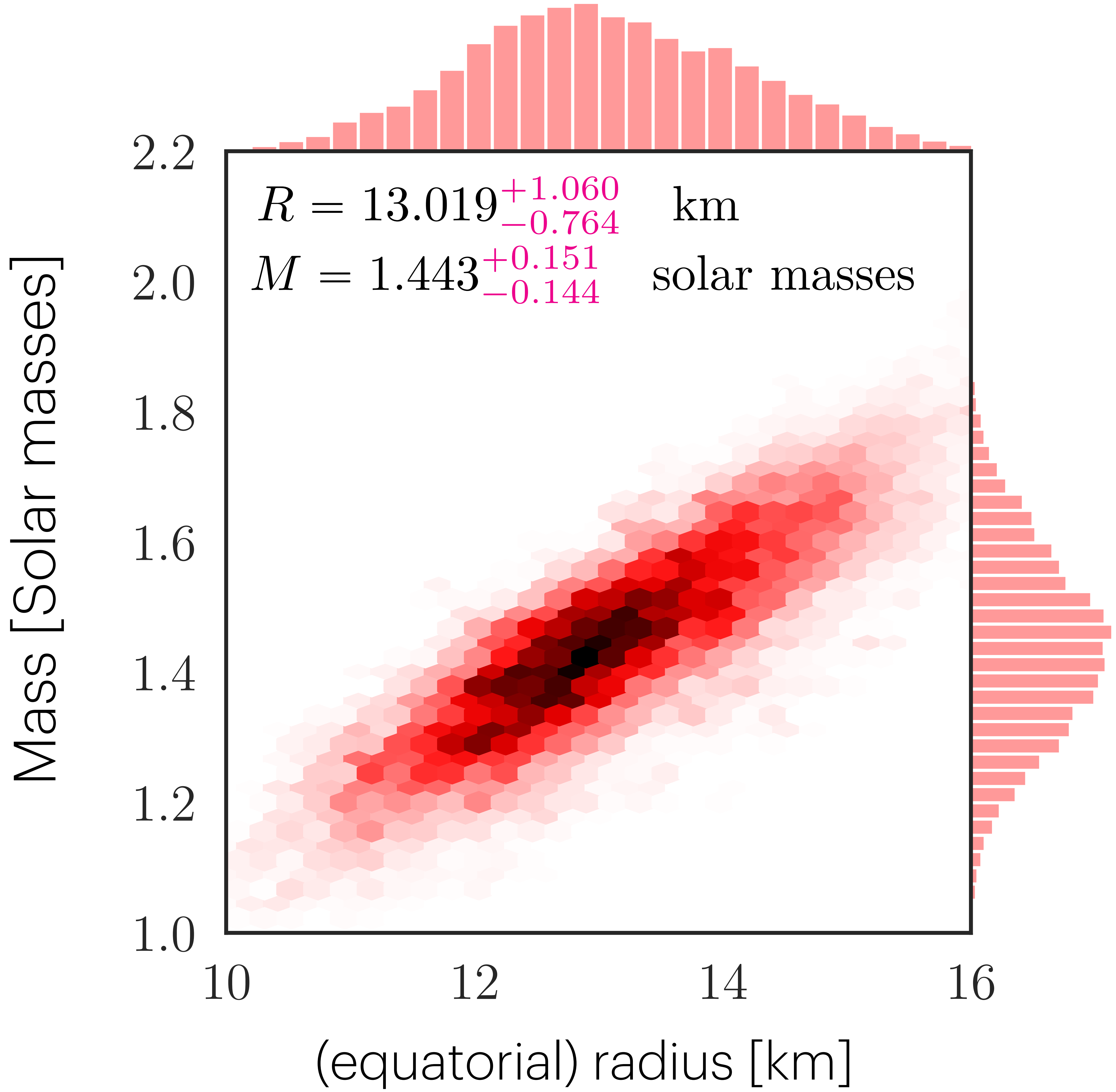


Imaging the surface of a 13-km-radius sphere, spinning at ~ 200 Hz, 325 pc away from us!

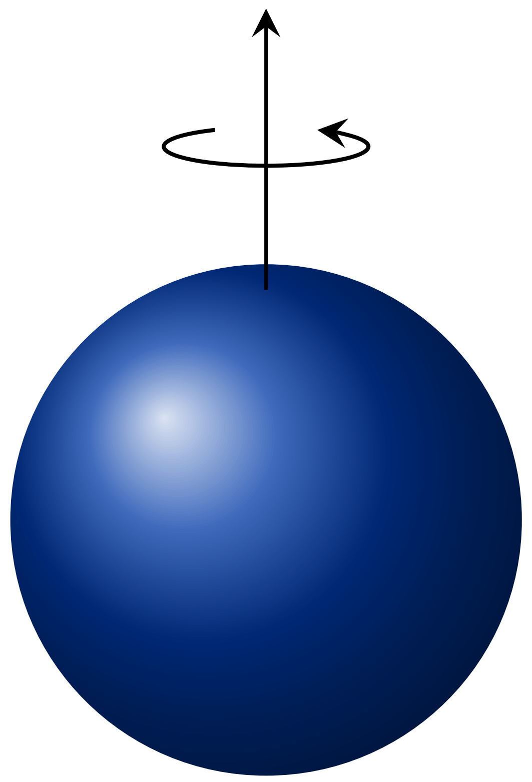


Thanks to relativistic effects we can infer simultaneously, to 10% precision, at 1σ level, the mass and radius of an **isolated** pulsar.

Can we do something more?

Going beyond mass and radius

Going beyond mass and radius



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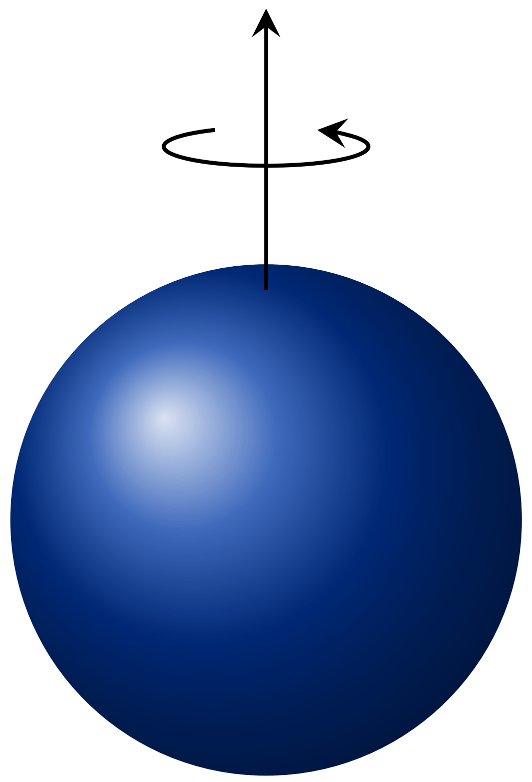
Going beyond mass and radius



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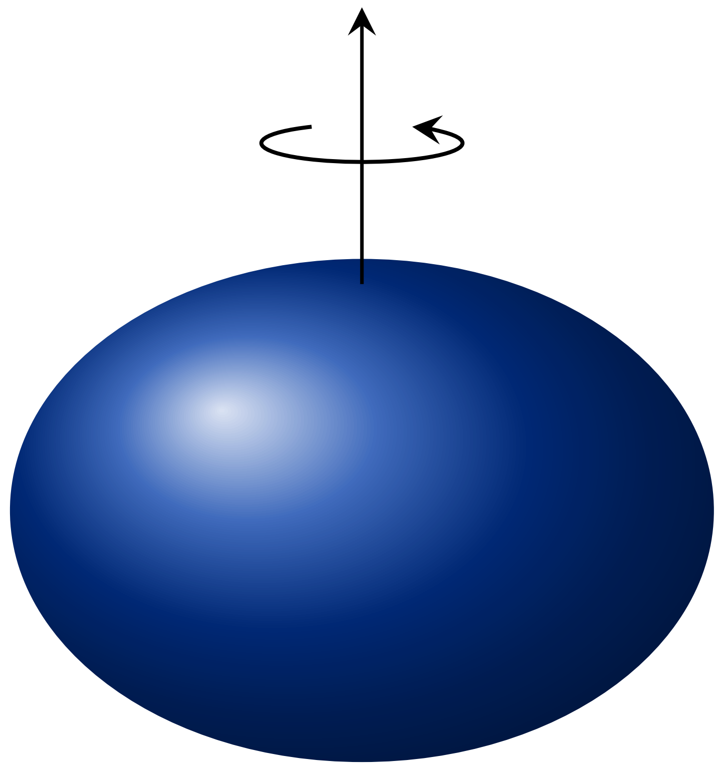
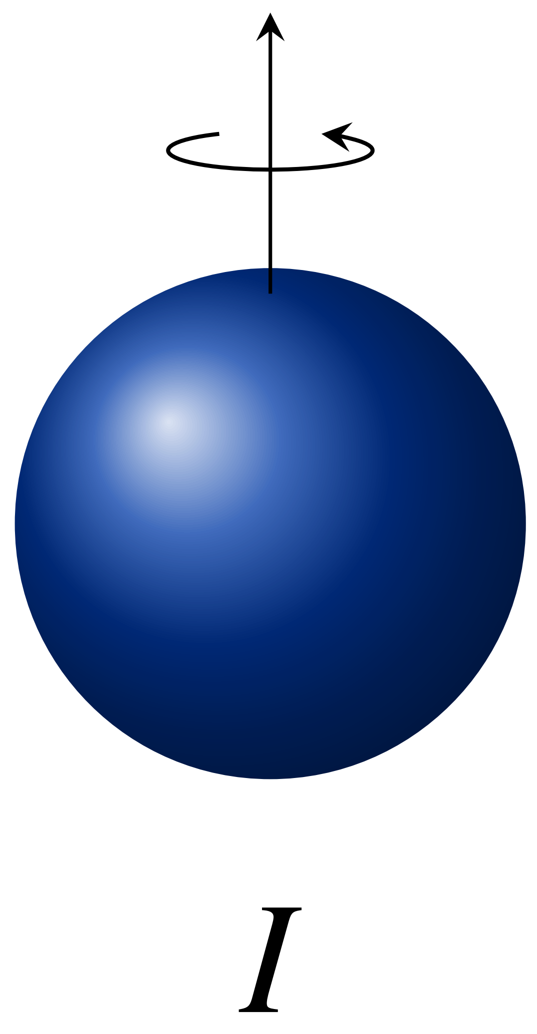
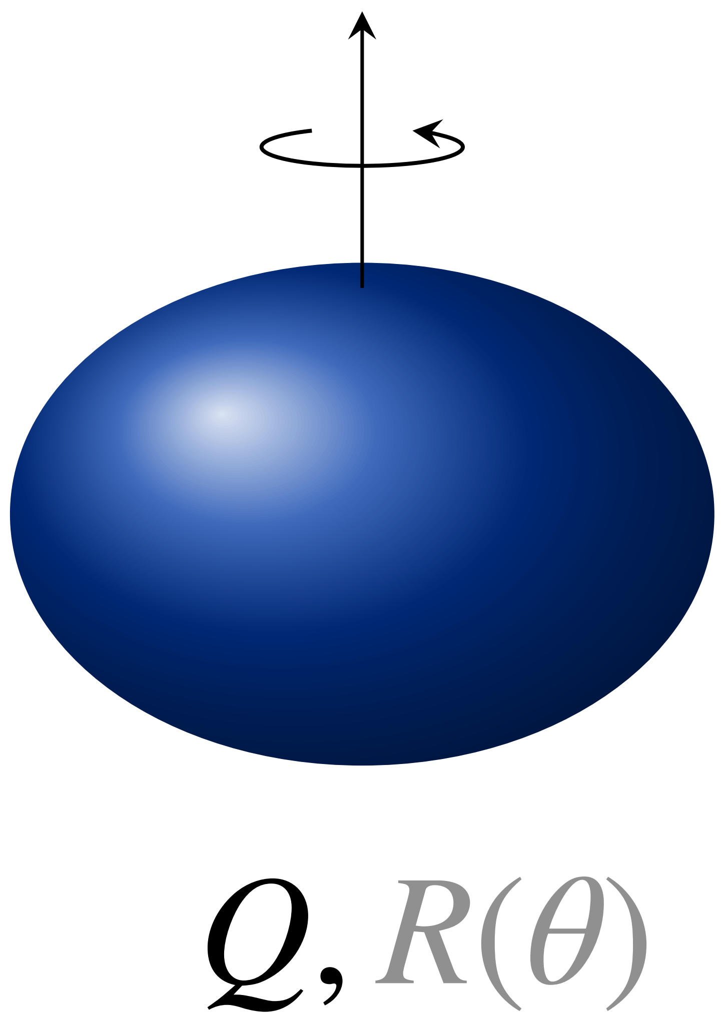
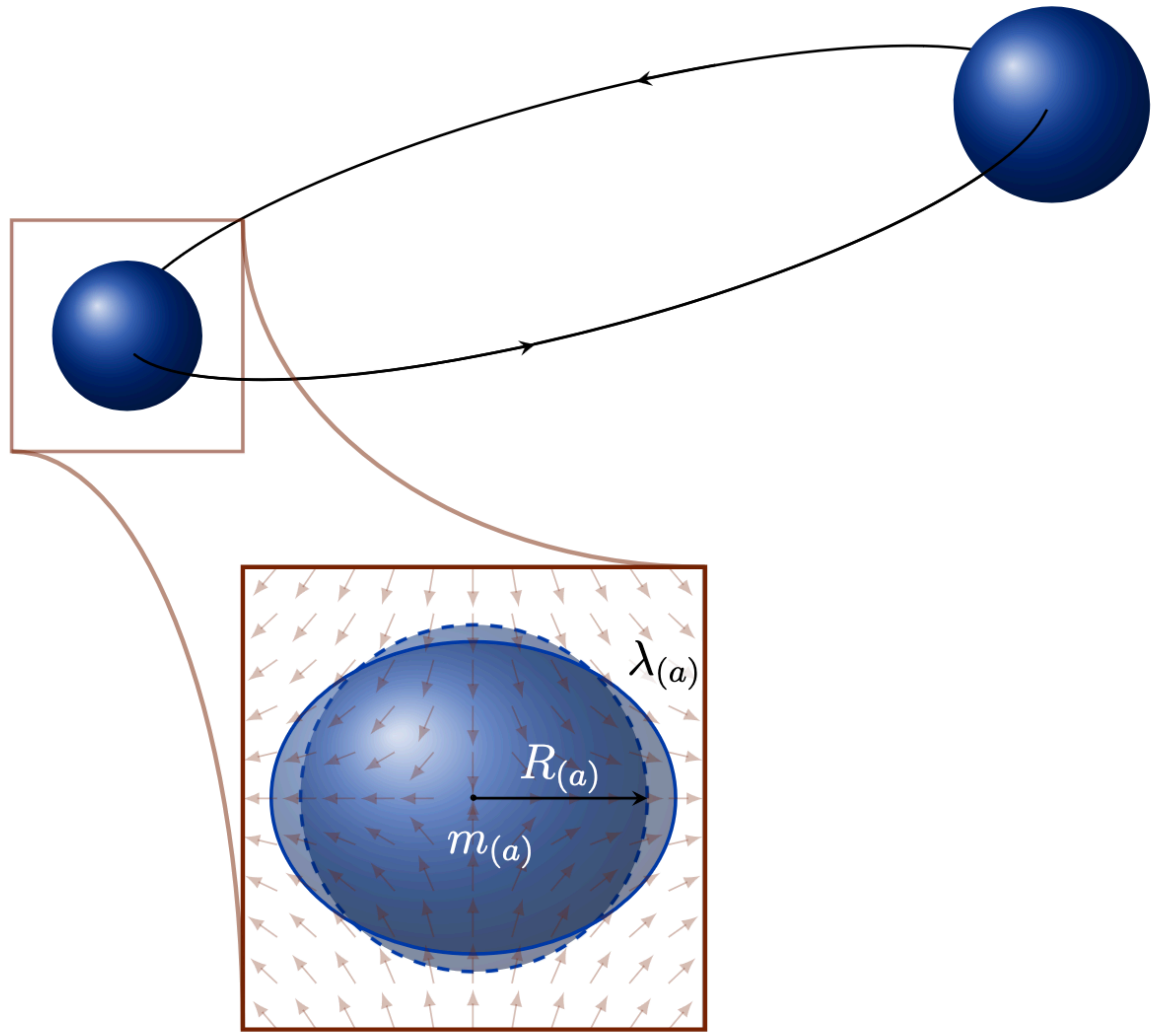


$Q, R(\theta)$

Going beyond mass and radius







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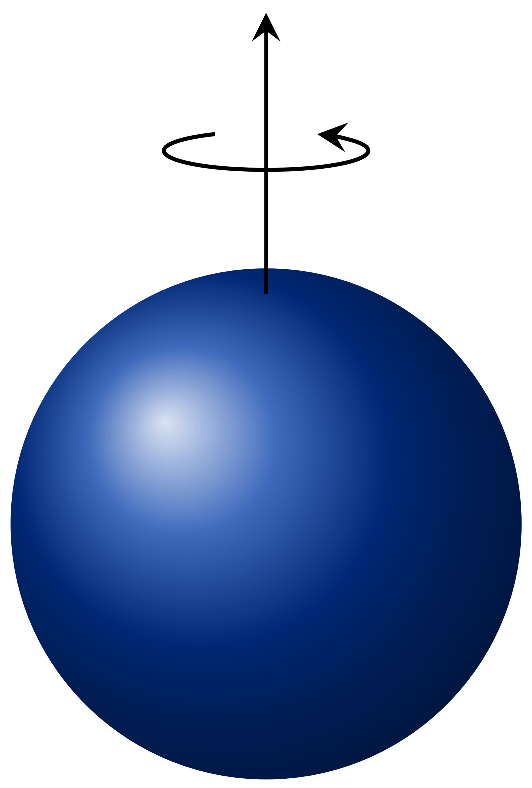

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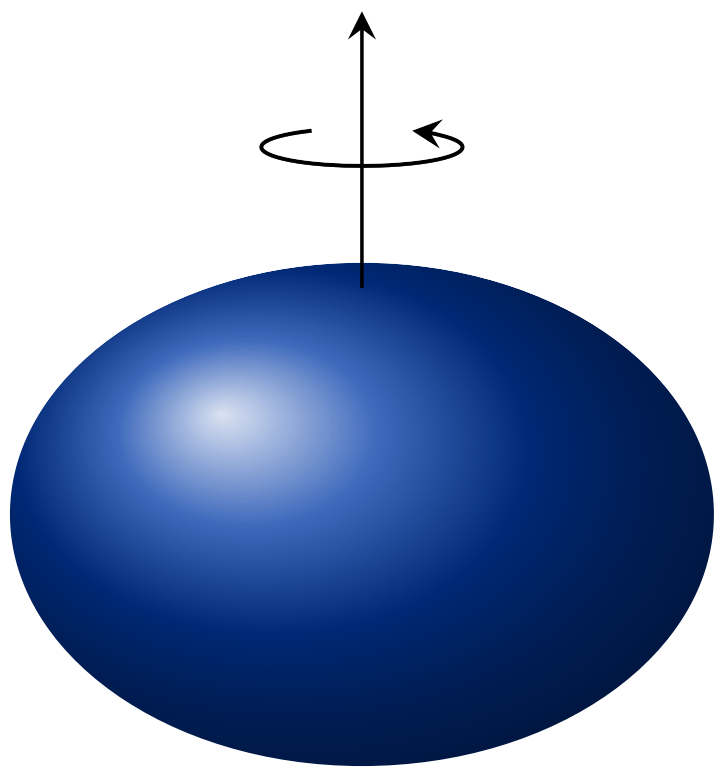

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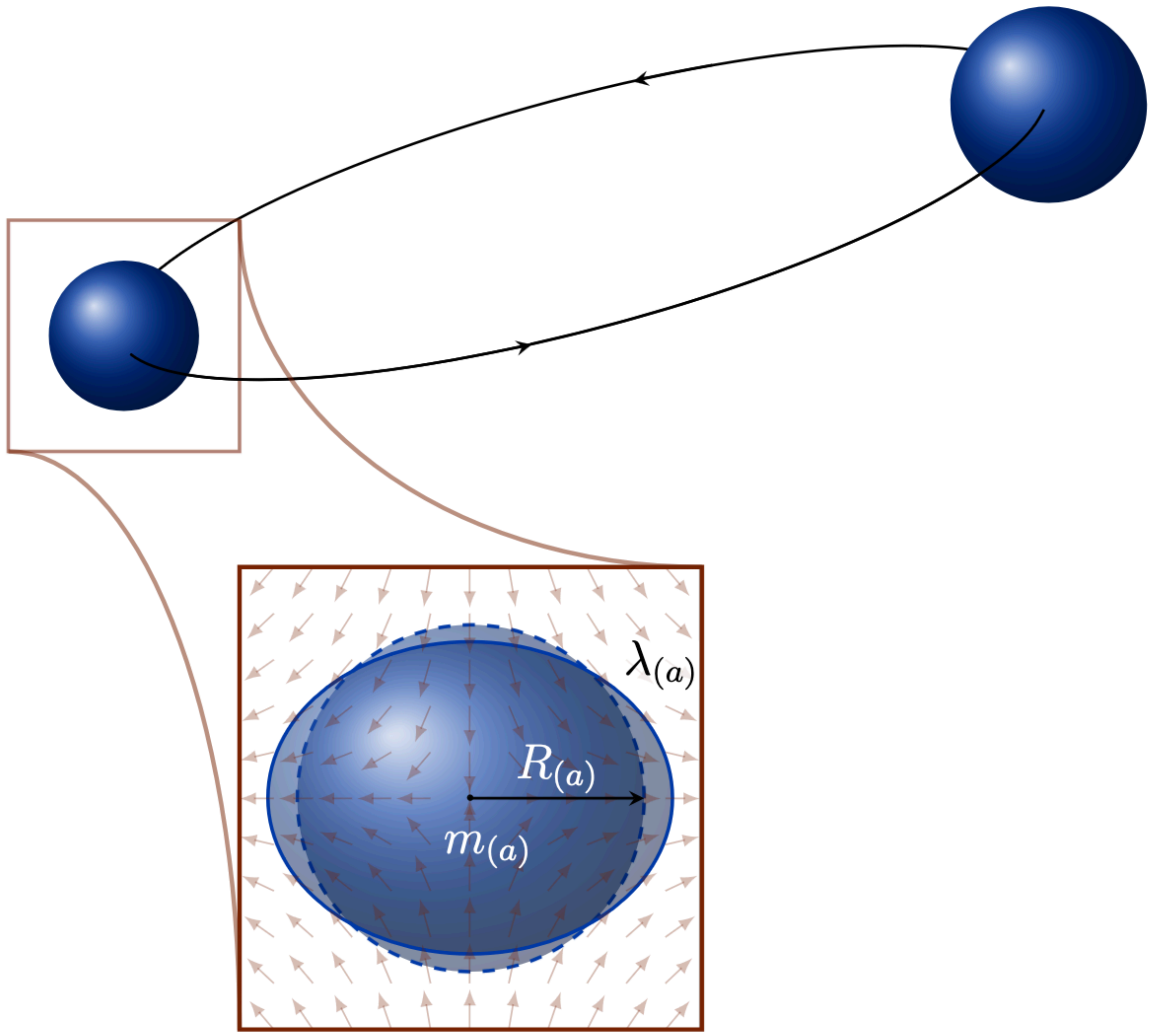
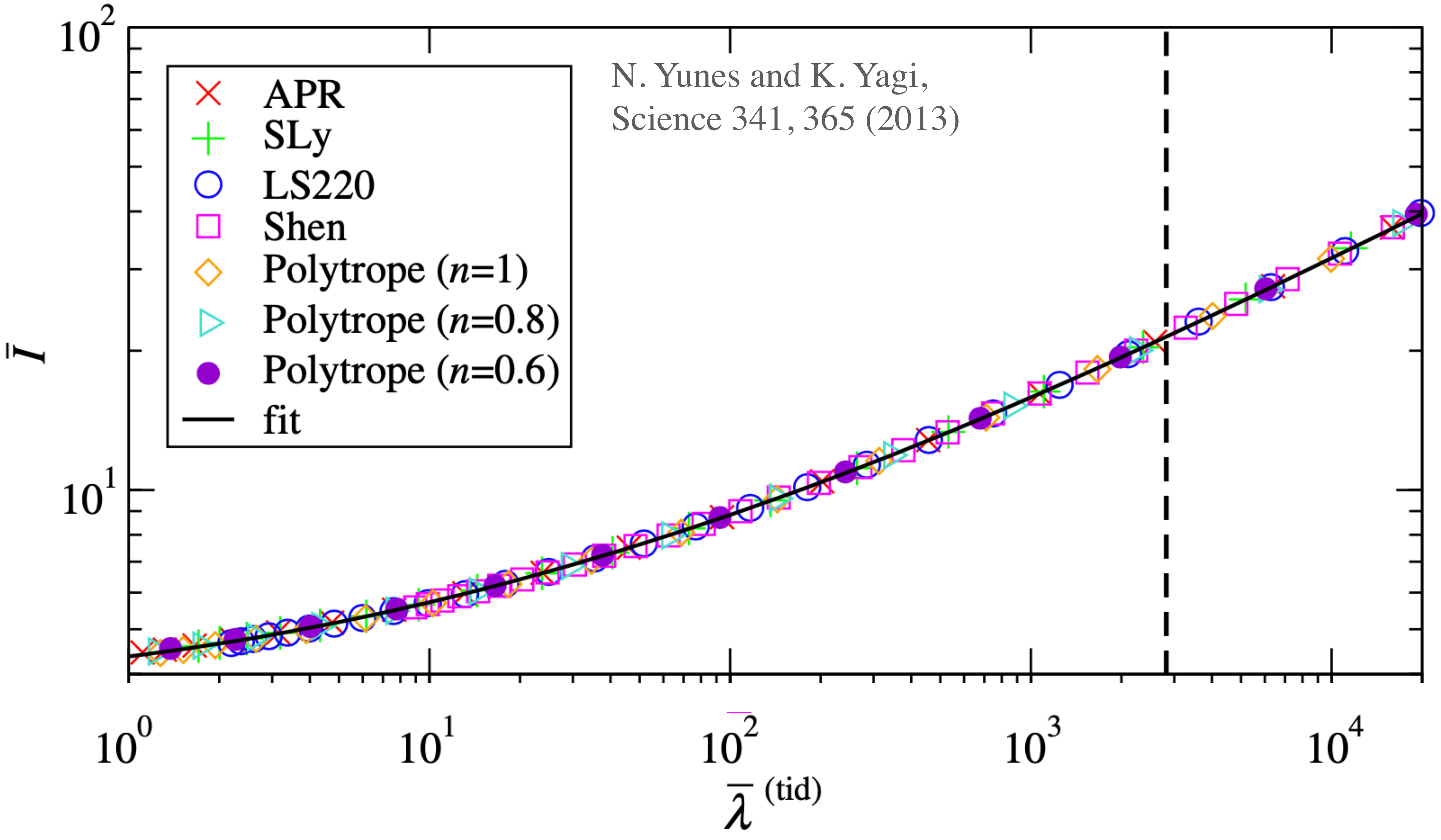


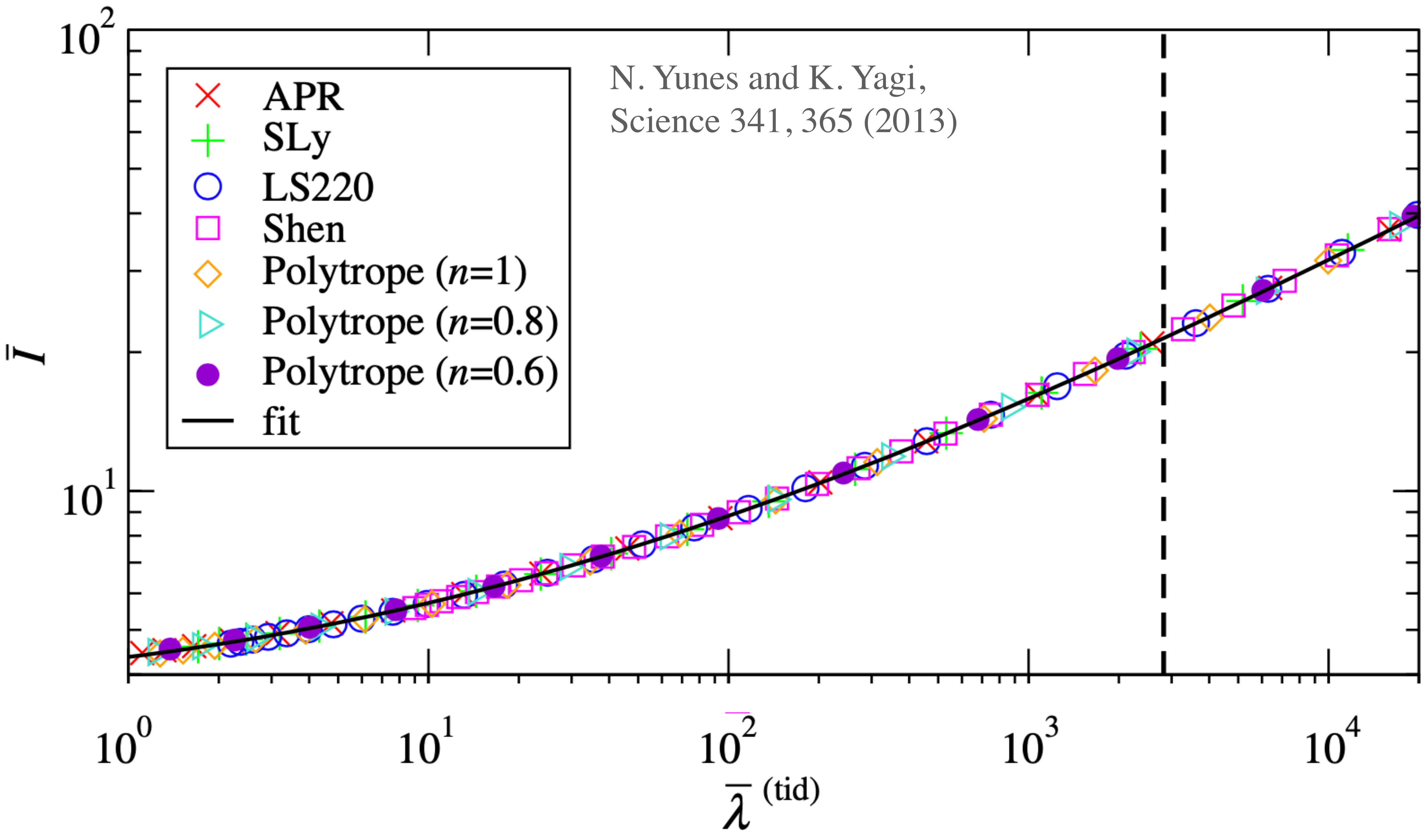
Can we learn something about these parameters?

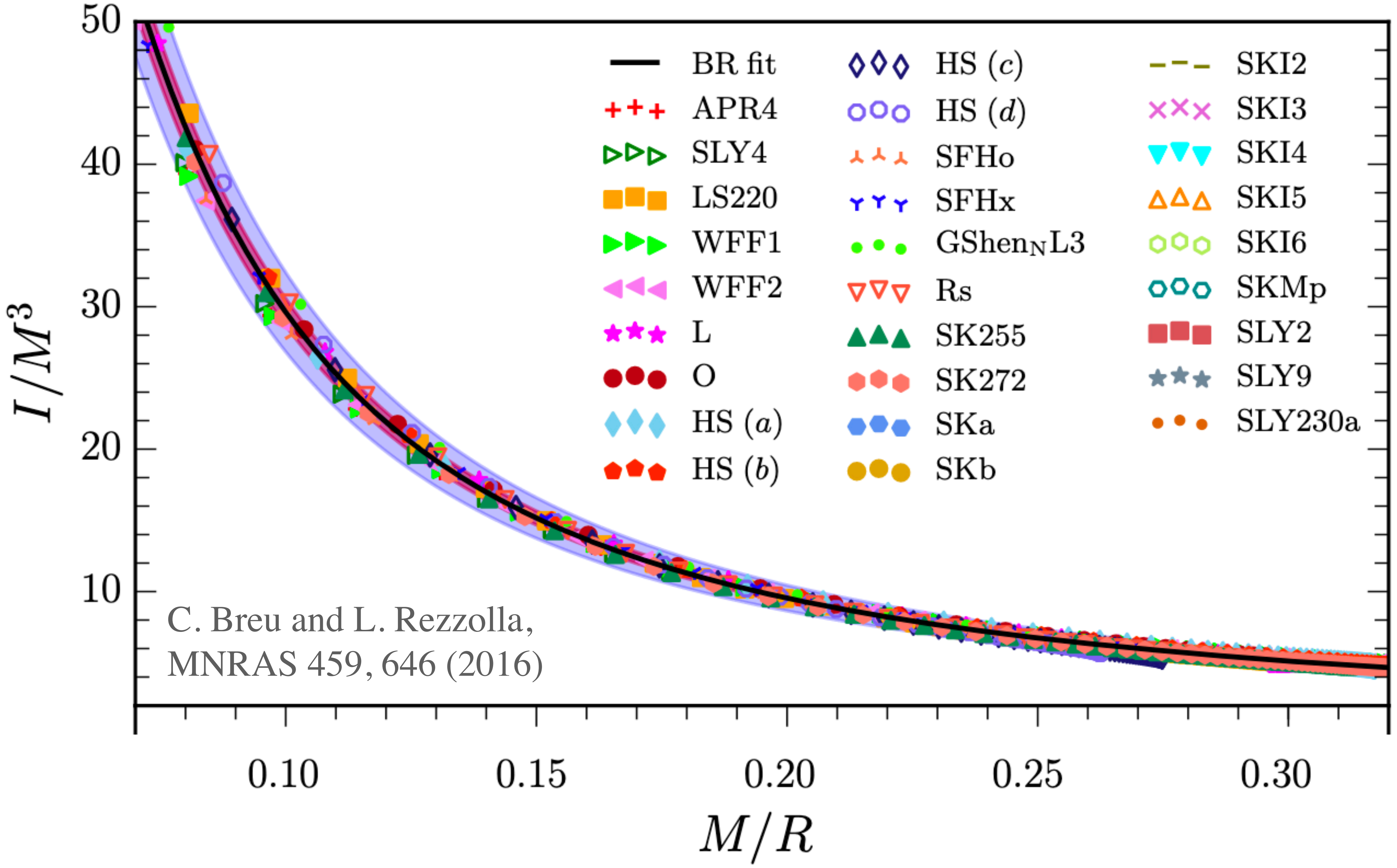
Collapsing the equation-of-state degeneracy

Collapsing the equation-of-state degeneracy



Collapsing the equation-of-state degeneracy





“Today’s posterior is tomorrow’s prior”

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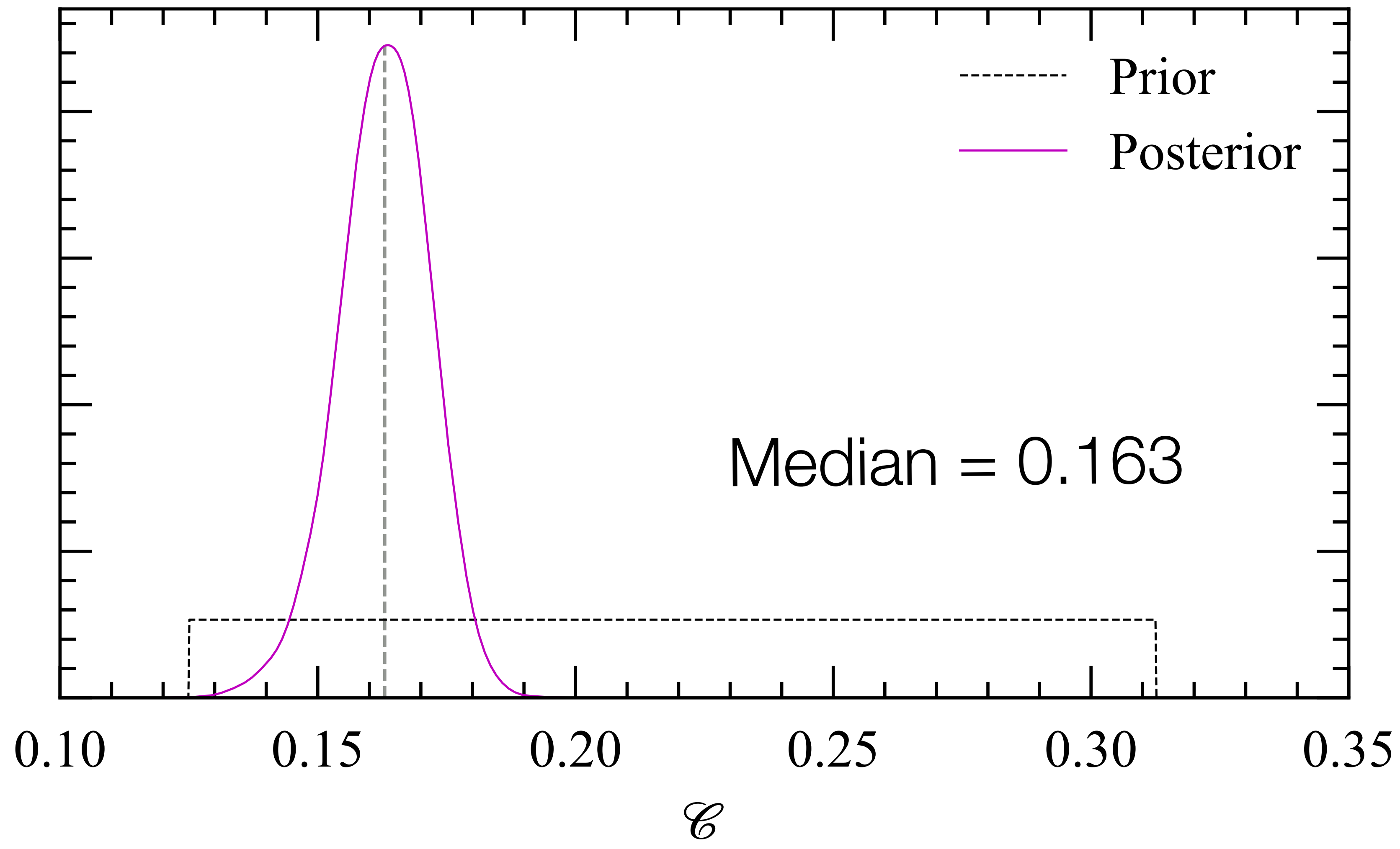
HOS, A. Miguel Holgado, A. Cárdenas-Avandaño, N. Yunes,
Phys. Rev. Lett. **127**, 031101, (2021)

“Today’s posterior is tomorrow’s prior”

$P(GM/Rc^2\,|\,\mathrm{NICER})\,\mathrm{d}\mathscr{C}$

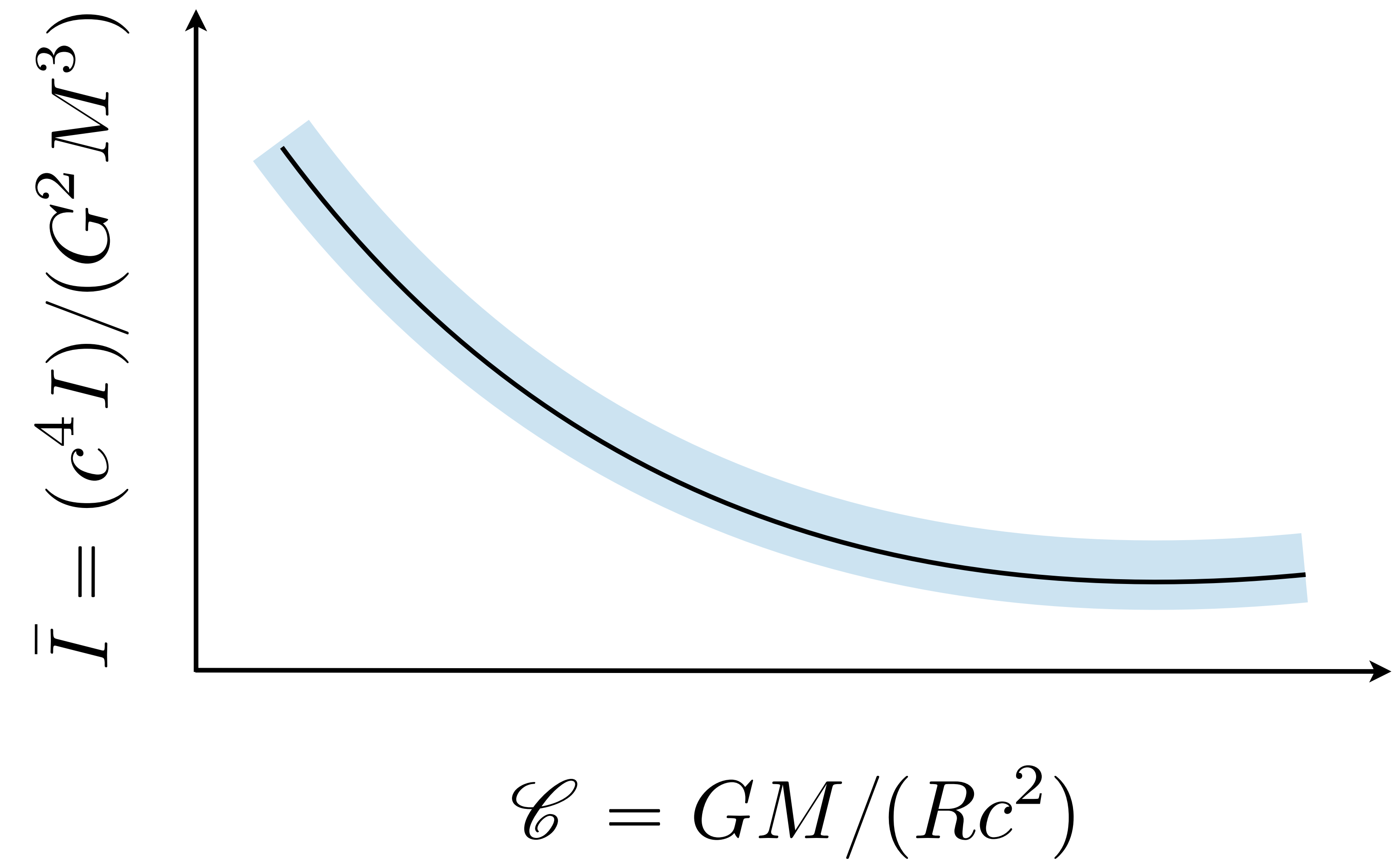


Prior

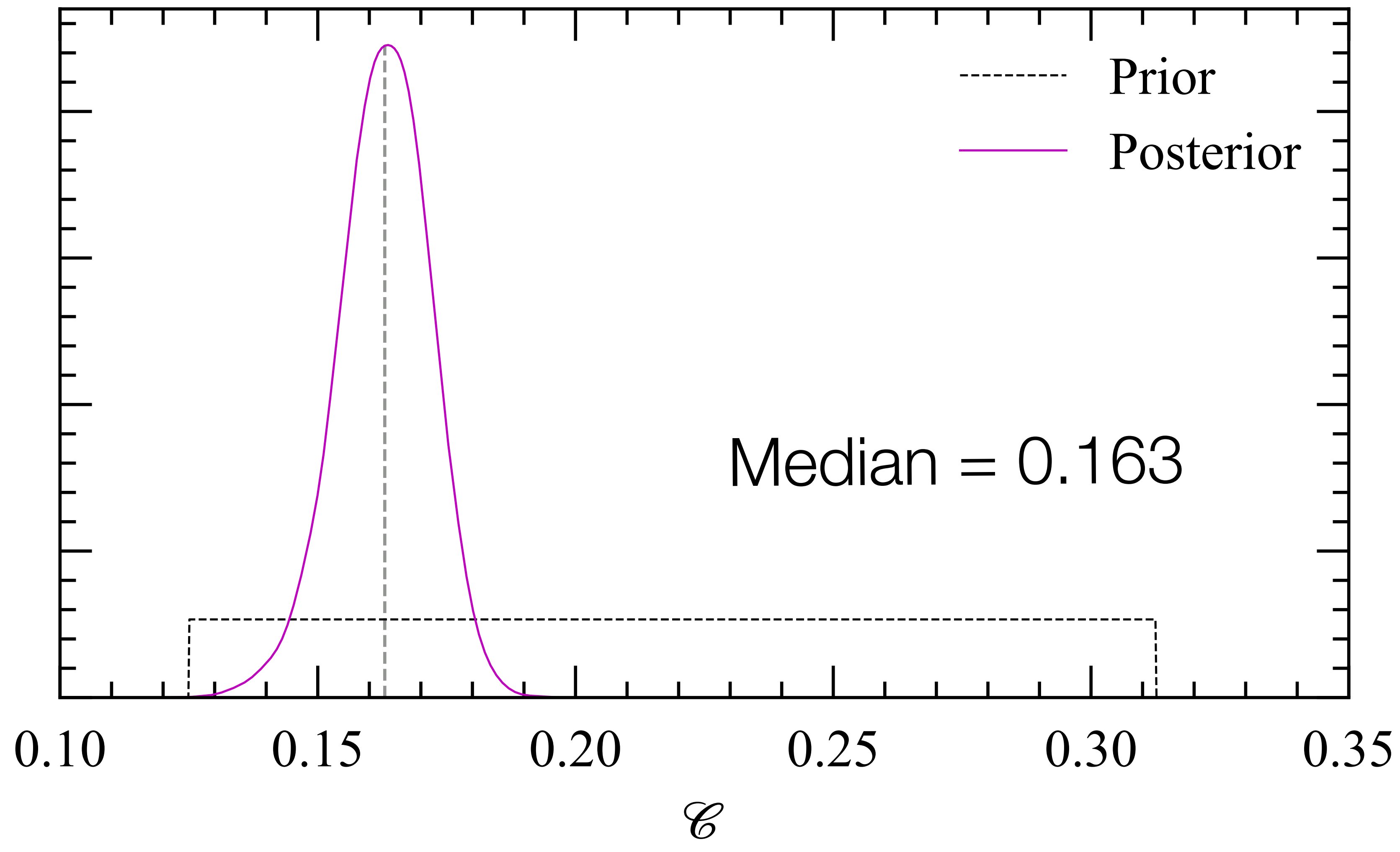
HOS, A. Miguel Holgado, A. Cárdenas-Avandaño, N. Yunes,
Phys. Rev. Lett. **127**, 031101, (2021)

“Today’s posterior is tomorrow’s prior”

$$\int P(y\,|\,\mathscr{C}) \times P(GM/Rc^2\,|\,\text{NICER})\,\mathrm{d}\mathscr{C}$$



Likelihood



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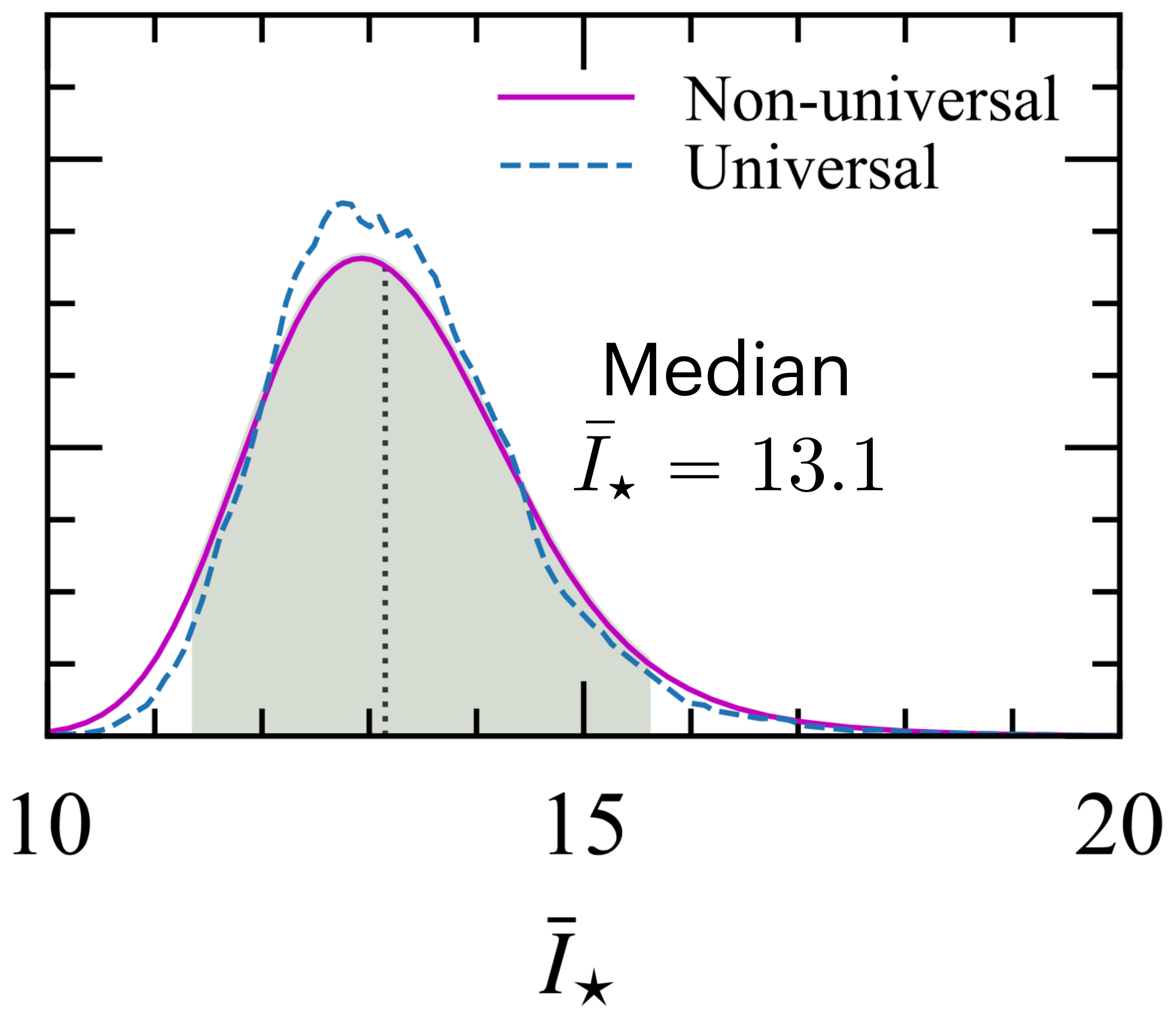
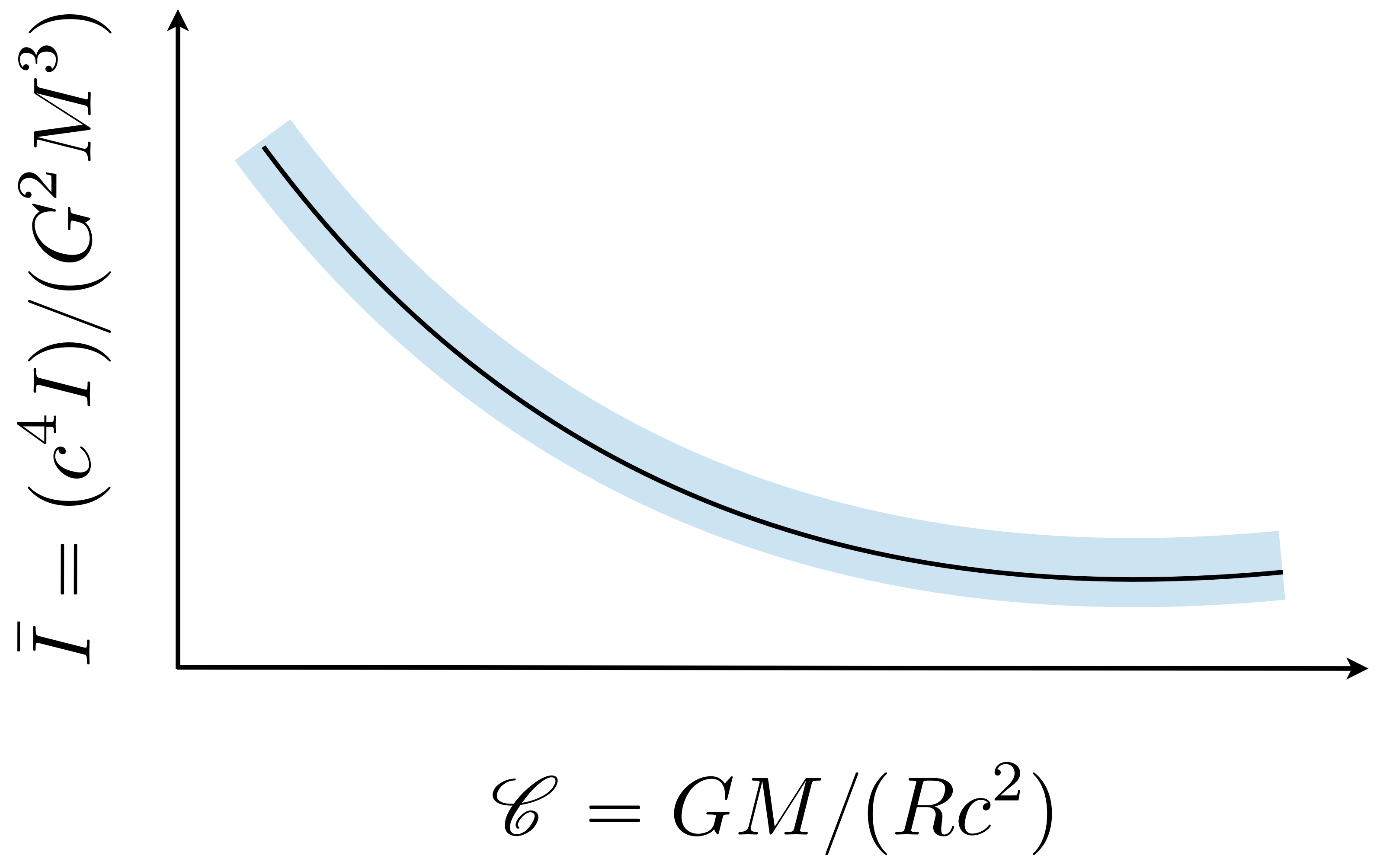
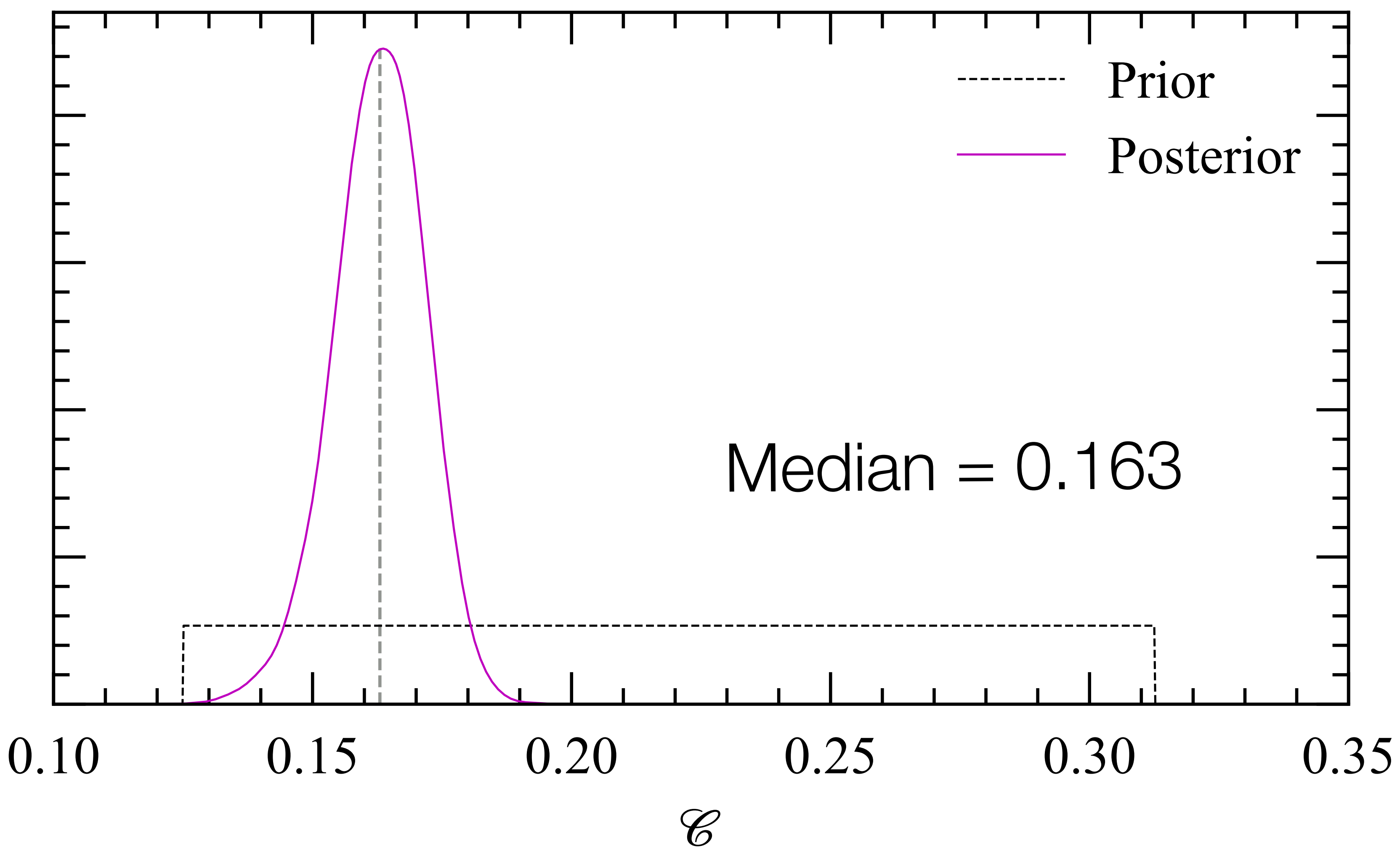
$$P(y\,|\,\mathrm{NICER}) = \int P(y\,|\,\mathscr{C}) \times P(GM/Rc^2\,|\,\mathrm{NICER})\,\mathrm{d}\mathscr{C}$$



Posterior



Likelihood



Prior

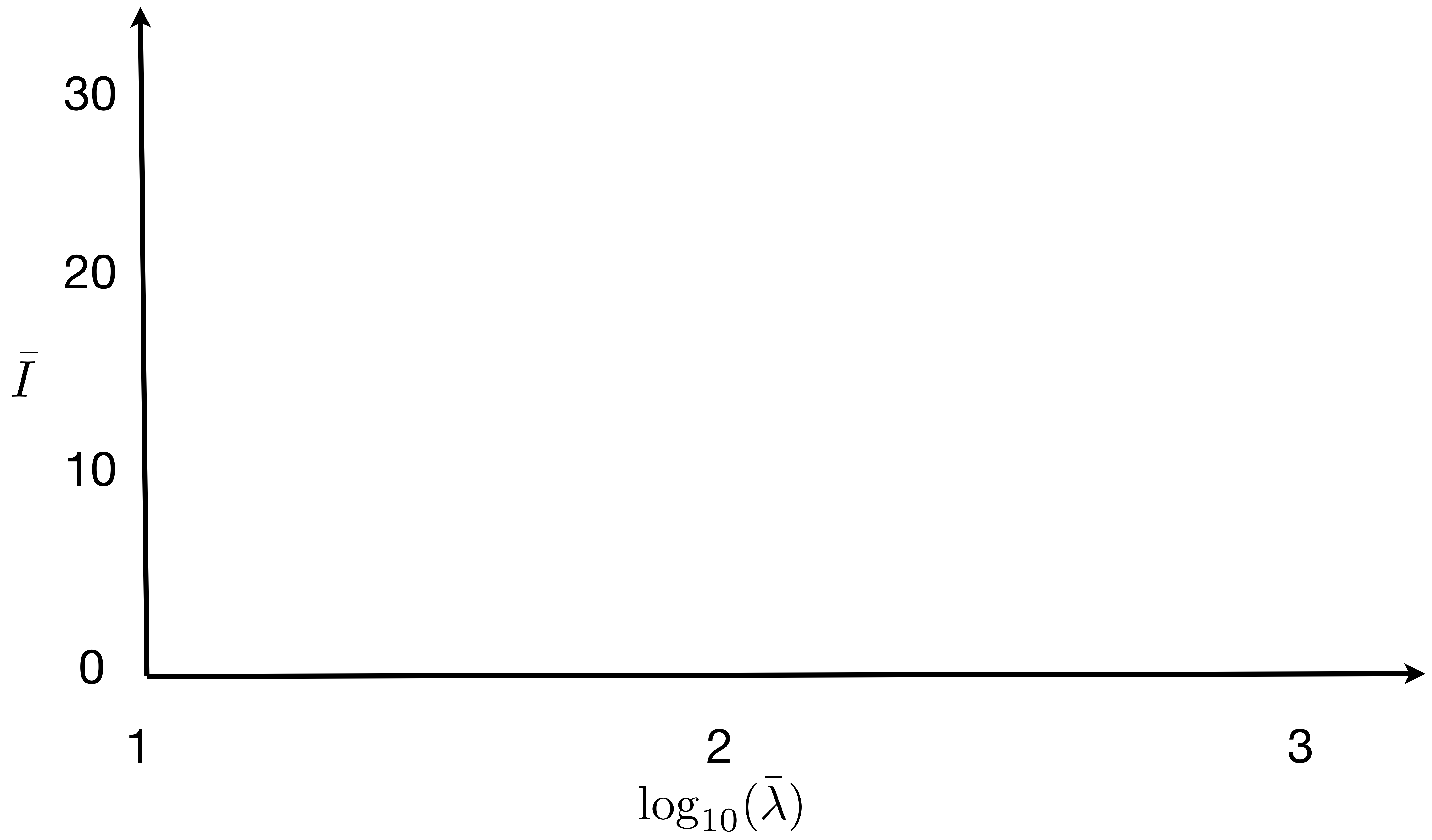
HOS, A. Miguel Holgado, A. Cárdenas-Avandaño, N. Yunes, Phys. Rev. Lett. **127**, 031101, (2021) Using **equation-of-state independent** relations between neutron star parameters, we can infer **additional quantities**, conditional on a **mass and radius measurement**.

“*Va bene,* but tell me about the **tests of gravity!**”

I-Love testing general relativity

(*) For a $1.4\ M_{\odot}$ neutron star

I-Love testing general relativity



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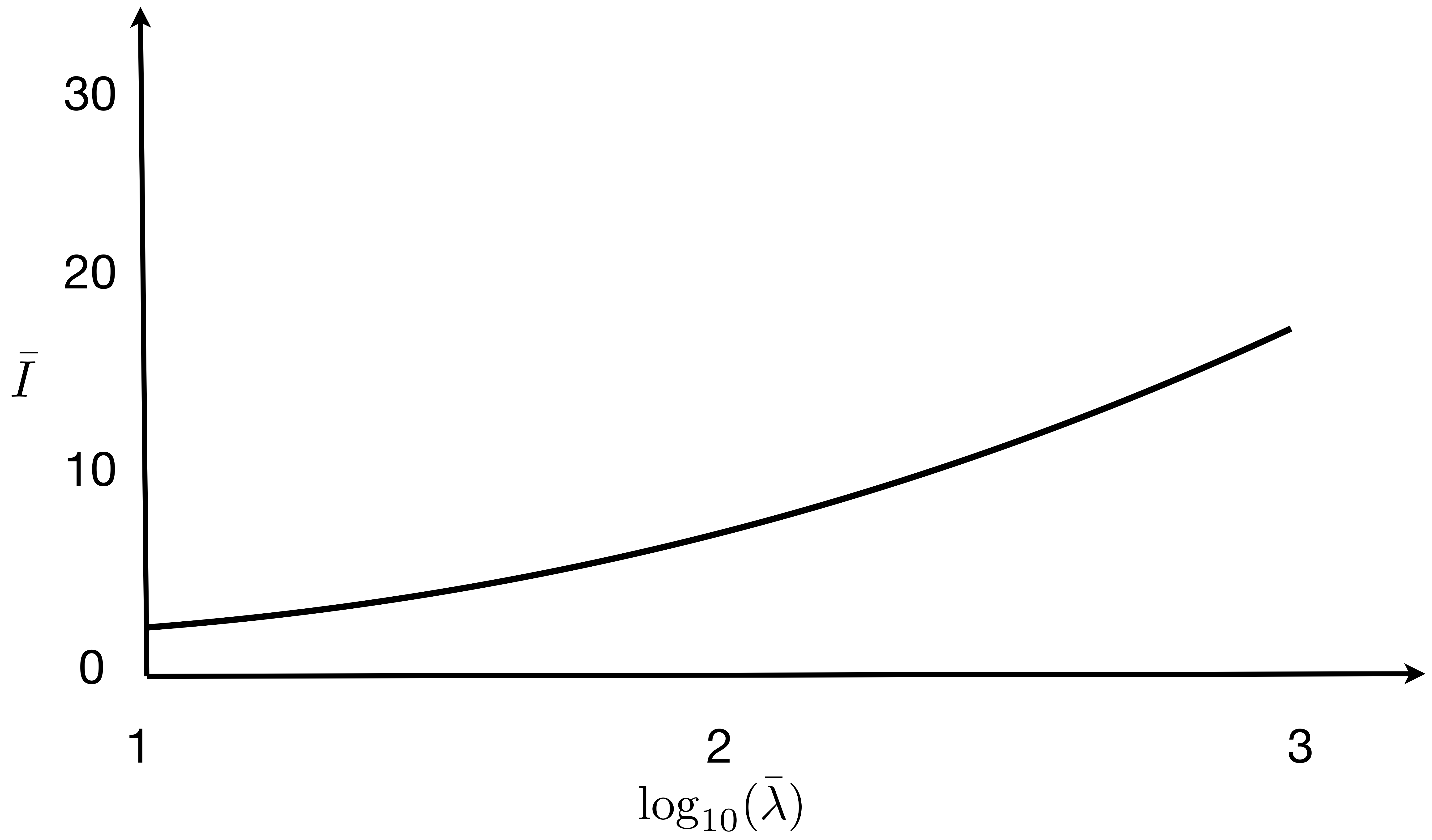

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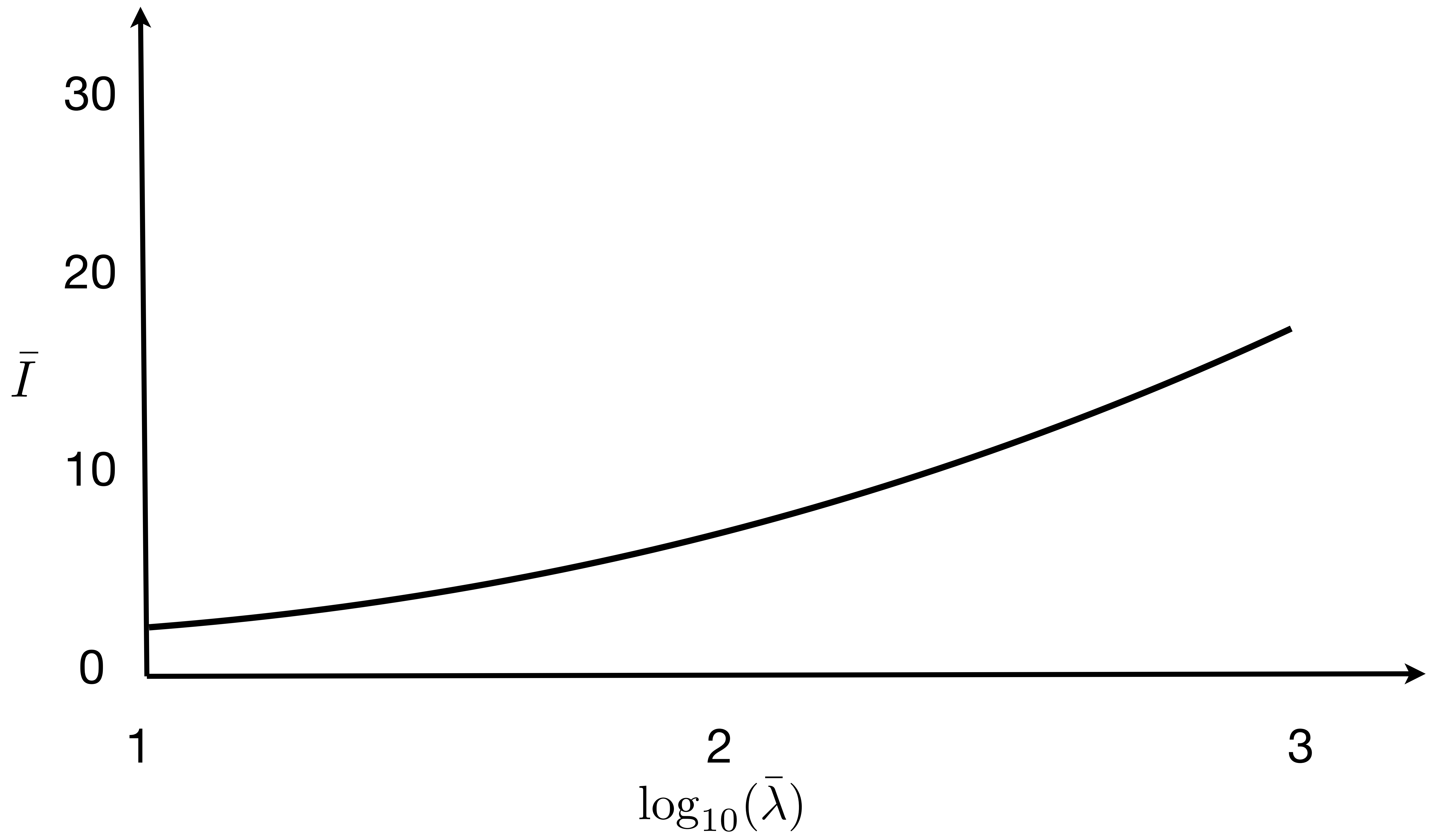
$$\bar{I} = \bar{\lambda}^{2/5} \left[c_0 + \qquad\qquad\qquad \right]$$

Newtonian



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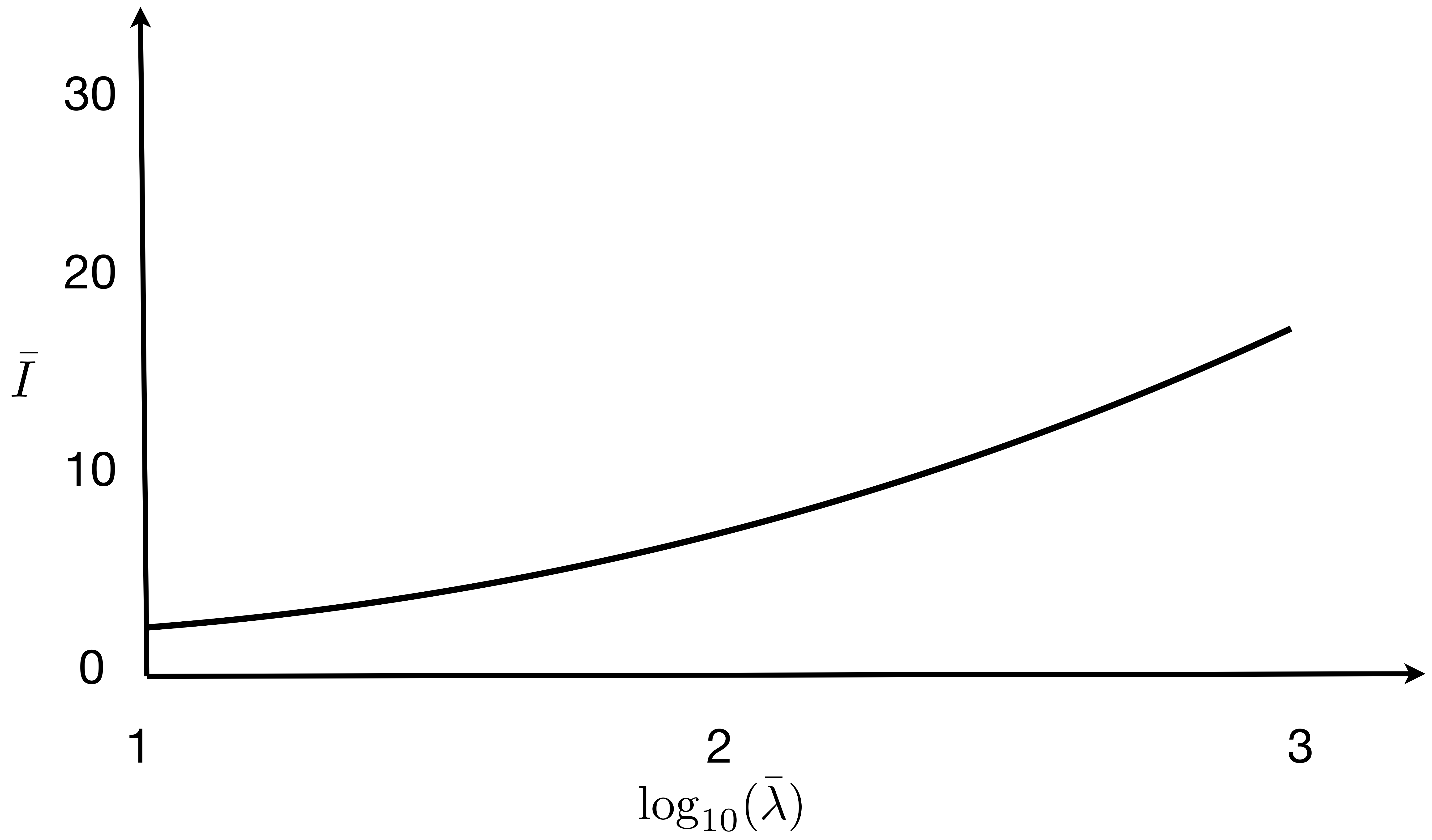
$$\bar{I} = \bar{\lambda}^{2/5}\left[c_0 + c_1\bar{\lambda}^{-1/5} + c_2\bar{\lambda}^{-2/5}\right]$$

Newtonian **Post-Minkowskian**



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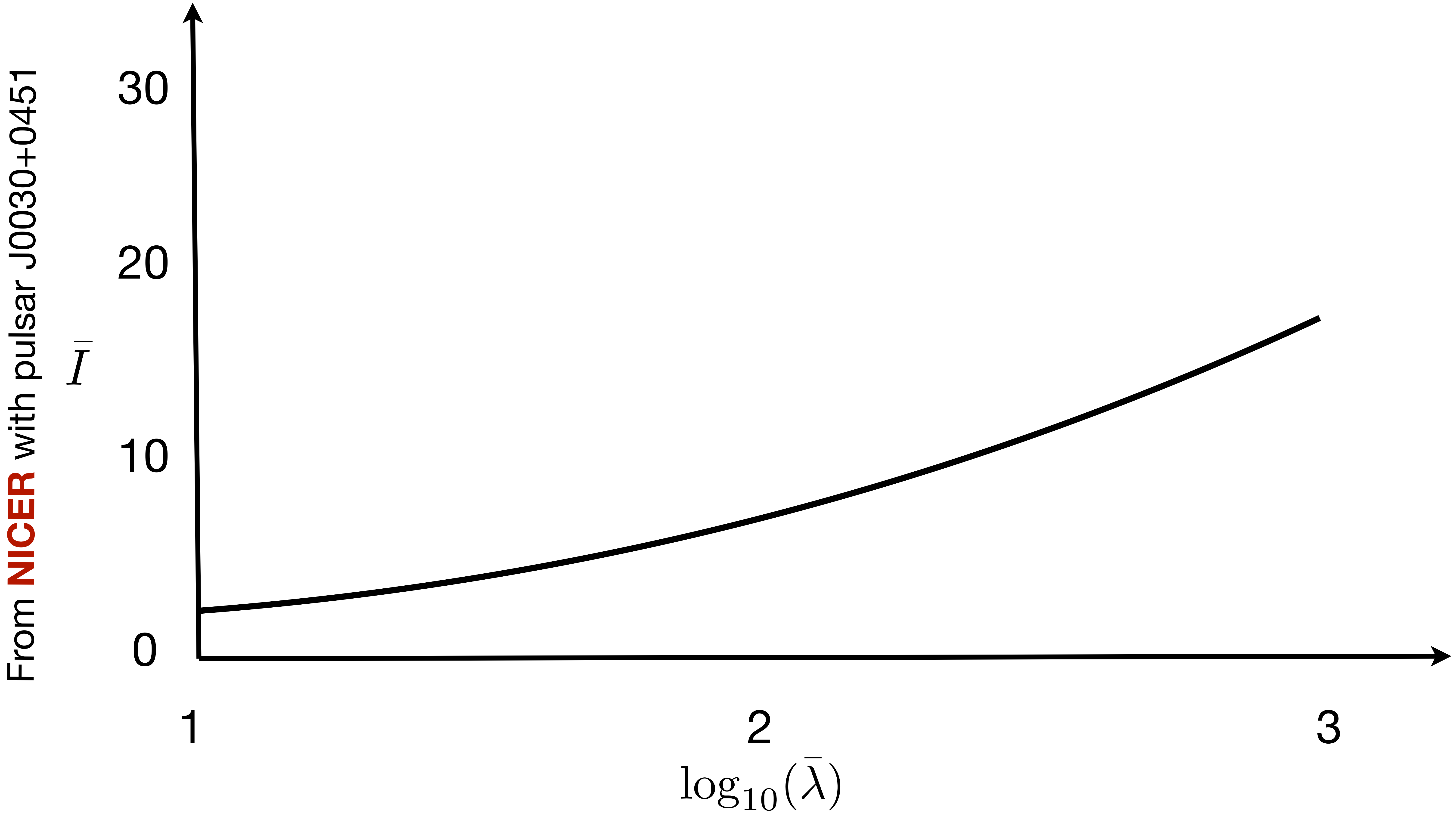

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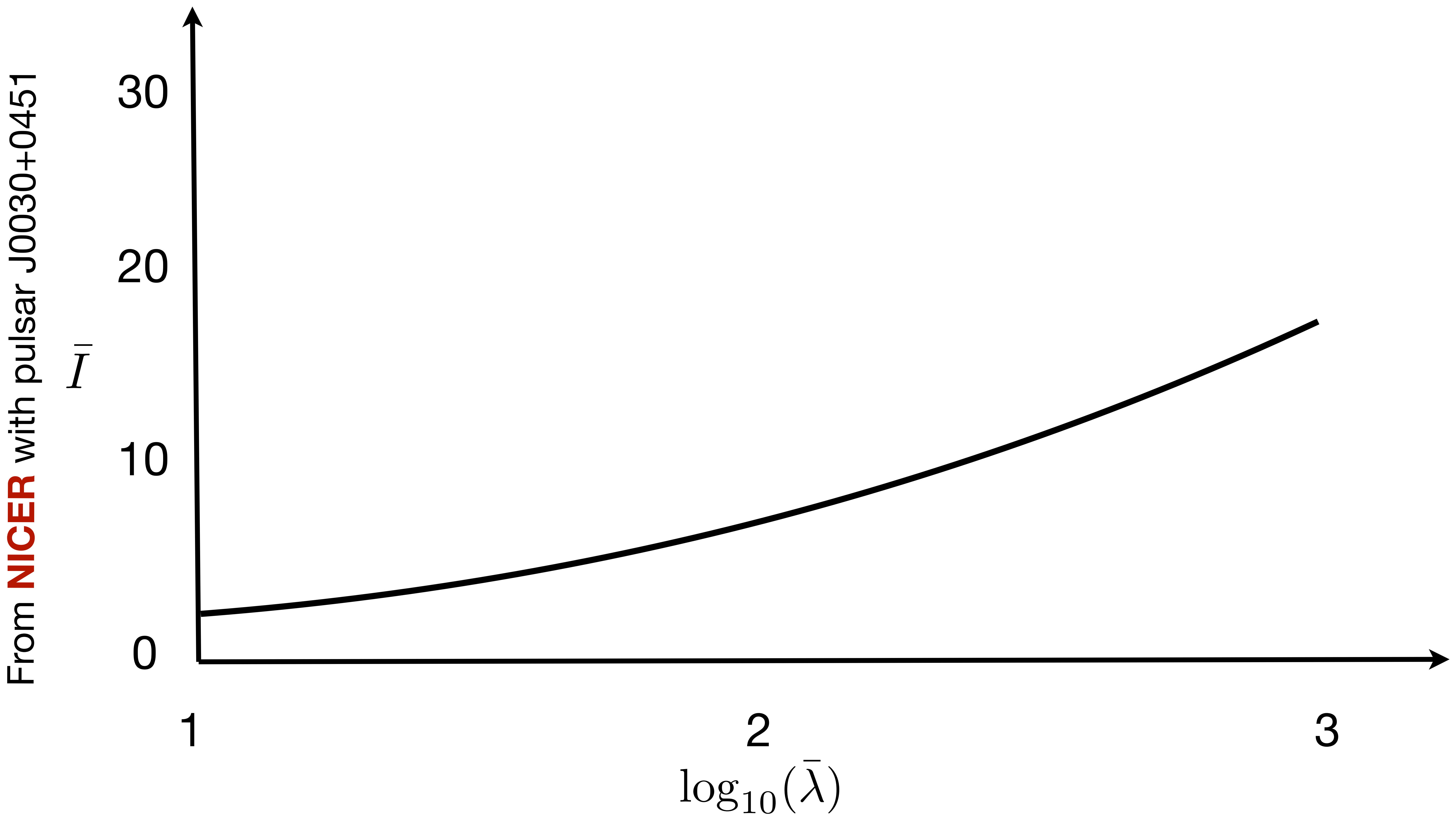

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From **LIGO-Virgo-Kagra** using GW170817

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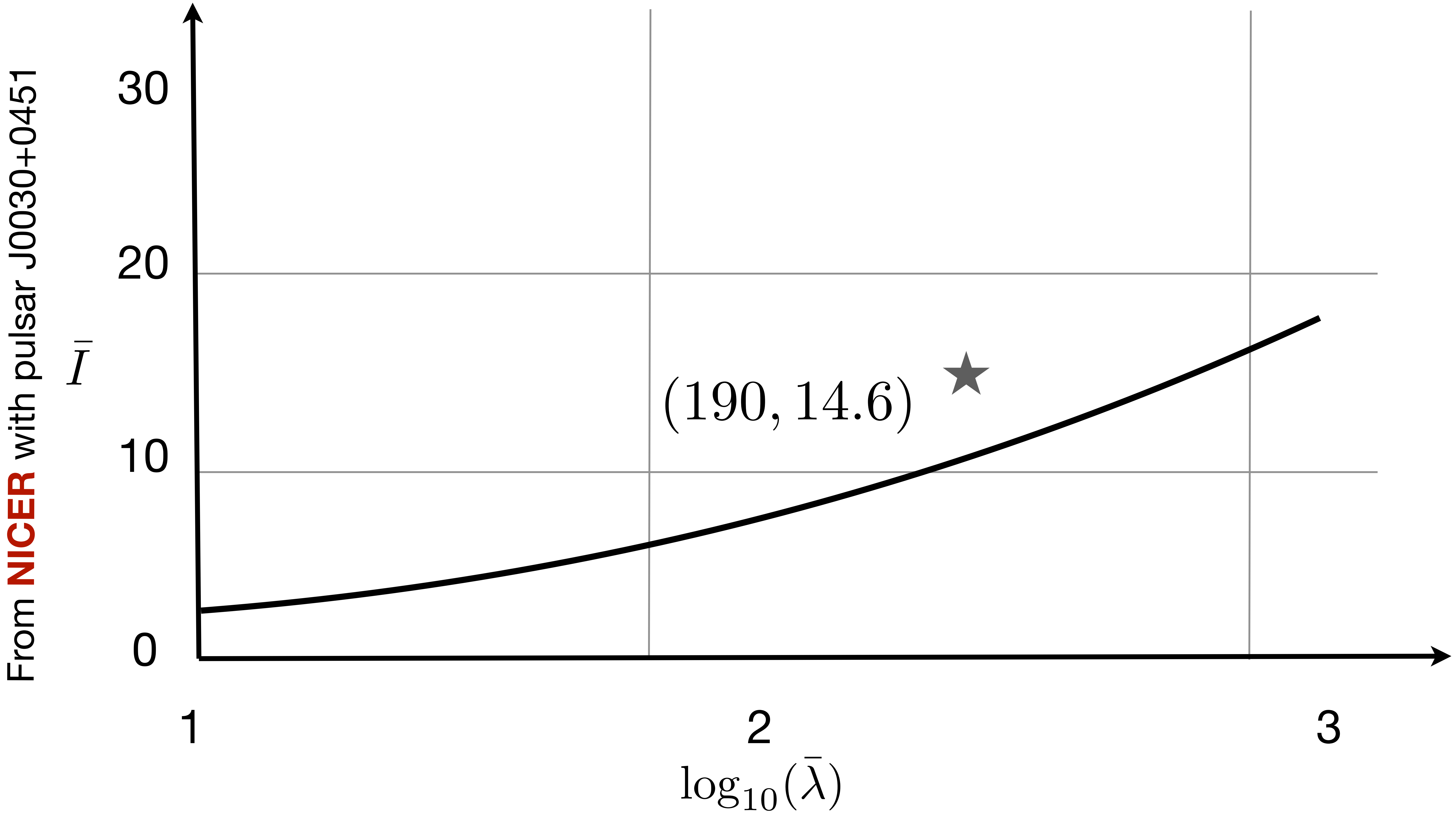

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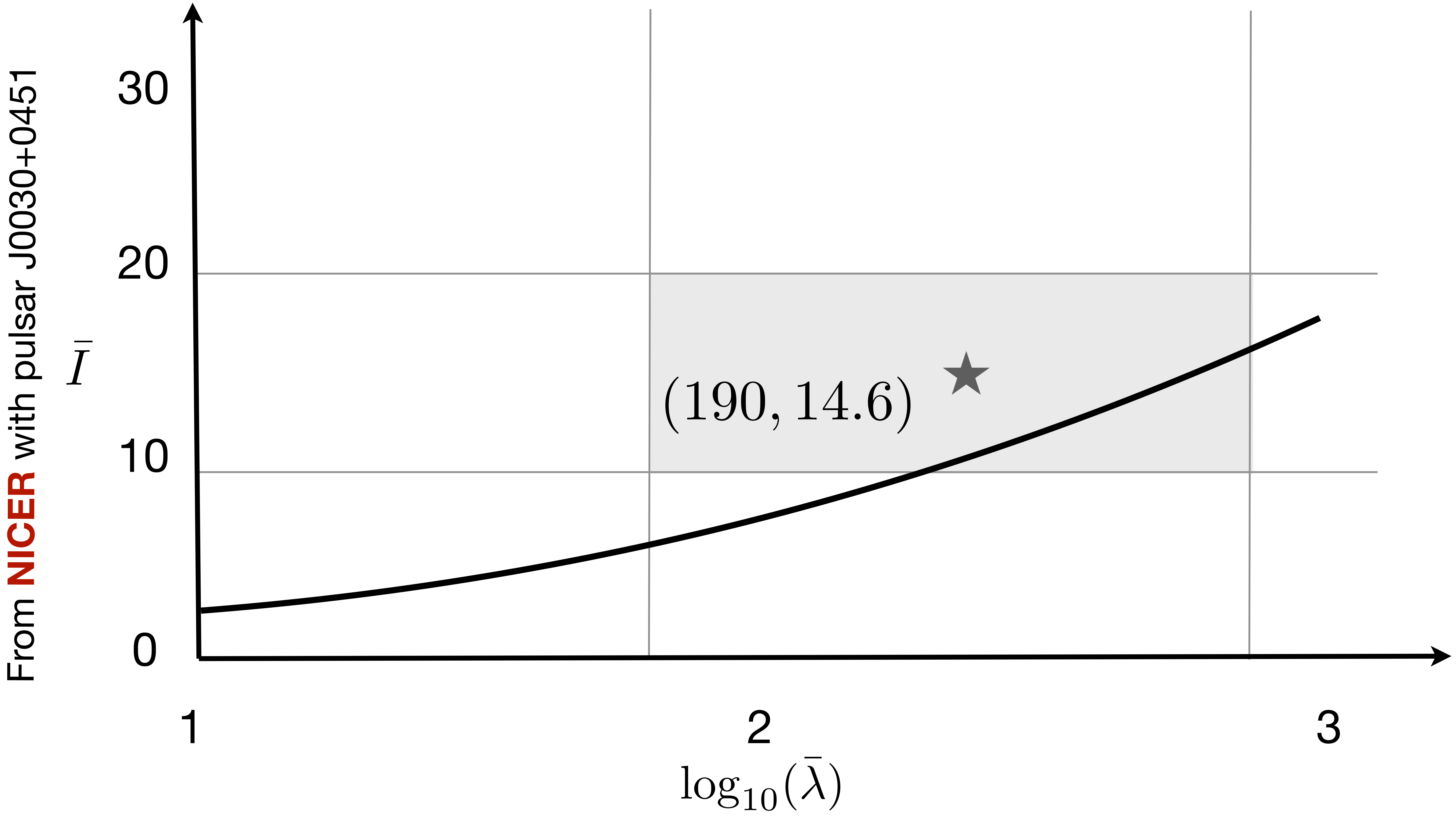

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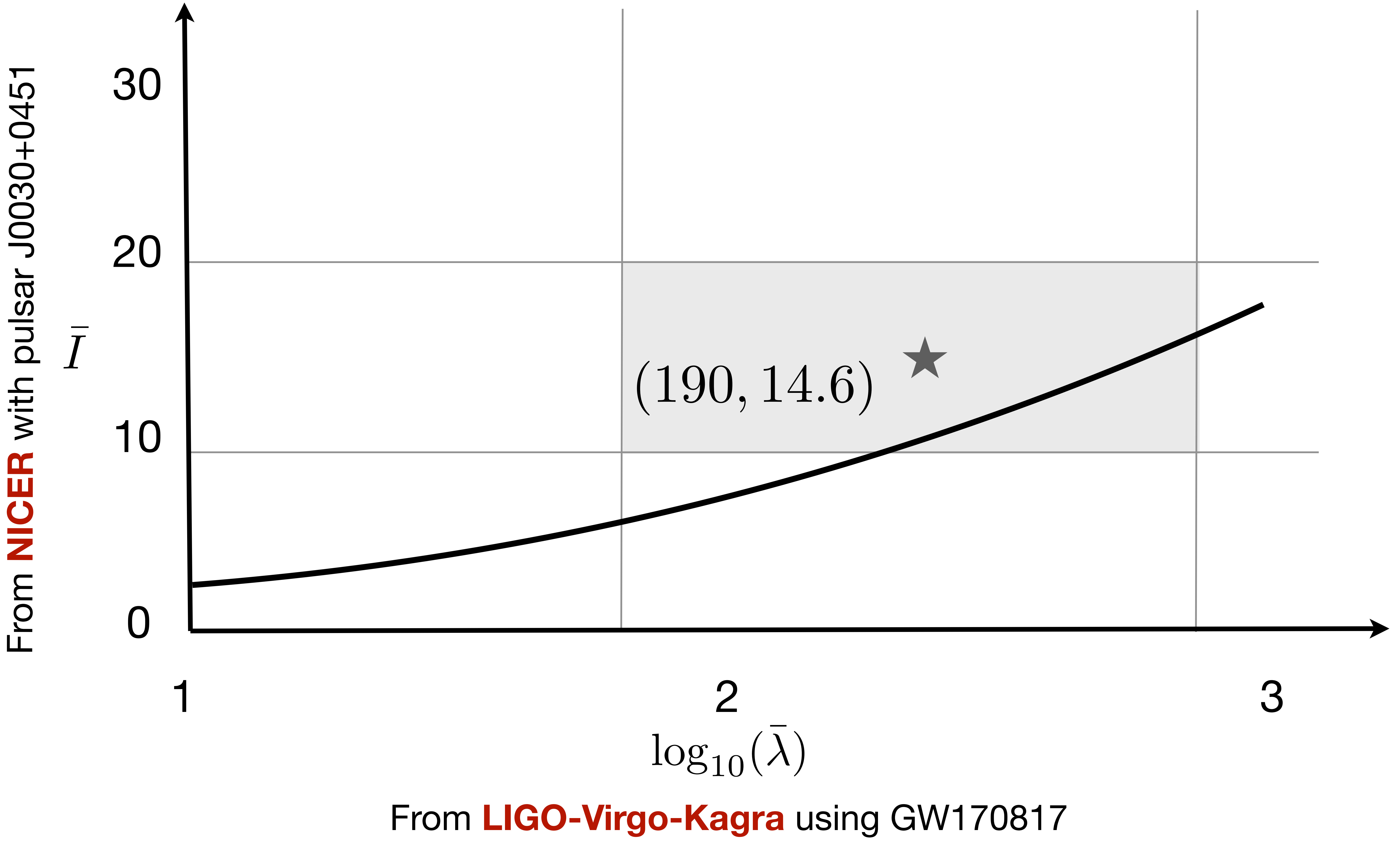
$$\bar{I} = \bar{\lambda}^{2/5}\left[c_0 + c_1\bar{\lambda}^{-1/5} + c_2\bar{\lambda}^{-2/5}\right] + \beta\bar{\lambda}^{-b/5}$$

Newtonian **Post-Minkowskian** **GR Deviation**



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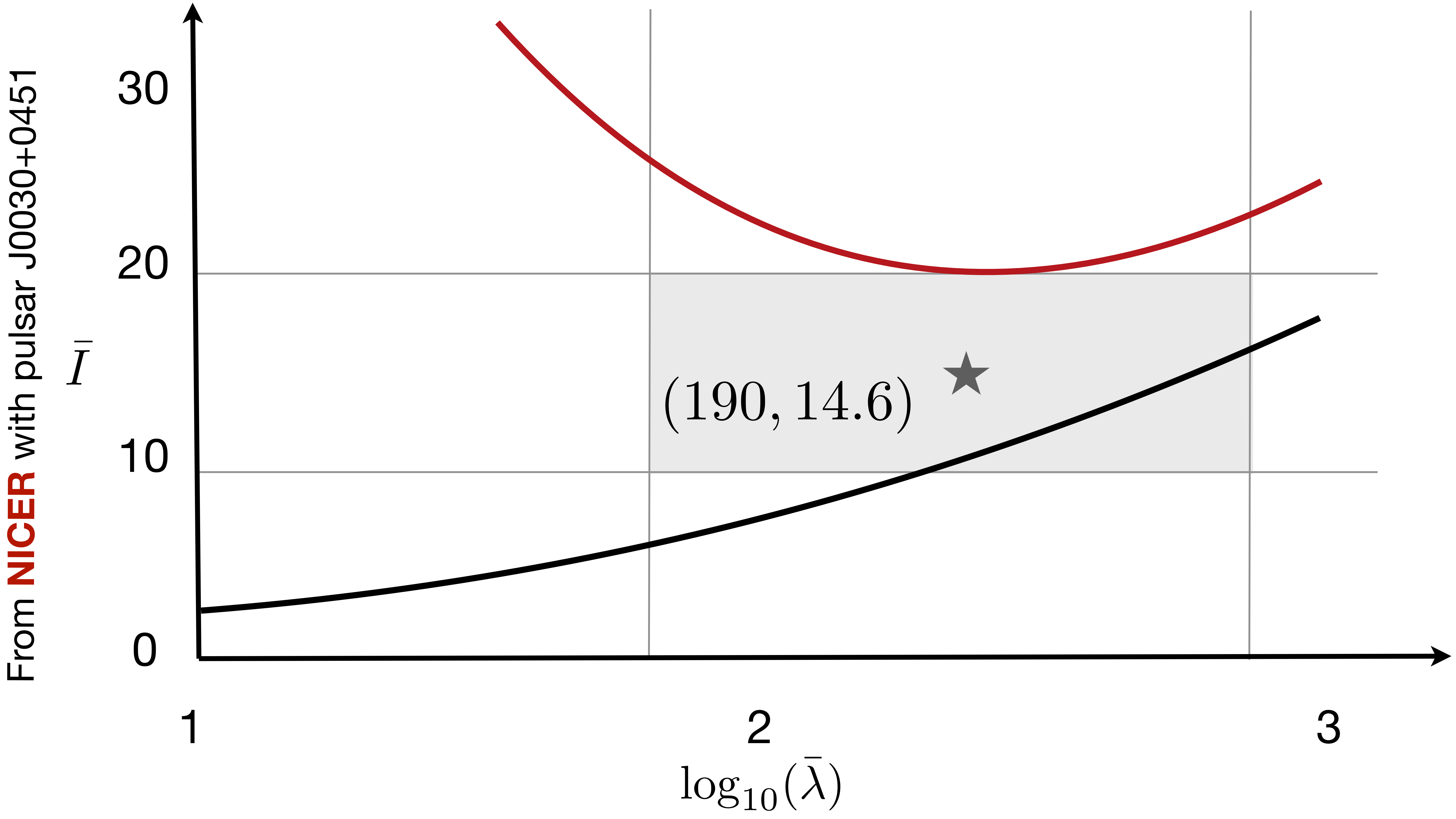

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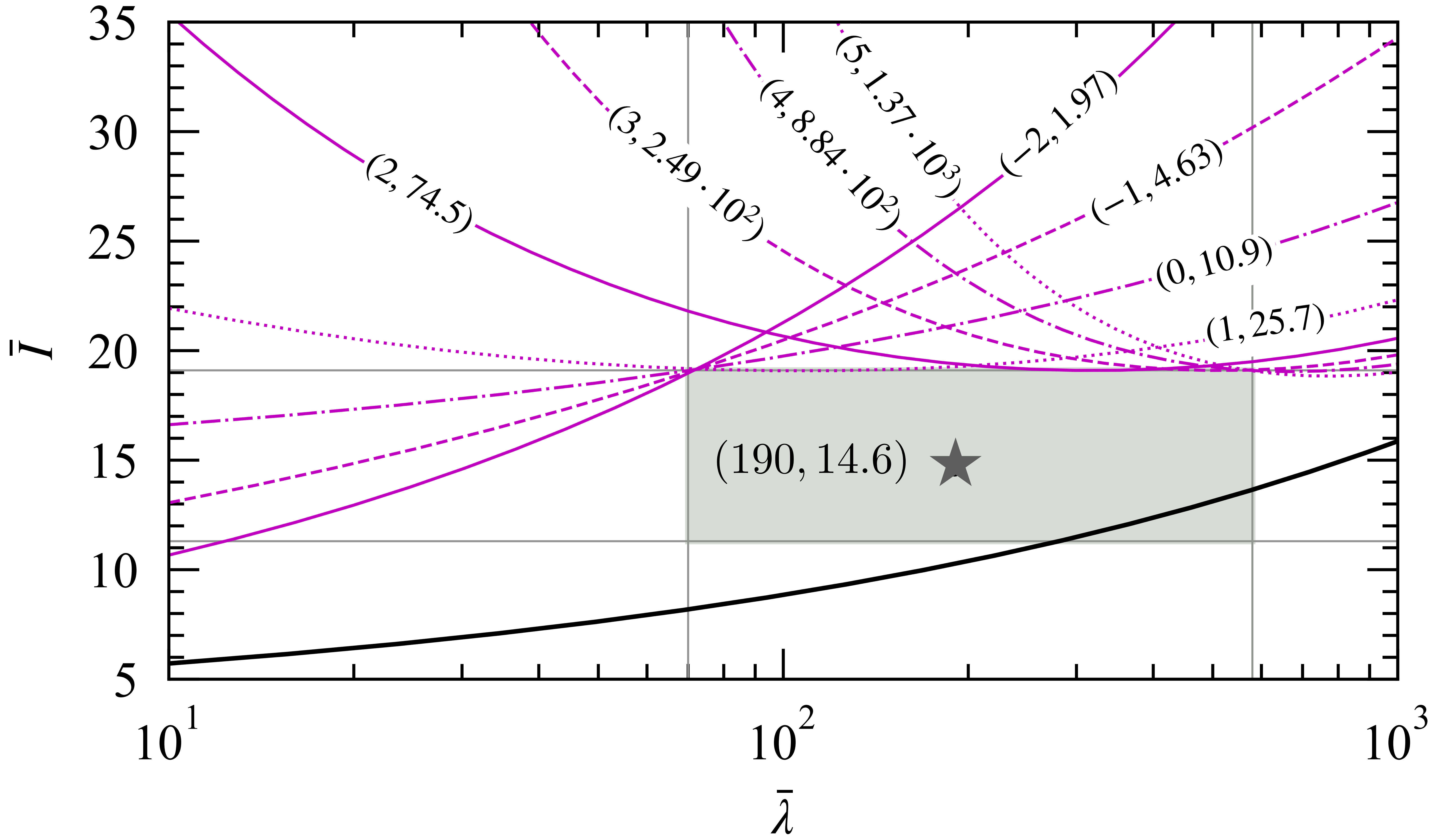
From **LIGO-Virgo-Kagra** using GW170817

I-Love parametrisations

$$\bar{I} = \bar{\lambda}^{2/5}\left[c_0 + c_1\bar{\lambda}^{-1/5} + c_2\bar{\lambda}^{-2/5}\right] + \beta\bar{\lambda}^{-b/5}$$



The **I-Love relation** offers a **simple equation-of-state independent null test of general relativity** (and the theory **passes** it.)

A simple **parametrised I-Love** relation can be used to test, in a **theory-agnostic** way, deviations from general relativity.

From theory-agnostic to theory-specific.

Does gravity violate parity?

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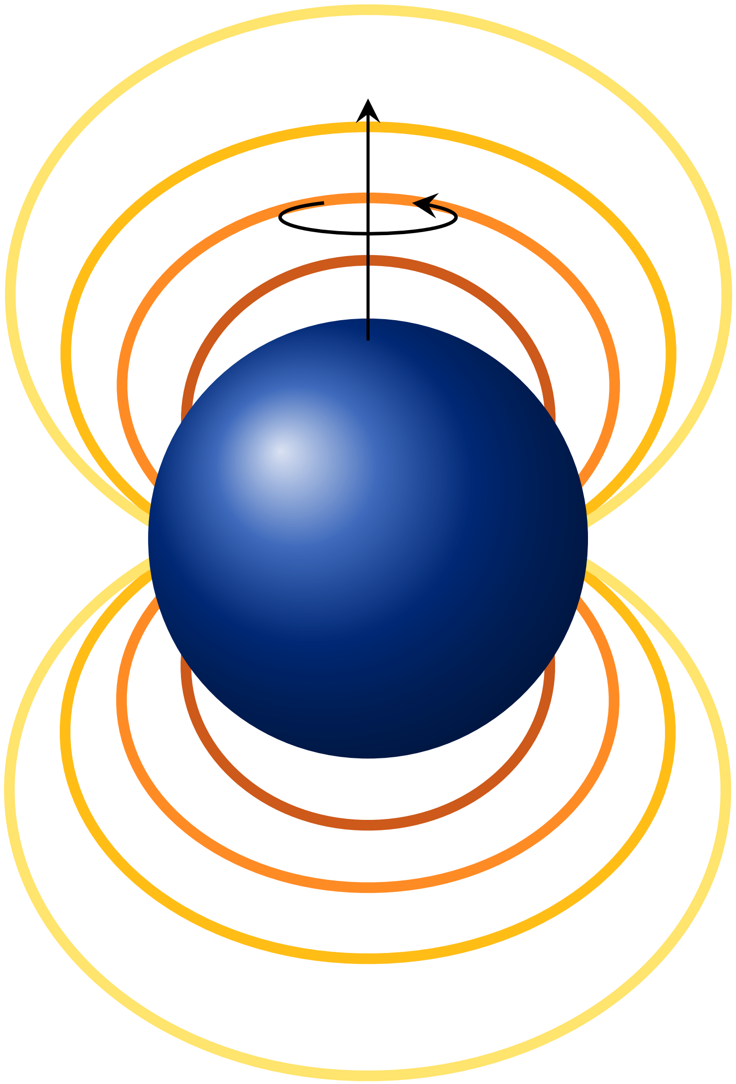

scalar field $\approx q/r$ scalar field $\approx d/r^2$

- Dynamical Chern-Simons gravity. (Higher-curvature theory.)

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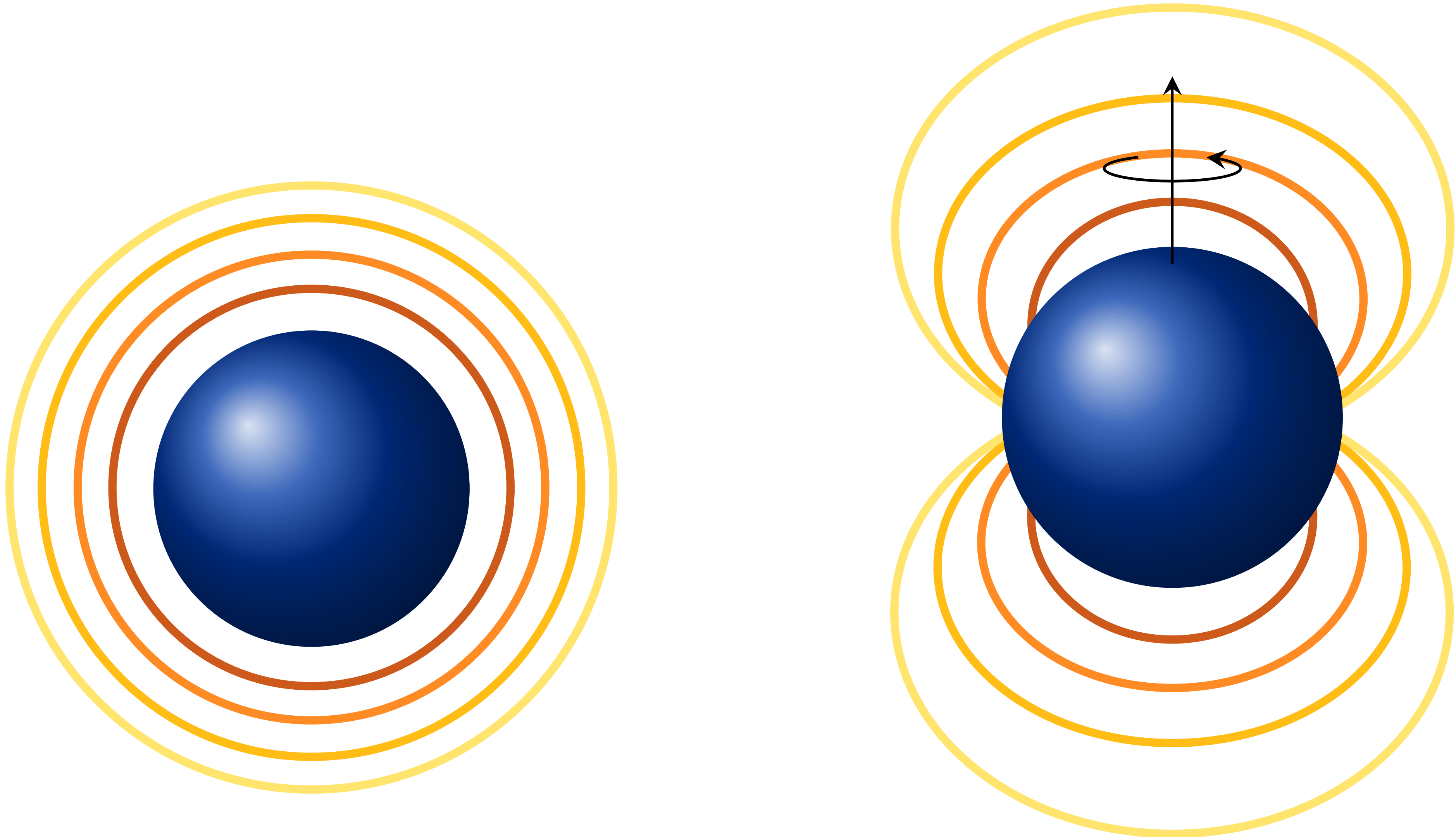

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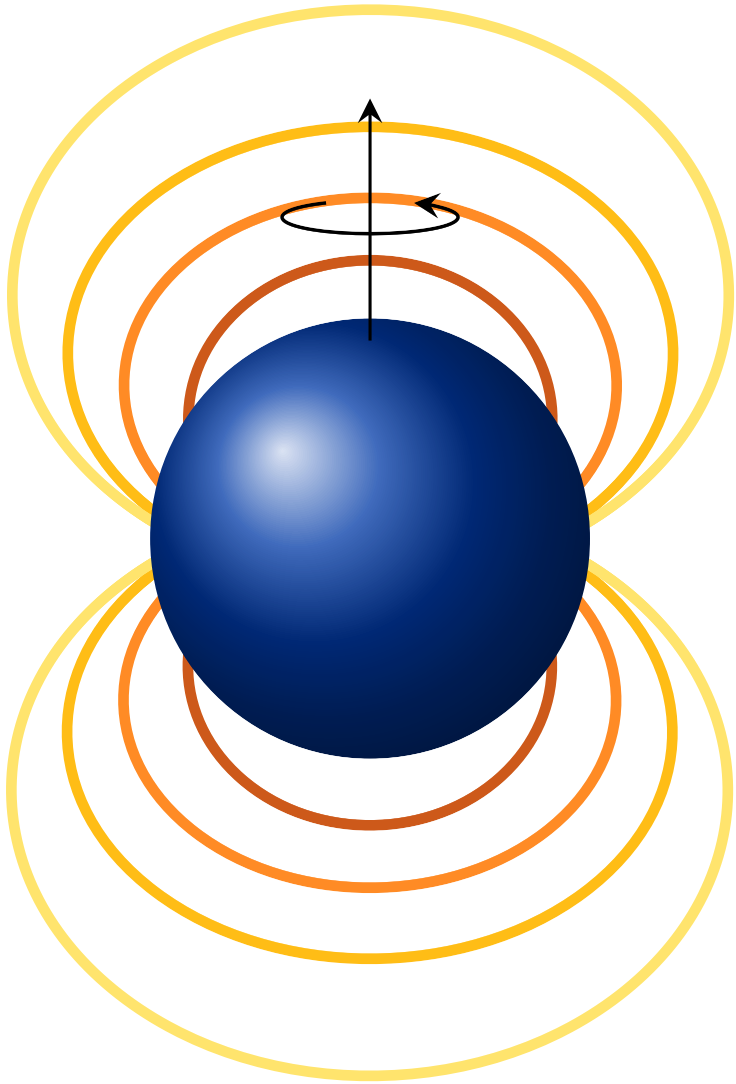

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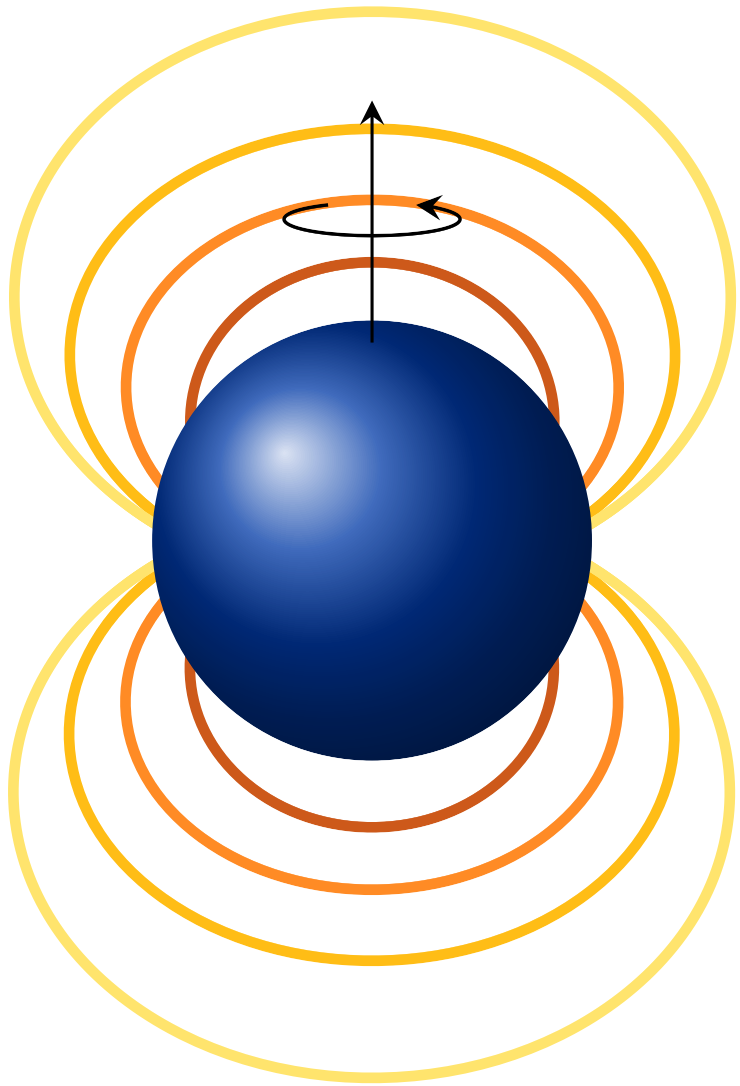

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- **Unconstrained** with binary pulsars.
- **Unconstrained** with current gravitational-wave events.

I-Love Chern-Simons?

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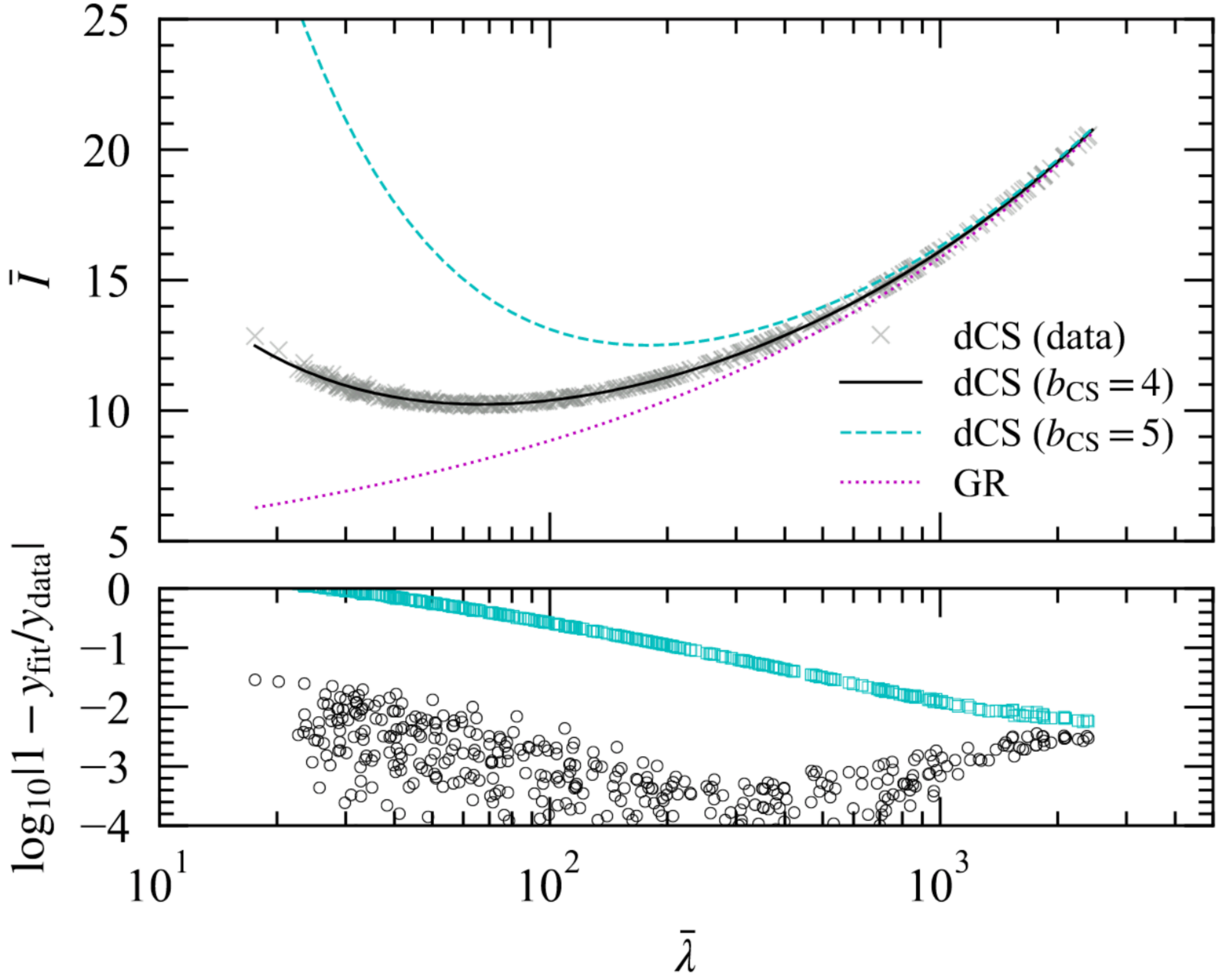

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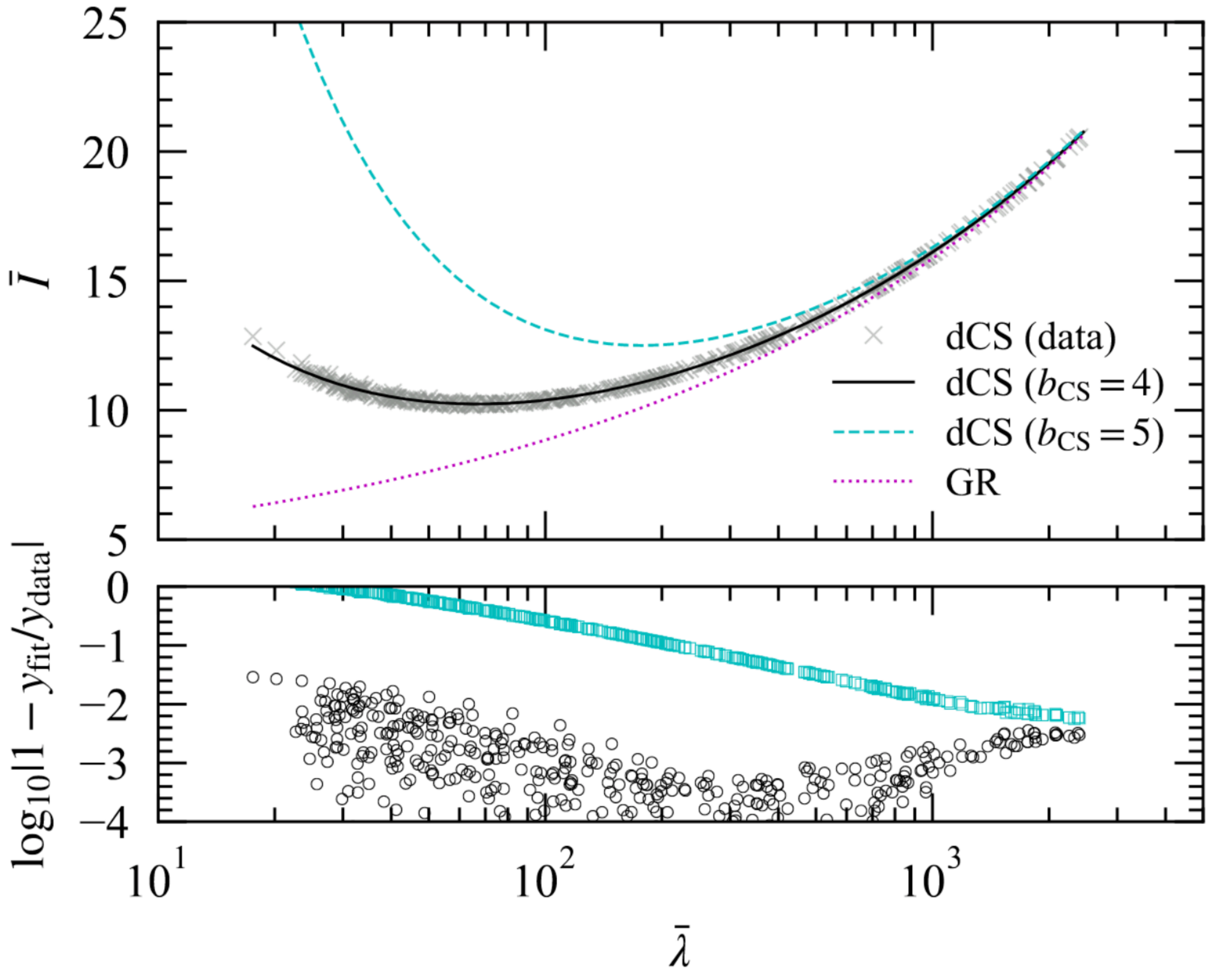
I-Love Chern-Simons?

$$\beta_{\rm CS} \approx 3\,(\alpha_{\rm CS}/M^2)^2\,,\;\; b_{\rm CS} = 4$$



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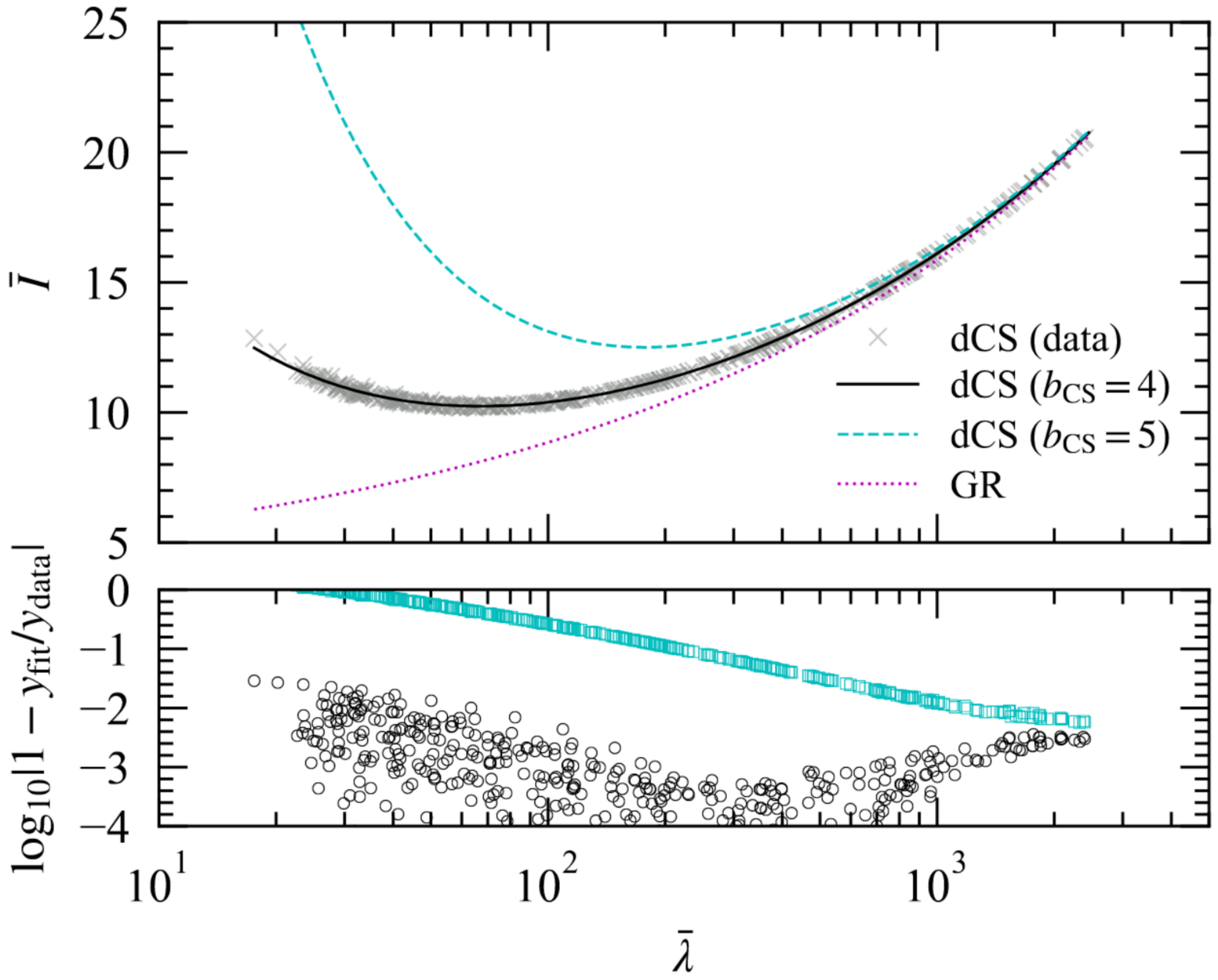

$$\sqrt{\alpha_{\rm CS}} \leqslant 8.5\,{\rm km} \ll 10^8\,{\rm km}$$

(and falls within the EFT-regime of the theory)

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The parametrised I-Love test can be used to **improve in seven orders of magnitude** previous bounds on otherwise a poorly constrained extension to general relativity.

Take-home messages

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- However, **equation-of-state independent relations** are a **powerful tool** to infer other neutron star observables and to perform **multimessenger tests of gravity**.

Take-home messages

- **Neutron stars are awesome**.
- In general, tests of gravity using neutron-star properties are hard due to our poor understanding of the equation of state.
- However, **equation-of-state independent relations** are a **powerful tool** to infer other neutron star observables and to perform **multimessenger tests of gravity**.
- Consistency with general relativity imposes the **strongest bound to date on gravitational parity violation**.