Matter of Love

@ INAF-Astronomical Observatory of Abruzzo

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MUR PRIN

Motivation

Flood of data coming from a web of current GW/EM detectors and of future GW/EM facilities

- Observations put at test the nature of compact objects, like neutron stars

  → *Can we use them to constrain the properties of stellar structure?*

  → *Can we use them to study fundamental forces in strong gravity regimes?*

Science cases

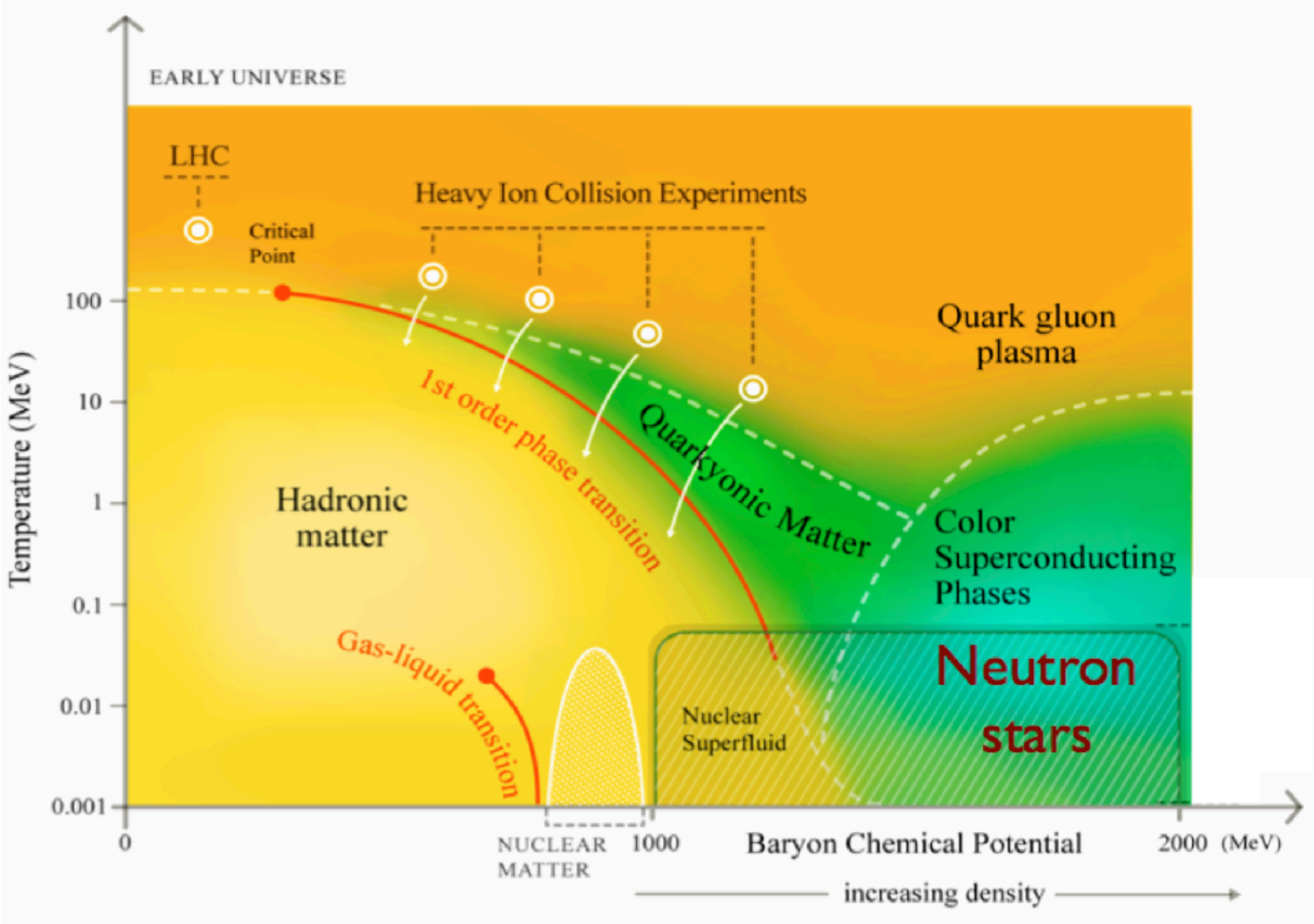
- The equation of state of dense matter
- Tests of gravity, of black hole nature, and of the existence of new families of compact objects

Observables and methodology

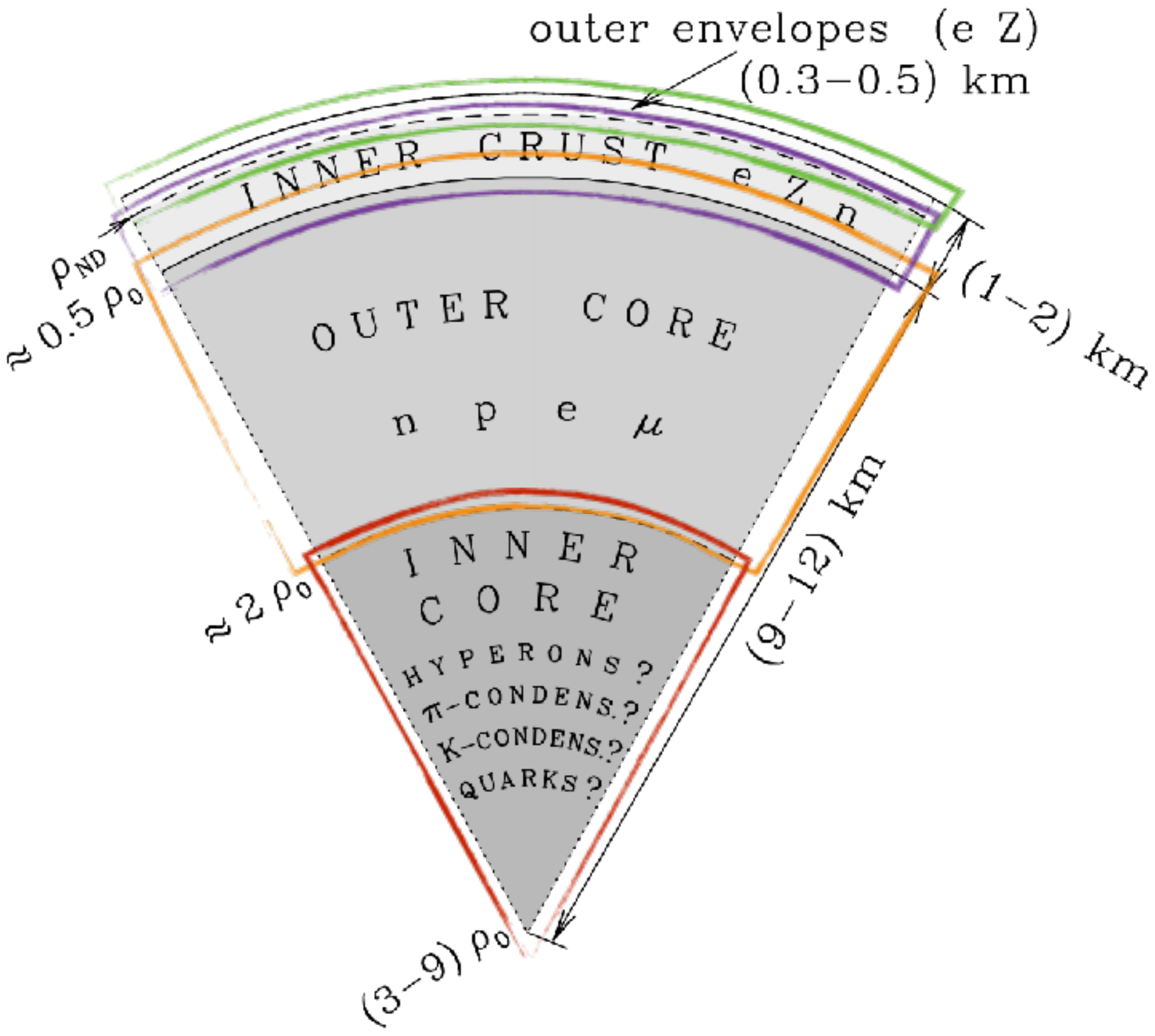
- Gravitational waves from binary neutron star binaries
- Gravitational waves from "exotic" binaries

State of matter

Magnifying lenses of fundamental forces



State of matter

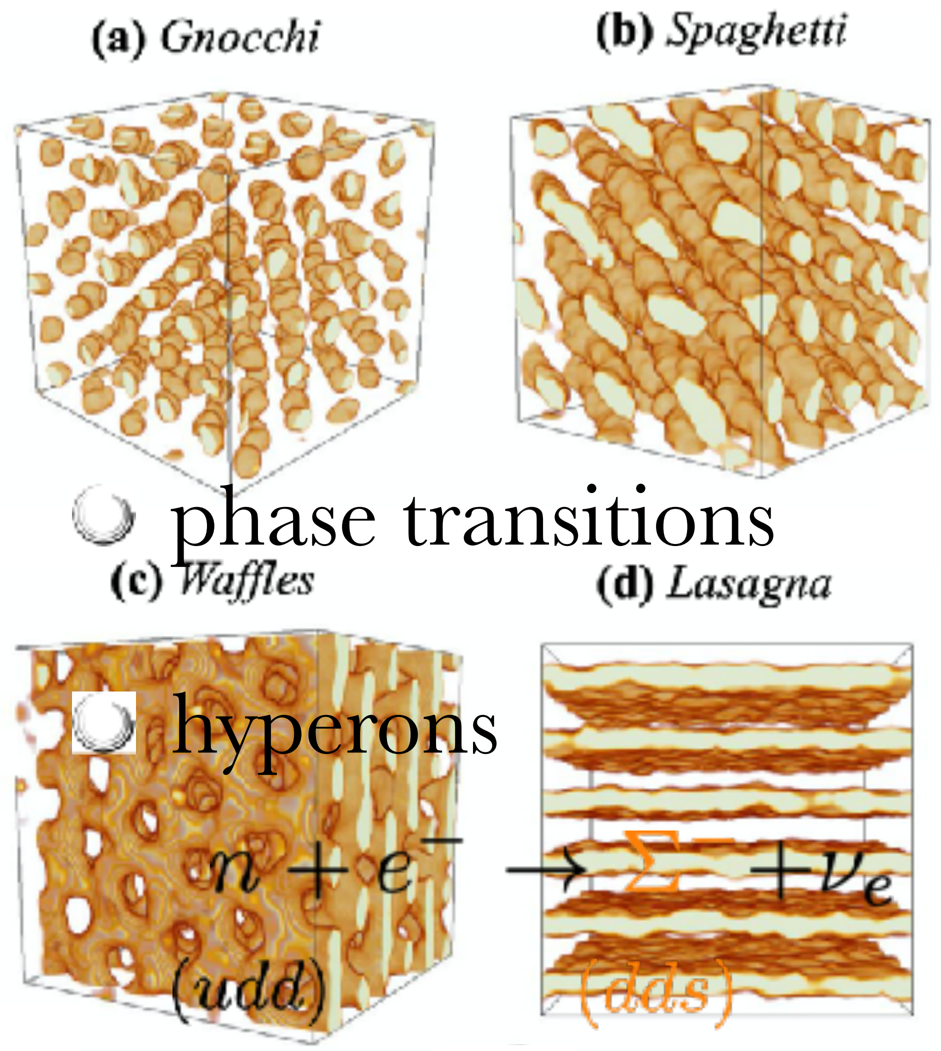


$\rho_0 \simeq 2.67 \times 10^{14}$g cm^{-3}

constraints at supranuclear density

Nuclei lattice within e^- gas

Pasta phases



- phase transitions
- hyperons

$n + e^- \to \Sigma + \nu_e$

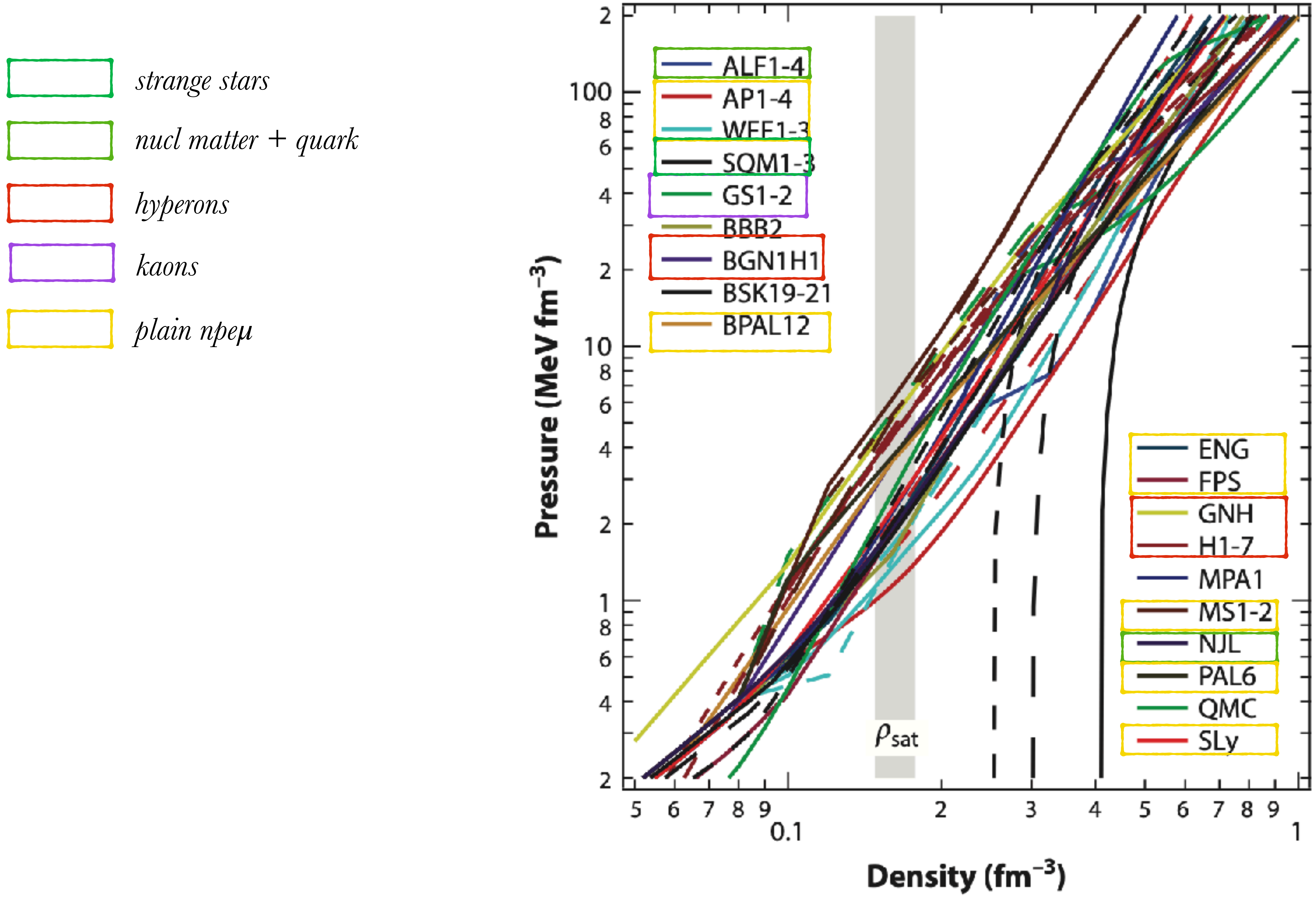
(udd) (dds)

- meson condensates
- quark deconfinement

J. Lattimer & M. Prakas, Phys. Rep. 621 (2016)

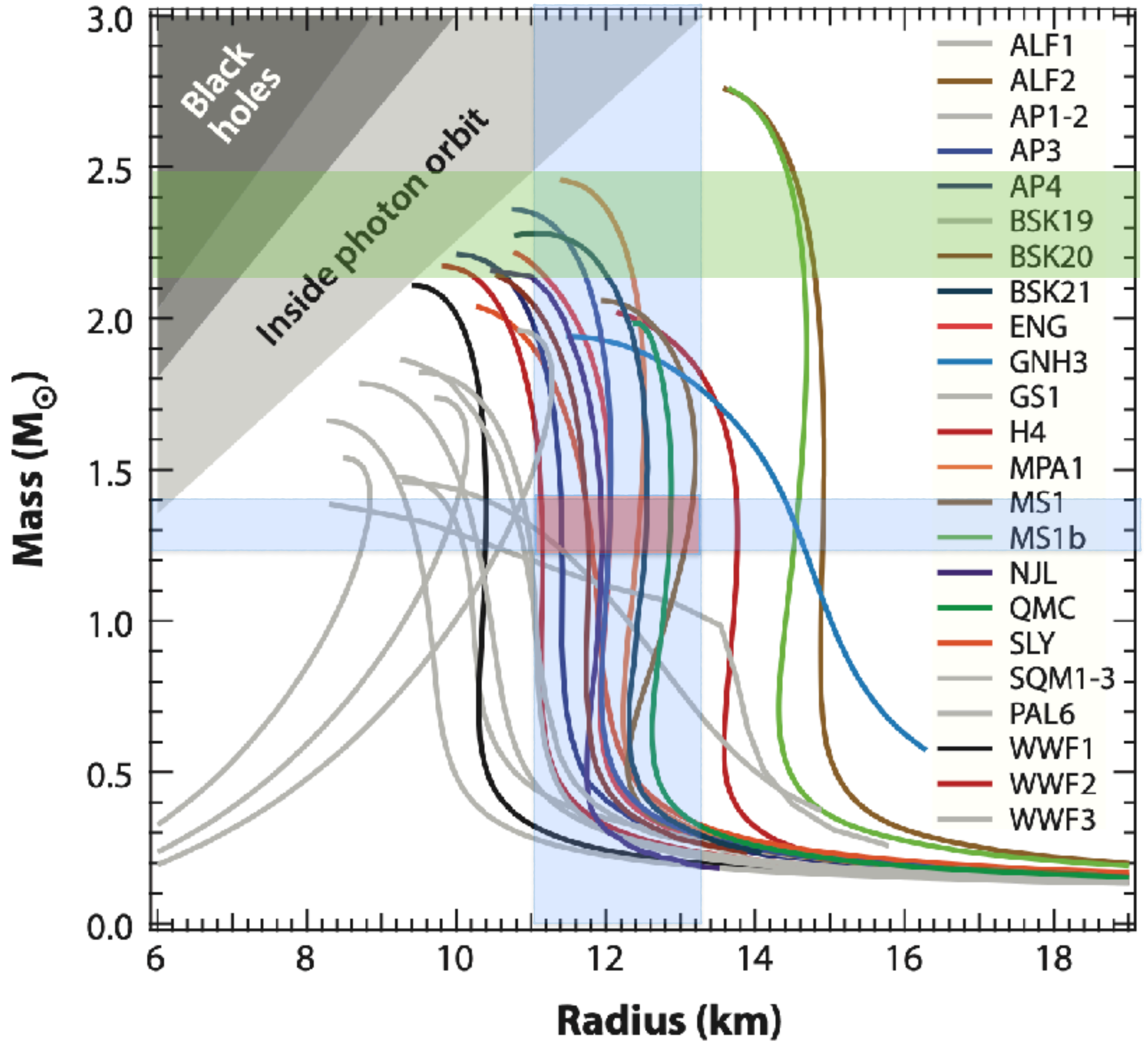
A micro-view: the equation of state

Microscopic relation $p = p(\epsilon)$



F. Özel & P. Freire, Ann. Rev. Astr. 5 (2016)

The equation of state



$2.32^{+0.17}_{-0.17} M_\odot$

PSR J0952+0607

F. Özel & P. Freire, Ann. Rev. Astr. 5 (2016)

From micro to macro

The holy grail of NS astrophysics

- (too) many models describing the NS interior
- how do we identify the correct one?

microscopic Equation of State

GWs
from binary NS

$$p = p(\epsilon, \dots)$$

EM *(pulsar, LMXB..)*
+
Labs

macroscopic observables $(M, R, I, \dots)$

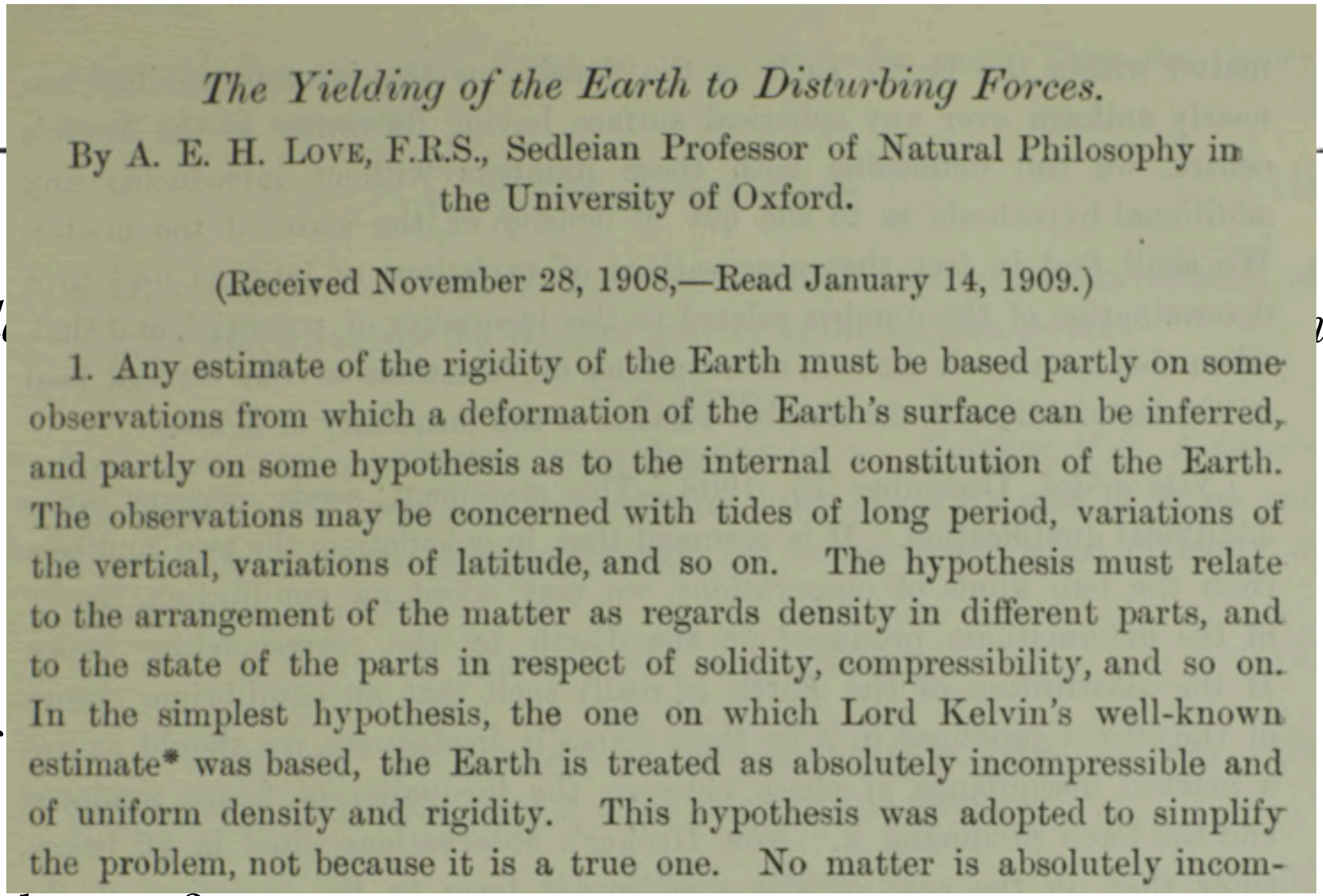
From micro to macro

Tidal interactions leave the footprint of the NS structure on the GW signal

- Deformation properties encoded within the Love numbers

star's quadrupol

al tidal field



The Yielding of the Earth to Disturbing Forces.

By A. E. H. Love, F.R.S., Sedleian Professor of Natural Philosophy in the University of Oxford.

(Received November 28, 1908,—Read January 14, 1909.)

1. Any estimate of the rigidity of the Earth must be based partly on some observations from which a deformation of the Earth's surface can be inferred, and partly on some hypothesis as to the internal constitution of the Earth. The observations may be concerned with tides of long period, variations of the vertical, variations of latitude, and so on. The hypothesis must relate to the arrangement of the matter as regards density in different parts, and to the state of the parts in respect of solidity, compressibility, and so on. In the simplest hypothesis, the one on which Lord Kelvin's well-known estimate* was based, the Earth is treated as absolutely incompressible and of uniform density and rigidity. This hypothesis was adopted to simplify the problem, not because it is a true one. No matter is absolutely incom-

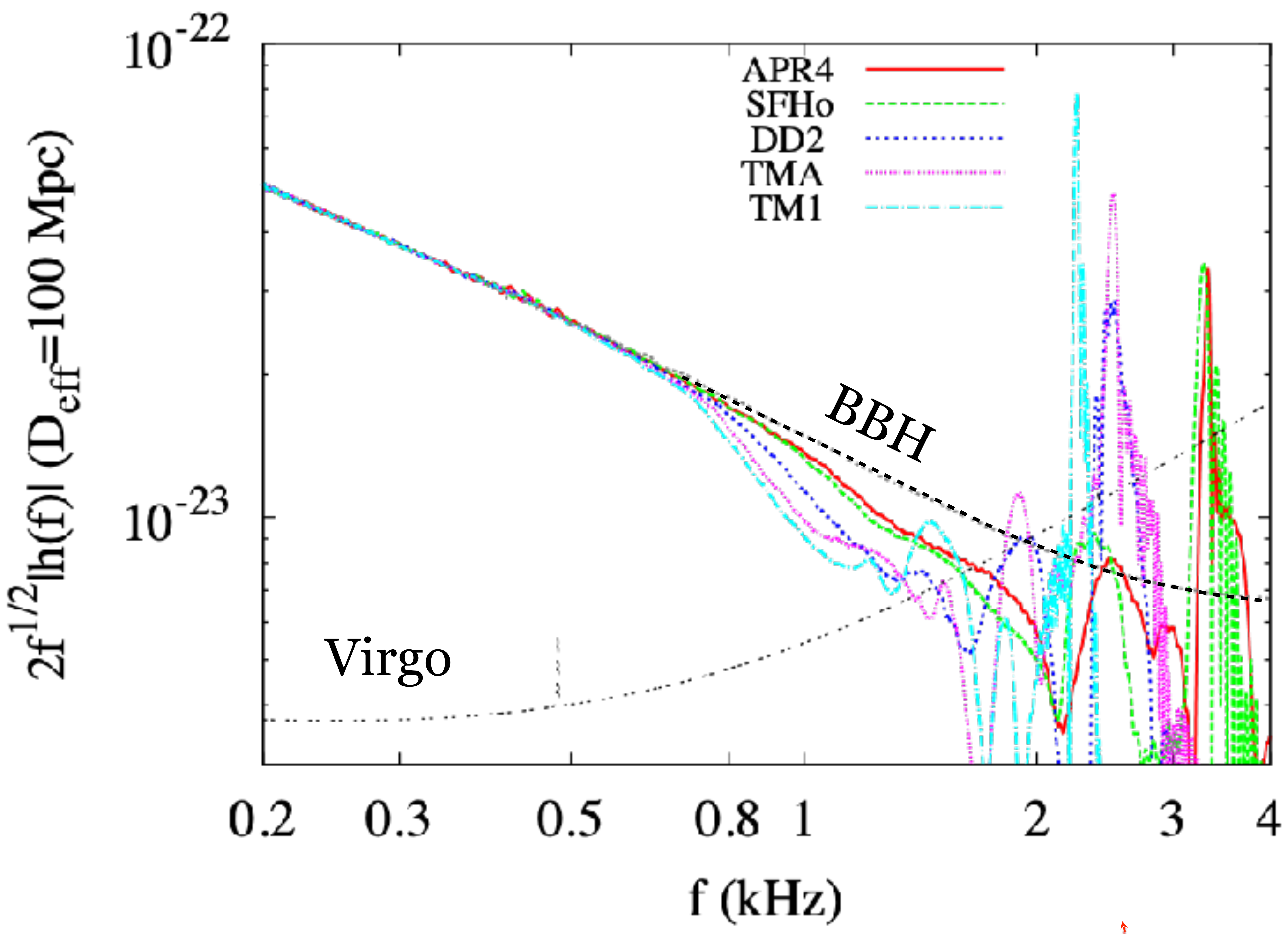
- λ depends on the EoS only, for

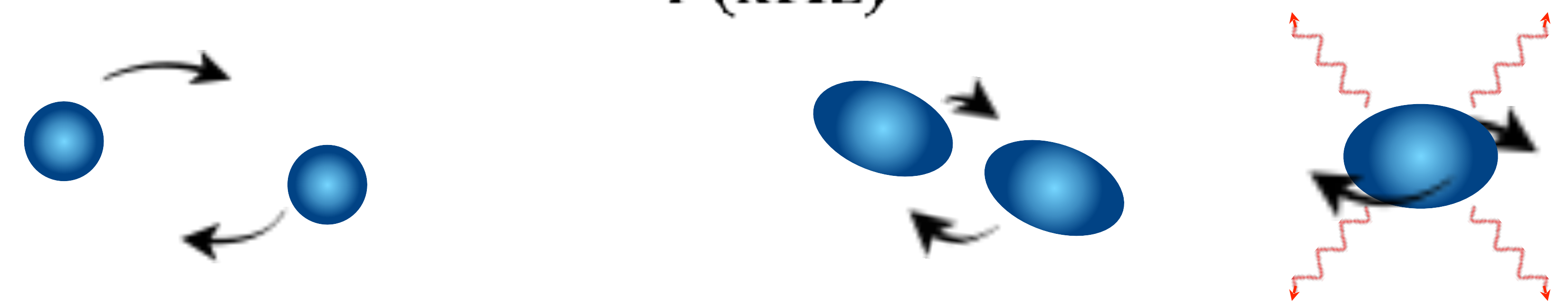
- λ enters within the gravitational waveform

T. Hinderer, The Astroph. J. 677 (2008);
T. Binnington & E. Poisson Phys. Rev. D 80, 084018 (2009)
T. Damour & A. Nagar, Phys. Rev. D 80, 084035 (2009)

How much love?

We classify EoS as stiff v.s. soft





inspiral

late inspiral

EoS	stiffness	R_{NS}	$10^3 \times \lambda$
APR4	very soft	11.09	10
SFHo	soft	11.91	13
DD2	medium soft	13.20	27
TMA	stiff	13.85	37
TM1	very stiff	14.48	45

Soft EoS

- larger densities
- smaller Love numbers

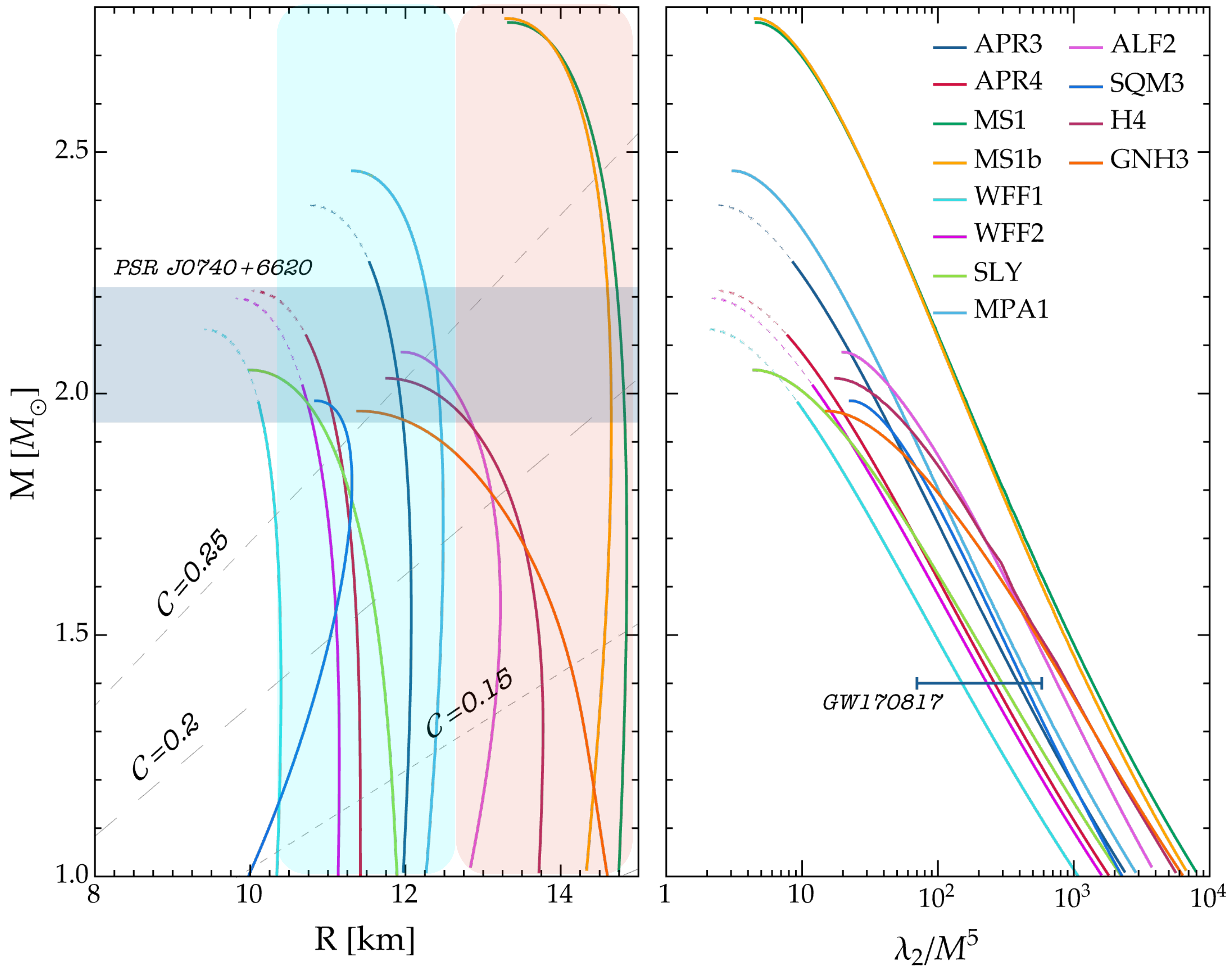
Stiff EoS

- smaller densities
- larger Love numbers

larger effect in the signal

Different types of Love

Build $\lambda - M$ profiles



soft stiff

neutron stars $M_{NS}/R_{NS} \in [0.1 - 0.2]$

$\lambda \neq 0 \quad \lambda \sim \mathcal{O}(10^4)$

BHs (in GR) $\lambda = 0$ ← *Schwarzschild Kerr*

P. Landry & E. Poisson Phys. Rev. D 91, 104018 (2015)
P. Pani + incl. A. M., Phys. Rev. D 92, 024010 (2015)
N. Gürlebeck, Phys. Rev. Lett. 114, 151102 (2015)
A. Le Tiec +, Phys.Rev. D 103 084021 (2021)

BHs non vacuum/ beyondGR ECOs $\lambda \neq 0$ ← *generic tests of gravity*

V. Cardoso + incl. A. M., Rev. Rev. D 95, 084014 (2017)
A. Maselli +, Phys. Rev. Lett 120, 081101 (2017)

Where do we look for Love?

Tidal effects add linearly to the phase $h(f) = \mathcal{A} e^{i[\psi_{\mathrm{PP}}(f)+\psi_{\mathrm{T}}(f)]}$

$$\psi_{\mathrm{PP}} \propto \left[1 - \left(\frac{743}{336} + \frac{11}{4}\eta\right)\frac{(m\pi f)^{2/3}}{c^2} + \frac{\cdots}{c^3} + \ \ldots\ + \frac{\cdots}{c^7}\right]$$

Newt

1 PN

3.5 PN

$$\psi_{\mathrm{T}} \propto \frac{1}{26}\left[\left(1 + 12\frac{m_2}{m_1}\right)\lambda_1 + \left(1 + 12\frac{m_1}{m_2}\right)\lambda_2\right]\frac{(m\pi f)^{10/3}}{c^{10}} + \frac{\cdots}{c^{12}}$$

Λ

average tidal deformability

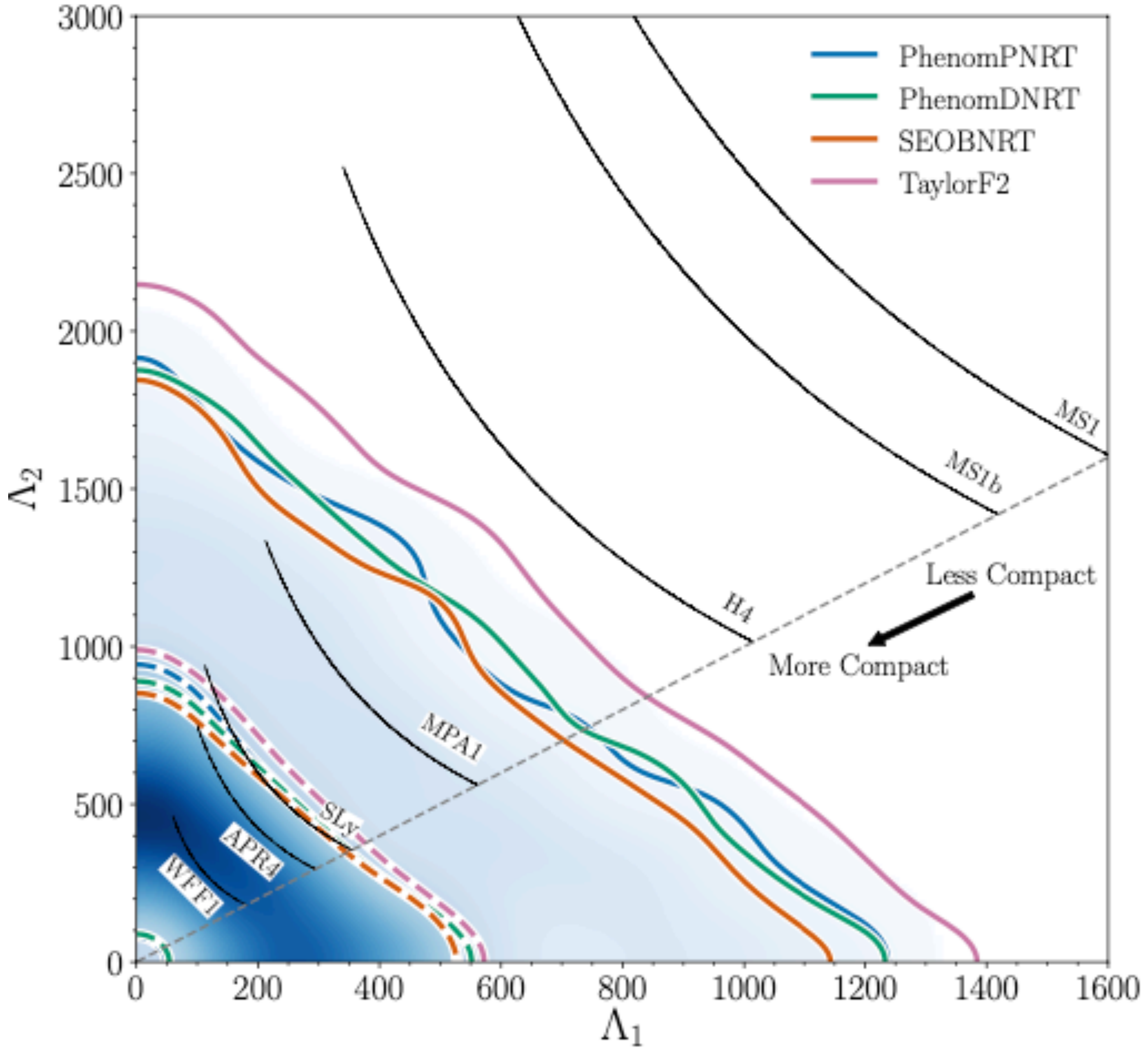
5 PN: small term!

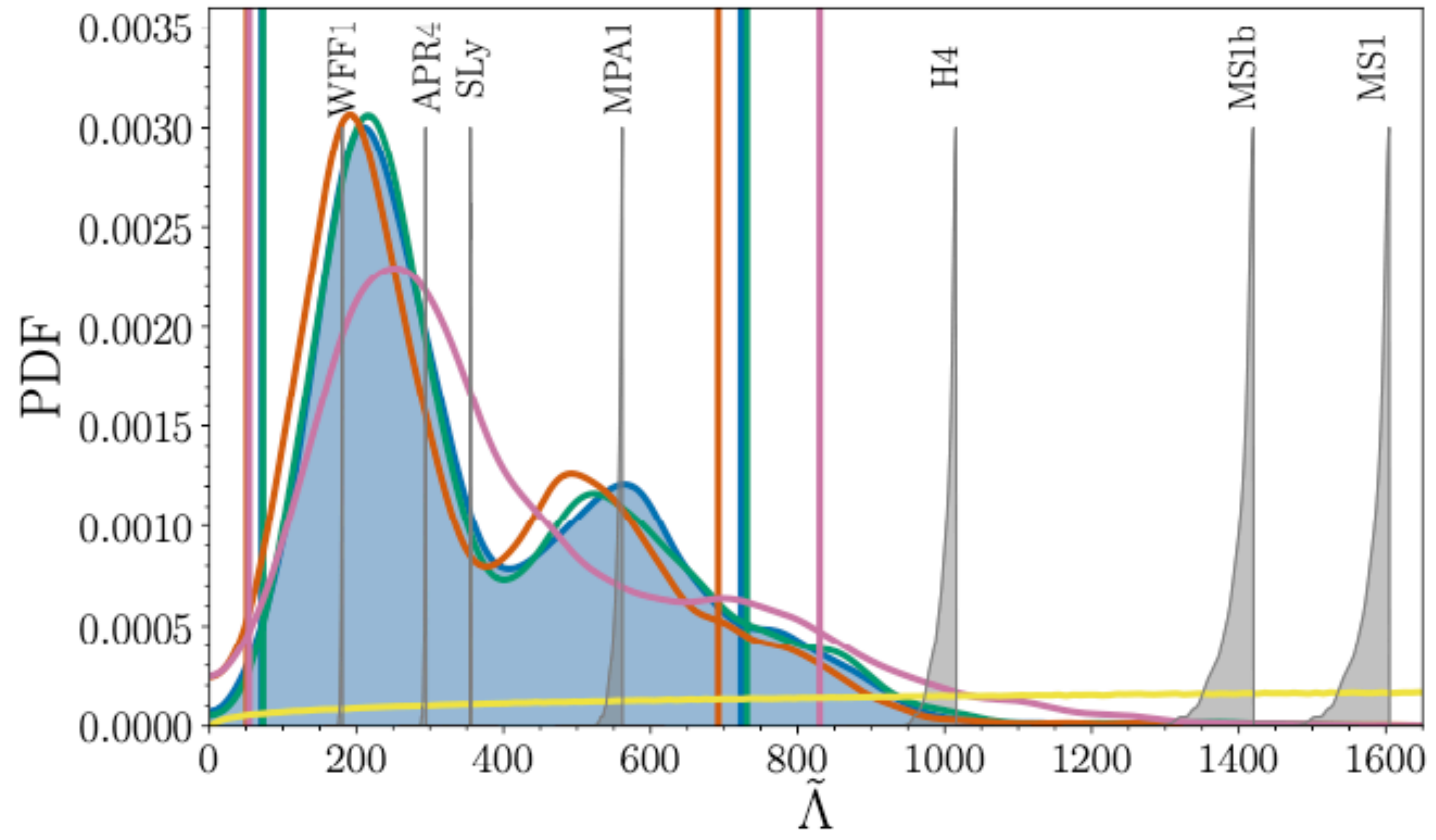
$\mathcal{O}(10^4)$

GW170817

The rest is history

$M_1(M_\odot)$	Λ_1	$M_2(M_\odot)$	Λ_2
$1.46^{+0.13}_{-0.09}$	255^{+416}_{-171}	$1.26^{+0.09}_{-0.12}$	661^{+858}_{-375}



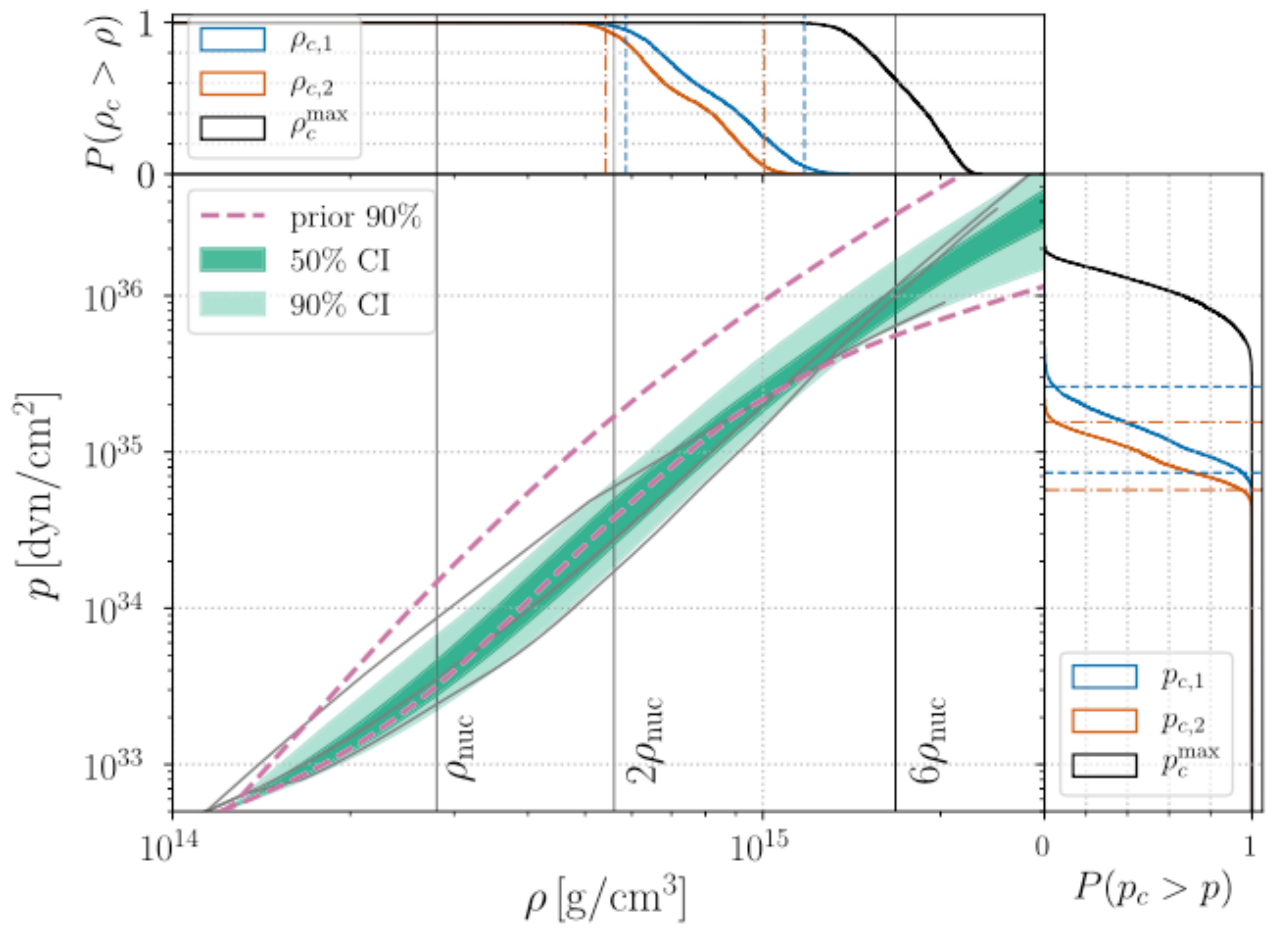


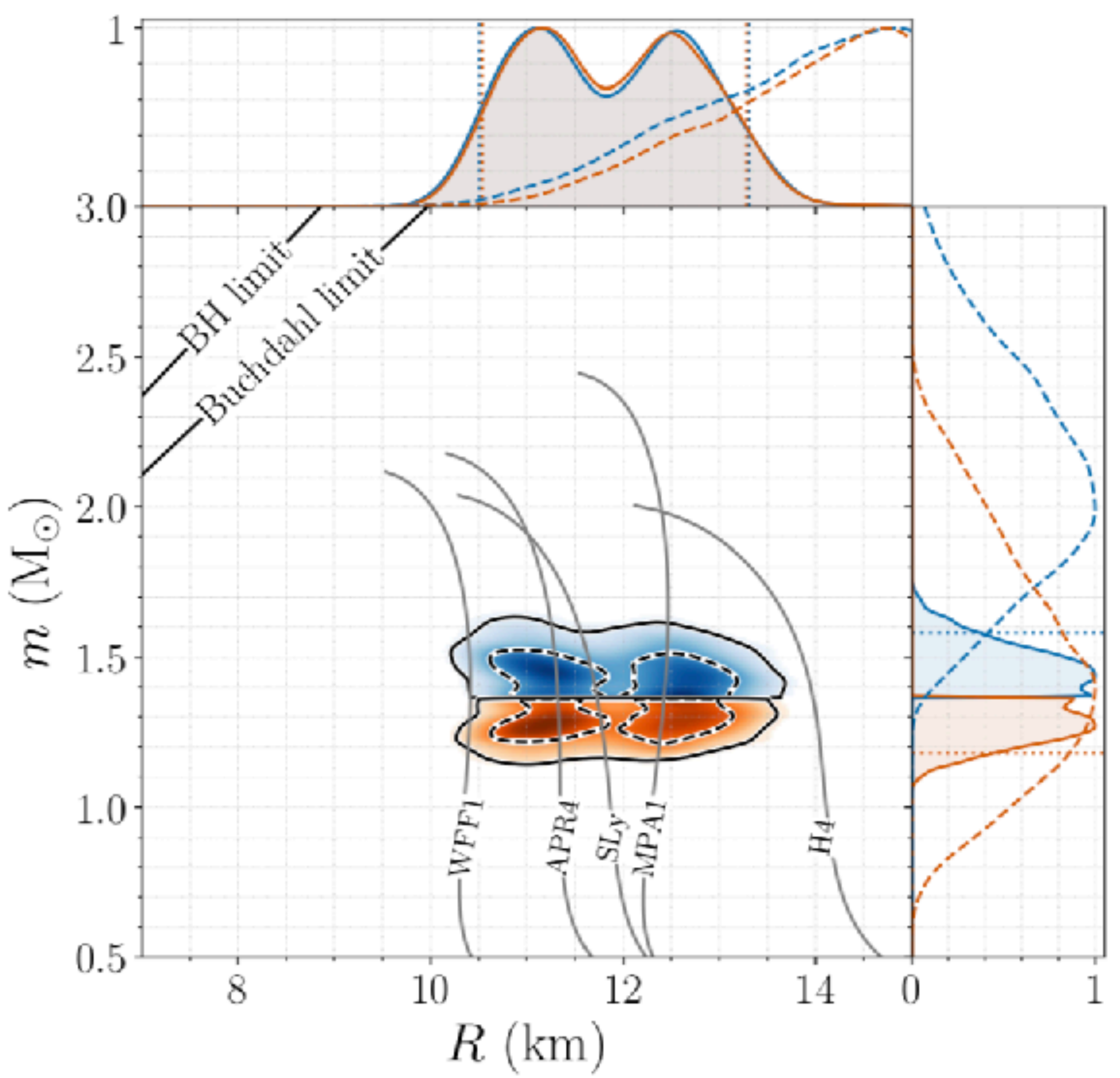
LVC, Phys. Rev. Lett. 119-121 (2018)
LVC, Phys. Rev. X 9 (2019)

First BNS detection seems to favour more compact nuclear matter

- ruling out stiff Equations of State

GW170817





- Reconstructed radii $R_1 = 10.8^{+2.0}_{-1.7}$ km and $R_1 = 10.7^{+2.1}_{-1.5}$ km
  - Adding maximum mass constraint $R_2 = R_1 = 10.9^{+1.4}_{-1.4}$ km

Ranking the Love

Can we discriminate among families of EoS which differ in particle content and ab-initio microscopic calculations

C. Pacilio, A. M. +, Phys. Rev. Lett. 128, 101101 (2022)

- Hierarchical Bayesian test which rank different EoS given GW binary NS observations

$$\mathcal{B}^1_2 = \frac{\mathcal{Z}(\mathcal{D}|\mathrm{EoS}_1)}{\mathcal{Z}(\mathcal{D}|\mathrm{EoS}_2)} \xrightarrow{n \text{ events}} \mathcal{B}^1_2 = \prod_{k=1}^{n} \frac{\mathcal{Z}(\mathcal{D}_k|\mathrm{EoS}_1)}{\mathcal{Z}(\mathcal{D}_k|\mathrm{EoS}_2)}$$

- Ranking criteria

$$\log_{10} \mathcal{B}^1_2 < -2$$

EoS 1 decisively disfavoured

$$-2 \leq \log_{10} \mathcal{B}^1_2 \leq -1$$

EoS 1 strongly disfavoured

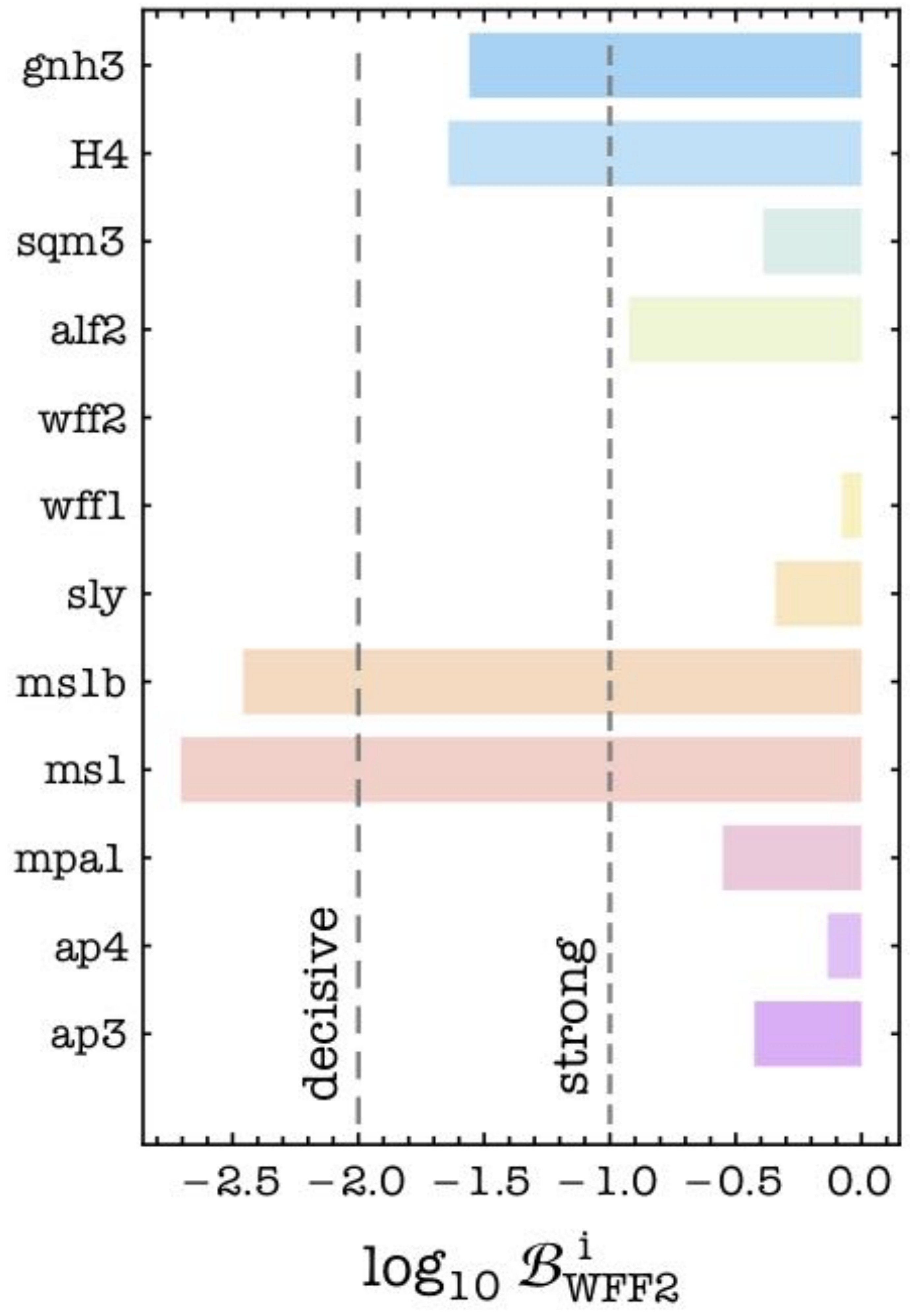
12 EoS based on microscopic calculations

EoS	family	particles
ALF2	nmbt+bag	$npe\mu + Q$
APR3	nmbt	$npe\mu$
APR4	nmbt	$npe\mu$
GNH3	rmft	$npe\mu + H$
H4	rmft	$npe\mu + H$
MPA1	rmft	$npe\mu$
MS1	rmft	$npe\mu$
MS1b	rmft	$npe\mu$
SLY	rmft	$npe\mu$
SQM3	rmft+bag	$npe\mu + H + Q$
WFF1	nmbt	$npe\mu$
WFF2	nmbt	$npe\mu$

Ranking with GW170817

Bayes factor normalised to the EoS with the largest evidence (WFF2)

WFF2 v.s. __



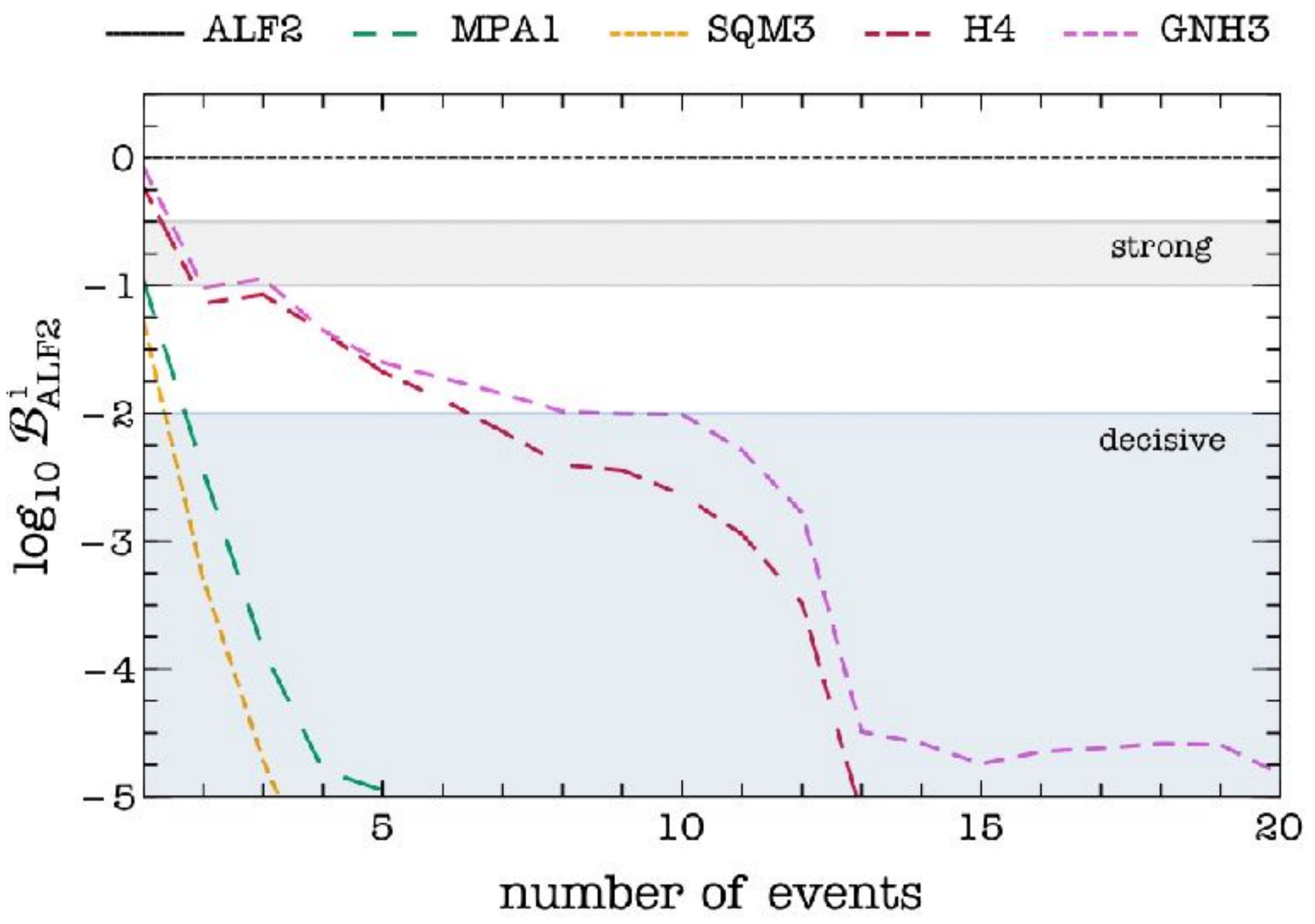
- The evidence against other EoS is weak beside GNH3 and H4
- Decisive evidence against MS1 and MS1b
    - Stiffest EoS of the catalogue

Can we do better with <u>more</u> help?

LVK stacking

Bayes factor as a function of # of events detected by HLV at design sensitivity

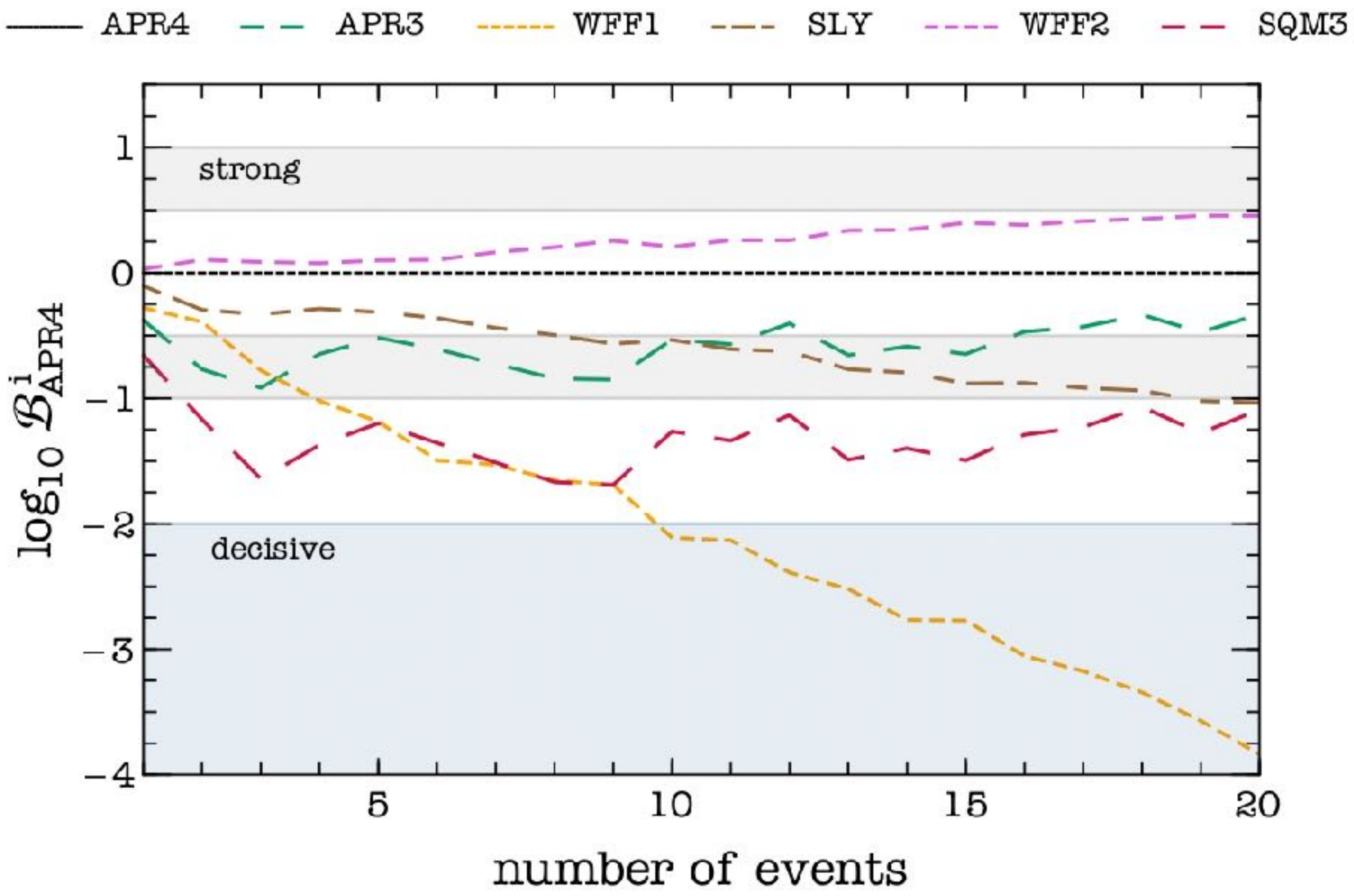
- Simulated catalogue of observations with 20 events ∈ [20,210]Mpc
- Injecting a stiff EoS (ALF2)



- EoS with stiffness different from ALF2 are immediately ruled out
- After ~ 10 events EoS with stiffness similar to ALF2 are ruled out

LVK stacking

Injecting a soft EoS (APR4)

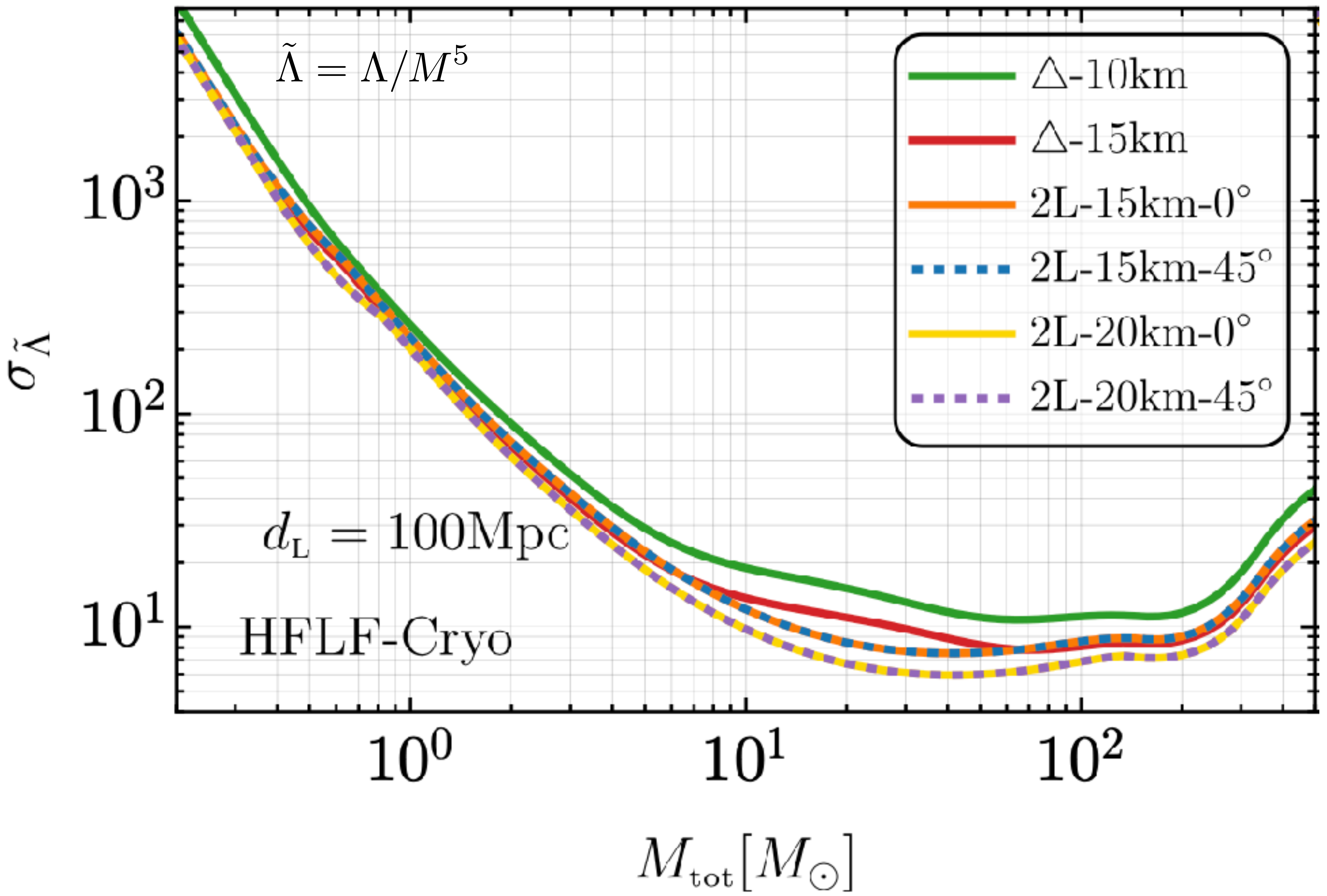


- Challenging to discriminate among EoS with similar stiffness
- Even multiple detections are not enough to discriminate models with different methods & particle content

Love forecasts with ET

Accuracy on the tidal deformability by different ET configurations

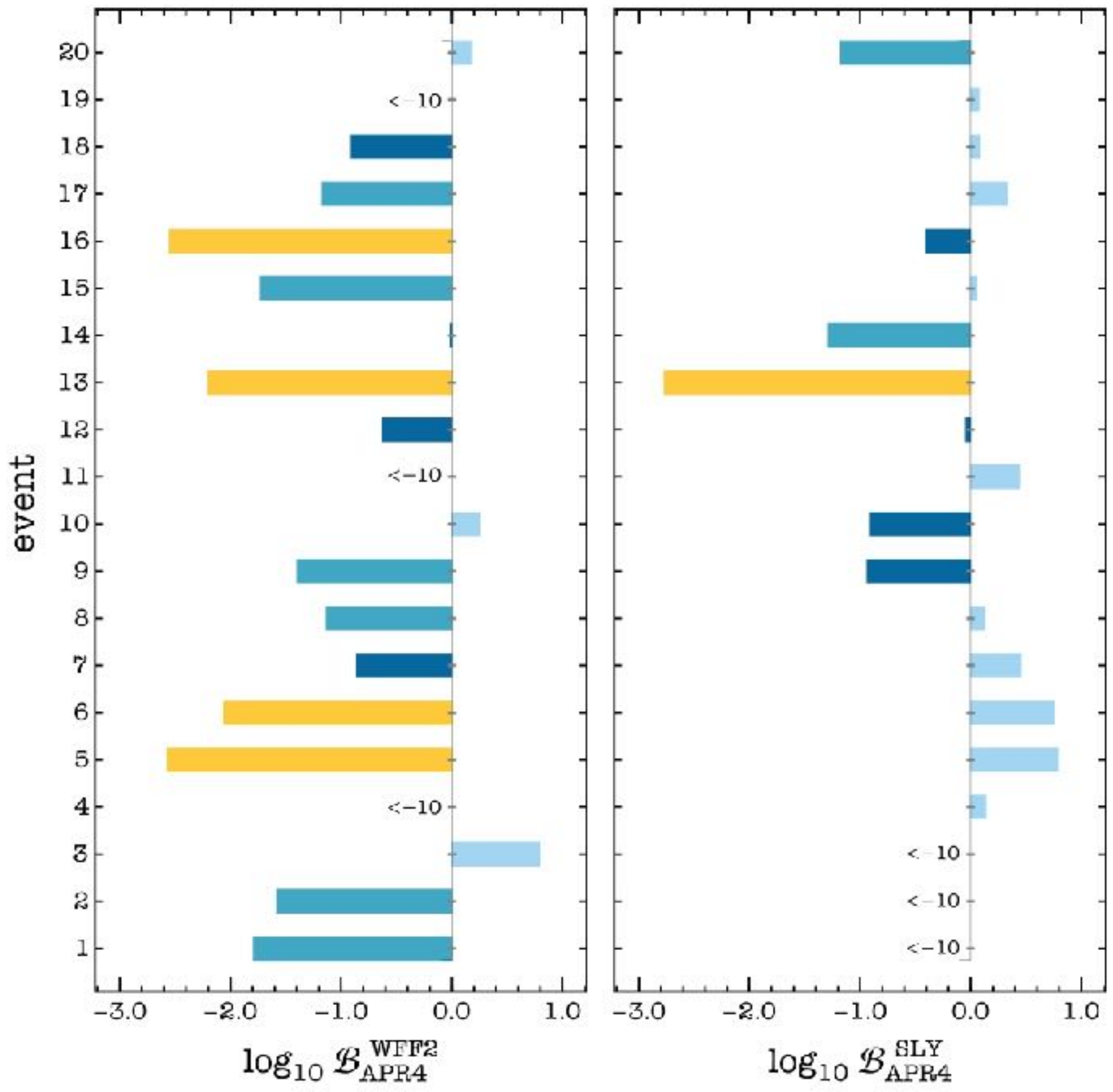
M. Branchesi + JCAP 07, 068 (2023)



ET ranking

Ranking the EoS with 3g detectors: the Einstein Telescope boost

- How does the pessimistic case of a <u>soft</u> EoS (APR4) injected into data behave?



- Just 2 EoS in the dataset survive to the selection
- Combining ~ 3 events rules out all EoS different from APR4

ET can distinguish <u>stiffness</u>
and <u>micro-physics</u>

APR4	nmbt	$npe\mu$
GNH3	rmft	$npe\mu + H$
H4	rmft	$npe\mu + H$
MPA1	rmft	$npe\mu$
MS1	rmft	$npe\mu$
MS1b	rmft	$npe\mu$
SLY	rmft	$npe\mu$

The era of multi-messenger

GW170817 triggered multi-messenger analyses of the EoS

- Exploiting properties of gamma ray burst, kilonova, and in general post merger phase of the event
- Maximum mass bound from heaviest pulsar observed $M \lesssim 2.3 M_\odot$
- Bound on the deformability from below $\Lambda \gtrsim 300$

Rezzolla +, The Astroph. J. 852, 2018
Magalit+, The Astroph. J.850, 2017
Ruiz +, Phys. Rev. D 97, 2017
Most +, Phys. Rev Lett. 120, 2018
Bauswein +, The Astroph. J.850, 2017
Coughlin +, Mon. Not. R. Astr. 480, 2018
Radice & Lai, Eur. Phys. J. 55 , 2019
Radice +, The Astroph. J. 852, 2018
Coughlin +, Mon. Not. R. Astr. 489, 2019
LVC, Class. Quant. Grav.37, 2020
Ai +, The Astroph. J. 893, 2020
Shibata+, Phys. Rev. D 96, 2017
Annala +, Phys. Rev. Lett. 120, 2018
Shibata+, Phys. Rev. D 100, 2019
Shao + , Phys. Rev. D 101, 2020
Carson +, Phys. Rev. D 100, 2019
……..

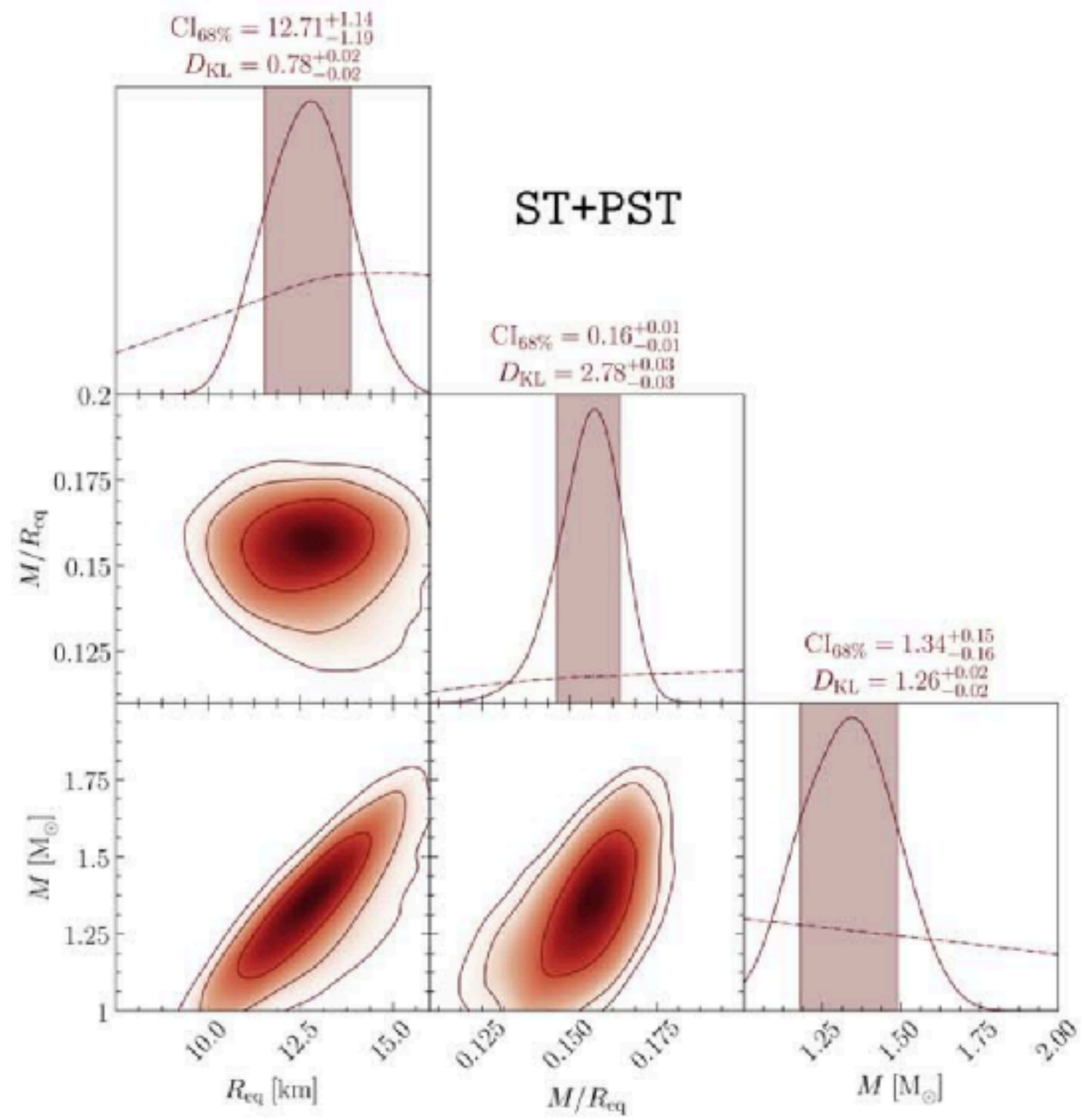
The NICER view

Observation of ms pulsar PSR J0030+0451

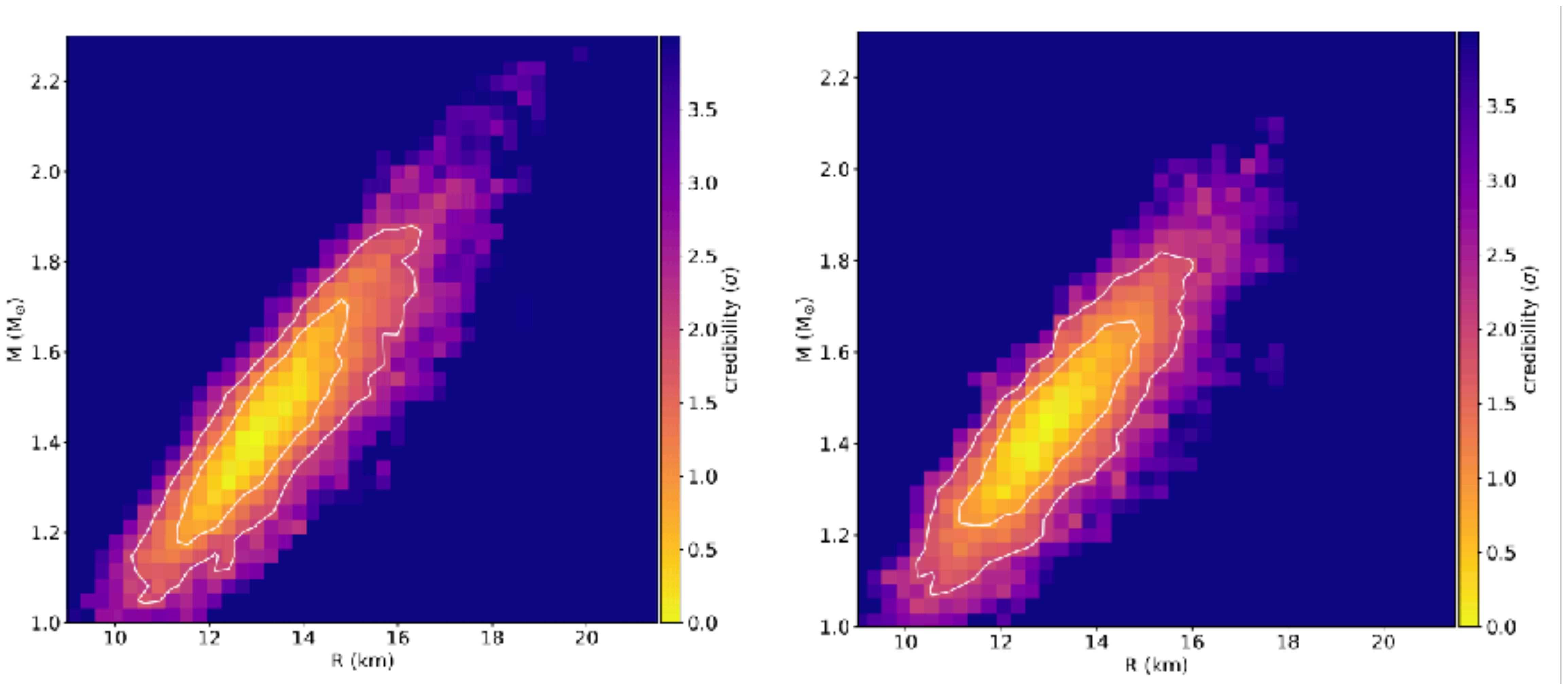
T. Riley +, The Astroph. J. Lett. 887 (2019)
C. Miller +, The Astroph. J. Lett. 887 (2019)

- Tracing thermal emission from hot-spot region of the stellar surface
- Two hot regions assumed & associated with two pulsed components

$M = 1.34^{+0.15}_{-0.16} M_\odot \qquad R_e = 12.71^{+1.14}_{-1.19}\mathrm{km}$



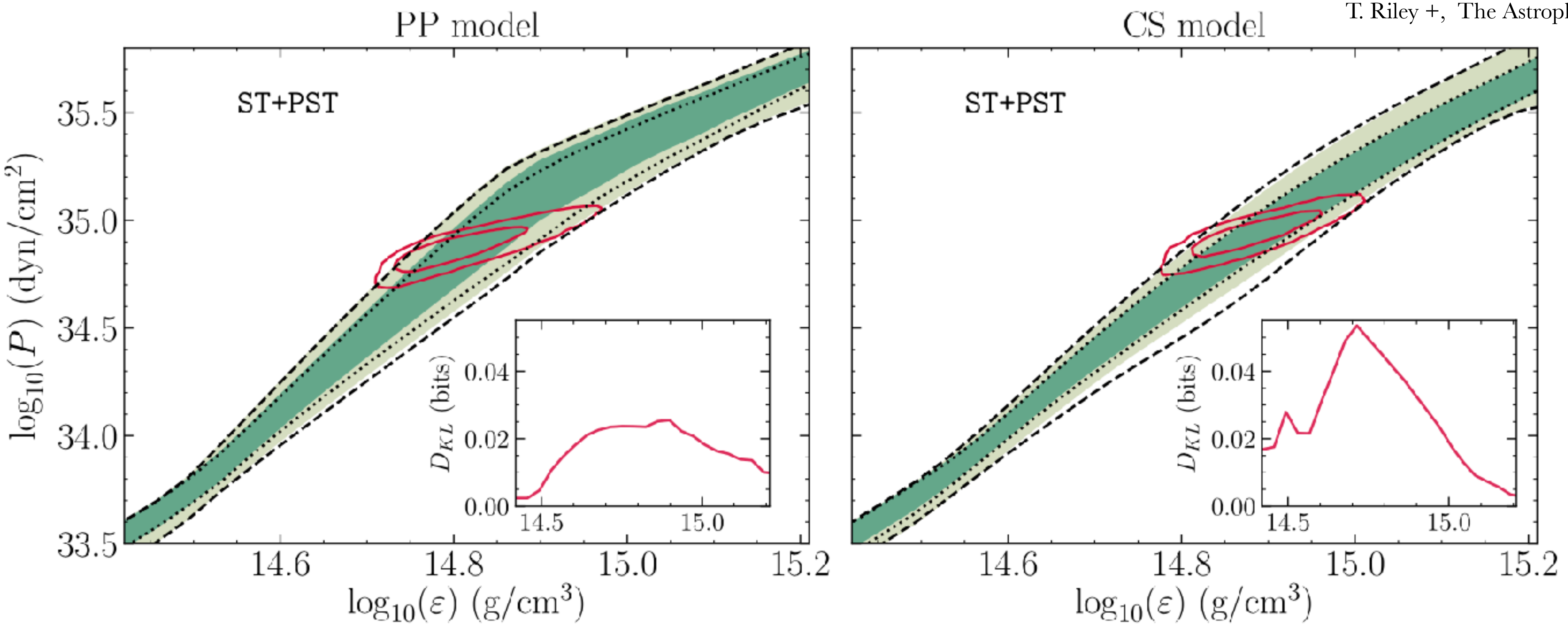
$M = 1.44^{+0.15}_{-0.14} M_\odot \qquad R_e = 13.02^{+1.24}_{-1.06}\mathrm{km}$



The NICER view

Implications for the stellar EoS

T. Riley +, The Astroph. J. Lett. 887 (2019)

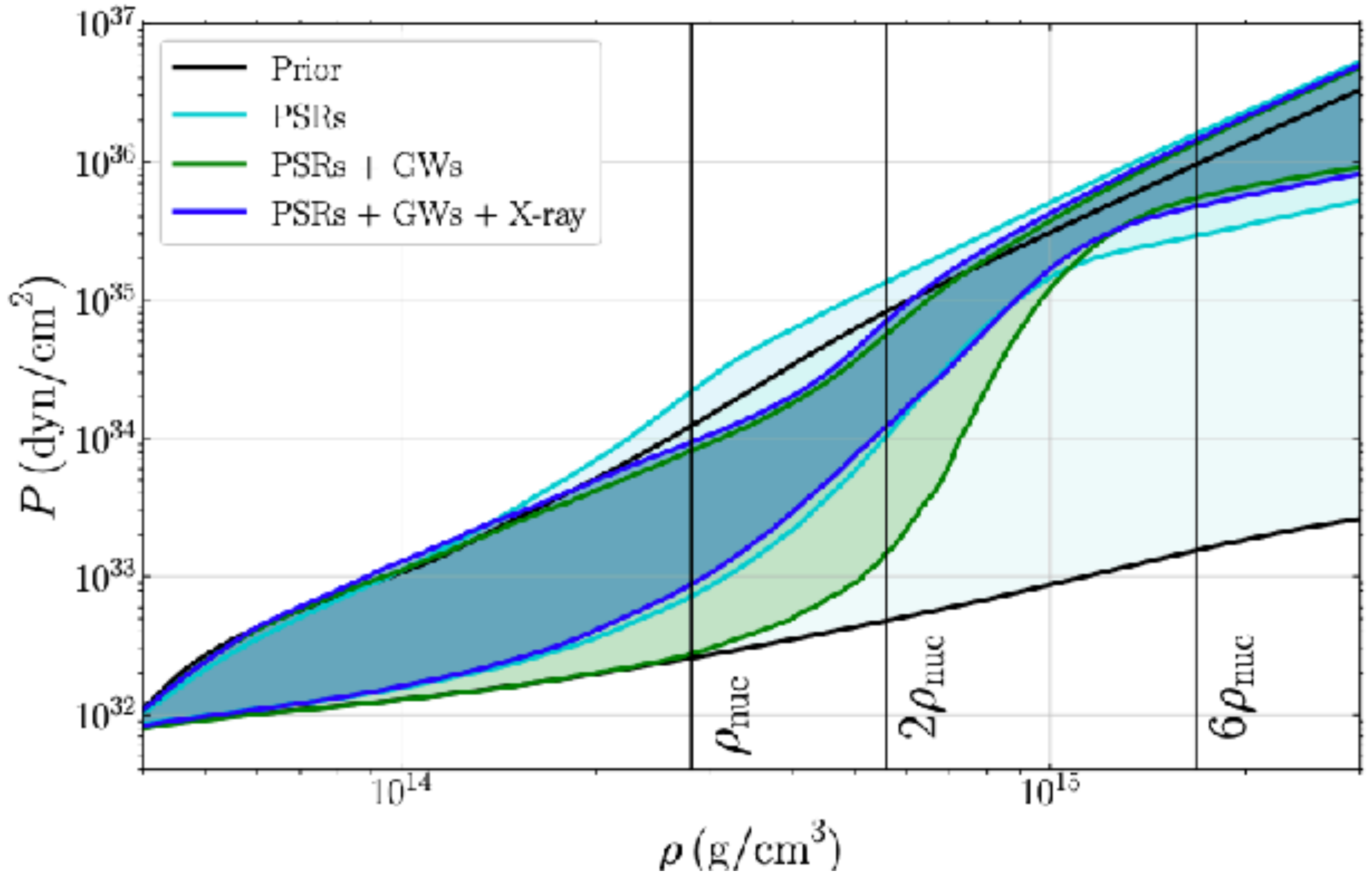


- Stiffer EoS compared to results from GW170817

GW170817 + NICER

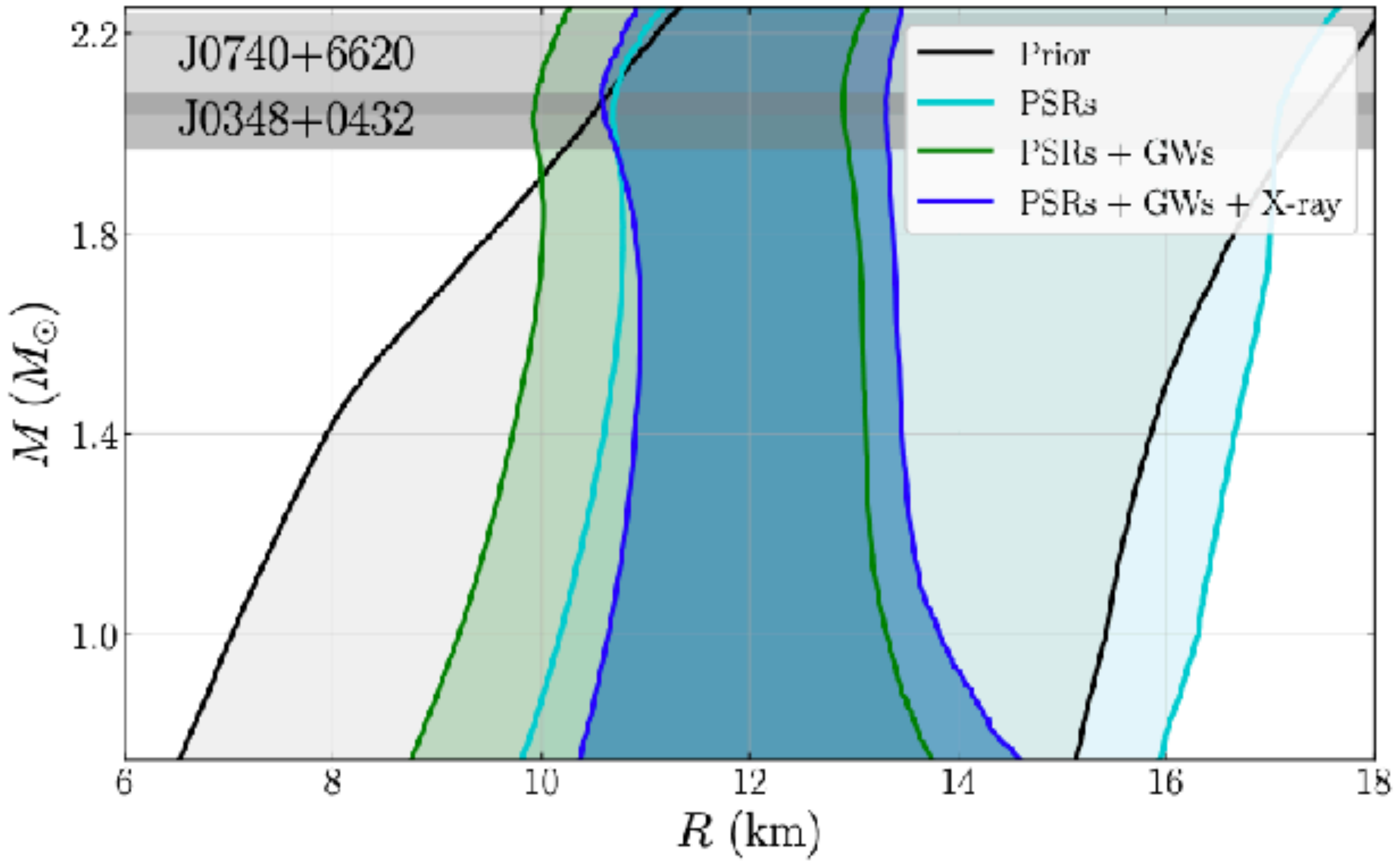
Combining GW and EM datasets

P. Landry +, Phys. Rev. D. 101 (2019)



PSR	m [$M_\odot$]
J1614−2230 [7, 91]	$1.928^{+0.017}_{-0.017}$
J0348+0432 [8]	$2.01^{+0.04}_{-0.04}$
J0740+6620 [9]	$2.14^{+0.10}_{-0.09}$

PSR	m [$M_\odot$]	R [km]
J0030+0451, 2-spot [60]	$1.44^{+0.19}_{-0.16}$	$13.27^{+1.41}_{-1.49}$
J0030+0451, 3-spot [60]	$\mathbf{1.44^{+0.15}_{-0.14}}$	$\mathbf{13.01^{+1.36}_{-1.06}}$
J0030+0451, ST+PST [61]	$\mathbf{1.34^{+0.16}_{-0.15}}$	$\mathbf{12.71^{+1.27}_{-1.18}}$
J0030+0451, ST+CST [61]	$1.43^{+0.19}_{-0.19}$	$13.86^{+1.34}_{-1.39}$

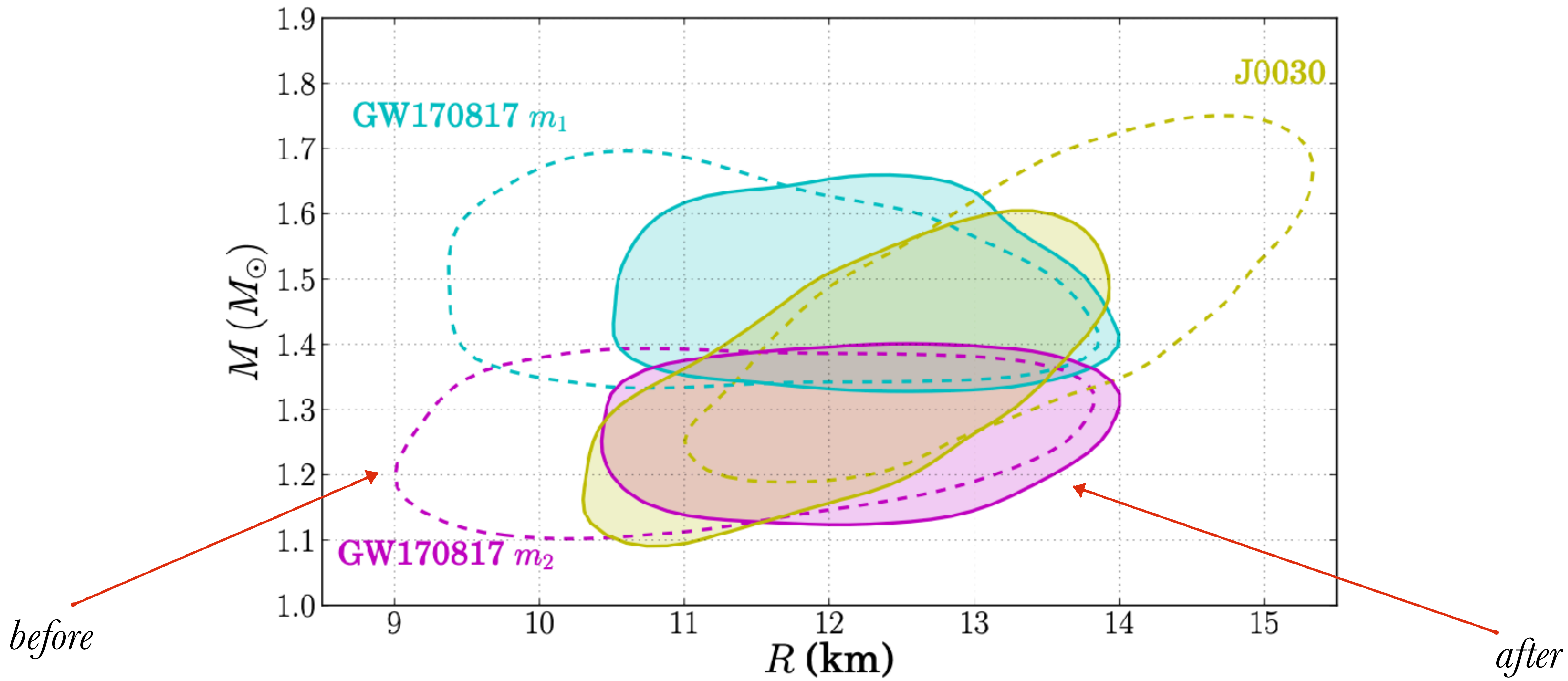


BNS	$\mathcal{M}$ [$M_\odot$]	q	$\tilde{\Lambda}$
GW170817 [29, 32]	$1.186^{+0.001}_{-0.001}$	(0.73, 1.00)	300^{+500}_{-190}
GW190425 [30]	$1.44^{+0.02}_{-0.02}$	(0.8, 1.0)	$\lesssim 600$

GW170817 + NICER

P. Landry +, Phys. Rev. D. 101 (2019)

Revisiting each observation after the joint analysis



Nucleon interactions

Love numbers provide an average description of the EoS

A. Maselli +, Phys. Rev. C 103, 065804 (2021)
A. Sabbatucci + incl A. M., Phys. Rev. D 106, 083010 (2022)
H. Rose + *Phys.Rev.C* 108, 025811 (2023)

- Can we go further and directly infer microscopic properties of nuclear interactions?

  → Strength of hadron interactions from GW/EM observations

- Nucleon dynamics for a given EoS based on non-relativistic many body theory

$$\mathcal{H} = \sum_i \frac{p_i^2}{2m} + \sum_{j>i} v_{ij} + \sum_{k>i>j} V_{ijk}$$

2-body (v_{ij}), *3-body* (V_{ijk})

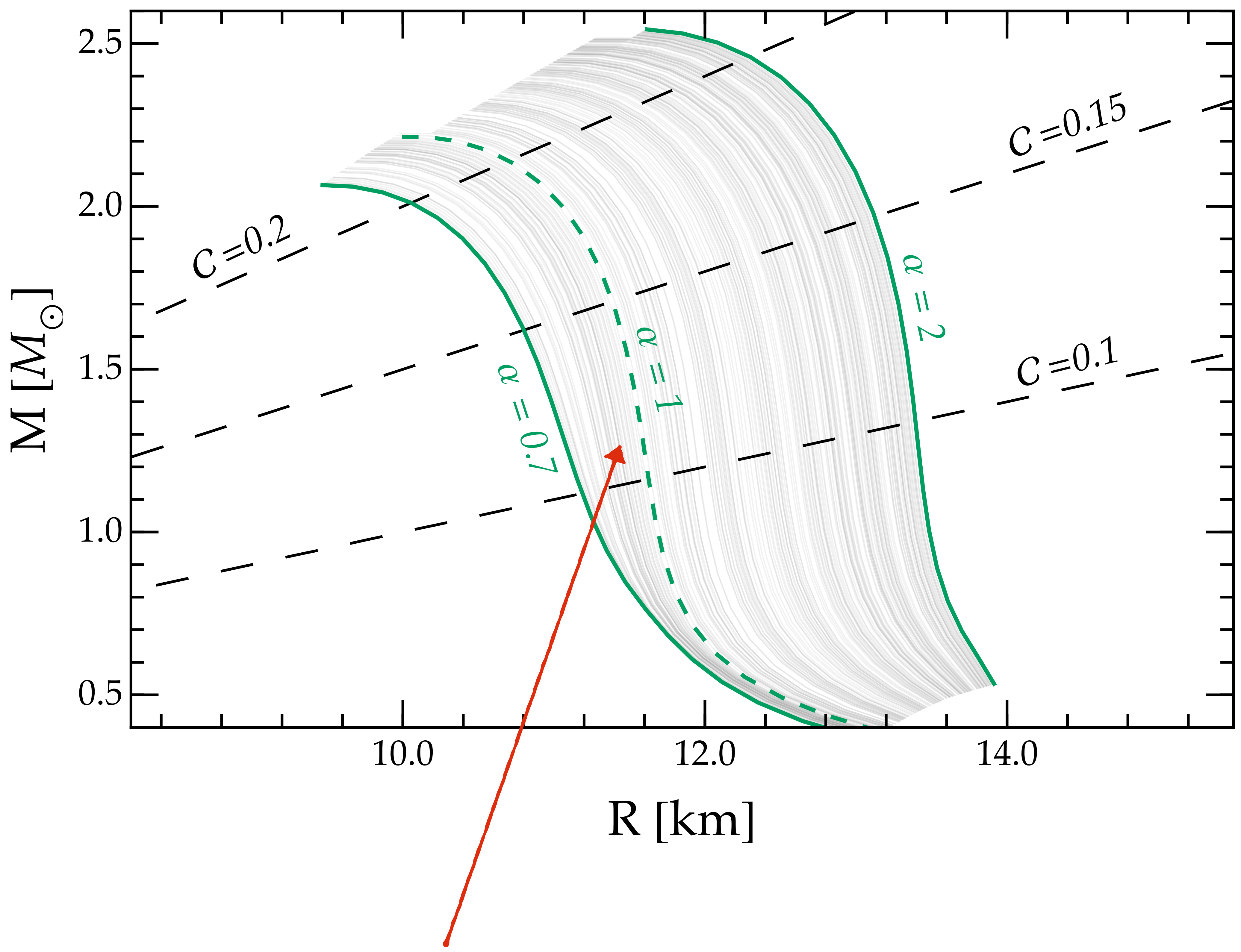
- 3-body nucleon potential, unconstrained at $\rho \gg \rho_0$

$$V_{ijk} = V_{ijk}^{2\pi} + V_{ijk}^{\mathrm{R}} \longrightarrow V_{ijk}^{\mathrm{R}} \to \alpha V_{ijk}^{\mathrm{R}}$$

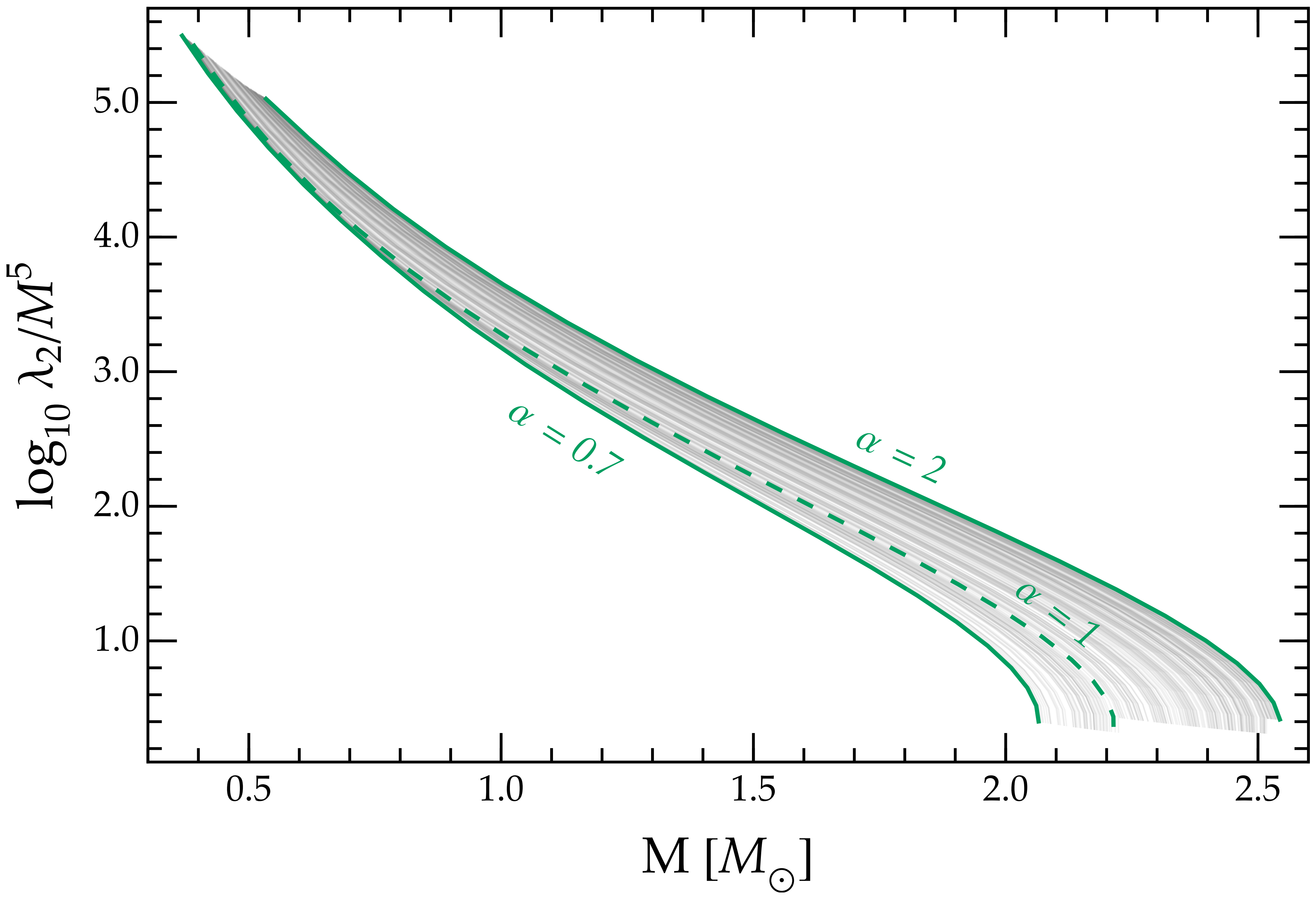
infer directly from the data (α)

3-body forces: stellar configurations

Change in the macroscopic observables due to 3-body forces



reference value



3-body forces: MM constraints

Multi-messenger constraints on the strength of 3-body forces from GW and EM observations

A. Sabbatucci + incl A. M., Phys. Rev. D 106, 083010 (2022)

- GW170817

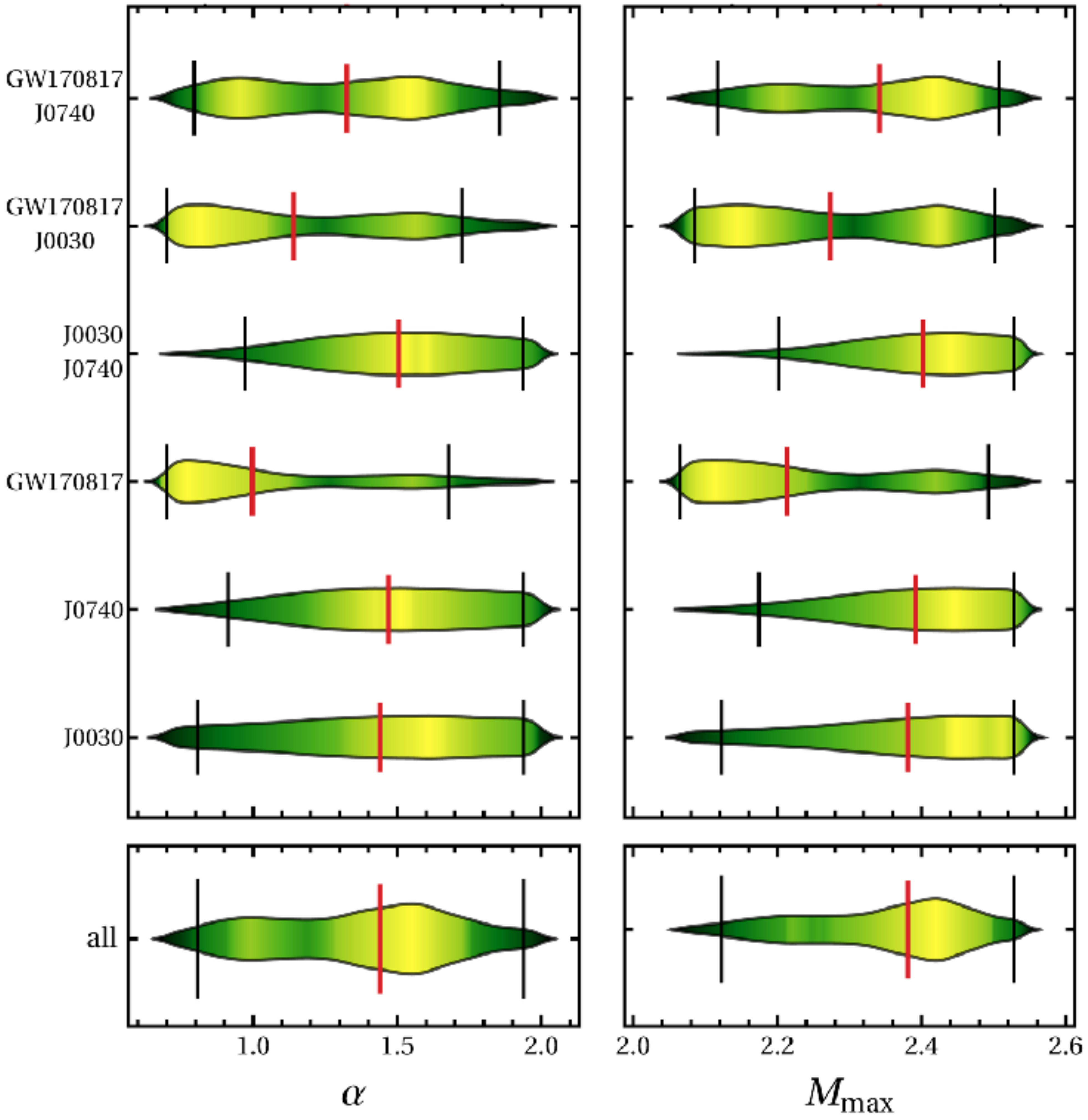
$m_1 \sim 1.16 M_\odot$ $\quad m_2 \sim 1.6 M_\odot$ $\quad \tilde{\Lambda} = 300^{+420}_{-230}$

- NICER pulsars

$M = 1.34^{+0.15}_{-0.16} M_\odot$ $\quad R_e = 12.71^{+1.14}_{-1.19}\mathrm{km}$

$M = 2.08^{+0.072}_{-0.069} M_\odot$ $\quad R = 12.39^{+1.30}_{-0.98}\mathrm{km}$

T. Riley +, The Astroph. J. Lett. 918 (2021)



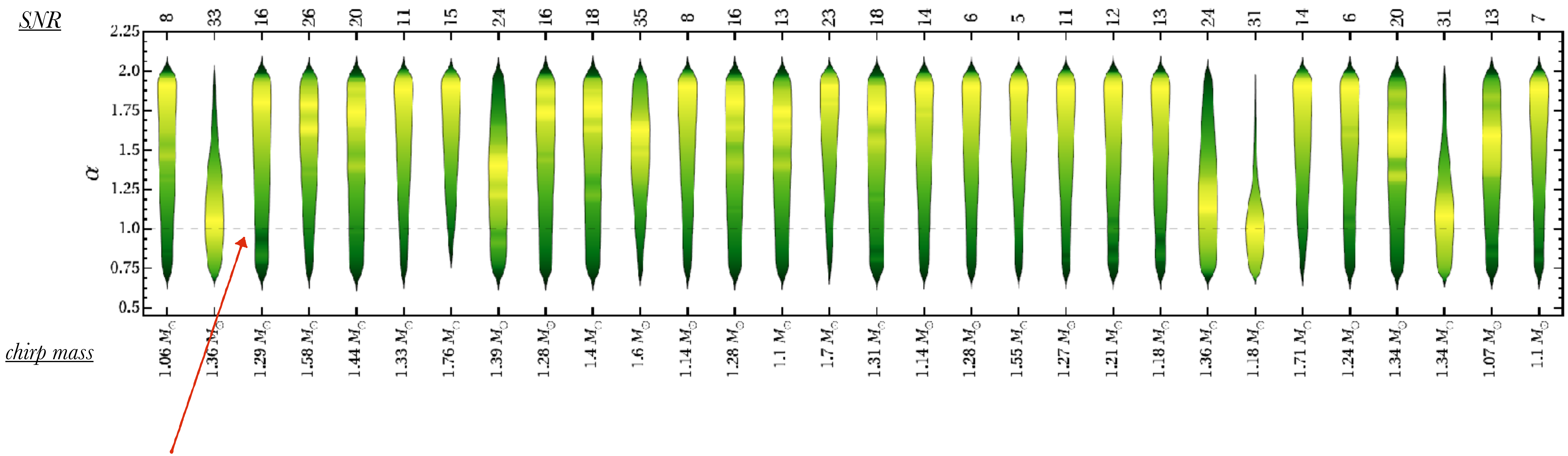
- NICER data seem to agree, and lead to stronger 3-body forces
- LVK data seem to predict lower values of α, closer to baseline

→ sensitivity of data to 3-body forces

3-body forces: 2g-3g forecasts

2g and 3g forecasts for LVK at design sensitivity and for the Einstein Telescope

- Set of simulated data observed by current detectors with different masses and luminosity distance

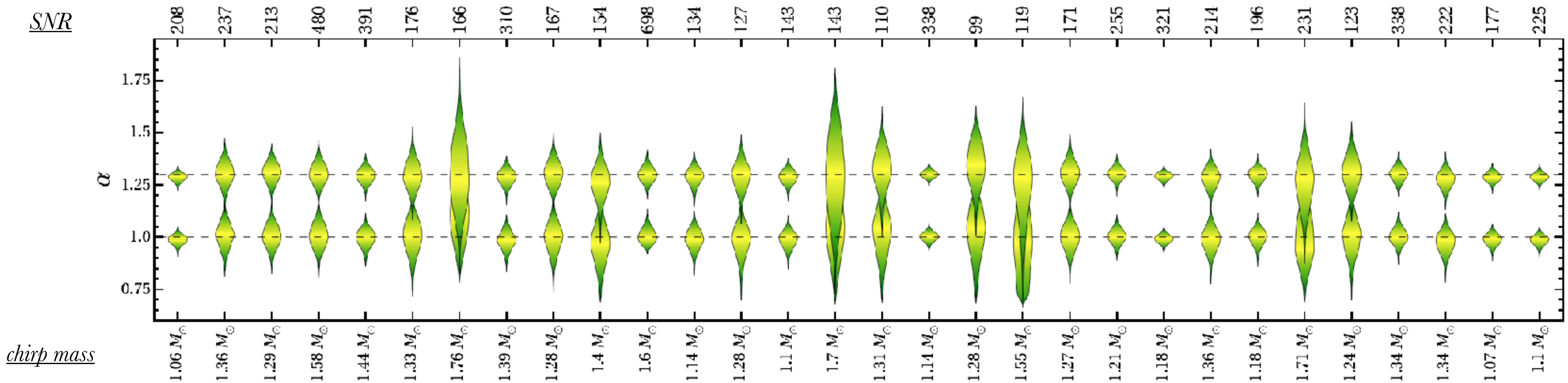


injected value

- Constraints require large SNRs and low mass systems

3-body forces: 2g-3g forecasts

Constraints with Einstein Telescope observations

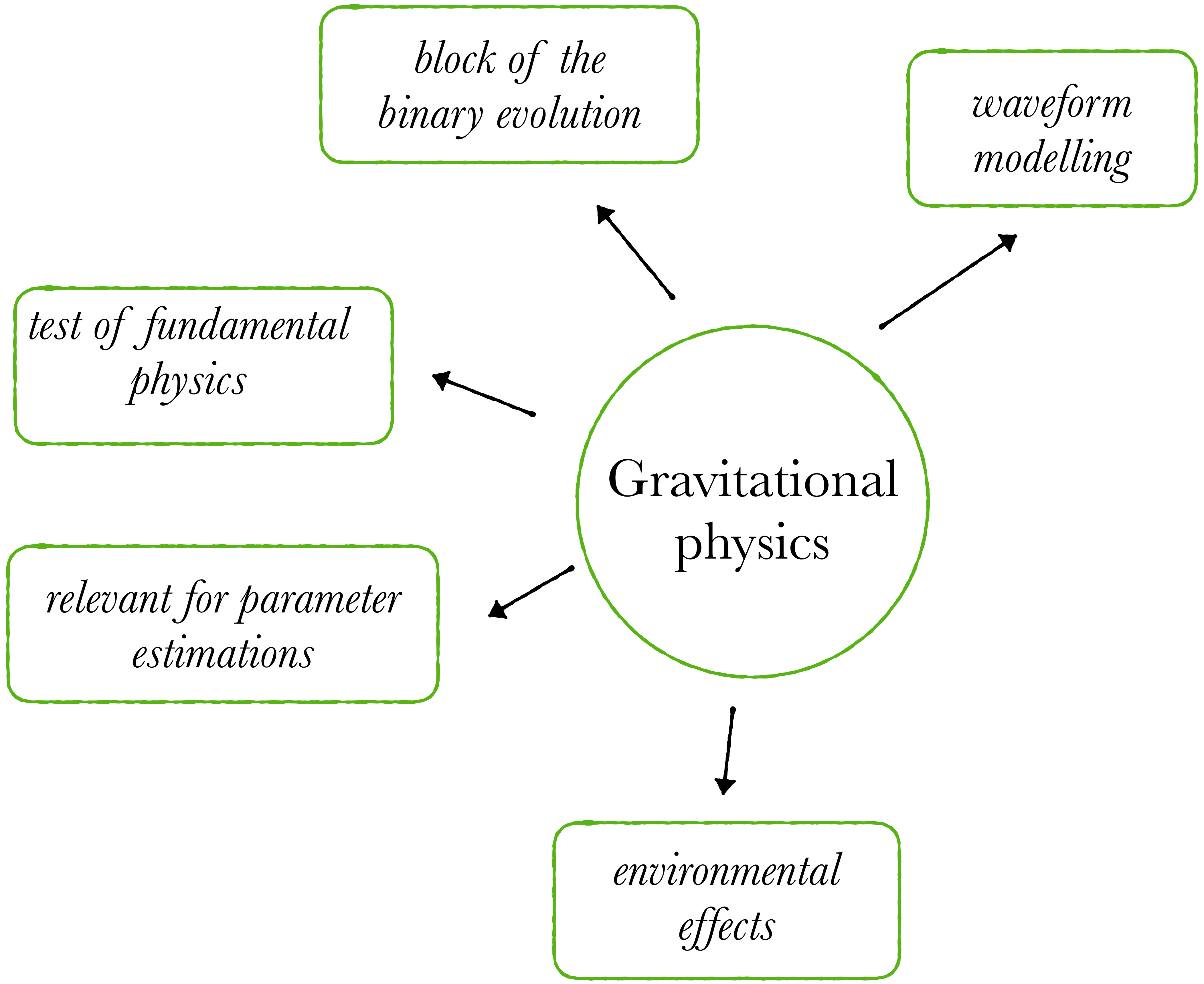


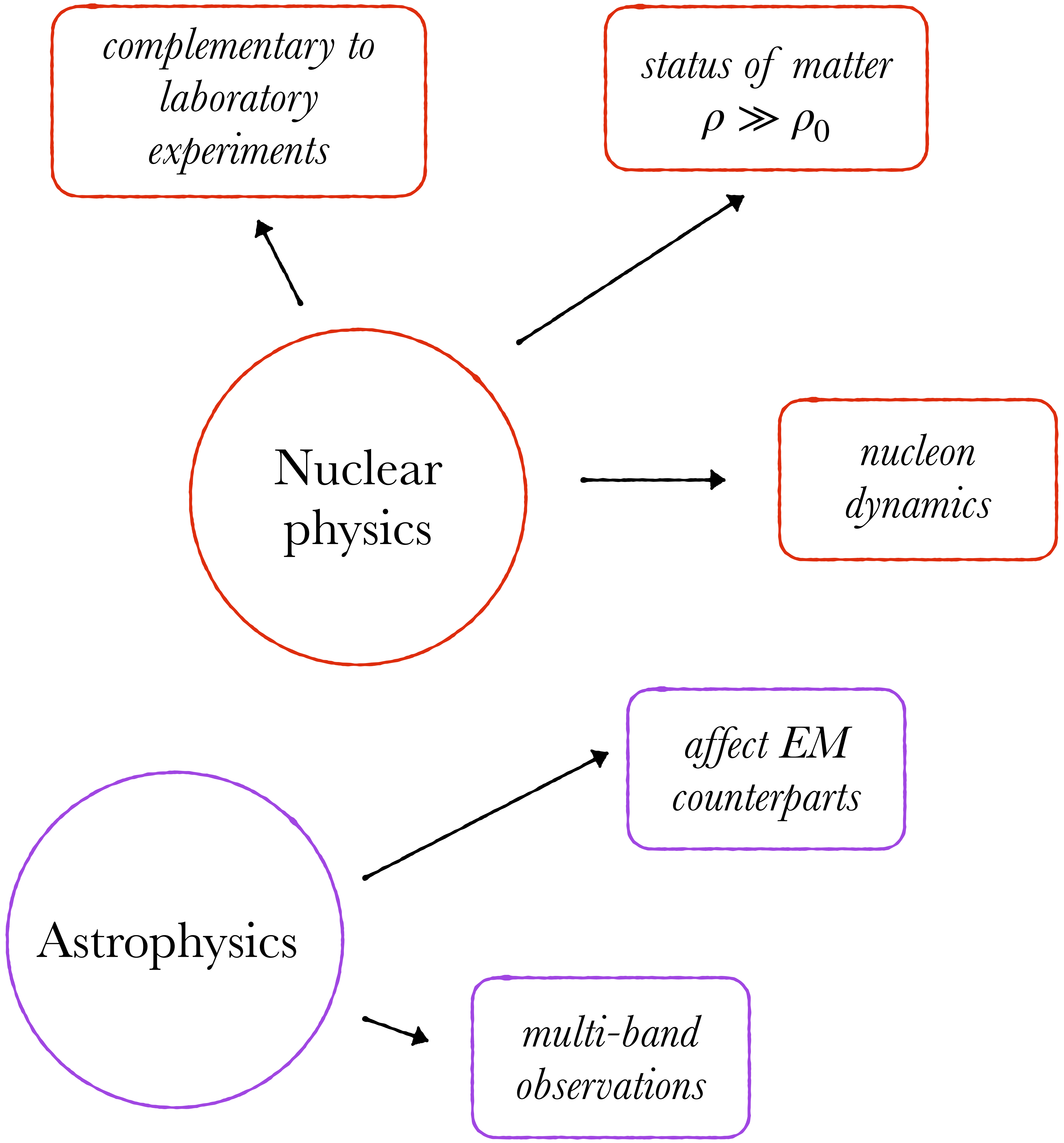
- 3g detectors can pinpoint the strength of 3-body forces at % level
- 3g detectors can distinguish two values of α with a single observation

Summary

GW observations are magnifying lenses of the fundamental interactions

- Tidal effects and Love number impact





Back up

Love for testing GR

Black holes in vacuum General Relativity have zero Love numbers

P. Landry & E. Poisson Phys. Rev. D 91, 104018 (2015)
P. Pani + incl. A. M., Phys. Rev. D 92, 024010 (2015)
N. Gürlebeck, Phys. Rev. Lett. 114, 151102 (2015)
A. Le Tiec +, Phys.Rev. D 103 084021 (2021)

- New tool for fundamental physics

Compact objects with with non-zero Love numbers

BHs beyond GR

Exotic Compact Objects

BHs in accretion disks/dark matter halo

test of the BH nature
are they all Kerr BH?

probe the astrophysical properties
in which BH evolve

- Possibility to explore a wider range of masses, from stellar to supermassive scales

V. Cardoso + incl. A. M., Rev. Rev. D 95, 084014 (2017)
A. Maselli +, Phys. Rev. Lett 120, 081101 (2017)
M. Vaglio + incl. A.M., Phys Rev D 108, 023021 (2023)
C. Pacilio + incl. A. M., Phys Rev D 102, 083002 (2020)

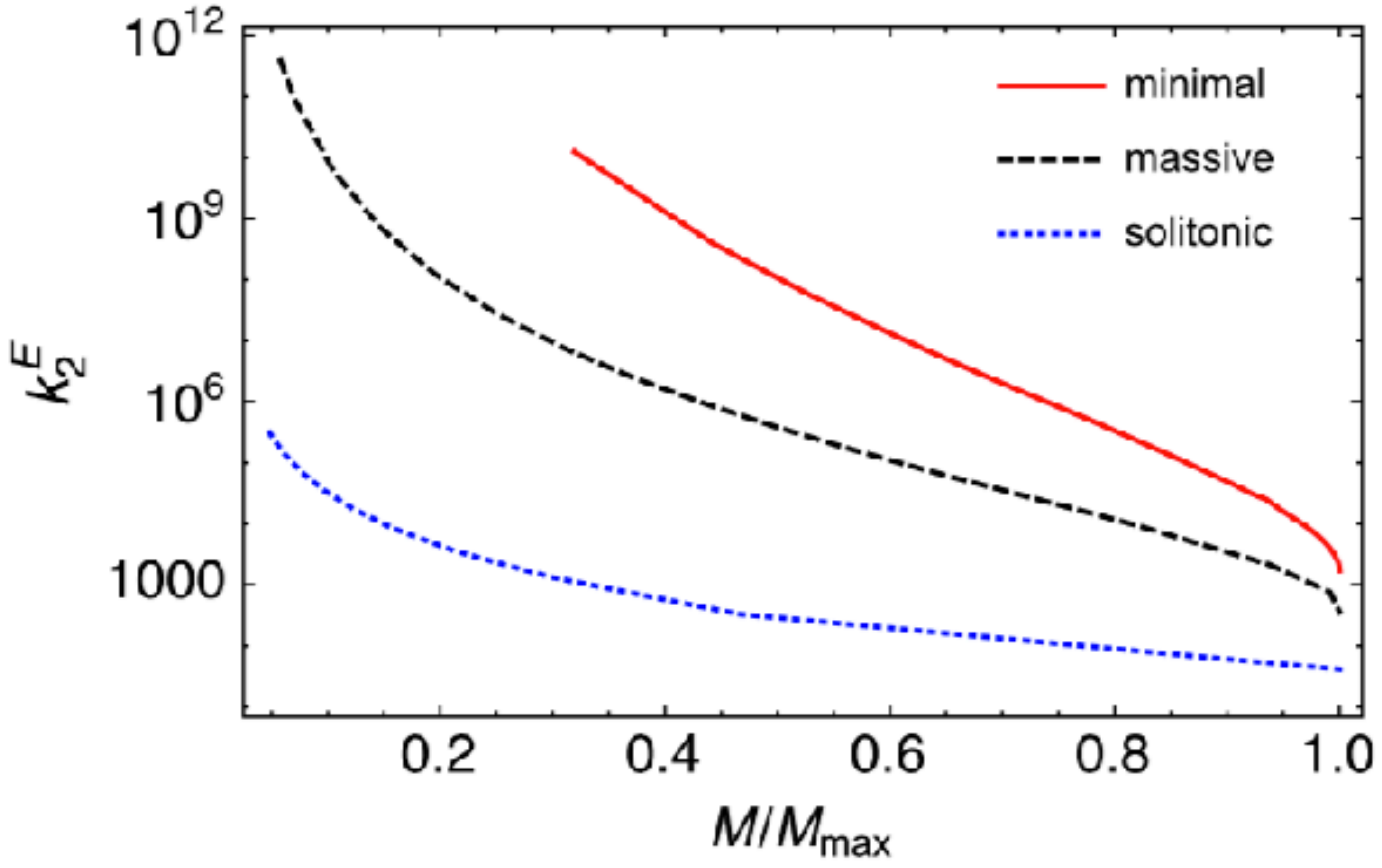
Examples of different types of Love

Scalar field condensates, i.e. Boson Stars

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi} - g^{\alpha\beta}\partial_\alpha\phi^\star\partial_\beta\phi - V(|\phi|^2)\right]$$

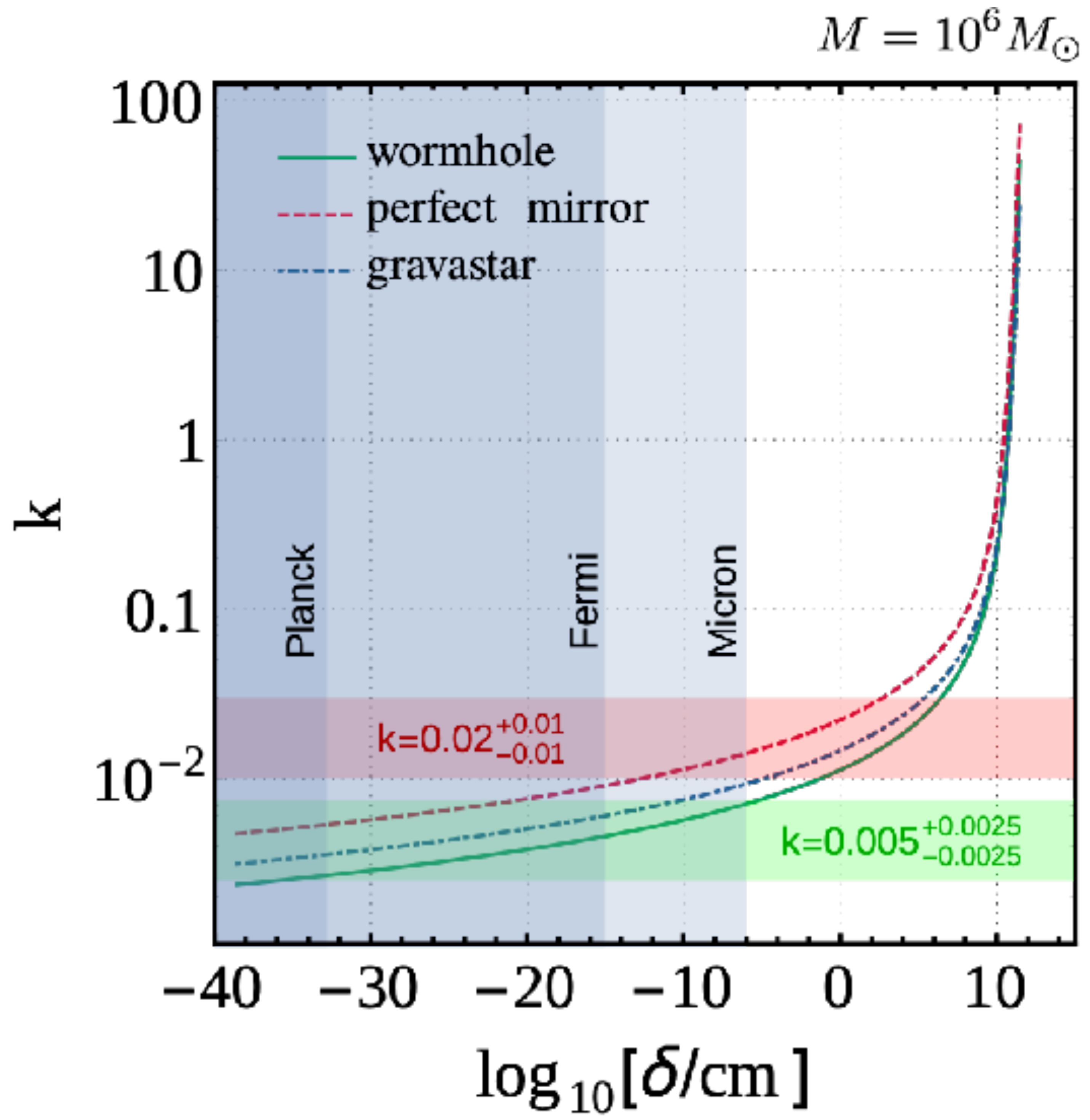
- Behaviour of in qualitative agreement with NSs
- For a compactness $C = M/R \sim 0.2$

$$k_2^{\rm NS} \sim 200 \qquad k_2^{\rm BS} \sim 40$$



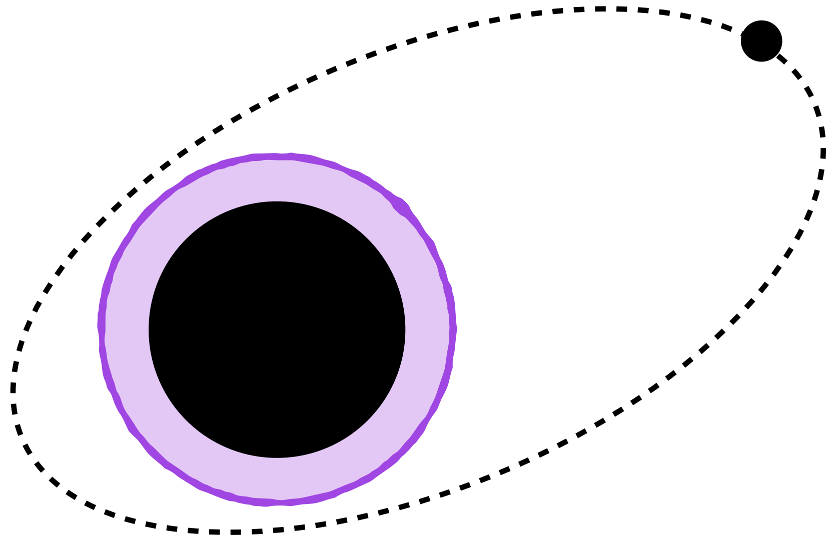
Black hole mimickers, i.e. exotic objects almost as compacts as BHs

$$R = R_{\rm horizon}(1+\delta)$$

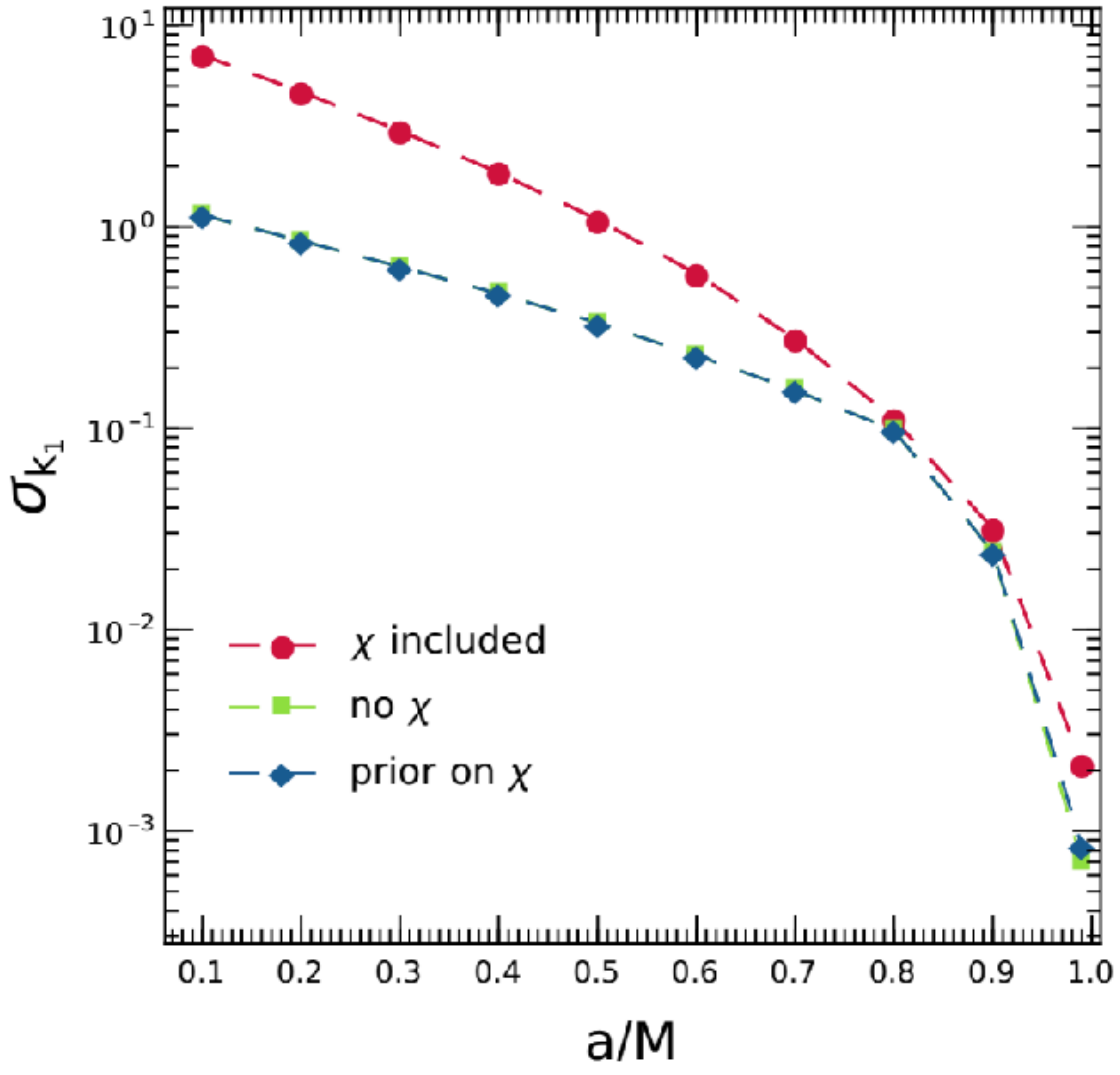


Love numbers and LISA

Measurements of the Love number by Extreme Mass Ratio Inspirals observed by LISA



G. Piovano, A. M., P. Pani, PRD 107, 024021 (2023)



- Constraints up to 6 orders of magnitude more stringent than what achievable by current detectors for stellar binaries

Love numbers and LISA

Map Love number measurements into properties of the new fields

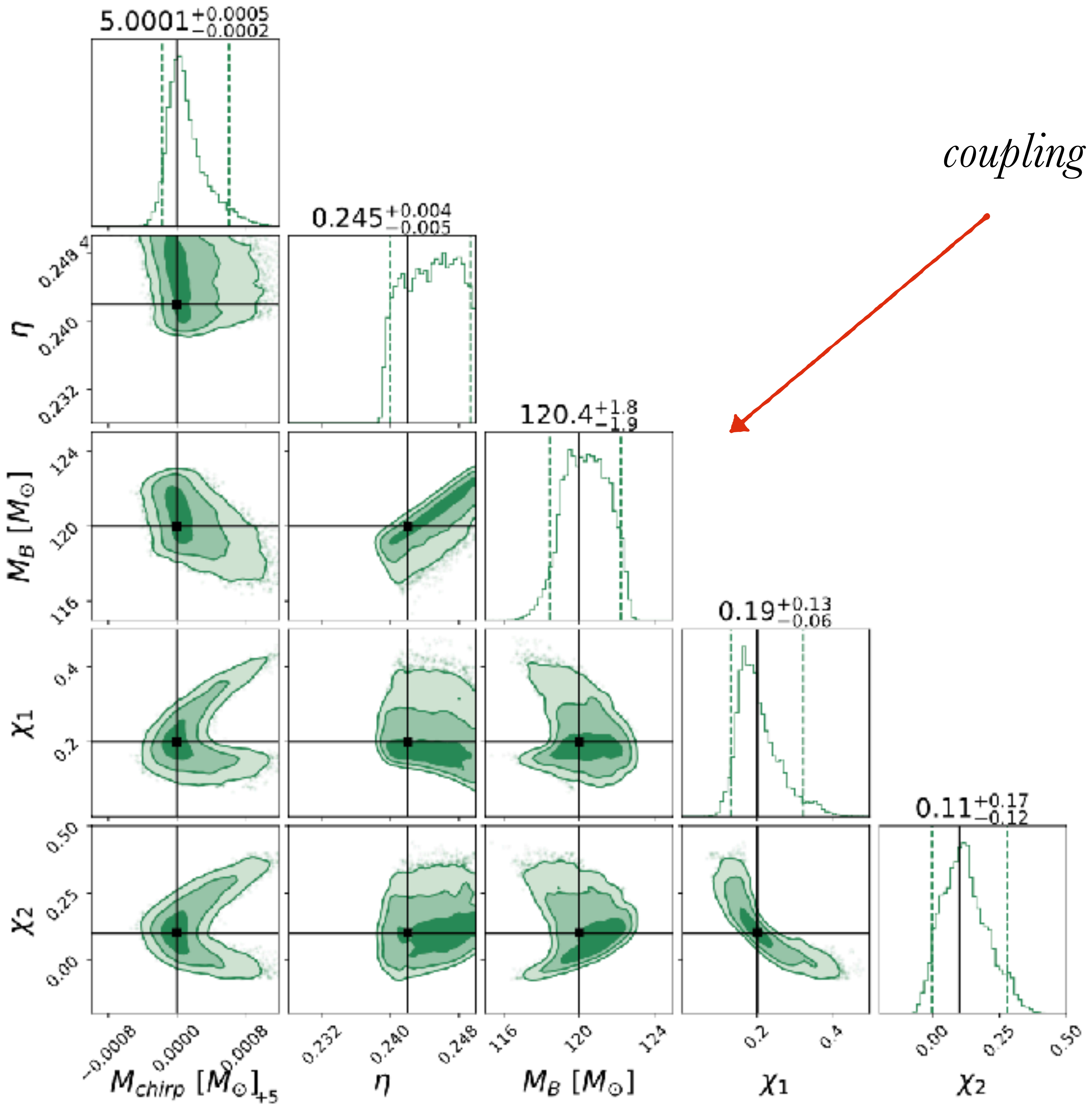
M. Vaglio + incl. A.M., Phys Rev D 108, 023021 (2023)
C. Pacilio + incl. A. M., Phys Rev D 102, 083002 (2020)

- Bayesian inference of a binary boson star signal with SNR ~ 130 in ET

$$\mathcal{L}_\phi = -\frac{1}{2}g^{\mu\nu}\phi^*_{,\mu}\phi_{,\nu} - \frac{1}{2}\mu^2|\phi|^2 - \frac{1}{4}\sigma|\phi|^4$$

stellar properties depend on $M_B = \sqrt{\sigma}/\mu^2$

$\lambda = \lambda(M_B)$ →



coupling M_B

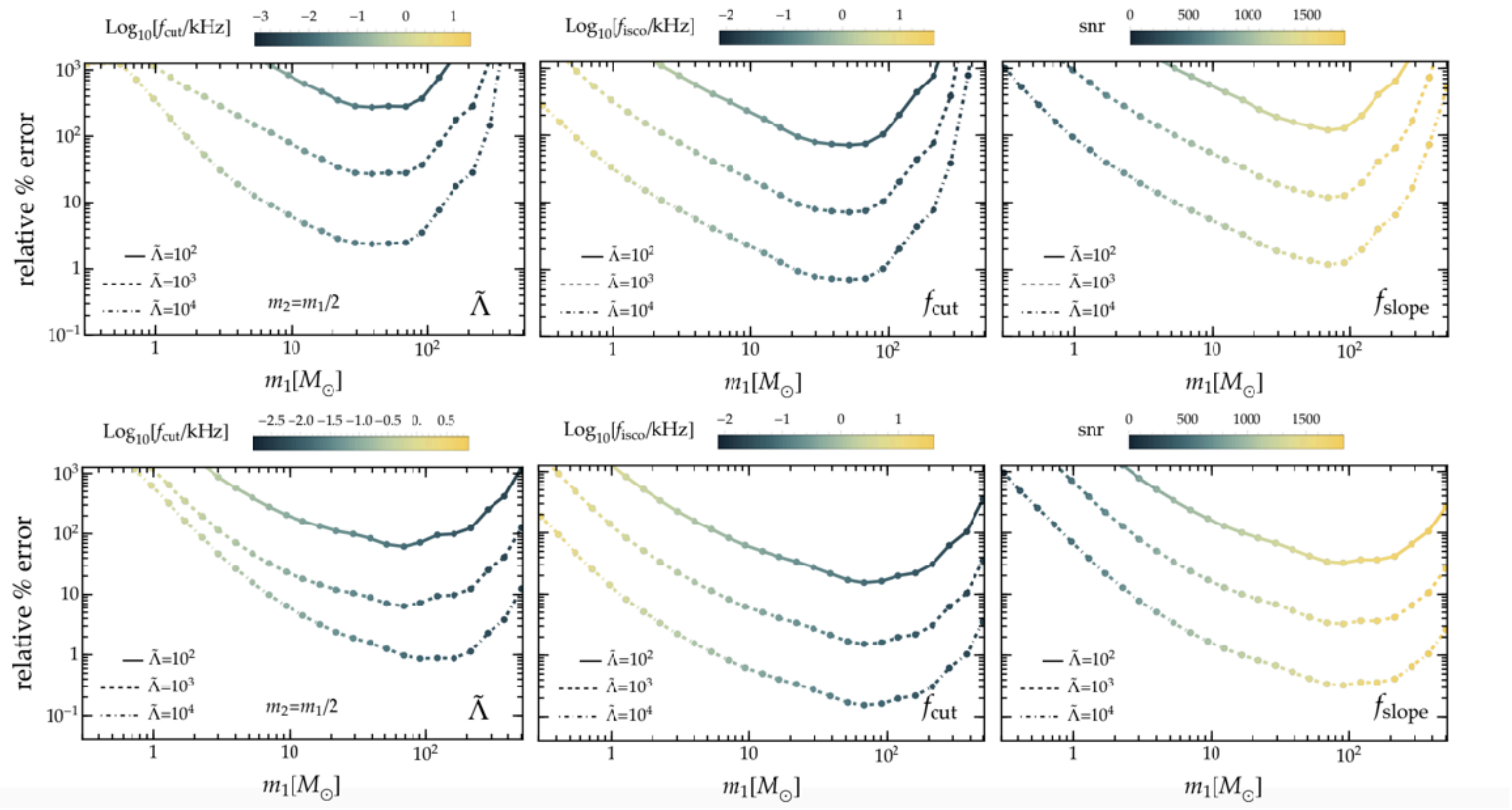
Fading Love

What happens to BH dressed by some matter/field configuration that get stripped by a binary companion?

V. De Luca, A. M., P. Pani, PRD 107, 044058 (2023)

- Time dependent Love number that goes from finite value (dressed BH) to zero (naked BH)

simulated binary observations with ET



$$\tilde{\Lambda} \to \mathcal{S}(f)\cdot\tilde{\Lambda} = \left[\frac{1+e^{-f_{\rm cut}/f_{\rm slope}}}{1+e^{(f-f_{\rm cut})/f_{\rm slope}}}\right]\cdot\tilde{\Lambda}$$

- Constraining the Love number and its dynamics
- Suited for multi-band LISA-ET observations