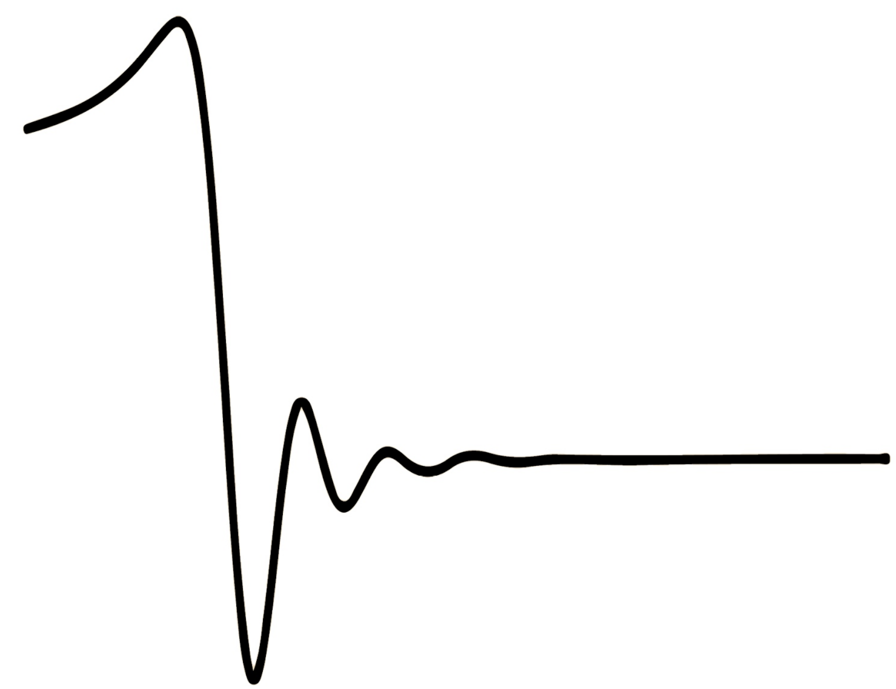
*From **multi-band** observations to the nuclear matter equation of state*

@ EPS Meeting, Rome, Feb 20

astro-ph: 1902.05078

with M.Fasano (***see poster***), T. Abdelsalhin, V. Ferrari



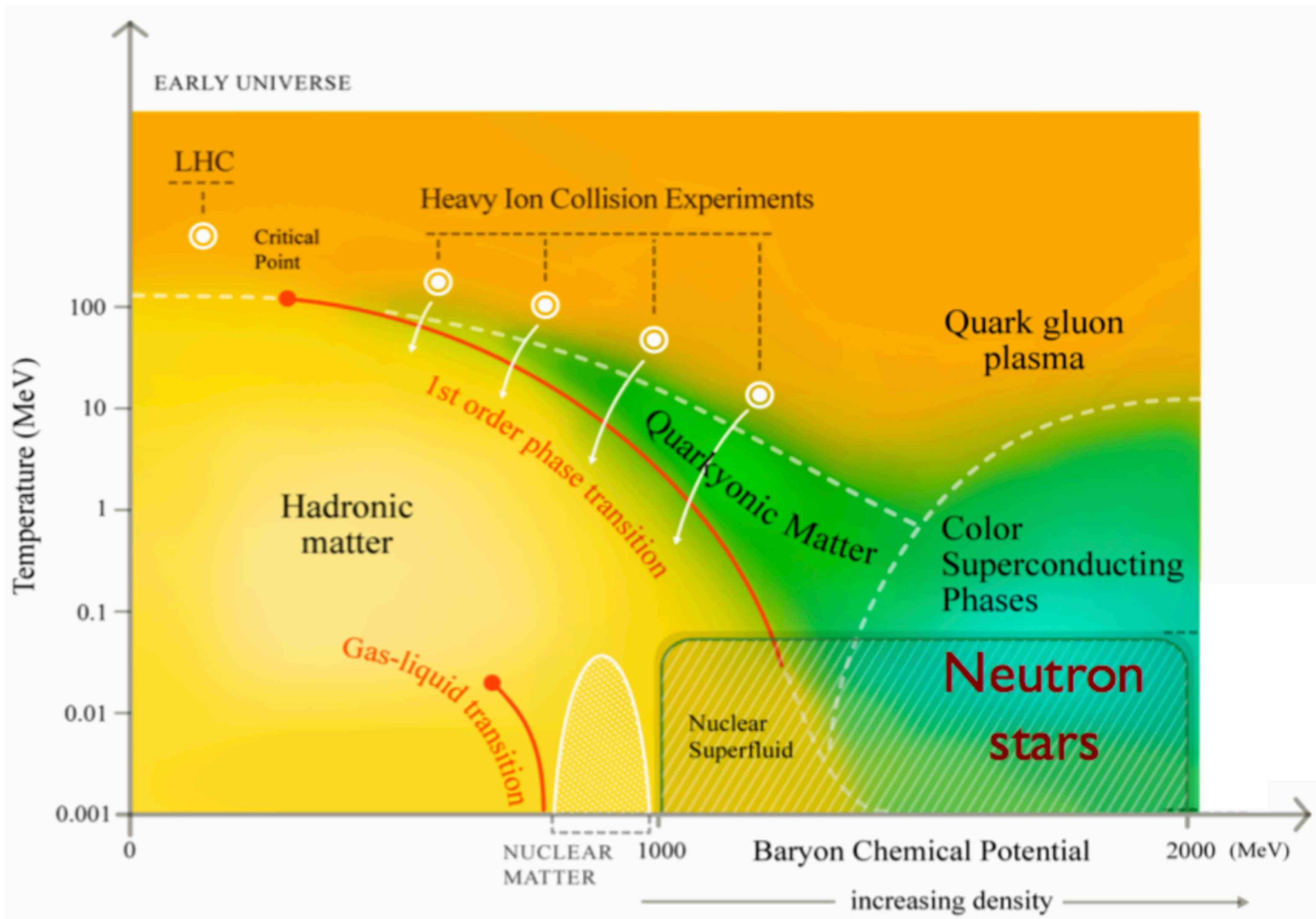
Andrea Maselli

AMALDI RESEARCH CENTER

STVDIVM VRBIS

Fundamental physics with NS

- *How nuclear matter behaves under* ***extreme*** *conditions?*



- *Which are the features of neutron stare cores ?*

Inverse Stellar Problem

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

***microscopic* *E*quation *of* *S*tate...**

GWs
from binary NS

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

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

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

Phenomenological EoS

$$p(\epsilon) \simeq p(\epsilon, \theta_1, \ldots, \theta_n)$$

- *Fit a large class of EoS with relatively* ***small*** *set of parameters*
- *Best approach to combine NS observables in* ***different*** *wavebands*
- *Useful to infer features of the EoS even if the true one is* ***not*** *within current models*

So far

- *Piecewise polytropes* *[Read PRD 79 '09]*
- *Spectral expansions* *[Lindblom PRD 82 '10]*
- *Two-step EoS at nuclear and higher densities* *[Steiner ApJ 722 '10]*
- *Polynomial fits* *[Burgio '10]*

⋮

Piecewise polytropes

EoS parametrised by polytropic segments $\rho_0 < \rho_1 < \rho_2 < \cdots$

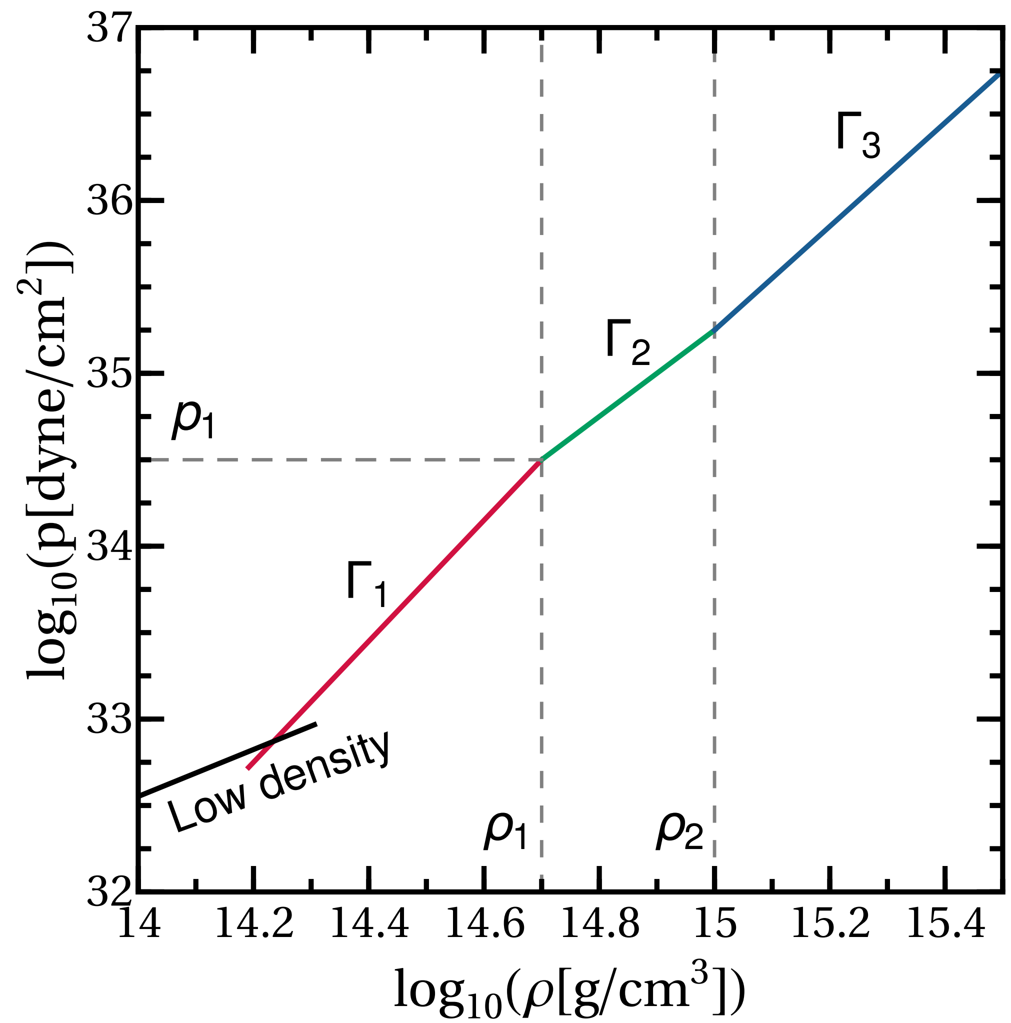
$$p(\rho) = K_i \rho^{\Gamma_i}$$

- *Each piece specified by* $\{K_i, \Gamma_i, \rho_i\}$
  - *If the EoS at low density is fixed*

continuity → $K_{i+1} = \dfrac{p(\rho_i)}{\rho_i^{\Gamma_{i+1}}}$

- *Fixing the initial density fixes the EoS to*

$$\Gamma_1, \Gamma_2, \Gamma_3 \qquad p_1 = p(\rho_1)$$



Spectral representation

Expansion of the adiabatic index in terms of a basis

$$\Gamma(p) = exp\left[\sum_{k=0}^{n} \gamma_k \Phi^k(p)\right] \longrightarrow \frac{d\epsilon}{dp} = \frac{\epsilon + p}{p\Gamma(p)}$$

- *Accurate fit of realistic EoS*

$$\Gamma(p) = exp\left[\sum_{k=0}^{3} \gamma_k \ln\left(\frac{p}{p_0}\right)^k\right]$$

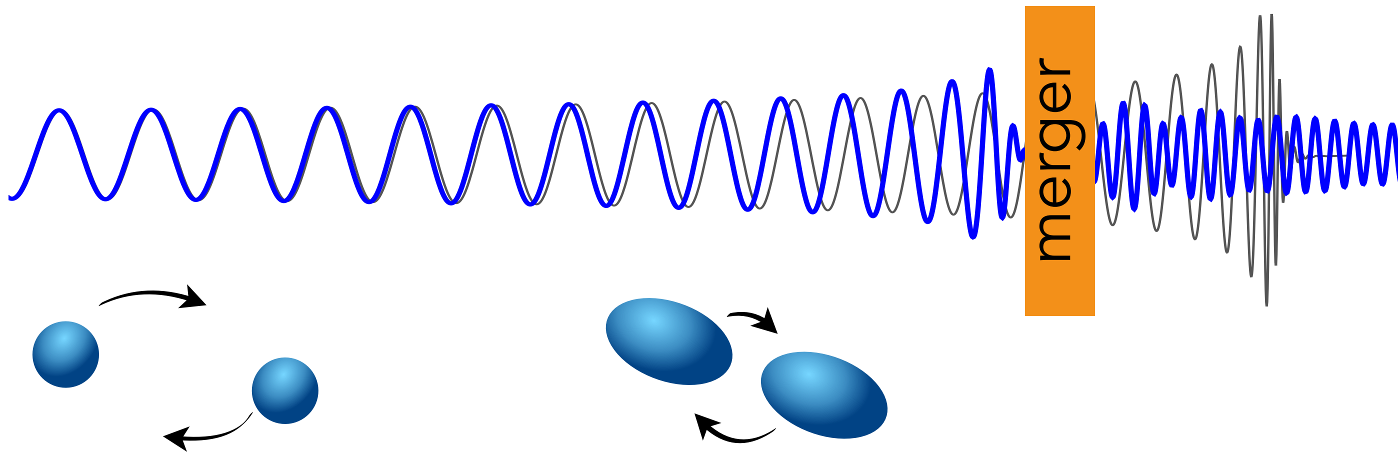
- *2 phenomenological EoS with **4** parameters to constrain*

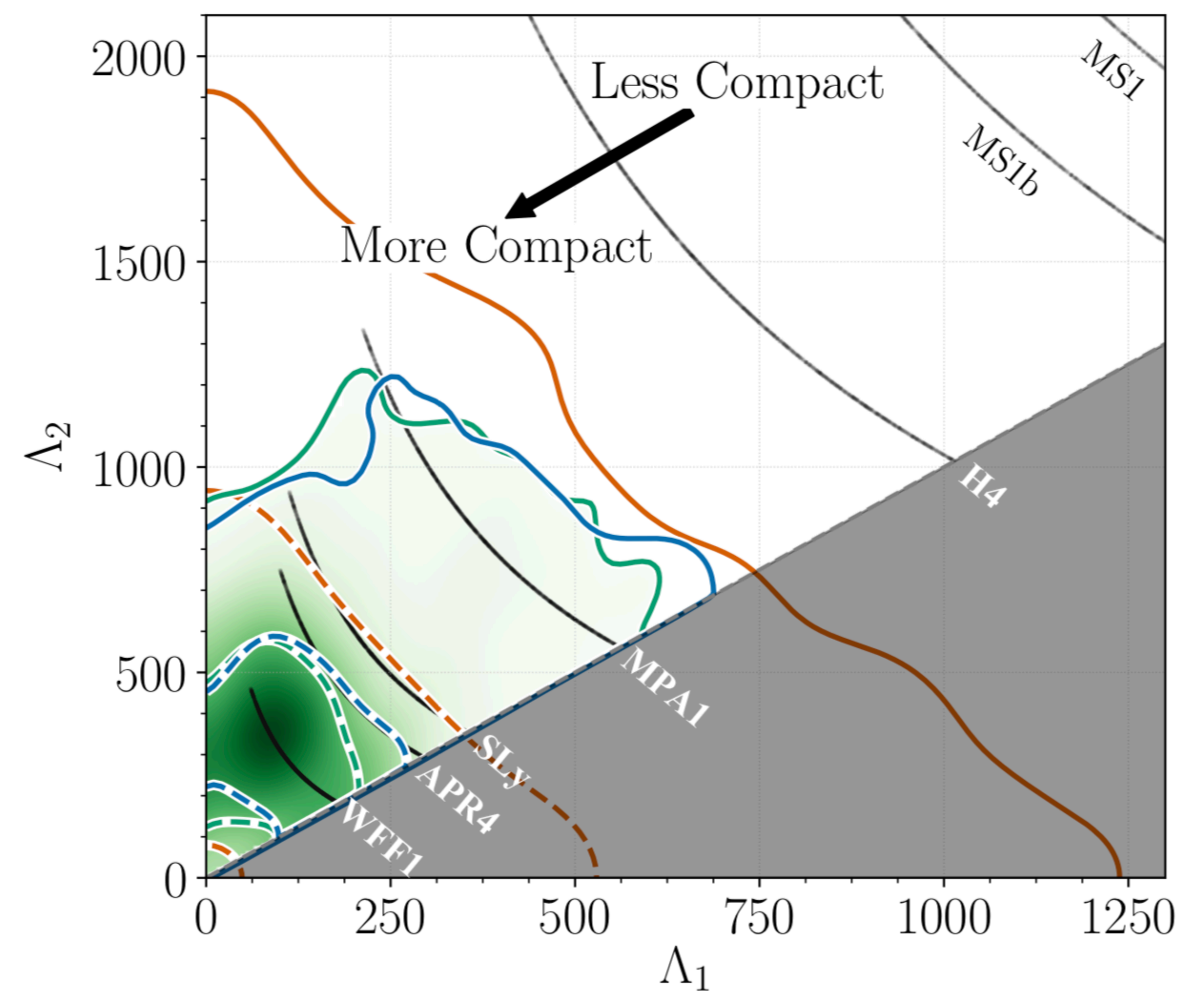
piecewise	***spectral***
$\{p_1, \Gamma_1, \Gamma_2, \Gamma_3\}$	$\{\gamma_0, \gamma_1, \gamma_2, \gamma_3\}$

The observables: GWs

Measurements of the ***Love Numbers*** from GW170817

[LVC PRL 121 '18]





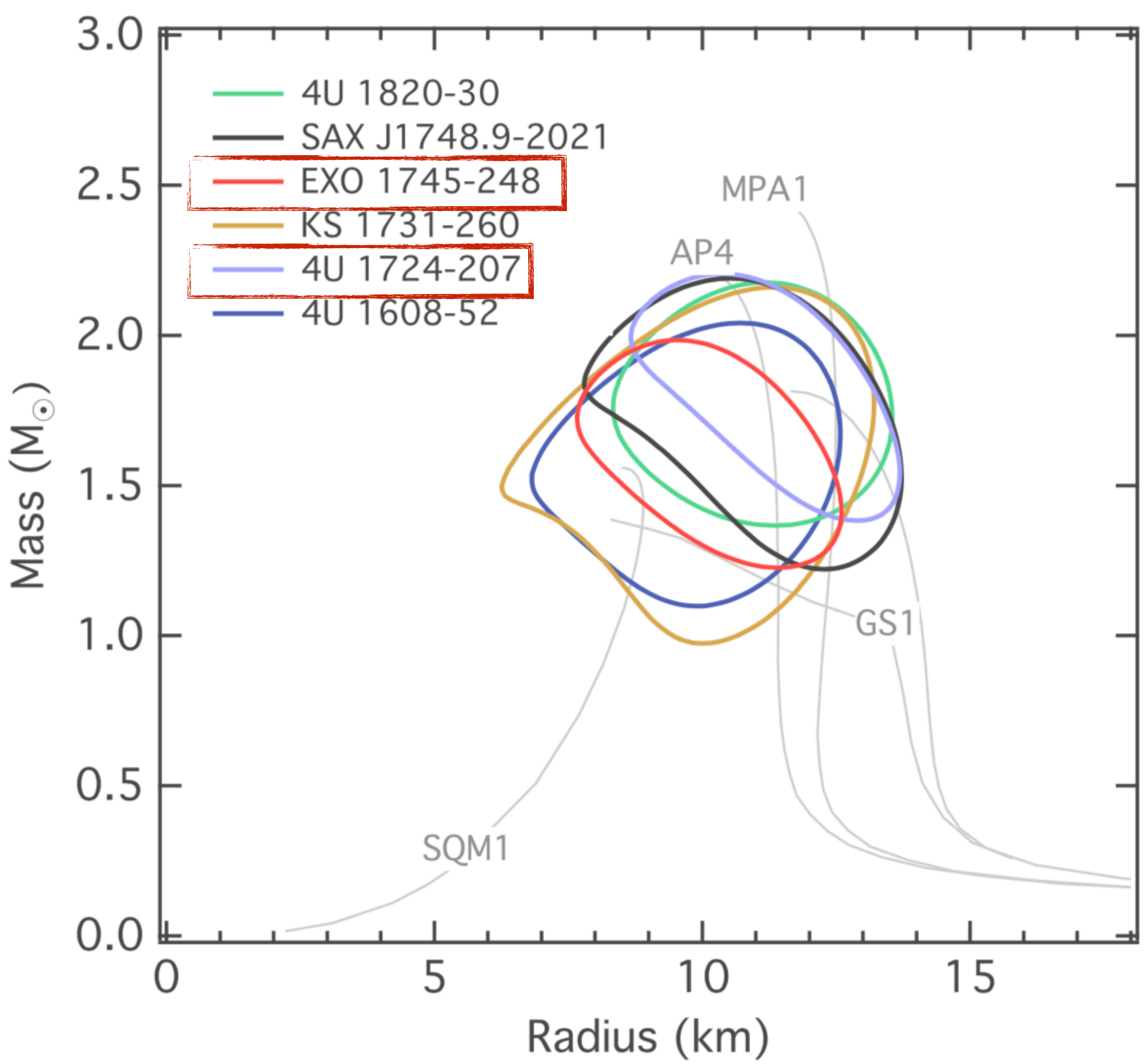
- *Tidal interactions show up within GWs through the Love Number* Λ

- *This parameter depends* ***solely*** *on the EoS*

The observables: EM

Mass-***radius*** measurements from thermonuclear burst in LMXB

[Ozel ApJ 220 '16]



Stay united GWs+EM

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}

GWs

M_3 $[M_\odot]$	R_3 [km]	M_4 $[M_\odot]$	R_4 [km]
$1.81^{+0.36}_{-0.48}$	$11.46^{+2.53}_{-2.49}$	$1.60^{+0.36}_{-0.42}$	$10.33^{+2.75}_{-2.38}$

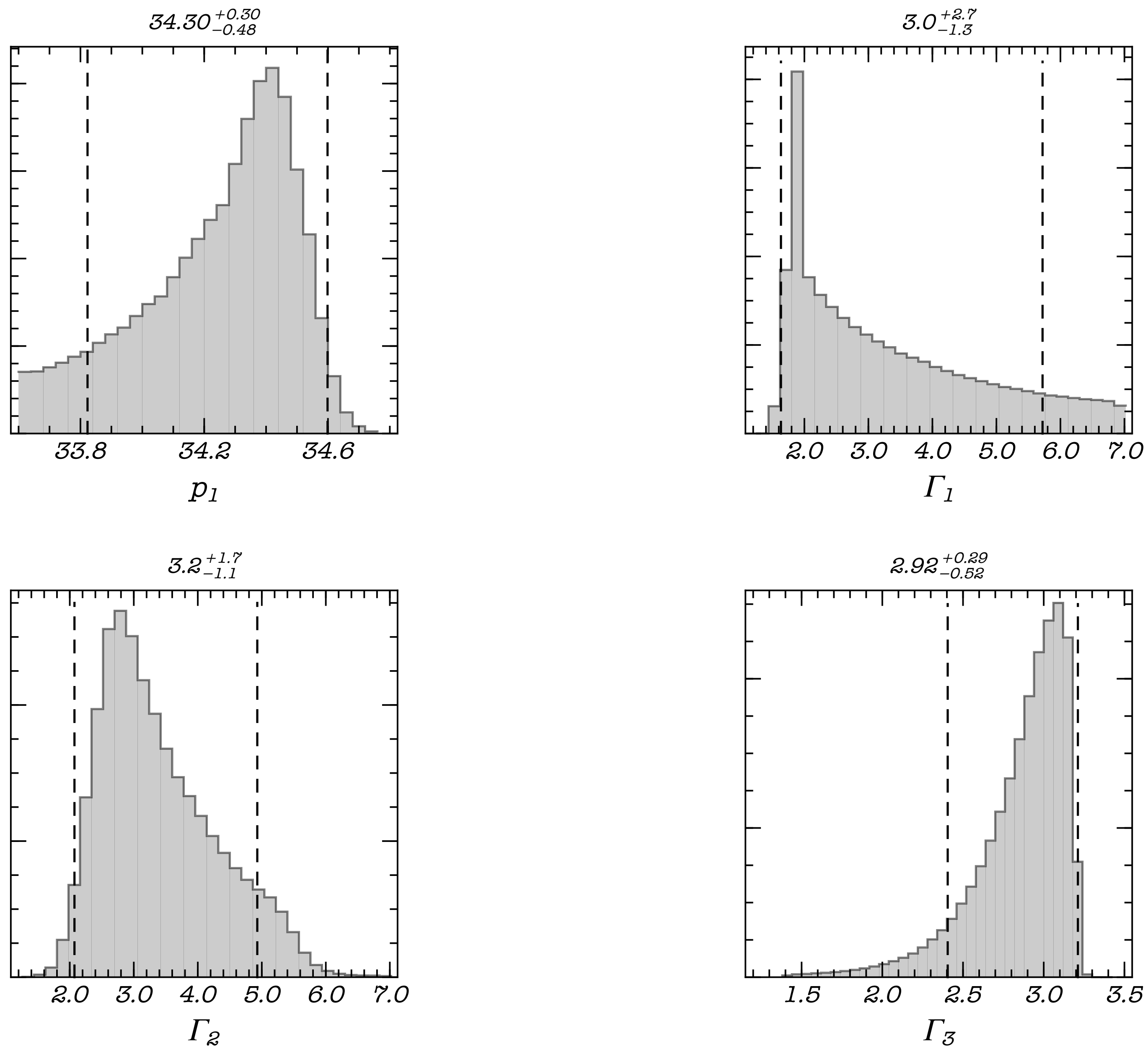
EM

- Λ_i *and* R_i *share a common basis, i.e.* $R_i(\gamma_0, \gamma_1, \gamma_2, \gamma_3)$ *or* $R_i(p_1, \Gamma_1, \Gamma_2, \Gamma_3)$

- *Bayesian sample of the EoS parameters using MCMC simulations*

$$\mathcal{P}(\theta|\mathbf{d}) \propto \mathcal{P}_0(\theta) \times \mathcal{L}^{\rm GW}(M_1, \Lambda_1, M_2, \Lambda_2) \times \mathcal{L}^{\rm EM}(M_3, R_3) \times \mathcal{L}^{\rm EM}(M_4, R_4)$$

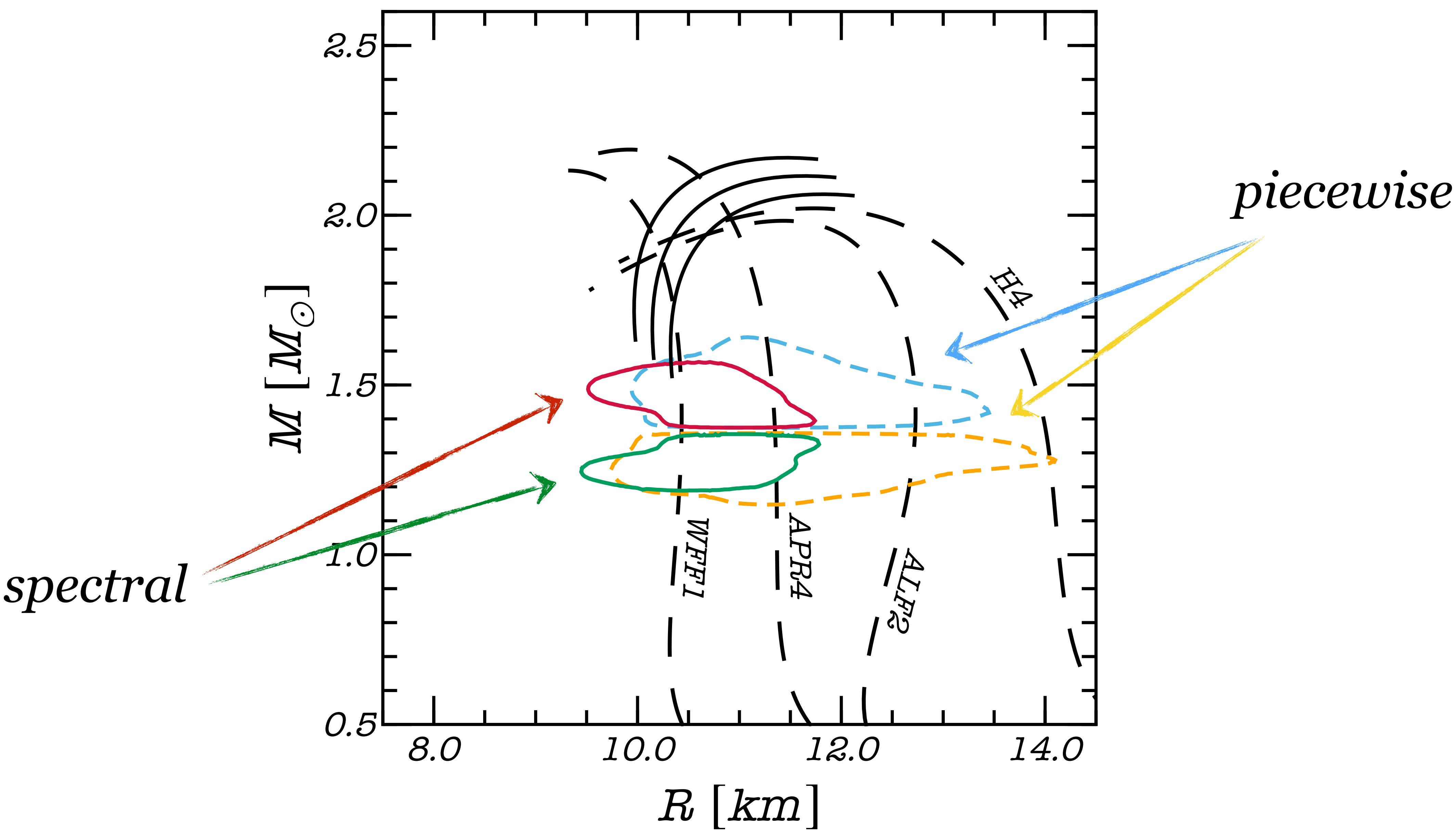
Piecewise parameters



Local complementary information to ***integrated*** quantities as masses and radii

Do we learn something?

Use the inferred parameters (GW+EM) to reconstruct the mass-radius distributions of GW170817



A new look at the radius

Final constraints on the GW170817 neutron stars

piecewise

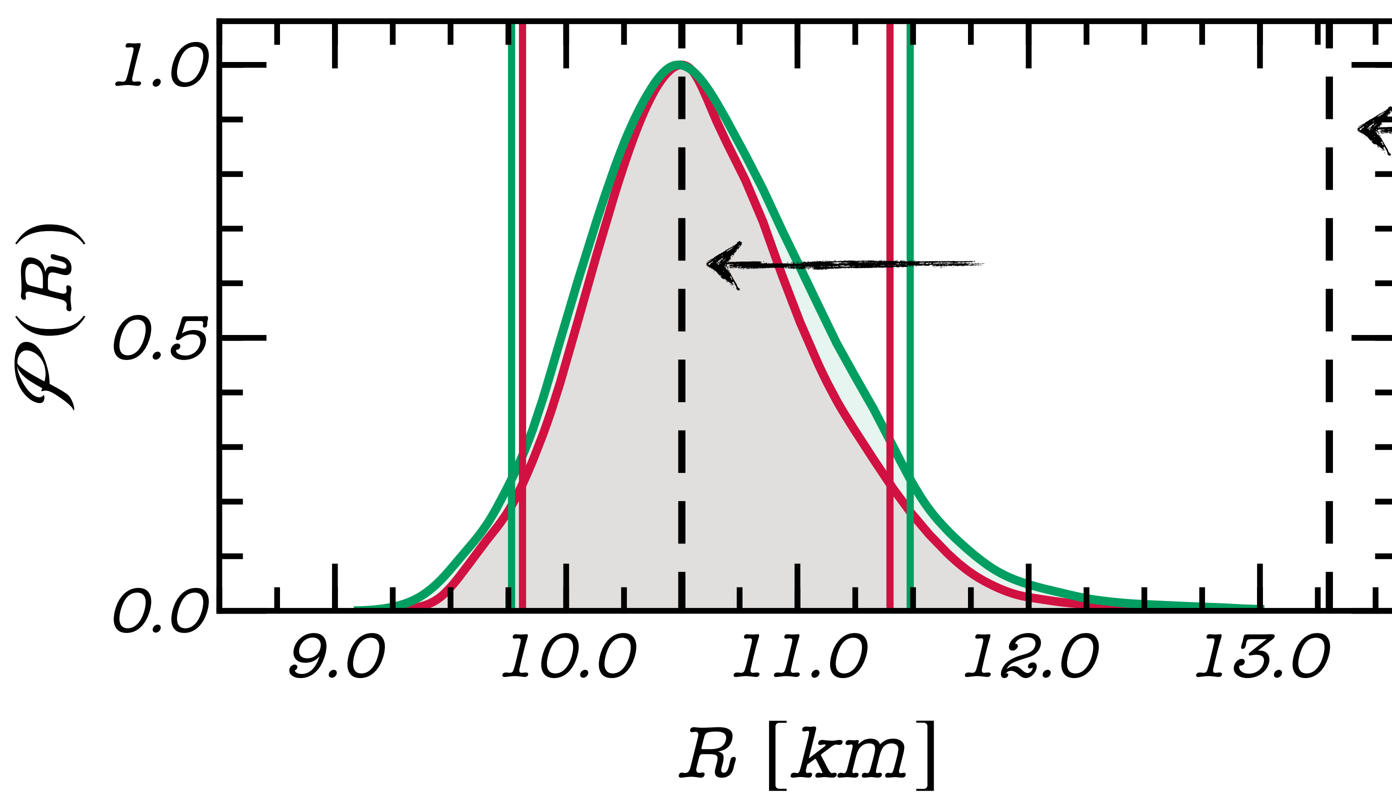
$$R_1 = 11.29^{+1.40}_{-1.18}$$

$$R_2 = 11.39^{+1.67}_{-1.45}$$

spectral

$$R_1 = 10.56^{+0.84}_{-0.75}$$

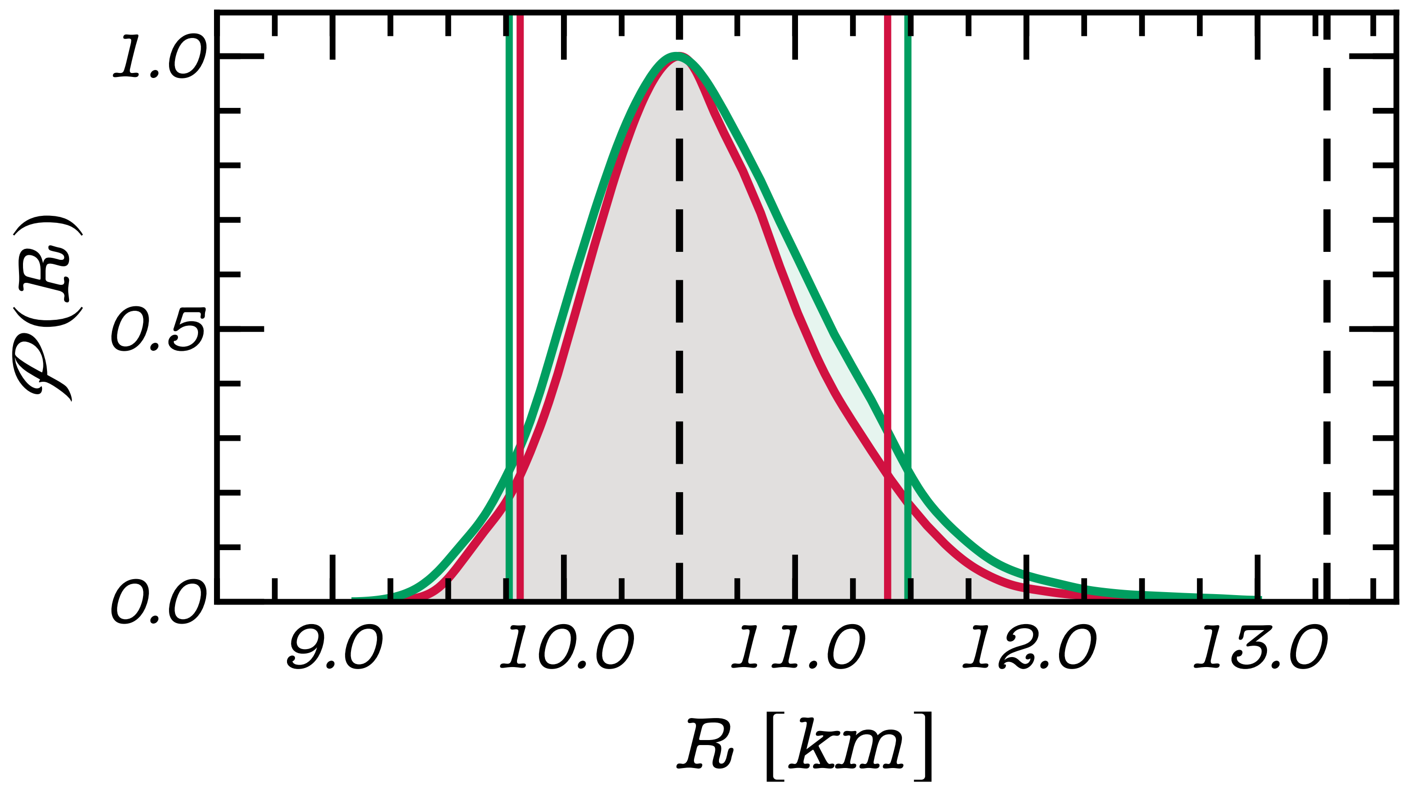
$$R_2 = 10.58^{+0.90}_{-0.82}$$



LVC

$$R_{1,2} = 11.9^{+1.4}_{-1.4}$$

Density matters



- *Final measurement benefit from the multi-band analysis*
- *High-masses in the EM channel provide extra information on NS cores with larger densities*

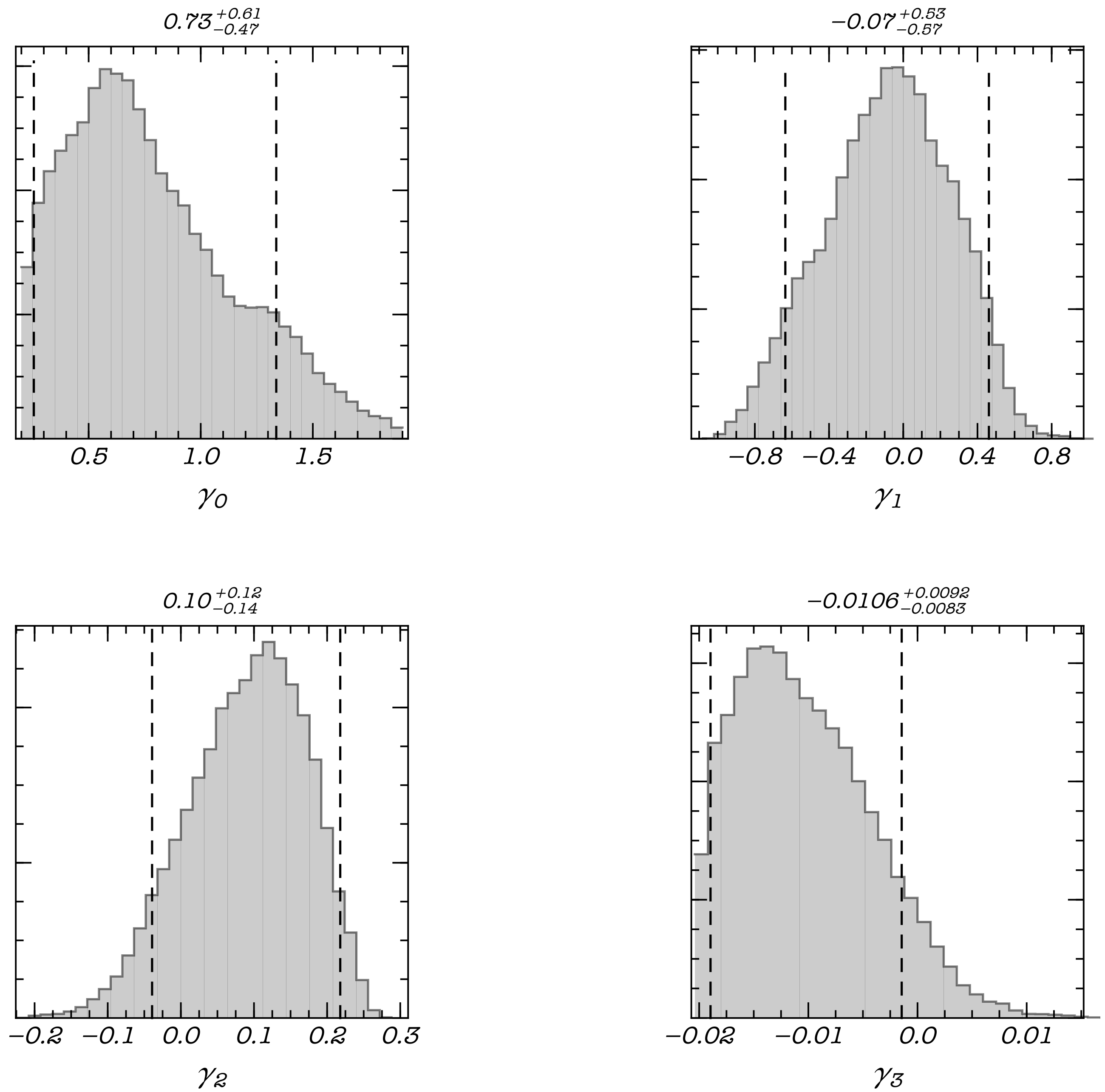
Back up

How it works in practise

Mapping realistic EoS

EOS	$\log(p_1)$	Γ_1	Γ_2	Γ_3	Residual	$v_{s,\max}$	%	$M_{\max}$	%	$z_{\max}$	%	$f_{\max}$	%	$I_{1.338}$	%	$R_{1.4}$	%
PAL6	34.380	2.227	2.189	2.159	0.0011	0.693	1.37	1.477	−0.47	0.374	−0.51	1660	−0.97	1.051	−2.03	10.547	−0.54
SLy	34.384	3.005	2.988	2.851	0.0020	0.989	1.41	2.049	0.02	0.592	0.81	1810	0.10	1.288	−0.08	11.736	−0.21
APR1	33.943	2.442	3.256	2.908	0.019	0.924	9.94	1.683	−1.60	0.581	2.79	2240	1.05	0.908	−2.57	9.361	−1.85
APR2	34.126	2.643	3.014	2.945	0.0089	1.032	0.42	1.808	−1.50	0.605	0.33	2110	−0.02	1.024	−2.34	10.179	−1.57
APR3	34.392	3.166	3.573	3.281	0.0091	1.134	2.72	2.390	−1.00	0.704	0.57	1810	−0.14	1.375	−1.59	12.094	−0.96
APR4	34.269	2.830	3.445	3.348	0.0068	1.160	1.45	2.213	−1.08	0.696	0.22	1940	0.05	1.243	−1.36	11.428	−0.90
FPS	34.283	2.985	2.863	2.600	0.0050	0.883	2.29	1.799	−0.03	0.530	0.67	1880	0.11	1.137	0.03	10.850	0.12
WFF1	34.031	2.519	3.791	3.660	0.018	1.185	7.86	2.133	−0.29	0.739	2.21	2040	0.30	1.085	0.10	10.414	0.02
WFF2	34.233	2.888	3.475	3.517	0.017	1.139	7.93	2.198	−0.14	0.717	0.71	1990	0.03	1.204	−0.59	11.159	−0.28
WFF3	34.283	3.329	2.952	2.589	0.017	0.835	8.11	1.844	−0.48	0.530	2.26	1860	0.59	1.160	−0.25	10.926	−0.12
BBB2	34.331	3.418	2.835	2.832	0.0055	0.914	7.75	1.918	0.10	0.574	0.97	1900	0.47	1.188	0.17	11.139	−0.29
BPAL12	34.358	2.209	2.201	2.176	0.0010	0.708	1.03	1.452	−0.18	0.382	−0.29	1700	−1.03	0.974	0.20	10.024	0.67
ENG	34.437	3.514	3.130	3.168	0.015	1.000	10.71	2.240	−0.05	0.654	0.39	1820	−0.44	1.372	−0.97	12.059	−0.69
MPA1	34.495	3.446	3.572	2.887	0.0081	0.994	4.91	2.461	−0.16	0.670	−0.05	1700	−0.18	1.455	−0.41	12.473	−0.26
MS1	34.858	3.224	3.033	1.325	0.019	0.888	12.44	2.767	−0.54	0.606	−0.52	1400	1.67	1.944	−0.09	14.918	0.06
MS2	34.605	2.447	2.184	1.855	0.0030	0.582	3.96	1.814	−0.87	0.359	−1.96	1250	2.25	1.659	0.42	13.711	2.65
MS1b	34.855	3.456	3.011	1.425	0.015	0.889	11.38	2.776	−1.03	0.614	−0.56	1420	1.38	1.888	−0.64	14.583	−0.32
PS	34.671	2.216	1.640	2.365	0.028	0.691	7.36	1.755	−1.53	0.355	−1.45	1300	−2.39	2.067	−3.06	15.472	3.72
GS1[a]	34.504	2.350	1.267	2.421	0.018	0.695	0.49	1.383	−1.08	0.402	−2.30	1660	9.05	0.771	−3.71	[b]	
GS2[a]	34.642	2.519	1.571	2.314	0.026	0.592	16.10	1.653	−0.30	0.339	7.71	1340	3.77	1.796	−3.33	14.282	0.18
BGN1H1	34.623	3.258	1.472	2.464	0.029	0.878	−7.42	1.628	0.39	0.437	−3.55	1670	−2.08	1.504	0.56	12.901	−1.96
GNH3	34.648	2.664	2.194	2.304	0.0045	0.750	2.04	1.962	0.13	0.427	0.37	1410	−0.04	1.713	0.38	14.203	−0.28
H1	34.564	2.595	1.845	1.897	0.0019	0.561	2.81	1.555	−0.92	0.311	−1.47	1320	−1.46	1.488	−1.45	12.861	−0.03
H2	34.617	2.775	1.855	1.858	0.0028	0.565	1.38	1.666	−0.77	0.322	−0.55	1280	−1.29	1.623	−0.82	13.479	0.29
H3	34.646	2.787	1.951	1.901	0.0070	0.564	7.05	1.788	−0.79	0.343	1.07	1290	−0.88	1.702	−1.18	13.840	0.31
H4	34.669	2.909	2.246	2.144	0.0028	0.685	4.52	2.032	−0.85	0.428	−1.01	1400	−1.28	1.729	−1.18	13.759	1.45
H5	34.609	2.793	1.974	1.915	0.0050	0.596	1.65	1.727	−1.00	0.347	−0.82	1340	−1.55	1.615	−1.31	13.385	0.40
H6[a]	34.593	2.637	2.121	2.064	0.0087	0.598	11.71	1.778	0.07	0.346	8.65	1310	5.33	1.623	−2.19	13.501	0.09
H7	34.559	2.621	2.048	2.006	0.0046	0.630	1.82	1.683	−1.12	0.357	−0.57	1410	−1.52	1.527	−2.33	12.992	0.23

Spectral parameters



- *Best constraints for the high-density parameters*

Radius: piecewise vs spectral