Constraining nuclear physics parameters using neutron star M-R measurements

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WUSTL physics/UvA

arXiv: 2303.17518

Collaborators: Anna Watts, Geert Raaijmakers, Laura Tolos, Constança Providência

2023/06/29

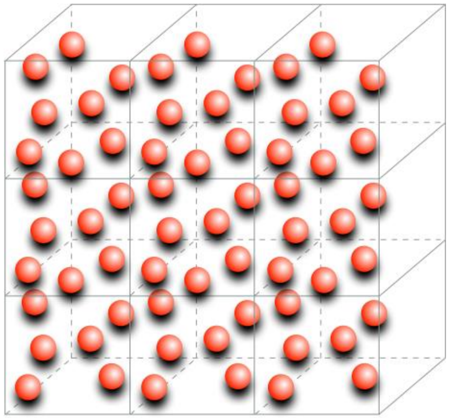
UW, INT workshop

Contents

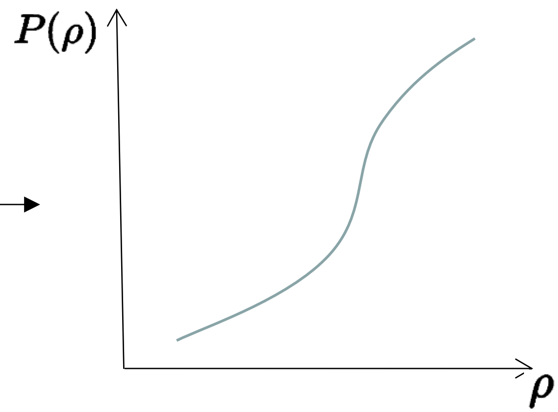
- Data we are using
  a) NICER mission
  b) Gravitational Wave detection
- Real physical model constrain
  a) RMF model construction
  b) Current observation study
  c) Future case study
  d) Future-X cases study
- Conclusion

How we constrain EoS

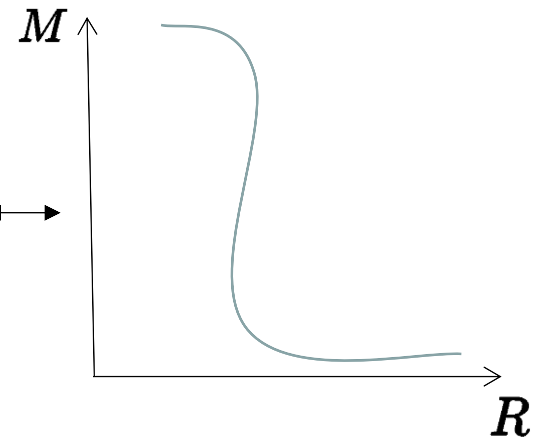
Micro physics

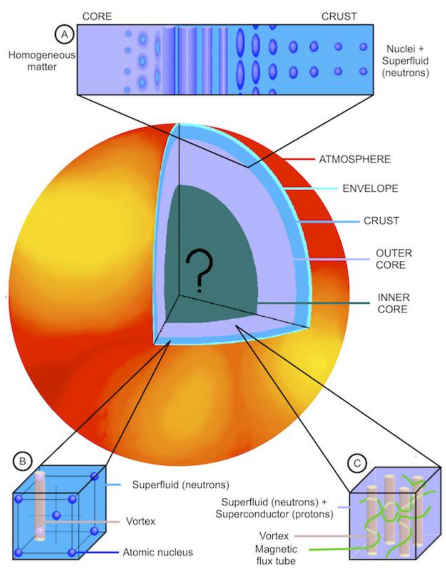


Equation of State

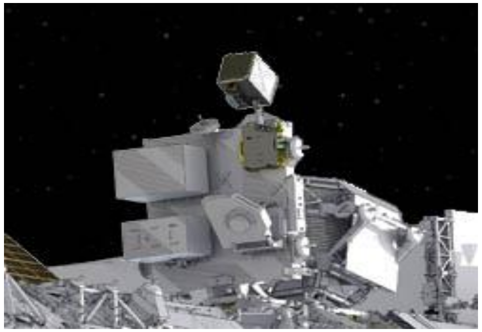


Mass and Radius





Neutron Star

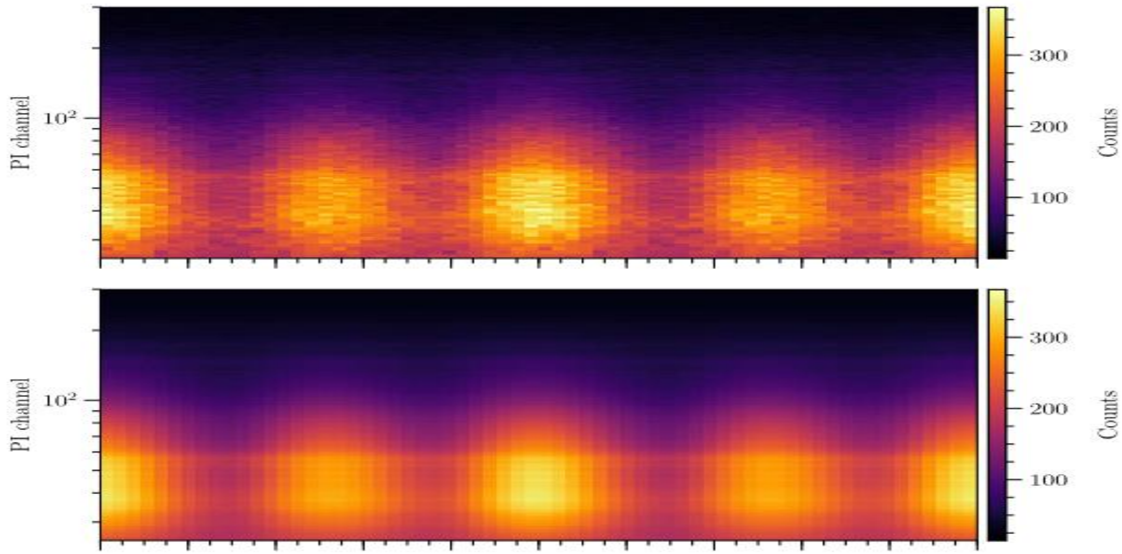


Detectors

Neutron star Interior Composition Explorer

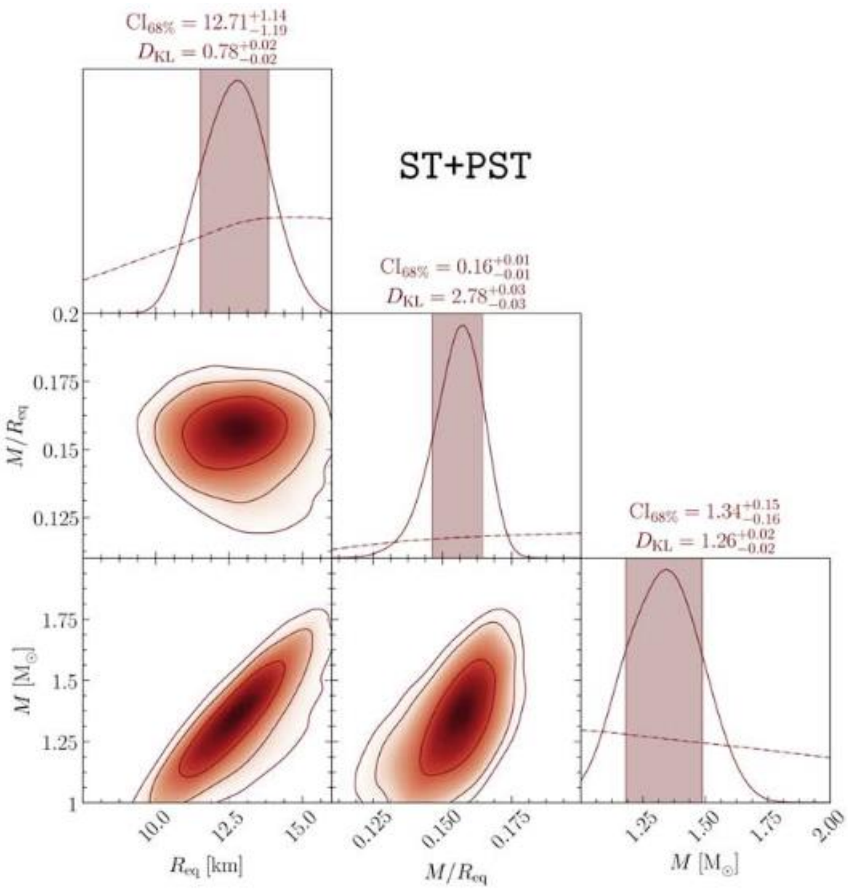
NICER mission:

- “To the study of neutron stars through soft X-ray timing”

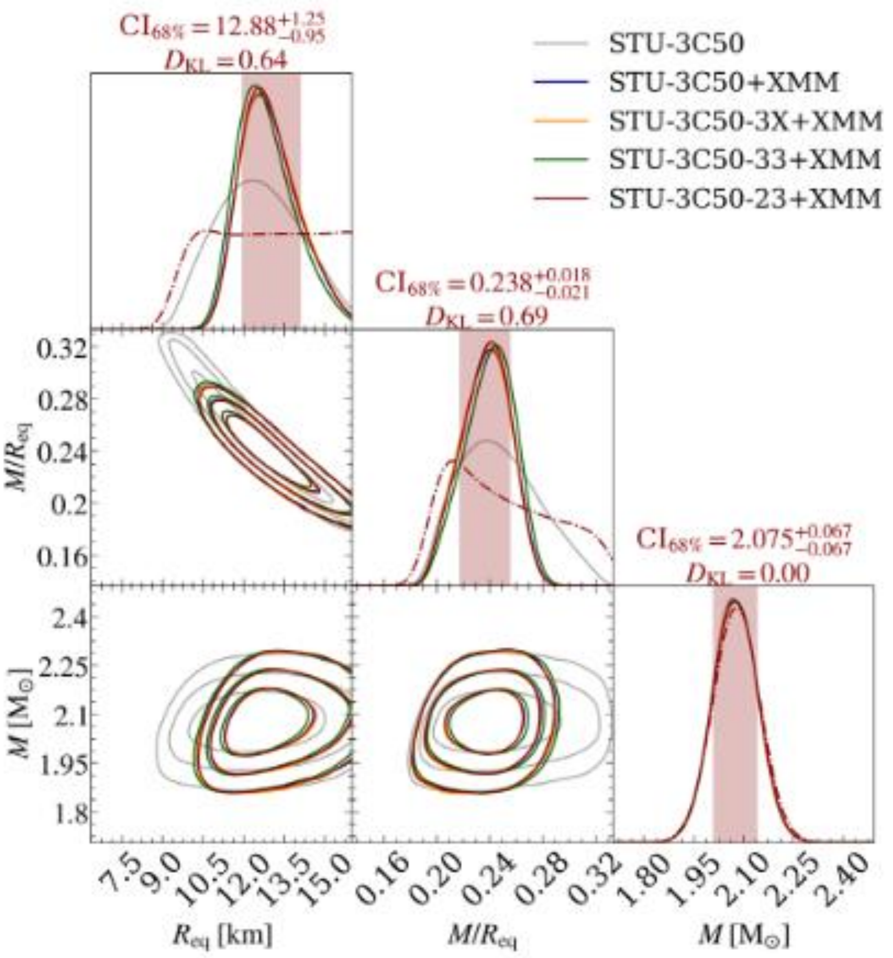



J0030
~1.4 solar masses
J0740
~2.1 solar masses

Neutron star Interior Composition Explorer

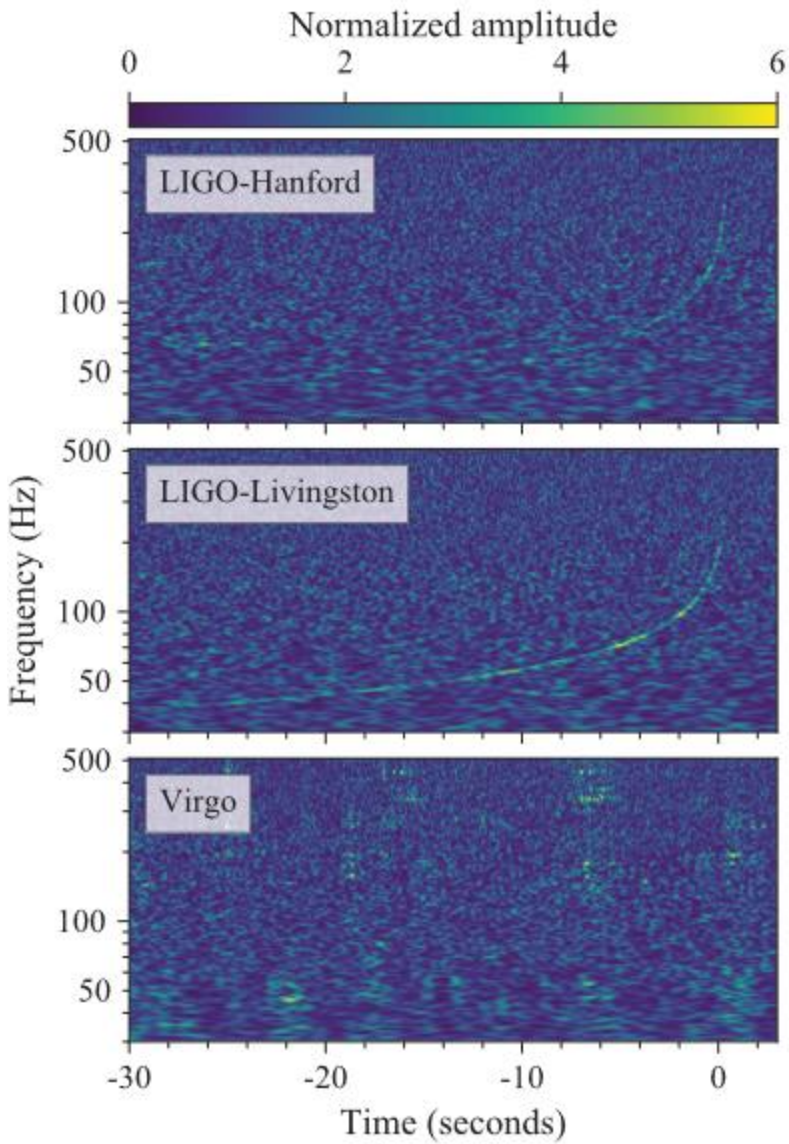


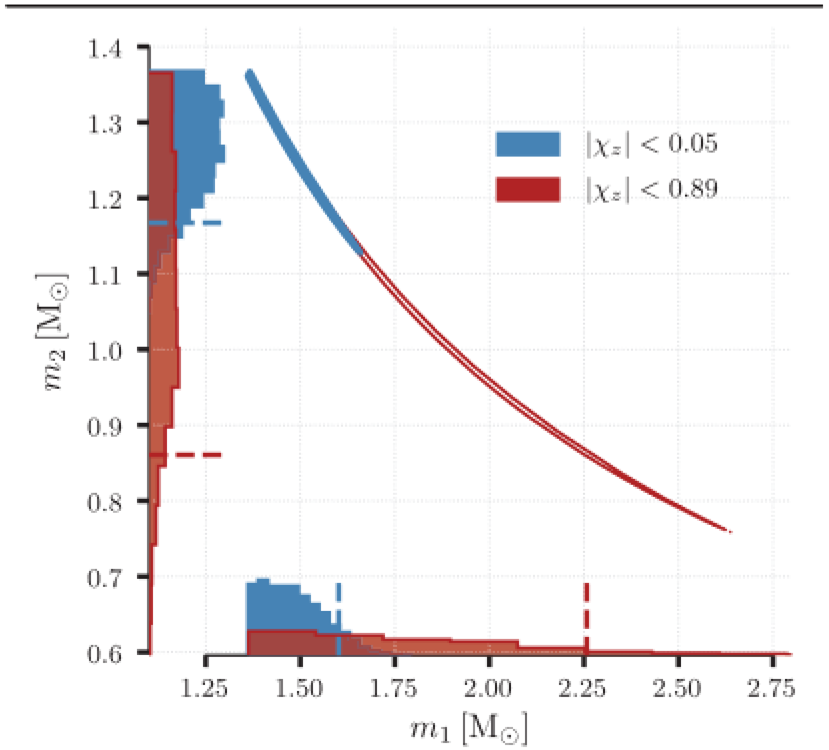
PSR J0030+0451 M-R (Riley+ 2019)



PSR J0740+6620 M-R (Salmi+ 2022)
(update compared to Riley et al. 2021,
uses NICER 3C50 background)

GW170817

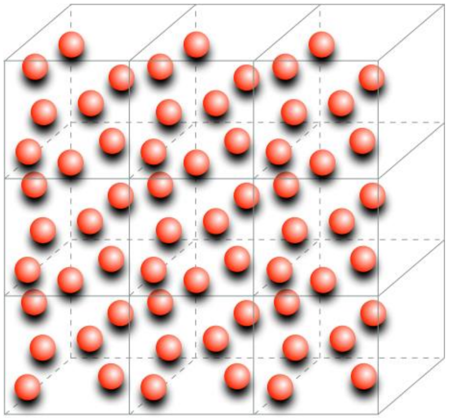




- Neutron star tidal deformability and mass as observables.

How we constrain EoS

Micro physics



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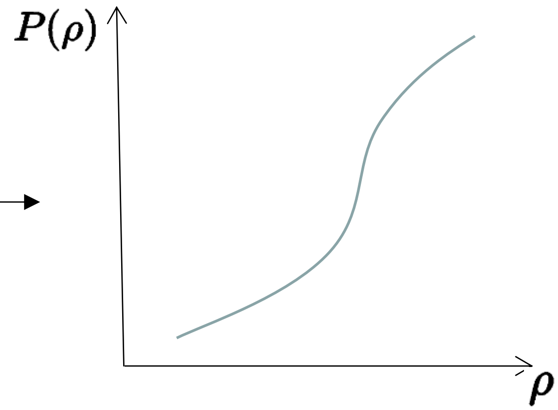

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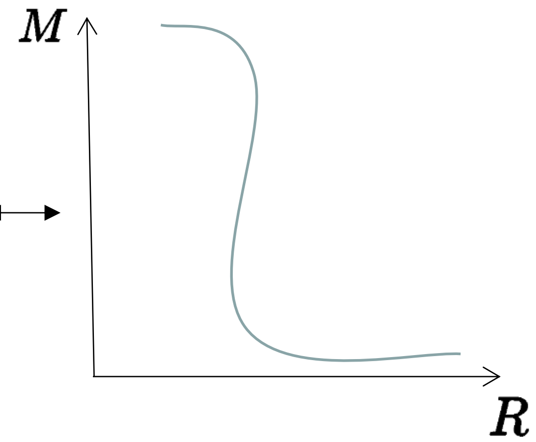

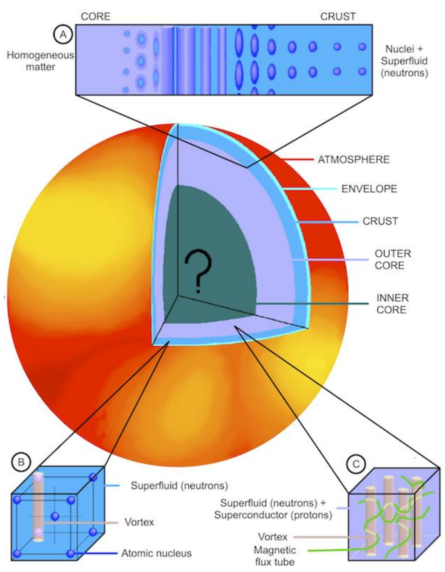

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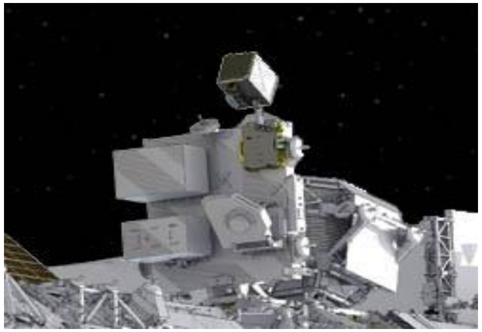

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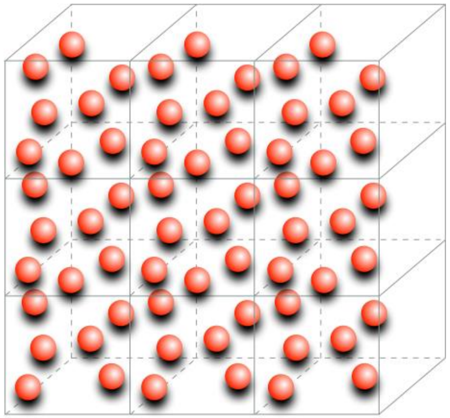

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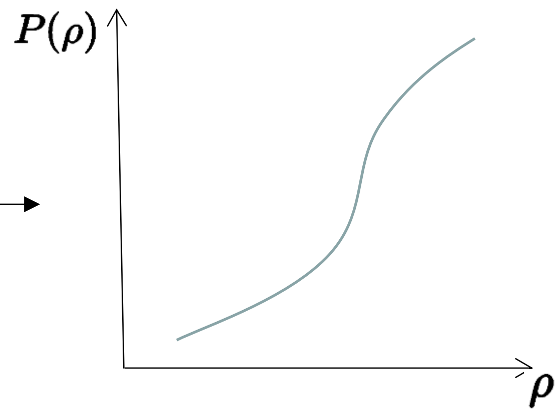

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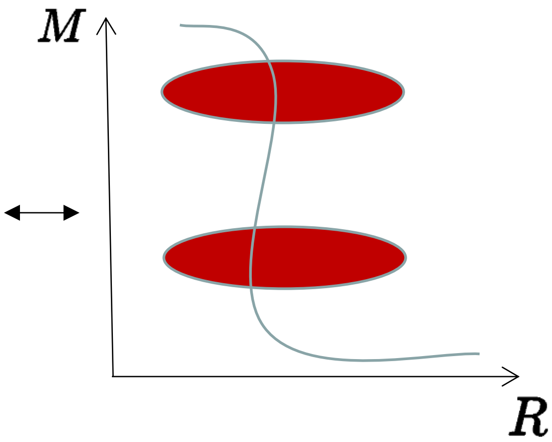

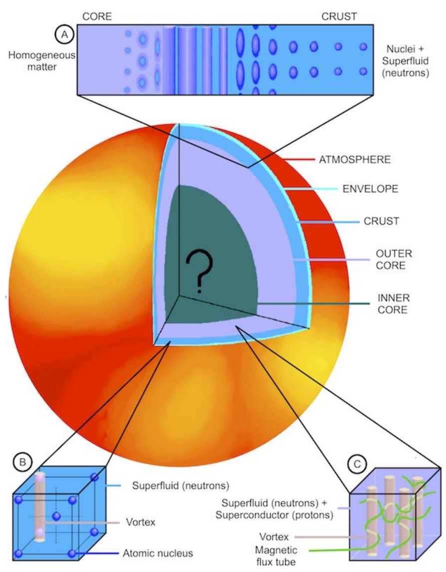

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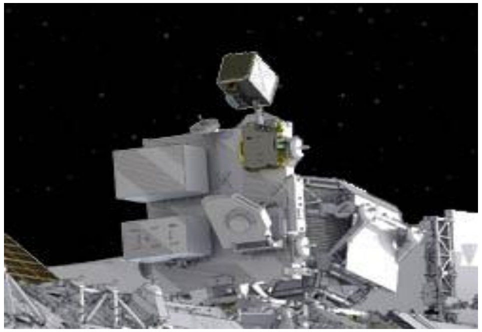

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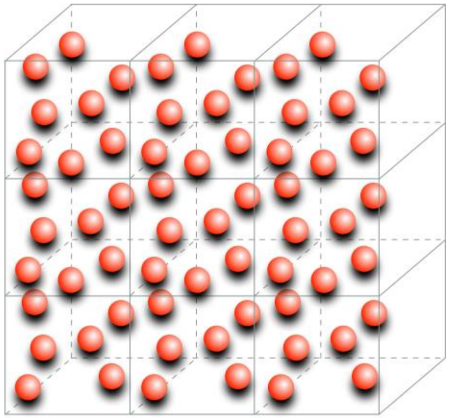

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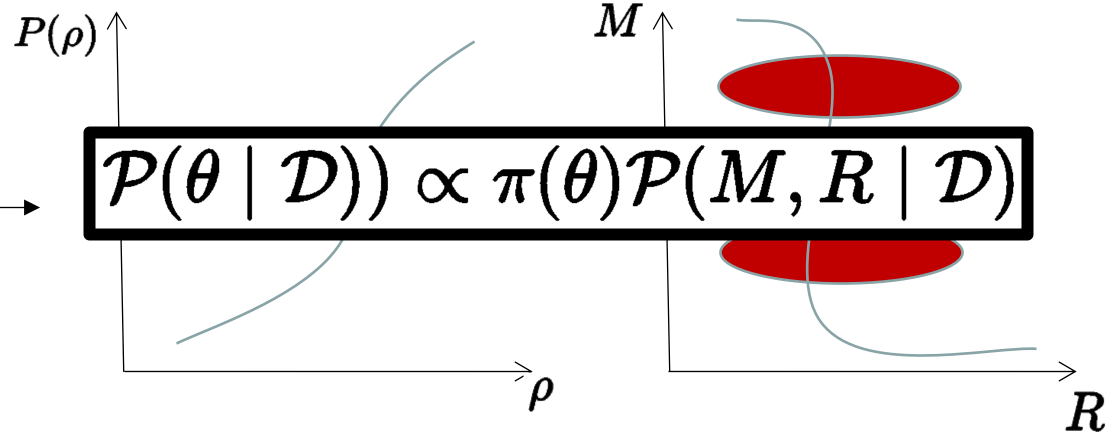
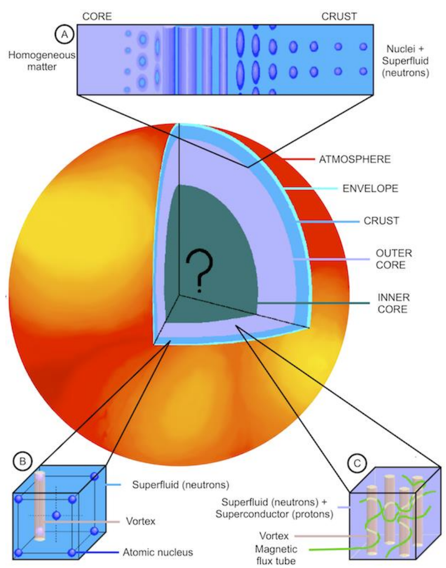


$$\mathcal{P}(\theta \mid \mathcal{D})) \propto \pi(\theta)\mathcal{P}(M, R \mid \mathcal{D})$$



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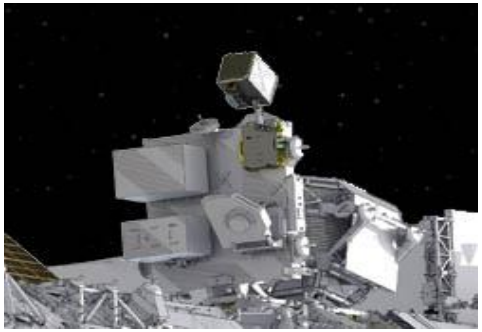

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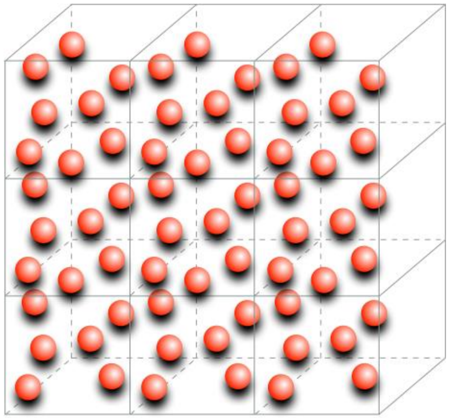

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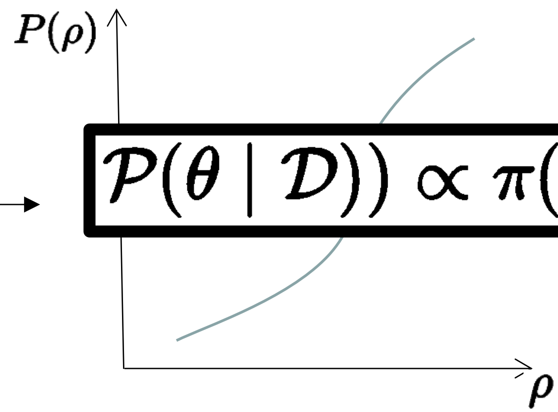

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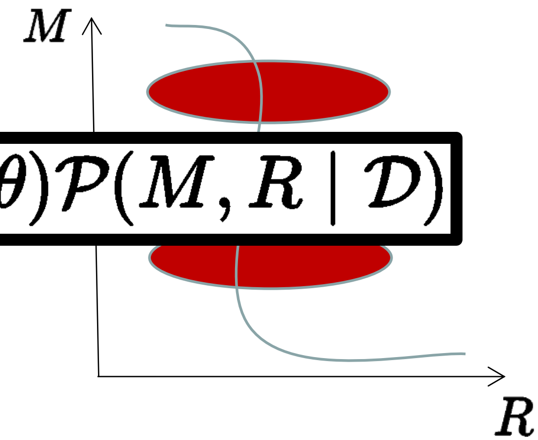

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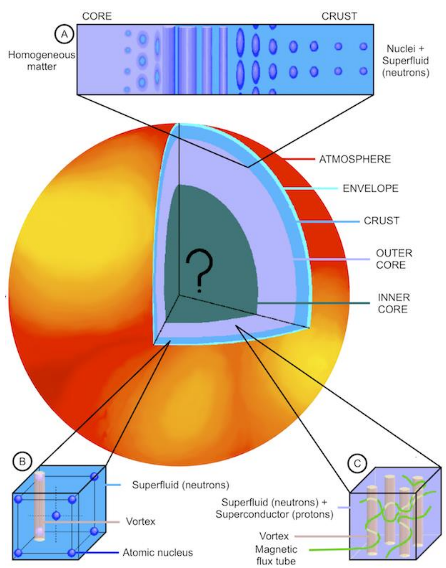

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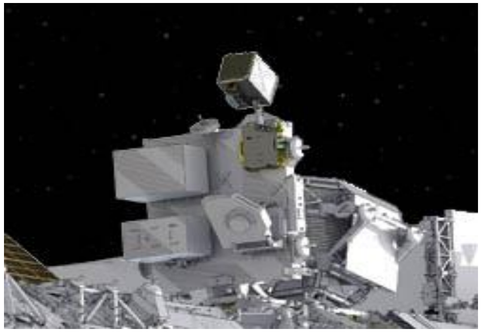

Detectors

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Moving to a more physical EoS model

- We would like to test a more physical EoS.
  Relativistic mean field theory construction:

Hypothetical Lagrangian — sigma meson, rho meson, phi meson.....
neutron, proton, hyperon.....

↓

equation of motion — Controlling equations of fields

↓

EoS ingredients (P, rho) — things we need....

Relativistic Mean Field Model

$$\mathcal{L} = \sum_b \mathcal{L}_b + \mathcal{L}_m + \sum_l \mathcal{L}_l$$

baryon | meson | lepton

$$\sum_N \mathcal{L}_N = \sum_N \bar{\Psi}_N \Big(i\gamma_\mu \partial^\mu - m_N + g_\sigma \sigma - g_\omega \gamma_\mu \omega^\mu - g_\rho \gamma_\mu \vec{I}_N \cdot \vec{\rho}^\mu \Big) \Psi_N,$$

$$\sum_l \mathcal{L}_l = \sum_l \bar{\psi}_l (i\gamma_\mu \partial^\mu - m_l) \psi_l,$$

$$\begin{aligned} \mathcal{L}_M = {} & \frac{1}{2}\partial_\mu \sigma \partial^\mu \sigma - \frac{1}{2} m_\sigma^2 \sigma^2 - \frac{\kappa}{3!}(g_\sigma \sigma)^3 - \frac{\lambda_0}{4!}(g_\sigma \sigma)^4 \\ & - \frac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu} + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu + \frac{\zeta}{4!} g_\omega^4 (\omega_\mu \omega^\mu)^2 \\ & - \frac{1}{4}\vec{R}^{\mu\nu} \cdot \vec{R}_{\mu\nu} + \frac{1}{2} m_\rho^2 \vec{\rho}_\mu \cdot \vec{\rho}^\mu + \Lambda_\omega g_\rho^2 \vec{\rho}_\mu \cdot \vec{\rho}^\mu g_\omega^2 \omega_\mu \omega^\mu, \end{aligned}$$

- FSU2R, Z272v, FSU, IUFSU, TM1$\omega\rho$, TM1e, TM1-2$\omega\rho$ and Big Apple.... Many EoS model are based on this same framework.

- Since all of them are in the same framework, we can do direct evidence computation for each of them using Bayesian inference.

Free Parameters

RMF construction

+

$\kappa \quad \lambda \quad \zeta \quad \Lambda_\omega$

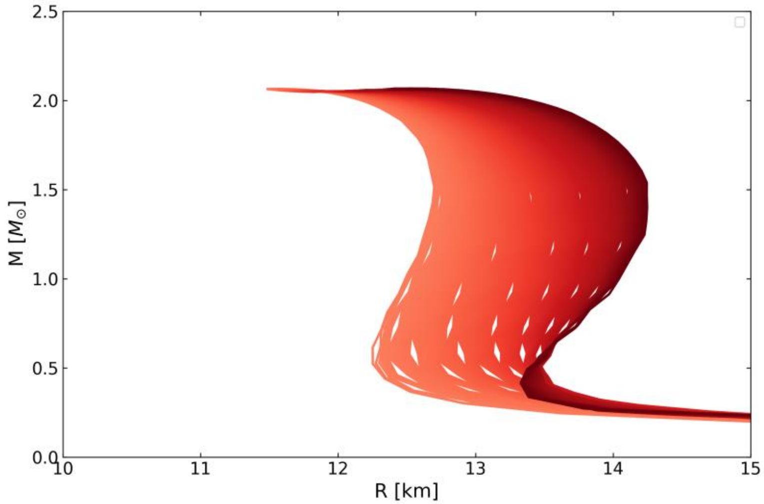
$g^2_{\sigma N} \quad g^2_{\rho N} \quad g^2_{\omega N}$

$m_\rho \quad m_\omega \quad m_\sigma$

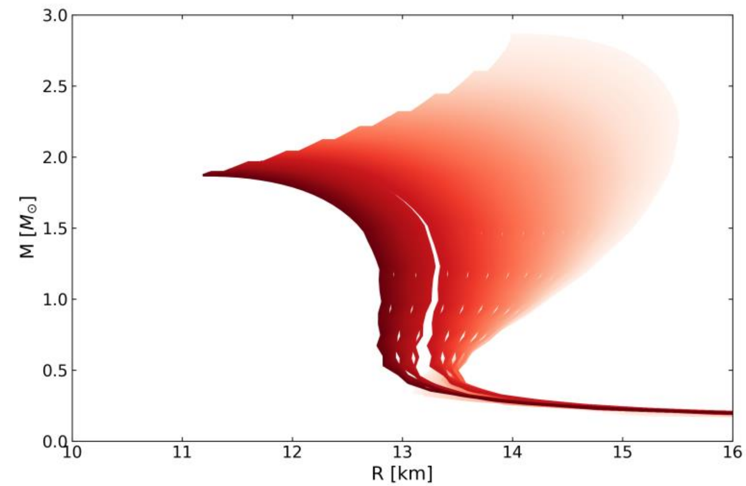
=

Infinite number of

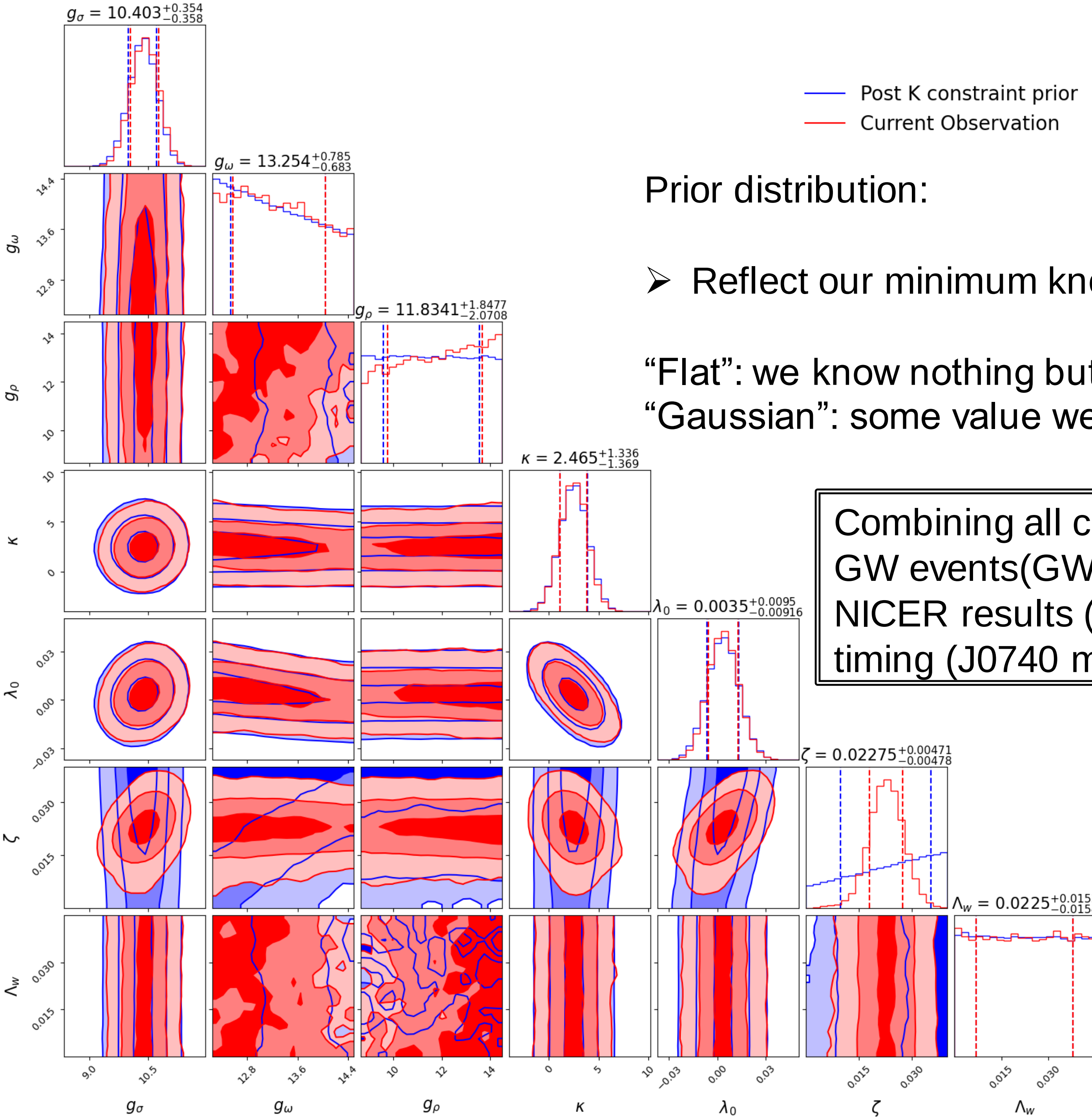
Nucleonic EoS models



σ meson self interaction



quadratic self-coupling of the ω meson

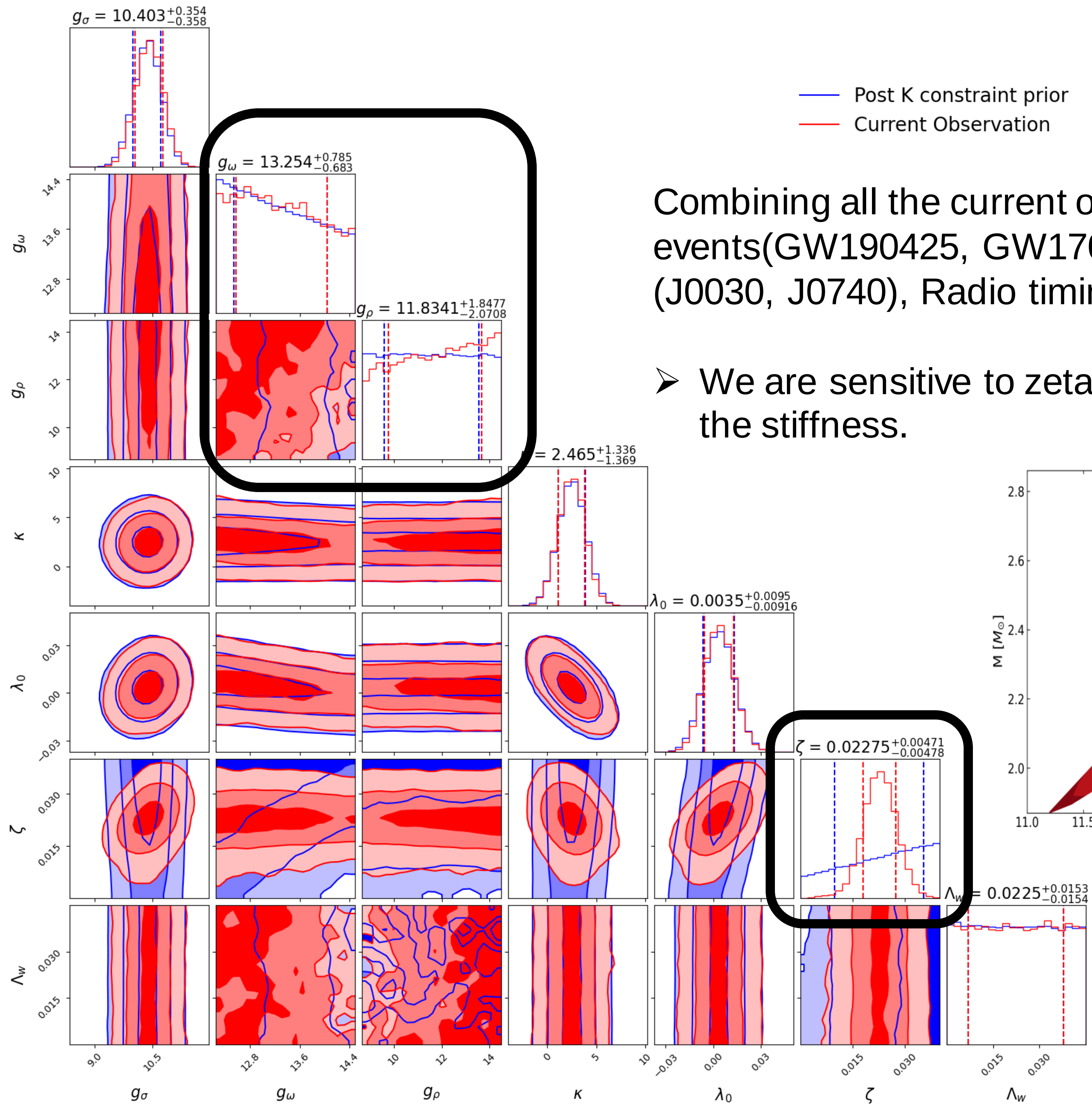


Prior distribution:

➢ Reflect our minimum knowledge.

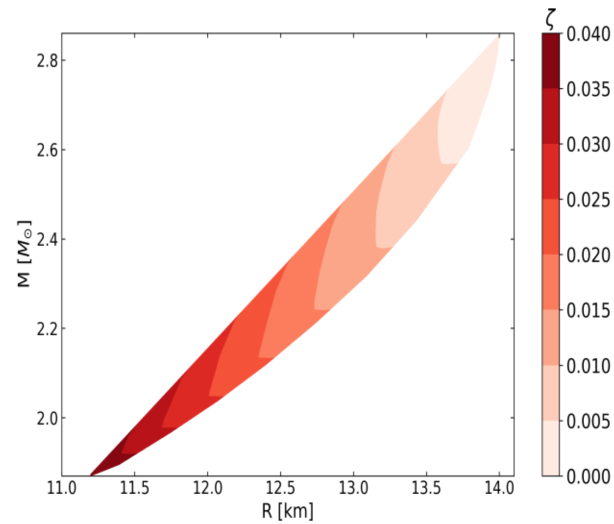
"Flat": we know nothing but hard cut
"Gaussian": some value we believe is more likely

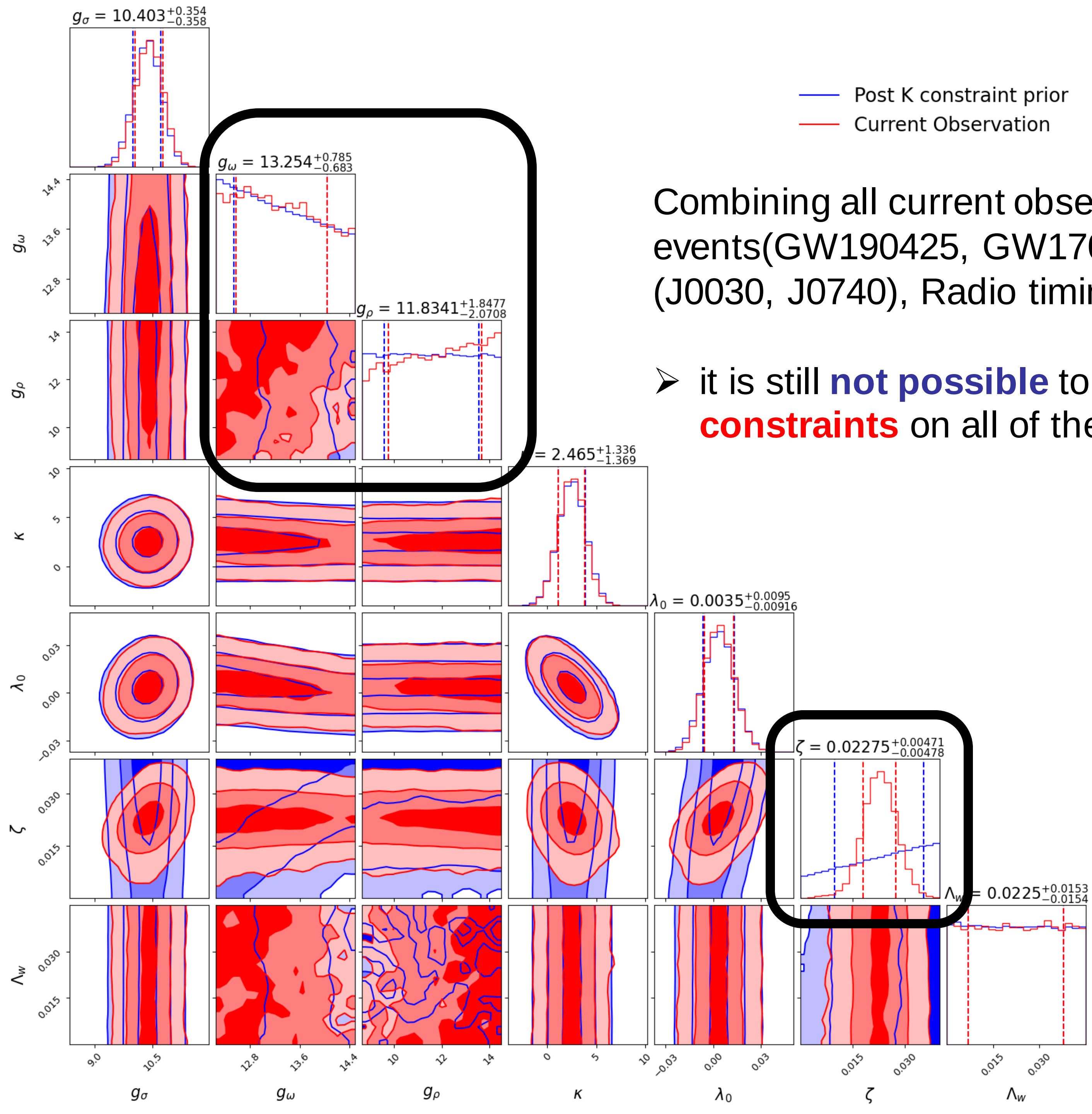
Combining all current observations: GW events(GW190425, GW170817), NICER results (J0030, J0740), Radio timing (J0740 mass)



Combining all the current observations: GW events(GW190425, GW170817), NICER results (J0030, J0740), Radio timing (J0740 mass)

- We are sensitive to zeta, since it determines the stiffness.

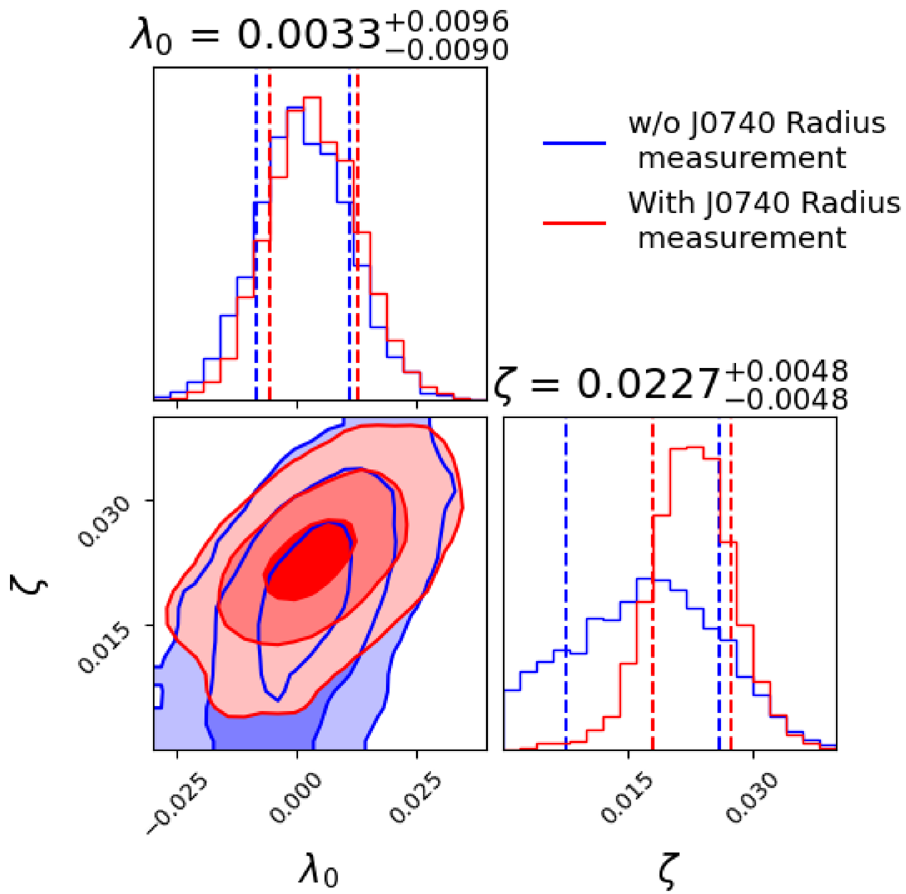


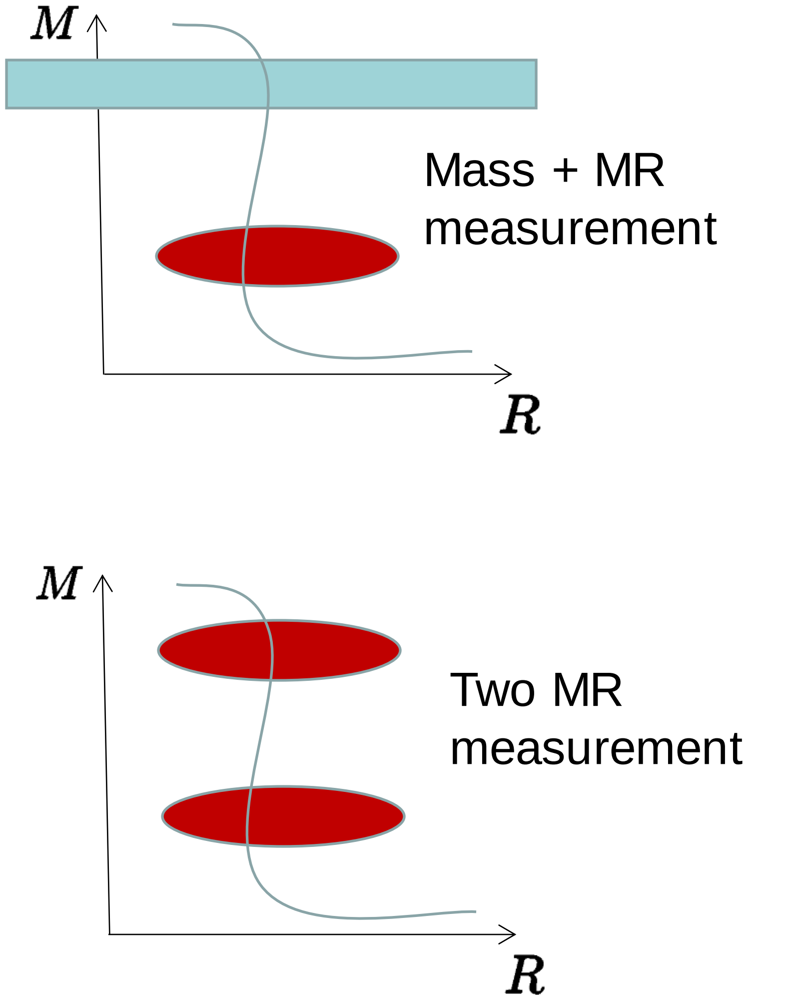


Combining all current observations: GW events(GW190425, GW170817), NICER results (J0030, J0740), Radio timing (J0740 mass)

- ➢ it is still **not possible** to extract **strong constraints** on all of the model parameters.

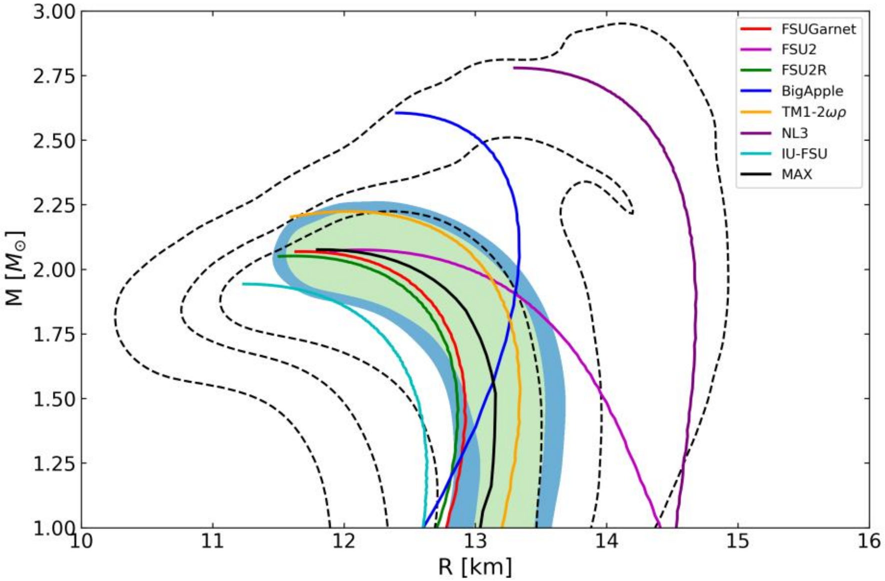
The importance of knowing radius ....





- It is good to know that **single radius** measurements can have such a significant effect.

Model comparison

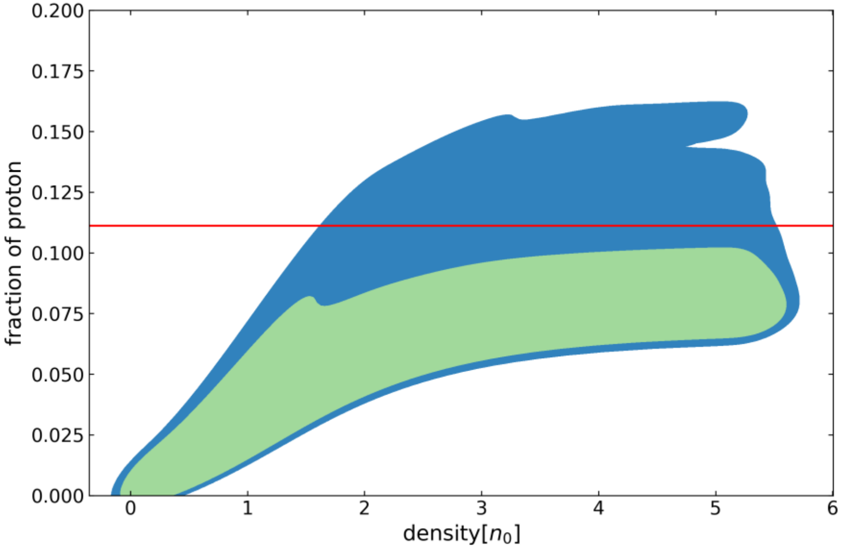


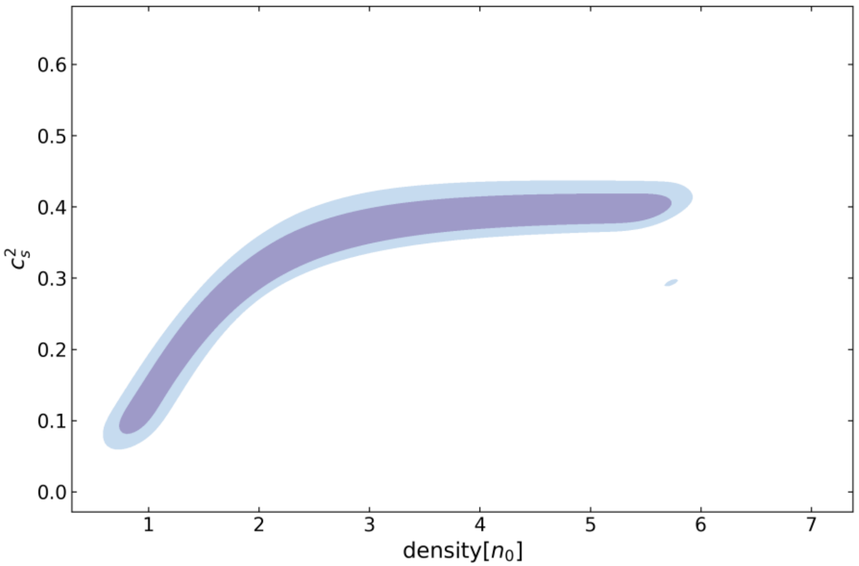
Model	$g^2_{\omega N}$	λ	ζ	Evidence
FSU2R	182.3949	-0.00168	0.024	0.8724
TM1-2$\omega\rho$	156.3384	-0.00474	0.012	0.0788
NL3	165.5854	-0.01591	0	0.0032
FSU2	183.7893	-0.00053	0.0256	0.7380
IU-FSU	169.8349	0.00030	0.03	0.0577
FSUGarnet	187.6947	-0.00355	0.02350	0.7558
BigApple	151.6839	-0.02174	0.0007	4.0×10^{-6}
MAX	174.337	0.0043	0.0235	1

$$\textbf{Evidence} = \frac{p\left(g_\omega^2\right) \times p\left(g_\rho^2\right) \times p(\zeta)}{p_{\max}\left(g_\omega^2\right) \times p_{\max}\left(g_\rho^2\right) \times p_{\max}(\zeta)}$$

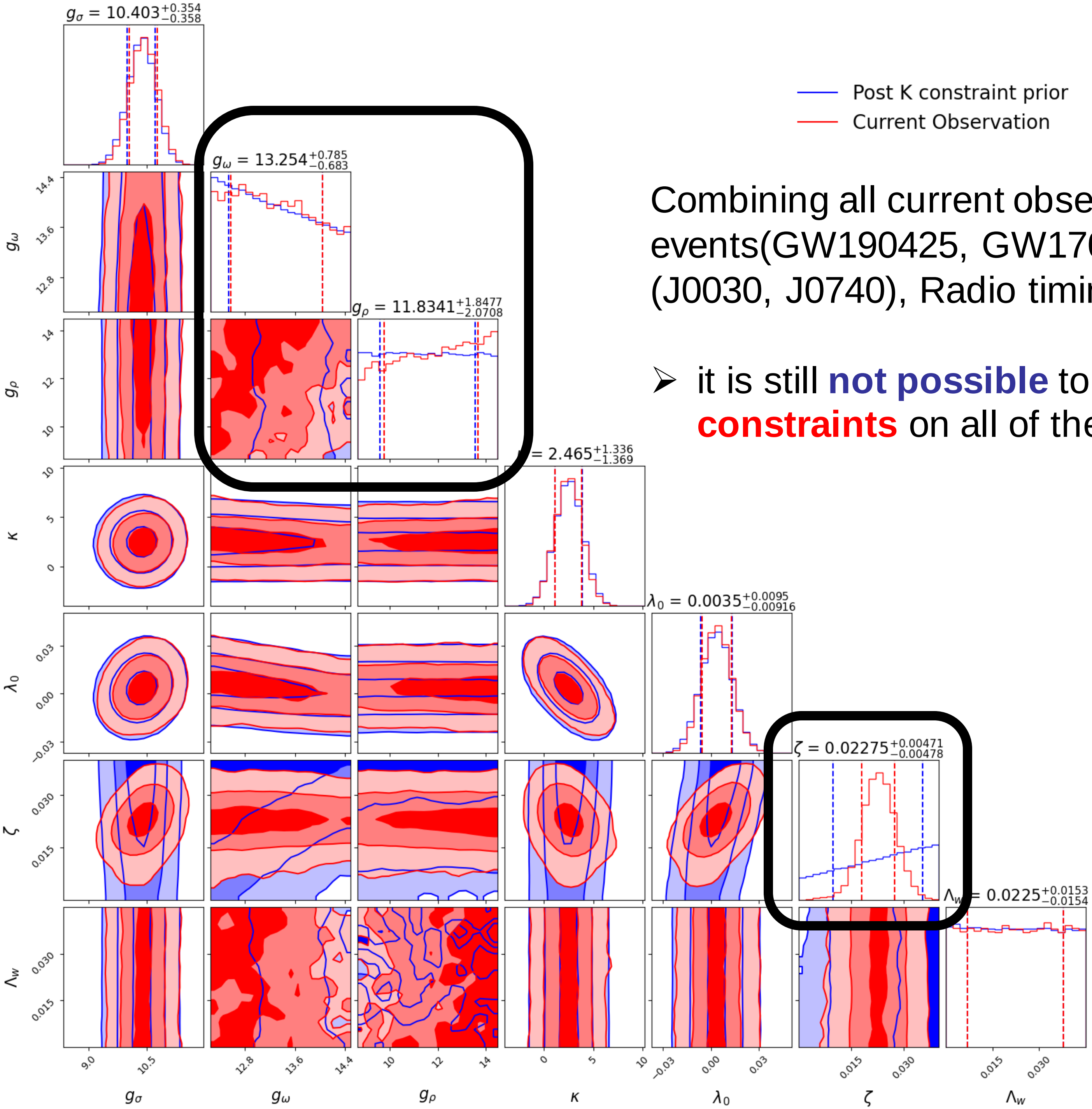
- Using the three decoupled parameters, we can **compute evidences** for different models, and test their reliability given **the current observations**. Some of them appear to be disfavoured.

Proton fraction and speed of sound



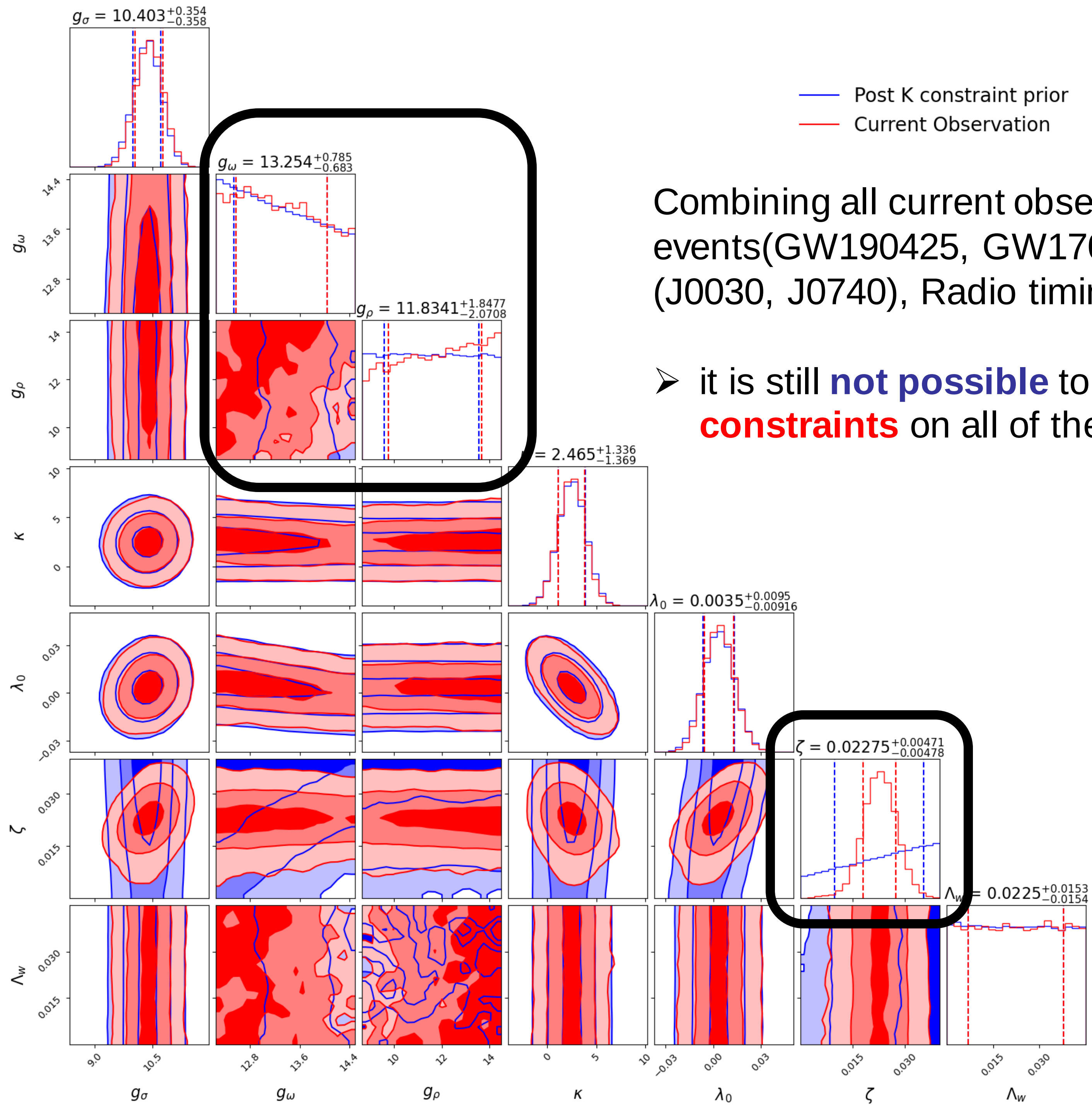


- We can derive the **proton fraction (related to cooling)** and **speed of sound** constraints from current observations.



Combining all current observations: GW events(GW190425, GW170817), NICER results (J0030, J0740), Radio timing (J0740 mass)

- it is still **not possible** to extract **strong constraints** on all of the model parameters.



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Probe class observatory Ray et al. 2019. Follow @STROBEXAstro on Twitter.

Larger effective area, broader band coverage than NICER

Proposal being prepared for NASA Probe-class mission call due November 2023

EAS 2022 – Special Session SS9 - Valencia - 27 June 2022
eXTP: a future China-EU X-ray mission to study matter under extreme conditions

SOC

M. Hernanz, chair (ICE/CSIC-IEEC, ES)
M. Feroci, co-chair (IAPS/INAF, IT)
N. Rea, co-chair (ICE/CSIC-IEEC, ES)
A. Santangelo, co-chair (EKUT, DE)
Y. XU (IHEP, CAS, CN)
F. LU (IHEP, CAS, CN)
Jean in 't Zand (SRON, NL)
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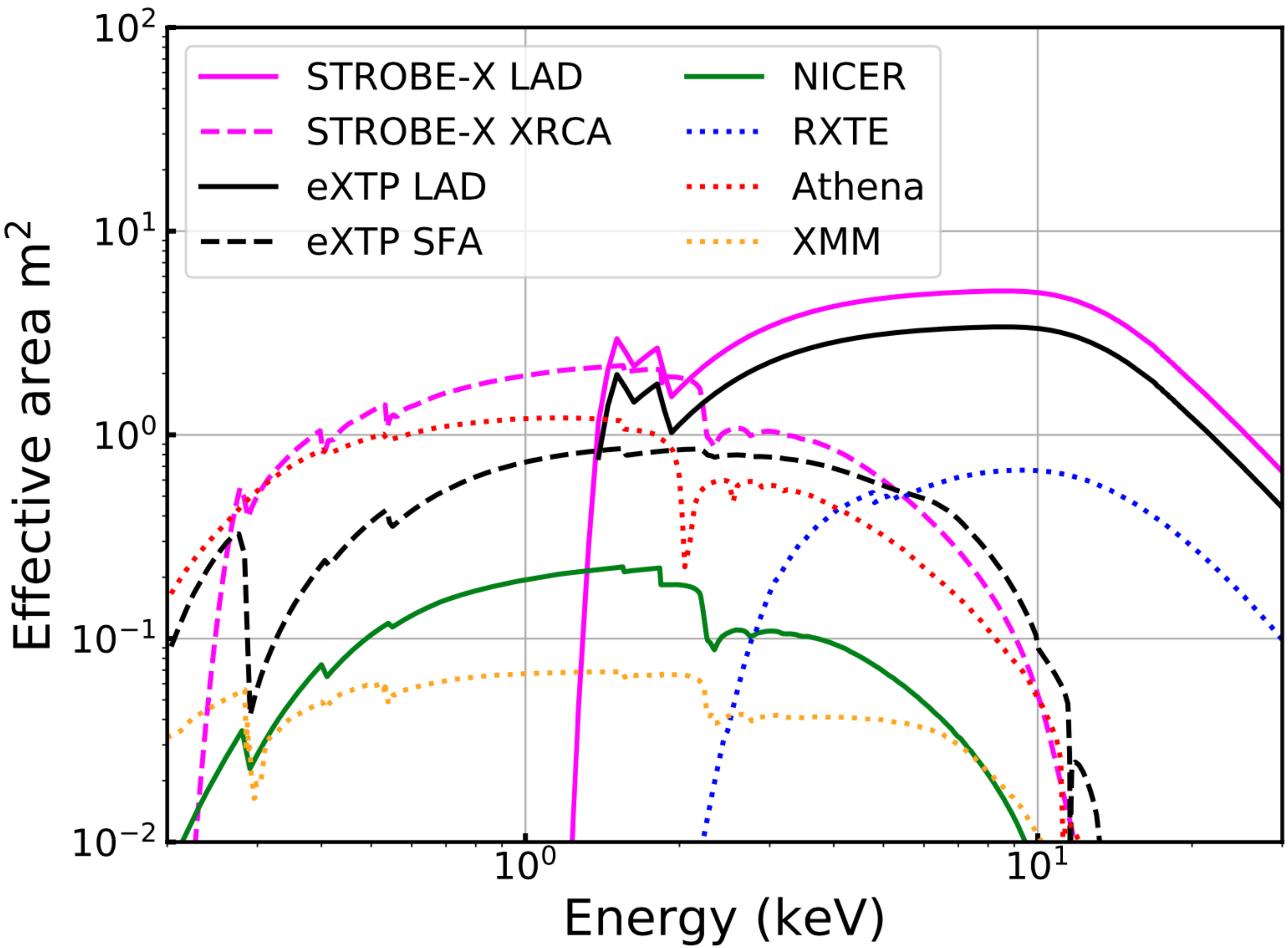
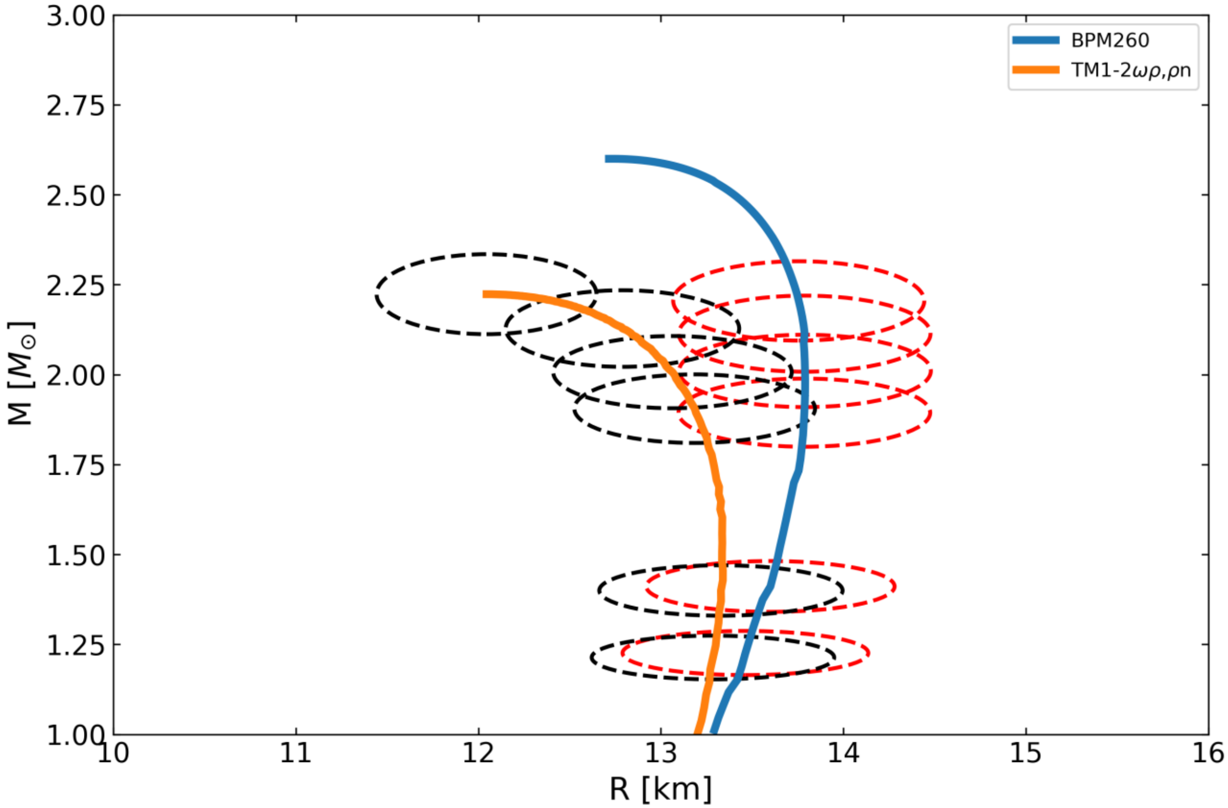
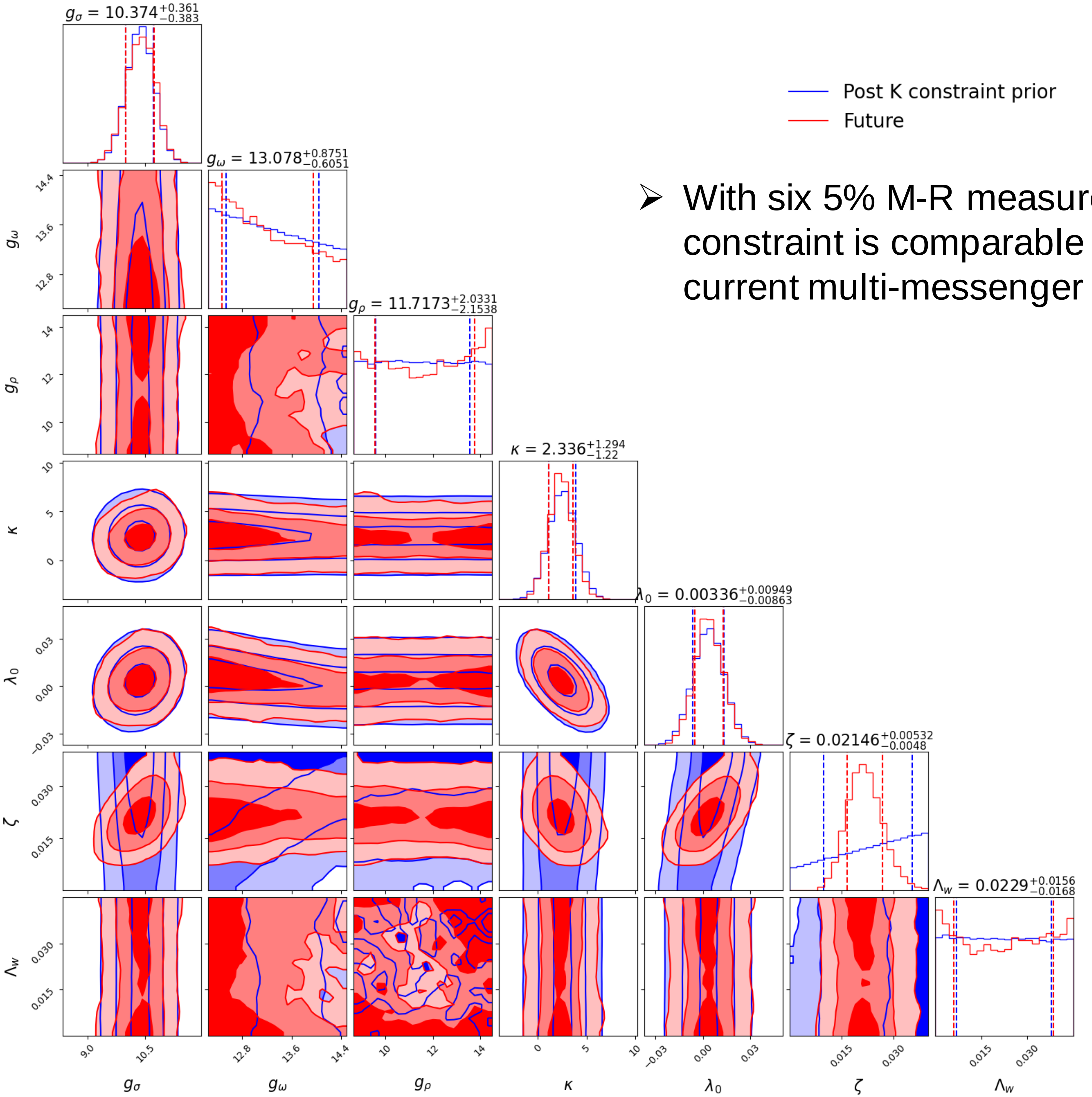
E. Kalemci (Sabanci Univ., TR)


STROBE-X LAD
STROBE-X XRCA
eXTP LAD
eXTP SFA
NICER
RXTE
Athena
XMM
Effective area m^2
Energy (keV)
10^2
10^1
10^0
10^{-1}
10^{-2}
10^0
10^1

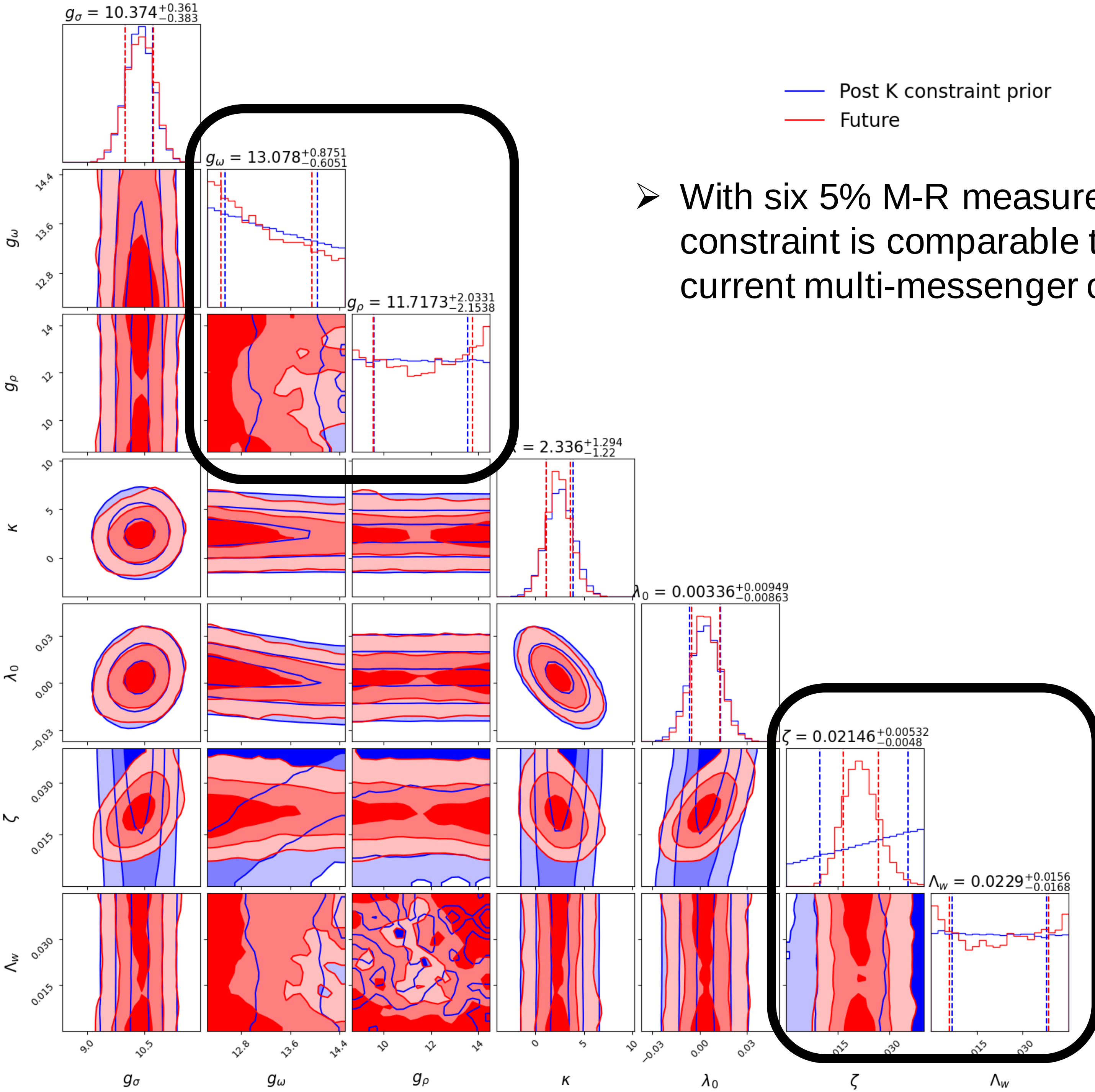
Future case: near future capability



- [1,2, 1.4, 1.9, 2.0, 2.1, 2.2] $M_\odot$, PSR J0740+6620 (2.1 $M_\odot$), PSR J1614-2230 (1.9 $M_\odot$) and PSR J0437-4715 (1.4 $M_\odot$).
- six +/- 5% uncertainty M-R measurements along two different "ground-truth" EoS. **ONLY consider the X-ray (M-R) measurements**



- With six 5% M-R measurements, the constraint is comparable to that achieved by current multi-messenger observations.



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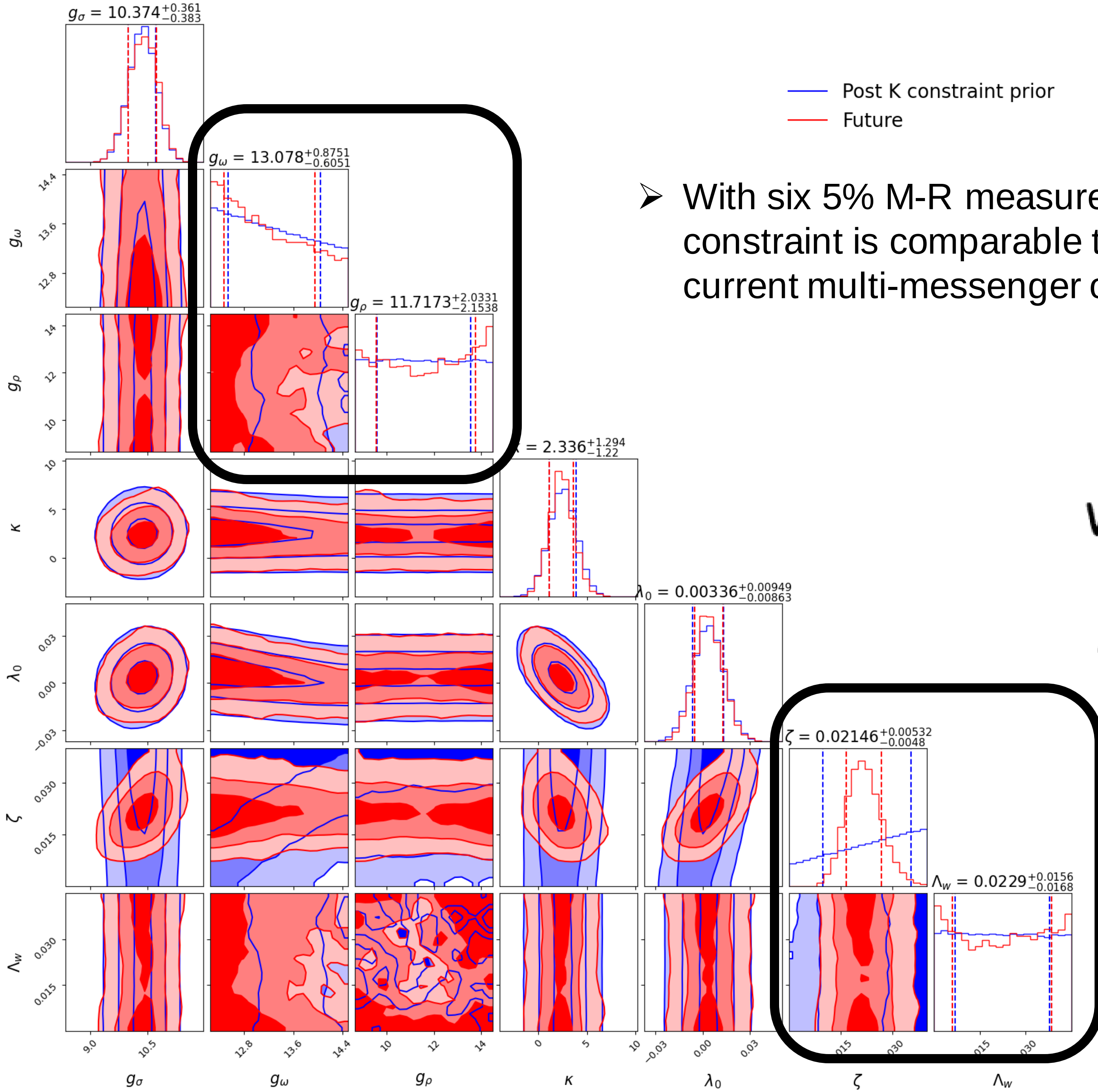
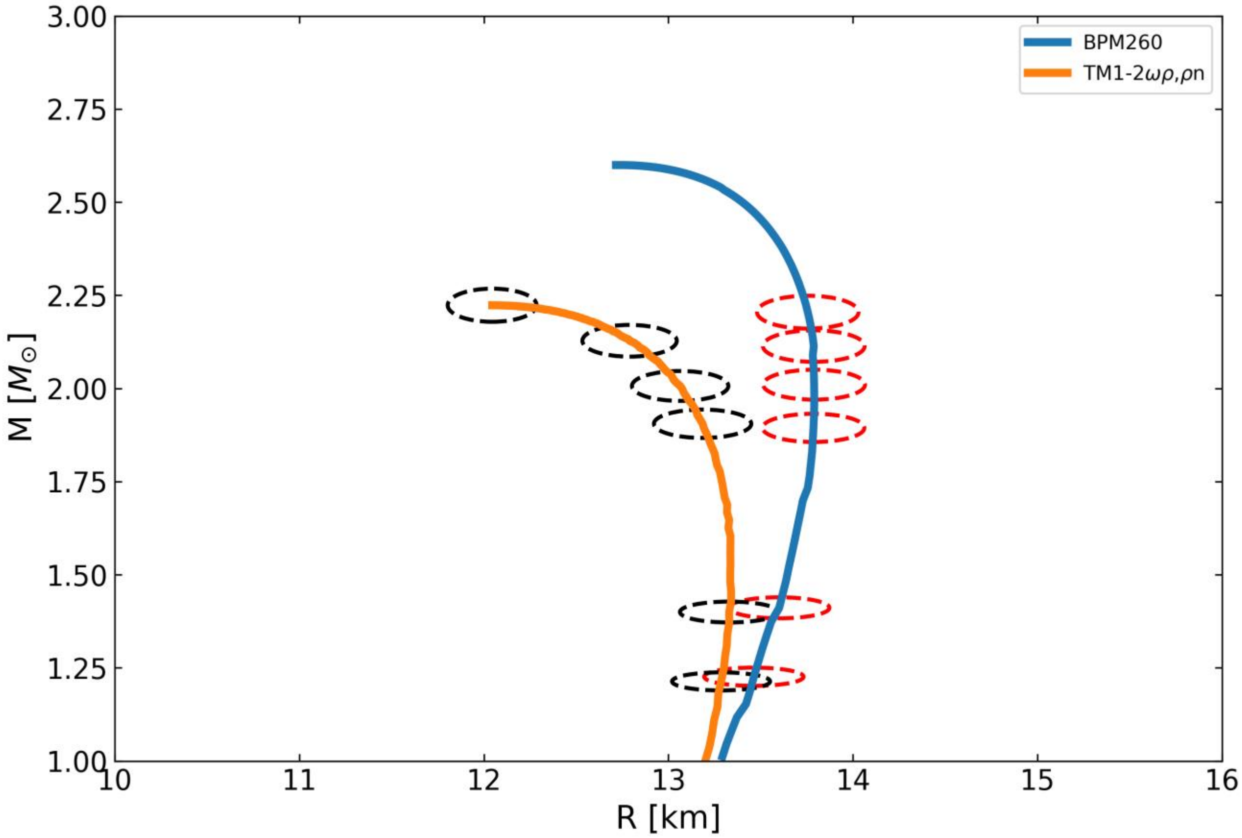


- With six 5% M-R measurements, the constraint is comparable to that achieved by current multi-messenger observations.

Future-X case:



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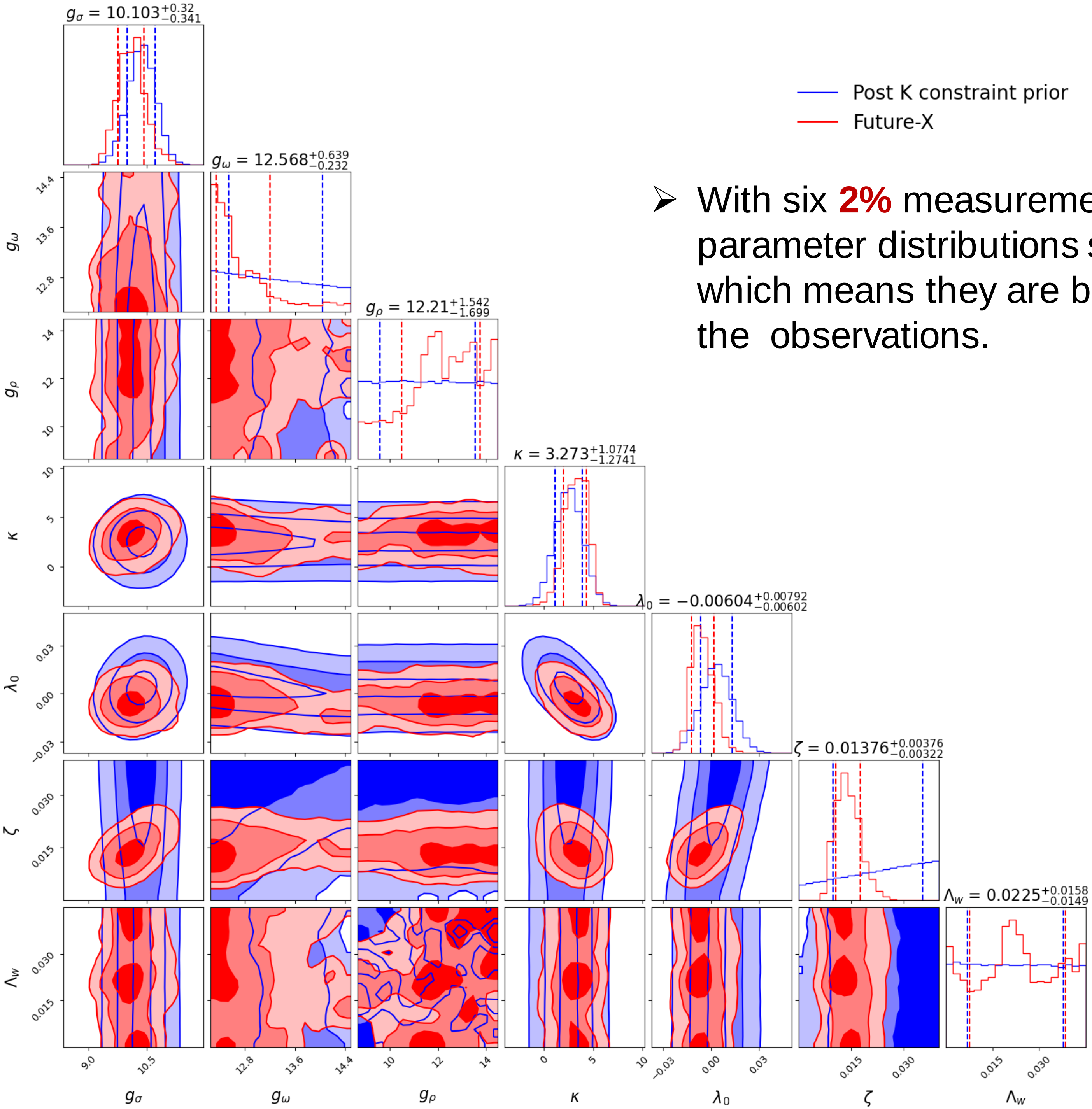
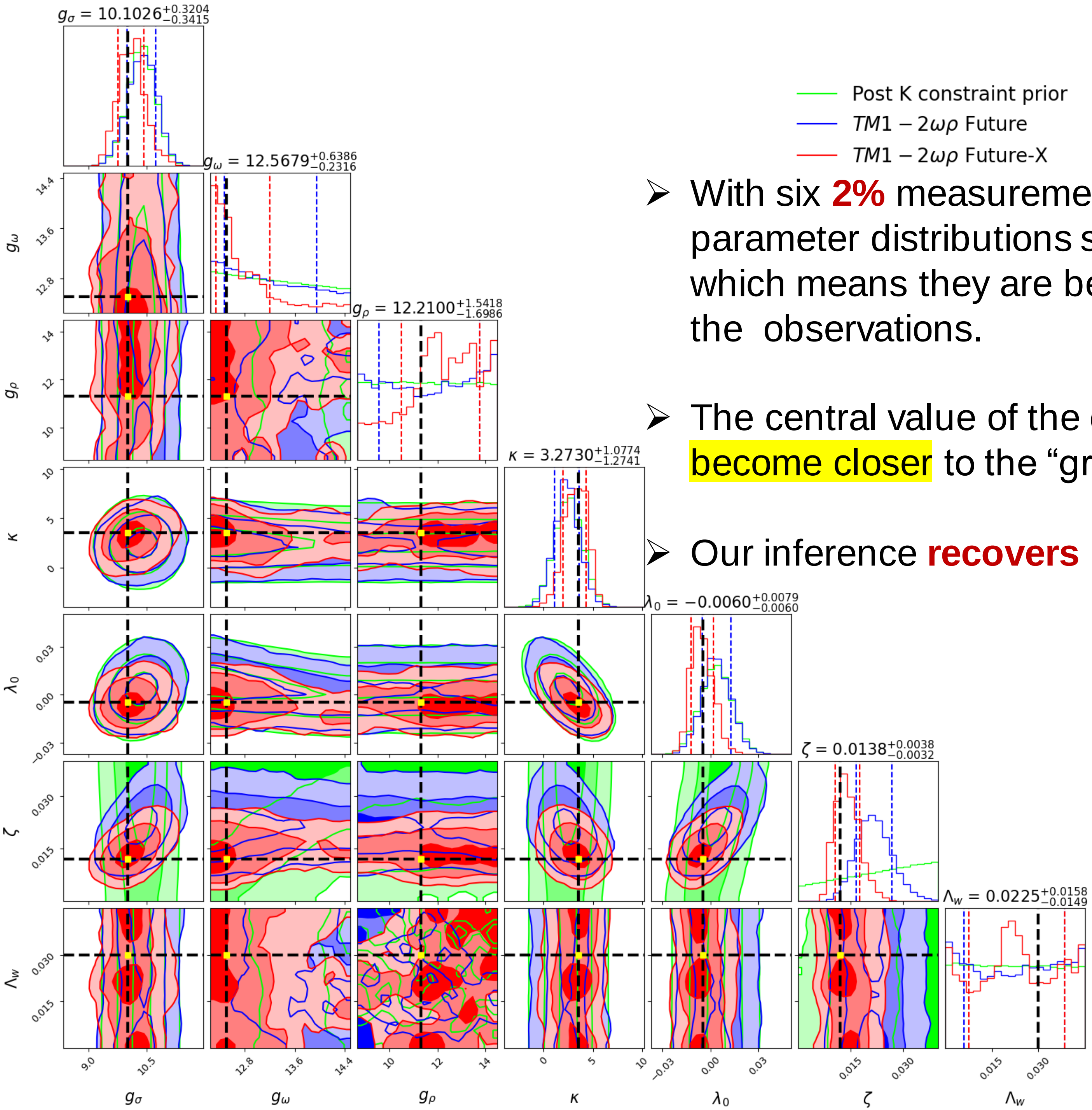
- six +/- **2%** uncertainty M-R measurements for two different "ground-truth" (injected) EoS. **This is a "best-case" study**



- With six **2%** measurements, all of the parameter distributions start to be re-shaped, which means they are being constrained by the observations.



- With six **2%** measurements, all of the parameter distributions start to be re-shaped, which means they are being constrained by the observations.
- The central value of the distribution will become closer to the "ground-truth" value.
- Our inference **recovers** the injected EoS!

Conclusions

- We have considered a **microscopic nuclear model** based on a field theoretical approach. and derive constraints from
  - All current observations,
  - Future observations (Future)
  - Best-case future observations with e.g. STROBE-X/eXTP (Future-X)

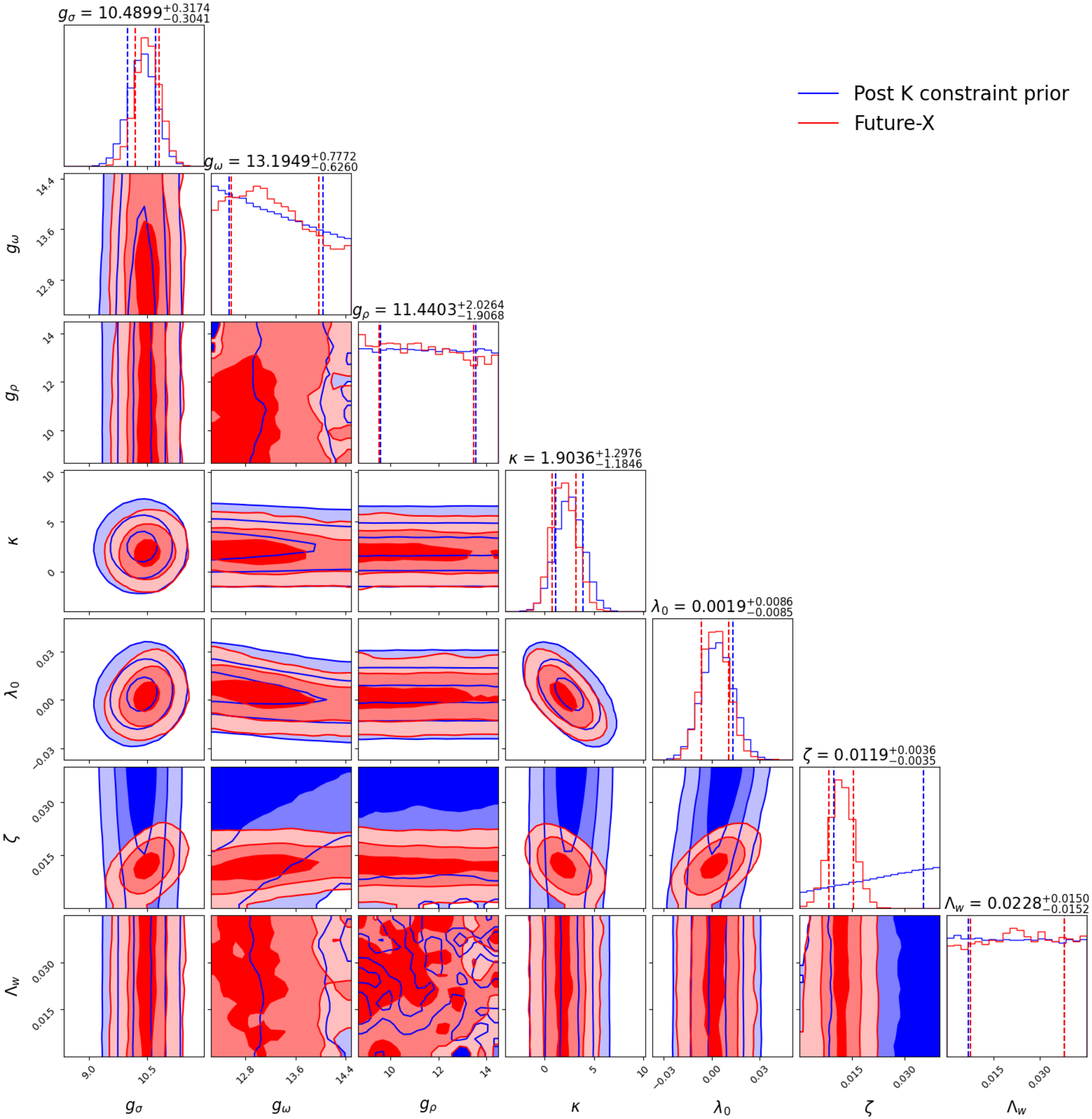
- With Current observations, we can constrain on the **proton fraction** and **speed of sound**, can compute **evidence** for all the models based on the same framework.

- When upgrading to the Future case, it just **comparable** with current multi-messenger observation constraint (using M-R alone, so we can crosscheck with GW).

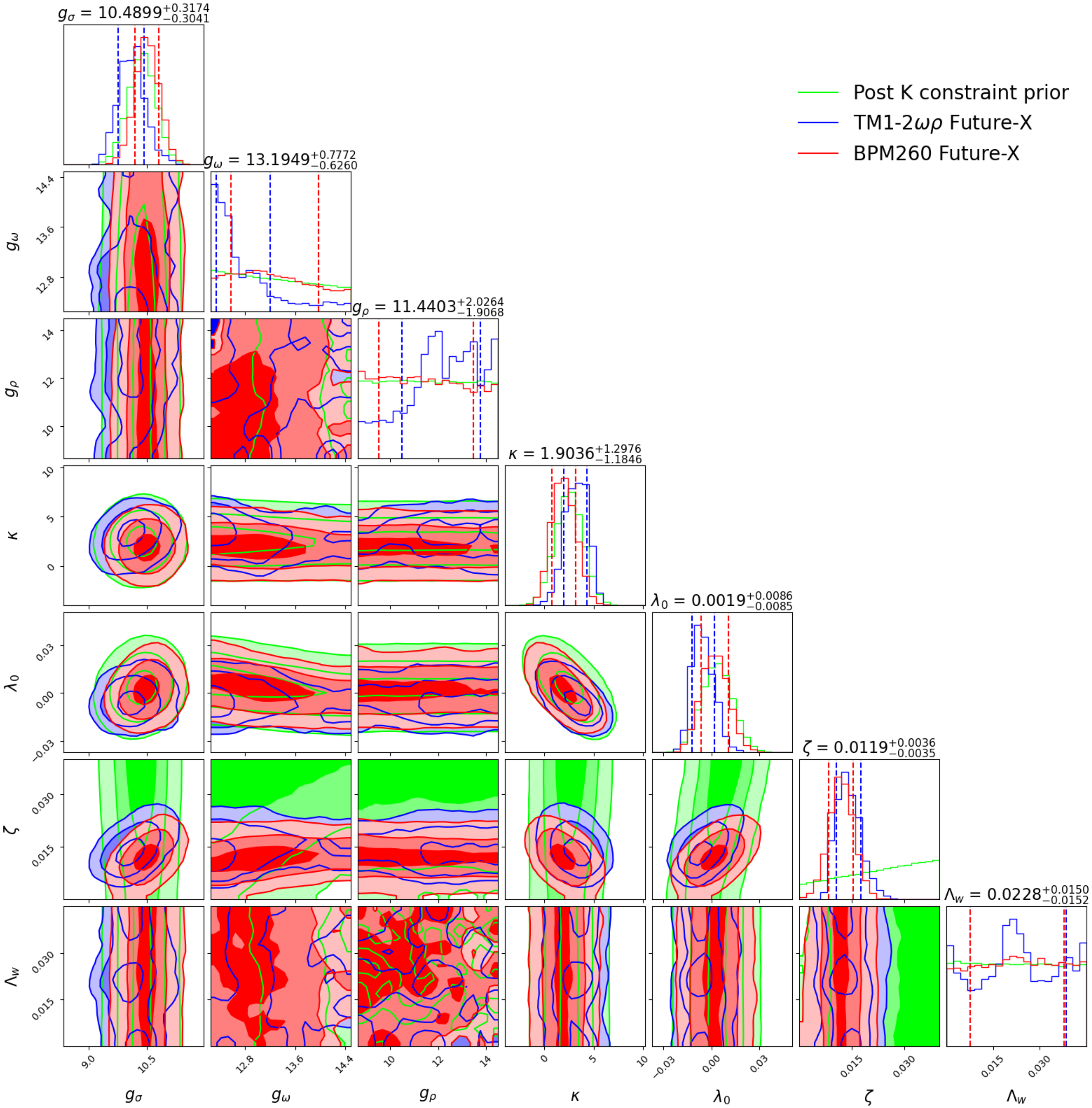
- When upgrading to the Future-X case, we can constrain the **whole parameter space** and **recover** the underlying EoS using X-ray observations alone.

- Next, Hyperon degrees of freedom will be added! We want to explore how future observations could inform this – important work for science case for future missions.

Thanks !!!



$g_\sigma = 10.4899^{+0.3174}_{-0.3041}$
$g_\omega = 13.1949^{+0.7772}_{-0.6260}$
$g_\rho = 11.4403^{+2.0264}_{-1.9068}$
$\kappa = 1.9036^{+1.2976}_{-1.1846}$
$\lambda_0 = 0.0019^{+0.0086}_{-0.0085}$
$\zeta = 0.0119^{+0.0036}_{-0.0035}$
$\Lambda_w = 0.0228^{+0.0150}_{-0.0152}$
Post K constraint prior
Future-X
g_σ
g_ω
g_ρ
κ
λ_0
ζ
Λ_w



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TM1-2$\omega\rho$ Future-X
BPM260 Future-X
g_σ
g_ω
g_ρ
κ
λ_0
ζ
Λ_w