CAU BSM @ 2023.02.23

Gravitational Waves and Neutron Star Equation of State

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in collaboration with

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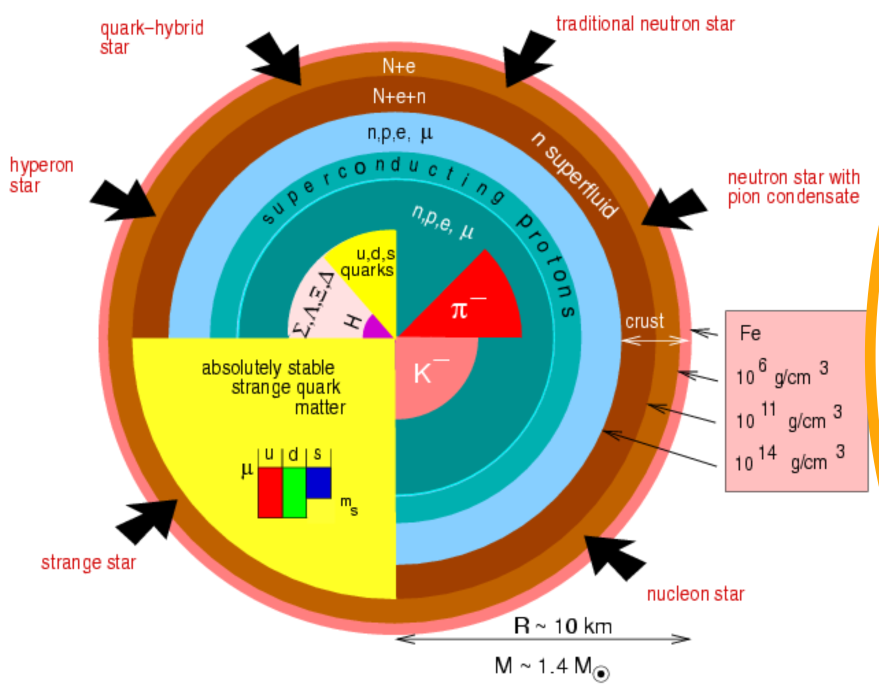
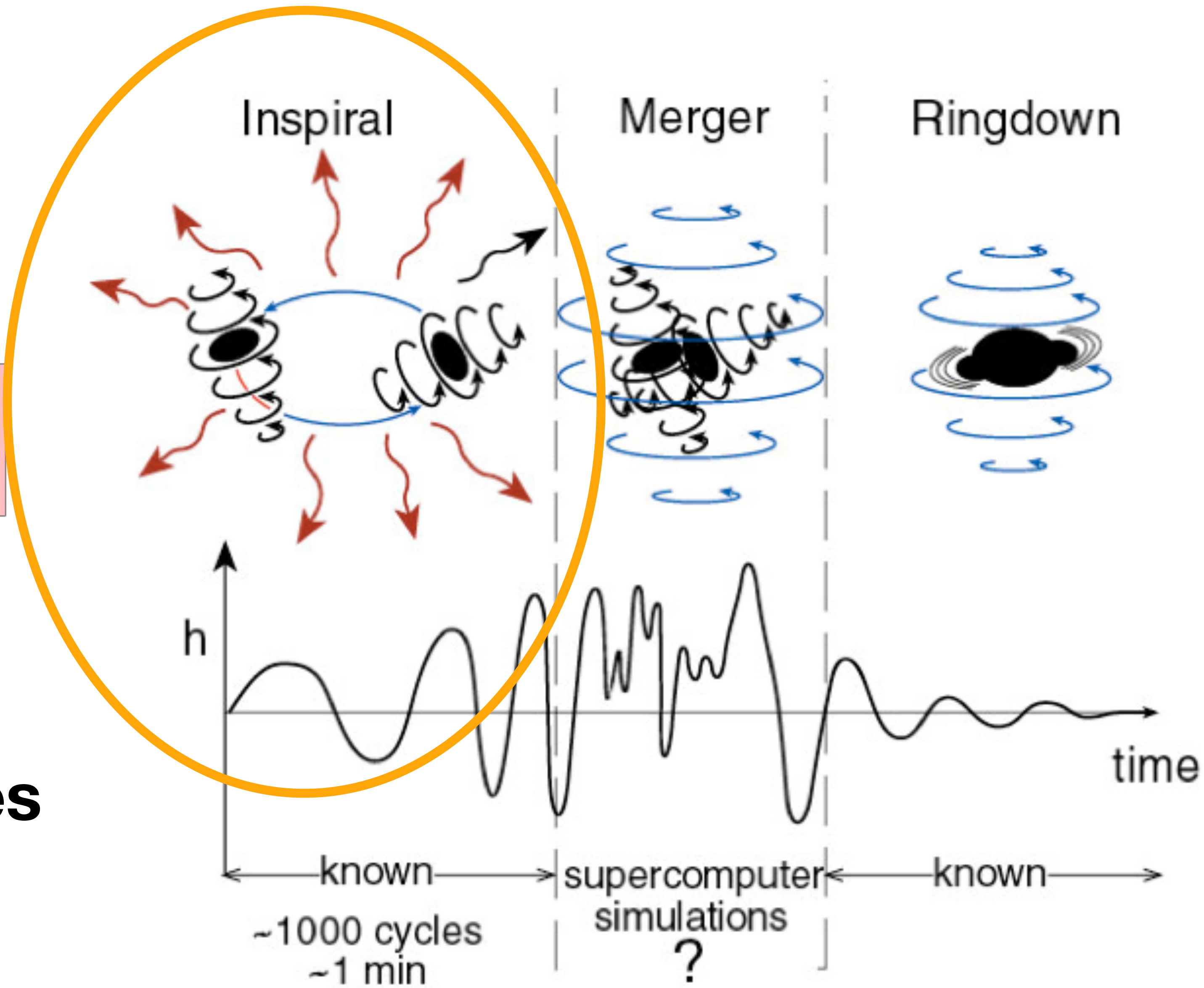
(BUD and KGWG)

Contents

NS Tidal deformability from GW





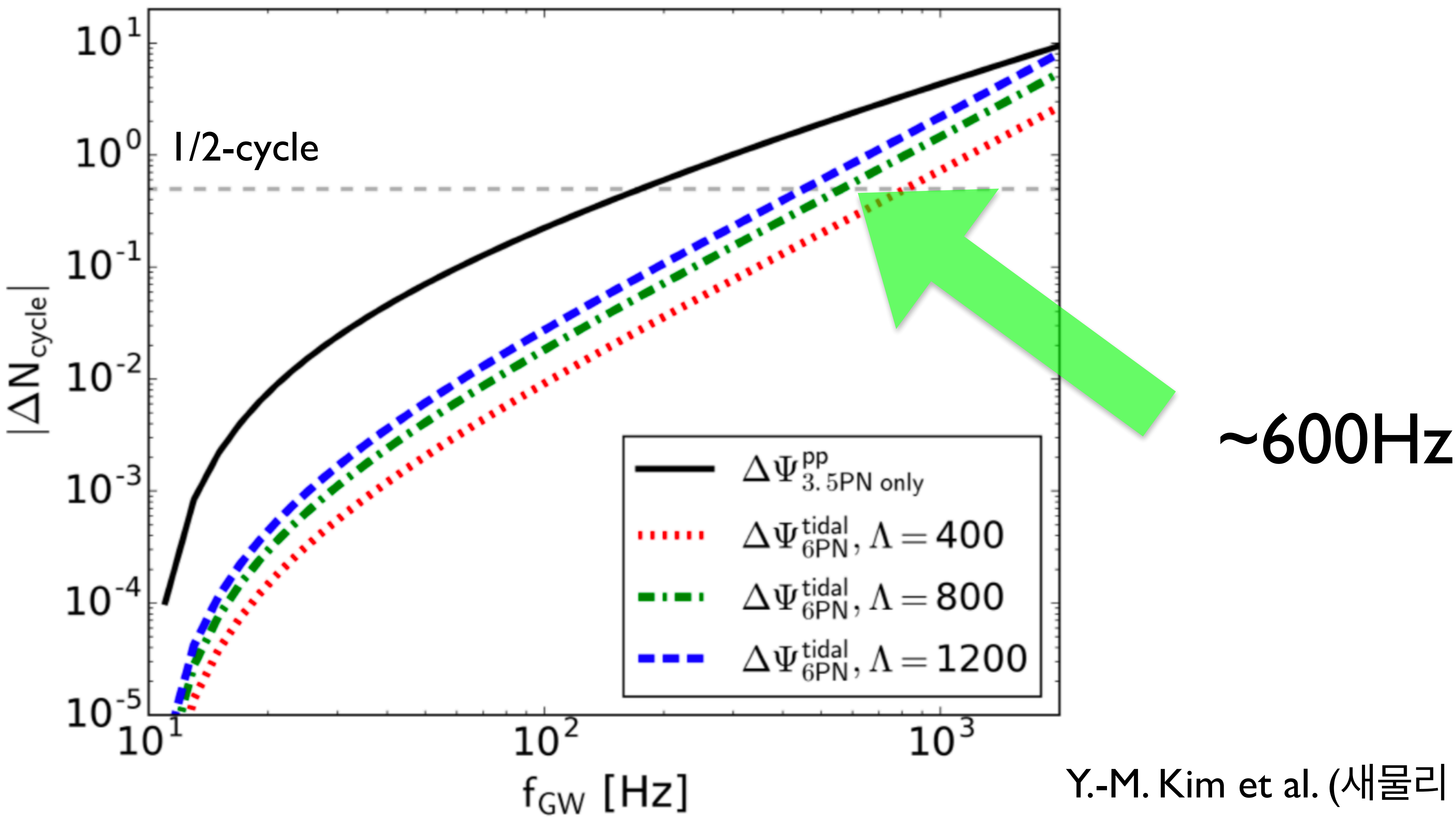
perturbative approaches

$$Q_{ij} = -\lambda \mathcal{E}_{ij}$$

$$\Lambda = \lambda / M^5 \rightarrow G \left(\frac{c^2}{GM} \right)^5 \lambda = \frac{2}{3} \left(\frac{Rc^2}{GM} \right)^5 k_2$$

λ : Tidal deformability
k2 : Tidal Love number

Possibility of Λ measurement



Y.-M. Kim et al. (새물리 2018)

First detection of GW from a BNS

GW170817

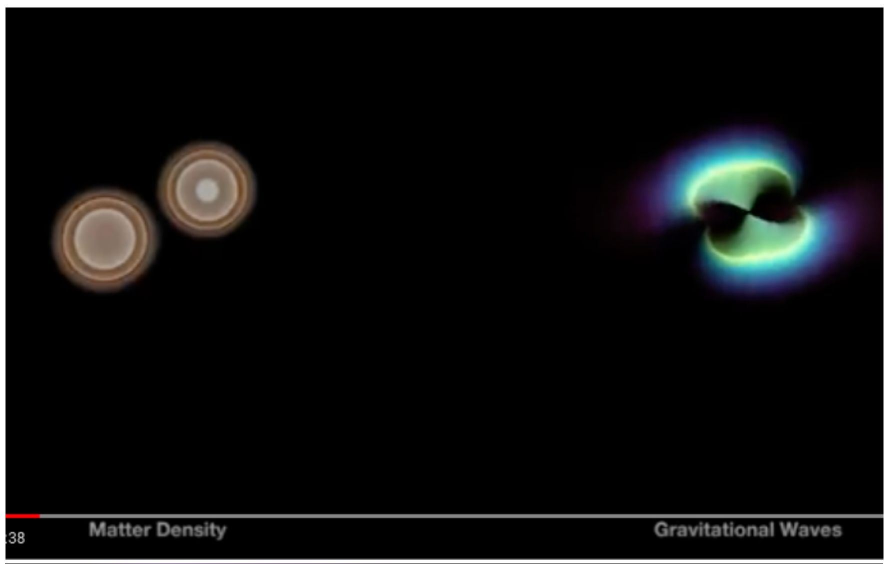
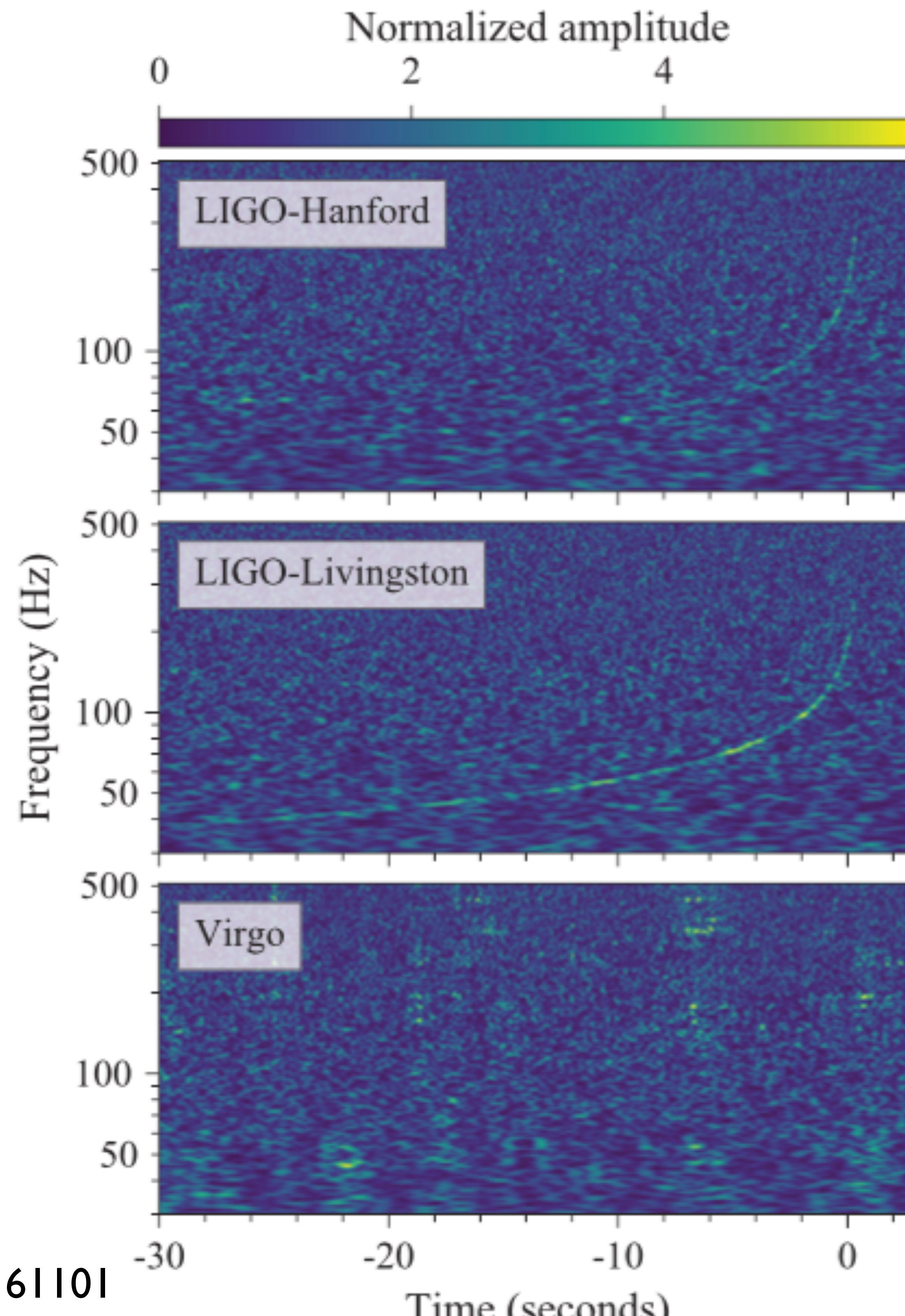


Image credit: Karan Jani/Georgia Tech.



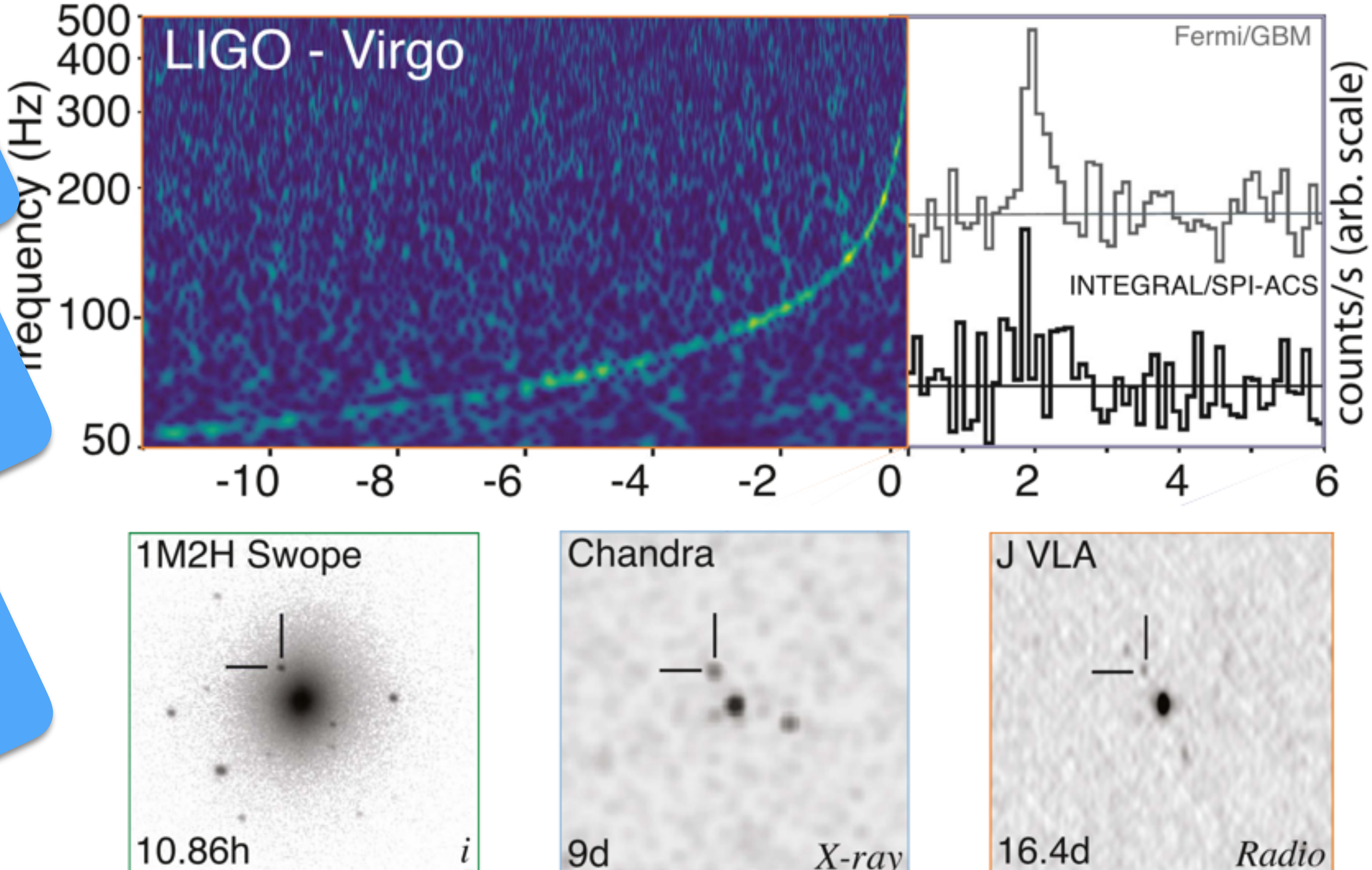
PhysRevLett.119.161101

First event of Multi-messenger Astronomy

GW170817

GRB170817A

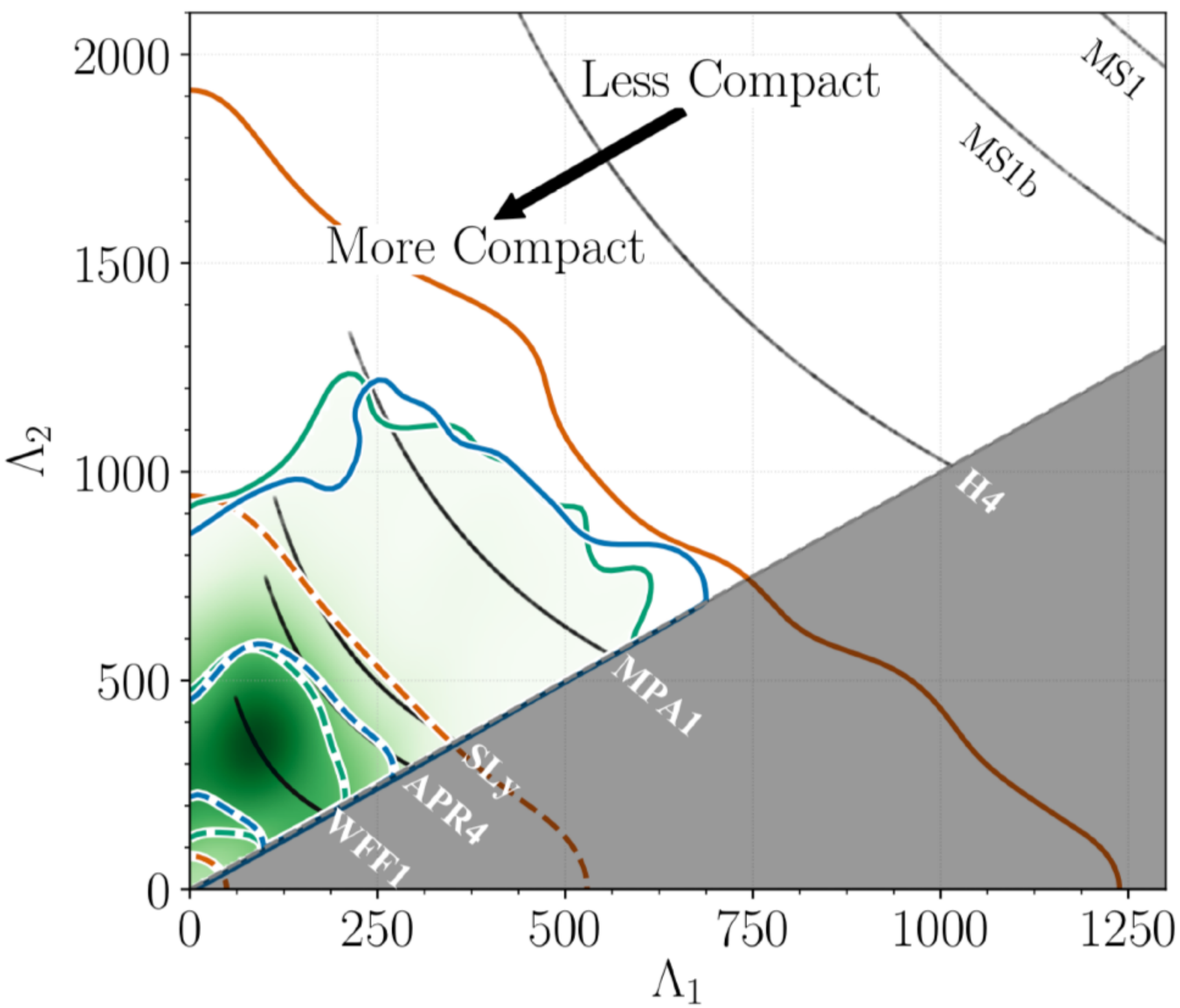
SSS17a/
AT2017gfo



ApJL.848.L12(2017)

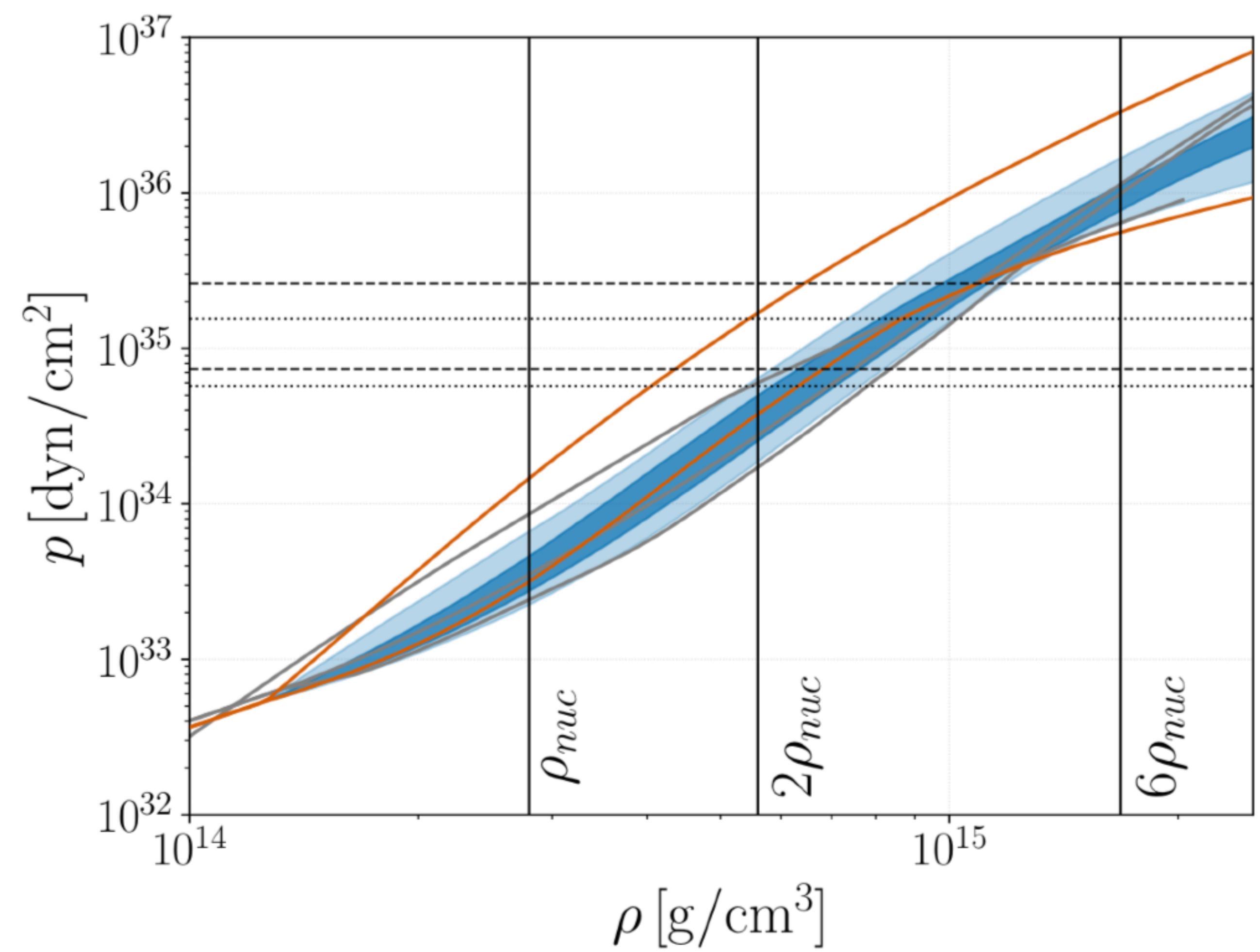
Measurements of Λ in GW170817

$\Lambda(1.4M_{\odot})=190^{+390}_{-120}$



$P(2\ \rho_{nuc})= 3.5^{+2.7}_{-1.7}\ x10^{34}$ dyne/cm^2

$P(6\ \rho_{nuc})= 9.0^{+7.9}_{-2.6}\ x10^{35}$ dyne/cm^2

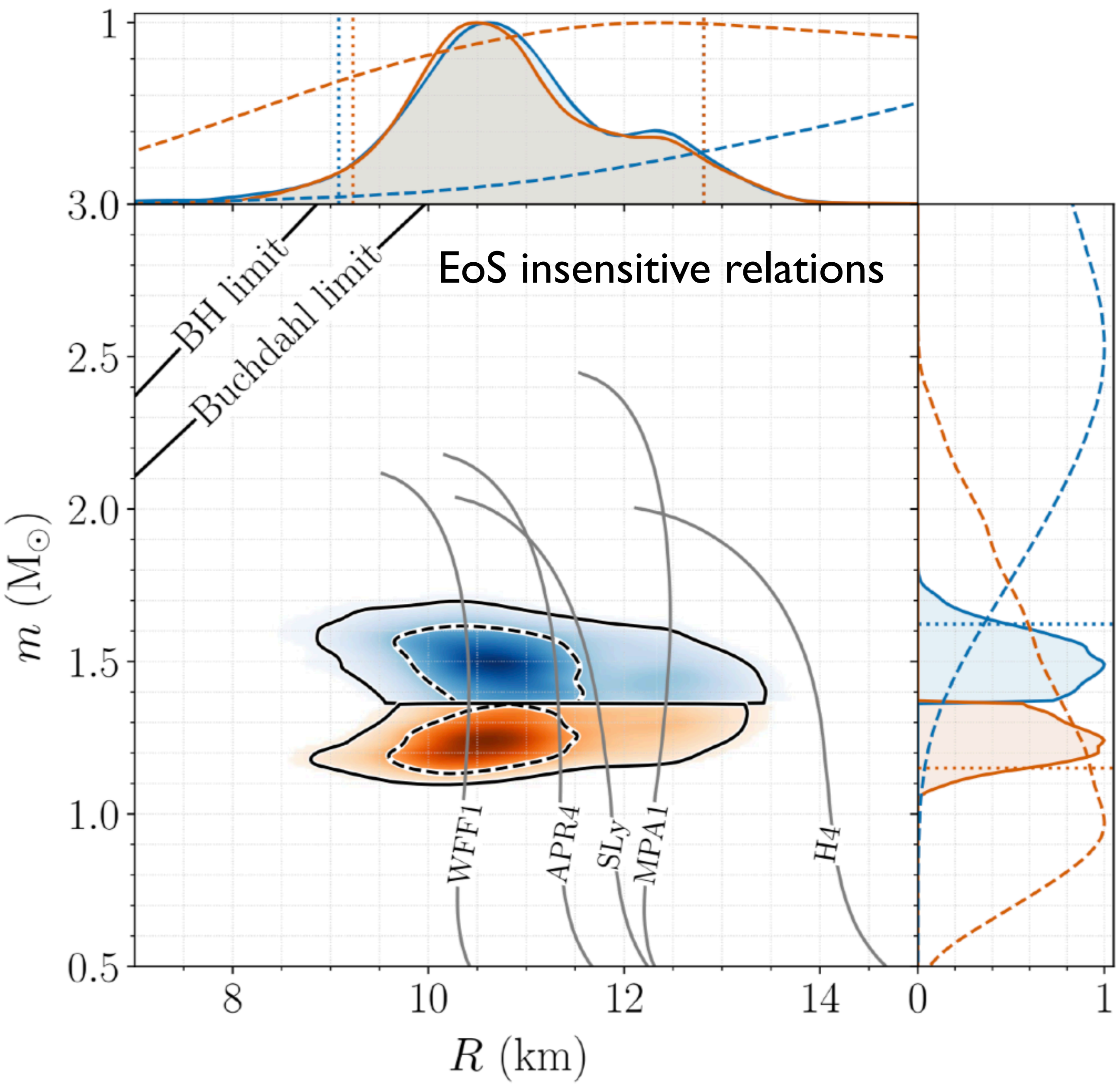


Abbott et al. (LSC and Virgo), arxiv:1805.11581 (PhysRevLett.121.161101)

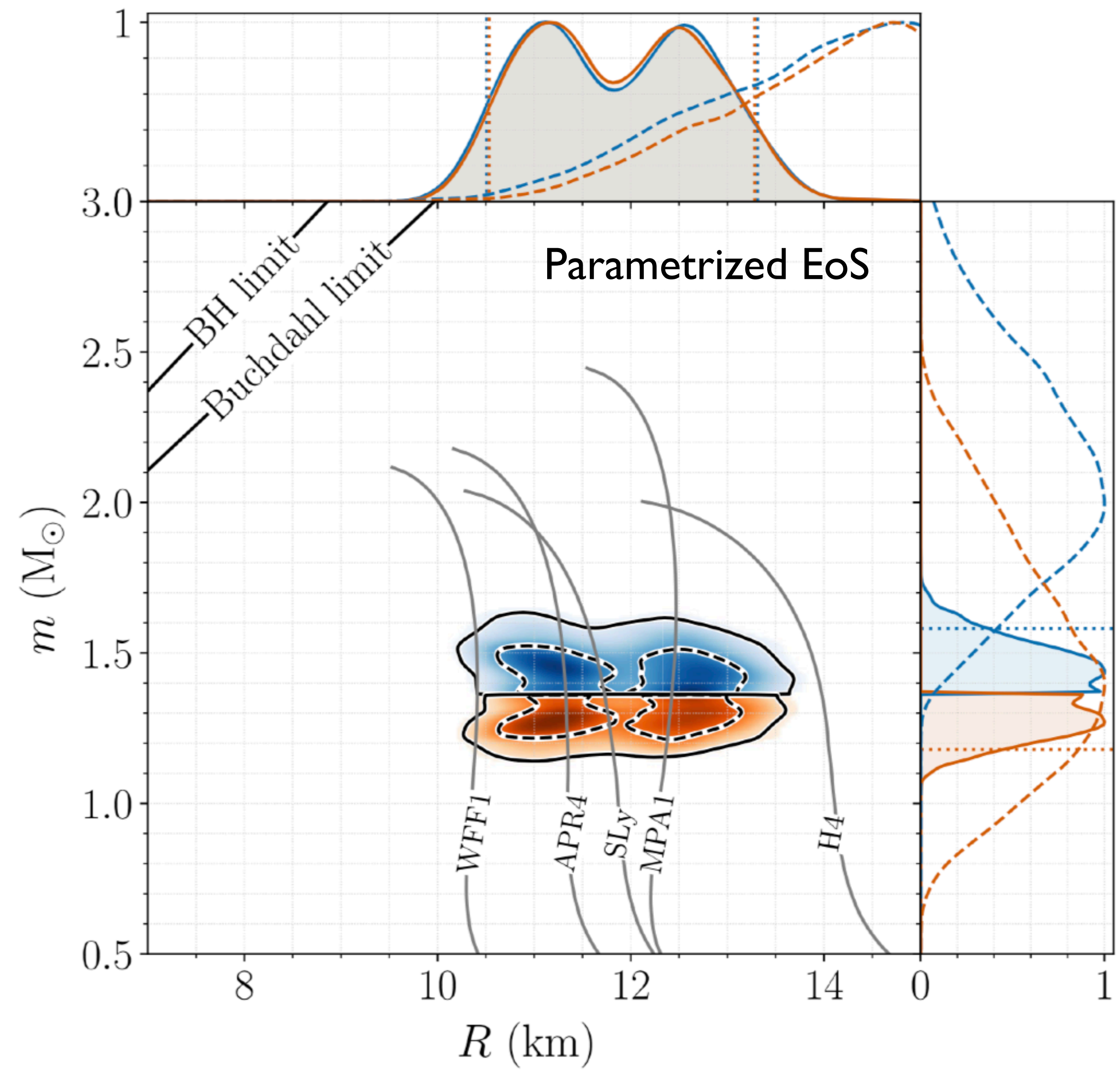
$\rho_{nuc}= 2.8\ x10^{14}$ g/cm^3

Measurements of Radii in GW170817

Abbott et al. (LSC and Virgo), PhysRevLett.121.161101



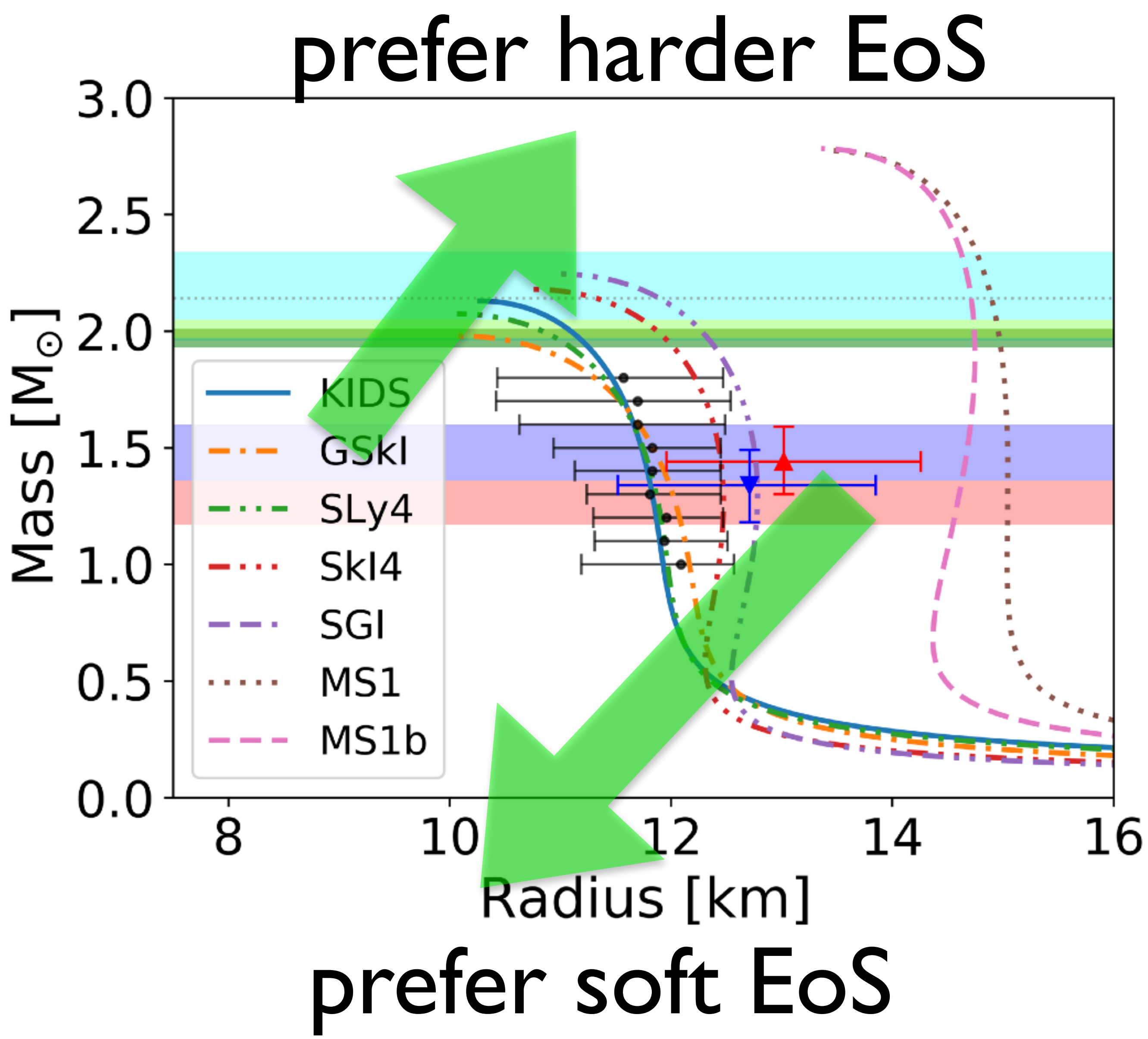
M1=(1.36,1.62) Msun, R1=$10.8^{+2.0}_{-1.7}$ km
M2=(1.15,1.36) Msun, R2=$10.7^{+2.1}_{-1.5}$ km
@90% CL

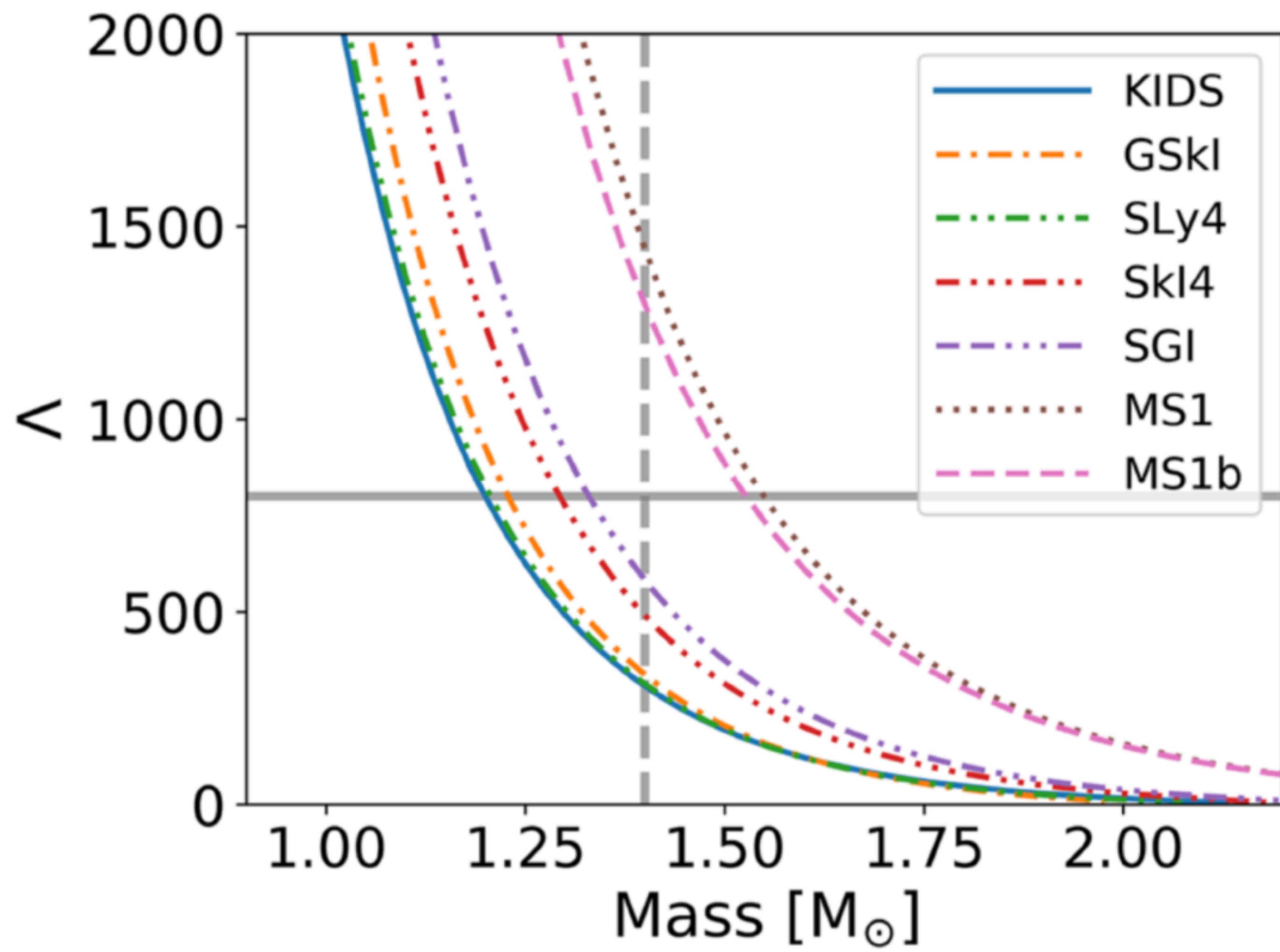


M1=(1.36,1.58) Msun, R1=$11.9^{+1.4}_{-1.4}$ km
M2=(1.18,1.36) Msun, R2=$11.9^{+1.4}_{-1.4}$ km
@90% CL

Tidal deformability for various EoSs

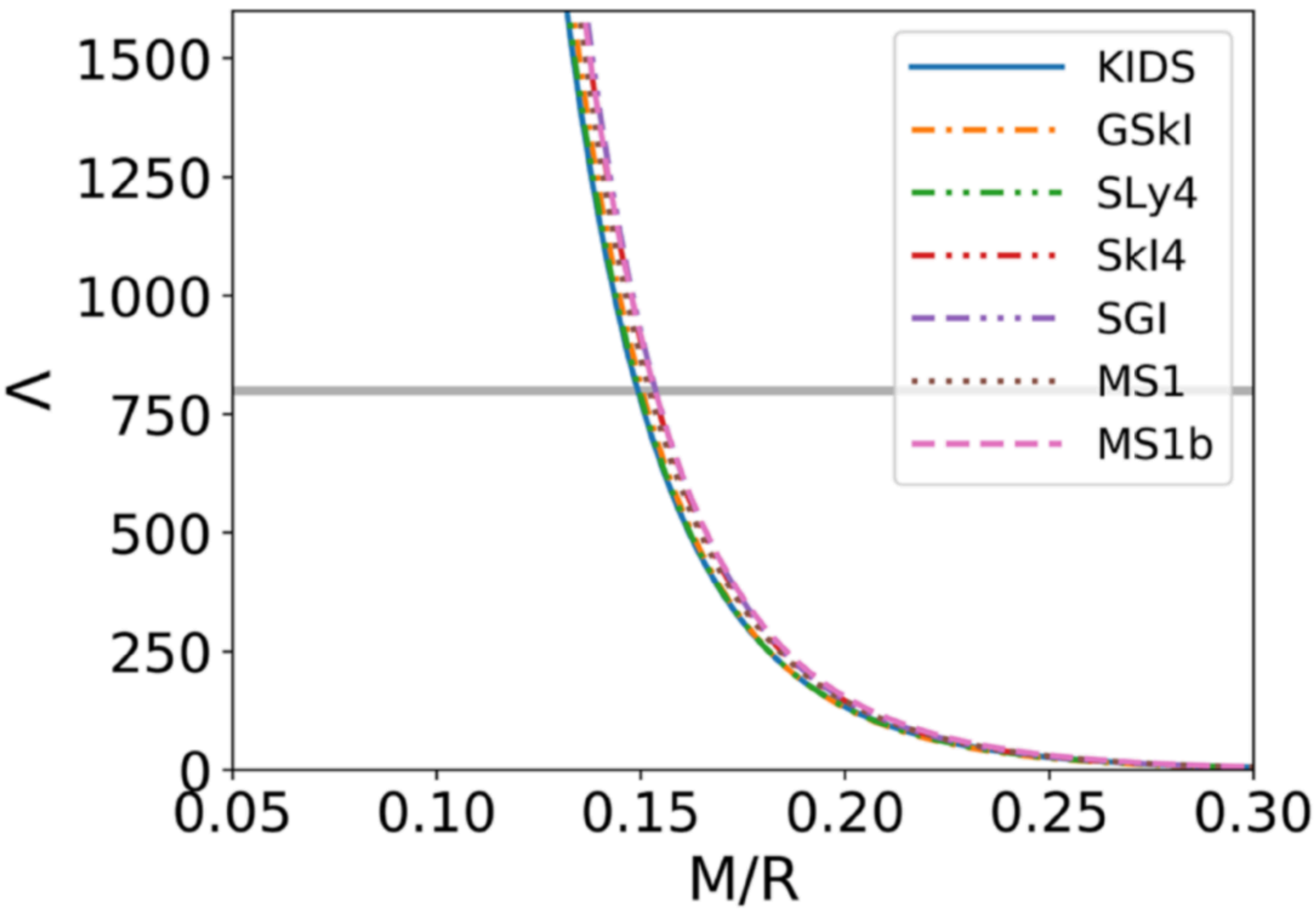
Y.-M. Kim et al. (EPJA 2020)

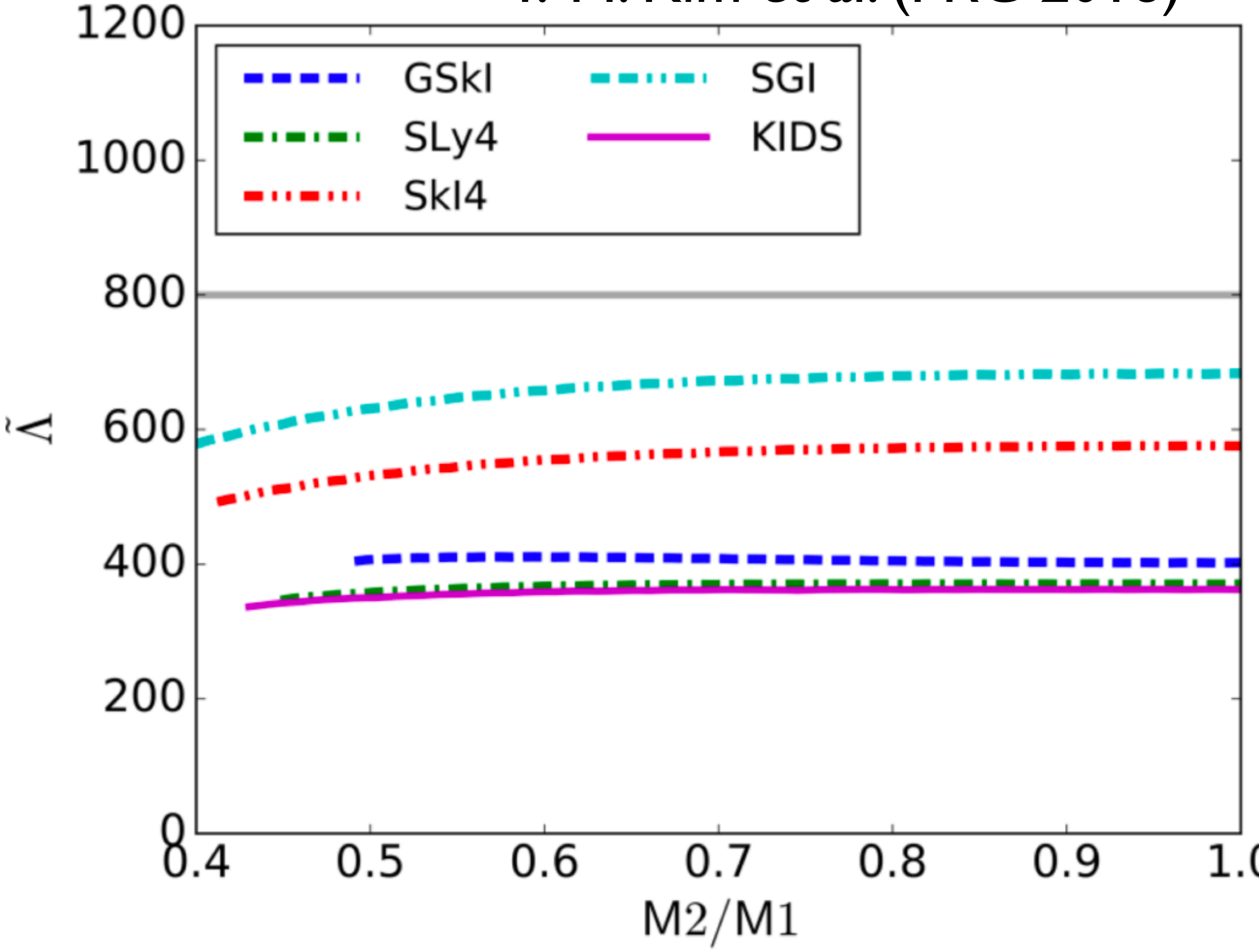




Universal relations for Λ

Y.-M. Kim et al. (PRC 2018)





Insensitive to EoS

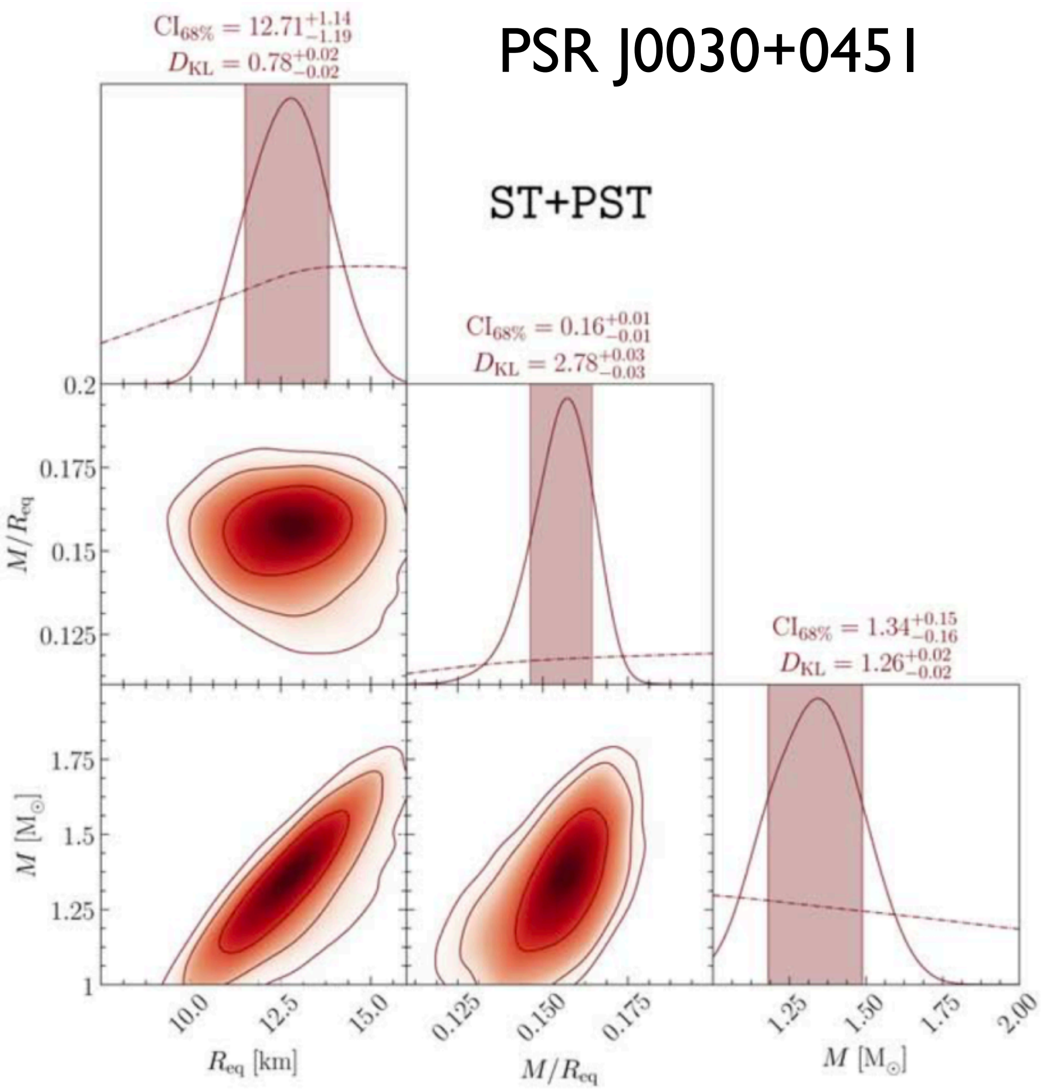
Insensitive to mass-ratio

$$C = a_0 + a_1(\ln\Lambda) + a_2(\ln\Lambda)^2$$

K. Yagi and N. Yunes, Phys. Rep. 681 (2017) 1

NICER observations

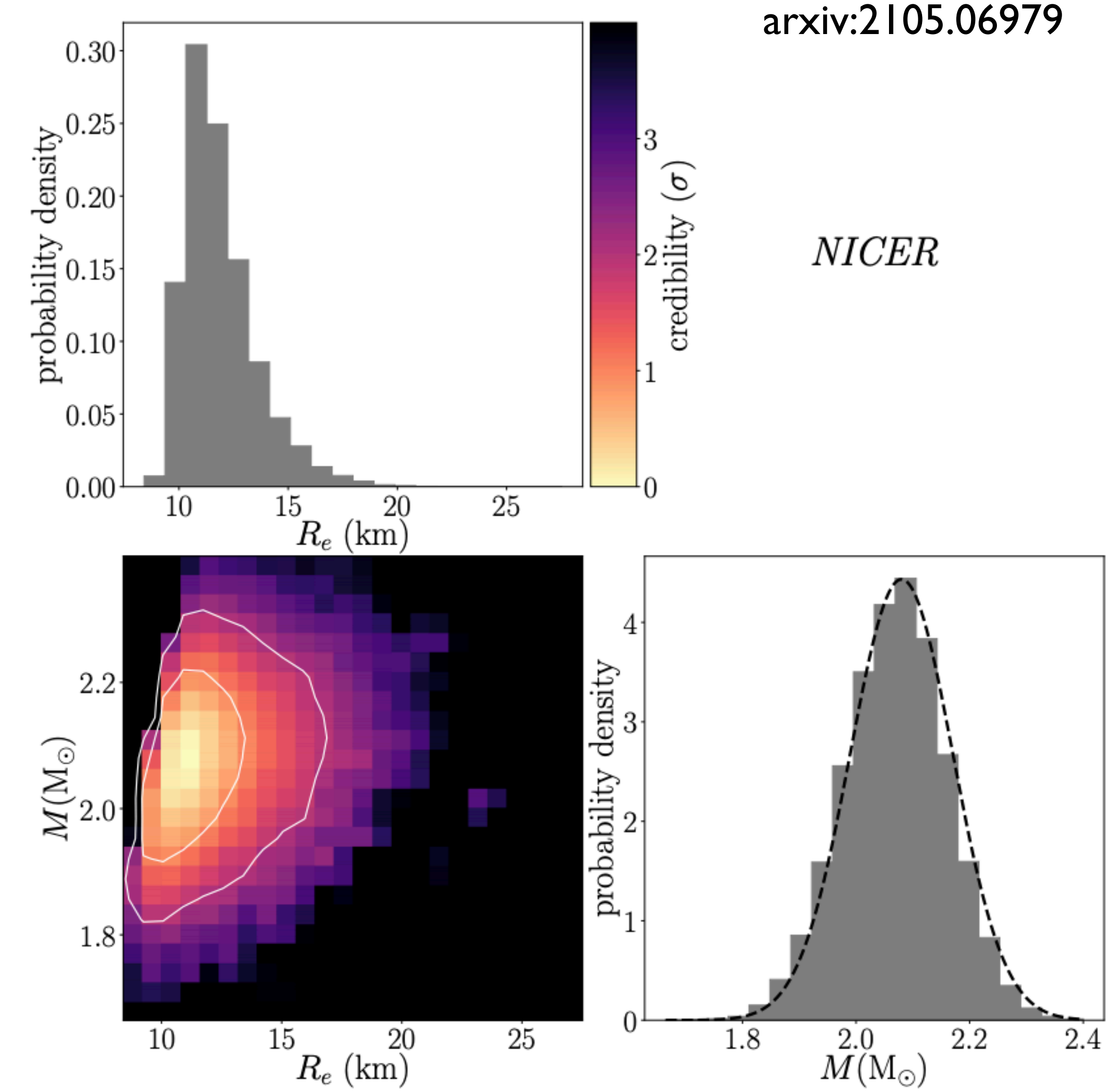
PSR J0030+0451



Riley_2019_ApJL_887_L21

PSR J0740+6620

arxiv:2105.06979

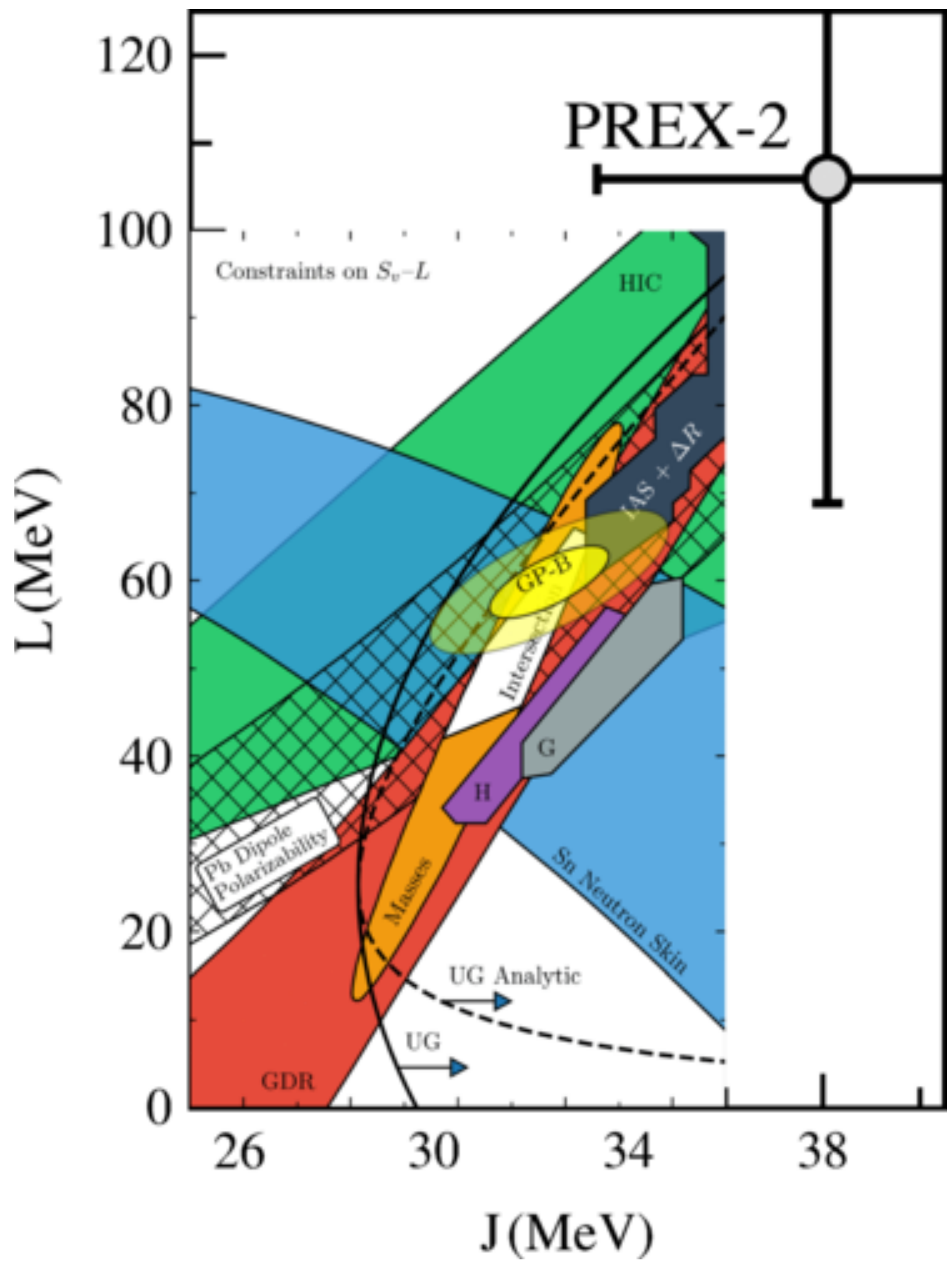


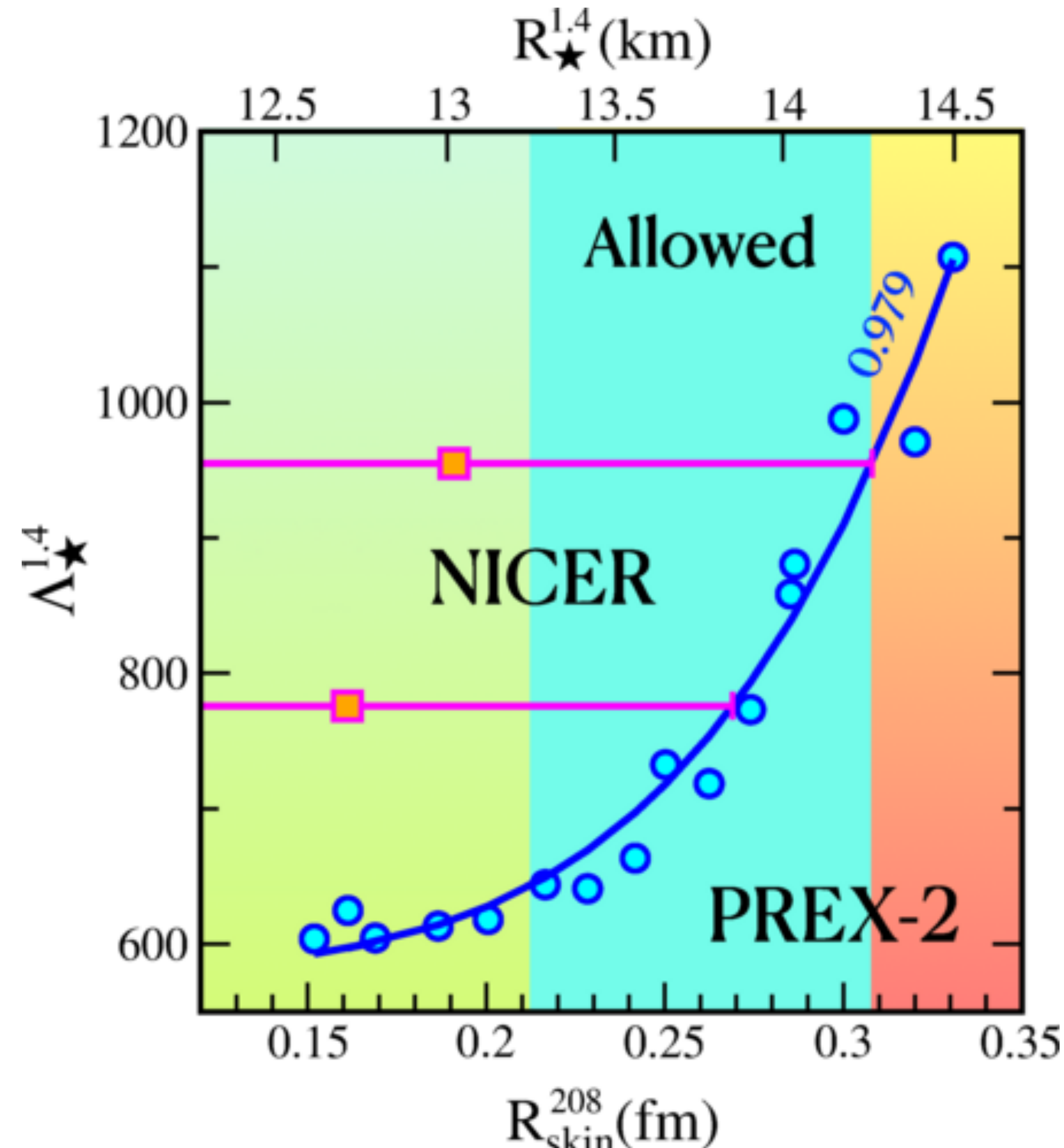
	Mass (M_{sun})	Radius (km)
Riley *et al.*[25]	$1.34^{+0.15}_{-0.16}$	$12.71^{+1.14}_{-1.19}$
Miller *et al.*[26]	$1.44^{+0.15}_{-0.14}$	$13.02^{+1.24}_{-1.06}$

Implication of PREX 2 and NICER Obs.

PREX 2 - PhysRevLett.126.172502 (2021) Neutron skin thickness, Rn-Rp = 0.278 +/- 0.078 (exp.) +/- 0.012 (theo.) fm

Implication of PREX 2 - PhysRevLett.126.172503 (2021)





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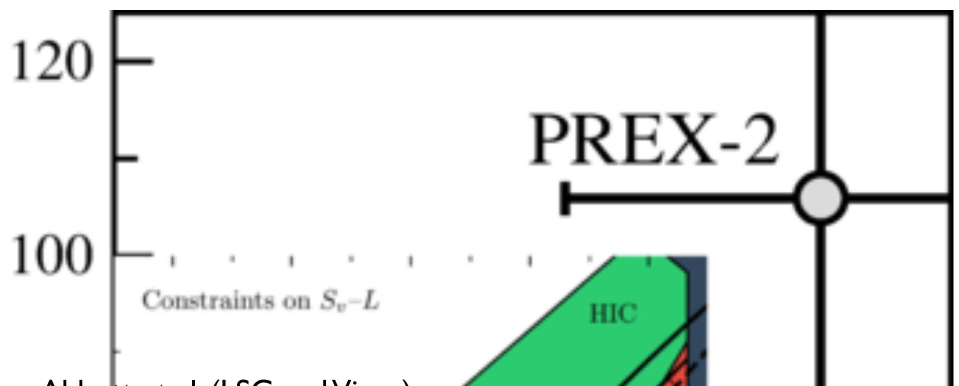
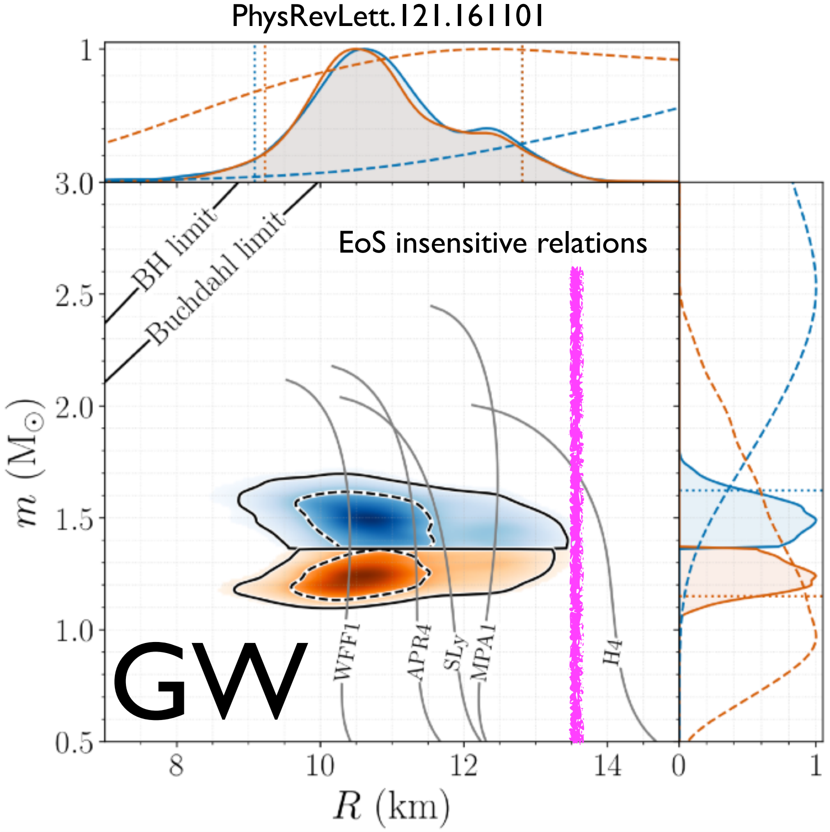
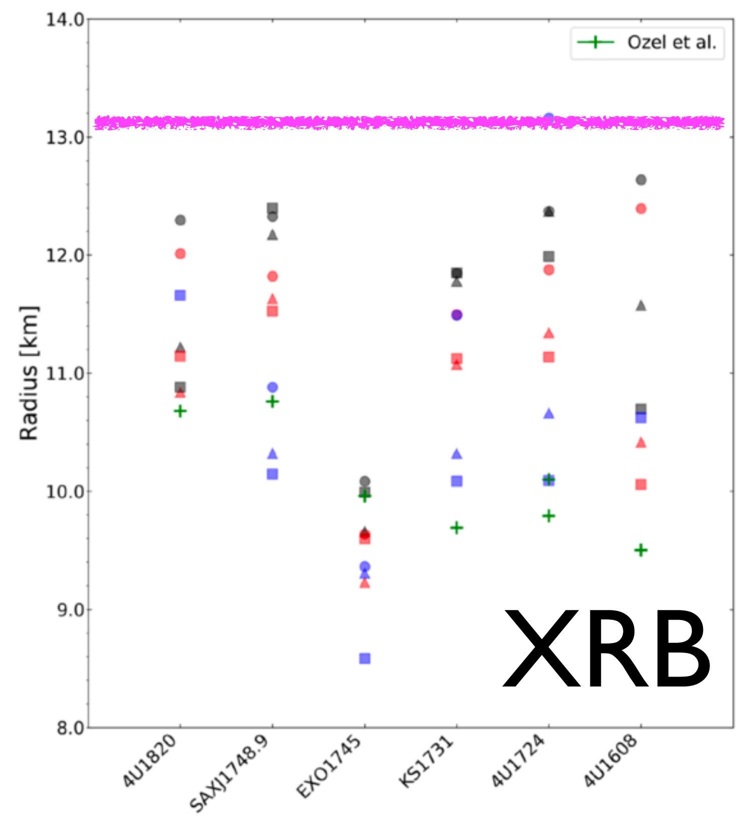
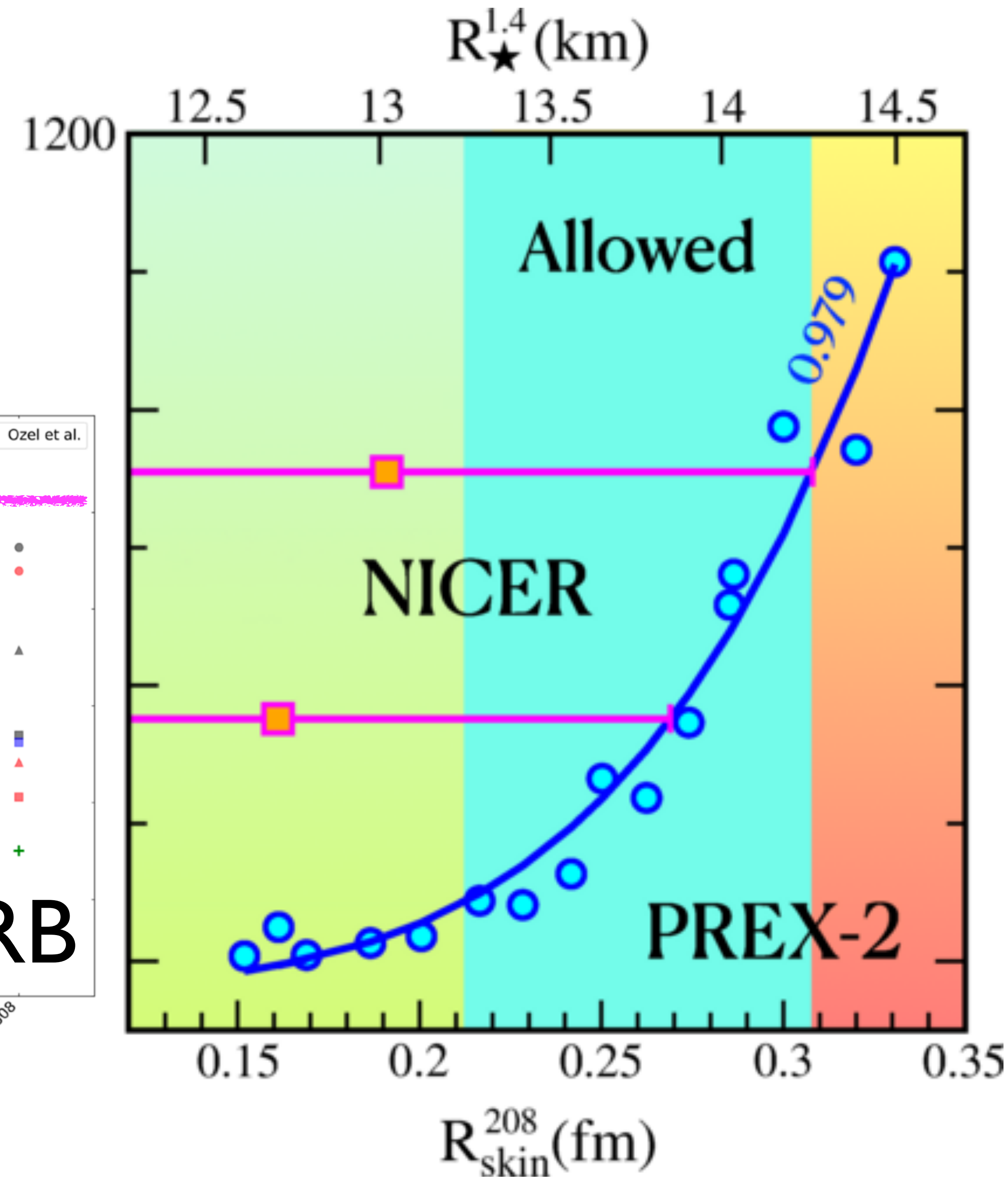


Abbott et al. (LSC and Virgo), PhysRevLett.121.161101

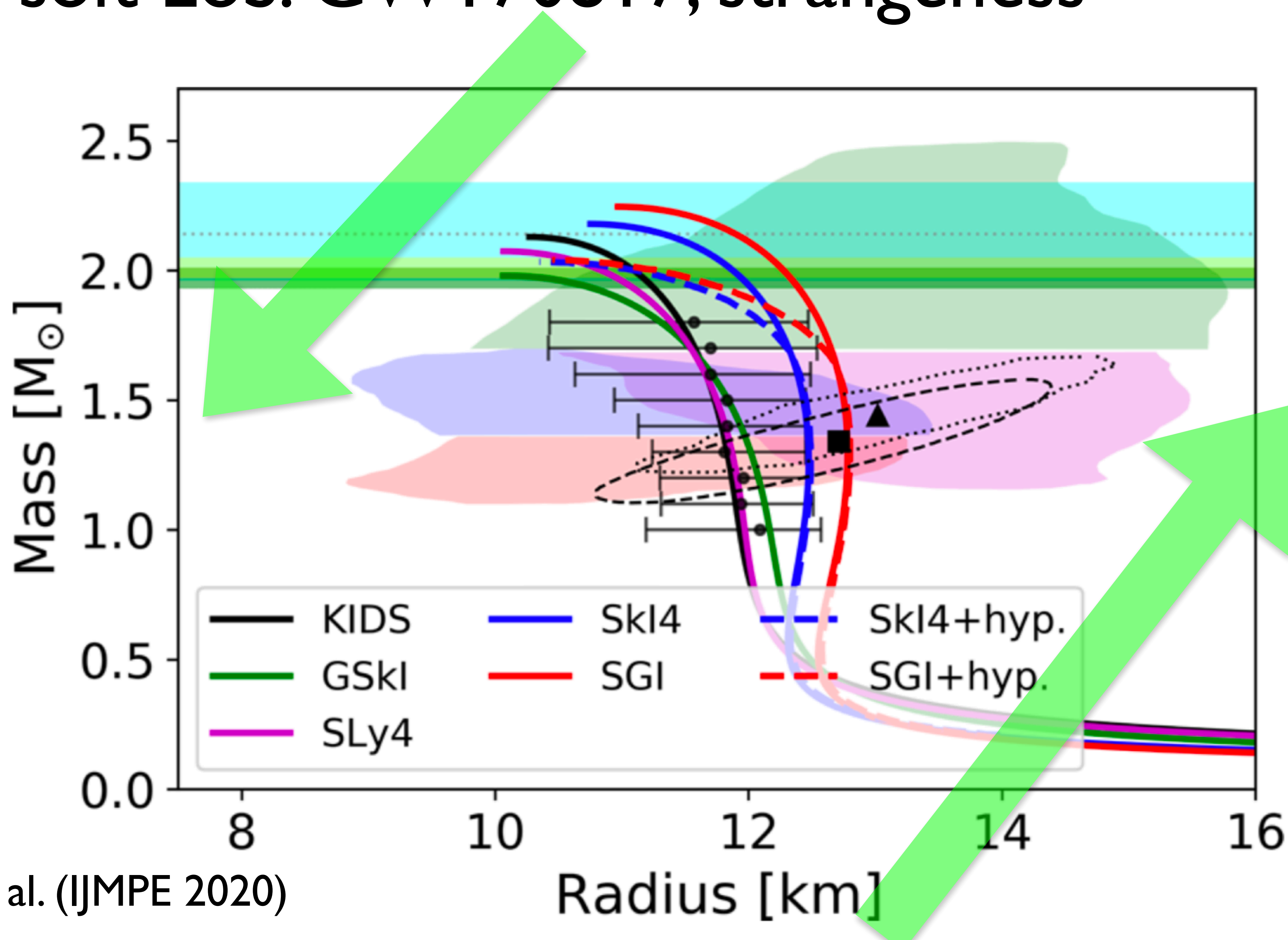






Constraints on Equation of State

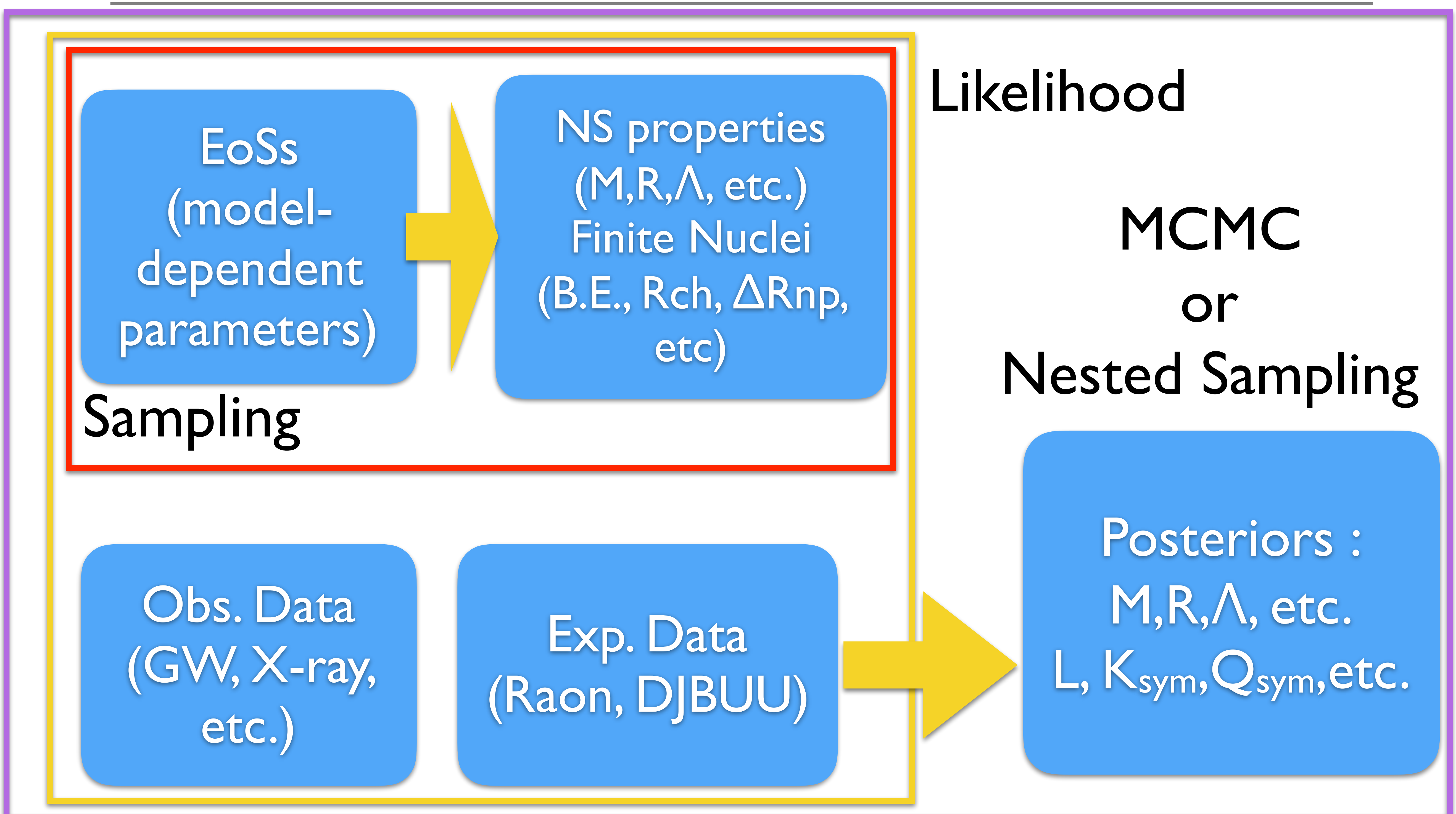
prefer soft EoS: GW170817, strangeness



M. Kim et al. (IJMPE 2020)

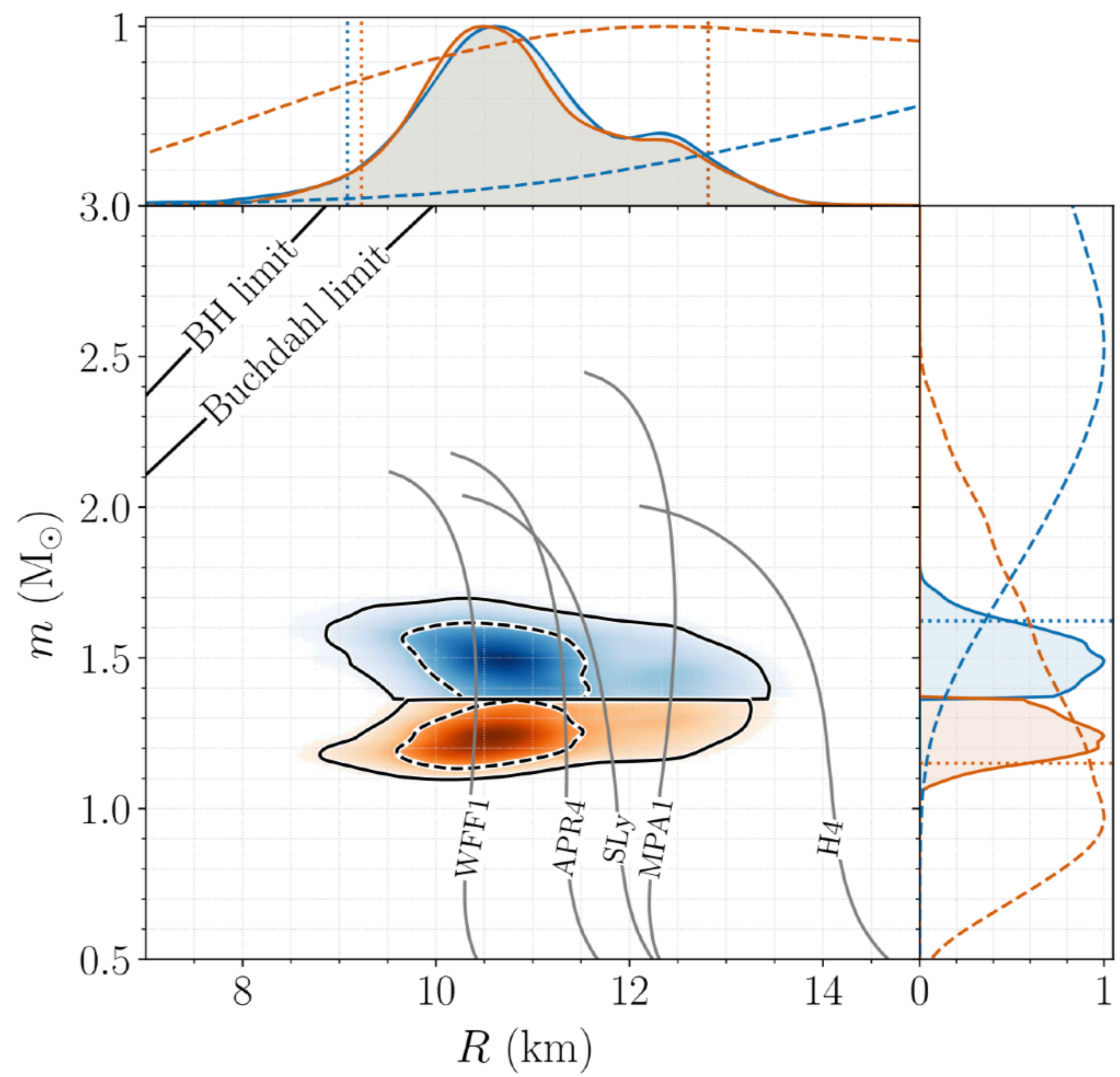
prefer harder EoS: M_max, NICER, PREX

Study on EoS w/ Bayesian in MMA



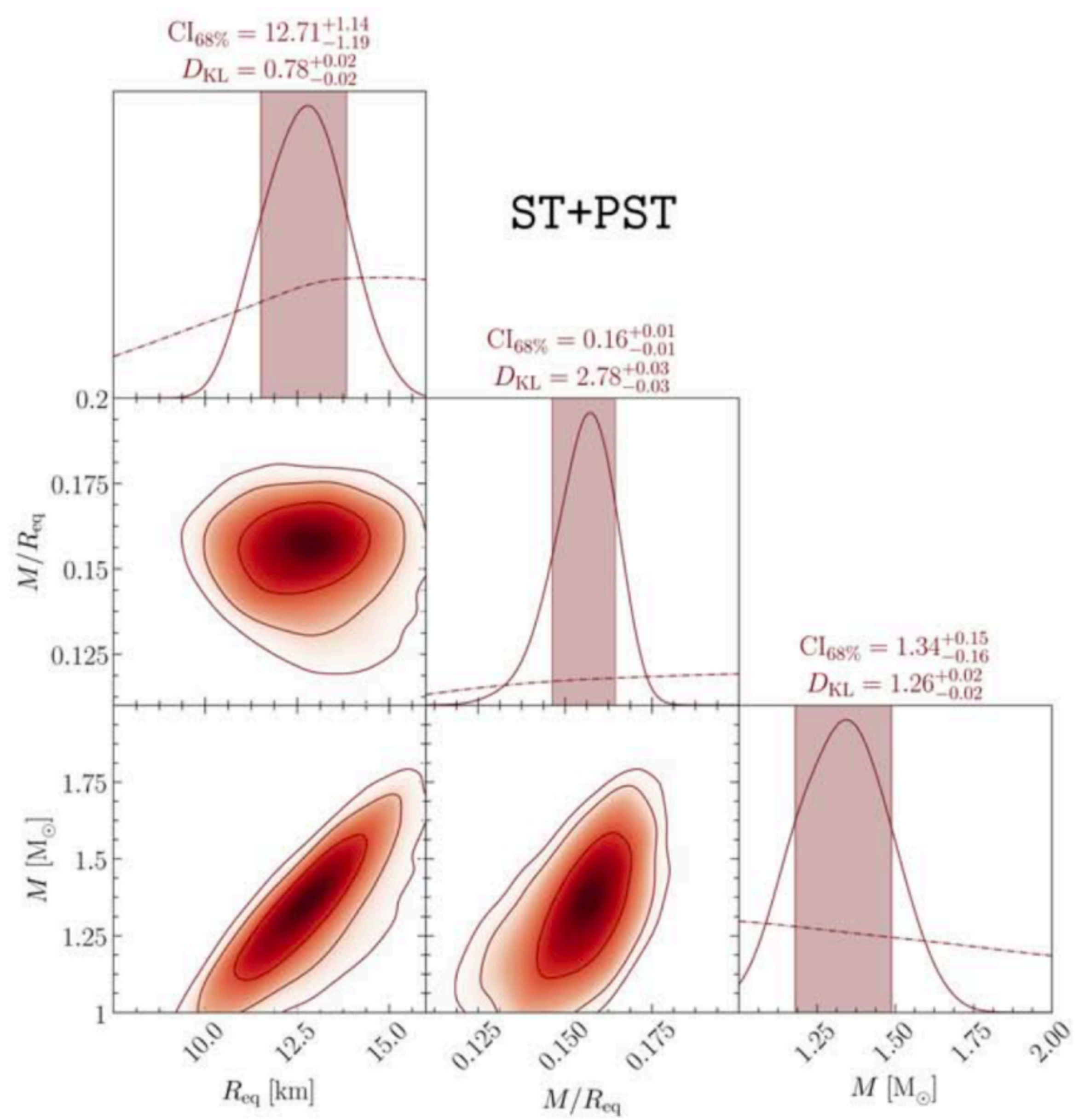
GW170817 vs. PSR J0030+0451

GW170817 (EoS-insensitive)



Abbott et al. (LSC and Virgo), PhysRevLett.121.161101

PSR J0030+0451



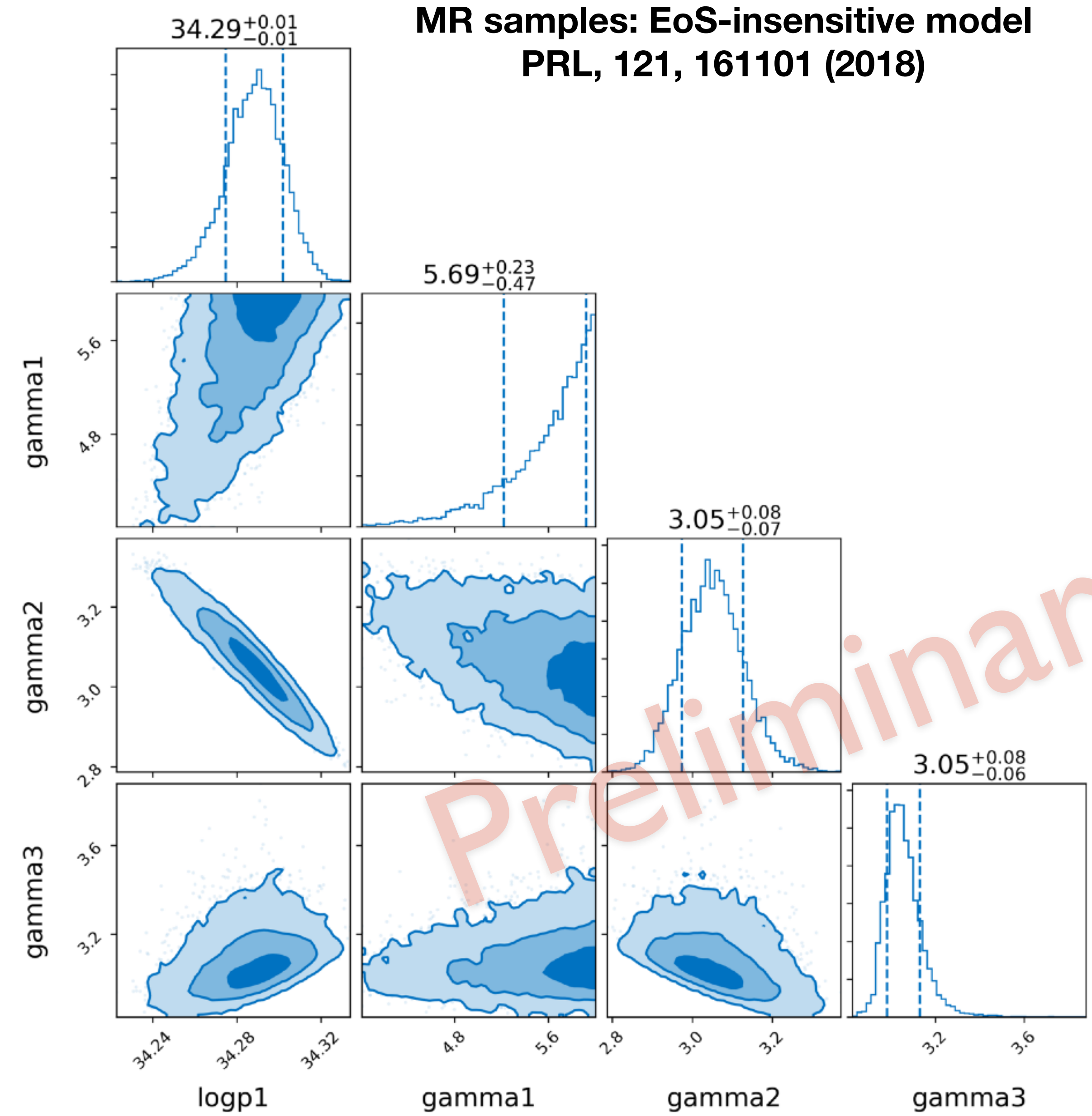
Riley_2019_ApJL_887_L21

Posteriors w/ Piece-wise Polytropic EoSs

Reference for Piece-wise Polytropic EoSs : Read et al. PRD 79, 124032 (2009)

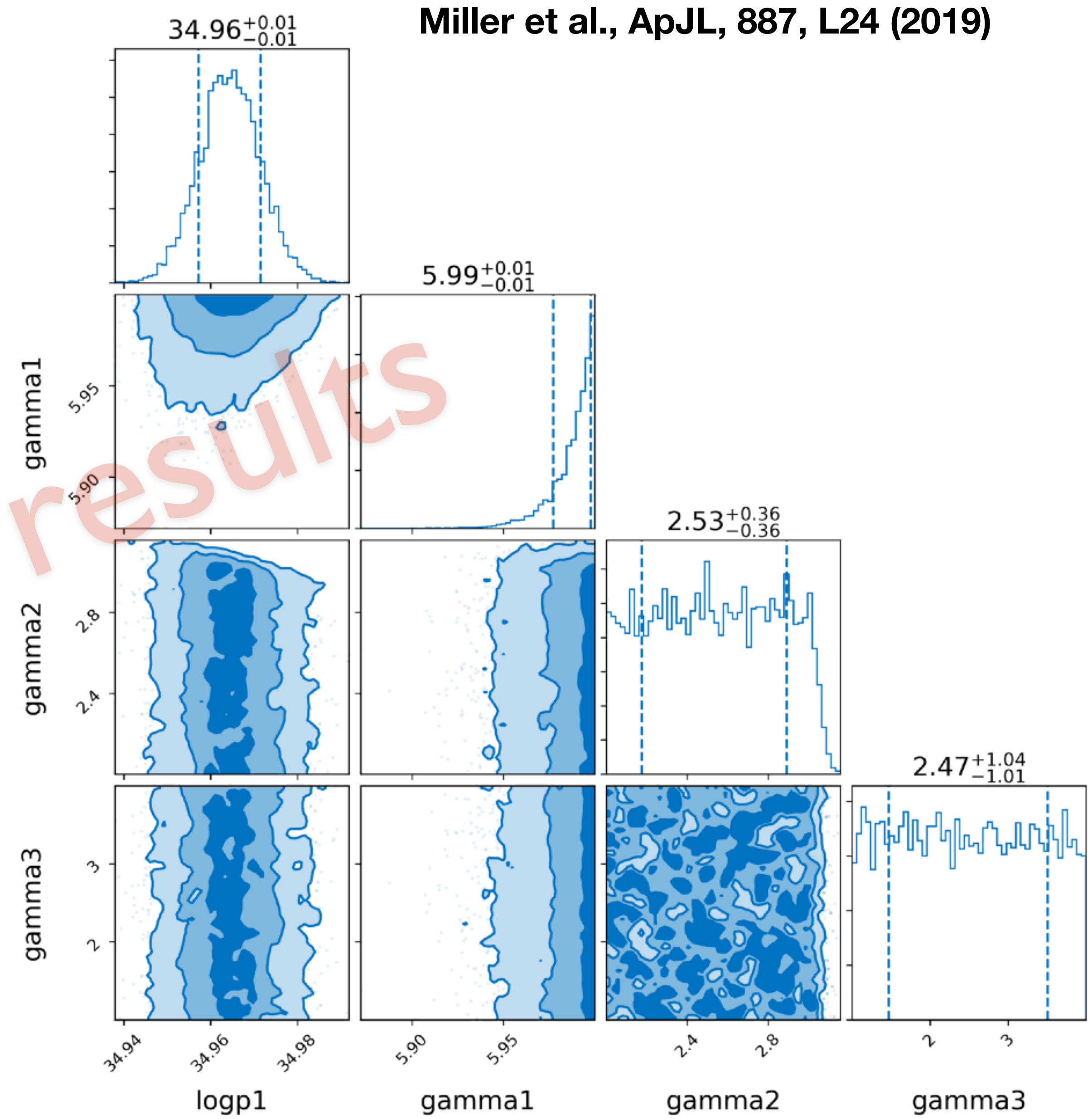
GW170817

MR samples: EoS-insensitive model
PRL, 121, 161101 (2018)



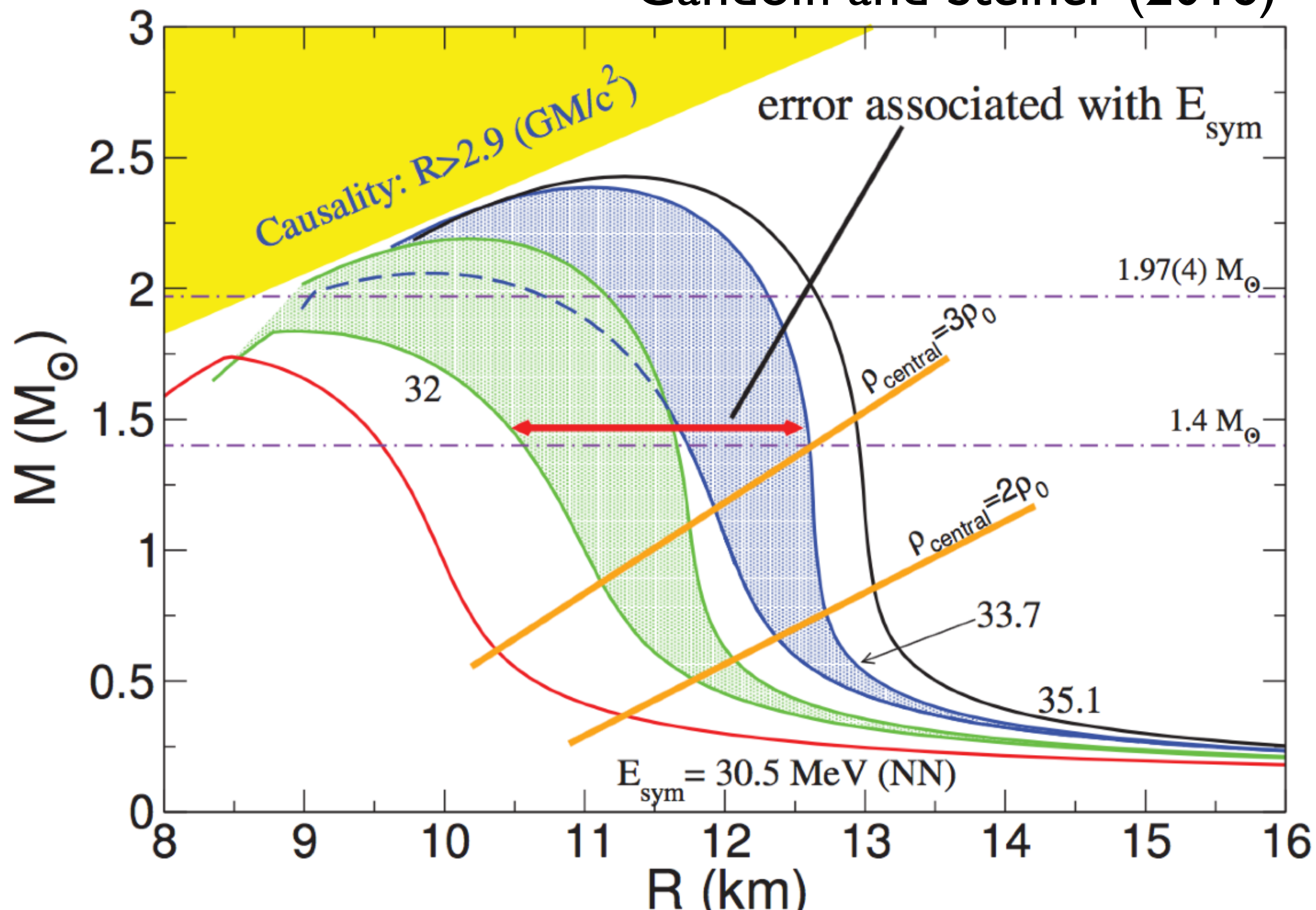
PSR J0030+0451

MR samples: 2 spot model
Miller et al., ApJL, 887, L24 (2019)

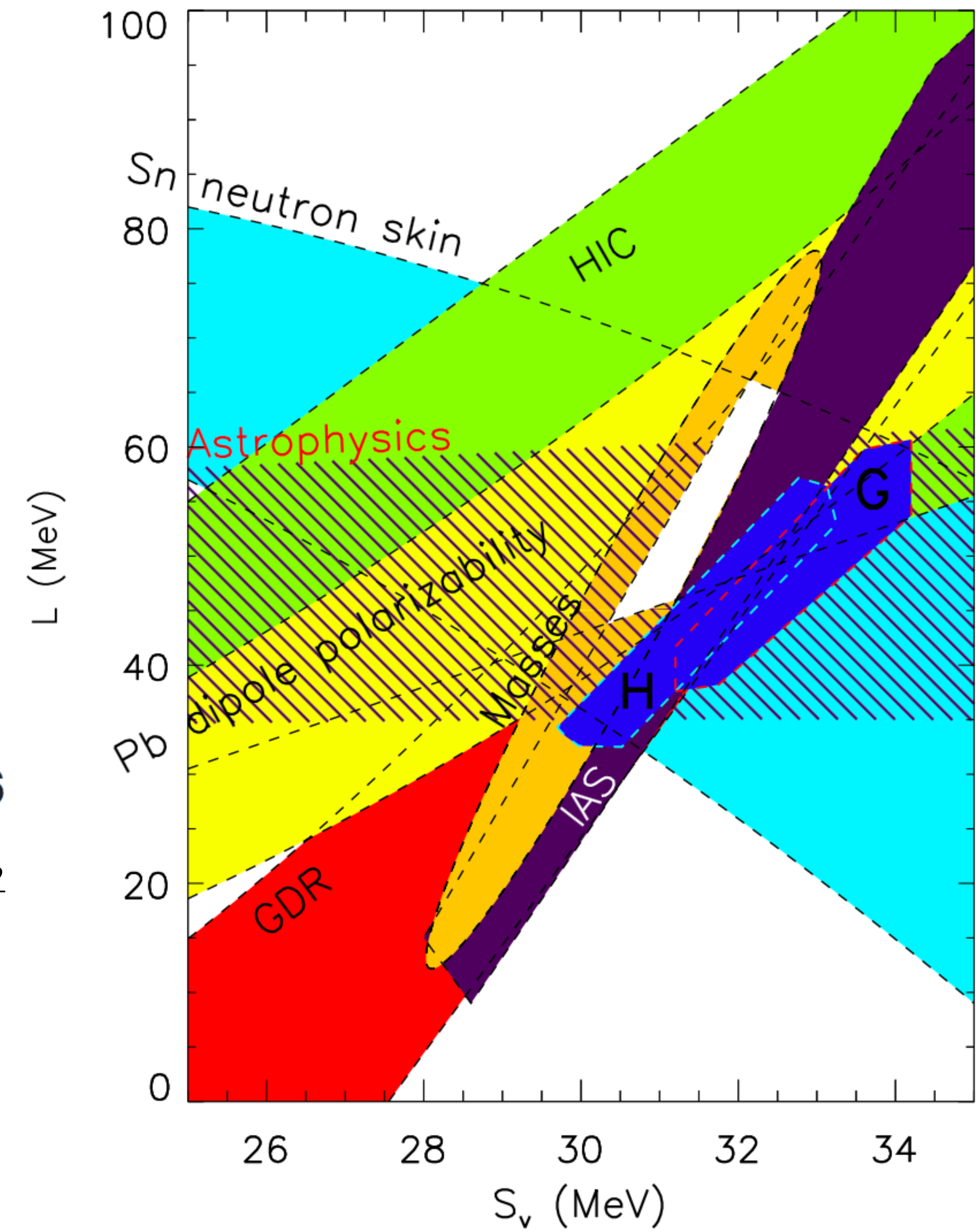


Nuclear Symmetry Energy

Gandolfi and Steiner (2016)



J.M. Lattimer / Nuclear Physics A 928 (2014) 276–295



$$\delta = \frac{\rho_n - \rho_p}{\rho}$$

$$\frac{E}{A} = E(\rho, \delta = 0) + E_{sym}(\rho)\delta^2 + \mathcal{O}(\delta^4) + \ldots,$$

$$E_{sym}(\rho) = E_{sym}(\rho_0) + \frac{L}{3}\left(\frac{\rho - \rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho - \rho_0}{\rho_0}\right)^2$$

$$L = 3\rho_0 \frac{\partial E_{sym}(\rho)}{\partial \rho}|_{\rho=\rho_0} \qquad K_{sym} = 9\rho_0^2 \frac{\partial^2 E_{sym}(\rho)}{\partial \rho^2}|_{\rho=\rho_0}.$$

KIDS Energy Density Functional

KIDS Energy density functional form

Phys. Rev. C 97, 014312 (2018)

$$\mathcal{E}(\rho,\delta) = \frac{E(\rho,\delta)}{A} = \mathcal{T}(\rho,\delta) + \Sigma_{i=0}^{N-1} c_i(\delta)\rho^{1+i/3}$$

$$\delta = \frac{\rho_n - \rho_p}{\rho}$$

$$\mathcal{T}(\rho,\delta) = \frac{3}{5}\left[\frac{\hbar^2}{2m_p}\left(\frac{1-\delta}{2}\right)^{5/3} + \frac{\hbar^2}{2m_n}\left(\frac{1+\delta}{2}\right)^{5/3}\right](3\pi^2\rho)^{2/3}$$

$$c_i(\delta) = \alpha_i + \beta_i\delta^2$$

to be determined by fitting to the observables

at zero temperature $k_F = (3\pi^2\rho/2)^{1/3}$ $k_{F_\tau} = k_F(1+\tau\delta)^{1/3}$

KIDS Parametrization

$$x = (\rho - \rho_0)/(3\rho_0)$$

$$\mathcal{S}(\rho) = \frac{1}{2}\frac{\partial^2}{\partial\delta^2}\mathscr{E}(\rho,\delta)\bigg|_{\delta=0} = \mathscr{T}_{\rm sym}(\rho) + \sum_{i=0}^{N-1}\beta_i\rho^{1+i/3}$$

$$\mathscr{E}(\rho,0) = E_0 + \tfrac{1}{2}K_0x^2 + \tfrac{1}{6}Q_0x^3 + O(x^4),$$

$$\mathcal{S}(\rho) = J + Lx + \tfrac{1}{2}K_{\rm sym}x^2 + \tfrac{1}{6}Q_{\rm sym}x^3 + \tfrac{1}{24}R_{\rm sym}x^4 + O(x^5),$$

$K_\tau = K_{sym} - (6+Q_0/K_0)L$

$$\begin{pmatrix}\alpha_0\\ \alpha_1\\ \alpha_2\end{pmatrix} = \begin{pmatrix}\rho_0 & \rho_0^{4/3} & \rho_0^{5/3}\\ 0 & 4\rho_0^{4/3} & 10\rho_0^{5/3}\\ 0 & -8\rho_0^{4/3} & -10\rho_0^{5/3}\end{pmatrix}^{-1}\begin{pmatrix}E_0-\tau_0\\ K_0+2\tau_0\\ Q_0-8\tau_0\end{pmatrix}$$

$\alpha_3 = 0$, ρ_0 = nuclear saturation density

τ_0 = Kinetic E at ρ_0, $\rho_n = \rho_p$

It works well. - PhysRevC.100.014312

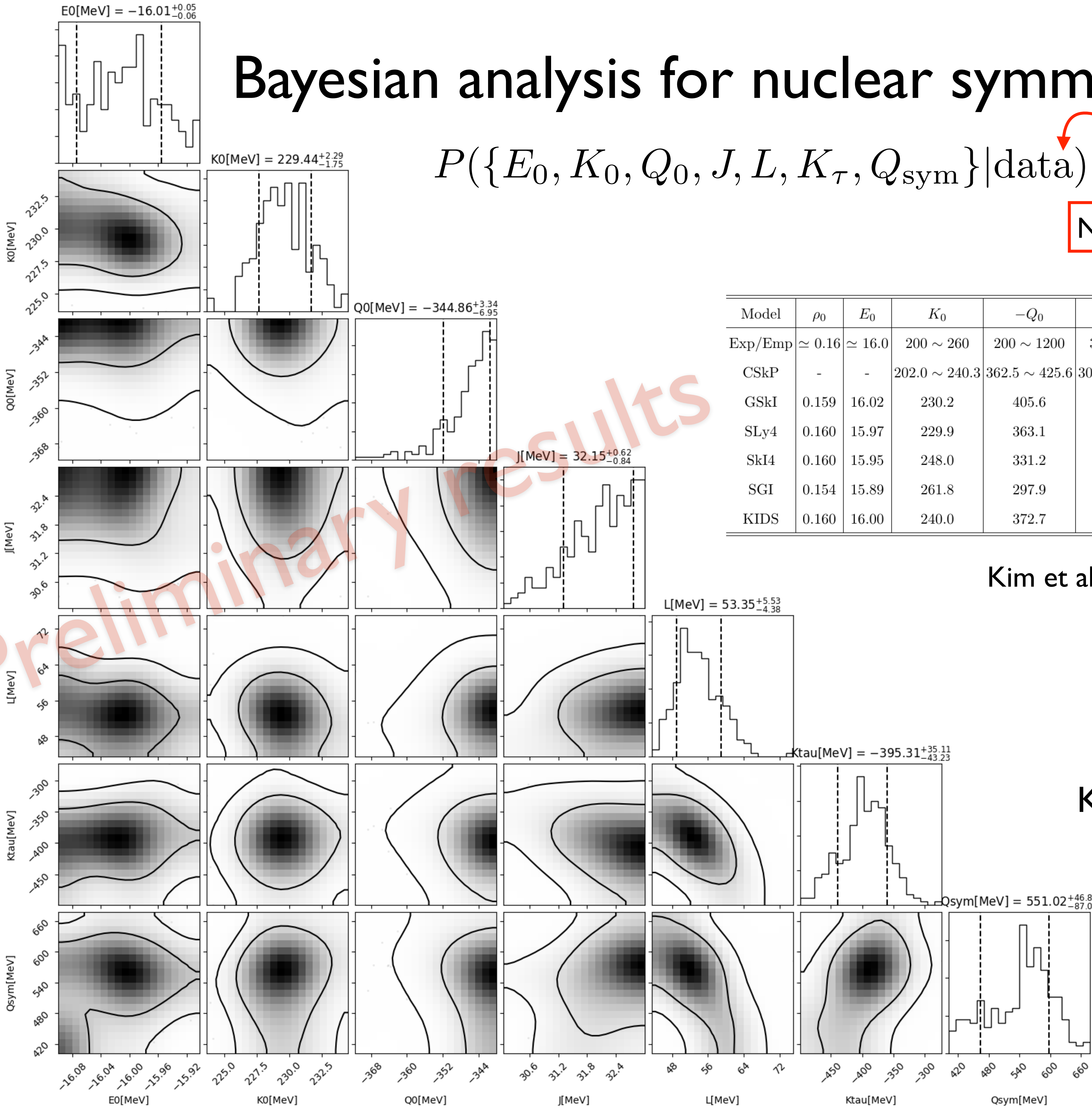
$$\begin{pmatrix}\beta_0\\ \beta_1\\ \beta_2\\ \beta_3\end{pmatrix} = \begin{pmatrix}\rho_0 & \rho_0^{4/3} & \rho_0^{5/3} & \rho_0^2\\ 3\rho_0 & 4\rho_0^{4/3} & 5\rho_0^{5/3} & 6\rho_0^2\\ 0 & 4\rho_0^{4/3} & 10\rho_0^{5/3} & 18\rho_0^2\\ 0 & -8\rho_0^{4/3} & -10\rho_0^{5/3} & 0\end{pmatrix}^{-1}\begin{pmatrix}J-\tau_{sym,0}\\ L-2\tau_{sym,0}\\ K_{sym}+2\tau_{sym,0}\\ Q_{sym}-8\tau_{sym,0}\end{pmatrix}$$

$\tau_{sym,0}$: Kinetic E at ρ_0, $\rho_p = 0$

Bayesian analysis for nuclear symmetry energy

$$P(\{E_0, K_0, Q_0, J, L, K_\tau, Q_{\rm sym}\}|{\rm data})$$

Nuclei properties (or APR)



Model	ρ_0	E_0	K_0	$-Q_0$	J	L	$-K_\tau$	$M_{\rm max}$
Exp/Emp	$\simeq 0.16$	$\simeq 16.0$	$200 \sim 260$	$200 \sim 1200$	$30 \sim 35$	$40 \sim 76$	$372 \sim 760$	$\geq 1.93 \sim 2.05$
CSkP	-	-	$202.0 \sim 240.3$	$362.5 \sim 425.6$	$30.0 \sim 35.5$	$48.6 \sim 67.1$	$360.1 \sim 407.1$	-
GSkI	0.159	16.02	230.2	405.6	32.0	63.5	364.2	1.98
SLy4	0.160	15.97	229.9	363.1	32.0	45.9	322.8	2.07
SkI4	0.160	15.95	248.0	331.2	29.5	60.4	322.2	2.19
SGI	0.154	15.89	261.8	297.9	28.3	63.9	362.5	2.25
KIDS	0.160	16.00	240.0	372.7	32.8	49.1	375.1	2.14

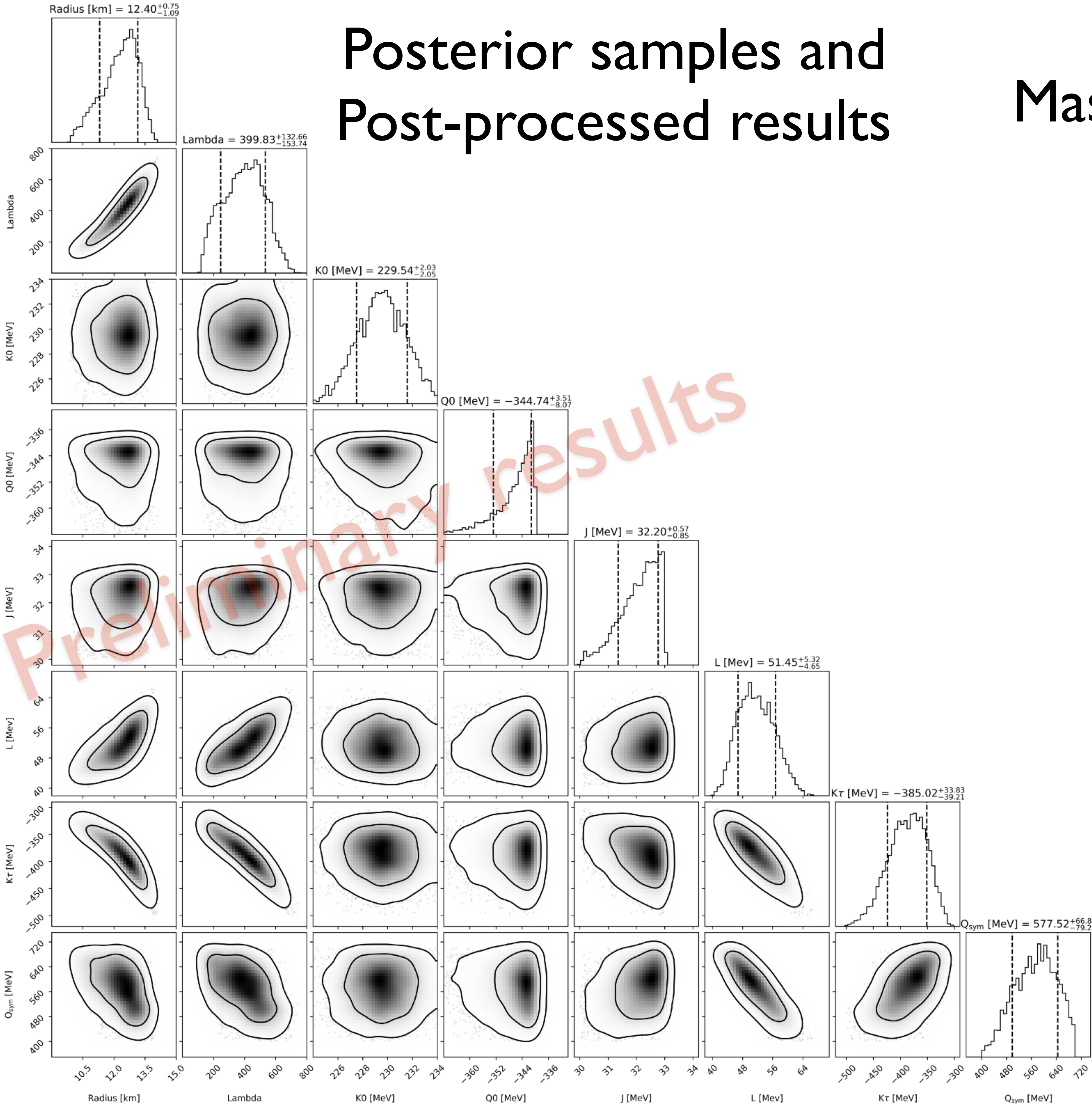
Kim et al., PhysRevC.98.065805

$K_\tau = K_{\rm sym} - (6 + Q_0/K_0)L$

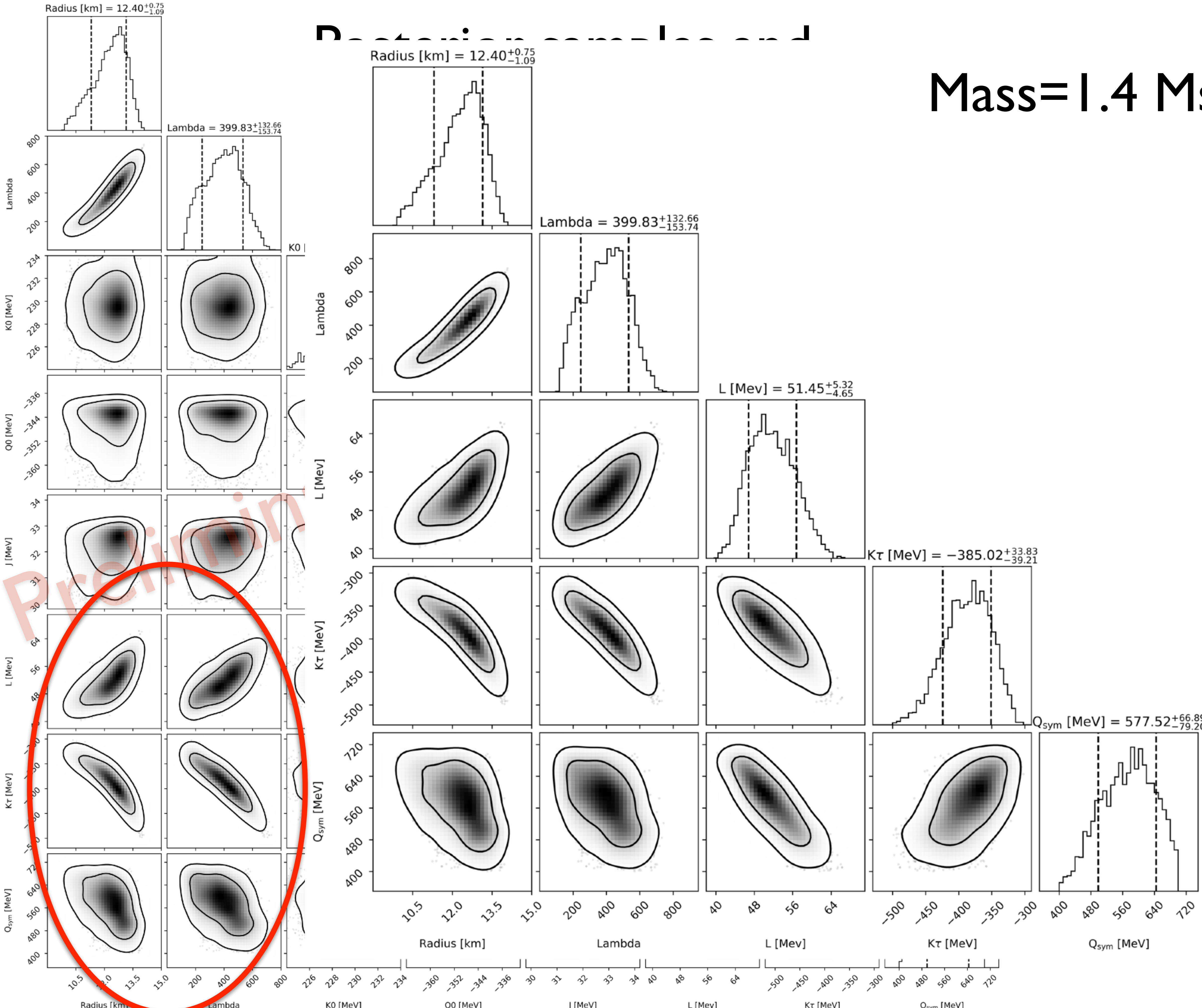
Y.-M. Kim, in progress

Posterior samples and Post-processed results

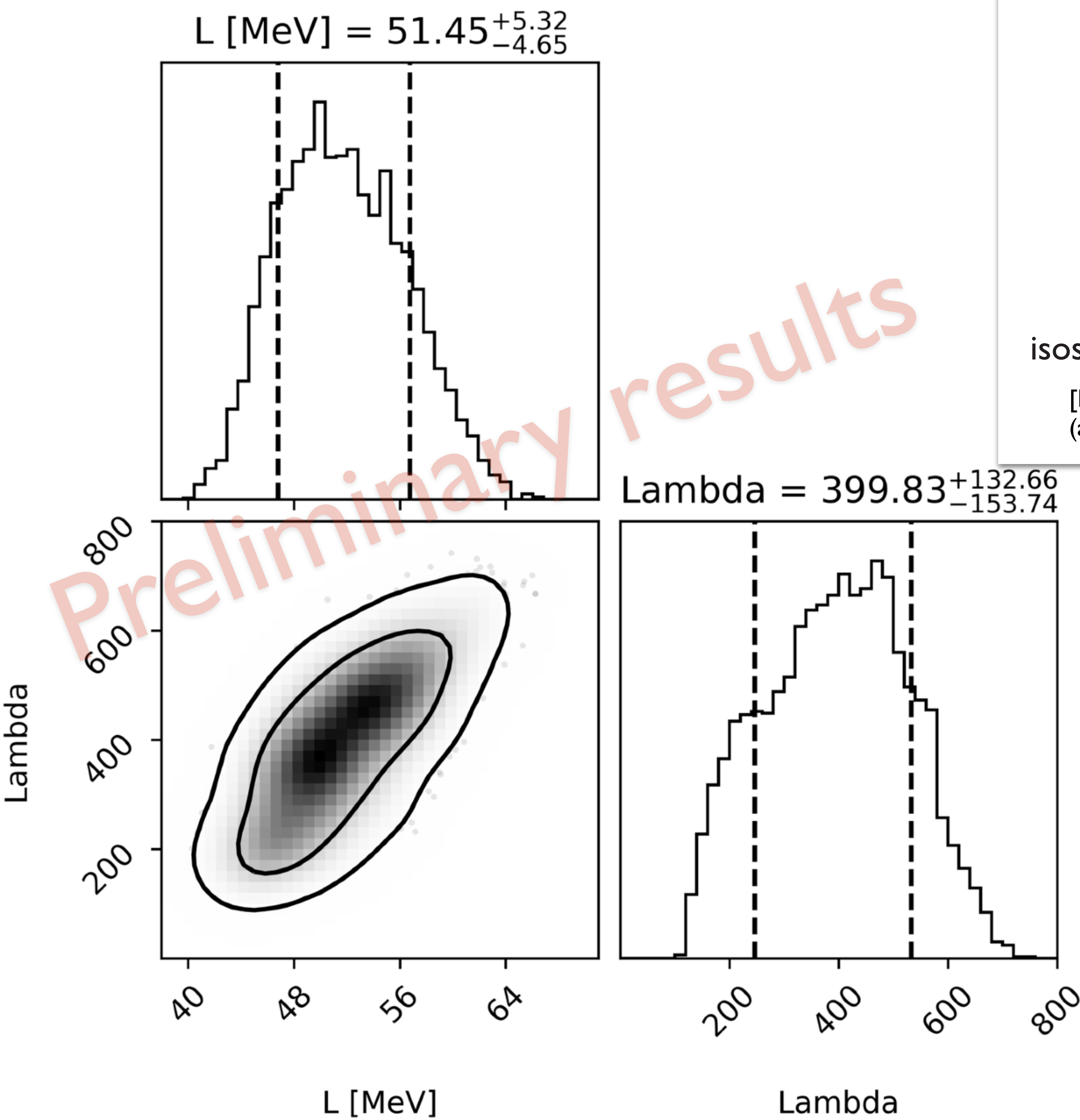
Mass=1.4 Msun

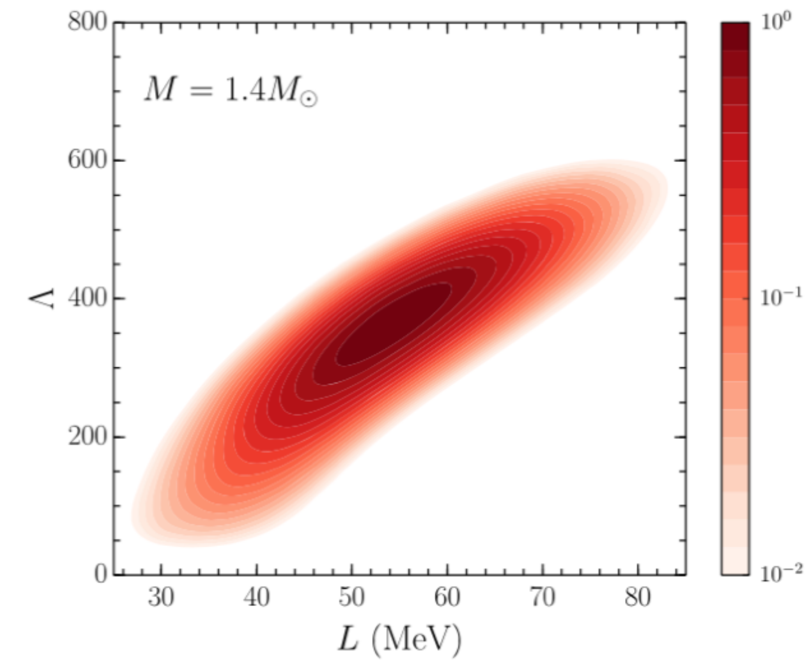


Mass=1.4 Msun



Radius [km] = $12.40^{+0.75}_{-1.09}$
Lambda = $399.83^{+132.66}_{-153.74}$
L [Mev] = $51.45^{+5.32}_{-4.65}$
Kτ [MeV] = $-385.02^{+33.83}_{-39.21}$
Q_{sym} [MeV] = $577.52^{+66.89}_{-79.20}$
Radius [km]
Lambda
L [Mev]
Kτ [MeV]
Q_{sym} [MeV]
K0 [MeV]
Q0 [MeV]
J [MeV]
Preliminary

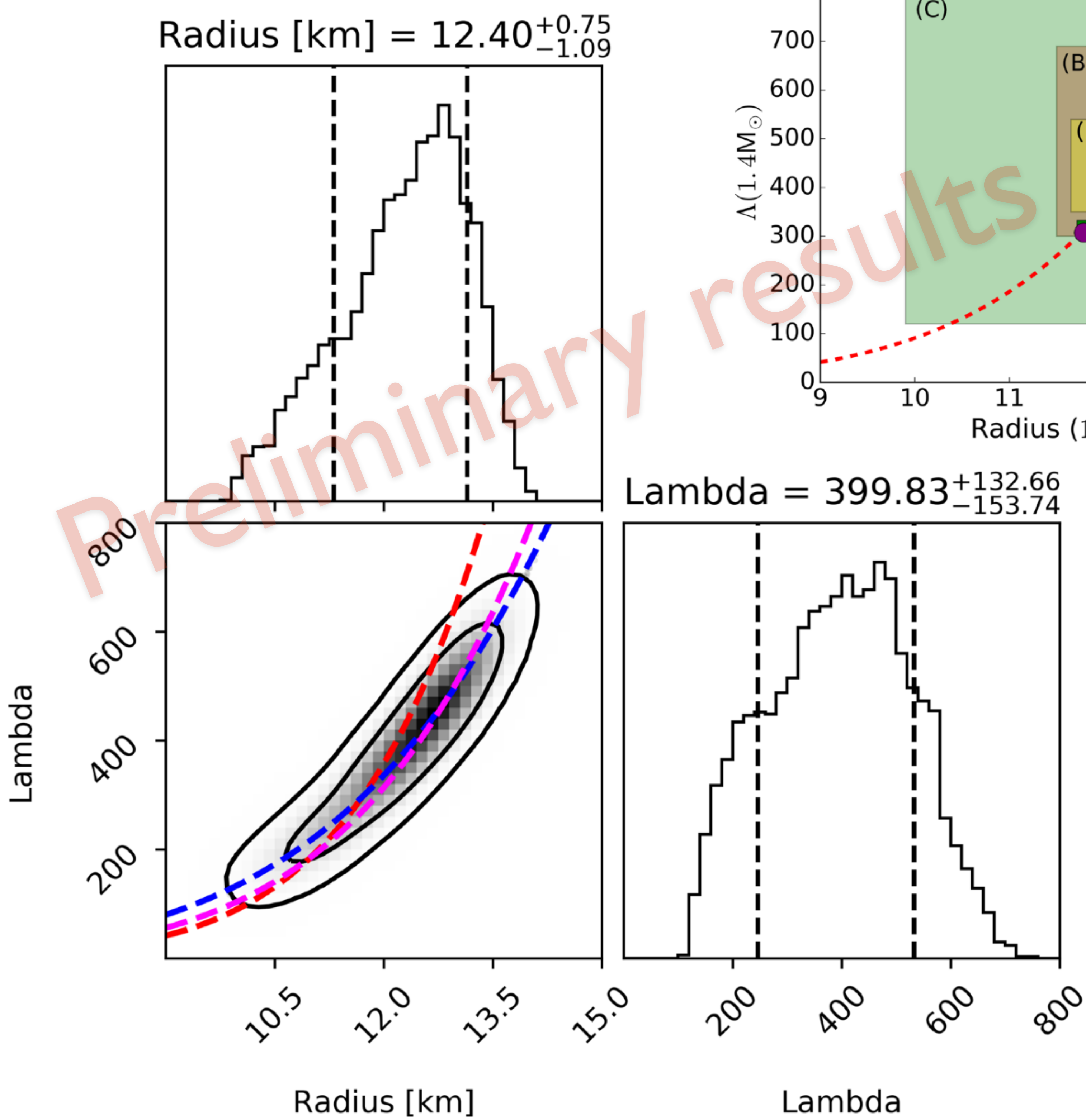




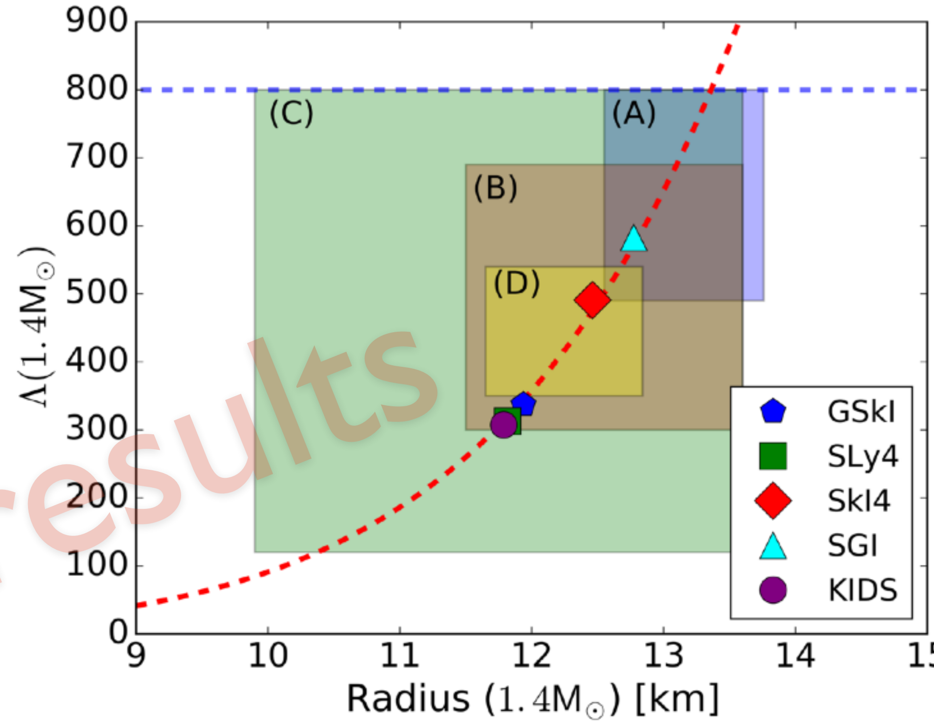
isospin-asymmetry energy slope parameter L

[D] Y.Lim and J. Holt, PRL.121.062701
(arXiv:1803.02803v2)

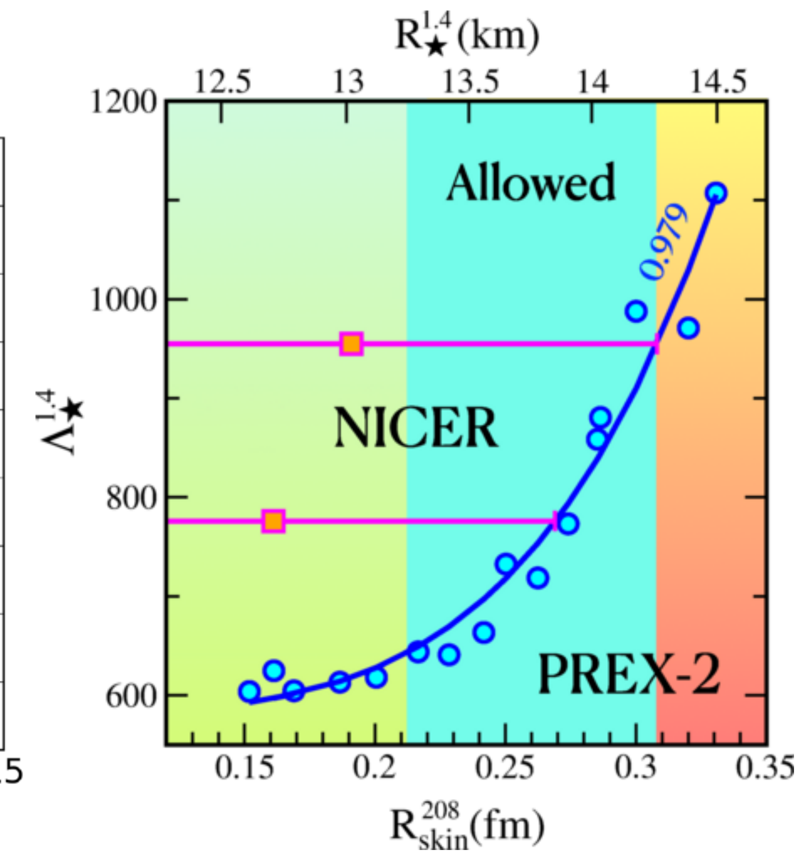
Lambda-Radius relation



Kim et al., PhysRevC.98.065805 (2018)



Implication of PREX 2 - PhysRevLett.126.172503 (2021)



Red line: $\Lambda(1.4M_\odot) = 2.88 * 10^{-6} (R/km)^{7.5}$

[C] PhysRevLett.120.172703.pdf

Blue line: $\Lambda(1.4M_\odot) = 1.35 * 10^{-3} (R/km)^{5.0}$

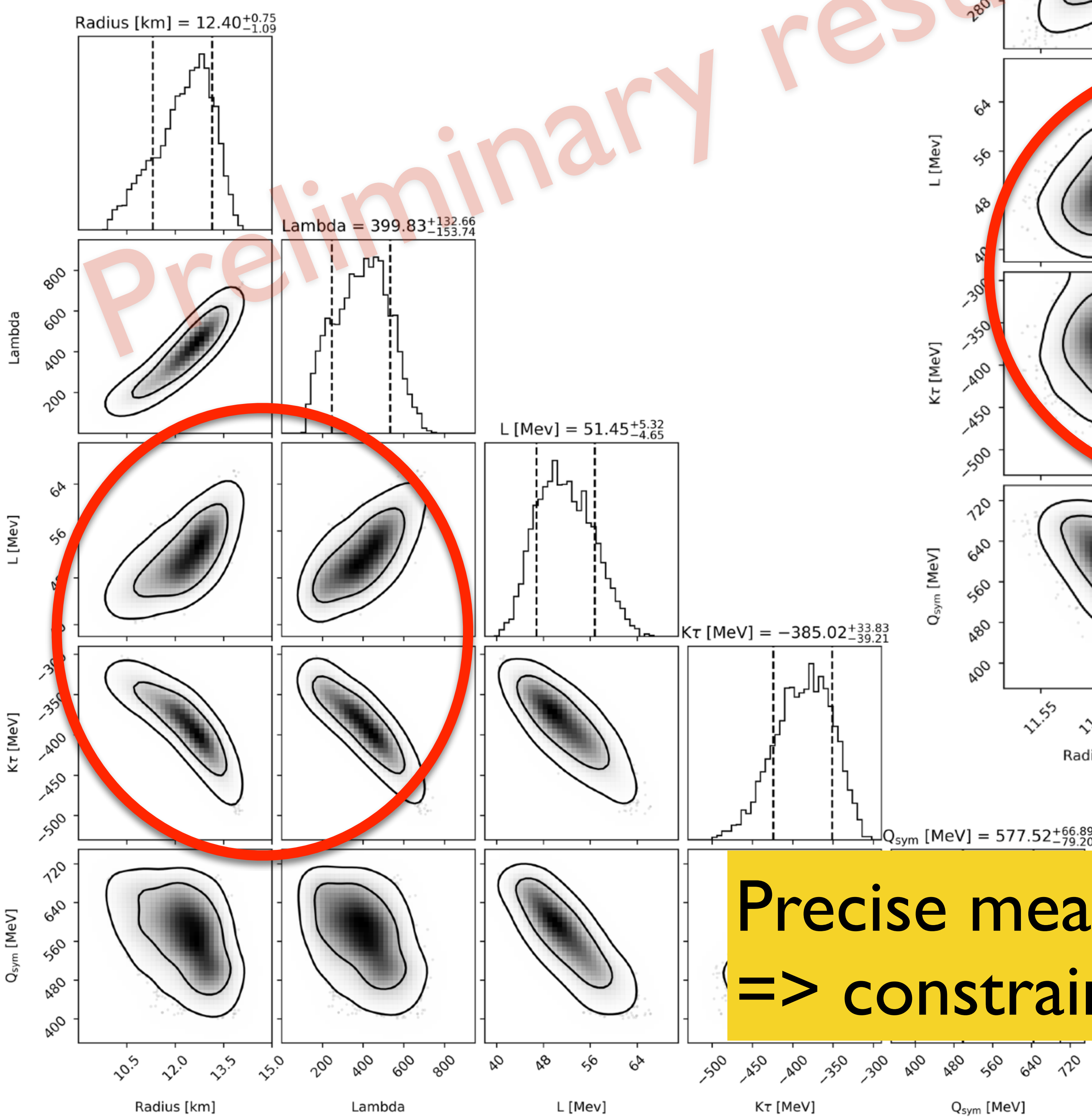
Implication of PREX 2 - PhysRevLett.126.172503 (2021)

=> $\Lambda \sim R^{4.8}$

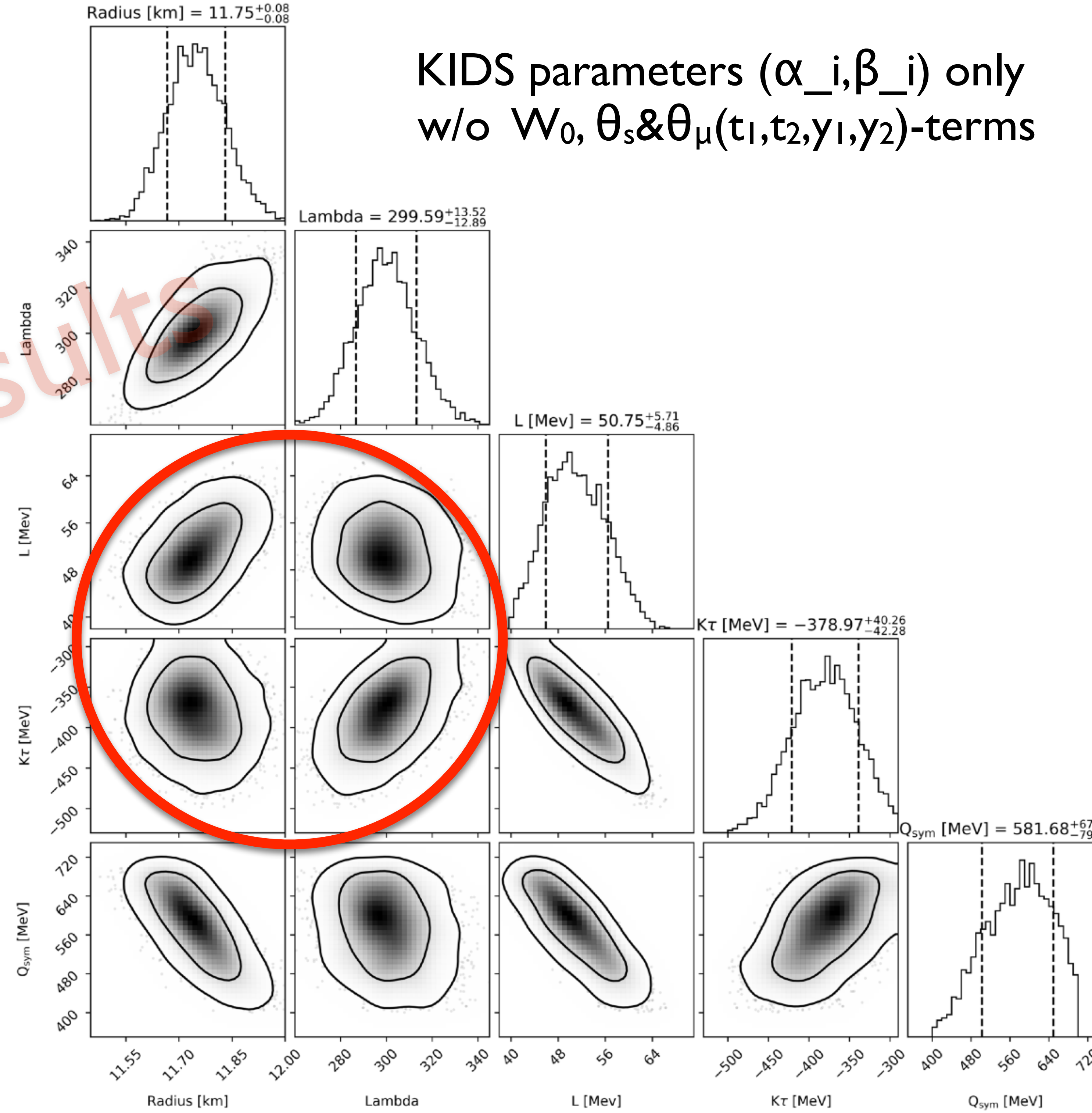
Magenta line: $\Lambda(1.4M_\odot) = 1.05 * 10^{-4} (R/km)^{6.0}$

Y.-M. Kim, in progress

KIDS -> Skyrme parametrization
w/ W_0, θ_s&θ_μ(t_1,t_2,y_1,y_2)-terms



KIDS parameters (α_i,β_i) only
w/o W_0, θ_s&θ_μ(t_1,t_2,y_1,y_2)-terms

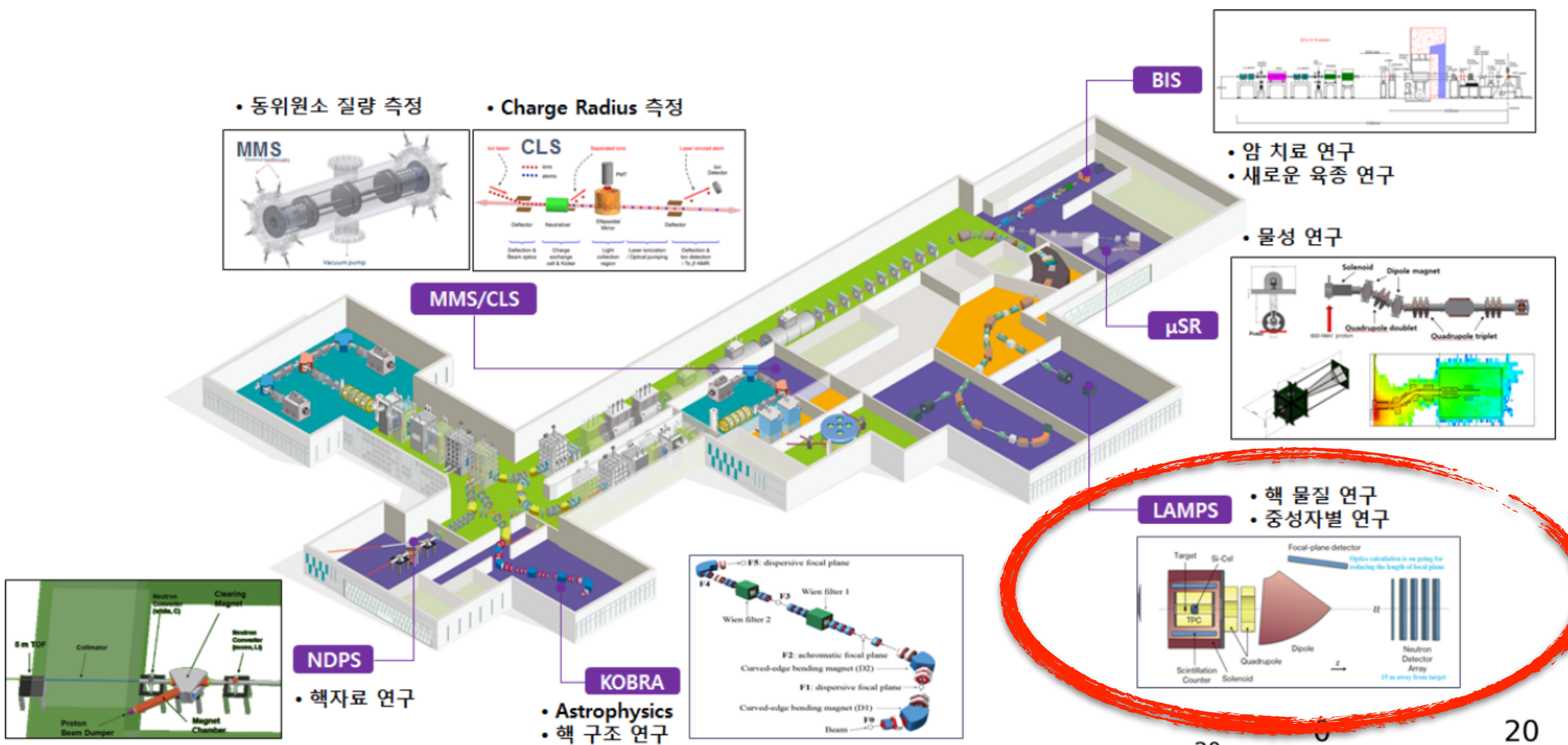


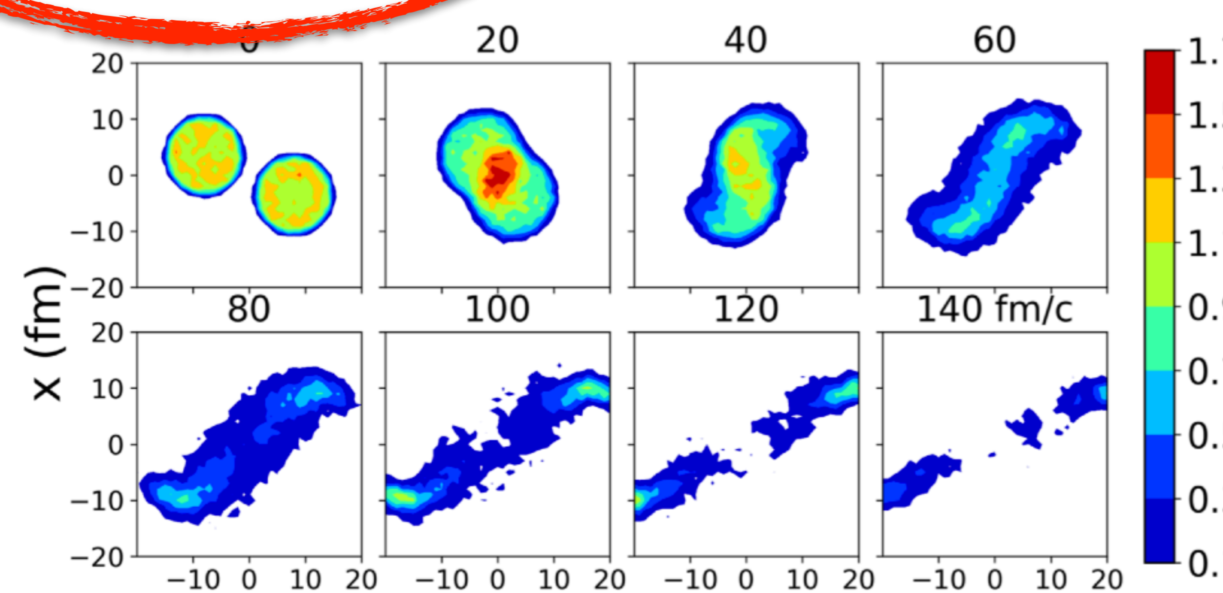
Preliminary results

Precise measurements of R, Λ
=> constraints of EoS & Nuclei properties

Application to HIC @ RAON

Experimental Systems





KIDS-DJBUU

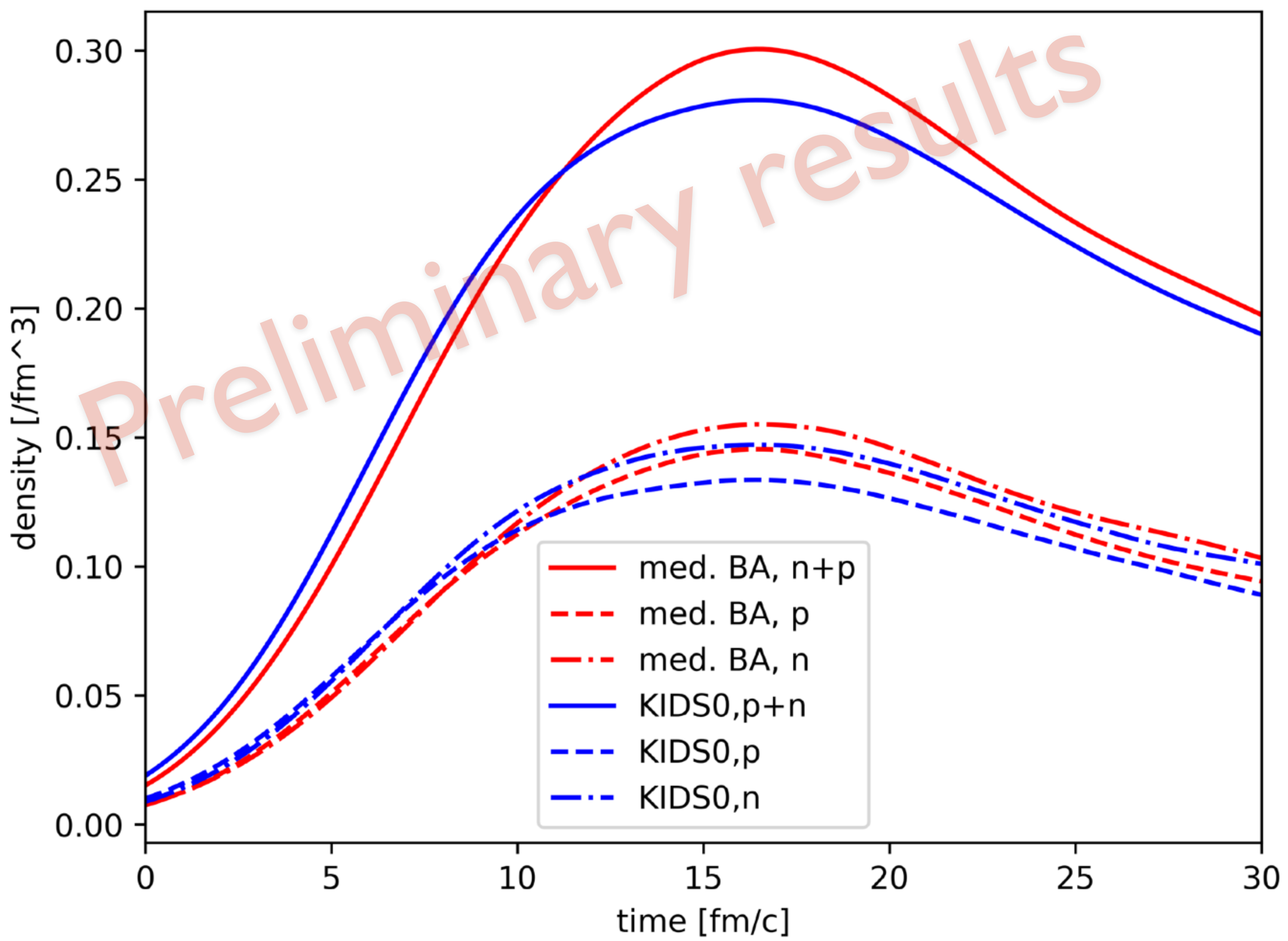
$$
\begin{aligned}
U_{0,q} &= \frac{1}{2}\left[(2t_0 + y_0)\rho - (t_0 + 2y_0)\rho_q\right], \\
U_{3,q} &= \frac{1}{24}\sum_{n=1}^{3}\frac{n}{3}\left[(2t_{3n} + y_{3n})\rho^2 - (t_{3n} + 2y_{3n})\sum_q \rho_q^2\right]\rho^{n/3-1} \\
&\quad + \frac{1}{12}\sum_{n=1}^{3}\left[(2t_{3n} + y_{3n})\rho - (t_{3n} + 2y_{3n})\rho_q\right]\rho^{n/3}, \\
U_{\mathrm{eff},q} &= \frac{1}{8\hbar^2}\left[(2t_1 + y_1) + (2t_2 + y_2)\right]\int d^3p'(\mathbf{p} - \mathbf{p}')^2 f(\mathbf{r}, \mathbf{p}') \\
&\quad + \frac{1}{8\hbar^2}\left[-(t_1 + 2y_1) + (t_2 + 2y_2)\right]\int d^3p'(\mathbf{p} - \mathbf{p}')^2 f_q(\mathbf{r}, \mathbf{p}').
\end{aligned}
$$

n! = 2, t_i,y_i can be determined by NS observations

n = 2, t_2, y_2, t_32, y_32 should be determined by Nuclei

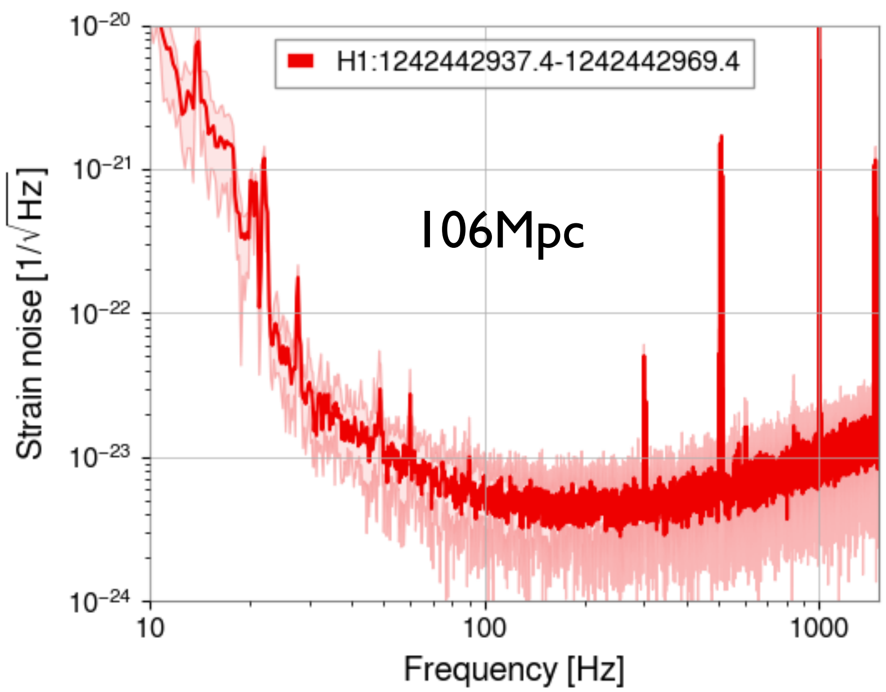
Application to Heavy Ion Collision

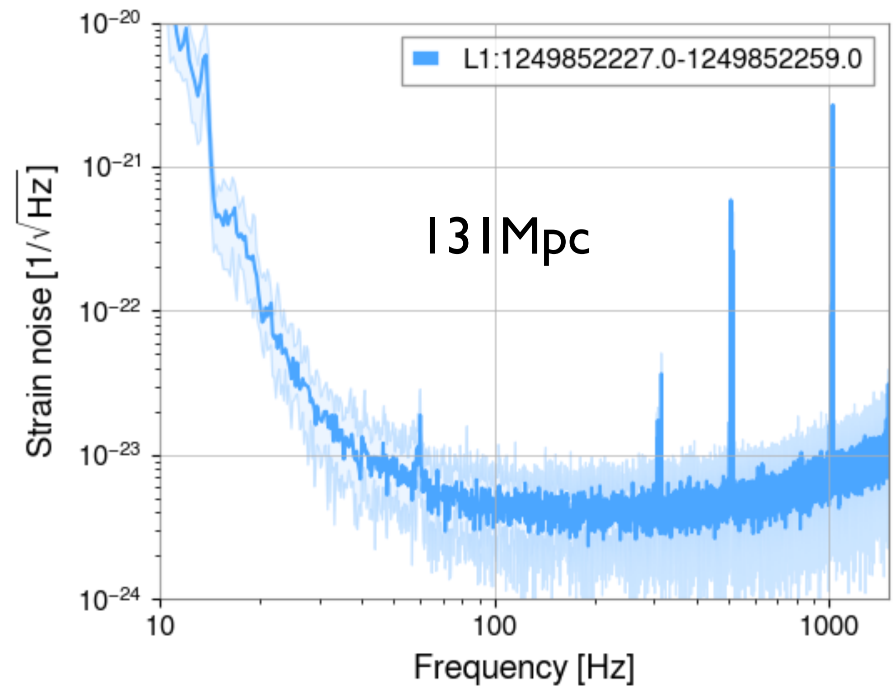
DJBUU simulation w/ KIDS
based on M.Kim's
preliminary code

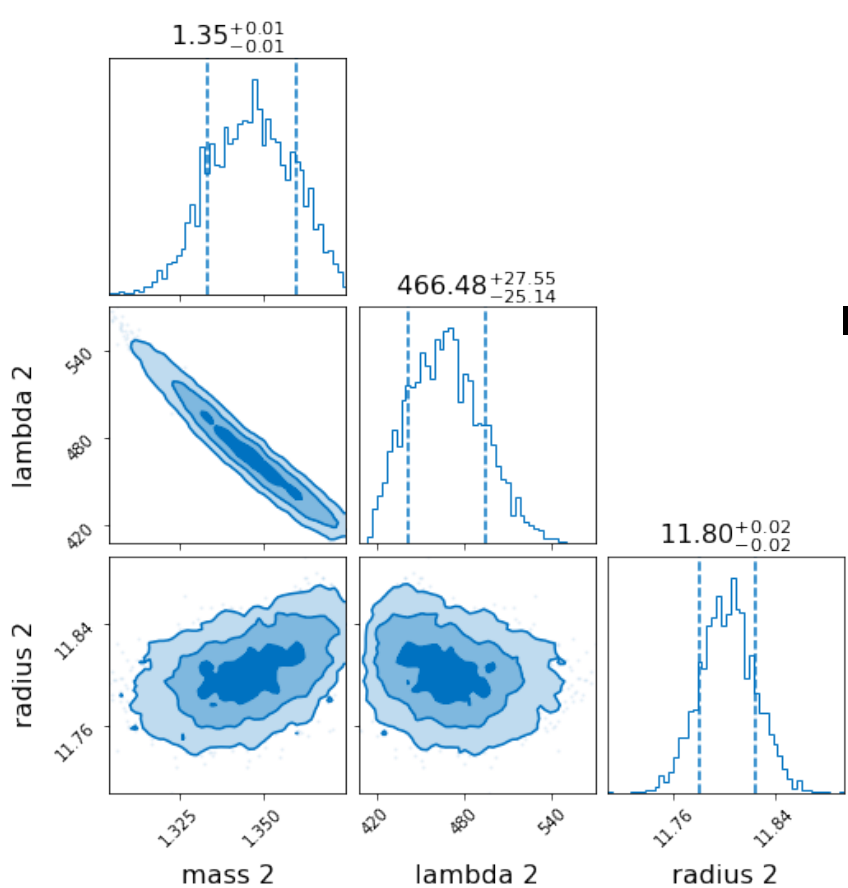


Study on Model Uncertainty or Uncertainty Quantification

Posteriors depending on DET status





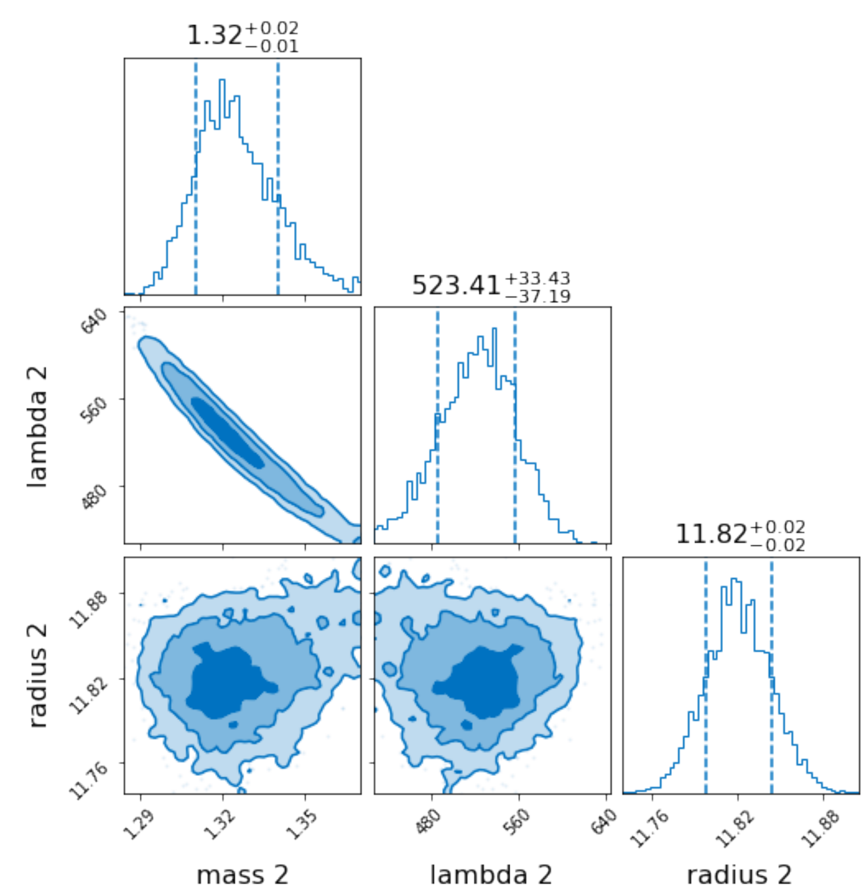


m1=1.4 Msun

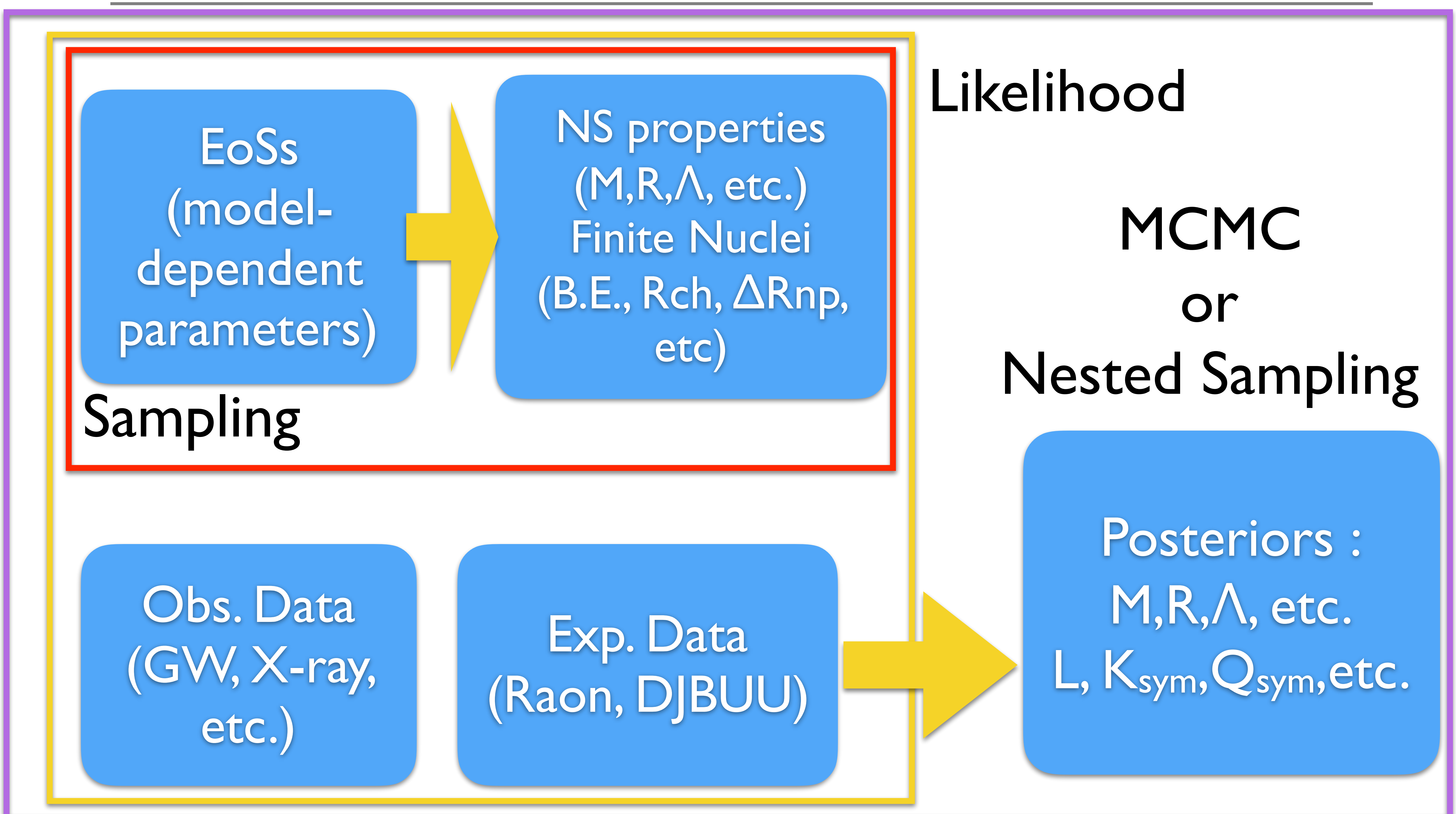
Λ1=400

m2=1.35 Msun

Λ2=450



Final Goal: EoS w/ Bayesian in MMA



Summary and future plans

1. Neutron Star is an ultimate testing place for physics of dense matter.
    - Multi-Messenger Astrophysics : analysis on GW, LMXB
    - RAON : Heavy Ion simulation (DJBUU)
2. Precise estimation of NS masses and radii is important for studying dense nuclear / stellar matter
    - More observations from BNSs and/or NSBHs via GWs
3. Future plans
    - Bayesian inference w/ hyperons, etc., and RMF model, FRG, etc.
    - Uncertainty Quantification for BNS merger and HIC
        - Acceleration with Deep Learning and/or multi-cores/GPU
    - Consideration of the spin and the magnetic field of NS
    - Towards next generation GW detectors

Thank you for your attention.