Towards consistent Multi-messenger nuclear & astrophysics with crust

William G. Newton

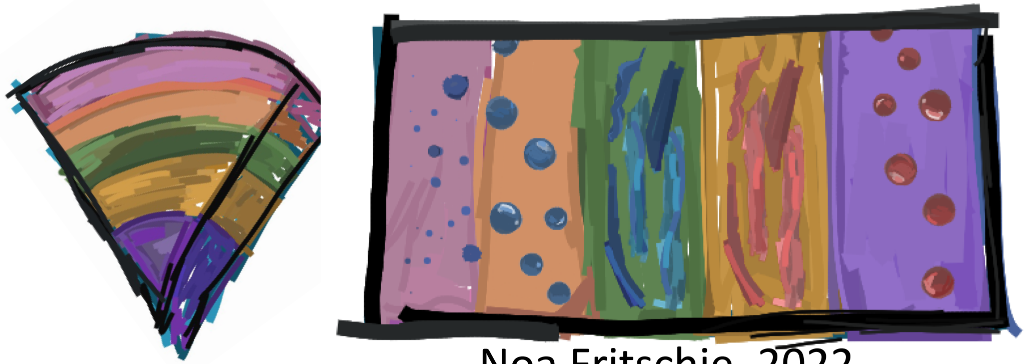
The work presented in this talk would not be possible without an amazing team of undergraduates and Master’s students, including

Rebecca Preston, Amber Stinson, Lauren Balliet, Michael Ross, Gabriel Crocombe, Blake Head, Josh Sanford, Zachary Langford

Texas A&M University-Commerce

Duncan Neill, David Tsang – University of Bath

With special thanks to Reed Essick, Ingo Tews and Achim Schwenk



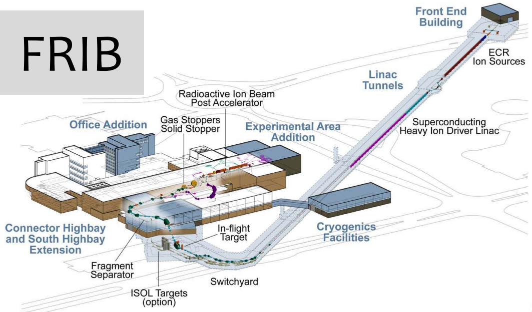
Noa Fritschie, 2022

Strong, Weak, EM signals

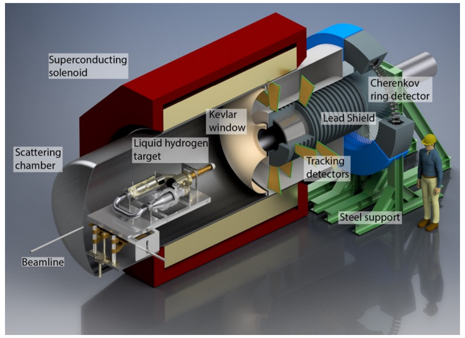
Multimessenger Nuclear & Astro Physics

Weak, EM, Grav signals

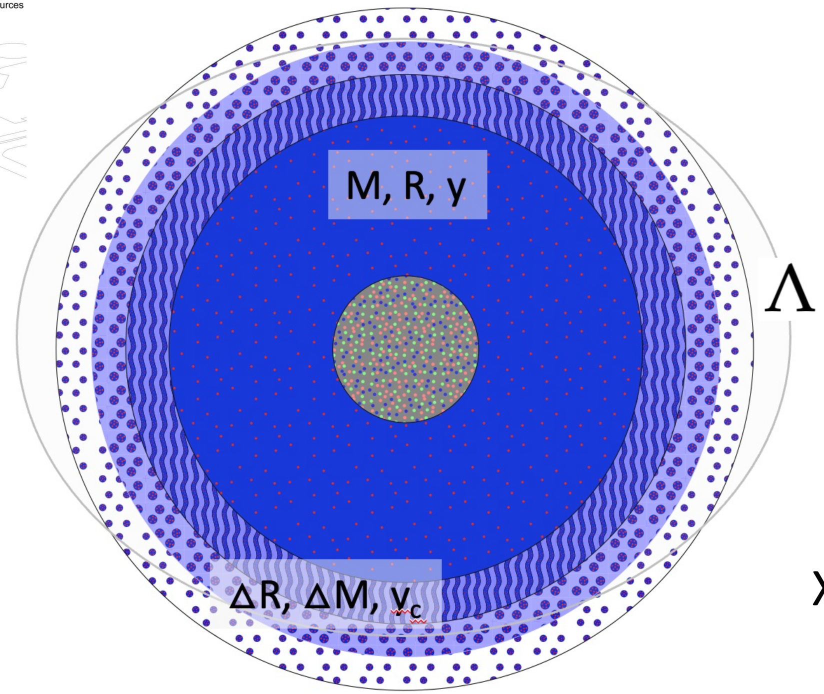
FRIB



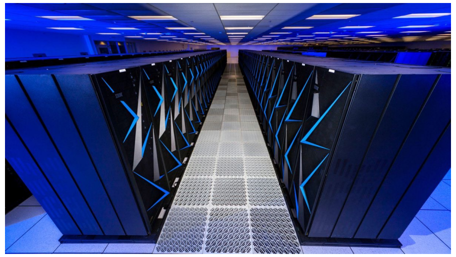
- Elliptic flow
- p/n ratios
- Pion production
- Resonance widths,
- Centroid energies
- Optical potentials
- Scattering X-sections



PREX/CREX/MREX

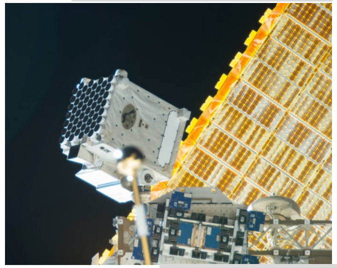


Computation



Randy Wong/LLNL

CHANDRA



NICER

- X-ray flux and light curves
- Gravitational waveforms
- Pulsar timing

PARKES

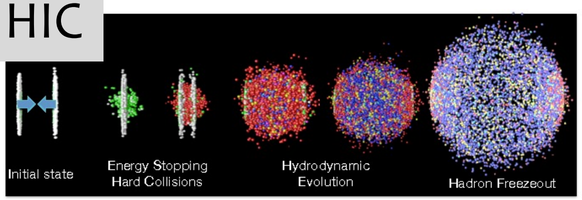
LIGO/ VIRGO

Nuclear structure/ dynamics

Multimessenger Nuclear & Astro Physics

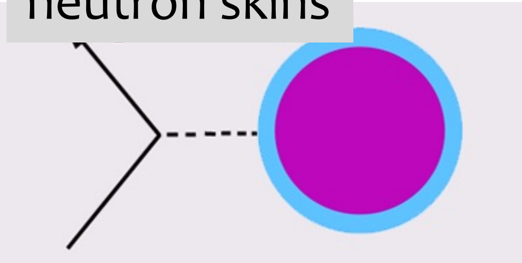
Neutron star structure/ dynamics

HIC

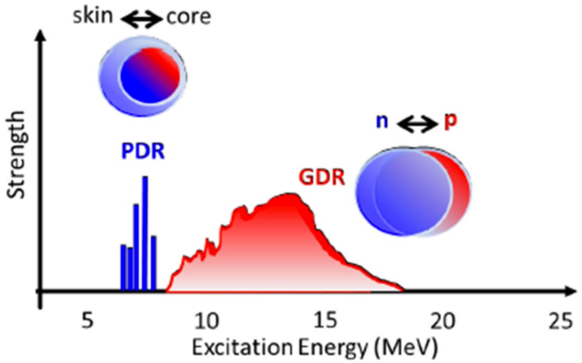


T.K.Nayak, arxiv:1201.4264

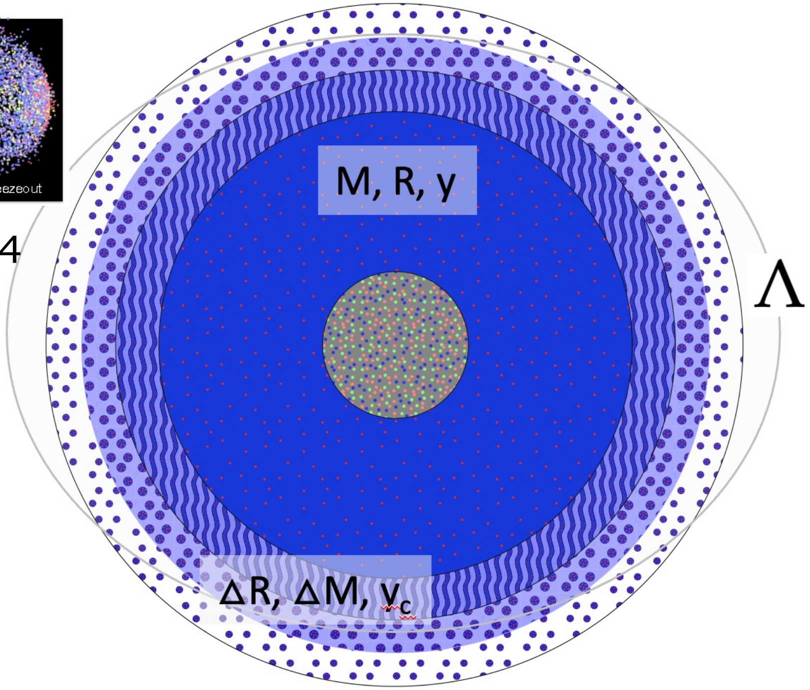
neutron skins

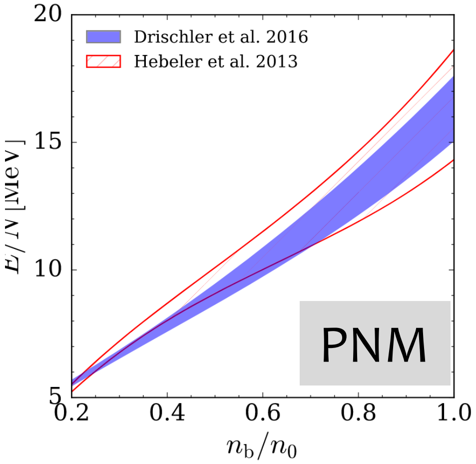


Abrahamyan+,
PRL 108, 112592 (2012)



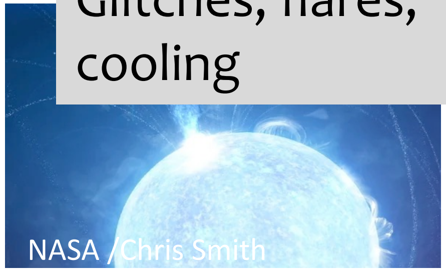
Bracco, Lanza, Tamii,
PPNP 106, 360 (2019)

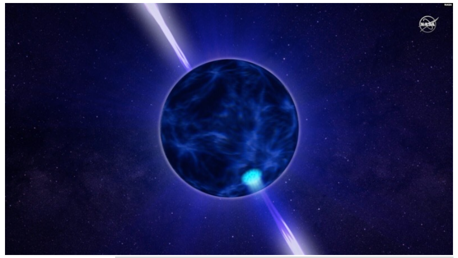




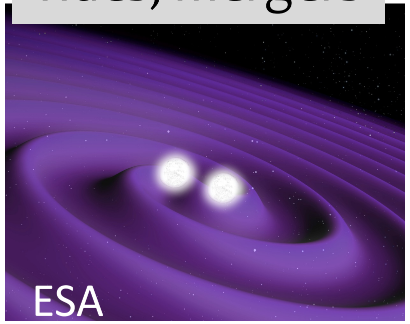
Haensel, Fortin JPhysG 2017

Glitches, flares, cooling





Tides, mergers



Hot spots
Oscillations,
Crust cooling

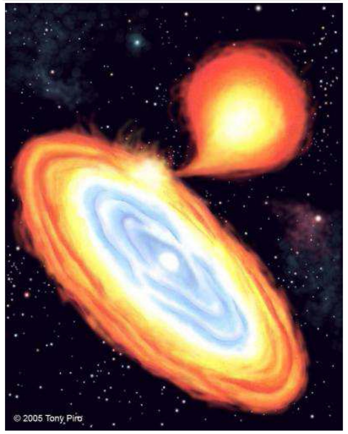


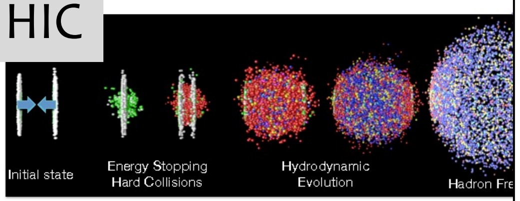
Figure: Artist's impression of a LMXB - credit Tony Piro, 2005.

Nuclear structure/ dynamics

Multimessenger Nuclear & Astro Physics

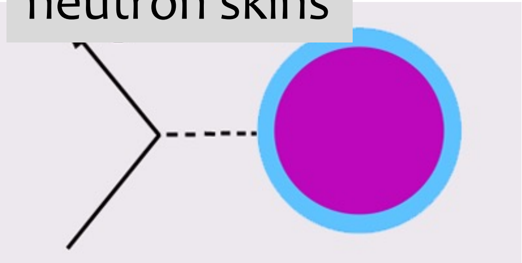
Neutron star structure/ dynamics

HIC



T.K.Nayak, arxiv:1201.426

neutron skins



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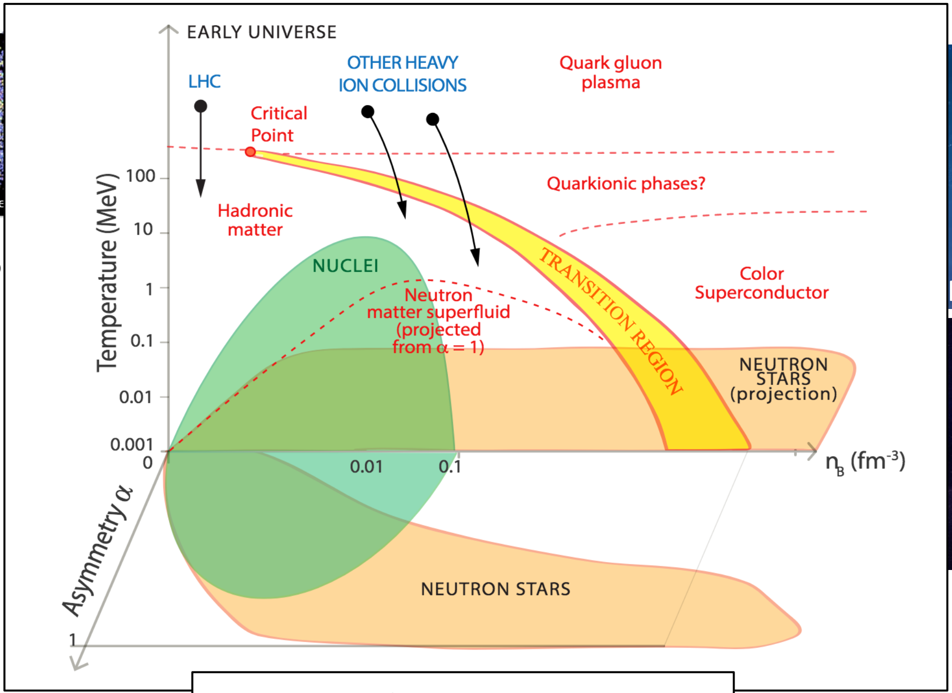
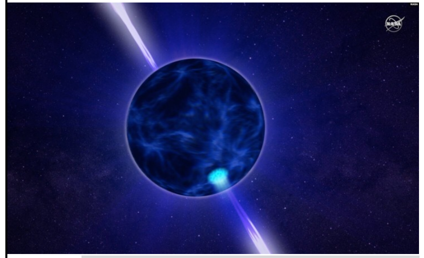


Watts et al arxiv:1501.00042

Glitches, flares, cooling

NASA /Chris Smith



Hot spots
Oscillations,
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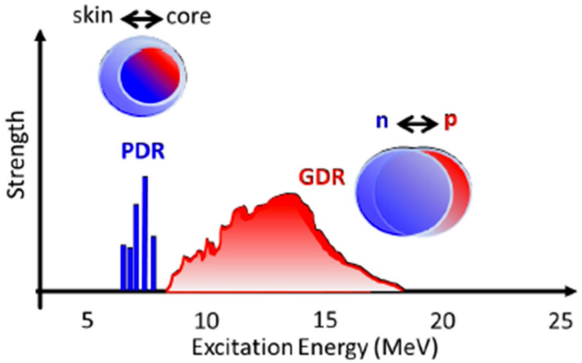

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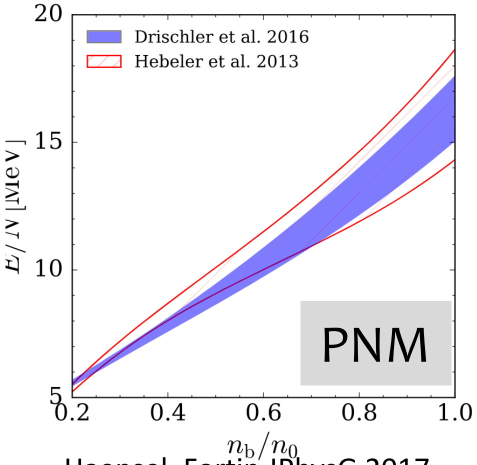

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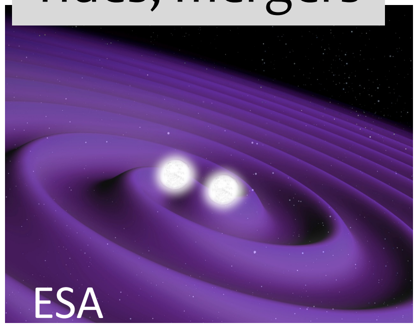
Tides, mergers



ESA

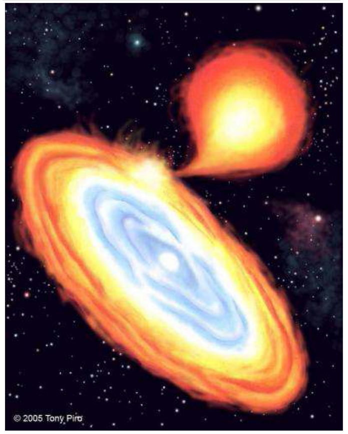
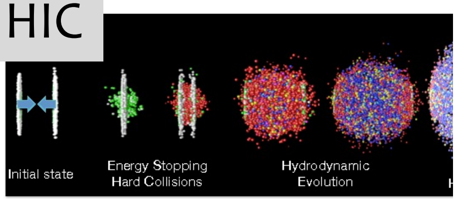


Figure: Artist's impression of a LMXB - credit Tony Piro, 2005.

Multimessenger Nuclear & Astro Physics

Nuclear structure/ dynamics

HIC



T.K.Nayak, arxiv:1201.4

neutron skins

Abrahamyan+,
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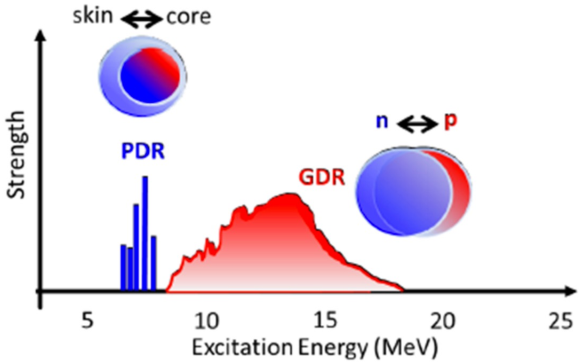

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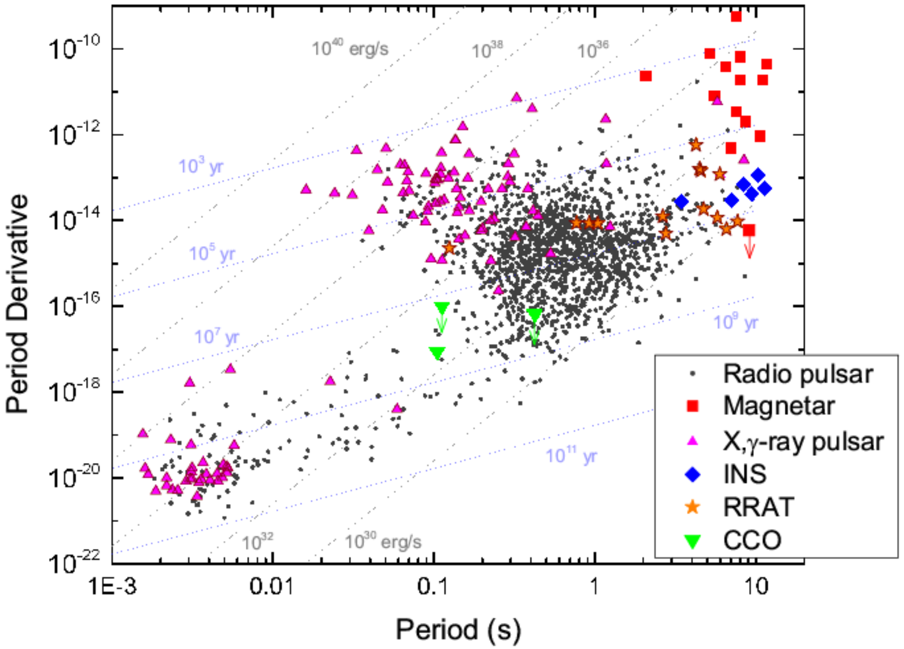
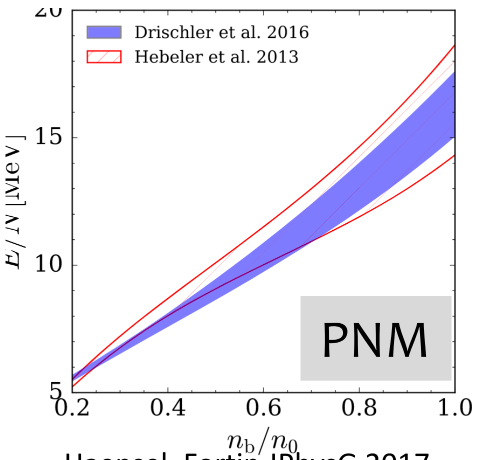
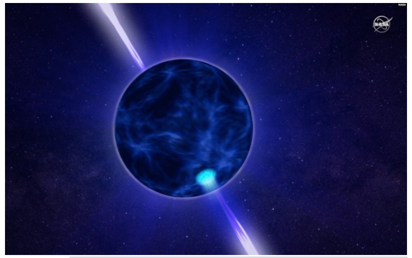




Haensel, Fortin JPhysG 2017

Neutron star structure/ dynamics

Glitches, flares, cooling



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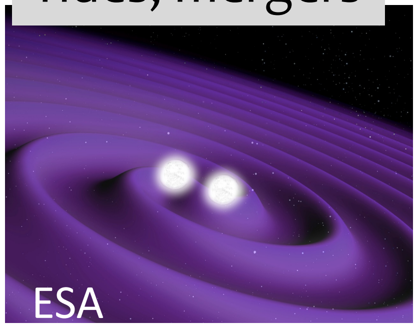
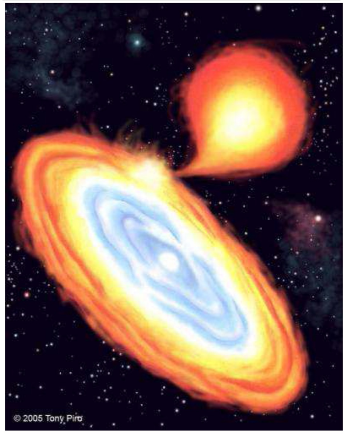


Hot spots
Oscillations,
Crust cooling



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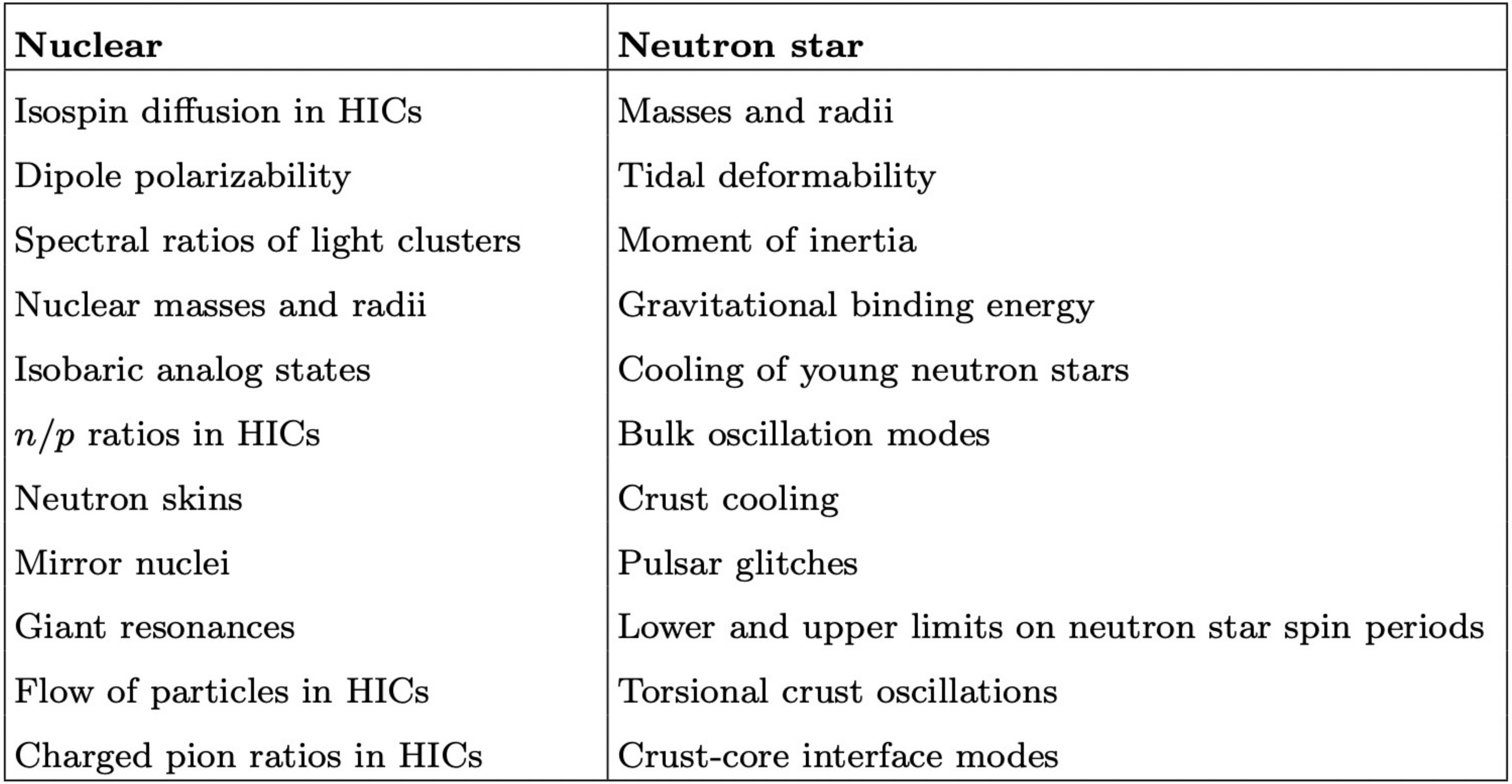
Putting the Multi in Multi-messenger

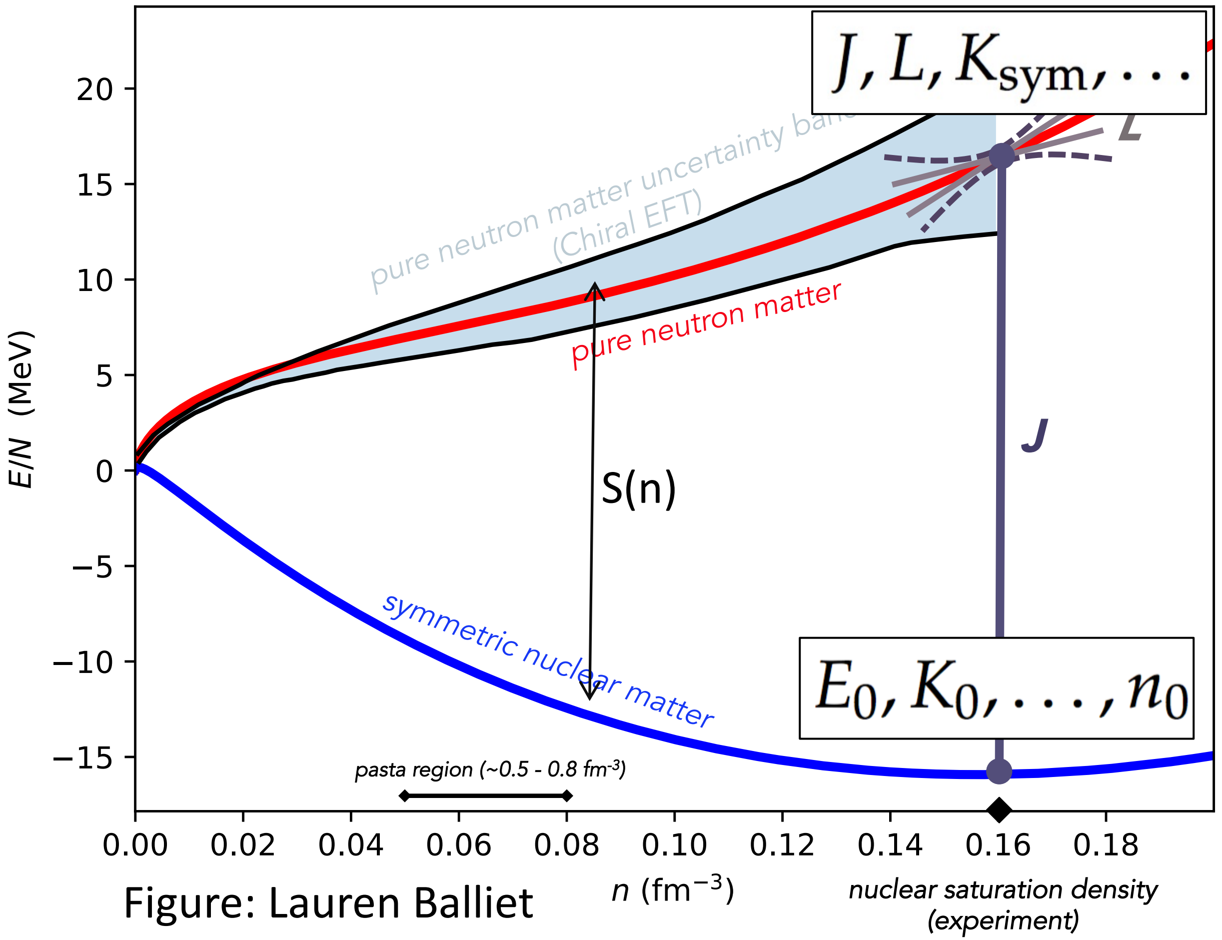


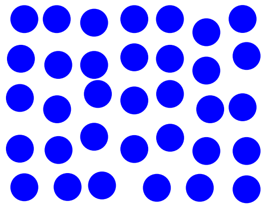
Nuclear	**Neutron star**
Isospin diffusion in HICs	Masses and radii
Dipole polarizability	Tidal deformability
Spectral ratios of light clusters	Moment of inertia
Nuclear masses and radii	Gravitational binding energy
Isobaric analog states	Cooling of young neutron stars
n/p ratios in HICs	Bulk oscillation modes
Neutron skins	Crust cooling
Mirror nuclei	Pulsar glitches
Giant resonances	Lower and upper limits on neutron star spin periods
Flow of particles in HICs	Torsional crust oscillations
Charged pion ratios in HICs	Crust-core interface modes

What do we want to do with this (potential data)?

The nuclear symmetry energy: parameterizing our ignorance in a physically meaningful way

$$E_{\mathrm{sym}}(\rho) \quad = \quad E_{\mathrm{sym}}(\rho_0) + L(\frac{\rho-\rho_0}{3\rho_0}) + \frac{K_{\mathrm{sym}}}{2}(\frac{\rho-\rho_0}{3\rho_0})^2 + \frac{Q_{\mathrm{sym}}}{6}(\frac{\rho-\rho_0}{3\rho_0})^3$$





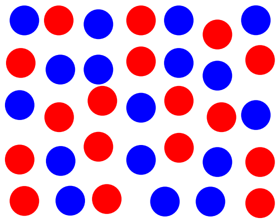


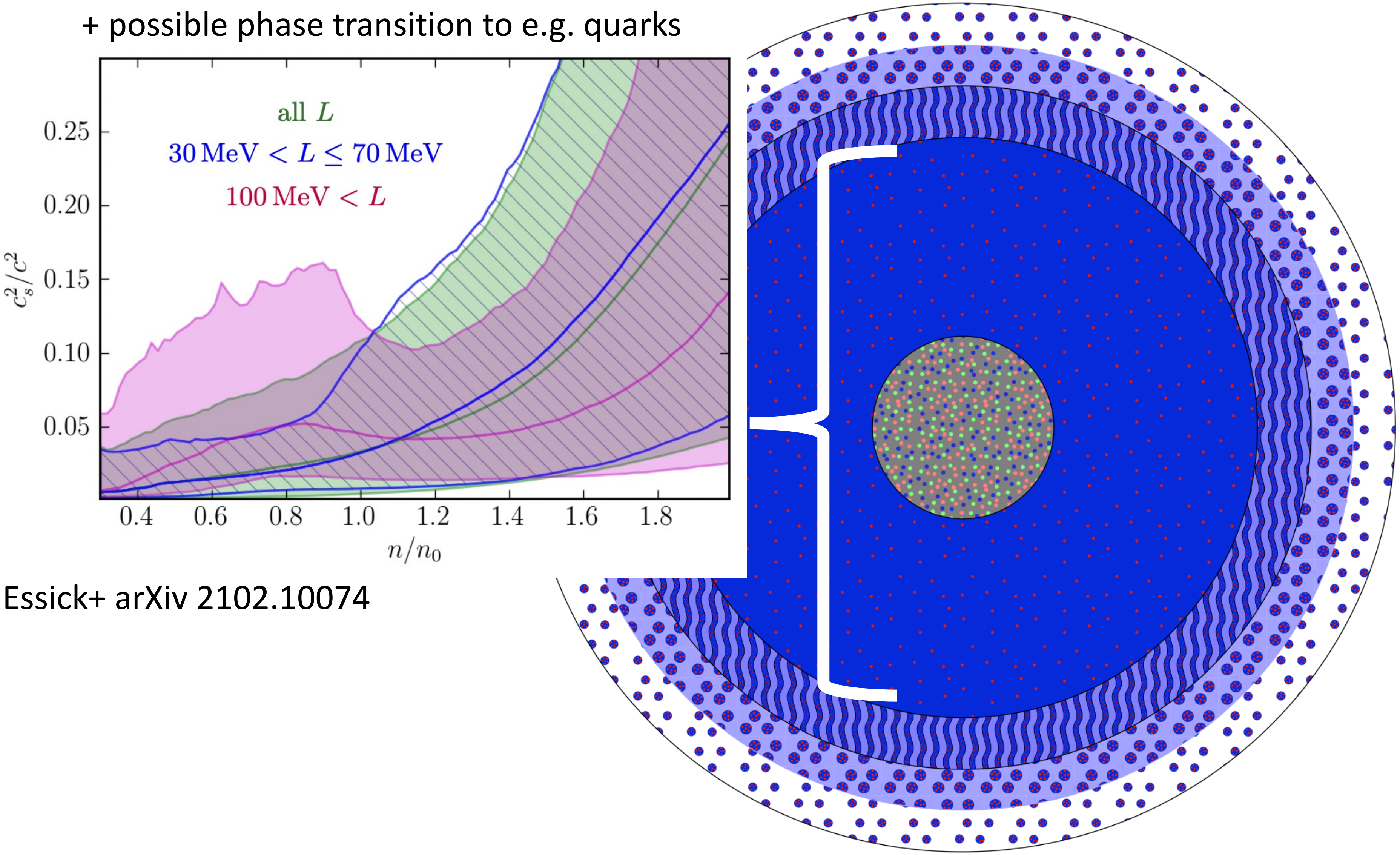
Figure: Lauren Balliet

$$E_0(\rho) \quad = \quad E_0(\rho_0) + \frac{K_0}{2}(\frac{\rho-\rho_0}{3\rho_0})^2 + \frac{Q_0}{6}(\frac{\rho-\rho_0}{3\rho_0})^3,$$

Li, arxiv:2105.04629

Modern approach: create distributions of EOSs/neutron star models for statistical inference

Core: neutron and proton fluid
+ possible phase transition to e.g. quarks

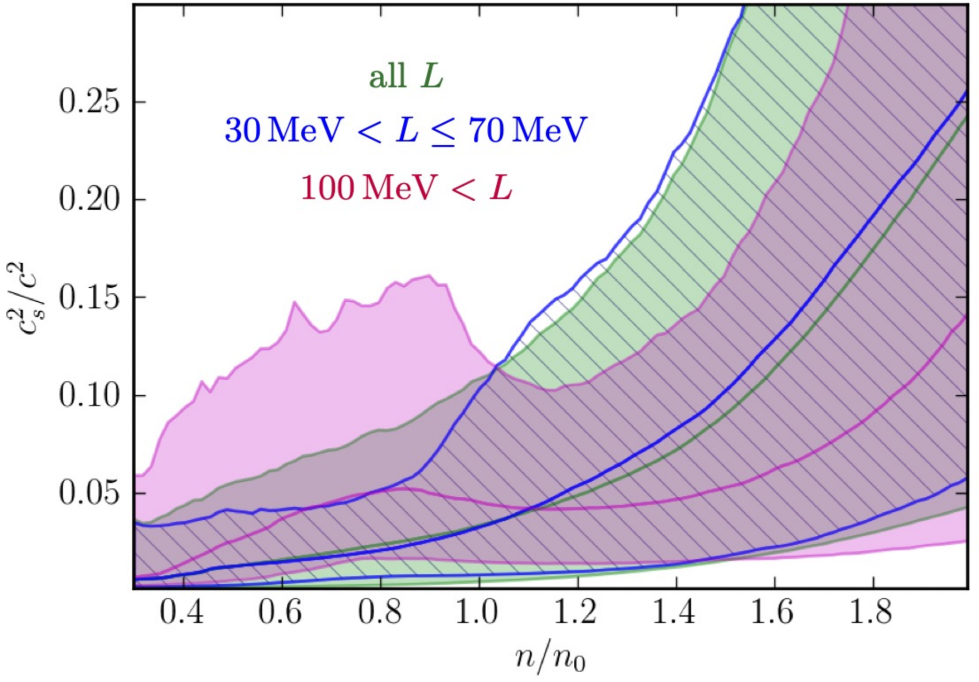


Essick+ arXiv 2102.10074

Modern approach: create distributions of EOSs/neutron star models for statistical inference

Can crust models get in on the action?

Core: neutron and proton fluid
+ possible phase transition to e.g. quarks



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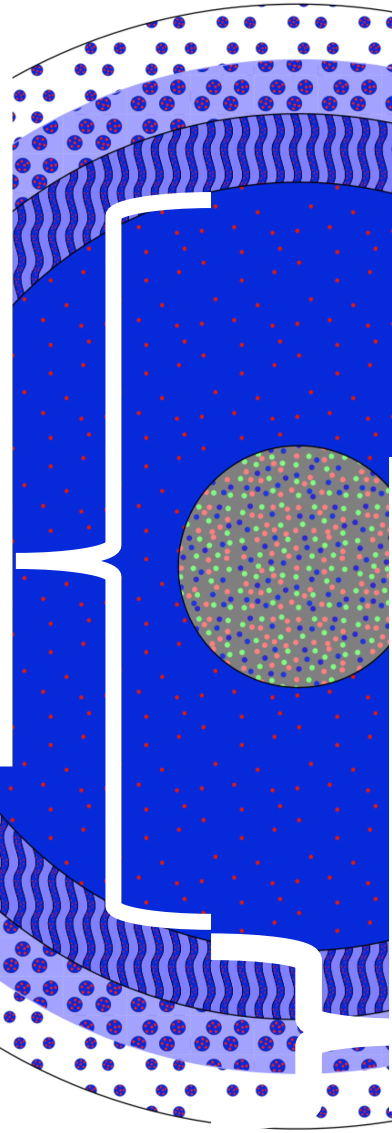
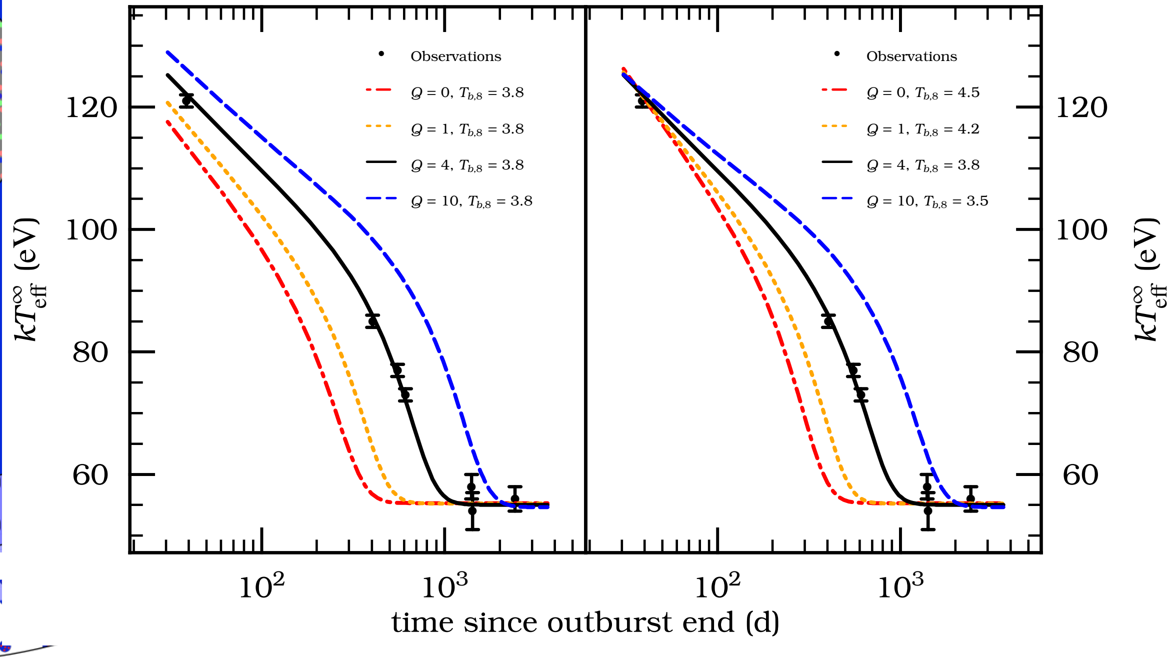
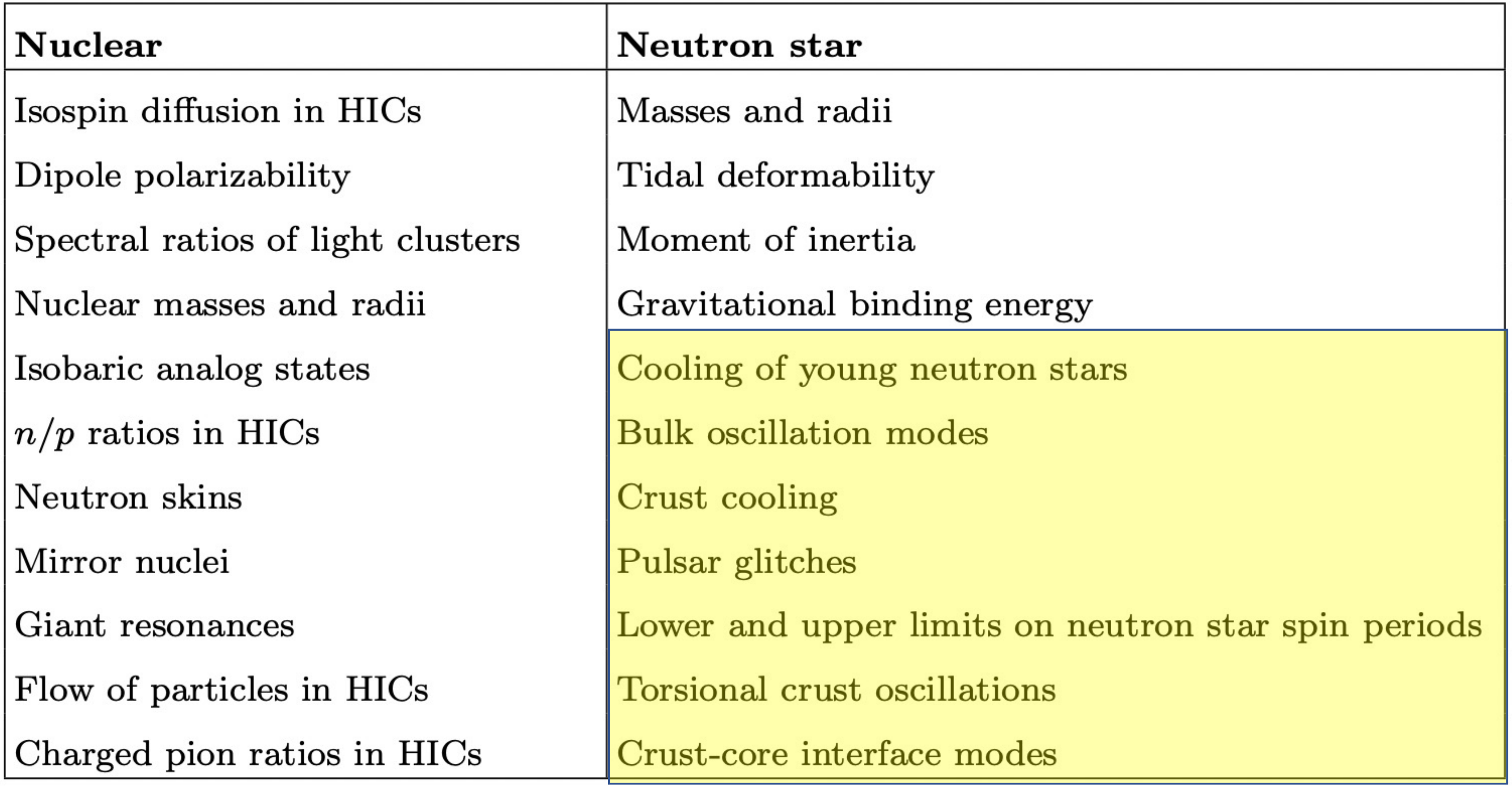


MXB 1659-29 in quiescence: Strong evidence for relatively pure crystalline crust with superfluid neutrons in the inner layer



Brown and Cumming, ApJ 2009

Putting the Multi in Multi-messenger



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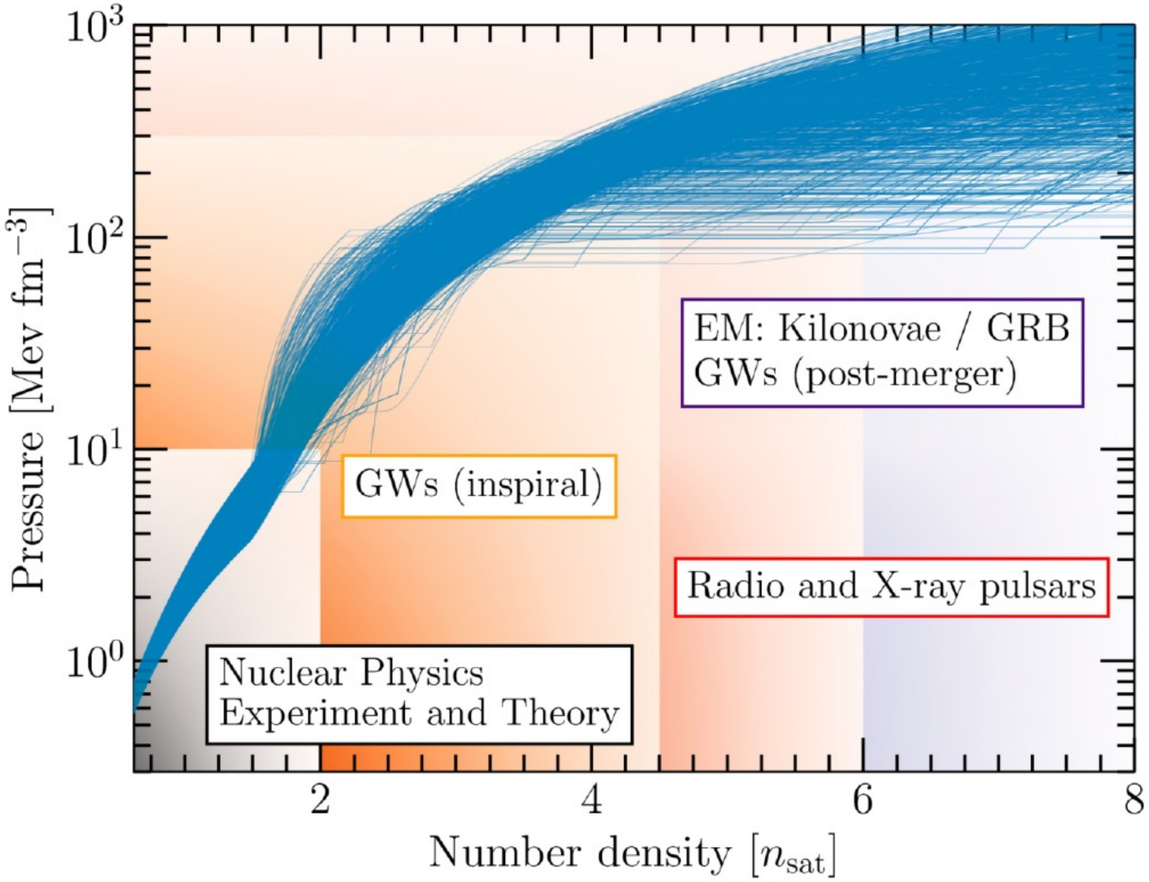
arxiv:2301.13253

What do we want to do with this (potential data)?

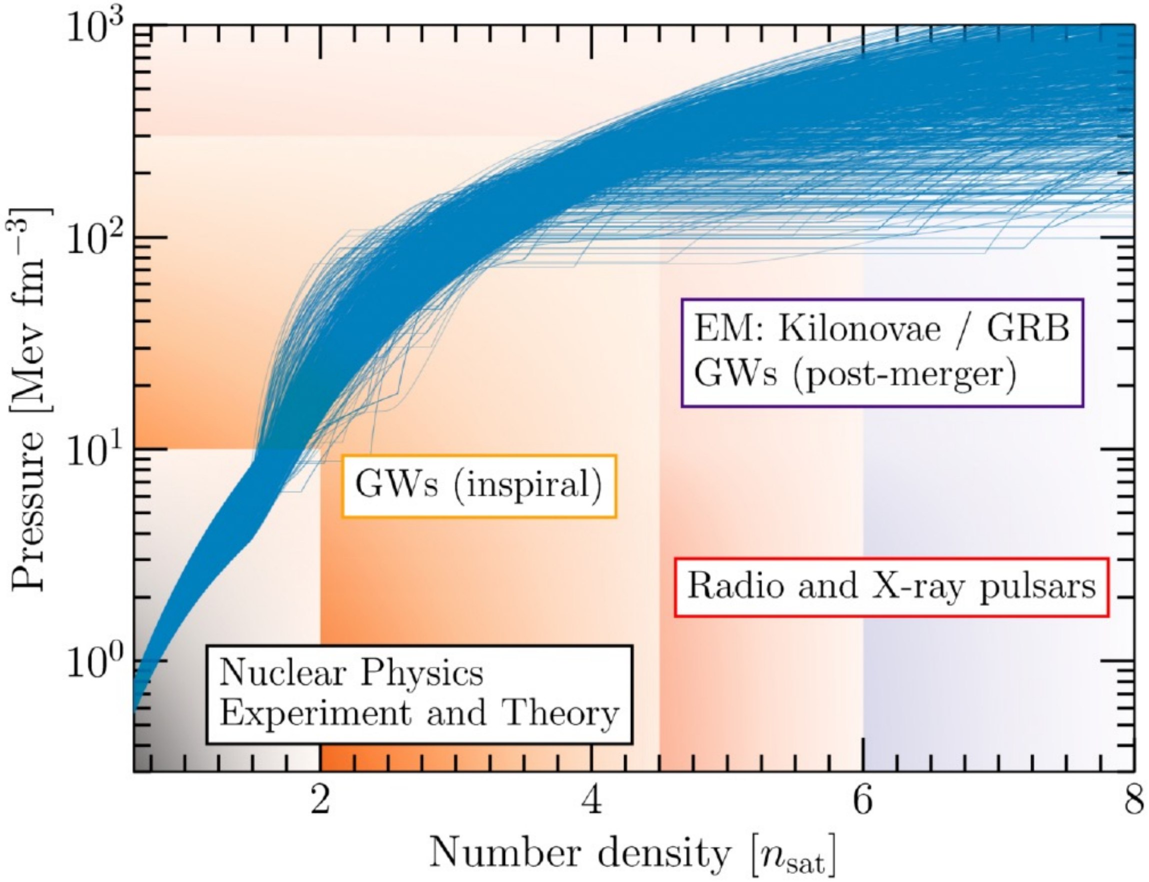
Modern approach: create distributions of EOSs/neutron star models for statistical inference

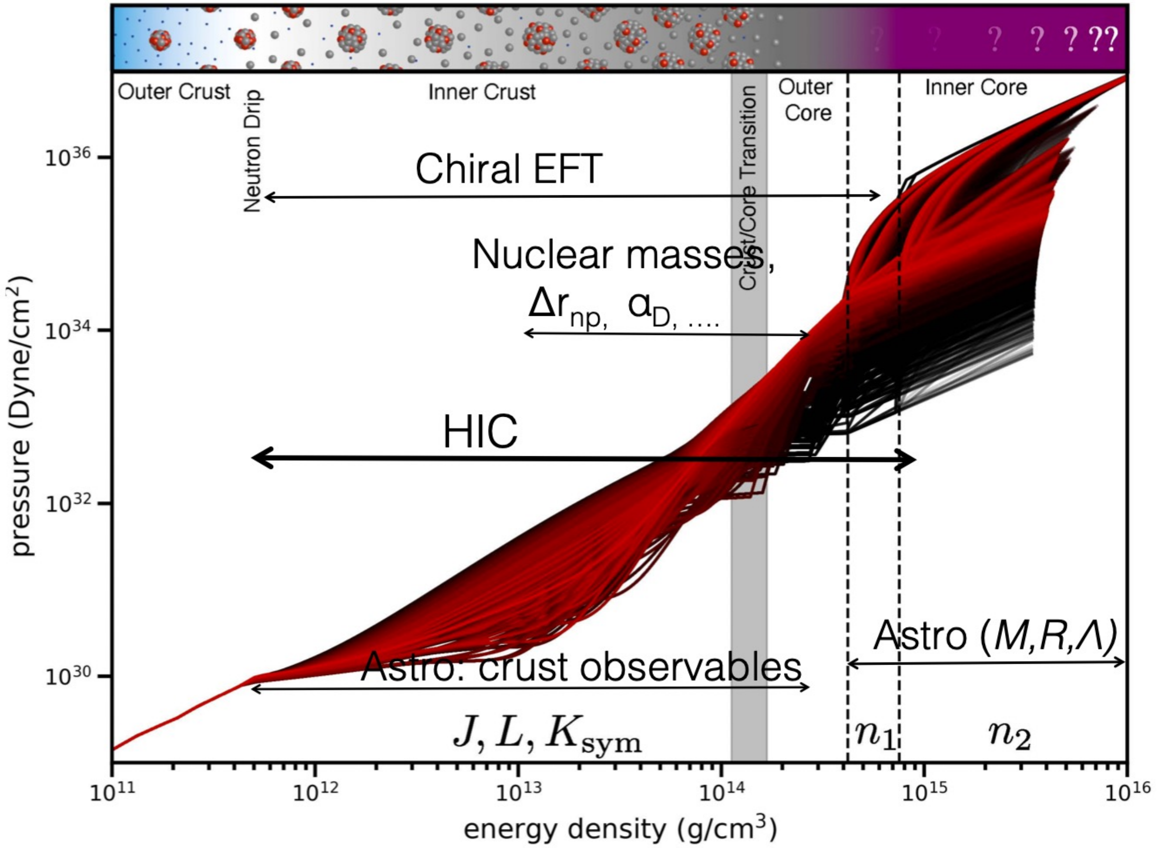


Pang et al, arxiv:2205.08513

Modern approach: create distributions of EOSs/neutron star models for statistical inference

Letting the crust join the party

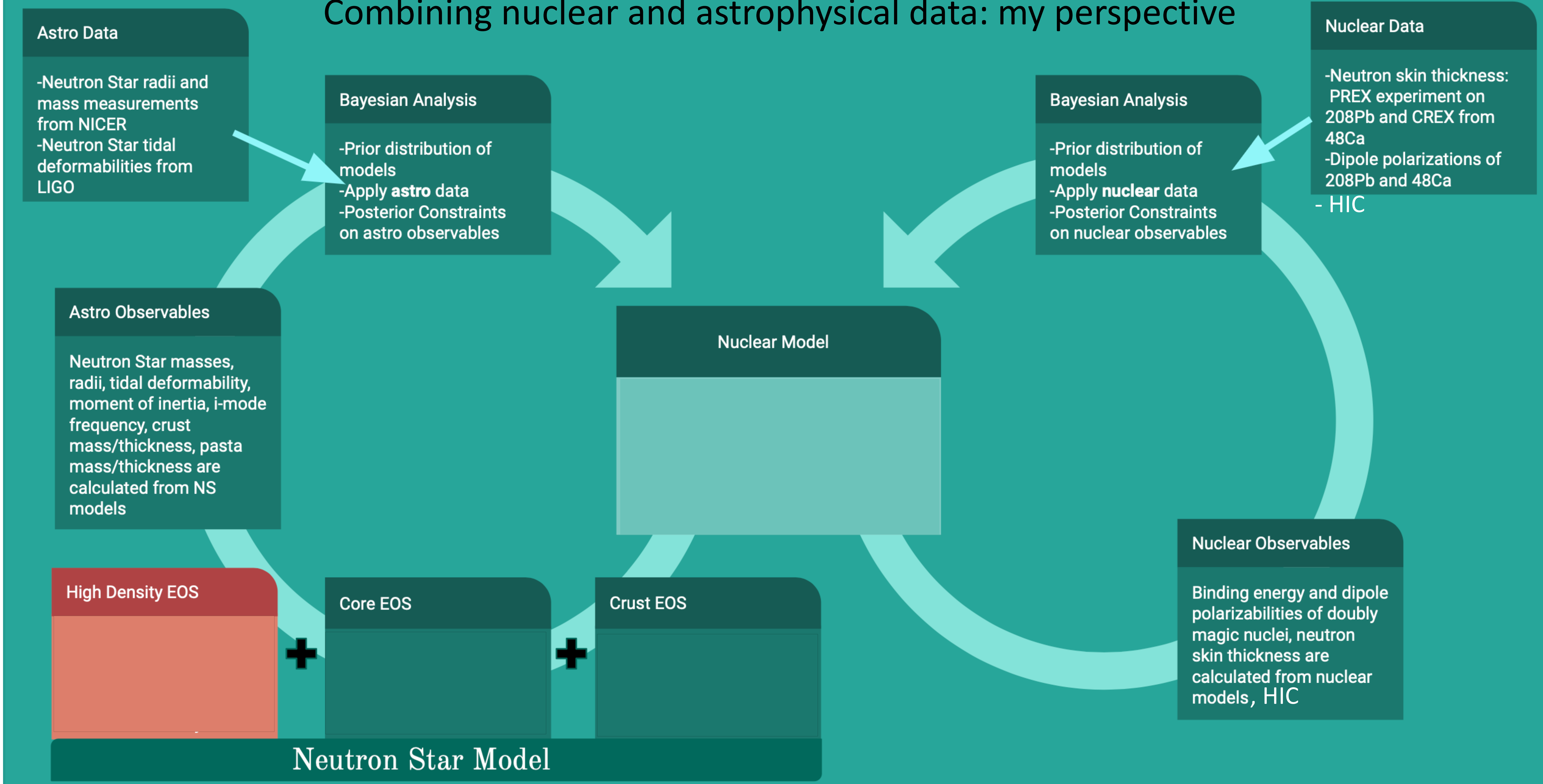




Pang et al, arxiv:2205.08513

Neill+ 2208.00994; Sorenson+ 2301.13253

Combining nuclear and astrophysical data: my perspective



Astro Data

-Neutron Star radii and mass measurements from NICER
-Neutron Star tidal deformabilities from LIGO

Bayesian Analysis

-Prior distribution of models
-Apply **astro** data
-Posterior Constraints on astro observables

Bayesian Analysis

-Prior distribution of models
-Apply **nuclear** data
-Posterior Constraints on nuclear observables

Nuclear Data

-Neutron skin thickness: PREX experiment on 208Pb and CREX from 48Ca
-Dipole polarizations of 208Pb and 48Ca
- HIC

Nuclear Model

Astro Observables

Neutron Star masses, radii, tidal deformability, moment of inertia, i-mode frequency, crust mass/thickness, pasta mass/thickness are calculated from NS models

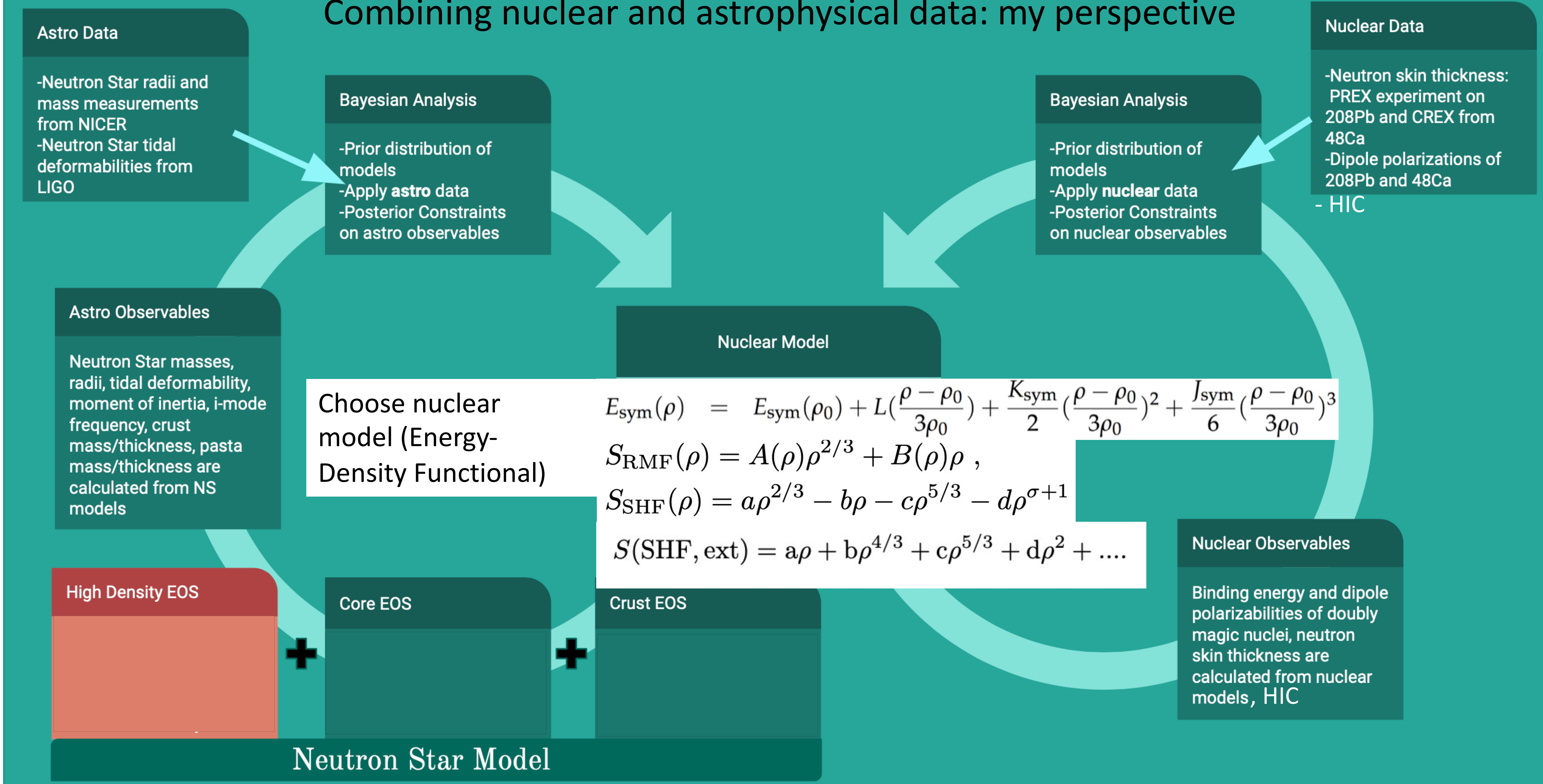
Nuclear Observables

Binding energy and dipole polarizabilities of doubly magic nuclei, neutron skin thickness are calculated from nuclear models, HIC

High Density EOS + **Core EOS** + **Crust EOS**

Neutron Star Model

Combining nuclear and astrophysical data: my perspective



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Bayesian Analysis

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-Posterior Constraints on nuclear observables

Astro Observables

Neutron Star masses, radii, tidal deformability, moment of inertia, i-mode frequency, crust mass/thickness, pasta mass/thickness are calculated from NS models

Nuclear Model

Choose nuclear model (Energy-Density Functional)

$$E_{\rm sym}(\rho) = E_{\rm sym}(\rho_0) + L\left(\frac{\rho-\rho_0}{3\rho_0}\right) + \frac{K_{\rm sym}}{2}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2 + \frac{J_{\rm sym}}{6}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^3$$

$$S_{\rm RMF}(\rho) = A(\rho)\rho^{2/3} + B(\rho)\rho \ ,$$

$$S_{\rm SHF}(\rho) = a\rho^{2/3} - b\rho - c\rho^{5/3} - d\rho^{\sigma+1}$$

$$S({\rm SHF, ext}) = {\rm a}\rho + {\rm b}\rho^{4/3} + {\rm c}\rho^{5/3} + {\rm d}\rho^2 + ...$$

Nuclear Observables

Binding energy and dipole polarizabilities of doubly magic nuclei, neutron skin thickness are calculated from nuclear models, HIC

High Density EOS + **Core EOS** + **Crust EOS**

Neutron Star Model

Different observables give nuclear matter constraints at different densities

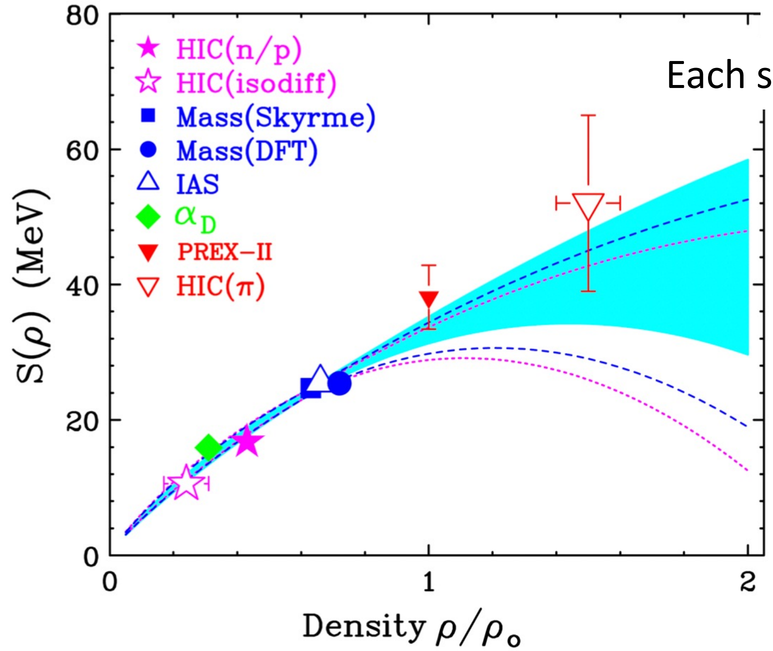
Different nuclear models used to extract symmetry energy, EOS from different observables. Uncontrolled systematic modeling error if we combine them

Exacerbated if take J,L,Ksym constraints, which involve extrapolation from density where the observable sits

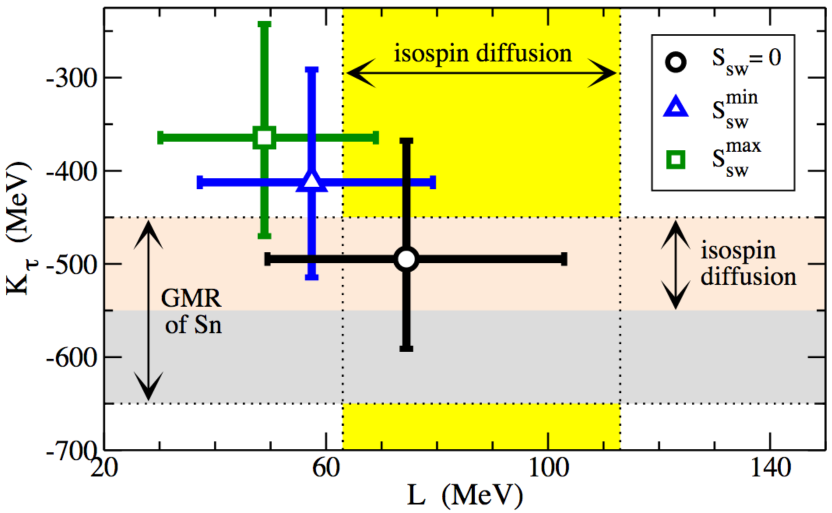
$$S_{\rm RMF}(\rho) = A(\rho)\rho^{2/3} + B(\rho)\rho \ ,$$

$$S_{\rm SHF}(\rho) = a\rho^{2/3} - b\rho - c\rho^{5/3} - d\rho^{\sigma+1}$$

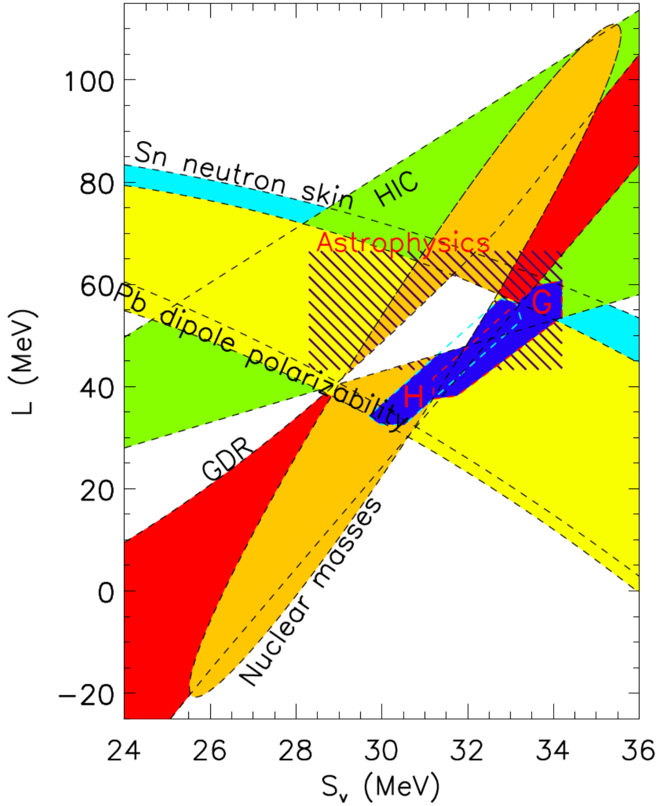
Each study makes a choice of the Energy-Density Functional



Tsang and Lynch, arxiv:2106.10119



Centelles et al, arxiv:0806.2886



Lattimer, Lim ApJ771(2013)
Lattimer, Steiner EPJA50 (2013)

What I want to do:

Start with an ensemble of nuclear models

Model parameter priors uninformed by experiment and observation

Systematically, and as consistently as possible, add nuclear and astro data to constrain parameters

What I’ll show:
- An example of systematic model uncertainty
- Steps towards eliminating it

Our choice of model: Skyrme-Hartree-Fock

Density Functional Theory (e.g. Skyrme)

$$\mathcal{H}_\delta = \frac{1}{4} t_0 \rho^2 [(2 + x_0) - (2x_0 + 1)(y_p^2 + y_n^2)]$$

Local interaction

$$\mathcal{H}_\rho = \frac{1}{4} t_3 \rho^{2+\alpha_3} [(2 + x_3) - (2x_3 + 1)(y_p^2 + y_n^2)] \\ + \frac{1}{4} t_4 \rho^{2+\alpha_4} [(2 + x_4) - (2x_4 + 1)(y_p^2 + y_n^2)]$$

Density dependent

$$\mathcal{H}_{\text{eff}} = \frac{1}{8} \rho [t_1(2 + x_1) + t_2(2 + x_2)] \tau \\ + \frac{1}{8} \rho [t_1(2x_1 + 1) + t_2(2x_2 + 1)](\tau_p y_p + \tau_n y_n)$$

3 body

$$\mathcal{H}_{\text{grad}} = \frac{1}{32} (\nabla \rho)^2 [3t_1(2 + x_1) - t_2(2 + x_2)] \\ - \frac{1}{32} [3t_1(2x_1 + 1) + t_2(2x_2 + 1)][(\nabla \rho_p)^2 + (\nabla \rho_n)^2)$$

Gradient…

Used in a variational principle on total energy leads to coupled Schrödinger-like equations for the wavefunctions.
Solutions converge to ground state (Hohenberg-Kohn theorem)

Map nuclear matter parameters to model parameters and systematically generate models

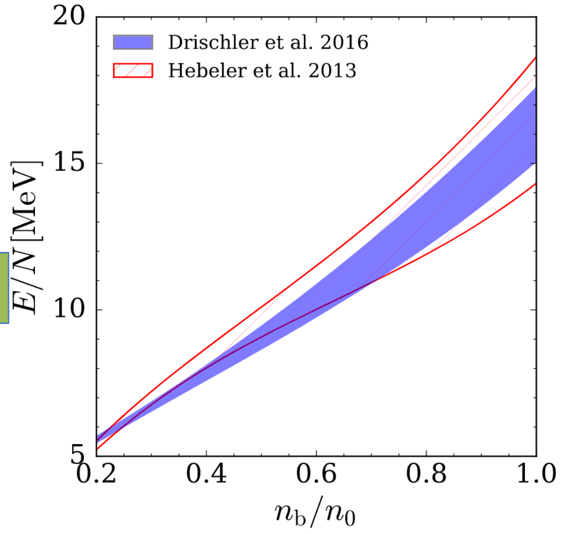
$$\begin{bmatrix} t_0 \\ \vdots \\ t_4 \\ x_0 \\ \vdots \\ x_4 \\ \alpha_3 \\ \alpha_4 \end{bmatrix} \longleftarrow \left[\begin{array}{c} E_0 \\ K_0 \\ n_0 \\ m_{\mathrm{p}}^* \\ m_{\mathrm{n}}^* \\ G_{\mathrm{s}} \\ G_{\mathrm{v}} \\ J \\ L \\ K_{\mathrm{sym}} \end{array}\right] \begin{array}{l} \\ \text{SNM} \\ \\ \text{Dynamics of} \\ \text{n,p} \\ \text{Surface} \\ \text{energy} \\ \text{Symmetry} \\ \text{Energy} \\ \\ \end{array}$$

Map nuclear matter parameters to model parameters and systematically generate models

$$\begin{bmatrix} x_0 \\ x_3 \\ x_4 \end{bmatrix} \longleftarrow \begin{bmatrix} J \\ L \\ K_{\mathrm{sym}} \end{bmatrix}$$

$$\begin{bmatrix} t_0 \\ \vdots \\ t_4 \\ x_1 \\ x_2 \end{bmatrix} \longleftarrow \begin{bmatrix} E_0 \\ K_0 \\ n_0 \\ m^*_{\mathrm{p}} \\ m^*_{\mathrm{n}} \\ G_{\mathrm{s}} \\ G_{\mathrm{v}} \end{bmatrix} \begin{bmatrix} x_0 \\ x_3 \\ x_4 \end{bmatrix}$$

$$\begin{bmatrix} \alpha_3 \\ \alpha_4 \end{bmatrix} \longleftarrow$$



Haensel, Fortin JPhysG 2017
Lim, Holt arXiv:1702.02898

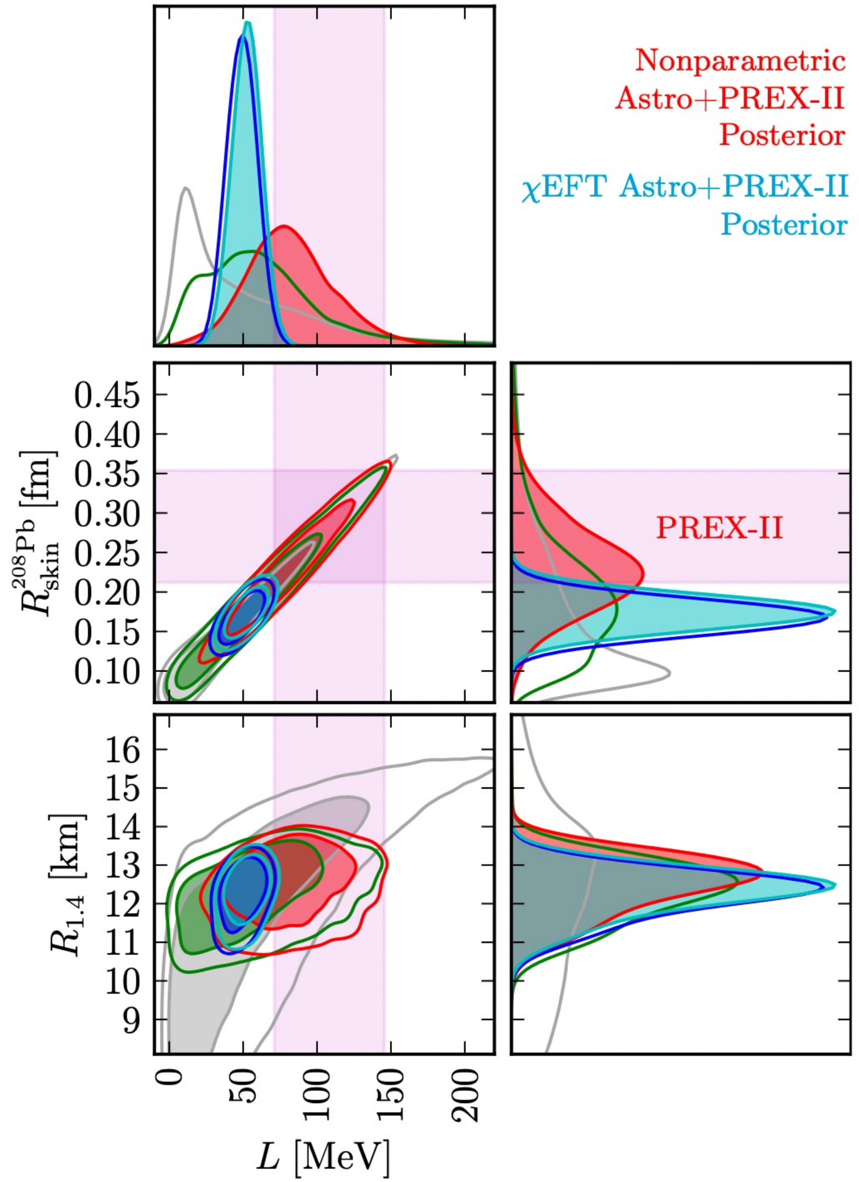
Fixed: potential source of systematic model error

Nuclear masses, giant resonances

ρ_0 (fm^{-3})	0.160 ± 0.005
B (MeV)	16.0 ± 0.5
K (MeV)	230 ± 30

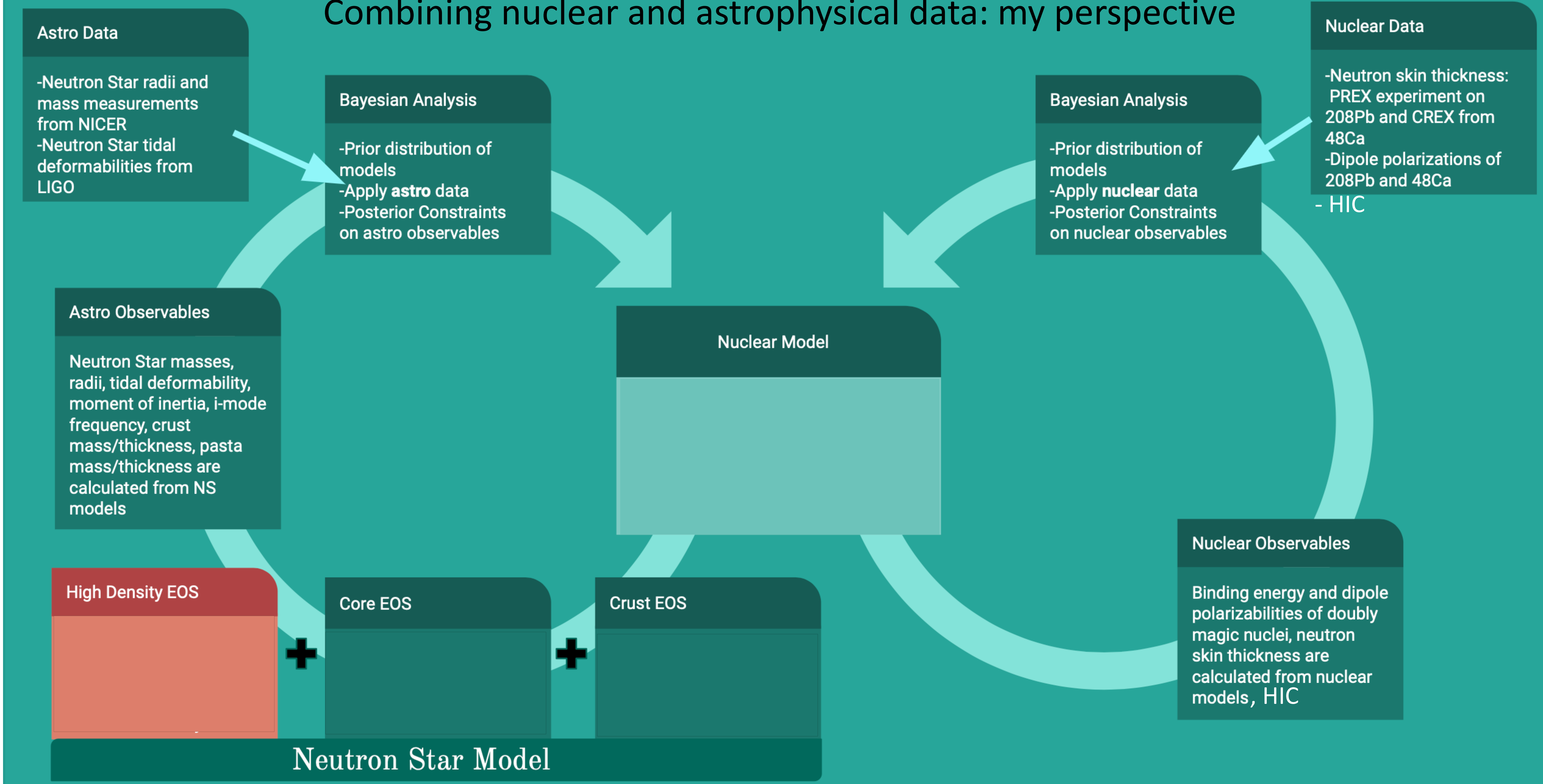
Lim, Holt arXiv:1702.02898

Systematic model uncertainties: an example



Essick+ arXiv 2102.10074

Combining nuclear and astrophysical data: my perspective



Astro Data

-Neutron Star radii and mass measurements from NICER
-Neutron Star tidal deformabilities from LIGO

Bayesian Analysis

-Prior distribution of models
-Apply **astro** data
-Posterior Constraints on astro observables

Astro Observables

Neutron Star masses, radii, tidal deformability, moment of inertia, i-mode frequency, crust mass/thickness, pasta mass/thickness are calculated from NS models

High Density EOS

Core EOS

Crust EOS

Neutron Star Model

Nuclear Model

Nuclear Data

-Neutron skin thickness: PREX experiment on 208Pb and CREX from 48Ca
-Dipole polarizations of 208Pb and 48Ca
- HIC

Bayesian Analysis

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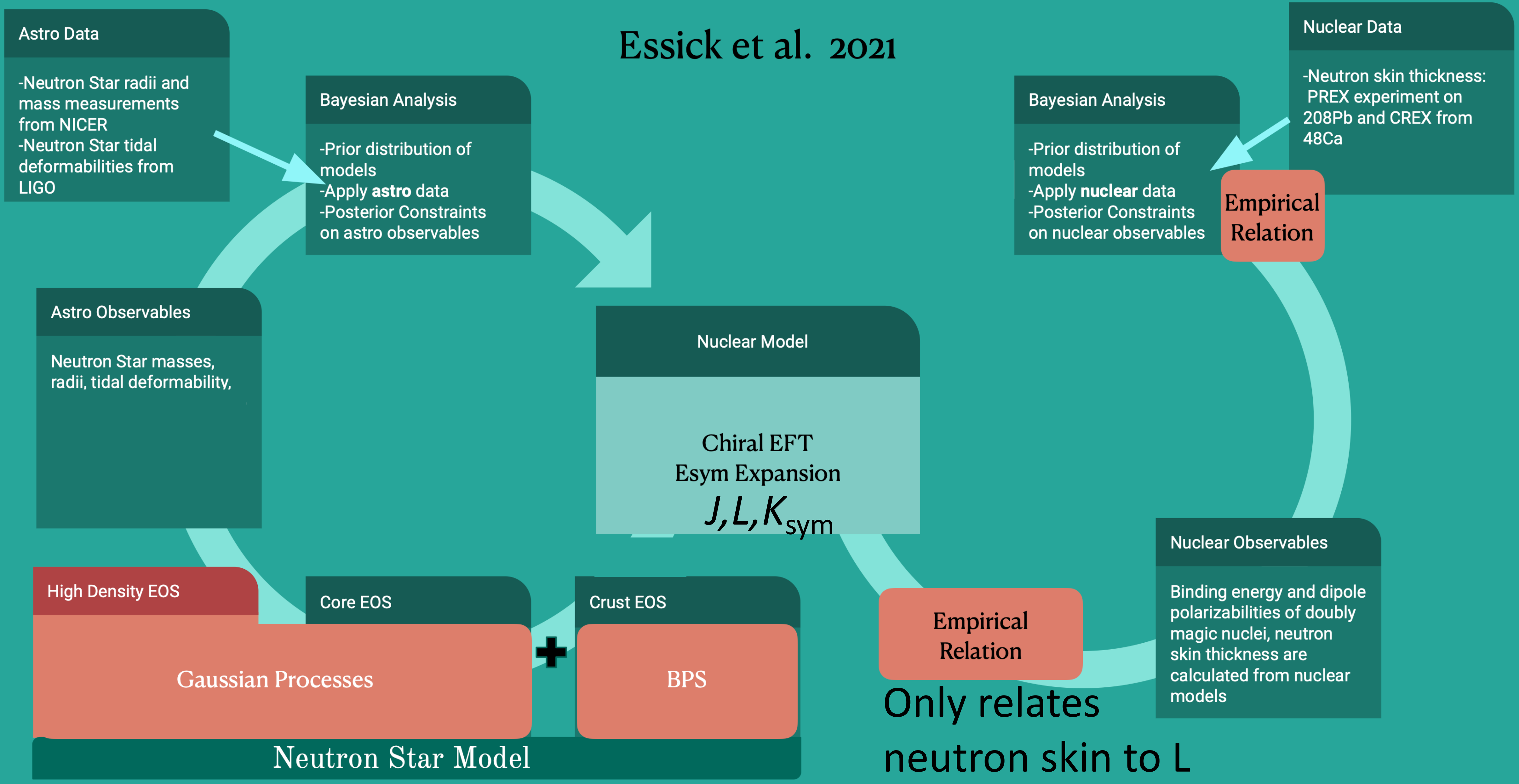
-Posterior Constraints on nuclear observables

Nuclear Observables

Binding energy and dipole polarizabilities of doubly magic nuclei, neutron skin thickness are calculated from nuclear models, HIC

Essick et al. 2021



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Nuclear Model

Chiral EFT
Esym Expansion
J, L, K_{sym}

Astro Observables

Neutron Star masses, radii, tidal deformability,

High Density EOS

Core EOS

Gaussian Processes

+

Crust EOS

BPS

Neutron Star Model

Nuclear Data

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Empirical Relation

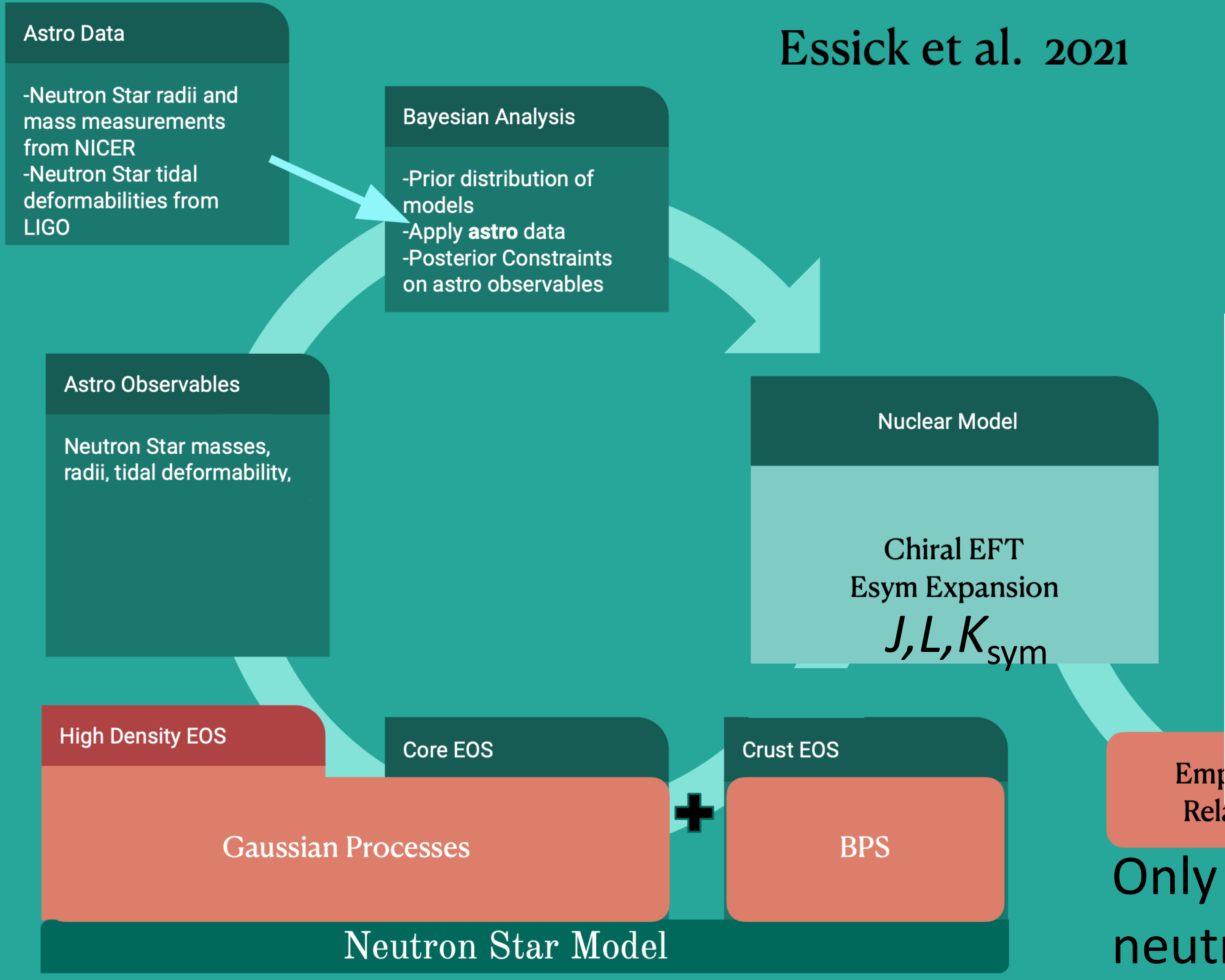
Nuclear Observables

Binding energy and dipole polarizabilities of doubly magic nuclei, neutron skin thickness are calculated from nuclear models

Empirical Relation

Only relates neutron skin to L

Essick et al. 2021



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Esym Expansion
J, L, K_{sym}

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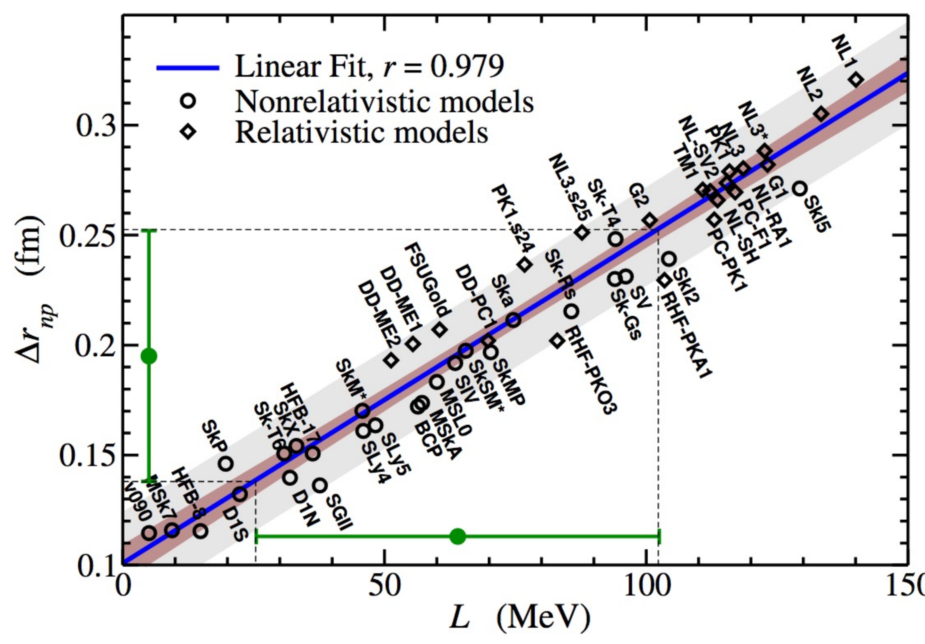
Empirical Relation



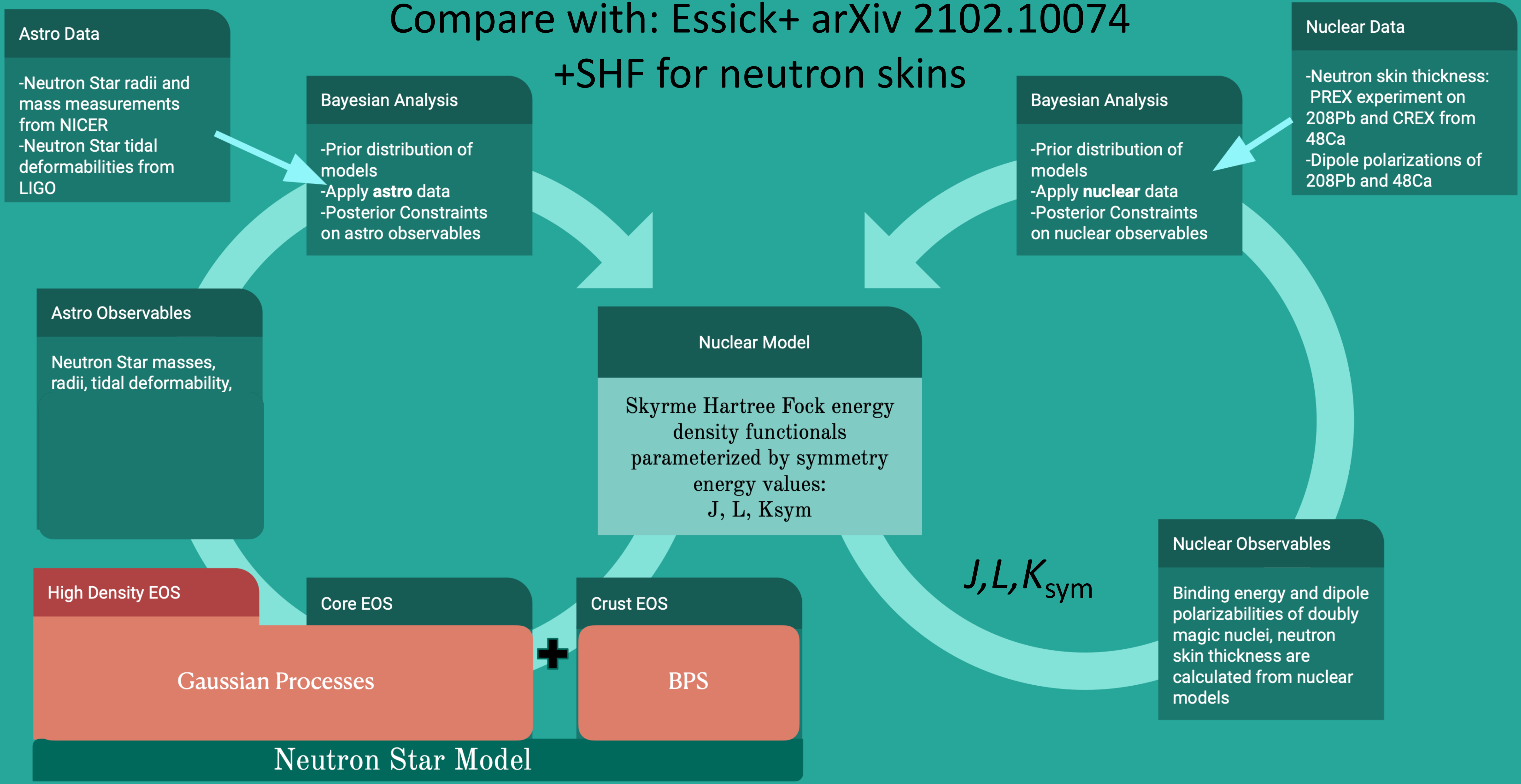
Emp
Relation

Roca-Maza et al, arxiv:1103.1762

models

Only relates neutron skin to L

Compare with: Essick+ arXiv 2102.10074 +SHF for neutron skins



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+

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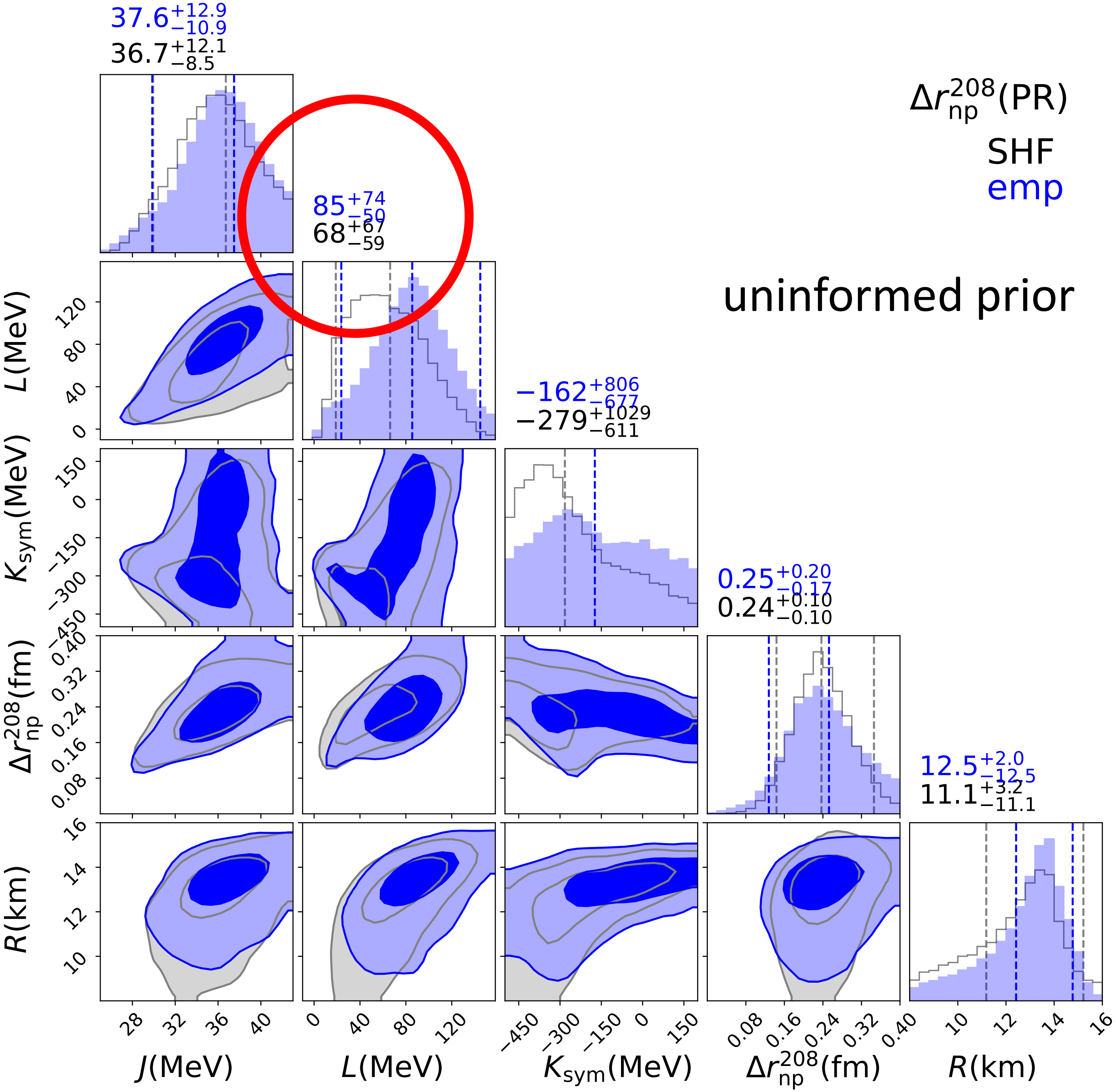
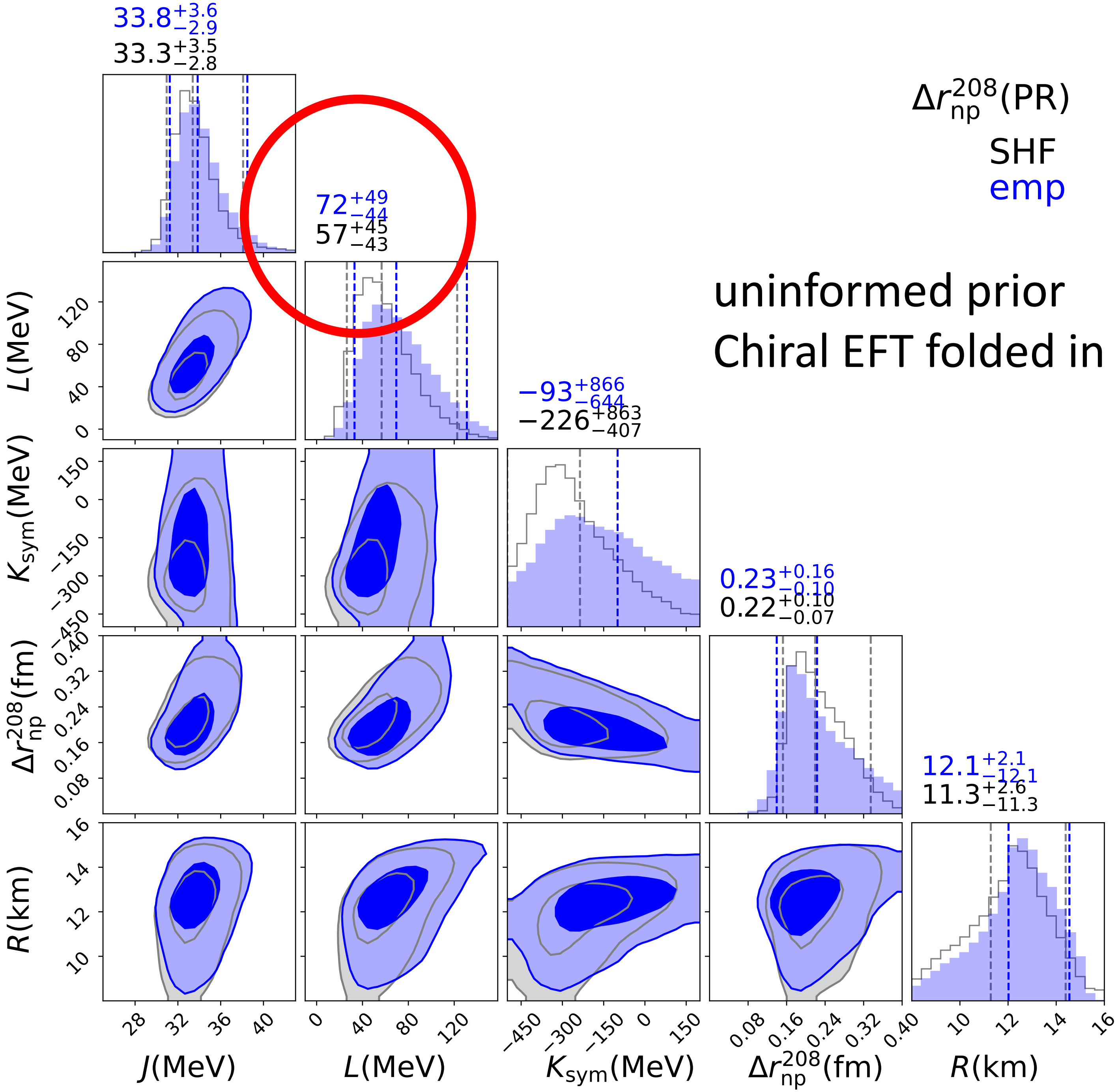
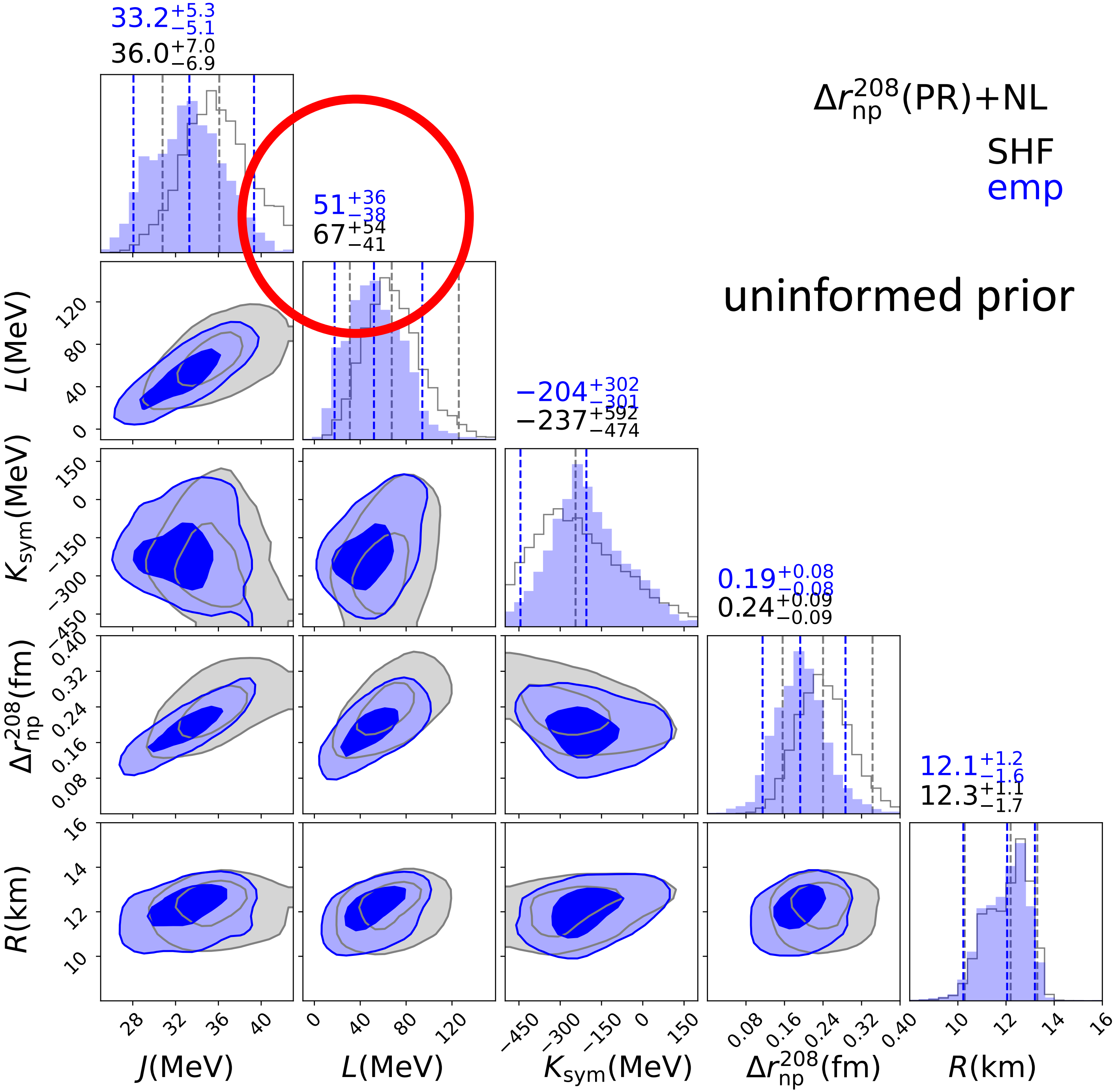




uninformed prior
Chiral EFT folded in

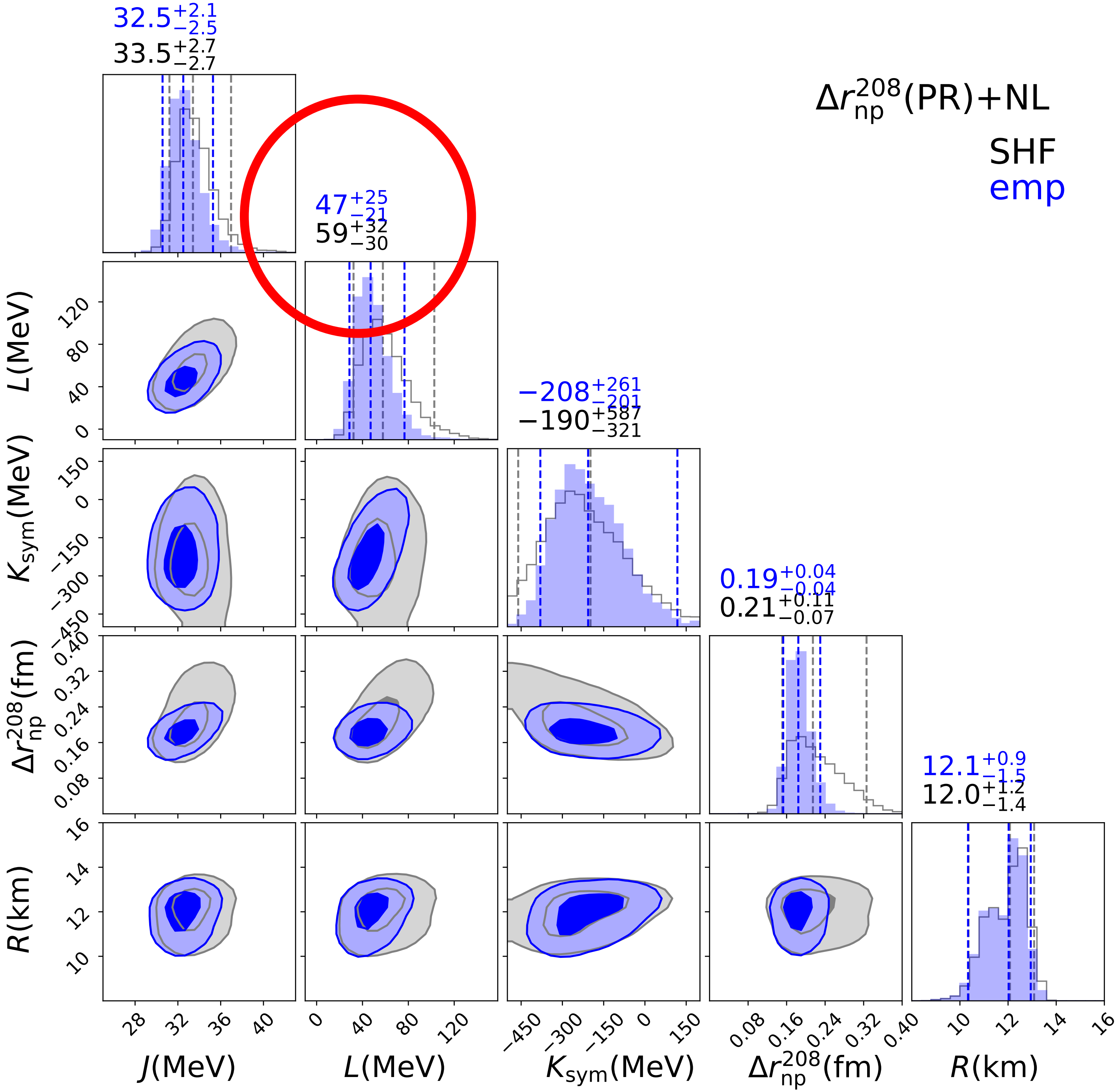


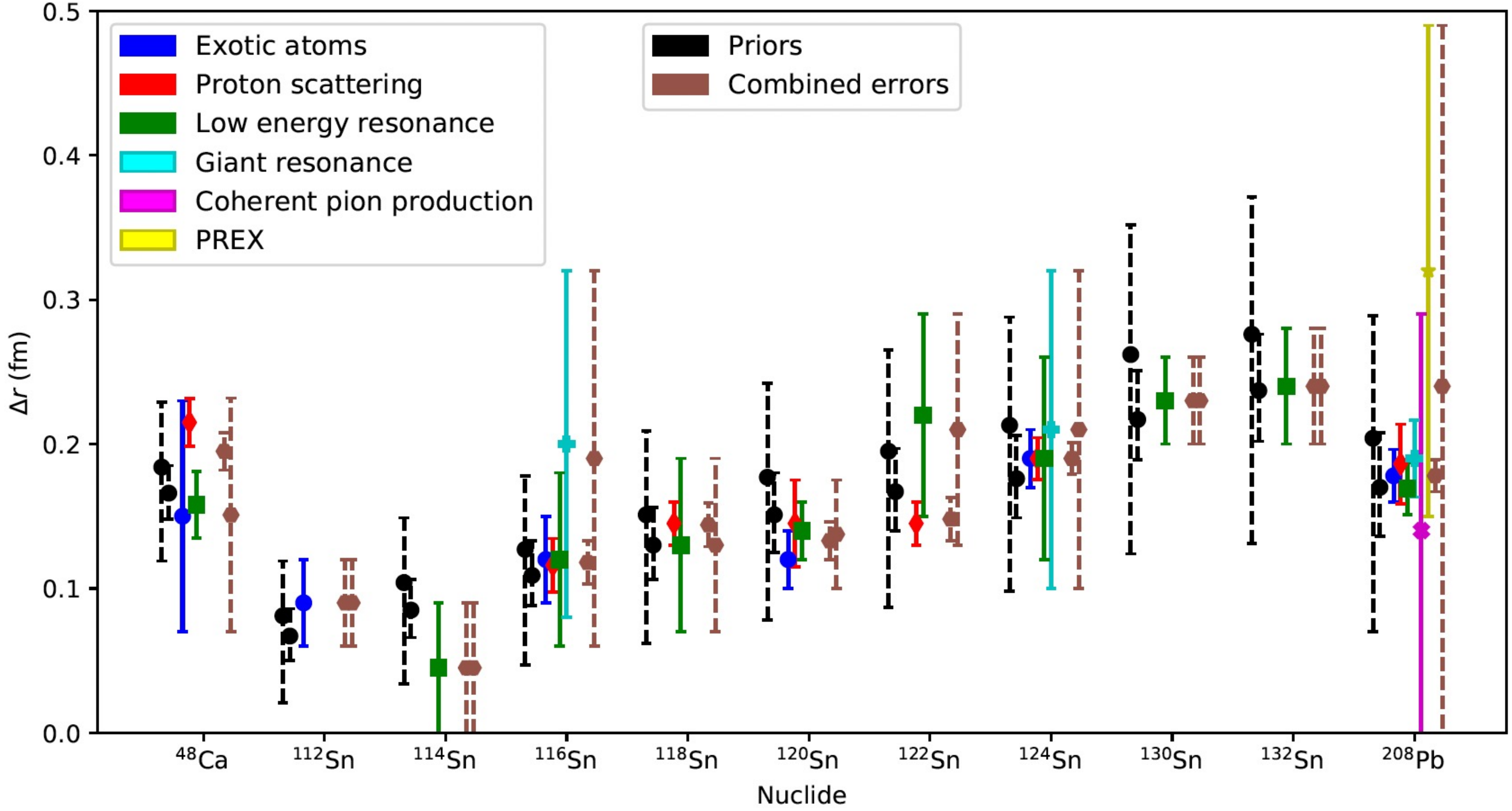
$\Delta r_{\rm np}^{208}$(PR)+NL

SHF

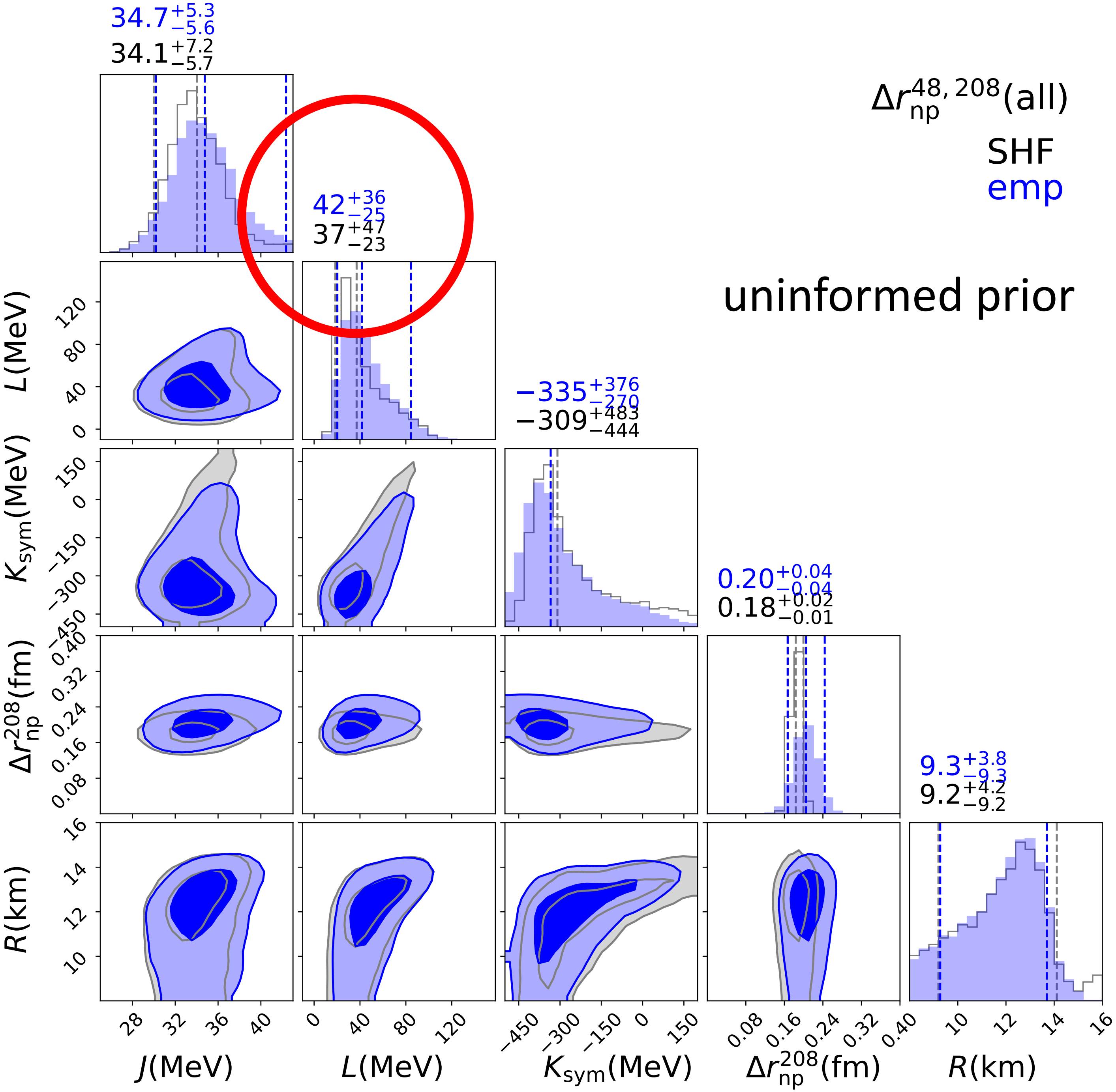
emp

uninformed prior

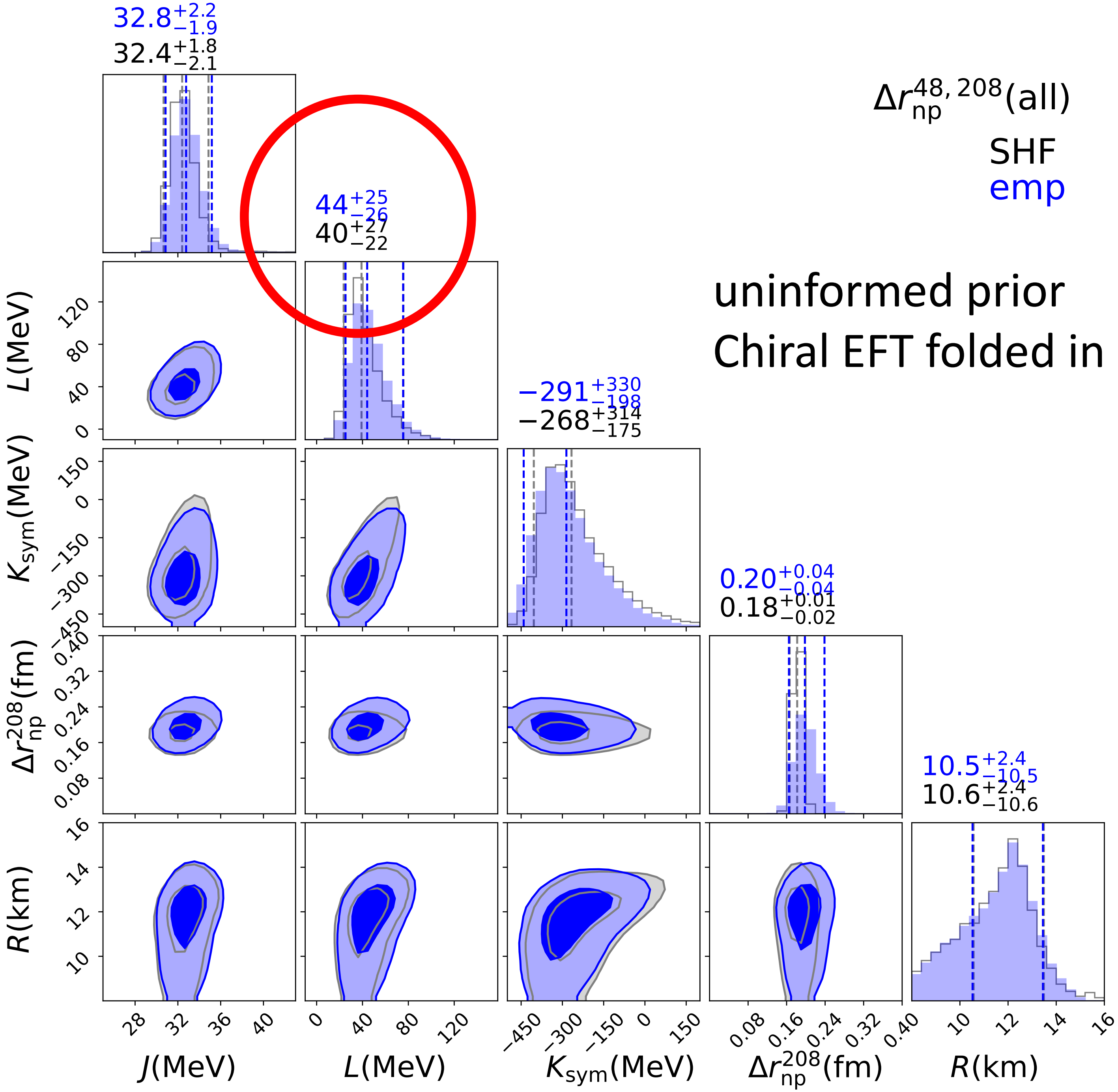

$\Delta r_{\rm np}^{208}$(PR)+NL
SHF
emp
$32.5^{+2.1}_{-2.5}$
$33.5^{+2.7}_{-2.7}$
47^{+25}_{-21}
59^{+32}_{-30}
-208^{+261}_{-201}
-190^{+587}_{-321}
$0.19^{+0.04}_{-0.04}$
$0.21^{+0.11}_{-0.07}$
$12.1^{+0.9}_{-1.5}$
$12.0^{+1.2}_{-1.4}$
L(MeV)
$K_{\rm sym}$(MeV)
$\Delta r_{\rm np}^{208}$(fm)
R(km)
J(MeV)
28
32
36
40
0
40
80
120
−450
−300
−150
0
150
0.08
0.16
0.24
0.32
0.40
10
12
14
16



Newton, Crocombe arxiv:2008.00042



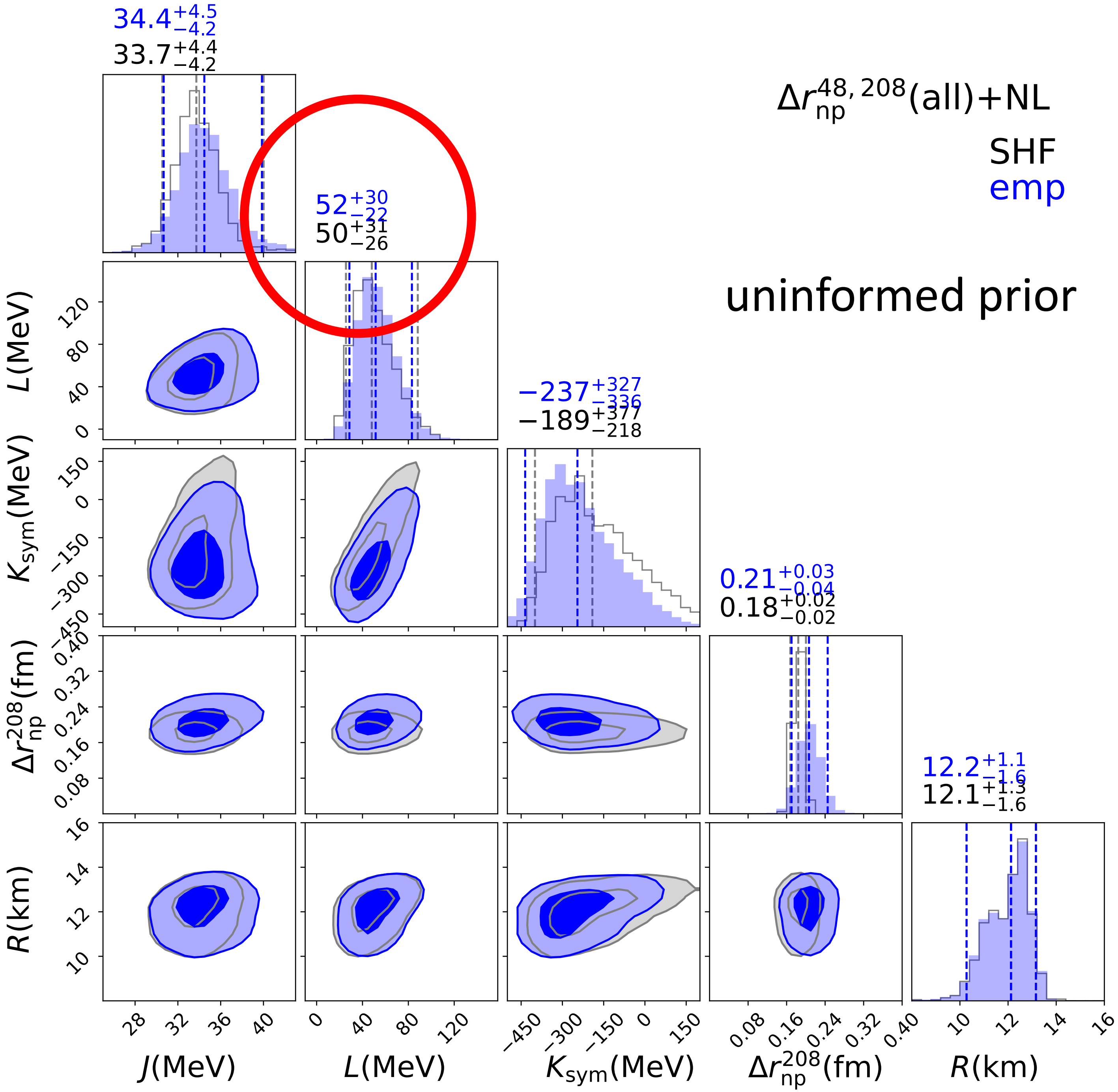
uninformed prior



$\Delta r_{\rm np}^{48,208}$(all)

SHF
emp

uninformed prior
Chiral EFT folded in

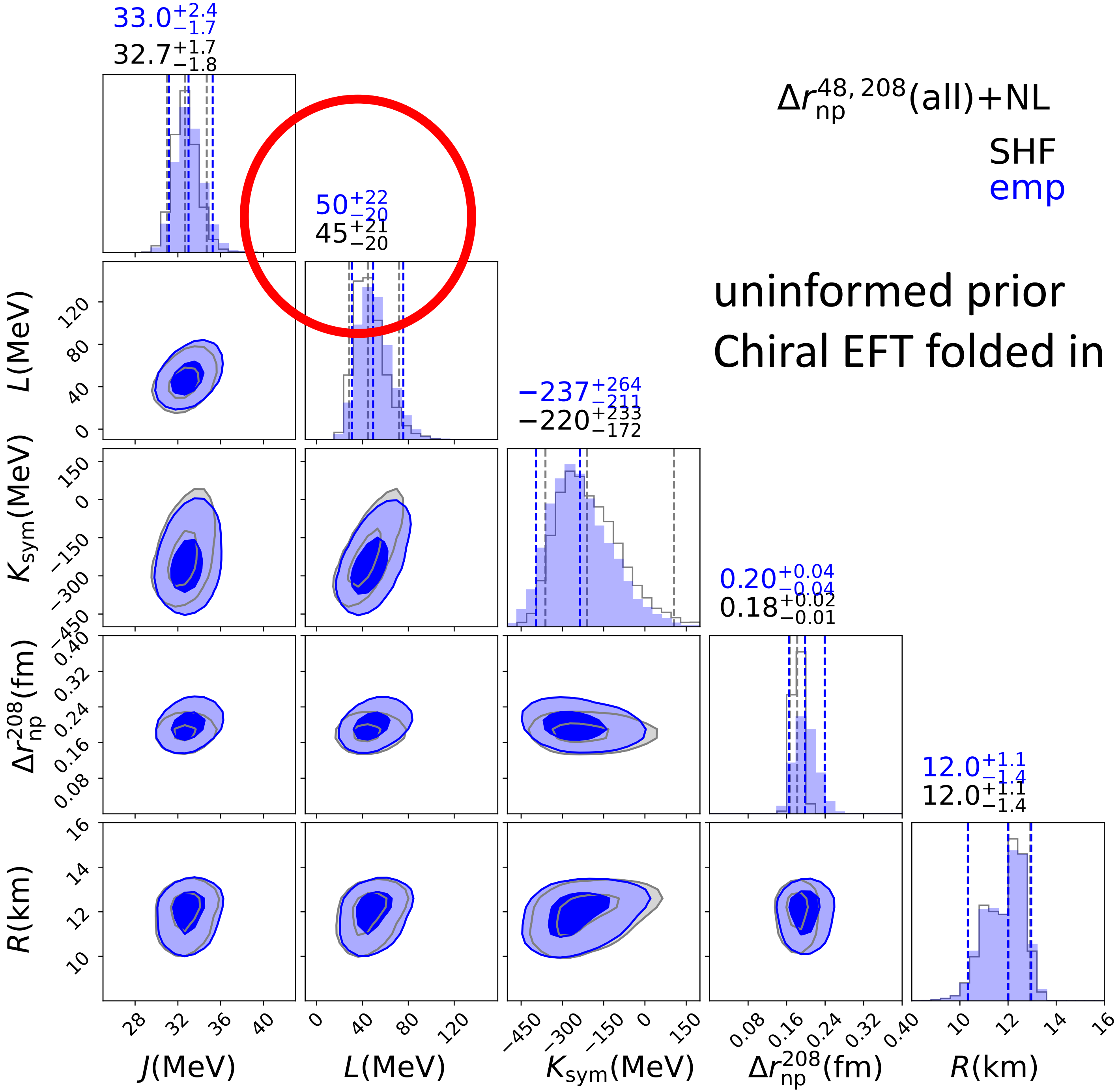


$\Delta r_{\mathrm{np}}^{48,208}$(all)+NL

SHF

emp

uninformed prior

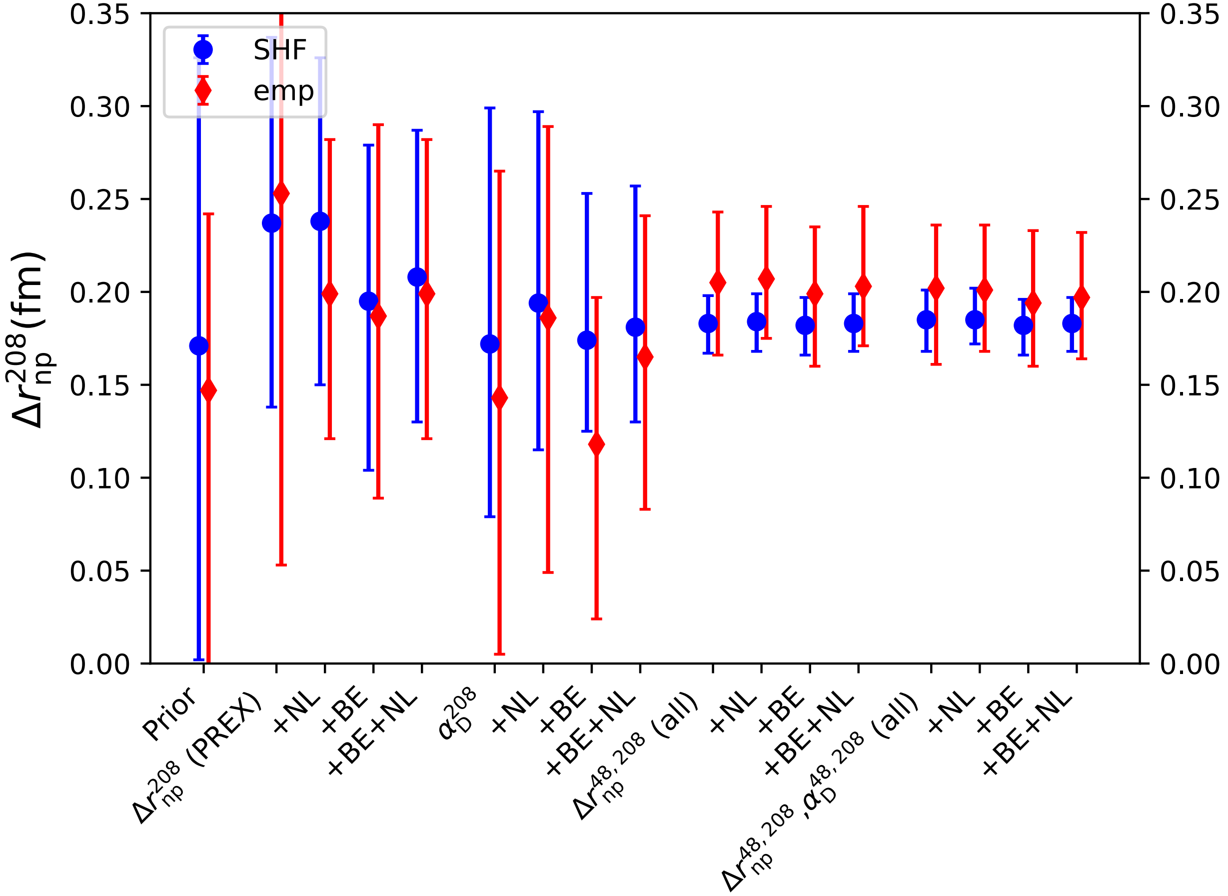


$\Delta r_{\rm np}^{48,208}$(all)+NL

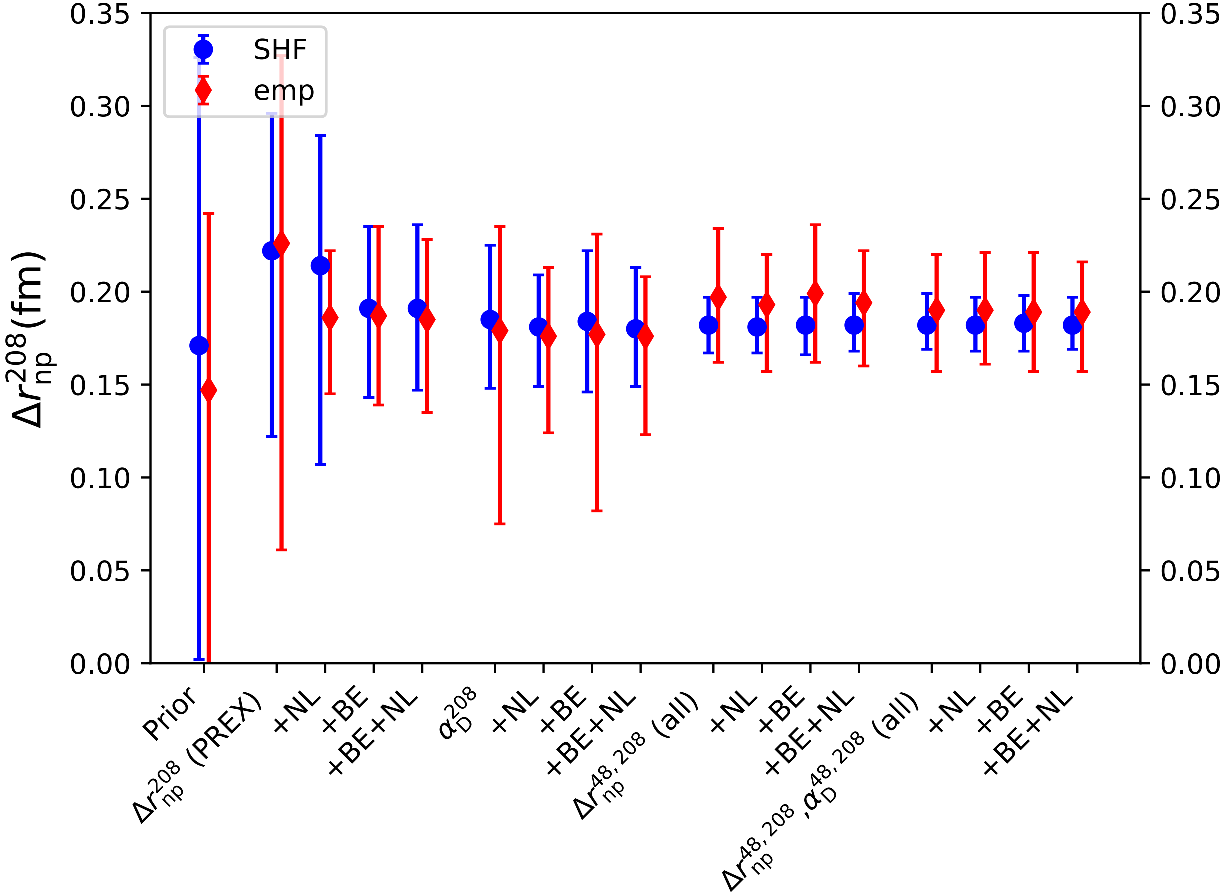
uninformed prior

Chiral EFT folded in

uninformed prior

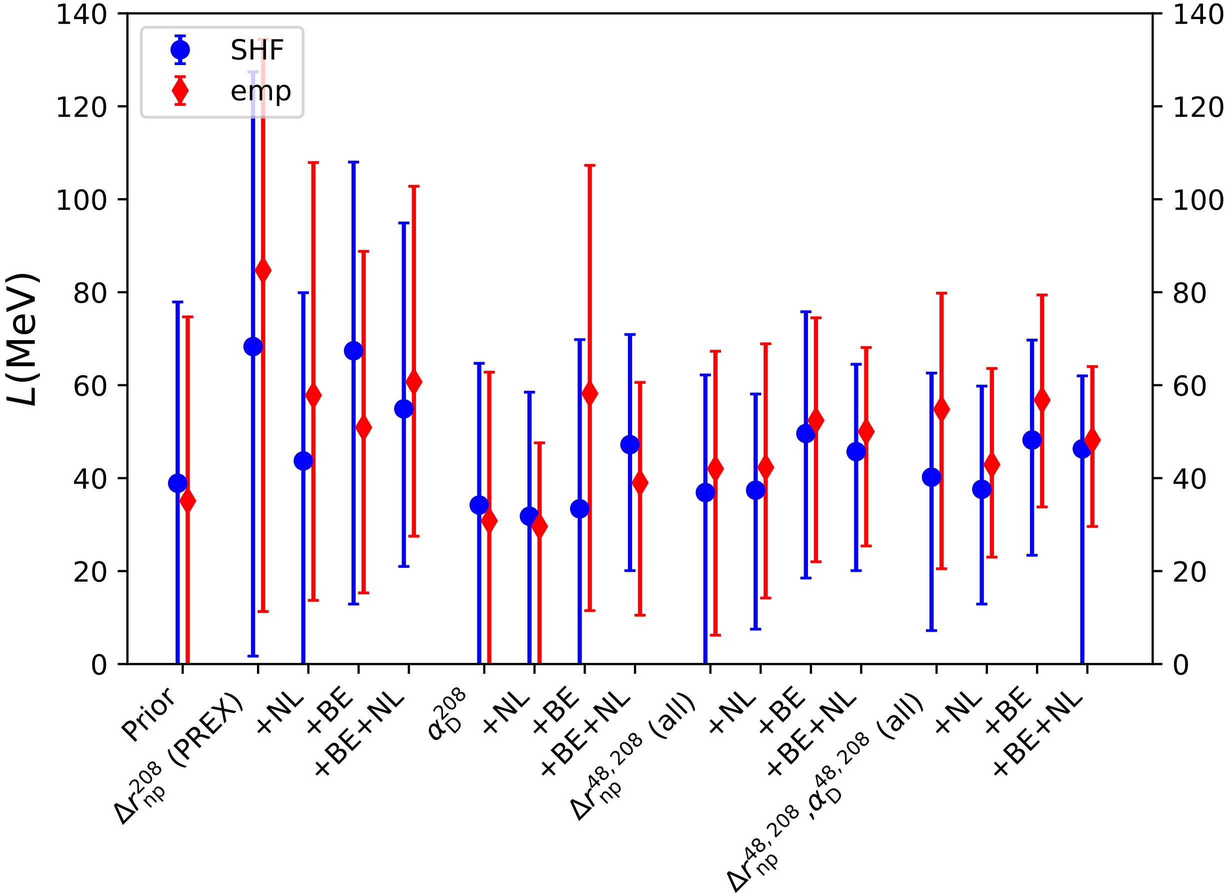


uninformed prior
Chiral EFT folded in

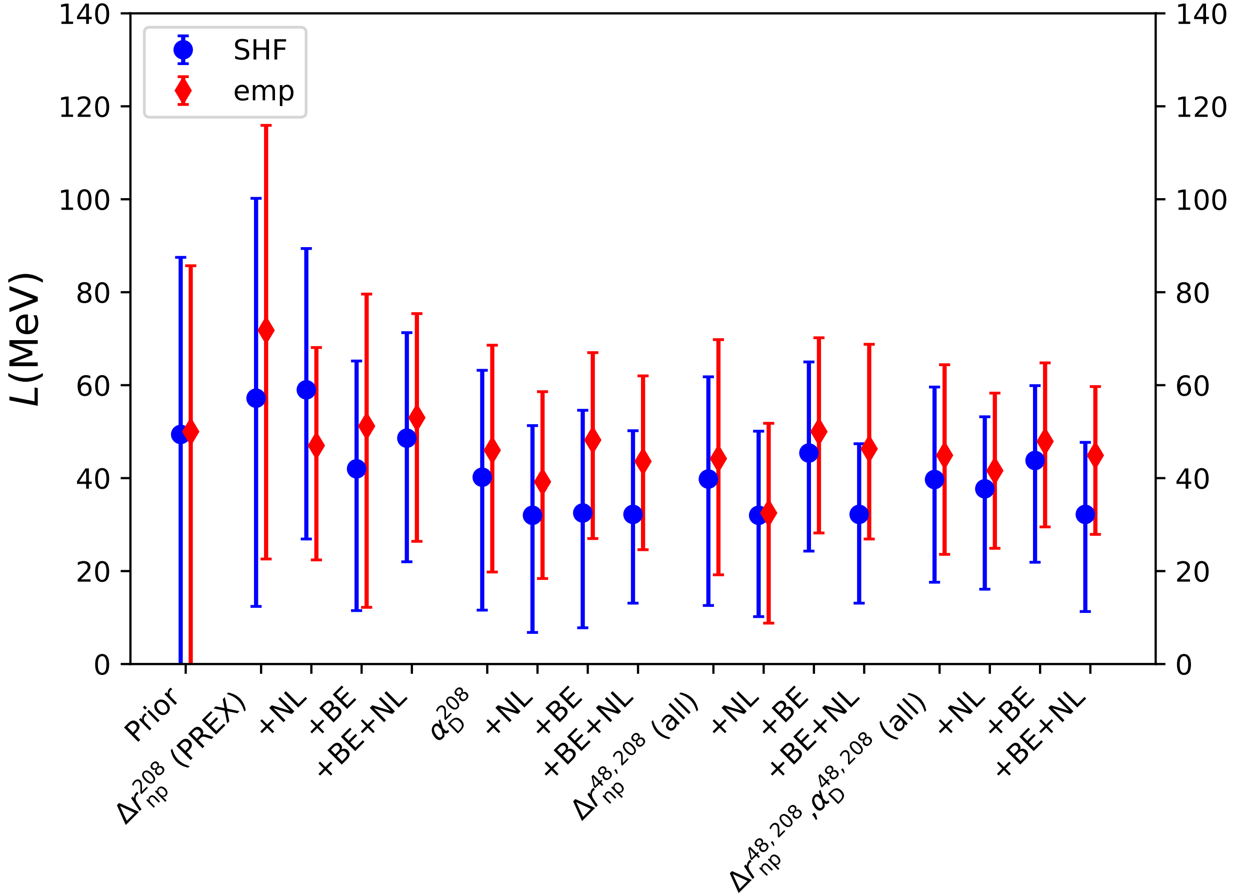


Neutron skin systematically different by 10%

uninformed prior



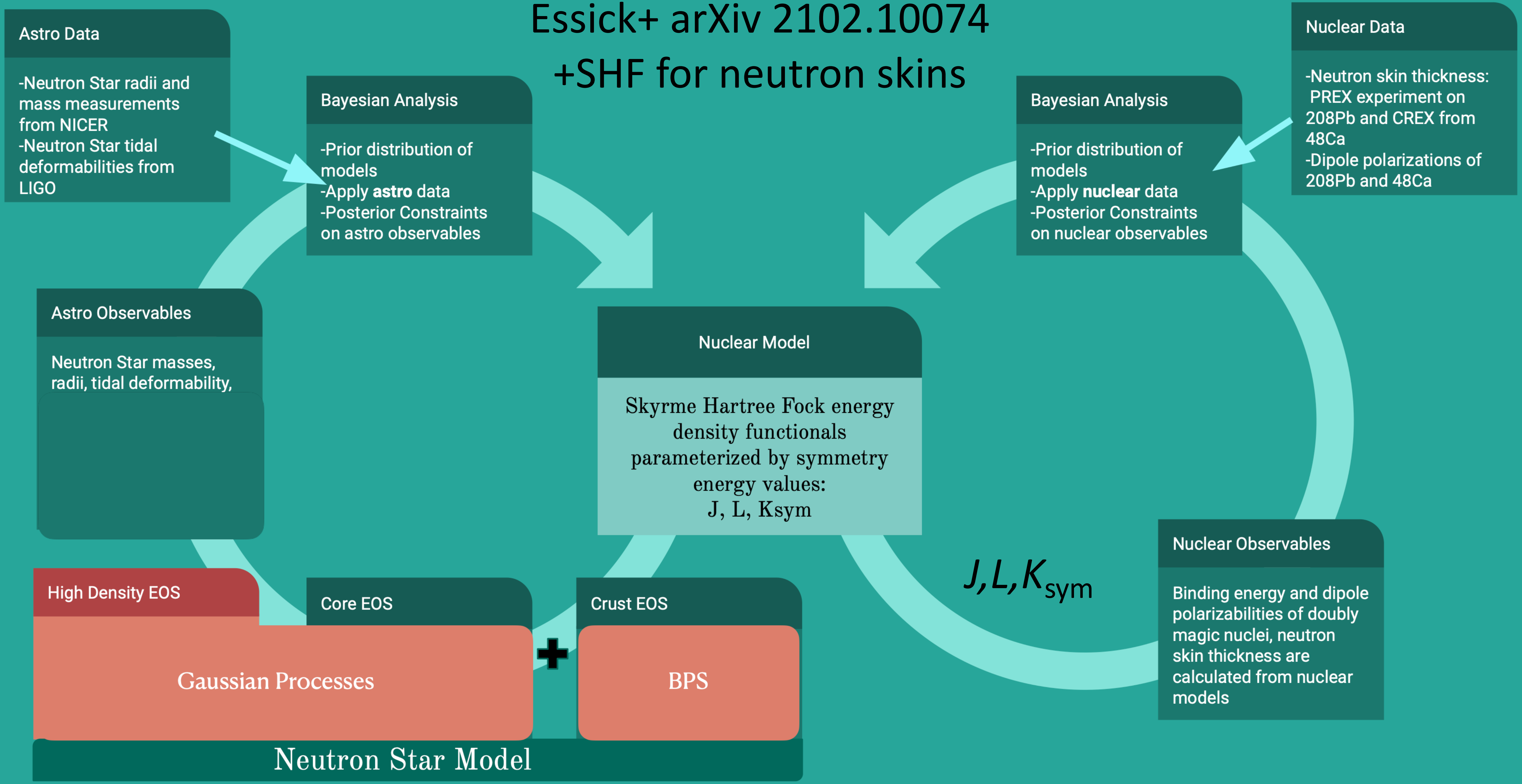
uninformed prior
Chiral EFT folded in



L systematically different by 10%

Systematic model uncertainties: towards mitigation

Essick+ arXiv 2102.10074
+SHF for neutron skins



Astro Data

-Neutron Star radii and mass measurements from NICER
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Bayesian Analysis

-Prior distribution of models
-Apply **astro** data
-Posterior Constraints on astro observables

Astro Observables

Neutron Star masses, radii, tidal deformability,

High Density EOS

Core EOS

Gaussian Processes

Crust EOS

BPS

Neutron Star Model

Nuclear Model

Skyrme Hartree Fock energy density functionals parameterized by symmetry energy values:
J, L, Ksym

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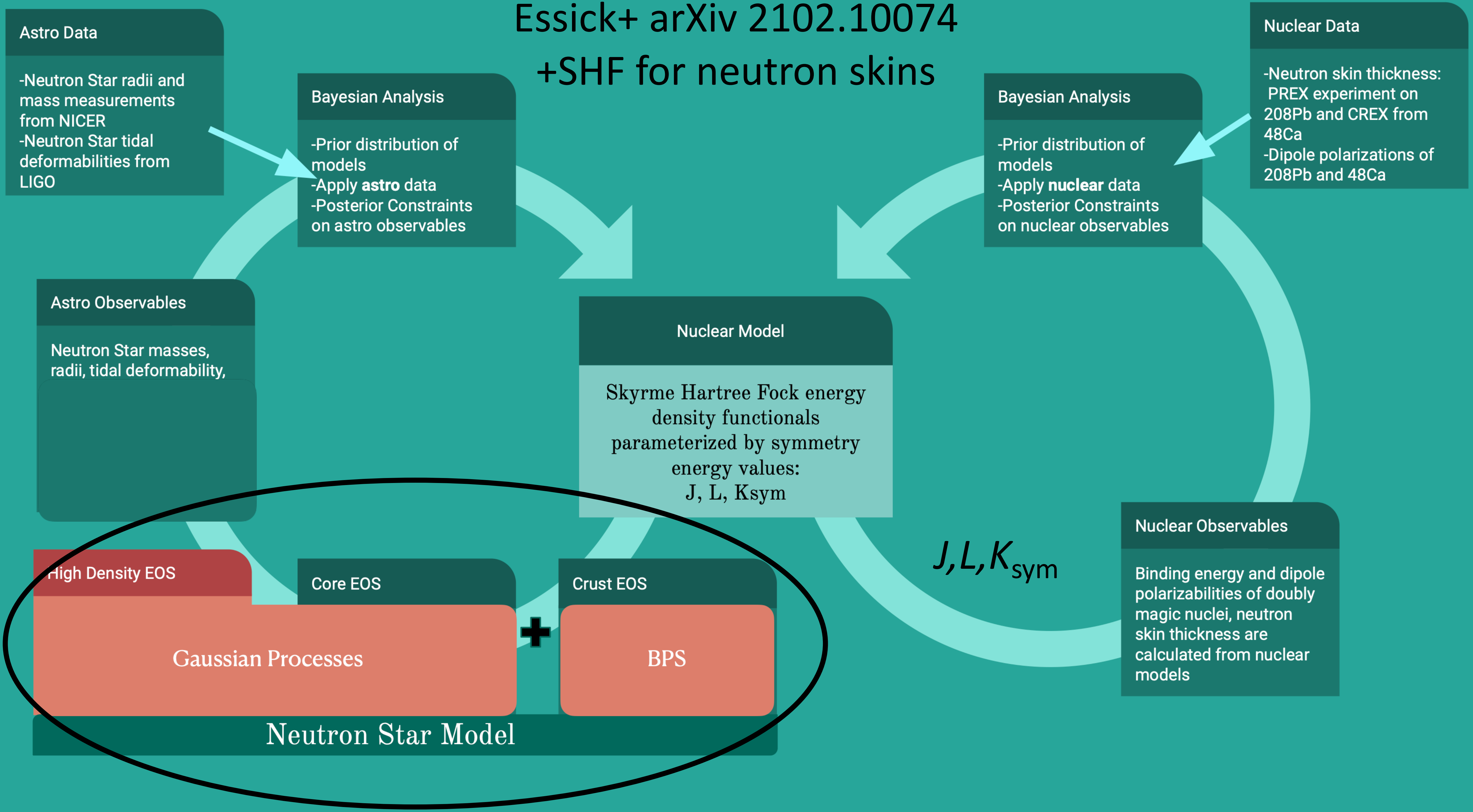
Binding energy and dipole polarizabilities of doubly magic nuclei, neutron skin thickness are calculated from nuclear models

Essick+ arXiv 2102.10074
+SHF for neutron skins



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+

Crust EOS

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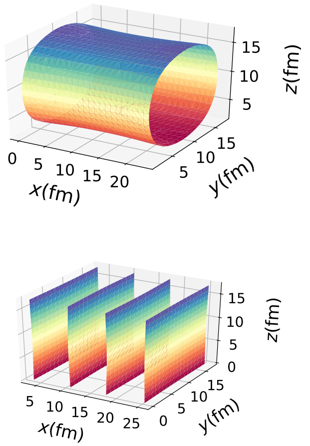
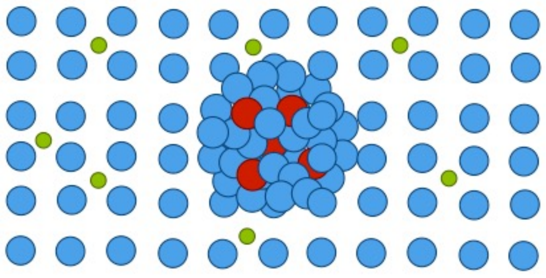
Nuclear Observables

Binding energy and dipole polarizabilities of doubly magic nuclei, neutron skin thickness are calculated from nuclear models

Modeling the crust



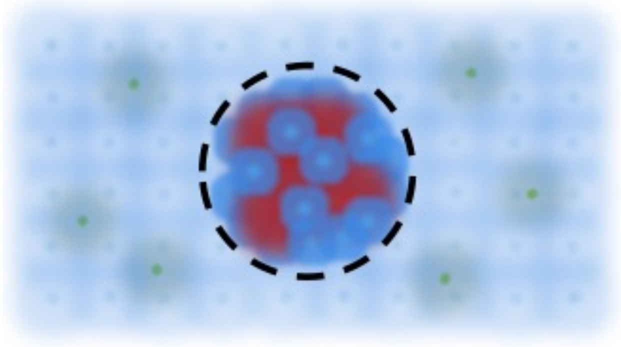
3D Skyrme HF:
n,p degrees of freedom



Newton+ arxiv:2104.11835

Pictures: Lauren Balliet

CLDM:Bulk fluid and surface degrees of freedom



Newton et al arxiv: 1110.4043
Balliet+; arxiv:2009.07696

$$\mathcal{H}_\delta + \mathcal{H}_\rho + \mathcal{H}_{\mathrm{eff}} + \mathcal{H}_{\mathrm{grad}} + \mathcal{H}_{\mathrm{Coul}}$$

Nuclear EDF: Bulk+Gradient
Specific model: Skyrme

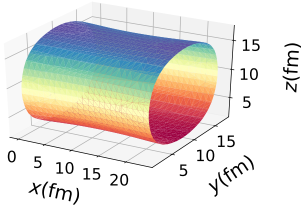
$$\mathcal{H}_\rho = \frac{1}{4}t_3\rho^{2+\alpha_3}[(2+x_3)-(2x_3+1)(y_p^2+y_n^2)] + \frac{1}{4}t_4\rho^{2+\alpha_4}[(2+x_4)-(2x_4+1)(y_p^2+y_n^2)]$$

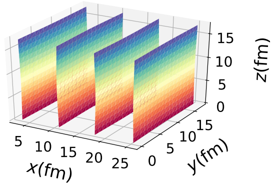
$$\mathcal{H}_\delta + \mathcal{H}_\rho + \mathcal{H}_{\mathrm{eff}} \quad \sigma(y_{\mathrm{p}})$$

Nuclear EDF: Bulk +
separate surface energy function
specific model: LLPR 1985

$$\sigma_{\mathrm{s}}(y_{\mathrm{p}}) = \sigma_0 \frac{2^{p+1}+b}{\frac{1}{y_{\mathrm{p}}^p} + b + \frac{1}{(1-y_{\mathrm{p}})^p}}$$

Modeling the crust





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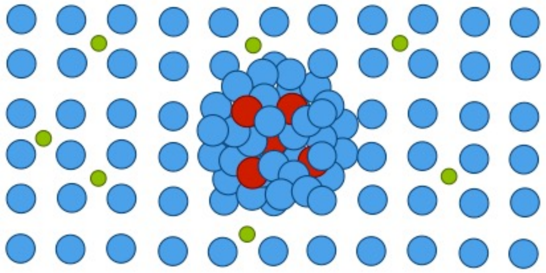
n,p degrees of freedom



Newton+ arxiv:2104.11835

Pictures: Lauren Balliet

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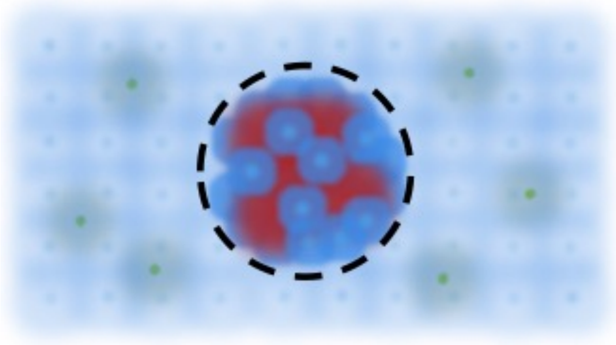

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$$+ \frac{1}{4} t_4 \rho^{2+\alpha_4}[(2 + x_4) - (2x_4 + 1)(y_p^2 + y_n^2)]$$

$$\mathcal{H}_\delta + \mathcal{H}_\rho + \mathcal{H}_{\text{eff}} \qquad \sigma(y_{\text{p}})$$

Nuclear EDF: Bulk +
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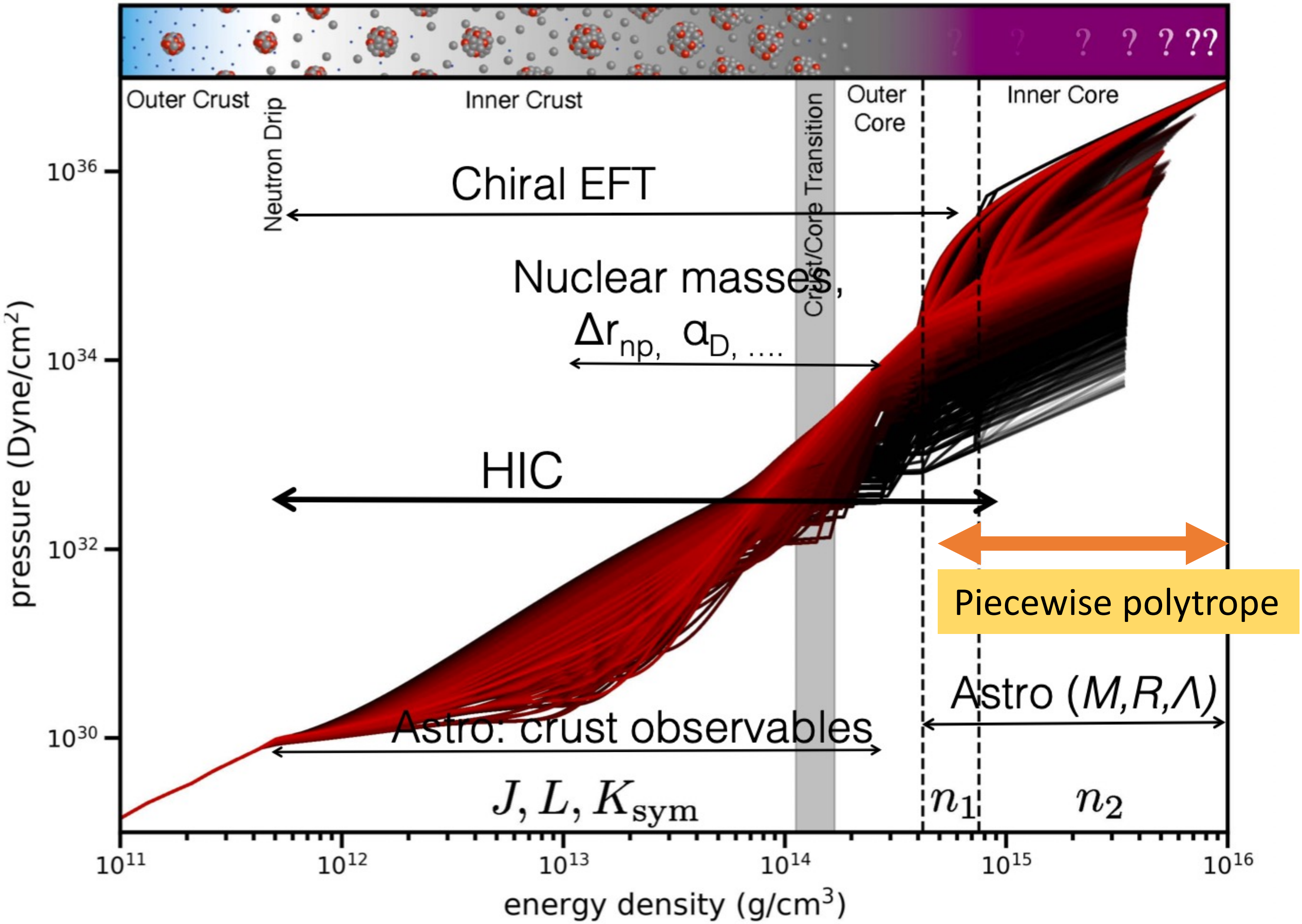
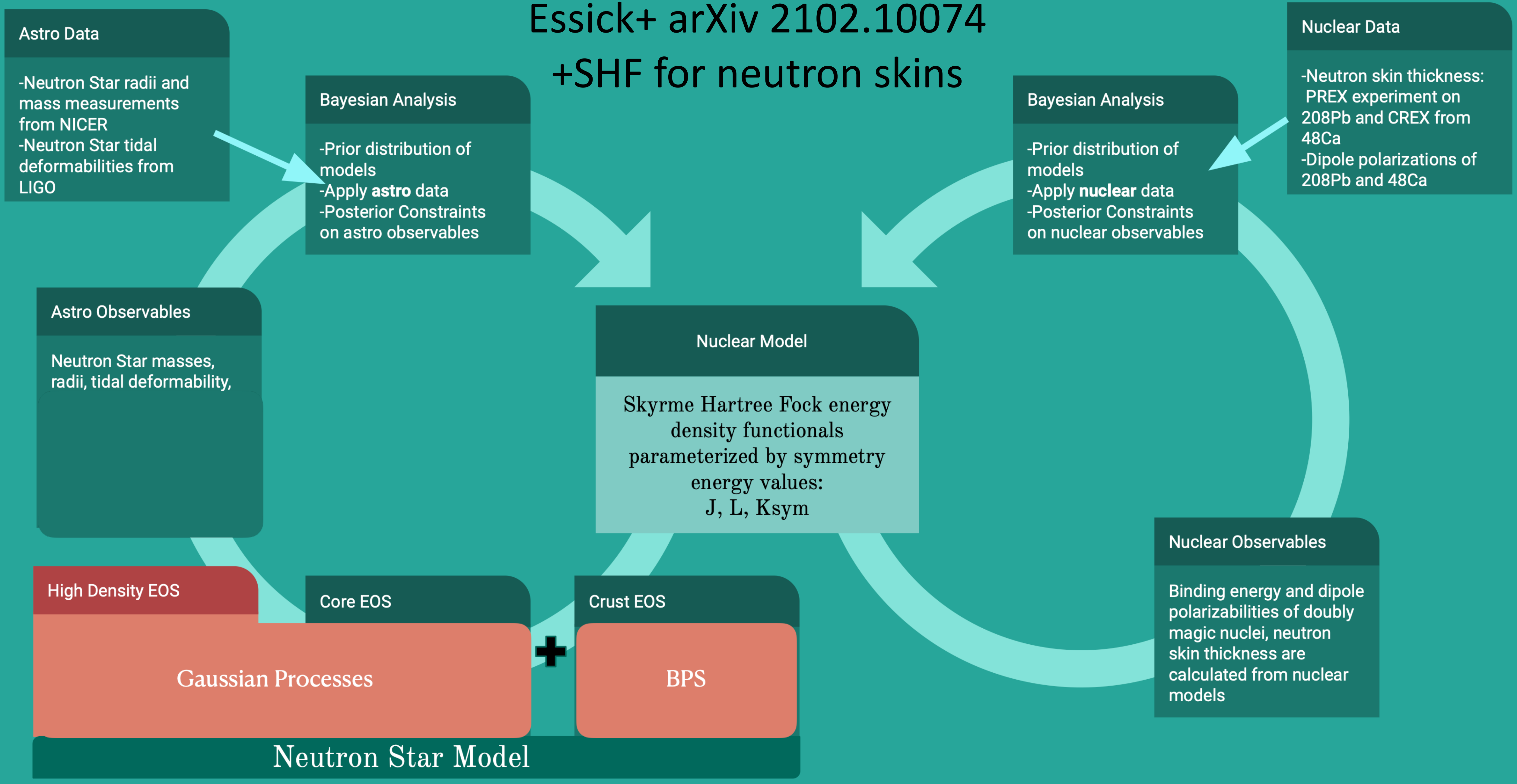
specific model: LLPR 1985

$$\sigma_{\text{s}}(y_{\text{p}}) = \sigma_0 \frac{2^{p+1} + b}{\frac{1}{y_{\text{p}}^p} + b + \frac{1}{(1-y_{\text{p}})^p}}$$



Neill+ 2208.00994; Sorenson+ 2301.13253

Essick+ arXiv 2102.10074
+SHF for neutron skins



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High Density EOS

Core EOS

Gaussian Processes

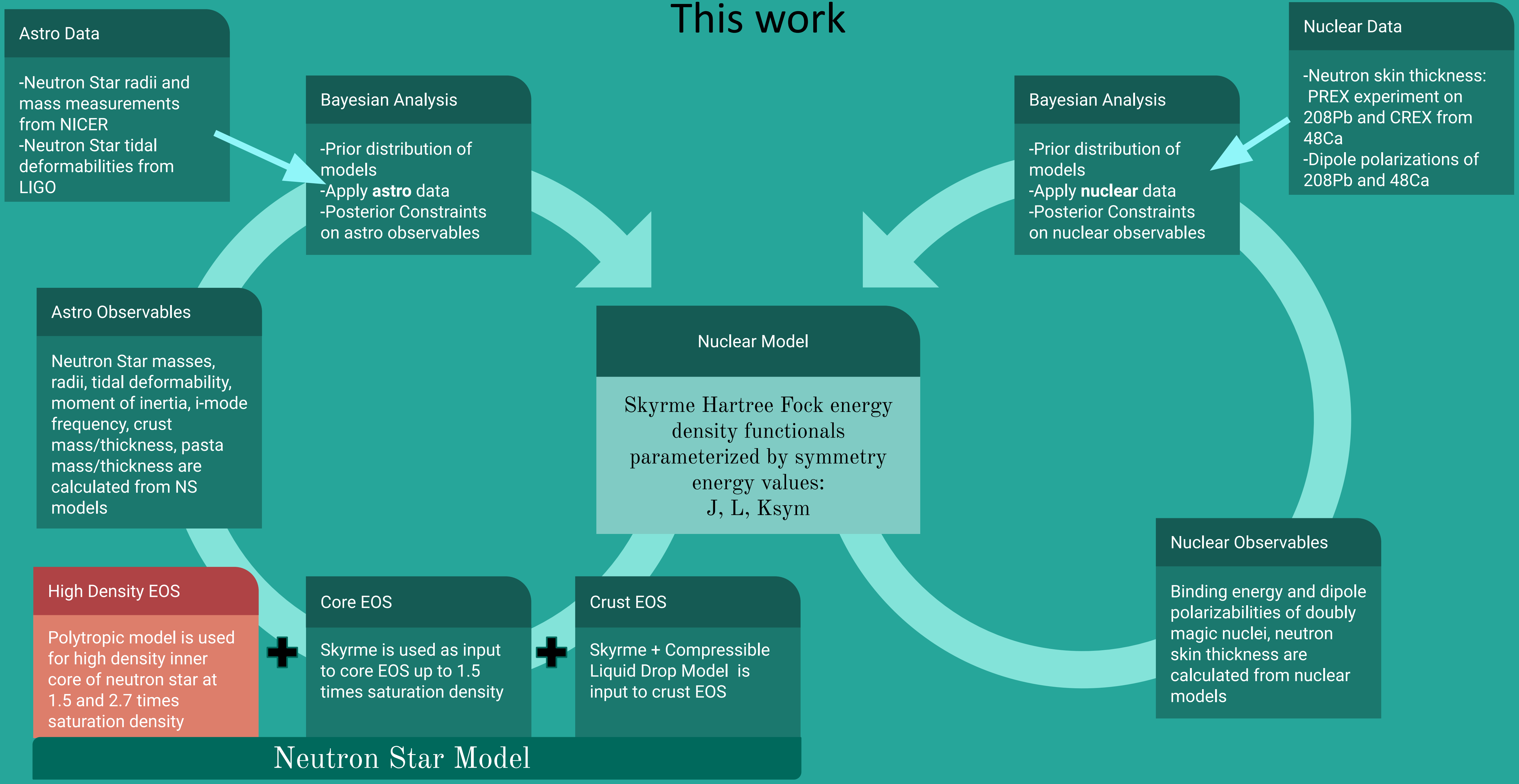
➕

Crust EOS

BPS

Neutron Star Model

This work



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Neutron Star masses, radii, tidal deformability, moment of inertia, i-mode frequency, crust mass/thickness, pasta mass/thickness are calculated from NS models

High Density EOS

Polytropic model is used for high density inner core of neutron star at 1.5 and 2.7 times saturation density

+

Core EOS

Skyrme is used as input to core EOS up to 1.5 times saturation density

+

Crust EOS

Skyrme + Compressible Liquid Drop Model is input to crust EOS

Neutron Star Model

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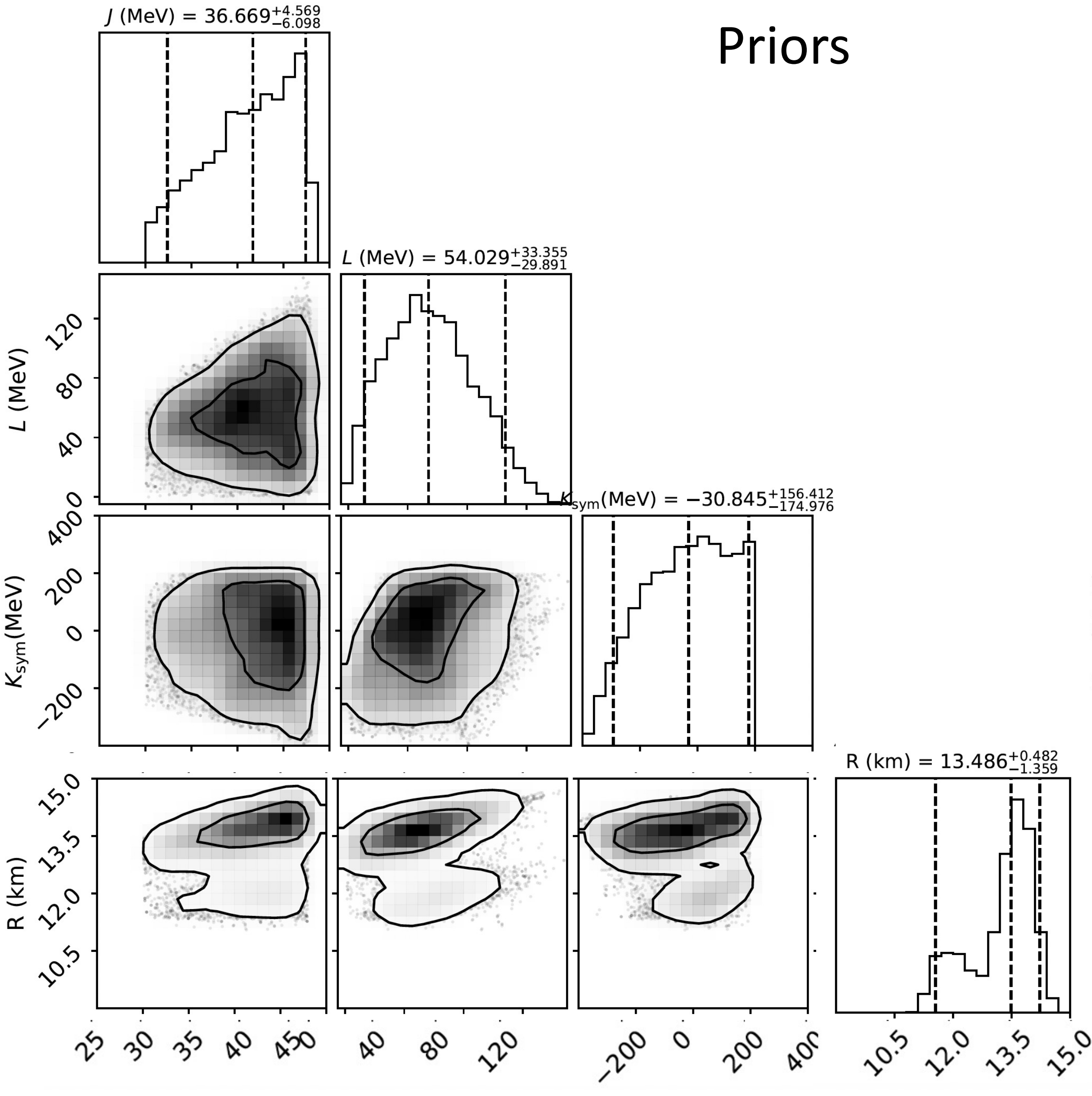
Binding energy and dipole polarizabilities of doubly magic nuclei, neutron skin thickness are calculated from nuclear models

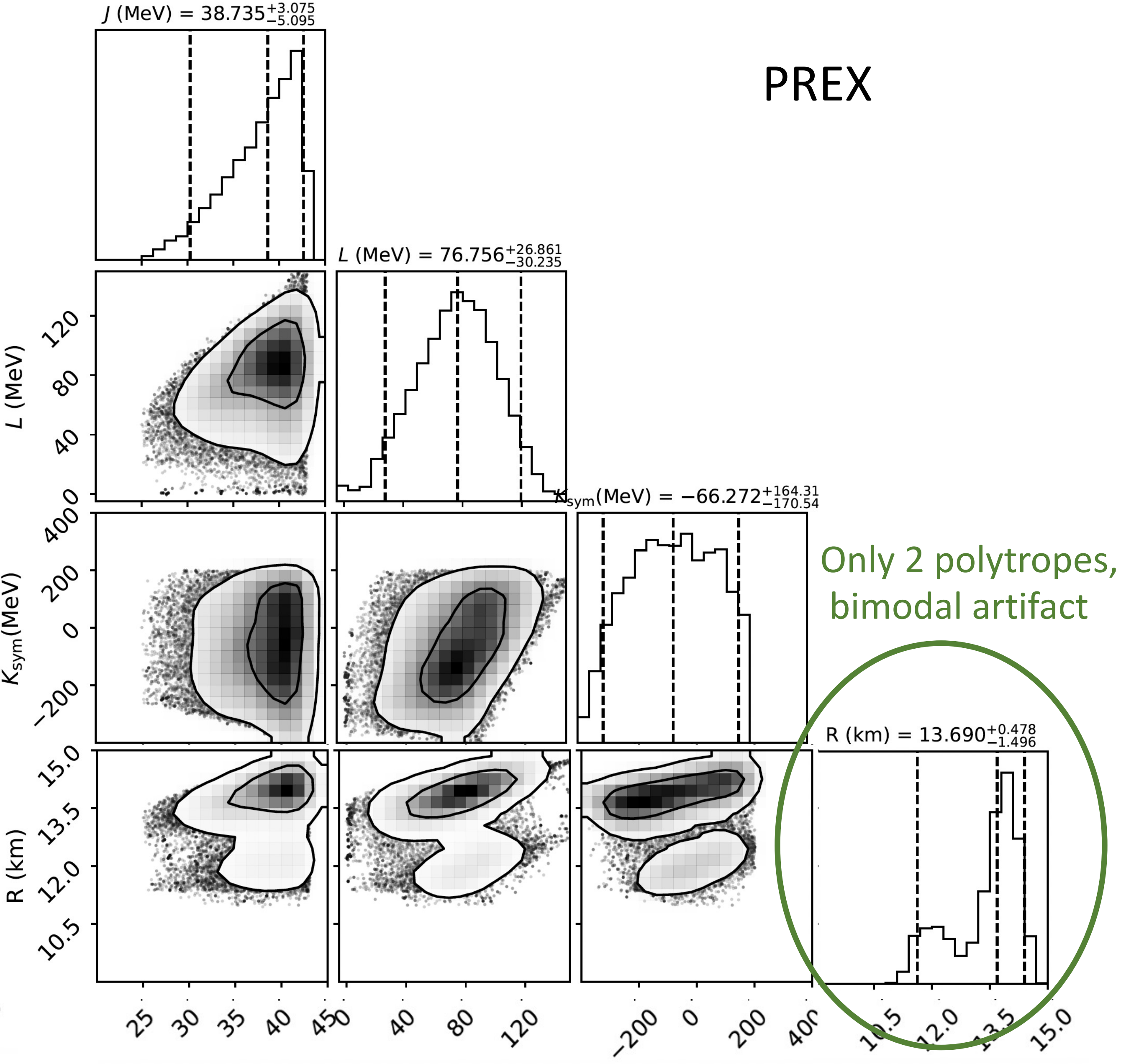
Preliminary

Demanding a stable crust removes the softer EOSs

Priors



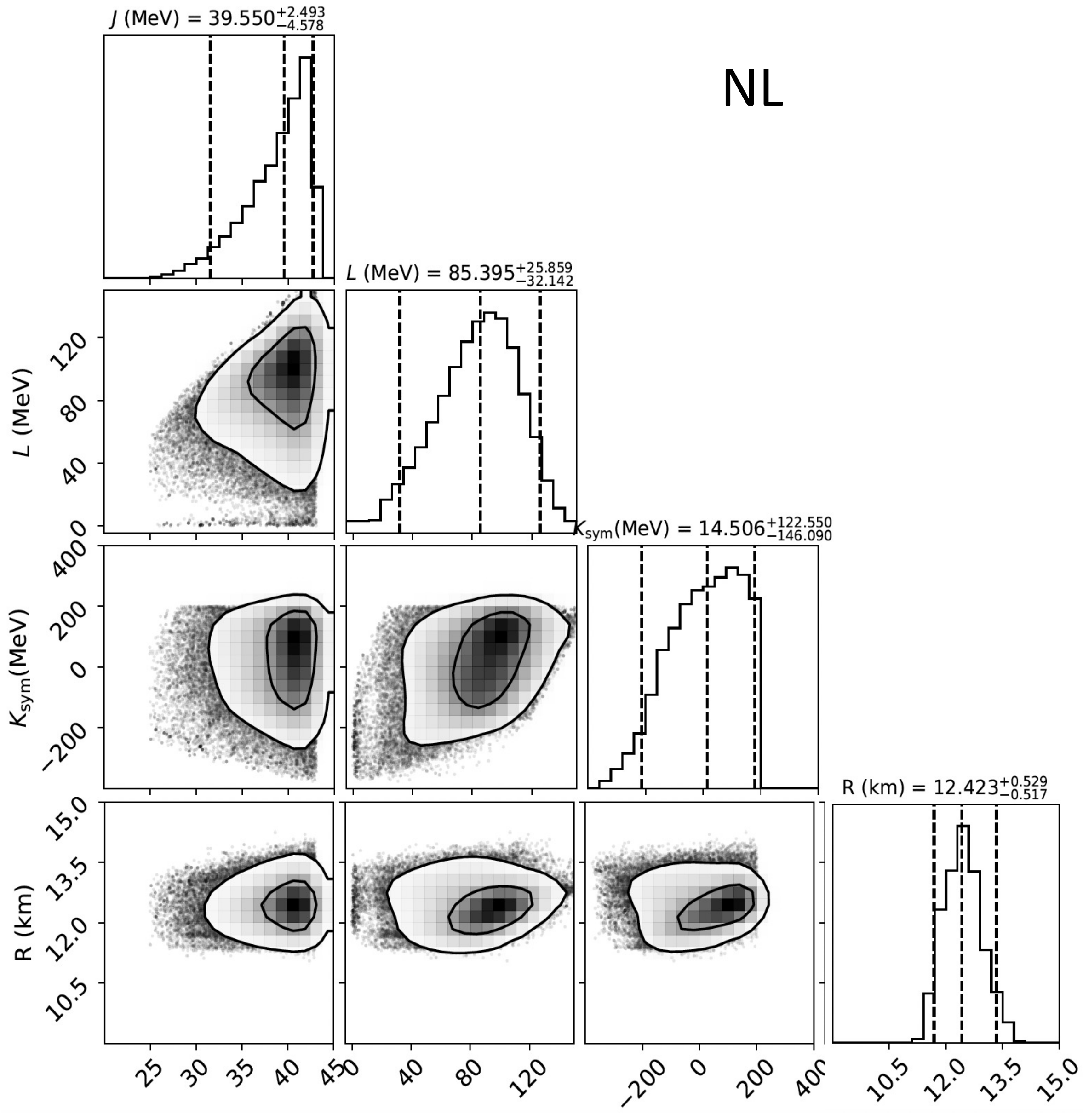
PREX

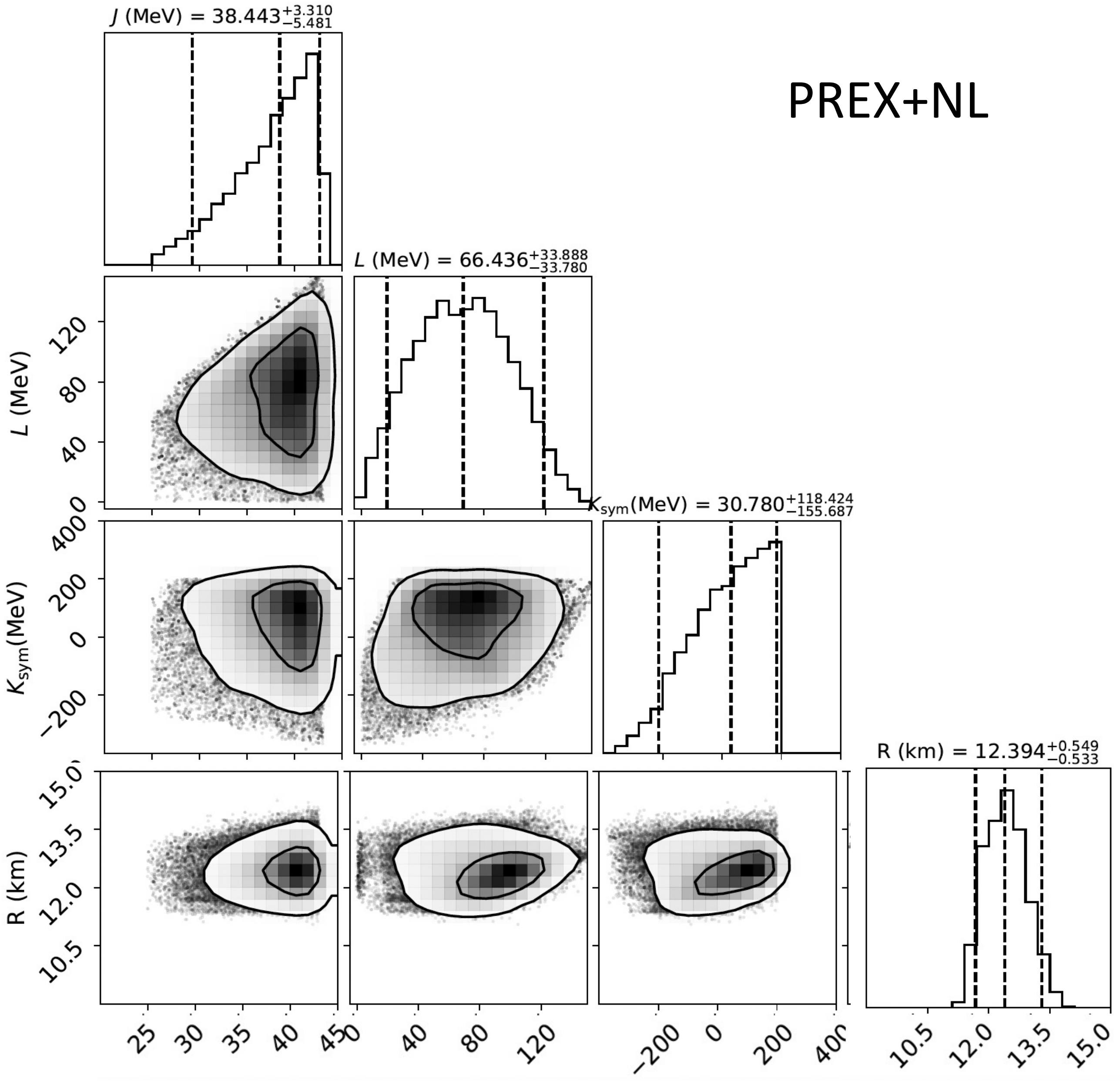


Only 2 polytropes,
bimodal artifact

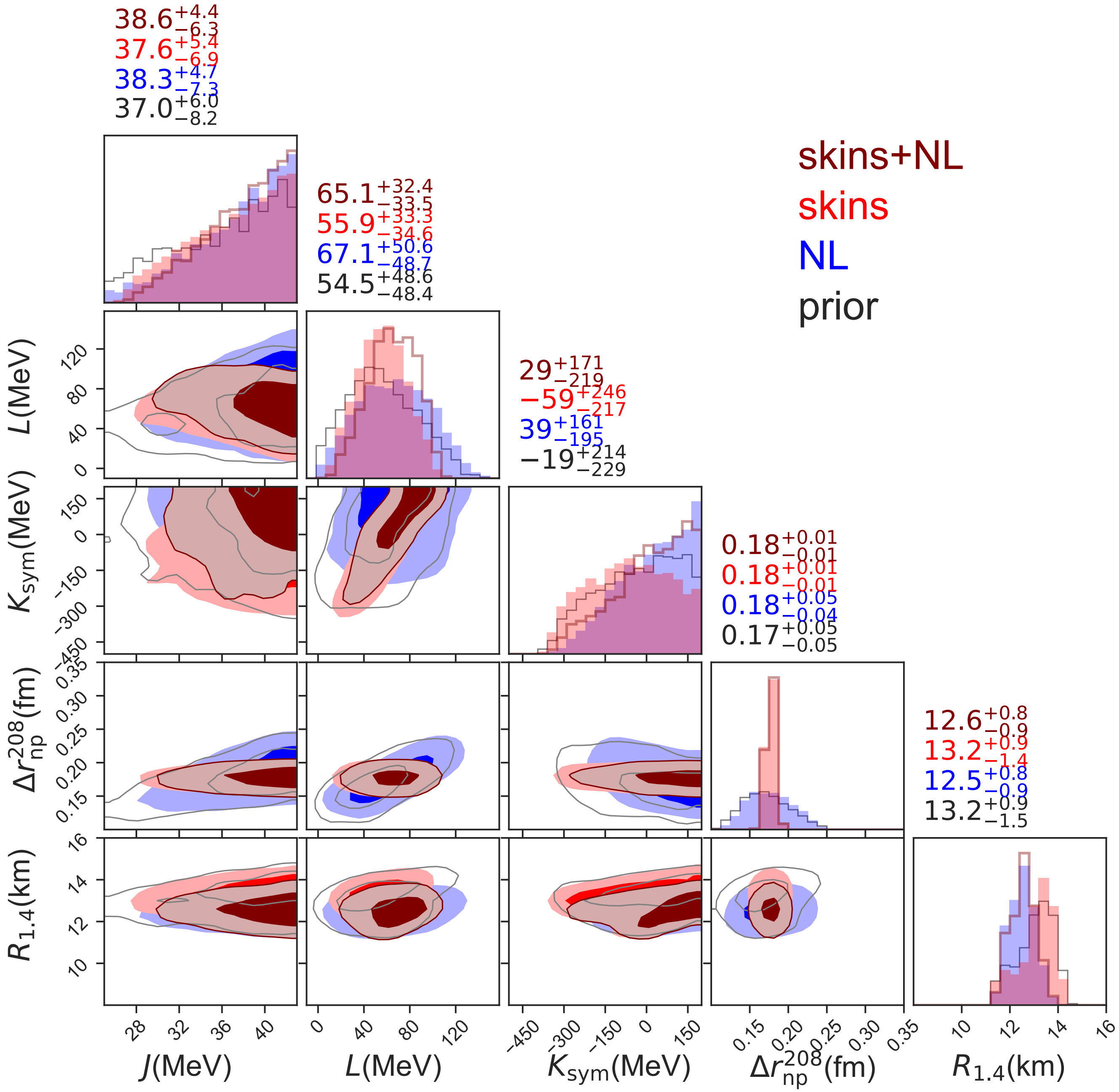
Preliminary

NL predicts high L, but addition of nuclear binding energies “corrects”


NL

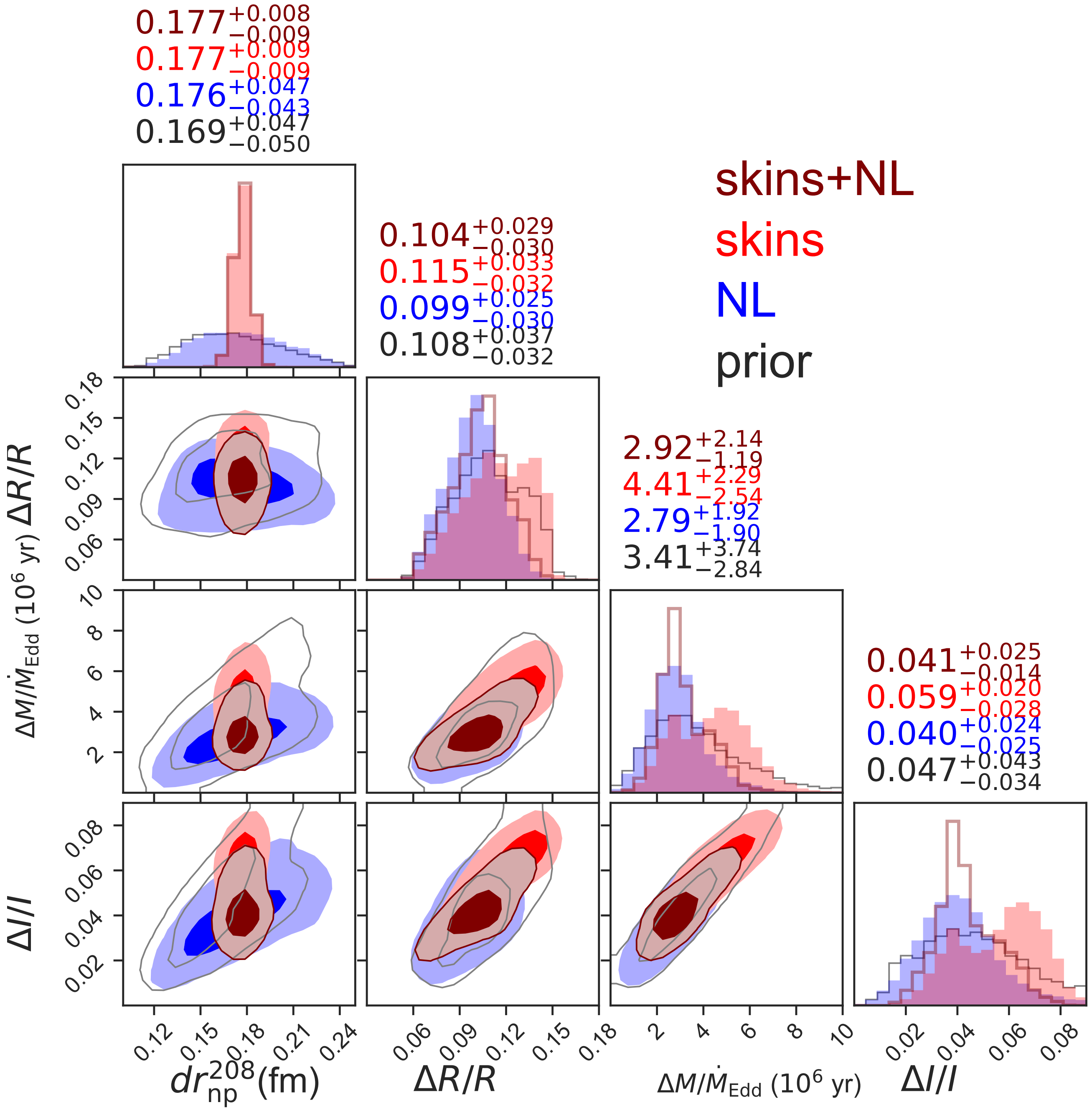

PREX+NL

Preliminary



Newton+ in prep

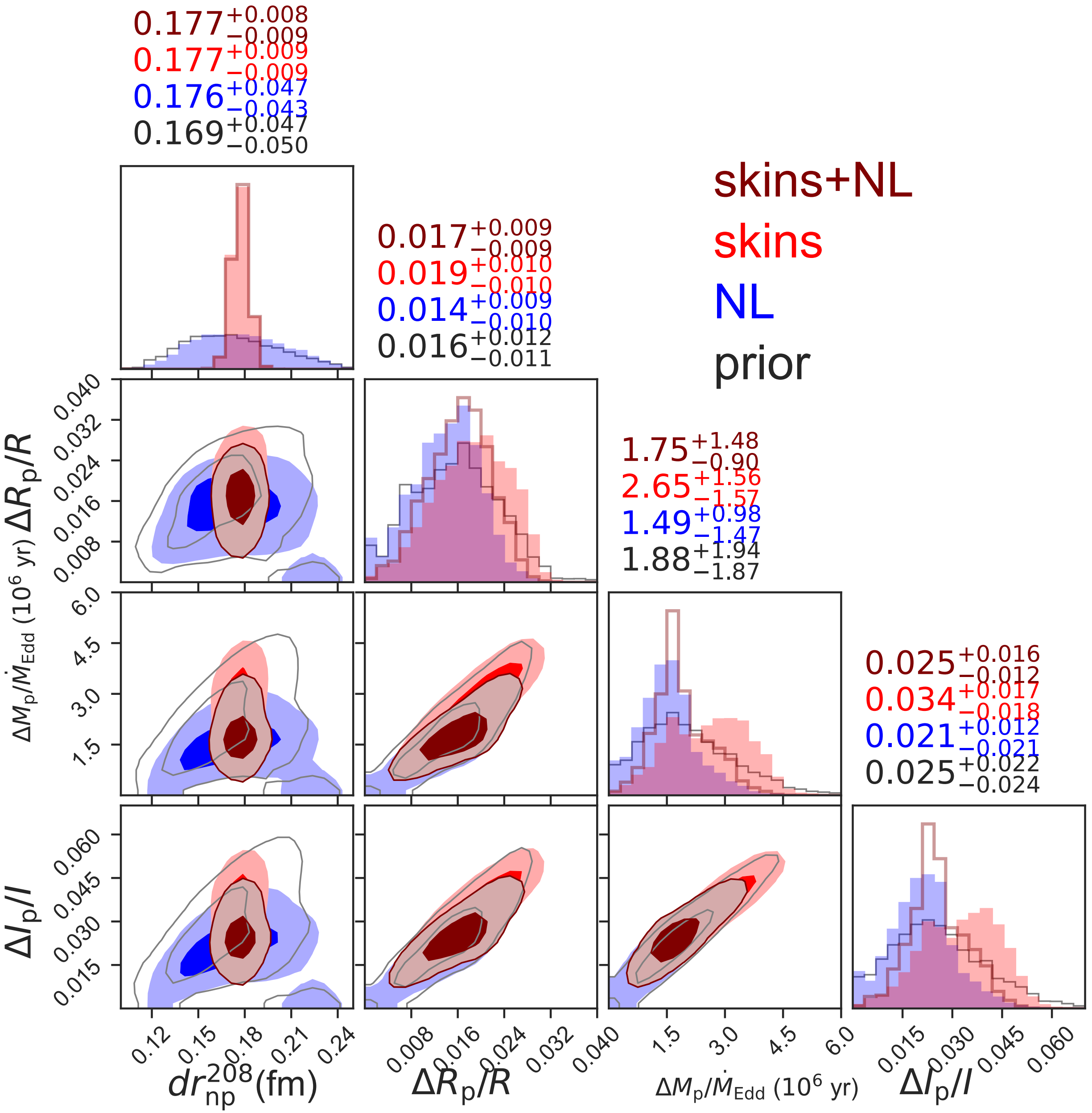
Preliminary



Crustal glitches:
0.018
0.08 (with entrainment)

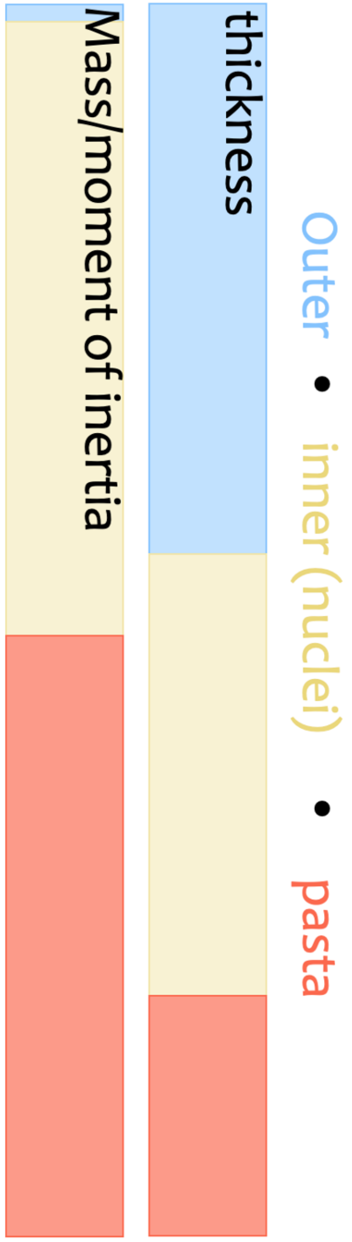
Newton+ in prep

Preliminary



Newton+ arxiv:2112.12108

Newton+ arxiv:2112.12108

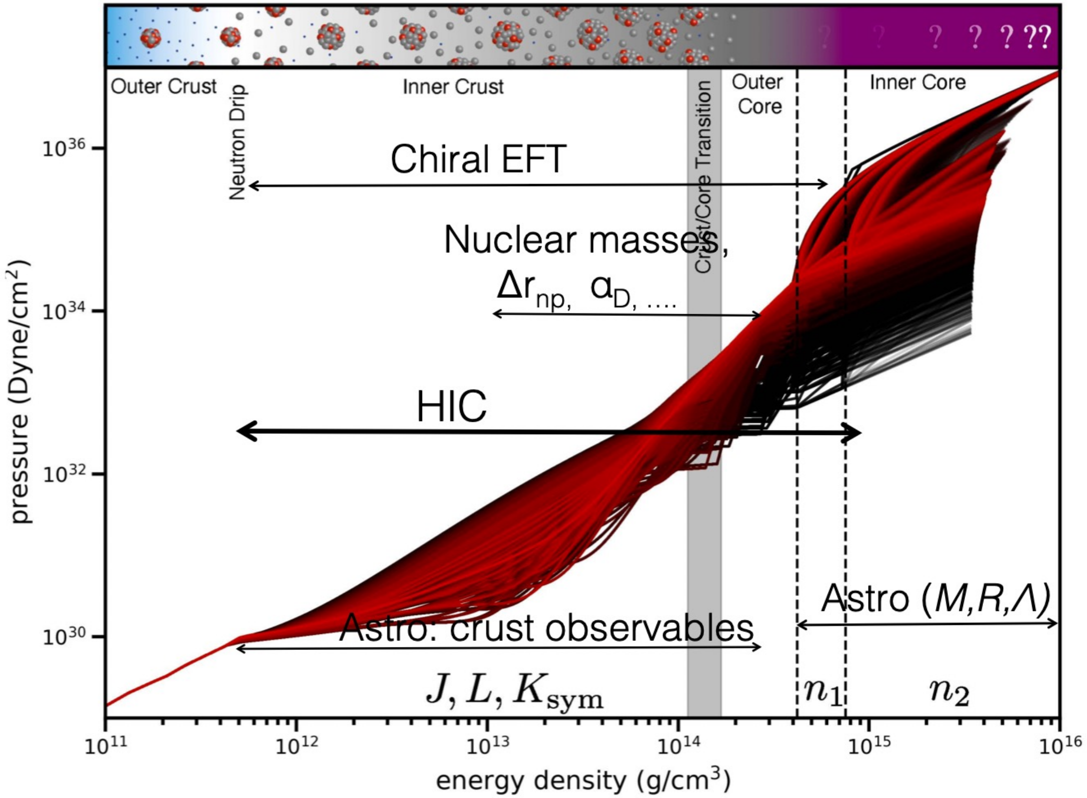


Take-aways

Different choices of nuclear model lead to systematically different inferences of nuclear and Astro observables

Example: using correlations between symmetry energy and nuclear observables from nuclear models already fit to disparate data can lead to systematically different predictions

One way forward is to center modeling around An energy density functional with sufficient degrees of freedom to explore EOS parameter space in an unbiased way, but no more



Nuclear physics has much to say about the *crust* so let’s include it; both nuclear and astro data can tell us about the crust.

Key questions

We can observationally probe the neutron star crust in several different ways: how can we reliably fold this data into our EOS and symmetry energy inferences?

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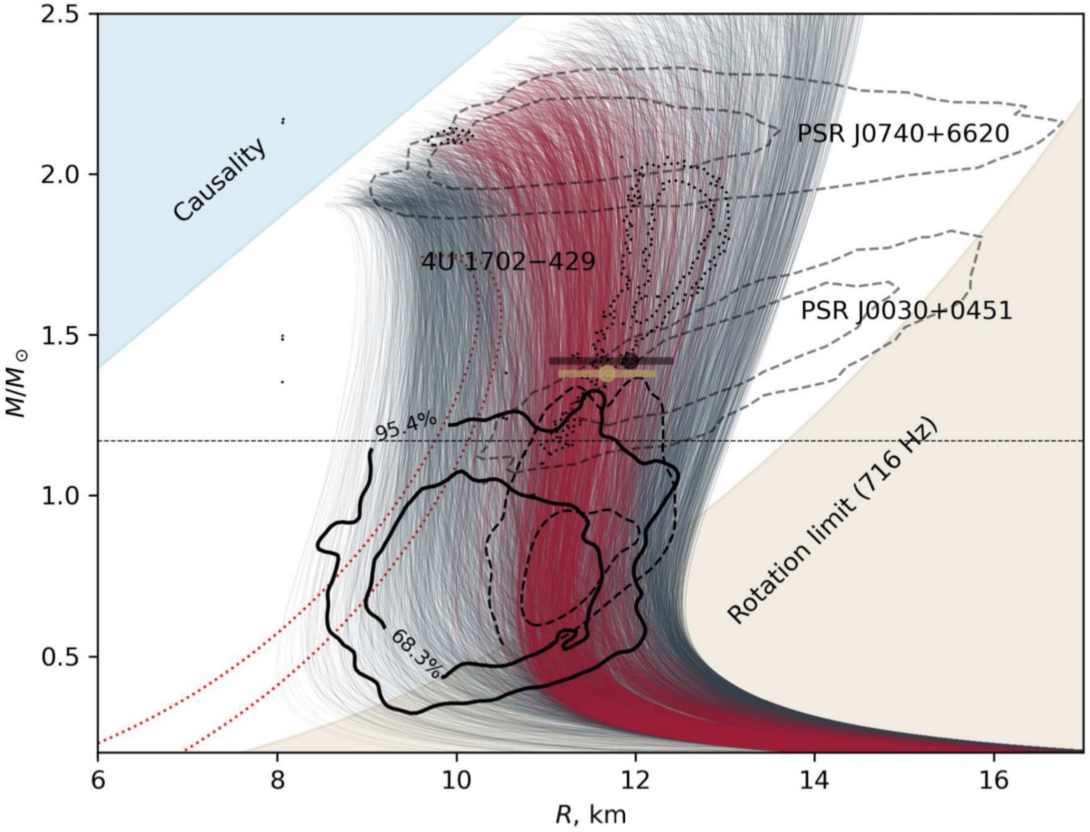
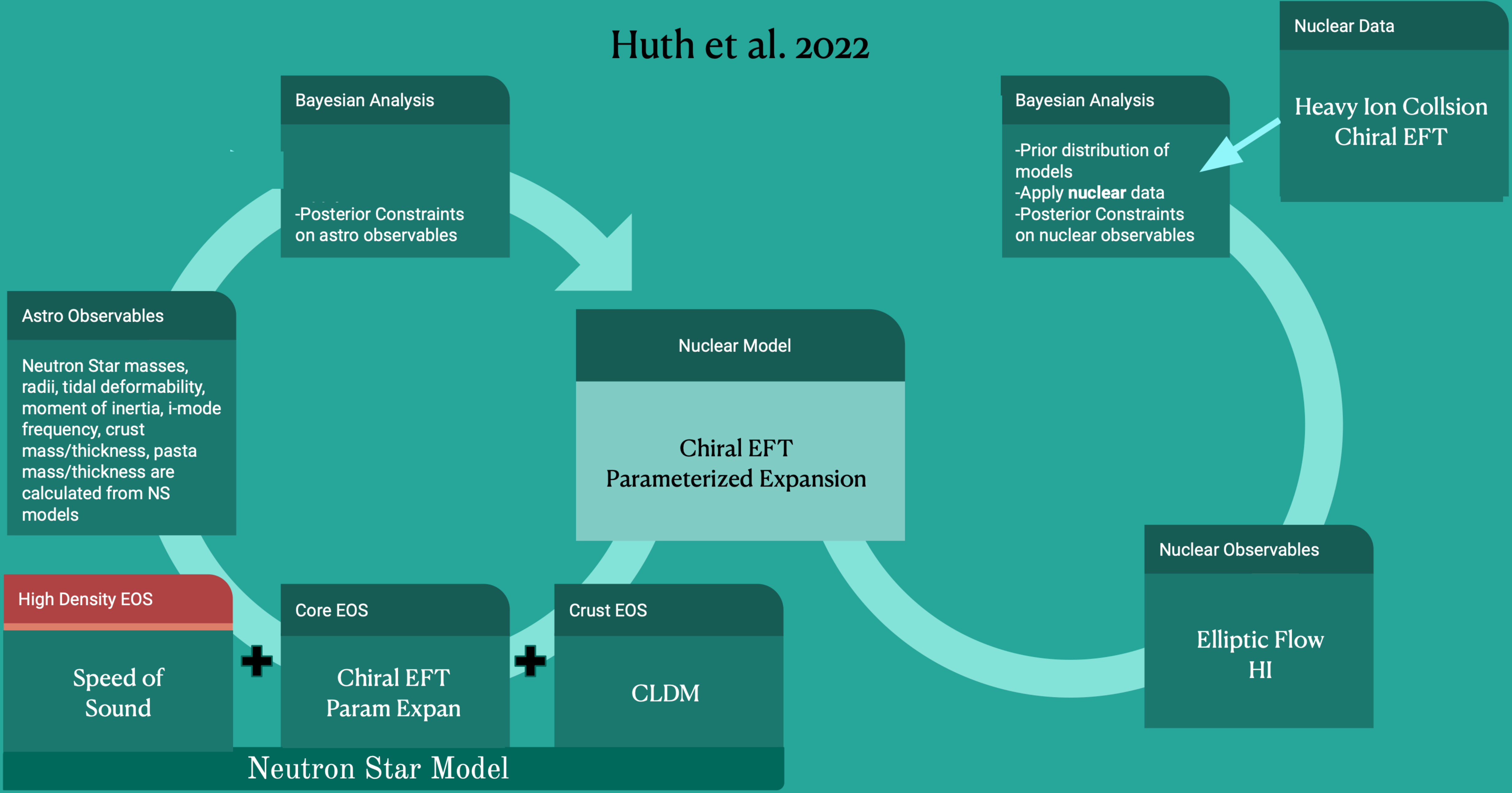
Can we keep this low mass neutron star please?

(0.77 +0.20/-0.17 M_{SUN})



Doroshenko+, Nature Astronomy, **6**, 1444 (2022)

Huth et al. 2022



Bayesian Analysis

-Posterior Constraints on astro observables

Astro Observables

Neutron Star masses, radii, tidal deformability, moment of inertia, i-mode frequency, crust mass/thickness, pasta mass/thickness are calculated from NS models

Nuclear Model

Chiral EFT
Parameterized Expansion

High Density EOS

Speed of Sound

Core EOS

Chiral EFT
Param Expan

Crust EOS

CLDM

Neutron Star Model

Nuclear Data

Heavy Ion Collsion
Chiral EFT

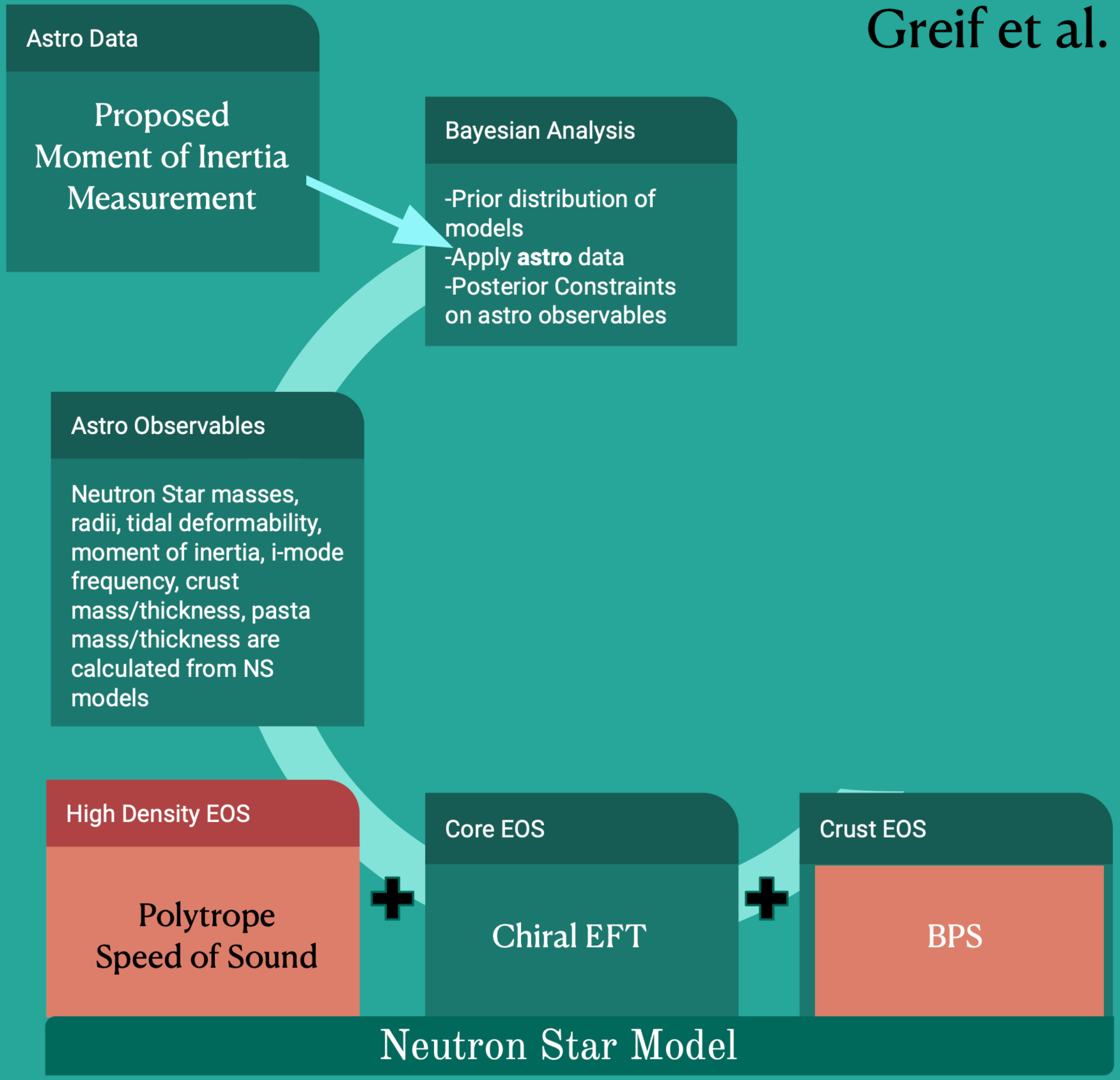
Bayesian Analysis

-Prior distribution of models
-Apply **nuclear** data
-Posterior Constraints on nuclear observables

Nuclear Observables

Elliptic Flow
HI

Greif et al. 2020



Astro Data

Proposed
Moment of Inertia
Measurement

Bayesian Analysis

-Prior distribution of models
-Apply **astro** data
-Posterior Constraints on astro observables

Astro Observables

Neutron Star masses, radii, tidal deformability, moment of inertia, i-mode frequency, crust mass/thickness, pasta mass/thickness are calculated from NS models

High Density EOS

Polytrope
Speed of Sound

+

Core EOS

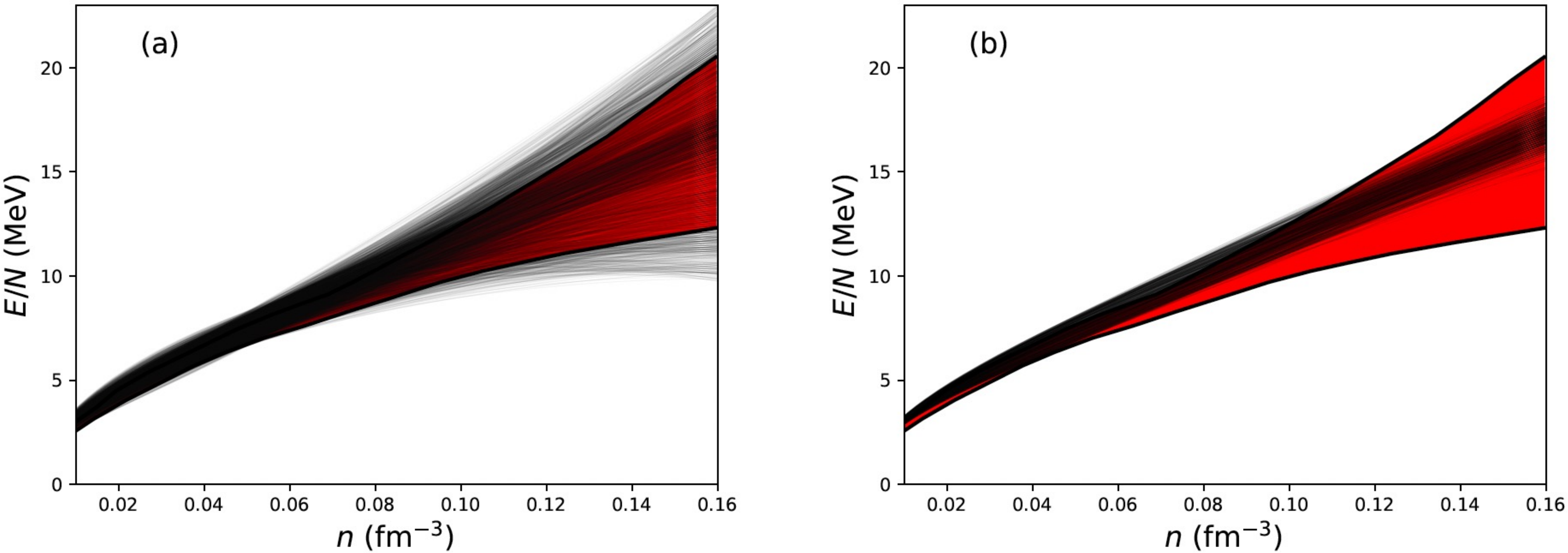
Chiral EFT

+

Crust EOS

BPS

Neutron Star Model



Newton and Crocombe arxiv:2008.00042