Crusty 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:

Rebecca Preston, Amber Stinson, Lauren Balliet, Brianna Douglas, Michael Ross, Gabriel Crocombe, Blake Head, Alex Westbrooks, Sarah Cantu, Josh Sanford, Srdj Budimir, Luis Rivera, Zachary Langford

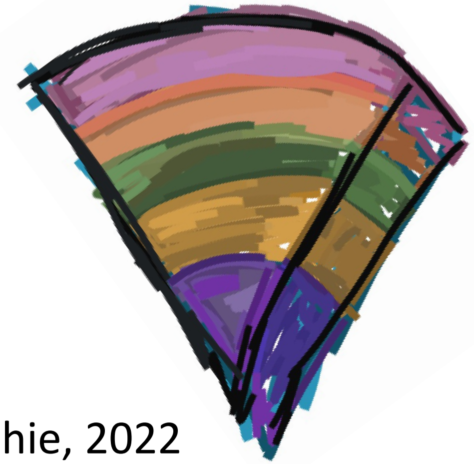
Texas A&M University-Commerce

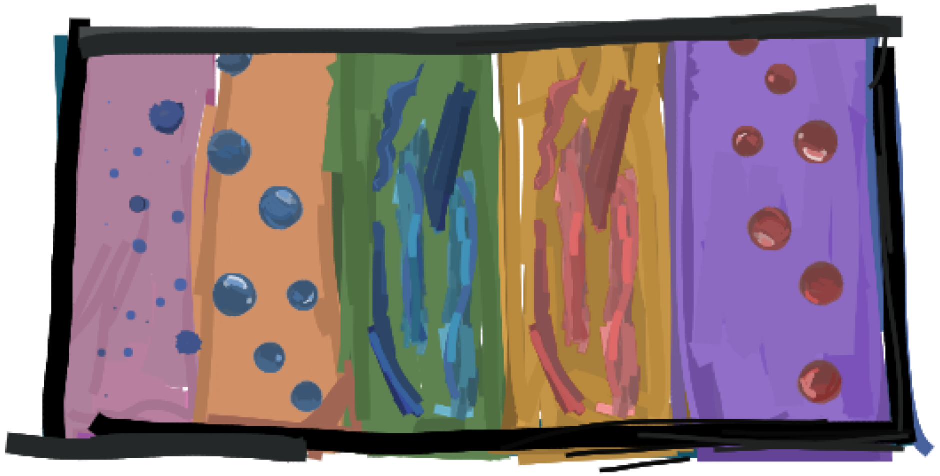
Duncan Neill, David Tsang – University of Bath

Farrukh Fattoyev – Manhattan College

Jirina Rikovska Stone, Alex Kaltenborn - University of Tennessee

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





Noa Fritschie, 2022

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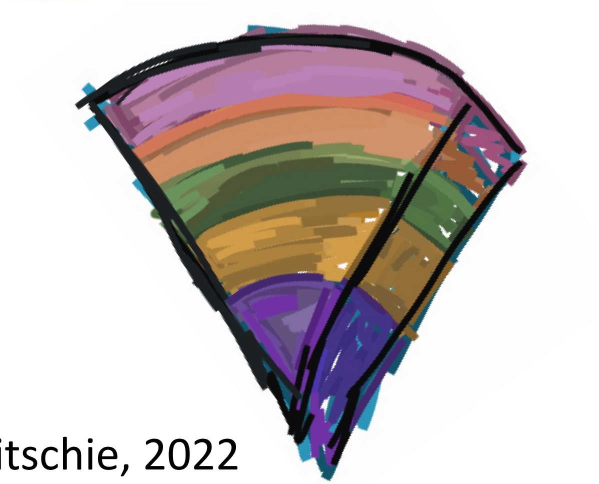
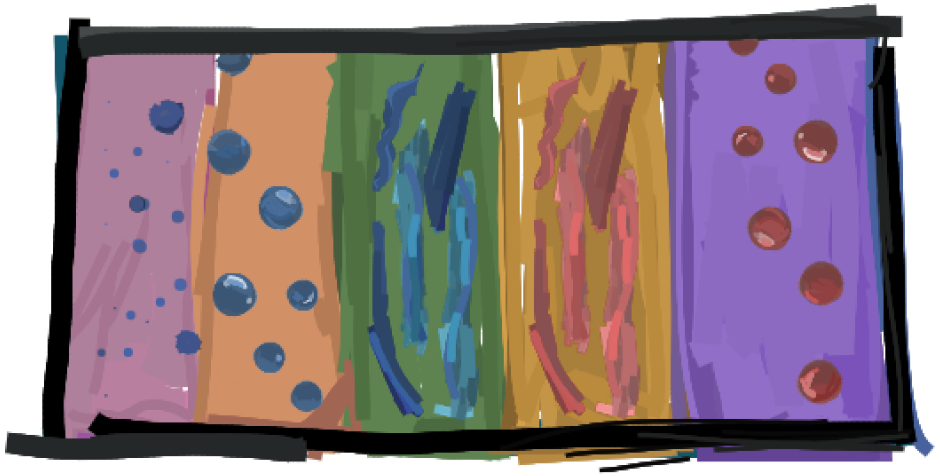
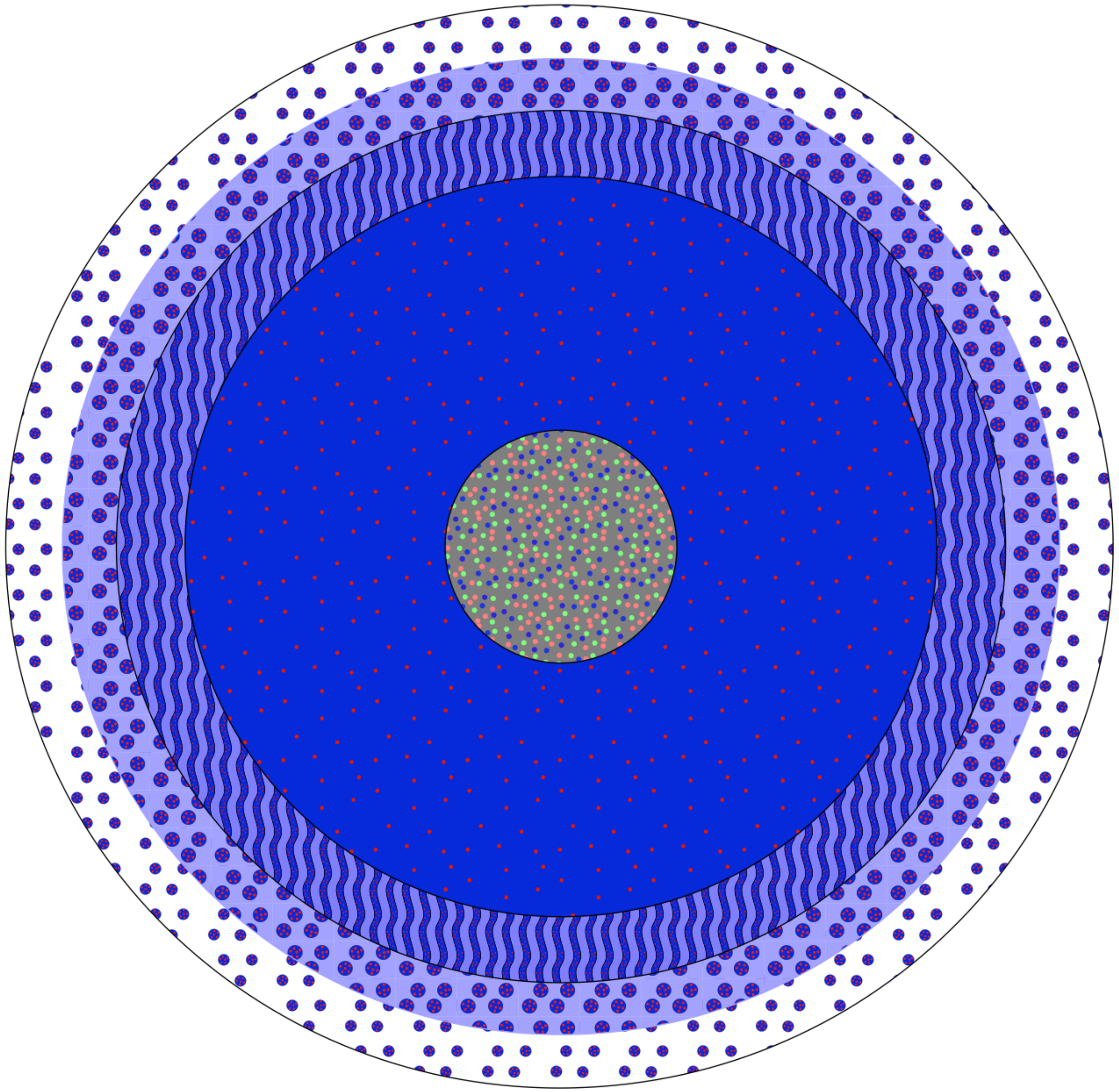




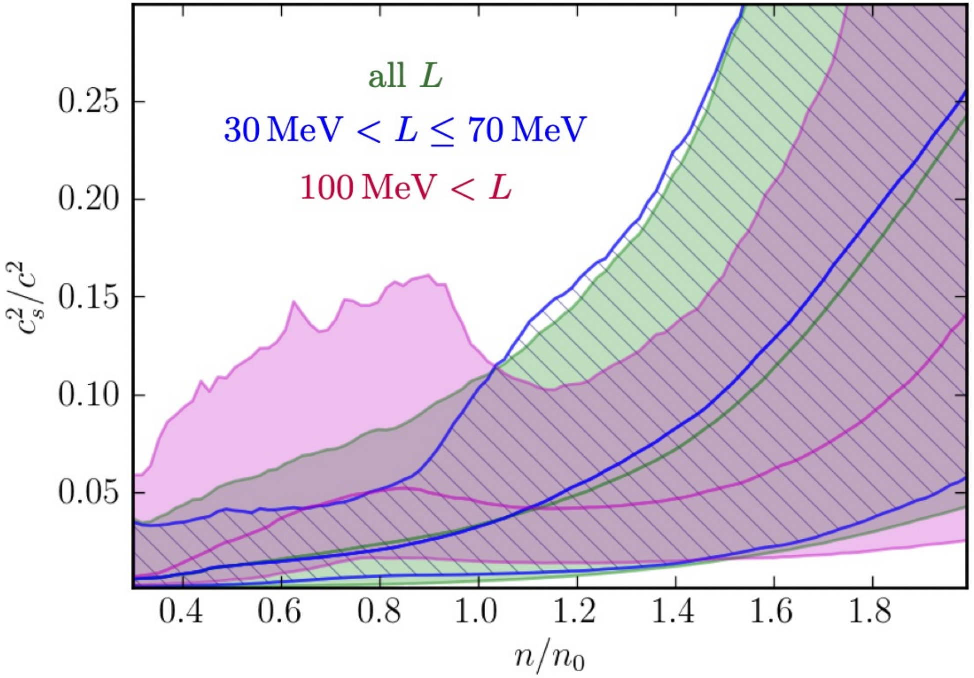
Noa Fritschie, 2022

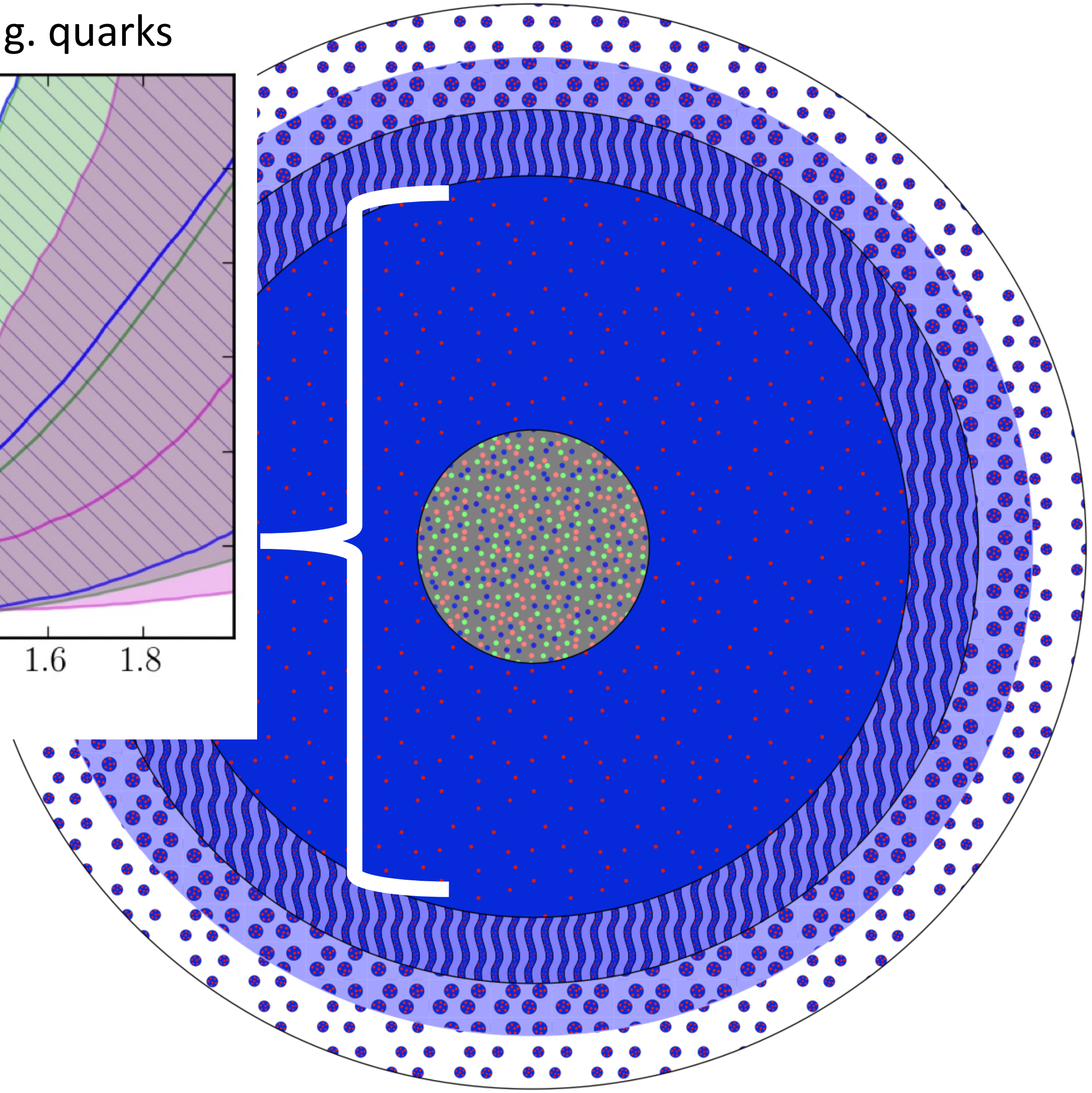
Reminder of Neutron Star Structure



Reminder of Neutron Star Structure

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





Essick+ arXiv 2102.10074

Reminder of Neutron Star Structure

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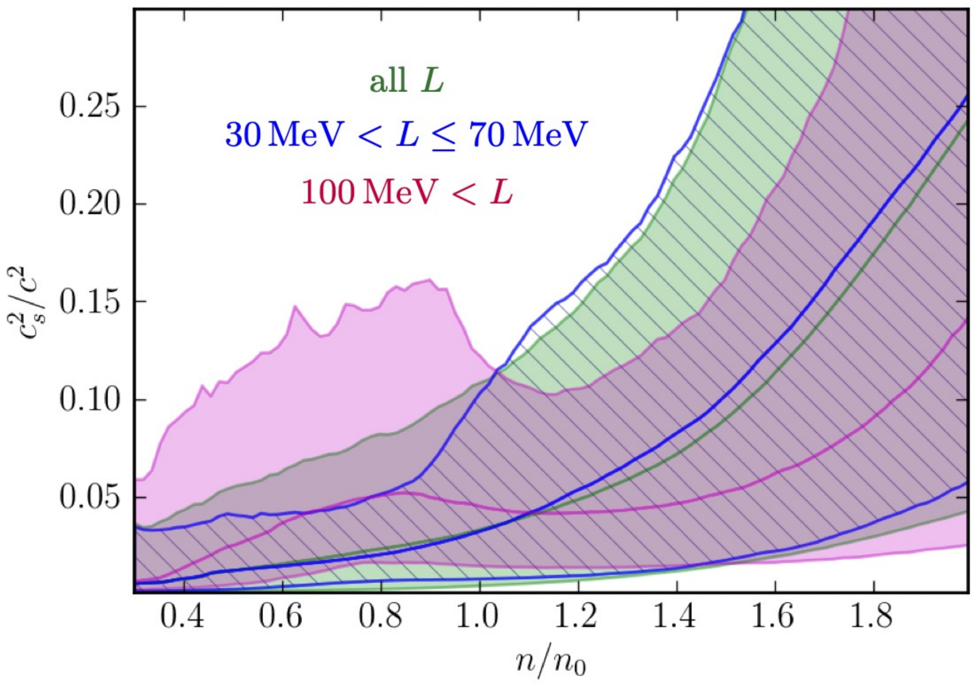
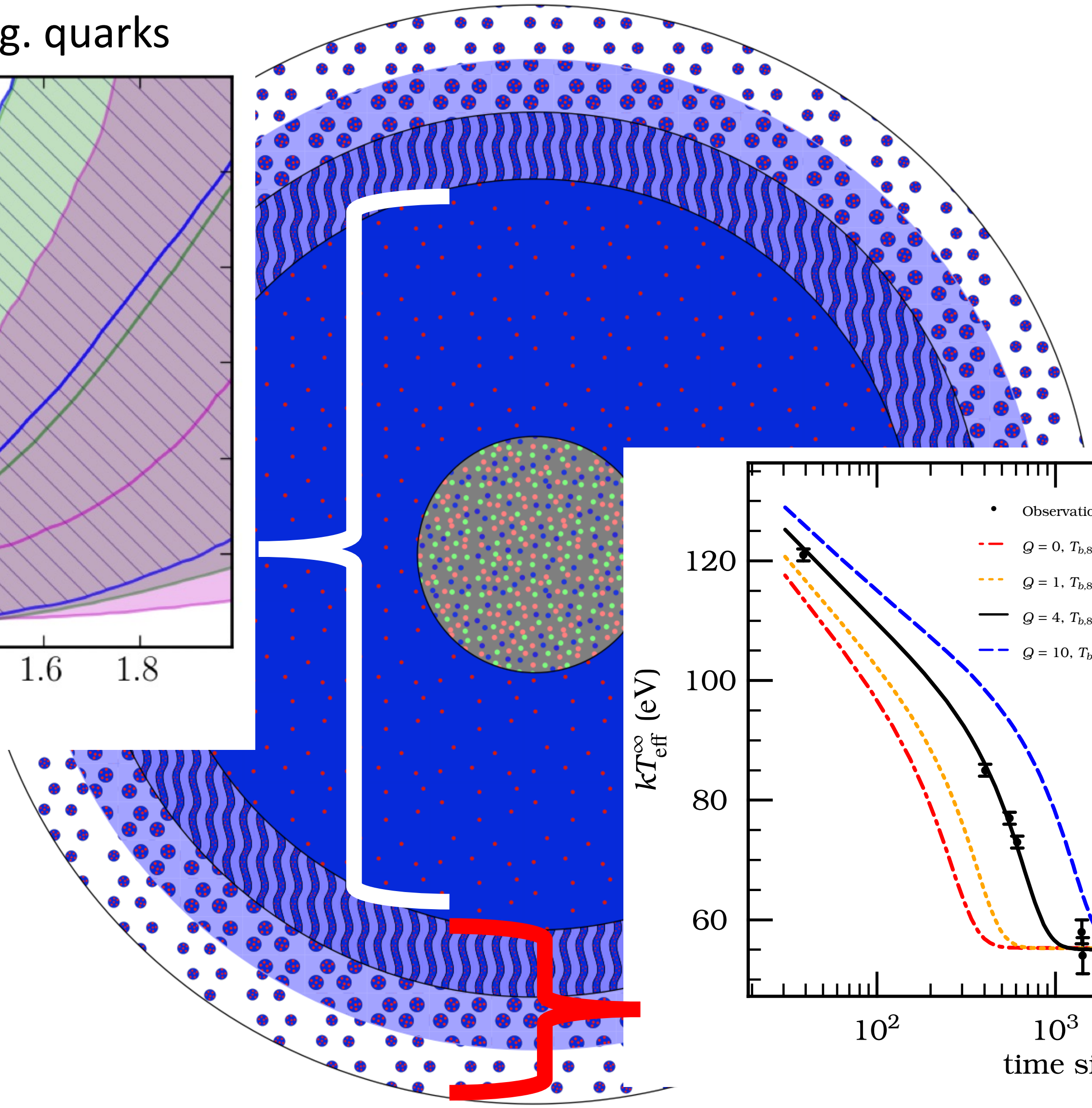
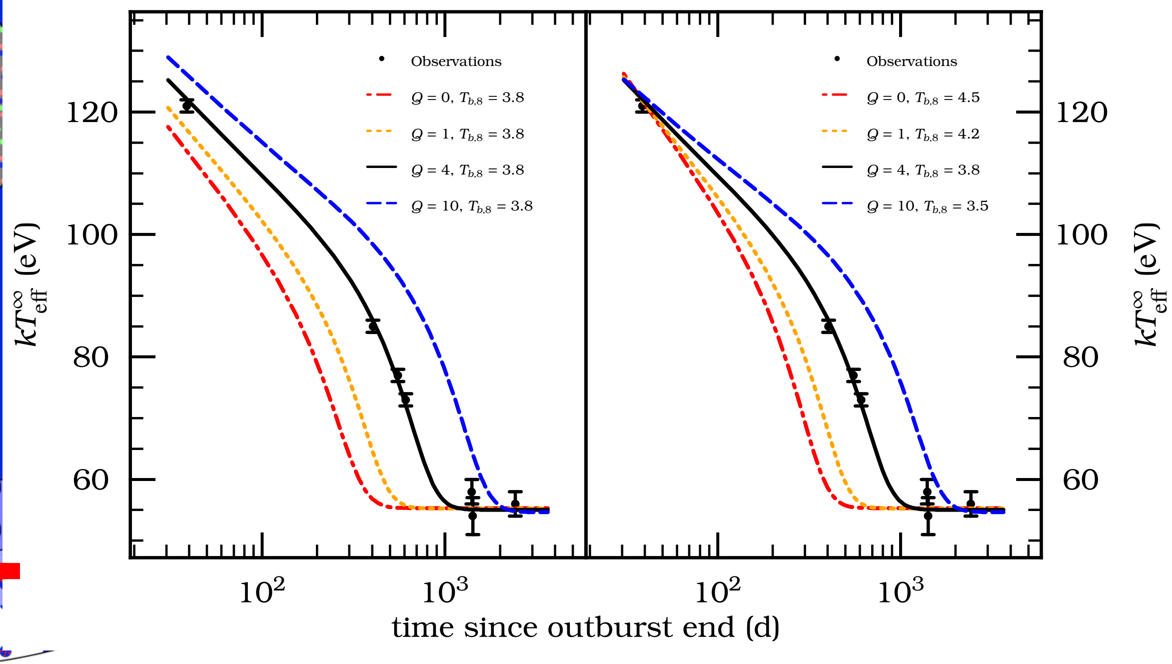


Essick+ arXiv 2102.10074



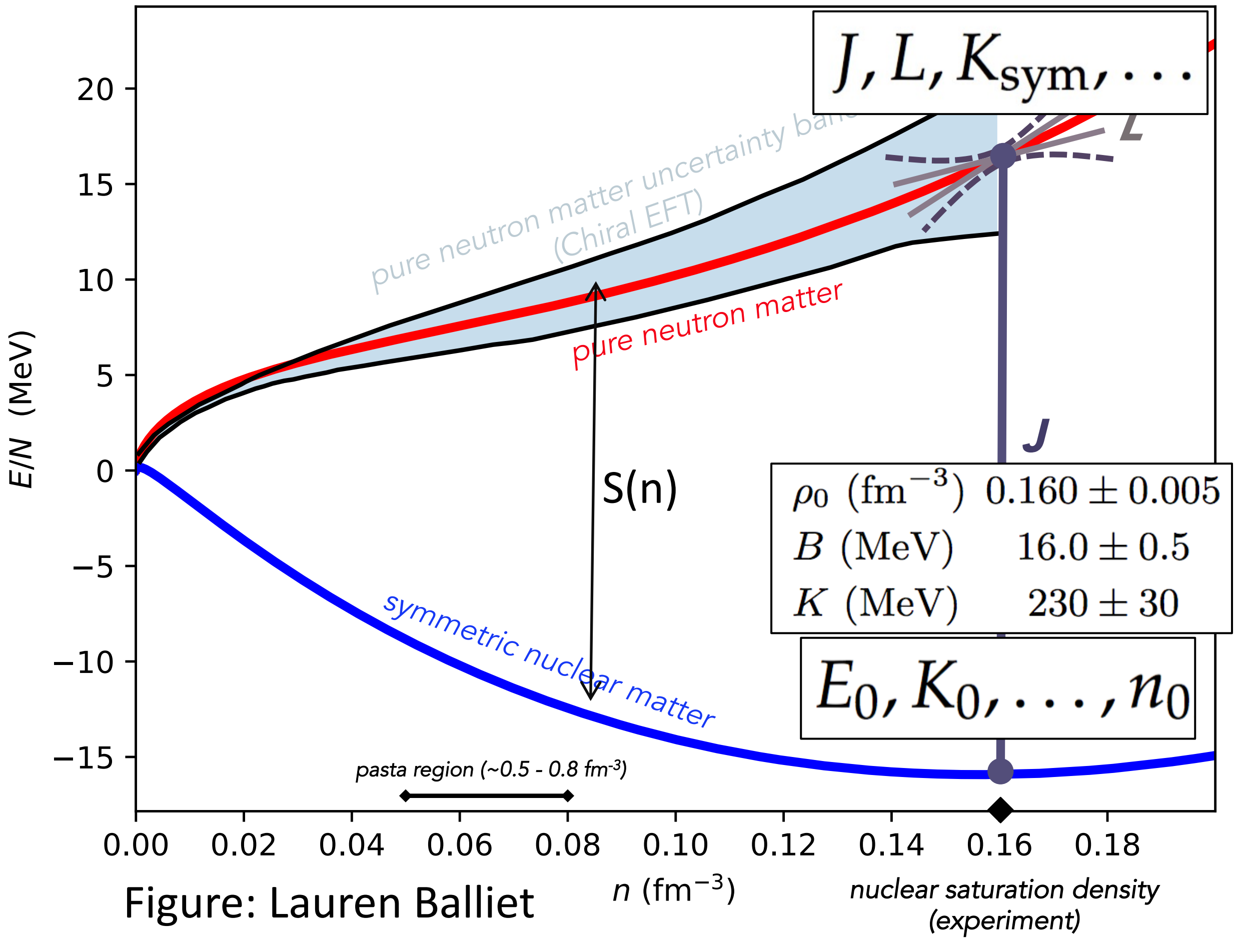
MXB 1659-29 in quiescence: Strong evidence for relatively pure crystalline crust with superfluid neutrons in the inner layer

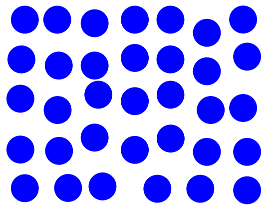


Brown and Cumming, ApJ 2009

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

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





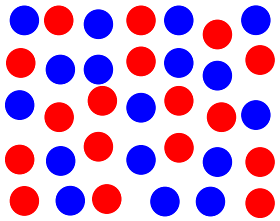


Figure: Lauren Balliet

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

Li, arxiv:2105.04629

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

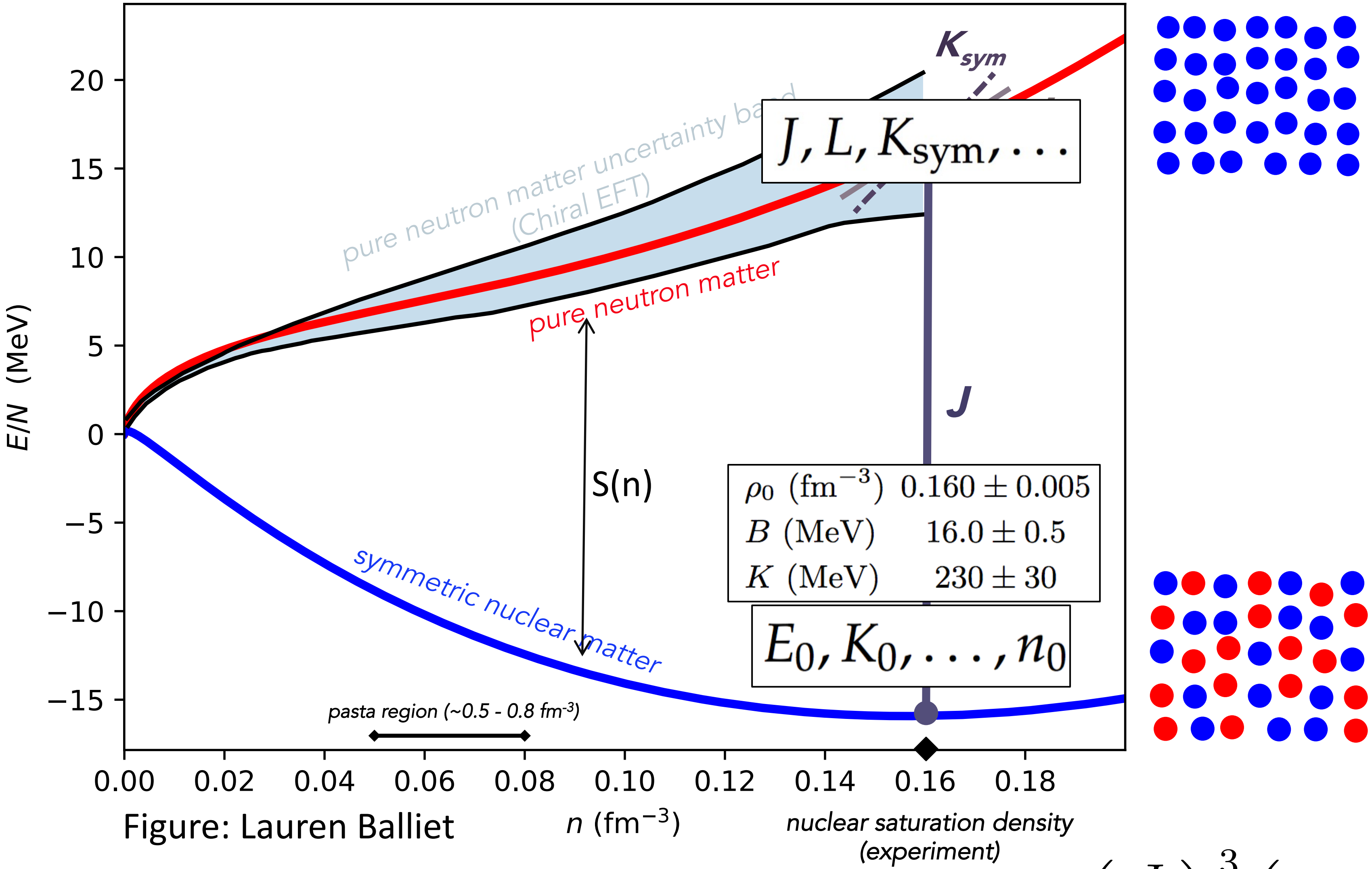
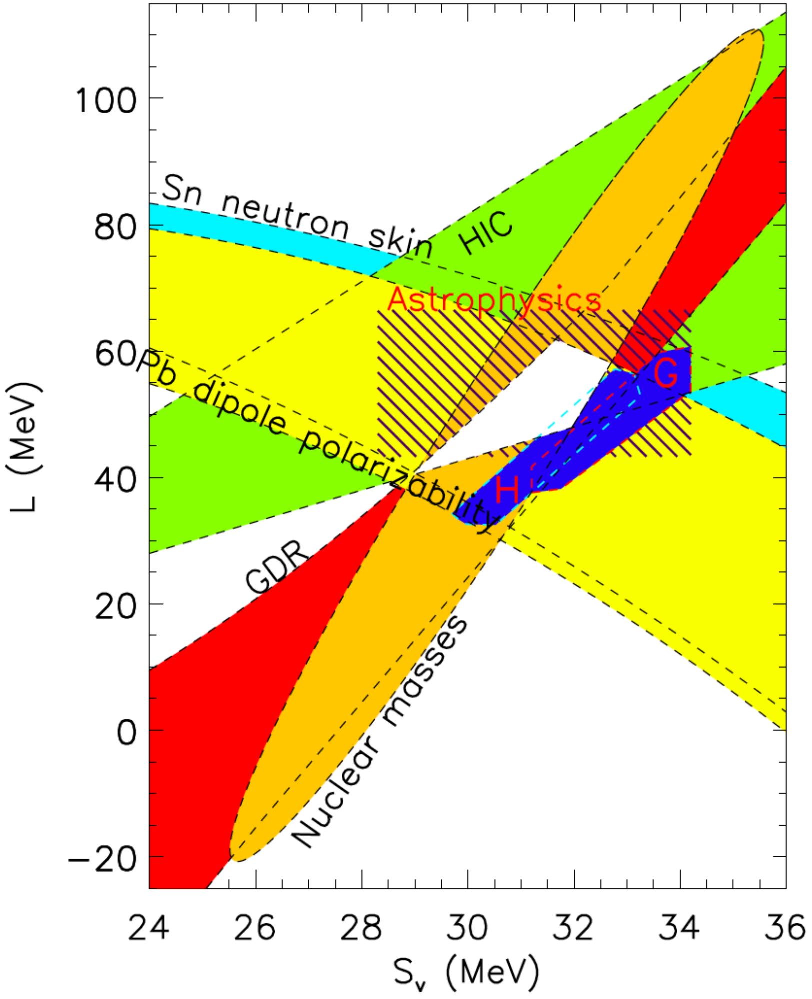


Figure: Lauren Balliet

$$P_{\mathrm{NS}}(n_0) \approx \frac{n_0}{3}L + 0.048 n_0 \left(\frac{J}{30}\right)^3 \left(J - \frac{4}{3}L\right)$$

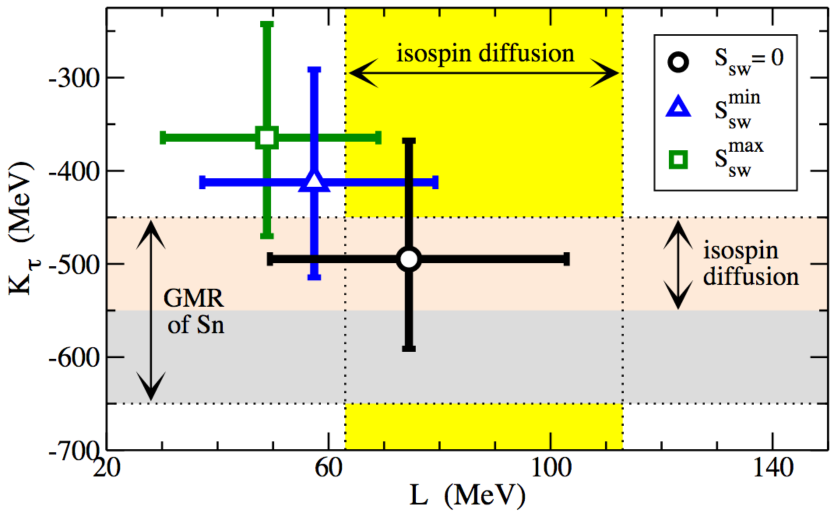
Lattimer,Prakash; astro-ph/0002232

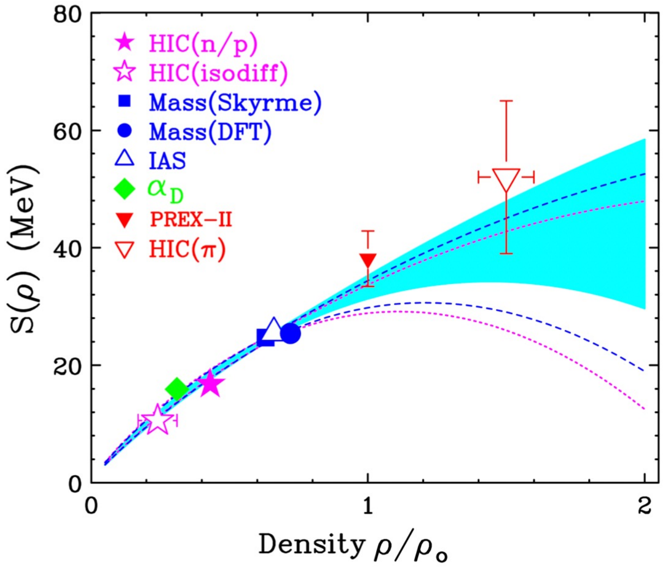
Symmetry energy constraints



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

Centelles et al, arxiv:0806.2886





Tsang and Lynch, arxiv:2106.10119

Take-aways

Different choices of nuclear models lead to systematically different inferences of nuclear and astro observables, mitigated by models which allow more parameter space exploration (at least J,L,K_{sym}, probably Q_{sym}, for extrapolations up to $2n_s$)

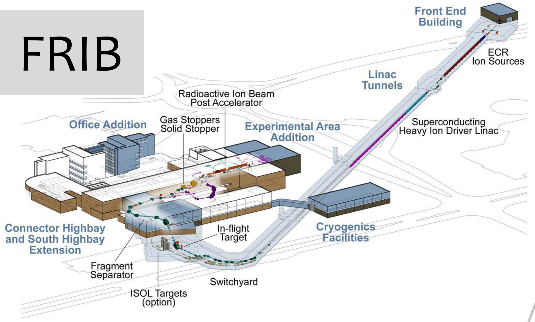
There are many observables that can be included in our EOS inference if we build ensembles of crust EOSs consistent with core EOSs; EDFs are best way to include crust, core and nuclear observables consistently

Strong, Weak, EM signals

Multimessenger Nuclear & Astro Physics

Weak, EM, Grav signals

FRIB



Elliptic flow

p/n ratios

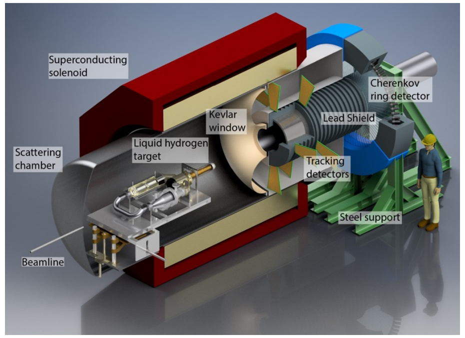
Pion production

Resonance widths,

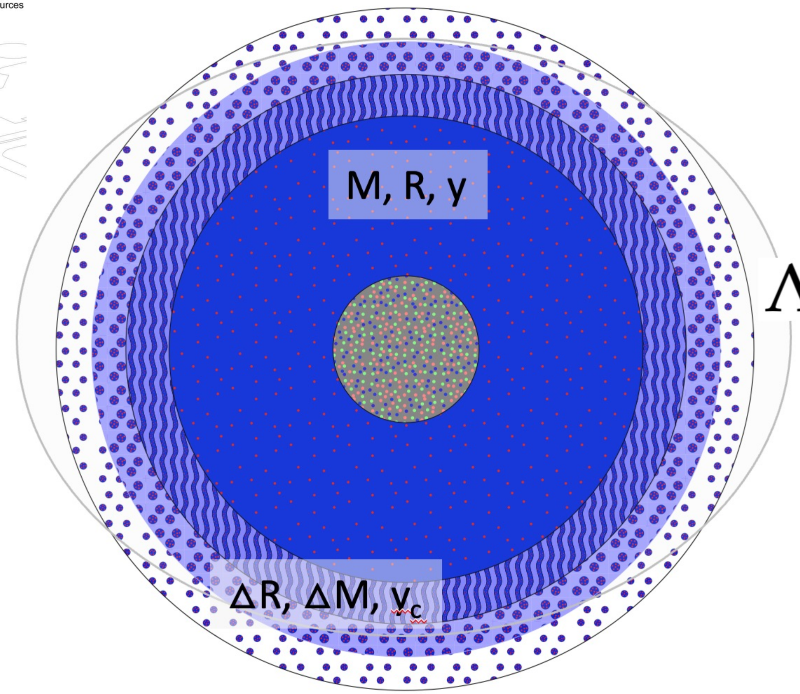
Centroid energies

Optical potentials

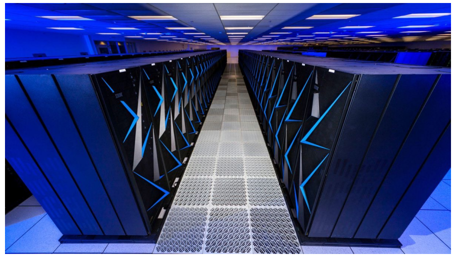
Scattering X-sections



PREX/CREX/MREX

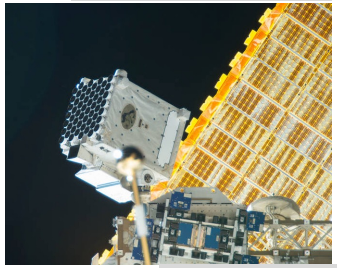


Computation



Randy Wong/LLNL

CHANDRA



NICER

X-ray flux and light curves

Gravitational waveforms

Pulsar timing

PARKES

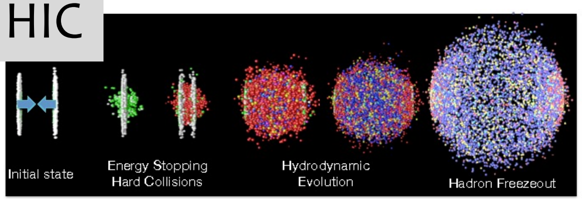
LIGO/ VIRGO

Nuclear structure/ dynamics

Multimessenger Nuclear & Astro Physics

Neutron star structure/ dynamics

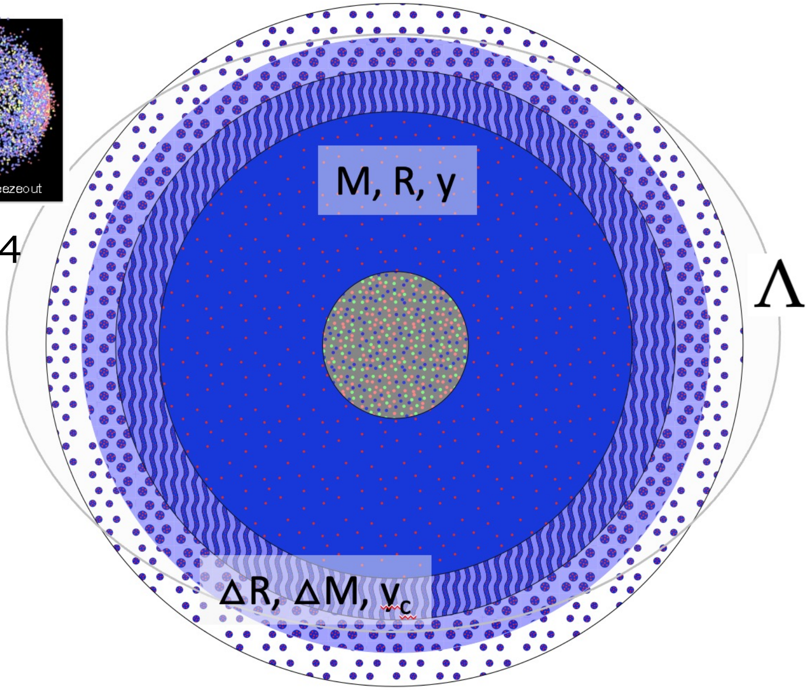
HIC



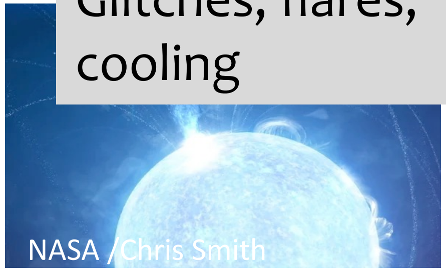
T.K.Nayak, arxiv:1201.4264

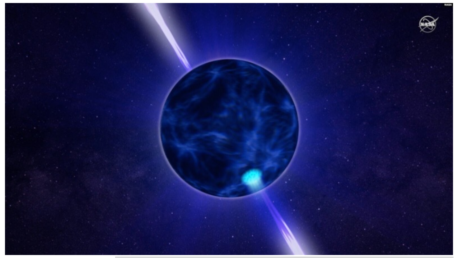
neutron skins

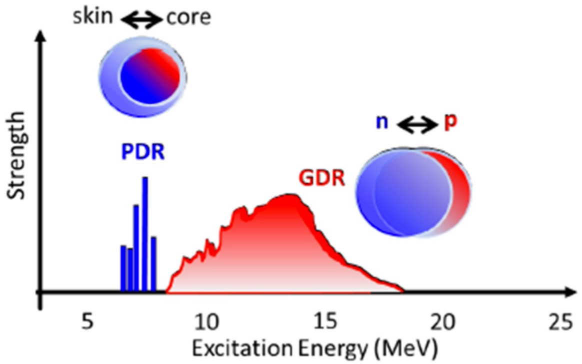
Abrahamyan+,
PRL 108, 112592 (2012)



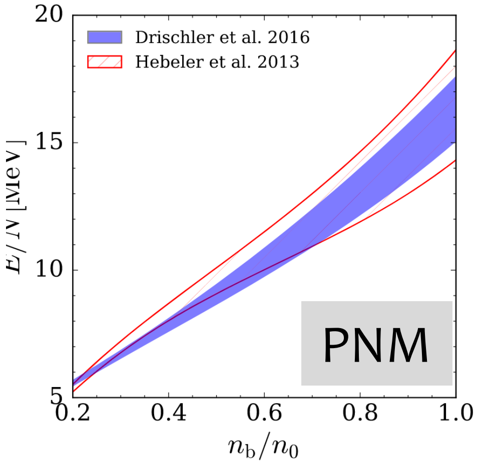
Glitches, flares, cooling





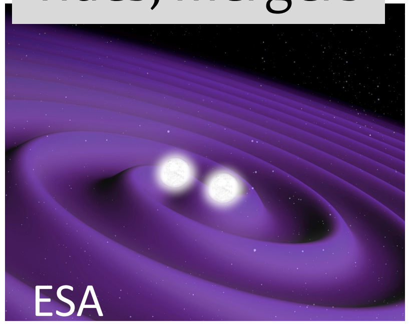


Bracco, Lanza, Tamii,
PPNP 106, 360 (2019)



Haensel, Fortin JPhysG 2017

Tides, mergers



Hot spots
Oscillations,
Crust cooling

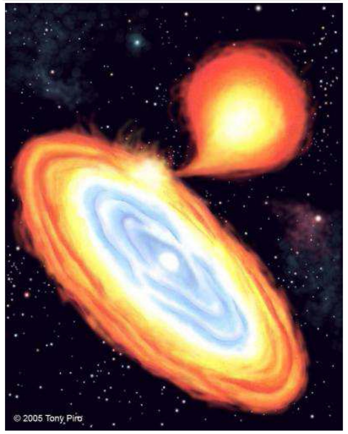
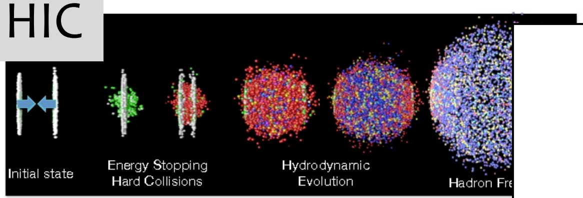


Figure: Artist's impression of a LMXB - credit Tony Piro, 2005.

Multimessenger Nuclear & Astro Physics

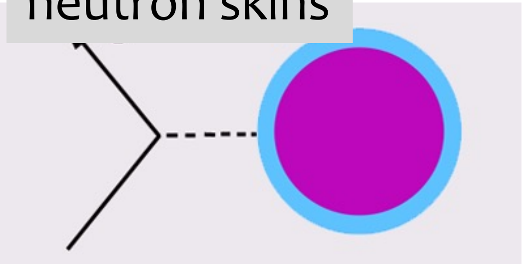
Nuclear structure/ dynamics

HIC



T.K.Nayak, arxiv:1201.426

neutron skins



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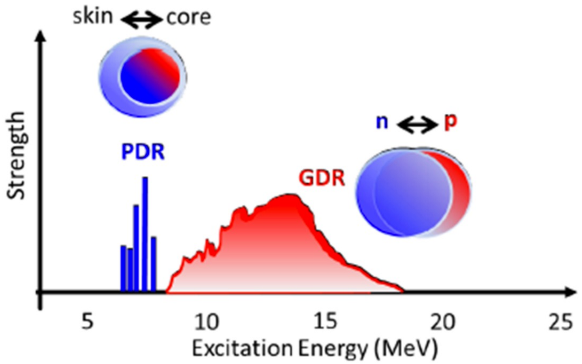
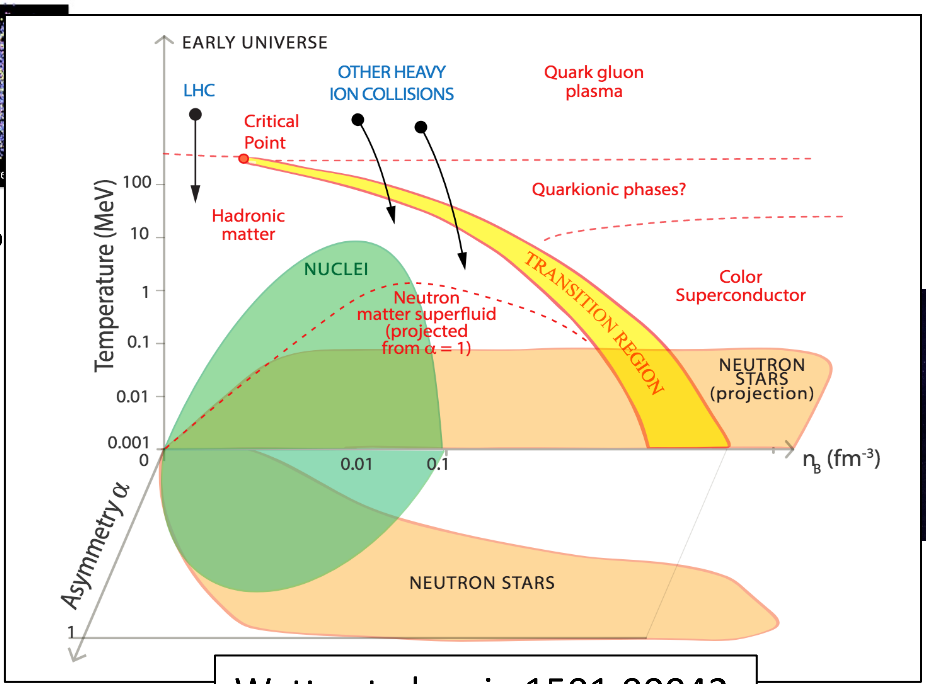
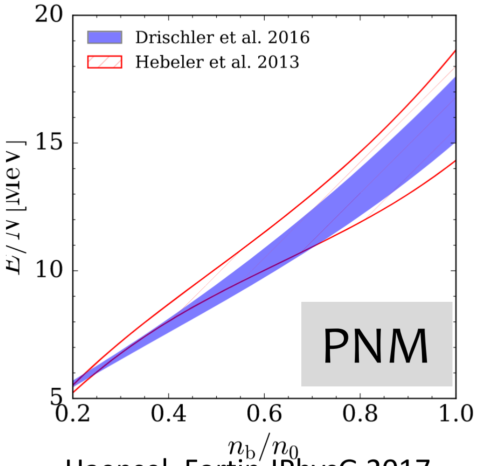


Bracco, Lanza, Tamii,
PPNP 106, 360 (2019)



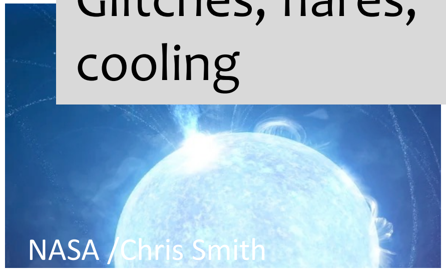
Watts et al arxiv:1501.00042

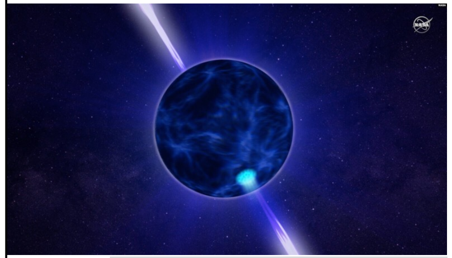


Haensel, Fortin JPhysG 2017

Neutron star structure/ dynamics

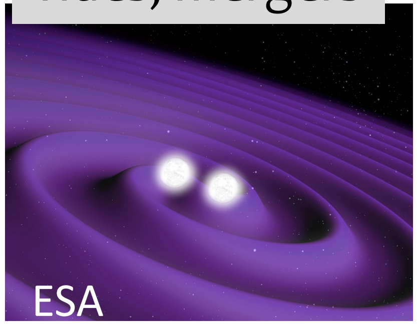
Glitches, flares, cooling





Hot spots Oscillations, Crust cooling

Tides, mergers



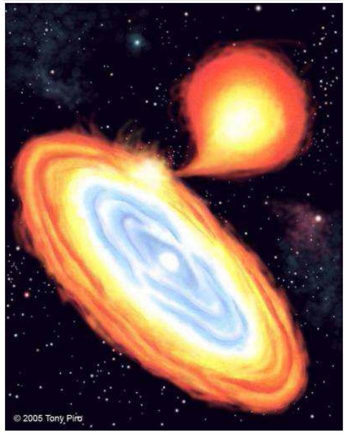


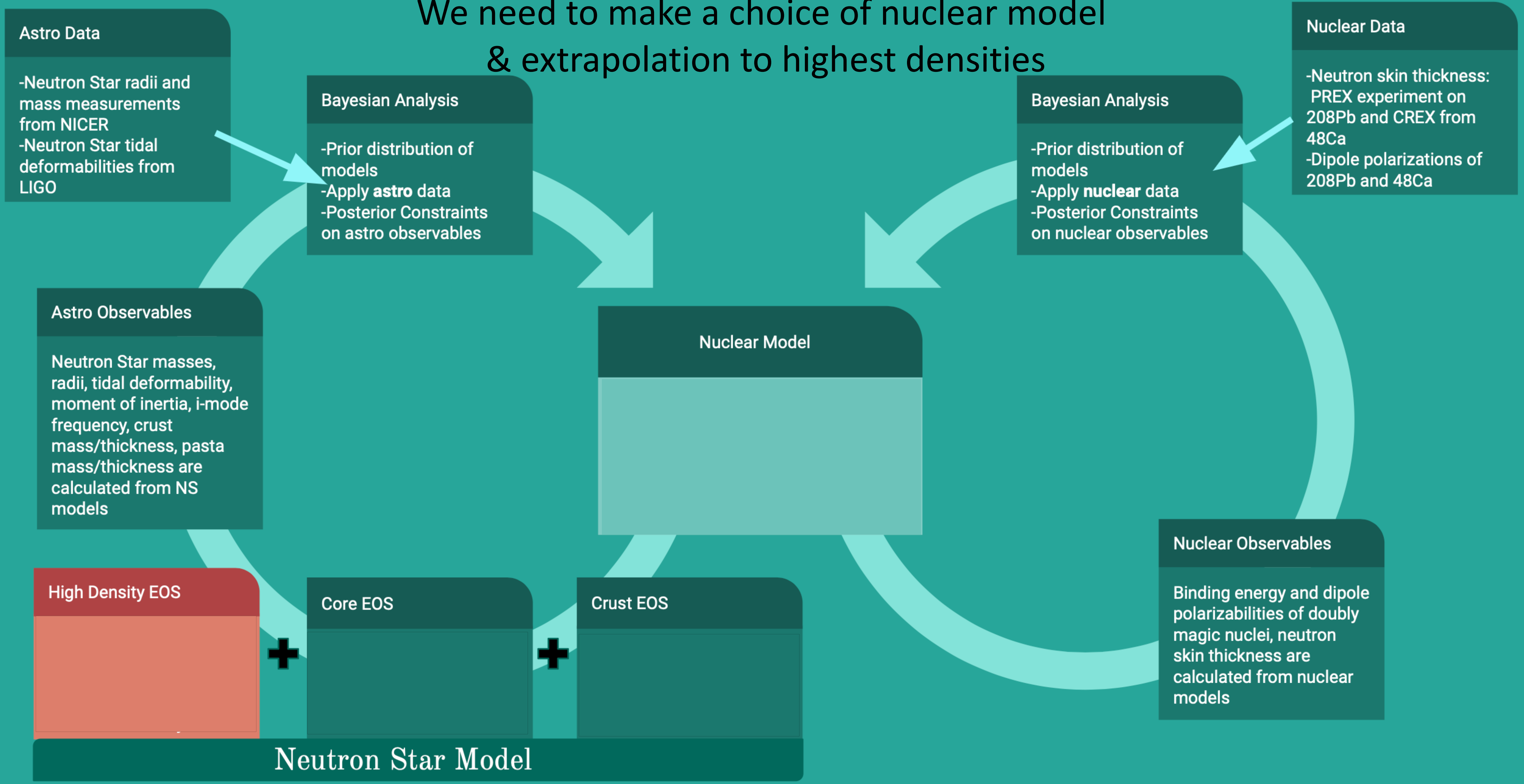
Figure: Artist's impression of a LMXB - credit Tony Piro, 2005.

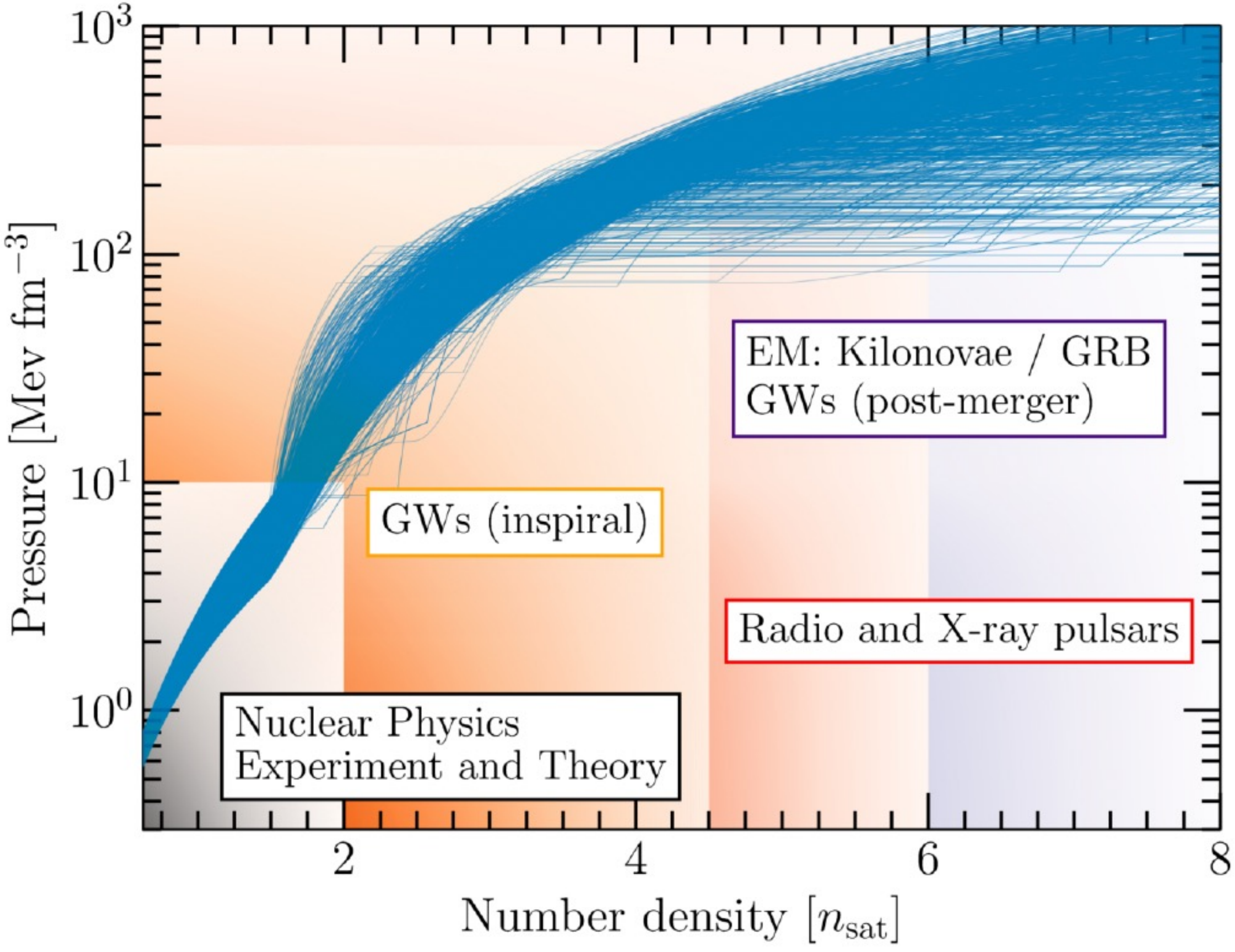
Putting the Multi in Multi-messenger

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

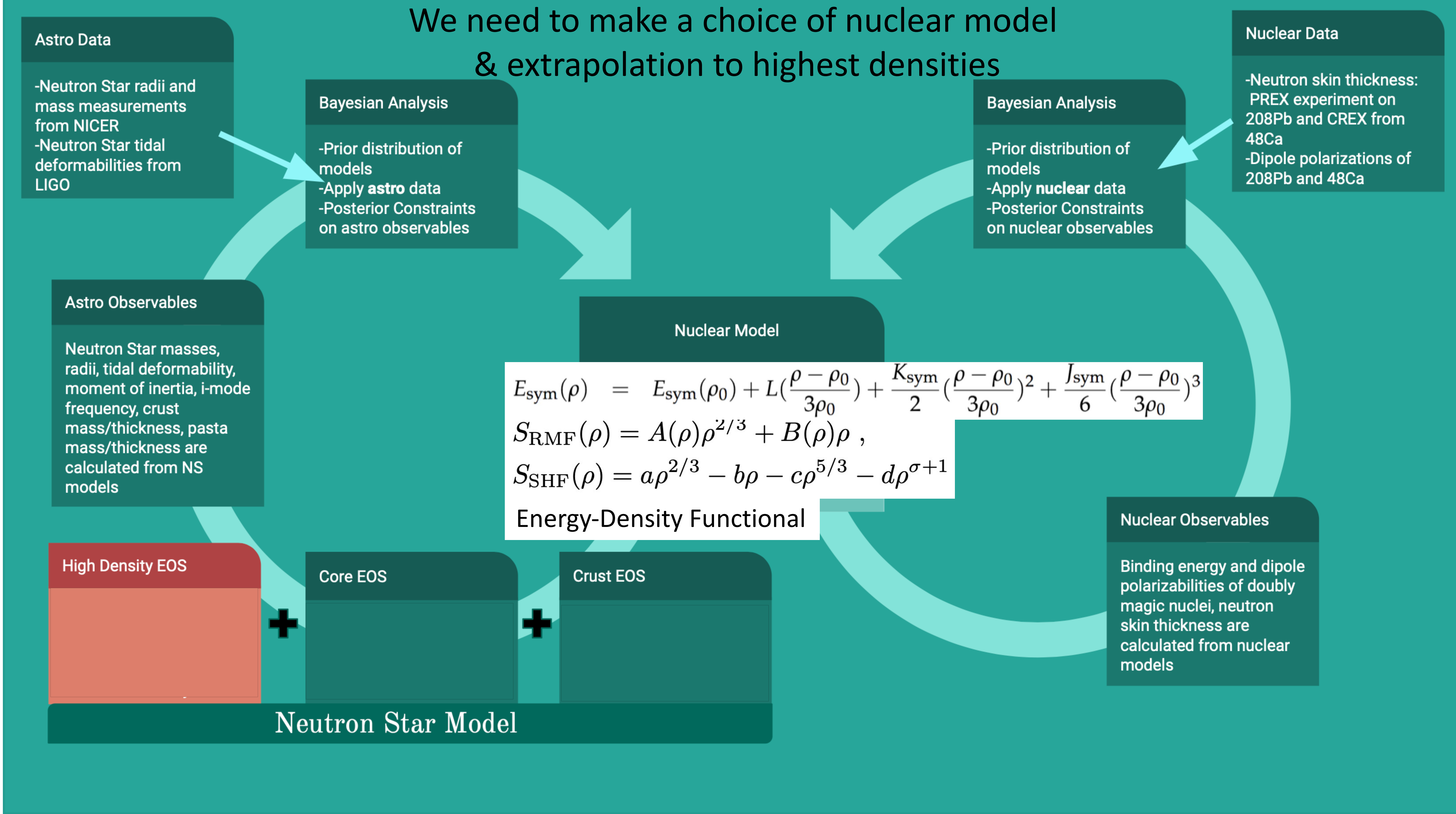
What do we want to do with this (potential data)?

We need to make a choice of nuclear model & extrapolation to highest densities

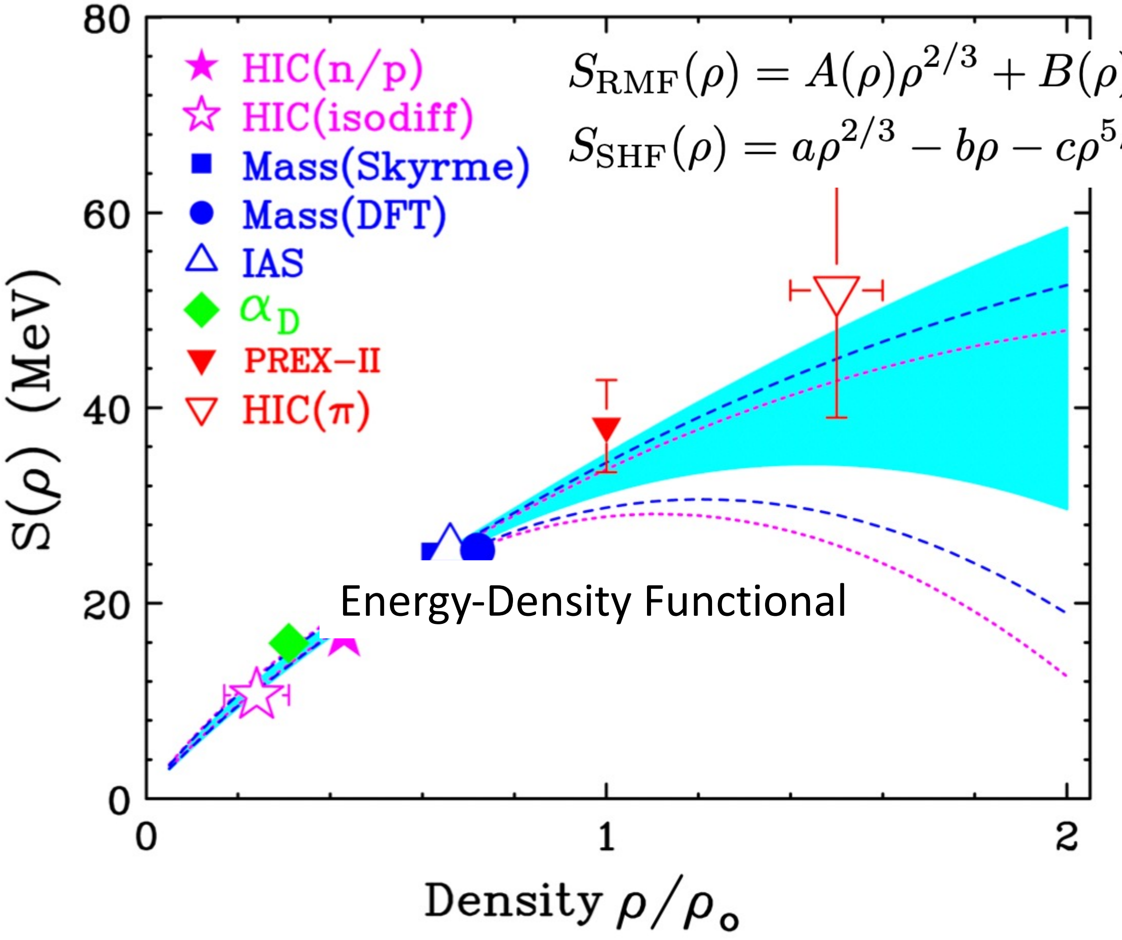




Pang et al, arxiv:2205.08513


We need to make a choice of nuclear model
& extrapolation to highest densities
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
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
$E_{\rm sym}(\rho) = E_{\rm sym}(\rho_0) + L(\frac{\rho-\rho_0}{3\rho_0}) + \frac{K_{\rm sym}}{2}(\frac{\rho-\rho_0}{3\rho_0})^2 + \frac{J_{\rm sym}}{6}(\frac{\rho-\rho_0}{3\rho_0})^3$
$S_{\rm RMF}(\rho) = A(\rho)\rho^{2/3} + B(\rho)\rho$,
$S_{\rm SHF}(\rho) = a\rho^{2/3} - b\rho - c\rho^{5/3} - d\rho^{\sigma+1}$
Energy-Density Functional
Nuclear Observables
Binding energy and dipole polarizabilities of doubly magic nuclei, neutron skin thickness are calculated from nuclear models
High Density EOS
Core EOS
Crust EOS
Neutron Star Model

Different observables give nuclear matter constraints at different densities

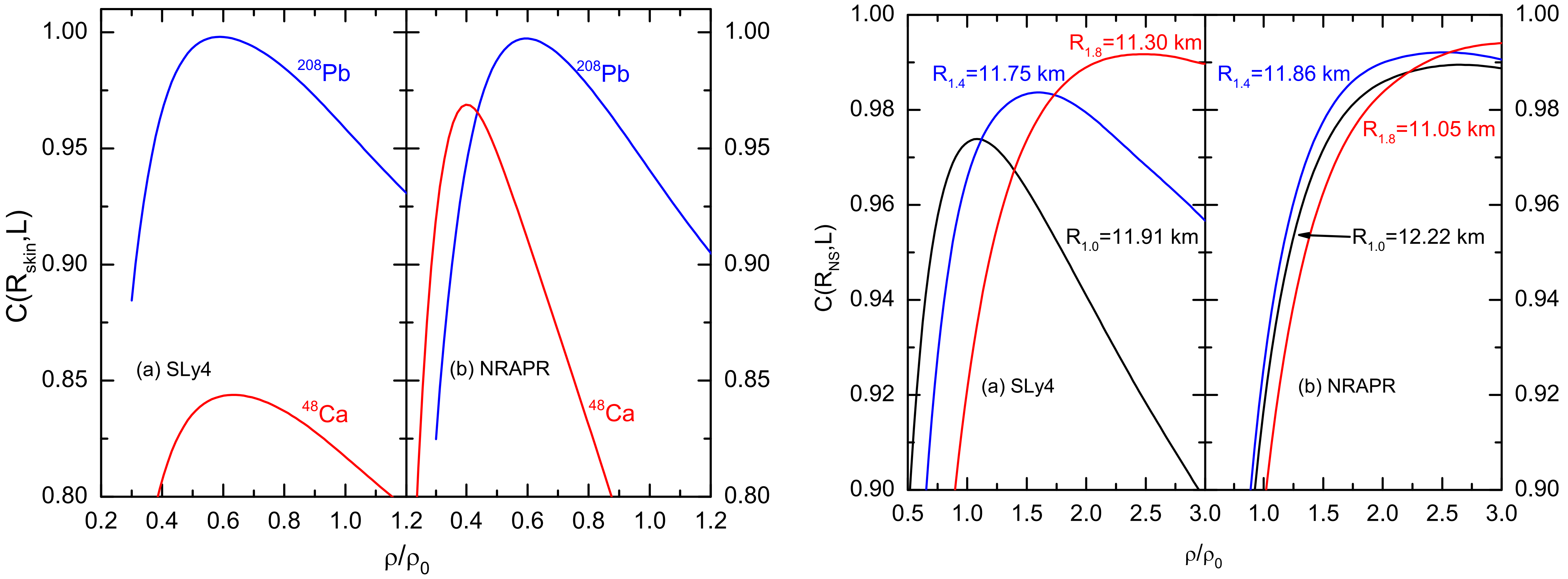


$$S_{\mathrm{RMF}}(\rho) = A(\rho)\rho^{2/3} + B(\rho)\rho\ ,$$

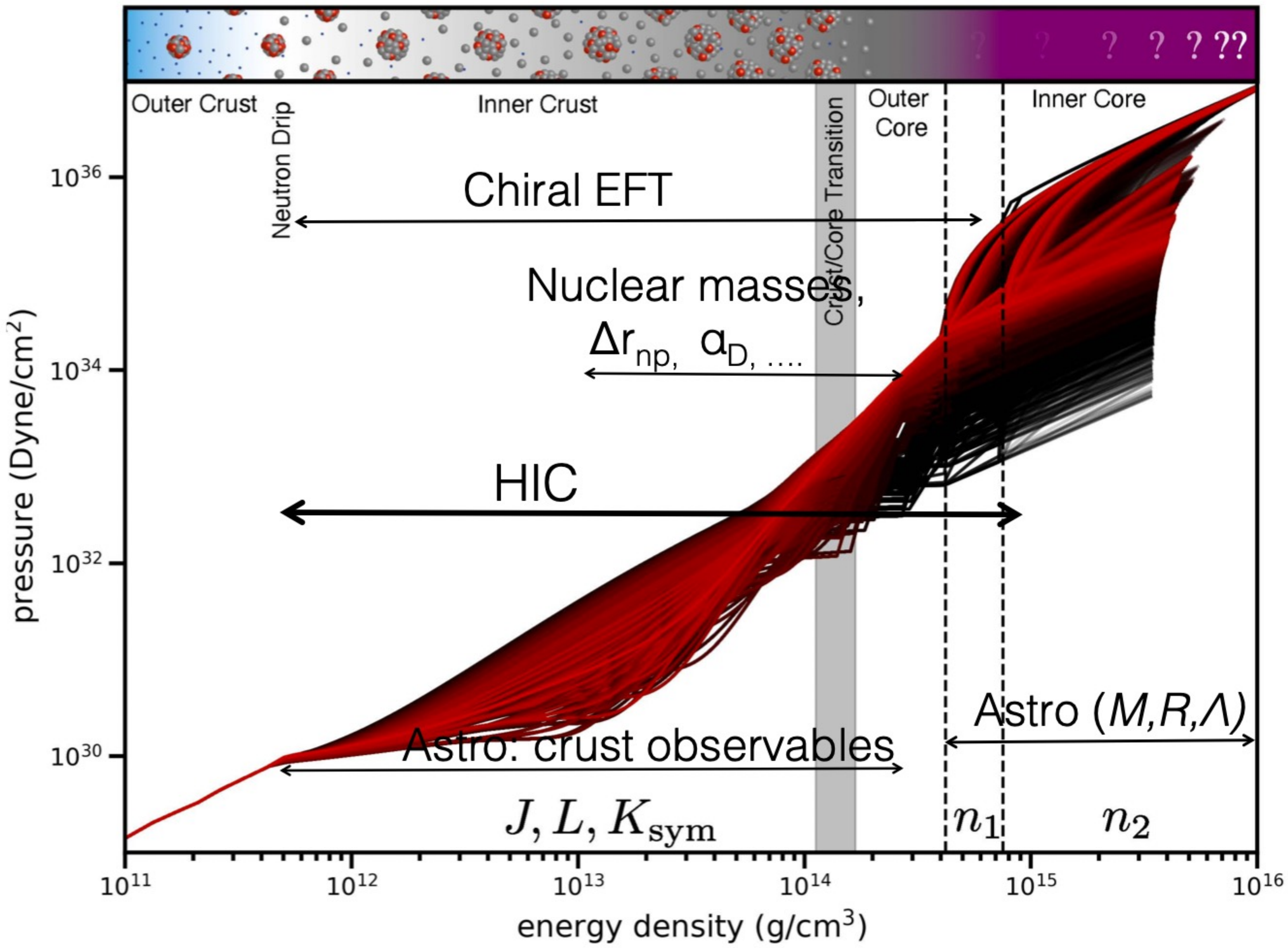
$$S_{\mathrm{SHF}}(\rho) = a\rho^{2/3} - b\rho - c\rho^{5/3} - d\rho^{\sigma+1}$$

Tsang and Lynch, arxiv:2106.10119

Different observables give nuclear matter constraints at different densities

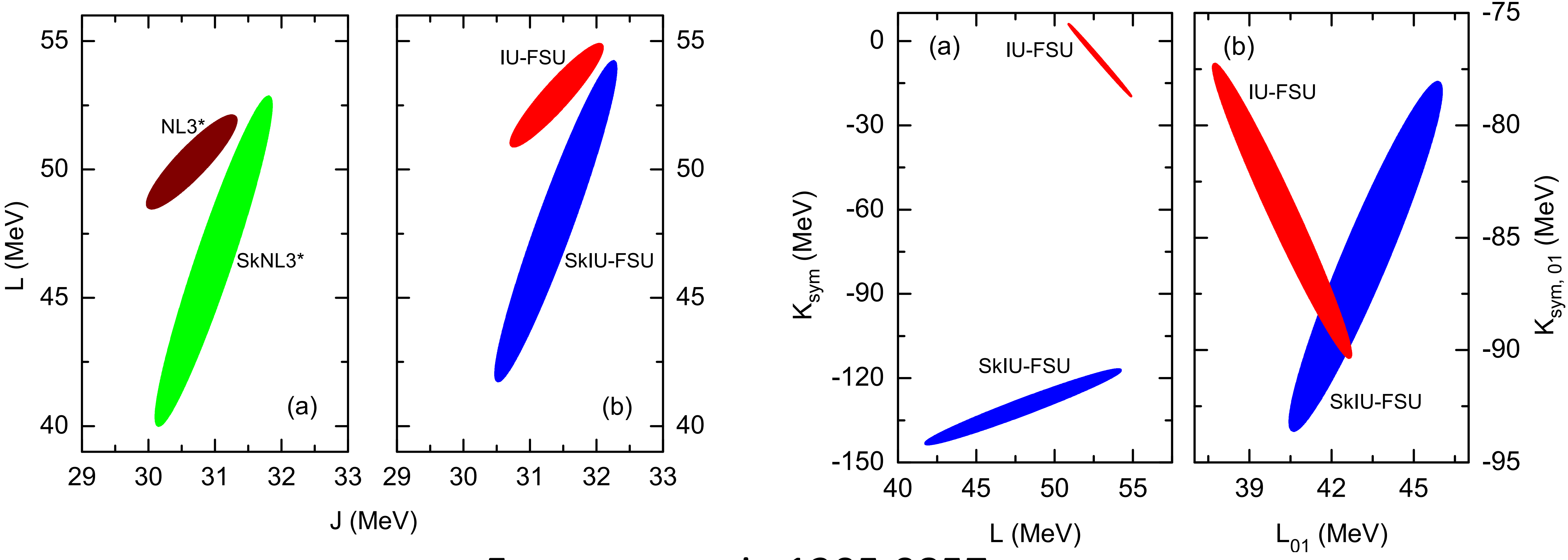


Fattoyev+ arxiv:1405.0750



Neill+ 2208.00994; Sorenson+ 2301.13253

Models can share some of the same nuclear matter parameters (e.g. J, L) but different density dependences leads to different inferences of the higher-order nuclear matter parameters (e.g. K_{sym})



Fattoyev+ arxiv:1205.0857

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)

More systematic: map nuclear matter parameters to model parameters and systematically generate models

$$\begin{bmatrix} t_0 \\ \vdots \\ t_4 \\ x_0 \\ \vdots \\ x_4 \\ \alpha_3 \\ \alpha_4 \end{bmatrix} \longleftarrow \begin{bmatrix} E_0 \\ K_0 \\ n_0 \\ m_{\mathrm{p}}^* \\ m_{\mathrm{n}}^* \\ G_{\mathrm{s}} \\ G_{\mathrm{v}} \\ J \\ L \\ K_{\mathrm{sym}} \end{bmatrix}$$

SNM

Dynamics of n,p

Surface energy

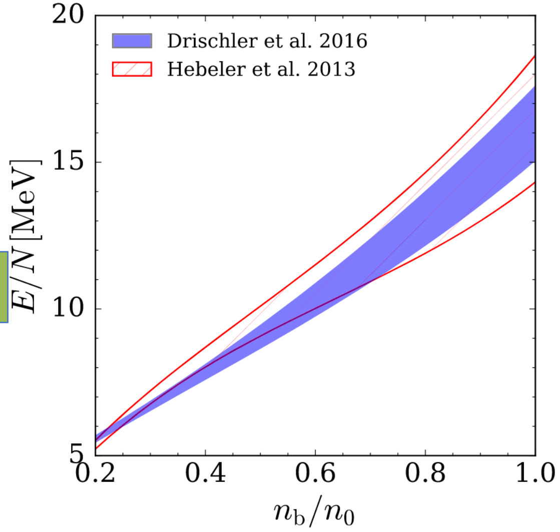
Symmetry Energy

More systematic: map nuclear matter parameters to model parameters and systematically generate models

$$\begin{bmatrix} x_0 \\ x_3 \\ x_4 \end{bmatrix} \leftarrow \begin{bmatrix} J \\ L \\ K_{\rm sym} \end{bmatrix}$$

$$\begin{bmatrix} t_0 \\ \vdots \\ t_4 \\ x_1 \\ x_2 \end{bmatrix} \leftarrow \begin{bmatrix} E_0 \\ K_0 \\ n_0 \\ m_{\rm p}^* \\ m_{\rm n}^* \\ G_{\rm s} \\ G_{\rm v} \end{bmatrix} \begin{bmatrix} x_0 \\ x_3 \\ x_4 \end{bmatrix}$$

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



Haensel, Fortin JPhysG 2017
Lim, Holt arXiv:1702.02898

Nuclear masses,
giant resonances

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

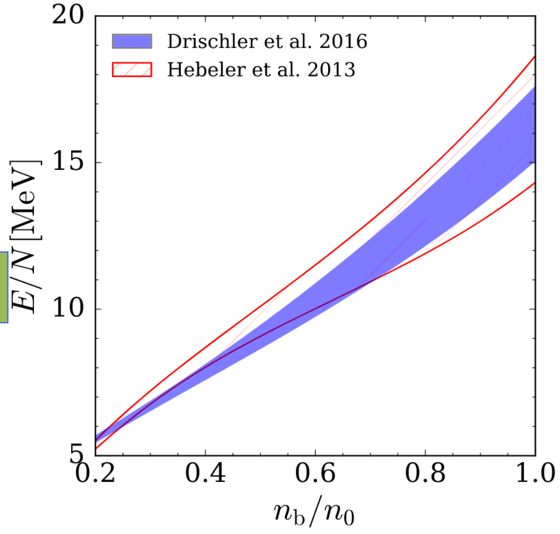
Lim, Holt arXiv:1702.02898

Let's put this to use

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

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

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

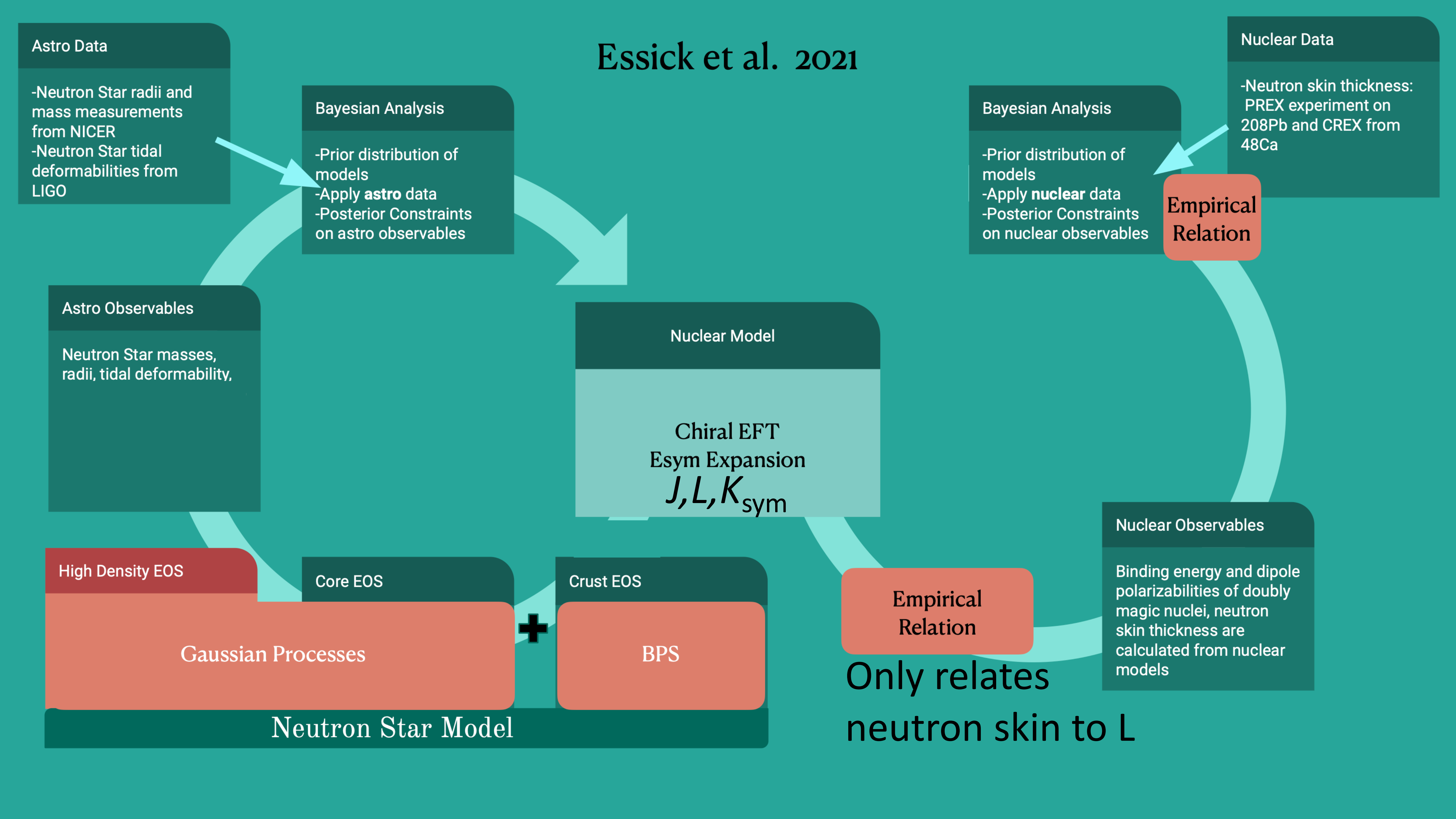


Haensel, Fortin JPhysG 2017
Lim, Holt arXiv:1702.02898

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



Essick et al. 2021
Astro Data
-Neutron Star radii and mass measurements from NICER
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Bayesian Analysis
-Prior distribution of models
-Apply **astro** data
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Neutron Star masses, radii, tidal deformability,
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Chiral EFT
Esym Expansion
J, L, K_{sym}
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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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Neutron Star masses, radii, tidal deformability,

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+

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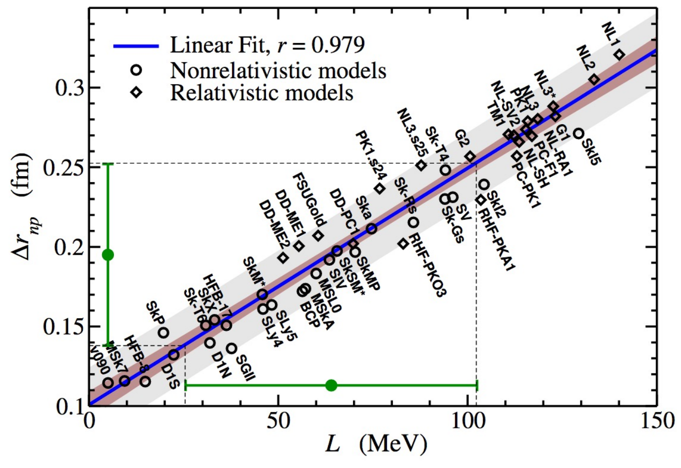
Empirical Relation



Roca-Maza et al, arxiv:1103.1762

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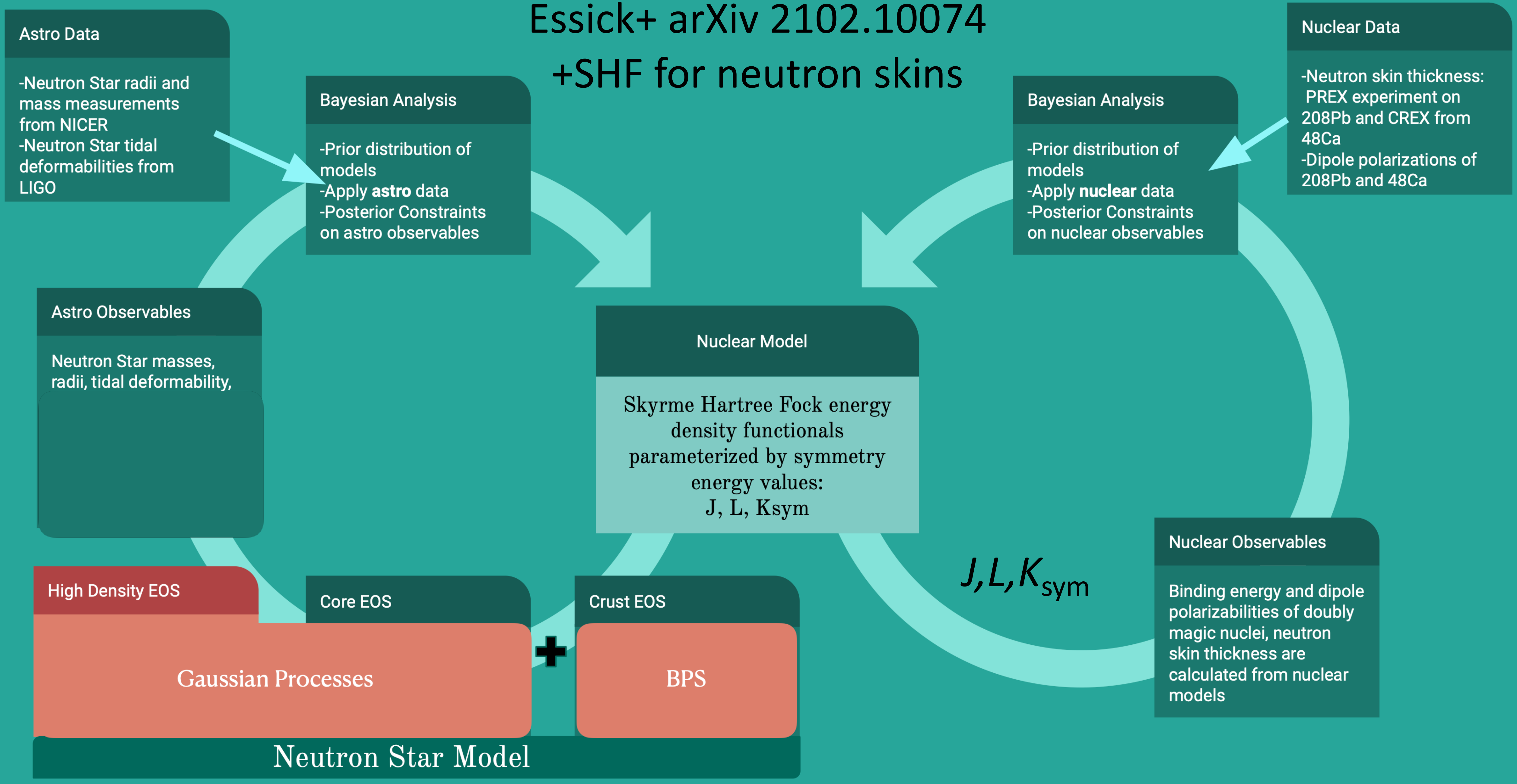
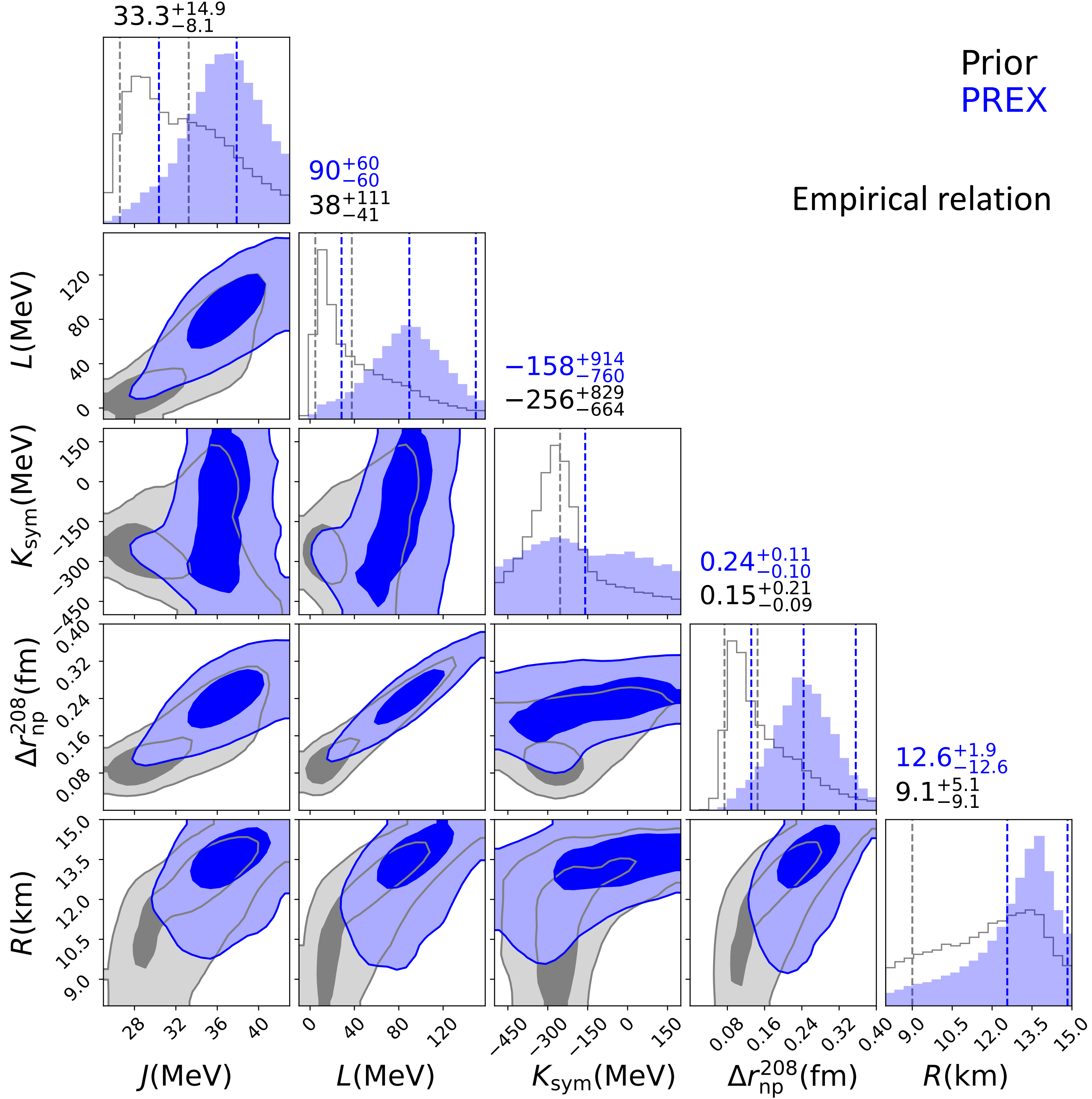
Empirical Relation

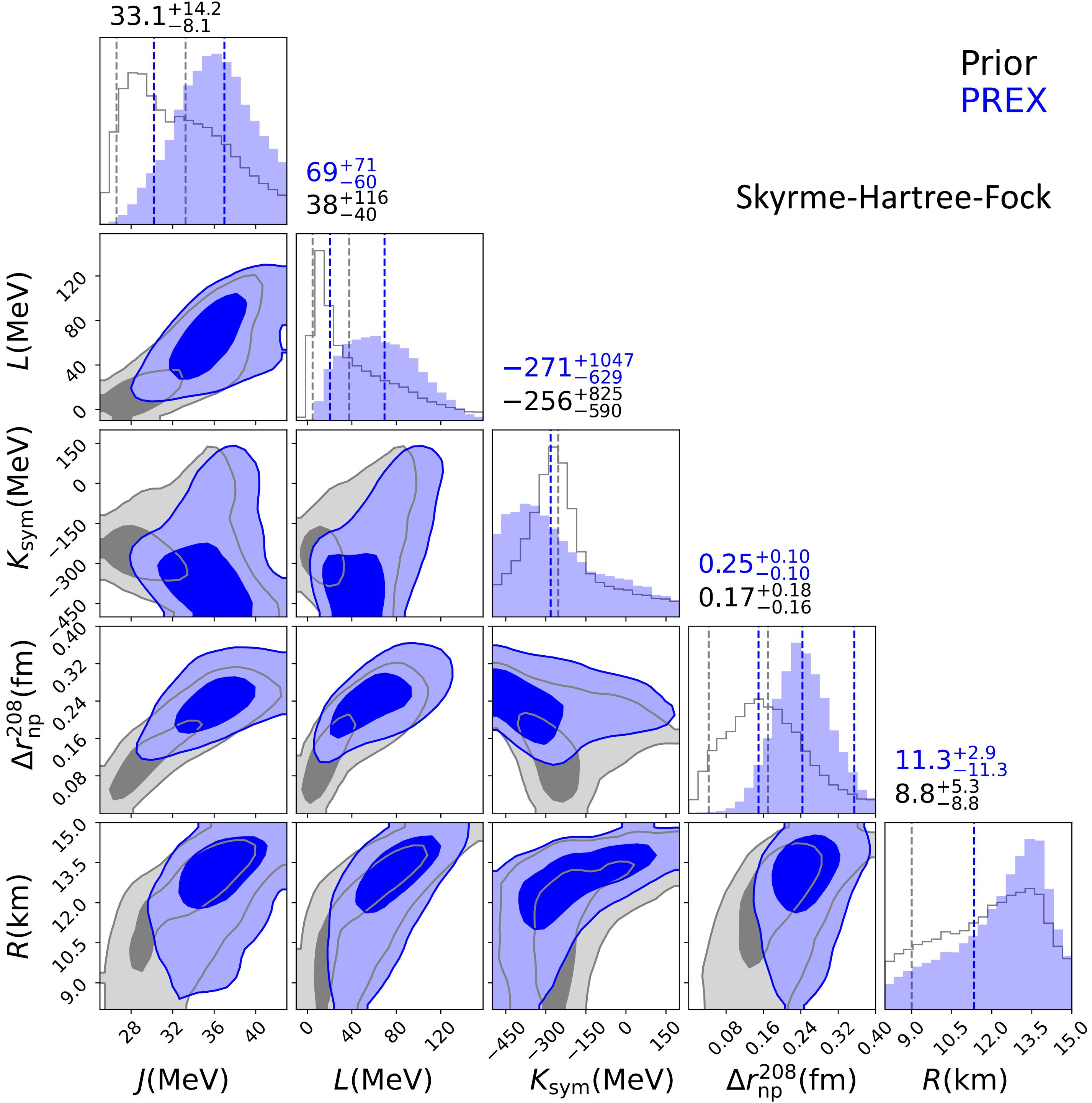
Only relates neutron skin to L

Essick+ arXiv 2102.10074
+SHF for neutron skins

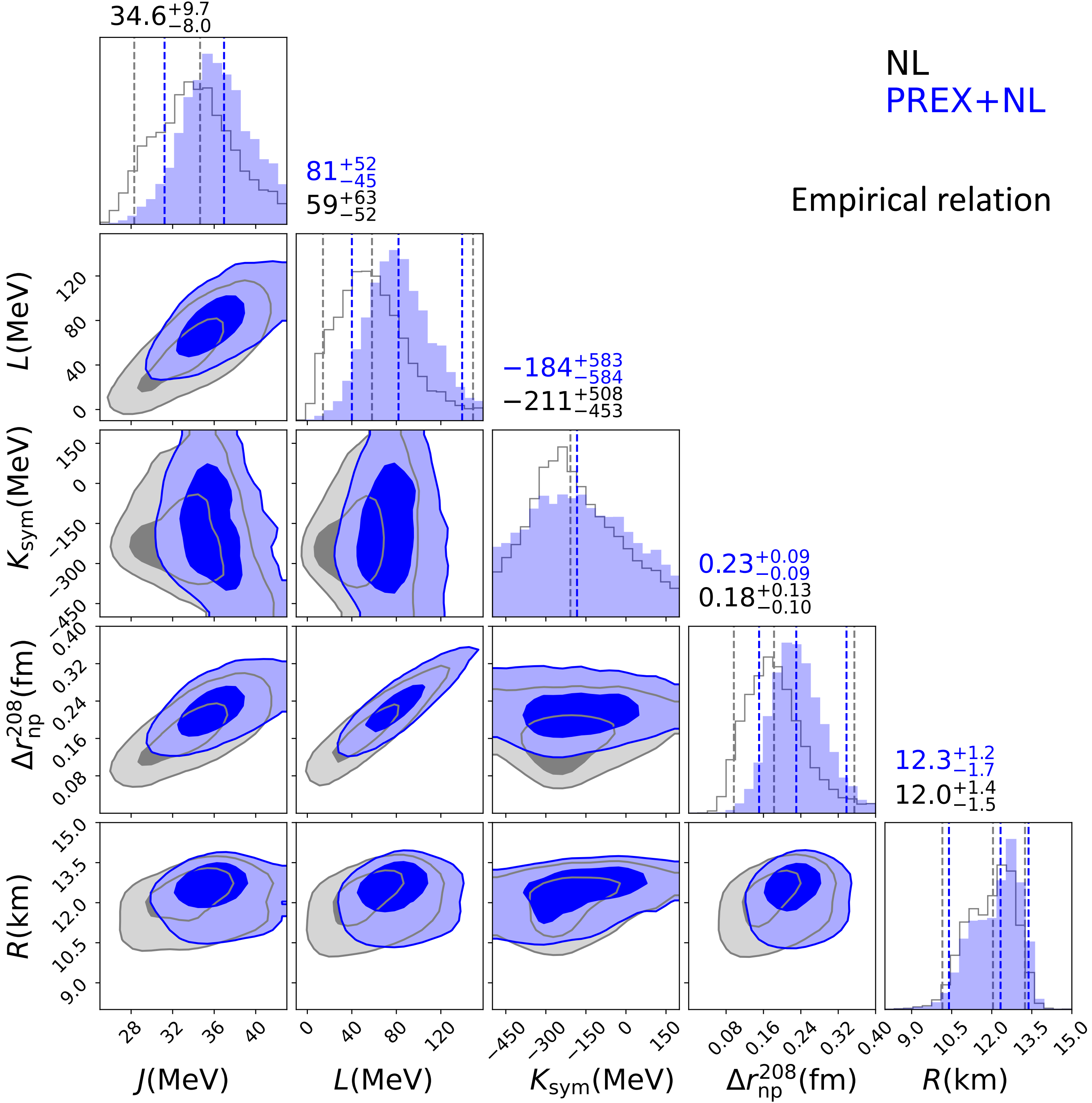




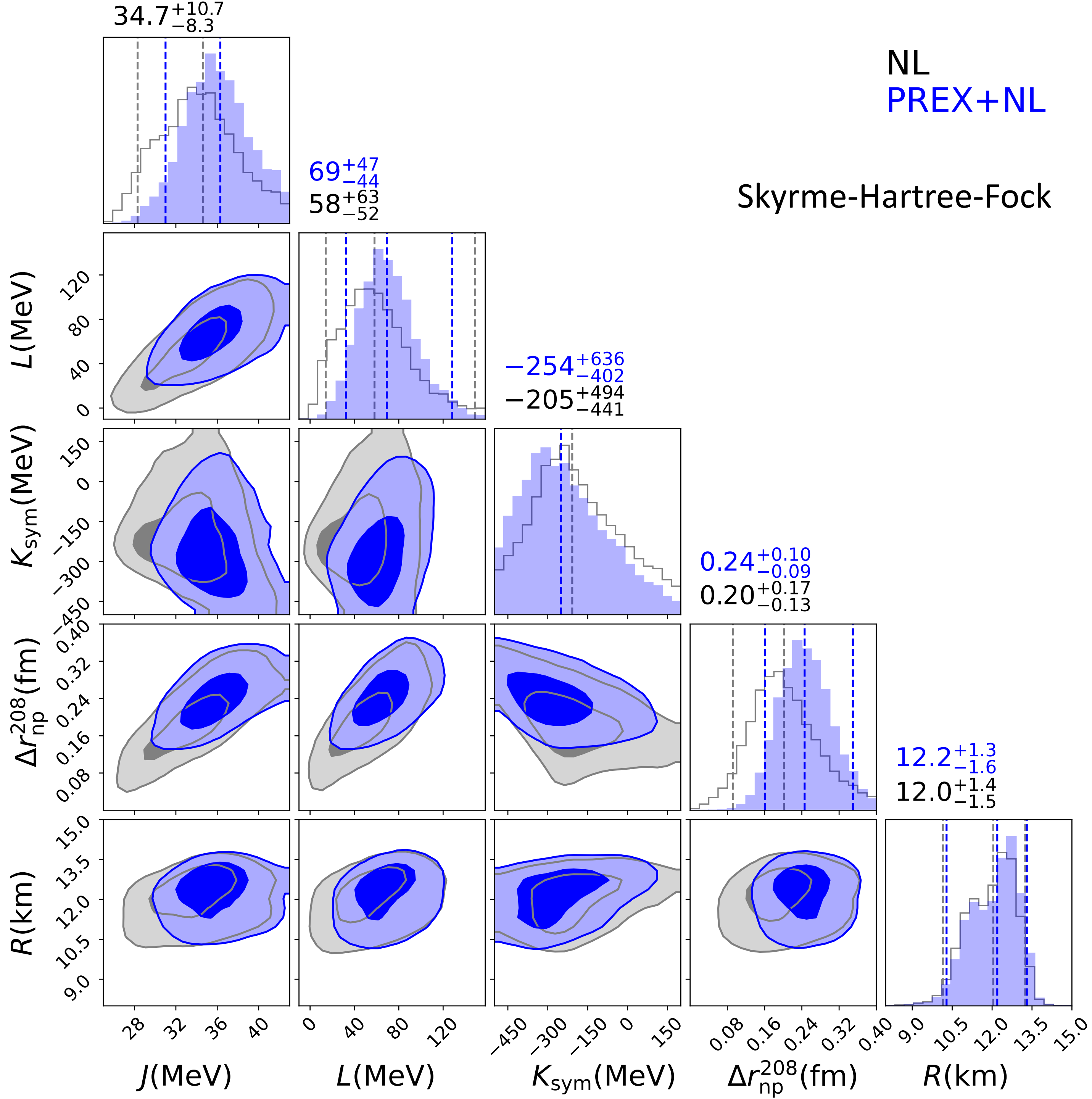
Prior
PREX
Empirical relation
33.3 +14.9 −8.1
90 +60 −60
38 +111 −41
−158 +914 −760
−256 +829 −664
0.24 +0.11 −0.10
0.15 +0.21 −0.09
12.6 +1.9 −12.6
9.1 +5.1 −9.1
J(MeV)
L(MeV)
K_sym(MeV)
Δr_np^208(fm)
R(km)



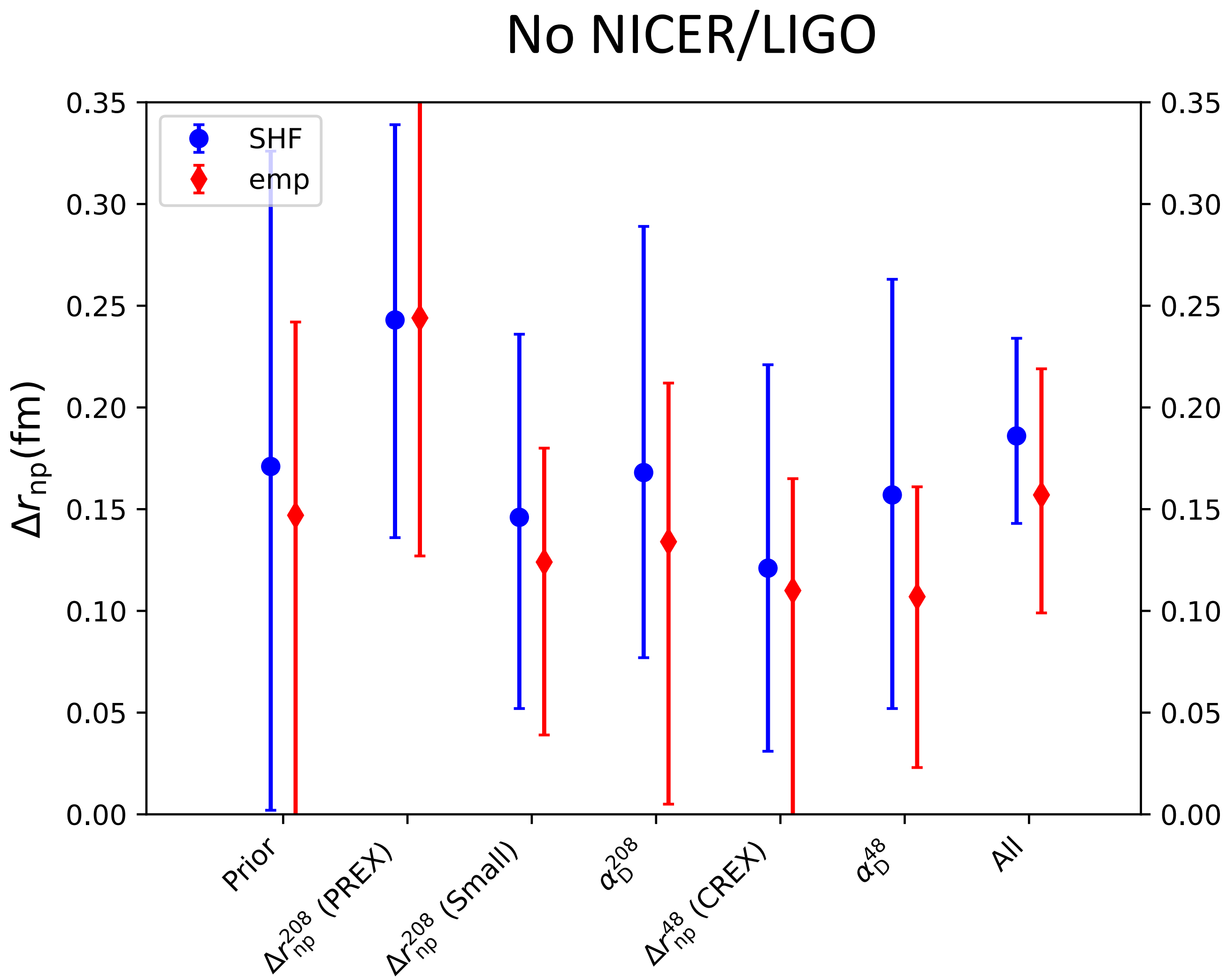
Prior
PREX
Skyrme-Hartree-Fock
33.1+14.2 −8.1
69+71 −60
38+116 −40
−271+1047 −629
−256+825 −590
0.25+0.10 −0.10
0.17+0.18 −0.16
11.3+2.9 −11.3
8.8+5.3 −8.8
J(MeV)
L(MeV)
Ksym(MeV)
Δr208np(fm)
R(km)

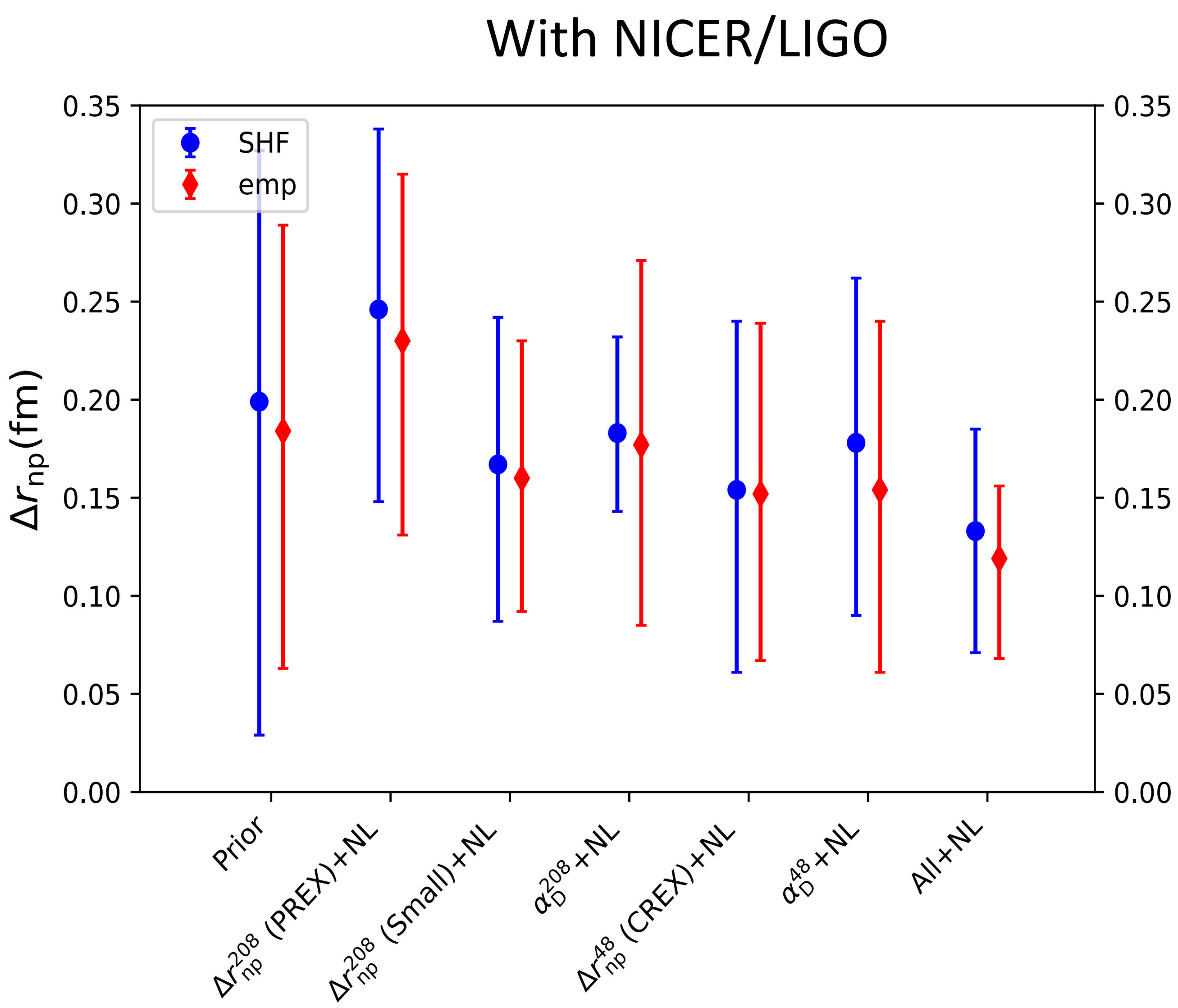


NL
PREX+NL
Empirical relation
34.6$^{+9.7}_{-8.0}$
81$^{+52}_{-45}$
59$^{+63}_{-52}$
−184$^{+583}_{-584}$
−211$^{+508}_{-453}$
0.23$^{+0.09}_{-0.09}$
0.18$^{+0.13}_{-0.10}$
12.3$^{+1.2}_{-1.7}$
12.0$^{+1.4}_{-1.5}$
L(MeV)
$K_{\rm sym}$(MeV)
$\Delta r_{\rm np}^{208}$(fm)
R(km)
J(MeV)



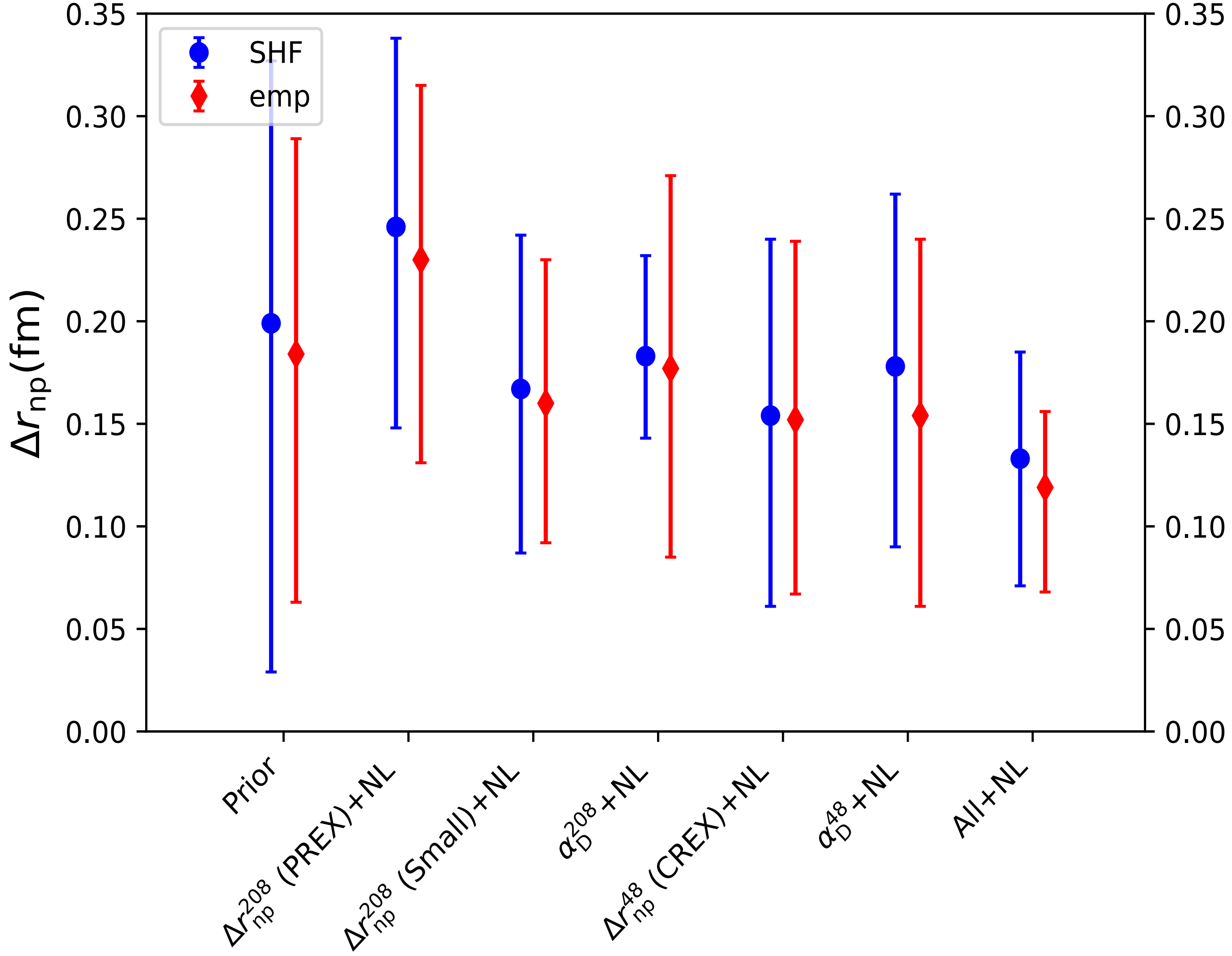
NL
PREX+NL
Skyrme-Hartree-Fock
$34.7^{+10.7}_{-8.3}$
69^{+47}_{-44}
58^{+63}_{-52}
-254^{+636}_{-402}
-205^{+494}_{-441}
$0.24^{+0.10}_{-0.09}$
$0.20^{+0.17}_{-0.13}$
$12.2^{+1.3}_{-1.6}$
$12.0^{+1.4}_{-1.5}$
J(MeV)
L(MeV)
K_{sym}(MeV)
Δr_{np}^{208}(fm)
R(km)


No NICER/LIGO
Δr_{np}(fm)
SHF
emp
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
Prior
Δr_{np}^{208} (PREX)
Δr_{np}^{208} (Small)
α_D^{208}
Δr_{np}^{48} (CREX)
α_D^{48}
All



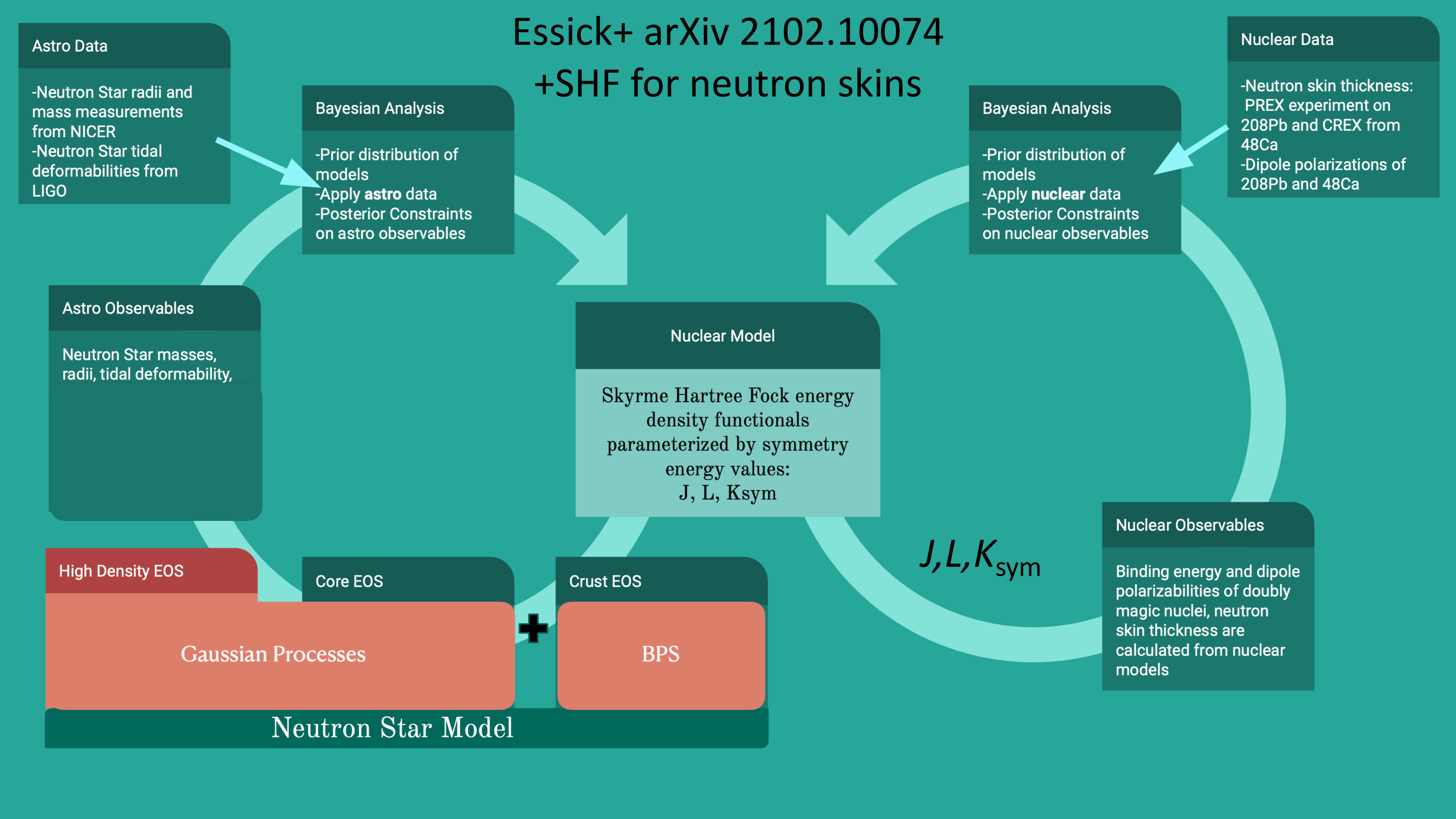
With NICER/LIGO
SHF
emp
Δr_{np}(fm)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Prior
Δr_{np}^{208} (PREX)+NL
Δr_{np}^{208} (Small)+NL
α_D^{208}+NL
Δr_{np}^{48} (CREX)+NL
α_D^{48}+NL
All+NL

With NICER/LIGO



There is a systematic difference in inferred values of nuclear and astrophysical observables when different models of nuclear matter and nuclear observables are used*

*(holds when chiral EFT PNM calculations are incorporated)


Essick+ arXiv 2102.10074
+SHF for neutron skins
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J, L, K_{sym}
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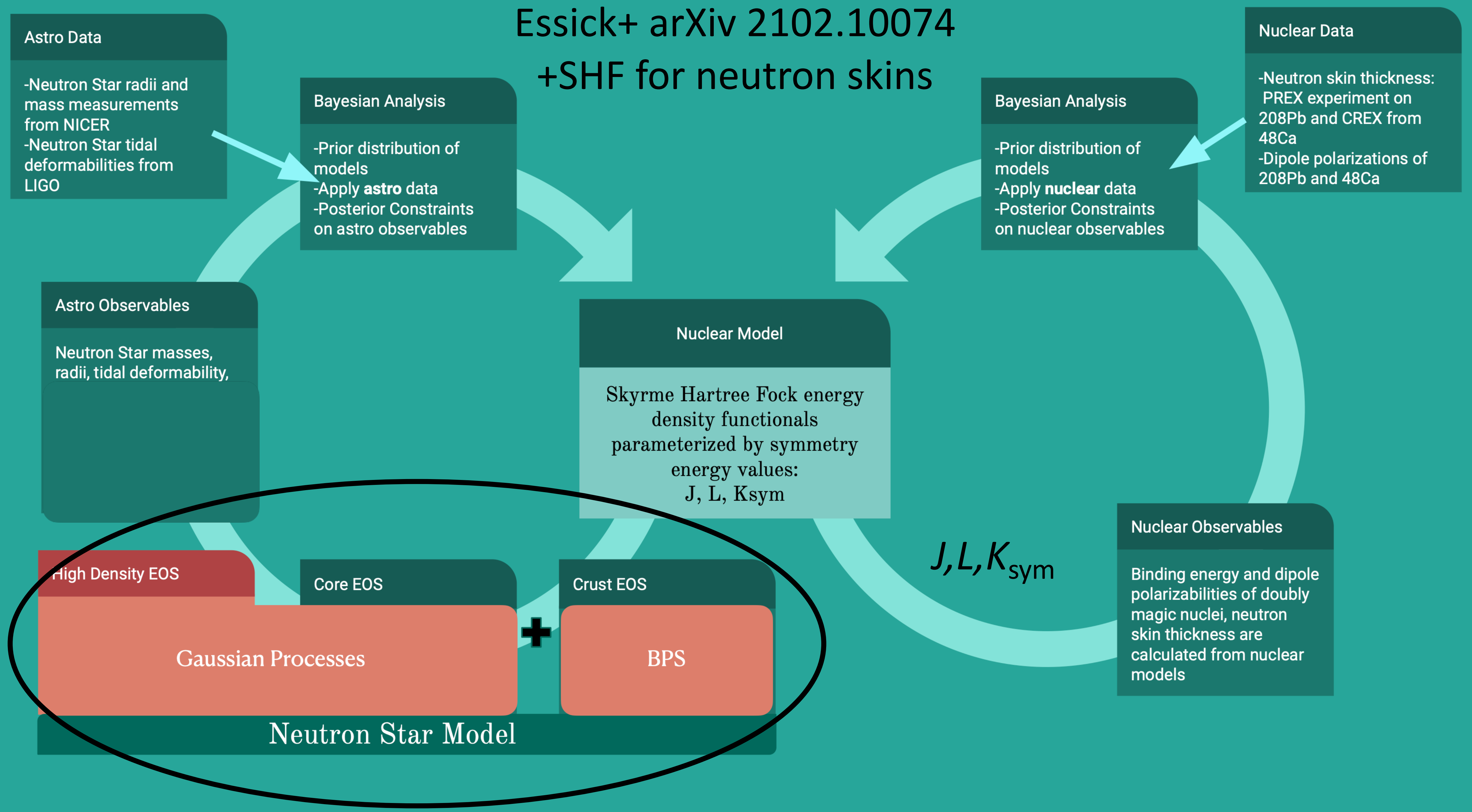
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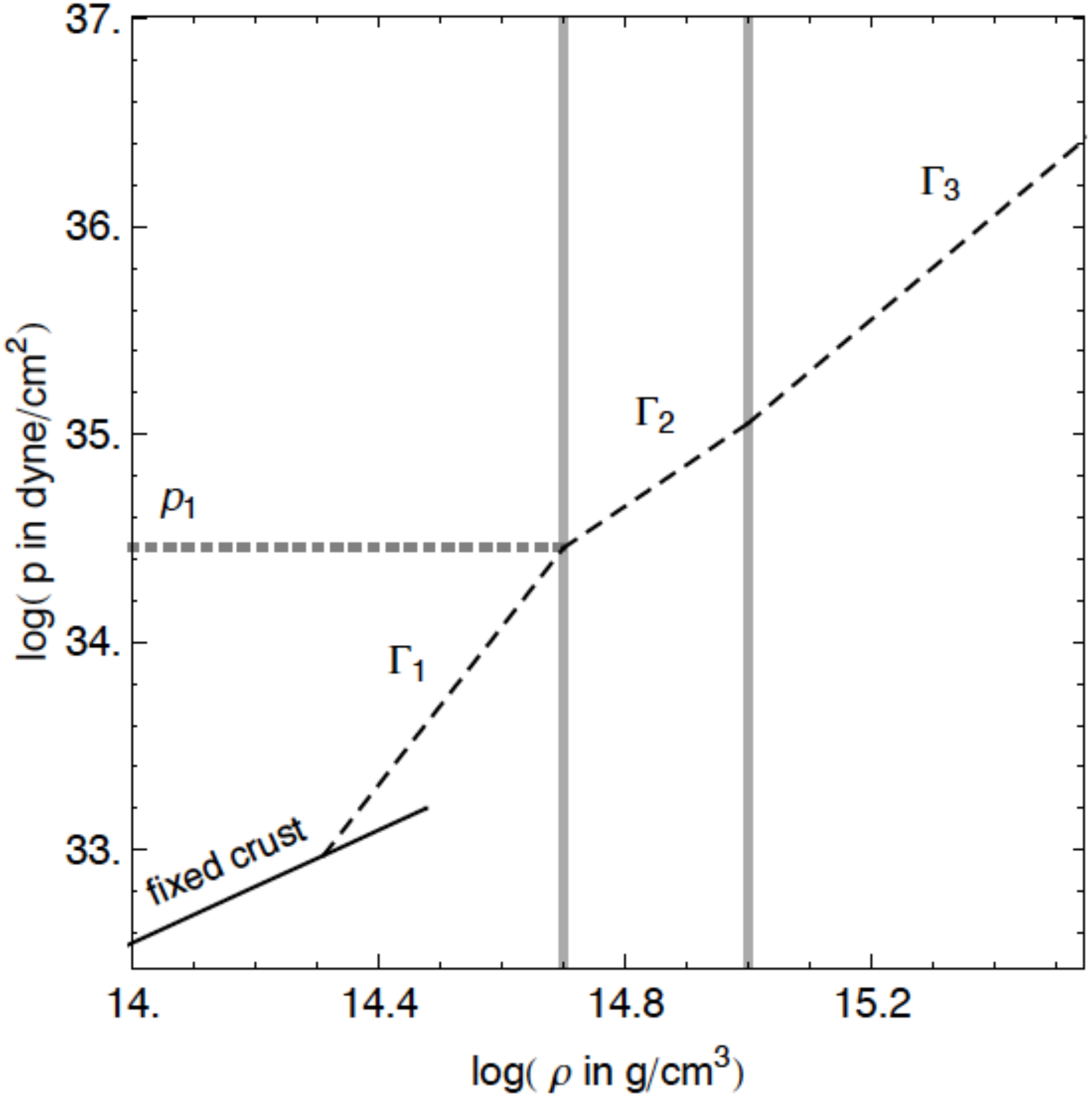
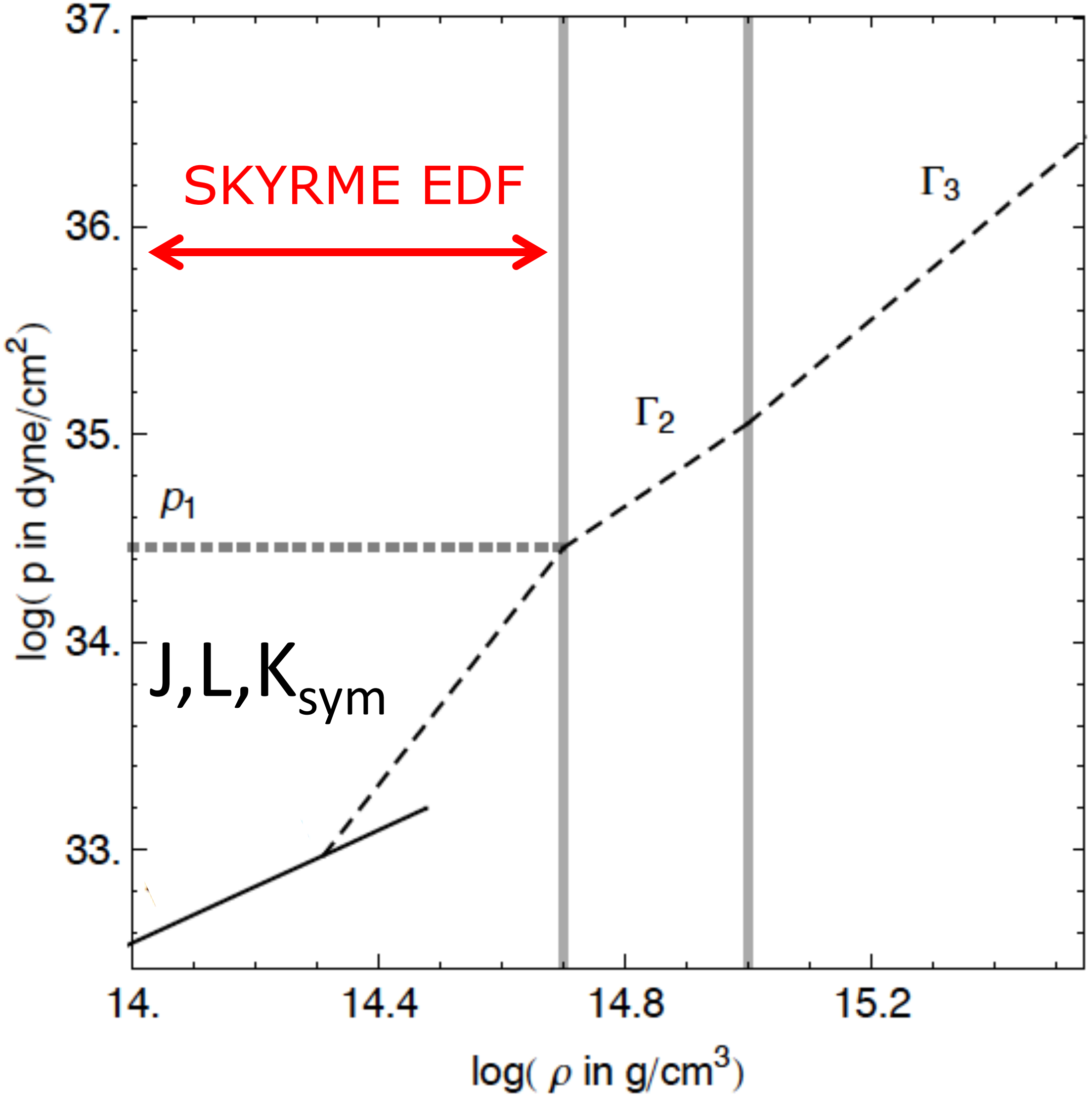
High density EOS: piecewise polytrope tuned to give max masses > 2.0 M_{SUN} up until causality is violated



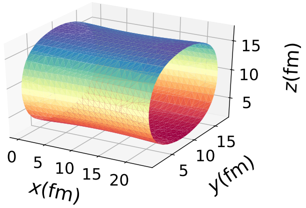
Read+, arxiv:0812.2163; see also works by Steiner, Lattimer, Özel

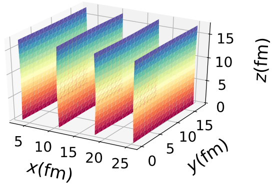
High density EOS: piecewise polytrope tuned to give max masses > 2.0 M_{SUN} up until causality is violated



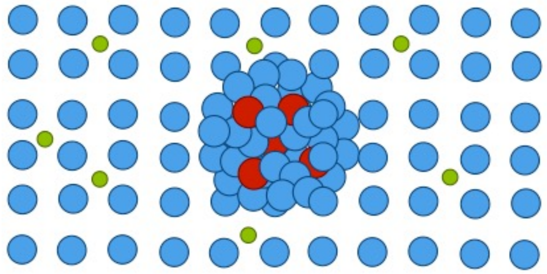
Read+, arxiv:0812.2163; see also works by Steiner, Lattimer, Özel...

Modeling the crust





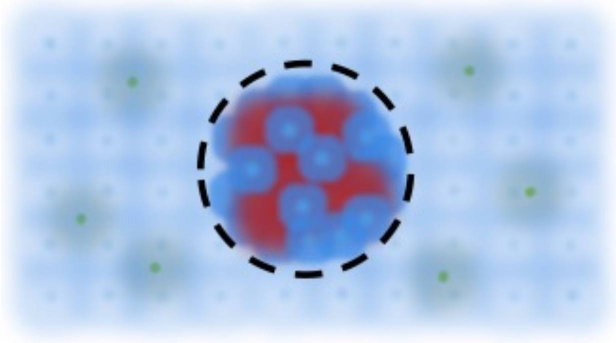
3D Skyrme HF:
n,p degrees of freedom



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

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

Nuclear EDF: Bulk+Gradient
Specific model: Skyrme

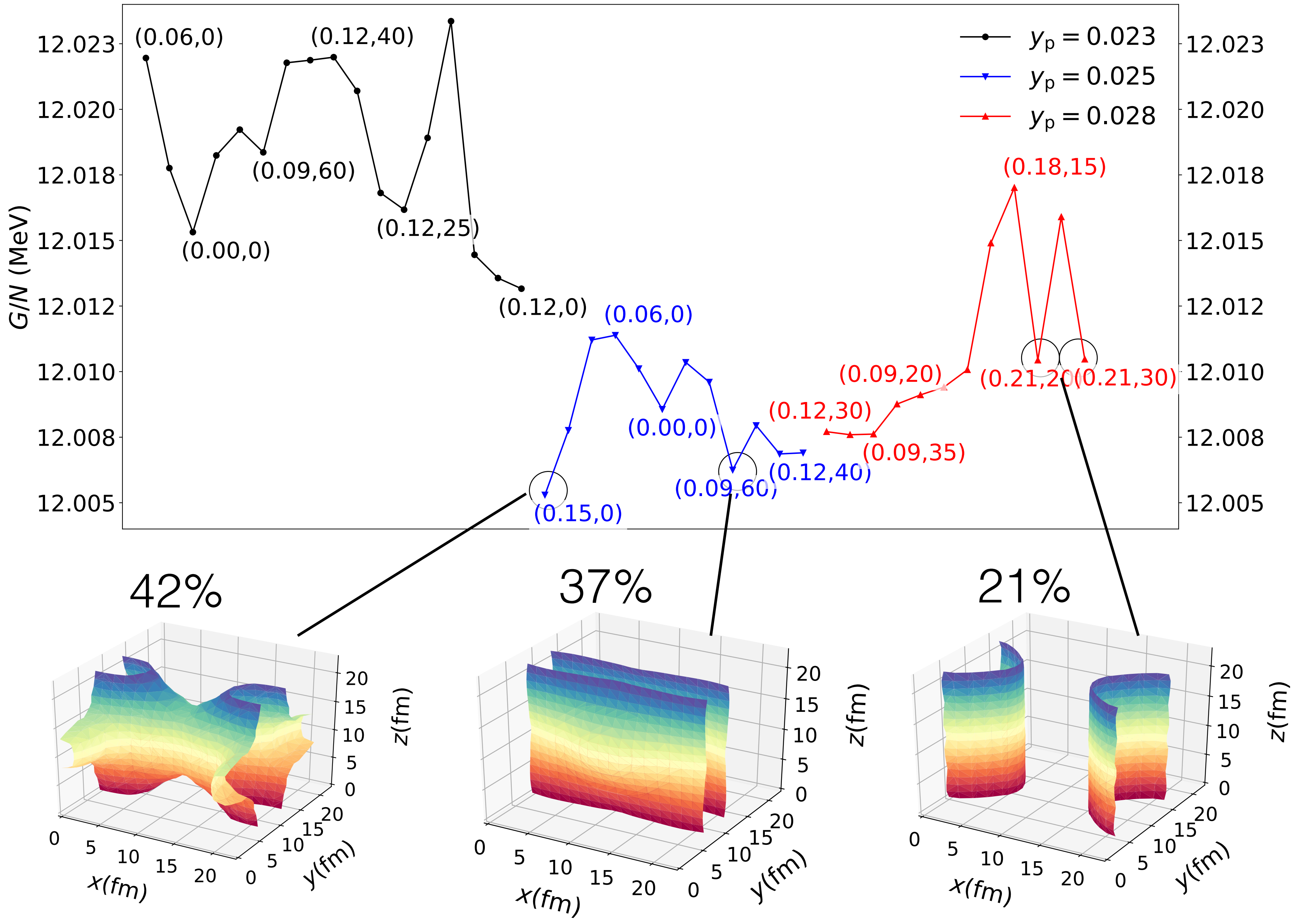
$$\mathcal{H}_\rho = \frac{1}{4}t_3\rho^{2+\alpha_3}[(2+x_3)-(2x_3+1)(y_p^2+y_n^2)] + \frac{1}{4}t_4\rho^{2+\alpha_4}[(2+x_4)-(2x_4+1)(y_p^2+y_n^2)]$$

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

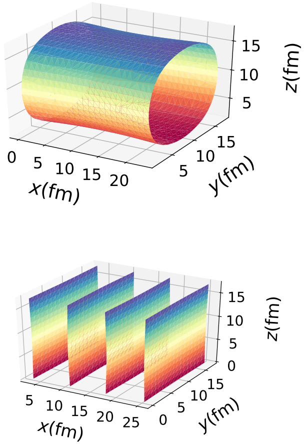
Nuclear EDF: Bulk +
separate surface energy function
specific model: LLPR 1985

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

Different pastas occupy different local minima



Modeling the crust



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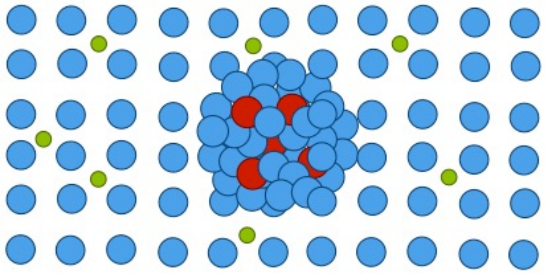

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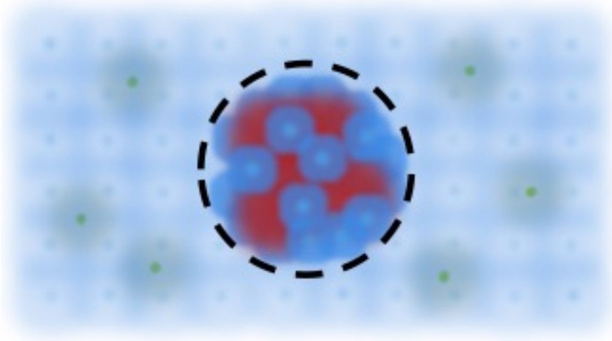
$$+ \frac{1}{4} t_4 \rho^{2+\alpha_4}[(2 + x_4) - (2x_4 + 1)(y_p^2 + y_n^2)]$$

CLDM:Bulk fluid and surface degrees of freedom



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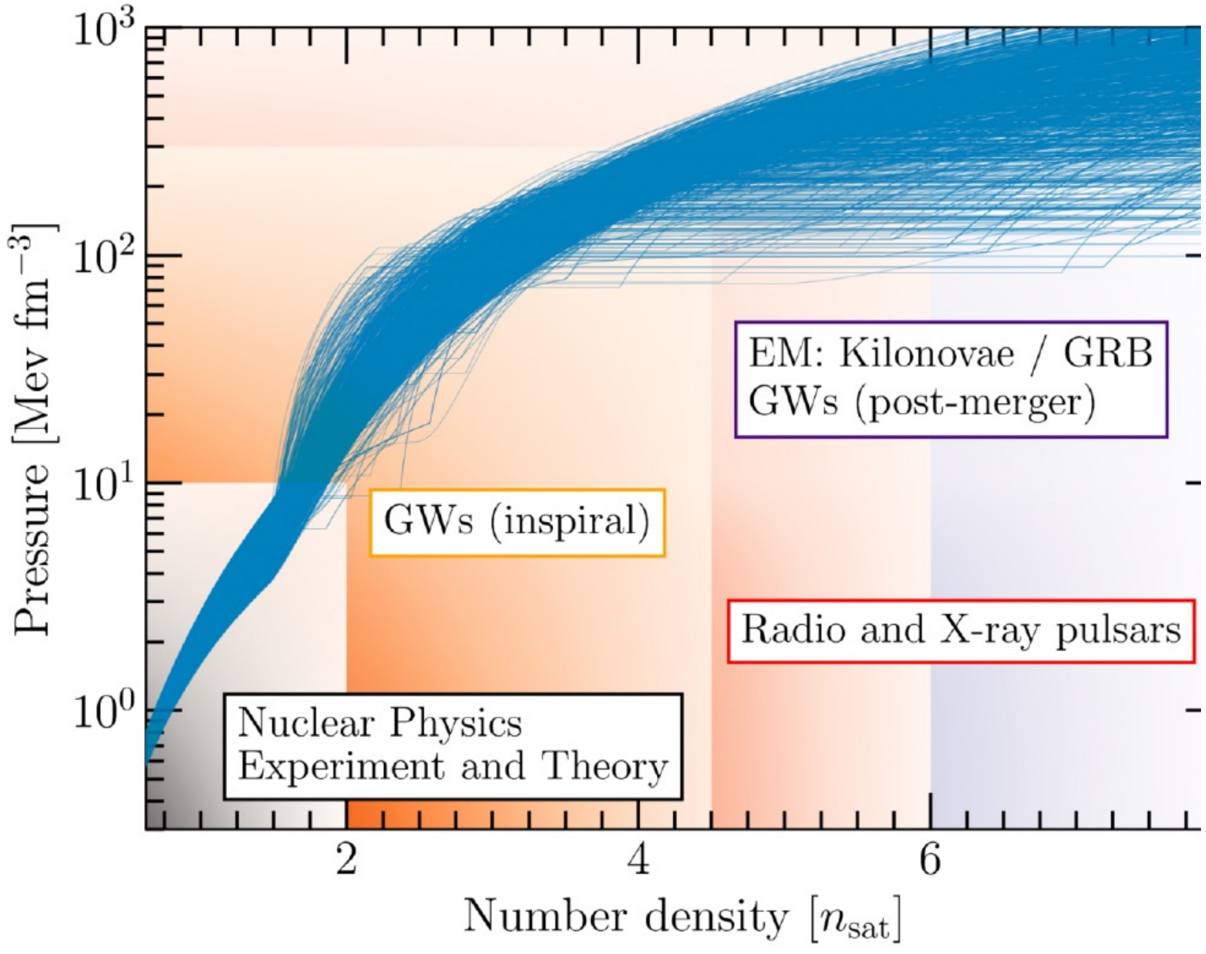
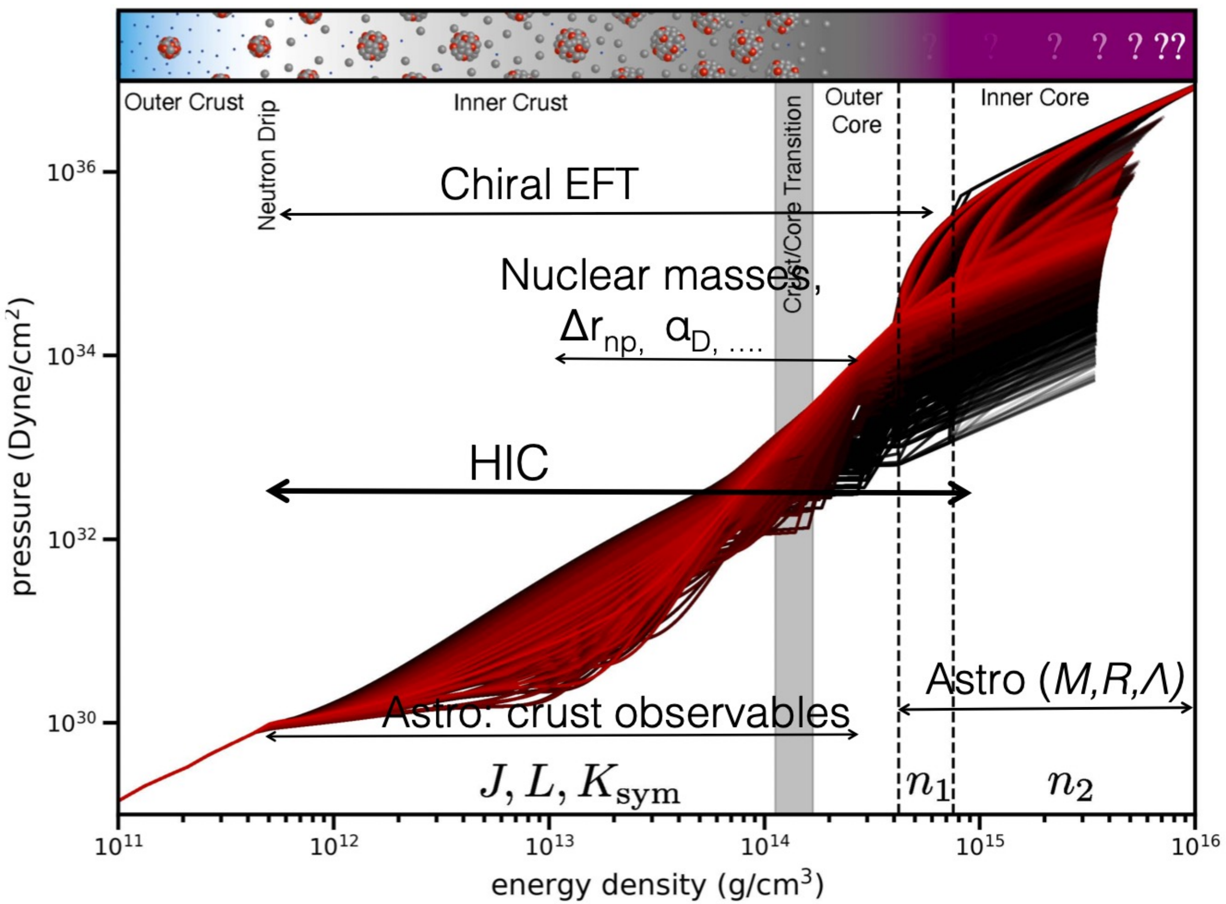
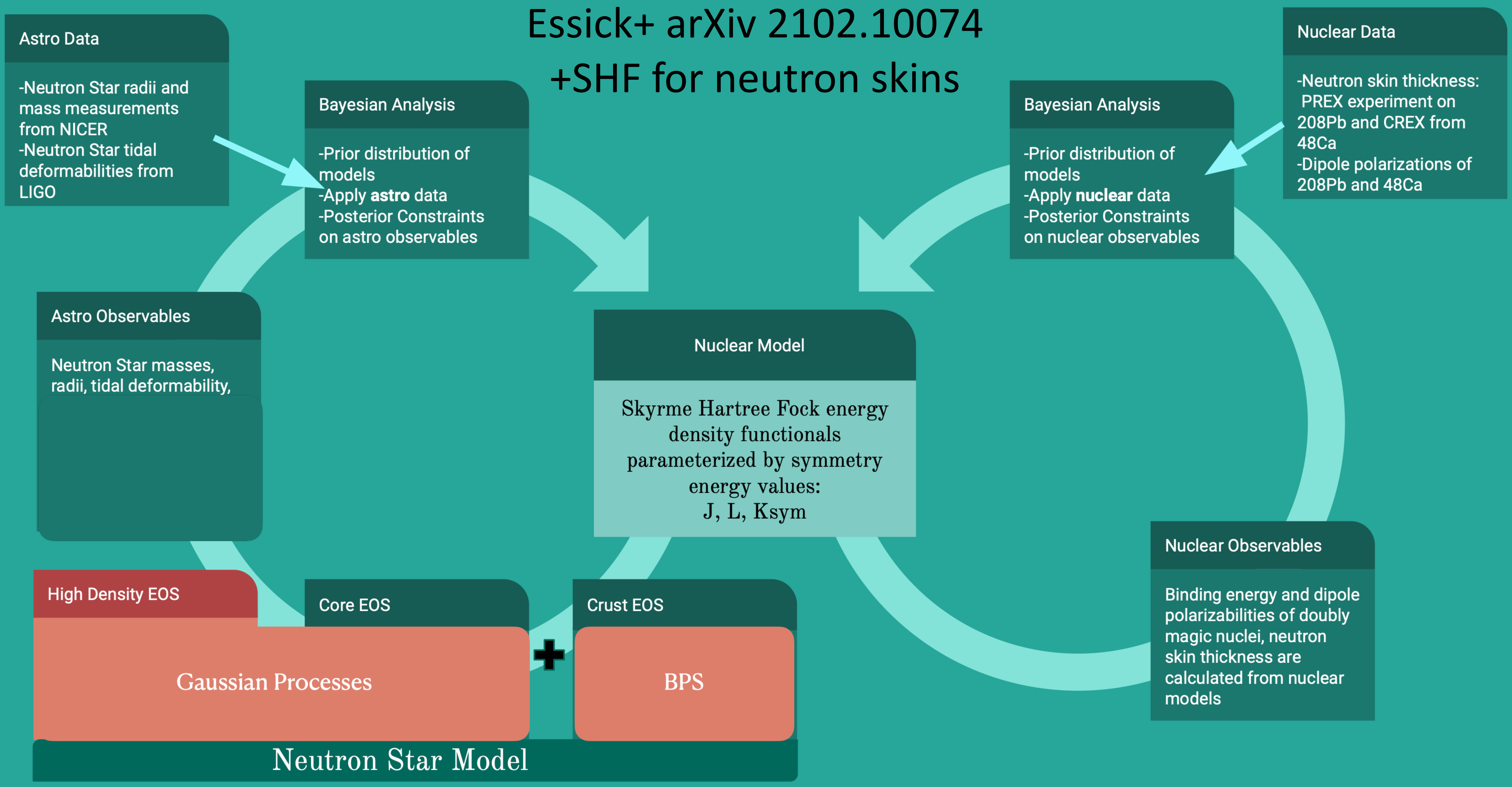
Different emphases



Pang et al, arxiv:2205.08513



Neill+ 2208.00994; Sorenson+ 2301.13253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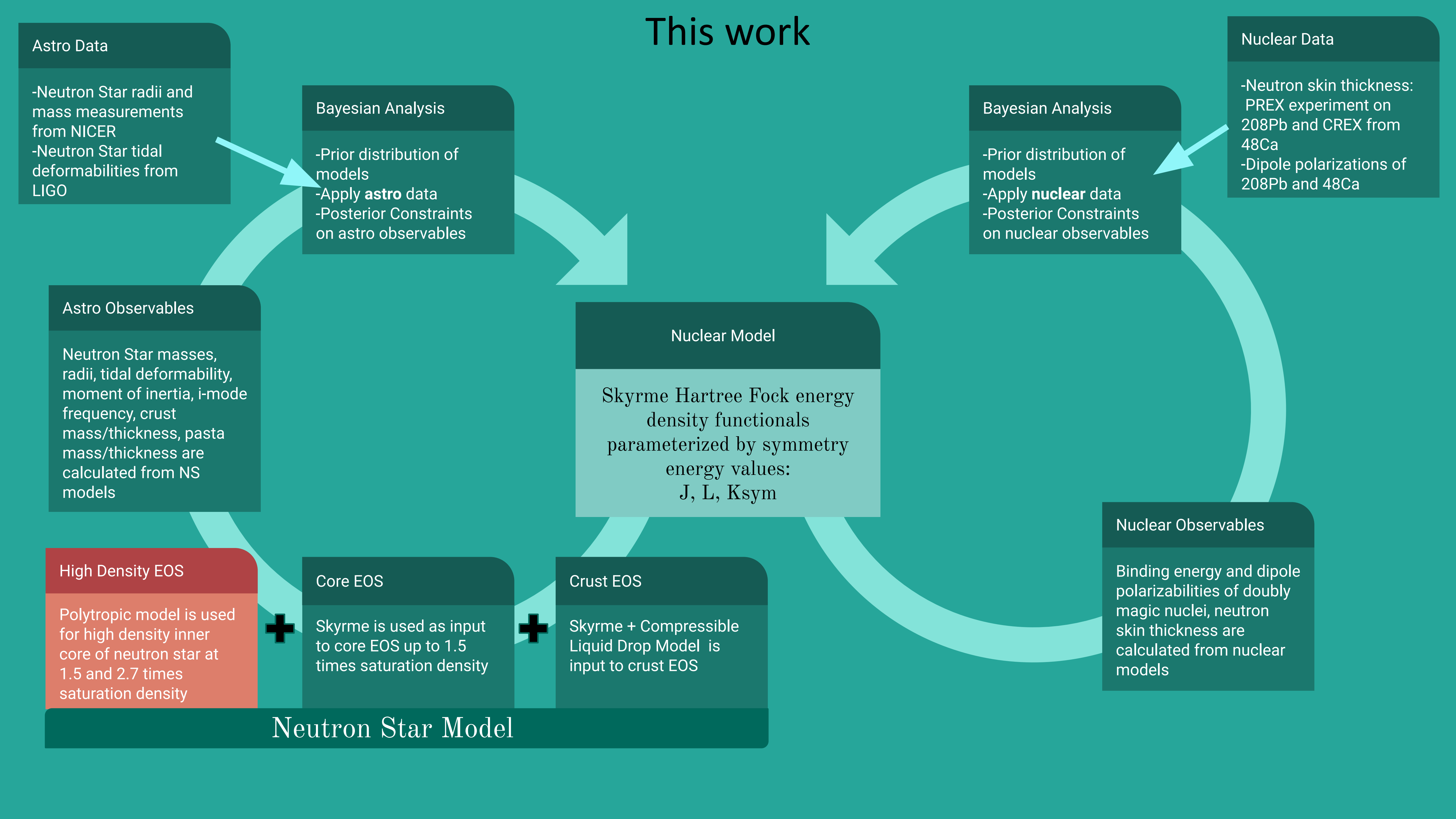
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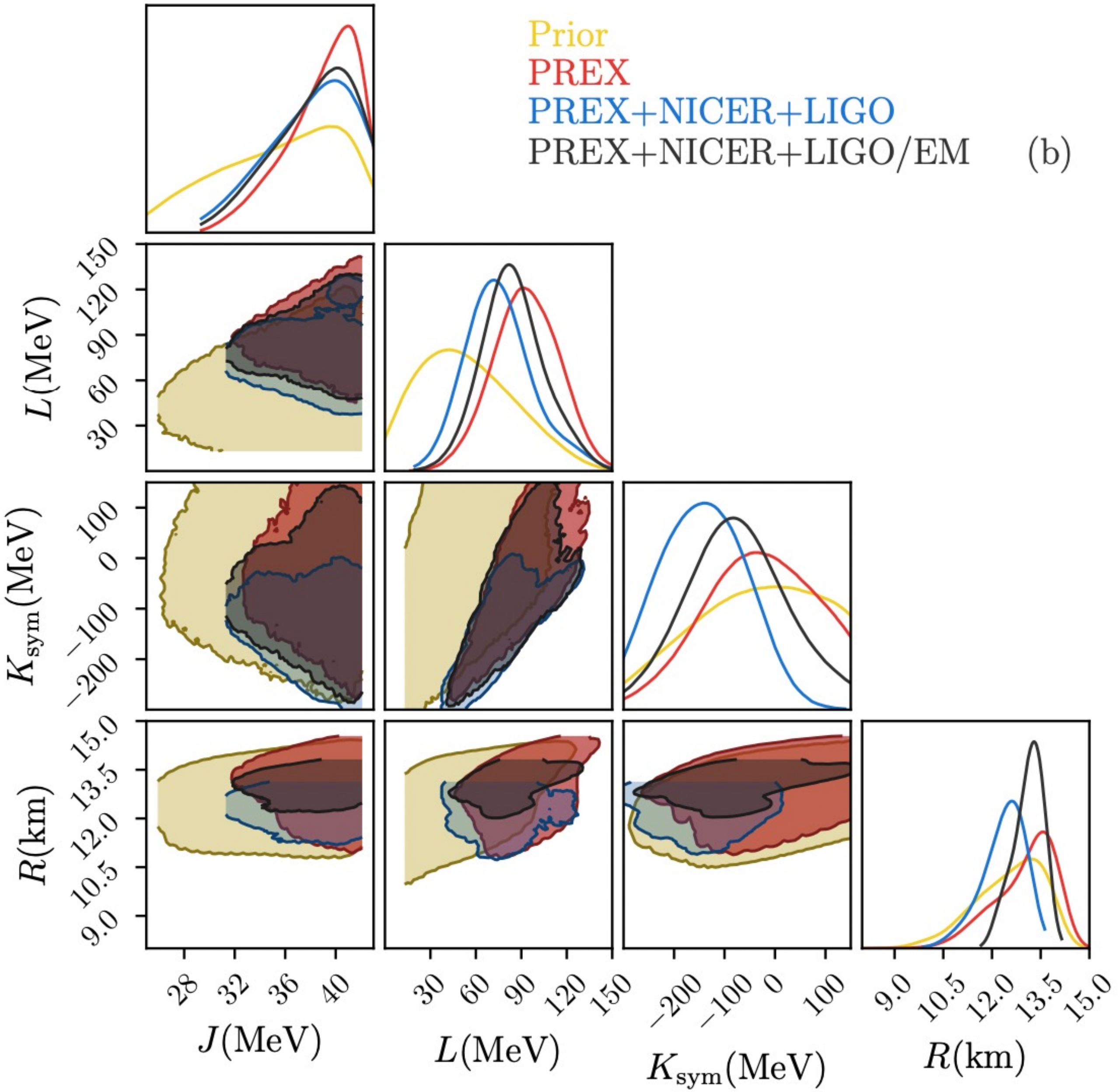
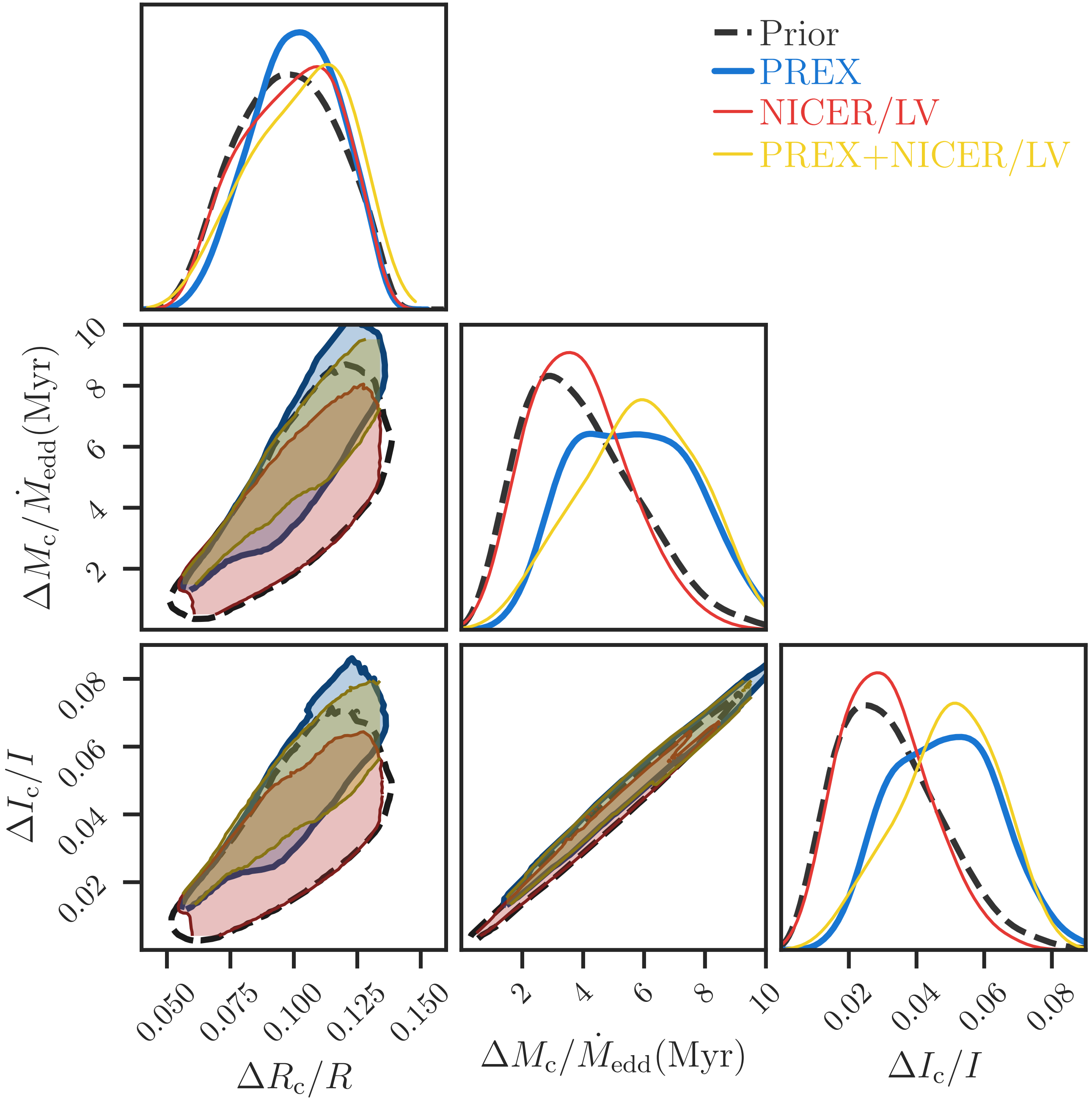
Polytropic model is used for high density inner core of neutron star at 1.5 and 2.7 times saturation density
Core EOS
Skyrme is used as input to core EOS up to 1.5 times saturation density
Crust EOS
Skyrme + Compressible Liquid Drop Model is input to crust EOS
Neutron Star Model

J,L relatively insensitive to Astro data, but K_{sym} is sensitive



Newton+ arxiv:2112.12108



Newton+ arxiv:2112.12108

First results using a simple filter for a $1.4M_{SUN}$ star

Initial analysis of full Bayesian inference confirms trends

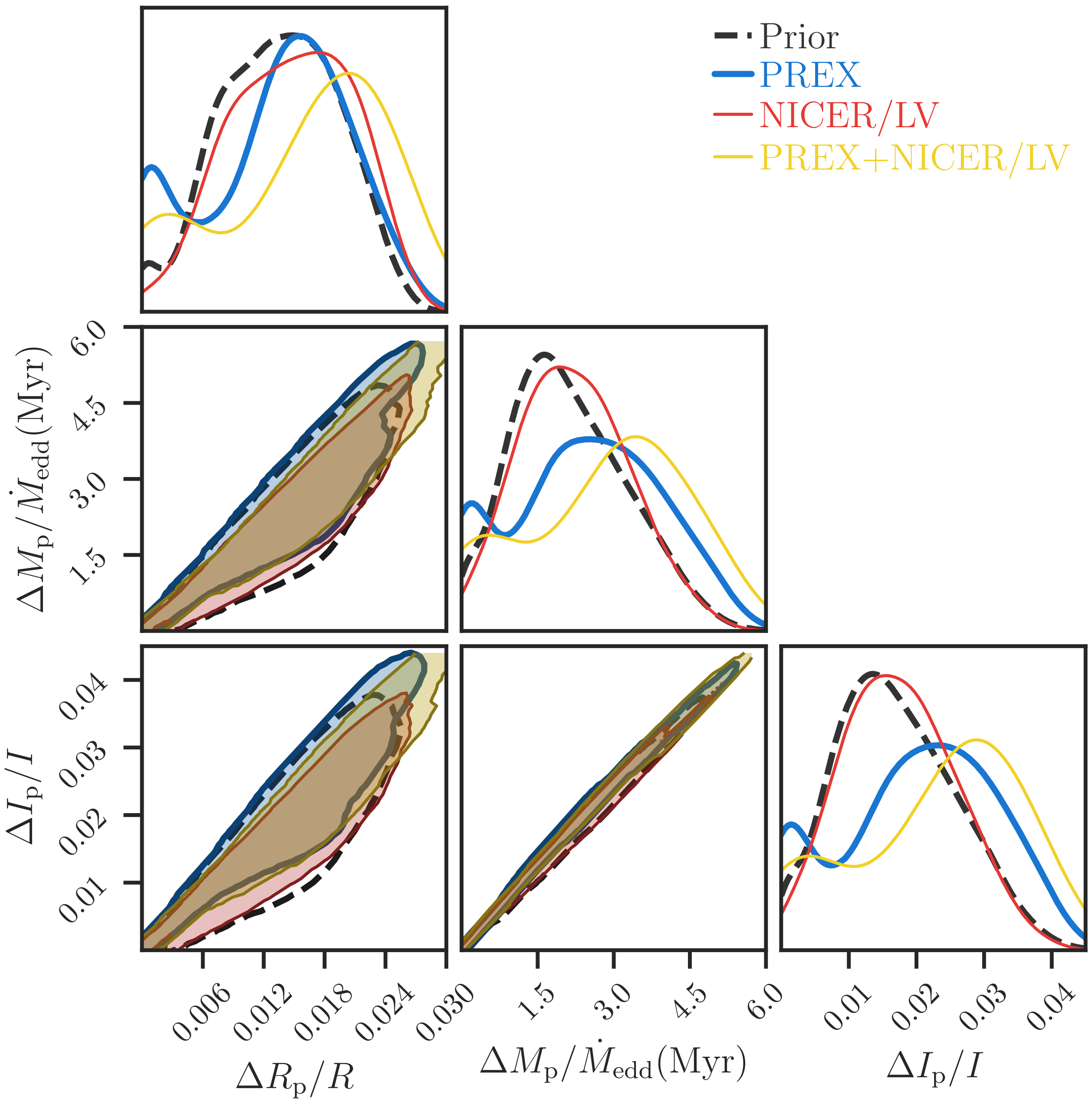
95% contours shown

Effect of PREX on amount of crust more than that of NICER/LIGO measurements

PREX+NICER/LIGO predicts slightly more pasta than PREX or NICER/LIGO separately

Crust replacement timescale, moment of inertia vary by an order of magnitude.

Crust thickness varies by a factor of 4



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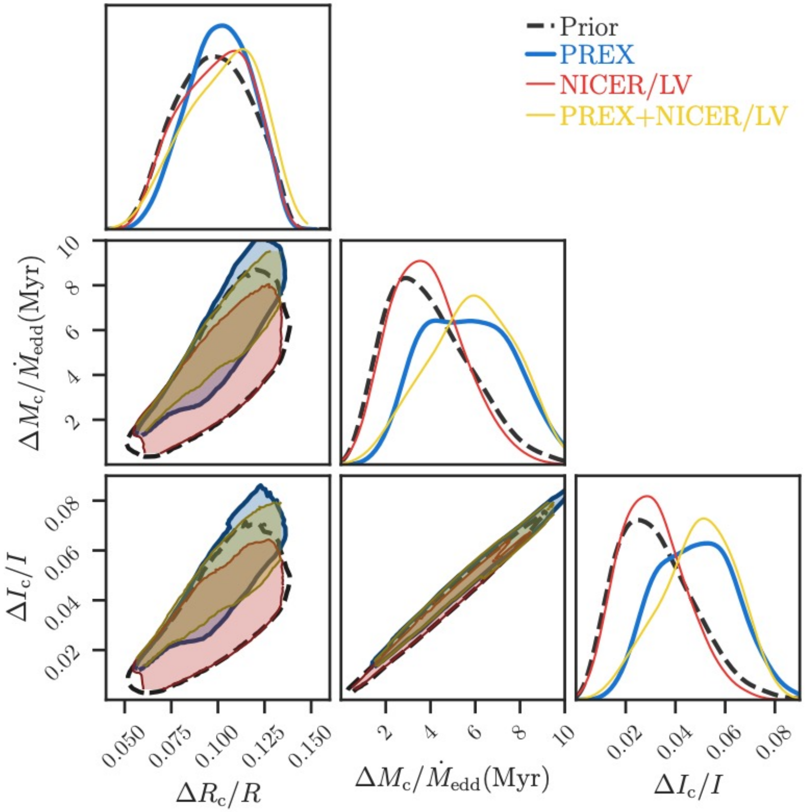
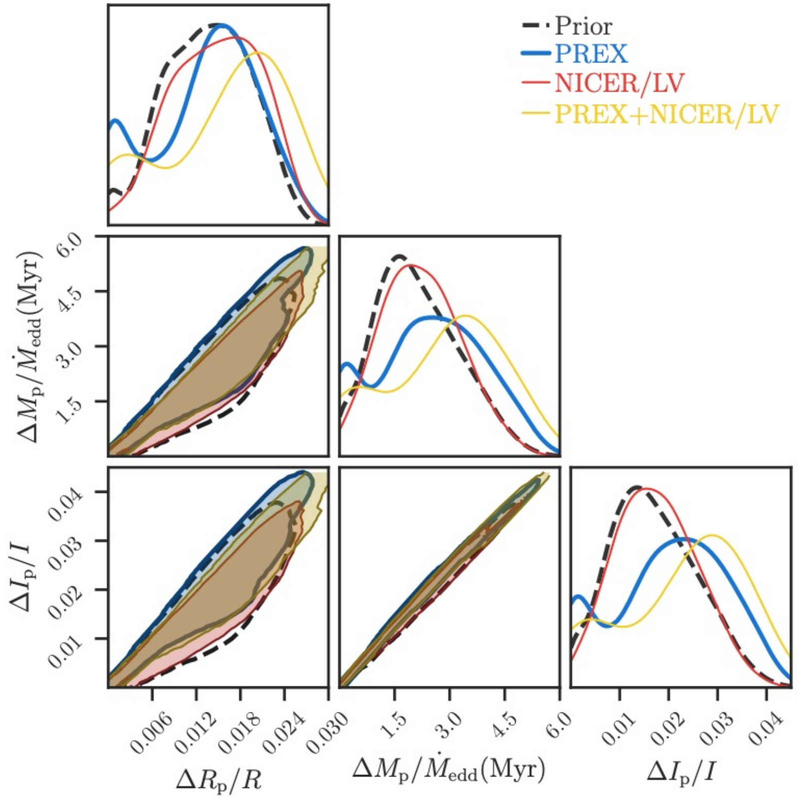
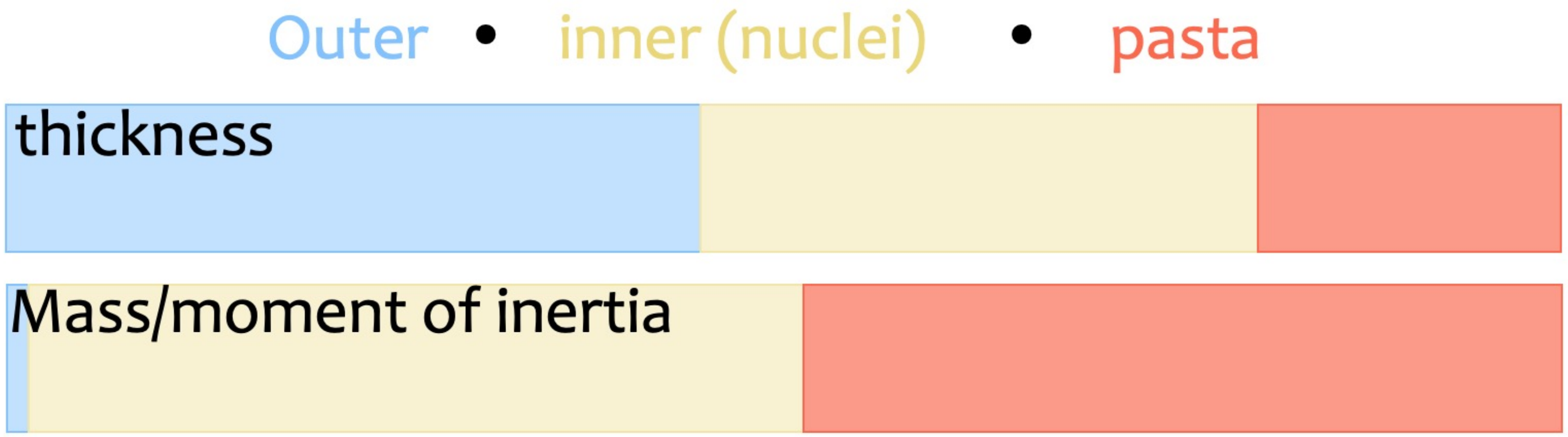






Newton+ arxiv:2112.12108

Take-aways

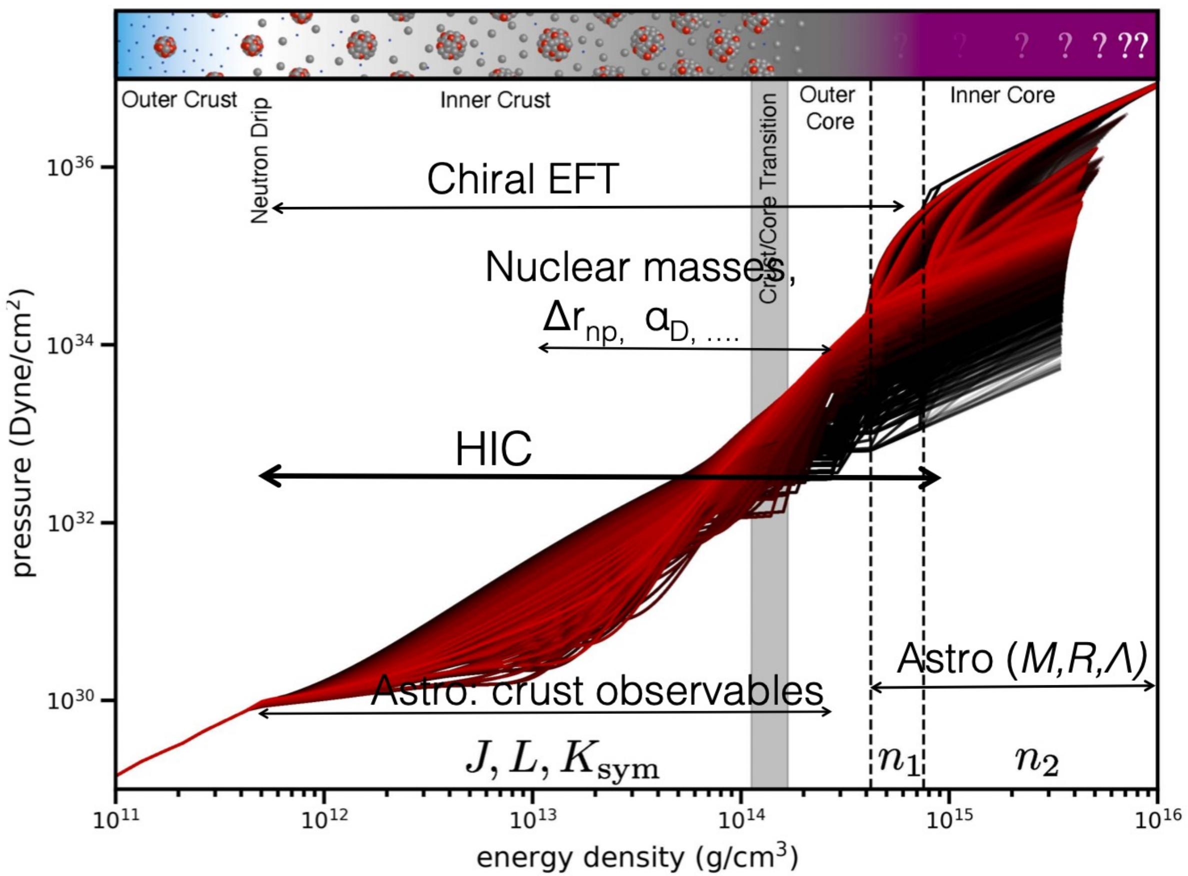
Different choices of nuclear model lead to systematically different inferences of nuclear and Astro observables

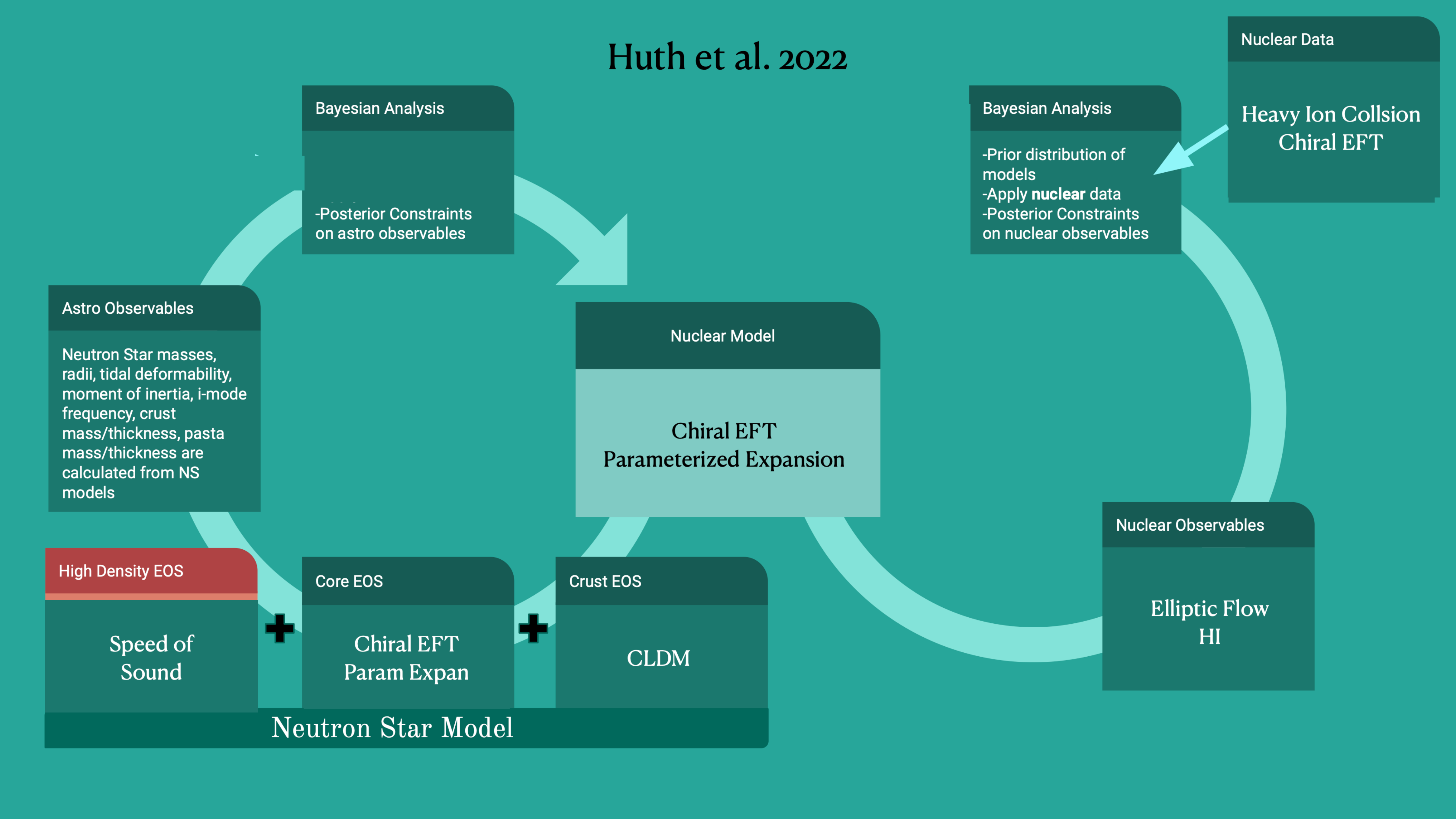
Mitigated by models which allow more parameter space exploration (at least J,L,K_{sym}, probably Q_{sym}, for extrpolations up to $2n_s$)

Crust properties, and K_{sym}, are sensitive to to nuclear and astro observables

There are many observables that can be included in our EOS inference if we build ensembles of crust EOSs consistent with core EOSs

SEE DAVID TSANG'S TALK FOR AN EXPLICIT EXAMPLE




Huth et al. 2022
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Greif et al. 2020