Neutron star crusts and multi-messenger nuclear-astrophysics

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

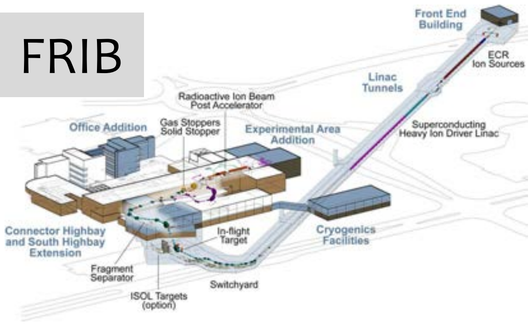
Noa Fritschie, 2022

Strong, Weak, EM signals

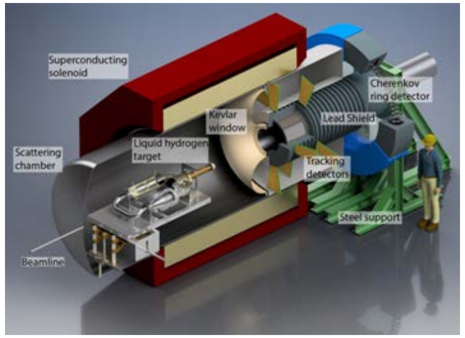
Multi-messenger Nuclear & Astro Physics

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

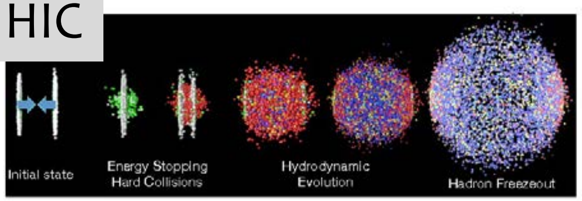
LIGO/
VIRGO

Nuclear structure/ dynamics

Multi-messenger Nuclear & Astro Physics

Neutron star structure/ dynamics

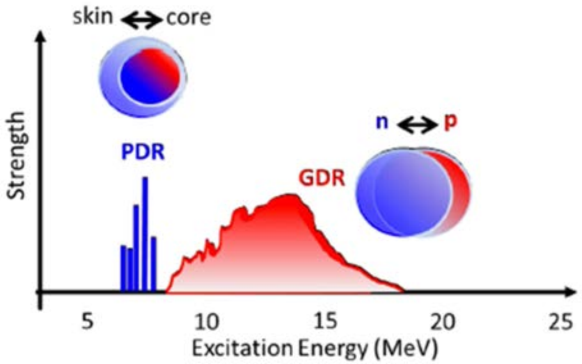
HIC



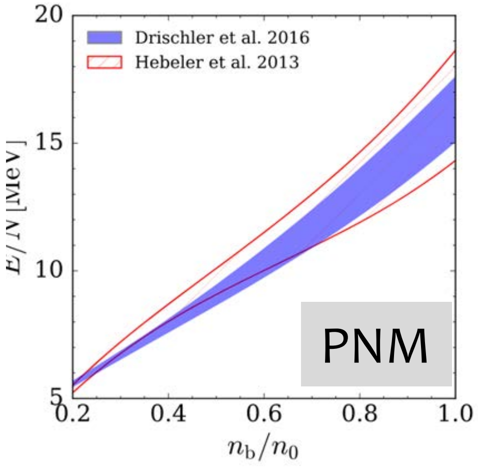
T.K.Nayak, arxiv:1201.4264

neutron skins

Abrahamyan+,
PRL 108, 112592 (2012)

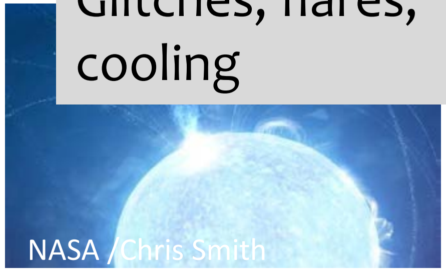


Bracco, Lanza, Tamii,
PPNP 106, 360 (2019)



Haensel, Fortin JPhysG 2017

Glitches, flares, cooling



Hot spots
Oscillations,
Crust cooling

Tides, mergers

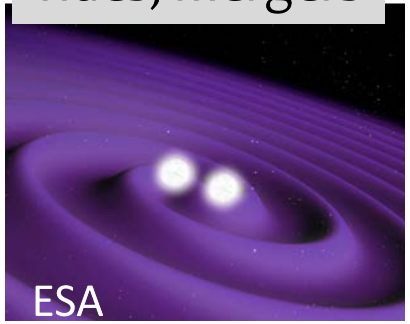


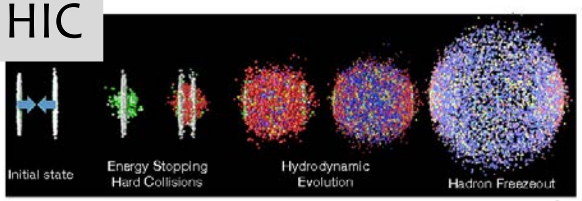
Figure: Artist's impression of a LMXB - credit Tony Piro, 2005.

Nuclear structure/ dynamics

Multi-messenger Nuclear & Astro Physics

Neutron star structure/ dynamics

HIC



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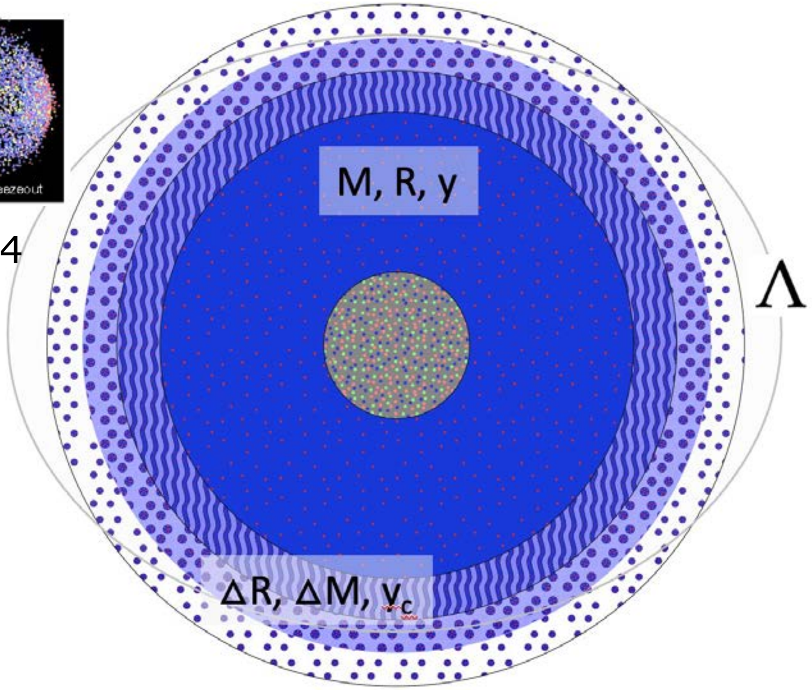
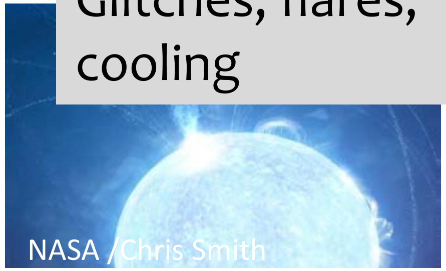


Glitches, flares, cooling



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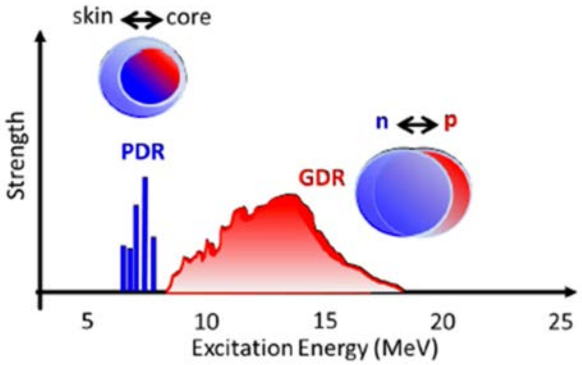
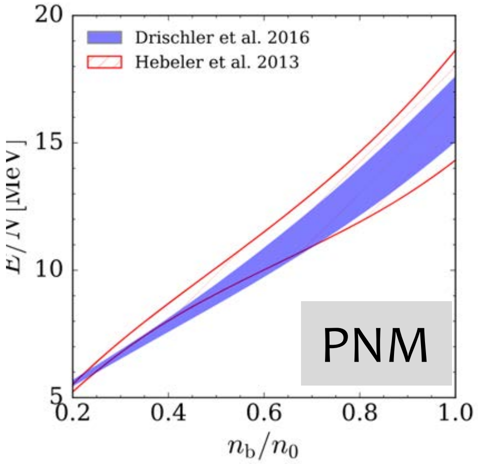
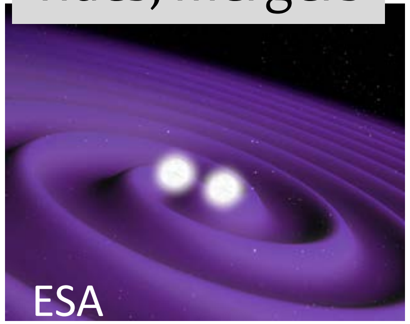


Bracco, Lanza, Tamii,
PPNP 106, 360 (2019)



Haensel, Fortin JPhysG 2017

Tides, mergers



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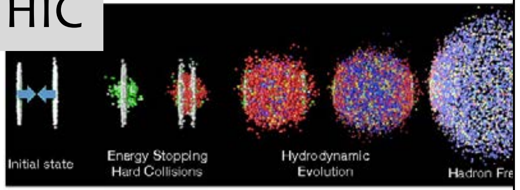
Nuclear structure/ dynamics

Mult-imessenger Nuclear & Astro Physics

Neutron star structure/ dynamics

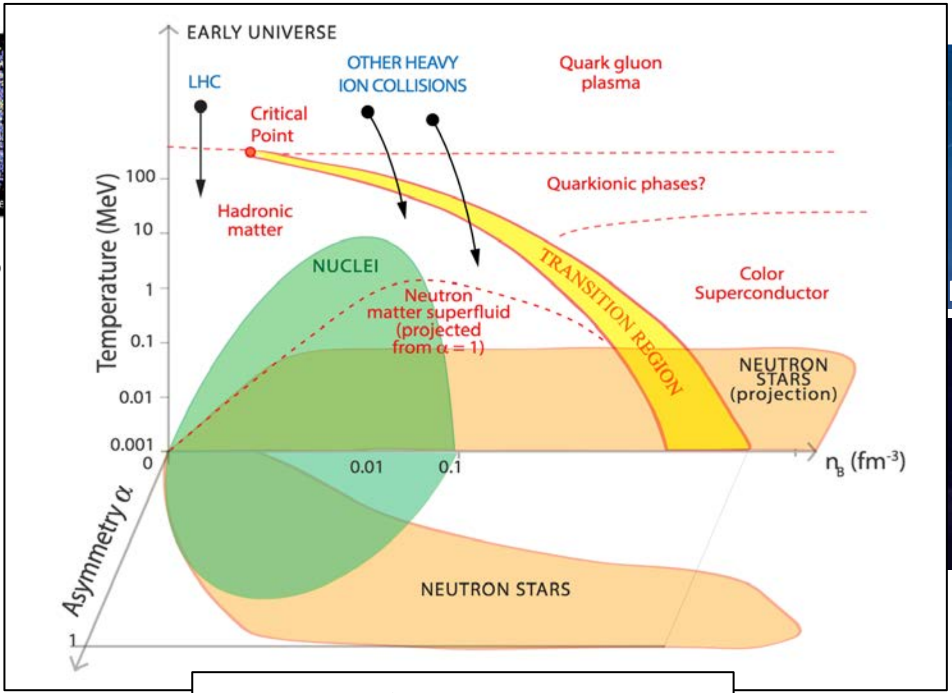
HIC



T.K.Nayak, arxiv:1201.426

neutron skins

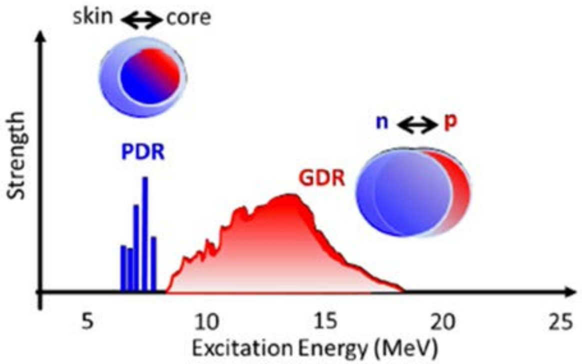
Abrahamyan+,
PRL 108, 112592 (2012)



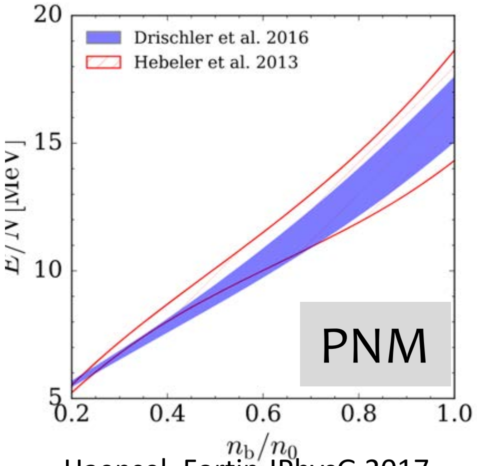
Watts et al arxiv:1501.00042

Glitches, flares, cooling

Hot spots
Oscillations,
Crust cooling

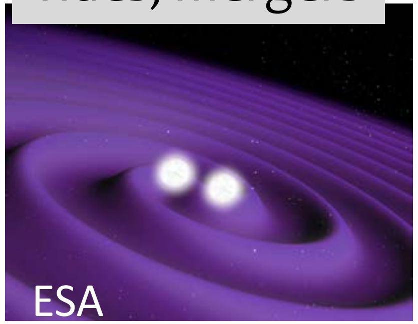


Bracco, Lanza, Tamii,
PPNP 106, 360 (2019)



Haensel, Fortin JPhysG 2017

Tides, mergers



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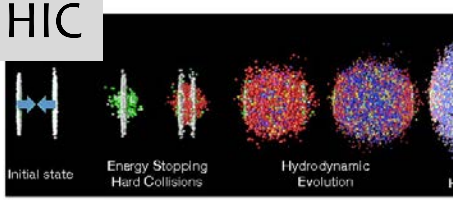
Nuclear structure/ dynamics

Multi-messenger Nuclear & Astro Physics

Neutron star structure/ dynamics

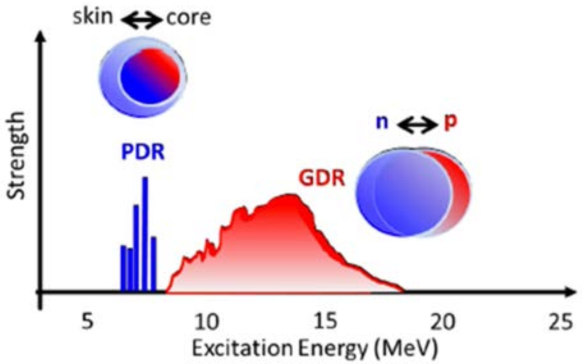
HIC



T.K.Nayak, arxiv:1201.4

neutron skins

Abrahamyan+,
PRL 108, 112592 (2012



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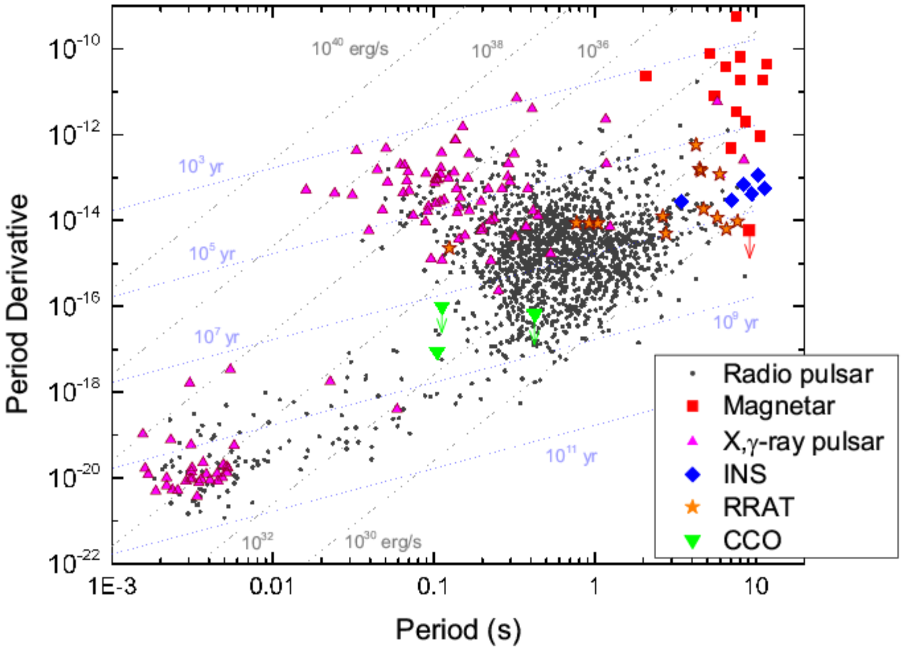
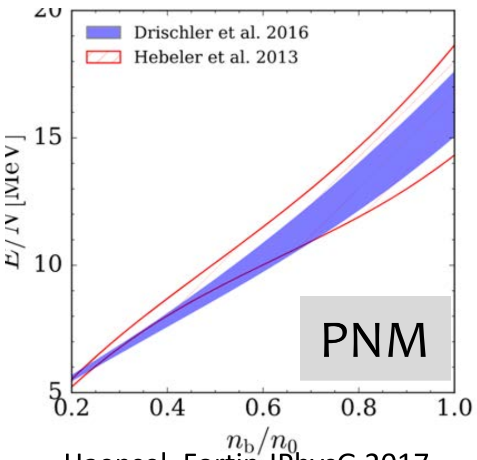
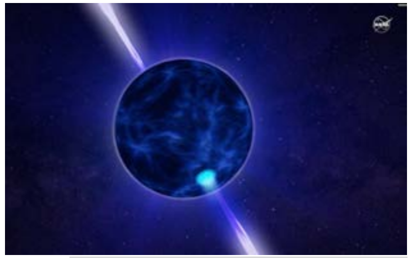




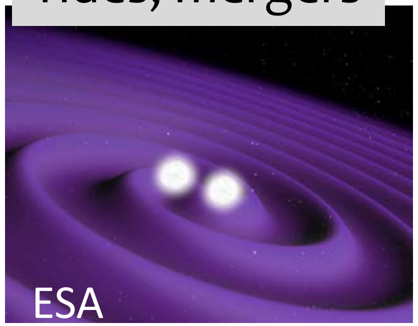
Haensel, Fortin JPhysG 2017

Glitches, flares, cooling



Hot spots
Oscillations,
Crust cooling

Tides, mergers



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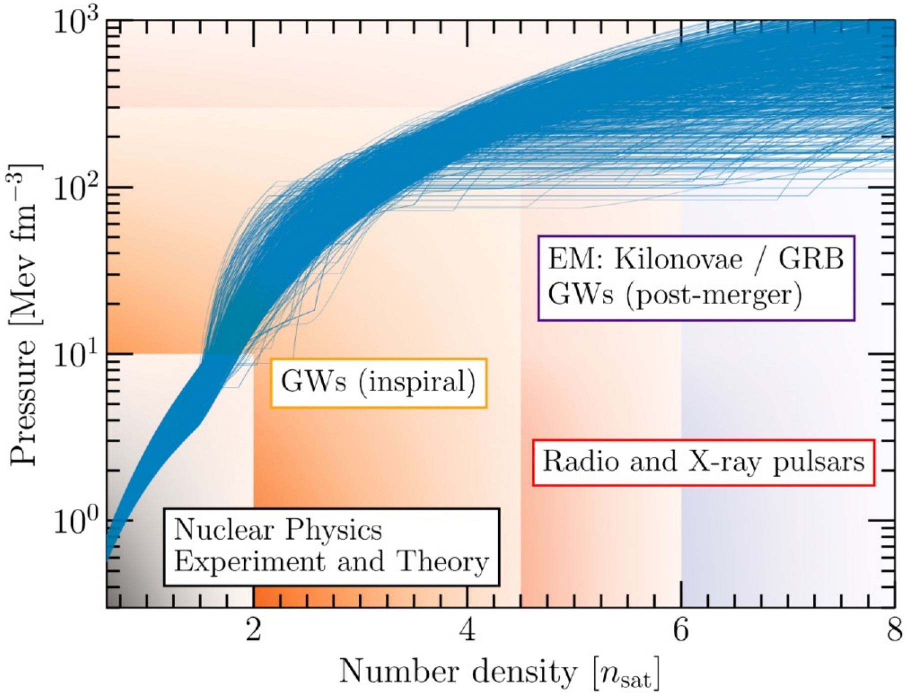
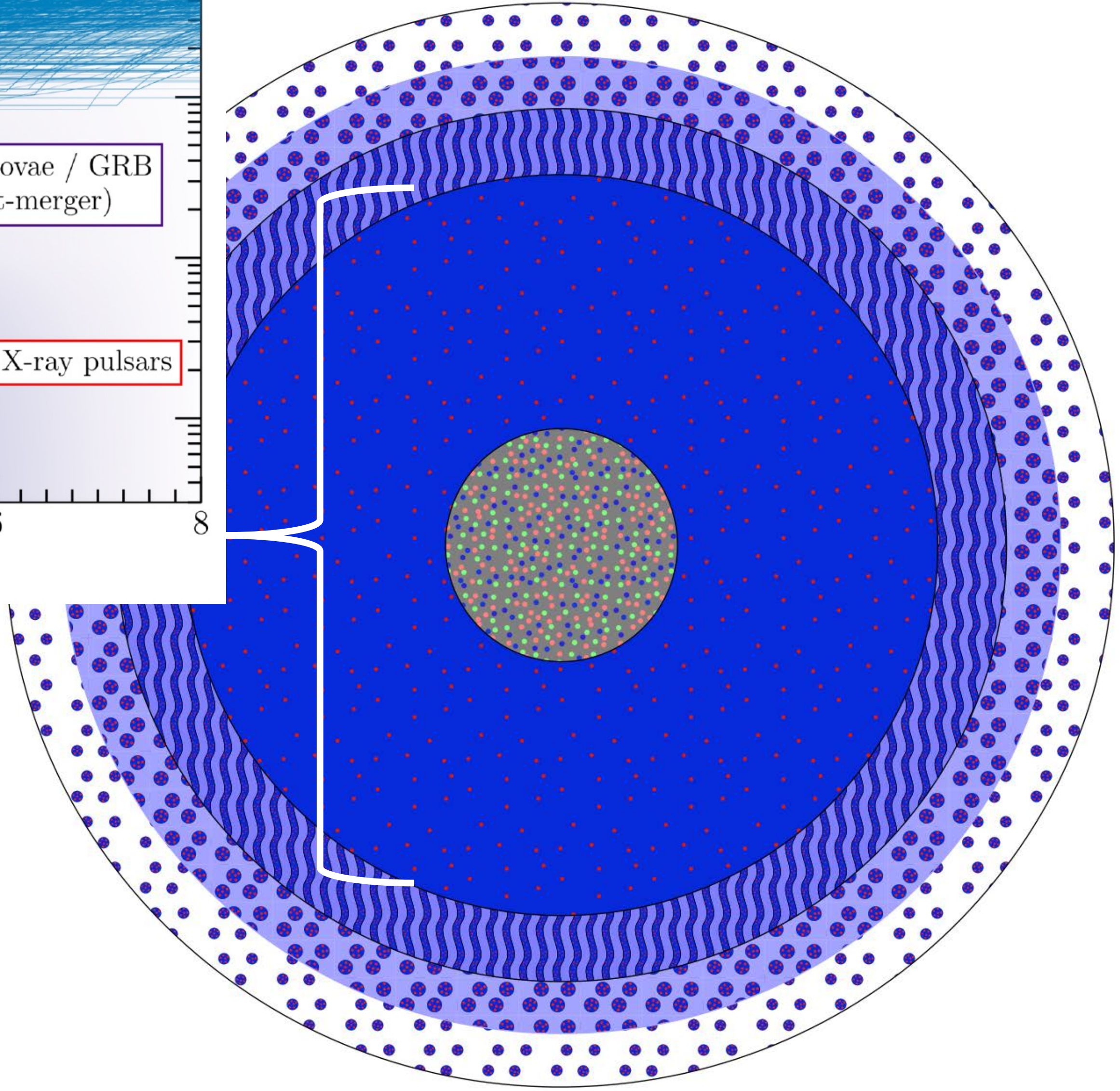
Putting the Multi in Multi-messenger

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)?

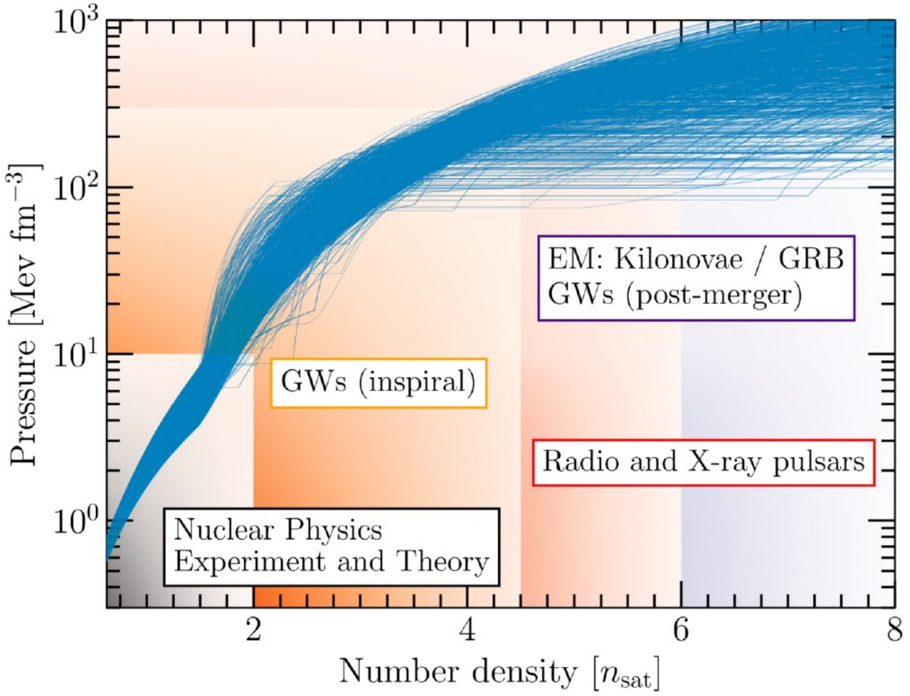
Modern approach: create ensembles of EOSs/neutron star models for statistical inference



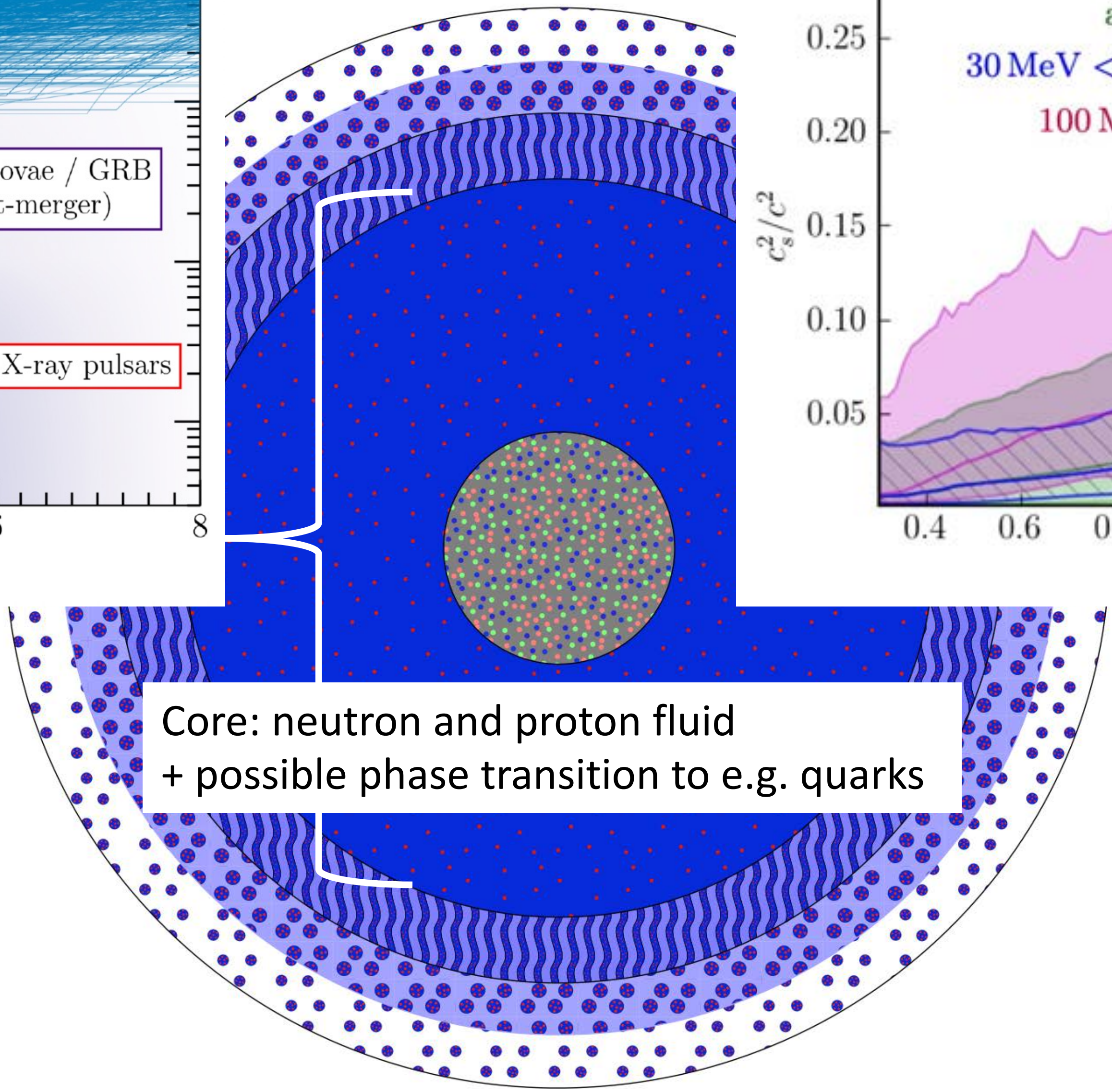


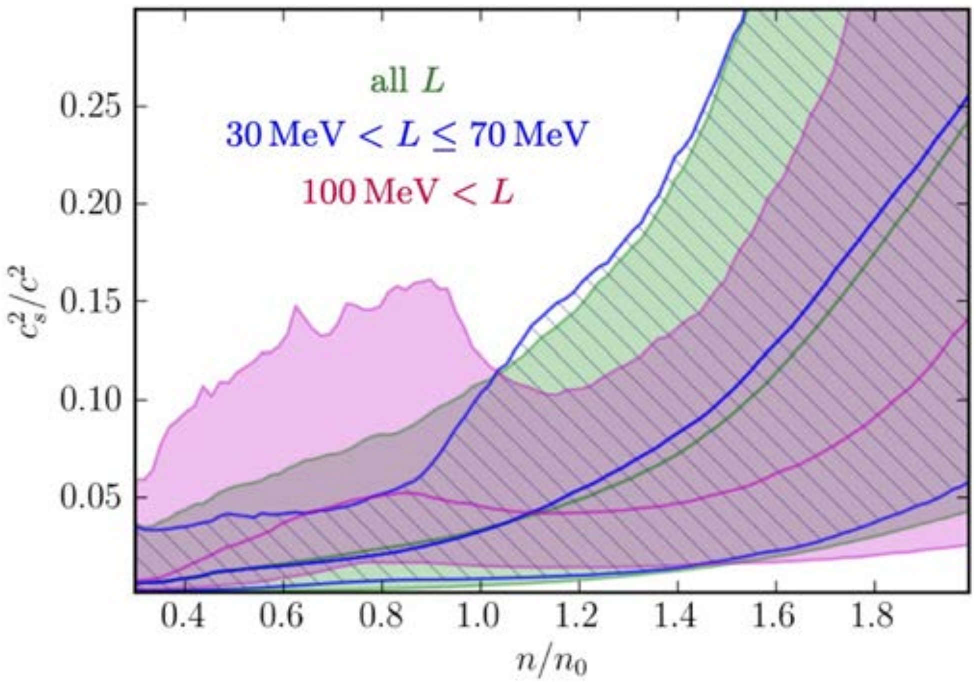
Pang et al, arxiv:2205.08513

And go ahead and infer! To date, emphasis has been on the EOS of the core



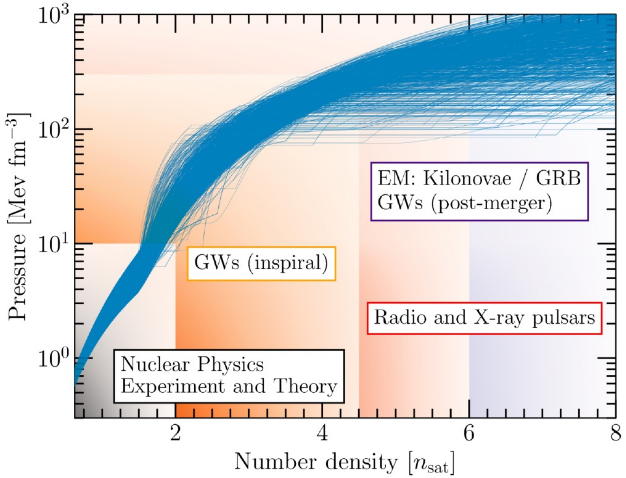
Pang et al, arxiv:2205.08513





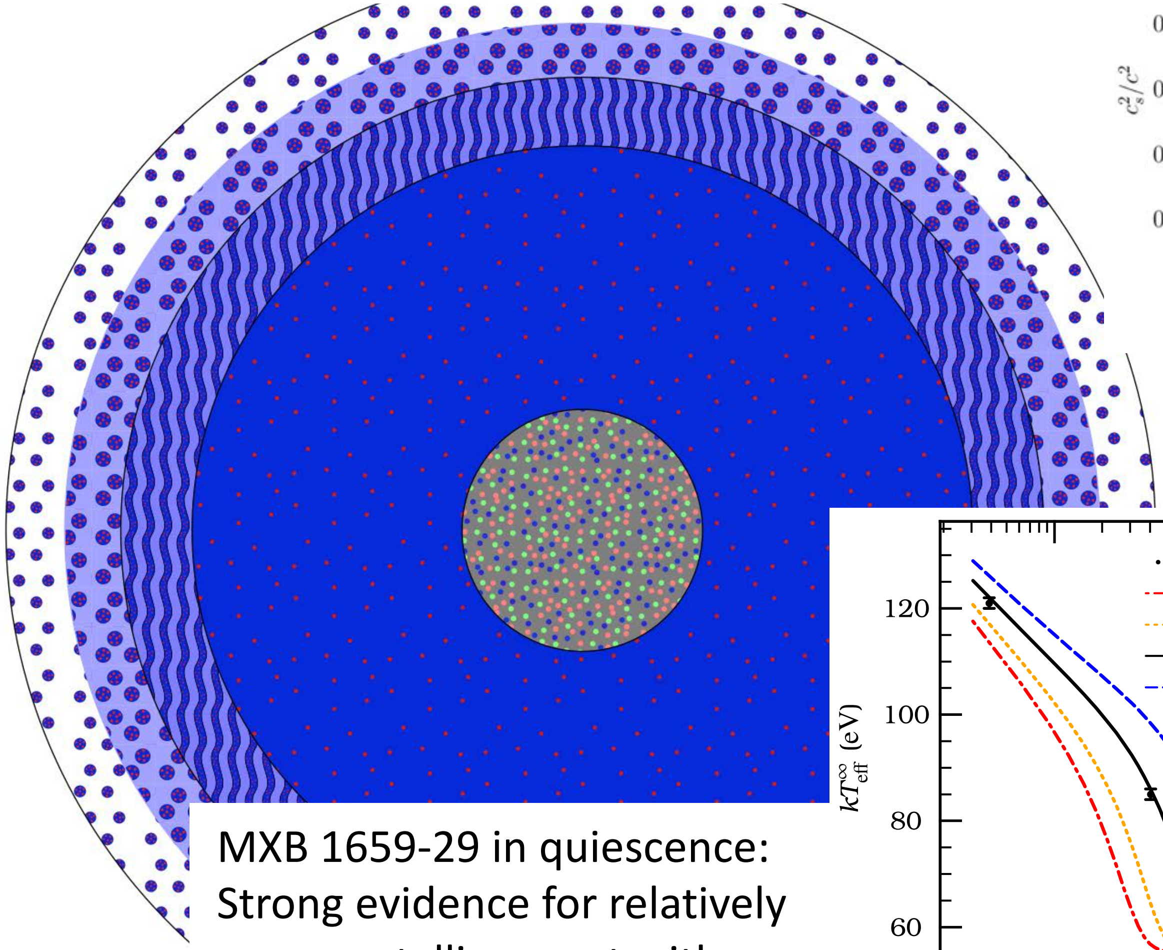
Essick+ arXiv 2102.10074

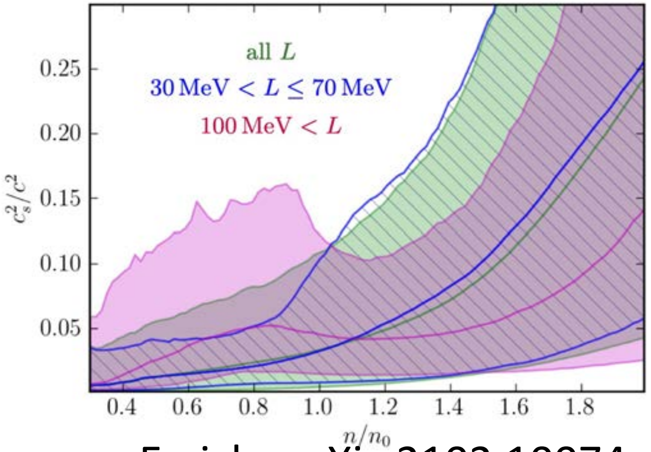
But the crust is there too, and several observables are sensitive to it



Pang et al, arxiv:2205.08513

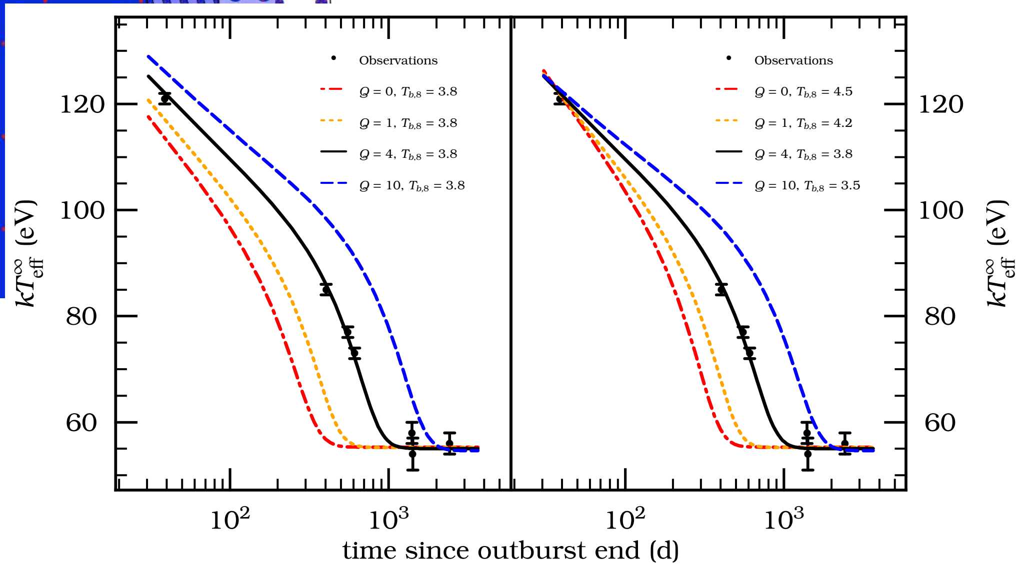
Core: neutron and proton fluid
+ possible phase transition to e.g. quarks





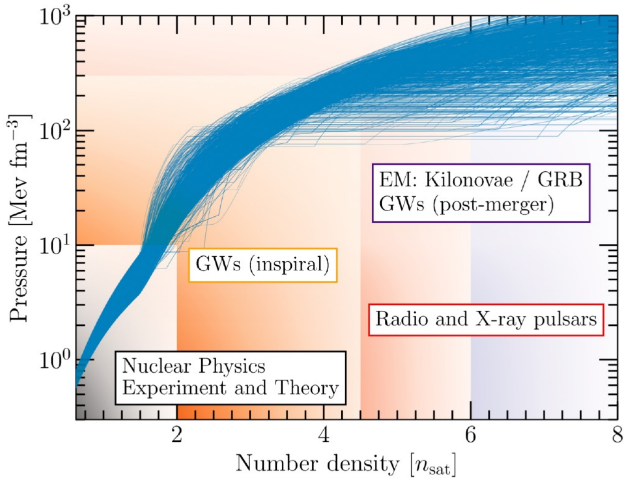
Essick+ arXiv 2102.10074

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

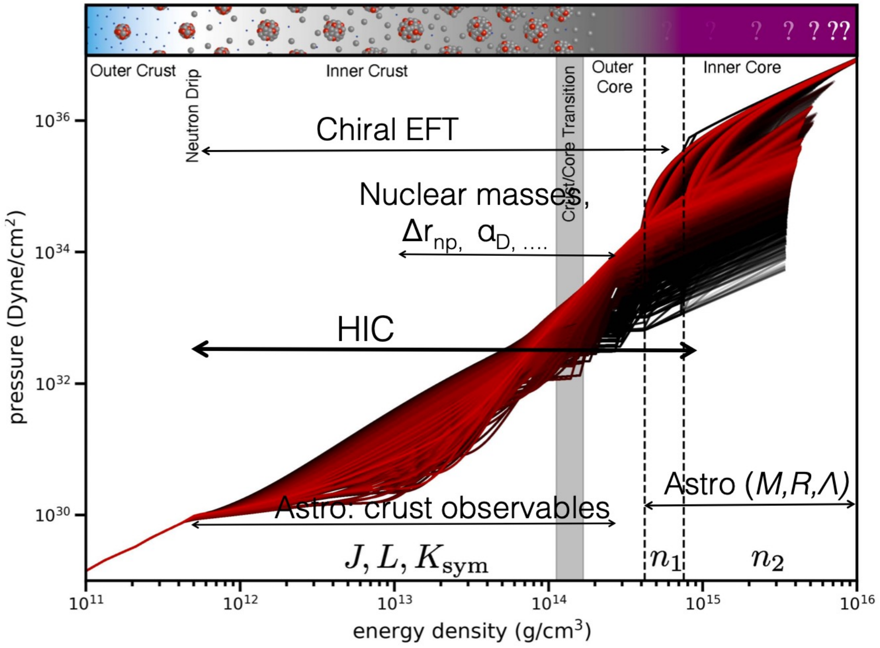


Brown and Cumming, ApJ 2009

So let's include the crust when we build our ensembles



Pang et al, arxiv:2205.08513



Neill+ 2208.00994; Sorenson+ 2301.13253

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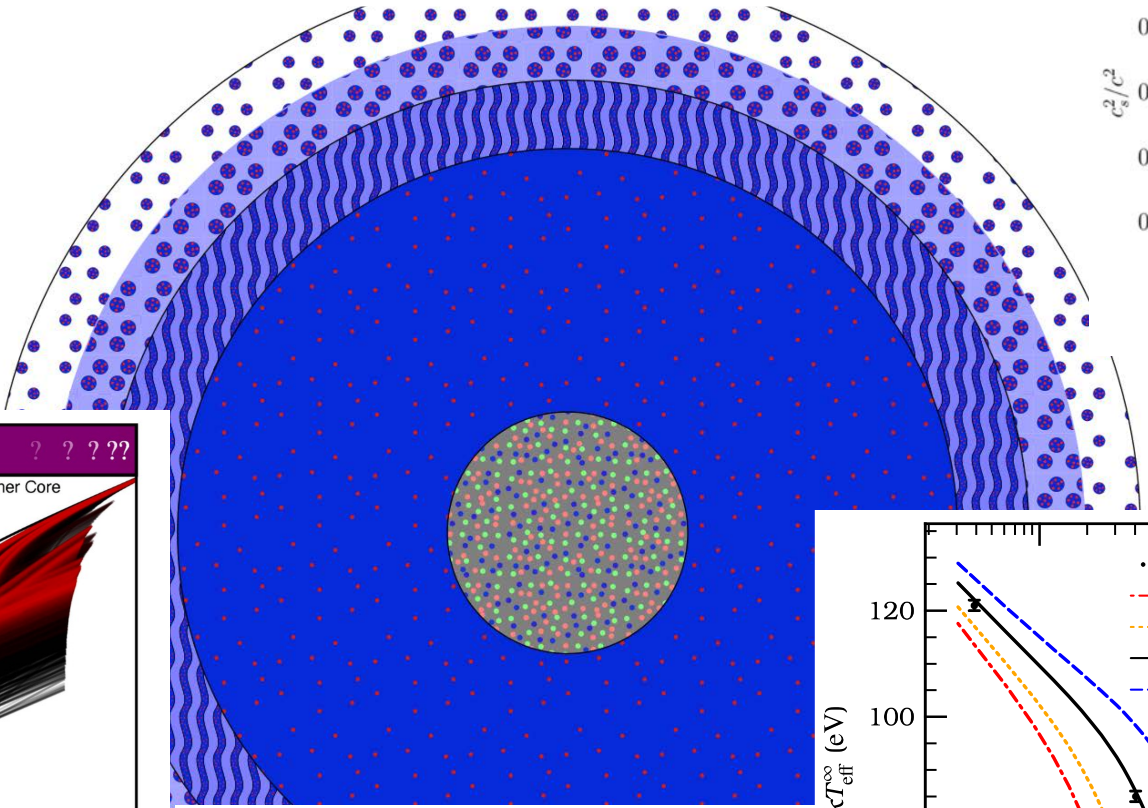

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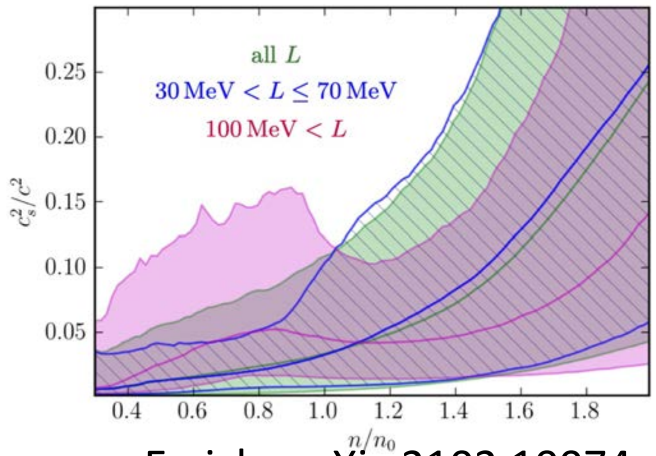

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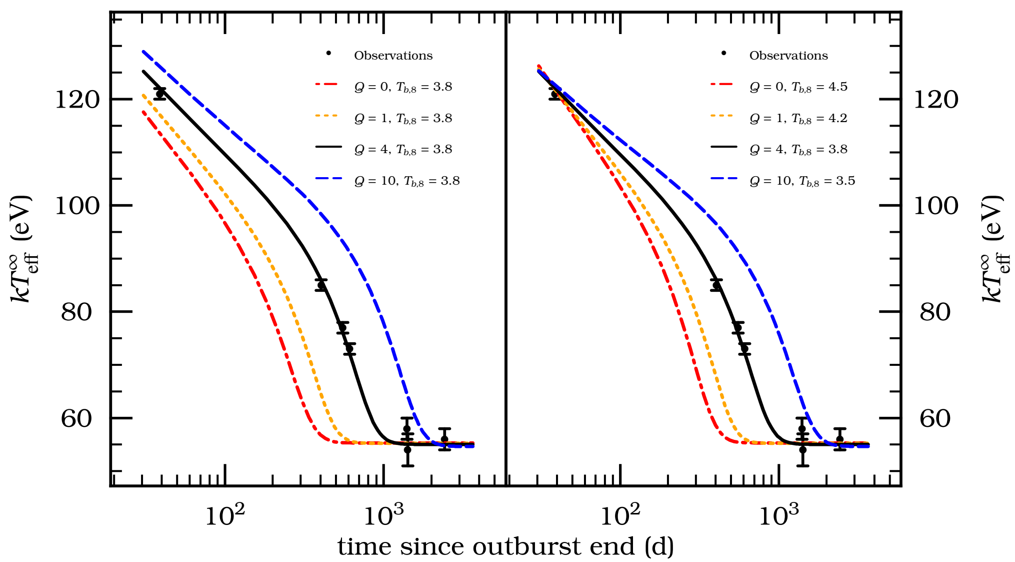

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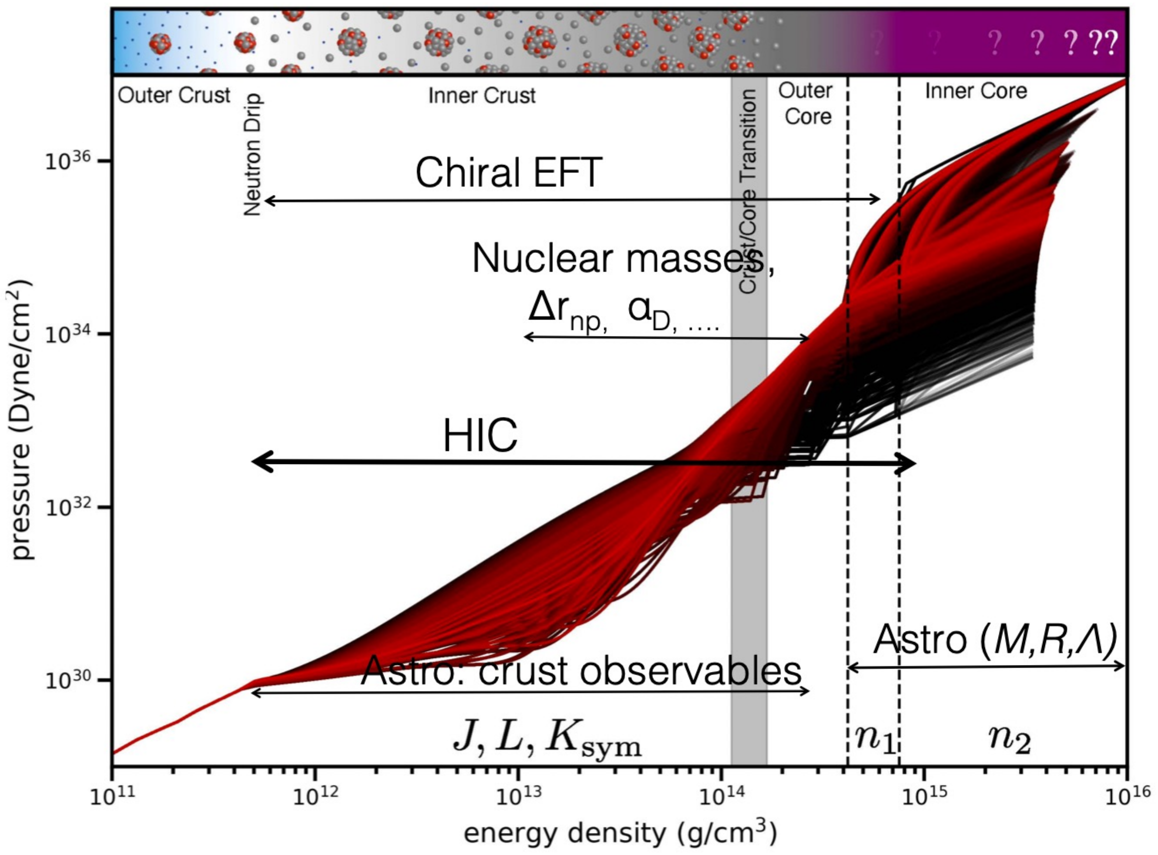
arxiv:2301.13253

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

So let's go about the task of creating consistent crust and core EOSs



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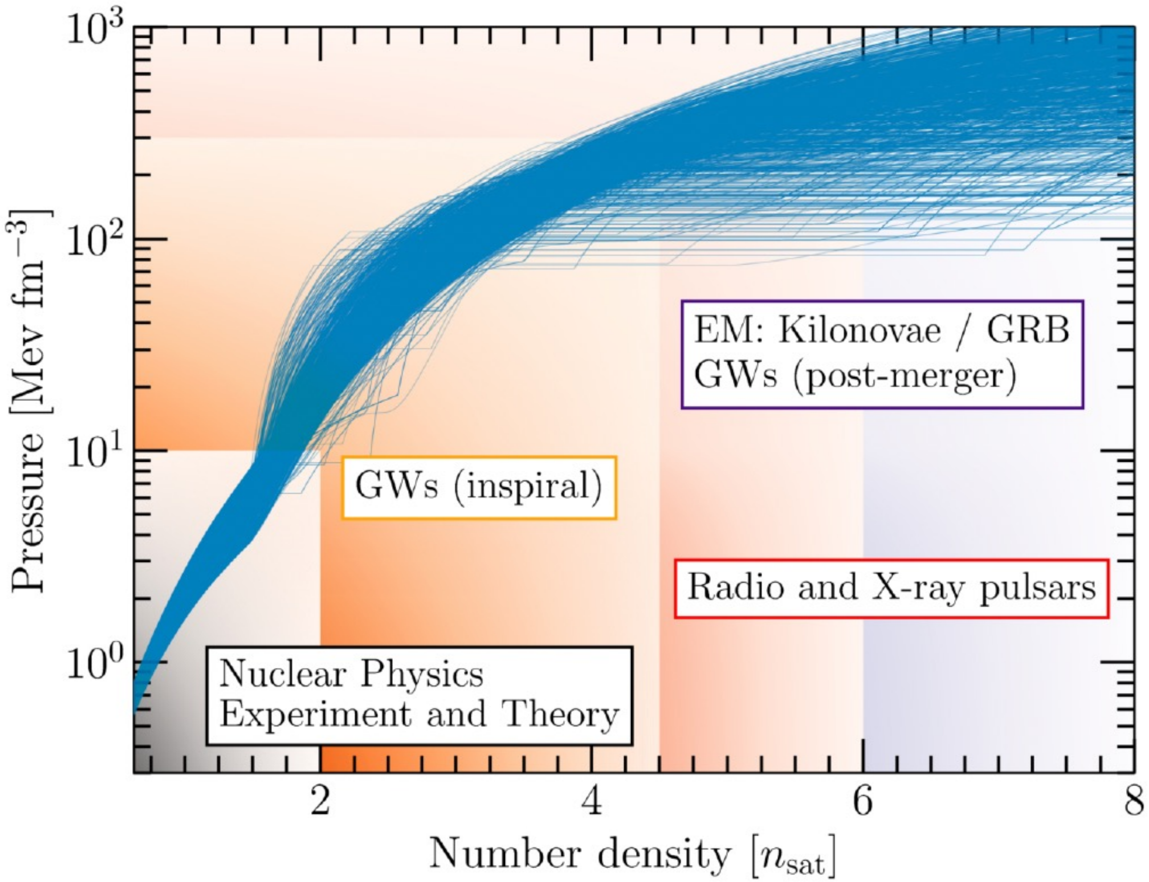
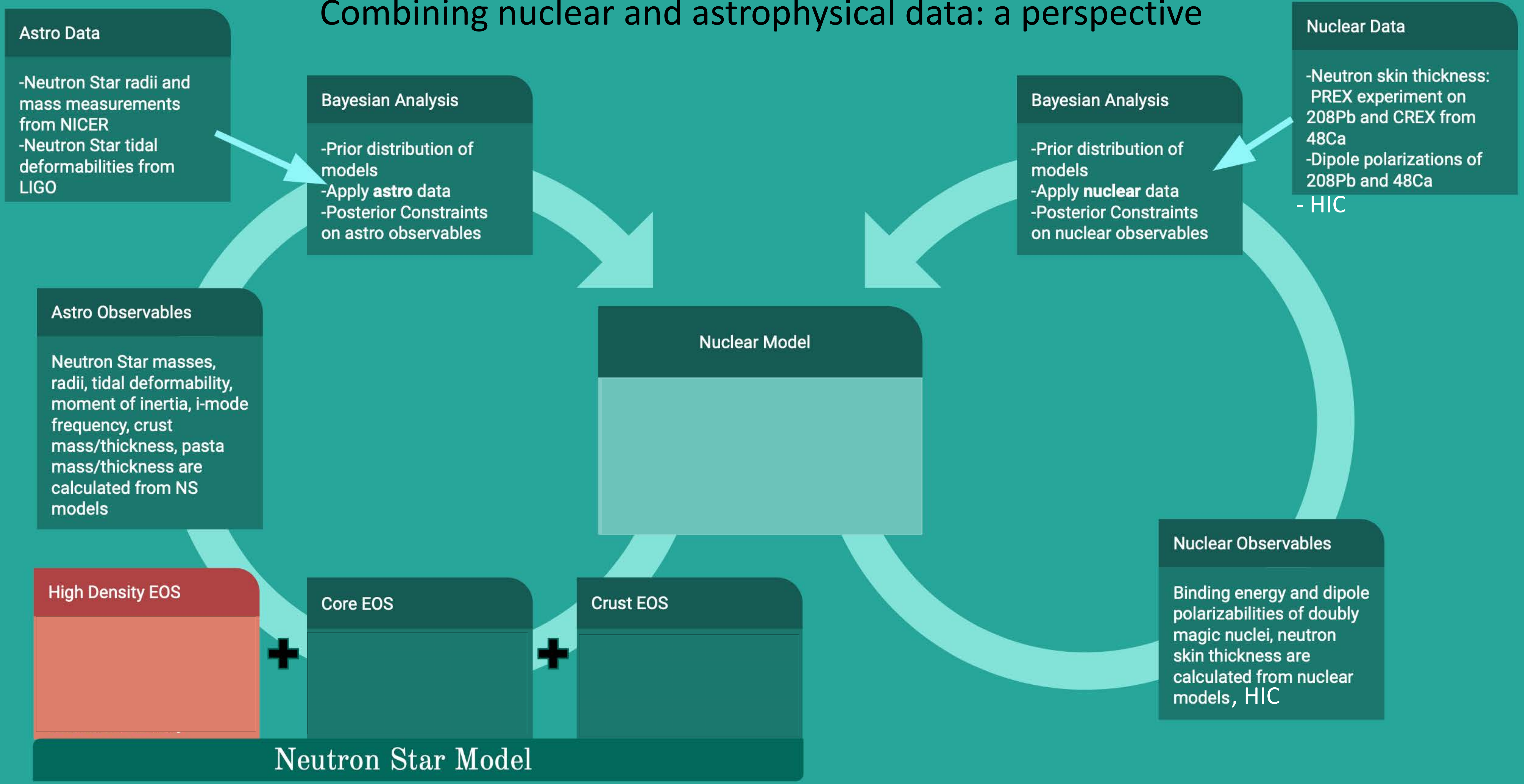


Pang et al, arxiv:2205.08513

Combining nuclear and astrophysical data: a perspective



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

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

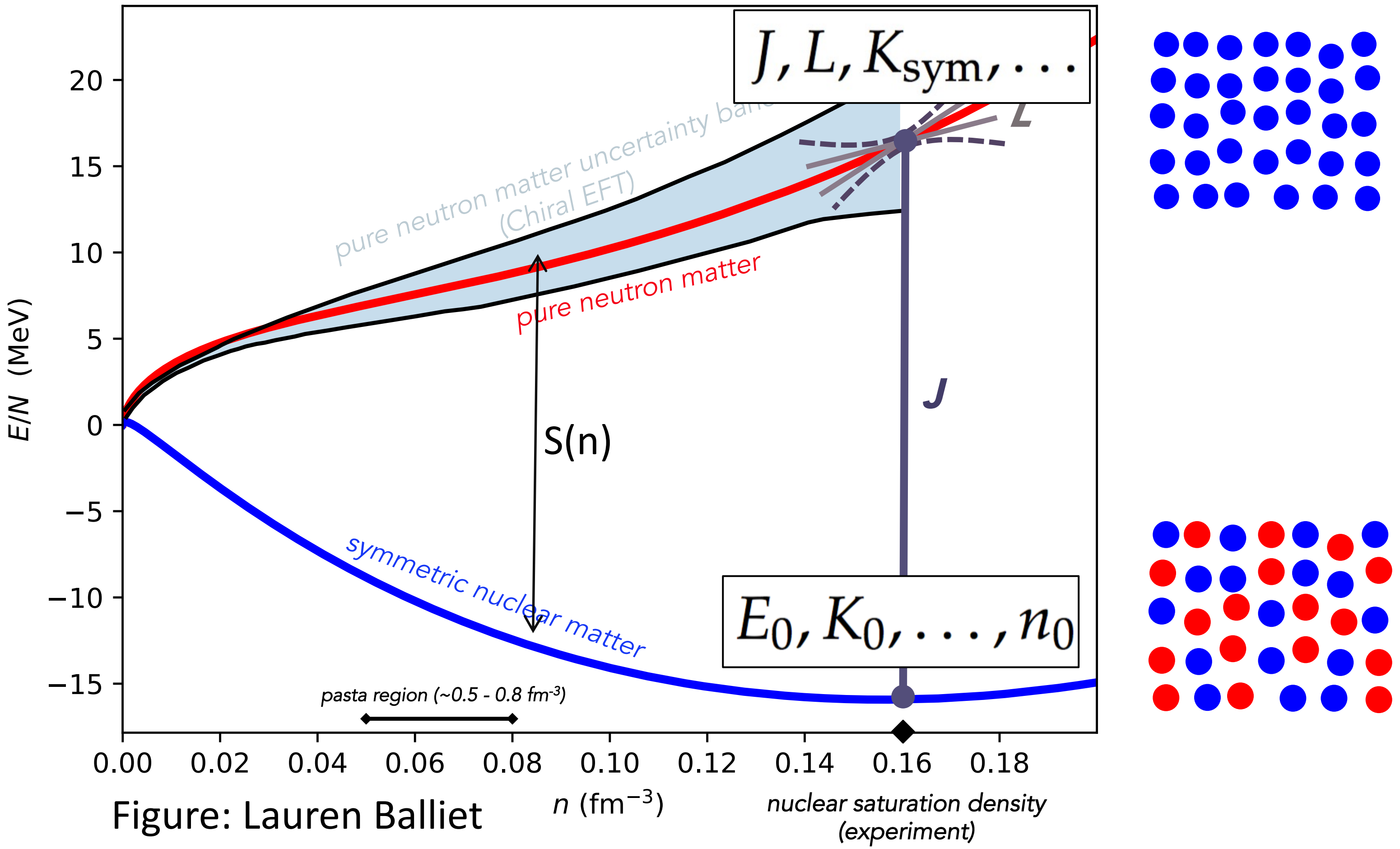


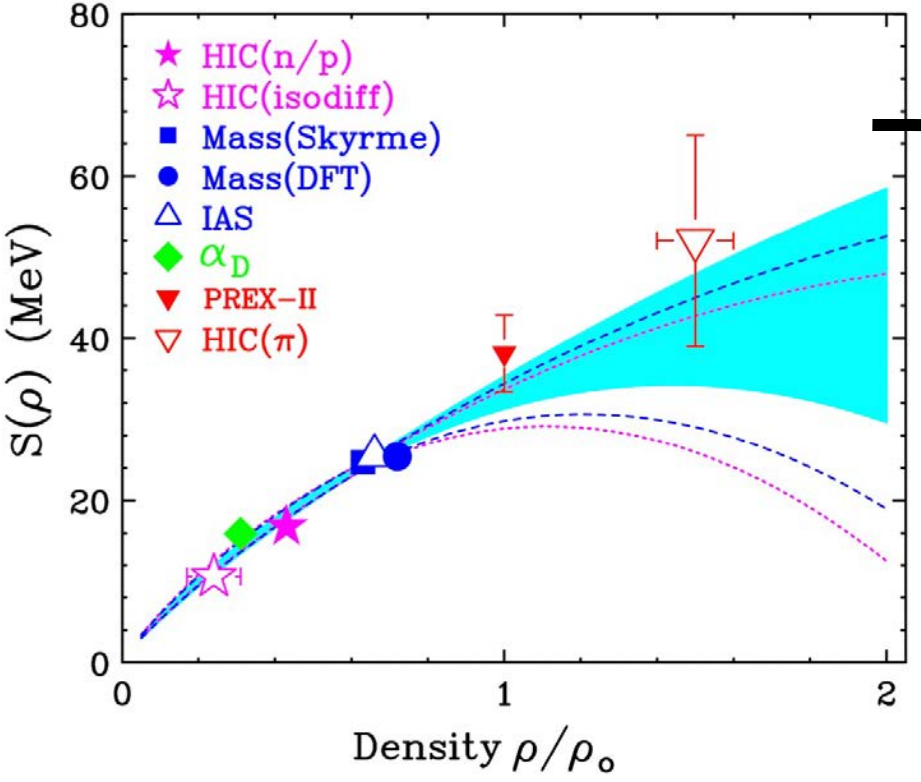
Figure: Lauren Balliet

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

Li, arxiv:2105.04629

Different observables constrain at different densities…

… so resulting constraints on nuclear matter parameters at saturation density involve model-dependent extrapolation

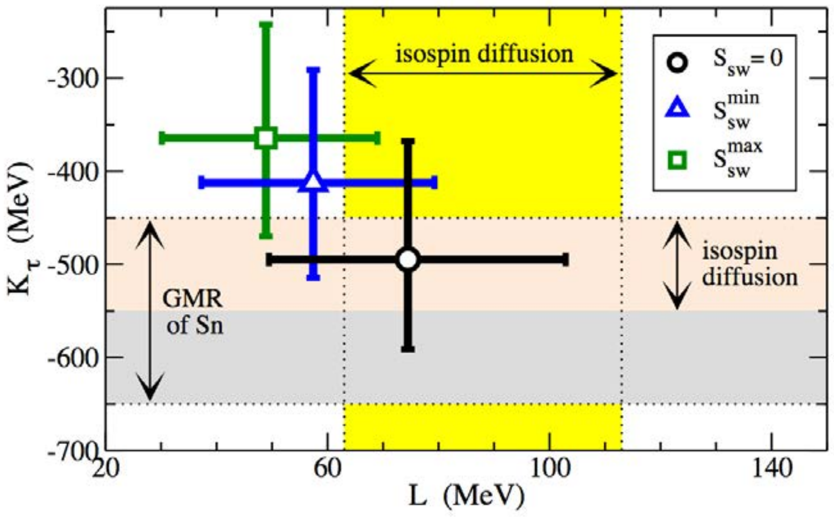


Tsang and Lynch, arxiv:2106.10119

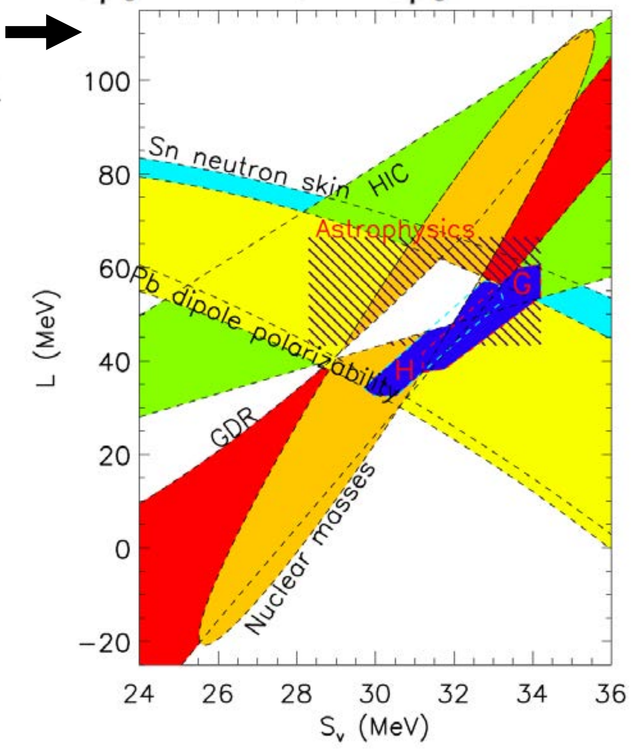
$$E_{sym}(\rho) = E_{sym}(\rho_0) + L(\frac{\rho-\rho_0}{3\rho_0}) + \frac{K_{sym}}{2}(\frac{\rho-\rho_0}{3\rho_0})^2 + \frac{J_{sym}}{6}(\frac{\rho-\rho_0}{3\rho_0})^3$$

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

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



Centelles et al, arxiv:0806.2886



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

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

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

3 body

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

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

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

SNM

Dynamics of n,p

Surface energy

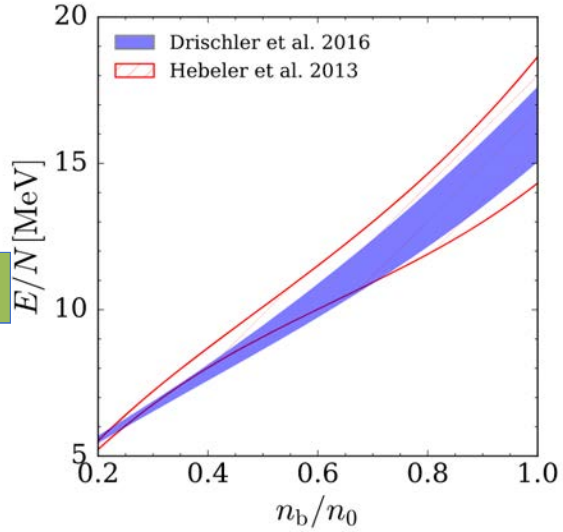
Symmetry Energy

Map nuclear matter parameters to model parameters and systematically generate models

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

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

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



Haensel, Fortin JPhysG 2017
Lim, Holt arXiv:1702.02898

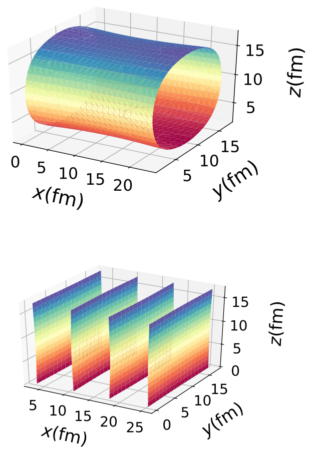
Fixed: potential source of systematic model error

Nuclear masses, giant resonances

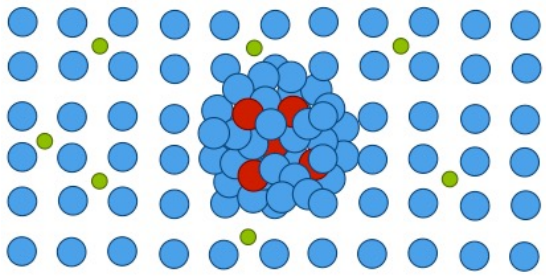
ρ_0 (fm^{-3})	0.160 ± 0.005
B (MeV)	16.0 ± 0.5
K (MeV)	230 ± 30

Lim, Holt arXiv:1702.02898

Modeling the crust



3D Skyrme HF:
n,p degrees of freedom



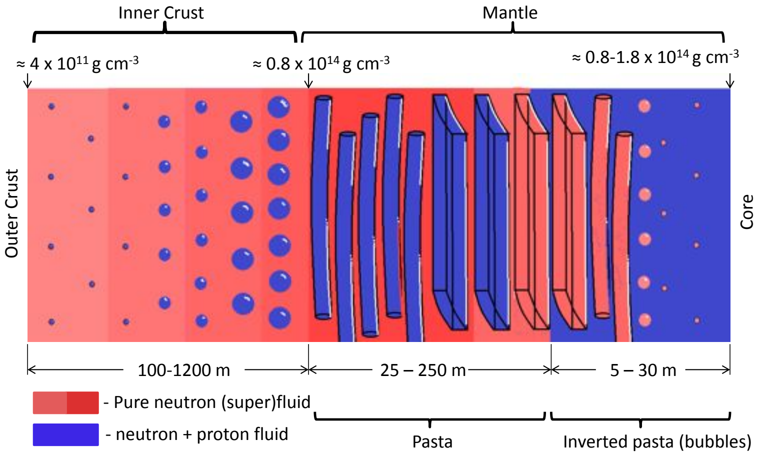
Newton+ arxiv:2104.11835

Pictures: Lauren Balliet

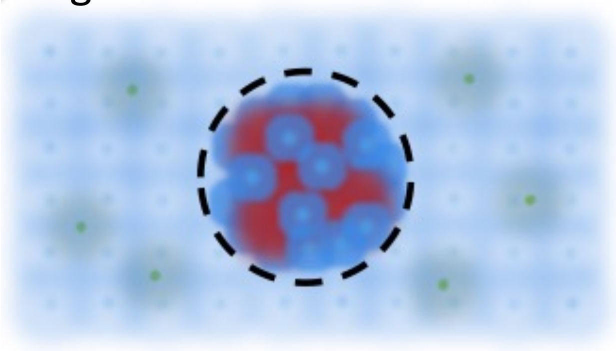
$$\mathcal{H}_\delta + \mathcal{H}_\rho + \mathcal{H}_{\mathrm{eff}} + \mathcal{H}_{\mathrm{grad}} + \mathcal{H}_{\mathrm{Coul}}$$

Nuclear EDF: Bulk+Gradient

Specific model: Skyrme



CLDM:Bulk fluid and surface
degrees of freedom



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

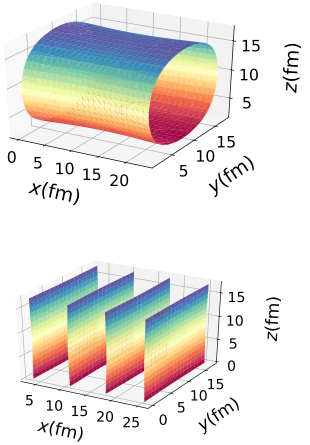
$$\mathcal{H}_\delta + \mathcal{H}_\rho + \mathcal{H}_{\mathrm{eff}} \quad \sigma(y_{\mathrm{p}})$$

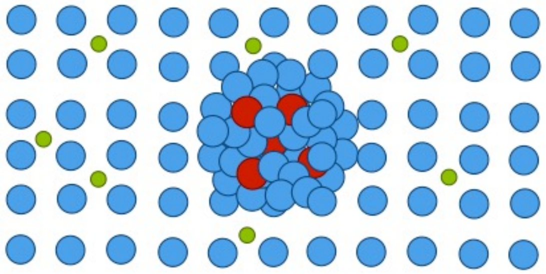
Nuclear EDF: Bulk +
separate surface energy function
specific model: LLPR 1985

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

Modeling the crust

3D Skyrme HF:
n,p degrees of freedom





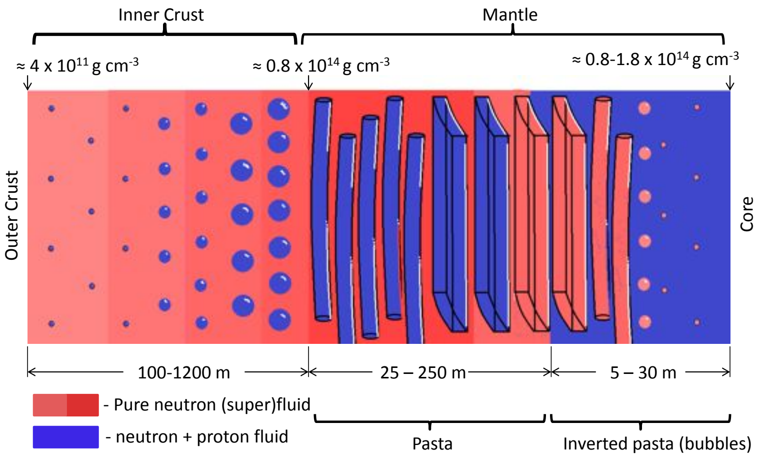
Newton+ arxiv:2104.11835

Pictures: Lauren Balliet

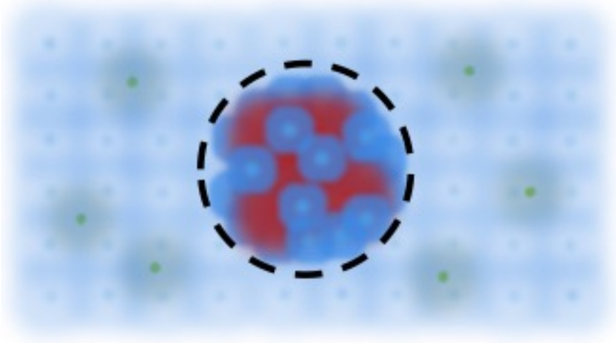
$$\mathcal{H}_\delta + \mathcal{H}_\rho + \mathcal{H}_{\rm eff} + \mathcal{H}_{\rm grad} + \mathcal{H}_{\rm Coul}$$

Nuclear EDF: Bulk+Gradient

Specific model: Skyrme



CLDM:Bulk fluid and surface degrees of freedom



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

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

Nuclear EDF: Bulk +
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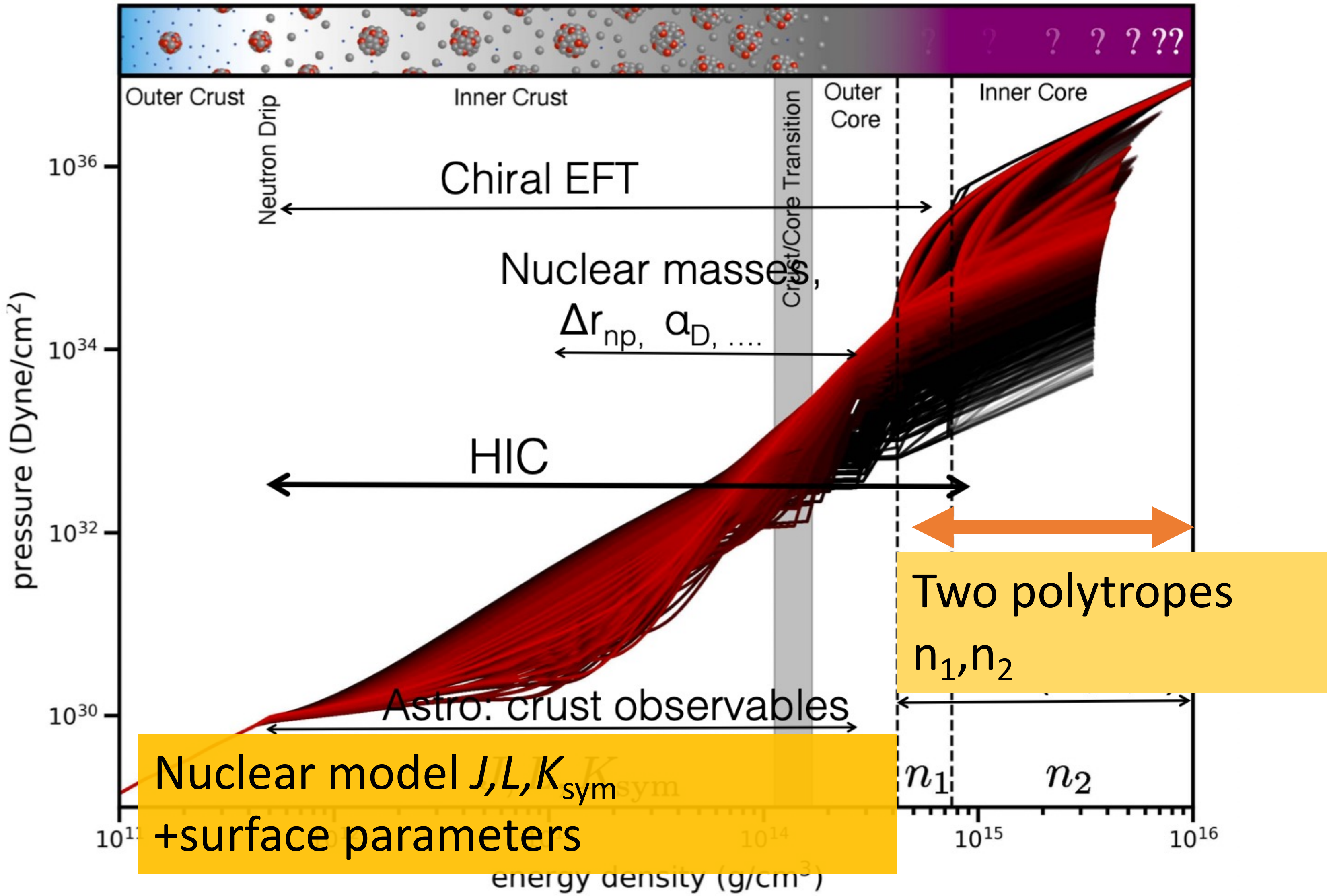
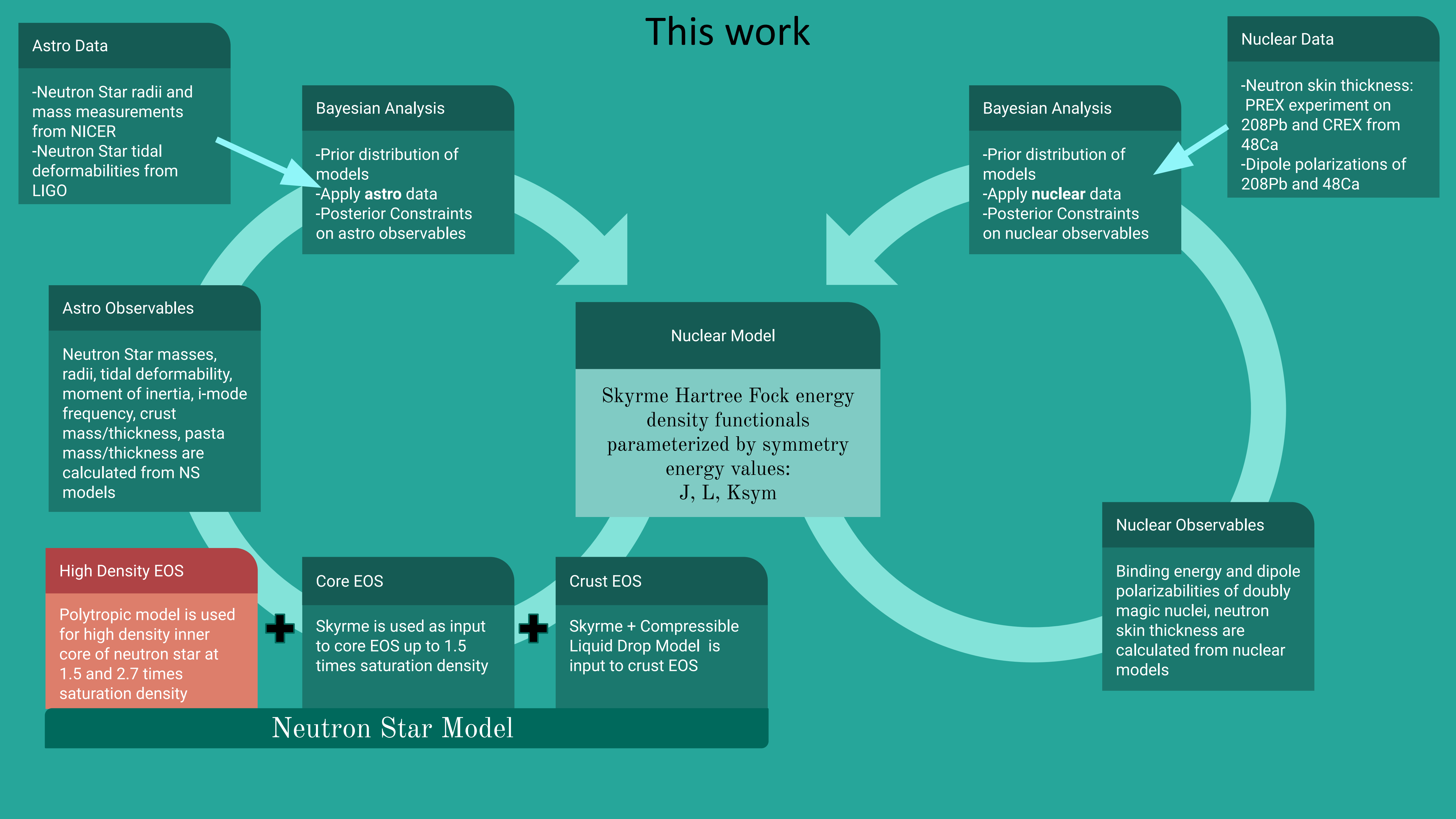
specific model: LLPR 1985

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

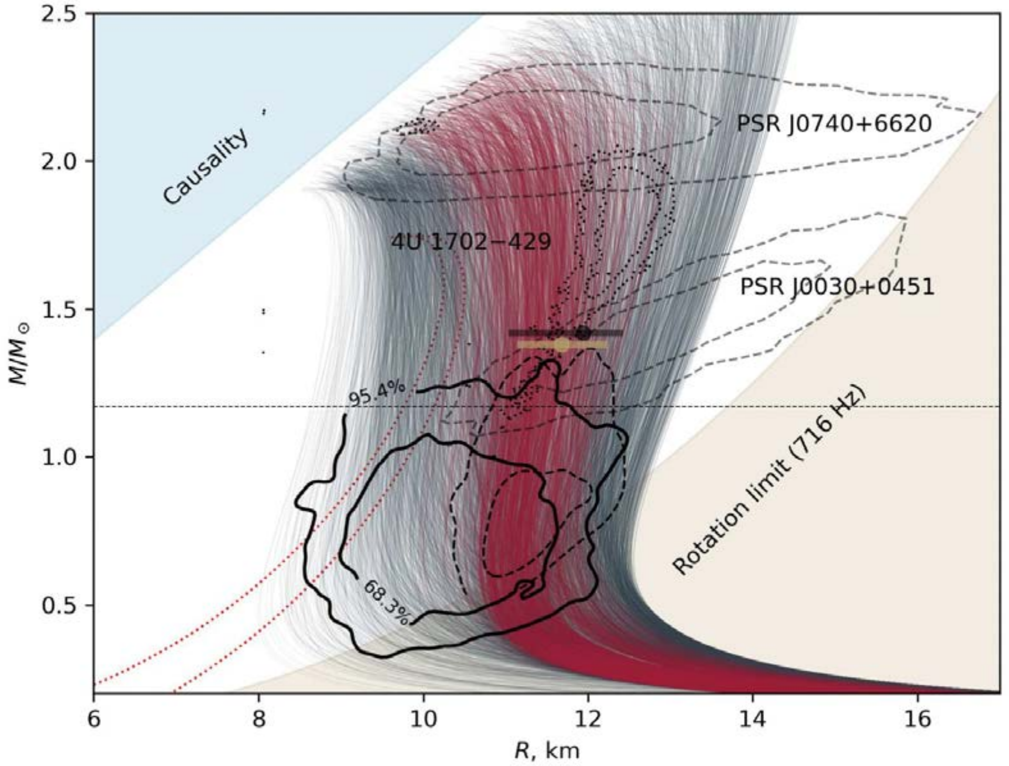
Model parameters



Neill+ 2208.00994; Sorenson+ 2301.13253

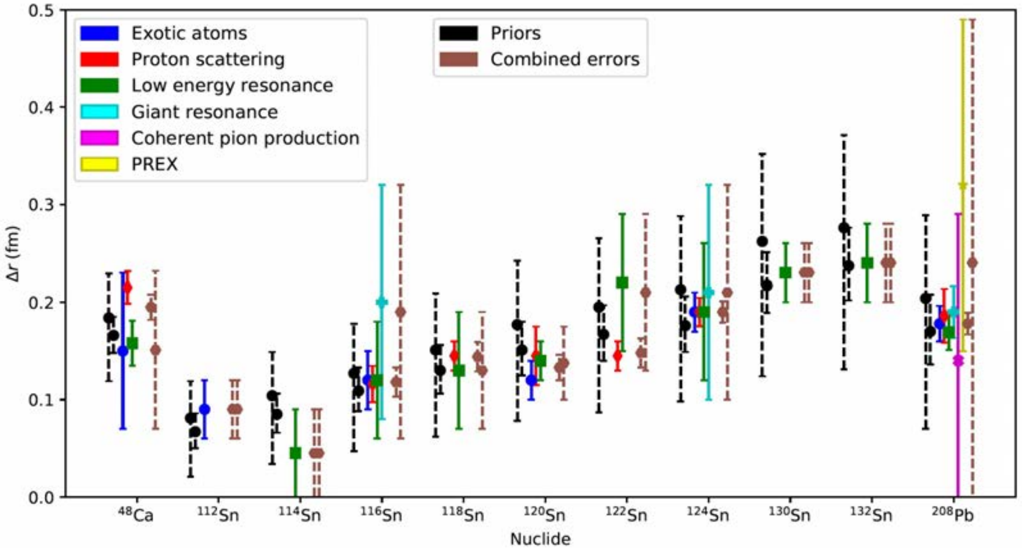

This work
Astro Data
-Neutron Star radii and mass measurements from NICER
-Neutron Star tidal deformabilities from LIGO
Bayesian Analysis
-Prior distribution of models
-Apply **astro** data
-Posterior Constraints on astro observables
Bayesian Analysis
-Prior distribution of models
-Apply **nuclear** 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
Skyrme Hartree Fock energy density functionals parameterized by symmetry energy values:
J, L, Ksym
Nuclear Observables
Binding energy and dipole polarizabilities of doubly magic nuclei, neutron skin thickness are calculated from nuclear 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

Data

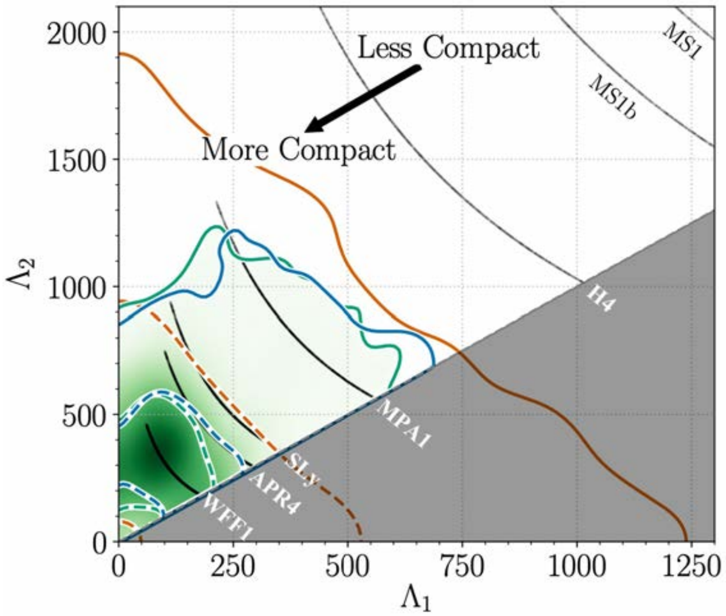


Doroshenko+, Nature Astronomy, **6**, 1444 (2022)

Raajimakers arxiv: 1912.05703,
2105.06981

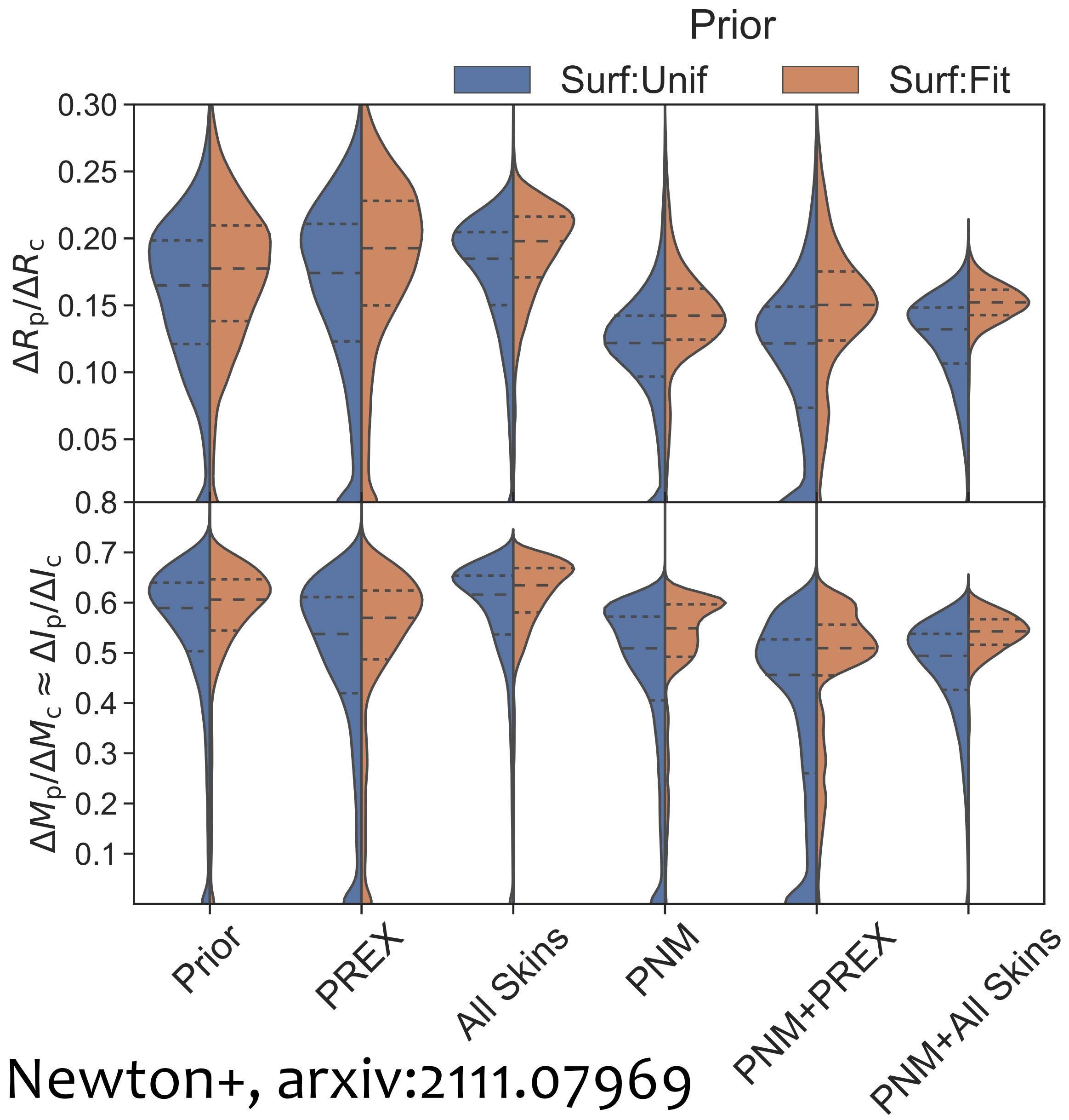


Newton, Crocombe arxiv:2008.00042

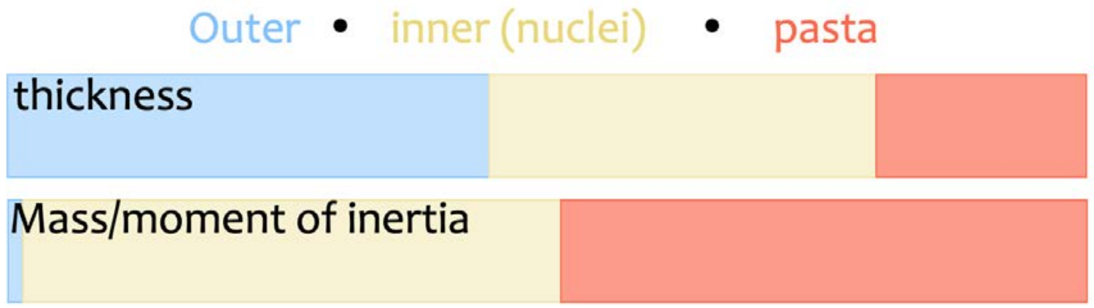


LIGO/Virgo arxiv:1805.11581

Results: Relative thickness and mass of pasta



$$
\begin{aligned}
\Delta R_{\rm p}/\Delta R_{\rm c} &= (0.122^{0.031}_{-0.47} \\
\Delta M_{\rm p}/\Delta M_{\rm c} &\approx \Delta I_{\rm p}/\Delta I_{\rm c} \\
&= 0.51^{0.08}_{-0.22}
\end{aligned}
$$

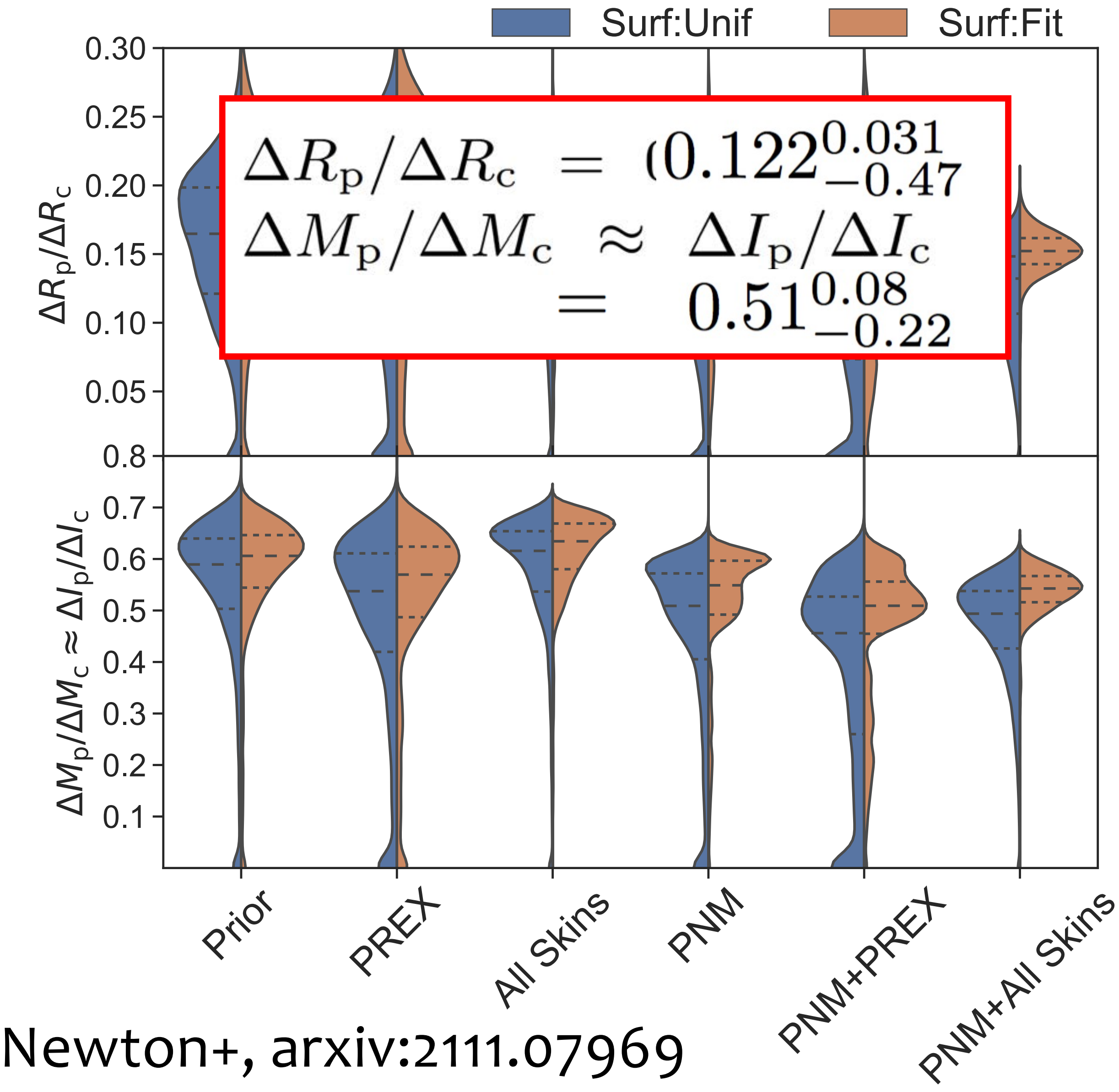


Newton+ arxiv:2112.12108

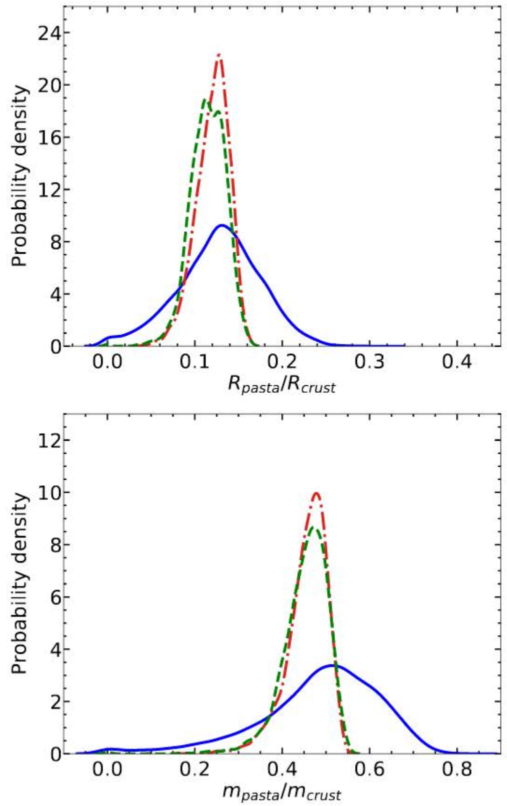
Newton+, arxiv:2111.07969

Balliet+, arxiv:2009.07696

Relative thickness and mass of pasta: agreement with other studies



$$\Delta R_{\rm p}/\Delta R_{\rm c} \;=\; (0.122^{0.031}_{-0.47}$$
$$\Delta M_{\rm p}/\Delta M_{\rm c} \;\approx\; \Delta I_{\rm p}/\Delta I_{\rm c} \;=\; 0.51^{0.08}_{-0.22}$$

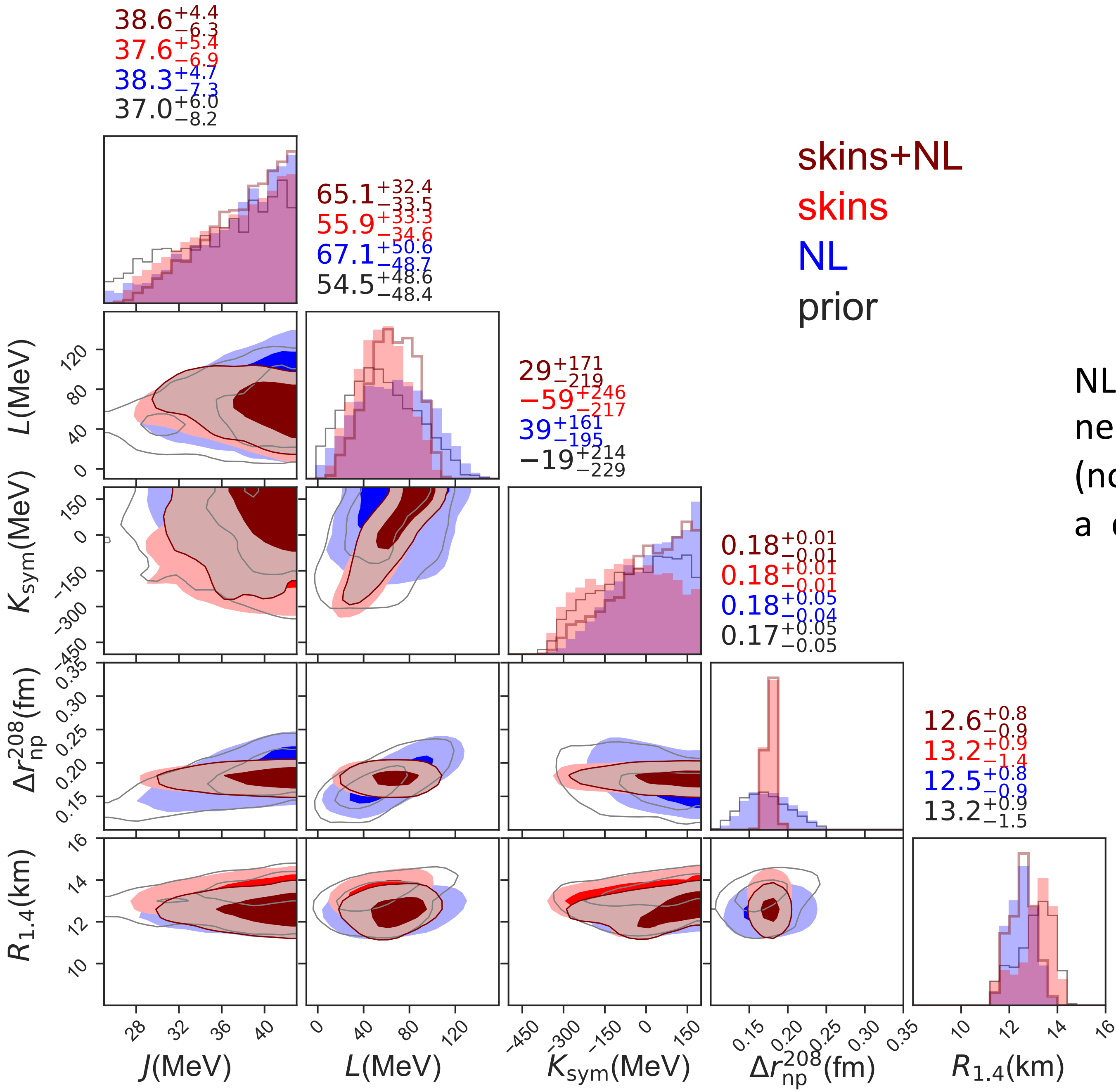


$R_{\rm pasta}/R_{\rm crust}$	0.128 ± 0.047
$I_{\rm pasta}/I_{\rm crust}$	0.480 ± 0.137
$m_{\rm pasta}/m_{\rm crust}$	0.485 ± 0.138

Newton+, arxiv:2111.07969
Balliet+, arxiv:2009.07696

Dinh Thi+ arxiv: 2109.13638

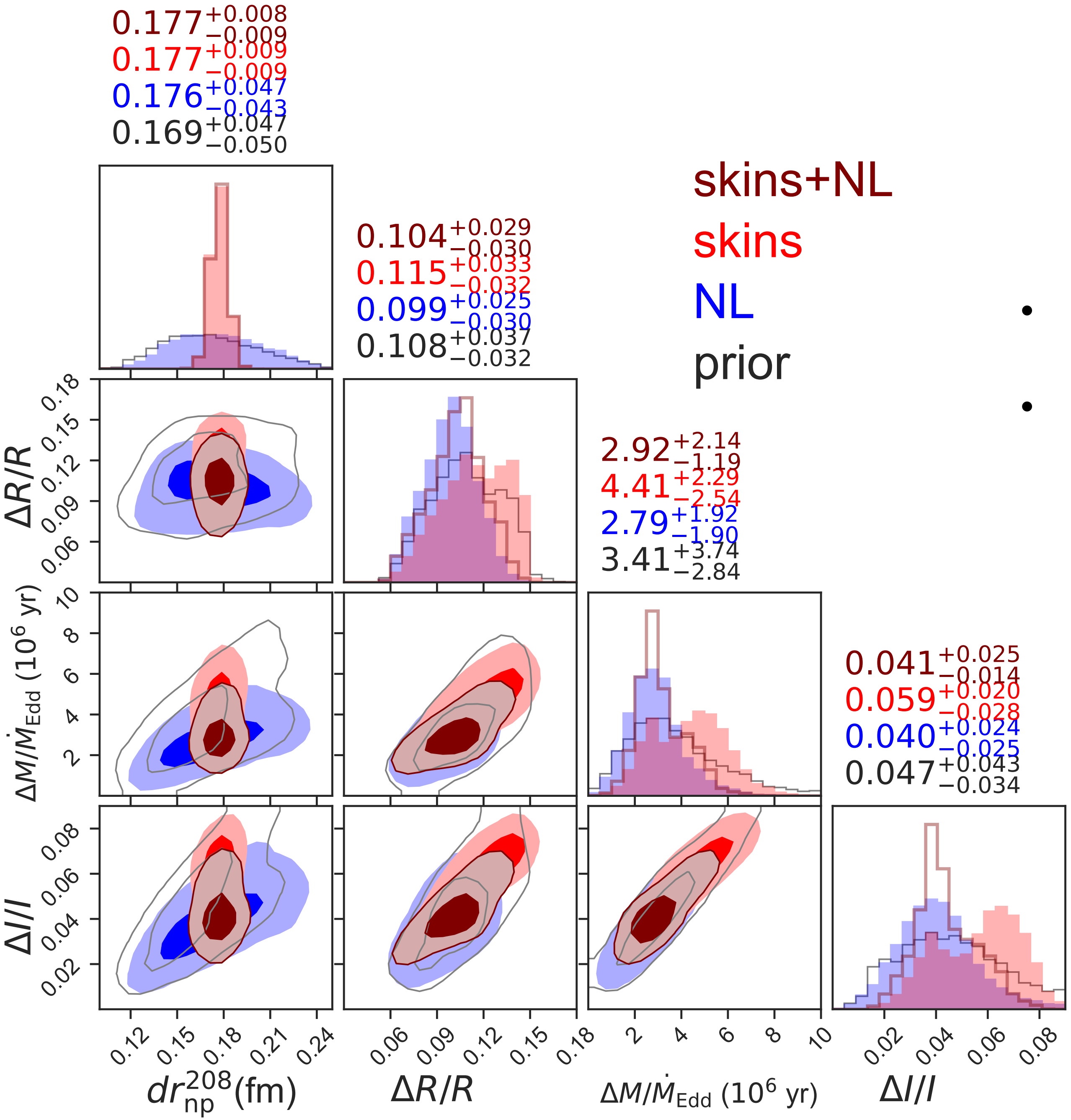
Preliminary



Newton+ in prep

NL prefers stiffer L, K_{sym}
neutron skins prefer softer
(note: PREX alone would come to a different conclusion)

Preliminary

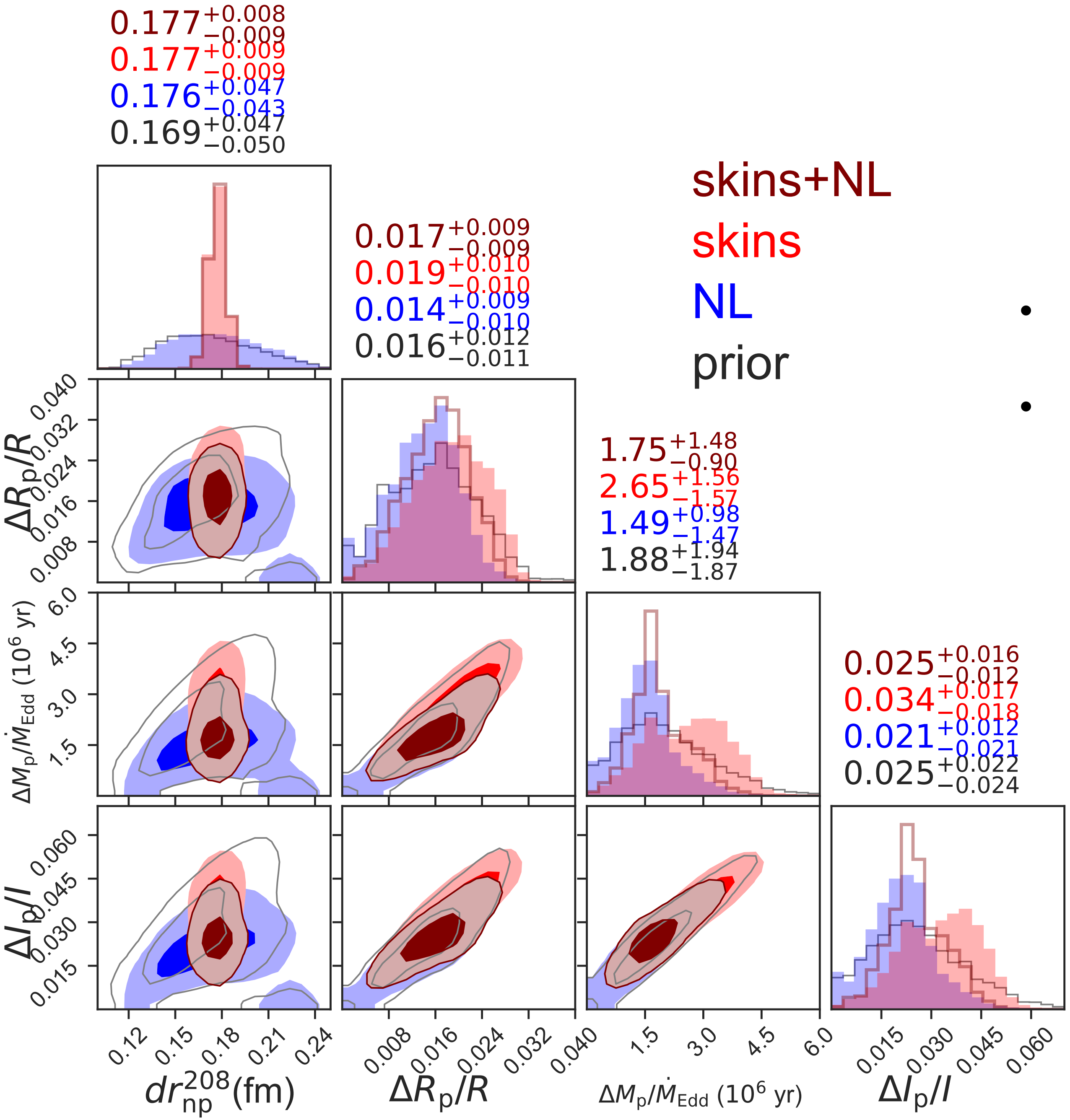


- NL prefers thinner, less massive crust
- Both neutron skin data and NL prove informative

Crustal glitches:
0.018
0.08 (with entrainment)

Newton+ in prep

Preliminary

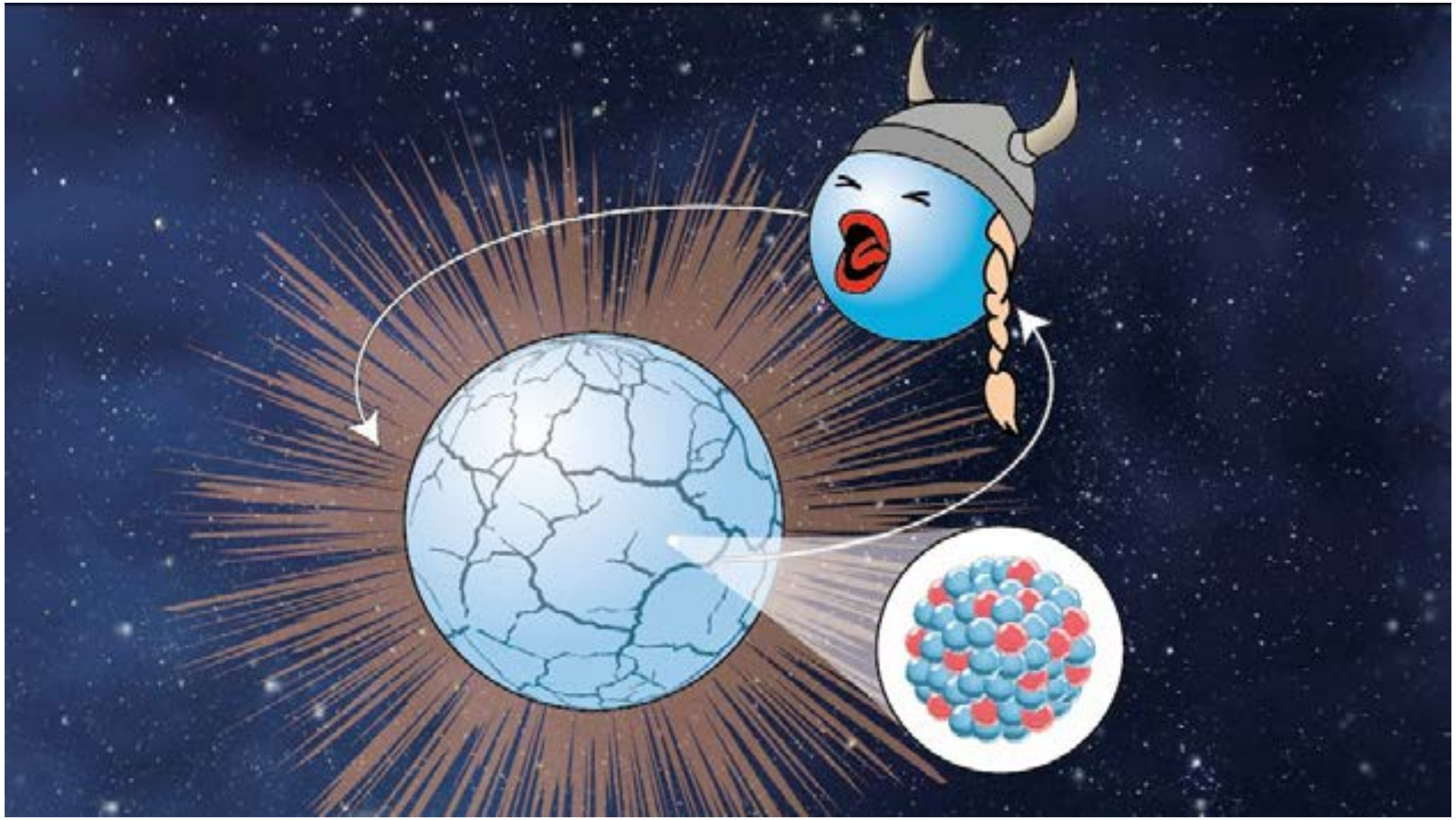


- NL prefers thinner, less massive pasta region
- Both neutron skin data and NL prove informative

Newton+ in prep

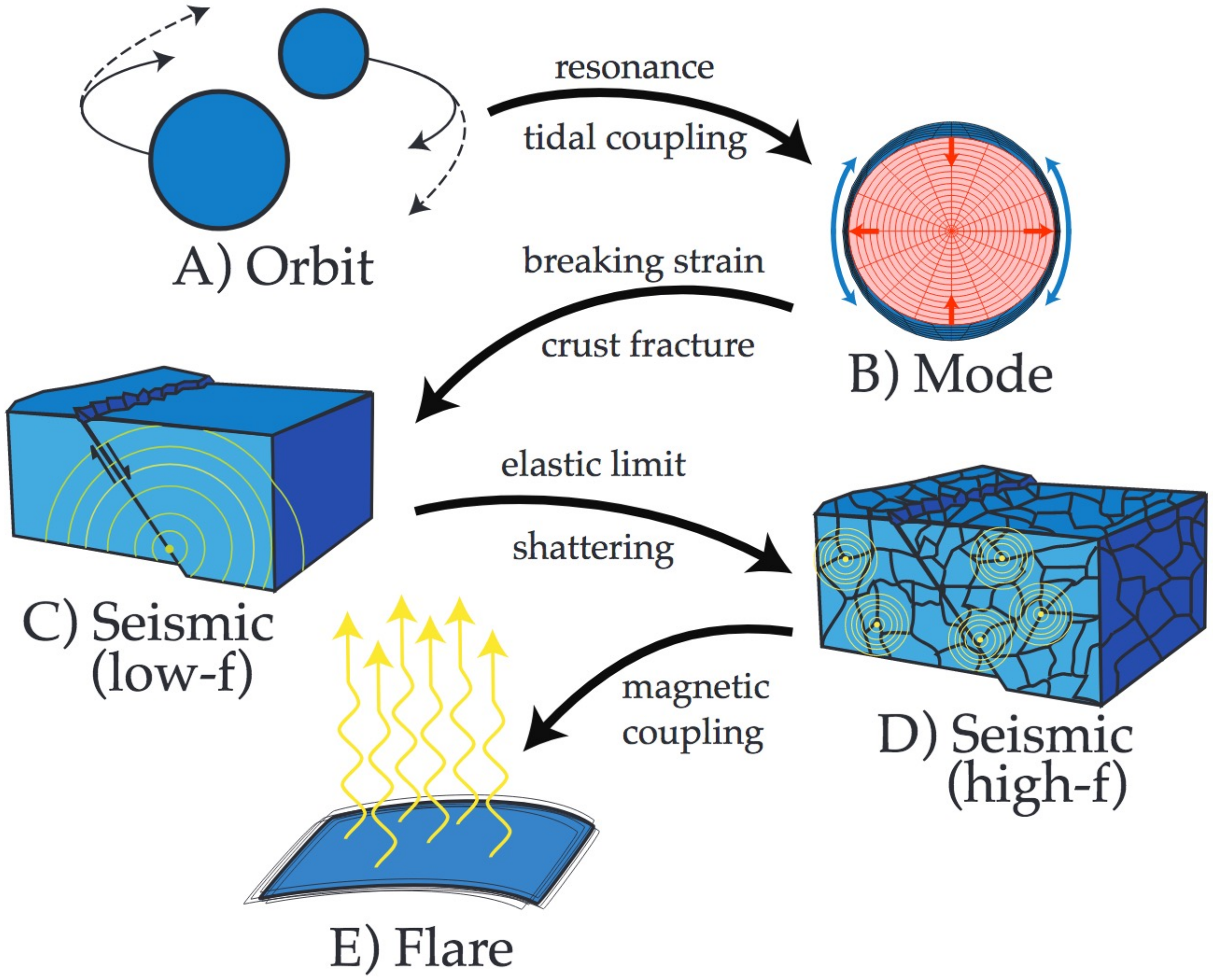
Application: resonant crust shattering flares

Neill, Newton & Tsang, MNRAS 504, 2021
Neill,Preston,Newton,Tsang, PRL130, 2022



Picture: David Tsang

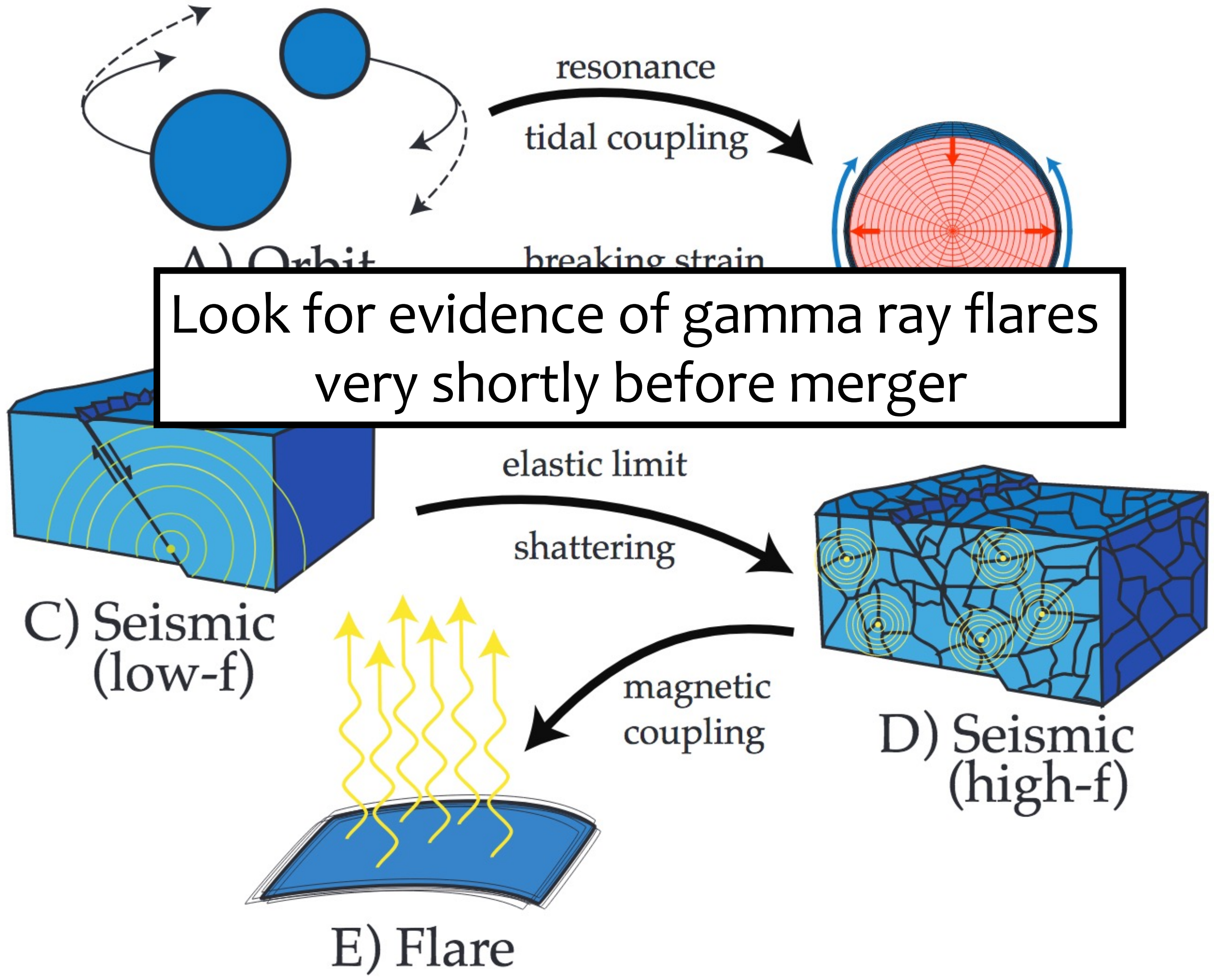
The elastic crust can be made to resonantly vibrate by the tidal field of its companion



D.Tsang, Apj 777, 2013

Neill, Newton & Tsang, MNRAS 504, 2021

The elastic crust can be made to resonantly vibrate by the tidal field of its companion

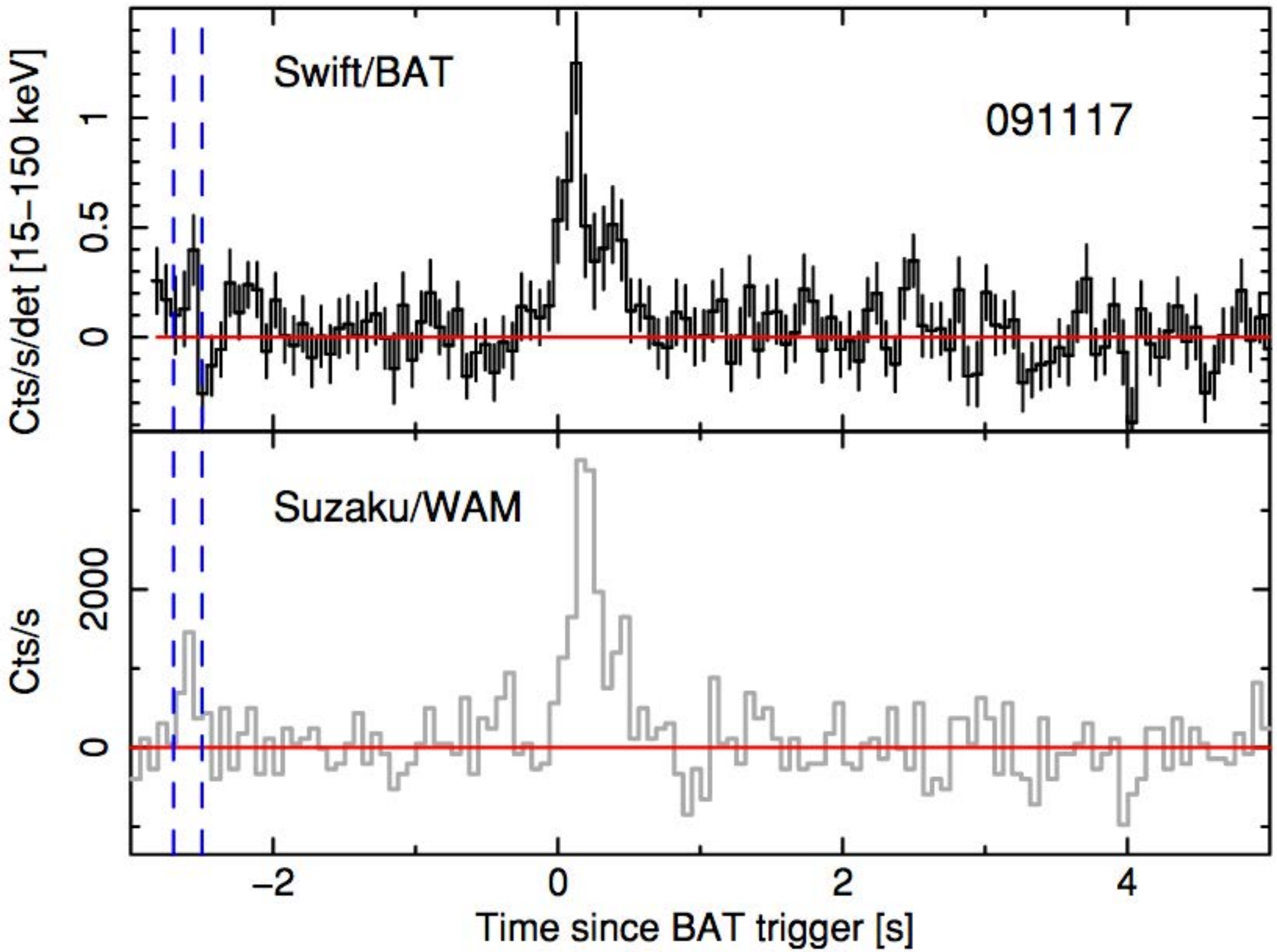


Look for evidence of gamma ray flares very shortly before merger

D.Tsang, Apj 777, 2013

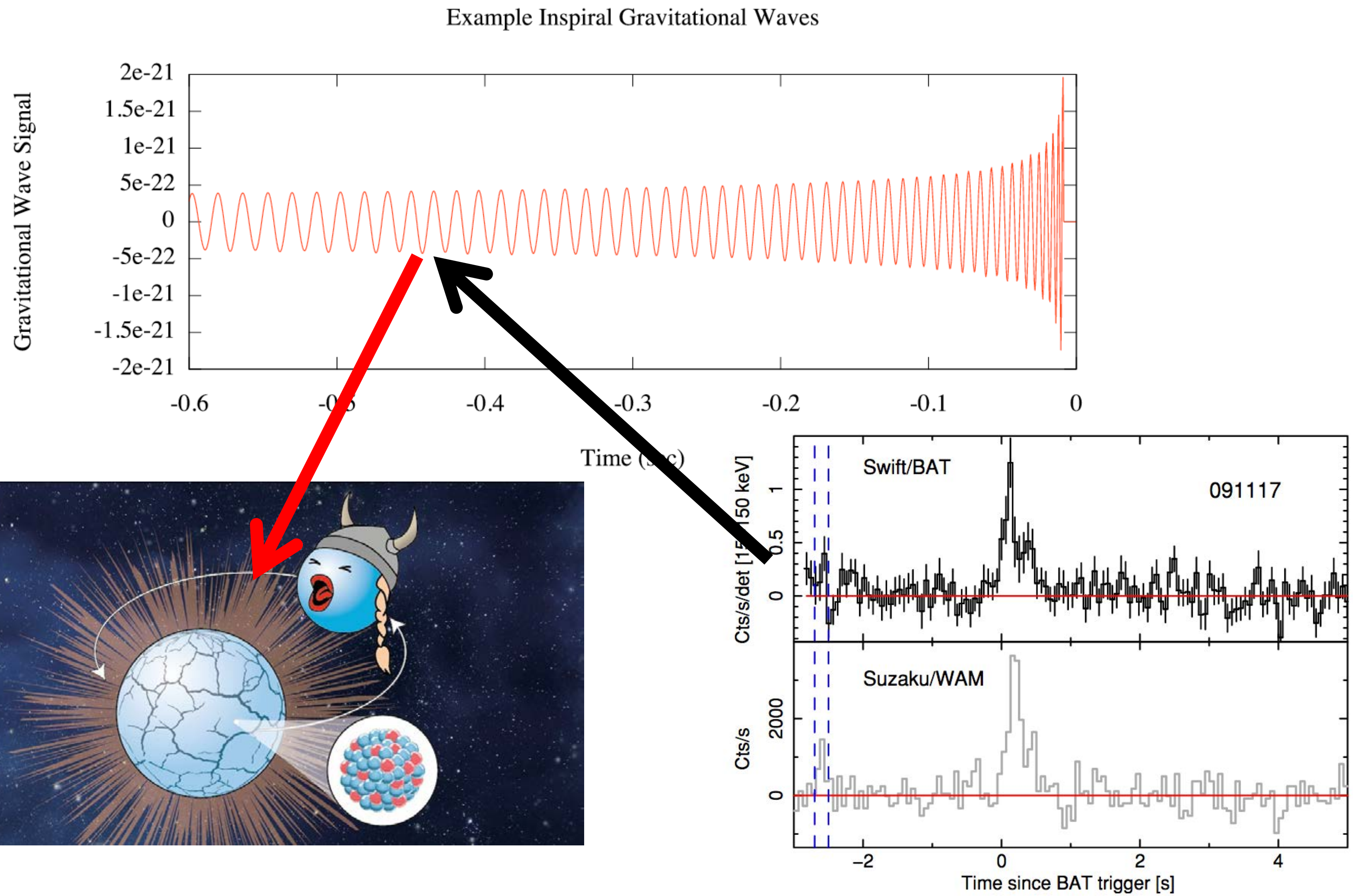
Neill, Newton & Tsang, MNRAS 504, 2021

Precursor flares 0.1-10s before main flare observed for ≈20 sources

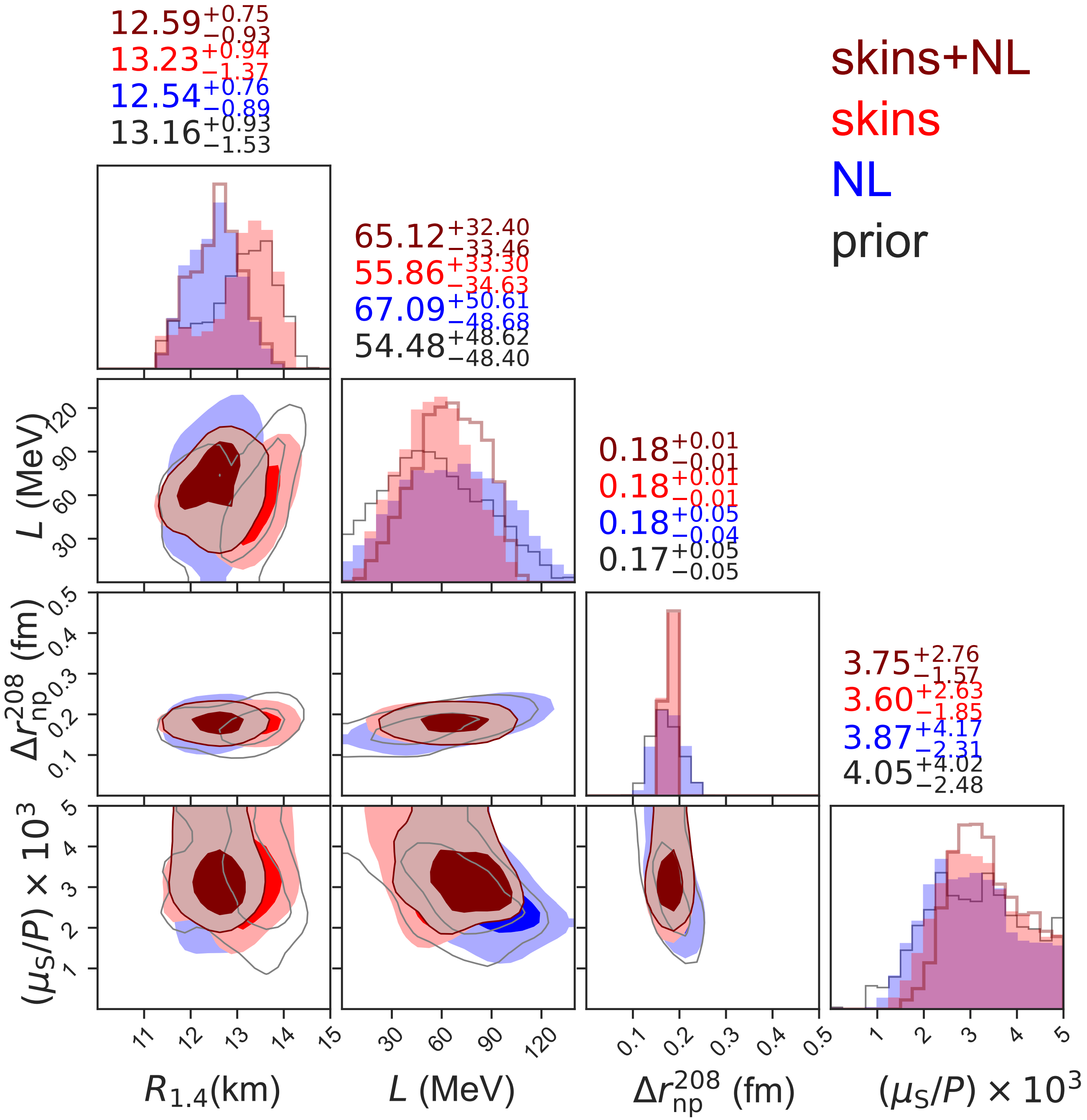


Troja, Rosswog, Gehrels, ApJ723, 2010

Time of gamma ray flare points out GW frequency at that time which gives the resonant frequency of the crust



Preliminary

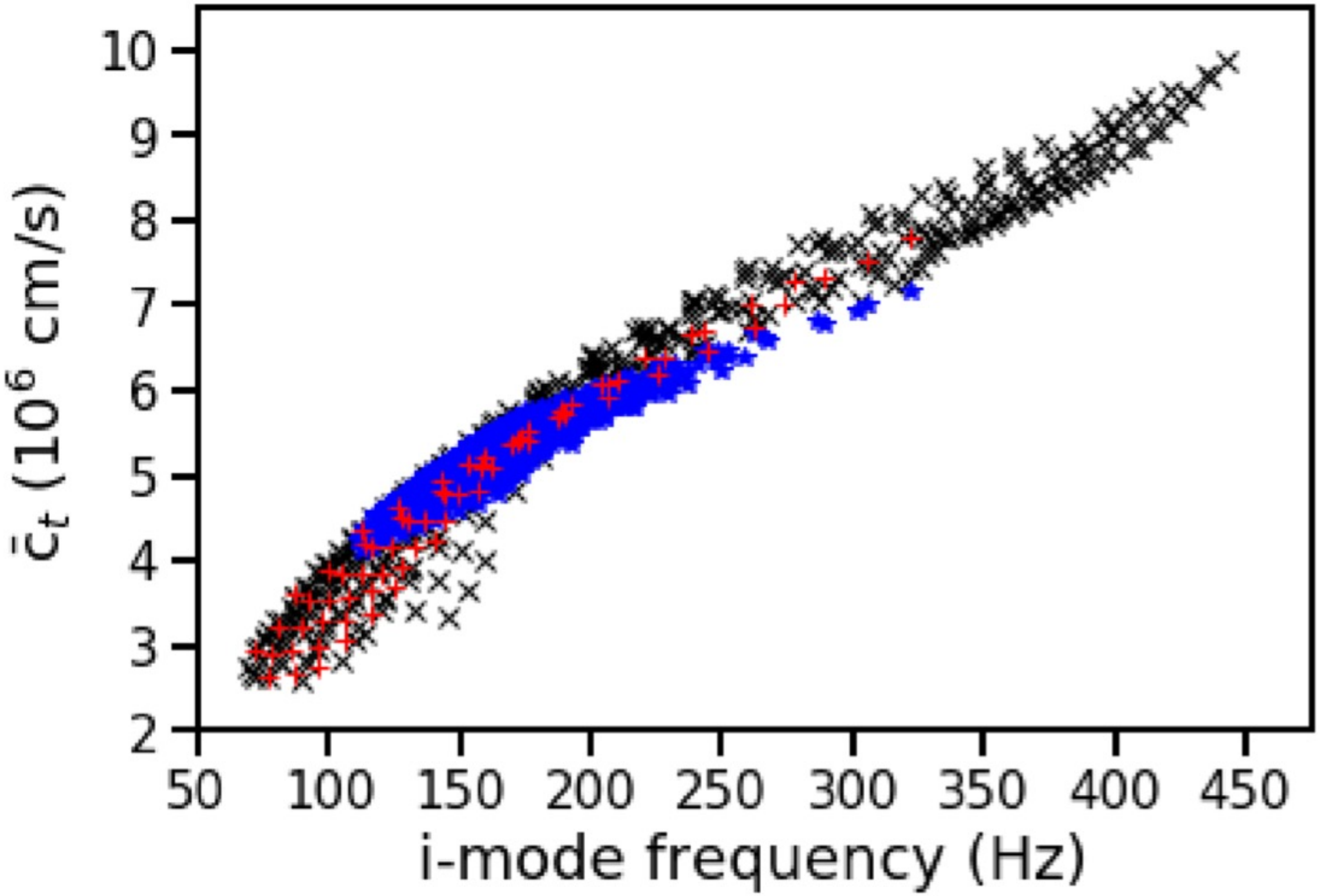


Newton+ in prep

We can also obtain the posteriors on the shear modulus at the base of crust

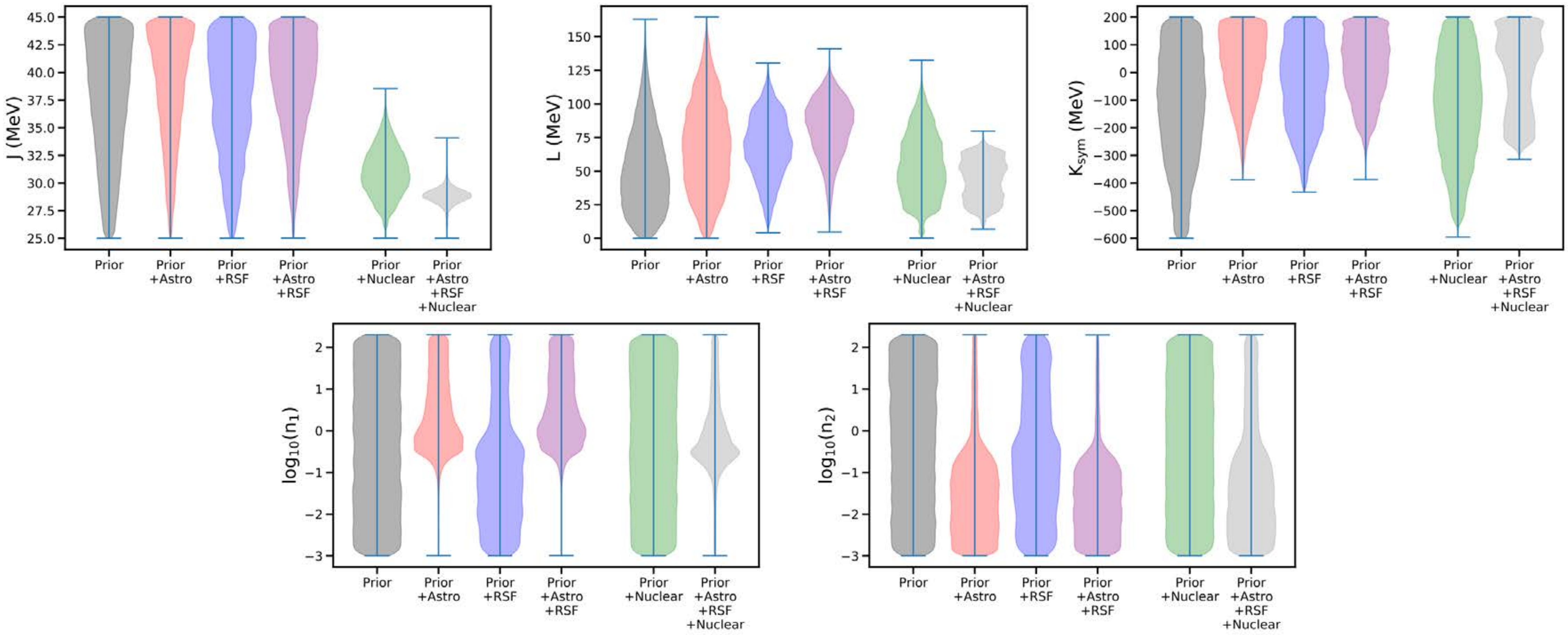
(using form of Strohmayer+ 1991)

Strong correlation between shear speed and *i*-mode frequency



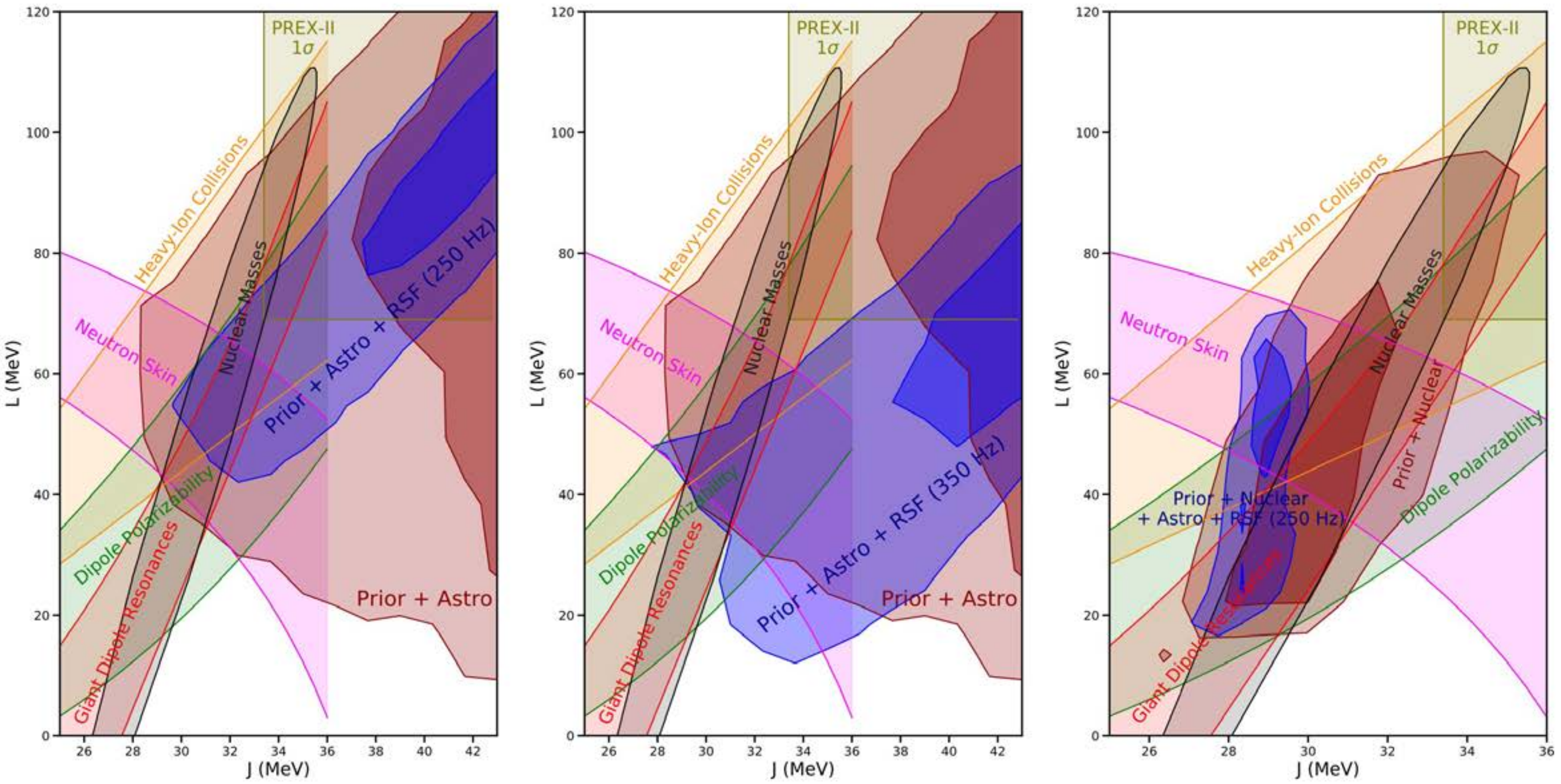
Neill, Newton & Tsang, MNRAS 504, 2021

Inference using a synthetic detection of an RSF at a frequency of 250 Hz, comparison with NL and nuclear binding energy data



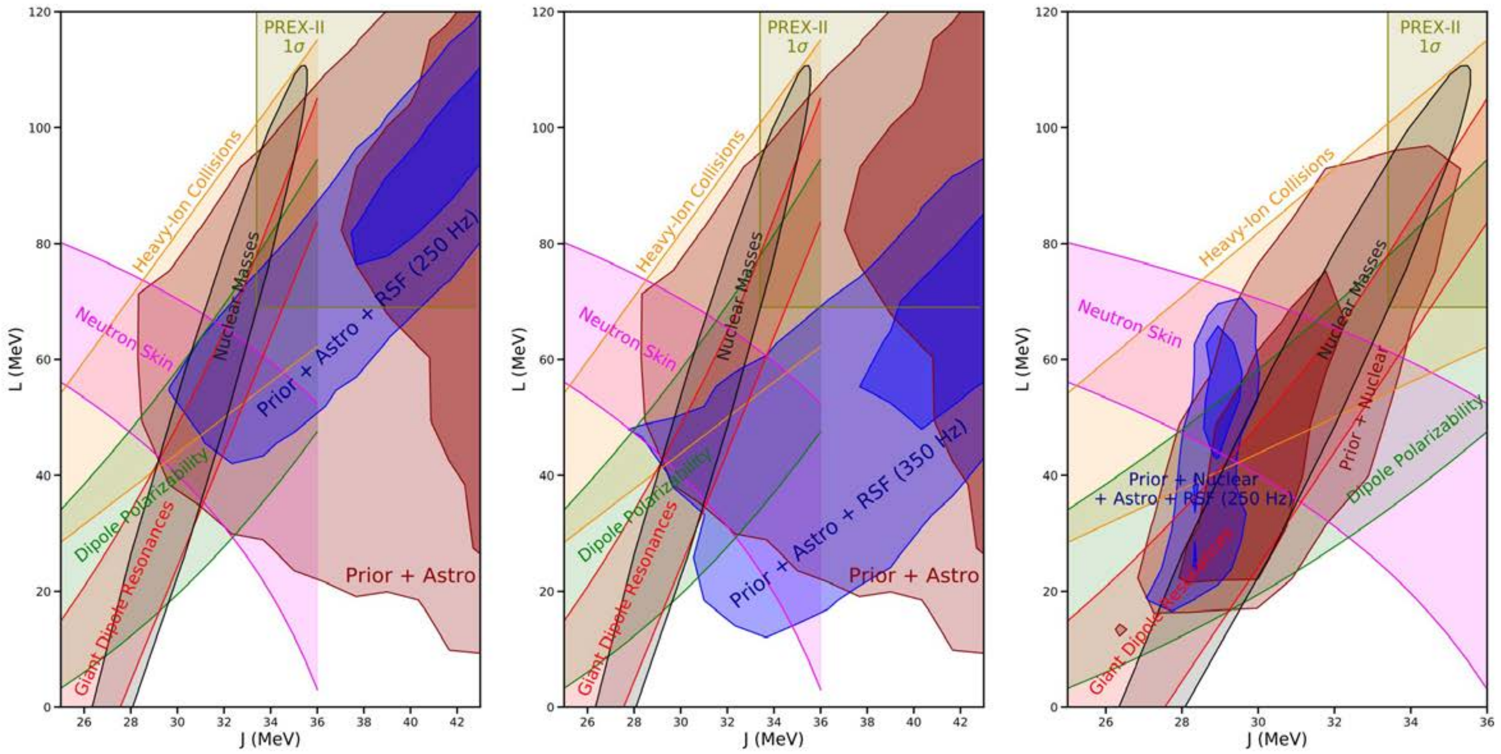
- *J* not constrained by RSF/NL
- Polytrope parameters not constrained by nuclear BEs
- *L* constrained by RSF and BE
- K_{sym} constrained by RSF/NL

An observation of an RSF can potentially constrain the symmetry energy



Take-aways

- We have a model that efficiently calculates crust, core and nuclear properties consistently, with polytropes added to account for uncertainty at high density
- Both nuclear and astrophysical data give us information about the neutron star crust, and consistent models are needed to take advantage of this



- During a neutron star merger, the stars may resonantly excite each other's solid crust to shattering
- A coincident detection of a flare and GW signal can measure the *i*-mode frequency and constrain the nuclear symmetry energy
- But can we know for sure that the flare is from an RSF?