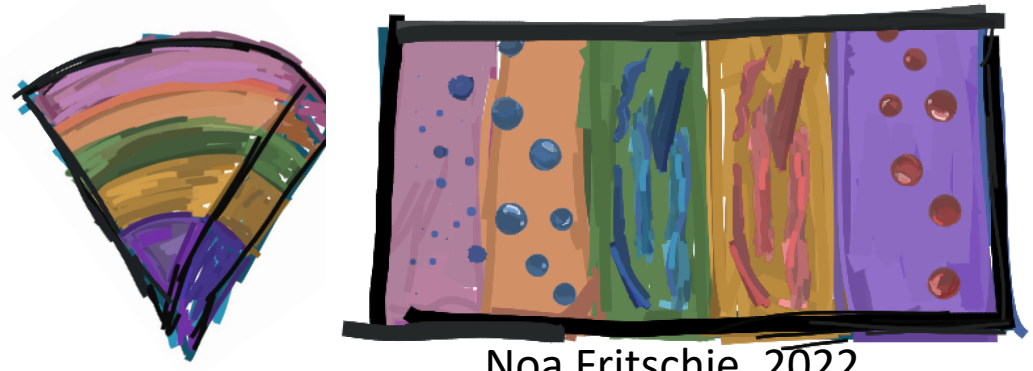
Nuclear physics constraints on neutron star physics

William G. Newton

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

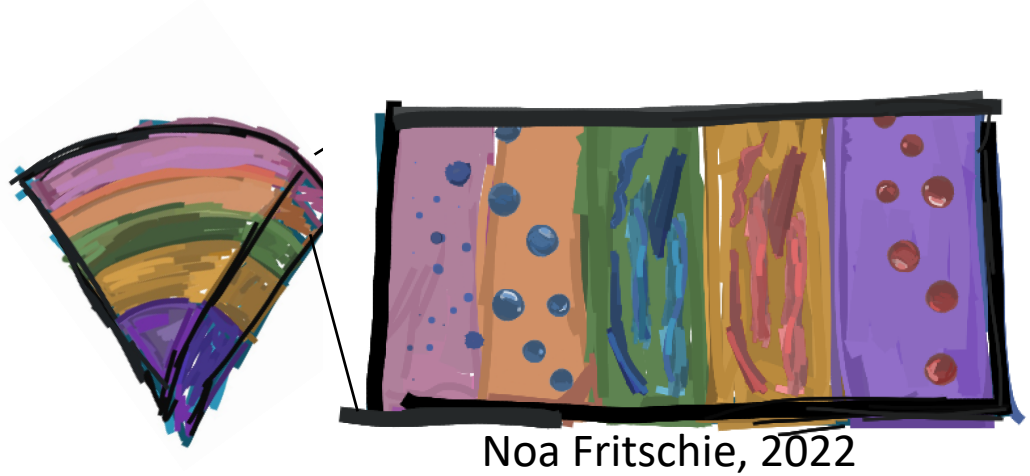
Rebecca Preston, Lauren Balliet, Michael Ross Amber Stinson, August Doss, Gabriel Crocombe, Josh Belieu, Savannah Wright, Parker Reeves

Duncan Neill, David Tsang – University of Bath

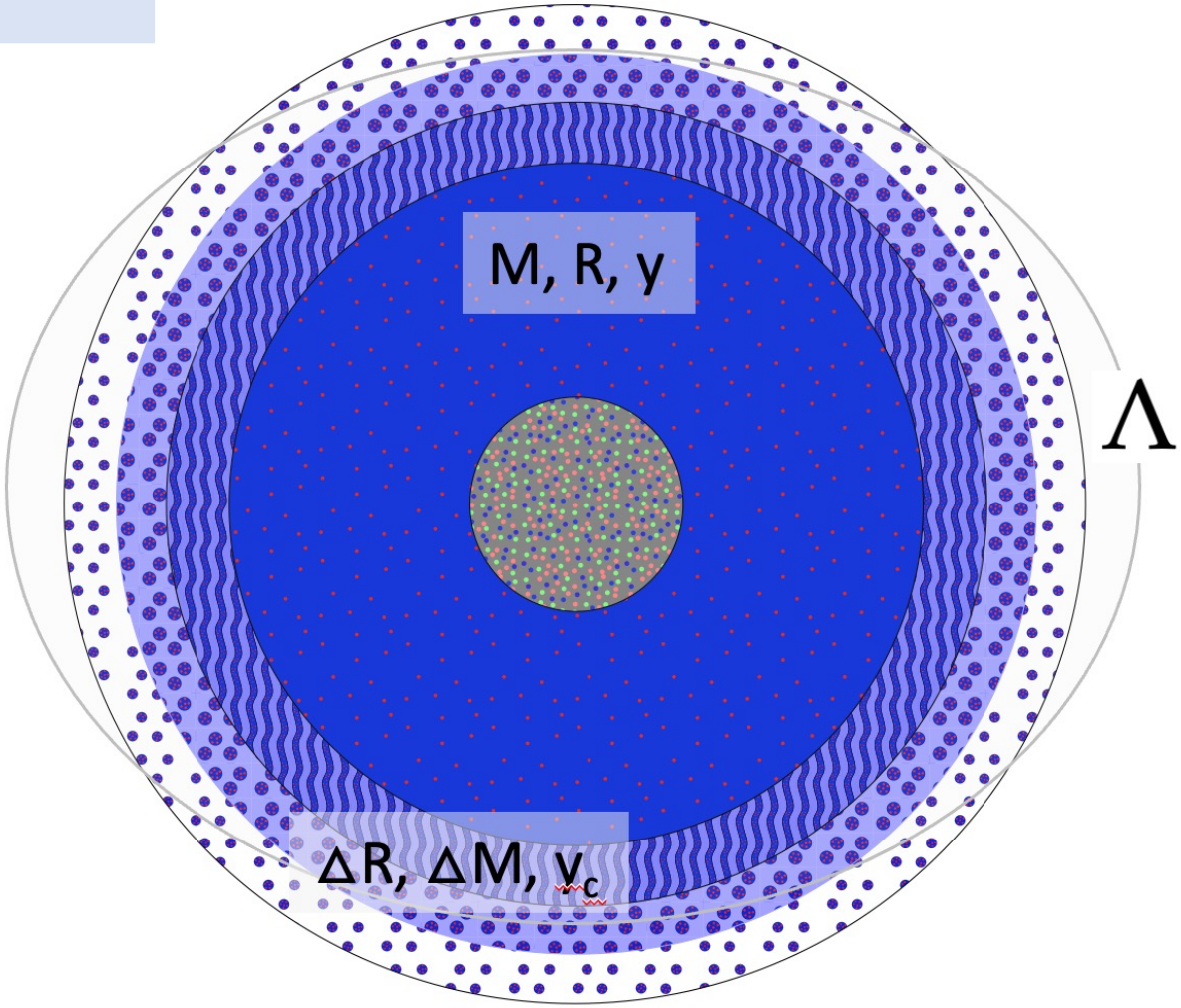


Noa Fritschie, 2022

A neutron star's intrinsic structure



Noa Fritschie, 2022

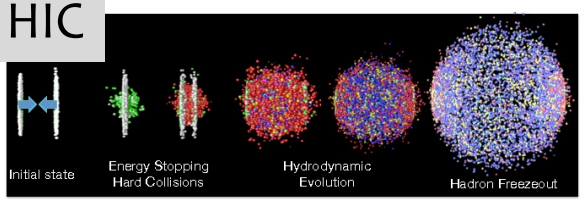


Outer crust/ inner crust/ mantle/ outer core/ inner core

N,e/ N,e,n/ N*,e,n(p)/ n,p,e,μ/ **Λ** or q or…

Nuclear structure/ dynamics

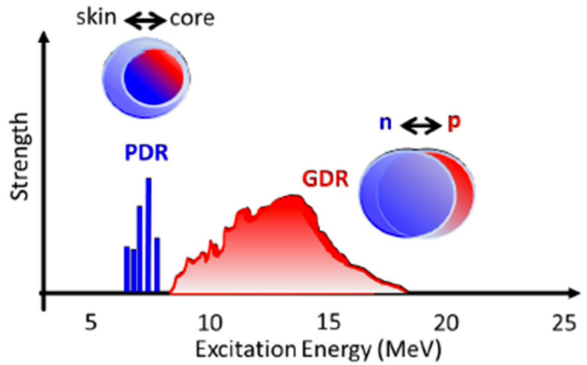
HIC



T.K.Nayak, arxiv:1201.4264

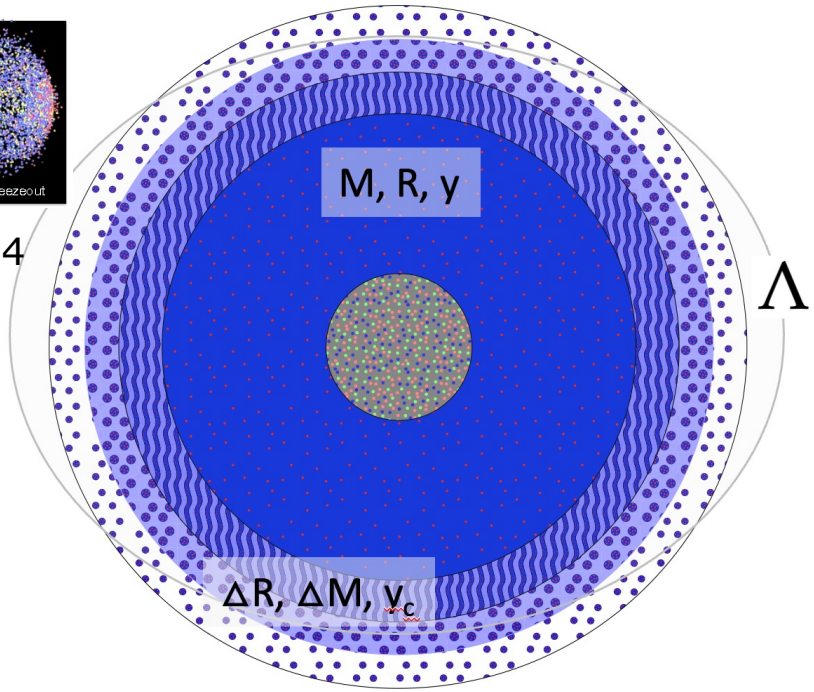
neutron skins

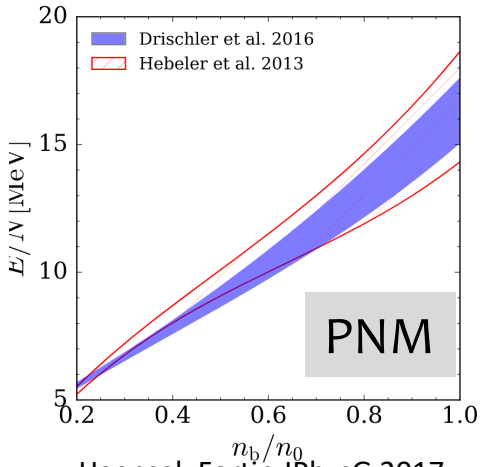
Abrahamyan+,
PRL 108, 112592 (2012)



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

Multi-messenger nuclear astrophysics

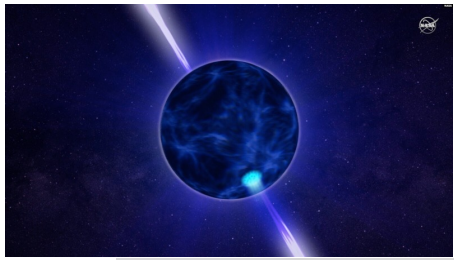




Haensel, Fortin JPhysG 2017

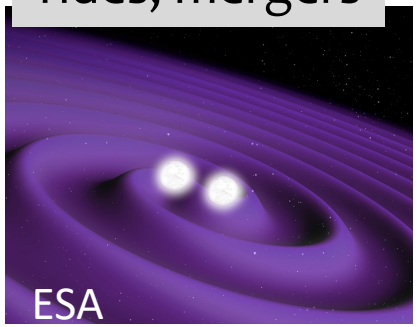
Neutron star structure/ dynamics

Glitches, flares, cooling



Hot spots Oscillations, Crust cooling

Tides, mergers



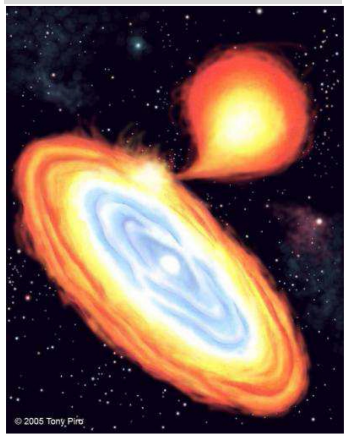


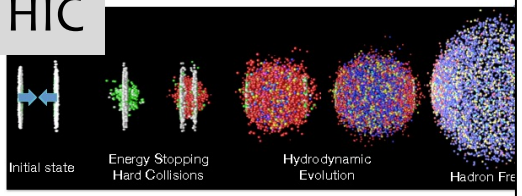
Figure: Artist's impression of a LMXB - credit Tony Piro, 2005.

Nuclear structure/ dynamics

Multi-messenger nuclear astrophysics

Neutron star structure/ dynamics

HIC



T.K.Nayak, arxiv:1201.426

neutron skins

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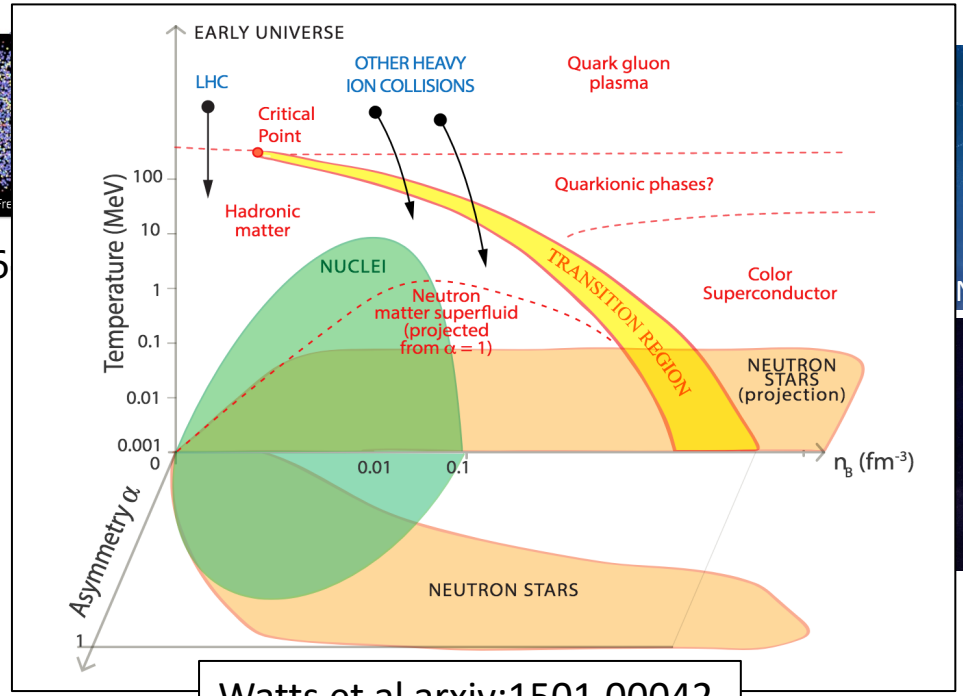
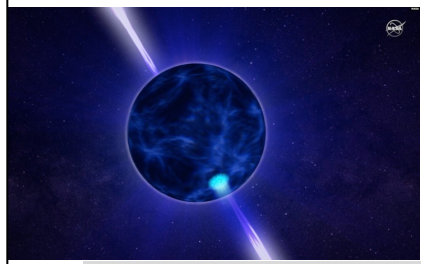
PRL 108, 112592 (2012)

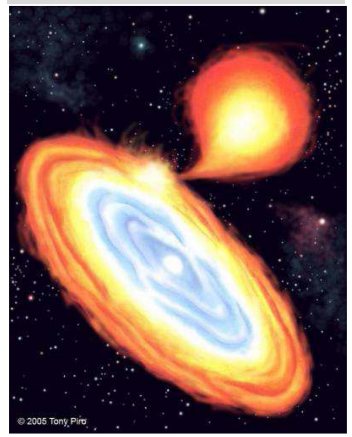


Watts et al arxiv:1501.00042

Glitches, flares, cooling



Hot spots Oscillations, Crust cooling



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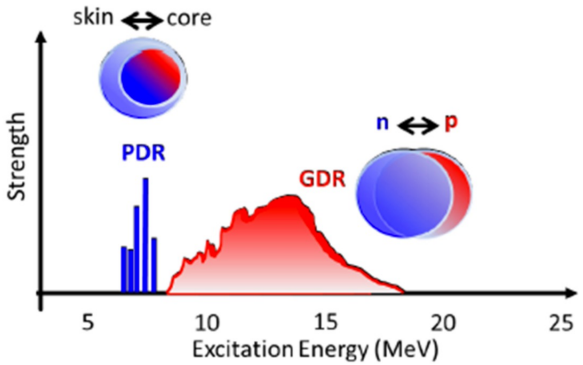
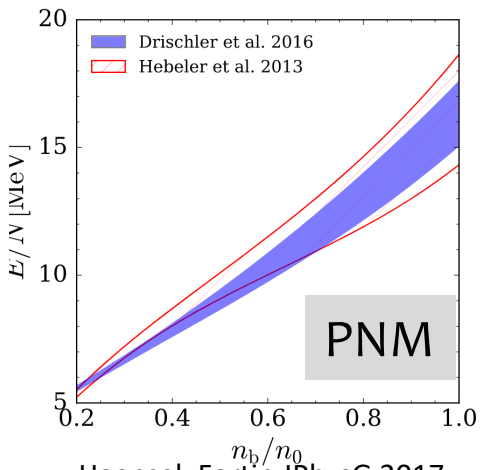
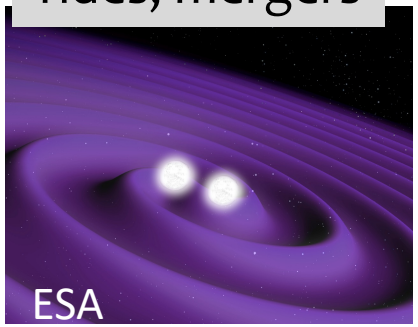


Bracco, Lanza, Tamii,
PPNP 106, 360 (2019)



Haensel, Fortin JPhysG 2017

Tides, mergers

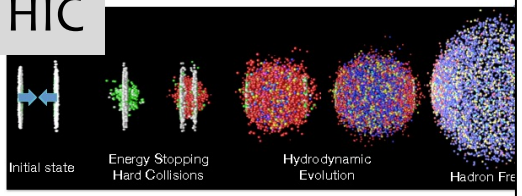


Nuclear structure/ dynamics

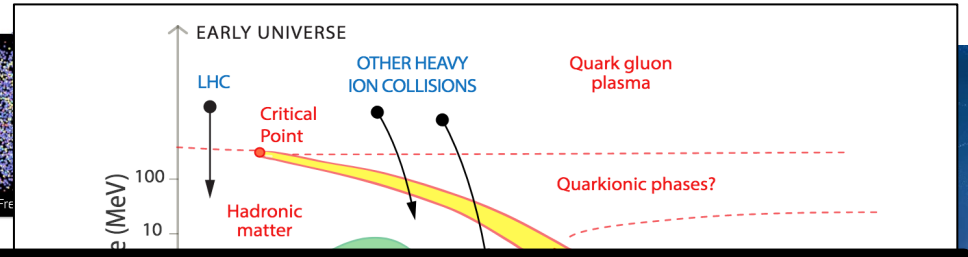
Multi-messenger nuclear astrophysics

Neutron star structure/ dynamics

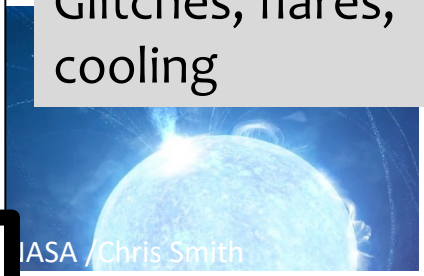
HIC

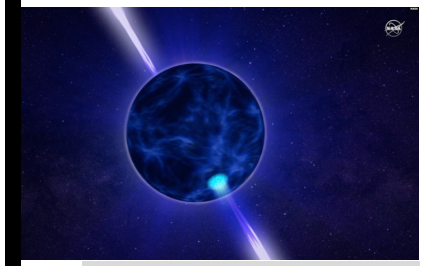


T.K.Nayak, arxiv:12

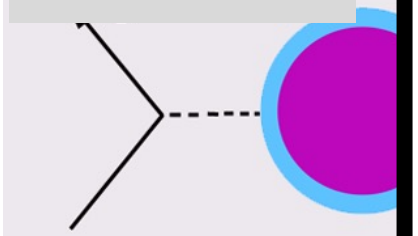


Glitches, flares, cooling





neutron skins

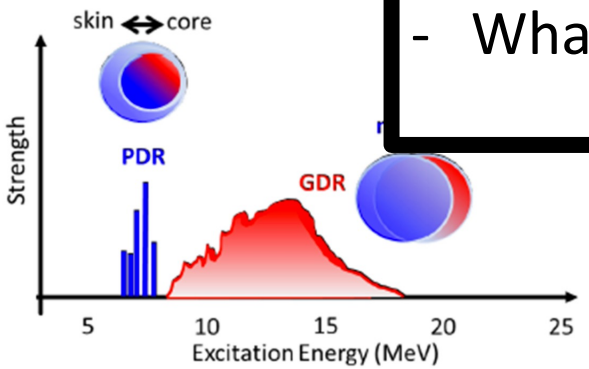


Abrahamyan+,
PRL 108, 112592 (2

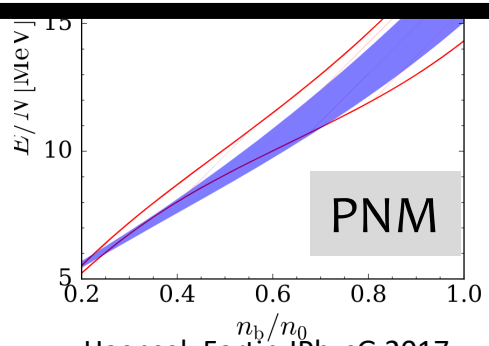
Communication between communities:

- What are we interested in?
- What do we need?
- How are we defining quantities?
- What are the limits of models?
- How are the uncertainties quantified?
- What are the model dependencies?

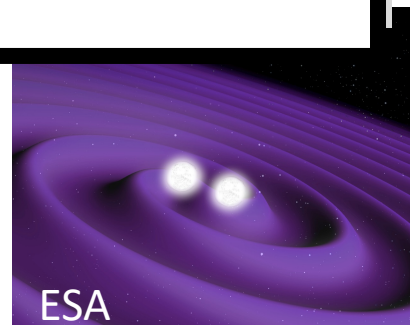
Hot spots
Oscillations,
Crust cooling



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



Haensel, Fortin JPhysG 2017



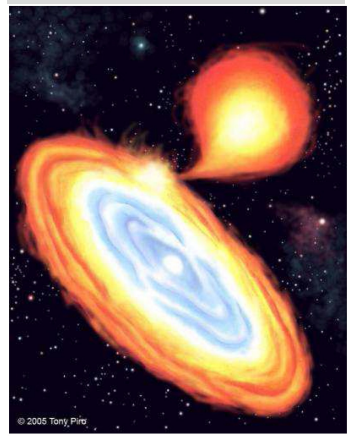
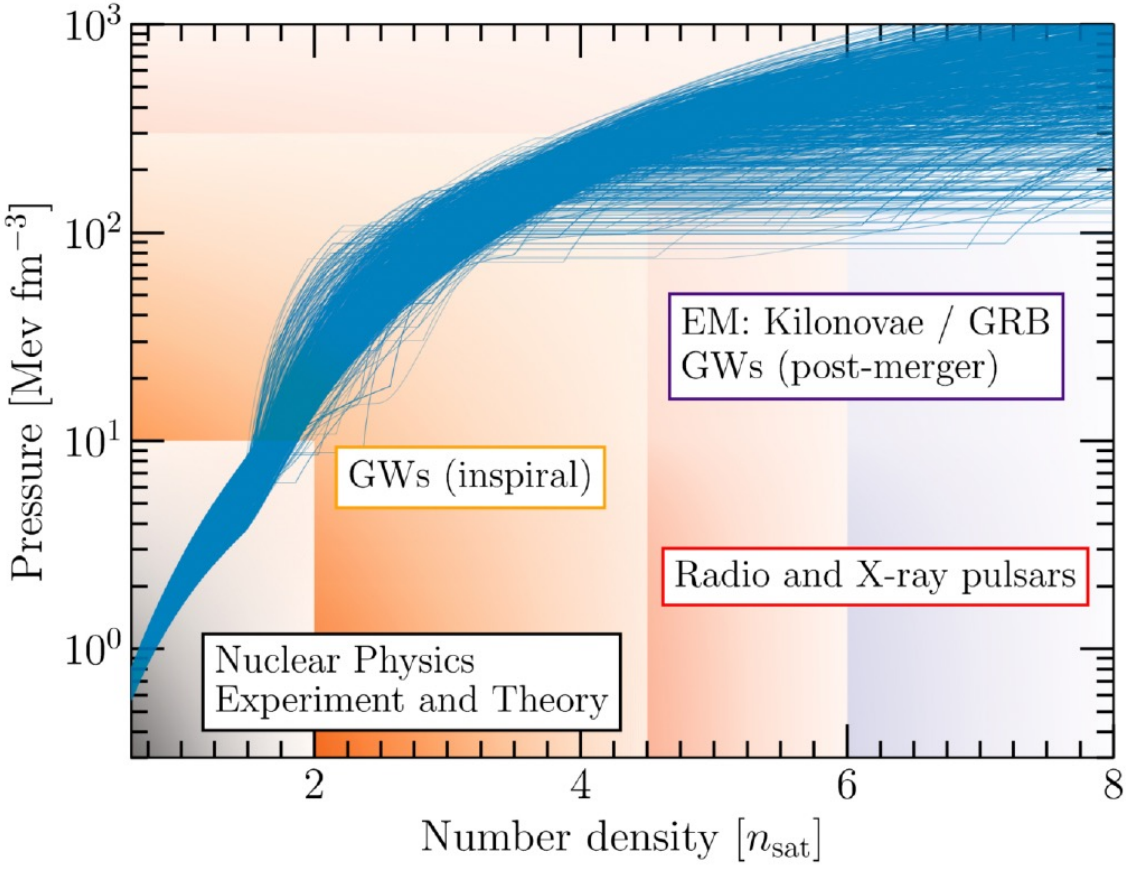


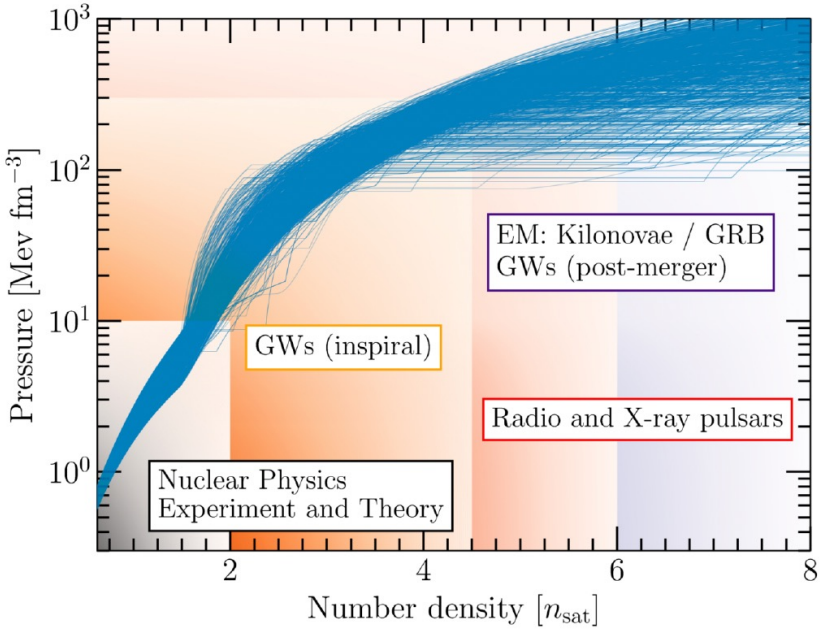
Figure: Artist's impression of a LMXB - credit Tony Piro, 2005.

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



Pang et al, arxiv:2205.08513

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



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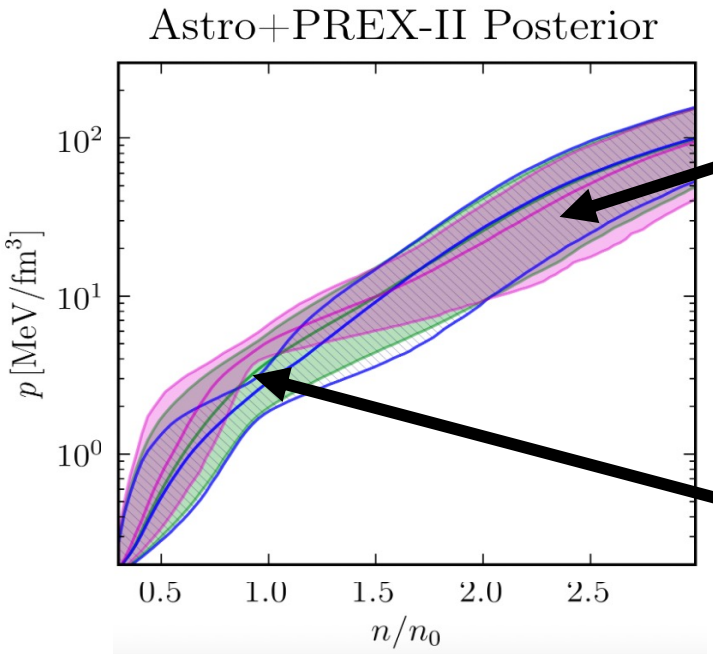
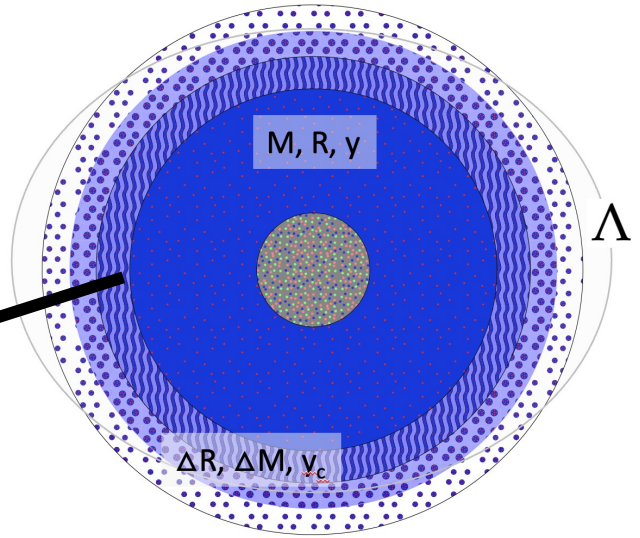
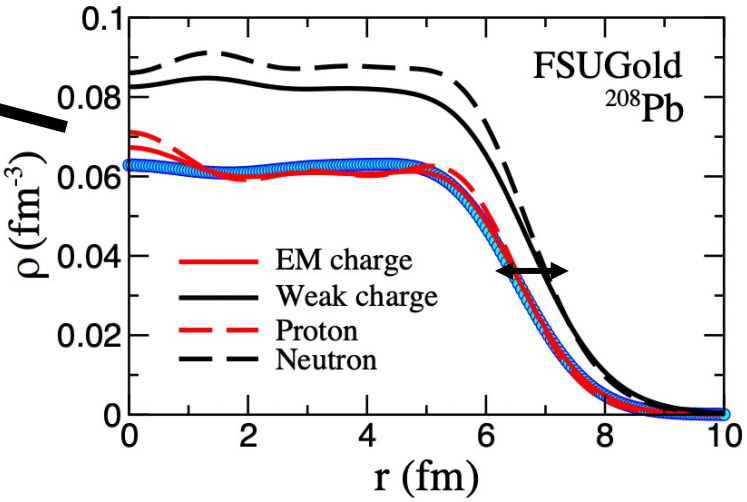


Essick+ arXiv 2102.10074

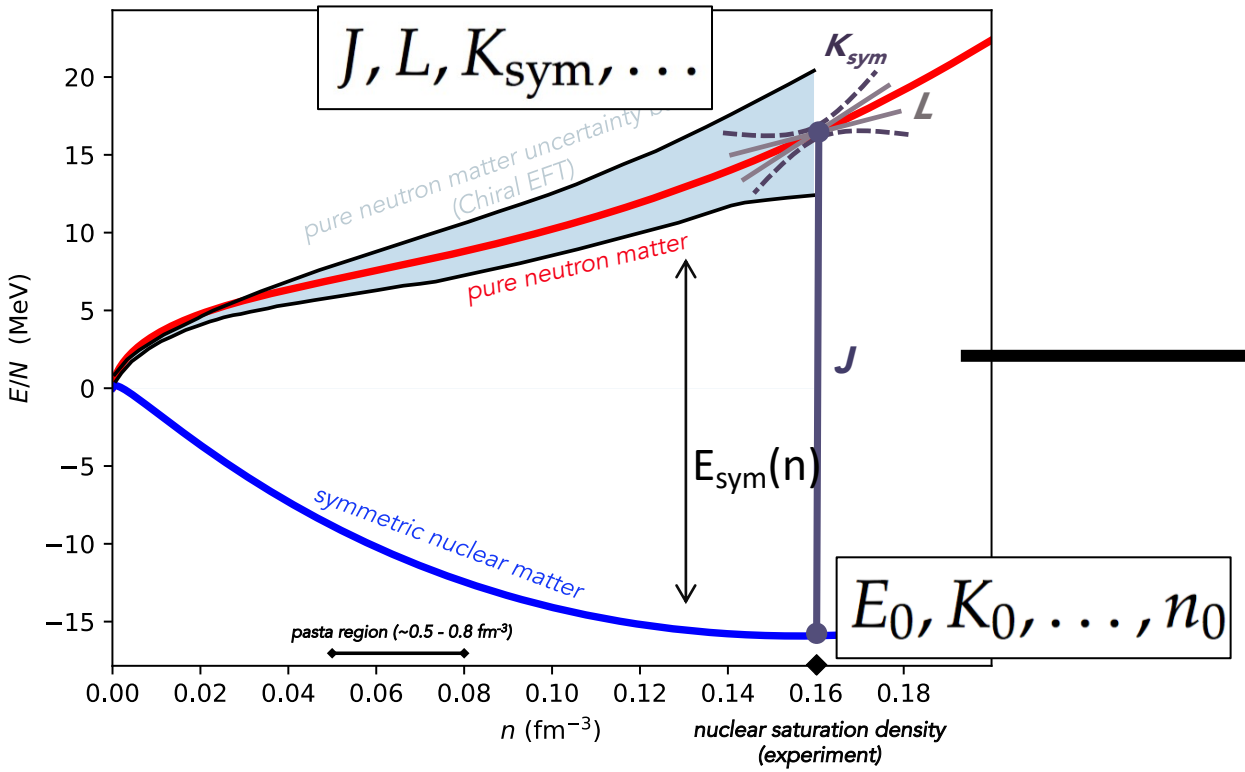




Thiel+ arXiv:1904.12269

The Nuclear Matter Equation of State

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



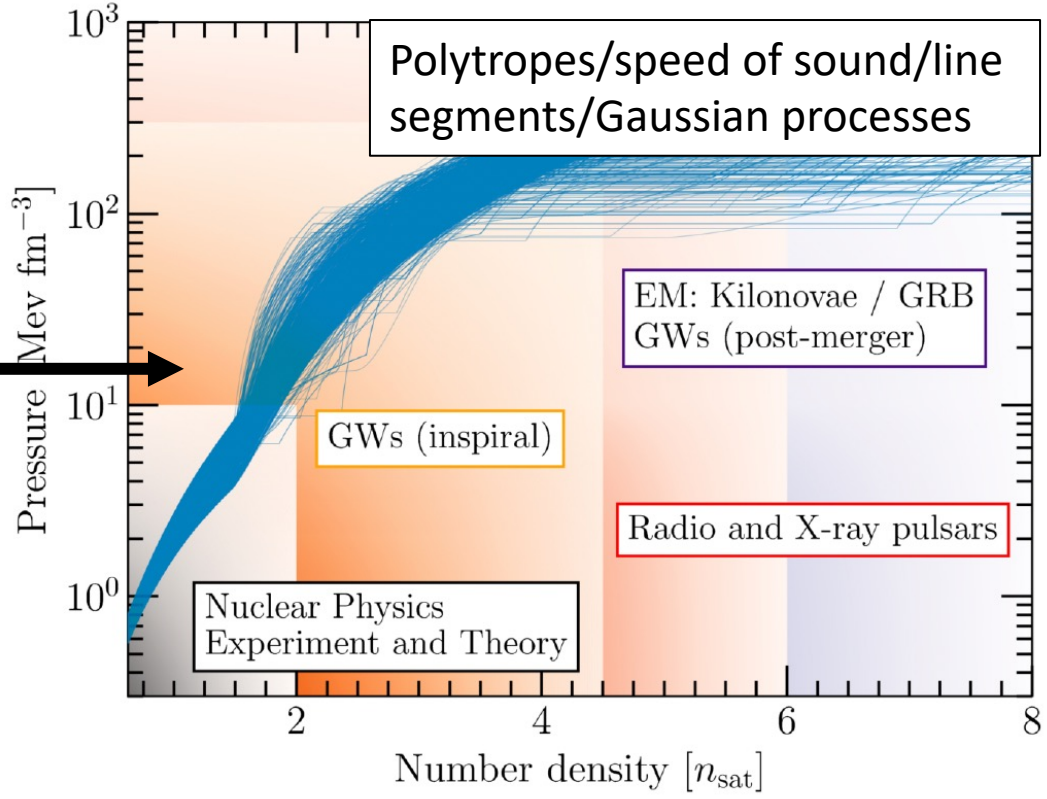


Figure: Lauren Balliet

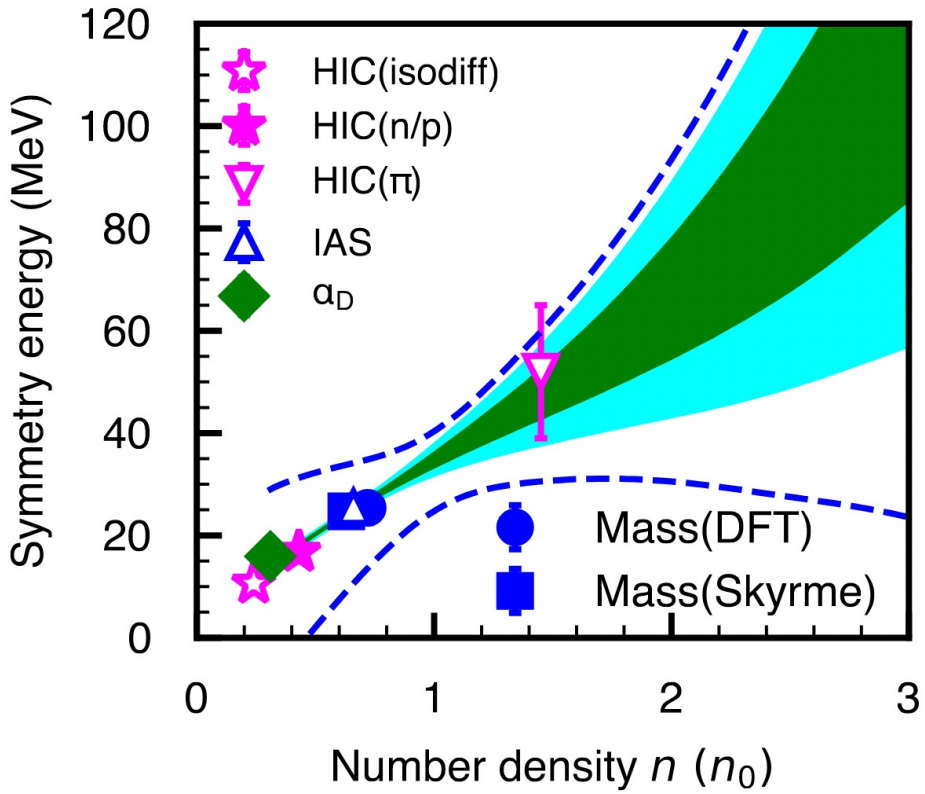
Pang et al, arxiv:2205.08513

$$E_0(\rho) = E_0(\rho_0) + \frac{K_0}{2}(\frac{\rho-\rho_0}{3\rho_0})^2 + \frac{J_0}{6}(\frac{\rho-\rho_0}{3\rho_0})^3,$$

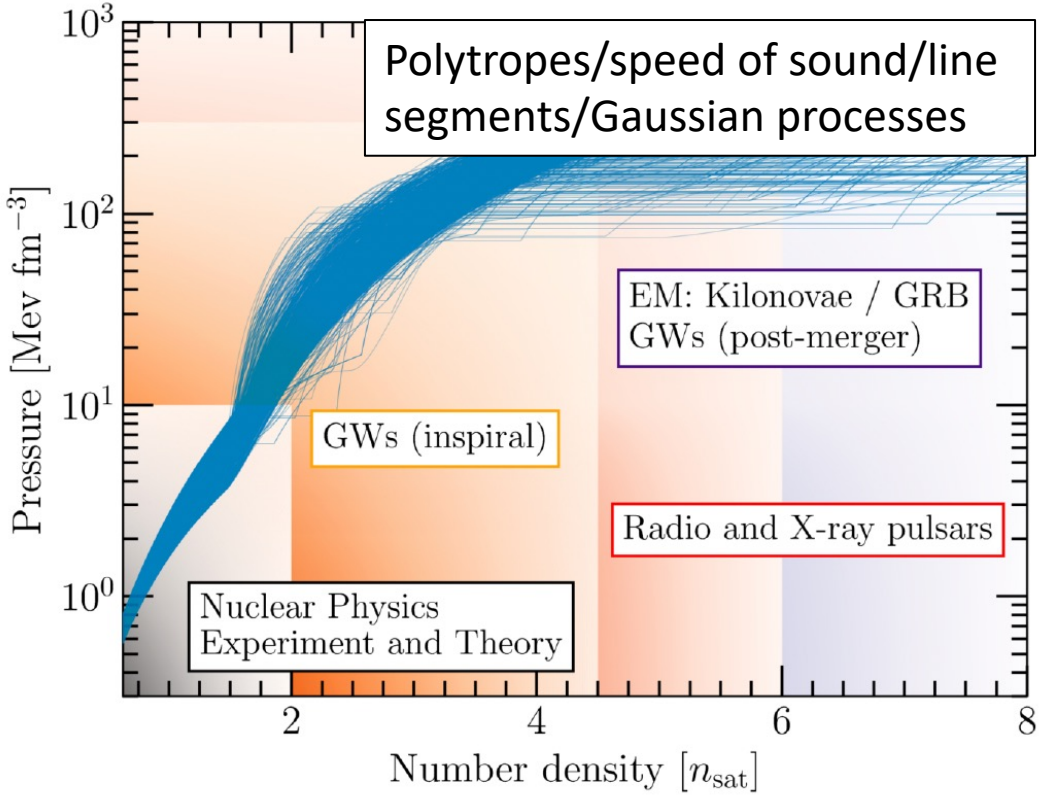
Li, arxiv:2105.04629

The Nuclear Matter Equation of State

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



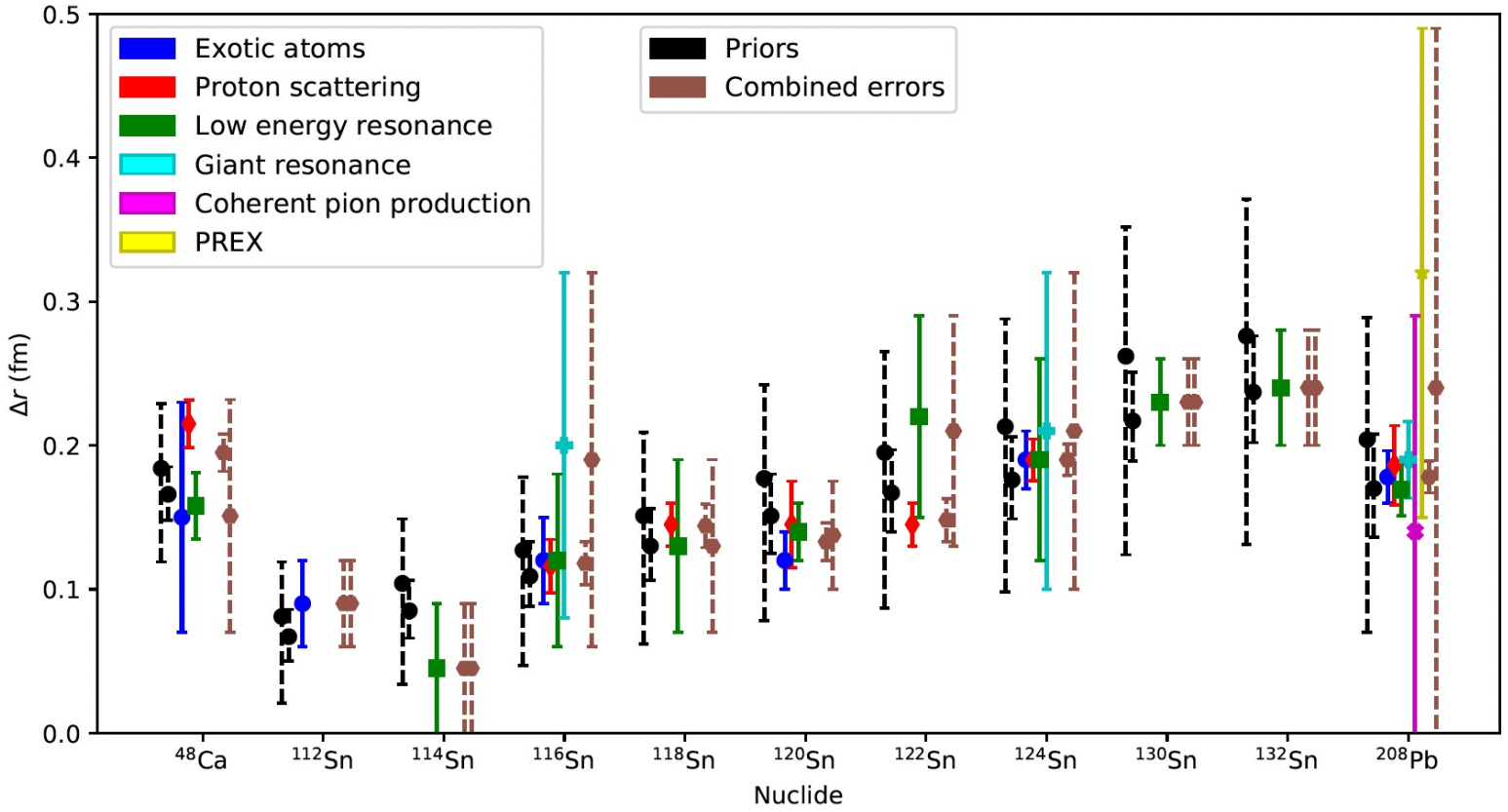
Lynch+, arXiv:2310.11588



Pang et al, arxiv:2205.08513

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

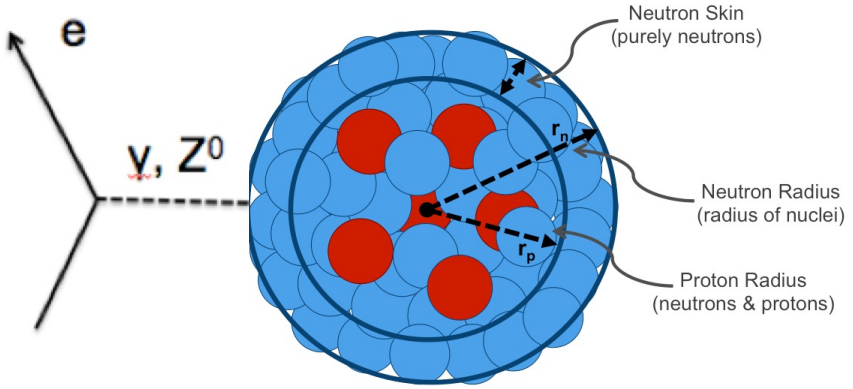
Data: Neutron Skins



Newton, Crocombe arxiv:2008.00042
Lattimer, arXiv:2301.03666
Xu+ arXiv:2007.07669

Data: Weak form factors

PREX, CREX



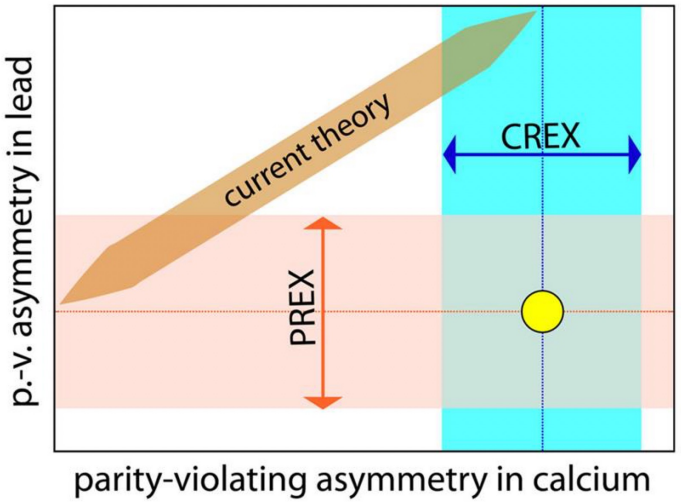
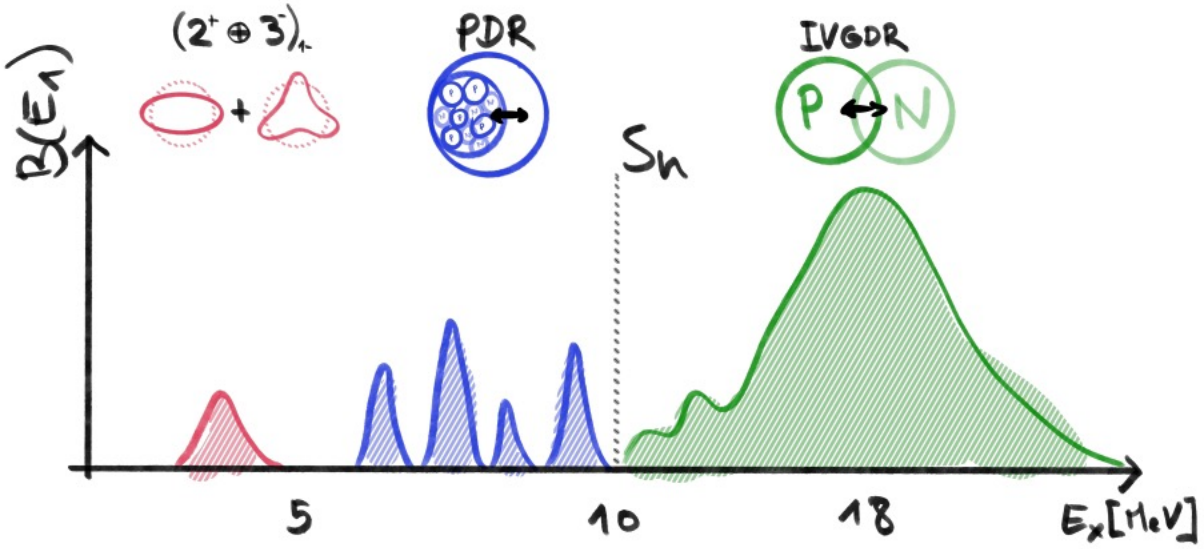
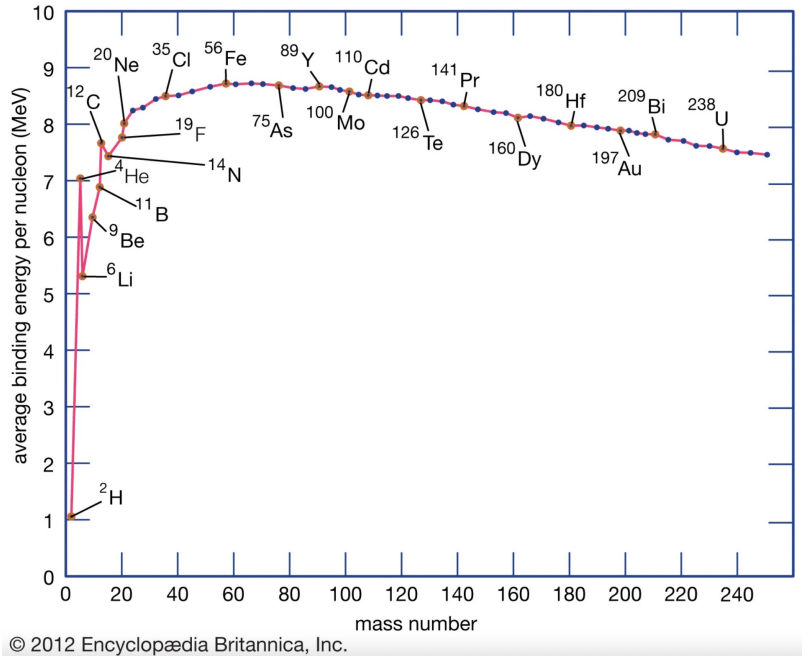


Image: Witold Nazarewicz

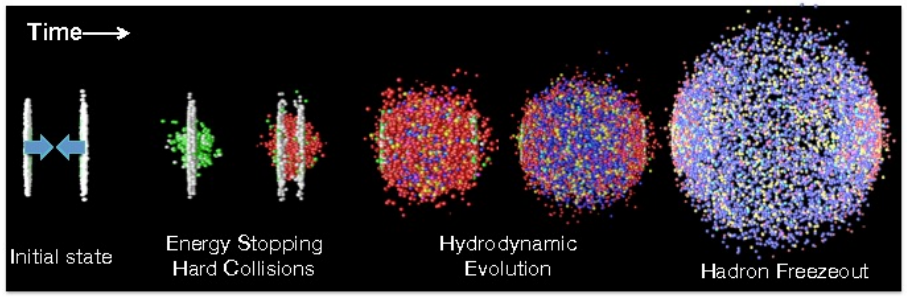
Data: Dipole Polarizability/Giant Resonances, Nuclear Masses, HIC, IAS



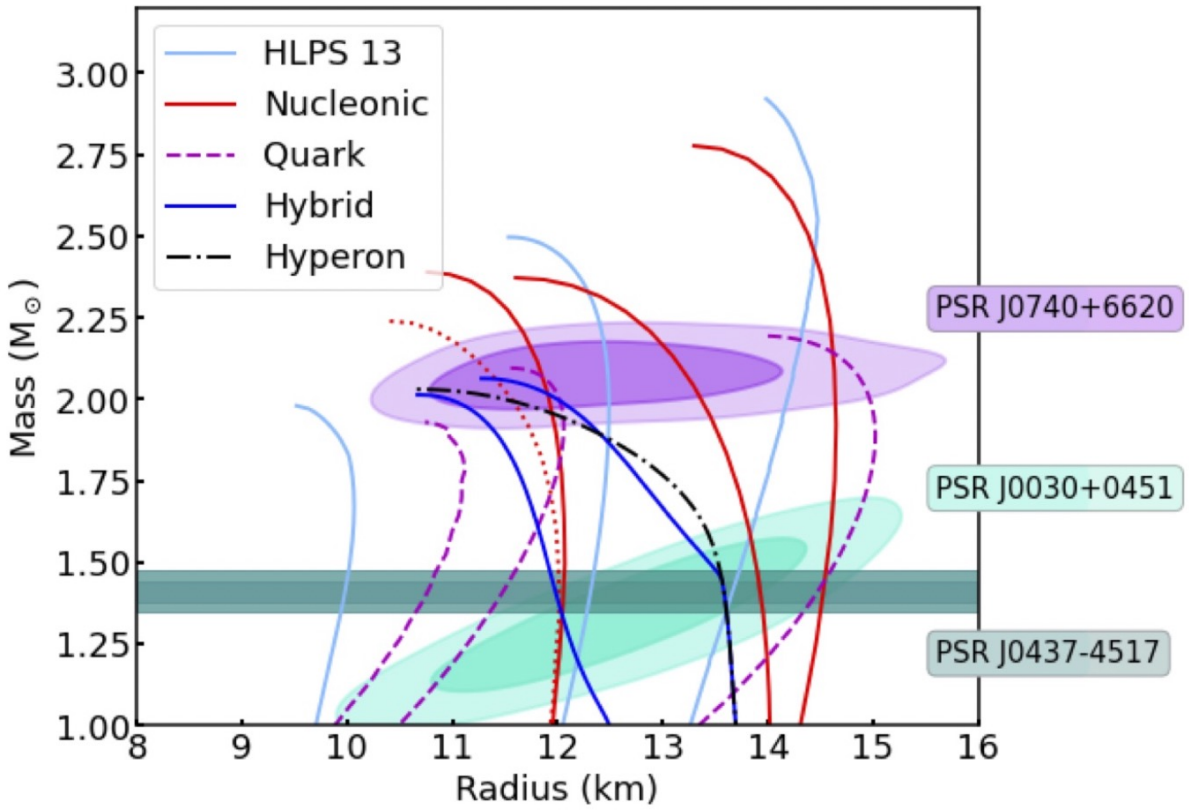


Thiel+ arXiv:1904.12269

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

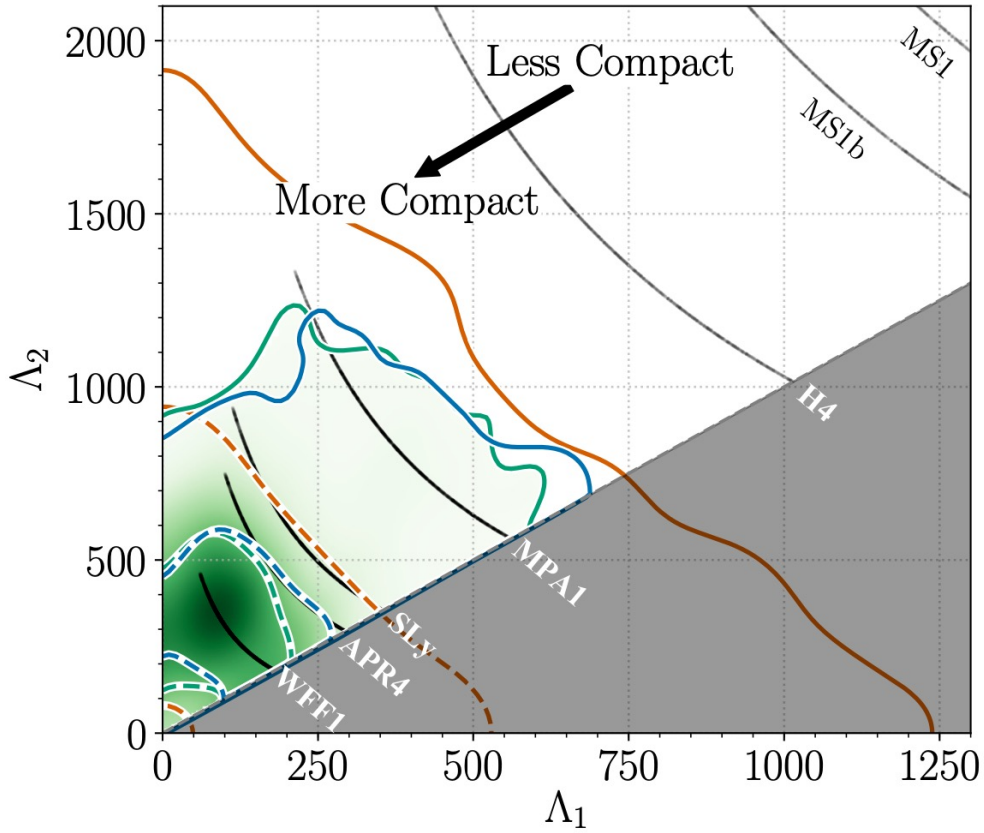


Data: Neutron star mass/radii (e.g. NICER)



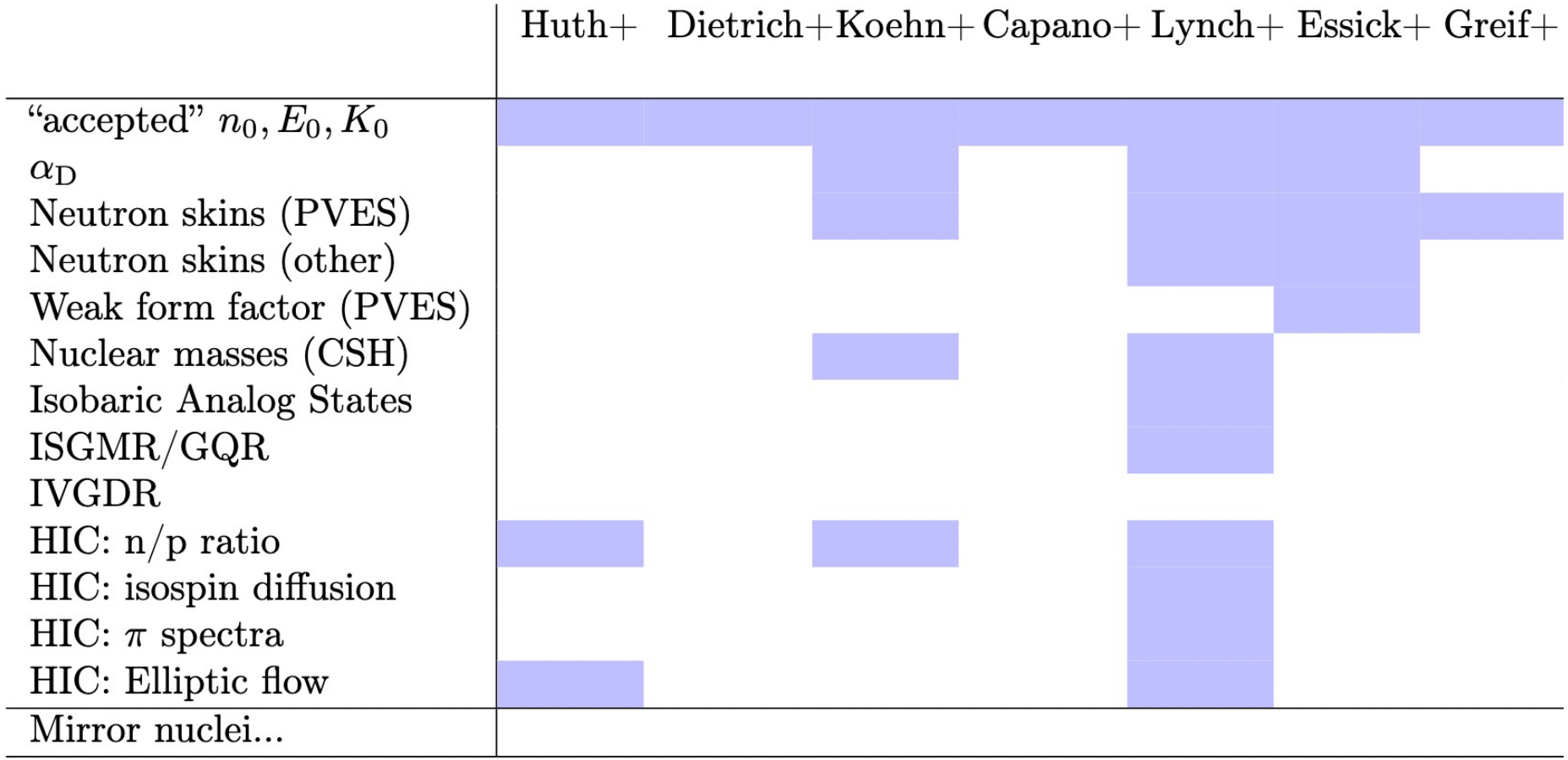
Riley arxiv:1912.05702, arxiv:2105.06980
Miller et al arxiv:2105.06979, arxiv:1912.05705
Raajimakers et al arxiv: 1912.05703, 2105.06981

Data: Tidal Deformability



LIGO/Virgo arxiv:1805.11581

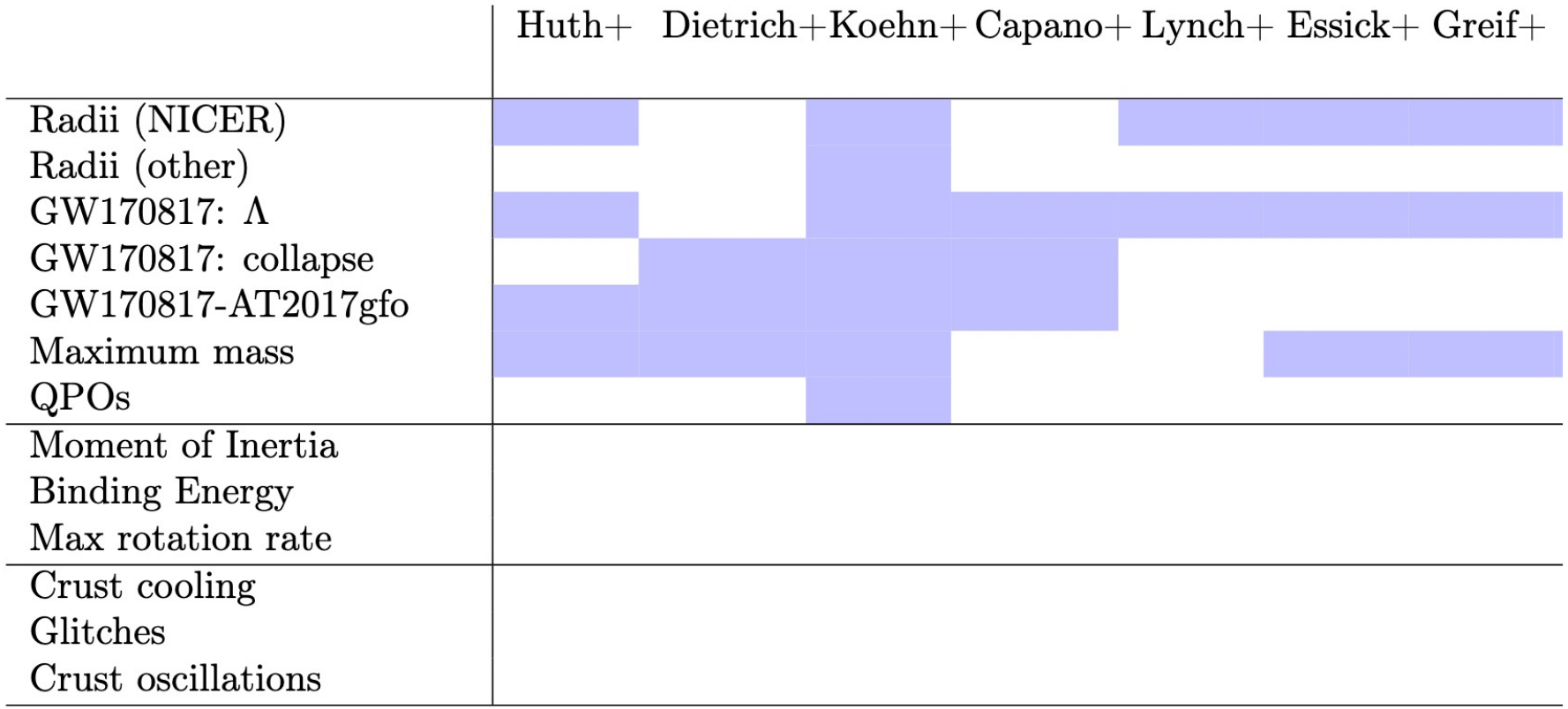
Increasing number of attempts to combine nuclear/Astro observables



Huth+ arxiv:2107.06222
Dietrich+ arXiv:2002.11355
Greif+ arXiv:2005.14164

Capano+ arXiv:1908.10352
Lynch+ arXiv:2310.11588
Koehn+ arXiv:2402.04172
Essick+ arXiv 2102.10074

Increasing number of attempts to combine lots of nuclear/Astro observables



Huth+ arxiv:2107.06222
Dietrich+ arXiv:2002.11355
Greif+ arXiv:2005.14164

Capano+ arXiv:1908.10352
Lynch+ arXiv:2310.11588
Koehn+ arXiv:2402.04172
Essick+ arXiv 2102.10074

Connecting NM params to nuclear observables

Density Functional Theory (e.g. Skyrme-type)

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

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

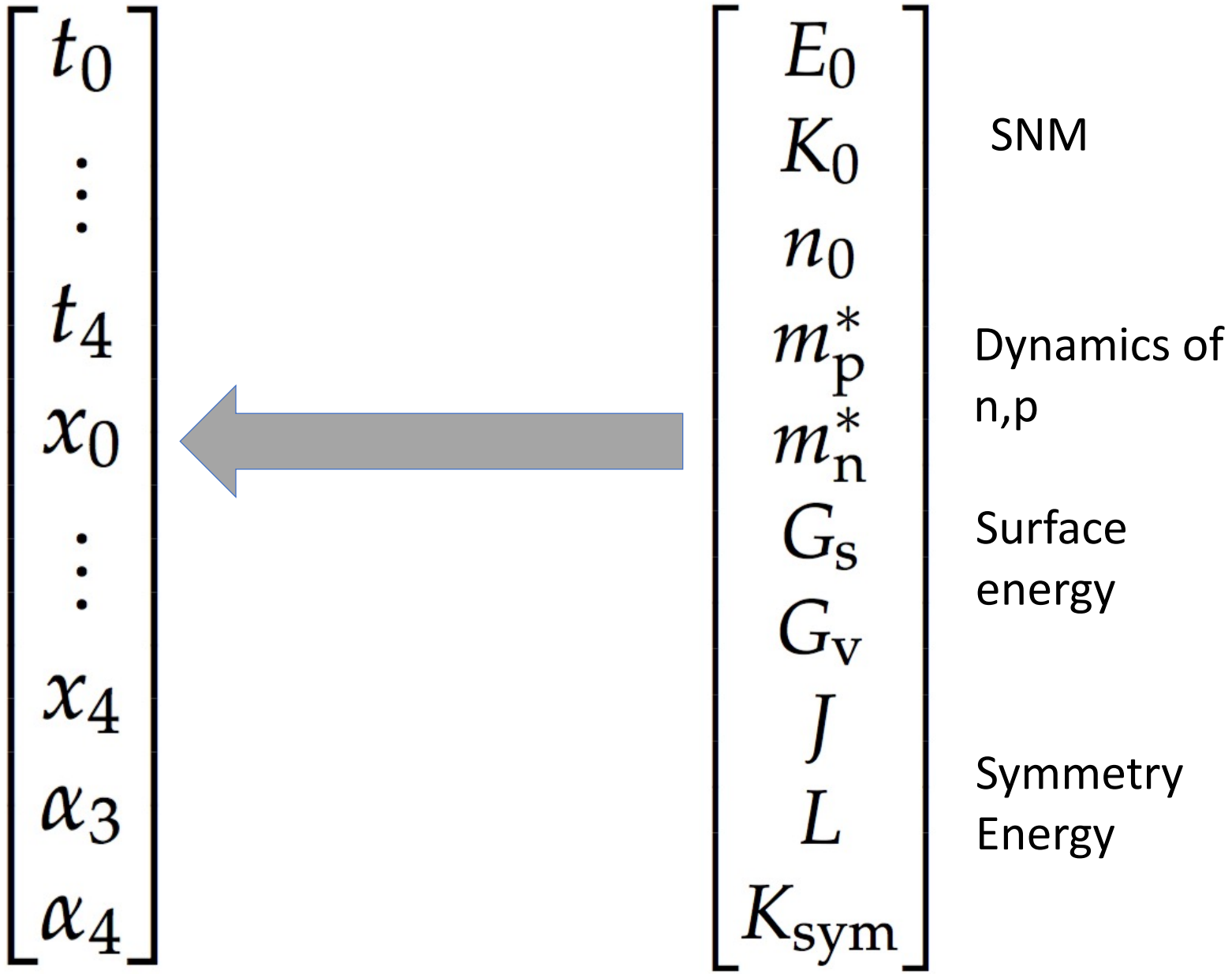
$$\mathcal{H}_{\text{eff}} = \frac{1}{8}\rho[t_1(2+x_1)+t_2(2+x_2)]\tau + \frac{1}{8}\rho[t_1(2x_1+1)+t_2(2x_2+1)](\tau_p y_p+\tau_n y_n)$$

3 body

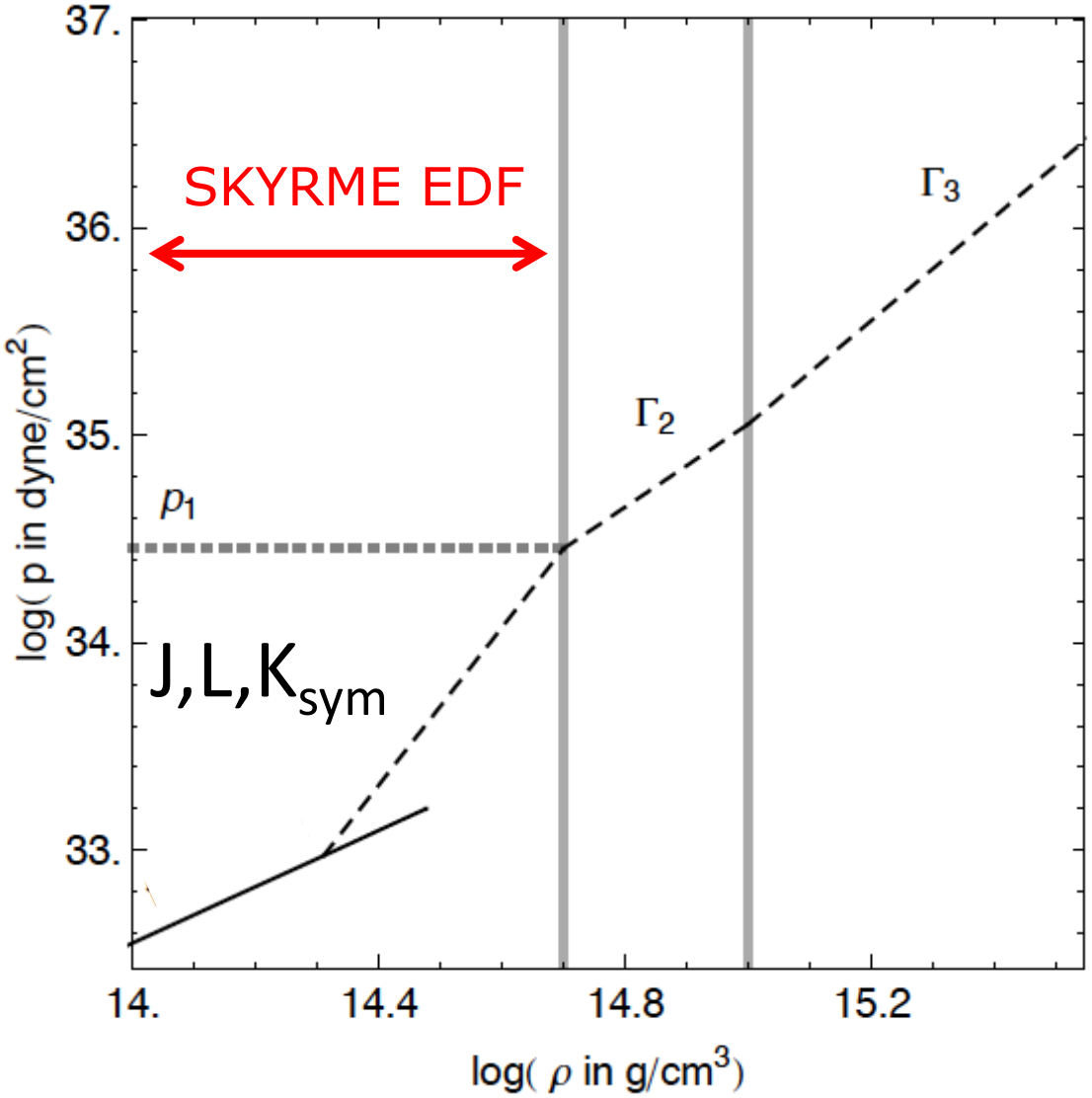
$$\mathcal{H}_{\text{grad}} = \frac{1}{32}(\nabla\rho)^2[3t_1(2+x_1)-t_2(2+x_2)] - \frac{1}{32}[3t_1(2x_1+1)+t_2(2x_2+1)][(\nabla\rho_p)^2+(\nabla\rho_n)^2)$$

Gradient…

Map nuclear matter parameters to model parameters and systematically generate models

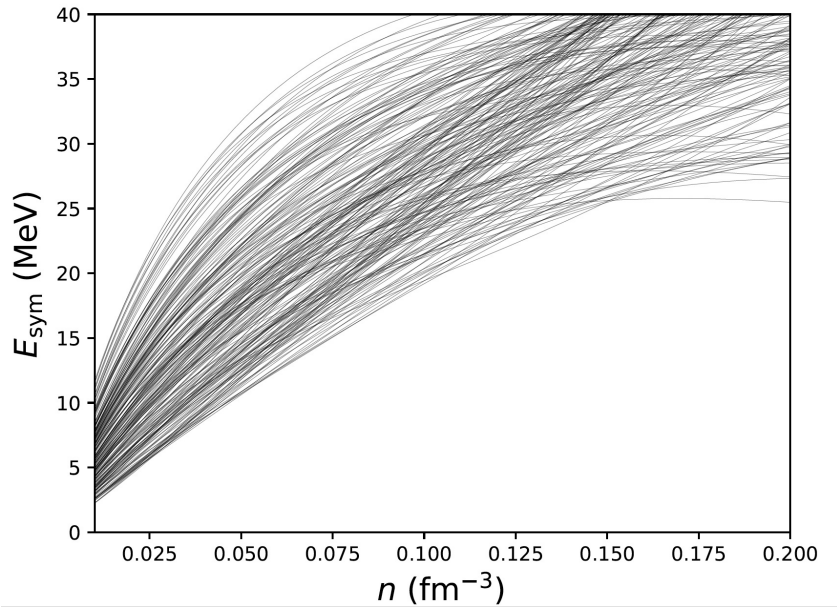


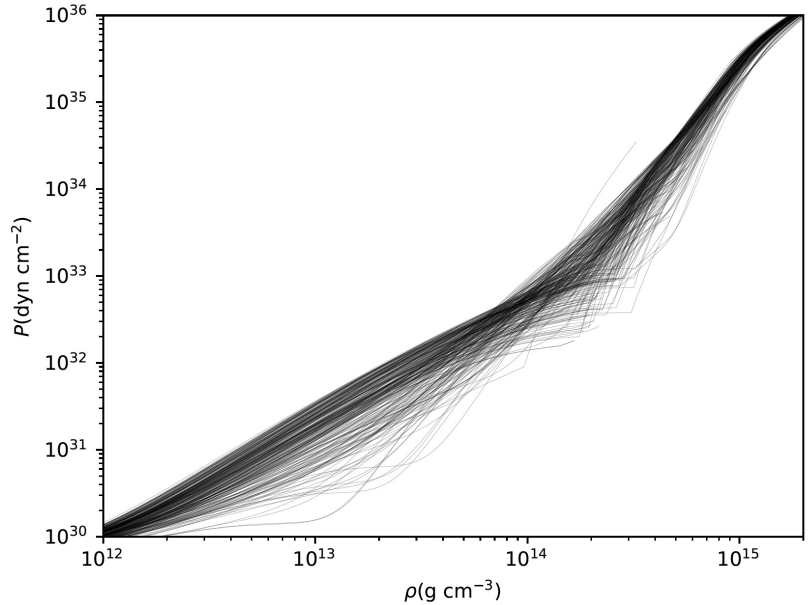
EOS model: Skyrme EDF + 2 Piecewise Polytrope or speed of sound model

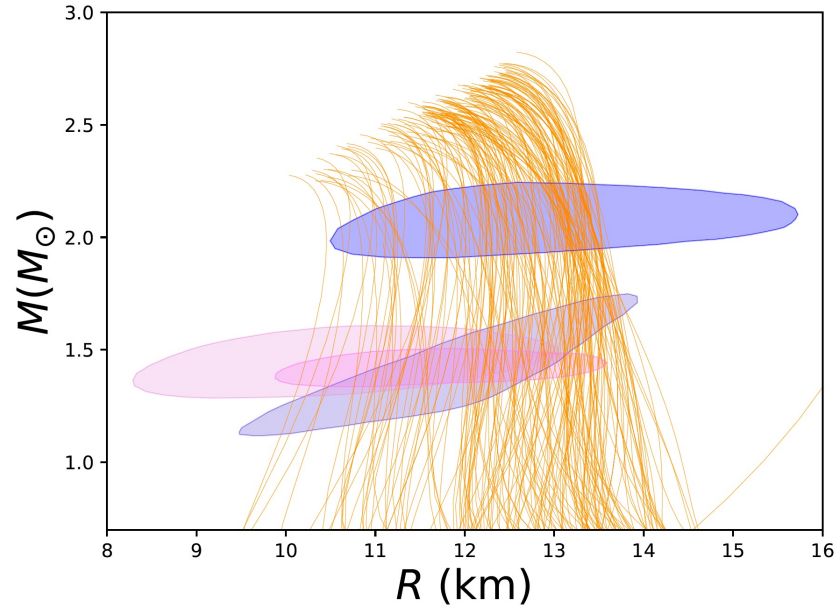


Read+, arxiv:0812.2163; see also works by Steiner, Lattimer, Özel...

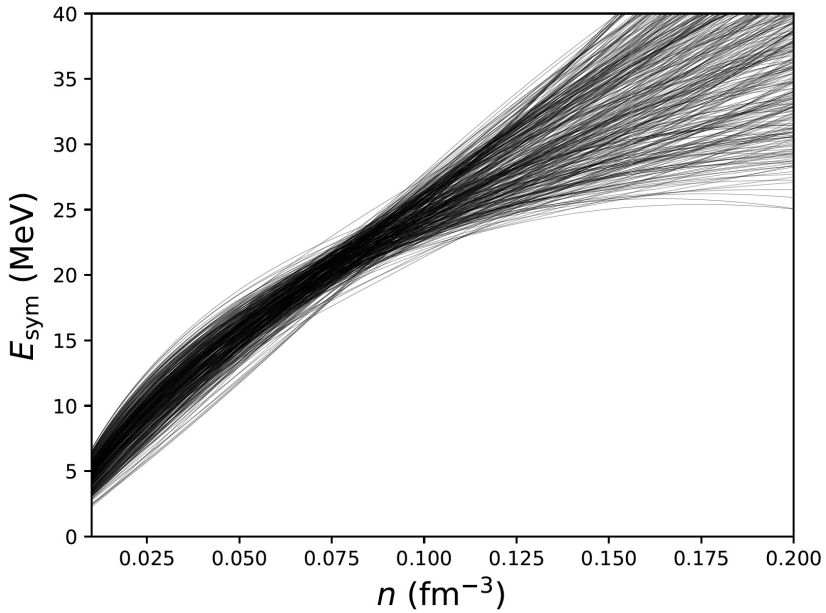
Prior

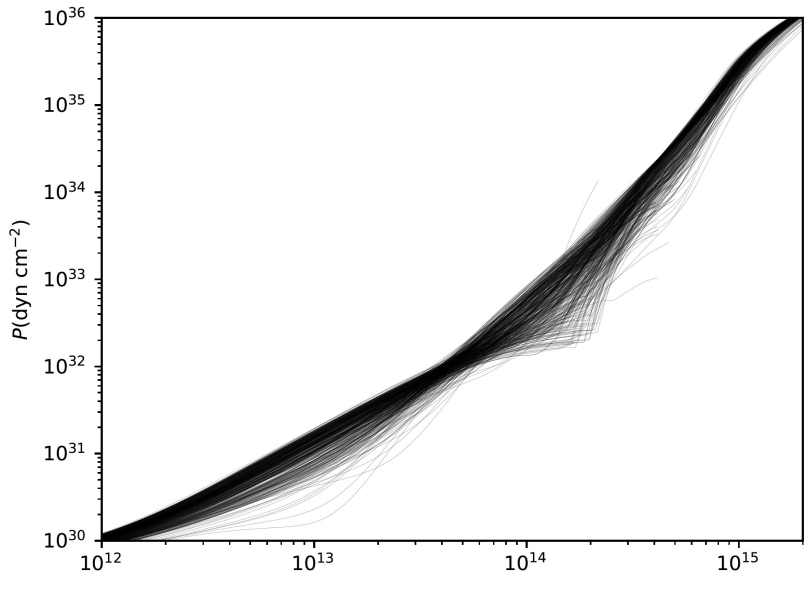


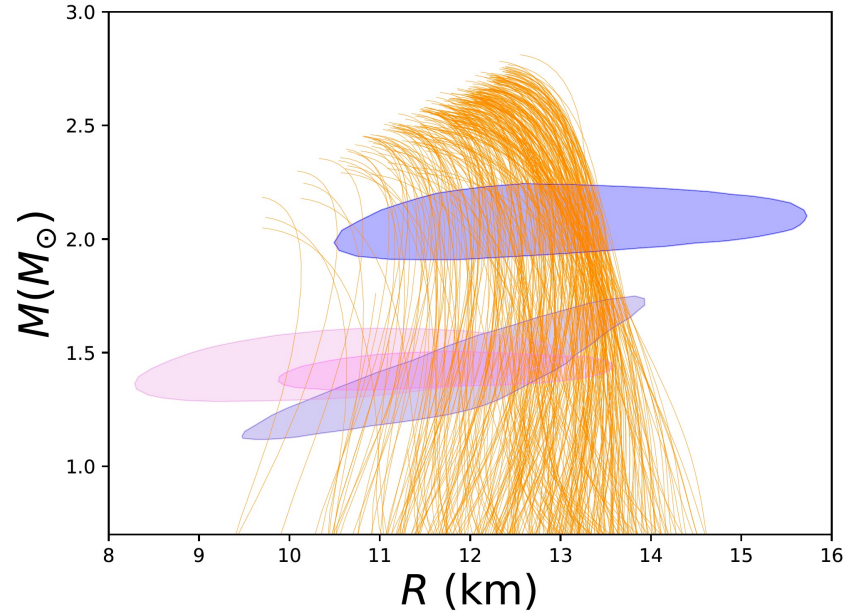




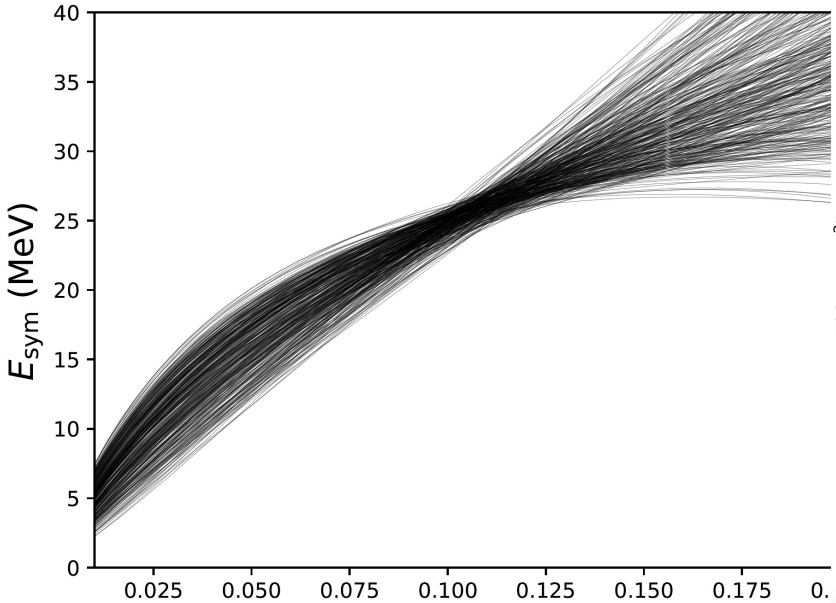
α_{D}

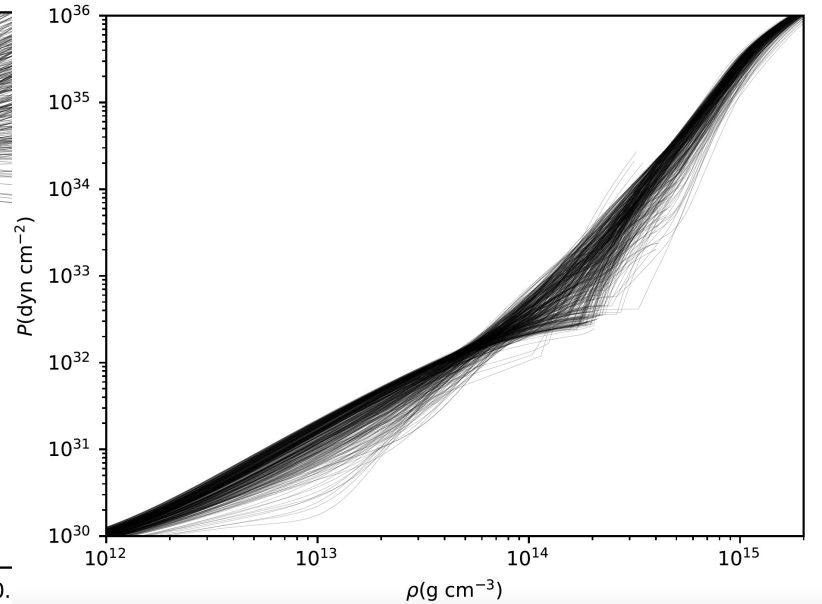


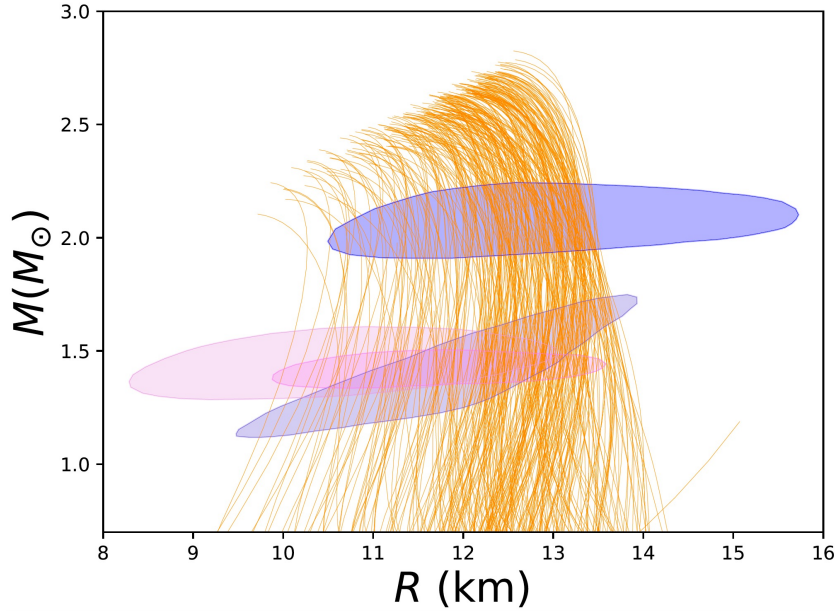




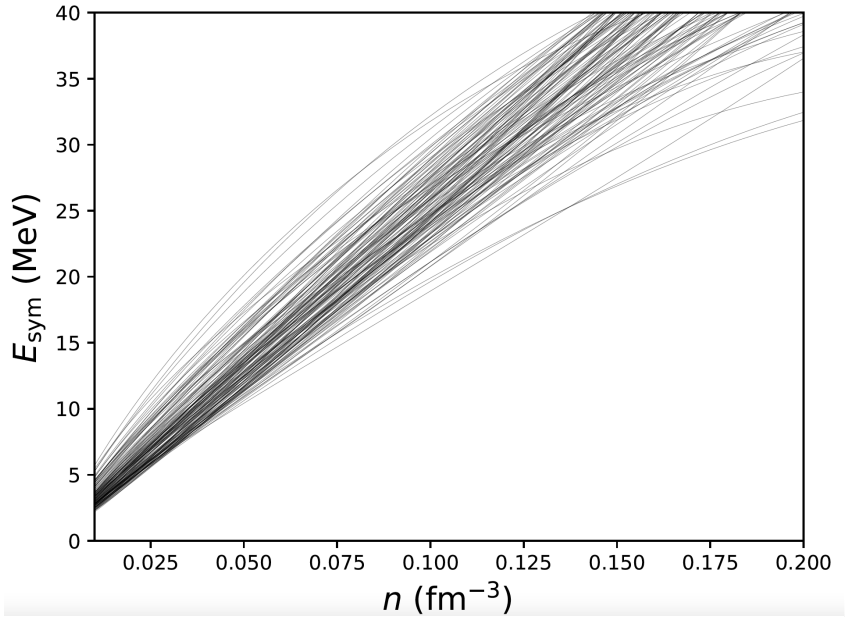
BE

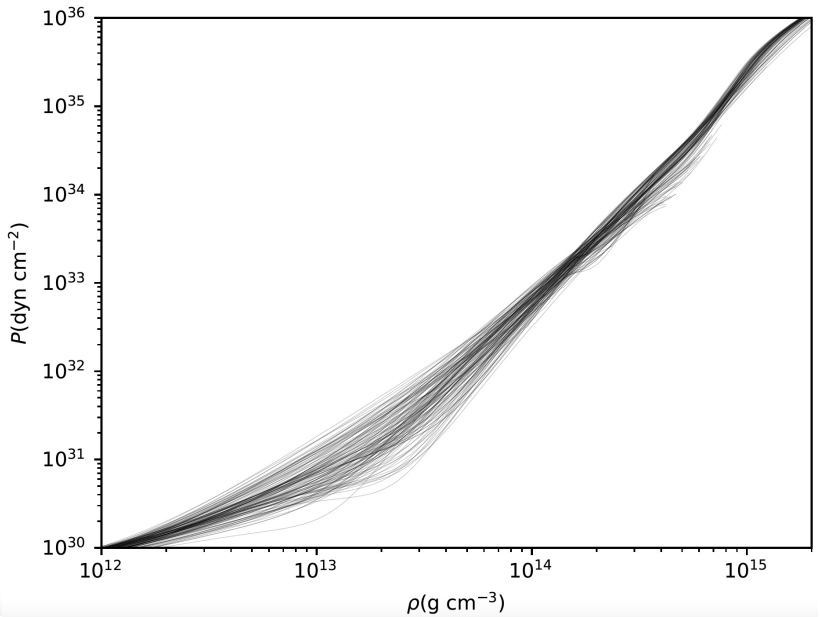

E_{sym} (MeV)
0
5
10
15
20
25
30
35
40
0.025
0.050
0.075
0.100
0.125
0.150
0.175

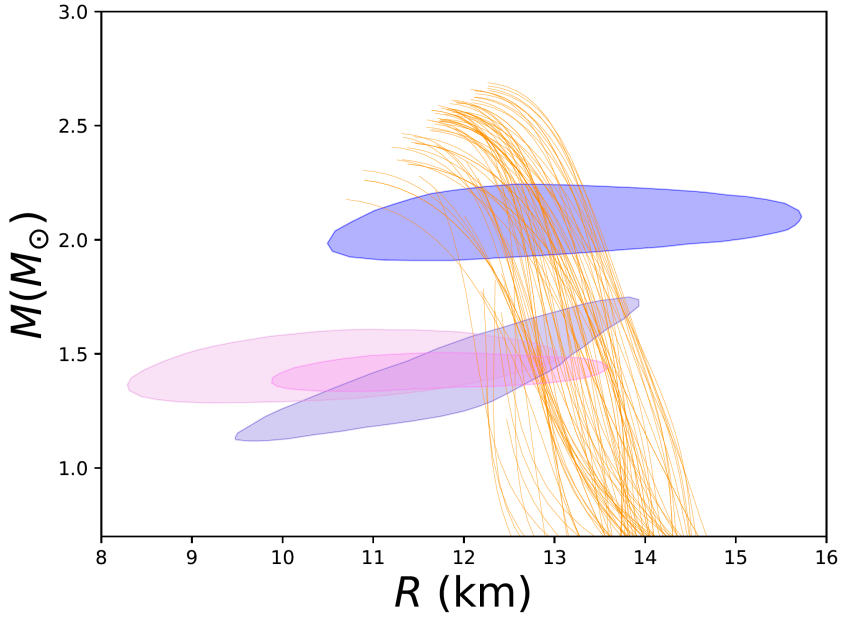

P(dyn cm^{-2})
10^{30}
10^{31}
10^{32}
10^{33}
10^{34}
10^{35}
10^{36}
10^{12}
10^{13}
10^{14}
10^{15}
ρ(g cm^{-3})


$M(M_\odot)$
1.0
1.5
2.0
2.5
3.0
8
9
10
11
12
13
14
15
16
R (km)

F_w^{208}

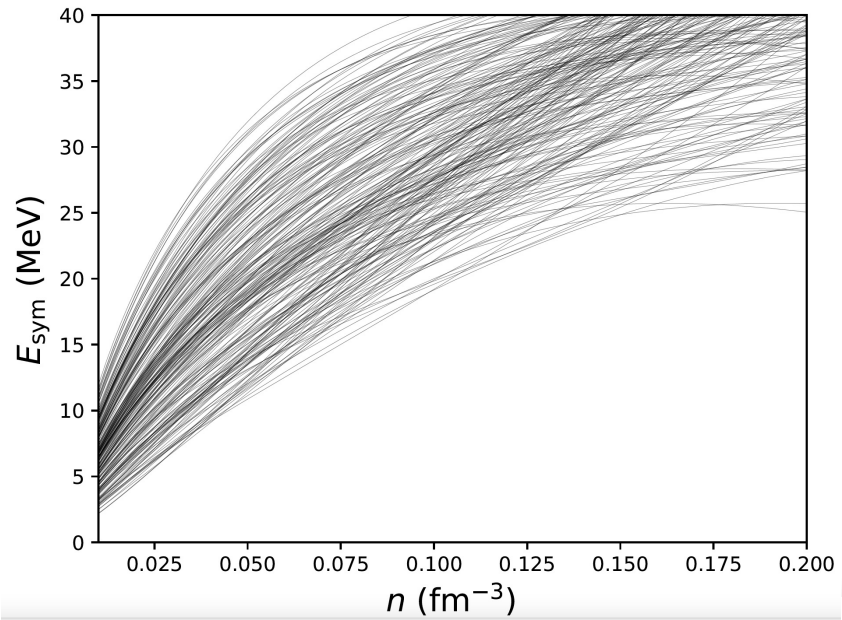

40
35
30
25
20
15
10
5
0
0.025
0.050
0.075
0.100
0.125
0.150
0.175
0.200
E_{sym} (MeV)
n (fm^{-3})

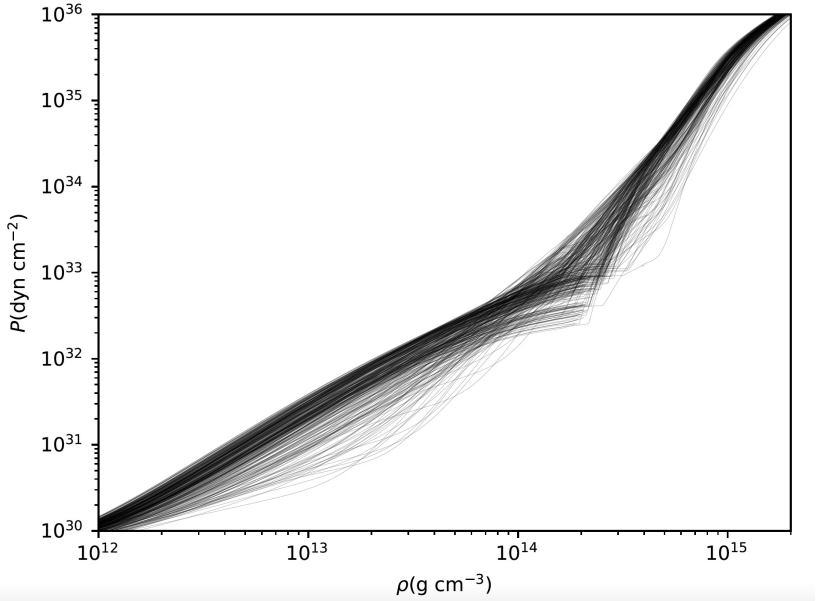

10^{36}
10^{35}
10^{34}
10^{33}
10^{32}
10^{31}
10^{30}
10^{12}
10^{13}
10^{14}
10^{15}
P(dyn cm^{-2})
ρ(g cm^{-3})

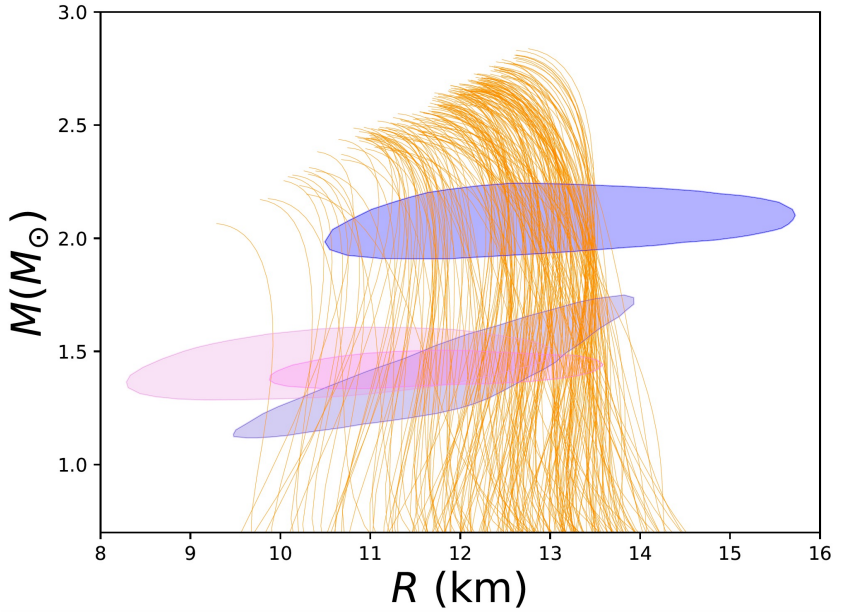

3.0
2.5
2.0
1.5
1.0
8
9
10
11
12
13
14
15
16
$M(M_\odot)$
R (km)

Pion spectral ratios

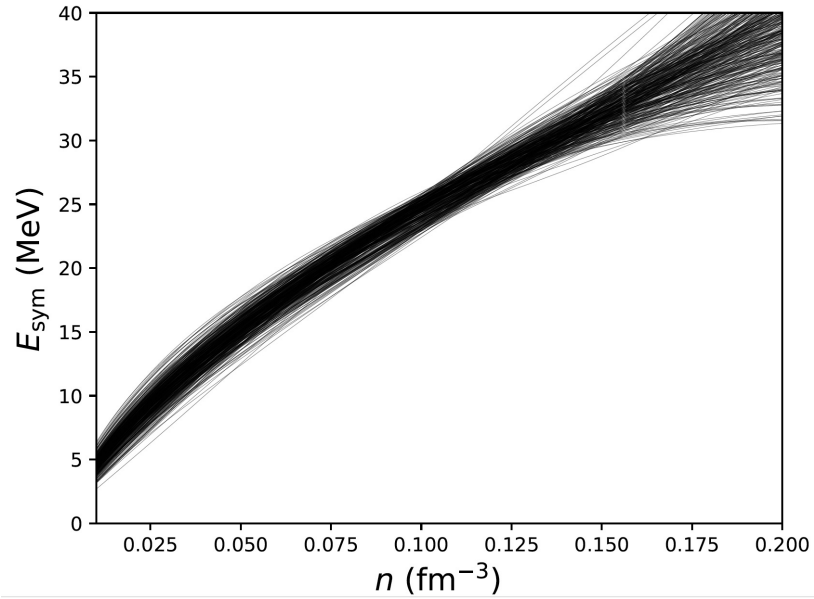
(From Lynch+ arXiv:2310.11588; Liu+ arxiv:2006.15861)

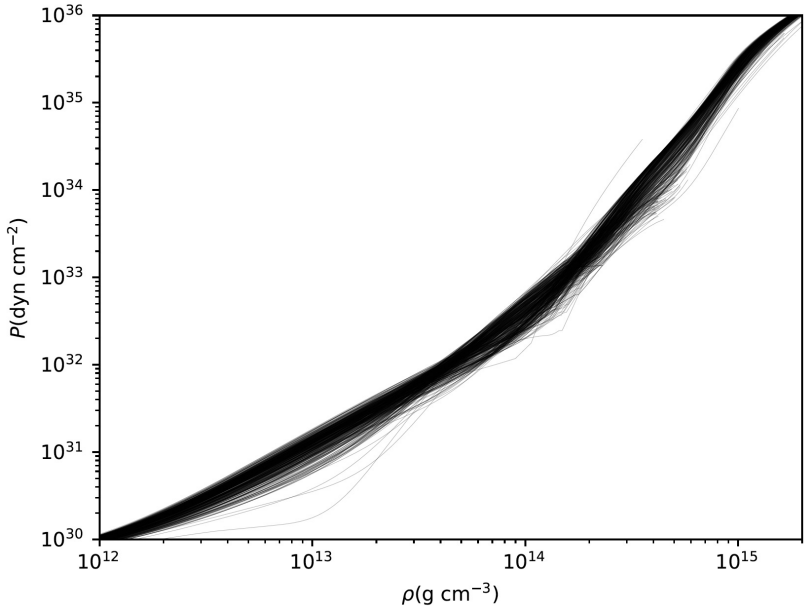


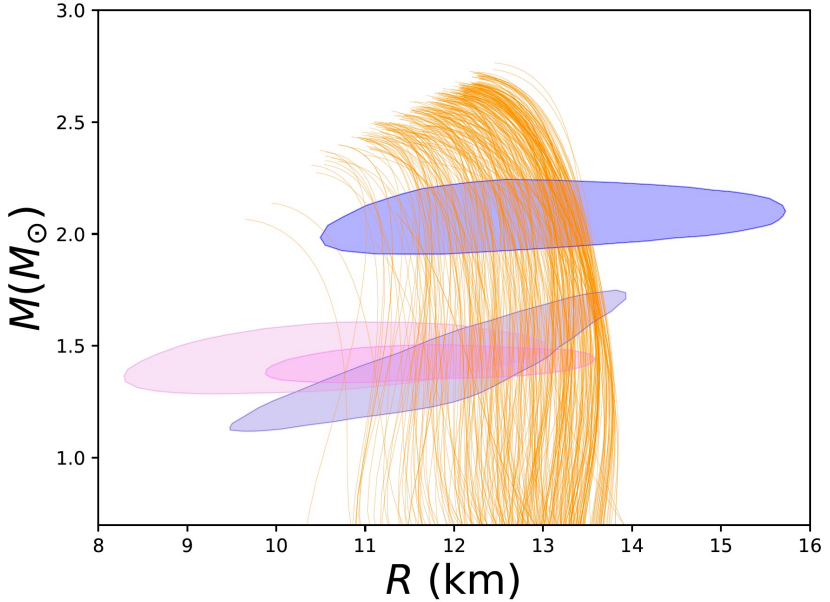




Combined – Slight preference for higher radii
- Nuclear has stuff to say!

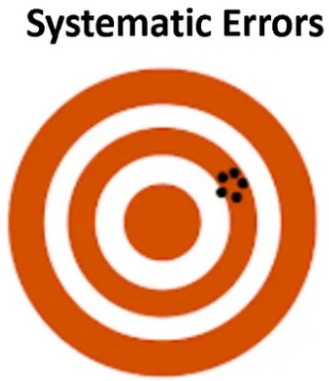






Systematic errors to look out for:

- Choice of model
- Choice of observables to include – and ignore
- Choice of model parameters
- Priors on those parameter
- Difference in definitions of parameters
- Model dependence extrapolating from one density to another
- Using “observables” that have already been inferred using a different model to yours
- Awareness of what is actually being measured
- No neutron star crust! – Systematic error in radius up to 0.5km



Pic: Aaron Zhu

Symmetry energy: some communication problems

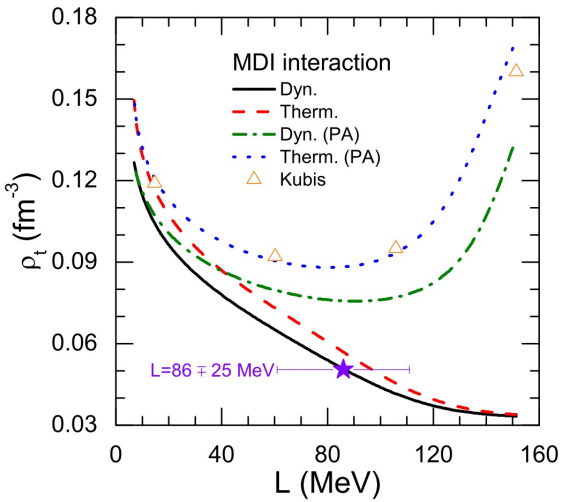
- Proliferation of nomenclature

E_{sym},S, J, a_{sym}, c_{sym}, …

- Second order or all orders?

$$E_{\mathrm{sym},2}(\rho) = \frac{1}{2}\frac{\partial^2 E(\rho,\delta)}{\partial \delta^2}\bigg|_{\delta=0}$$

Xu et al, arxiv:0807.4477



$$E_{\mathrm{sym}}(\rho) = E(\rho,\delta=1) - E(\rho,\delta=0) = E_{\mathrm{PNM}}(\rho) - E_{\mathrm{SNM}}(\rho)$$

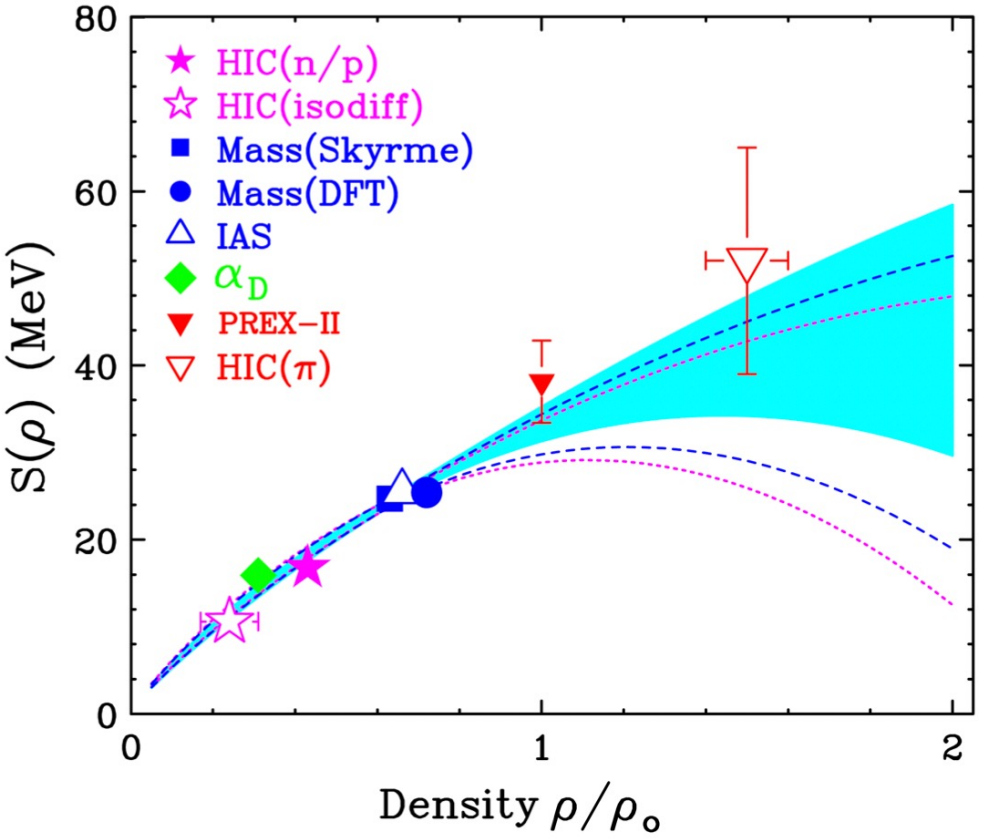
Difference < 3 MeV at saturation density BUT could be larger in RMF models (e.g. Zhao+ arXiv:2406.05267: ”CREX1” RMF model: J_2=32.9 MeV, J=54.3MeV!
In neutron-rich matter $\delta \cong 1$ so higher order terms become important

- Non-analytic terms in δ Expansion

$$E_{\mathrm{sym,log}}\delta^4 \log\delta$$

(Somasundarum+ 2009.04737, Kaiser arXiv:1504.00604

Different observables constrain at different densities…



Tsang and Lynch, arxiv:2106.10119

Different observables constrain at different densities…

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

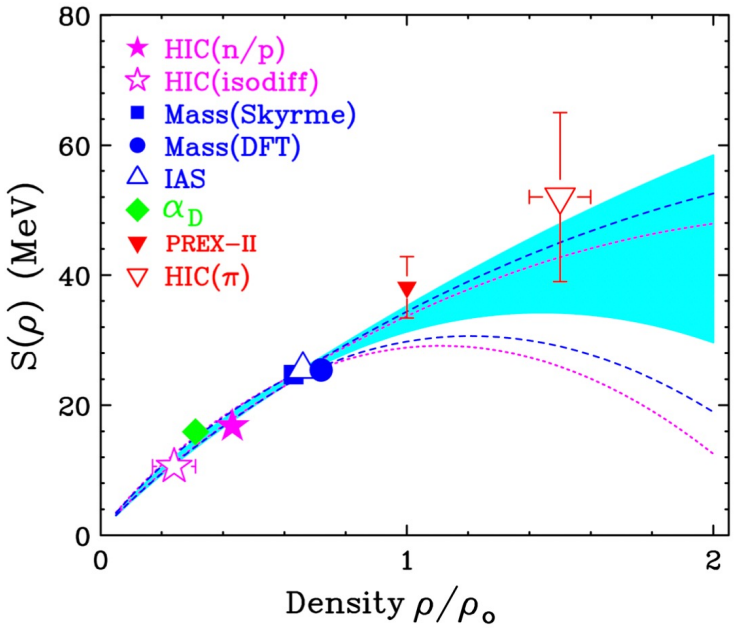
$$E_{\rm sym}(\rho) = E_{\rm sym}(\rho_0) + L(\frac{\rho-\rho_0}{3\rho_0}) + \frac{K_{\rm sym}}{2}(\frac{\rho-\rho_0}{3\rho_0})^2 + \frac{J_{\rm sym}}{6}(\frac{\rho-\rho_0}{3\rho_0})^3$$

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

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

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

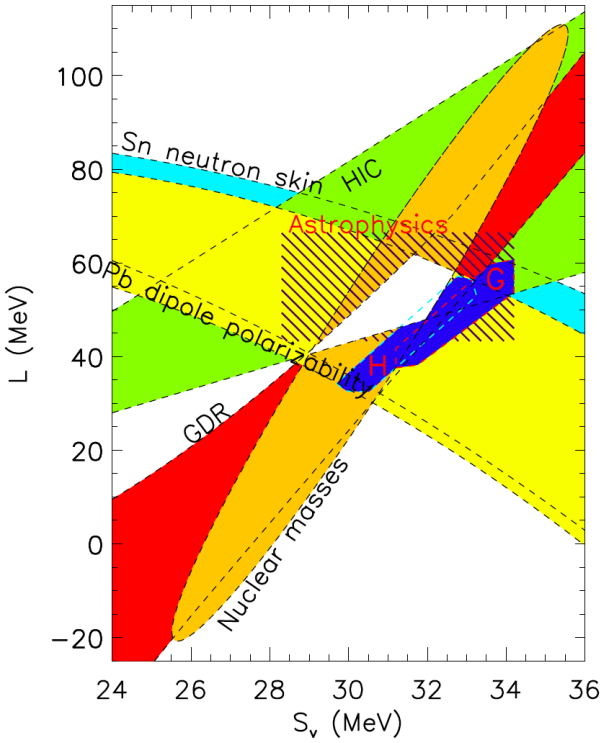
$$S(n) = E_{\rm kin,0}\left(\frac{n}{n_{\rm sat}}\right)^{2/3} + E_{\rm pot,0}\left(\frac{n}{n_{\rm sat}}\right)^{\gamma_{\rm asy}} .$$



Tsang and Lynch, arxiv:2106.10119

Systematic Errors

Low Accuracy
High Precision



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

Why pay attention to model systematics

One can argue they are small compared with uncertainties in measurements

…until someone checks and finds out they're not…

We don't know how multiple systematics compound

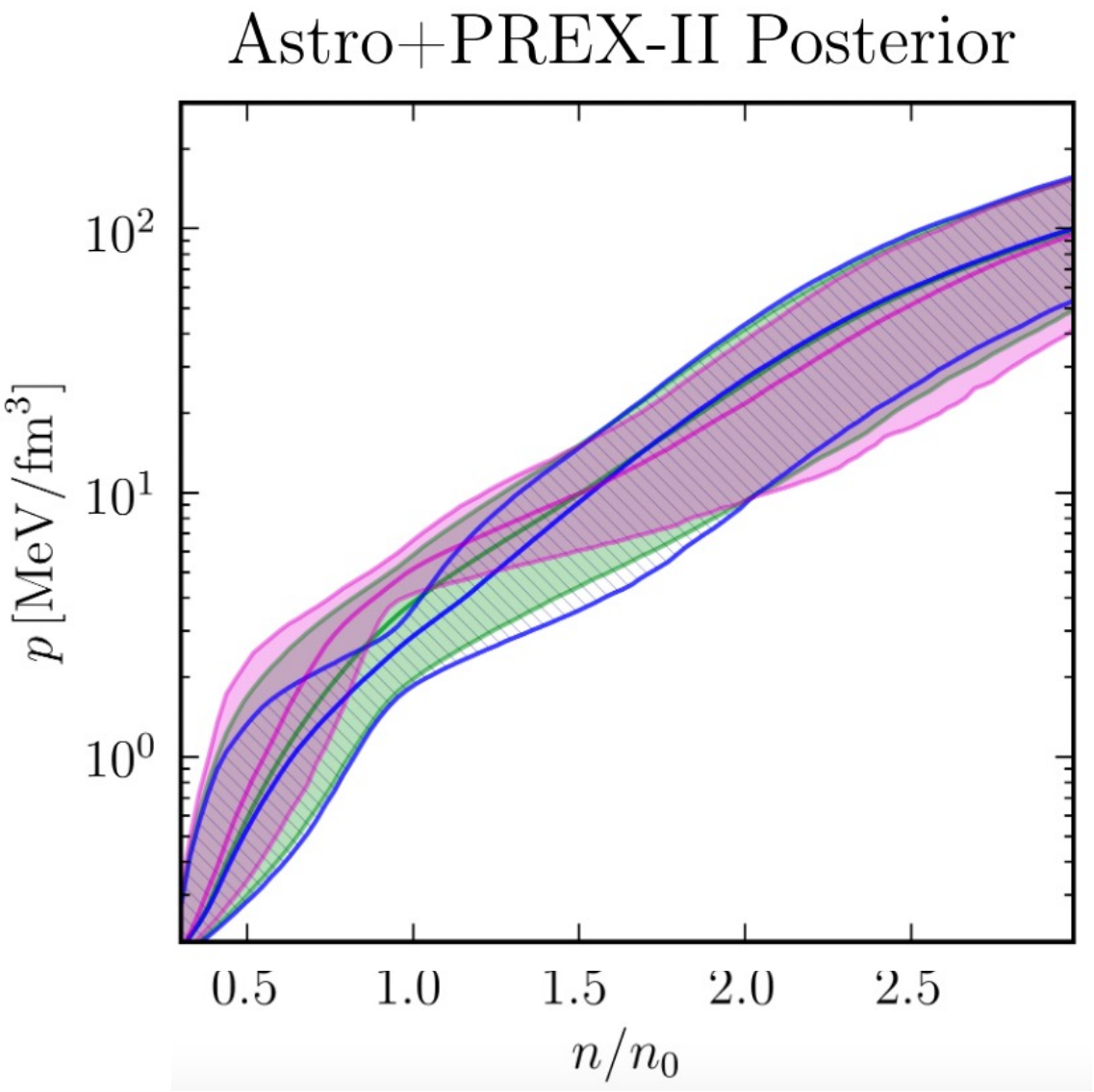
Over next 1-2 decades, much more data at current and proposed facilities:

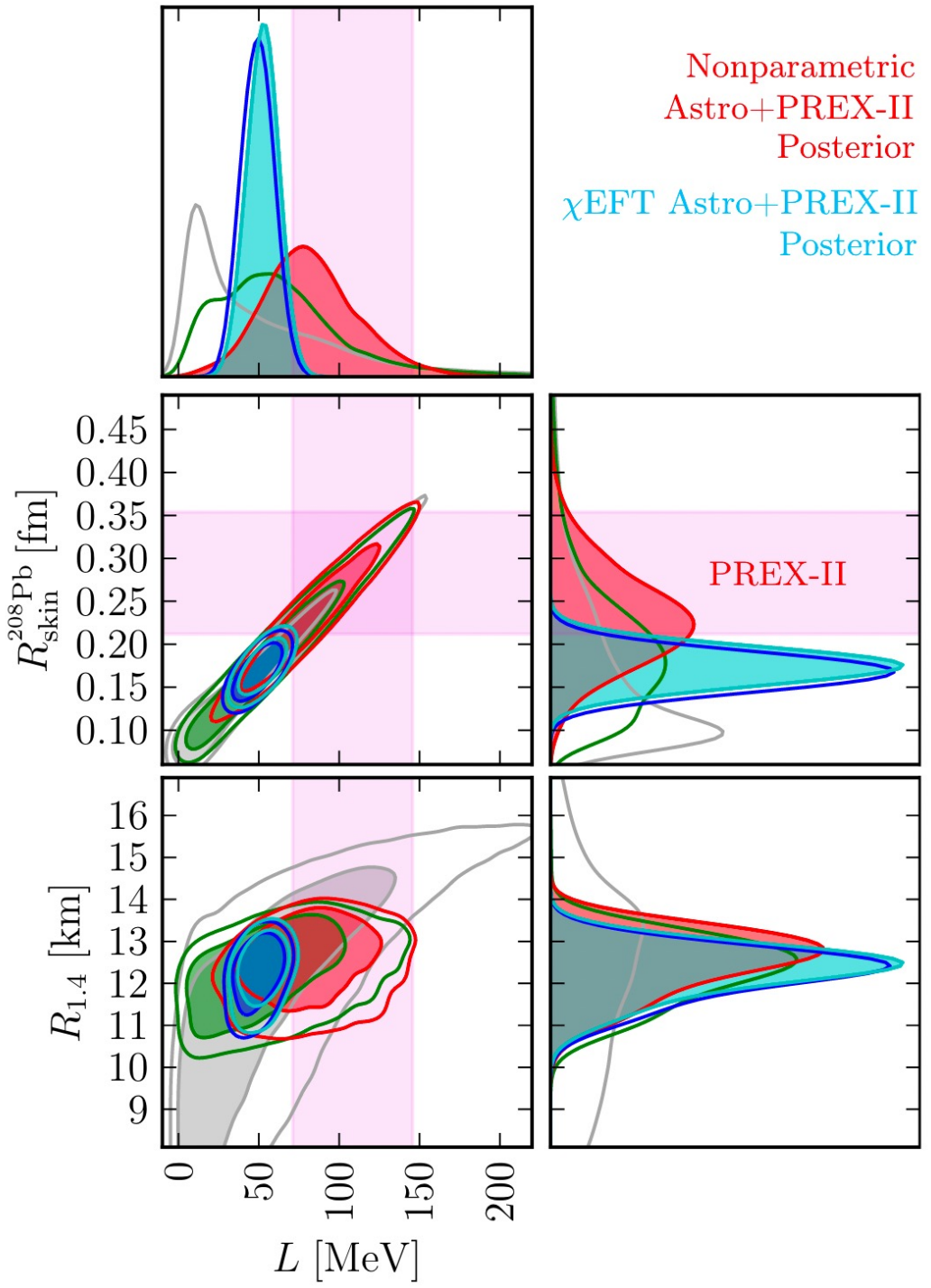
MREX: ΔF_w improved by **factor of 3**
NewAthena/eXTP **ΔR ~ 0.5km** or better, crust cooling, X-ray glitches
Einstein/Cosmic Explorer **ΔR ~ 0.1km** (optimistic estimate! and converted from tidal deformability)
Moment of inertia: **10% by 2030**, increasing in precision thereafter
If a galactic supernova goes off: **Binding energy of NS to 10%**
SkA: Order of magnitude more pulsars
More info across density/temperature space from GSI/FAIR, FRIB, RIKEN, RHIC….
Much more data on crust cooling, pulsar glitches, crust oscillations

For example, neglecting crust&rotation both lead to systematic errors close to 0.5km

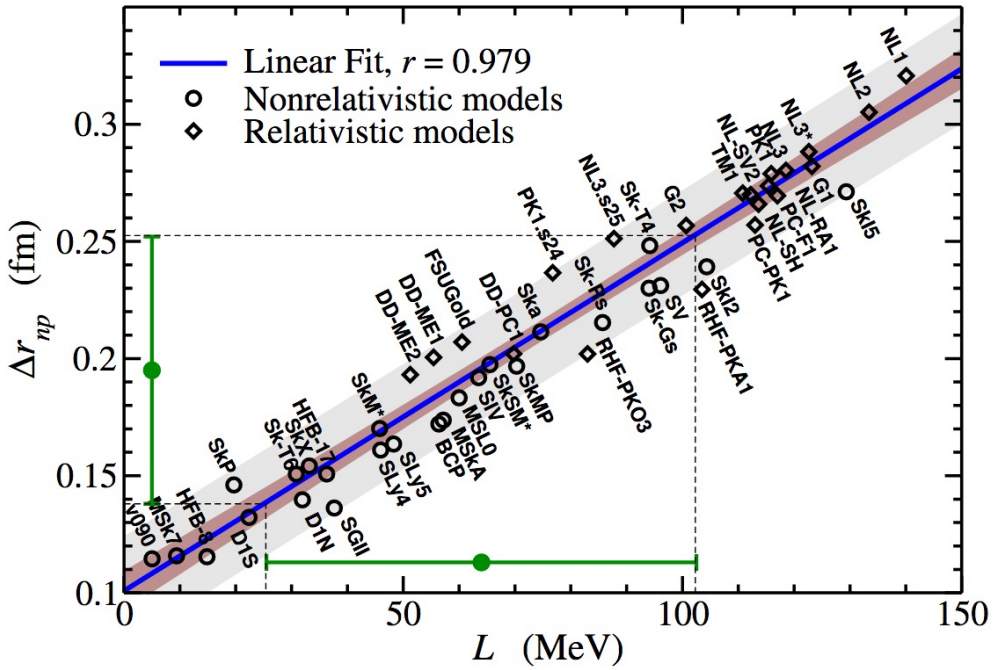
Not overly optimistic to expect significant improvement in precision of measurements over the next 1-2 decades.
Suddenly "small" systematics are not so small

Example 1: Essick+ arXiv 2102.10074





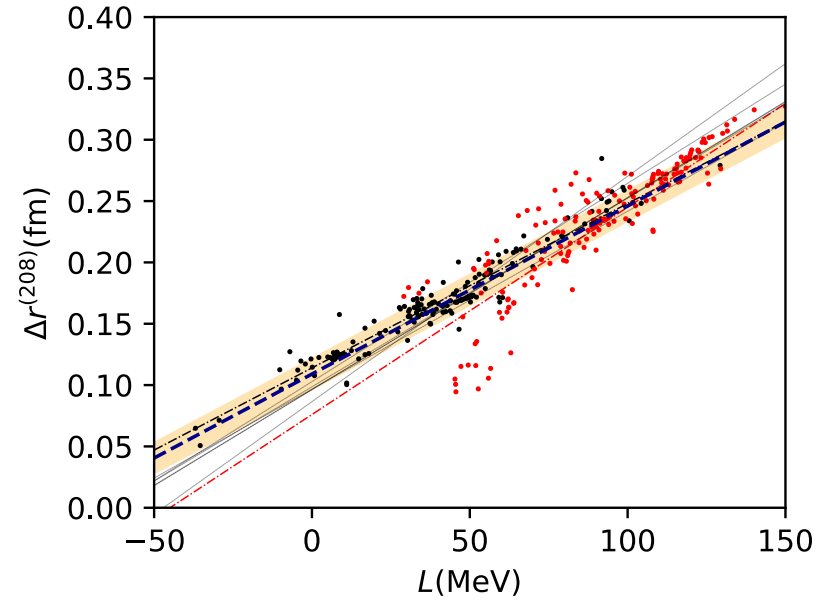
Connecting L to neutron skin: Existing DFTs predict neutron skin-L relation

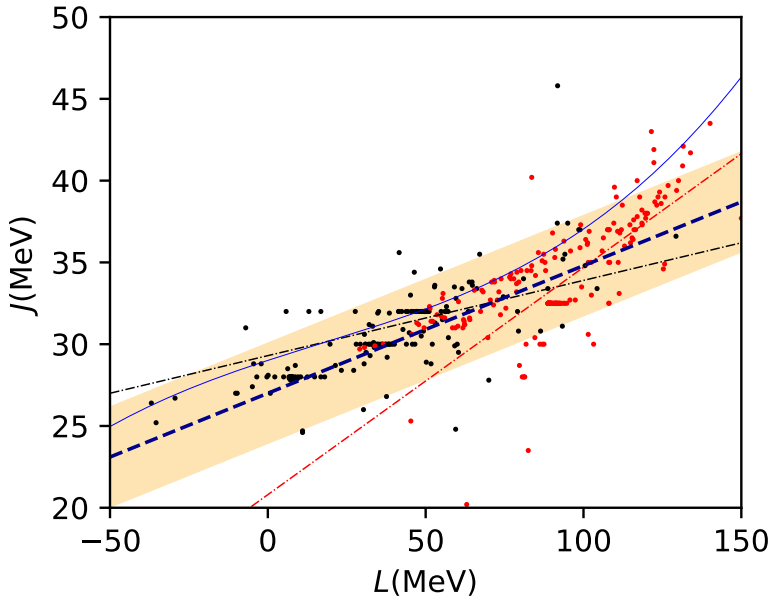


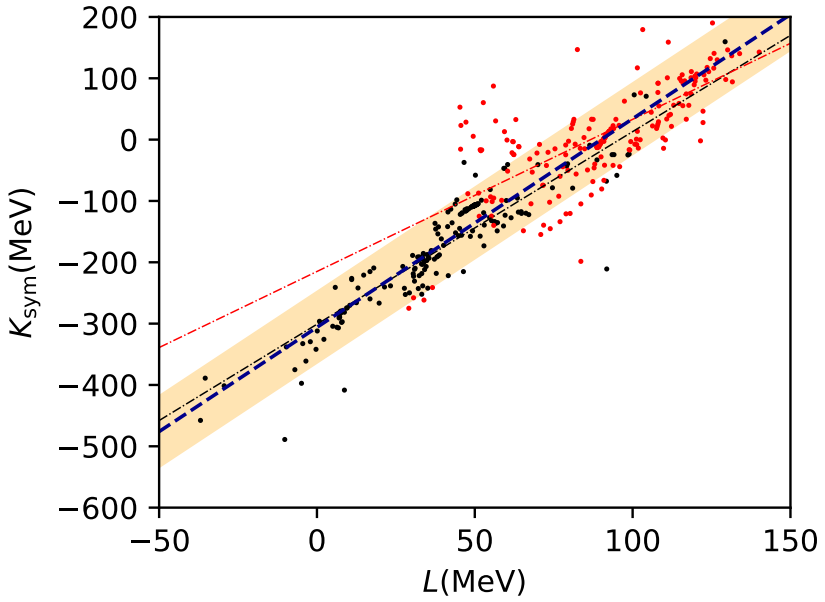
Roca-Maza et al, arxiv:1103.1762

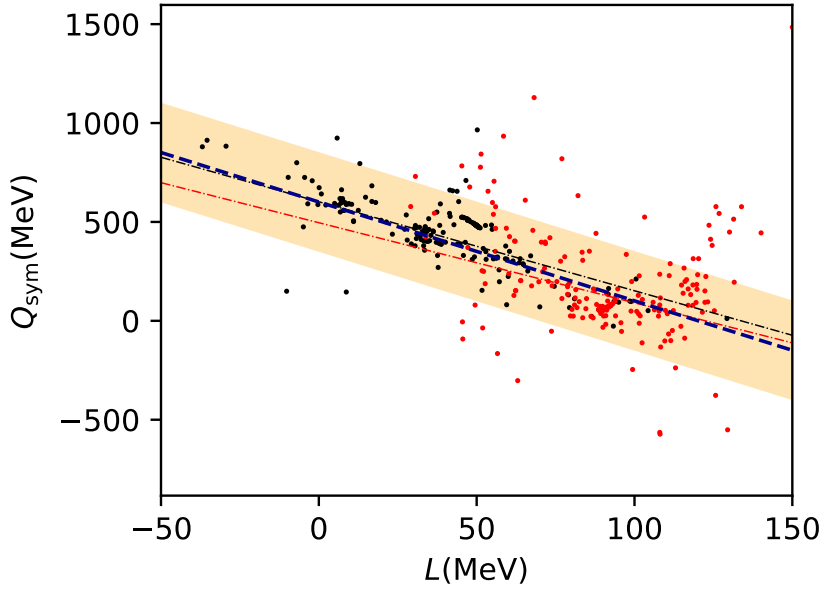
- This relation *includes* the aggregate effects of including the nuclear binding energy data in fitting individual models, not something that is controlled
- This induces correlations between J,L, K_{sym}

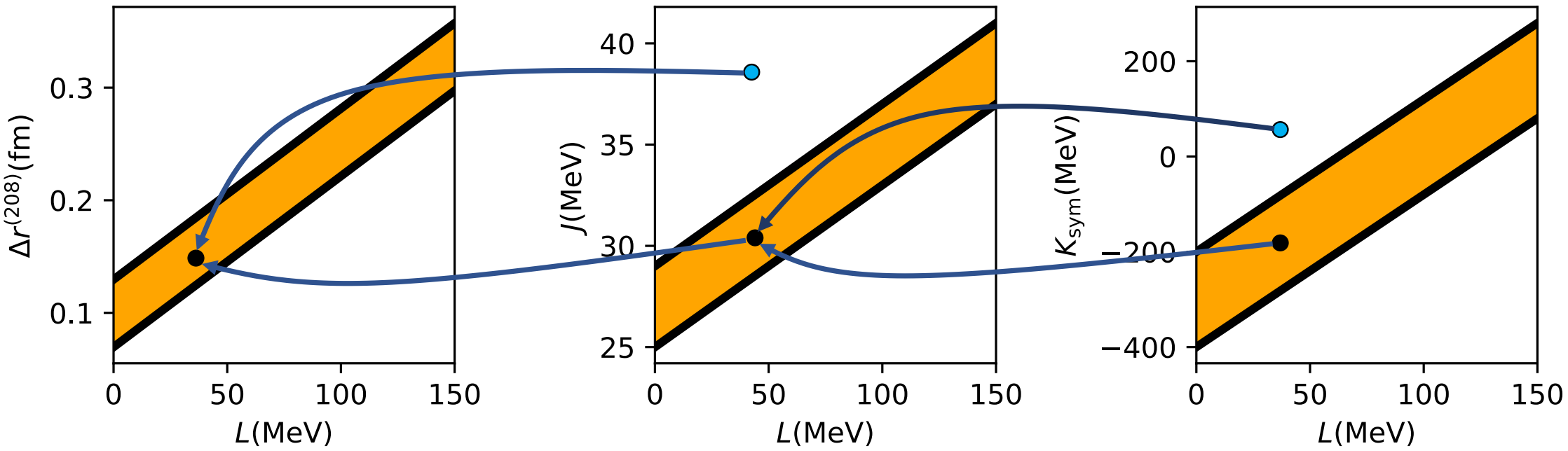
Using 200+Skyrmes and 100+RMF (Dutra arXiv:1202.3902,1405.3633)



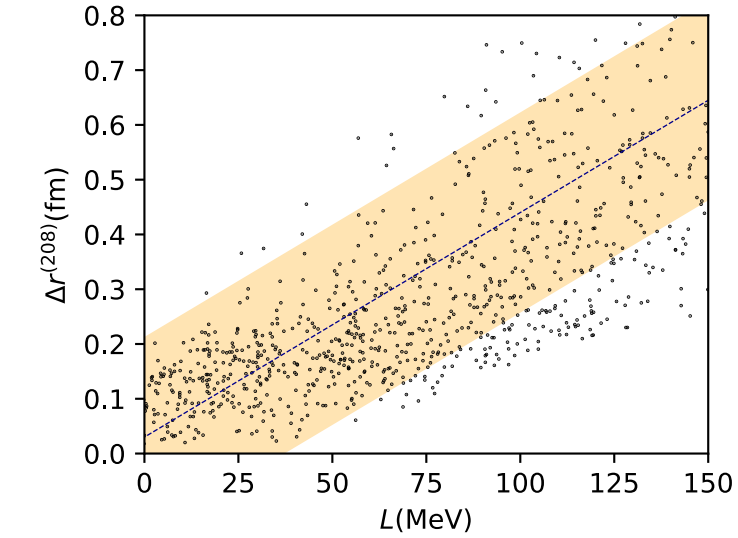


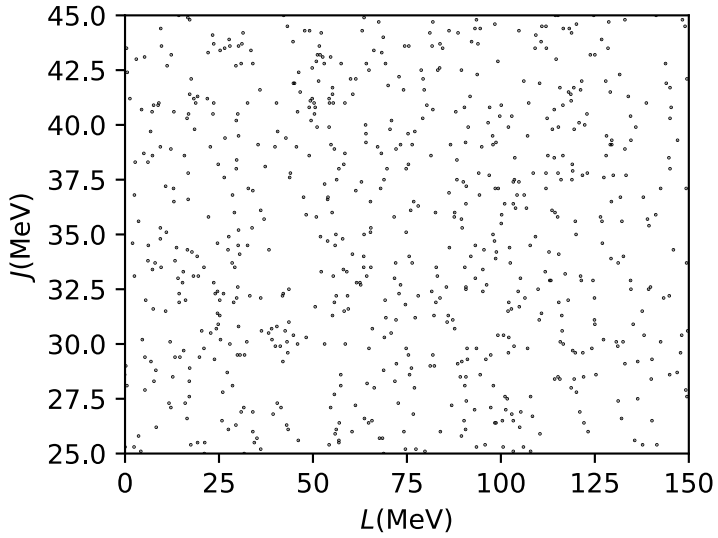


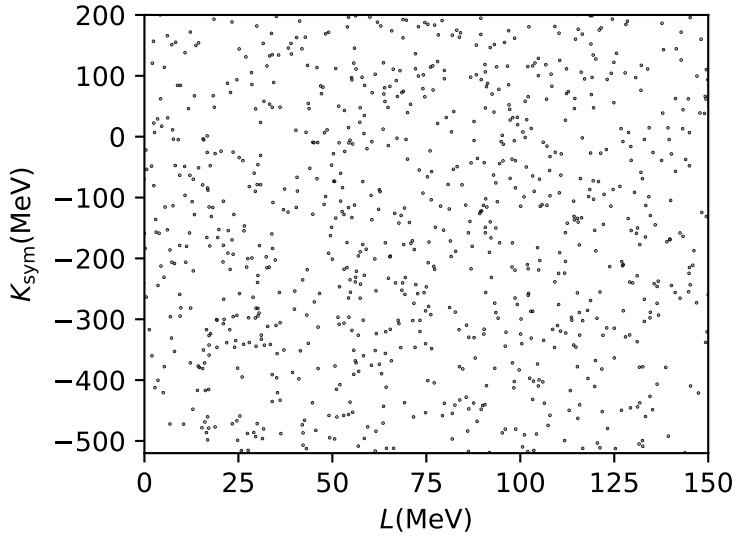


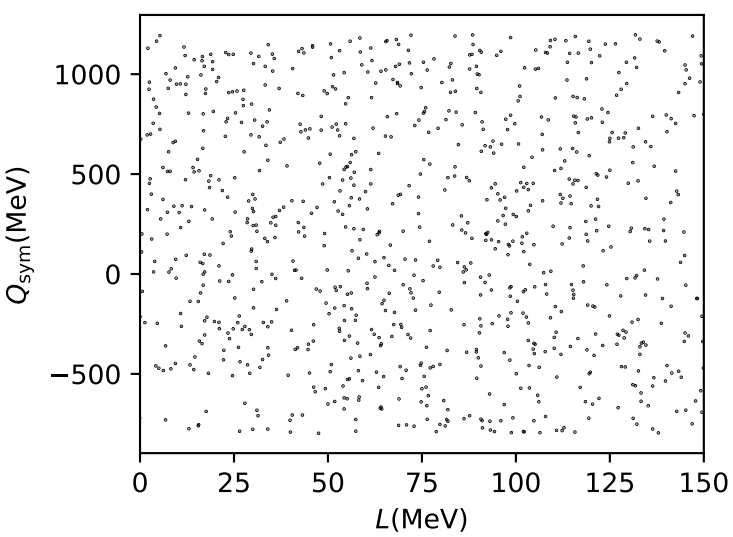

0.3
0.2
0.1
$\Delta r^{(208)}$(fm)
0
50
100
150
L(MeV)
40
35
30
25
J(MeV)
0
50
100
150
L(MeV)
200
0
−200
−400
$K_{\rm sym}$(MeV)
0
50
100
150
L(MeV)

Skyrme EDF: neutron skin of ^{208}Pb, uniform priors on symmetry energy params J,L,K_{sym},Q_{sym}

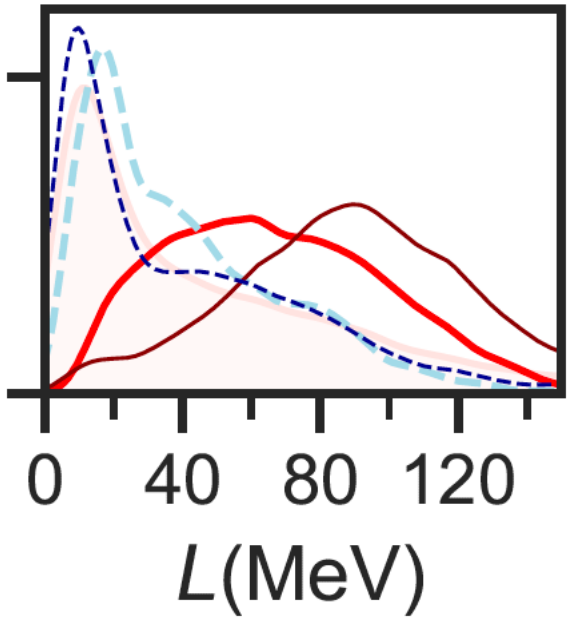


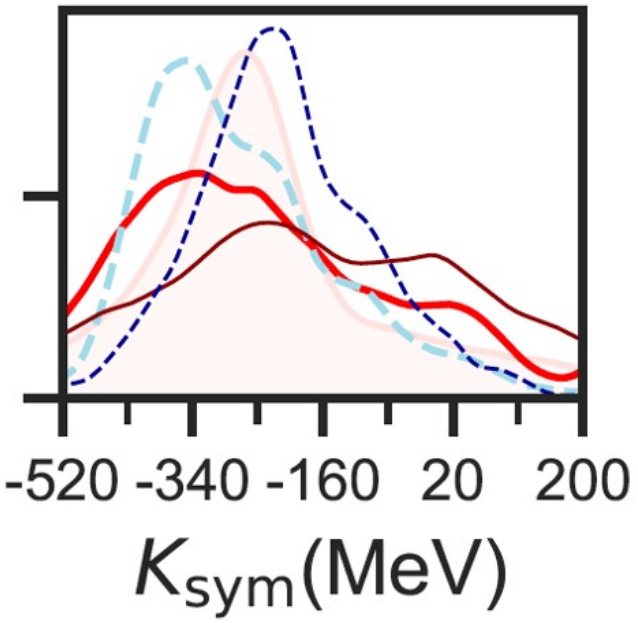


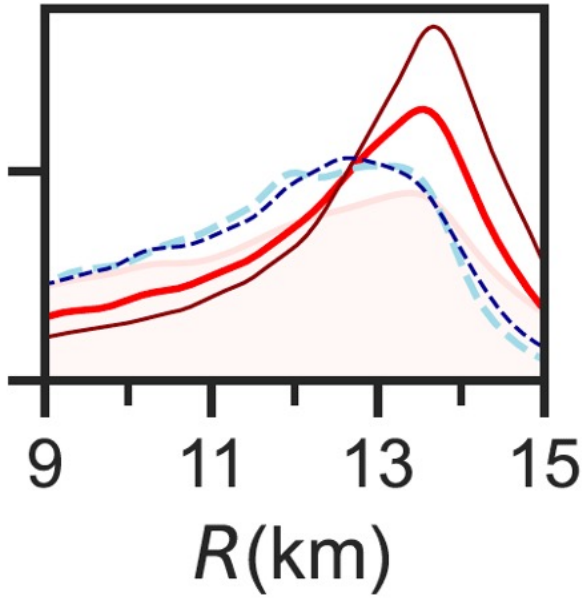




Using priors from Essick+ arXiv 2102.10074







Prior
PREX $65.47^{38.33}_{32.05}$
Dip.Pol.
PREX_emp
Dip.Pol._emp $89.41^{34.67}_{35.06}$

(MeV)

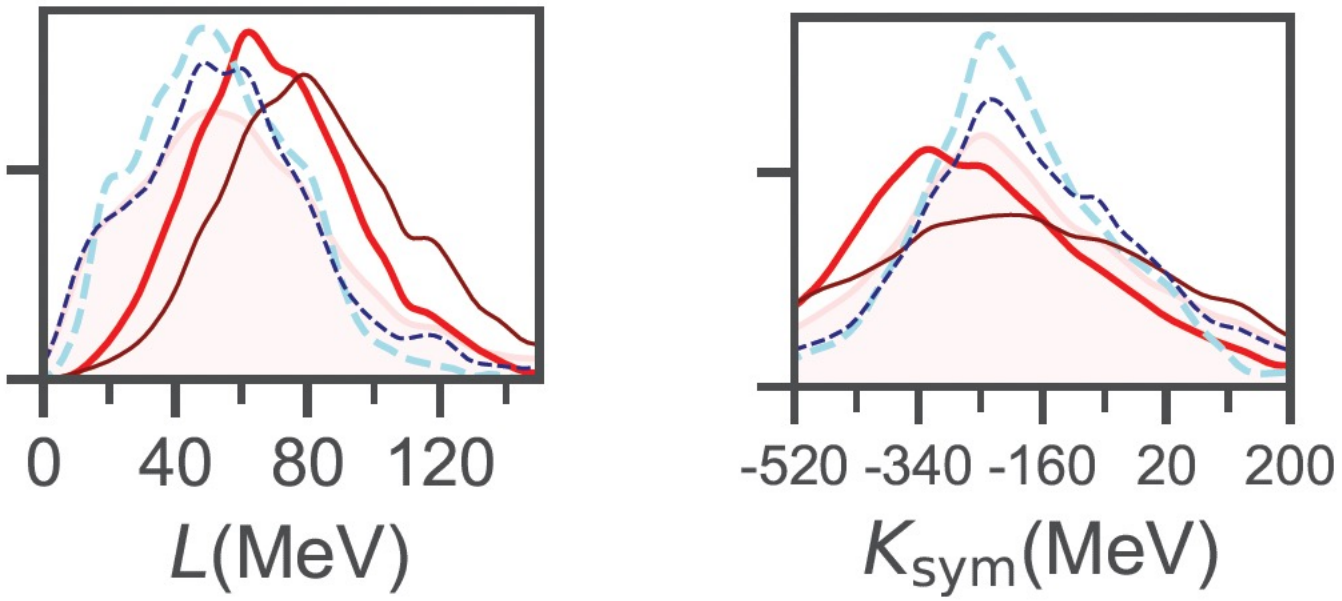
Prior
PREX -316.91
Dip.Pol.
PREX_emp
Dip.Pol._emp $-215.09^{300.40}_{284.37}$

(MeV)

PREX $12.86^{1.45}_{2.61}$
Dip.Pol.
PREX_emp $13.21^{1.08}_{2.23}$
Dip.Pol._emp

(km)

Using NICER-LIGO from Essick+ arXiv 2102.10074



$68.73^{27.84}_{23.01}$ (MeV)

$81.74^{33.59}_{25.98}$ (MeV)

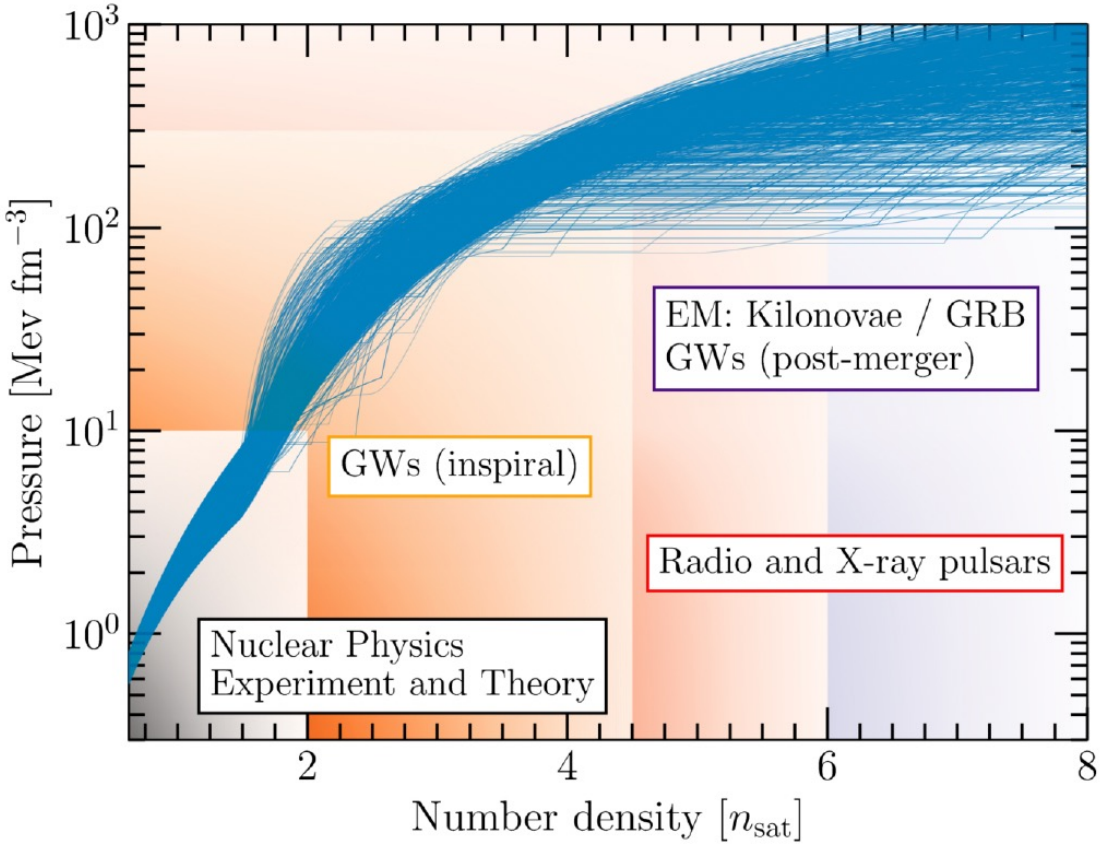
$-267.82^{216.80}_{174.47}$ (MeV)

$-208.36^{249.26}_{250.34}$ (MeV)

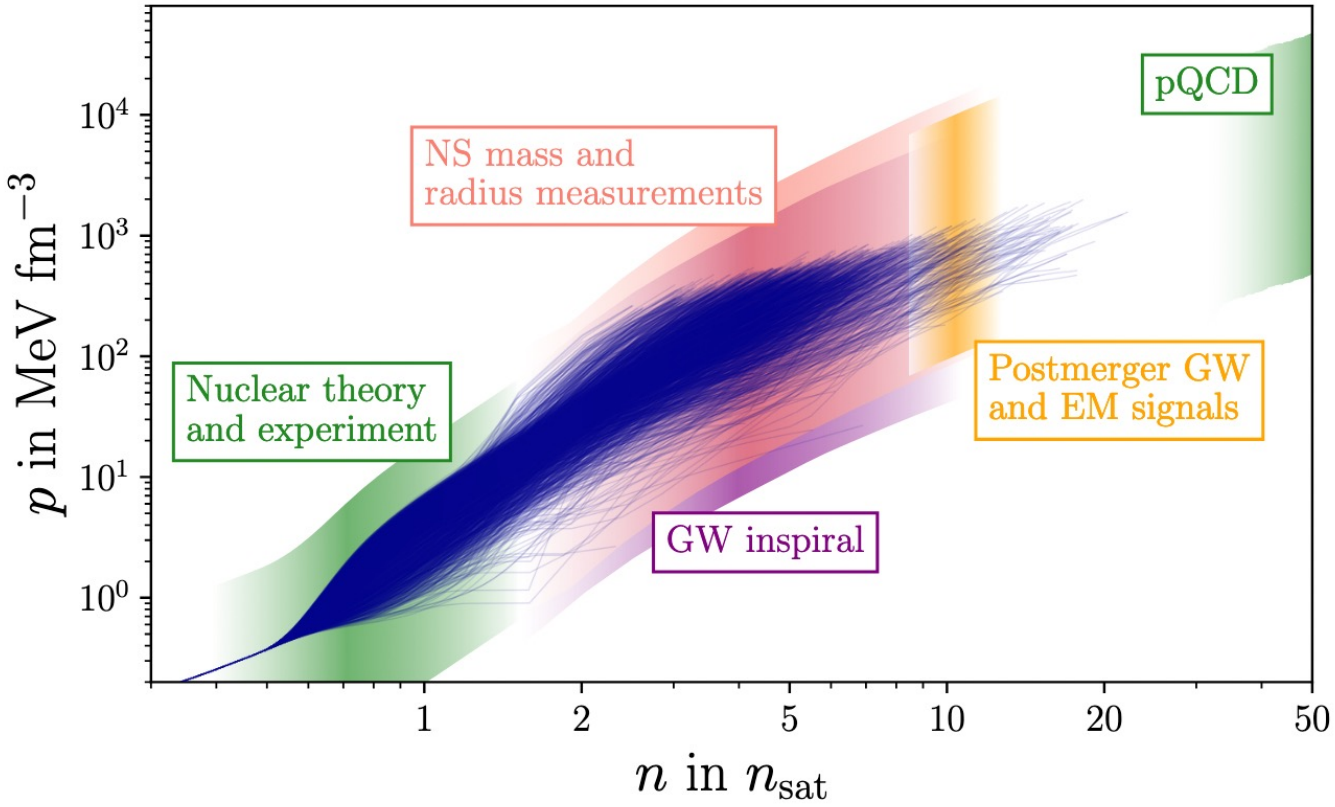
Experiments such as neutron skin and dipole polarizability probes EOS below mostly saturation density, how relevant are those in determine neutron star properties?

(with apologies to Matt Groening)

Crust usually de-emphasized in EOS plots

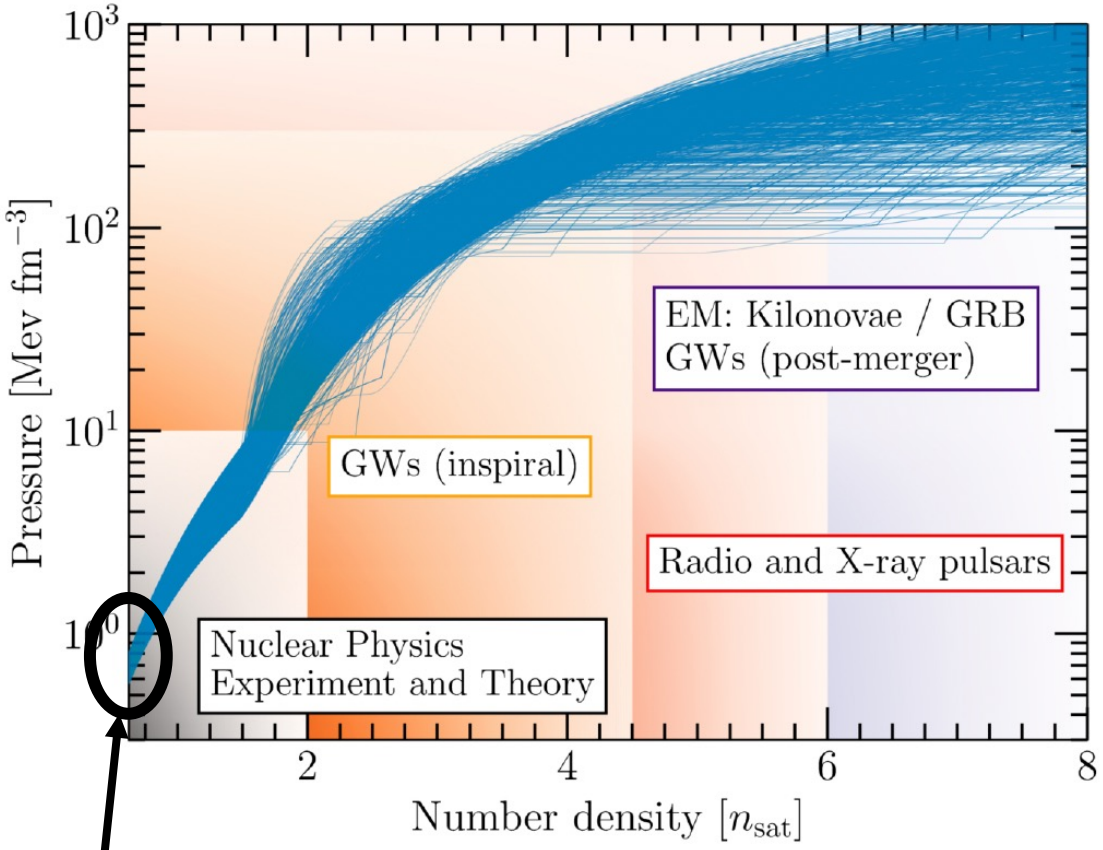


Pang et al, arxiv:2205.08513



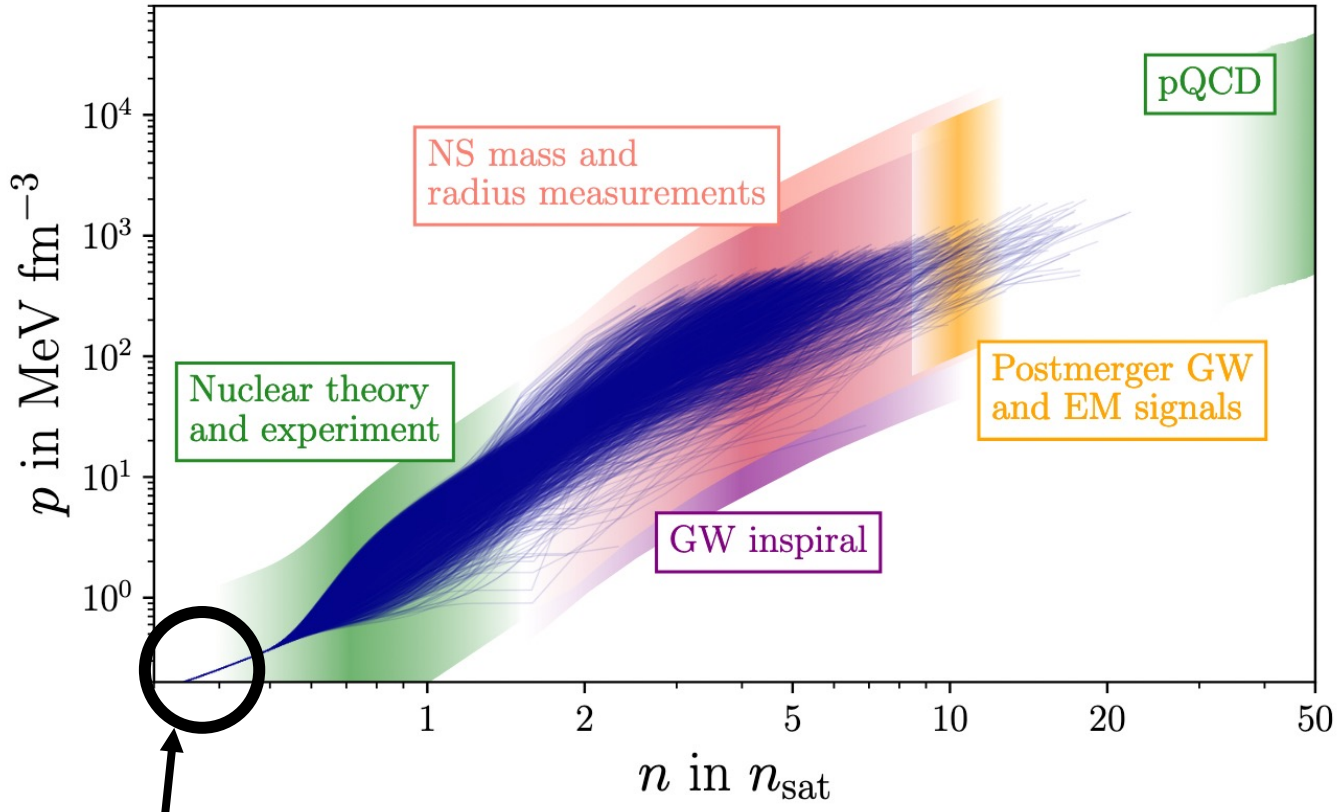
Koehn+ arXiv:2402.04172

Crust usually de-emphasized in EOS plots



Pang et al, arxiv:2205.08513

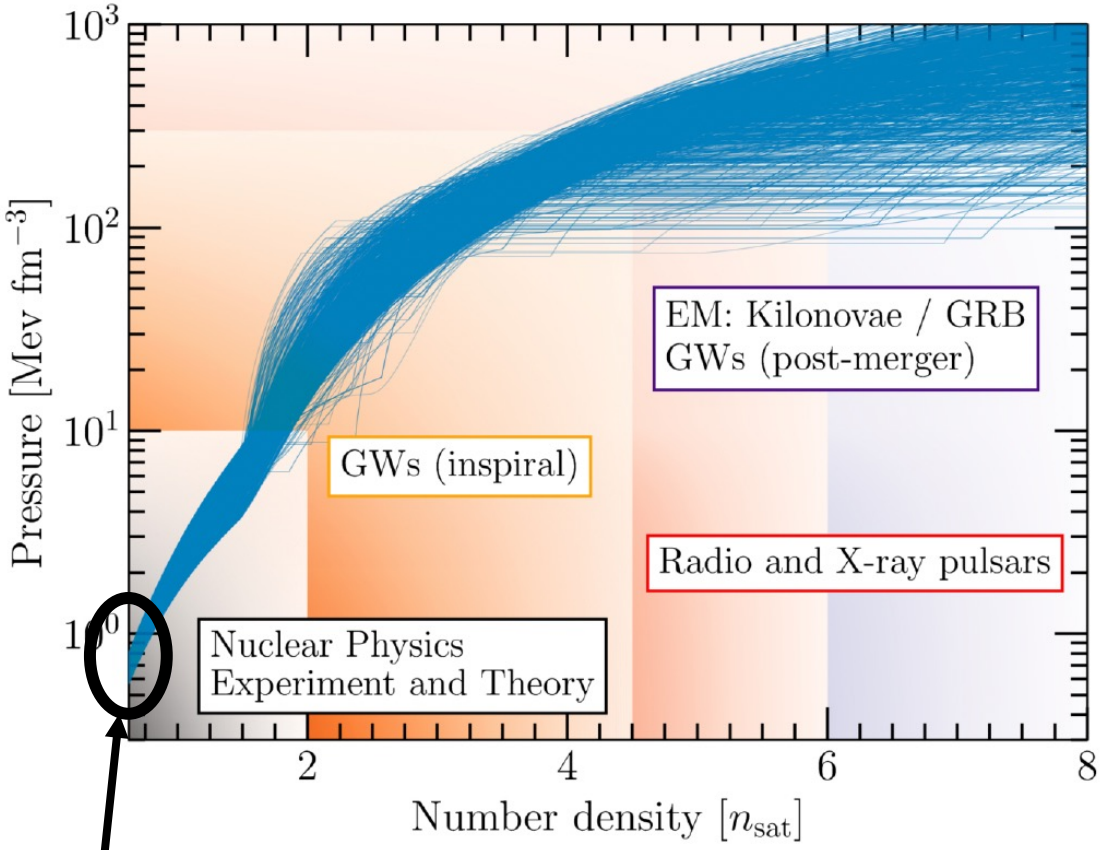
There's the crust!



Koehn+ arXiv:2402.04172

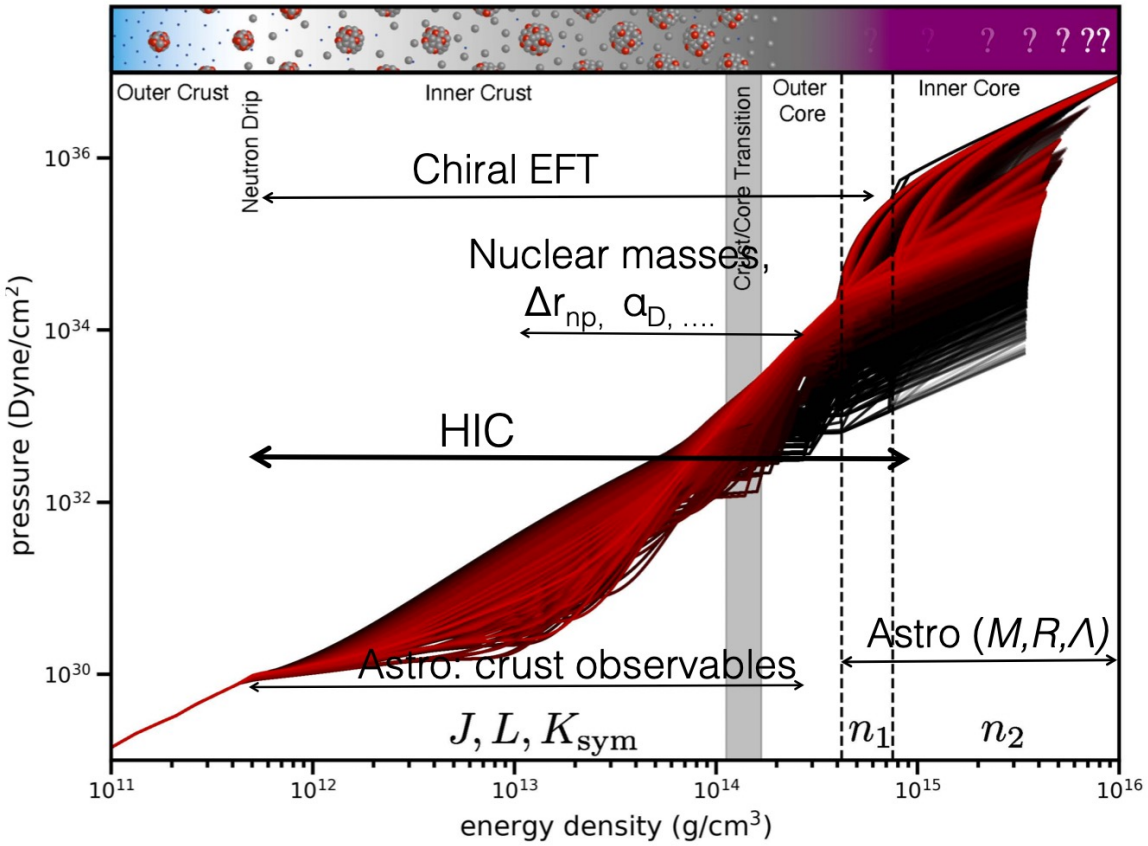
Just one crust EOS!

Crust usually de-emphasized in EOS plots



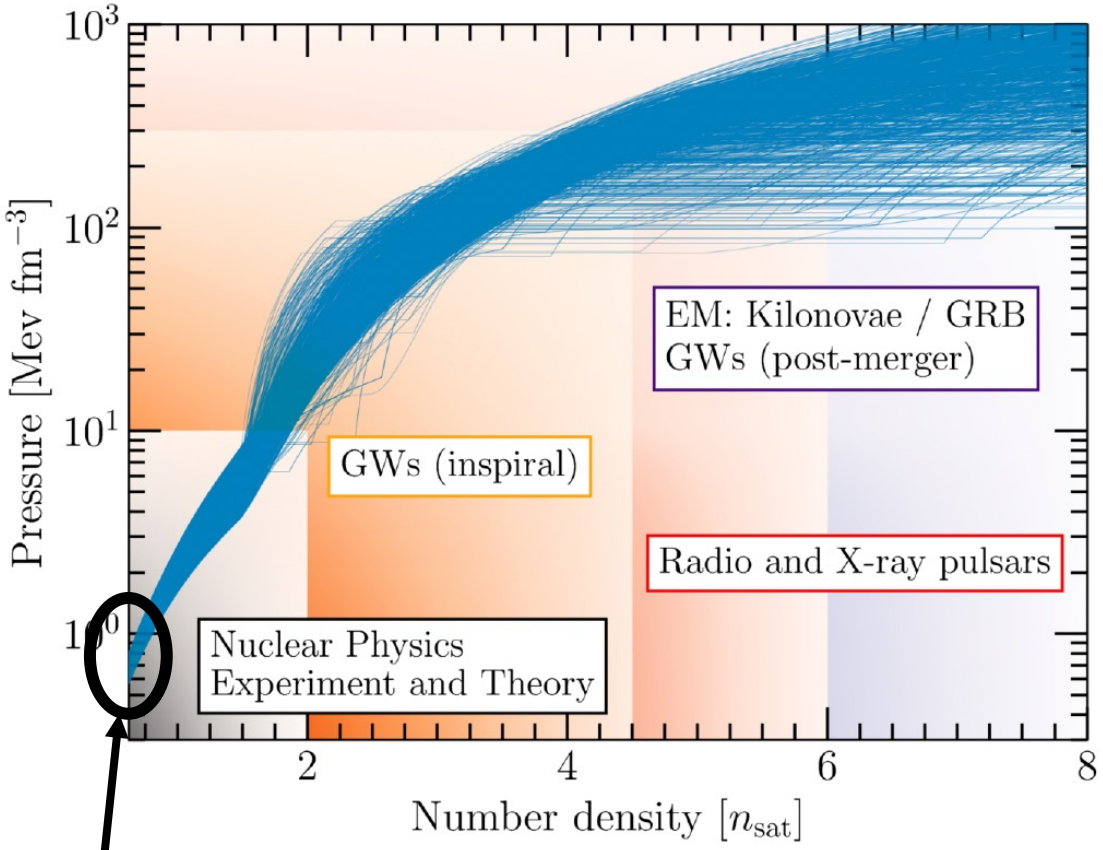
Pang et al, arxiv:2205.08513

There's the crust!



Neill+ 2208.00994; Sorenson+ 2301.13253

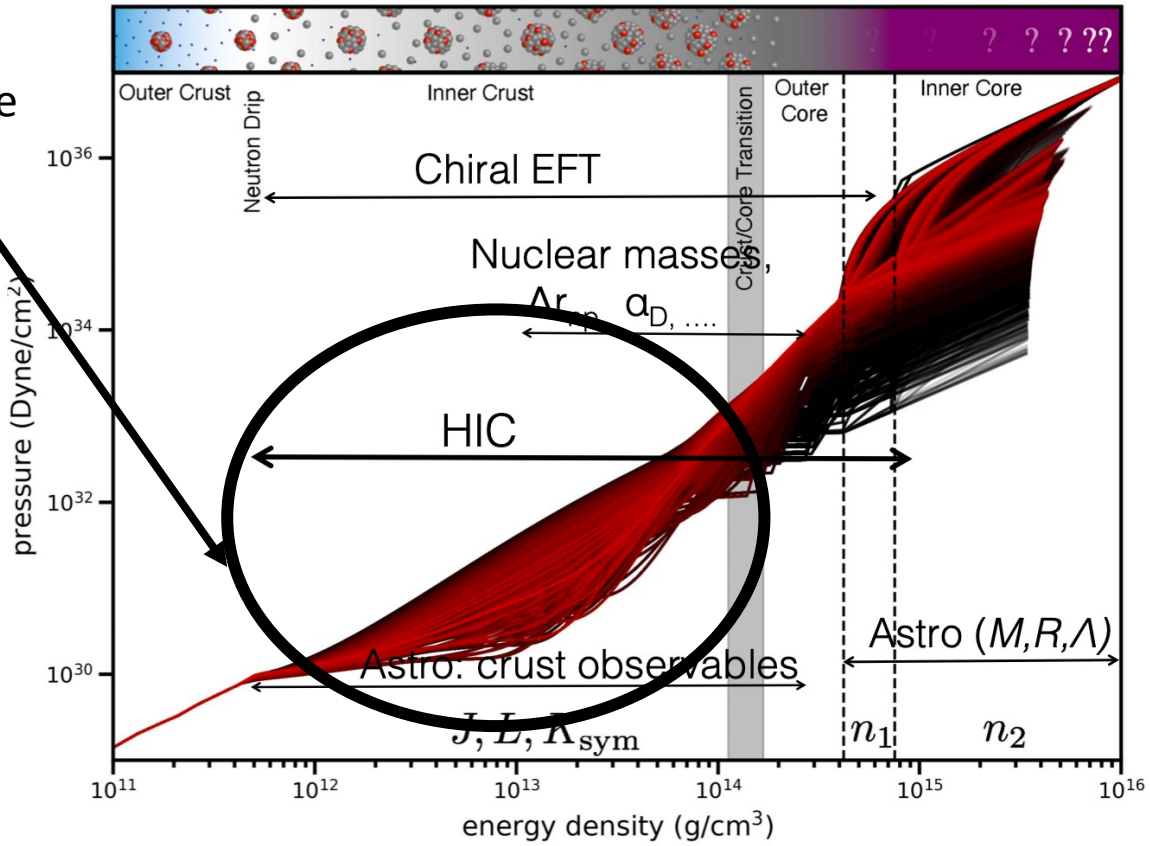
Crust usually de-emphasized in EOS plots



There's the crust!

Pang et al, arxiv:2205.08513

There's the crust!



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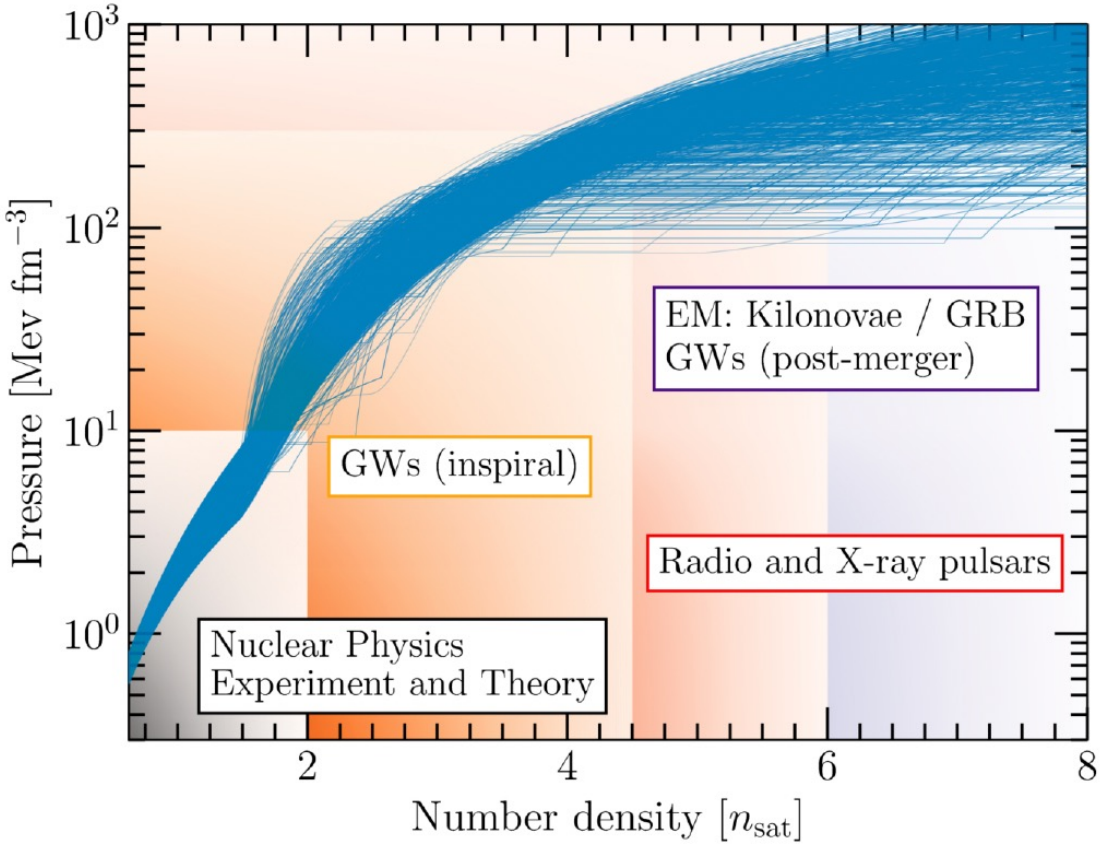
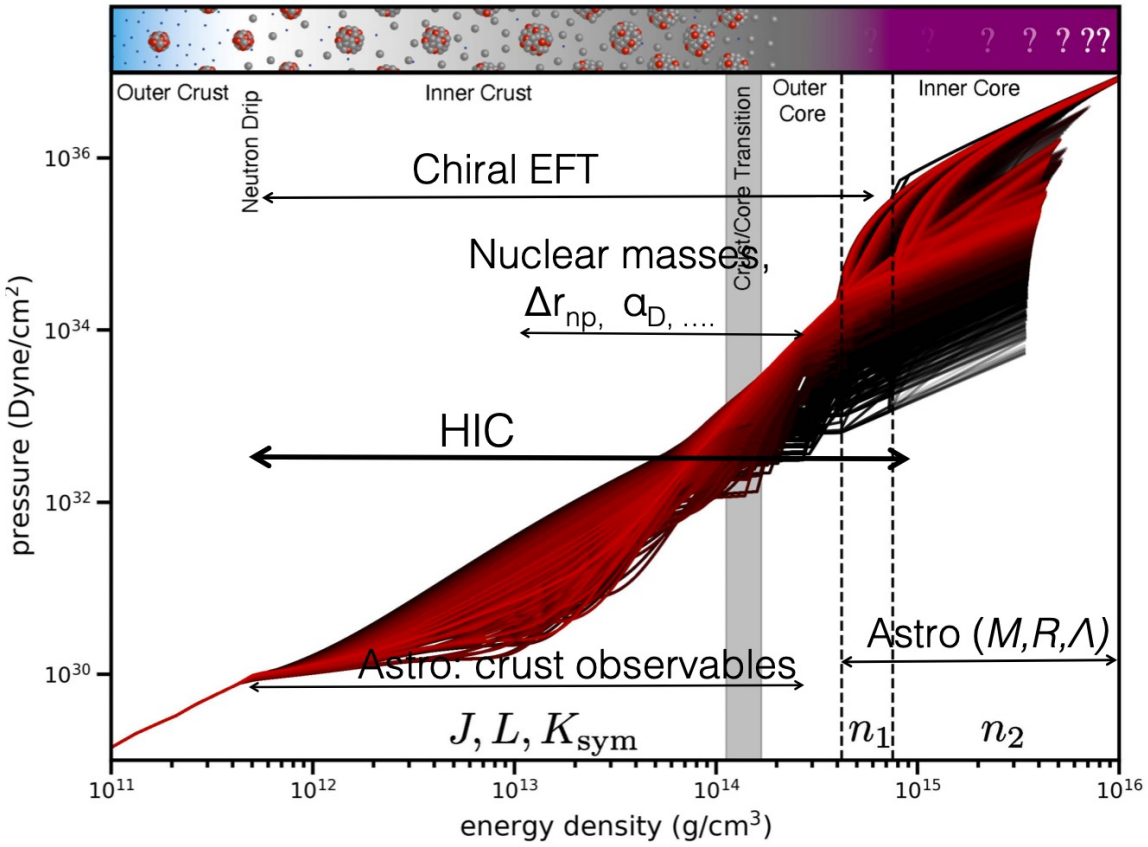
Core consistent with crust needed for inference of bulk properties



Pang et al, arxiv:2205.08513



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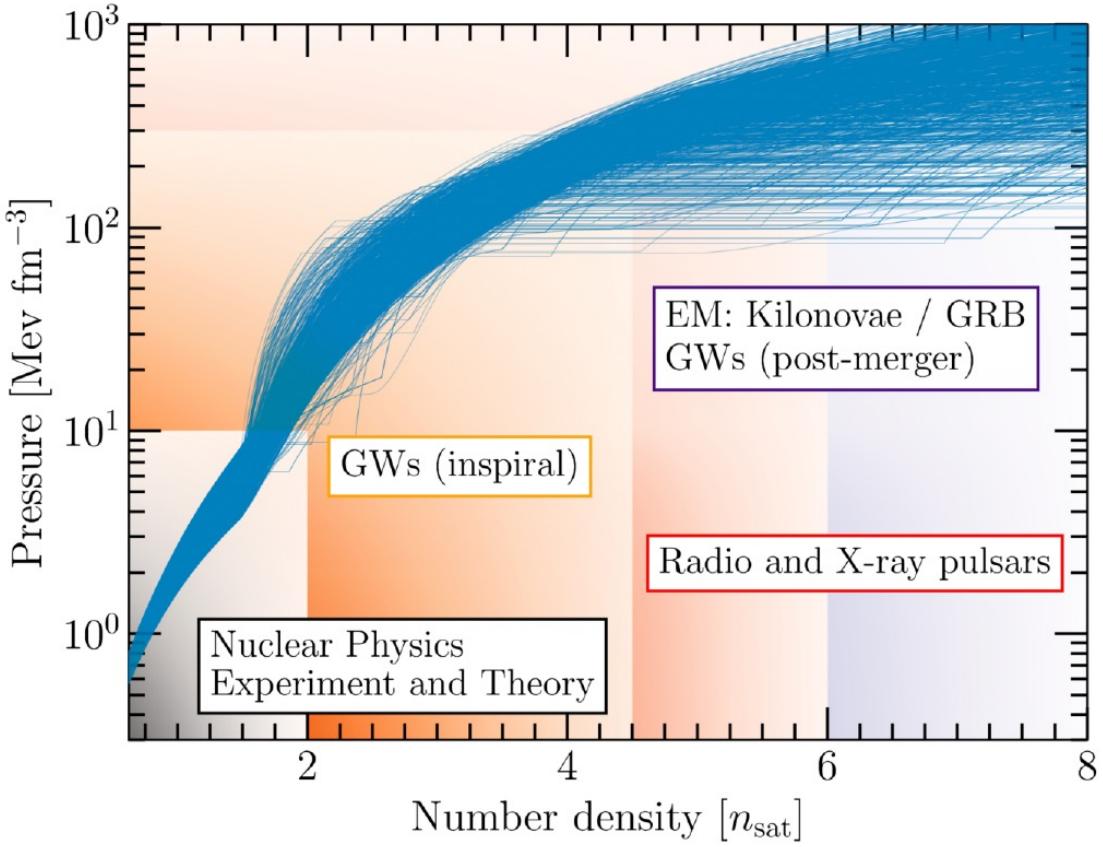
Lami Suleiman + *Phys.Rev.C* 104 (2021) 1, 015801

Crust inconsistent with core EOS leads to **errors up to 5% in radius inference – that's 0.5km**

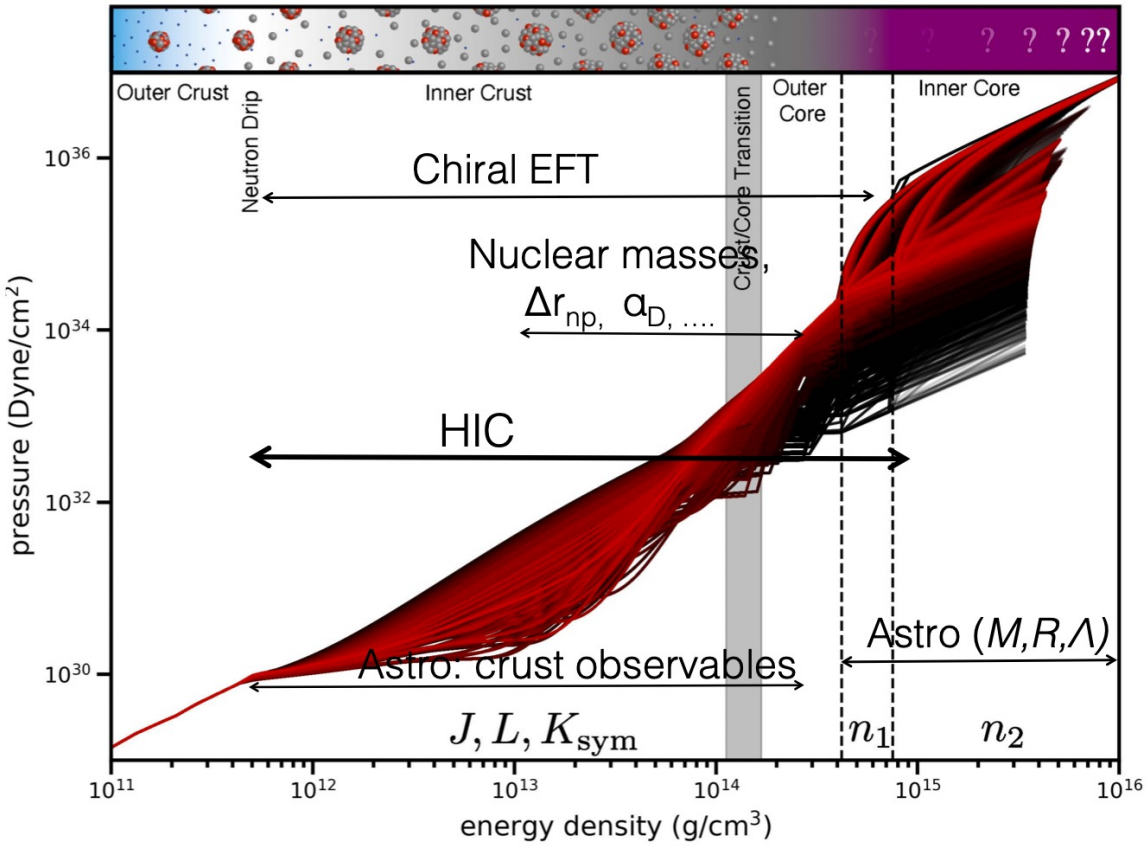
Precision of universal relations underestimated

NEXT GENERATION X-RAY/GW MEASUREMEMENTS WILL NEED BETTER CRUST MODELING

Core consistent with crust needed for inference of bulk properties



Pang et al, arxiv:2205.08513



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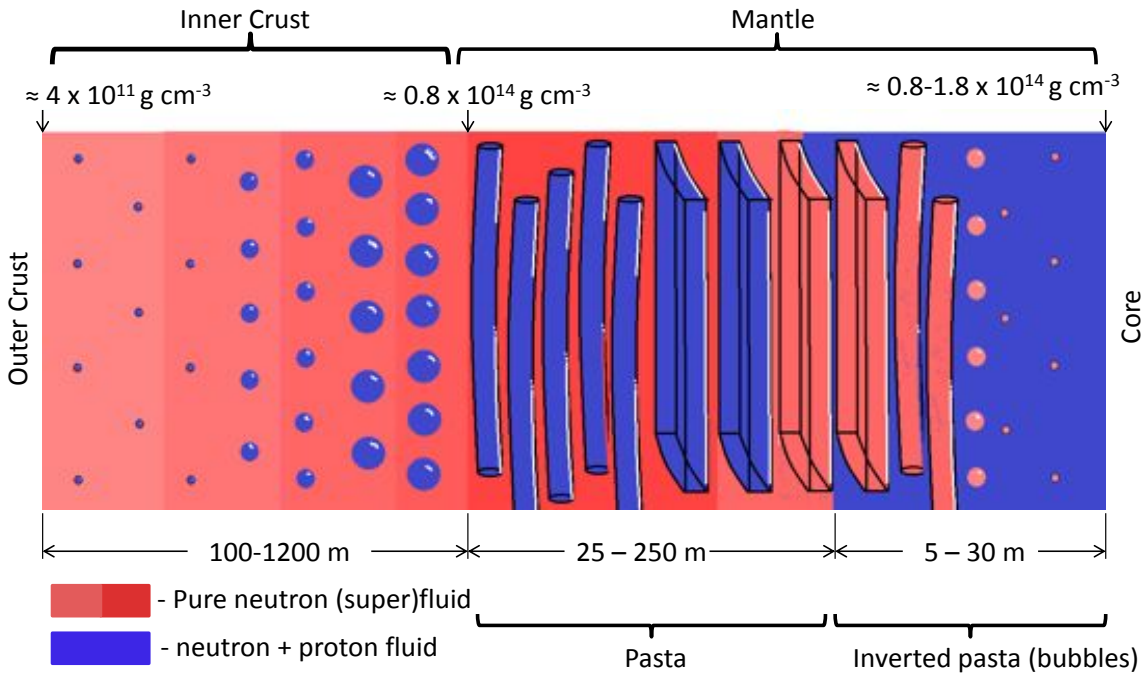
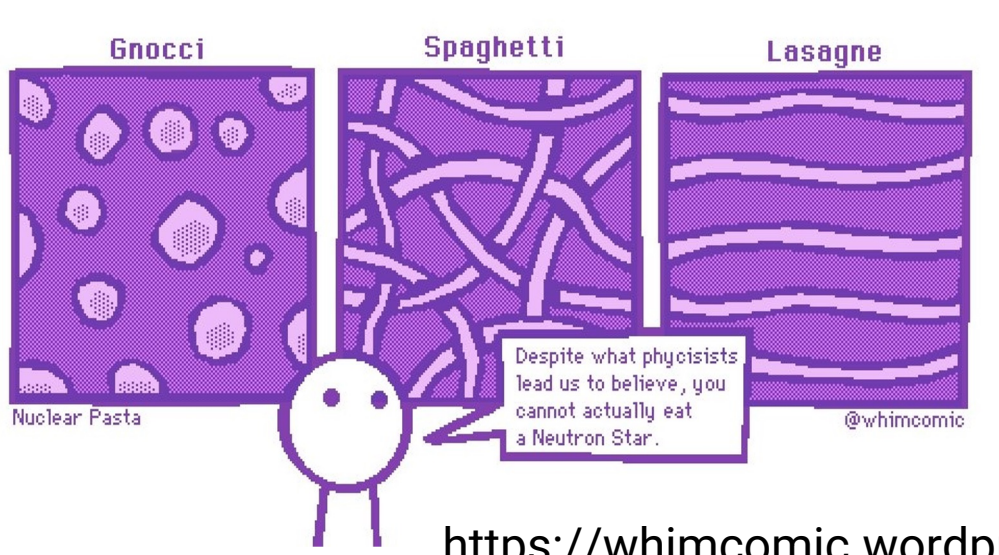
Modeling the crust





https://whimcomic.wordpress.com/2019/03/09/nuclear-pasta/

Structure of Matter below Nuclear Saturation Density

D. G. Ravenhall

Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801

and

C. J. Pethick

Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, and NORDITA, DK-2100 Copenhagen Ø, Denmark

and

J. R. Wilson

Lawrence Livermore National Laboratory, Livermore, California 94550

(Received 5 May 1983)

It will be interesting to explore the consequences of these spaghettilike and lasagnalike phases of dense matter. Their physical properties will have to reflect the great departure from isotropy that these phases possess. Neutrino scattering

properties. After all, the cooking of spaghetti, while it spoils the perfect straightness of the strands, does not destroy the characteristic short-range order.

Neutron star mantle as a complex nuclear fluid

DYNAMICAL SIMULATION OF NUCLEAR "PASTA": SOFT CONDENSED MATTER IN DENSE STARS

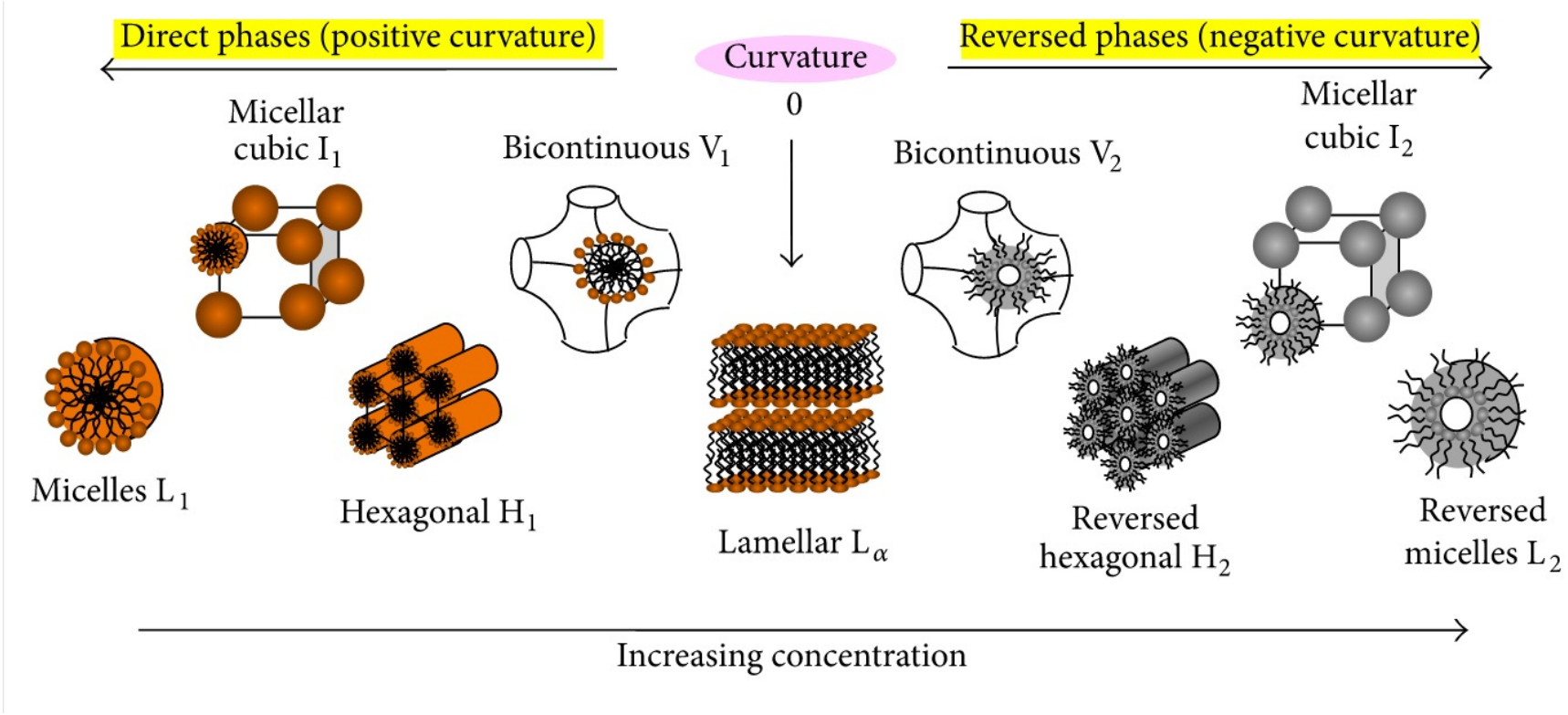
Gentaro Watanabe[a,b*] *and Hidetaka Sonoda*[c,b]

Arxiv:cond-mat/0502515v2

Colloquium: Astromaterial science and nuclear pasta

M. E. Caplan and C. J. Horowitz

Rev. Mod. Phys. **89**, 041002 — Published 23 October 2017



Lombardo et al, Advances in Condense Matter Physics 151683, 2015

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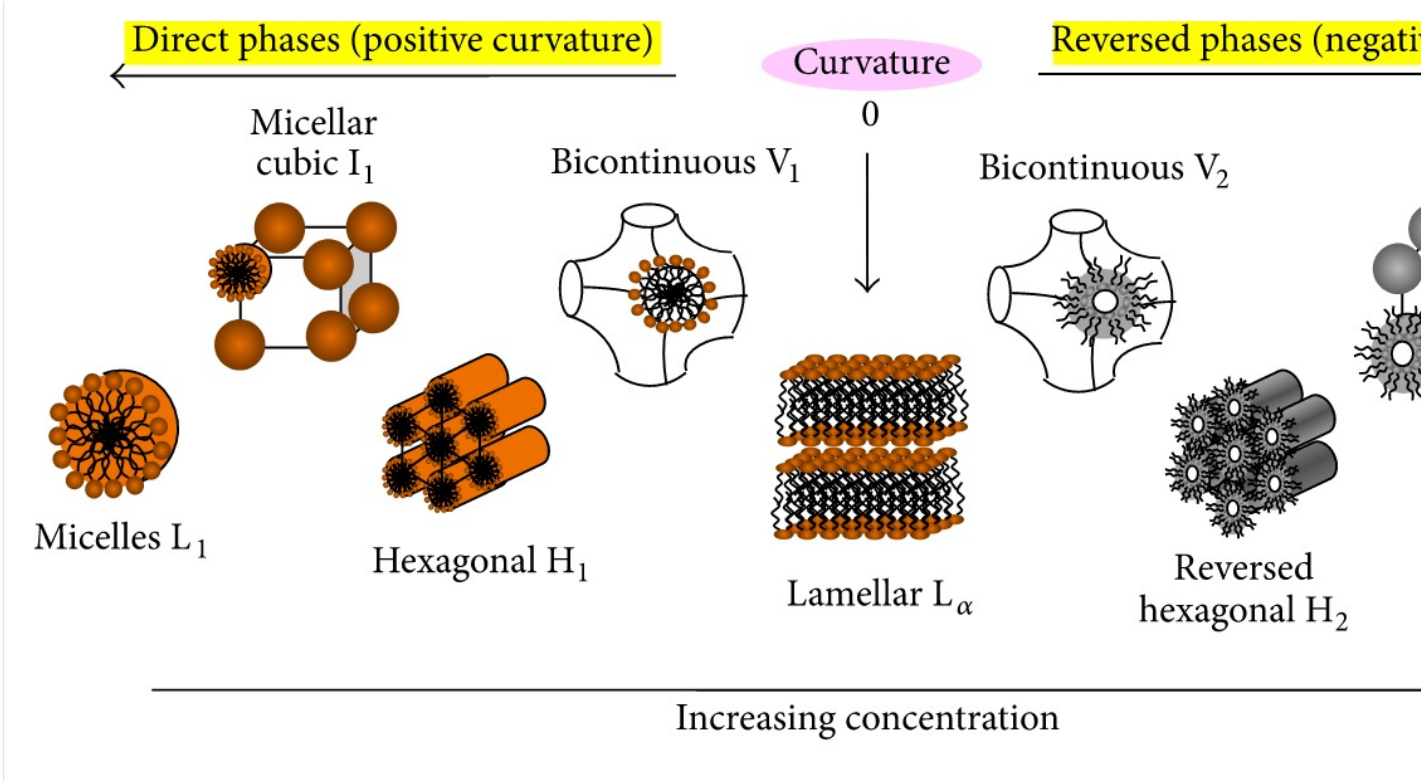
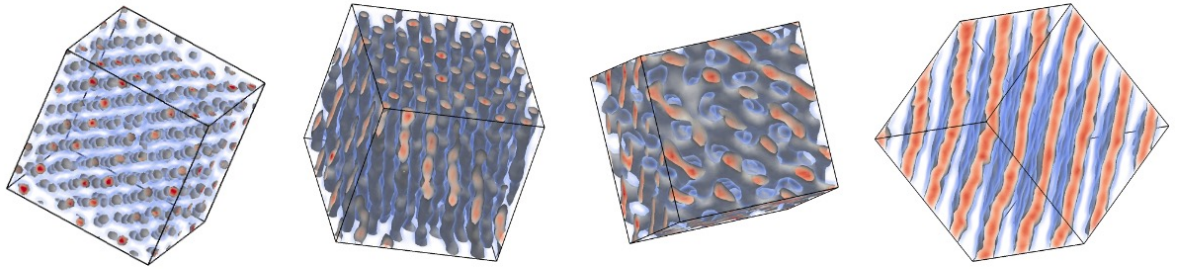


Lombardo et al, Advances in Condense Matter Physics 151683, 2015

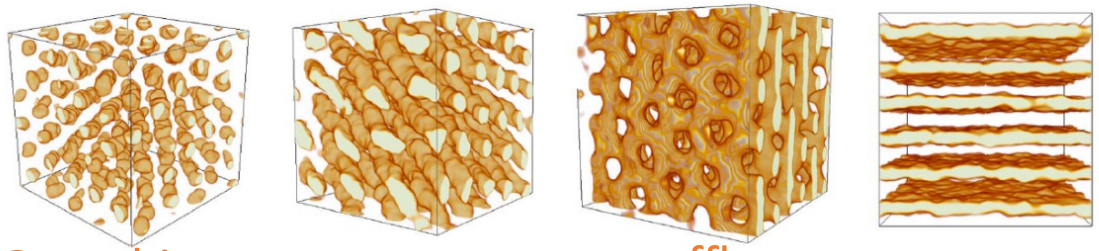
Driven by competition between short range attractive and long-range repulsive interactions - a generic feature of soft-condensed matter systems

bcc | hex | perforated lamellae | lam

Polyelectrolyte blend



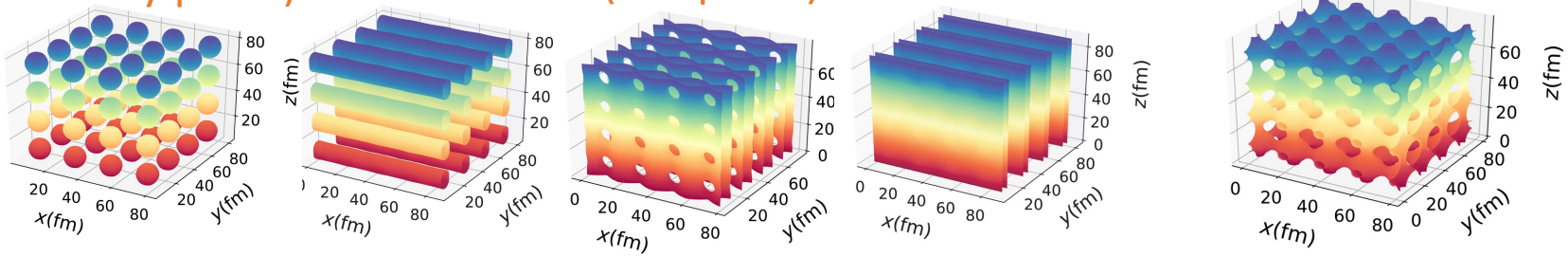
Nuclear pasta
Molecular dynamics



Gnocchi (not really pasta) | spaghetti | waffles (not pasta) | lasagna

Pending progress in Italian food engineering

Quantum SHF



Rumyantsev, dePablo: Macromolecules 53, 2020

Molecular dynamics simulations: Caplan, Horowitz, Rev. Mod. Phys. 89, 041002 (2017)

Quantum simulations: Newton et al, arxiv:2104.11835

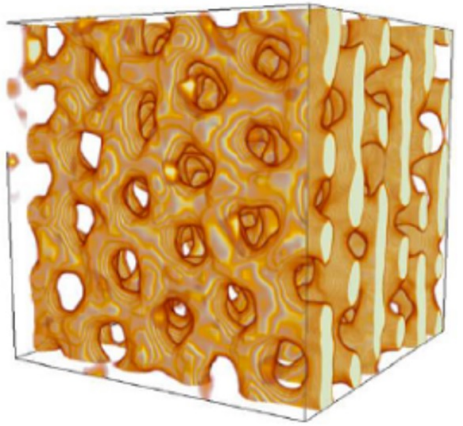
Nuclear Waffles

A. S. Schneider,[1,*] D. K. Berry,[2,†] C. M. Briggs,[1,‡] M. E. Caplan,[1,§] and C. J. Horowitz[1,¶]

[1] *Department of Physics and Nuclear Theory Center, Indiana University, Bloomington, IN 47405, USA*

[2] *University Information Technology Services, Indiana University, Bloomington, IN 47408, USA*

(Dated: May 14, 2018)



Elastic properties of phases with nonspherical nuclei in dense matter

C. J. Pethick,[1,2] Zhaowen Zhang,[1] and D. N. Kobyakov[3]

[1] *The Niels Bohr International Academy, The Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, DK-2100 Copenhagen Ø, Denmark*

[2] *NORDITA, KTH Royal Institute of Technology and Stockholm University, Roslagstullsbacken 23, SE-106 91 Stockholm, Sweden*

[3] *Institute of Applied Physics of the Russian Academy of Sciences, 603950 Nizhny Novgorod, Russia*

[3] In Ref. [22] phases with spatially modulated plate-like elements are referred to as "waffles" but, to avoid proliferation of nomenclature, we shall refer to them as "lasagna".

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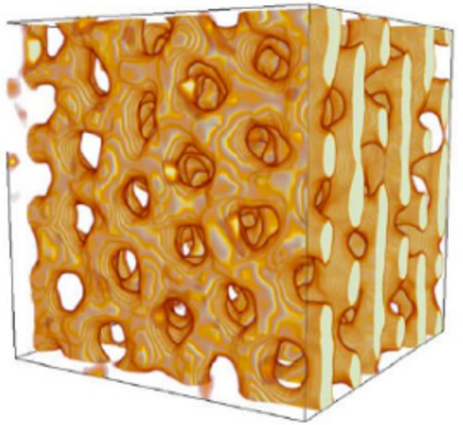

The New Y

Sunday, August 30, 2022

Nuclear pasta controversy

Rowdy scenes broke out at the 5th annual conference on food based analogies in astrophysics. Nuclear pasta expert Chuck Horowitz was forced to defend his breaking of the pasta naming convention for nuclear shapes in the inner crust of neutron stars. Chris Pethick, notorious for his belligerent questioning, interrupted Horowitz's talk to complain that introducing nuclear waffles was unnecessary, to which Horowitz responded "but then I can't refer the neutron superfluid as nuclear maple syrup".

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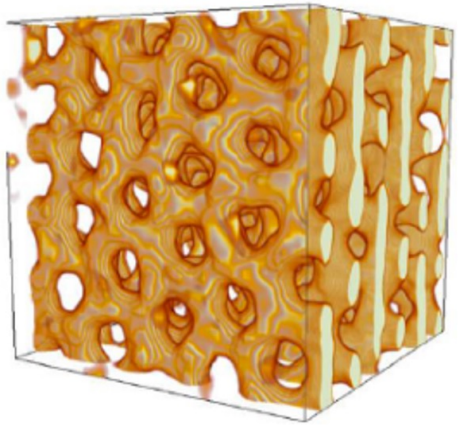

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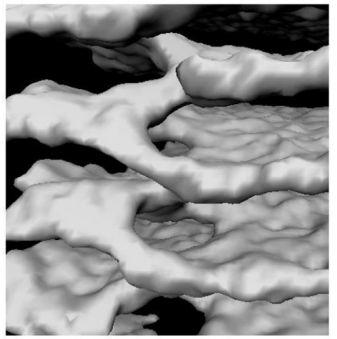
Parking-garage structures in astrophysics and biophysics

C. J. Horowitz,[1,*] D. K. Berry,[1,†] M. E. Caplan,[1,‡] Greg Huber,[2,§] and A. S. Schneider



Horowitz et al, PRL.114.031102 (20

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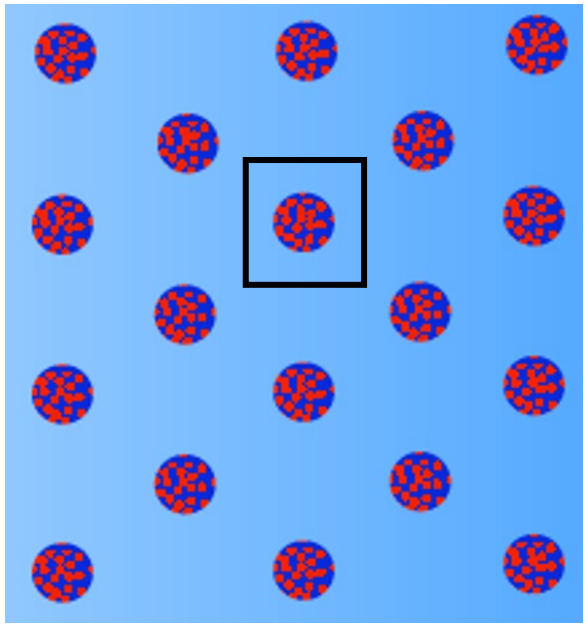
NUCLEAR PASTA RECIPE: ANGEL HAIR WITH CARROTS

crammed into a 20km-wide sphere... Because of the immense gravity, the outer layers of neutron stars freeze solid to form a crust that surrounds a liquid core. Below the crust, protons and neutrons compete and end up forming long cylindrical shapes or flat planes. These have become known as 'spaghetti' and 'lasagna'—or nuclear pasta."

Given this exciting discovery, Barilla Executive Chef Lorenzo Boni decided to get creative and make his own version of nuclear pasta using Barilla Angel Hair, carrots, red bell peppers and Romano cheese. A few pieces of Barilla Collezione Orecchiette and some sprinkles of Barilla Pastina make the perfect garnish for the plate. Try it for dinner tonight—it's out of this world!

https://www.barilla.com/en-us/posts/2018/10/22/nuclear-pasta-recipe-angel-hair-with-carrots

Modeling the crust with the Compressible liquid drop model



CLDM:Bulk fluid and surface degrees of freedom

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

Nuclear EDF: Bulk + separate surface energy function

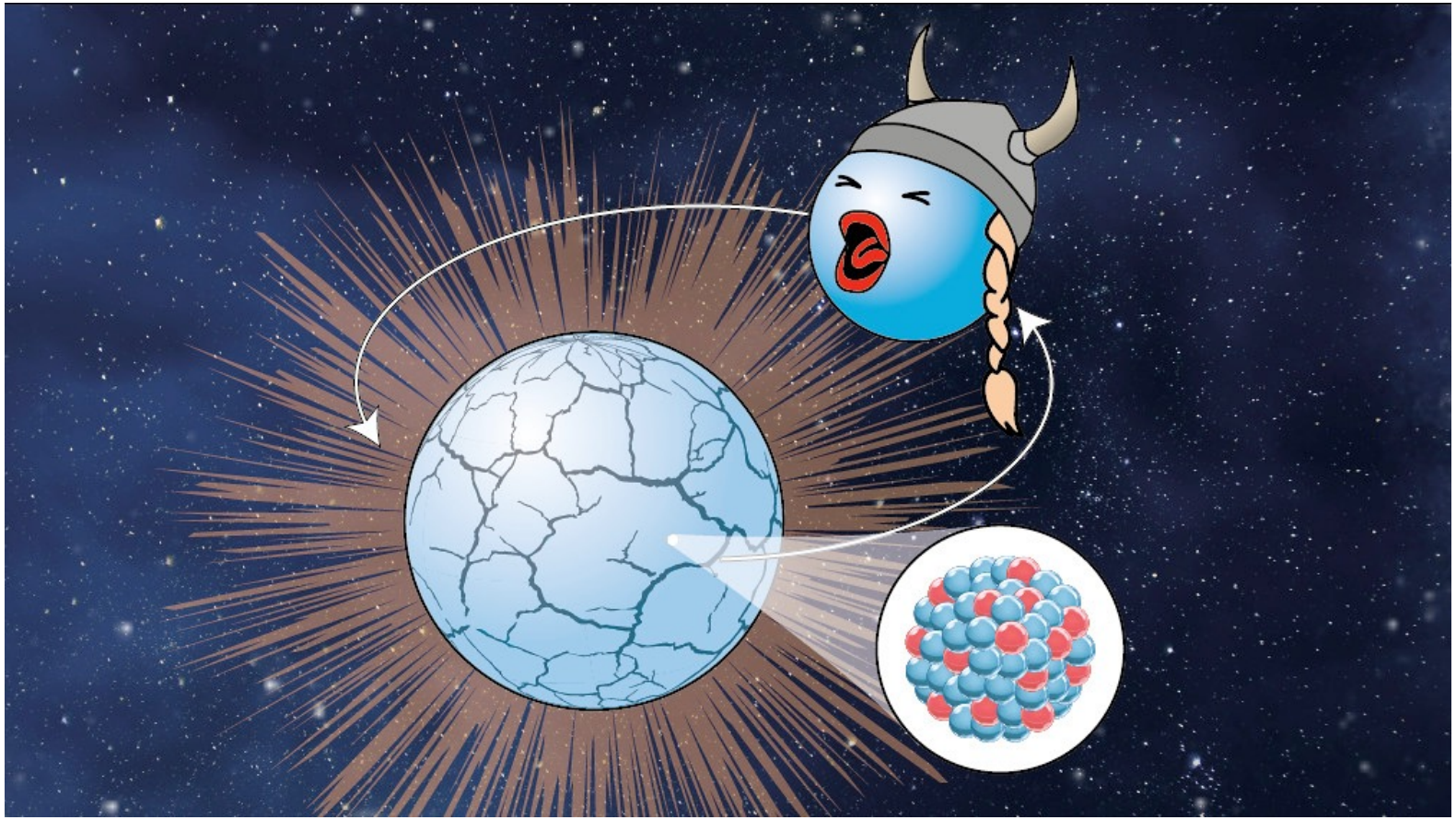
specific model: LLPR 1985

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

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

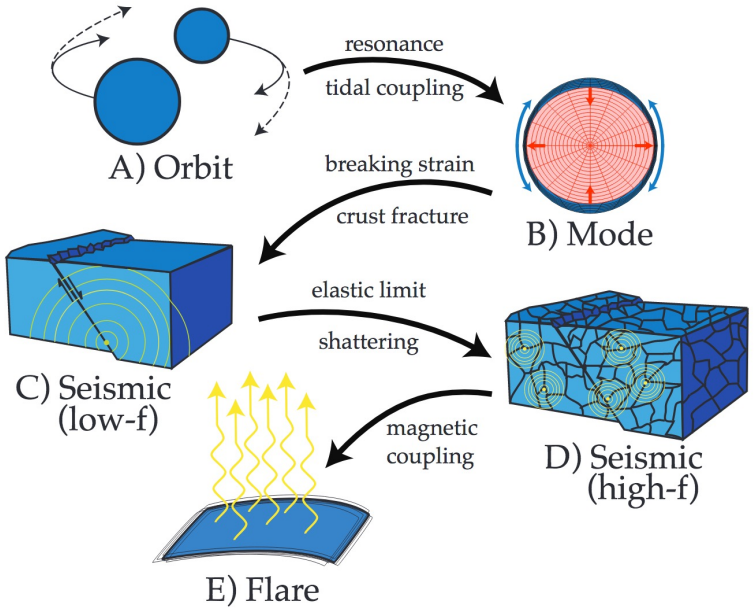
Application: resonant crust-shattering flares

Neill, Newton & Tsang, MNRAS 504, 2021
Neill,Preston,Newton,Tsang, PRL130, 2022
Neill, Tsang, Newton, MNRAS 532, 1, 827



Picture: David Tsang

The elastic crust can be made to resonantly vibrate by the tidal field of its companion – something we can potentially measure!



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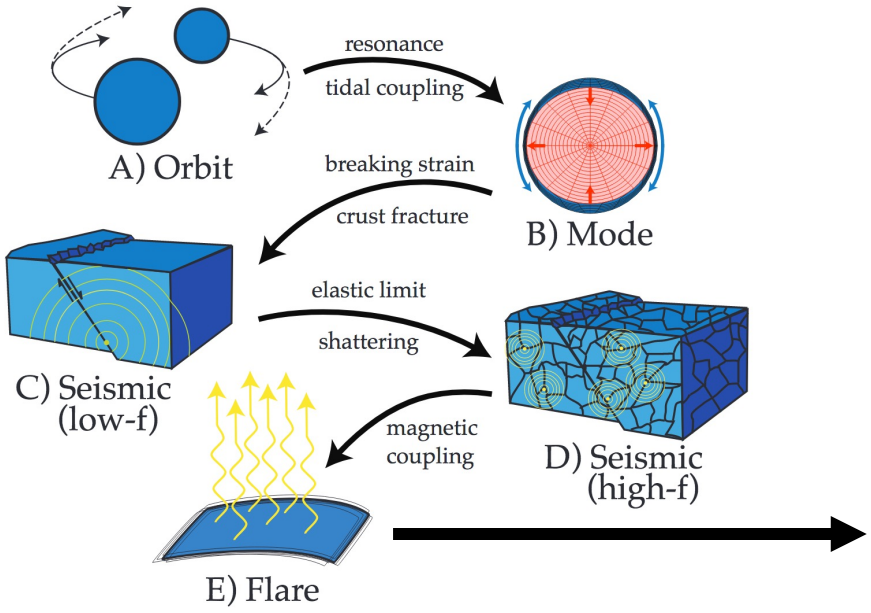

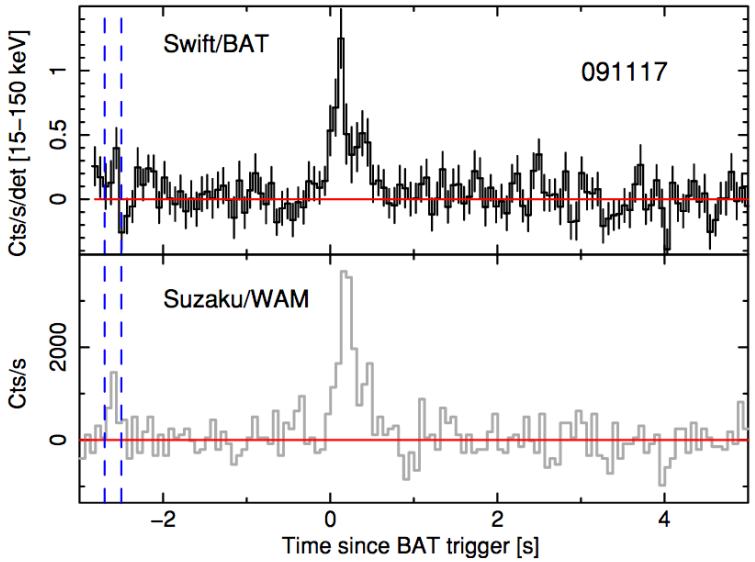

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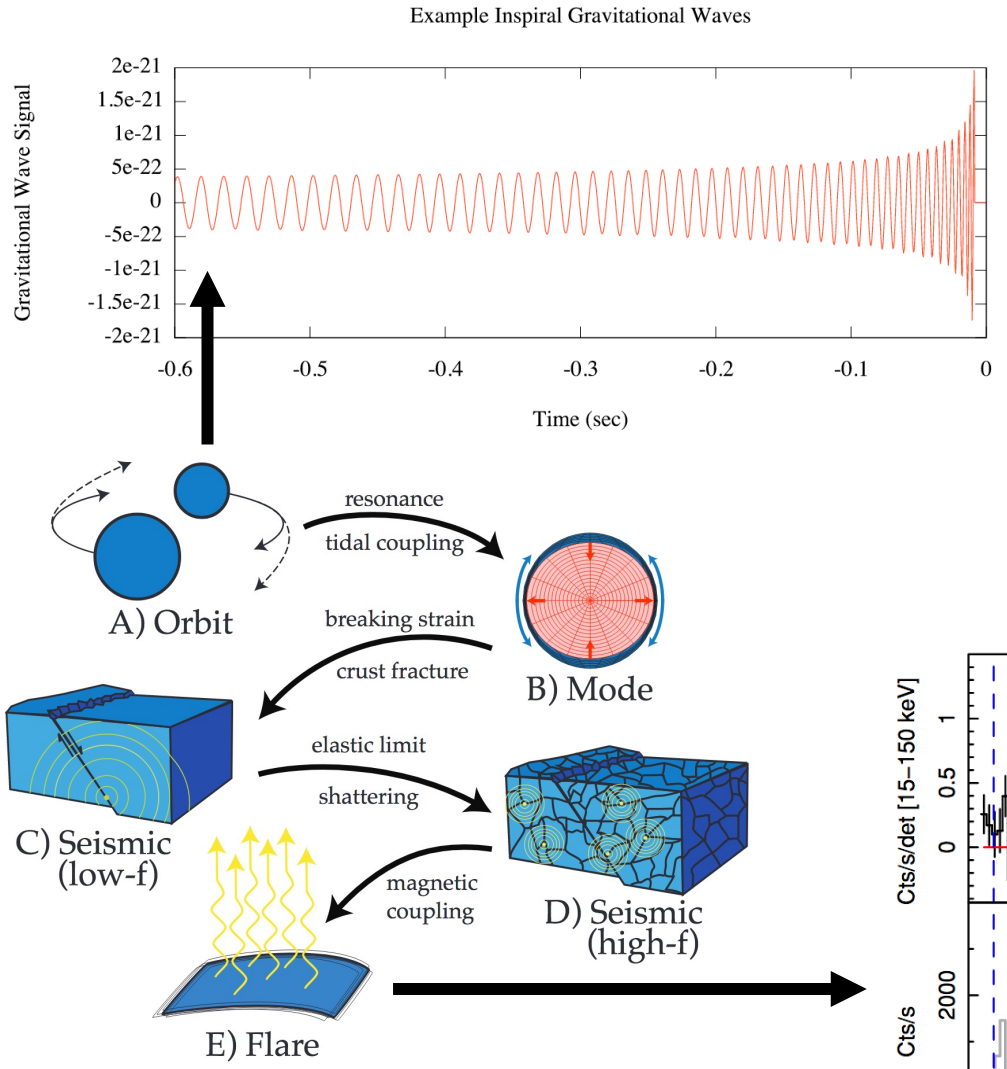

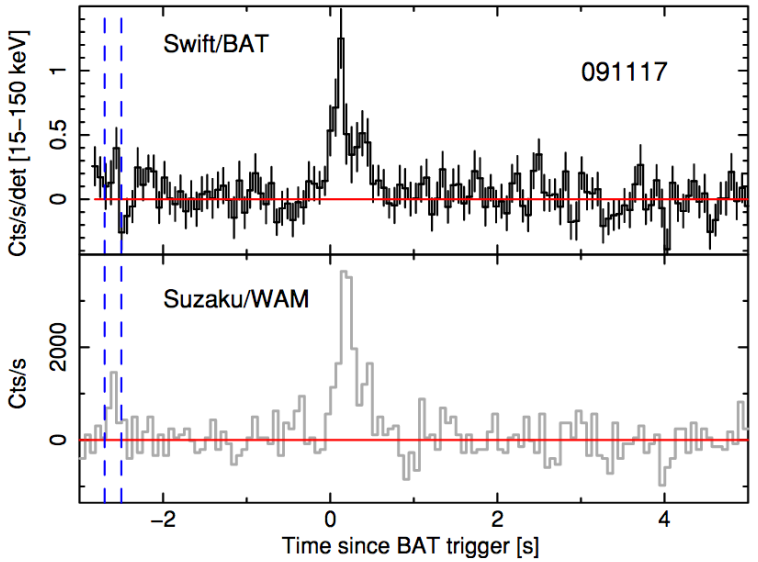

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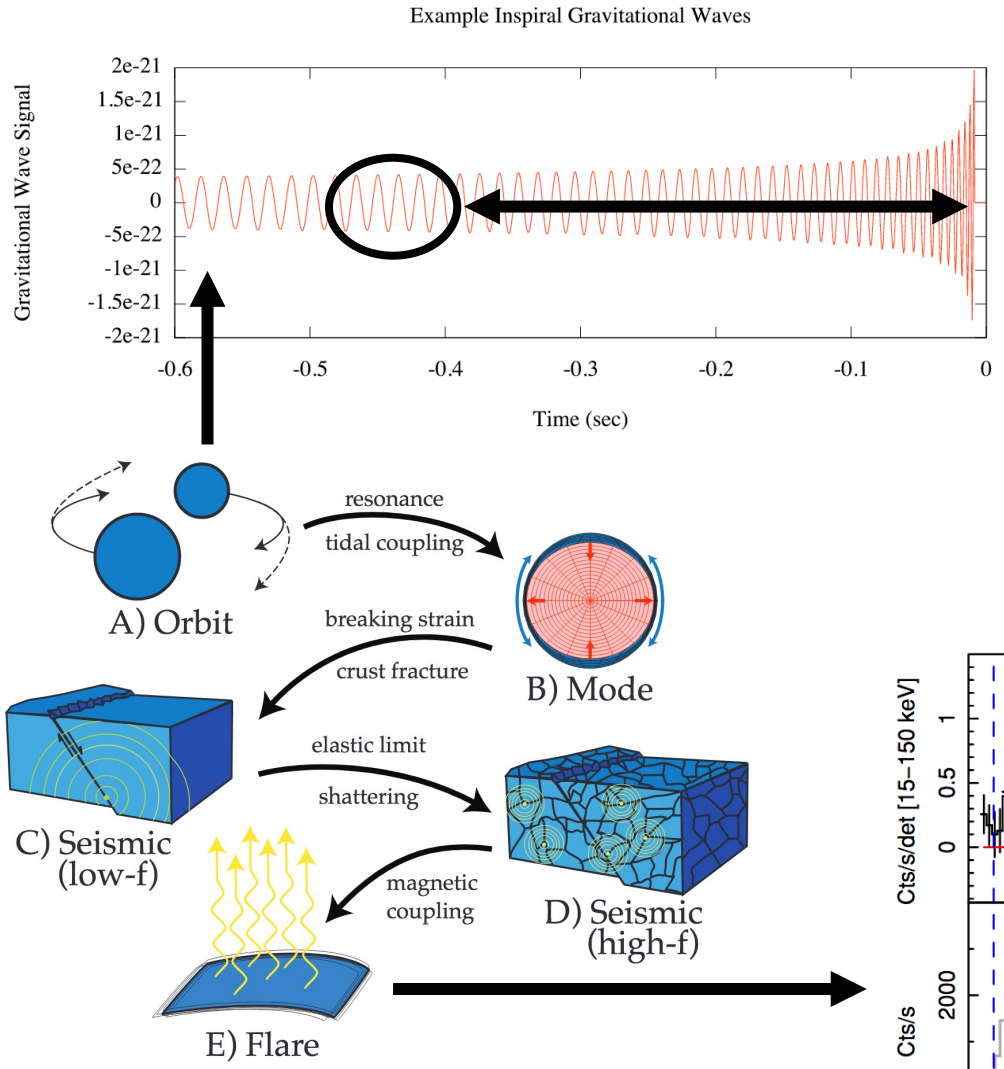

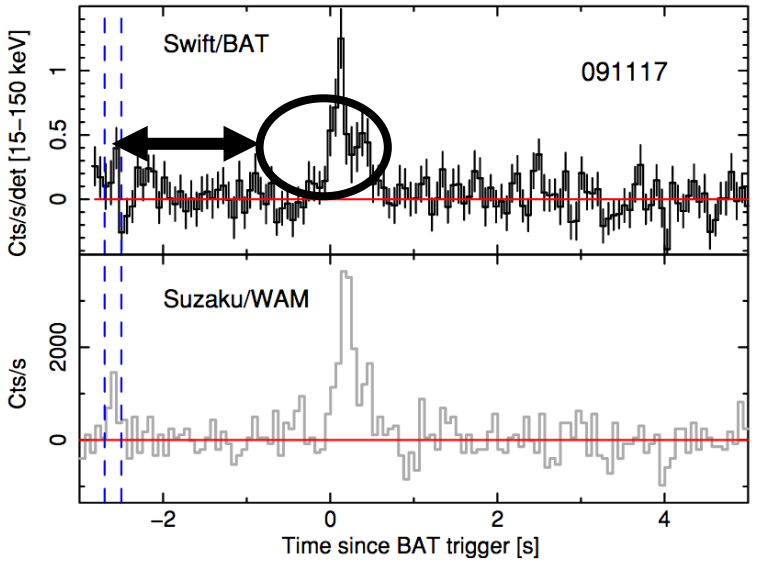

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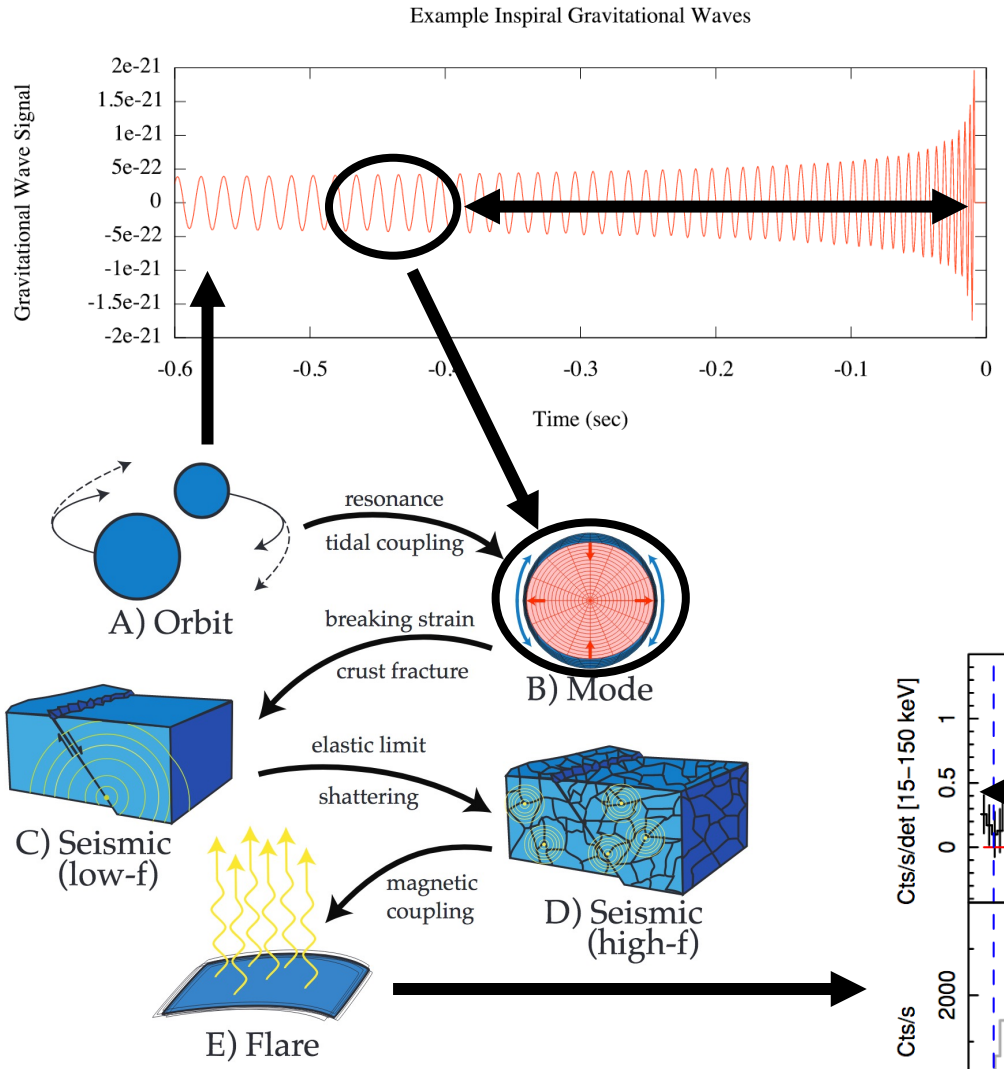

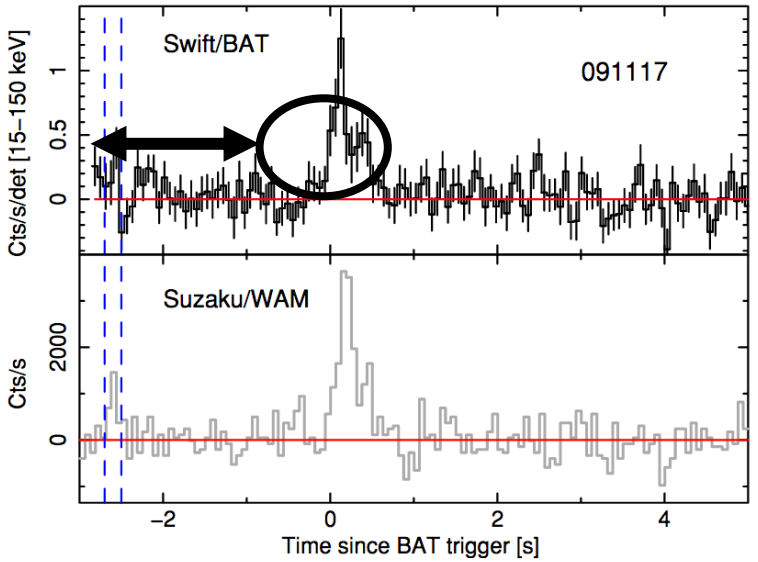

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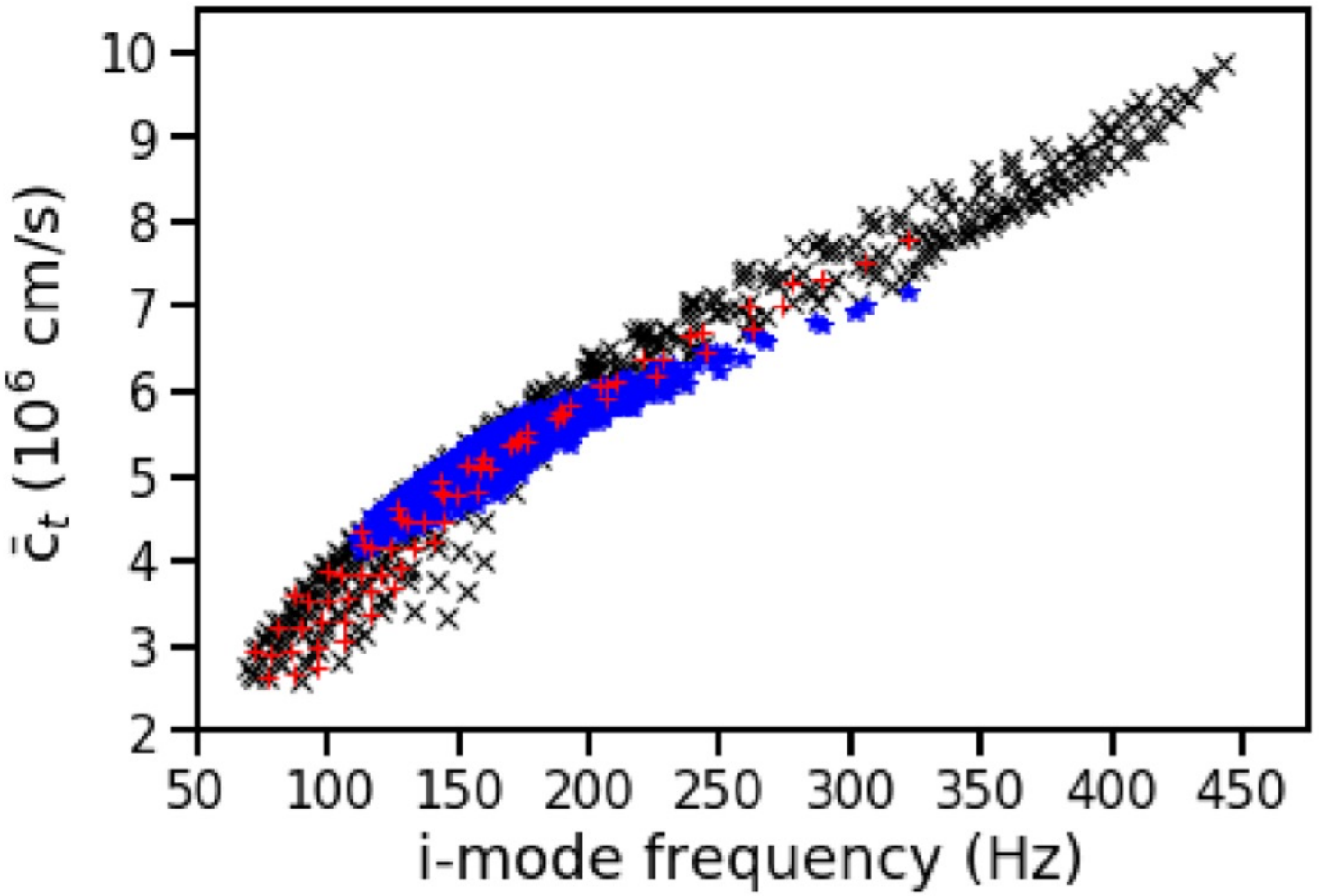
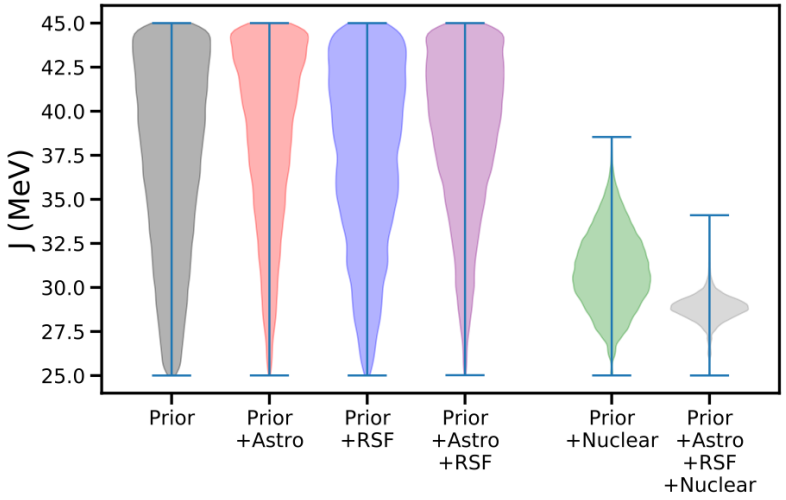
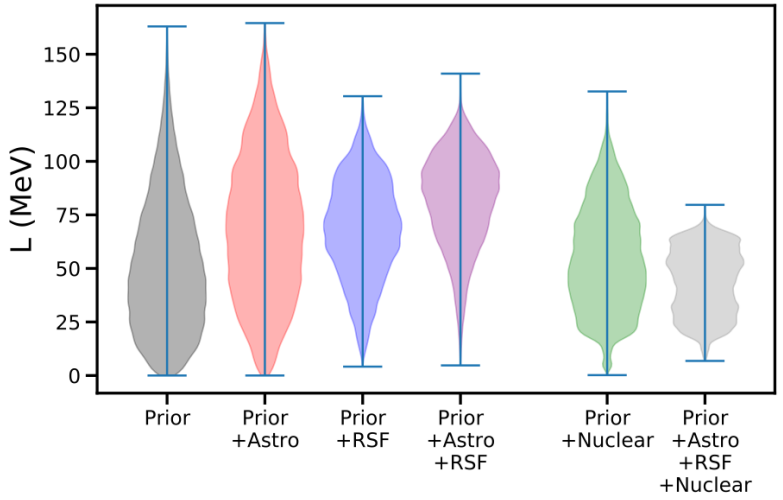
Strong correlation between shear speed and *i*-mode frequency

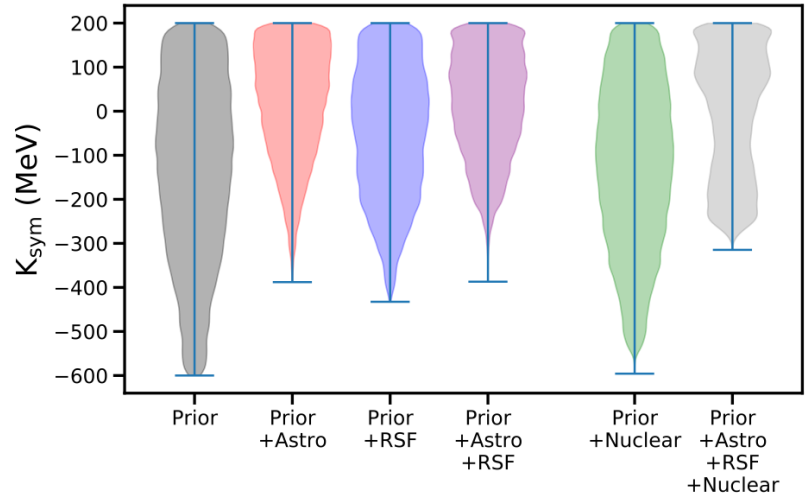


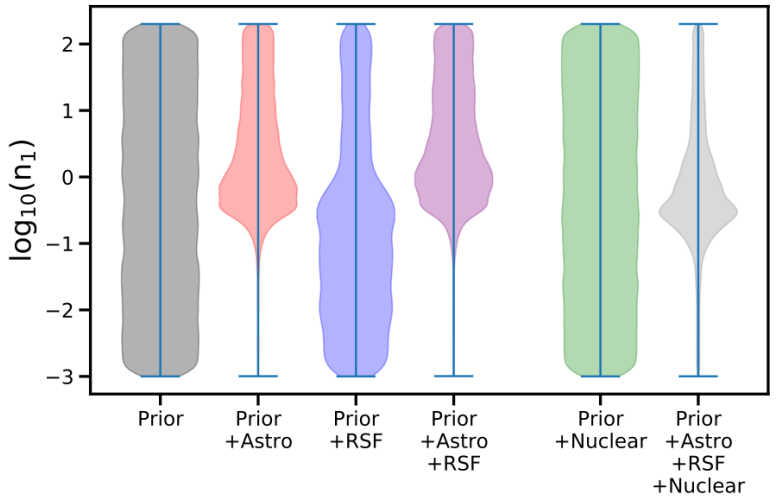
Neill, Newton & Tsang, MNRAS 504, 2021

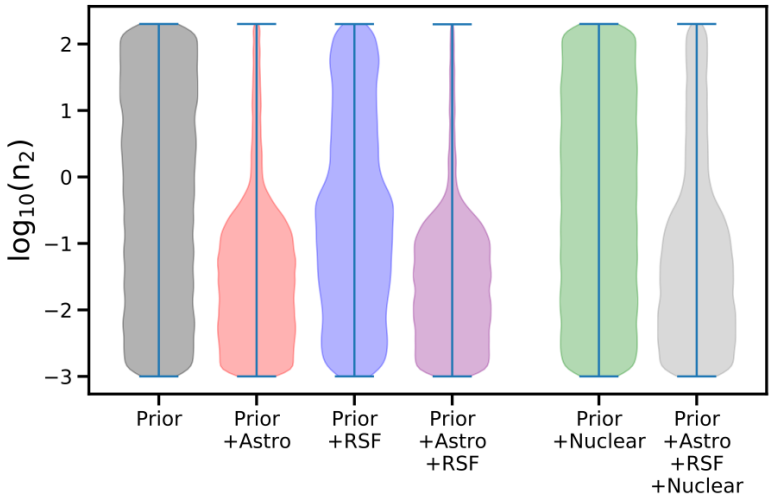
Inference using a synthetic detection of an RSF at a frequency of 250 Hz, comparison with Nicer-Ligo and nuclear binding energy data











- *J* not constrained by astro
- *L* constrained by nuclear, RSF
- K_{sym} constrained by RSF/NL
- Polytrope parameters constrained by NL

Take-aways:

- Many nuclear physics observables have a say on the behavior of the EOS in the crust up to $2n_{sat}$
- Communities need to communicate!
- Many systematic errors, good news: some of them aren't *terribly* hard to address
- And we need to address them before next gen experiments/observatories
- Inconsistent neutron star crust!
  - Systematic error in radius up to 0.5km
  - Bring crust observables into play
- L, K_{sym} are sensitive to astrophysical observables from crust to core, even when inner core non-nucleonic
- During a neutron star merger, the stars may resonantly excite each other's solid crust to shattering
- We can harness multi-messenger observations to test this and potentially measure the material properties of neutron star crusts