# Multi-messenger nuclear & astrophysics with added crust

William G. Newton

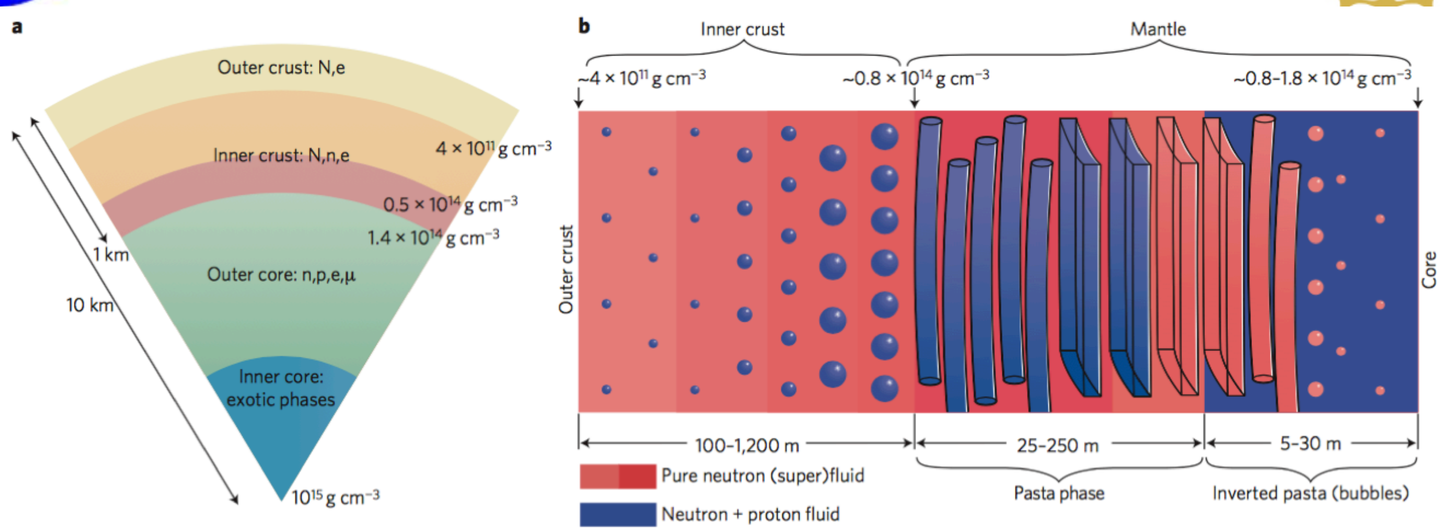
The work presented in this talk would not be possible without an amazing team of undergraduates and Master's students:

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

Jirina Rikovska Stone, Alex Kaltenborn - University of Tennessee



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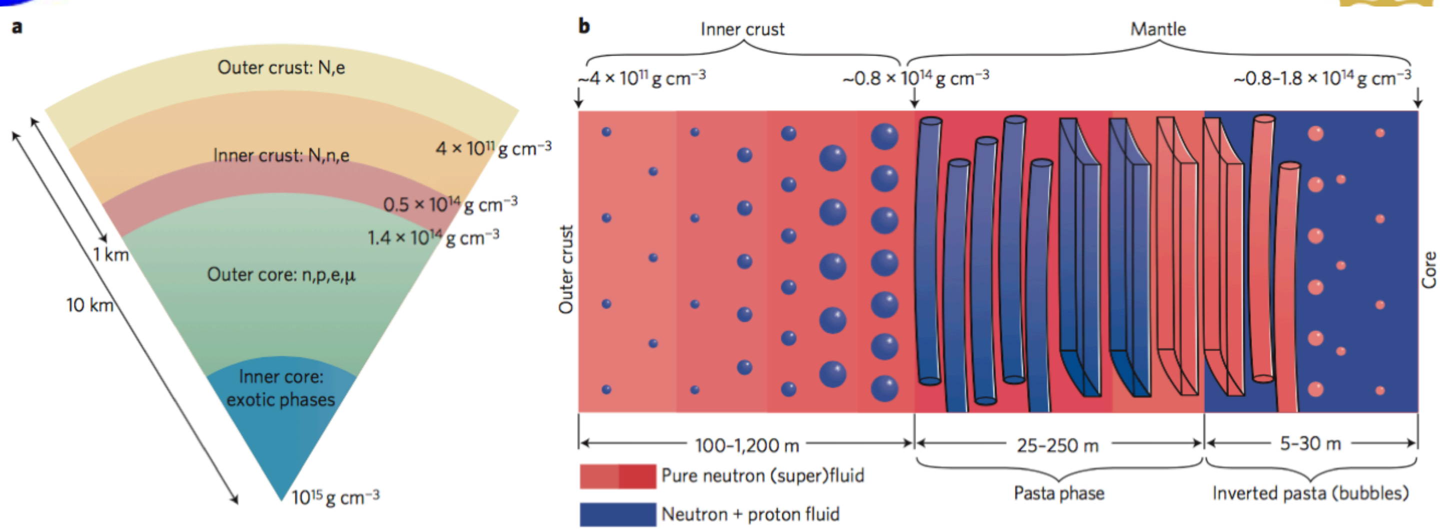

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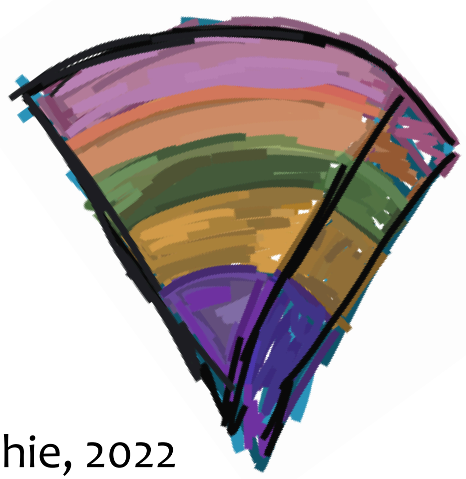
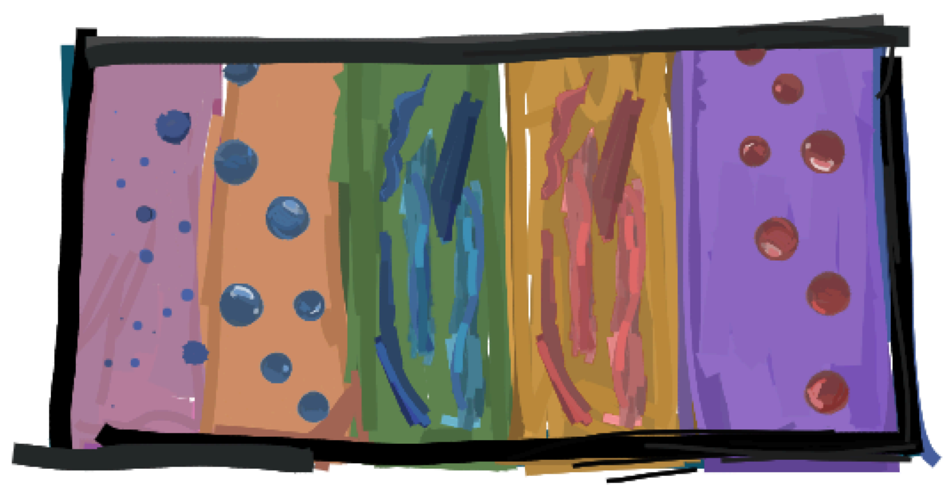
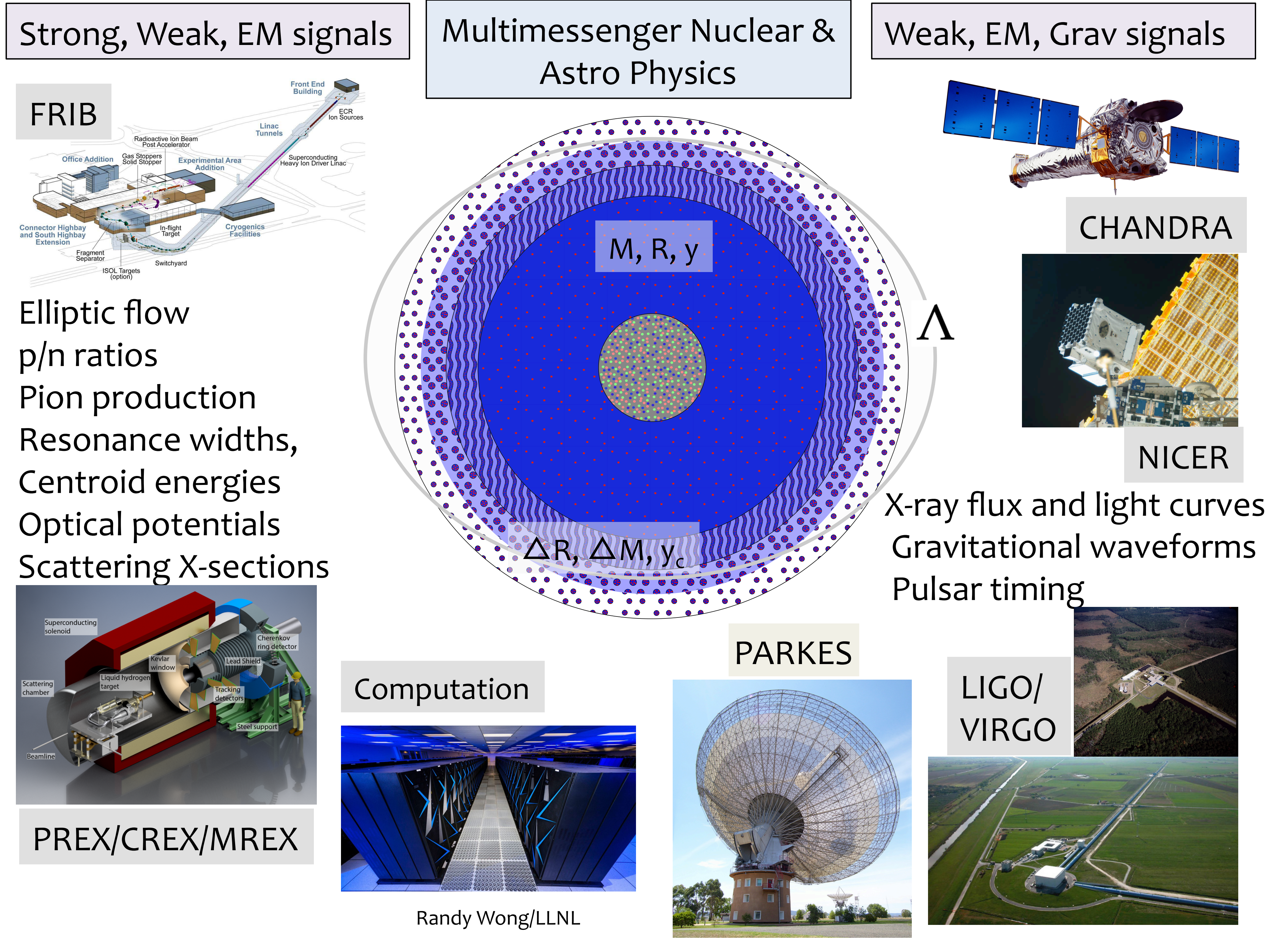




Noa Fritschie, 2022



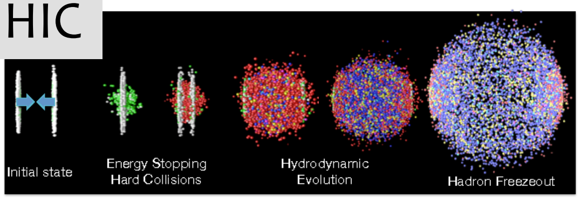
Strong, Weak, EM signals
Multimessenger Nuclear & Astro Physics
Weak, EM, Grav signals
FRIB
Front End Building
ECR Ion Sources
Linac Tunnels
Radioactive Ion Beam Post Accelerator
Superconducting Heavy Ion Driver Linac
Office Addition
Gas Stoppers Solid Stopper
Experimental Area Addition
Connector Highbay and South Highbay Extension
In-flight Target
Cryogenics Facilities
Fragment Separator
ISOL Targets (option)
Switchyard
Elliptic flow
p/n ratios
Pion production
Resonance widths,
Centroid energies
Optical potentials
Scattering X-sections
M, R, y
ΔR, ΔM, $y_c$
Λ
CHANDRA
NICER
X-ray flux and light curves
Gravitational waveforms
Pulsar timing
Superconducting solenoid
Cherenkov ring detector
Kevlar window
Lead Shield
Scattering chamber
Liquid hydrogen target
Tracking detectors
Steel support
Beamline
PREX/CREX/MREX
Computation
Randy Wong/LLNL
PARKES
LIGO/ VIRGO

# Nuclear structure/ dynamics

# Multimessenger Nuclear & Astro Physics

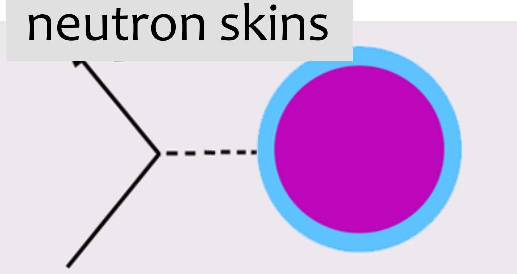
# Neutron star structure/ dynamics

## HIC

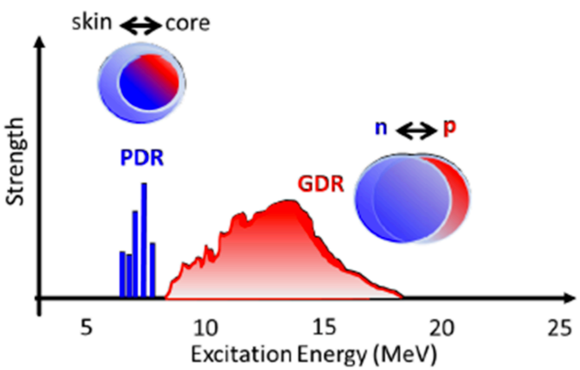



T.K.Nayak, arxiv:1201.4264

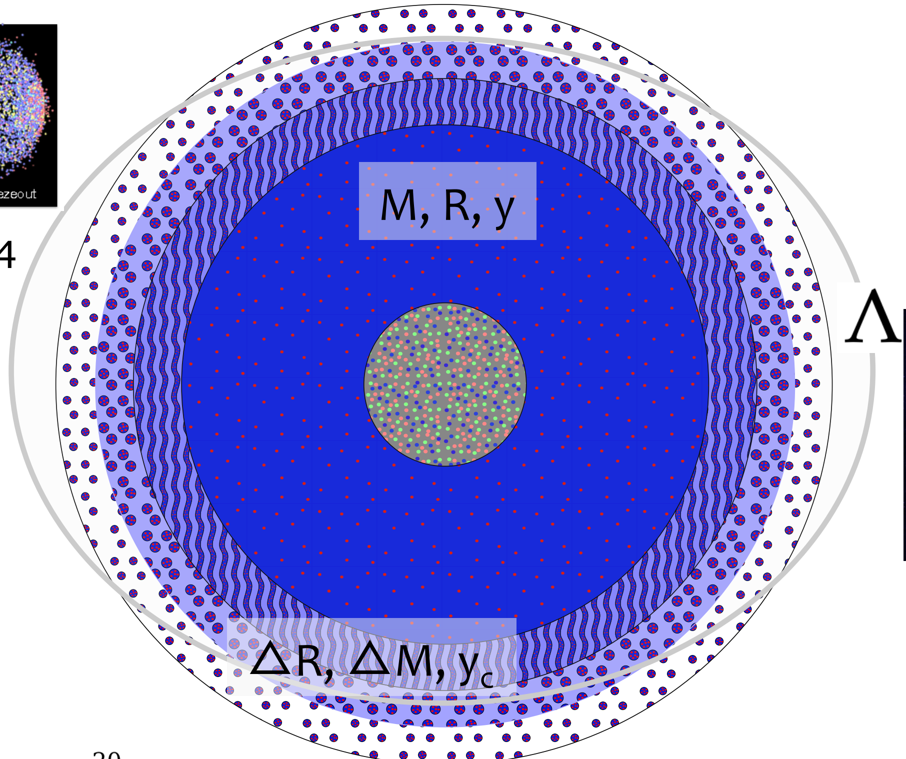
## neutron skins

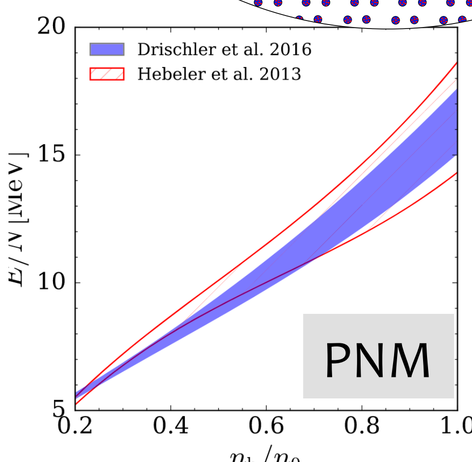


Abrahamyan+,
PRL 108, 112592 (2012)



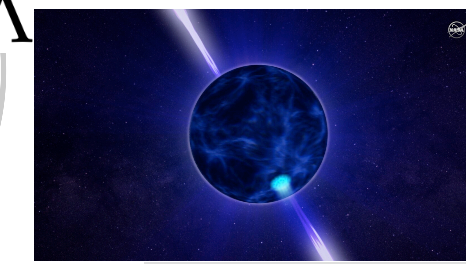

Bracco, Lanza, Tamii,
PPNP 106, 360 (2019)



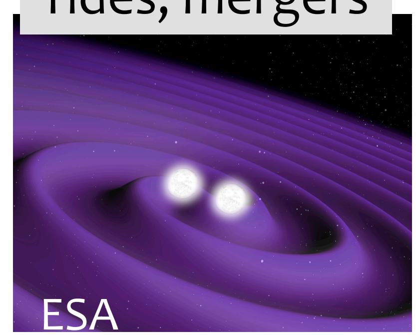




Haensel, Fortin JPhysG 2017

## Glitches, flares, cooling

## Tides, mergers




## Hot spots Oscillations, Crust cooling

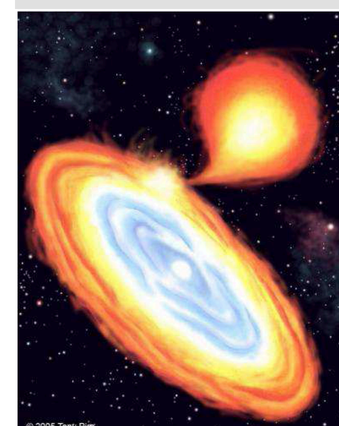
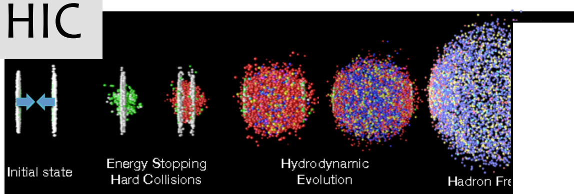



Figure: Artist's impression of a LMXB - credit Tony Piro, 2005.

# Multimessenger Nuclear & Astro Physics

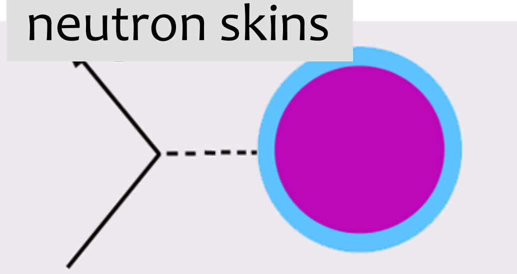
## Nuclear structure/ dynamics

### HIC




T.K.Nayak, arxiv:1201.426

### neutron skins



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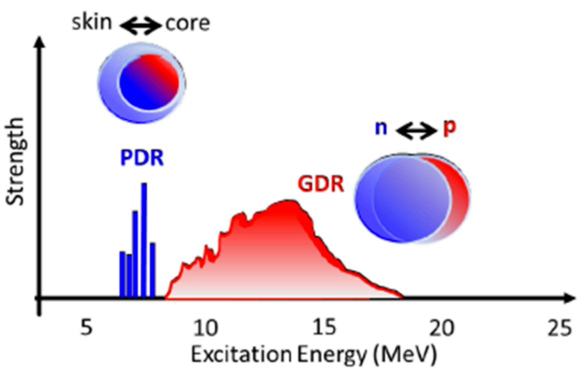
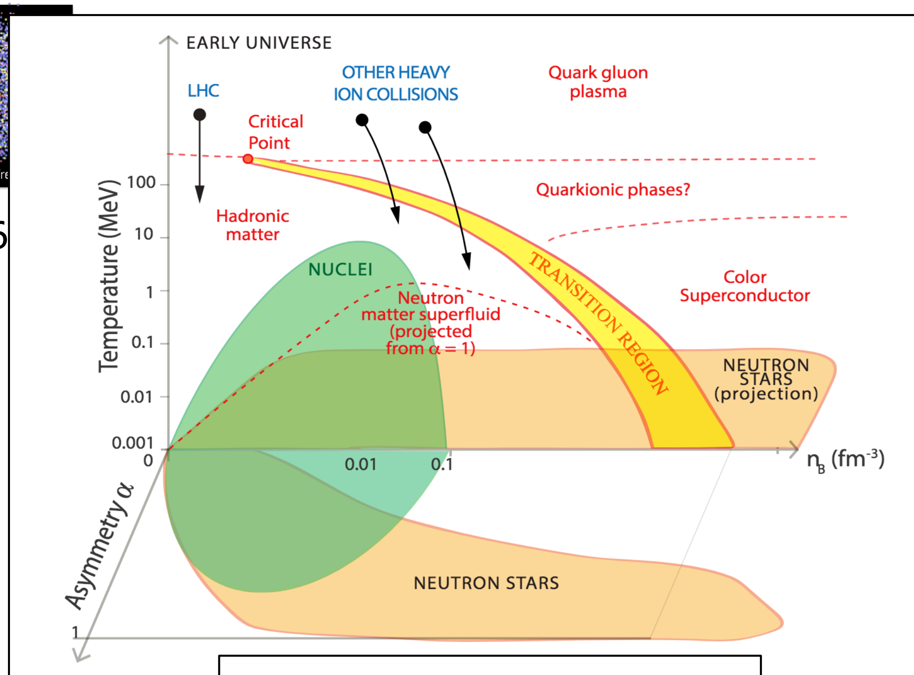
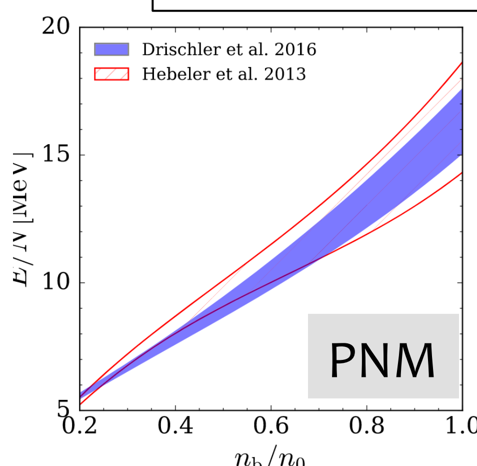



Bracco, Lanza, Tamii,
PPNP 106, 360 (2019)



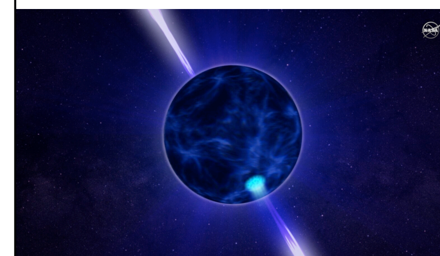

Watts et al arxiv:1501.00042




Haensel, Fortin JPhysG 2017

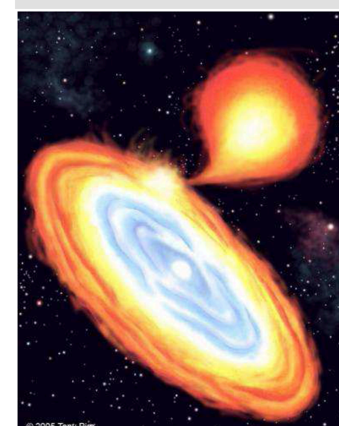
## Neutron star structure/ dynamics

### Glitches, flares, cooling

### Tides, mergers


### Hot spots Oscillations, Crust cooling

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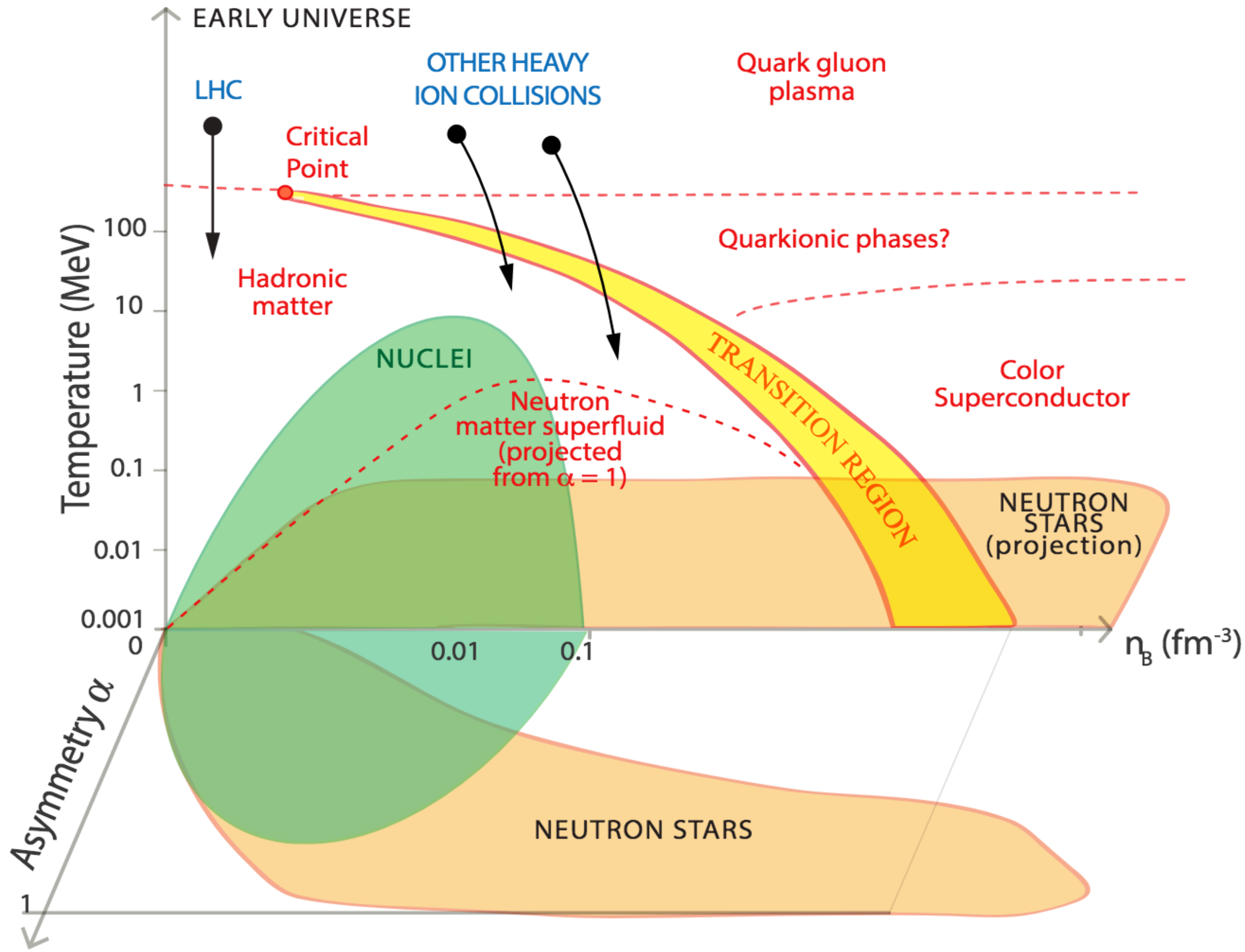
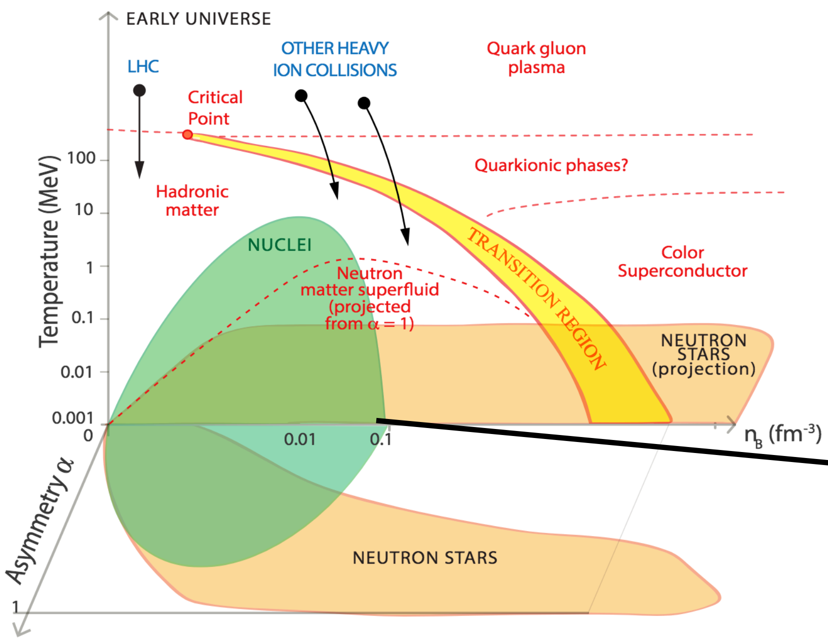
# The phase diagram of nuclear matter




Watts et al arxiv:1501.00042

# The phase diagram of nuclear matter to the EOS




Watts et al arxiv:1501.00042

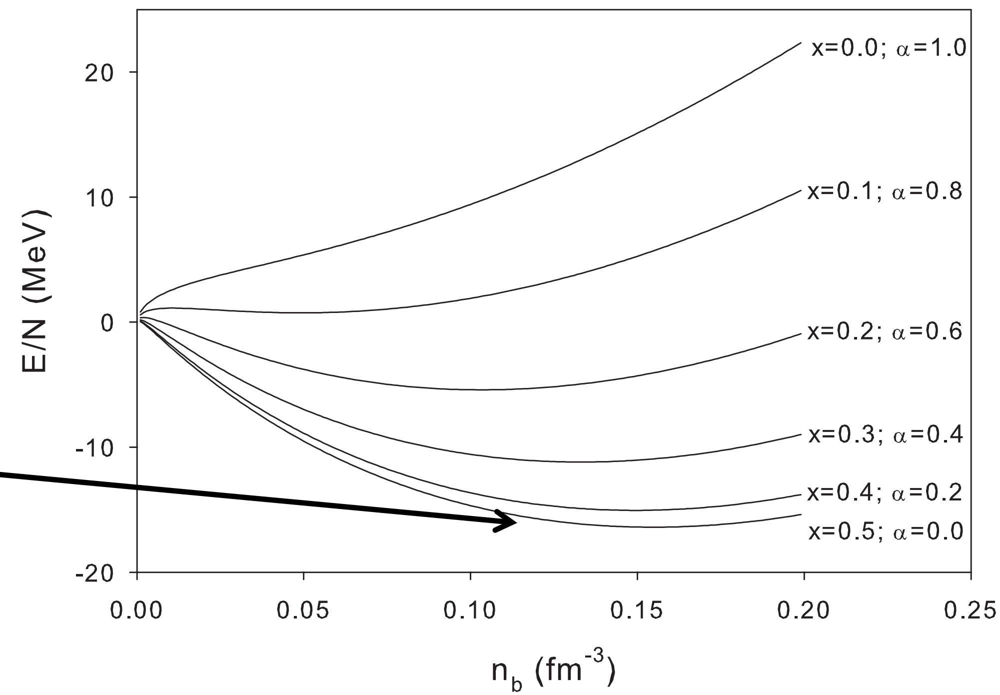
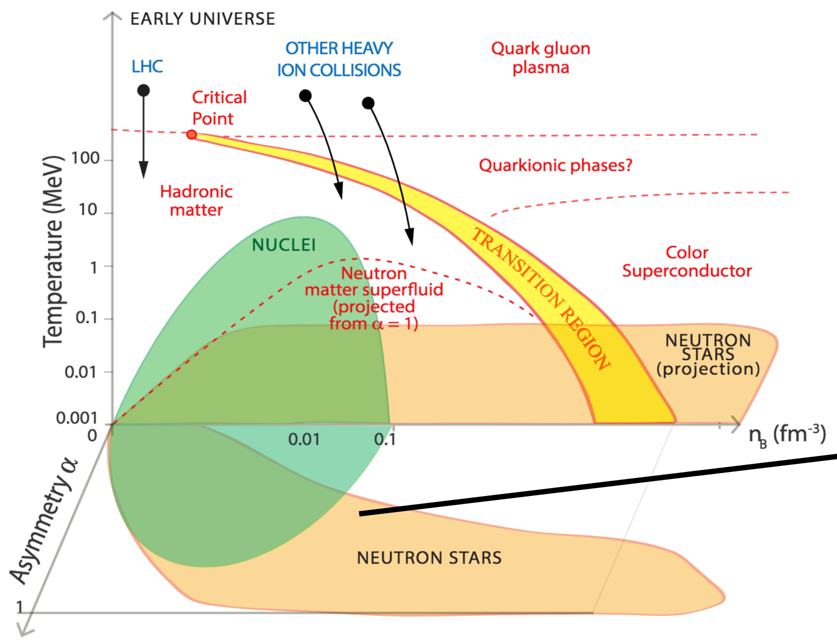
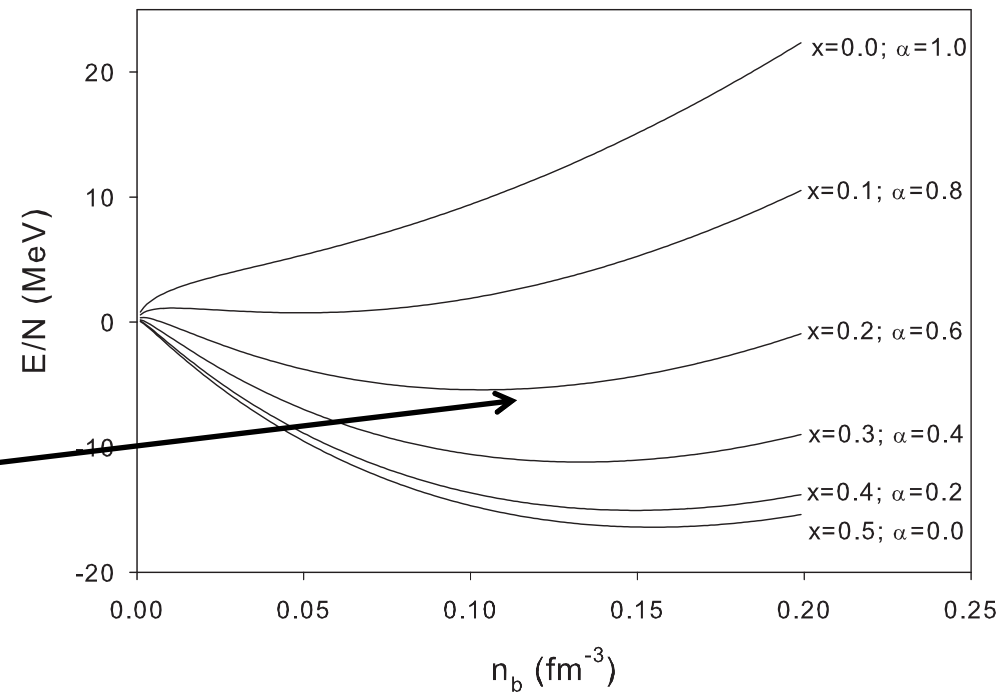



Figure: Lauren Balliet

# The phase diagram of nuclear matter to the EOS




Watts et al arxiv:1501.00042

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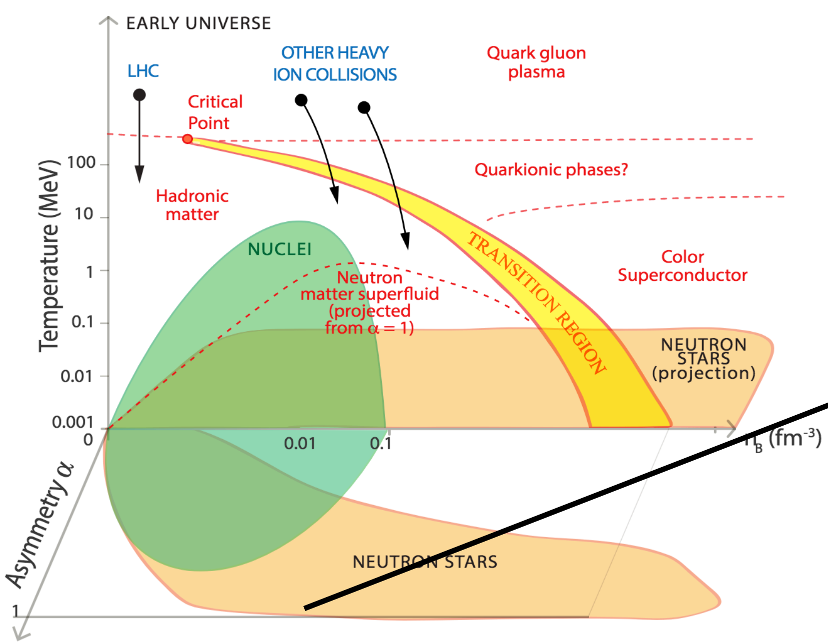


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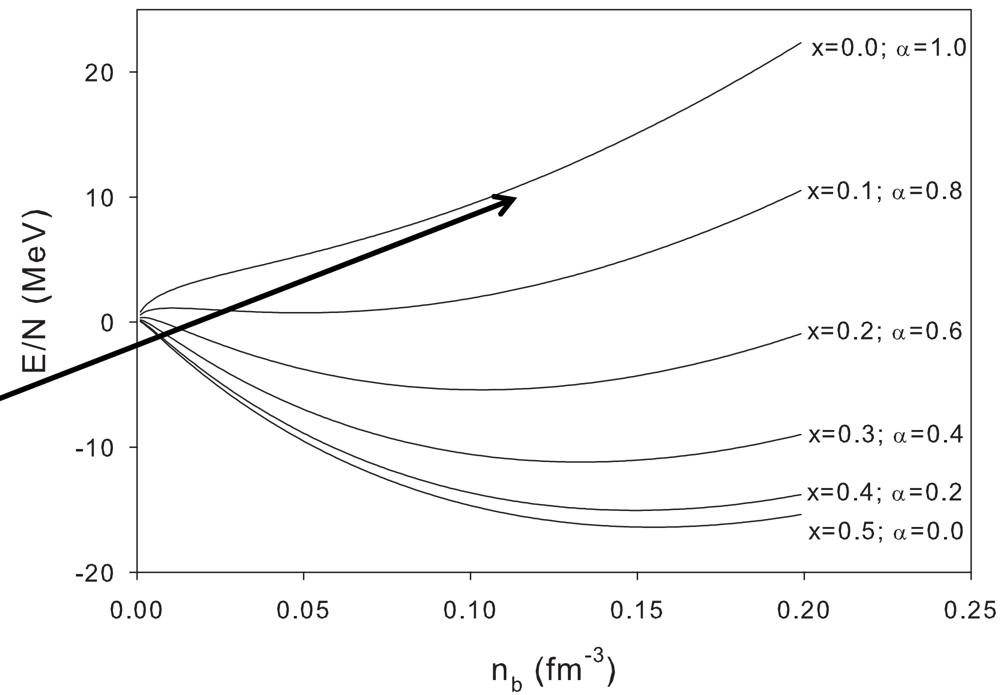


Figure: Lauren Balliet

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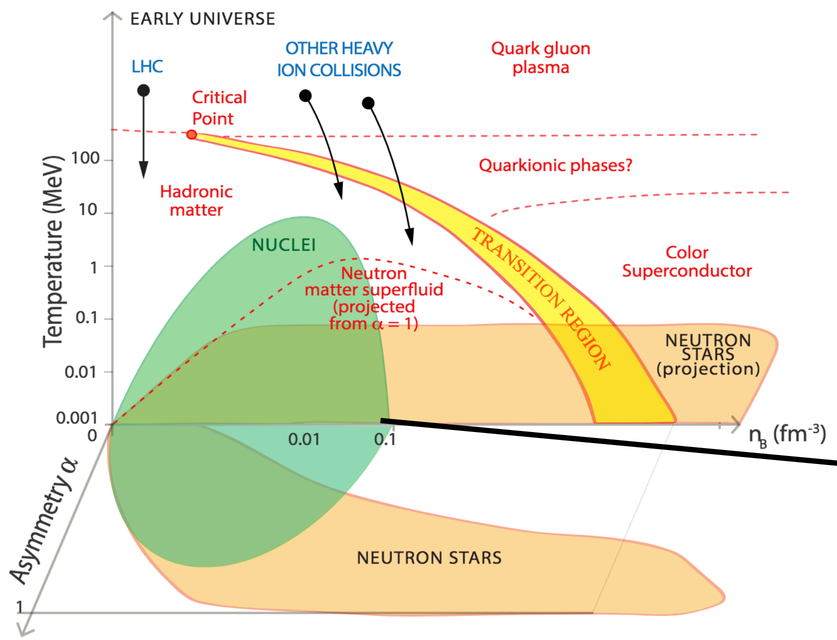


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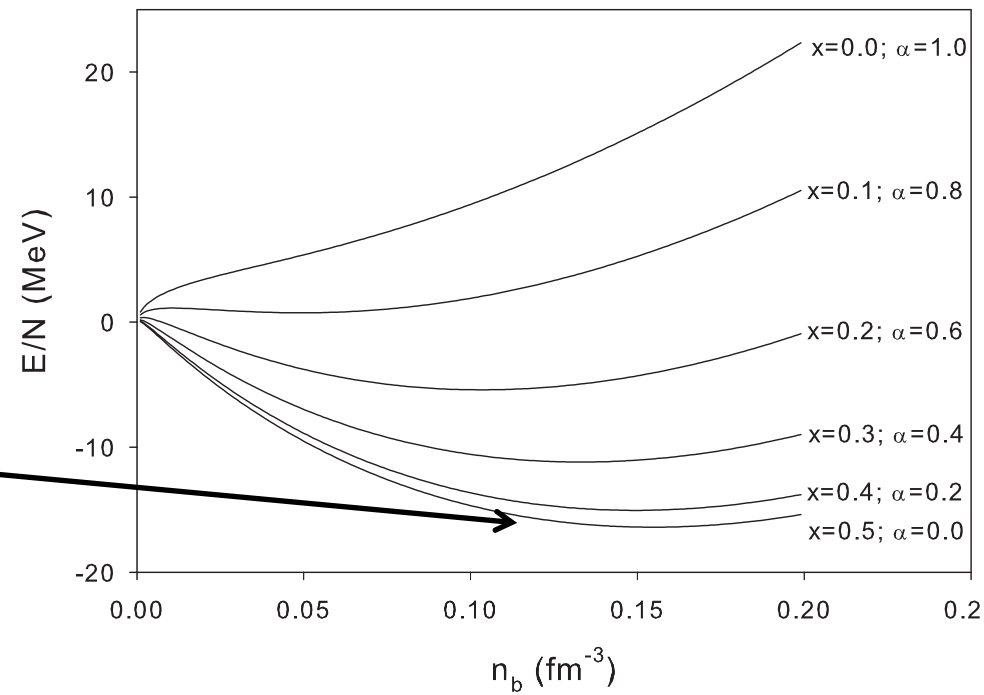
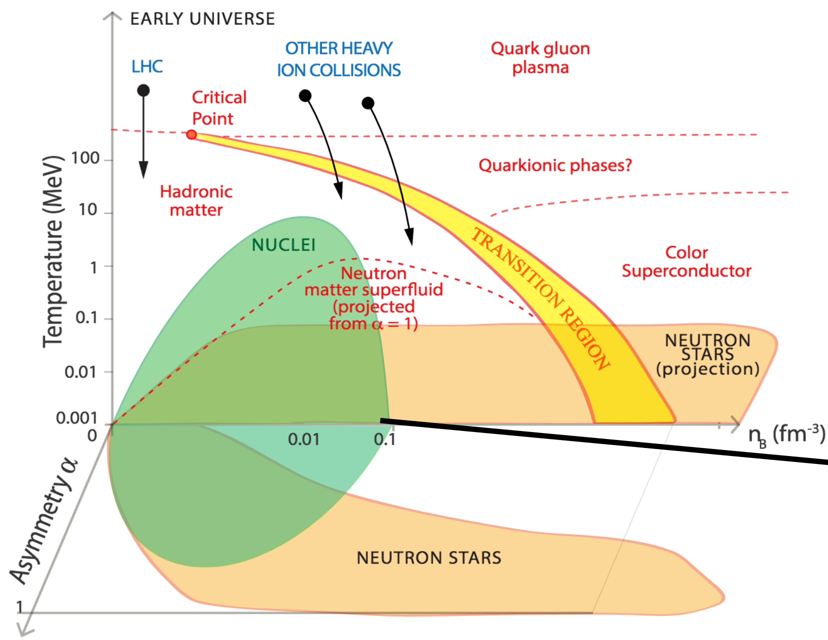



Figure: Lauren Balliet

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

# The phase diagram of nuclear matter to the EOS

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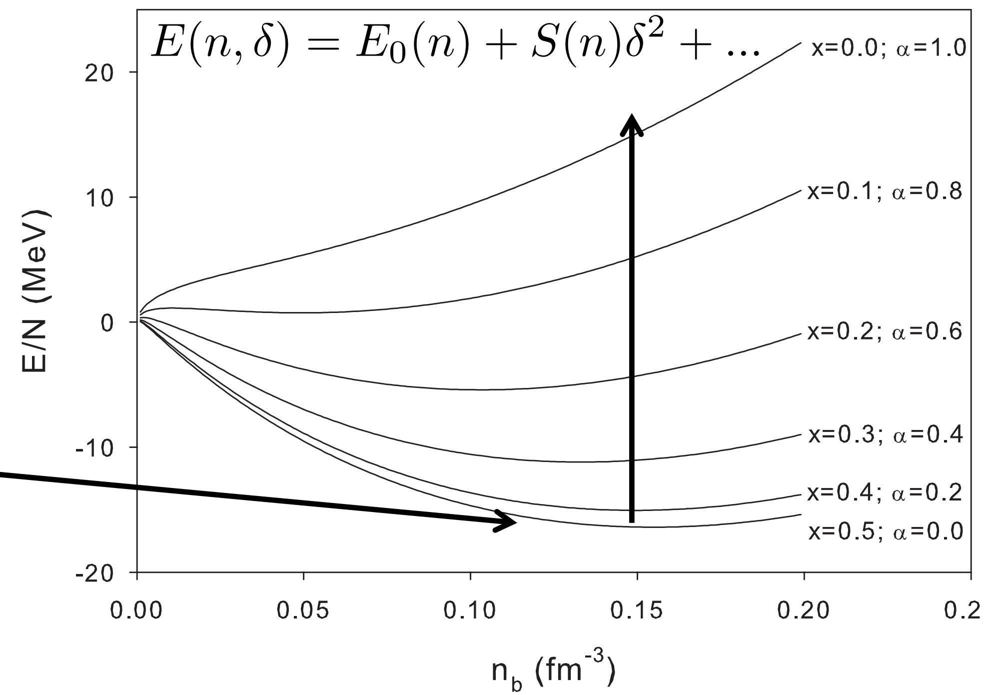


Figure: Lauren Balliet

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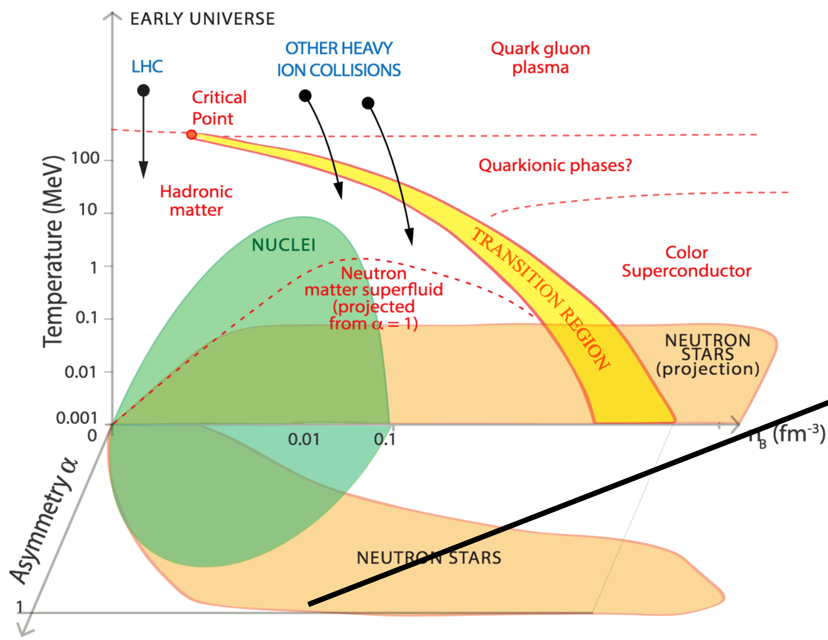
# The phase diagram of nuclear matter to the EOS

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




Watts et al arxiv:1501.00042

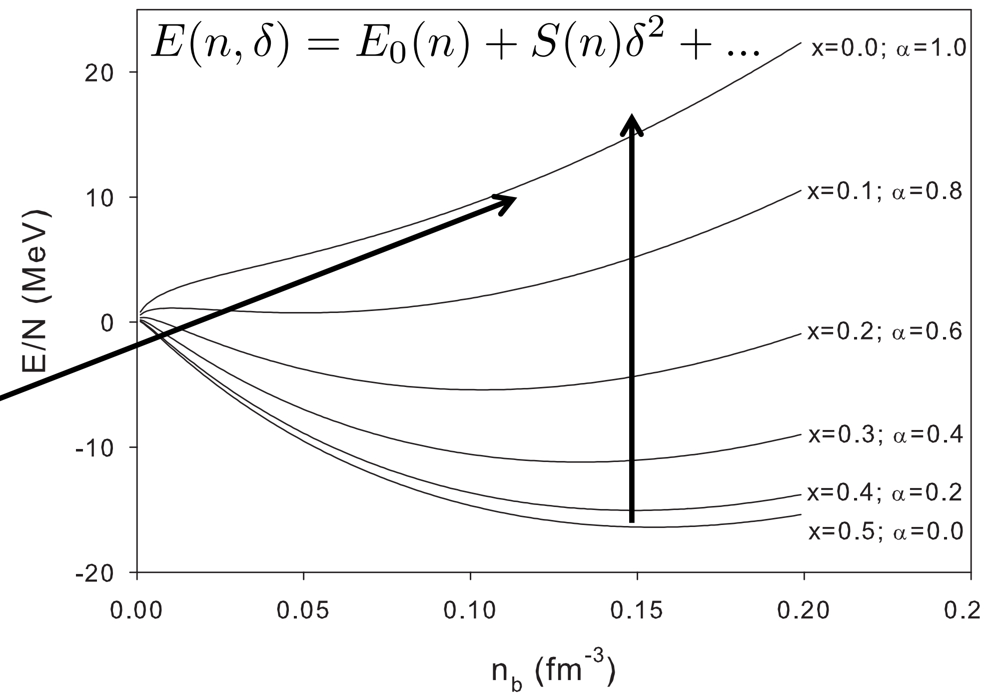


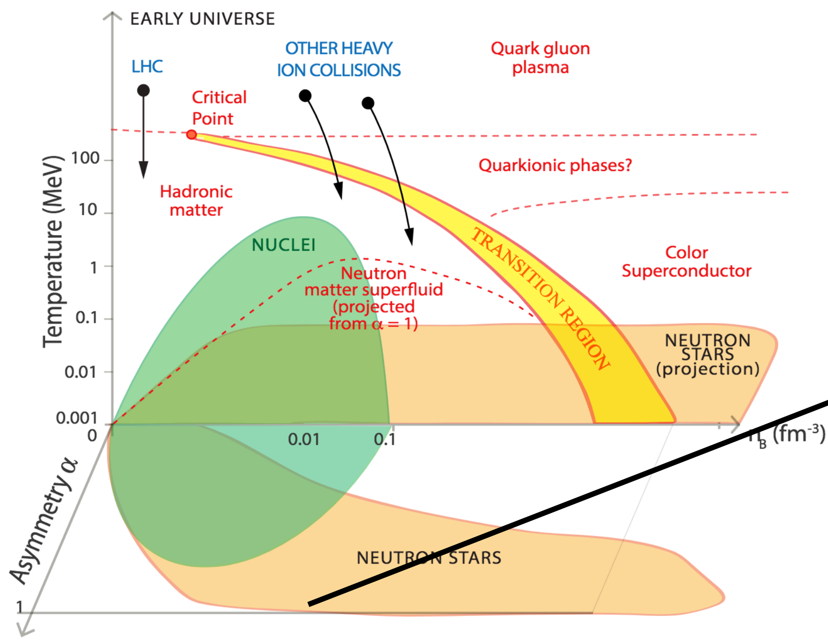

Figure: Lauren Balliet

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

Li, arxiv:2105.04629

# The phase diagram of nuclear matter to the EOS

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




Watts et al arxiv:1501.00042

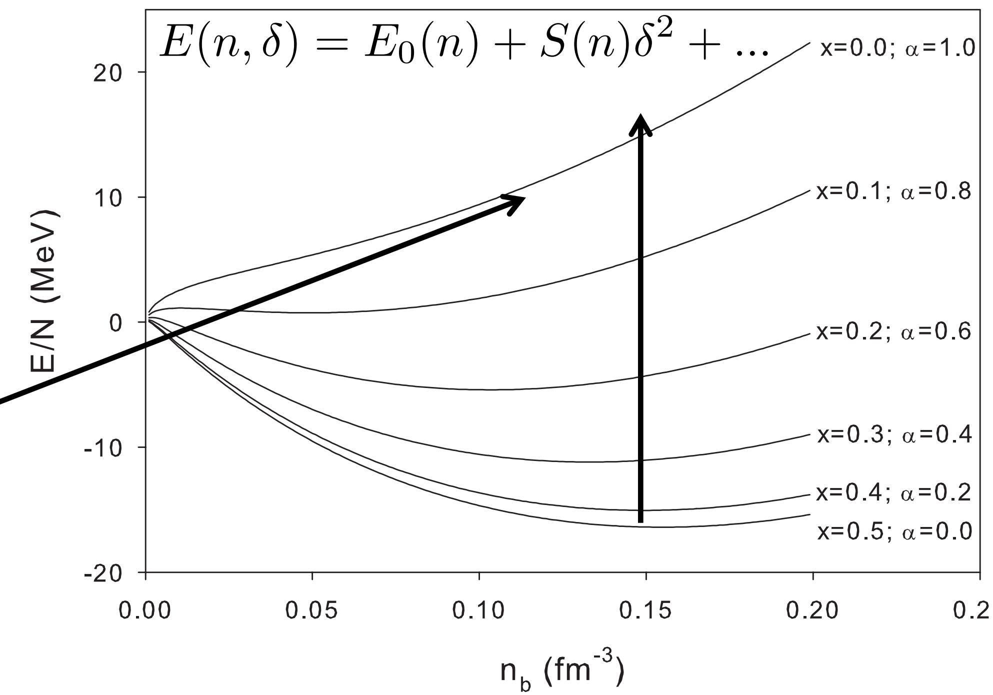



Figure: Lauren Balliet

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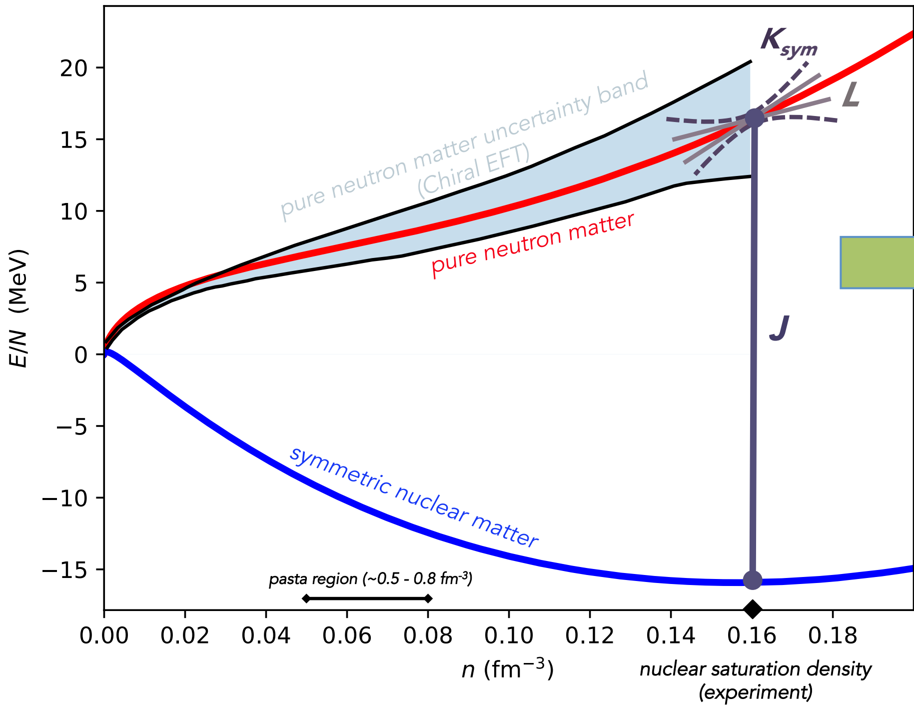
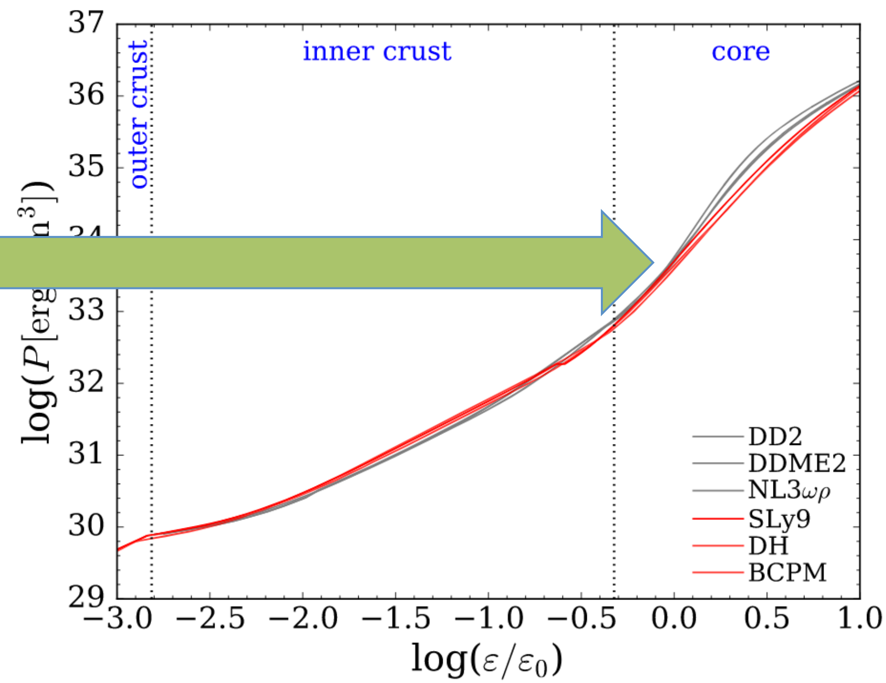
Li, arxiv:2105.04629




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

Lattimer,Prakash; astro-ph/0002232

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

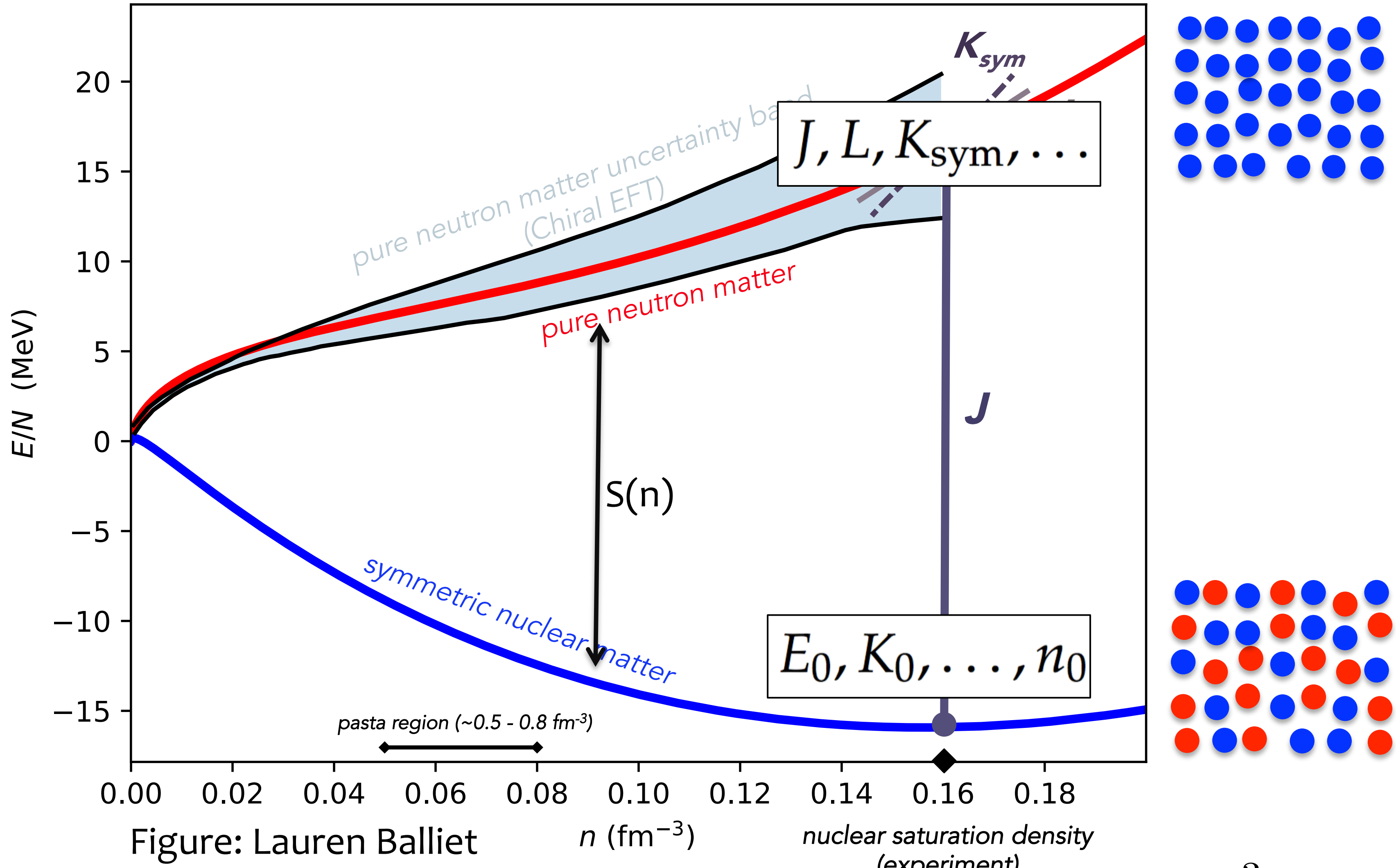



Figure: Lauren Balliet

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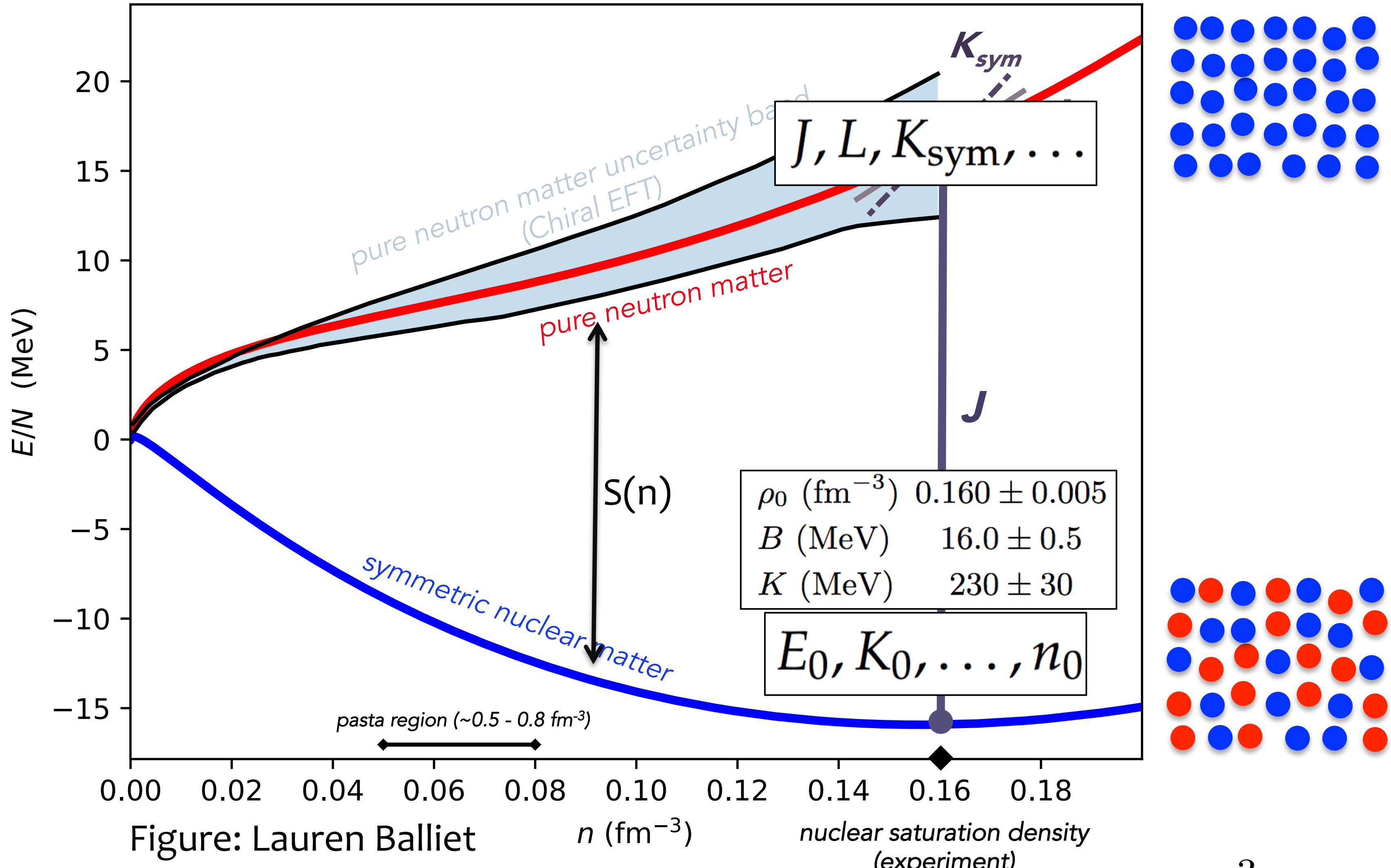
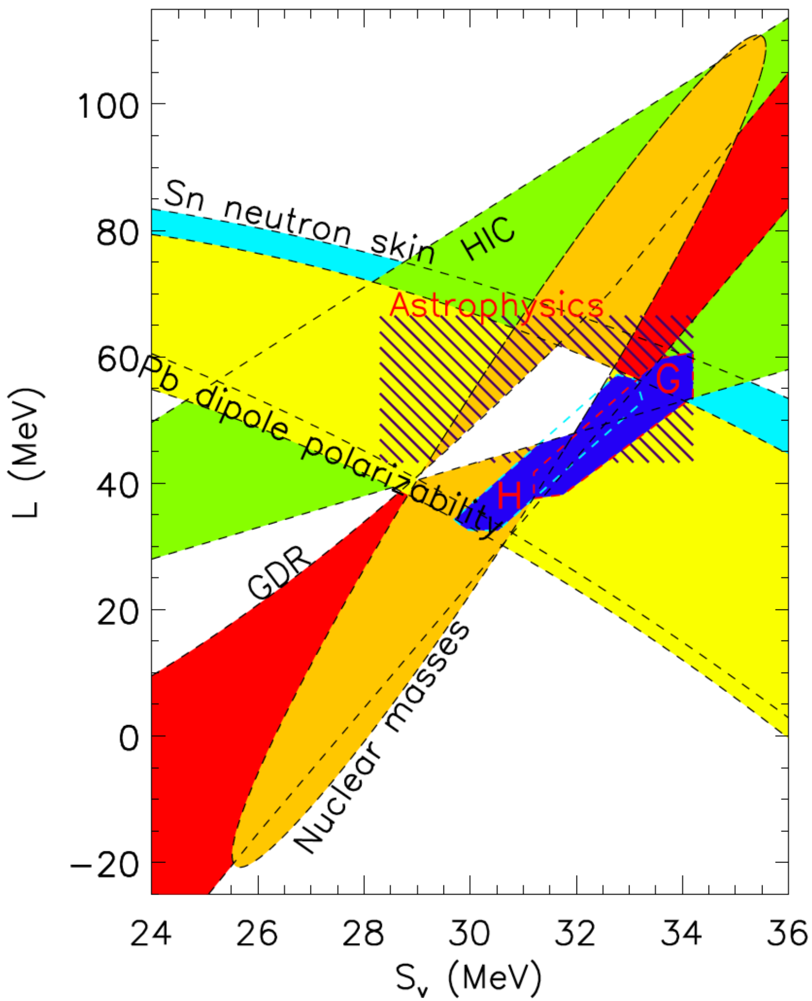



Figure: Lauren Balliet

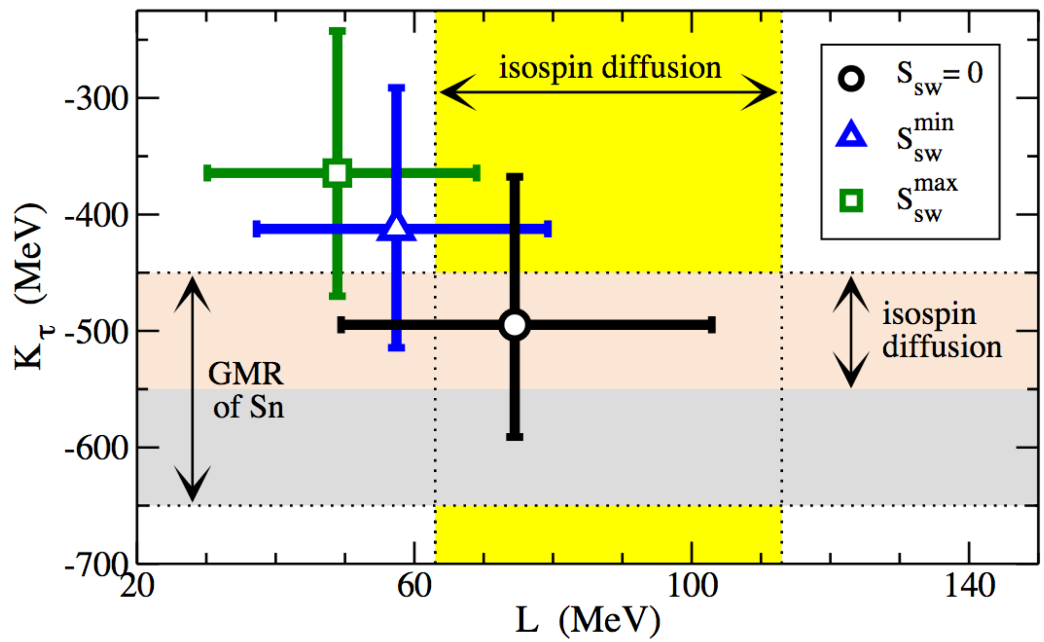
$$P_{\rm NS}(n_0) \approx \frac{n_0}{3} L + 0.048 n_0 \left(\frac{J}{30}\right)^3 \left(J - \frac{4}{3} L\right)$$

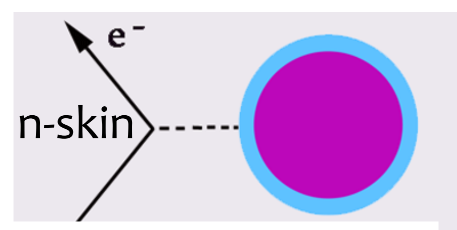
# Symmetry energy constraints

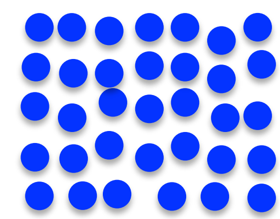
Centelles et al, arxiv:0806.2886



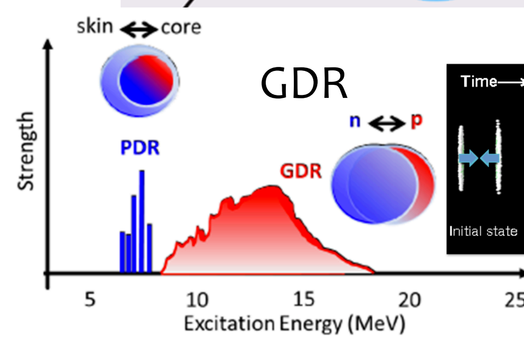

Lattimer, Lim ApJ771(2013)
Lattimer, Steiner EPJA50 (2013)

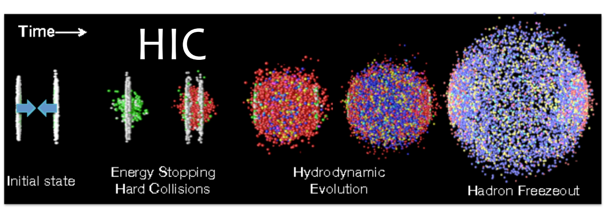


PNM



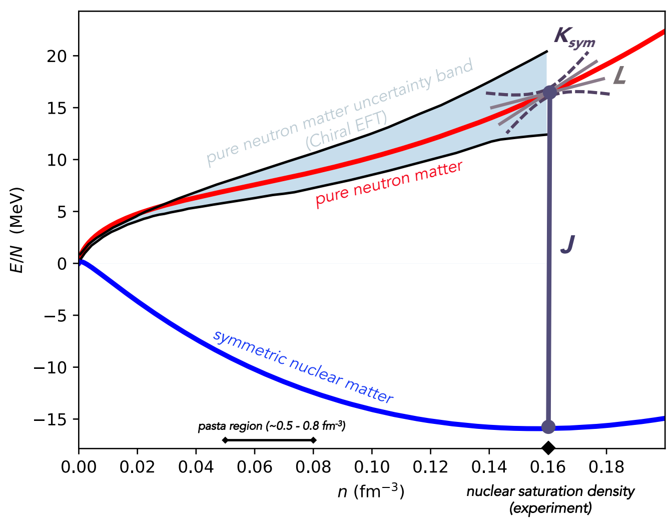
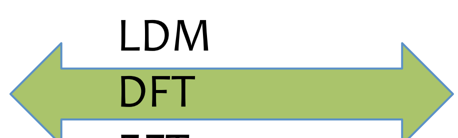
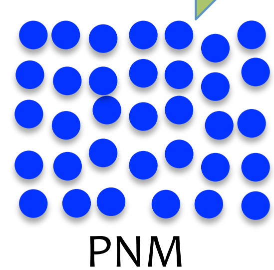
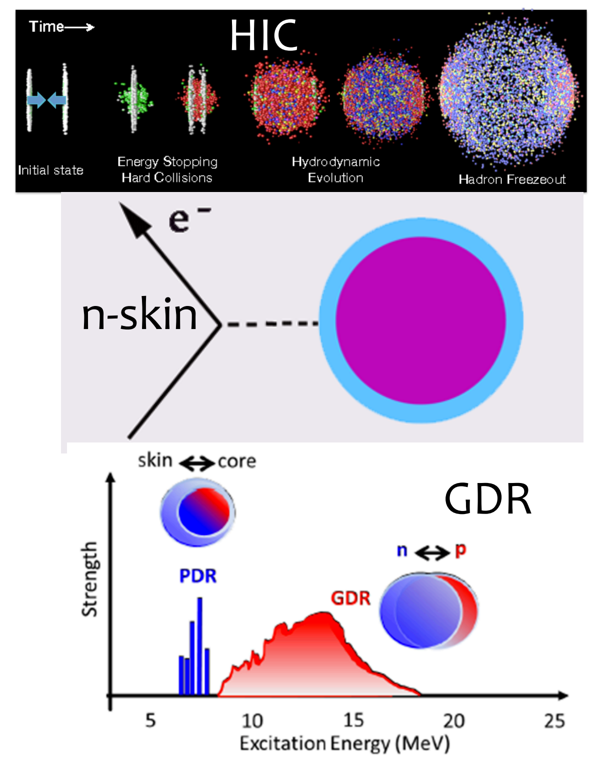



Figure: Lauren Balliet



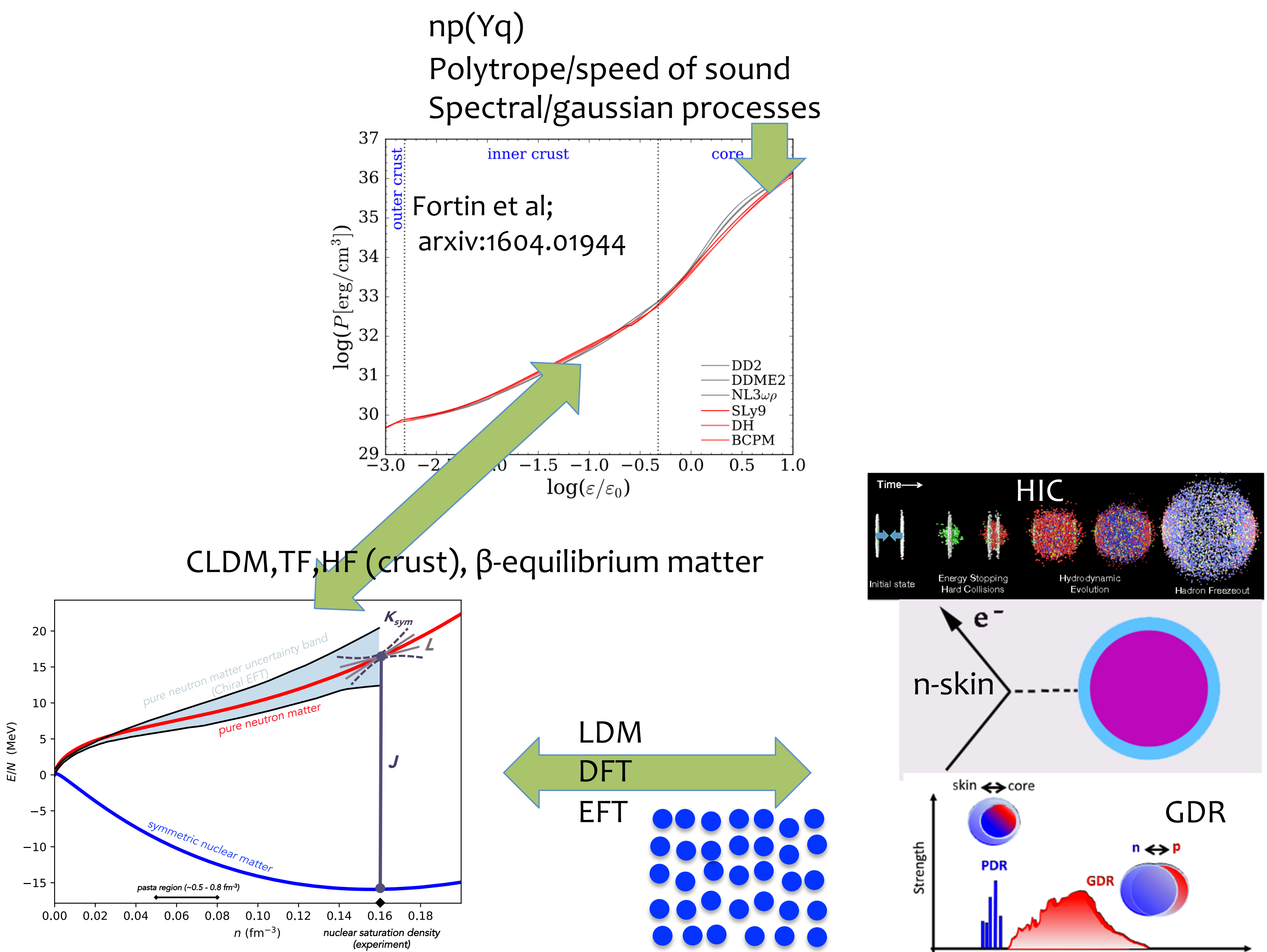
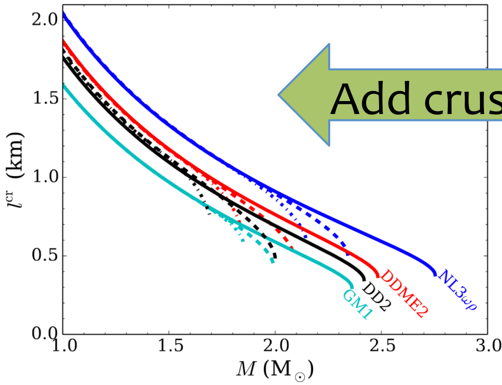
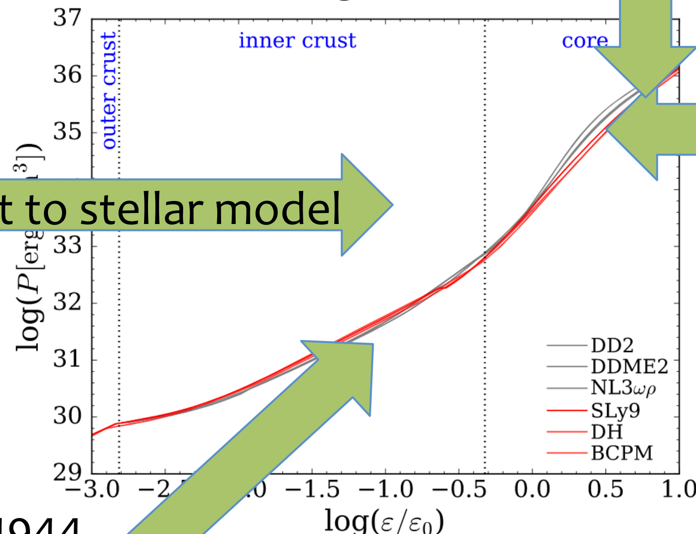


Figure: Lauren Balliet

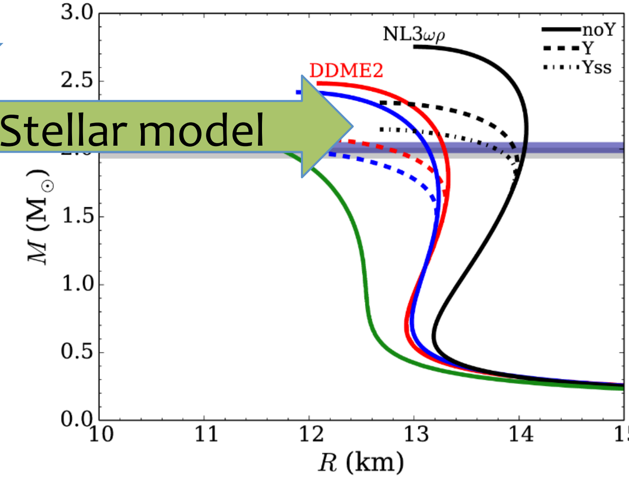
np(Yq)
Polytrope/speed of sound
Spectral/gaussian processes



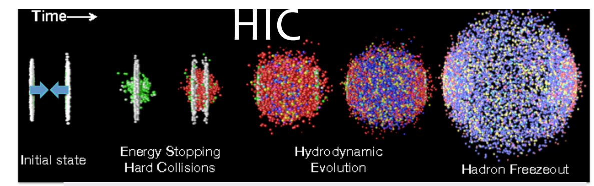

Add crust to stellar model



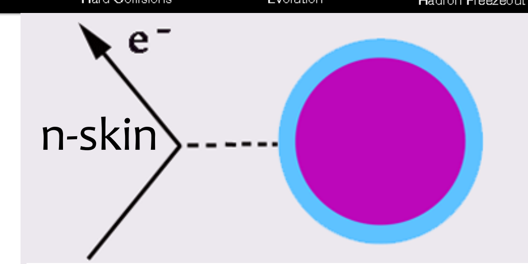

Stellar model

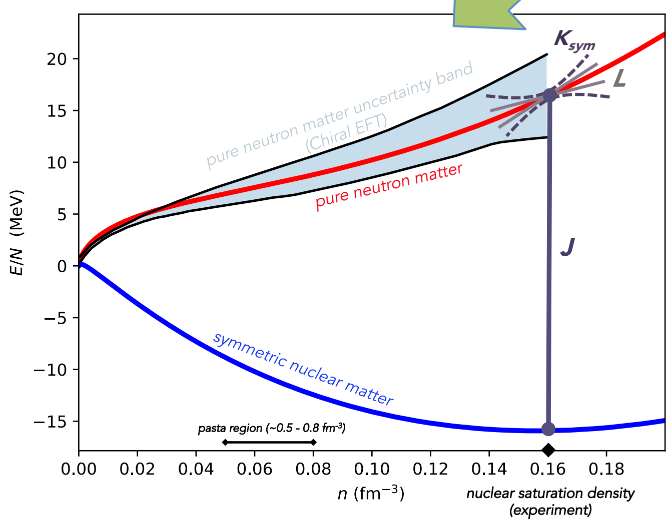



Fortin et al; arxiv:1604.01944

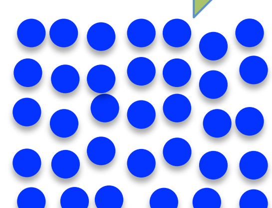



CLDM,TF,HF (crust), β-equilibrium matter




LDM
DFT
EFT



PNM

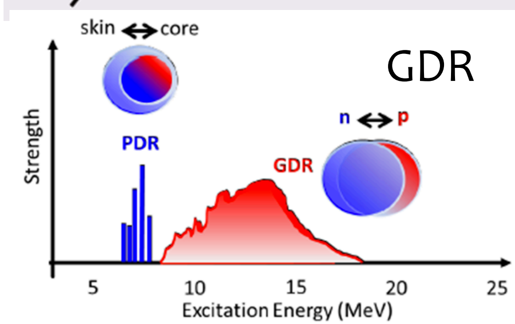
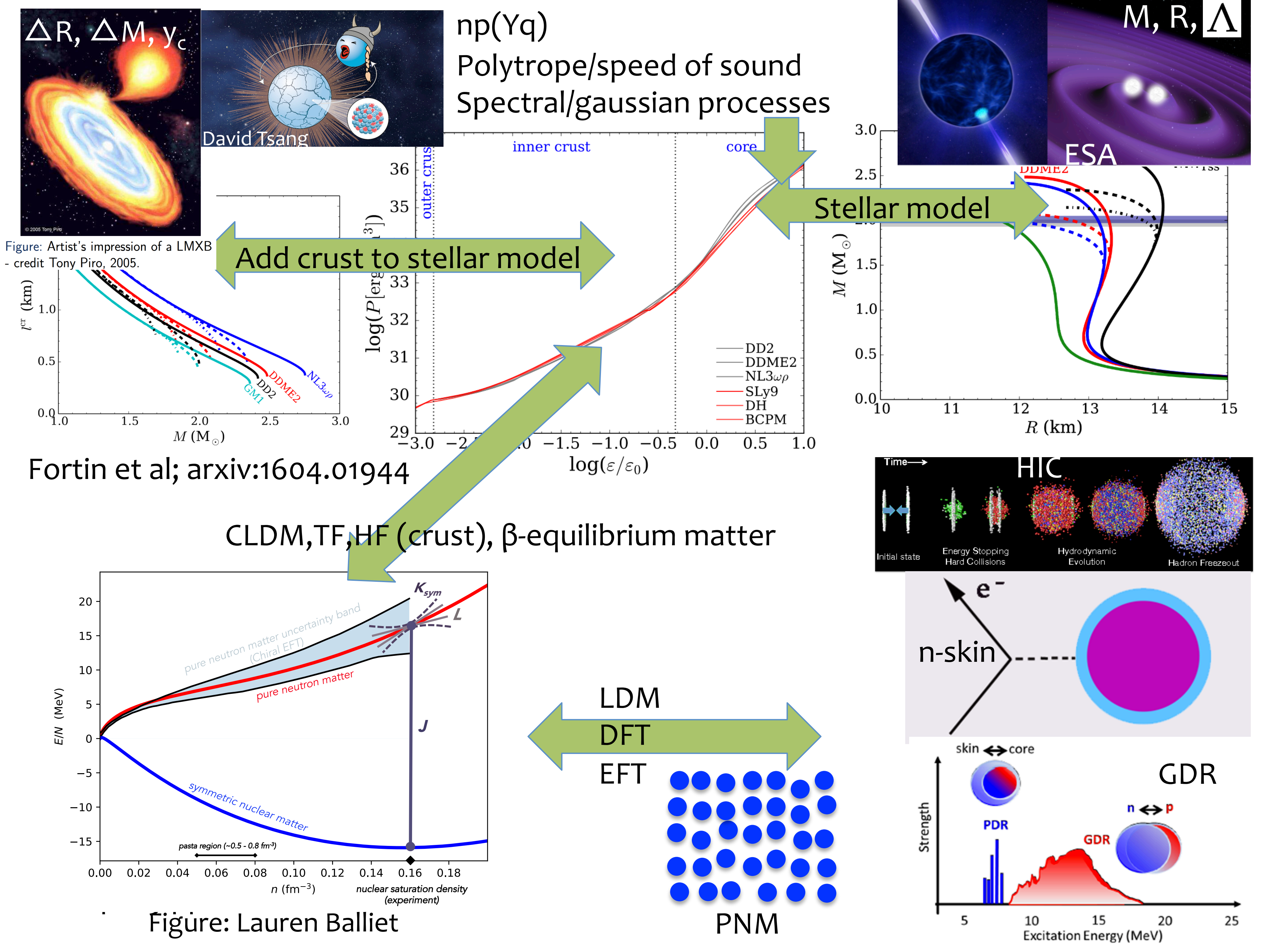
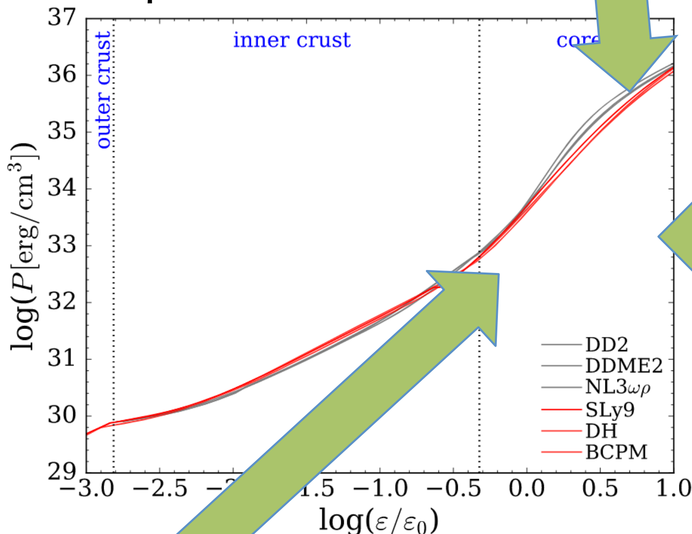



Figure: Lauren Balliet


△R, △M, $y_c$
David Tsang
Figure: Artist's impression of a LMXB - credit Tony Piro, 2005.
np(Yq)
Polytrope/speed of sound
Spectral/gaussian processes
M, R, Λ
ESA
inner crust
core
outer crust
Add crust to stellar model
Stellar model
$l^{cr}$ (km)
$M$ ($M_\odot$)
NL3ωρ
DDME2
DD2
GM1
log($P$[erg cm$^{-3}$])
log($\varepsilon/\varepsilon_0$)
DD2
DDME2
NL3ωρ
SLy9
DH
BCPM
$M$ ($M_\odot$)
$R$ (km)
Fortin et al; arxiv:1604.01944
CLDM,TF,HF (crust), β-equilibrium matter
HIC
Time
Initial state
Energy Stopping Hard Collisions
Hydrodynamic Evolution
Hadron Freezeout
$e^-$
n-skin
$K_{sym}$
$L$
$J$
pure neutron matter uncertainty band (Chiral EFT)
pure neutron matter
symmetric nuclear matter
pasta region (~0.5 - 0.8 fm$^{-3}$)
$E/N$ (MeV)
$n$ (fm$^{-3}$)
nuclear saturation density (experiment)
LDM
DFT
EFT
PNM
skin ↔ core
GDR
n ↔ p
PDR
GDR
Strength
Excitation Energy (MeV)
Figure: Lauren Balliet

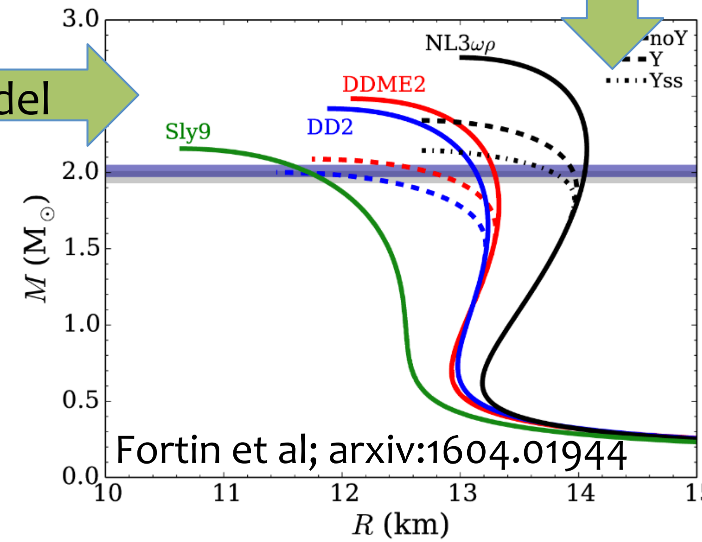
# Example: Huth et al; Nature 606, 276 (2022)

Speed of sound model





Stellar model




BBP crust

β-equilibrium matter

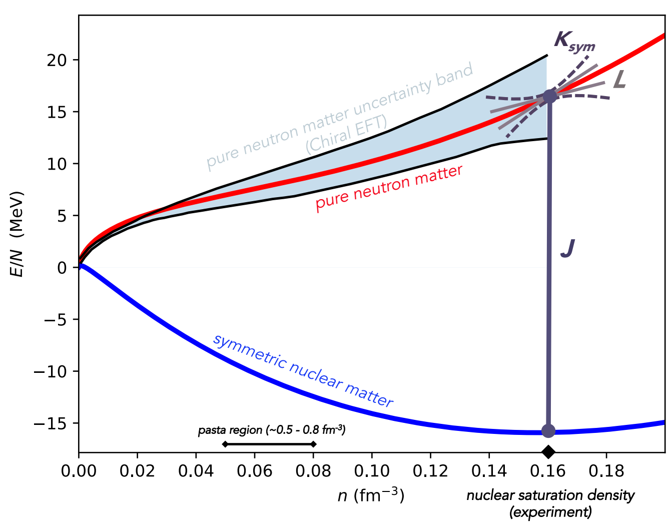
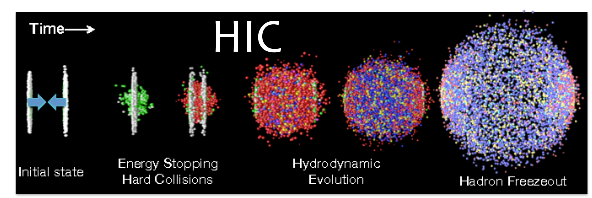
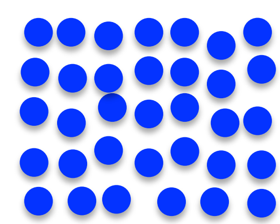



Figure: Lauren Balliet




$$E_{\rm sym}(\rho) = A\left(\frac{\rho}{\rho_0}\right)^{2/3} + B\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

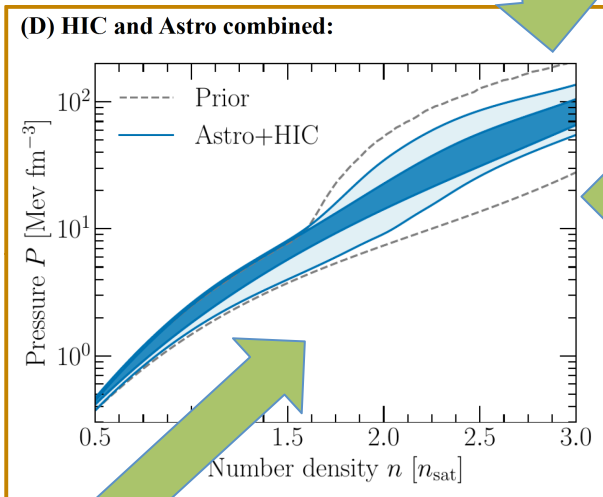
χEFT



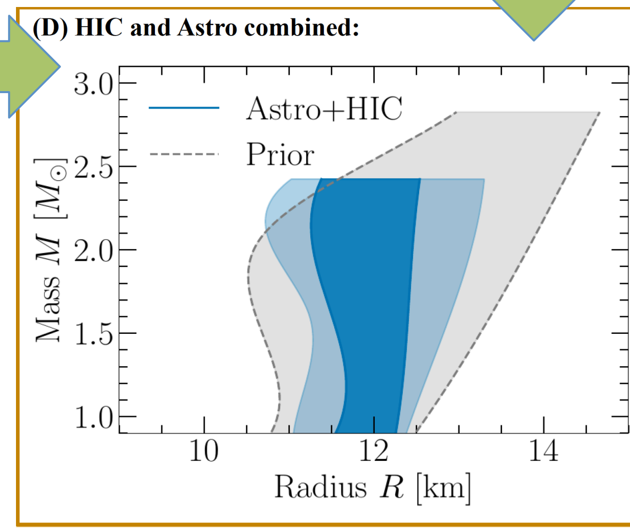
PNM

Huth et al; Nature 606, 276 (2022)


Speed of sound model




Stellar model




BBP crust

β-equilibrium matter

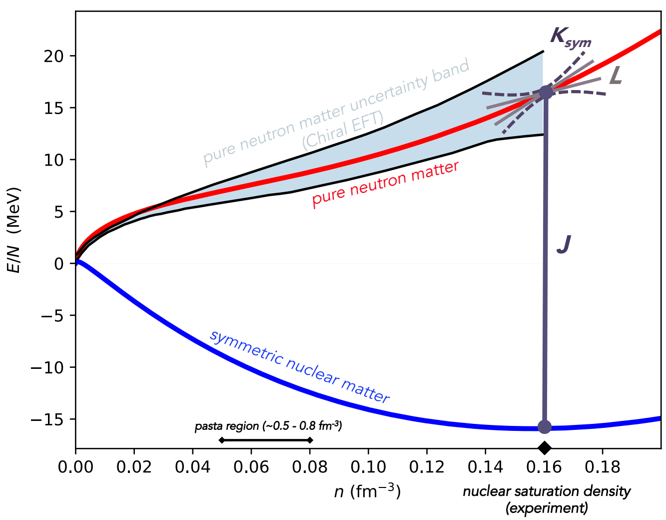
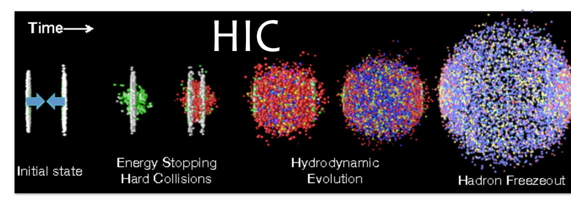
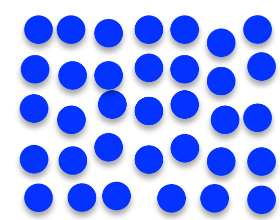



Figure: Lauren Balliet




$$E_{\mathrm{sym}}(\rho) = A\left(\frac{\rho}{\rho_0}\right)^{2/3} + B\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

χEFT



PNM

# Let’s dig deeper into this strategy

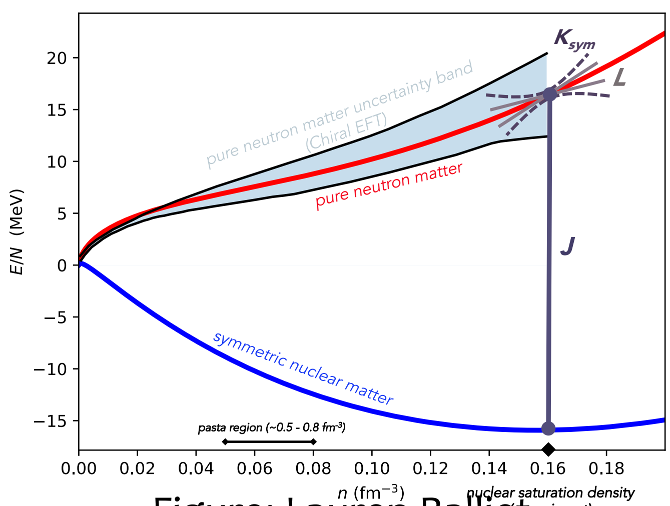
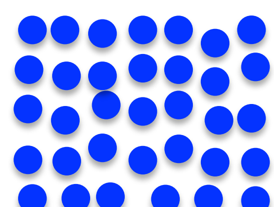
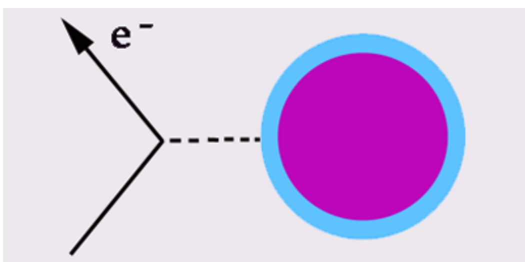
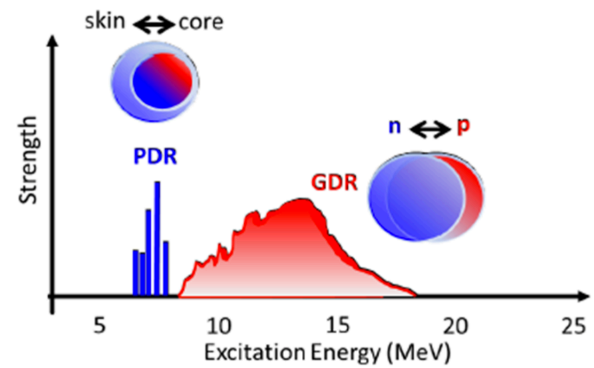



Figure: Lauren Balliet

LDM
DFT
EFT





# Let’s dig deeper into this strategy

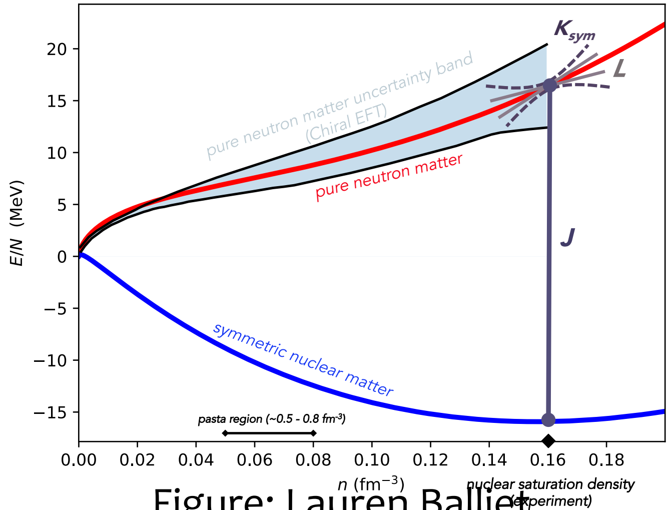
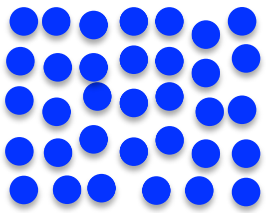
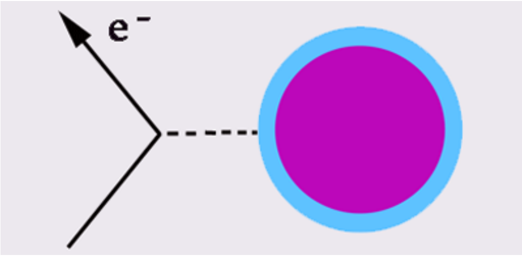
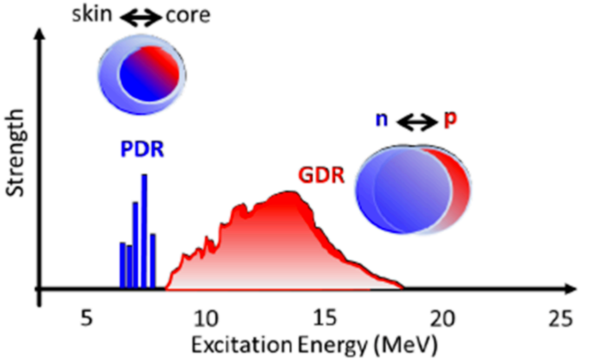


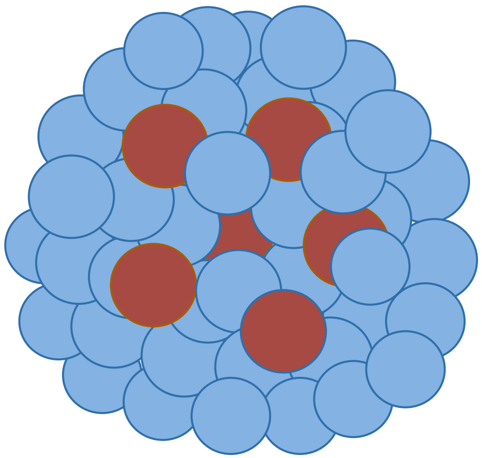

Figure: Lauren Balliet

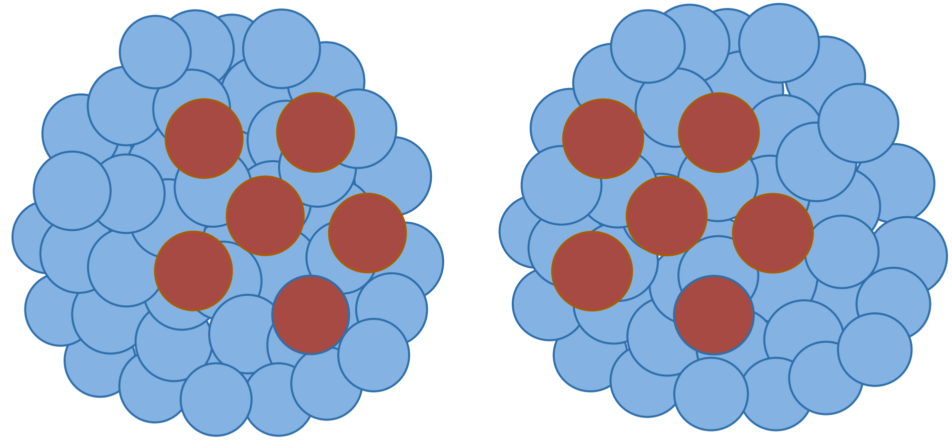
DFT





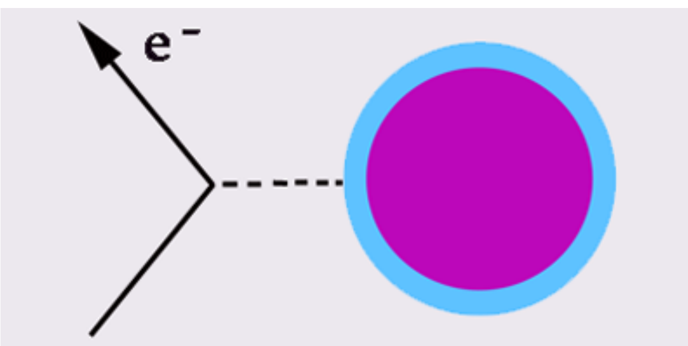





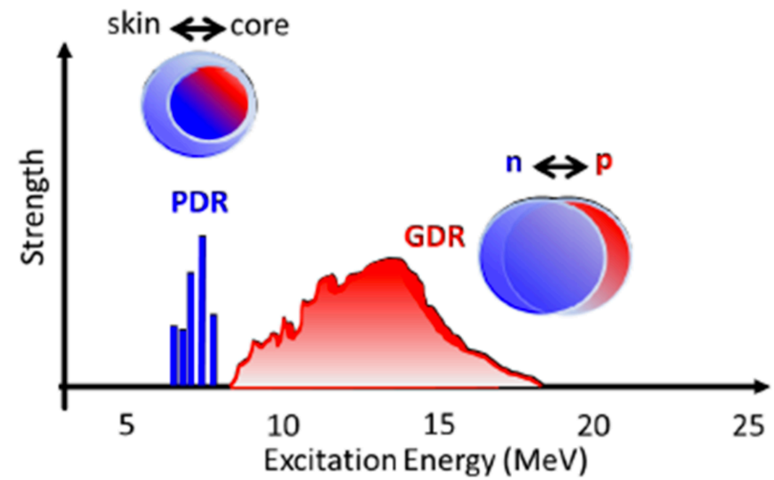


Neutron skin thickness

Collective isovector dipole excitations (PDR, GDR)




Abrahamyan+, PRL 108, 112592 (2012)




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

Parity-violating electron scattering

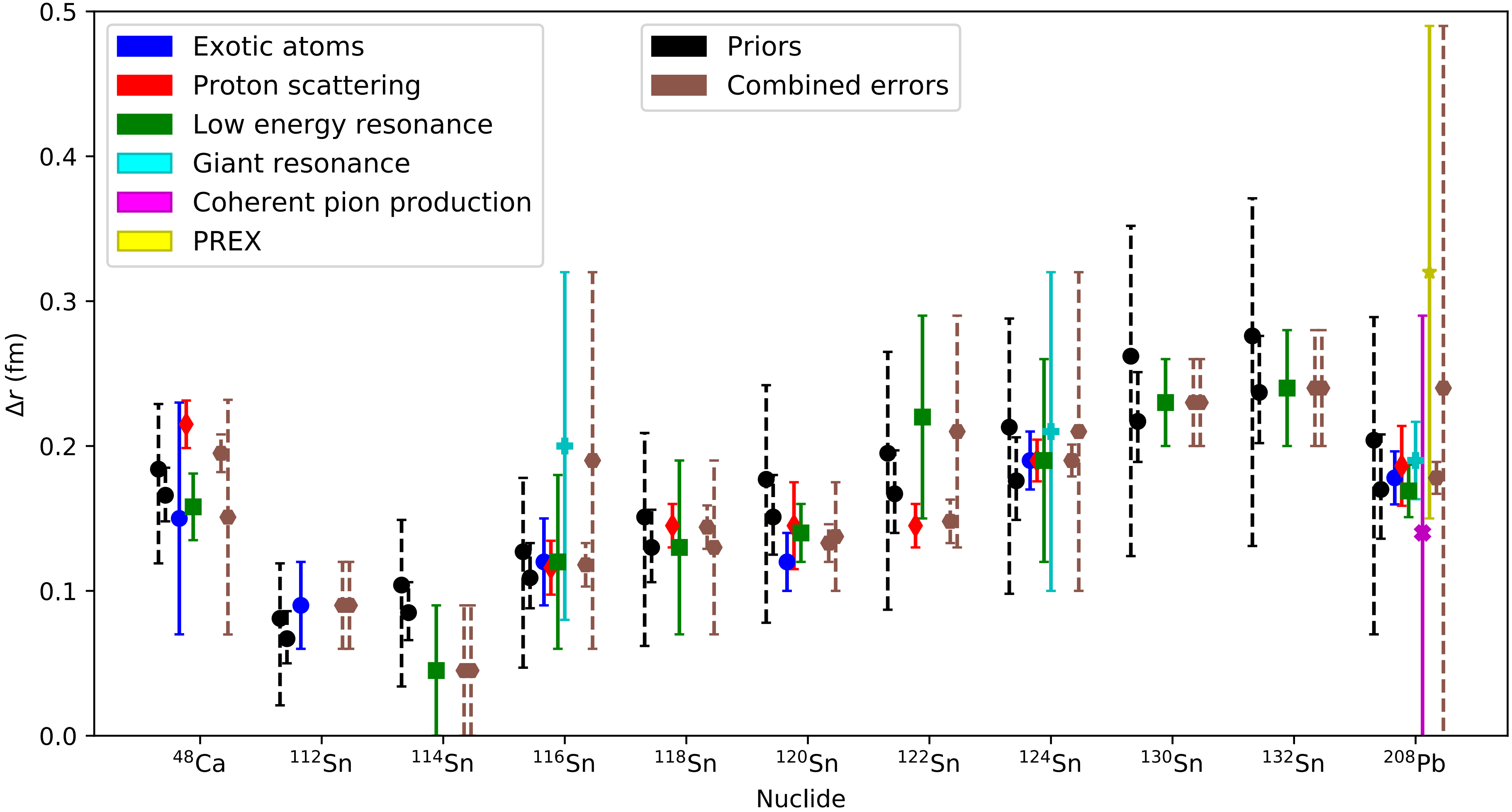
Proton inelastic scattering

$$\text{PREX } \Delta r_{\text{np}}^{208\text{Pb}} = 0.283 \pm 0.071 \text{ fm}$$

$$\text{CREX: } \Delta r_{\text{np}}^{48\text{Ca}} = 0.121 \pm 0.035 \text{ fm}$$

$$\text{RCNP: } \alpha_{\text{D}}^{208\text{Pb}} = 20.1 \pm 0.6 \text{ fm}$$

$$\text{RCNP: } \alpha_{\text{D}}^{48\text{Ca}} = 2.07 \pm 0.22 \text{ fm}$$




Newton, Crocombe arxiv:2008.00042

# Calculating nuclear structure

## 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

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

3 body

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

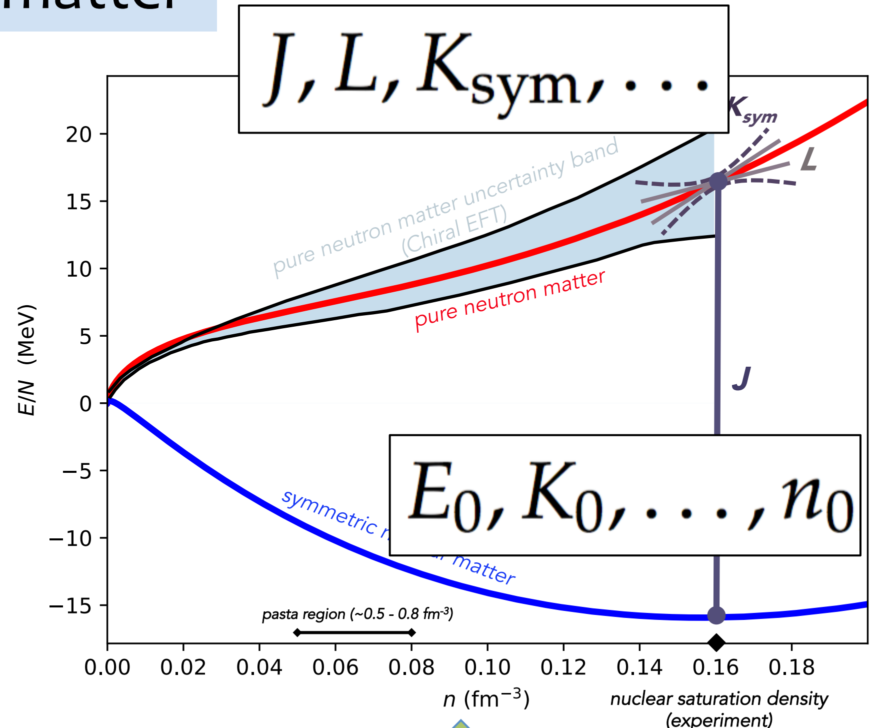
Gradient…

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)

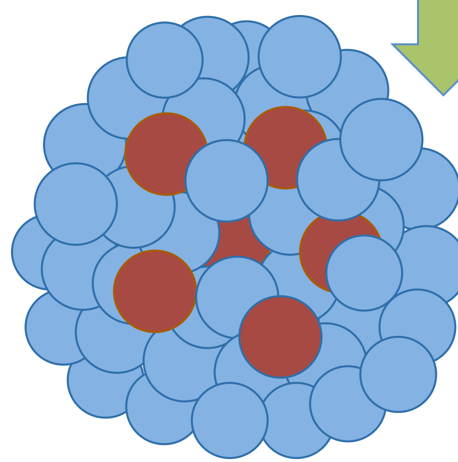
# From models to nuclei and nuclear matter

Parameterization
Based on fits to
masses, radii,
s.p. levels, fission barriers…

$$\begin{bmatrix} t_0 \\ \vdots \\ t_4 \\ x_0 \\ \vdots \\ x_4 \\ \alpha_3 \\ \alpha_4 \end{bmatrix}$$

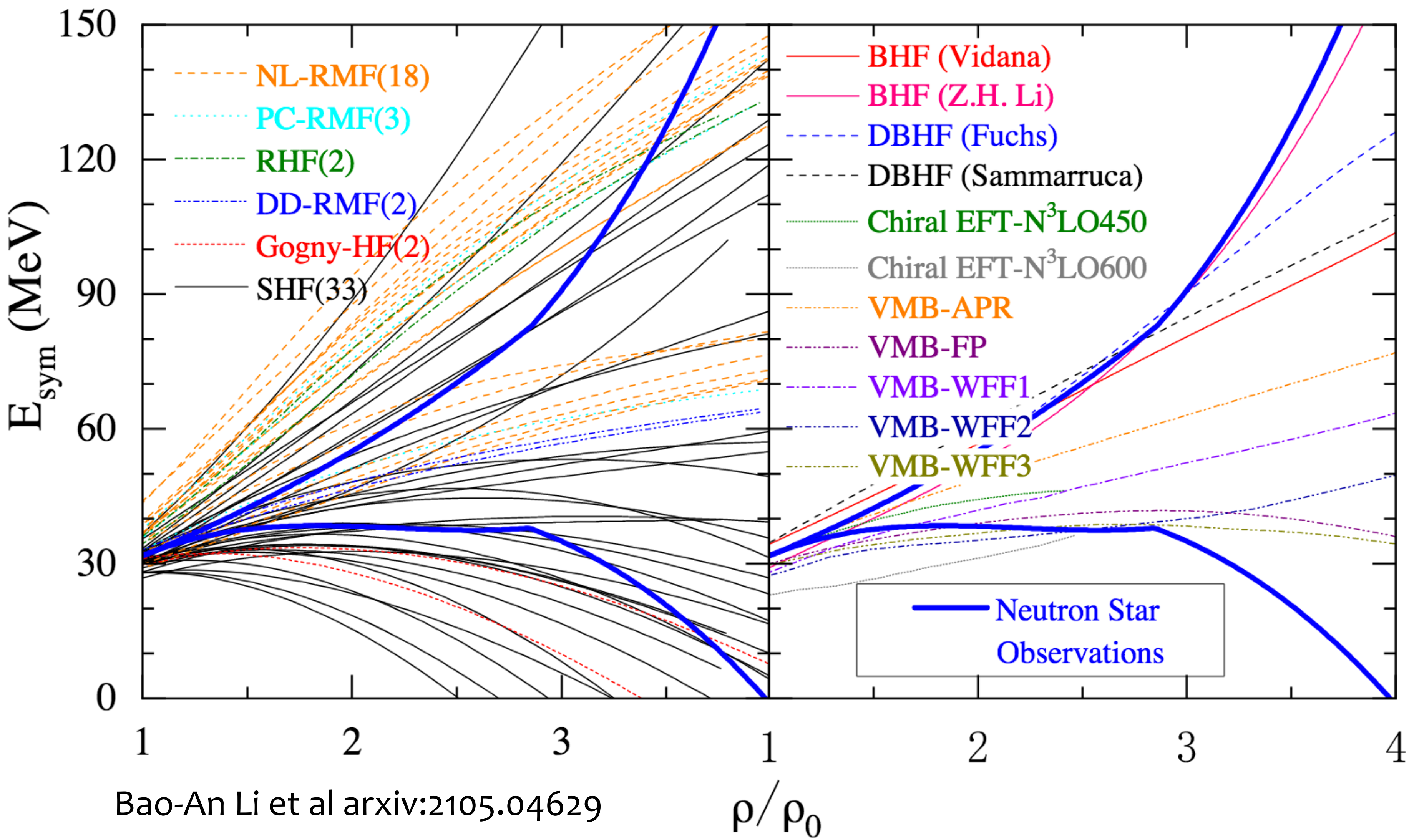



Predict
Correlations



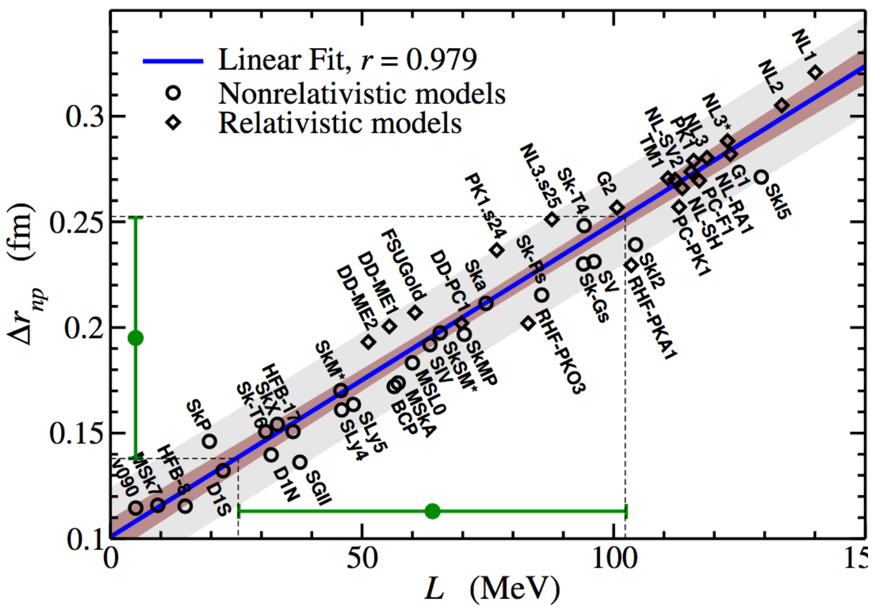
$$\begin{bmatrix} \Delta r_{\mathrm{np}} \\ \alpha_{\mathrm{D}} \end{bmatrix}$$

# Wide range of symmetry energy dependence

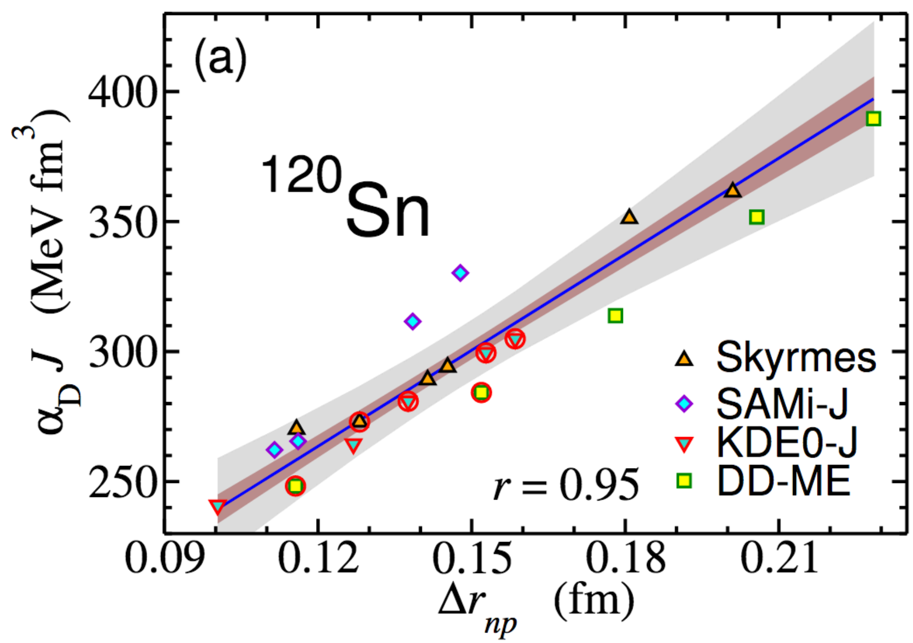



Bao-An Li et al arxiv:2105.04629

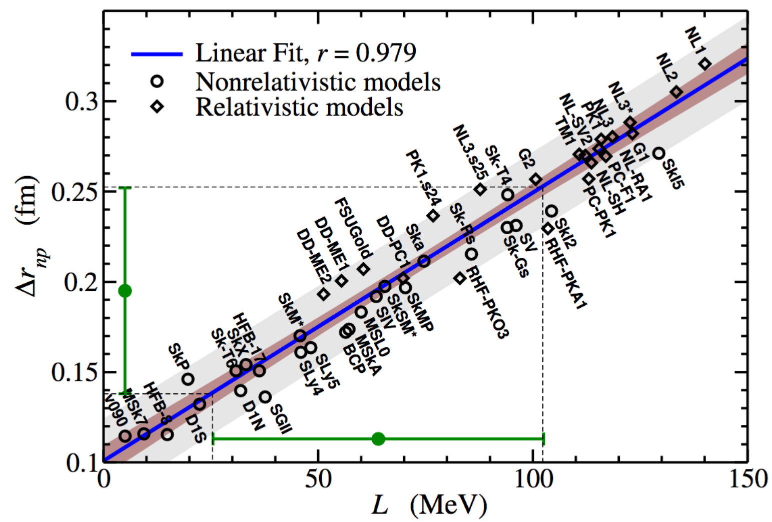
# Correlations are revealed between nuclear matter parameters and nuclear properties

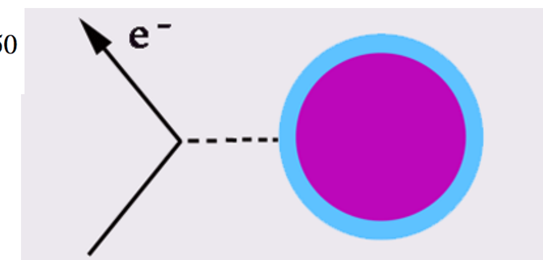



Roca-Maza et al, arxiv:1103.1762




Roca-Maza et al, arxiv: 1510.01874



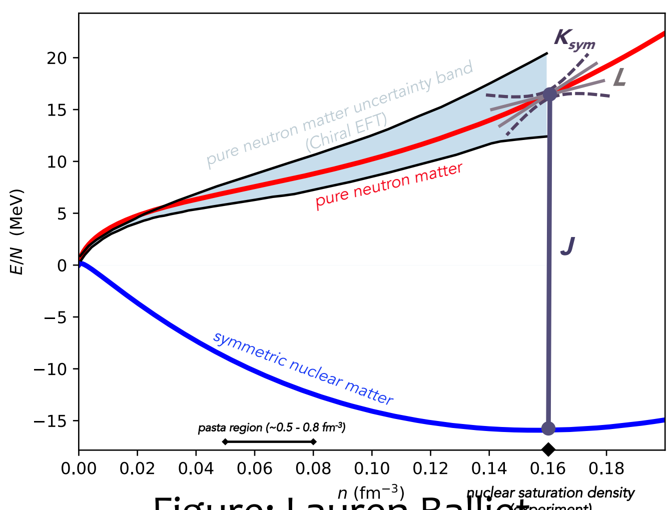
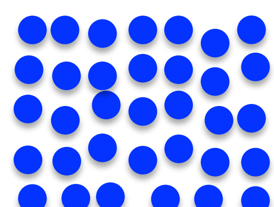
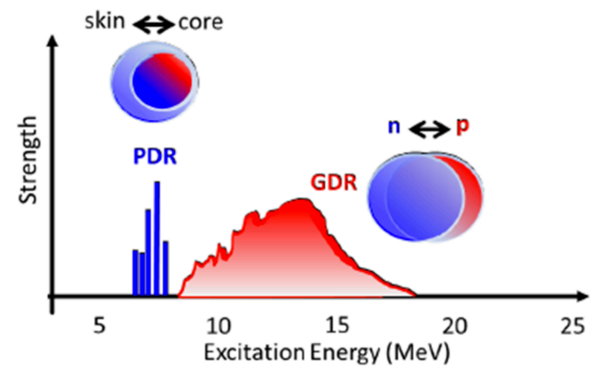



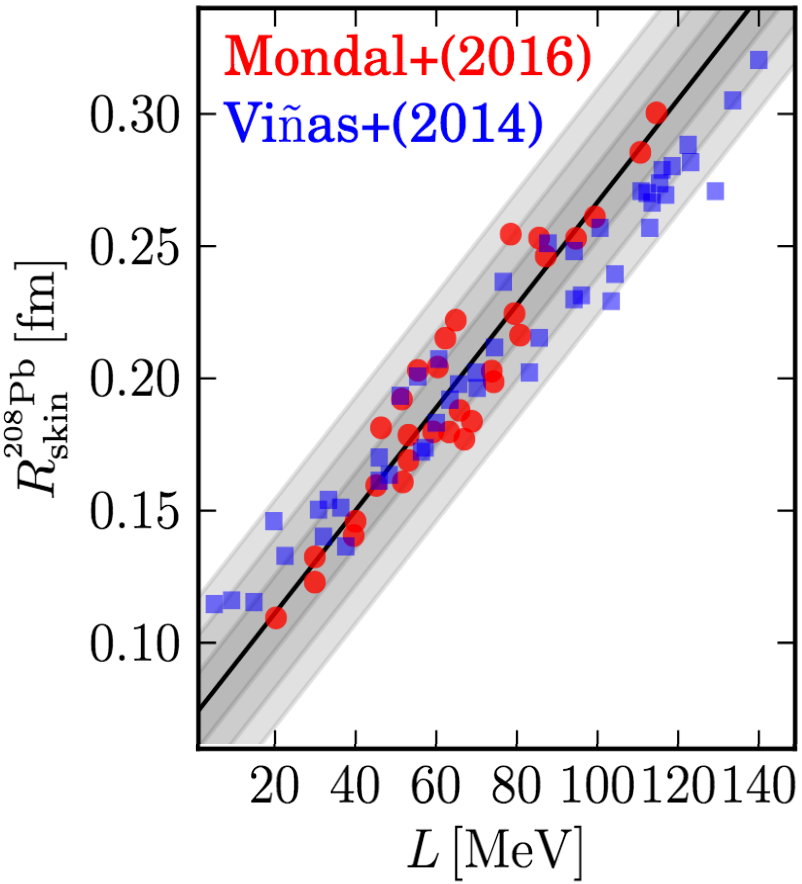

Figure: Lauren Balliet

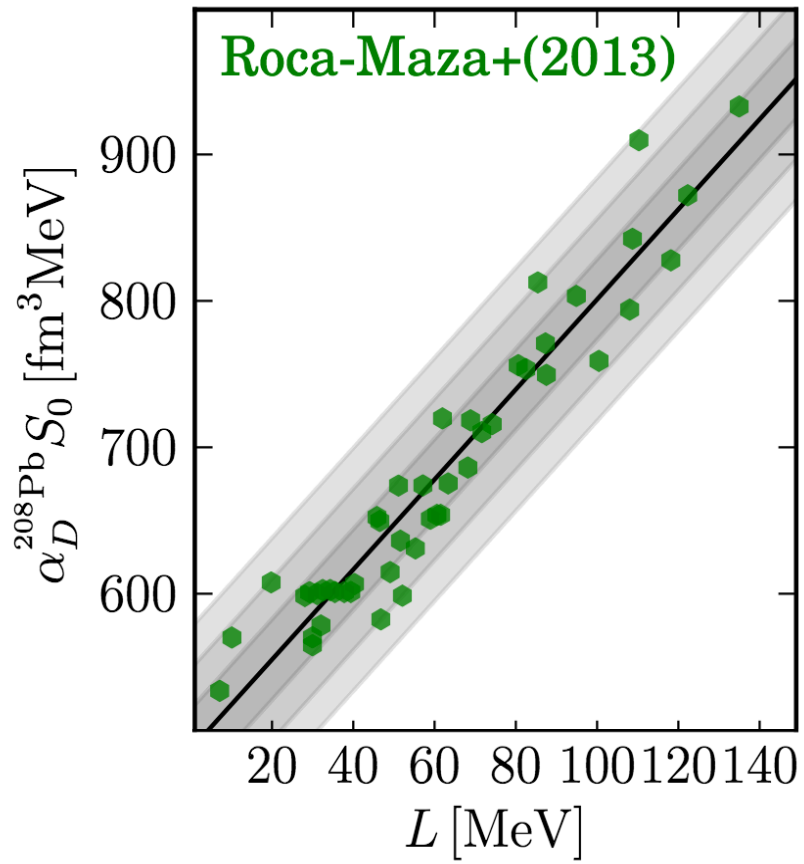
DFT



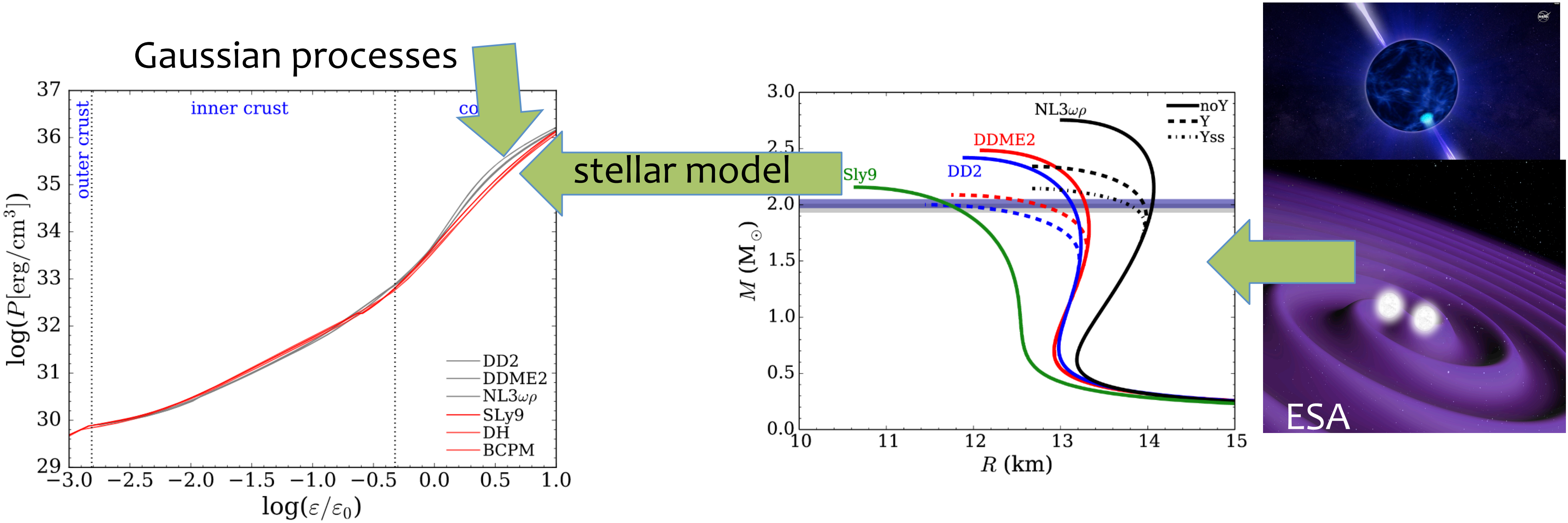


# Correlations are revealed between nuclear matter parameters and nuclear properties



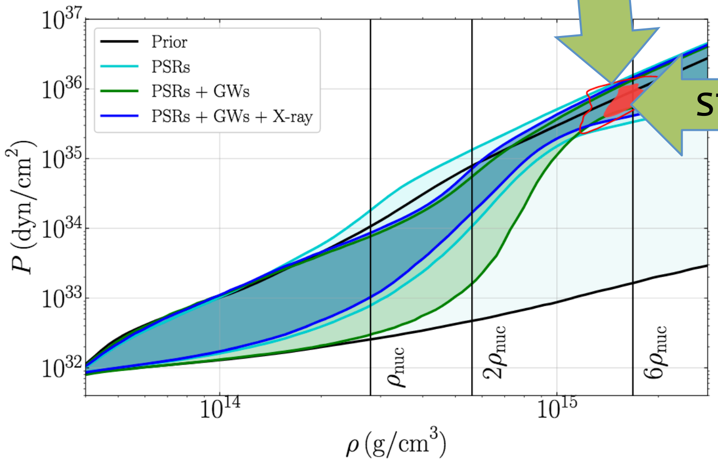

Essick et al: 2107.05528

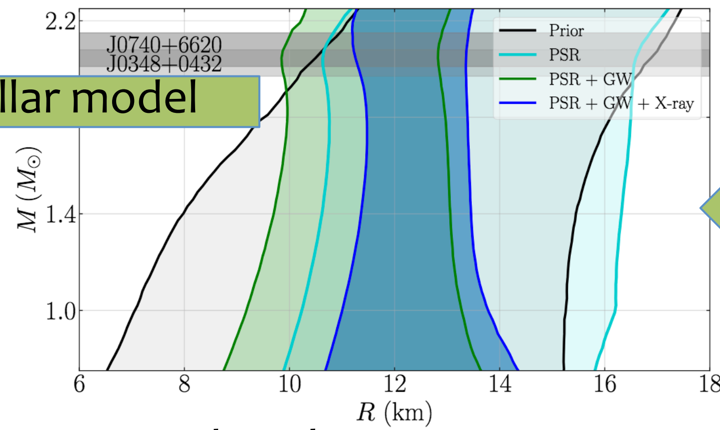


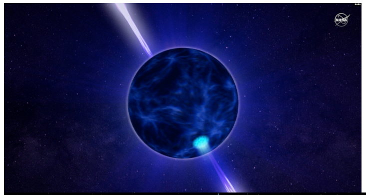
Gaussian processes
stellar model
outer crust
inner crust
co
DD2
DDME2
NL3ωρ
SLy9
DH
BCPM
log(P[erg/cm^3])
log(ε/ε_0)
NL3ωρ
DDME2
DD2
Sly9
noY
Y
Yss
M (M_⊙)
R (km)
ESA

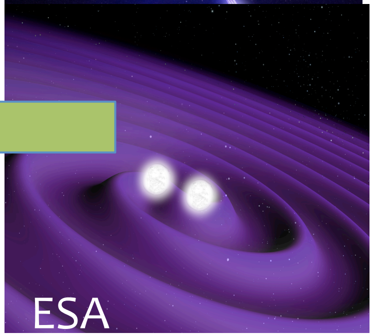
Gaussian processes

stellar model

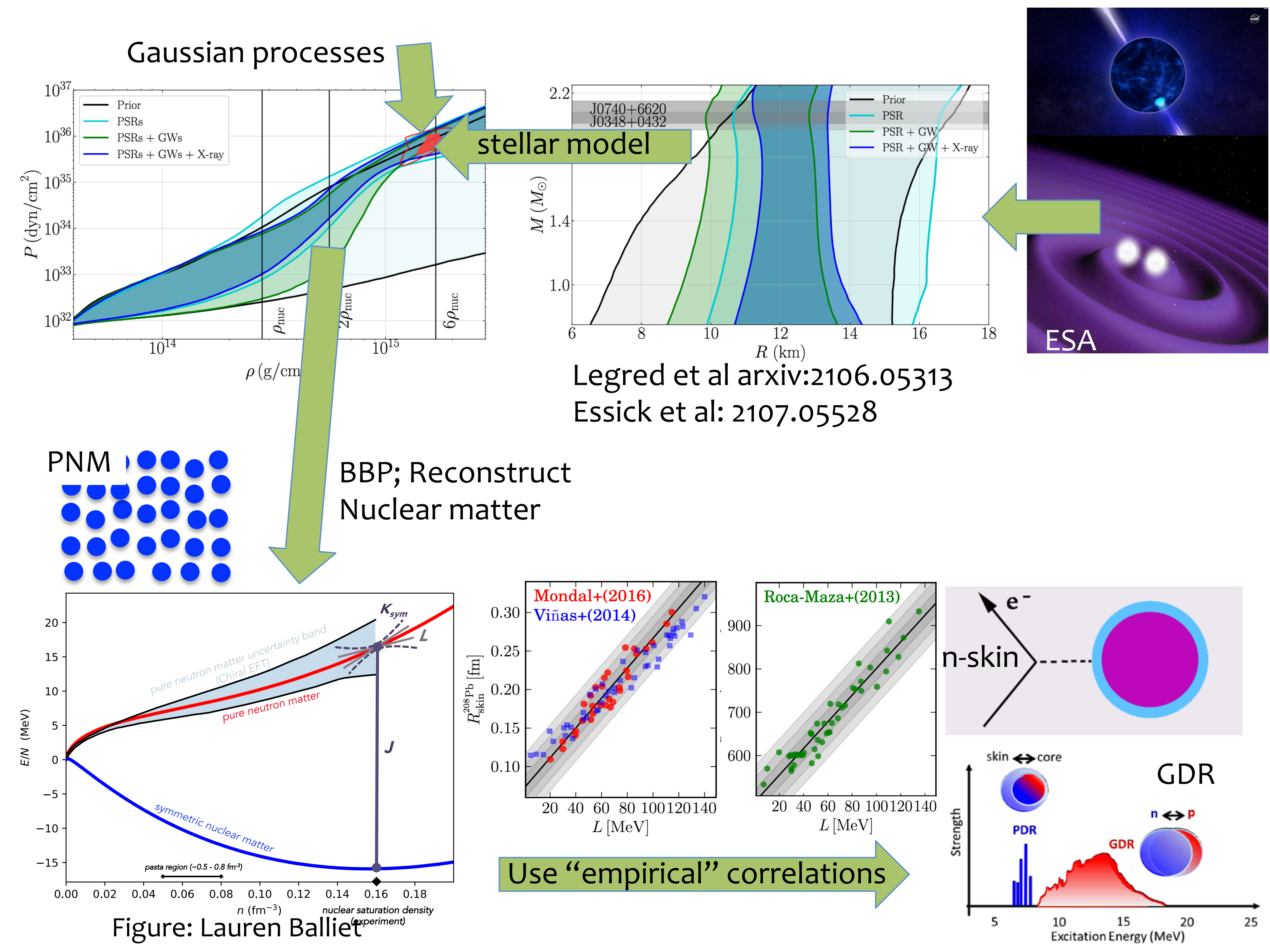


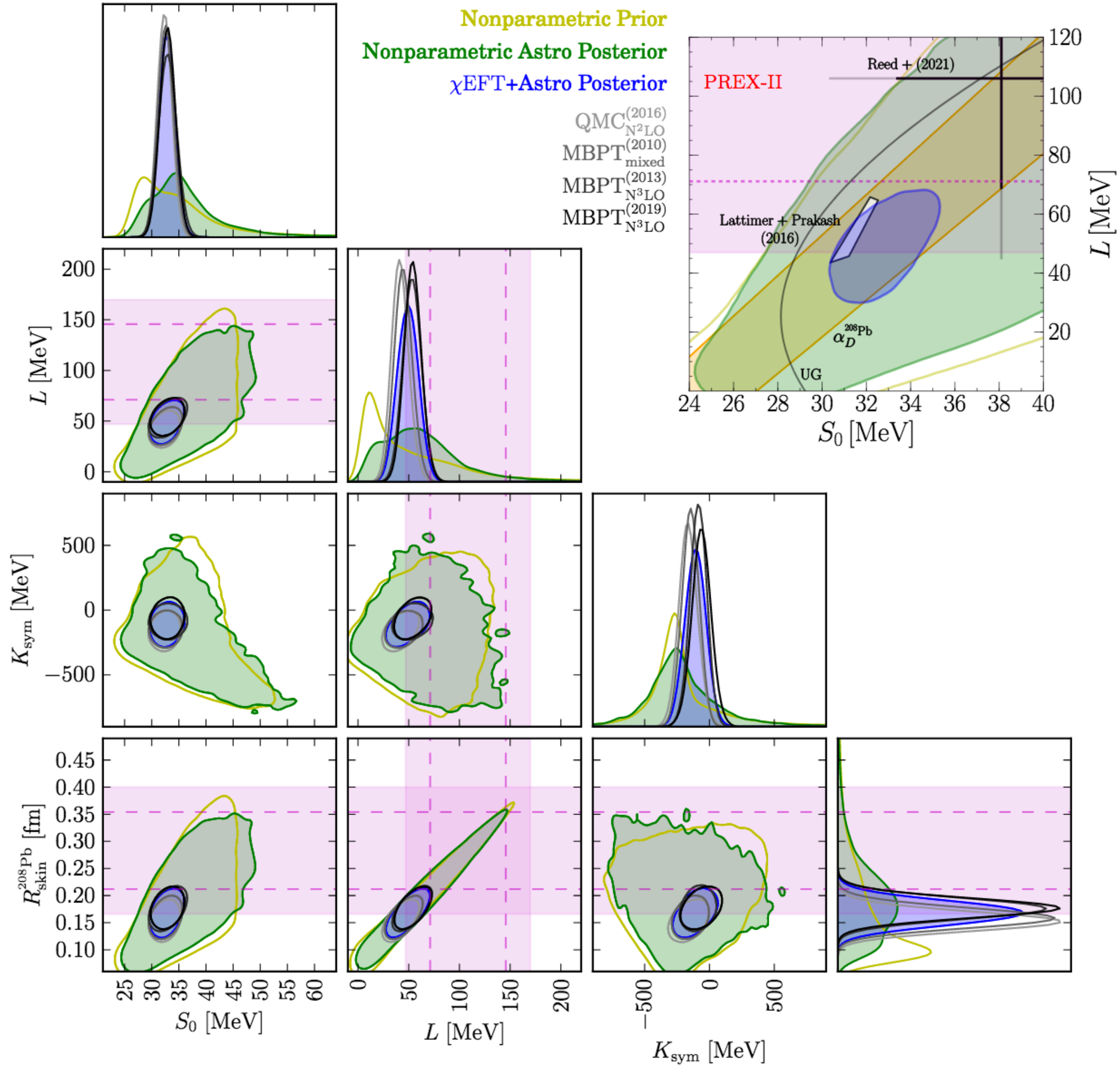






Legred et al arxiv:2106.05313

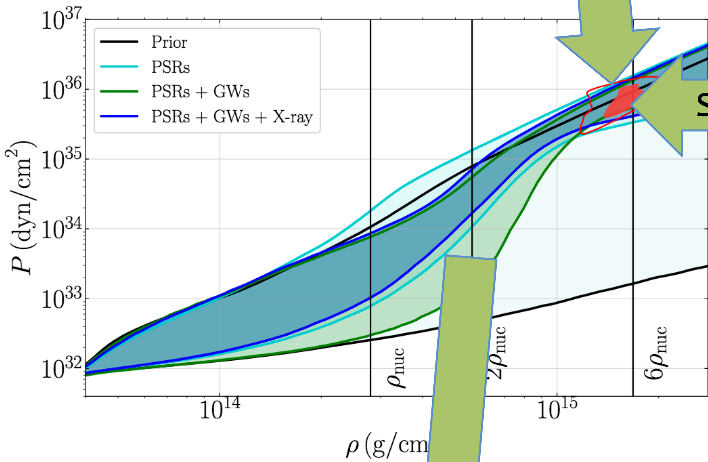


Gaussian processes
stellar model
Prior
PSRs
PSRs + GWs
PSRs + GWs + X-ray
J0740+6620
J0348+0432
PSR
PSR + GW
PSR + GW + X-ray
ESA
Legred et al arxiv:2106.05313
Essick et al: 2107.05528
PNM
BBP; Reconstruct
Nuclear matter
pure neutron matter uncertainty band (Chiral EFT)
pure neutron matter
symmetric nuclear matter
pasta region (~0.5 - 0.8 fm⁻³)
nuclear saturation density (experiment)
Figure: Lauren Balliet
Mondal+(2016)
Viñas+(2014)
Roca-Maza+(2013)
n-skin
skin ↔ core
PDR
GDR
n ↔ p
Strength
Excitation Energy (MeV)
Use "empirical" correlations

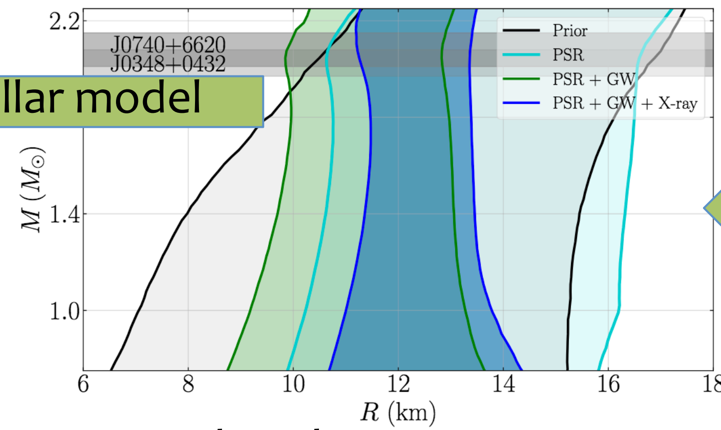


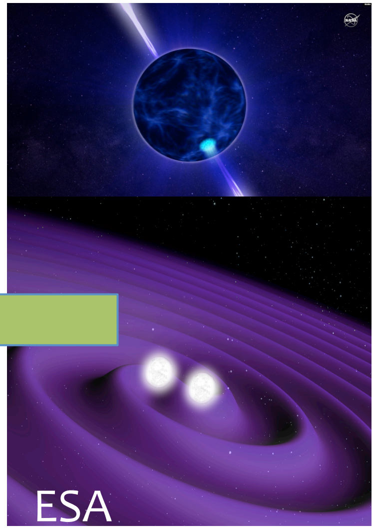

Essick et al: 2107.05528

Gaussian processes



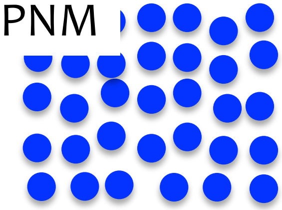

stellar model




Legred et al arxiv:2106.05313
Essick et al: 2107.05528

PNM



BBP; Reconstruct
Nuclear matter

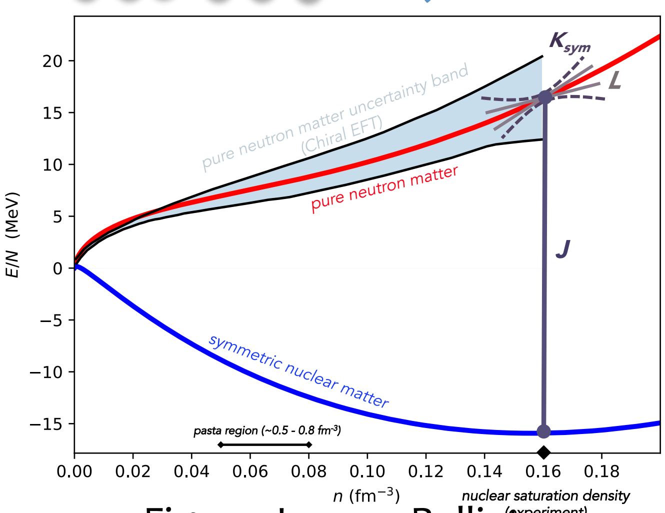
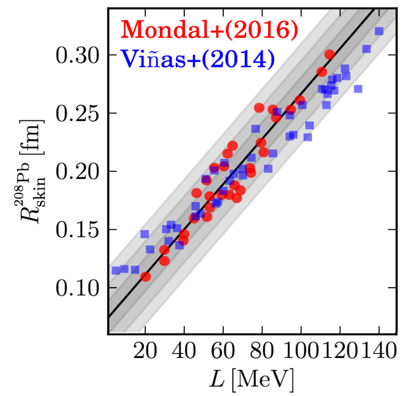
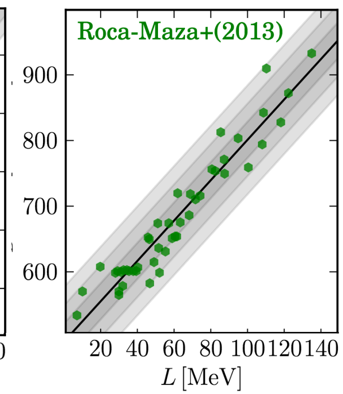
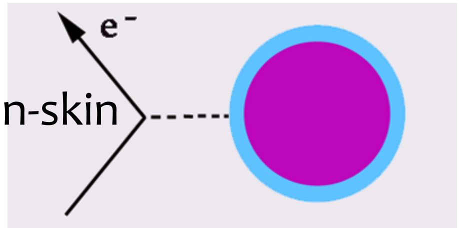
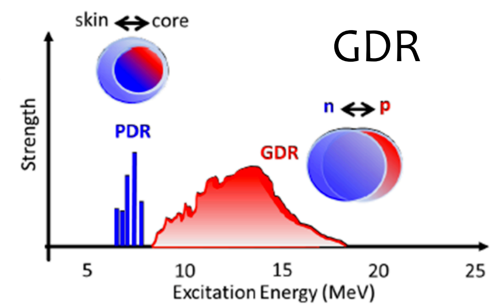



Figure: Lauren Balliet

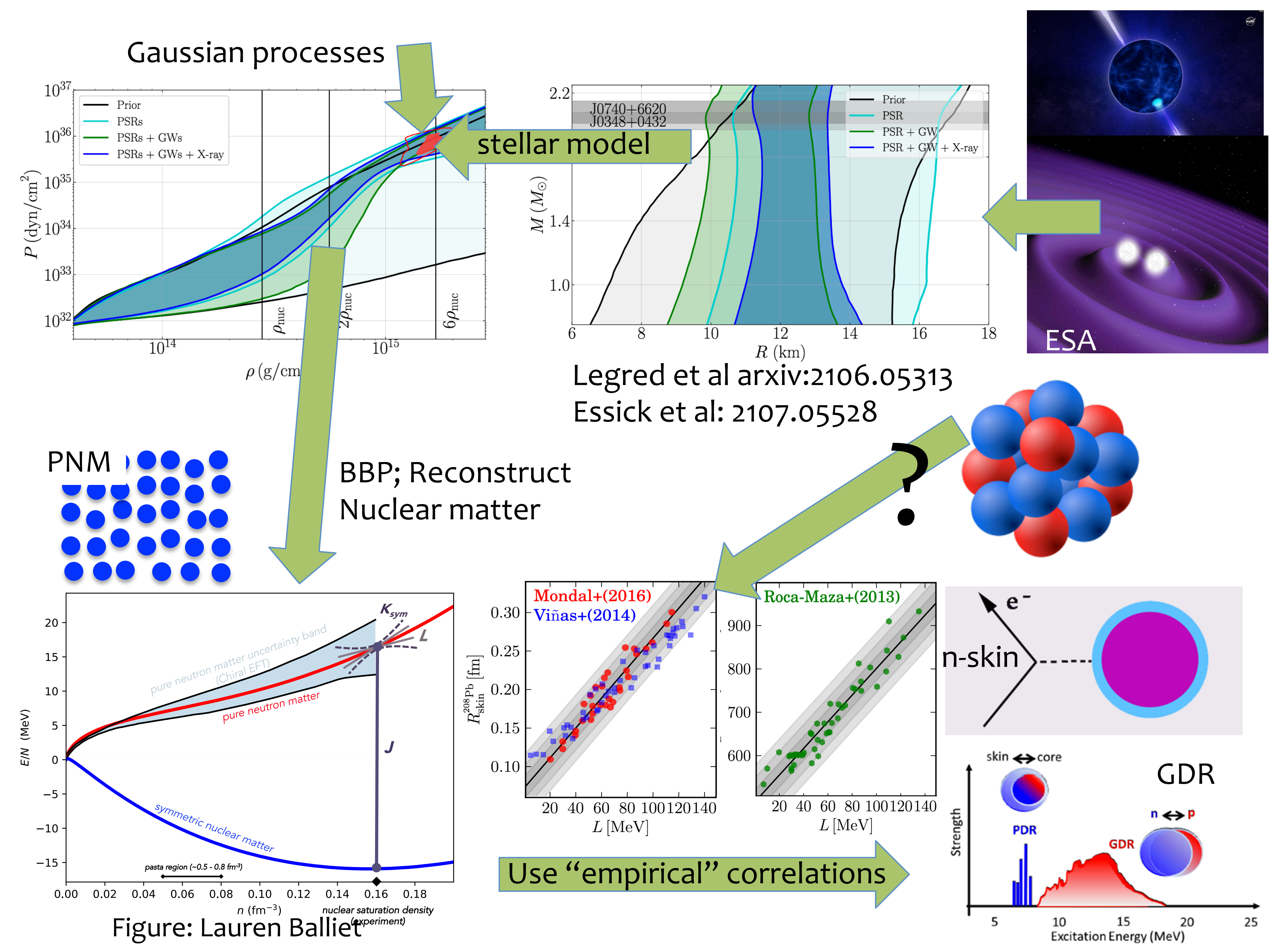



Use “empirical” correlations


Gaussian processes
Prior
PSRs
PSRs + GWs
PSRs + GWs + X-ray
$P$ (dyn/cm$^2$)
$\rho$ (g/cm
$\rho_{nuc}$
$2\rho_{nuc}$
$6\rho_{nuc}$
stellar model
J0740+6620
J0348+0432
Prior
PSR
PSR + GW
PSR + GW + X-ray
$M$ ($M_\odot$)
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Legred et al arxiv:2106.05313
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PNM
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(experiment)
Figure: Lauren Balliet
Mondal+(2016)
Viñas+(2014)
Roca-Maza+(2013)
$R_{skin}^{208Pb}$ [fm]
$L$ [MeV]
$L$ [MeV]
Use “empirical” correlations
$e^-$
n-skin
skin ↔ core
GDR
PDR
GDR
n ↔ p
Strength
Excitation Energy (MeV)

# 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

# The overarching strategy

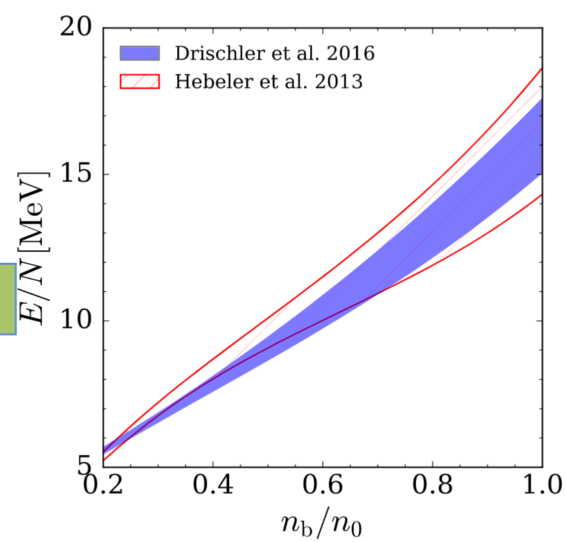
- Choose an EDF with enough degrees of freedom to mitigate the influence of choosing that EDF rather than any other.
- Prepare ensembles of parameterizations of the EDF that distributed over a wide range of the space of nuclear matter parameters (Priors)
- Choose methods of modeling nuclei and neutron star crust which account for as much physics as possible in as reasonable way as possible while being computationally expeditious (10,000s-100,000s models will need to be sampled)
- Use ensemble to calculate nuclear observables, unified crust-core EOS and astro observables
- Add data, construct Likelihoods -> MCMC sampling of posterior probability distribution of the EOSs

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

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

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

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




Haensel, Fortin JPhysG 2017
Lim, Holt arXiv:1702.02898

Nuclear masses, giant resonances

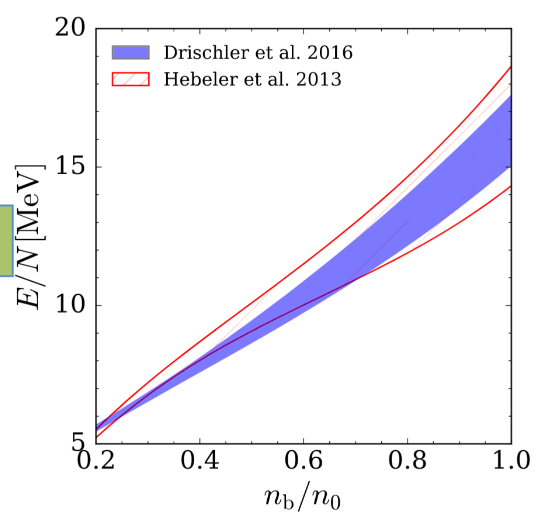
| | | |
|---|---|---|
| $\rho_0$ | ($\mathrm{fm}^{-3}$) | $0.160 \pm 0.005$ |
| $B$ | (MeV) | $16.0 \pm 0.5$ |
| $K$ | (MeV) | $230 \pm 30$ |

Lim, Holt arXiv:1702.02898

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

$$\begin{bmatrix} x_0 \\ x_3 \\ x_4 \end{bmatrix} \leftarrow \begin{bmatrix} J \\ L \\ K_{\rm sym} \end{bmatrix} \qquad \begin{bmatrix} t_0 \\ \vdots \\ t_4 \\ x_1 \\ x_2 \end{bmatrix} \leftarrow \begin{bmatrix} E_0 = 15.9\ \text{MeV} \\ K_0 = 239.5\ \text{MeV} \\ n_0 = 0.156\ \text{fm}^{-3} \\ m_p^* = 0.99 \\ m_n^* = 1.06 \\ G_s = 110.6\ \text{MeV} \\ G_v = 11.8\ \text{MeV} \end{bmatrix} \begin{bmatrix} x_0 \\ x_3 \\ x_4 \end{bmatrix}$$

$$\begin{bmatrix} \alpha_3 = 1/3 \\ \alpha_4 = 1 \end{bmatrix} \leftarrow$$

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# Potential sources of systematic error

Had to choose an EDF (Skyrme). Enough degrees of freedom?
Can add more ($Q_{sym}$)

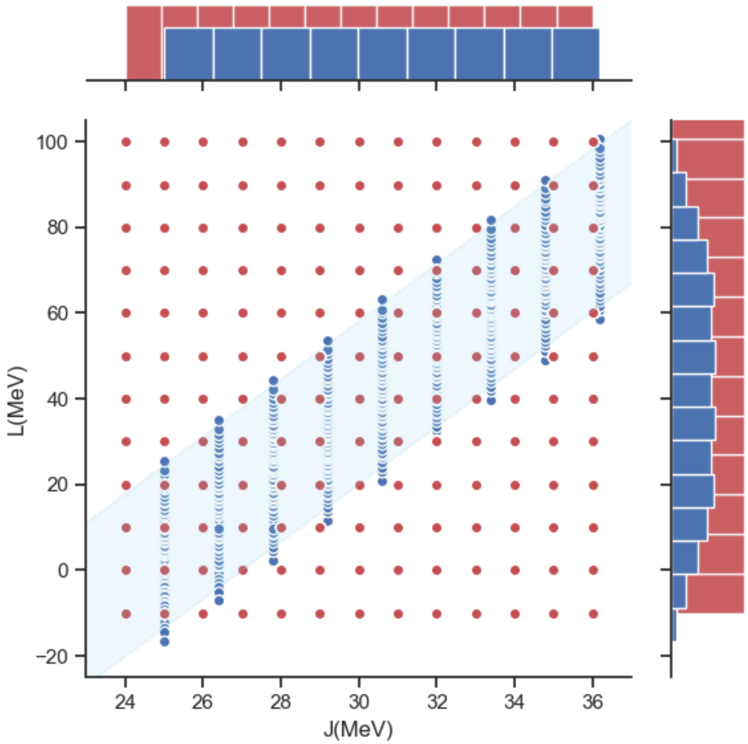
Symmetric nuclear matter and gradient parameters held fixed; extending inference to those parameters may change posteriors

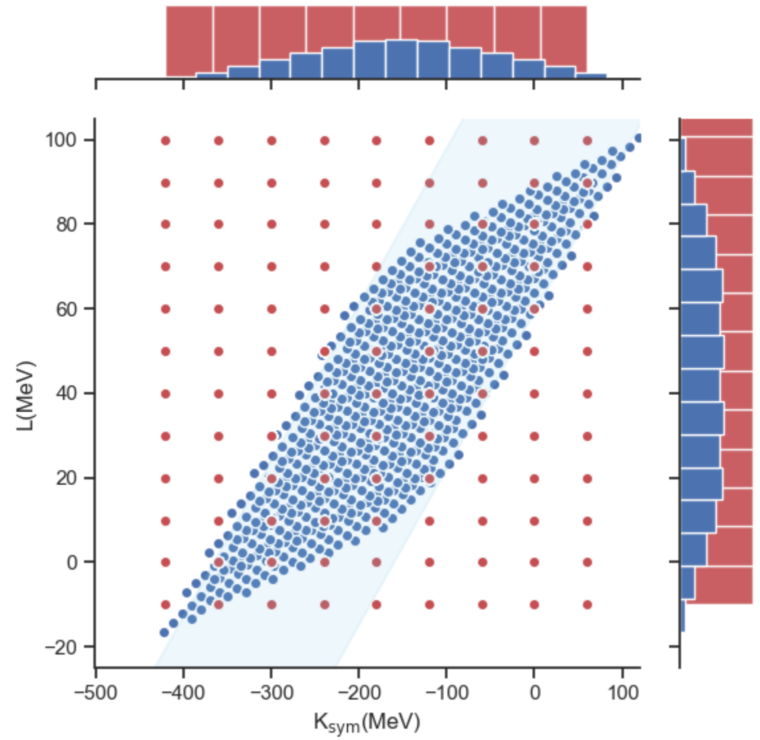
# Priors

$$P(J, L, K_{sym})$$

A uniform grid of Skyrme models

Red – Uninformative priors
Blue – Pure neutron matter priors (Fermi liquid theory) Holt&Lim PLB 2018

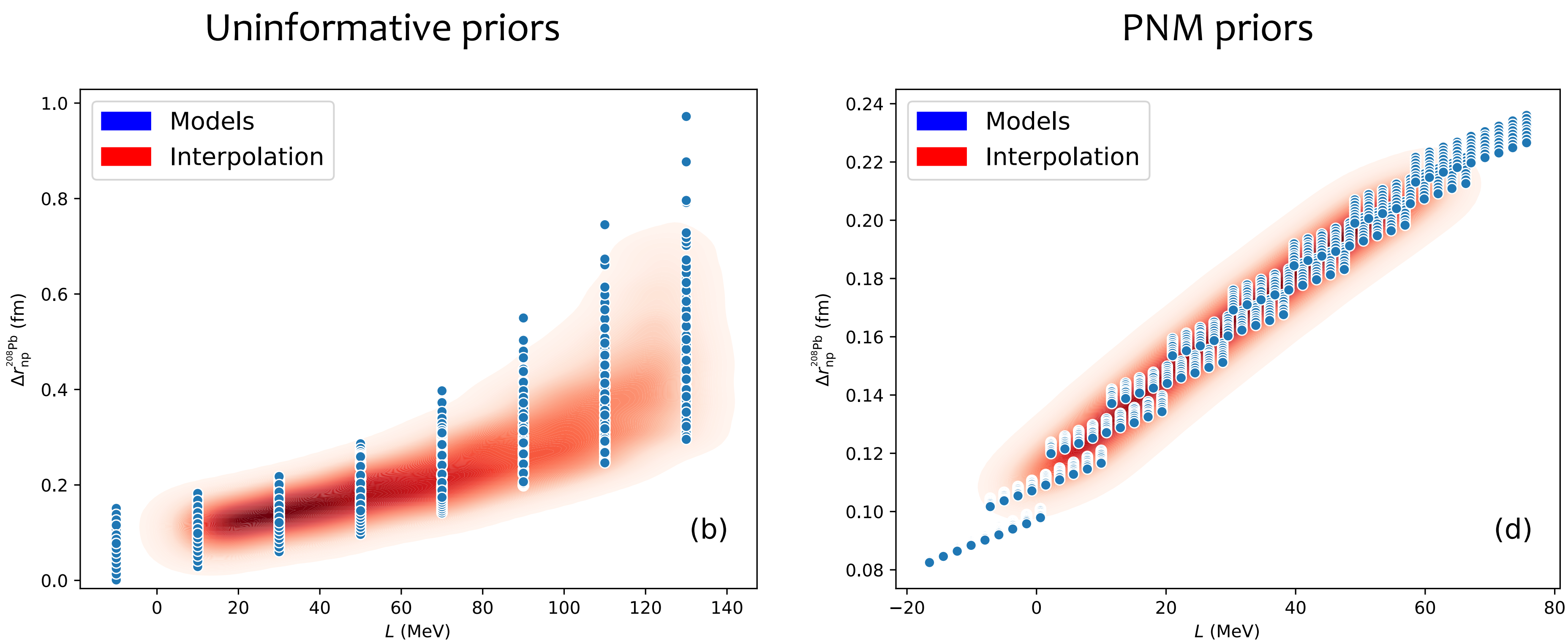


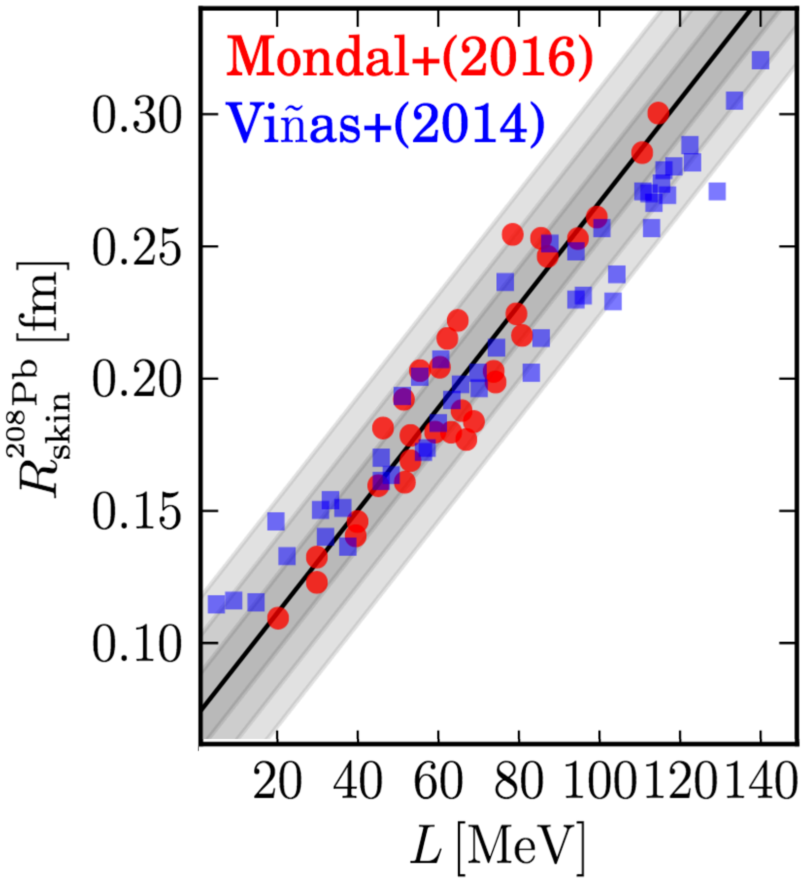



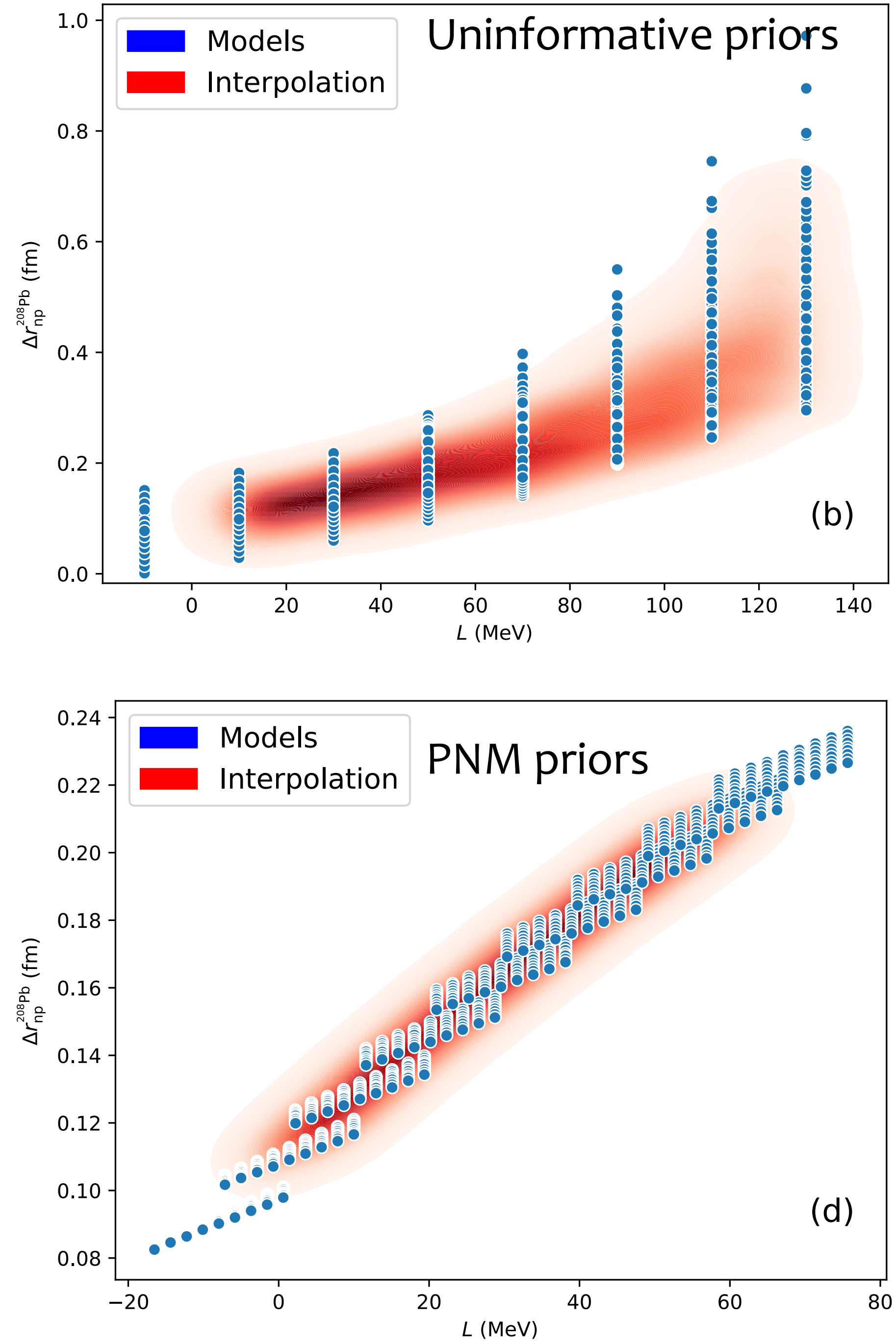

*J*: 25-43 MeV
*L:* 5-145 MeV
$K_{sym}$: -500- +200 MeV

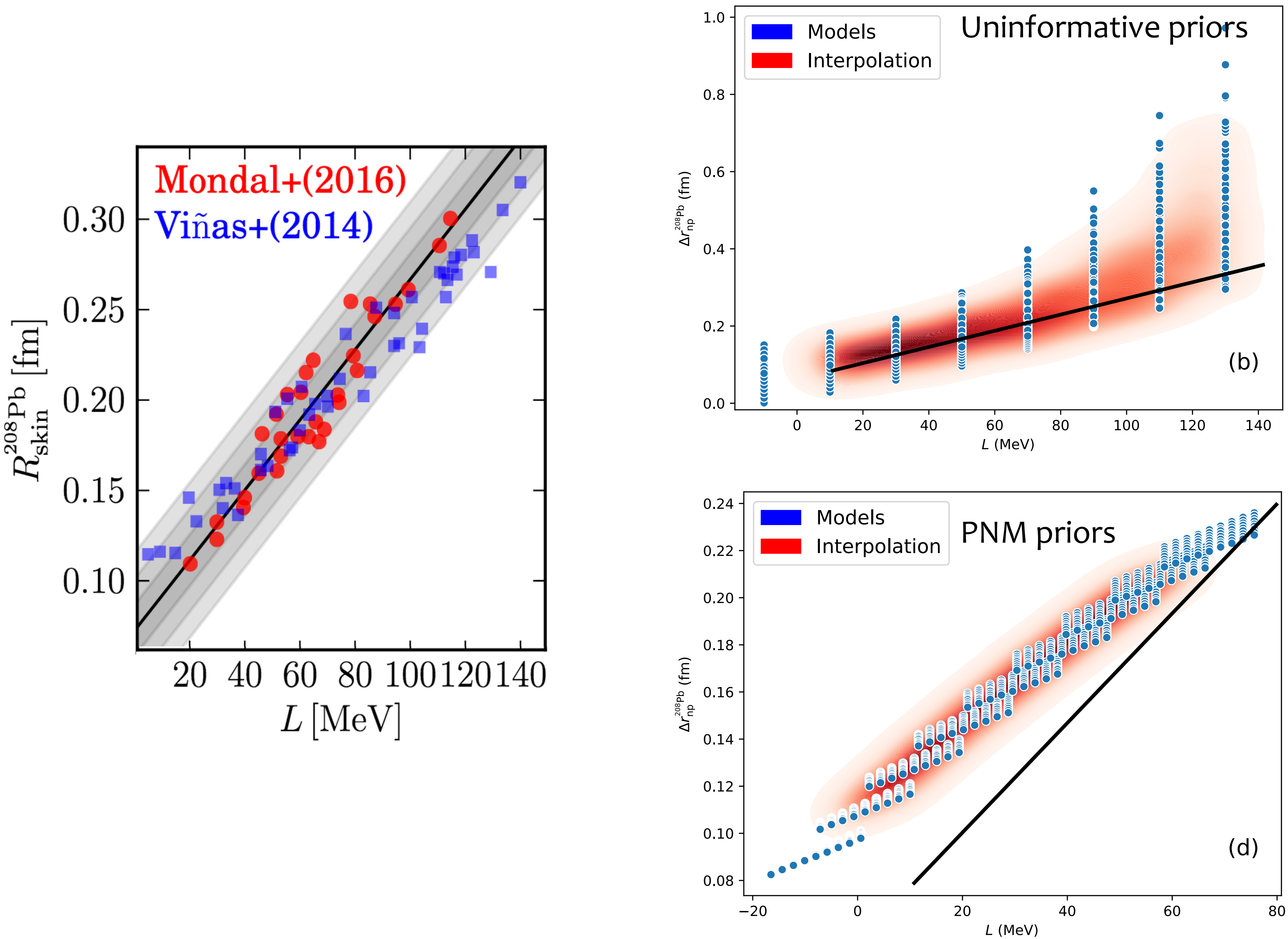
Newton, Crocombe arxiv:2008.00042

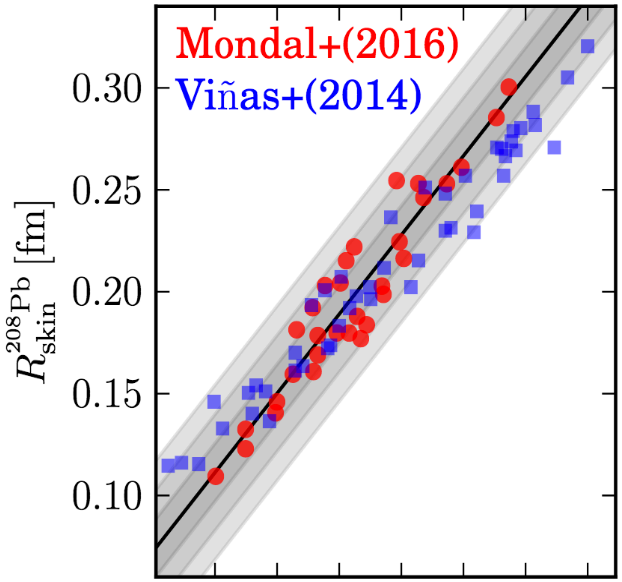
Starting from a set of systematically generated EDFs with minimal symmetry energy assumptions

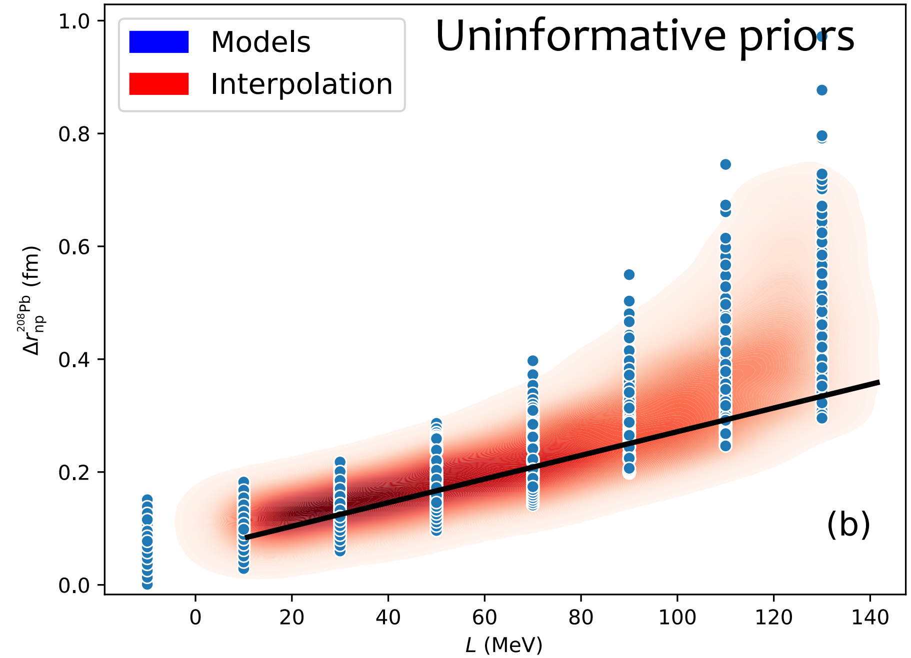


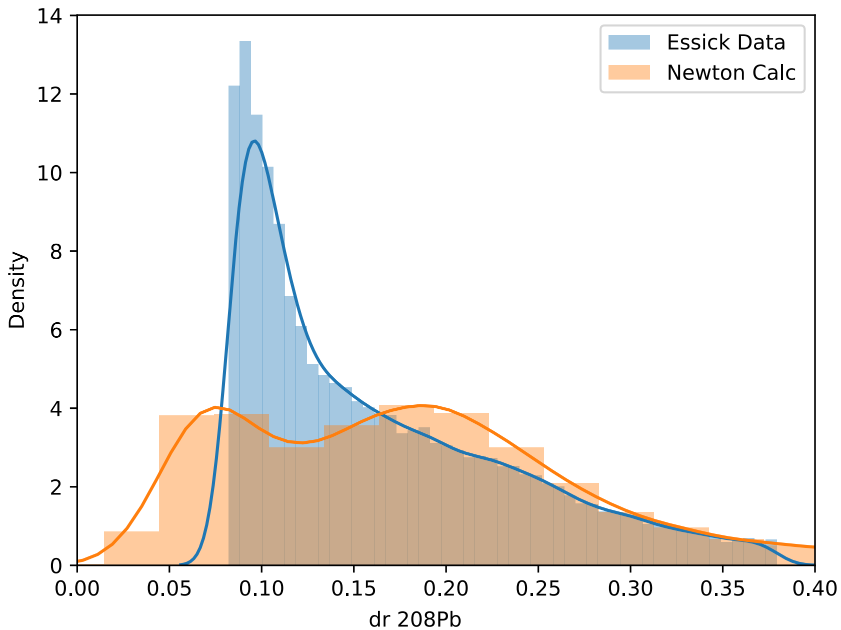

Mondal+(2016)
Viñas+(2014)
$R_{\rm skin}^{208\rm Pb}$ [fm]
0.10
0.15
0.20
0.25
0.30
20 40 60 80 100 120 140
$L$ [MeV]


Models
Interpolation
Uninformative priors
(b)
$\Delta r_{\rm np}^{208\rm Pb}$ (fm)
0.0
0.2
0.4
0.6
0.8
1.0
0 20 40 60 80 100 120 140
$L$ (MeV)
Models
Interpolation
PNM priors
(d)
$\Delta r_{\rm np}^{208\rm Pb}$ (fm)
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.22
0.24
−20 0 20 40 60 80
$L$ (MeV)

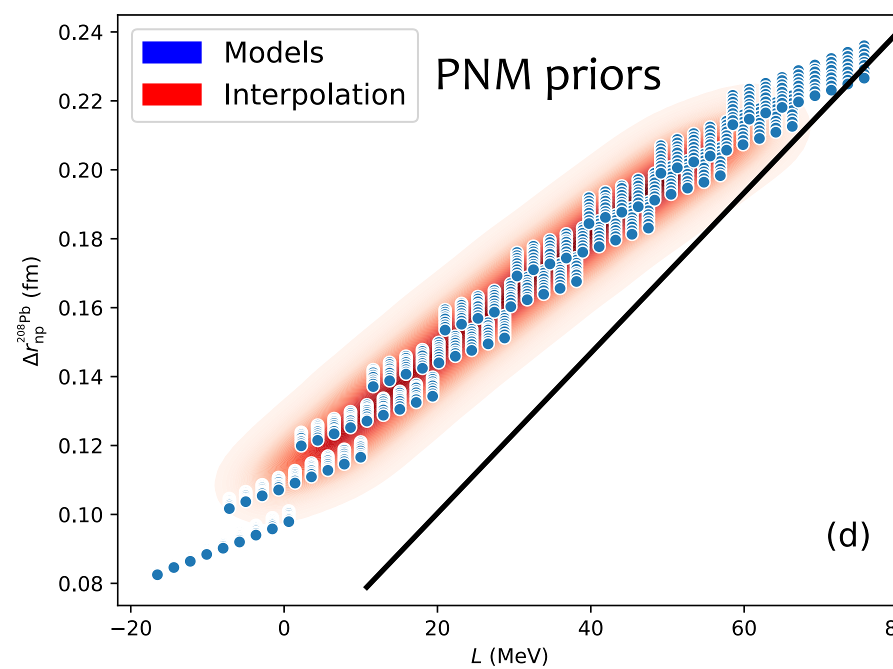

Mondal+(2016)
Viñas+(2014)
$R_{\rm skin}^{208{\rm Pb}}$ [fm]
$L$ [MeV]
Models
Interpolation
Uninformative priors
$\Delta r_{\rm np}^{208{\rm Pb}}$ (fm)
$L$ (MeV)
(b)
Models
Interpolation
PNM priors
$\Delta r_{\rm np}^{208{\rm Pb}}$ (fm)
$L$ (MeV)
(d)




Rebecca Preston, yesterday



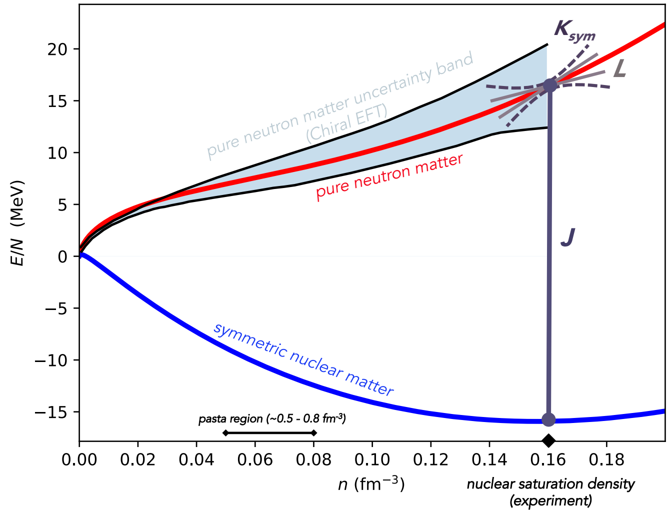
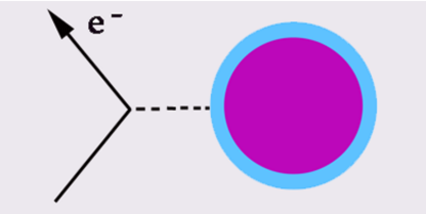
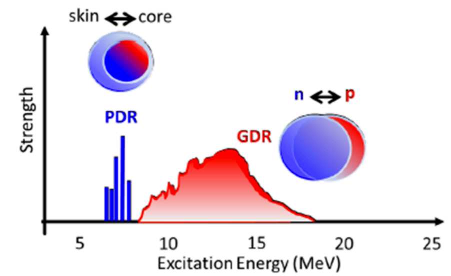



Figure: Lauren Balliet

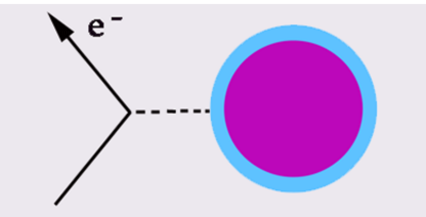
$$P(J, L, K_{\mathrm{sym}} | \mathcal{D})$$



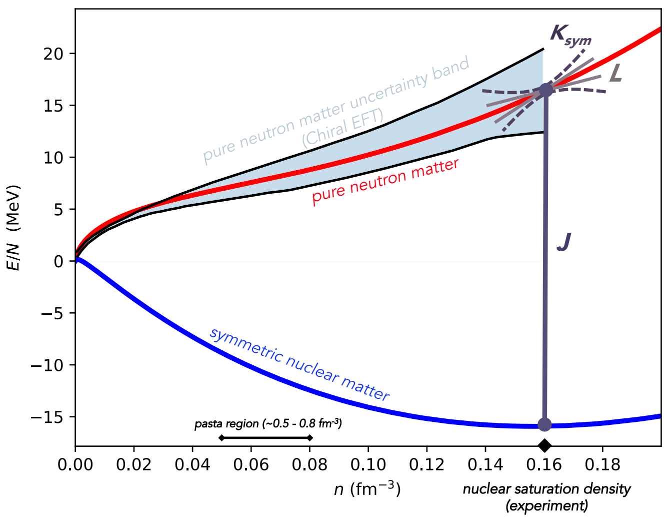



$$\begin{bmatrix} J \\ L \\ K_{\mathrm{sym}} \end{bmatrix} \Rightarrow \begin{bmatrix} x_0 \\ x_3 \\ x_4 \end{bmatrix} \Rightarrow \Delta r$$

Skyrme Hartree-Fock
SkyrmeRPA Comp Phys Comms, 184, (2013)




$$P(J, L, K_{\mathrm{sym}} | \mathcal{D})$$



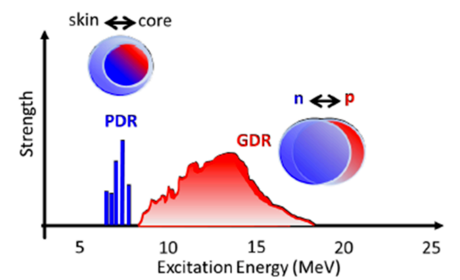




Figure: Lauren Balliet

Skyrme Hartree-Fock
SkyrmeRPA Comp Phys Comms, 184, (2013)

$$\underbrace{\begin{bmatrix} J \\ L \\ K_{\mathrm{sym}} \end{bmatrix} \rightarrow \begin{bmatrix} x_0 \\ x_3 \\ x_4 \end{bmatrix} \rightarrow \Delta r}_{P(\Delta r | J, L, K_{\mathrm{sym}})}$$

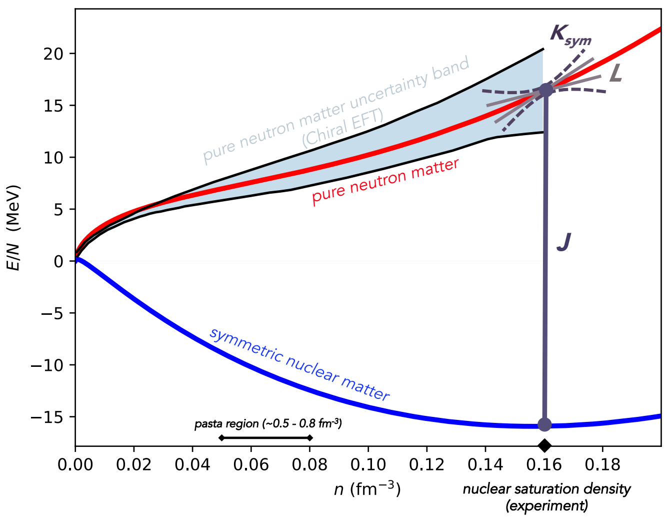
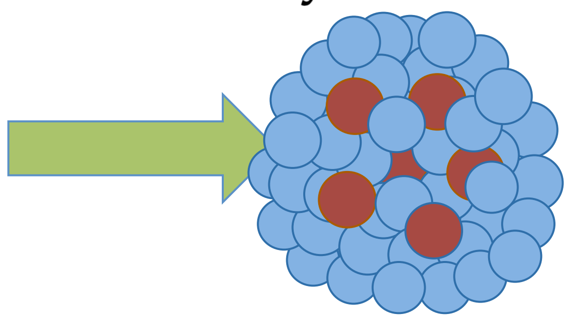
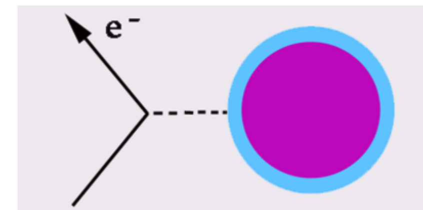
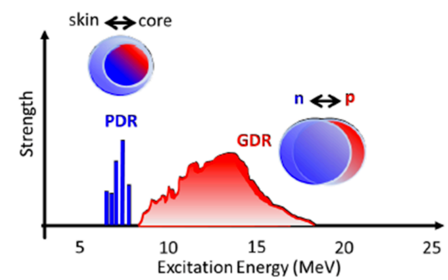



Figure: Lauren Balliet





Skyrme Hartree-Fock
SkyrmeRPA Comp Phys Comms, 184, (2013)

$$\underbrace{\begin{bmatrix} J \\ L \\ K_{\mathrm{sym}} \end{bmatrix} \longrightarrow \begin{bmatrix} x_0 \\ x_3 \\ x_4 \end{bmatrix} \longrightarrow \Delta r}_{P(\Delta r | J, L, K_{\mathrm{sym}})}$$

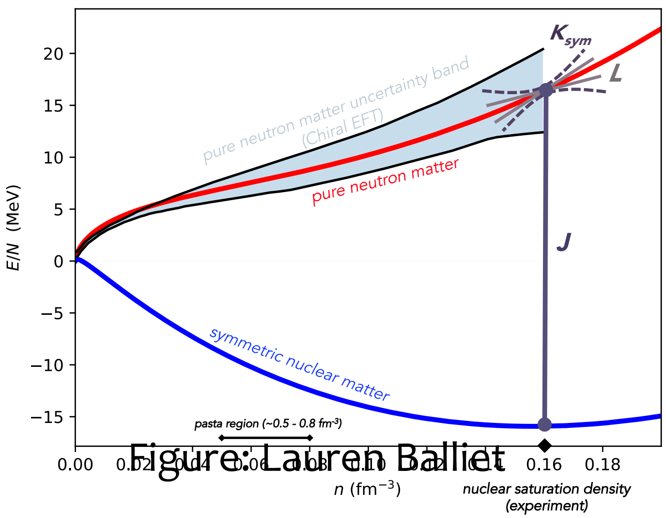
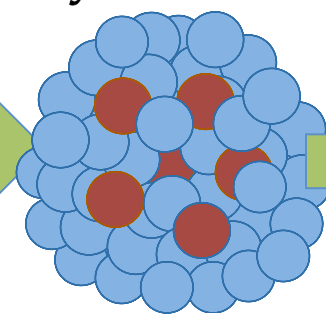
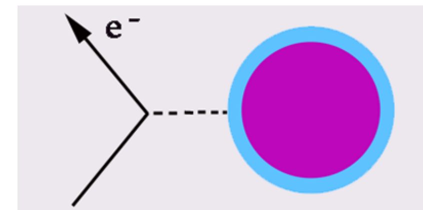
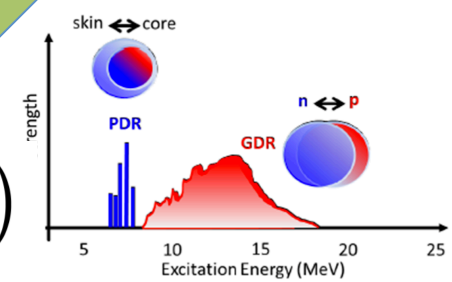


Figure: Lauren Balliet



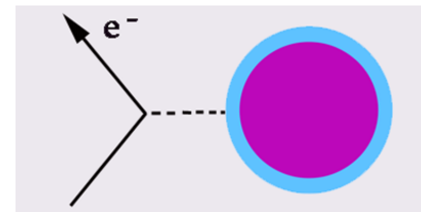



$$P(\mathcal{D} | \Delta r) = \exp\left[ - \frac{(\Delta r_{\mathrm{np}}^{\mathrm{data}} - \Delta r_{\mathrm{np}}(J, L, K_{\mathrm{sym}}))^2}{2\sigma^2_{\mathrm{data}}} \right]$$

Skyrme Hartree-Fock
SkyrmeRPA Comp Phys Comms, 184, (2013)

$$\underbrace{\begin{bmatrix} J \\ L \\ K_{\text{sym}} \end{bmatrix} \longrightarrow \begin{bmatrix} x_0 \\ x_3 \\ x_4 \end{bmatrix} \longrightarrow \Delta r}_{P(\Delta r | J, L, K_{\text{sym}}) P(\mathcal{D} | \Delta r)}$$



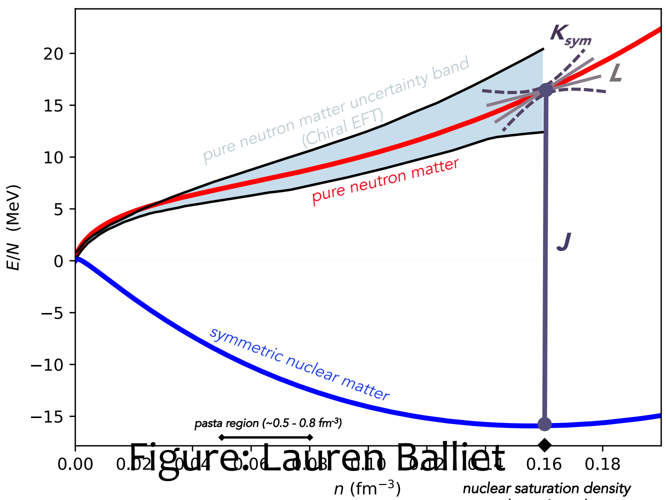
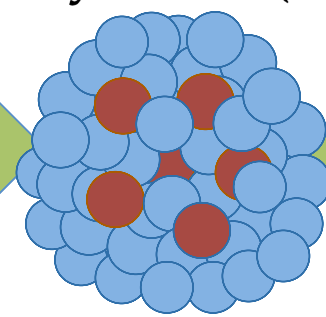
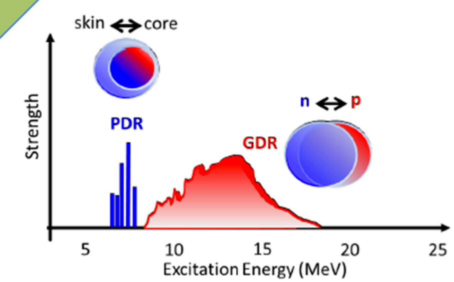




Figure: Lauren Balliet






$$P(J, L, K_{sym} | \mathcal{D}) = \frac{1}{N} P(\mathcal{D} | J, L, K_{sym}) P(J, L, K_{sym})$$

Posterior sampled
Using MCMC

Likelihood

Prior

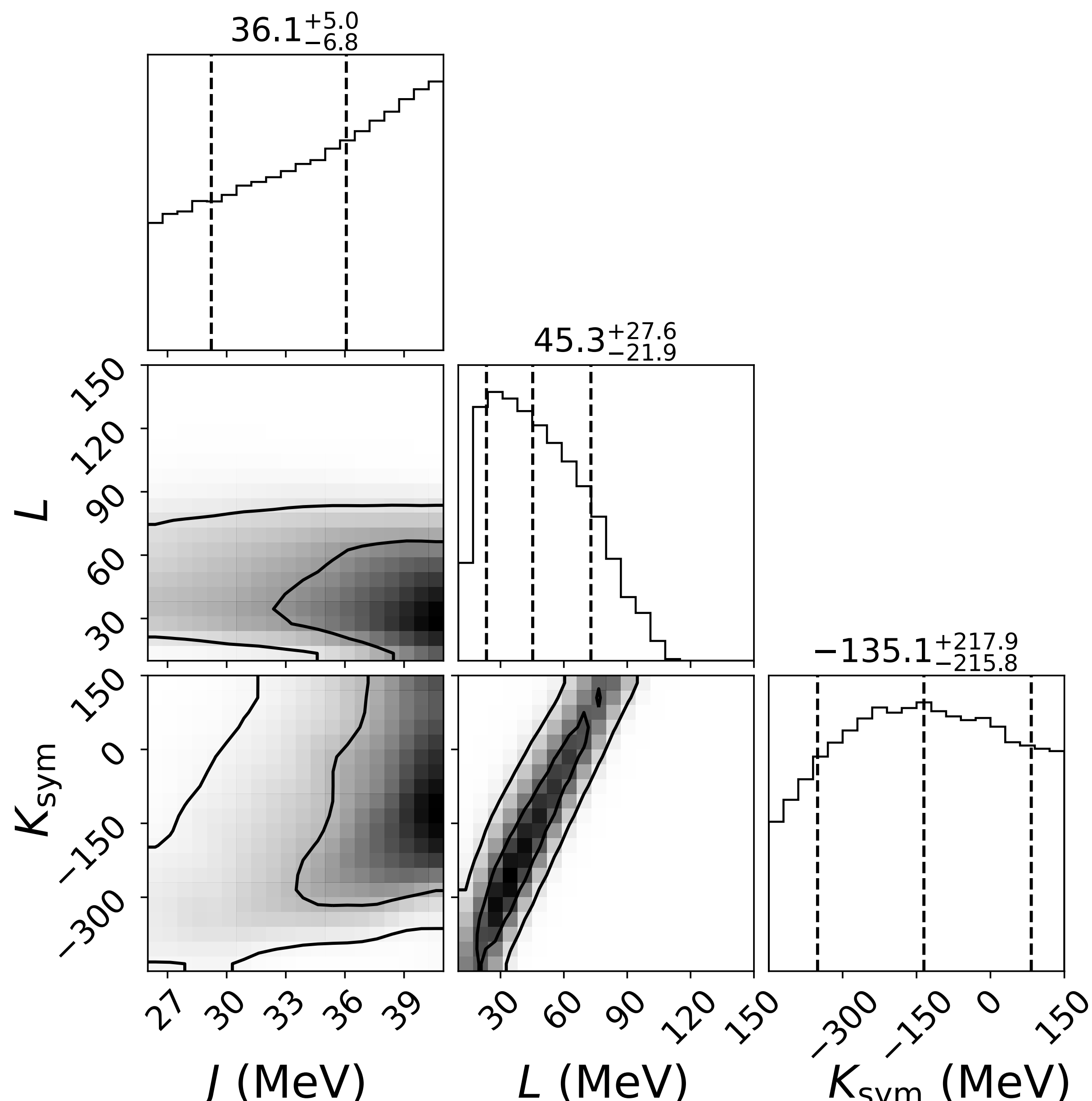
# Potential sources of systematic error

Had to choose an EDF (Skyrme). Enough degrees of freedom?
Can add more ($Q_{sym}$)

Symmetric nuclear matter and gradient parameters held fixed; extending inference to those parameters may change posteriors

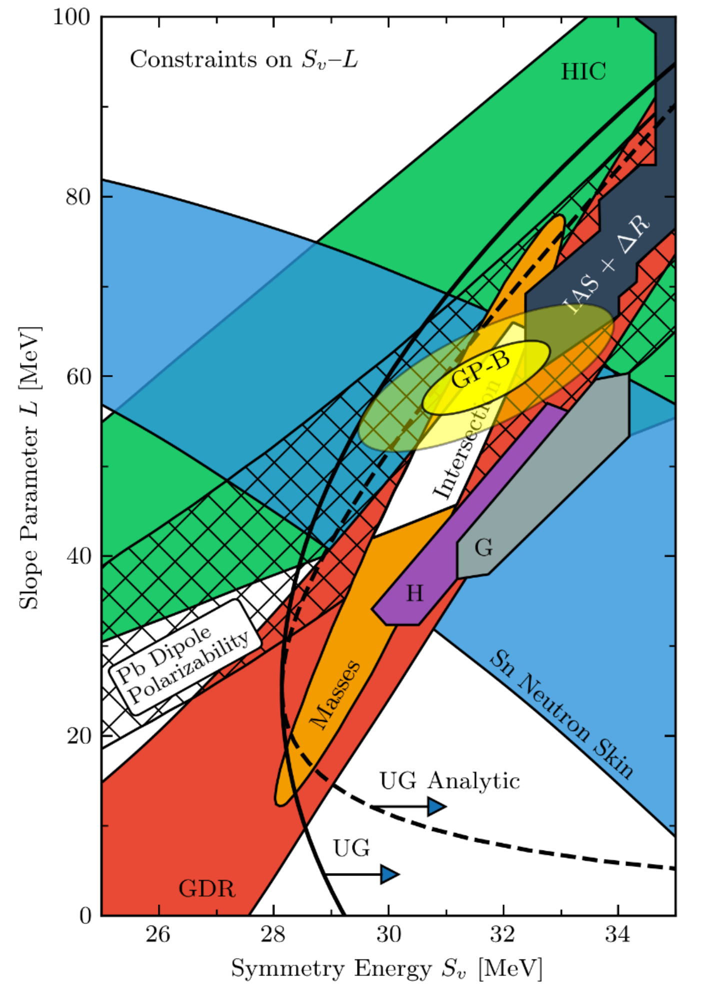
We're usually not directly modeling nuclear observables - but in some cases we could (e.g. weak form factor) and thus improve consistency

# Neutron skins: Sn

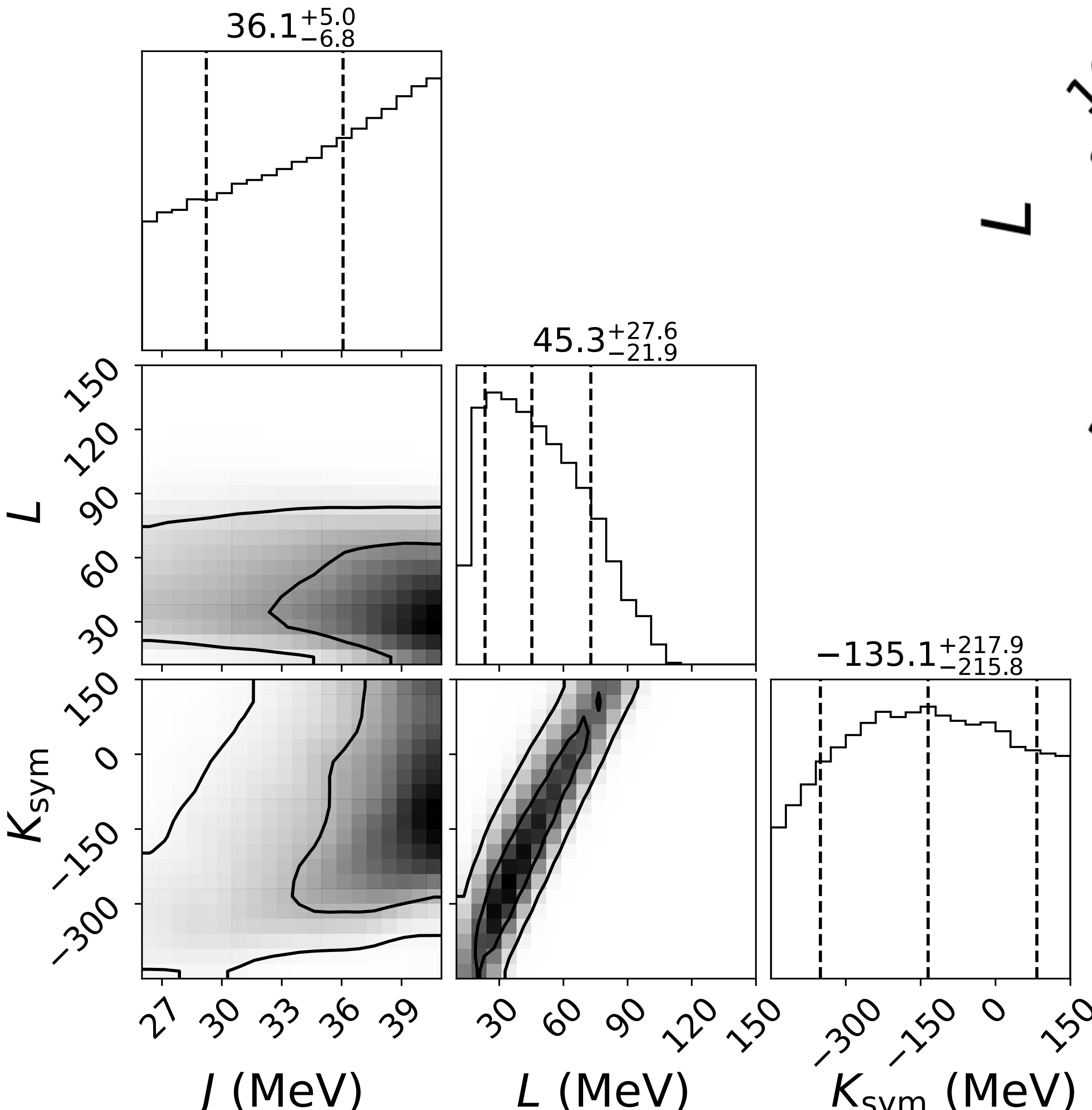


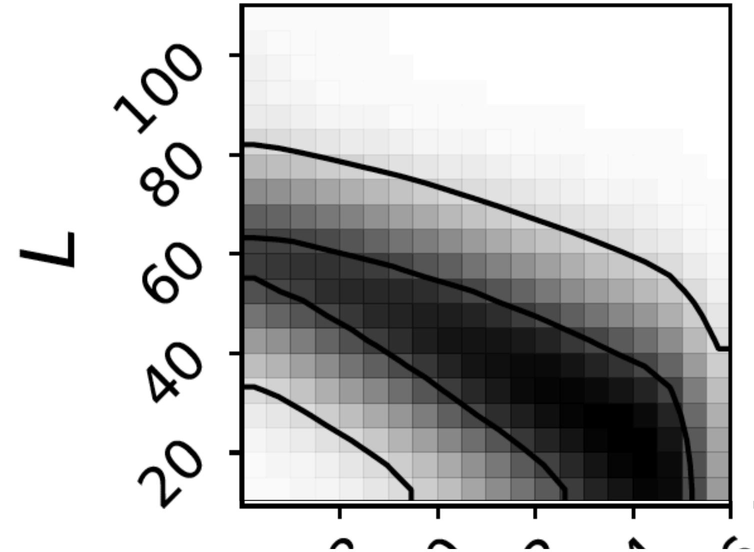

Li,Xie,Xu arxiv:2007.07669

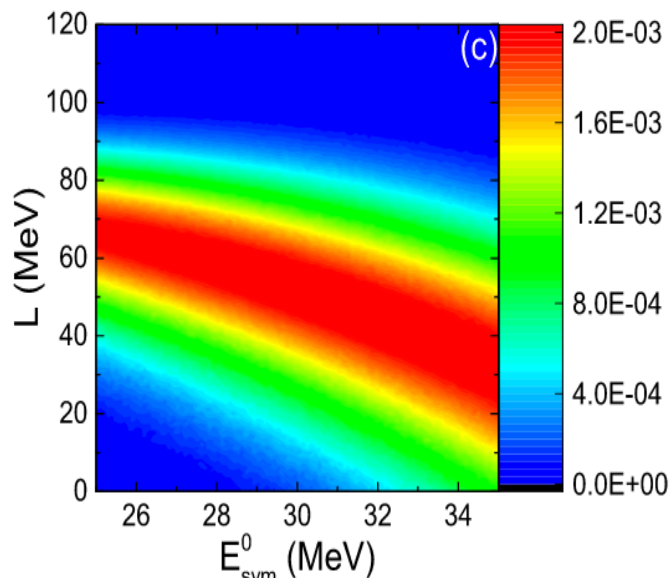
Drischler, arxiv:2004.07232



# Neutron skins: Sn

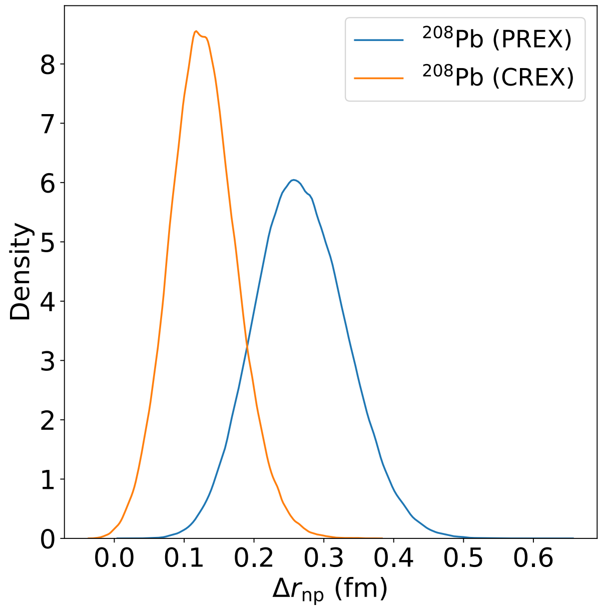


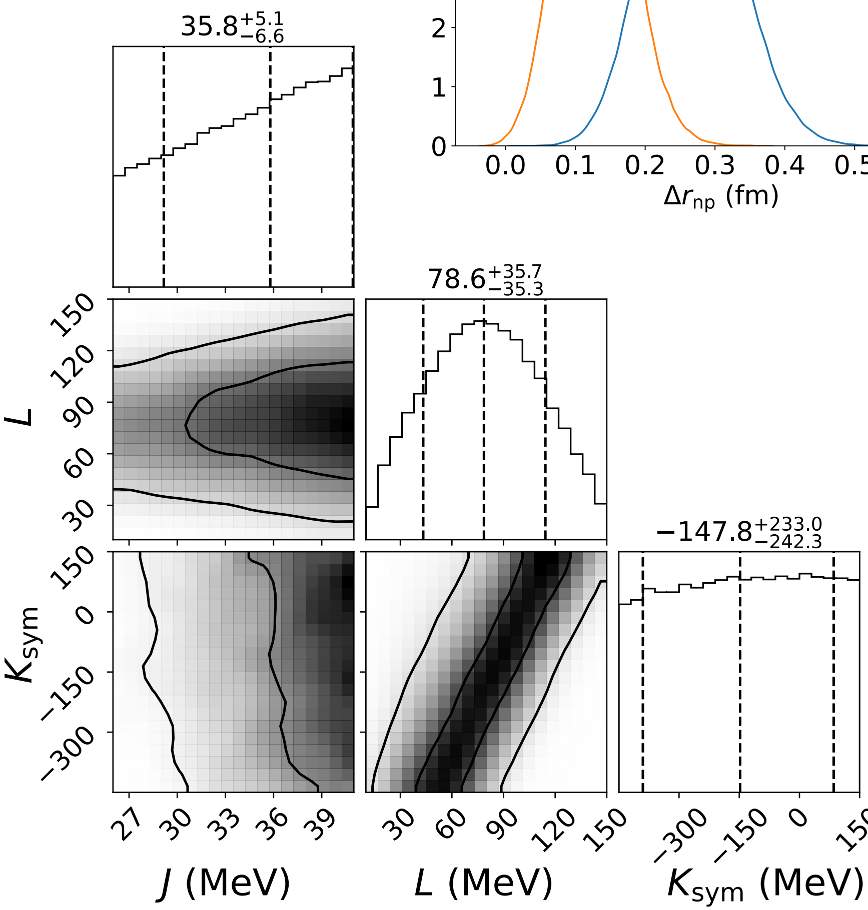



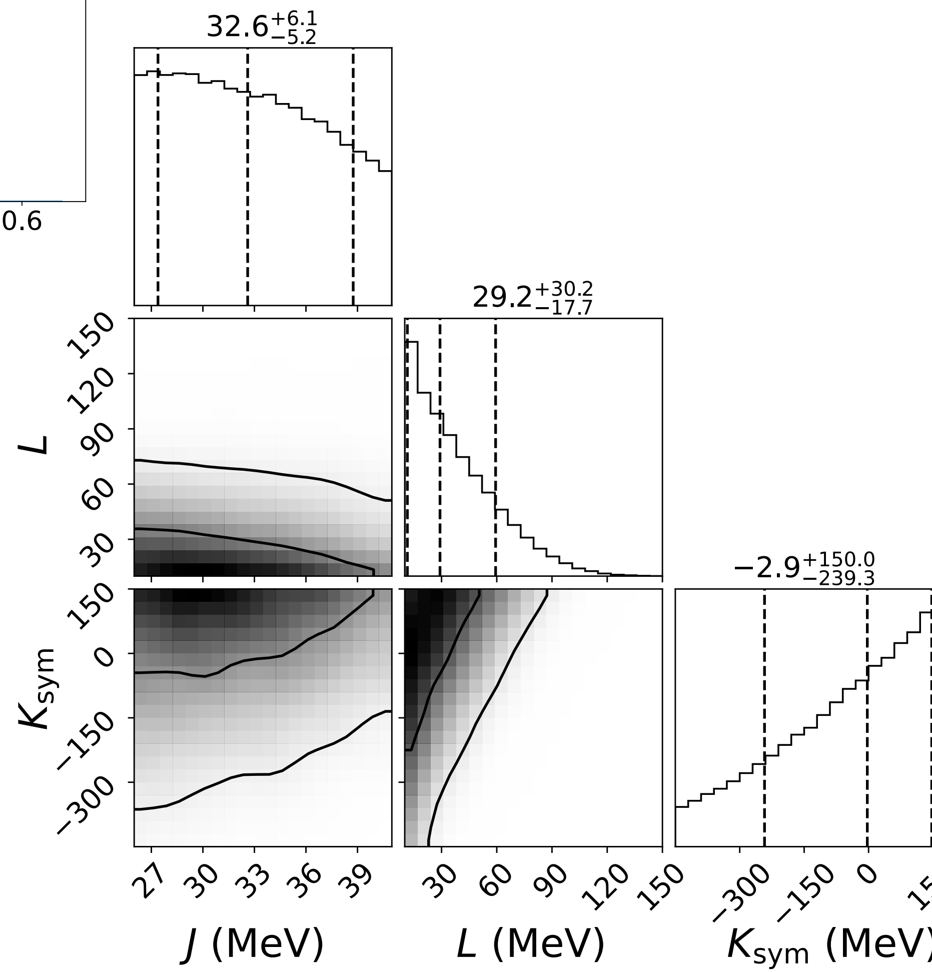




Li,Xie,Xu arxiv:2007.07669

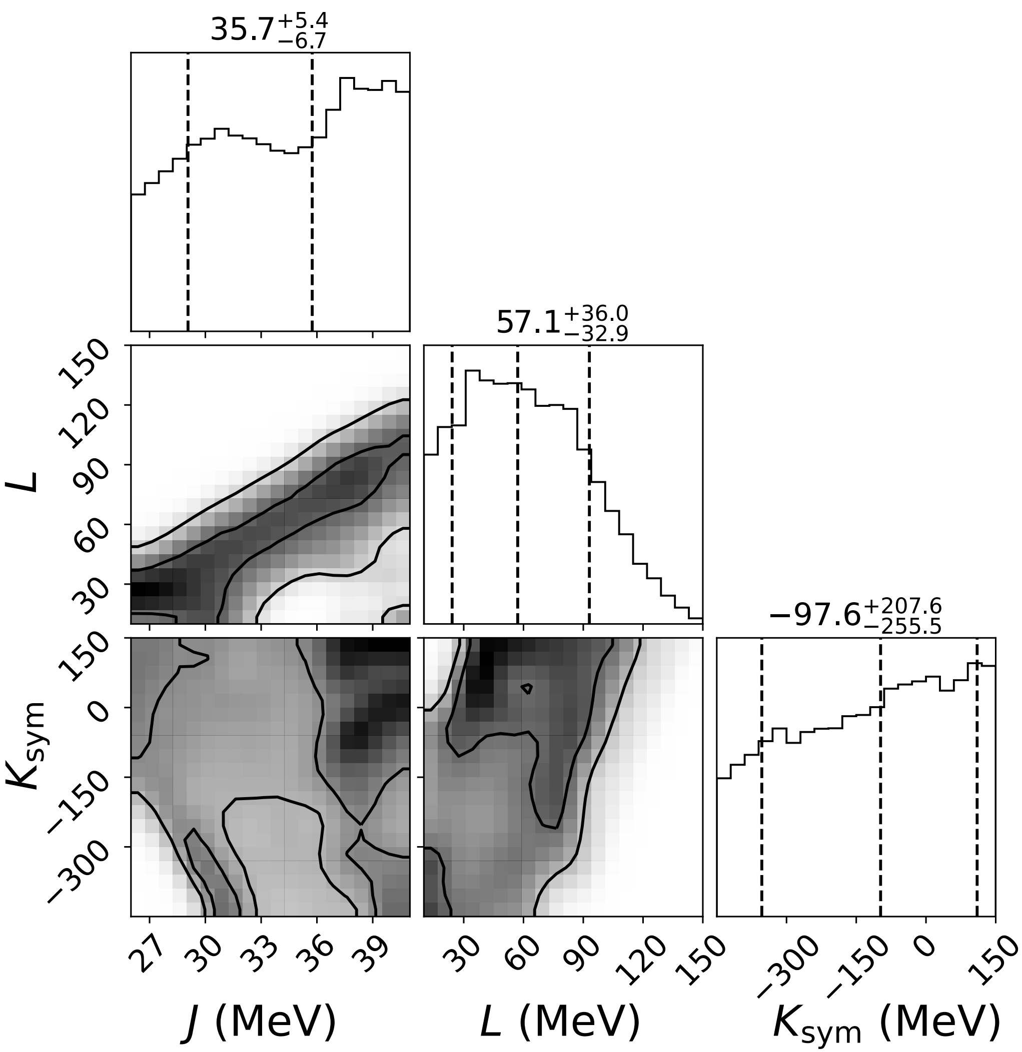
# Neutron skins: PREX & CREX



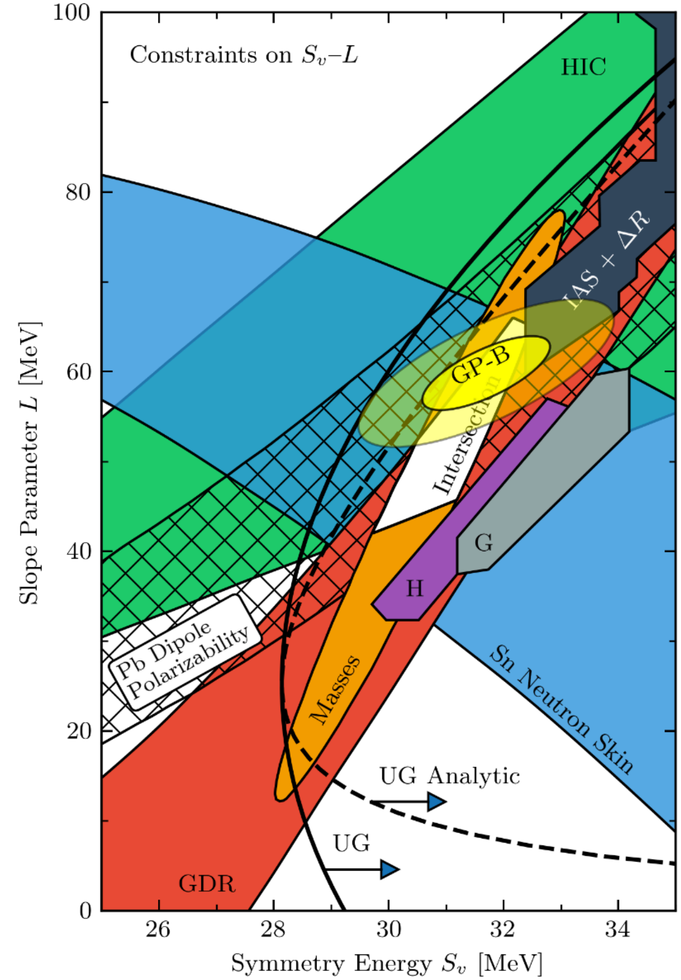



# Pb208, Ca48 Dipole Polarizability




Drischler, arxiv:2004.07232



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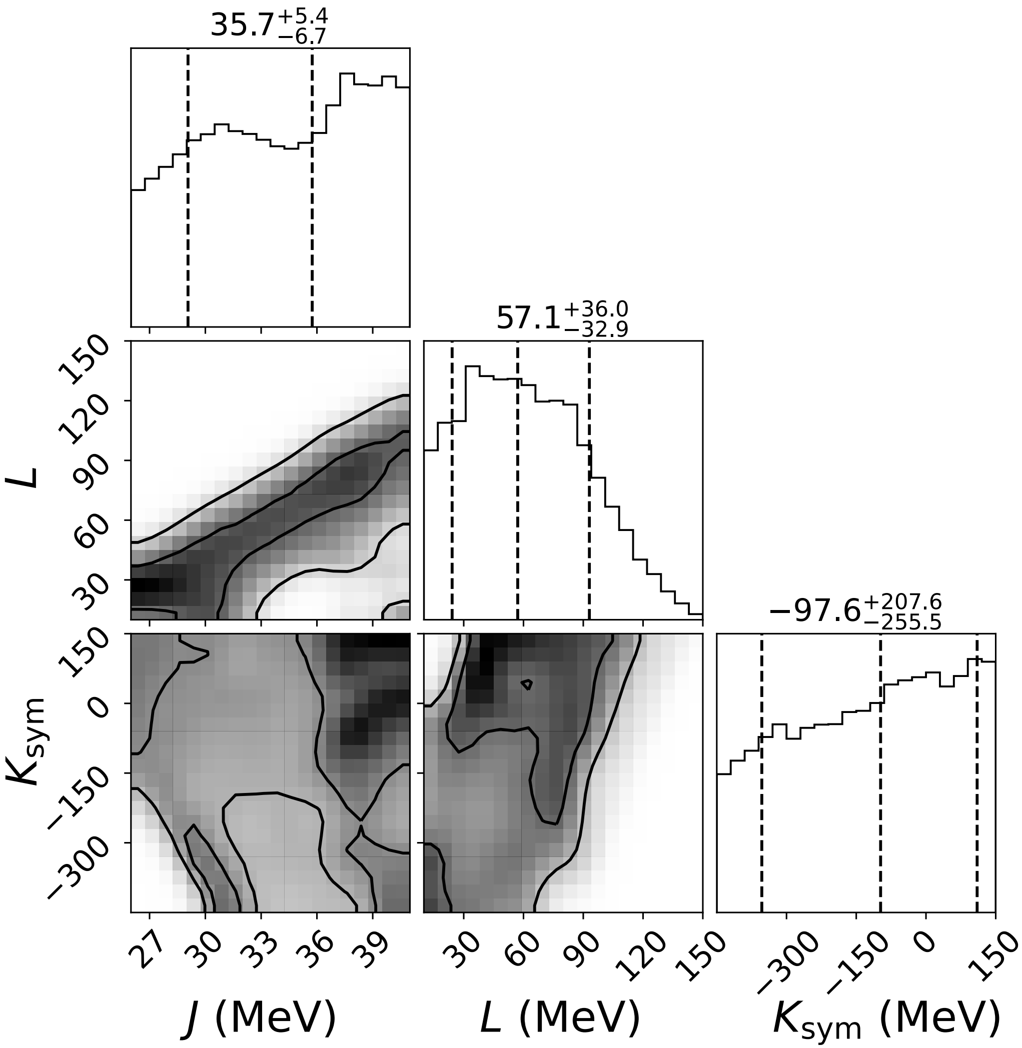
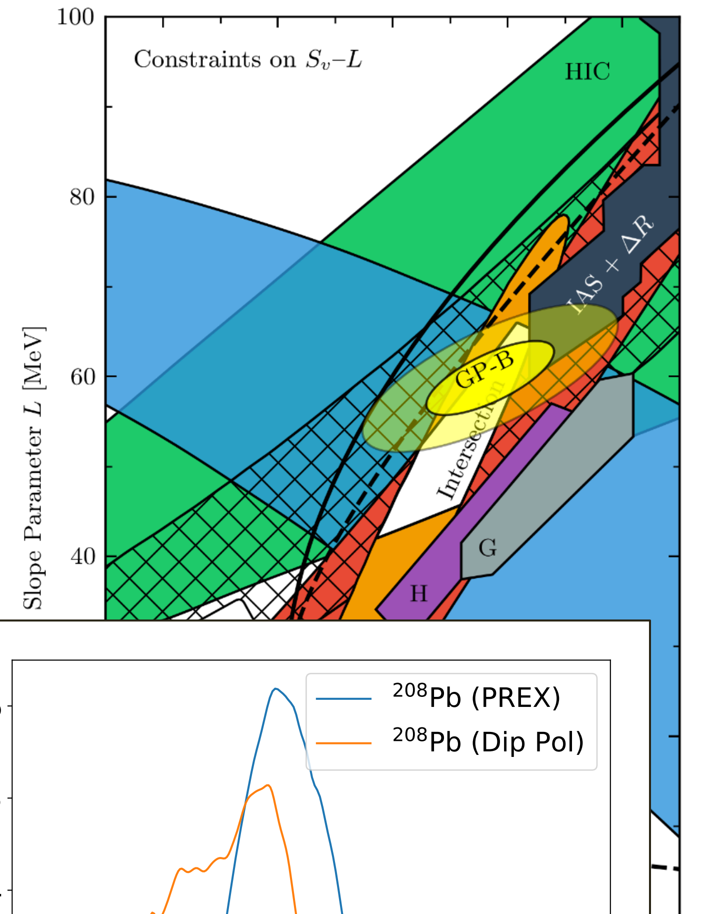
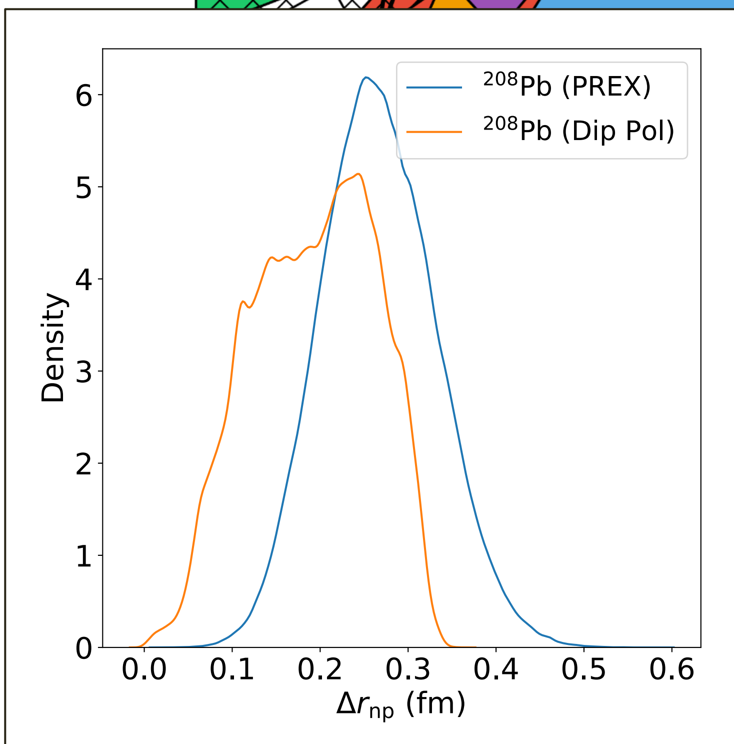
Drischler, arxiv:2004.07232

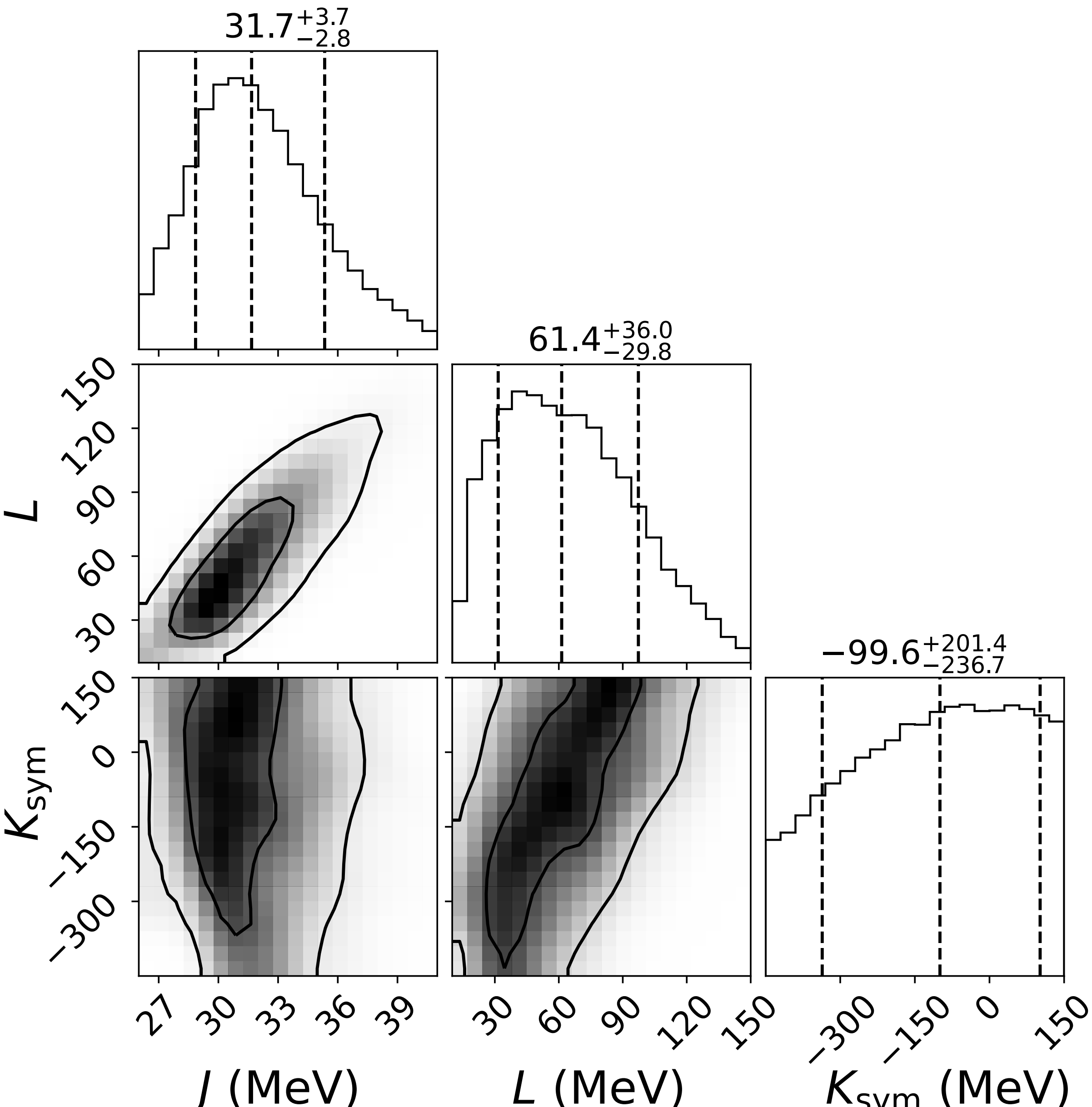


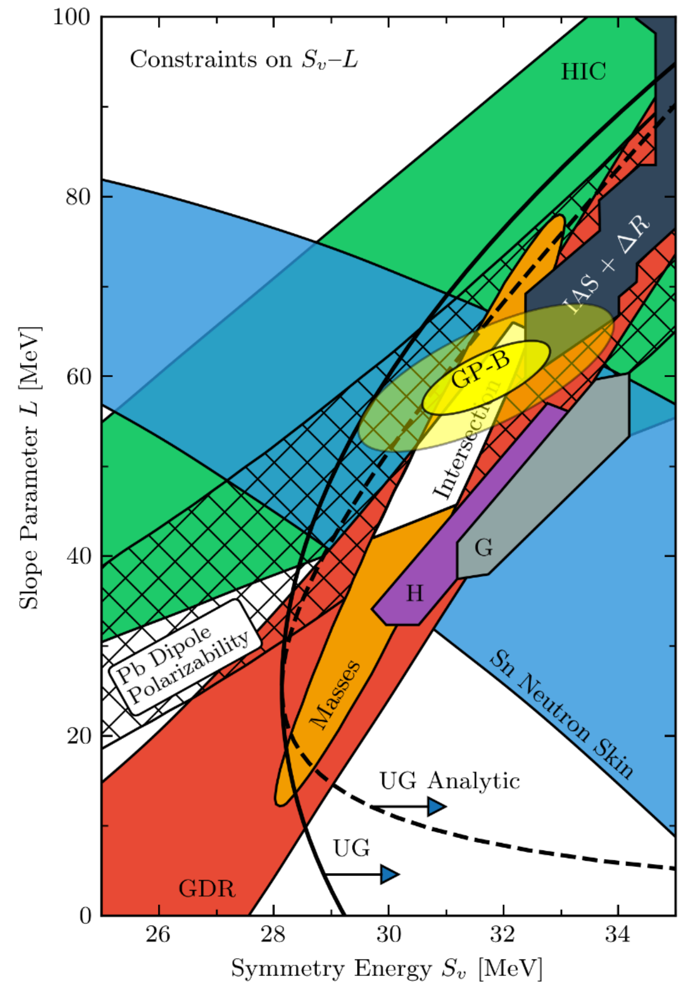



Drischler, arxiv:2004.07232

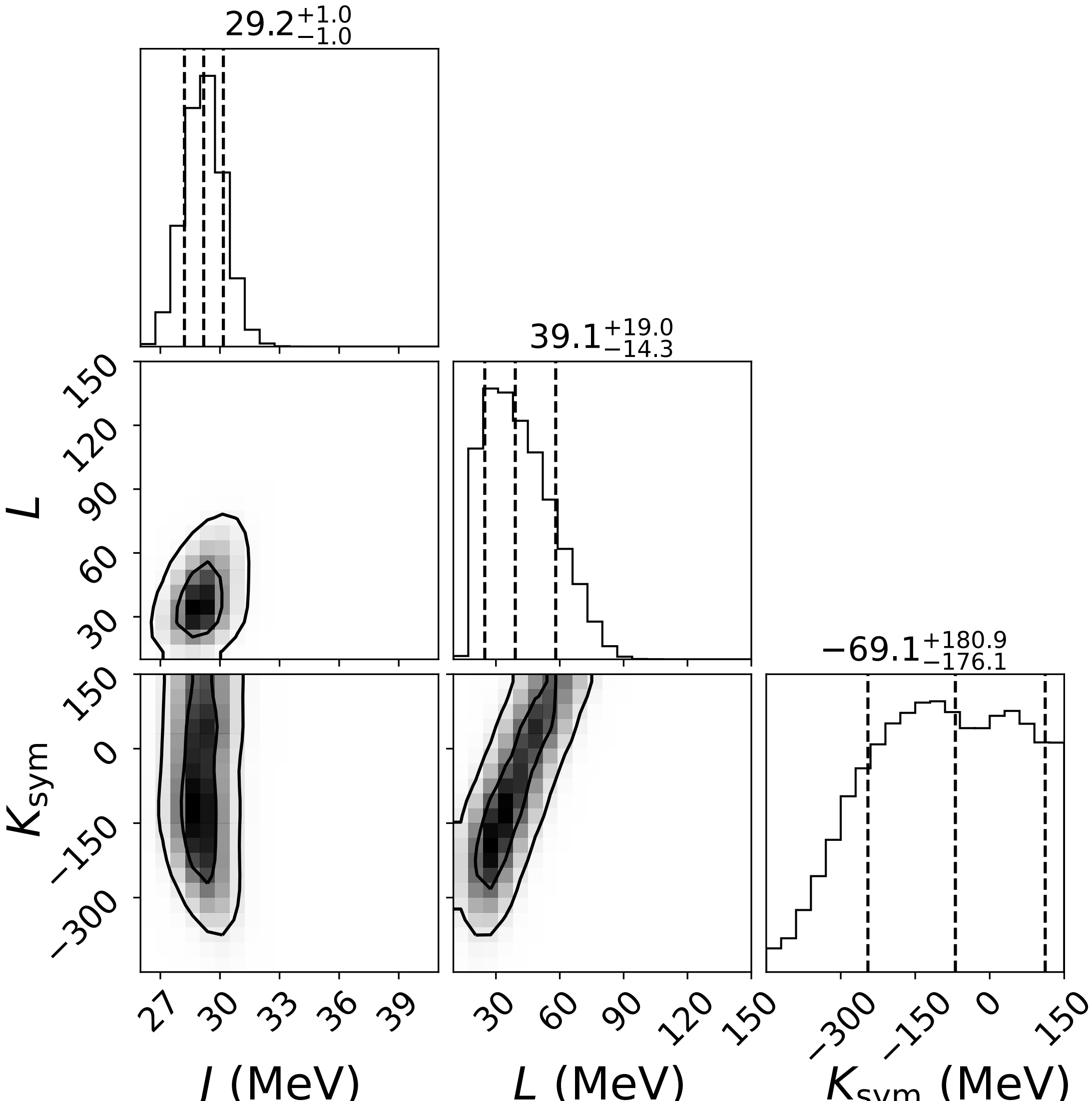
# Binding energies/charge radii

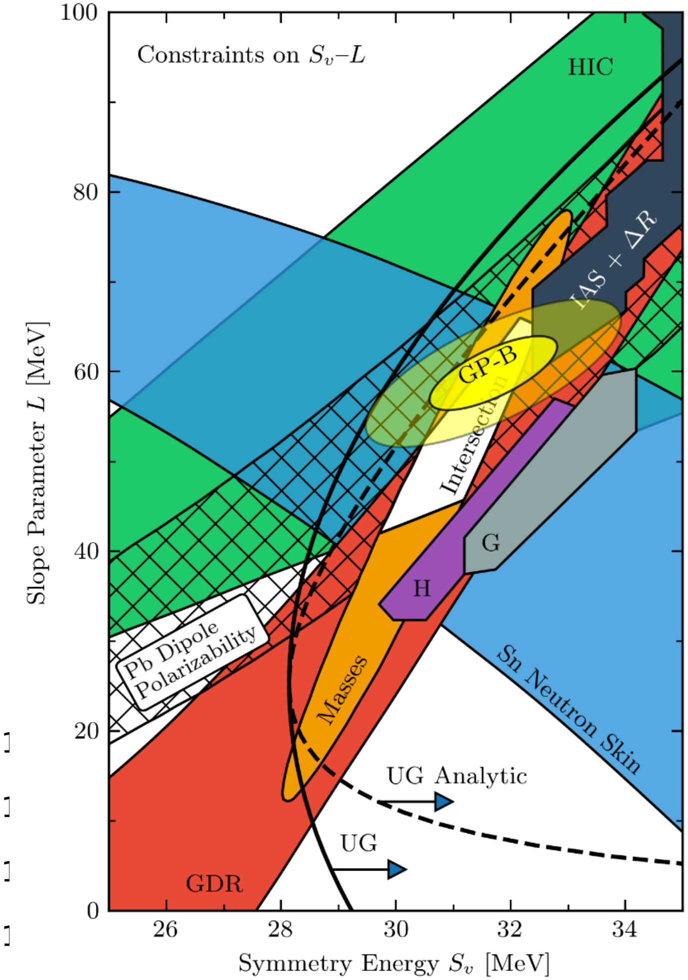


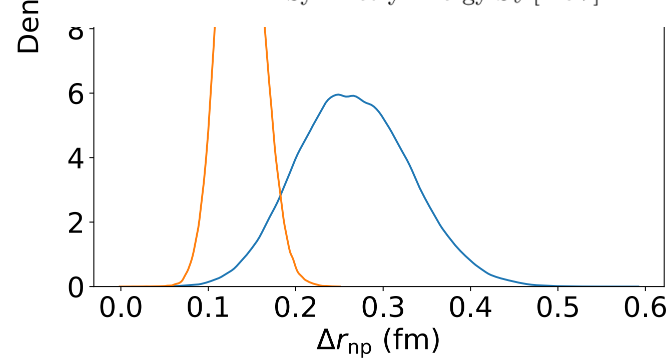



Drischler, arxiv:2004.07232

Skins (no PREX)+dip pol+BE+rp

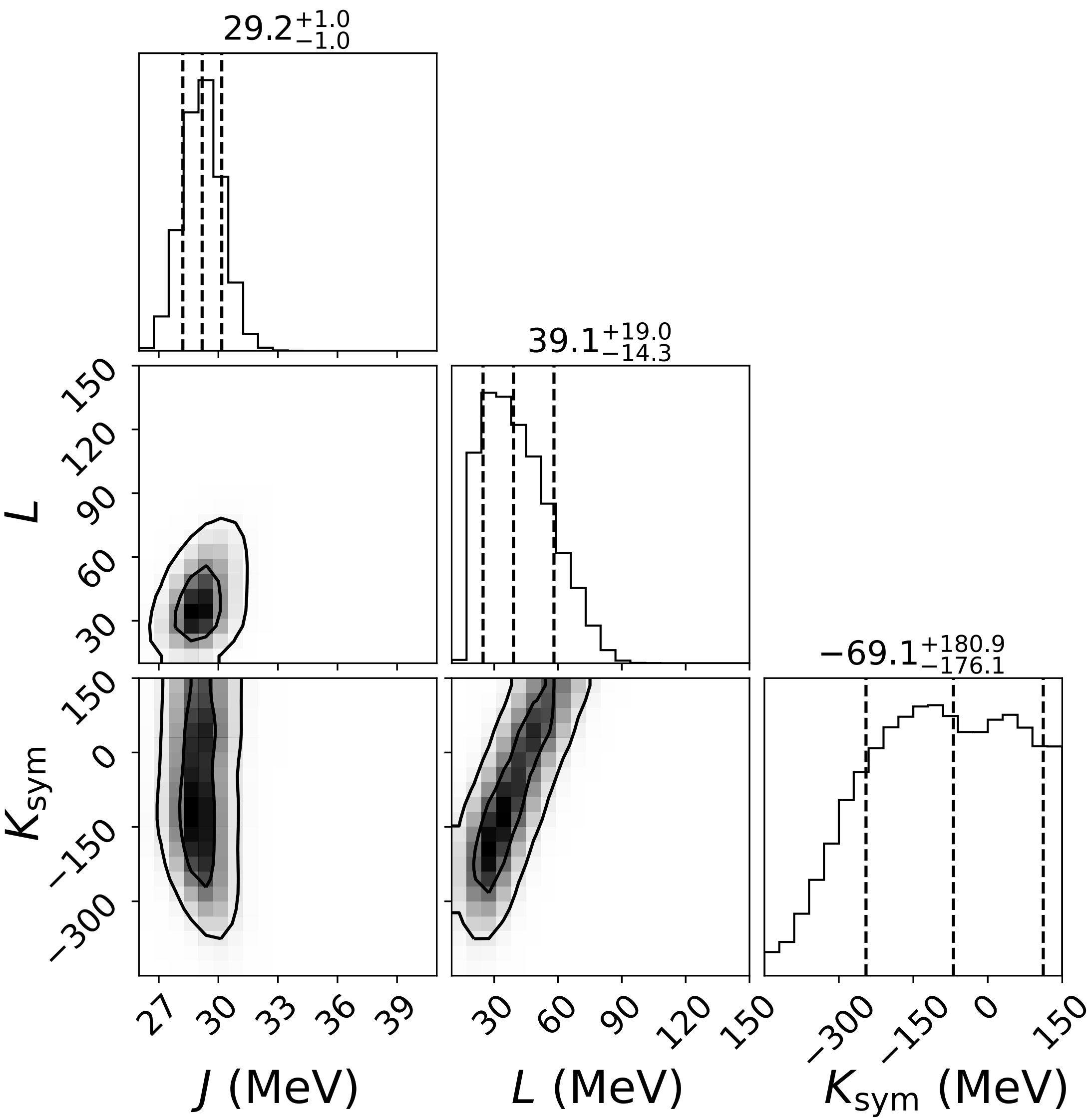


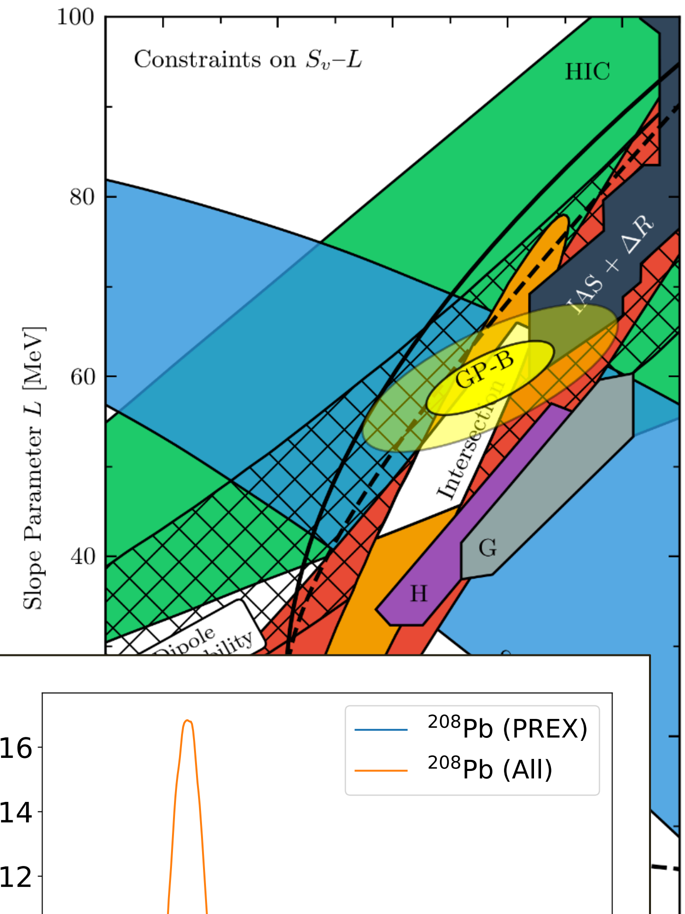



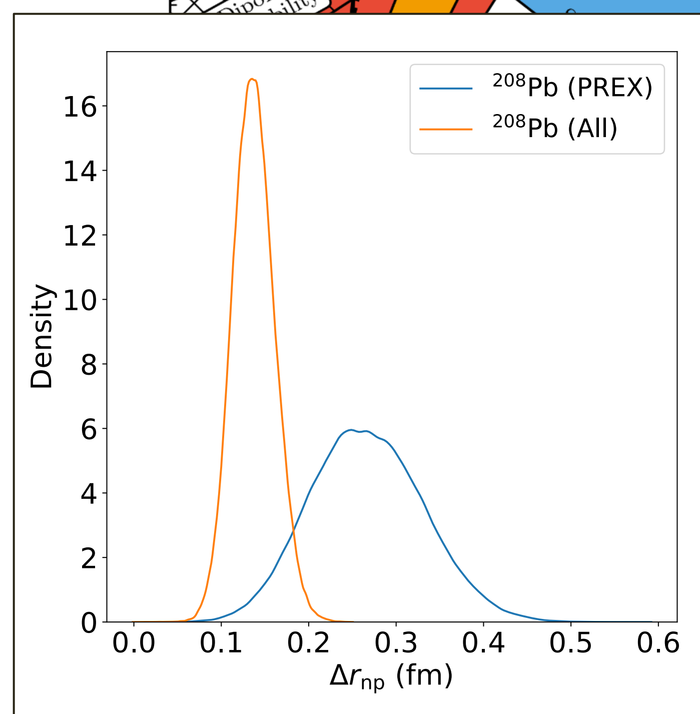



Drischler, arxiv:2004.07232

Skins (no PREX)+dip pol+BE+rp



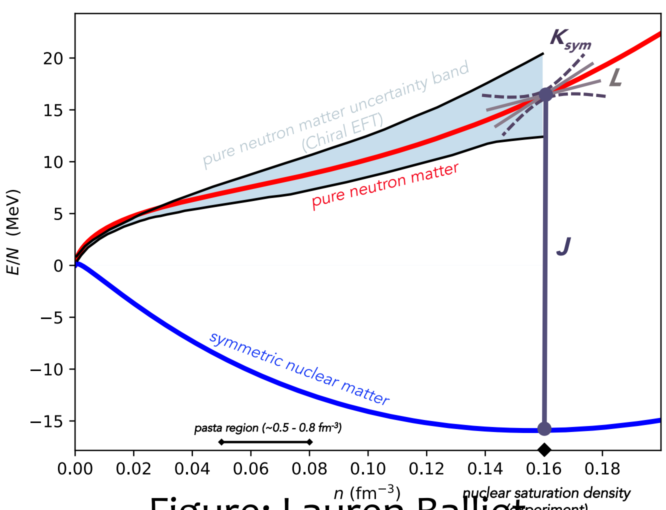
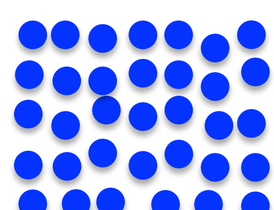
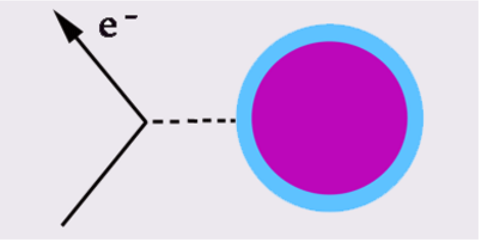


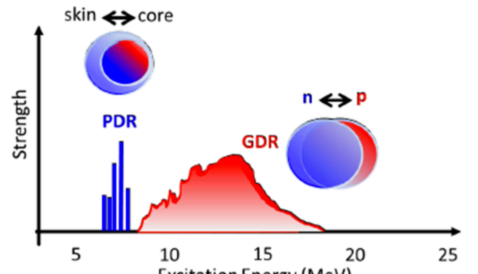

Figure: Lauren Balliet

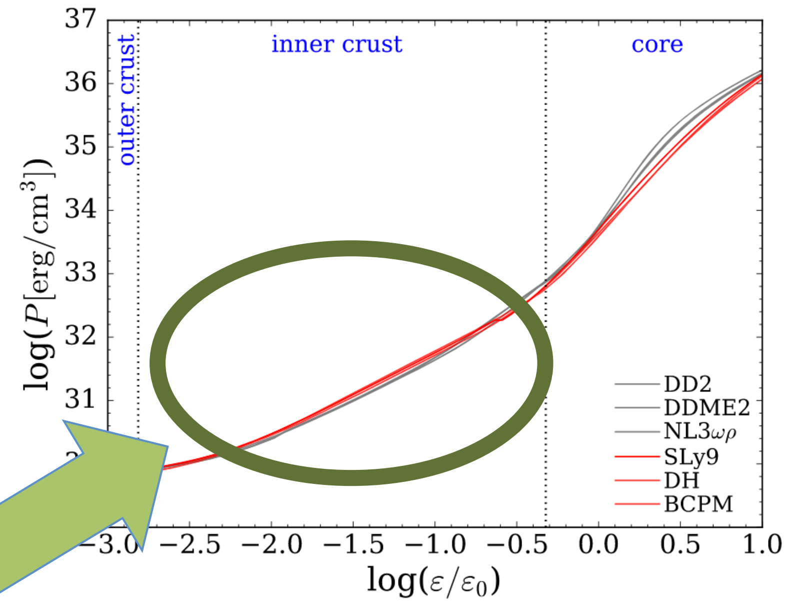
$$P(J, L, K_{\mathrm{sym}} | \mathcal{D})$$

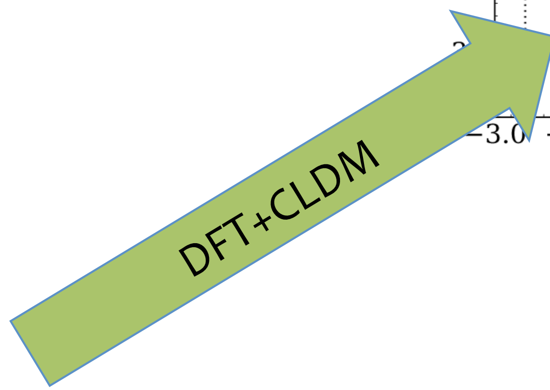
DFT







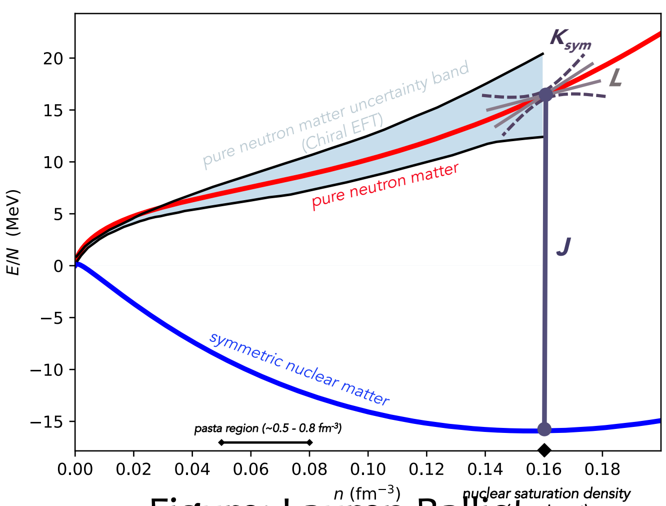
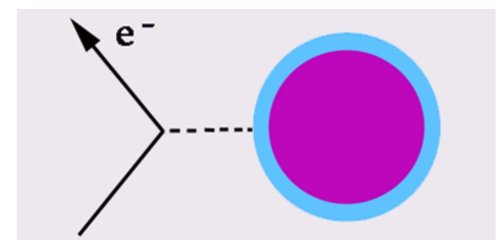
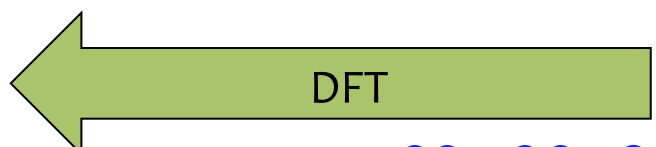
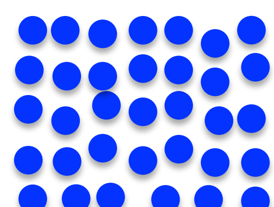



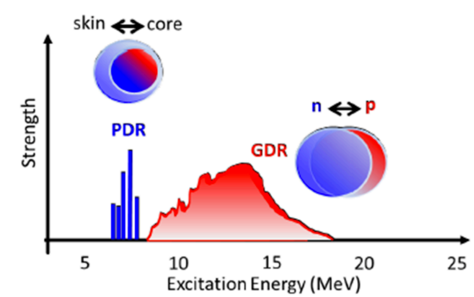

Figure: Lauren Balliet

$$P(J, L, K_{\mathrm{sym}} | \mathcal{D})$$

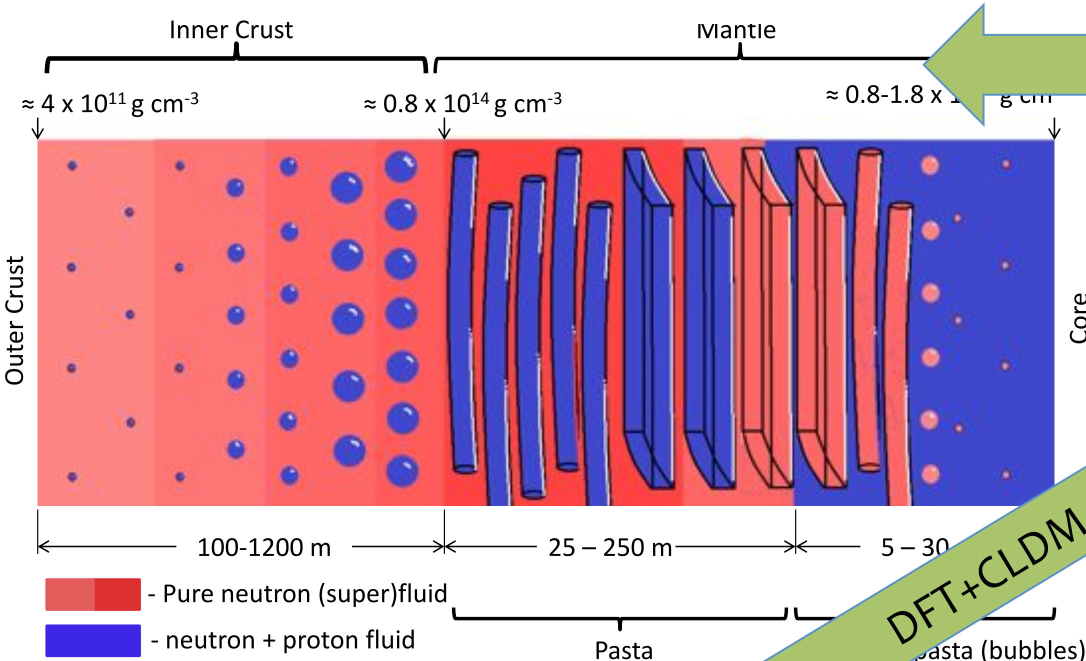


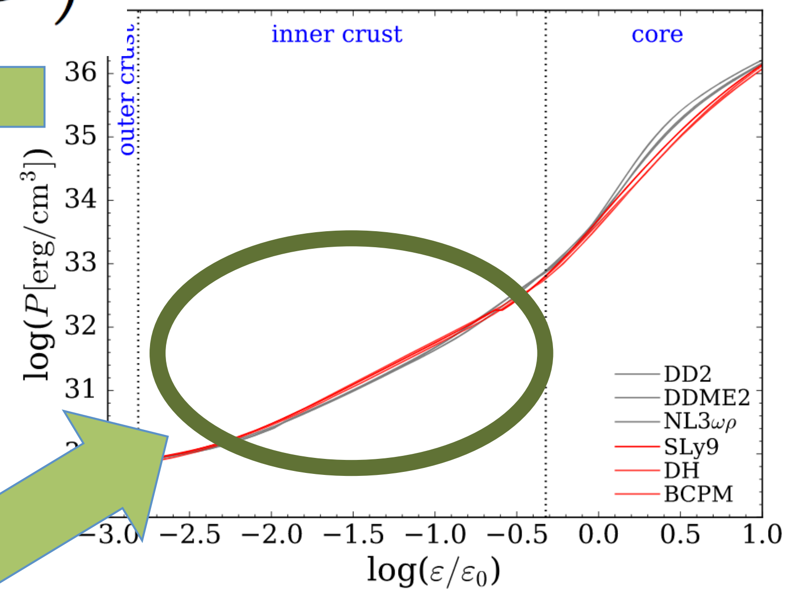





$$P(\text{Fraction of pasta}|\mathcal{D})$$




DFT+CLDM

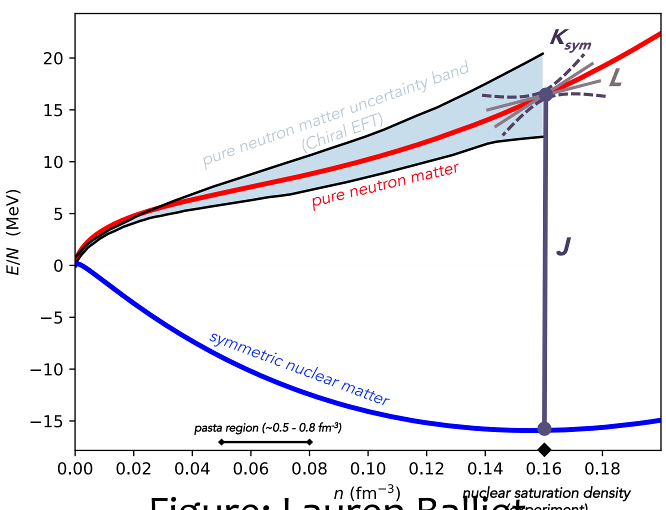
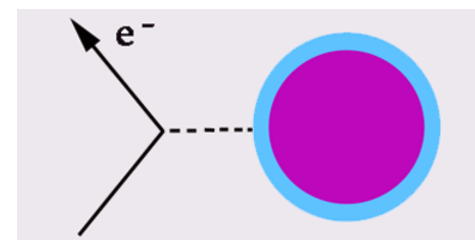
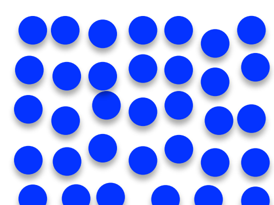


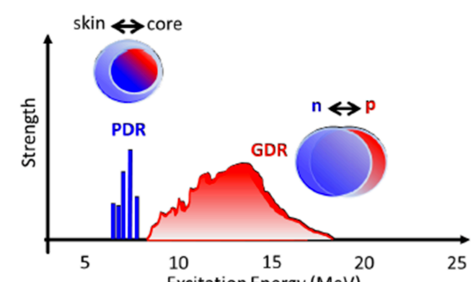

Figure: Lauren Balliet

$$P(J, L, K_{\text{sym}}|\mathcal{D})$$

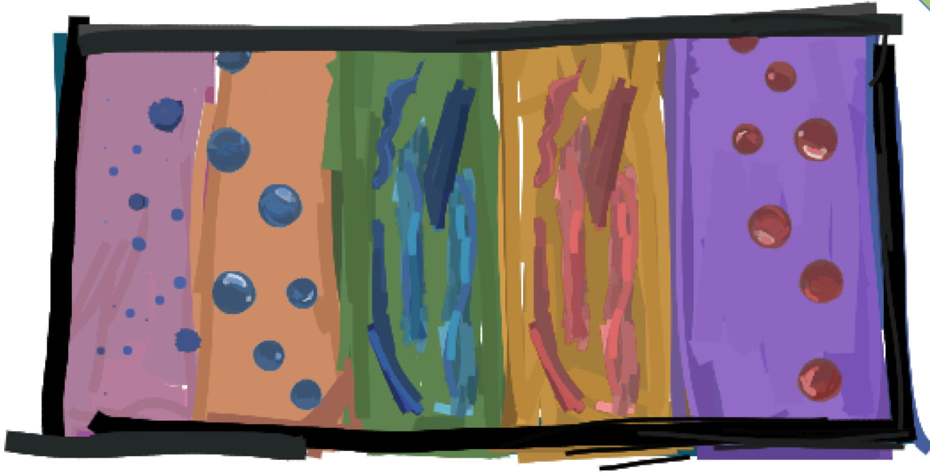
DFT



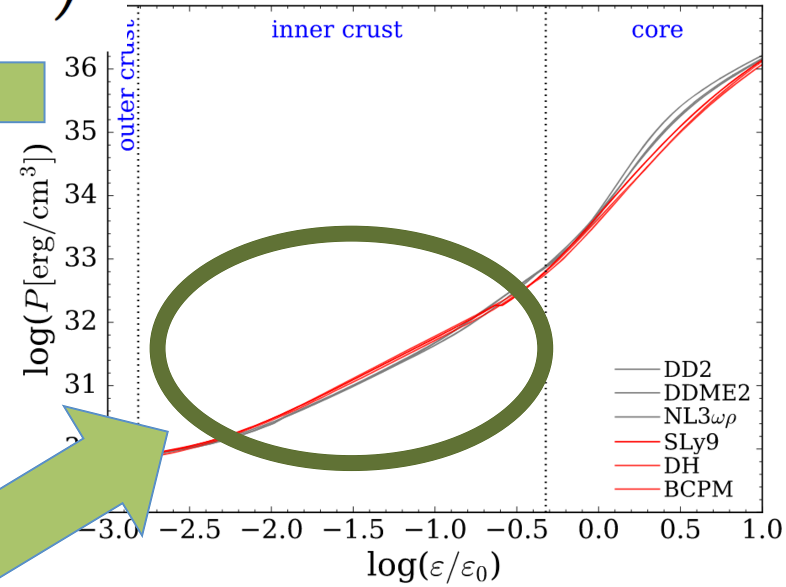





$$P(\text{Fraction of pasta}|\mathcal{D})$$



Noa Fritschie, 2022




DFT+CLDM

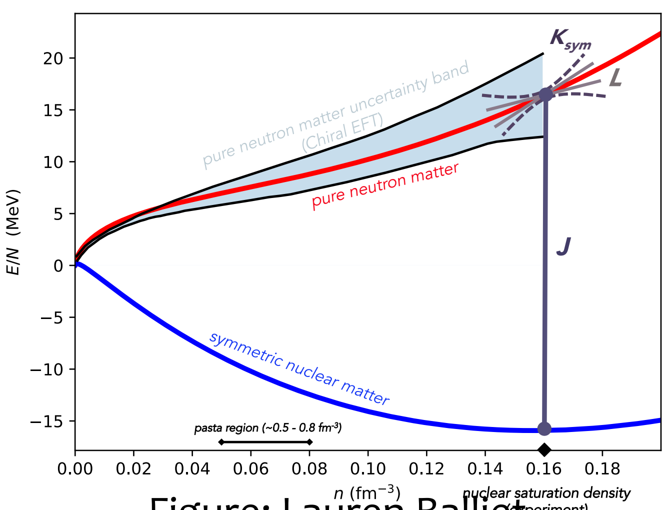
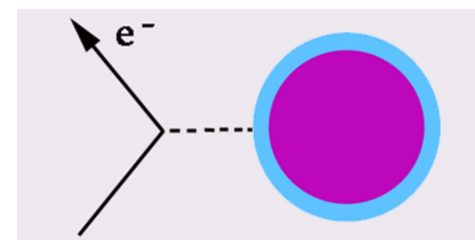
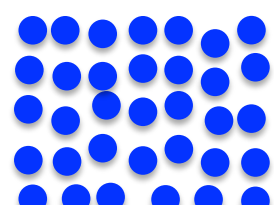


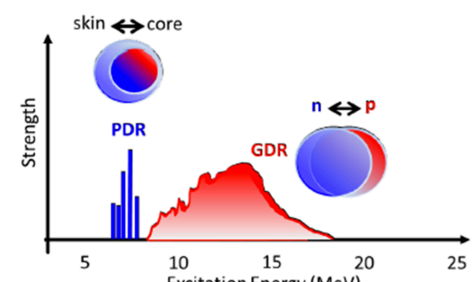

Figure: Lauren Balliet

$$P(J, L, K_{\mathrm{sym}}|\mathcal{D})$$



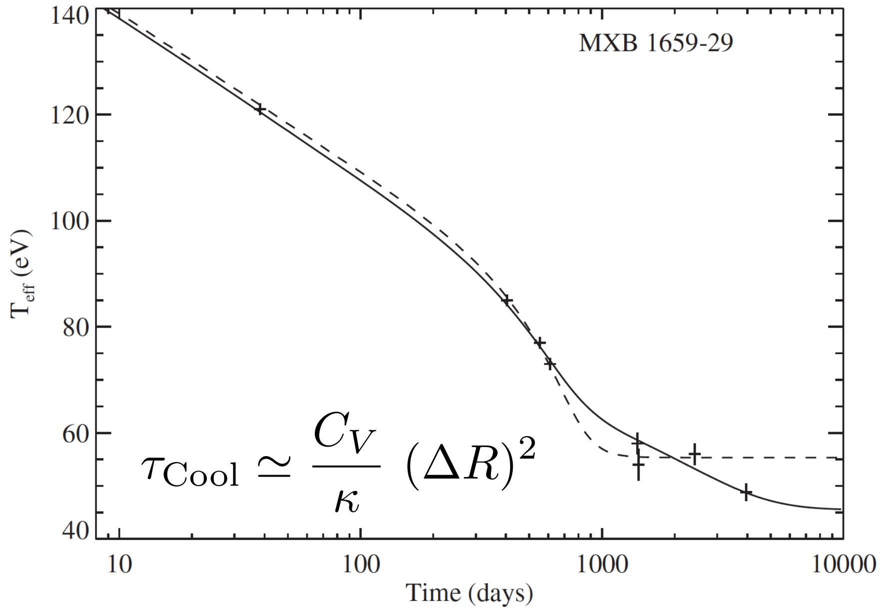

DFT



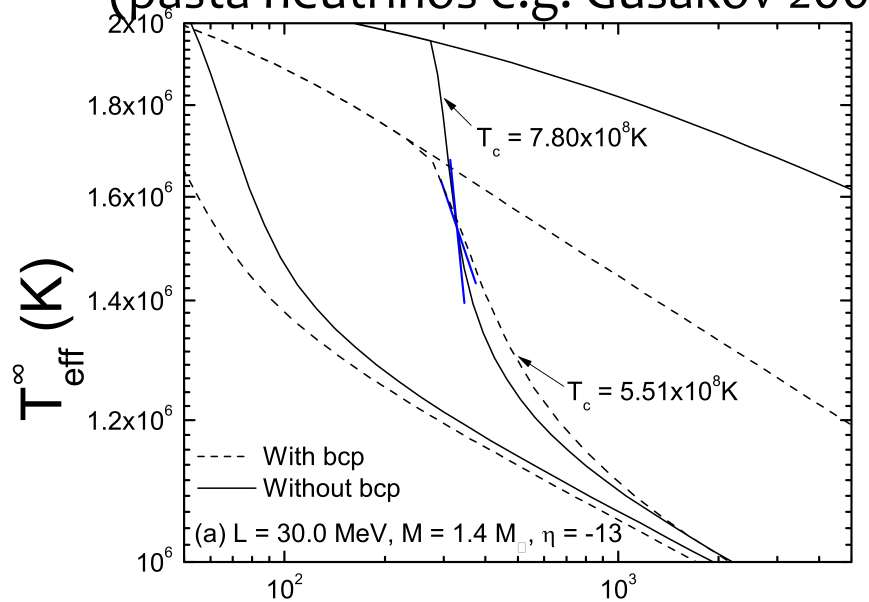


# A number of ways pasta and the physics of the crust-core boundary leave signatures on observables have tentatively been put forward

Horowitz+, PRL114, 031102 (2015)
Cooling of accreted crusts




Newton+, ApJL 779, 4 (2013)
Cooling in isolated neutron stars
(pasta neutrinos e.g. Gusakov 2004)




Magnetic field evolution - Pons Nature Physics, 9, 7, 431-434 (2013)
Mountains on neutron stars - Gearheart, Newton, Li, MNRAS 418 (2011)
Crust oscillations… - Gearheart+, MNRAS 418 (2011)
… leading to resonant shattering – Neill+, MNRAS 504, 2021
Pulsar glitches – Graber+, Apj 865, 23 (2018)
Evolution of r-modes – Wen+Phys Rev C, 85, 025801 (2012)
Vidana Phys Rev C 85, 045808 (2012)

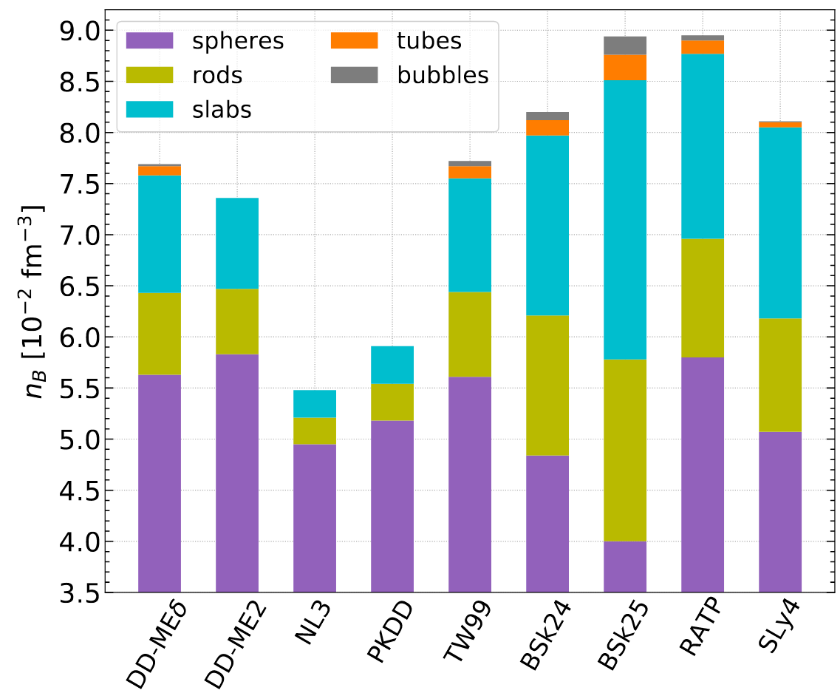
# The amount of crust and pasta is highly nuclear-EOS dependent

| Model | $\rho_{tt}$ [fm$^{-3}$] | $Y_{p,tt}$ | $P_{tt}$ [MeVfm$^{-3}$] | $\rho_{td}$ [fm$^{-3}$] | $Y_{p,td}$ | $P_{td}$ [MeVfm$^{-3}$] |
|---|---|---|---|---|---|---|
| Microscopic | | | | | | |
| BHF-1 | 0.061 | 0.023 | 0.193 | | | |
| BHF-1$_{\text{para}}$ | 0.083 | 0.026 | 0.400 | | | |
| BHF-2 | 0.078 | 0.027 | 0.370 | | | |
| BHF-2$_{\text{para}}$ | 0.094 | 0.028 | 0.571 | | | |
| Skyrme | | | | | | |
| BSk14 | 0.090 | 0.033 | 0.483 | 0.081 | 0.030 | 0.381 |
| BSk16 | 0.096 | 0.037 | 0.502 | 0.087 | 0.035 | 0.402 |
| BSk17 | 0.095 | 0.036 | 0.499 | 0.086 | 0.034 | 0.397 |
| G$_\sigma$ | 0.063 | 0.013 | 0.278 | 0.054 | 0.010 | 0.172 |
| R$_\sigma$ | 0.067 | 0.014 | 0.312 | 0.058 | 0.012 | 0.202 |
| LNS | 0.088 | 0.031 | 0.614 | 0.077 | 0.028 | 0.469 |
| NRAPR | 0.083 | 0.034 | 0.545 | 0.073 | 0.030 | 0.413 |
| RATP | 0.097 | 0.037 | 0.500 | 0.086 | 0.034 | 0.390 |
| SV | 0.071 | 0.021 | 0.372 | 0.061 | 0.016 | 0.235 |
| SGII | 0.086 | 0.026 | 0.401 | 0.077 | 0.024 | 0.311 |
| SkI2 | 0.064 | 0.014 | 0.291 | 0.054 | 0.011 | 0.170 |
| SkI3 | 0.071 | 0.022 | 0.363 | 0.062 | 0.018 | 0.244 |
| SkI4 | 0.081 | 0.024 | 0.332 | 0.072 | 0.021 | 0.234 |
| SkI5 | 0.061 | 0.014 | 0.271 | 0.051 | 0.010 | 0.149 |
| SkI6 | 0.082 | 0.026 | 0.352 | 0.073 | 0.024 | 0.257 |
| SkMP | 0.072 | 0.020 | 0.357 | 0.062 | 0.017 | 0.241 |
| SkO | 0.073 | 0.020 | 0.413 | 0.062 | 0.017 | 0.270 |
| Sly230a | 0.090 | 0.039 | 0.404 | 0.081 | 0.037 | 0.319 |
| Sly230b | 0.089 | 0.038 | 0.462 | 0.080 | 0.036 | 0.362 |
| SLy4 | 0.089 | 0.038 | 0.461 | 0.080 | 0.036 | 0.361 |
| SLy10 | 0.091 | 0.042 | 0.447 | 0.083 | 0.041 | 0.369 |

Ducoin+ Phys Rev C83 045810 (2011)

| Force | BBP | SKM | FPS |
|---|---|---|---|
| $R$ | 10.49 | 10.78 | 10.79 |
| $\Delta M_c$ | 0.0299 (2.07%) | 0.0122 (0.84%) | 0.0125 (0.86%) |
| $\Delta M_d$ | 0.0242 (1.67%) | 0.0103 (0.71%) | 0.0084 (0.58%) |
| $\Delta M_n$ | ... | ... | 0.0062 (0.43%) |
| $\Delta M_{dn}$ | ... | ... | 0.0051 (0.35%) |
| $I$ | 61.56 | 60.89 | 62.57 |
| $\Delta I_c$ | 2.74 (4.45%) | 1.21 (1.99%) | 1.22 (1.94%) |
| $\Delta I_d$ | 2.22 (3.60%) | 1.02 (1.68%) | 0.82 (1.32%) |
| $\Delta I_n$ | ... | ... | 0.59 (0.94%) |
| $\Delta I_{dn}$ | ... | ... | 0.48 (0.77%) |

Lorenz et al PRL70 (1993)




Dinh Thi+ arxiv: 2109.13638

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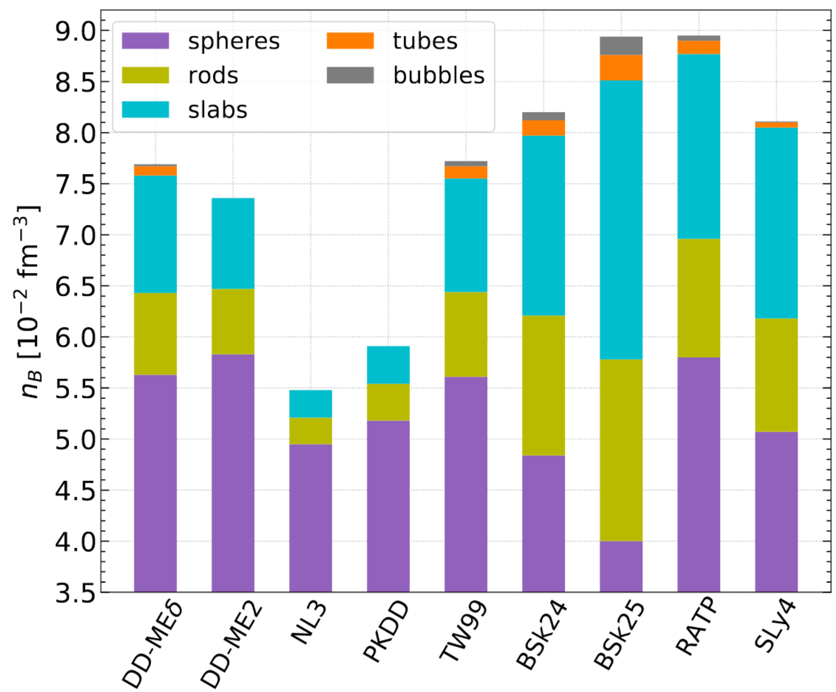
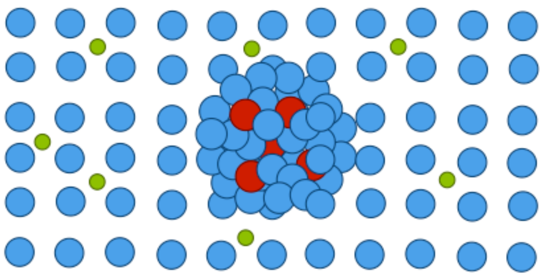



Dinh Thi+ arxiv: 2109.13638

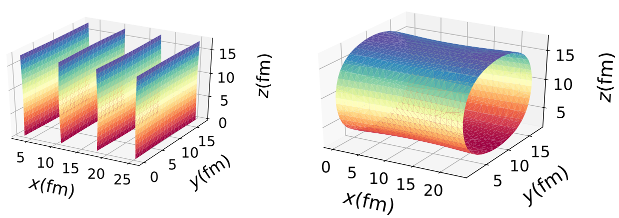
# Modeling the crust

3D Skyrme HF:
n,p degrees of freedom



Newton+ arxiv:2104.11835

Pictures: Lauren Balliet



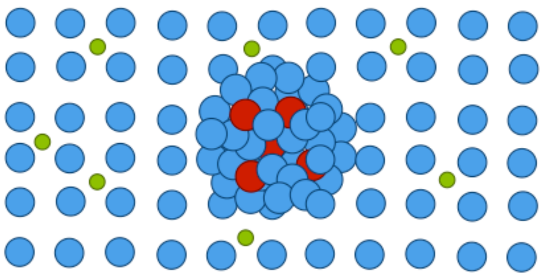

$$\mathcal{H}_\delta + \mathcal{H}_\rho + \mathcal{H}_{\text{eff}} + \mathcal{H}_{\text{grad}} + \mathcal{H}_{\text{Coul}}$$

## Nuclear EDF: Bulk+Gradient
## Specific model: Skyrme

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

# Modeling the crust

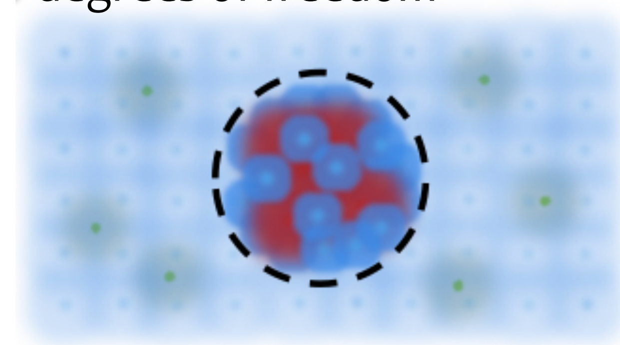
3D Skyrme HF:
n,p degrees of freedom



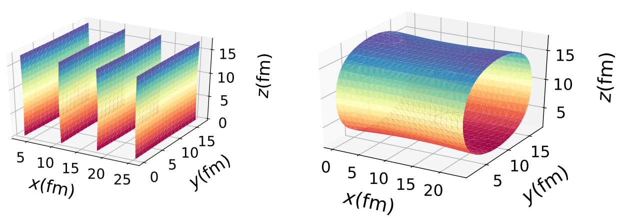
Newton+ arxiv:2104.11835

Pictures: Lauren Balliet

CLDM:Bulk fluid and surface degrees of freedom



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




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

Nuclear EDF: Bulk+Gradient
Specific model: Skyrme

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

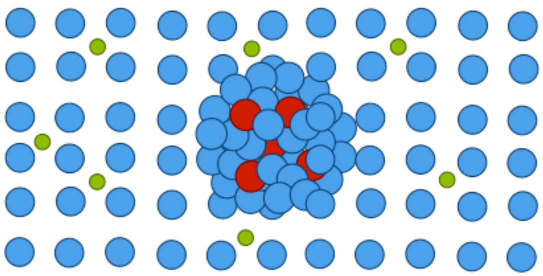
$$\mathcal{H}_\delta + \mathcal{H}_\rho + \mathcal{H}_{\mathrm{eff}} \quad \sigma(y_{\mathrm{p}})$$

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

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

# Modeling the crust

3D Skyrme HF:
n,p degrees of freedom



Newton+ arxiv:2104.11835

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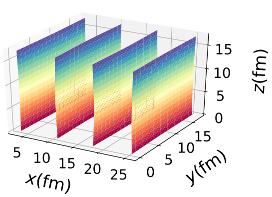
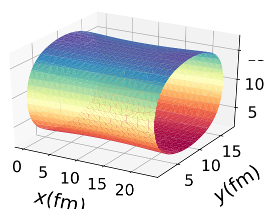
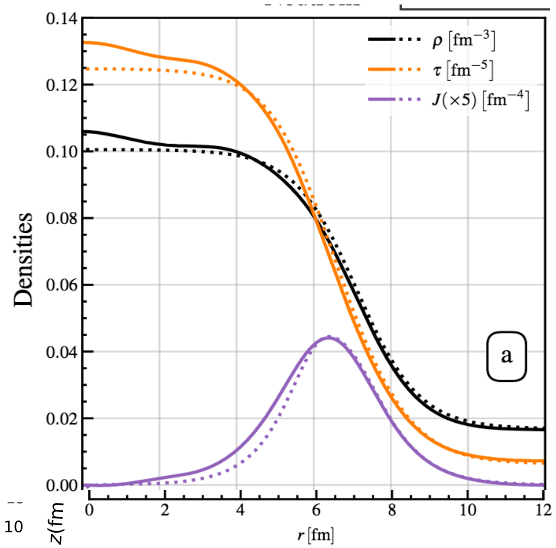


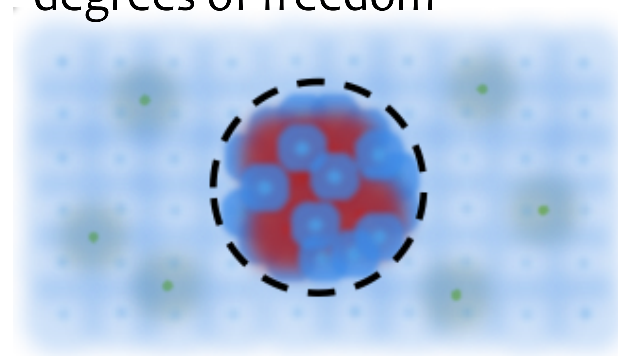




Thomas-Fermi: density profile degree of freedom




Shelley, arxiv:2011.10511

CLDM:Bulk fluid and surface degrees of freedom



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

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

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

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

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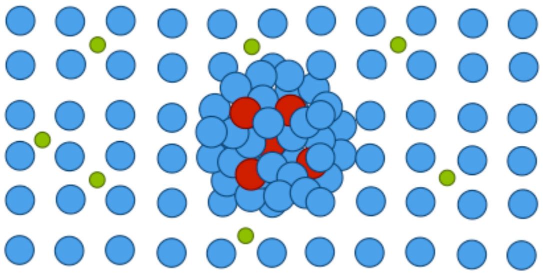

Newton+ arxiv:2104.11835

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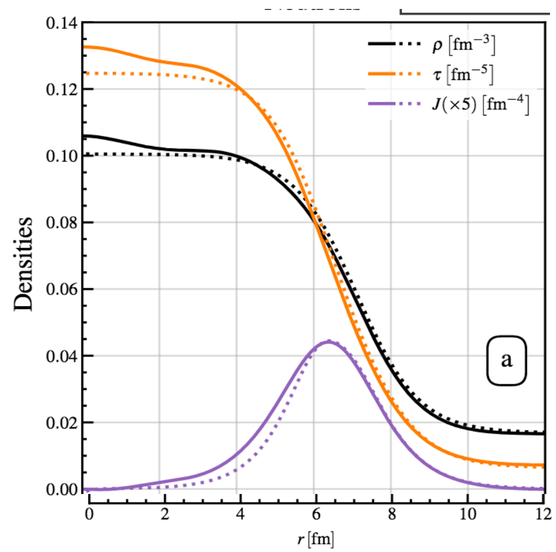


Shelley, arxiv:2011.10511

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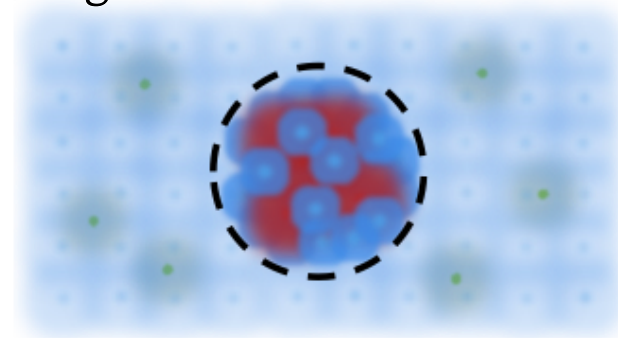

Newton et al arxiv: 1110.4043
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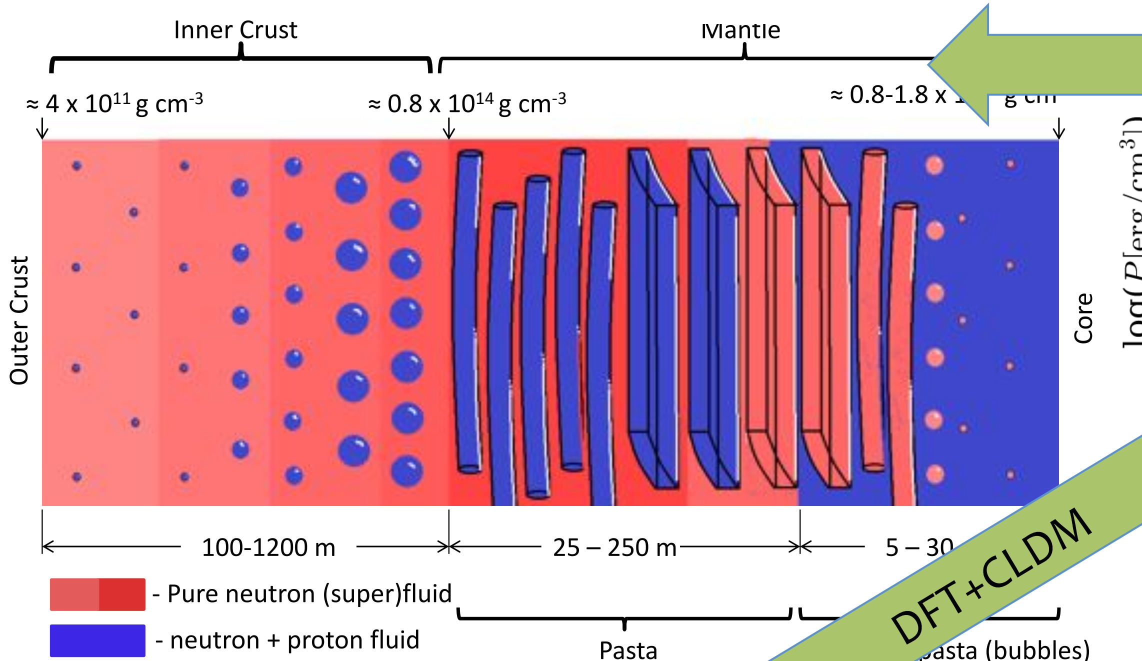
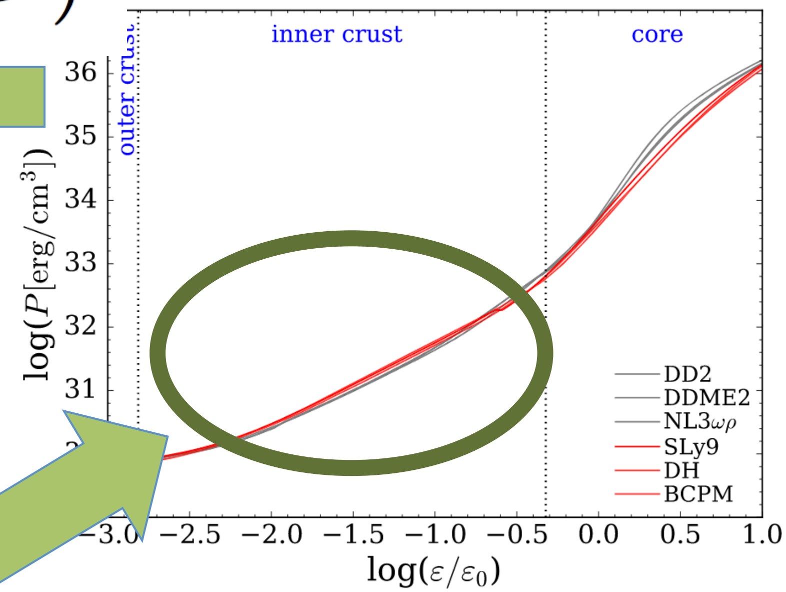
$$\sigma_{\rm s}(y_{\rm p}) = \sigma_0 \frac{2^{p+1}+b}{\frac{1}{y_{\rm p}^p}+b+\frac{1}{(1-y_{\rm p})^p}}$$

$$P(\text{Fraction of pasta}|\mathcal{D})$$




DFT+CLDM

$$P(J, L, K_{\mathrm{sym}}|\mathcal{D})$$

DFT

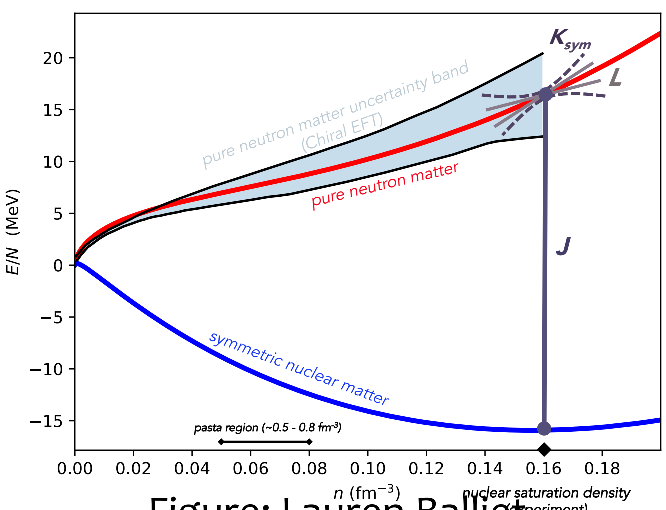
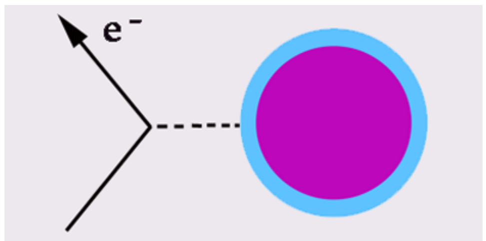
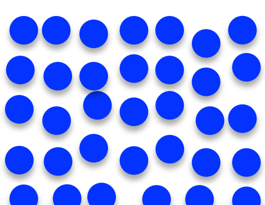
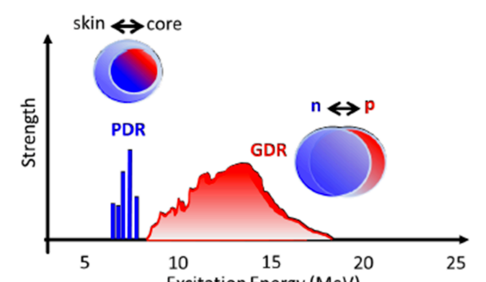


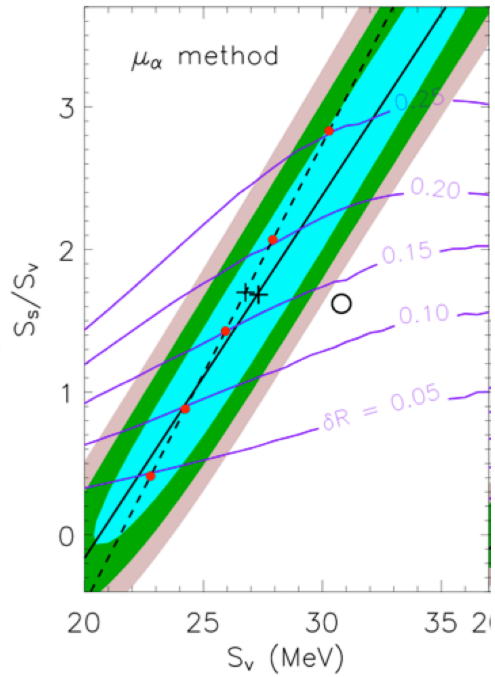

Figure: Lauren Balliet



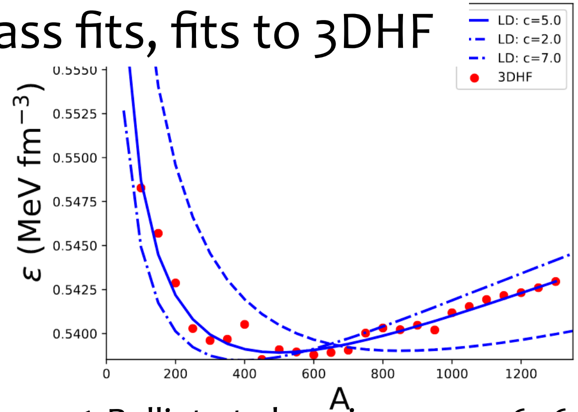





# Correlations from mass fits, fits to 3DHF

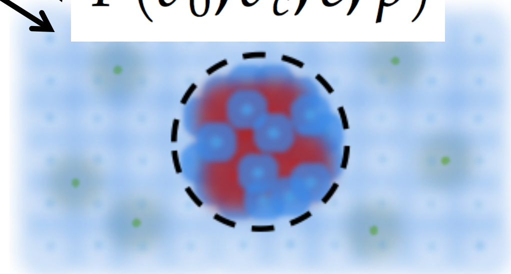


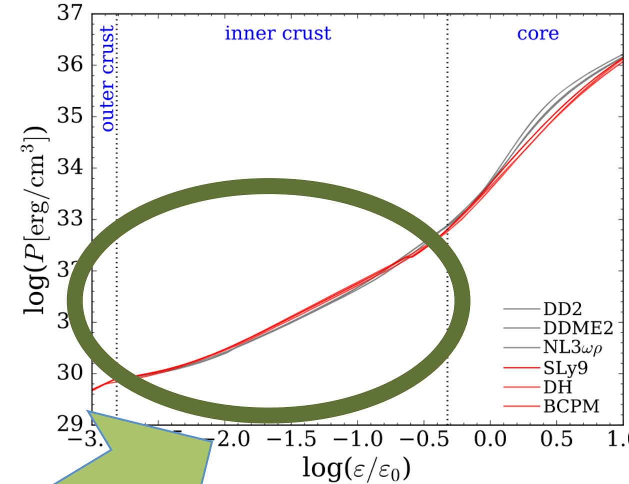

Steiner+ nucl-th/0410066



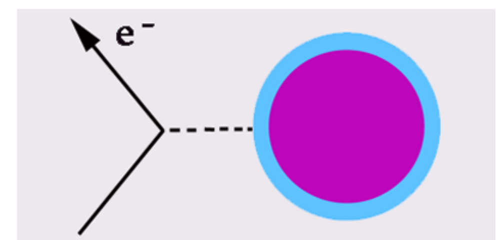

Balliet et al, arxiv:2009.07696

$$P(\sigma_0, \sigma_c, c, p)$$






$$P(J, L, K_{\mathrm{sym}} | \mathcal{D})$$



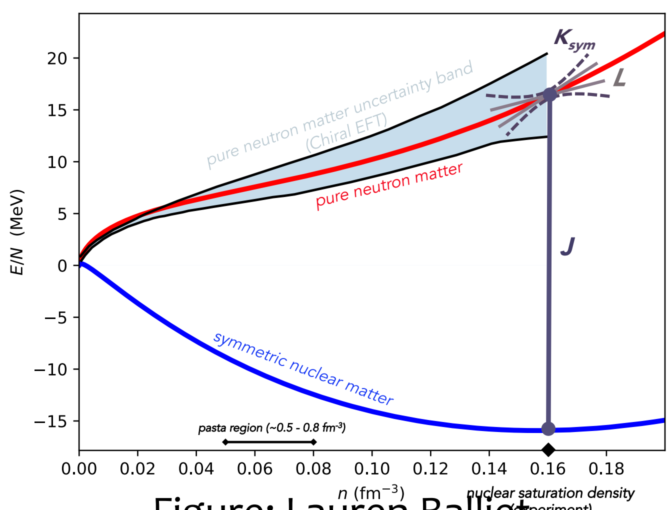
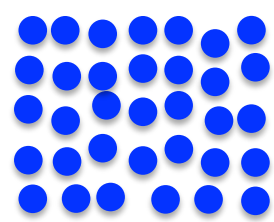
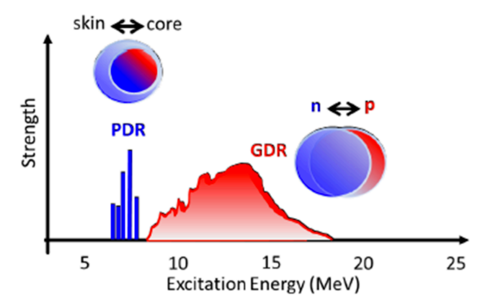



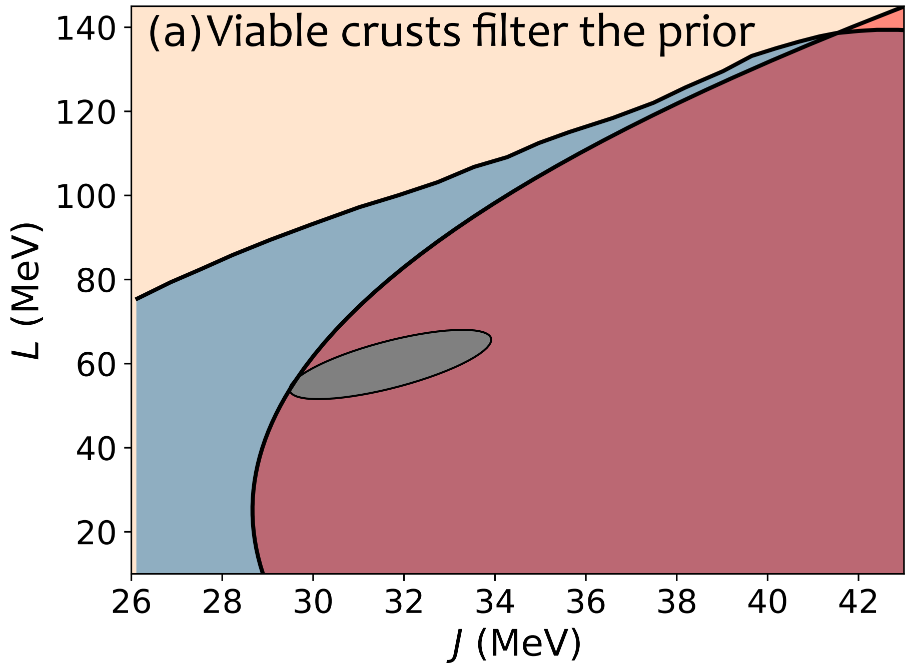

Figure: Lauren Balliet

DFT





# Priors: crust models




| Prior | $\sigma_0$ | $p$ | $c$ | $\sigma_{0,c}$ |
|---|---|---|---|---|
| Surf:Unif | 0.8-1.3 | 2.0-4.0 | 2.0-7.0 | 0.0-1.0 |
| Surf:Fit | 1.1 | 3.8±0.02 | 4.5 | 0.6 |

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

(Unitary gas bounds: Tews et al, arxiv:1611.07133 PNM: Drischler, arxiv:2004.07232)

# Potential sources of systematic error

Had to choose an EDF (Skyrme). Enough degrees of freedom?
Can add more ($Q_{sym}$)

Symmetric nuclear matter and gradient parameters held fixed; extending inference to those parameters may change posteriors

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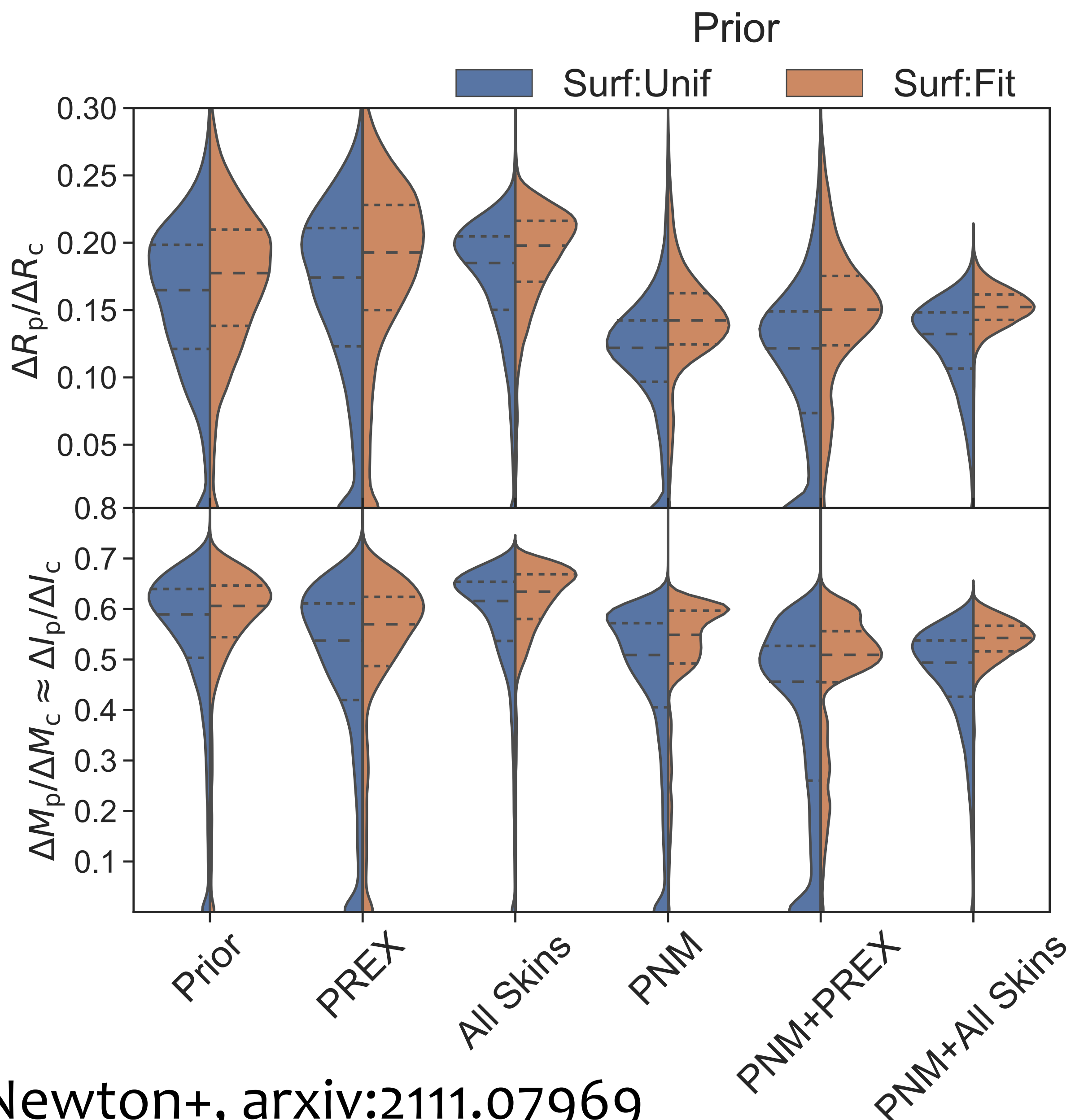
We've chosen a model of crust (CLDM) different to modeling of the nuclei (1D SHF+RPA)

Need more information to constrain surface parameters of crust model (mass fits, semi-inifinite nuclear matter, Thomas-Fermi calculations)

# Results: relative thickness and mass of pasta




$$\frac{\Delta R_{\rm p}}{\Delta R_{\rm c}} \approx \frac{\mu_{\rm cc}-\mu_{\rm p}}{\mu_{\rm cc}-\mu_0}$$

$$\frac{\Delta M_{\rm p}}{\Delta M_{\rm c}} \approx \frac{P_{\rm p}}{P_{\rm cc}}$$

Combining our best experimental and computational data:

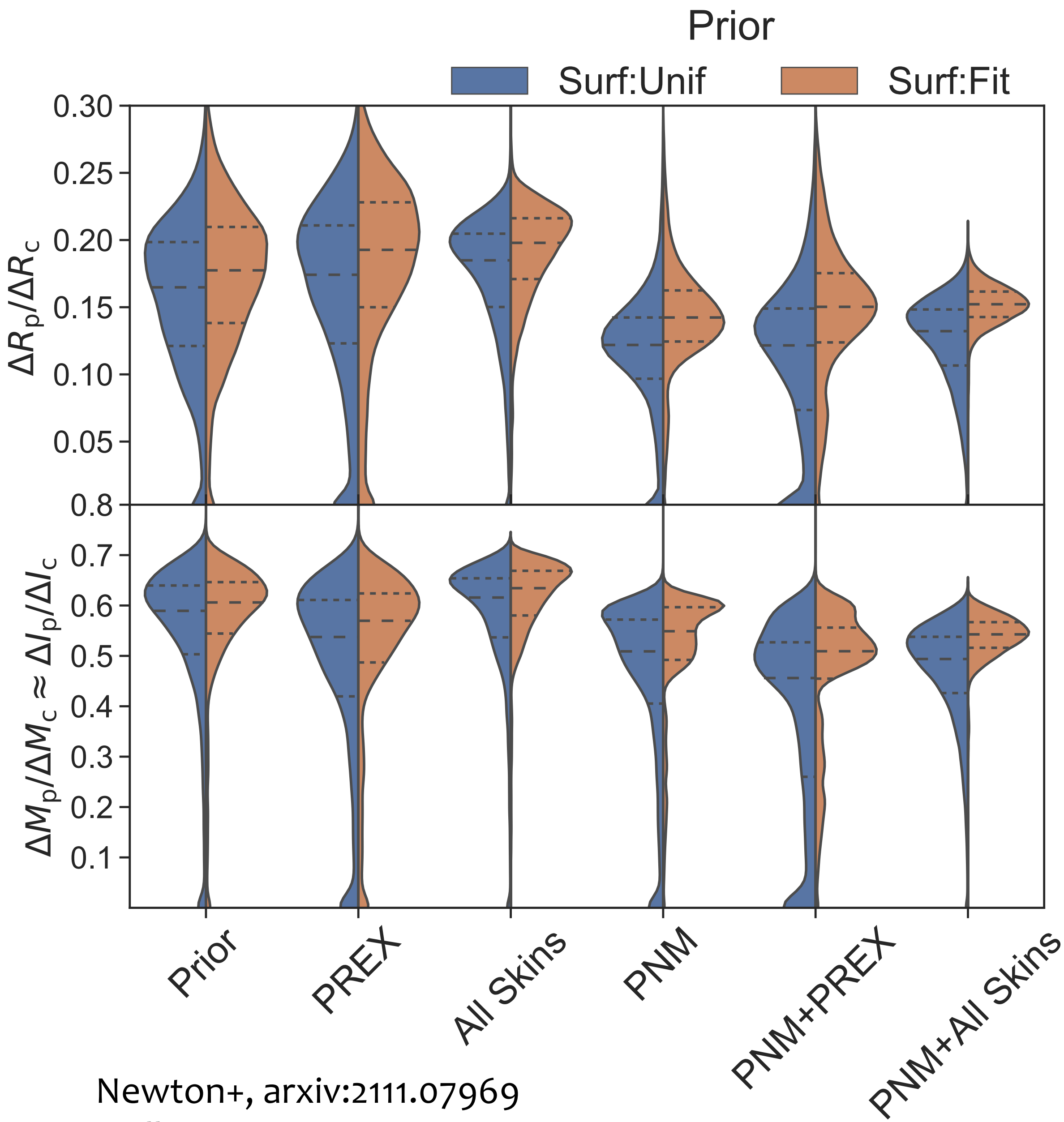
$$\Delta R_{\rm p}/\Delta R_{\rm c} = 0.132^{+0.023}_{-0.041}$$

$$\Delta M_{\rm p}/\Delta M_{\rm c} \approx \Delta I_{\rm p}/\Delta I_{\rm c} = 0.49^{+0.06}_{-0.11}$$

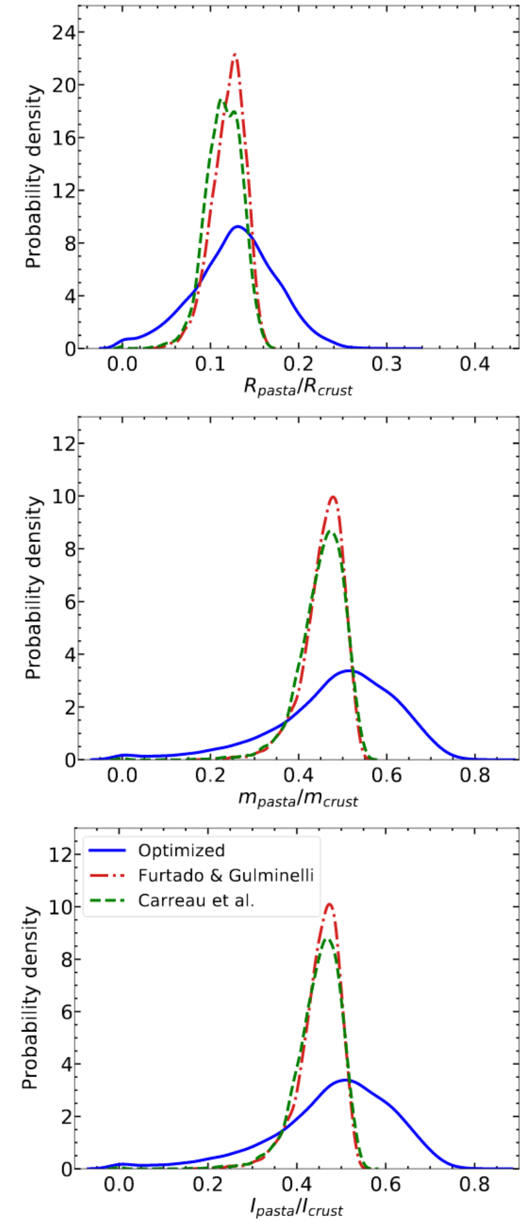
Newton+, arxiv:2111.07969

Balliet+, arxiv:2009.07696

# Relative thickness and mass of pasta: agreement with other studies

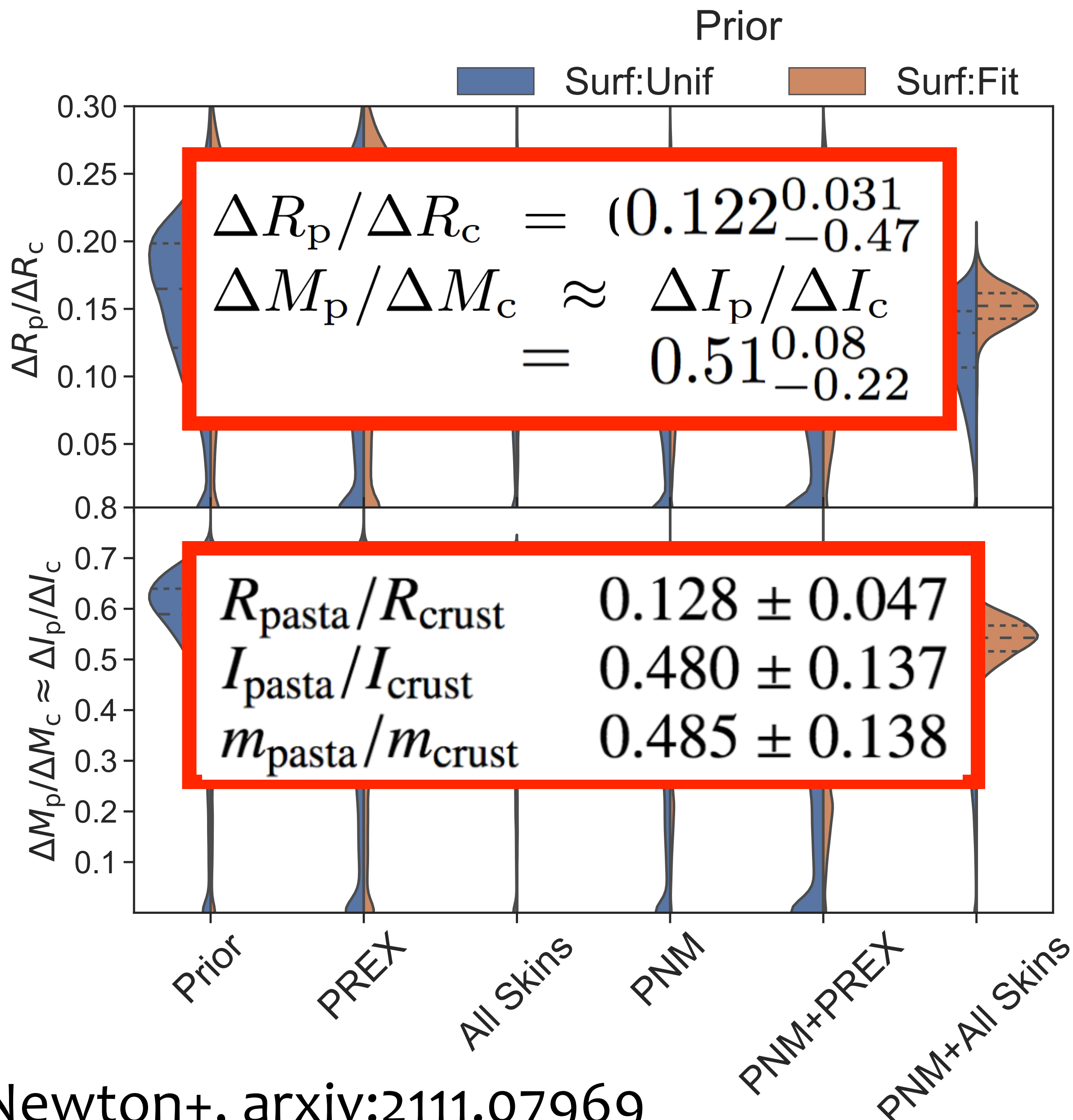



Newton+, arxiv:2111.07969
Balliet+, arxiv:2009.07696




Dinh Thi+ arxiv: 2109.13638

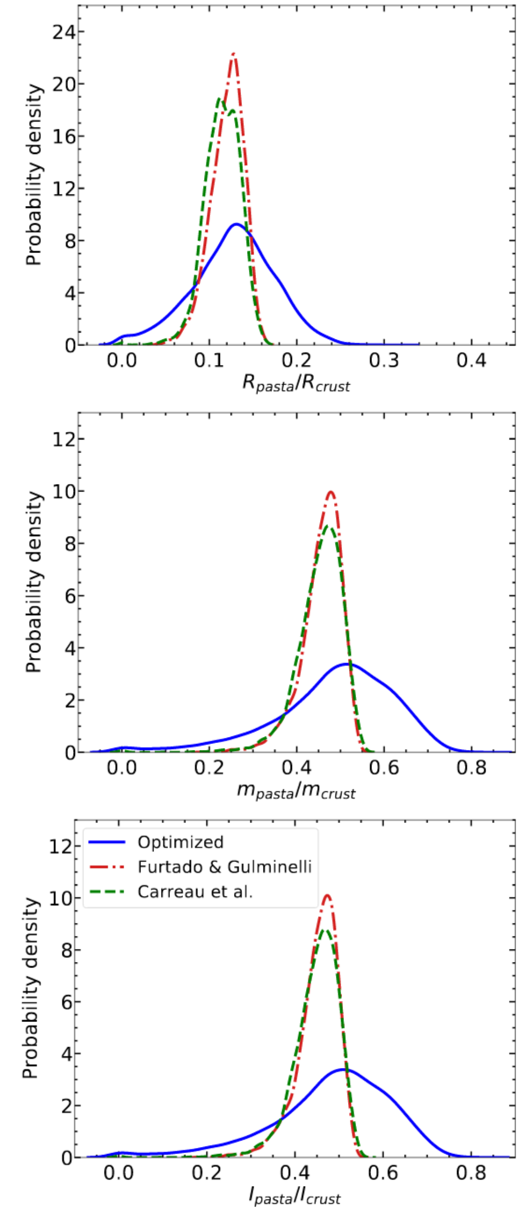
# Relative thickness and mass of pasta: agreement with other studies




$$\Delta R_\mathrm{p}/\Delta R_\mathrm{c} = (0.122^{0.031}_{-0.47}$$

$$\Delta M_\mathrm{p}/\Delta M_\mathrm{c} \approx \Delta I_\mathrm{p}/\Delta I_\mathrm{c} = 0.51^{0.08}_{-0.22}$$

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

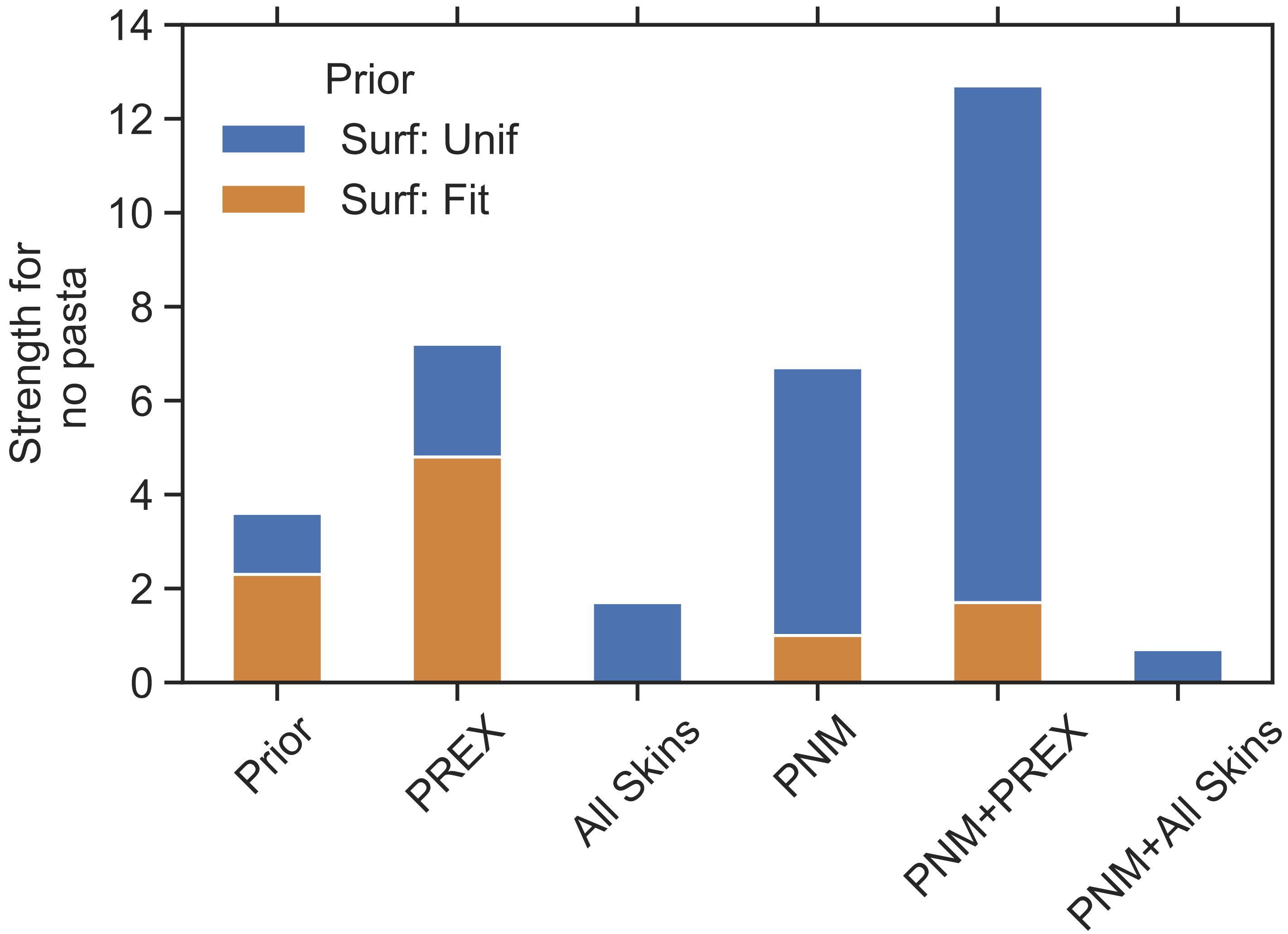



Newton+, arxiv:2111.07969

Balliet+, arxiv:2009.07696

Dinh Thi+ arxiv: 2109.13638

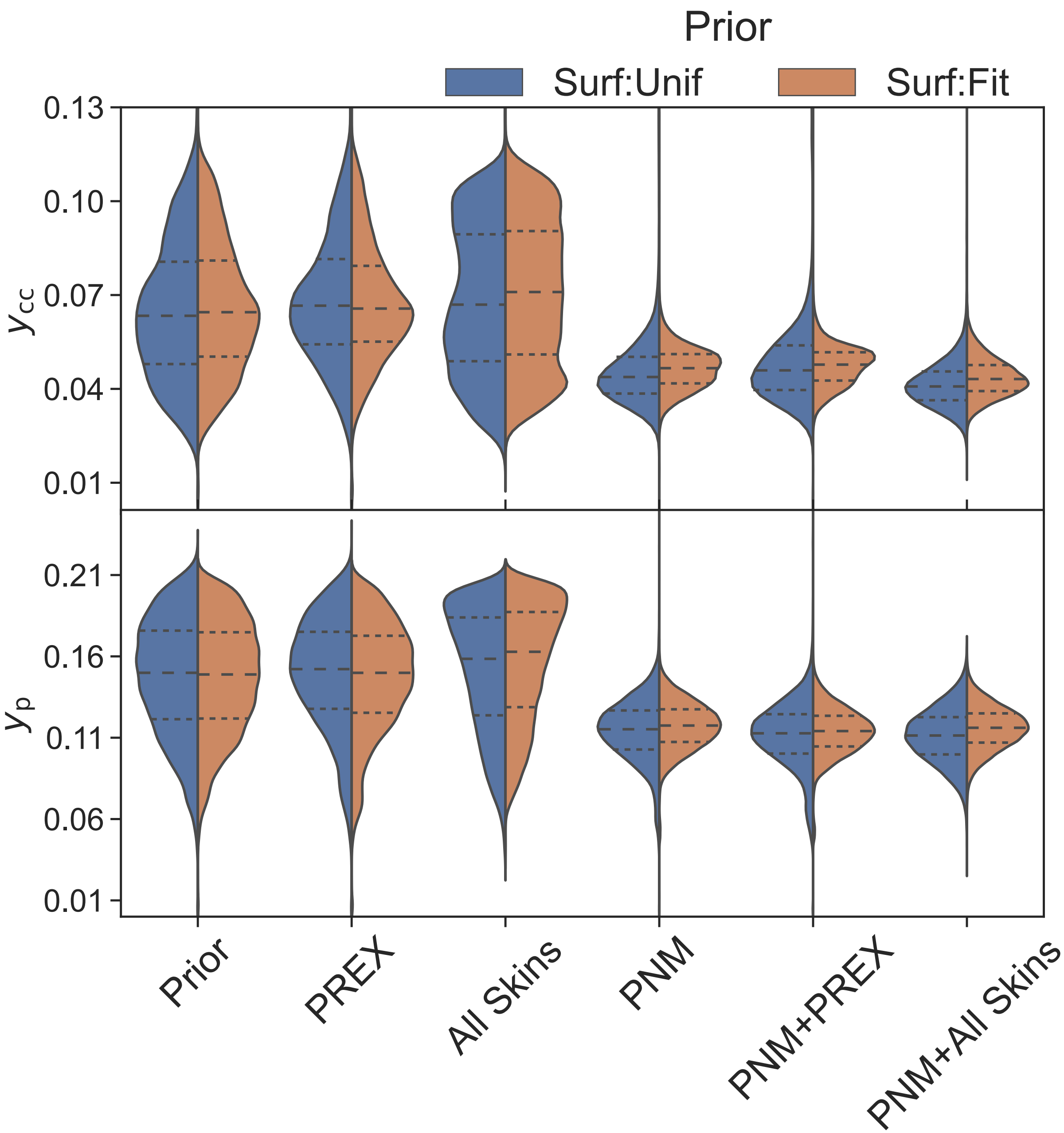
# There's a non-negligible range of models that predicts no pasta




Newton+, arxiv:2111.07969

Balliet+, arxiv:2009.07696

# Proton fractions

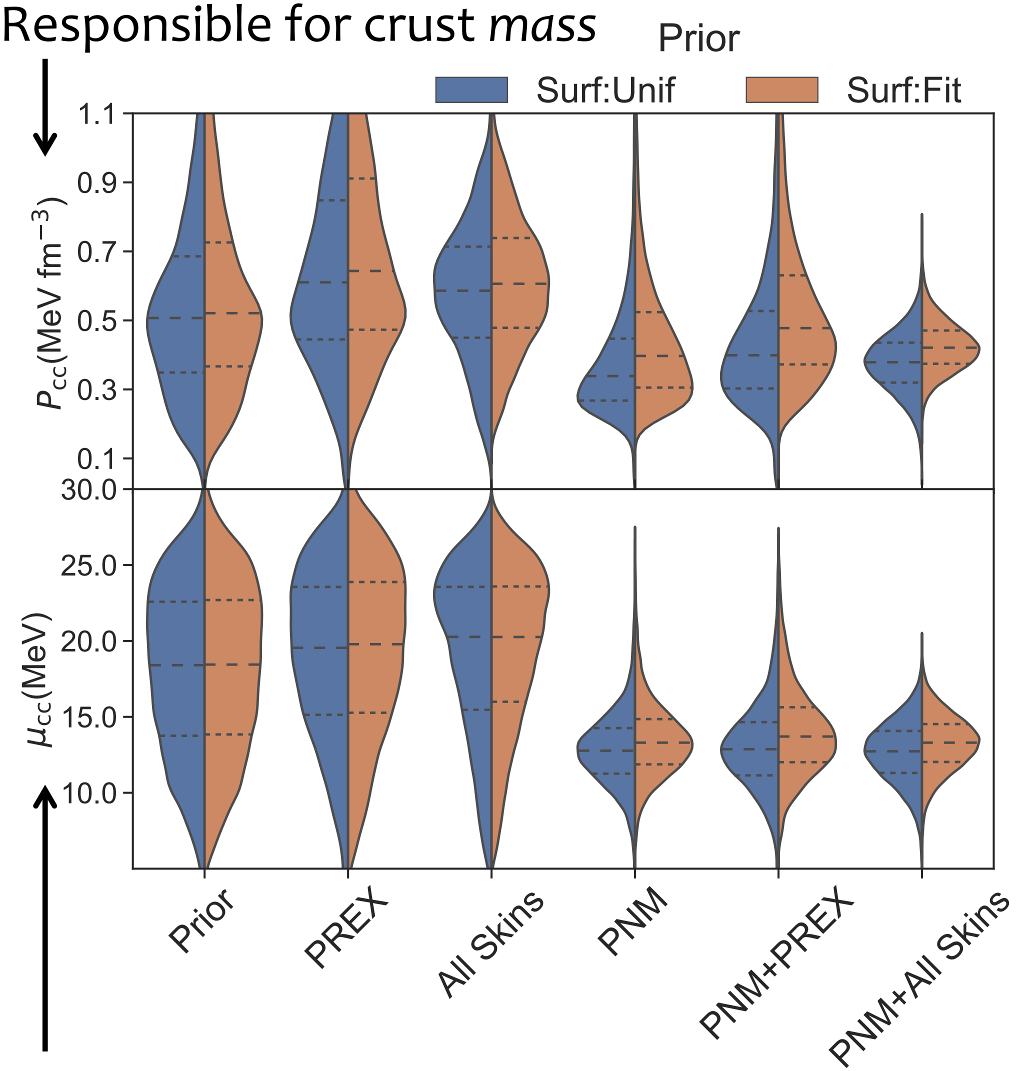



$$y_p = 0.111^{0.017}_{-0.17}$$

$$y_{cc} = 0.041^{0.007}_{-0.006}$$

# Crust-core transition pressure and chemical potential

Responsible for crust *mass*




$$P_{cc} = 0.38(0.42)^{+0.08(0.07)}_{-0.09(0.07)}$$

$$\mu_{cc} = 12.7(13.3)^{+2.0(1.8)}_{-2.1(1.9)}$$

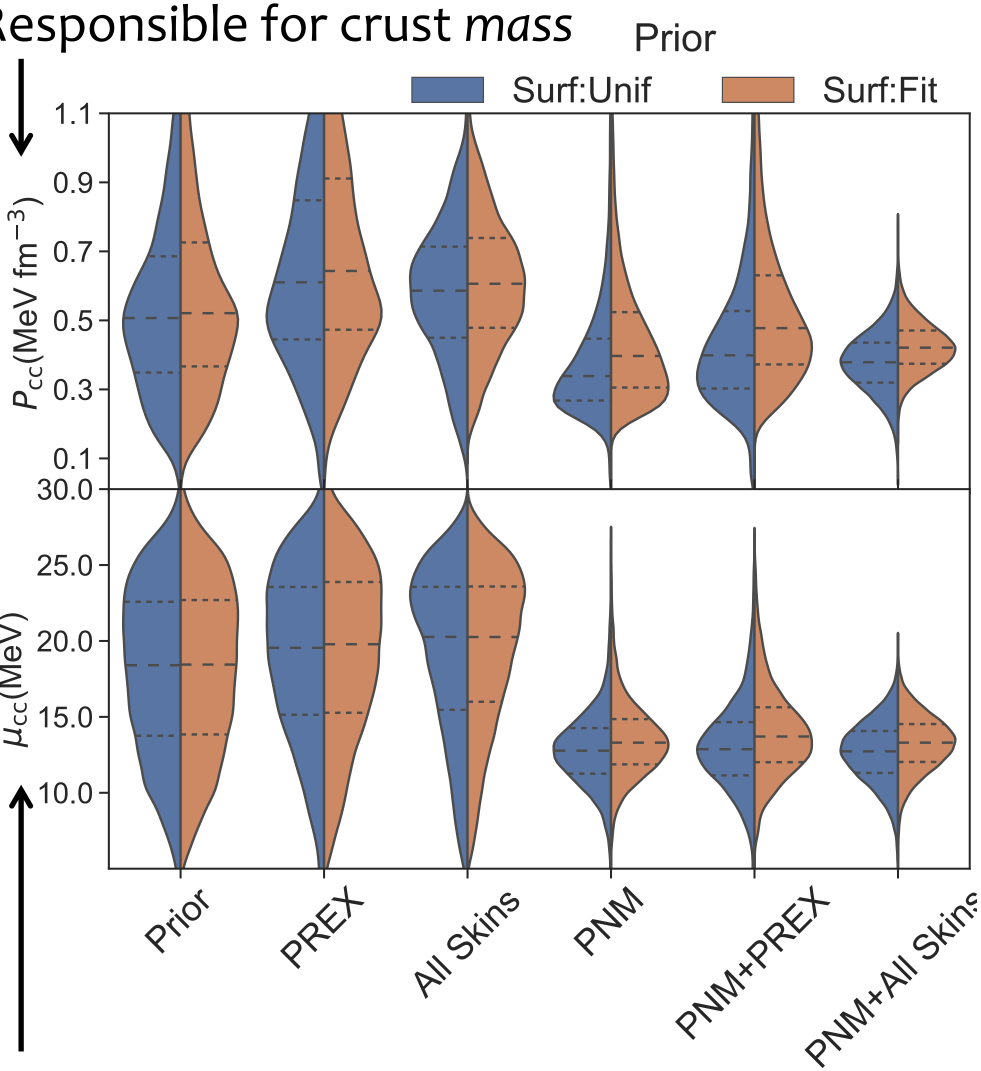
Responsible for crust *thickness*

Newton+, arxiv:2111.07969

Balliet+, arxiv:2009.07696

# Crust-core transition pressure and chemical potential

Responsible for crust *mass*



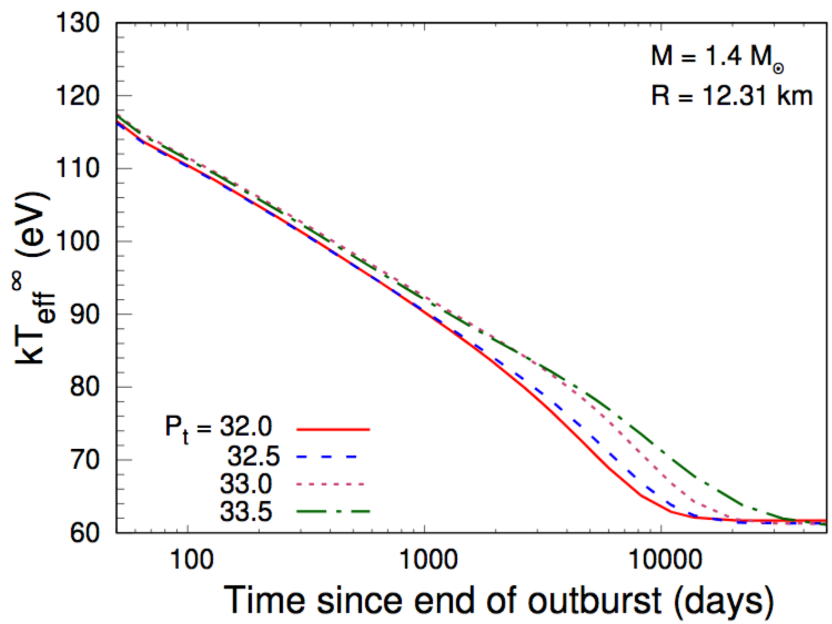

Responsible for crust *thickness*

Newton+, arxiv:2111.07969

Balliet+, arxiv:2009.07696

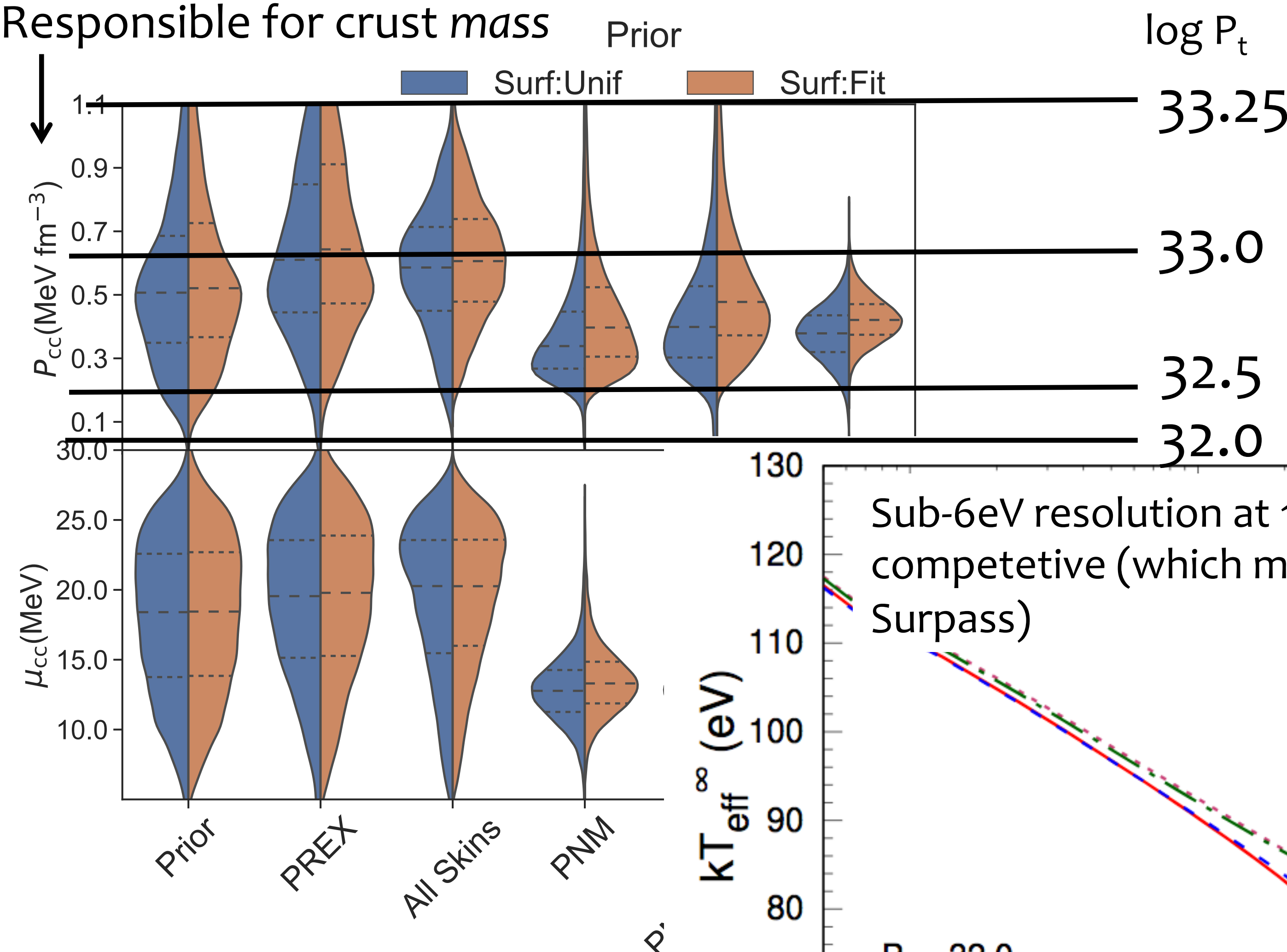
Lalit+ arxiv:1906.01535

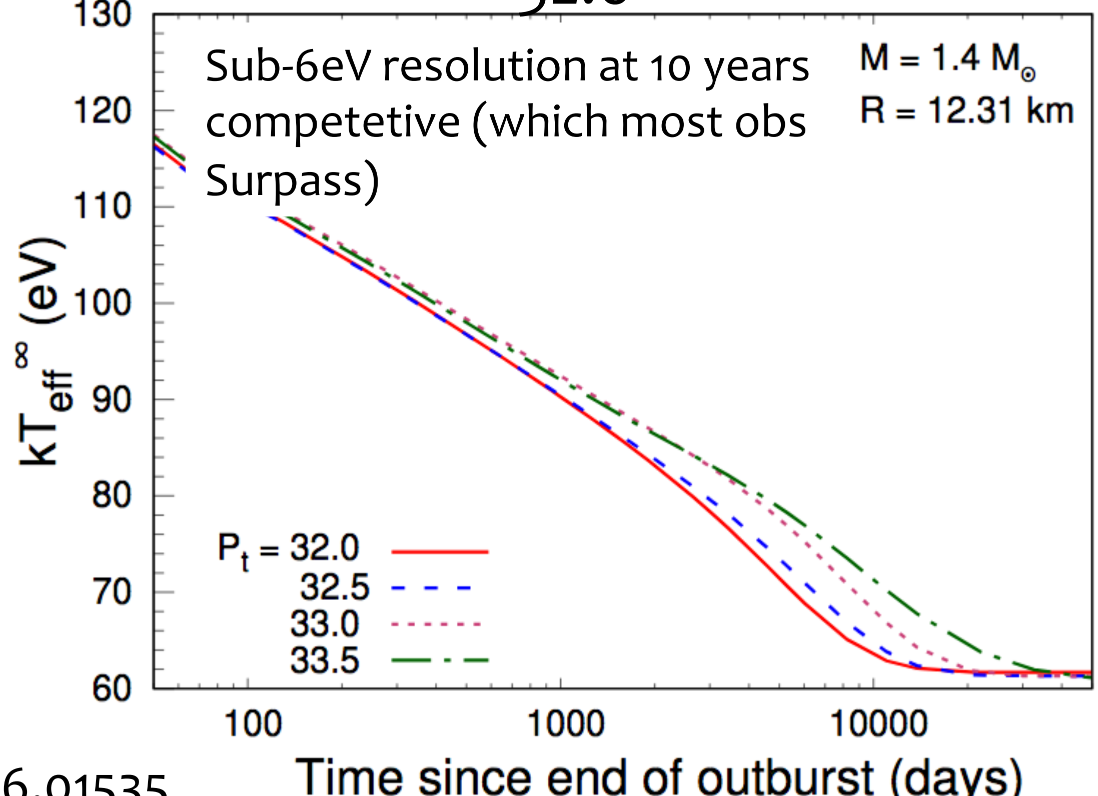
How much does the cooling light curve care about the base of the crust?



# Crust-core transition pressure and chemical potential

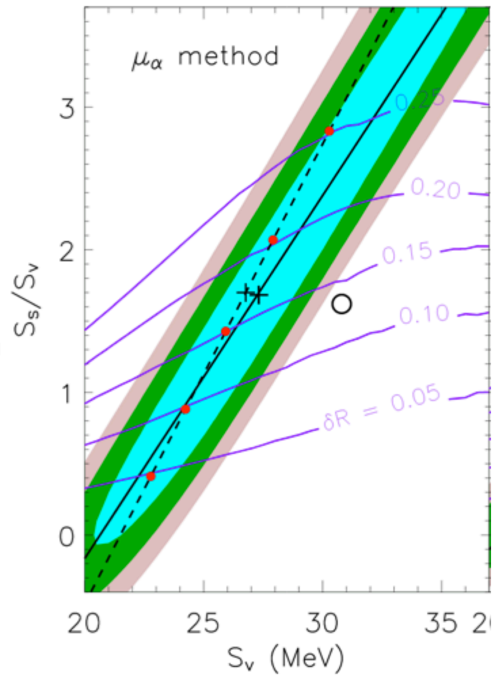
Responsible for crust *mass*



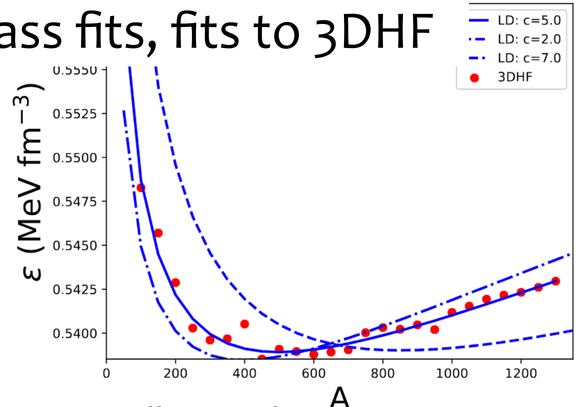




Lalit+ arxiv:1906.01535

# Correlations from mass fits, fits to 3DHF

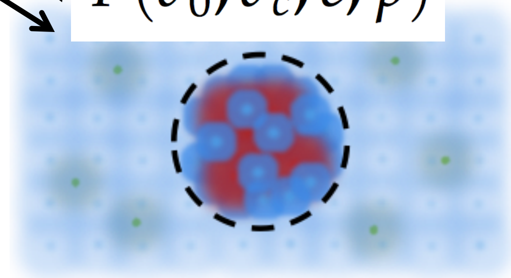


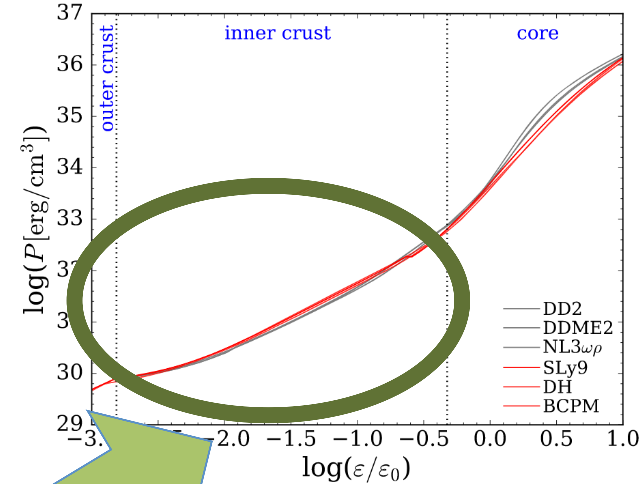

Steiner+ nucl-th/0410066




Balliet et al, arxiv:2009.07696

$$P(\sigma_0, \sigma_c, c, p)$$






$$P(J, L, K_{\text{sym}} | \mathcal{D})$$

DFT

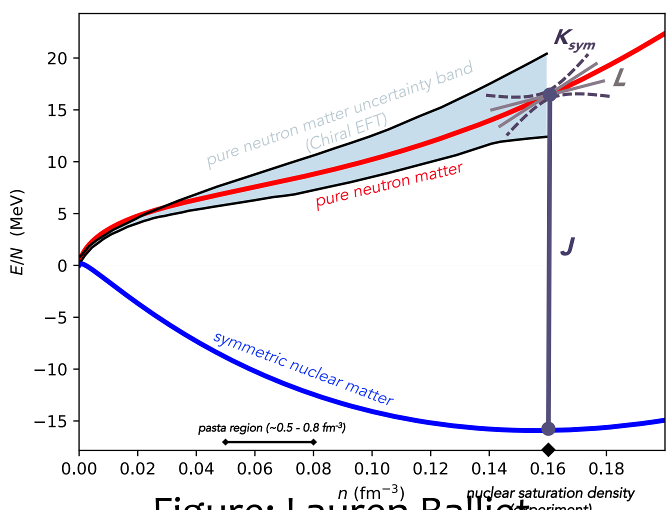
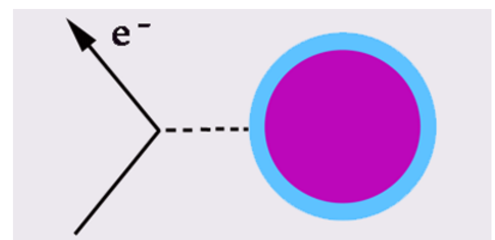
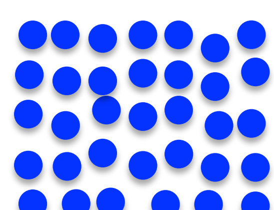
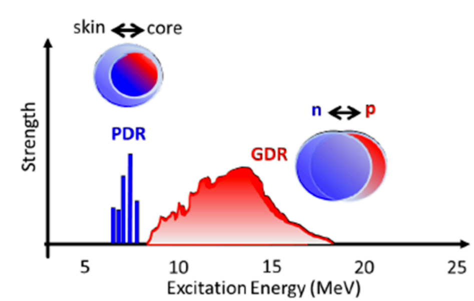
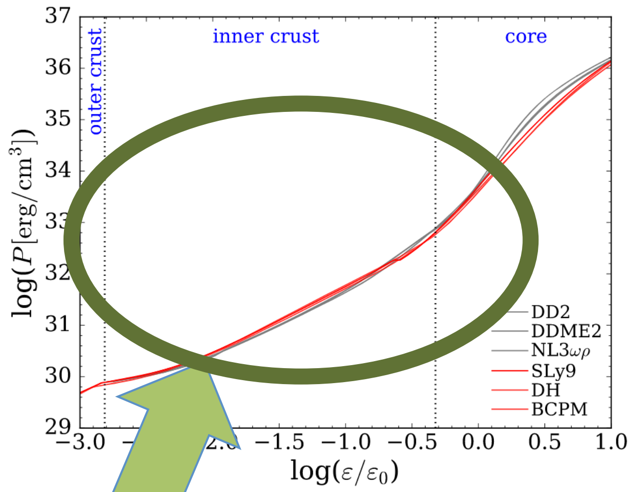


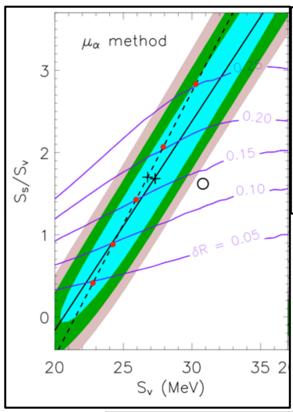

Figure: Lauren Balliet

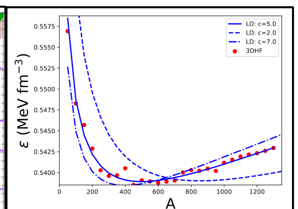


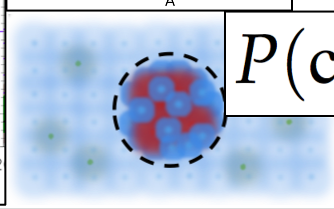







$$P(\text{crust+outer core}(J, L, K_{\text{sym}})\,|\,\mathcal{D}_{\text{nuc}}; \sigma_0, \sigma_c, c, p)$$

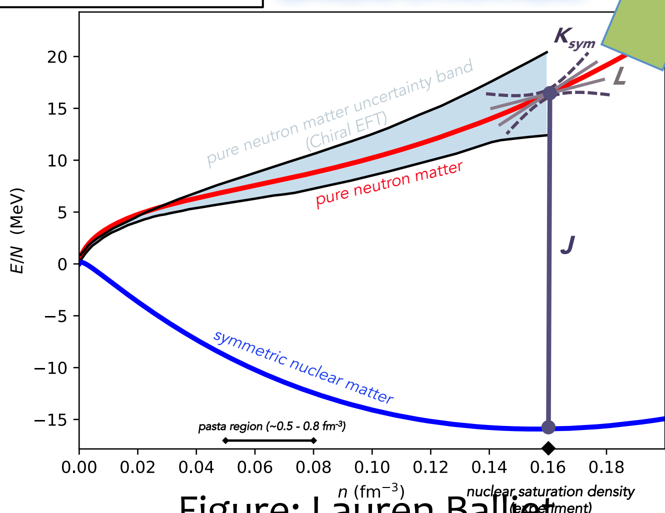
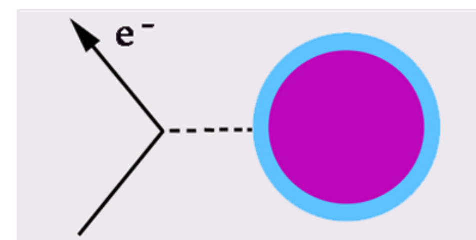
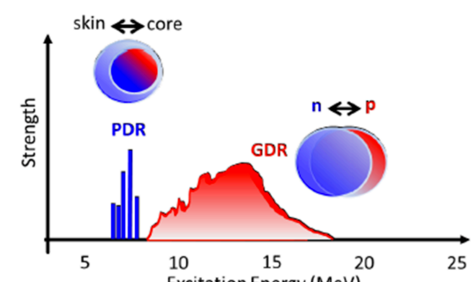


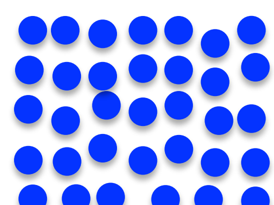

Figure: Lauren Balliet

$$P(J, L, K_{\text{sym}}\,|\,\mathcal{D})$$

DFT



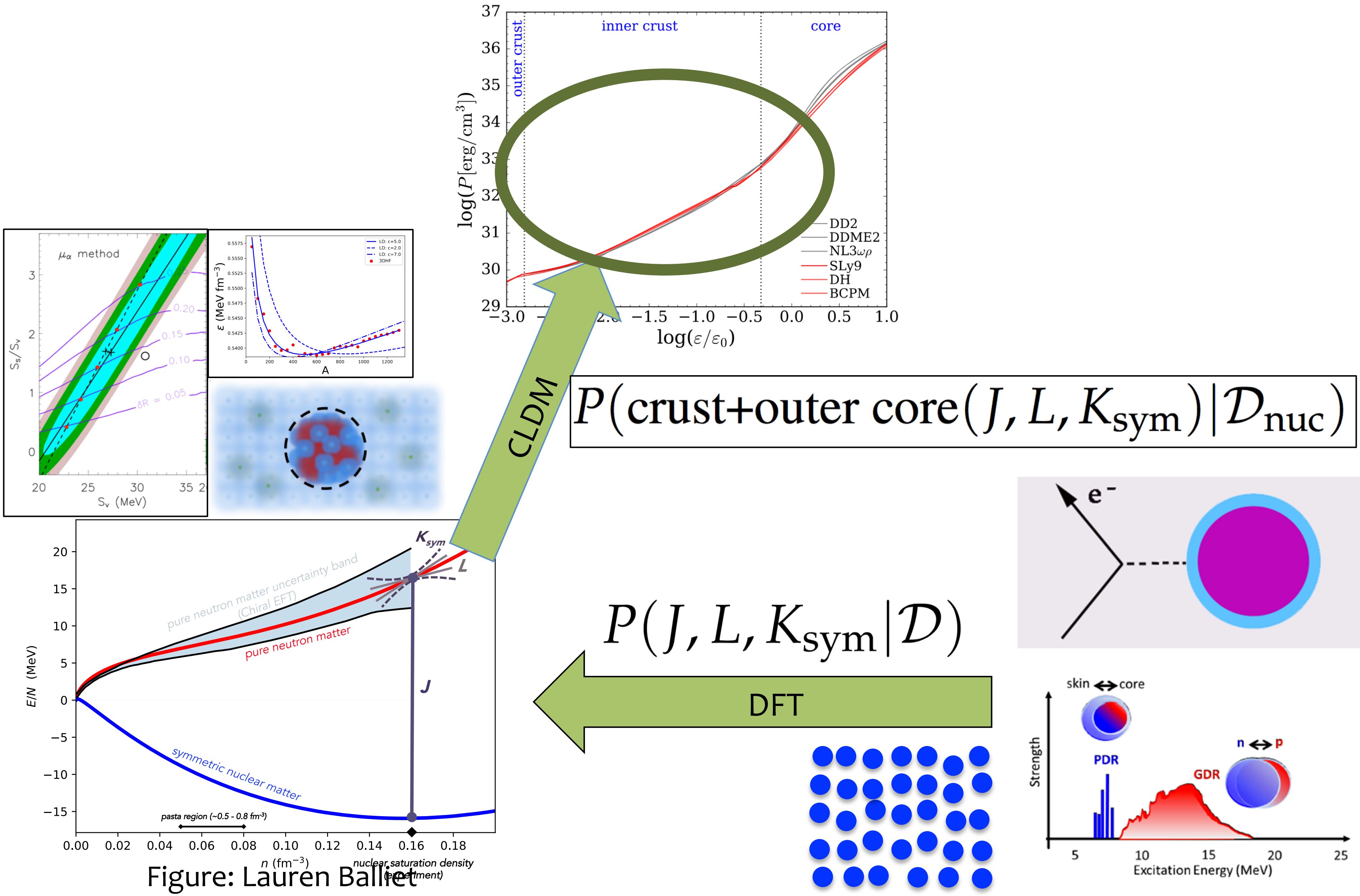
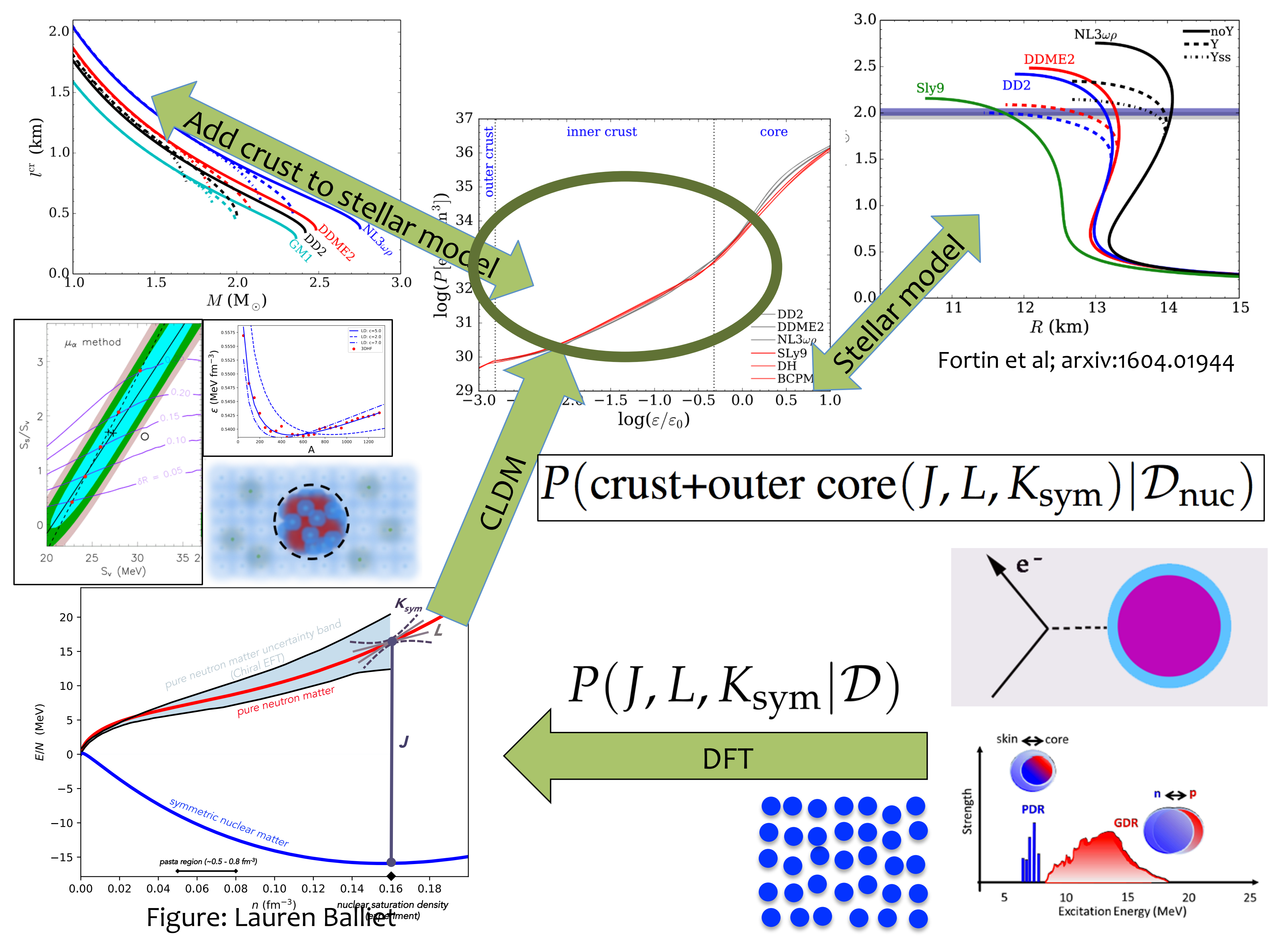
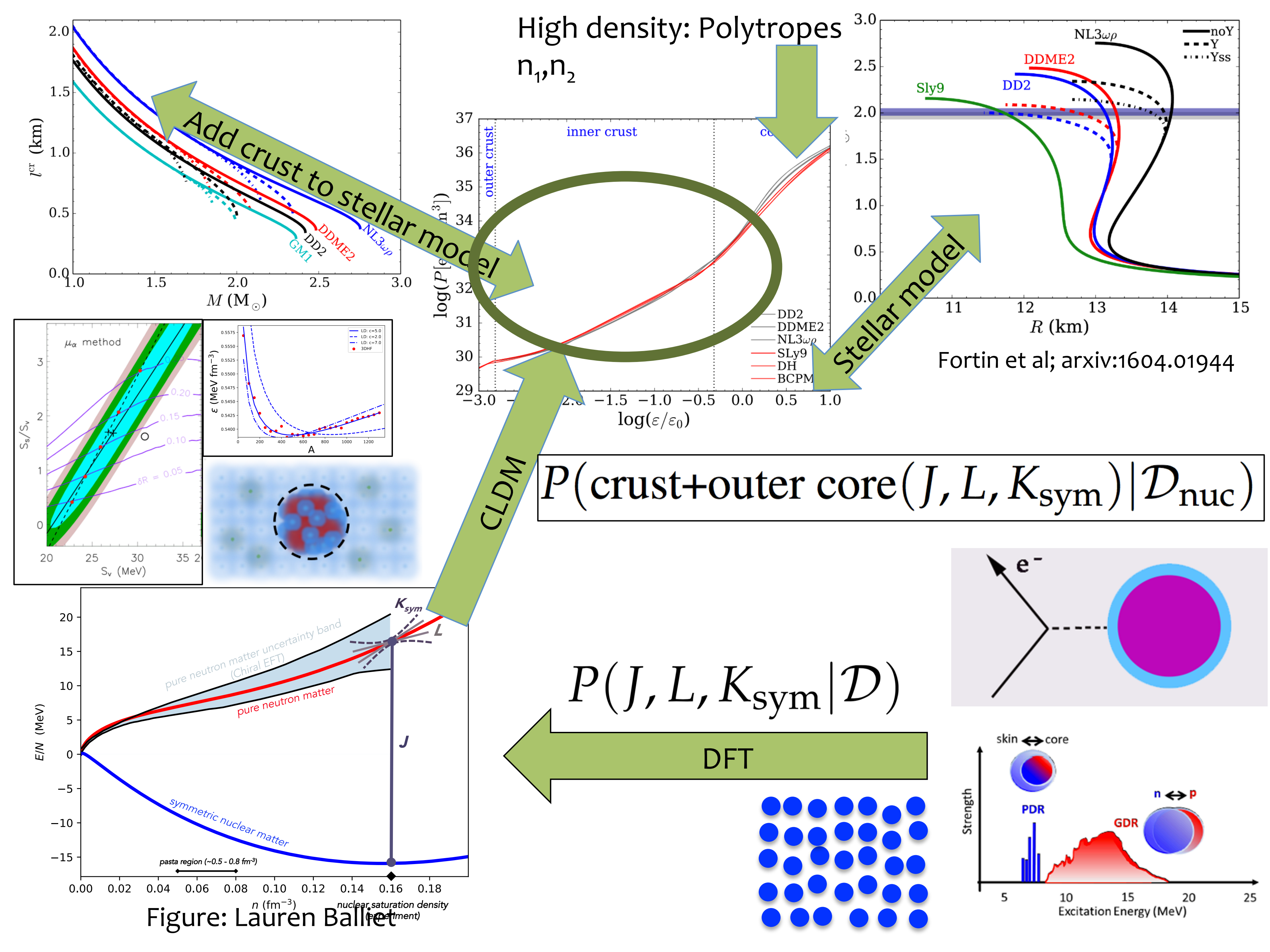


Figure: Lauren Balliet


Add crust to stellar model
Stellar model
CLDM
DFT
$P(\text{crust+outer core}(J, L, K_{\text{sym}}) | \mathcal{D}_{\text{nuc}})$
$P(J, L, K_{\text{sym}} | \mathcal{D})$
Fortin et al; arxiv:1604.01944
Figure: Lauren Balliet
$l^{cr}$ (km)
$M$ ($M_\odot$)
DDME2
NL3ωρ
DD2
GM1
outer crust
inner crust
core
$\log(\varepsilon/\varepsilon_0)$
DD2
DDME2
NL3ωρ
SLy9
DH
BCPM
noY
Y
Yss
Sly9
$R$ (km)
$\mu_\alpha$ method
$S_s/S_v$
$S_v$ (MeV)
$\varepsilon$ (MeV fm$^{-3}$)
A
pure neutron matter uncertainty band (Chiral EFT)
pure neutron matter
symmetric nuclear matter
$K_{sym}$
L
J
E/N (MeV)
pasta region (~0.5 - 0.8 fm$^{-3}$)
$n$ (fm$^{-3}$)
nuclear saturation density (experiment)
e⁻
skin ↔ core
n ↔ p
PDR
GDR
Strength
Excitation Energy (MeV)



High density: Polytropes
n1,n2
Add crust to stellar model
Stellar model
CLDM
DFT
$P(\text{crust+outer core}(J, L, K_{\rm sym})|\mathcal{D}_{\rm nuc})$
$P(J, L, K_{\rm sym}|\mathcal{D})$
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Figure: Lauren Balliet
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SLy9
DH
BCPM
noY
Y
Yss
Sly9
R (km)
μα method
Ss/Sv
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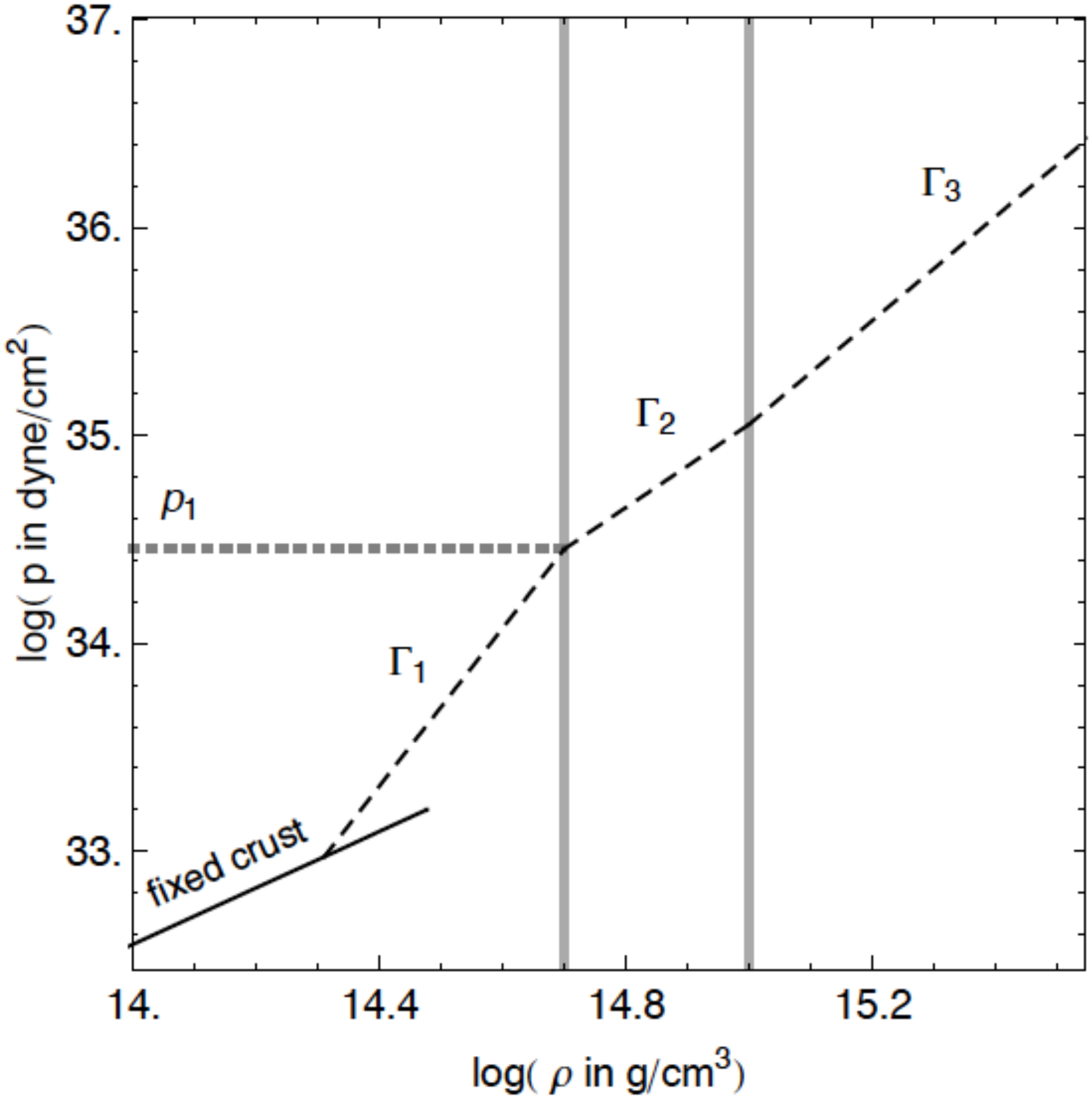
Ksym
L
J
pure neutron matter uncertainty band (Chiral EFT)
pure neutron matter
symmetric nuclear matter
pasta region (~0.5 - 0.8 fm⁻³)
E/N (MeV)
n (fm⁻³)
nuclear saturation density (experiment)

# 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

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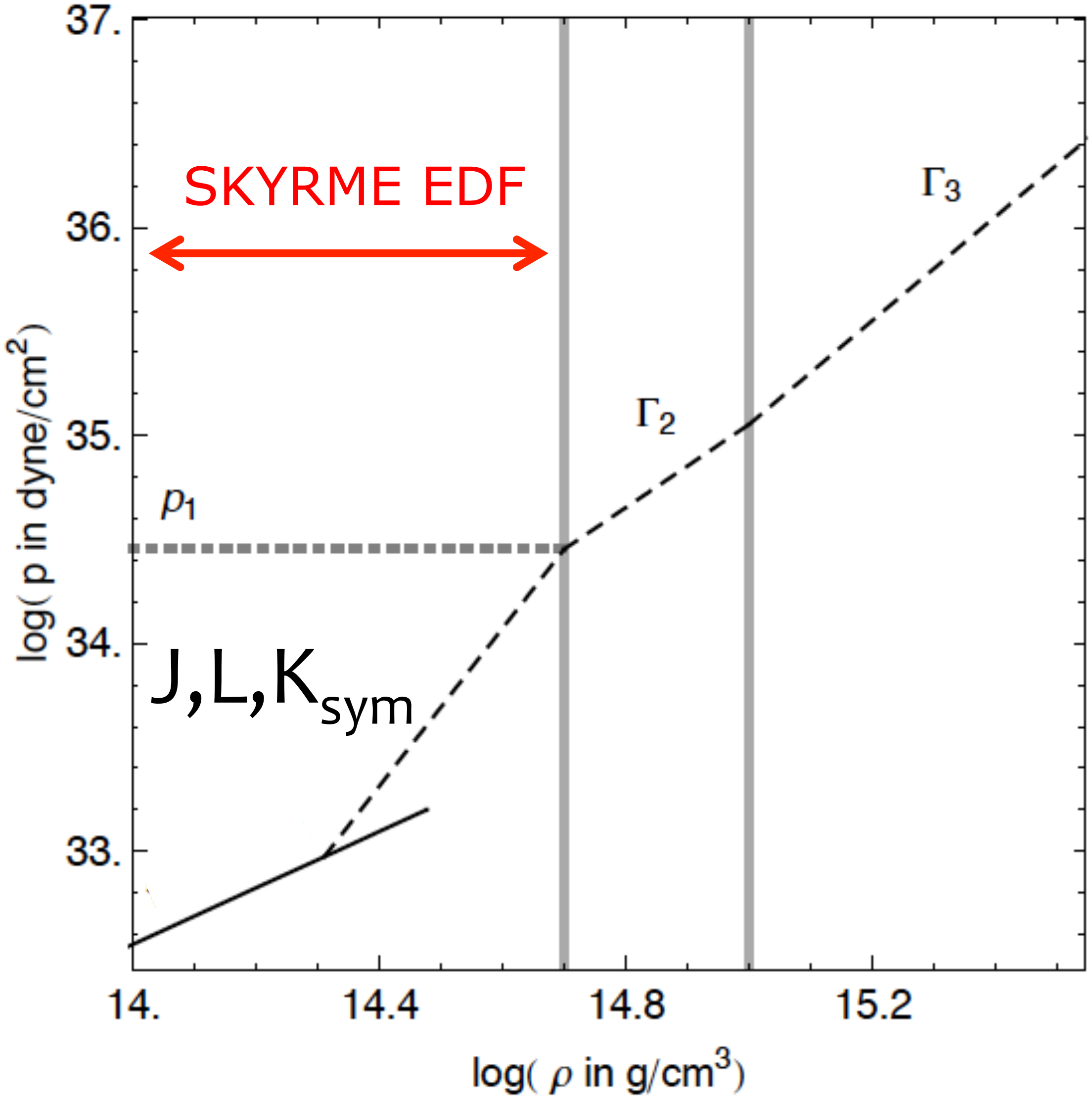
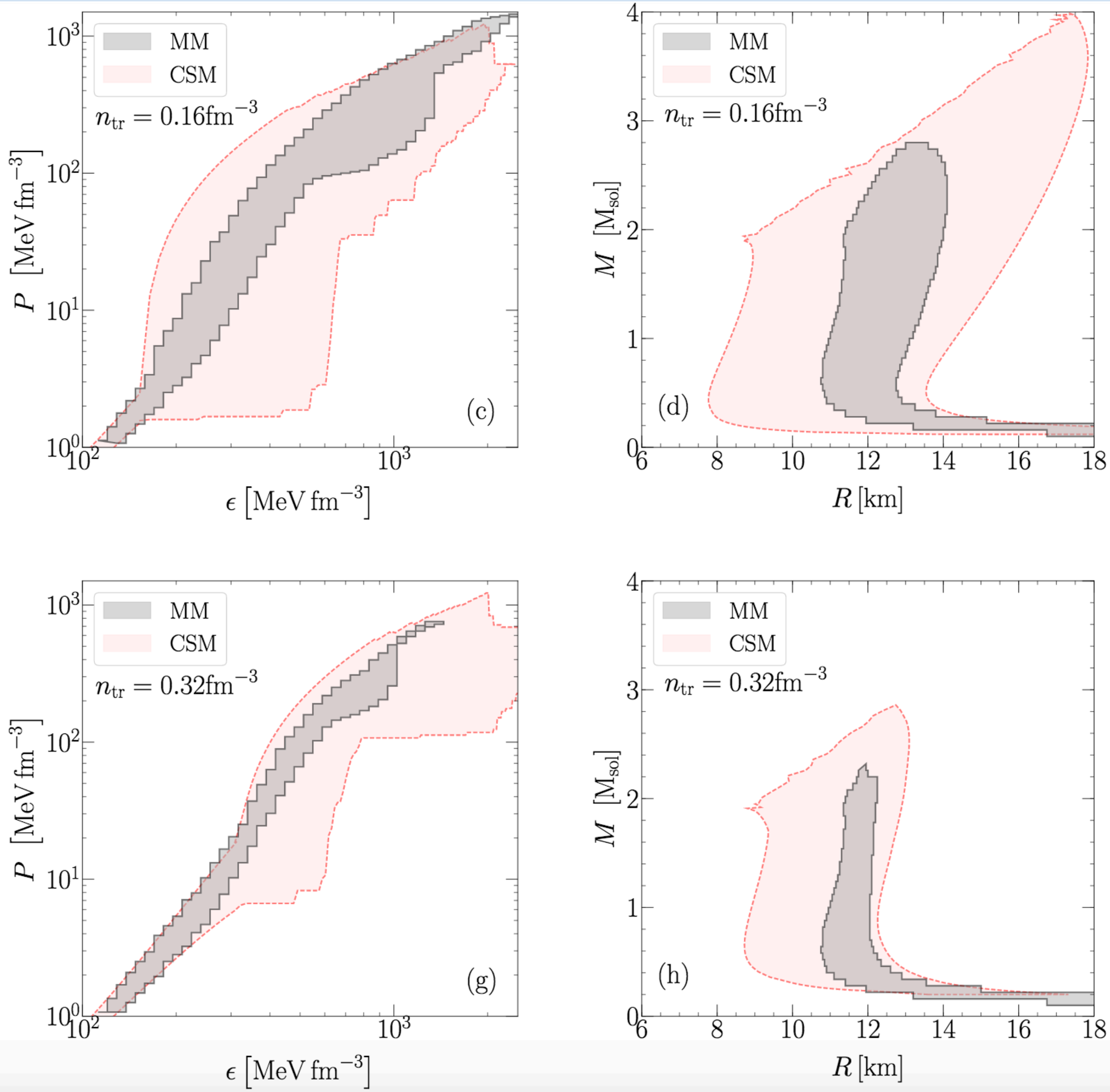



Read+, arxiv:0812.2163; see also works by Steiner, Lattimer, Özel...

# Polytropes versus continuing the nuclear matter comparison/ extrapolating EDF to arbitrarily highly




Tews, Margueron, Reddy arxiv:1804.02783

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Symmetric nuclear matter and gradient parameters held fixed; extending inference to those parameters may change posteriors

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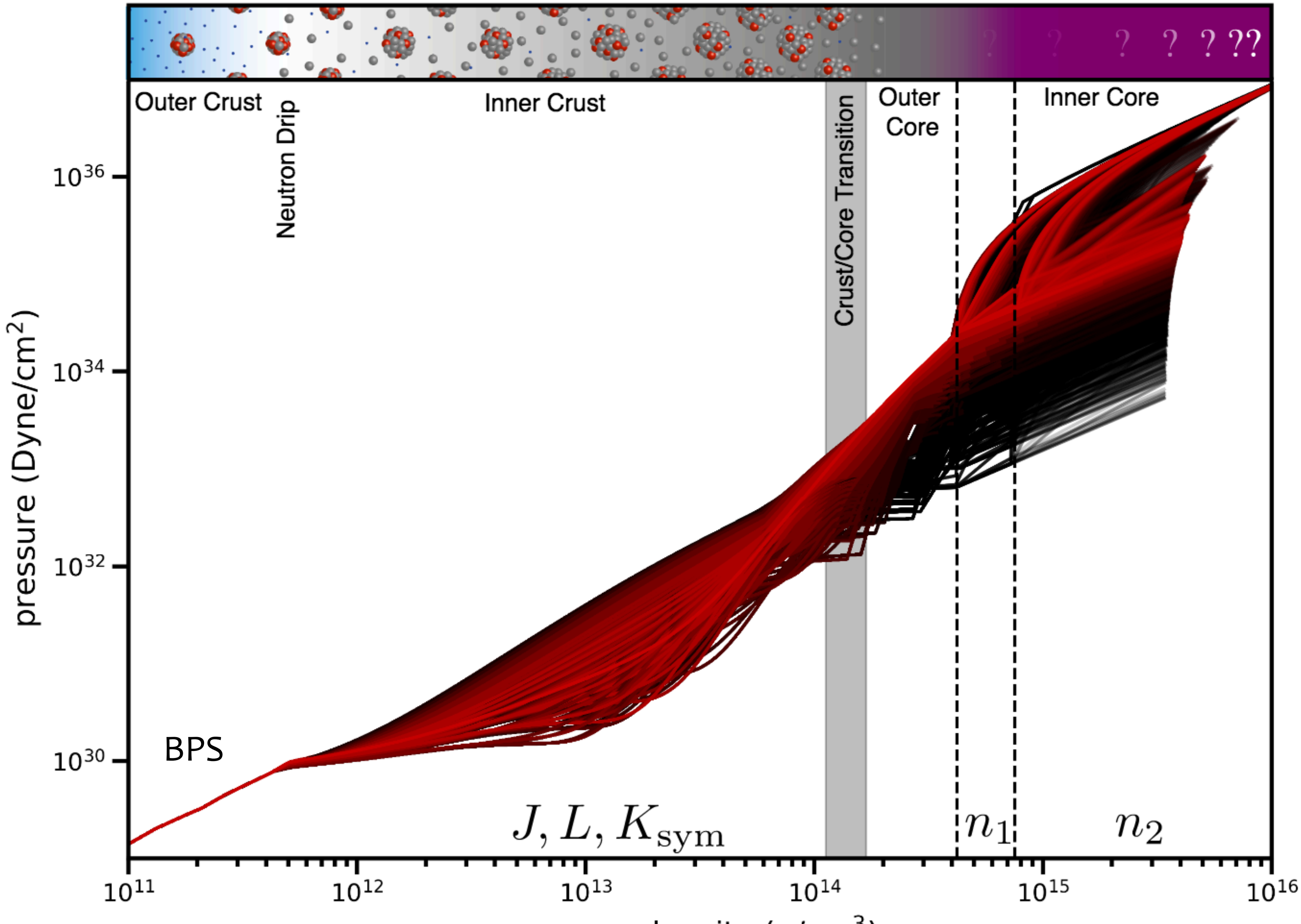
We've chosen a model of crust (CLDM) different to modeling of the nuclei (1D SHF+RPA)

Need more information to constrain surface parameters of crust model (mass fits, semi-inifinite nuclear matter, Thomas-Fermi calculations)

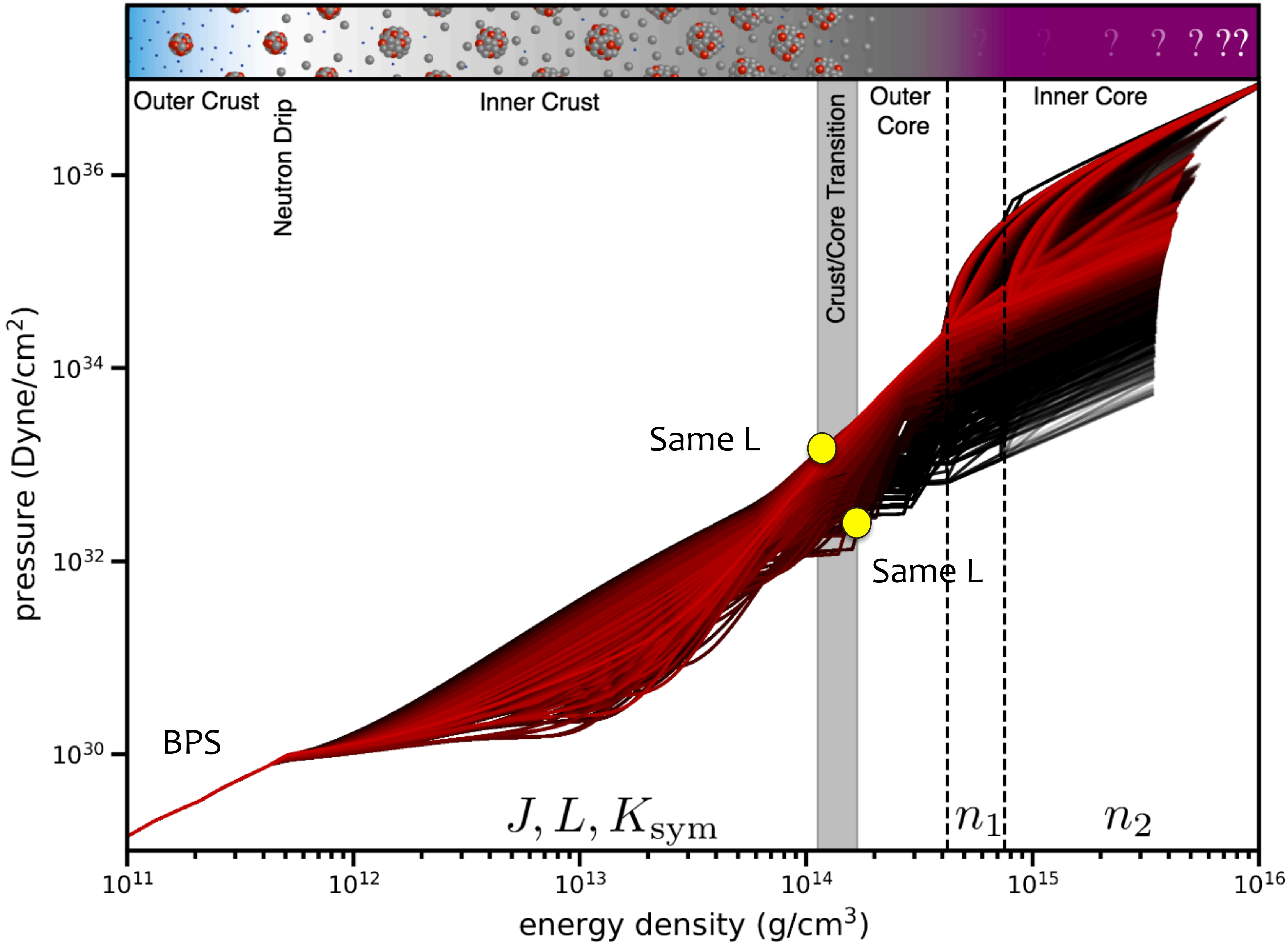
2 polytropes in the core is bare minimum: can be more sophisticated

# Sample of our resulting equations of state




Neill, Preston, Tsang, Newton in prep

# By the way, about the crust core transition…




Neill, Preston, Tsang, Newton in prep

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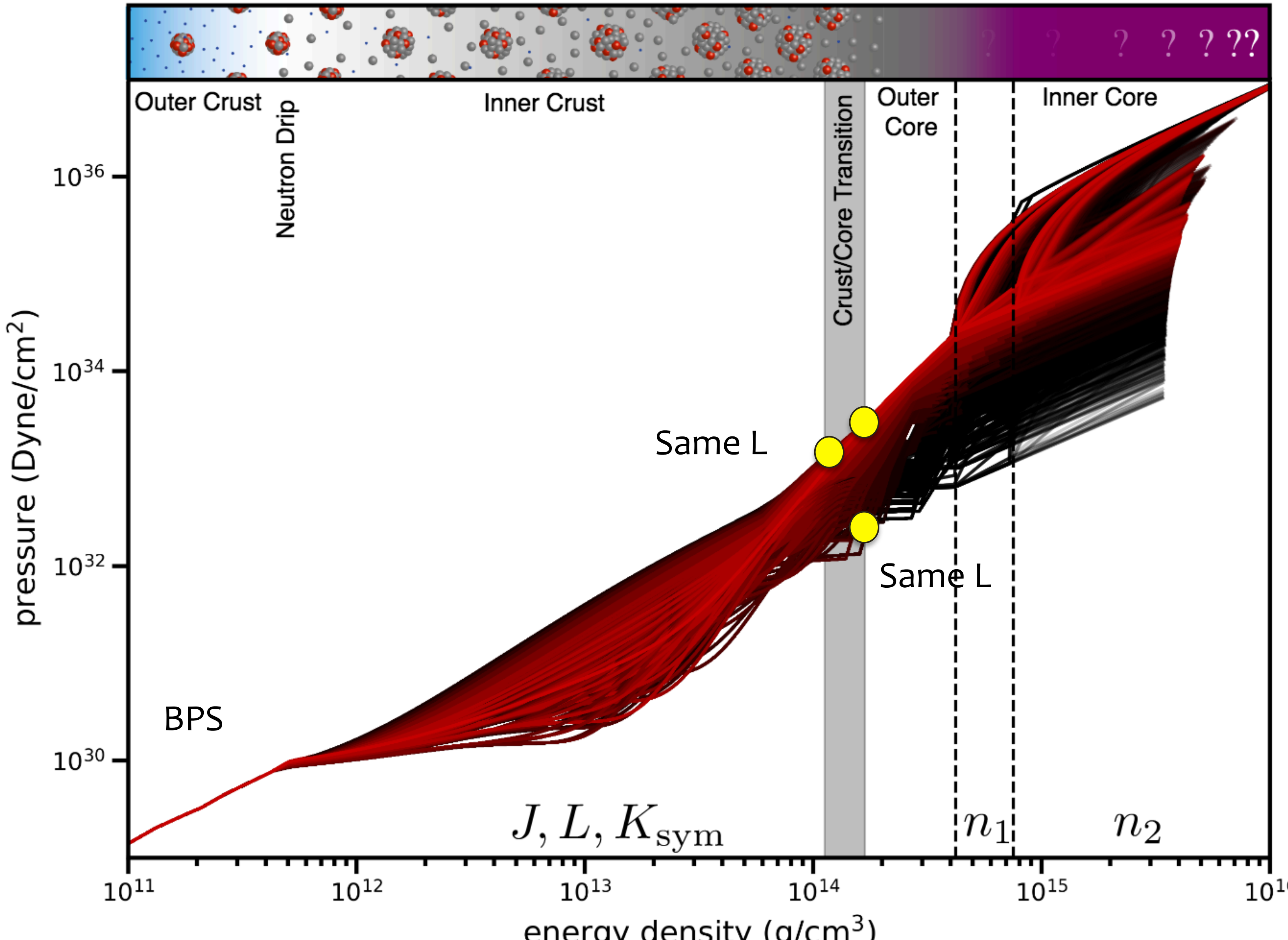
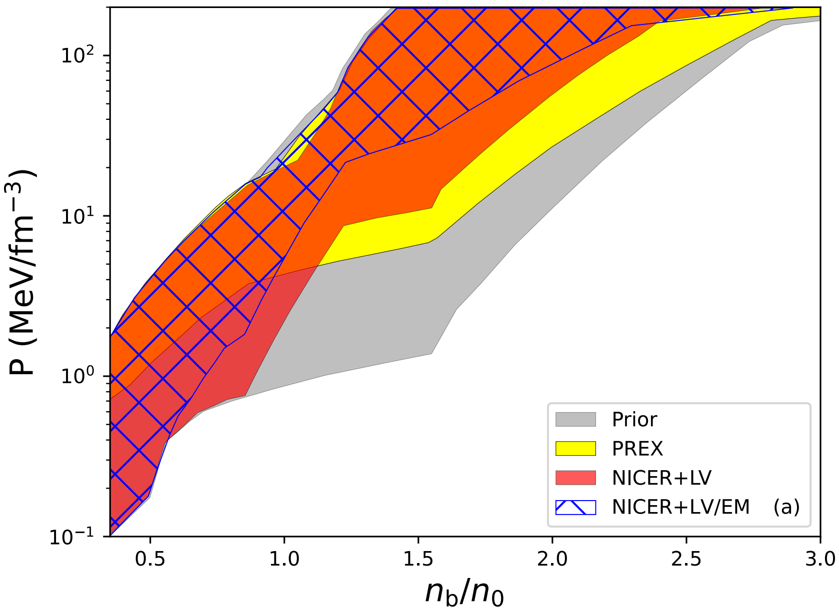
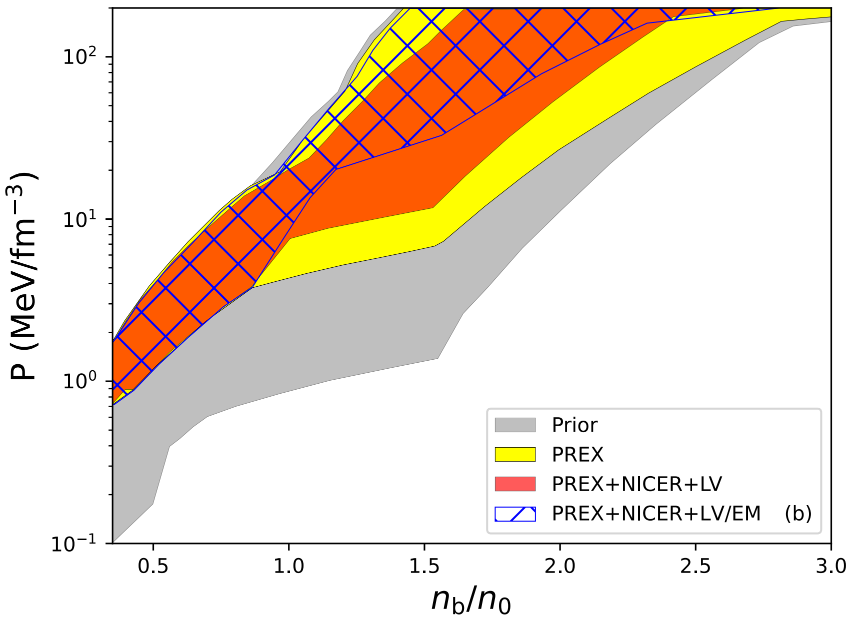



Neill, Preston, Tsang, Newton in prep

# Nuclear *and* astro data can be bought to bear with greater consistency




Newton et al; arxiv:2112.12108

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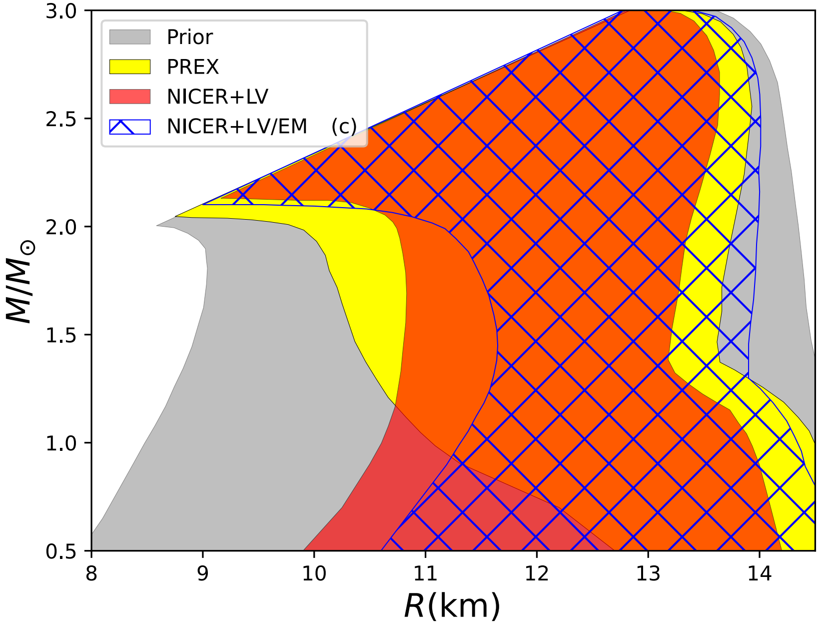
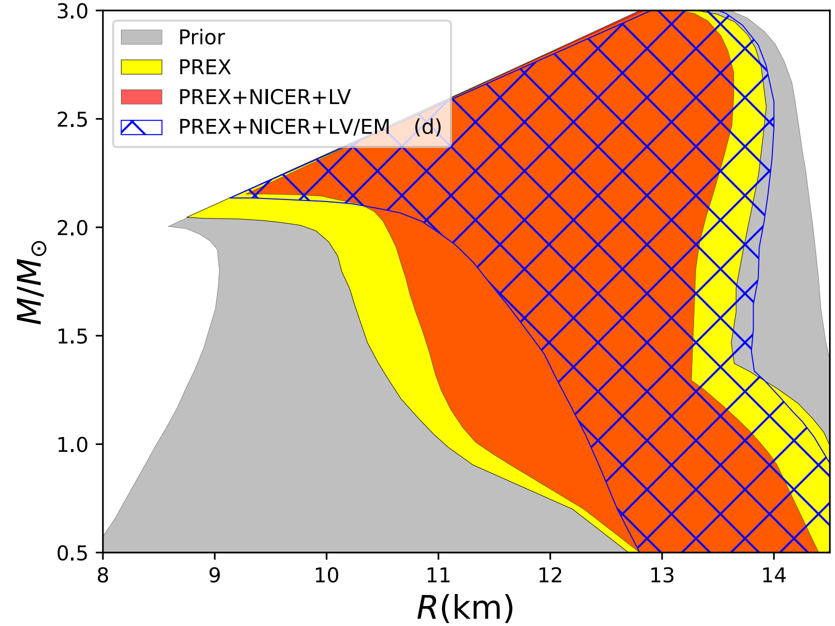
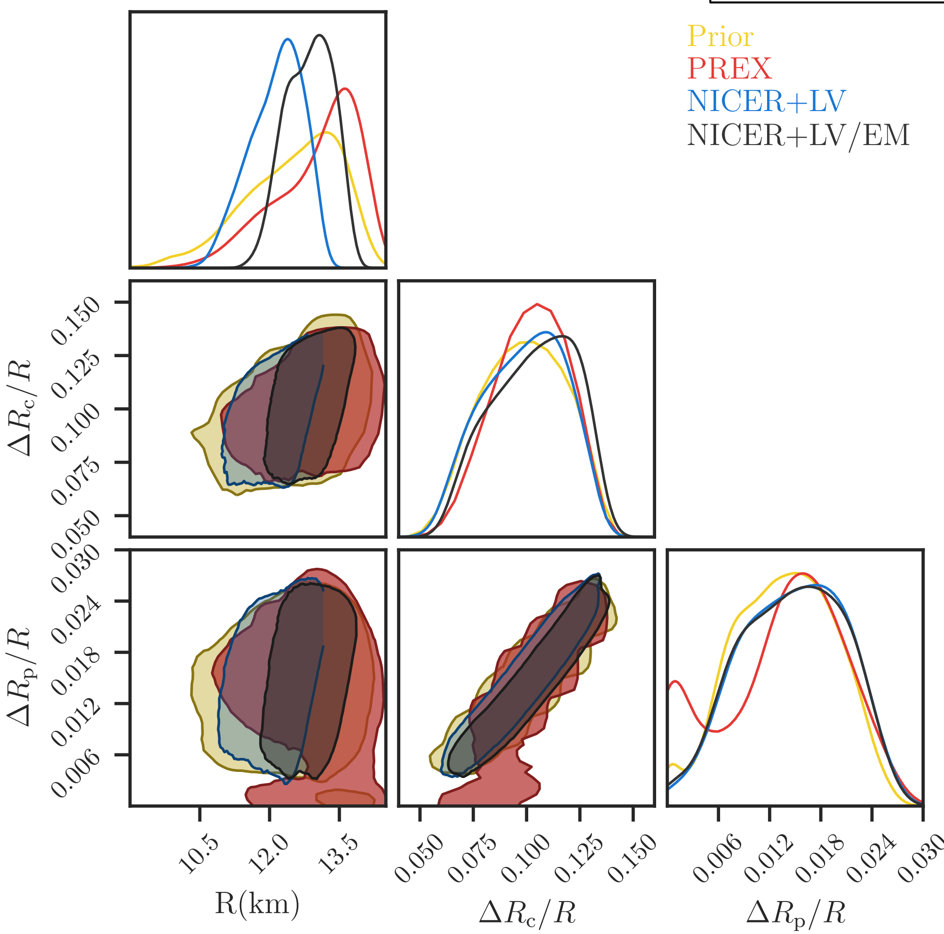


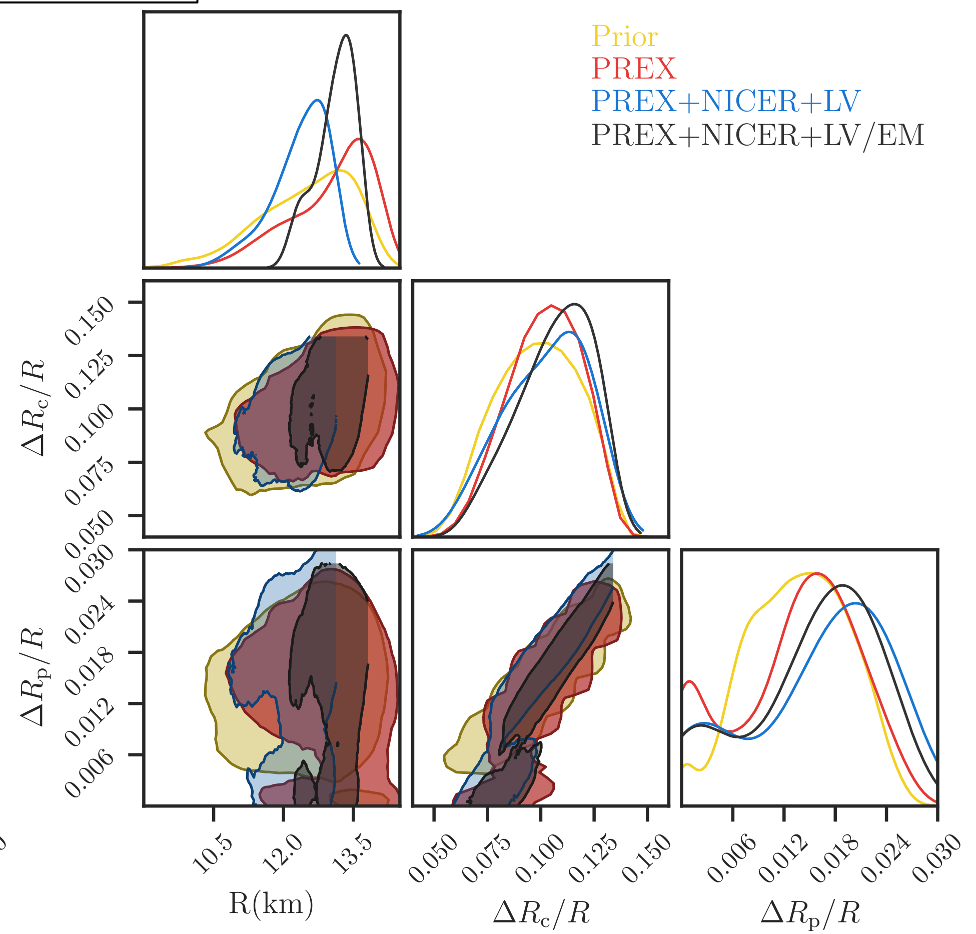




Newton et al; arxiv:2112.12108

# Linking crust and core models, nuclear and astro data: $M=1.4M_{SUN}$

## Radial extents



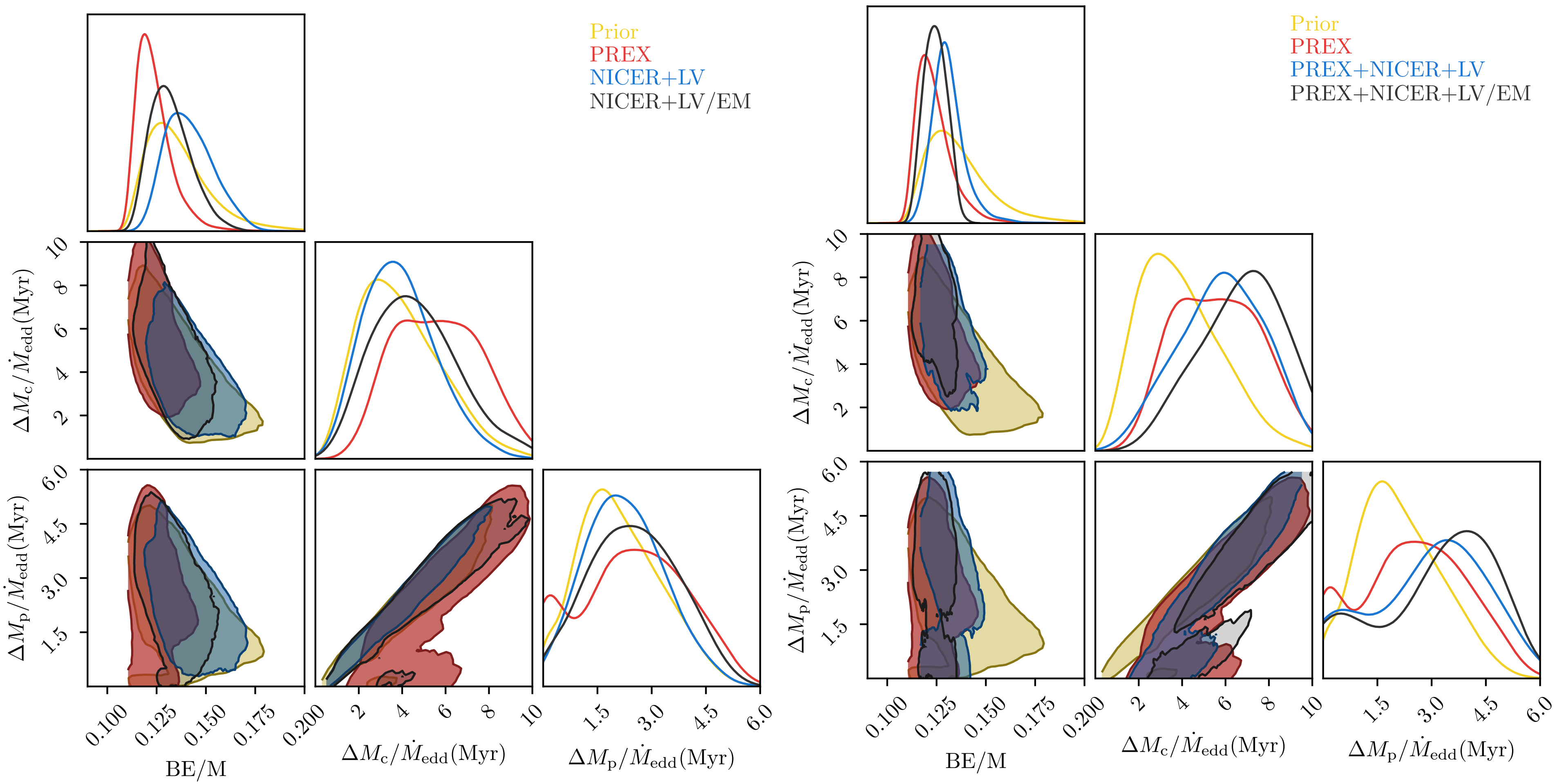

Newton et al; arxiv:2112.12108

12km star: With just NICER/LIGO data, crust can contribute 0.96-1.8 km

c.f. uncertainty from different ways of matching EoS ≈ 0.7km; Fortin et al arxiv: 1604.01944

# Linking crust and core models, nuclear and astro data: $M=1.4M_{SUN}$

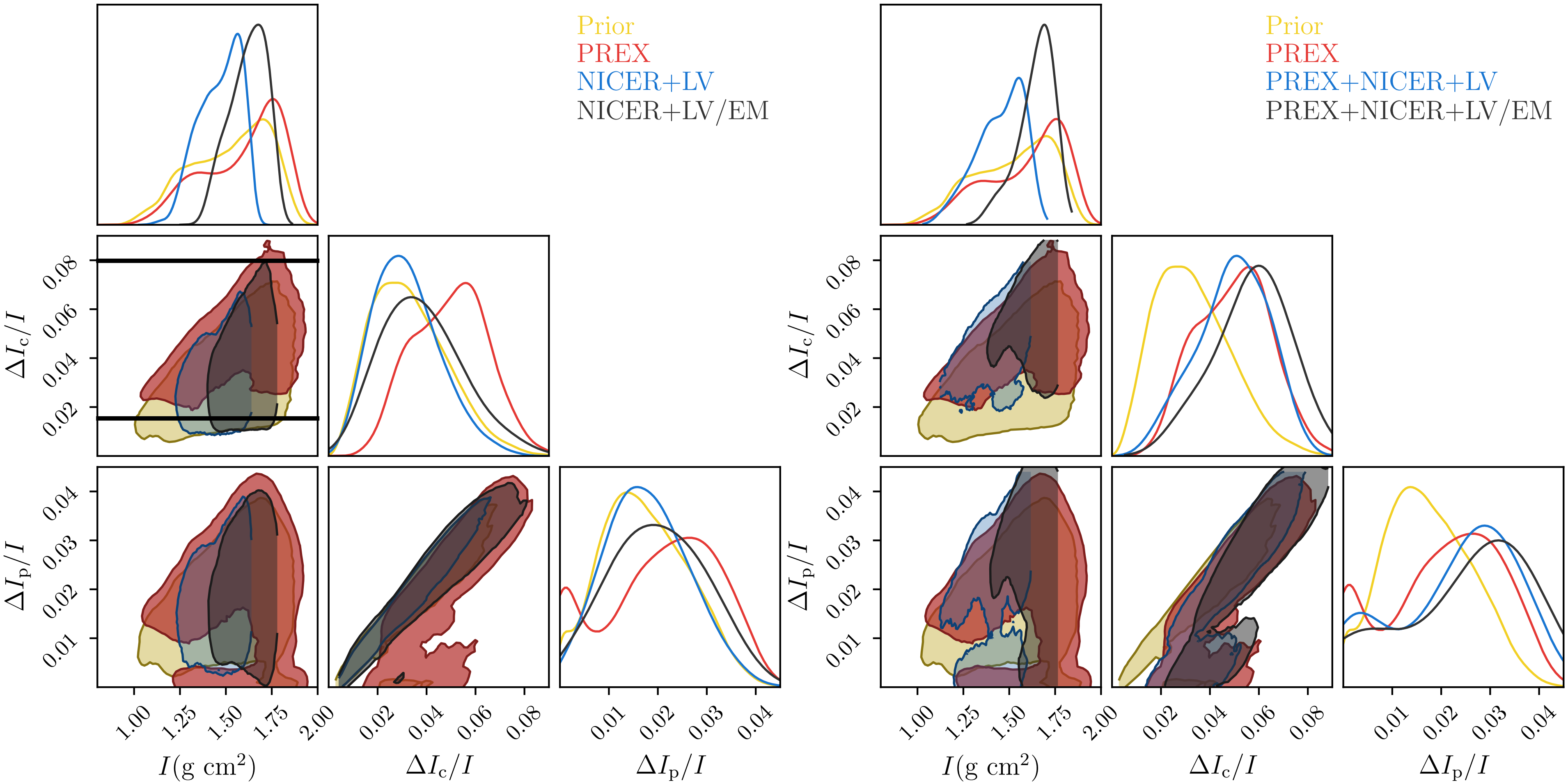
**Masses**




Newton et al; arxiv:2112.12108

# Linking crust and core models, nuclear and astro data: $M=1.4M_{SUN}$

## Moments of inertias

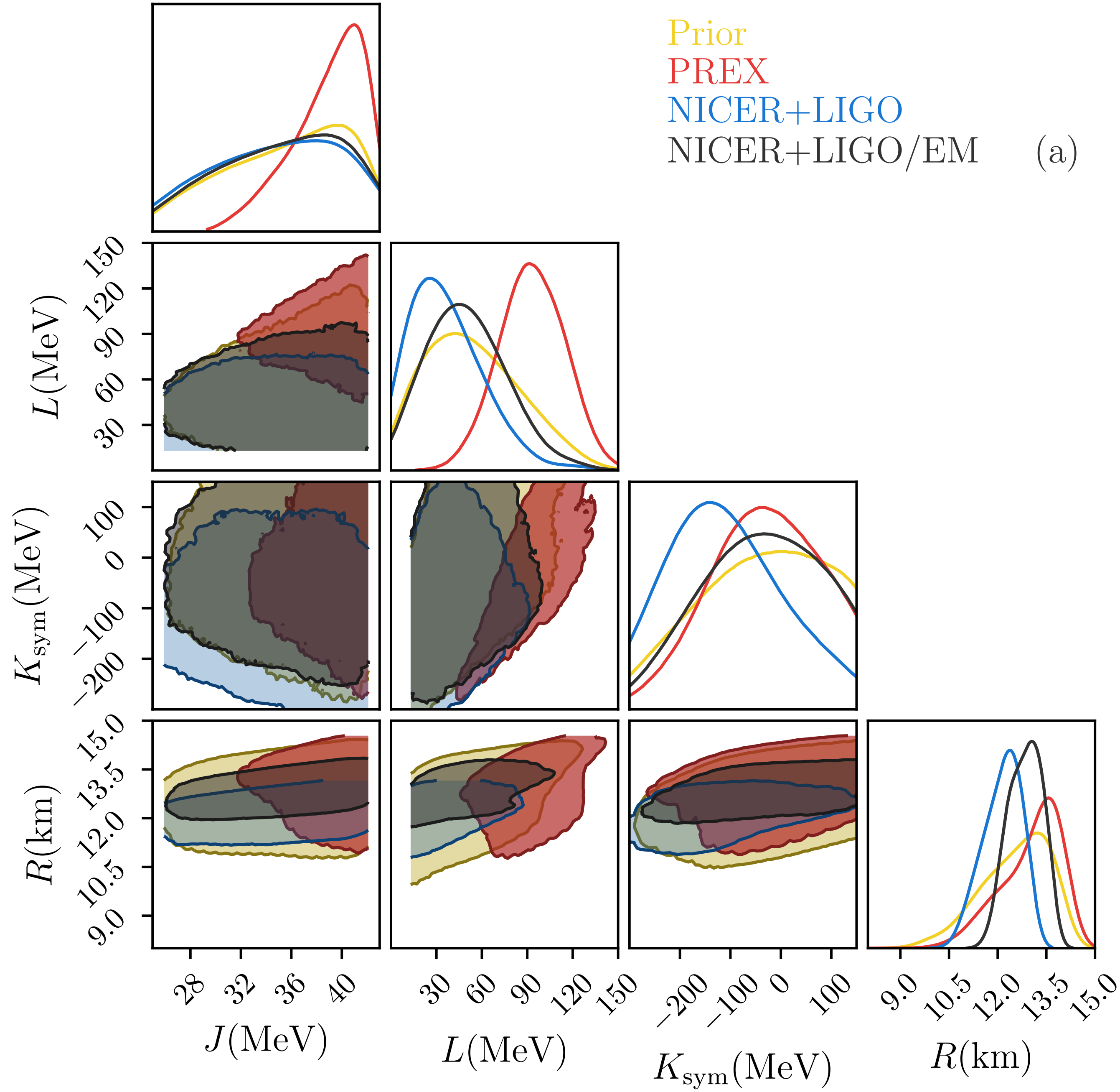



Newton et al; arxiv:2112.12108

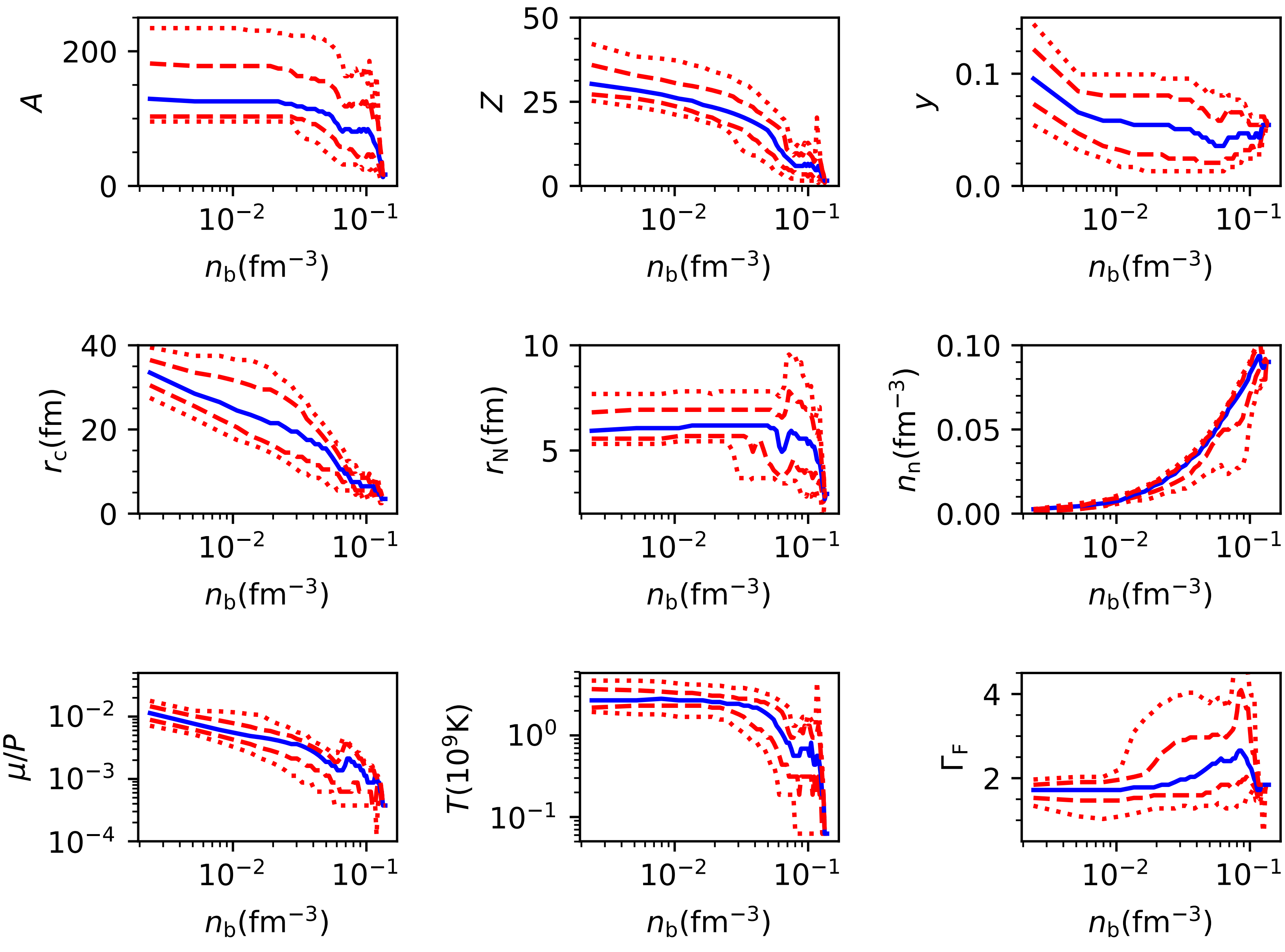
Glitches: MoI of fraction of crust must exceed 0.016 (0.08 when entrainment is high)

(crust is not/maybe enough Andersson arxiv:1207.0633/Piekarewicz arxiv:1404.2660)

# Symmetry energy constraints from nuclear and astro



# Crust Composition: Uninformative Priors

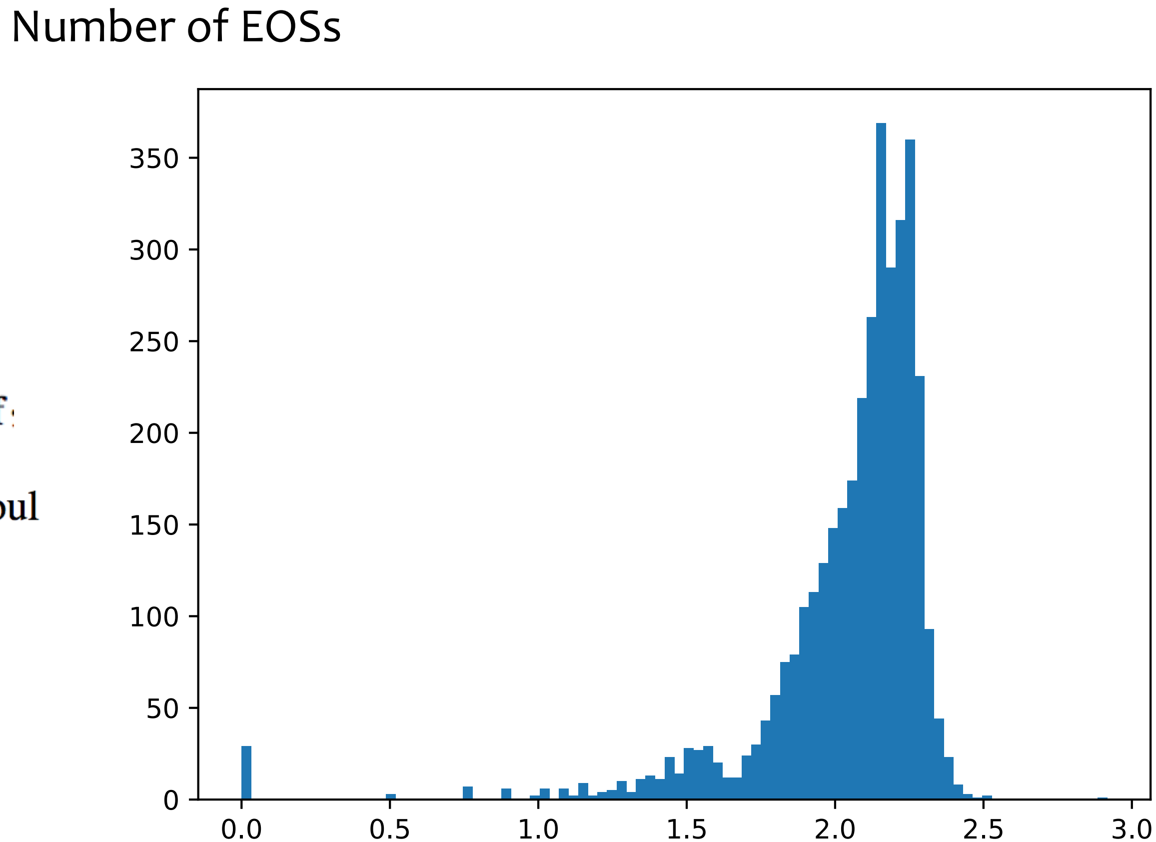



Balliet+; arxiv:2009.07696

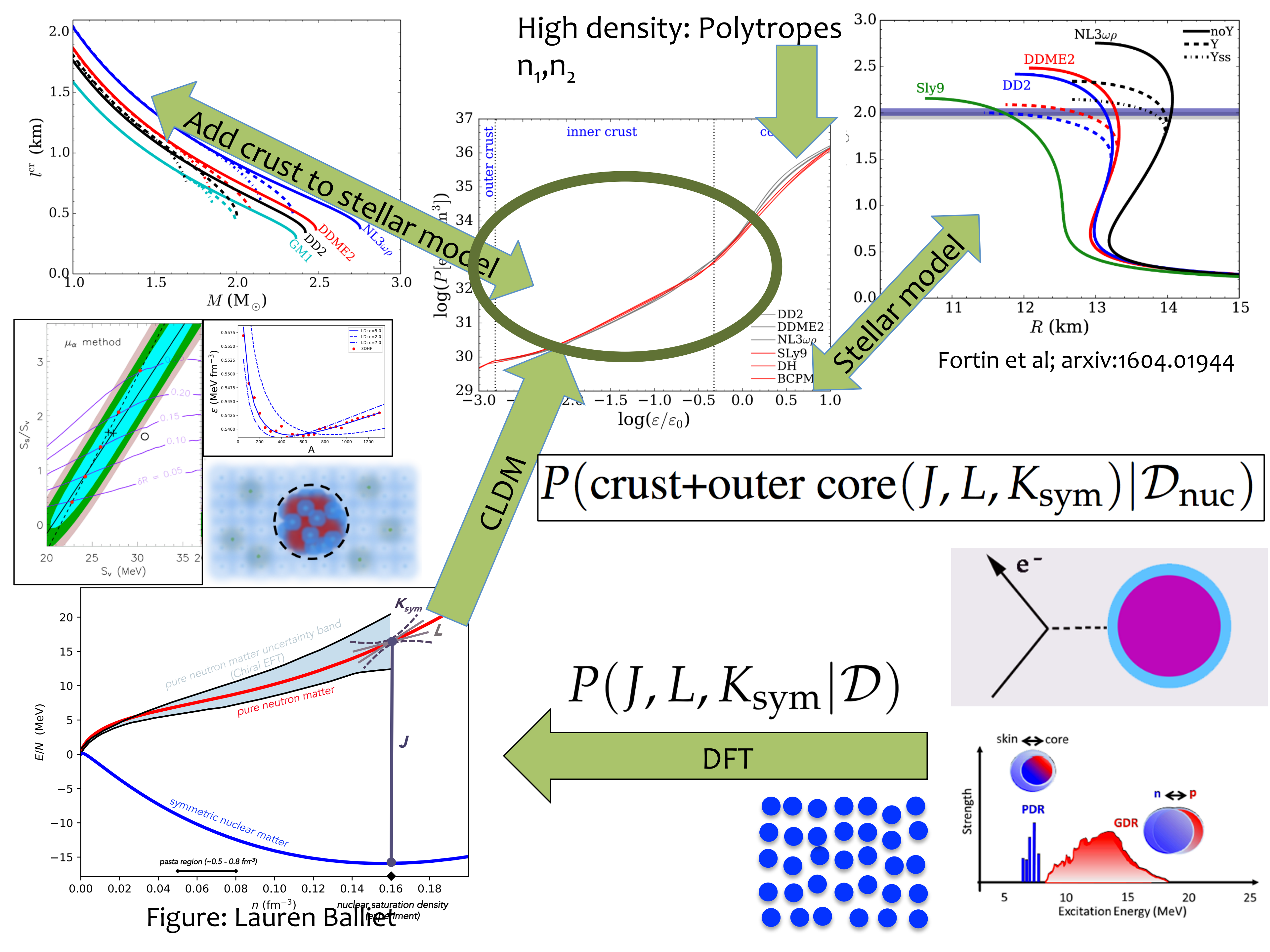
# Shear modulus is likely overestimated by *at least* a factor of two in the pasta layers

$$c_{33} = 3E_{\mathrm{surf}}$$

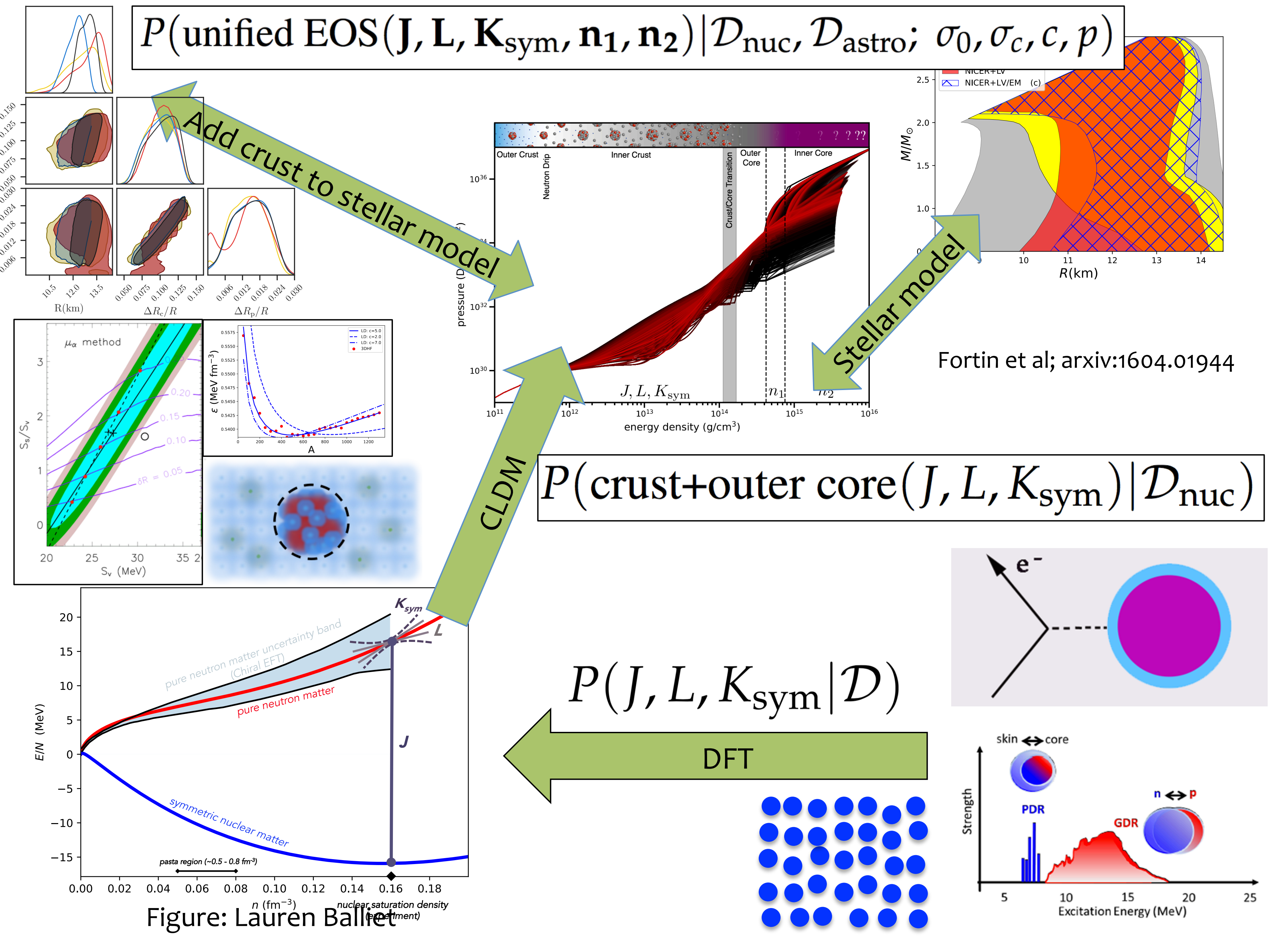
$$E_{\mathrm{surf}} = 2E_{\mathrm{Coul}}$$



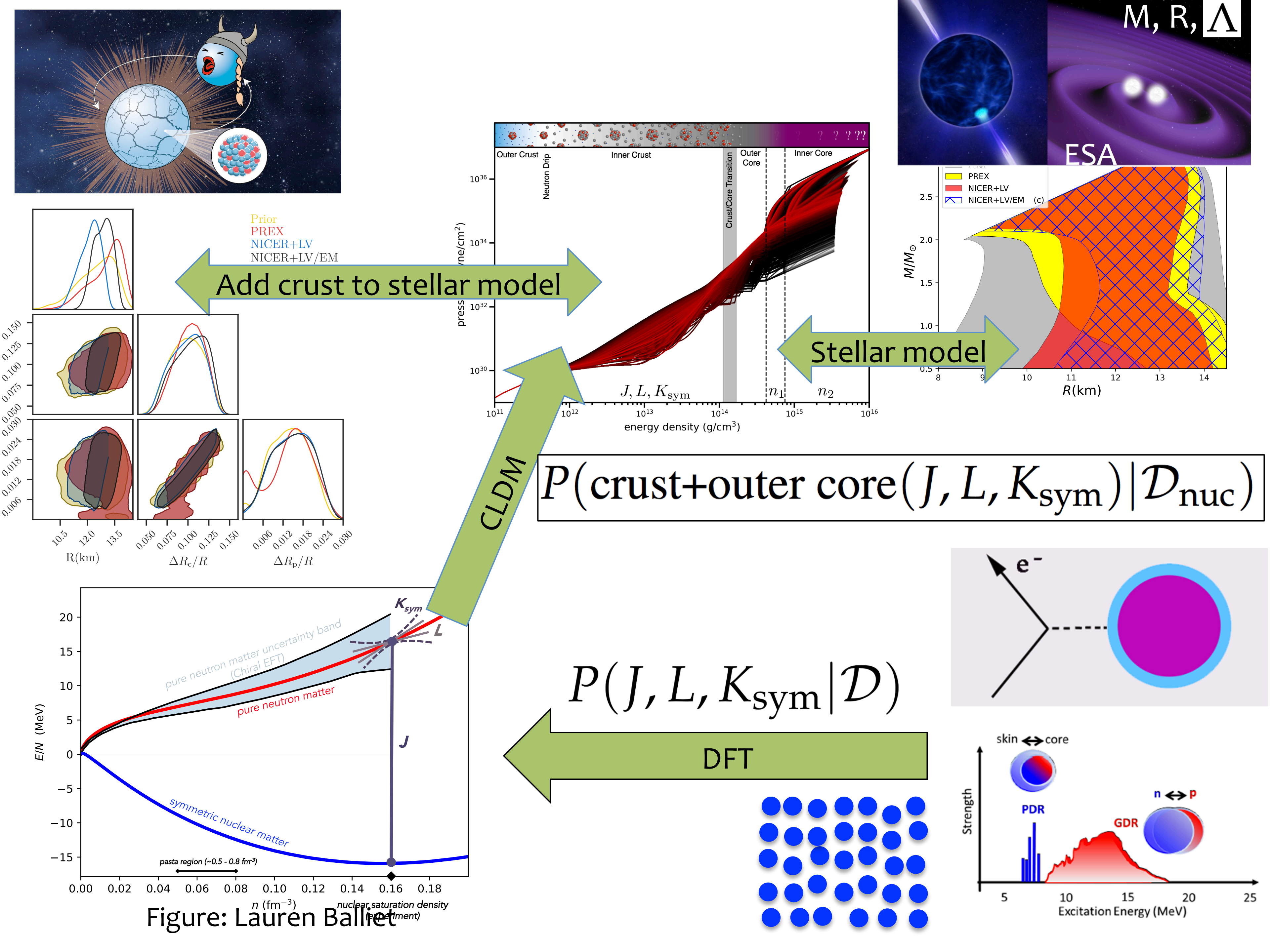

$$\mu = \frac{0.1194}{1 + 0.595(\Gamma_0/\Gamma)^2} \frac{n_i (Ze)^2}{a} \Bigg/ \mu_V \simeq \frac{c_{33}}{15}$$



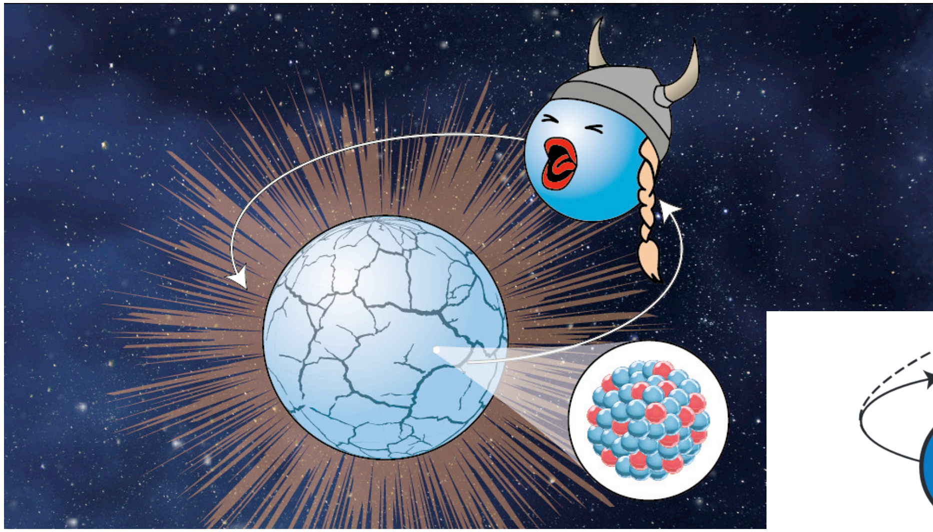
High density: Polytropes
n1,n2
Add crust to stellar model
Stellar model
CLDM
DFT
$P(\text{crust+outer core}(J, L, K_{\text{sym}}) | \mathcal{D}_{\text{nuc}})$
$P(J, L, K_{\text{sym}} | \mathcal{D})$
Fortin et al; arxiv:1604.01944
Figure: Lauren Balliet
outer crust
inner crust
DD2
DDME2
NL3ωρ
SLy9
DH
BCPM
GM1
noY
Y
Yss
Sly9
$\log(\varepsilon/\varepsilon_0)$
R (km)
M (M☉)
$\mu_\alpha$ method
$S_v$ (MeV)
$S_s/S_v$
A
pure neutron matter uncertainty band
(Chiral EFT)
pure neutron matter
symmetric nuclear matter
pasta region (~0.5 - 0.8 fm⁻³)
nuclear saturation density
(experiment)
E/N (MeV)
$K_{sym}$
L
J
e⁻
skin ↔ core
n ↔ p
PDR
GDR
Strength
Excitation Energy (MeV)



$P(\text{unified EOS}(\mathbf{J}, \mathbf{L}, \mathbf{K_{sym}}, \mathbf{n_1}, \mathbf{n_2}) | \mathcal{D}_{\text{nuc}}, \mathcal{D}_{\text{astro}};\ \sigma_0, \sigma_c, c, p)$
Add crust to stellar model
Stellar model
CLDM
DFT
$P(\text{crust+outer core}(J, L, K_{\text{sym}}) | \mathcal{D}_{\text{nuc}})$
$P(J, L, K_{\text{sym}} | \mathcal{D})$
Fortin et al; arxiv:1604.01944
Figure: Lauren Balliet
Outer Crust
Neutron Drip
Inner Crust
Crust/Core Transition
Outer Core
Inner Core
pressure
energy density (g/cm$^3$)
$J, L, K_{\text{sym}}$
$n_1$
$n_2$
NICER+LV
NICER+LV/EM (c)
$M/M_\odot$
$R$(km)
R(km)
$\Delta R_c/R$
$\Delta R_p/R$
$\mu_\alpha$ method
$S_s/S_v$
$S_v$ (MeV)
$\delta R = 0.05$
LD: c=5.0
LD: c=2.0
LD: c=7.0
3DHF
$\varepsilon$ (MeV fm$^{-3}$)
A
$K_{sym}$
$L$
$J$
pure neutron matter uncertainty band (Chiral EFT)
pure neutron matter
symmetric nuclear matter
pasta region (~0.5 - 0.8 fm$^{-3}$)
nuclear saturation density (experiment)
$E/N$ (MeV)
$n$ (fm$^{-3}$)
e$^-$
skin ↔ core
n ↔ p
PDR
GDR
Strength
Excitation Energy (MeV)

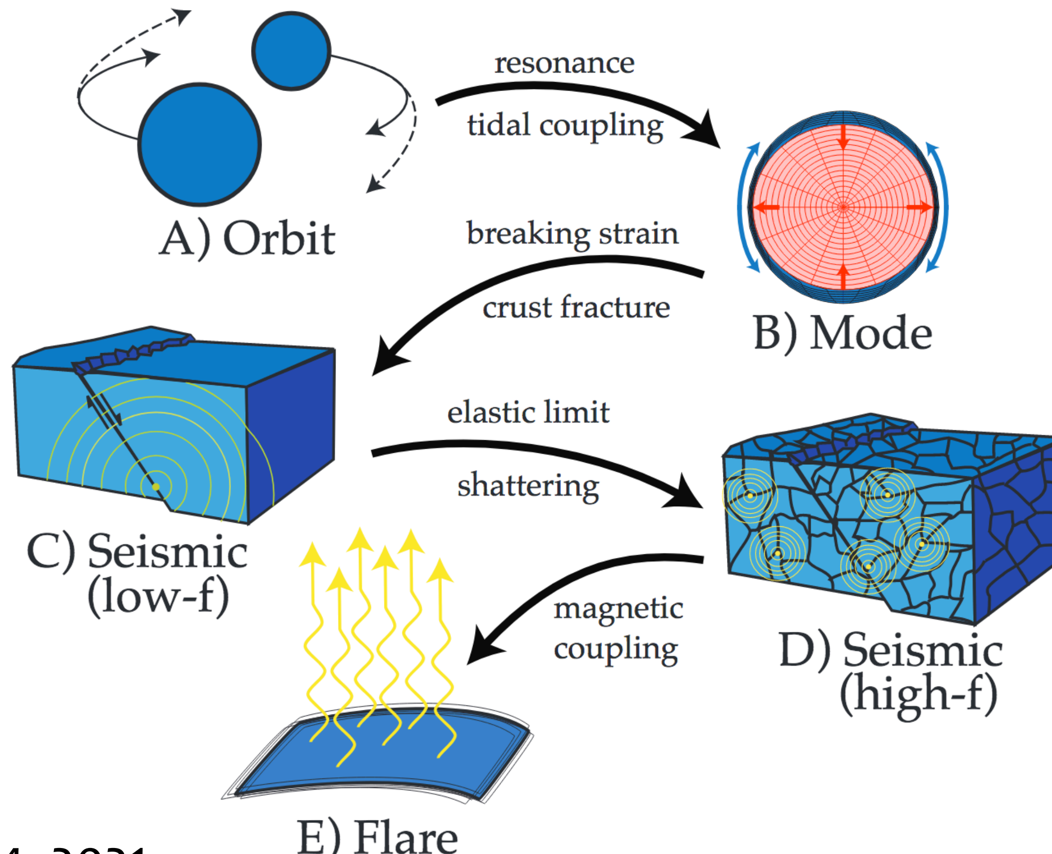

M, R, Λ
ESA
Add crust to stellar model
Prior
PREX
NICER+LV
NICER+LV/EM
R(km)
$\Delta R_c/R$
$\Delta R_p/R$
Outer Crust
Neutron Drip
Inner Crust
Crust/Core Transition
Outer Core
Inner Core
$J, L, K_{\rm sym}$
$n_1$
$n_2$
energy density (g/cm$^3$)
Stellar model
$M/M_\odot$
R(km)
CLDM
$P(\text{crust+outer core}(J, L, K_{\rm sym})|\mathcal{D}_{\rm nuc})$
$P(J, L, K_{\rm sym}|\mathcal{D})$
DFT
e⁻
skin ↔ core
PDR
GDR
n ↔ p
Strength
Excitation Energy (MeV)
$K_{sym}$
L
J
pure neutron matter uncertainty band (Chiral EFT)
pure neutron matter
symmetric nuclear matter
pasta region (~0.5 - 0.8 fm⁻³)
E/N (MeV)
$n$ (fm$^{-3}$)
nuclear saturation density (experiment)
Figure: Lauren Balliet

# Resonant shattering flares: combining crust and core observables



Picture: David Tsang

(See David's talk next Wednesday!)



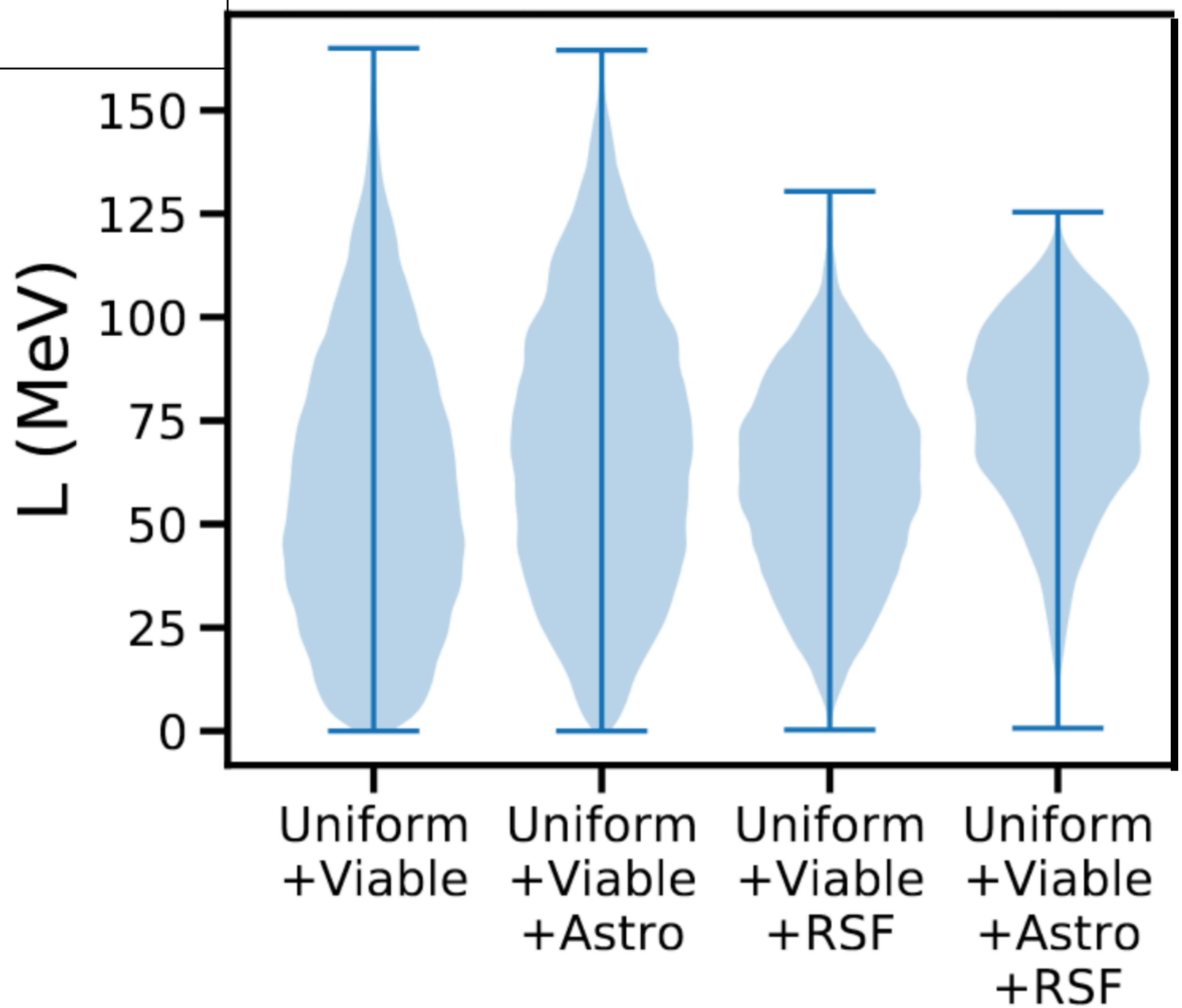

D.Tsang, Apj 777, 2013

Neill, Newton & Tsang, MNRAS 504, 2021

Neill, Preston, Tsang, Newton in prep

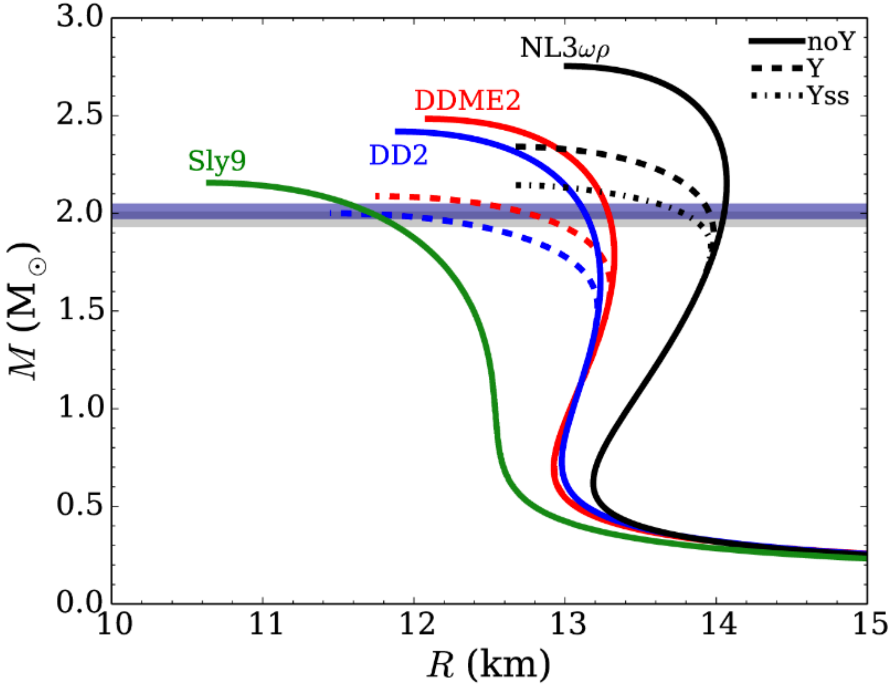
# Resonant shattering flares: combining crust and core observables

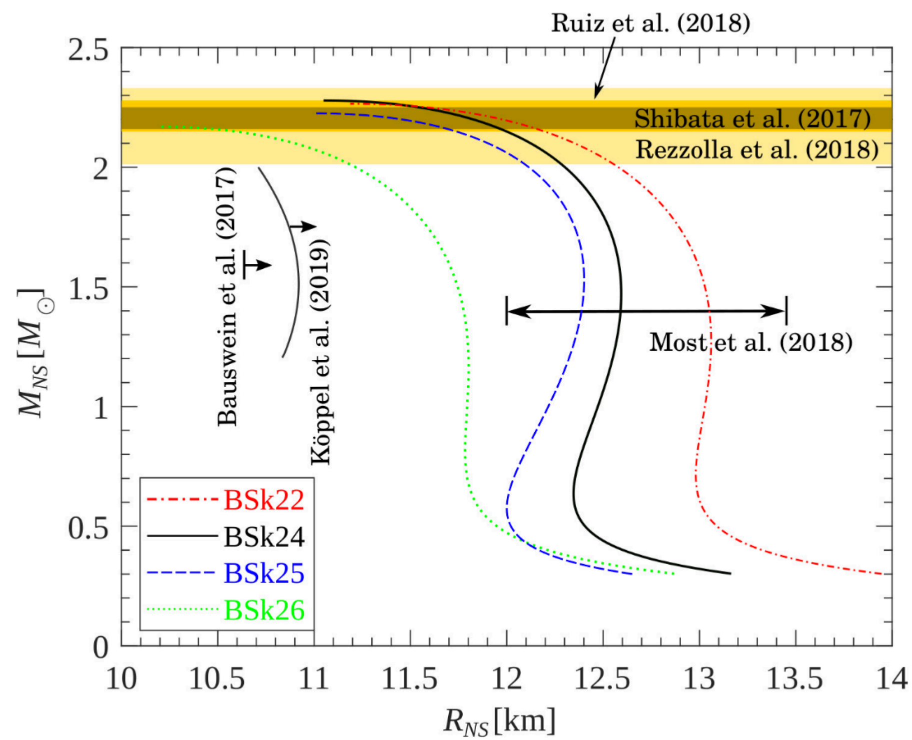
(See David's talk next Wednesday!)




Neill,Preston,Tsang,Newton in prep

# Complementary approach: Precision model fits




Fortin et al; arxiv:1604.01944

Pearson et al MNRAS481,2994–3026 (2018)
Chamel et al arxiv:1904.12477

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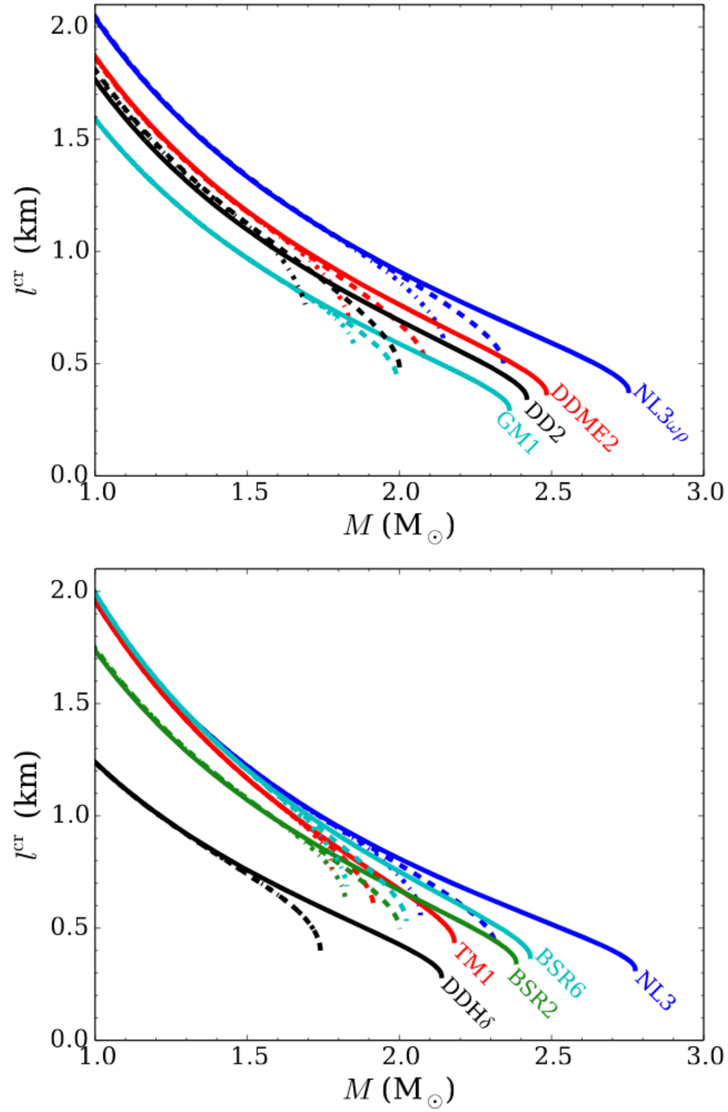
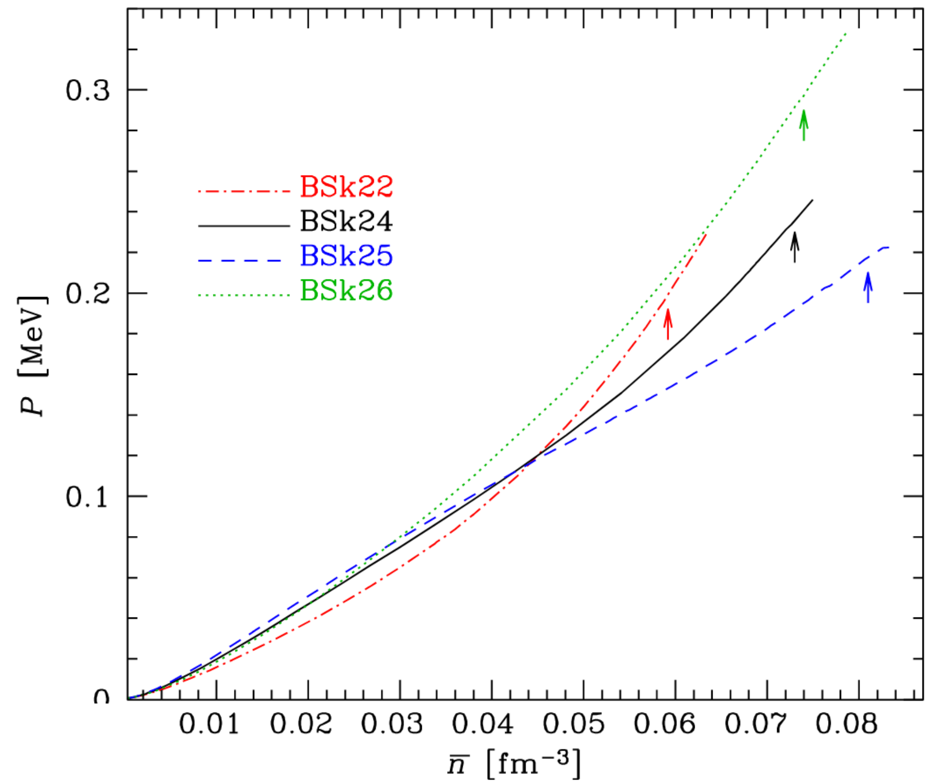



Fortin et al; arxiv:1604.01944




Pearson et al MNRAS481,2994–3026 (2018)
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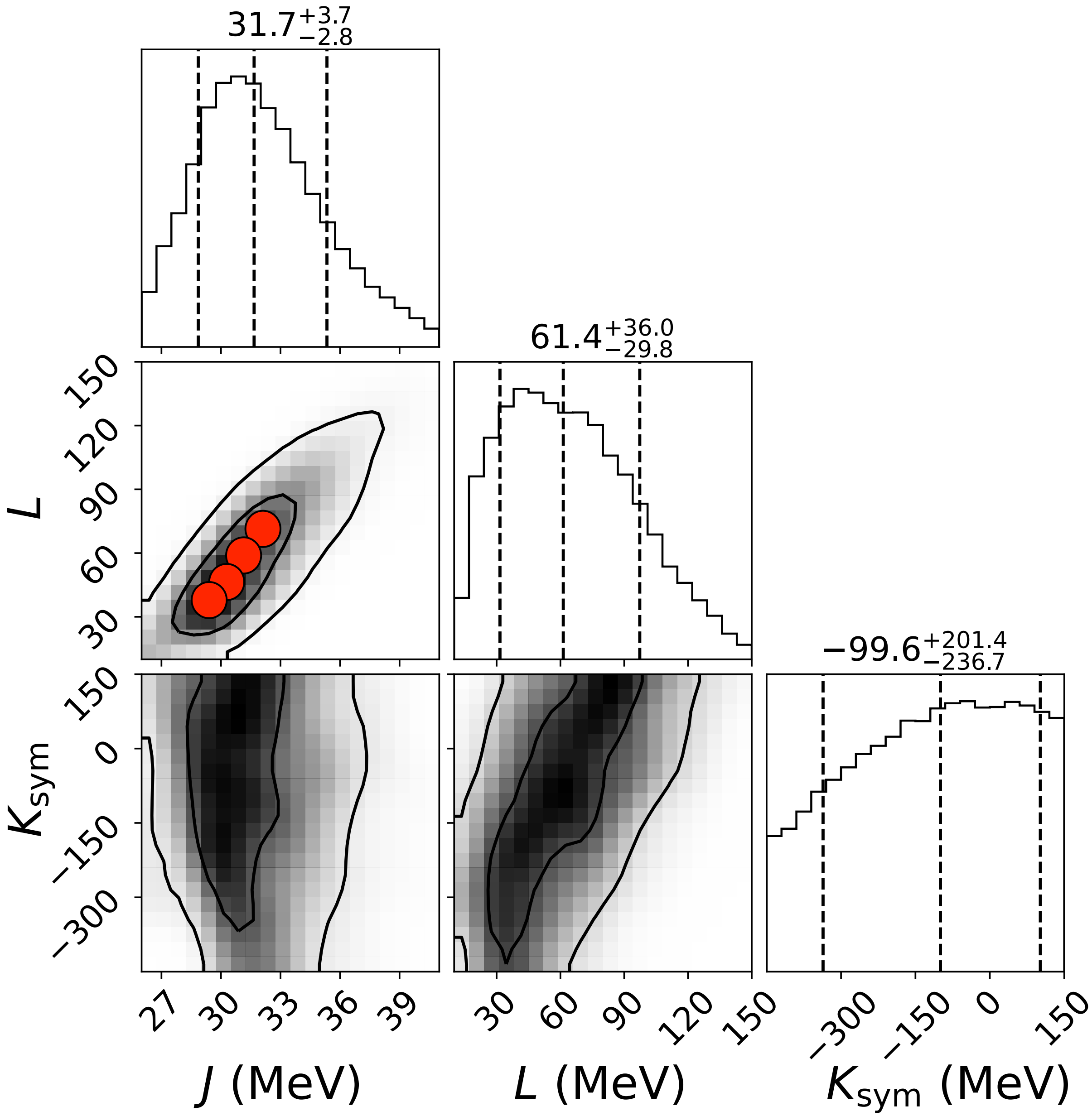

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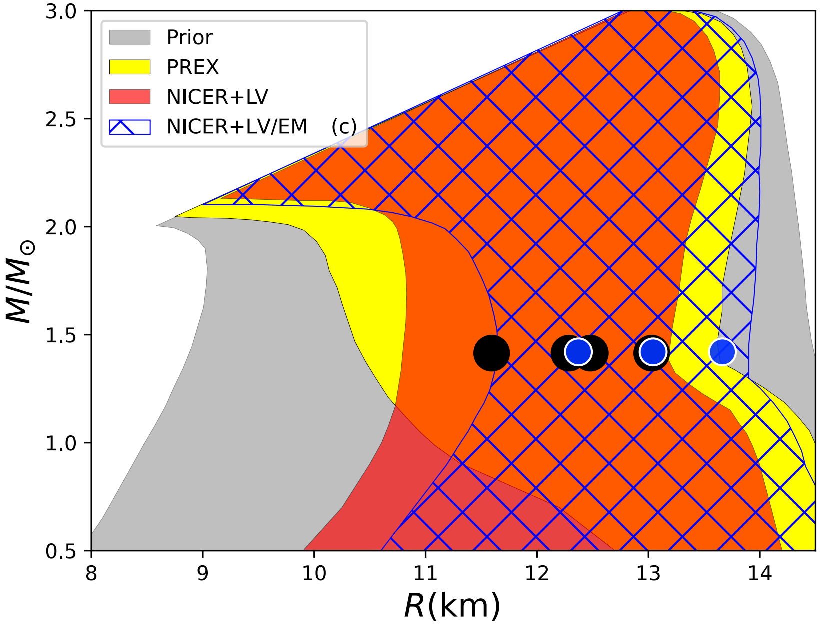
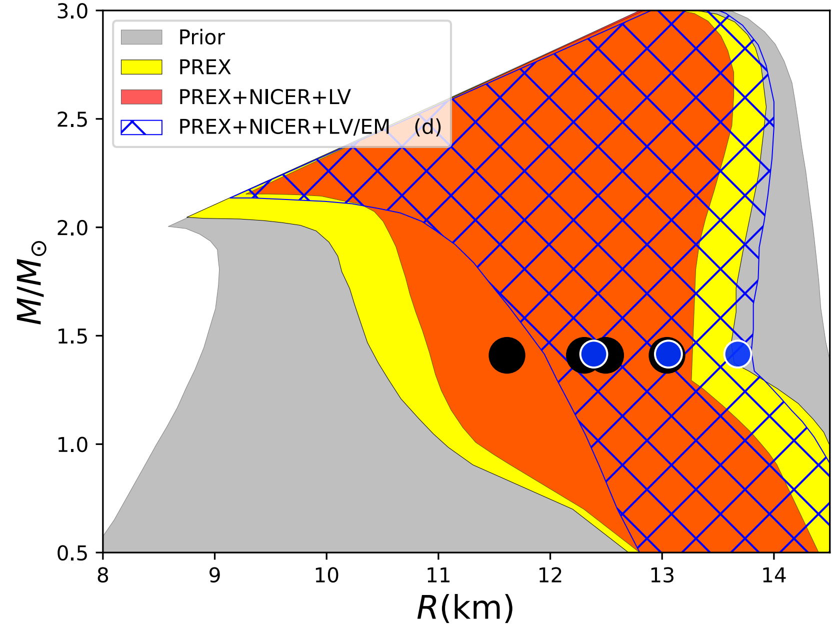



Newton et al; arxiv:2112.12108

# Some thoughts

Attempt at a framework to connect neutron star bulk and crust observables with nuclear data as consistently as possible

Consistency: eliminate systematic errors that may arise when different models are used to propagate information across multiple physical characteristics

Many rich astro datasets require crust modeling to interpret. We want to bring these into our multimessenger club

Not a replacement for precision modeling

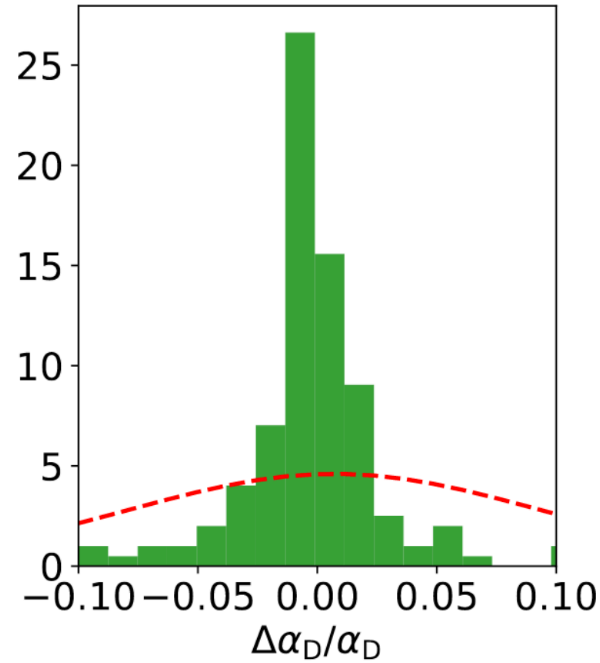
Radius measurements are not going to be able to ignore the crust too much longer

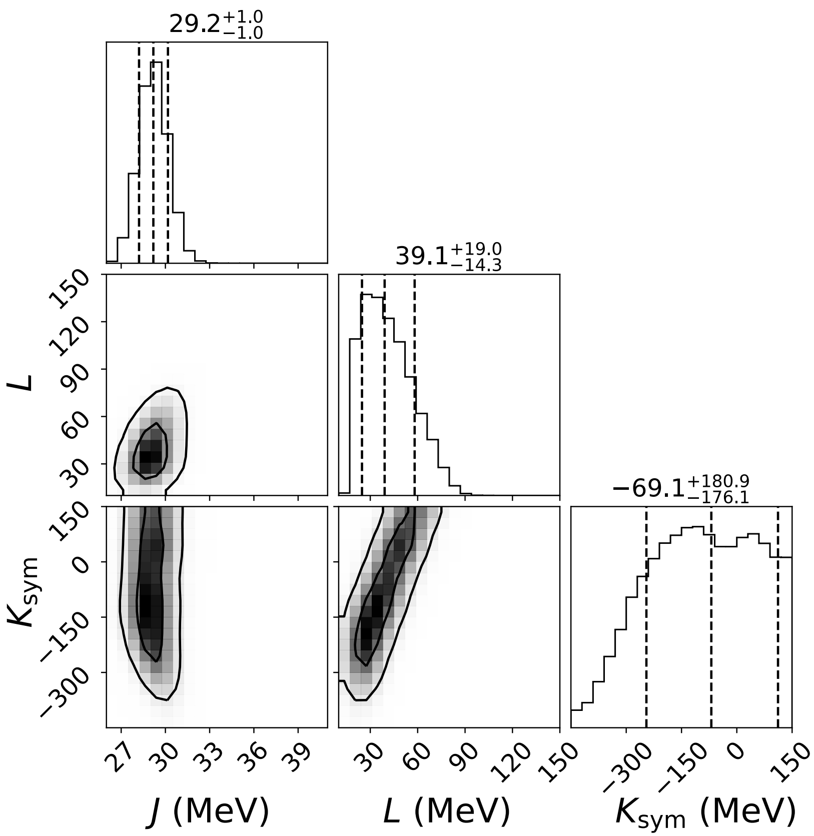
# Assumptions/limitations

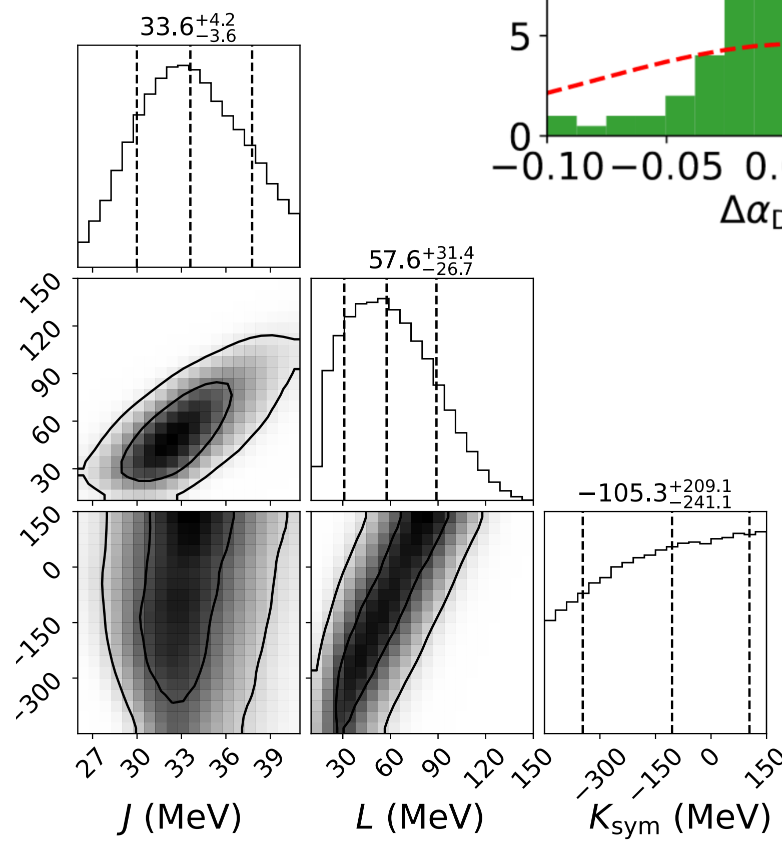
Had to choose an EDF (Skyrme). Enough degrees of freedom?
    Can add more ($Q_{sym}$)
Symmetric nuclear matter and gradient parameters held fixed, underestimate model
Need more information to constrain surface parameters of crust model (mass fits,
    semi-inifinite nuclear matter, Thomas-Fermi calculations)
2 polytropes in the core is bare minimum: can be more sophisticated
We're usually not directly modeling nuclear observables - but in some cases we can
    (e.g. weak form factor) and thus improve consistency

What about the other parameters?

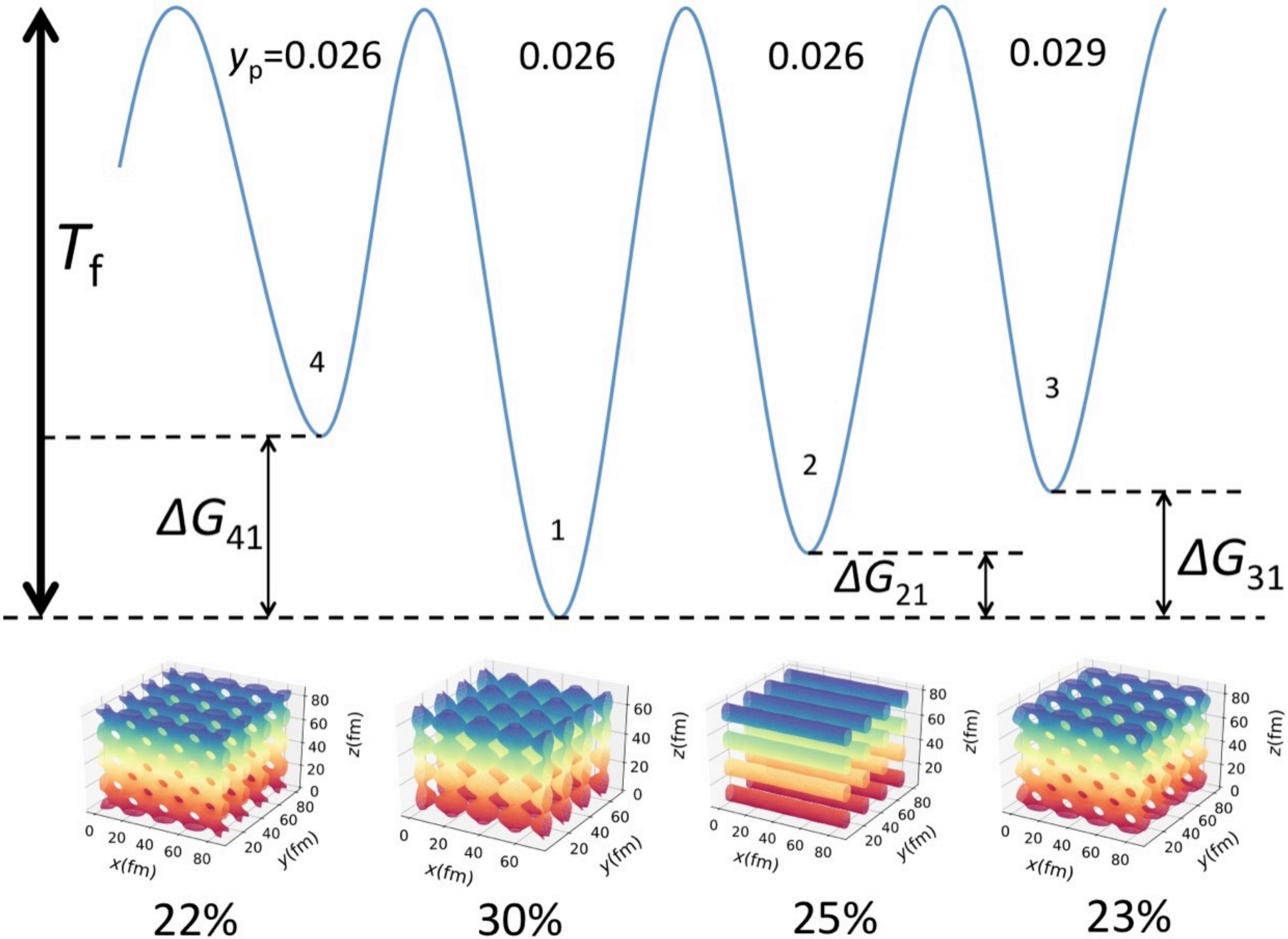
- Refit a subset of our 1000 Skyrmes using simulated annealing method
- Fit the resulting differences in observables with Gaussian – a conservative estimate



Pasta: a complex, glassy system. Multiple shapes coexist in microscopic domains. *Should* affect transport properties. How much is there?



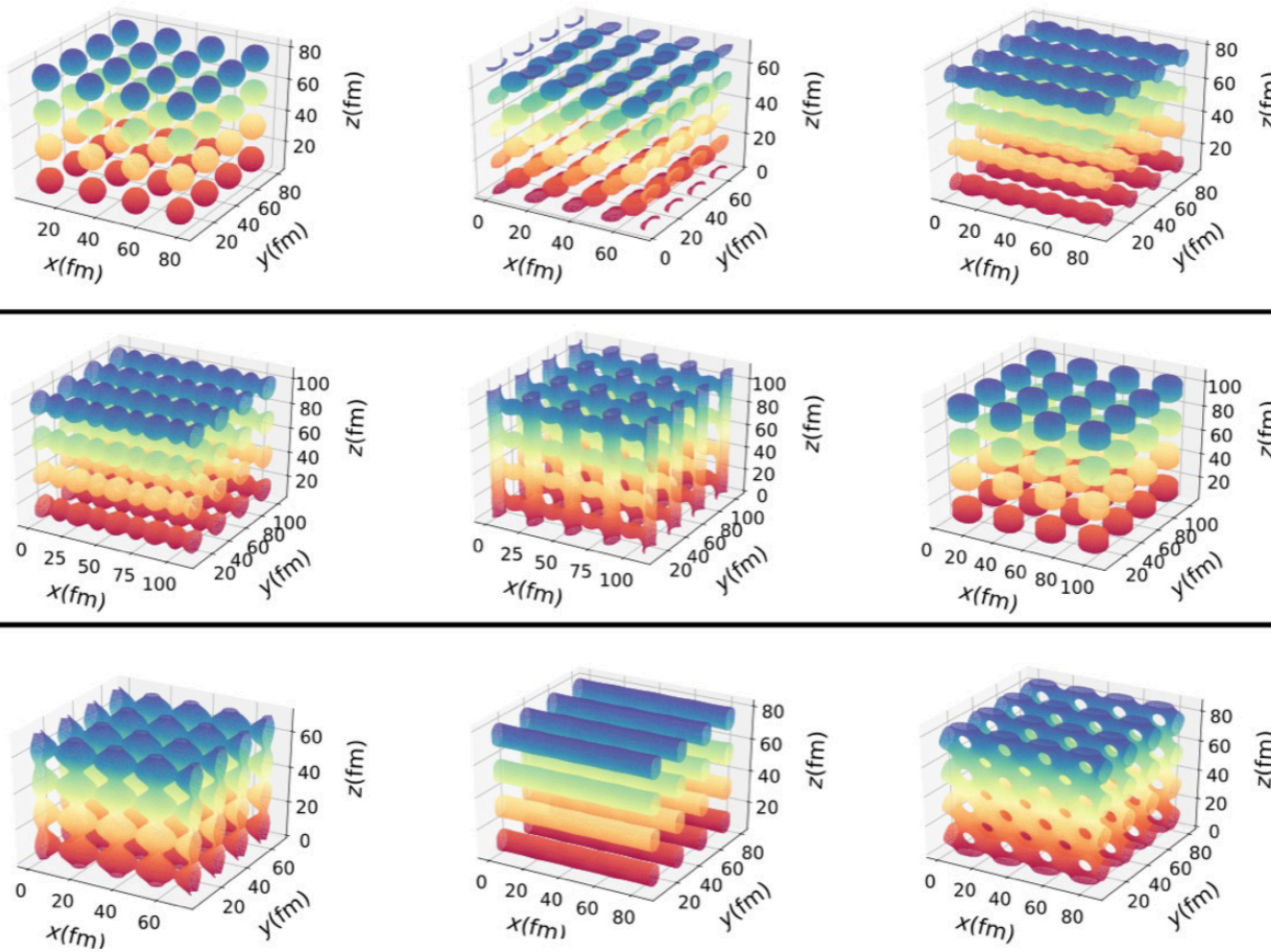

Newton et al arxiv:2104.11835

Increasing energy of local minimum

0.04-0.05

0.05-0.06

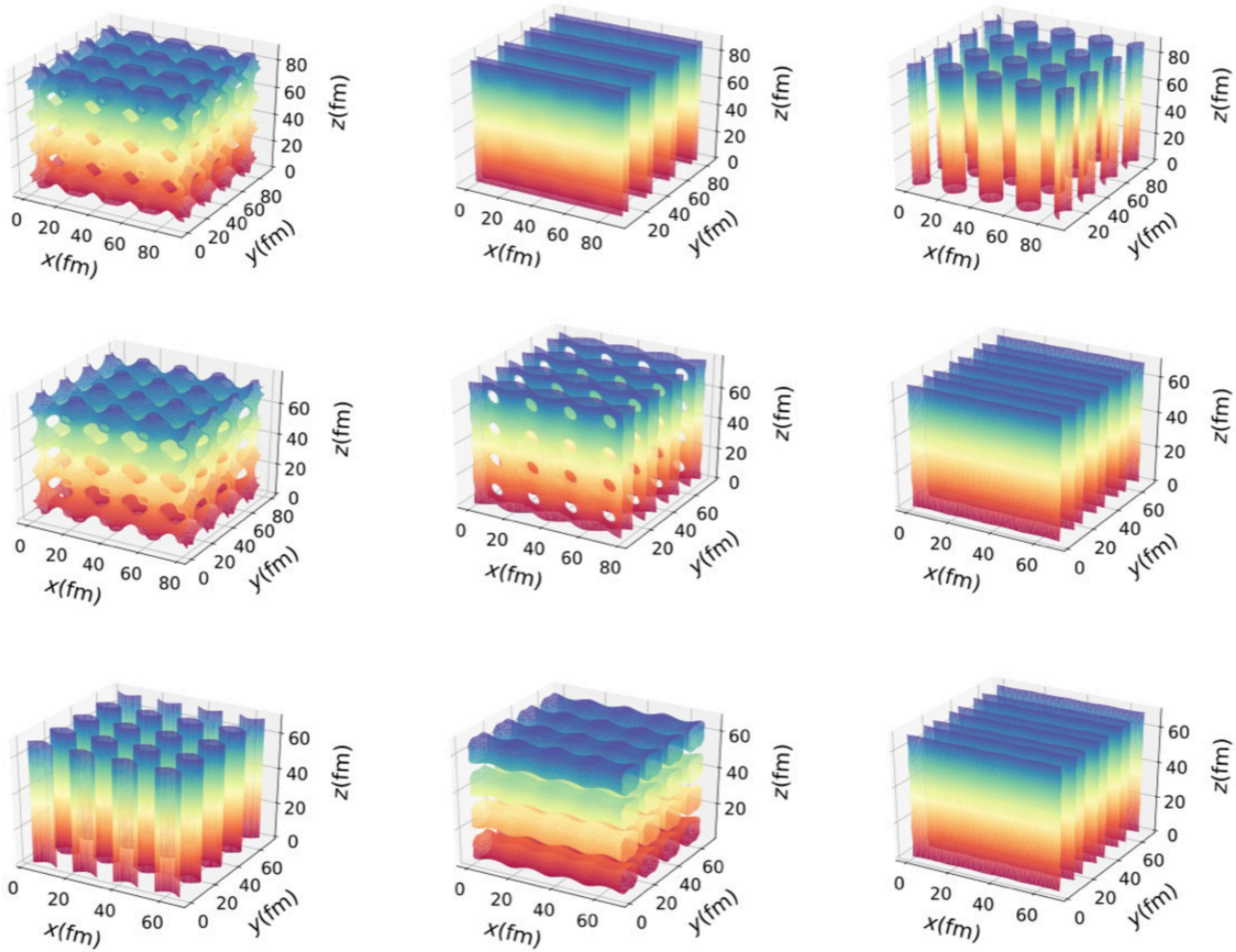
0.06-0.07



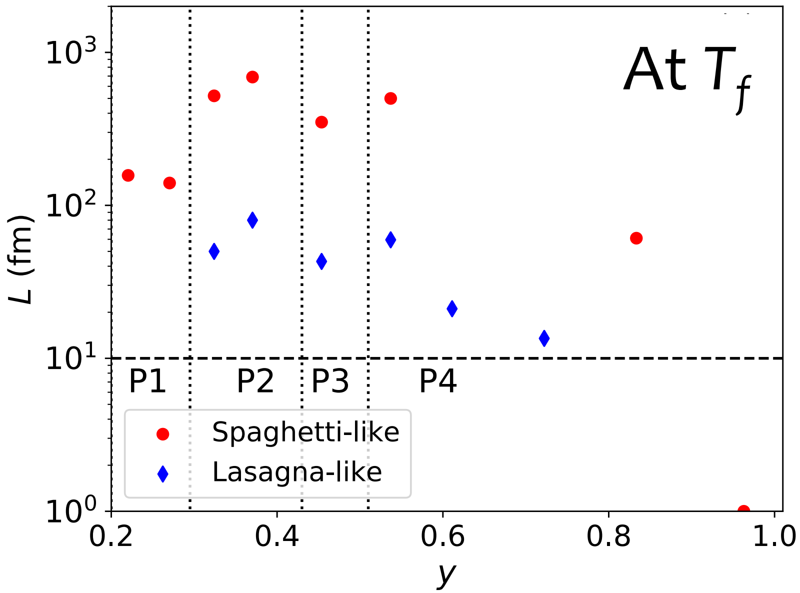

$fm^{-3}$

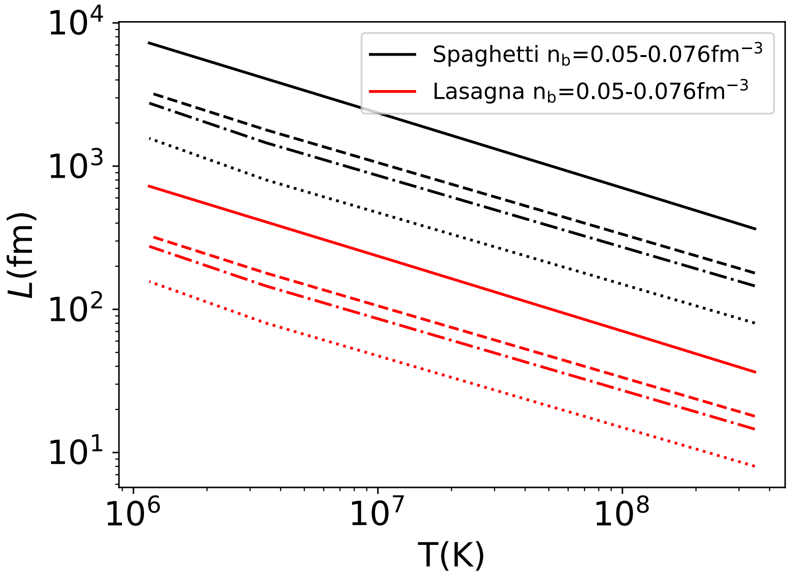
Increasing energy of local minimum

0.07-
0.09
$fm^{-3}$



# Possible sources of resistivity

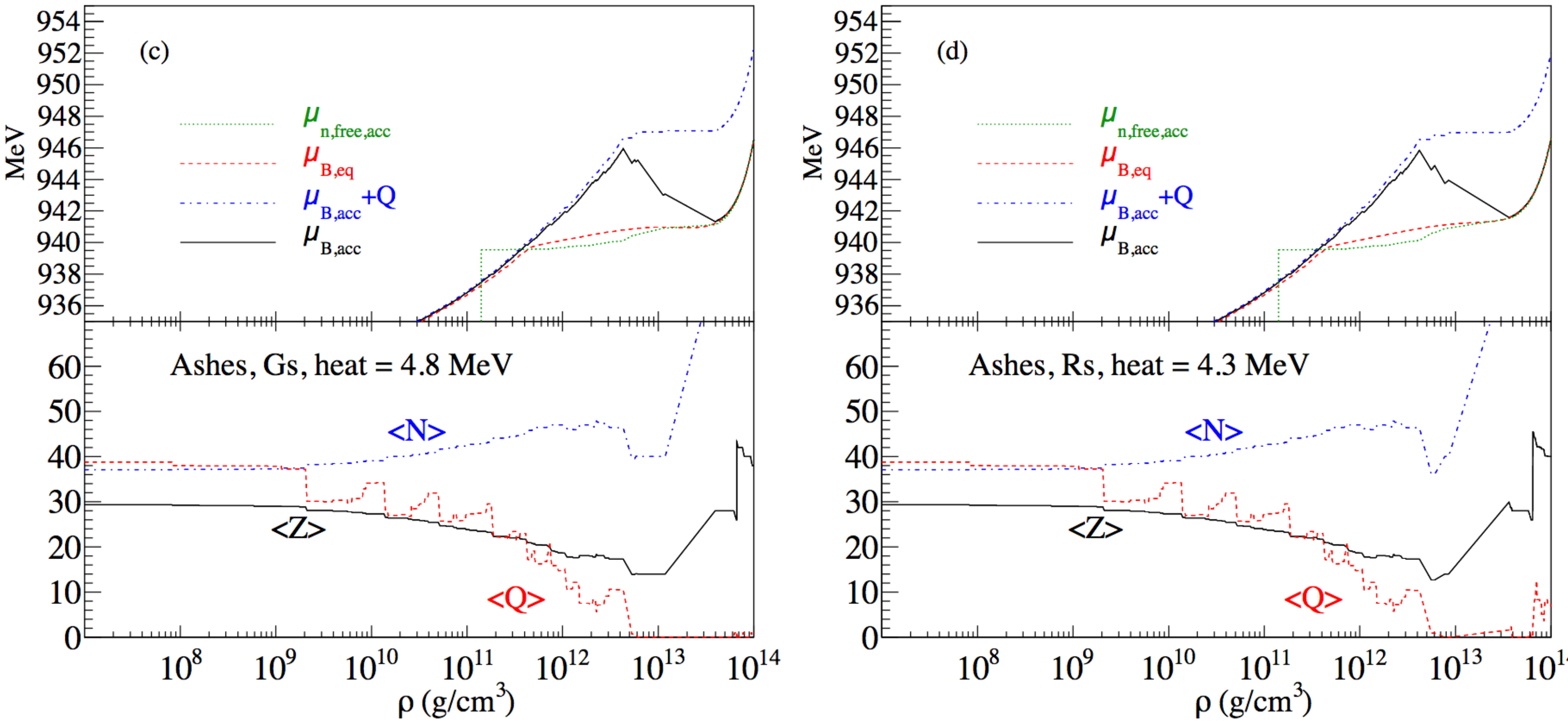



Electron scattering off domain boundaries (annealing may lead to most energetically favorable domain growing)

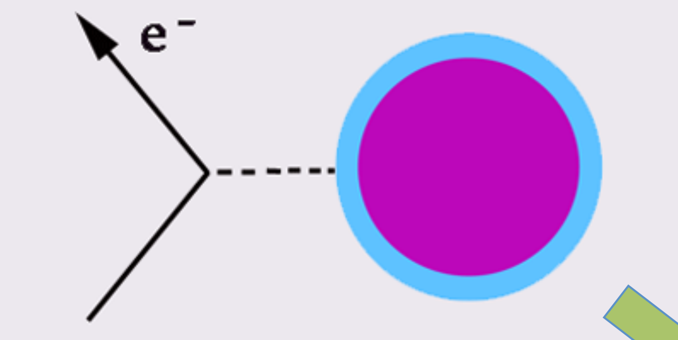
Electron scattering off disordered pasta (temperature dependent)

# Accreted Crusts: Deep crustal heating, impurity (J,L,$K_{sym}$)




Steiner, arxiv:1202.3378

Partially accreted: Sulieman et al, arxiv:2203.14735



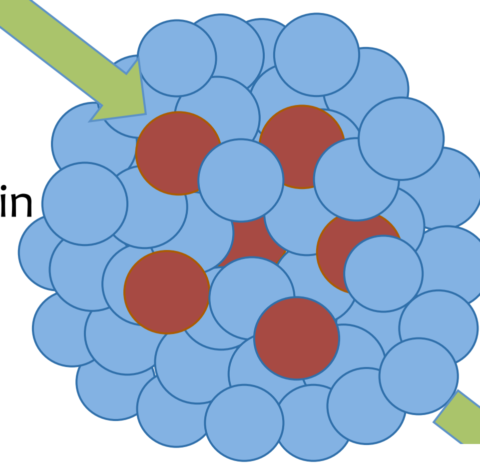

Scattering
cross sections

Weak charge density

Set of EDFs

n-p densities

neutron skin



Us: completely different set of EDFs