The Nuclear EOS After PREX/CREX

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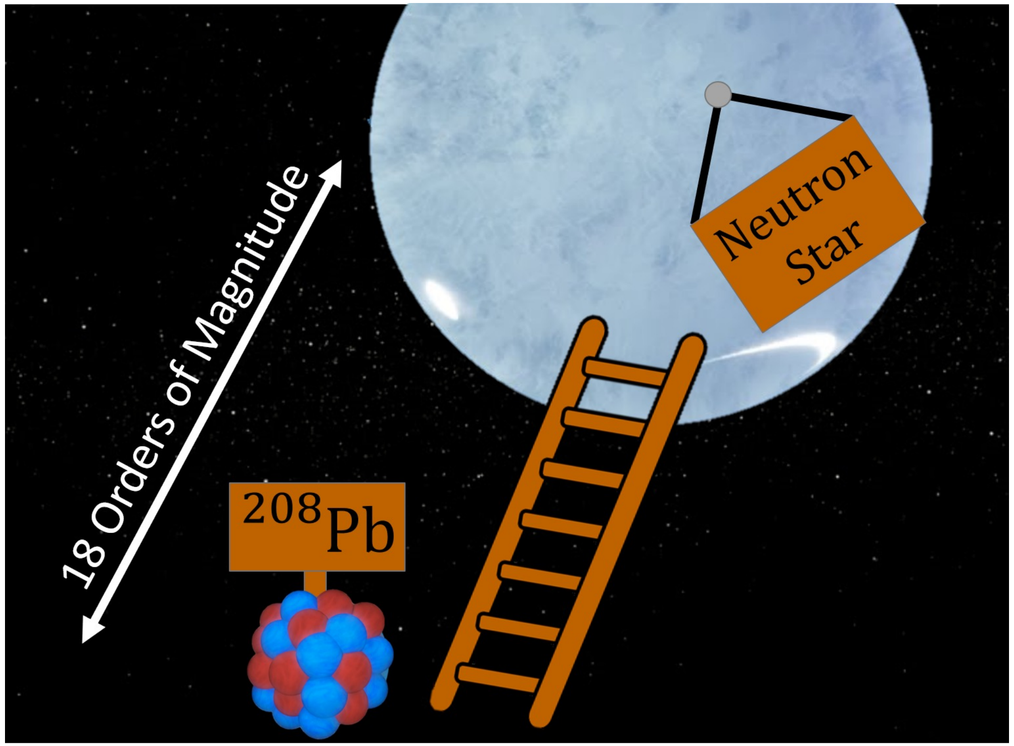
Symmetry Energy

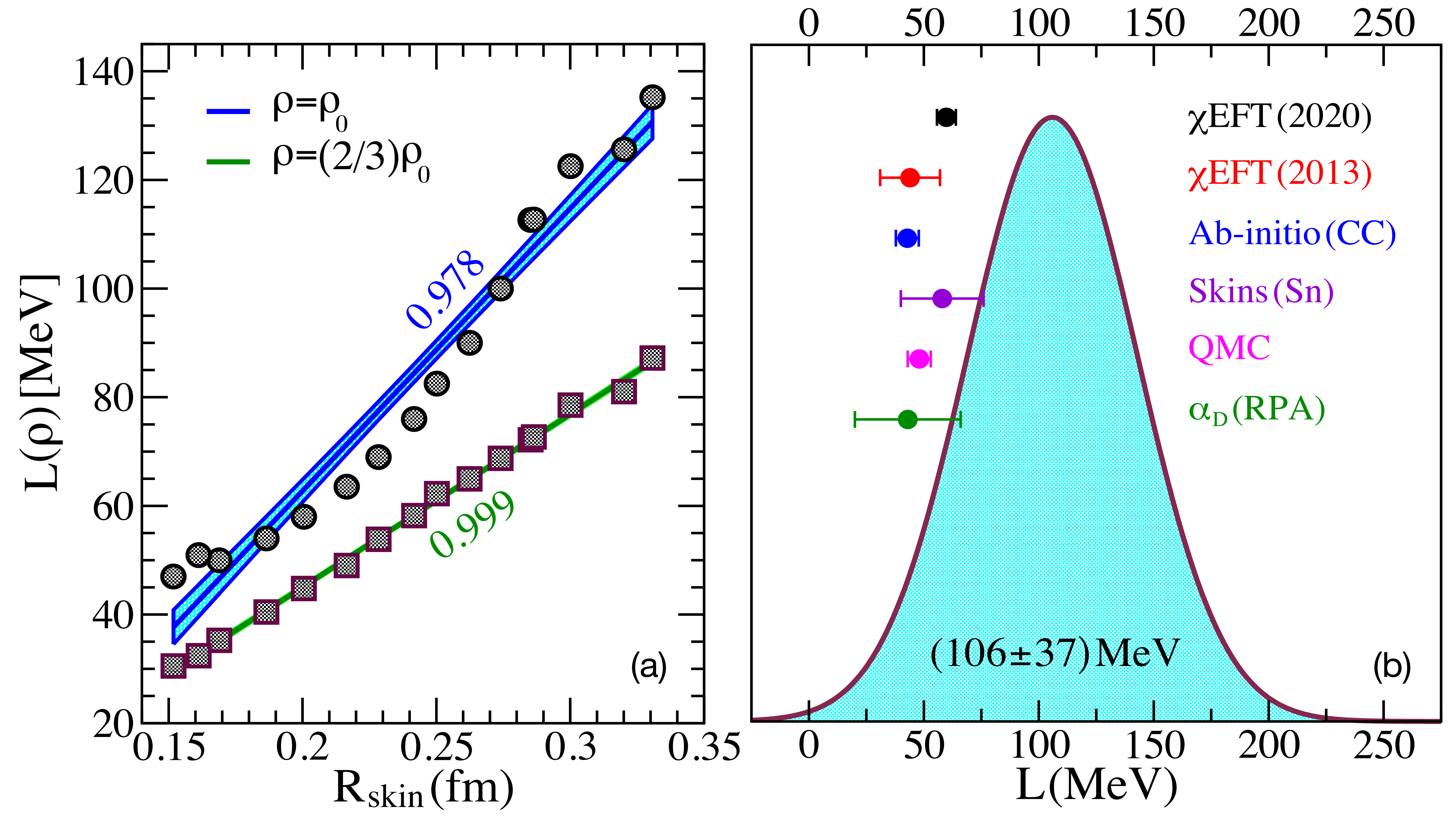
- Energy of asymmetric matter contained in $S(\rho)$
  - Describes change in energy as N-Z deviates from symmetry
- Characterization of density dependence very important for my work
- J, L, K_{sym} are isovector bulk properties of EOS
- L, K_{sym} are important in discussion of neutron stars and neutron-rich systems

$$S(\rho) = J + Lx + \frac{1}{2}K_{sym}x^2 + \cdots \qquad L = 3\rho_0 \frac{\partial S}{\partial \rho}\Big|_{\rho=\rho_0}$$

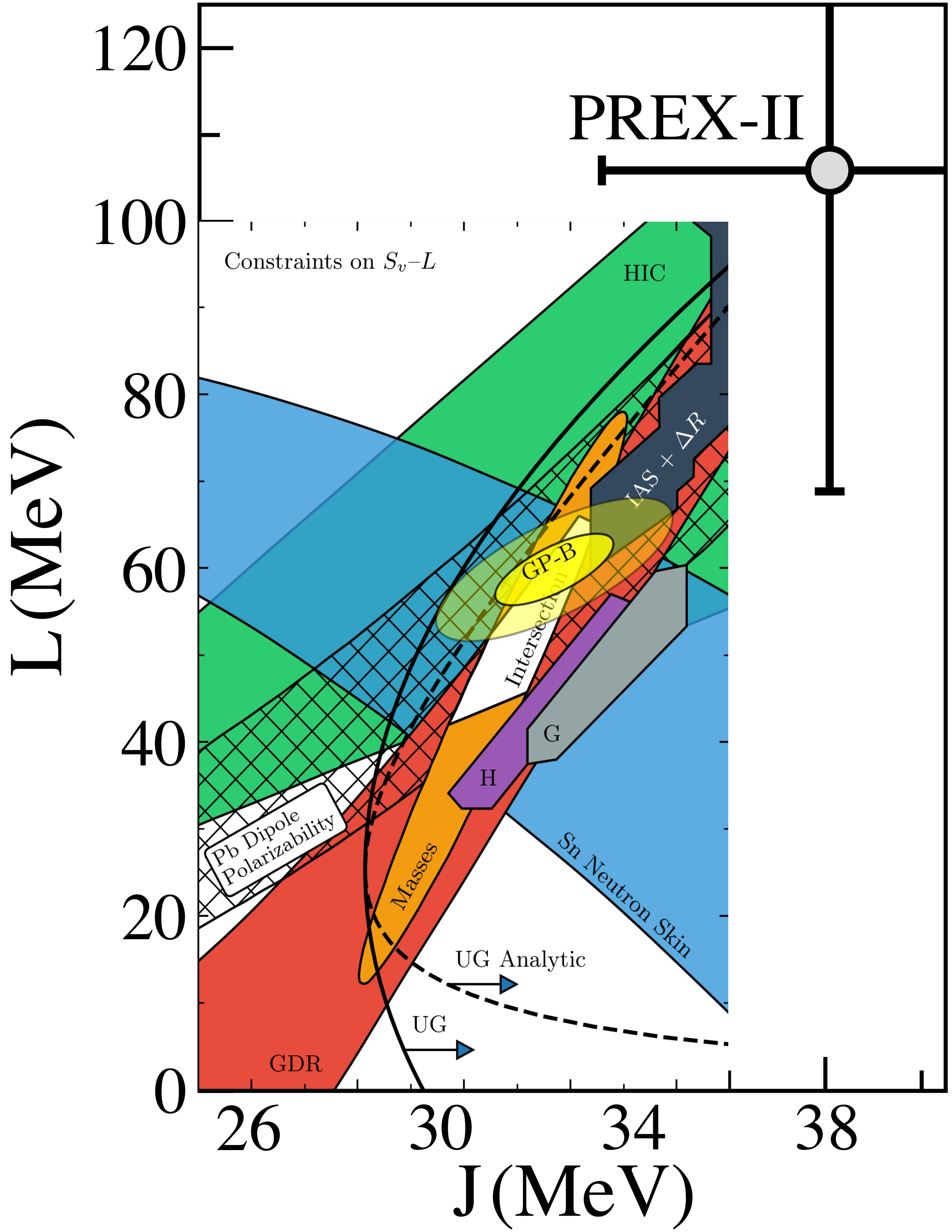
Neutron stars and Neutron Skins

- Pressure of neutron matter pushes neutrons out against surface tension
- Neutron star properties also depend on pressure of neutron matter
- Neutron skin measurement constrains DDS
  - $P_{pnm}(\rho_0) \approx \frac{1}{3} L \rho_0$



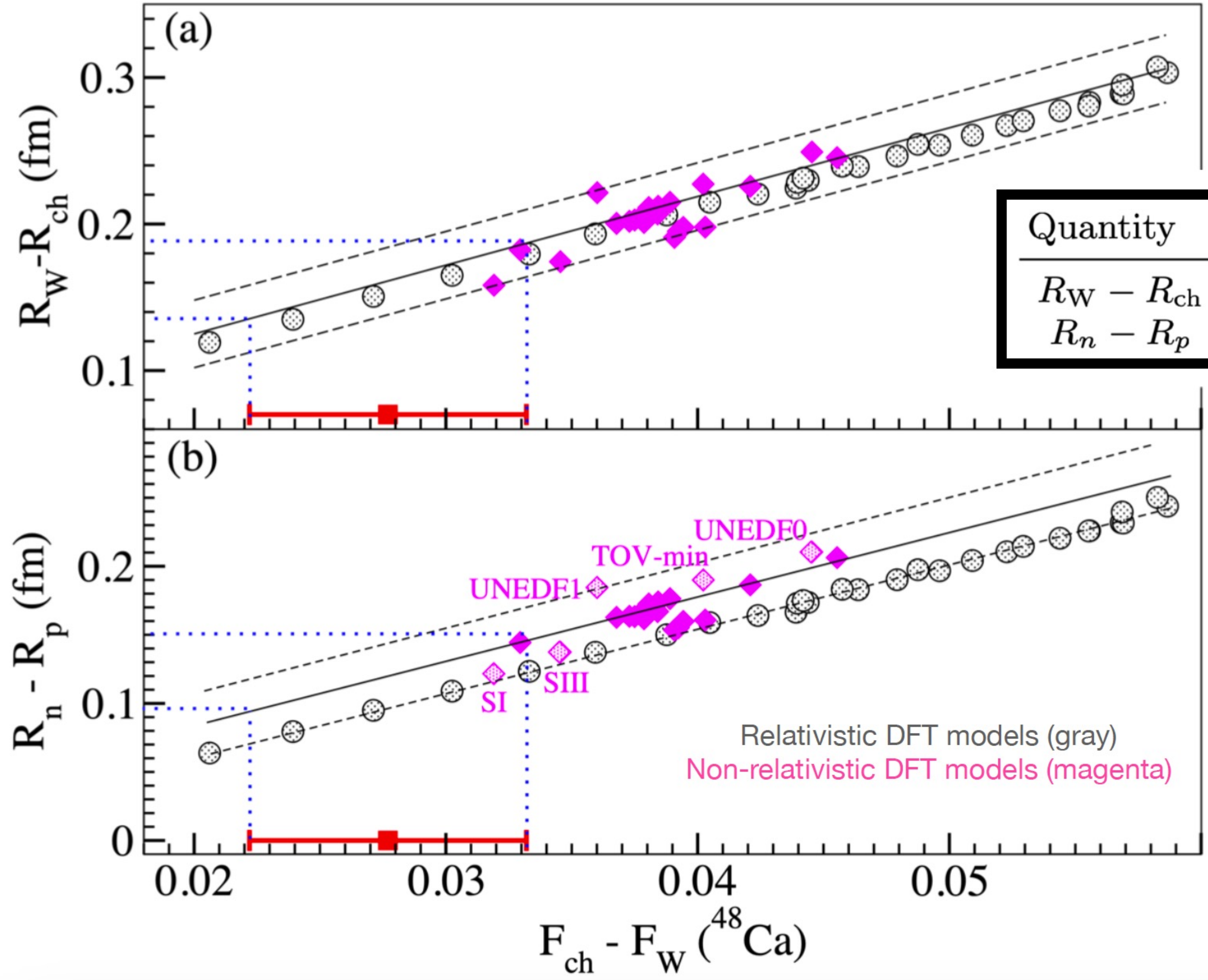


ρ=ρ0
ρ=(2/3)ρ0
0.978
0.999
(a)
L(ρ) [MeV]
Rskin (fm)
140
120
100
80
60
40
20
0.15
0.2
0.25
0.3
0.35
χEFT (2020)
χEFT (2013)
Ab-initio (CC)
Skins (Sn)
QMC
αD (RPA)
(106±37) MeV
(b)
L(MeV)
0
50
100
150
200
250



$J = 38.1 \pm 4.7$ MeV
$L = 106 \pm 37$ MeV

Suggests a moderately stiff EOS



Quantity	Value ± (exp) ± (model) [fm]
$R_W - R_{ch}$	$0.159 \pm 0.026 \pm 0.023$
$R_n - R_p$	$0.121 \pm 0.026 \pm 0.024$

Model error in extraction of R_W-R_{ch} or R_n-R_p from spread in model predictions for given F_{ch}-F_W.

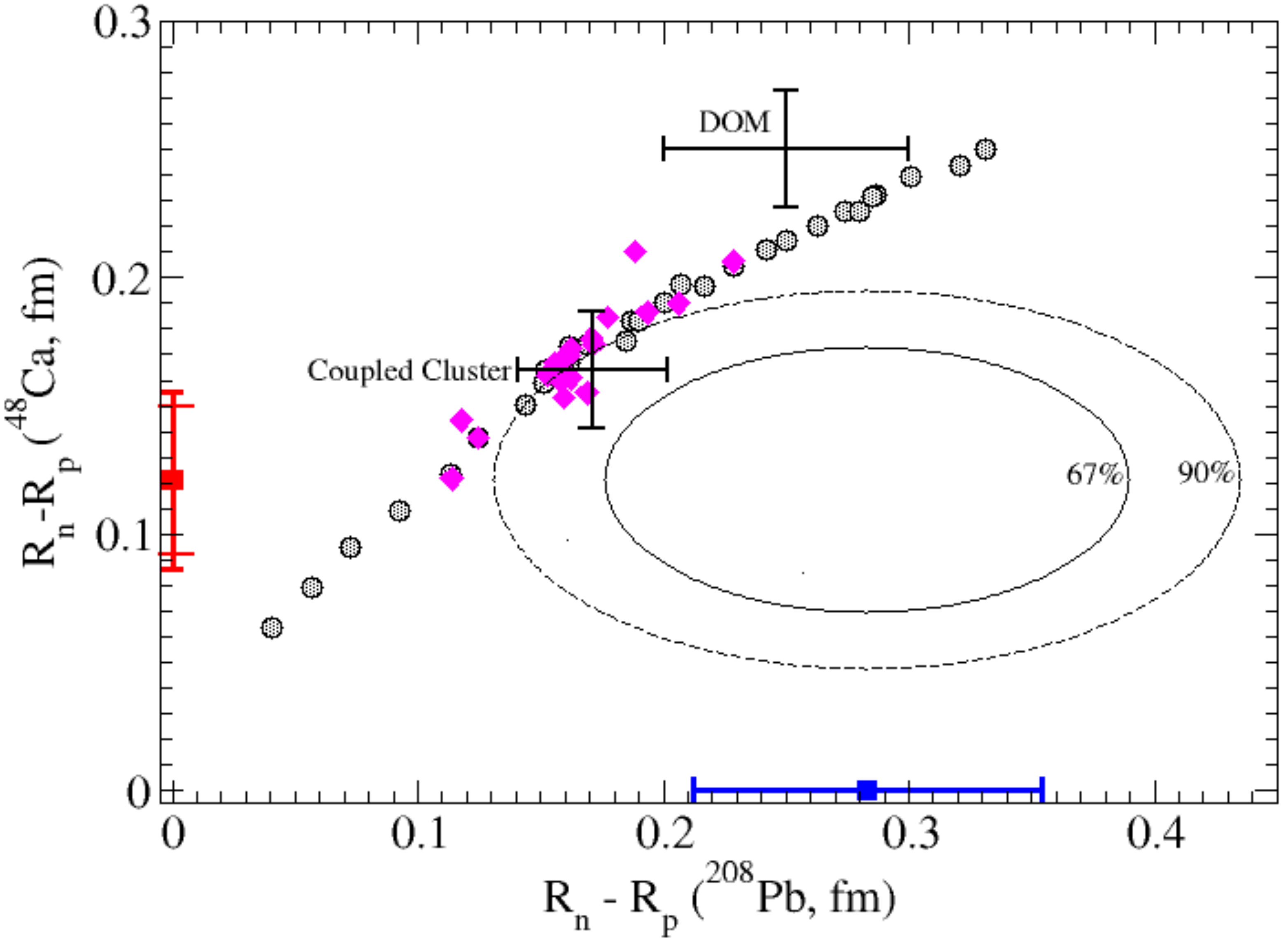
Exp. error in R_n +/-0.026 fm (.7%)
Total error in R_n +/-0.035 fm (1%)

$$R_n - R_p = 0.121 \pm 0.035(\text{total})\ \text{fm}$$

No model error in F_{ch}-F_W

$$F_{ch}(q) - F_W(q) = 0.0277 \pm 0.0055\ (\text{exp})$$

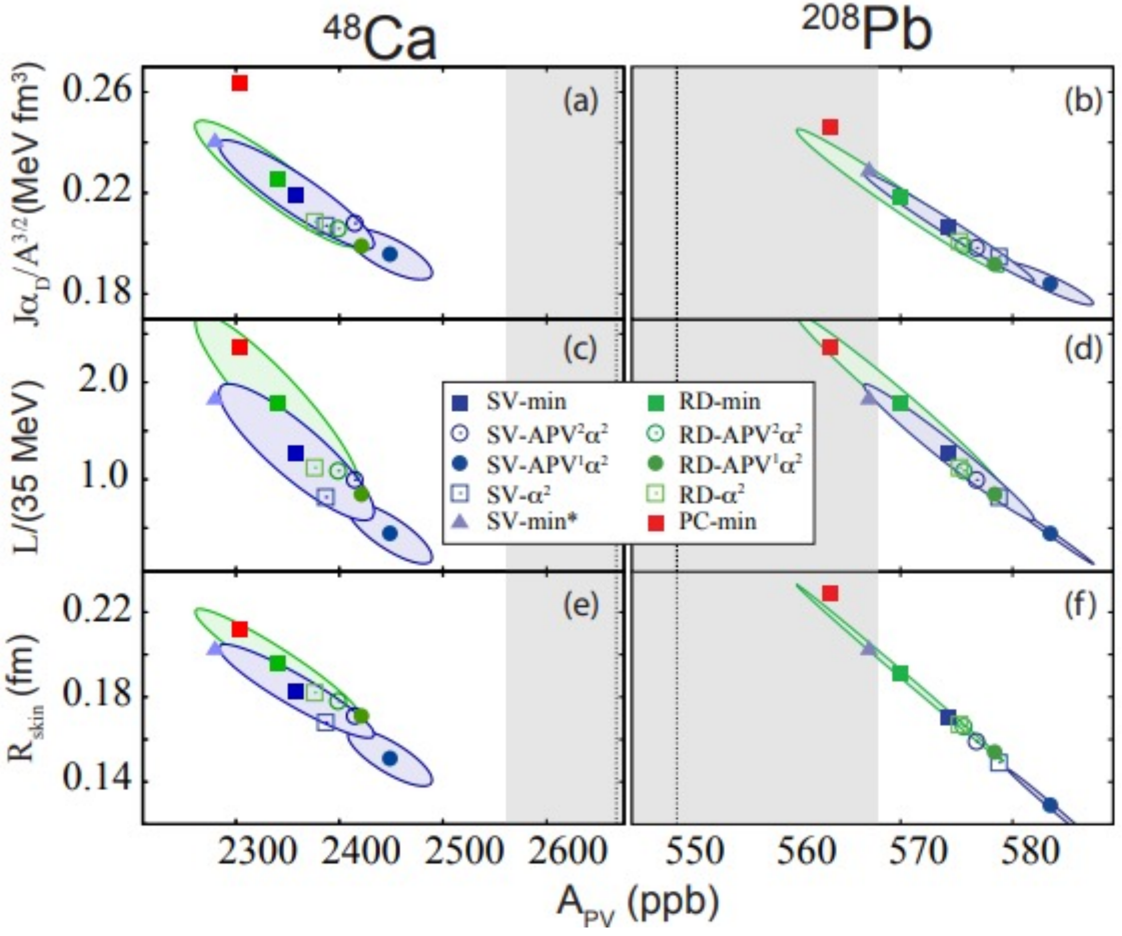
PREX measured R_n to 1.3%



0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
DOM
Coupled Cluster
67%
90%
R_n - R_p (208Pb, fm)
R_n-R_p (48Ca, fm)

Why the Discrepancy?

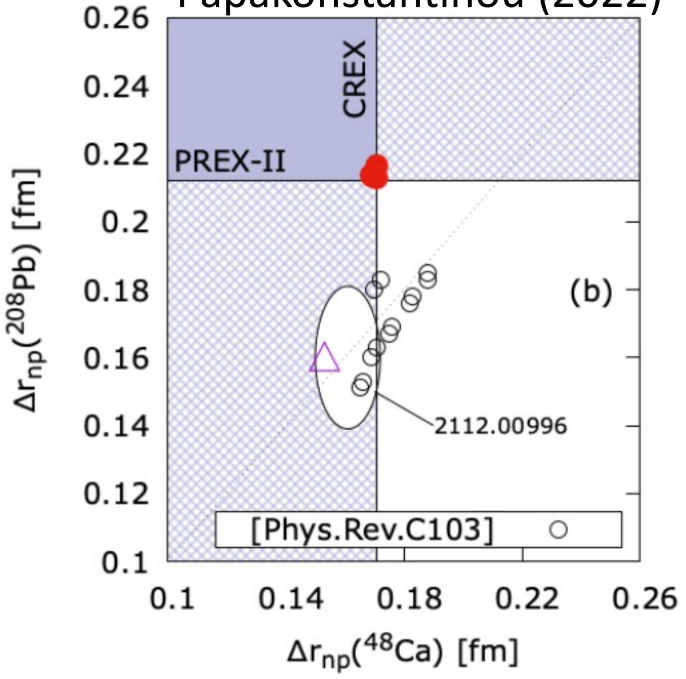
- Large discrepancy between PREX and CREX yet to be explained by existing models alone
- Suggests theory and experiment are in tension
  1. Experiment uncertainty is missing something
  2. Theory is incomplete



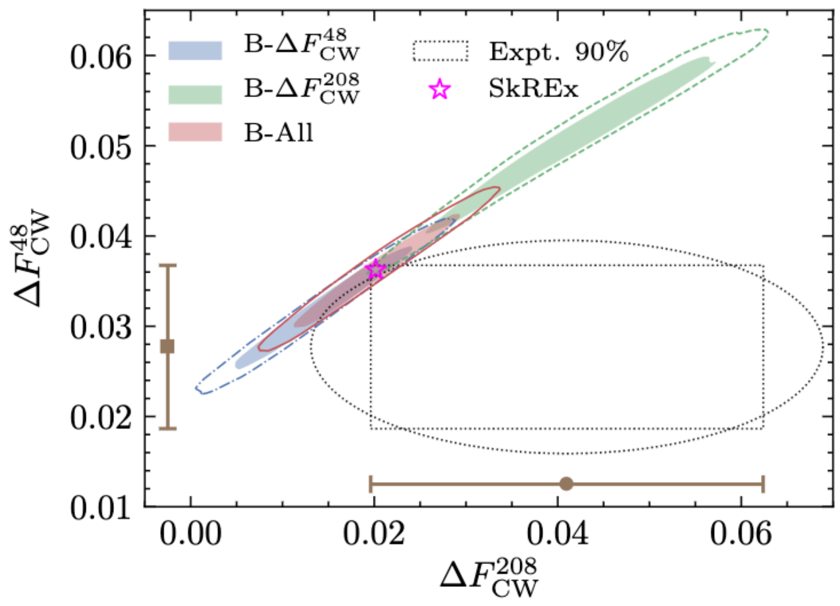
Reinhard+ (2022)

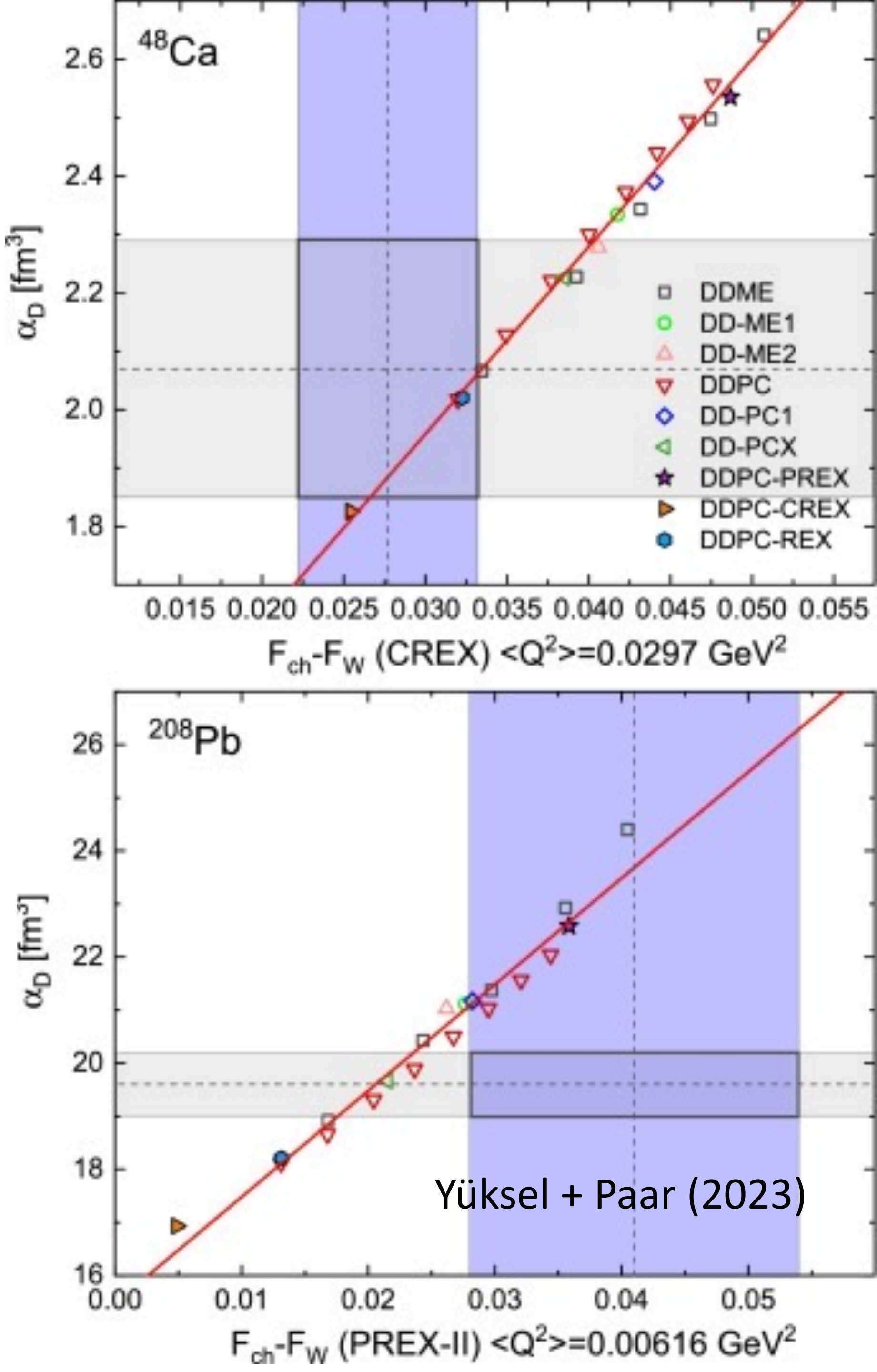
Attempts to Alleviate Tension

Papakonstantinou (2022)

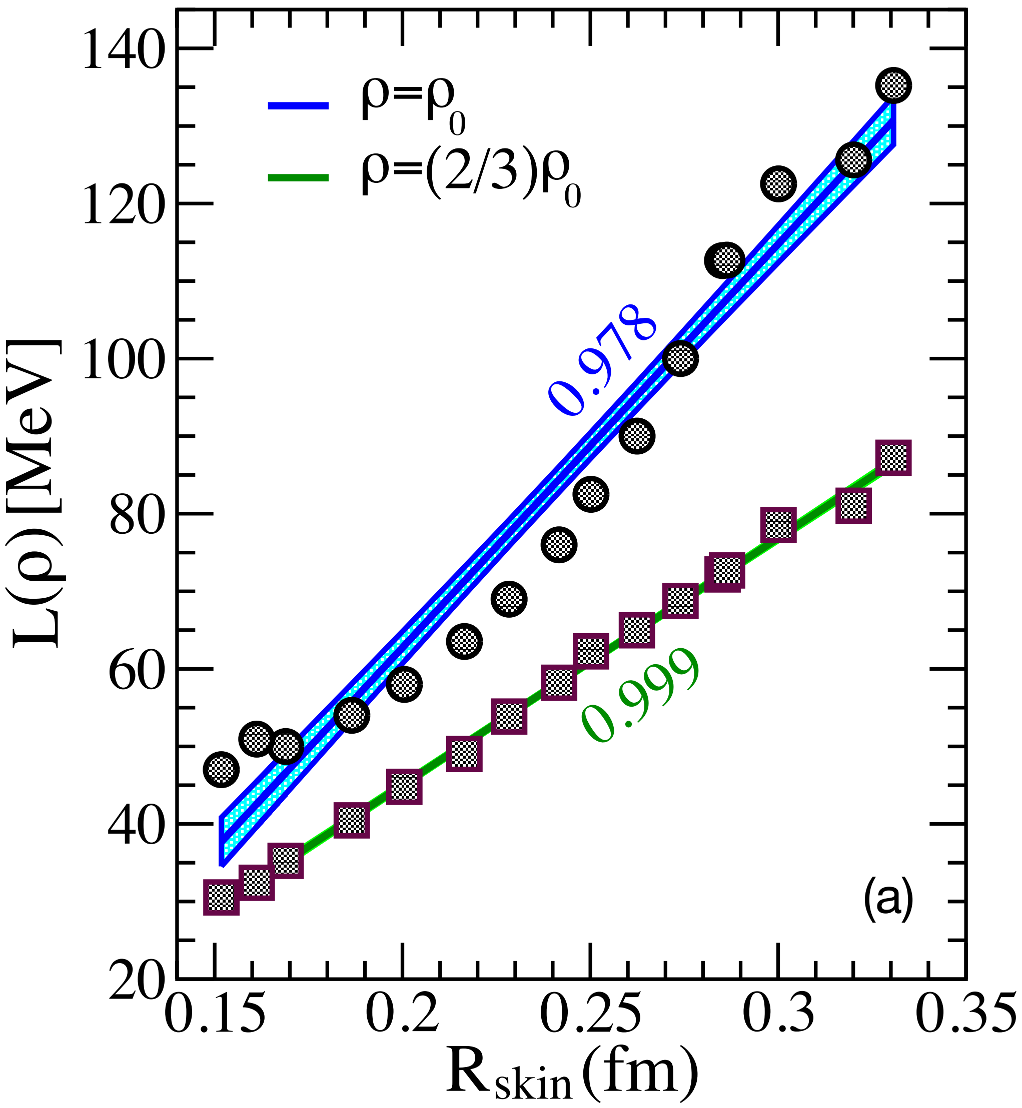


Zhang + Chen (2022)





Yüksel + Paar (2023)



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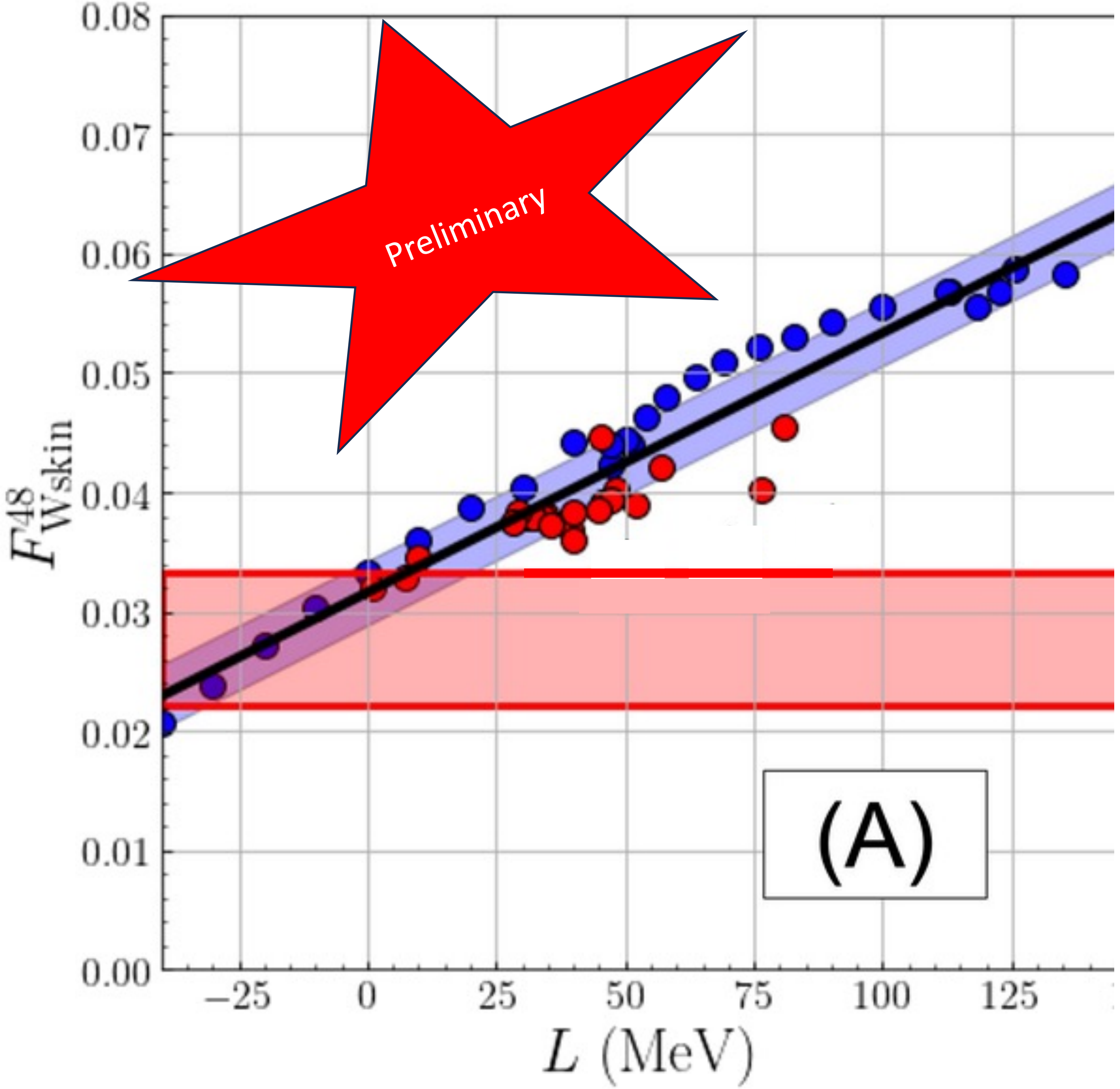


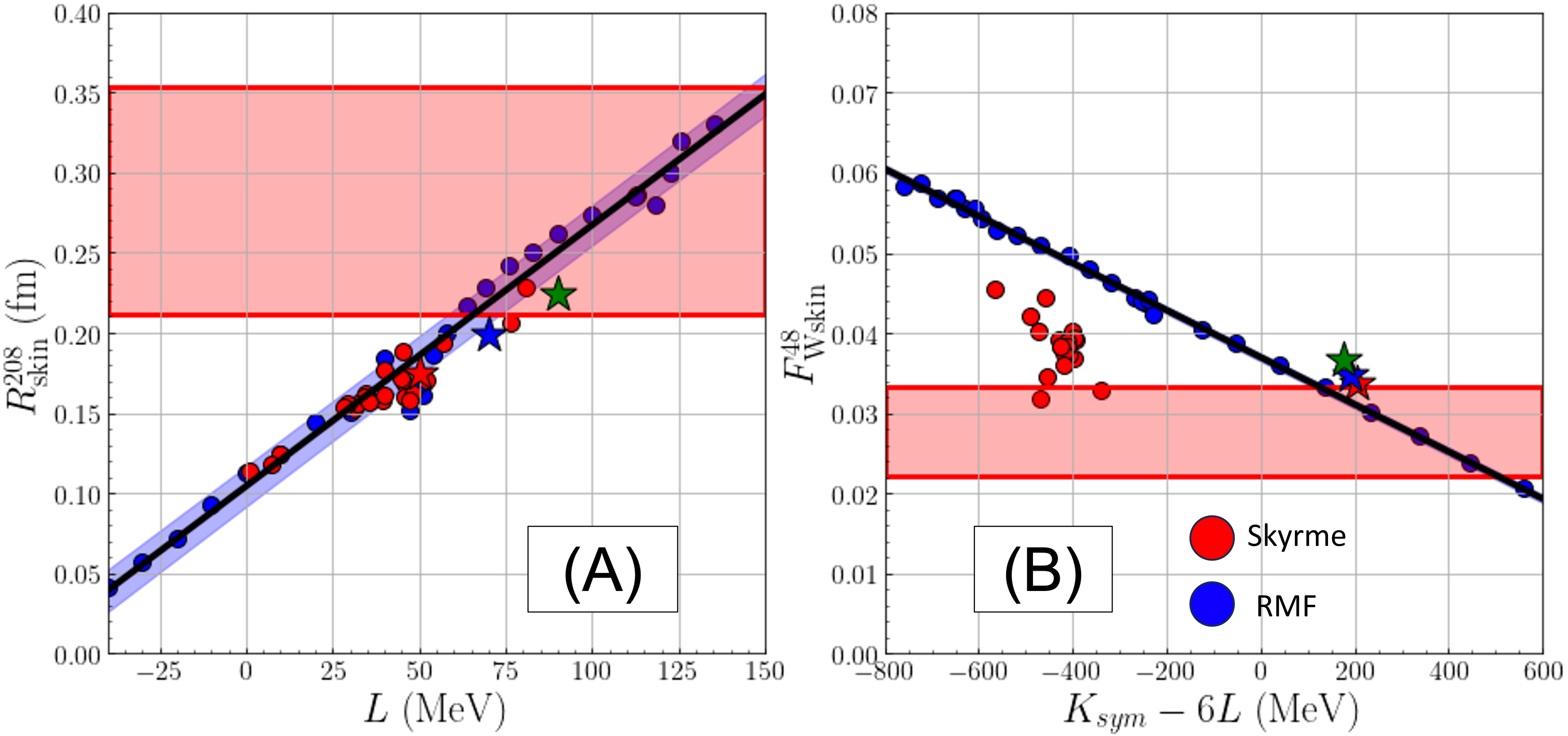
Correlation with ^{48}Ca

How about K_{sym}?

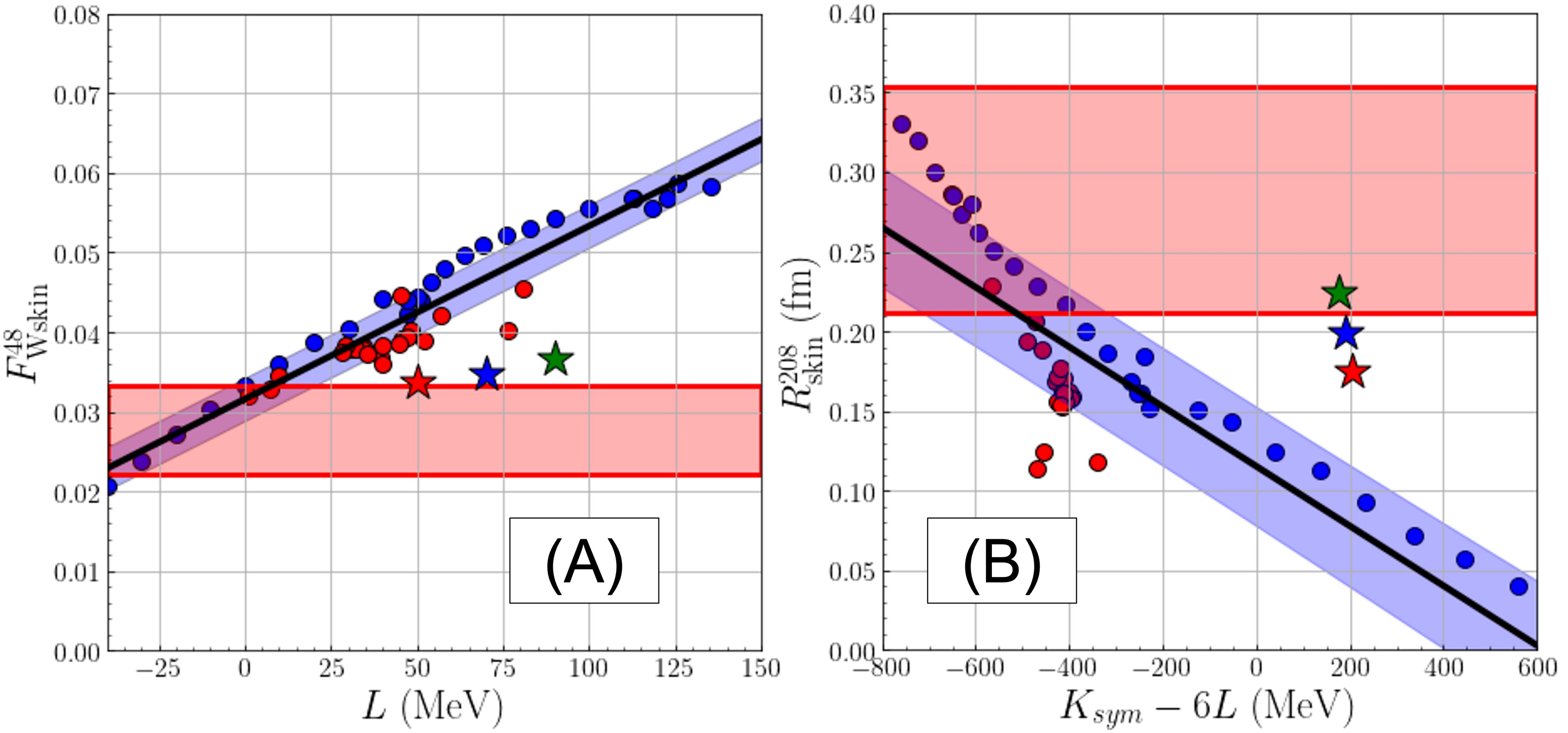
- Correlation between L and isovector skins well documented
- K_{sym} not thought to be easily constrained by nuclei
  - Largely insensitive to K_{sym} with normal asymmetries
- Some light on EDF theory may come from looking at K_{sym}

$$K(\alpha) = K_0 + \alpha^2 K_\tau + \cdots$$

$$K_\tau = K_{sym} - 6L - \frac{Q_0}{K_0} L$$



(A)
(B)
Skyrme
RMF
$R^{208}_{\rm skin}$ (fm)
L (MeV)
$F^{48}_{\rm Wskin}$
$K_{sym} - 6L$ (MeV)



0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
F^{48}_{Wskin}
−25
0
25
50
75
100
125
150
L (MeV)
(A)
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
R^{208}_{skin} (fm)
−800
−600
−400
−200
0
200
400
600
$K_{sym} - 6L$ (MeV)
(B)

Extraction of L and K_{sym}

- Set up Chi-square

$$\chi^2 = \sum \frac{\left(y_{obs} - \hat{y}\left(L, K_{sym}\right)\right)^2}{\sigma_{ex}^2 + \sigma_{th}^2}$$

  - Experimental errors are errors from experiment
  - Theory errors are calculated using 68% prediction interval from previous relations
- Defined log-likelihood function with uniform priors on L

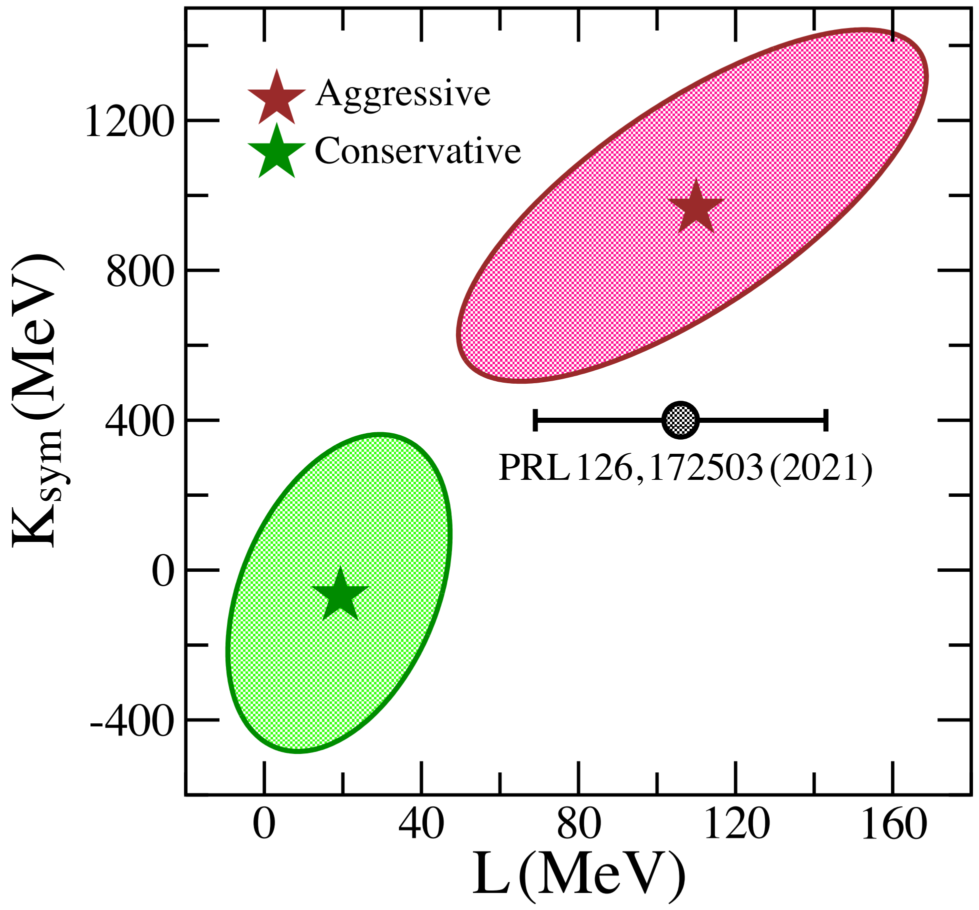
$$\mathcal{L} \sim \exp(-\frac{1}{2}\chi^2)$$

- Use Bayesian inference and MCMC code emcee to generate posteriors

Aggressive	Conservative
• Only use PREX vs L and CREX vs K_{sym}-6L • Only use RMF models	• Use all 4 relations • Use both RMF and Skyrme models

Wildly Different Scenarios

- Aggressive fit
  - Predicts large and *positive* K_{sym} values
  - L is consistent with our original work and likely large
- Conservative fit
  - Favors very small L
  - K_{sym} less conclusive



Fit	L (MeV)	Ksym (MeV)
Aggressive	110 ± 40	970 ± 320
Conservative	19 ± 19	-61 ± 280

New Calibrated Interaction DINO

- FSUGold family of RMF models + delta meson
  - Interaction of σ, ω, ρ mesons with nucleons + δ
  - Changes the DDS
  - Gives another DoF to fit K_{sym}
- 3 models with different values of L
- All have K_{sym} in excess of 500 MeV
- This parameter space largely untouched

$$\mathcal{L}_{\text{int}} = \bar{\psi}\Big[\mathcal{S}(\phi, \boldsymbol{\delta}) - \mathcal{V}_\mu(V_\mu, \boldsymbol{b_\mu}, A_\mu)\gamma^\mu\Big]\psi - U(\phi) + \frac{\zeta}{4!}g_v^4(V_\mu V^\mu)^2 + \Lambda_v g_v^2 g_\rho^2 V_\mu V^\mu \boldsymbol{b_\mu}\cdot\boldsymbol{b^\mu}$$

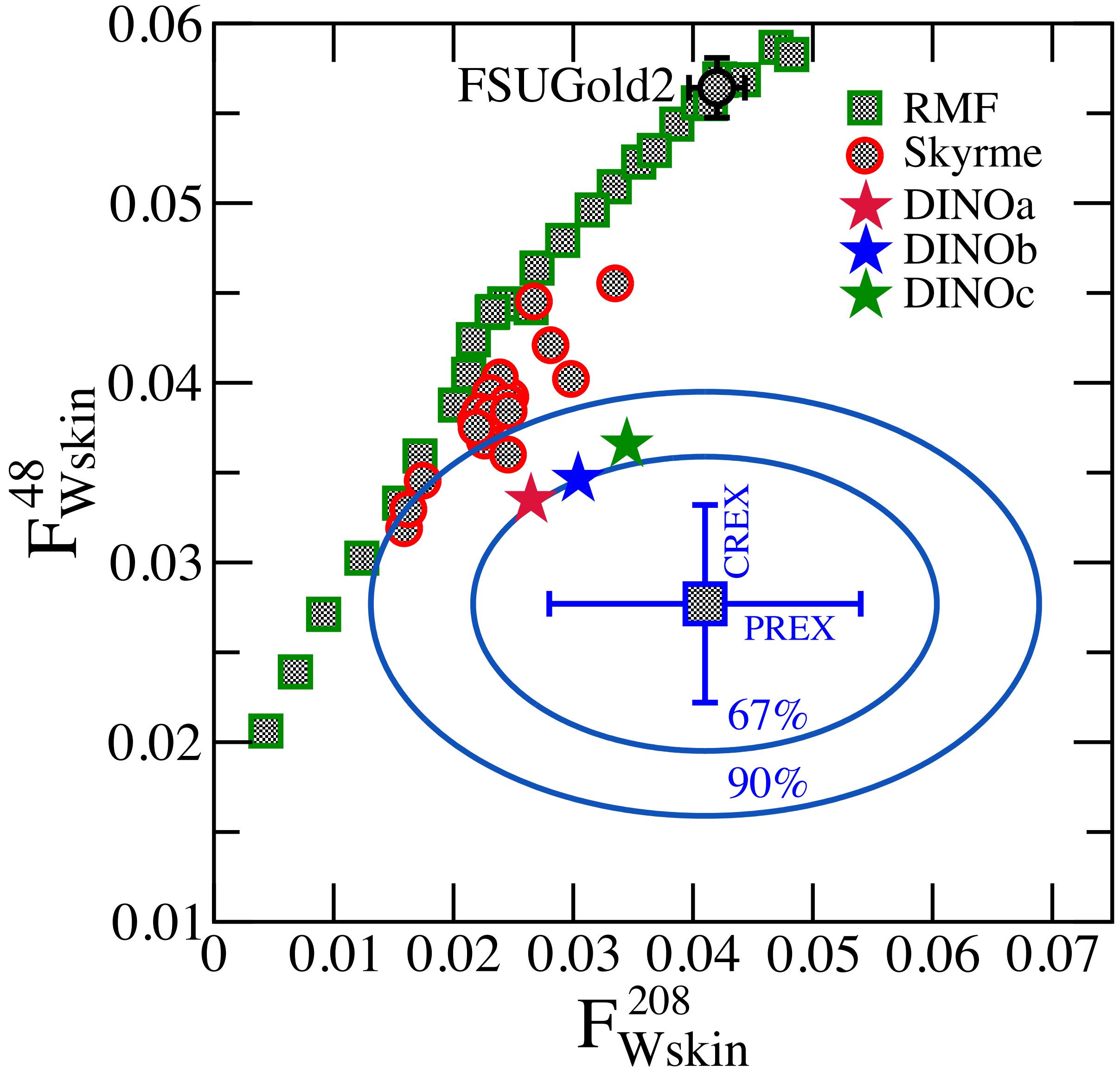
where

$$\mathcal{S}(\phi, \boldsymbol{\delta}) = g_s\phi + \frac{g_\delta}{2}\boldsymbol{\tau}\cdot\boldsymbol{\delta}$$

$$\mathcal{V}_\mu(V_\mu, \boldsymbol{b_\mu}, A_\mu) = g_v V_\mu + \frac{g_\rho}{2}\boldsymbol{\tau}\cdot\boldsymbol{b_\mu} + \frac{e}{2}(1+\tau_3)A_\mu$$

$$U(\phi) = \frac{\kappa}{3!}(g_s\phi)^3 + \frac{\lambda}{4!}(g_s\phi)^4$$

Model	ρ_0 (fm^{-3})	ϵ_0 (MeV)	K_0 (MeV)	Q_0 (MeV)	$\tilde{J}$ (MeV)	J (MeV)	L (MeV)	K_{sym} (MeV)
DINOa	0.1522	−16.16	210.0	−361.4	27.00	31.42	50.00	506.0
DINOb	0.1525	−16.21	207.0	−412.0	27.00	33.07	70.00	610.0
DINOc	0.1519	−16.22	206.0	−426.1	27.00	34.58	90.00	715.0



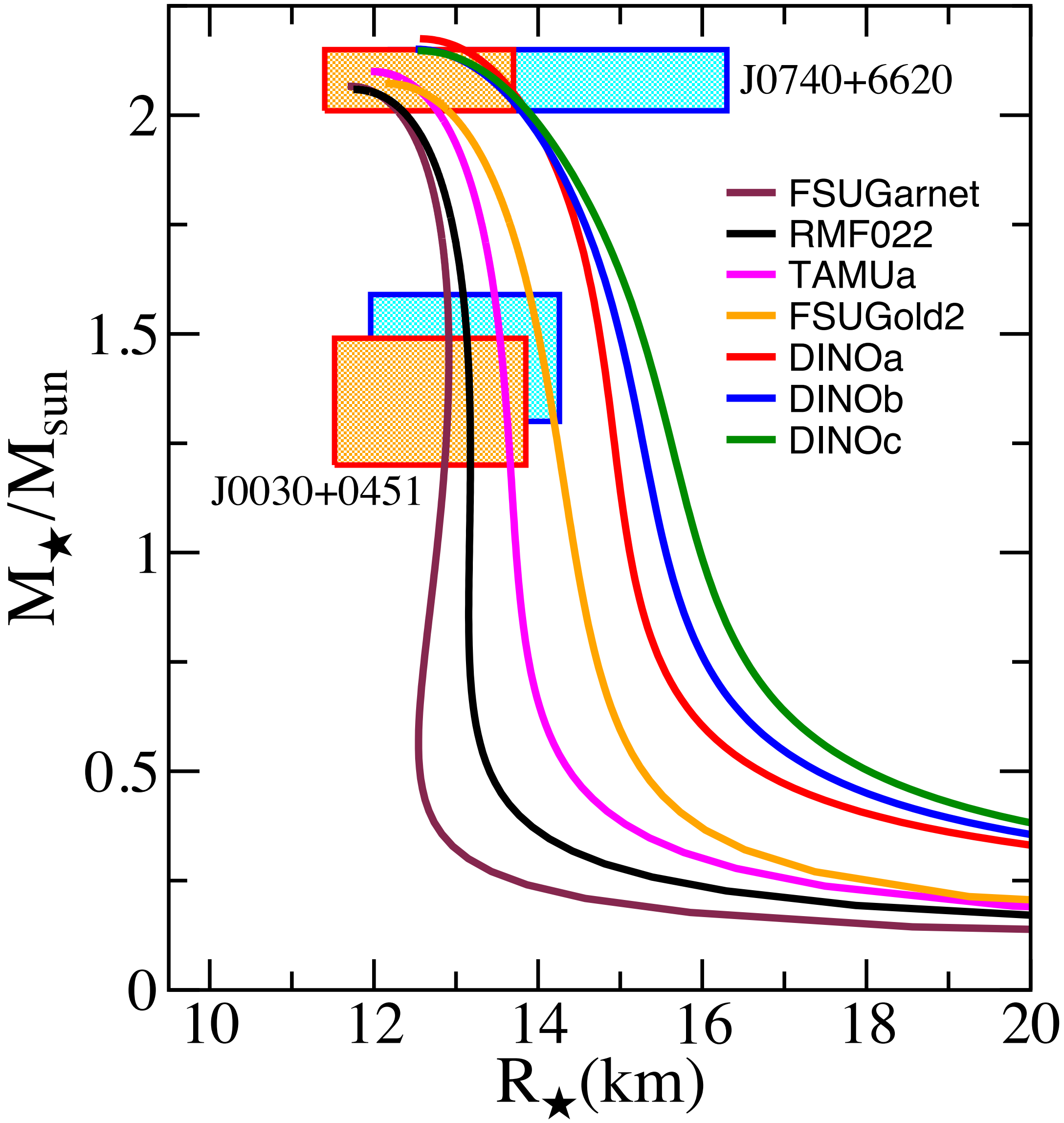
- Large K_{sym} makes small skins in ^{48}Ca and leaves ^{208}Pb skin mostly unaffected
- Outperform every other model used in CREX analysis
- Have very large isovector couplings

Model	m_s	g_s^2	g_δ^2	g_v^2	g_ρ^2	κ	λ	ζ	Λ_v
DINOa	490.050	93.9422	1115.15	154.436	805.891	4.9860	−0.01370	0.015	0.0016497
DINOb	485.795	91.0316	1252.71	150.824	877.121	5.2914	−0.01488	0.015	0.0014014
DINOc	484.162	90.6481	1343.25	151.048	922.617	5.3209	−0.01497	0.015	0.0012312

Problems at High Density

- Large K_{sym} stiffens symmetry energy at high density
- Stiffens EOS at high density → large neutron stars
- Radii are much too big
  - Tidal deformabilities also too big
- Consistent with maximum mass
  - Radius problem may be fixable with phase transition

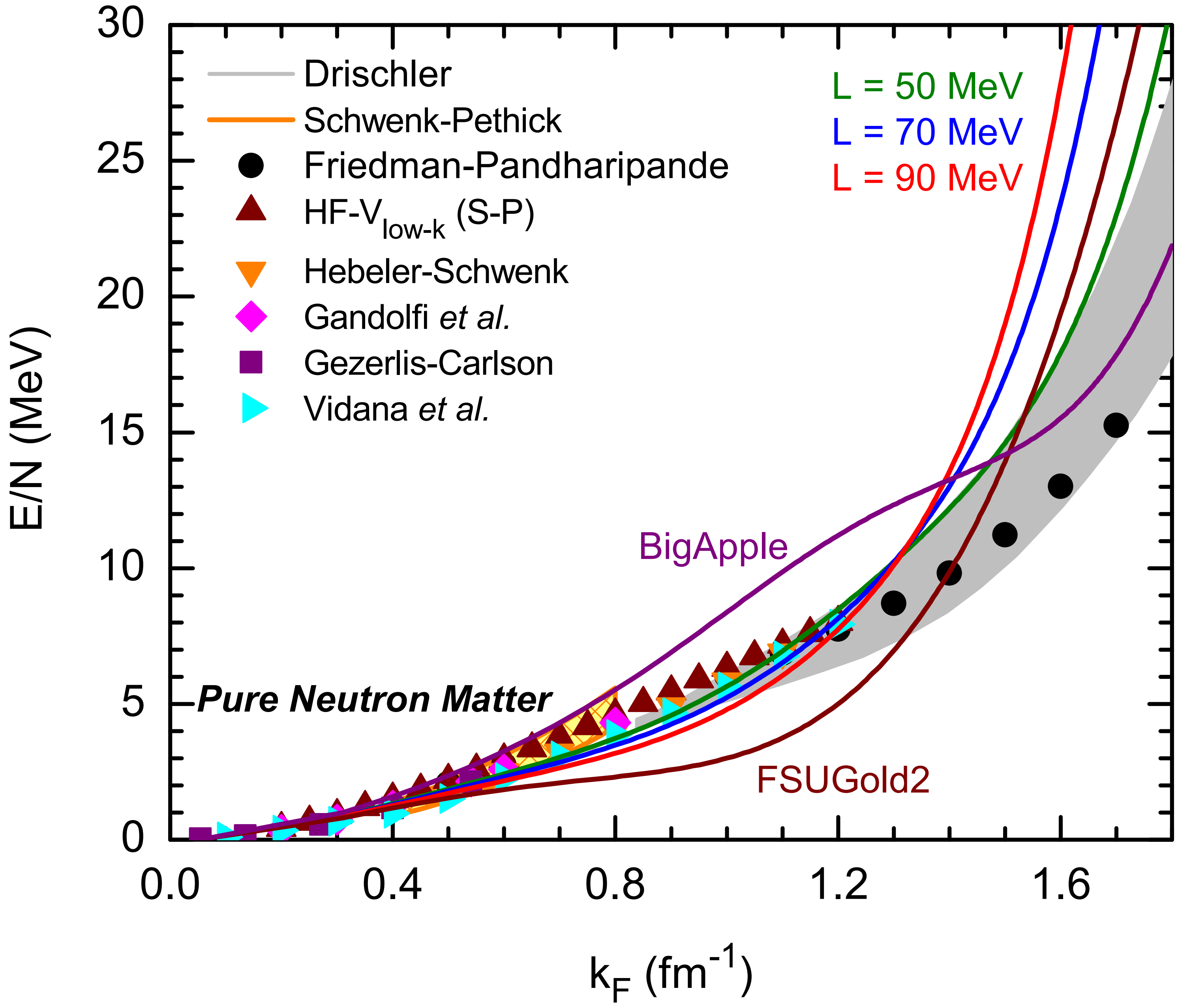
Model	M_{max} ($M_\odot$)	$R_{1.4}$ (km)	$\Lambda_{1.4}$	ρ_t (fm^{-3})	ρ_{Urca} (fm^{-3})	M_{Urca} ($M_\odot$)
DINOa	2.17	14.82	1050.6	0.0914	0.1580	0.418
DINOb	2.15	15.11	1128.2	0.0846	0.1438	0.427
DINOc	2.14	15.41	1240.4	0.0789	0.1373	0.458

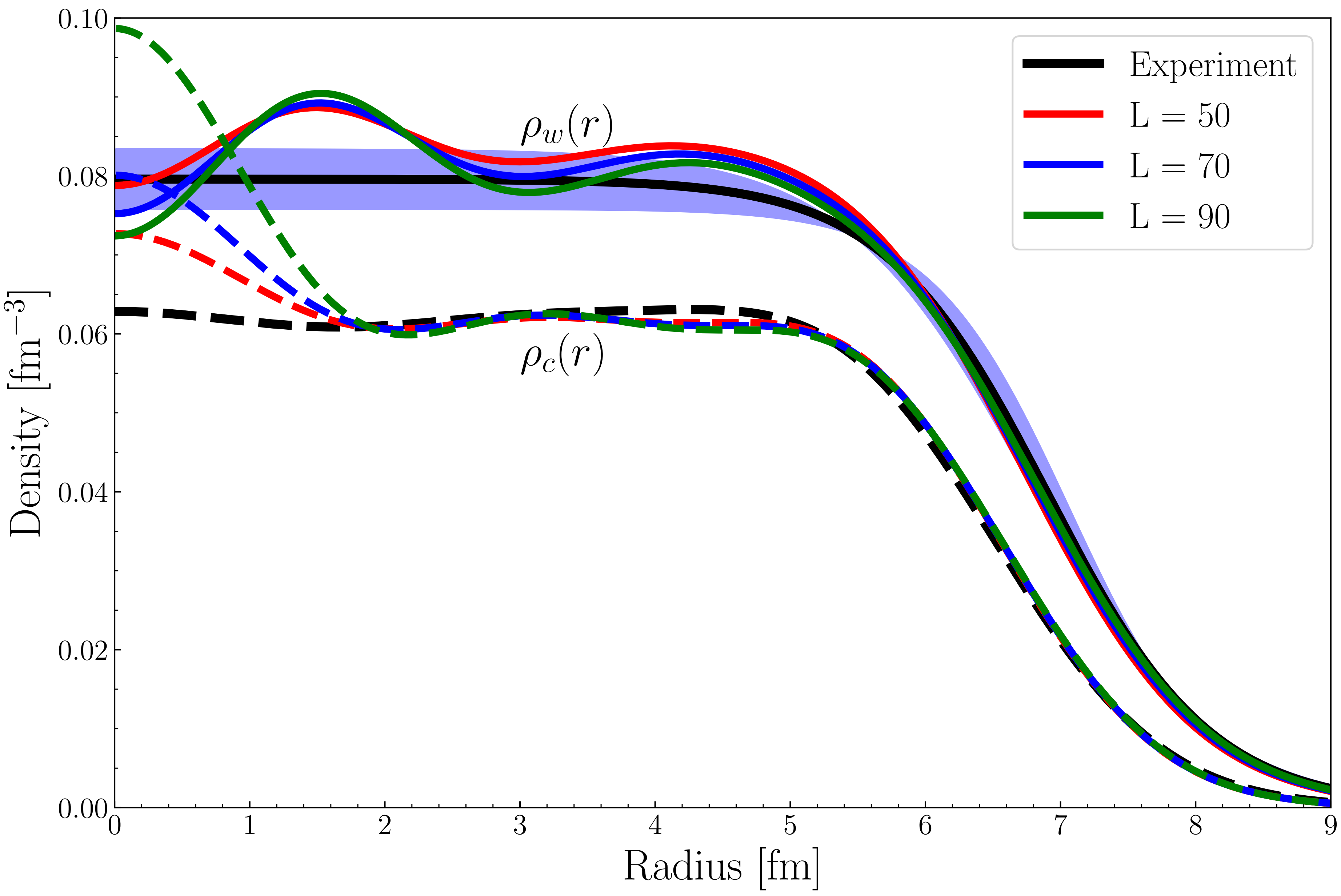


Conclusions

- EDFs need some work
  - CREX and PREX-2 are hard to reconcile at 67% confidence
- One possible avenue is higher order symmetry energy derivatives
- K_{sym}-6L shows strong correlation with RMF models and CREX
- Large and positive K_{sym} favored from model analysis with RMF models
- DINO models have large K_{sym} values and beat other models at reproducing PREX+CREX
- Blow up at high density…among other issues

Special thanks to Jorge and Farrukh for this work
In collaboration with PREX/CREX collaboration


Drischler
Schwenk-Pethick
Friedman-Pandharipande
HF-V_{low-k} (S-P)
Hebeler-Schwenk
Gandolfi *et al.*
Gezerlis-Carlson
Vidana *et al.*
L = 50 MeV
L = 70 MeV
L = 90 MeV
BigApple
FSUGold2
Pure Neutron Matter
E/N (MeV)
k_F (fm^{-1})
0
5
10
15
20
25
30
0.0
0.4
0.8
1.2
1.6



Experiment
L = 50
L = 70
L = 90
$\rho_w(r)$
$\rho_c(r)$
Density [fm^{-3}]
Radius [fm]
0.00
0.02
0.04
0.06
0.08
0.10
0
1
2
3
4
5
6
7
8
9