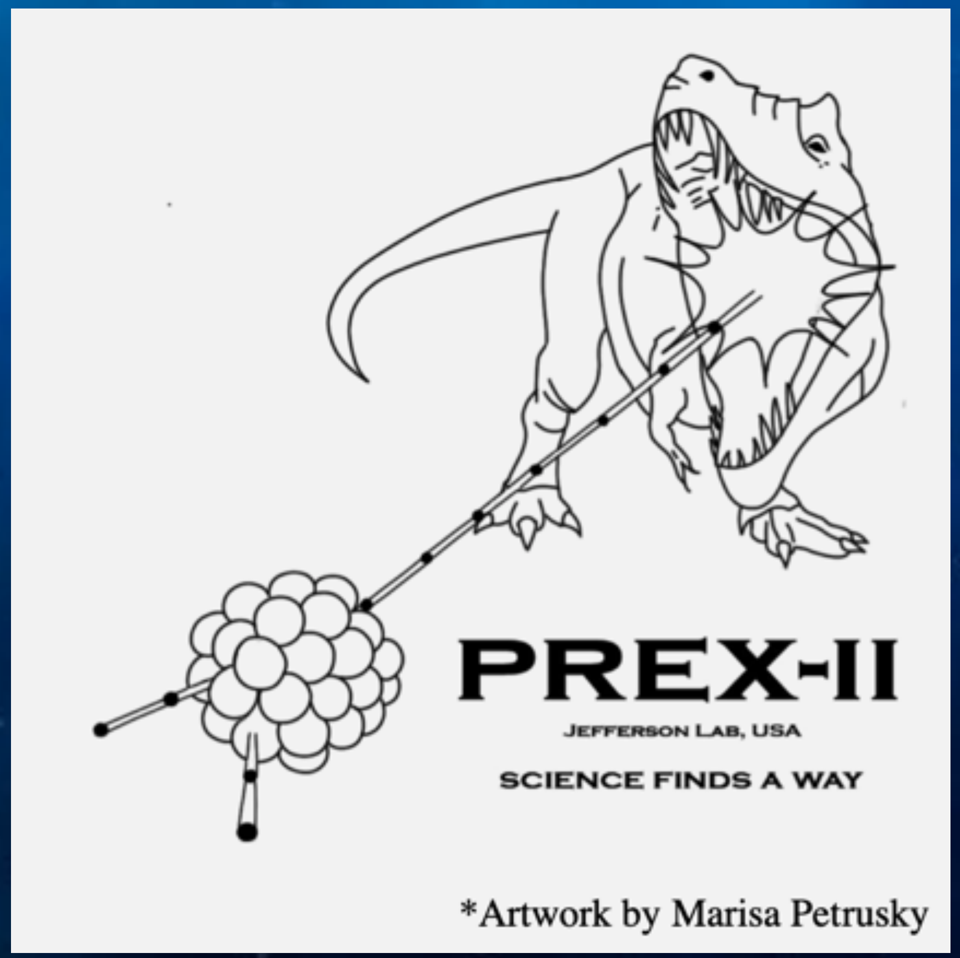
EOS and neutrino interactions in dense matter



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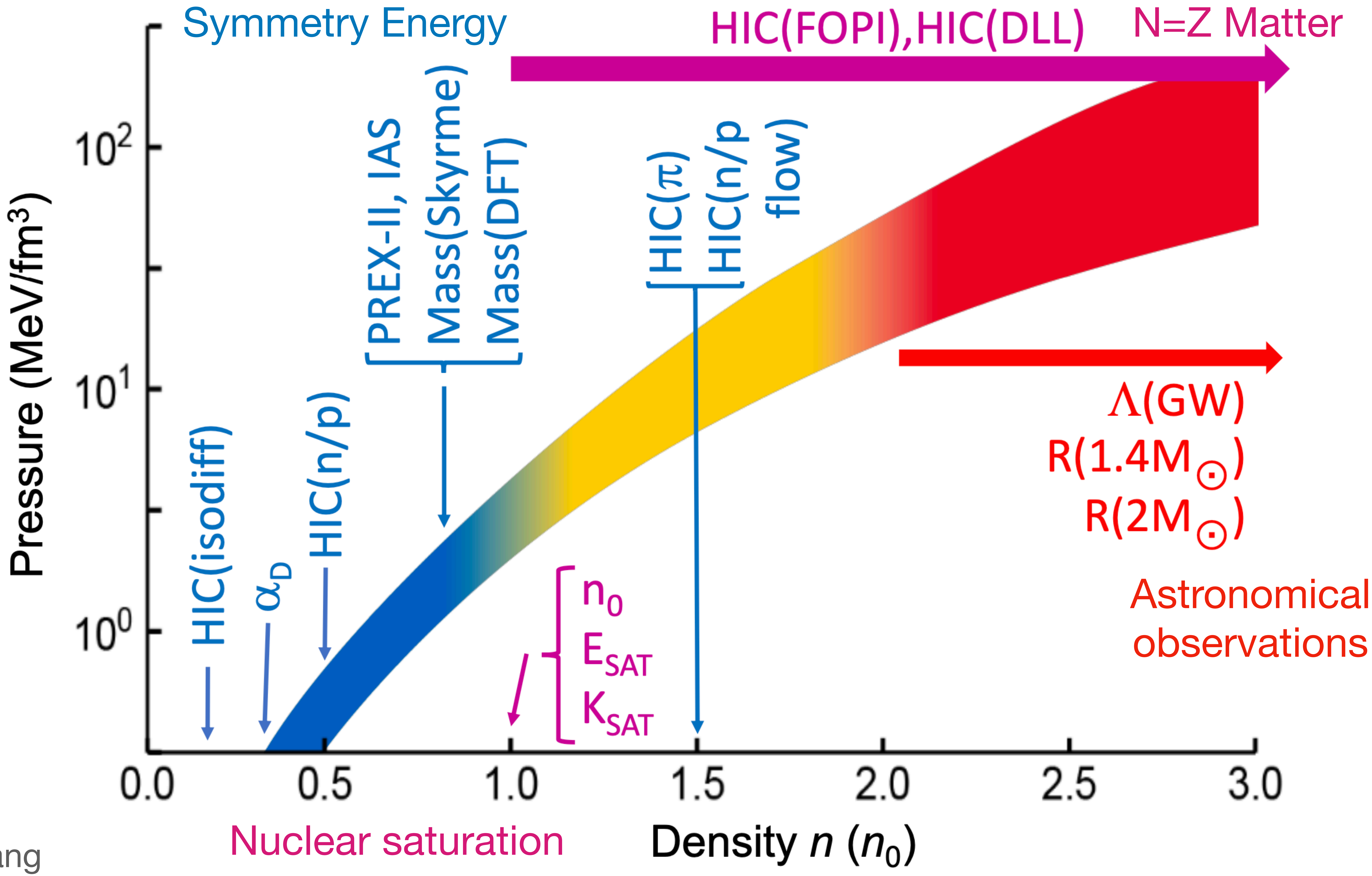
Chuck Horowitz, Indiana U.   INT, Aug. 2023

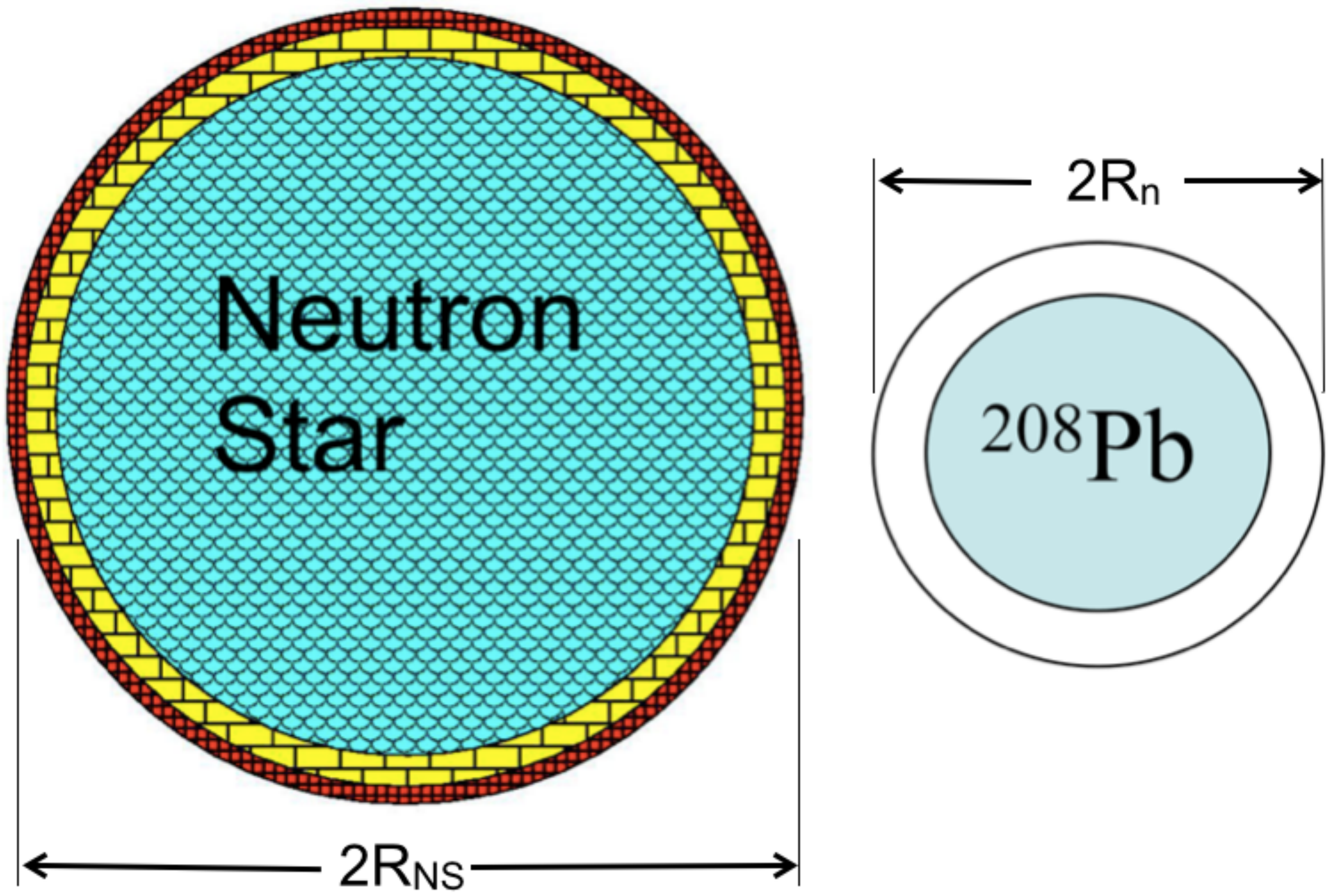


Symmetry Energy
HIC(FOPI),HIC(DLL)
N=Z Matter
Pressure (MeV/fm^3)
10^2
10^1
10^0
PREX-II, IAS
Mass(Skyrme)
Mass(DFT)
HIC(π)
HIC(n/p
flow)
HIC(isodiff)
α_D
HIC(n/p)
n_0
E_{SAT}
K_{SAT}
Λ(GW)
R(1.4M$_\odot$)
R(2M$_\odot$)
Astronomical
observations
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Nuclear saturation
Density n (n_0)

Betty Tsang

Radii of ^{208}Pb and Neutron Stars

- Pressure of neutron matter pushes neutrons out against surface tension ==> R_n-R_p of ^{208}Pb correlated with P of neutron matter.
- Radius of a neutron star also depends on P of neutron matter.
- Measurement of R_n (^{208}Pb) in laboratory has important implications for the structure of neutron stars.



Neutron star is 18 orders of magnitude larger than Pb nucleus but both involve neutron rich matter at similar densities with the same strong interactions and equation of state.

PREX uses Parity V. to Isolate Neutrons

- In Standard Model Z^0 boson couples to the weak charge.
- Proton weak charge is small:

$$Q_W^p = 1 - 4\sin^2\Theta_W \approx 0.05$$

- Neutron weak charge is big:

$$Q_W^n = -1$$

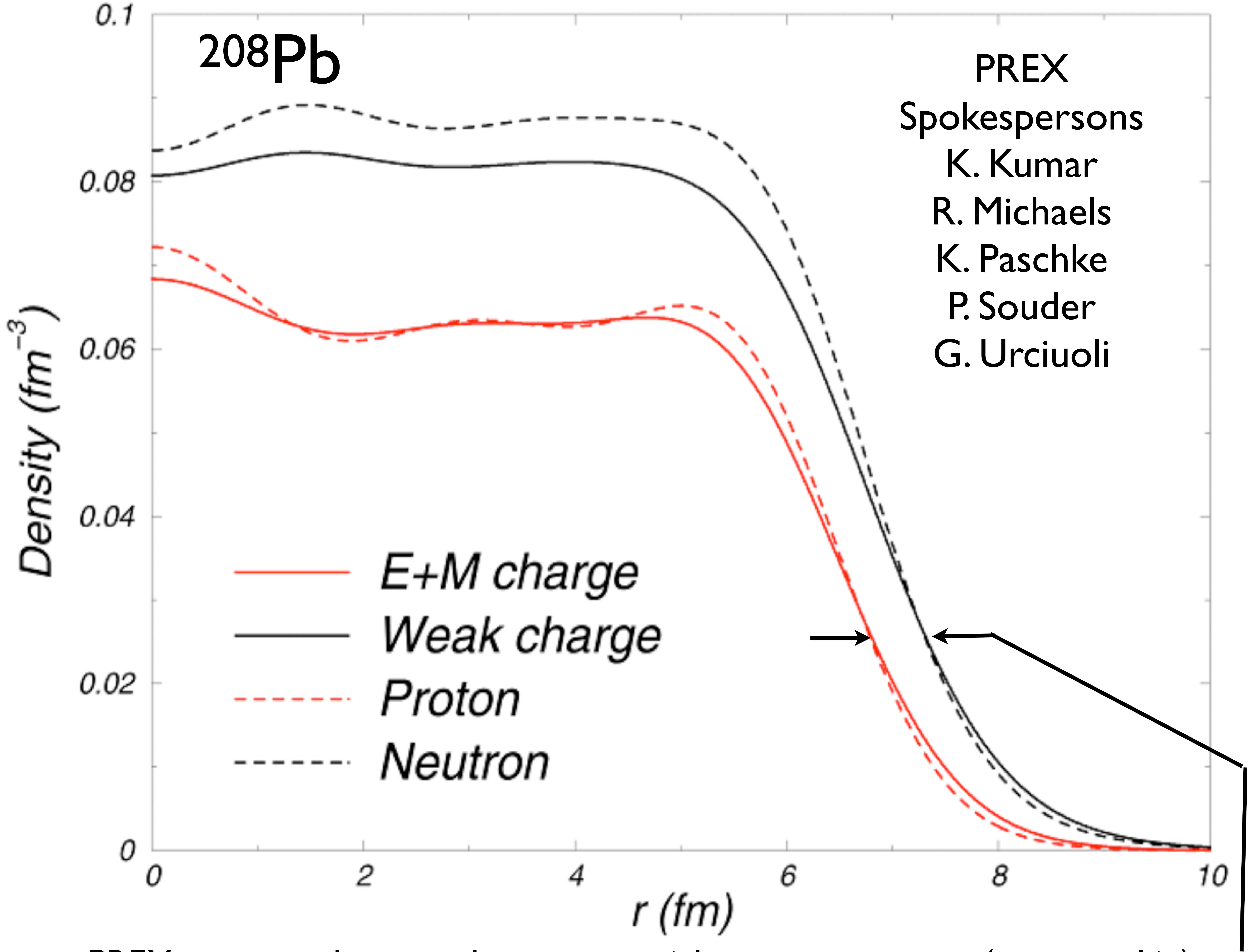
- Weak interactions, at low Q^2, probe neutrons.
- Parity violating asymmetry A_{pv} is cross section difference for positive and negative helicity electrons

- A_{pv} from interference of photon and Z^0 exchange.
- Determines weak form factor

$$F_W(q) = \frac{1}{Q_W}\int d^3r\, j_0(qr)\rho_W(r)$$

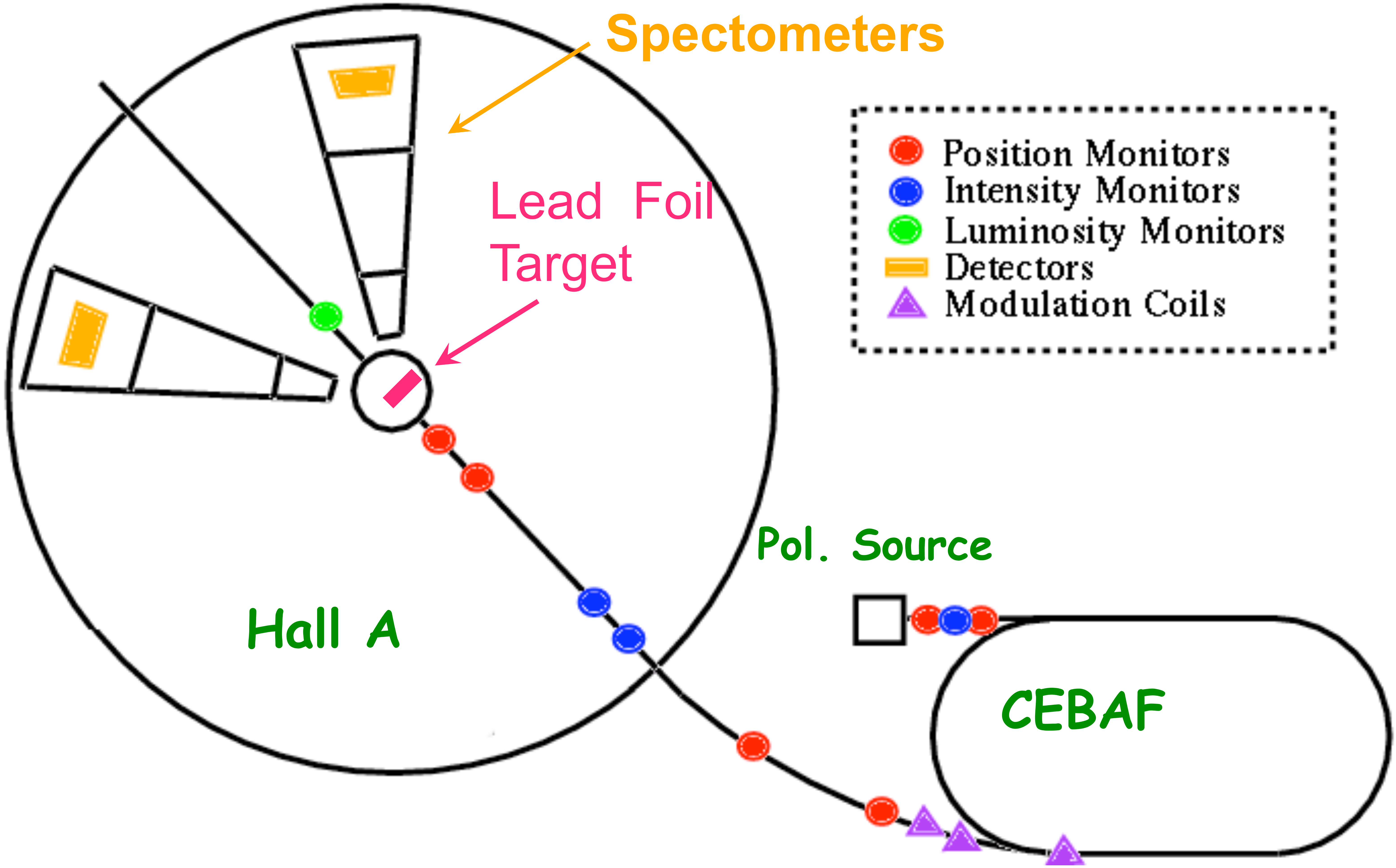
- Model independently map out distribution of weak charge in a nucleus.
- **Electroweak reaction free from most strong interaction uncertainties.**

$$A_{pv} = \frac{d\sigma/d\Omega_+ - d\sigma/d\Omega_-}{d\sigma/d\Omega_+ + d\sigma/d\Omega_-} \approx \frac{G_F Q^2 |Q_W|}{4\pi\alpha\sqrt{2}Z}\frac{F_W(Q^2)}{F_{ch}(Q^2)}$$



- PREX measures how much neutrons stick out past protons (neutron skin).

PREX in Hall A at JLab



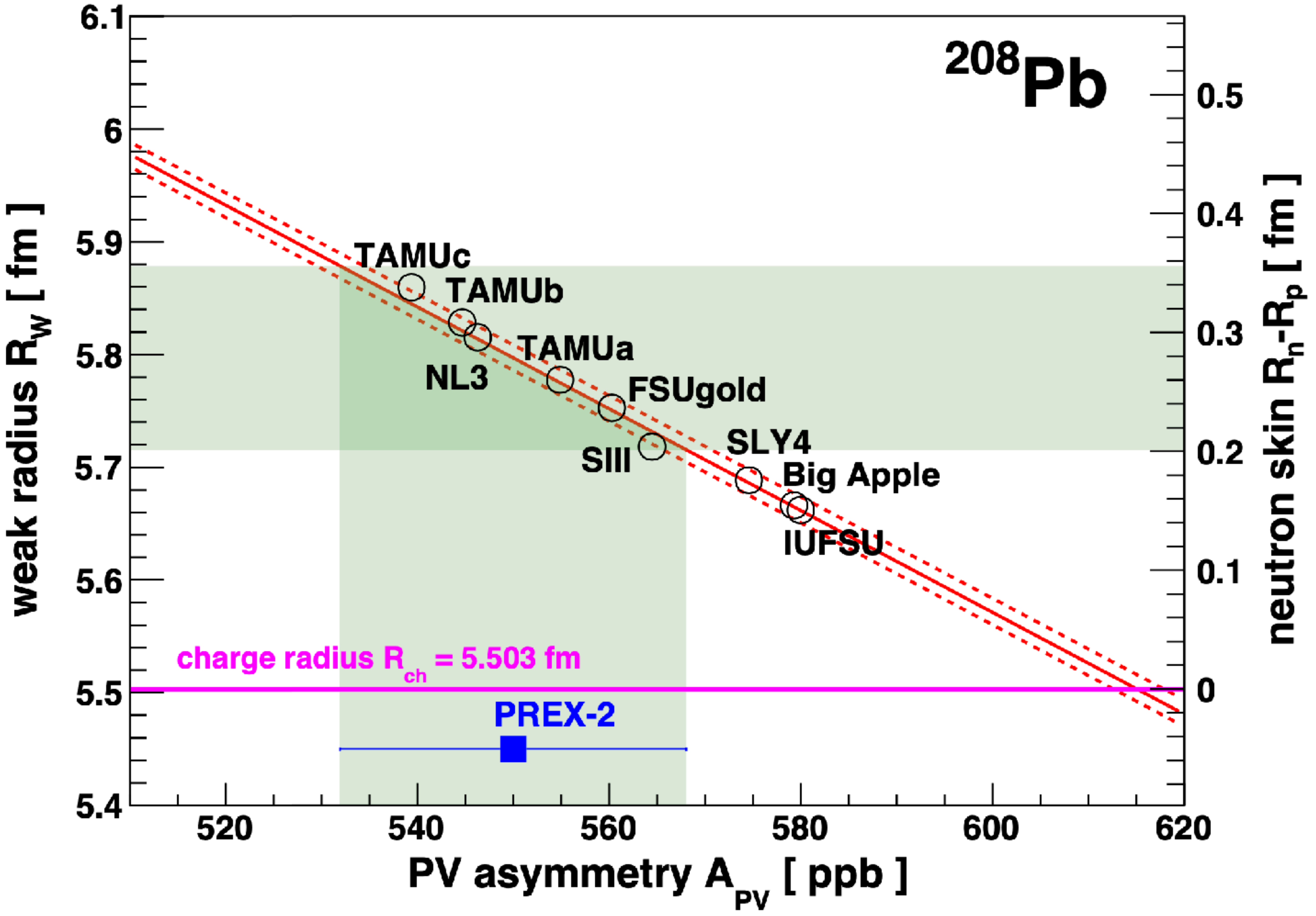
R. Michaels

PREX-II

$$A_{pv} = \frac{d\sigma/d\Omega_+ - d\sigma/d\Omega_-}{d\sigma/d\Omega_+ + d\sigma/d\Omega_-}$$

$$\approx \frac{G_F Q^2 |Q_W|}{4\pi\alpha\sqrt{2}Z} \frac{F_W(Q^2)}{F_{ch}(Q^2)}$$

$$A_{\rm PV}^{\rm meas} = 550 \pm 16\,({\rm stat}) \pm 8\,({\rm syst})\ {\rm ppb}$$



PREX-I+II Results

^{208}Pb Parameter	Value
Weak radius (R_W)	5.800 ± 0.075 fm
Interior weak density (ρ^0_W)	-0.0796 ± 0.0038 fm^{-3}
Interior baryon density (ρ^0_b)	0.1480 ± 0.0038 fm^{-3}
Neutron skin ($R_n - R_p$)	0.283 ± 0.071 fm

$$F_W(q) = \frac{1}{Q_W}\int d^3r\, j_0(qr)\rho_W(r)$$

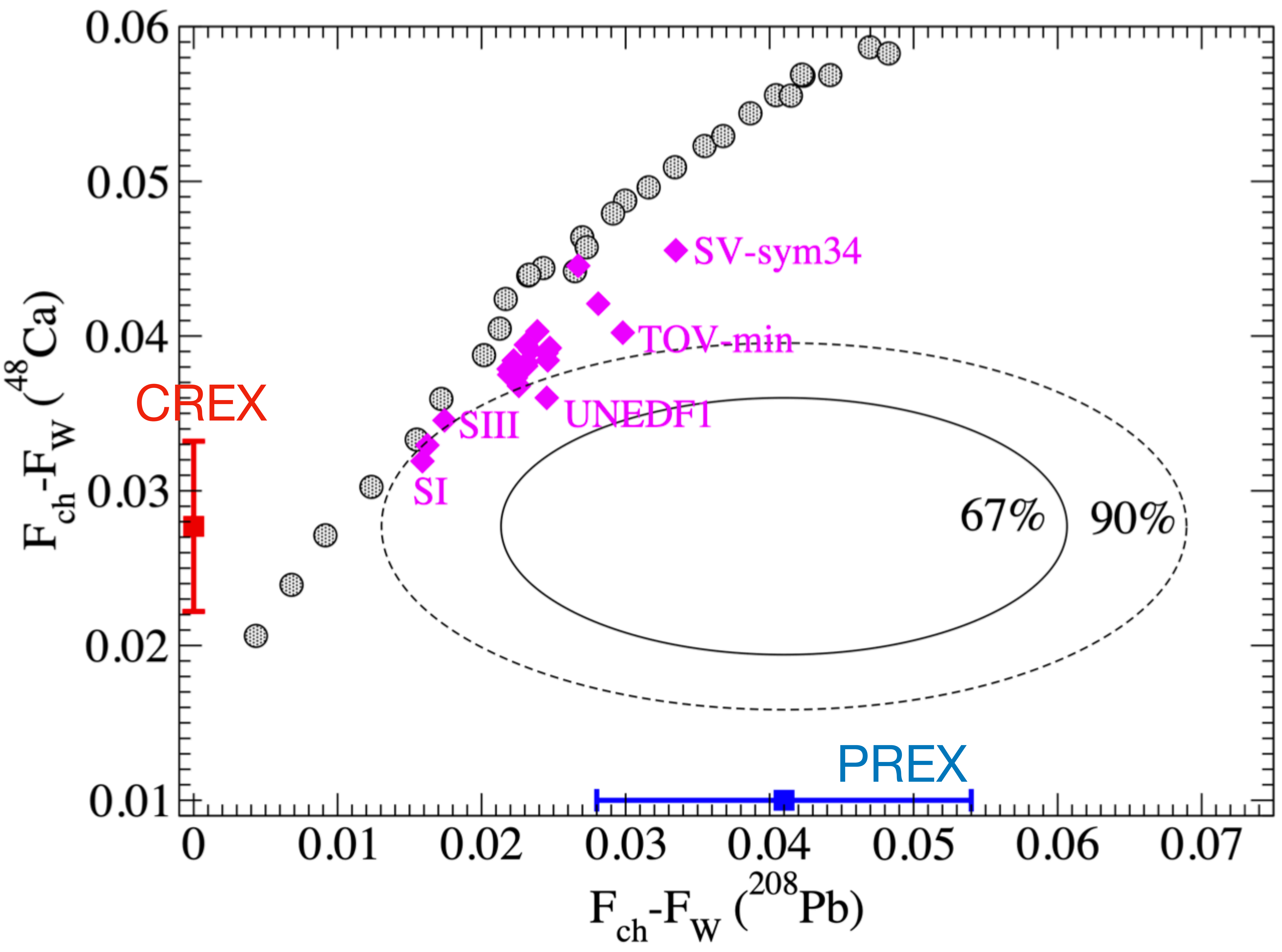
$F_W(q=0.398\text{fm}^{-1})=0.3676$+/-.0125

CREX ^{48}Ca

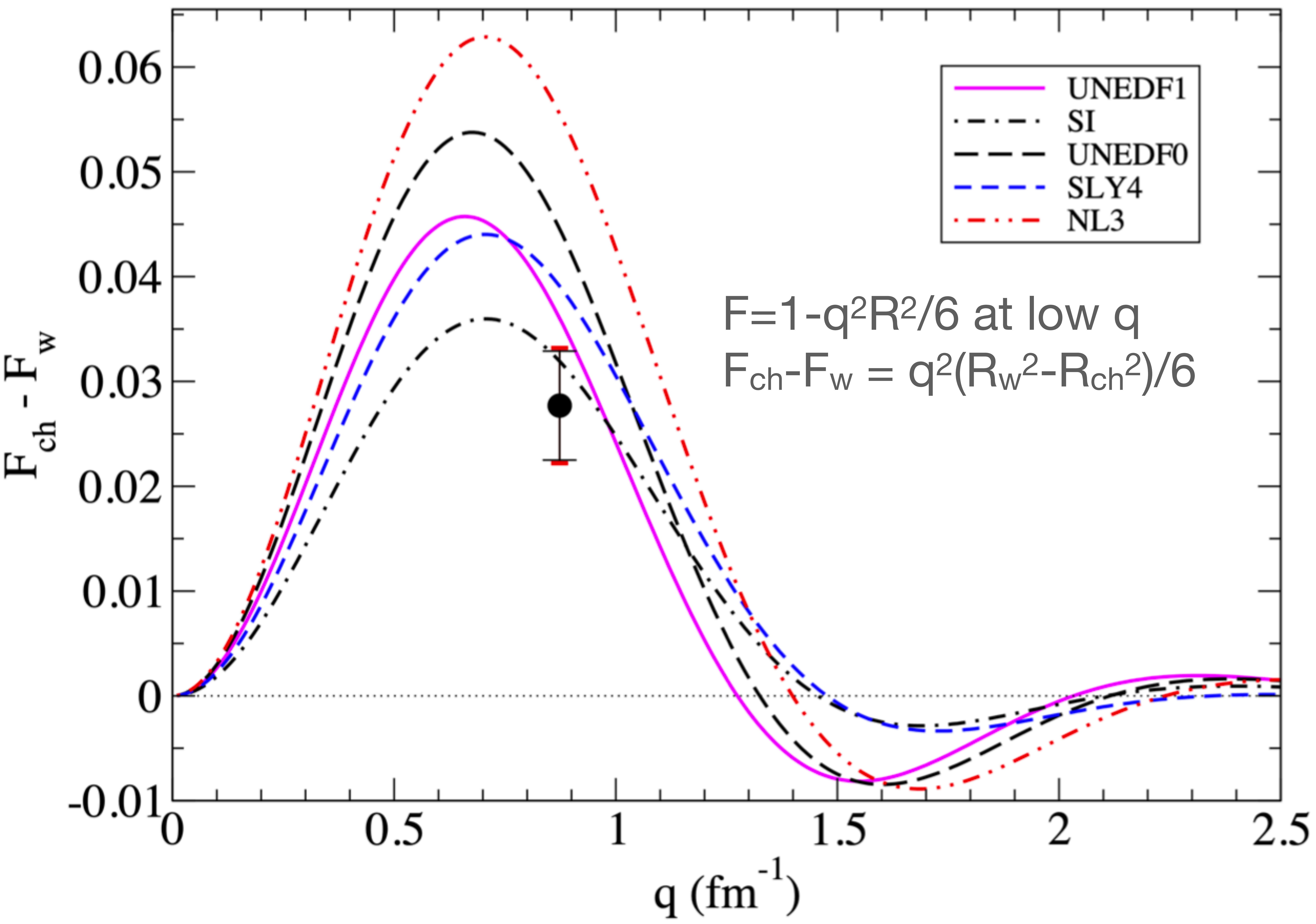
A_{PV} corrections and corresponding systematic errors

- Closed shell neutron rich nuclei: ^{208}Pb better related to symmetry energy and EOS while lighter ^{48}Ca better compared to Chiral EFT calculations with three neutron forces.
- 2.182 GeV electrons scattering with q=0.8733 fm^{-1} from ^{48}Ca.
- A_{PV}=2668+/-106+/-40 ppb
- Target 8% ^{40}Ca, 0.6%, 0.6%, 0.2% of rate from first three excited states (2^+,3^-,3^-).

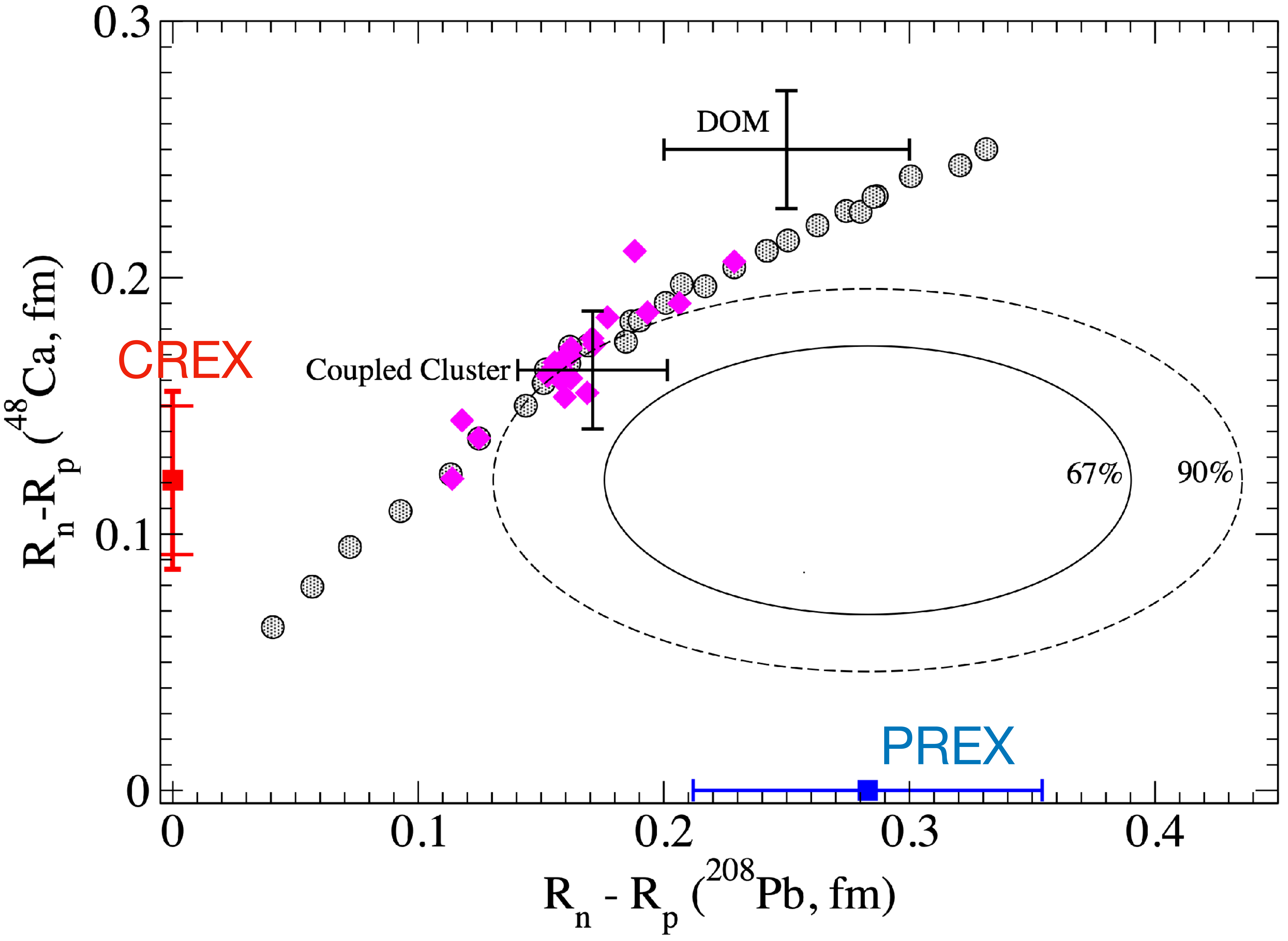
Correction	Absolute [ppb]	Relative [%]
Beam polarization	382 ± 13	14.3 ± 0.5
Beam trajectory & energy	68 ± 7	2.5 ± 0.3
Beam charge asymmetry	112 ± 1	4.2 ± 0.0
Isotopic purity	19 ± 3	0.7 ± 0.1
3.831 MeV (2^+) inelastic	-35 ± 19	-1.3 ± 0.7
4.507 MeV (3^-) inelastic	0 ± 10	0 ± 0.4
5.370 MeV (3^-) inelastic	-2 ± 4	-0.1 ± 0.1
Transverse asymmetry	0 ± 13	0 ± 0.5
Detector non-linearity	0 ± 7	0 ± 0.3
Acceptance	0 ± 24	0 ± 0.9
Radiative corrections (Q_W)	0 ± 10	0 ± 0.4
Total systematic uncertainty	40 ppb	1.5%
Statistical Uncertainty	106 ppb	4.0%



CREX
PREX
SV-sym34
TOV-min
UNEDF1
SIII
SI
67%
90%
F_{ch}-F_W (^{48}Ca)
F_{ch}-F_W (^{208}Pb)
0.06
0.05
0.04
0.03
0.02
0.01
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07



UNEDF1
SI
UNEDF0
SLY4
NL3
F=1-q²R²/6 at low q
Fch-Fw = q²(Rw²-Rch²)/6
Fch - Fw
q (fm-1)
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
0
0.5
1
1.5
2
2.5



CREX
PREX
DOM
Coupled Cluster
67%
90%
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
$R_n - R_p$ (^{208}Pb, fm)
$R_n - R_p$ (^{48}Ca, fm)

Nuclear measurement vs Astronomical Observation

To probe equation of state

PREX, CREX measure neutron radius of ^{208}Pb and ^{48}Ca. Clean electroweak rxn.

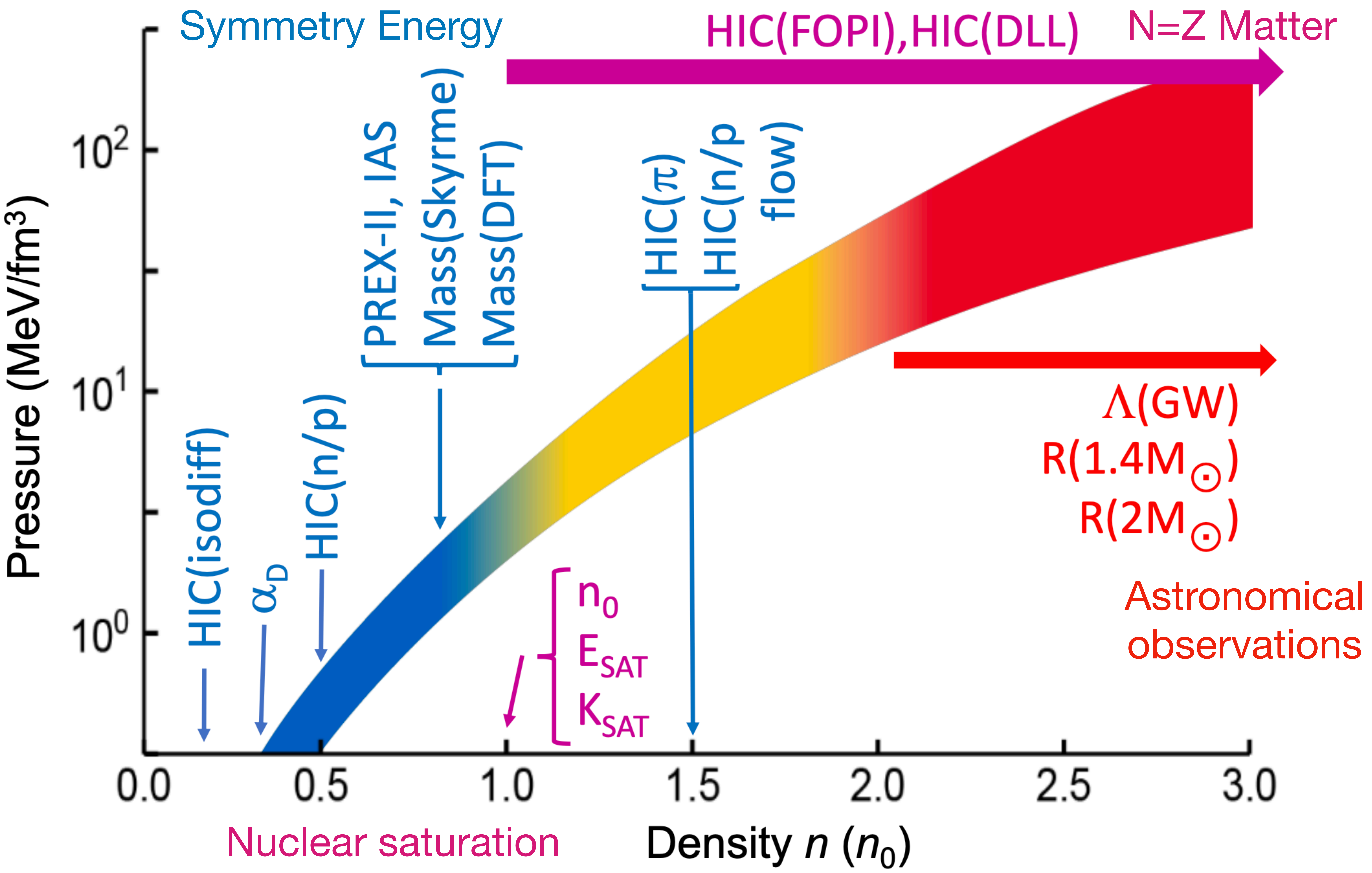
NICER measures NS radius from X-ray light curve. Some systematic errors.

Electric **dipole polarizability** from coulomb excitation. Potential systematic error from sum over excited states. Encourage ab initio calculations.

LIGO measured **gravitational deformability** (quadrupole polarizability) of NS from tidal excitation. Statistics limited but systematic errors controllable.

$$\Lambda \propto \Sigma_f \frac{|\langle f|r^2 Y_{20}|i\rangle|^2}{E_f - E_i} \quad \propto \quad R^5$$

	Laboratory measurements on nuclei	Astronomical observations of neutron stars
Radius	PREX, CREX	NICER
Polarizability	Electric dipole	Gravitational deformability



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0.5
1.0
1.5
2.0
2.5
3.0
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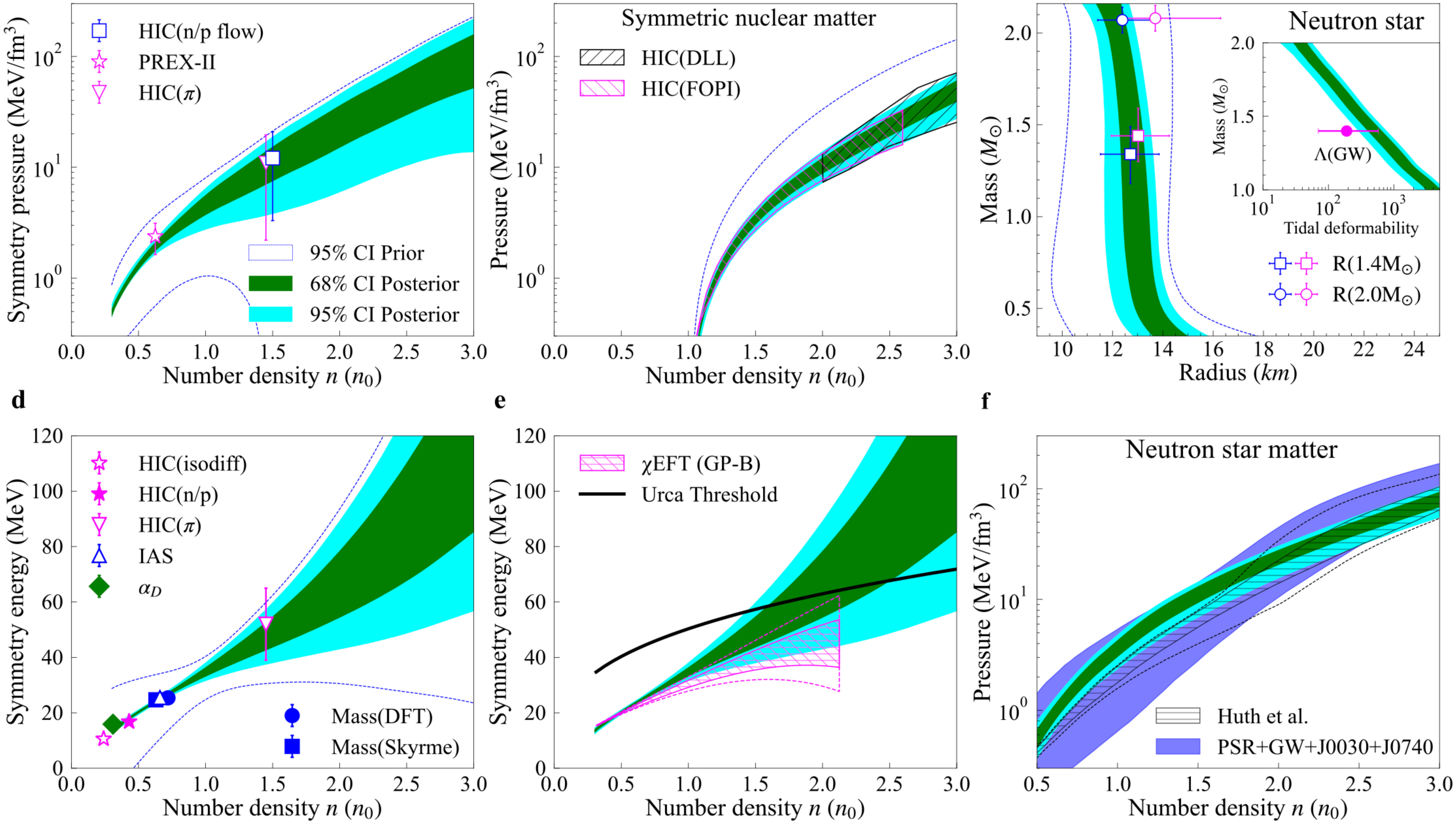
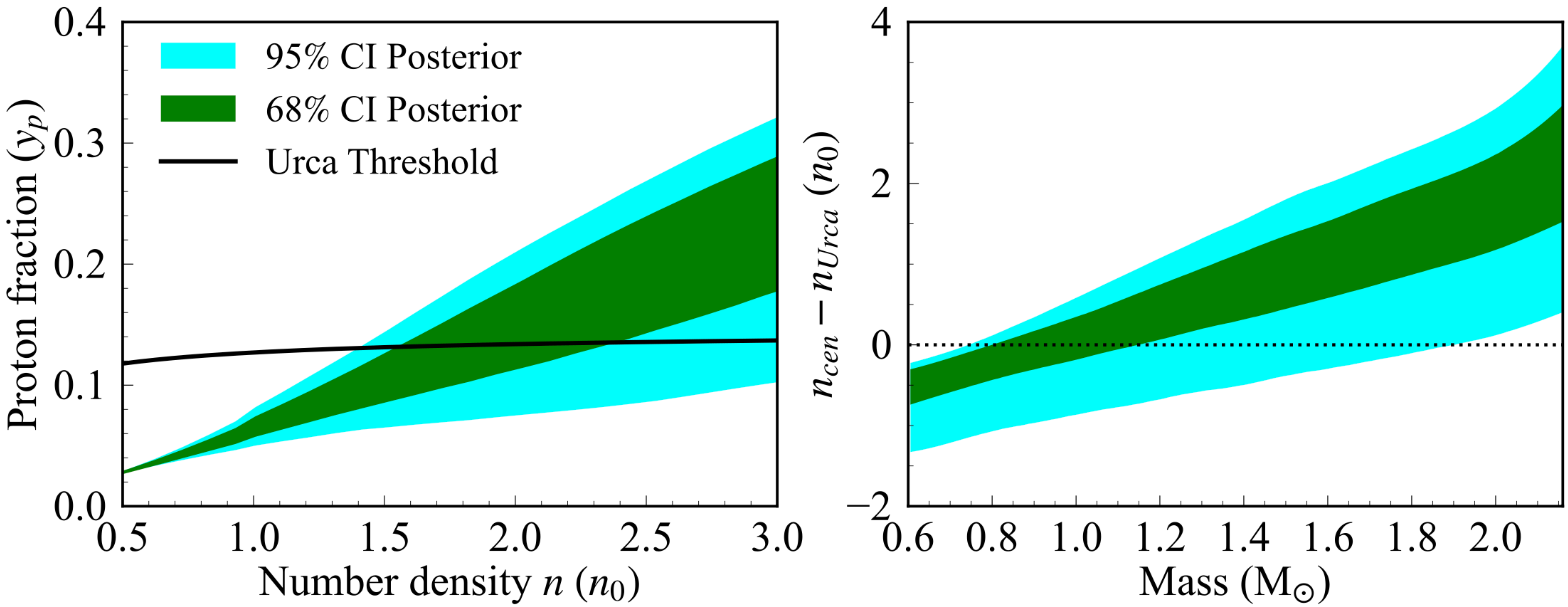
Density n (n_0)

Symmetry energy

- Symmetry energy $S(n)$ describes how energy rises as one moves away from $N=Z$
- Energy of pure neutron matter is approx. energy of symmetric nuclear matter + symmetry energy: $E_n(n) = E_{sym}(n) + S(n)$
- Symmetry pressure: $P_s=-dS/dV$ so $P_n=P_{sym} + P_s$



C Y Tsang, Betty Tsang, Bill Lynch, Rohit Kumar, CJH

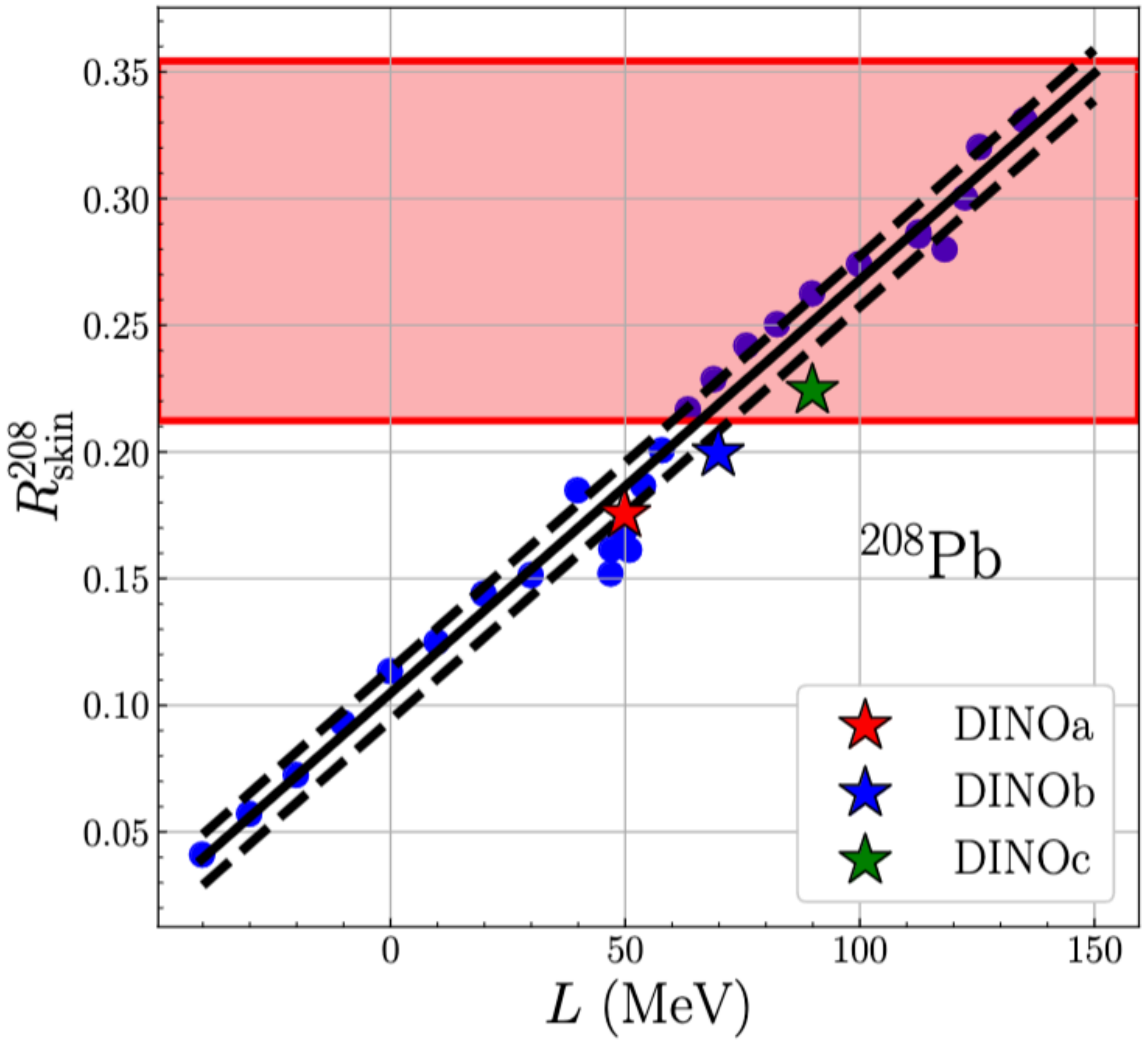


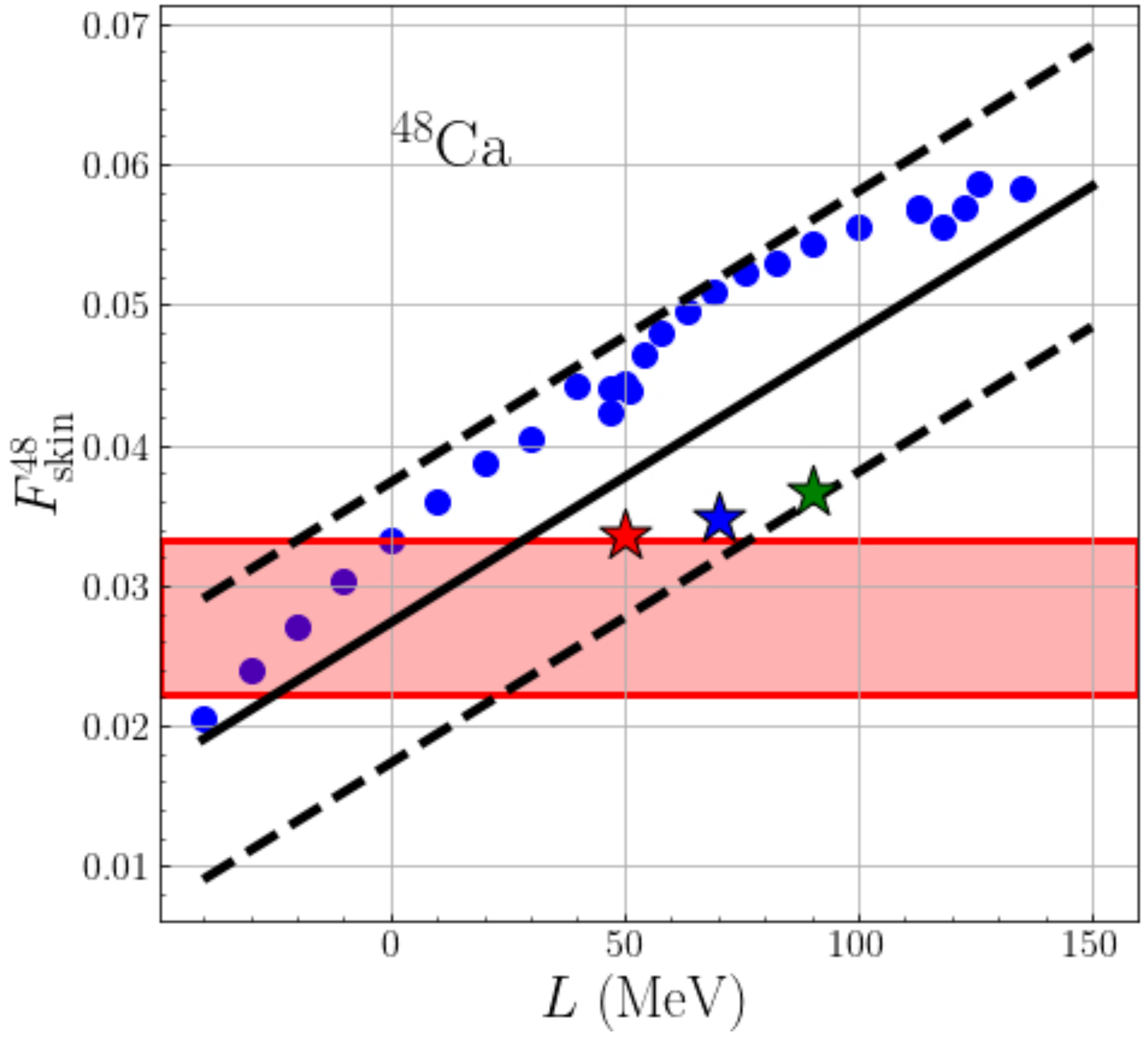
$$[4S(n)(1-2y_p)]^3 + \{[4S(n)(1-2y_p)]^2 - m_\mu^2\}^{3/2} = 3\pi^2 n y_p,$$

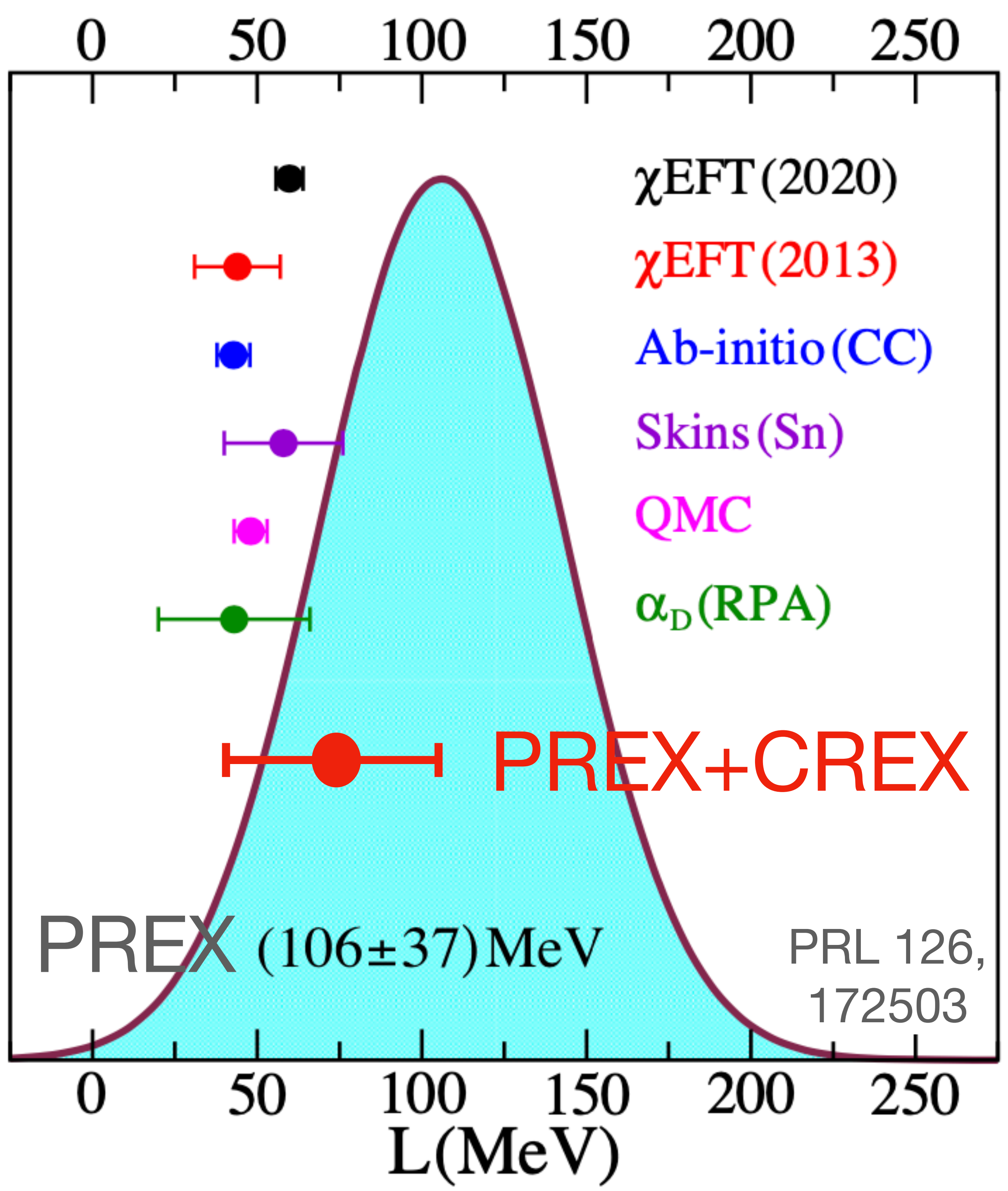
$\mu_e = k_{Fe}$

Beta equil: $\mu_n - \mu_p = \mu_e$, Direct Urca threshold: $k_{Fp} + k_{Fe} > k_{Fn}$

Symmetry Energy from PREX, CREX

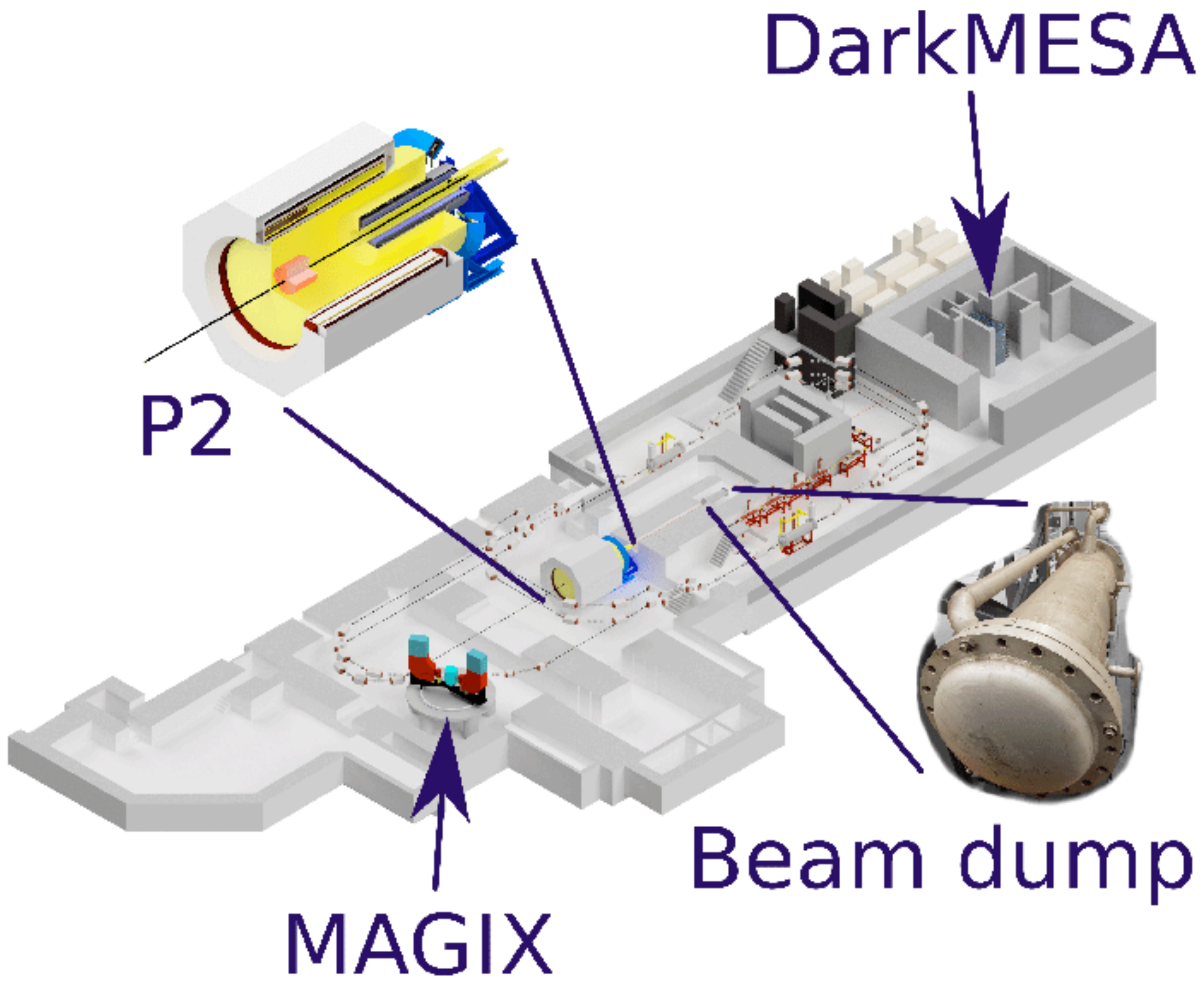






- Symmetry energy S(n) describes how E of nuc. matter rises as one moves away from N=Z
- $L=3n_0 dS(n)/dn|_{n0}$ Extracting L from CREX is more model dependent than from PREX.
- L=106 +/- 37 MeV (PREX), 69 +/- 34 MeV (PREX+CREX)
- The DINO RMF interactions have unusual density dependence, fit to both PREX and CREX

MREX experiment at Mainz



- MESA is high current low energy electron accelerator being built at Mainz.
- Mainz Radius Experiment (MREX) will use MESA and large acceptance P2 detector to measure the neutron skin of ^{208}Pb more accurately than PREX.
- PREX measured R_n to 1.3% (+/- 0.07 fm), MREX goal 0.5% (+/- 0.03 fm)

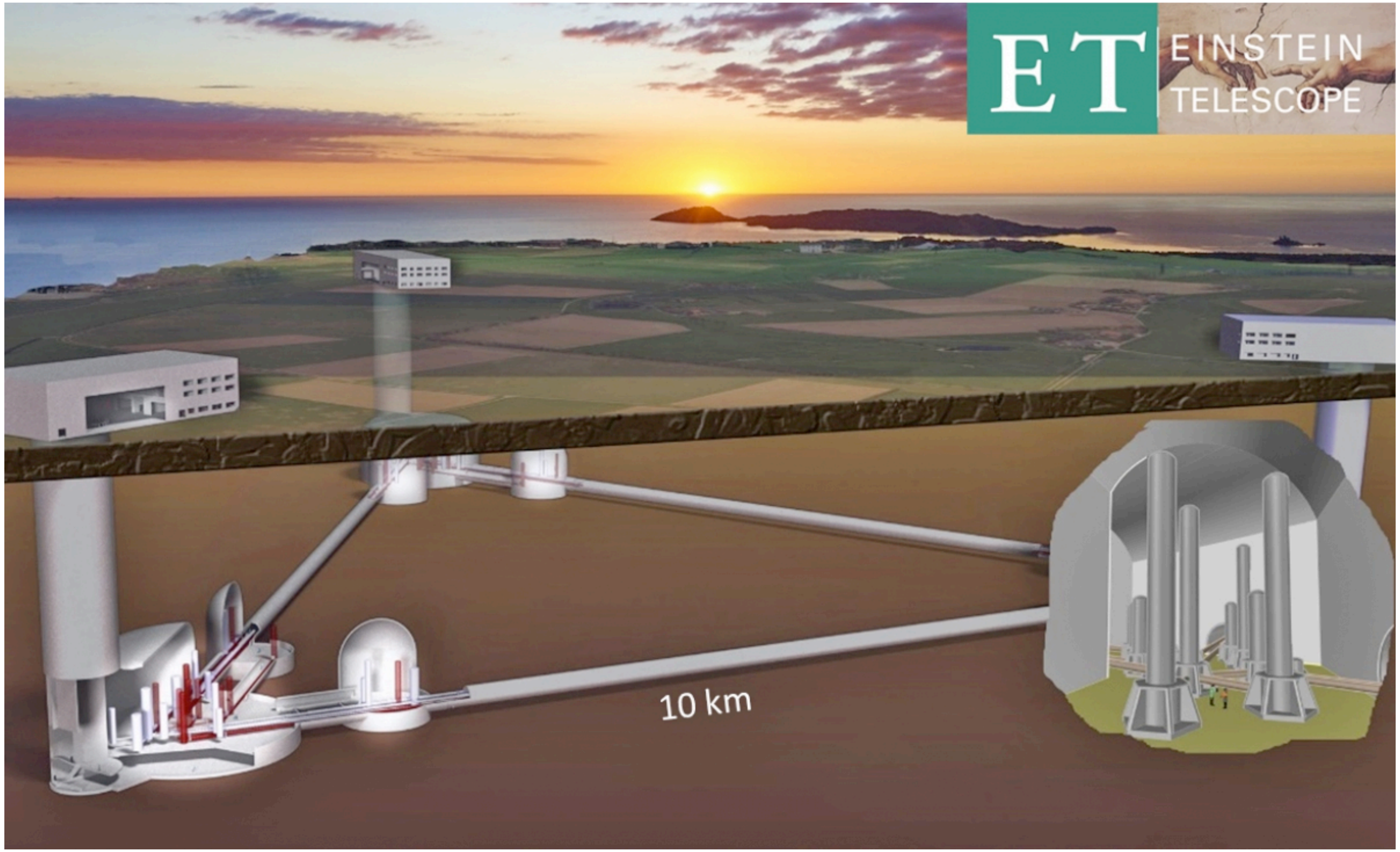
beam energy	155 MeV
beam current	150 μA
target density	0.28 g/cm^2
polar angle step size	$\Delta\theta = 4°$
polar angular range	30° to 34°
degree of polarization	85 %
parity violating asymmetry	0.66 ppm
running time	1440 hours
systematic uncertainty	1 %
$\delta A^{PV}/A^{PV}$	1.39 %
$\delta R_n/R_n$	0.52 %

Observation+Exp. Status Circa 2030

- ^{208}Pb skin: MREX +/0.03 fm (.07 fm PREX)
- NICER X-ray NS radii: more stars, more statistics, massive NS still ~+/- 1 km because of systematic errors from NS atmospheres and spot shapes.
- LIGO->A+ configuration: Deformability +/- ~100 (now +/- 200 from GW170817)

Next generation gravitational wave observatories

- The Einstein Telescope is proposed GW detector to be built at Dutch-Belgian-German border or in Sardinia.
- Cosmic explorer is proposed US detector with 40 km arms.
- 10 times more sensitive, 1000 x detection rate, of existing LIGO and VIRGO.
- They could accurately measure deformability of neutron stars. Only depends on GR and EOS.



Neutrino interactions in dense matter are related to EOS

Example: Linear response of a mean field EOS is RPA
where RPA interactions determined by EOS model.

Macroscopic quantum #s of Supernova

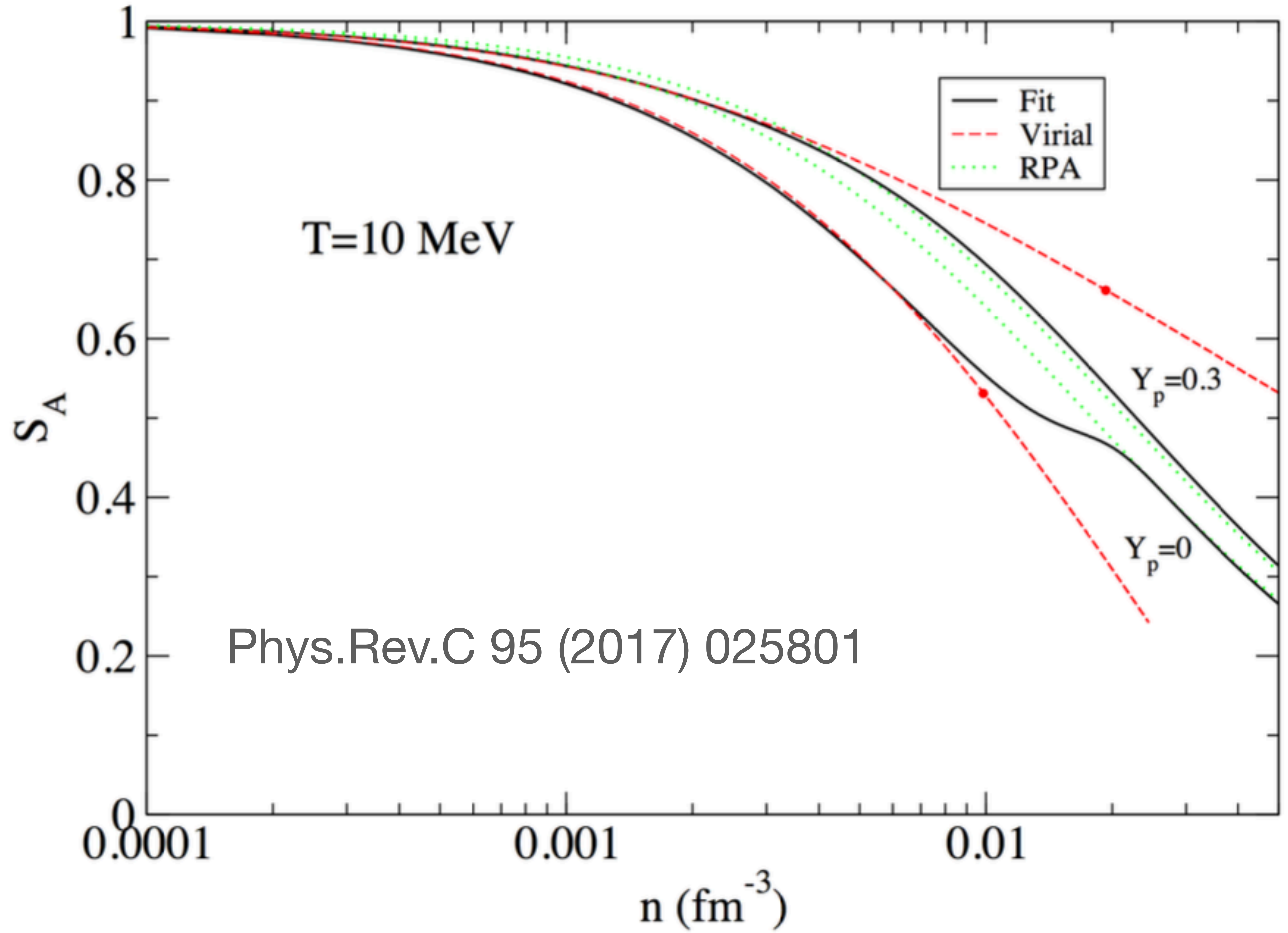
	Stellar core	Proto-NS	Neutron star
Neutrinos radiated		10^{58}	
Baryon number	10^{57}	10^{57}	10^{57}
Electron number	10^{57}	decreasing	10^{56}
Muon number	0	increasing	10^{55}
Tau number	0	10^{54}	0

Neutrino luminosity

- Effects that allow the proto neutron star neutrino sphere to collapse faster to smaller radius and larger gravitational binding energy can increase neutrino luminosity and aid shock expansion.
- Cold EOS not so important for warm proto NS radius.

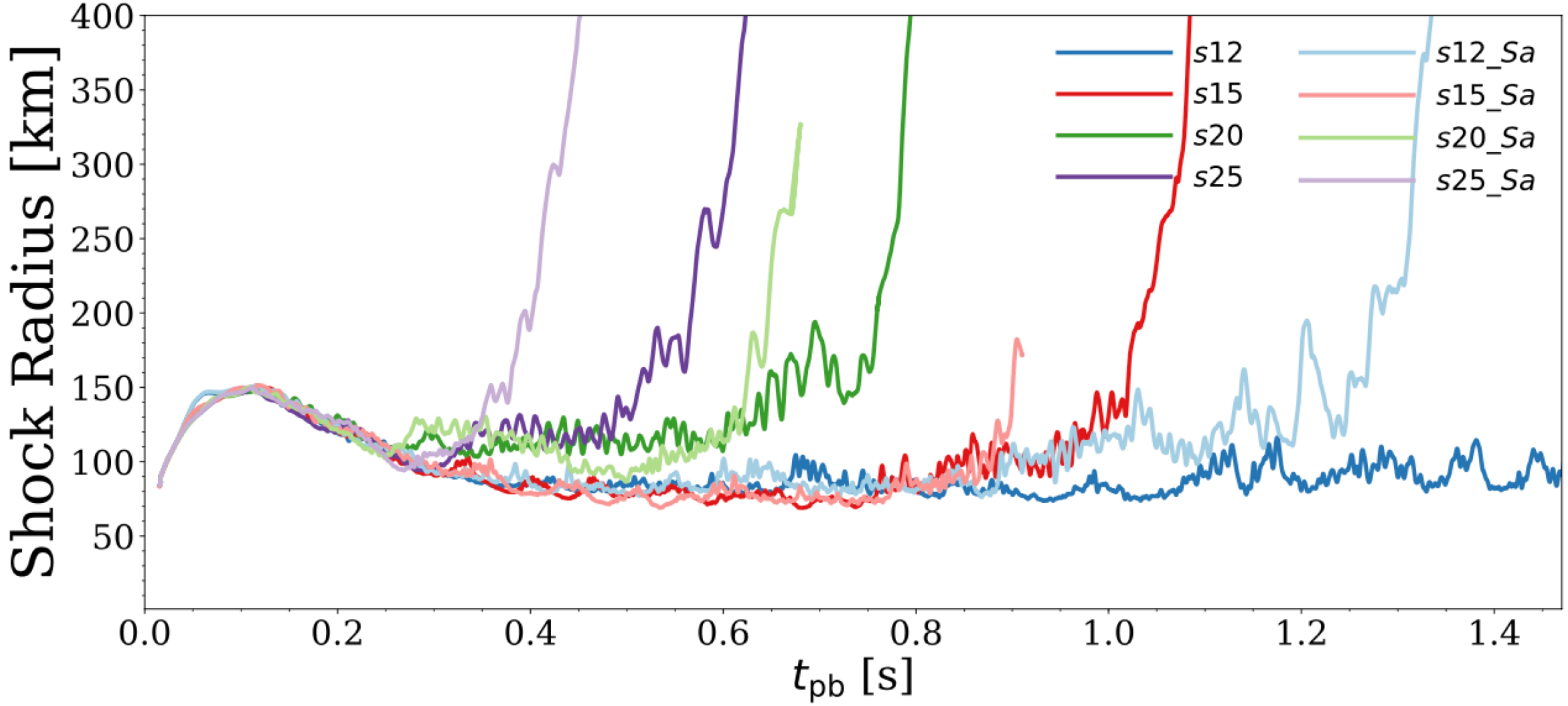
Neutral current interactions

- Long scattering length of nn interaction correlates two neutrons into a spin zero state that reduces spin (axial) response.
- Correlations can be important even at relatively low densities near neutrino sphere because of long scattering length. Effect not captured in most mean field or RPA models but included in viral EOS.
- These correlations reduce neutral current scattering and increase mu and tau nu mean free paths. This allows more transport of energy helping shock.



Fit
Virial
RPA
T=10 MeV
Y_p=0.3
Y_p=0
Phys.Rev.C 95 (2017) 025801
S_A
n (fm^{-3})
1
0.8
0.6
0.4
0.2
0
0.0001
0.001
0.01

O'Connor *et al.*



Two dimensional SN simulations including correlation effects (light lines) explode earlier than calculations with free spin response (solid lines) for 12 to 25 solar mass stars (right to left).

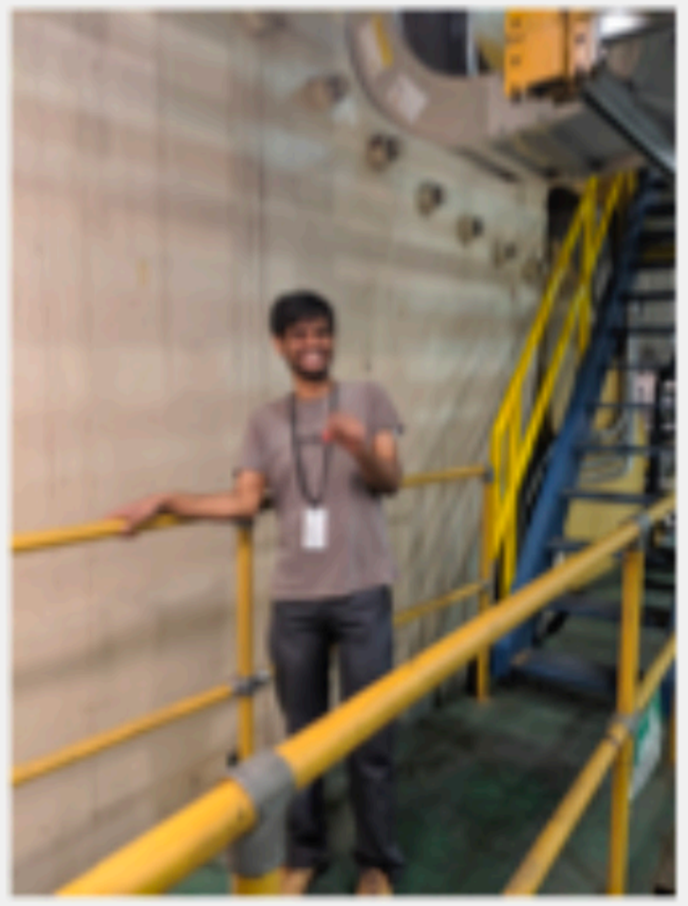
Charged current response

- Difference between proton, neutron, and electron chemical potentials important for charged current absorption. (Binding energy or mean field shift)
- Note long scattering lengths imply binding energy shift is more important at low densities than simple mean field EOS might suggest.
- Other interaction effects still incompletely examined.

PREX and CREX Collaborations

Students: Devi Adhikari, Devaki Bhatta Pathak, Quinn Campagna, Yufan Chen, Cameron Clarke, Catherine Feldman, Iris Halilovic, Siyu Jian, Eric King, Carrington Metts, Marisa Petrusky, Amali Premathilake, Victoria Owen, Robert Radloff, Sakib Rahman, Ryan Richards, Ezekiel Wertz, Tao Ye, Adam Zec, Weibin Zhang




Post-docs and Run Coordinators: Rakitha Beminiwattha, Juan Carlos Cornejo, Mark-Macrae Dalton, Ciprian Gal, Chandan Ghosh, Donald Jones, Tyler Kutz, Hanjie Liu, Juliette Mammei, Dustin McNulty, Caryn Palatchi, Sanghwa Park, Ye Tian, Jinlong Zhang

Spokespeople: Kent Paschke (contact), Krishna Kumar, Robert Michaels, Paul A. Souder, Guido M. Urciuoli

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