Study of asymmetric nuclear matter EoS from terrestrial nuclear experiments

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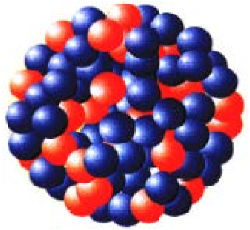
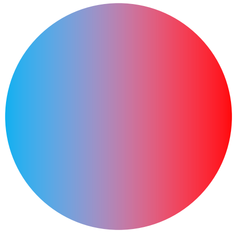
April 23, 2025 From Quarks to Neutron Stars: Insights from kHz gravitational waves

Nuclei: many body system composed of protons and neutrons

- Many-body quantum-system with spontaneous order and self organization
  - Shell structure without inner core
- Two aspects: microscopic and macroscopic
- Superposition of single state nucleon ←→ bulk matter



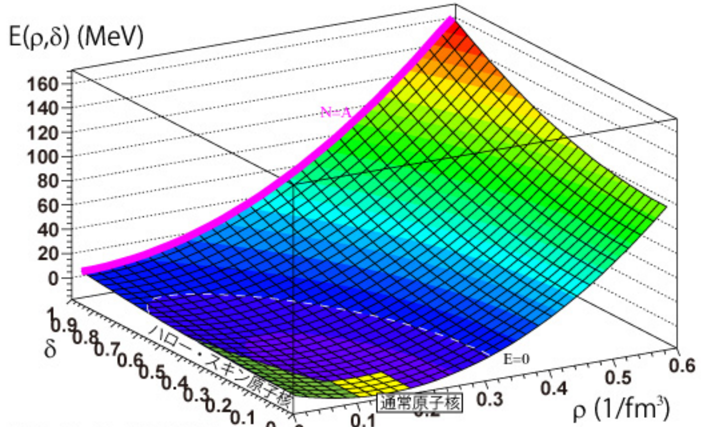


- Deriving the equation of state (EOS) of nuclear matter, i.e. neutron star, based on the experimental study in the laboratory.
- Richness of physics in the phase diagram of matter thanks for the interaction among the nuclei.
  - “New physics in NS?” “Internal structure of NS?” are our curiosity as nuclear physics.

Important term in nuclear EOS : Symmetry energy

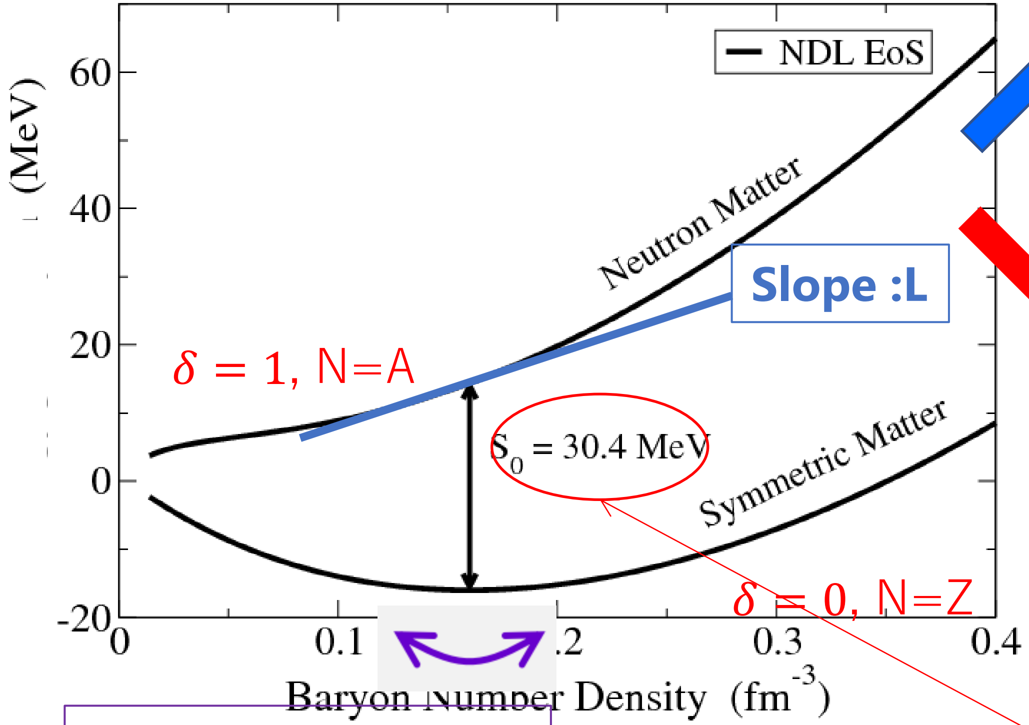
$$E(T,\rho,\delta) = E(T,\rho,\delta=0) + E_{sym}(T,\rho)\delta^2 + O(\delta^4)$$

$$\delta = (\rho_n - \rho_p)/\rho$$



FSU in PhysRevC.79.054311

arXiv:1303.0064



$\delta = 1$, N=A

Slope :L

$\delta = 0$, N=Z

stiff

soft

Incompressibility :K

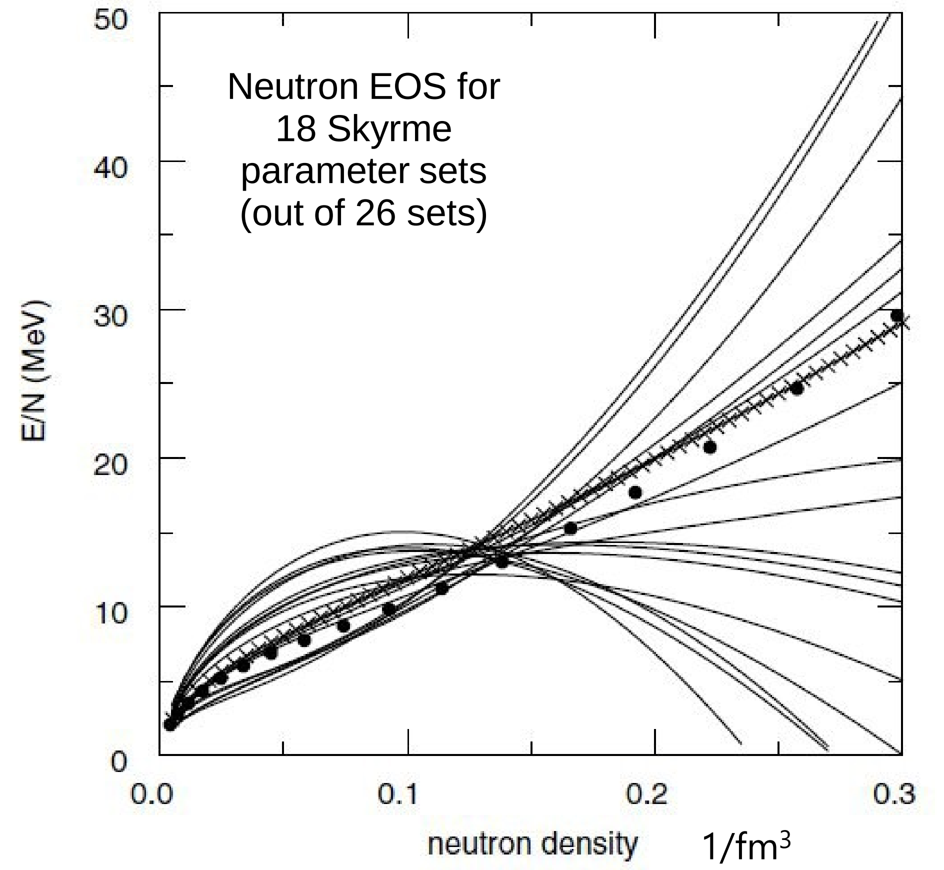
Symmetry Energy at $\rho=\rho_0$:S (or J)

Experimental study of symmetry energy as input for astrophysical researches

- 20 years ago, Brown showed that many different Skyrme effective interactions can fit the binding energies of Sn nuclei between ^{100}Sn and ^{132}Sn

- Well determined only around $\rho \sim \rho_0$ and Z~N

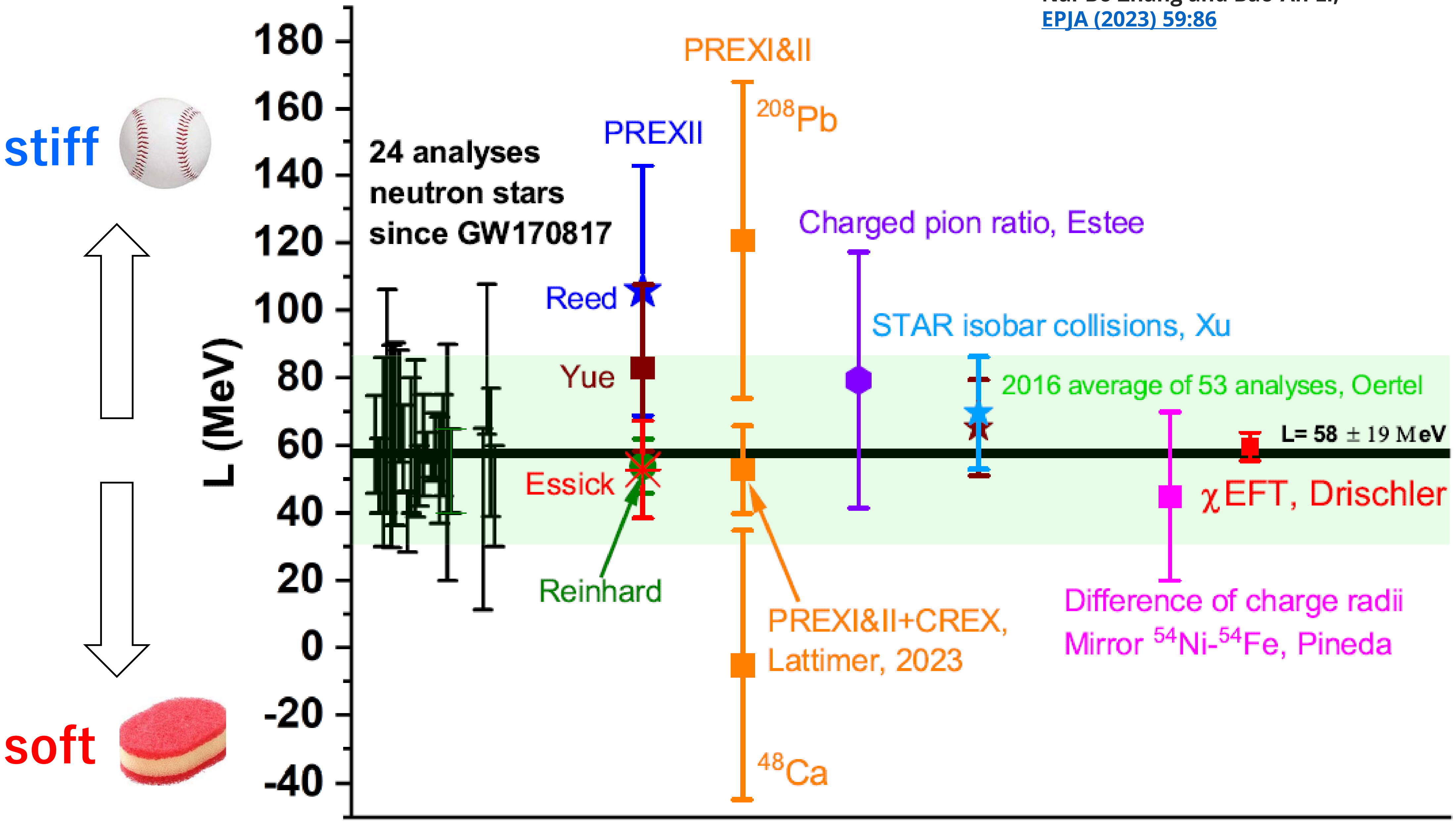
●: Friedman-Pandharipande EOS
×: SkX



B.A. Brown, Phys. Rev. Lett. 85, 5296 (2000).

Slope L of symmetry energy as of Feb. 2023

Nai-Bo Zhang and Bao-An Li,
[EPJA (2023) 59:86]



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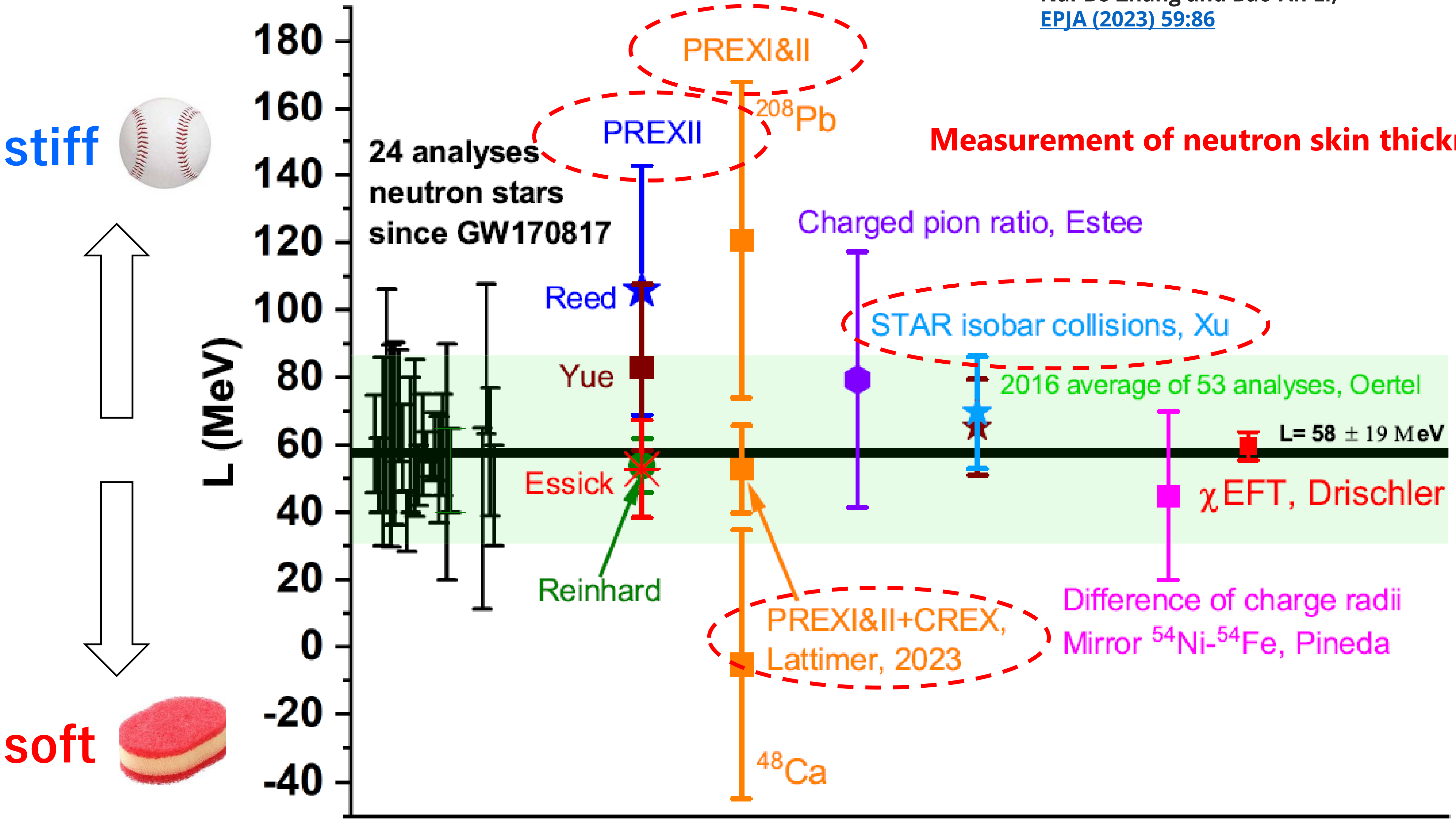
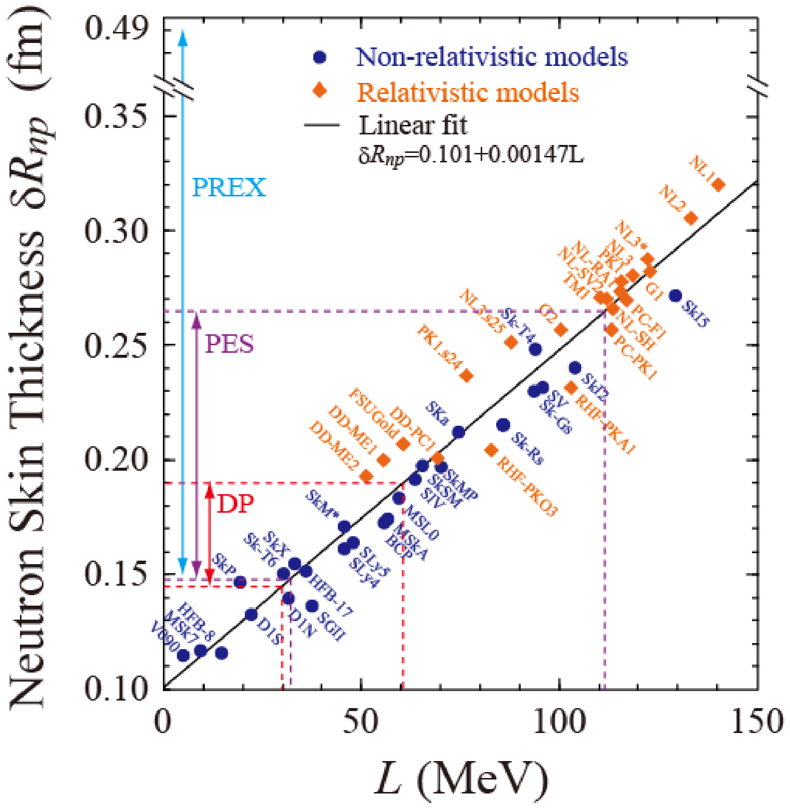


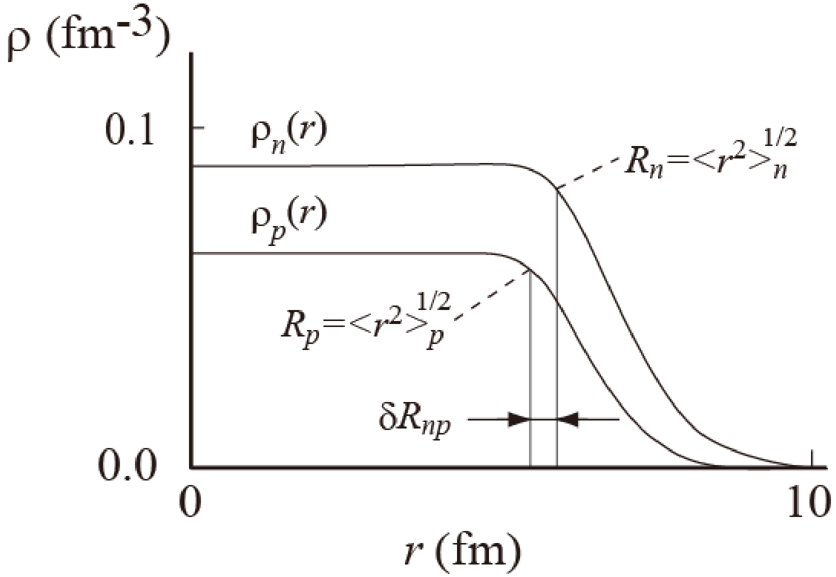
Constraint on nuclear symmetry energy based on nuclear structure: Nuclear skin thickness

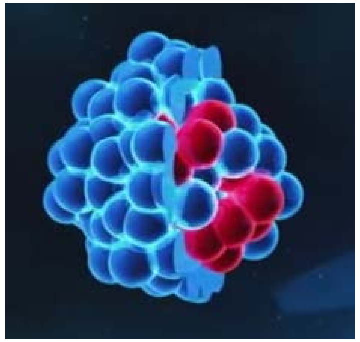
- Relation of Slope parameter (L) and Neutron Skin
  - Large L ⇔ Small E_{sym} in low ρ ⇔ Thick neutron skin (neutron goes to outside)
  - Small L ⇔ Large E_{sym} in low ρ ⇔ Thin neutron skin



X. Roca-Maza *et al.*, PRL**106**, 252501 (2011)

Density distribution of protons and neutrons in a nucleus





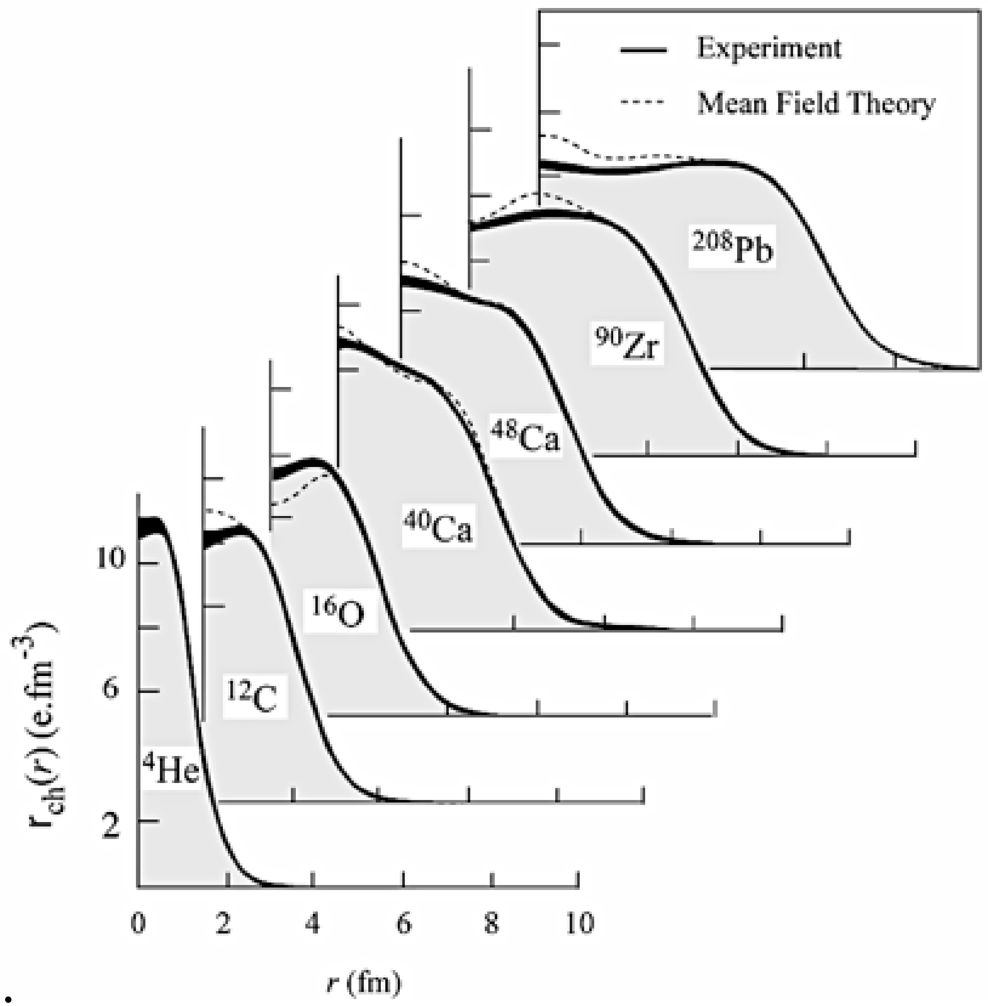
Two ways to measure δnp: r_n-r_p

- parity-violating electron elastic scattering
  - →PREX-I,II CREX @JLab
- proton elastic scattering, isovector skin
  - →ESPRI @RIBF, HIRA @NSCL
  - PRC 82 (2010) 044611, NPA 958 (2017) 147

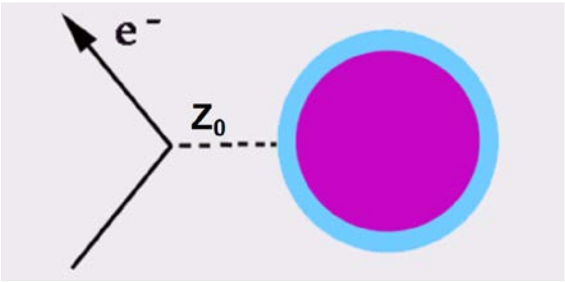
- Proton distribution in nucleus is precisely measured through electron scattering.
  - electromagnetic interaction between electron and nucleus.
  - Neglecting recoil, form factor F(q) is the Fourier transform of charge distribution

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} |F(q)|^2$$

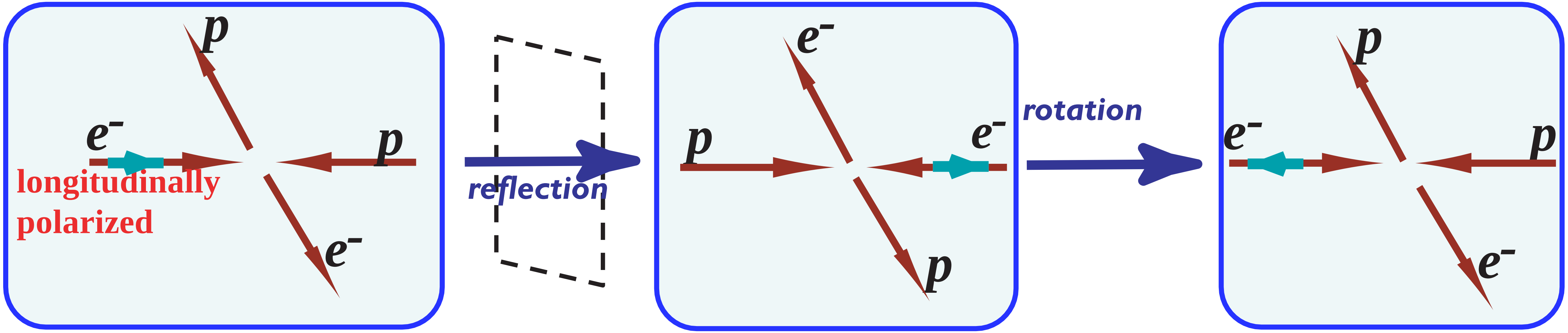
  - Atomic data and Nuclear data table 36 (1987) 495 : 0.4% accuracy



Parity Violating Signature: weak interaction between electron and nucleon



- Effect of the weak interaction can be distinguished by exploring the fact that weak interaction violates the parity.



•One of the incident beams longitudinally polarized
•Change sign of longitudinal polarization
•Measure fractional rate difference → A_{PV}

A_{PV}~1/1,000,000 for Pb (PREX)

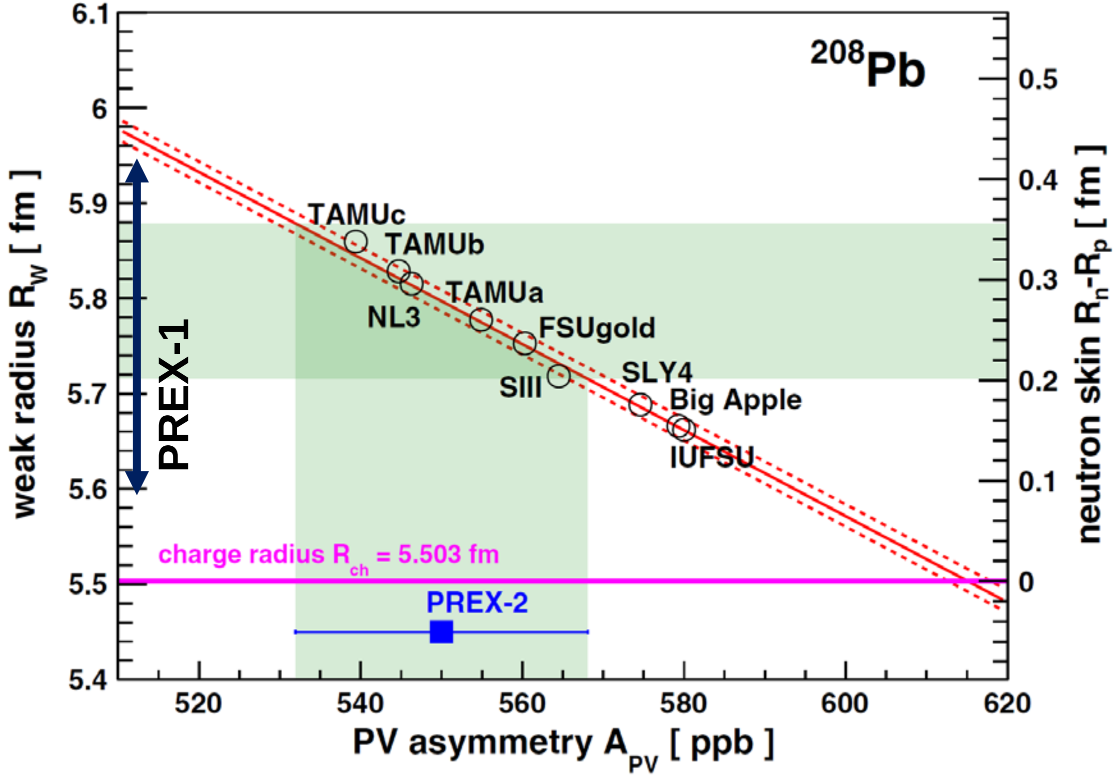
$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx \frac{G_F Q^2 |Q_W|}{4\sqrt{2}\pi\alpha Z} \frac{F_W(Q^2)}{F_{ch}(Q^2)}$$

	proton	neutron
Electric charge	1	0
Weak charge	~0.08	–1

- Need to determine A_{PV} with small uncertainty to see the contribution from weak interaction.
- The big technical challenge is that one must flip the spin very precisely without changing any other parameter of the beam, for example the energy or position.
  - Beam positions at the level of 5 nanometers between flips of the spin, when averaged over a week of running

PREX results

PRL 126 (2021) 172502

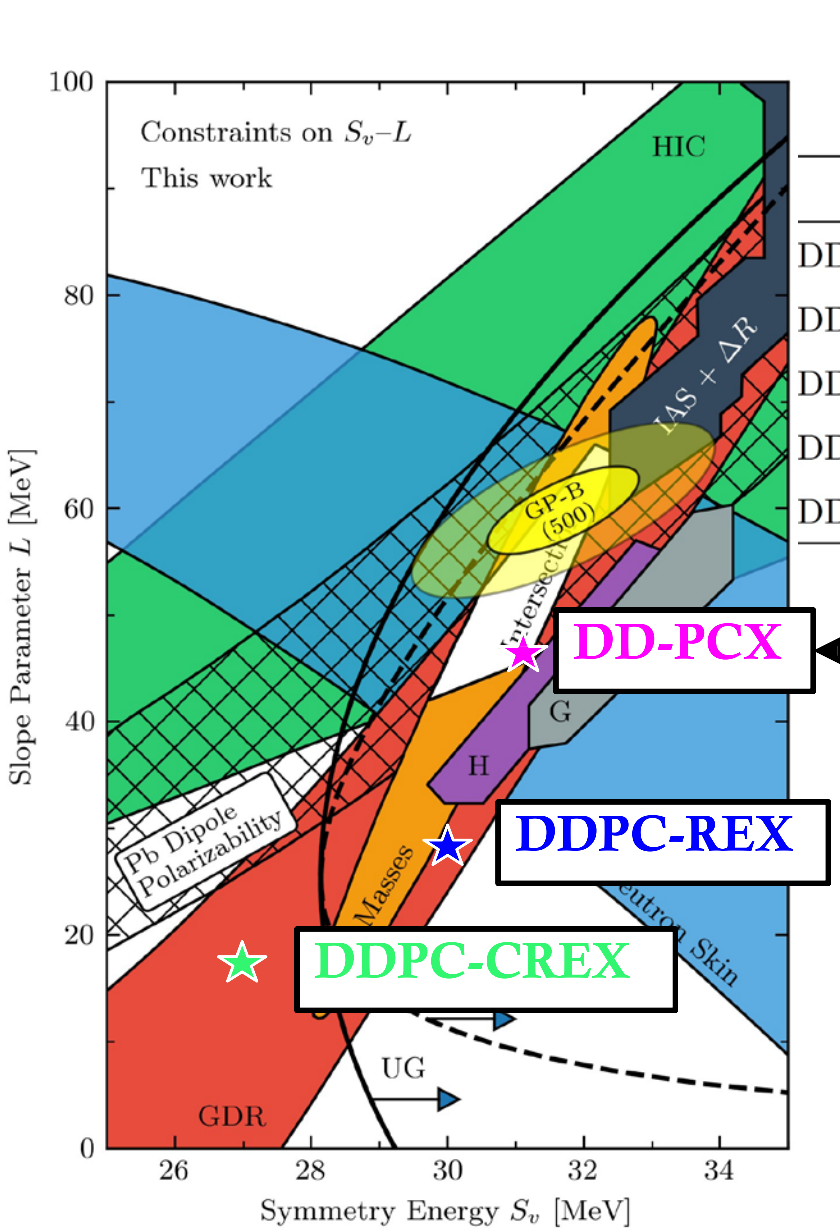


- PREX
- Phys. Rev. Lett. 108 (2012) 112502
- Rn = 5.78+0.16-0.18 fm (3%)
- Rn – Rp = 0.33+0.16-0.18 fm (50%)

- PREX-II
- Phys. Rev. Lett. 126 (2021) 172502
- Rn ~ Rw = 5.795 ± 0.082(exp) ± 0.013(theo) fm (1%)
- Rn – Rp = 0.278 ± 0.078(exp) ± 0.012(theo) fm (25%)

- Nucleus with thick neutron skin is better in terms of precise measurement of δr_{np}
- → RI beam?

Different result from PREX and CREX



	E/A (MeV)	m^*_D/m	K_0 (MeV)	J (MeV)	L (MeV)
DDPC-CREX	-15.989(15)	0.5672(13)	225.48(4.69)	27.01(16)	19.60(64)
DDPC-PREX	-16.108(17)	0.5680(15)	235.41(5.20)	36.18(47)	101.78(4.87)
DDPC-REX	-16.019(15)	0.5696(7)	242.95(2.04)	28.86(15)	30.03(63)
DD-PC1	-16.061	0.580	230.0	33.0	70.1
DD-PCX	-16.026(18)	0.5598(8)	213.03(3.54)	31.12(32)	46.32(1.68)

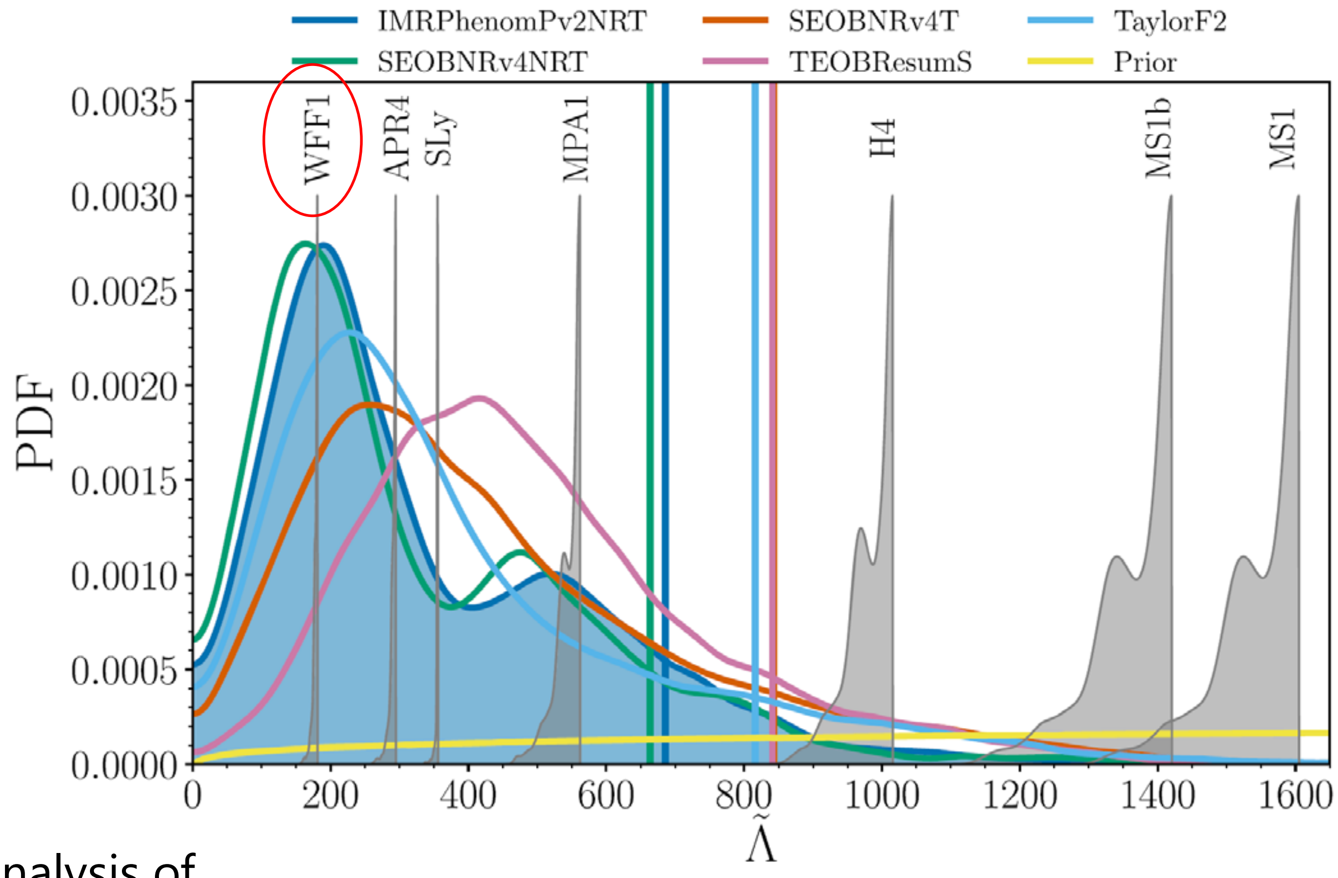
Constrained by collective nuclear excitations

- Point coupling EDFs constrained by CREX and PREX data result in rather different values of the symmetry energy (J) and its slope parameter (L)
- Discrepancy with the DD-PCX interaction (the same EDF formalism) constrained by nuclear ground state and collective excitation properties

C. Drischler, R. J. Furnstahl, J. A. Melendez, and D. R. Phillips PRL, 125, 202702, 2020.
https://github.com/buqeye/nuclear-matter-convergence/tree/master/analysis/Esym-L

Courtesy of N. Paar

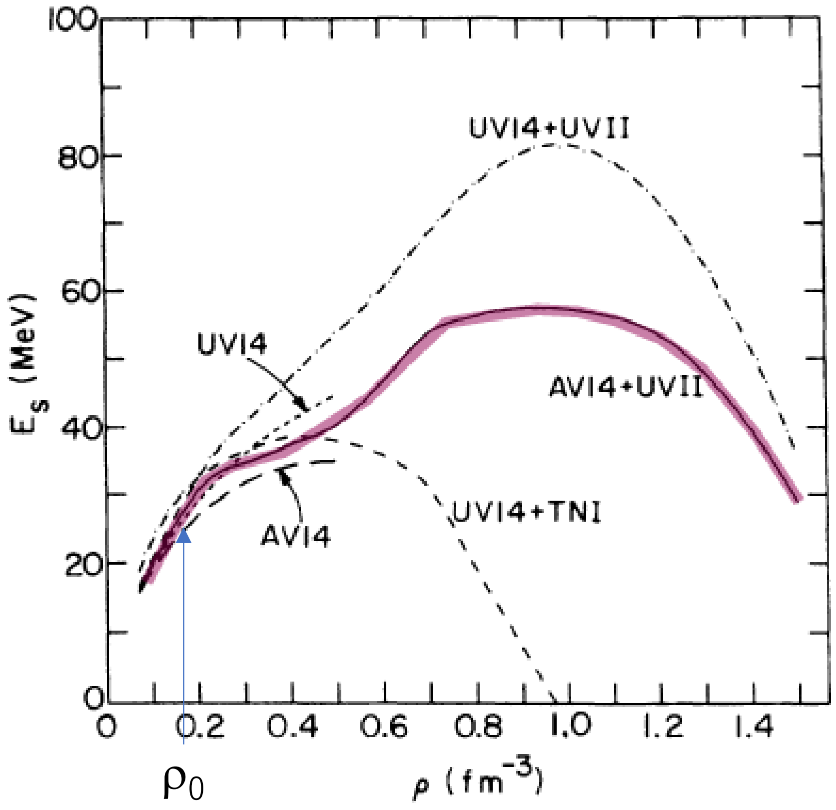
High dense neutron matter EoS is essential in terms of NS physics



Analysis of GW170817 data

PHYSICAL REVIEW X 9, 031040 (2019)

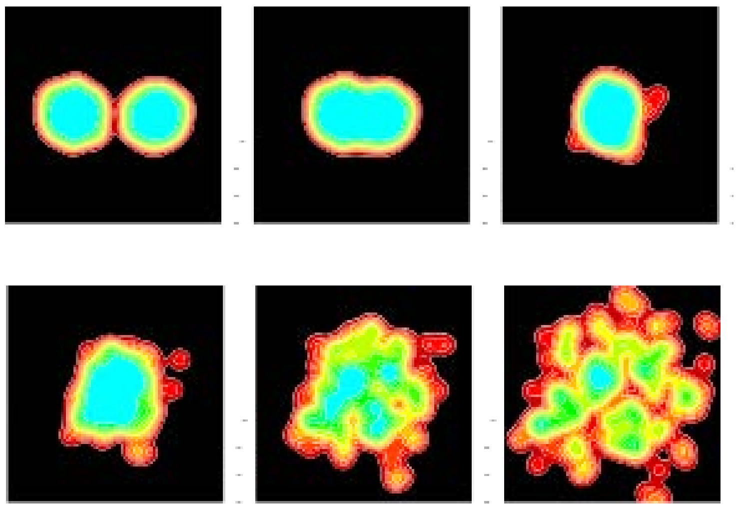
Wiringa, Fiks, & Fabrocini 1988



- Determination of L (gradient @$\rho=\rho_0$) and S_0 (constant @$\rho=\rho_0$) is not essential to see high dense neutron matter EoS.

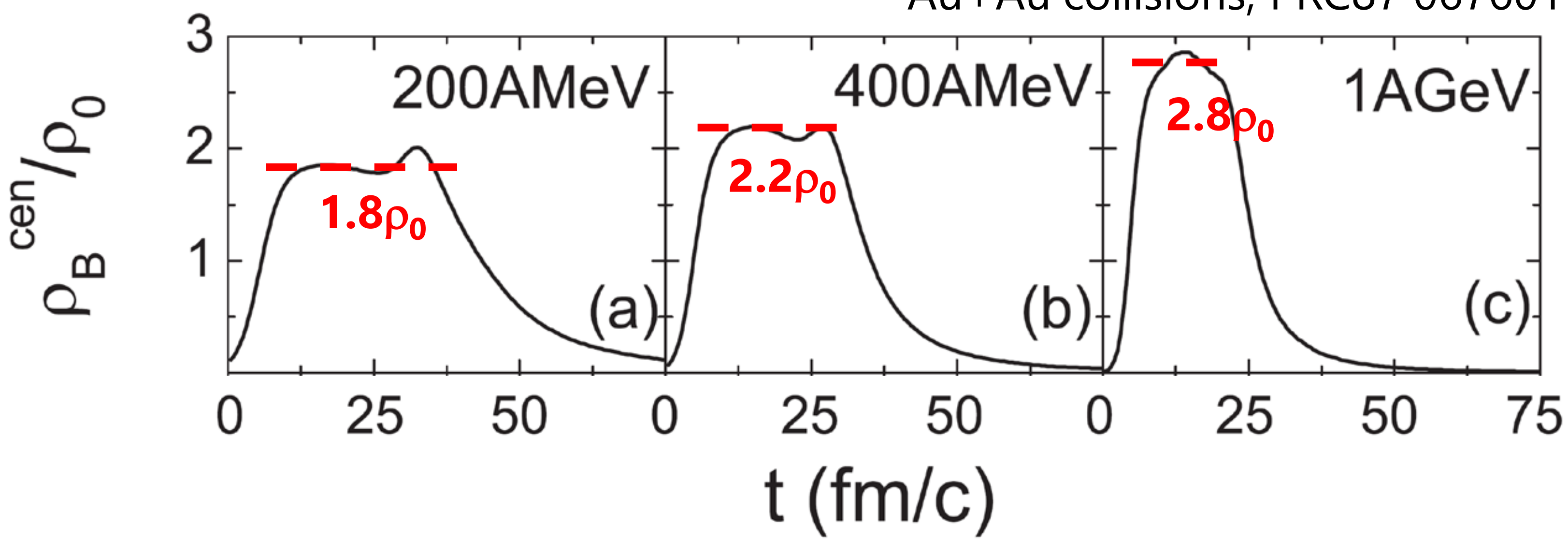
Terrestrial experimental study of high dense matter nuclear symmetry energy → Heavy Ion Collision (HIC)

Sn+Sn @300MeV/u



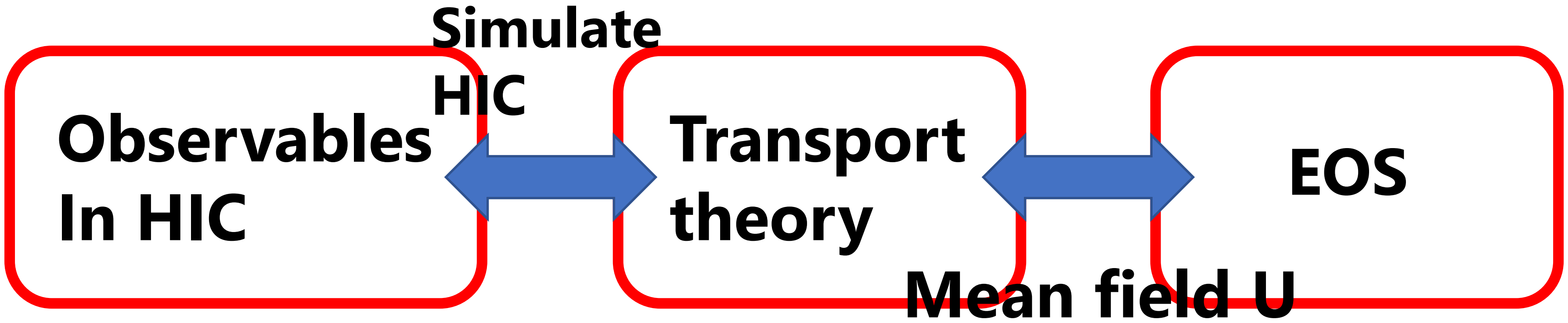
Central density as a function of time.

Au+Au collisions, PRC87 067601



- Unique way to realize high dense matter in laboratory.
  - Elab: 100~1000 MeV is optimum. Higher than coulomb barrier. Low enough to see nuclear matter.
- Quite challenging to extract the information of high dense matter symmetry energy since we need the help of <u>transport model</u>.
  - Mixture of equilibrium and non-equilibrium state.

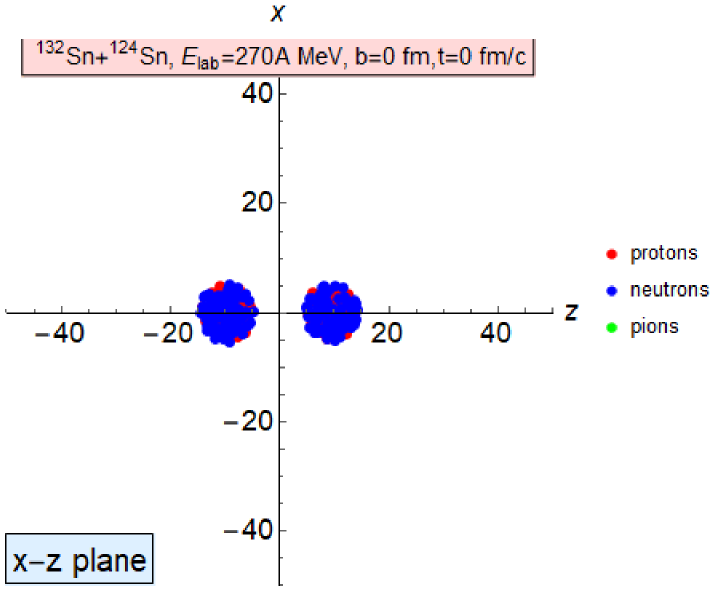
We need to rely on transport theory to reproduce heavy ion collisions



- Theoretical tool to describe HIC dynamics: transport theory:
  - QMD: Quantum Molecular Dynamics
  - BUU: Boltzmann-Uehling-Uhlenbeck eq. (Bertsch Phys. Rep. 160, 189 (1988).).
- Each nucleon is represented by ~1000 test particles that propagate classically under the influence of the self-consistent mean field U and subject to collisions due to the residual interaction.
- They can describe nucleon flows, the nucleation of weakly bound light particles and the production of nucleon resonances.

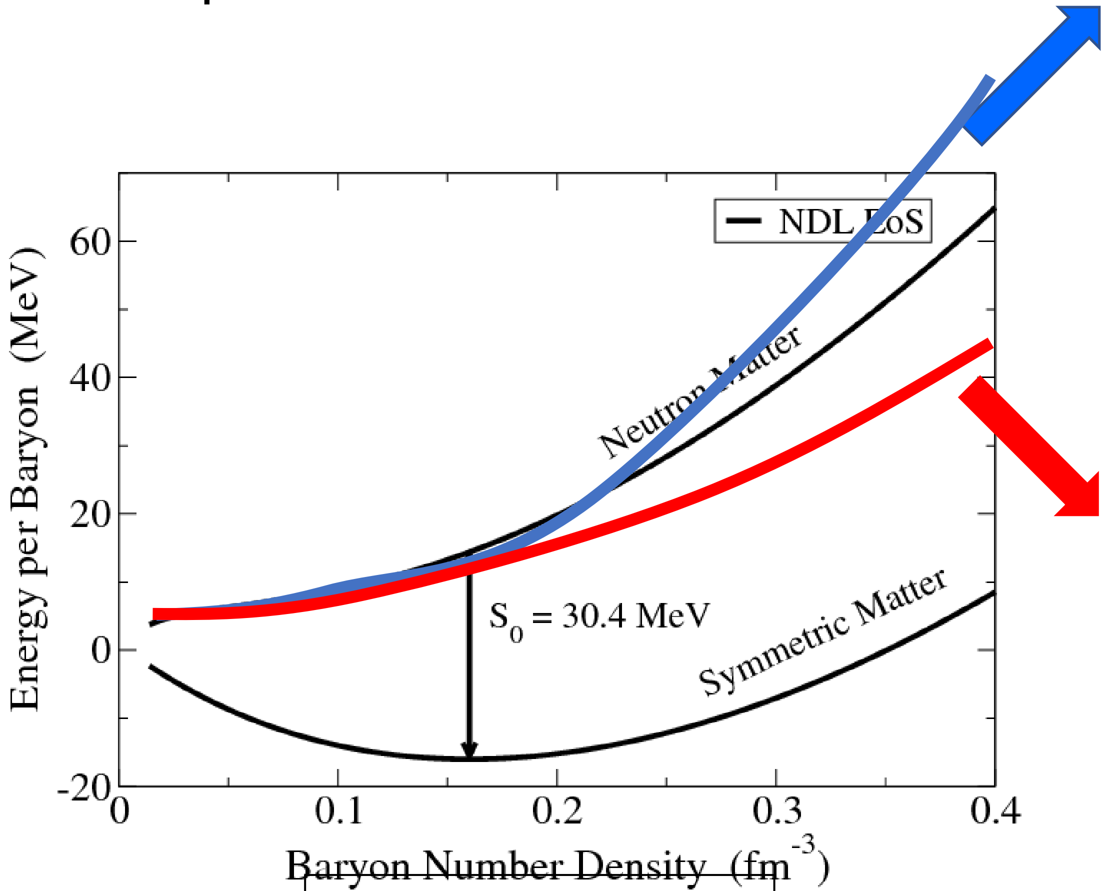
→What we can observe experimentally

- Need to account for nuclear effect
  - momentum dependence of U, σ_{NN} in matter



Charged pion as one of the experimental observables from heavy ion collision to constrain the symmetry energy

- No direct observables, but contains the information of symmetry energy
- Symmetry energy → appeared as pressure difference between neutron and proton



$\rho_0 = 2.5 \times 10^{14}$ g/cm^3

Stiff symmetry energy (large L)
→ lower ρ_n/ρ_p in higher dense region
→ lower n/p in high ρ

Soft symmetry energy (small L)
→ larger ρ_n/ρ_p in higher dense region
→ larger n/p in high ρ

Charged pion as one of the experimental observables from heavy ion collision to constrain the symmetry energy

- No direct observables, but contains the information of symmetry energy
- Symmetry energy → appeared as pressure difference between neutron and proton

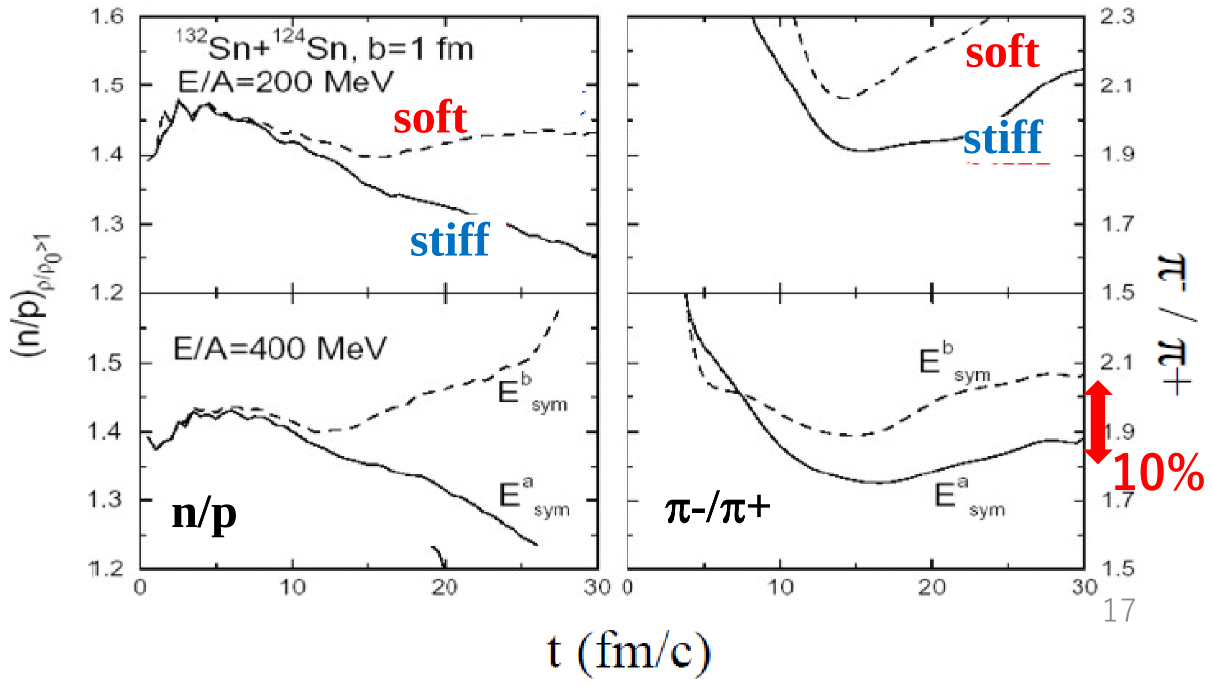
π^- production (main reaction)

$$nn \to p\Delta^-$$
$$\Delta^- \to n\pi^-$$

π^+ production (main)

$$pp \to n\Delta^{++}$$
$$\Delta^{++} \to p\pi^+$$

Li et al., Nucl.Phys. A734 (2004) 593.



Stiff symmetry energy (large L)

→ lower ρ_n/ρ_p in higher dense region

→ lower n/p, lower π-/π+

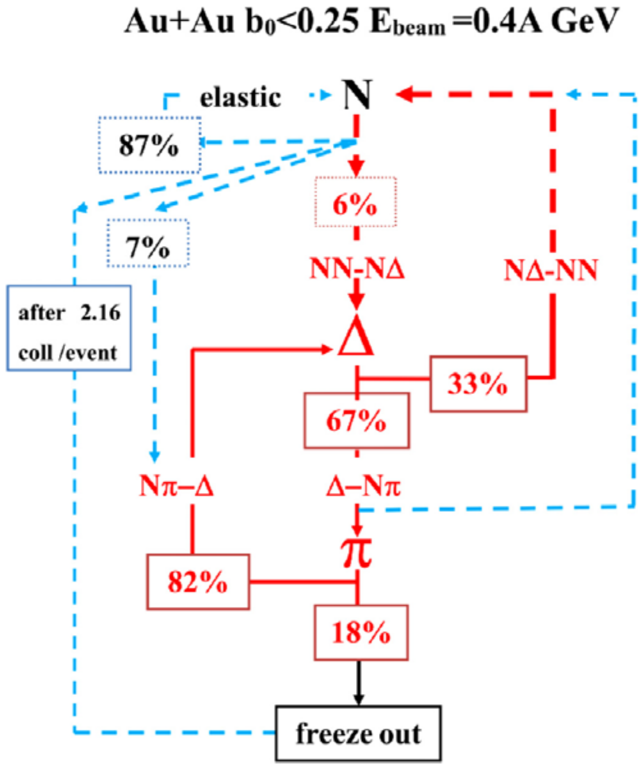
Soft symmetry energy (small L)

→ larger ρ_n/ρ_p in higher dense region

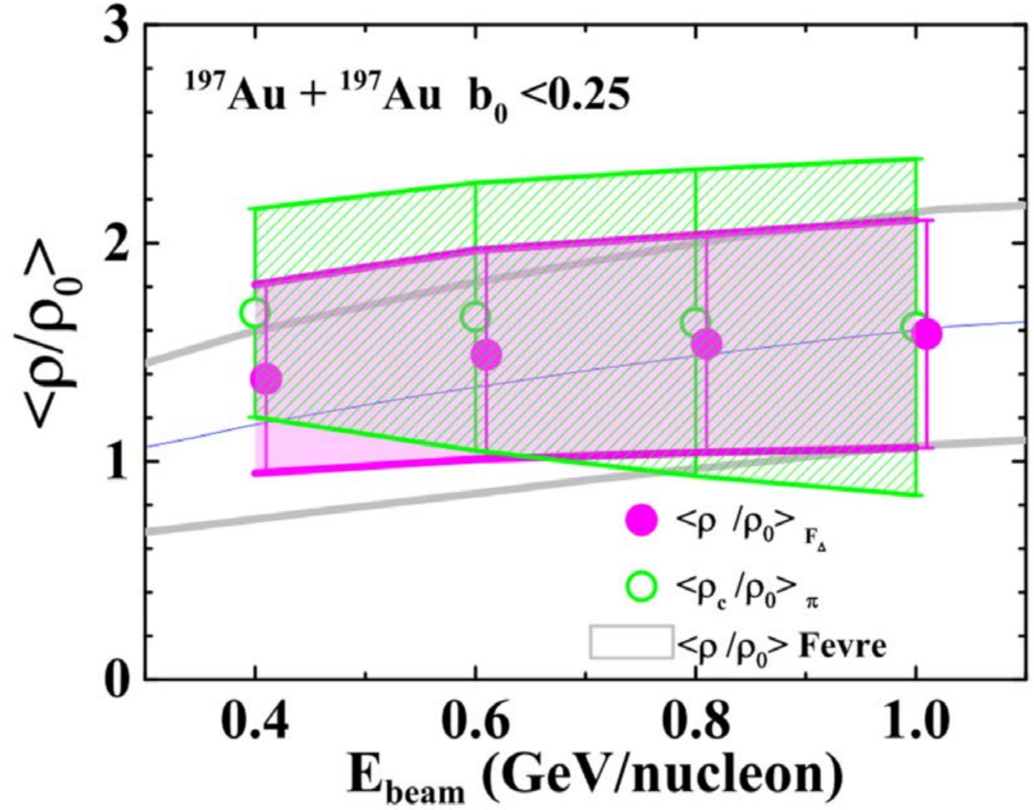
→ larger n/p, higher π-/π+

pion probes the symmetry energy at $\rho \sim 1.5\rho_0$

- Pions are expected to be produced through Δ baryon productions
  - $nn \rightarrow p\Delta^-, \Delta^- \rightarrow n\pi^-$
  - $pp \rightarrow n\Delta^{++}, \Delta^{++} \rightarrow p\pi^+$



Sensitive density region of each probe in HIC



Phys. Rev. C 103, 014616 (2021).

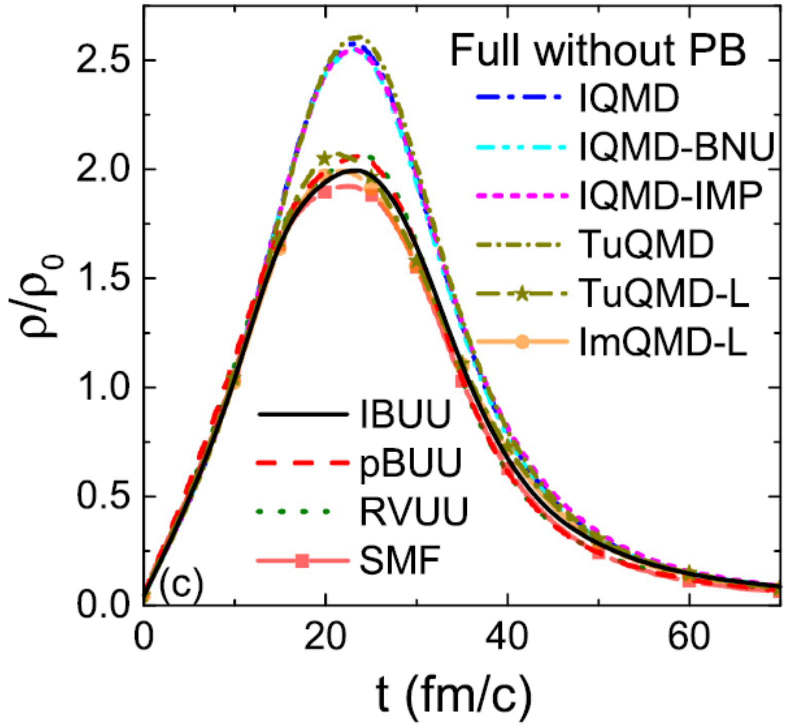
Heavy RI Collision program to study EoS @RIBF

- Effect of symmetry energy on each observables is expected to be largest around this energy region. (especially pion emission)
- 1st experimental campaign using Sn (Z=50) isotopes in 2016 spring.

Primary	Beam	Target	E_{beam}/A	$(N\text{-}Z/A)_{sys}$
^{238}U	^{132}Sn	^{124}Sn	270	0.22
	^{124}Sn	^{112}Sn	270	0.15
^{124}Xe	^{108}Sn	^{112}Sn	270	0.09
	^{112}Sn	^{124}Sn	270	0.15

- 2nd campaign using primary Xe beam in 2024

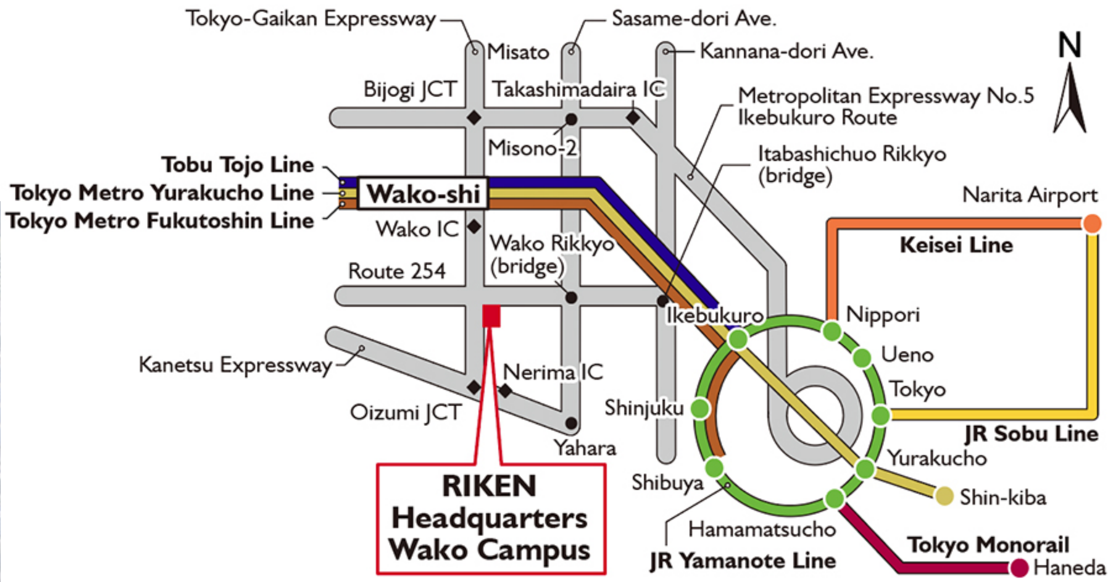
Primary	Beam	Target	E_{beam}/A	$(N\text{-}Z/A)_{sys}$
^{136}Xe	^{136}Xe	^{124}Sn	320	0.20
^{124}Xe	^{124}Xe	^{112}Sn	320	0.11



$^{132}Sn+^{124}Sn$ E/A=270MeV
Central (r=0) density
PRC109 (2024) 044609

RI=Radioactive Isotope B=Beam F=Factory

Mass production of radioactive isotopes as secondary beams

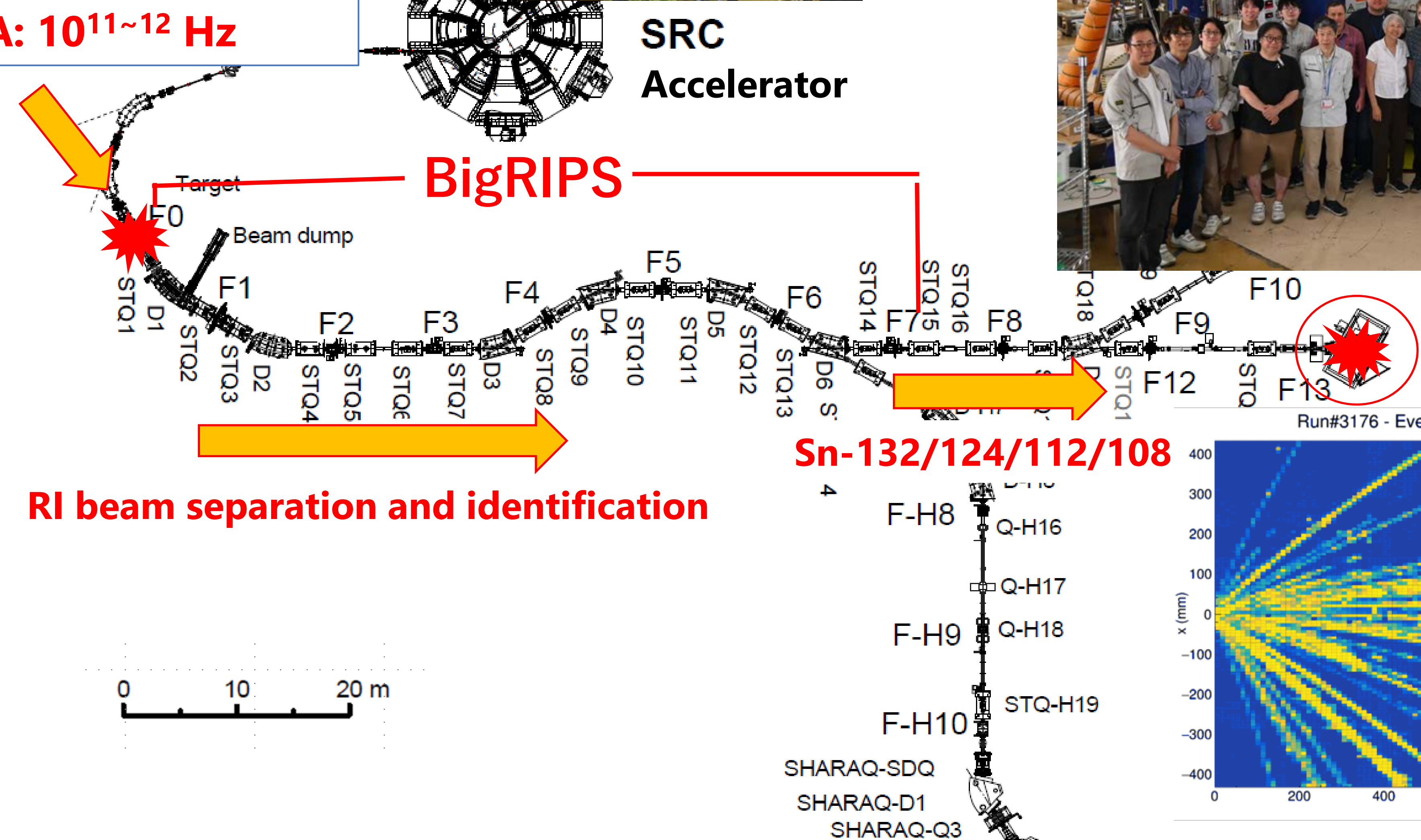


RIKEN-RIBF: RI production at world leading RI facility

U-238 345 MeV/u beam
Z=92, N=146
100pnA: $10^{11\sim12}$ Hz

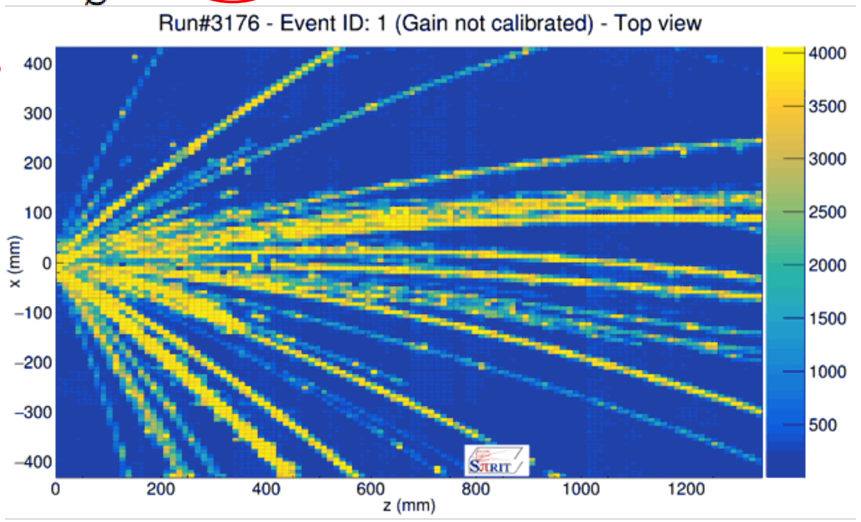
SRC
Accelerator

BigRIPS

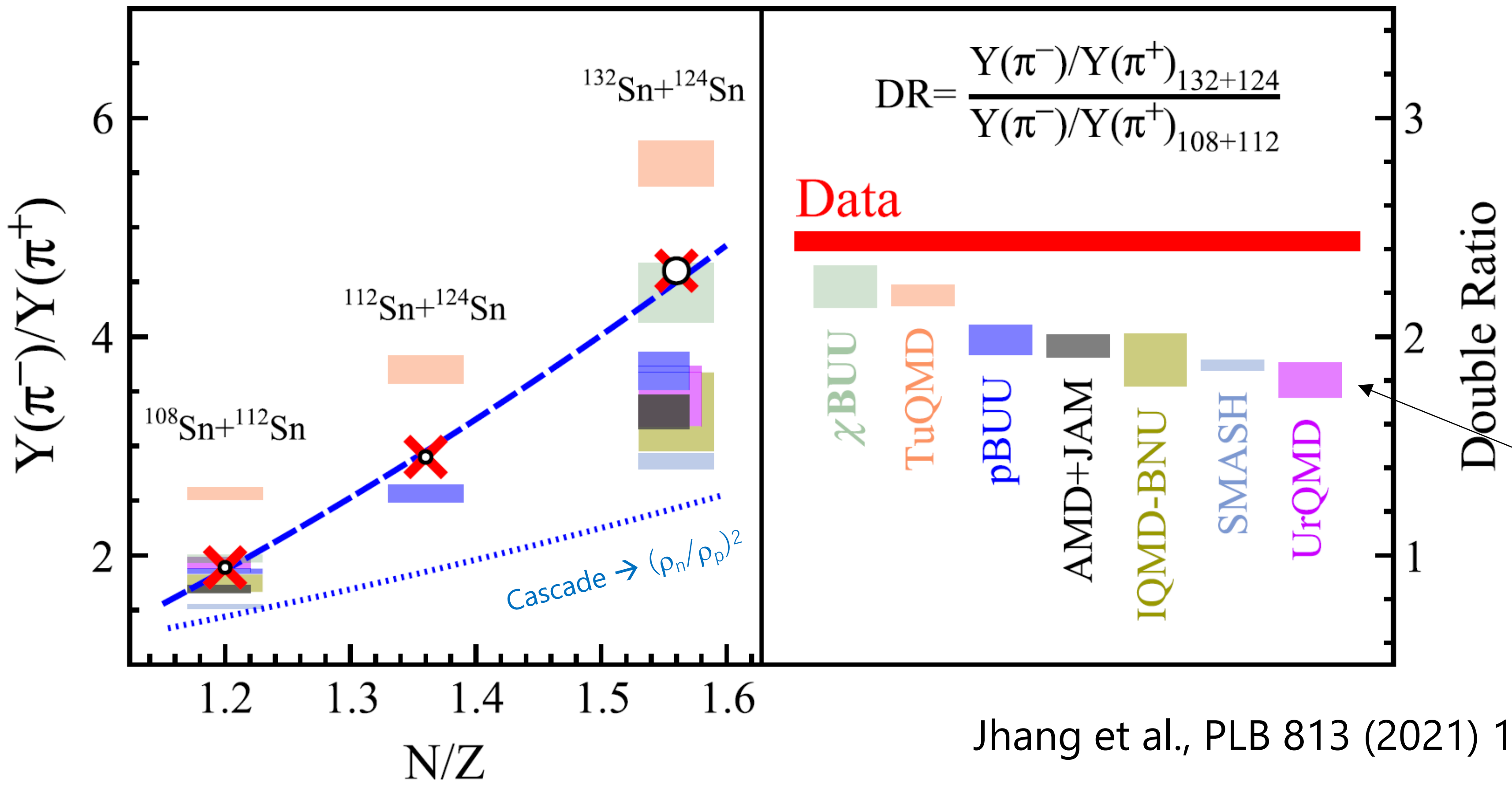


Sn-132/124/112/108

RI beam separation and identification



Result on pion multiplicity: pion ratio
→Large discrepancy among theoretical models

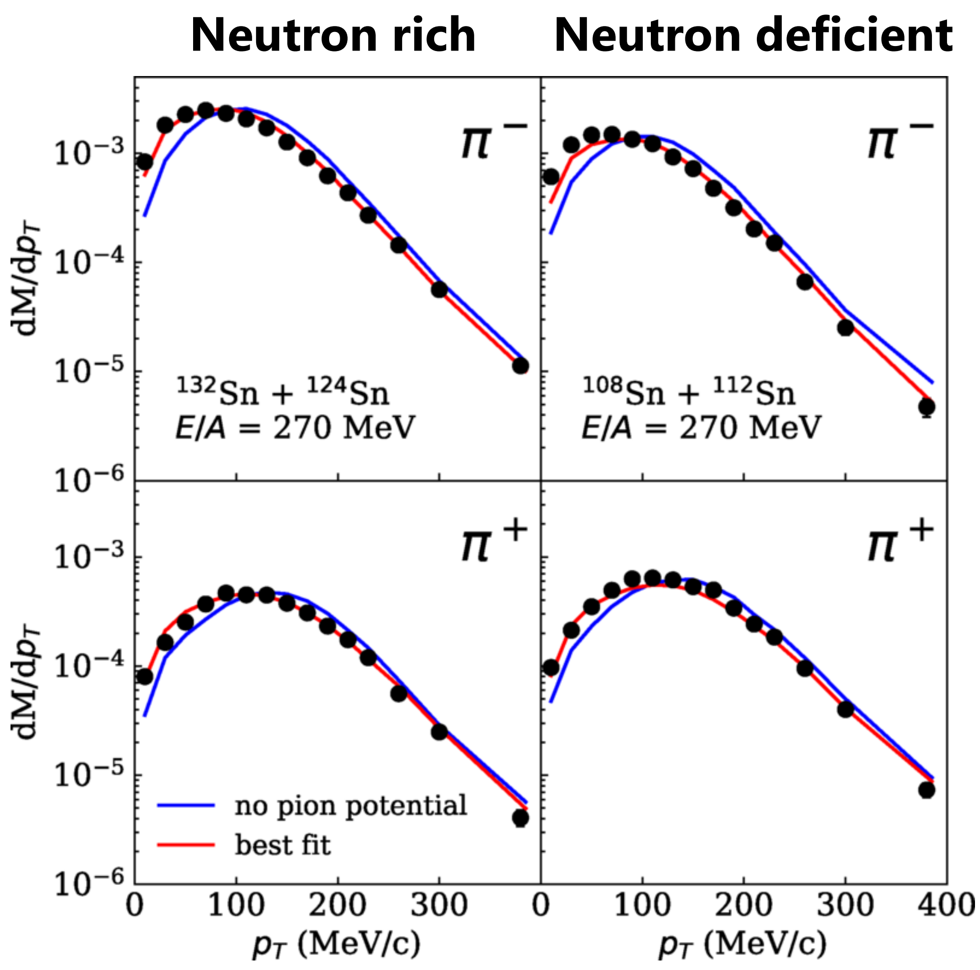


Size of error bar corresponds to the difference between Soft and stiff EoS.

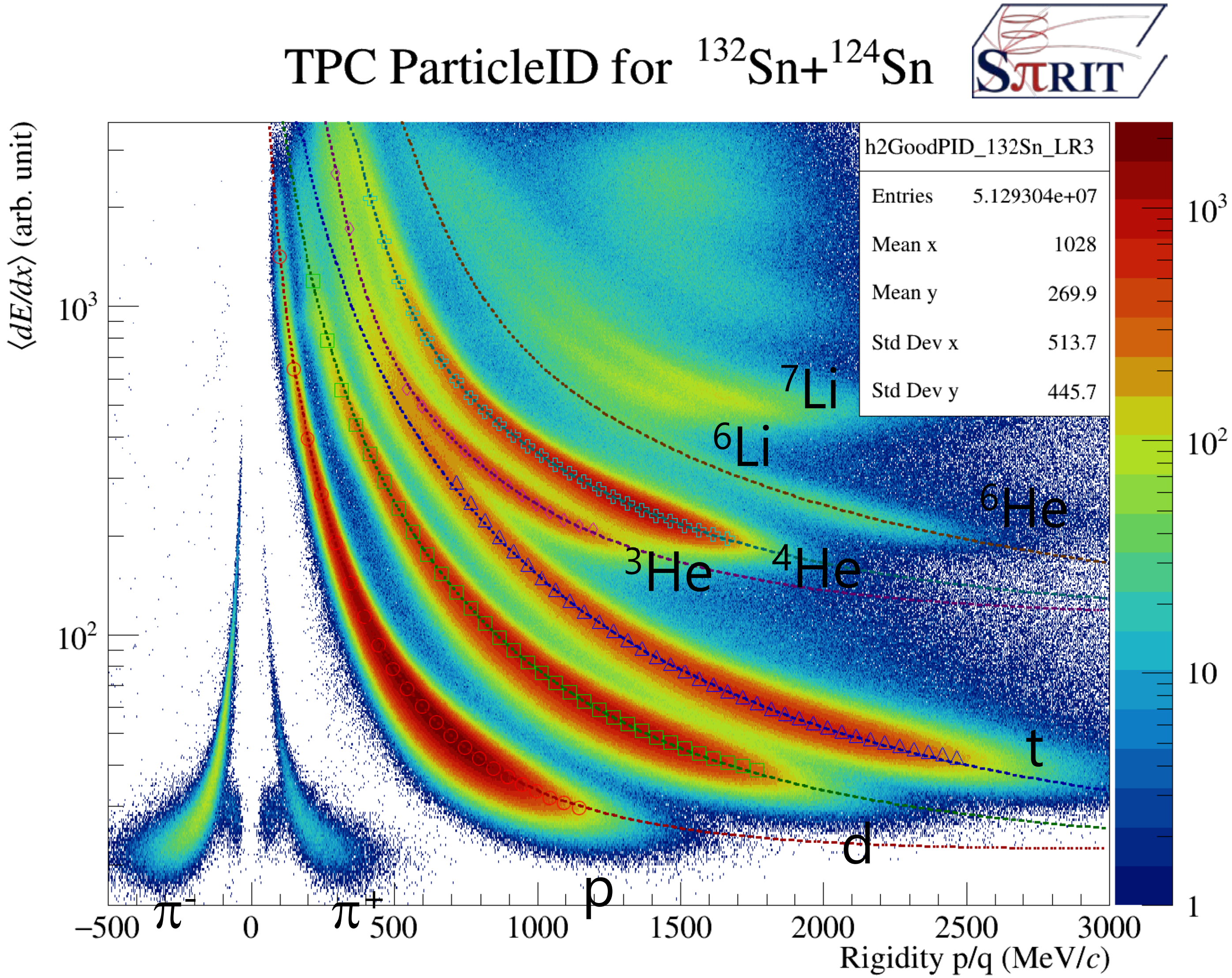
Jhang et al., PLB 813 (2021) 136016

- Numerical calculation of HIC dynamics by using transport theory.
- Predictions with same EoS are supposed to be same →Larger discrepancy than experimental result.
- Different assumptions regarding the mean field potentials for Δ baryons and pions can influence the pion multiplicities.

Charged particle measurement with Time Projection Chamber

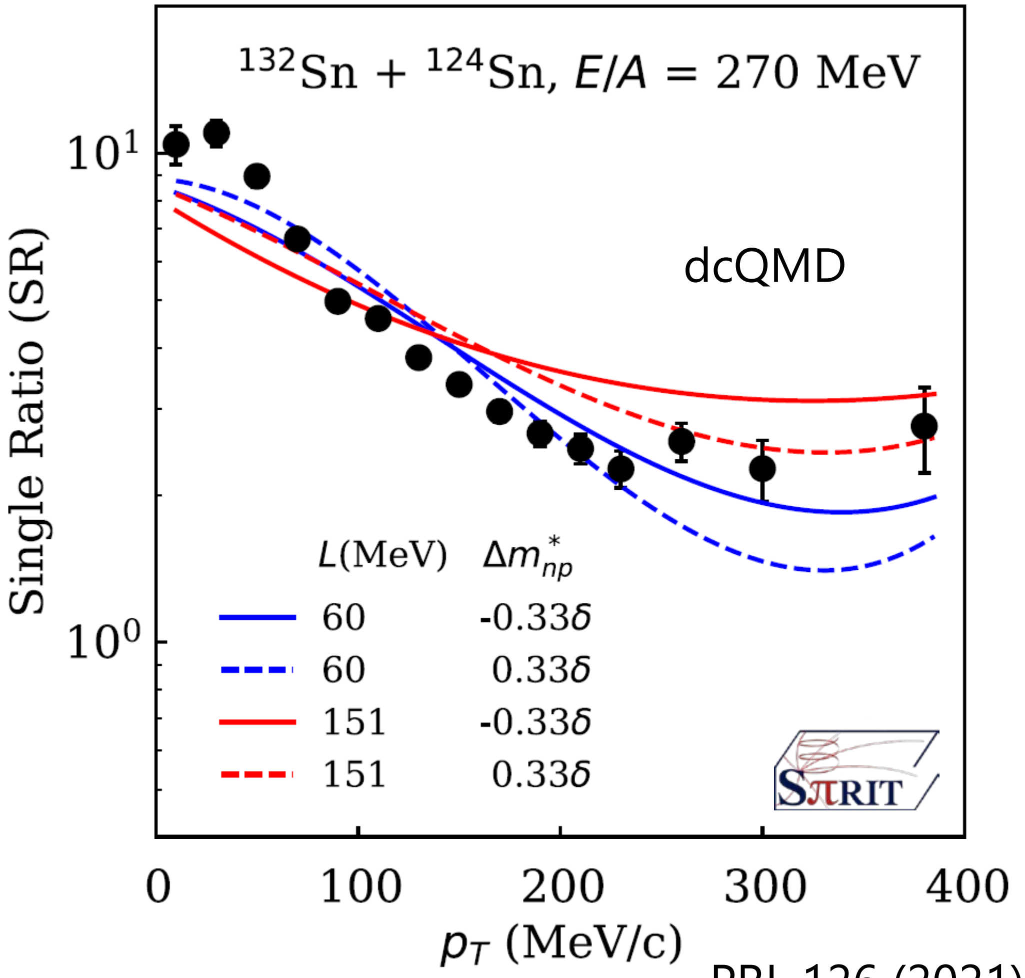


Estee et al., PRL 126 (2021) 162701

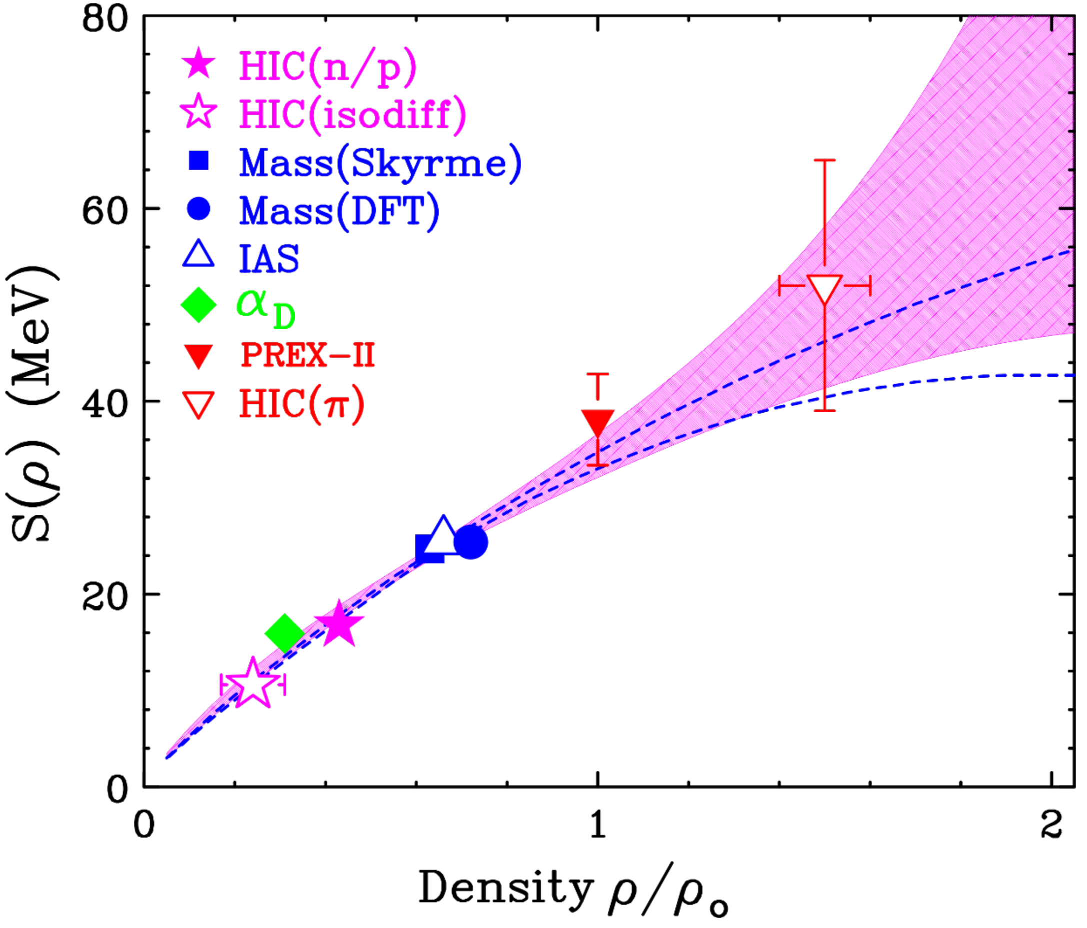


Constraint on $S(\rho\sim 1.5\rho_0)$ based on charged pion spectrum ratio: 42<L<117

- First point above the nuclear saturation density : discussion only with L/S → discussion with density dependence of symmetry energy

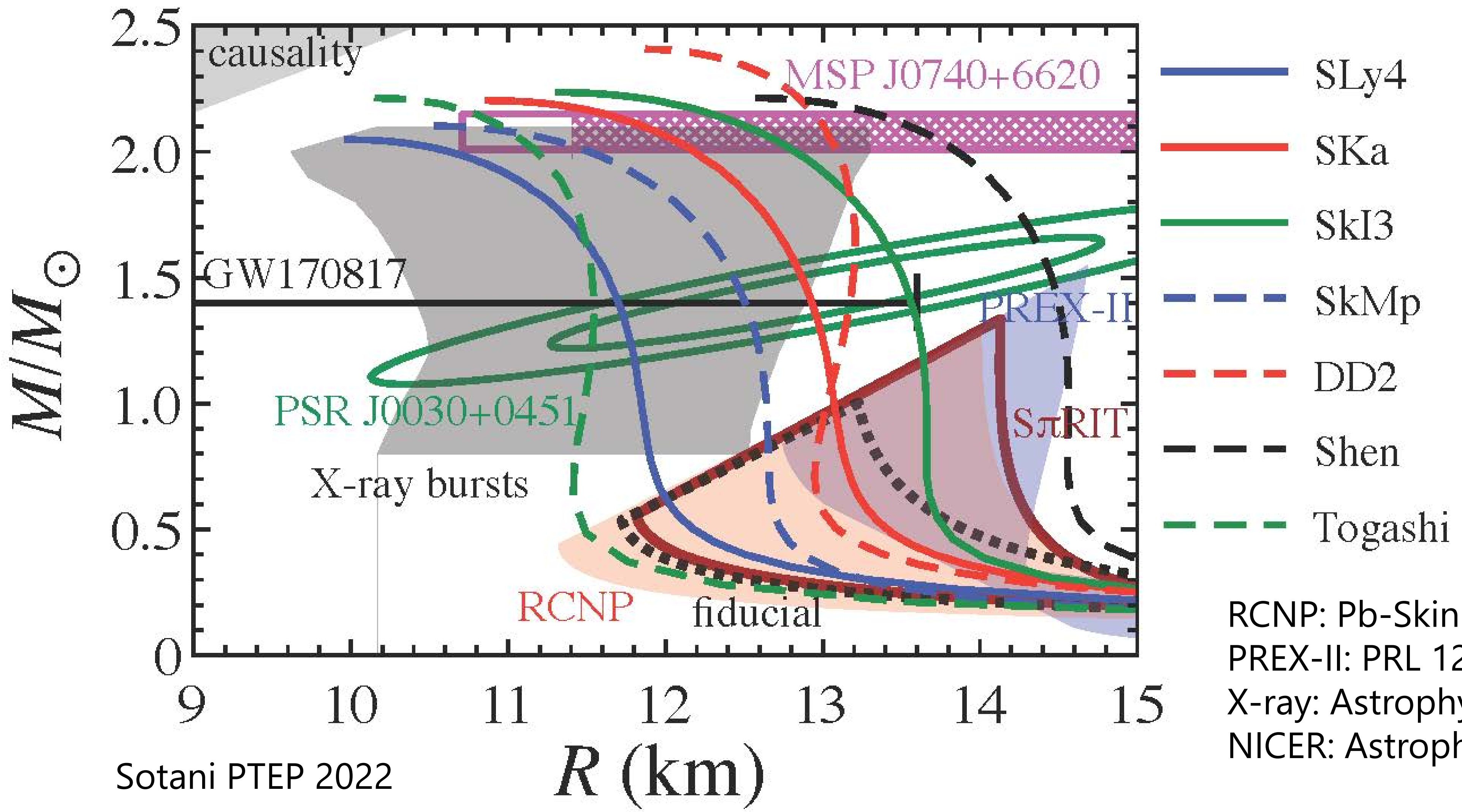


PRL 126 (2021) 162701



PLB 830, 137098 (2022)

Constrain given by HIC shows consistency with other constrains by neutron star observation: 10fm to 10km (10^{18}!)



Sotani PTEP 2022

RCNP: Pb-Skin PRC 82 (2010) 044611
PREX-II: PRL 126 (2021) 172502
X-ray: Astrophys. J. Lett. 765 (2013) L5
NICER: Astrophys. J. Lett. 887 (2019) L24

Summary

- Density dependence of symmetry energy (neutron matter EoS) is now being discussed based on the result given by terrestrial experiments.
- Nuclear structure → $\rho < \rho_0$
  - Neutron skin thickness, collective nuclear excitation
- Heavy ion collisions → $\rho > \rho_0$
  - pions
- Each results including the constrains by NSM-GW and NICER data are consistent within the error.

- Is it possible to investigate the neutron star internal structure through the analysis of GW from binary NSM?