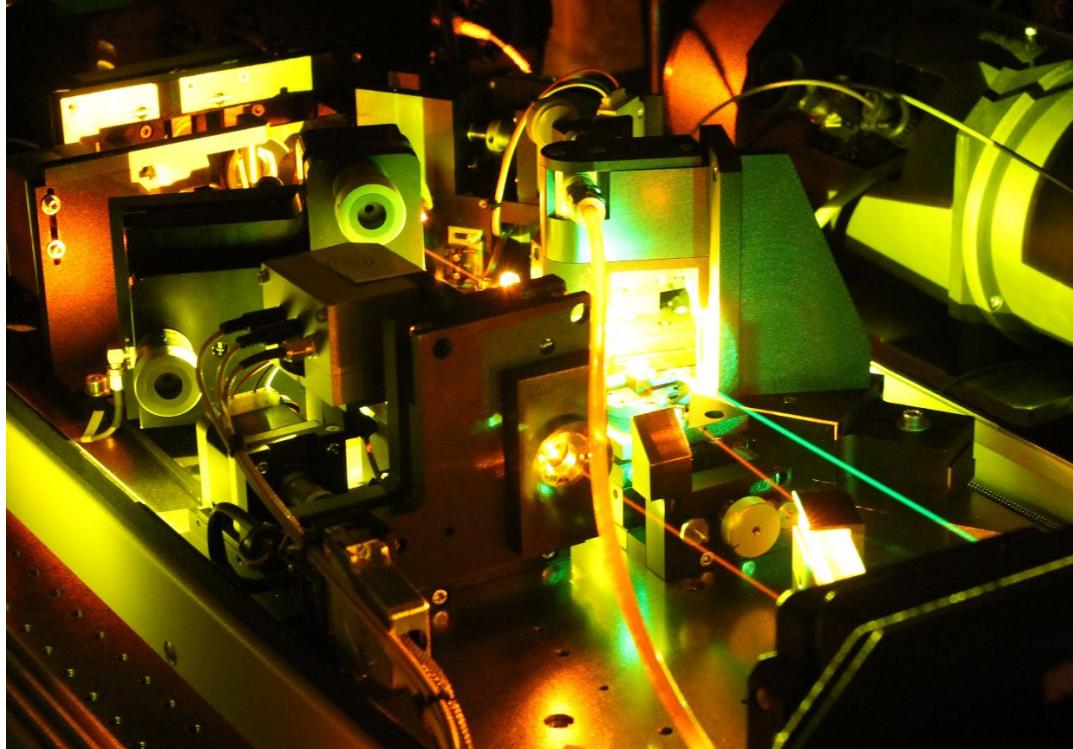


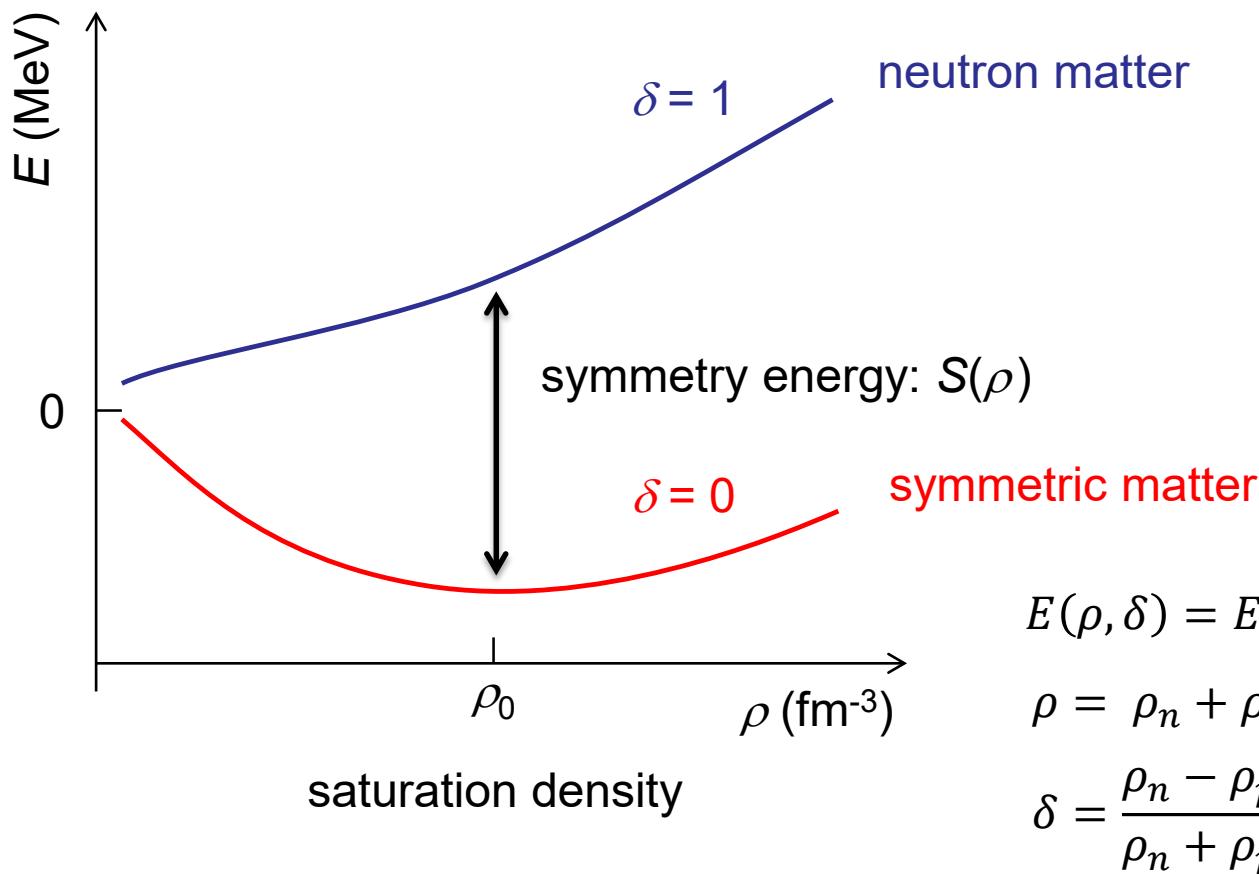
Neutron Equation of State and Difference of Charge Radii between ^{54}Ni and ^{54}Fe Mirror Nuclei



Kei Minamisono

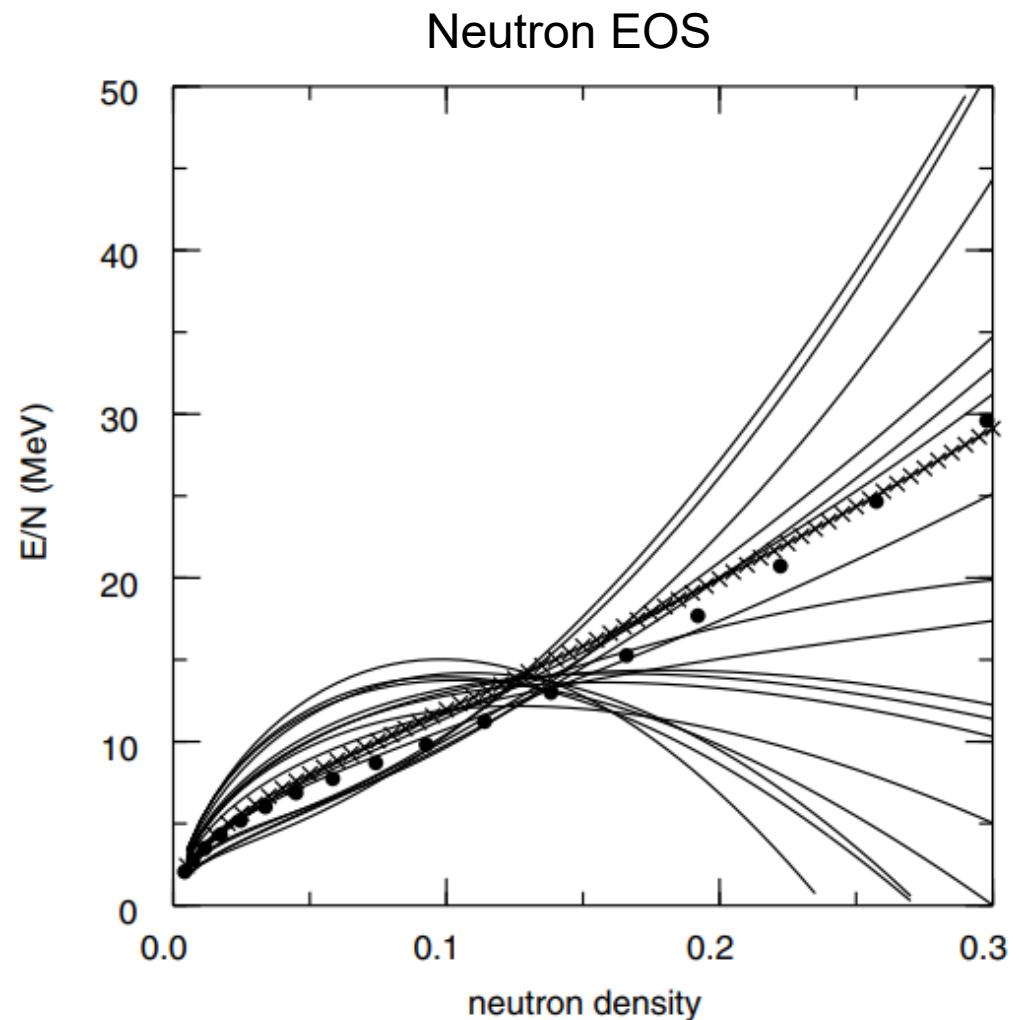
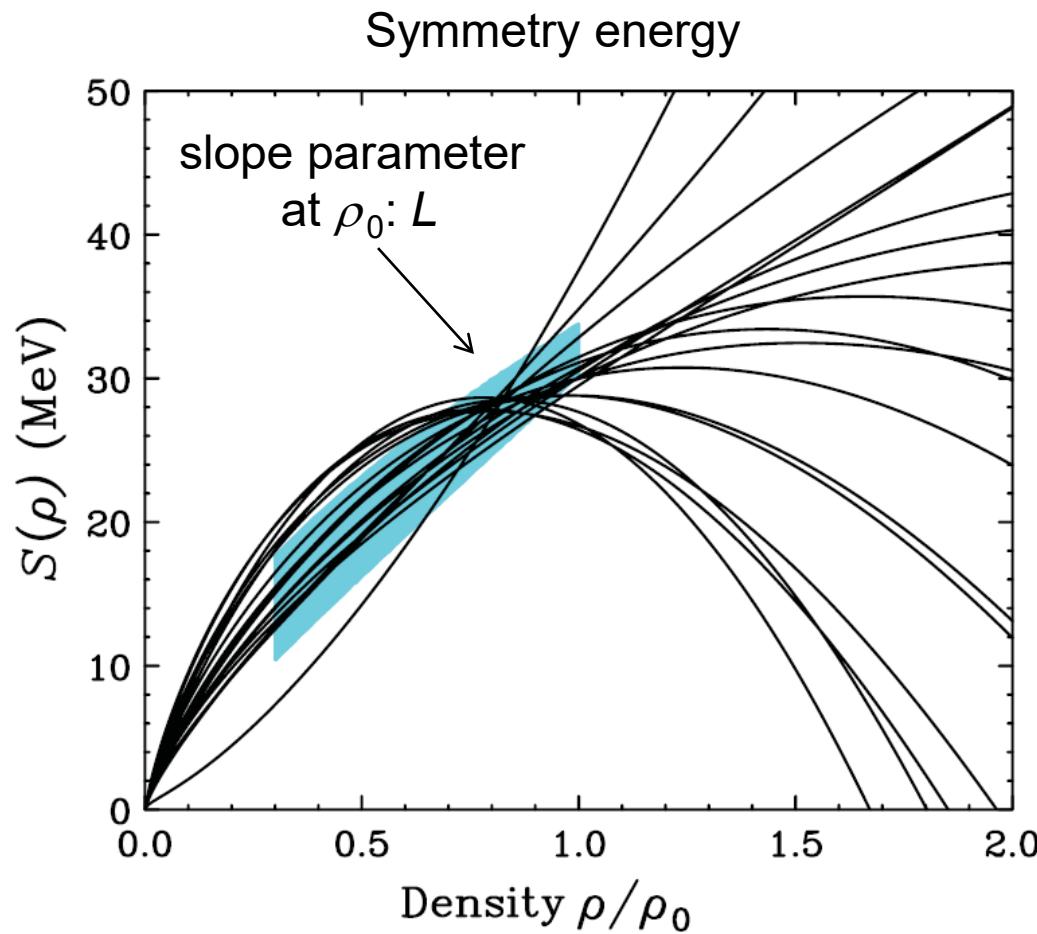
Nuclear Equation of State and Its Implications on Astrophysics

CONCEPTUAL MODEL



- Structure of halo/skin structure, heavy/super heavy elements
- Gravitational collapse supernovae within a galaxy
- Radii of neutron star
- Gravitational signal of merging binary neutron stars
- Crust's thickness and thermal relaxation time
- Observable in cooling and accreting neutron stars
- ...

Neutron Equation of State and Slope Parameter L

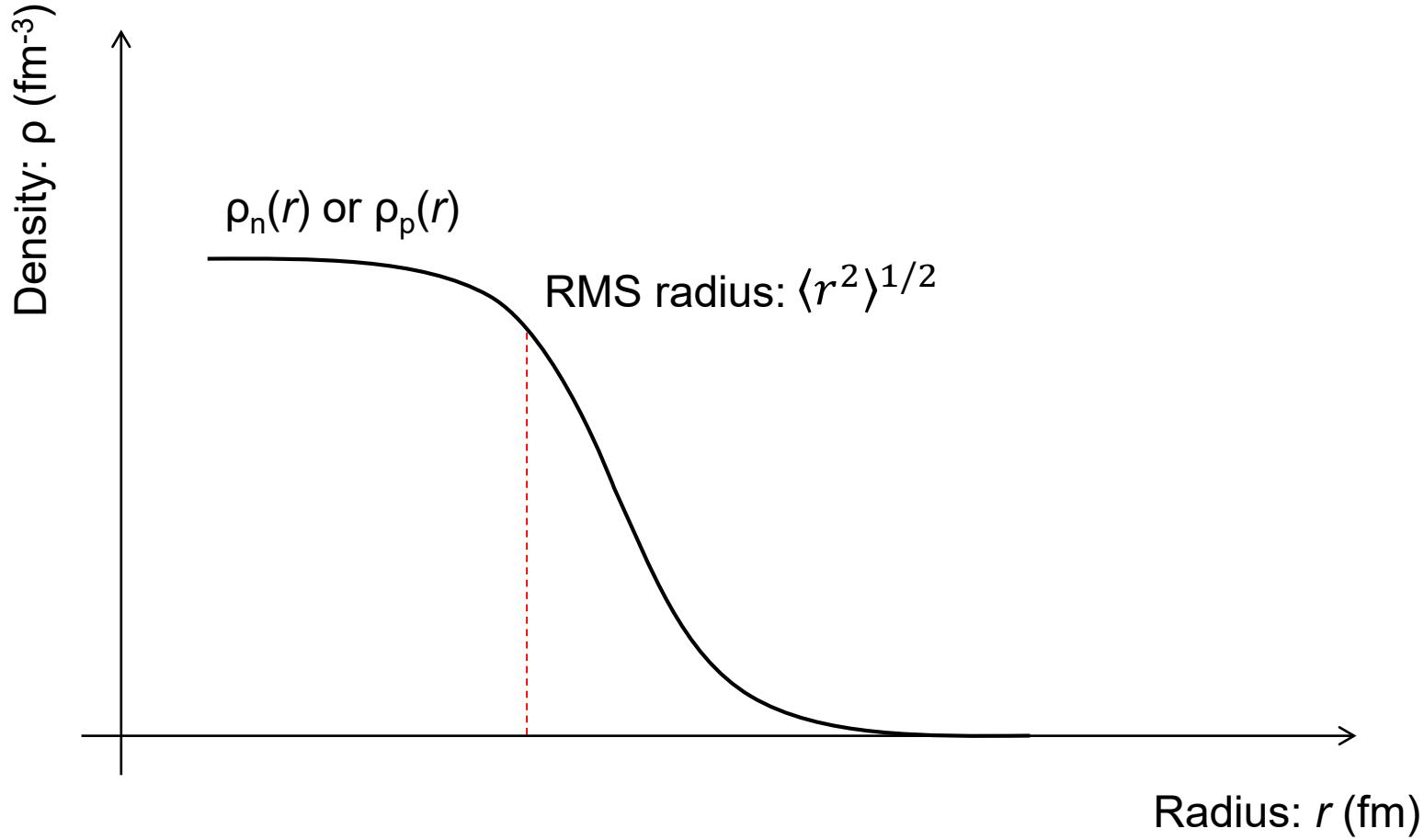


How to Determine L ?

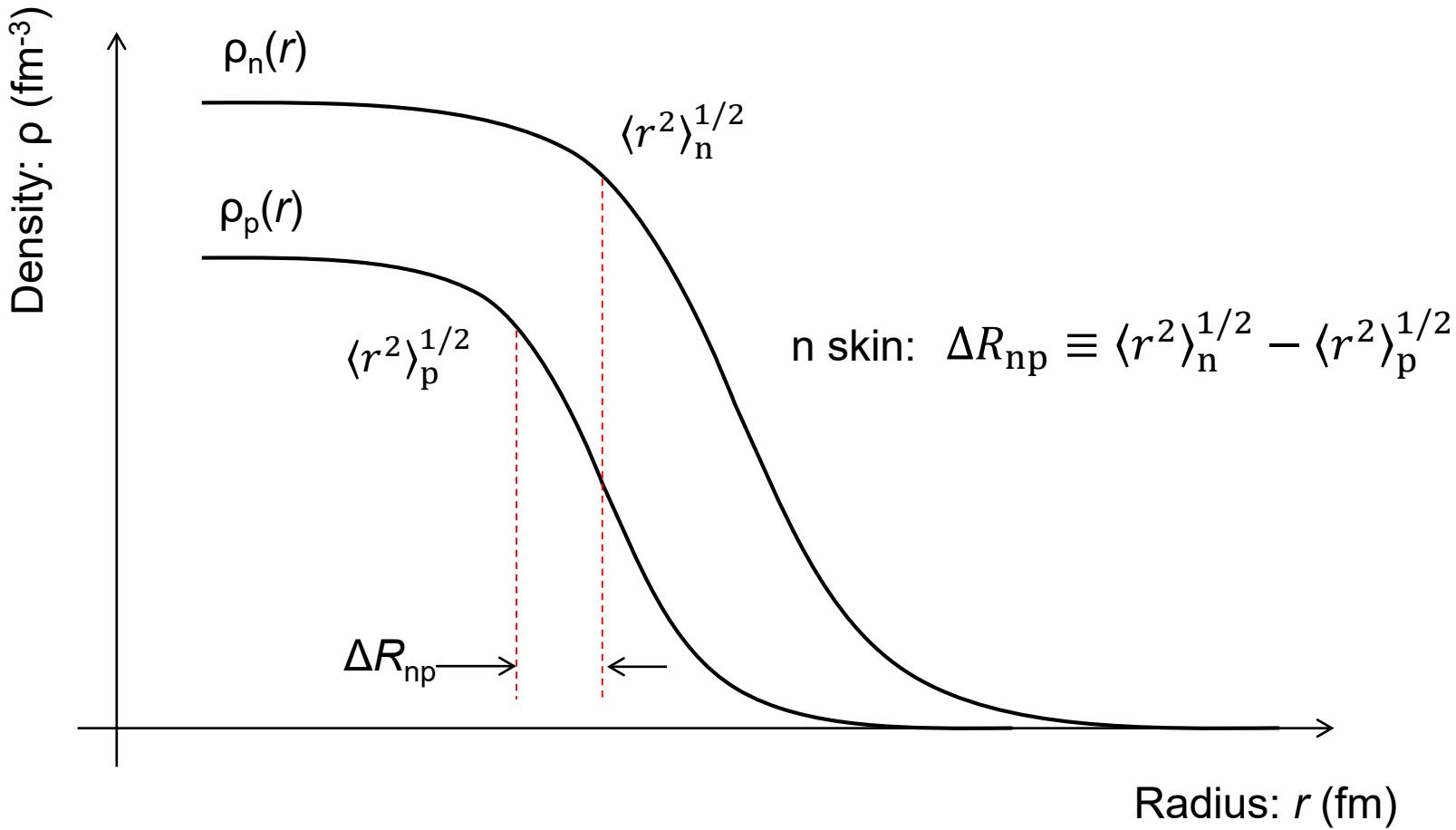
- Heavy ion collisions
 - B. -A. Li et al., PR 464, 113 (2008).
- Nuclear Mass (binding energy)
 - P. Möller et al., PRL 108, 052501 (2012).
- Isobaric analogue state
 - Danielewicz and J. Lee, NPA 818, 36 (2009).
- Gravity: gravitational wave: neutron star merger (tidal polarizability)
 - C. A. Raithel and F. Özel, Astrophys. J. 885, 121 (2019).
- ...
- Neutron skin
 - Weak: parity violating e scattering (PREX)
 - S. Abrahamyan et al., PRL 108, 112502 (2012).
 - Electromagnetic: electric dipole polarizability
 - A. Tamii et al., PRL. 107, 062502 (2011).
 - D. M. Rossi et al., PRL 111, 242503 (2013).
 - Strong: p-elastic scattering
 - J. Zenihiro, et al.: PRC 82, 044611 (2010).
 - ...

More or less all are model dependent.

RMS Radius of Stable Nucleus

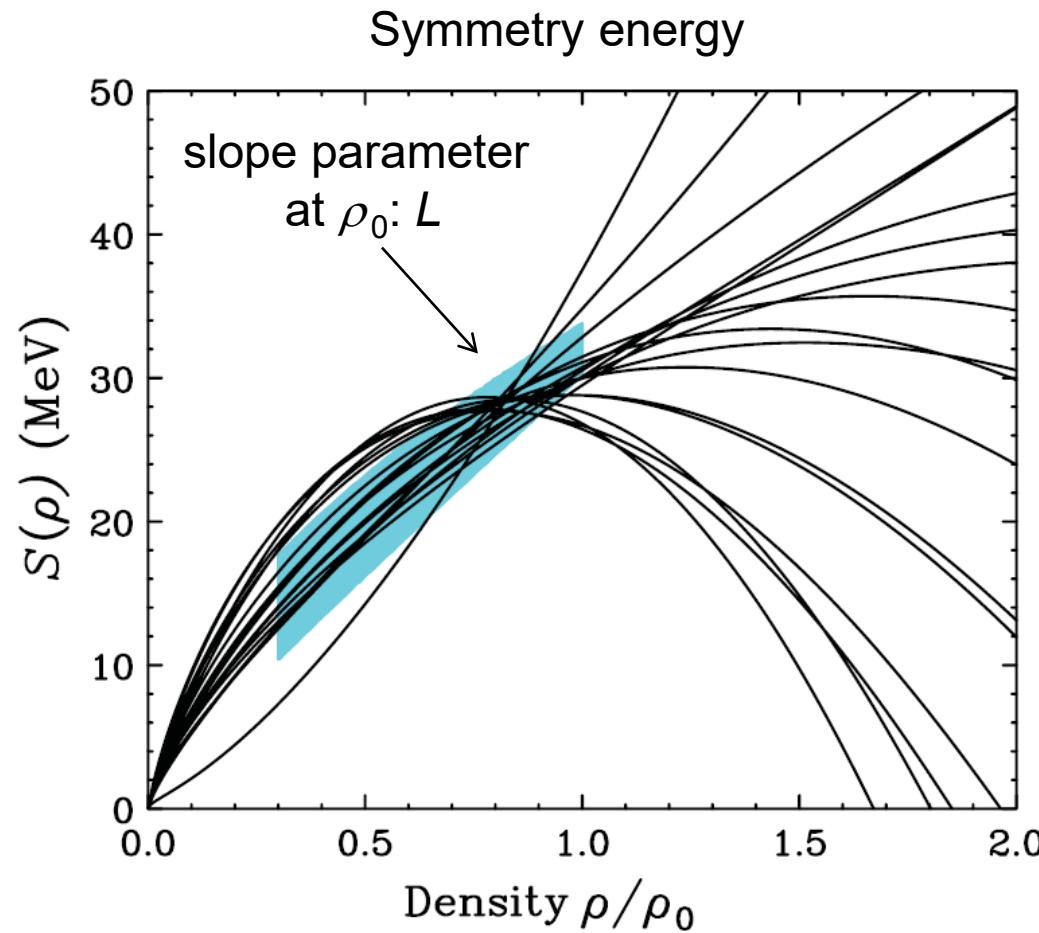


RMS radius of neutron-rich nucleus



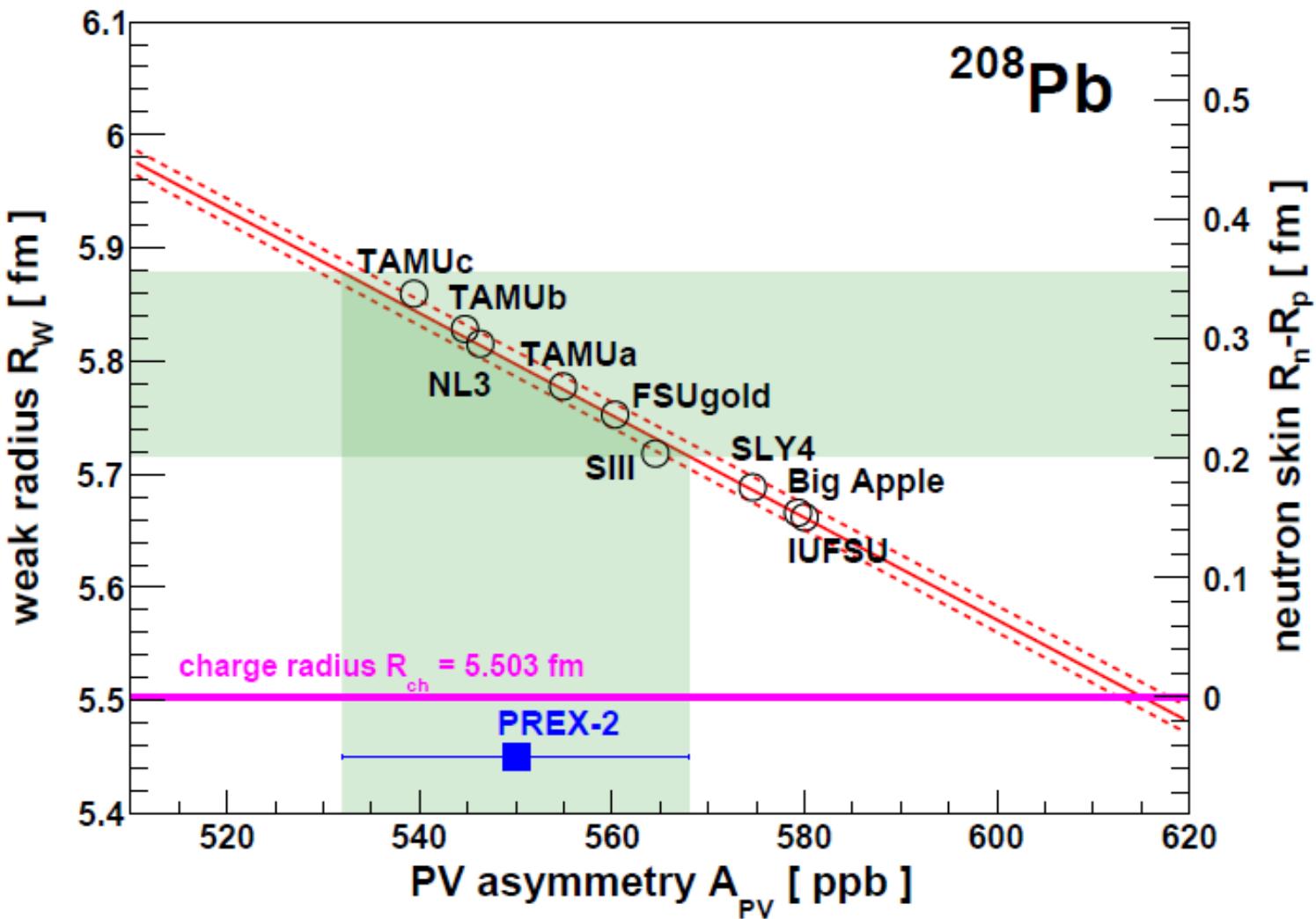
EOS drives the extent neutron can seeps out.

Neutron Equation of State and Slope Parameter L

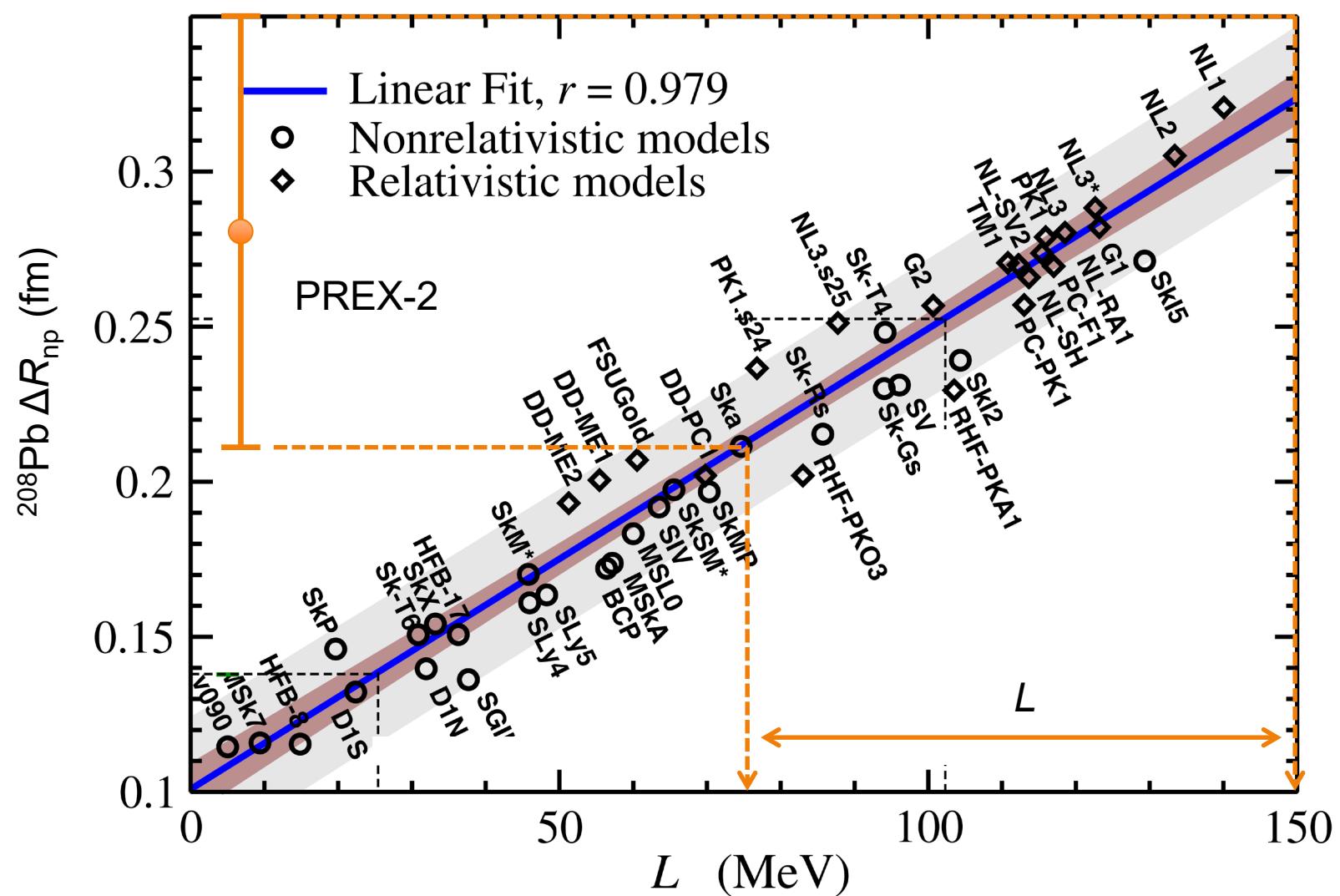


Neutrons skin/radius $\leftrightarrow L$: slope of the symmetry energy

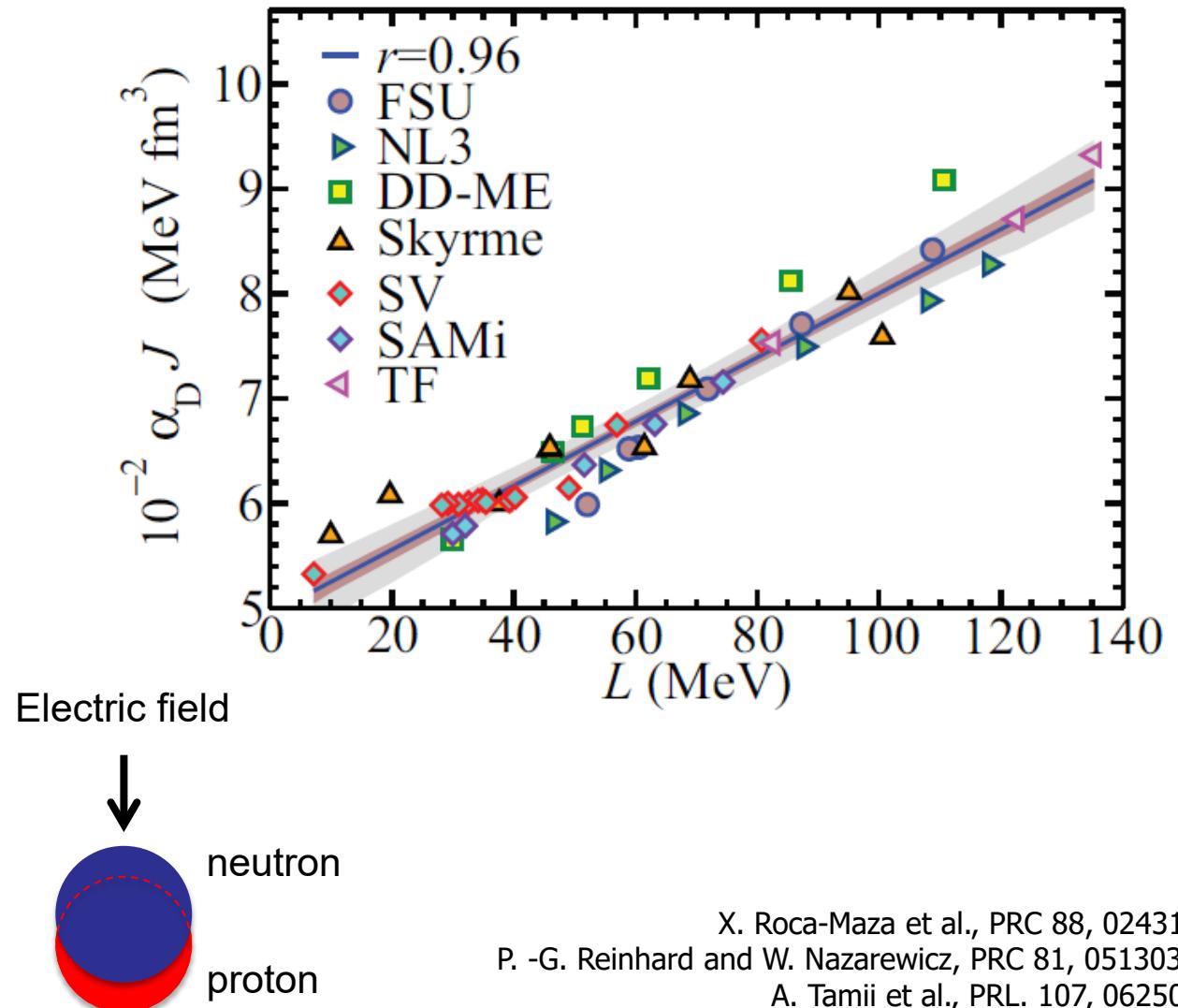
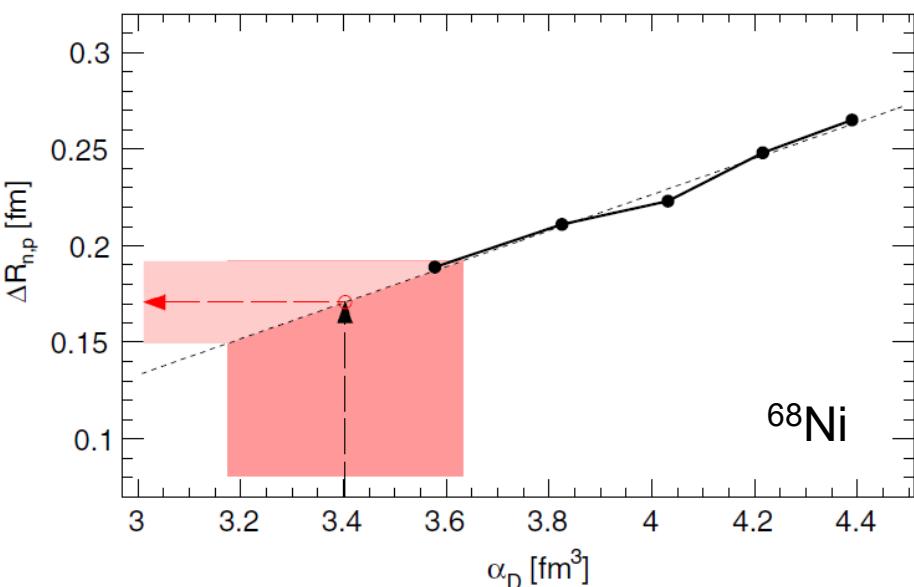
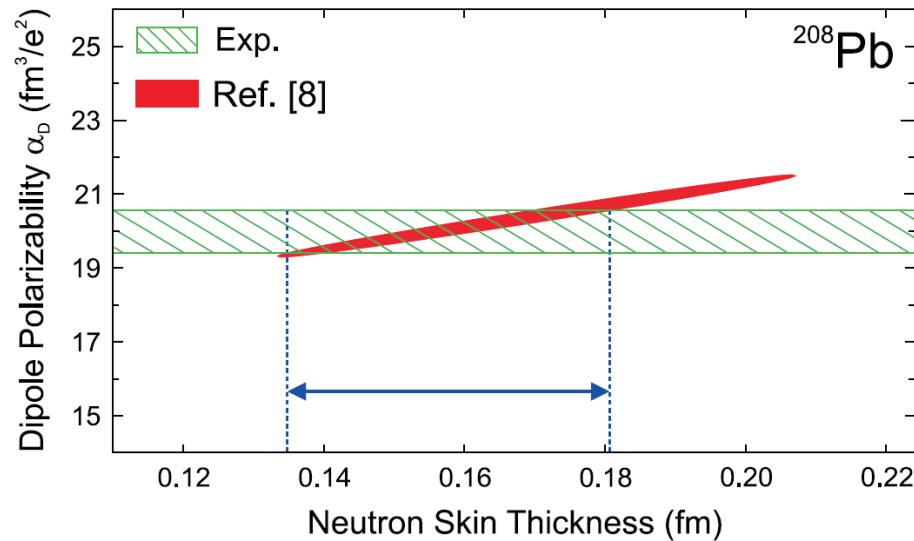
ex. PREX to Determine ΔR_{np}



Ex. PREX Correlation between ΔR_{np} vs L



ex. Electric Dipole Polarizability to Determine L



X. Roca-Maza et al., PRC 88, 024316 (2013);
P. -G. Reinhard and W. Nazarewicz, PRC 81, 051303R (2010);
A. Tamii et al., PRL 107, 062502 (2011);
D. M. Rossi et al., PRL 111, 242503 (2013).

Difference of Mirror Charge Radii

ASSUMING the charge symmetry is a perfect symmetry:

Neutrons radius of a nucleus is equal to protons radius of its mirror nucleus.

$$\Delta R_{np} \equiv R_n(^A_Z X_N) - R_{ch}(^A_Z X_N)$$

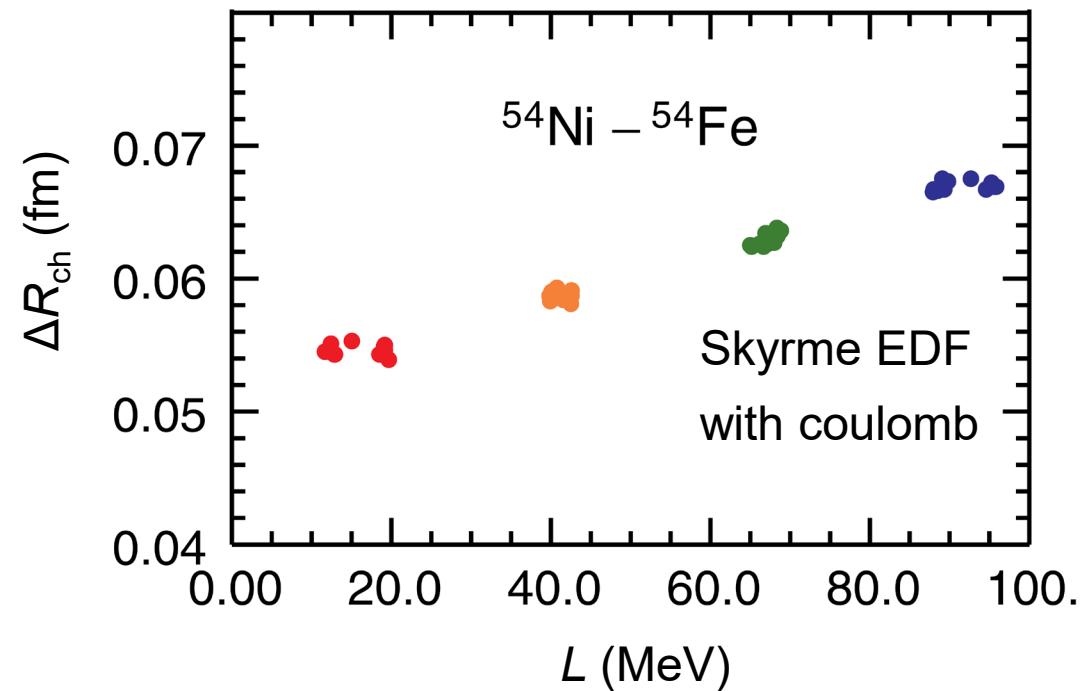
$$\rightarrow R_{ch}(^A_N Y_Z) - R_{ch}(^A_Z X_N) \equiv \Delta R_{ch}$$

- pure electromagnetic probe
- model independent determination of R_{ch}

$$\Delta R_{ch} \sim |N - Z| \times L$$

Present: ^{54}Ni (114 ms)- ^{54}Fe (stable) pair

$|N - Z| = 2$: not so large (the largest is 6), and good experimental precision is required.



$$\Delta R_{np}(^{208}\text{Pb}) = \begin{cases} 0.12 \text{ fm: red} \\ 0.16 \text{ fm: orange} \\ 0.20 \text{ fm: green} \\ 0.24 \text{ fm: blue} \end{cases}$$

NSCL/MSU Experimental Layout until 2021

NATIONAL SUPERCONDUCTING CYCLOTRON LABORATORY

FAST BEAM AREA
GAS STOPPING
STOPPED BEAM AREA
REACCELERATED BEAMS

UNDER CONSTRUCTION
PLANNED
NSF MRI

RTECR
SUSI

K500
CYCLOTRON

K1200
CYCLOTRON

A1900 FRAGMENT
SEPARATOR

MICHIGAN STATE
UNIVERSITY

CYCLOTRON GAS STOPPER

HELIUM-JET
ION-GUIDE SOURCE

DIAMOND
HODOSCOPE

Harvesting

MOMENTUM COMPRESSION
ANL GAS CATCHER
CRYOGENIC GAS STOPPER

SEETF
ISOTOPE HARVESTING
RFFS
BCS, NERO
CAESAR, SUN
PROTON DETECTOR
CLOVERSHARE
(ANL,LBNL,LLNL,MSU)
NEUTRON WALLS, SWEEPER/MoNA-LISA

JENSA
(DOE-SC/NP&NSF/JINA)
BECOLA
 β^+ POLARIMETER
MULTIPURPOSE
STOPPED BEAM
EXPERIMENTAL
STATIONS
LEBIT
SIPT

ANASEN (FSU/LSU/TAMU)
SuN, CFFD
JANUS (LLNL,U. Rochester,Sloan Foundation, NSCL)

SECAR
DOE-SC/NP & NSF

AT-TPC

SOLARIS

ReA6
HALL

REA3

LOW ENERGY BEAM LINE
EBIT COOLER BUNCHER

SeGa, HiRa
TRIPLEX PLUNGER
CAESAR, LENDA
GRETINA (DOE NATIONAL USER FACILITY)
URSINUS LH₂ TARGET



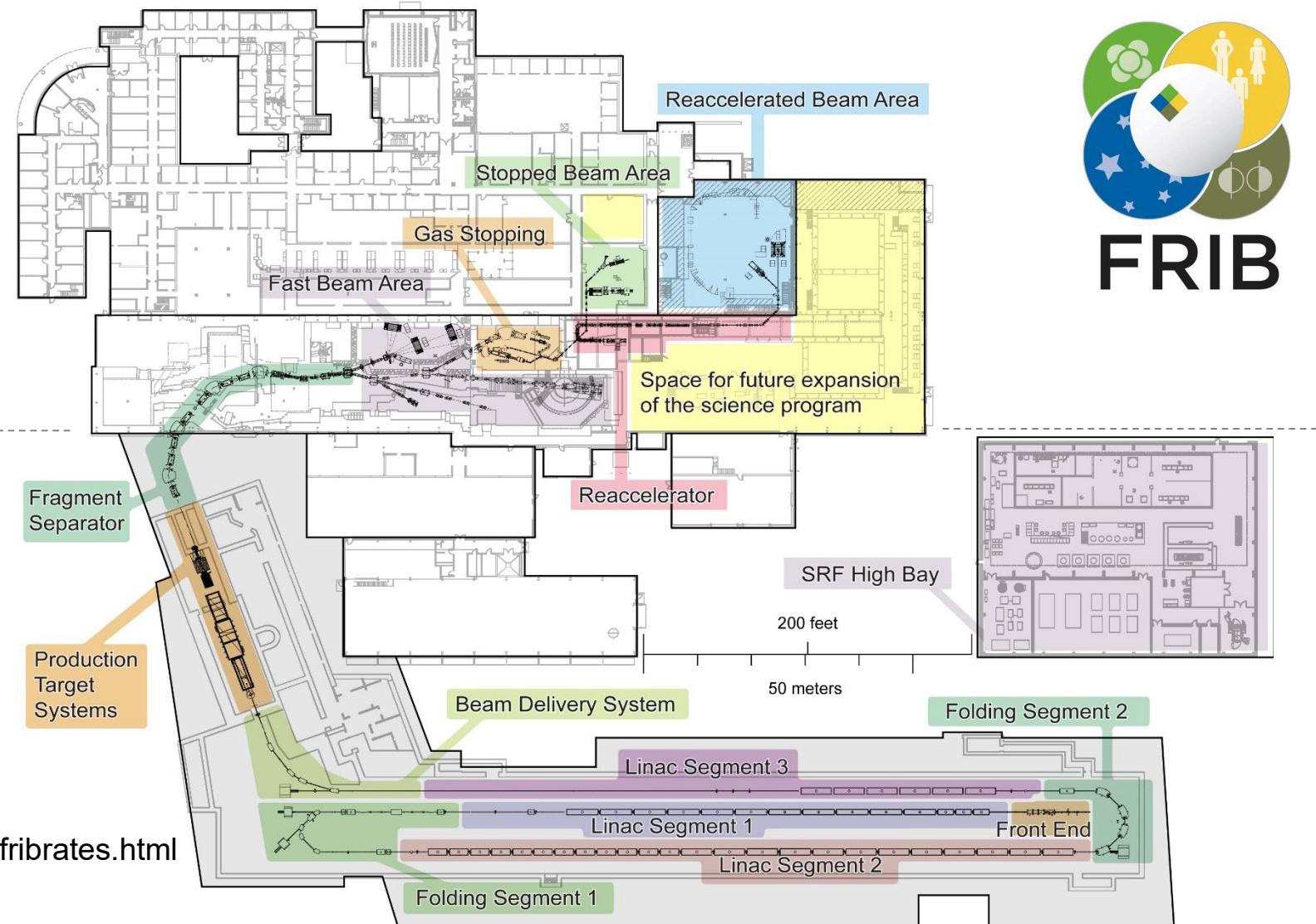
Now: Facility for Rare Isotope Beams: FRIB



old facility

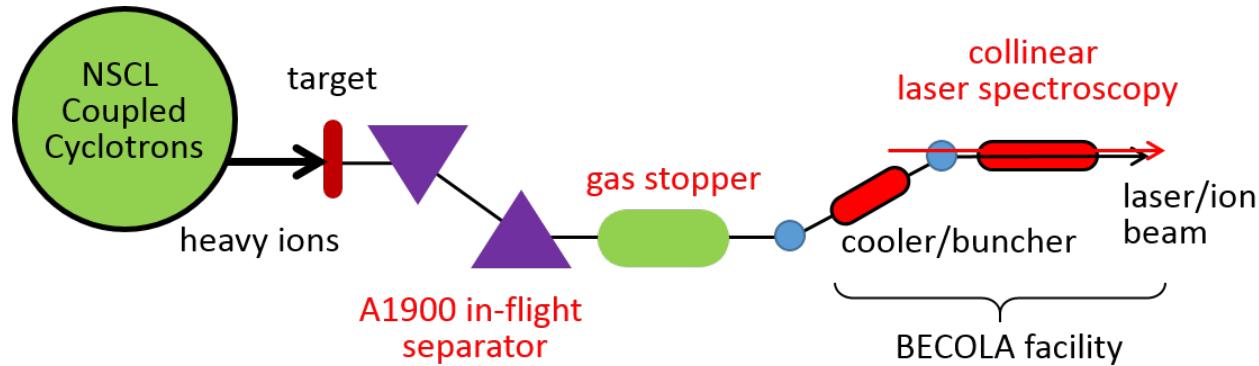
- up to 400 kW primary beam
- wider reach of radio isotopes
- no need to rearrange existing experimental devices
- 1st beam scheduled in May 2022
- FRIB yields estimate

<https://groups.nscl.msu.edu/frib/rates/fribrates.html>

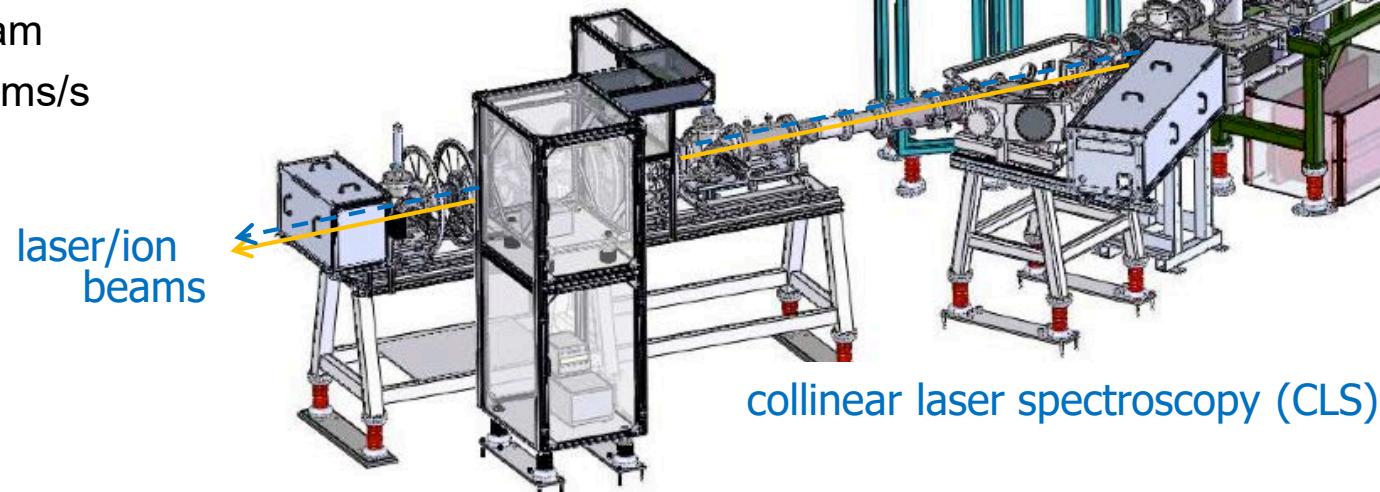


BECOLA Facility for Laser Spectroscopy

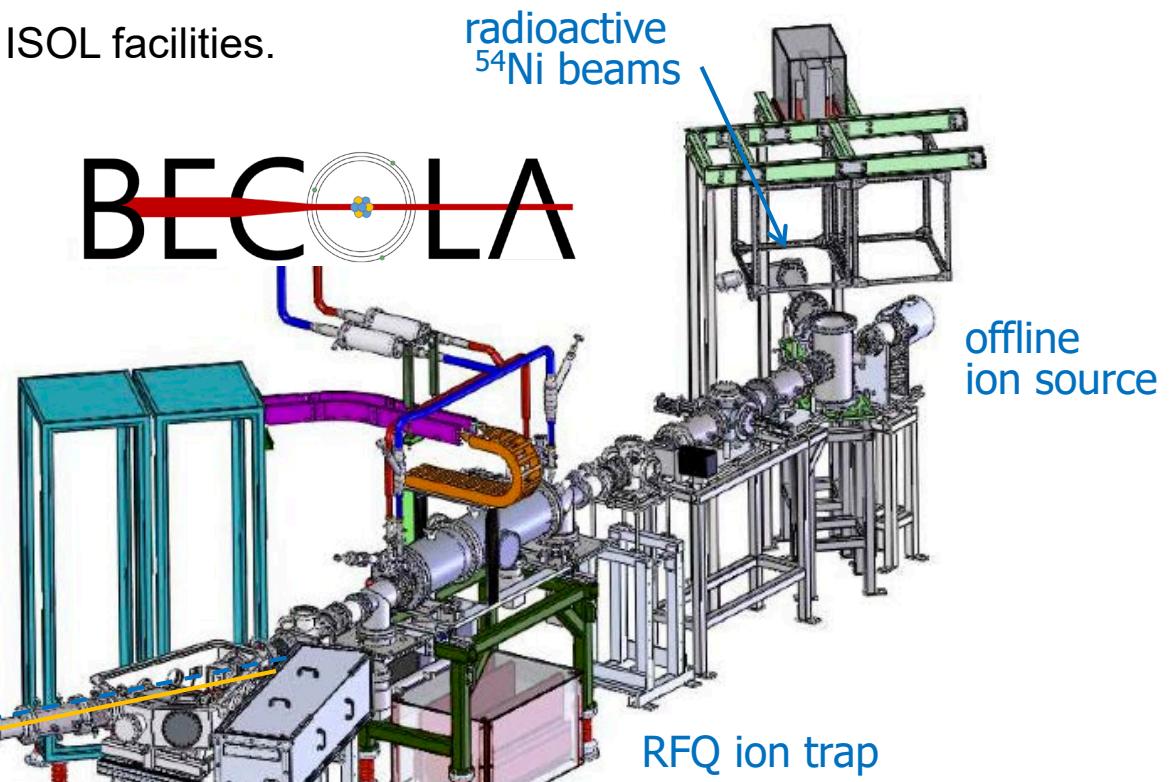
The production scheme complements existing capabilities of ISOL facilities.



- ~30 keV beam energy
- bunched beam
- ^{54}Ni ~ 15 atoms/s

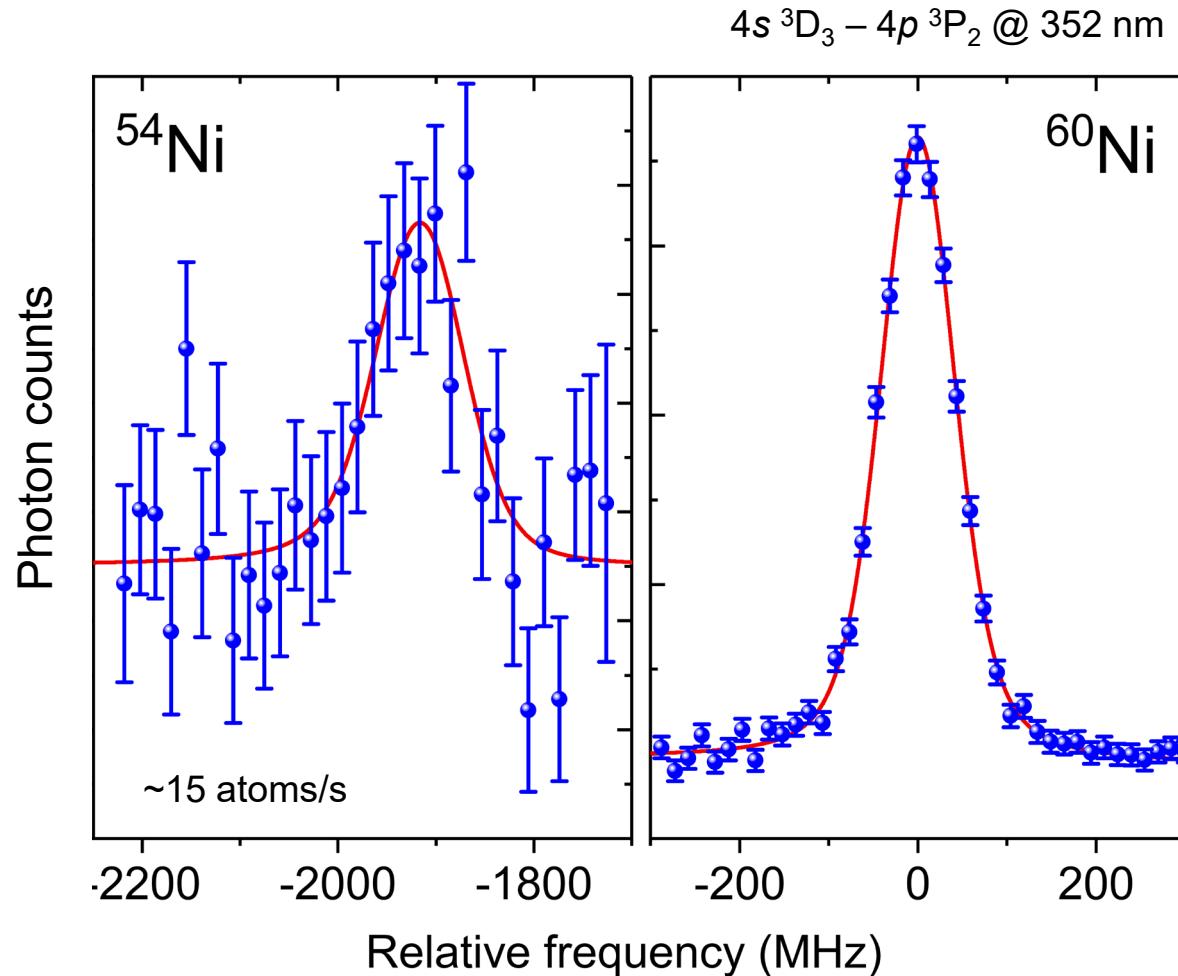


collinear laser spectroscopy (CLS)



laser system

^{54}Ni Hyperfine Spectrum



$$\begin{aligned}\delta\nu^{A,A'} &= \nu^{A'} - \nu^A \\ &= k \frac{M' - M}{M'M} + F \times \delta\langle r^2 \rangle^{A,A'}\end{aligned}$$

Atomic factors well determined using King plot analysis

$$\begin{cases} k = 1266(26) \text{ GHz amu} \\ F = -804(66) \text{ MHz fm}^{-2} \end{cases}$$

K. König et al., PRC 103, 054305 (2021).

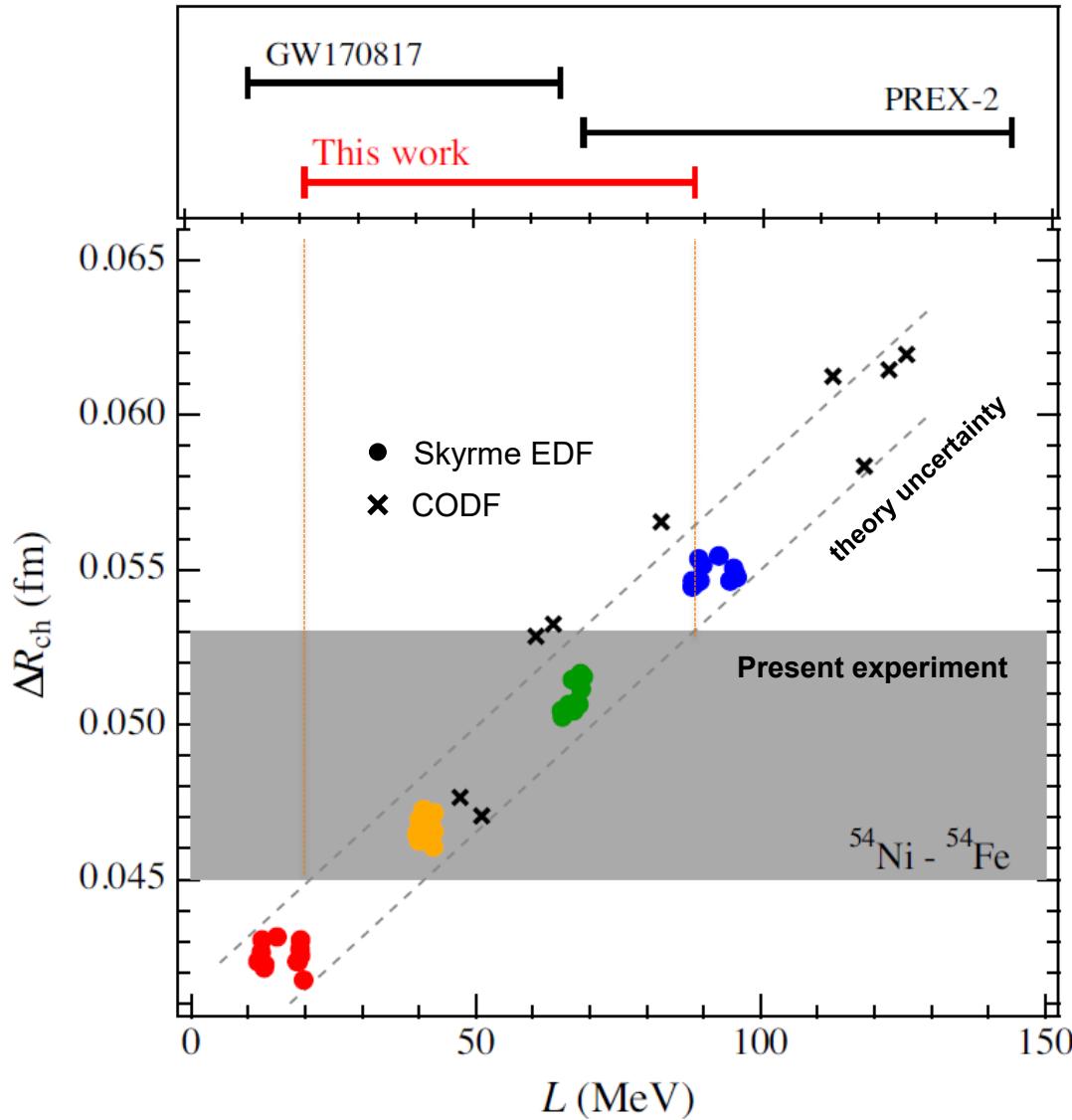
Absolute radii well determined from the e-scattering and μ -X ray measurements.

$$\begin{cases} R(^{60}\text{Ni}) = 3.8059(17) \text{ fm} \\ R(^{54}\text{Fe}) = 3.6880(17) \text{ fm} \end{cases}$$

G. Fricke and K. Heilig,
Nuclear Charge Radii, Springer, (2004).

$$\Delta R_{\text{ch}} = 0.049(4) \text{ fm}$$

Constraint on Symmetry Energy in EOS using Difference of Mirror Charge Radii ^{54}Ni and ^{54}Fe



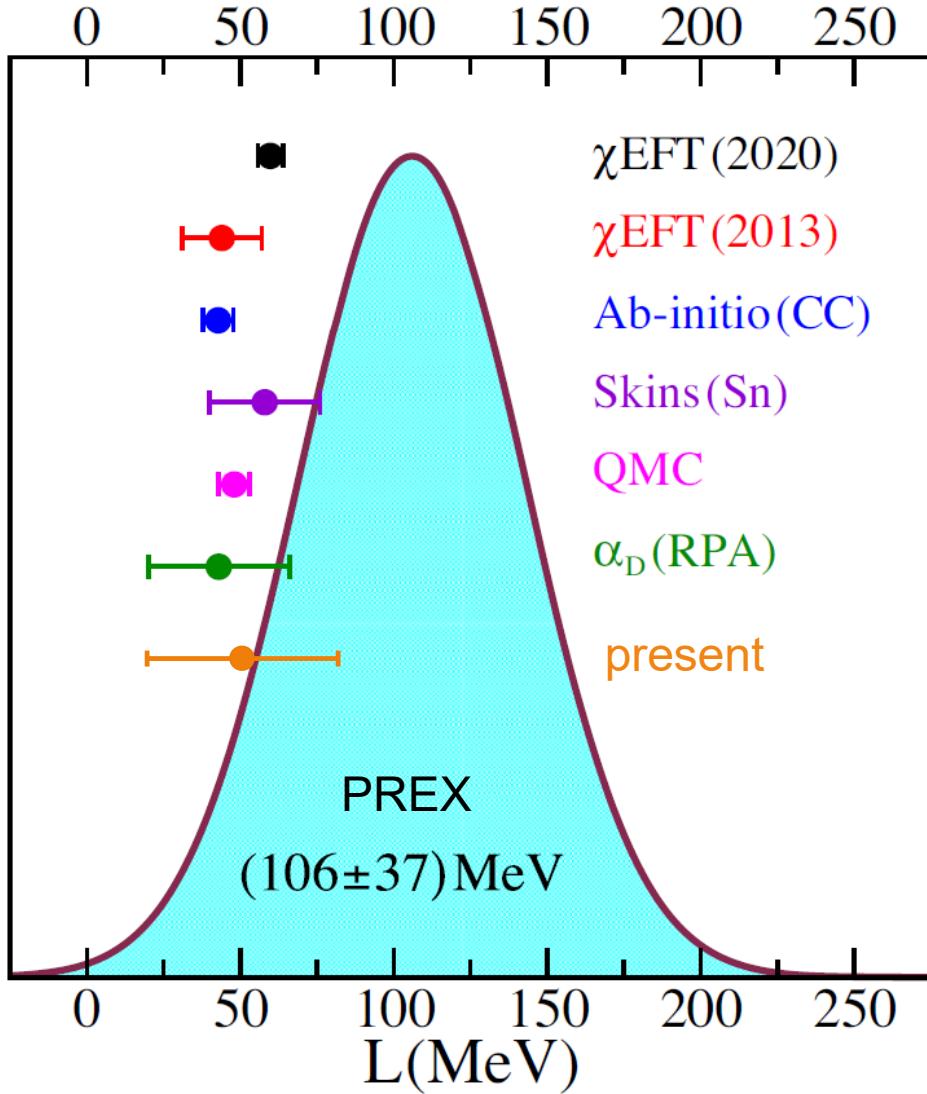
Present result: $L = 20 \sim 90$ MeV

Our result:

- indicates soft EOS, and rather small radius of a neutron star
- is consistent with the binary neutron star merger GW170817 and PREX
- PREX, however, points to stiffer EOS and a larger neutron star radius.

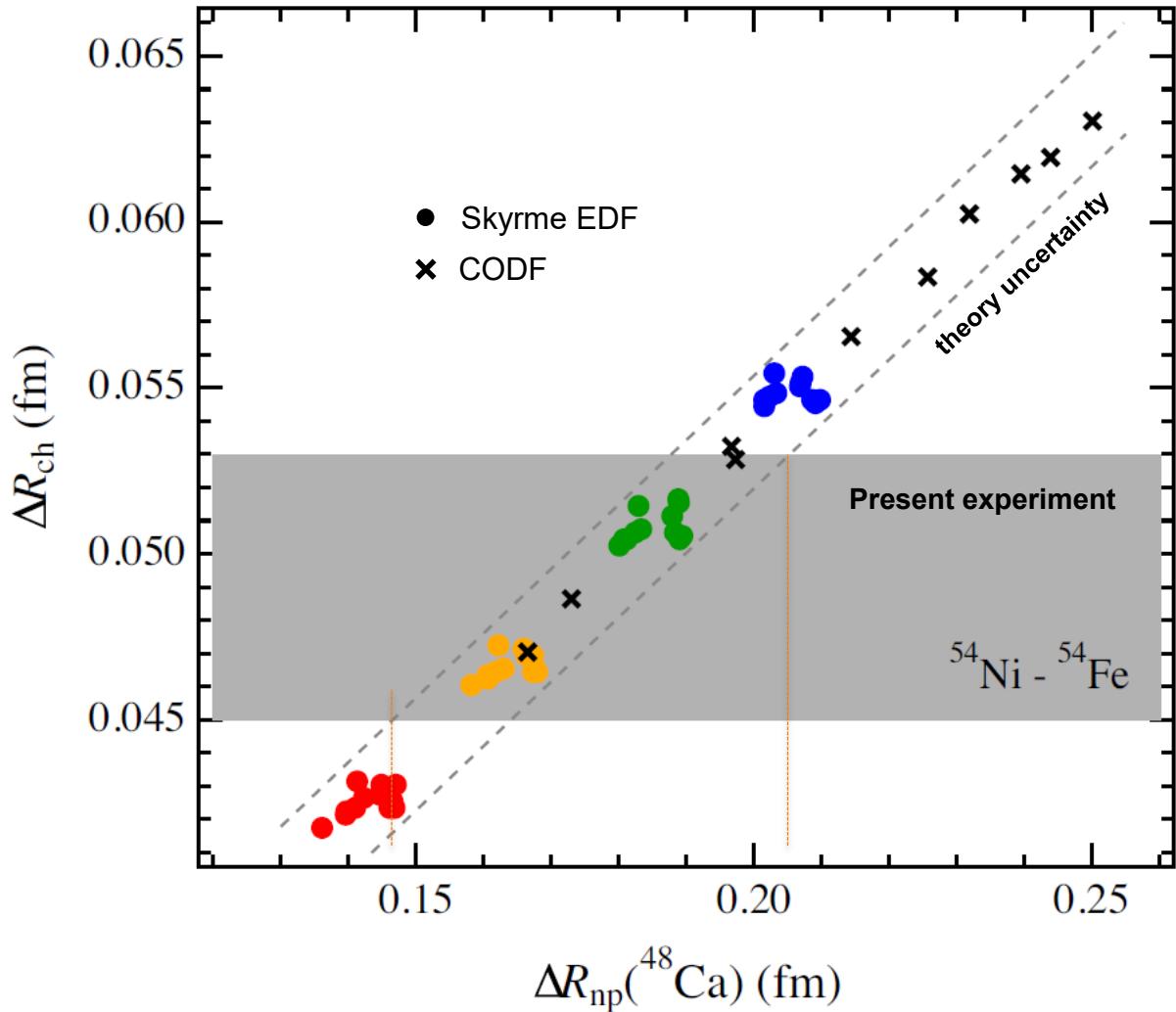
$$\Delta R_{\text{np}}(^{208}\text{Pb}) = \begin{cases} 0.12 \text{ fm: red} \\ 0.16 \text{ fm: orange} \\ 0.20 \text{ fm: green} \\ 0.24 \text{ fm: blue} \end{cases}$$

Constraint on Symmetry Energy in EOS using Difference of Mirror Charge Radii ^{54}Ni and ^{54}Fe



- PREX suggests a rather stiff EOS and a larger neutron star radius.
- What about CREX?
- our ΔR_{ch} is also sensitive to the neutron skin of ^{48}Ca .

^{48}Ca Neutron Skin from Difference of Mirror Charge Radii ^{54}Ni and ^{54}Fe



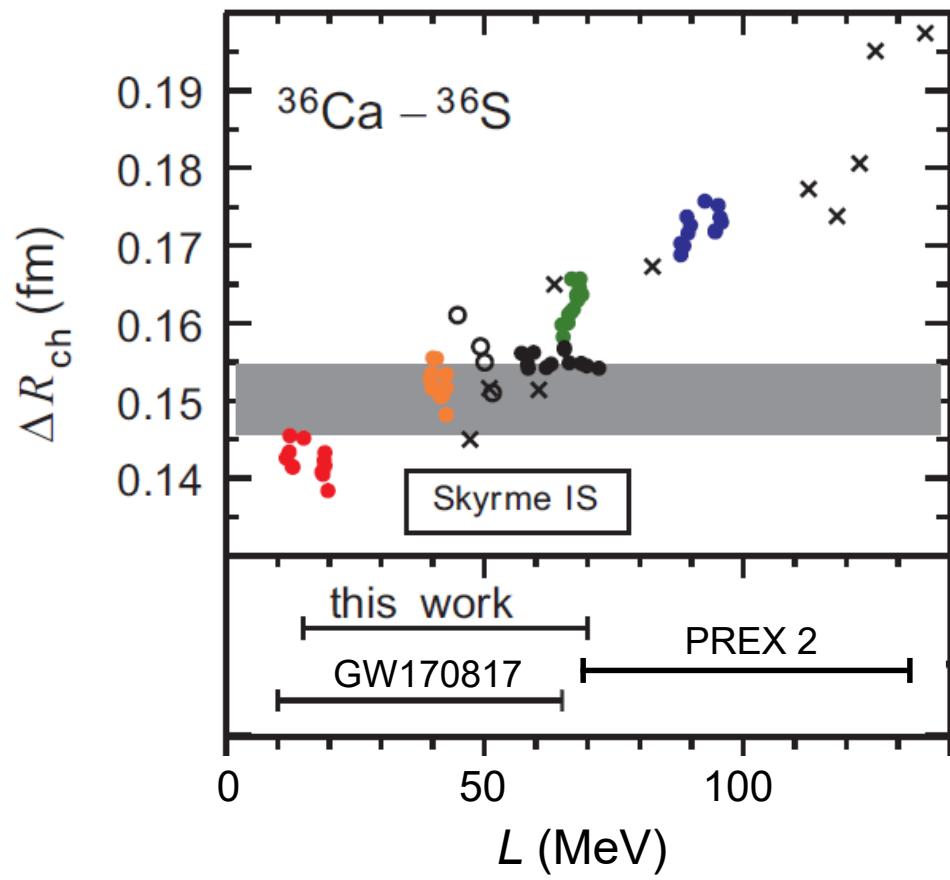
our prediction:

$$\Delta R_{\text{np}}(^{48}\text{Ca}) = 0.15 - 0.21 \text{ fm}$$

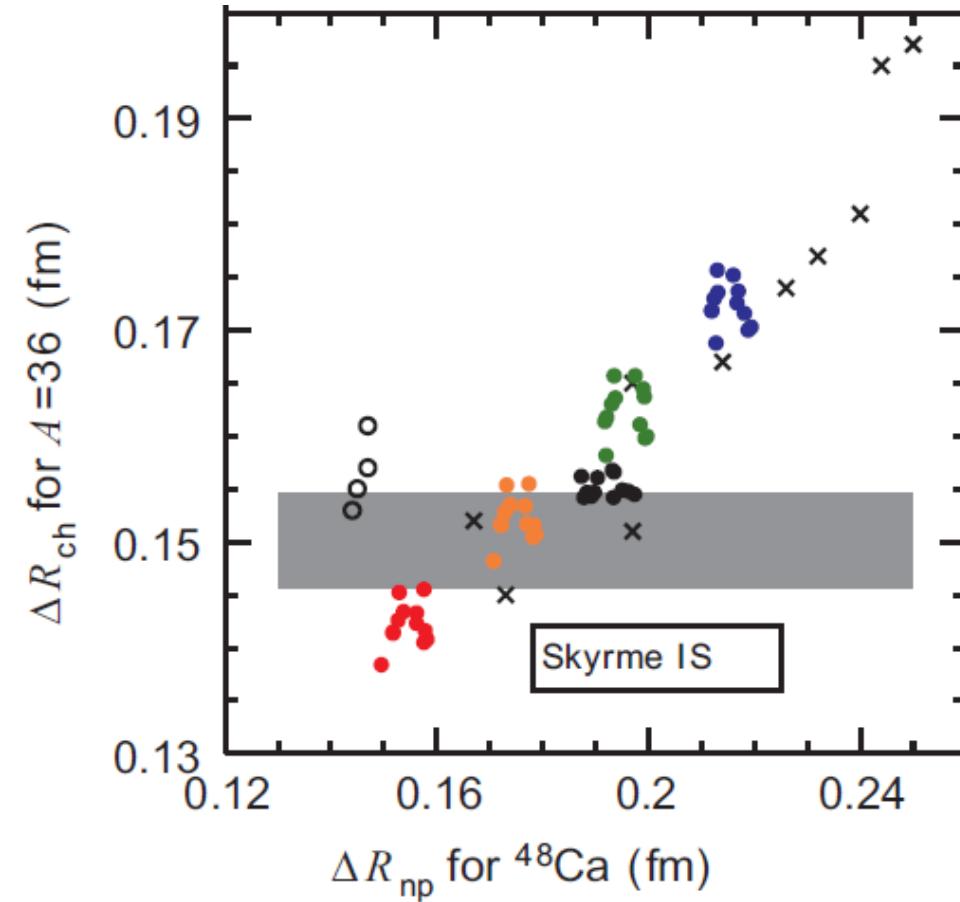
- Our results show tight correlation $\Delta R_{\text{ch}} - \Delta R_{\text{np}}$
- CREX (^{48}Ca radius) experiment completed.
- Preliminary analysis indicates small $\Delta R_{\text{np}}(^{48}\text{Ca})$, contradicting PREX result.

It is of particular interest whether CREX will confirm the soft EOS or reveal a larger ΔR_{np} as the PREX-2.

Difference of Mirror Charge Radii ^{36}Ca and ^{36}S



$L = 5 \sim 70$ MeV
(20 - 90 MeV: $^{54}\text{Ni}/\text{Fe}$)



$\Delta R_{\text{np}}(^{48}\text{Ca}) = 0.15 - 0.20$ fm
(0.15 - 0.21 fm: $^{54}\text{Ni}/\text{Fe}$)

Assessing Model Dependence

Typical EDF (purple)

- No good
- Correction for deformation required

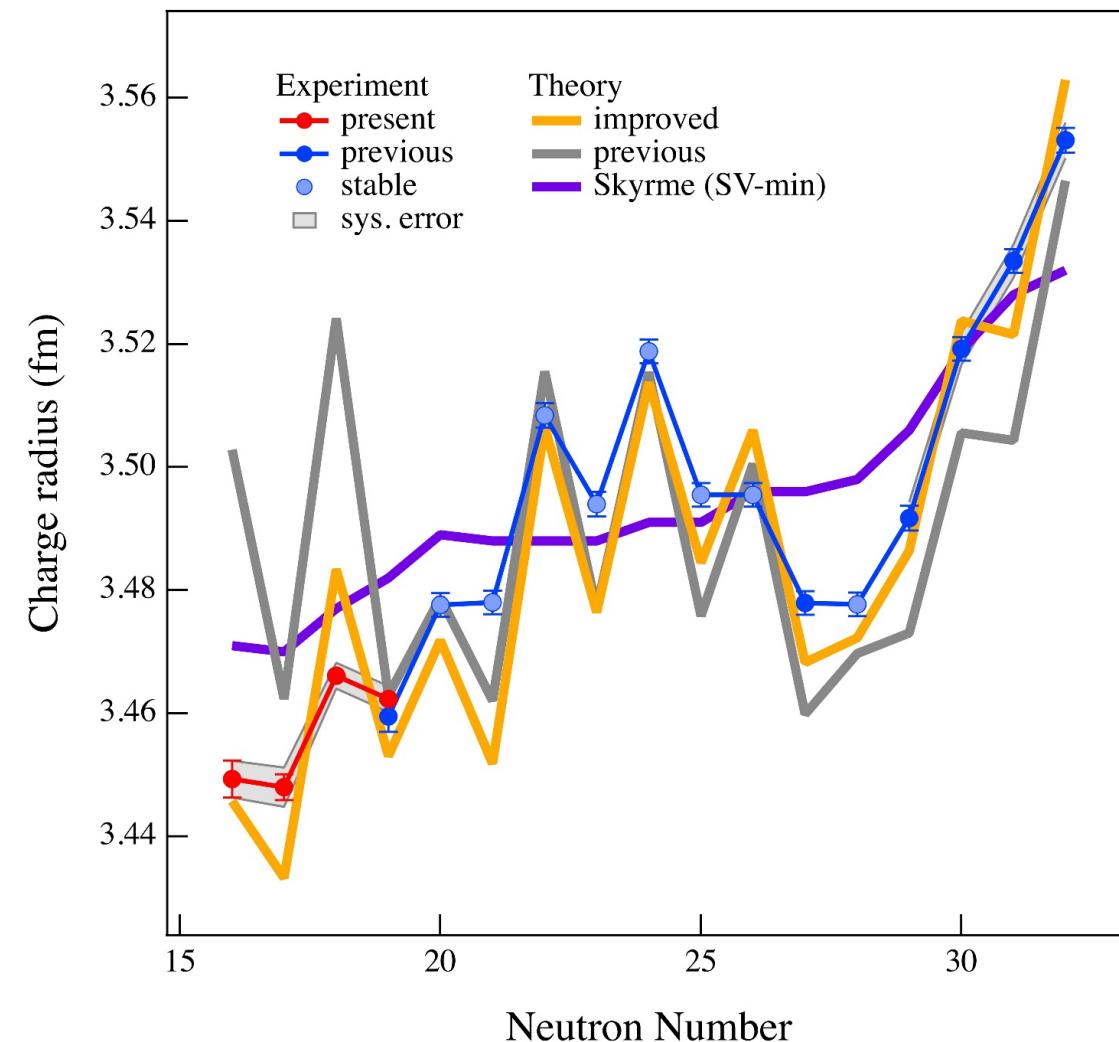
Fayans EDF (yellow)

Density gradient dependent

- pairing term
- the surface term

BCS vs HFB (gray vs yellow)

- Proper treatment of proton continuum effects



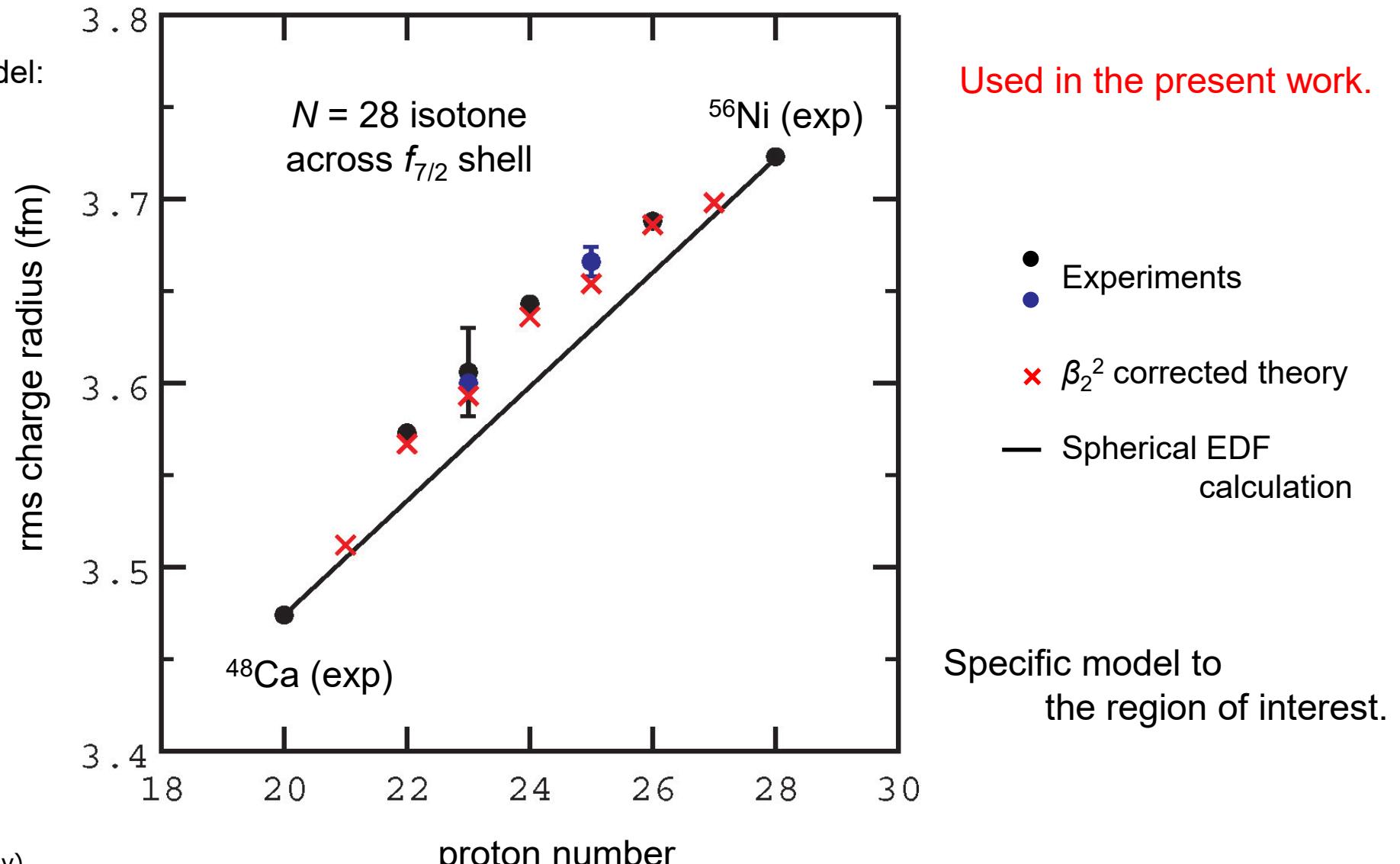
Assessing Model Dependence: β^2 Model

According to Bohr collective model:

$$\langle r^2 \rangle = \langle r^2 \rangle_0 \left(1 + \frac{5}{4\pi} \sum_{\lambda \geq 2} \beta_\lambda^2 \right)$$

$$\sum_{\lambda \geq 2} \beta_\lambda^2 \sim \beta_2^2$$

$$\beta_2^2 = \frac{B(E2, \uparrow)}{\left(\frac{3}{4\pi} Z R_0^2 \right)^2}$$

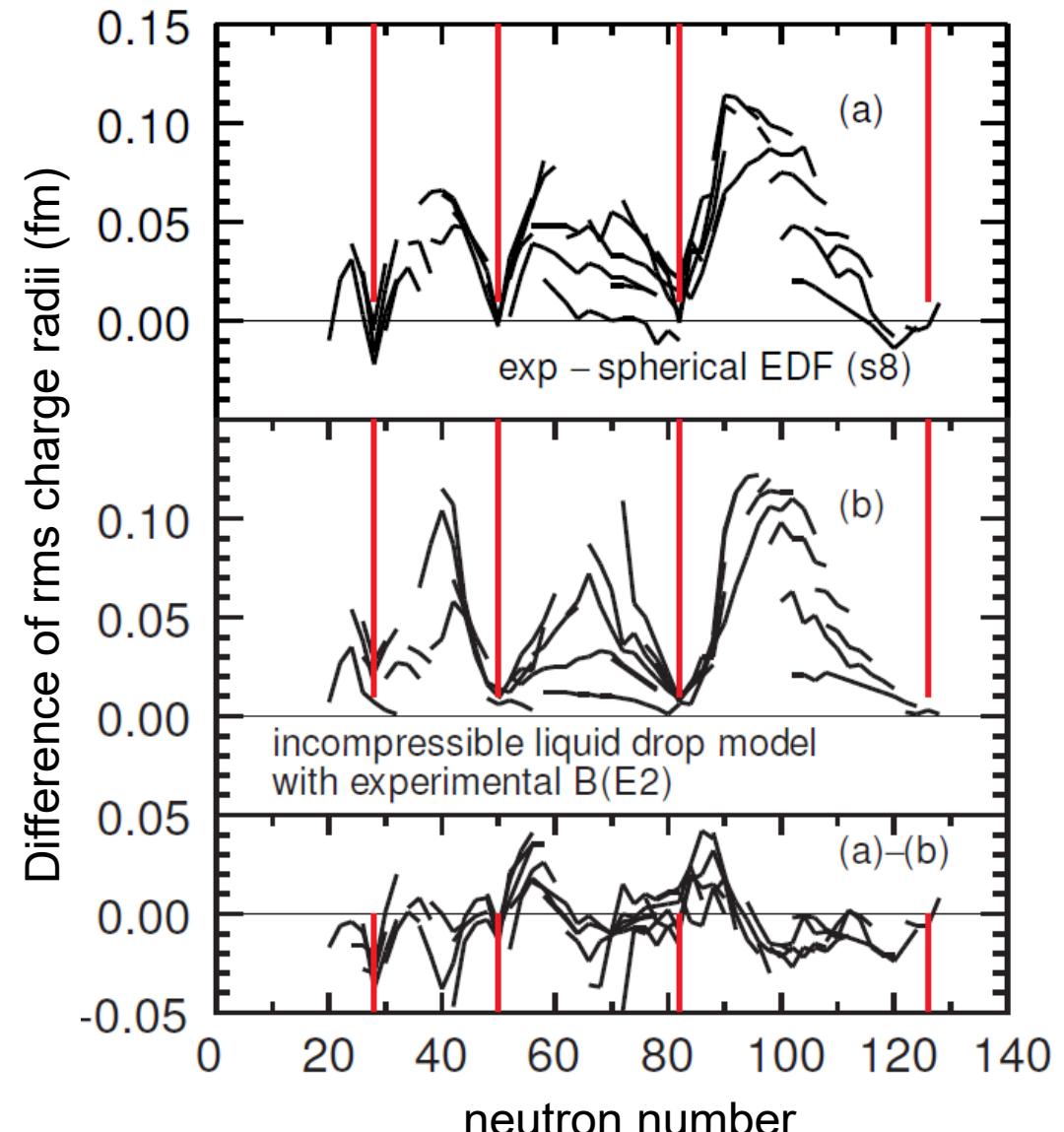


Assessing Model Dependence: β^2 Model

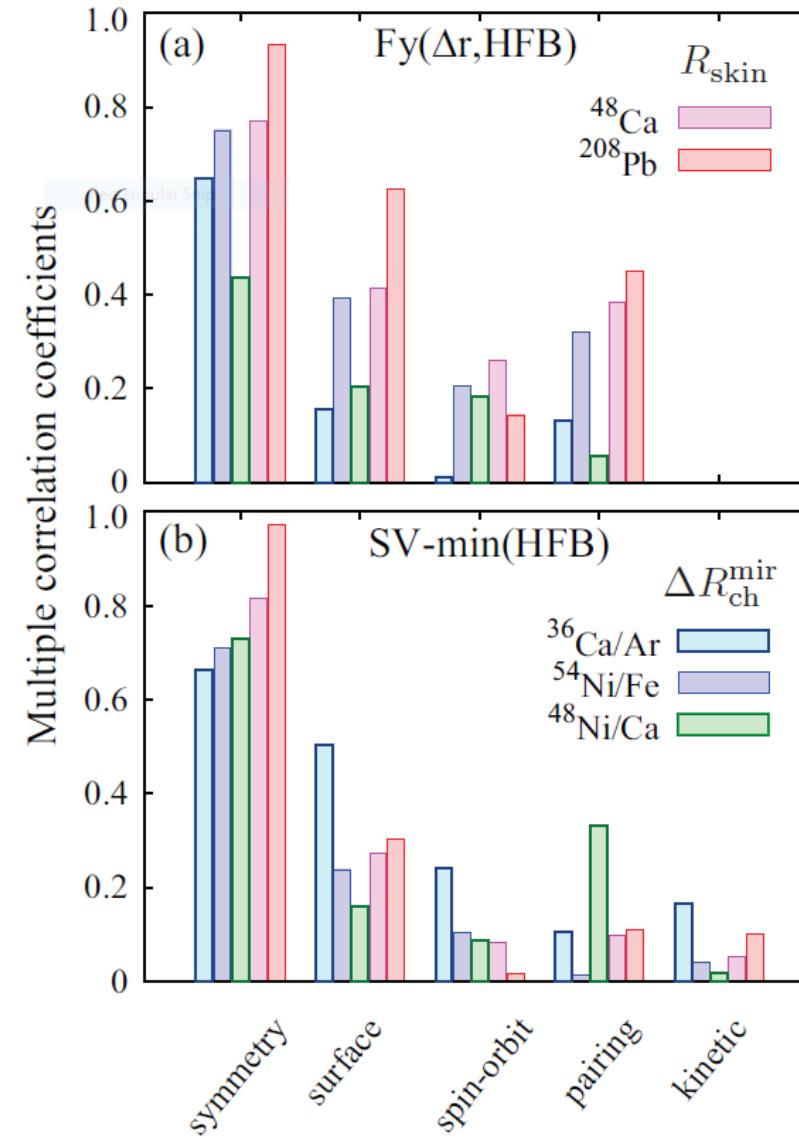
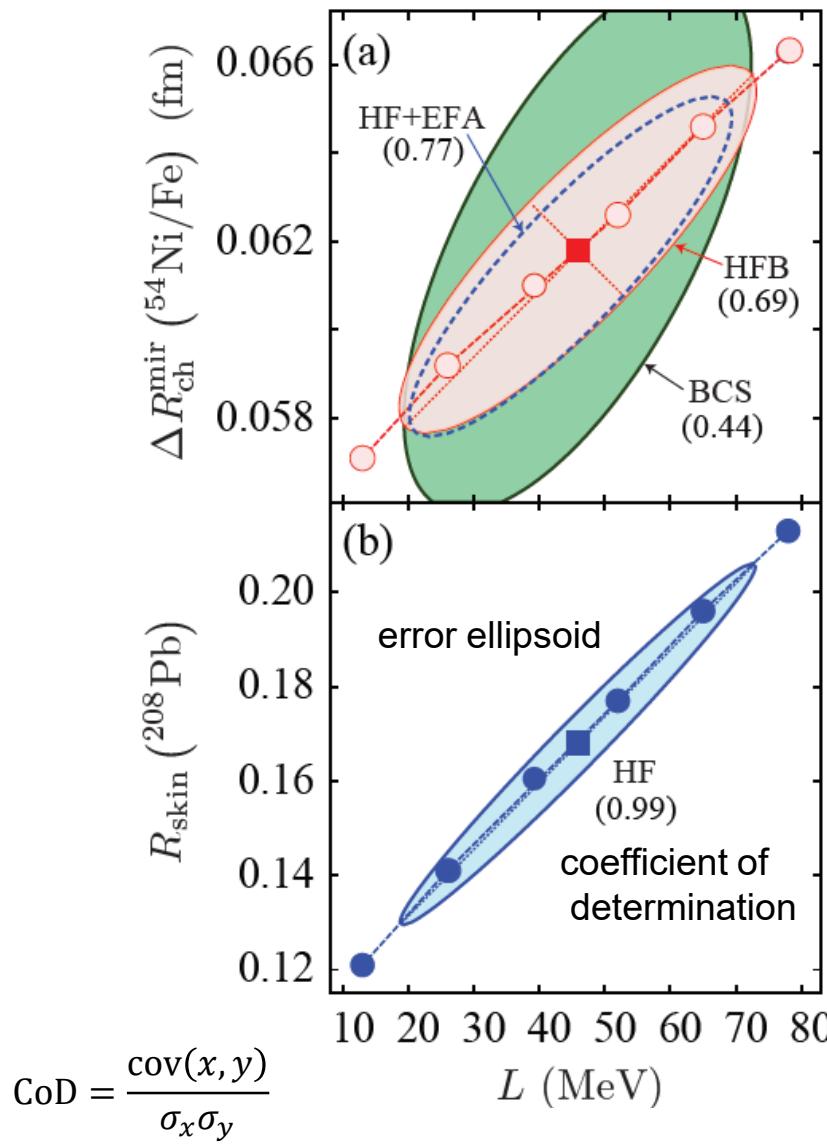
Deformation effect missing in spherical EDF

Deformation (β_2^2) corrected spherical EDF

Unexplained experiment - theory difference



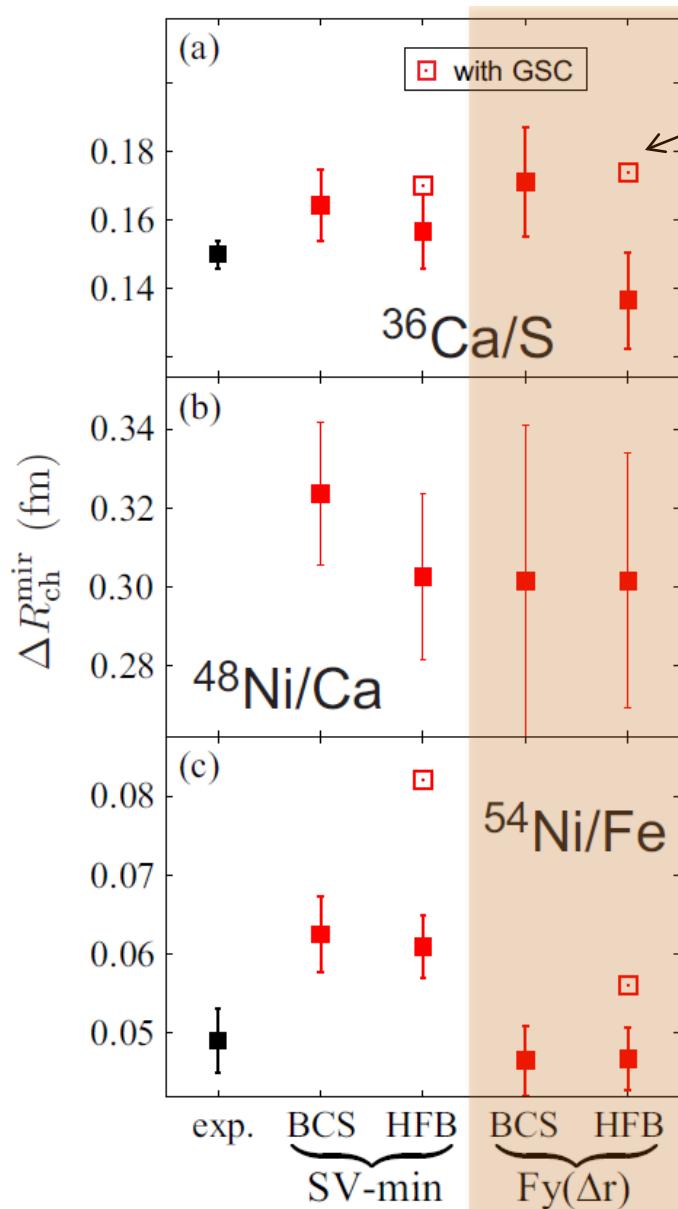
Assessing Model Dependence: Fayans Model



“...precise data on mirror charge radii with an error of about 0.005 fm, while extremely valuable for studying isospin effects in nuclei and model developments, cannot provide a stringent constraint on L ” in this model.

Global fit with rich pairing interactions

Assessing Model Dependence: Fayans Model



with corrective ground state correlation

- ΔR_{ch} of $^{54}\text{Ni}/\text{Fe}$ pair is not sensitive to BCS/HFB.
- ΔR_{ch} of $^{36}\text{Ca}/\text{S}$ pair has some proton continuum effect.
- Collective ground state correlation may be significant.

Proton continuum effect

- BCS gives unphysical results
- HFB is the proper treatment

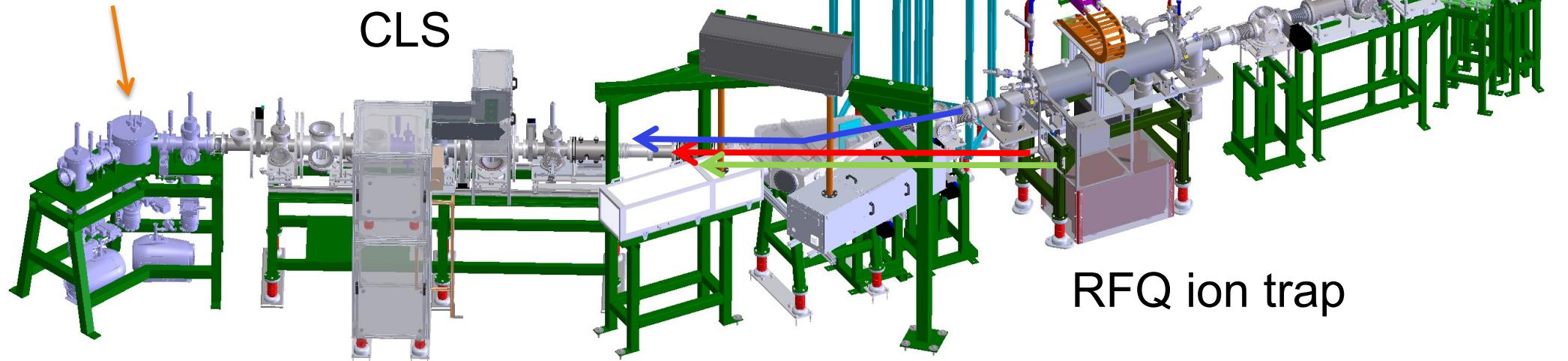
Summary

- Slope parameter, L , of EOS was deduced from the difference of mirror charge radii ^{54}Ni and ^{54}Fe .
- L is consistent with PREX-2 and GW170817 indicating soft EOS, though PREX points rather stiffer EOS.
- $\Delta R_{\text{np}}(^{48}\text{Ca})$ was predicted, and it is smaller than $\Delta R_{\text{np}}(^{208}\text{Pb})$, contradicting with PREX results.
- It is critical to have variety of experimental observables. Mirror charge radii is one of them.
- Assessment of theoretical model is critical.
- More experimental and theoretical investigations are encouraged.
- The analysis of ^{32}Si and ^{32}Ar pair is on going. **Atomic calculation needed for Si!**
- ^{52}Ni and ^{52}Cr , ^{22}O and ^{22}Si ... pairs are targeted at FRIB in near future.
- 2 more slides for future prospects

Future Prospects: RiSE

BECOLA

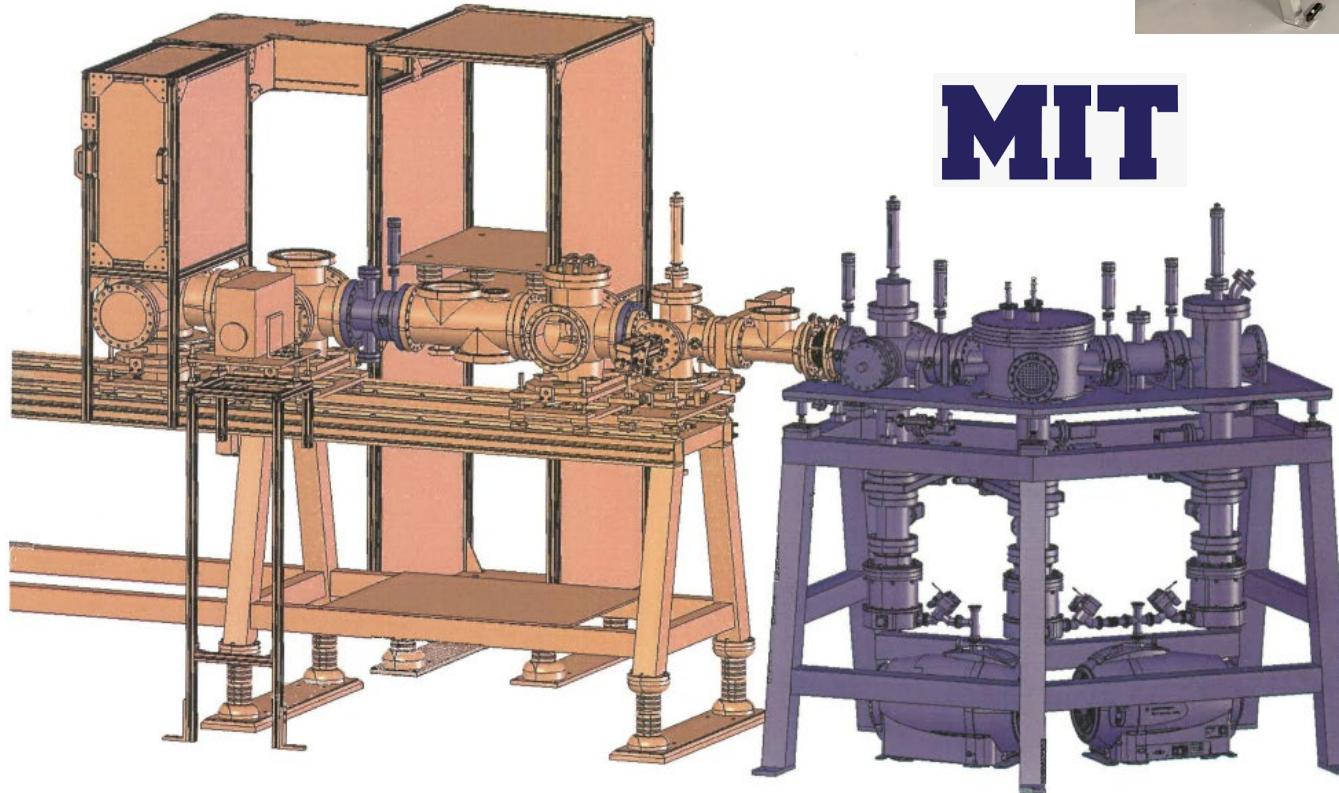
Resonance ionization Spectroscopy
Experiments: RiSE



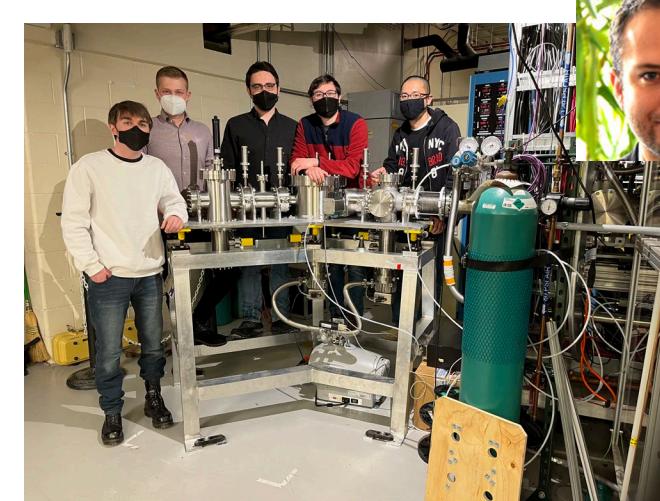
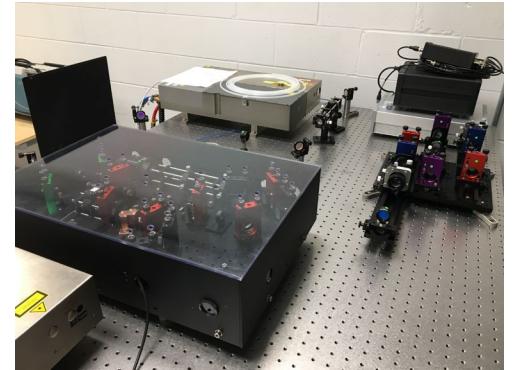
MIT

Future Prospects: RiSE

- Commissioning runs May ~ August
 - FRIB experiment ~ end of 2022
- on neutron deficient Al, **Atomic calculation needed!**
The experiment approved too.



MIT



BECOLA Collaboration for ^{54}Ni

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Anthony Incorvati^{1,5}, Jeremy Lantis^{1,2}, Kei Minamisono^{1,5}, Wilfried Nörtershäuser³,
Jorge Piekarewicz⁶, Robert Powell^{1,5}, and Felix Sommer³**

¹*National Superconducting Cyclotron Laboratory, Michigan State University,*

²*Department of Chemistry, Michigan State University,*

³*Institut für Kernphysik, Technische Universität Darmstadt*

⁴*GSI Helmholtzzentrum für Schwerionenforschung mbH*

⁵*Department of Physics and Astronomy, Michigan State University*

⁶*Department of Physics, Florida State University*

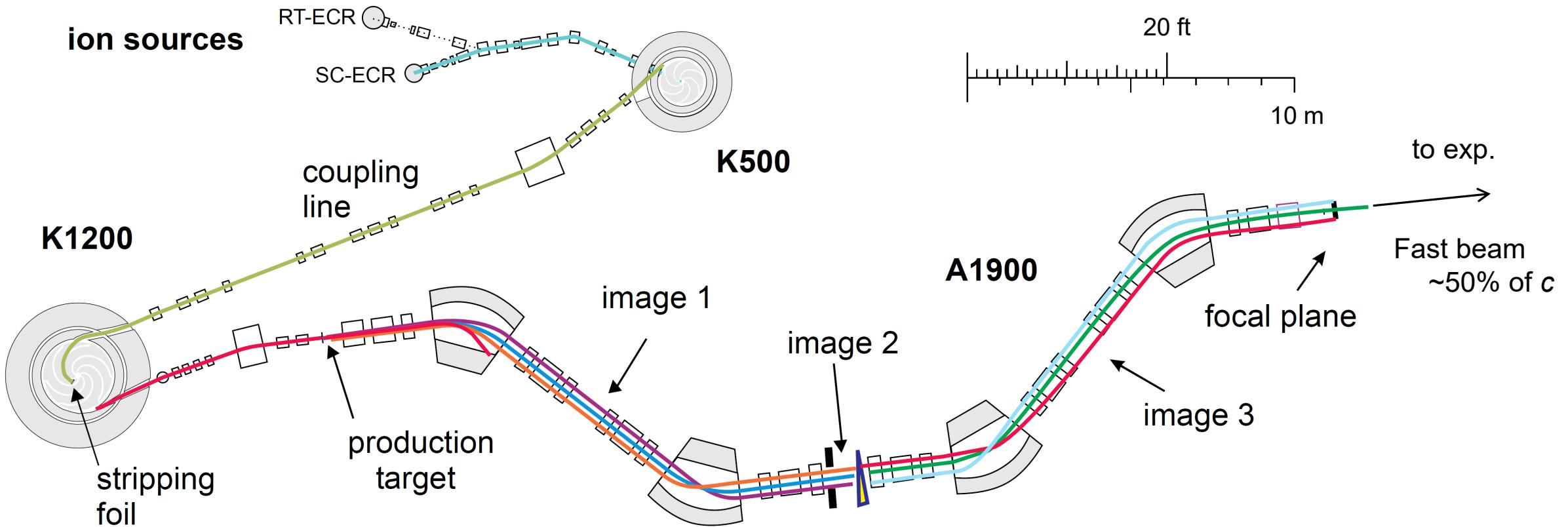
Acknowledgement

This work is support in part by the National Science Foundation Grant No. PHY-14-30152, No. PHY-15-65546, No. PHY-18-11855, No. PHY-21-10365 and No. PHY-21-11185, and by the U.S. Department of Energy Office of Science, Office of Nuclear Physics under Award No. DE-FG02-92ER40750, and by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) - Project-ID 279384907 - SFB 1245.

Any Questions?

Thank you!

Coupled Cyclotron Facility at NSCL/MSU



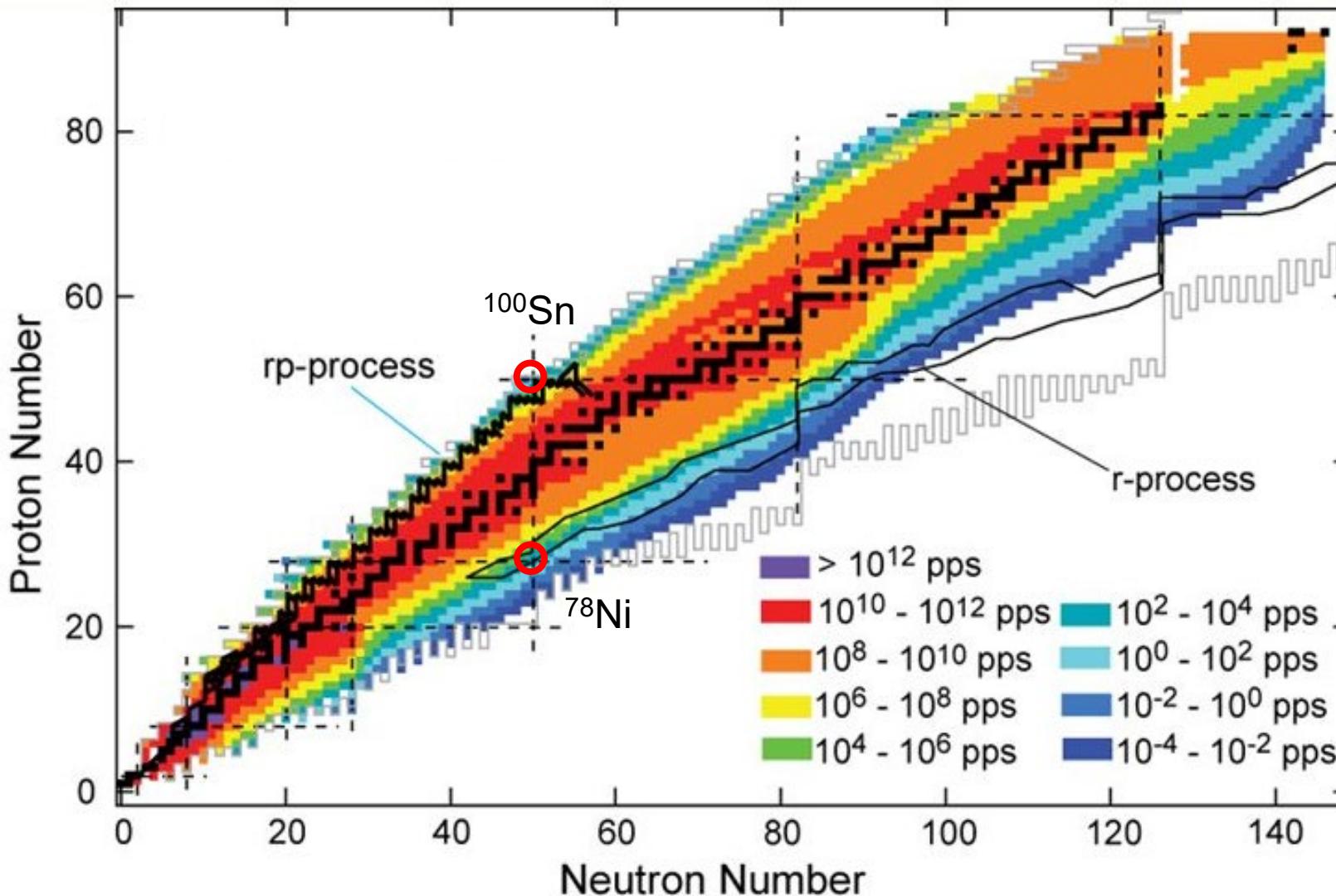
Projectile-fragment reactions

- Forward focusing, fast separation
- Produces nuclei lighter than primary beam (so far the heaviest is U)
- Chemistry free
- Complementary to e.g. ISOL mechanism

Good at

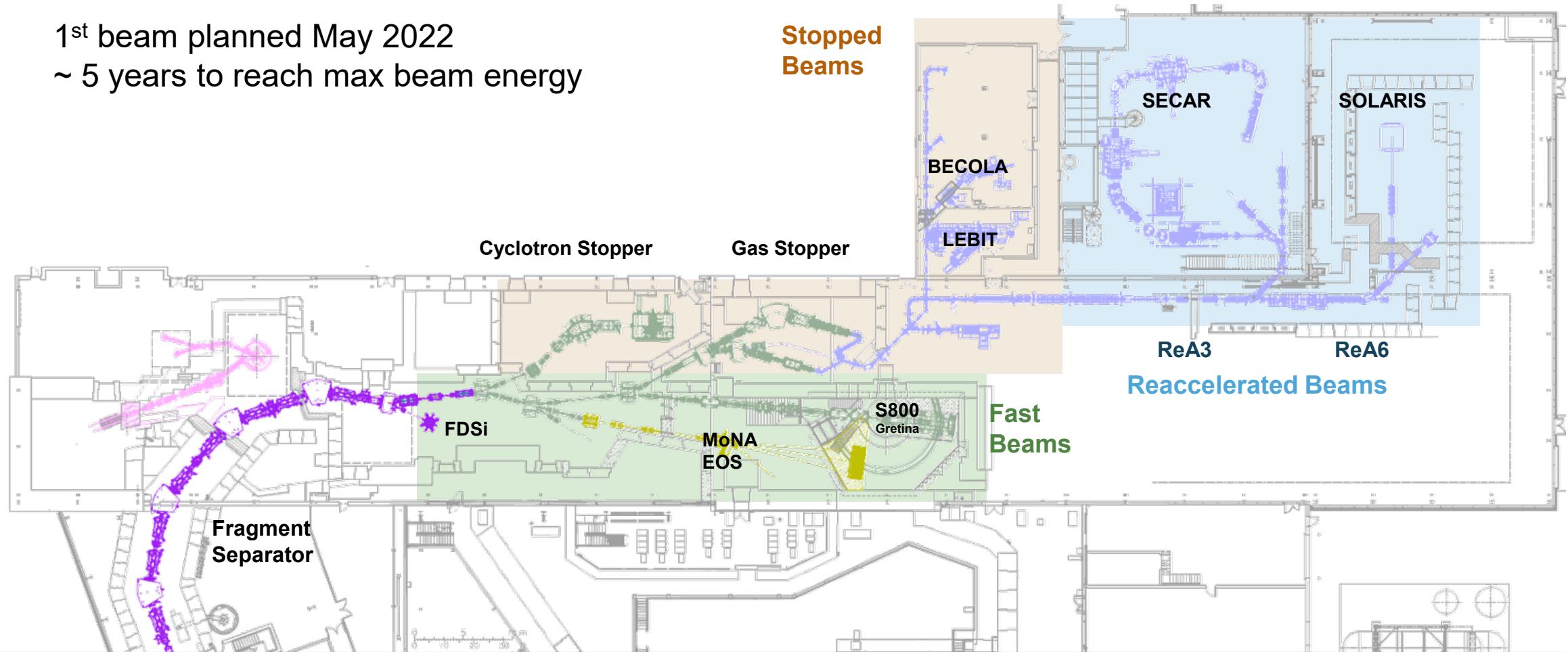
- Short lived isotopes
- Neutron-deficient side

FRIB Fast Beam Rates

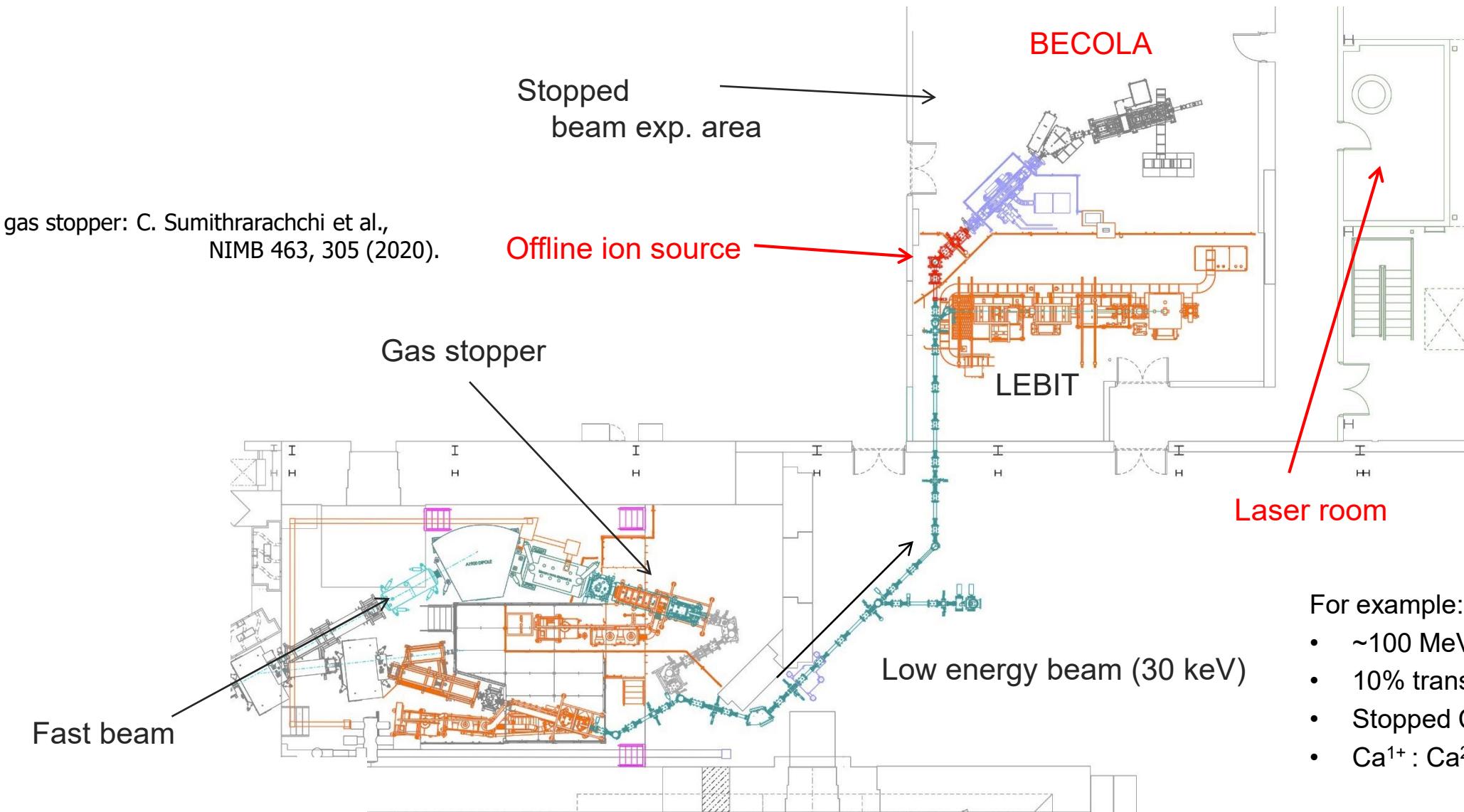


FRIB Experimental Layout

1st beam planned May 2022
~ 5 years to reach max beam energy

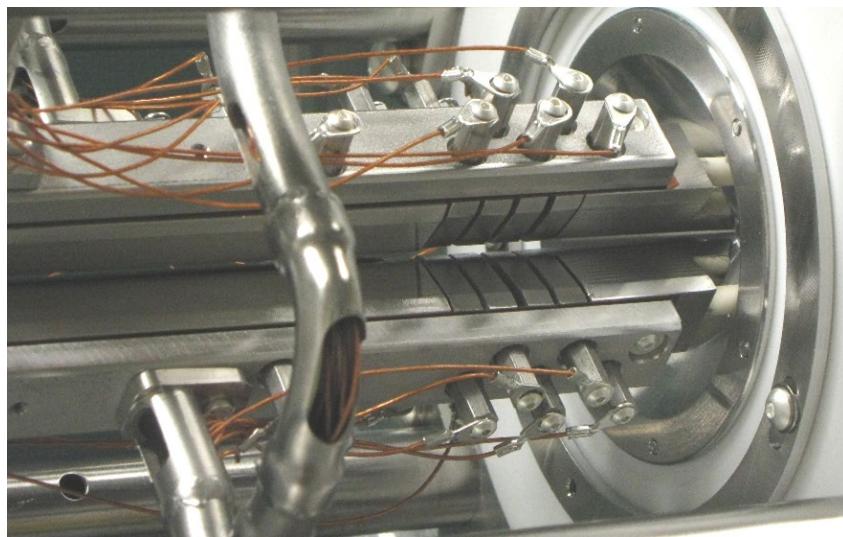


Gas Stopping & Ion Beam Transport to BECOLA

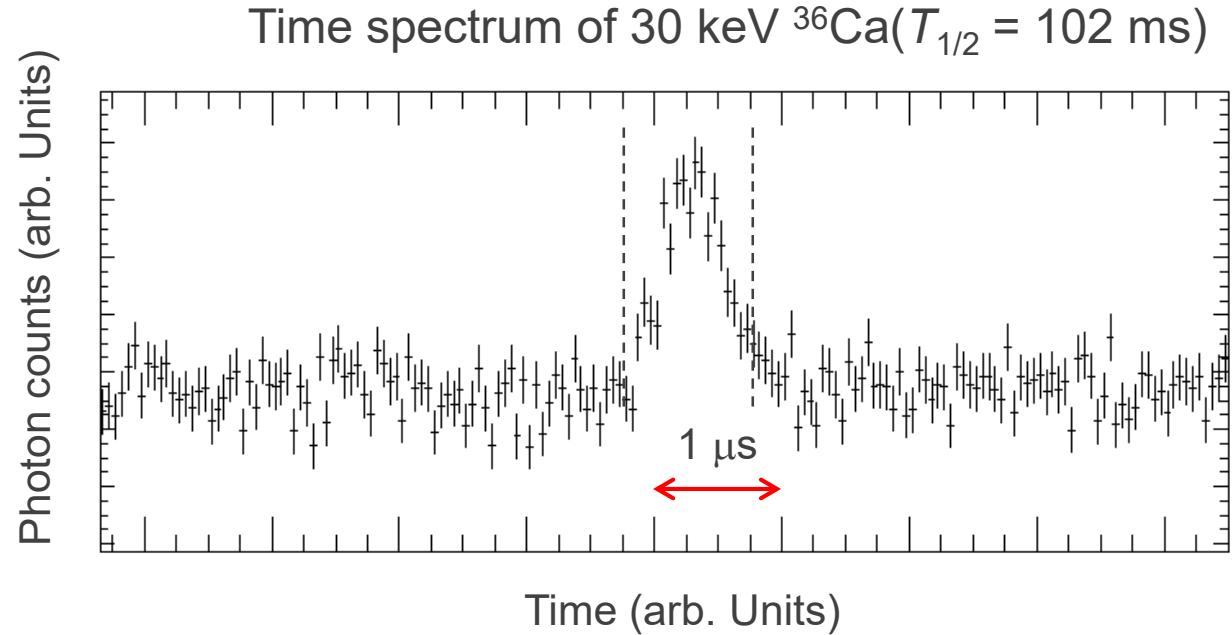
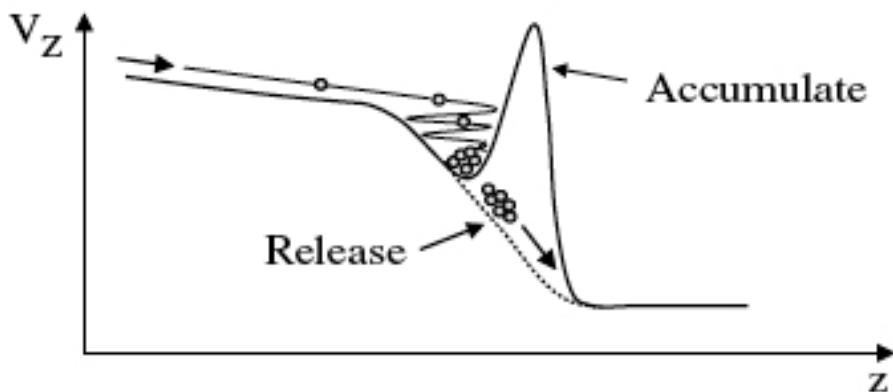


- For example: Ca gas stopping
- ~100 MeV/A injection
 - 10% transmission efficiency
 - Stopped Ca nH₂O attached
 - Ca¹⁺ : Ca²⁺ = 1 : 1 after CID

High Sensitivity: Bunched Beam CLS



RFQ bunching section



Bunched beam CLS

- Gate on ion-beam bunches
- No loss of signal, but suppresses background \rightarrow high SN
- Suppression factor $\sim 10^6$ for 1 s bunch cycle
- Lifetime consideration for short-lived isotopes

High Resolution: Kinematical Compression

