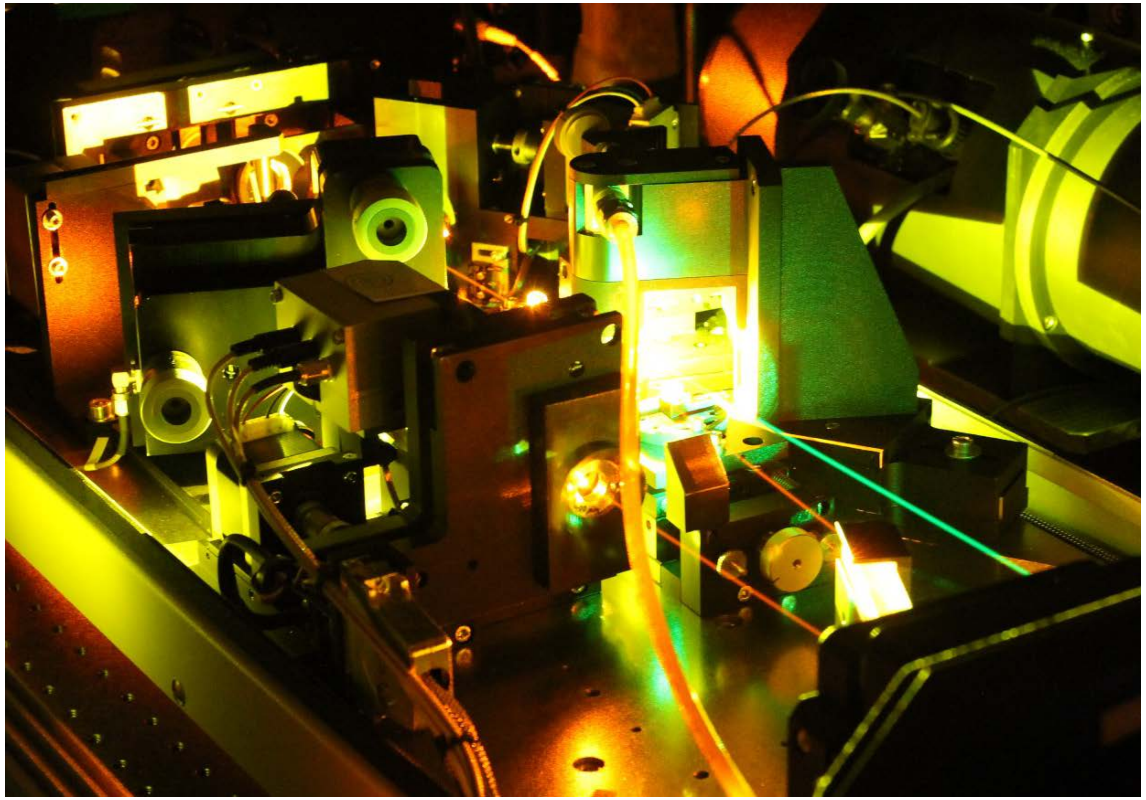
Recent laser spectroscopy results at NSCL / MSU



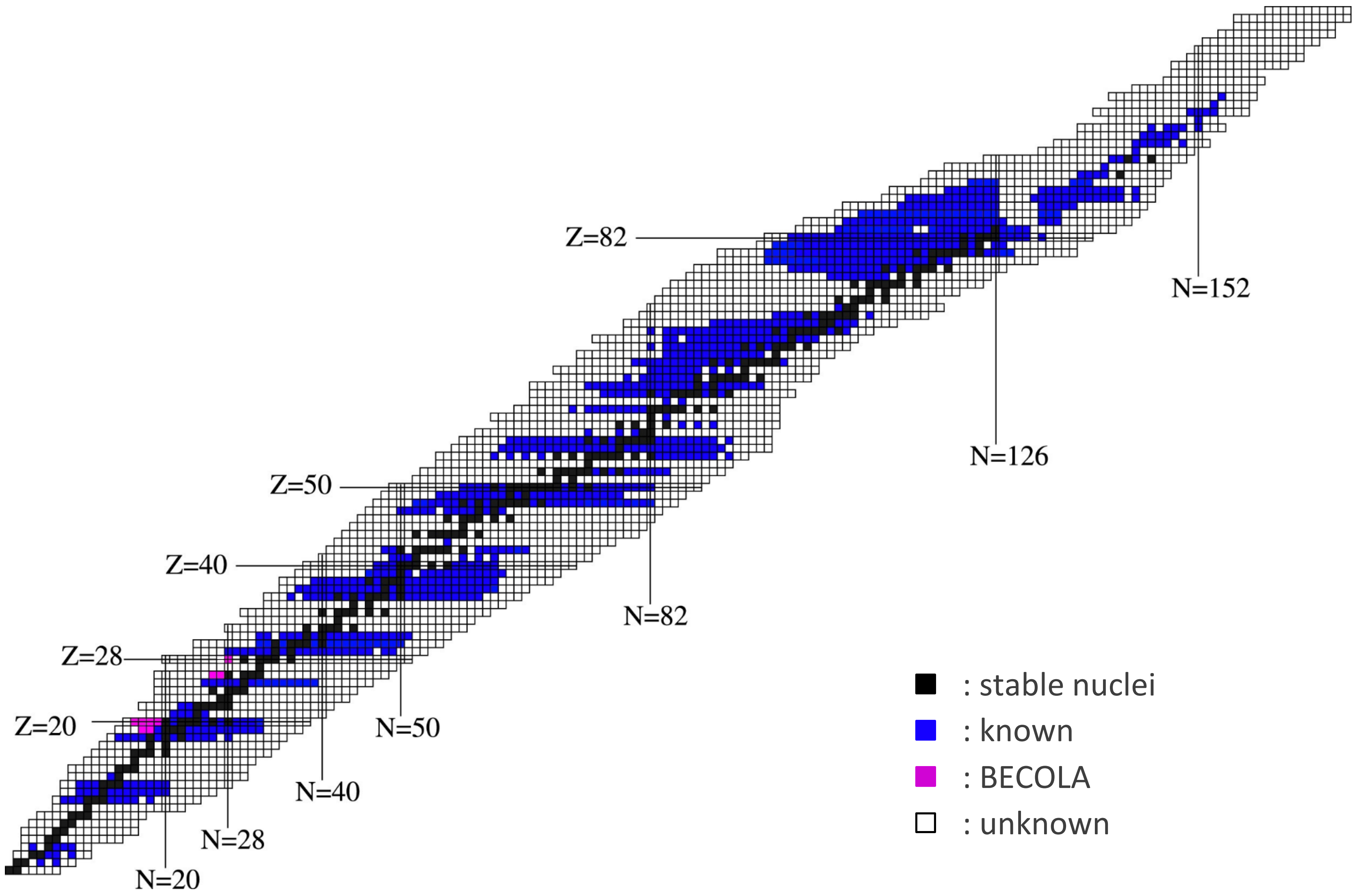
Kei Minamisono

LSTNT2019, CEA, France, October 7-11, 2019

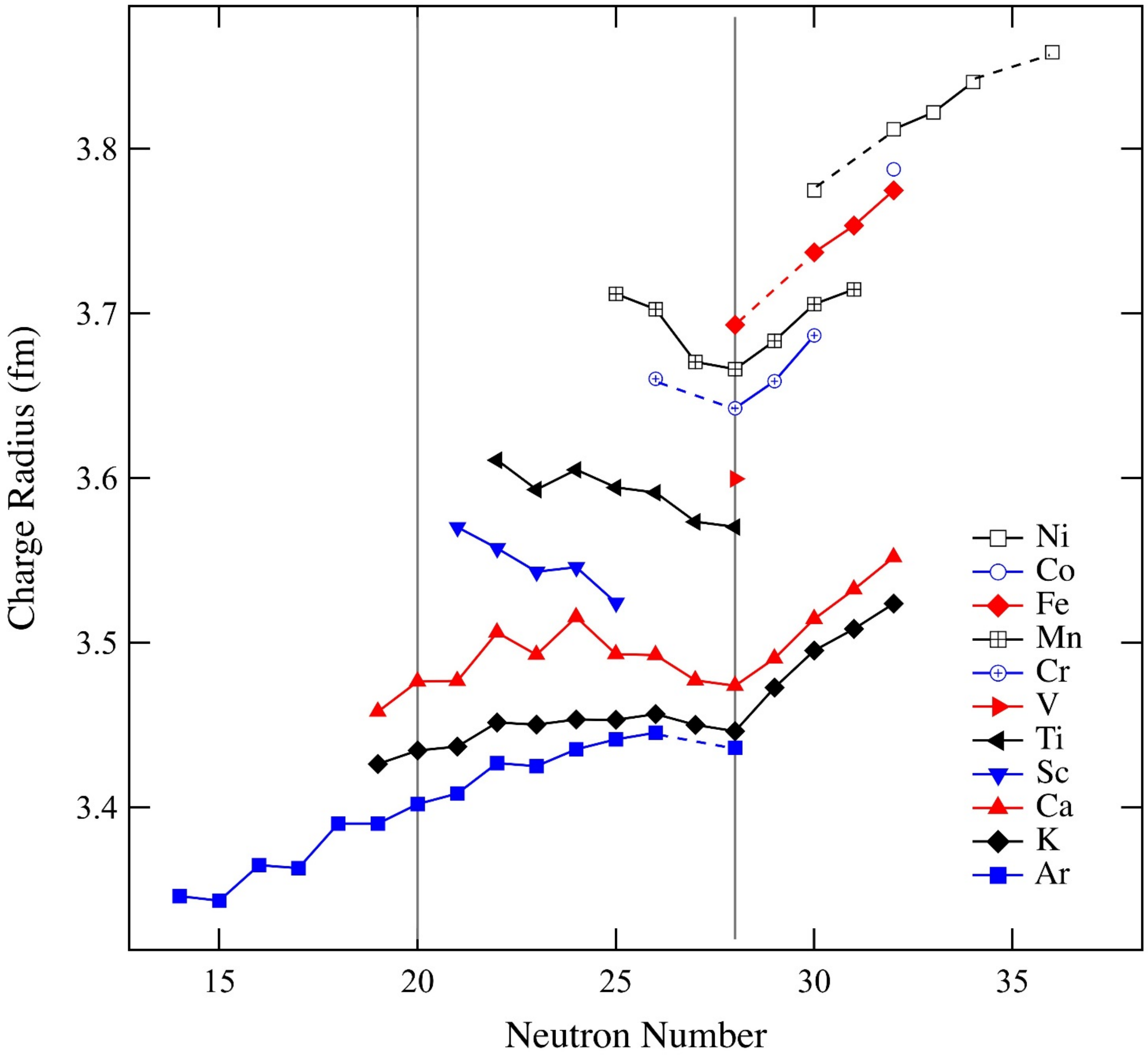
Plan of my talk

- Very brief introduction
- NSCL, and its transition to FRIB
- About BECOLA
- Some science cases
- Future prospects

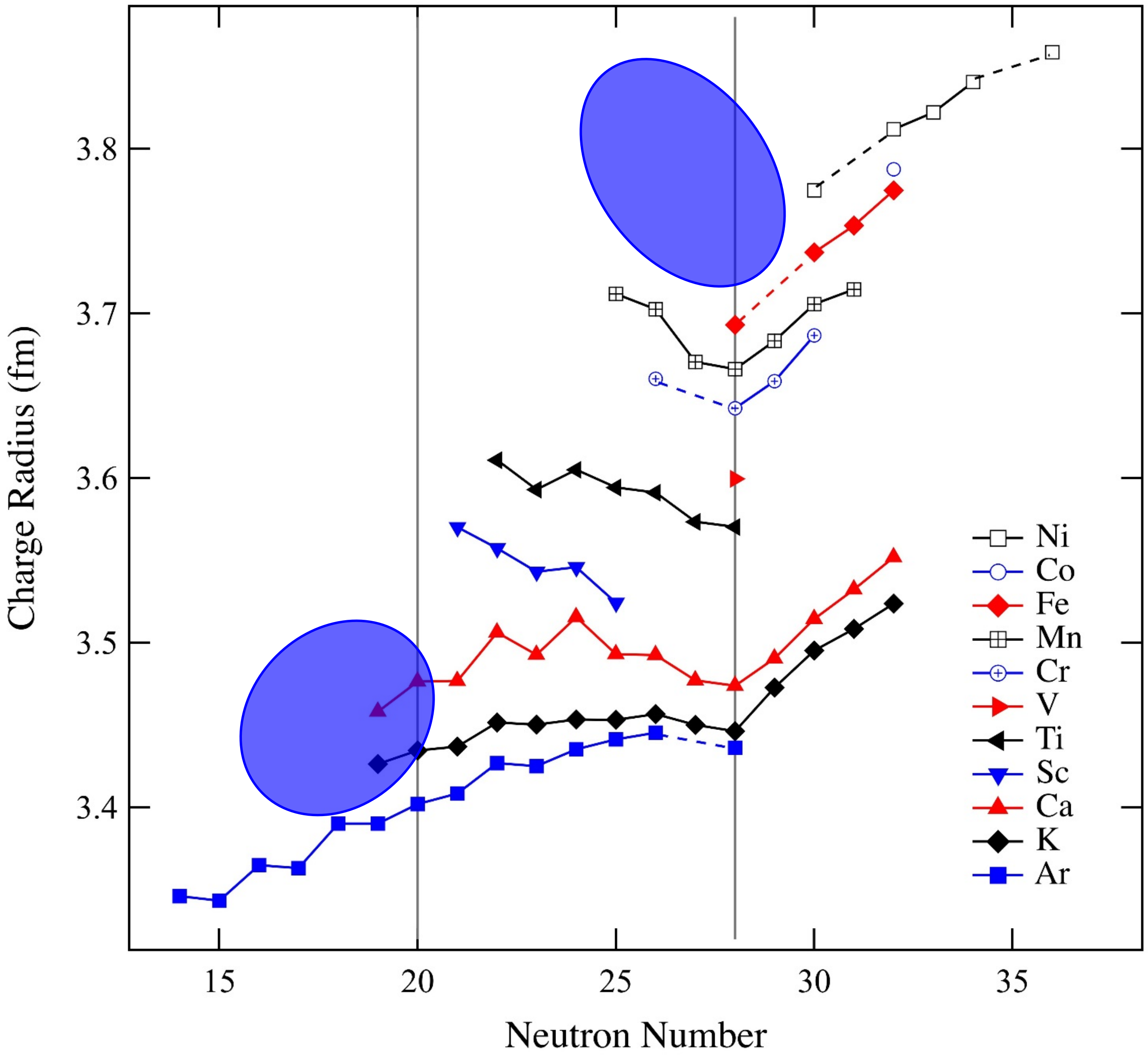
Laser spectroscopy experiments at BECOLA



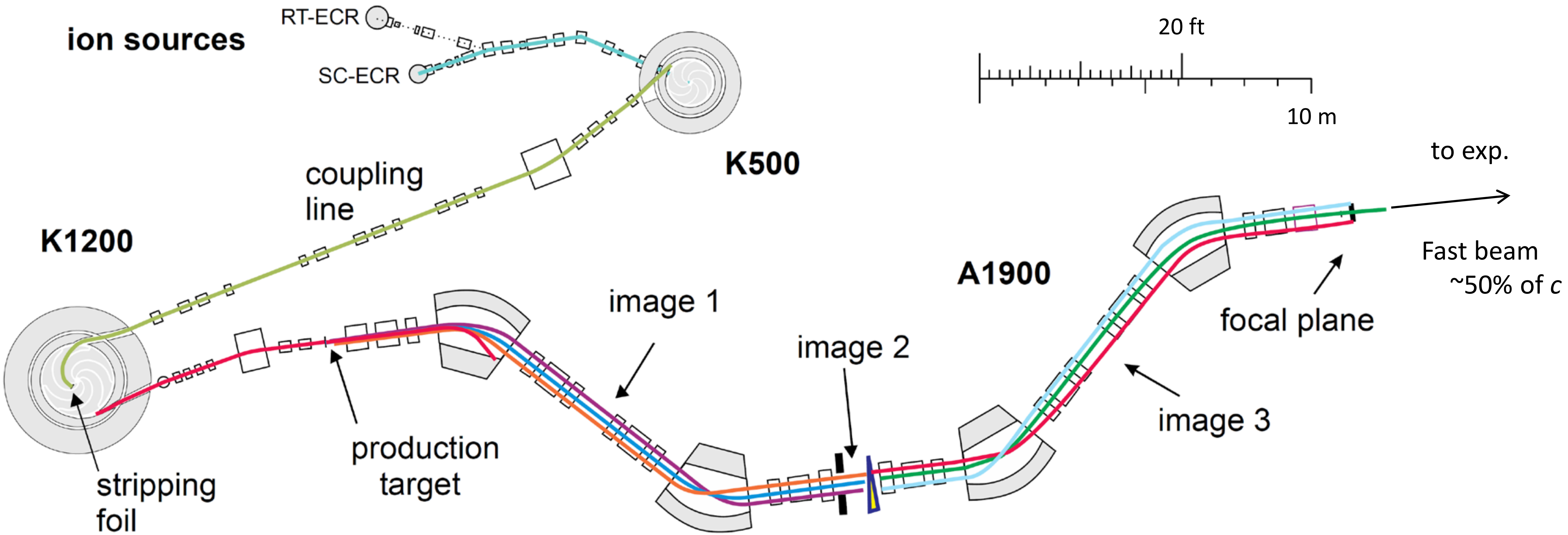
Recent interests: Ca & Ni at *N* = 20 & 28



Recent interests: Ca & Ni at N = 20 & 28



Coupled cyclotron facility at NSCL / MSU



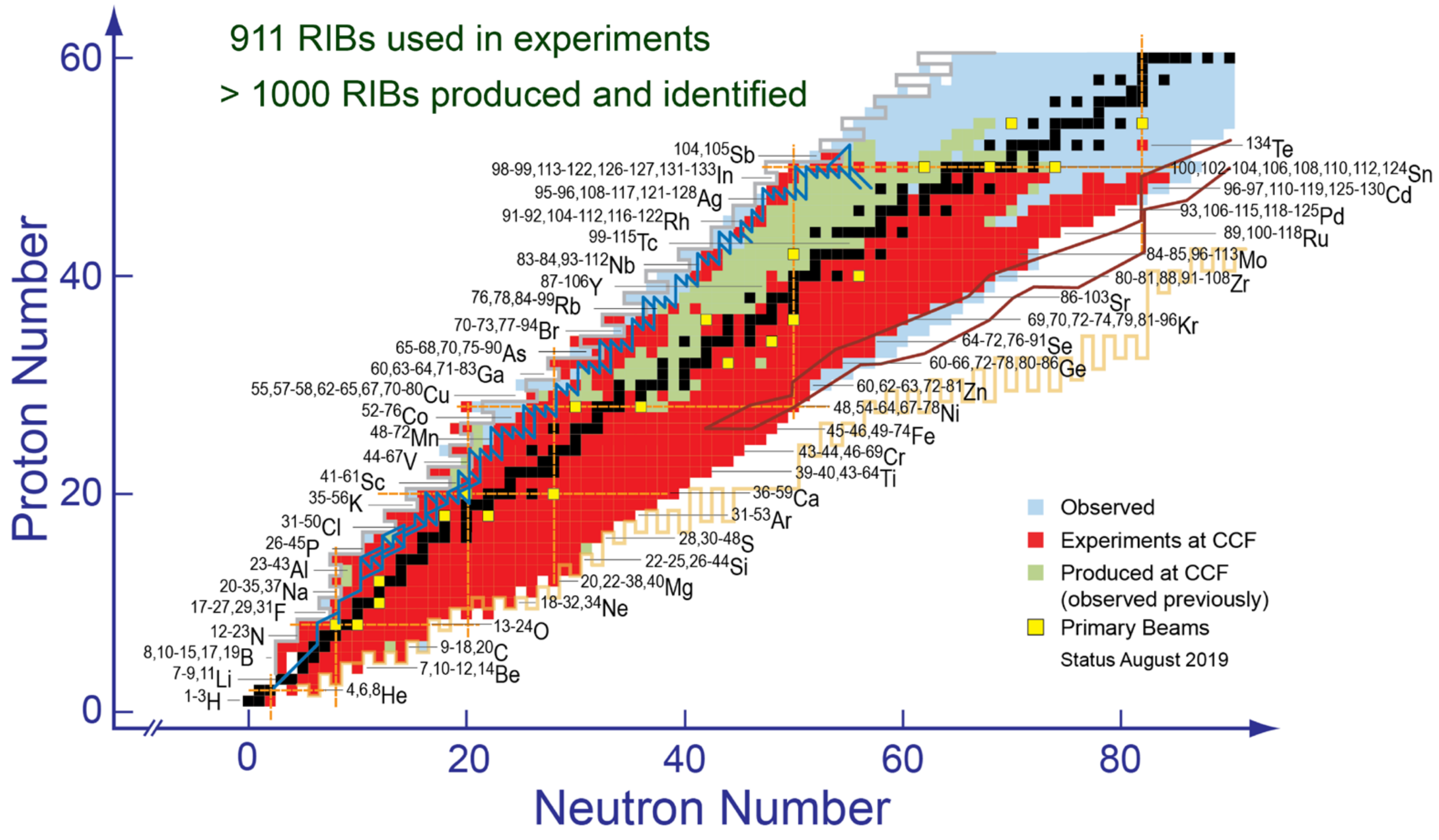
Projectile-fragment reactions

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

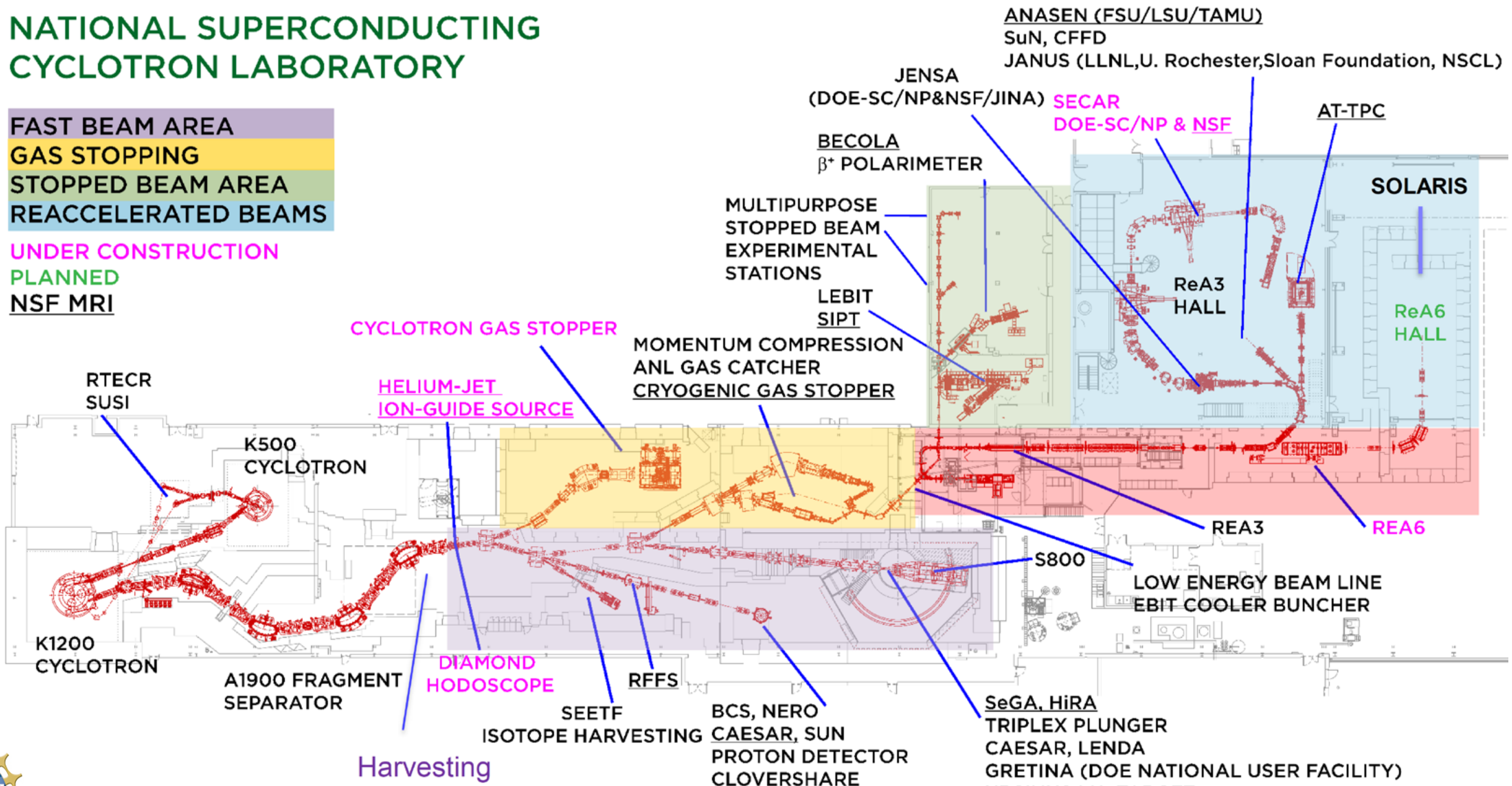
Good at

- Short lived isotopes
- Neutron-deficient side

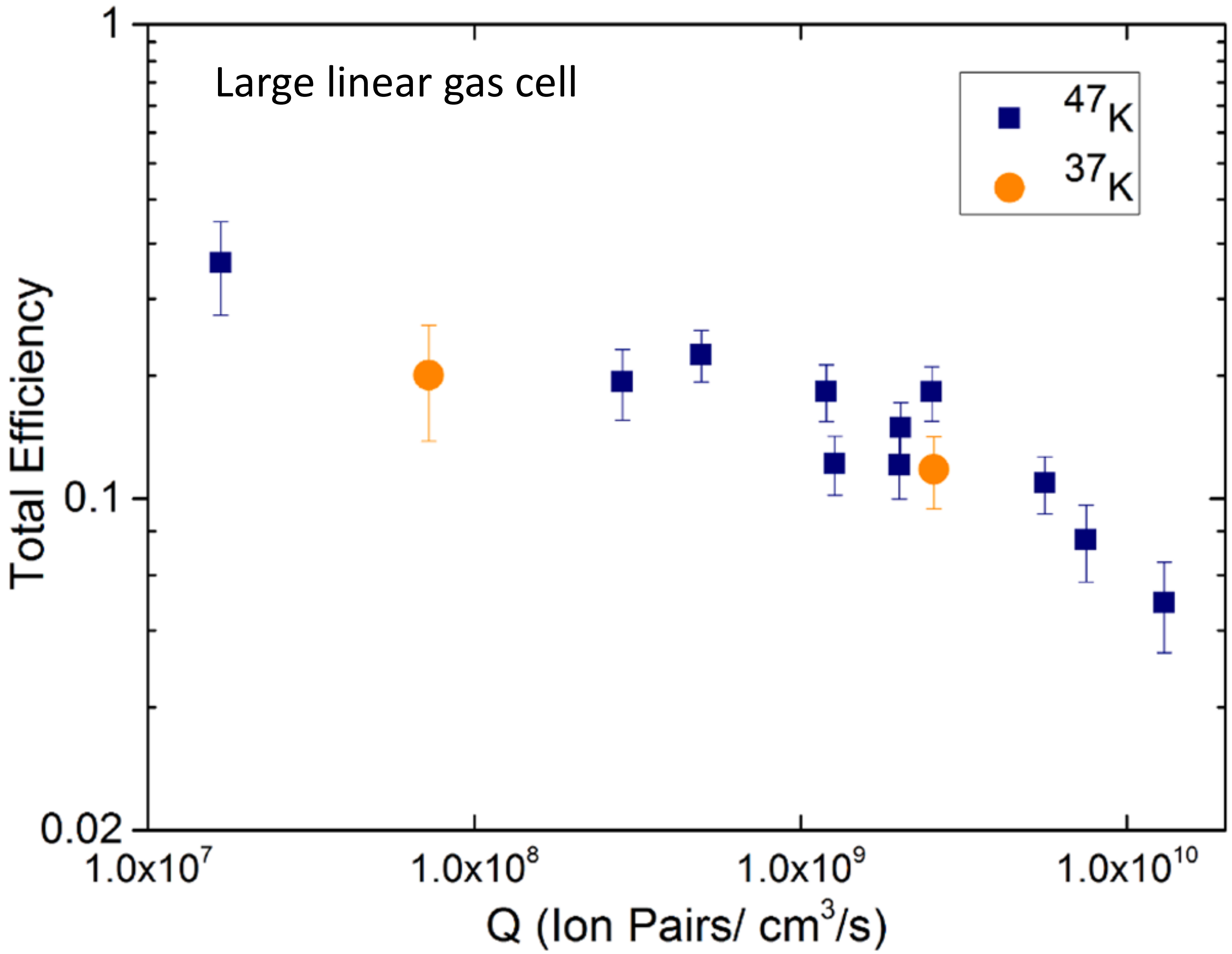
Production at NSCL



Current NSCL experimental layout

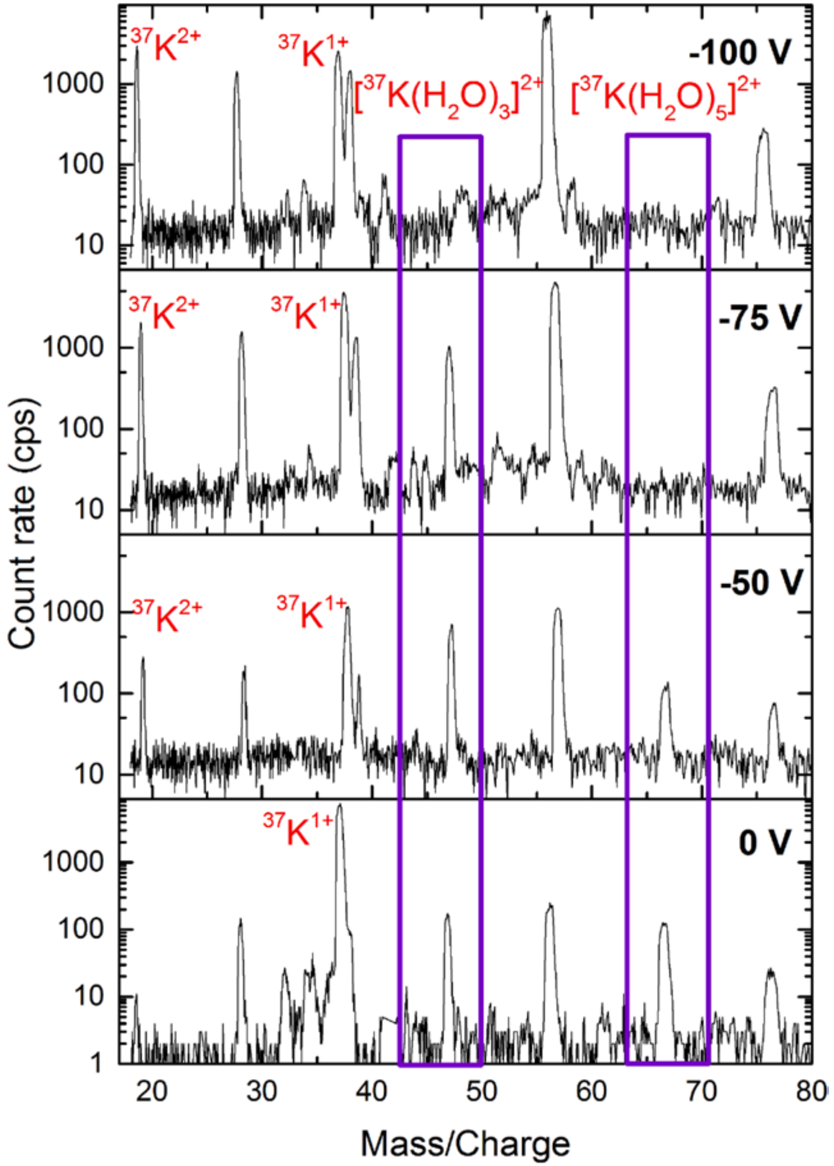


Gas stopping at NSCL



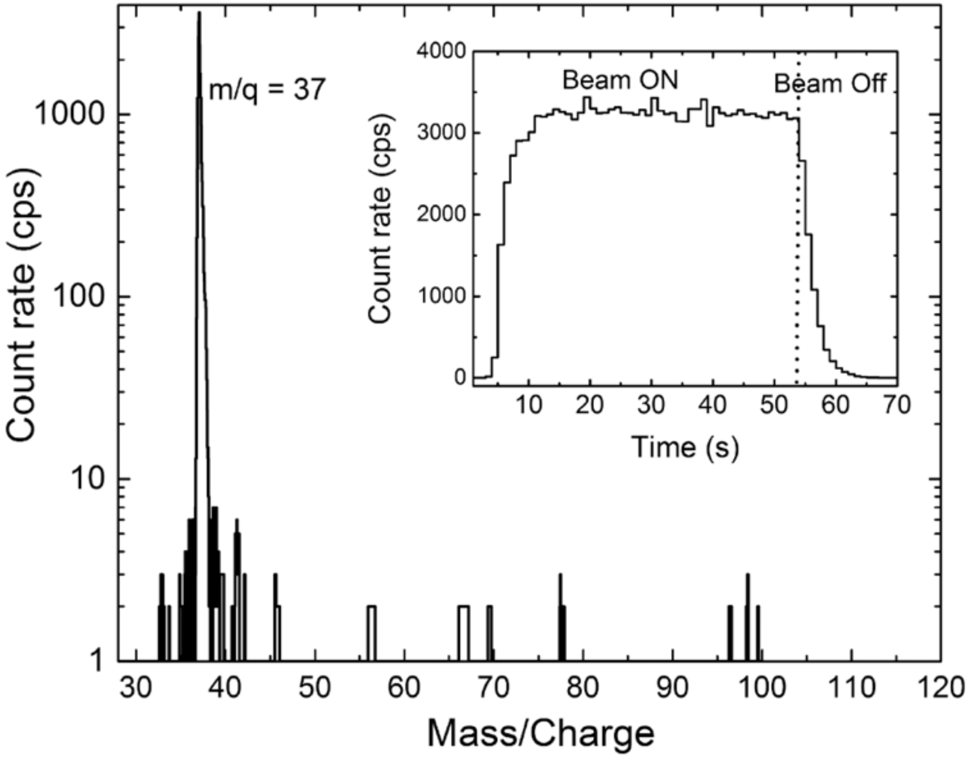
NSCL gas stopping team.
C. Sumithrarachchi et al., NIMB (https://doi.org/10.1016/j.nimb.2019.04.077).

Gas stopping at NSCL



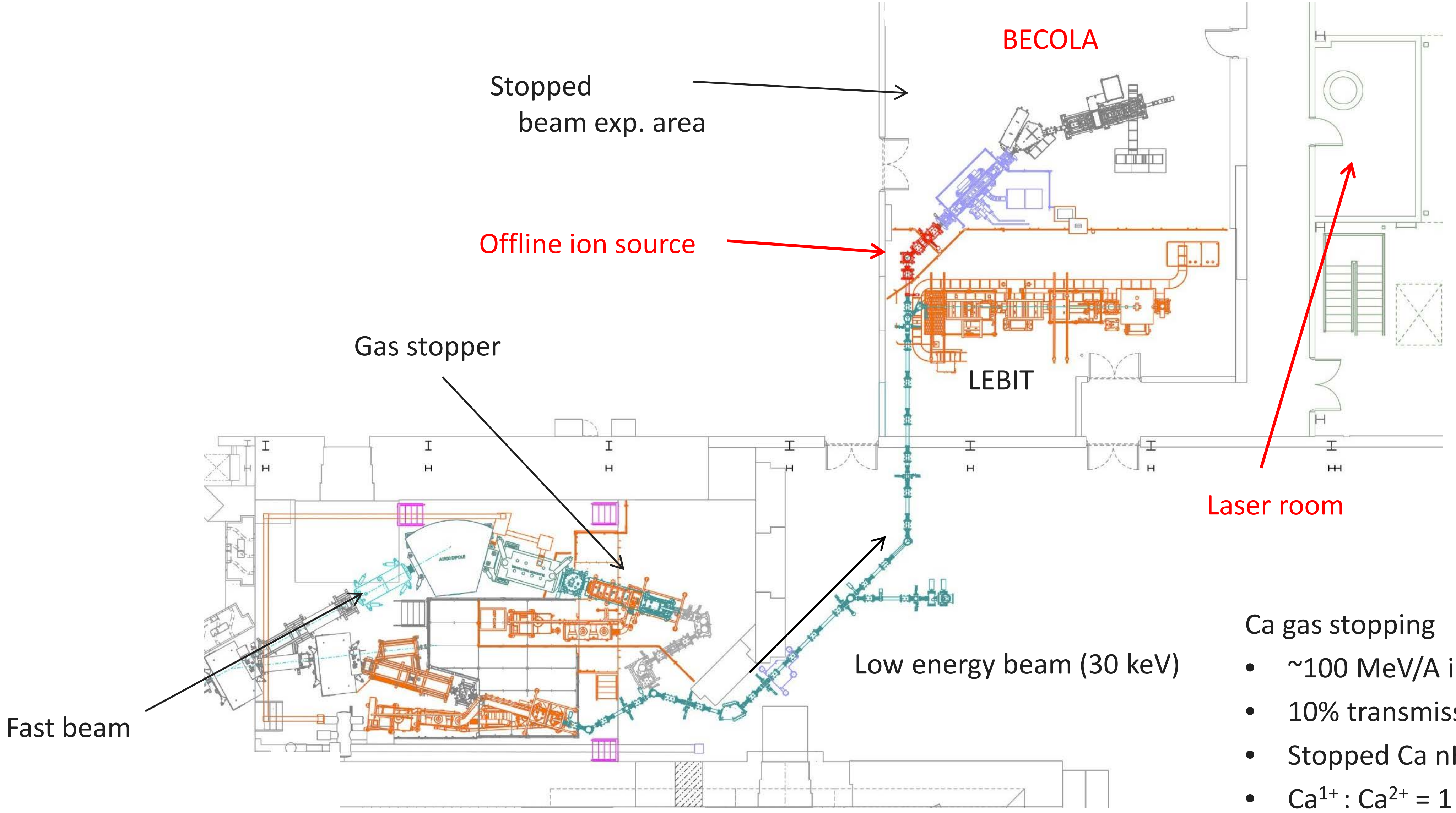
When the cell is “dirty”.

With “cleaner” cell condition



C. Sumithrarachchi et al., NIMB (https://doi.org/10.1016/j.nimb.2019.04.077).

Gas stopping & ion beam transport to BECOLA



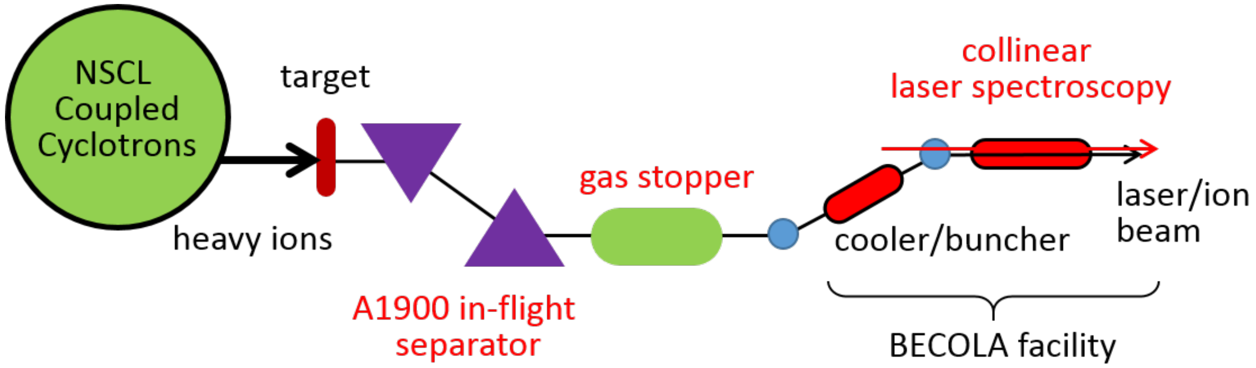
Ca gas stopping

- ~100 MeV/A injection
- 10% transmission efficiency
- Stopped Ca nH_2O attached
- Ca^{1+} : Ca^{2+} = 1 : 1 after CID

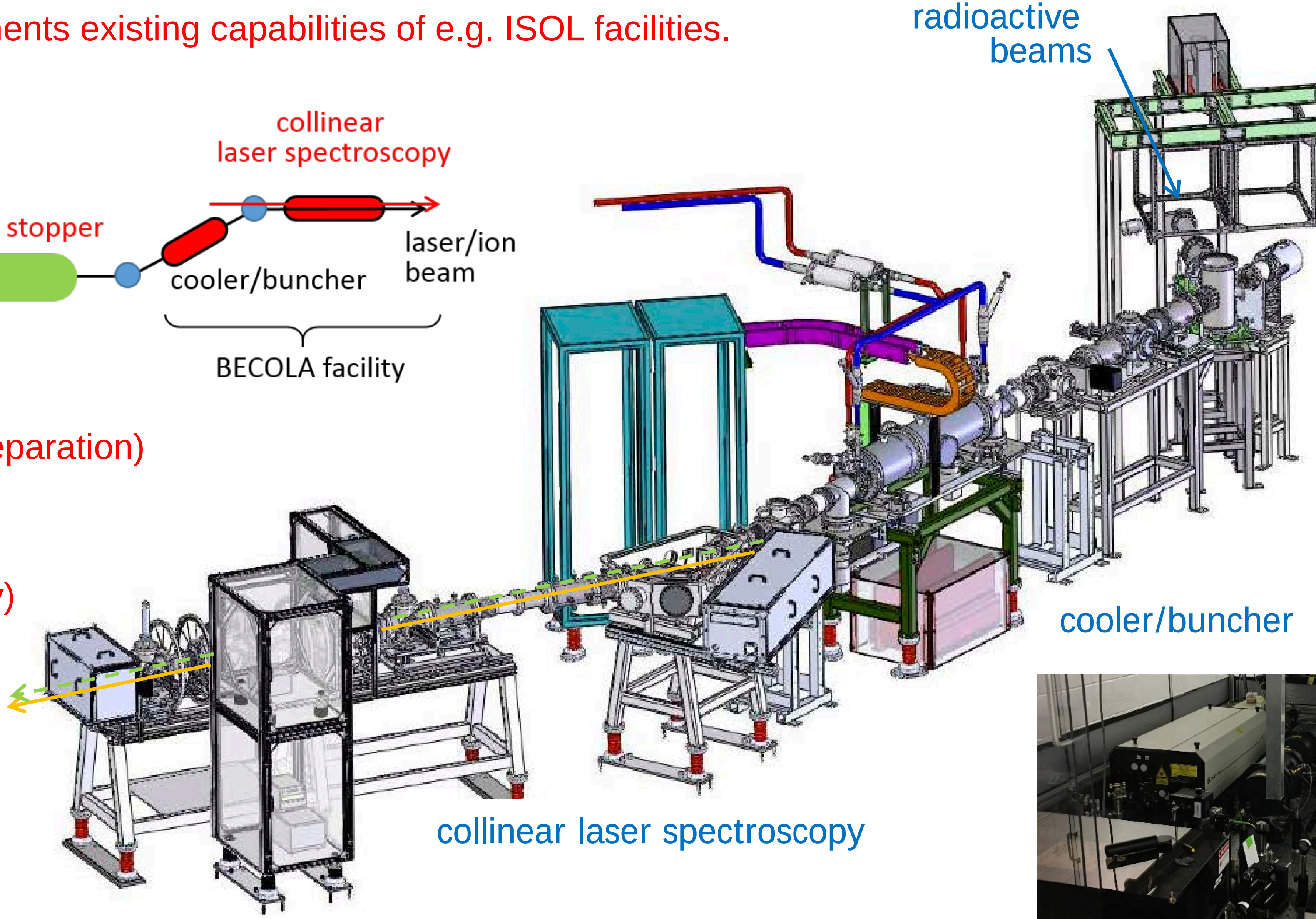
gas stopper: K. Cooper et al., NIMA763, 543 (2014).

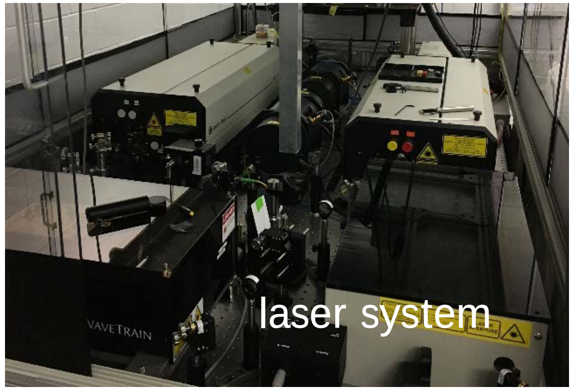
BECOLA facility @ NSCL / MSU
- Bunched beam collinear laser spectroscopy -

The production scheme complements existing capabilities of e.g. ISOL facilities.



- Shorter lived isotopes (fast separation)
- Neutron-deficient nuclei
- Transition metals
  elements (no chemistry)



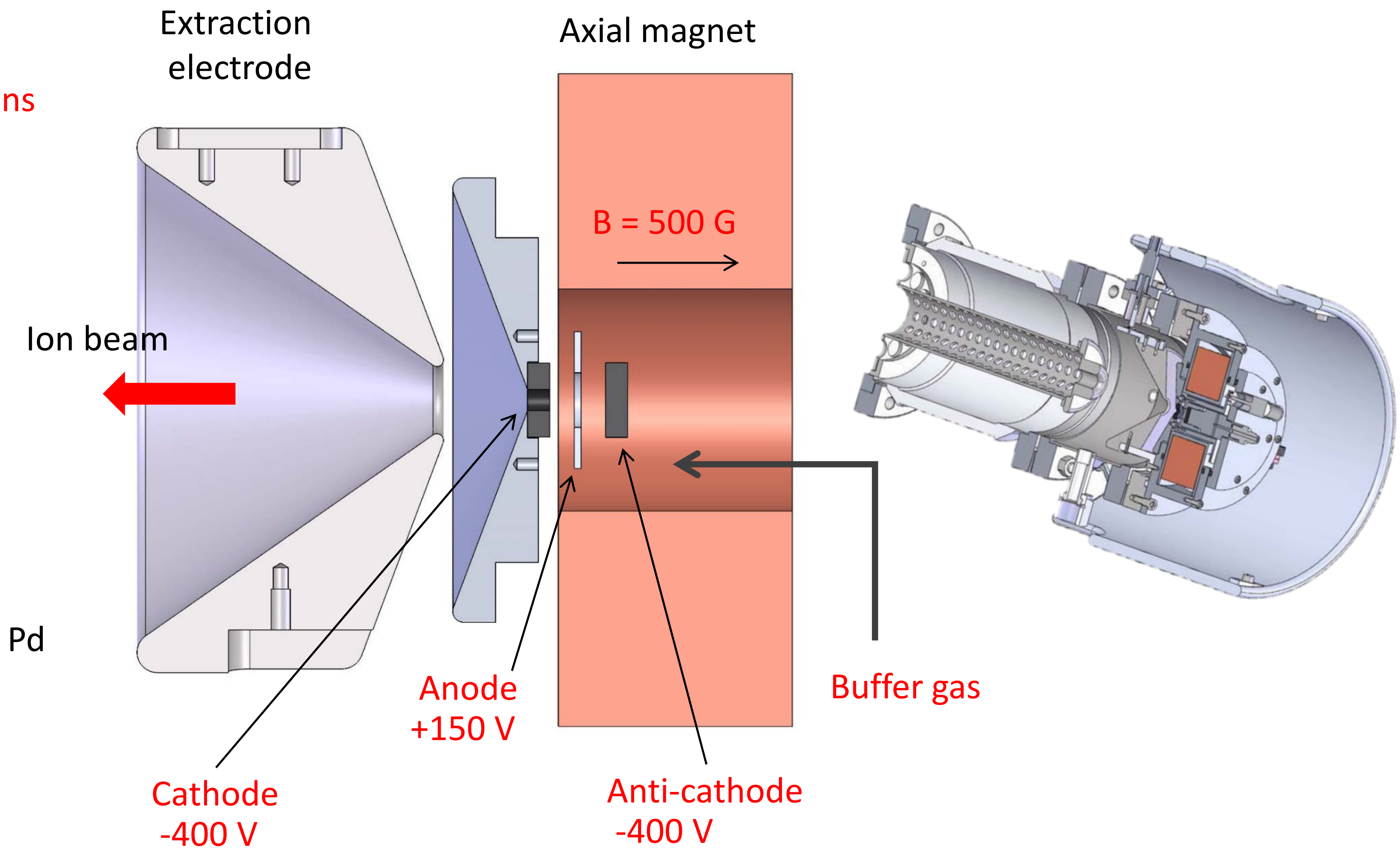


K. Minamisono et al, NIMA 709, 85 (2013);
D. M. Rossi, K. M. et al., RSI 85, 093503 (2014).

Penning ionization gauge (PIG) ion source

Critical for offline testing and online cariblations

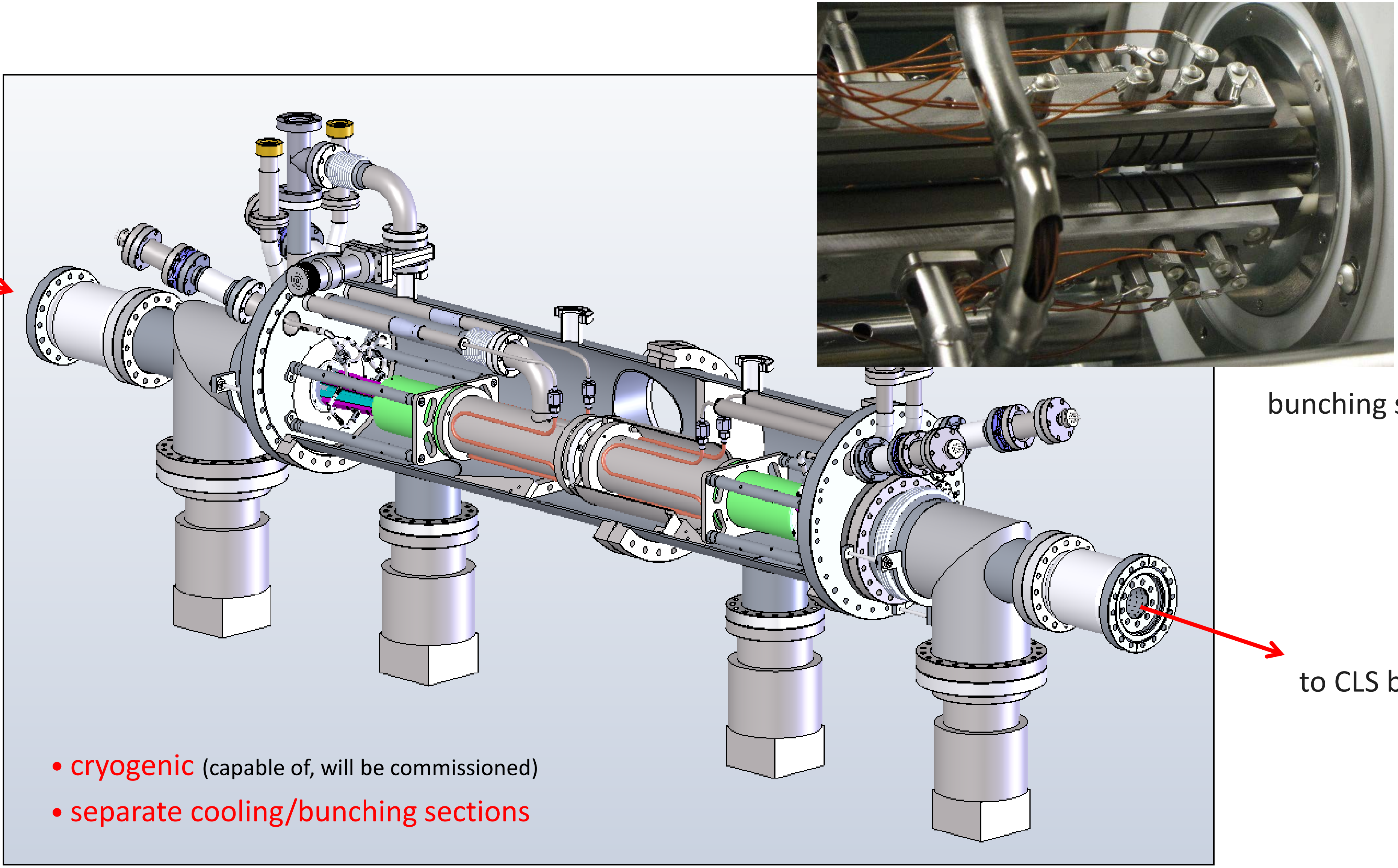
- Plasma/discharge sputter source
- generates ions from
  - cathodes
  - buffer gas
- He, Ne, Ar, Ca, Sc, Mn, Fe, Ni, Zr, Sn, Pd



C. A. Ryder et al, Spectrochim. Acta B113, 16 (2015).

BECOLA cryogenic cooler / buncher

low energy beam



bunching section

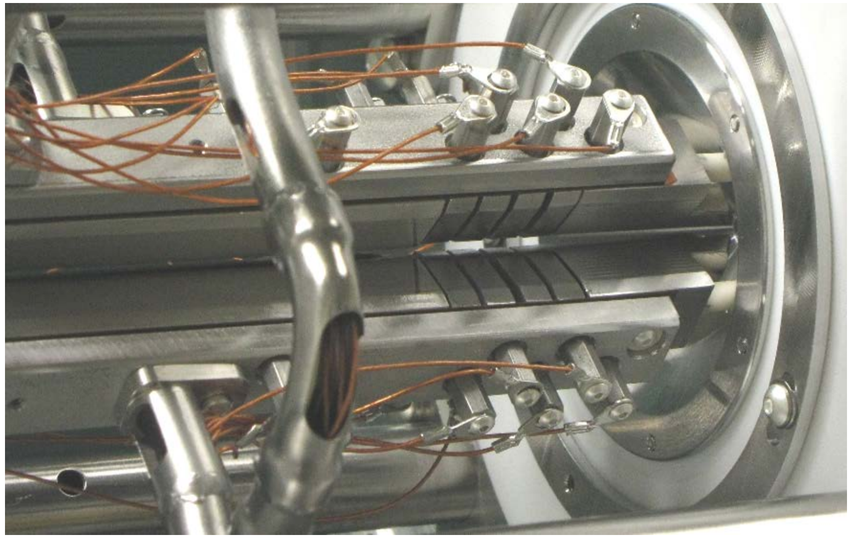
to CLS beam line

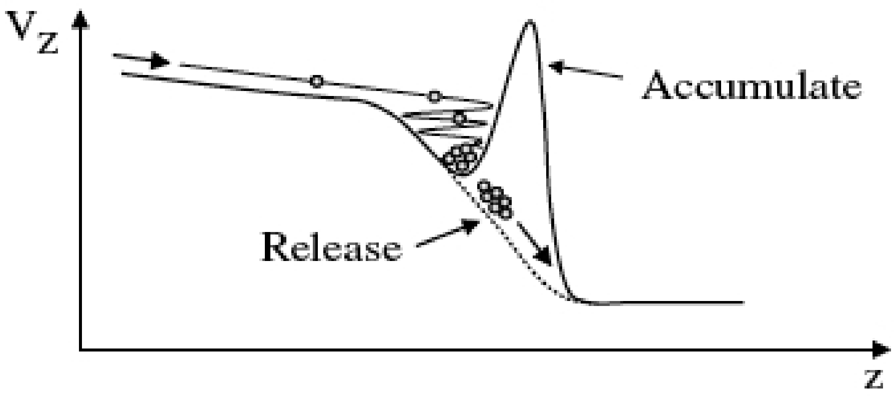
- cryogenic (capable of, will be commissioned)
- separate cooling/bunching sections

B. R. Barquest et al., NIMA 866, 18 (2017).

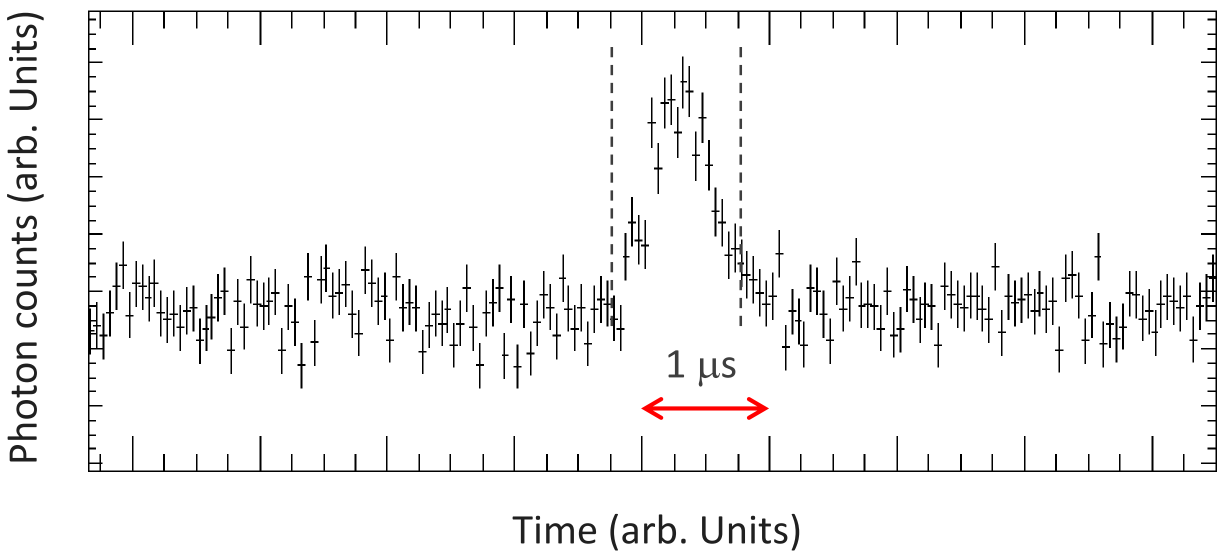
High sensitivity: bunched beam CLS

RFQ bunching section





Time spectrum of 30 keV $^{36}Ca(T_{1/2} = 102$ ms)

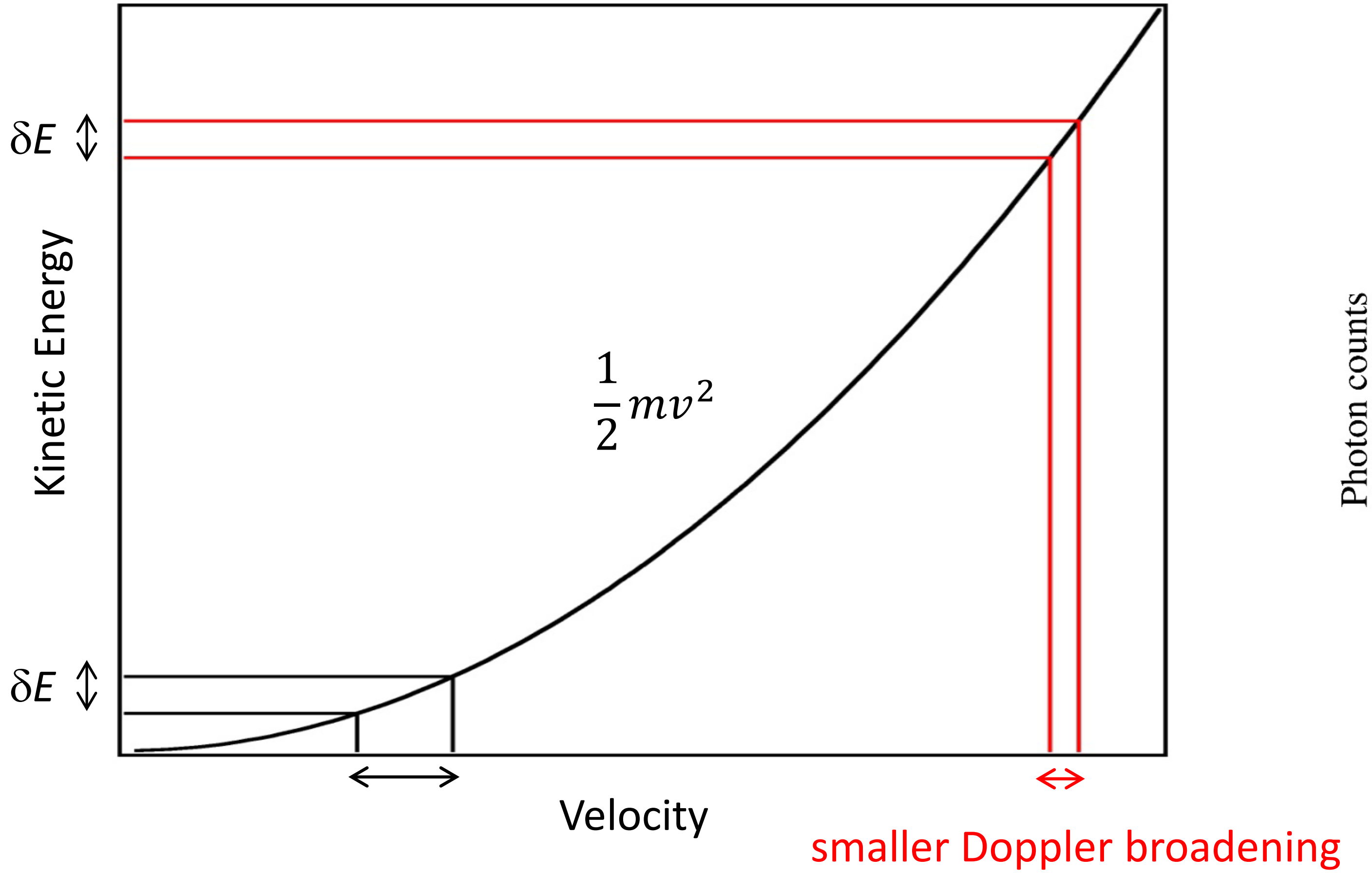


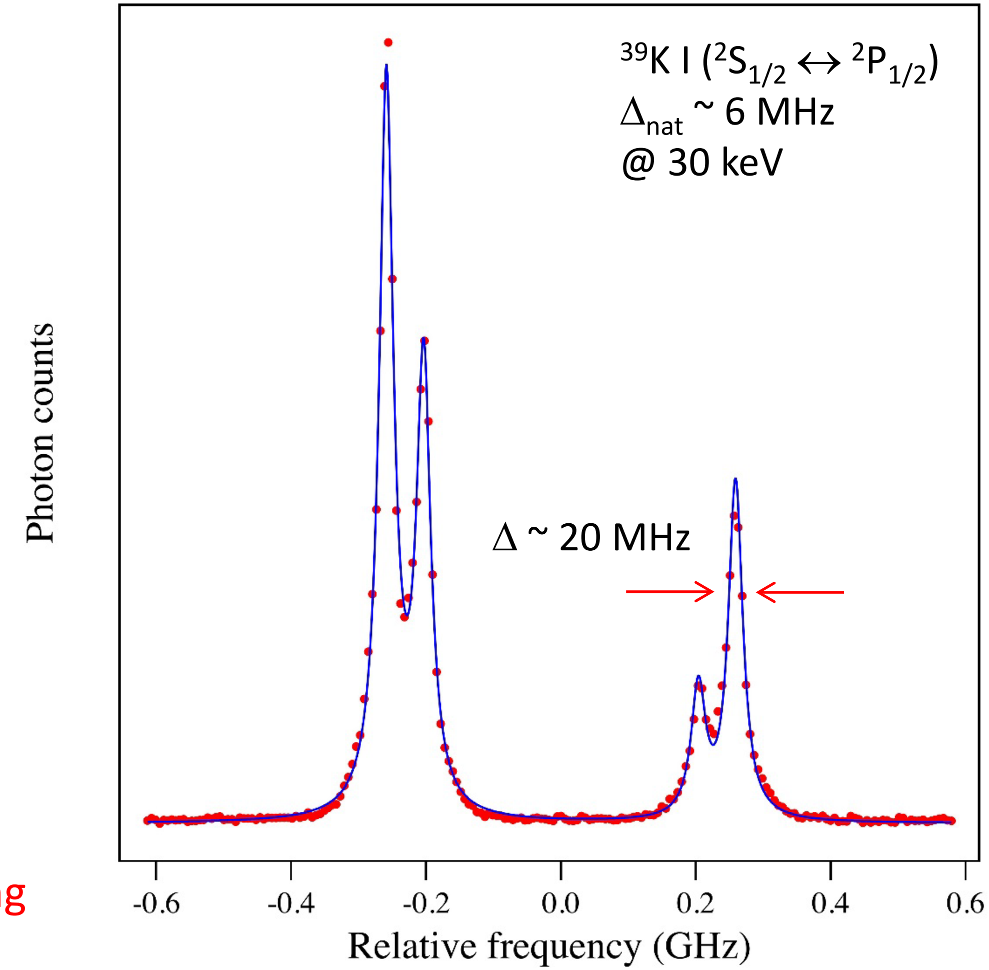
Bunched beam CLS

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

B. R. Barquest et al., NIMA 866, 18 (2017);
P. Campbell et al., PRL 89, 082501 (2002);
A. Nieminen et al., PRL 88, 094801 (2002).

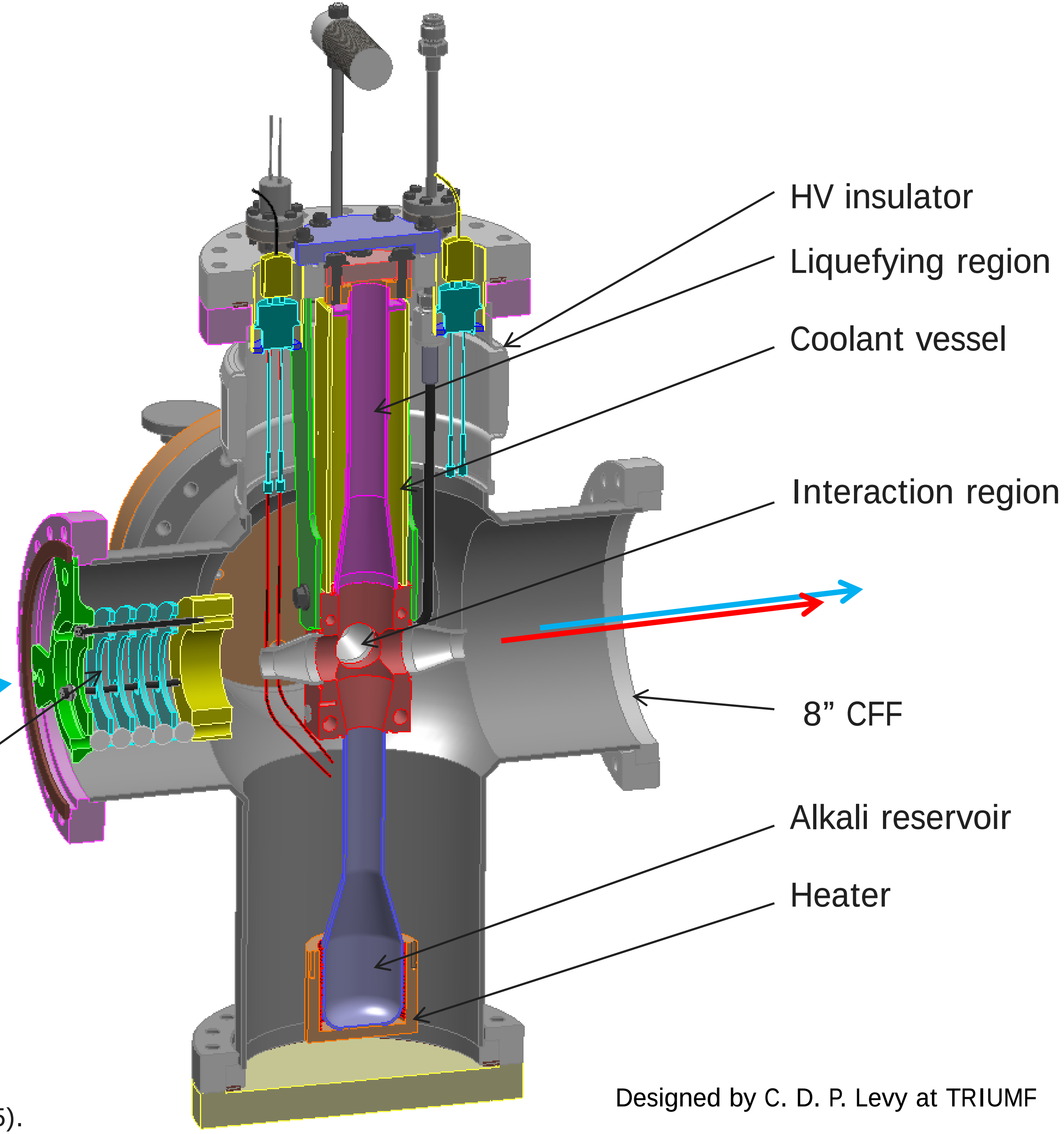
High resolution: kinematical compression (velocity bunching)





S. L. Kaufman, Optic. Comm. 17, 309 (1976).

CEC



A. Klose, K.M. et al., NIMA678, 114 (2012);
A. Klose, K.M. et al., PRA 88, 042701 (2013);
C. A. Ryder, K.M. et al., Spectrochim. Acta B 113, 16 (2015).

Designed by C. D. P. Levy at TRIUMF

Atomic charge exchange

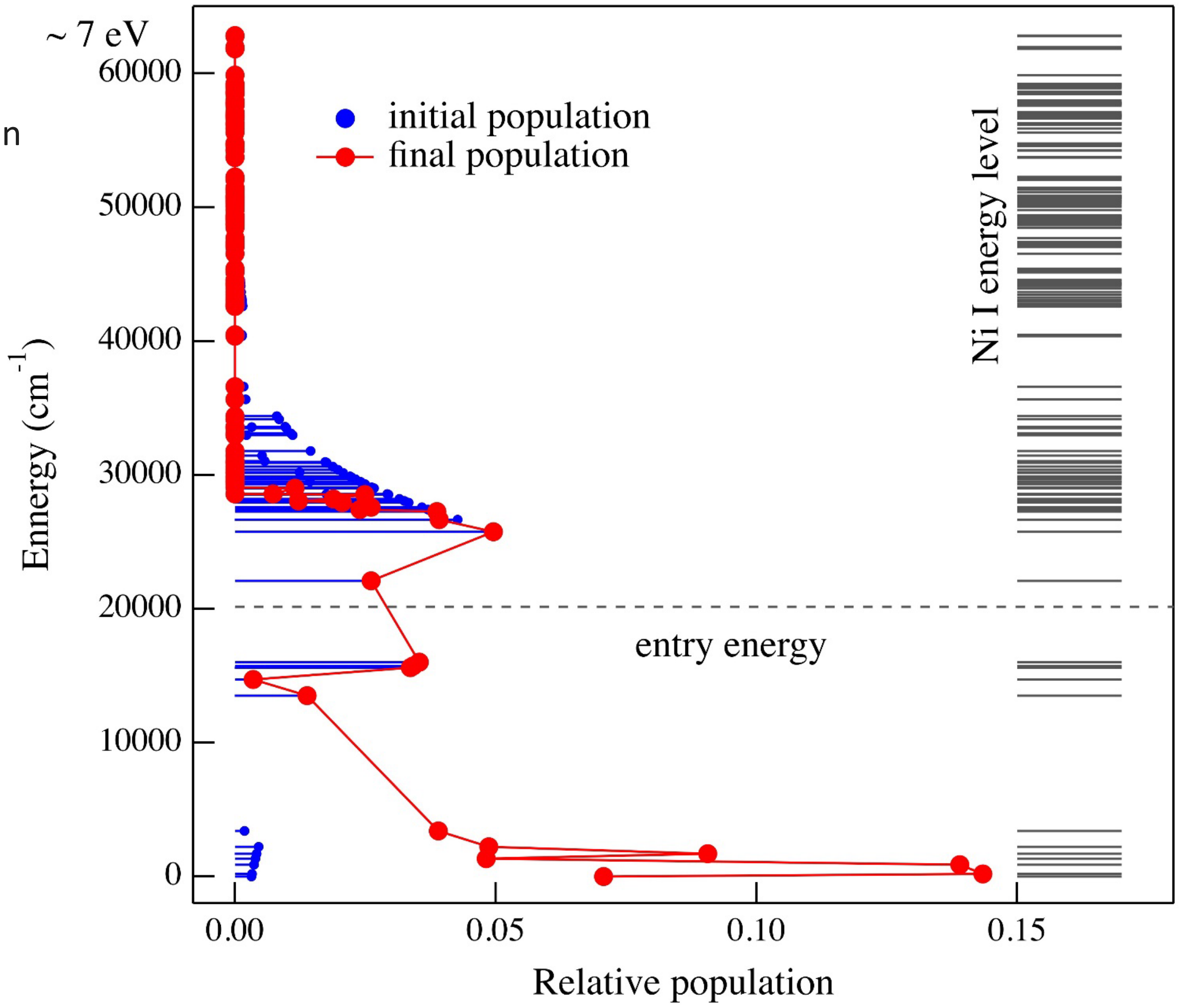
- charge exchange with Na vapor

  $Ni^{+} + Na \rightarrow Ni + Na^{+} + \Delta E$
- High atomic energy-level density of Ni leads to severe fractionalization of population

→ Small signal for laser spectroscopy

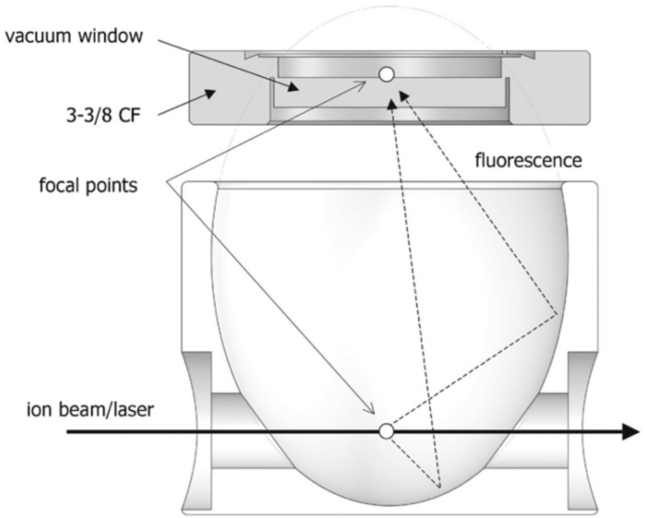
- Common issue for transition metal elements
- In Ni experiment only 15% was probed

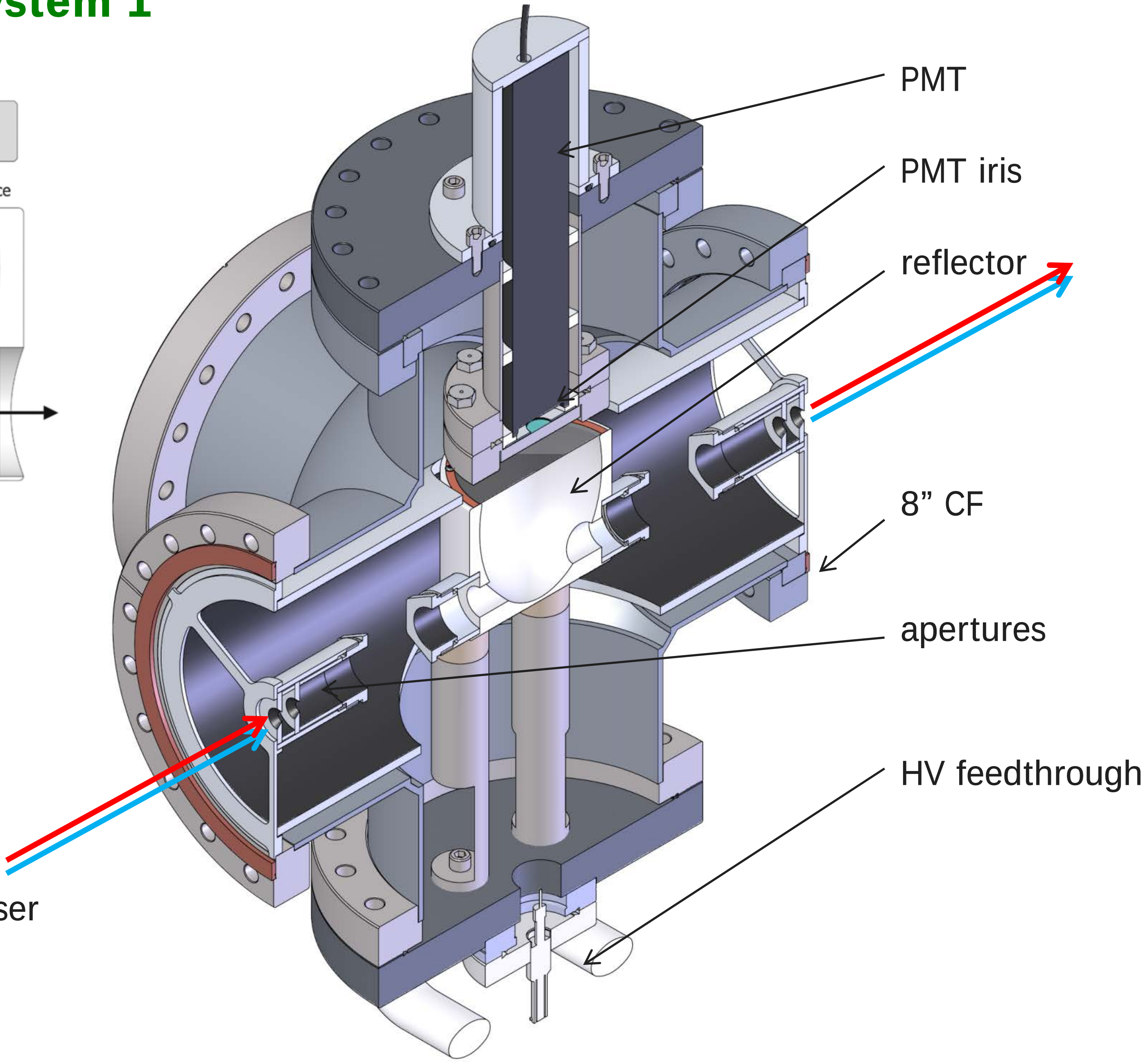
Simulation: 30 keV Ni^{+} on Na vapor



C. A. Ryder et al, Spectrochim. Acta B 113, 16 (2015).

Photon detection system 1

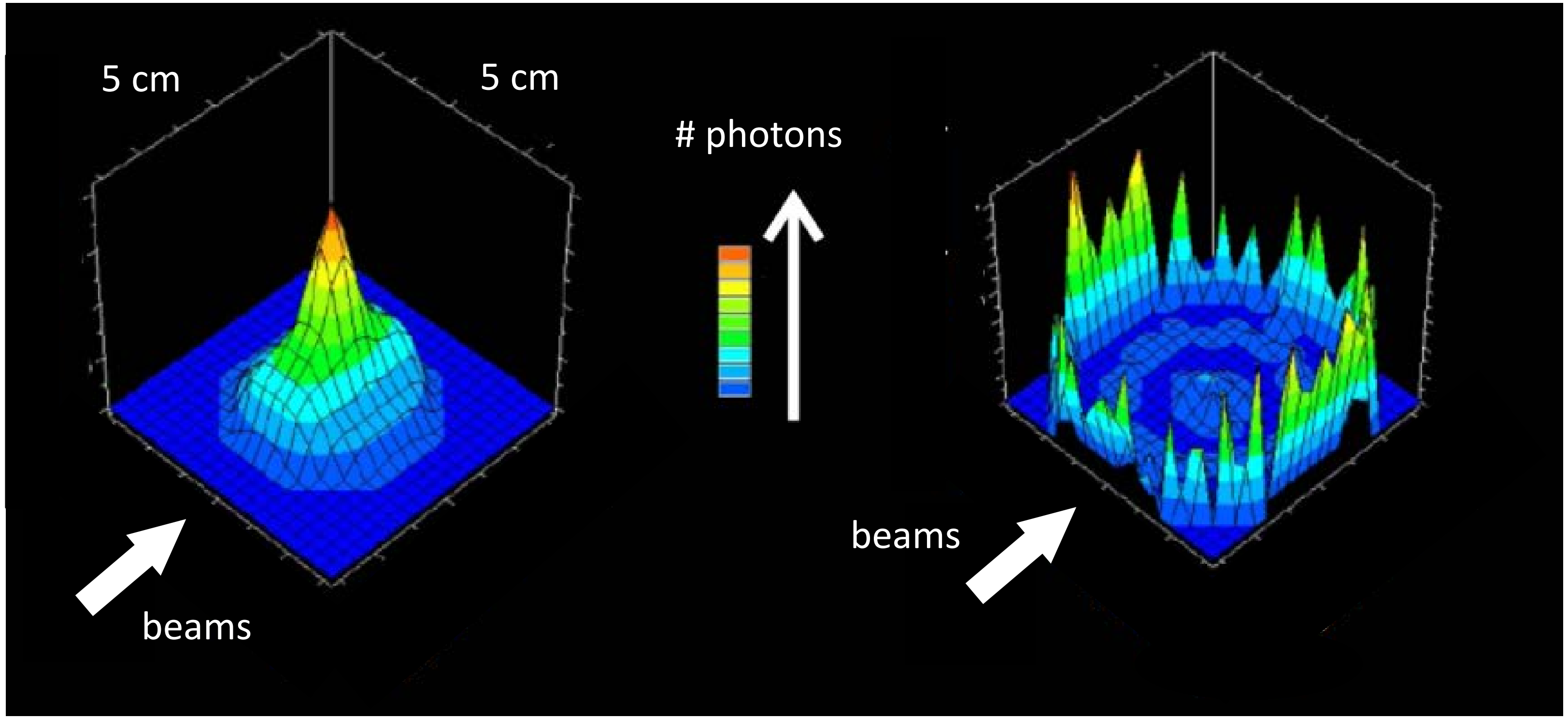




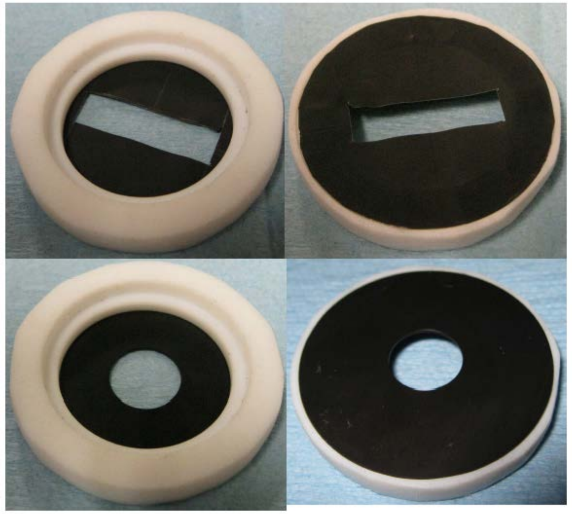
In collaboration with W. Nörtershäuser, J. Krämer;
K. Minamisono et al, NIMA 709, 85 (2013).

Photon detection system 1: ellipsoidal reflector

Ellipsoidal reflector
simulation: at the detection plane



signal background

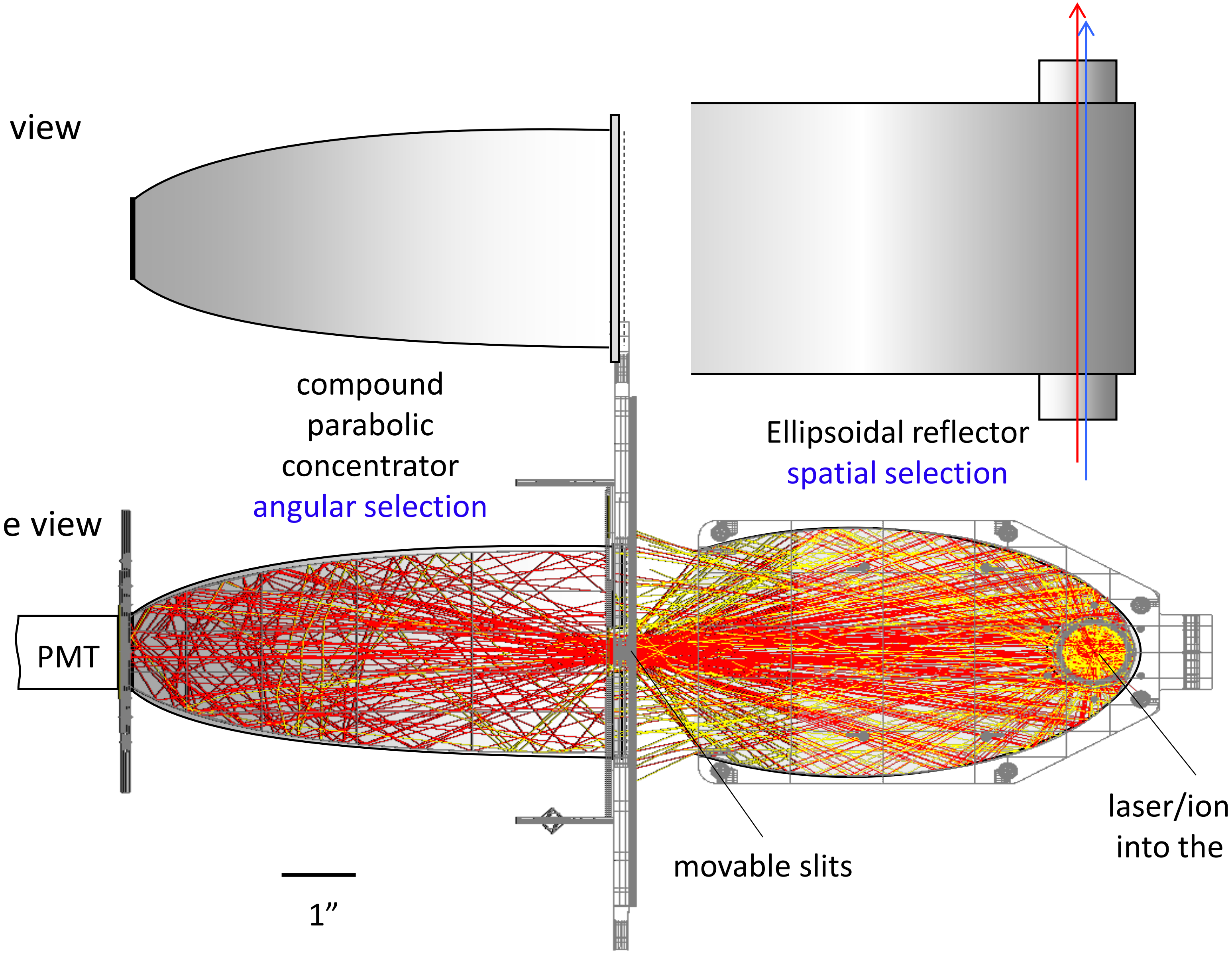


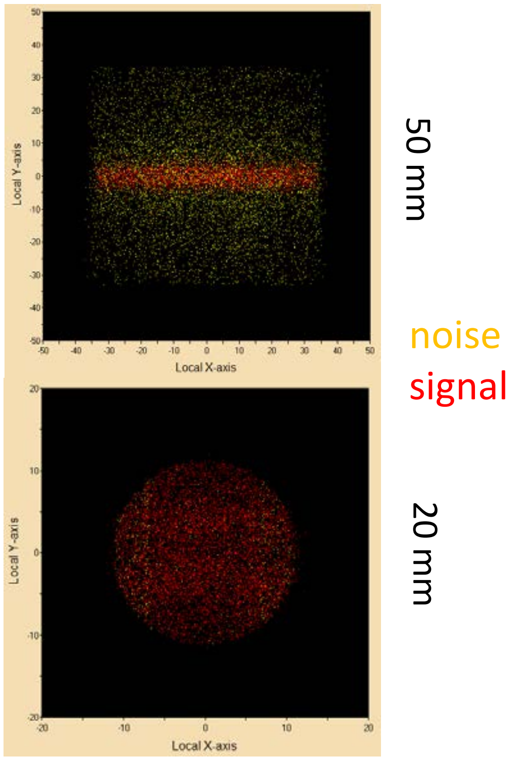
apertures

- Large solid angle
- Maximizing signal
- Relatively large background
- Wins **S**/N

FRED optical engineering software: http://www.photonengr.com/

Photon detection system 2

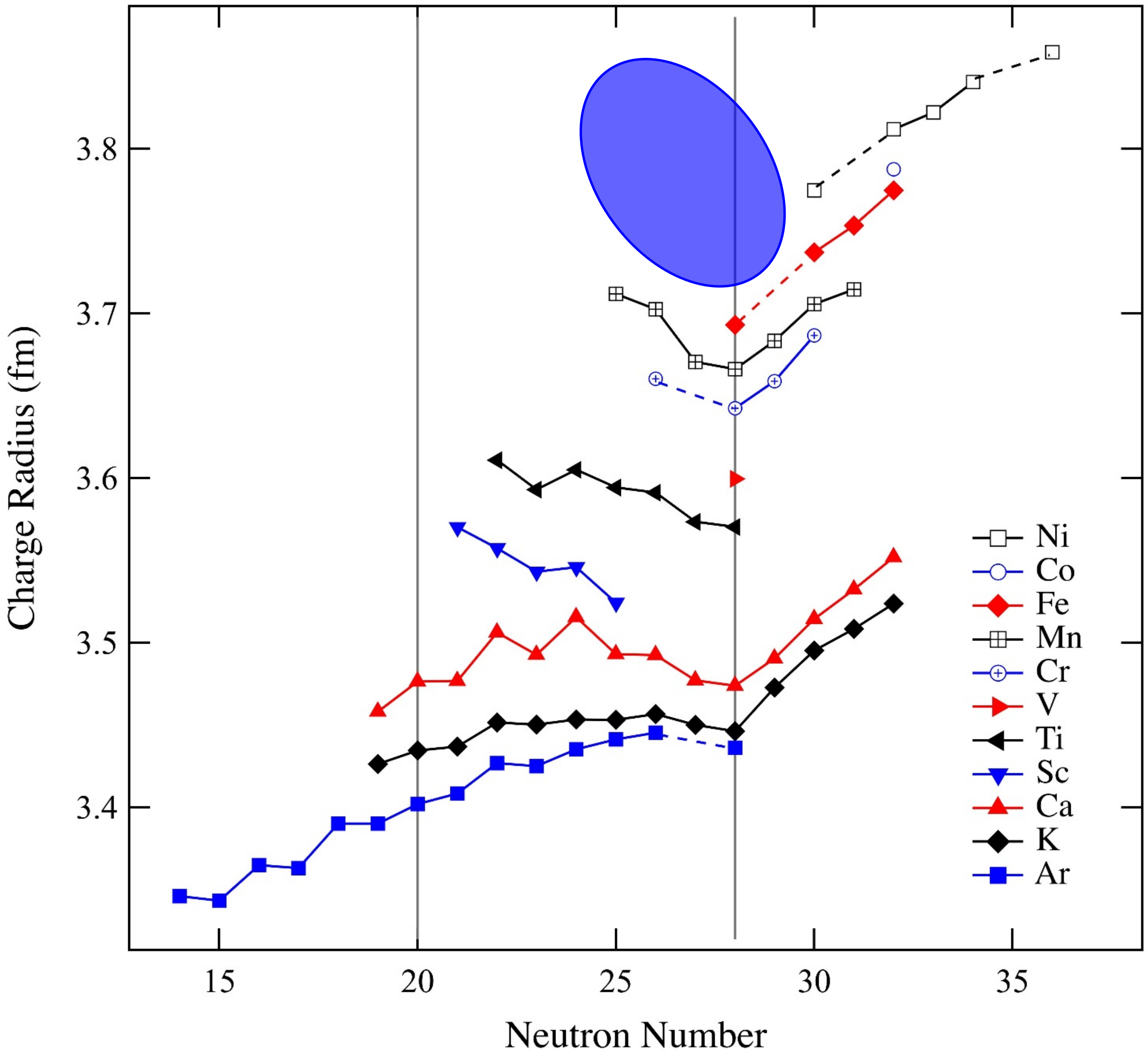




- Filter background
- Minimizing background
- Relatively small signal
- Wins *S*/***N***

In collaboration with W. Nörtershäuser, M. Hammen, B. Maaß.
FRED optical engineering software: http://www.photonengr.com/

Current interests: Ca & Ni at *N* = 20 & 28



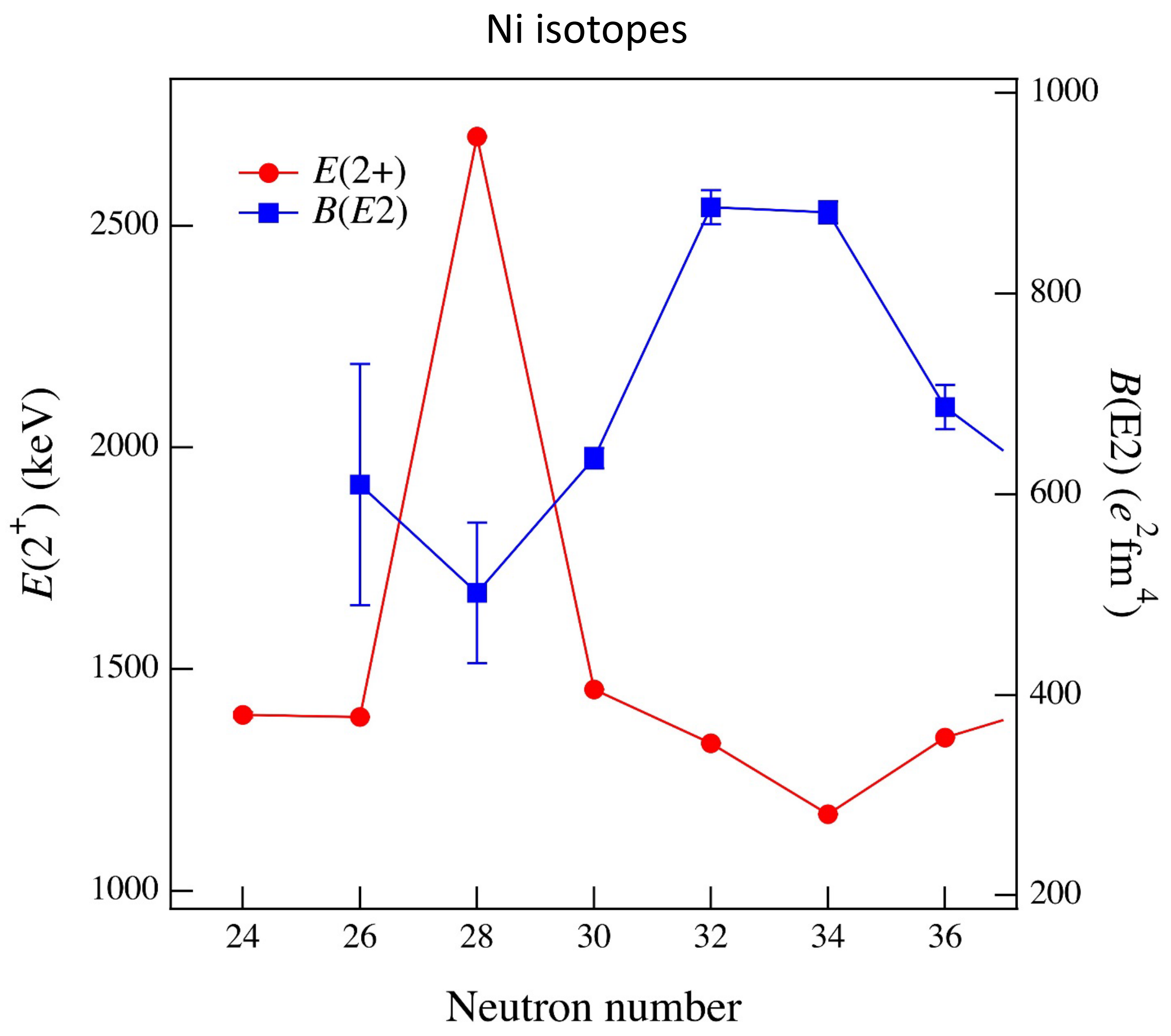
^{56}Ni nucleus is "soft"

- High $E(2^+_1)$, but no significant change in $B(E2)$
  - Canonical ^{56}Ni nucleon configuration: 50% in *fp* shell with FPD6

- Magnetic moment of ^{56}Ni ± one nucleon nucleus (^{55}Ni, ^{55}Co, ^{57}Cu, ^{57}Ni)
  - Canonical ^{56}Ni nucleon configuration: 60% in *fp* shell with GXPF1

➡ What about the charge radius?

size, shape and deformation



M. Honma et al., PRC69, 034335 (2004); T. Otsuka et al., PRL81, 1588 (1998);
Data compilation: B. Pritychenko et al., ADNDT107, 1 (2016).

Isotope shift ^{52,53}Fe & ^{56}Fe

$\delta\nu^{56,52} = -1834 \pm 3 \pm 3$ (MHz)

$\delta\nu^{56,53} = -1249 \pm 4 \pm 3$ (MHz)

Theory + King plot

$F = -0.52 \pm 0.08$ (GHz/fm^2): theory

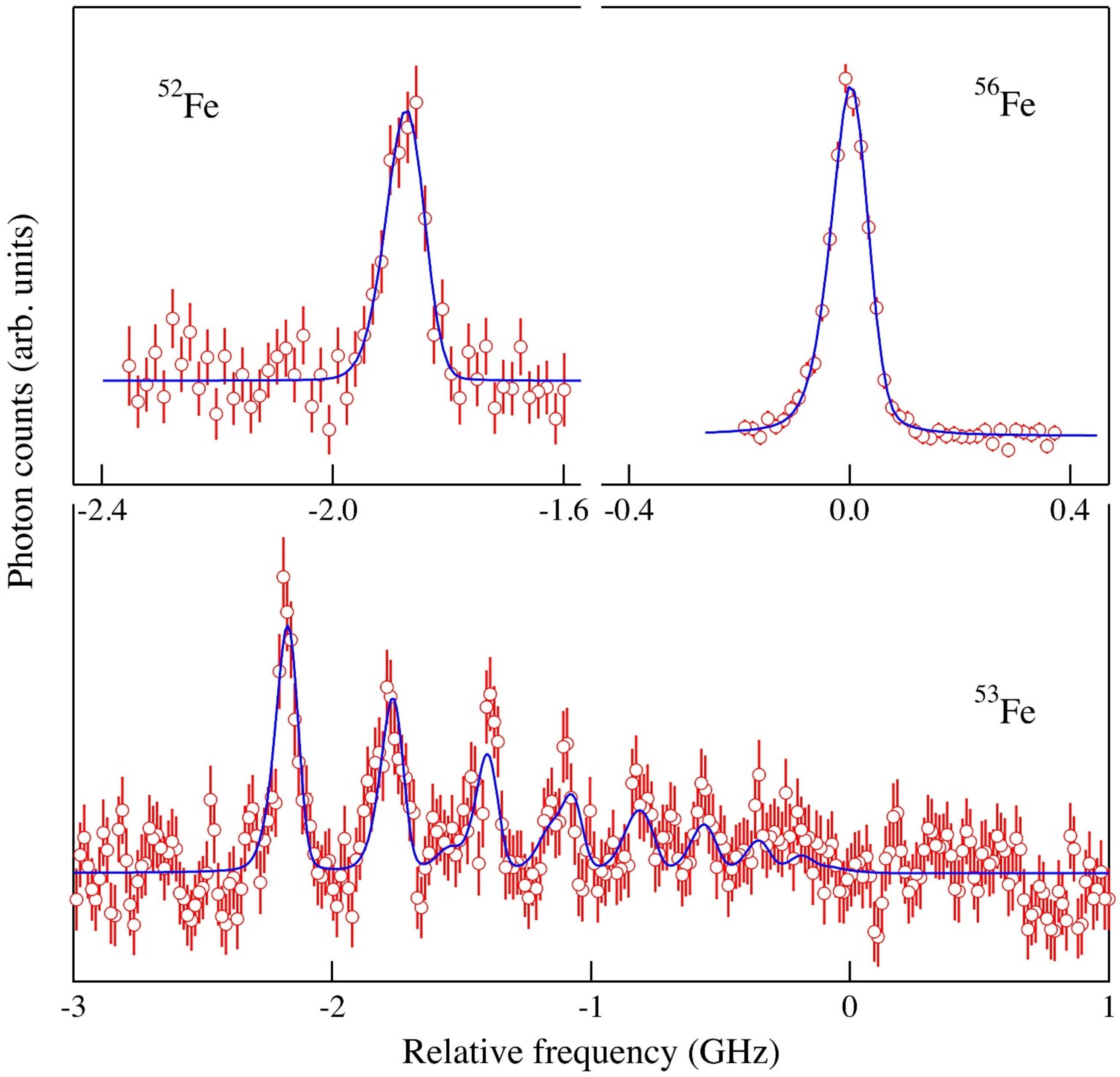
$k_{SMS} = 911 \pm 43$ (GHz amu)

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

$\delta\langle r^2\rangle^{56,52} = -0.034 \pm 0.013$ (fm^2)

$\delta\langle r^2\rangle^{56,53} = -0.218 \pm 0.013$ (fm^2)

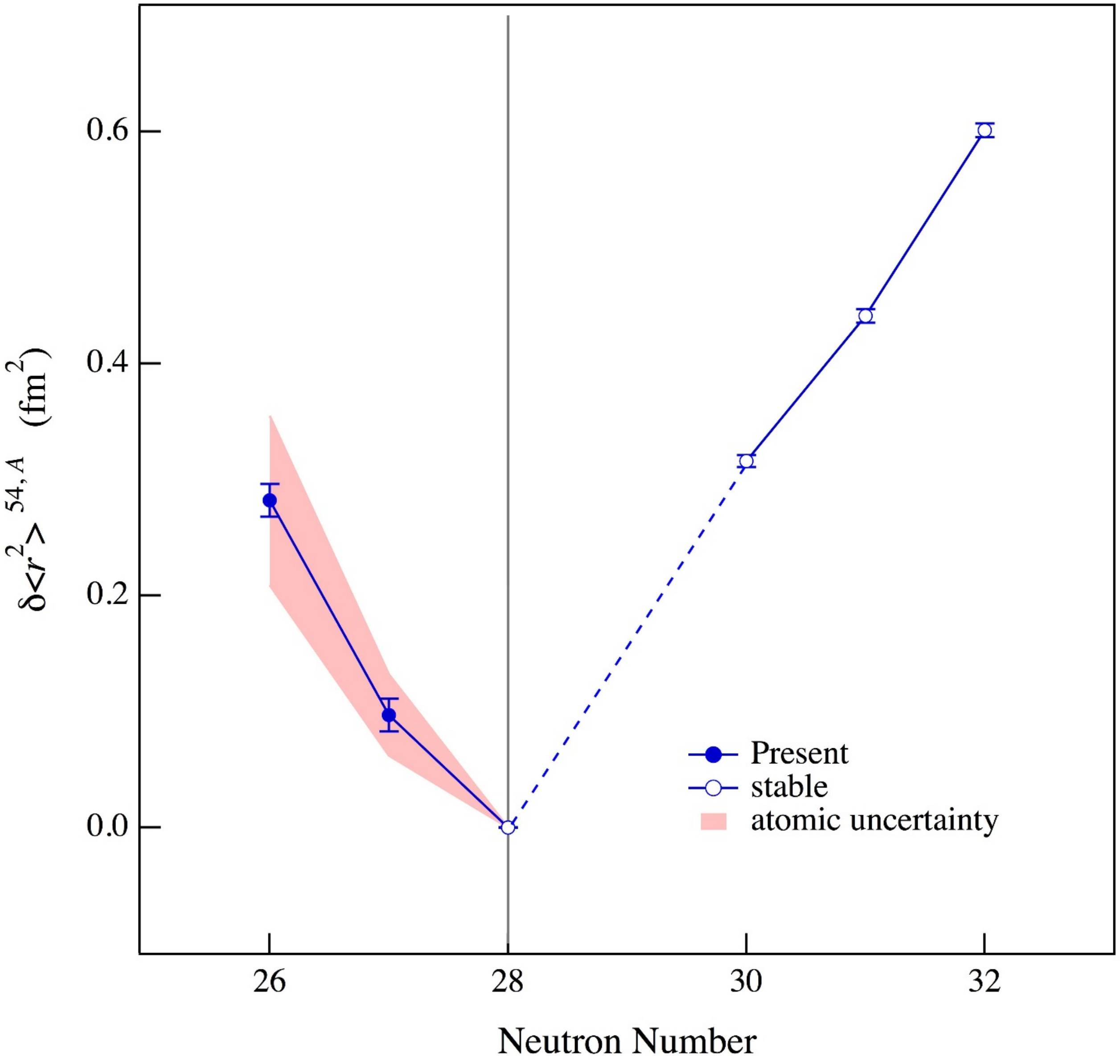
$^5D_4 \leftrightarrow {}^5F_5$ transition in Fe I at 26874.550 cm^{-1}



Stable Fe-isotope shift: S. Krins et al., PRA 80, 062508 (2009);
Stable Fe $\delta\langle r^2\rangle$: G. Fricke & K. Heilig, *Nuclear Charge Radii* (Springer, 2004);
Field shift calculation: Multi-configuration Dirac-Fock (MCDF) method;
K. Minamisono et al., Phys. Rev. Lett. 117, 252501 (2016);
A. J. Miller, K. M. et al., Phys. Rev. C 96,054314 (2017).

$\delta\langle r^2\rangle^{54,A}$ of Fe isotopes

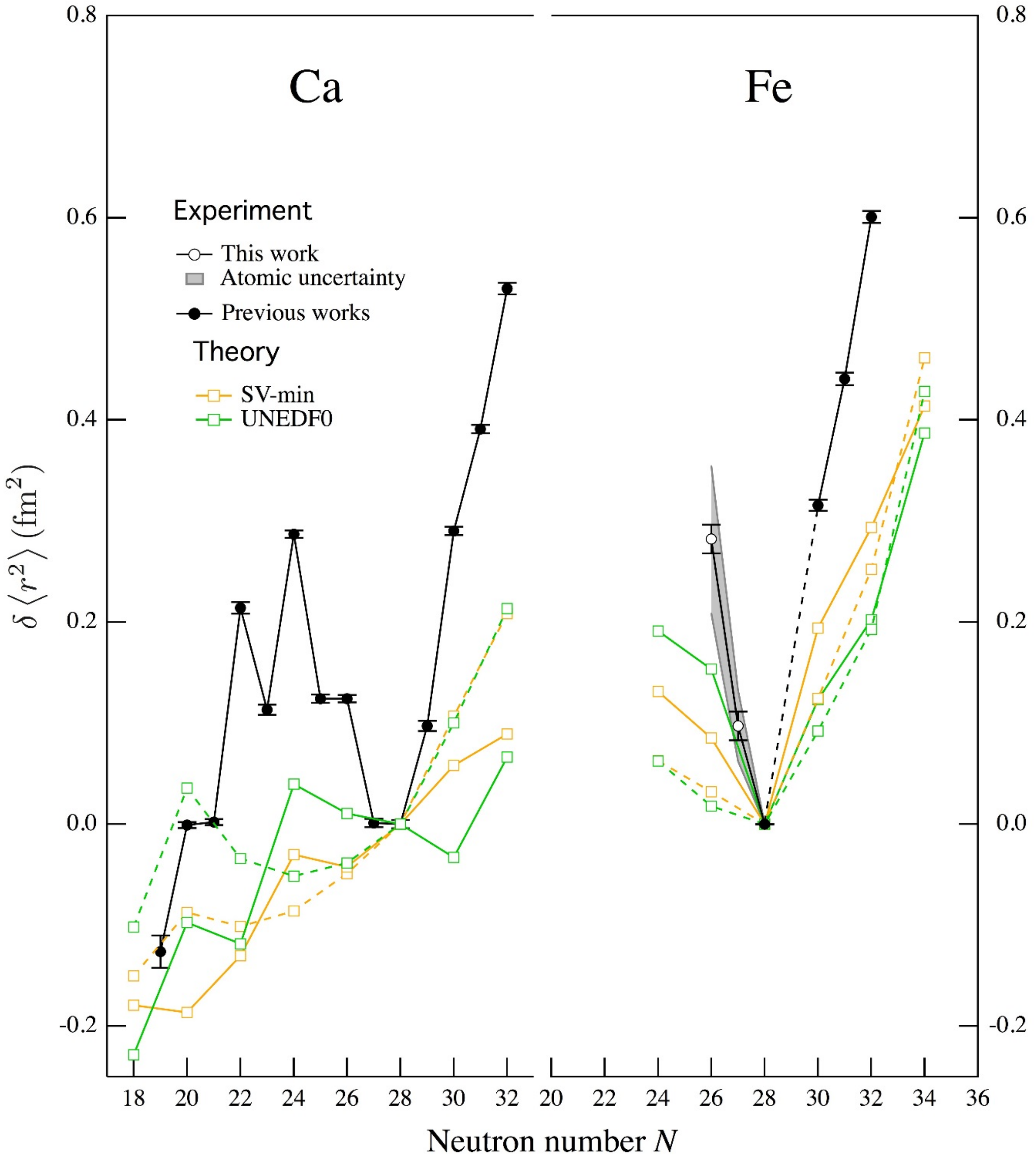
- Shell closure signature; “Kink” at $N = 28$
- Radii of ^{52}Fe and ^{56}Fe similar



K. Minamisono et al., Phys. Rev. Lett. 117, 252501 (2016).

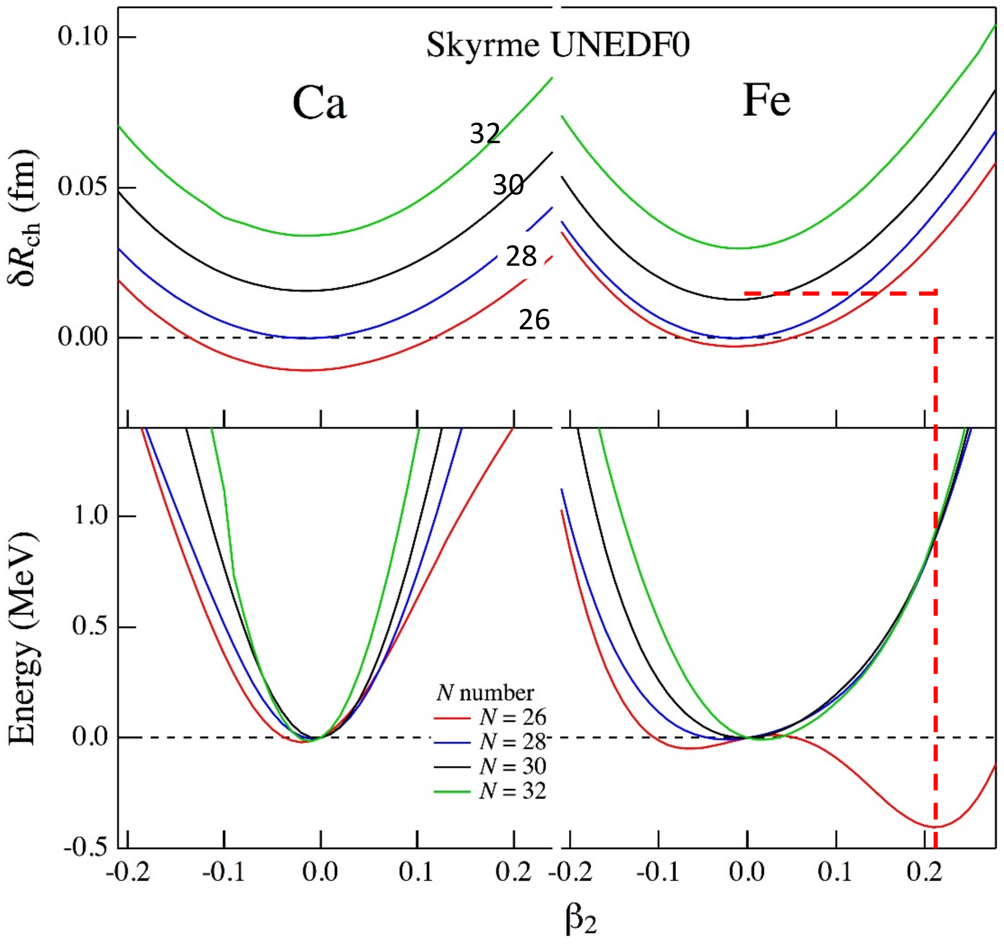
DFT calculation for Ca & Fe
Skyrme EDF

- Spherical shape (dashed line)
  No good agreement
- Deformed shape (solid line)
  No good for Ca
  Kink better reproduced for Fe

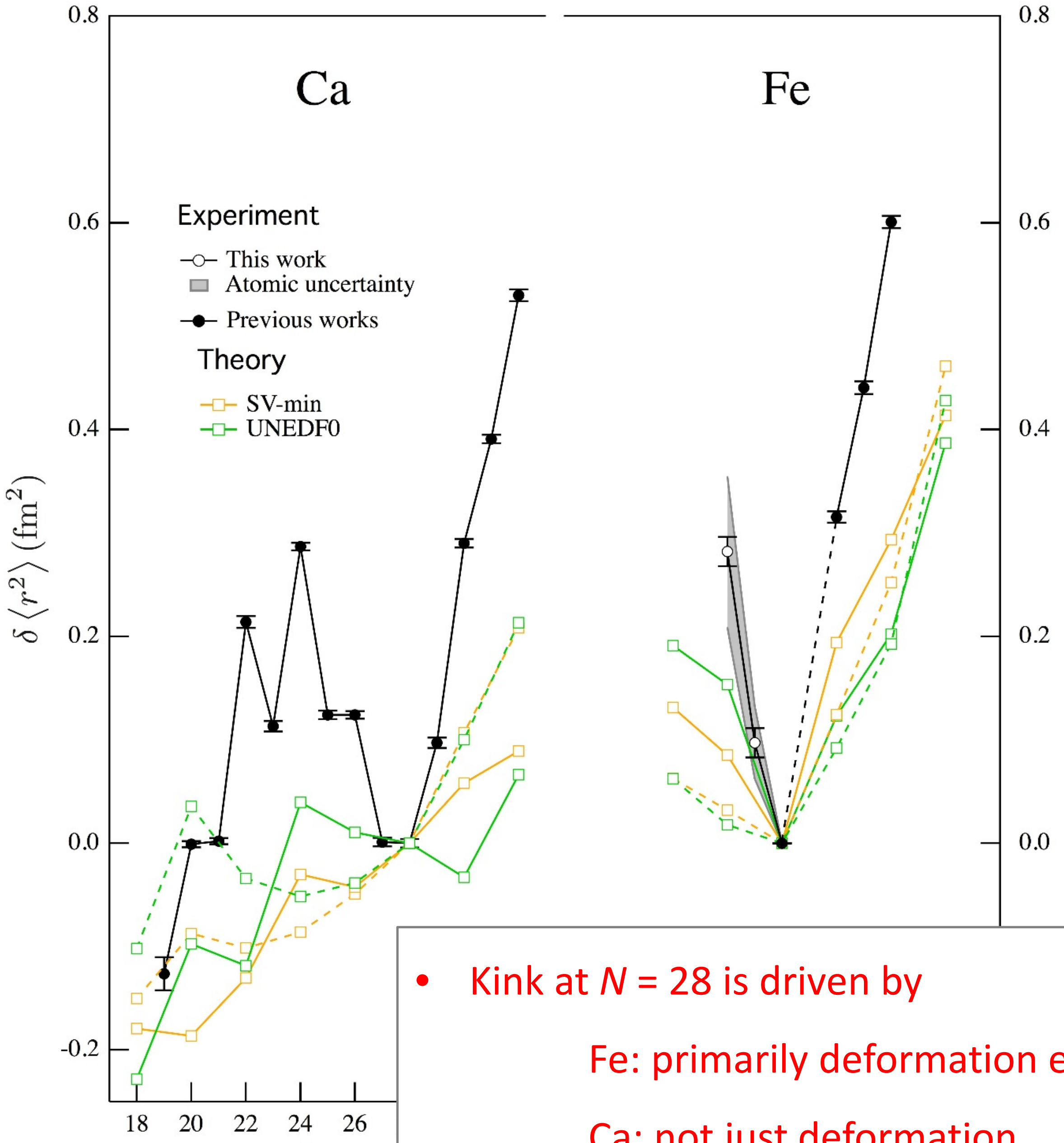


K. Minamisono et al., Phys. Rev. Lett. 117, 252501 (2016);
SV-min: P. Klöpfel et al., PRC79, 034310 (2009);
UNEDF0: M. Kortelainen et al., PRC82, 024313 (2010).

DFT calculation for Ca & Fe
Skyrme EDF



Consistent with $B(E2)$ of ^{52}Fe isotopes.
K. L. Yurkewicz et al. PRC70, 034301 (2004).

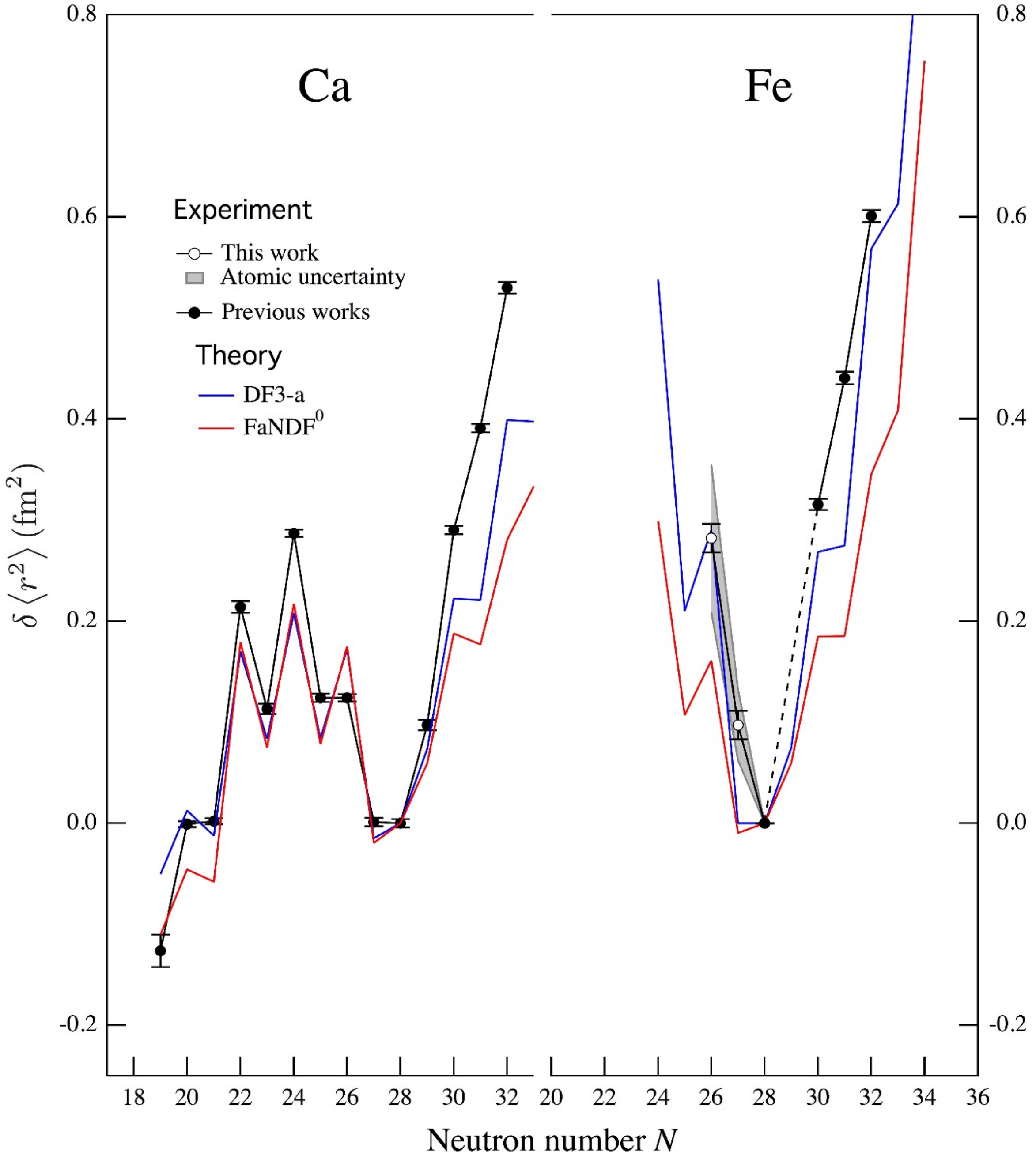


- Kink at N = 28 is driven by
  - Fe: primarily deformation effect
  - Ca: not just deformation

E. Caurier et al., Phys. Lett. B 522, 240 (2001); H. Nakada, Phys. Rev. C 92, 044307 (2015); …

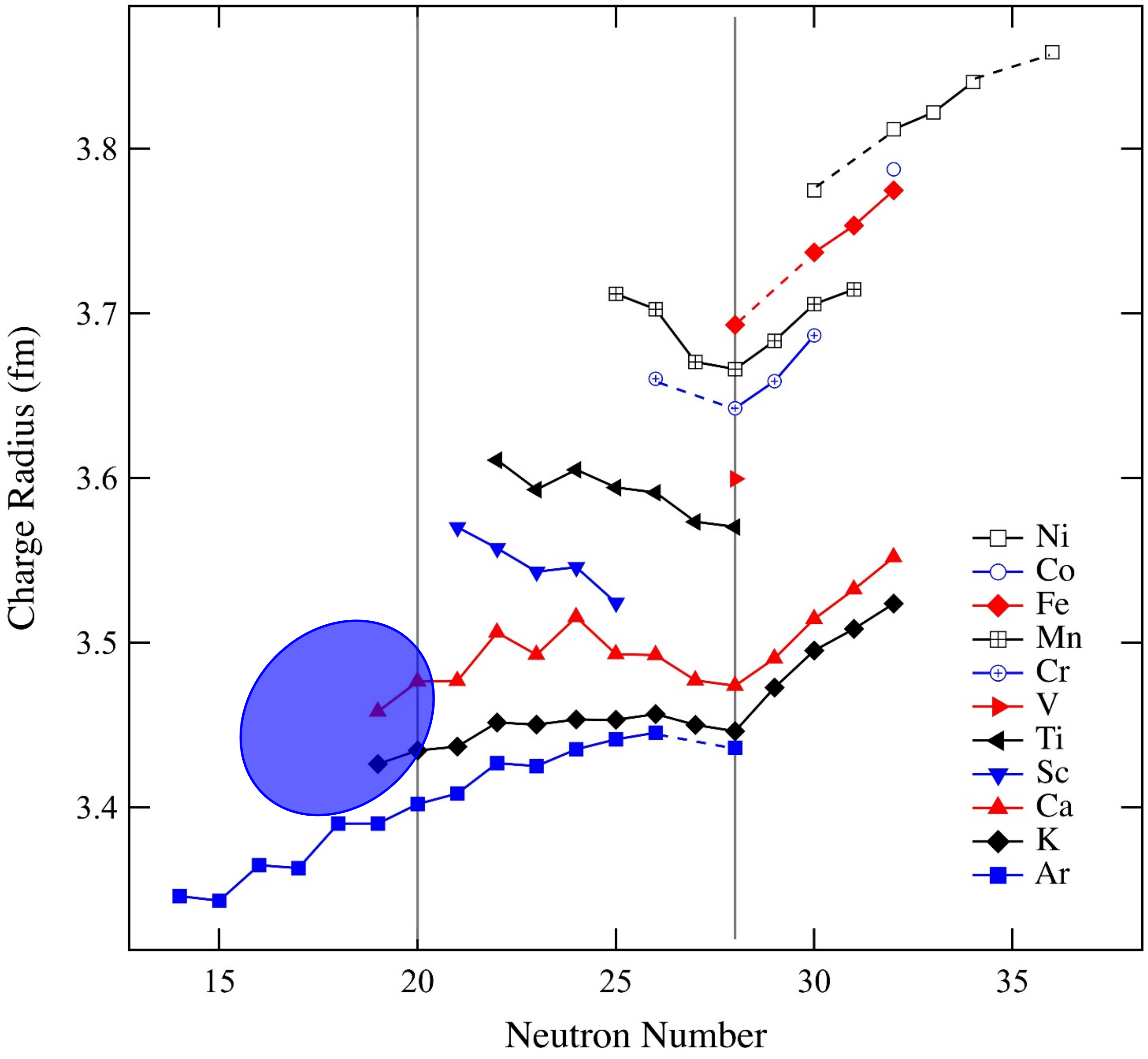
DFT calculation for Ca and Fe: 2
Fayans EDF

- a nuclear-density gradient dep. pairing term.
  (coupling to surface vibrations)
- Parameters for the paring term fitted to S_n.
- Spherical shape
- Very good overall agreement though
  - underestimate R_{ch} of very heavy Ca
  - overestimate odd-even staggering for Fe



K. Minamisono et al., Phys. Rev. Lett. 117, 252501 (2016);
DF3-a: S. V. Tolokonnikov & E. E. Saperstein, PAN73, 1684 (2010);
FaNDF0: S. A. Fayans, JETP Lett. 68, 169 (1998).

Current interests: Ca & Ni at *N* = 20 & 28

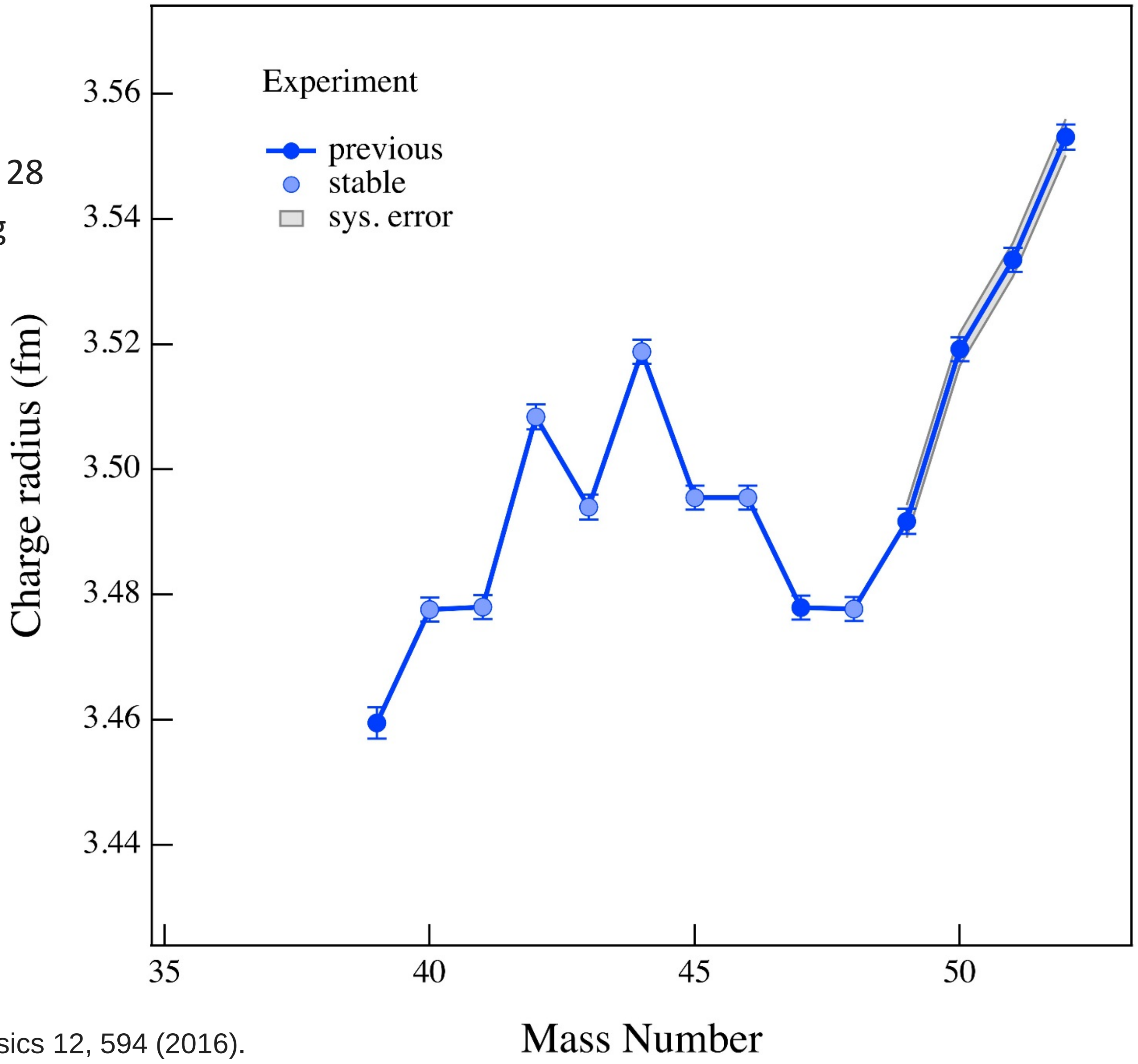


Example: charge radii of Ca isotopes

A "textbook" example

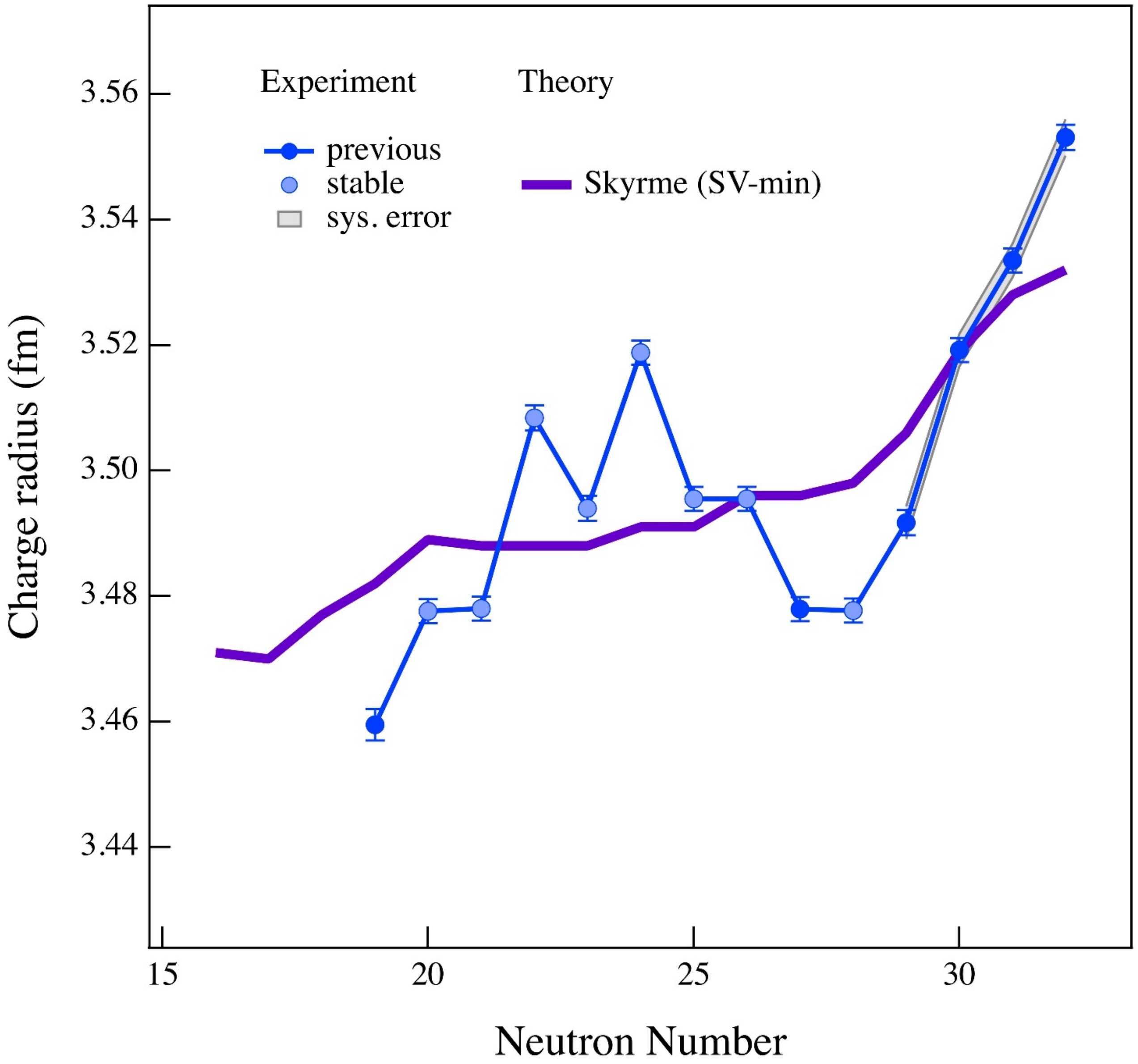
- $r\,(^{48}Ca) \approx r\,(^{40}Ca)$
- Parabolic shape in $20 \leq N \leq 28$
- Strong odd-even staggering
- Steep increase $N \geq 28$
- No "kink" at $N = 20$

Ca radii show a very intricate pattern.



Data: R. E. Garcia Ruiz et al., Nature Physics 12, 594 (2016).
R(^{40}Ca): G. Fricke and K. Heilig, Nuclear charge radii (Springer Berlin, 2004).

Charge radii of Ca isotopes

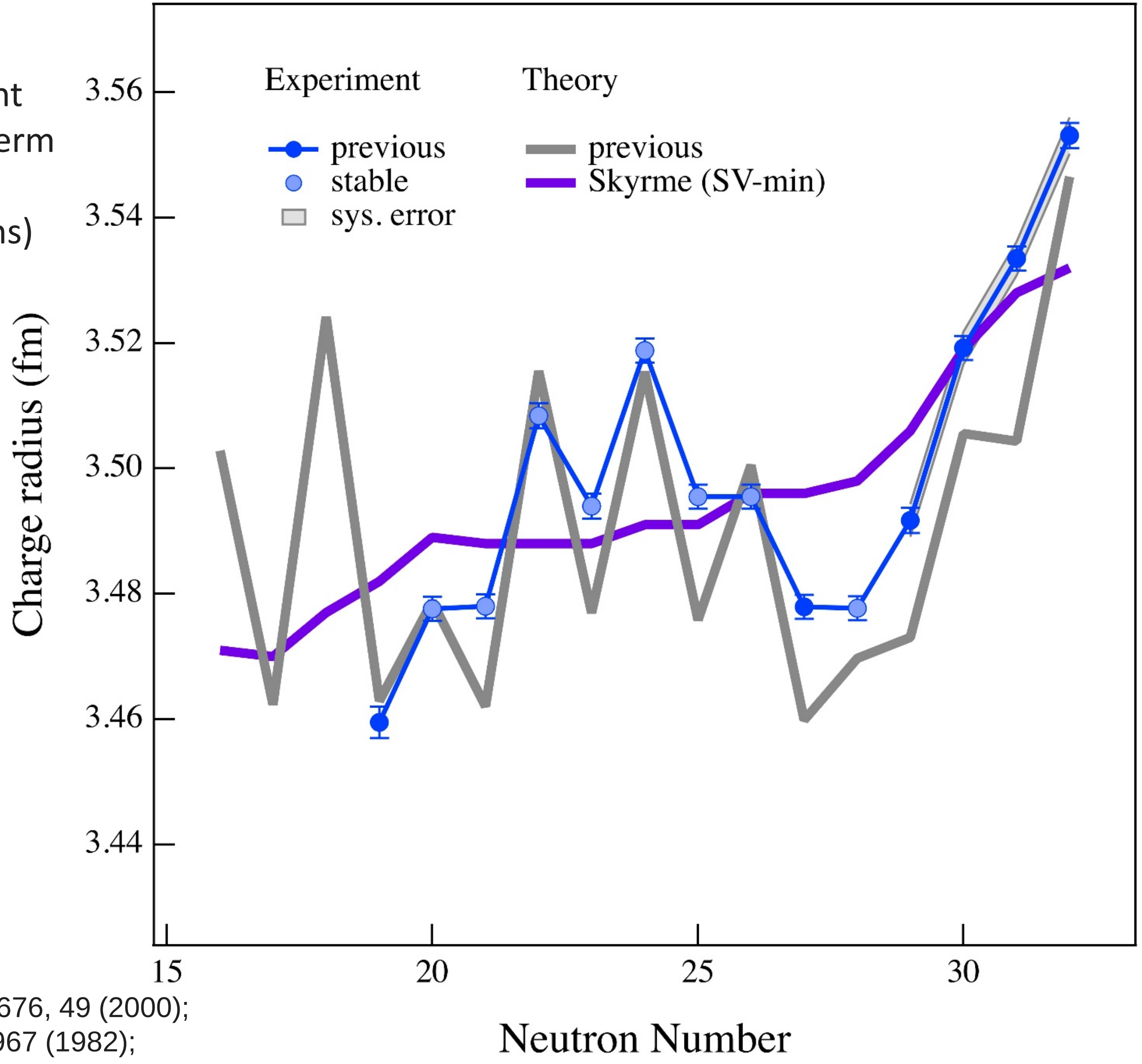


Typically DFT with Skyrme EDF does not reproduce details of the chain of Ca charge radii.

Theory: P. -G. Reinhard and W. Nazarewicz, PRC 95, 064328 (2017).

Charge radii of Ca isotopes

Fayans EDF
- Density gradient dependent pairing term
- Reflects surface phonons (vibrations)

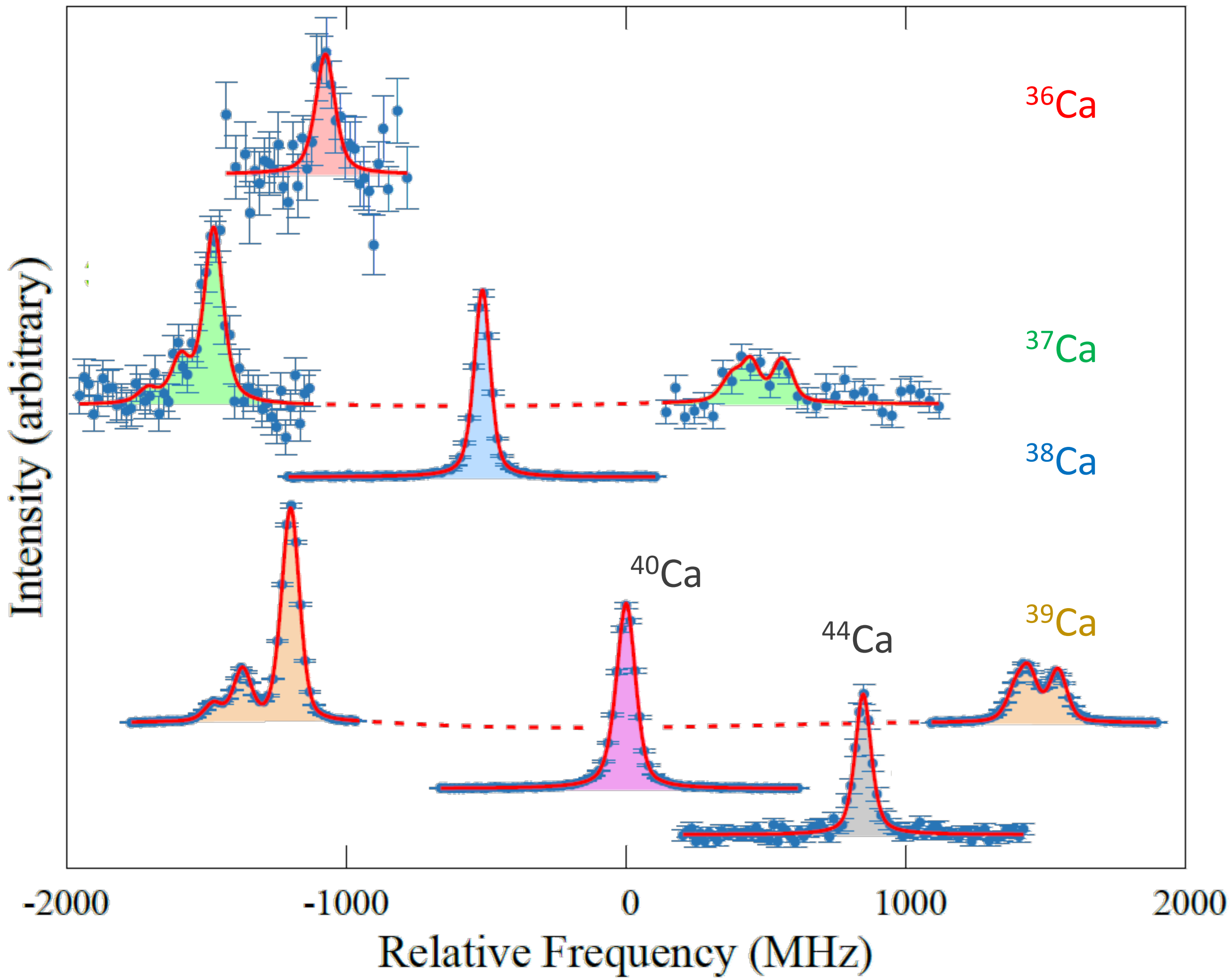


Fayans EDF does good job, but some discrepancy, and predicts very large radii for light Ca.

Theory: S. A. Fayans et al., Nucl. Phys. A676, 49 (2000);
V. A. Khodel et al., J. Phys. G 8, 967 (1982);
P. -G. Reinhard and W. Nazarewicz, PRC 95, 064328 (2017).

Isotope shift of HFS for neutron-deficient Ca

Ca II: 4s $^2S_{1/2} \leftrightarrow$ 4p $^2P_{3/2}$



	rate (1/s)	$T_{1/2}$ (ms)
^{36}Ca	50	102
^{37}Ca	960	181
^{38}Ca	13.5k	440
^{39}Ca	60k	859.6

A. J. Miller et al., Nature Physics, (2019) 15, 432 (2019).

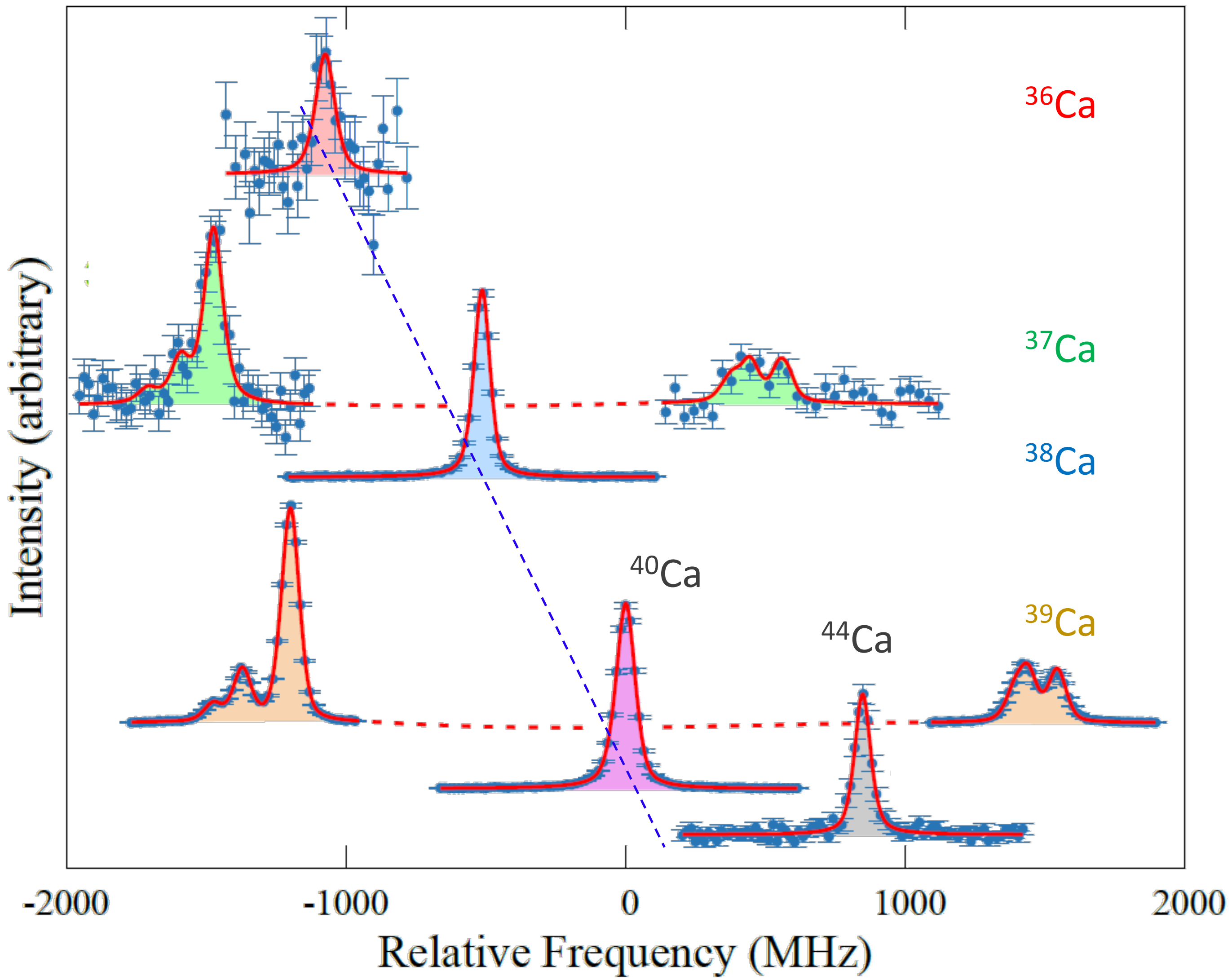
Isotope shift of HFS for neutron-deficient Ca

Ca II: 4s $^2S_{1/2} \leftrightarrow$ 4p $^2P_{3/2}$

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

Atomic factors well determined:

$$\begin{cases} k = 409.35(42) \text{ GHz amu} \\ F = -284.7(82) \text{ MHz fm}^{-2} \end{cases}$$



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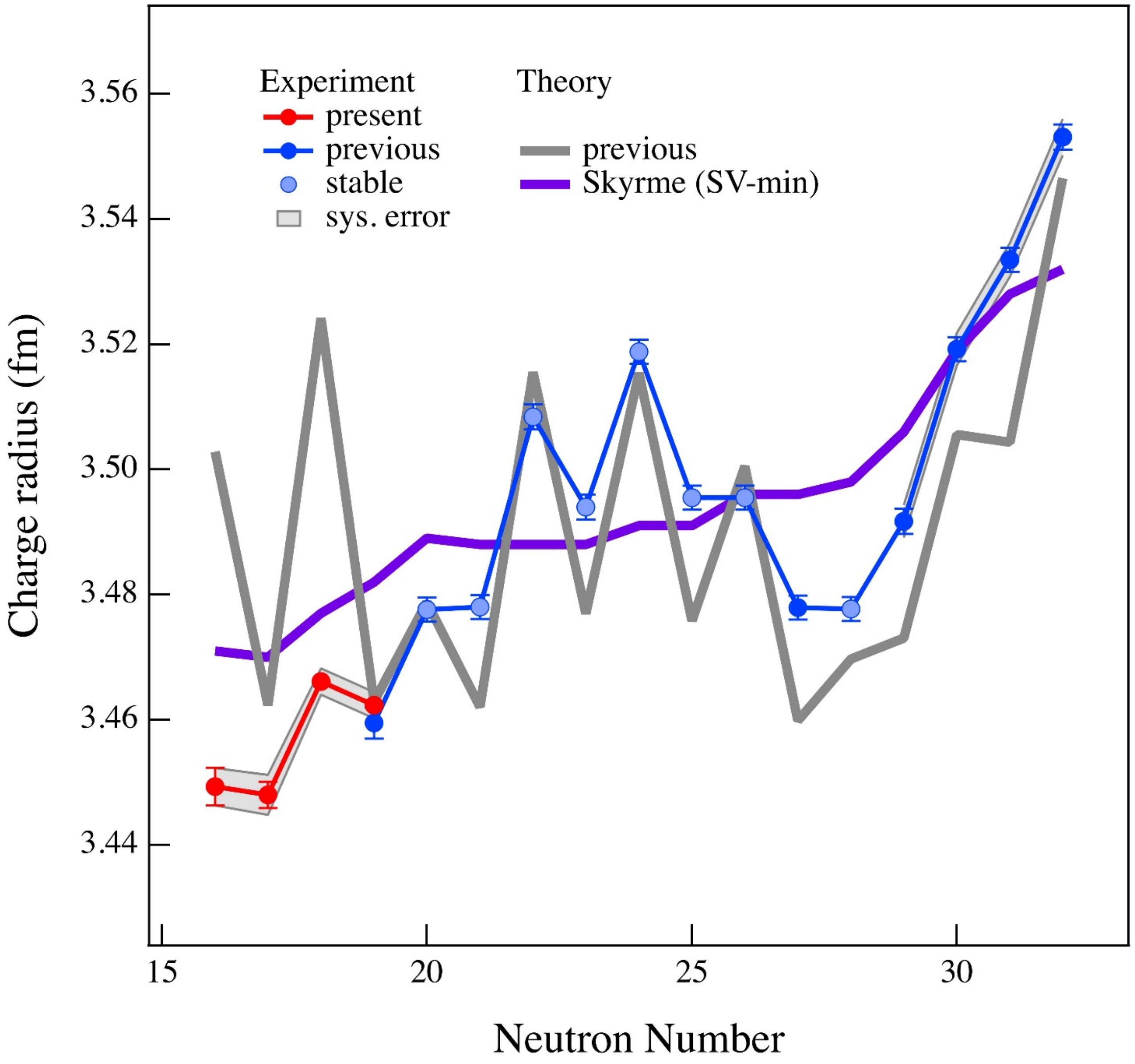
A. J. Miller et al., Nature Physics 15, 432 (2019).
Atomic factor: C. Shi et al., Appl. Phys. B123, 2 (2016).

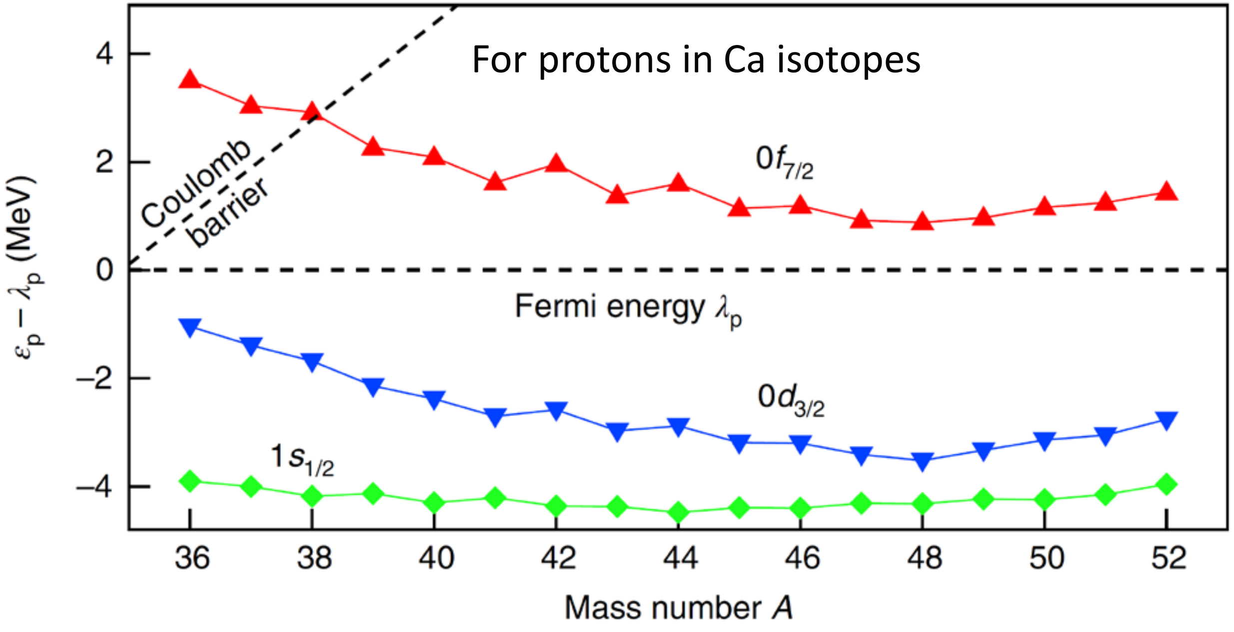
Charge radii of Ca isotopes

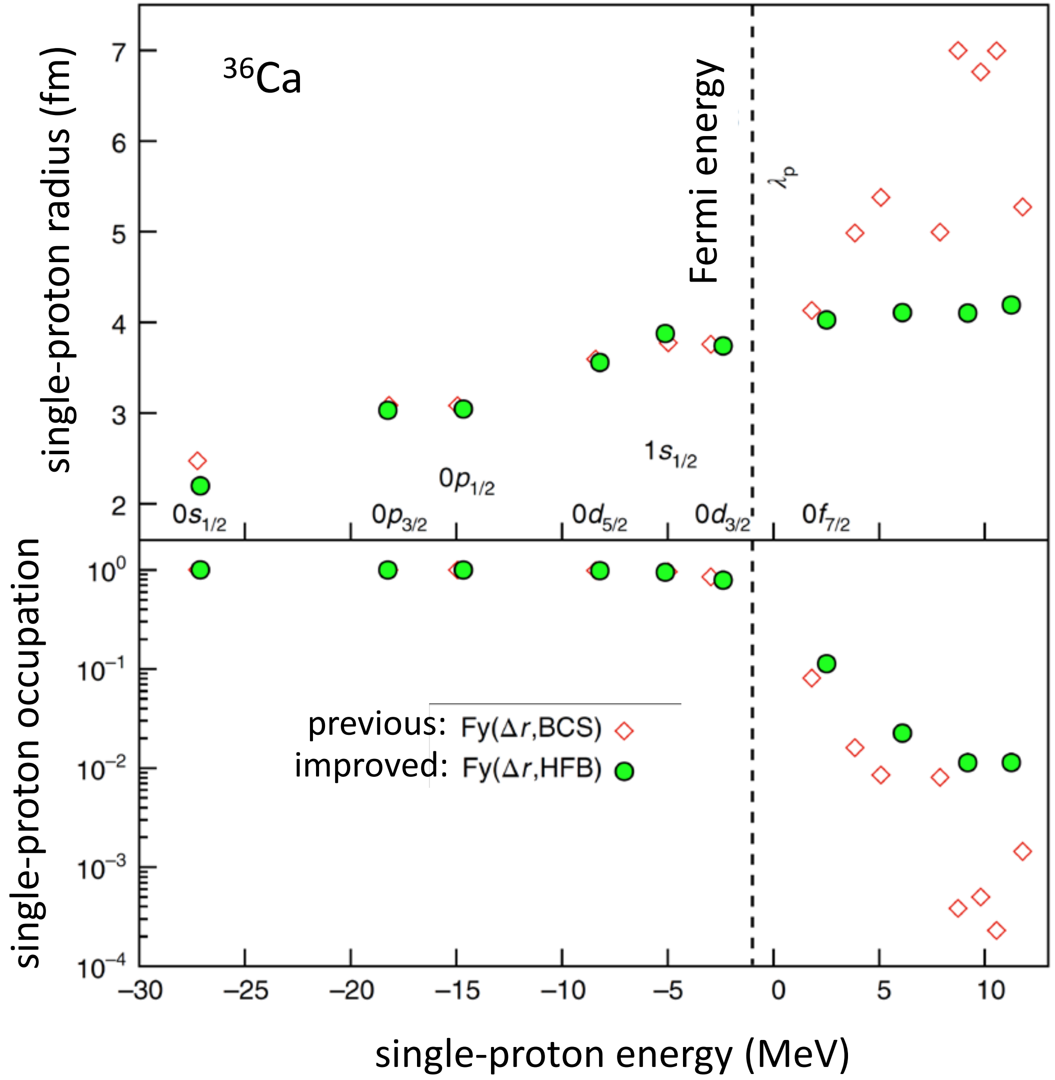


A. J. Miller et al., Nature Physics 15, 432 (2019).

Weakly-bound protons

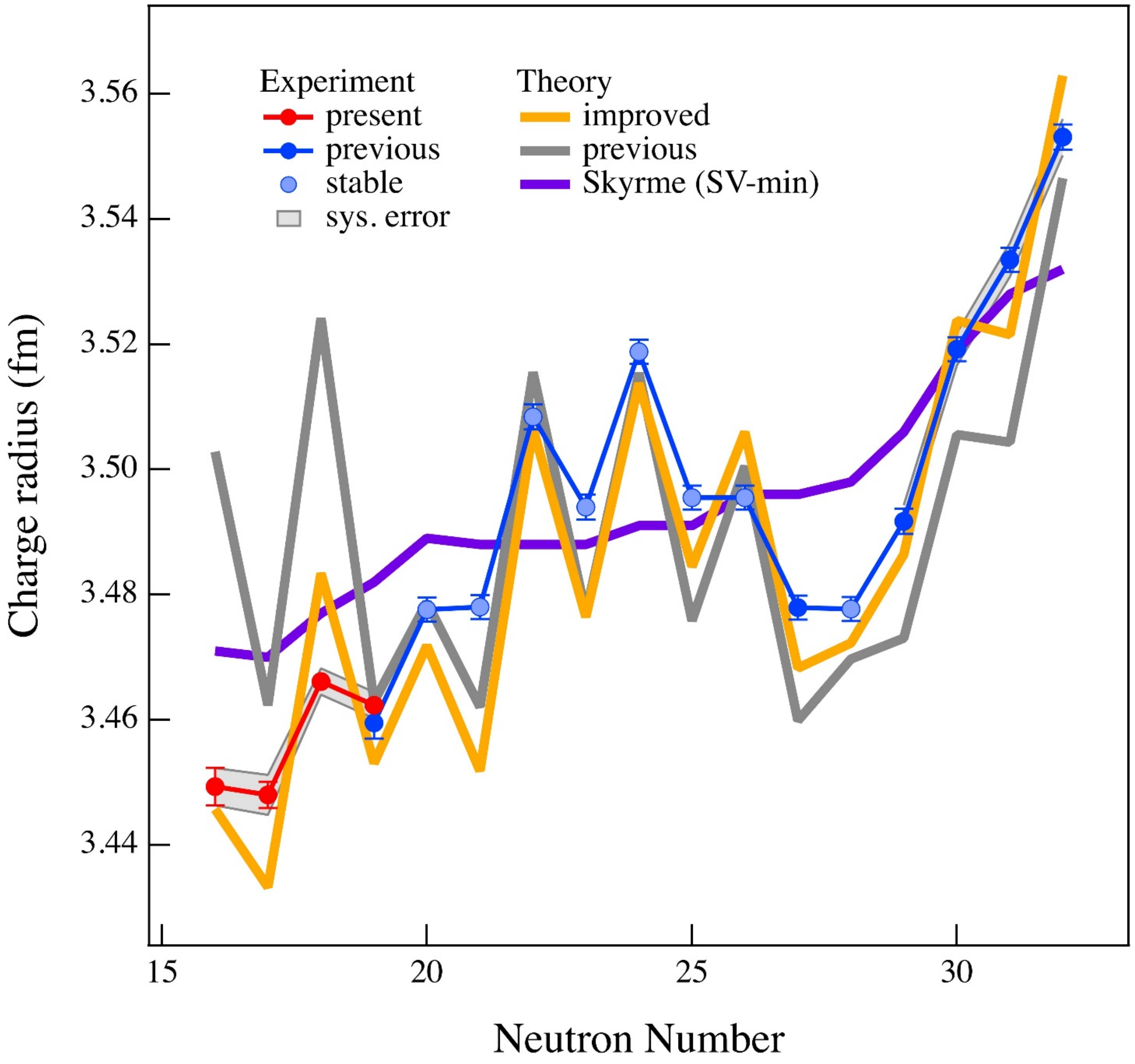
- Moving toward ^{36}Ca, the $0f_{7/2}$ state rises above the Coulomb barrier.
- Pairing interaction can scatter proton pairs into particle continuum (superfluidity).
- Improved theory avoids the nonphysical increase of radius in the continuum





A. J. Miller et al., Nature Physics 15, 432 (2019).

Charge radii of Ca isotopes



Improved theory explains Cd radii very well.

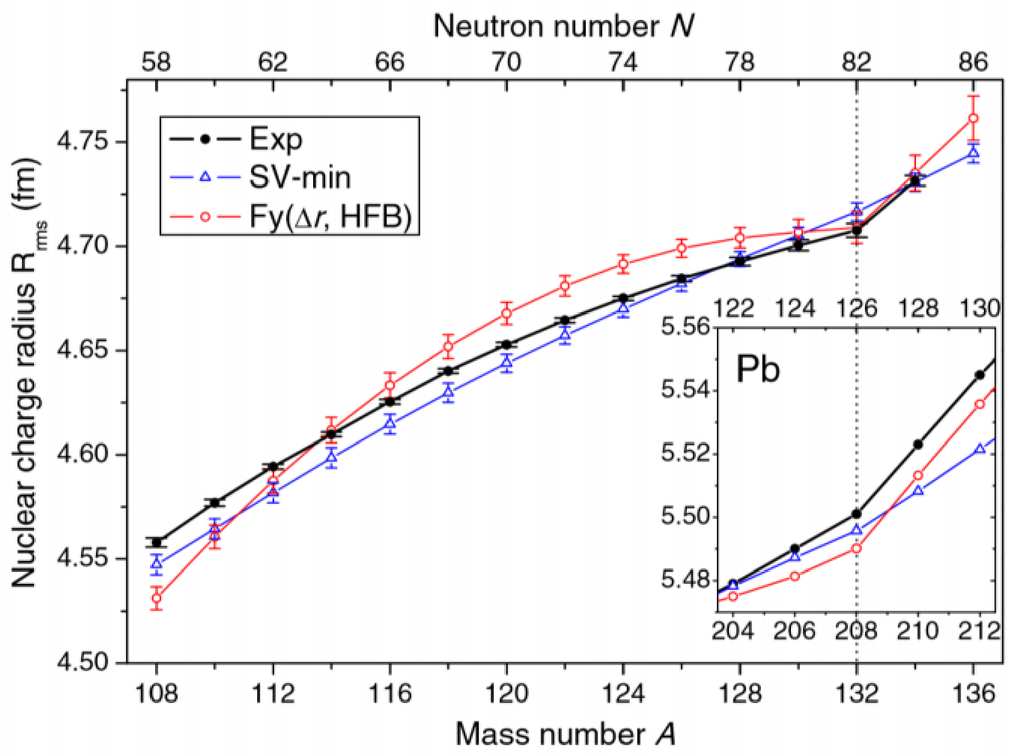
Need better understanding of odd-even staggering.

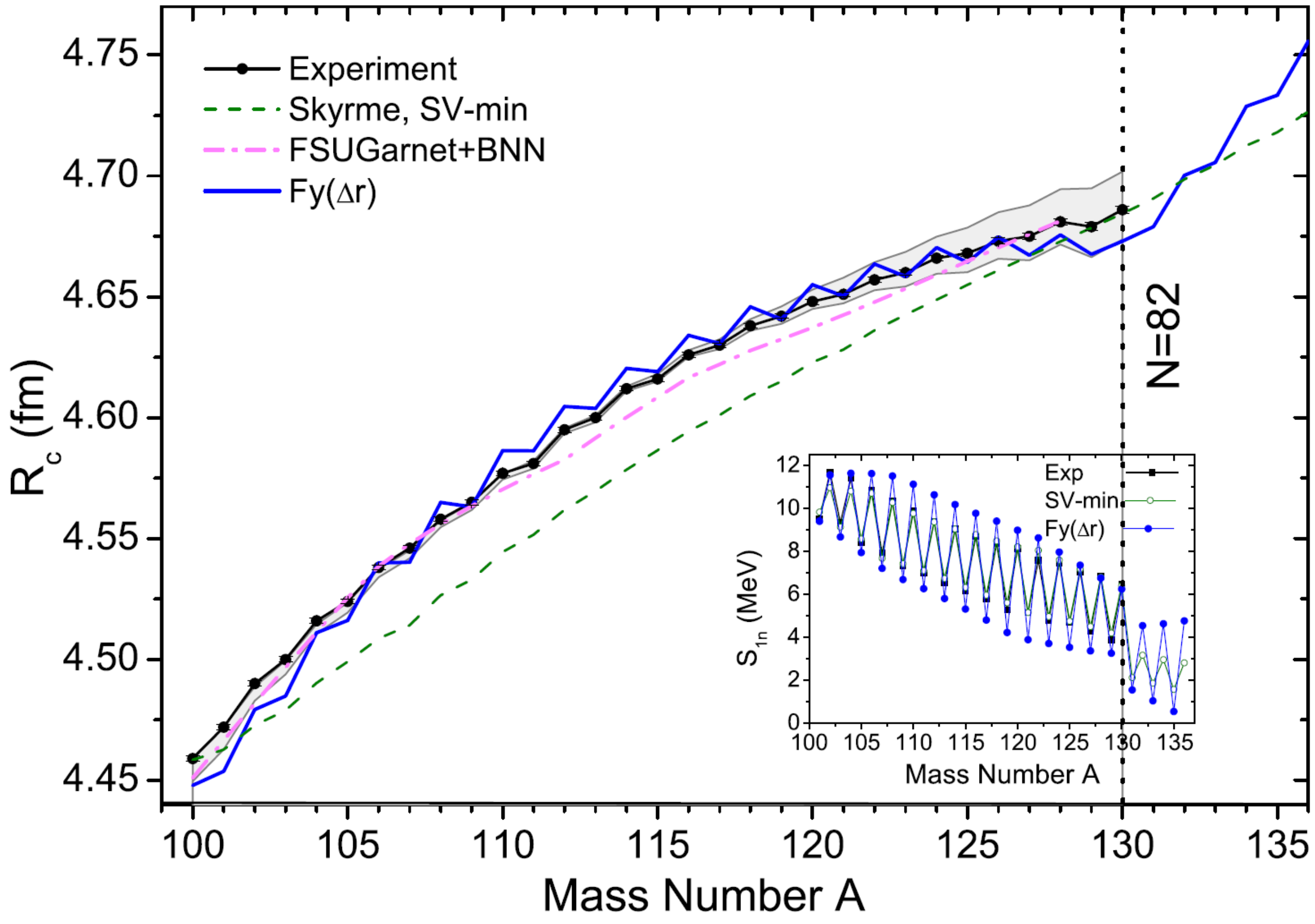
A. J. Miller et al., Nature Physics 15, 432 (2019).

Fayans EDF for Cd and Sn isotopes

Fayans EDF for Ca works for Cd and Sn

- Fayans EDF captures important mechanism that works at (far) different locations in the nuclear chart.
- Important step towards a global model



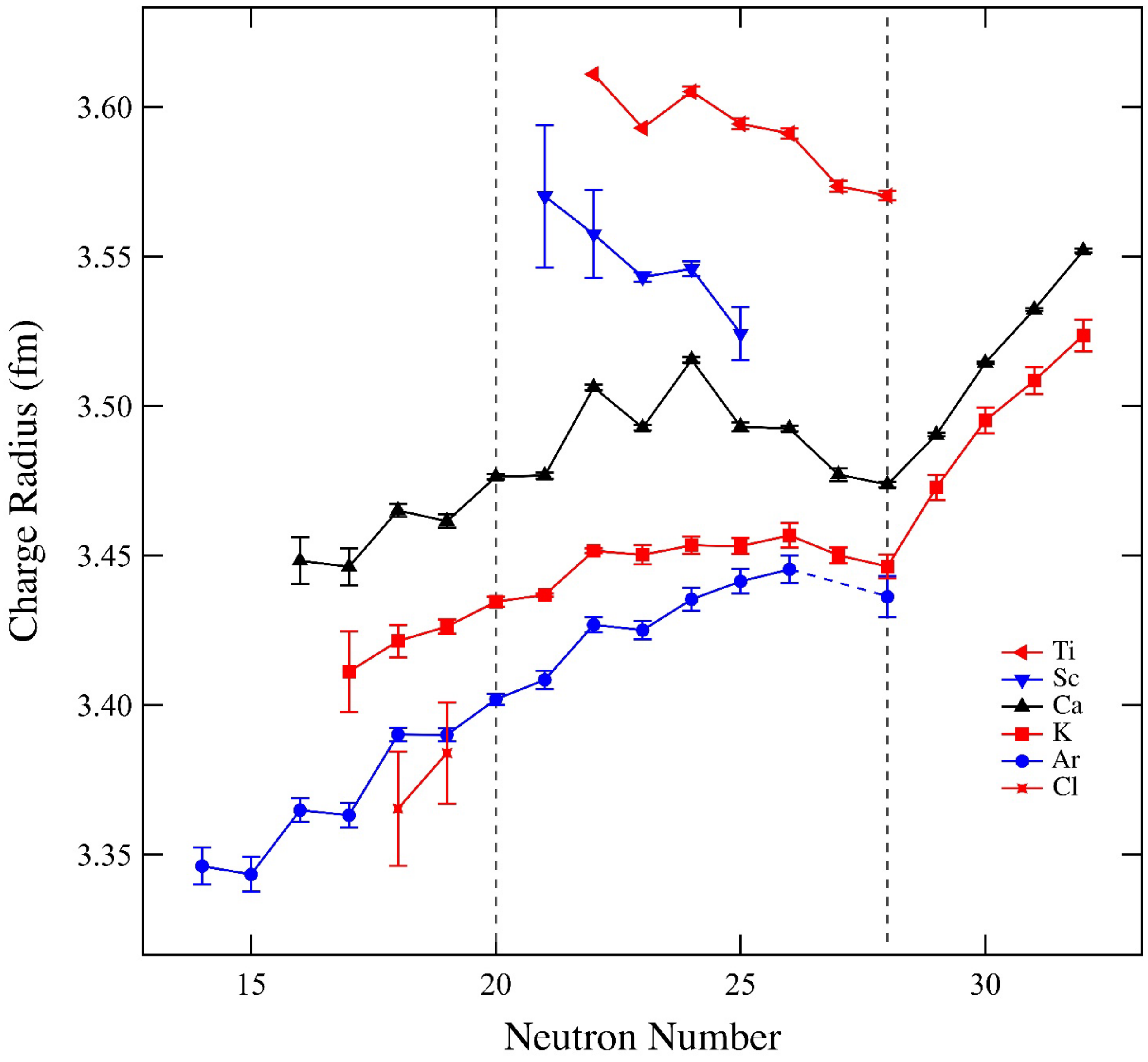


Cd: M. Hammen et al., Phys. Rev. Lett. 121, 102501 (2018).
Sn: C. Gorges et al. Phys. Rev. Lett. 122, 192502 (2019).

Charge radii around Ca

- No “kink” at $N = 20$
- Change the sign of slope at $N = 20$ between Ca and Sc
- Approved experiment on Sc

(NSCL e18024: A. Klose spokesperson)



Data compilation: I. Angeli and K. P. Marinova, ADNDT 99, 69 (2013).
D. Rossi et al., PRC 92, 014305 (2015).

Summary/future prospects

BECOLA is a laser spectroscopy facility at NSCL/FRIB/MSU,
complementing capabilities at ISOL type facilities.

Experiments on neutron-deficient Sc and Ni before NSCL is shut down.

FRIB operation anticipated to start in 2022.

"Day 1" experiment for BECOLA

- **^{52}Ni for mirror charge radii**
- **Proton emitters e.g. ^{147}Tm, ^{156}Ta^{g,m}**
- **Extending radii of key nuclei e.g. Ca**
- **Light mass elements e.g. O and F**
- **……**

and last but not least…

BECOLA collaboration

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