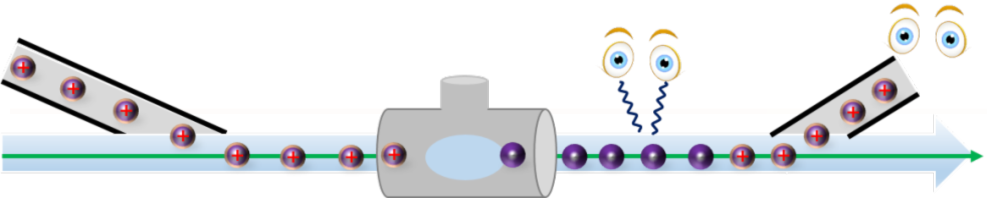

用于原子核基本性质测量的激光核谱技术

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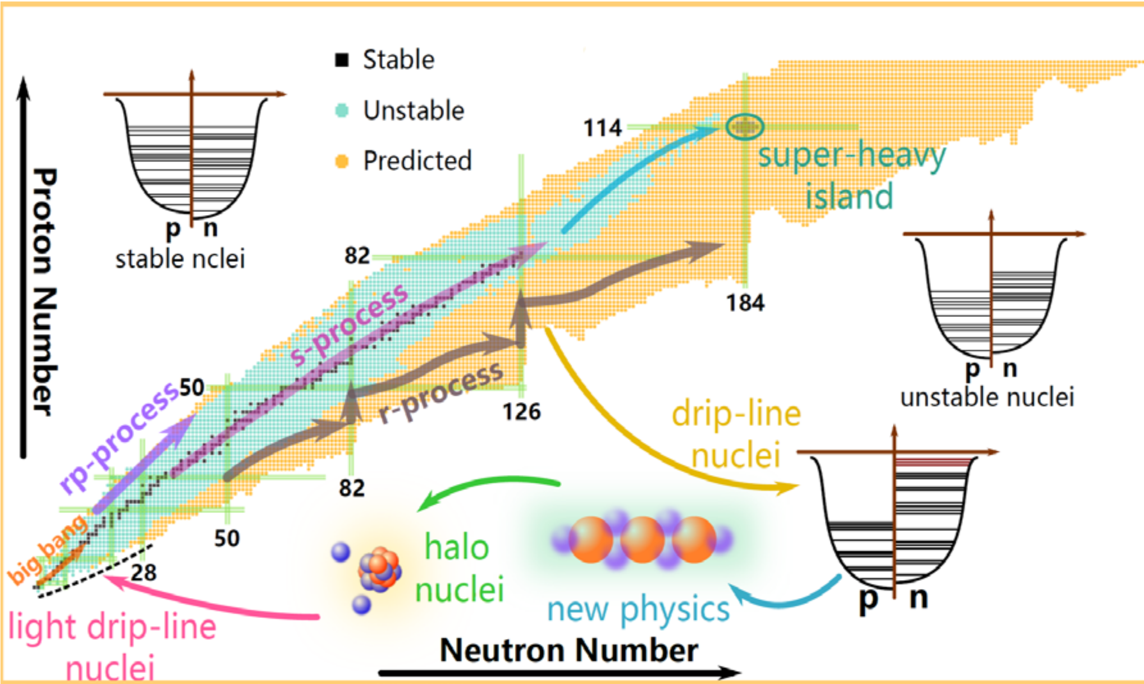
北京大学物理学院
核物理与核技术国家重点实验室

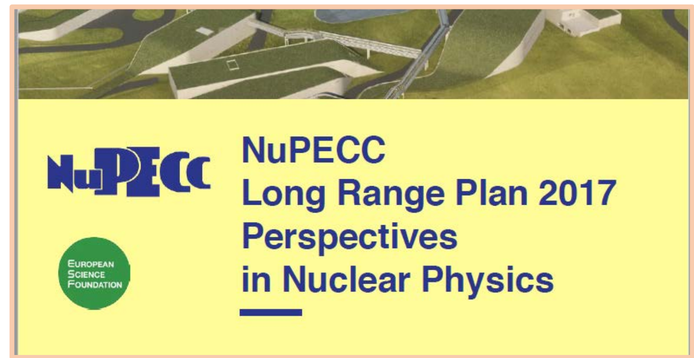
Contents

北京大學 PEKING UNIVERSITY

- General physics motivation
- Hyperfine structure and nuclear properties
- Laser spectroscopy technique and recent highlights
- Development of Laser spectroscopy

Nuclear structure of exotic isotopes



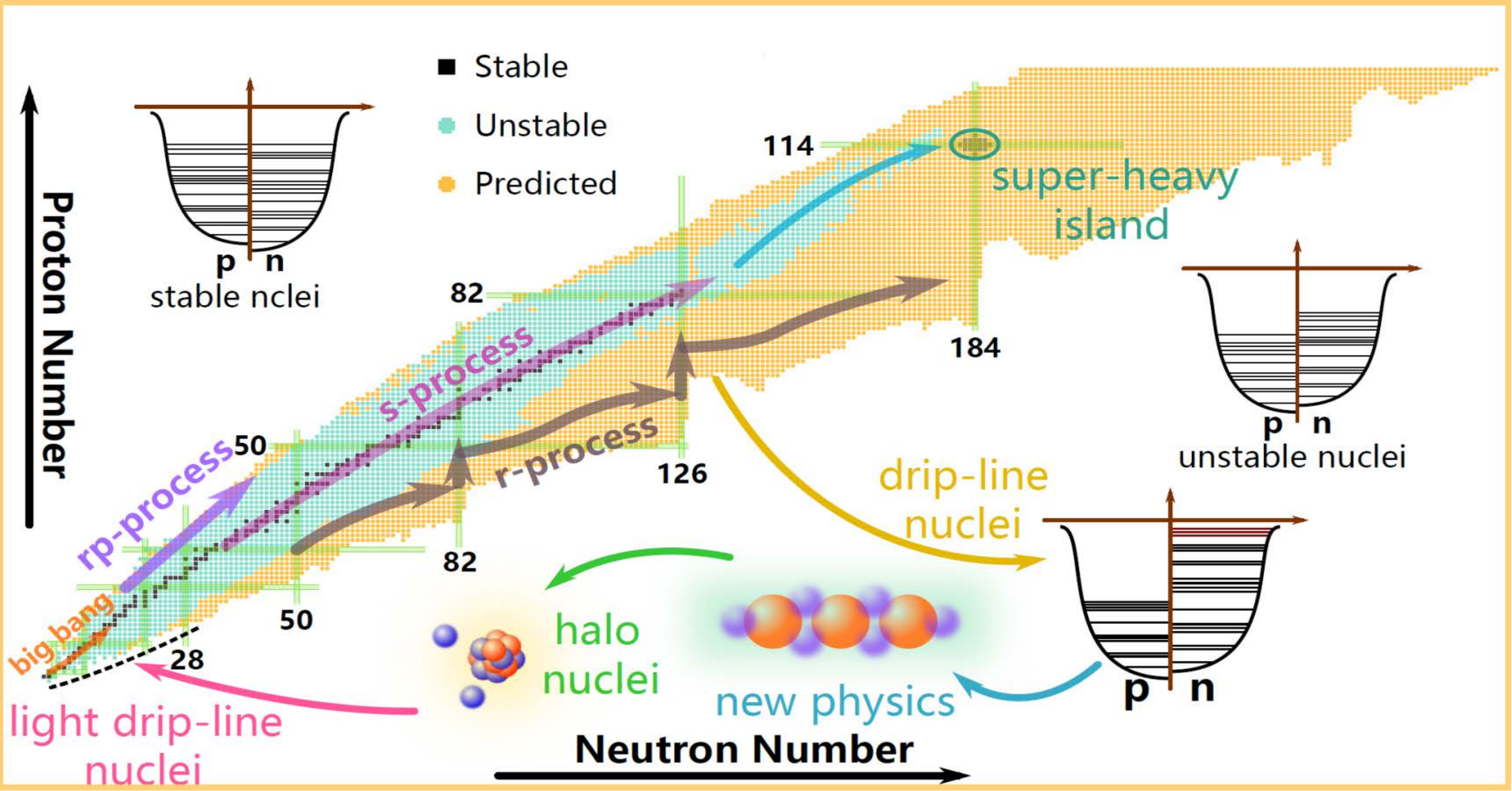


- How does the nuclear chart emerge from **underlying interactions**?
- How does **nuclear structure evolve** across the nuclear landscape?
- What **shape can nuclei adopt**?
- What are the **limits of existence of nuclei?**
- ……….   **《NuPECC LRP 2017》**

Nuclear structure of exotic isotopes

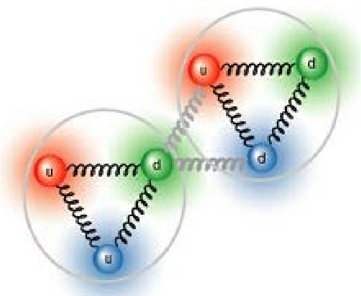
- □ Exotic phenomena near dripline
- □ Nuclear astrophysics
- □ Super heavy element

- ➢ Radioactive ion beam
- ➢ Experimental investigation
- ➢ Theoretical development



◆ Experiments: Reactions, αβγ decay, basic properties measurement……

Nuclear properties of (exotic) nuclei

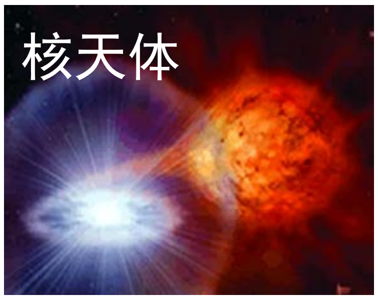


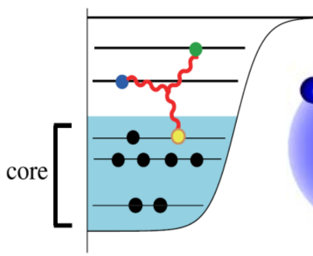
→ test for state-of-the-art nuclear theories

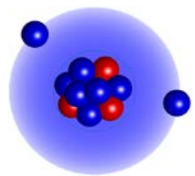
→ input for nuclear astrophysics models

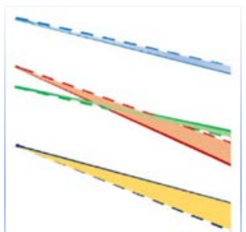
→ insight into the nuclear structure

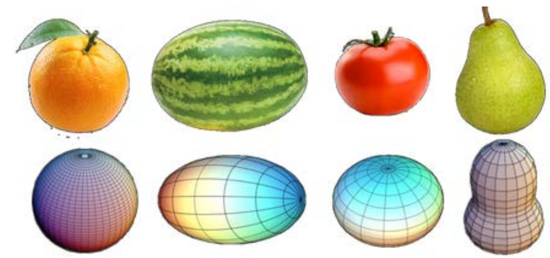
→ study of the nucleon-nucleon interaction



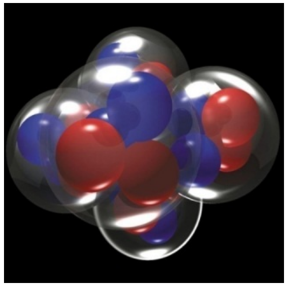


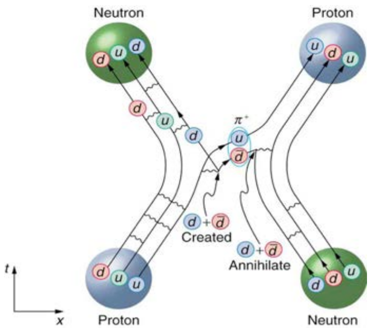






- Mass and Lifetime
- Spin and Parity
- Nuclear Magnetic dipole and Electric quadrupole moments
- Charge Radii and matter radii

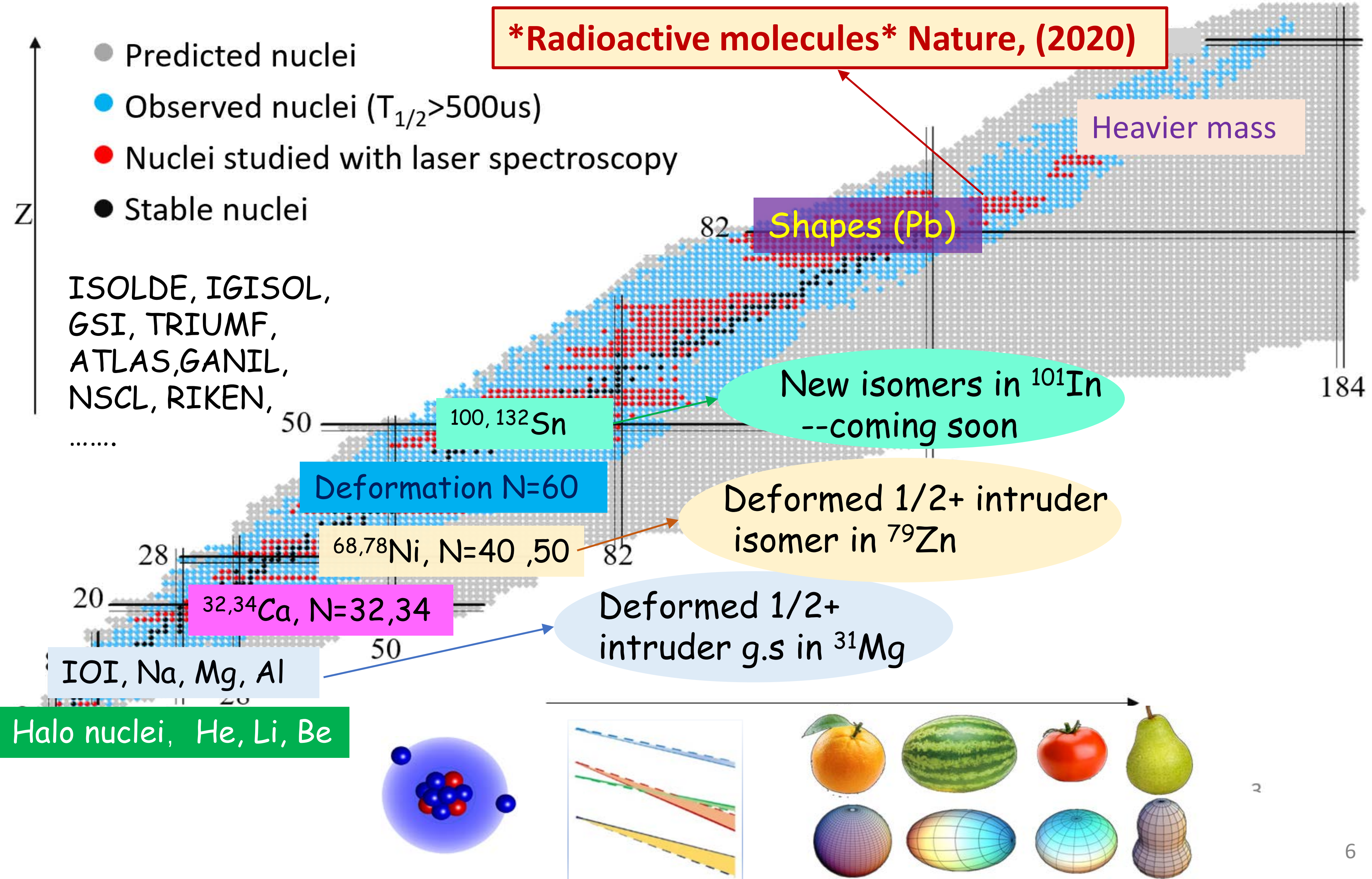




Can be measured with one technique: laser spectroscopy

Achievements until now

- **Exotic phenomenon** **(halo， shell evolution， deformation…)**



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- Laser spectroscopy technique and recent highlights
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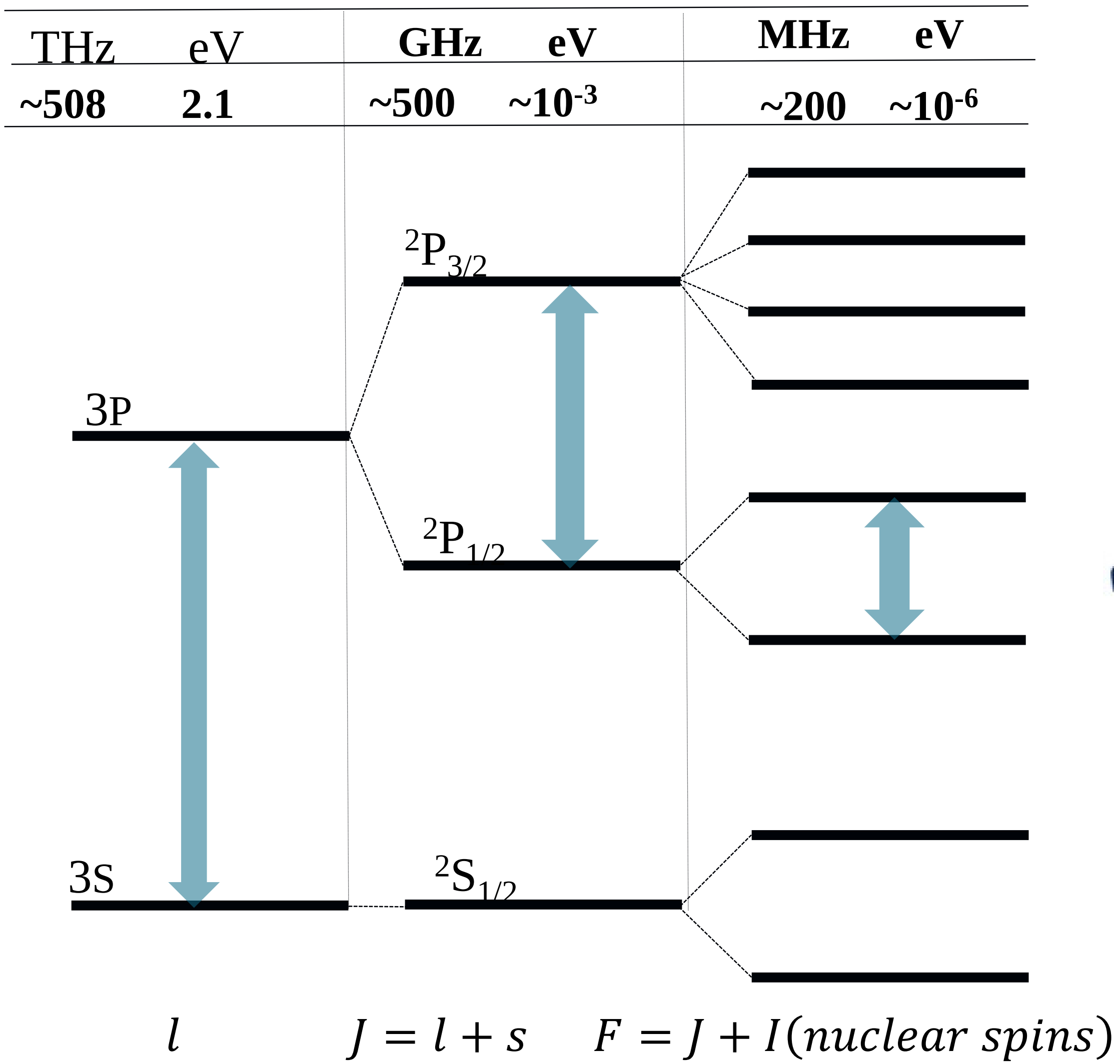
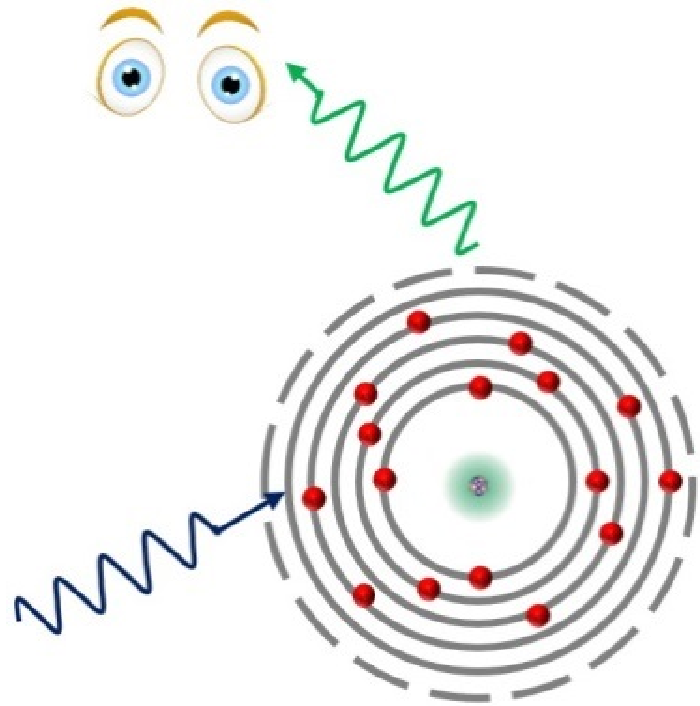
From Atoms to Nuclei

--Spectroscopy of electronic transitions of atoms / ions

Electronic energy level structure





Only in HFS precision level, nuclear information are involved

Atomic hyperfine structure

$\Delta E = A \cdot K/2 + B \cdot \{3K(K+1)/4 - I(I+1)J(J+1)\}/\{2(2I-1)(2J-1)IJ\}$, $K = F(F+1) - I(I+1) - J(J+1)$

Atomic parameters

- Magnetic dipole HF parameter

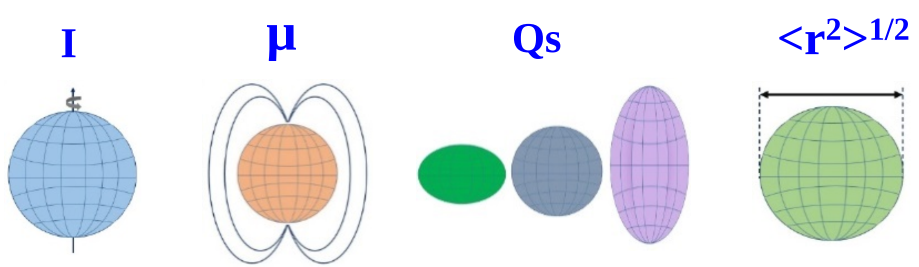
$$A = \frac{\mu_I B_J}{IJ}$$ **I, μ**

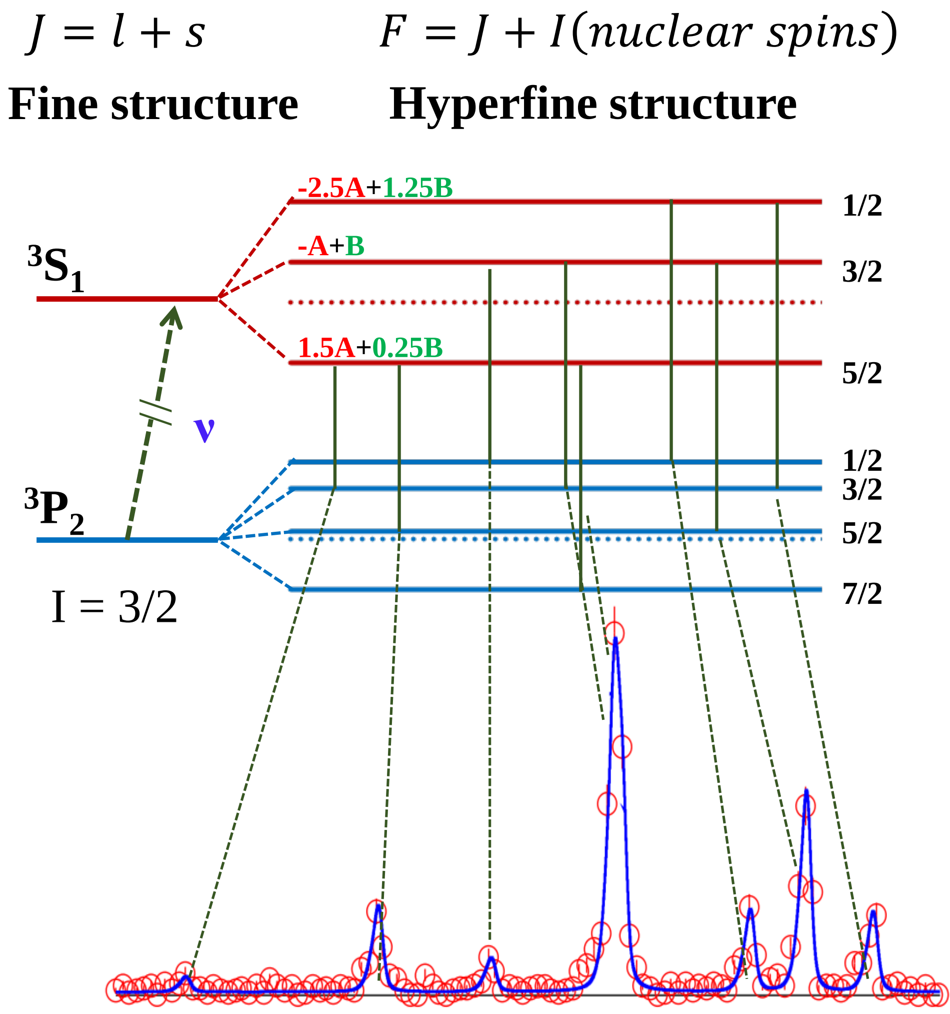
- Electric quadrupole HF parameter

$$B = eQV_{zz}$$ **Qs**

- Centroid ν_0 => Isotopes shift

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





All quantities are deduced (nuclear) model-independently

Observables from laser spectroscopy

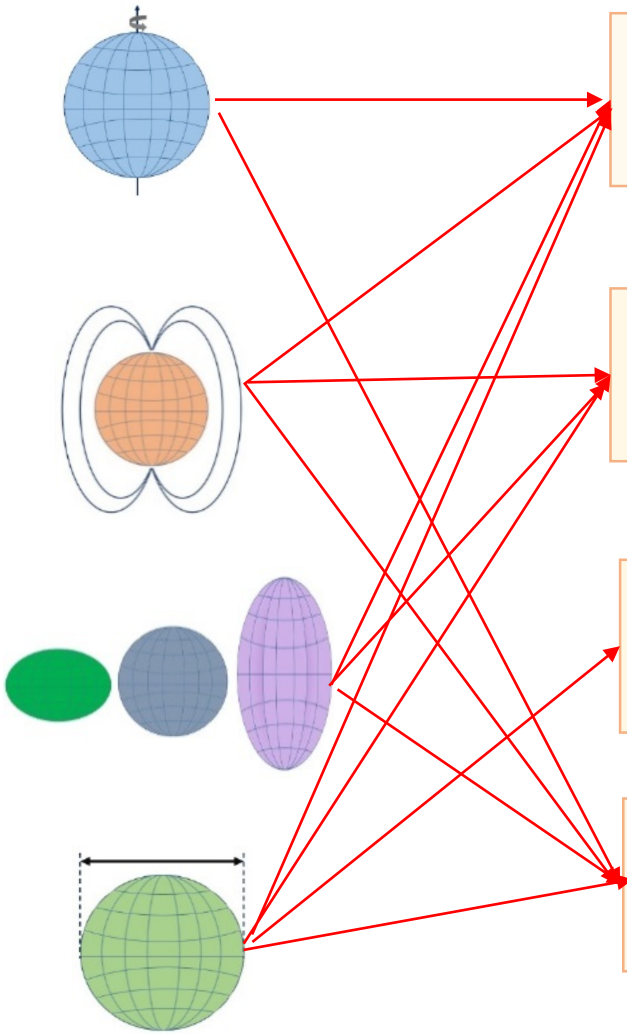
---and its link to nuclear information

Spin
Parity

Magnetic
Moment

Quadrupole
Moments

Charge
Radii



Shell evolution/Magicity

PRL110(2013)172503, PRL 203(2009)142501

Correlations/deformation

PRL 116(2016)032501, Nat. Phys. 14(2018)1163

Halo, astrophysics…

PRL 112, 162502 (2014);PRL 119(2017)122502

Input for nuclear theories

Nat. Phys. 12(2016)596; Nat. Phys.15(2019)432

Providing complementary nuclear information!

Contents

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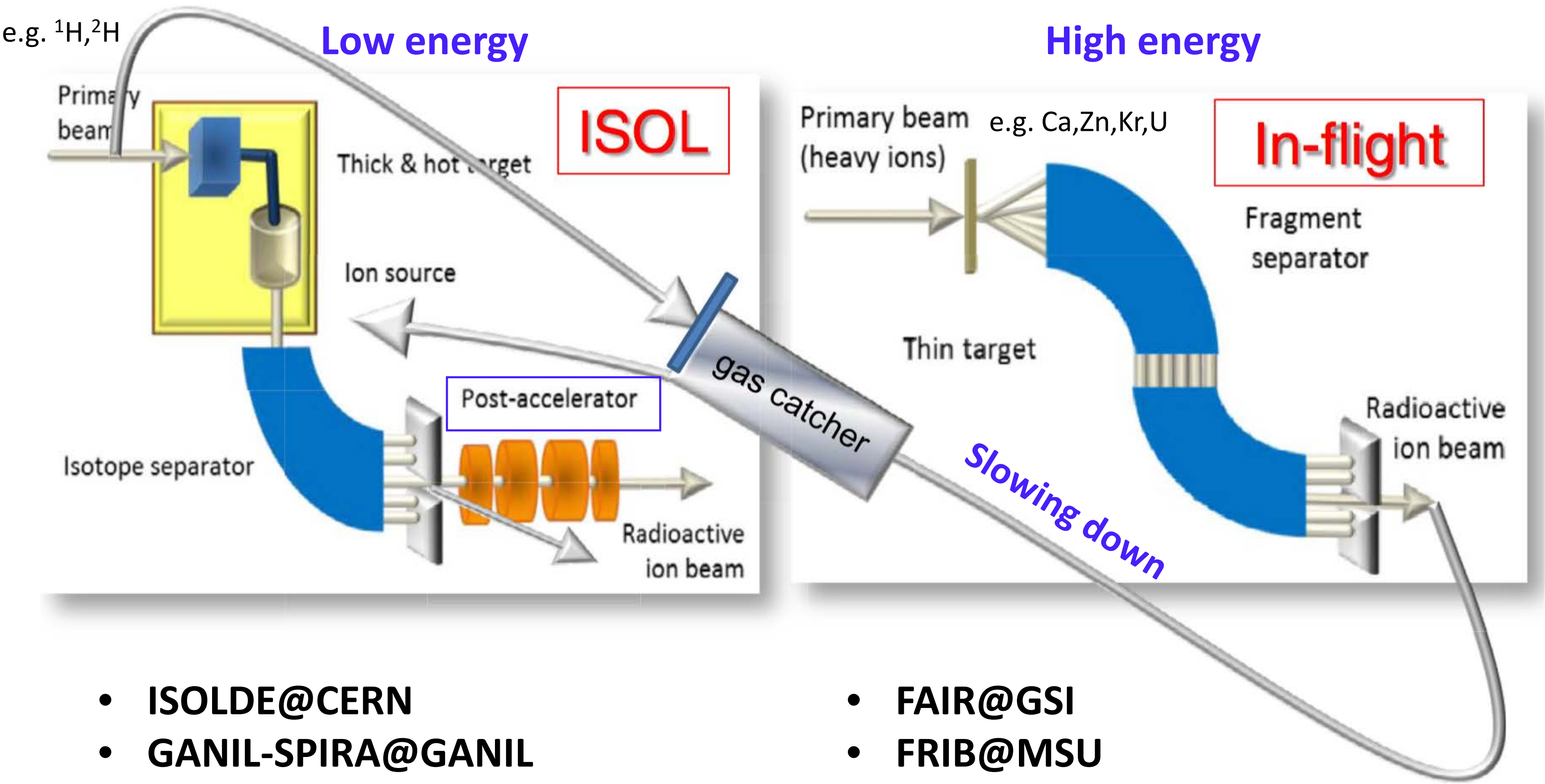
Production of radioactive beams



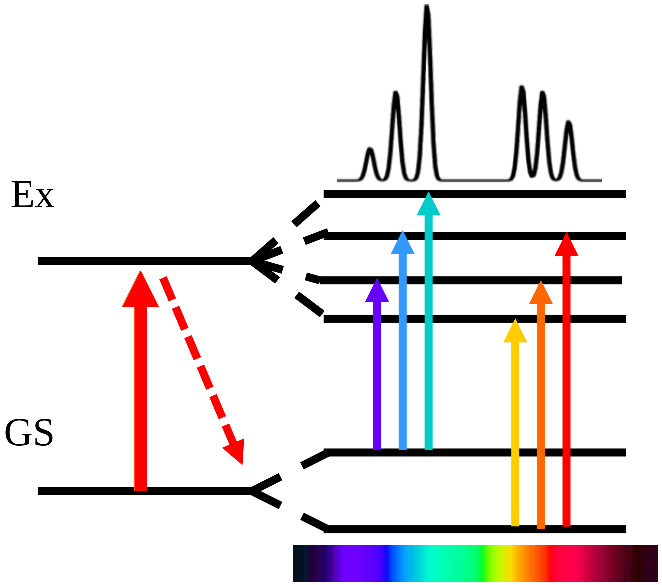
- ISOLDE@CERN
- GANIL-SPIRA@GANIL
- ISAC@TRIUMF
- EUROSOL@EU (planned)
- BISOL @CIAE/PKU(Planned)

- FAIR@GSI
- FRIB@MSU
- BigRIPS, RIPIS@RIKEN
- HIAF@IMP (Funded)

Phys. Scr. T152 (2013) 014023 (24pp)

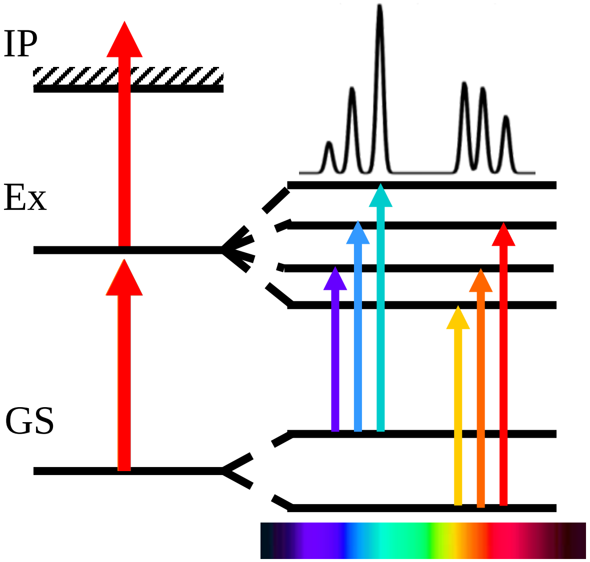
Laser spectroscopy methods

Single laser beam



Photon detection

Multiple laser beams



Ion detection

-Collinear laser spectroscopy

-Laser spectroscopy of trapped atoms

·········

-Collinear resonant ionization

-In source spectroscopy

-In gas cell/ gas-jet spectroscopy

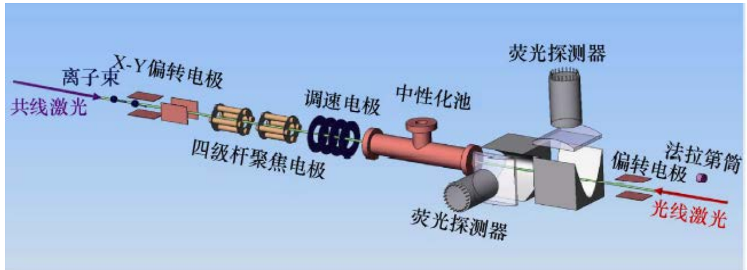
·········

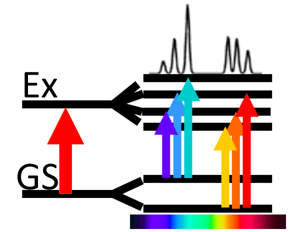
J. Phys. G: Nucl. Part. Phys. 37 (2010) 113101 ; Prog. Part. Nucl. Phys. 86, 127 (2016).

Laser spectroscopy techniques

J. Phys. G: Nucl. Part. Phys. 37 (2010) 113101 (38pp)
Prog. Part. Nucl. Phys. 86, 127 (2016).

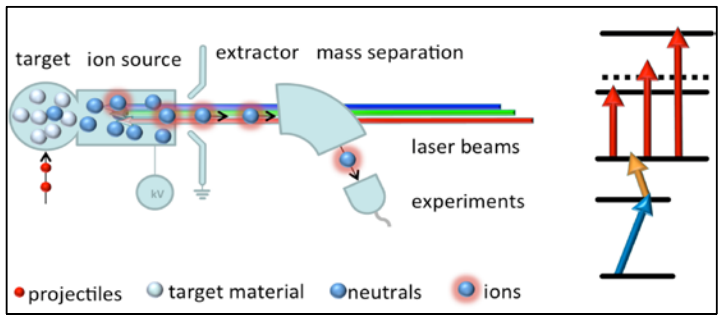
Collinear laser spectroscopy

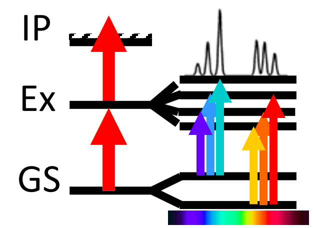




=>polarized beam
=>decay/β-NMR

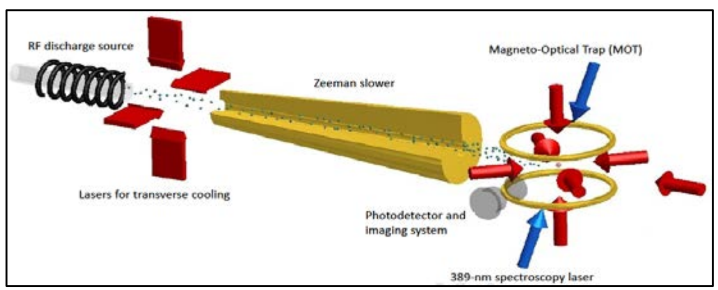
In source spectroscopy

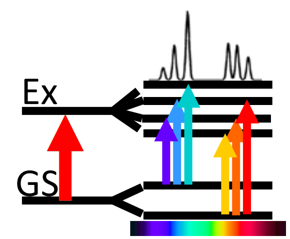




=> Laser ion source

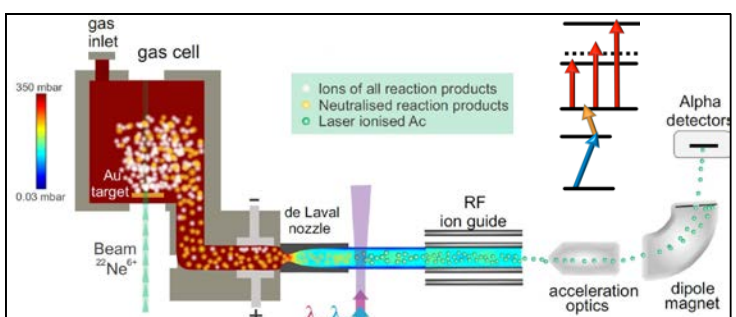
Ion/atom trap (e.g MOT)

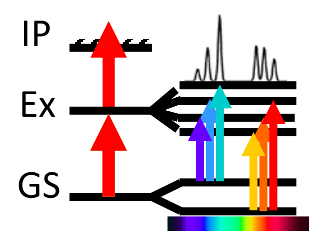




=>decay/application

In-gas-cell/Jet



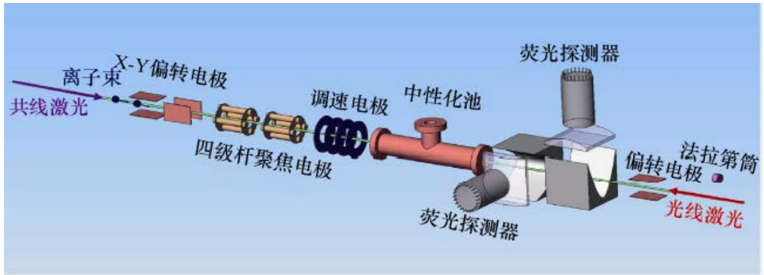


=> Laser ion source

Laser spectroscopy techniques

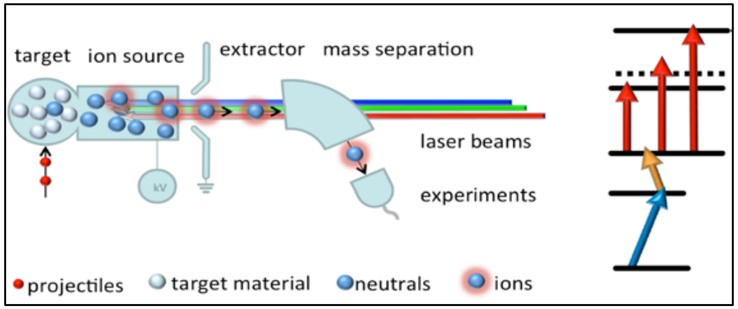
J. Phys. G: Nucl. Part. Phys. 37 (2010) 113101 (38pp)
Prog. Part. Nucl. Phys. 86, 127 (2016).

Collinear laser spectroscopy



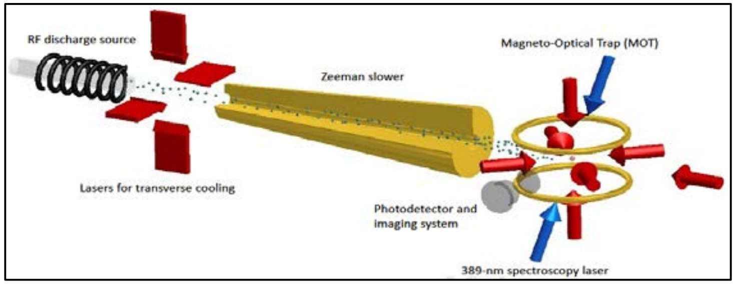
<100MHz
10^{2-3} ions/s
I, u, Q, $\langle r^2 \rangle$

In source spectroscopy



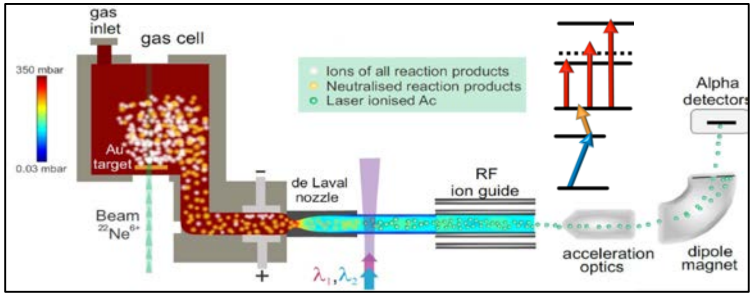
~ GHz
<1 ions/s
I, u, $\langle r^2 \rangle$

Ion/atom trap (e.g MOT)



<10 MHz
I, u, Q, $\langle r^2 \rangle$

In-gas-cell/Jet

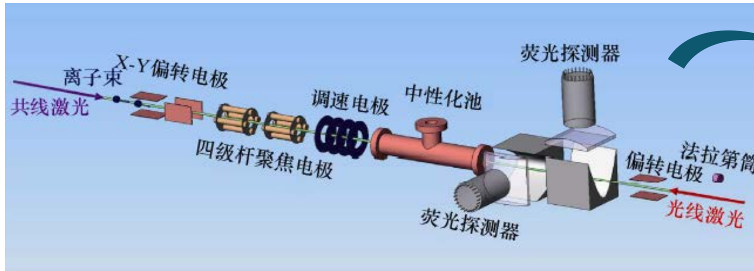


> 200 MHz
< 10 ions/s
I, u, $\langle r^2 \rangle$

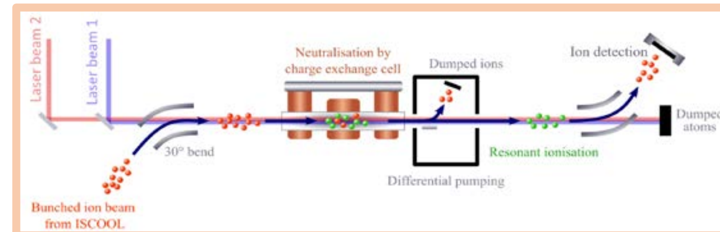
Laser spectroscopy techniques

J. Phys. G: Nucl. Part. Phys. 37 (2010) 113101 (38pp)
Prog. Part. Nucl. Phys. 86, 127 (2016).

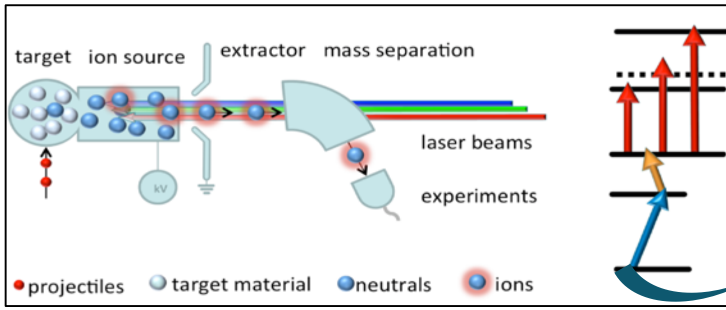
Collinear laser spectroscopy



Collinear resonance ionization spectroscopy



In source spectroscopy

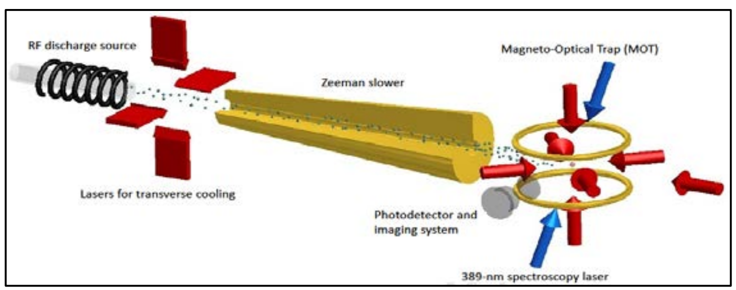


<100MHz

<50 ions/s

I, u, Q, $\langle r^2 \rangle$

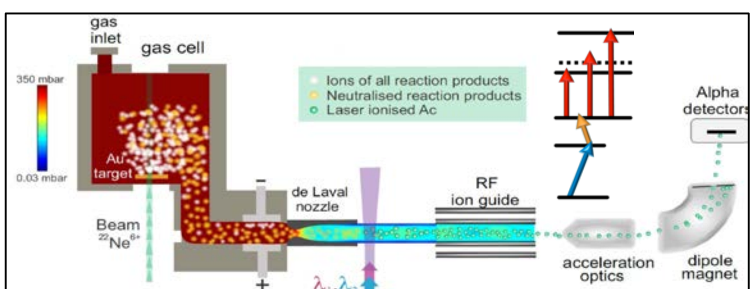
Ion/atom trap (e.g MOT)



<10 MHz

I, u, Q, $\langle r^2 \rangle$

In-gas-cell/Jet



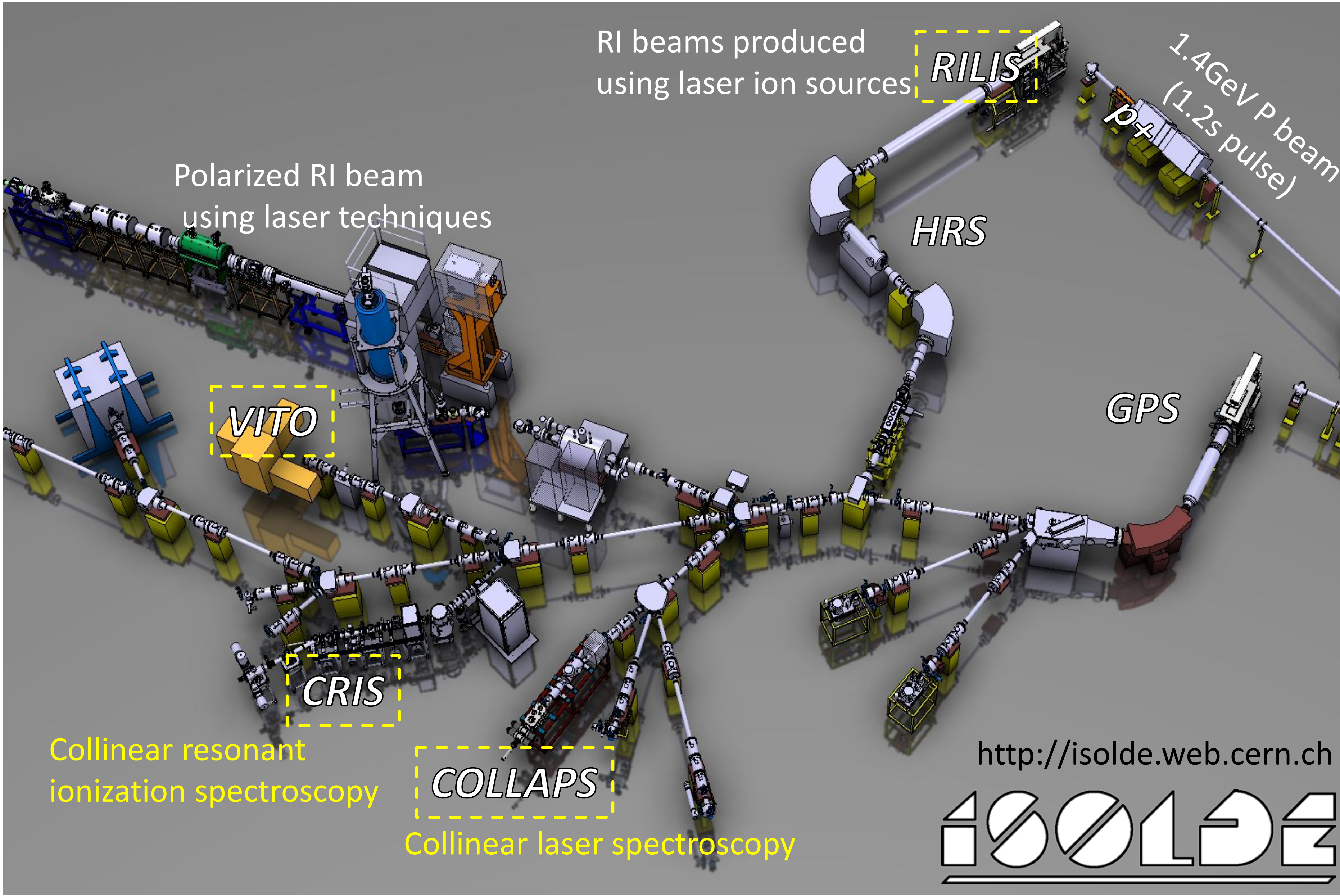
> 200 MHz

< 10 ions/s

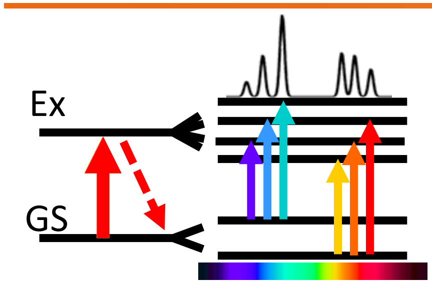
I, u, $\langle r^2 \rangle$

CERN-ISOLDE（COLLAPS/CRIS）

http://isolde.web.cern.ch/

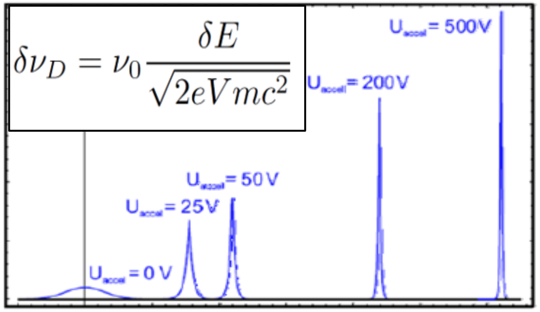


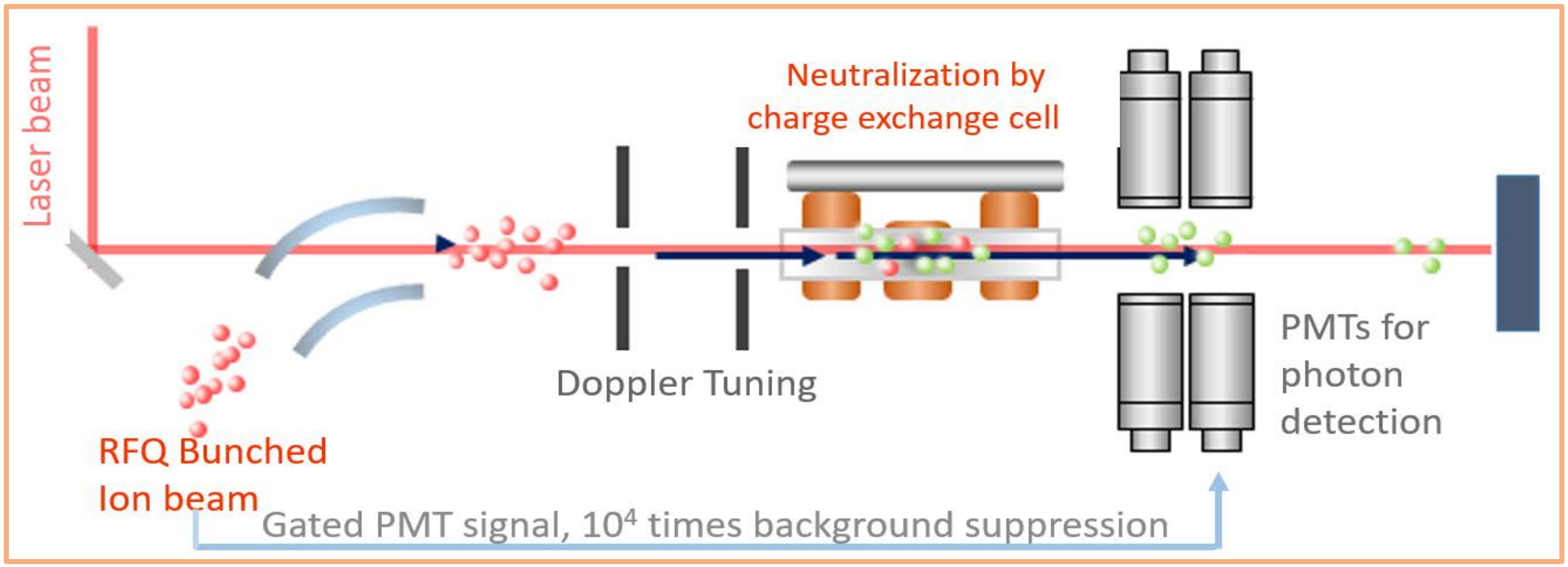
Collinear laser spectroscopy (COLLAPS)

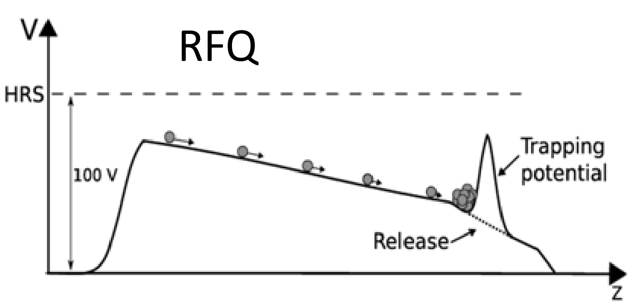


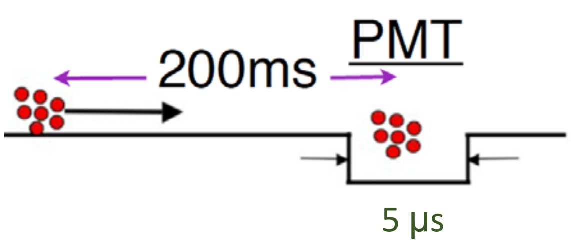
http://collaps.web.cern.ch/

- ✓ **Collinear : High resolution**
- ✓ **Photon detec.: Sensitivity 10^3 pps**





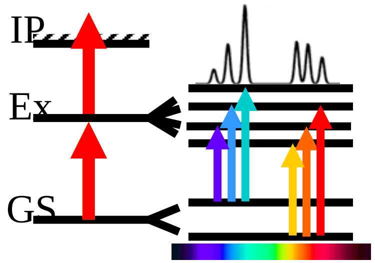




$$\nu_{transition} = \nu_{laser} \frac{1-\beta}{\sqrt{1-\beta^2}}$$

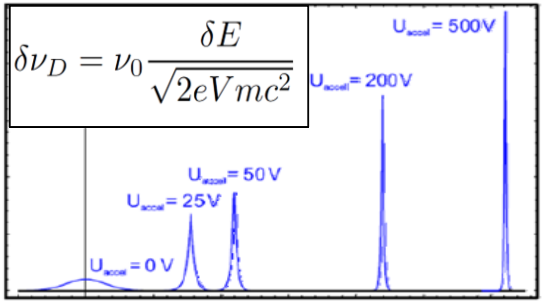
$$\beta = \sqrt{1 - \frac{M_0^2 c^4}{(Uq + M_0 c^2)^2}}$$

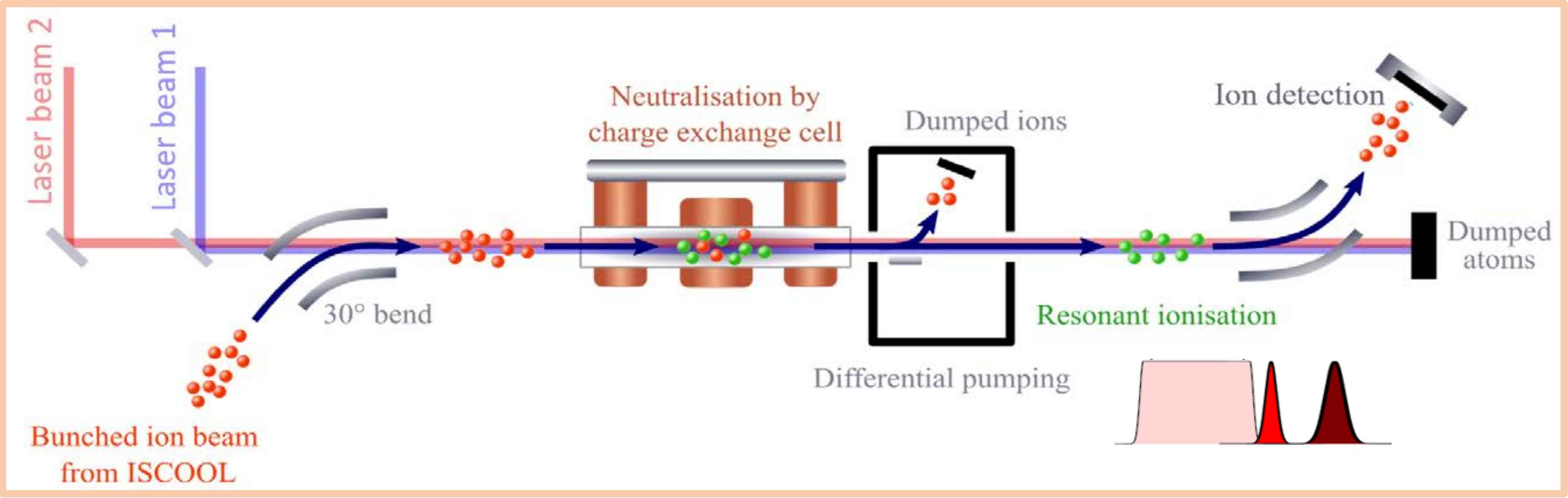
Collinear ionization laser spectroscopy（CRIS）

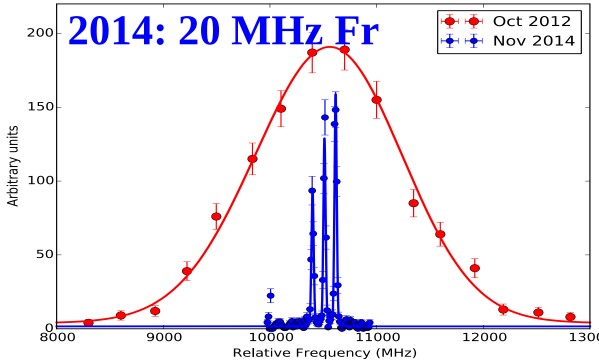


http://isolde-cris.web.cern.ch/isolde-cris/

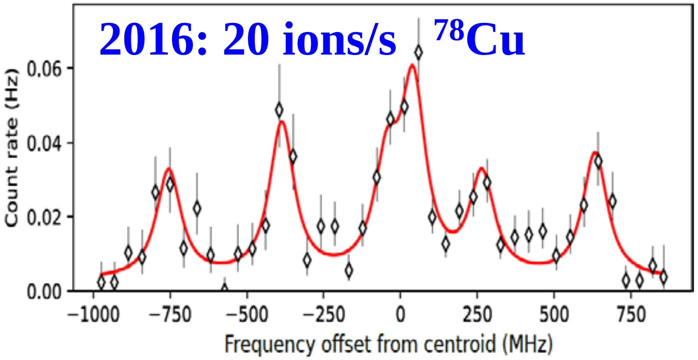
- ✓ **Collinear: High resolution**
- ✓ **Ion detection: Higher sensitivity**





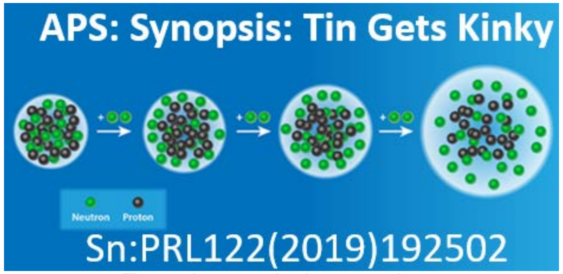


R.P. De Groote et al.,PRL. 115 (2015) 132501

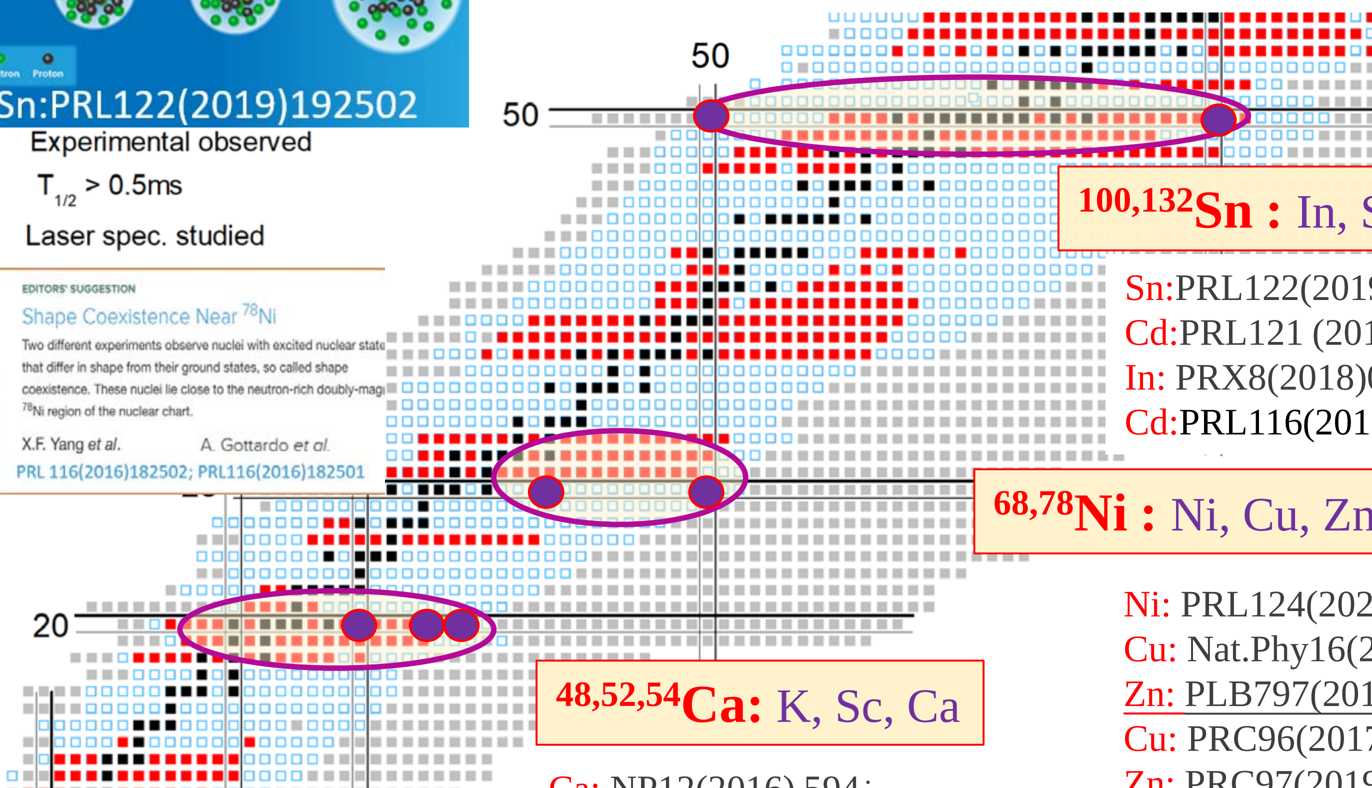


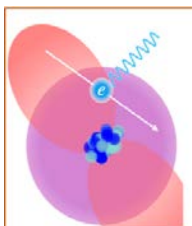
R.P. De Groote et al.,PRL C96(2017)041302(R)

Research interests （COLLAPS/CRIS）



***Radioactive molecules* Nature581(2020)396**





^{100,132}Sn : In, Sn, Sb…

Sn:PRL122(2019)192502
Cd:PRL121 (2018)102501
In: PRX8(2018)041005
Cd:PRL116(2016) 032501

^{68,78}Ni : Ni, Cu, Zn, Ga, Ge…

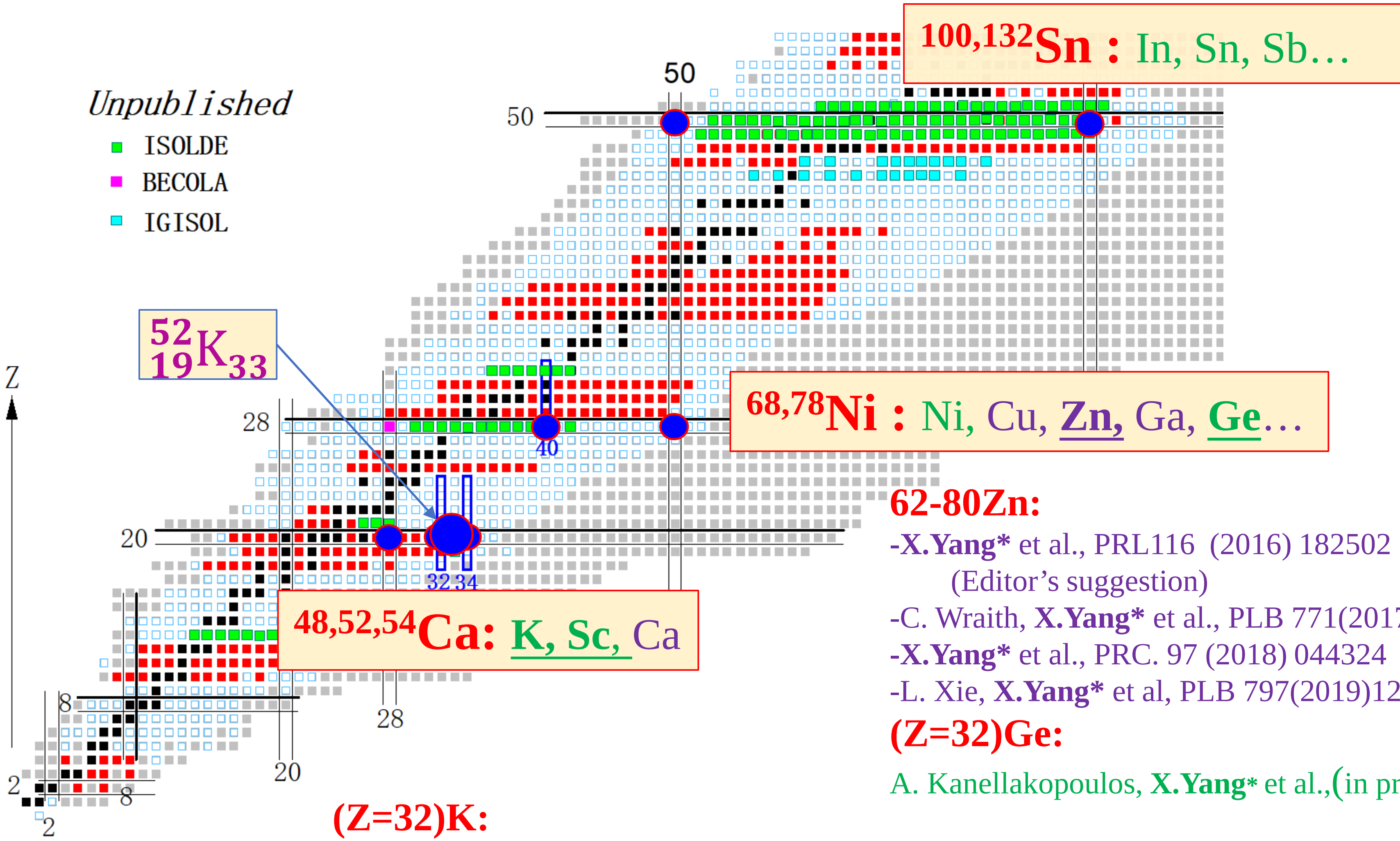
Ni: PRL124(2020)132502;
Cu: Nat.Phy16(2020)620;
Zn: PLB797(2019)134805;
Cu: PRC96(2017)041302(R);
Zn: PRC97(2019)044324
Zn: PLB771(2017) 385;
Zn: PRL116(2016)182502 ;

^{48,52,54}Ca: K, Sc, Ca

Ca: NP12(2016) 594;
Ca: PPC750(2015)041304(R);
K: PRC100(2019)034304;

- http://collaps.web.cern.ch/people
- http://isolde-cris.web.cern.ch/isolde-cris/
- With strong collaboration with theoretical collages

Research interests （COLLAPS/CRIS）



62-80Zn:

-**X.Yang*** et al., PRL116 (2016) 182502 (Editor's suggestion)

-C. Wraith, **X.Yang*** et al., PLB 771(2017)385

-**X.Yang*** et al., PRC. 97 (2018) 044324

-L. Xie, **X.Yang*** et al, PLB 797(2019)124805

(Z=32)Ge:

A. Kanellakopoulos, **X.Yang*** et al.,(in preparation)

(Z=32)K:

A.Koszorus, **X.Yang*** et al., PRC100(2019)034304

A.Koszorus, **X.Yang*** et al., (in preparation)

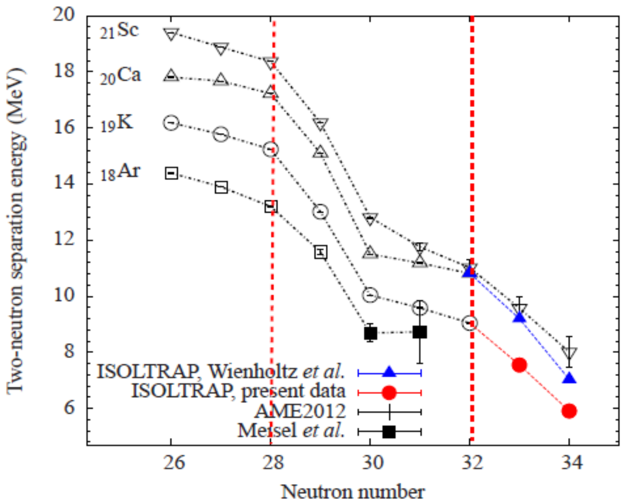
A.Koszorus*, **X.Yang*** et al., (Submitted to Nat.Phys)

(Z=21) Sc:

S.W. Bai, **X. Yang*** et al (In preparation)

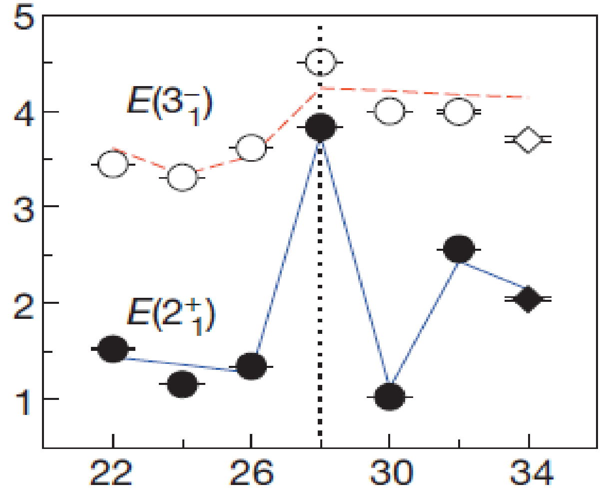
"New magic numbers" (N = 32, N = 34)!!

K, Ca (Z = 19,21): S_{2n}



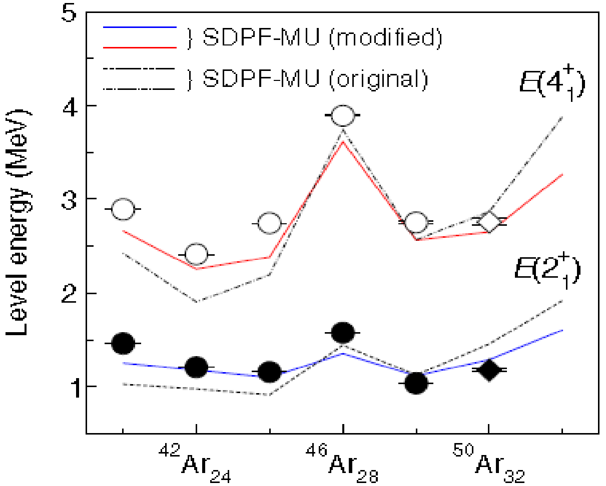
Wienholtz *et al*, Nature, 2013
Rosenbusch et al., PRL, 2015

Ca (Z = 20) : E(2$^+$)



Steppenbeck *et al*, Nature 2013 (RIKEN)

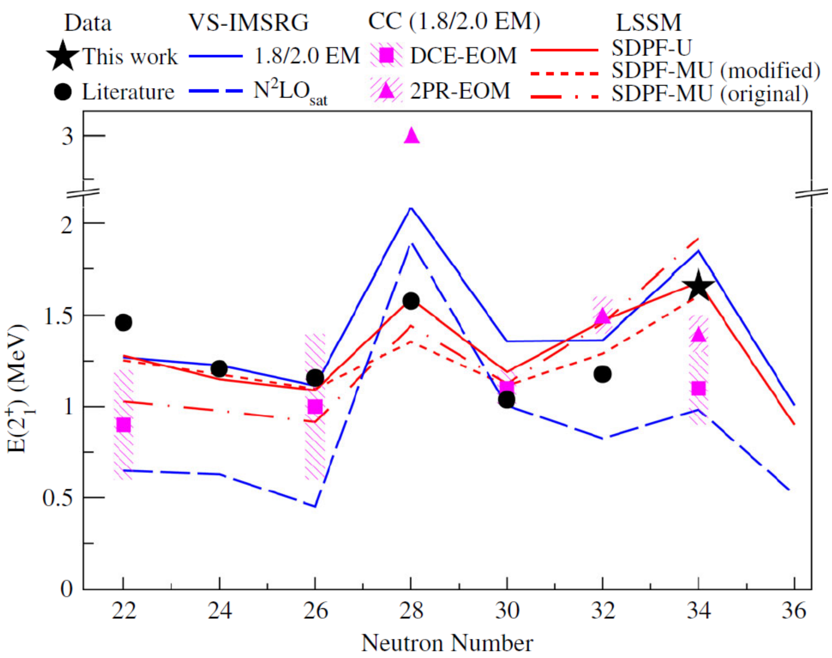
Ar (Z = 18) : E(2$^+$)

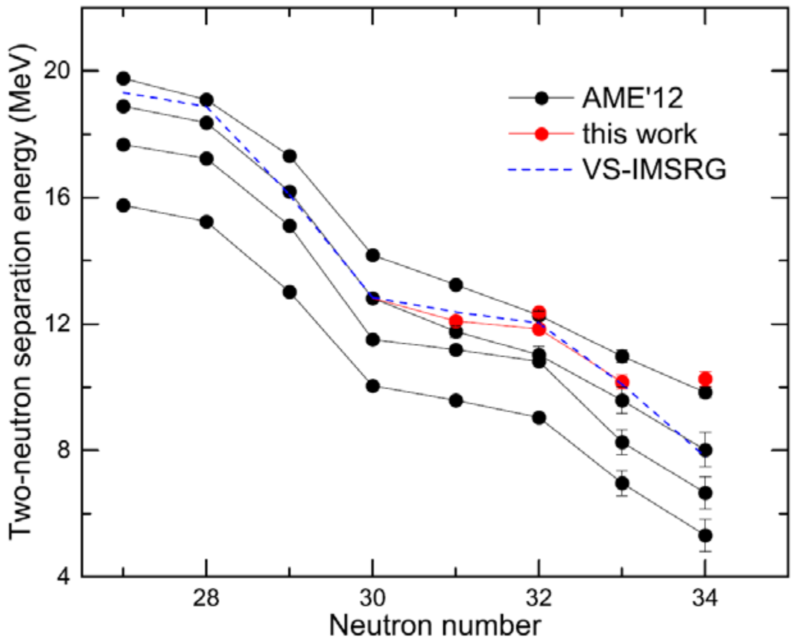


PRL 114, 252501 (2015)

Theory	N=32 (Ca)	N=34 (Ca)	Ref.
Shell model	GXPF1A, KB3G **E(2$^+$), S_{2n}**	GXPF1Br **E(2$^+$)**	**PRC 65, 061301(R) (2002)** **JPS Conf. Proc. 6 (2015) 010007** **Nature 498,346(2013)**
Shell model Chiral EFT (3N)	MBPT **E(2$^+$), S_{2n}**	MBPT **E(2$^+$)**	**Annu. Rev. Nucl. Part. Sci. 2015. 65**
Ab initio Chiral EFT (3N)	CC **E(2$^+$), S_{2n}**	CC **E(2$^+$)**	**Annu. Rev. Nucl. Part. Sci. 2015. 65**
Beyond MF	**E(2$^+$)**		**PRL 99, 062501 (2007)**

"New magic numbers" (N = 32, N = 34)!!??





PHYSICAL REVIEW LETTERS **122,** 072502 (2019)

How Robust is the $N = 34$ Subshell Closure? First Spectroscopy of ^{52}Ar

PHYSICAL REVIEW C **99**, 064303 (2019)

Masses of neutron-rich $^{52-54}$Sc and ^{54,56}Ti nuclides: The N = 32 subshell closure in scandium

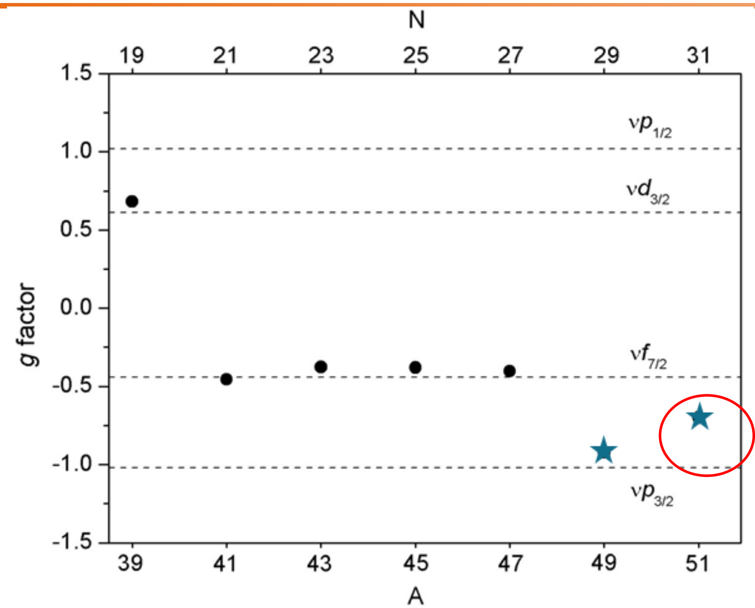
Quenching of the $N = 32$ neutron shell closure studied via precision mass measurements of neutron-rich vanadium isotopes

M. P. Reiter *et al.*
Phys. Rev. C **98**, 024310 – Published 15 August 2018

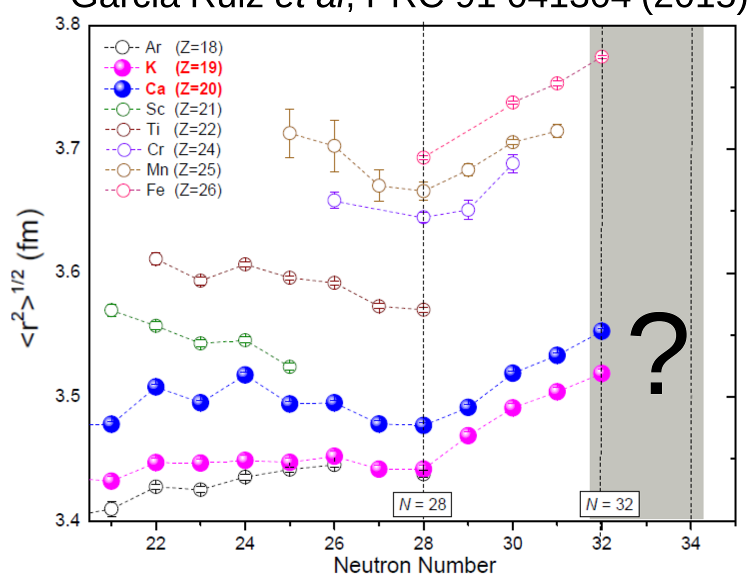
Magic Nature of Neutrons in ^{54}Ca: First Mass Measurements of $^{55-57}$Ca

S. Michimasa *et al.*
Phys. Rev. Lett. **121**, 022506 – Published 11 July 2018

“New magic numbers” (N = 32, N = 34) ??

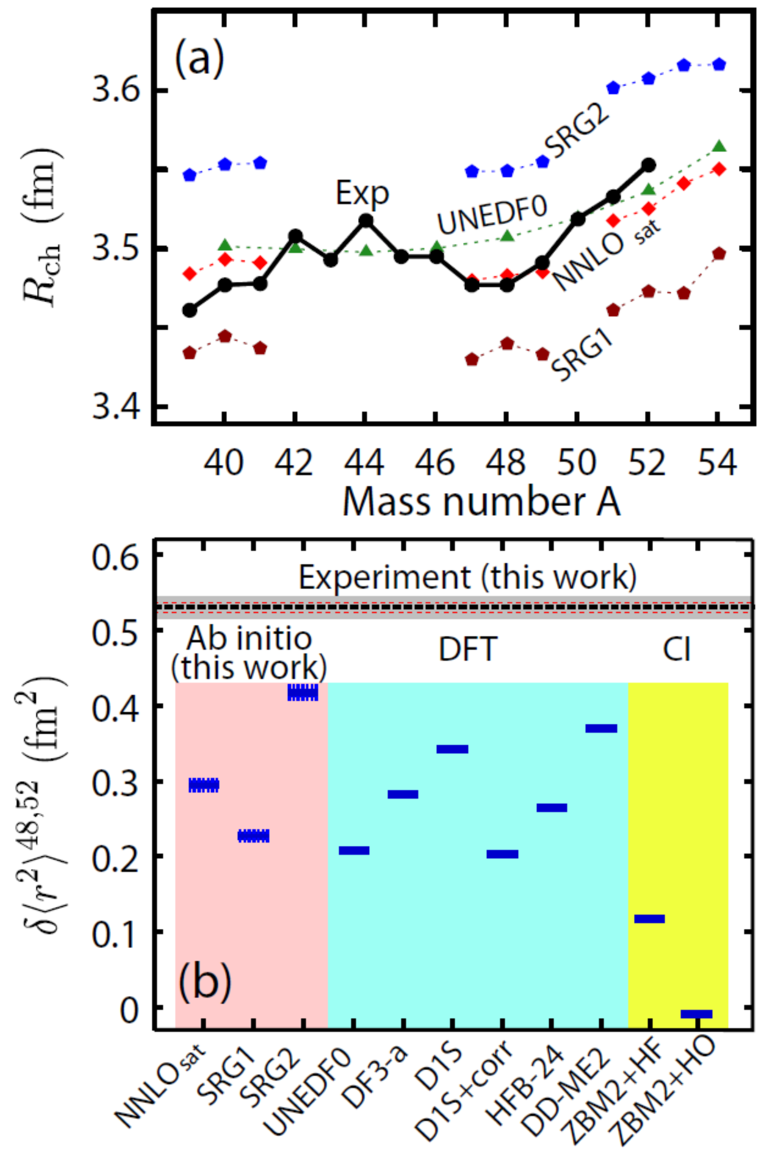


Garcia Ruiz *et al*, PRC 91 041304 (2015)



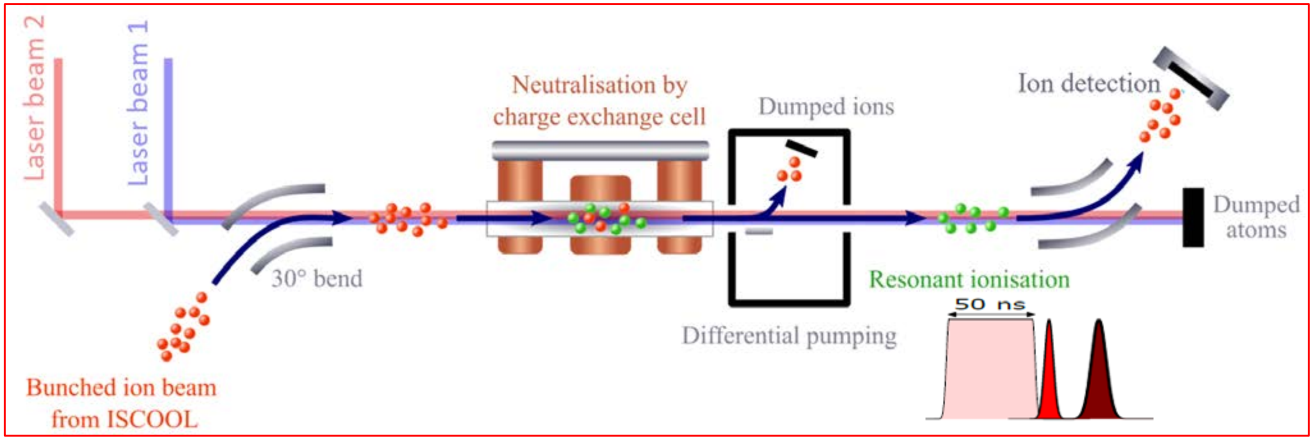
Garcia Ruiz *et al*, Nature Physics 2016,
Kreim *et al*, PLB 2014

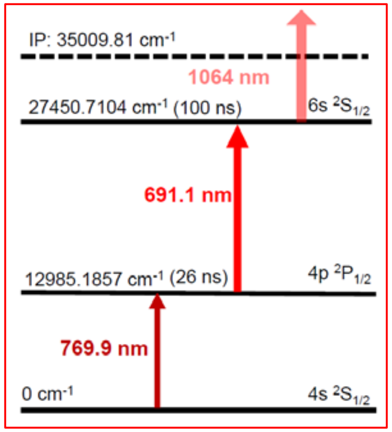
Theoretical challenges

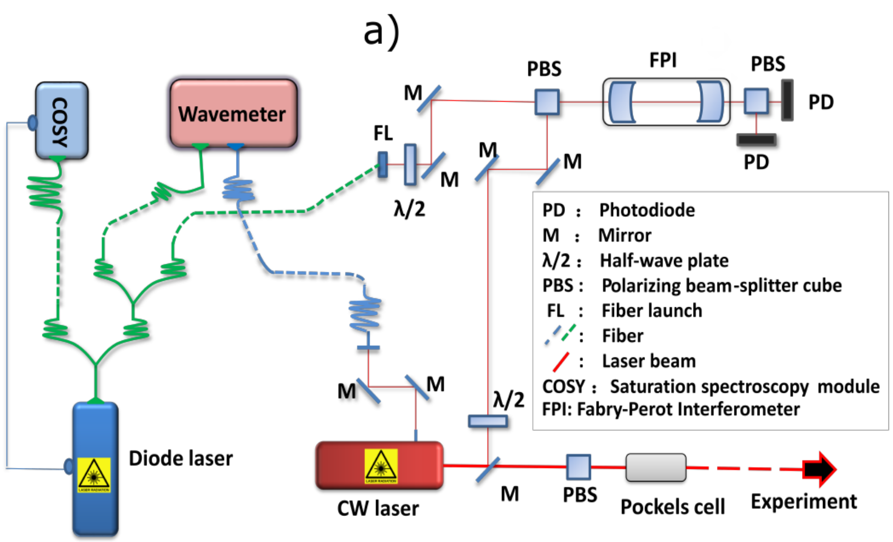


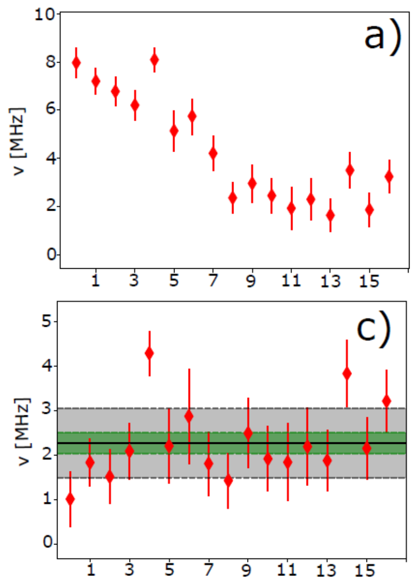
Charge radius of ^{52}K (N=32 magic?)

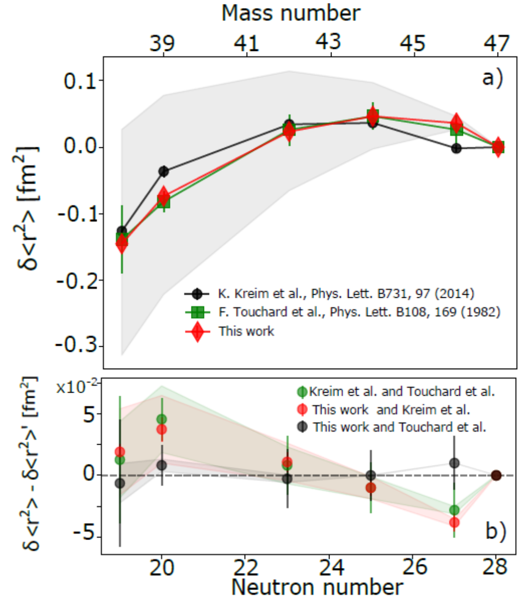
$$\delta\nu^{AA'} = M\frac{A'-A}{AA'} + F\ \delta\langle r^2\rangle^{AA'}$$







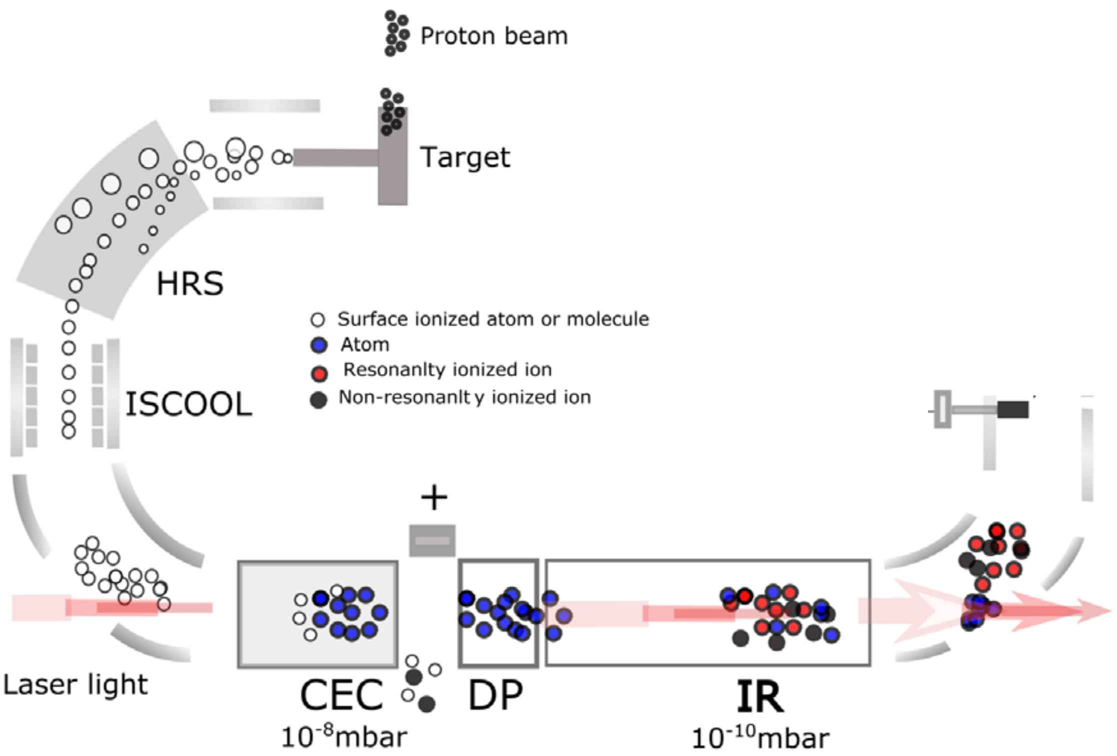




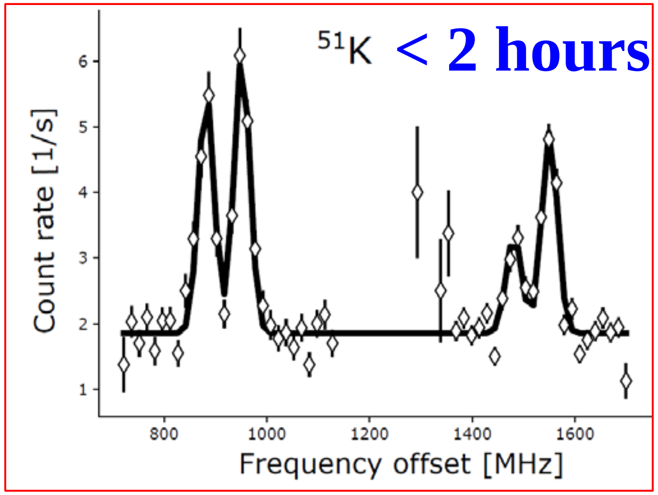
A.Koszorus, **X.F. Yang*** et al., PRC100, 034304 (2019):

Reaching higher precision of ~1 MHz for light mass isotopes.

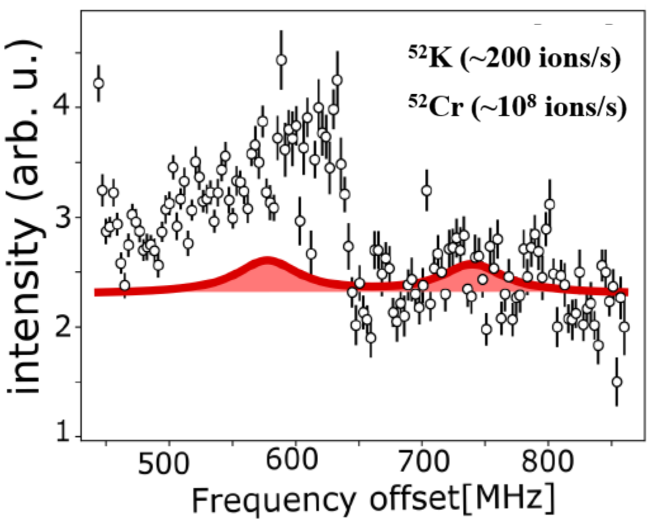
Charge radius of ^{52}K (N=32 magic?)



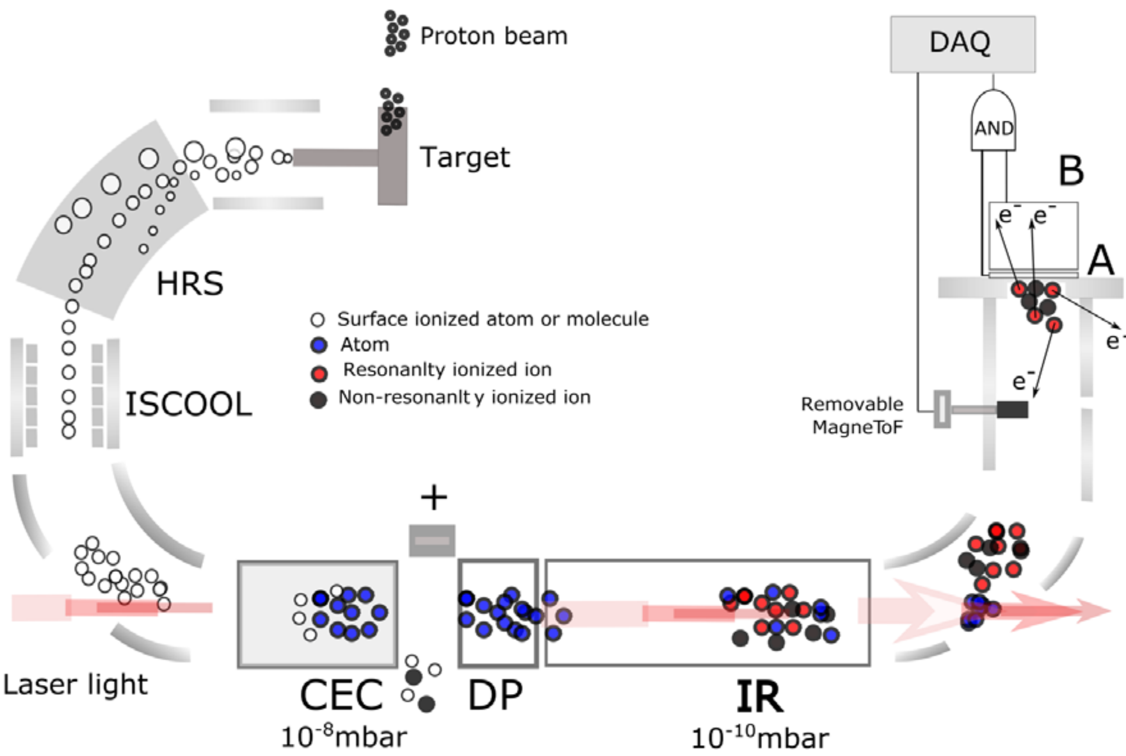
- **CRIS for $^{47\text{-}51}$K**



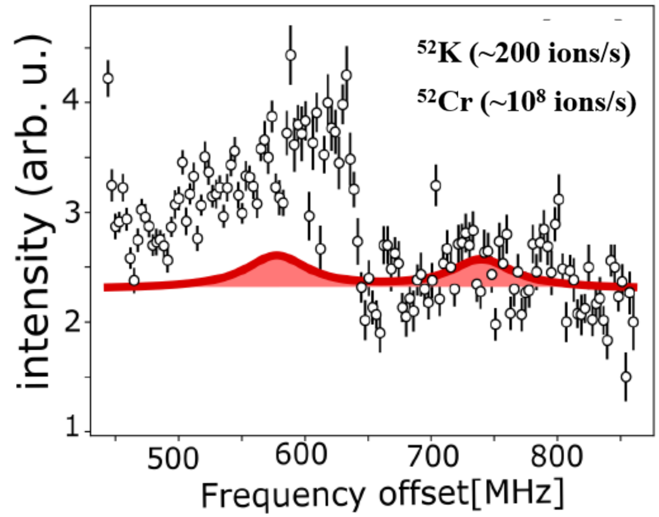
- **CRIS for ^{52}K**

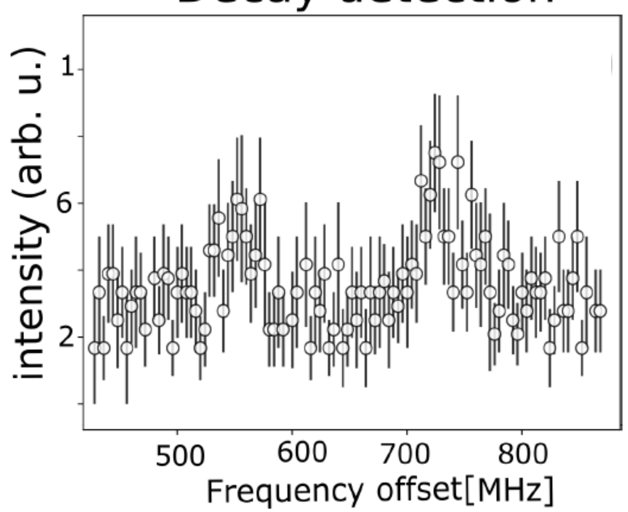


Charge radius of ^{52}K (N=32 magic?)

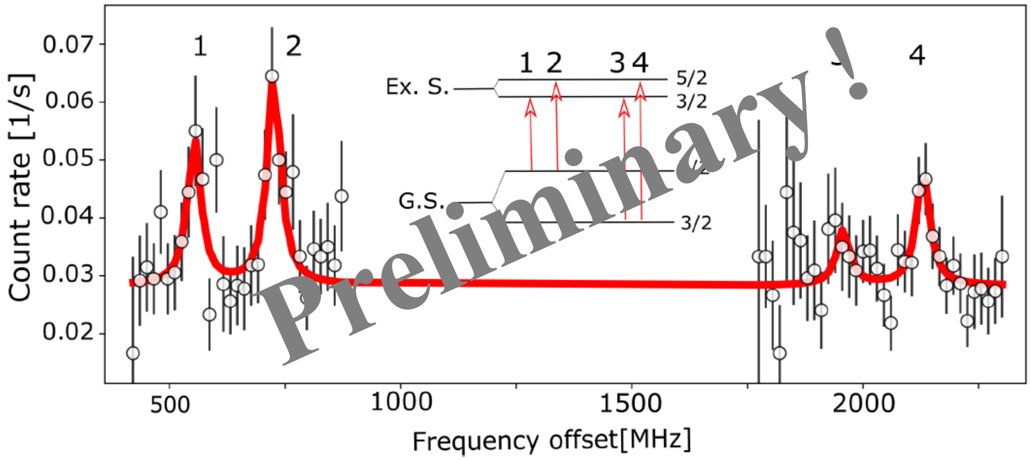


- **CRIS for ^{52}K**

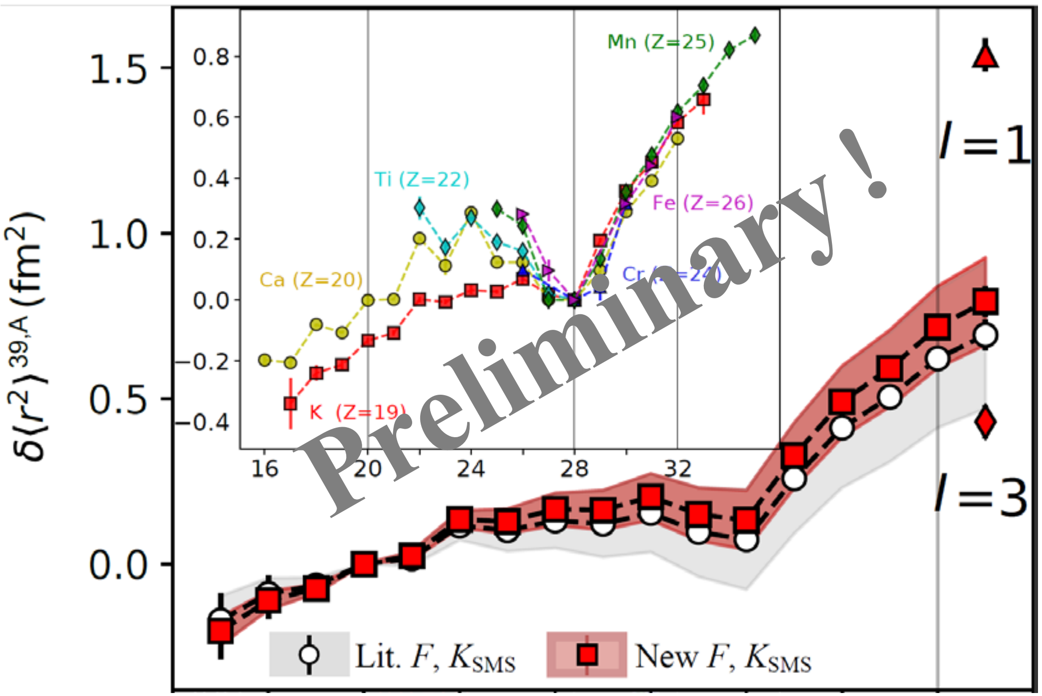




Charge radius of ^{52}K (N=32 magic?)



Cross N = 32 for the first time!!



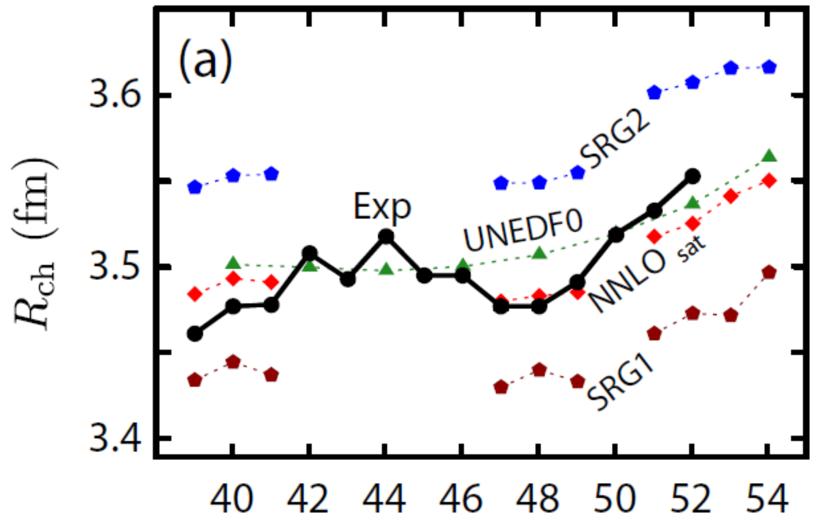
- New F, M largely reduced the systematic errors

  New Journal of Physics 22, 012001(2020)

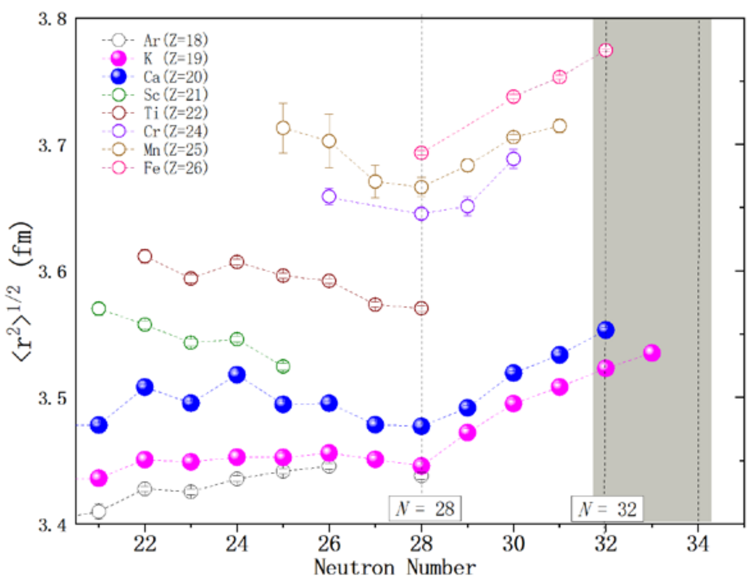
- The increased radii at N =32 has similar trend for open-shell e.g. Mn

- No sign of magicity at N=32

Charge radius of ^{52}K (N=32 magic?)



R.F. Garcia Ruiz et al., Nat.Phys.12(2016) 594



2016

Ab initio CC （NNLOsat)

Fitting to the data of binding energies and radii of selected nuclei up to mass number A = 25.

SRG1 and SRG2

Fitting only to properties of A≤4

2020

Newly developed ΔNNLOgo

- Fitting only to properties of A≤4 and nuclear saturation properties
- Includes pion-physics and effects of the (1232) isobar.

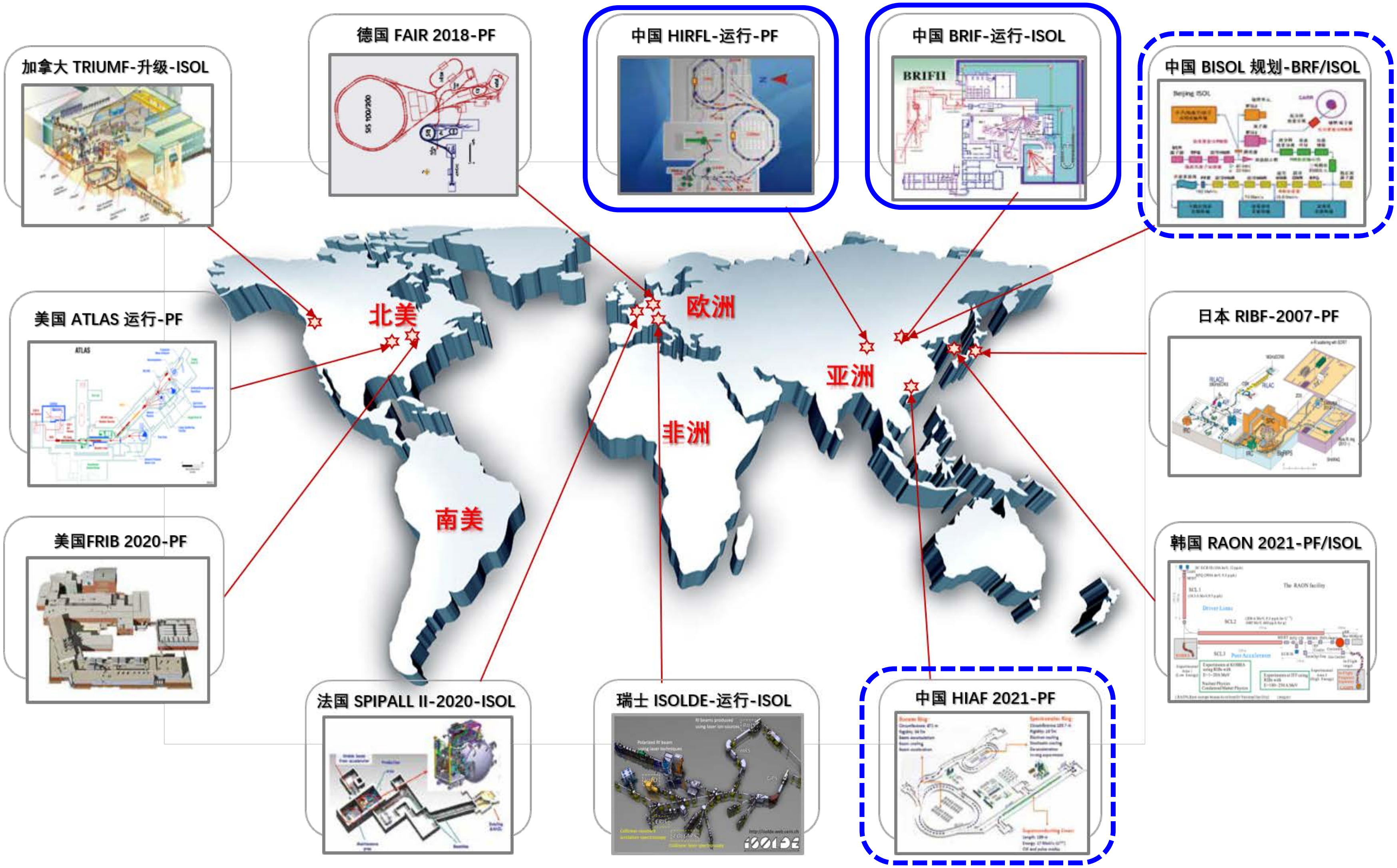
Improved CC method

- start from a symmetry-breaking reference state
- Allow to calculate the radii of whole K chain

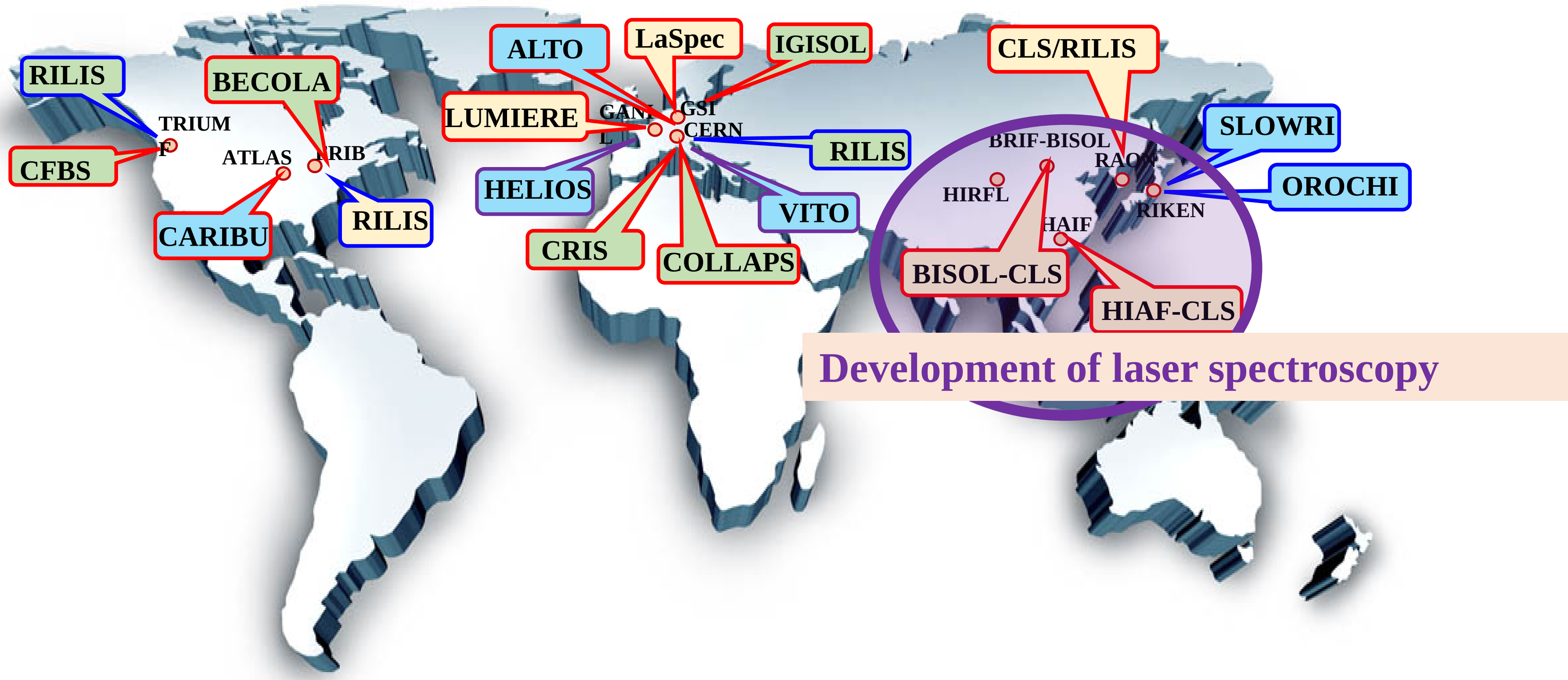
Contents

北京大學 PEKING UNIVERSITY

World-wide RI beam facilities



World-wide laser spectroscopy



operation

under construction/test

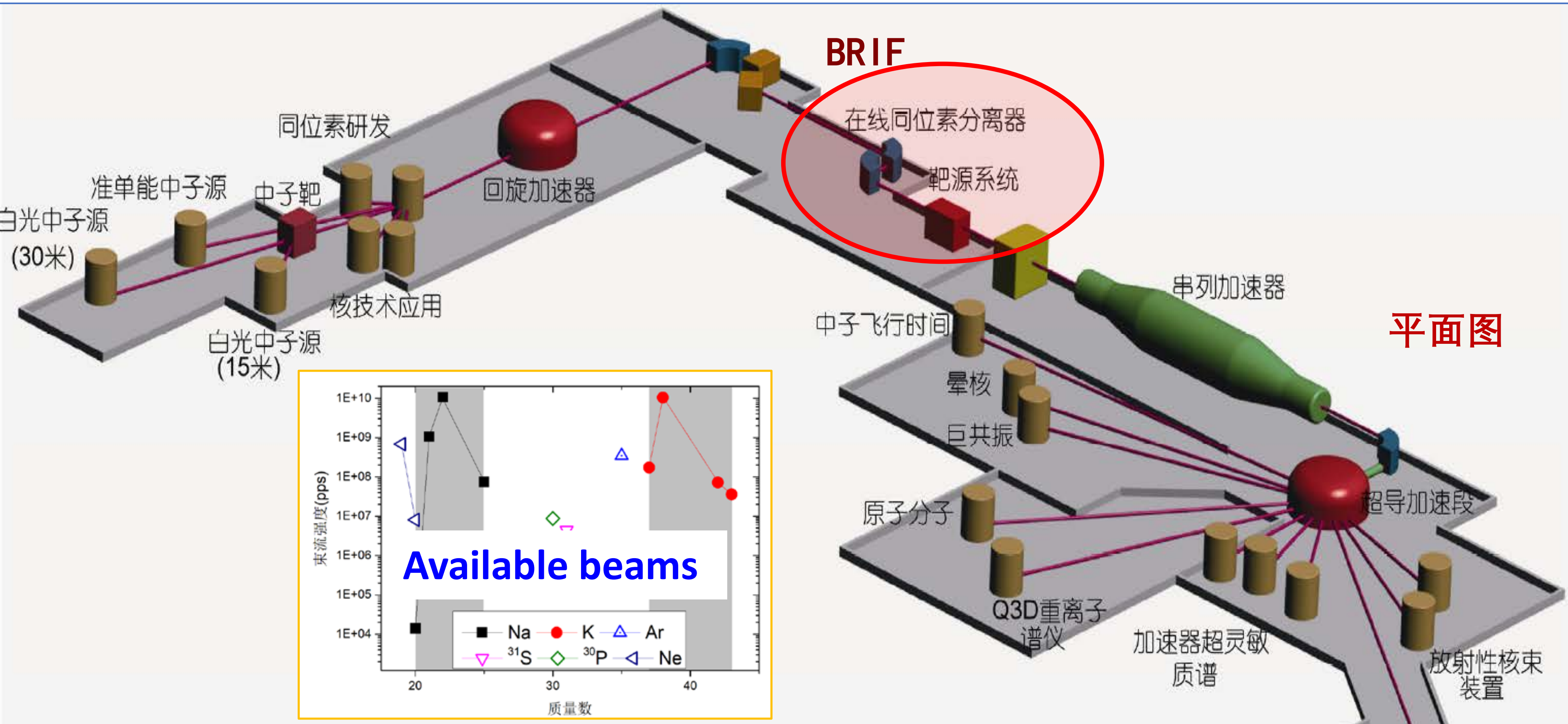
planned

Nuclear properties

Laser ion source

Application

First application：BRIF@CIAE （北京放射性离子装置）

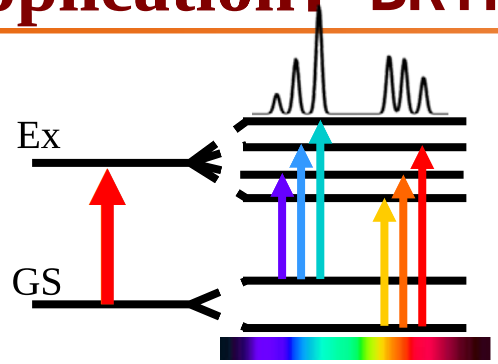


• **100 MeV proton beam (200uA) +Target**

• **kW ISOL Target +online separator**

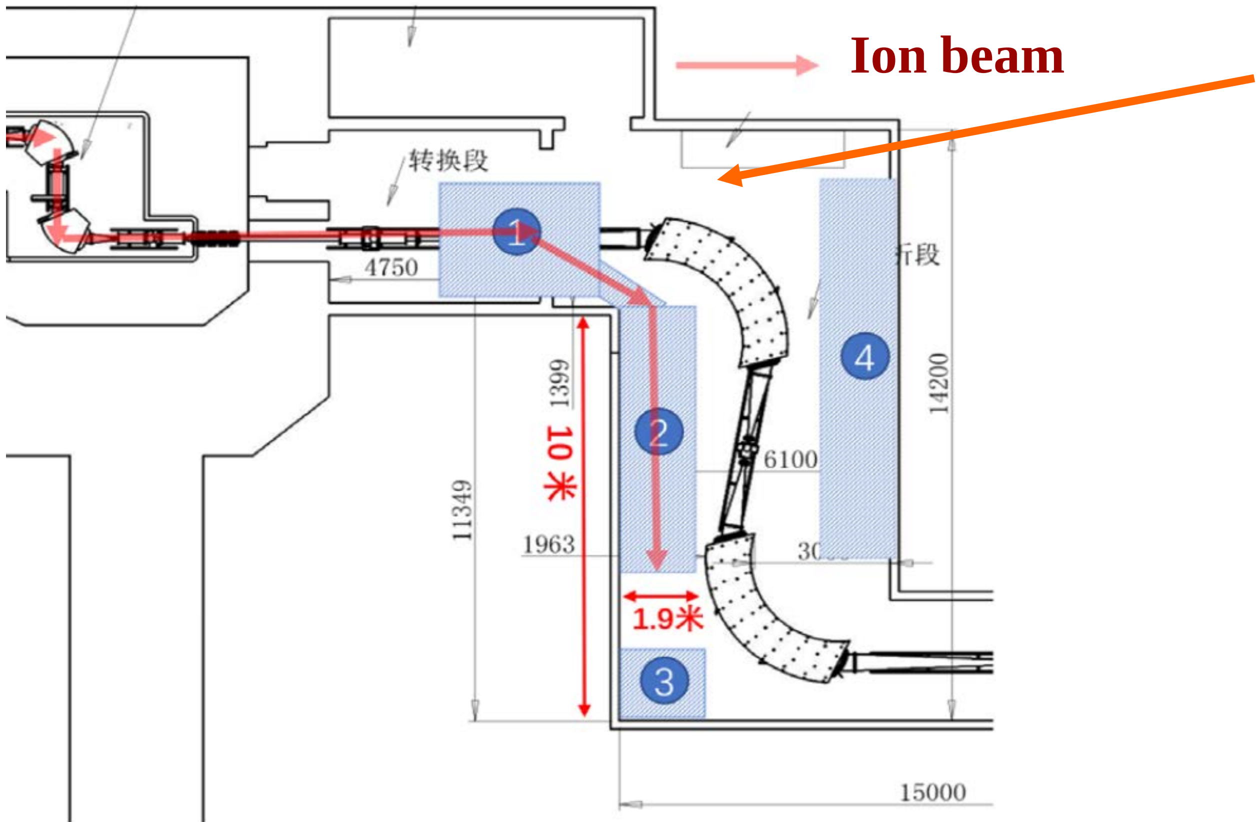
First online measurement！ ！

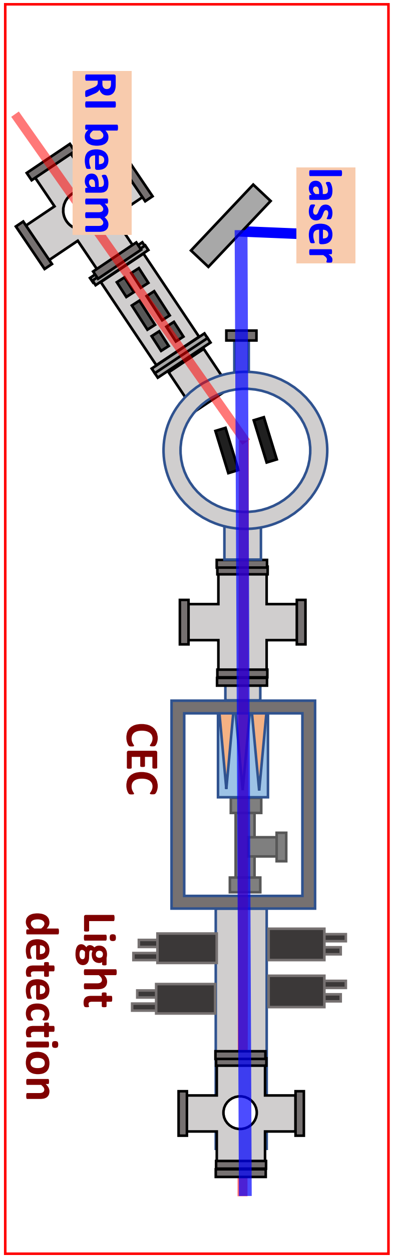
First application：BRIF@CIAE （北京放射性离子装置）



Photon detection

Layout around BRIF

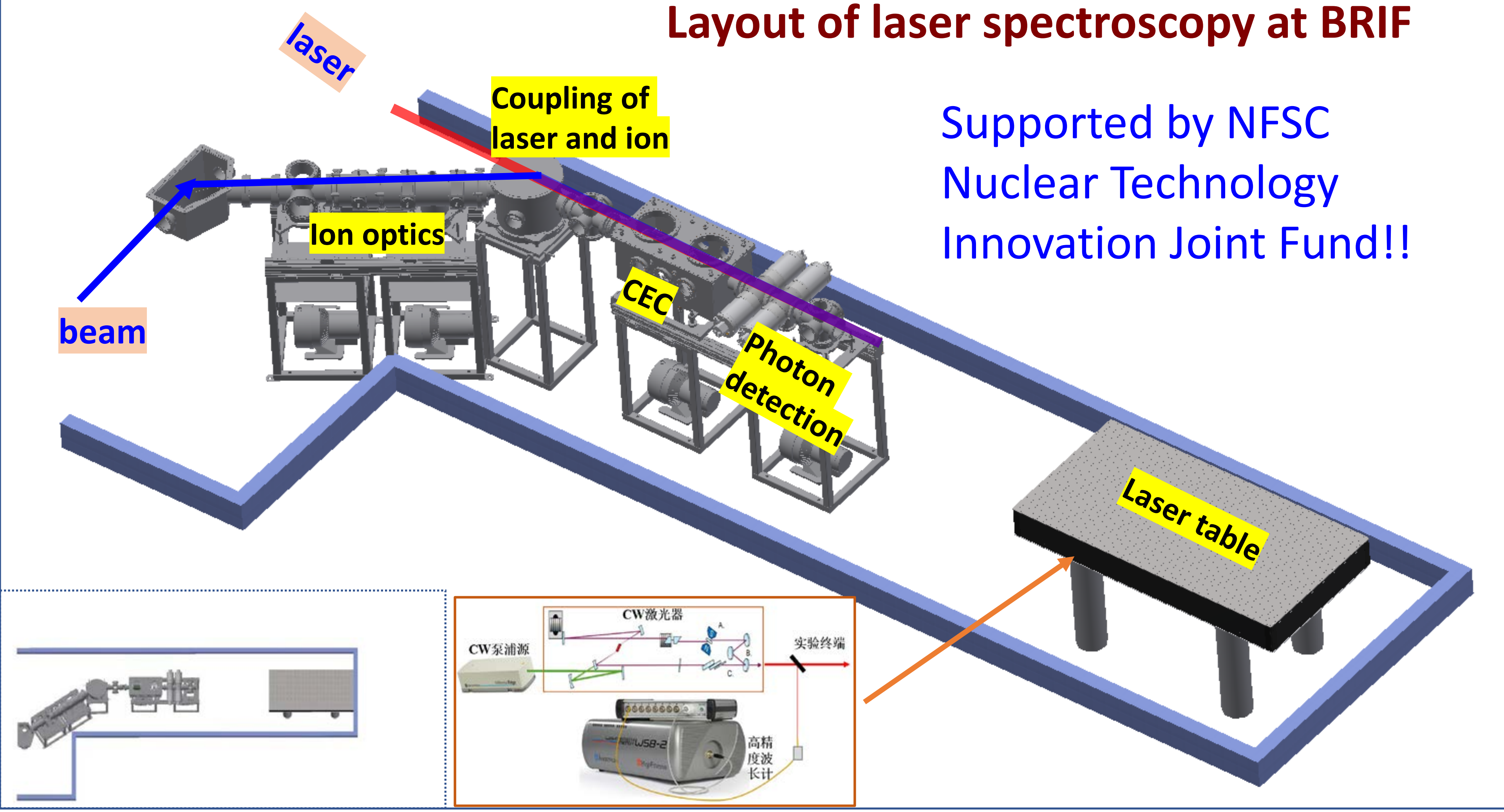




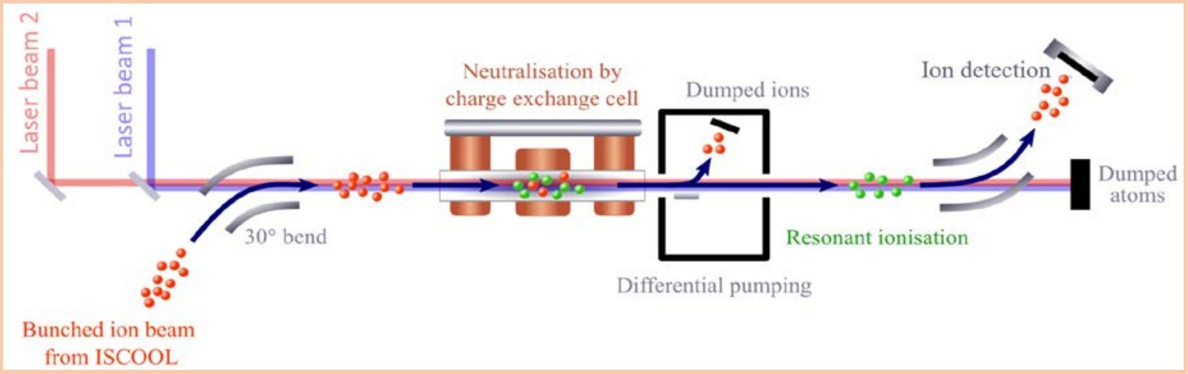
First application：BRIF@CIAE （北京放射性离子装置）

Layout of laser spectroscopy at BRIF

Supported by NFSC
Nuclear Technology
Innovation Joint Fund!!



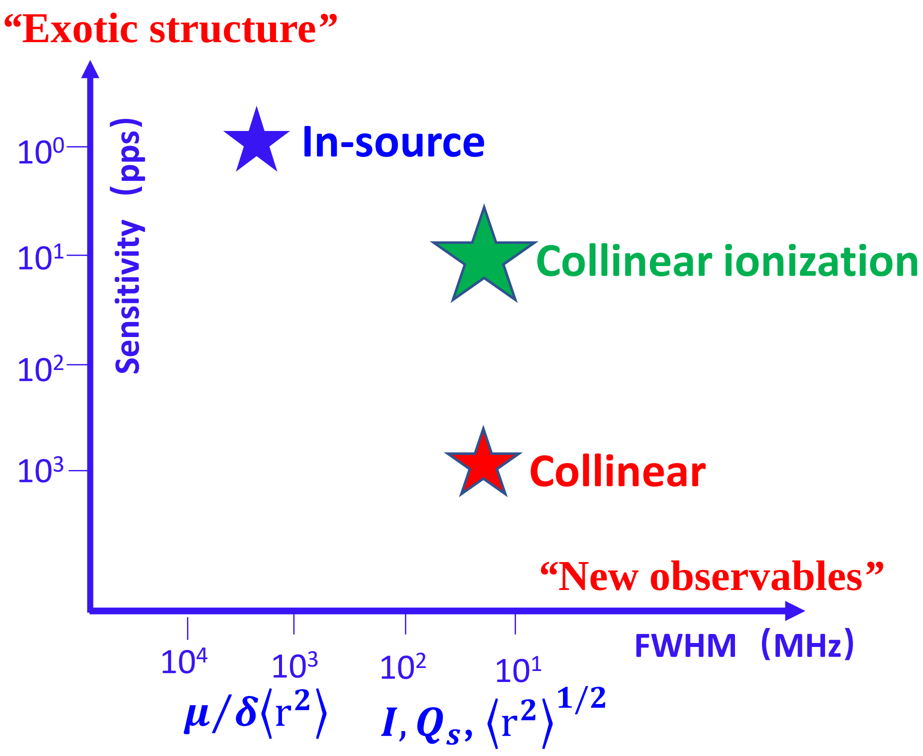
Collinear ionization resonance spectroscopy

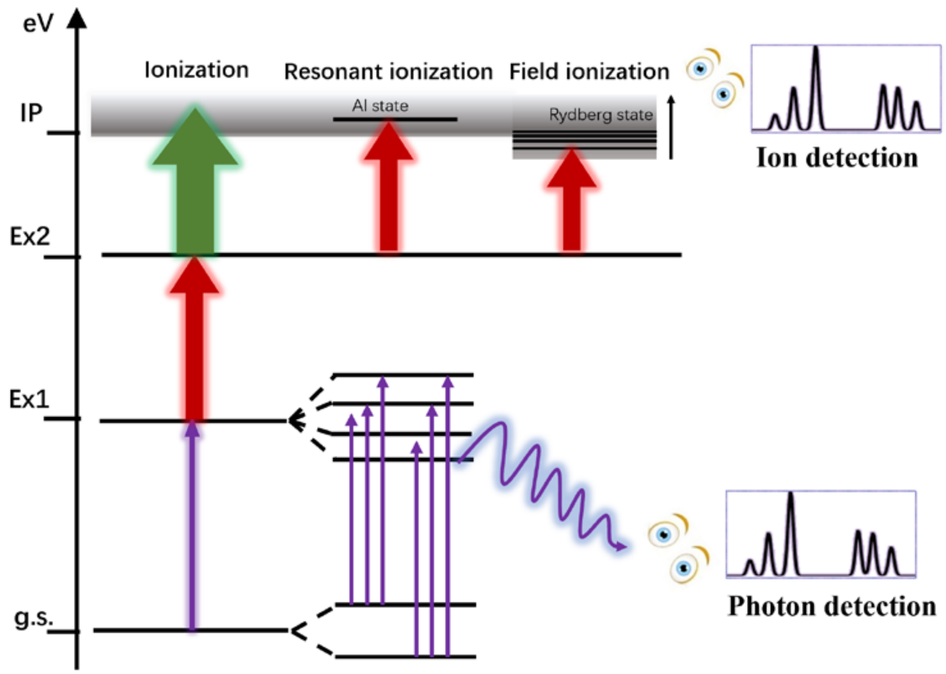


FWHM： <100 MHz

Sensitivity： $10^{1\text{-}2}$ pps

Observables： I, u, Q, <r^2>

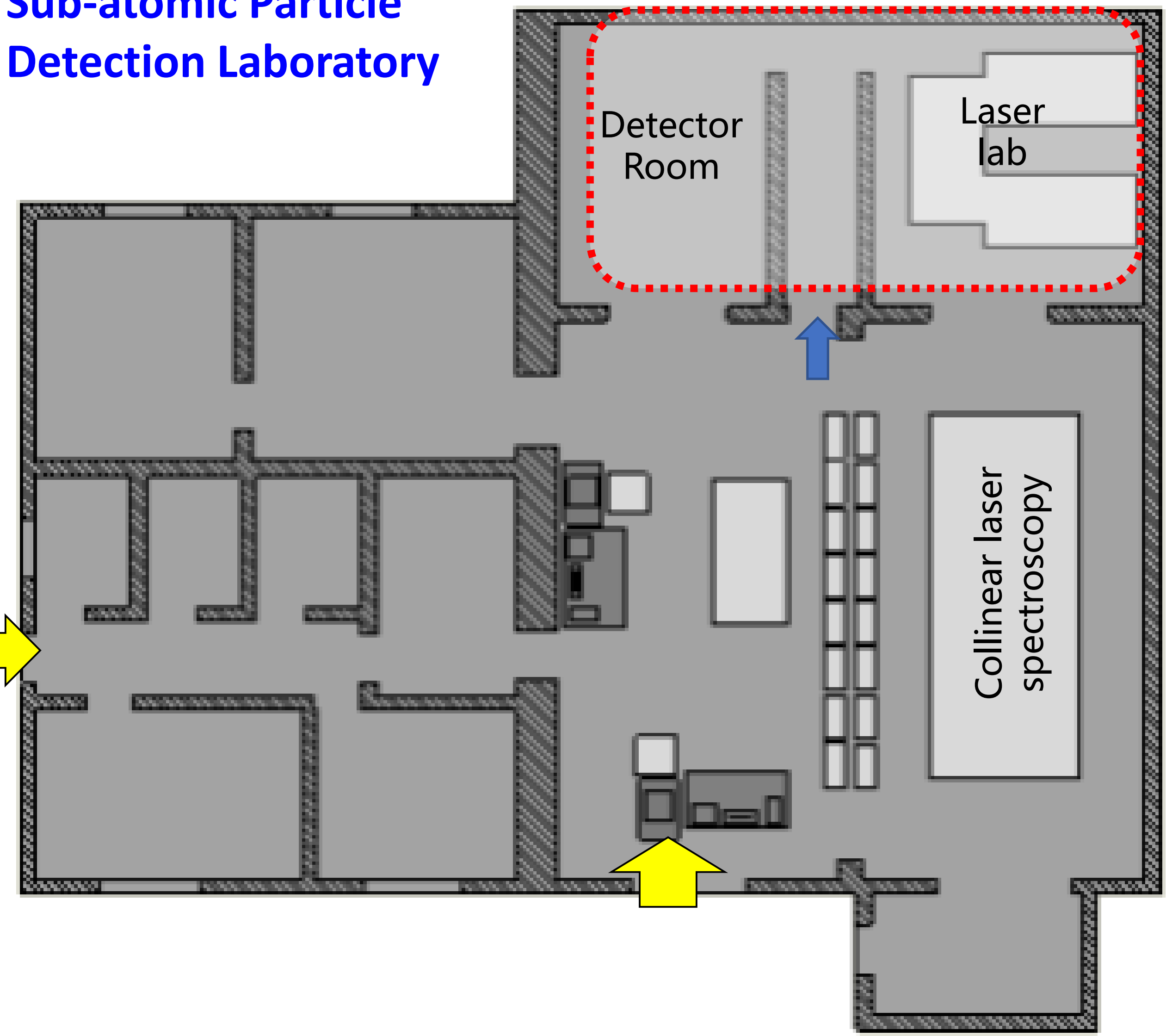


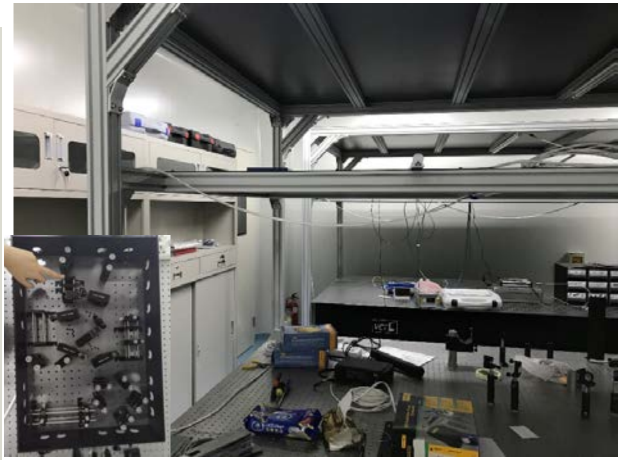


Sub-atomic Particle Detection Laboratory

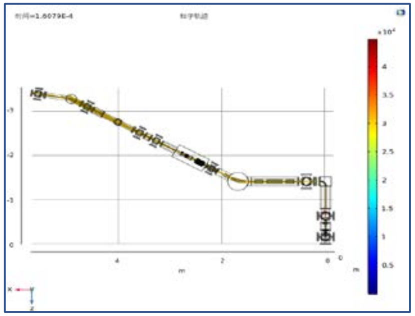
Offline laser spectroscopy lab

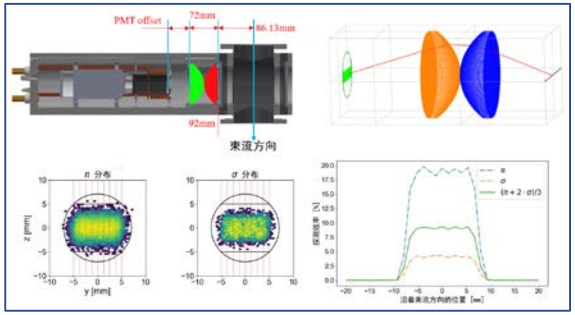
SKL
Sub-atomic Particle Detection Laboratory

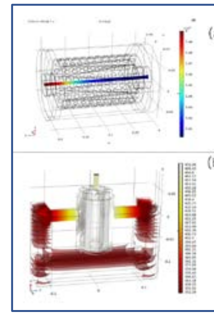




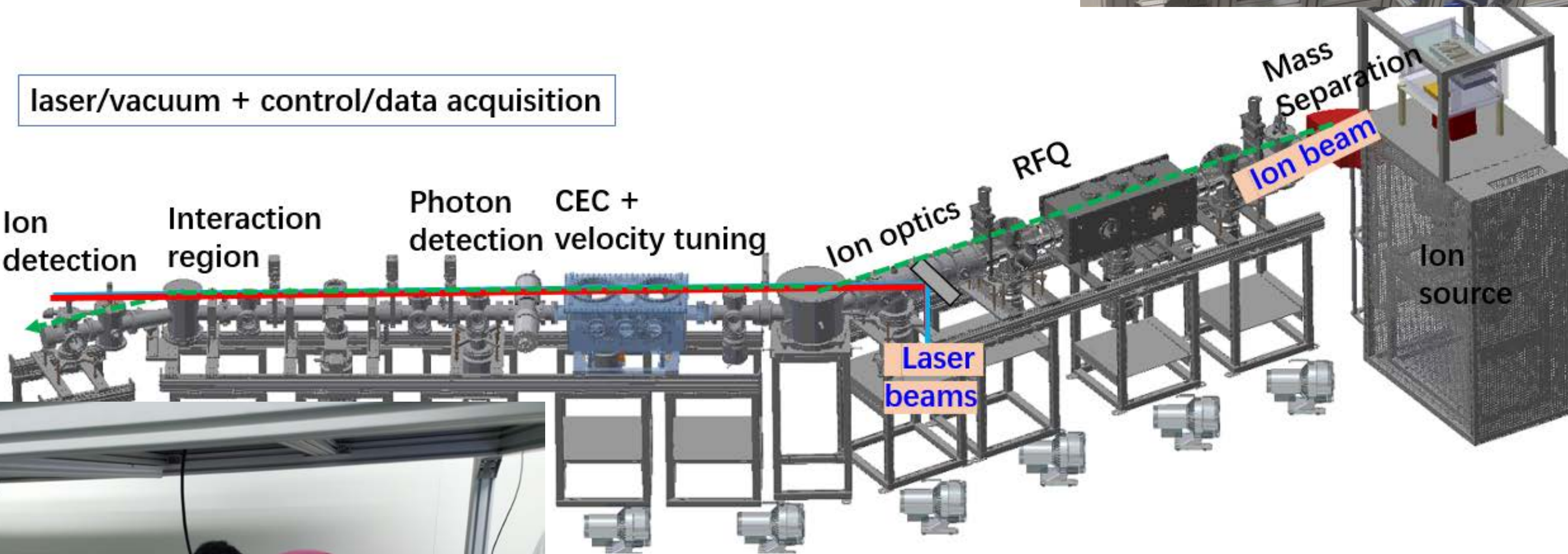
Offline laser spectroscopy lab

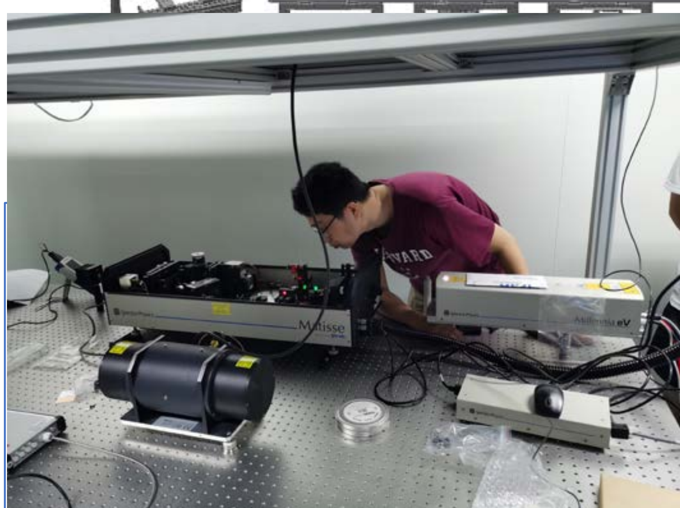


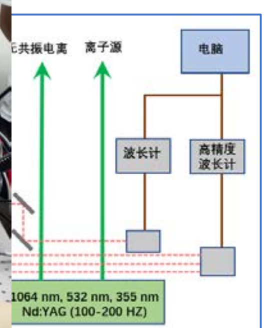


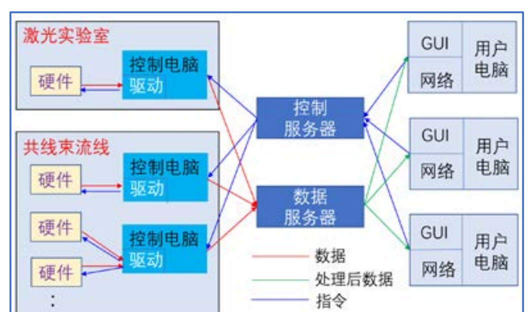


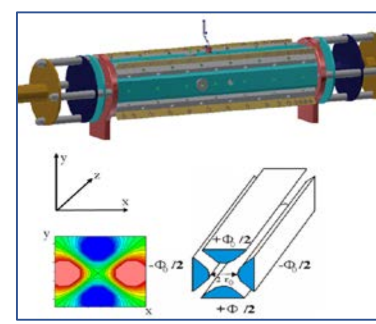
laser/vacuum + control/data acquisition









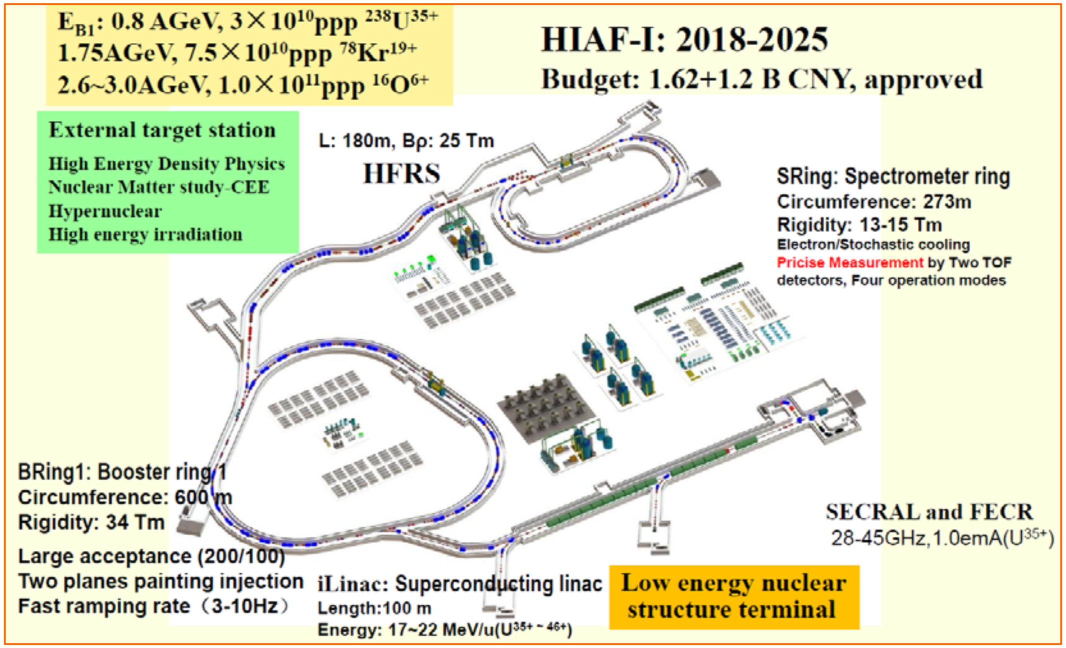


Final goal: To be applied at the new facilities at their early stage

Under construction

"HIAF"

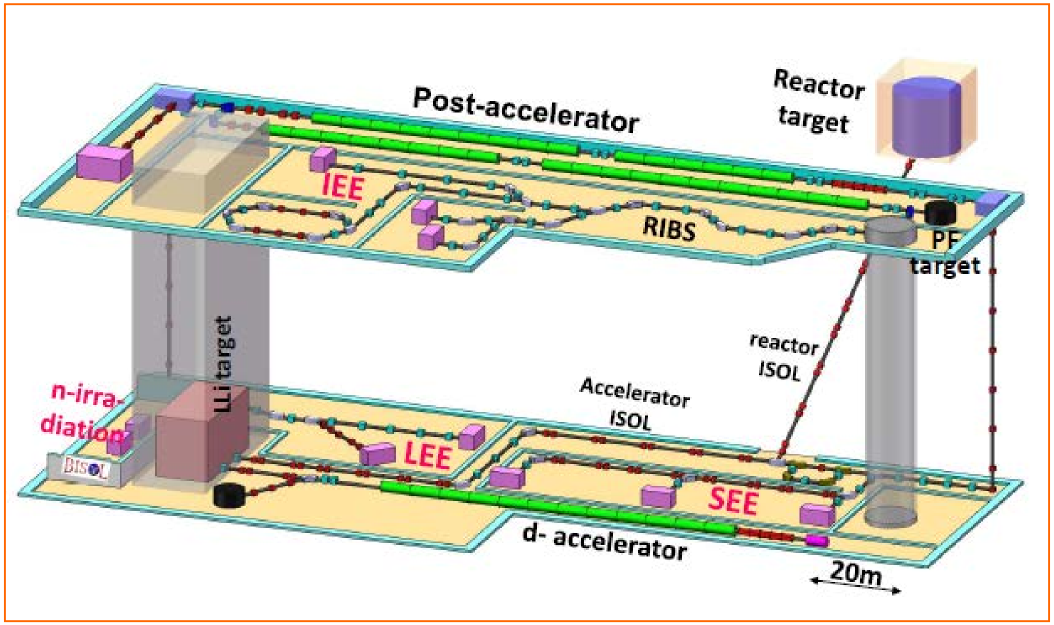
High-Intensity Heavy Ion Accelerator Facility



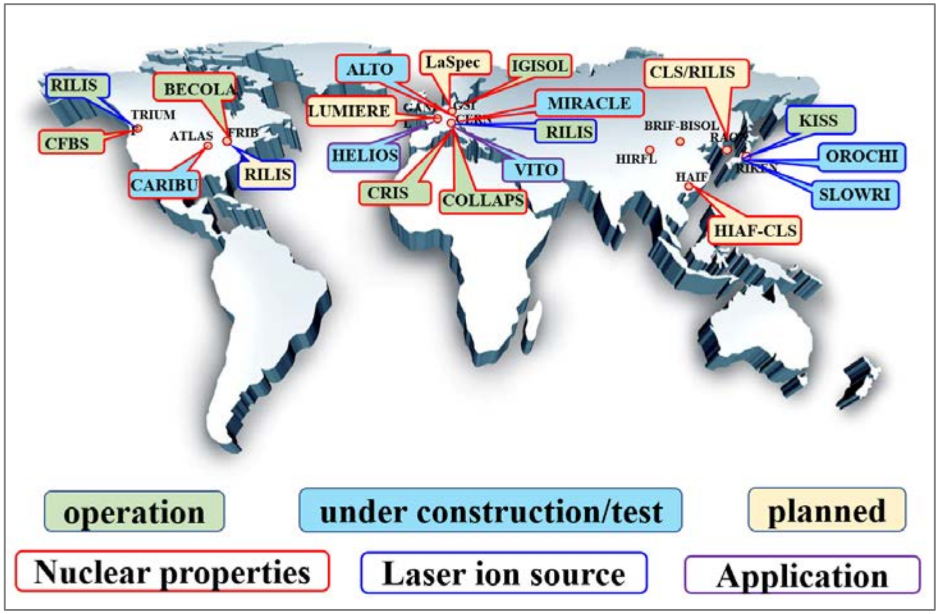
Planned

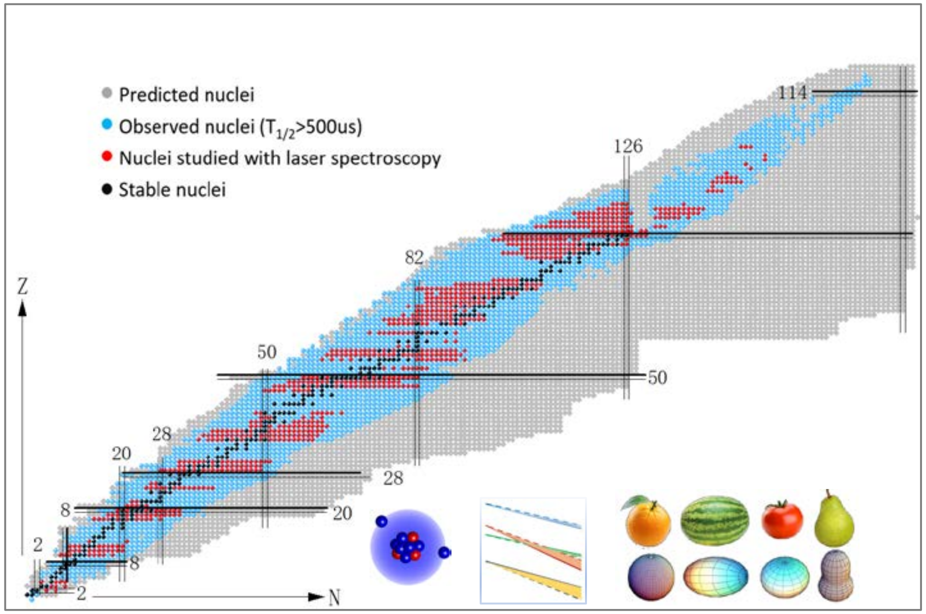
"BISOL"

Beijing Isotope-Separation-On-Line



Summary and outlook!!





- Laser spectroscopy is a powerful tool to access multiple nuclear properties of exotic isotopes.
- For the exotic nuclear structure study in different mass region of nuclear chart.
- Continues efforts are still on going toward a higher resolution and higher sensitivity.
- Important benchmark for the test and development of state-of-art nuclear theory.

Potentially have many aspects of applications using RI beams

“An atomic nucleus is an elephant”

Prof. Jacek Dobaczewski

https://collaps.web.cern.ch

COLLAPS

M. Bissell, K. Blaum, B. Cheal, R.F. Garcia Rniz, C. Gorges, H. Heyle ,S. Kanfma , M. Kowalska, S. Malbrunot-Ettenauer, R. Nengart, G. Neyens,W. Nortershanser, L. Vazqnez-Rodrignez, X.F. Yang, D. Yordanov

http://isolde-cris.web.cern.ch/isolde-cris/

CRIS

J. Billowes, C. Binnersley, T.E. Cocolios, G. Farooq-Smith, K.T. Flanagan, W. Gins, K.M. Lynch,S. Franchoo, M. Bissell, R.P. De Groote, R.F. Garcia Ruiz, A. Koszorus G. Neyens, C. Ricketts, H.H. Stroke, A. Vernon, K. Wendt, S. Wilkins, X.F Yang

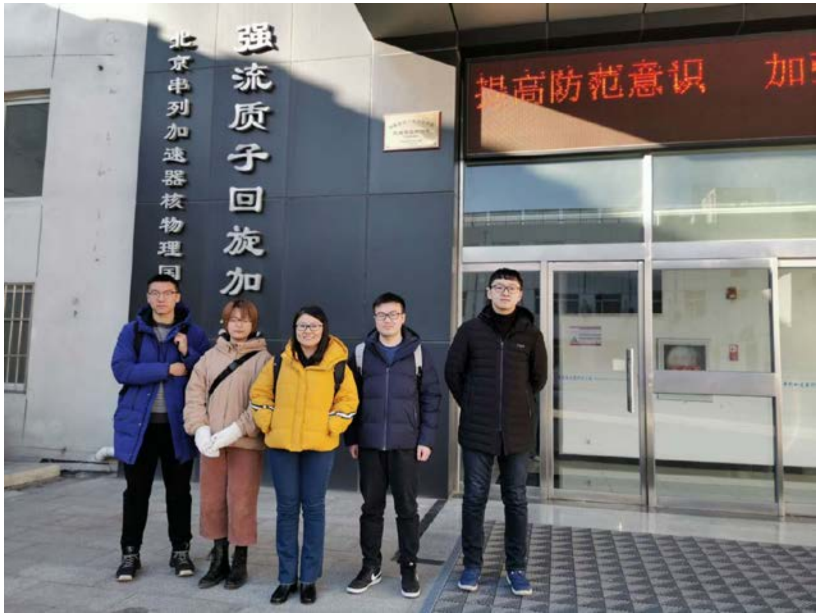
Experimental Nuclear Physics Group

http://genp.pku.edu.cn/News.html

Sep. 22th, 2019

Laser Spectroscopy and Nuclear properties

http://genp.pku.edu.cn/LPNP/research.html



Thanks for your attention!