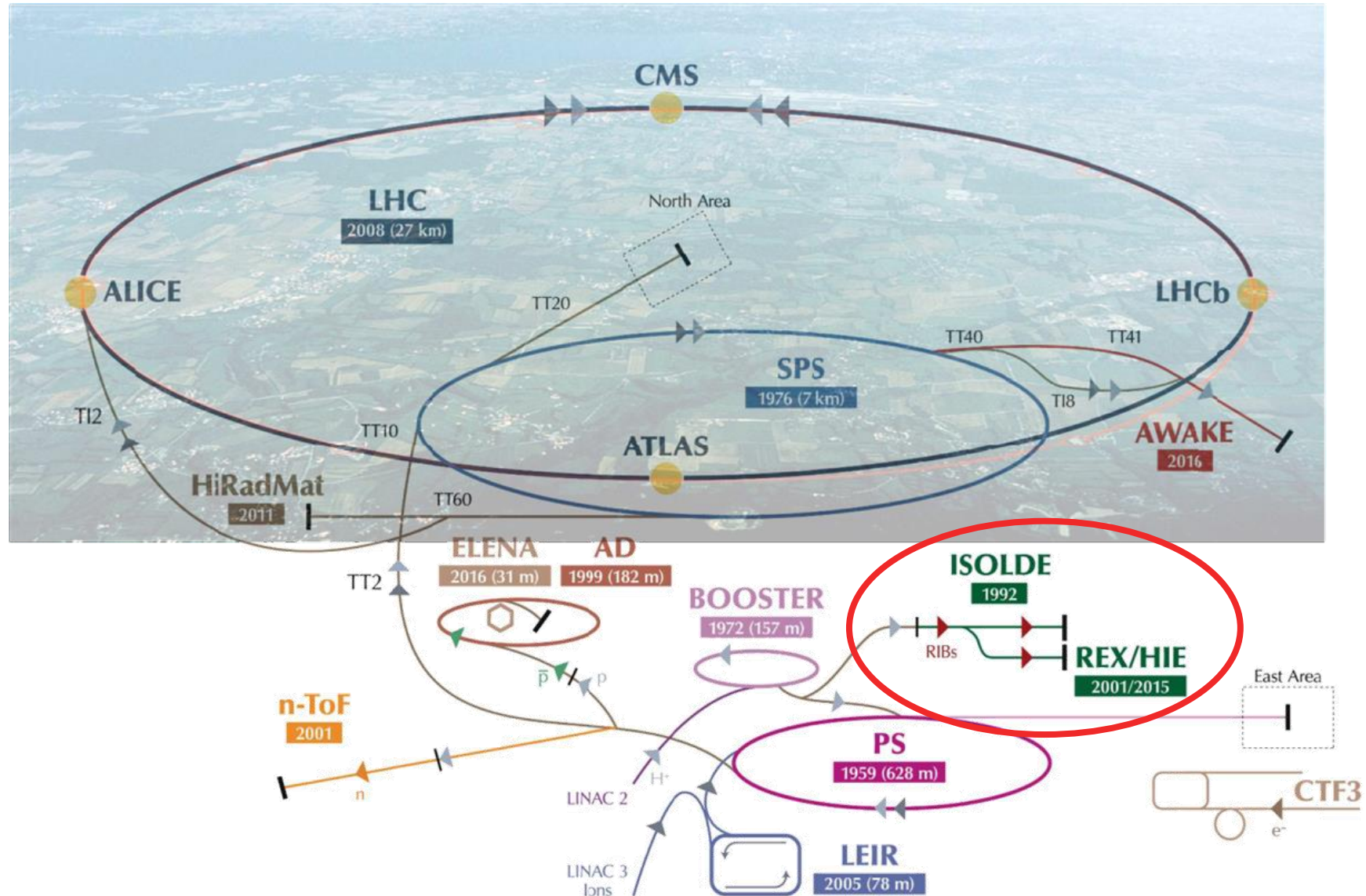


# CERN-ISOLDE's new high-resolution laser ion source PI-LIST: Results, characteristics, and developments

Reinhard Heinke  
for the **PI-LIST** collaboration

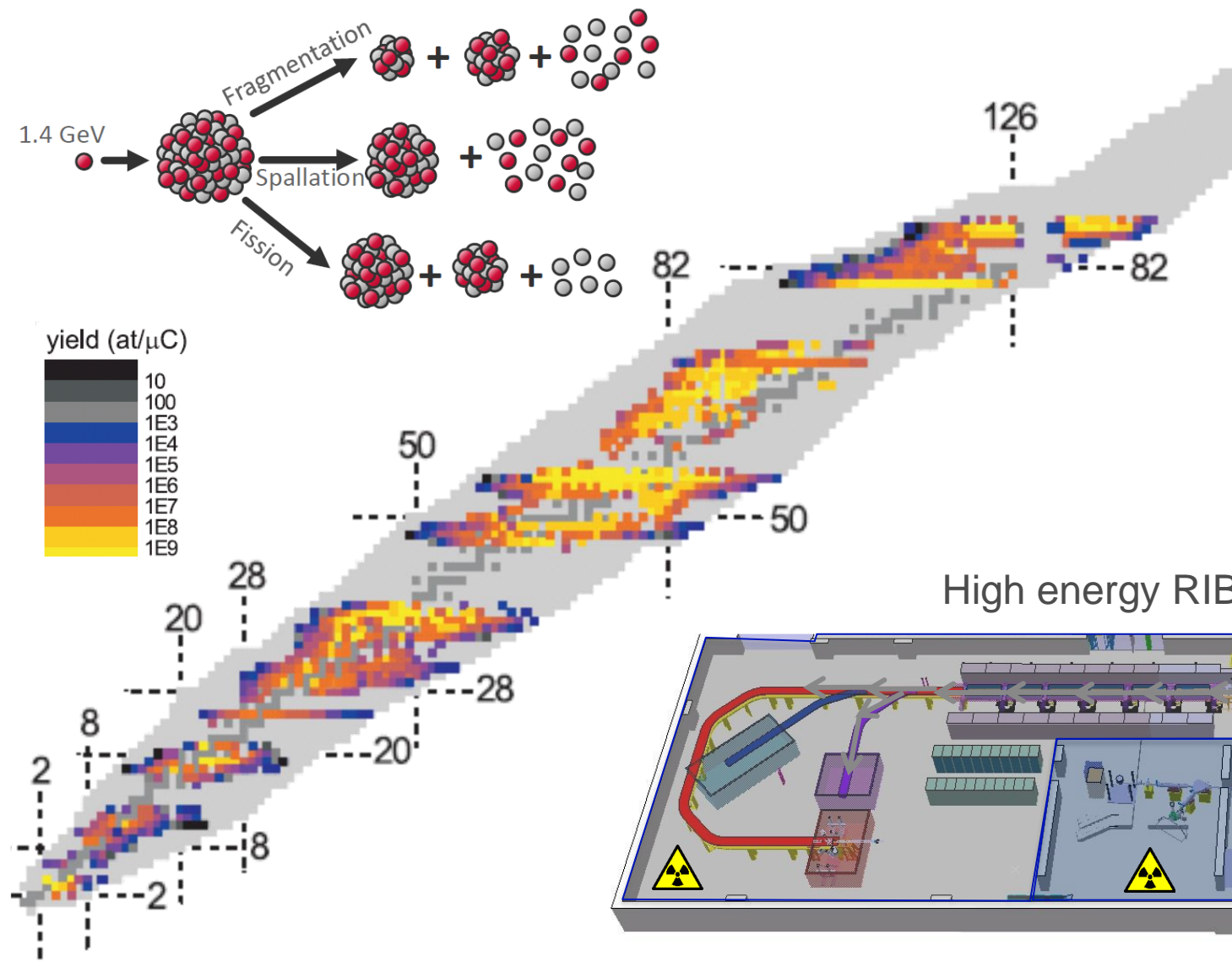


# ISOLDE at CERN





# The ISOLDE facility at CERN



Radioactive laboratory

MEDICIS

HRS

High Resolution Separator

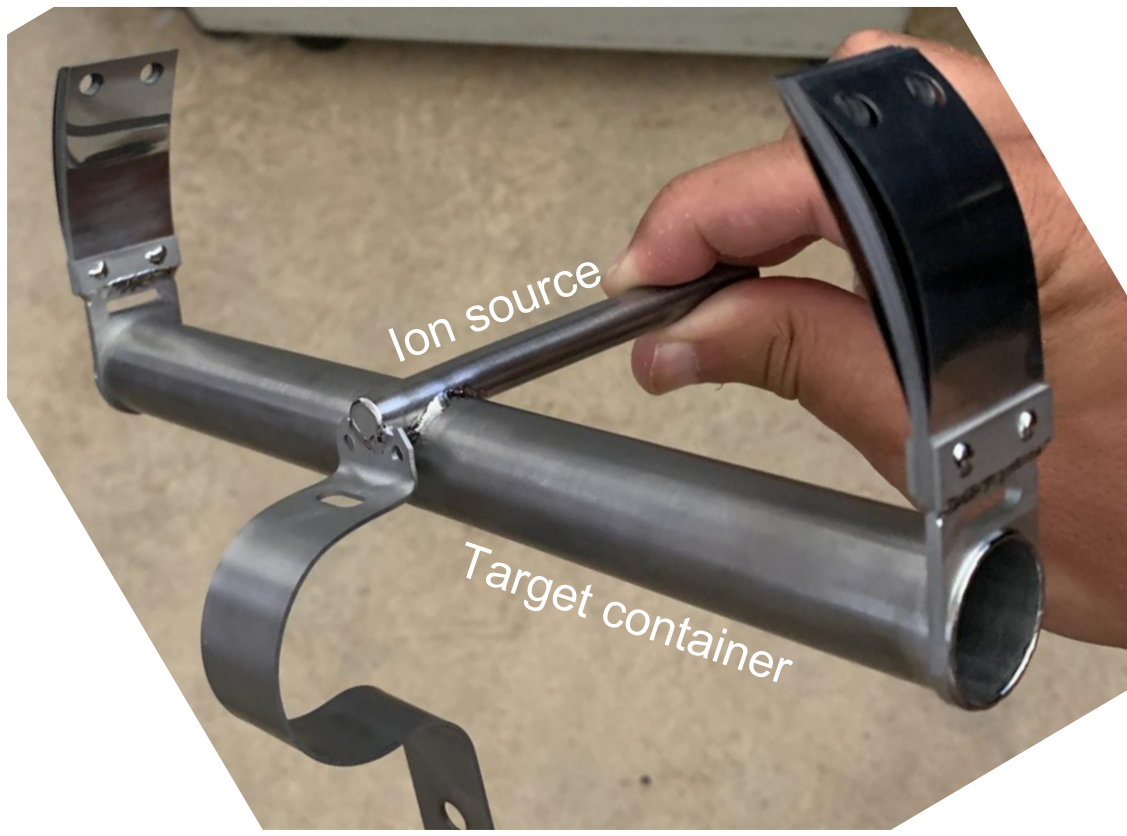
Target area

GPS

General Purpose Separator

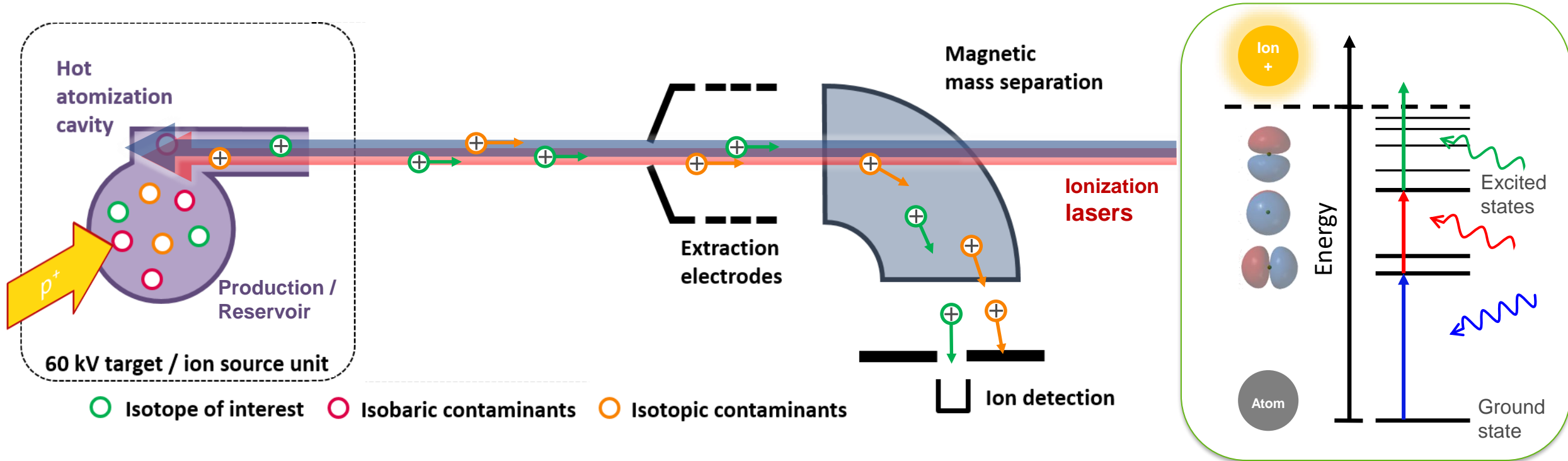
Low energy RIB

# ISOLDE frontend and target/ion source unit





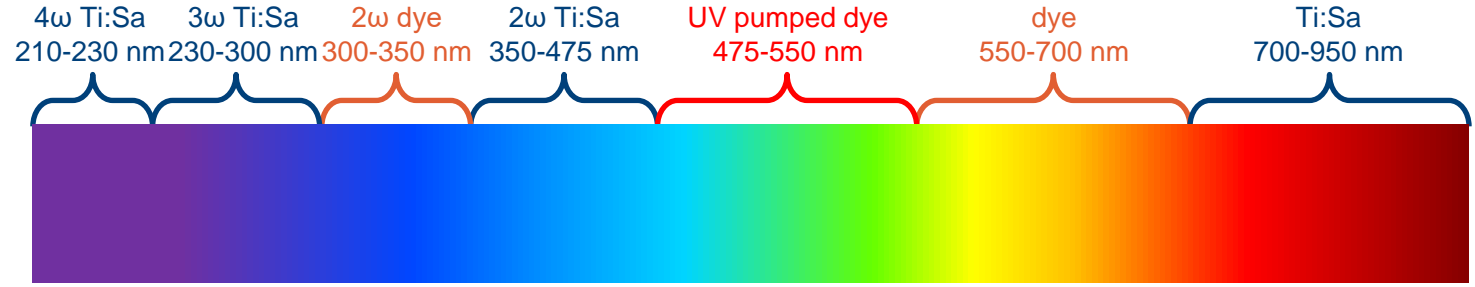
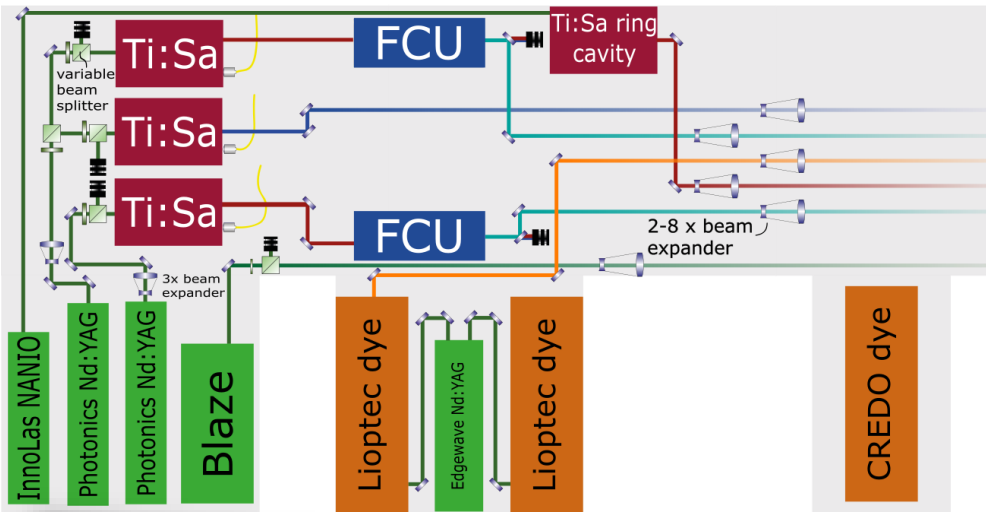
# ISOLDE's resonance ionization laser ion source RILIS



- Effusion of reaction products provided as **hot atomic vapor** ( $> 2000^\circ\text{C}$ )
- Highly efficient laser ionization of **element of choice** *as function of laser wavelength*  $\rightarrow$  *in-source spectroscopy* ( $\ll 1\text{pps}$ )
- Extraction and mass separation as **ion beam**

# The RILIS laser setup

10kHz rep-rate wavelength-tunable systems (commercial + development)



Solid state laser development:  
 Mixing (poster J. Wessolek),  
 Raman shifting (poster C. Bernerd)



# A new community-driven laser scheme database

**A new community hub for collecting resonance ionization schemes and associated tools**

EPFL Reto Trappitsch<sup>1</sup>, Anmol Aggarwal<sup>2</sup>, Mia Au<sup>3</sup>, Katerina Chrysalidis<sup>1</sup>, Line Le<sup>1</sup>, Reinhard Heineke<sup>2</sup>, Sebastian Rothe<sup>2</sup>  
<sup>1</sup>EPFL, <sup>2</sup>CERN

**The What:**

- ➔ Gather and share resonance ionization schemes (RIS)
- ➔ Currently contains 137 RIS spectra
- ➔ Combination of CERN RILIS database and new schemes
- ➔ Possibility to add more schemes and tools!

**The Why:**

- ➔ Enable everybody to contribute easily
- ➔ Modernize the look and feel of the database
- ➔ Allow for additional information, e.g., saturation curves, etc.
- ➔ Move the workload from one group to the community!

**The Where & How:**

- ➔ <https://rims-code.github.io>
- ➔ Website hosted on GitHub as a static page
- ➔ Members of community maintain the website

**Draw your own RIS Schemes:**

- ➔ Scheme drawer program
- ➔ Downloadable for any platform
- ➔ Documentation and installation instructions
- ➔ What element is it?

**CONTRIBUTE TO MAKE IT BETTER!**

**Submit a scheme**

Check out the detailed guide if you need help

Fill out the submission mask with the details of your scheme

Do you have a GitHub account?

Yes: Click "Submit via Github"

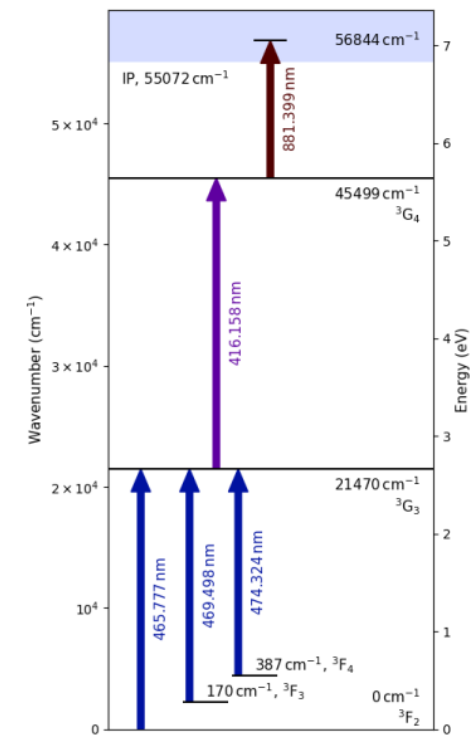
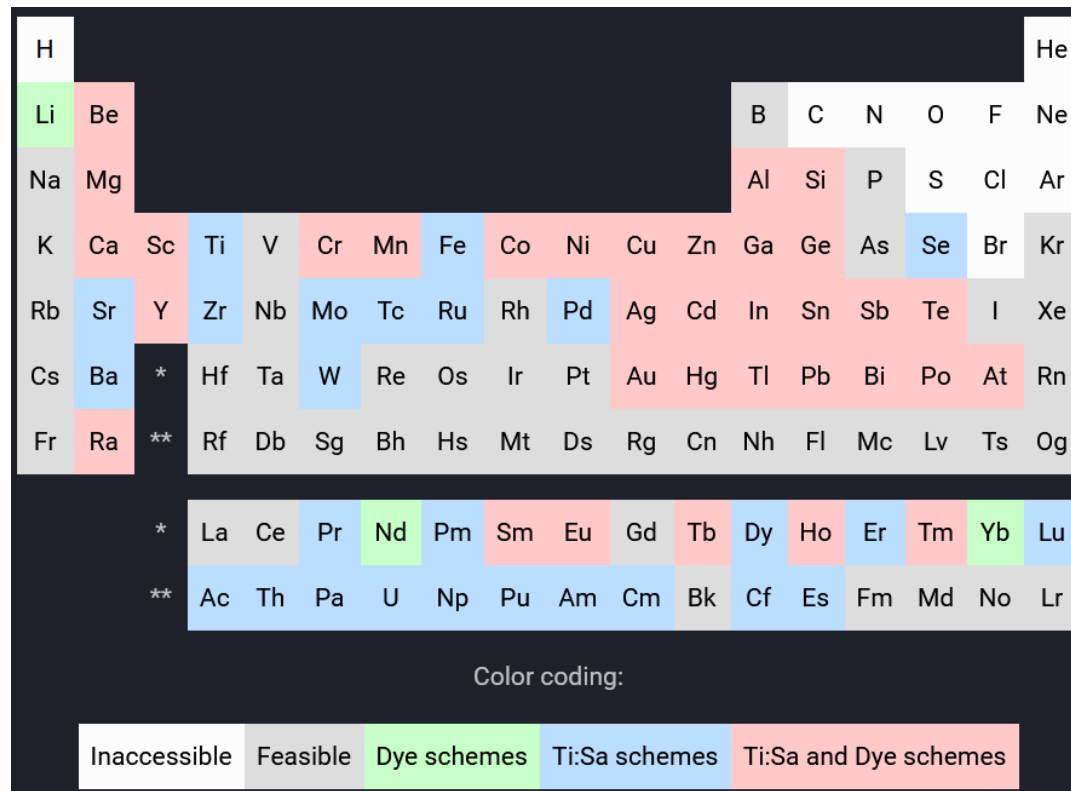
No: [Other options]

Maintainer will check and ask questions about the scheme. After approval, the scheme will be online in the community!

**Contribute to the website**

- ➔ We would appreciate your feedback!
  - ➔ What is missing?
  - ➔ What features would you like to see?
  - ➔ Did you find any errors, bugs, ...?
- ➔ Send us your tools, links, tips to add to the website! It does not have to be "just" RIS schemes.
- ➔ Submit new schemes from the community and for the community!

And more information if you scan the QR code in the corner and keep on scrolling



<https://rims-code.github.io>

From community for community:  
 Feedback, feature requests, extension to tool hub, ...

# RILIS @ ISOLDE: The workhorse ion source

## 2023 ISOLDE operation schedule



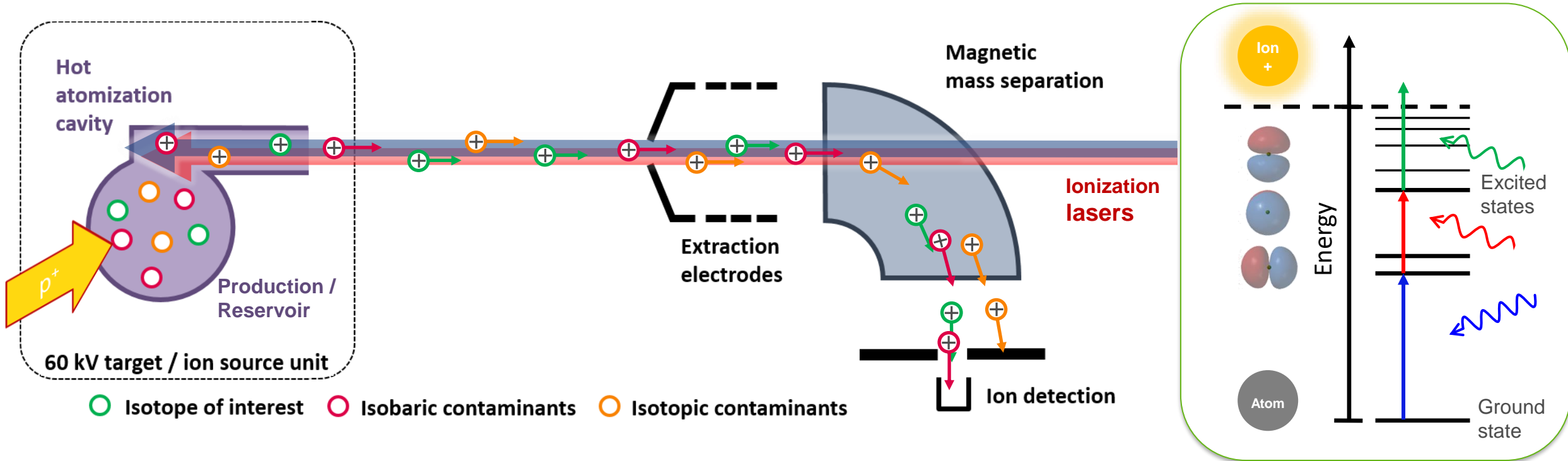
22 elements: Pm, Er, Yb, Gd, In, Dy, Ti, Cd, Hg, Al, Cr, Ac, Ca, Mg, Tm, Zn, Mn, Pb, Sb, Be, Ag, Pr

28 out of 33 weeks (including weekends) + development

RIB delivery and nuclear structure experiments

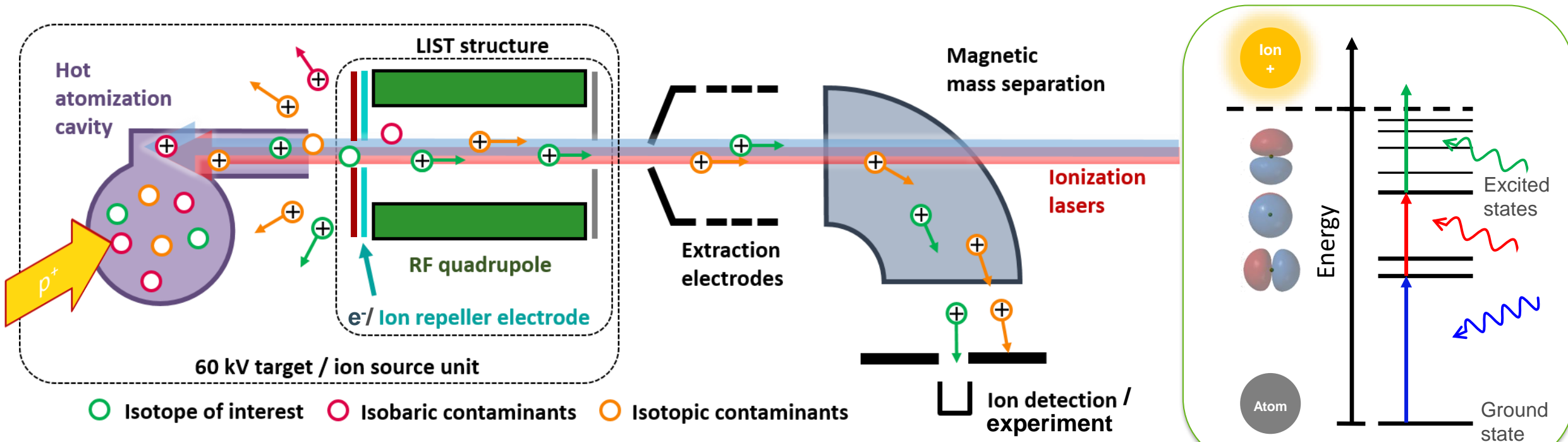


# ISOLDE's resonance ionization laser ion source RILIS

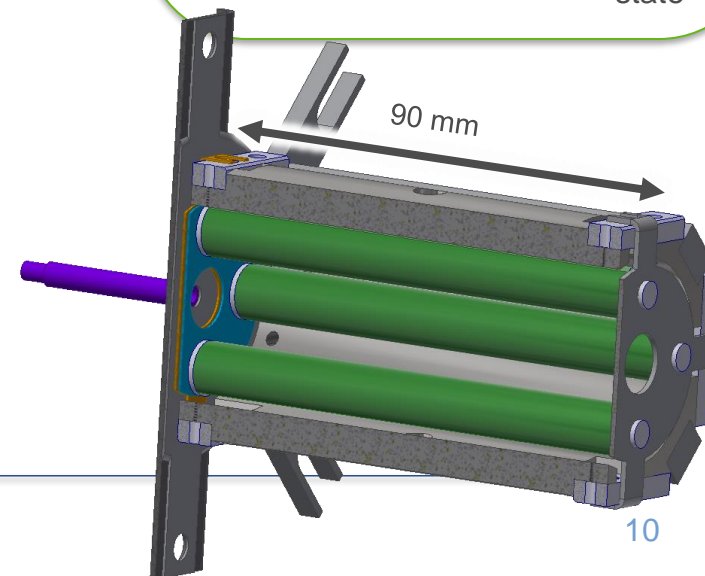


- Effusion of reaction products provided as **hot atomic vapor** ( > 2000°C )
- Highly efficient laser ionization of **element of choice** *as function of laser wavelength* → *in-source spectroscopy* (<< 1pps)
- Extraction and mass separation as **ion beam**
- **Beam purity influenced by competing ionization mechanisms**

# The Laser Ion Source and Trap LIST



- **Spatial separation:** hot cavity ↔ laser ionization volume
- **Suppression** of surface ionized species
- **Pure laser ionization** inside RF quadrupole structure
- **Factor up to  $10^6$  in suppression** ↔ **Factor 20-100 reduction in beam intensity**
- Versatility: Mimic standard RILIS by extracting and guiding ions from hot cavity

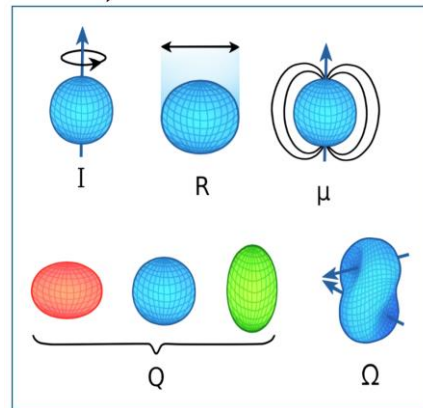
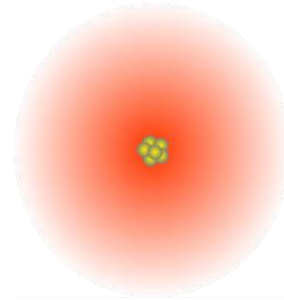
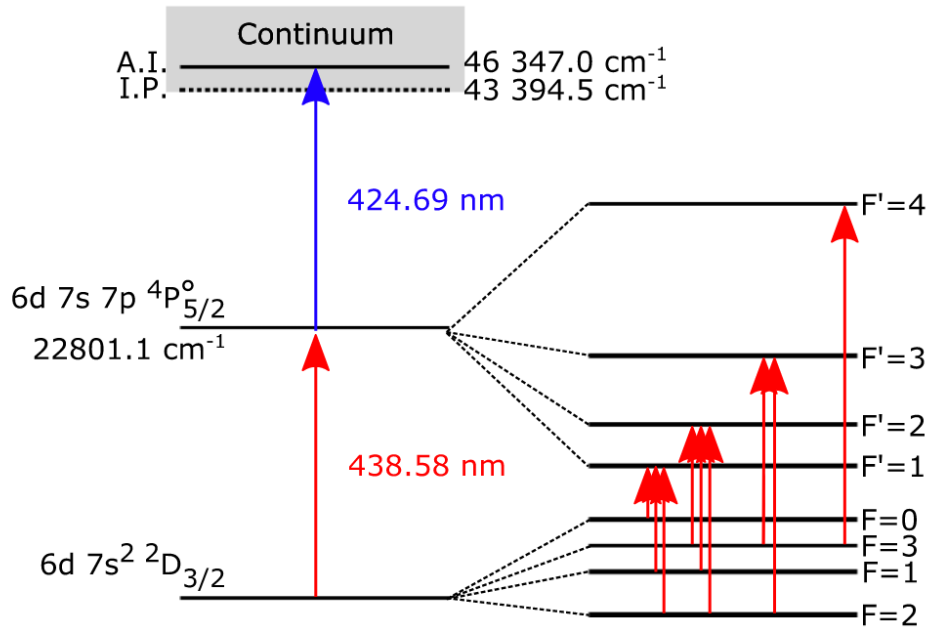




# Nuclear structure laser spectroscopy

## Ac laser ionization scheme

(used at LISOL, TRIUMF, ISOLDE, JGU, ...)

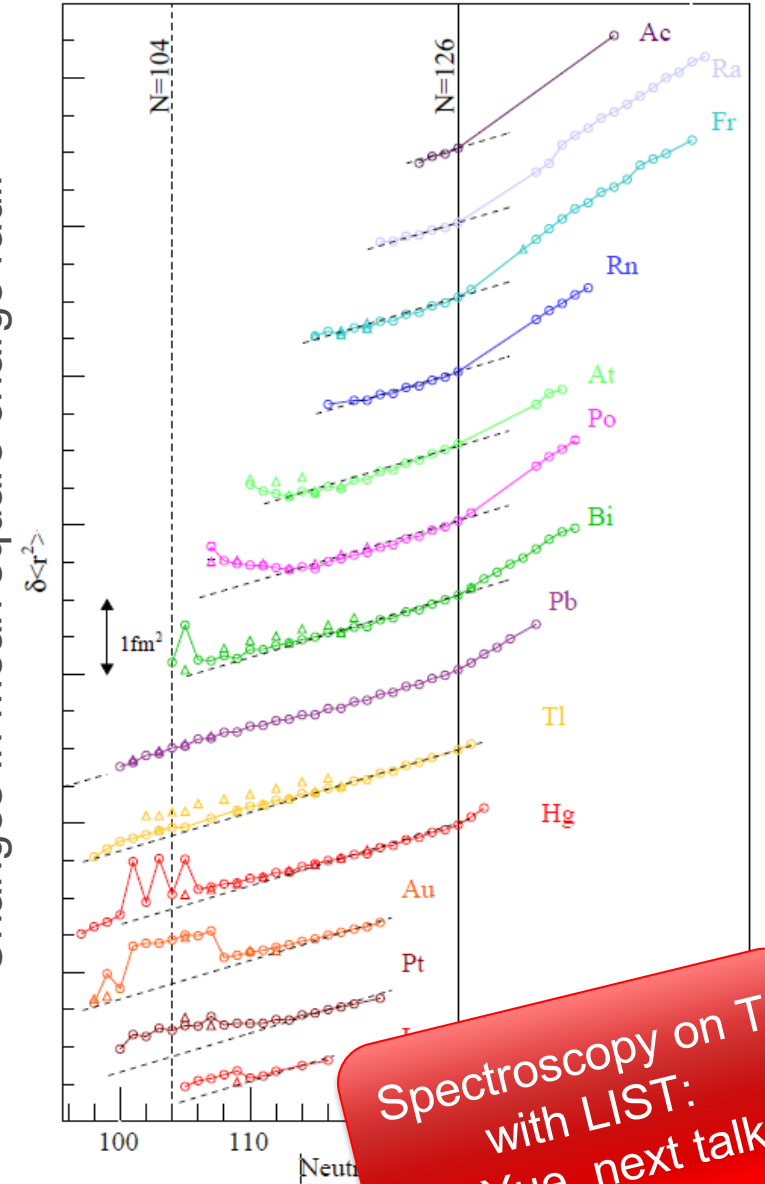


## Hyperfine structure spectroscopy:

### Interaction of nucleus with electron shell

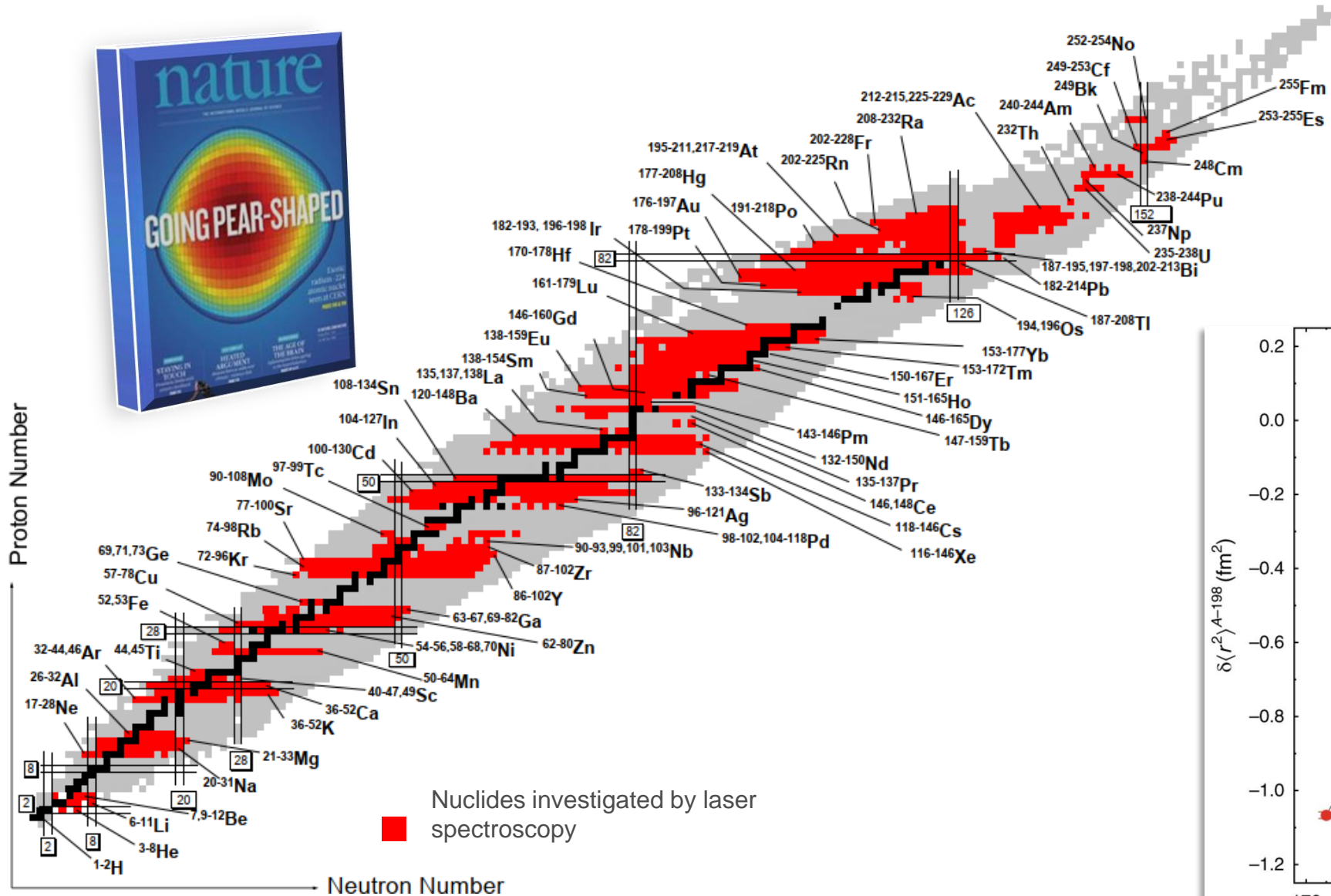
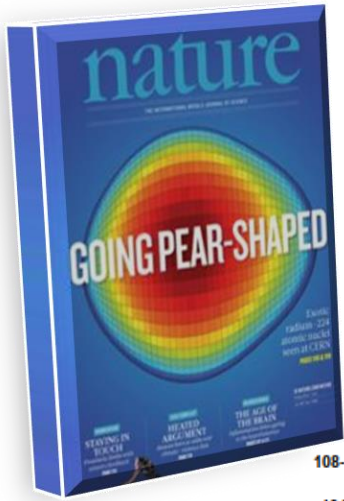
- Nuclear spin, deformation
- Changes in charge radii

## Changes in mean square charge radii



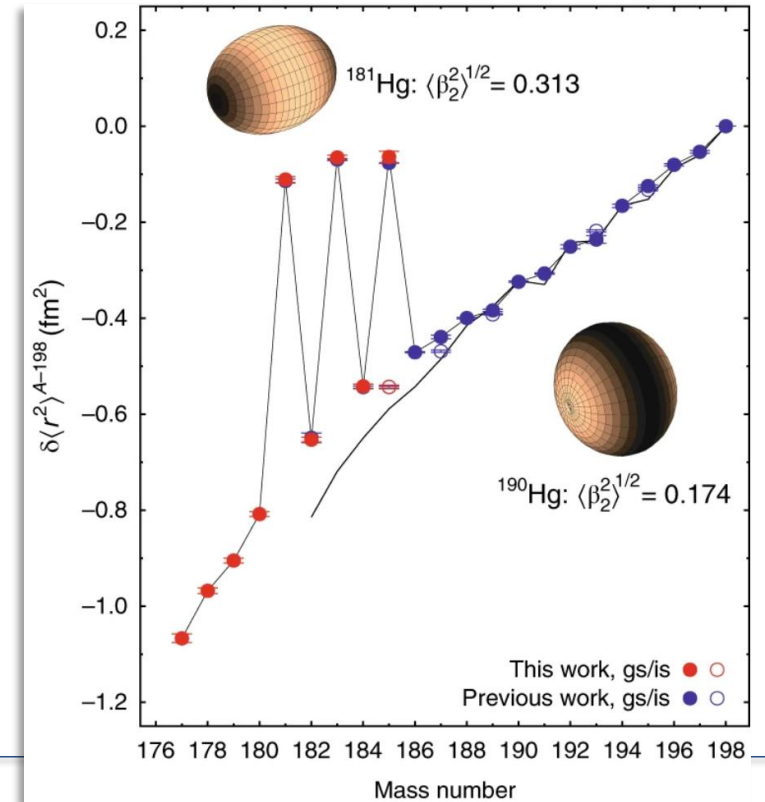
Spectroscopy on Tl with LIST:  
Z. Yue, next talk!

# A laser spectroscopist's playground



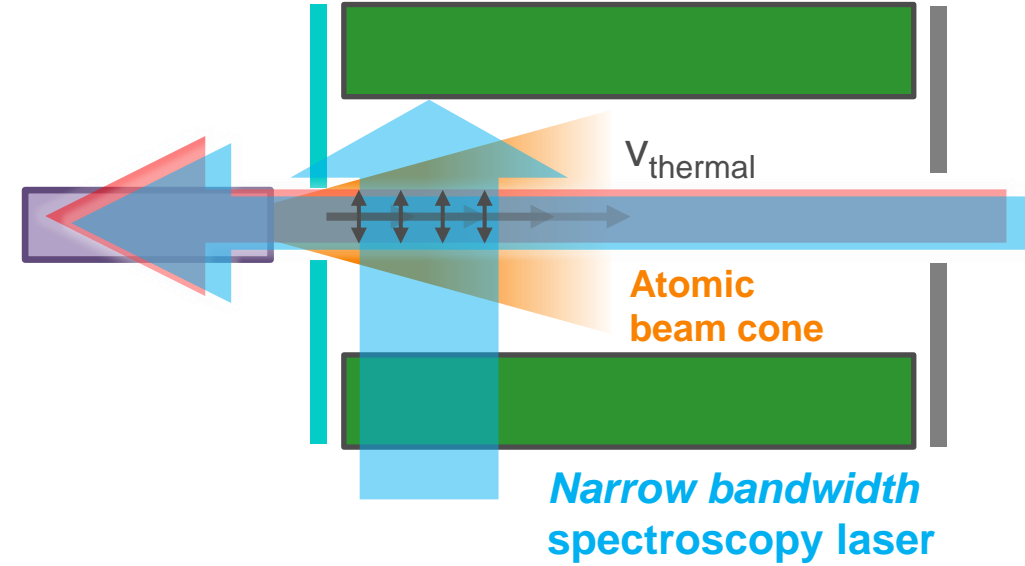
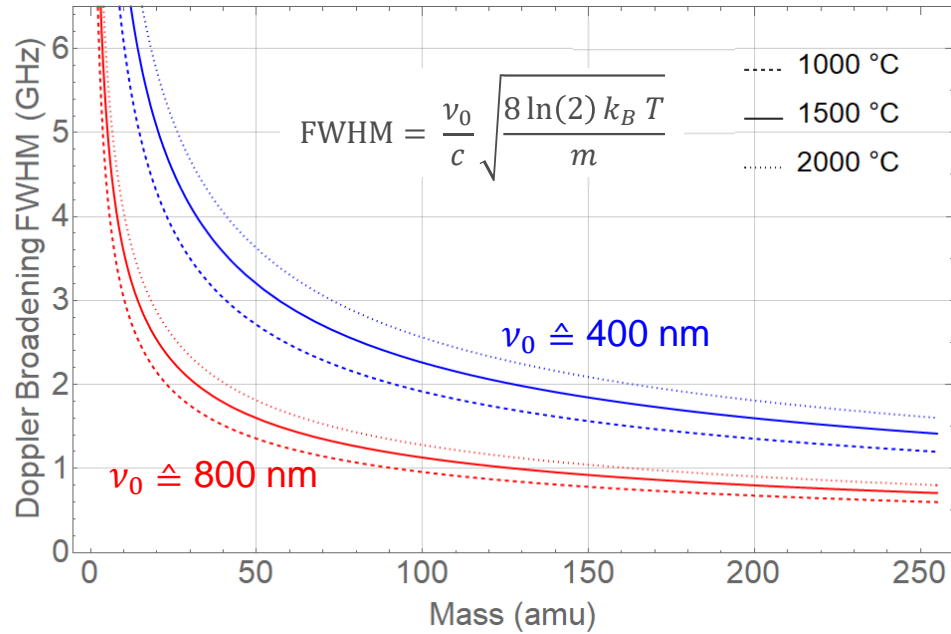
Collective effects of protons and neutrons

→ How to derive from first principles / strong force?



B. Marsh et al, Nature Physics 14, 1163–1167 (2018)

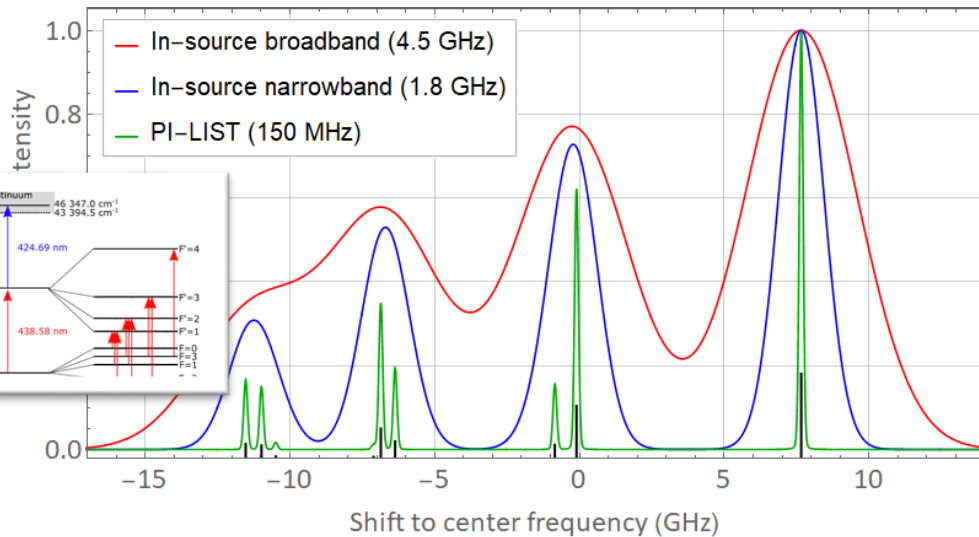
# “Sub-Doppler” hot cavity in-source spectroscopy



Crossed atom beam / laser geometry in LIST structure:

The **P**erpendicularly **I**lluminated **PI-LIST**

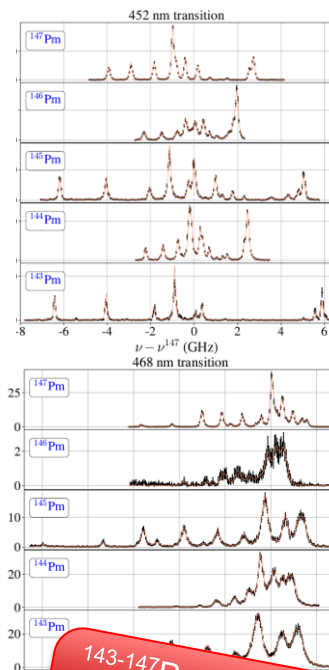
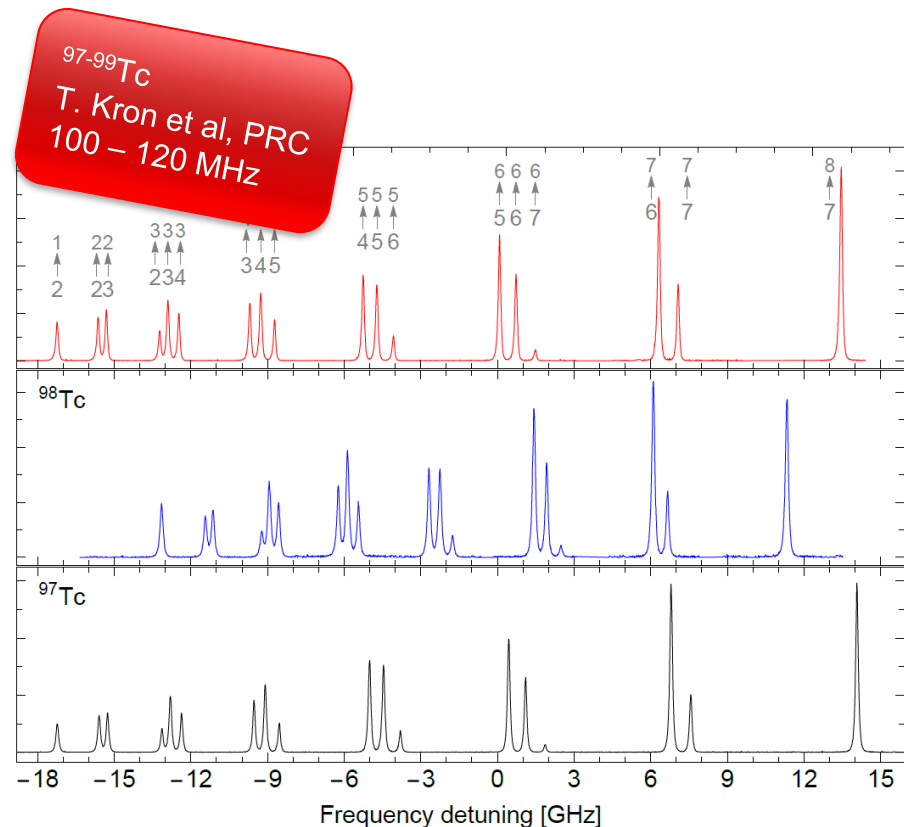
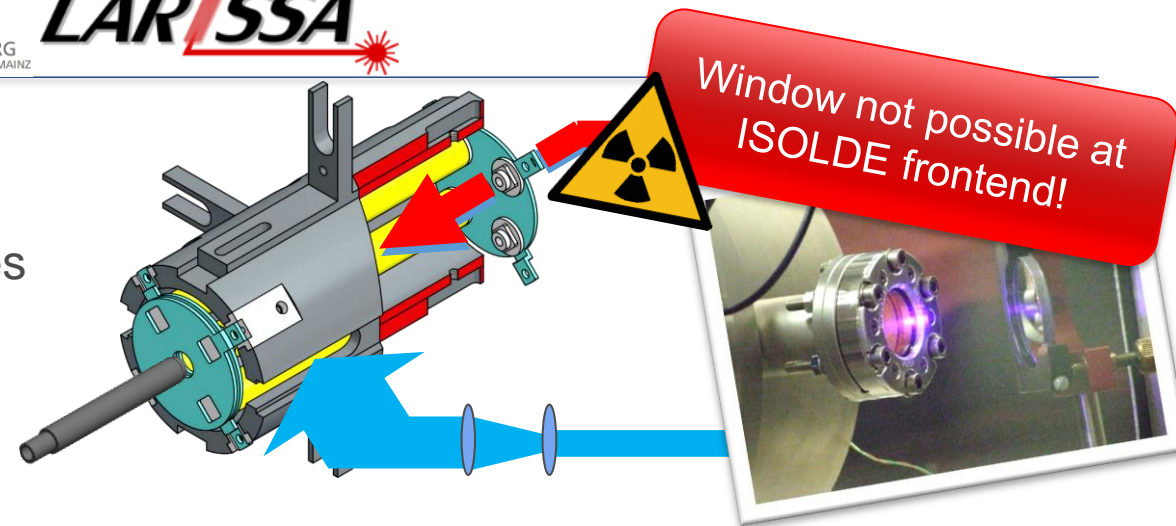
- Selection of **reduced Doppler ensemble** in laser intersection volume
- Suitable **narrow-band laser**
  - Resolution improvement by >1 order of magnitude



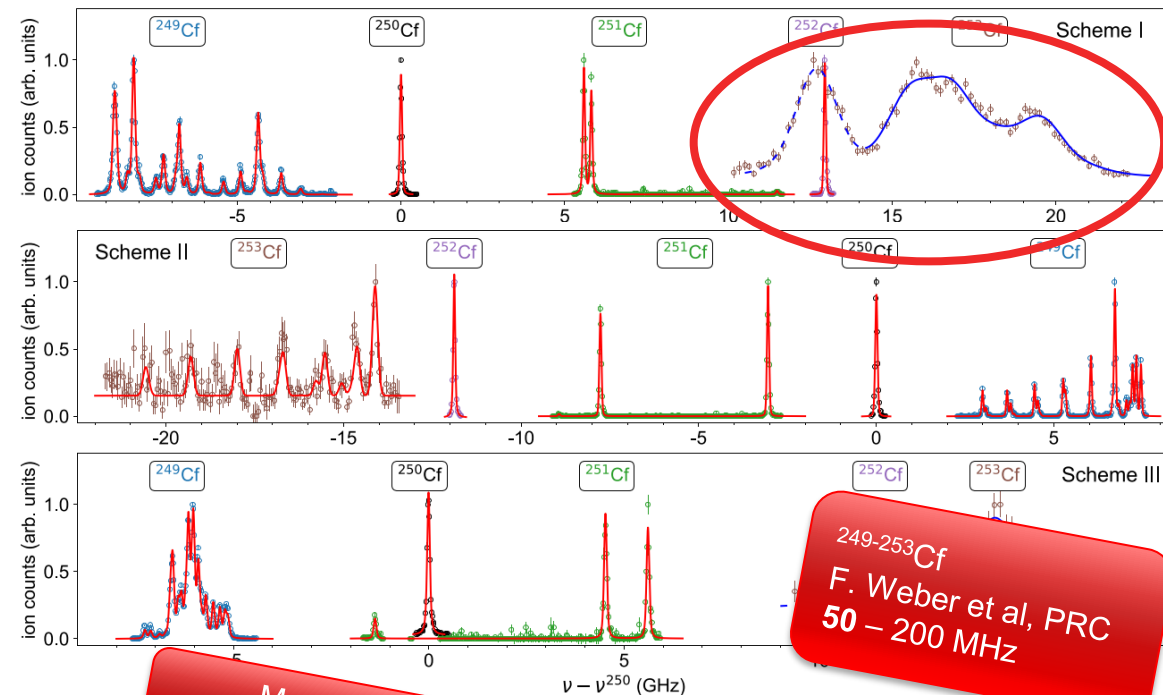


# Off-line results from PI-LIST

- Lateral laser incoupling through window in vacuum vessel
- Nuclear structure investigations on long-lived radioisotopes
- Standard tool for high resolution spectroscopy



143-147Pm  
D. Studer et al,  
Eur. Phys. J. A.  
100 – 250 MHz

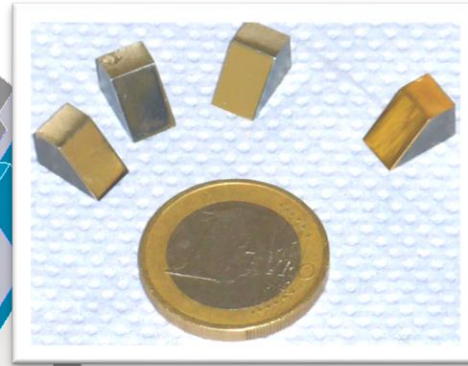


249-253Cf  
F. Weber et al, PRC  
50 – 200 MHz

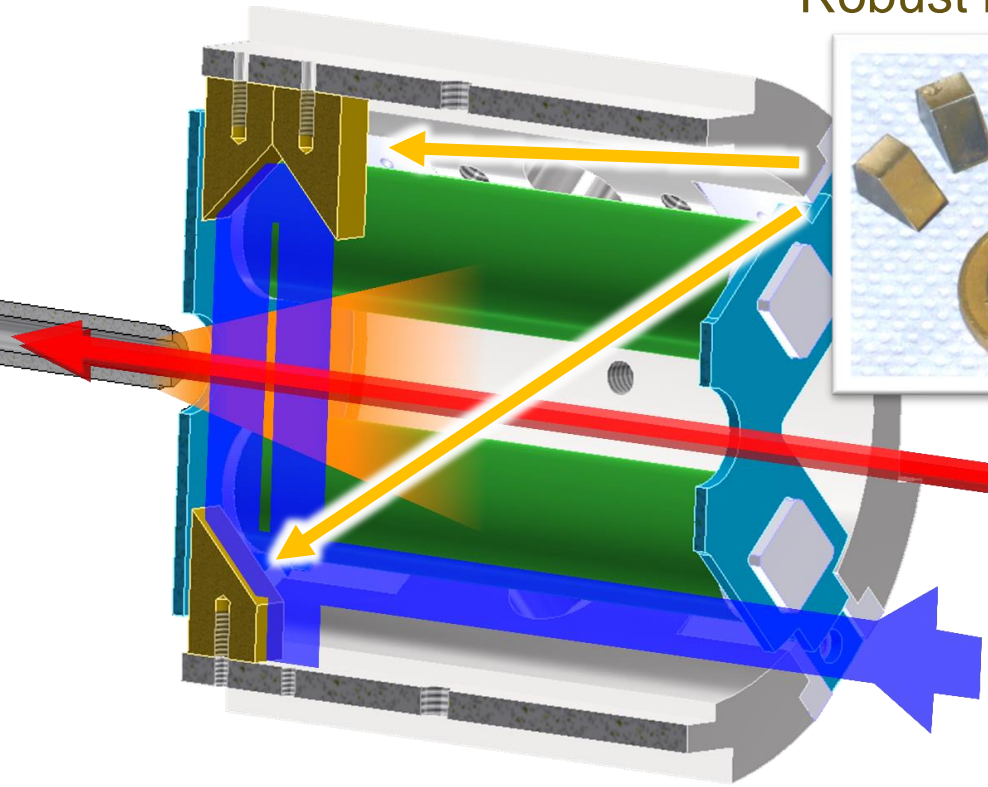
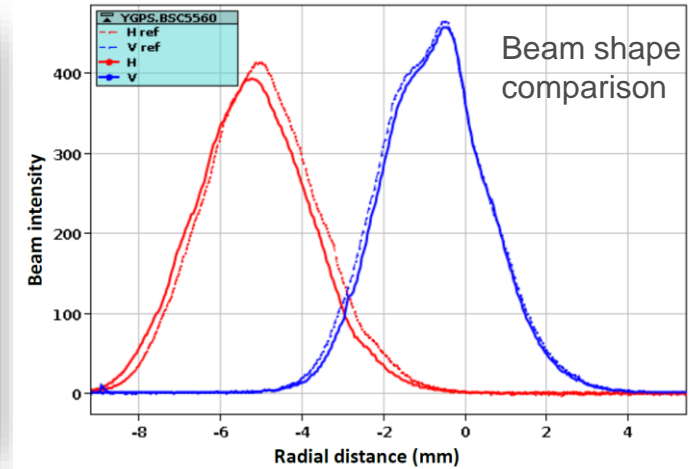
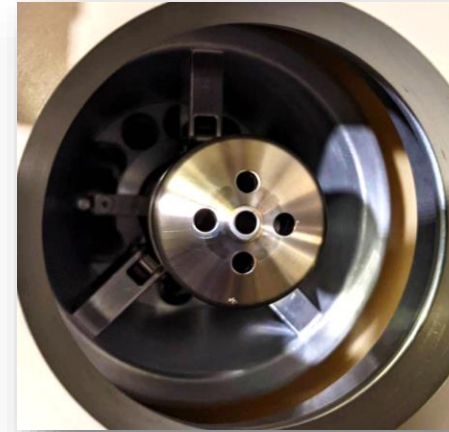
More from Mainz!  
Es, Fm, ... (Tuesday talks)

# ISOLDE adaption of PI-LIST

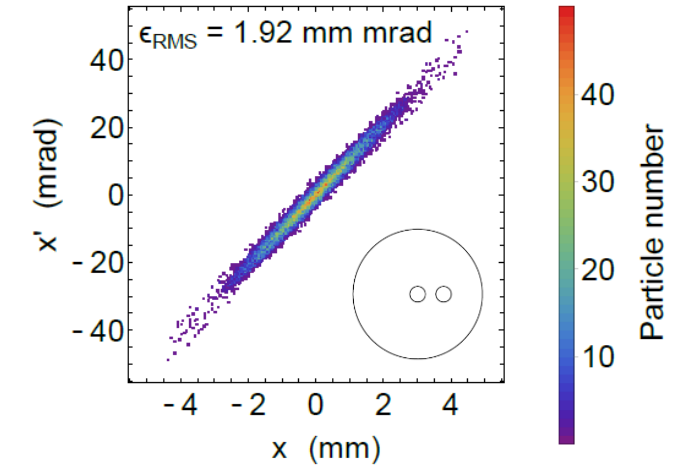
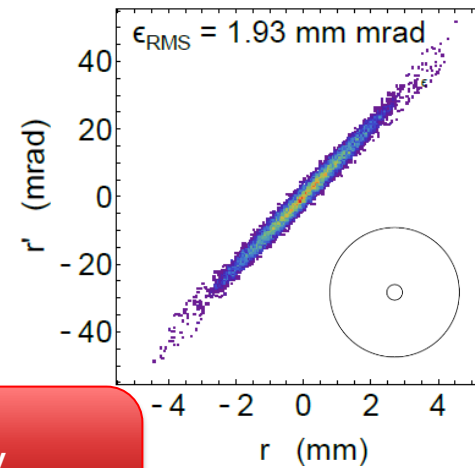
Robust metallic mirrors



Adapted extraction electrode



Emittance simulations



No windows possible in ISOLDE frontend

- Reflection by **metallic mirror** surfaces
- **Off-axis guiding** of laser through

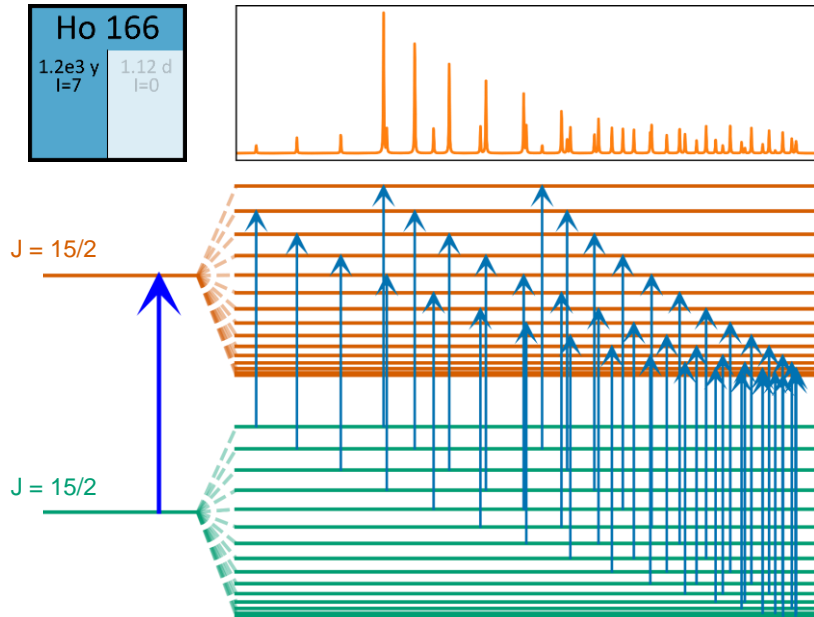
PI-LIST ready  
for on-line experiment!

# Holmium – a showcase

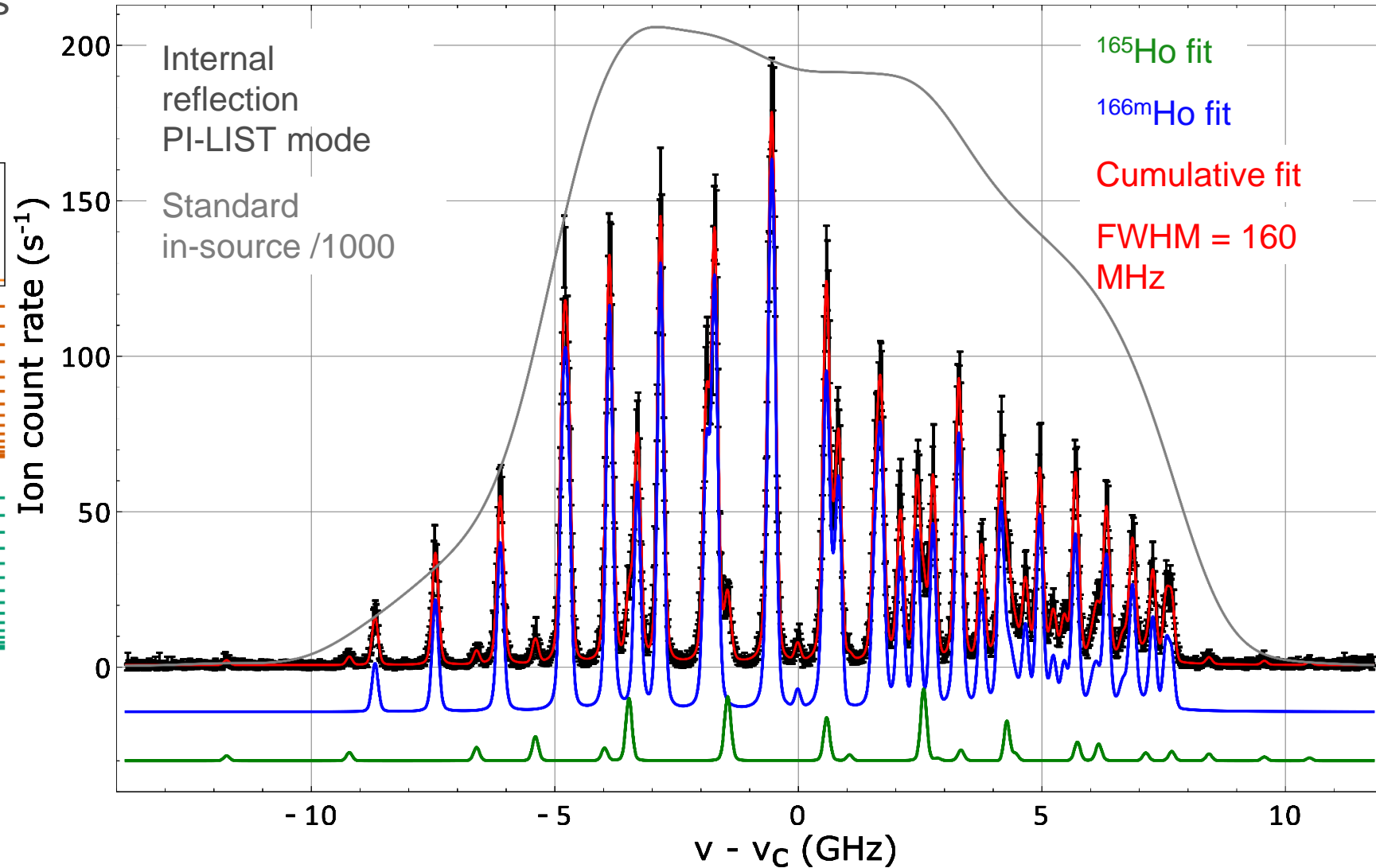
ECHo

Hyperfine structure studies  
on long-lived  $^{163,166\text{m}}\text{Ho}$   
for the ECHo project

Ho 166	
1.2e3 y	1.12 d
$l=7$	$l=0$



43 HFS components  
+ 23 from leaking  $^{165}\text{Ho}$

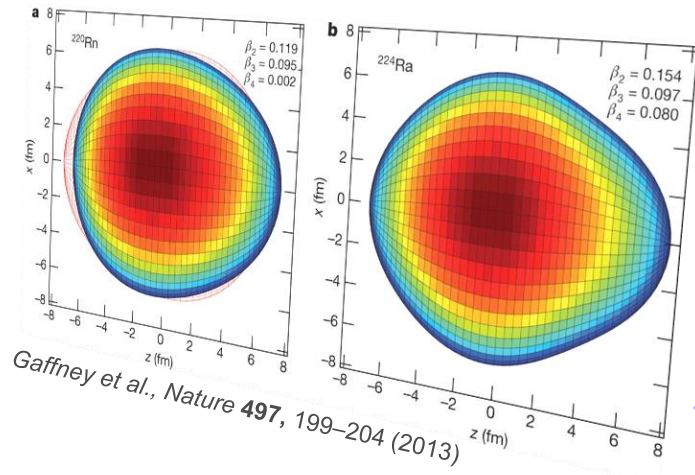




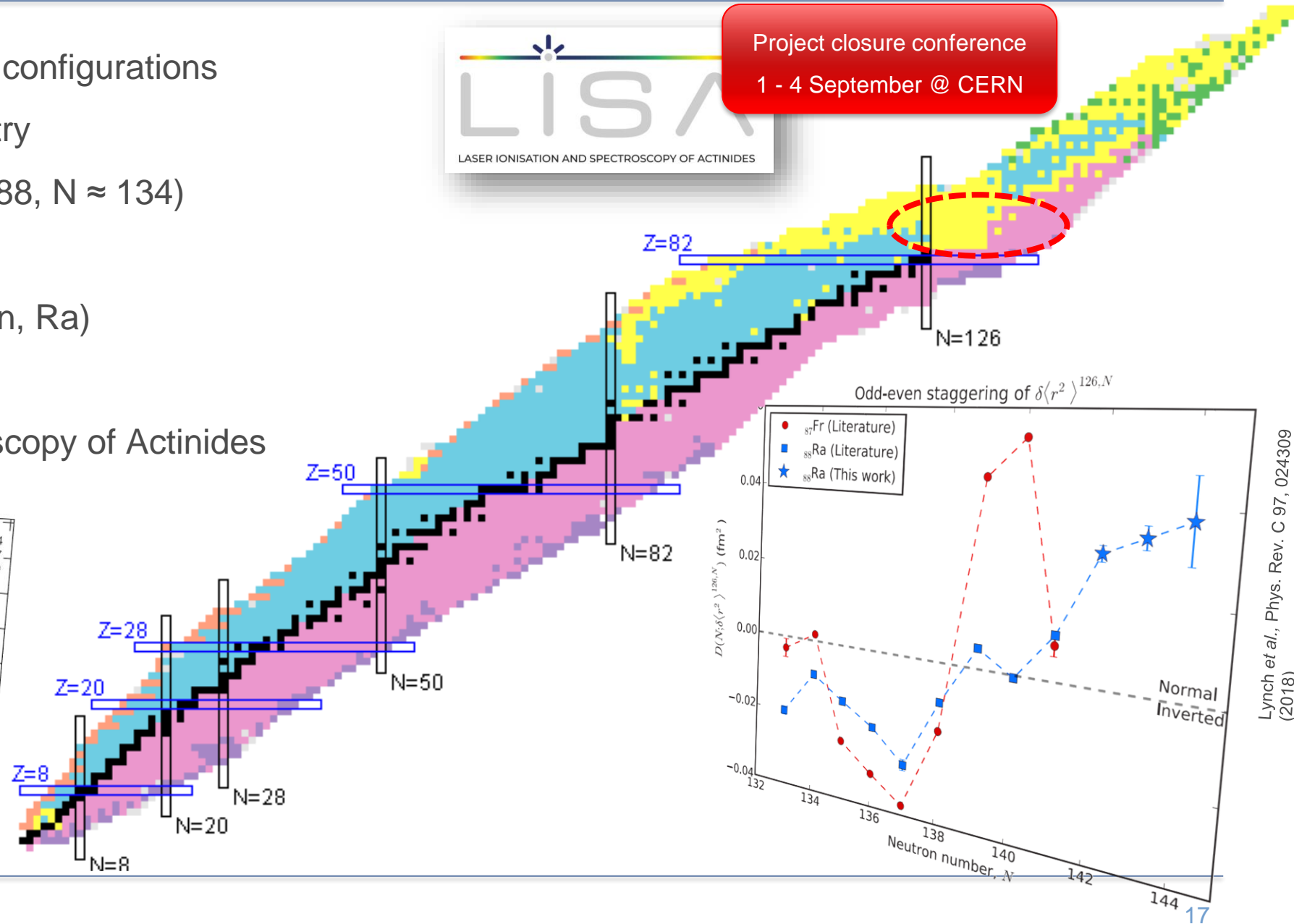
# Nuclear shape effects in the heavy-element region

- Pear shaped intrinsic nuclear configurations
- Breaking of reflection symmetry
- Prominent around  $^{222}\text{Ra}$  ( $Z \approx 88$ ,  $N \approx 134$ )
- Inverted odd-even staggering of charge radii? (Po, At, Fr, Rn, Ra)
- Within EU ITN LISA:

## Laser Ionization and Spectroscopy of Actinides

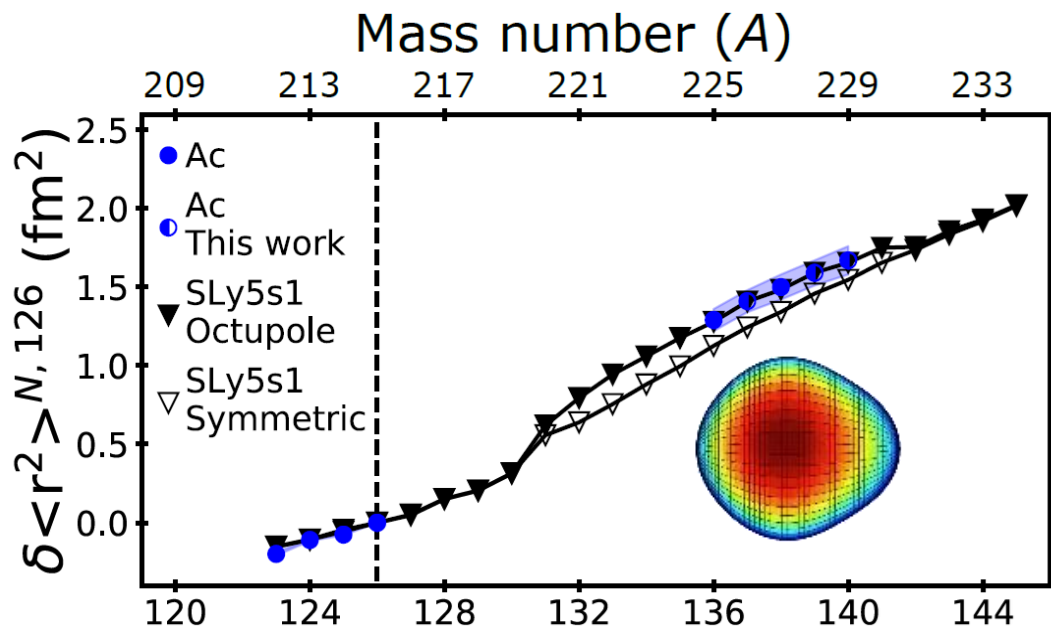


Gaffney et al., Nature 497, 199–204 (2013)



Lynch et al., Phys. Rev. C 97, 024309 (2018)

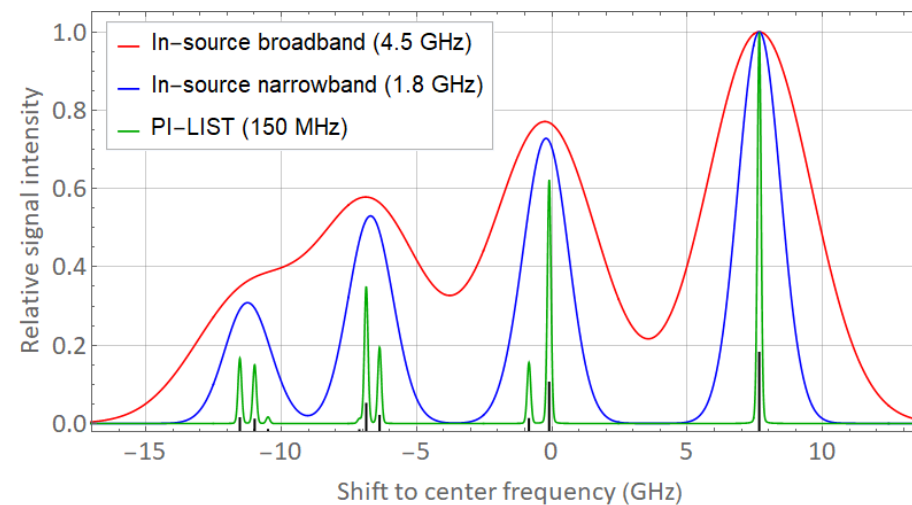
# Octupole deformation in Ac isotopes



E. Verstraelen et al, PHYSICAL REVIEW C 100, 044321 (2019)

0	Ac 221	Ac 222	Ac 223	Ac 224	Ac 225	Ac 226	Ac 227	Ac 228	Ac 229	Ac 230	Ac 231	Ac 232	Ac 233
9	1.36e+9	1.02e+9	1.04e+9	7.71e+8	7.66e+8	5.31e+8	5.24e+8	3.30e+8	3.03e+8	1.72e+8	1.37e+8	6.27e+7	3.82e+7
219	52 ms 2	5.0 ± 0.5	2.10 m 0.05	2.78 h 0.16	9.920 d 0.003	29.37 h 0.12	21.772 y 0.003	6.15 h 0.02	62.7 m 0.5	122 ± 3	7.5 m 0.1	1.98 m 0.08	145 ± 10
9	Ra 220	Ra 221	Ra 222	Ra 223	Ra 224	Ra 225	Ra 226	Ra 227	Ra 228	Ra 229	Ra 230	Ra 231	Ra 232
8	8.07e+8	3.58e+8	3.23e+8	1.89e+8	1.70e+8	9.58e+7	8.45e+7	4.30e+7	3.77e+7	1.59e+7	1.11e+7	3.58e+6	2.39e+6
9	17.9 ms 1.4	28 ± 2	33.6 ± 0.4	11.4377 d 0.0028	6319 d 0.0025	14.9 d 0.2	1.600 ky 0.007	42.2 m 0.5	5.78 y 0.03	4.0 m 0.2	93 m 2	104 ± 1	4.0 m 0.3
8	Fr 219	Fr 220	Fr 221	Fr 222	Fr 223	Fr 224	Fr 225	Fr 226	Fr 227	Fr 228	Fr 229	Fr 230	Fr 231
8	9.98e+7	5.66e+7	4.73e+7	2.67e+7	2.67e+7	1.58e+7	1.66e+7	9.09e+6	8.28e+6	3.04e+6	1.91e+6	4.98e+5	2.70e+5
6	20 ms 2	27.4 ± 0.3	4.801 m 0.005	14.2 m 0.3	22.00 m 0.07	3.33 m 0.10	3.95 m 0.14	49 ± 1	2.47 m 0.03	38 ± 1	50.2 ± 0.4	19.1 ± 0.5	17.6 ± 0.6
7	Rn 218	Rn 219	Rn 220	Rn 221	Rn 222	Rn 223	Rn 224	Rn 225	Rn 226	Rn 227	Rn 228	Rn 229	Rn 230
7	1.71e+7	9.72e+6	1.20e+7	9.20e+6	1.37e+7	8.90e+6	1.00e+7	4.79e+6	5.24e+6	1.54e+6	7.07e+5	1.48e+5	1.25e+5

Significant isobaric contamination → LIST suppression



Low sensitivity to  $Q_S$  → PI-LIST high resolution

Recent investigations and EDF theory on Ac:

- Available data matched only with octupole asymmetry
- Distinct kink as benchmark case
- Nuclear moments as supporting data

# IS664: Experimental setup

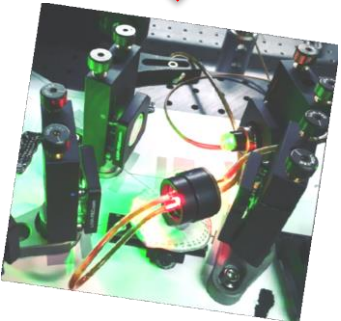
## Joined NB laser infrastructure



CRIS Matisse  
cw Ti:Sa



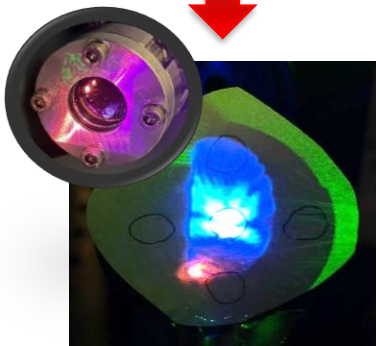
Cross-hall fiber



RILIS injection-locked  
pulsed ring cavity



Separator launch



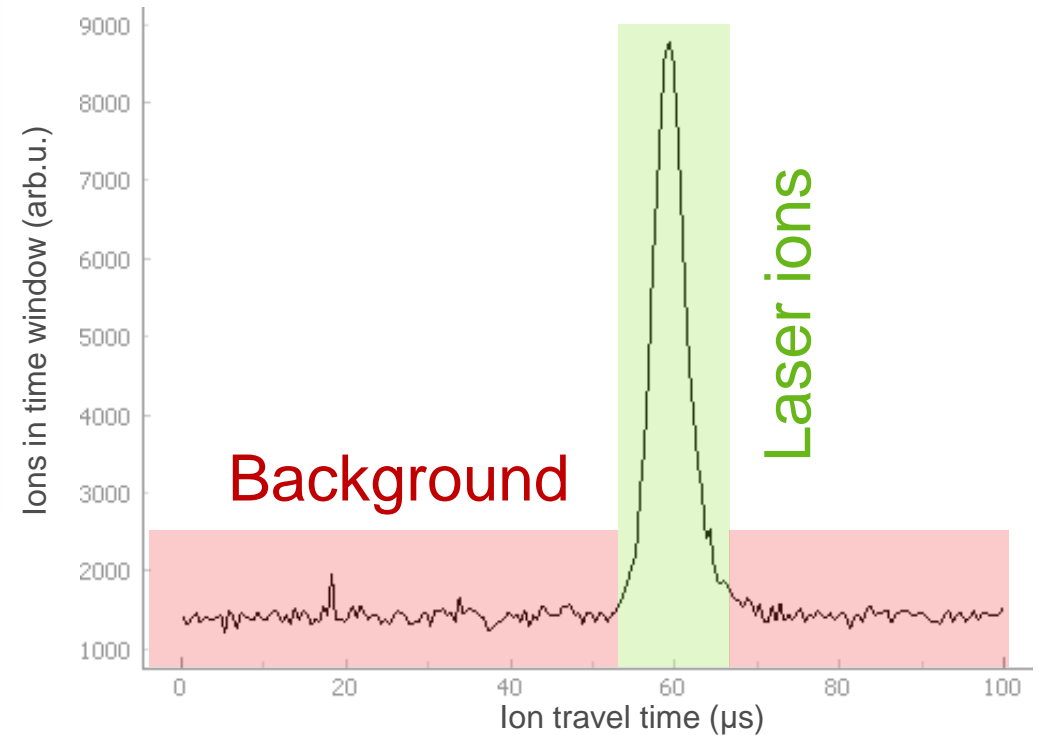
PI mode  
referencing



## Detector and DAQ

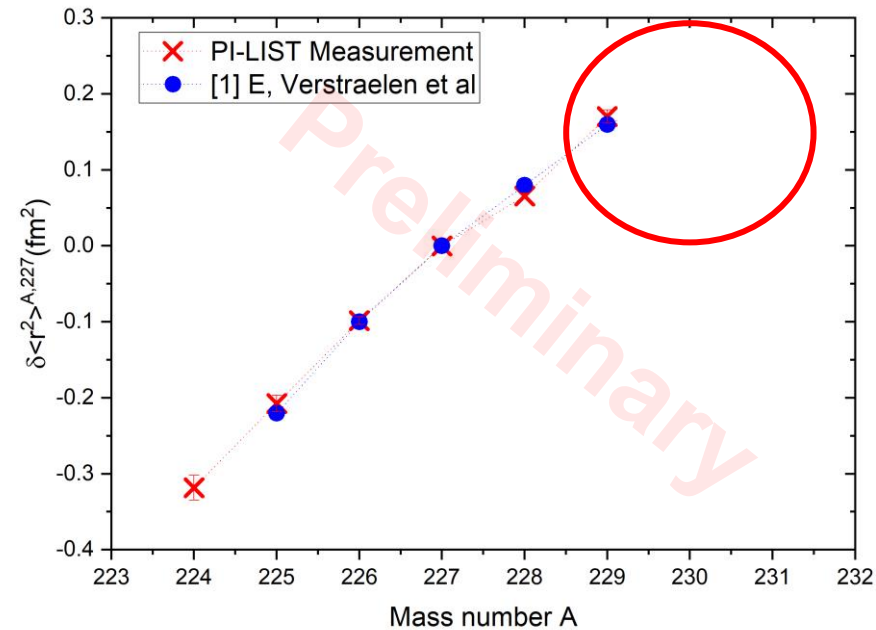
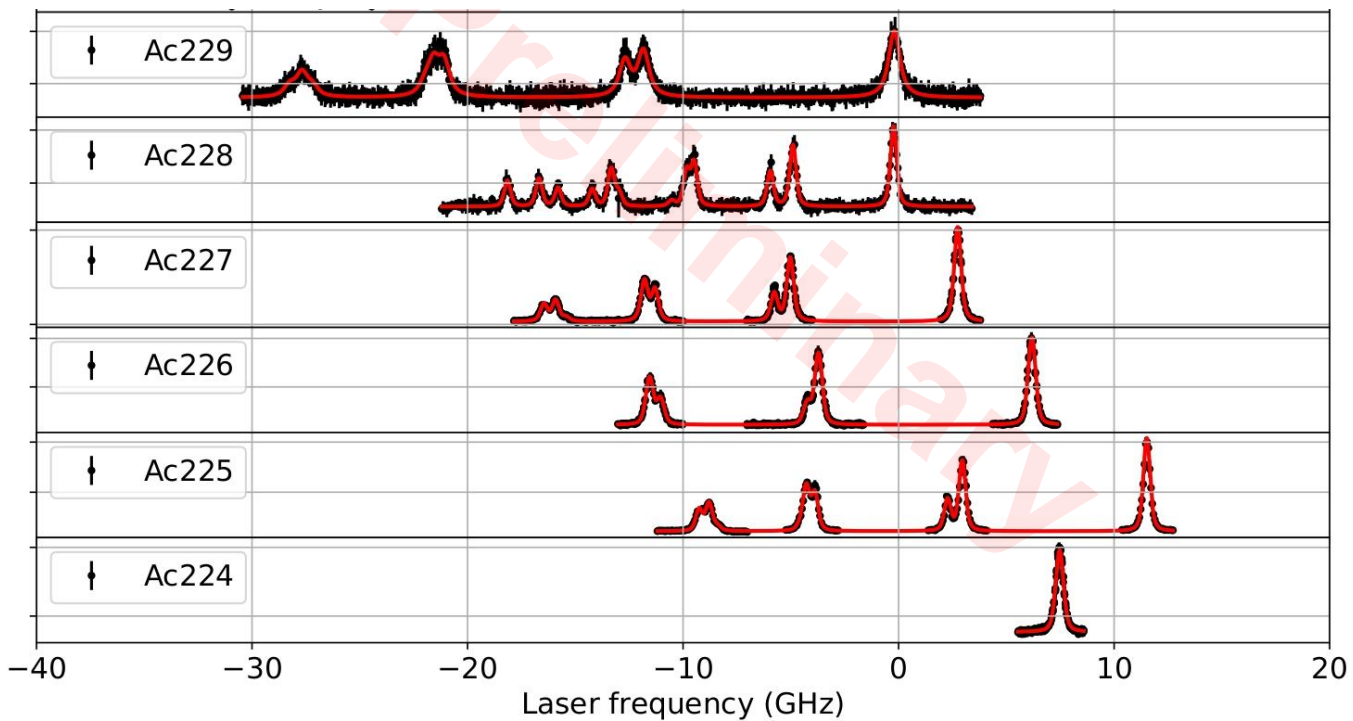
MagneTOF single ion counter at GLM/LA1 beam lines

- Highly sensitive
- Laser-synchronized 10kHz DAQ (CRIS time tagger)

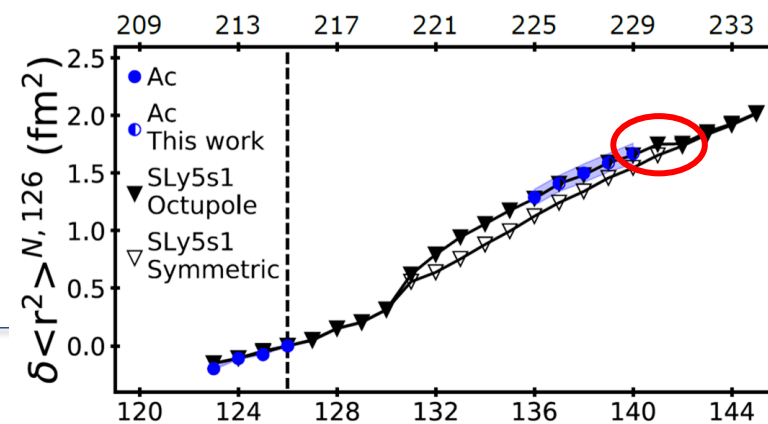




# Preliminary results: Radii kink confirmed?

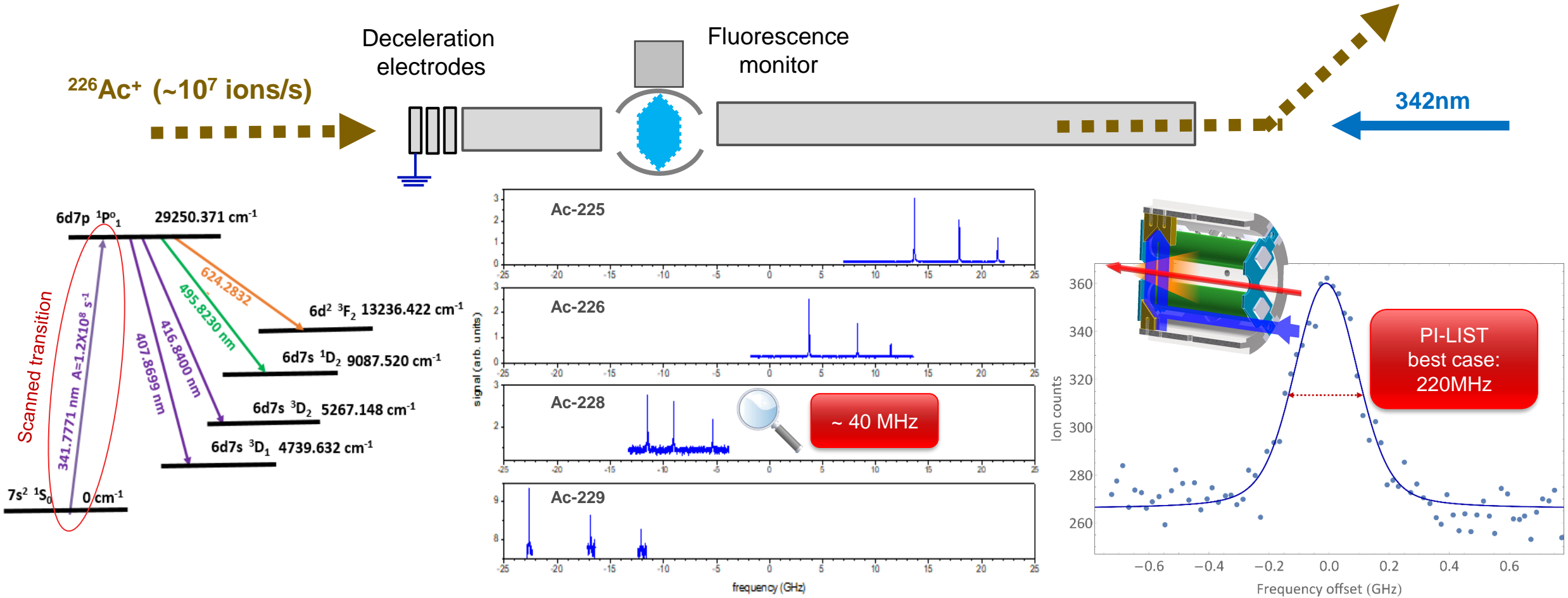


In-situ analysis by Michael Heines



# Complementary data: Collinear laser spectroscopy at TRIUMF

COLLAPS principle: Fluorescence detection after exciting ionic transition



→ Complementary high-resolution data; Systematic check of nuclear structure results

# PI-LIST for isomer-pure RIB production

Example case for inspiration

Search for the  $0_2^+$  state in  $^{80}\text{Ge}$  from isomerically purified  $^{80}\text{Ga}$  states

g	1894...	755...	m, g	$\beta$
<b>Ge 80</b> 29.5 s	<b>Ge 81</b> 7.6 s	<b>Ge 81</b> 7.6 s	<b>Ge 82</b> 4.0 s	
$\beta^-$ 2.4... $\gamma$ 266, 1564 937...	$\beta^-$ 6.9... $\gamma$ 93, 336 197...	$\beta^-$ 3.6 5.2... $\gamma$ 336 793...	$\beta^-$ 3.6, 4.2... $\gamma$ 1092, 843, 249... g	$\beta$ $\gamma$ 1
<b>Ga 79</b> 2.848 s	<b>Ga 80</b> 1.3 s	<b>Ga 80</b> 1.9 s	<b>Ga 81</b> 1.22 s	
$\beta^-$ 7.0... $\gamma$ 465, 516 1187, 2140..., g $\beta_n$	$\beta^-$ $\beta_n?$ , IT?	$\beta^-$ 10.4... $\gamma$ 659 1083 1109... $\beta_n$	$\beta^-$ 4.5, 7.6... $\gamma$ 216, 828 711..., g, m $\beta_n$	$\beta$ $\beta$ $\gamma$ 7

$I = 3^- / 6^-$

Isomer-pure RIB's

- Direct spectroscopy in clean samples
- (Spin-)Controlled feeding
- Switch ID  $\leftrightarrow$  efficiency

B. Cheal et al., Phys. Rev. C 82, 051302(R) (2010)

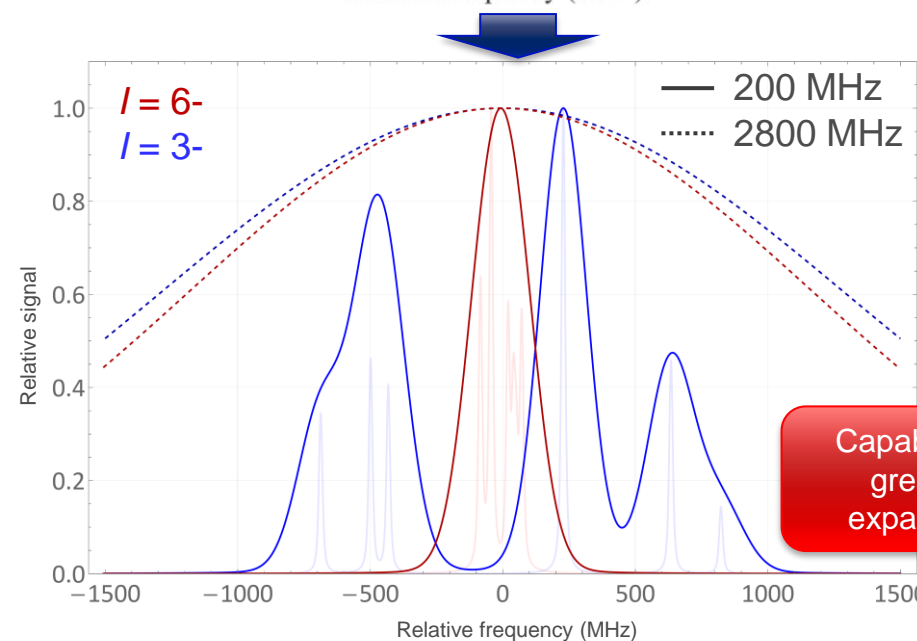
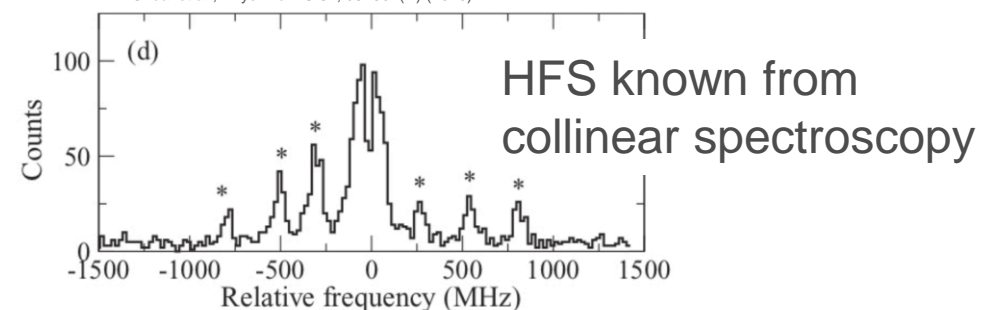


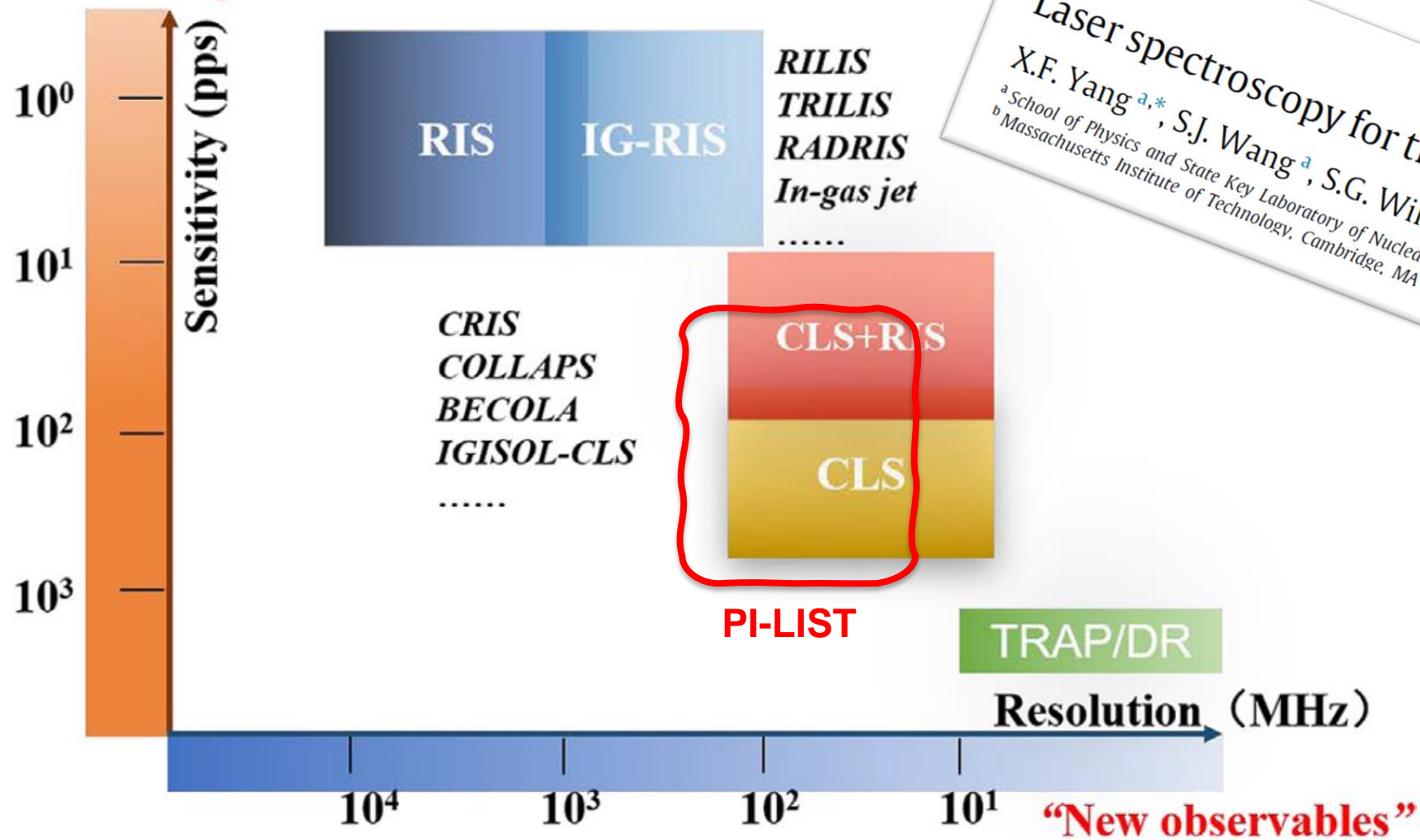
Table 1: Summary of estimated implanted ions.

$^{80}\text{Ga}$ state	$T_{1/2}$ (s)	Yield (ions/ $\mu\text{C}$ )	p current ( $\mu\text{A}$ )	trans. (%)	PI-LIST eff. (%)	ions /s	duty cycle (%)	ions /hour	ions /shift
$3^-$	1.3	4.5E6	1.7	90	0.1	6.9E3	74	1.8E7	1.5E8
$6^-$	1.9	4.5E6					65	1.6E7	1.3E8



# PI-LIST in the landscape of laser spectroscopy

“Terra incognita”



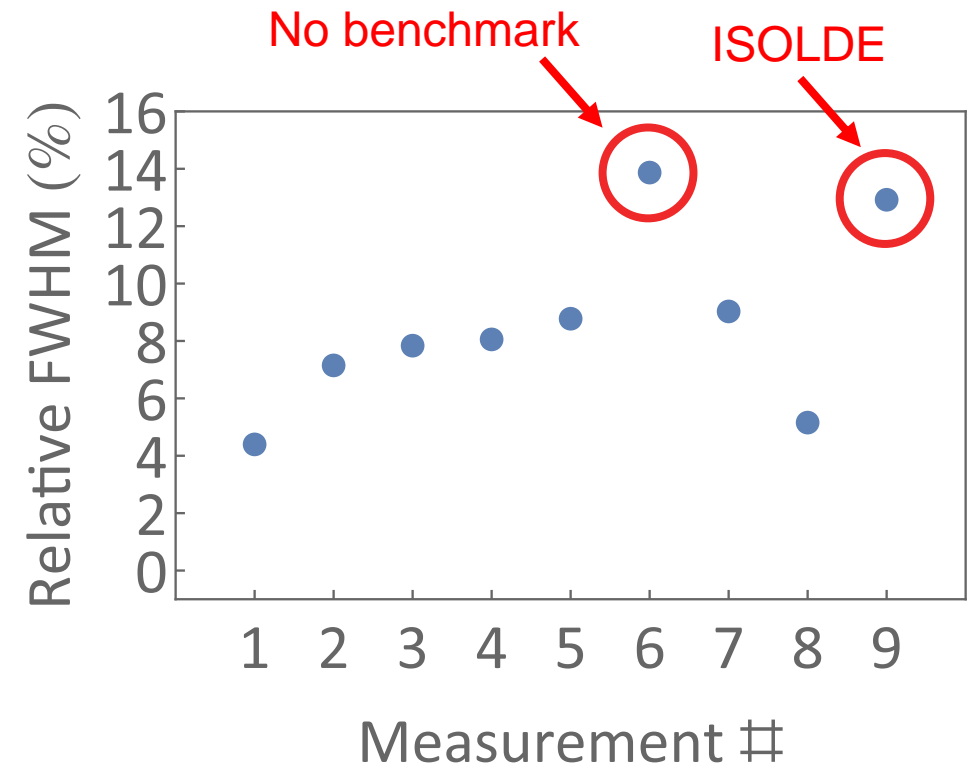
Review  
**Laser spectroscopy for the study of exotic nuclei**  
 X.F. Yang<sup>a,\*</sup>, S.J. Wang<sup>a</sup>, S.G. Wilkins<sup>b,\*</sup>, R.F. Garcia Ruiz<sup>b,\*</sup>  
<sup>a</sup>School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China  
<sup>b</sup>Massachusetts Institute of Technology, Cambridge, MA 02139, USA

- PI-LIST still “young”
- “Simple” unit instead of beamline
- Versatile operation modes
- Isomer-selective RIB production

# Resolution meta-analysis

#		Mass (amu)	WL (nm)	Temp. (C)	LIST type	FWHM (MHz)	Opt?	Doppler (MHz)	Fraction
1	Tc	99	430	1700	JGU	98	yes	2230	4%
2	Ho	165	410	1000	JGU	104	yes	1455	7%
3	Ho	165	410	1000	JGU mirror	114	yes	1455	8%
4	U	238	830	1700	JGU	60	yes	745	8%
5	Rb	87	780	300	JGU mirror	62	yes	707	9%
6	Ac	225	418	1500	JGU	200		1442	14%
7	Pm	145	452	1500	JGU	150		1661	9%
8	Cf	250	417	800	JGU	55	yes	1067	5%
9	Ac	227	439	2000	ISOLDE	200	yes	1548	13%

$$\text{FWHM}_{\text{Doppler}} = \frac{v_0}{c} \sqrt{\frac{8 \ln(2) k_B T}{m}}$$



# Efficiency considerations

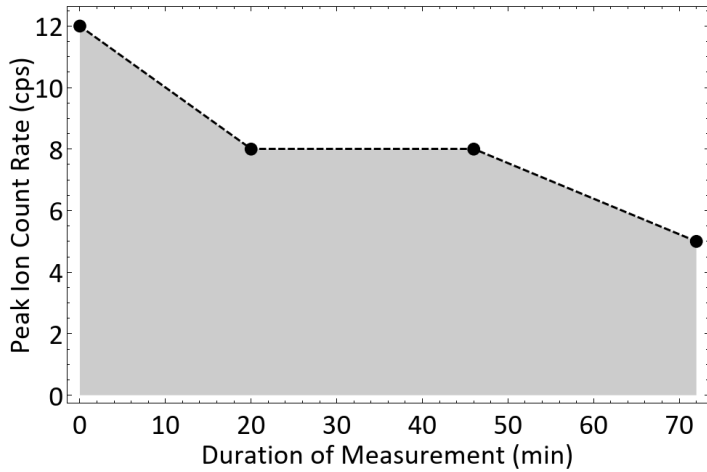
## Loss factors

RILIS → LIST ~ 30

LIST → PI-LIST ~ 2

PI-LIST opt. ~ 10

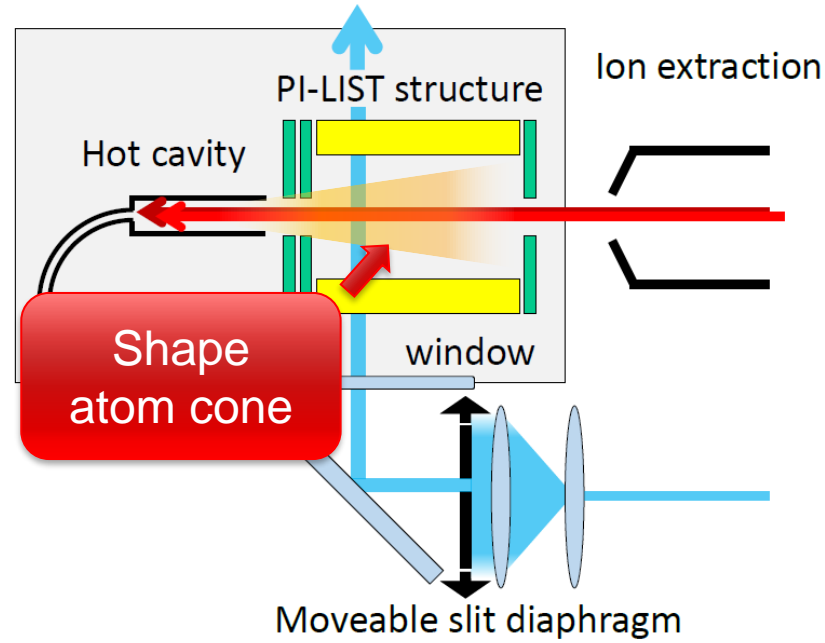
**Total: ~ 500 - 1000**



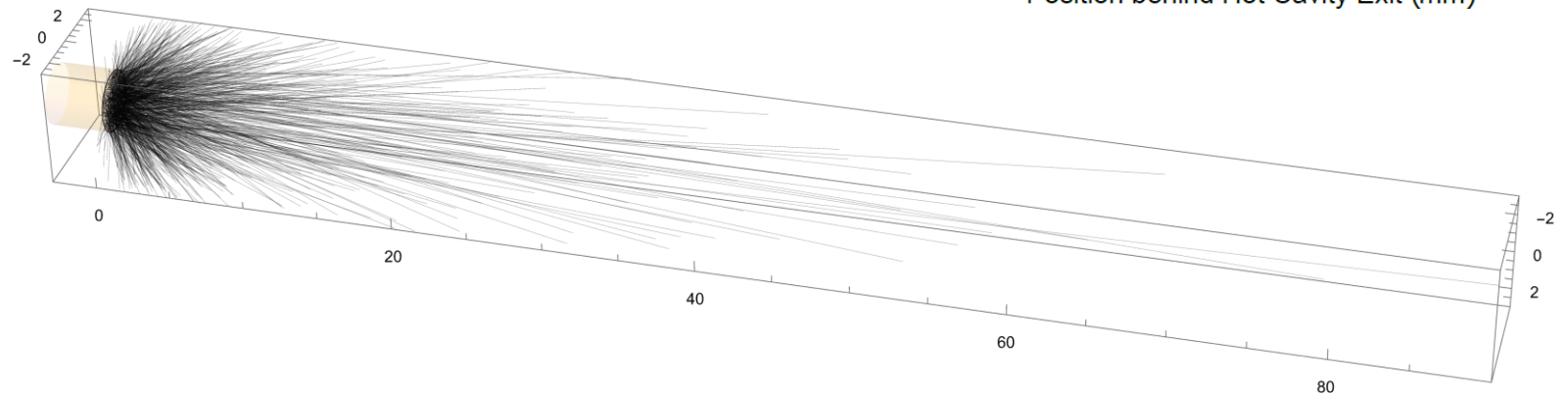
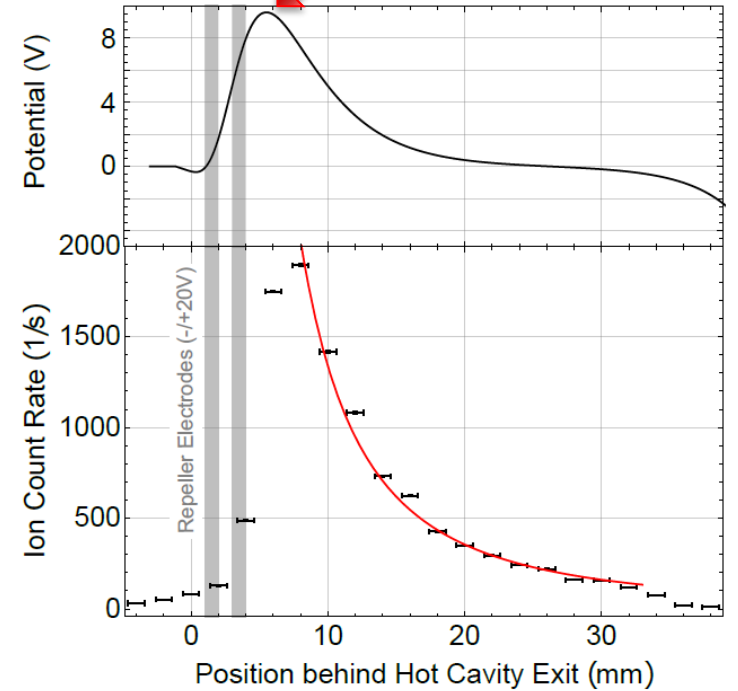
Efficiency extrapolation with  $^{225}\text{Ac}$ :

~ $10^{-4}$  (Standard RILIS: 10%)

## Geometric atom beam losses: Opening angle



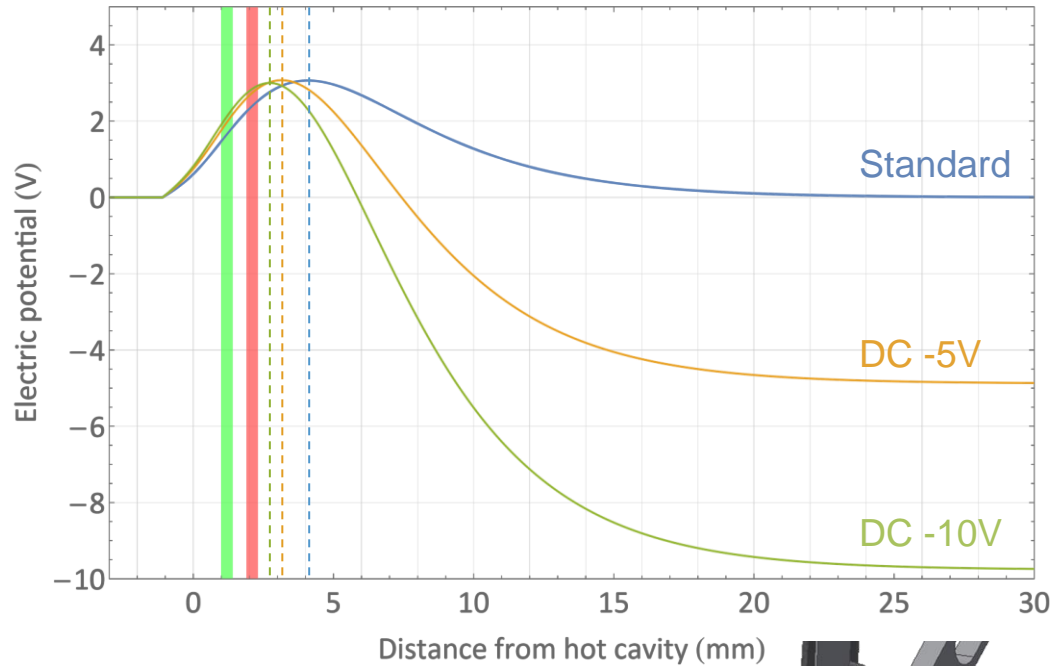
Move potential ridge closer



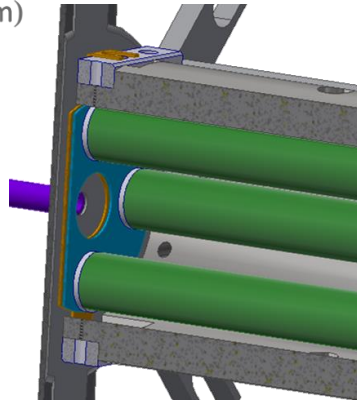


# Optimization pathways

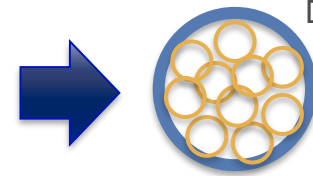
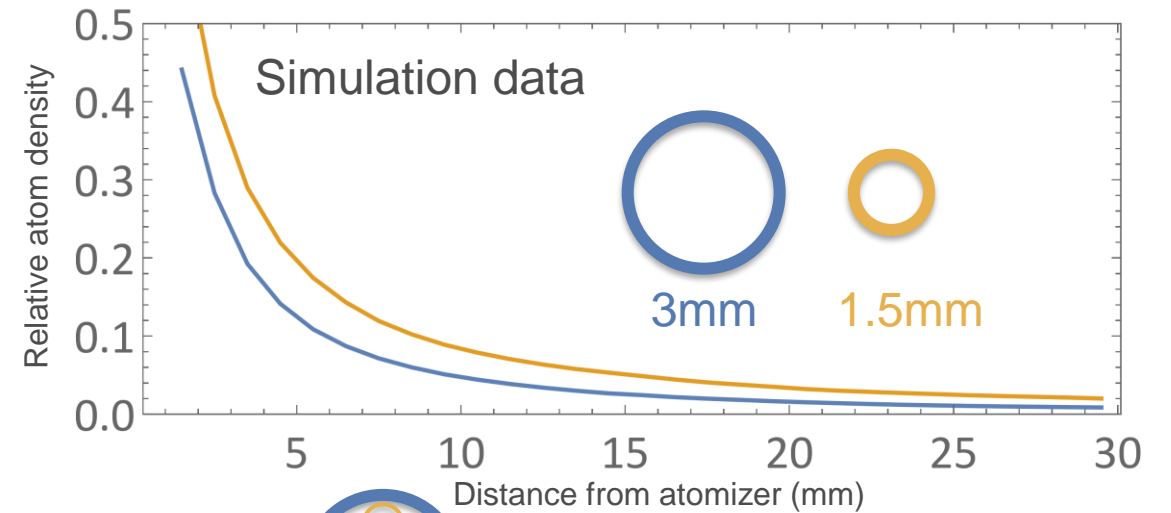
→ Improve active volume: Shape electric potential



- DC offset of LIST corpus
- Improve repeller geometry
- Also facilitates ion guiding



→ Shape effusing atom cone



Multi-tube



Orifice design

→ Laser duty cycle

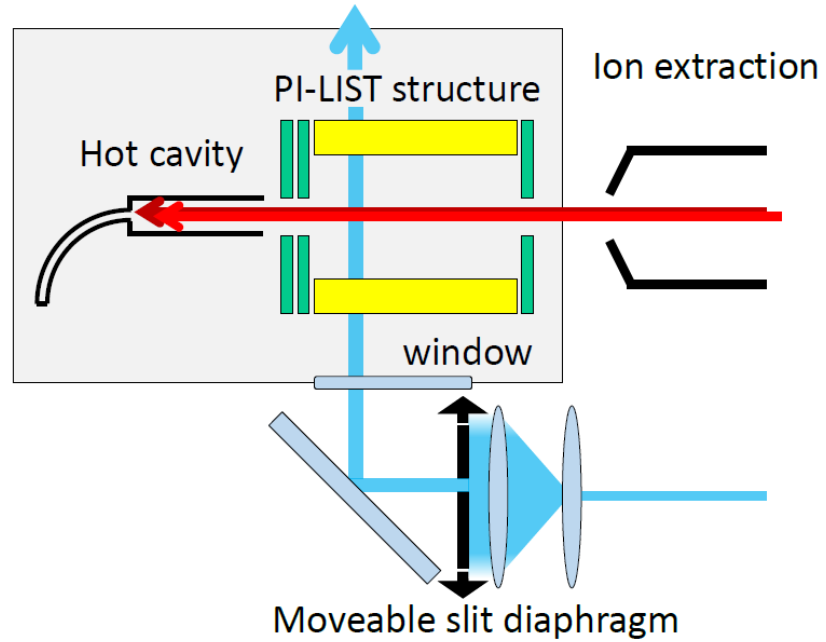
- Multiple chances in tube vs. ~1 in atom cone

→ RF phase synchronization

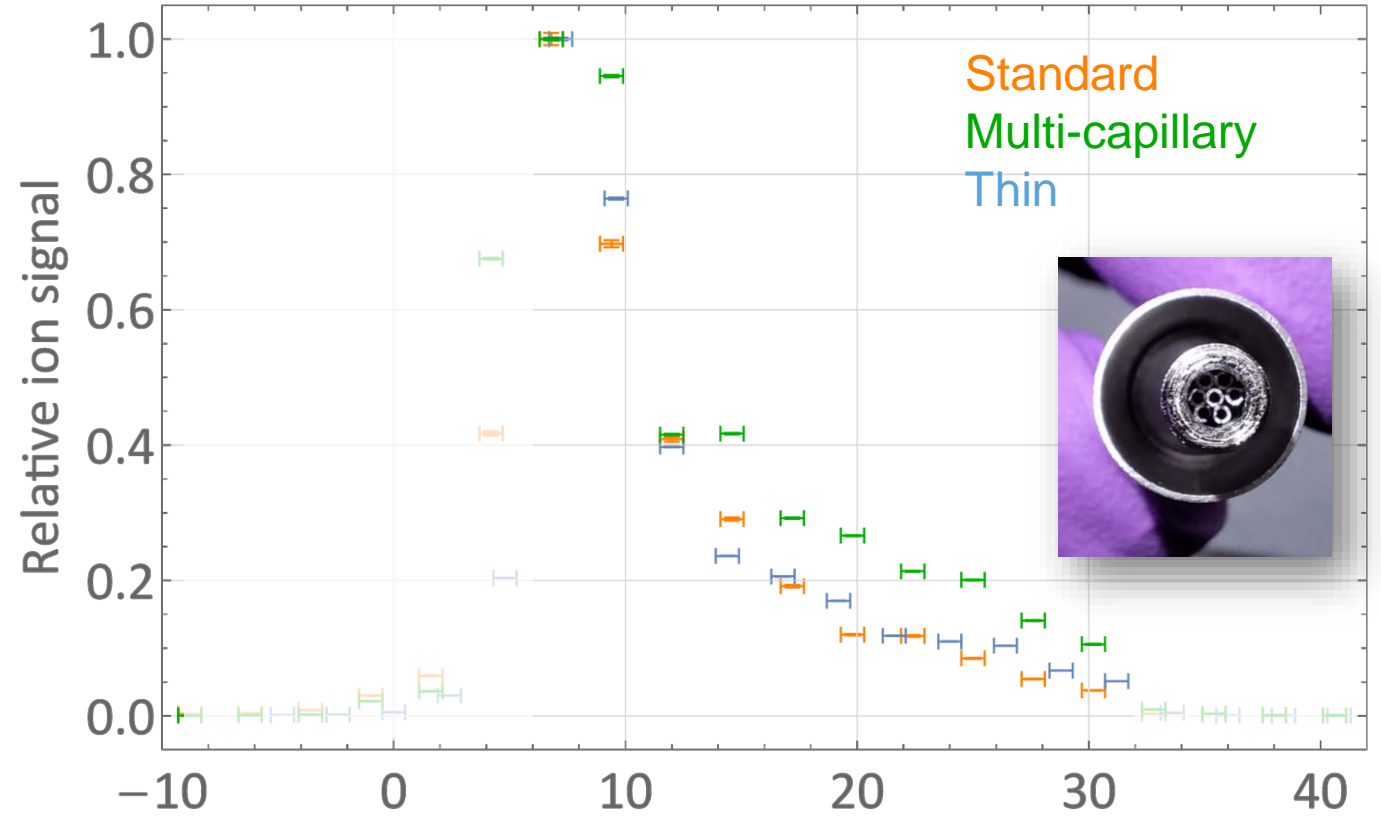
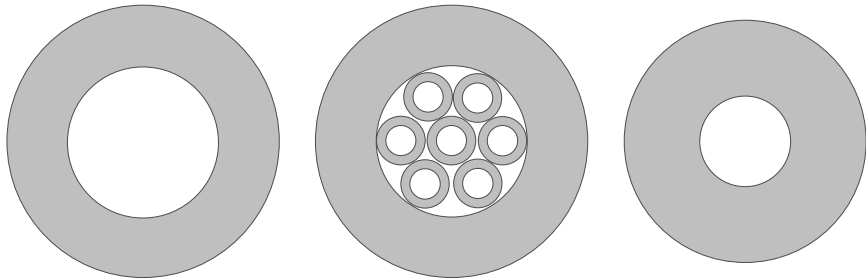
- Trapping efficiency, investigated at TRIUMF

Dedicated off-line development infrastructure highly beneficial

# Atom beam collimation – experimental investigation

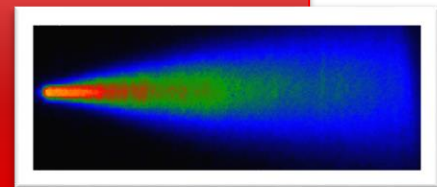


Test atomizer cross sections



Data analysis and feedback into simulation infrastructure ongoing

Experimental alternatives:  
Planar laser induced fluorescence /  
Deposition on catcher foils



A. Zadornaya et al.,  
Phys. Rev. X 8, 041008

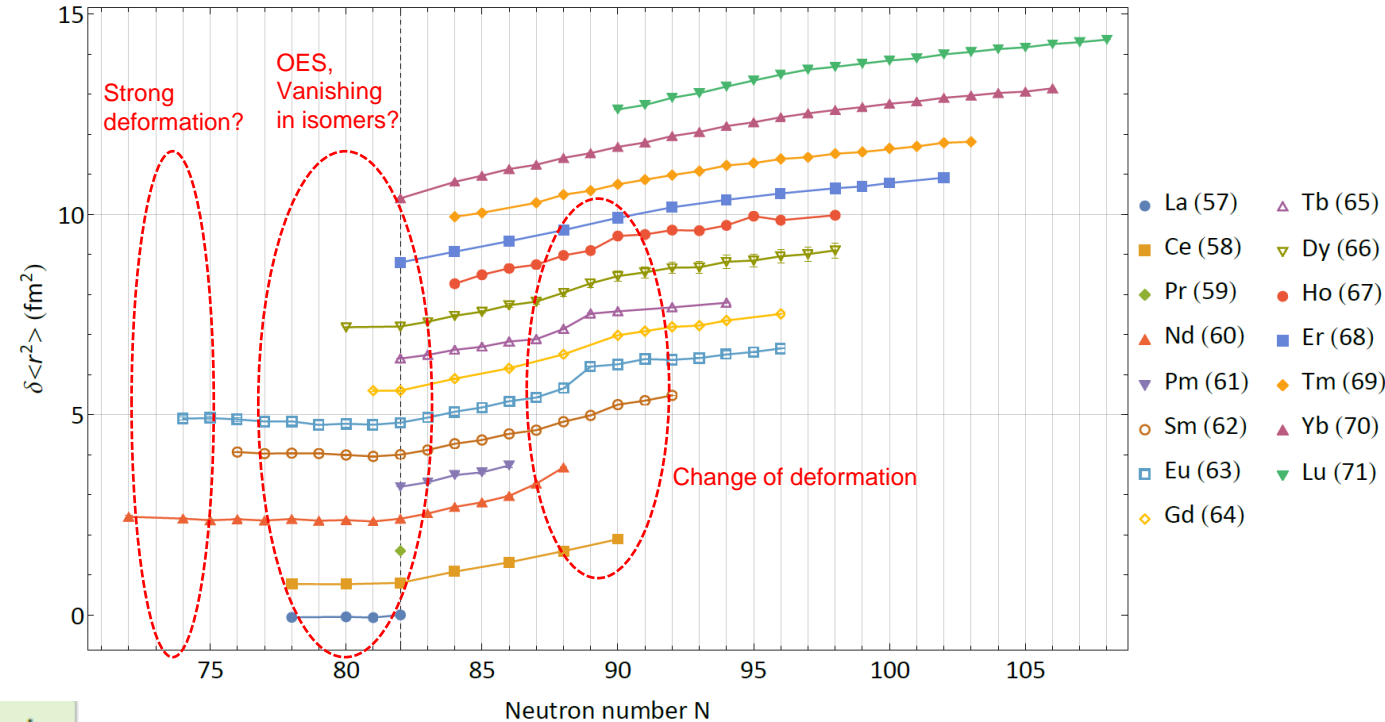
# Future plans: Lanthanide campaign (LoI246)

Lanthanide elements as fitting case for (PI-)LIST:

- Surface-ionizable → suppression needed
- Extensive laser scheme groundwork done
- PI-LIST off-line spectroscopy successful
- Release behavior studied (MEDICIS)
- High atomic level density (open shells) disadvantage for charge exchange
- Interest in various nuclear structure phenomena, including **p+ emitters beyond dripline**

Plans for laser spectroscopy at the proton drip line *Kara Marie Lynch*

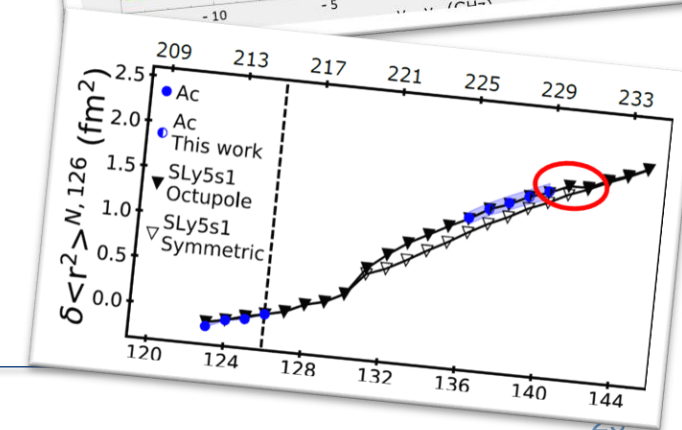
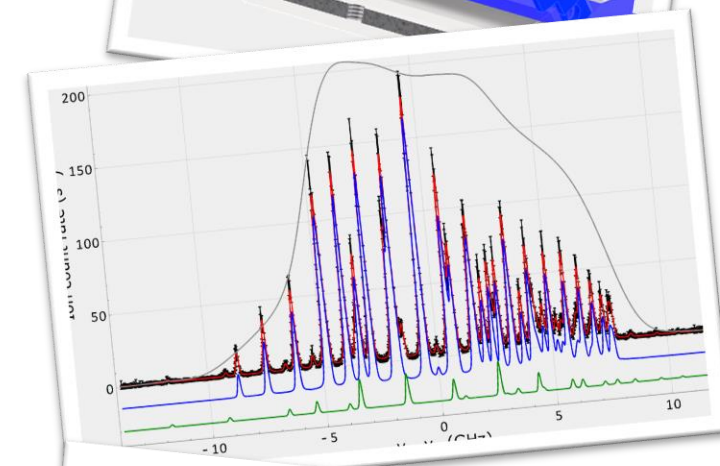
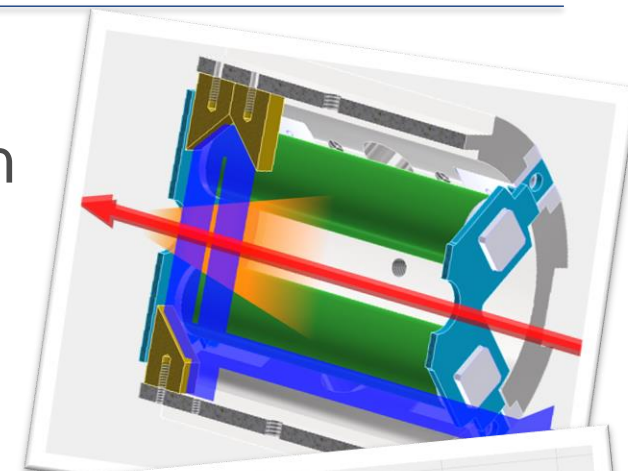
Charge radii around N = 82



→ Ta target + LIST: lanthanide yield measurement campaign up to CERN LS3

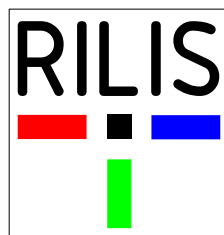
# Summary

- RILIS @ ISOLDE: The workhorse RIB source and its evolution
- PI-LIST: “Sub-Doppler” resolution enhancement
  - High resolution spectroscopy: Ac octupole deformation
  - Isomer-selective ionization
  - Ongoing developments (FI-LIST → K. Wendt later)

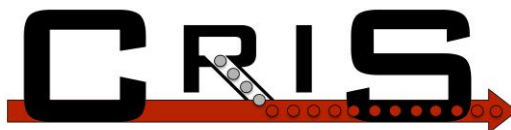




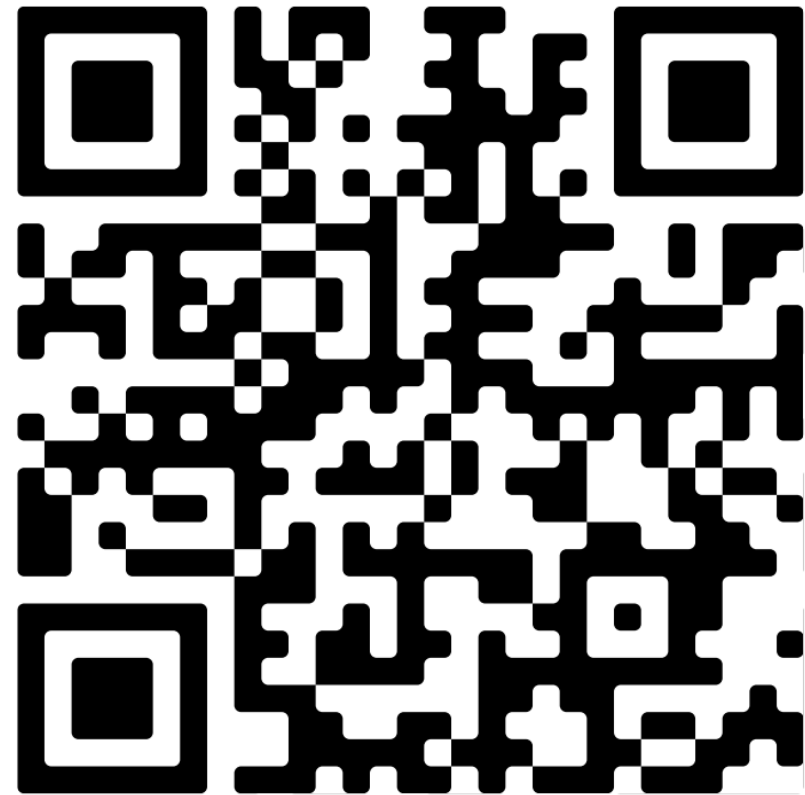
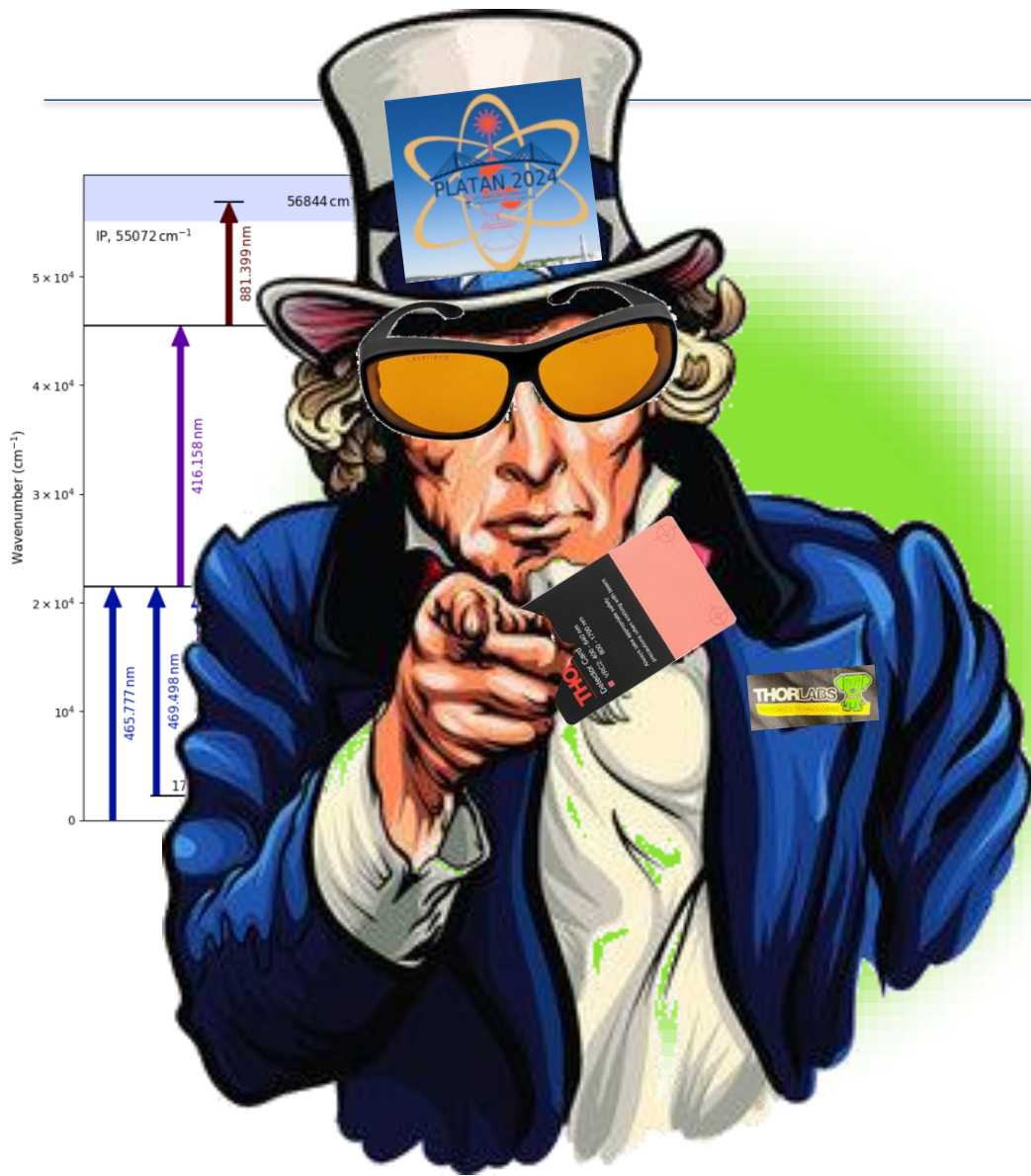
Thanks to you for *LIST*ening...



JOHANNES GUTENBERG  
UNIVERSITÄT MAINZ



... and to all the collaborators!



<https://rims-code.github.io>

Contribute to sharing!

# IS664: Experimental setup

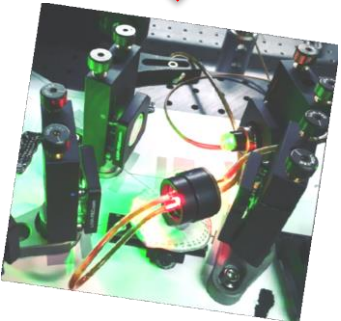
## Joined NB laser infrastructure



CRIS Matisse  
cw Ti:Sa



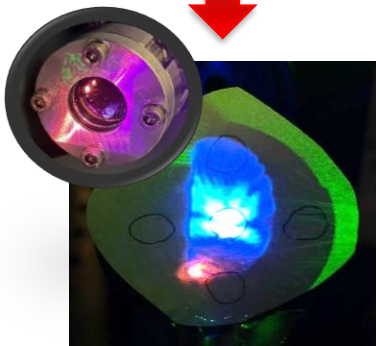
Cross-hall fiber



RILIS injection-locked  
pulsed ring cavity



Separator launch



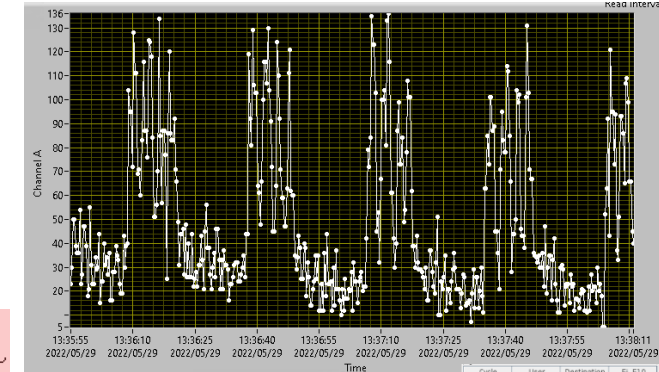
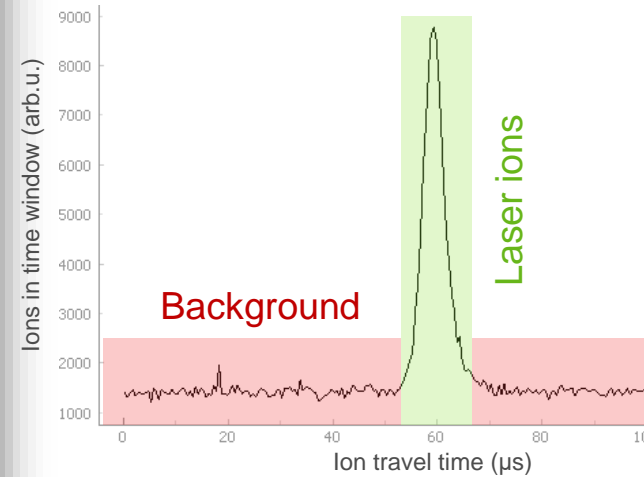
PI mode  
referencing



## Detector and DAQ

MagneTOF single ion counter at GLM/LA1 beam lines

- Highly sensitive
- Laser-synchronized 10kHz DAQ (CRIS time tagger)

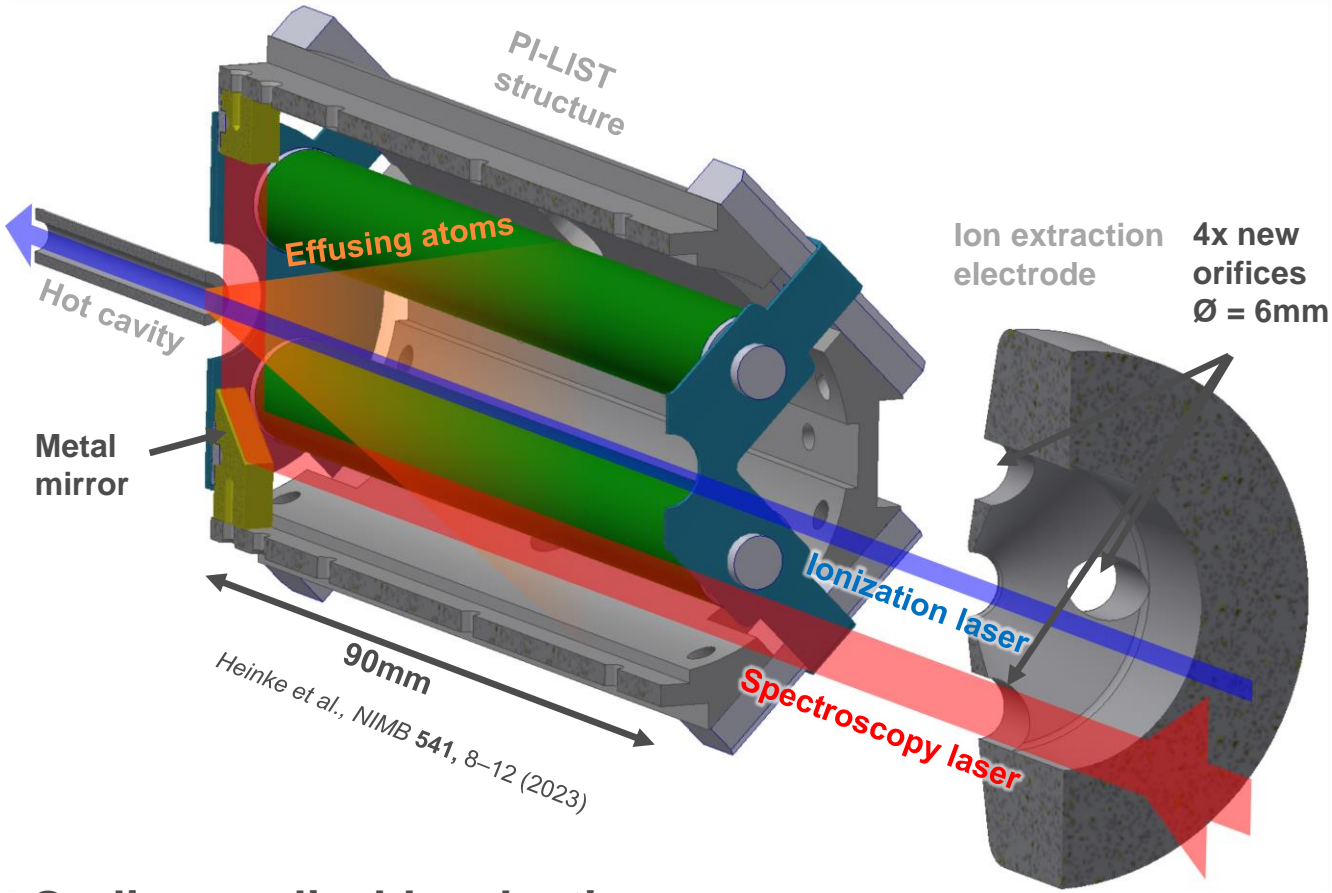


Cycle	User	Destination	El. ELO
24	WIKINGS	ROOMS	1184
22	WIKINGS	ROOMS	1184
20	WIKINGS	ROOMS	1228
18	WIKINGS	ROOMS	1228
16	WIKINGS	ROOMS	1228
14	WIKINGS	ROOMS	1228
12	WIKINGS	ROOMS	1228
10	WIKINGS	ROOMS	1228
8	WIKINGS	ROOMS	1228
6	WIKINGS	ROOMS	1228
4	WIKINGS	ROOMS	1228
2	WIKINGS	ROOMS	1228

Radioactive noble gases from target on  $p^+$  impact

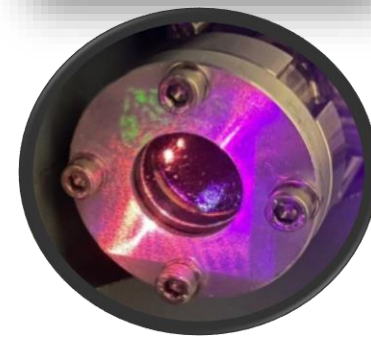
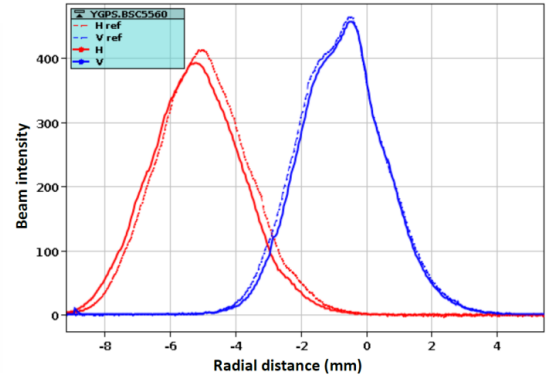
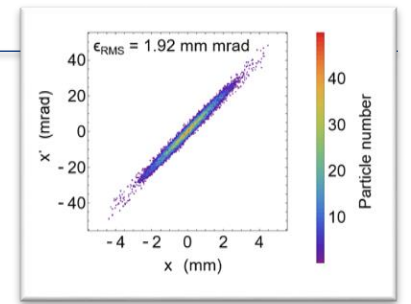
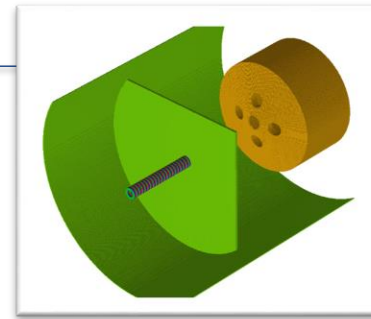
- Group protons, measure later (slow release of Ac)
- Detector moved to CB0
- IDS/ASET on standby / parallel experiments





## On-line applicable adaption

- Alternative for external laser access through window
- Robustness



## Technical implementation

- Confirmation of operation transparency of changes
- Control and feedback systems (LabVIEW)