Resonance ionization schemes for high resolution and high efficiency study of exotic nuclei at the CRIS experiment

Agi Koszorus

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Contents

- Motivation: Need for suitable techniques
- Challenges:
  - High efficiency and high resolution
  - Precision and accuracy
- CRIS: Laser lab
- Results: Selected Resonance Ionization Schemes
- Summery and Outlook

Motivation: Need for suitable techniques

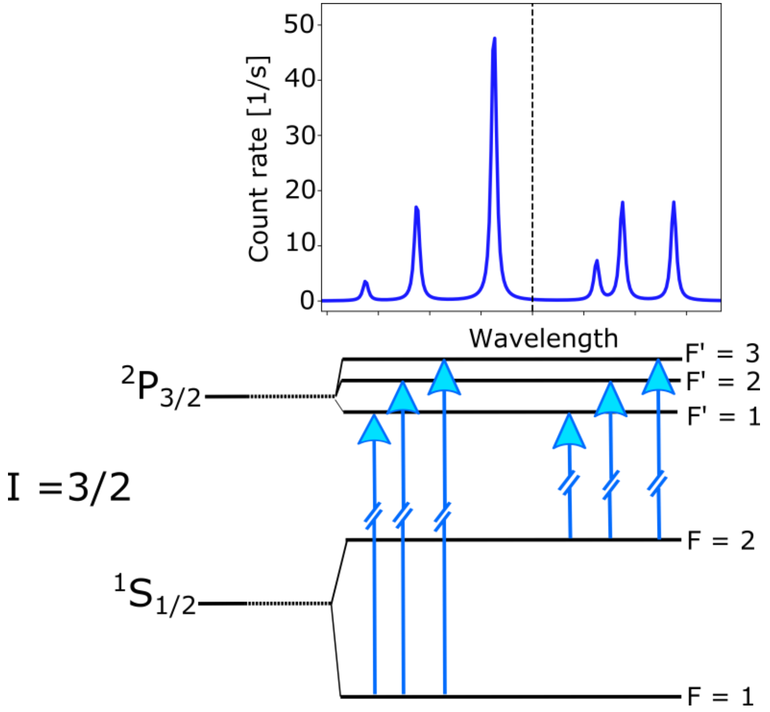
Model independent study of the

- Nuclear spin ***I***
- Magnetic dipole moment ***μ***
- Electric quadrupole moment ***Q***
- Changes in the mean square charge radii ***δ<r²>***

of the ground state and long lived isomeric states of exotic isotopes

High resolution

High efficiency



- The distance between the peaks carries the magnetic moment information
- The centroid (relative to the reference) gives us the changes in the ms in the chain
- Spin assignment: number/ relative intensities / ratio of HF parameters / …

Motivation: Need for new techniques

Model independent study of the

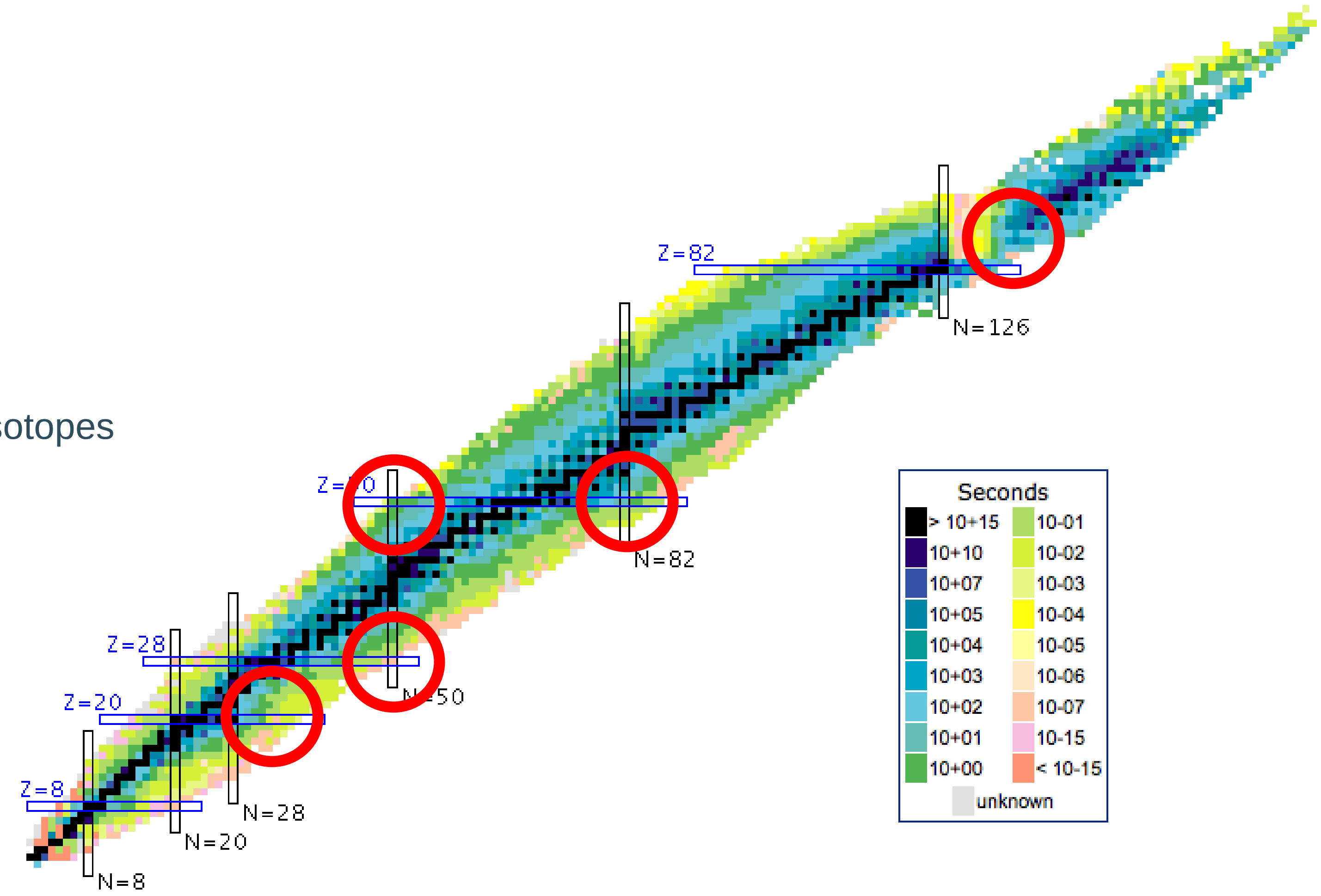
- ❖ Nuclear spin ***I***
- ❖ Magnetic dipole moment ***μ***
- ❖ Electric quadrupole moment ***Q***
- ❖ Changes in the mean square charge radii ***δ<r²>***

of the ground state and long lived isomeric states of exotic isotopes

High resolution – collinear laser spectroscopy

High efficiency – In-source RIS

→ **CRIS**



Principle of CRIS

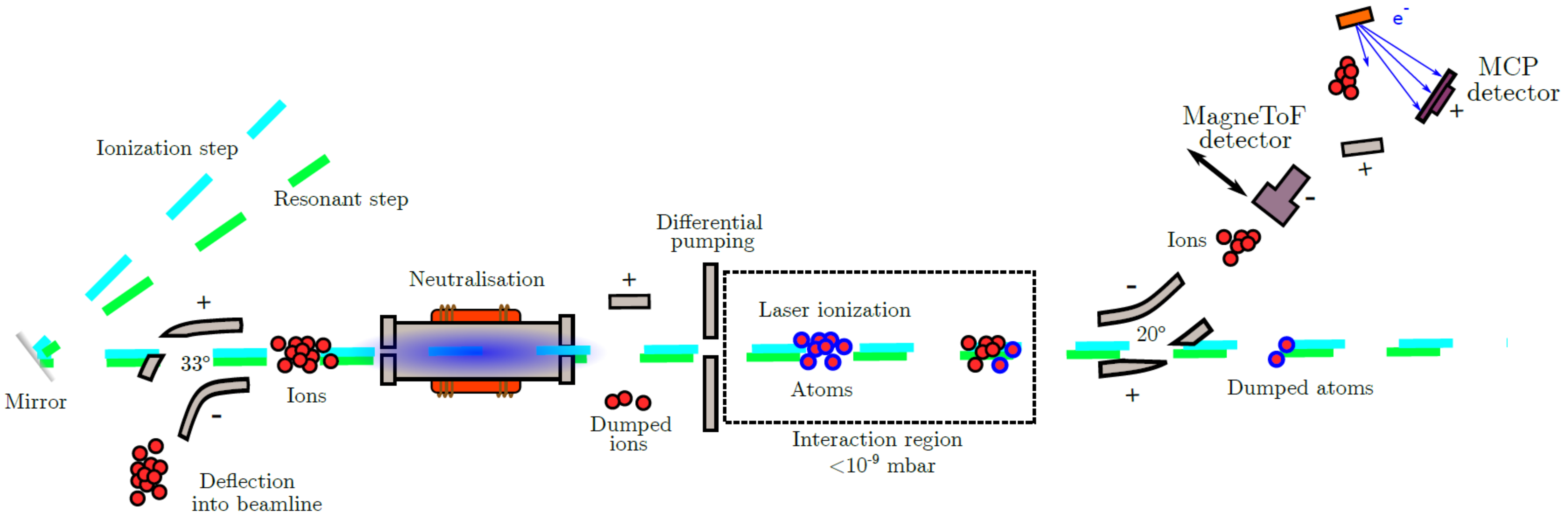
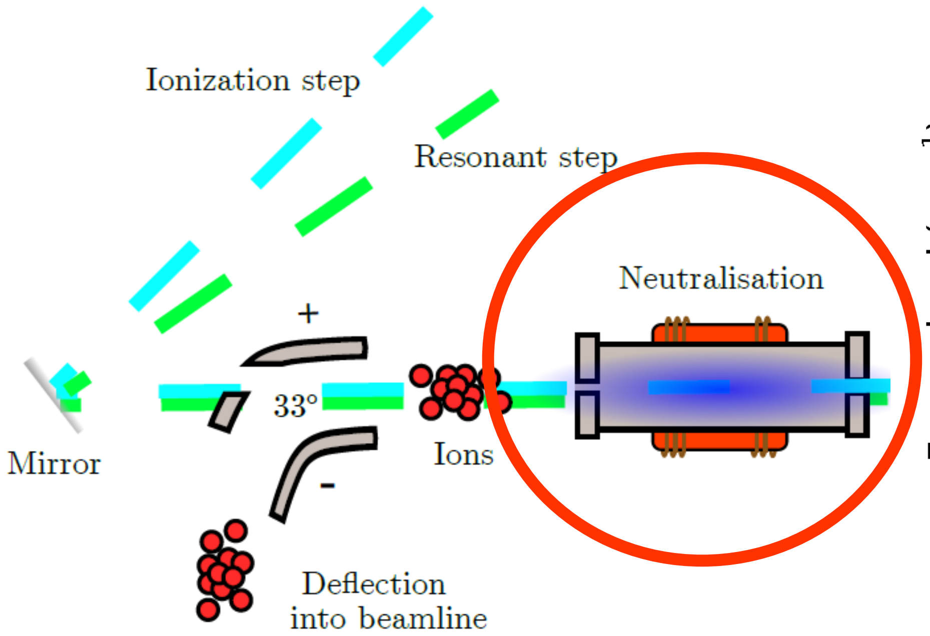
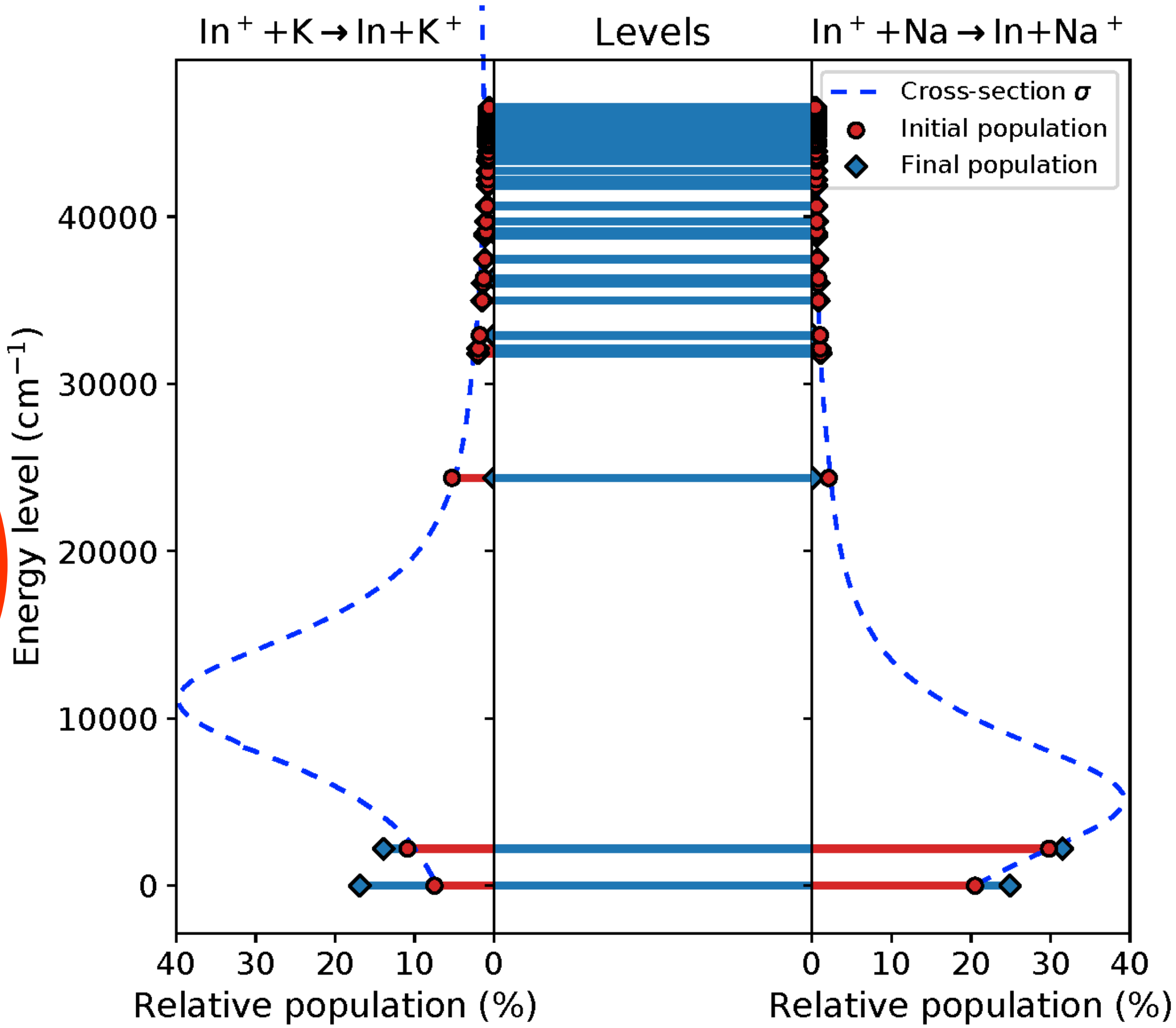


Figure by A. R. Vernon*

Principle of CRIS





R. Vernon*

Principle of CRIS

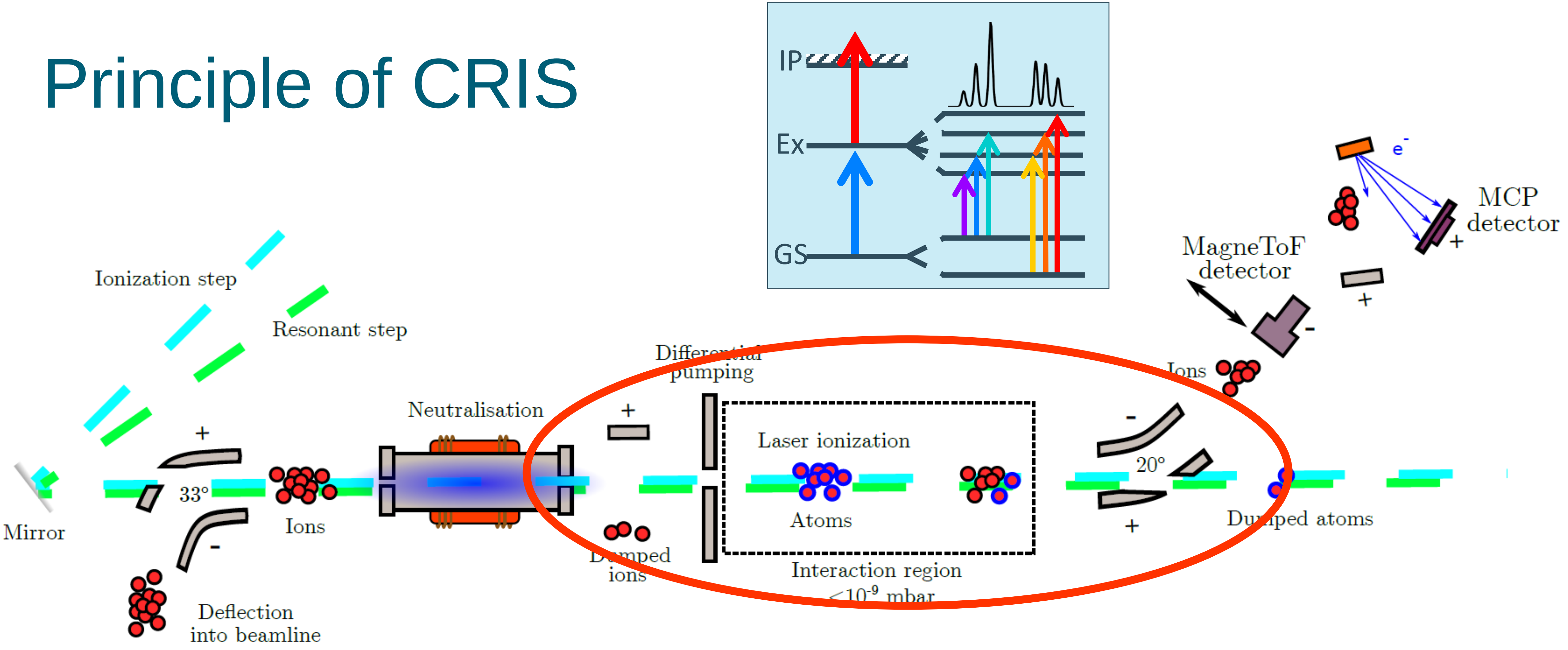


Figure by A. R. Vernon*

Resonantly ionized atoms and
Nonresonant background
Lowest limit 1 count/h background rate (dark count rate)

Principle of CRIS

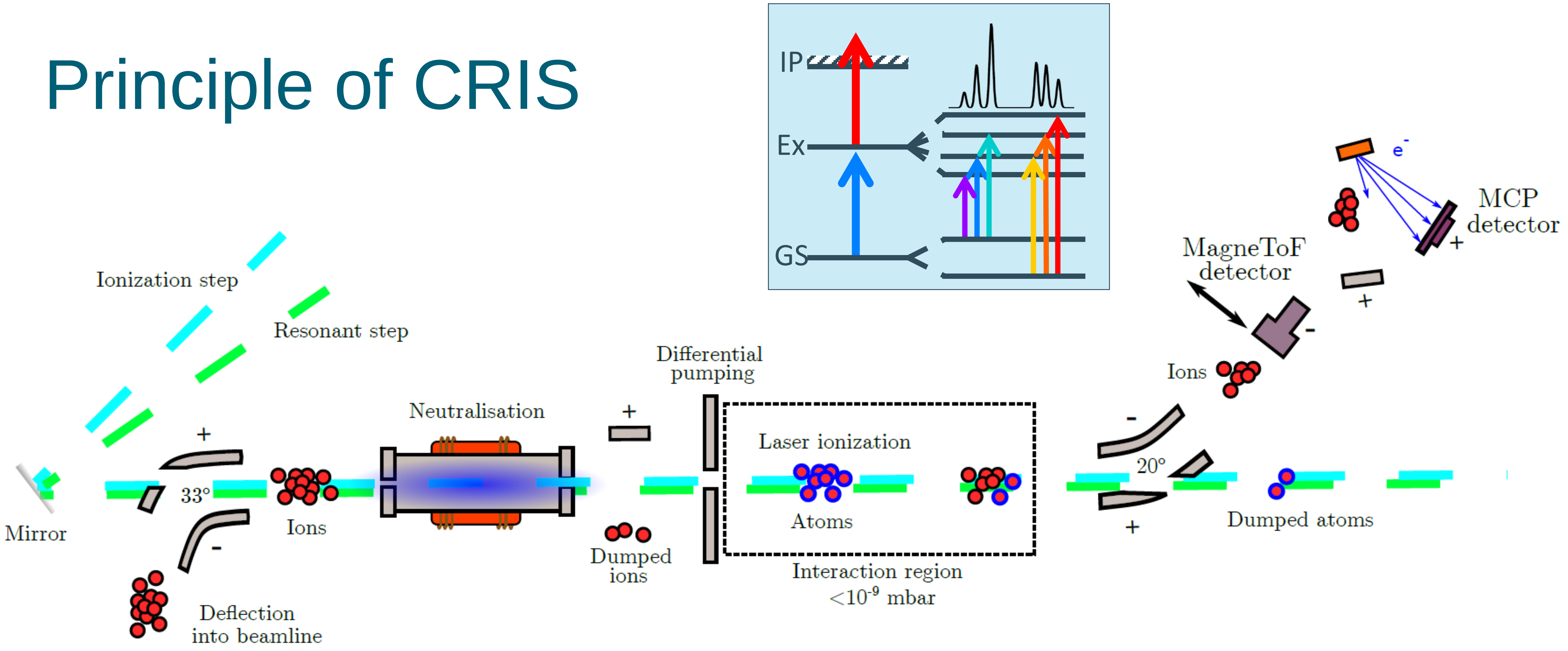


Figure by A. R. Vernon*

Resonantly ionized atoms and
Nonresonant background
Lowest limit 1 count/h background rate (dark count rate)

Challenges:

High efficiency and high resolution

- Resolution
    - Narrow band lasers
    - Remove power broadening
    - Laser atom related line shape distortion and shifts
- Efficiency = $\varepsilon_{TRANS} * \varepsilon_{CEC} * \varepsilon_{RIS} * \varepsilon_{DET}$
    - Particle detection
    - Efficient RIS
    - 1% → 100 ions/s before ISCOOL = 1 count/s signal

isobaric/nonresonant background suppression

- Ultra high vacuum in the interaction region
- Reduction of non-resonant ionization rate
- Suppression of 1:10^6→ 10^6 ions/s beam = 1 count/s background

Precision and accuracy in case of light systems

- Precision of laser scanning and frequency measurement

High resolution CRIS studies preformed since 2014

$_{19}K$ — 16 nuclear states $^{38-52}K$

$_{21}Sc$

$_{29}Cu$ — 17 nuclear states $^{63-66,\ 68-78}Cu$

$_{31}Ga$

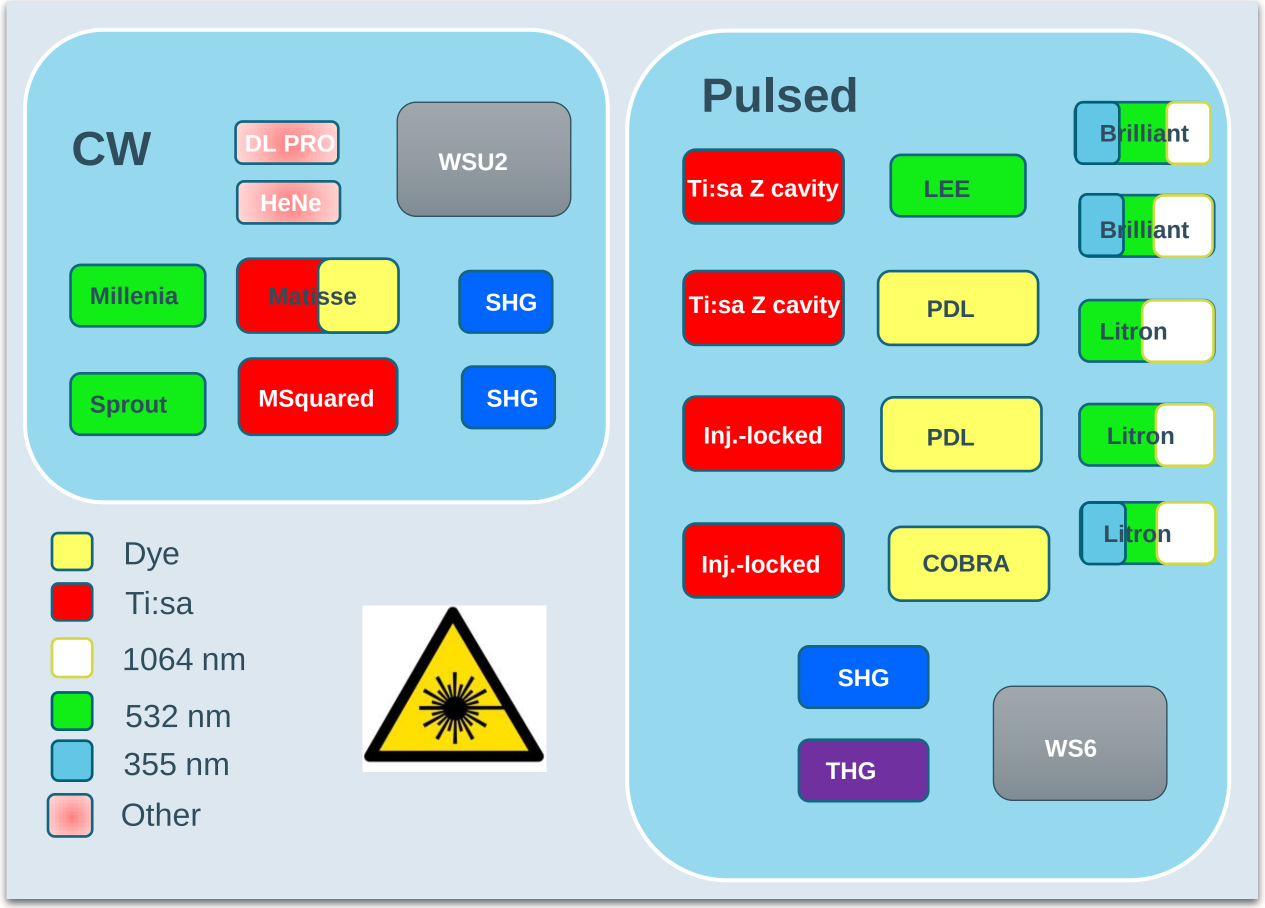
$_{49}In$ — >60 nuclear states $^{101-131}In$

$_{50}Sn$

$_{87}Fr$ — 7 nuclear states $^{203,206,207,219,221}Fr$

$_{88}Ra$

CRIS: Laser lab

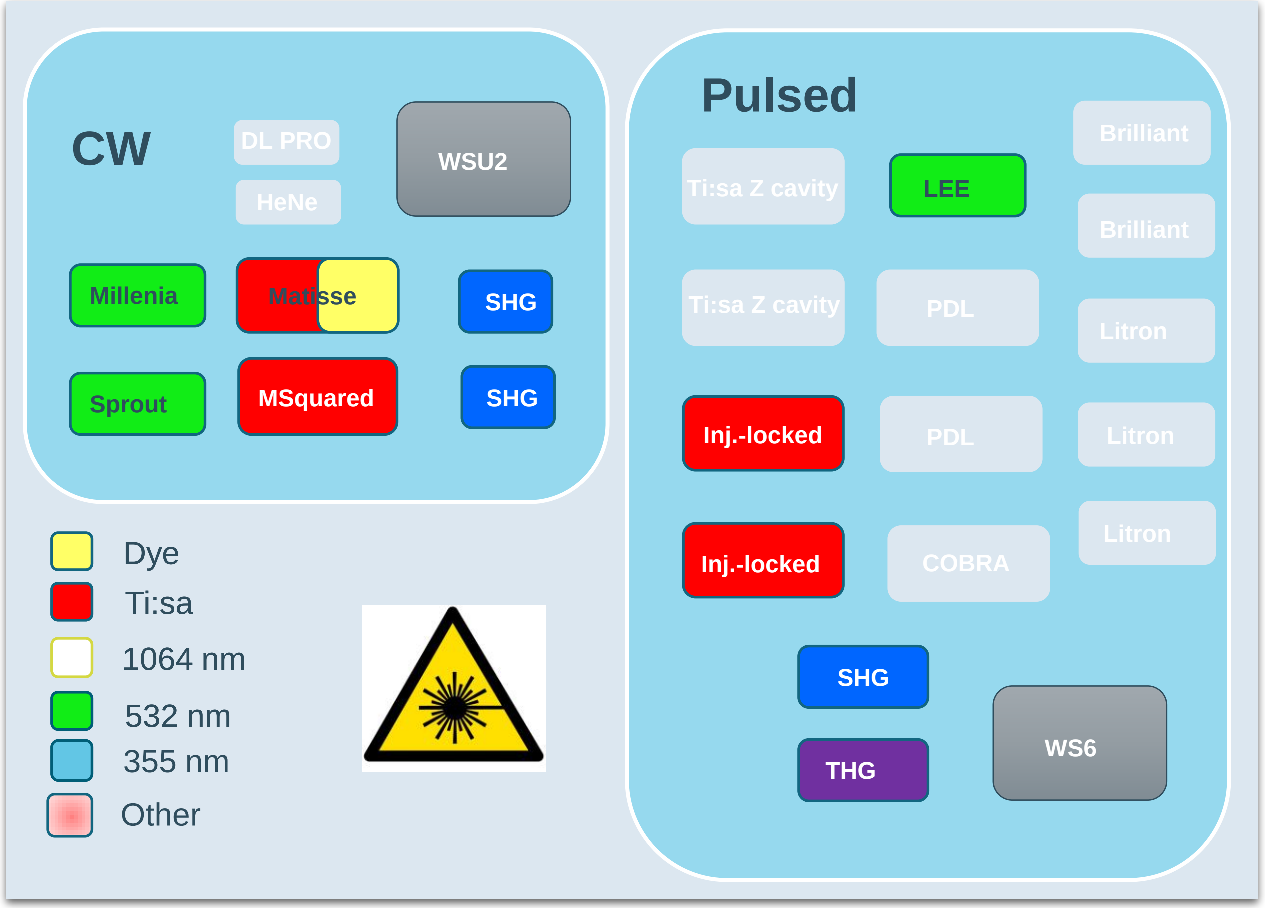


* Details of the laser lab can be fount the PhD thesis of dr. Shane G. Wilkins

CRIS: Laser lab

Narrow band laser in at CRIS

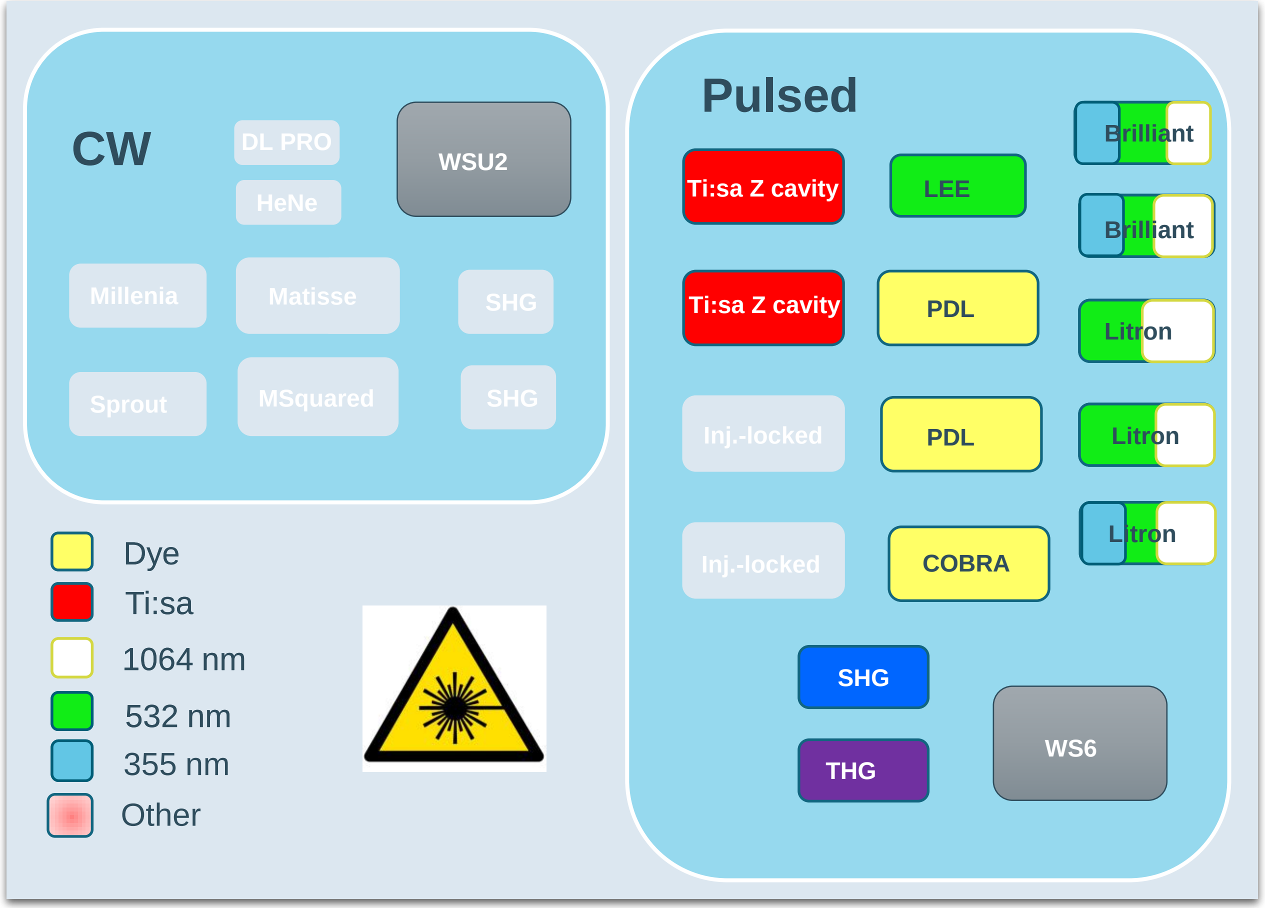
Laser	Type		Bandwidth	Power/ Energy	SHG	THG
MSquared	Ti:sa	CW	<1 MHz	5 W	Y	N
Matisse	Ti:sa	CW	< 1MHz	2.5 W	Y	N
	Dye	CW	<1 MHz	2.5 W	Y	N
Injection-locked*2	Ti:sa	Pulsed	~ 20 MHz	~ 300 uJ*1	Y	Y



*1Energy /pulse

*2Mikael Reponen Poster 97
V. Sonnenschein Poster 31

CRIS: Laser lab



Broadband lasers at CRIS

Laser	Type	Rep.rate	Bandwidth	Energy	SHG	THG
Z cavity	Ti:sa	1 kHz	6 GHz	260 uJ	Y	Y
PDL	Dye	100 Hz	~10 GHz	0.5-4 mJ	Y	Y
COBRA	Dye	100 Hz	1.8 GHz	6 mJ	Y	Y
Litron	Nd:YAG	100 Hz		80 mJ	Y	N
Litron	Nd:YAG	100 Hz		250 mJ	Y	Y
Brillinat	Nd:YAG	20 Hz		850 mJ	Y	Y

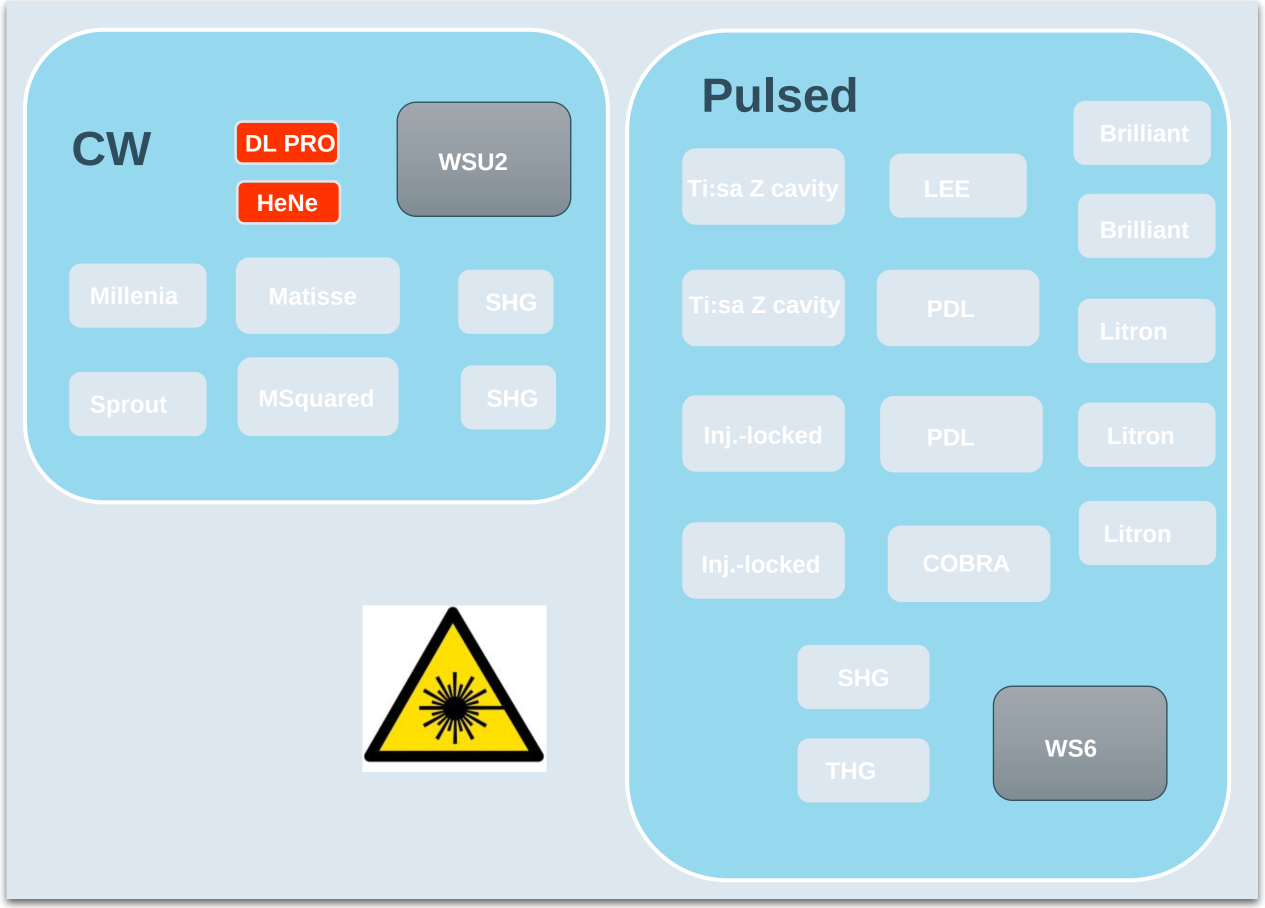
CRIS: Laser lab

Wavelength meters
WSU2: 2 MHz absolute accuracy
4 channel switchbox

WS6: absolute accuracy 600 MHz

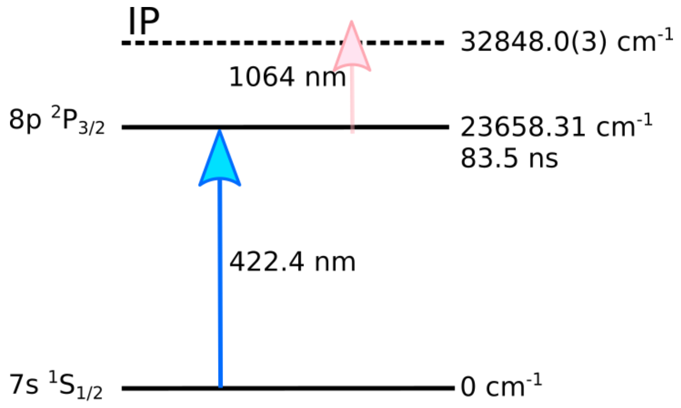
Both recorded in the CRIS DAQ, CRISTAL*

Frequency references
HeNe (temperature stabilized)
DL PRO 780 → Toptica diode laser locked to a hyperfine transition in Rb



*Developed by R.P. de Groote
Poster 122

First High resolution CRIS – $_{87}$Fr



High resolution resonance ionization spectroscopy

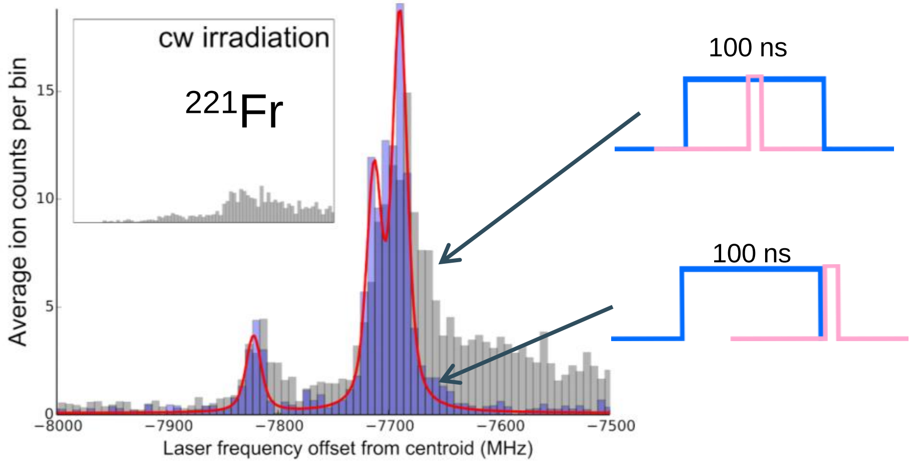
RIS:

- Chopped cw light (25 mW) + 1064 nm
  - Reduce optical pumping
  - 20(1) MHz FWHM
- Delayed ionization
  - AC Stark effect

Efficiency ~ 1:1000

Isobaric/nonresonant background suppression 1:10^5

Contamination @ mass 202	~ 10^5 ion/s
^{202}Fr yields	~100 ion/s



R.P. de Groote et al., Physical review letters 115 (13), 132501
R.P. de Groote et al., Physical Review A 95 (3), 032502

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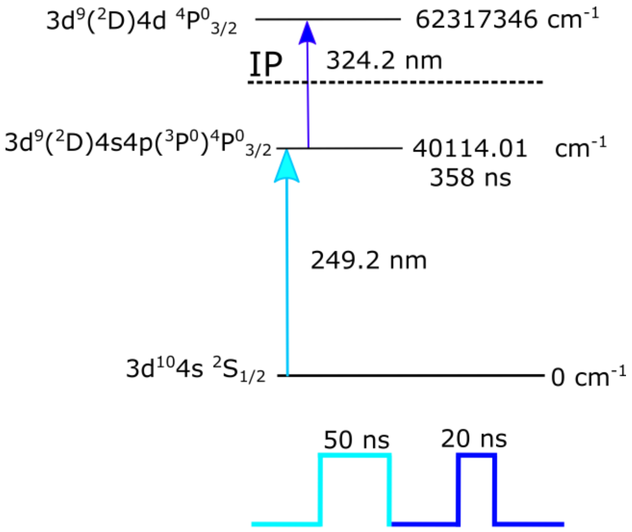
High resolution **and highest efficiency** – $_{29}$Cu

High resolution and efficiency

RIS:

- Injection-locked laser and THG (~ 1mW @ 1 kHz)
- 60 MHz FWHM
- Delayed ionization
- Autoionizing (AI) state

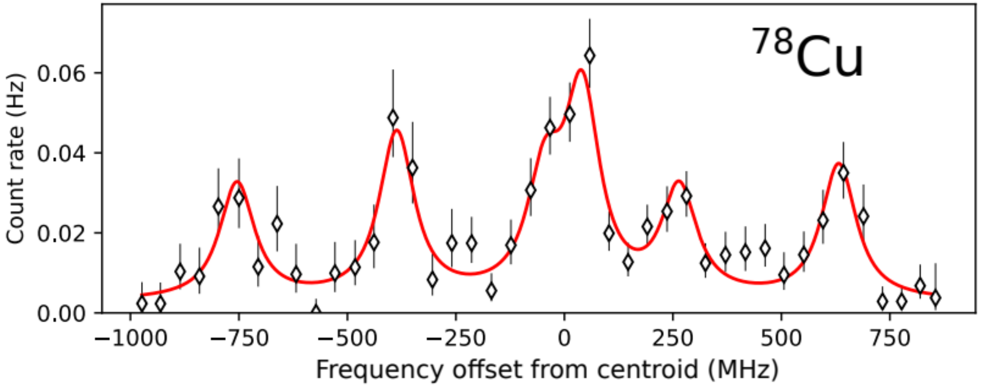


Efficiency 1:100

Background suppression 1:10^{7}

background of 1 count in every 400 s

- **Background free spectra**



Contamination @ mass 78	~10^{5} ion/s
^{78}Cu yields	~20 ion/s

R. P. de Groote et al., Phys. Rev. C **96**, 041302(R) – Published 4 October 2017
V. Sonnenschein. PhD thesis, University of Jyväskylä, 2015.

Mikael Reponen Poster 97
V. Sonnenschein Poster 31

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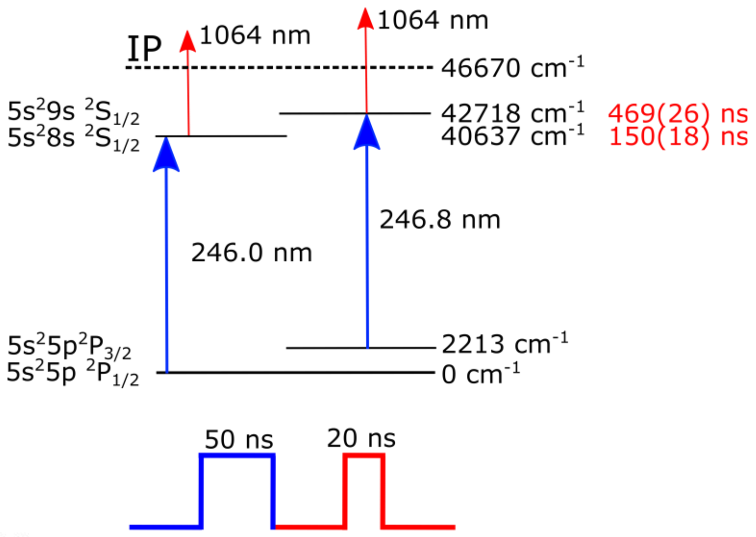
High resolution and high efficiency– $_{49}$In

RIS:

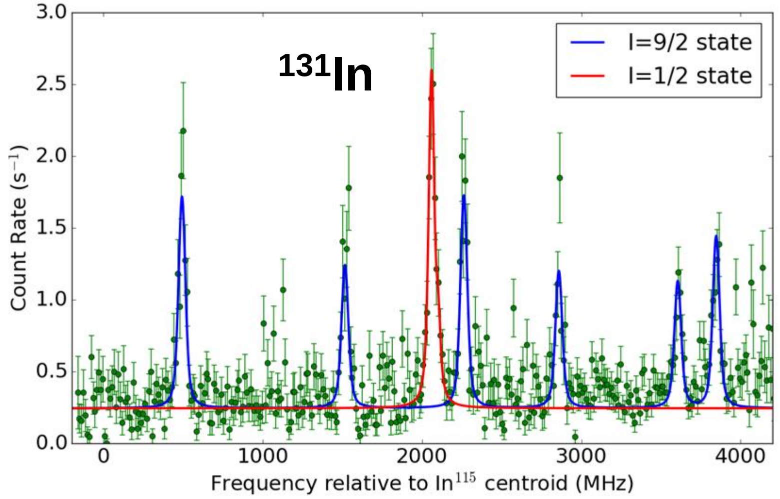
- Injection-locked laser and THG
    - 60 MHz FWHM (~0.5 mW @ 1kHz rate)
- Delayed ionization
- 1064 nm ionizing step



Efficiency 1:2000

Isobaric/nonresonant background suppression 1:10^7

- 10^{-10} mbar in the interaction region
- High non-resonant background due to
    - non resonant 1064 step
    - collisional background



Contamination @ mass 131	10^7
^{131}In yields	10^3 ion/s

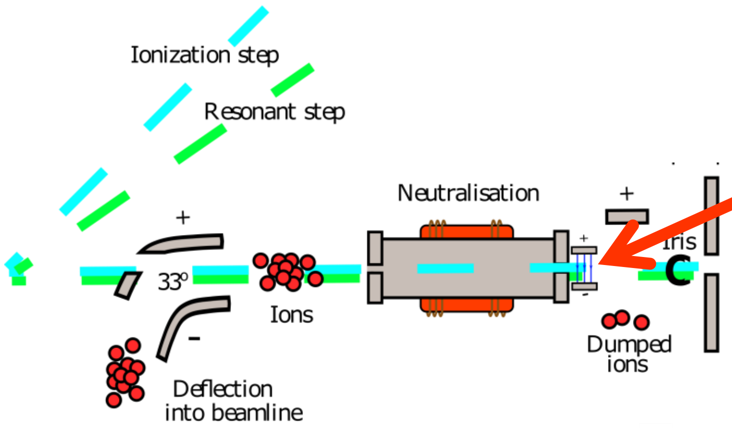
R. F. Garcia Ruiz, A.R. Vernon, C. L. Binnersley PRX accepted for publication

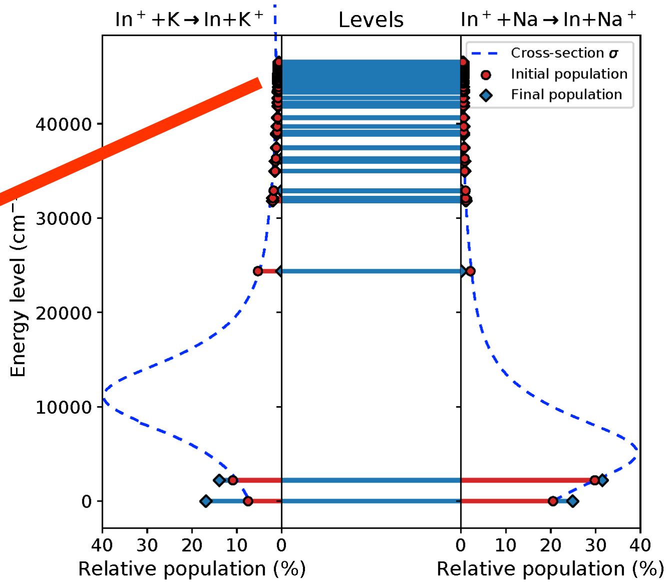
Lessons we learned:

Background suppression needs to be improved

- High power nonresonant ionization introduced background → Use AI when possible
- 1064 nm laser pulse fired before the RIS steps to clean the beam (30% times lower background in In)
- Field ionization of Rydberg atoms before the IR (3 times less background in In)
- Different mass regions have different contributions to background

  - Cross section for collisional ionization?
  - Laser ionization?
  - Role of molecular beams?





High sensitivity –$_{19}$K

RIS:

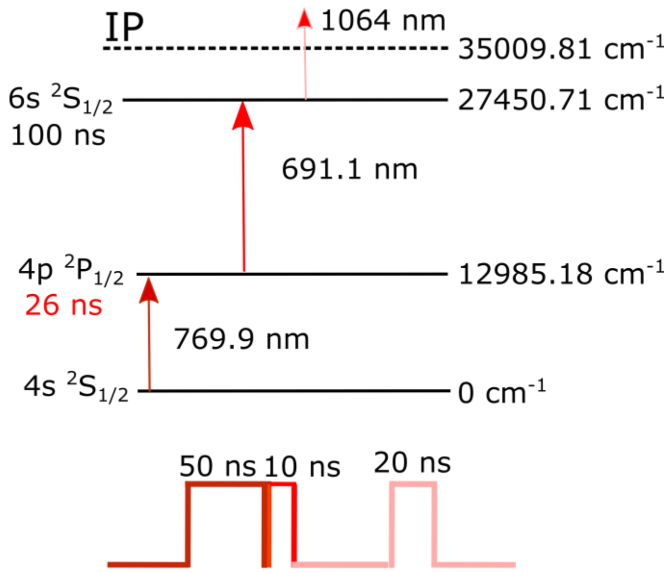
- ➢ Chopped cw light + Dye + 1064 nm
- ➢ Delayed ionization – efficiency loss

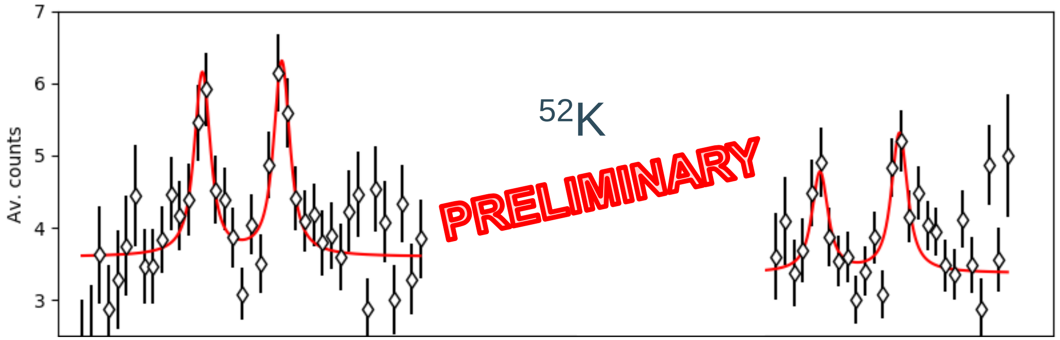
Efficiency 1:1500

Isobaric/nonresonant background suppression 1:10^7

- ➢ Rydberg atoms removed → 8 times lower background
- ➢ 1064 nm related background → 2 times lower background
- ➢ Still, high collisional background rate (stable Cr)
- ➢ **Beta detection**

Contamination @ mass 52	~ 10^7 ion/s
^{52}K yields	~300 ion/s

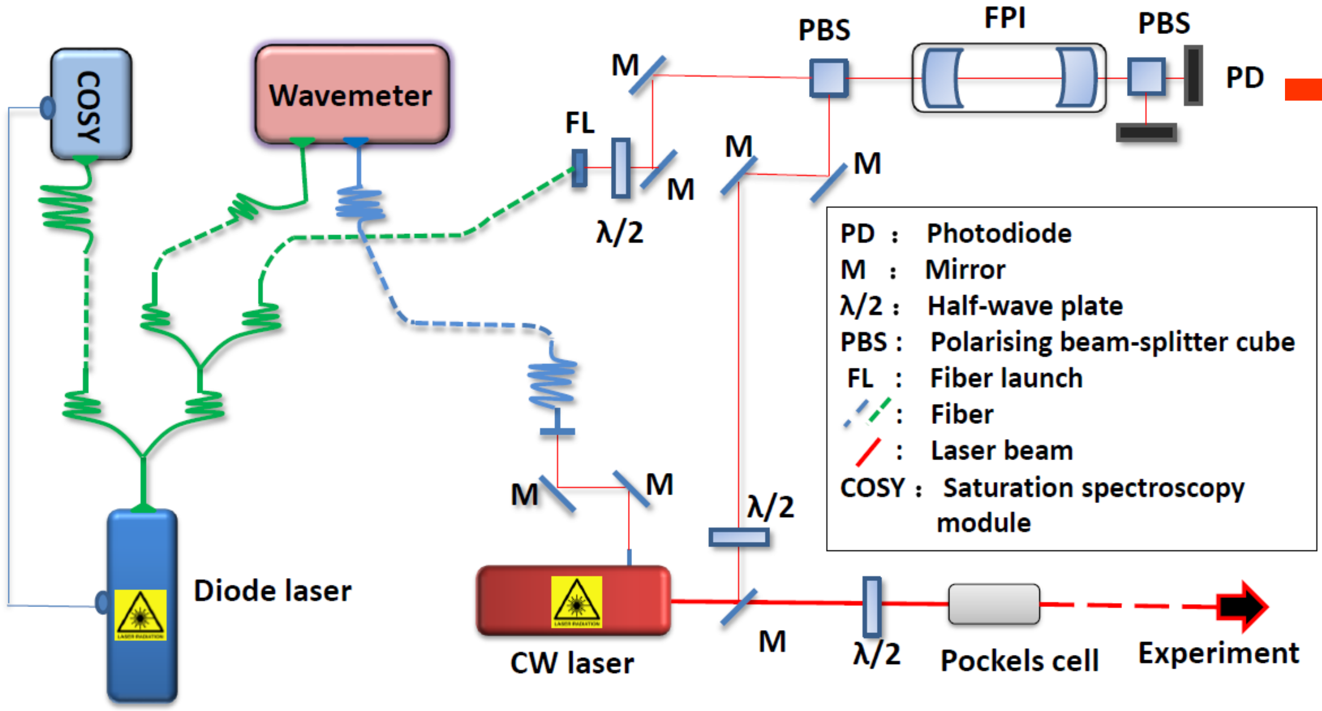


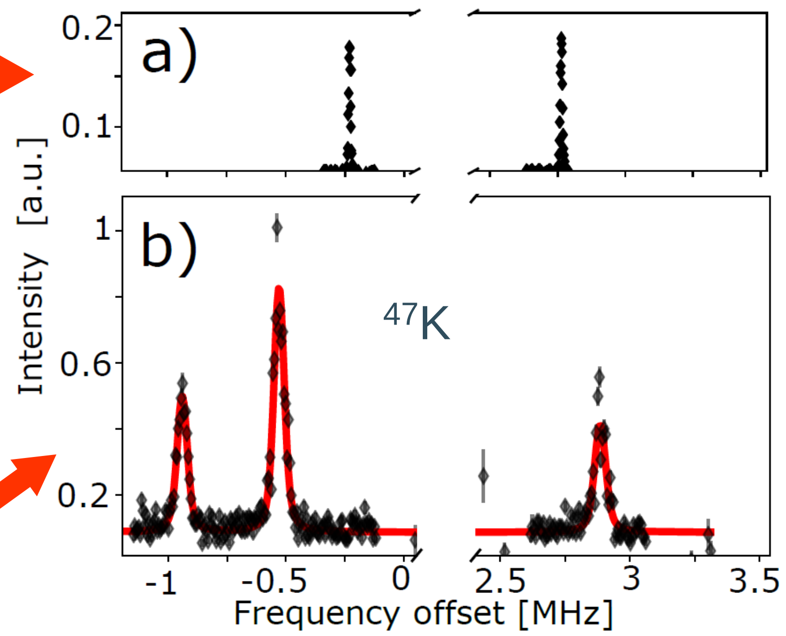


Hyperfine structure of ^{52}K obtained by detecting the beta decay of resonantly ionized ^{52}K isotopes

*Wasn't the first time decay spectroscopy was used at CRIS (Phys. Rev. X **4**, 011055 – Published 28 March 2014)

Precision and accuracy

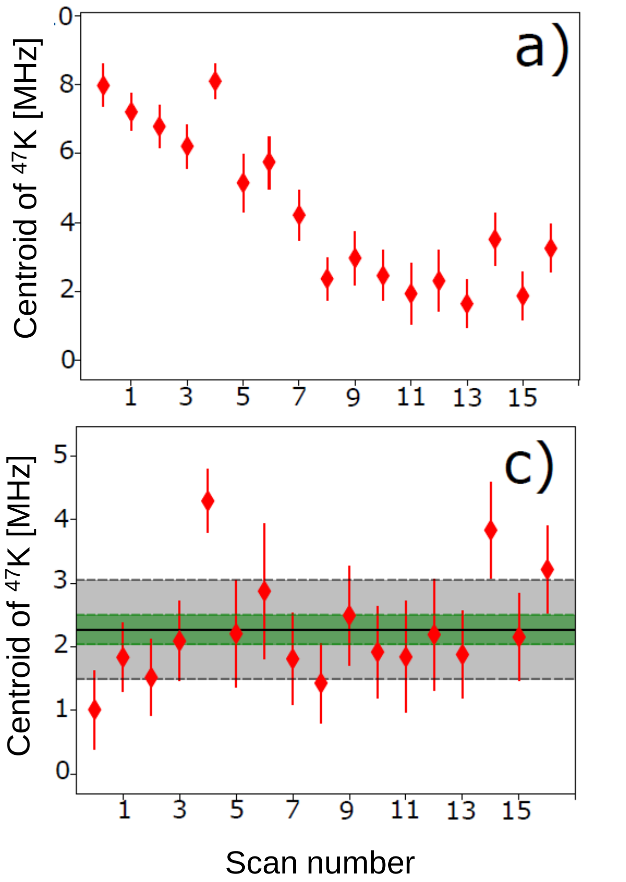




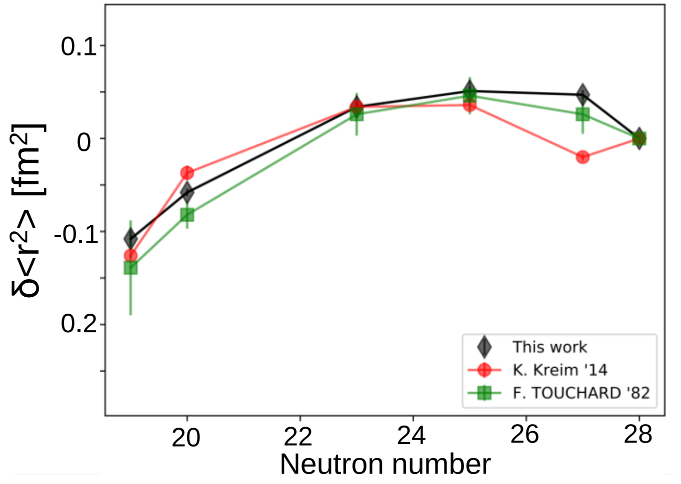
a) FPI transmission peaks detected using photodiodes during each ^{47}K scan; **b)** Hyperfine structure of ^{47}K

Precision and accuracy

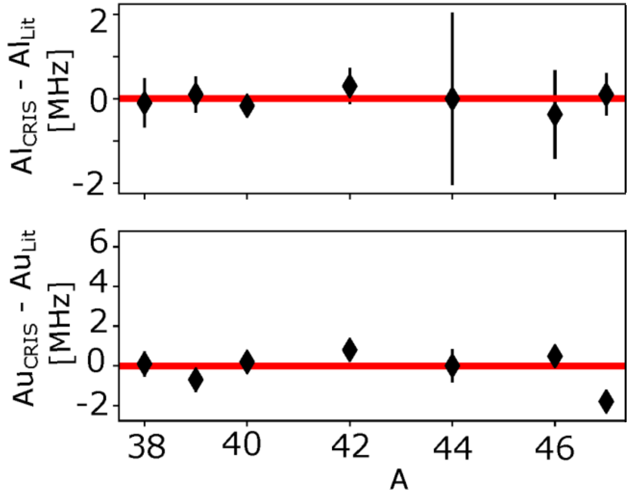
- Precision of the wavelength measurement
  - σ = 0.77 MHz
- Consistency of hyperfine parameters
  - In good agreement with literature



a) Uncorrected raw data showing the drift of the centroid of ^{47}K during the experiment; **b)** Centroid of ^{47}K after corrections using the stable frequency reference



Comparison of the changes in the ms charge radii obtained at CRIS to literature

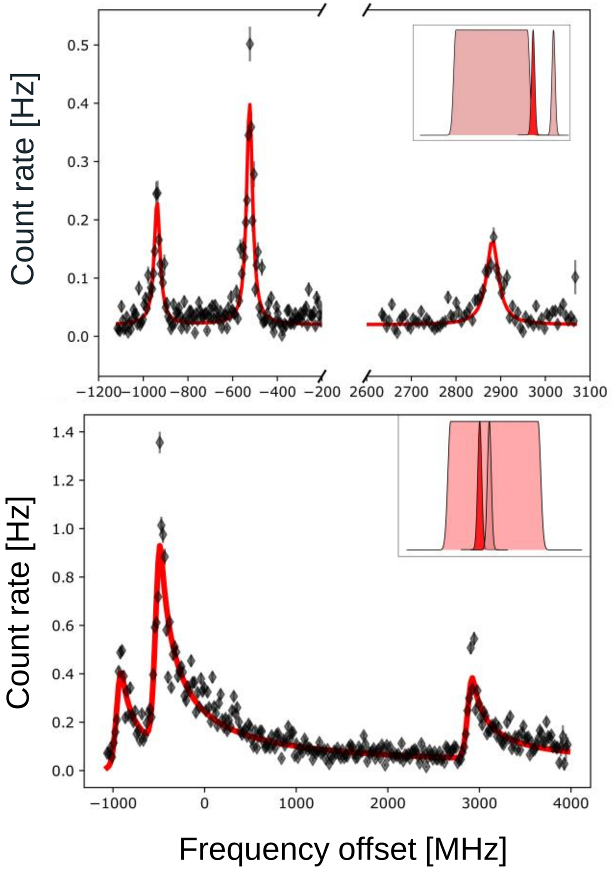


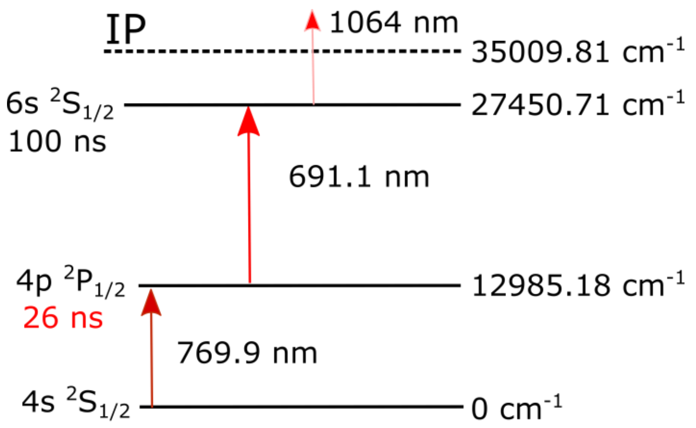
Comparison of the hyperfine parameters obtained at CRIS to literature

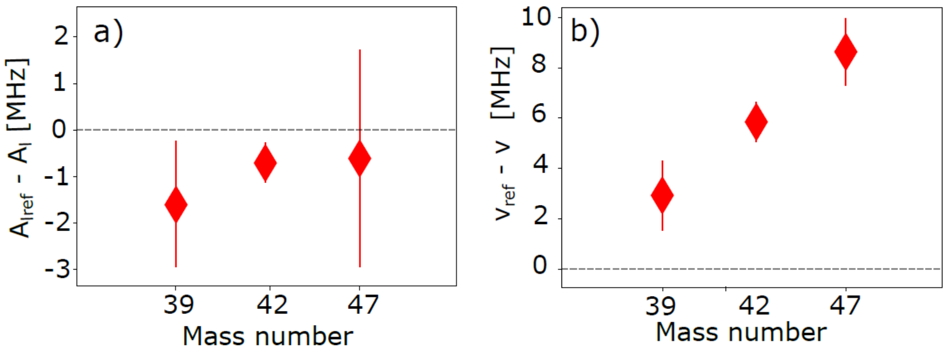
References:
Kreim et al, PLB 731 97 (2014)
F. Touchard et al., Physics Letters B 108, 169 (1982).

Precision and accuracy

- AC Stark shift
  - Asymmetric peaks
  - Higher efficiency
- Consistency of hyperfine parameters
- Centroid shifts
  - Different for different isotopes
  - Increase with laser leaser power







A. Koszorus, X. F. Yang et. al., in preparation

Summary and Outlook

- High resolution and high efficiency achieved at CRIS → Weak transition ($A \sim 10^6$ 1/s) and delayed ionization
- Background suppression → ultra high vacuum 10^{-10}

  → ionization from Rydberg states after the CEC

  → 1064 nm for cleaning

  Understanding source of background rates is the key to sensitive measurements

- Laser atom interaction investigated (better understood) → delayed ionization solves the problem of line shape distortion

  → frequency shifts have to be investigated in light systems

- Precision less than 1 MHz

- Isobaric/nonresonant background suppression still the bottleneck:
  - AI
  - Field ionization
  - Decay spectroscopy
  - Energy filter?
  - Electron ion coincidence?

Thank you for your attention!

The University of Manchester
Institut de Physique Nucléaire d'Orsay
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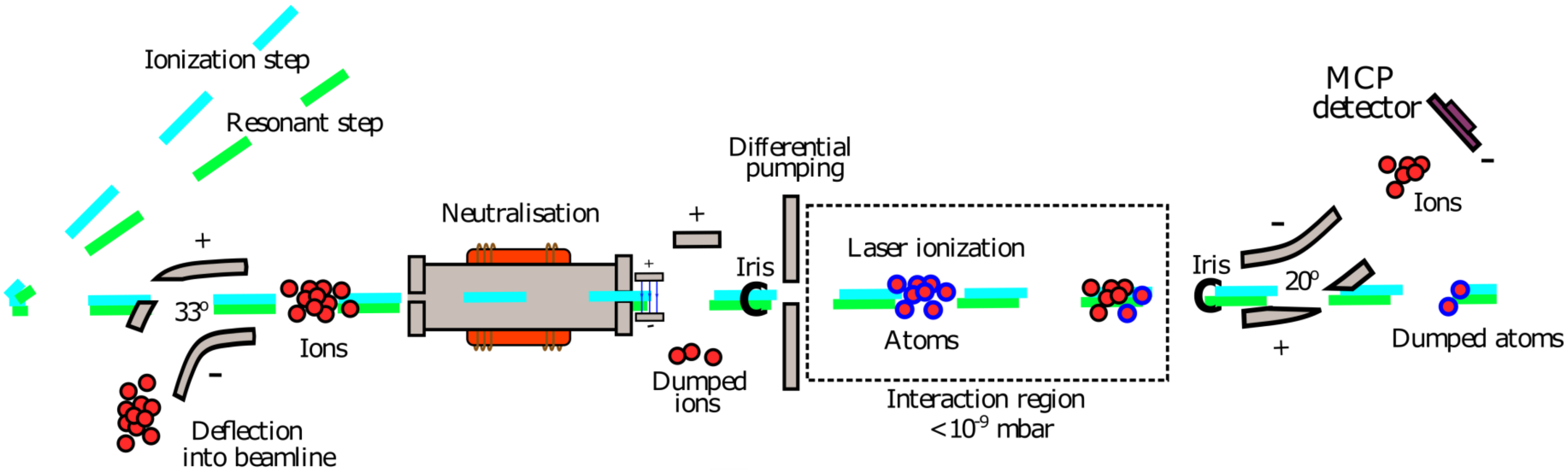
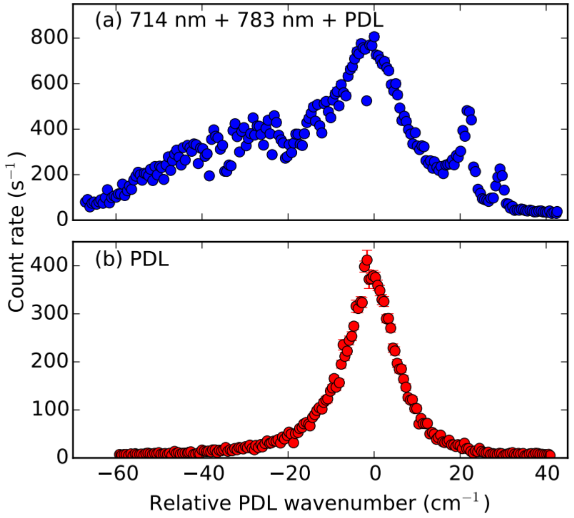
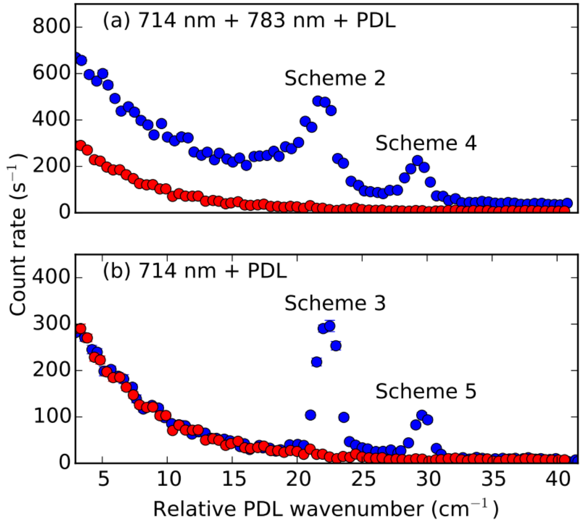

Ionization step
Resonant step
+
33°
-
Ions
Deflection
into beamline
Neutralisation
+
Dumped
ions
Differential
pumping
Iris
Laser ionization
Atoms
Interaction region
<10-9 mbar
Iris
-
20°
+
MCP
detector
-
Ions
Dumped atoms

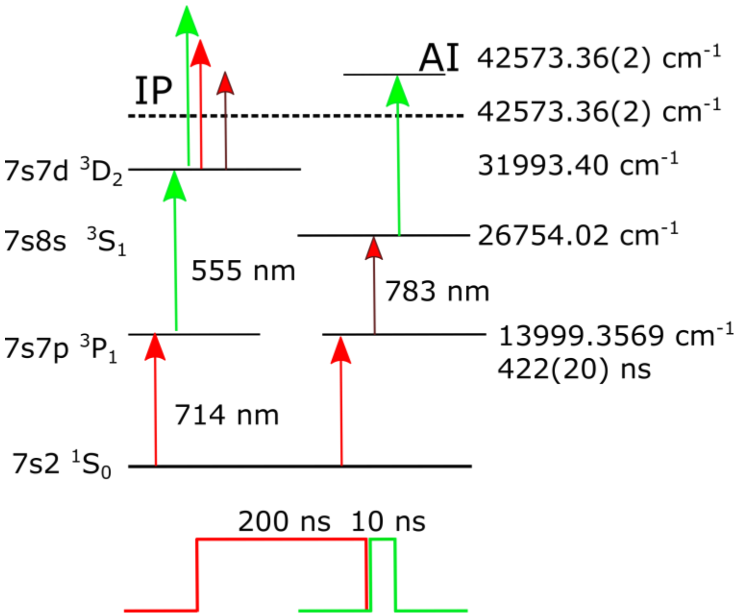
Selected RIS: High resolution – $_{87}$Fr and $_{88}$Ra

Ra experiment 2016

- 25(2) MHz FWHM
- Delayed ionization
- RIS full of surprises – online developments
- Chopped and cw light both worked
- Importance of RIS developments







No.	Scheme [nm]	PDL [cm-1]
1	714+783+555	17971
2	714+783+555	17994
3	**714+555+555**	**17994**
4	714+783+555	18001
5	714+555+555	18001

S.G. Wilkins PhD thesis
K. M. Lynch et al., PRC 2017

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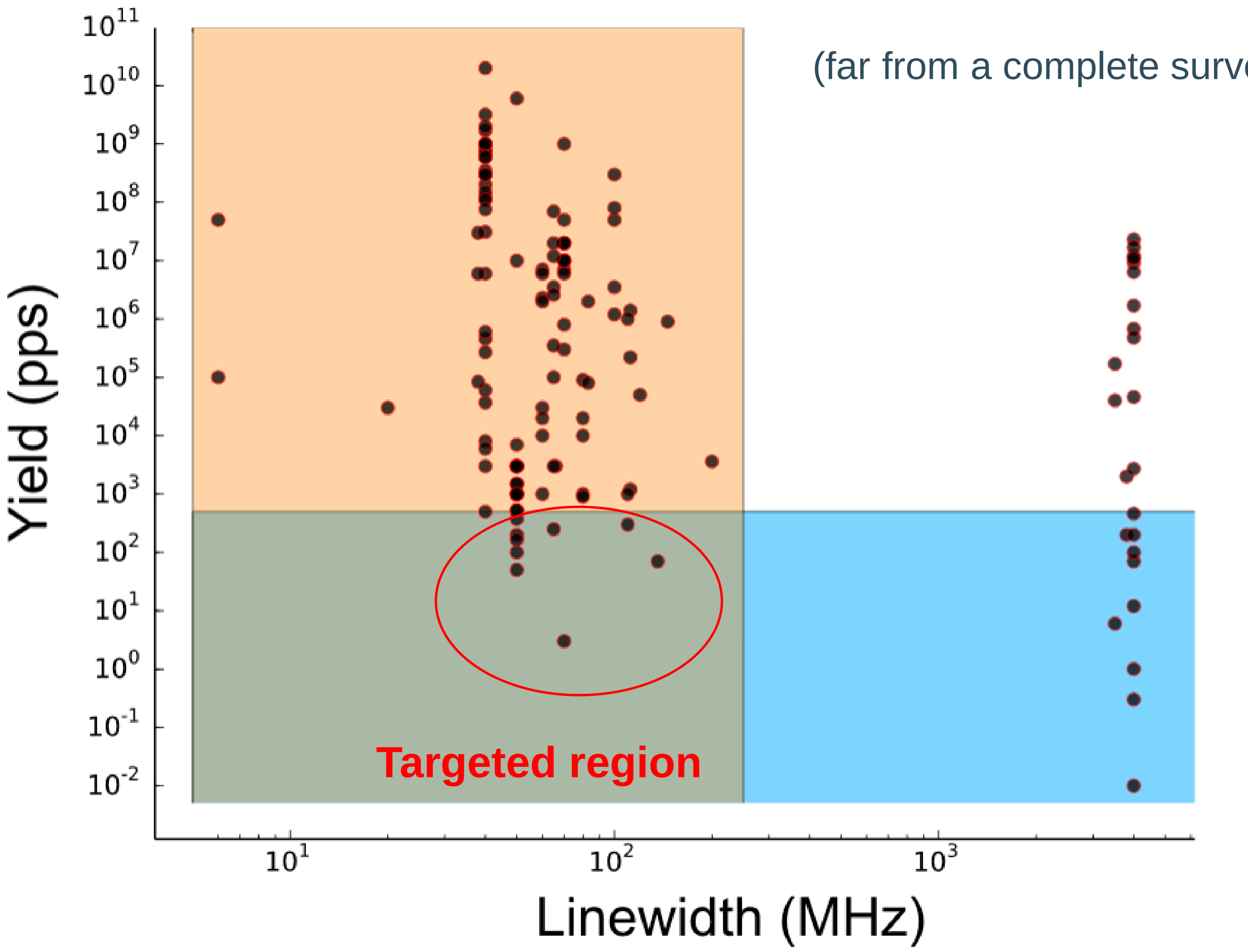
Motivation: Need for new techniques

- High efficiency: in-source
- High resolution : collinear las
- High sensitivity

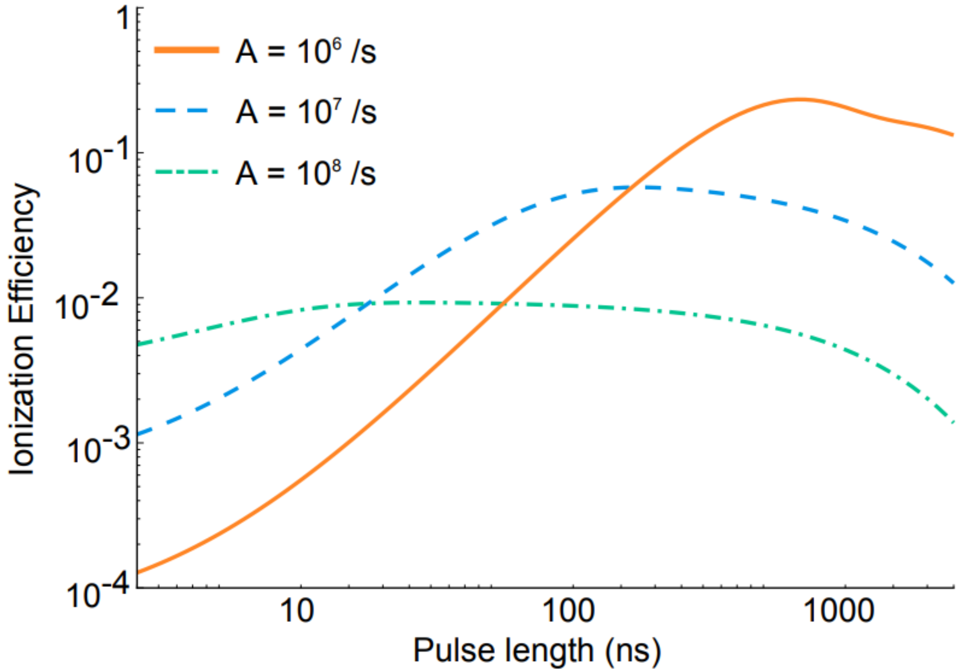


High resolution **and high efficiency**

- Chopped cw light for weak transitions
- Pulsed light for strong transitions

Weakness:

- Spectral range of cw light
  - Production of UV light
  - Photons density

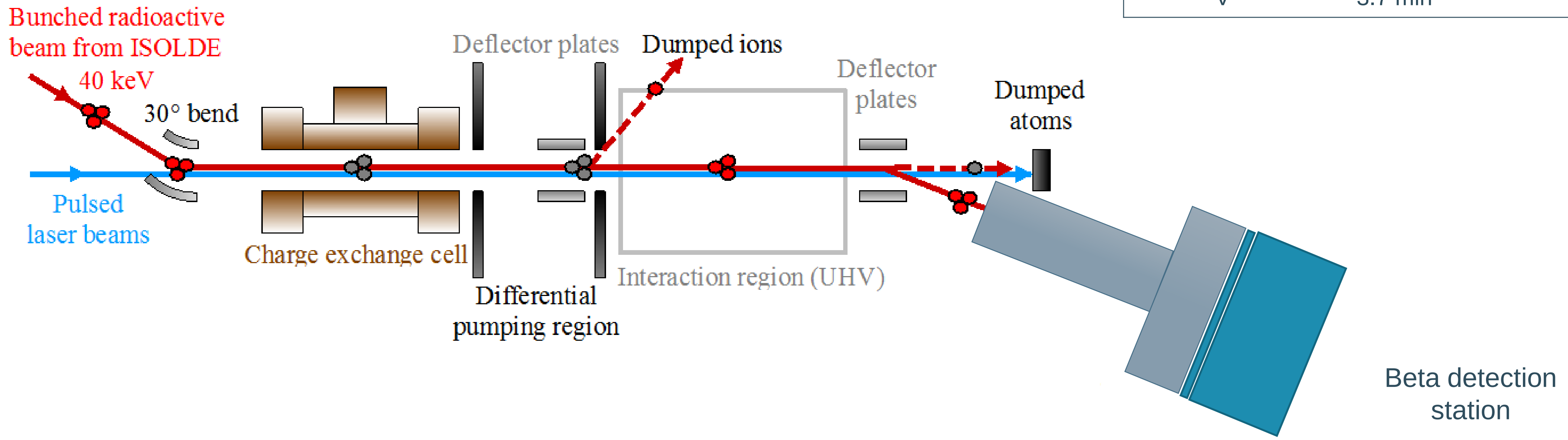


R.P. de Groote et al., PRL 2015
R.P. de Groote et al., PRA 2017

Technique

Collinear Resonance Ionization Spectroscopy

Isotope	$T_{1/2}$	Q_β [MeV]
^{52}K	110 ms	17.130
^{52}Ca	4.6 s	6.1
^{52}Sc	200 ms	9
^{52}Ti	1.7 min	1.9
^{52}V	3.7 min	3.9



As a function of the laser frequency we measure beta particles emitted by ^{52}K and its daughters