# LIST, Lasers and Lanthanides

## LISA Conference 2024, CERN

Julius Wessolek

CERN

MANCHESTER 1824 The University of Manchester

LISA LASER IONISATION AND SPECTROSCOPY OF ACTINIDES

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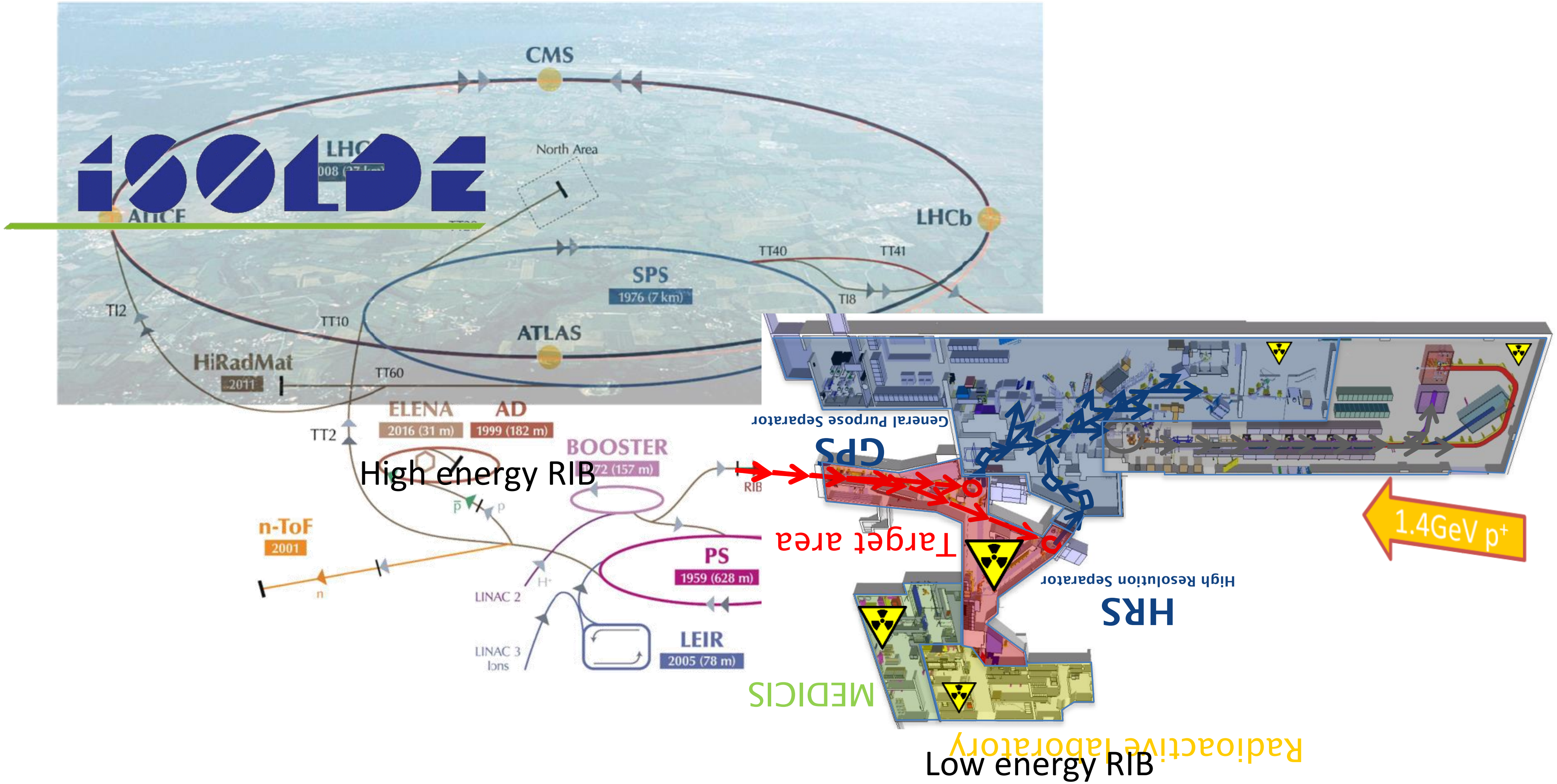
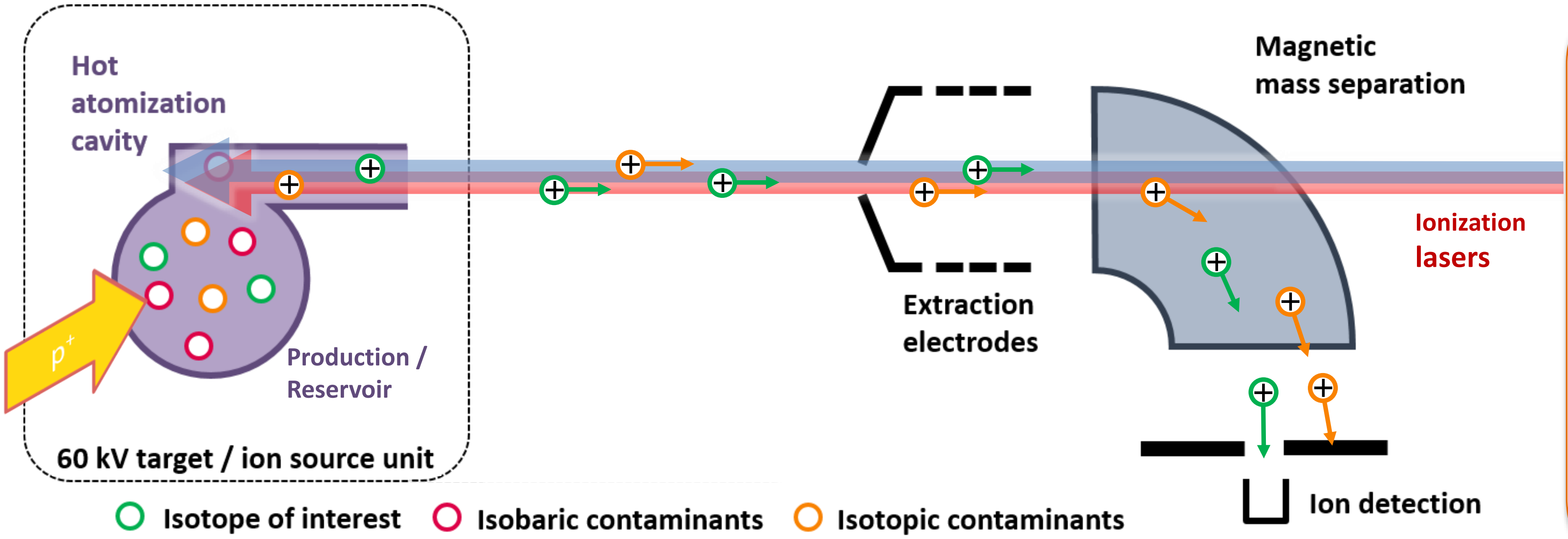
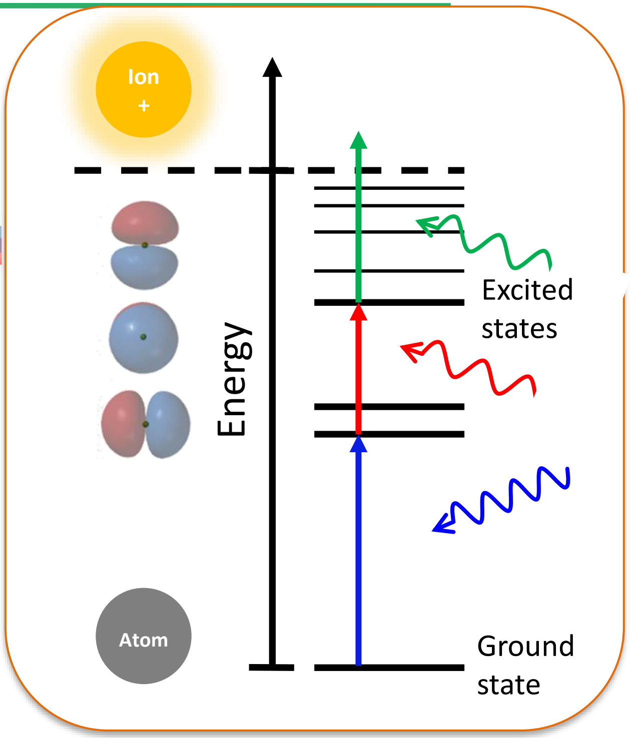
# ISOLDE at CERN



# ISOLDE's resonance ionization laser ion source RILIS

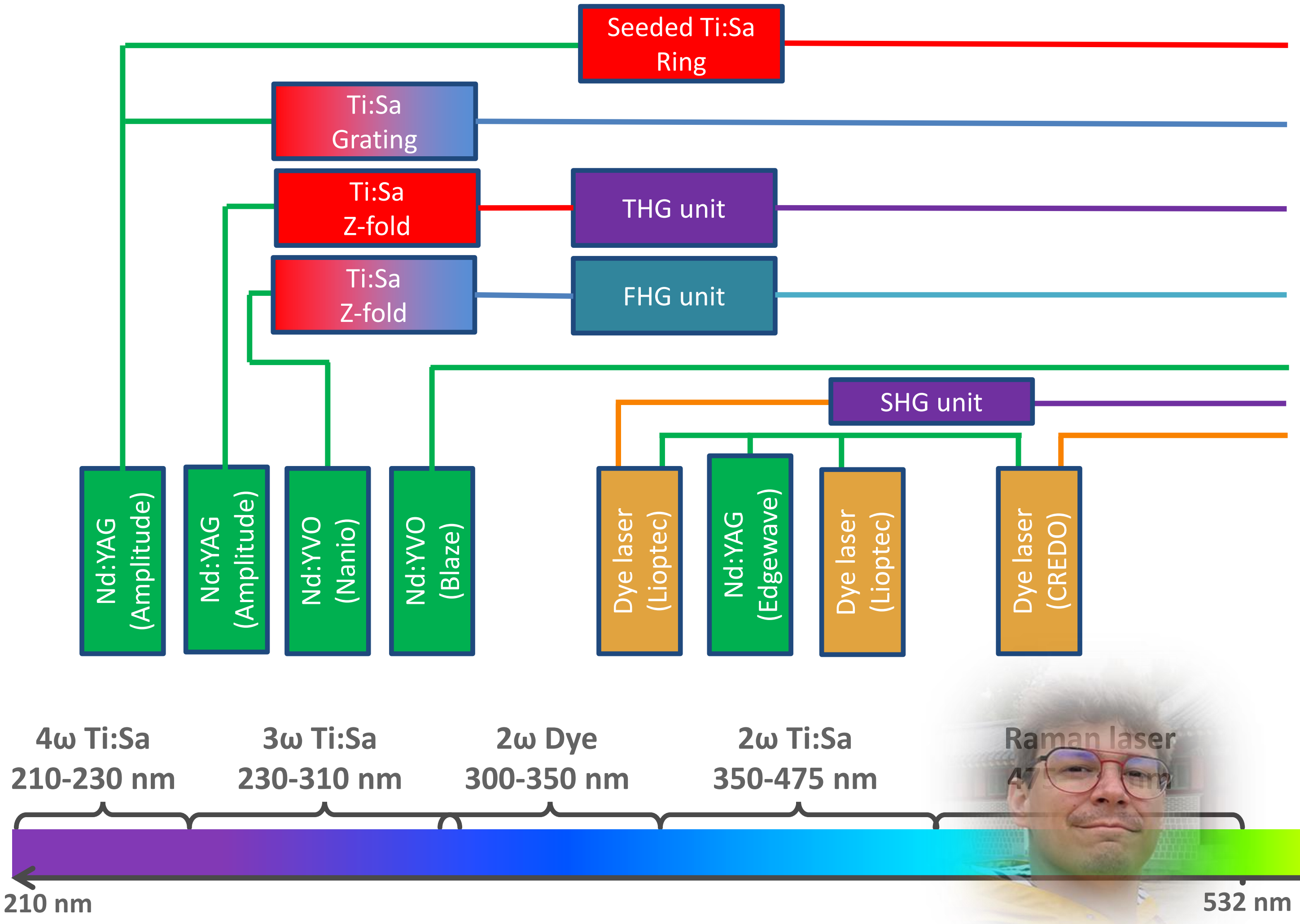


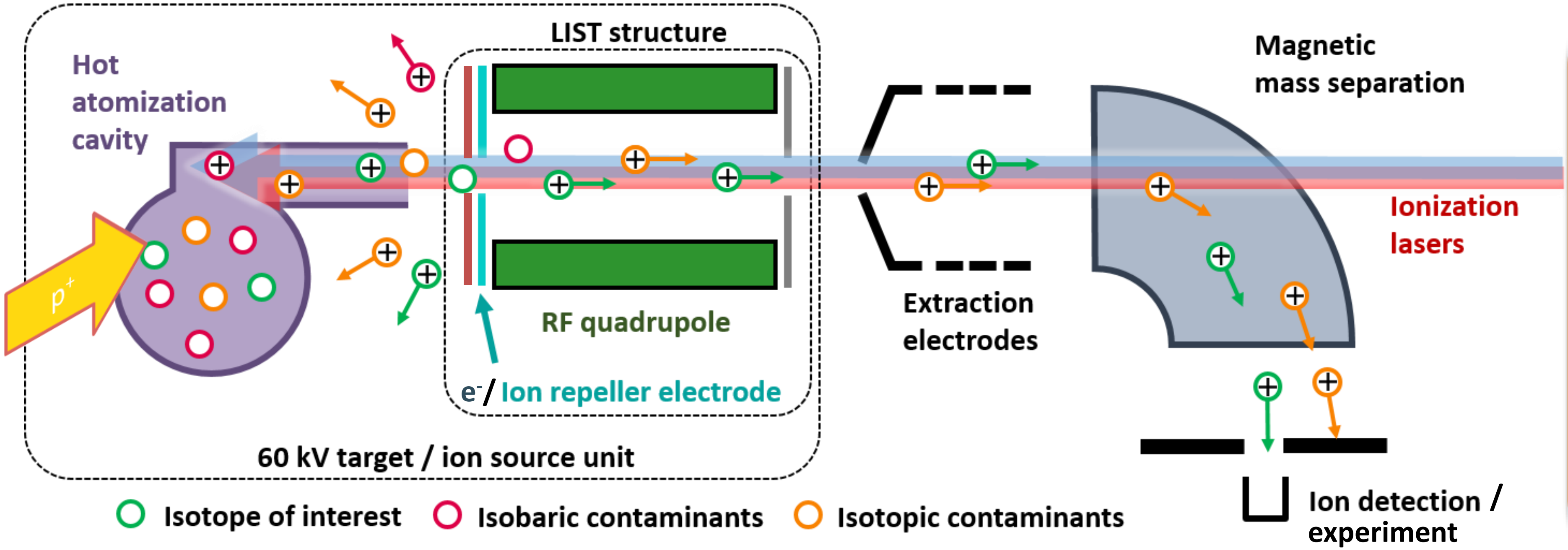

- Effusion of reaction products provided as **hot atomic vapor** ( > 2000°C )
- Highly efficient laser ionization of **element of choice**
- Extraction and mass separation as **ion beam**

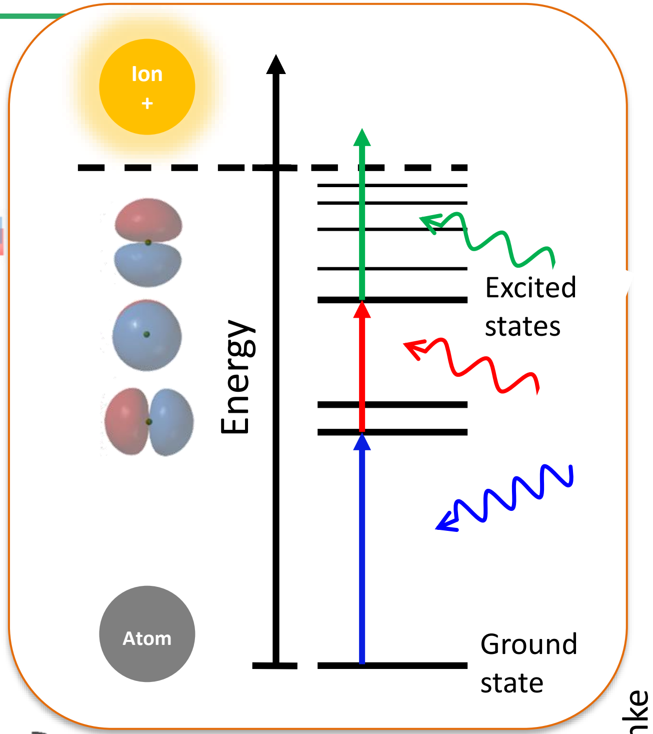
Slide courtesy of R. Heinke

# ISOLDE's resonance ionization laser ion source RILIS

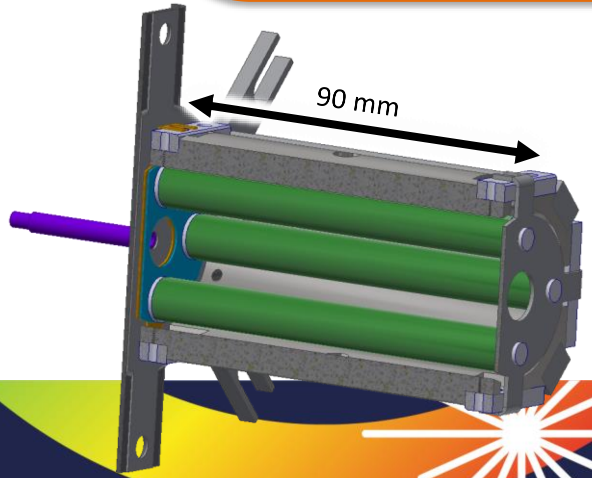



# The Laser Ion Source and Trap LIST



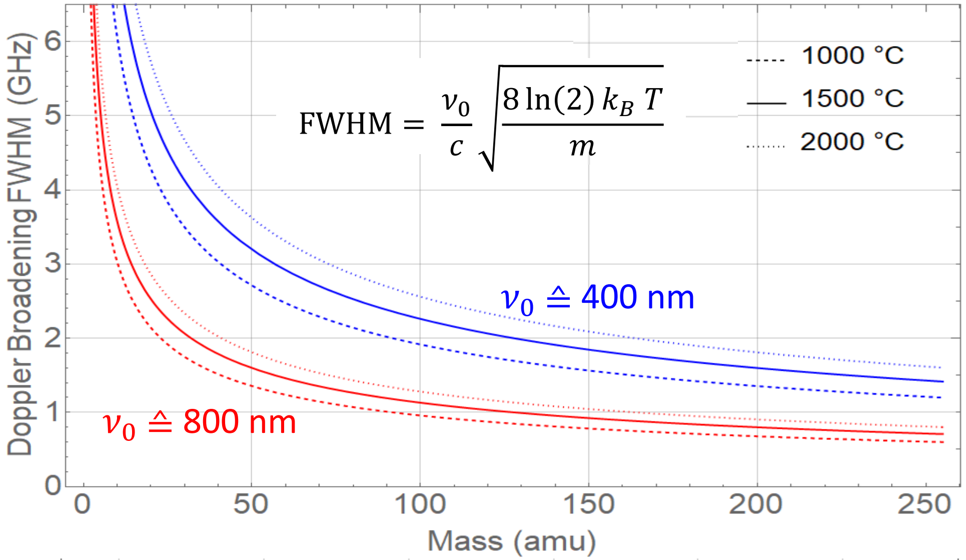



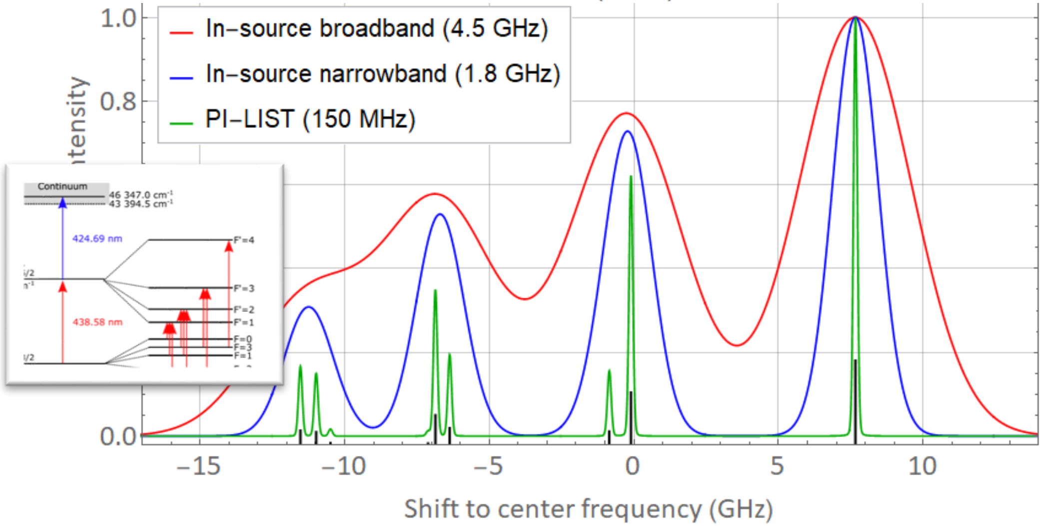

- **Spatial separation:** hot cavity ↔ laser ionization volume
- **Suppression** of surface ionized species
- **Pure laser ionization** inside **RF quadrupole** structure
- Factor up to $10^6$ in suppression ↔ Factor 20-100 reduction in beam intensity
- Versatility: Mimic standard RILIS by extracting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

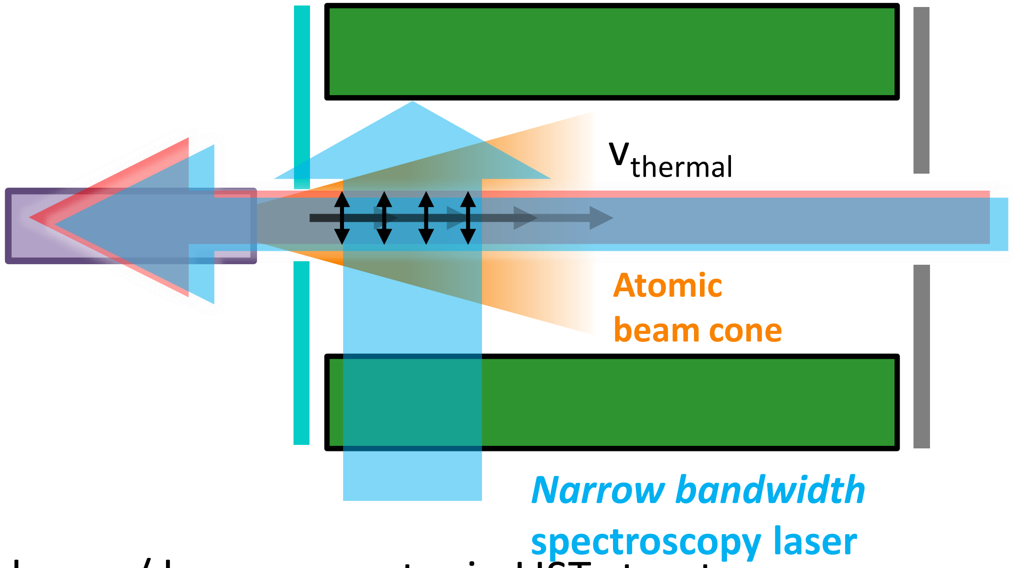



Slide courtesy of R. Heinke

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




Crossed atom beam / laser geometry in LIST structure:

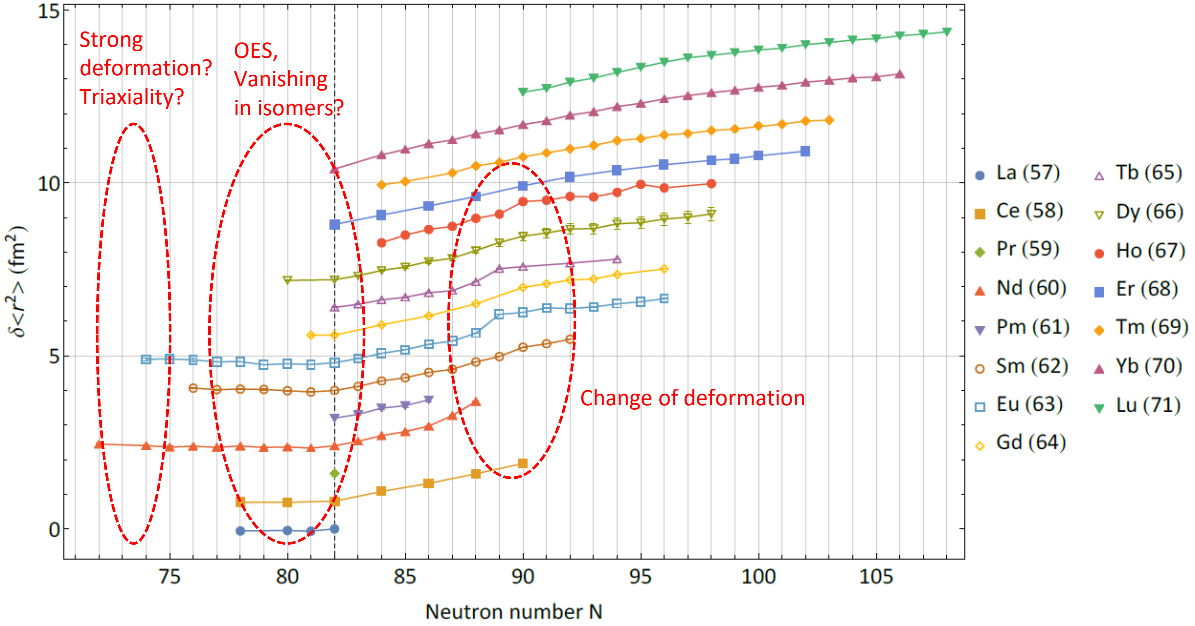
The **P**erpendicularly **I**lluminated **PI-LIST**

- Selection of **reduced Doppler ensemble**
- Suitable **narrow-band laser**
  - Resolution improvement by >1 order of magnitude
- Successfully used in the actinide region: Ac

Slide courtesy of R. Heinke

# Lanthanides at ISOLDE – a prime case for (PI-)LIST

- Lanthanides are surface ionizable, so isobaric contamination makes LIST suppression necessary
- High level density caused by open f-shell gives disadvantage for charge exchange
- Successful off-line PI-LIST spectroscopy in Mainz and many laser schemes known




**Yield measurements for lanthanide elements with Ta-foil target and a LIST ion source**

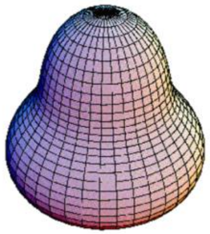
September 27, 2022


Katerina Chrysalidis[1], Reinhard Heinke[1], Mia Au[1,2], Cyril Bernerd[1,3], Asar A H Jaradat[1,4], Ulli Köster[5], Ralitsa Mancheva[1,3], Bruce Marsh[1], Edgar Reis[1], Maximilian Schütt[1], Sebastian Rothe[1], Simon Stegemann[1], Julius Wessolek[1,4]


https://cds.cern.ch/record/2834598?ln=de

- ✓ Dy, Pm, Tm, Er, Yb, Gd yields measured in 2023
- ➢ Lu & Ho yield measurements later this month
- ➢ COLLAPS laser spectroscopy of $Tm^{+}$ later this month

- Nuclear shape evolution at the N=82 shell and Z=64 subshell closure
- Properties of p+ emitters in n-deficient Tm, Lu and Ho
- Some evidence for octupole deformation in Pm and Eu
- HIE-ISOLDE experiments are interested in shell structure studies



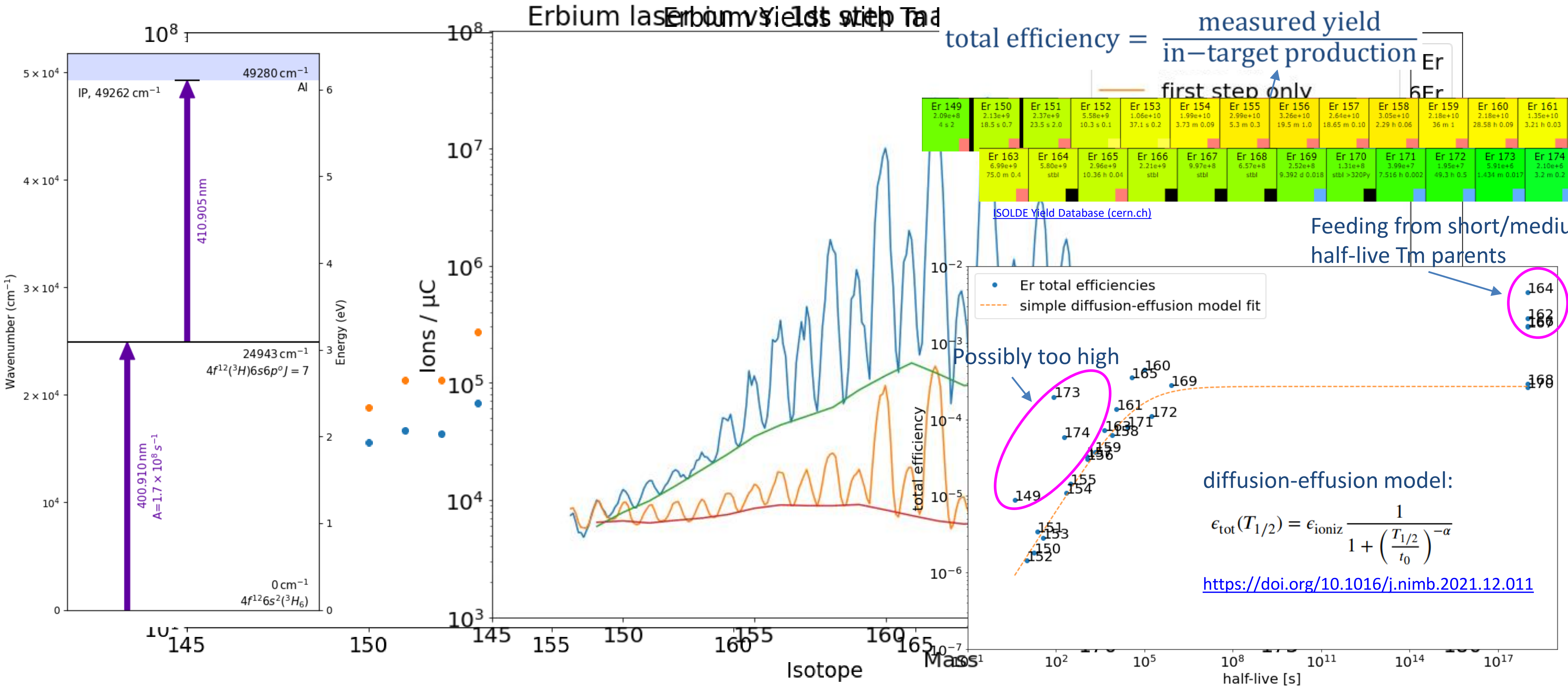
**In-source laser spectroscopy of neutron-deficient lutetium and holmium isotopes, towards the proton emitters**

April 9, 2024


K. M. Lynch[1], T. E. Cocolios[2], B. Cheal[3] K. Chrysalidis[4], A. de Roubin[5], S. Geldhof[6], R. Heinke[4], A. A. H. Jaradat[1,4], J. Reilly[1,4], M. Reponen[7], L. V. Rodríguez[8,9], J. Wessolek[1,4]


INTC-I-278.pdf (cern.ch)

# Yields from a mass scan: Er as example




$$\text{total efficiency} = \frac{\text{measured yield}}{\text{in-target production}}$$

| Er 149 | Er 150 | Er 151 | Er 152 | Er 153 | Er 154 | Er 155 | Er 156 | Er 157 | Er 158 | Er 159 | Er 160 | Er 161 | Er 162 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2.09e+8 | 2.13e+9 | 2.37e+9 | 5.58e+9 | 1.06e+10 | 1.99e+10 | 2.99e+10 | 3.26e+10 | 2.64e+10 | 3.05e+10 | 2.18e+10 | 2.18e+10 | 1.35e+10 | 1.24e+10 |
| 4 s 2 | 18.5 s 0.7 | 23.5 s 2.0 | 10.3 s 0.1 | 37.1 s 0.2 | 3.73 m 0.09 | 5.3 m 0.3 | 19.5 m 1.0 | 18.65 m 0.10 | 2.29 h 0.06 | 36 m 1 | 28.58 h 0.09 | 3.21 h 0.03 | stbl >140Ty |

| Er 163 | Er 164 | Er 165 | Er 166 | Er 167 | Er 168 | Er 169 | Er 170 | Er 171 | Er 172 | Er 173 | Er 174 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 6.99e+9 | 5.80e+9 | 2.96e+9 | 2.21e+9 | 9.97e+8 | 6.57e+8 | 2.52e+8 | 1.31e+8 | 3.99e+7 | 1.95e+7 | 5.91e+6 | 2.10e+6 |
| 75.0 m 0.4 | stbl | 10.36 h 0.04 | stbl | stbl | stbl | 9.392 d 0.018 | stbl >320Py | 7.516 h 0.002 | 49.3 h 0.5 | 1.434 m 0.017 | 3.2 m 0.2 |

ISOLDE Yield Database (cern.ch)

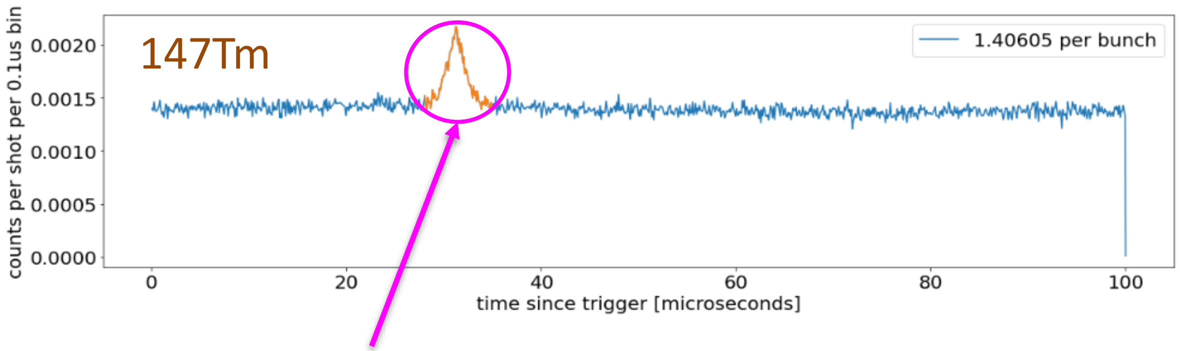
diffusion-effusion model:

$$\epsilon_{tot}(T_{1/2}) = \epsilon_{ioniz} \frac{1}{1 + \left(\frac{T_{1/2}}{t_0}\right)^{-\alpha}}$$

https://doi.org/10.1016/j.nimb.2021.12.011

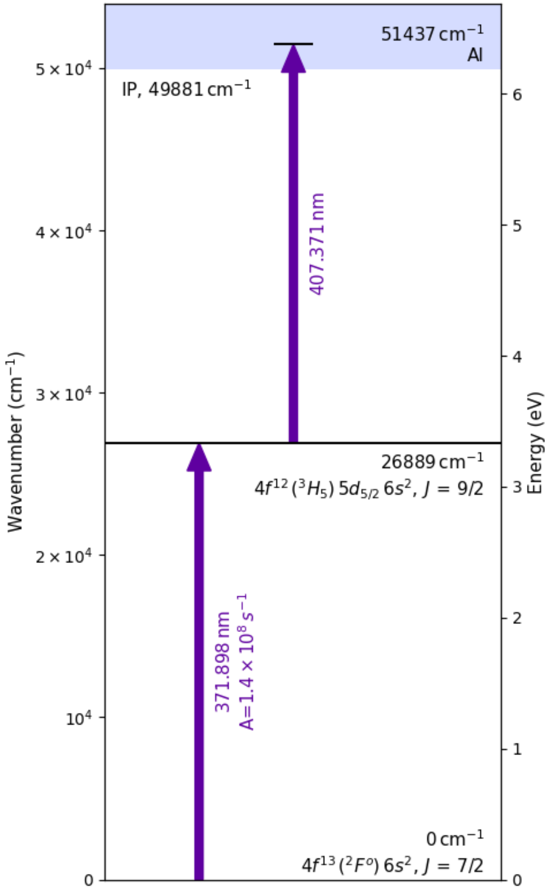
# Tm as a cautionary tale

Yields from time structure on MagneToF detector:

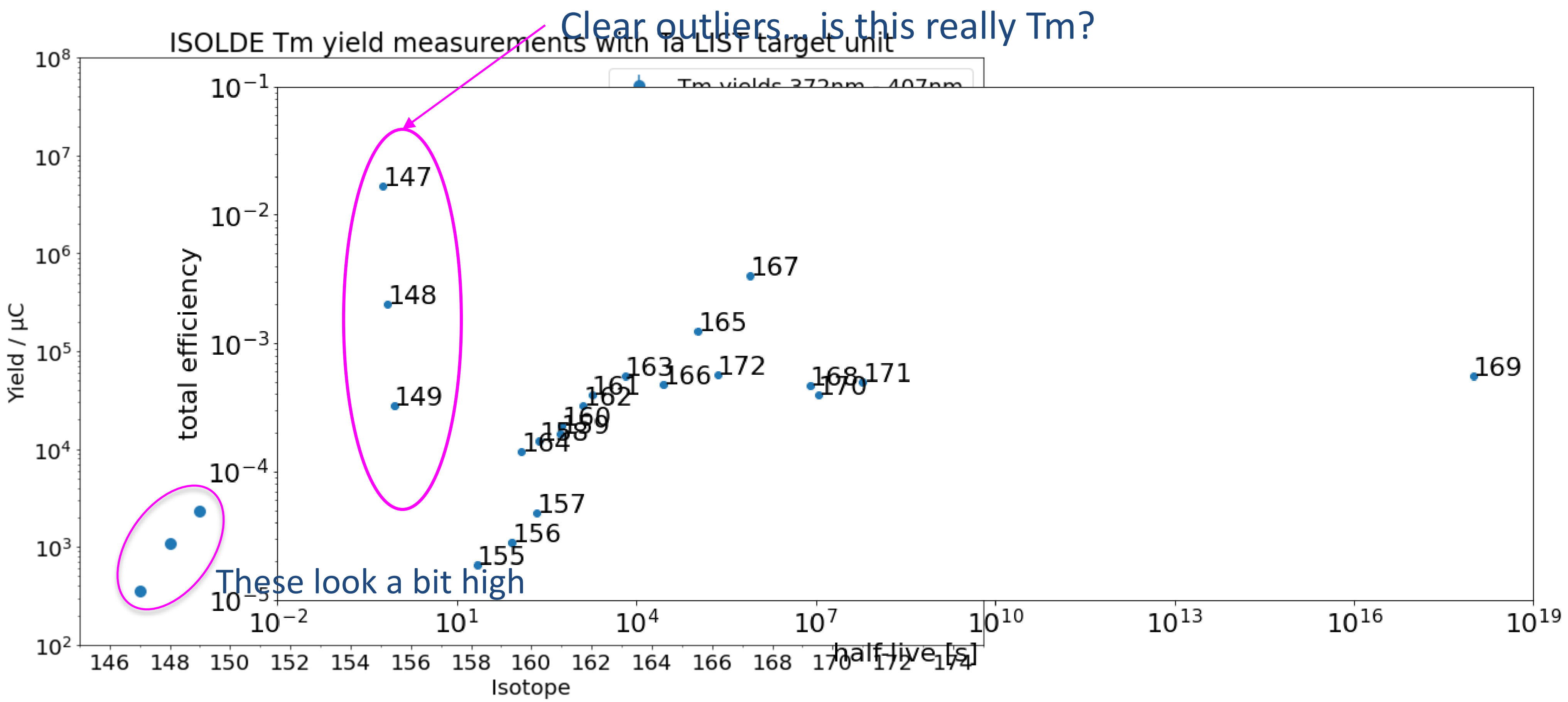



- both lasers on: 192cps over background
- 1st step only: 17cps over background
- 2nd step only: 105cps over background

Yield as (both lasers on) – (1st step only + 2nd step only)

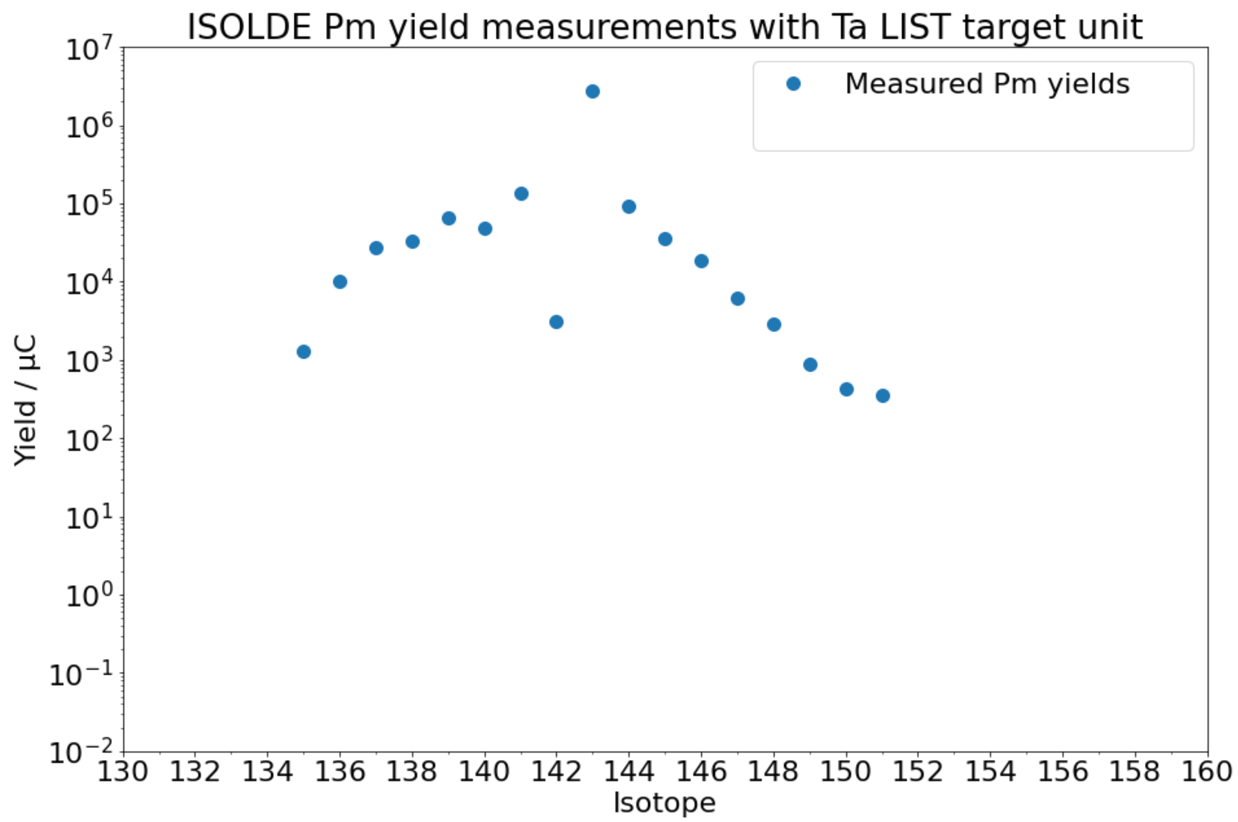


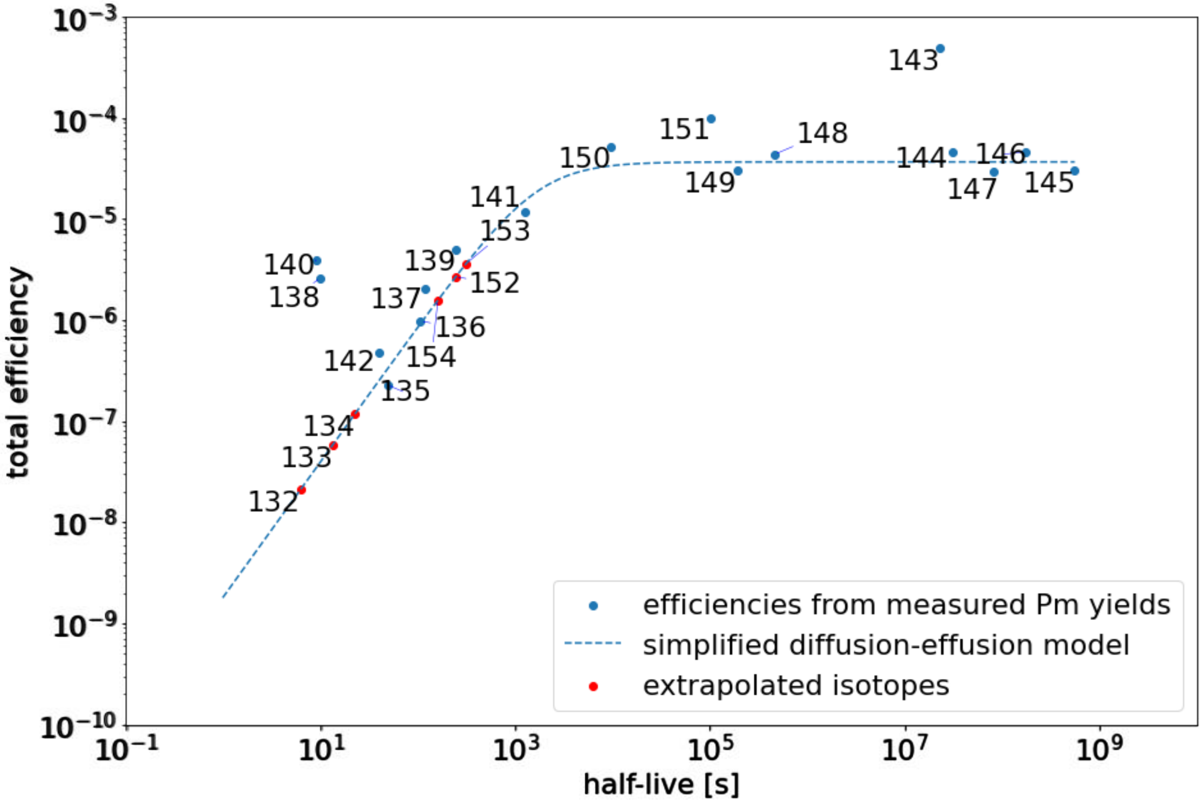
# Tm as a cautionary tale



# Estimating yields: extrapolating a measured chain

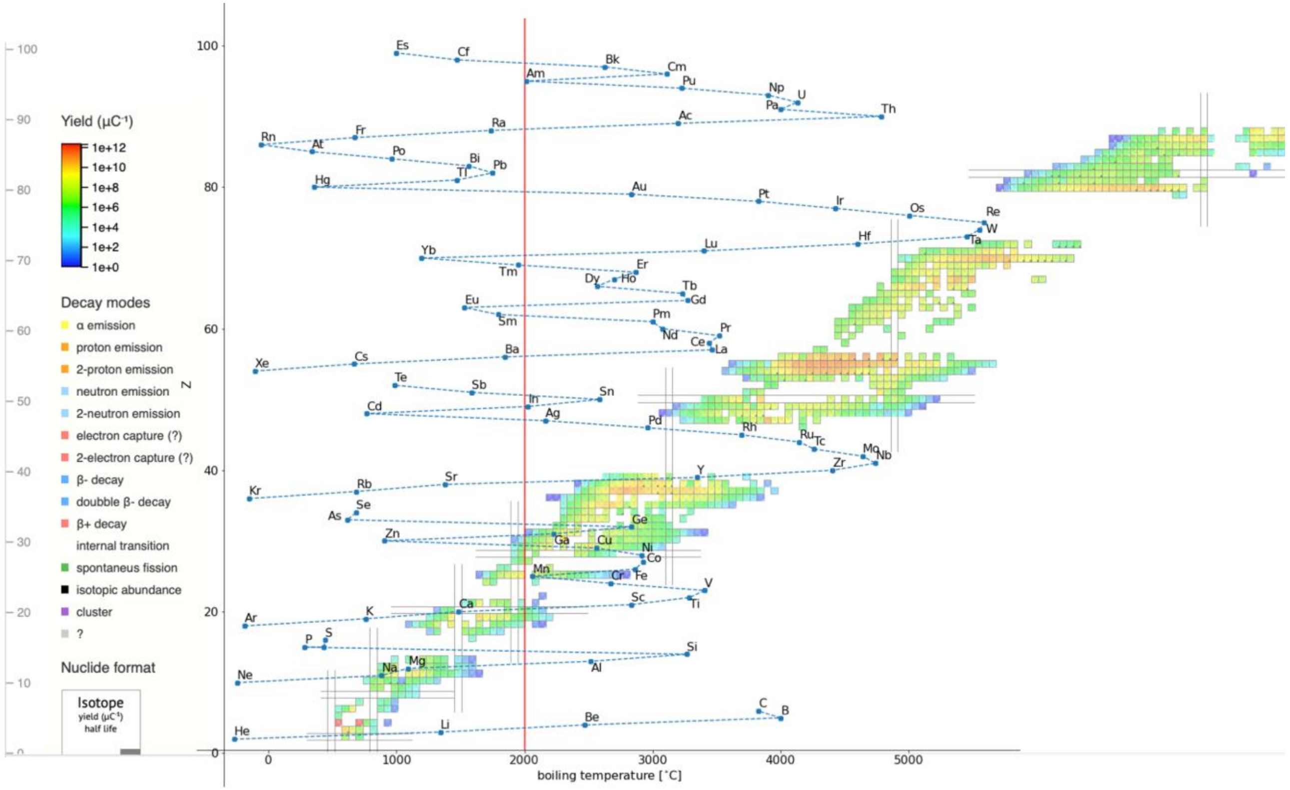
- Fitted diffusion-effusion model can give a yield estimation



# Predicting yields: unmeasured chains

- Enthalpy, boiling point and vapor pressure can give a rough idea about the release compared to measured species



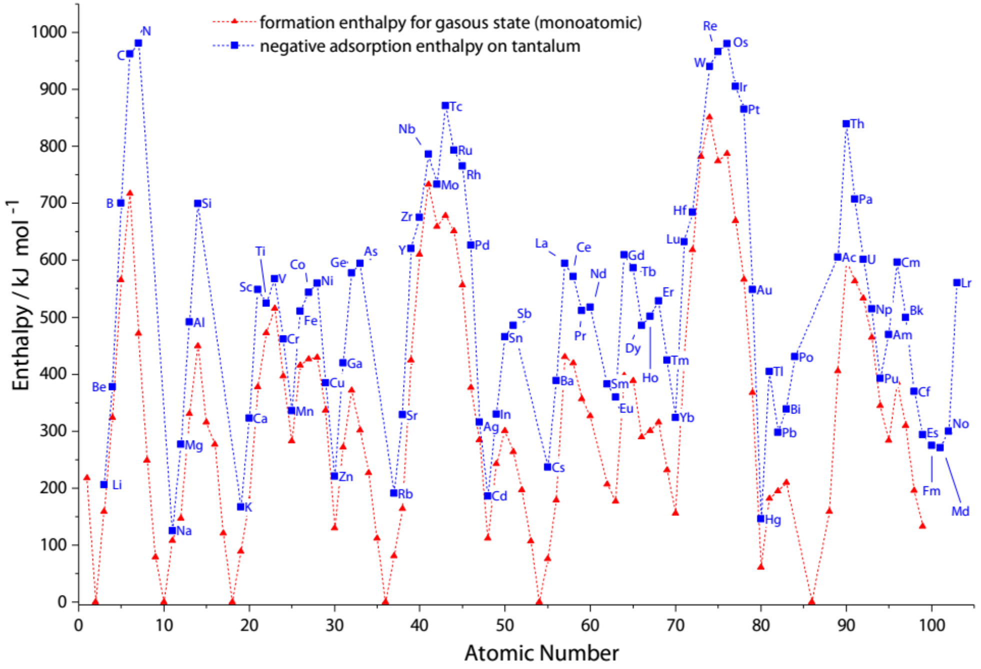
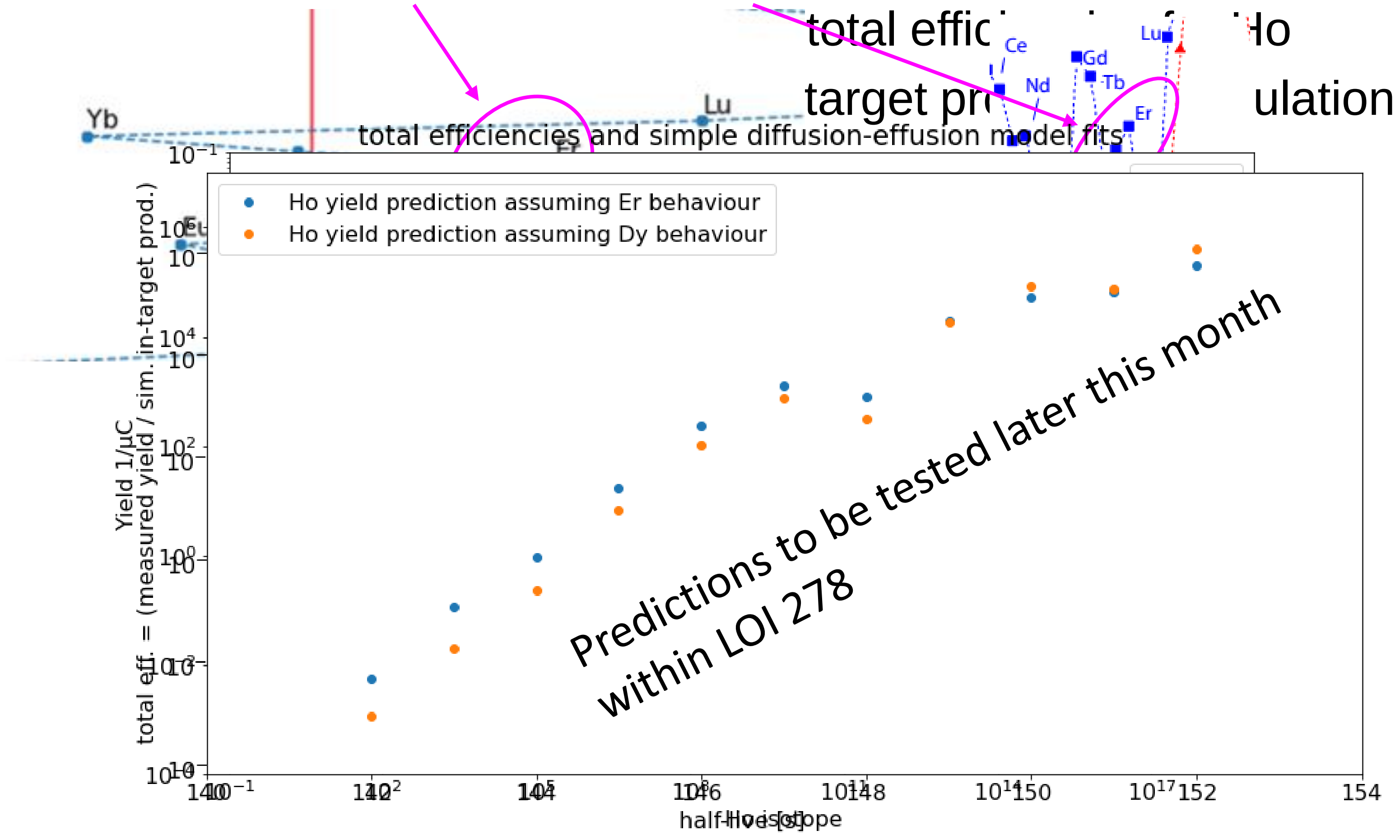




Figure 2.5: Enthalpy of formation of the the gasous monoatomic elements, which equals their sublimation enthalpy [154], in comparison to the adsorption enthalpy on tantalum calulated with the Eichler-Miedema model [155]. The trends are a measure for the volatility of the elements. Values taken from [81, 156–158]. The formation enthalpy of nobles gases equals zero by definition. Connecting lines serve to guide the eye only.

http://doi.org/10.25358/openscience-6636

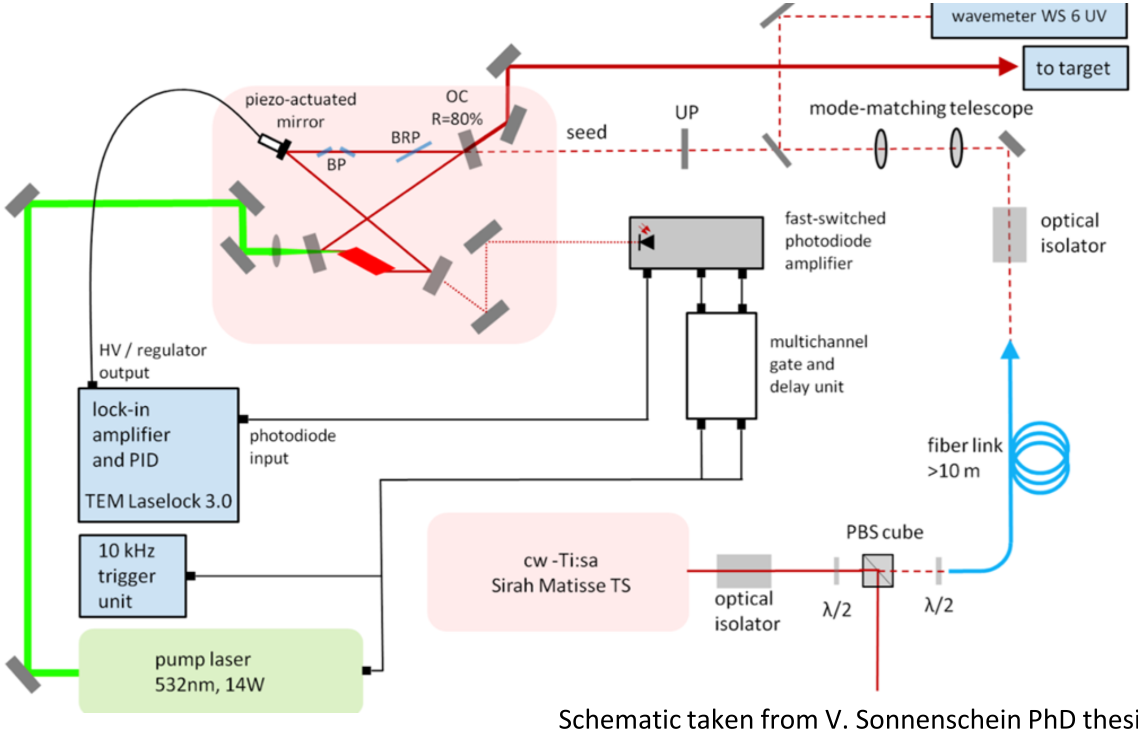
# Neutron deficient Holmium prediction

- Ho boiling point and enthalpy are between Dy and Er



# PI-LIST needs narrowband pulsed Ti:Sa lasers

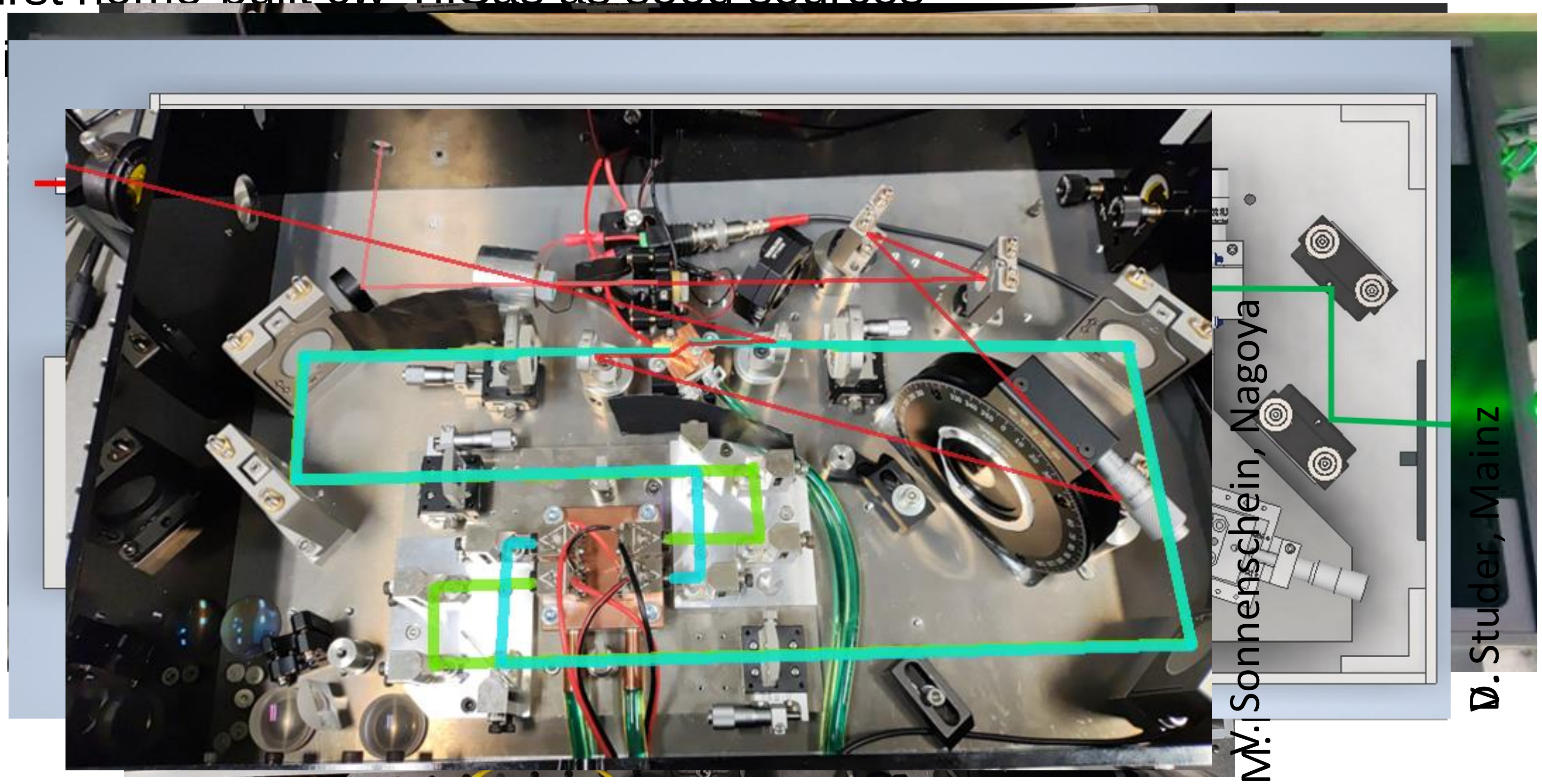
- Ti:Sa lasers used at RILIS for production have several GHz linewidth
  - Not sufficiently narrow for high-resolution spectroscopy
- Injection seeded Ti:Sas are the go-to technique:
- Laser cavity is locked to light of a cw seed laser at the desired wavelength
- Seed photons give this cavity mode a head start when pump pulse arrives
  - Seeded mode outperforms all other modes
  - Pulsed lasing with narrow linewidth at seed wavelength
- Requires additional lasers and electronics
  - Additional headaches




Schematic taken from V. Sonnenschein PhD thesis

# PI-LIST needs narrowband pulsed Ti:Sa lasers

- Developments in different labs over the last 10-15 years have made injection-seeded Ti:Sa lasers a standard source
- First home-built cw-Ti:Sas as seed sources
- Di



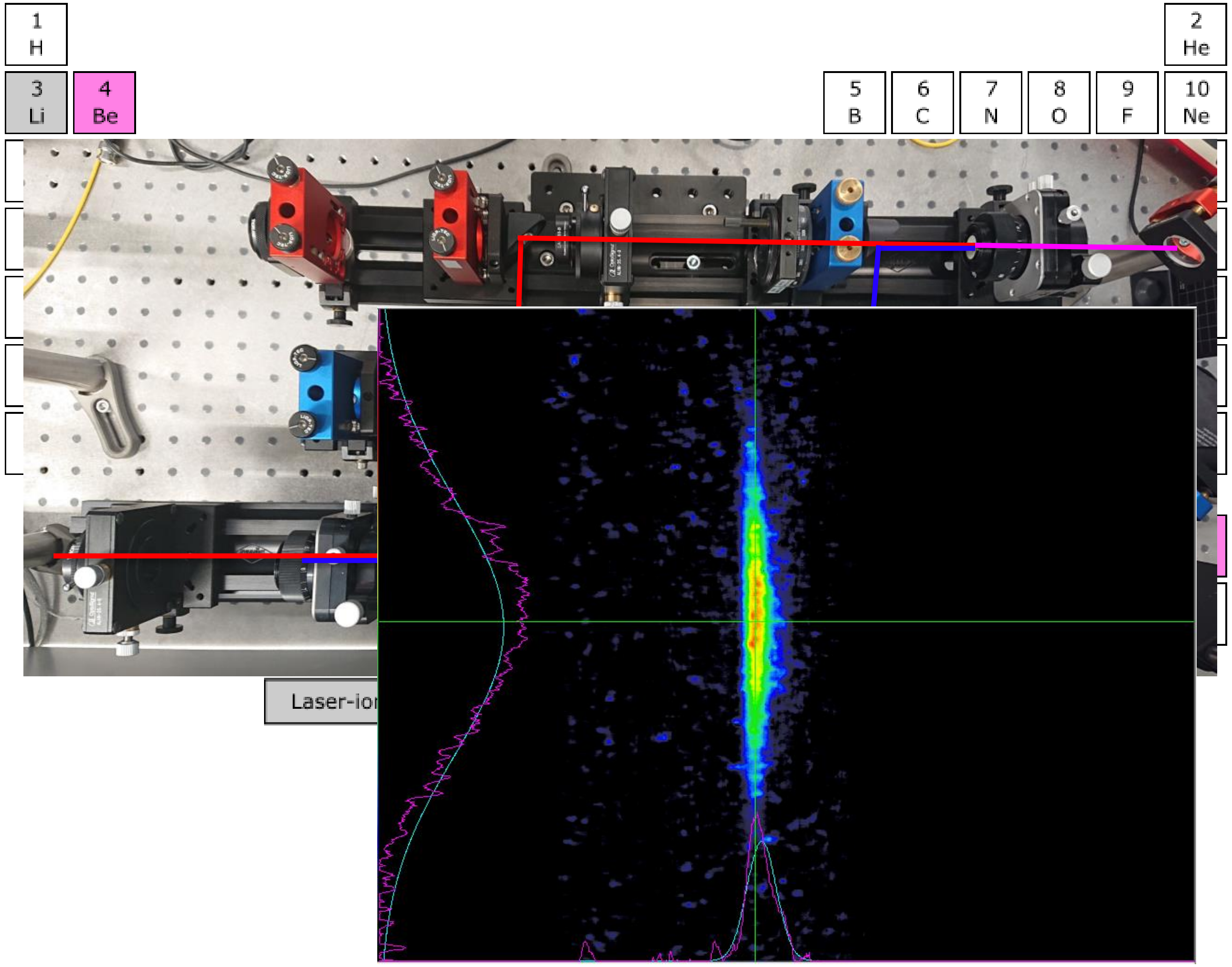
Sonnenschein, Nagoya

D. Studer, Mainz

D. Studer, Mainz

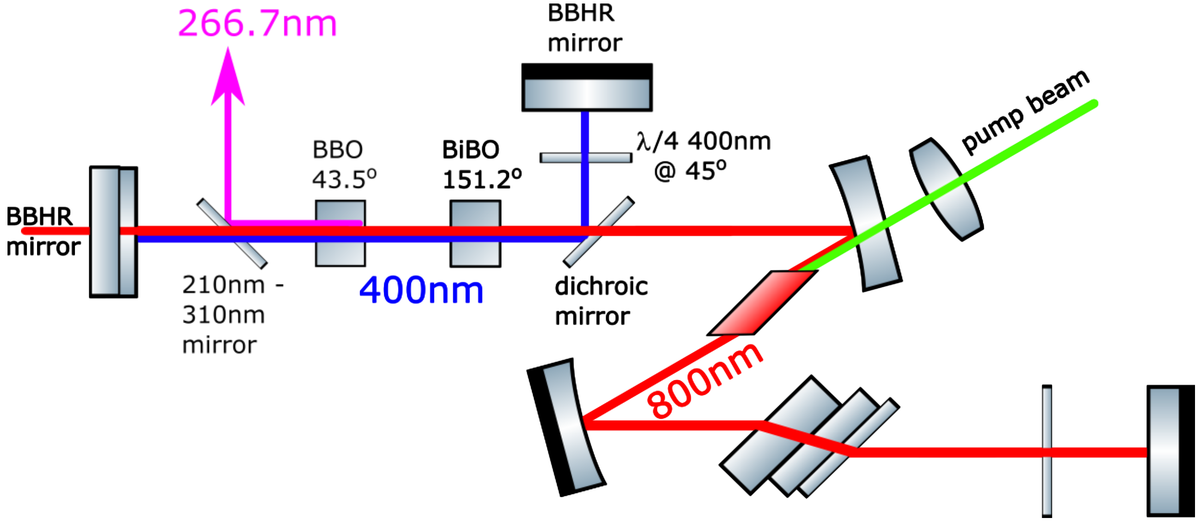
# Intra-cavity generation of the third harmonic

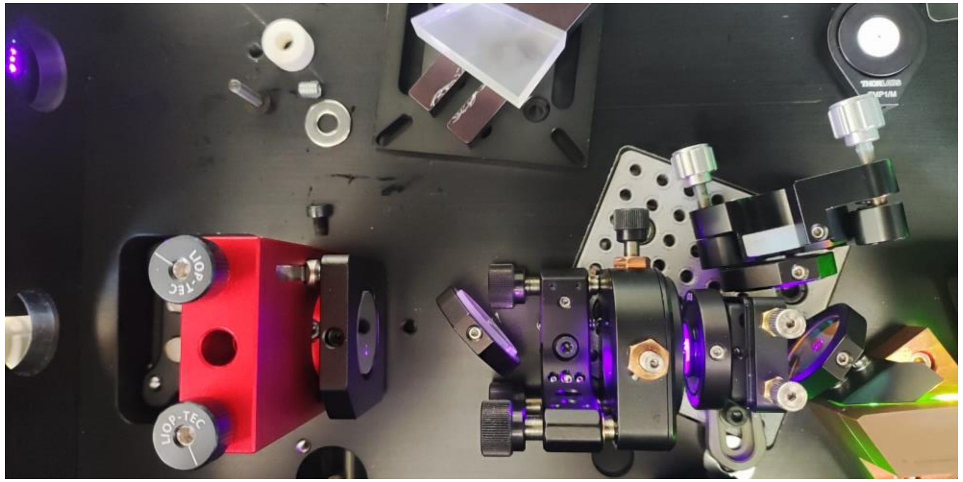
- Many cases with excitation step in the tripled Ti:Sa range, even in the lanthanides
- External tripling units are large, and setup is tedious
- Beam profile needs additional shaping with cylindrical telescope
- IC-doubling gives nice beam shape
  - IC-tripling possible?



# Intra-cavity generation of the third harmonic

- Close the cavity
- SHG with a BiBO crystal and couple out blue light
- Reflect blue back into cavity with double pass through quarter wave plate
  - Aligns polarization with fundamental light
- Sum frequency generation in BBO and couple out UV light

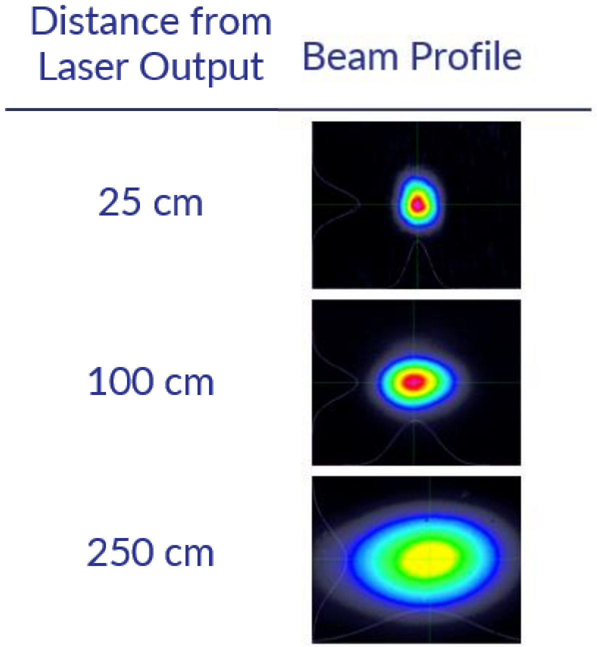


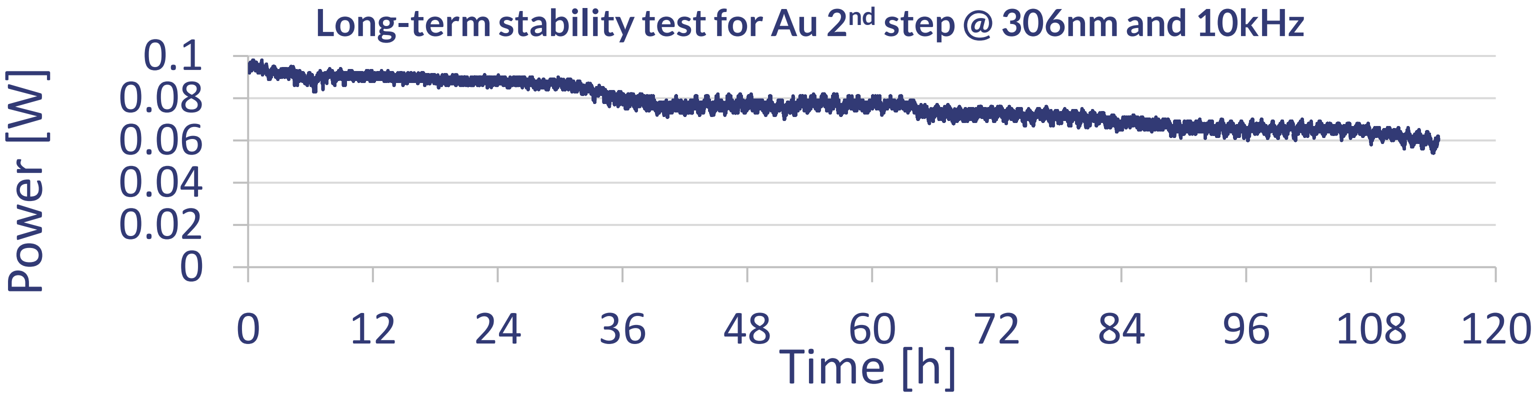
# Intra-cavity generation of the third harmonic

- Comparable efficiency to external tripling:

1.2 W pump power @ 1 kHz → 480 mW of fundamental light at 800 nm → 40 mW of 266.7 nm generated both ways, external and IC




- Better beam profile doesn't require further shaping!
- Power stability is sufficient for on-line use

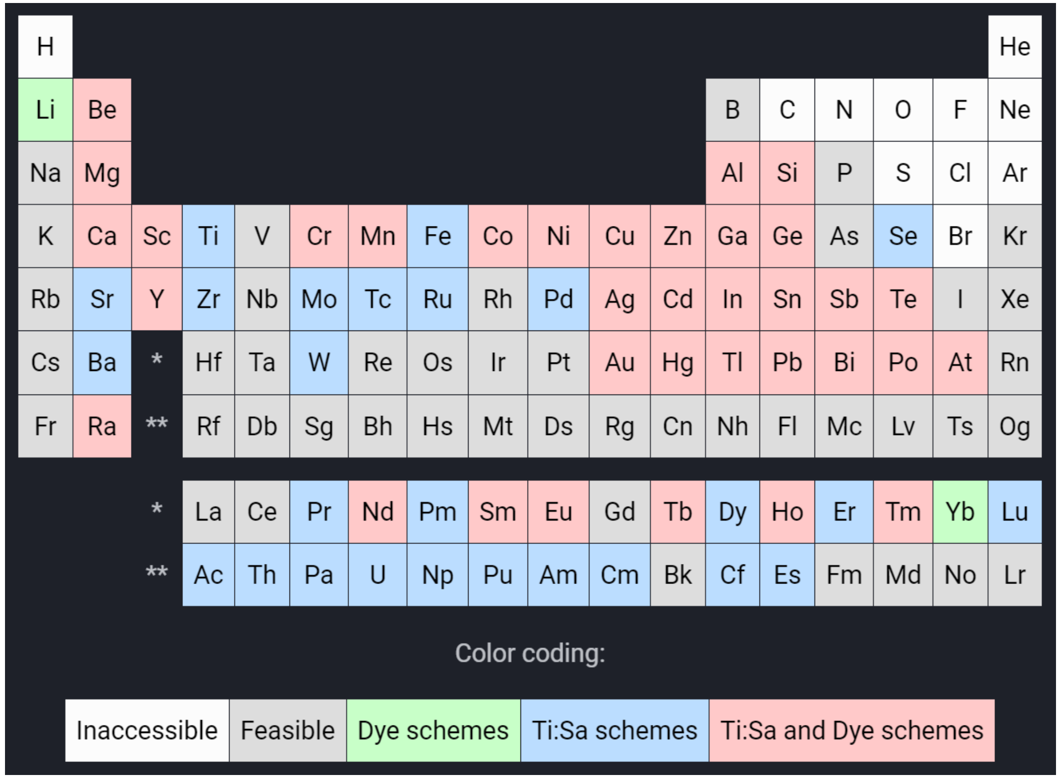



- First on-line application with delivery of In earlier this year

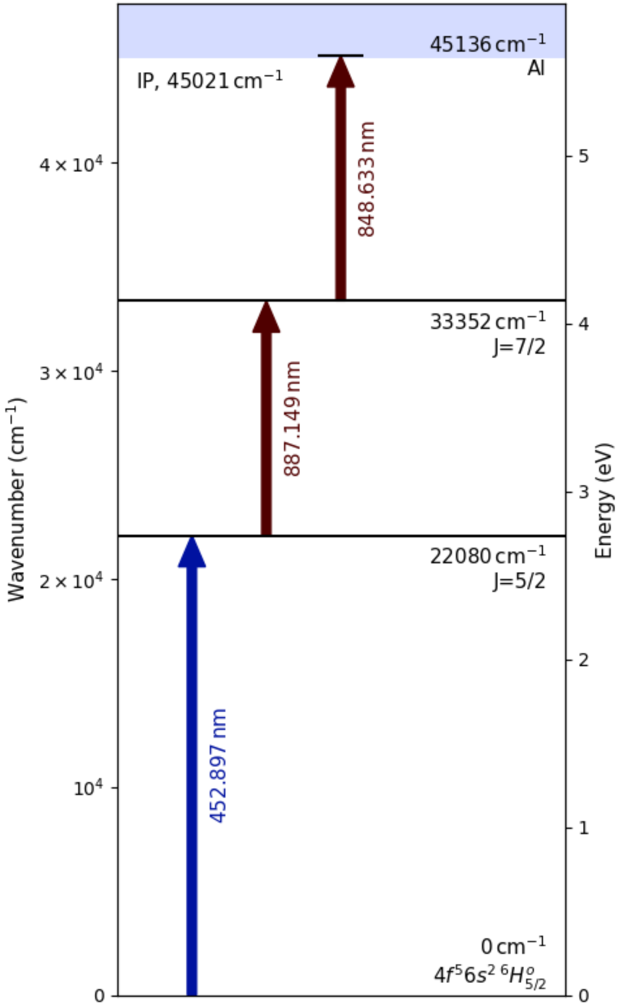
# Conclusions and Prospects

- Yields of several lanthanides with Ta LIST target unit have been measured at ISOLDE
- Many interesting cases in the region for which PI-LIST can be a fitting tool
  - Yields of Lu and Ho will be measured later this month in preparation for a proposal
  - Benchmark for yield estimates
- The necessary injection-seeded Ti:Sa lasers are ever evolving
- Other laser developments like intra-cavity tripling can take load off the RILIS team
  - ➢ More time to collaborate and do some nice spectroscopy ☺

# A new community-driven laser scheme database




https://rims-code.github.io




Reto Trappitsch (EPFL) in collaboration with LP and RBS

From community for community:

Feedback, feature requests, extension to tool hub, …

# Thank you for your attention!

Special thanks to: Anjali Ajayakumar, Mia Au, Cyril Bernerd, Katerina Chrysalidis, Kieran Flanagan, Reinhard Heinke, Asar A H Jaradat, Kara Lynch, Ralitsa Mancheva, Bruce Marsh, Jordan Reilly, Sebastian Rothe, Volker Sonnenschein, Simon Stegemann, Dominik Studer, Hideki Tomita

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