IJCLab
Irène Joliot-Curie

P,T-violation through laser spectroscopy of molecules

(Radioactive molecules at Ganil)

S Franchoo & A Vicente

IJClab, Orsay

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1/ What are we looking for?

- . eEDM
- . Schiff moment
- . heavy (radioactive) molecules

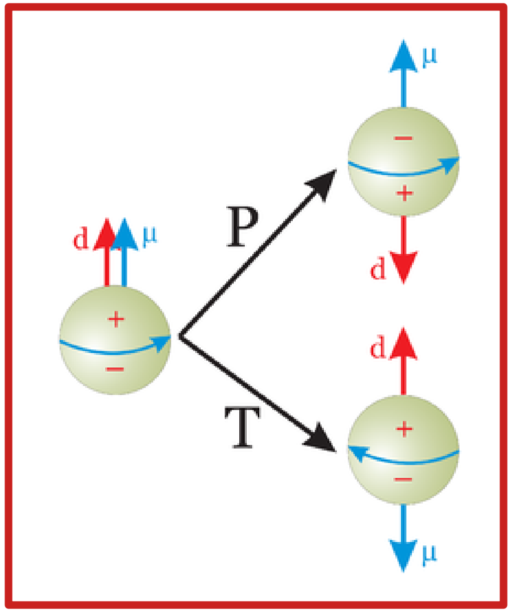
2/ How do we want to do it?

- . Ganil-S3 low-energy branch
- . intrajet laser spectroscopy at Ganil-S3
- . precision experiments at Ganil-Desir

P,T-violation exists in Standard Model

weak force: complex phase in CKM
strong force: θ vacuum

eEDM(SM) ~ 10^{-38} e·cm does not explain M-AM problem
eEDM(HfF^+) < 4 x 10^{-30} e·cm equivalent to m > 10 TeV/c^2
T Roussy et al (Jila), Science 381 (2023)



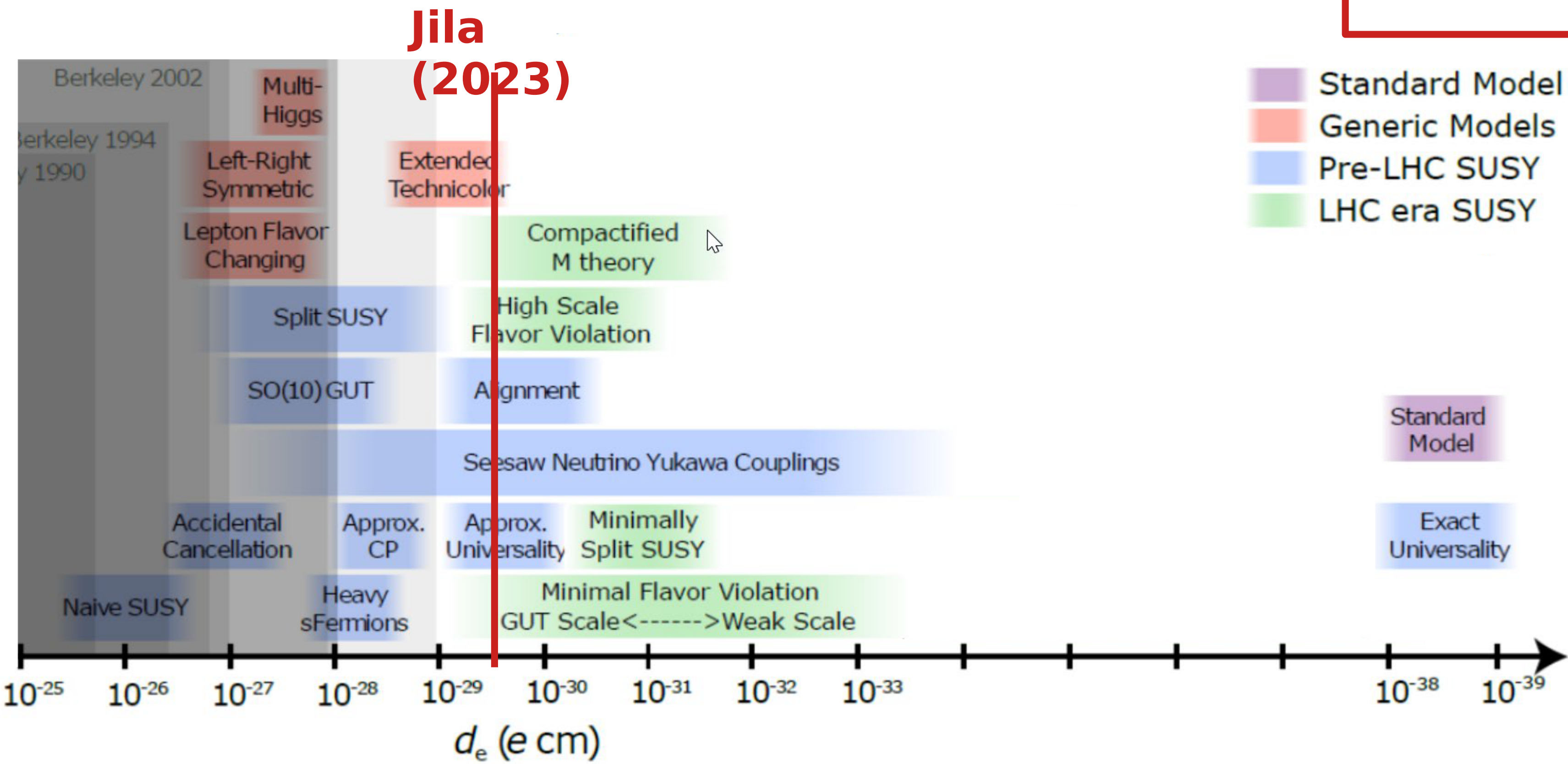
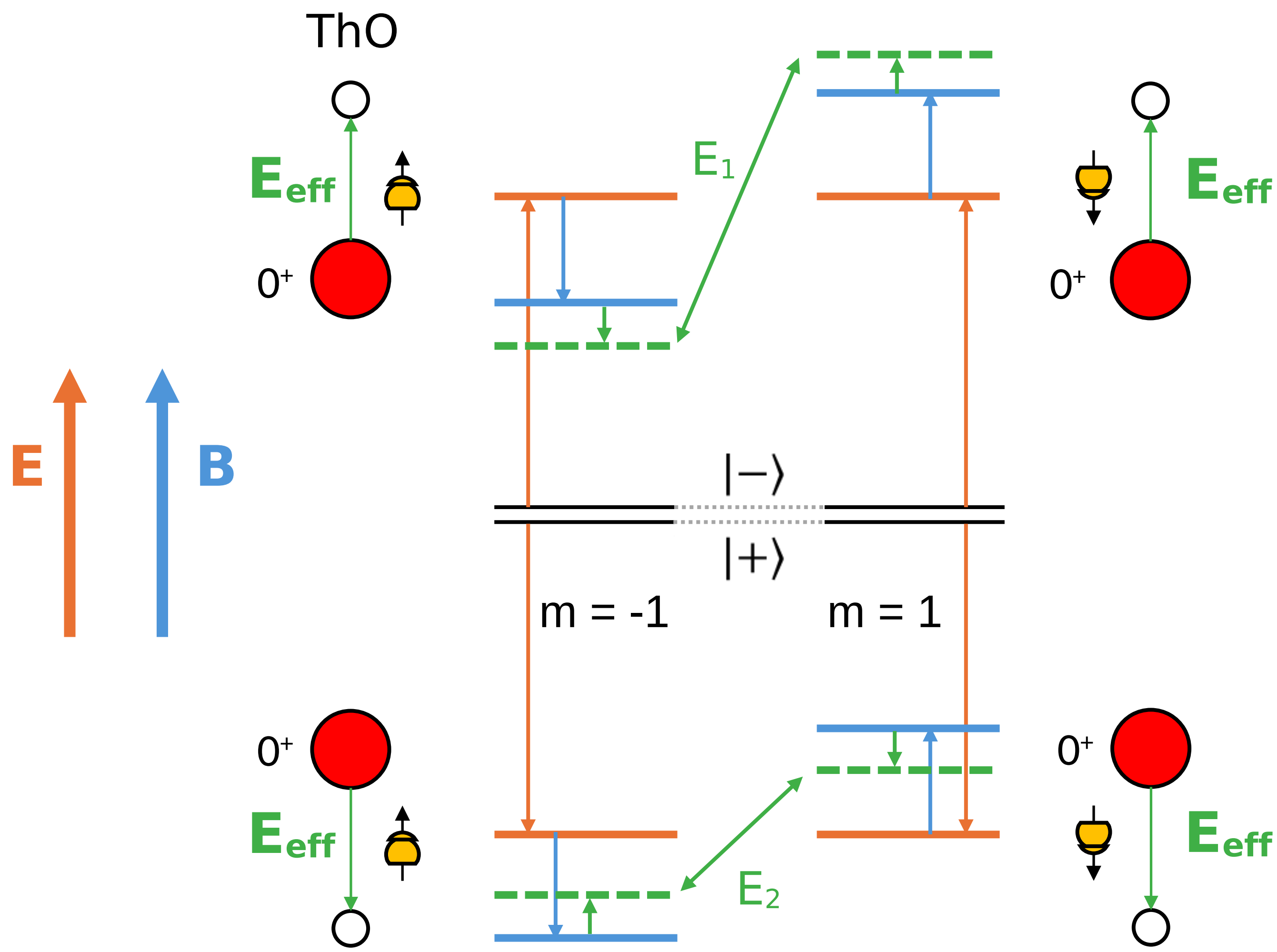


figure modified from D DeMille demillegroup.psd.uchicago.edu/

external **E**: Stark effect
external **B**: Zeeman effect

if there is an **eEDM:**
$H_{EDM} = \Sigma \cdot d_e \cdot \mathbf{E}_{eff}$

$\Rightarrow$ $\mathbf{E_1 - E_2 = 2\Sigma \cdot d_e \cdot E_{eff}}$



$$\vec{L} = \vec{2} \longrightarrow \Lambda = \vec{L} \cdot \vec{n} = 0, \pm 1, \pm 2$$
$$\vec{S} = \vec{1} \longrightarrow \Sigma = \vec{S} \cdot \vec{n} = 0, \pm 1$$
$$\vec{J} = \vec{1} \longrightarrow \Omega = \vec{J} \cdot \vec{n} \Rightarrow \Omega = 0, \pm 1$$

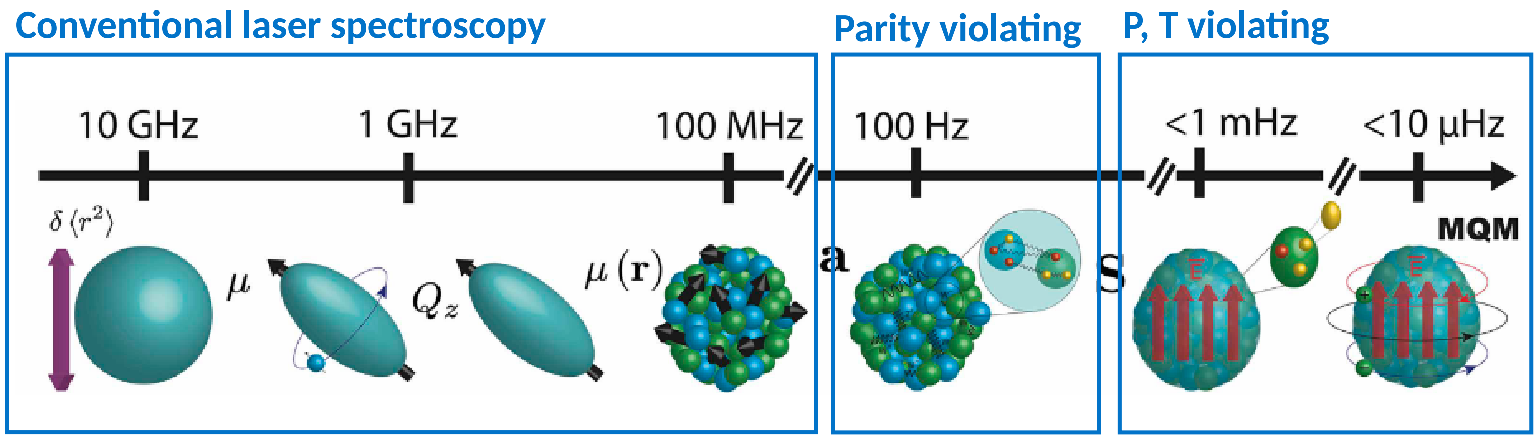
Coriolis & Stark mixing $\begin{cases} |+\rangle = (|\Omega = 1\rangle + |\Omega = -1\rangle)/\sqrt{2} \\ |-\rangle = (|\Omega = 1\rangle - |\Omega = -1\rangle)/\sqrt{2} \end{cases}$

modified from J Baron et al, New J Phys 19 (2017)

Schiff theorem: electron screening cancels nuclear EDM but can be overcome by spin-magnetic & finite-size effects

> From a classical point of view, there can be no average electric field at the nucleus unless some non-electric force is available to keep the nucleus from accelerating under the influence of this electric field. In the finite size effect, this force is supplied by the non-electric interactions between nucleons and mesons. These give the nucleus a finite size, and make it possible for whatever electric dipole moment it may possess to be in a region where the electric field is not exactly zero.

L Schiff, Physical Review 132 (1963)



S Wilkins et al, Science 390 (2025)

P,T-odd octupole deformation **heavy nuclei**

$$S \propto \eta e \frac{\beta_2 \beta_3^2 Z A^{2/3} r_0^3}{E_+ - E_-}$$

coupling strength

parity doublets

Chupp, Fierlinger, Ramsey-Musolf & Singh, RMP 91 (2019)

^{229}Th : β_2 = 0.240 and β_3 = 0.115 (Z=90, ΔE = 133 keV)

N Minkov & A Pálffy, PRL 118 (2017) vz deformed shell model with reflection-asymmetric WS potential from S Cwiok, J Dudek, W Nazarewicz, J Skalski & T Werner, Comp Phys Comm 46, 379 (1987) and BCS pairing correlations from P Walker and N Minkov, PLB 694 (2010)

⇒ **S(^{229}Th) ~ 600 × S(spherical Hg, Tl)**

V Flambaum, PRC 99 (2019)

1.3 What are we looking for: heavy molecules

Energy shift in parity doublet

in nuclei, $\Delta E \sim$ keV
in atoms, $\sim$ eV
in ThO, $\Delta E(\Omega^+,\Omega^-) = 2\pi \times 360$ kHz = **9 neV**

N Hutzler, Ph D thesis, Harvard university (2014)

if $|\mathbf{D}.\mathbf{E}| >> \Delta E(\Omega^+,\Omega^-)$ then system can be fully polarised
thereby reaching enormous internal fields

HfF^+ : 18 GV/cm
ThO : 80 GV/cm — Denis & Fleig, J Chem Phys 145 (2016); Skripnikov, J Chem Phys 145 (2016)
HgF : 100 GV/cm — Prasannaa, Vutha, Abe & Das, PRL 114 (2015)
TlF^+ : 160 GV/cm — Bala, Prasannaa, Abe & Das, EPJ Plus 138 (2023)

amplifying P,T violating energy shifts by 3 to 5 orders of magnitude

M Kozlov & L Labzowsky, J Phys B: At Mol Opt Phys 28 (1995)
M Safronova et al, Rev Mod Phys 90 (2018)

in radioactive molecules,
combine heaviest possible nucleus with molecular enhancement
Ganil will be able to produce these

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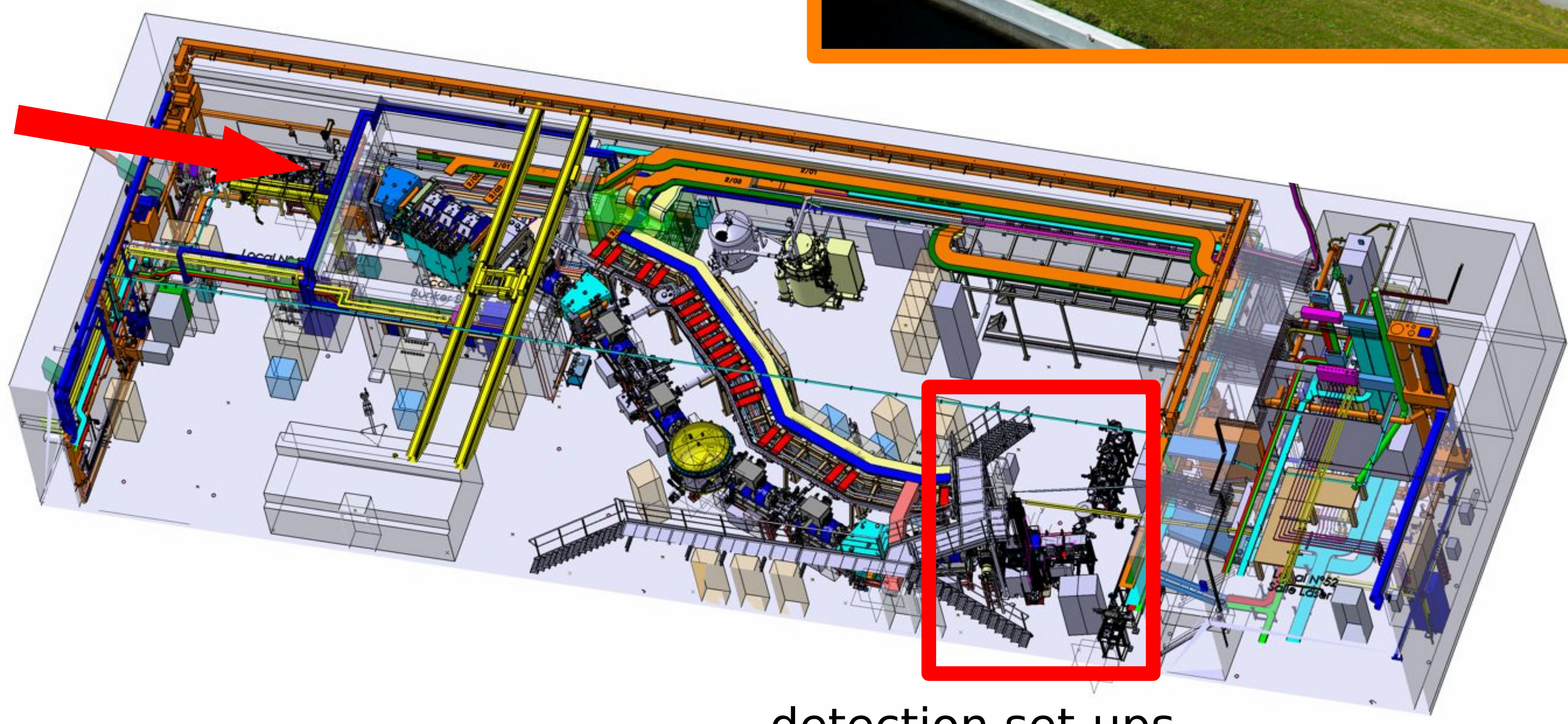
- . Ganil-S3 low-energy branch
- . intrajet laser spectroscopy at Ganil-S3
- . precision experiments at Ganil-Desir

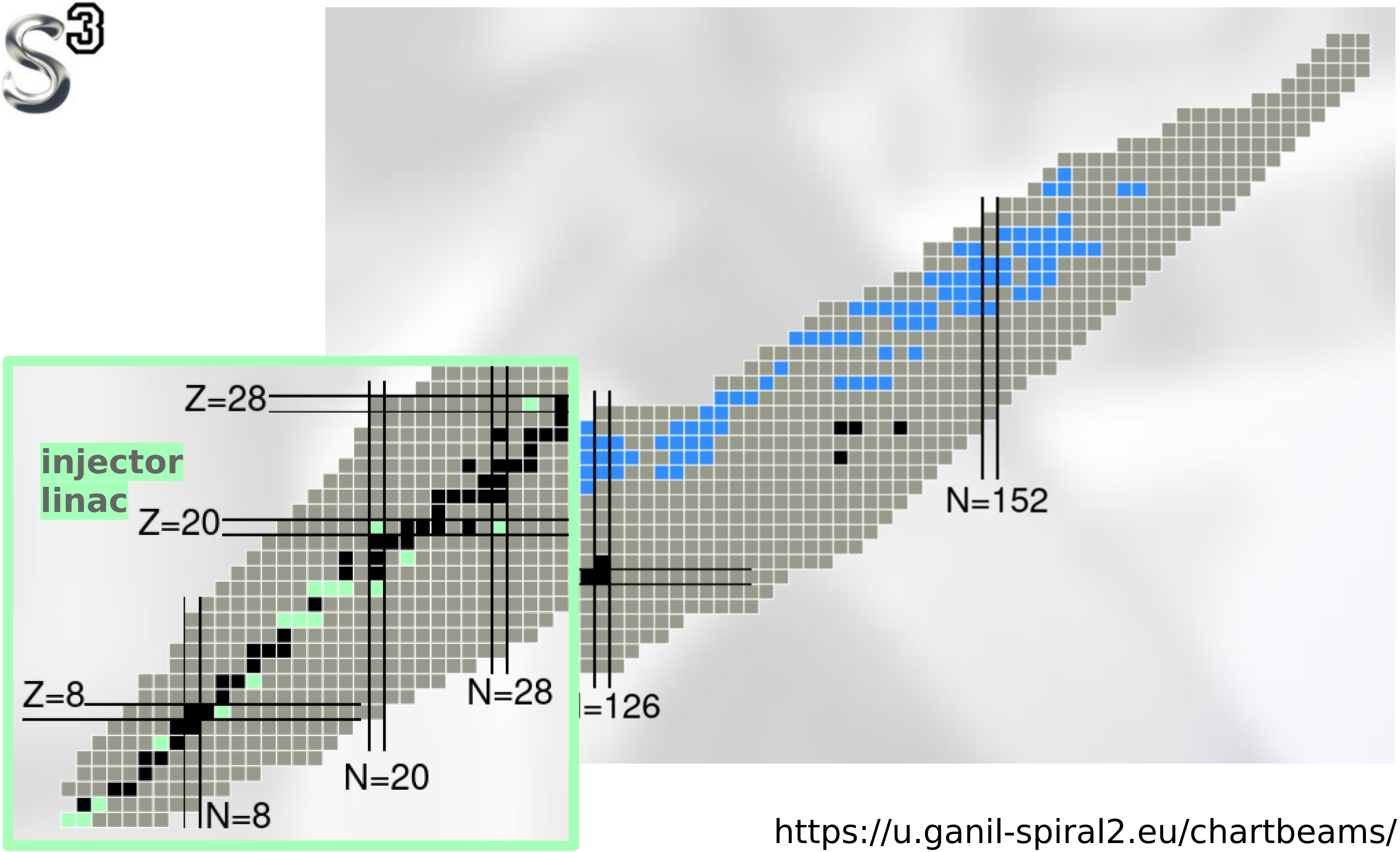
2.1 How do we want to do it: Ganil-S3 low-energy branch



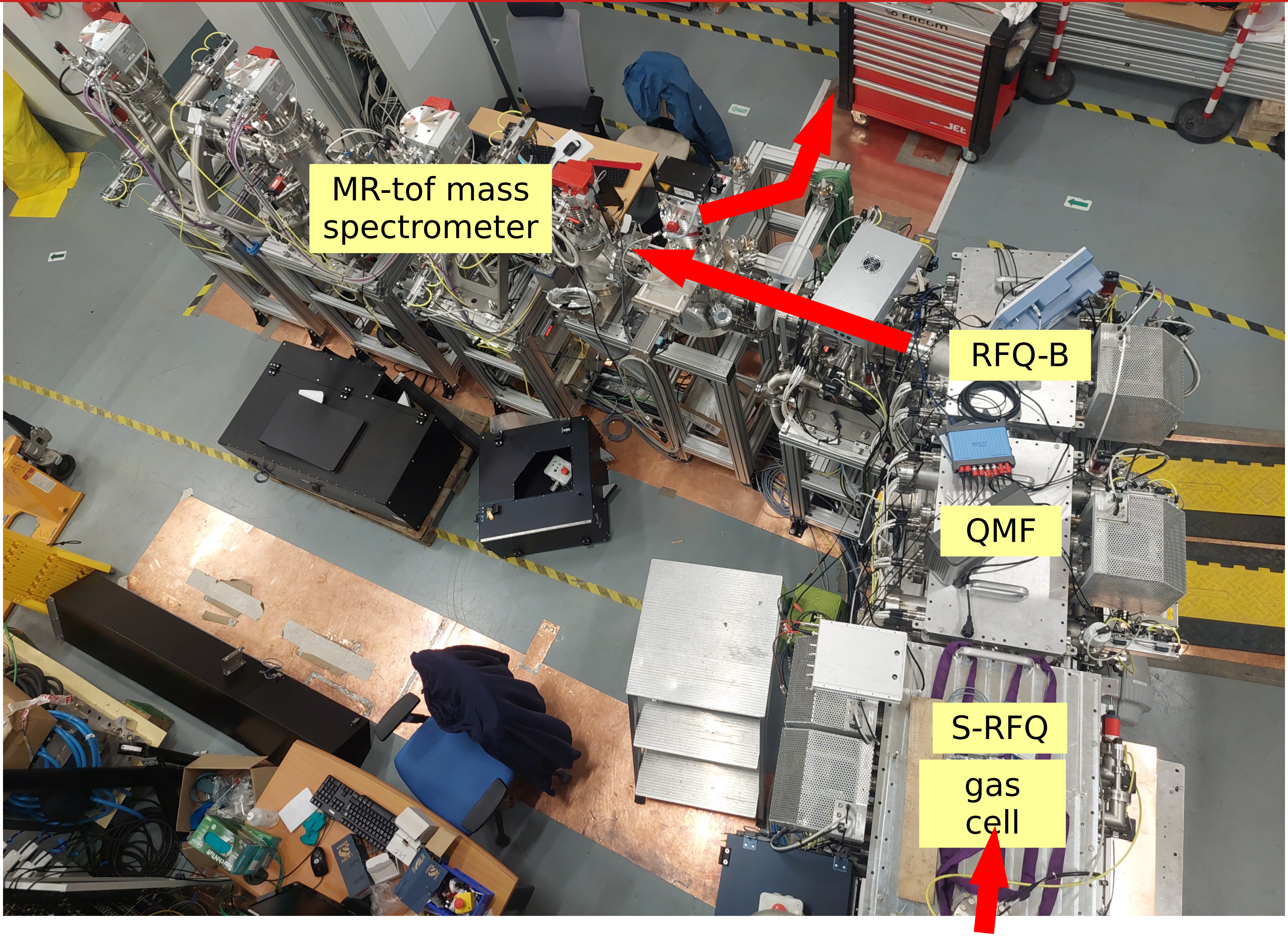
detection set-ups

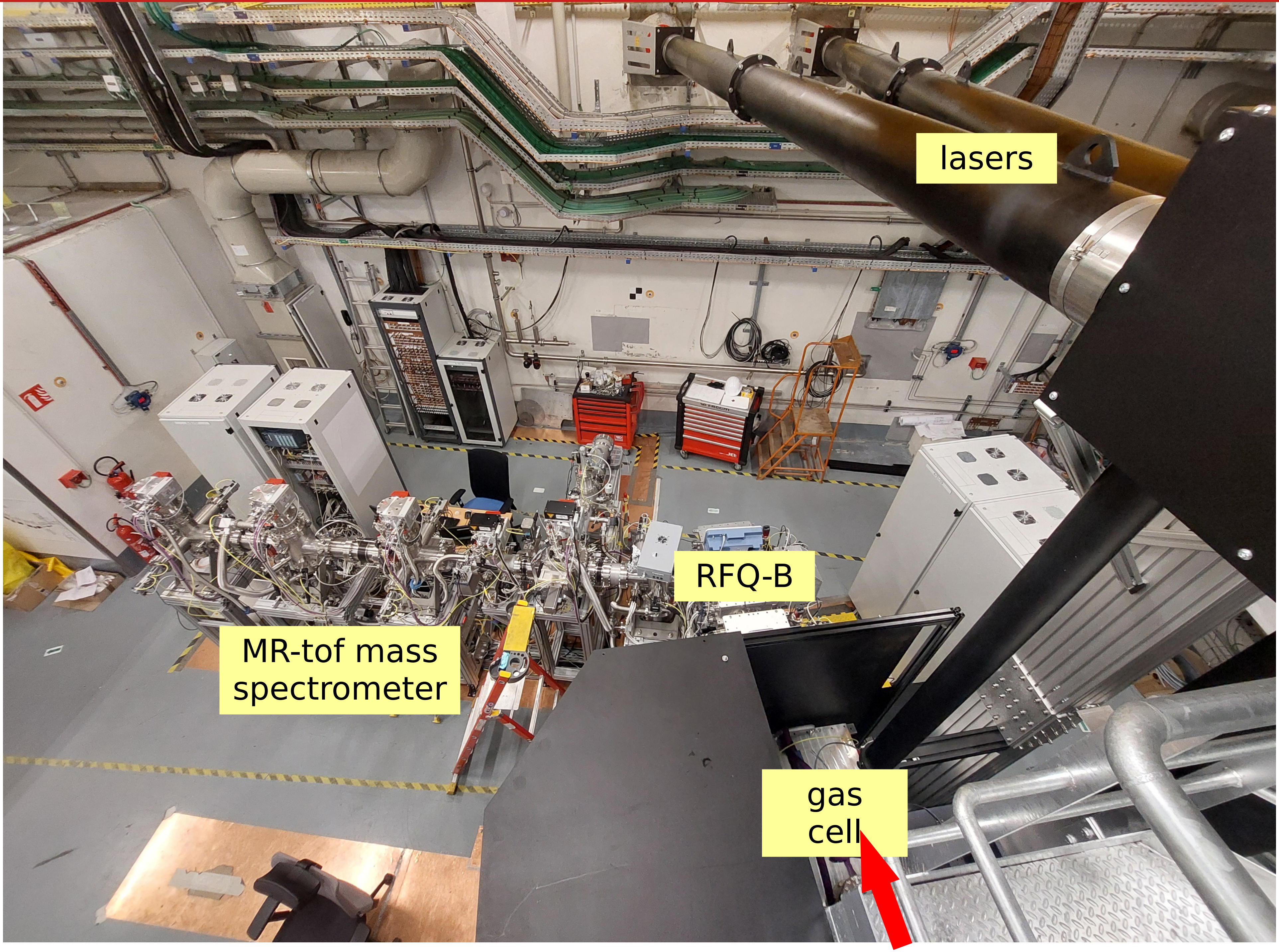
10 pμA = 10^{14} pps beam on target
10^{13} beam rejection
1/300 m/Δm
±50 mrad Δϑ
±10% ΔBρ

2.1 How do we want to do it: Ganil-S3 low-energy branch

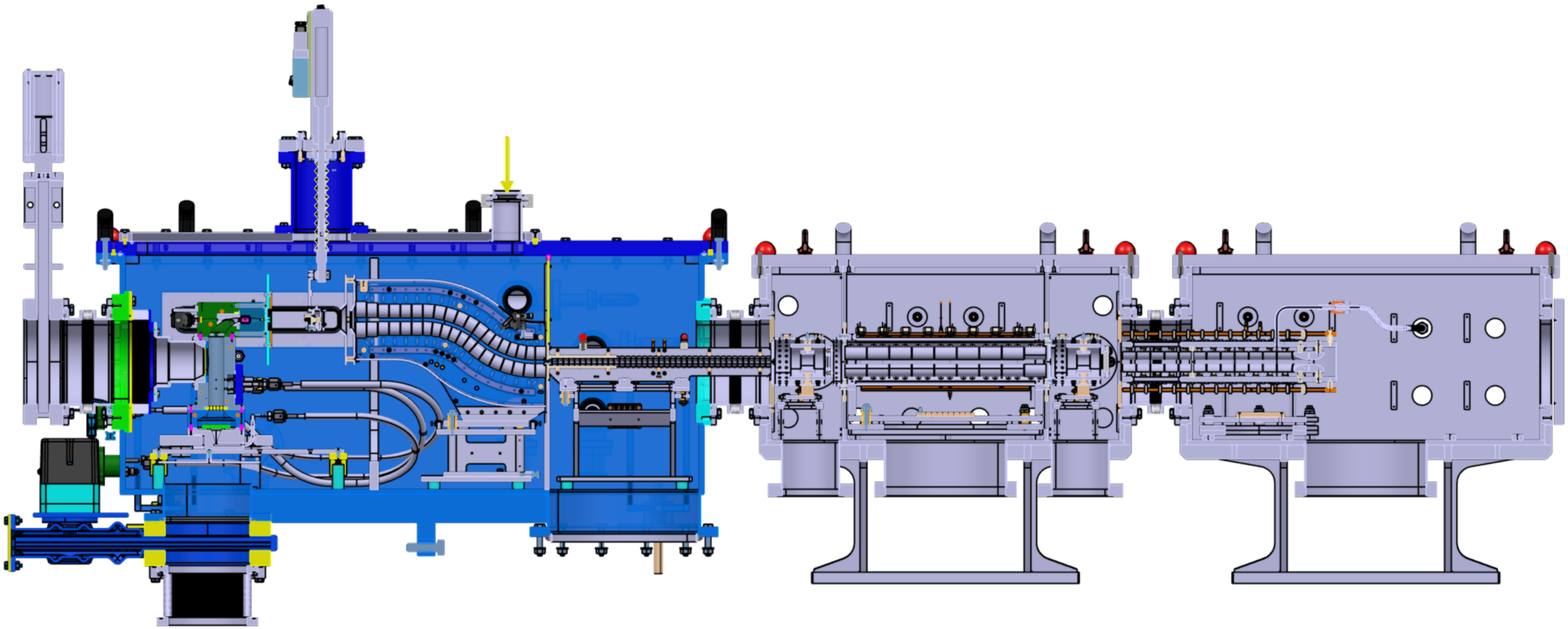


https://u.ganil-spiral2.eu/chartbeams/

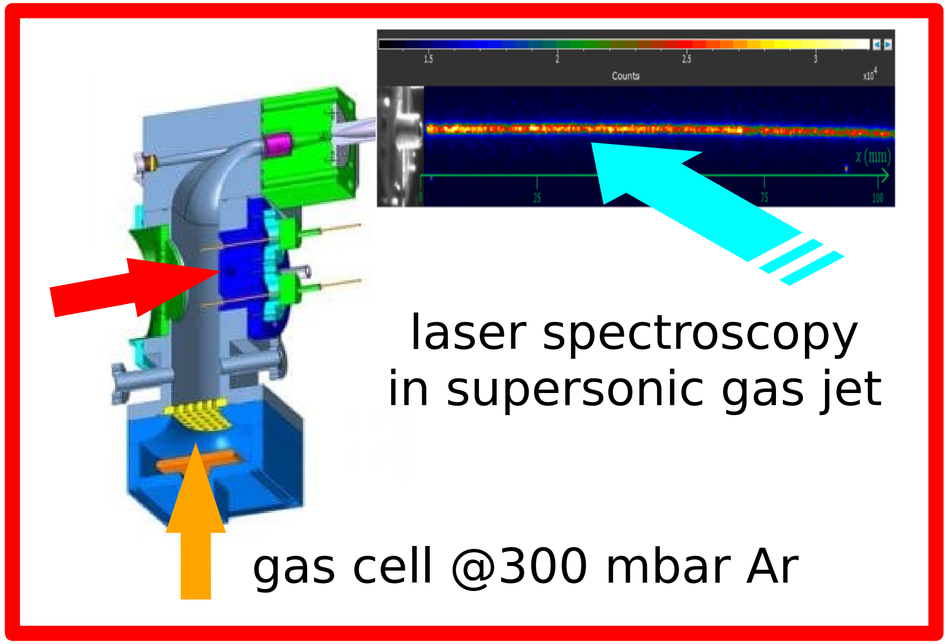

MR-tof mass spectrometer
RFQ-B
QMF
S-RFQ
gas cell

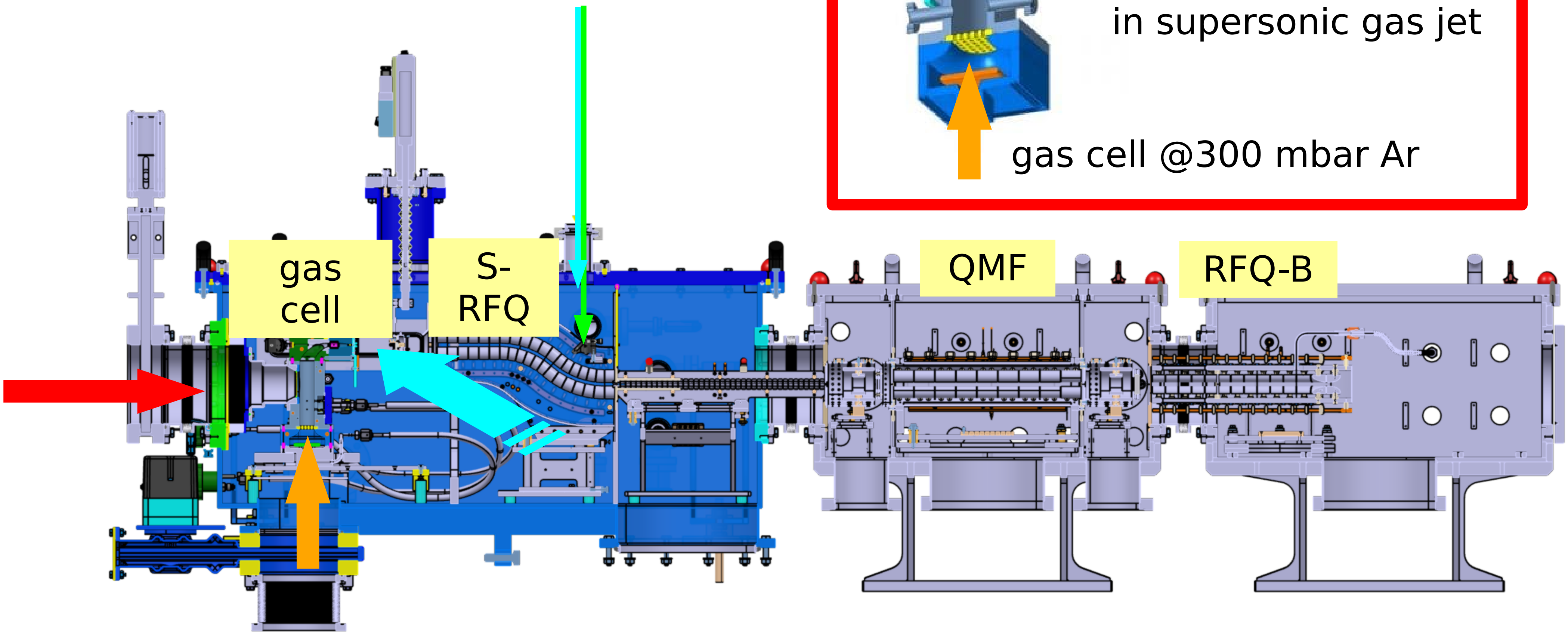

lasers
RFQ-B
MR-tof mass spectrometer
gas cell

2.1 How do we want to do it: Ganil-S3 low-energy branch



2.2 How do we want to do it: intrajet laser spectroscopy at Ganil-S3

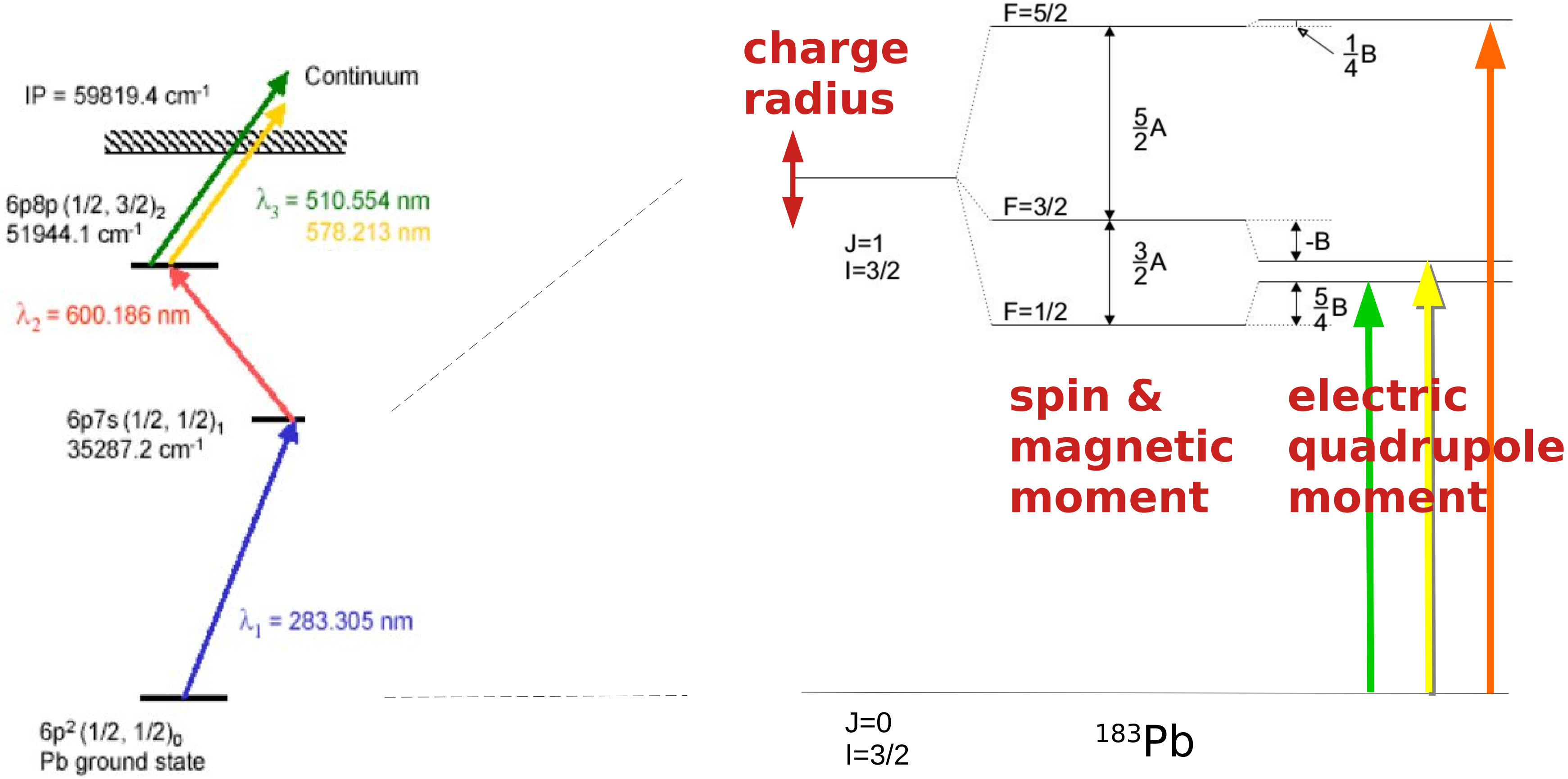




2.2 How do we want to do it: intrajet laser spectroscopy at Ganil-S3

laser ion source:
broadband lasers (~10 GHz)

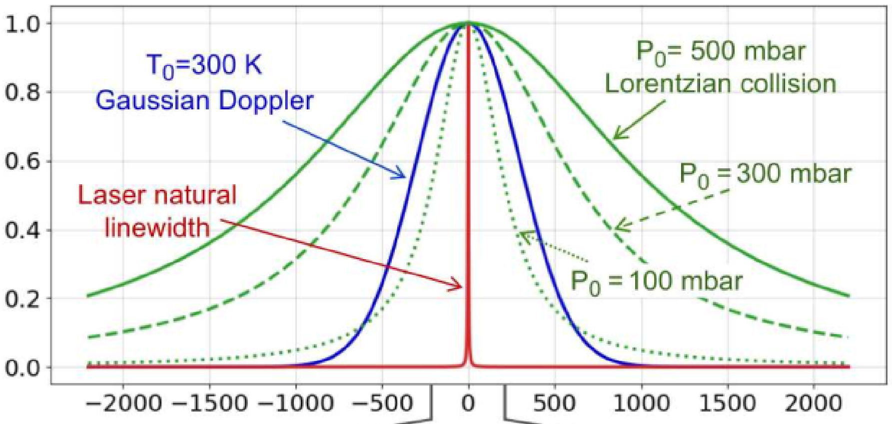
laser spectroscopy:
narrowband lasers (<100 MHz)



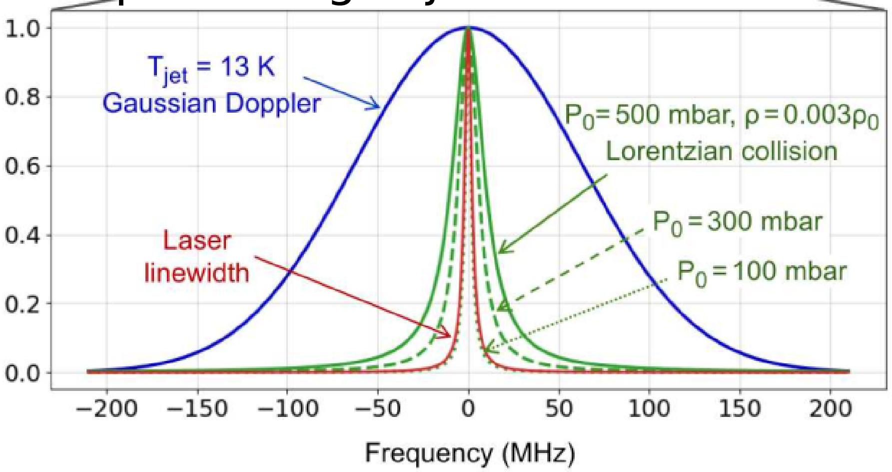
- resonant laser ionisation selects one element within many
- probing hyperfine interaction gives access to nuclear structure
- intrasource > intrajet > collinear spectroscopy for increased resolution

2.2 How do we want to do it: intrajet laser spectroscopy at Ganil-S3

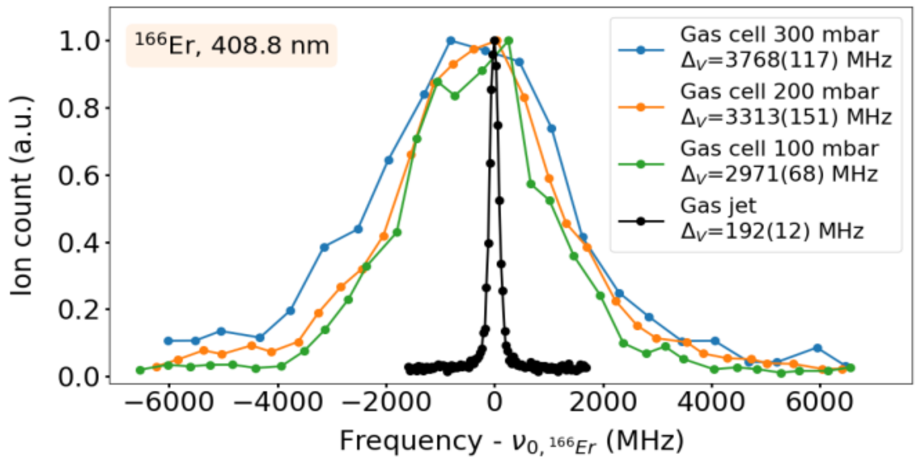
expected / gas cell

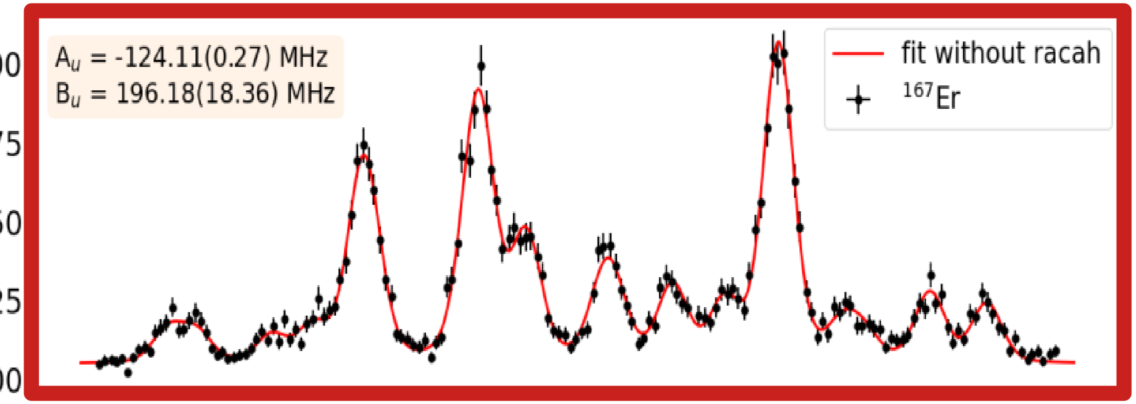


expected / gas jet



measured / gas cell & jet



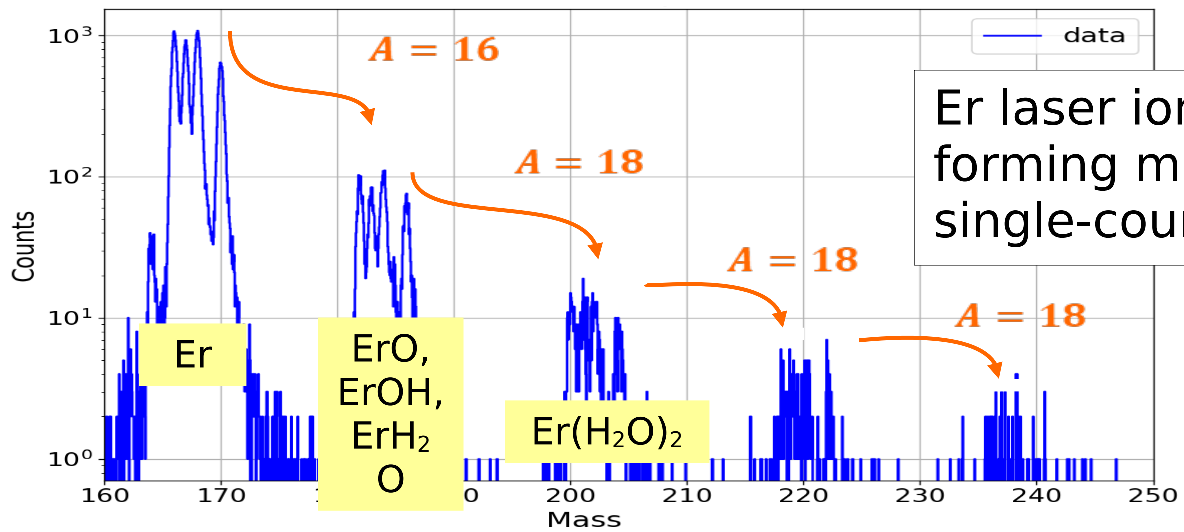


200 MHz FWHM, M~8, T~13 K

W Dong, Ph D thesis, university Paris-Saclay (2024)

T_{trans} = 12 K, T_{rot} = 7 K, T_{vib} < 250 K

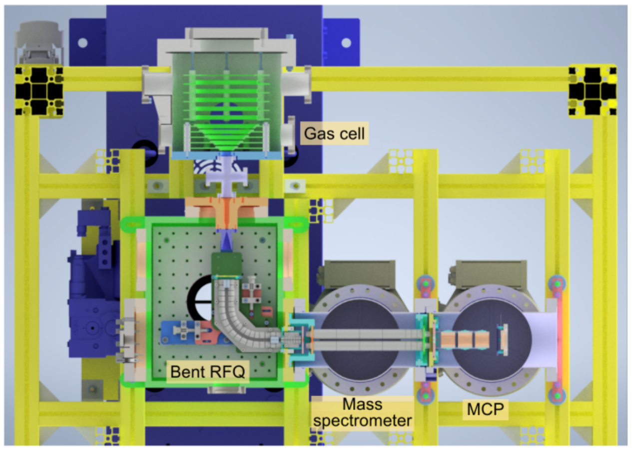
R Ferrer, university of Louvain, private communication oxide & hydroxide molecules are readily available!



Er laser ionised in gas cell
forming molecule afterwards
single-course MR-tof spectrum

controlled production of molecules:

1. gas mixtures
2. accelerated neutralisation, extraction with EM fields
   (related to R&D on fast gas cell for Desir)



identify our molecule of choice
& perform initial spectroscopy

2.3 How do we want to do it: precision experiments at Ganil-Desir

actual precision experiment would require Desir
(setting up collaboration with LAC at CNRS Physique)

- measure temperature after transport at collinear spectroscopy line
- cryocrystal set-up?

Conclusions

- P,T violation amplified in heavy molecules
- heavy molecules can be produced at Ganil-S3
- initial laser spectroscopy in supersonic gas jet

thank you that's all