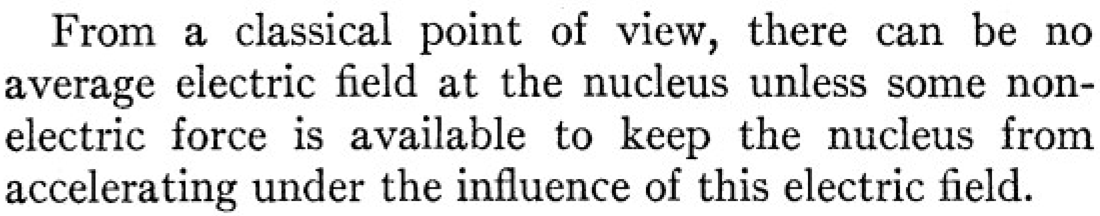
P,T-violation through laser spectroscopy of molecules

S Franchoo
IJClab, Orsay



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.

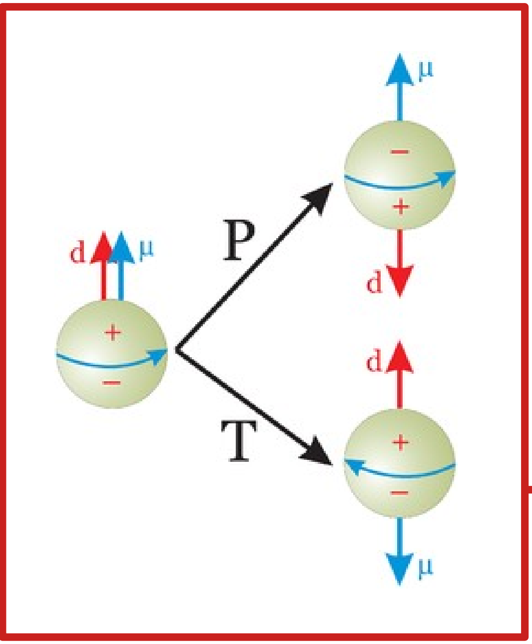
Schiff, Physical Review 132 (1963)

1.1 What are we looking for: eEDM

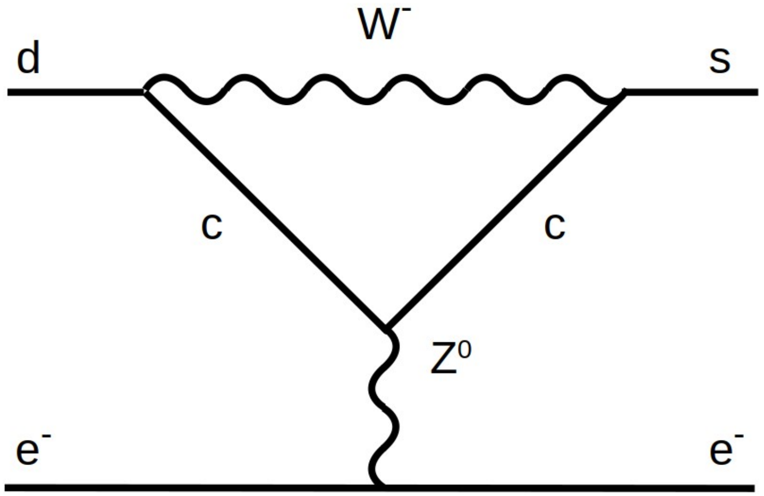
P,T-violation exists in Standard Model

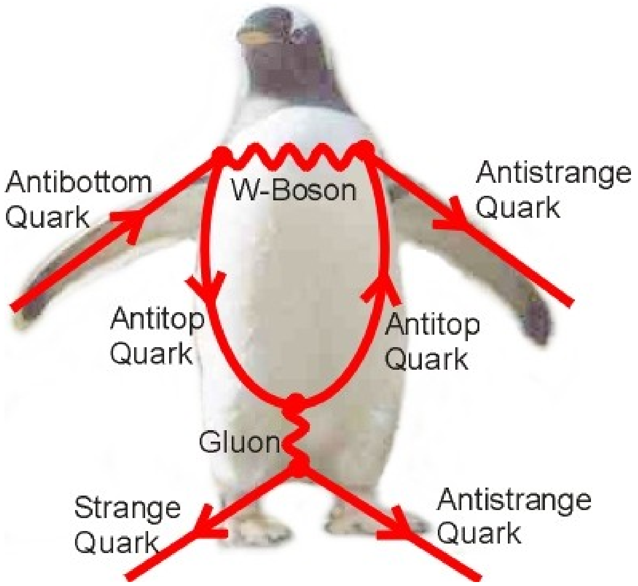
CP-odd weak force: complex phase in CKM
CP-odd strong force: θ vacuum

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
Roussy et al, arXiv:2212.11841

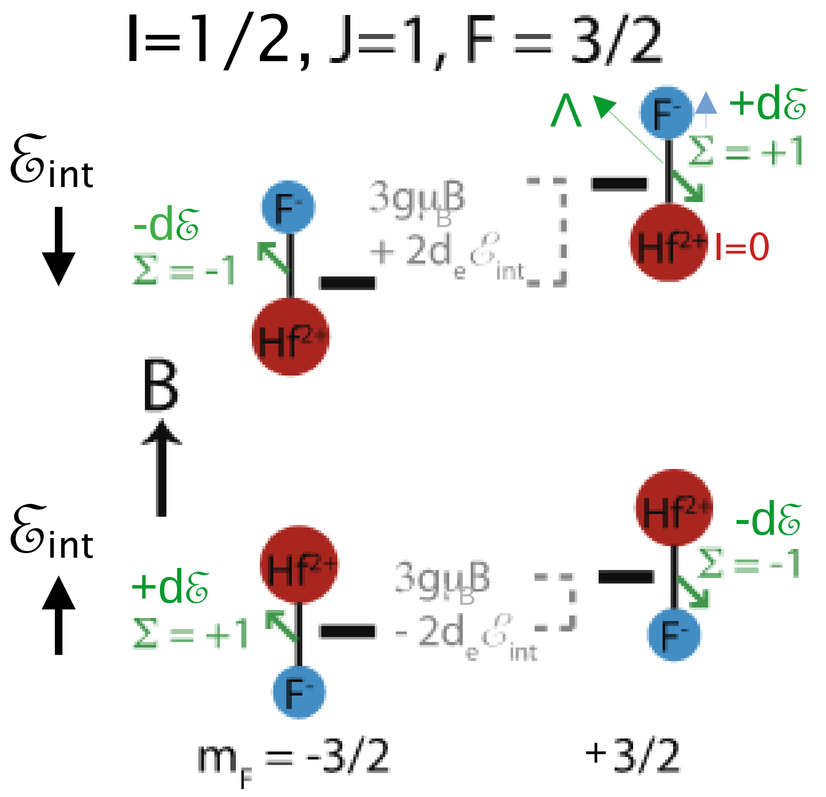


in β decay: <e|W|ν>
in laser spectroscopy: neutral weak current <e|Z^0|e>





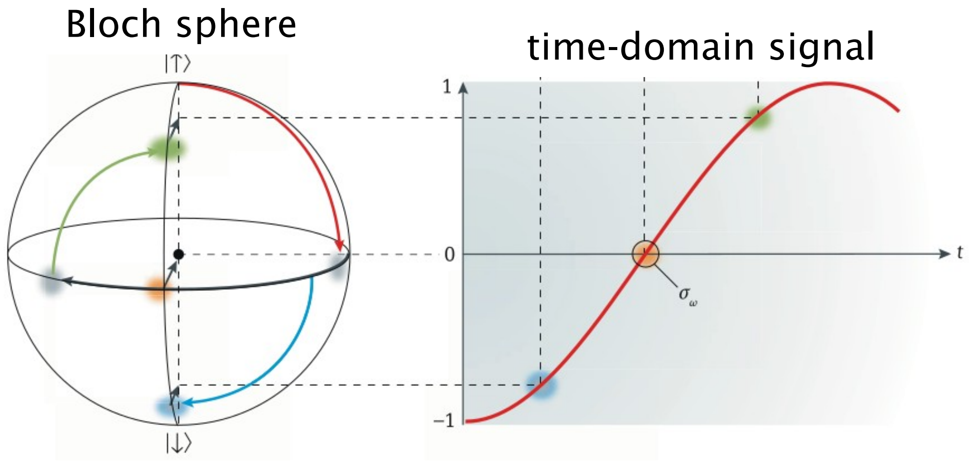
1.1 What are we looking for: eEDM



HfF$^+$ $^3\Delta_1$ molecular state: Λ=2, Σ=1, Ω=2-1=1 projected on intranuclear axis F$^-$→Hf^{2+} whereas I+J=F=3/2 relative to magnetic field eEDM along Σ

ΔE(-3/2,+3/2) in applied magnetic field same when swapping the molecule... unless EDM in internal electric field!

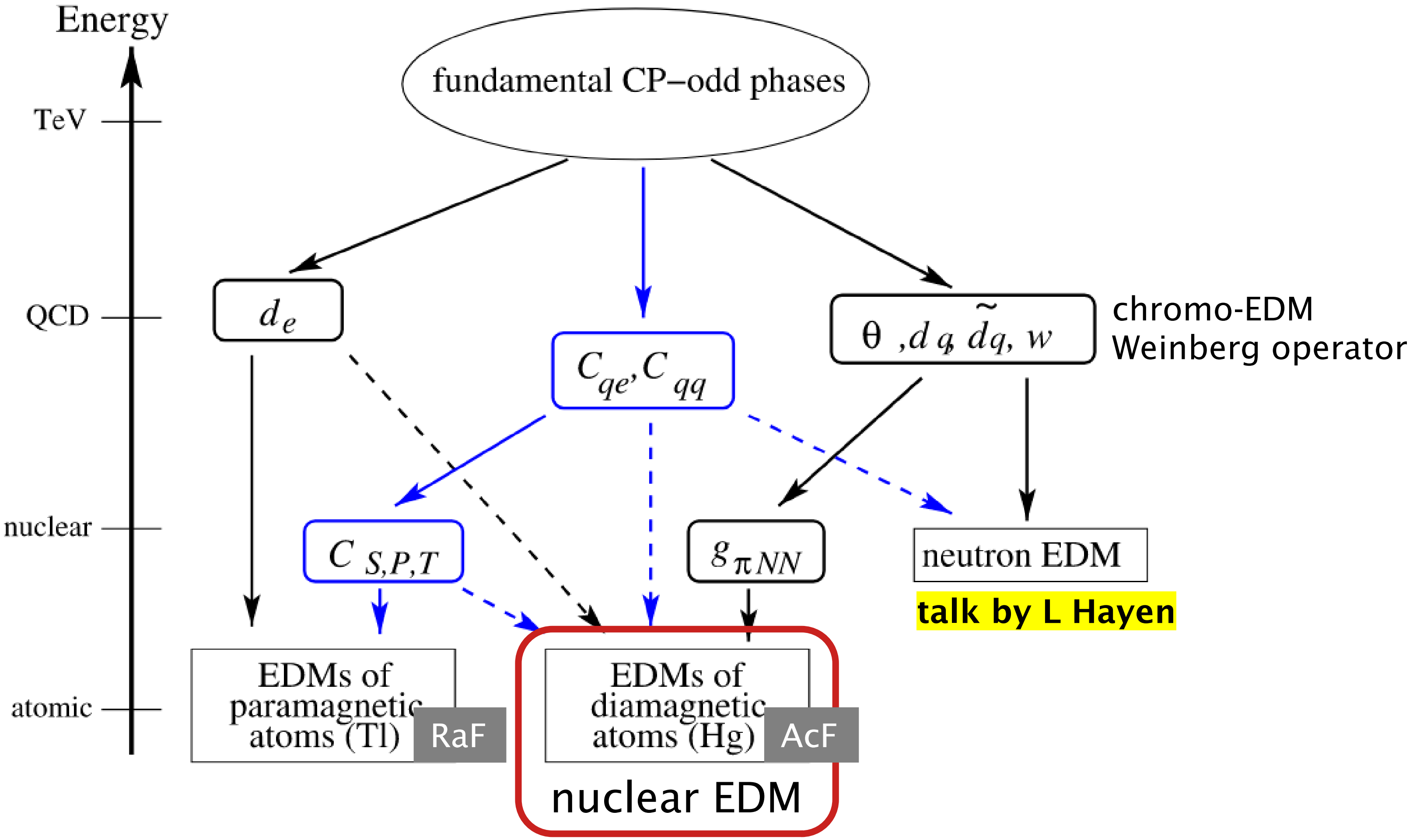
Cossel et al., Chemical Physics Letters 546, 1 (2012)
Cairncross and Ye, Nature Reviews Physics 1, 510 (2019)



Ramsey spectroscopy
$P = \cos^2((\omega-\omega_0)t/2)$

for unpaired electrons:
electron paramagnetic resonance

1.2 What are we looking for: Schiff moment



talk by L Hayen

Pospelov and Ritz, Annals of Physics 318 (2005)

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

Schiff, Physical Review 132 (1963)

1.2 What are we looking for: Schiff moment

outlying p-electron falls back into s-orbital by screened EDM ie Schiff moment

P-odd EDM scatters core-penetrating s-electron into p-orbital

$$d_{\text{atom}} = 2\sum_{m} \frac{\langle ns|-e\varphi(\mathbf{R})|mp\rangle\langle mp|-e\mathbf{R}|ns\rangle}{E_{ns}-E_{mp}}$$

the closer the energy, the larger the contribution

$$\langle s|-e\varphi^{(1)}|p\rangle = 4\pi e\mathbf{S}\cdot(\nabla\psi_s^{\dagger}\psi_p)_{R\to 0}$$

$$\mathbf{S} = \frac{e}{10}\left[\langle r^2\mathbf{r}\rangle - \frac{5}{3Z}\langle r^2\rangle\langle\mathbf{r}\rangle\right]$$

P,T-odd deformation

EDM screening

Flambaum and Ginges, PRA 65 (2002)

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)

1.2 What are we looking for: Schiff moment

in atoms

- relativistic s-electrons dive deep into heavy **Z** nucleus...
- ... and sense octupole deformation **β_3** from within

  $\beta_3(^{229}\mathrm{Th}) = 0.115$

  Minkov and Palffy, Phys. Rev. Lett. 118 (2017)

  $S(^{229}\mathrm{Th}) \sim 600 \times S(^{\mathrm{nat}}\mathrm{Tl})$ ie **2–3 orders of magnitude**

  Flambaum, Phys. Rev. C 99 (2019)

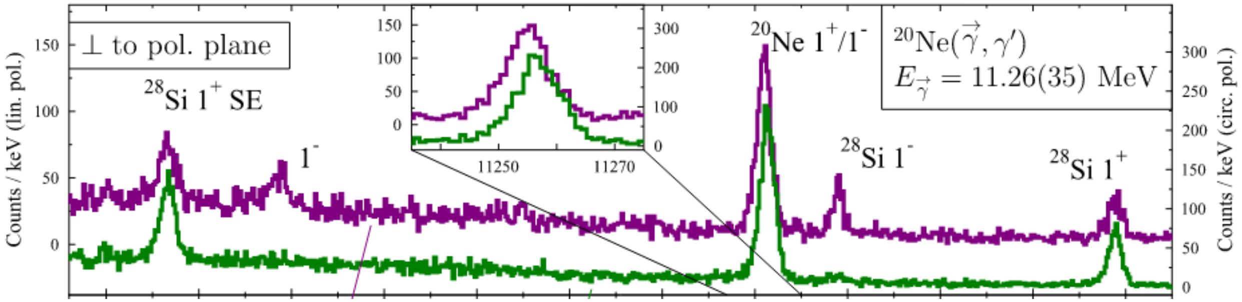
in molecules

- $\Delta E(-m_F, m_F)$ amplified by **internal fields** as strong as 104 GV/cm in HgF

  Prasannaa, Vutha, Abe, and Das, Phys. Rev. Lett. 114 (2015)
- energy shift in parity doublet $\Delta E(F^+, F^-) = \dfrac{D\mathcal{E}}{\sqrt{(\boldsymbol{\Delta}/2)^2 + D^2\mathcal{E}^2}}\,\delta_{P,T}$

  6-9 orders of magnitude smaller than in atoms

  Safronova et al., Rev. Mod. Phys. 90 (2018)



Beller et al, Physics Letters B 741 (2015) 128

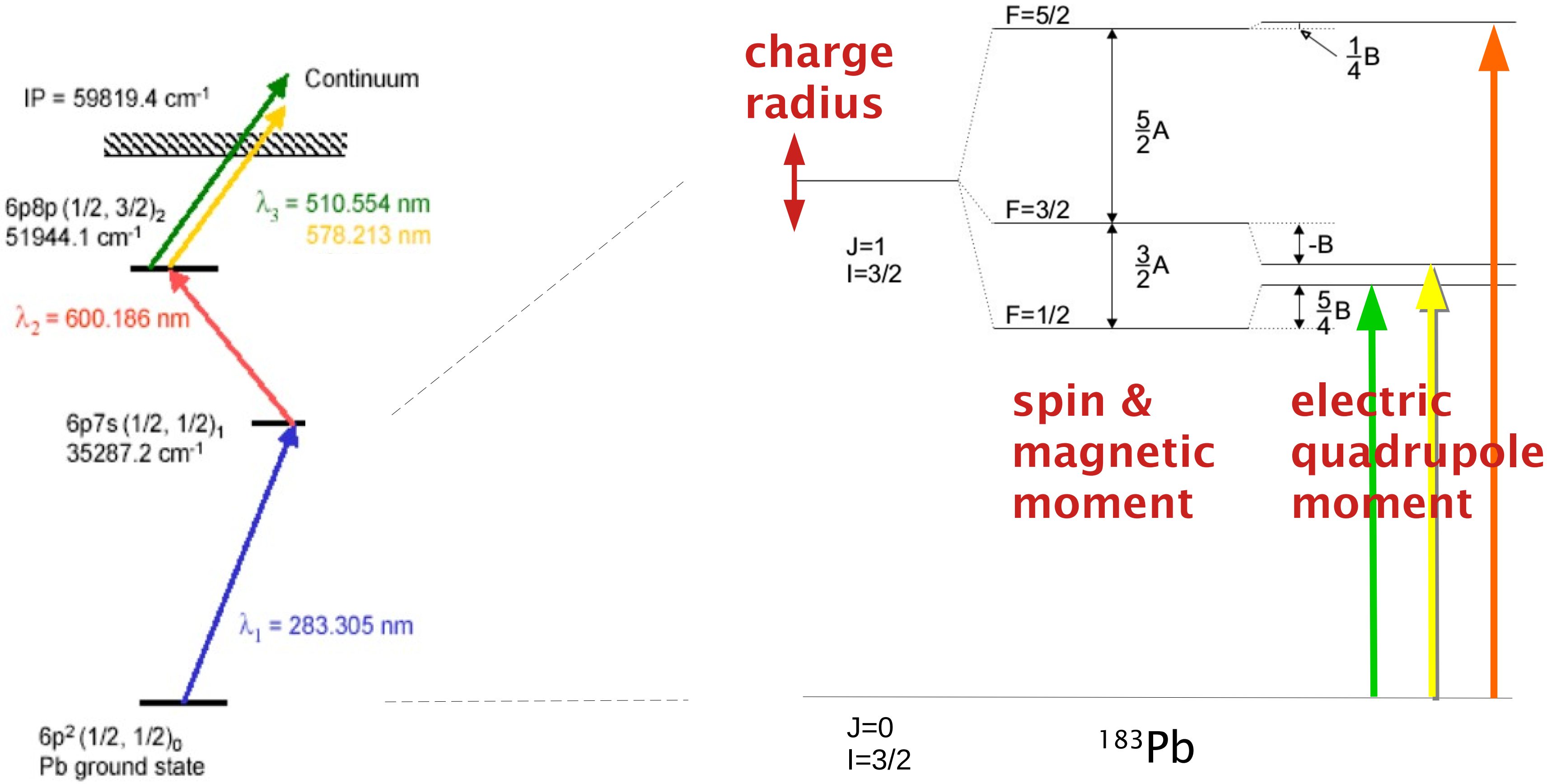
in ^{20}Ne, ΔE=3.2 keV
in atoms, ~ eV
in ThO, ~ neV !

in radioactive molecules, combine heavy nucleus with molecular enhancement:
laser spectroscopy of RaF and AcF at Isolde

1.3 Laser spectroscopy

laser ion source:
broadband lasers (~10 GHz)

laser spectroscopy:
narrowband lasers (<100 MHz)



charge radius

spin & magnetic moment

electric quadrupole moment

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

2.1 at Isolde

RaF: 10^3 available states...
Theory predicts 13300(1000) cm^{-1} ($\lambda\nu=c$, 1.65 eV, 752 nm)

R Berger, priv. comm.

Scanning 1000 cm^{-1} = 30 THz at 10 MHz/min
... 2080 days!

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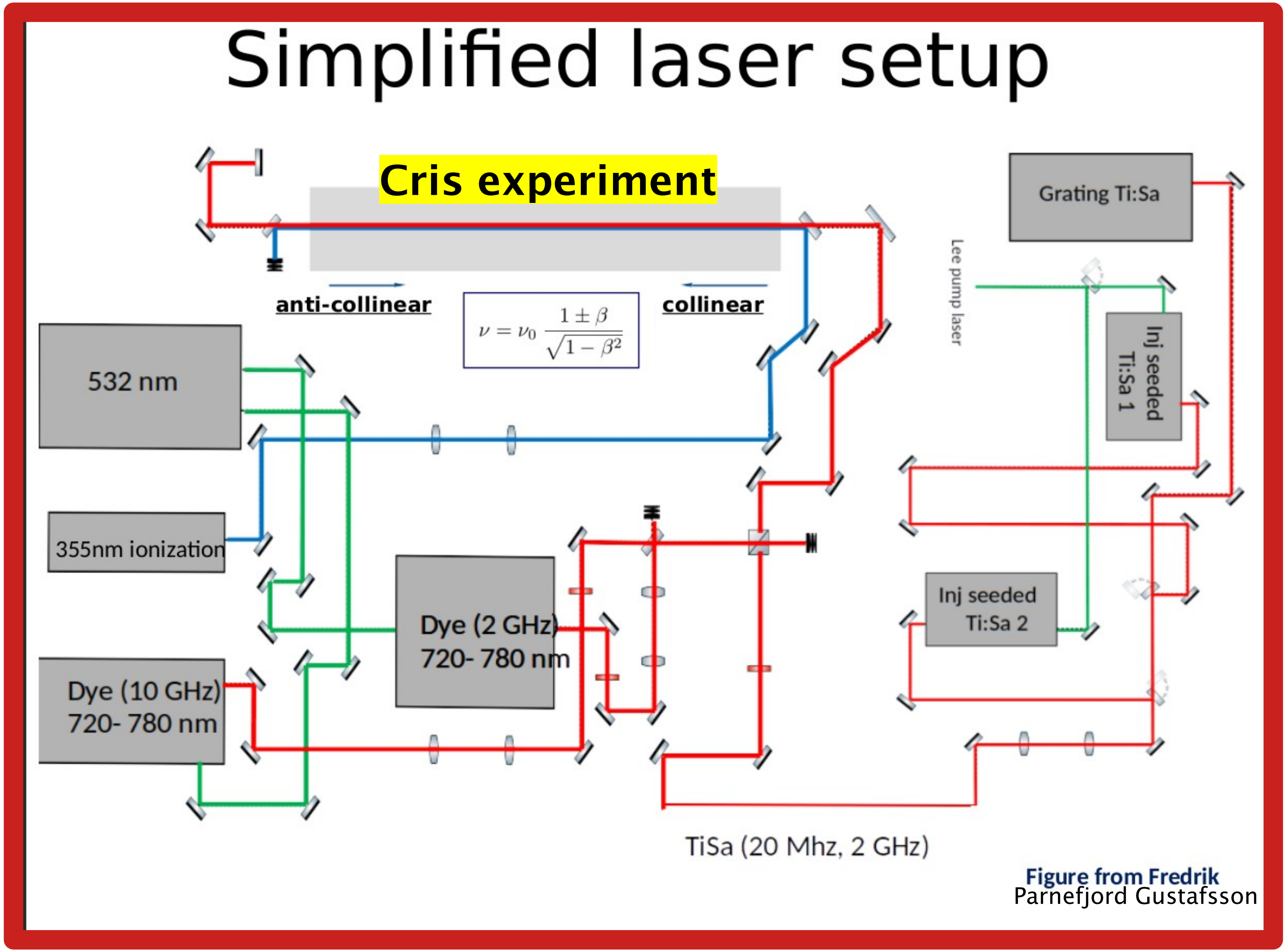

Figure from Fredrik Parnefjord Gustafsson

- many lasers
- cooling in RFQ-B

... signal already within 4 hours!

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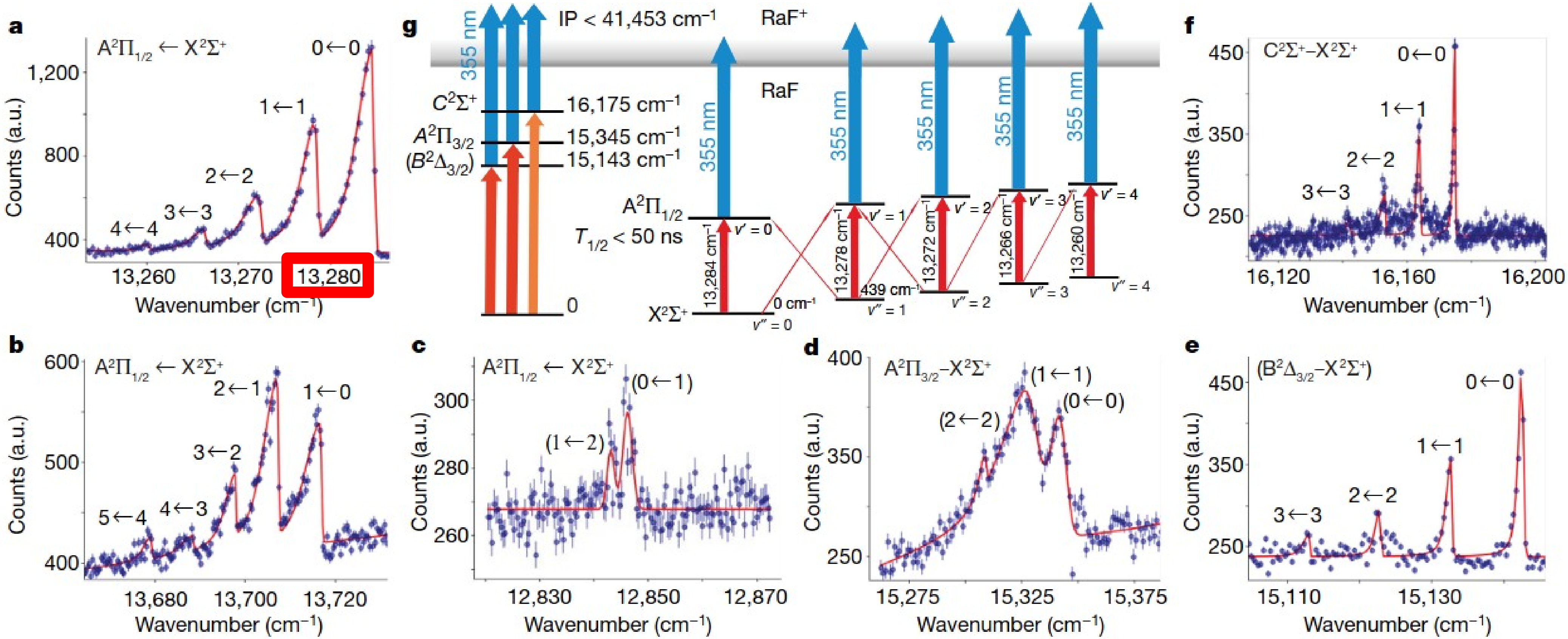

- low-lying structure & Ionisation potential
- laser cooling scheme
- ^{223}RaF, ^{224}RaF, ^{225}RaF, ^{226}RaF, ^{228}RaF

Garcia Ruiz et al, Nature 581, 396 (2020)

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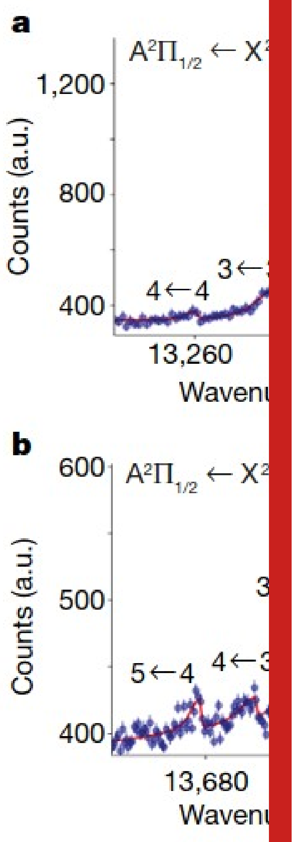
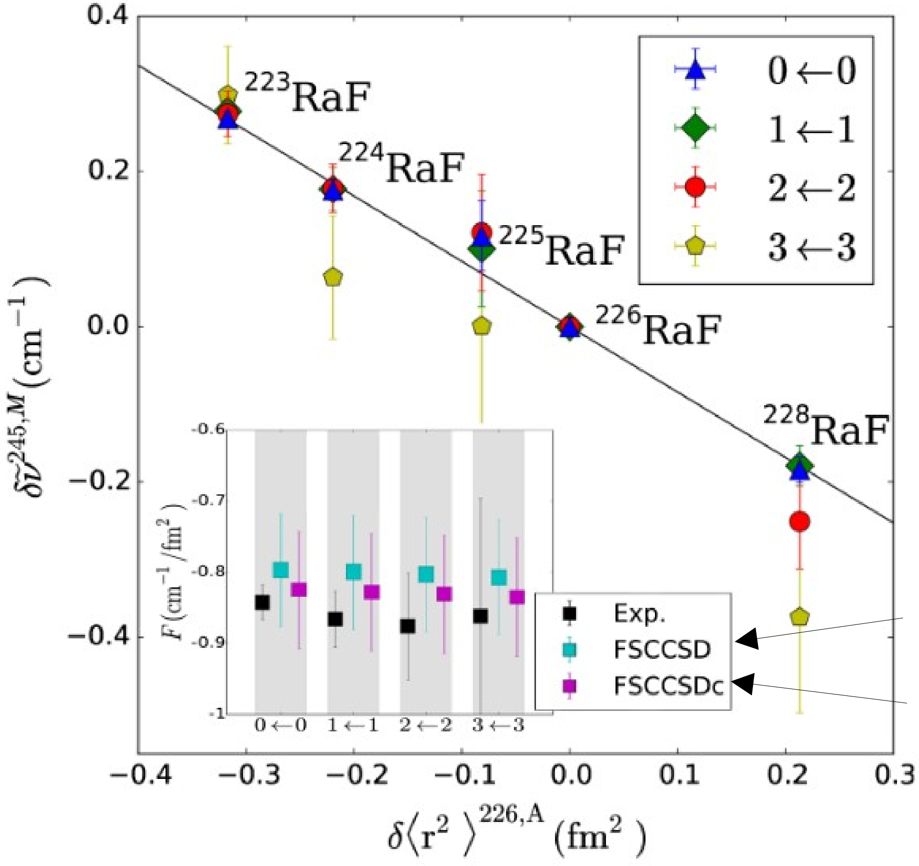
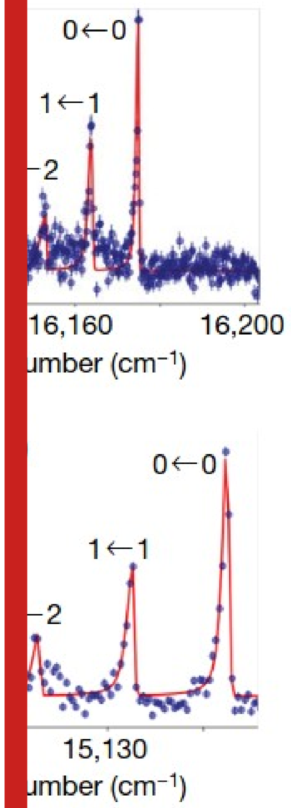




relativistic Fock-Space Coupled Cluster Single and Double amplitudes correlating 17 electrons

estimation for extended basis with 27 electrons

Udrescu et al., Phys. Rev. Lett. 127, 033001 (2021)



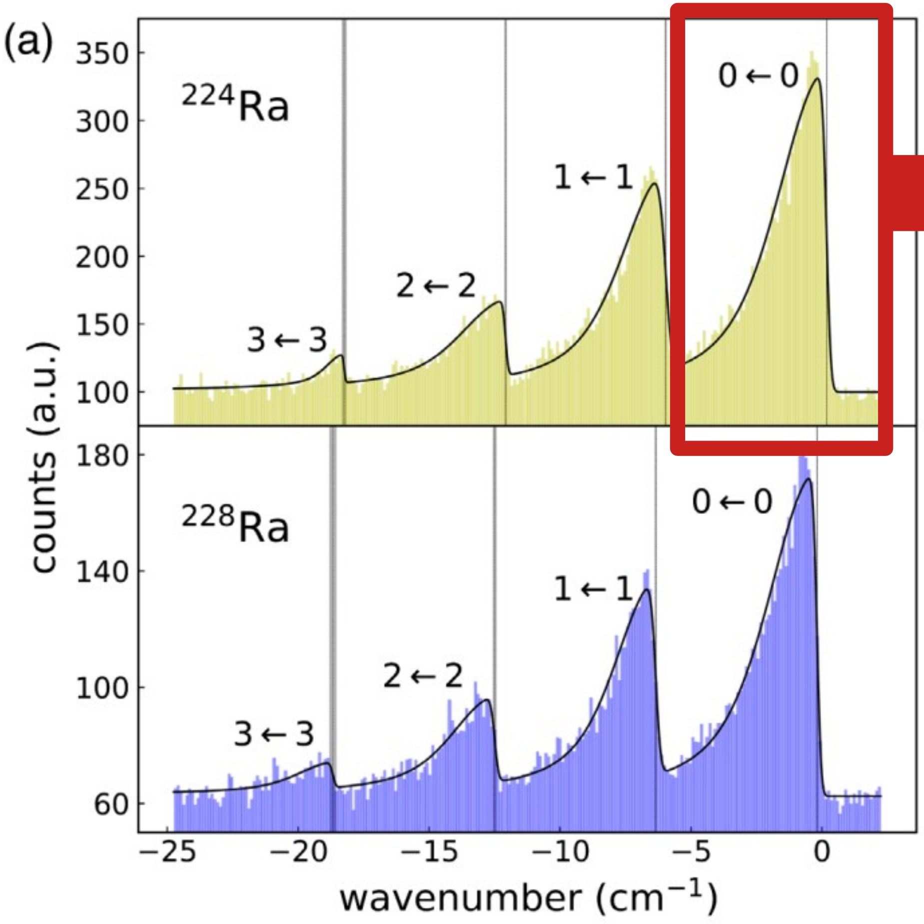
- laser cooling scheme
- ^{223}RaF, ^{224}RaF, ^{225}RaF, ^{226}RaF, ^{228}RaF

Garcia Ruiz et al., Nature 581, 396 (2020)

2.1 at Isolde

RaF low resolution

$A^2\Pi \leftarrow X^2\Sigma$ isovibrational bands
FWHM ~10 GHz

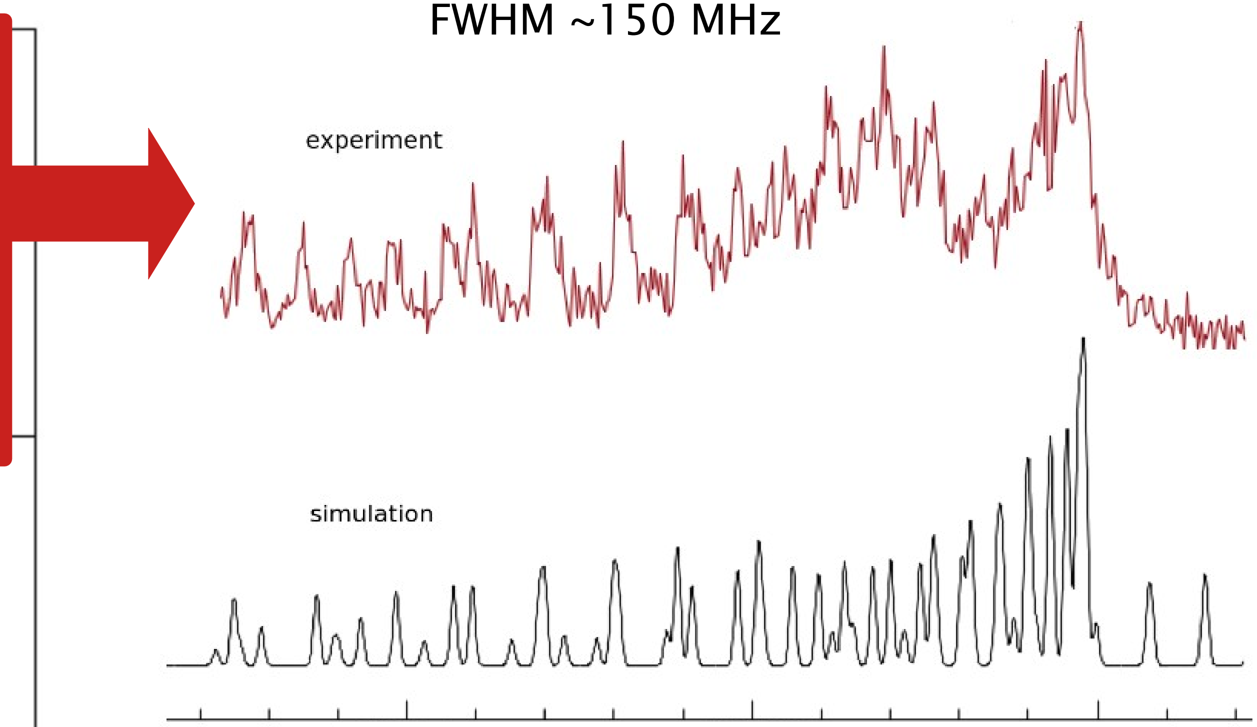


extract isotope shift

RaF high resolution

rotational spectrum
within one band

FWHM ~150 MHz



rotational & hyperfine parameters needed for accessing fundamental physics

Udrescu et al, submitted to Nature Physics (2023)

2.1 at Isolde

why?

search for symmetry breaking in relativistic heavy nuclei
molecular enhancement by several orders of magnitude

how?

probe tiny anomalies in hyperfine structure
need large number of particles in small number of states
cooling to room temperature in RFQB yields v=v'

2.2 at S3

set-up for laser spectroscopy in gas jet... can be used rightaway!

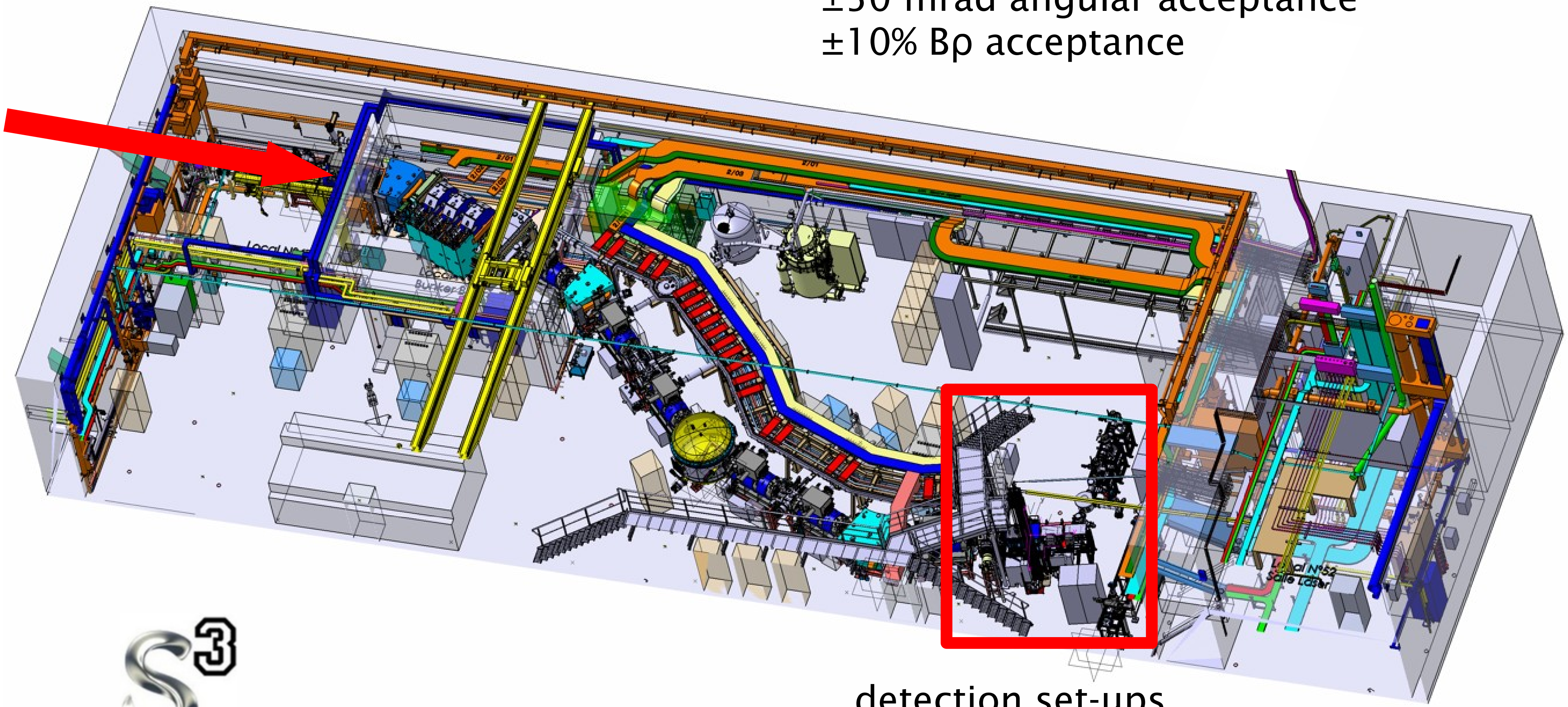
supersonic expansion cools to 20 K
implement gas mixture for molecule formation
look for scheme with scanning laser + 355 nm
reduce background with intermediate step + 1064 nm

(trans)actinides are major physics case at S3

2.2 at S3

Spiral-2 S^3 spectrometer

10 pμA = 10^{14} pps beam on target
10^{13} beam rejection
1/300 mass resolution
±50 mrad angular acceptance
±10% Bρ acceptance



detection set-ups

2.2 at S3

Heavy & Very Heavy Nuclei

Nuclear structure ◌ A/Q=3 ○ A/Q=7

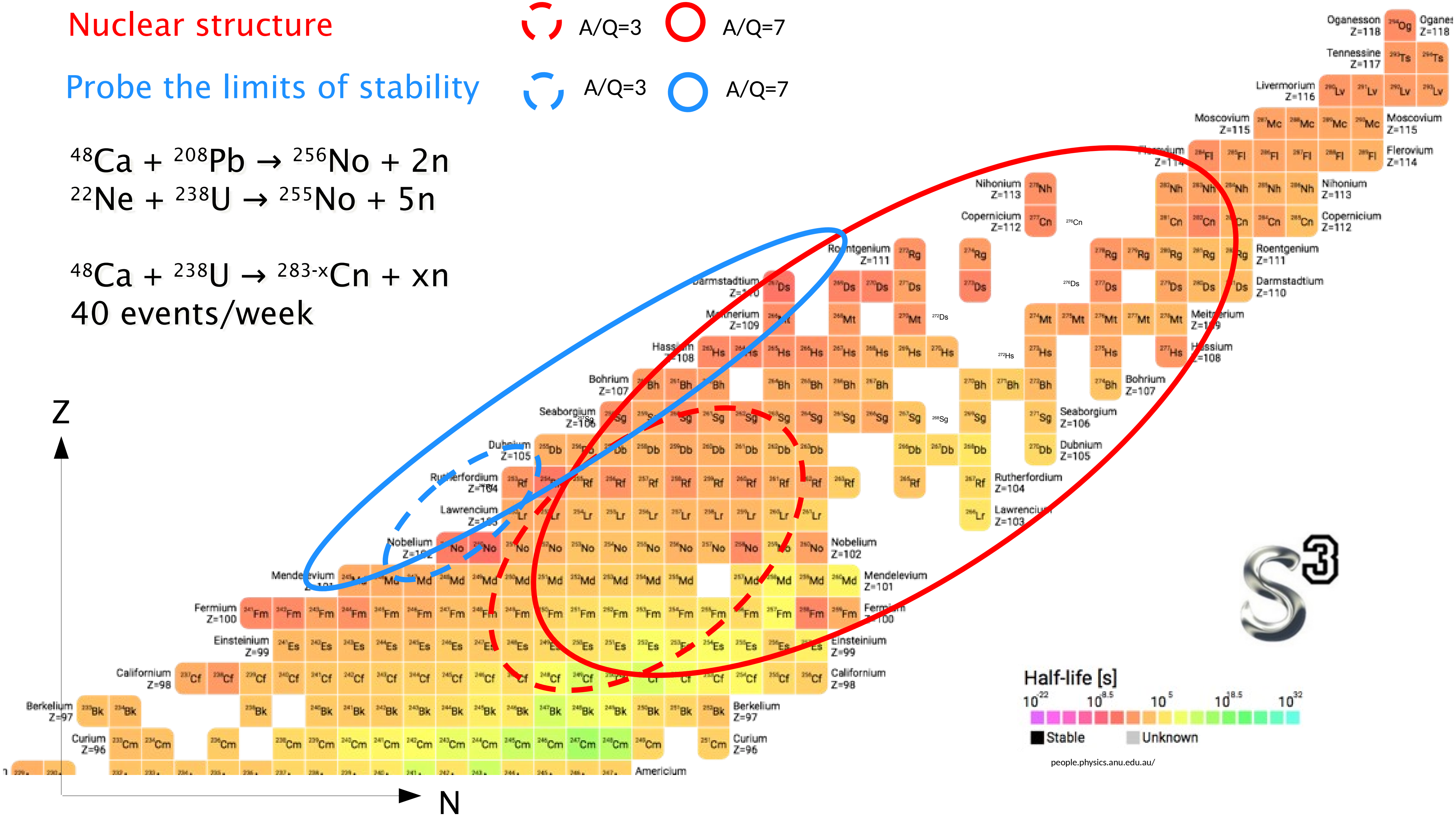
Probe the limits of stability ◌ A/Q=3 ○ A/Q=7

$^{48}Ca + ^{208}Pb \rightarrow ^{256}No + 2n$

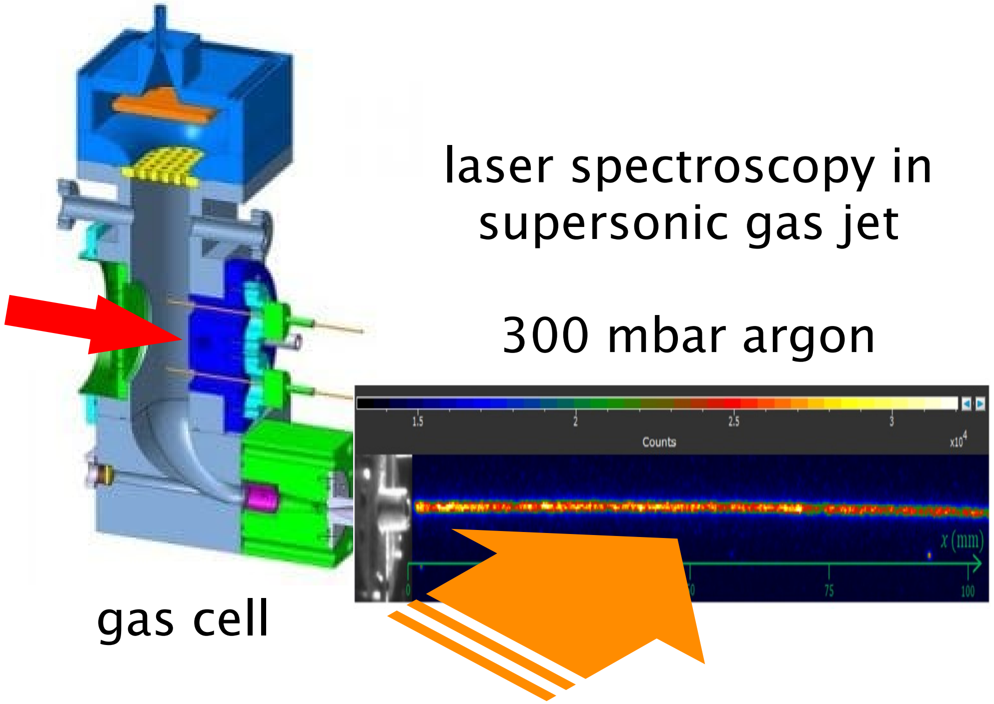
$^{22}Ne + ^{238}U \rightarrow ^{255}No + 5n$

$^{48}Ca + ^{238}U \rightarrow ^{283-x}Cn + xn$

40 events/week



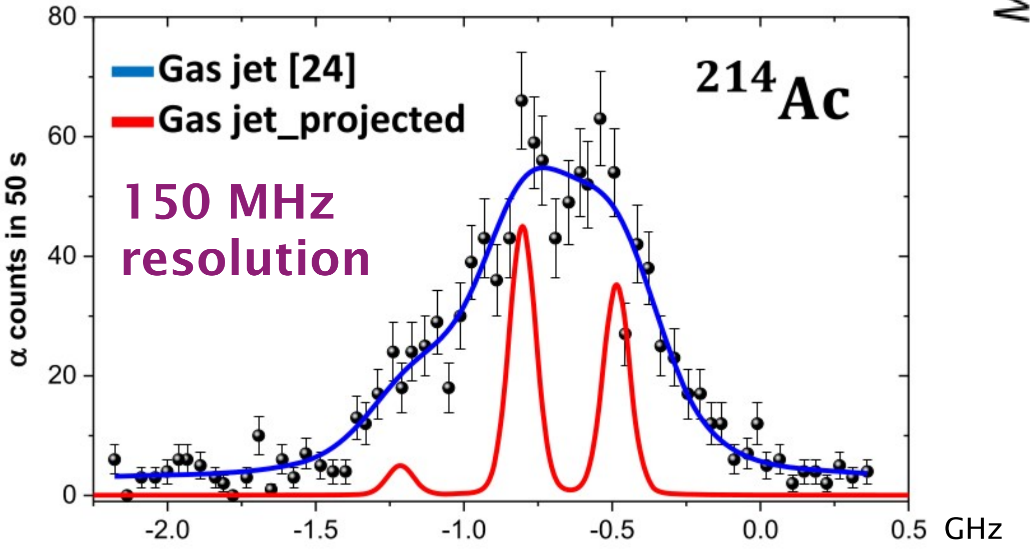
2.2 at S3



laser spectroscopy in supersonic gas jet

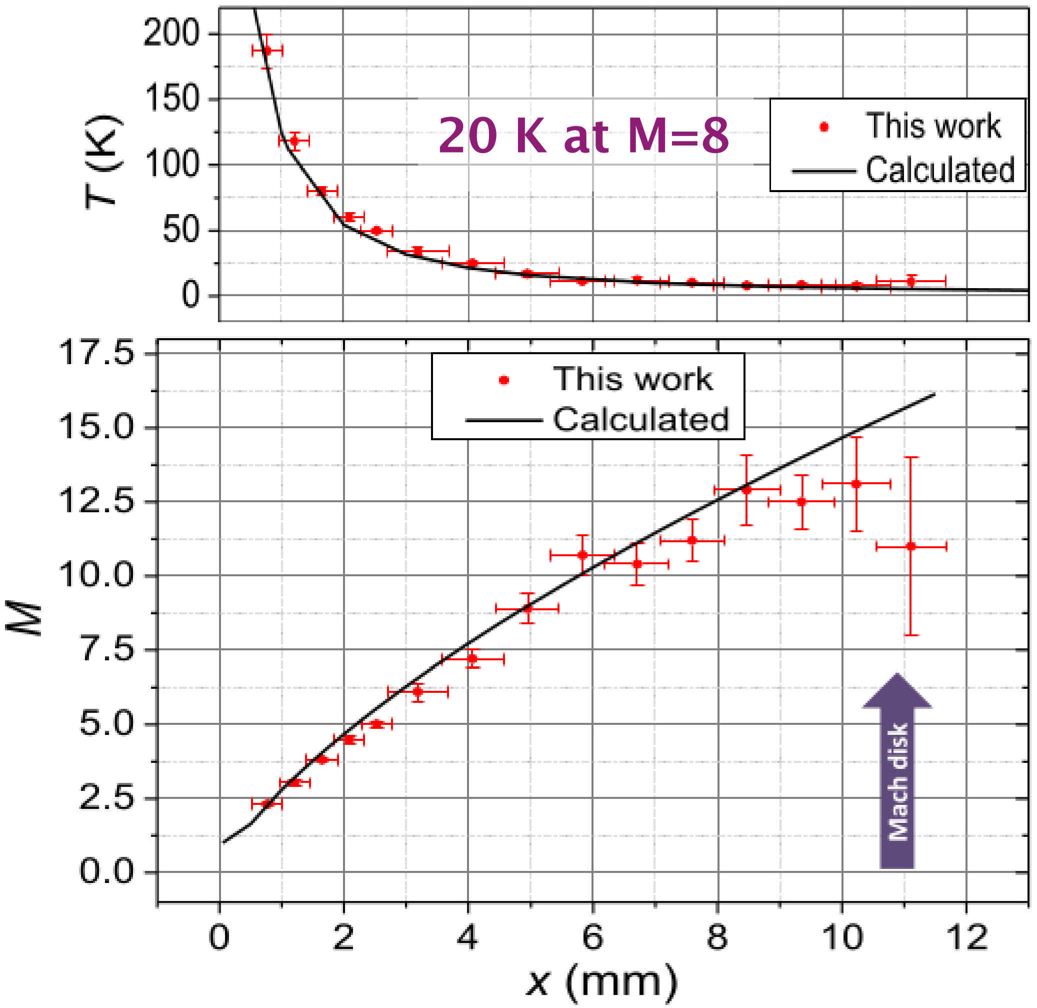
300 mbar argon

gas cell



150 MHz resolution

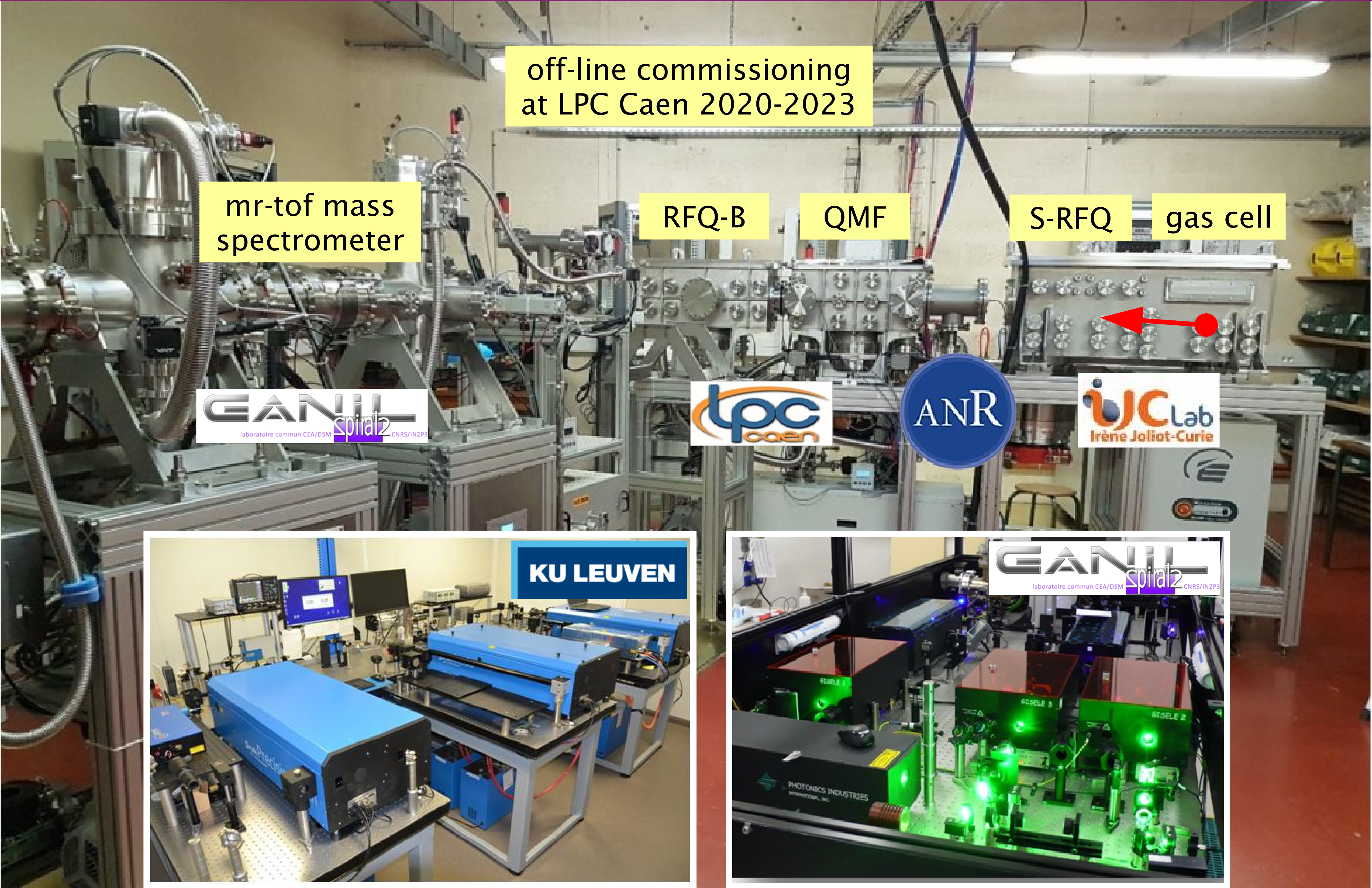
Ferrer et al., Nat. Comm. 8 (2017)



20 K at M=8

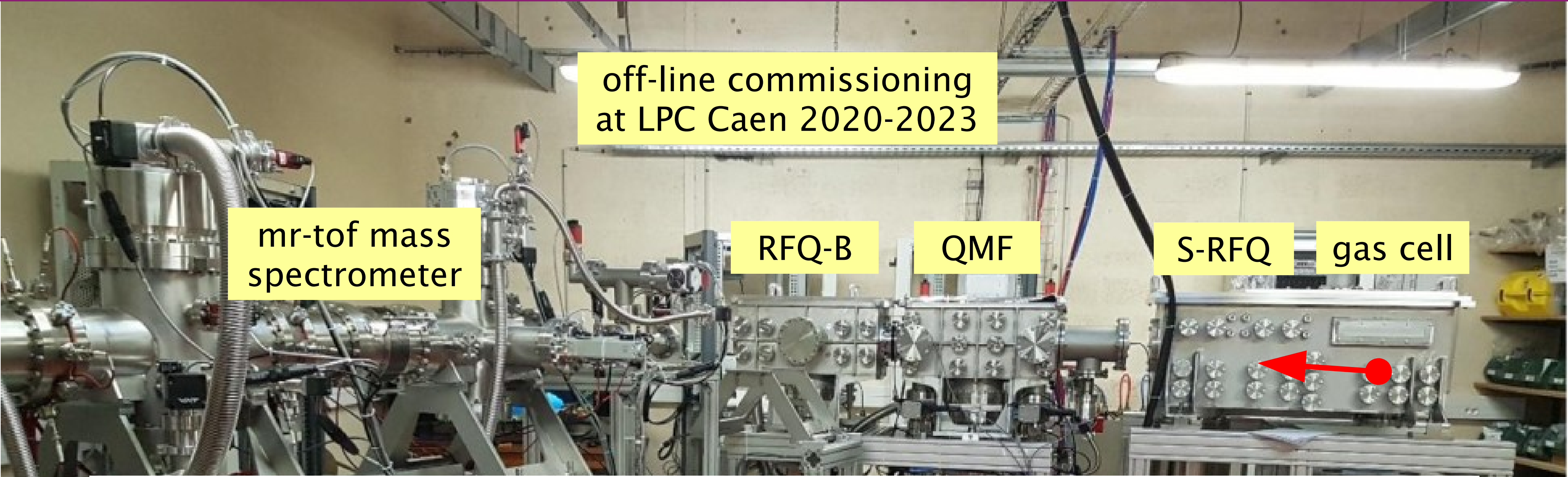
Zadvornaya et al., Phys. Rev. X 8, 041008 (2018)

2.2 at S3



off-line commissioning at LPC Caen 2020-2023

2.2 at S3



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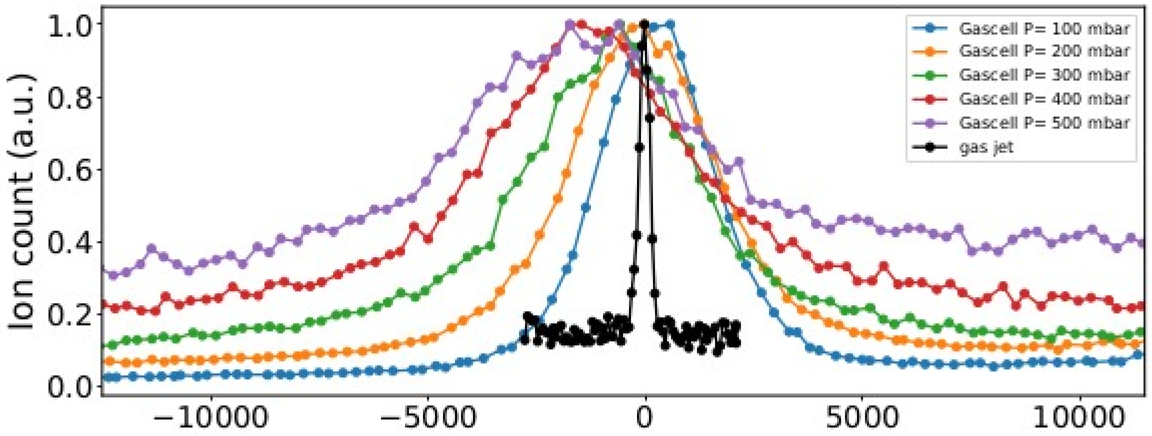
mr-tof mass spectrometer

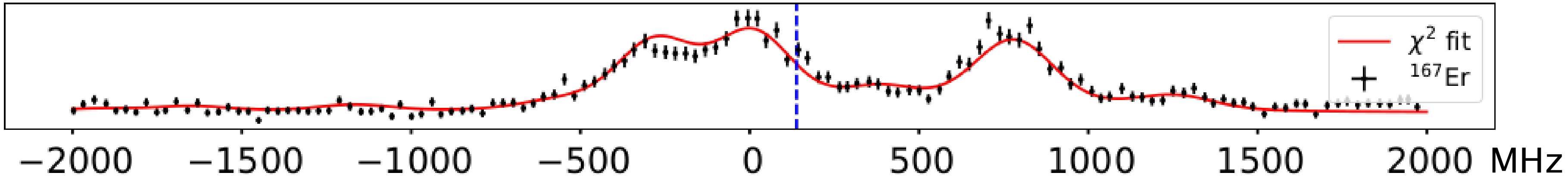
RFQ-B

QMF

S-RFQ

gas cell





A Ajayakumar et al, accepted in NIMB (2023)

Conclusions

8 orders of magnitude between Standard Model and experiment

Schiff theorem is overcome in heavy, octupole-deformed nuclei;
enormous enhancement from parity doublets in molecules

laser spectroscopy at Cris limited by T = 300 K
laser spectroscopy at S3 down to T = 20 K
genuine precision experiments at Desir or Orsay?

need nuclear spectroscopy of parity doublets
need theoretical guidance for S, MQM...

to be continued...

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Irène Joliot-Curie