Radioactive Molecules

Novel Probes for New Physics

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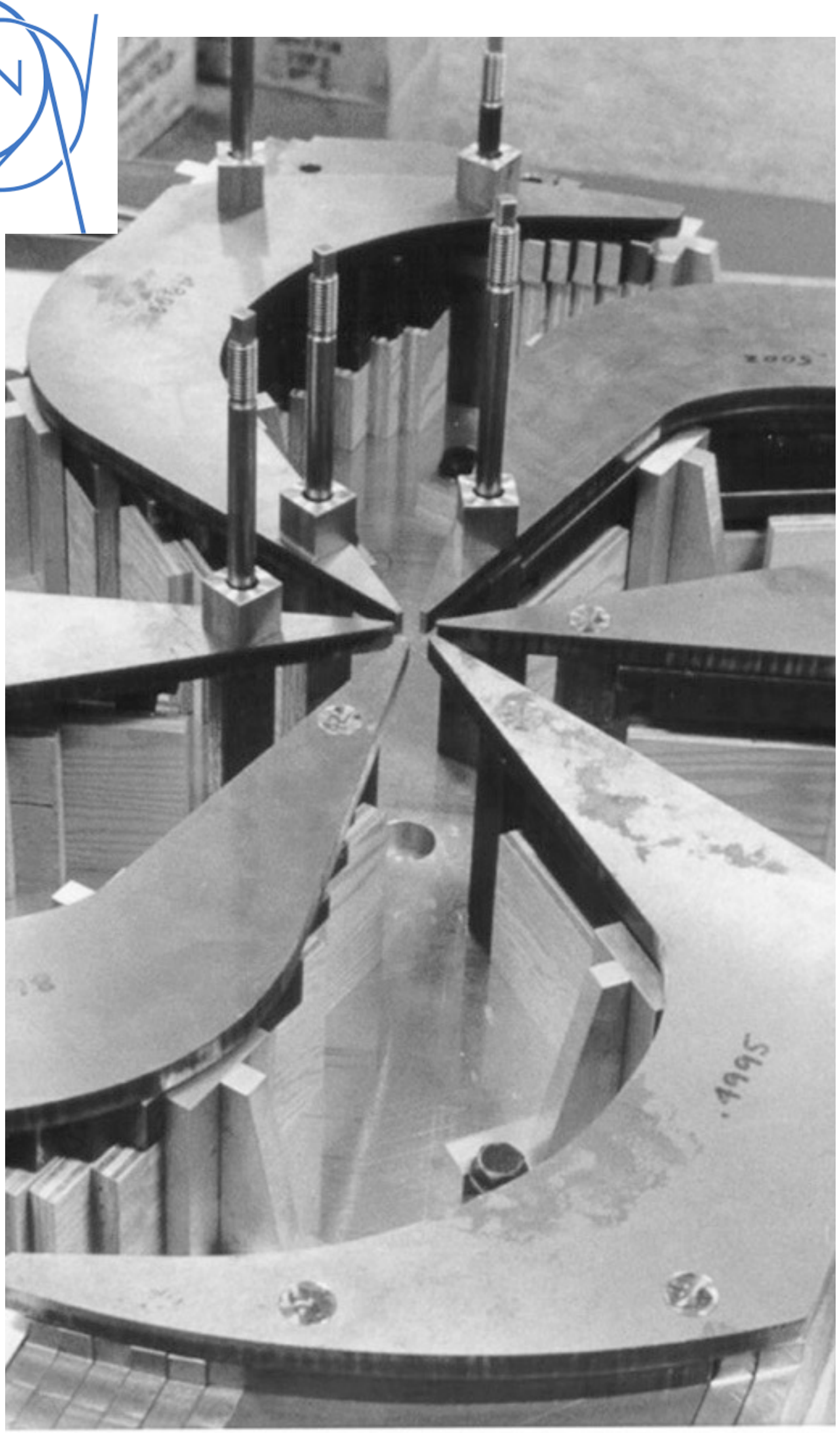
TRIUMF, University of Toronto, CERN

Humboldt Kolleg Kitzbühl 2022

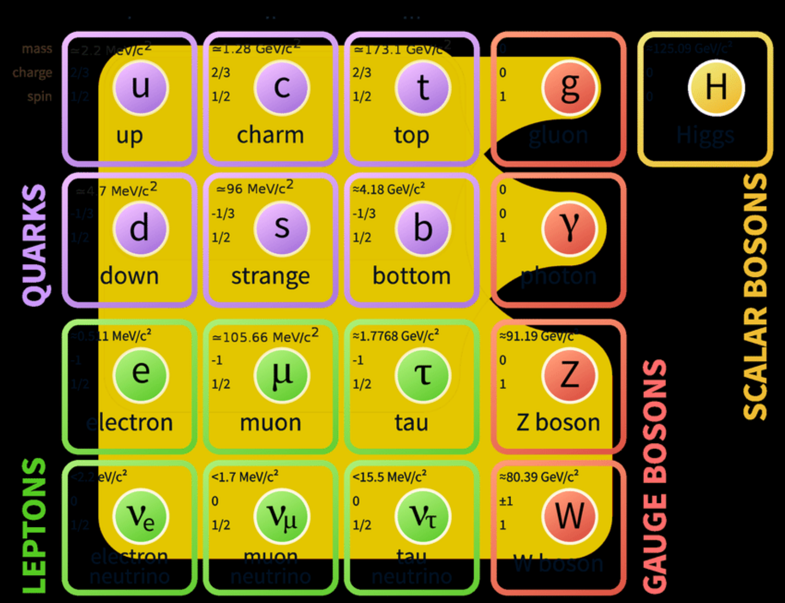


Discovery, accelerated

Fundamental symmetries

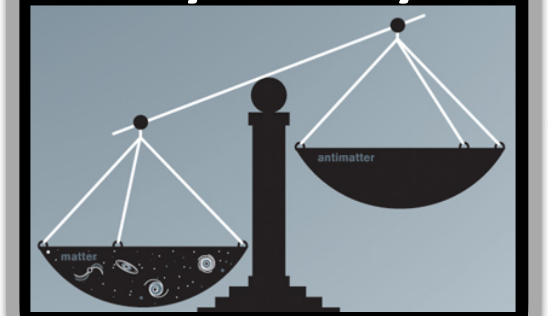
incredibly successful

Standard Model

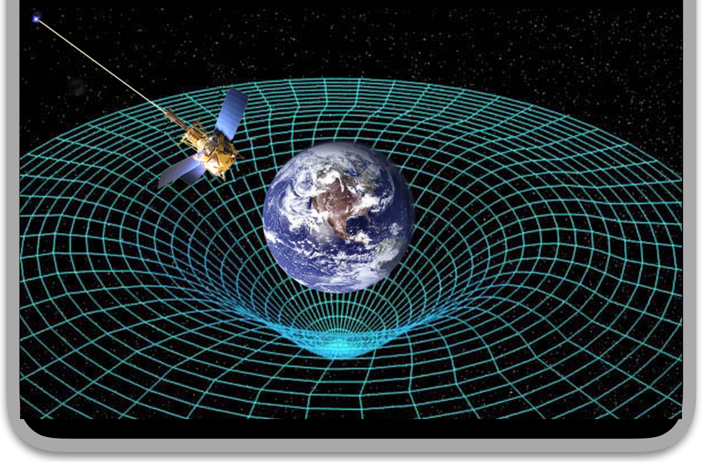


Fundamental symmetries

matter-antimatter asymmetry

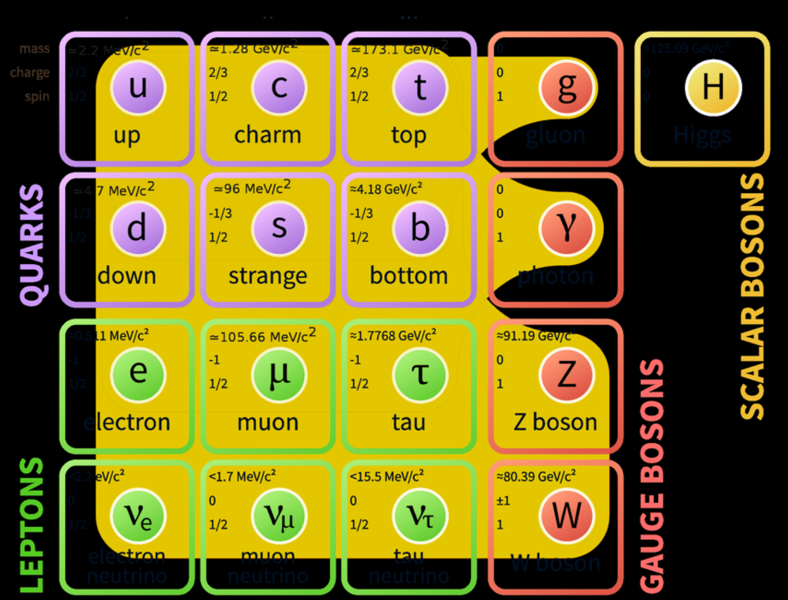


misses gravity



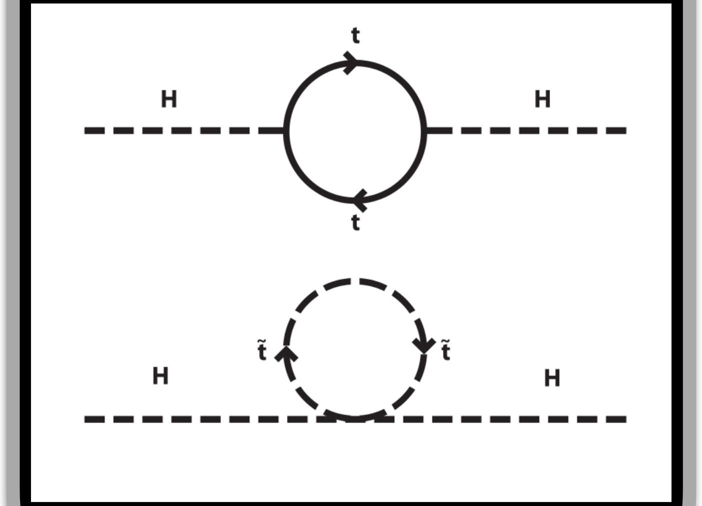
incredibly successful

Standard Model

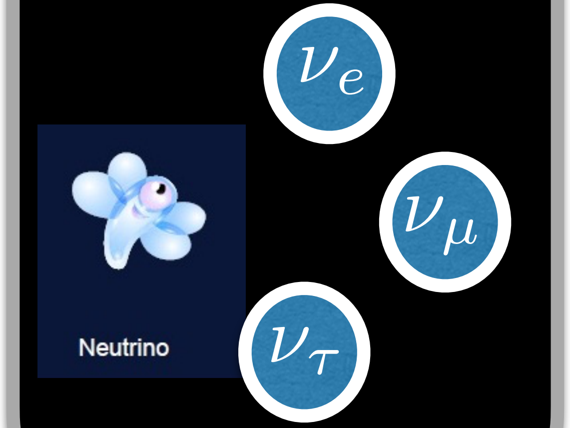


dark matter
dark energy

hierarchy problem



origin of neutrino masses



... yet incomplete

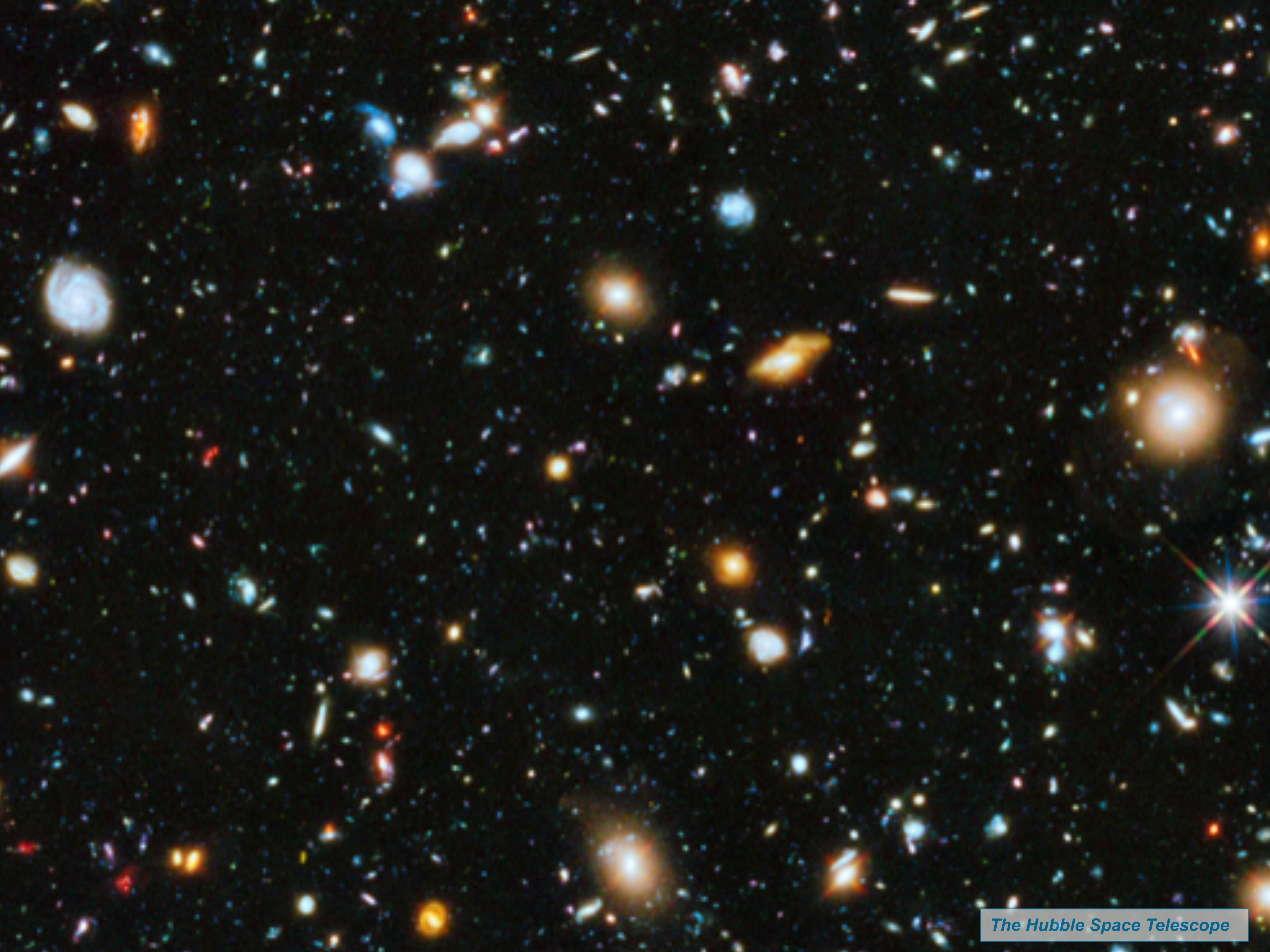
arbitrary constants:

m_e, m_μ, m_τ, m_u m_d, m_s, m_c, m_b, m_t, m_H,

$\theta_{12}, \theta_{13}, \theta_{23}, \delta, g_1, g_2, g_3, \theta_{QCD}$, v

? $m_{\nu e}$, $m_{\nu\mu}$, $m_{\nu\tau}$

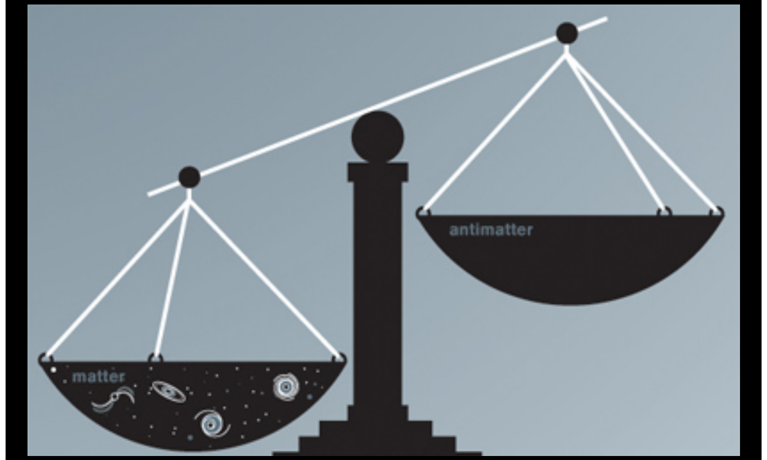
$\theta_{12}, \theta_{13}, \theta_{23}$, α_1, α_2 ?



The Hubble Space Telescope

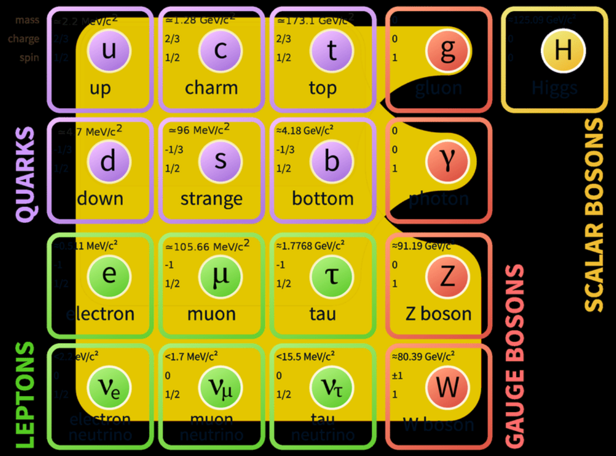
where is all the antimatter?

Macrocosmos



only matter

Microcosmos

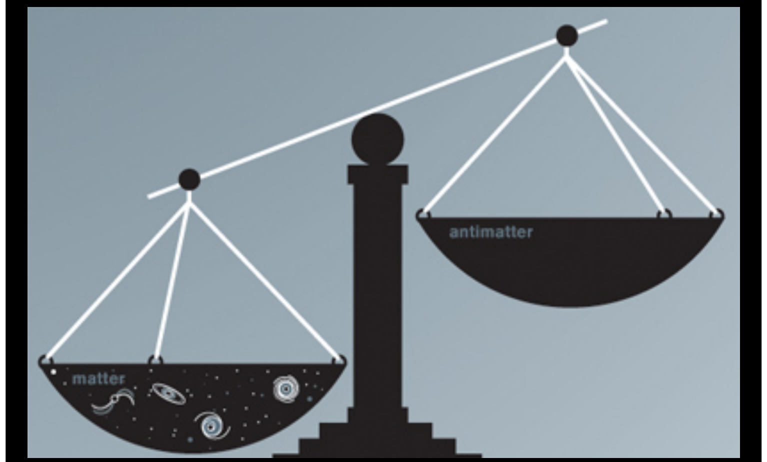


|matter|=|antimatter|

The Hubble Space Telescope

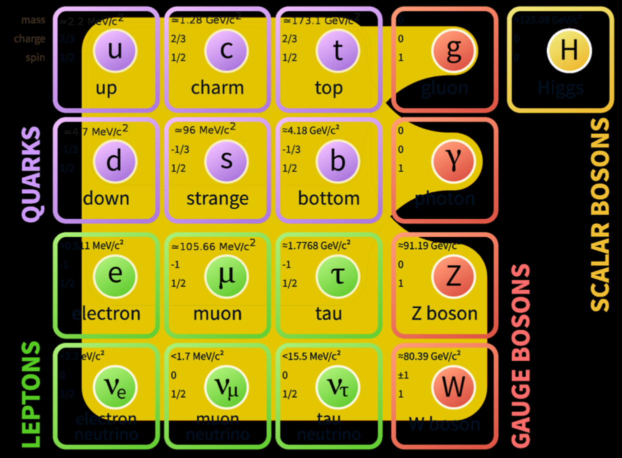
where is all the antimatter?

Macrocosmos



only matter

Microcosmos

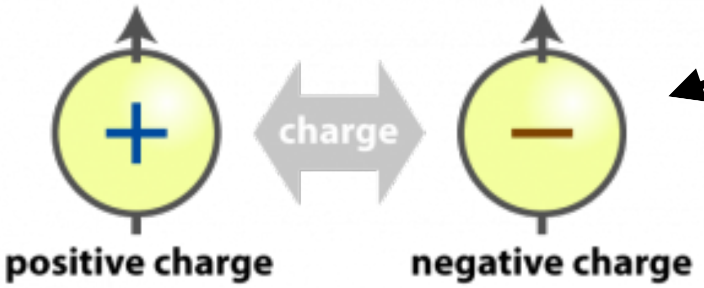


|matter|=|antimatter|

Sakharov, 1967

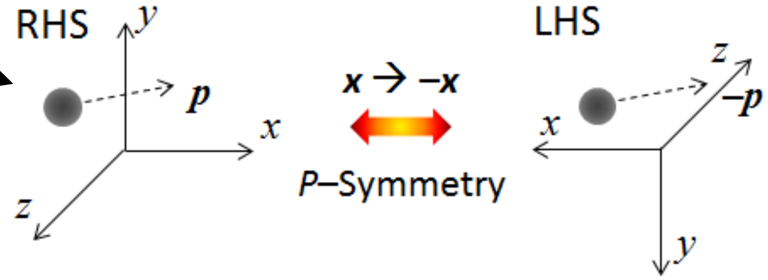
ingredient to resolve universe's matter-antimatter asymmetry:

C P violation



positive charge

negative charge

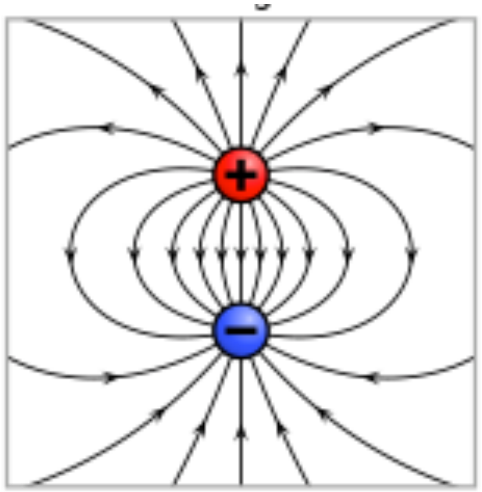


P–Symmetry

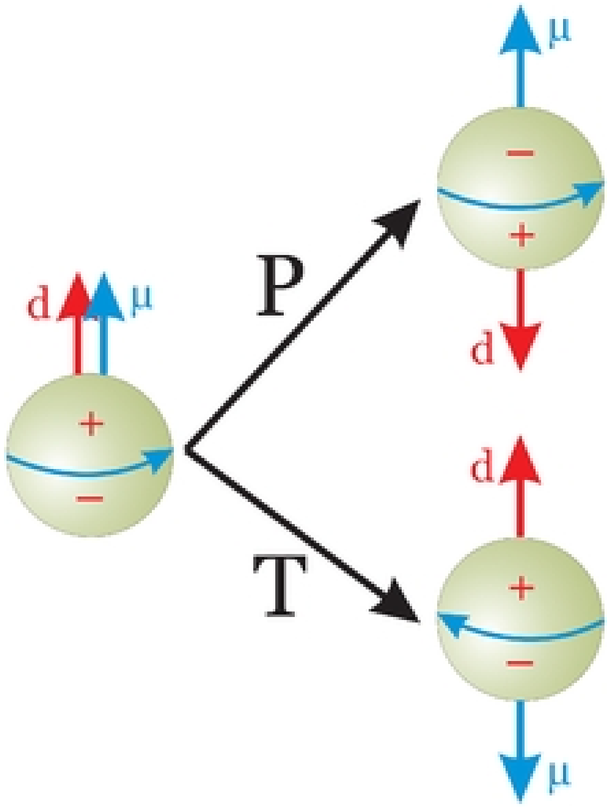
The Hubble Space Telescope

Permanent electric dipole moment

- local separation of the electric charge along a particle’s spin axis



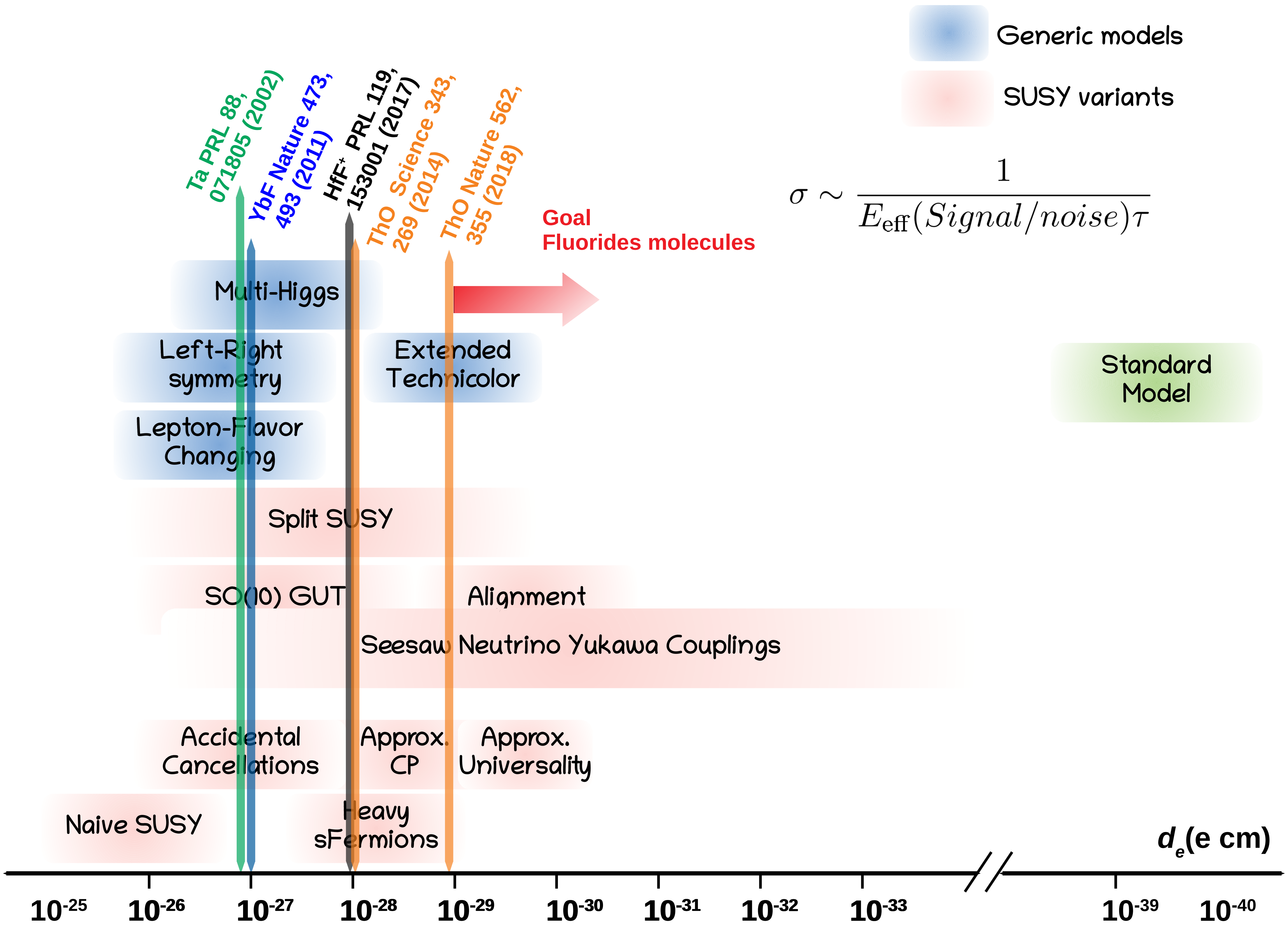
- implies time-reversal (T) violation ⇒ violation of CP symmetry (assuming CPT)



↕

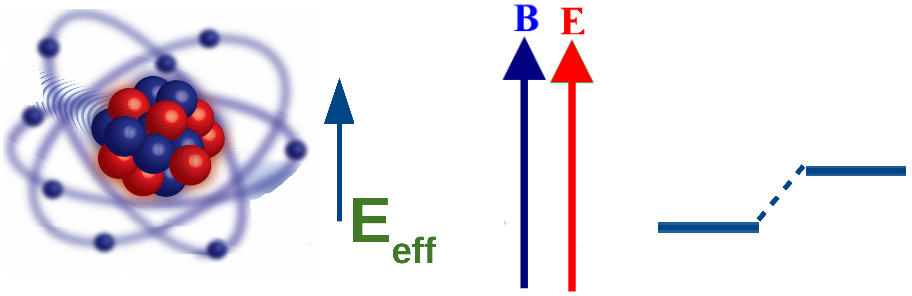
matter-antimatter asymmetry in the universe

Searches for an electron EDM



$$\sigma \sim \frac{1}{E_{\text{eff}}(Signal/noise)\tau}$$

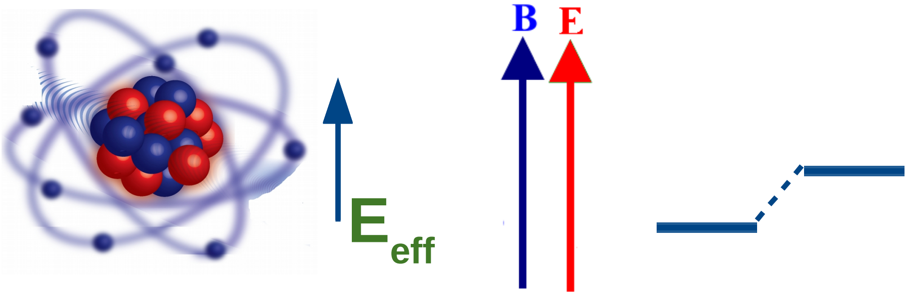
EDM searches in molecules



} $2\mu B + e_{\text{EDM}} E_{\text{eff}}$

$$\sigma_d \sim \frac{1}{E_{\text{eff}}\,\tau\sqrt{\dot{N}T}}$$

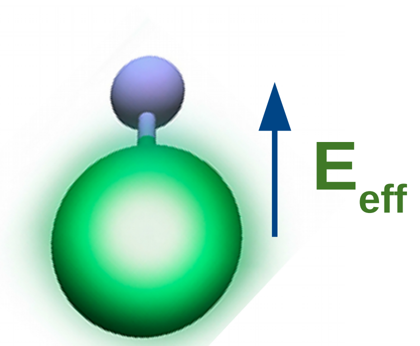
EDM searches in molecules



} $2\mu B + e_{EDM}E_{eff}$

$$\sigma_d \sim \frac{1}{E_{\text{eff}}\,\tau\sqrt{\dot{N}T}}$$

Molecules:



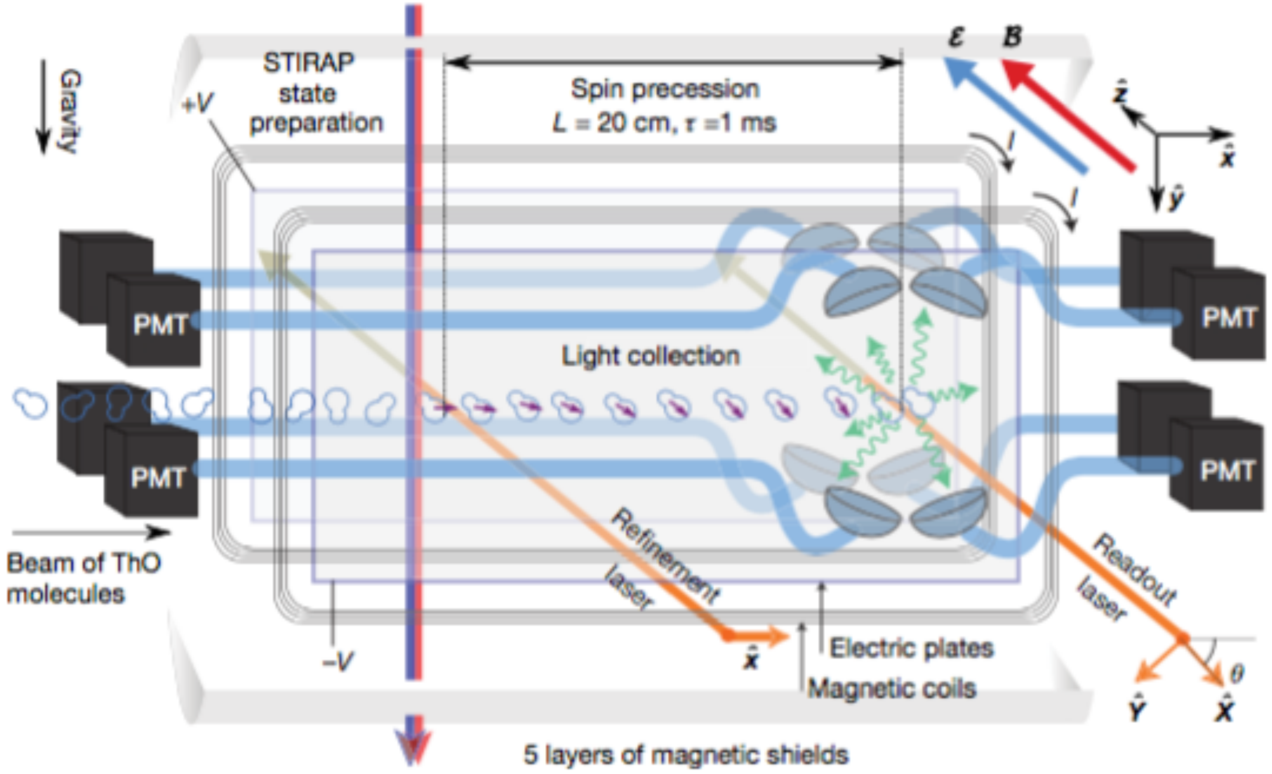
E_{ext} ~1 V/cm

E_{eff} ~80 GV/cm ⟶

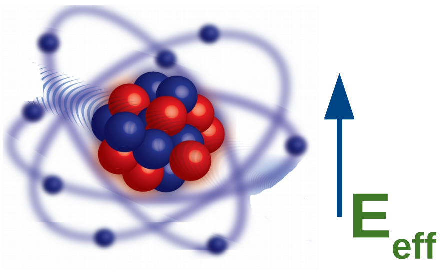
- enhancement by 10^3 in sensitivity!

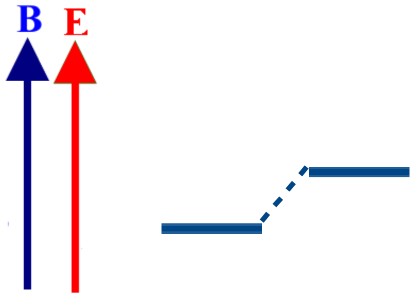
ThO

ACME collaboration
Science 343, 269(2014)
Nature 562, 355 (2018)



EDM searches in molecules





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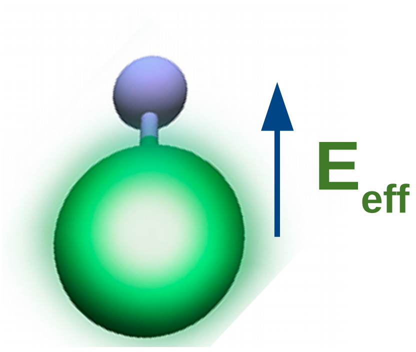
Molecules:



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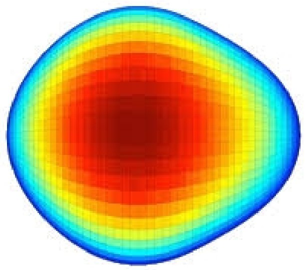
- scales as $Z^2R(Z)$

⇒ opportunity for radioactive molecules

Schiff moment



nuclear-spin-dependent component

‘Designer Molecules’

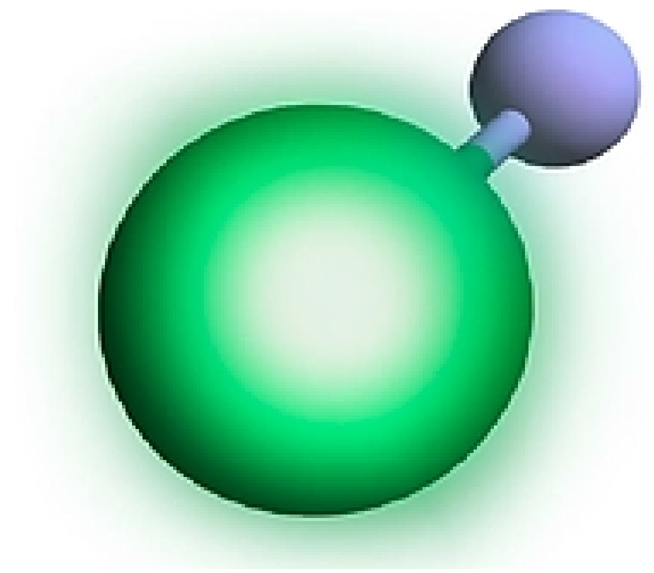
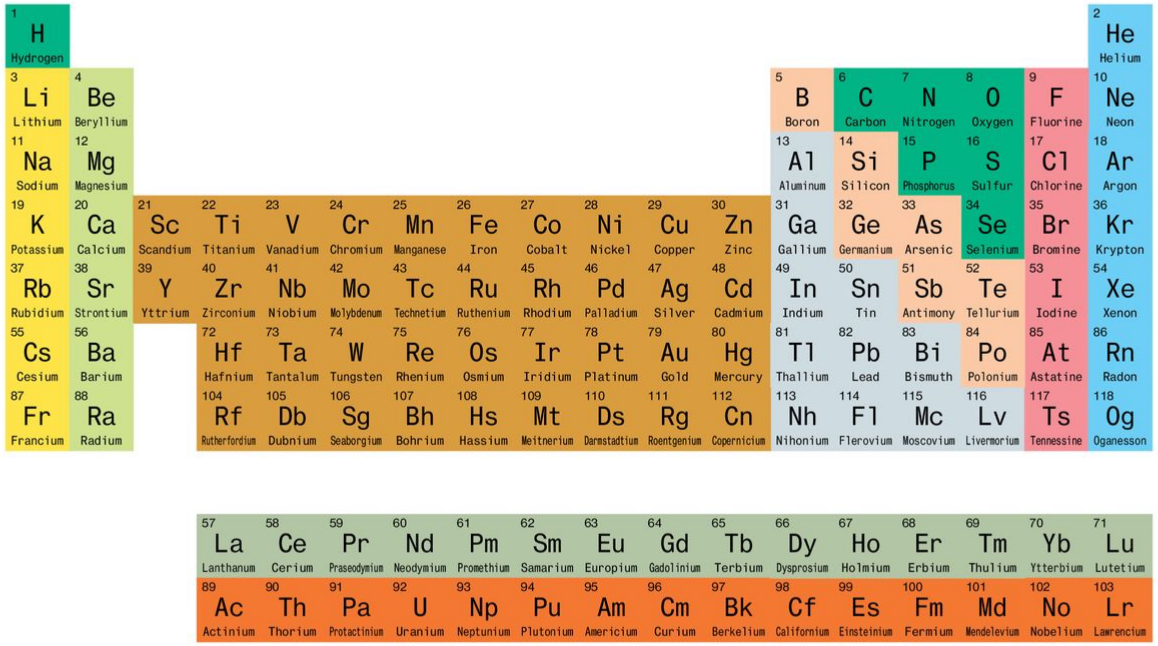


Table of Elements

80 chemical elements
(with stable nuclides)



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37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon
55 Cs Cesium	56 Ba Barium		72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
87 Fr Francium	88 Ra Radium		104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 Ds Darmstadtium	111 Rg Roentgenium	112 Cn Copernicium	113 Nh Nihonium	114 Fl Flerovium	115 Mc Moscovium	116 Lv Livermorium	117 Ts Tennessine	118 Og Oganesson

57 La Lanthanum	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium
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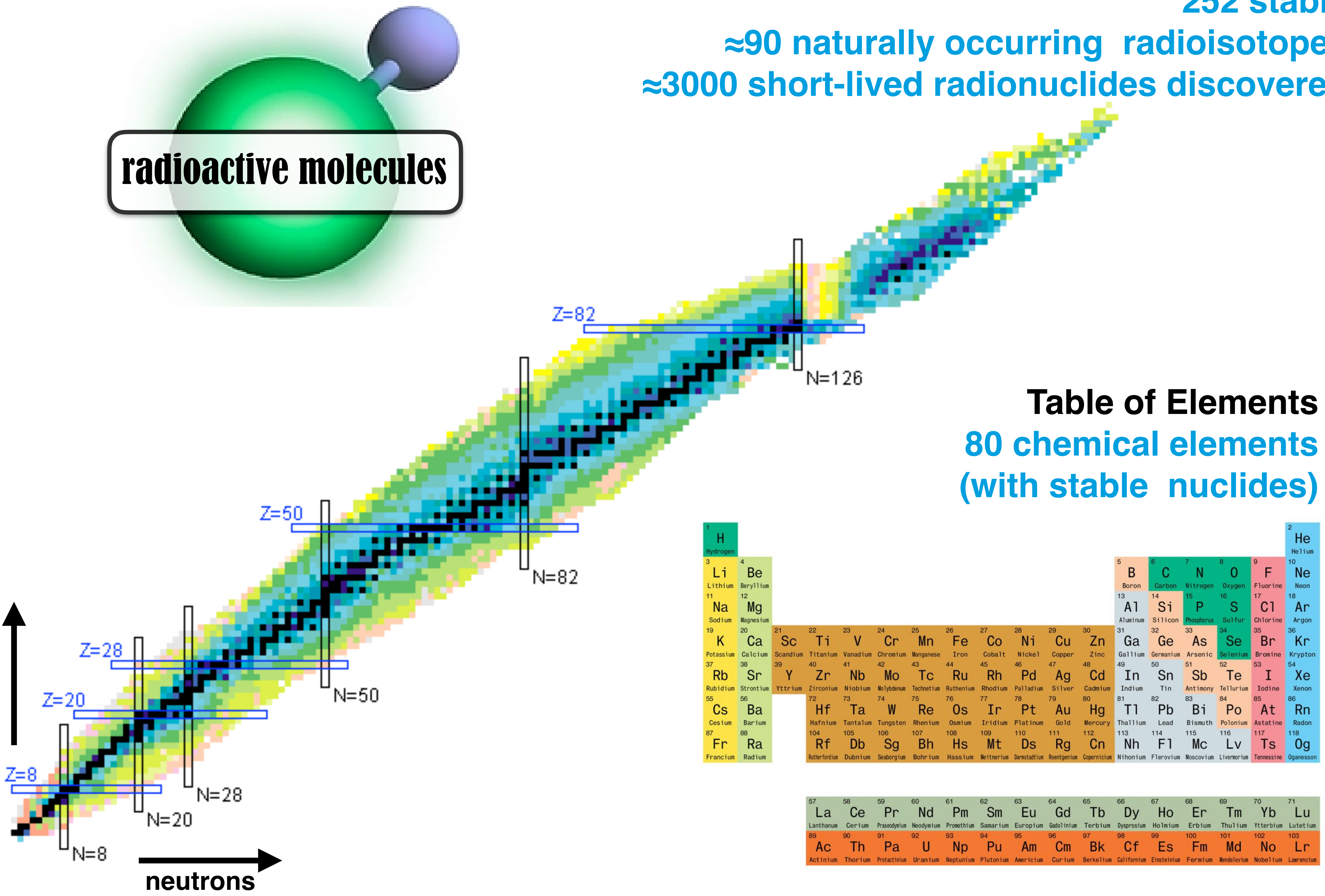
‘Designer Molecules’

Table of Isotopes

252 stable

≈90 naturally occurring radioisotopes

≈3000 short-lived radionuclides discovered



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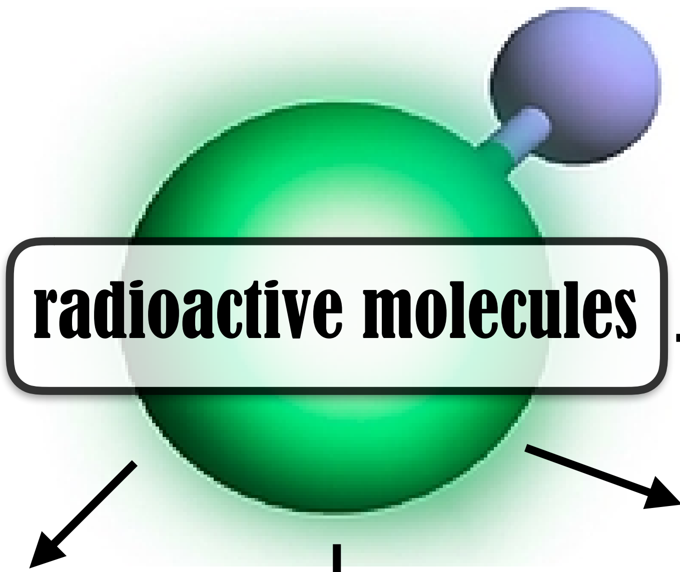


radioactive molecules

probes for new physics
- EDM searches
- P violation

Applied science
- nuclear engineering
- medicine

Astrophysics

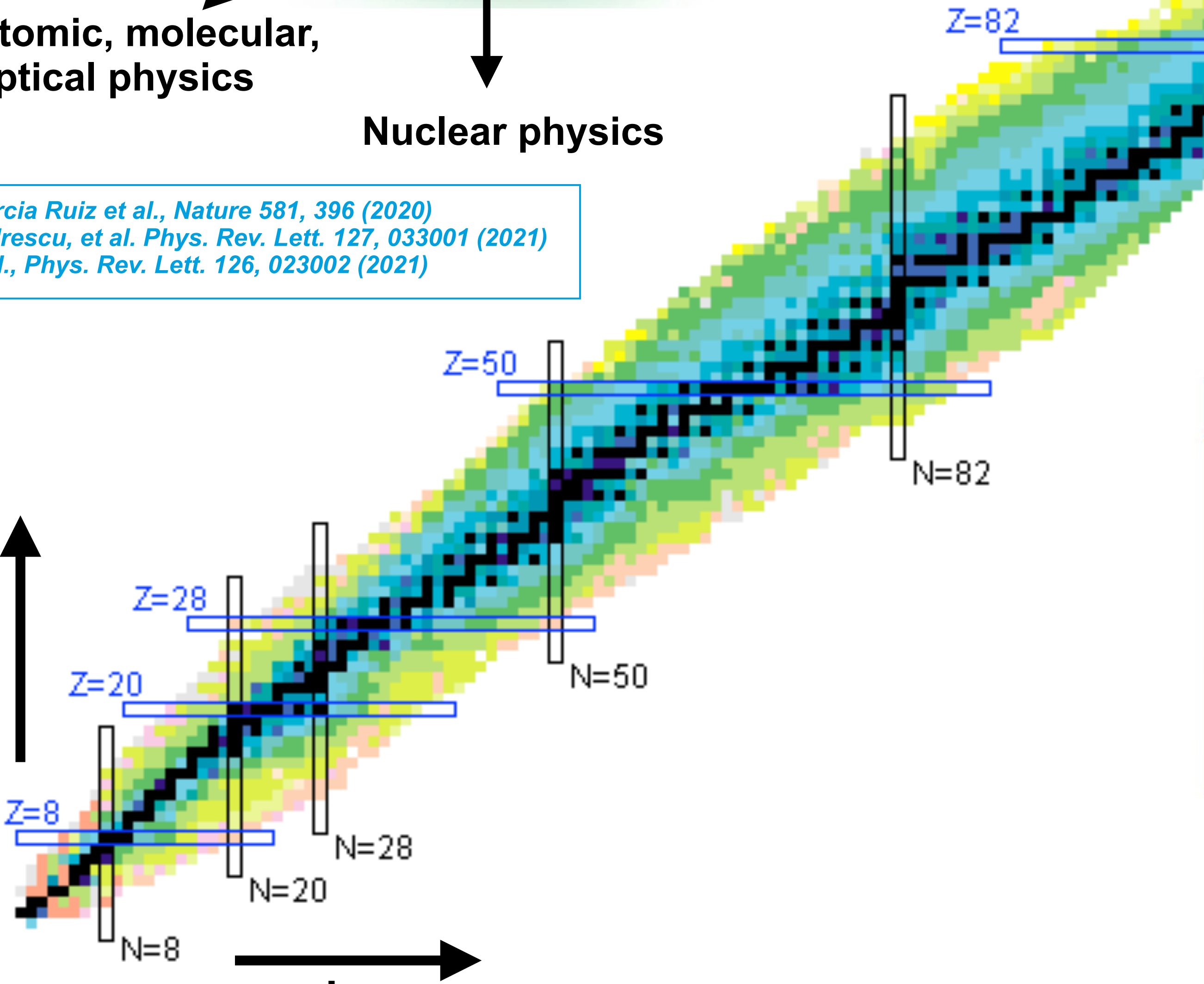
Quantum Chemistry

Atomic, molecular, optical physics

Nuclear physics

⇒ many, exciting science opportunities

R. F. Garcia Ruiz et al., Nature 581, 396 (2020)
S. M. Udrescu, et al. Phys. Rev. Lett. 127, 033001 (2021)
Fan et al., Phys. Rev. Lett. 126, 023002 (2021)



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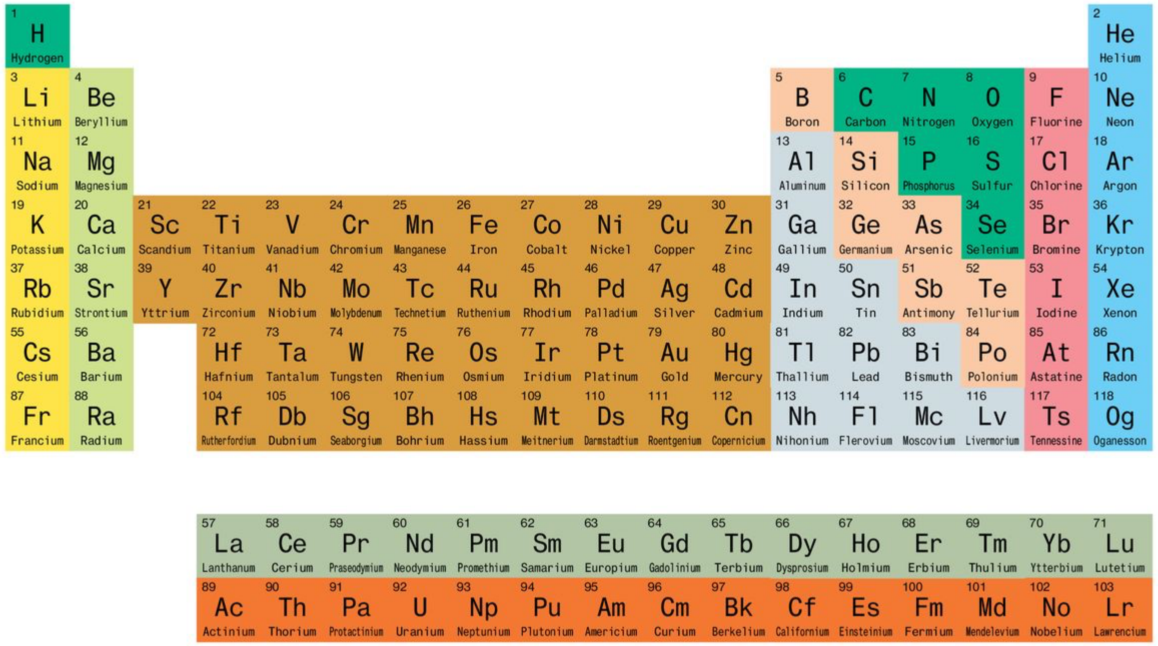

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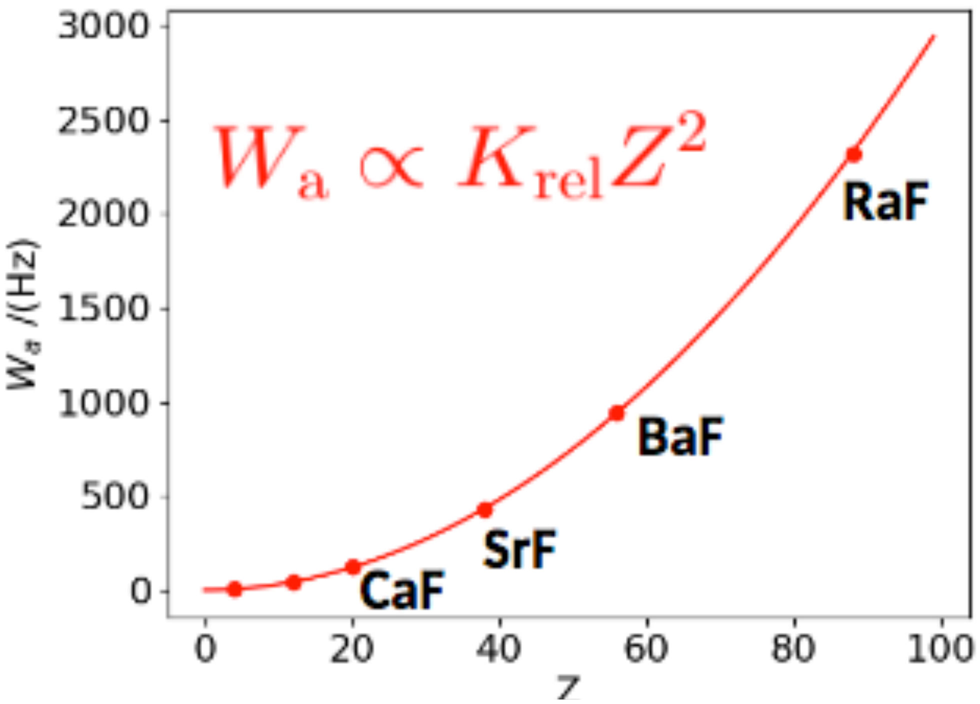
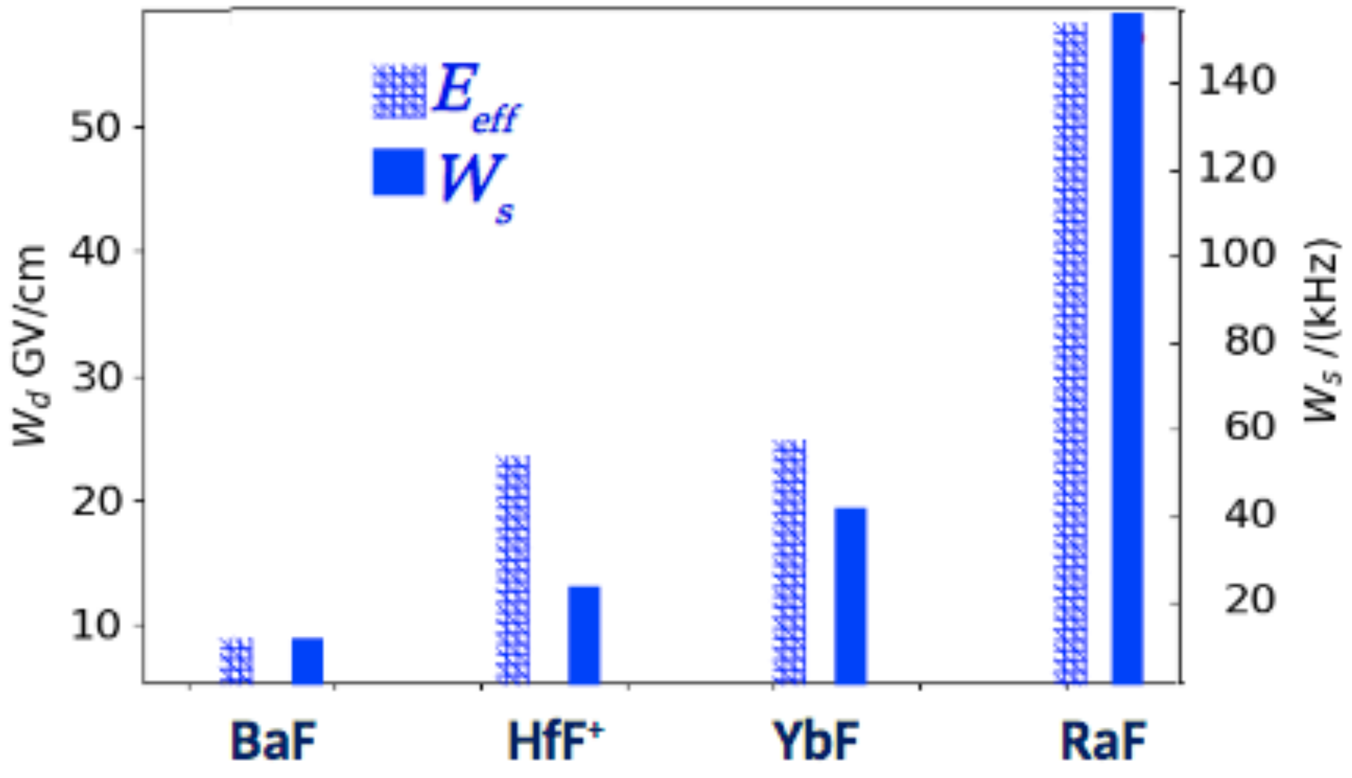
Sensitivity of Fluoride Molecules

$$\widehat{H}_{\rm sr} = B\vec{\mathcal{N}}^2 + \gamma\,\vec{\mathbf{S}}^{\rm eff}\cdot\vec{\mathcal{N}} + \vec{\mathbf{S}}^{\rm eff}\cdot\widehat{\mathbf{A}}\cdot\vec{\mathbf{I}} + \vec{\mathcal{N}}\cdot\widehat{\mathbf{C}}\cdot\vec{\mathbf{I}} + \cdots$$

$$+W_a(K_A/2)[\vec{\lambda}\times\vec{S}^{\rm eff}].\vec{I} + (W_s k_s + E_{\rm eff} d_e)\vec{\lambda}.\vec{S}^{\rm eff}$$

P-odd and P,T -odd effects





Gaul & Berger J. Chem. Phys 147, 014109(2017)
Fleig. Phys. Rev. A 96, 040502 (2017)

Sensitivity of Fluoride Molecules

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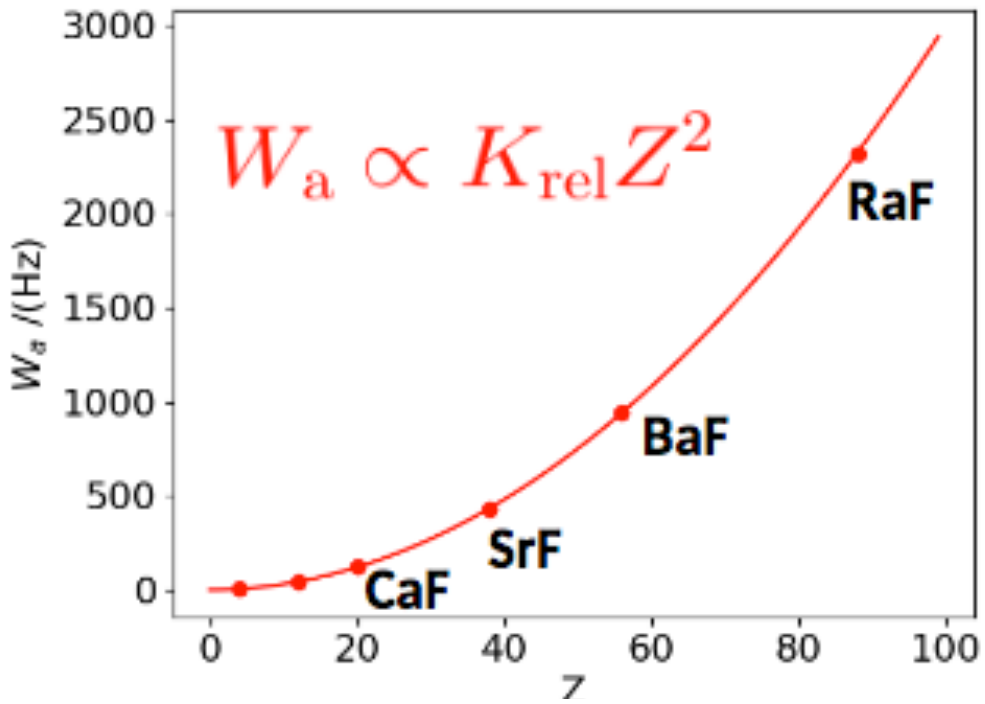
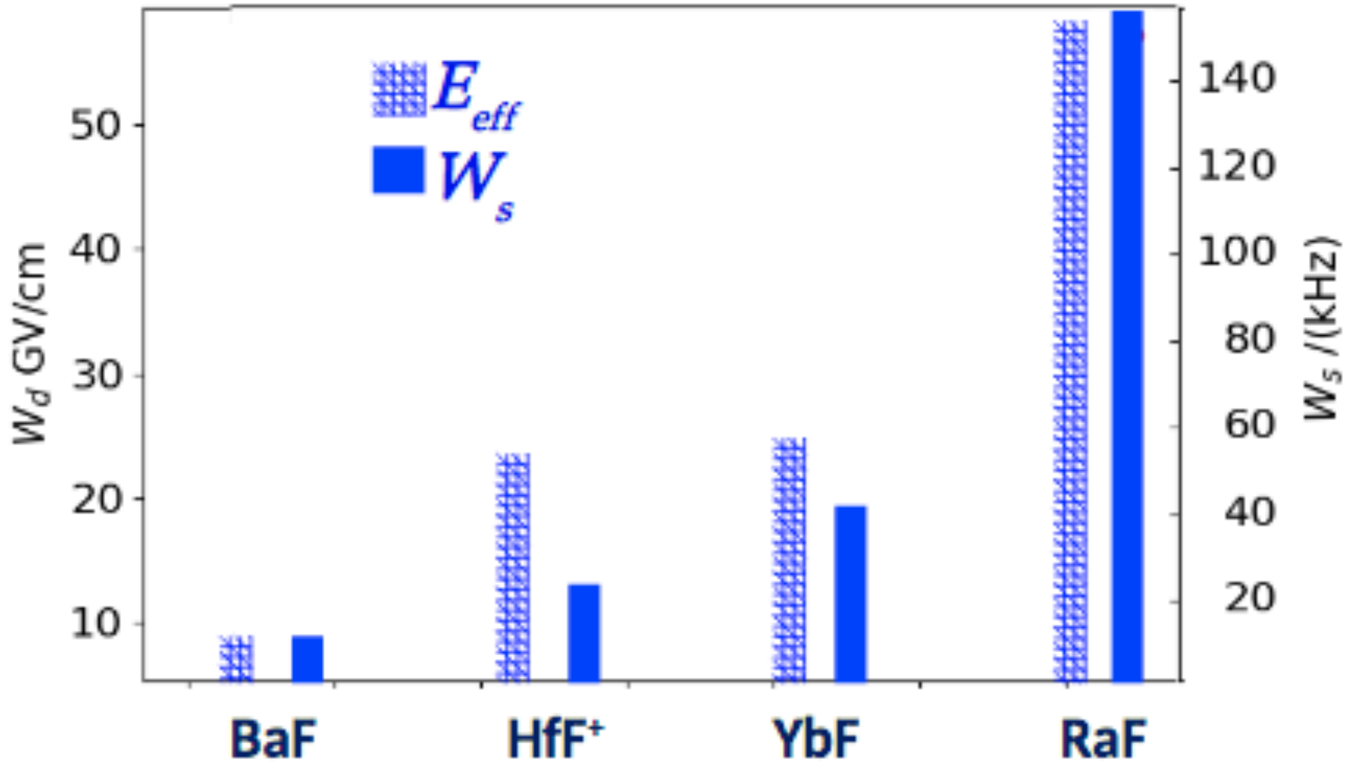


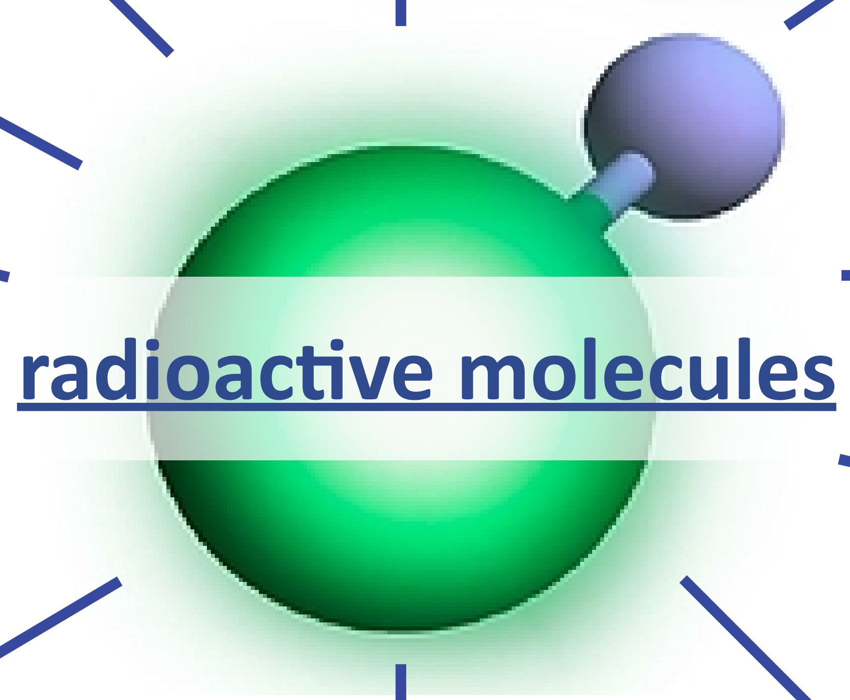


Gaul & Berger J. Chem. Phys 147, 014109(2017)
Fleig. Phys. Rev. A 96, 040502 (2017)

Nomen est omen: Radium is radioactive

222Ra 38.0 S α: 100.00% 14C: 3.0E-8%	223Ra 11.43 D α: 100.00% 14C: 8.9E-8%	224Ra 3.6319 D α: 100.00% 14C: 4.0E-9%	225Ra 14.9 D β-: 100.00%	226Ra 1600 Y α: 100.00% 14C: 3.2E-9%	227Ra 42.2 M β-: 100.00%	228Ra 5.75 Y β-: 100.00%	229Ra 4.0 M β-	230Ra 93 M β-: 100.00%

Radioactive molecules & EDMs



radioactive molecules

long coherence time

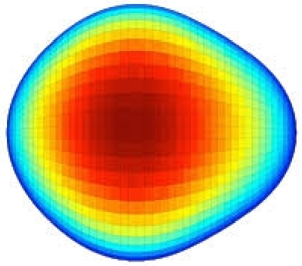
laser cooling

co-magnetometry
/ B-field insensitivity

close-lying opposite parity states

large E_{eff} $\propto Z^2 R(Z)$

nuclear T-breaking Schiff moment
deformed nuclei



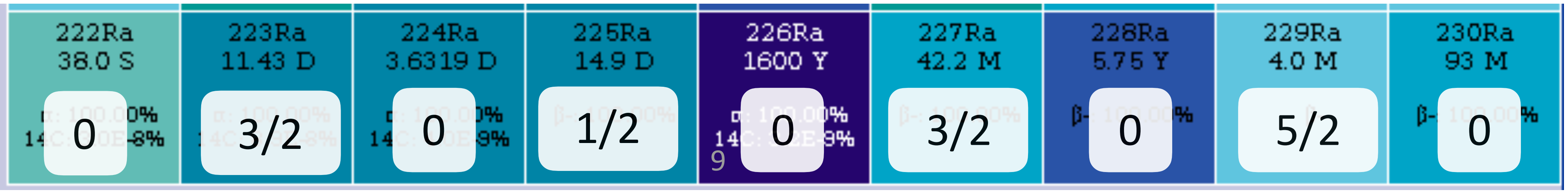
same chemistry
different physics sensitivity
systematic spin dependence

complementary physics
- parity violation
- quantum chemistry
- nuclear structure

nuclear-spin-independent component
& electron EDM

CP violating nuclear Magnetic Quadrupole Moment

nuclear-spin-dependent component



	222Ra 38.0 S	223Ra 11.43 D	224Ra 3.6319 D	225Ra 14.9 D	226Ra 1600 Y	227Ra 42.2 M	228Ra 5.75 Y	229Ra 4.0 M	230Ra 93 M
Spin=	0	3/2	0	1/2	0	3/2	0	5/2	0

Examples of proposed radioactive molecules

Fundamental symmetries & new physics

RaF

Isaev et al., Phys. Rev. A 82, 052521 (2010)
Kudashov, Phys. Rev. A 90, 052513 (2014)
Garcia Ruiz et al., Nature 581, 396 (2020)

RaOH

Isaev et al., J. Phys. B: At. Mol. Opt. Phys. 50 225101 (2017)
Kozyryev et al., Phys. Rev. Lett. 119, 133002 (2017)

RaO

Flambaum, Phys Rev A 77, 024501 (2008).

RaH

Fazil et al., Phys. Rev. A 99,052502 (2019).

FrAg

PaF^{3+}

C. Zülch et al., arXiv:2203.10333 (2022)

light nuclei for nuclear P-violation

$RaOCH_3^+$

Fan et al., Phys. Rev. Lett. 126, 023002 (2021)
Yu and Hutzler, Phys. Rev. Lett. 126, 023003 (2021)

short-lived ThO

Flambaum, Phys. Rev. C 99 035501 (2019)

AcO^+

Flambaum and V. A. Dzuba, Phys. Rev. A 101, 042504 (2020).

EuO^+

Flambaum and V. A. Dzuba, Phys. Rev. A 101, 042504 (2020).

ThF^+

C. F. Liang et al., Phys. Rev. C, 51:1199–1210, (1995)
N. J. Hammond et al., Phys. Rev. C, 65:064315 (2002)
D. N. Gresh et al., . J. Mol. Spectrosc., 319:1–9, (2016)

Nuclear physics

KF- nuclear quadruple moments

Teodoro et al., Phys. Rev. A 91, 032516 (2015)

CaCl- nuclear quadruple moments

nuclear anapole moments to study electroweak properties of short-lived nuclei

R. Garcia, personal communications

Astrophysics

^{26}AlF

T. Kamiński et al., Nat. Astron. 2, 778 (2018).

Actinide molecules in nuclear engineering

NpO, NpO_2

Examples of proposed radioactive molec

Fundamental symmetries & new physics

RaF
Isaev et al., Phys. Rev. A 82, 052521 (2010)
Kudashov, Phys. Rev. A 90, 052513 (2014)
Garcia Ruiz et al., Nature 581, 396 (2020)

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N. J. Hammond et al., Phys. Rev. C, 65:064315 (2002)
D. N. Gresh et al., . J. Mol. Spectrosc., 319:1–9, (2016)

no experimental knowledge about radioactive molecules

Nuclear physics

KF- nuclear q ents
Teodoro et al., Phys. Rev. A 91, 032516 (2015)

CaCl- nu ple moments

nu moments to study electroweak properties of short-lived nuclei
R. Garcia, personal communications

A ysics

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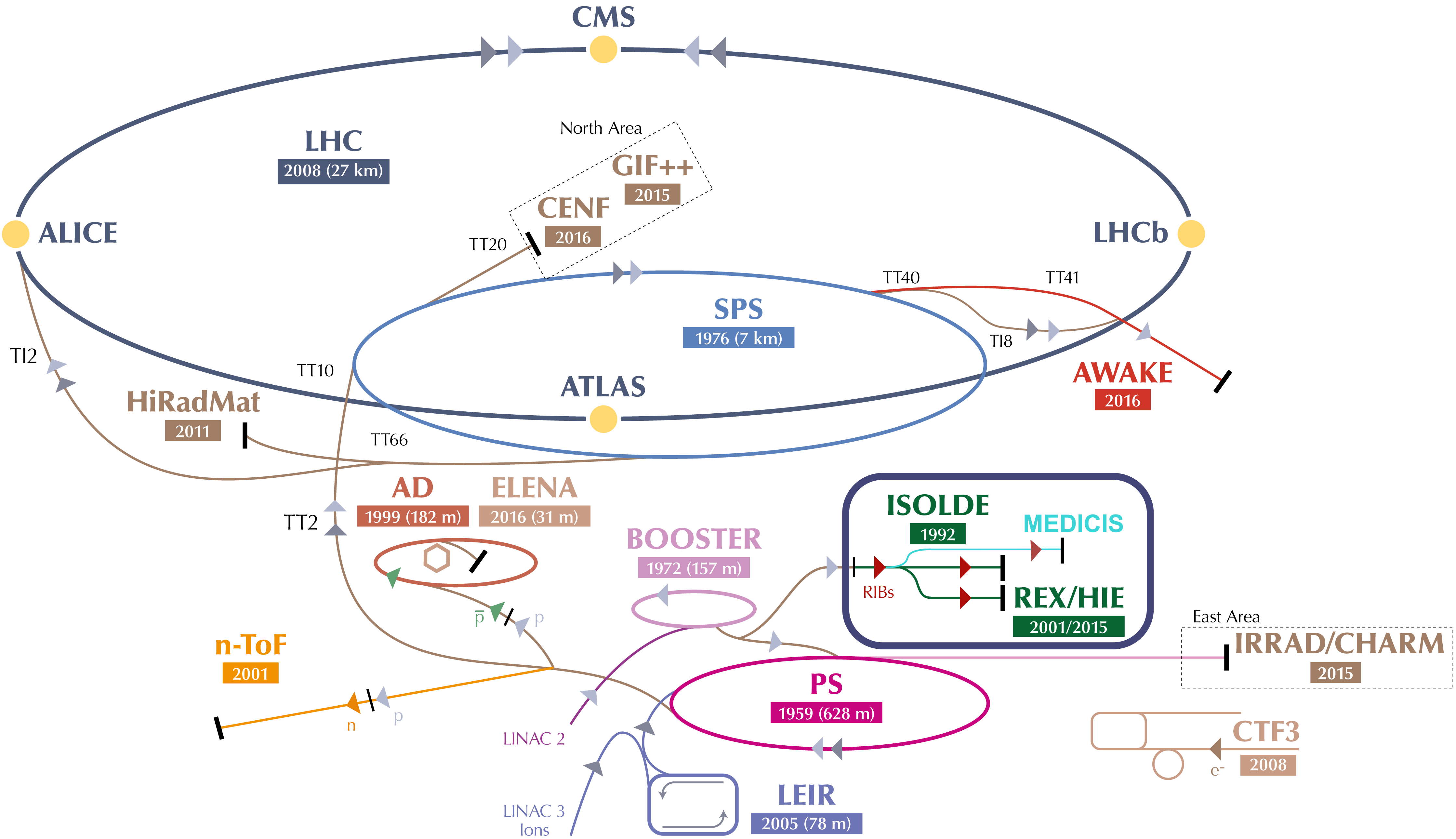
T. Kamiński et al., Nat. Astron. 2, 778 (2018).

Actinide molecules in nuclear engineering

NpO, NpO_2

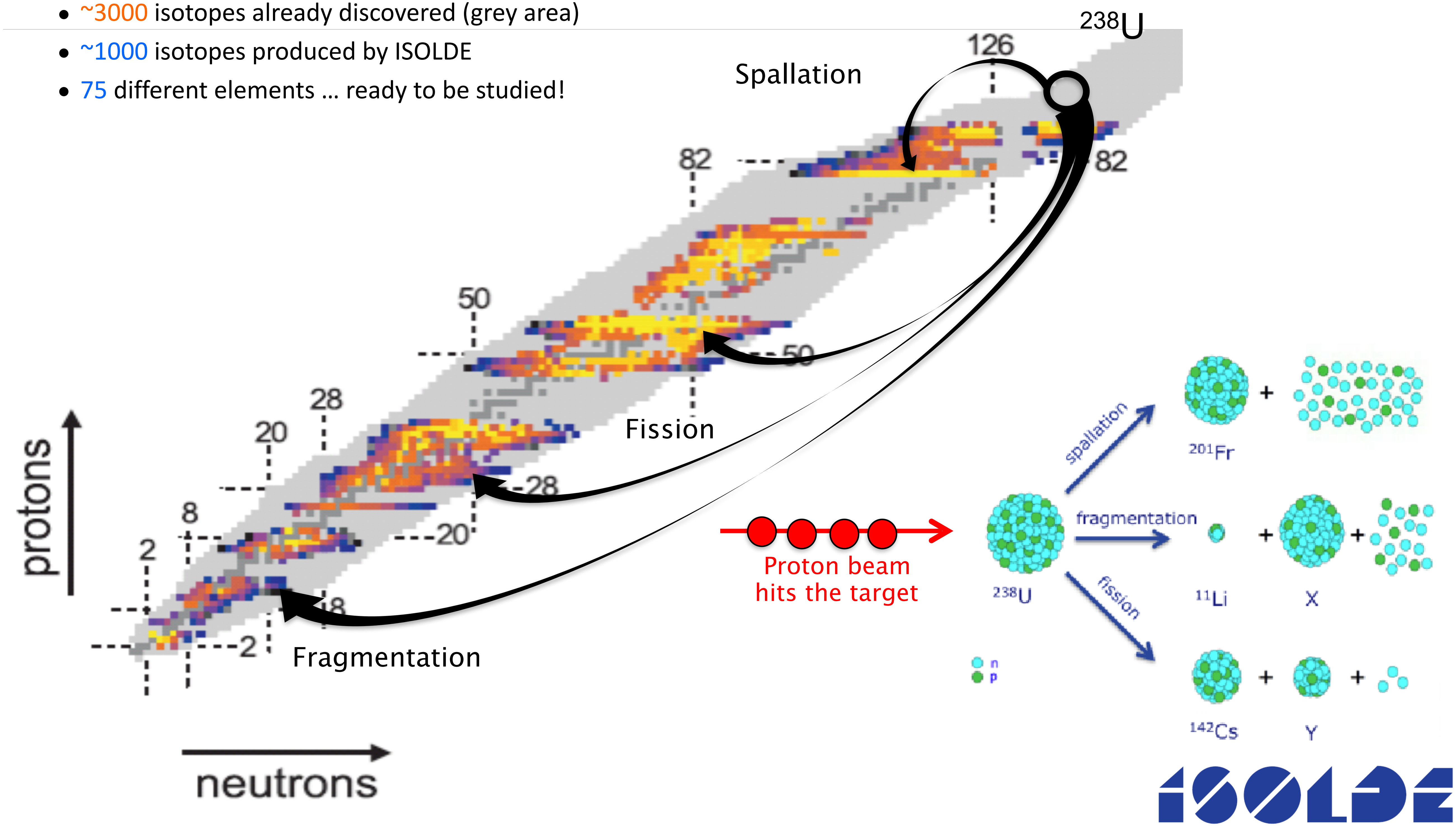
CERN accelerator complex



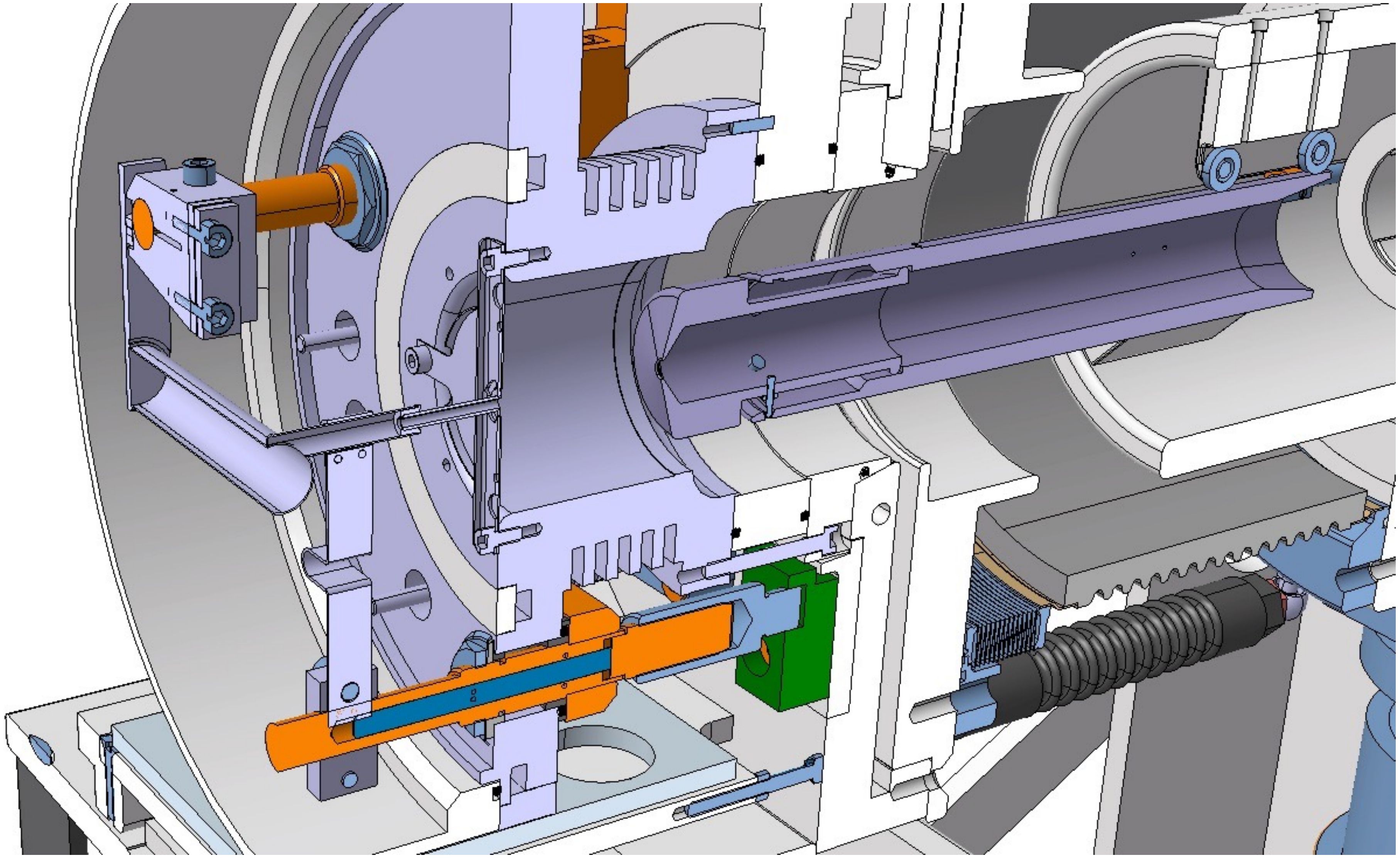
Isotope Production at ISOLDE

high energy (1.4 GeV) protons onto a thick target, e.g. ^{238}U

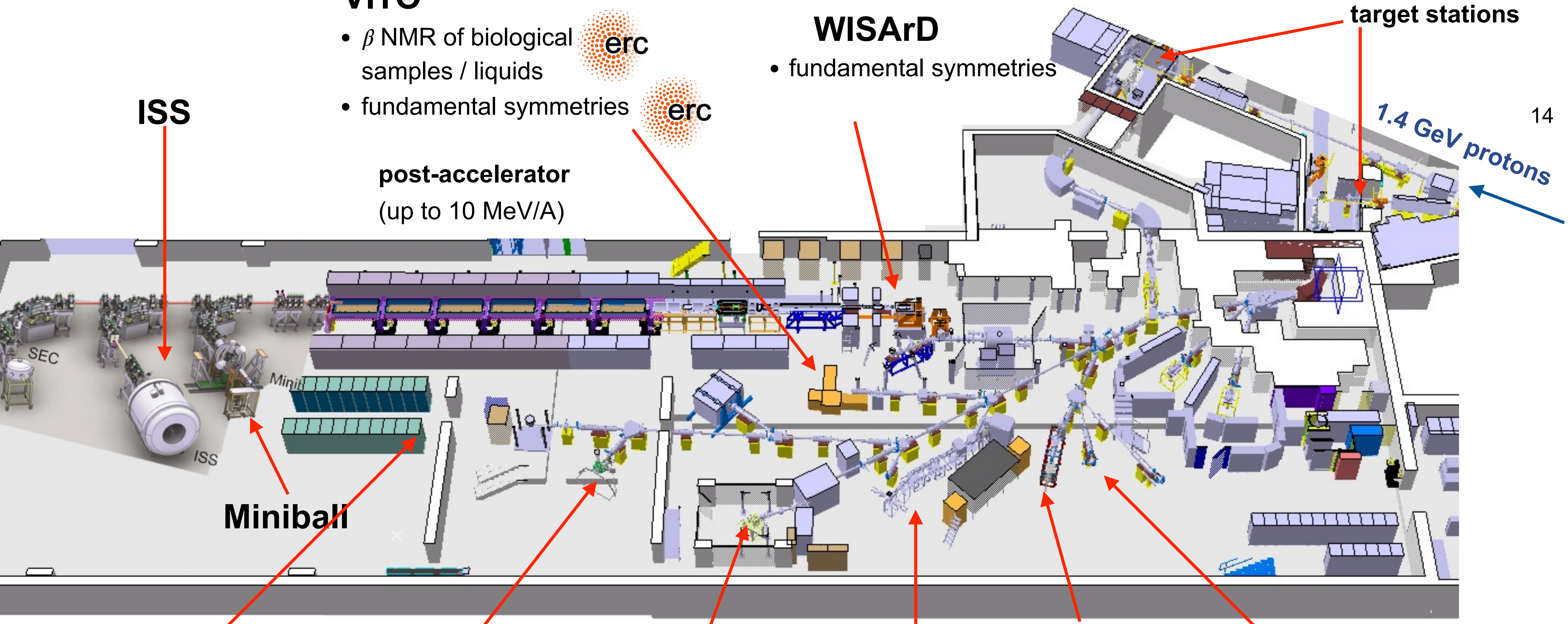
- ~6000 isotopes predicted by theory
- ~3000 isotopes already discovered (grey area)
- ~1000 isotopes produced by ISOLDE
- 75 different elements … ready to be studied!



Rare Isotope Production



ISOLDE at CERN



VITO

- β NMR of biological samples / liquids erc
- fundamental symmetries erc

WISArD

- fundamental symmetries

target stations

ISS

post-accelerator
(up to 10 MeV/A)

Miniball

IDS
decay spectroscopy

ISOLTRAP

- Penning traps for
- precise masses

COLLAPS
laser spectroscopy

MIRACLS erc

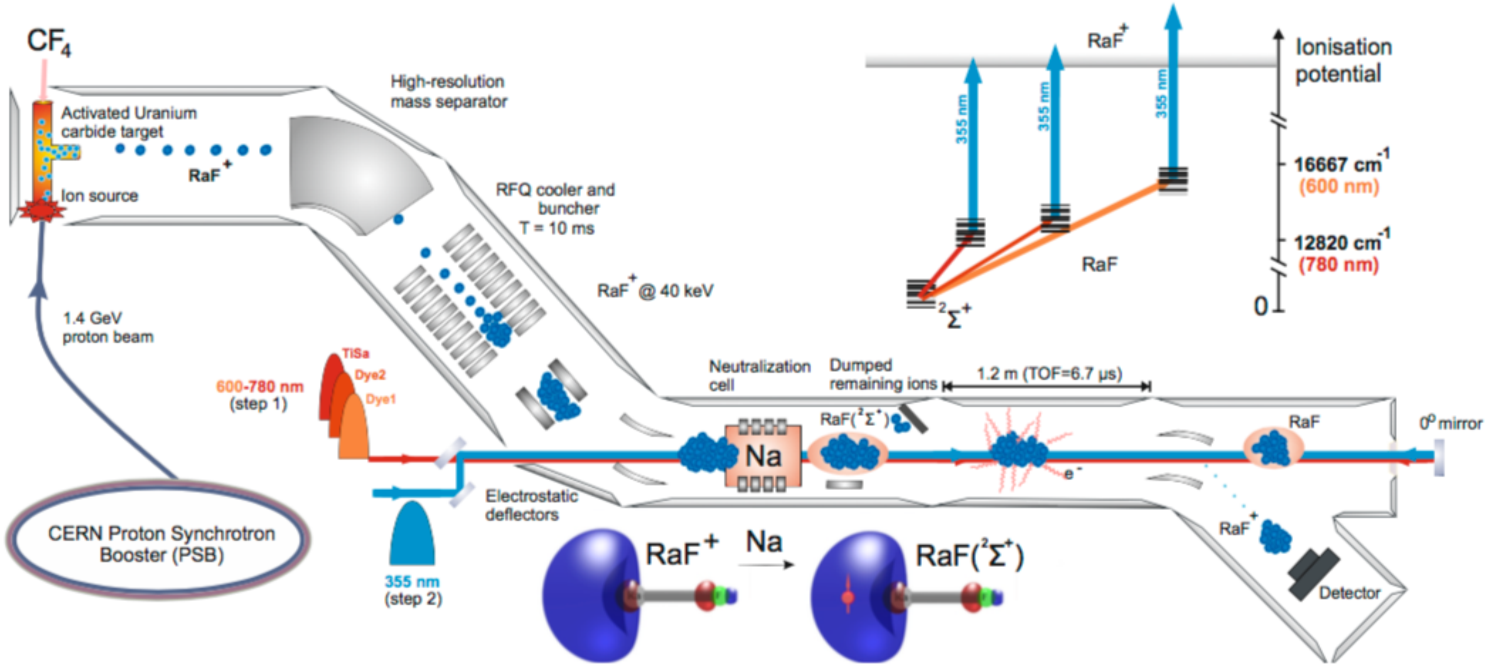
- highly sensitive laser spectroscopy
- high-capacity, high resolution mass separation

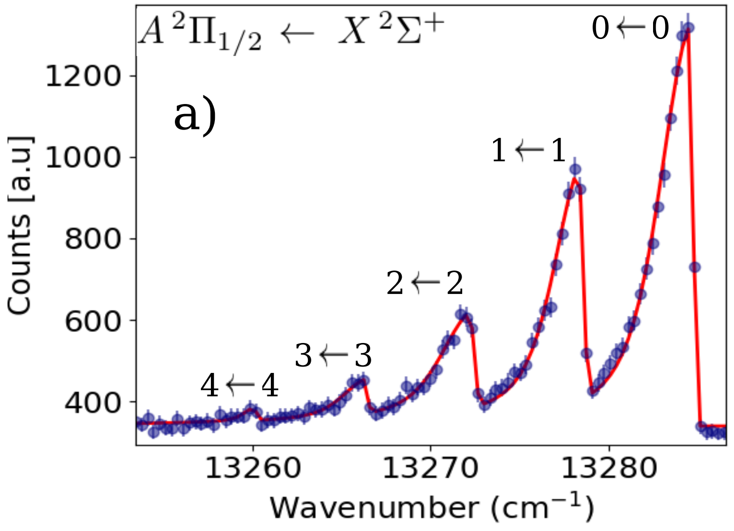
CRIS erc
highly sensitive laser spectroscopy

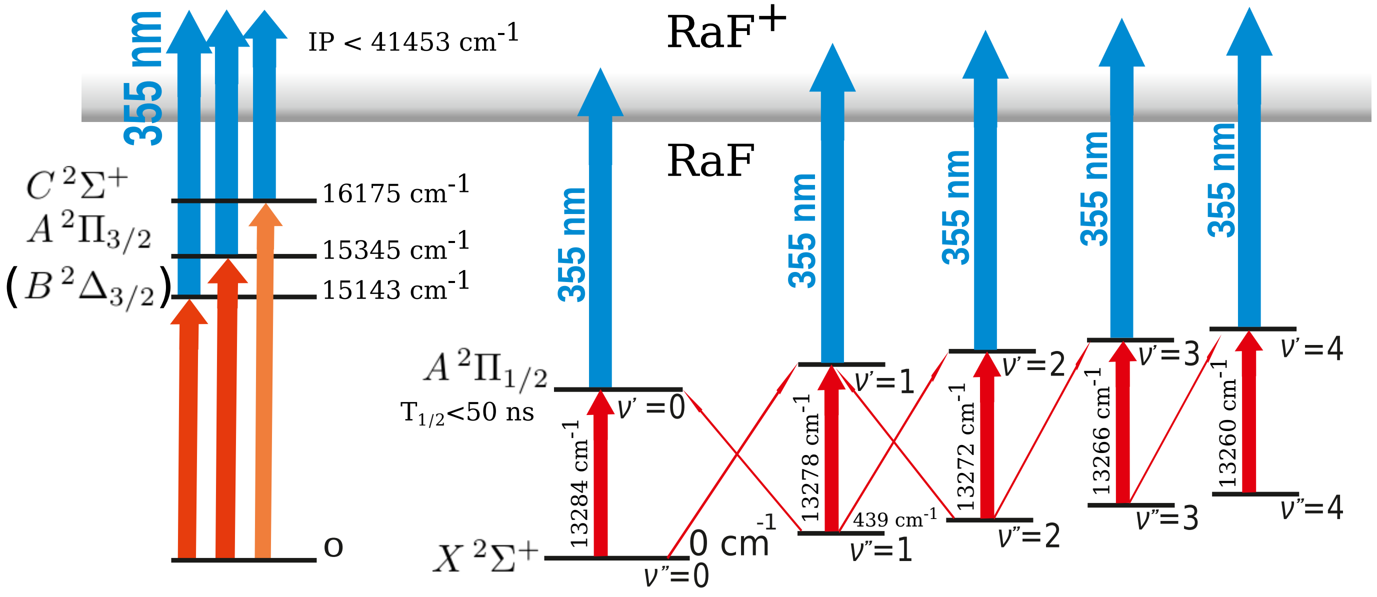
PUMA (near future) erc
study of nuclear skins with antiprotons

First spectroscopy of radioactive molecules

CRIS







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

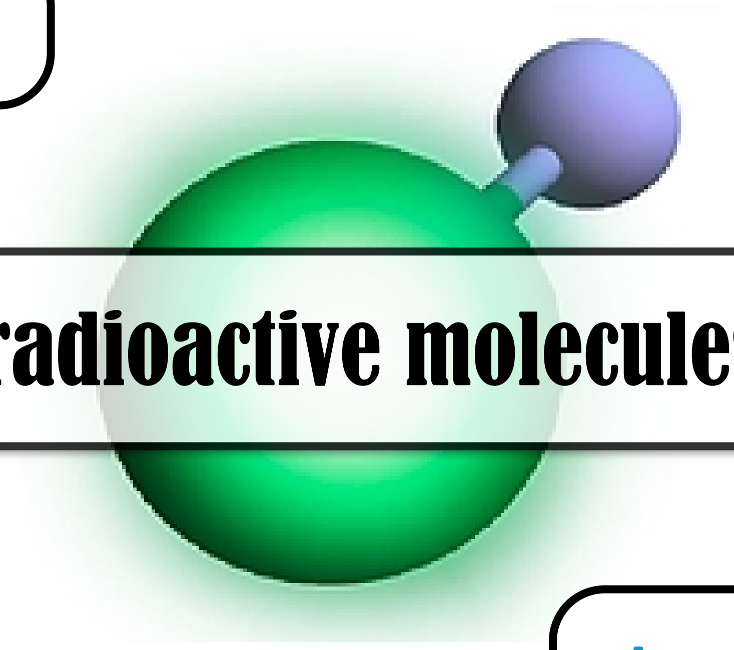
Multidisciplinary

BSM interpretation

quantum chemistry

particle physics

molecular physics



radioactive molecules

nuclear theory

EDM expertise

RIB facility

atomic physics techniques

RIB techniques

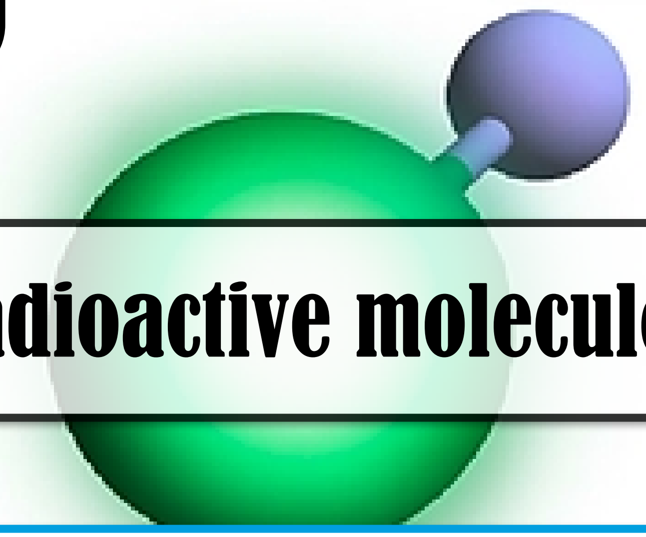
Multidisciplinary

BSM interpretation

quantum chemistry

particle physics

molecular physics



radioactive molecules

nuclear theory

EDM expertise

RIB facility

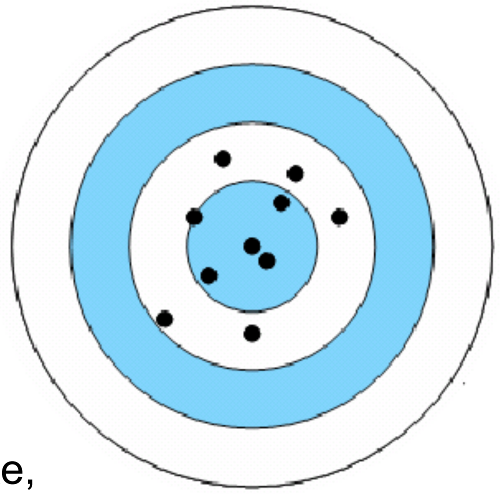
atomic physics techniques

RIB techniques

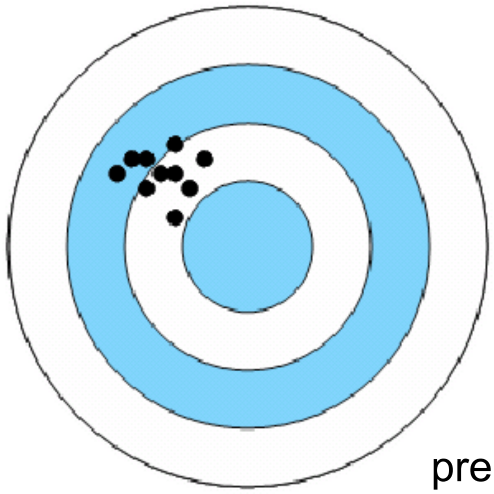
Atomic physics techniques at RIB facilities

high **precision and accuracy**

K. Blaum, et al., Phys. Scr. T152, 014017 (2013)
P. Campbell et al., Prog. Part. and Nucl. Phys. 86, 127-180 (2016)
J. Dilling et al., Annu. Rev. Nucl. Part. Sci. 68, 45 (2018)



accurate,
but not precise



precise,
but not accurate

ion traps

- masses
- RIB preparations
- mass separation
- in-trap decay

laser spectroscopy

- hyperfine structure
- isotope shifts
- optical pumping

atom traps

- in-trap decay
- laser spectroscopy
- APV

Atomic physics techniques at RIB facilities

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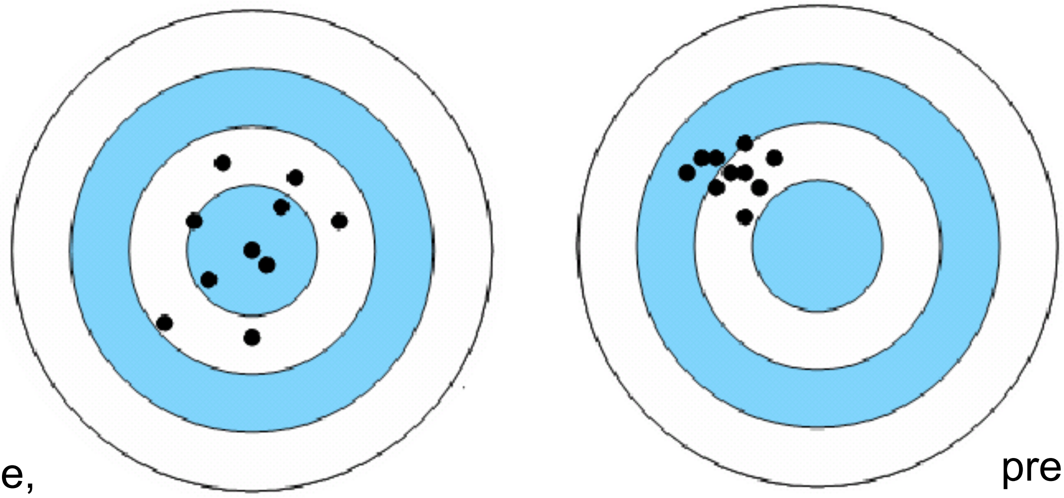

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atom traps

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- APV

Challenges

short half-lives

$T_{1/2} < 10$ ms

($\Delta m/m = 6 \cdot 10^{-8}$)

M. Smith et al., PRL 101, 202501 (2008)

low intensity

masses: 0.5 ions / h

M. Block et al., Nature 463, 785 (2010)
E. Minaya Ramirez et al., Science 337, 1207(2012)

temperature

buffer gas cooling

(selected cases of laser cooling)

purity

$R = m/\Delta m > 5 \cdot 10^6$

limited ion capacity

S. Eliseev et al., PRL 110, 082501 (2013)

Atomic physics techniques at RIB facilities

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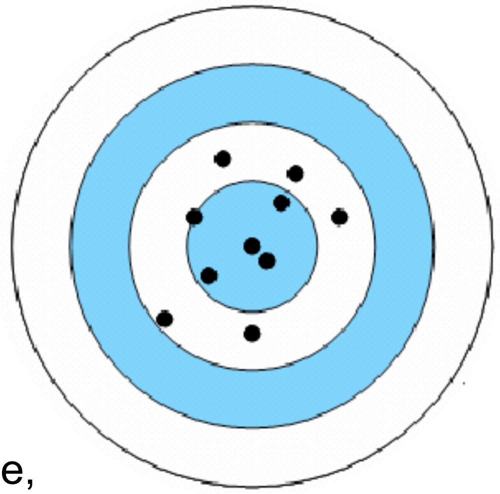

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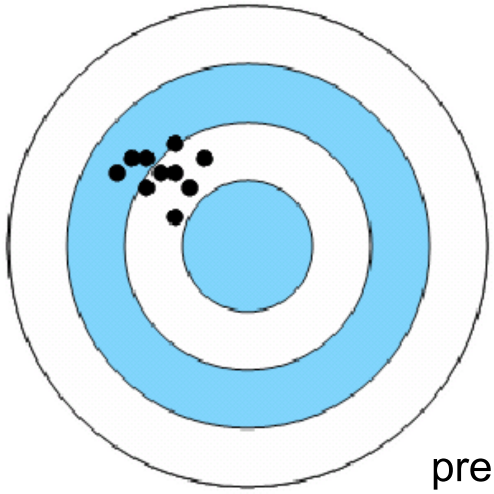

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temperature

buffer gas cooling

(selected cases of laser cooling)

300 K

↕

μK - mK - K

purity

$R = m/\Delta m > 5 \cdot 10^{6}$

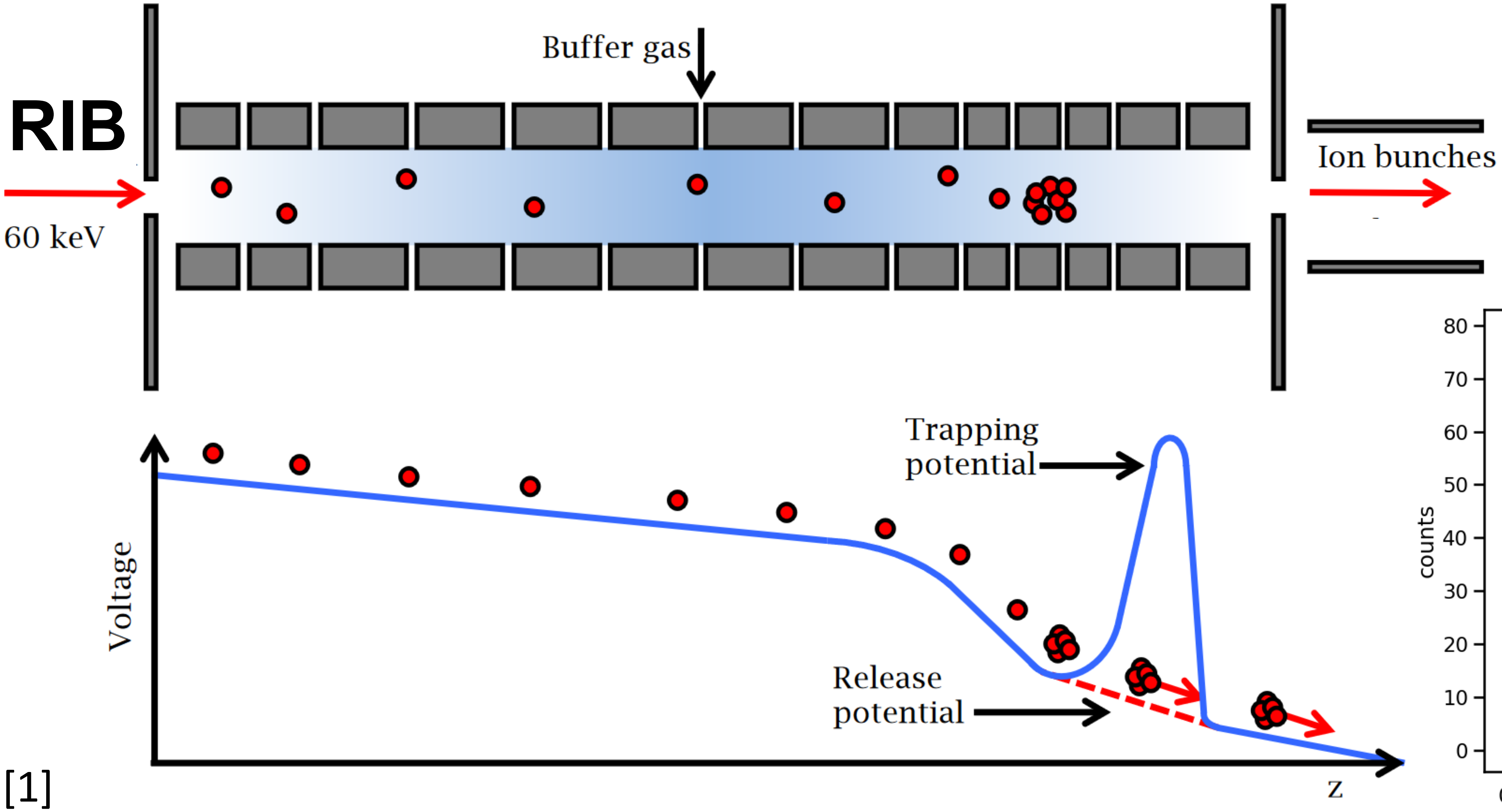
limited ion capacity

S. Eliseev et al., PRL 110, 082501 (2013)

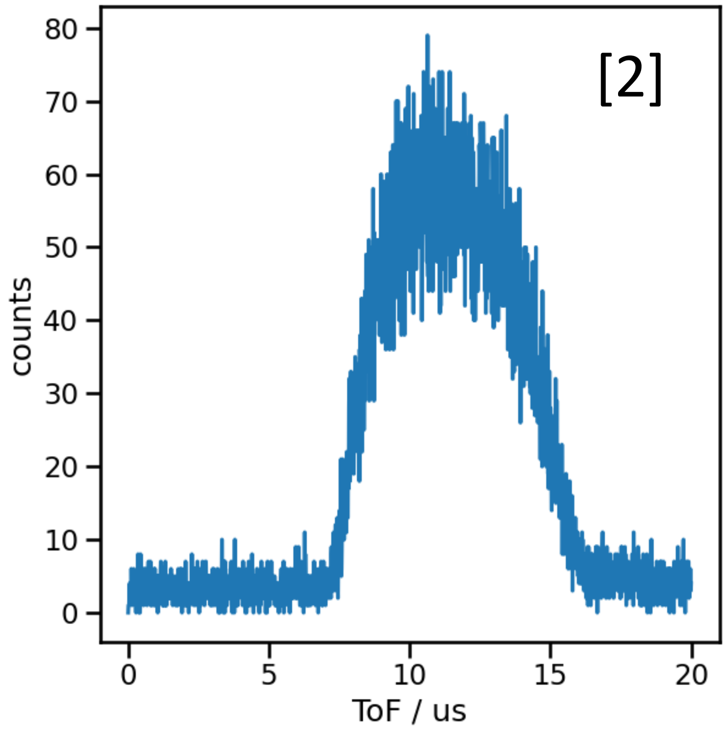
Standard buffer gas cooling

cooler and bunchers at RIB facilities , operated at 300 K buffer gas

Cooling limit: 300 K



[1]



[2]

[1] K. Lynch, PhD thesis, University of Manchester, 2013.

[2] Sb run COLLAPS, 2018.

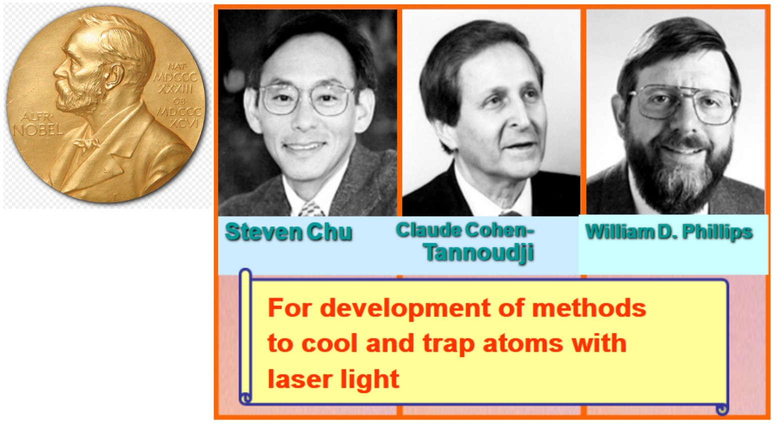
Doppler Cooling

- Powerful technique to reach sub-K atom and ion temperatures [1]
- Standard tool for high-precision measurements: atomic clocks [2], quantum information science [3], physics beyond the standard model [4]

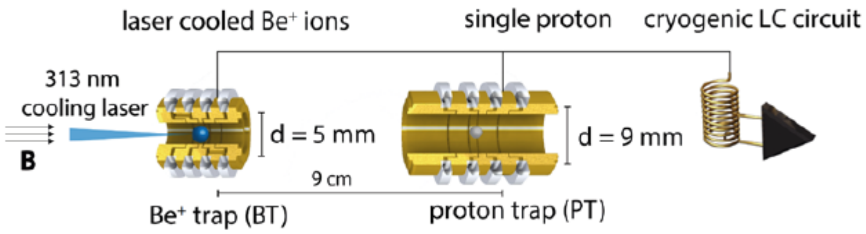
nature

LASER-COOLED ANTIMATTER

Ultraviolet beam manipulates and cools antihydrogen atoms



For development of methods to cool and trap atoms with laser light



[1] T. Haensch and A. Schawlow, Optics Communications 13, 68 (1975).
D. J. Wineland and W. M. Itano, Phys. Rev. A 20, 1521 (1979).
J. Eschner et al, J. Opt. Soc. Am. B20, 1003 (2003).

[2] D. Ludlow et al, Rev. Mod. Phys. 87, 637 (2015).
[3] C. D. Bruzewicz et al, Applied Physics Reviews 6, 021314 (2019).
[4] M. S. Safronova et al, Rev. Mod. Phys. 90, 025008 (2018).

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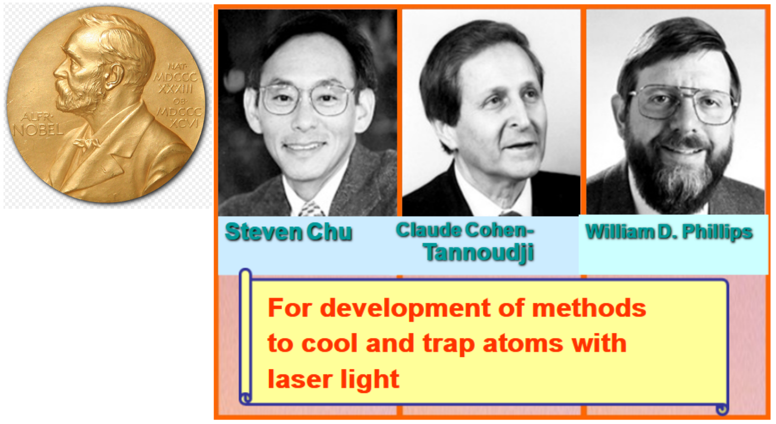

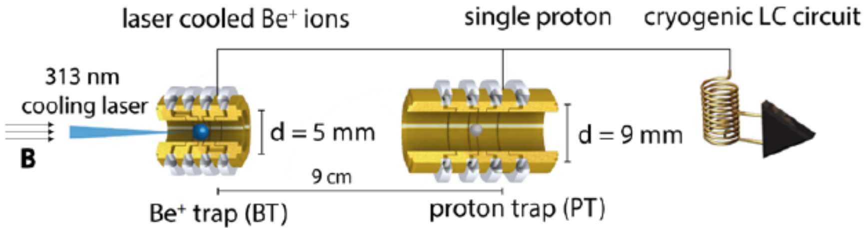

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[3] C. D. Bruzewicz et al, Applied Physics Reviews 6, 021314 (2019).
[4] M. S. Safronova et al, Rev. Mod. Phys. 90, 025008 (2018).

- Specific applications with RIBs

G. D. Sprouse and L. A. Orozco, Annu. Rev. Nucl. Part. Sci.. 47, 429 (1997)
J. A. Behr et al., Phys. Rev. Lett. 79, 375 (1997).
M. Trinczek et al., Phys. Rev. Lett. 90, 012501 (2003).
L. B. Wang et al., Phys. Rev. Lett. 93, 142501 (2004).

P. A. Vetter et al., Phys. Rev. C 77, 035502 (2008).
J. R. A. Pitcairn et al., RRC 79, 015501 (2009)
A. Takamine et al., Phys. Rev. Lett. 112, 162502 (2014)
B. Fenker et al., Phys. Rev. Lett. 120, 062502 (2018)

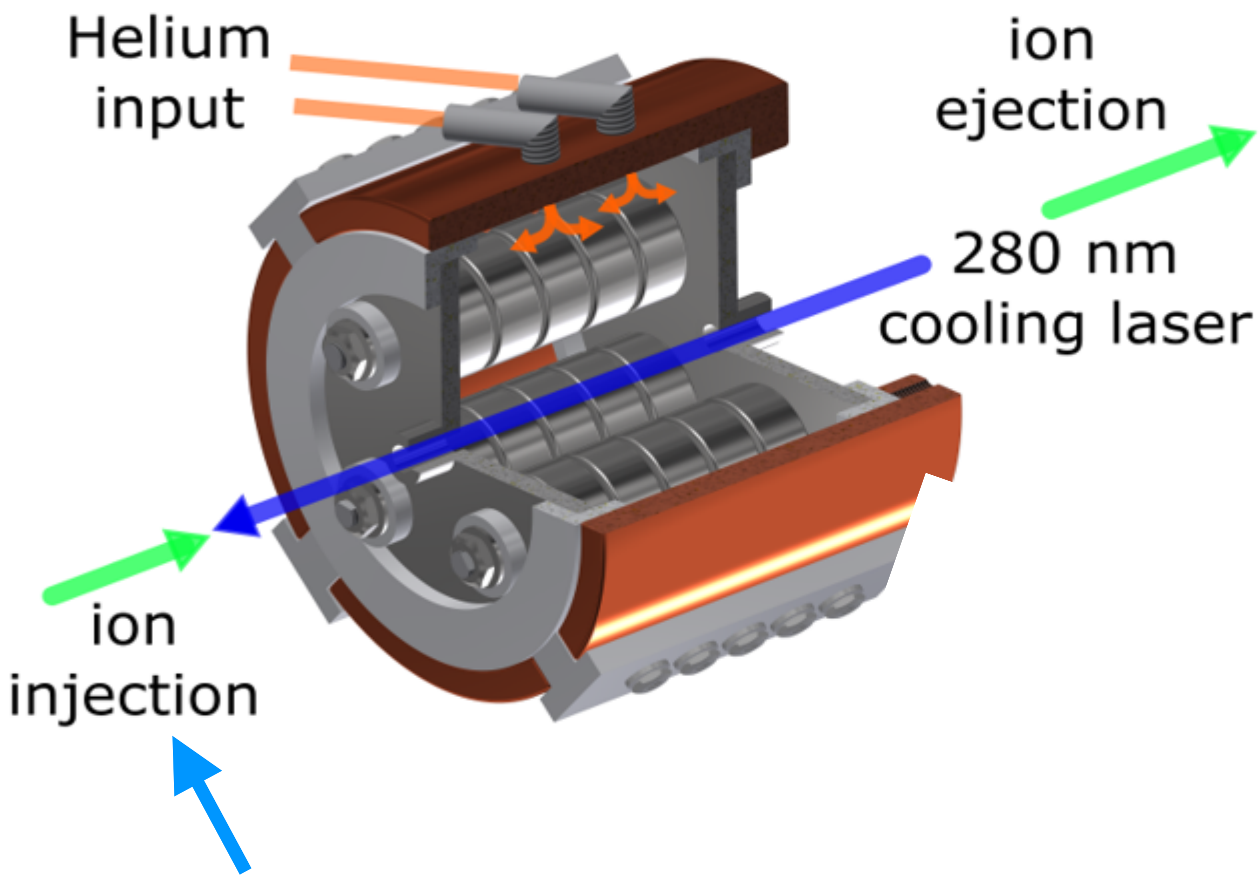
- unexplored as cooling technique to deliver high quality (molecular) RIBs

Goal: provide ultra-cold (molecular) RIBs

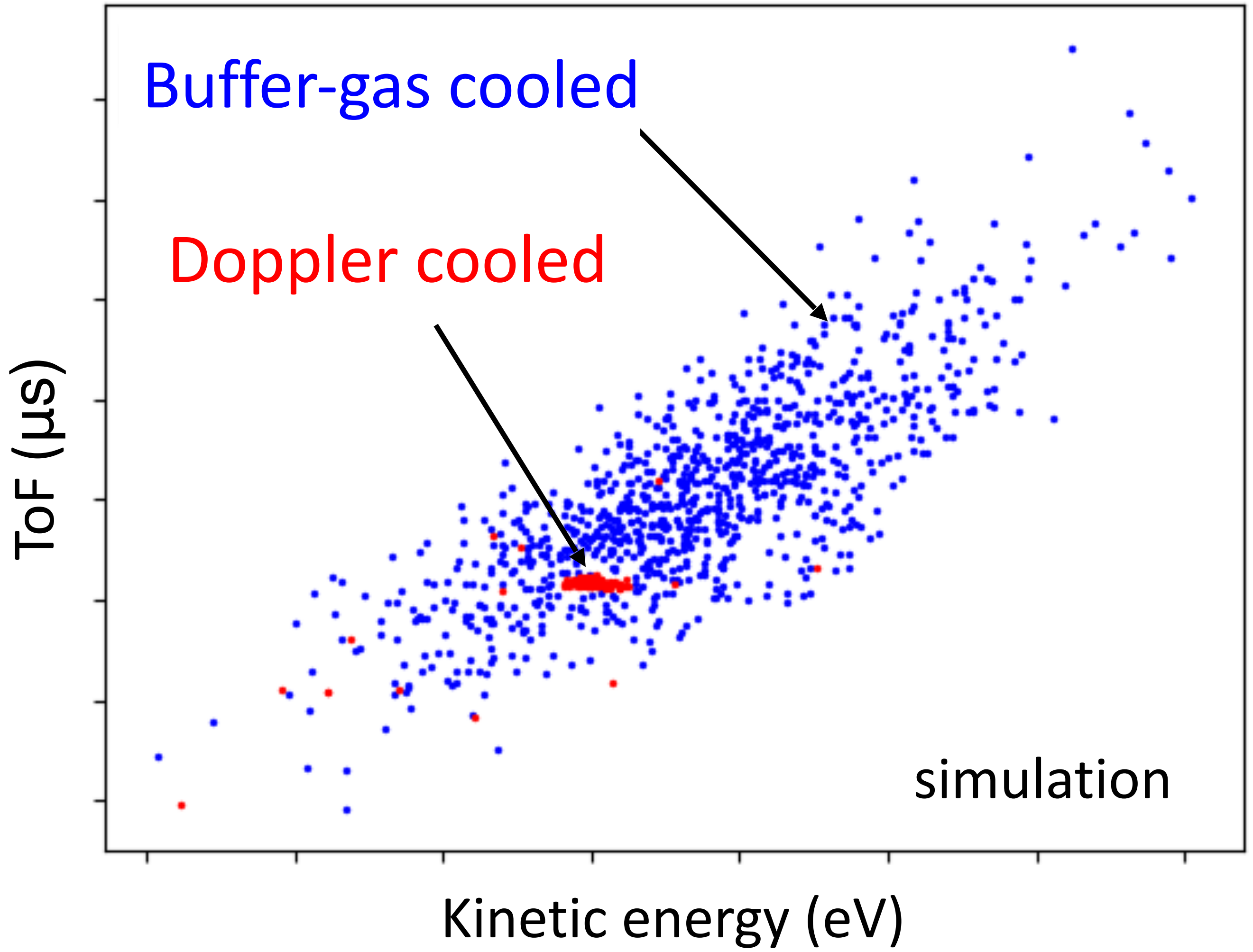
- ... compatible with short half-lives
- ... universally applicable (via sympathetic cooling)

Experimental Demonstration at MIRACLS

Paul trap:

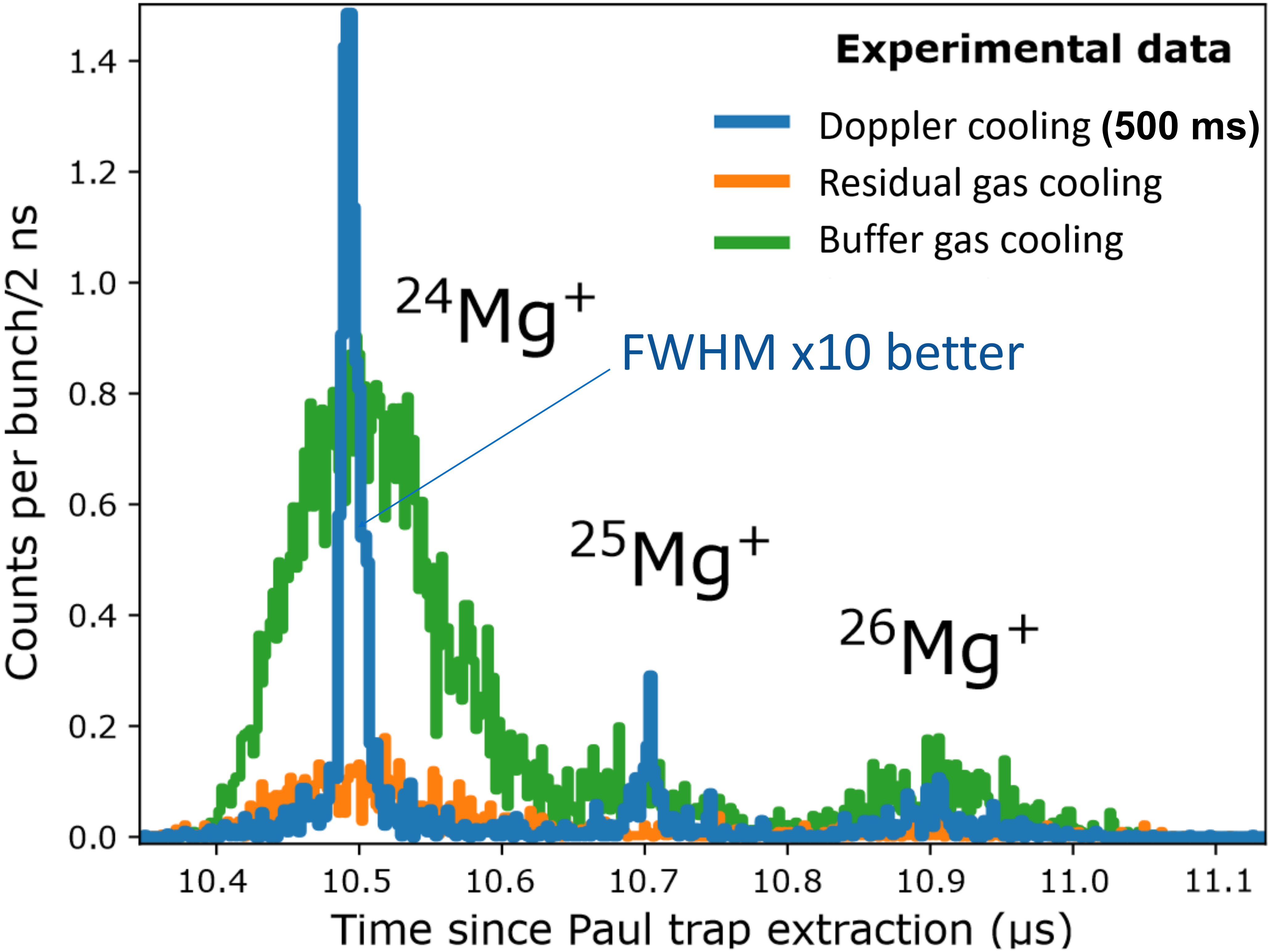


externally produced, fast and 'hot' Mg^+ ion beam



S. Sels, F. Maier et al., accepted in Phys. Rev. Research

Experimental results

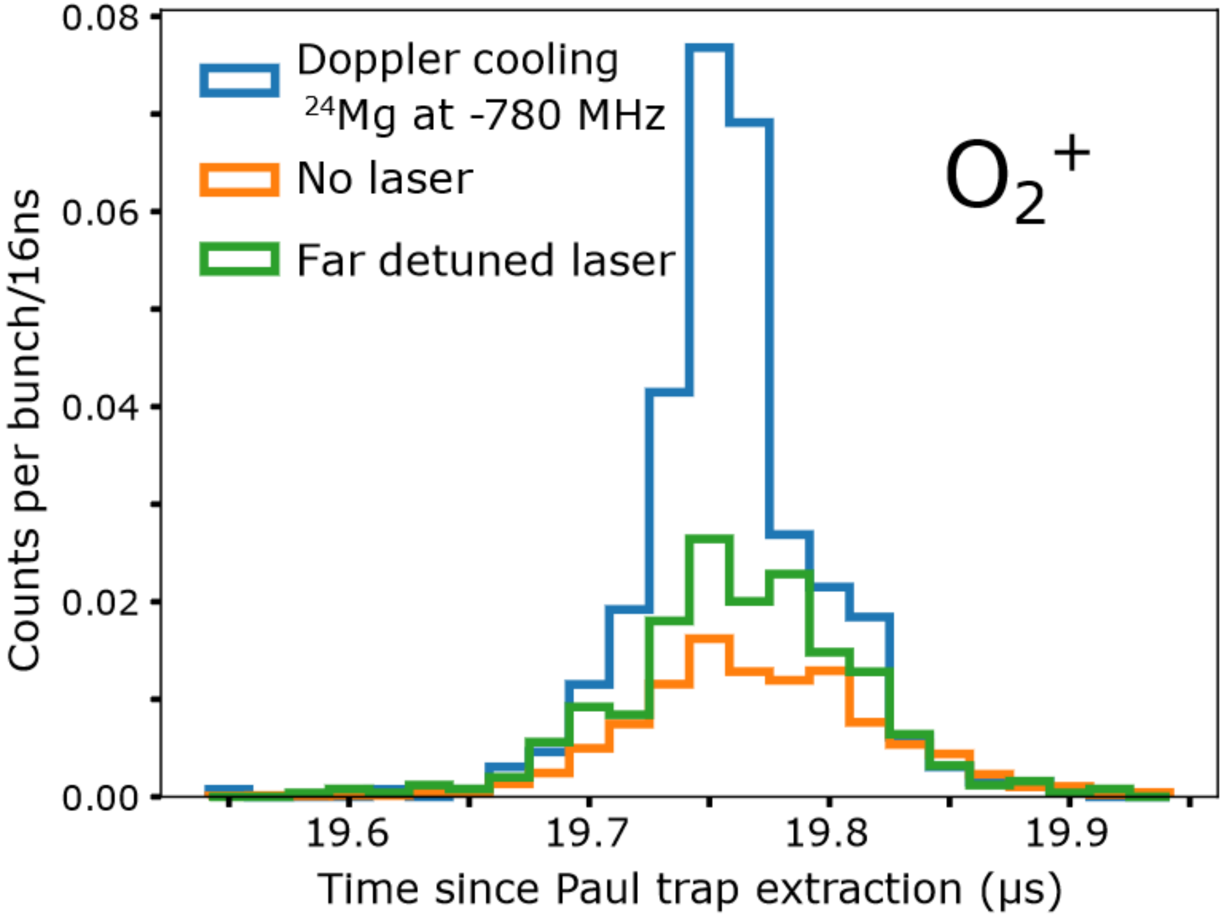


FWHM x10 better

S. Sels, F. Maier et al., accepted in Phys. Rev. Research

Sympathetic cooling

- ‘universal’ availability of cold ion ensembles
- including ionic systems which cannot be directly laser-cooled



opportunity for cold molecular RIBs

	O_2^+
Peak width residual-gas or buffer-gas cooling	113(5) ns
Sympathetic cooling	58(4) ns
Improvement in countrate	Factor 2.6

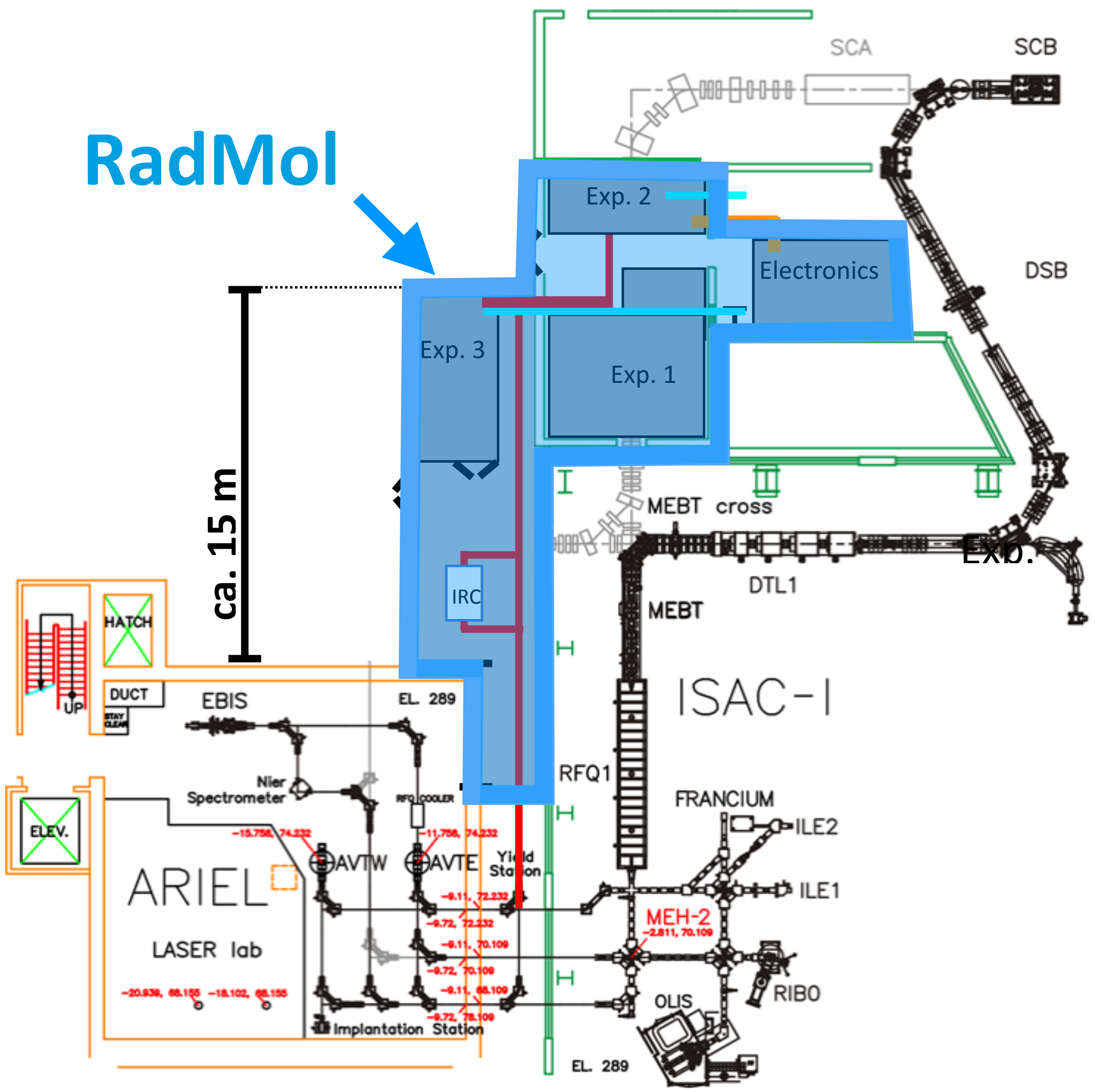
S. Sels, F. Maier et al., accepted in Phys. Rev. Research

Can be done better analogous to existing work, e.g. [1],[2]

J. Wuebbena et al, Phys. Rev. A 85, 043412,2012.
[2] M. Guggemos. New Journal of Physics 17, 103001, 2015.

RadMol TRIUMF

a radioactive molecule lab for fundamental physics



Goals:

- world-wide unique laboratory for radioactive molecules
- precision studies for searches for new physics

TRIUMF advantages

- **large variety in radioactive ion beams (RIB)**
- **high beamtime availability** (3 independent RIBs)
- **existing laboratory space for large, multi-station program**
- **fast connection of RadMol lab to online facility**

RadMol Collaboration

TRIUMF
UNIKASSEL VERSITÄT
MANCHESTER 1824 The University of Manchester
THE UNIVERSITY OF CHICAGO
KU LEUVEN
University of Manitoba
uOttawa
McGill
California Institute of Technology
Massachusetts Institute of Technology
Philipps Universität Marburg
OAK RIDGE National Laboratory
The University of Edinburgh
UBC
UNIVERSITY OF TORONTO

Summary

- **Radioactive Molecules**
  - ➡ entirely new science path
  - ➡ intriguing&unexplored **probes for New Physics**

- **First Spectroscopy at ISOLDE/CERN**

- **RadMol**
  - ➡ dedicated laboratory for radioactive molecules & precision studies at TRIUMF
  - ➡ designed to master experimental challenges

- **Cold radioactive, molecular beams**
  - ➡ Doppler + sympathetic cooling

team members:

I. Belosevic, **L. Croquette**, P. Fischer,
C. Kanitz, F. Hummer, E. Leistenschneider,
S. Lechner, F. Maier, P. Plattner, A. Roitman, M. Rosenbusch, **S. Sels**, F. Wienholtz,
M. Vilen, R. Wolf, F. Buchinger, W. Nörtershäuser, L. Schweikhard, S. Malbrunot- Ettenauer

collaboration:

CERN UNIVERSITÄT GREIFSWALD Wissen lockt. Seit 1456 TECHNISCHE UNIVERSITÄT DARMSTADT McGill TRIUMF UNIVERSITY OF TORONTO

funding:

European Research Council ATTRACT CERN Medical Applications Funds NSERC CRSNG

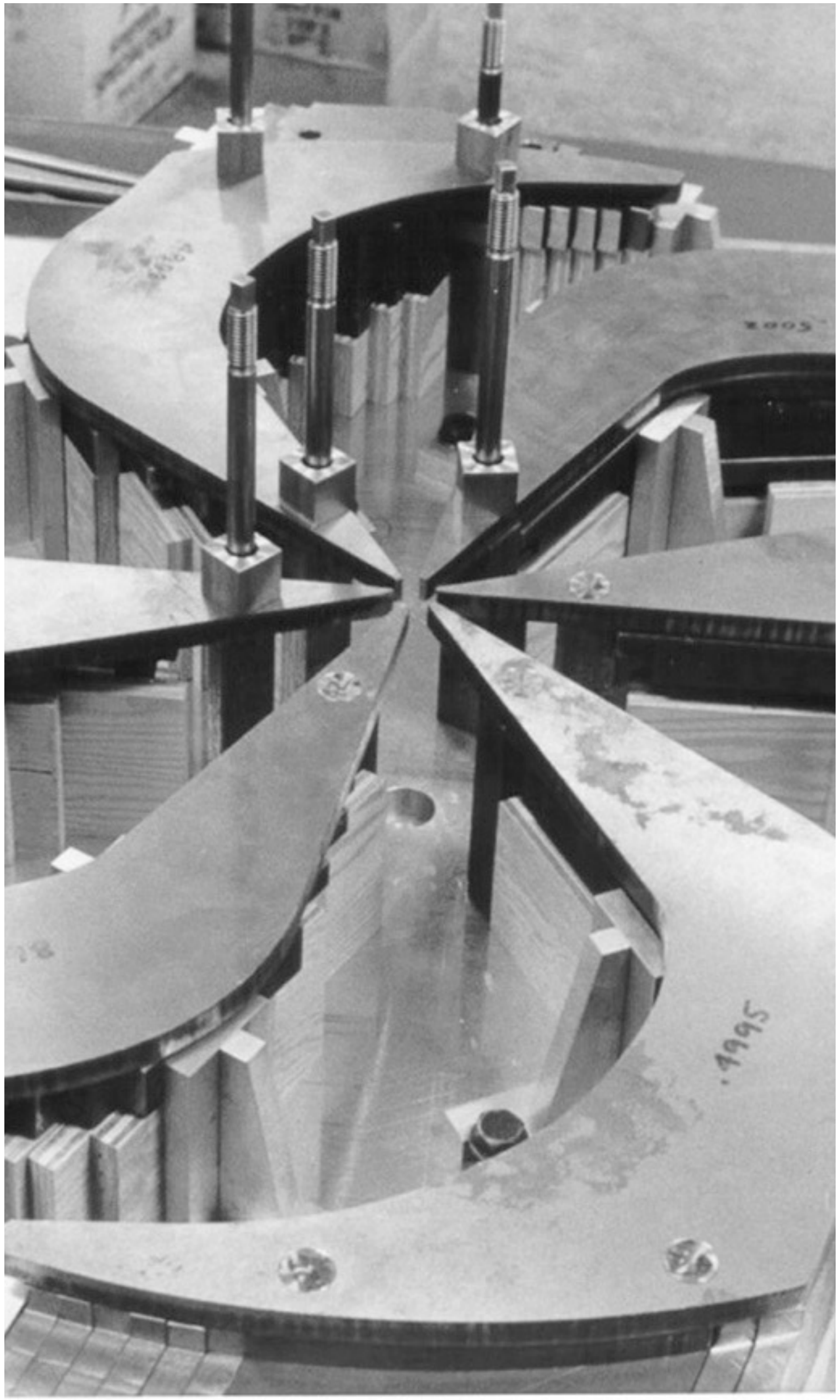
https://miracls.web.cern.ch

TRIUMF

Thank you
Merci

www.triumf.ca

Follow us **@TRIUMFLab**

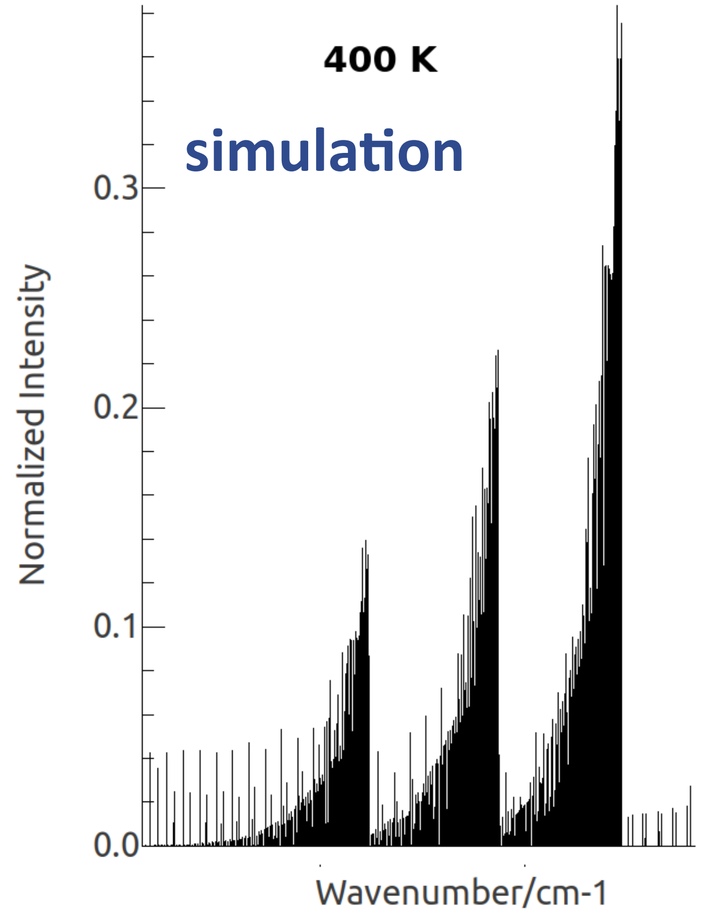


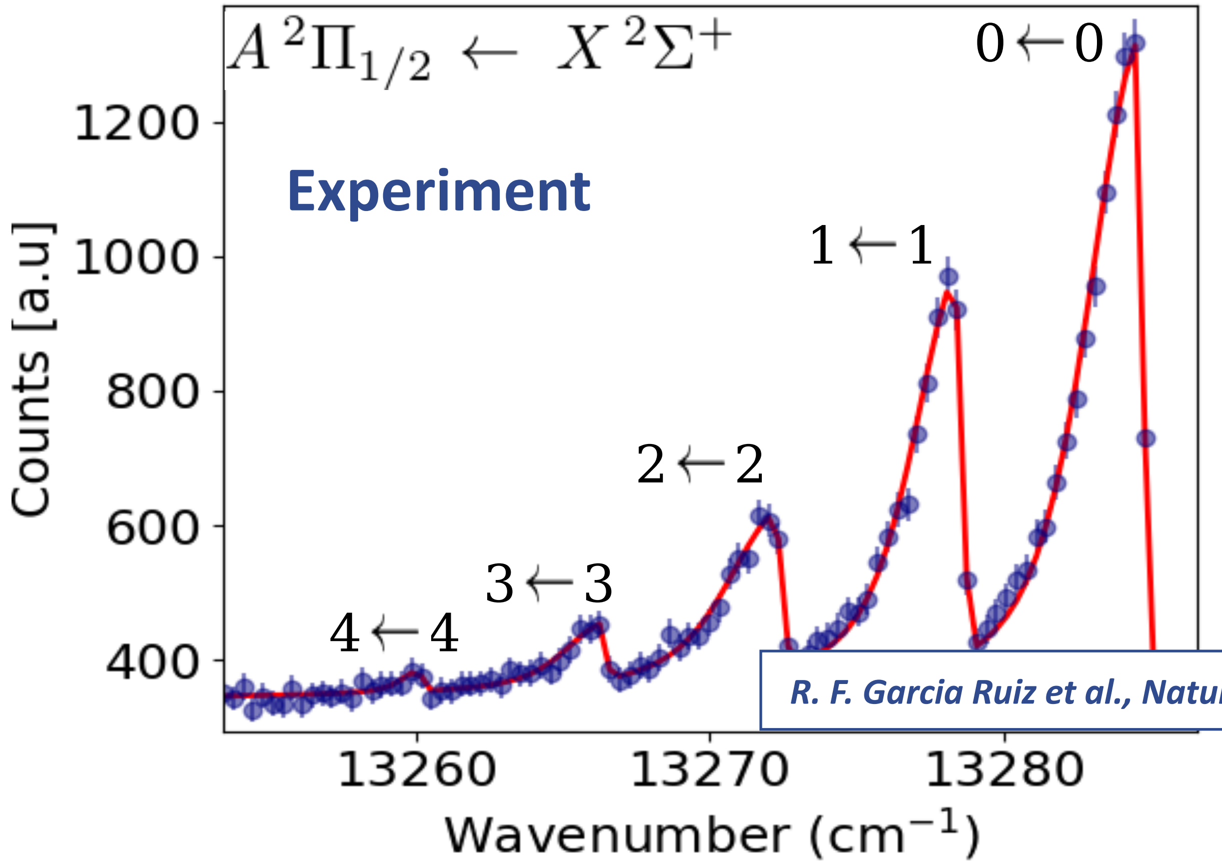
Discovery,
accelerated

laser spectroscopy of molecules

- cooling of internal degrees of freedom
  ➡ higher population of the low-lying states
  ➡ simpler spectra ⇒ more easily identification
- buffer-gas cooling in cryogenic Paul trap:
  ➡ overall the gain could be more than x100 in scanning time.
  ➡ enables efficient initial state preparation for later EDM searches

RaF spectra





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

simulation by R. F. Garcia Ruiz

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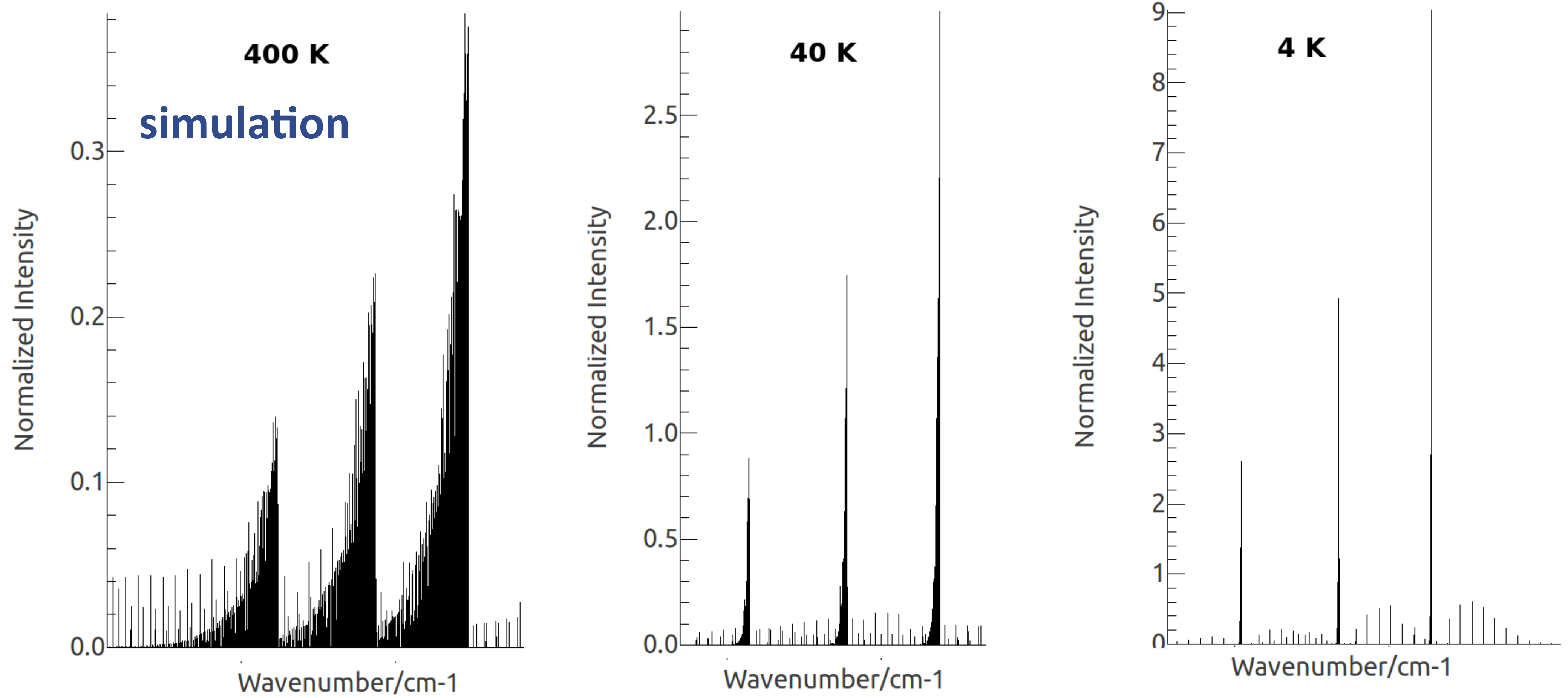
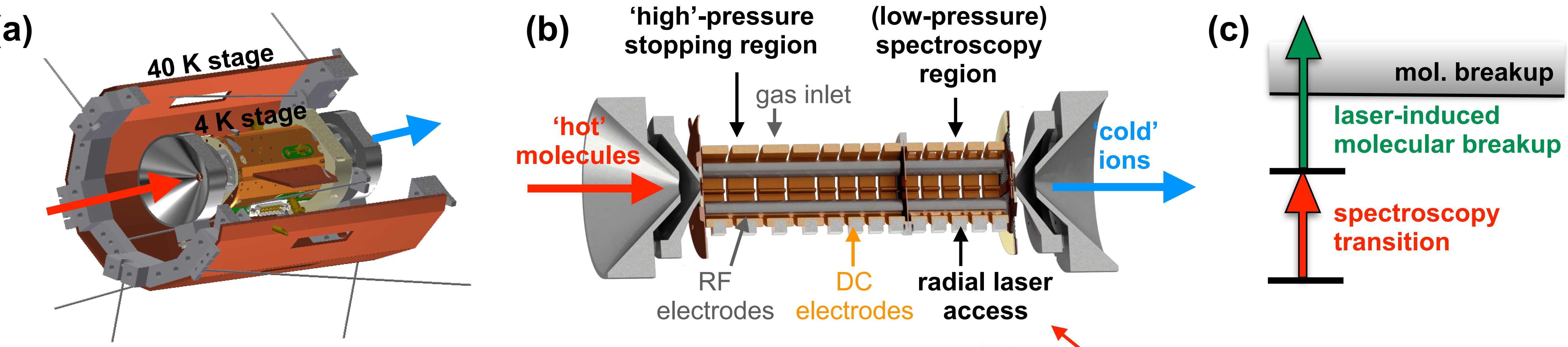


simulation by R. F. Garcia Ruiz

MIRACLS & rad. molecules

a cryogenic Paul trap for cooling and spectroscopy of of (ionic) radioactive molecules



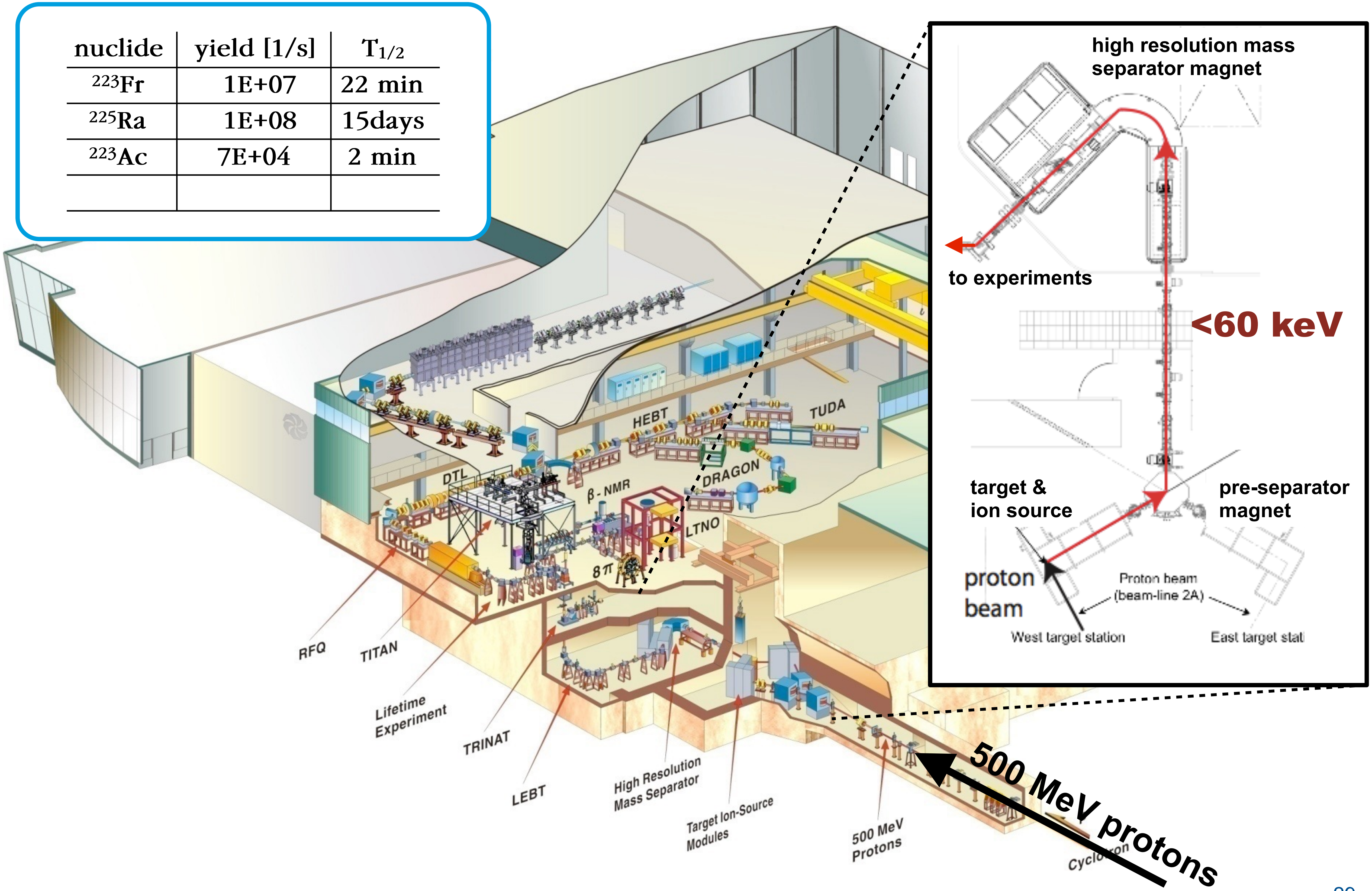
laser access for,
spectroscopy,
state preparations and
laser cooling

S. Sels., F. Maier et al., submitted

- ➡ higher population of the low-lying states
- ➡ higher resolution (compared to RT-trap)
- ➡ high experimental sensitivity for trapped ions
- ➡ MIRACLS' MR-ToF method for search for laser-cooling transitions in ionic molecules

Radioactive Ions TRIUMF

nuclide	yield [1/s]	$T_{1/2}$
^{223}Fr	1E+07	22 min
^{225}Ra	1E+08	15days
^{223}Ac	7E+04	2 min



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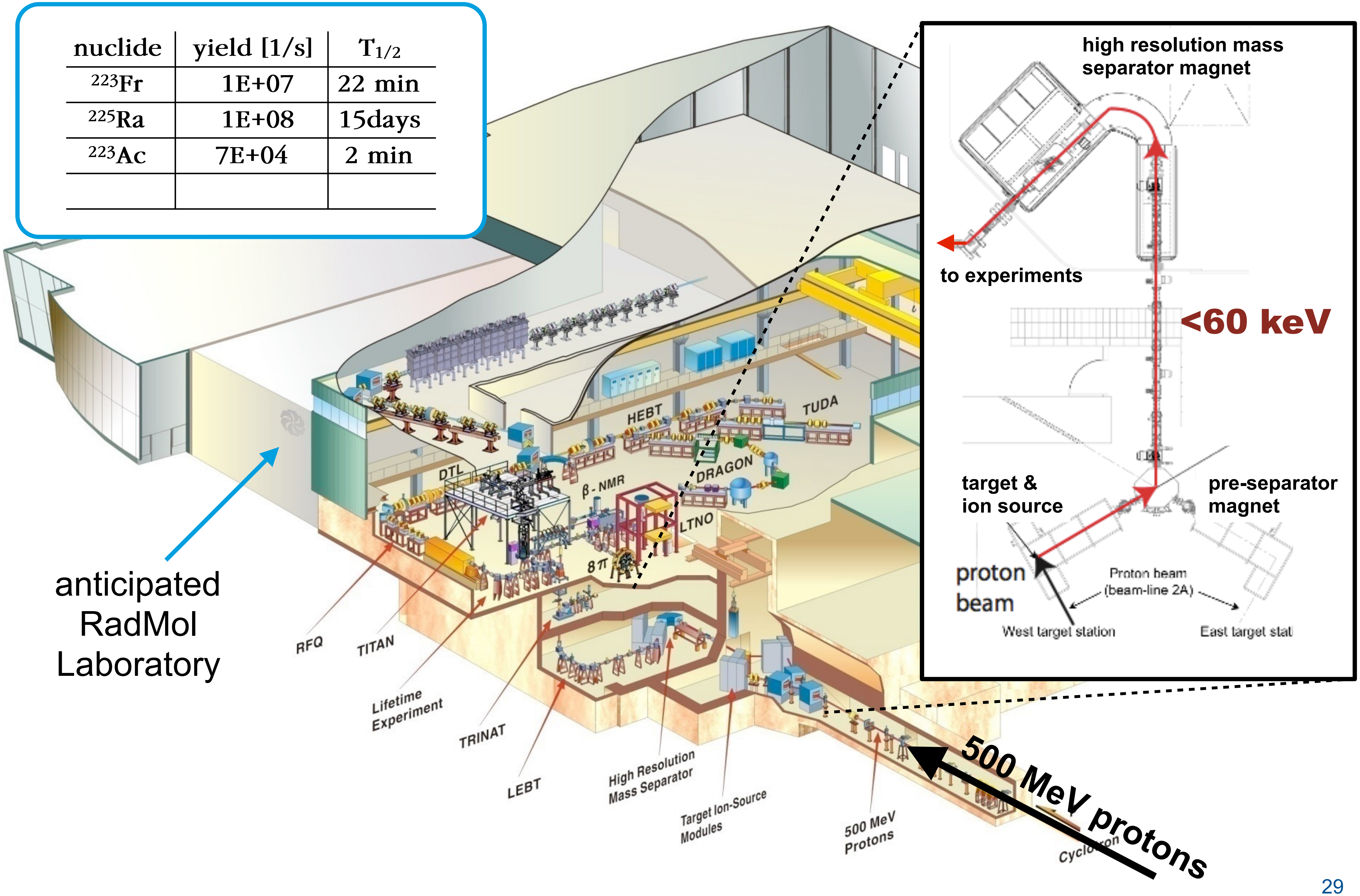
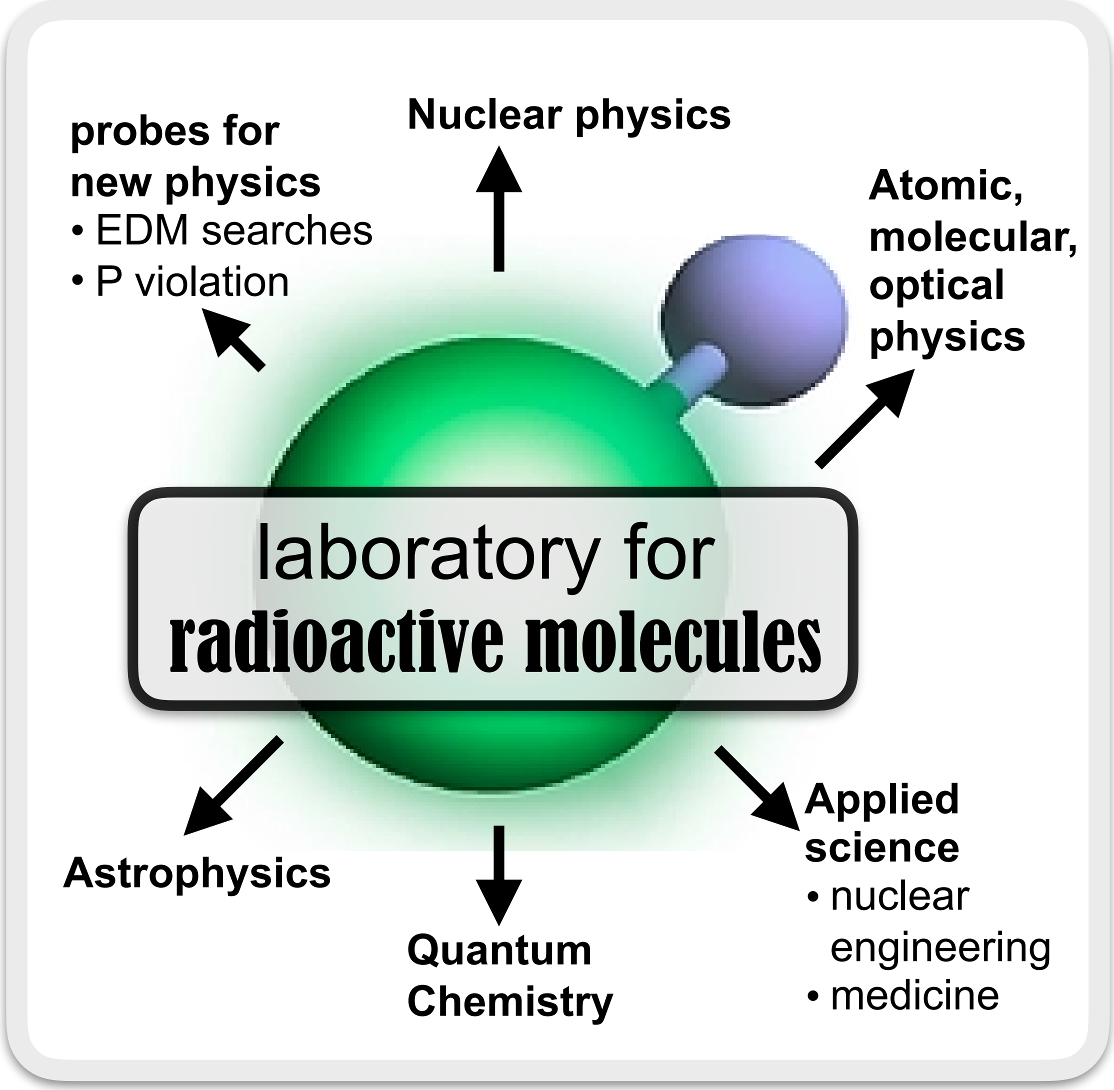


anticipated RadMol Laboratory

RadMol @ TRIUMF

- **Radioactive molecules as novel precision probes for fundamental physics**
- Initial physics program:
  - octuple-deformed nuclei incorporated into polar molecules → Molecular EDM with unprecedented sensitivity to nuclear T-breaking
  - access nuclear anapole moments via diatomic molecules
- New laboratory for radioactive molecules @ TRIUMF:
  - dedicated laboratory for the study of radioactive molecules
  - to host 3 experimental stations
  - provision for expansions into other fields
- Current Canadian team: 12 faculty and staff physicists from UofToronto, TRIUMF, UBC, U. Manitoba, McGill, UofOttawa
- Current International team: MIT, Caltech, UoChicago, Manchester, KU Leuven, Marburg, Edinburgh, Kassel, etc.
- strengthens and builds on the initiative for a TRIUMF Precision&Quantum Centre



laboratory for **radioactive molecules**

probes for new physics
- EDM searches
- P violation

Nuclear physics

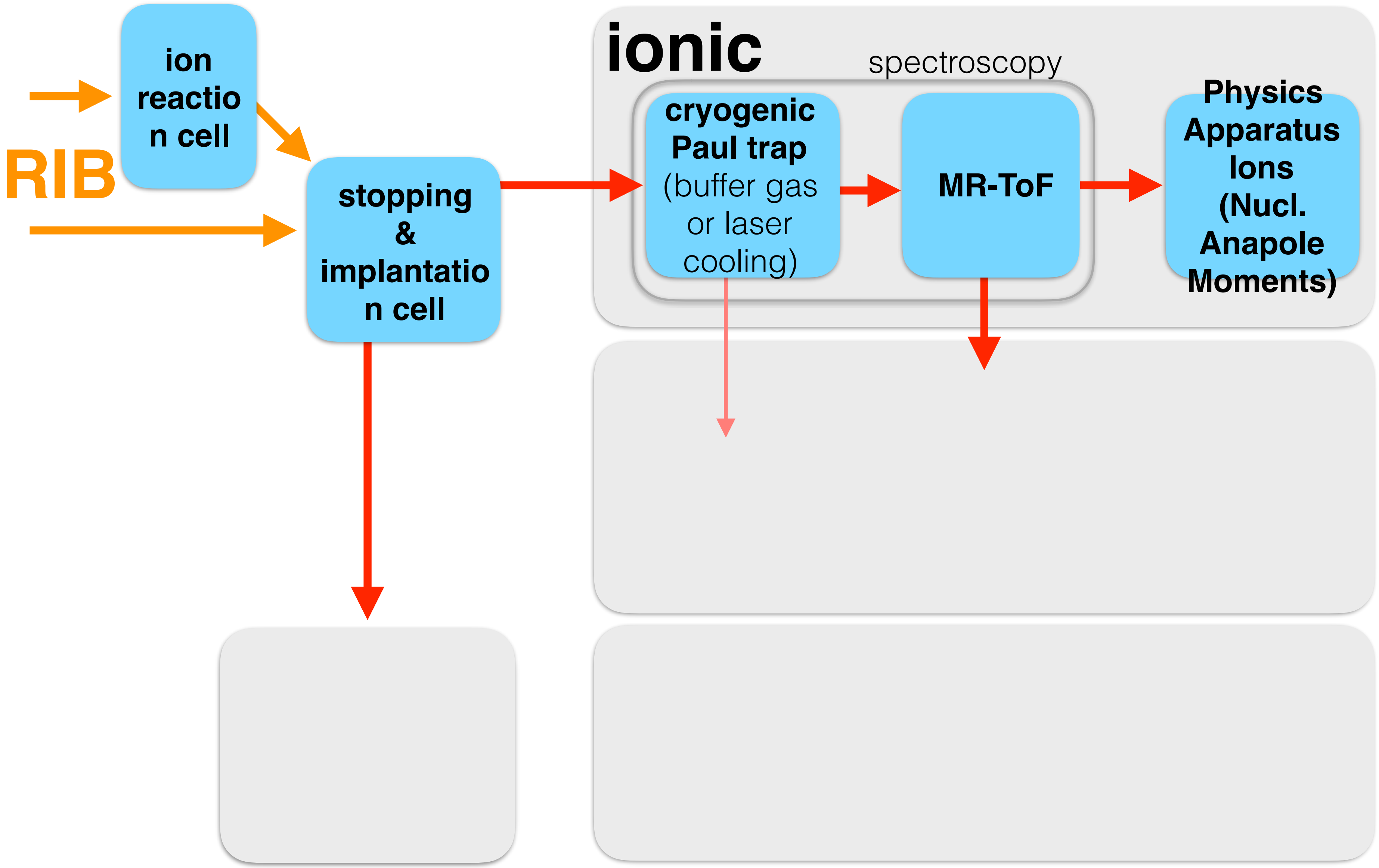
Atomic, molecular, optical physics

Astrophysics

Quantum Chemistry

Applied science
- nuclear engineering
- medicine

Two LOI's, ^{223}FrAg and ^{227,229}ThF$^+$, have two-five orders mag. discovery potential of nuclear time reversal compared to ^{199}Hg



RIB

ion reaction cell

stopping & implantation cell

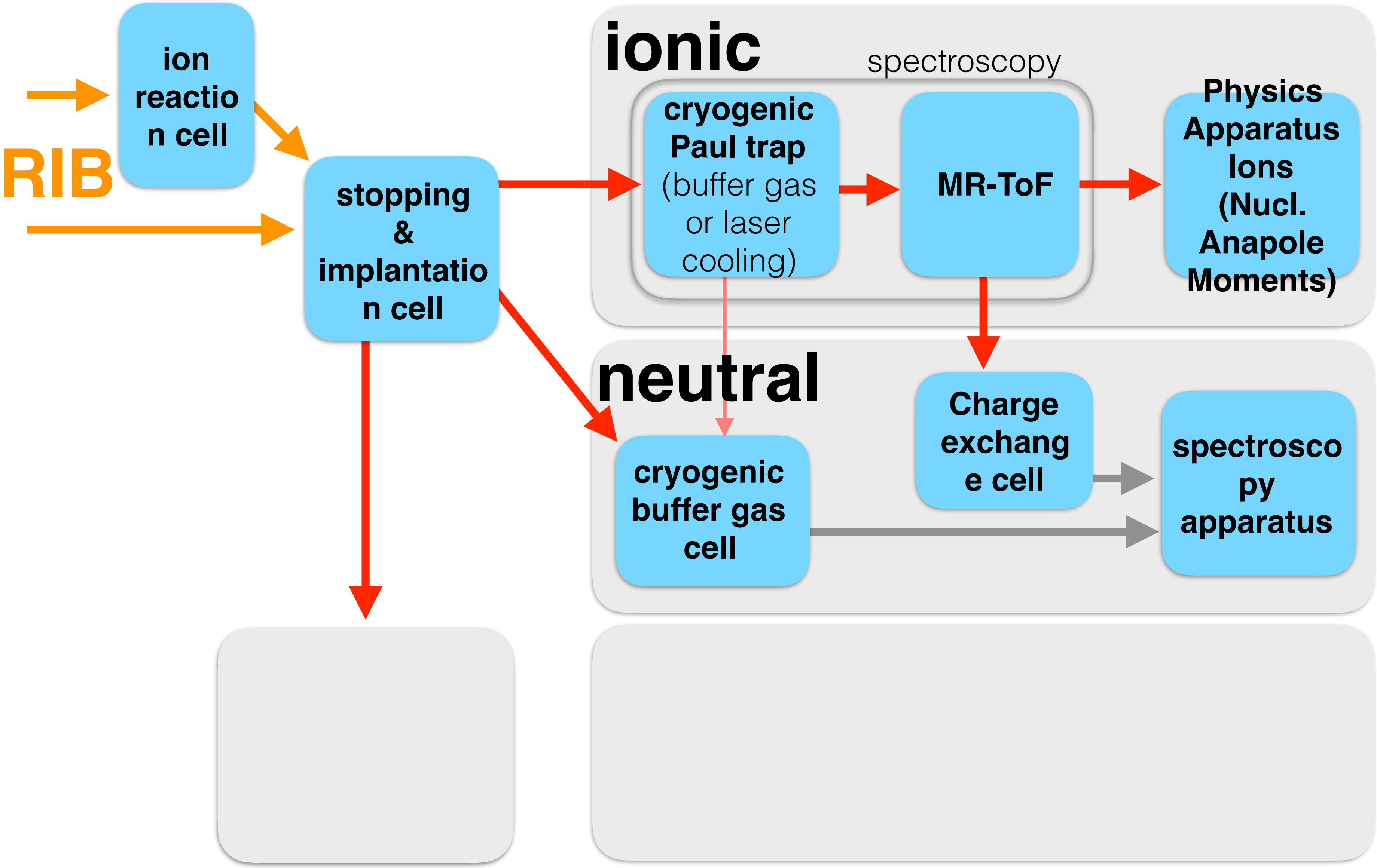
ionic

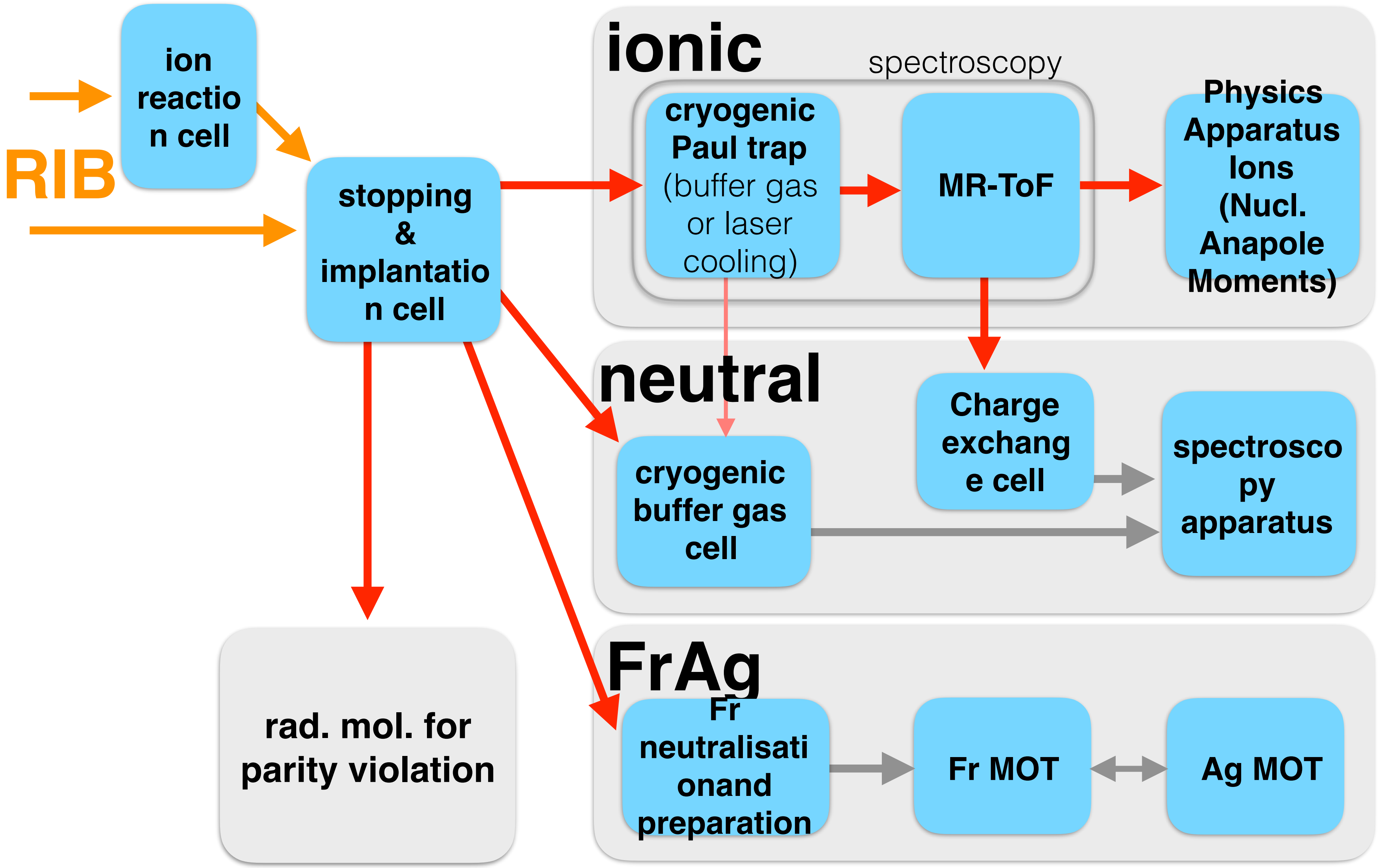
spectroscopy

cryogenic Paul trap (buffer gas or laser cooling)

MR-ToF

Physics Apparatus Ions (Nucl. Anapole Moments)


RIB
ion reaction cell
stopping & implantation cell
ionic
spectroscopy
cryogenic Paul trap (buffer gas or laser cooling)
MR-ToF
Physics Apparatus Ions (Nucl. Anapole Moments)
neutral
cryogenic buffer gas cell
Charge exchange cell
spectroscopy apparatus



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Physics Apparatus Ions (Nucl. Anapole Moments)

neutral

cryogenic buffer gas cell

Charge exchange cell

spectroscopy apparatus

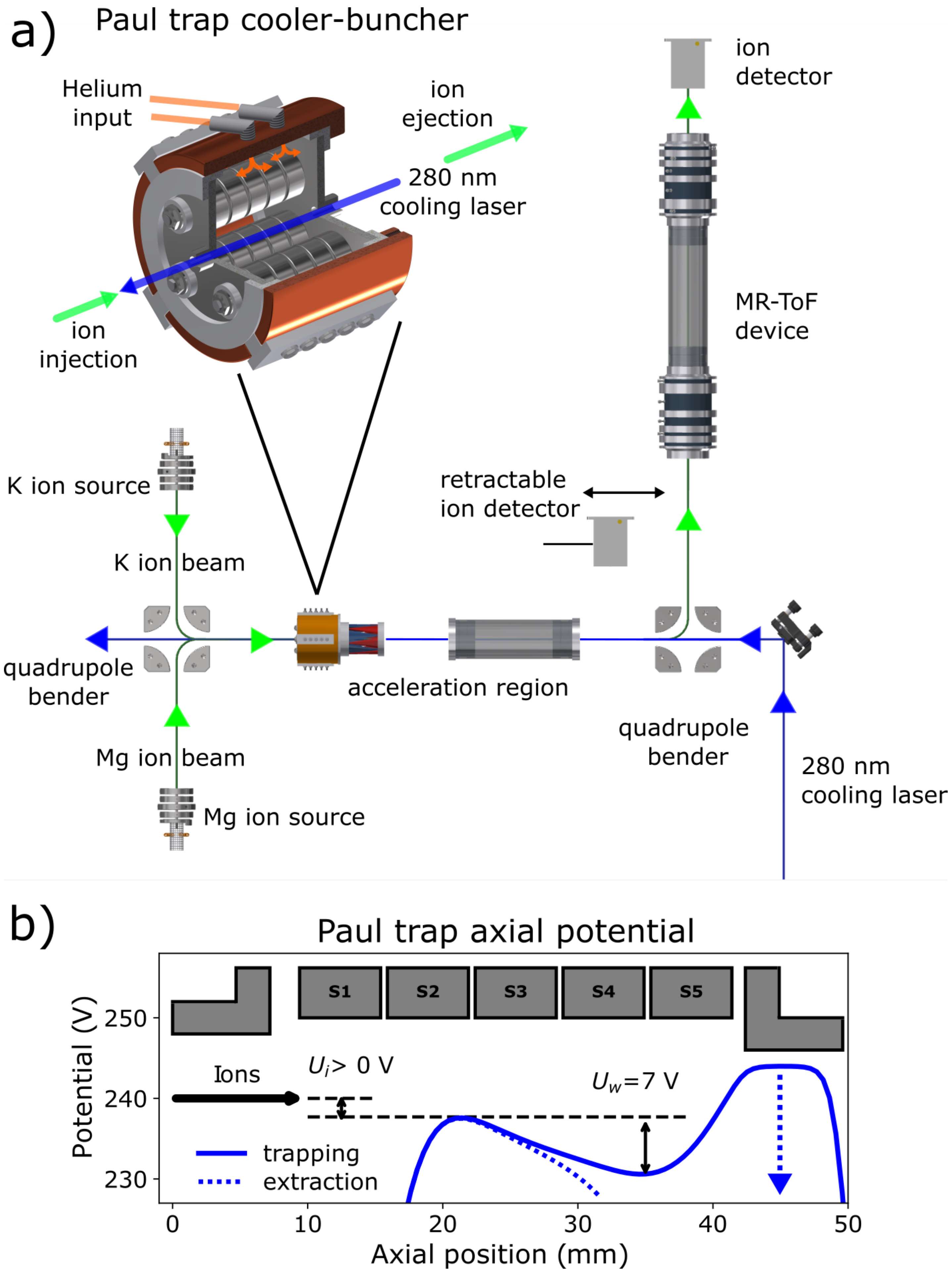
FrAg

Fr neutralisationand preparation

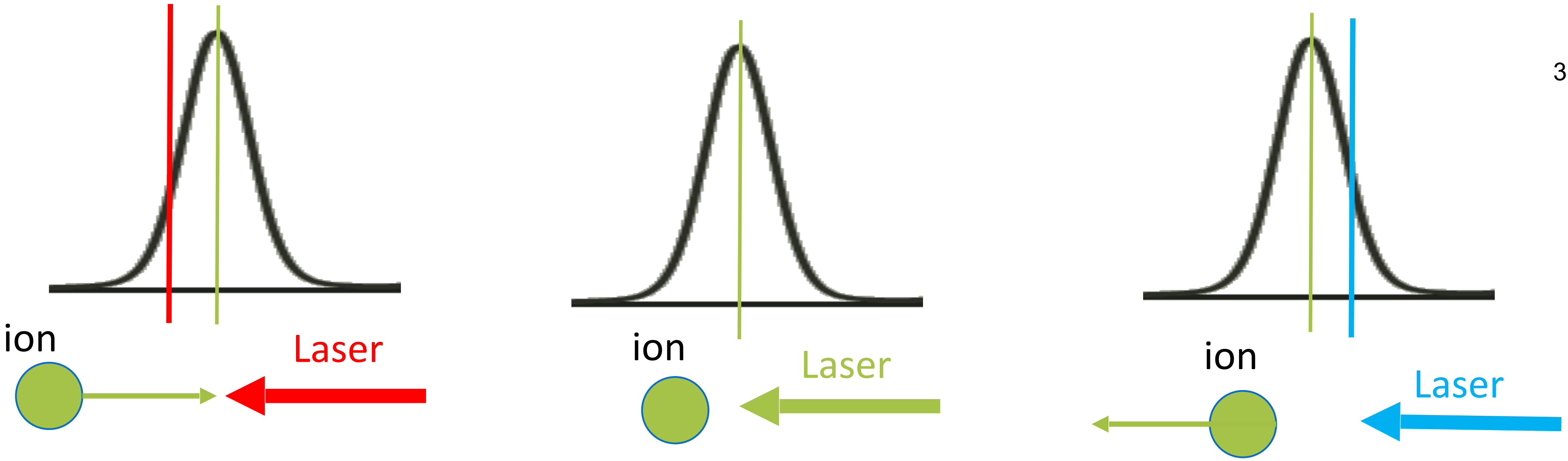
Fr MOT

Ag MOT

rad. mol. for parity violation


a)
Paul trap cooler-buncher
Helium input
ion ejection
280 nm cooling laser
ion injection
ion detector
MR-ToF device
K ion source
K ion beam
retractable ion detector
quadrupole bender
acceleration region
quadrupole bender
Mg ion beam
Mg ion source
280 nm cooling laser
b)
Paul trap axial potential
S1
S2
S3
S4
S5
Ions
U_i> 0 V
U_w=7 V
trapping
extraction
Potential (V)
250
240
230
0
10
20
30
40
50
Axial position (mm)

Doppler Cooling principle



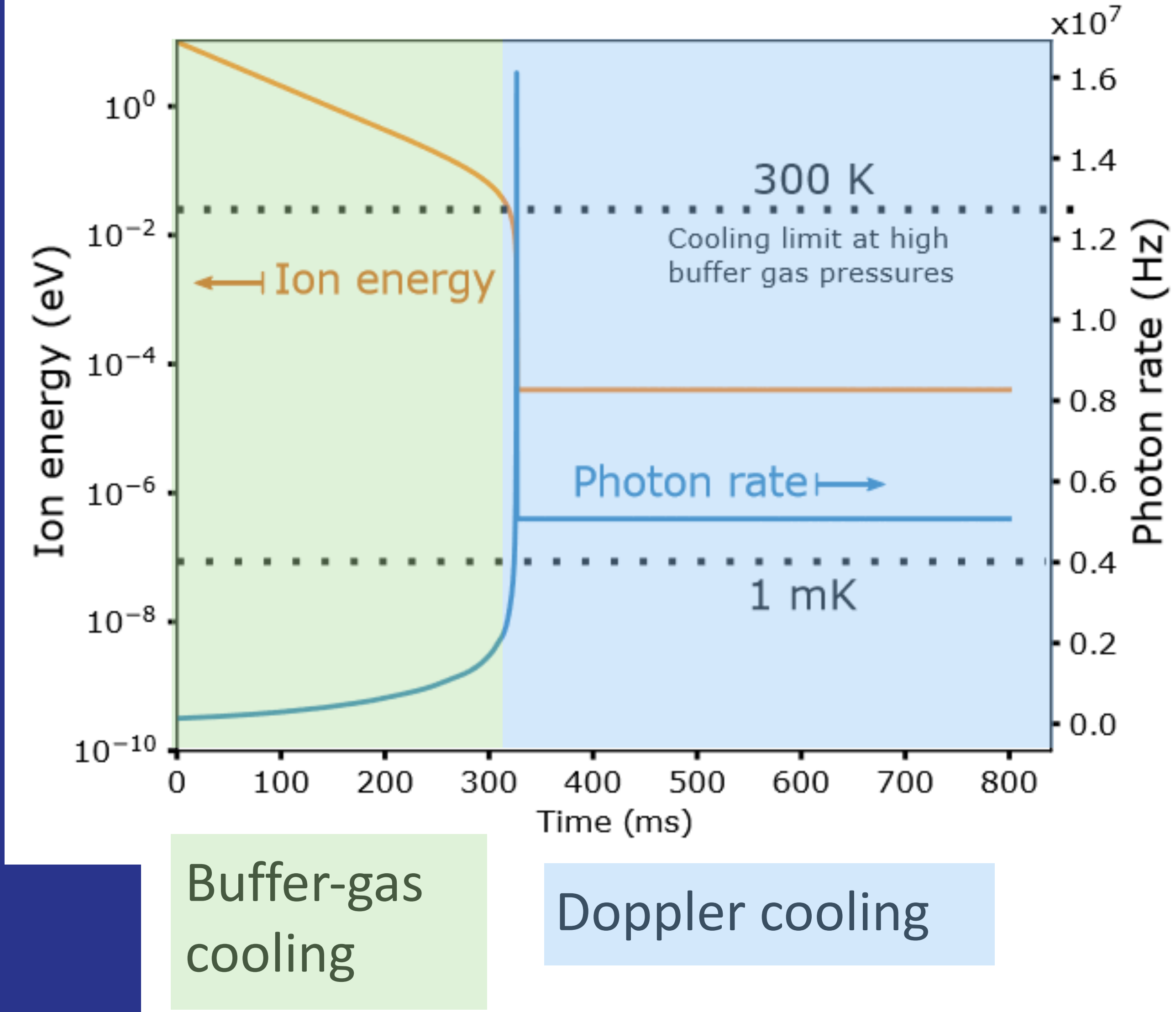
- Moving ions observe Doppler shift in laser frequency
- Absorption of photon in one direction
- Spontaneous emission of photon in random direction
- Net-cooling or heating effect since photon momentum is subtracted from/added to the Mg ion momentum
  Red-detuning: cooling, blue detuning: heating

Needed cooling time

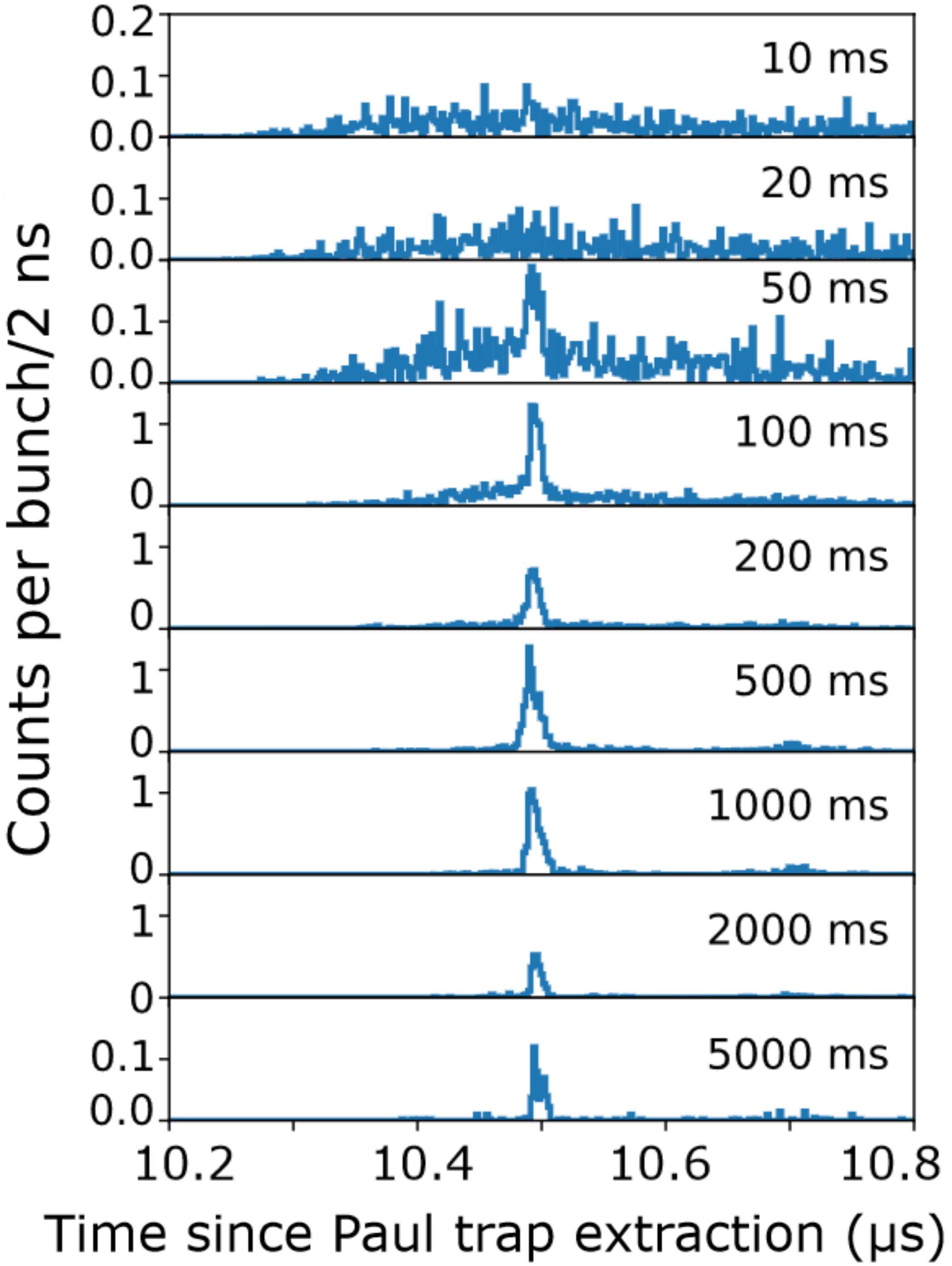
Experiment:

- ➢ 1e-5 to 1e-8 mbar residual gas present within Paul trap
- ➢ cooling time ≈ 100 ms

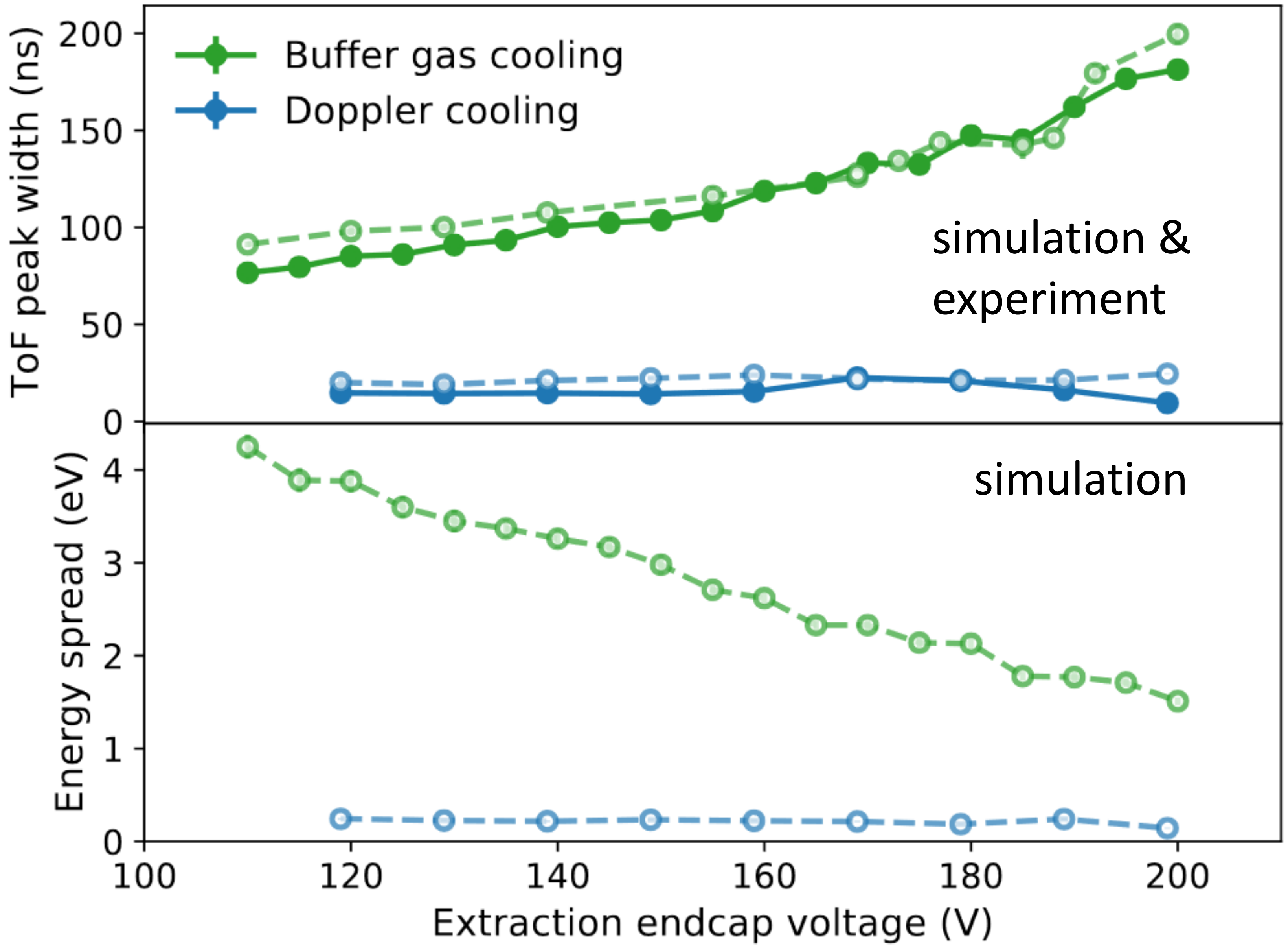
Simulations + numerical model: Presence of buffer gas speeds up the cooling

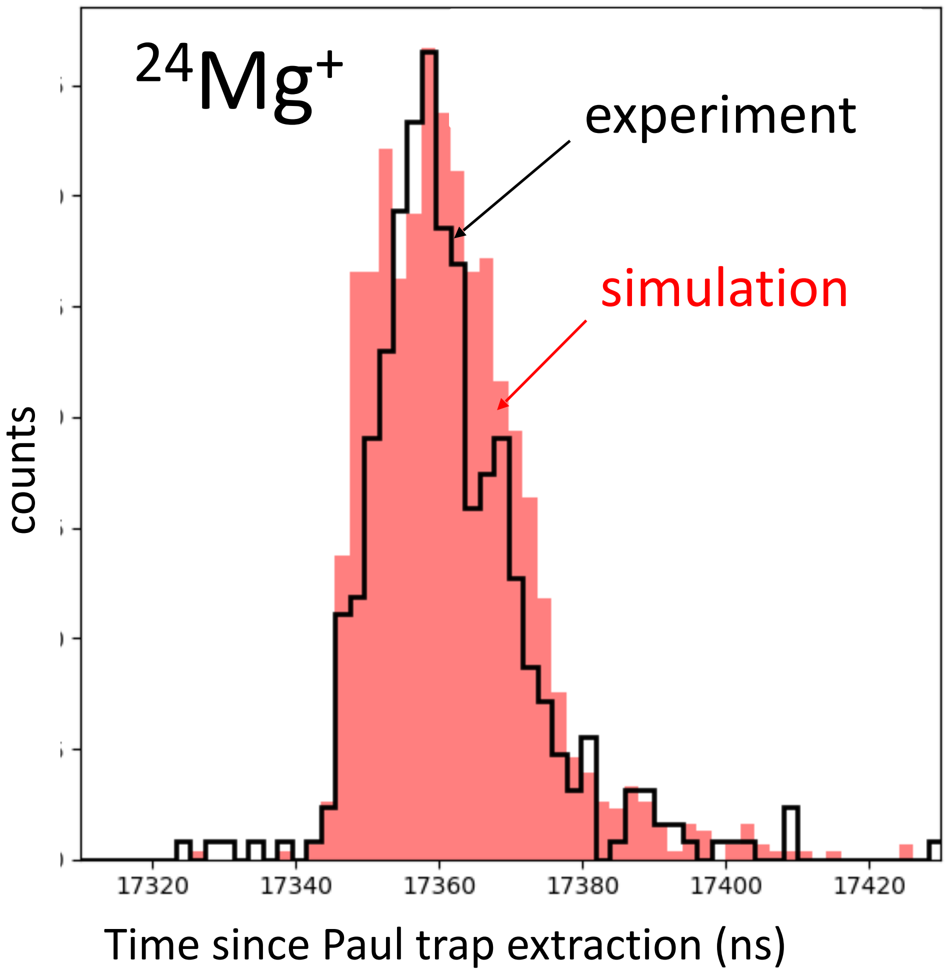


3 mW & -200 MHz detuning, varying cooling times:



Applications at RIB facilities





Simultaneously
small Dt & DE

→ Improvements in precision and/or sensitivity for various experimental techniques such as collinear laser spectroscopy or mass spectrometry