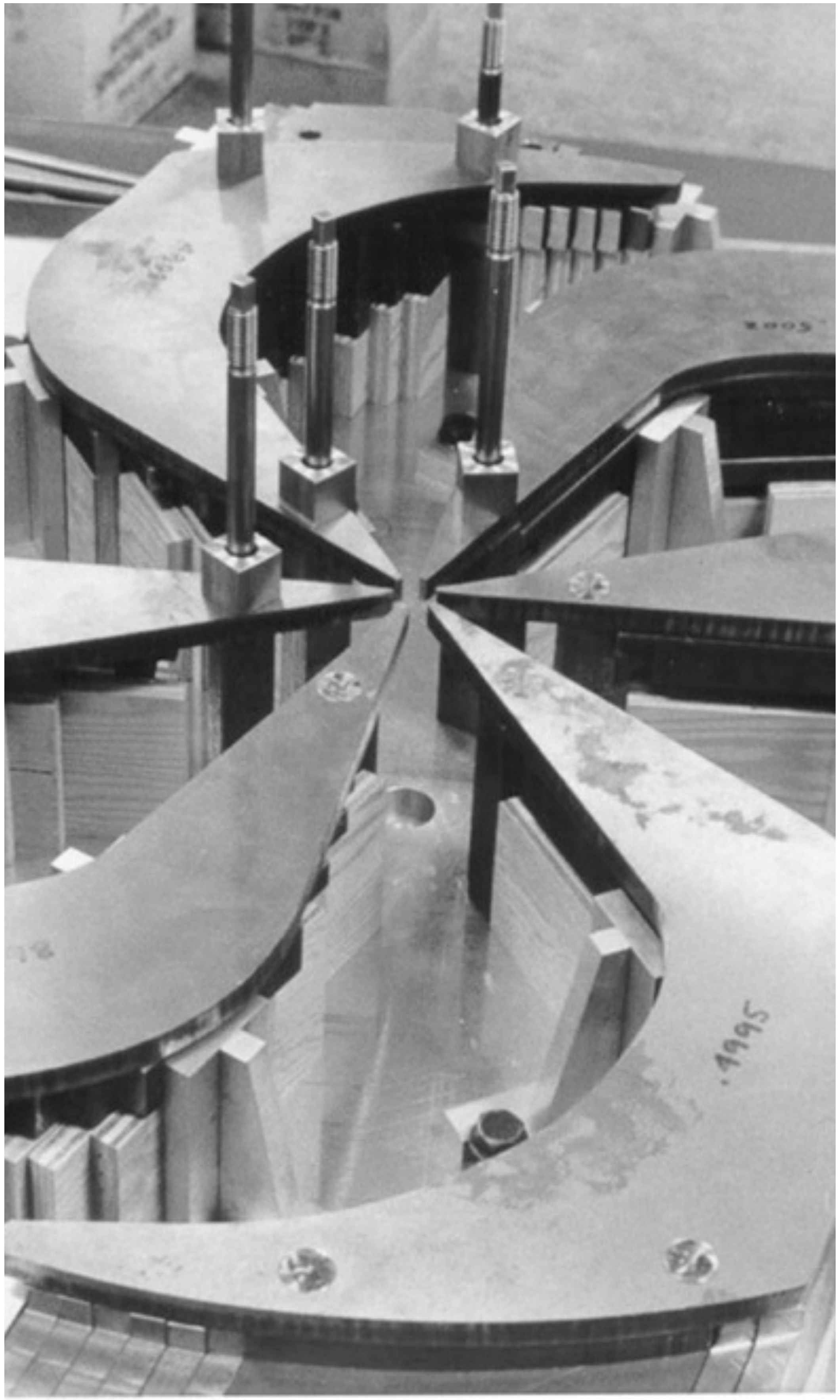
Radioactive Molecules
Novel Probes for New Physics

Stephan Malbrunot-Ettenauer
TRIUMF, University of Toronto

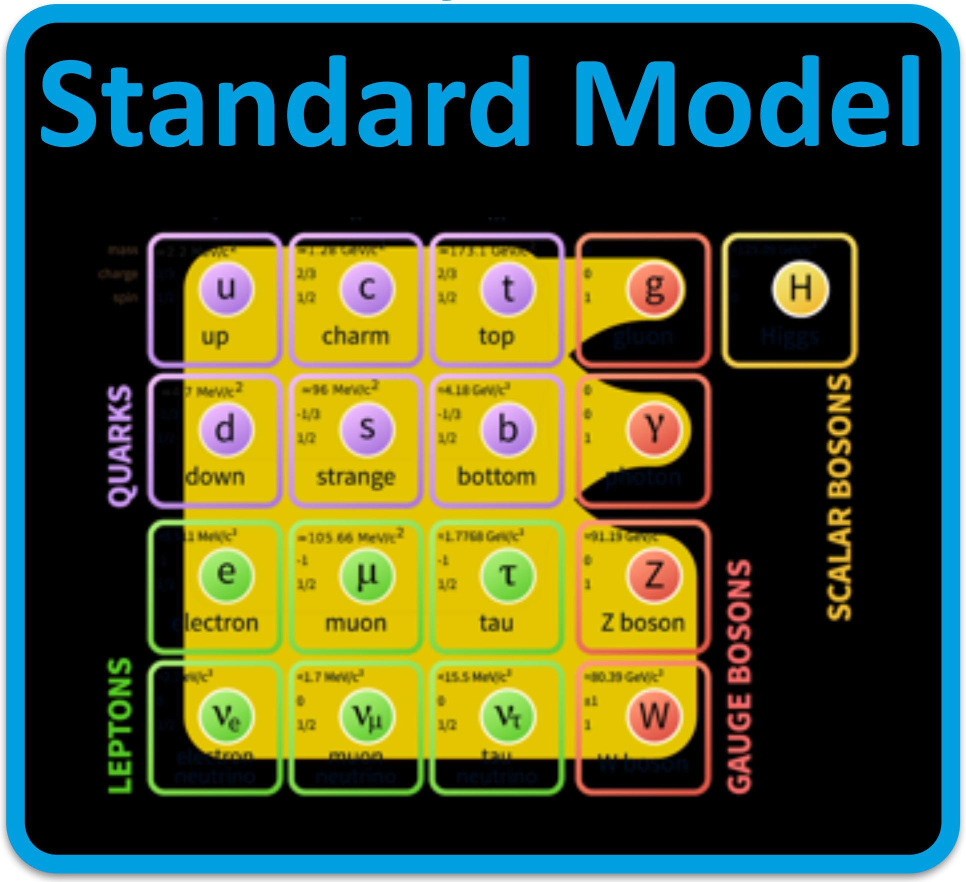
WNPPC 2022

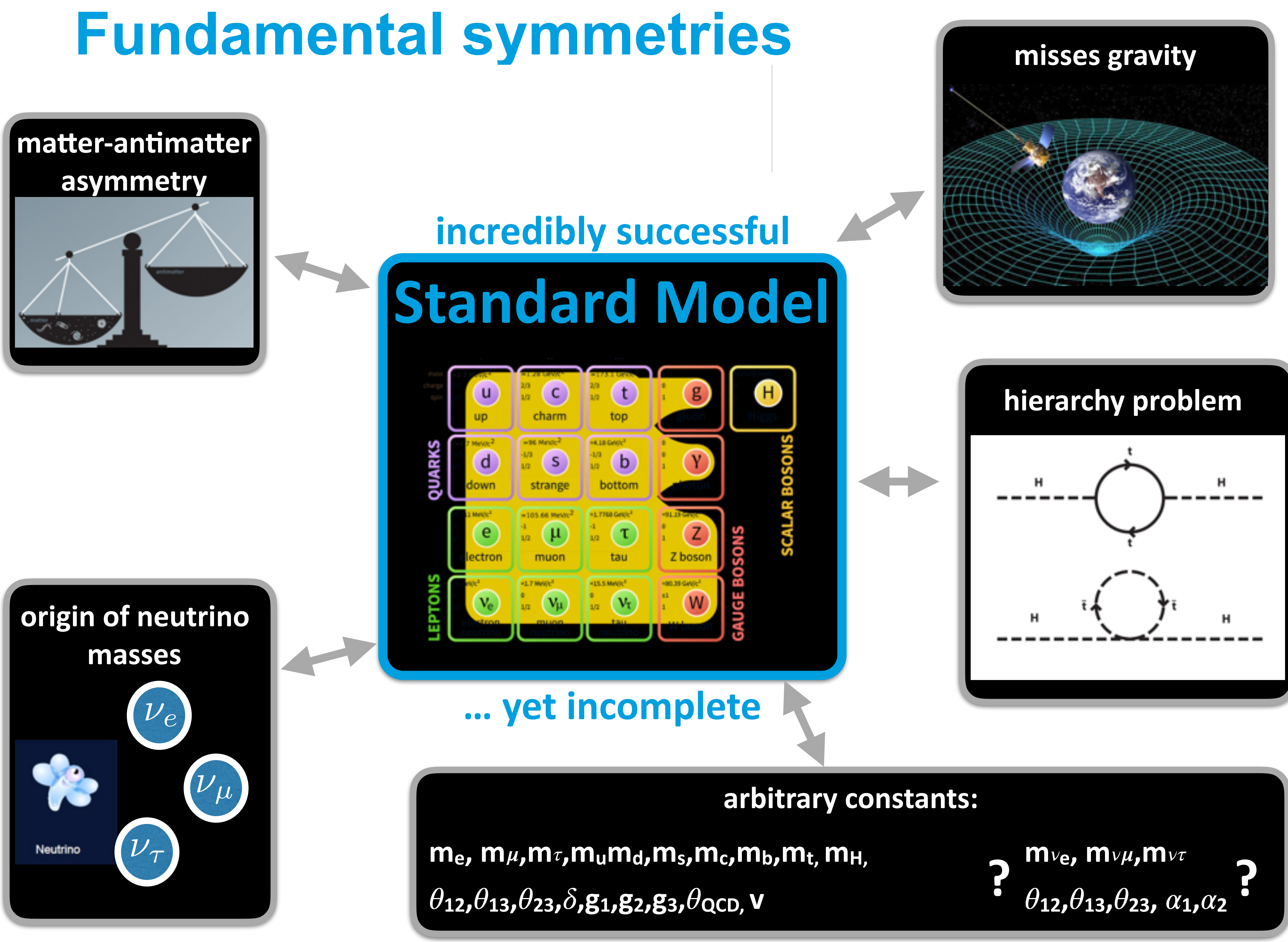


Discovery, accelerated

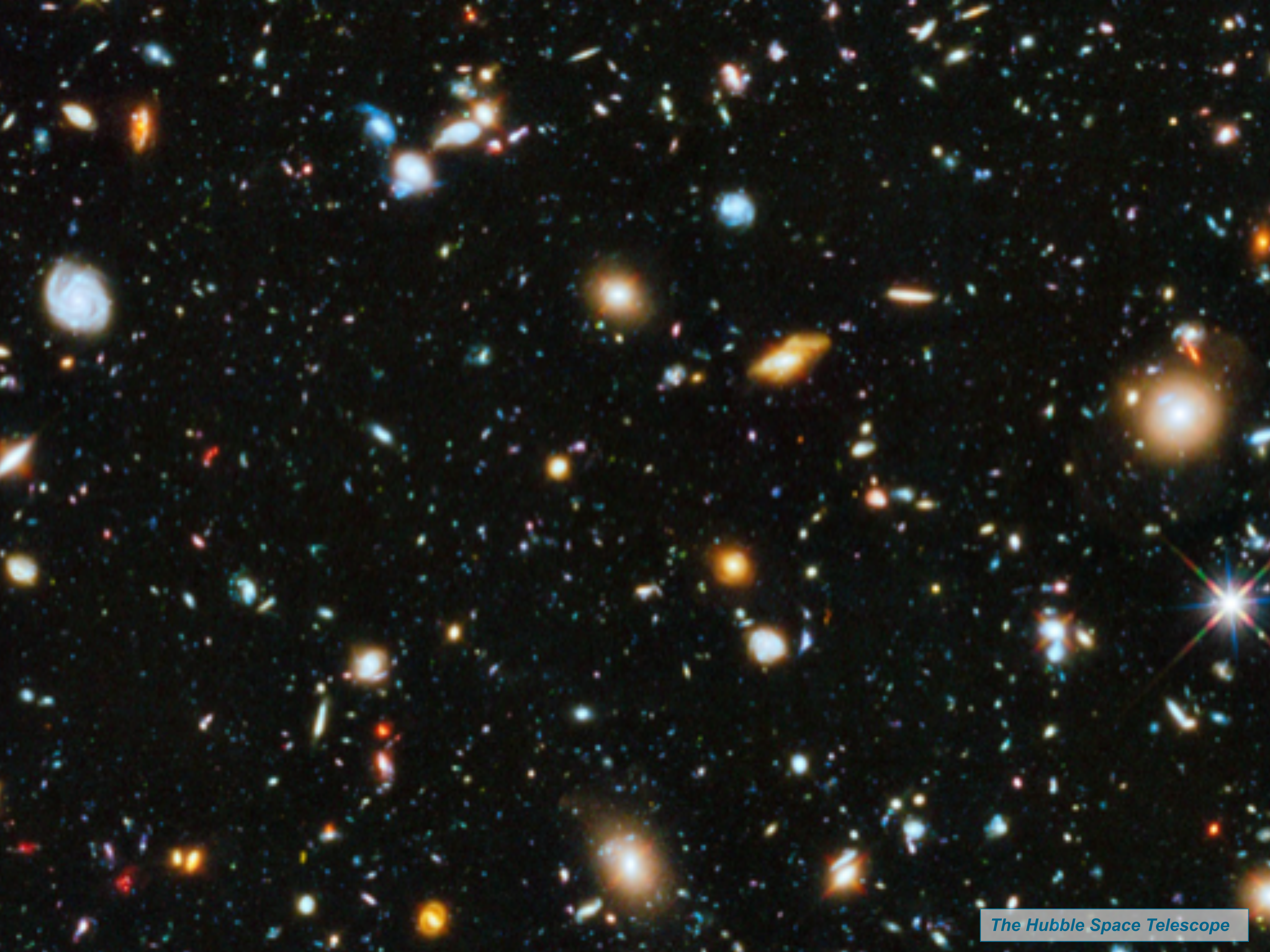
Fundamental symmetries

incredibly successful





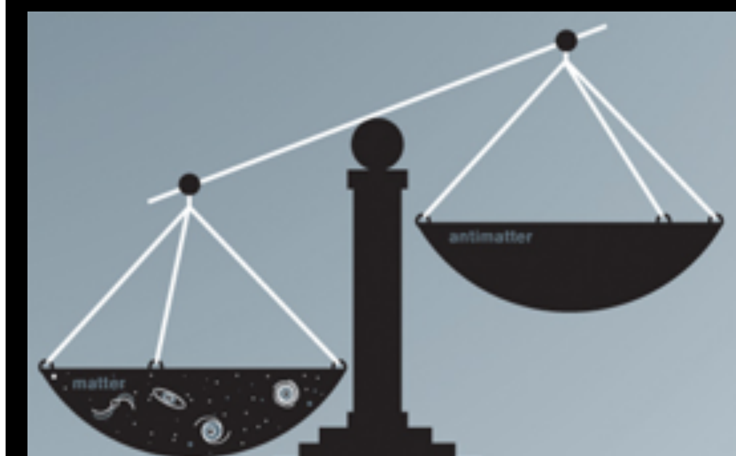
Fundamental symmetries
matter-antimatter asymmetry
misses gravity
incredibly successful
Standard Model
QUARKS
LEPTONS
GAUGE BOSONS
SCALAR BOSONS
u up
c charm
t top
g
H
d down
s strange
b bottom
γ
e electron
μ muon
τ tau
Z Z boson
ν_e
ν_μ
ν_τ
W
hierarchy problem
H
t
origin of neutrino masses
ν_e
ν_μ
ν_τ
Neutrino
... yet incomplete
arbitrary constants:
$m_e, m_\mu, m_\tau, m_u m_d, m_s, m_c, m_b, m_t, m_H,$
$\theta_{12}, \theta_{13}, \theta_{23}, \delta, g_1, g_2, g_3, \theta_{QCD}, v$
?
$m_{\nu e}, m_{\nu\mu}, m_{\nu\tau}$
$\theta_{12}, \theta_{13}, \theta_{23}, \alpha_1, \alpha_2$
?



The Hubble Space Telescope

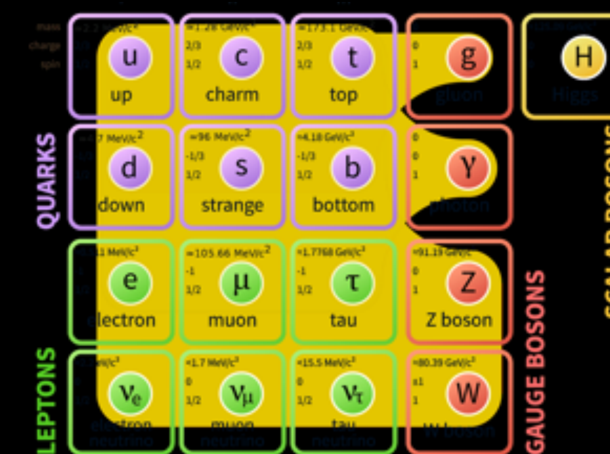
where is all the antimatter?

Macrocosmos



only matter

Microcosmos

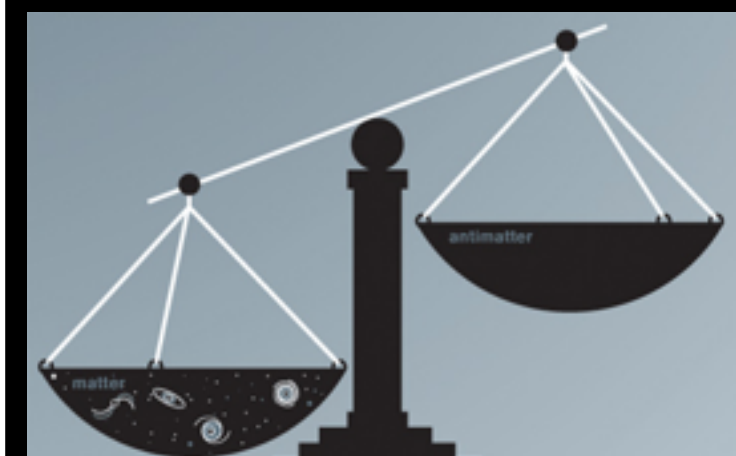


|matter|=|antimatter|

The Hubble Space Telescope

where is all the antimatter?

Macrocosmos



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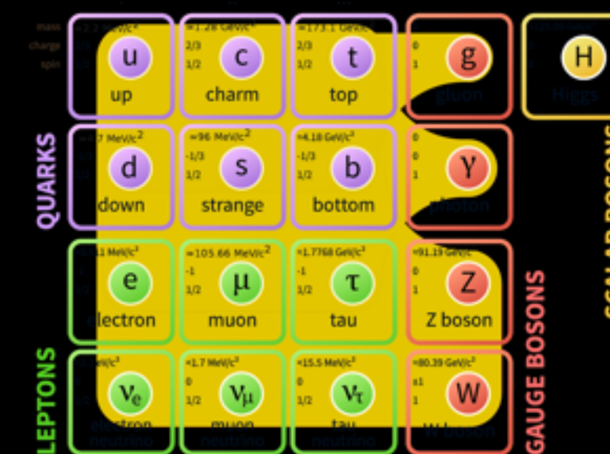
Microcosmos

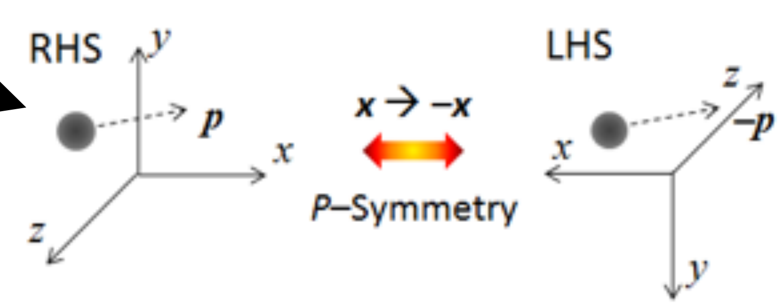


|matter|=|antimatter|

Sakharov, 1967

ingredient to resolve universe's matter-antimatter

C P violation

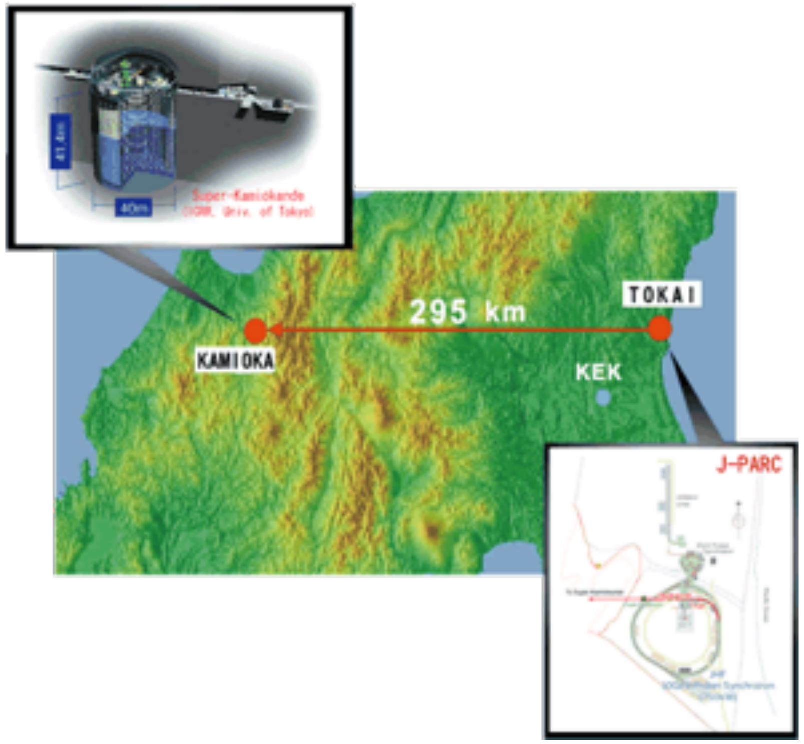


The Hubble Space Telescope

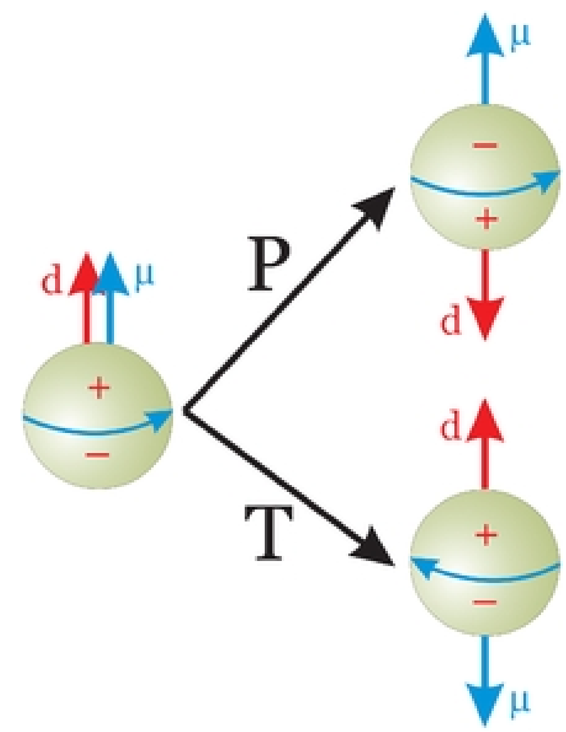
Searches for CP violation

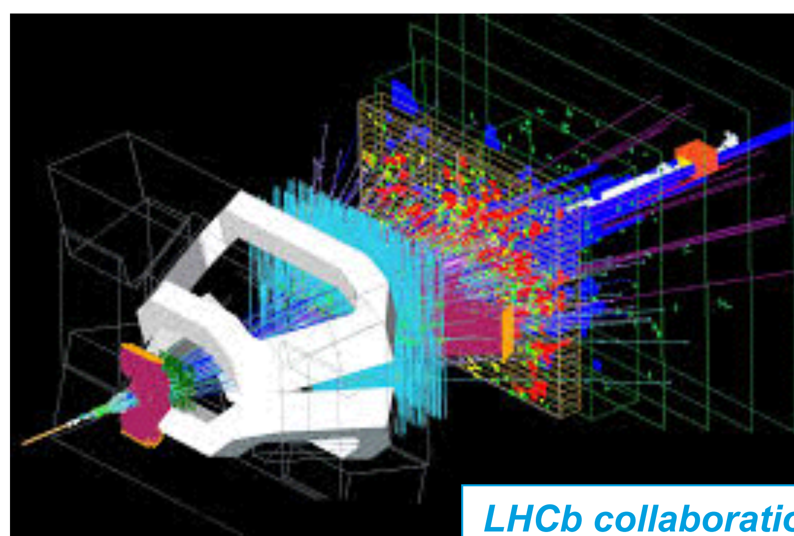
Intensity
Precision
CP
Energy

T2K collaboration, Nature 580, 339 (2020)



ACME collaboration, Nature 562, 355 (2018)
C. Abel et al., PRL 124, 081803 (2020)

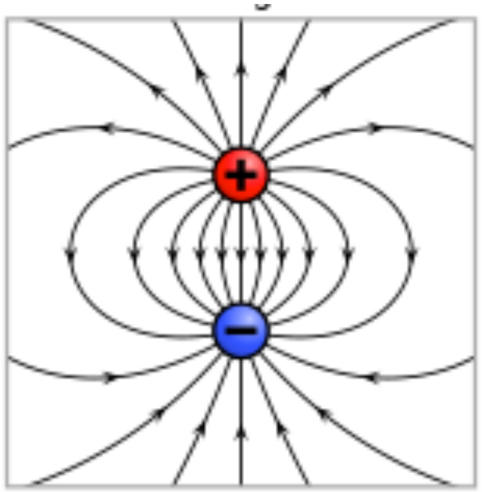




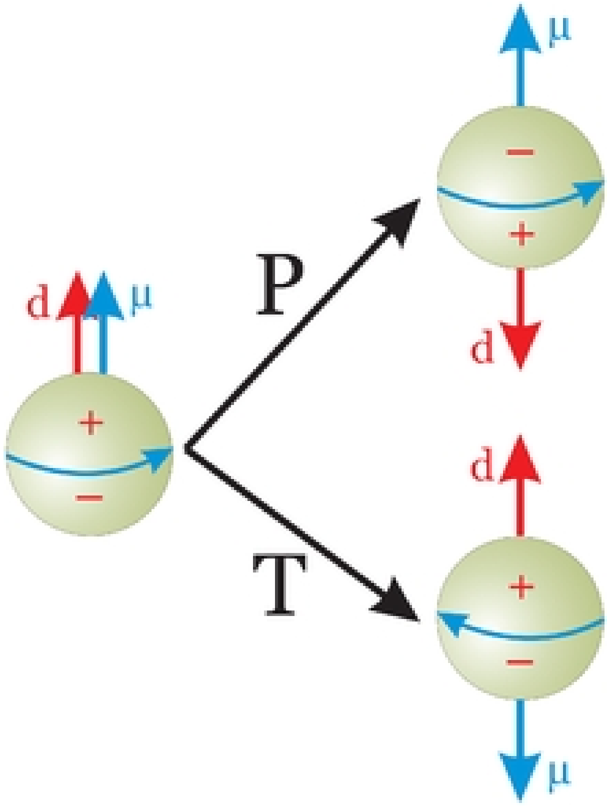
LHCb collaboration
Phys. Rev. Lett. 122, 211803 (2019)

Permanent electric dipole moment

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

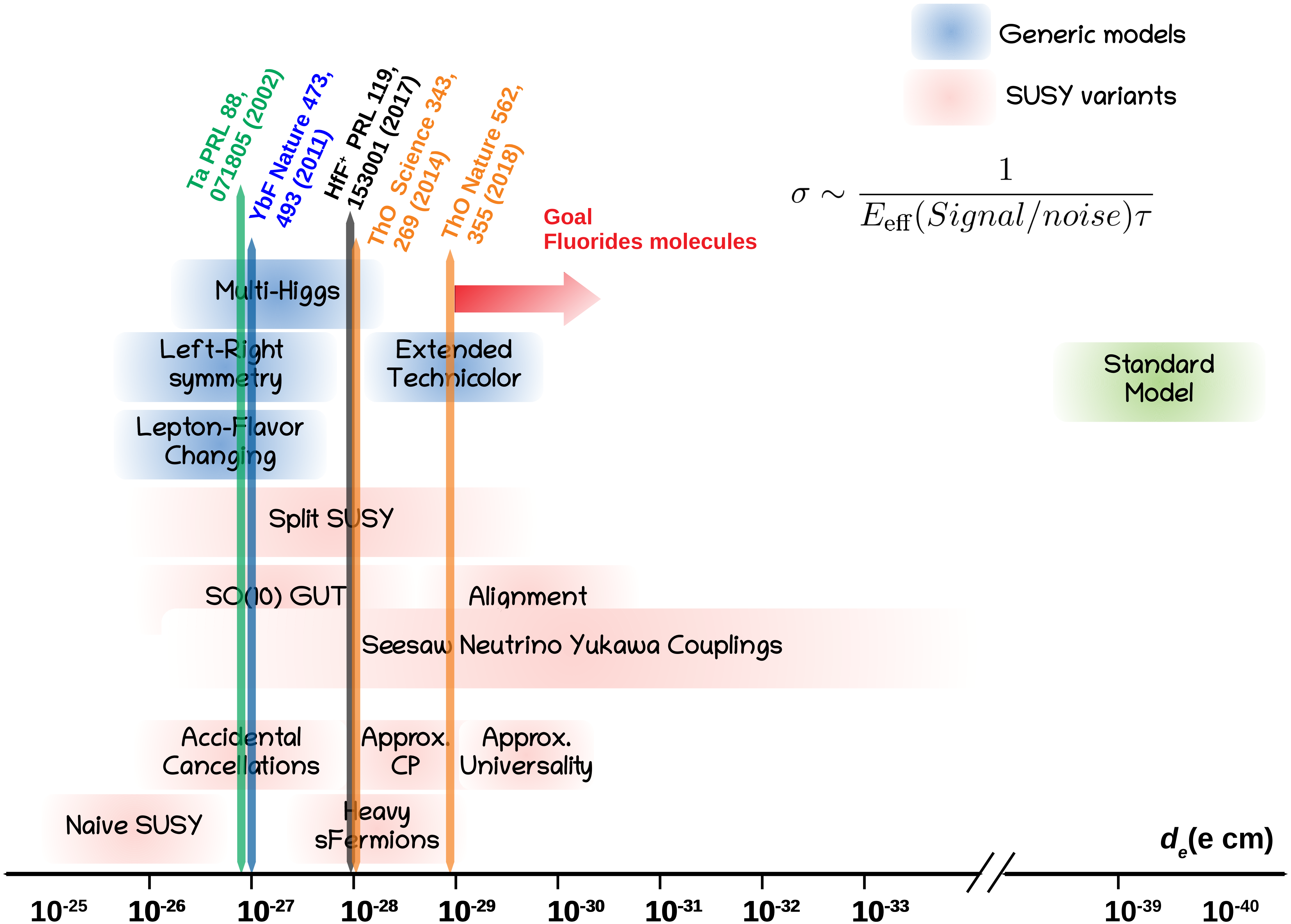


- implies time-reversal (T) violation ⇒ violation of CP symmetry (assuming CPT)



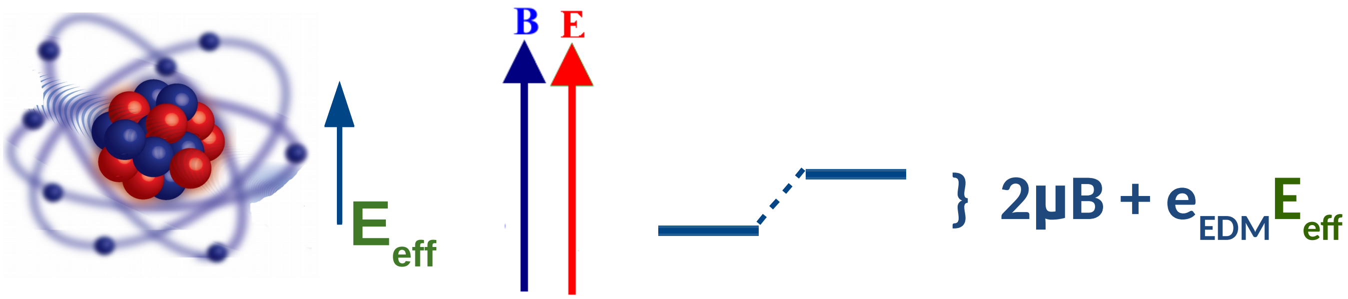
matter-antimatter asymmetry in the universe

Searches for an electron EDM



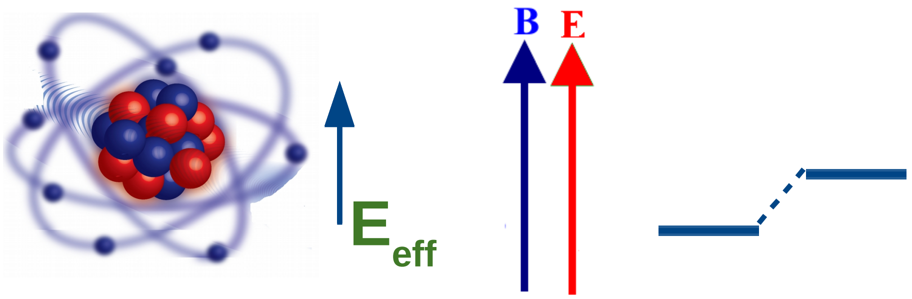
$$\sigma \sim \frac{1}{E_{\text{eff}}(Signal/noise)\tau}$$

EDM searches



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

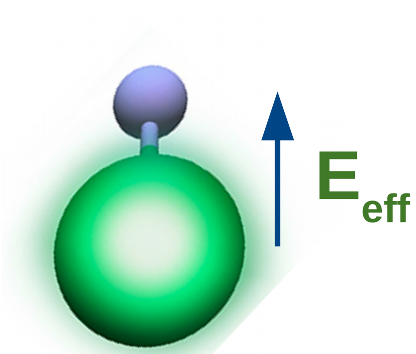
EDM searches



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

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

Molecules:

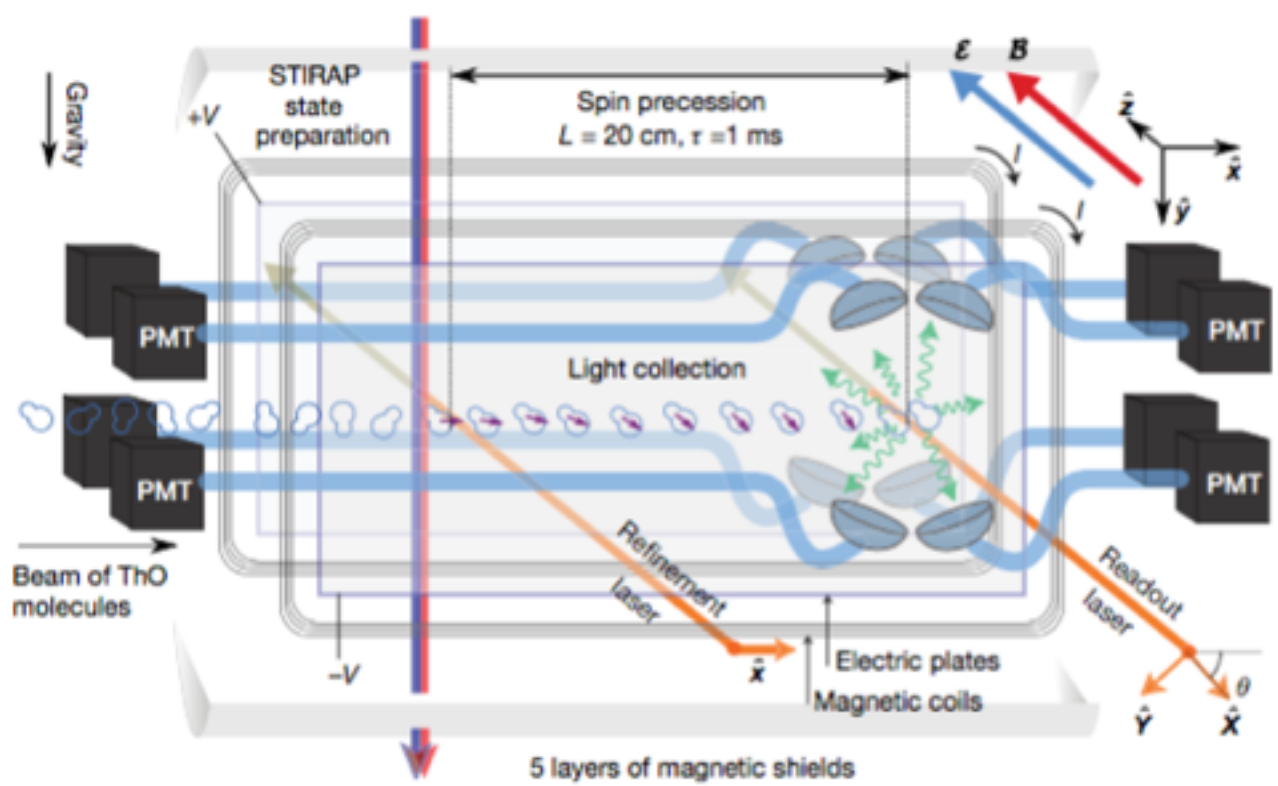


E_{ext} ~1 V/cm

E_{eff} ~80 GV/cm → • enhancement by 10^3 in sensitivity!

ThO

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



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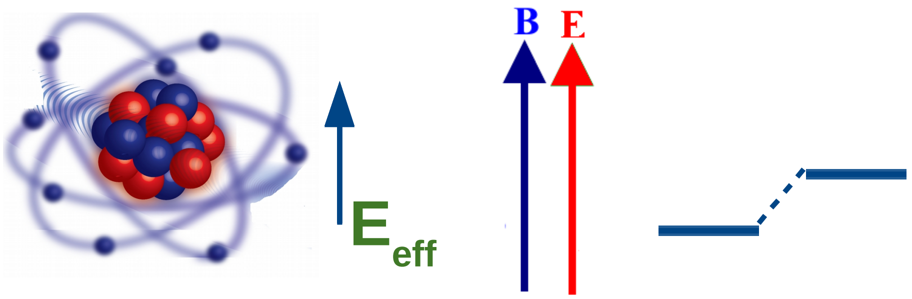

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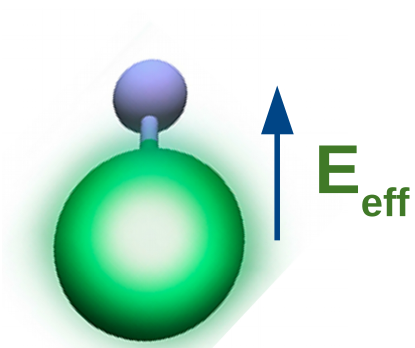

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ACME collaboration
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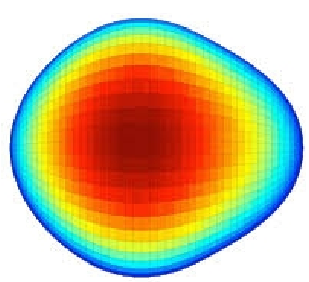
- scales as $Z^2R(Z)$

⇒ opportunity for radioactive molecules

Schiff moment



nuclear-spin-dependent component

‘Designer Molecules’

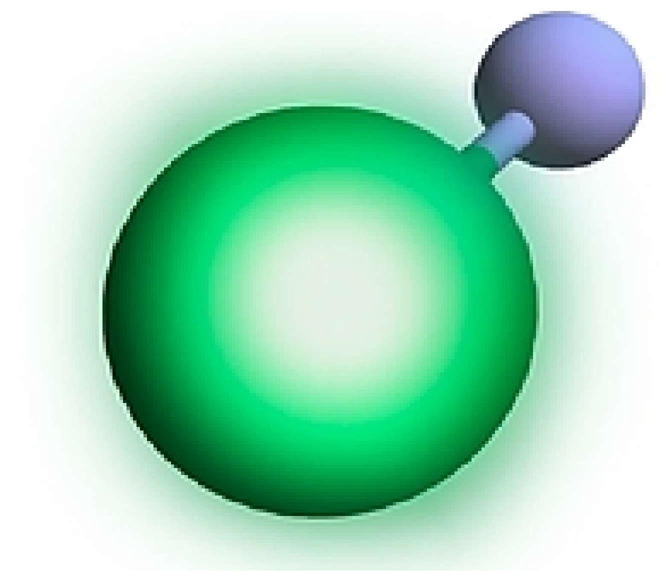
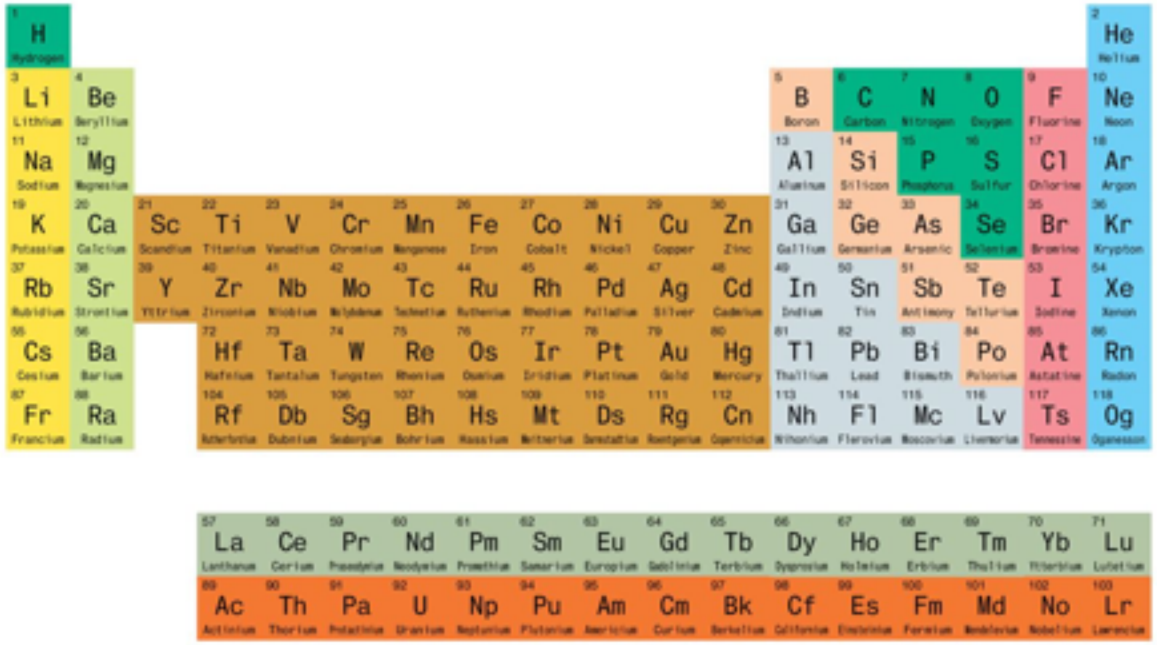


Table of Elements
80 chemical elements
(with stable nuclides)



‘Designer Molecules’

Table of Isotopes
252 stable
≈90 naturally occurring radioisotopes
≈3000 short-lived radionuclides discovered

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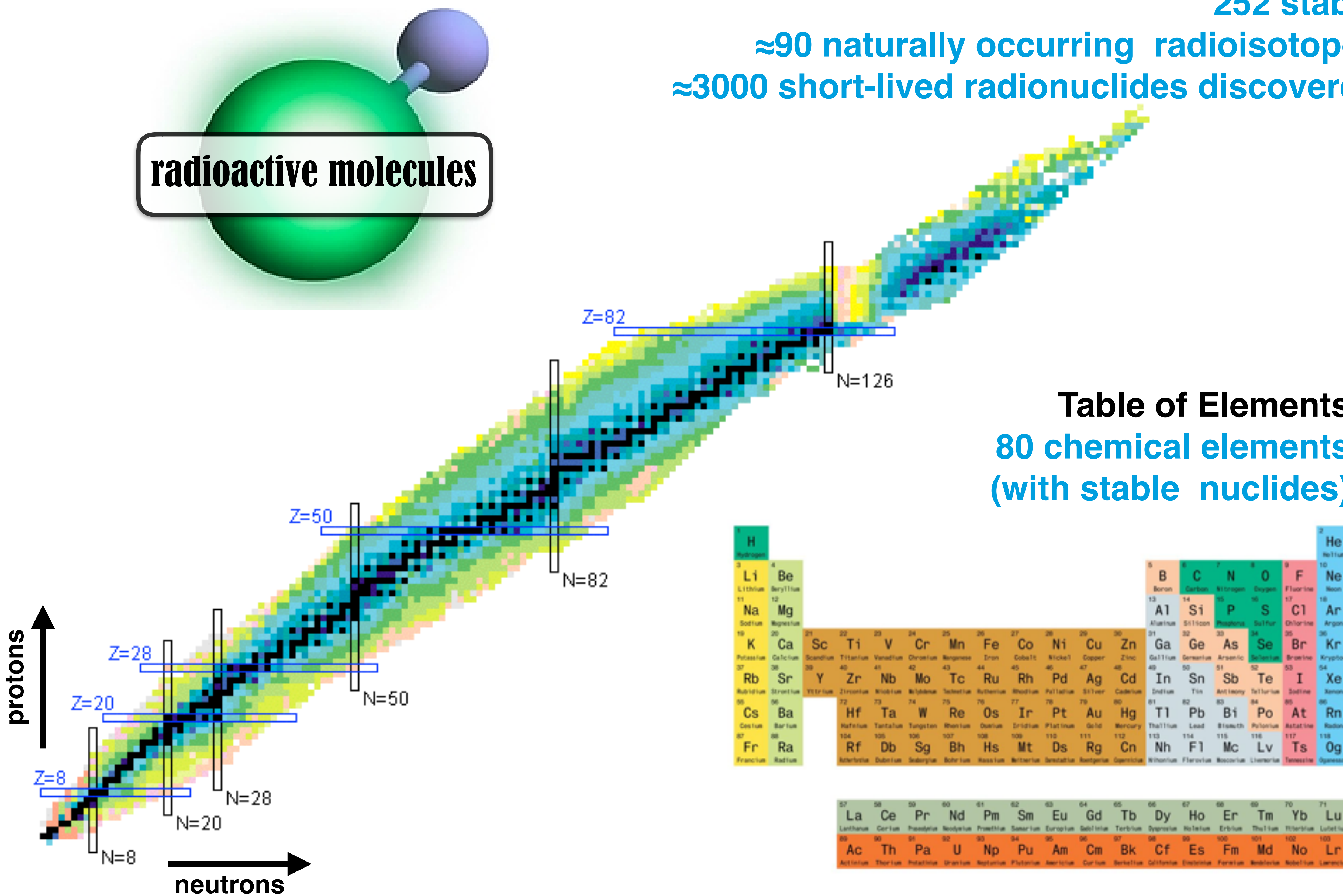

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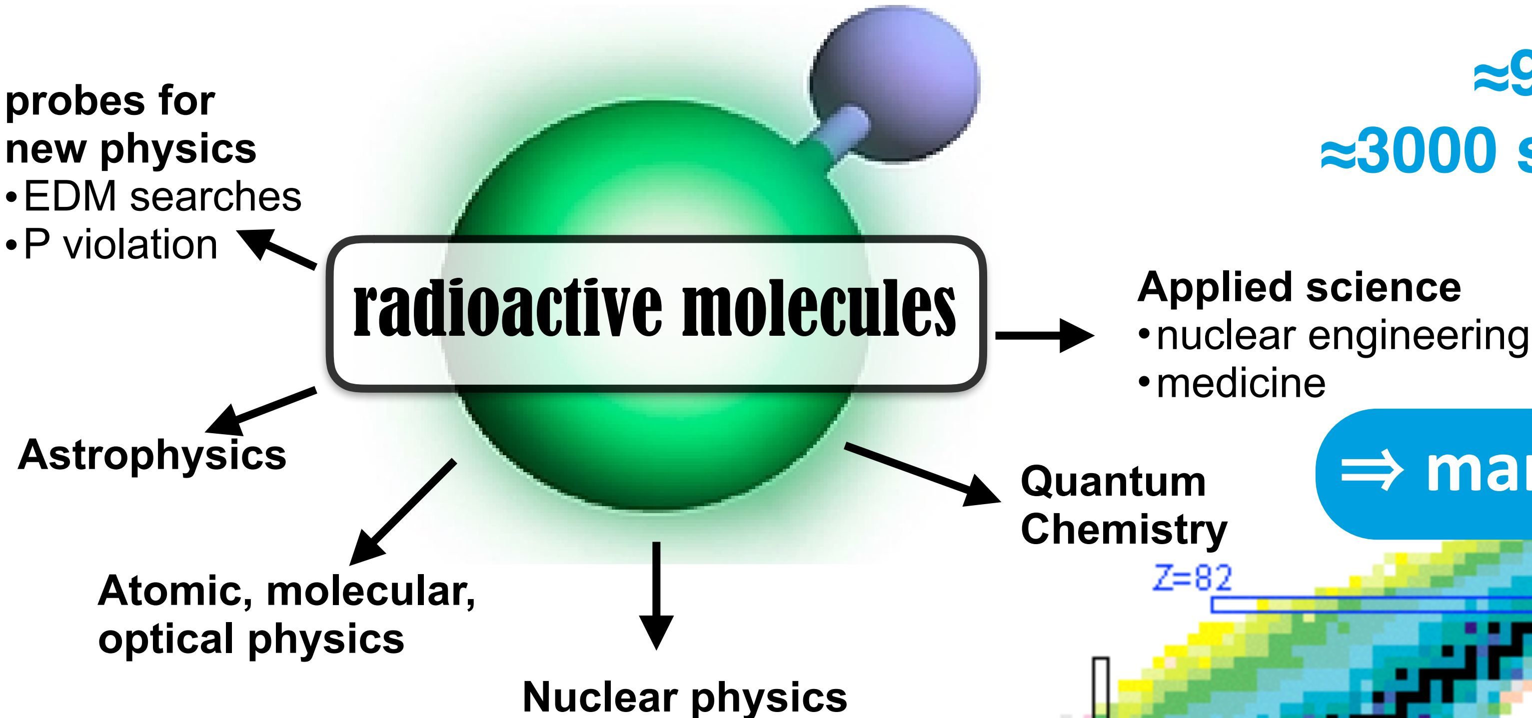
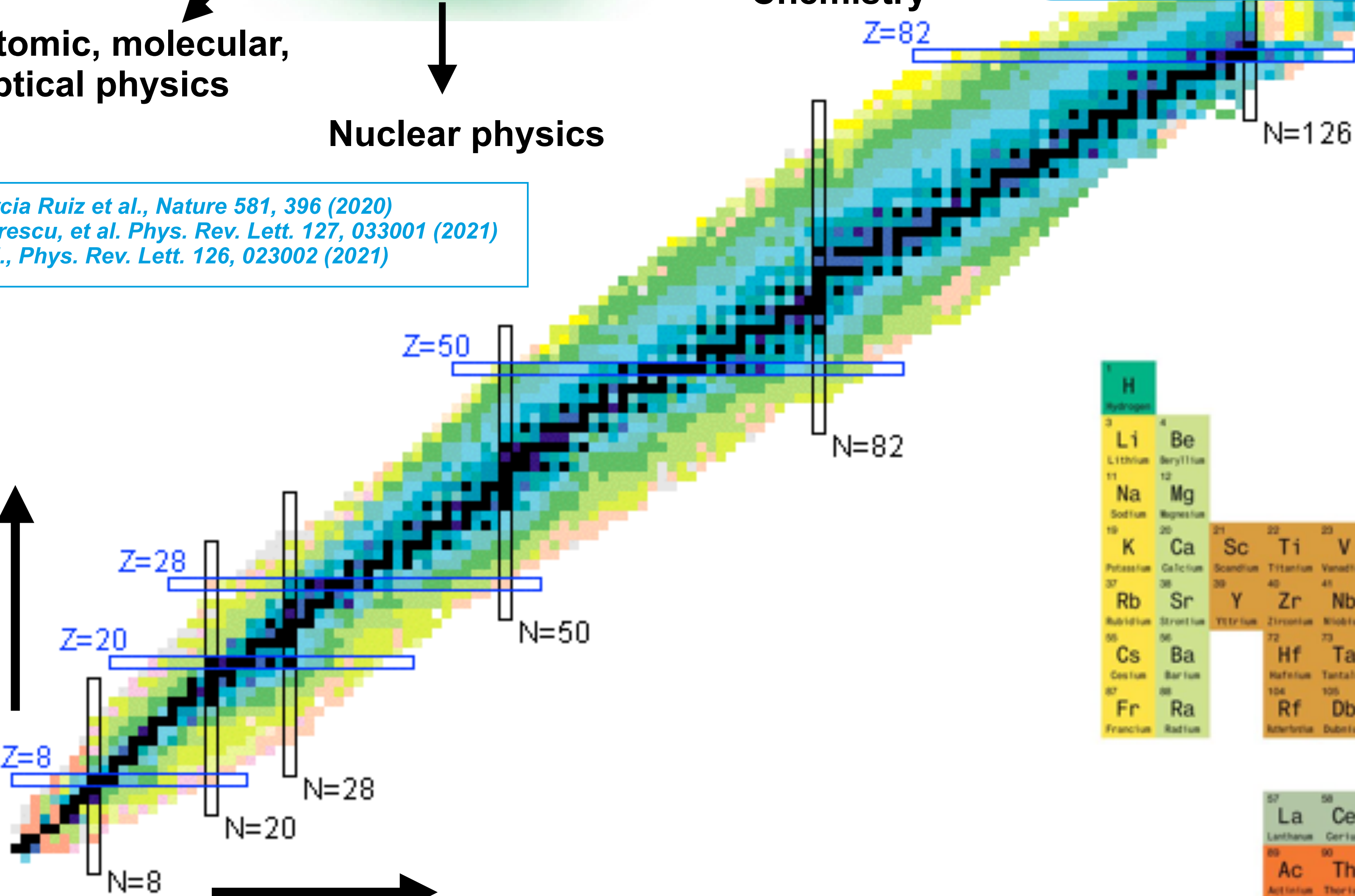


⇒ many, exciting science opportunities

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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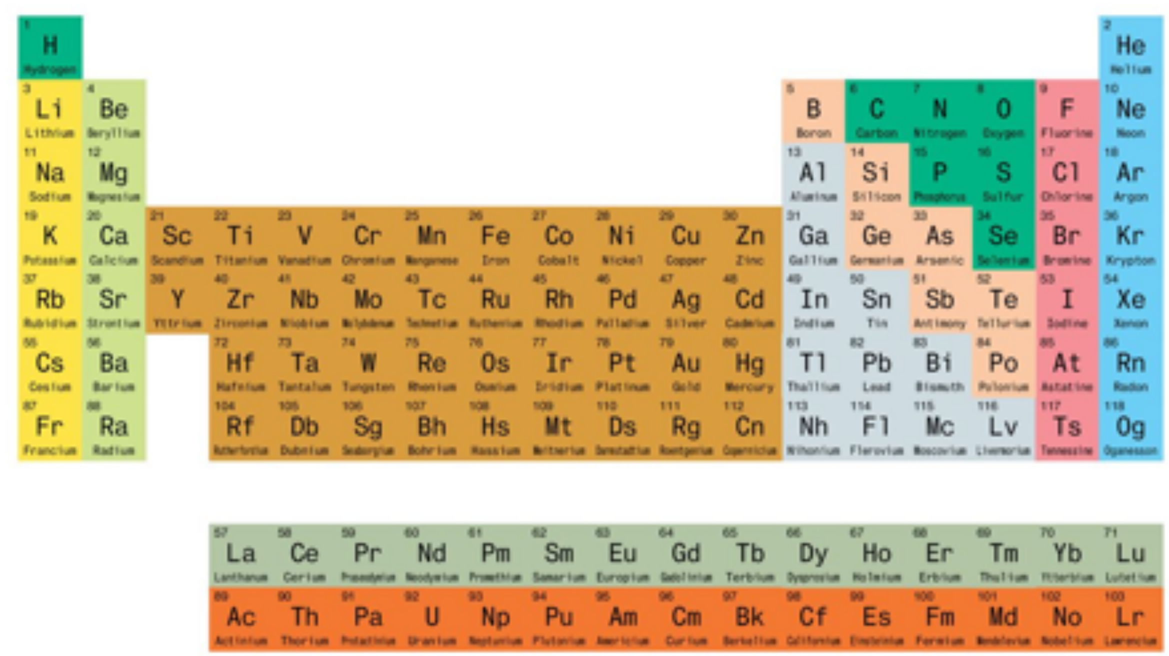
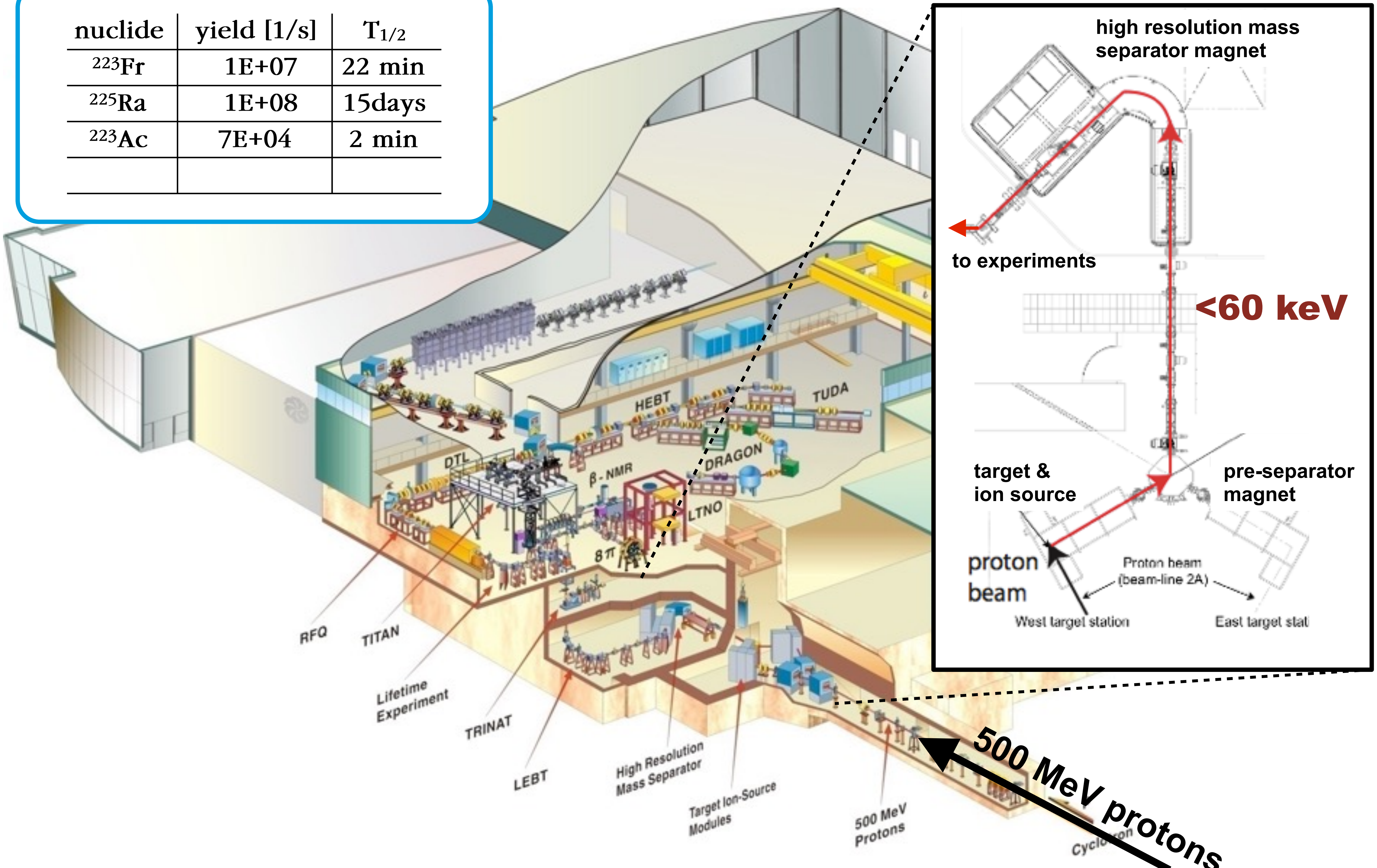


Radioactive Ions TRIUMF

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



9

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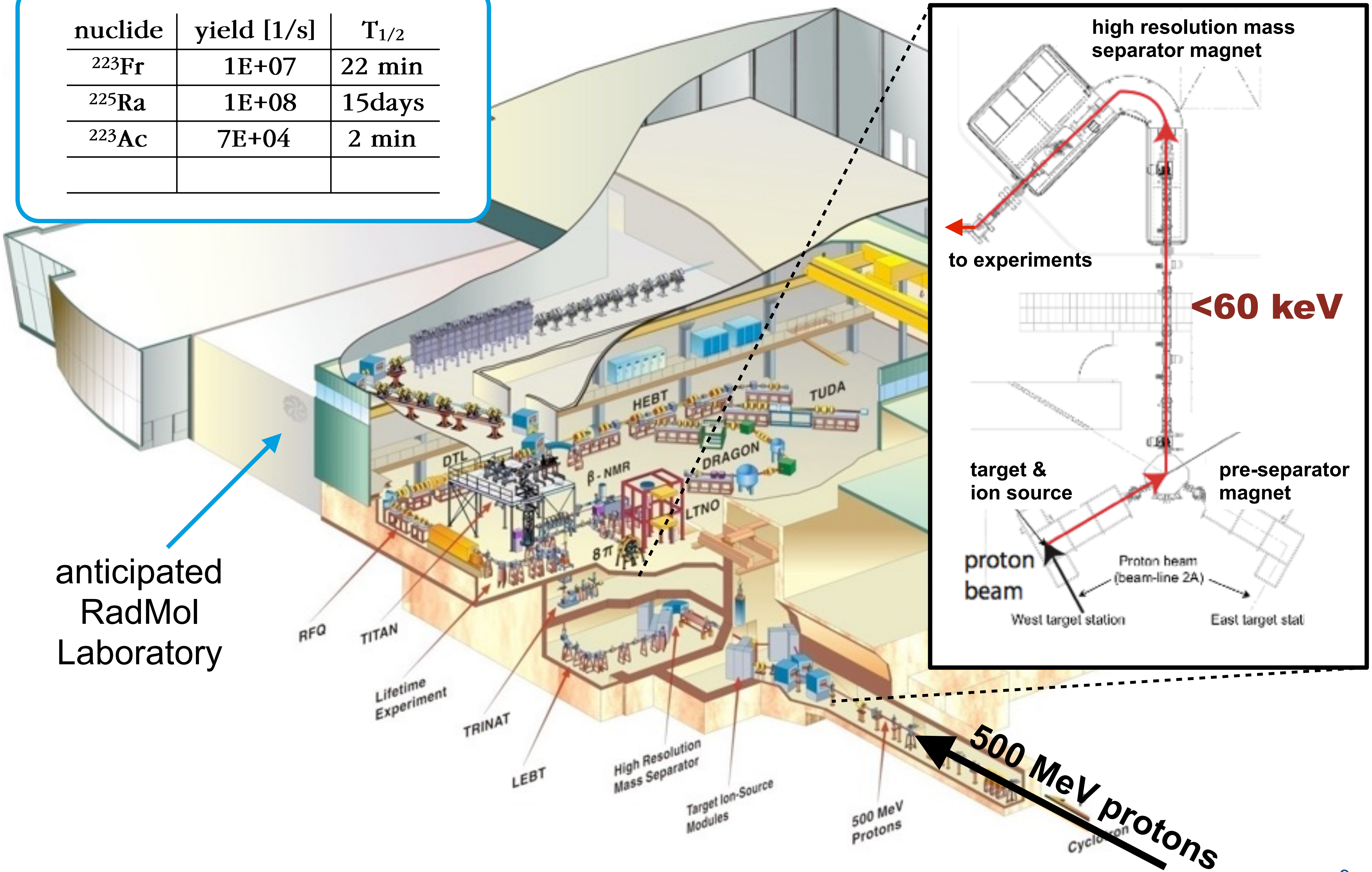

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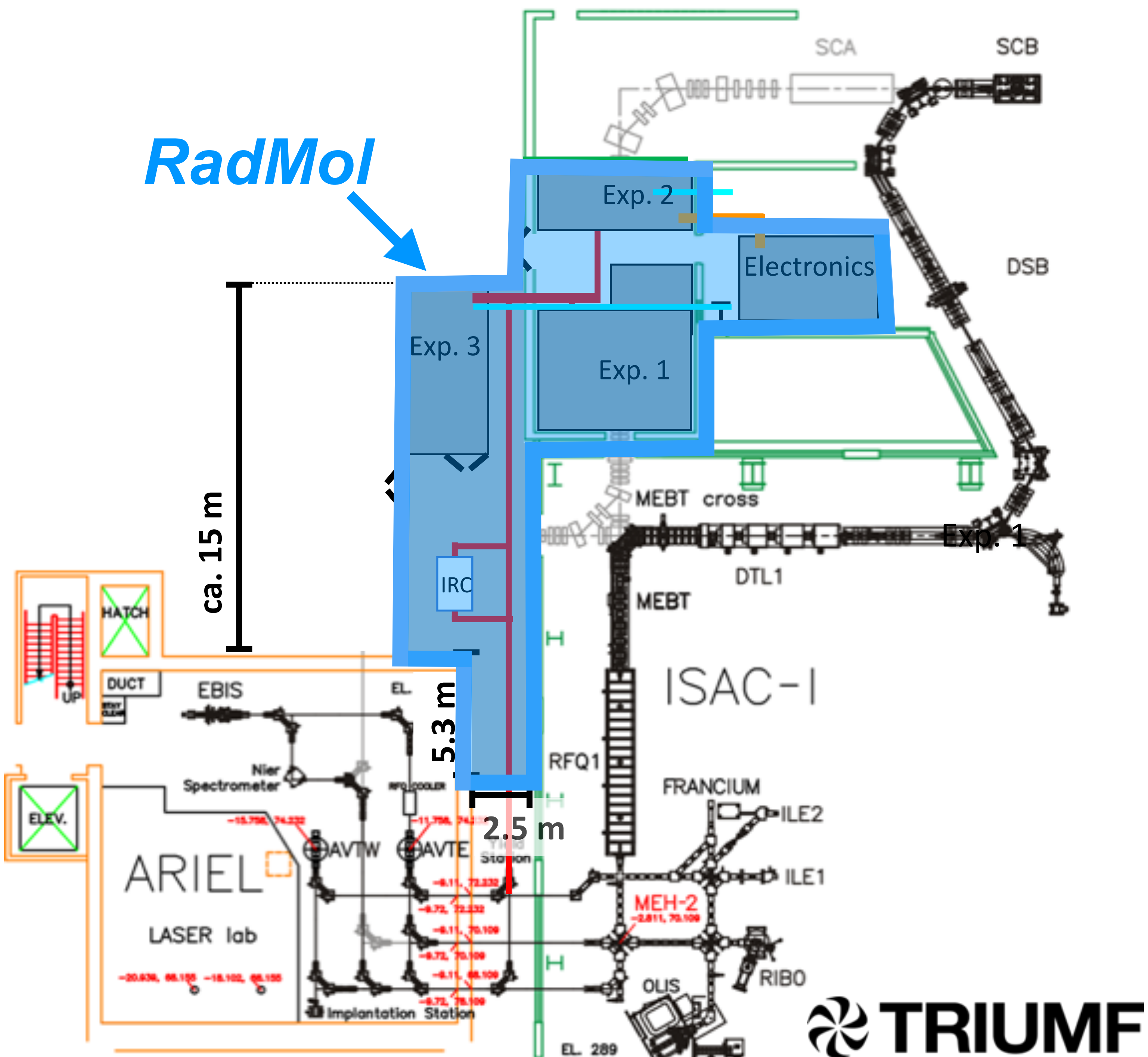
RadMol

a radioactive molecule lab for fundamental physics



Goals:

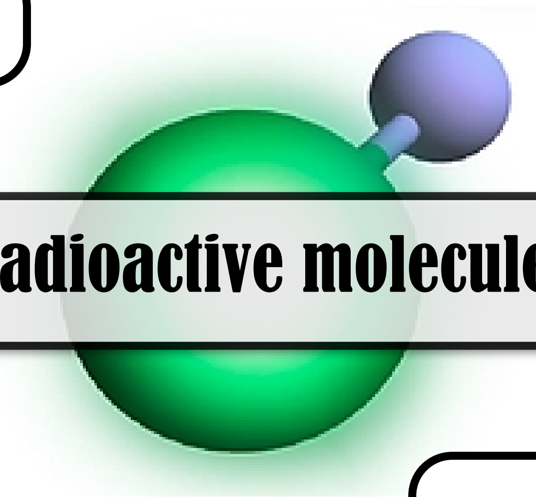
- world-wide unique laboratory for radioactive molecules
- precision studies for searches for new physics

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**

Multidisciplinary

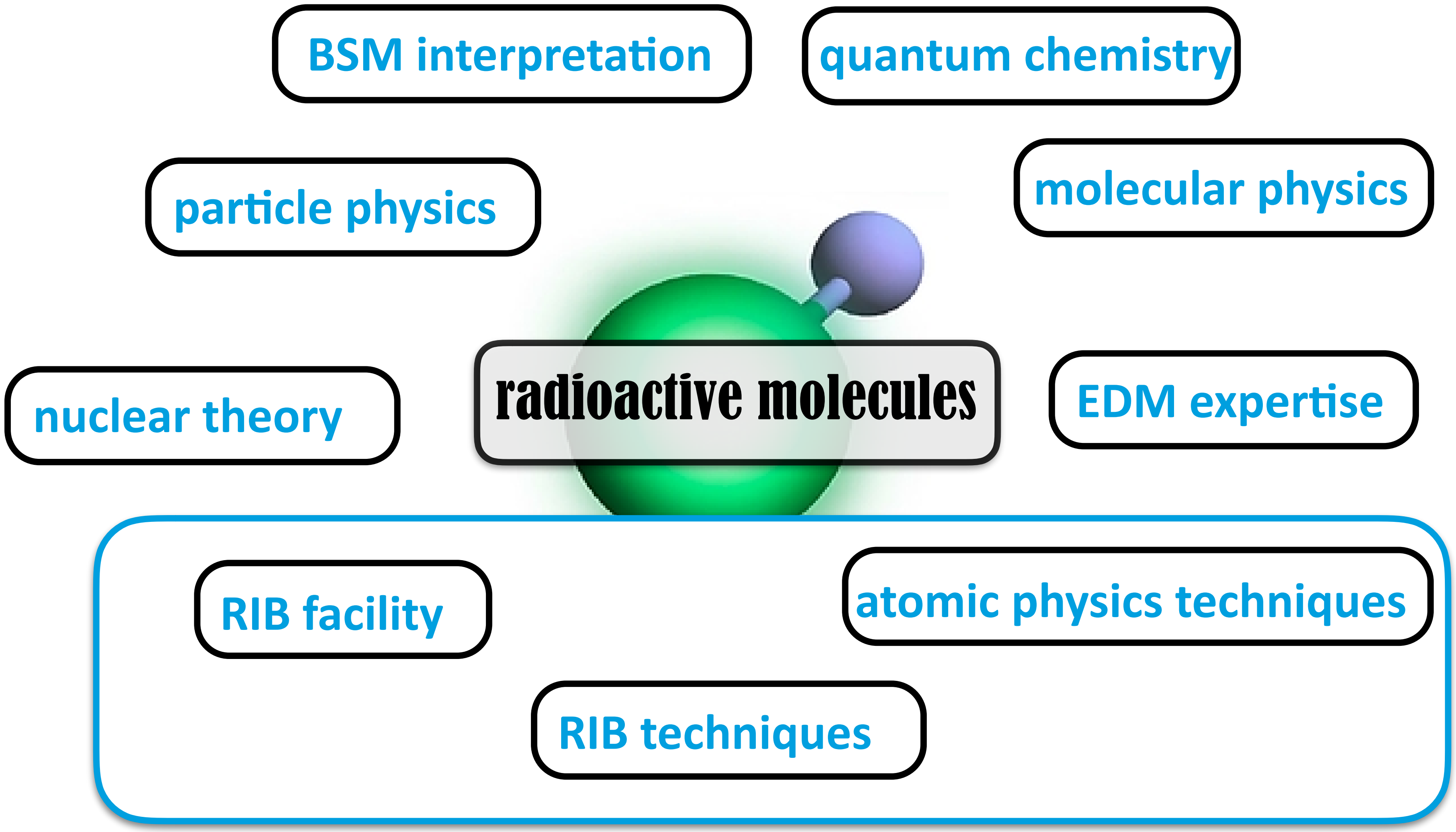
- BSM interpretation
- quantum chemistry
- particle physics
- molecular physics



- nuclear theory
- **radioactive molecules**
- EDM expertise
- RIB facility
- atomic physics techniques
- RIB techniques

University of Toronto
TRIUMF
Universität Kassel
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

Multidisciplinary

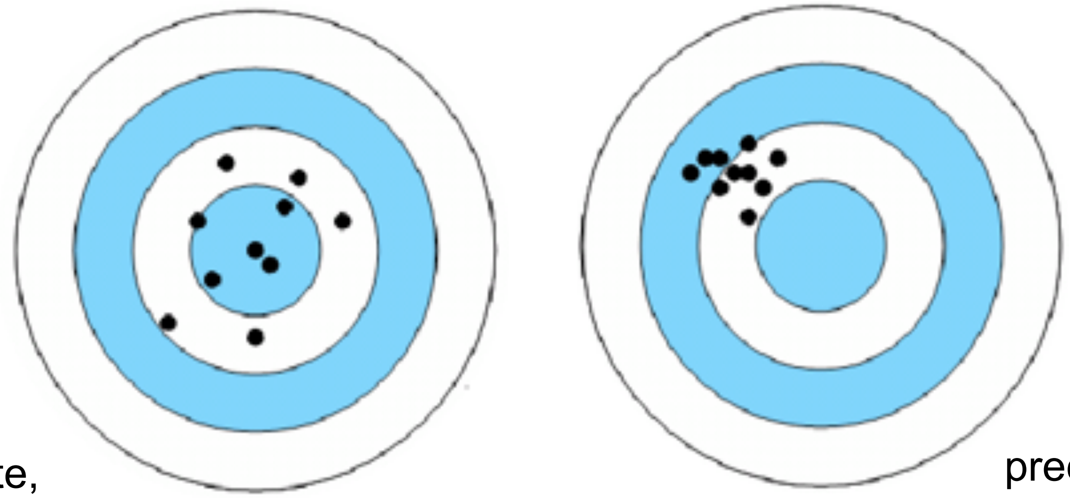


TRIUMF
UNIKASSEL VERSITÄT
MANCHESTER 1824 The University of Manchester
THE UNIVERSITY OF CHICAGO
KU LEUVEN
UNIVERSITY OF TORONTO
University of Manitoba
uOttawa
McGill
California Institute of Technology
Massachusetts Institute of Technology
Philipps Universität Marburg
OAK RIDGE National Laboratory
The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

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)



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

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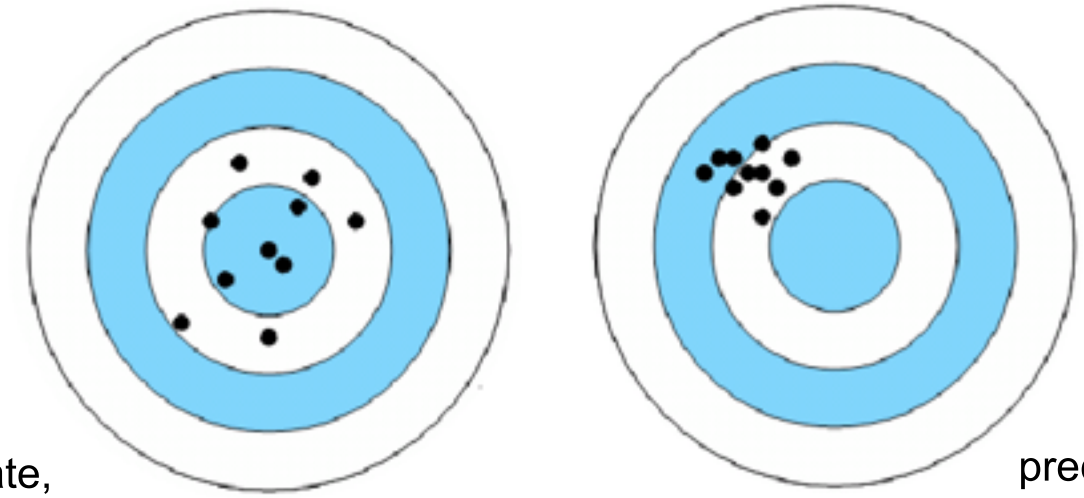

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Challenges

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)

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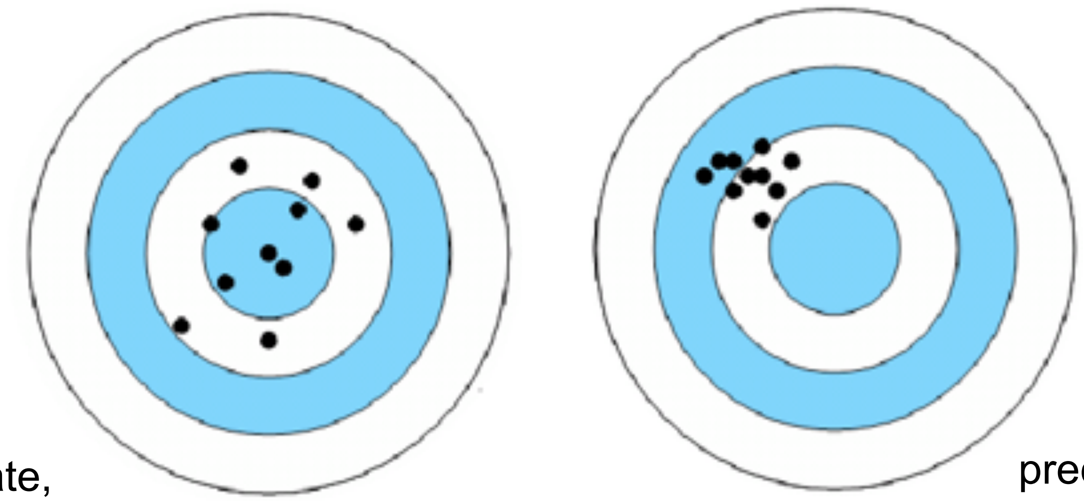

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temperature
buffer gas cooling
(selected cases of laser cooling)

300 K

↕

µK - mK - K

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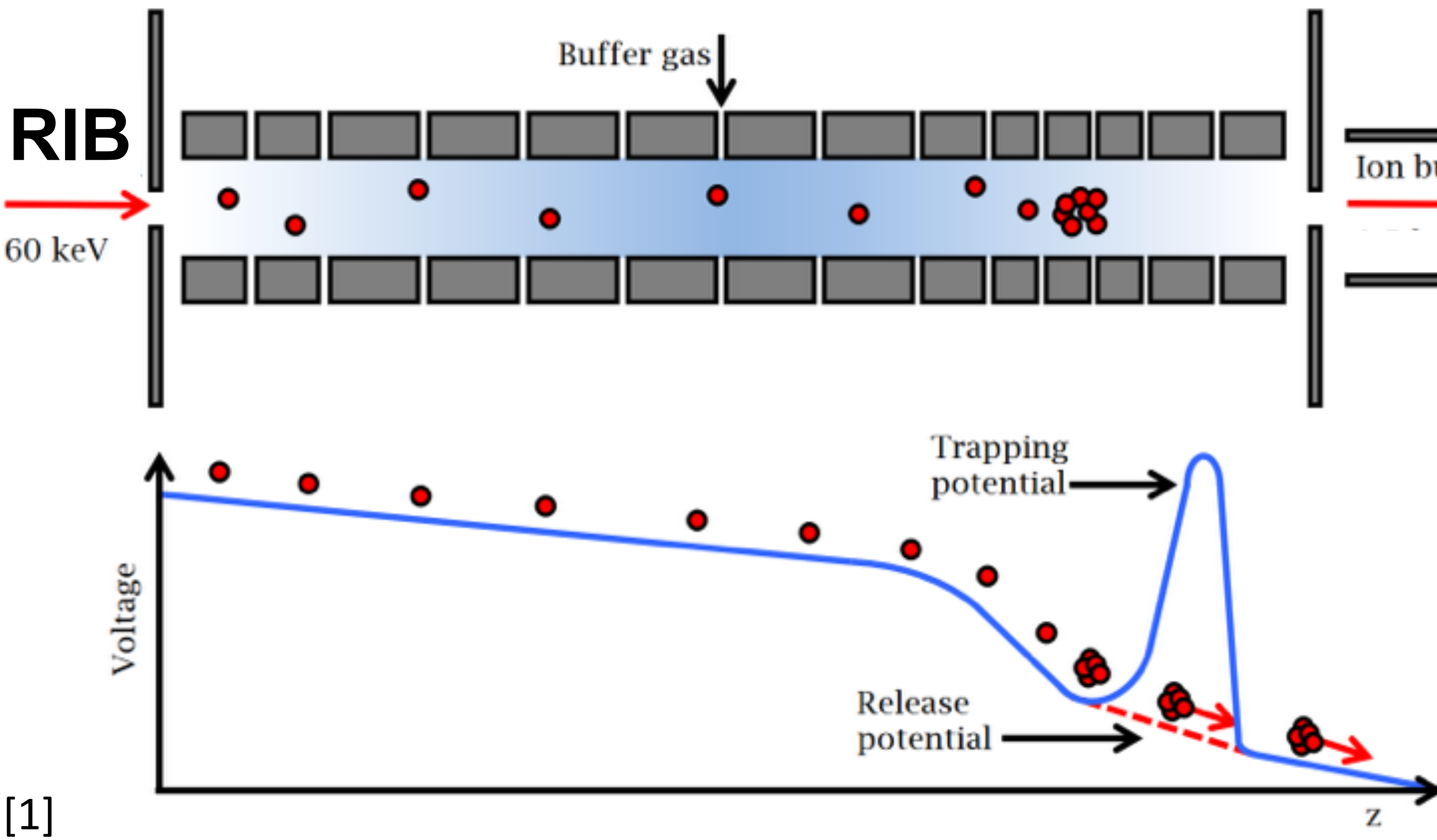
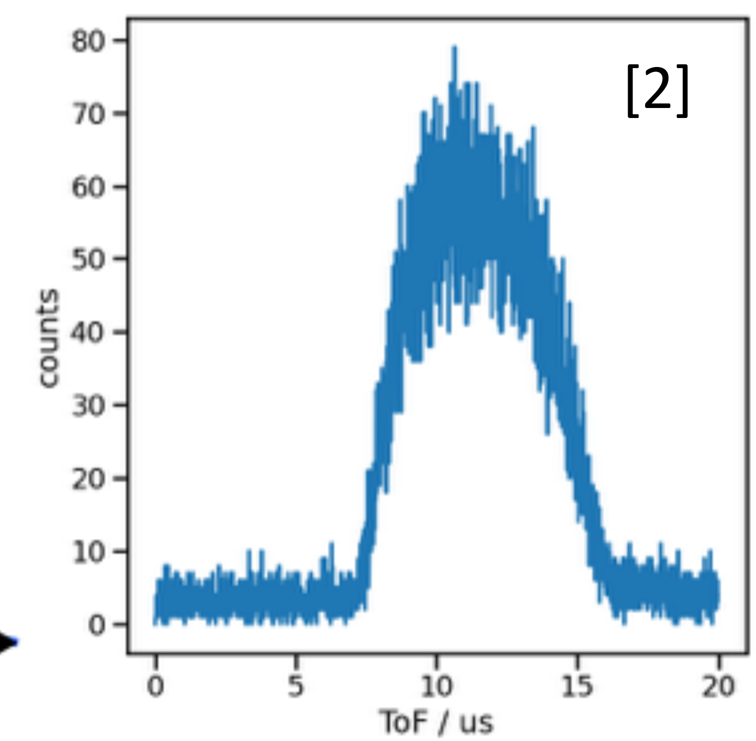
S. Eliseev et al., PRL 110, 082501 (2013)

Standard buffer gas cooling

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

Cooling limit: 300 K

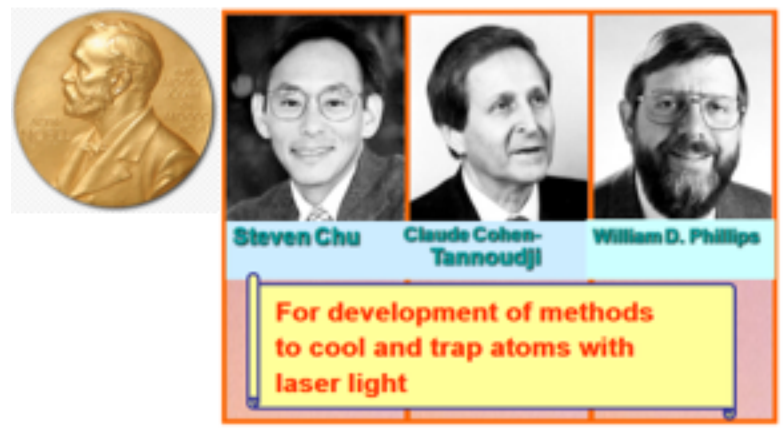


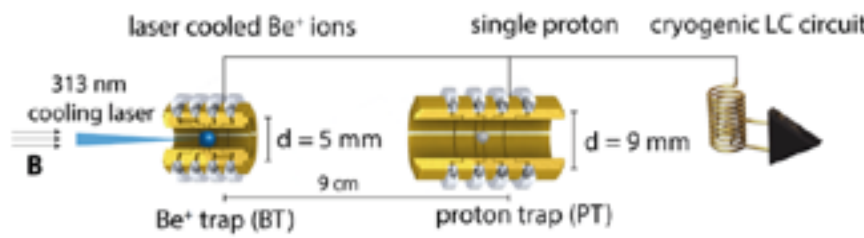


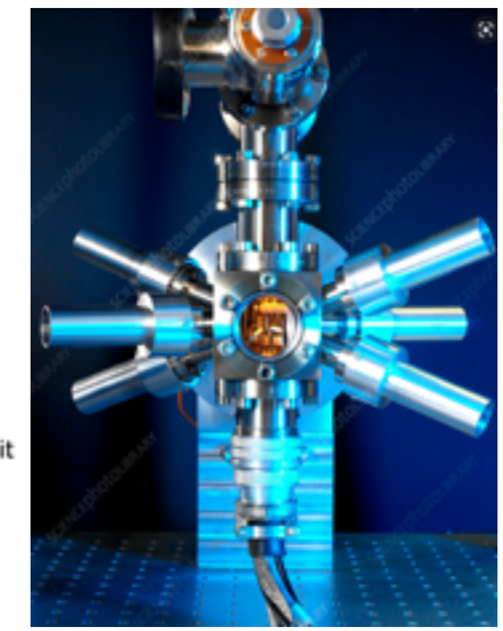
[1] K. Lynch, PhD thesis, University of Manchester, 2013.
[2] Sb run COLLAPS, 2018.

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]







[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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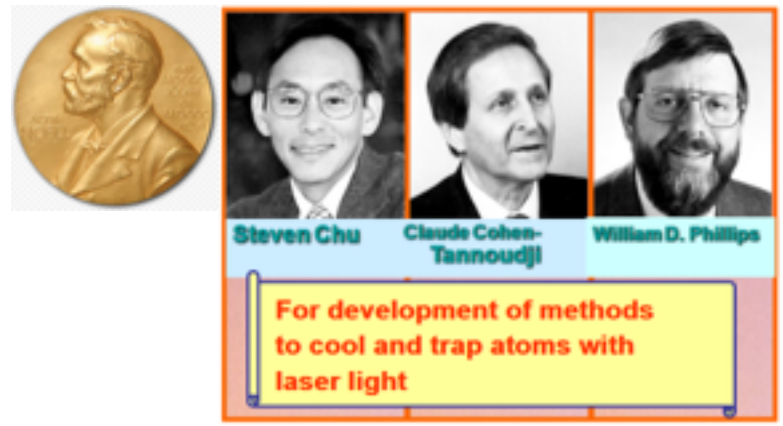

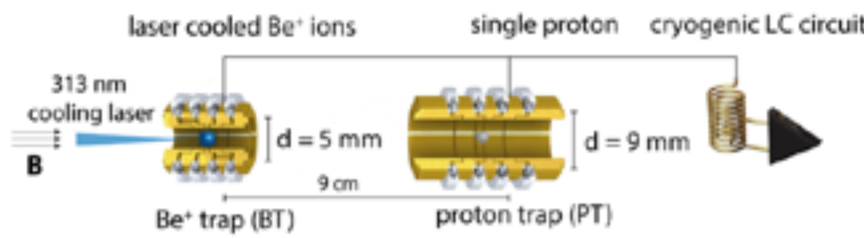

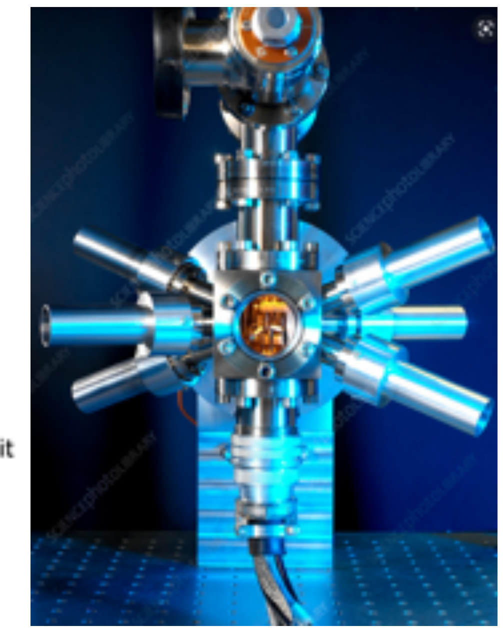

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[3] C. D. Bruzewicz et al, Applied Physics Reviews 6, 021314 (2019).
[4] M. S. Safronova et al, Rev. Mod. Phys. 90, 025008 (2018).

- Specific applications with RIBs

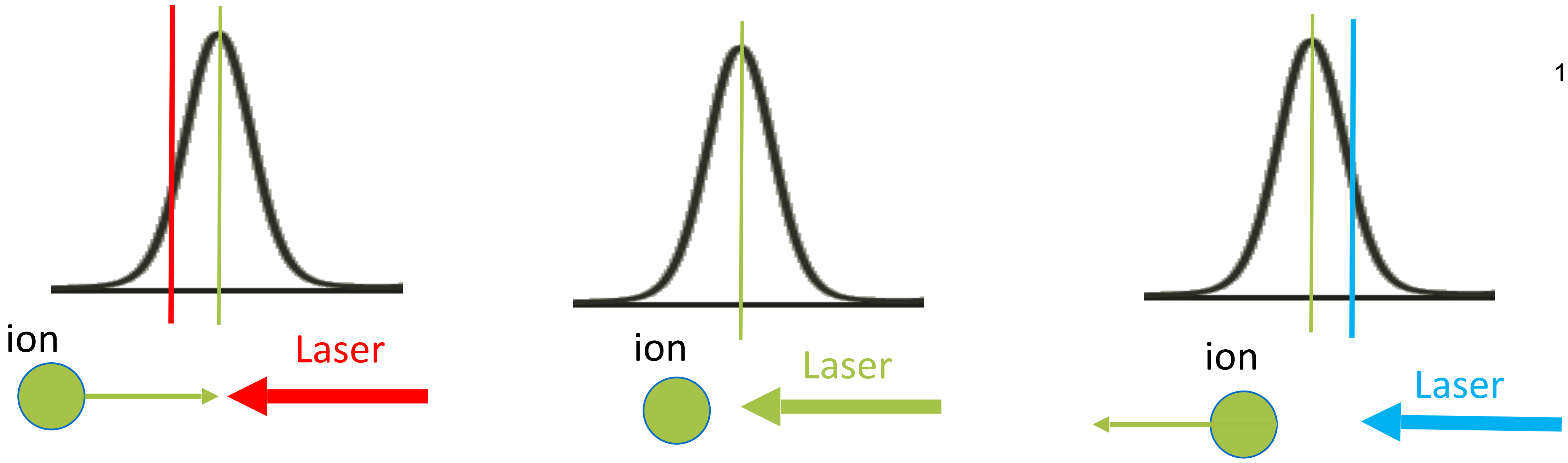
G. D. Sprouse and L. A. Orozco, Annu. Rev. Nucl. Part. Sci.. 47, 429 (1997)
J. A. Behr et al., Phys. Rev. Lett. 79, 375 (1997).
M. Trinczek et al., Phys. Rev. Lett. 90, 012501 (2003).
L. B. Wang et al., Phys. Rev. Lett. 93, 142501 (2004).
P. A. Vetter et al., Phys. Rev. C 77, 035502 (2008).
J. R. A. 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)

Doppler Cooling principle

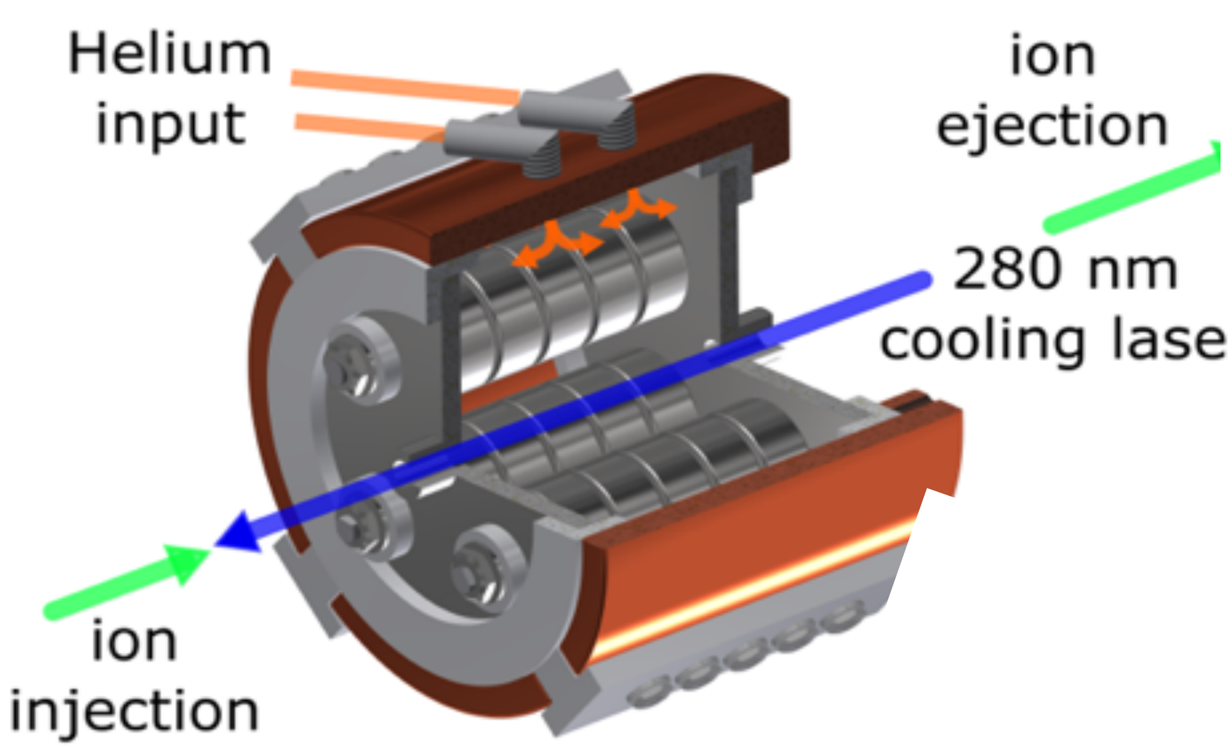


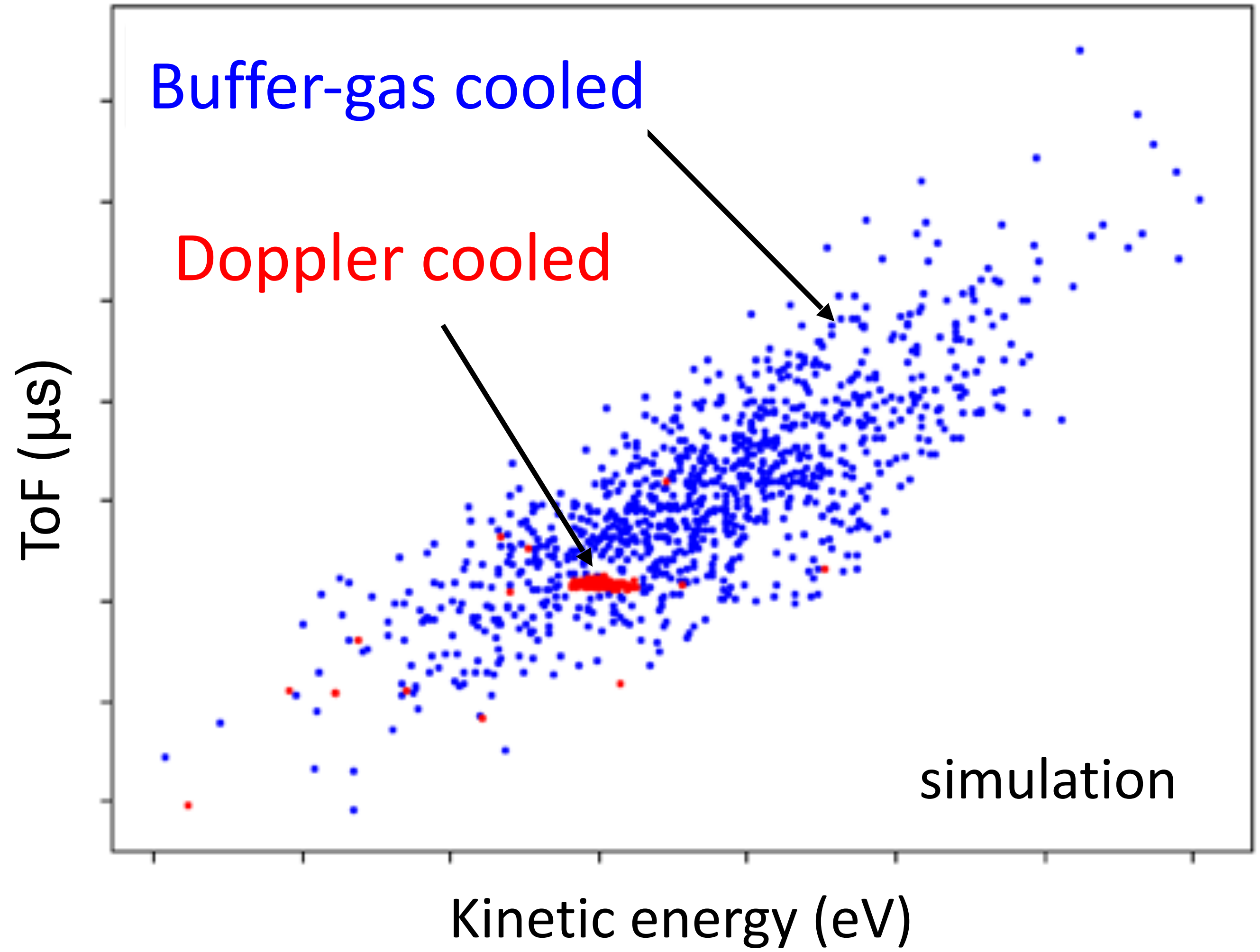
- Moving ions observe Doppler shift in laser frequency
- Absorption of photon in one direction
- Spontaneous emission of photon in random direction
- Net-cooling or heating effect since photon momentum is subtracted from/added to the Mg ion momentum

  Red-detuning: cooling, blue detuning: heating

Experimental Demonstration at MIRACLS

Paul trap:





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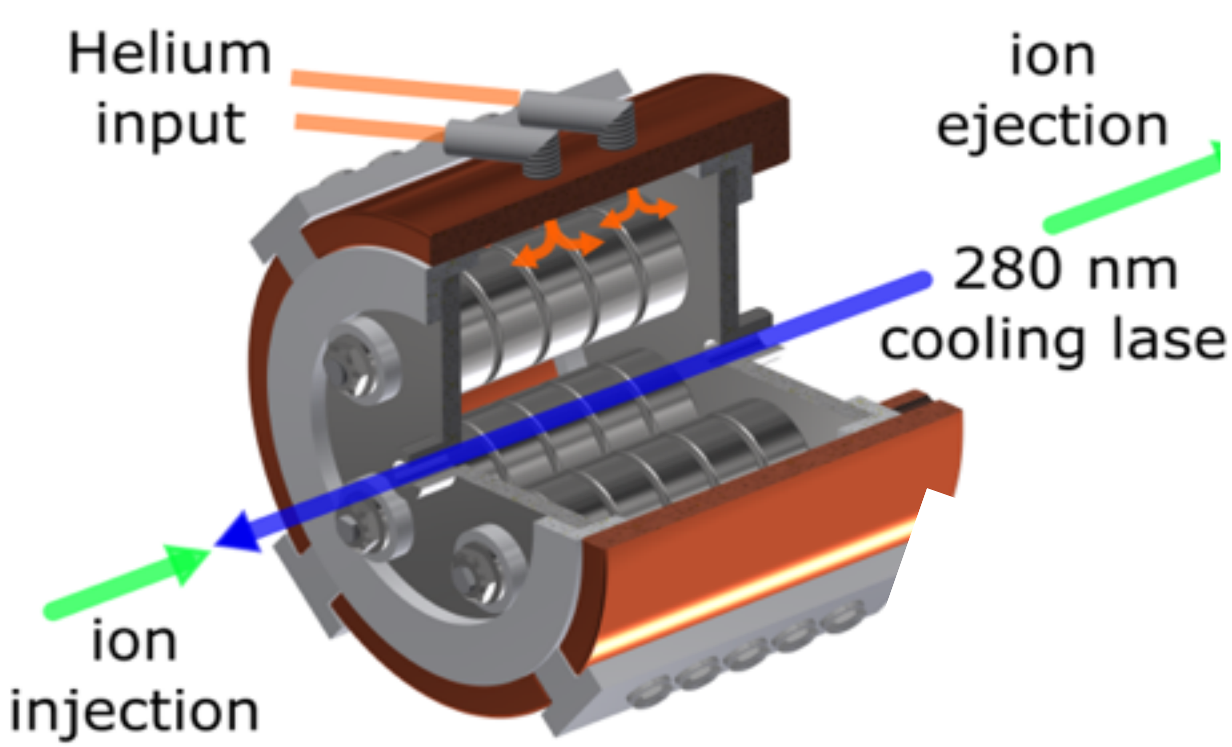
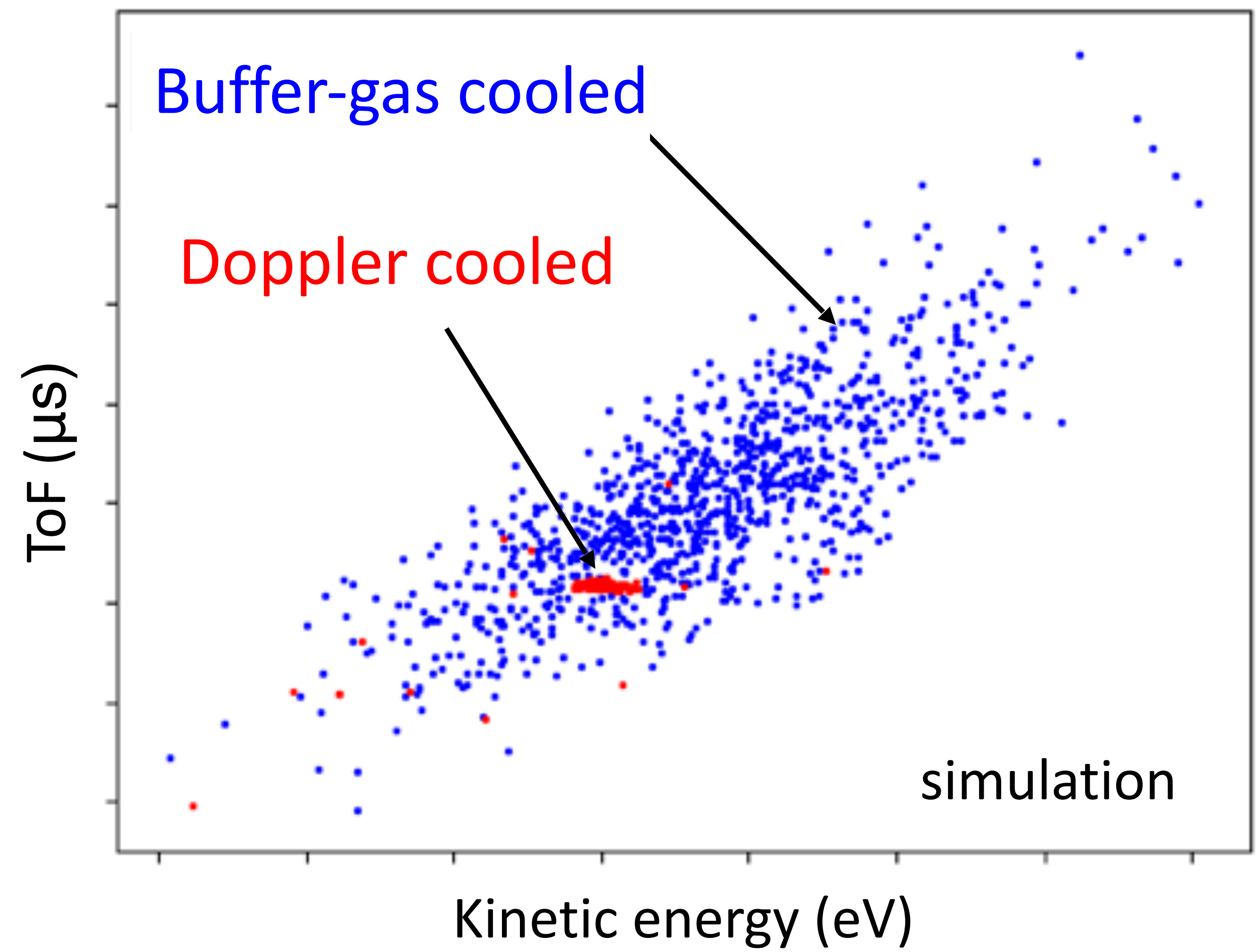
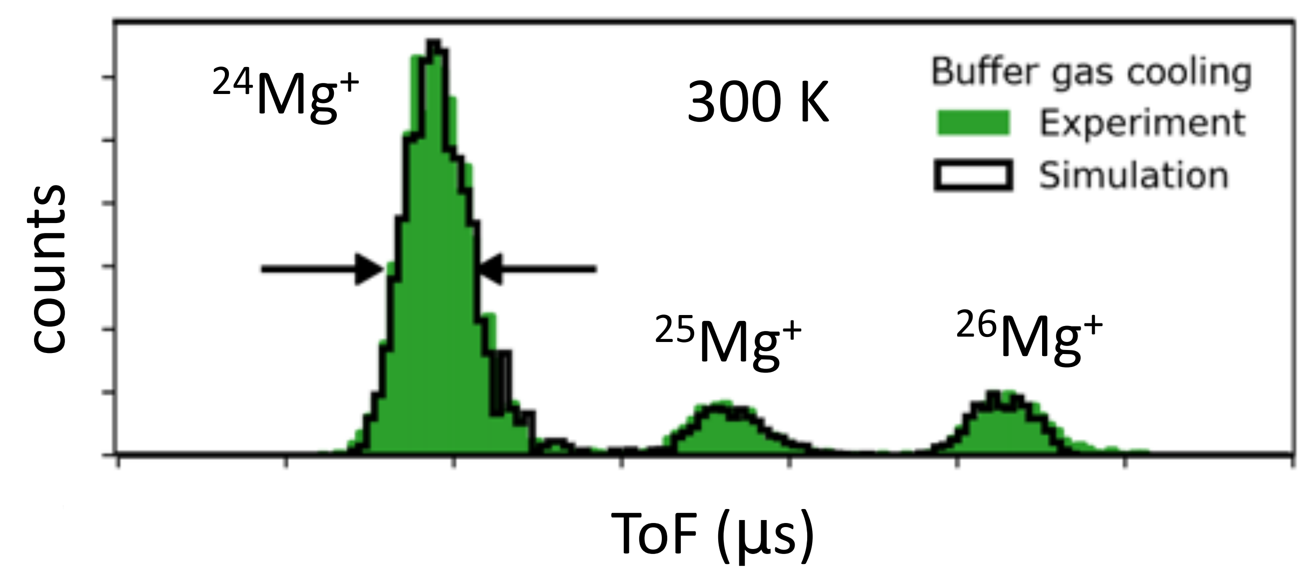


externally produced, fast and ‘hot’ Mg^+ ion beam





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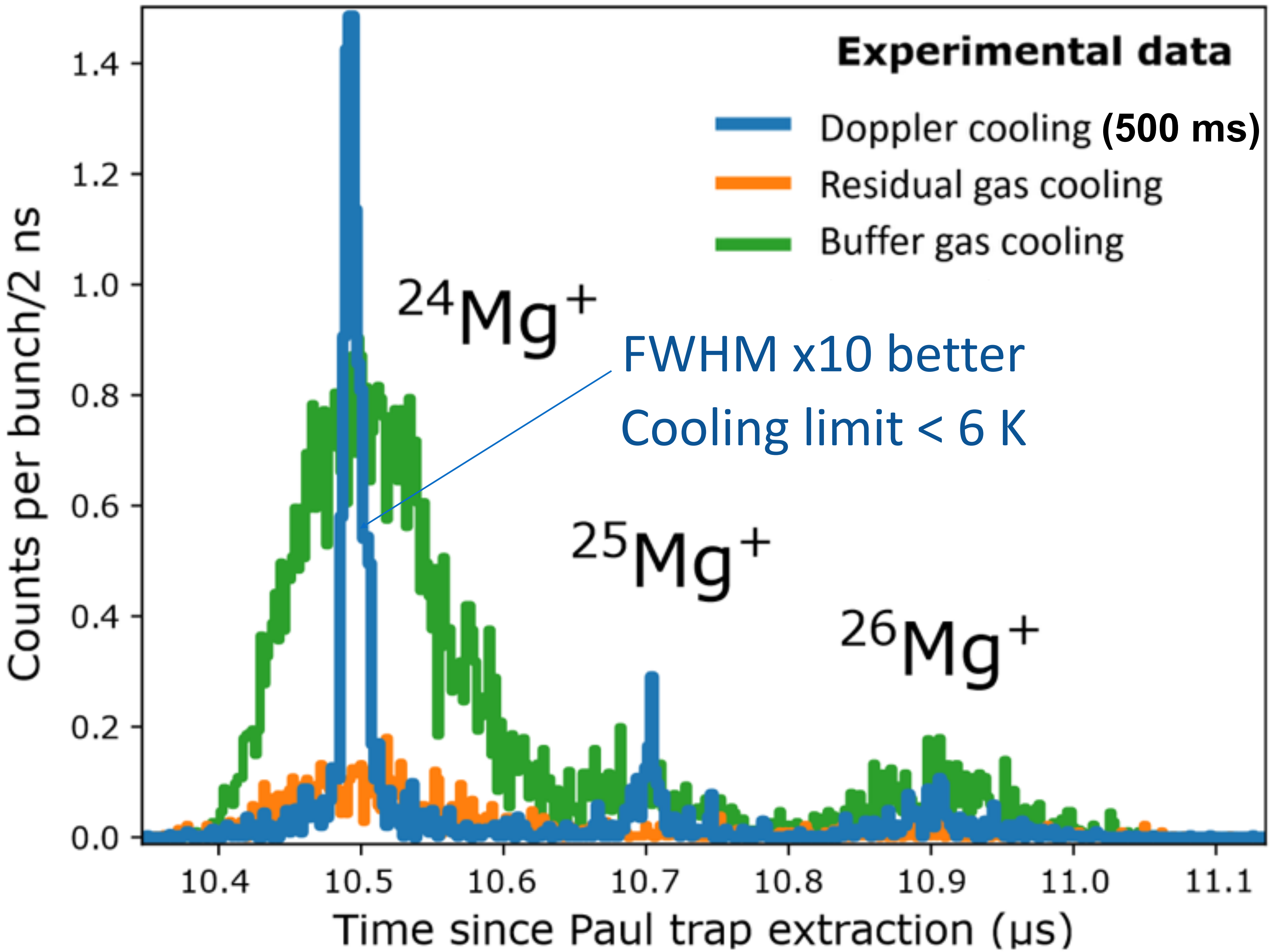
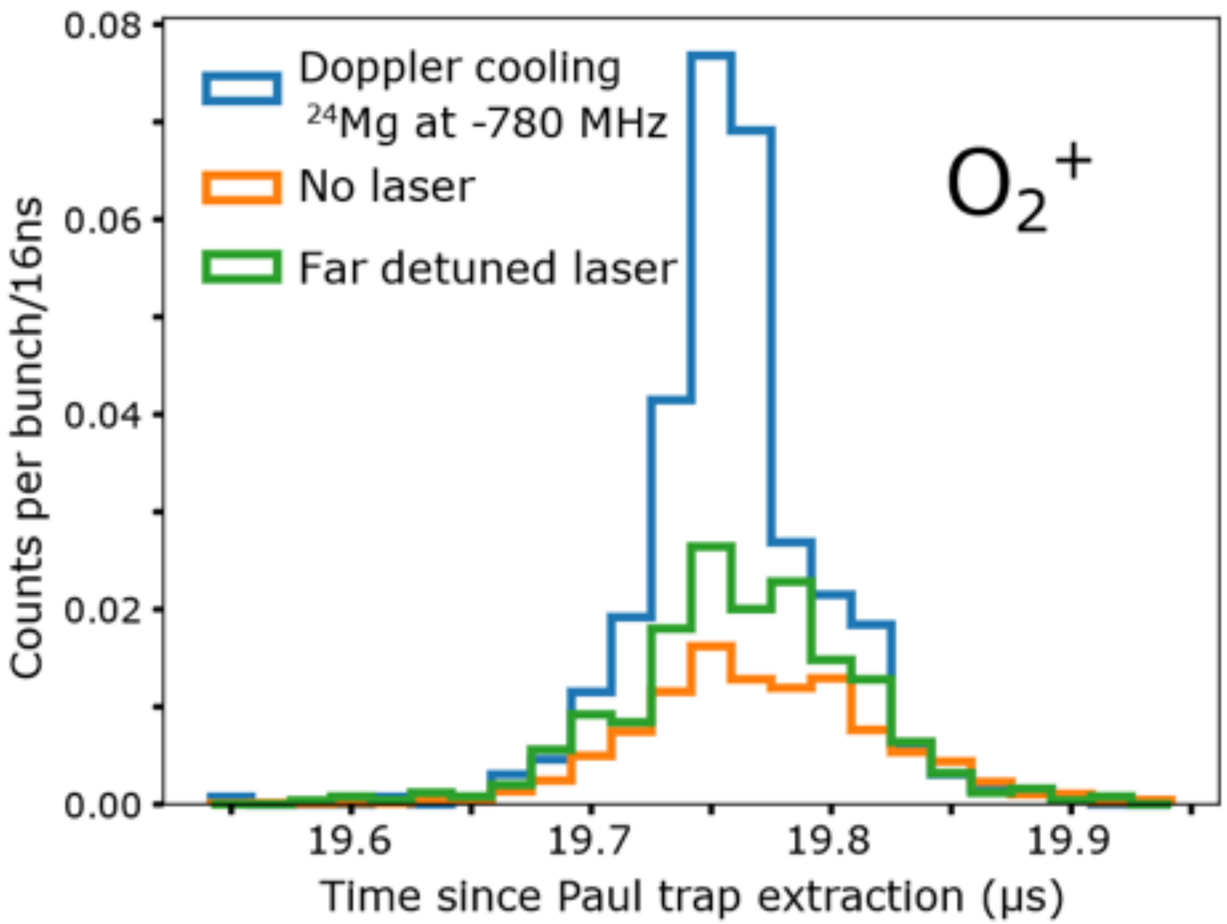
Experimental results



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

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.. submitted

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.

Summary

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

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

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

TRIUMF

Thank you
Merci

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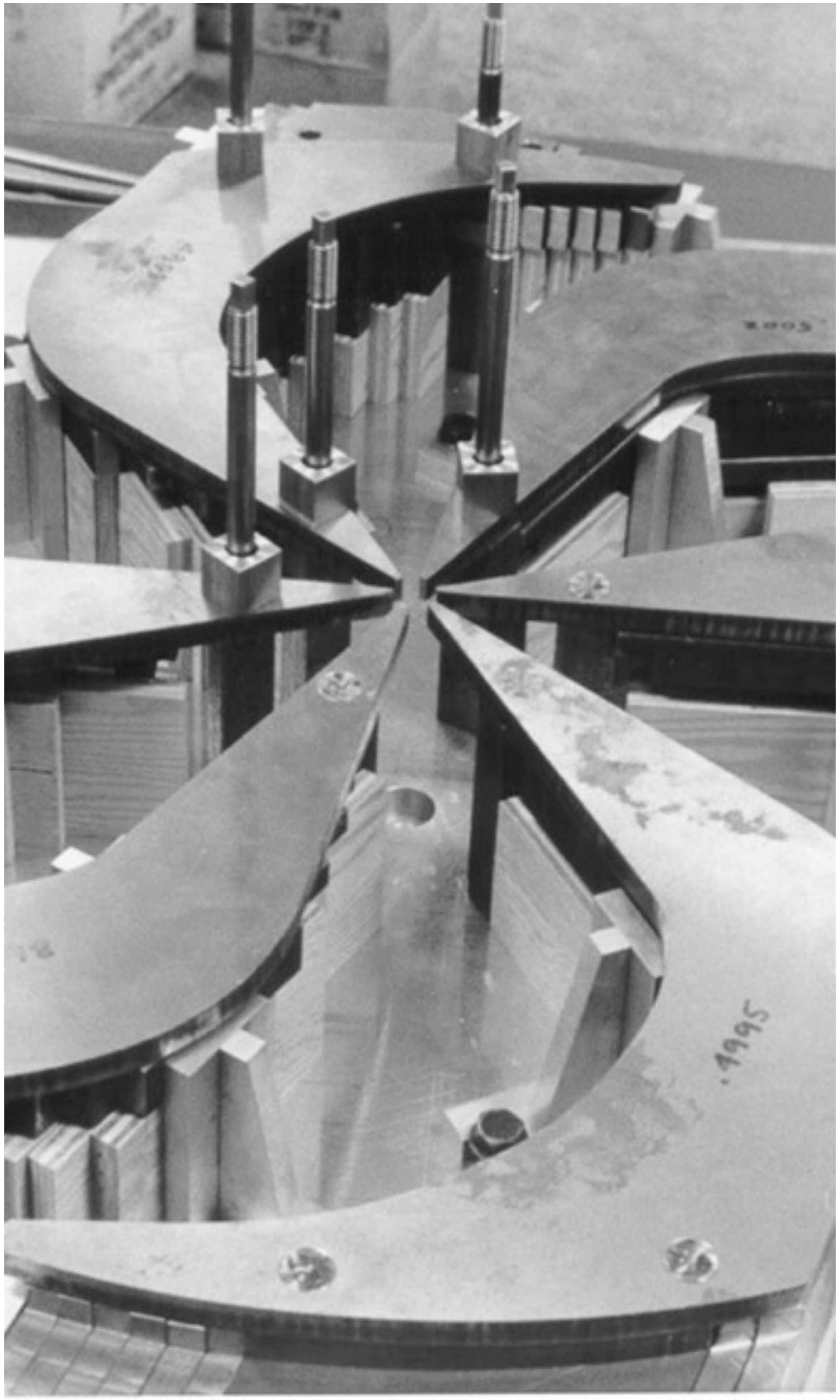

Discovery, accelerated