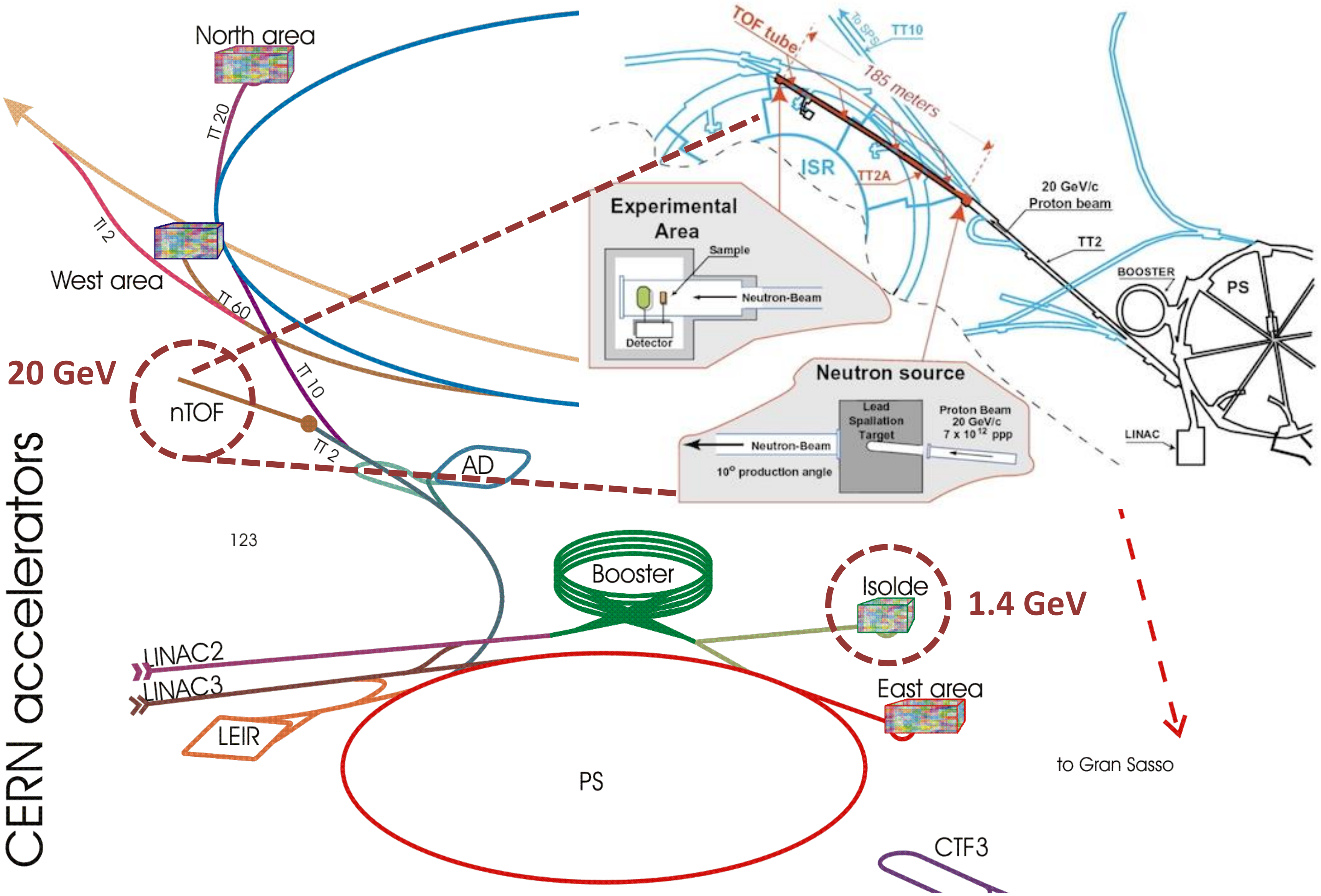
Probing the Standard Model with Radionuclides

- **Motivation for experiments with radioactive ion and neutron beams**
- **Stringent tests of the SM**
- **Future opportunities**

Klaus Blaum, MPI for Nuclear Physics, Heidelberg
Chair of the INTC

CERN, Geneva, September 7th, 2016

Locations


CERN accelerators
North area
TT 20
TT 2
West area
TT 60
TT 10
TT 2
20 GeV
nTOF
AD
123
Booster
Isolde
1.4 GeV
LINAC2
LINAC3
LEIR
PS
East area
to Gran Sasso
CTF3
TOF tube
To SPS
TT10
185 meters
ISR
TT2A
20 GeV/c
Proton beam
TT2
BOOSTER
PS
LINAC
Experimental Area
Sample
Neutron-Beam
Detector
Neutron source
Lead Spallation Target
Proton Beam 20 GeV/c 7 x 10^12 ppp
Neutron-Beam
10° production angle

Characteristics of a nucleus

its weight

its size

its life-time/decay

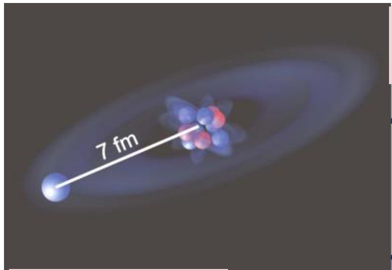
its shape

its e.m. property

its mood (state)

We have developed at ISOLDE and n_ToF unique tools to determine experimentally and to describe theoretically these characteristics.

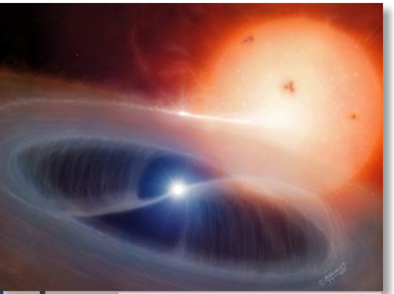
Radioactive nuclides as probes



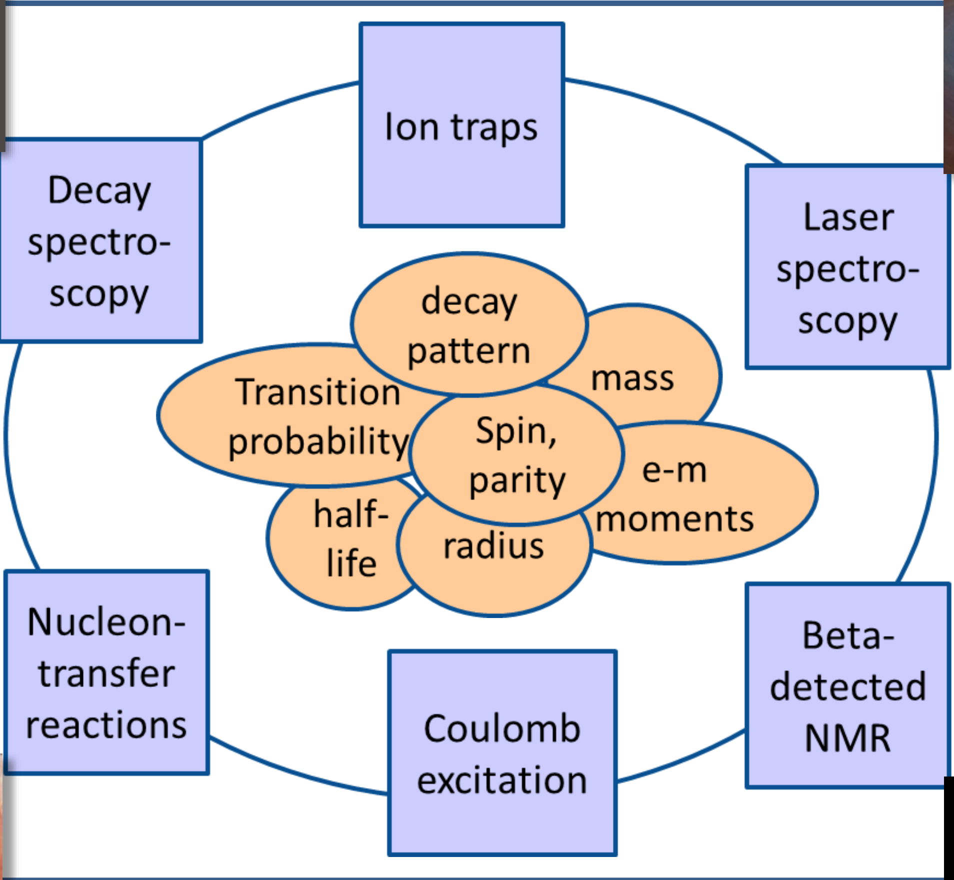
Atomic physics

Nuclear physics

Astrophysics



Nucleo-synthesis

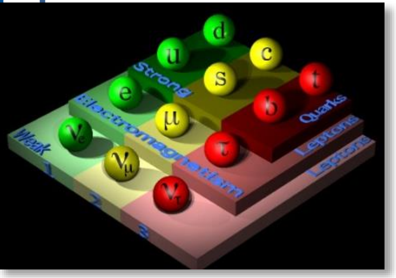


Techniques: all available at ISOLDE

Material science

Life sciences

Interactions Symmetries

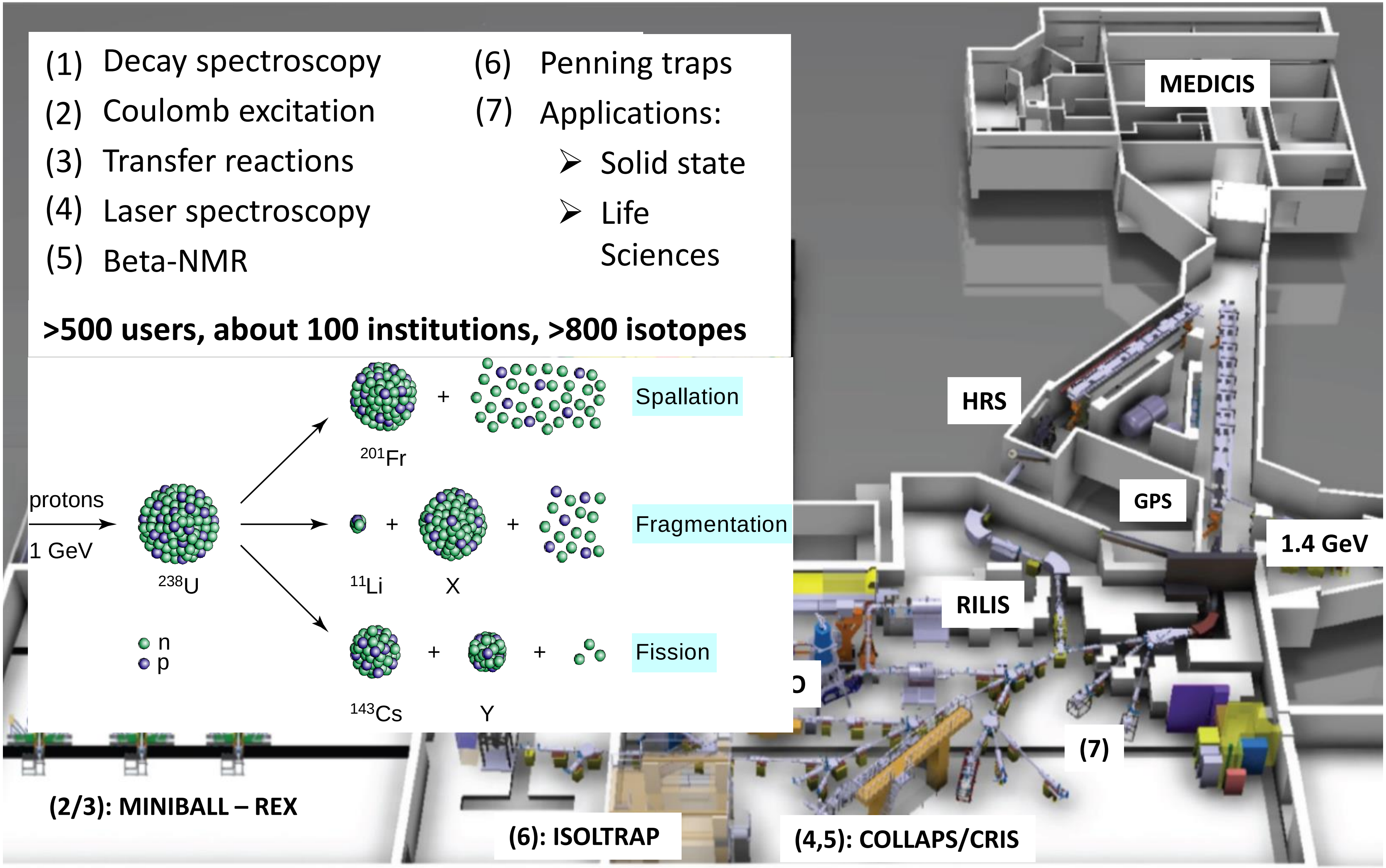


Test of the SM

The ISOLDE radioactive beam facility

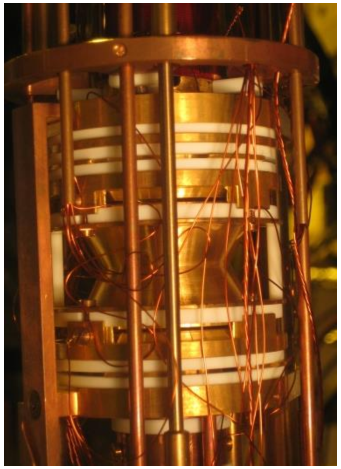
(1) Decay spectroscopy
(2) Coulomb excitation
(3) Transfer reactions
(4) Laser spectroscopy
(5) Beta-NMR
(6) Penning traps
(7) Applications:
  - Solid state
  - Life Sciences

>500 users, about 100 institutions, >800 isotopes



Experimental tools

Penning traps for masses

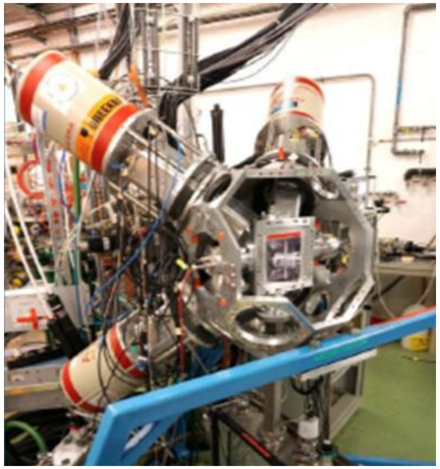


$\omega_c = qB / m$

Lasers for radii and moments

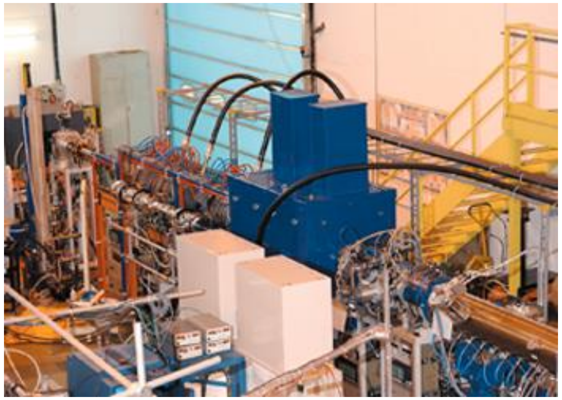
$$\delta\nu_{\mathrm{IS}}^{AA'} \propto \Delta|\Psi(0)|^2 \, \delta\langle r^2\rangle^{AA'}$$

Detectors for decays / life times



$N(t) = N_0 \, e^{-t/\tau}$

Post-acceleration for shapes



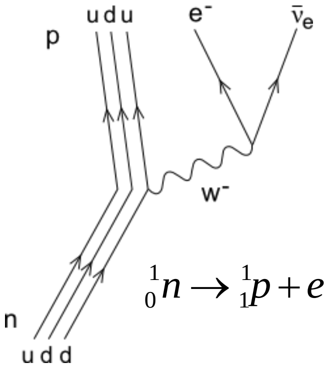
$$R = \frac{B(E2, 2_i^+ \rightarrow I^+)}{B(E2, 2_i^+ \rightarrow 0_1^+)}$$

The CKM matrix

Test of the unitarity of the quark-mixing matrix

Weak Interaction

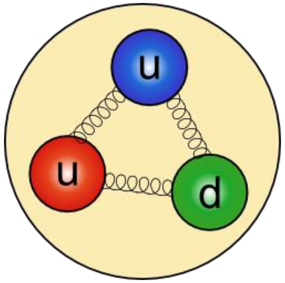
- Radioactive decay



$${}^{1}_{0}n \rightarrow {}^{1}_{1}p + e^{-} + \bar{\nu}_{e}$$

Strong Interaction

- Binding between quarks within hadrons



Superallowed β-decays

- Corrected value:

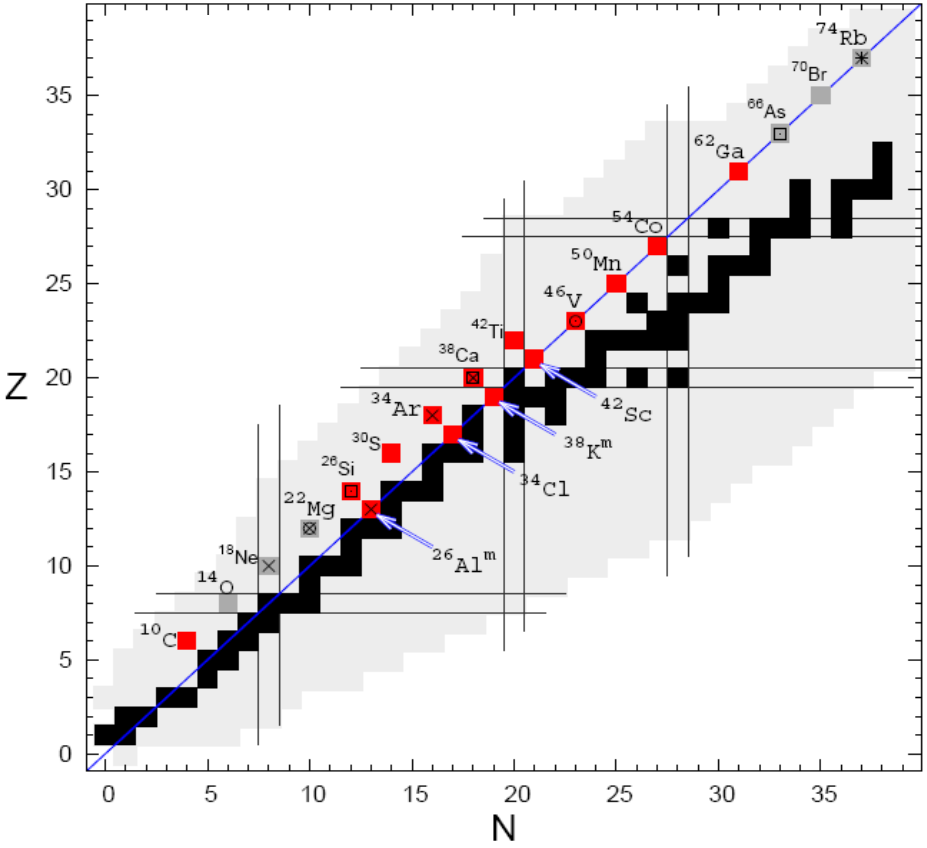
$$\mathcal{F}t = ft\,(1+\delta'_R)\,(1+\delta_{\mathrm{NS}}-\delta_C) = \frac{K}{2G_V^2\,(1+\Delta_V^R)}$$

- Corrections about 1% [Towner and Hardy, Phys. Rev. C 77, 025501 (2008)]
- Cabibbo-Kobayashi-Ma matrix

$$\begin{bmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{bmatrix}$$

- Quark-mass eigenstate

$$V_{\mathrm{ud}} = \frac{\quad}{2G_F^2\,(1+}$$



Test of the CKM unitarity

Check unitarity via first row elements:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \quad + \mathit{\Delta}$$

V_{us} and V_{ub} from particle physics data

(*K* and *B* meson decays)

Present status:

V_{ud} (nuclear β-decay) = 0.97417(21)

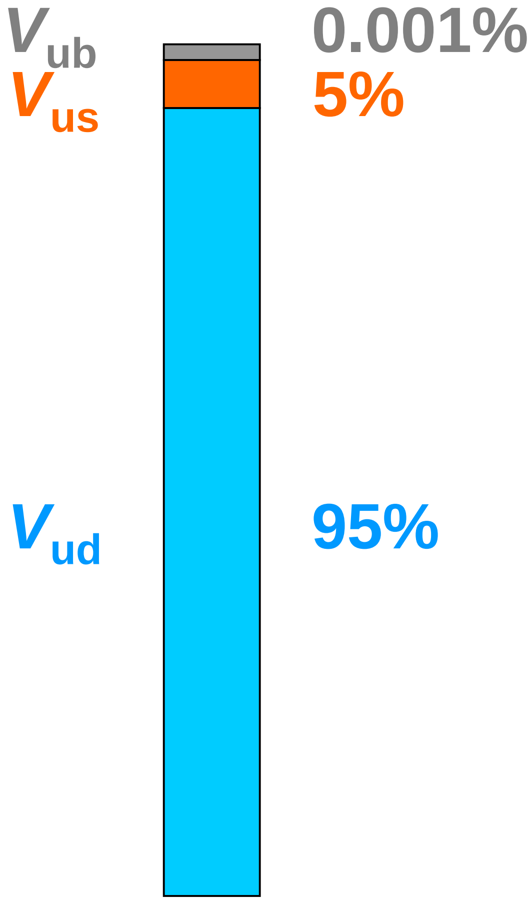
V_{us} (kaon-decay) = 0.2253(14)

V_{ub} (B meson decay) = 0.0037(5)

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.99978(55)$$

Hardy&Towner, Phys. Rev. C 91 (2015) 025501

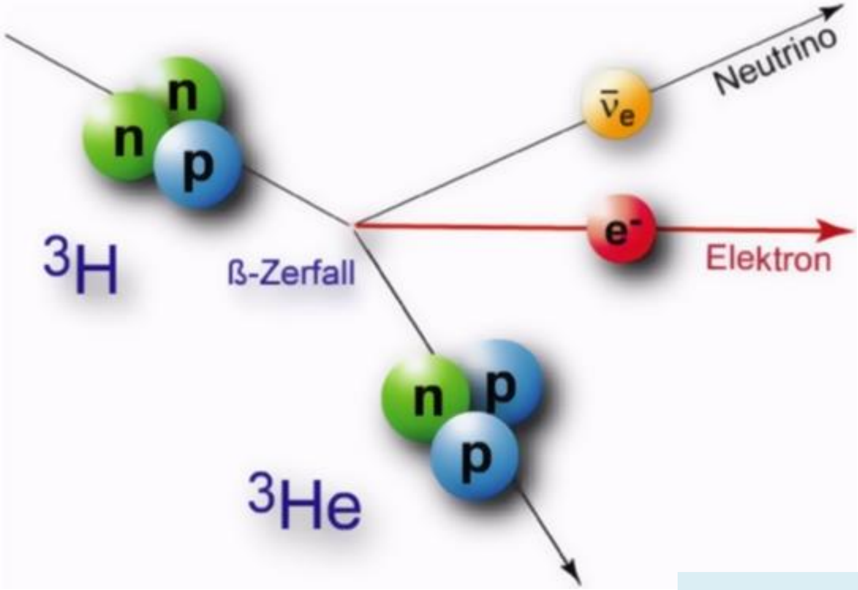
Unitarity contribution:



More systems to be studied for more stringent tests.

The mass of the neutrino

Nuclear masses for neutrino physics



Δm, Q

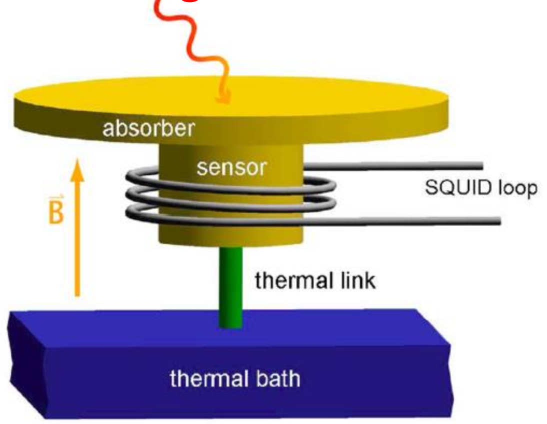
$m(\bar{\nu}_e) < 2$ eV/c^2 (95% CL)

The ECHo (^{163}Ho) project

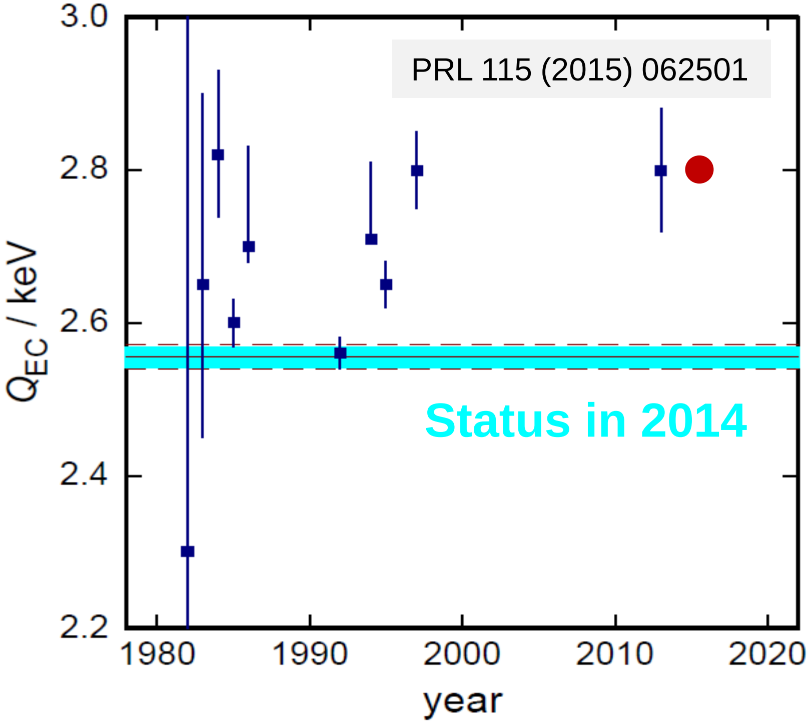
$$^{163}_{67}\mathrm{Ho} + e^- \rightarrow {}^{163}_{66}\mathrm{Dy}^* + \nu_e$$

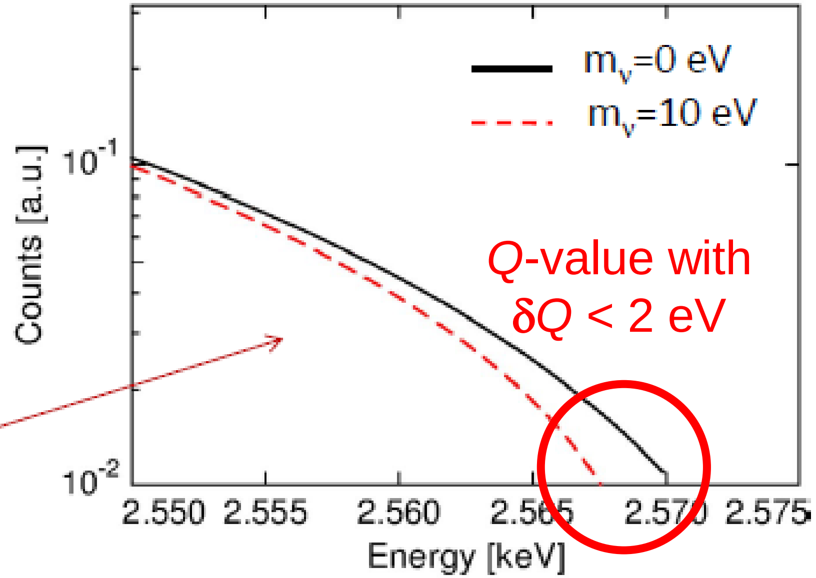
$$^{163}_{66}\mathrm{Dy}^* \rightarrow {}^{163}_{66}\mathrm{Dy} + E_C$$

Metallic Magnetic Calorimetry



Q-value of EC in ^{163}Ho





A $\delta m/m = 10^{-11}$ mass measurement (δQ < 2 eV) is needed!

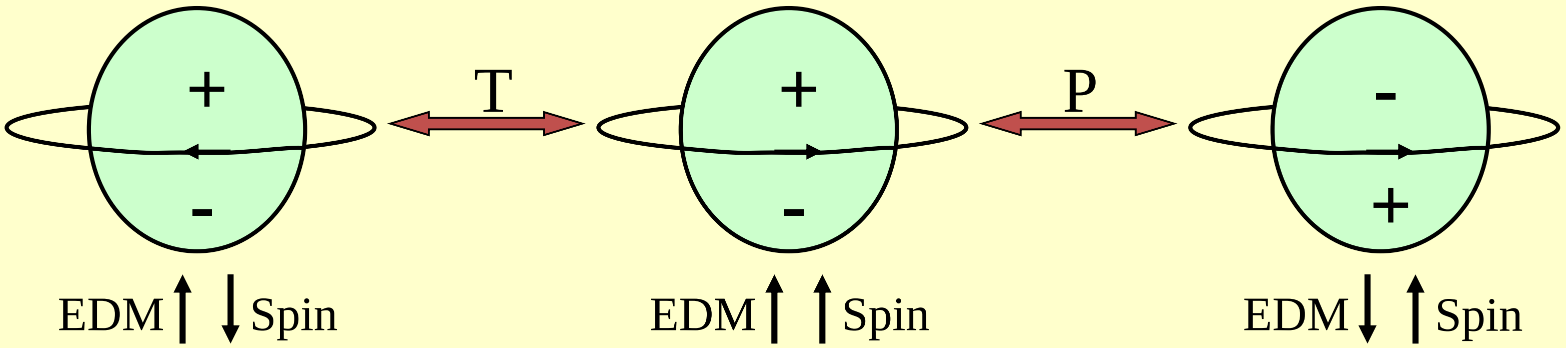
EDM and parity violation

Q_2, Q_3, $\delta\langle r^2\rangle$

Nuclear structure for parity violation and EDM searches

I, Q, μ

A permanent EDM violates both time-reversal symmetry and parity



Octupole enhanced atomic EDM

related to Q_3

P,T-violating n-n interaction

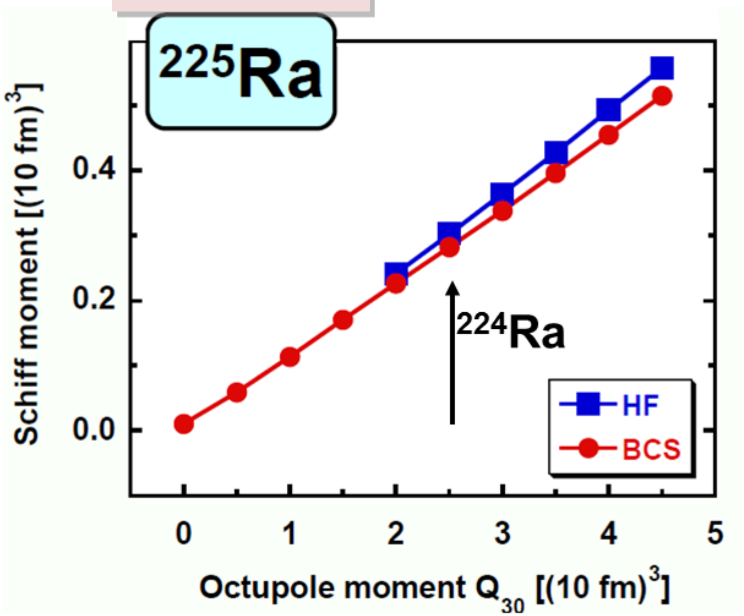
Schiff moment:

$$S = -2\frac{J}{J+1}\frac{<\hat{S}_z><\hat{V}_{PT}>}{\Delta E}$$

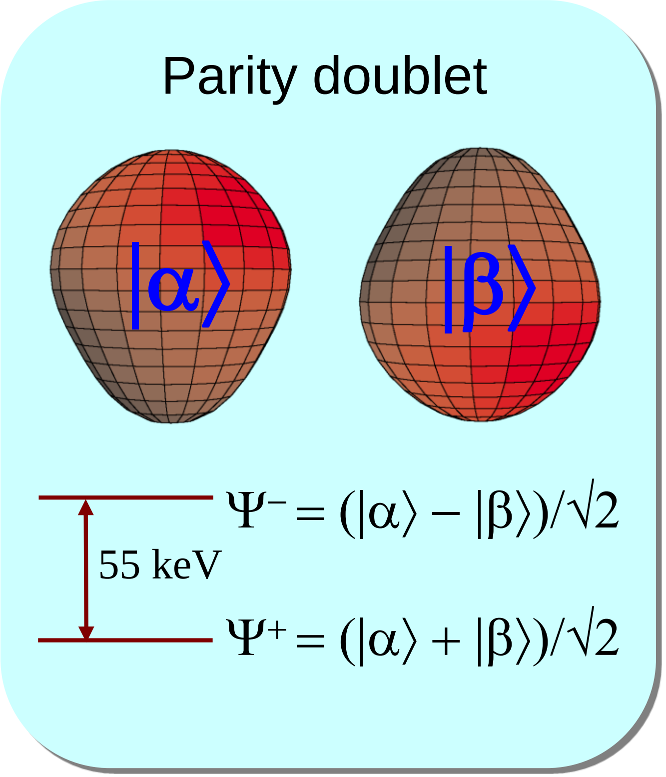
energy splitting of parity doublet

$I = ½$

$t_{1/2}$ = 15 d



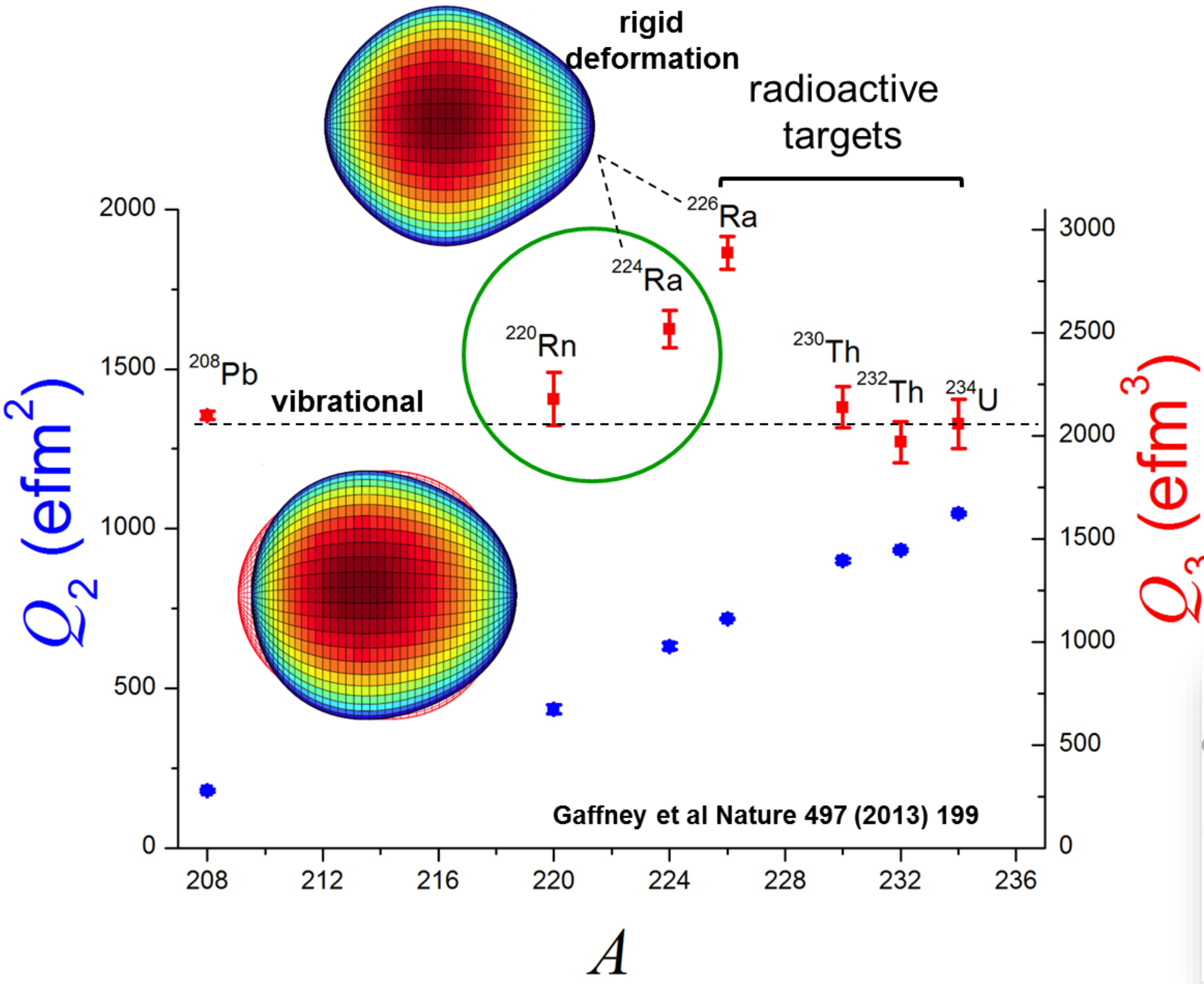
Shiff moment enhanced by ~ 3 orders of magnitude in pear-shaped nuclei


Parity doublet

$$\Psi^- = (|\alpha\rangle - |\beta\rangle)/\sqrt{2}$$

$$\Psi^+ = (|\alpha\rangle + |\beta\rangle)/\sqrt{2}$$

Pear-shaped nuclei at ISOLDE



Gaffney et al Nature 497 (2013) 199


nature

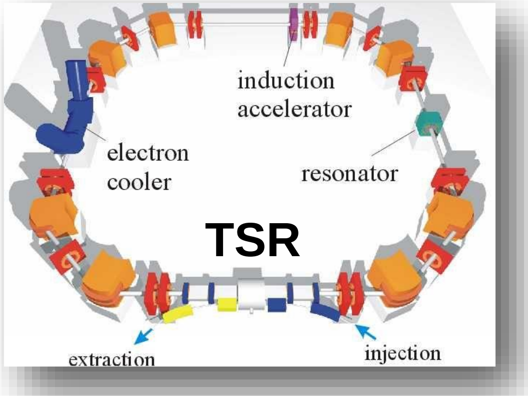
GOING PEAR-SHAPED

Exotic radium-224 atomic nuclei seen at CERN

STAYING IN TOUCH

HEATED ARGUMENT

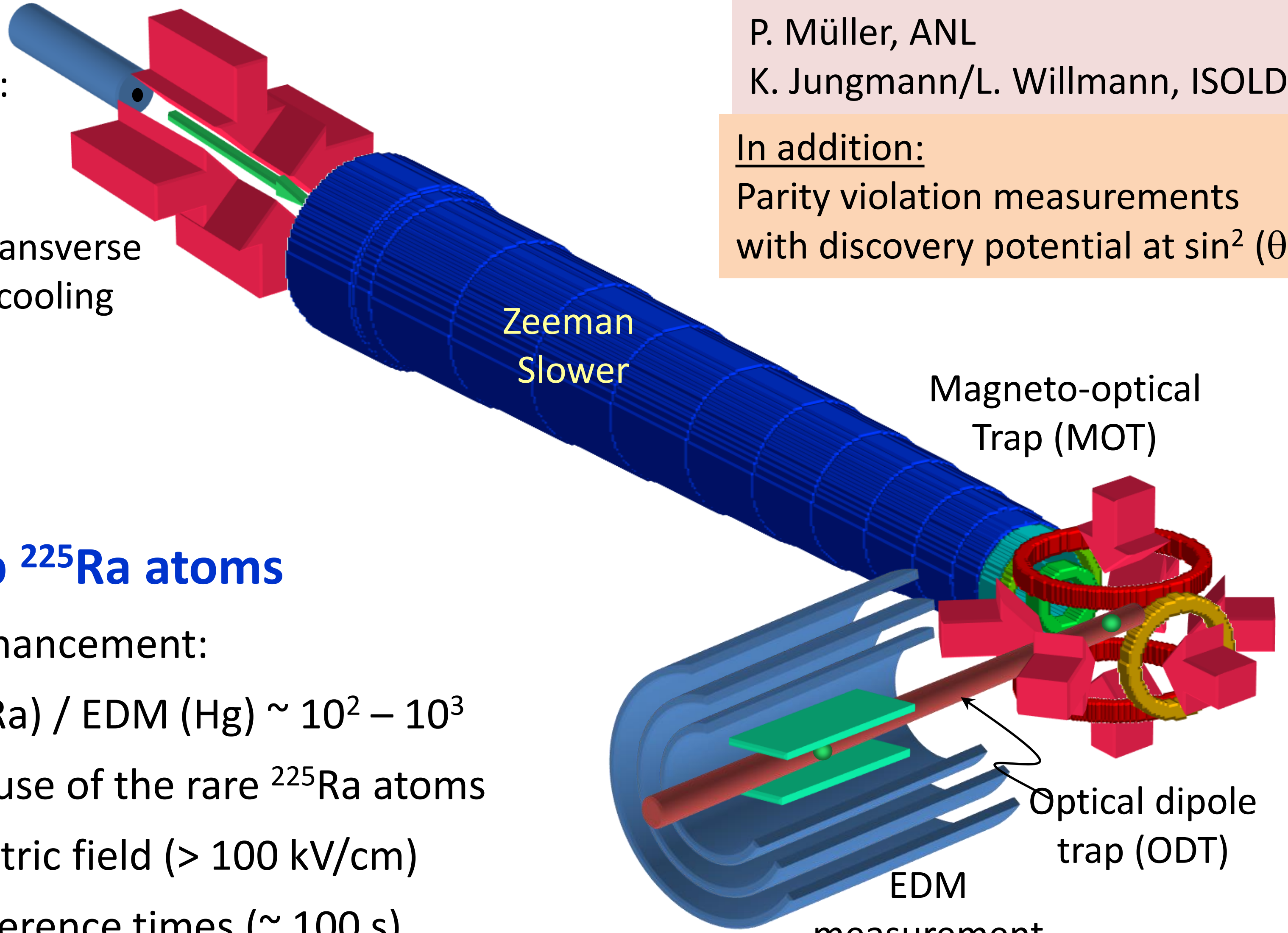
THE AGE OF THE BRAIN



More to come with the 10 MeV/u upgrade of HIE-ISOLDE.

EDM measurement on ^{225}Ra

P. Müller, ANL
K. Jungmann/L. Willmann, ISOLDE



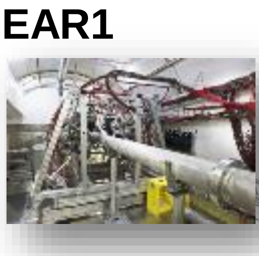
In addition:
Parity violation measurements
with discovery potential at $\sin^2(\theta_W)$

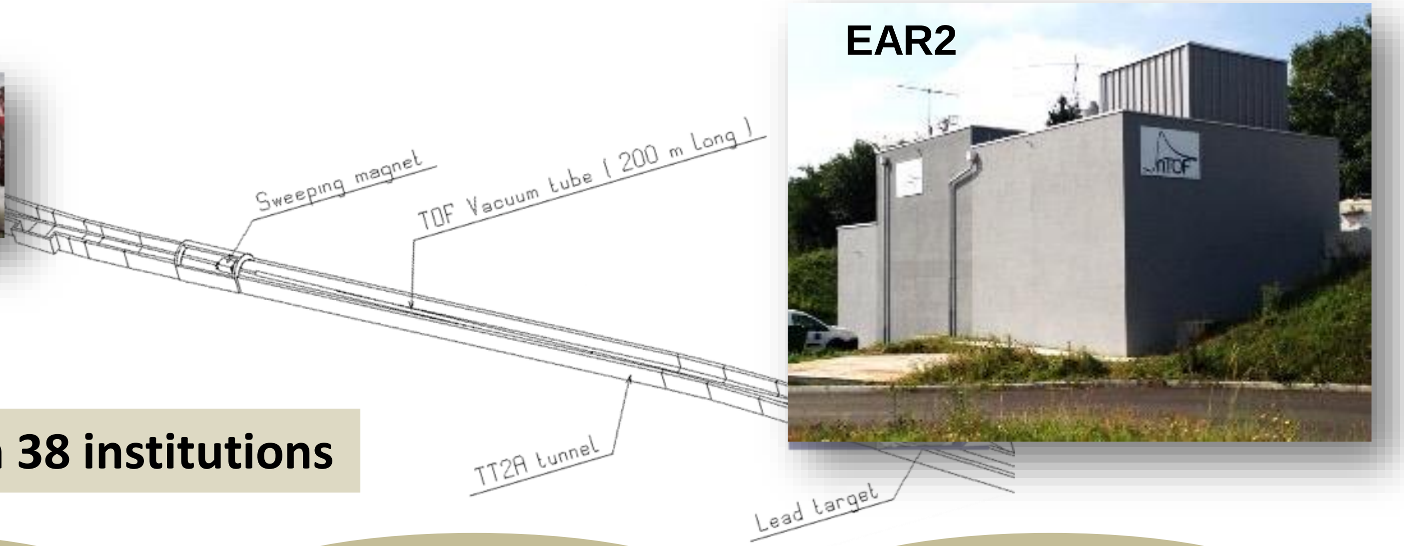
Why trap ^{225}Ra atoms

- Large enhancement:
  EDM (Ra) / EDM (Hg) ~ $10^2 - 10^3$
- Efficient use of the rare ^{225}Ra atoms
- High electric field (> 100 kV/cm)
- Long coherence times (~ 100 s)
- Negligible "v x E" systematic effect

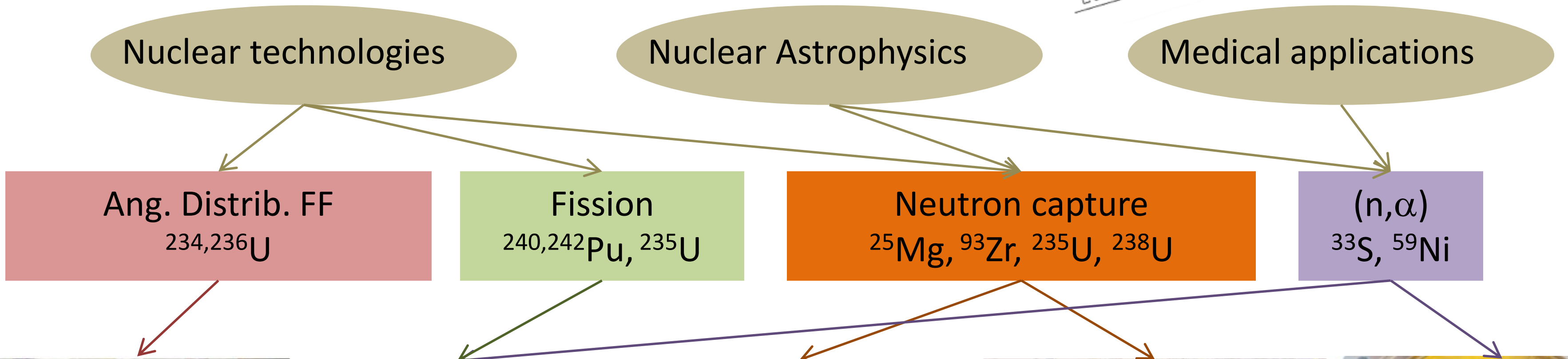
Courtesy of Peter Müller

The n_TOF facility





>100 members from 38 institutions



Nuclear technologies

Nuclear Astrophysics

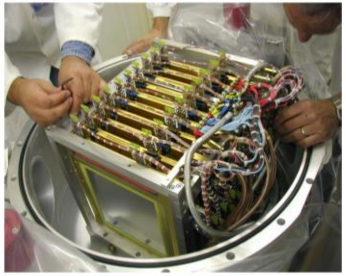
Medical applications

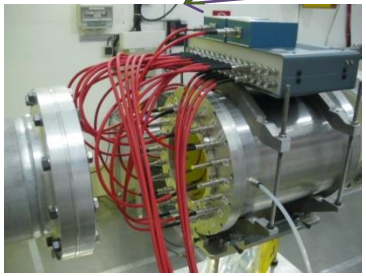
Ang. Distrib. FF
^{234,236}U

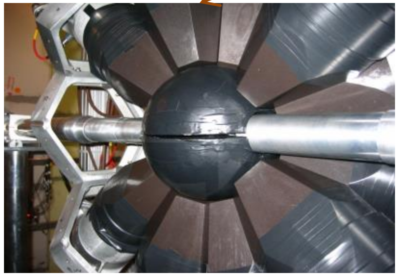
Fission
^{240,242}Pu, ^{235}U

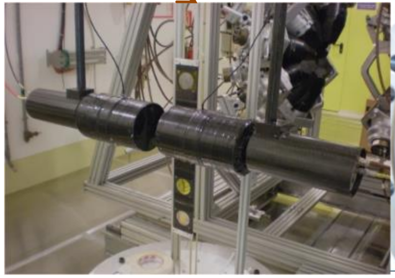
Neutron capture
^{25}Mg, ^{93}Zr, ^{235}U, ^{238}U

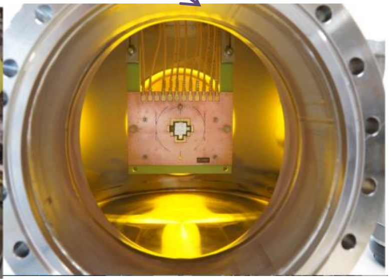
(n,α)
^{33}S, ^{59}Ni









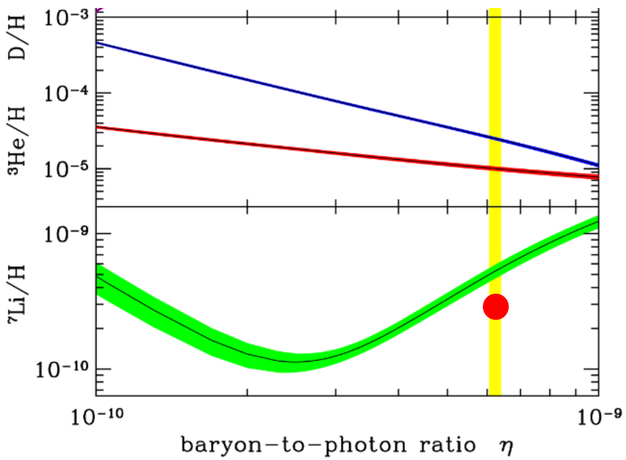


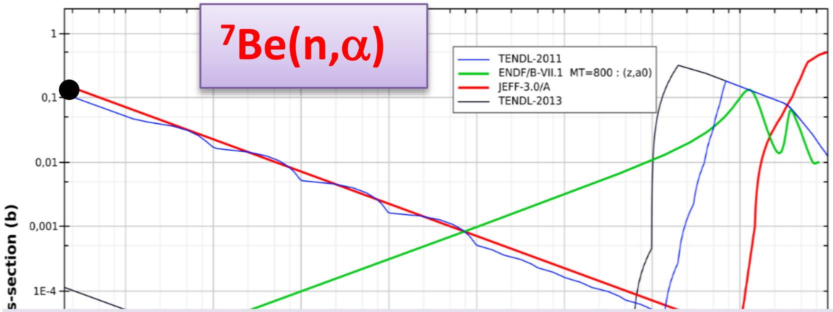
The cosmological Li problem

A serious discrepancy (factor 2-4) between the predicted abundance of **^{7}Li** and value inferred by measurements (Spite et al.)

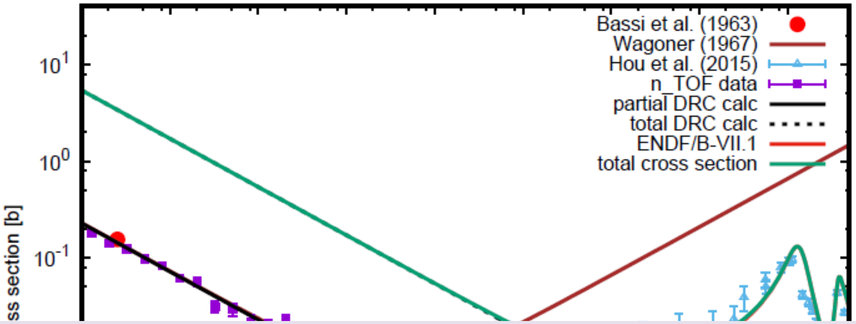
Approximately 95% of primordial **^{7}Li** is produced from the electron capture decay of **^{7}Be** (**$T_{1/2}$=53.2 d**).

^{7}Be is destroyed via **(n,p)** and (p,x), (d,x), (^{3}He,x), … reactions. Small contribution of the **(n,α)** reactions according to **estimated** cross section.





M. Barbagallo *et al.*, submitted to PRL (2016)



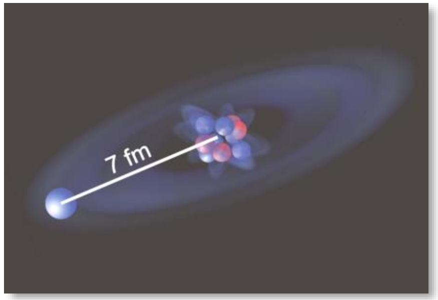
The long-standing cosmological lithium problem remains unsolved.

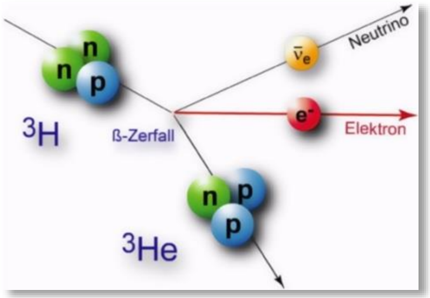
→ Alternative resonance in ^{8}Be at around 20 MeV excitation energy could be responsible for the ^{7}Li deficiency. → Search at HIE-ISOLDE.

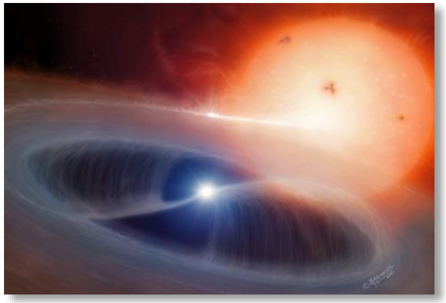
Summary

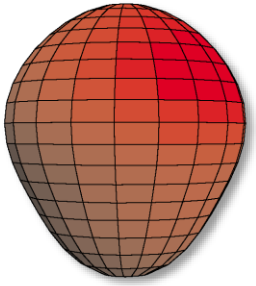
Exciting results in physics with neutron and radioactive ion beams have been achieved …

… with numerous applications in the search for physics beyond the SM









Nuclear researchers and especially young scientists from both collaborations played a prominent role in this field of research; at ISOLDE as well as at n_ToF.

Thanks a lot for your attention!