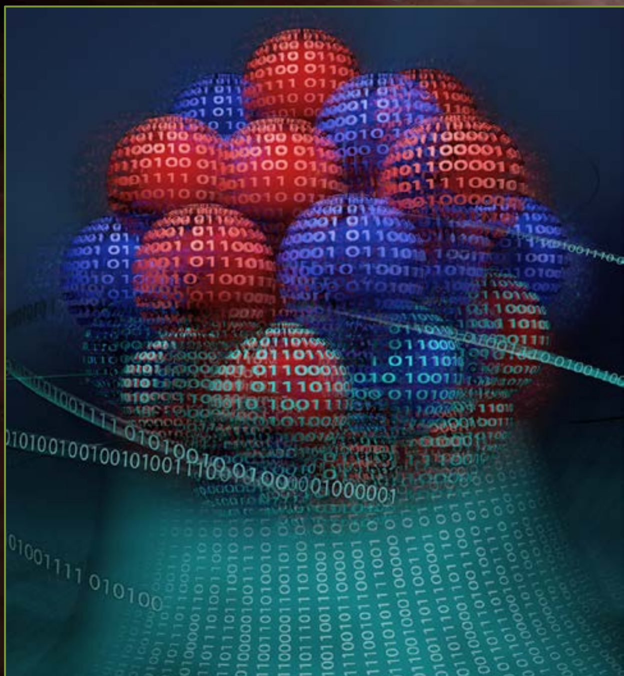
SPES Radioactive Ion Beam facility at LNL and EDM search

Giacomo de Angelis
INFN - LNL



Menu

- Objectives
- Status of the project

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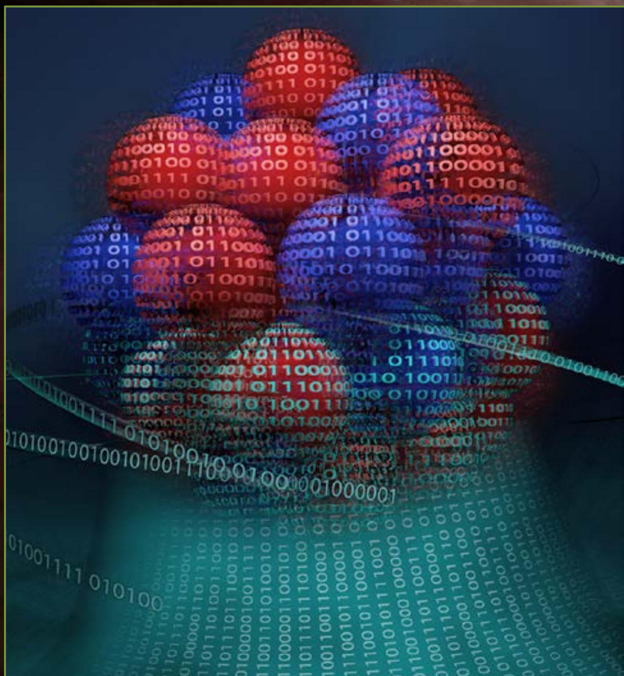


- SPES – NuSPRASEN workshop "Probing fundamental symmetries and interactions by low energy excitations with RIBs" Pisa 1-2 february 2018

Menu

- Objectives
- Status of the project

SPES project goals

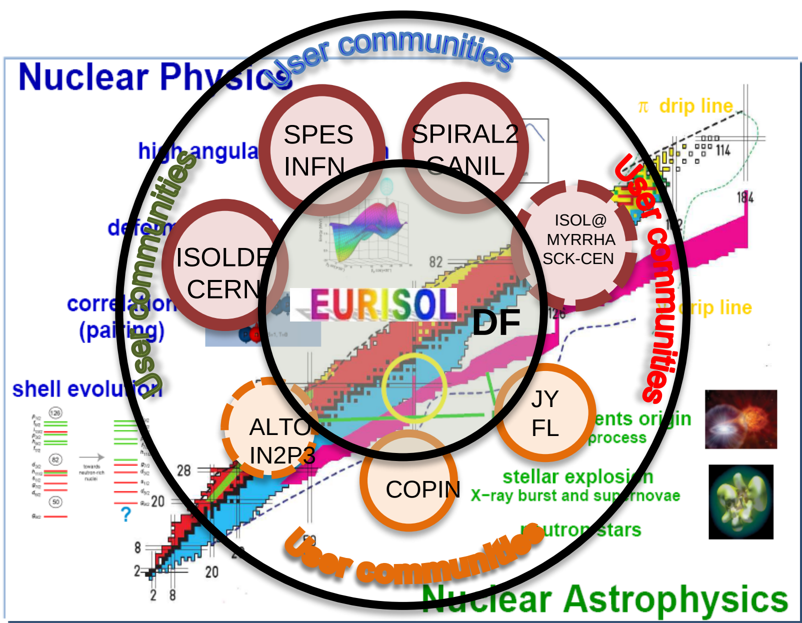
- Second generation ISOL facility for nuclear physics as part of the EURISOL_DF initiative (ESFRI_2020): **Production & re-acceleration** of **exotic beams**
- Research and Production of **Radio-Isotopes for Nuclear Medicine**
- Accelerator-based neutron source (**Proton and Neutron Facility for Applied Physics**)

α β δ γ **Cyclotron**

α β δ γ **ISOL RIBs+ Post-Acc.**

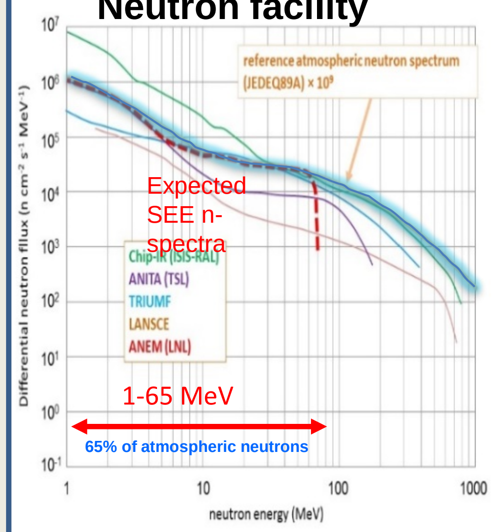
α β δ γ **Nuclear Medicine**

α β δ γ **Nuclear Applications**

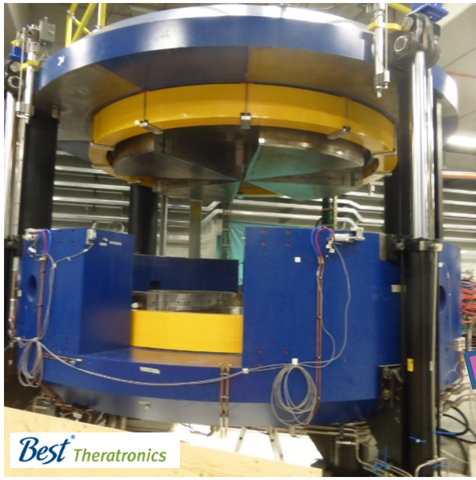


Radioisotpes for medicine

Neutron facility

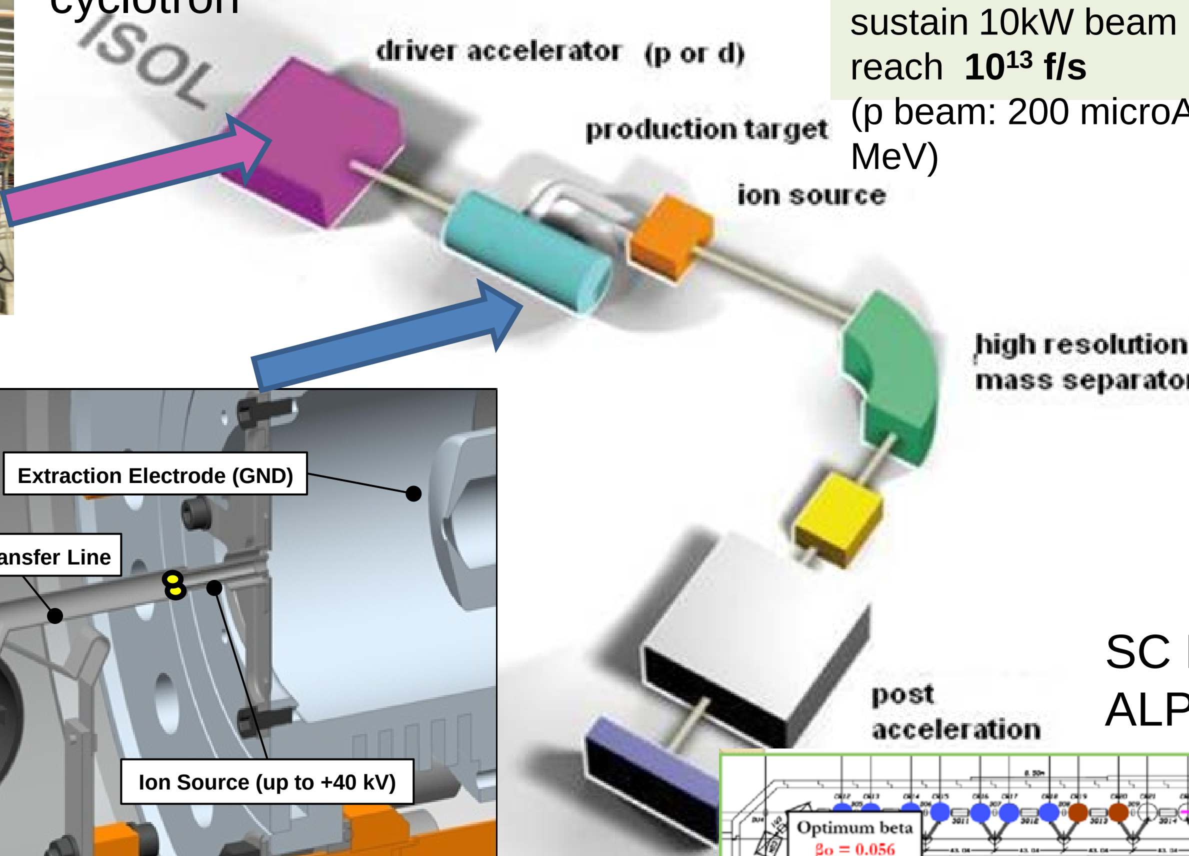


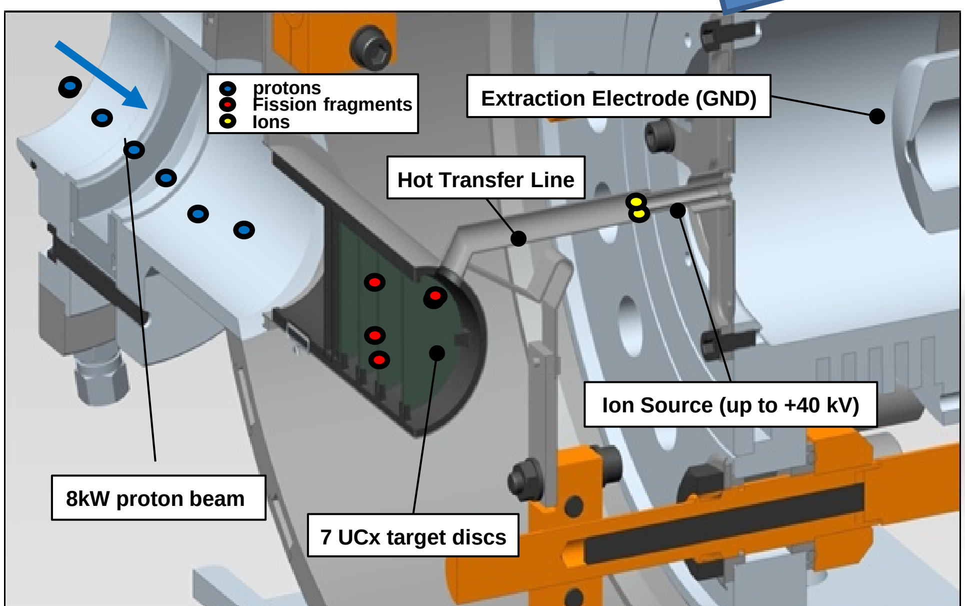
The SPES ISOL complex



35-70 MeV, 750 microA proton cyclotron

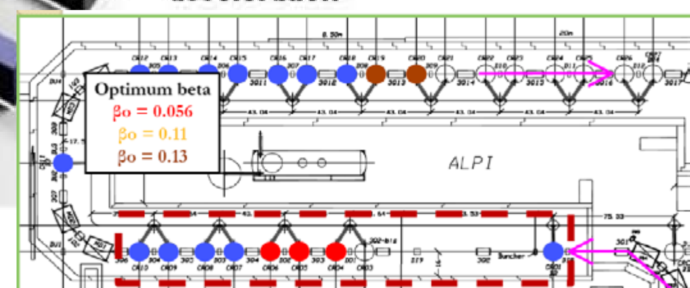
NEW concept developed for the SPES Direct Target: **Multi-foil UCx** designed to sustain 10kW beam power to reach **10^{13} f/s**
(p beam: 200 microA, 40 MeV)



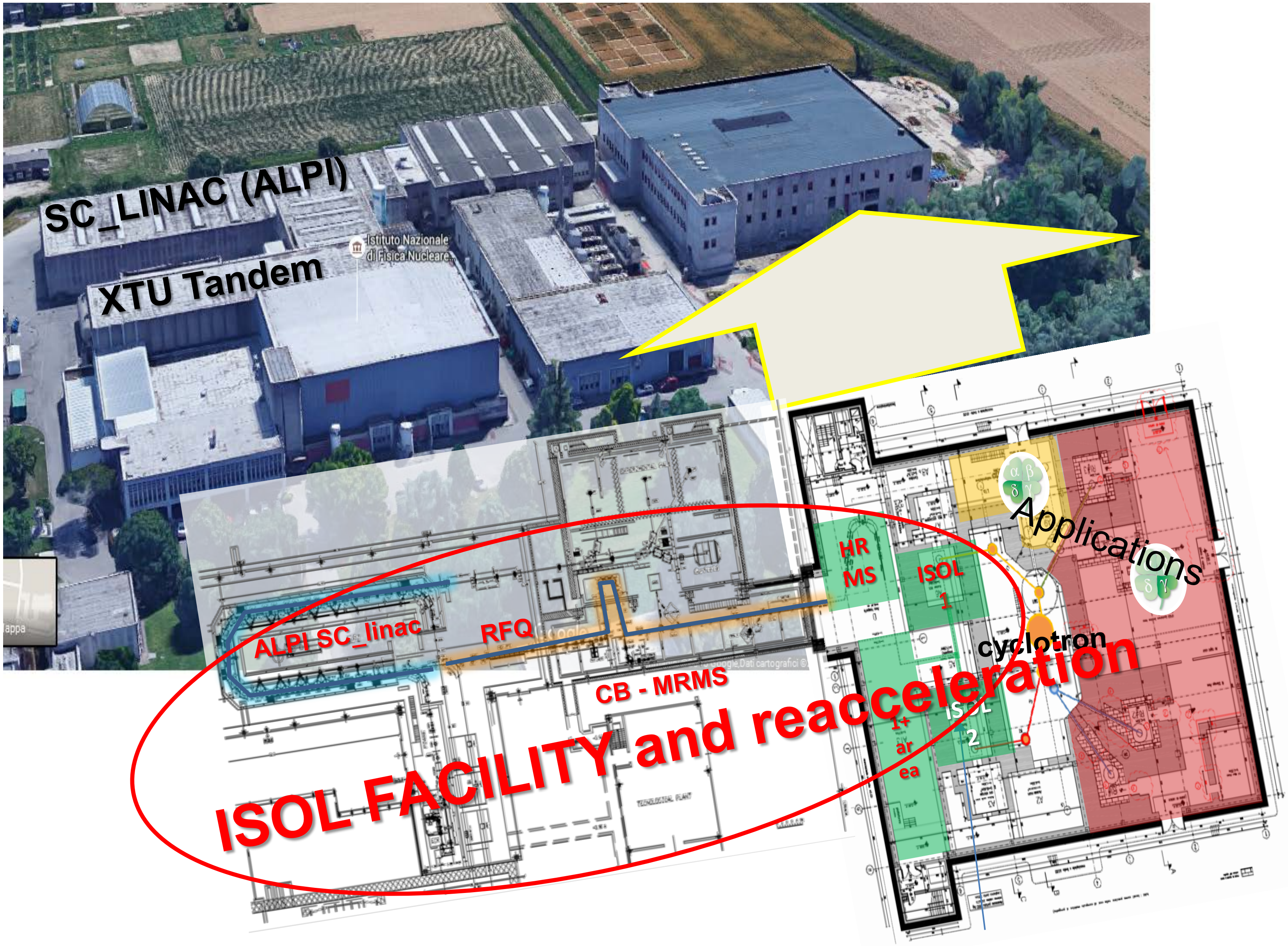


10 kW ISOL target

SC LINAC
ALPI

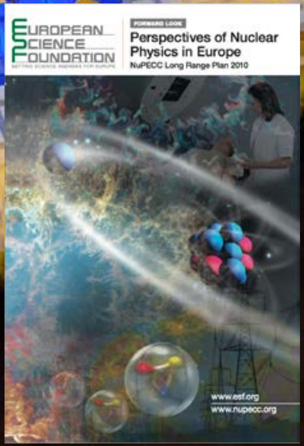


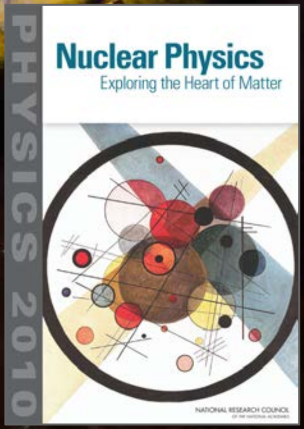
Operating facilities at Legnaro National Laboratories

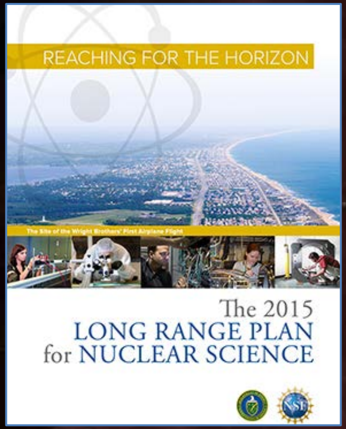


The Nuclear Landscape and the Big Questions

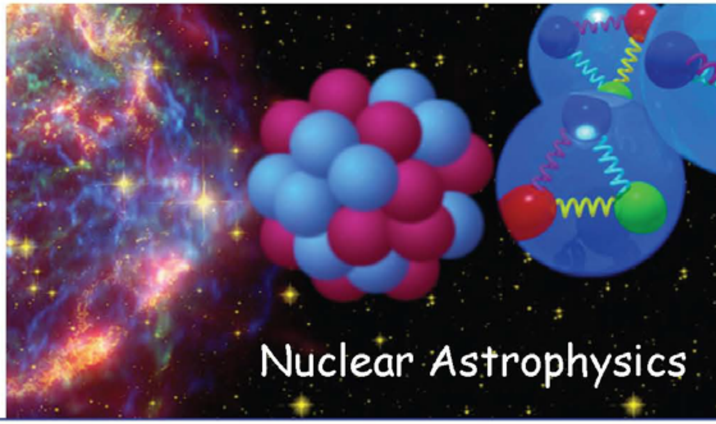
- Where did the atoms and atomic nuclei come from?
- How are the nuclei of atoms made and organized?
- What are the fundamental particles and forces at work inside atomic nuclei?
- What are practical and scientific uses of nuclei?



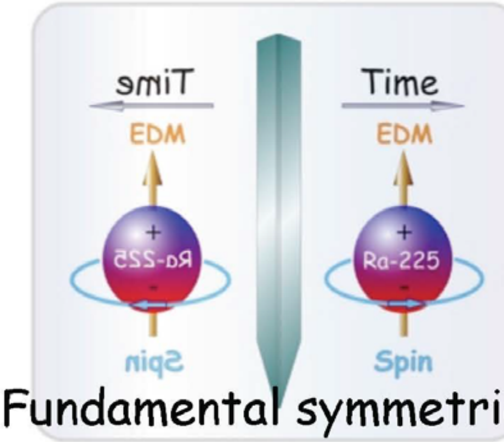




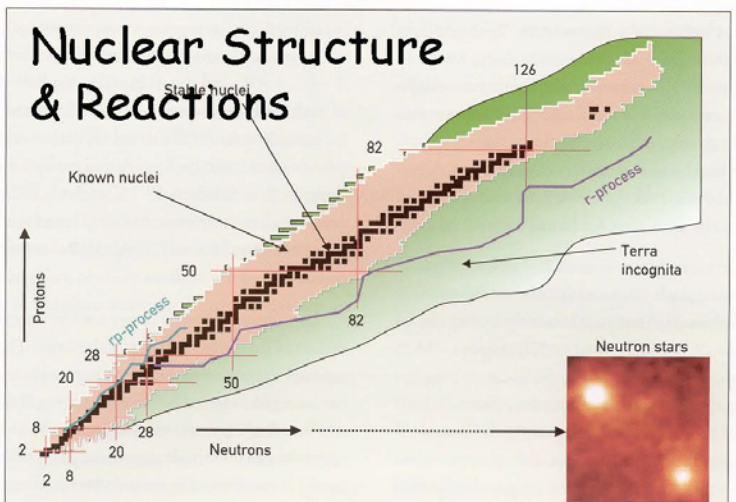
Which science drives physics with rare isotopes?



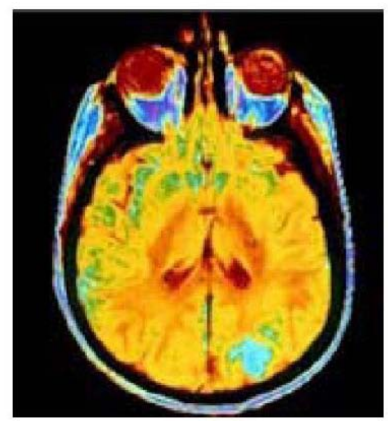
Origin of new elements, rare isotopes powering stellar explosions, neutron star crust

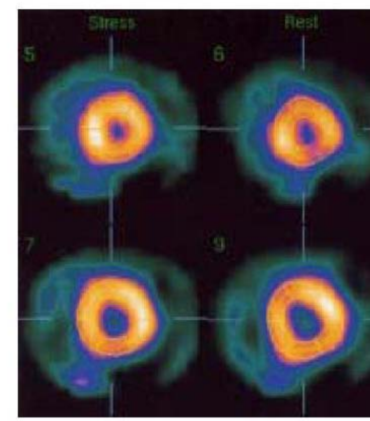


Use of rare isotopes as laboratories where symmetry violations are amplified.



Limits of existence: what makes nuclei stable? New shapes, new collective behavior.





Materials, medical physics, reactors,..

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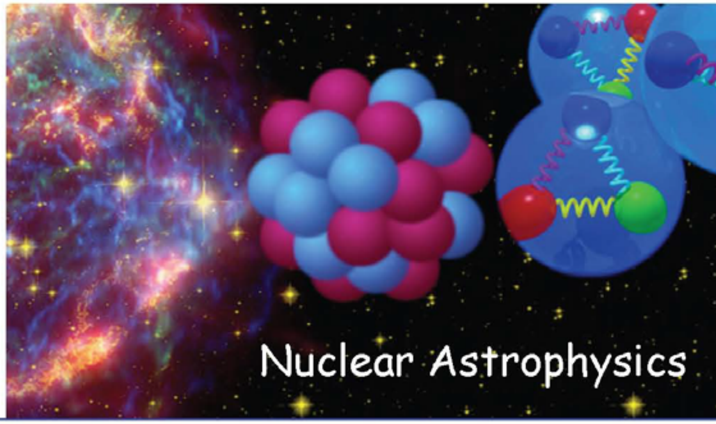

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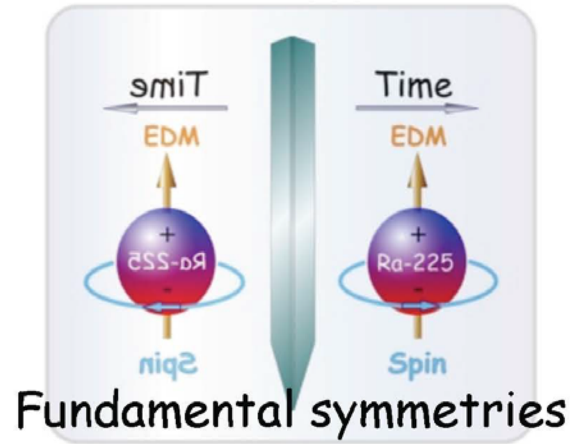

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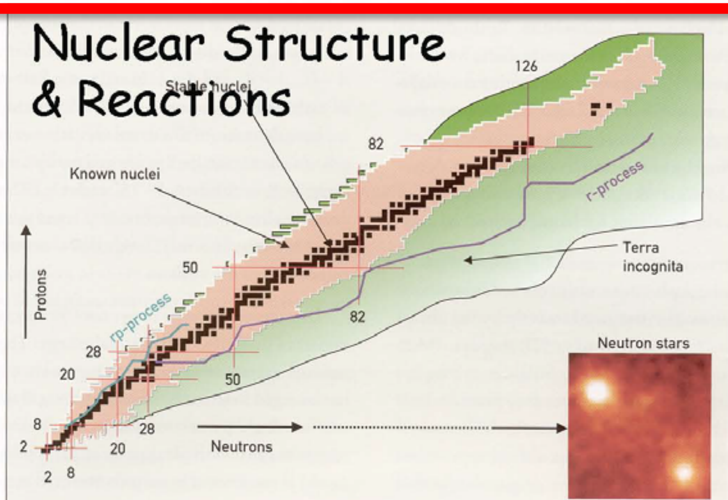

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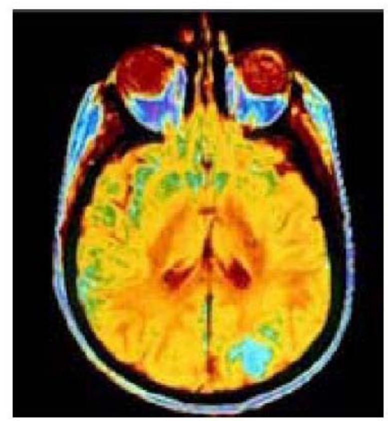
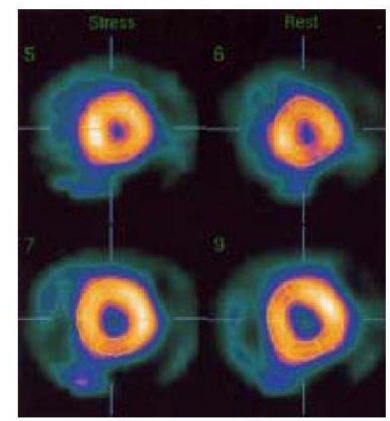


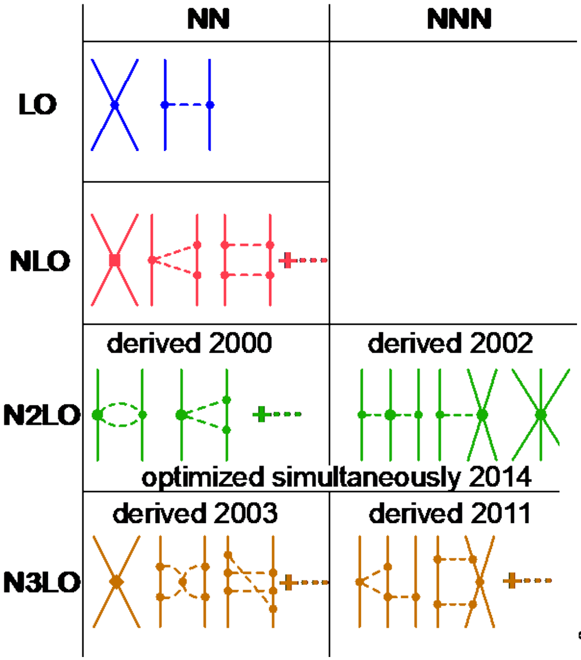


Materials, medical physics, reactors,..

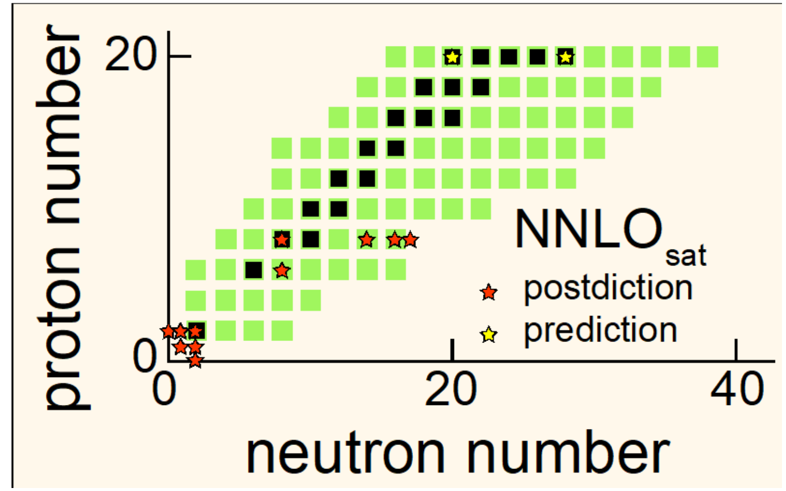
Linking few-body with many-body

Quantified input

Nuclear Forces
from |EFT

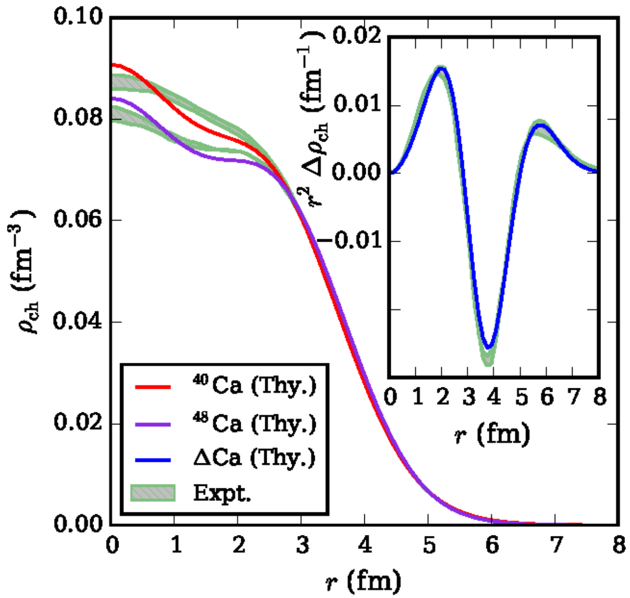


Comprehensive model of light and heavy nuclei

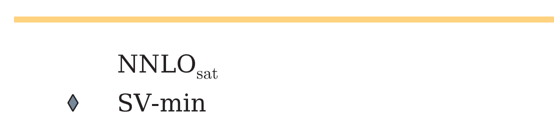


Nature Physics **12**, 186 (2016)

Consistency with known data



Prediction



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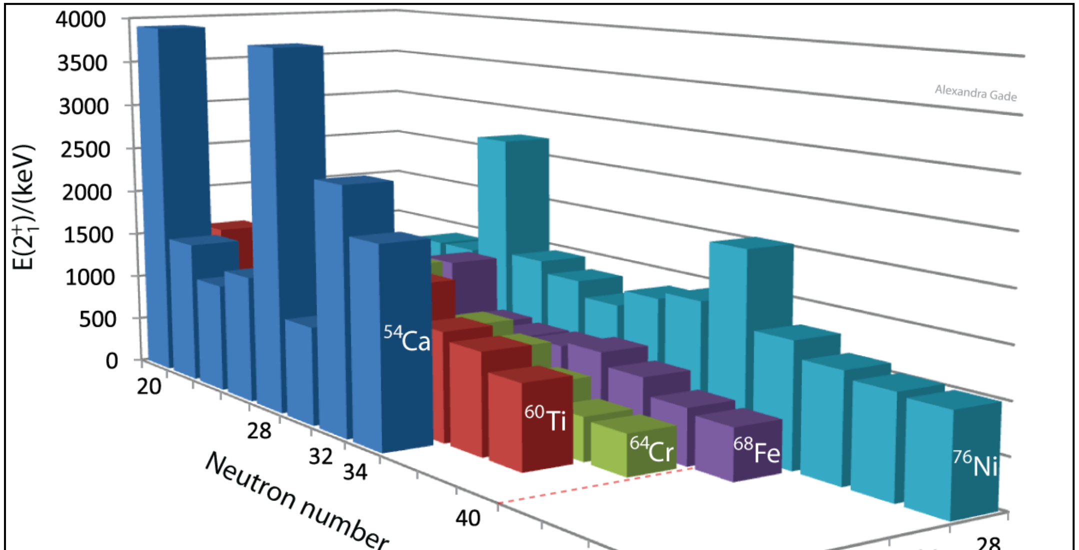
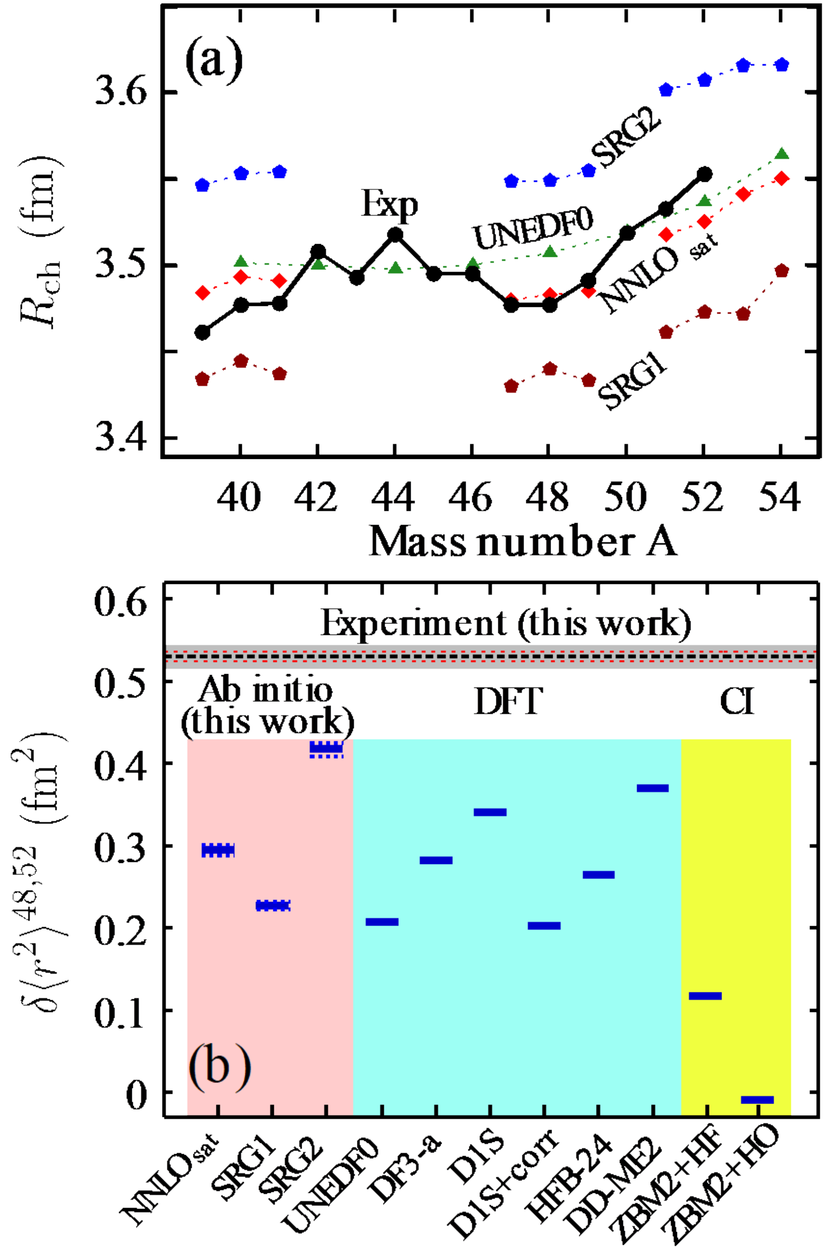
The frontier: calcium isotopes (where *ab-initio* and DFT meet)



Phys. Scripta 91, 053003 (2016)

Nature Physics 12, 594 (2016)

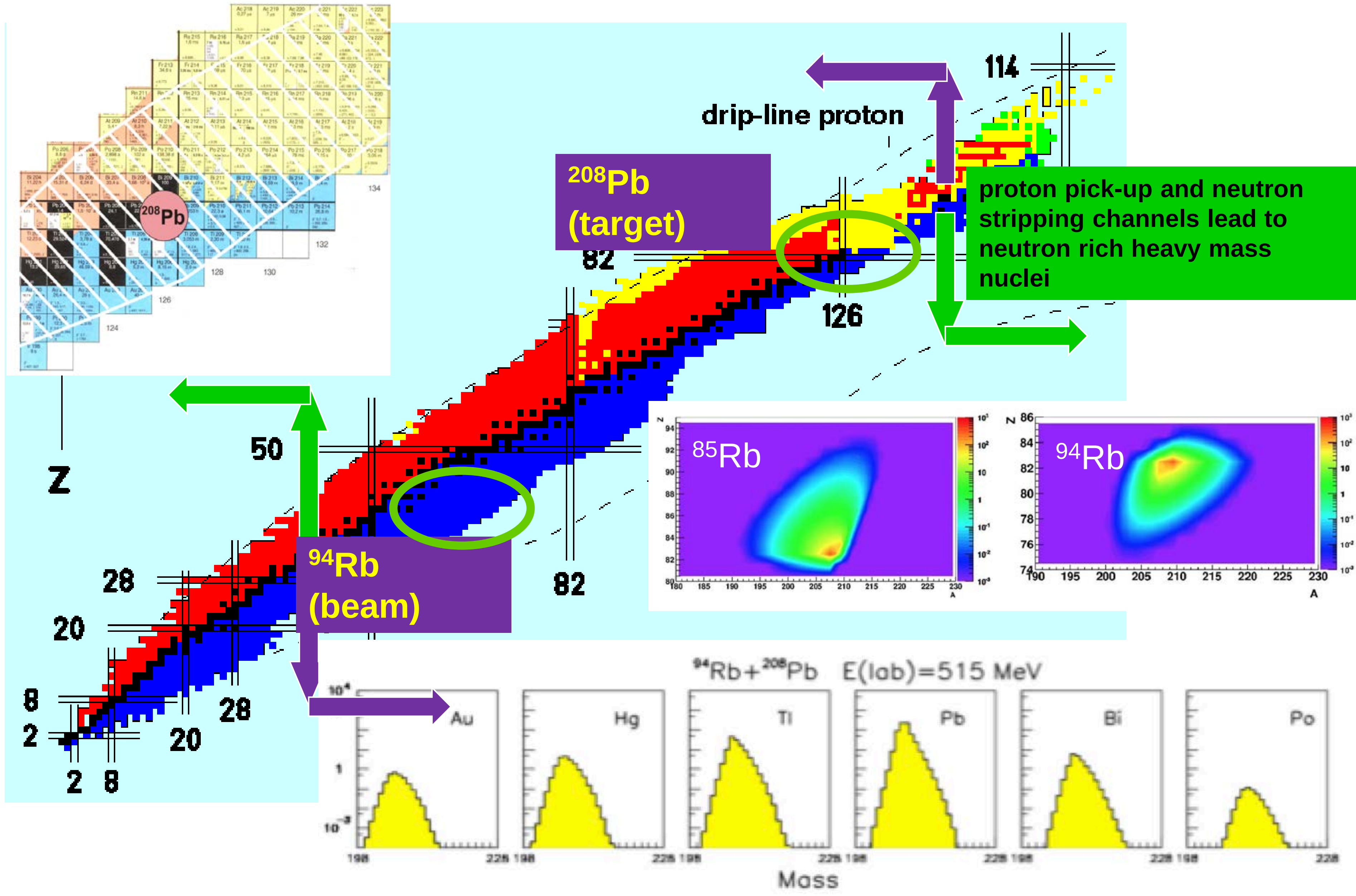


New shell closures at N = 32 & 34?

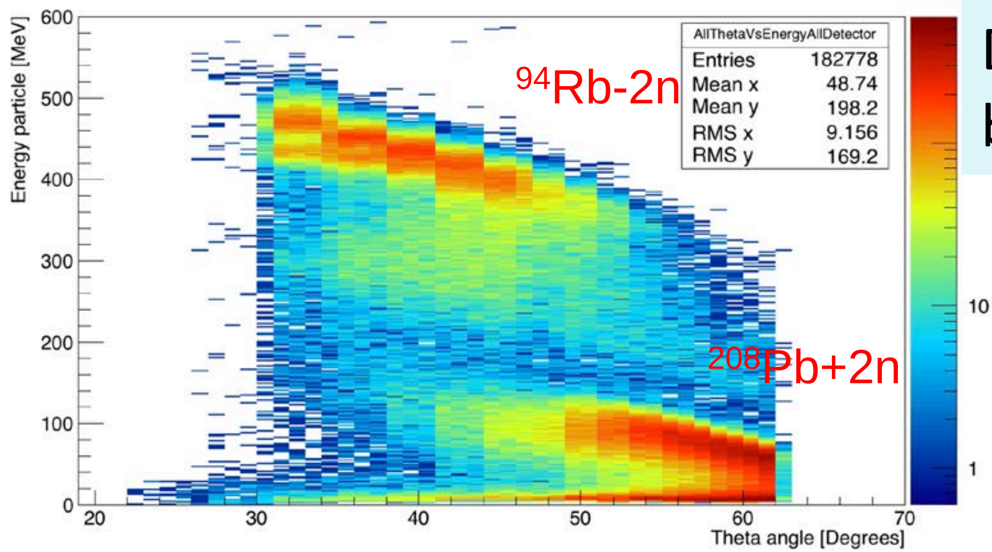
→ Shell closure at Z=82 N=126

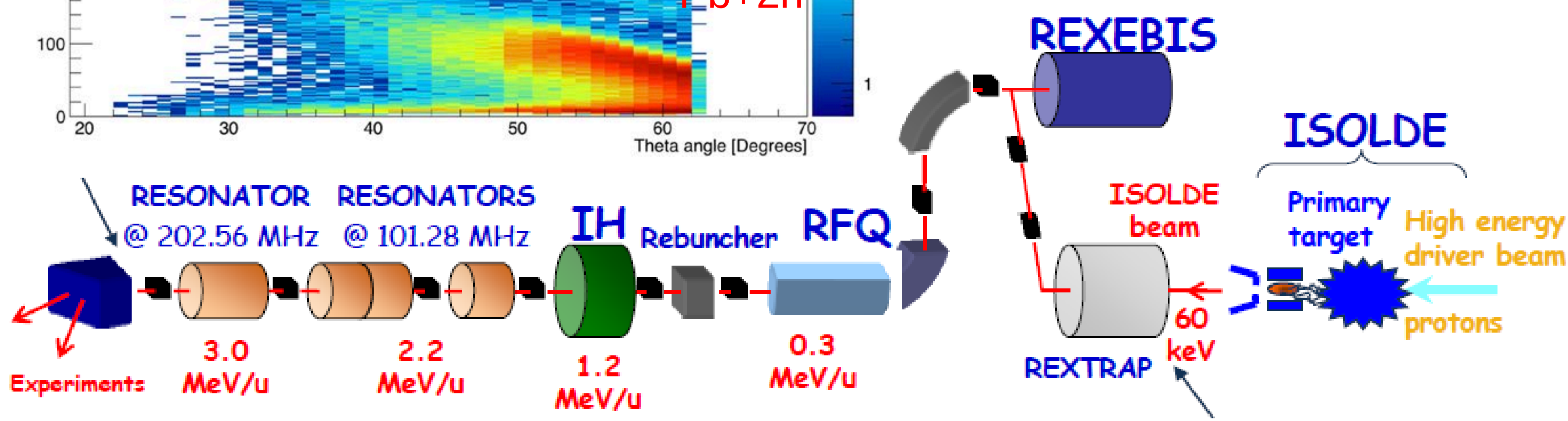
Developing new nuclear paradigms

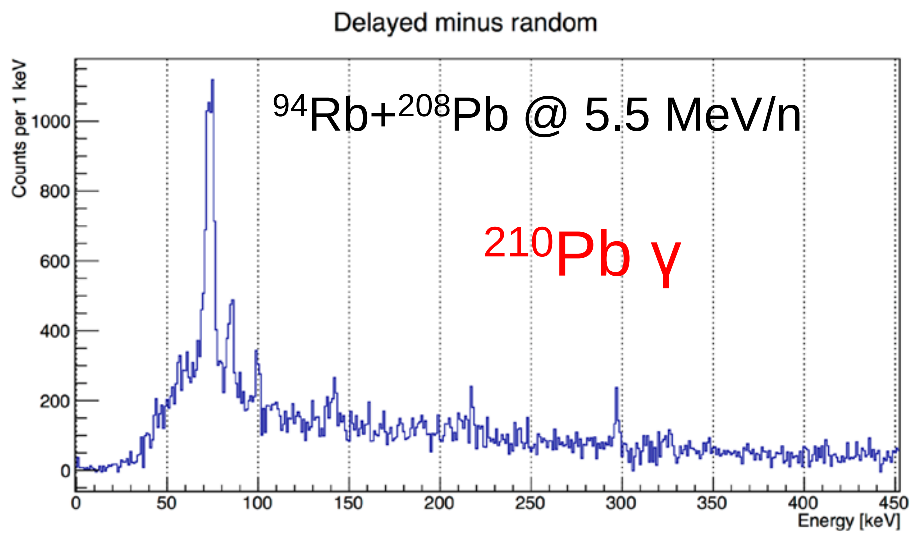
The N=82 region via **multinucleon transfer with n-rich secondary beams**

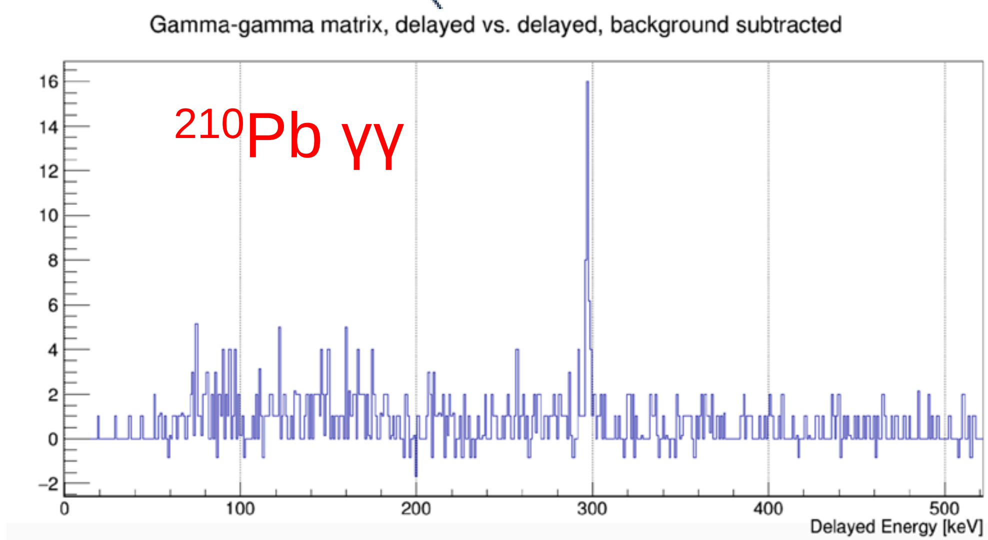


Deep Inelastic with n-rich beams at HIE-ISOLDE









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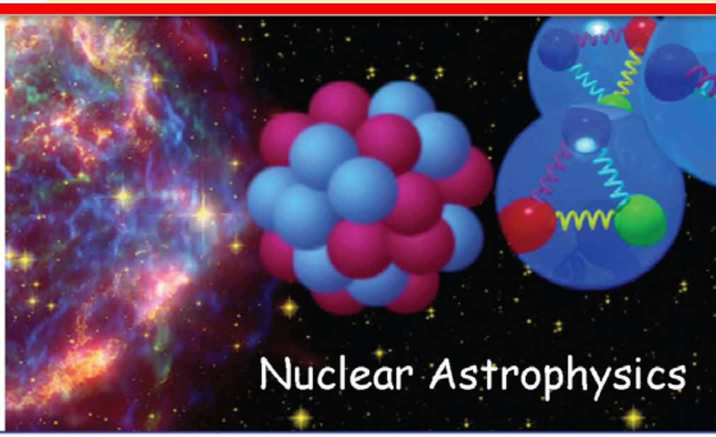

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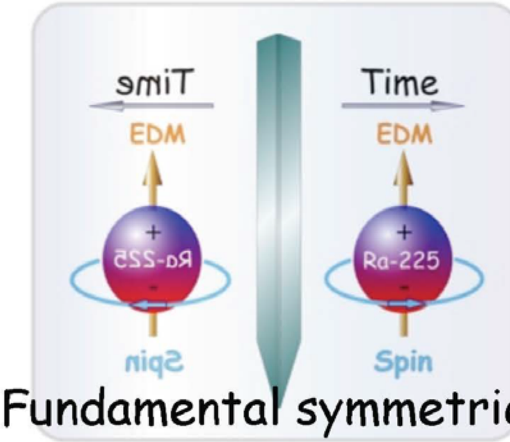

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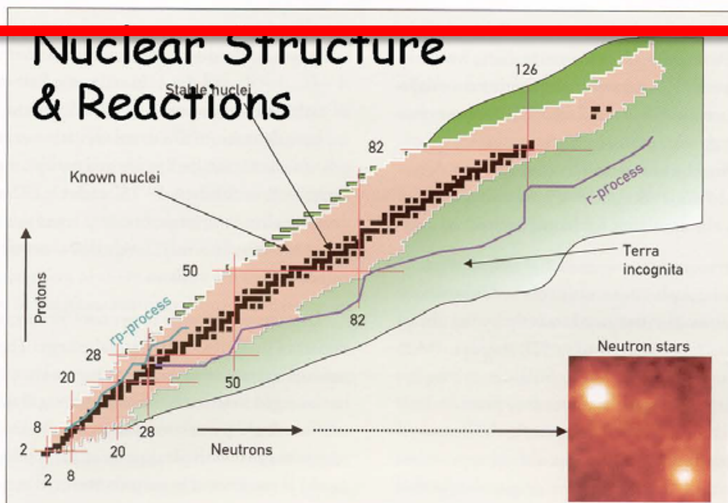

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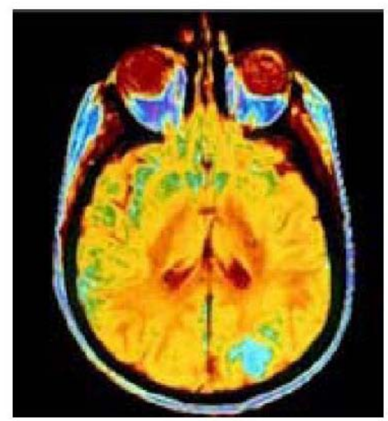
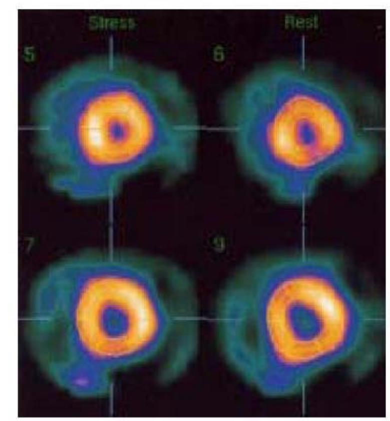


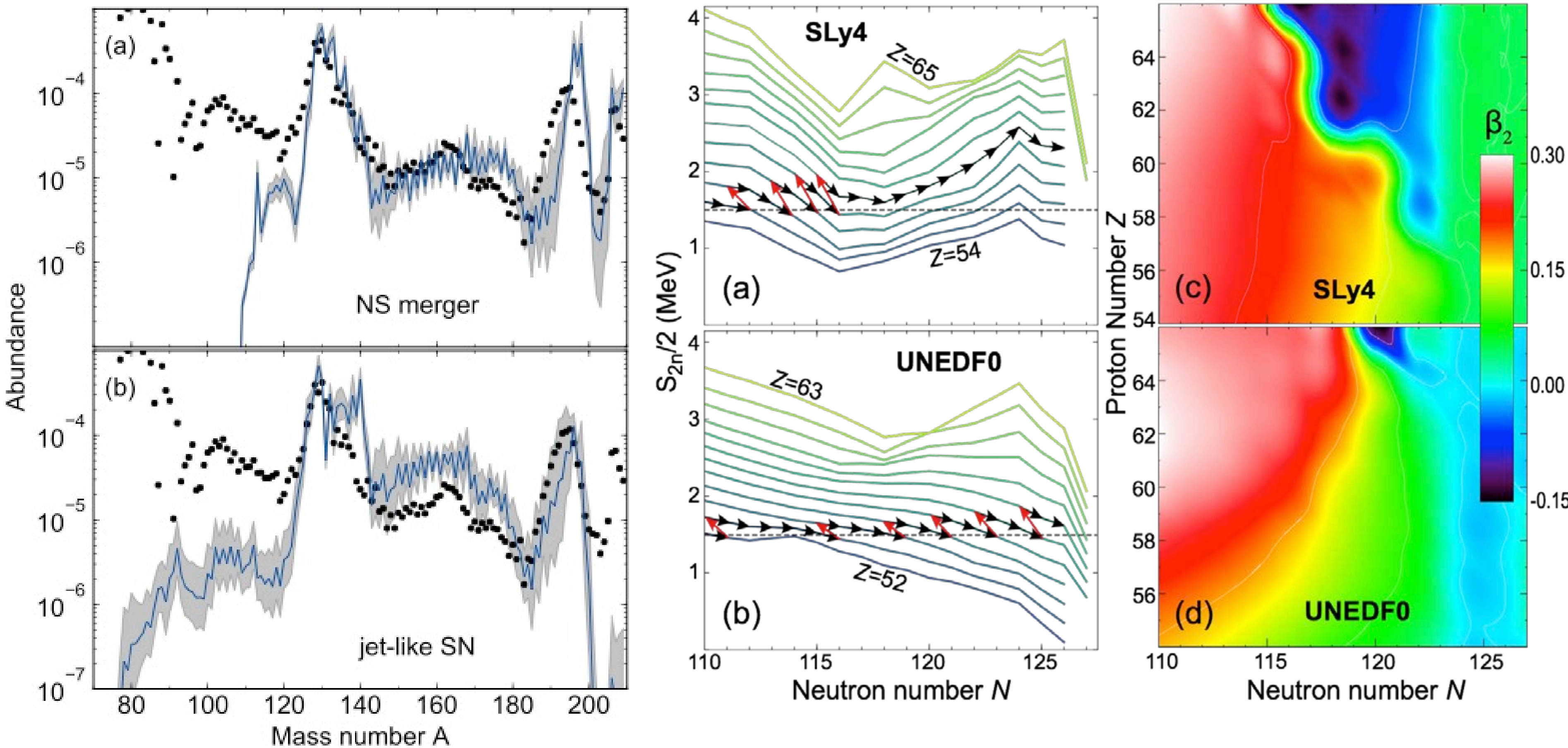


Materials, medical physics, reactors,..

Indeed, in many cases, nuclear modeling MUST involve massive extrapolations...

Impact of Nuclear Mass Uncertainties on the r Process

Phys. Rev. Lett., **116,** 121101 (2016)



Uncertainty quantification

Getting critical measurements

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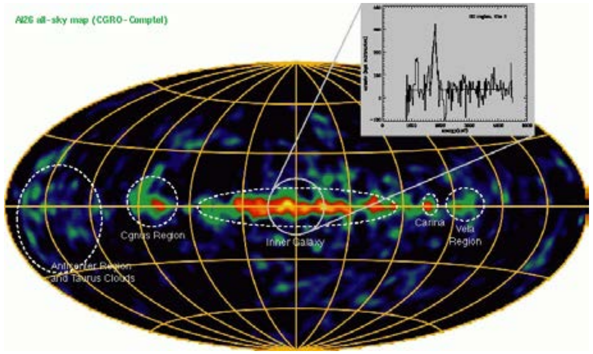
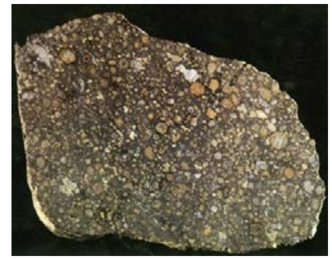
Measurements of astrophysical relevant reactions induced by alpha, protons and neutrons at the Gamow peak using the Trojan Horse method



r-process reactions
can be studied as well

Observation of 1808.65 keV γ-rays from the decay of ^{26}Al to ^{26}Mg in the interstellar medium demonstrated that ^{26}Al nucleosynthesis does occur in the **present Galaxy**.

Meteorites formed before the birth of the solar system show excesses in ^{26}Mg, pointing to $^{26}Al/^{27}Al$ at least **100 times larger than the solar value**



The radioisotopes ^{26}Al ($T1/2 = 7.17 \times 10^5$ yr) and $^{26}Al^m$ ($T1/2 = 6.34$ s) are of outstanding importance in astrophysics

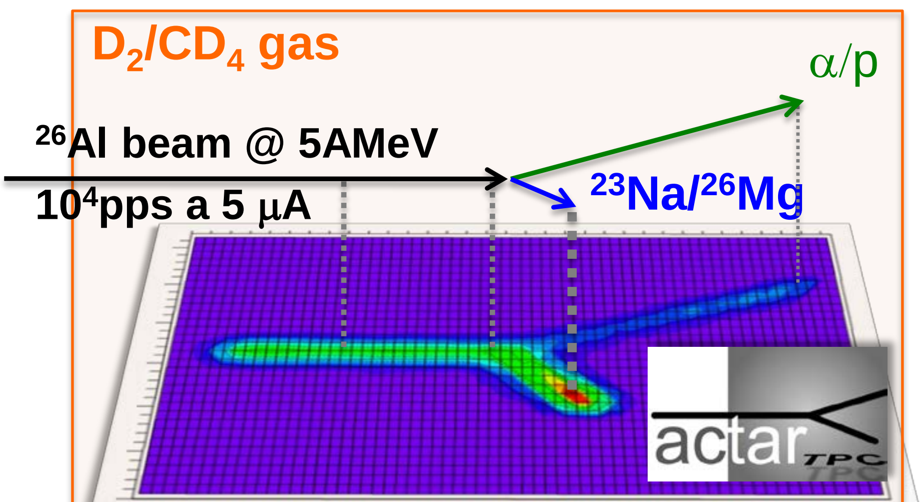
$^{26}Al^*(n,\alpha)^{23}Na$ via $^{26}Al^*(d,\alpha^{23}Na)p$
$^{26}Al^*(n,p)^{26}Mg$ via $^{26}Al^*(d,p^{26}Mg)p$

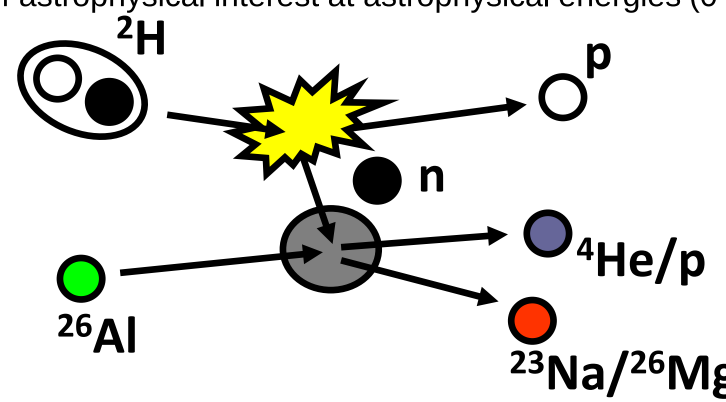
M. La Cognata, S. Palmerini and the ASFIN collaboration LNS

SPES phase 1 (using silicon carbide as primary target) can supply $^{26}Al^m$ beam

→ Isomeric state at 228 keV with a lifetime of 6.34 s cannot be as target in neutron induced reactions

→ **The THM** can be used to transfer a neutron and deduce the cross sections of astrophysical interest at astrophysical energies (0-2 MeV)

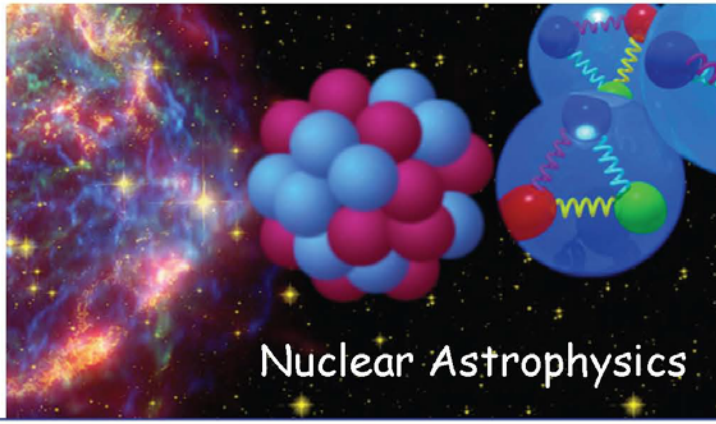




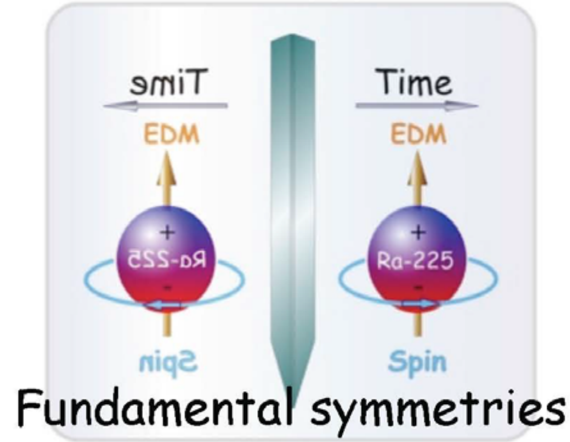
SPES exotic beams for science

INFN Istituto Nazionale di Fisica Nucleare

Which science drives physics with rare isotopes?



Origin of new elements, rare isotopes powering stellar explosions, neutron star crust



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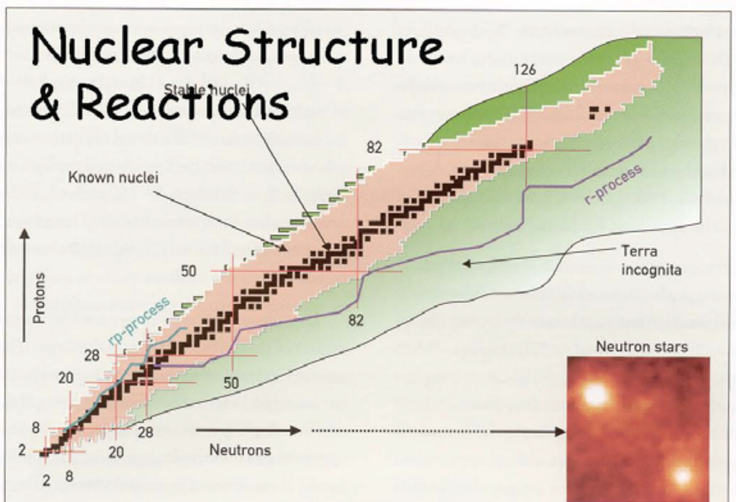

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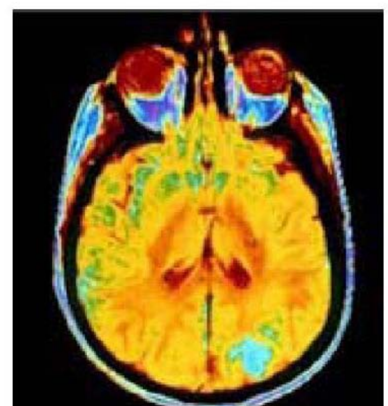
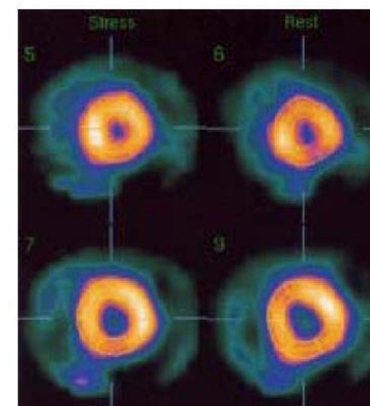
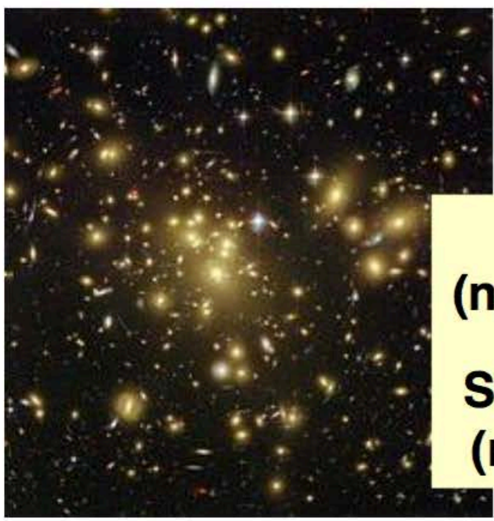




Materials, medical physics, reactors,..

Nuclear Structure and EDM search

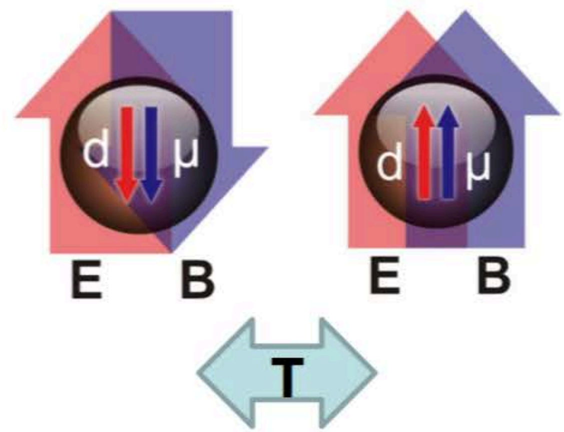
- Explanations of the Baryon Asymmetry of the Universe require additional CP violation
- Permanent EDM of fundamental spin systems are the most sensitive probes for bejond Standard Model CP violation
- Axion like Dark Matter probe?



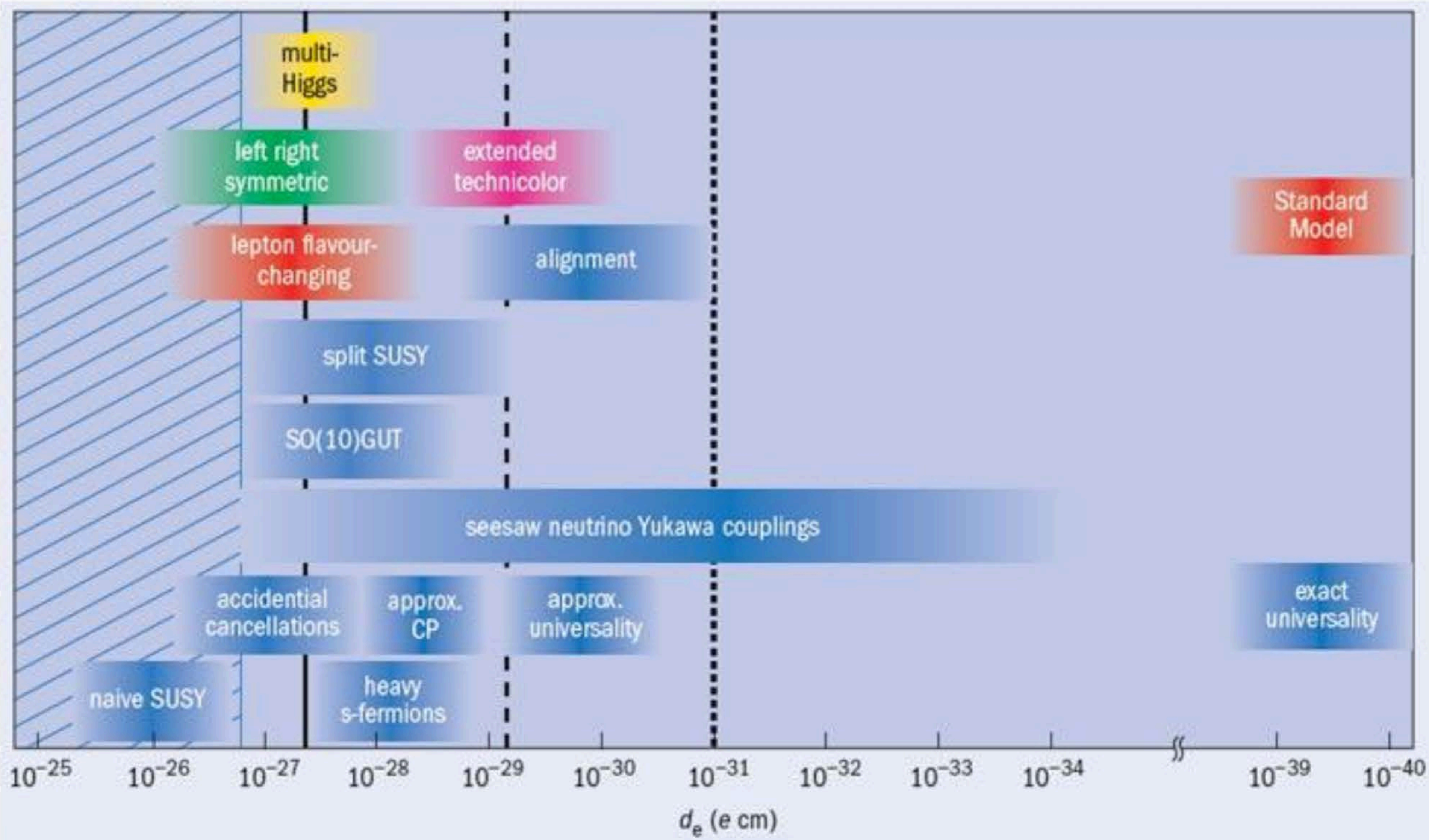
Observed:
$(n_B - n_{\bar{B}})/n_\gamma = 6 \times 10^{-10}$

SM expectation:
$(n_B - n_{\bar{B}})/n_\gamma \sim 10^{-18}$

Sakharov 1967:
B-violation
C & CP-violation
non-equilibrium
JETP Lett.5(1967)24

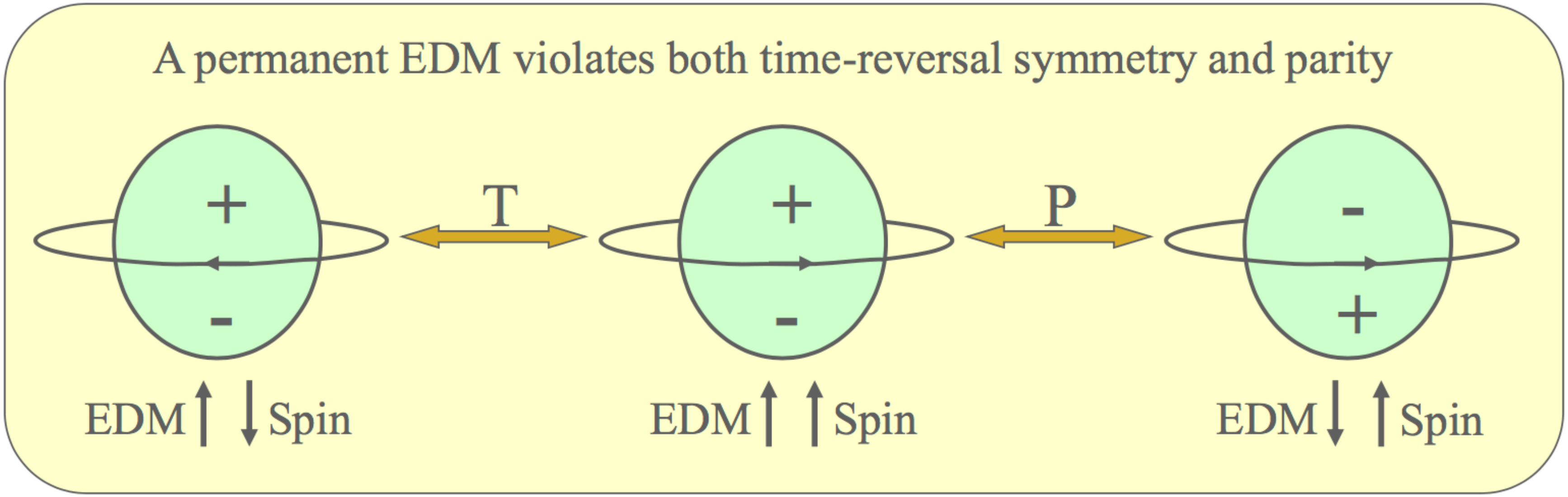


More CP-Violation Mechanisms?



Fortson, Sandars, Barr, Physics Today (June 2003)

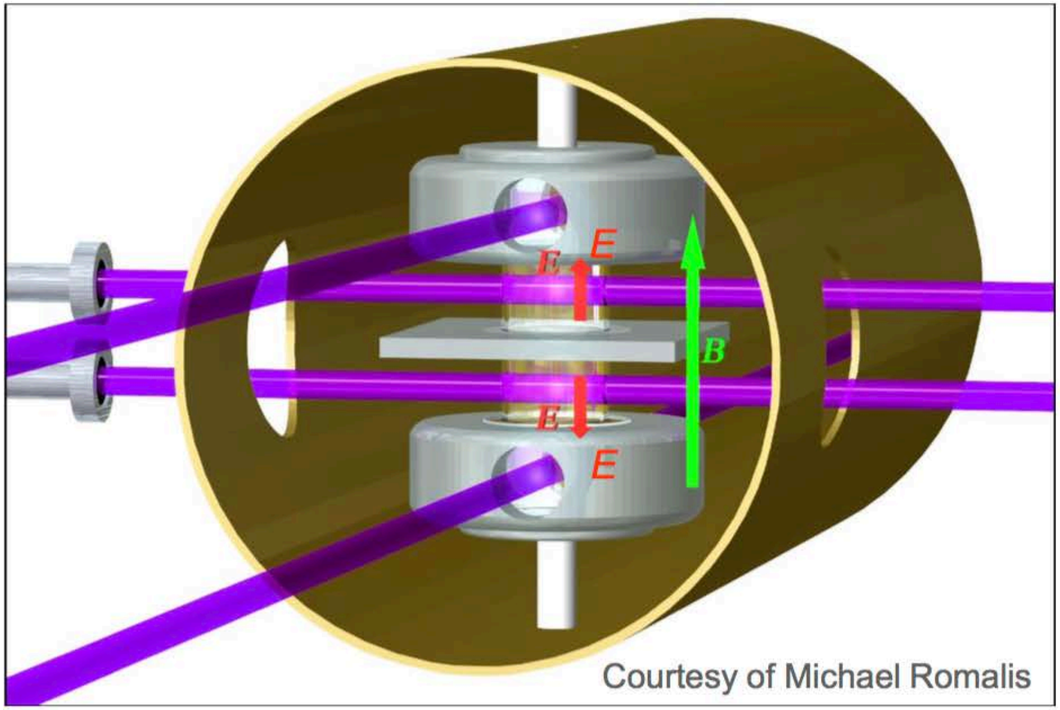
Electric Dipole Moment (EDM) Violates Both P and T



Sector	Exp Limit (e-cm)	Location	Method	Standard Model
Electron	9×10^{-29}	Harvard (ACME)	ThO molecules in a beam	10^{-38}
Neutron	3×10^{-26}	ILL	UCN in a bottle	10^{-31}
Nuclear	7×10^{-30}	U. Washington	^{199}Hg atoms in a cell	10^{-33}

The Seattle EDM Measurement

^{199}Hg stable, high Z, J = 0, I = ½, high vapor pressure



Courtesy of Michael Romalis

$$f_+ = \frac{2\mu B + 2dE}{h} \approx 15 \text{ Hz}$$

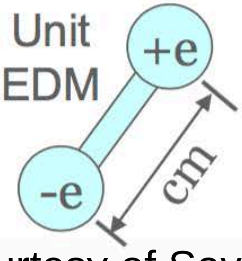
$$f_- = \frac{2\mu B - 2dE}{h} \approx 15 \text{ Hz}$$

$$|f_+ - f_-| < 0.2 \text{ nHz}$$

The best limit on atomic EDM

EDM (^{199}Hg) < 7.4 x 10^{-30} e-cm

Graner *et al.*, Phys Rev Lett (2016)

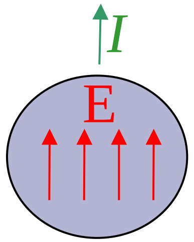


Courtesy of Savard

Atomic EDM proportional to Shiff moment

- No atomic EDM due to EDM of the nucleus – Schiff' s Theorem
  - Electrons screen applied electric field

- *d*(Hg) is due to finite nuclear size
  - nuclear Schiff moment *S* – Difference between mean square radius of the charge distribution and electric dipole moment distribution



$$S = \frac{2\pi}{5}\int dx^3 \rho(x)\left(x^2 x - \frac{5}{3}\langle r^2 \rangle_{ch}\, x \right)$$

Recent work by Haxton, Flambaum on form of Schiff moment operator

- Schiff moment induces parity mixing of atomic states, giving an atomic EDM:

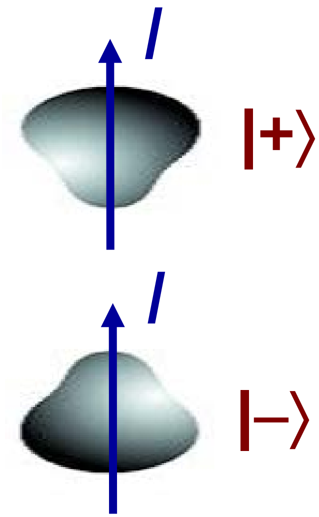
$$d_a = R_A\, S$$

- R_A - from atomic wavefunction calculations, uncertainty 50%

B. P. Das *et al*,
V. Dzuba *et al*.

Courtesy of M. Romalis

Octupole Enhancement



$$\Delta E \qquad \Psi^+ = (|+\rangle + |-\rangle)/\sqrt{2} \qquad \Psi^- = (|+\rangle - |-\rangle)/\sqrt{2}$$

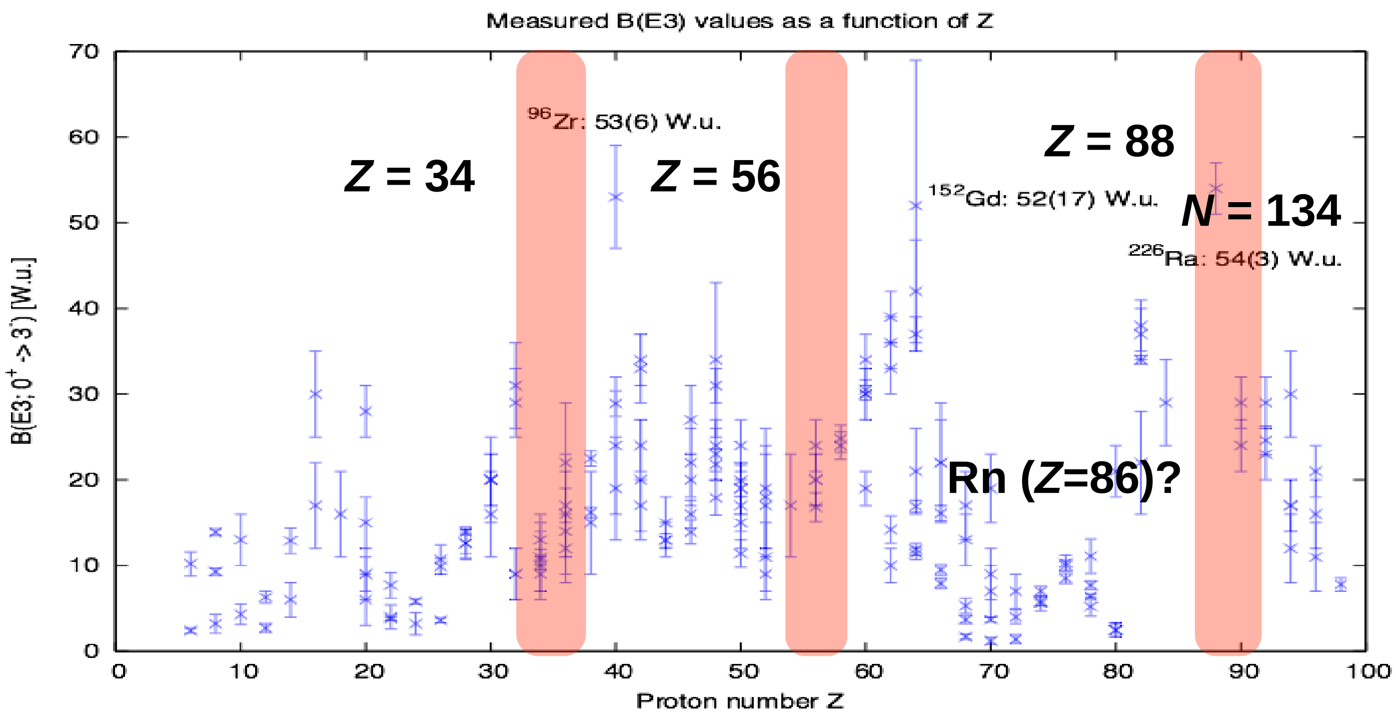
$$\cancel{P}, \cancel{T} \Rightarrow$$

$$\Psi^+ = ((1+\alpha)|+\rangle + (1-\alpha)|-\rangle)/\sqrt{2}$$

$$\Psi^- = ((1-\alpha)|+\rangle + (1+\alpha)|-\rangle)/\sqrt{2}$$

$$\alpha = \frac{\langle \Psi^- | V^{PT} | \Psi^+ \rangle}{\Delta E} \sim \frac{\beta_3 A^{-1/3}}{\Delta E}$$

$S_{intr} \sim eZA\beta_2\beta_3$ $\qquad$ $S_{lab} \sim e\, Z\, A^{2/3}\, \beta_2\, \beta_3^{\,2}/\Delta E$ $\qquad$ $\beta_2, \beta_3 \sim 0.1$



Octupole enhanced atomic EDM moment

V Spevak, N Auerbach, and VV Flambaum
PR C **56** (1997) 1357

related to Q_3

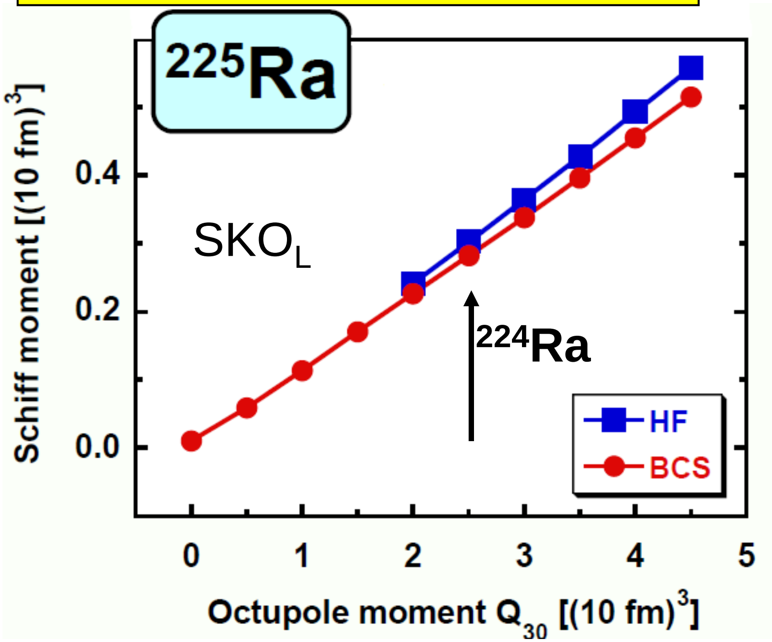
P,T-violating n-n interaction

Schiff moment:

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

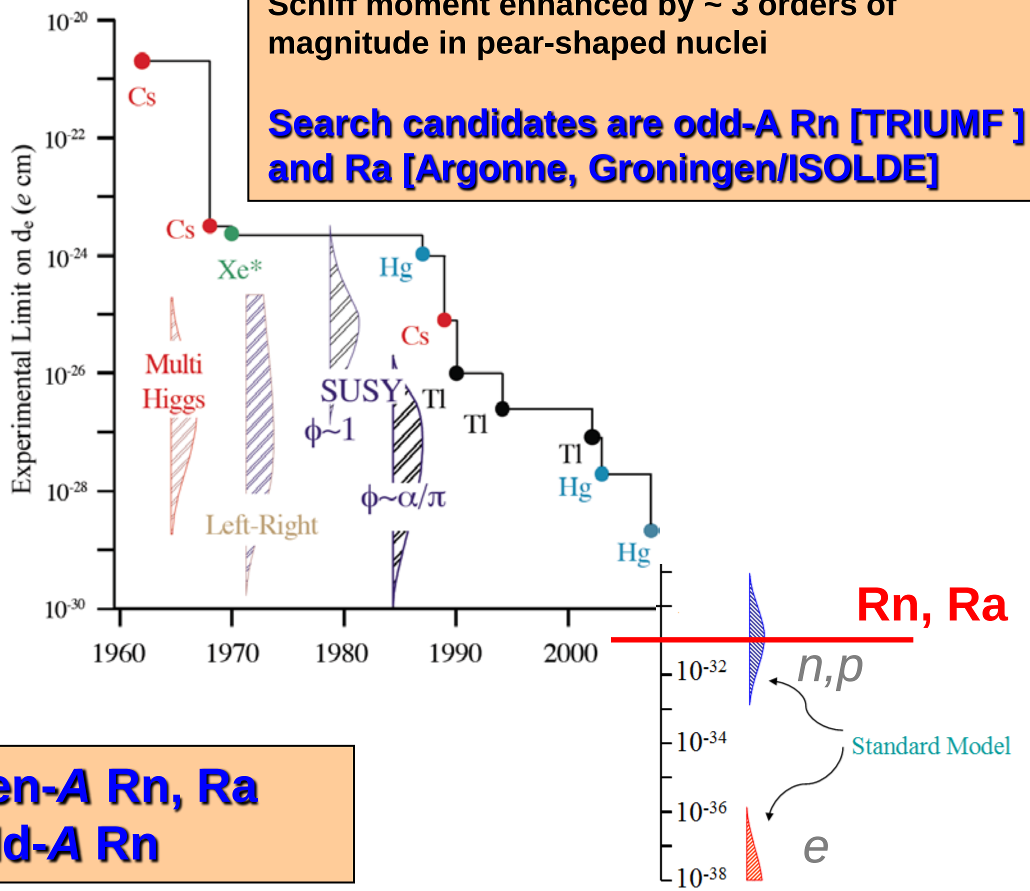
energy splitting of parity doublet

J Dobaczewski (Trento, 2010)



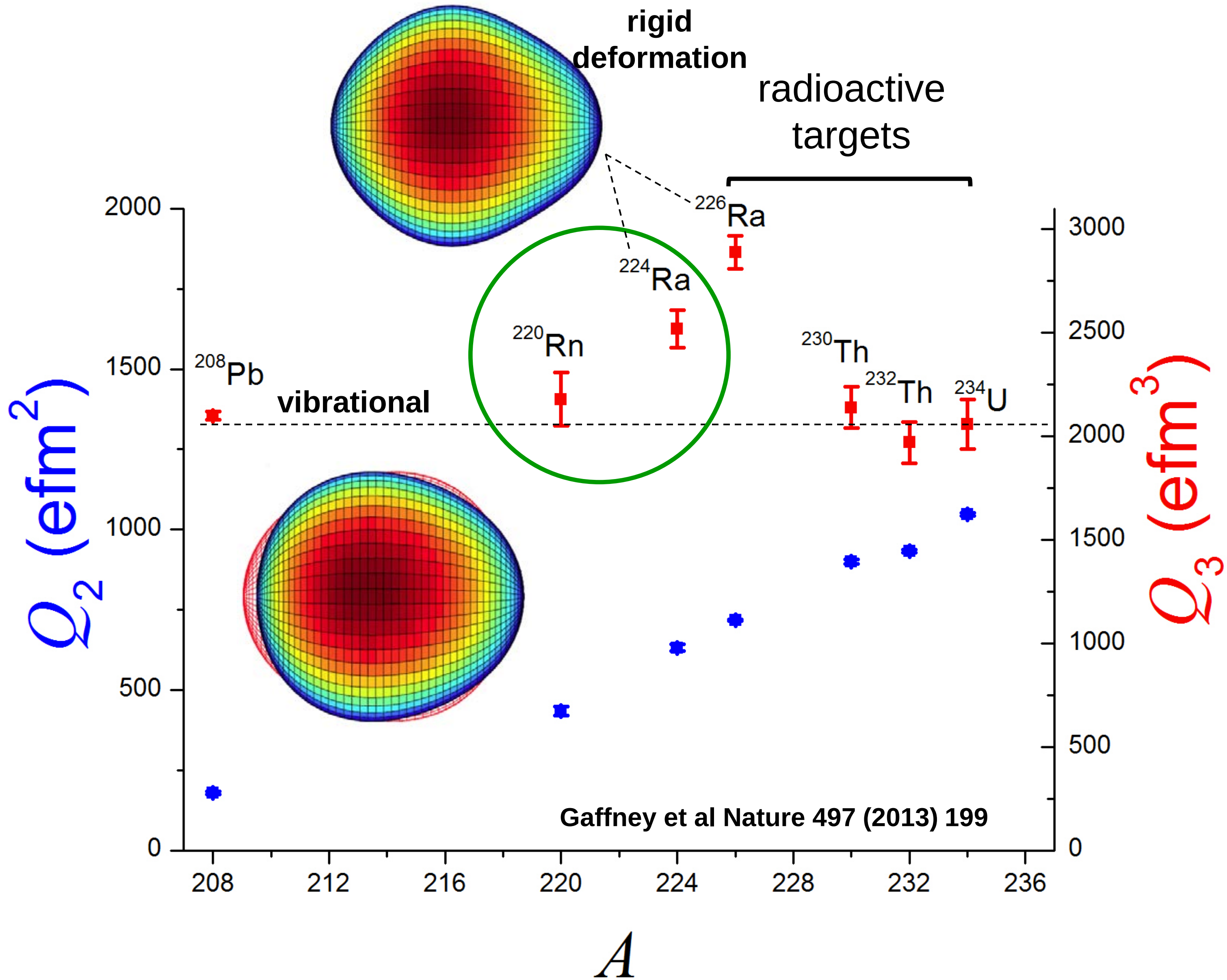
Schiff moment enhanced by ~ 3 orders of magnitude in pear-shaped nuclei

Search candidates are odd-A Rn [TRIUMF] and Ra [Argonne, Groningen/ISOLDE]

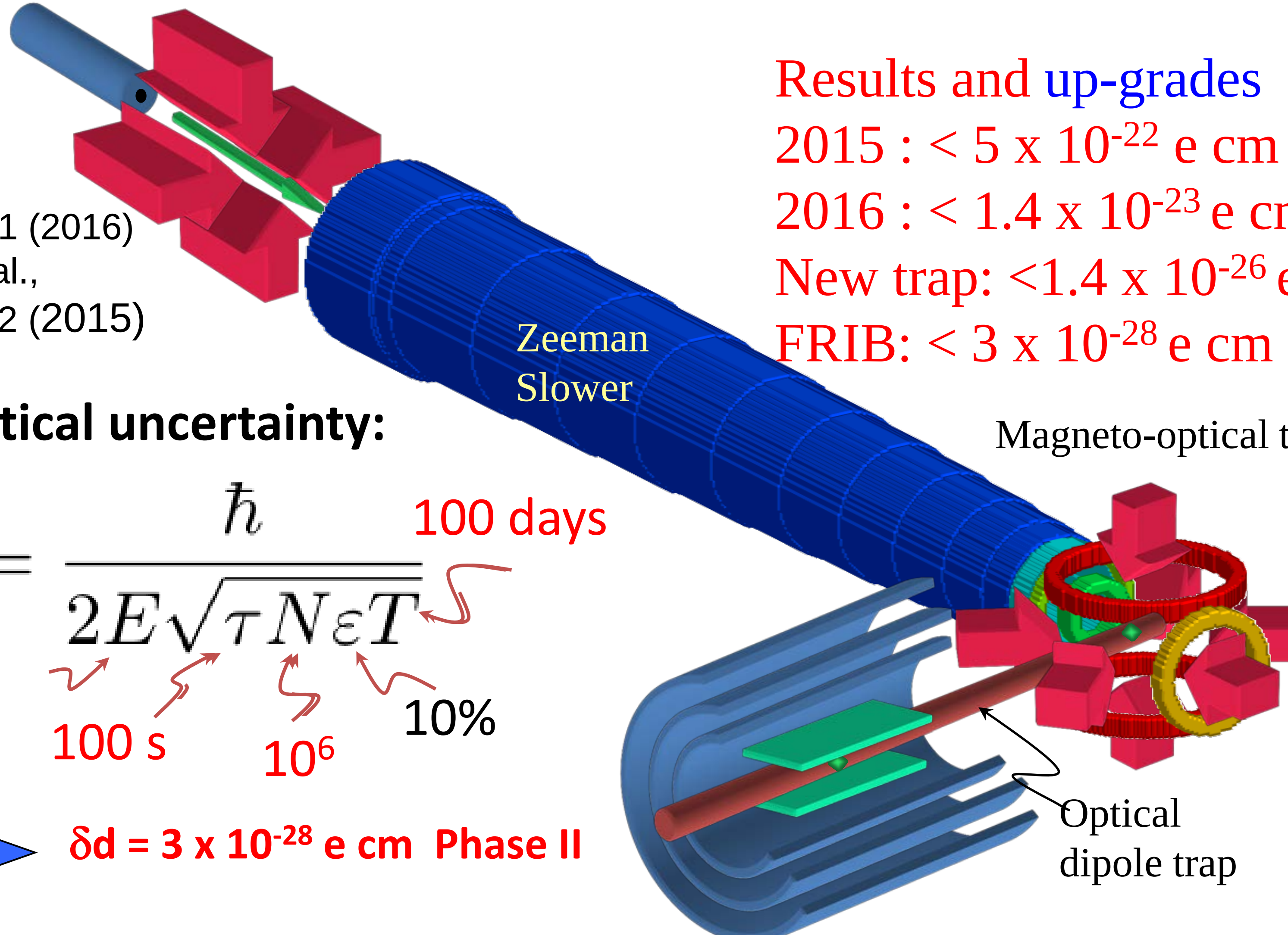


Measure: Q_3 in even-A Rn, Ra
ΔE in odd-A Rn

Signature of pear-shape: B(E3)



EDM measurement with ^{225}Ra



Results and up-grades
2015 : < 5 x 10^{-22} e cm
2016 : < 1.4 x 10^{-23} e cm
New trap: <1.4 x 10^{-26} e cm
FRIB: < 3 x 10^{-28} e cm

M. Bishof et al
PRC 94, 025501 (2016)
R.H. Parker et al.,
PRL 114 233002 (2015)

Statistical uncertainty:

$$\delta d = \frac{\hbar}{2E\sqrt{\tau N \varepsilon T}}$$

100 days

100 kV/cm

100 s

10^6

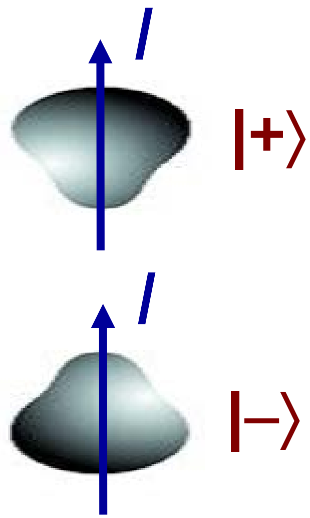
10%

δd = 3 x 10^{-28} e cm Phase II

- ^{225}Ra / ^{199}Hg enhance factor ~ 10^2
- δd(^{199}Hg) = 1.5 x 10^{-29} e cm

Courtesy of Savard

Octupole Enhancement



$$\Delta E \quad \Psi^+ = (|+\rangle + |-\rangle)/\sqrt{2}$$

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

$$\xrightarrow{\cancel{P},\ \cancel{T}}$$

$$\Psi^+ = ((1+\alpha)|+\rangle + (1-\alpha)|-\rangle)/\sqrt{2}$$

$$\Psi^- = ((1-\alpha)|+\rangle + (1+\alpha)|-\rangle)/\sqrt{2}$$

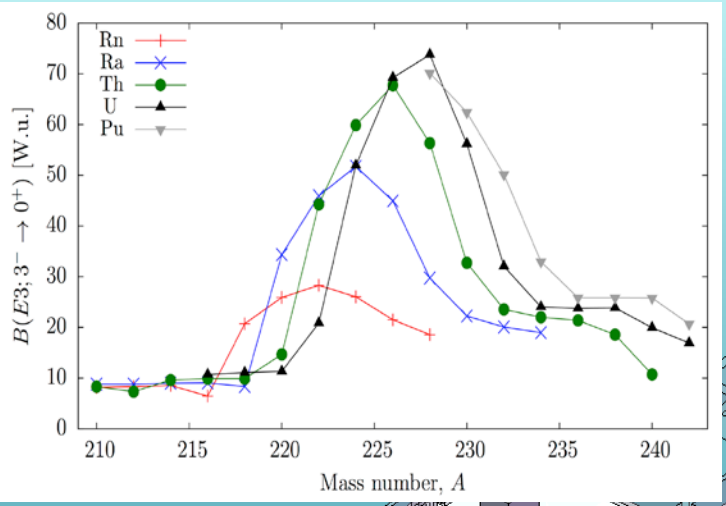
$$\alpha = \frac{\langle \Psi^- | V^{PT} | \Psi^+ \rangle}{\Delta E} \sim \frac{\beta_3 A^{-1/3}}{\Delta E}$$

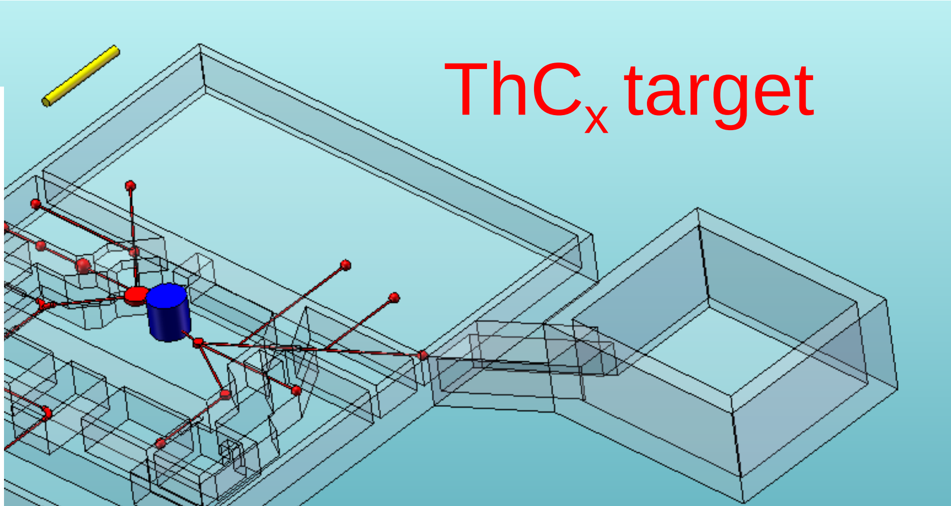
$S_{intr} \sim eZA\beta_2\beta_3$ $\quad$ $S_{lab} \sim e\,Z\,A^{2/3}\,\beta_2\,\beta_3^{\,2}/\Delta E$ $\quad$ $\beta_2,\ \beta_3 \sim 0.1$

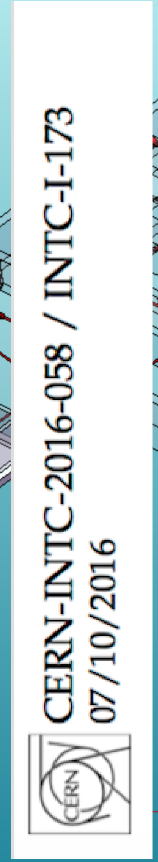
Haxton & Henley; Auerbach, Flambaum & Spevak; Hayes, Friar & Engel; Dobaczewski & Engel

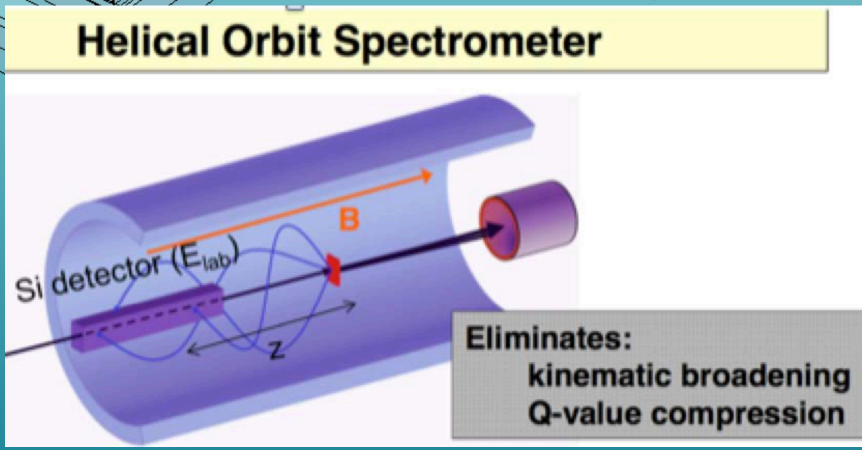
	^{223}Rn	^{223}Ra	^{225}Ra	^{223}Fr	^{225}Ac	^{229}Pa	^{199}Hg	^{129}Xe
$t_{1/2}$	23.2 m	11.4 d	14.9 d	22 m	10.0 d	1.5 d		
I	7/2	3/2	1/2	3/2	3/2	5/2	1/2	1/2
Δe_{th} (keV)	37	170	47	75	49	5		
ΔE_{exp} (keV)	--	50.2	55.2	160.5	40.1	0.22		
10^5 S ($e$fm^3)	1000	400	300	500	900	12000	-1.4	1.75
10^{28} d_A (e cm)	**2000**	**2700**	**2100**	**2800**			-5.6	0.8

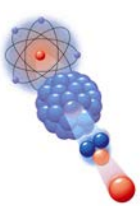
^{229}Pa production at SPES?



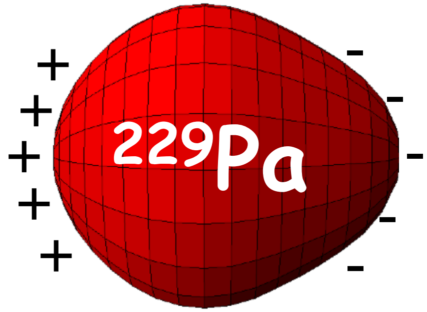








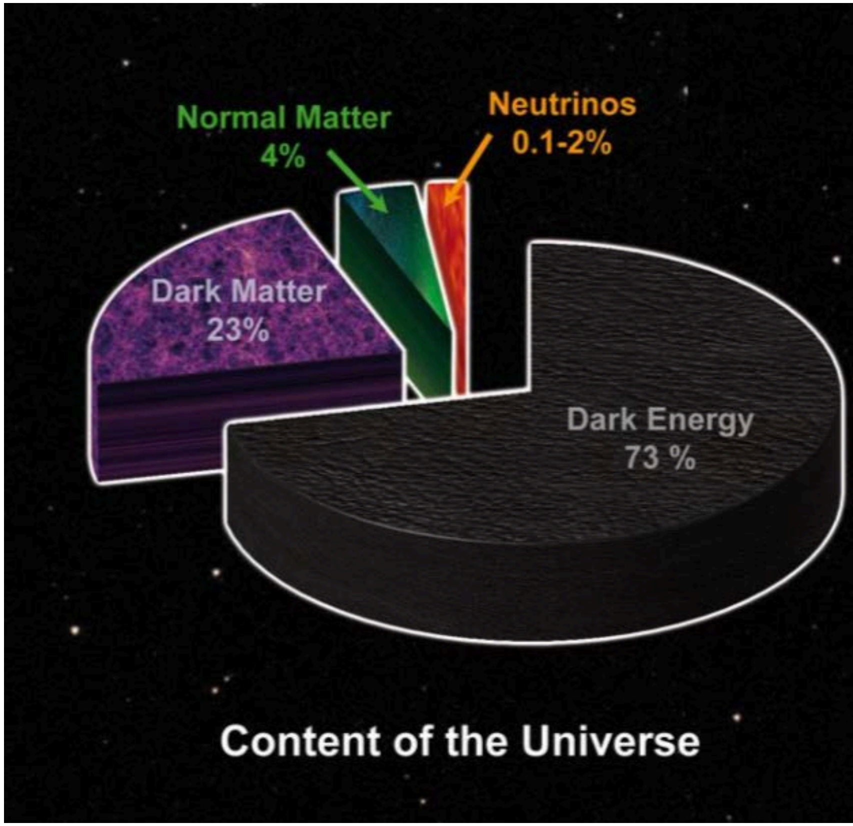
HIE-ISOLDE for ^{223}Fr ~ 2x10^6 s^{-1}
SPES for ^{229}Pa by ^{232}Th(p,4n)
I ≈ 10^{16} atoms in 10 days
SPIRAL2 (Linag) for ^{229}Pa by ^{232}Th(p,4n)

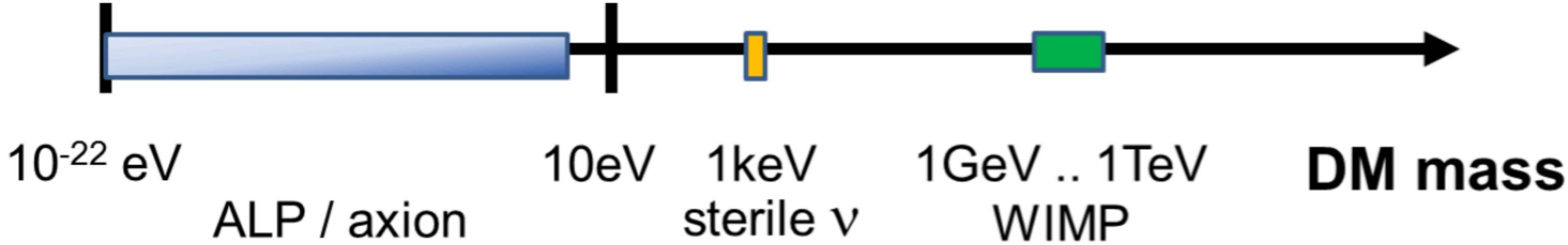


30000 more sensitive then ^{199}Hg

EDM and Axions or Axions like particles

- The smallness of θ_{QCD} can be explained invoking axions
- Axions and ALPs are viable candidates for Dark Matter
- The neutron EDM is sensitive to axions and ALPs, some of which produce oscillating EDM values



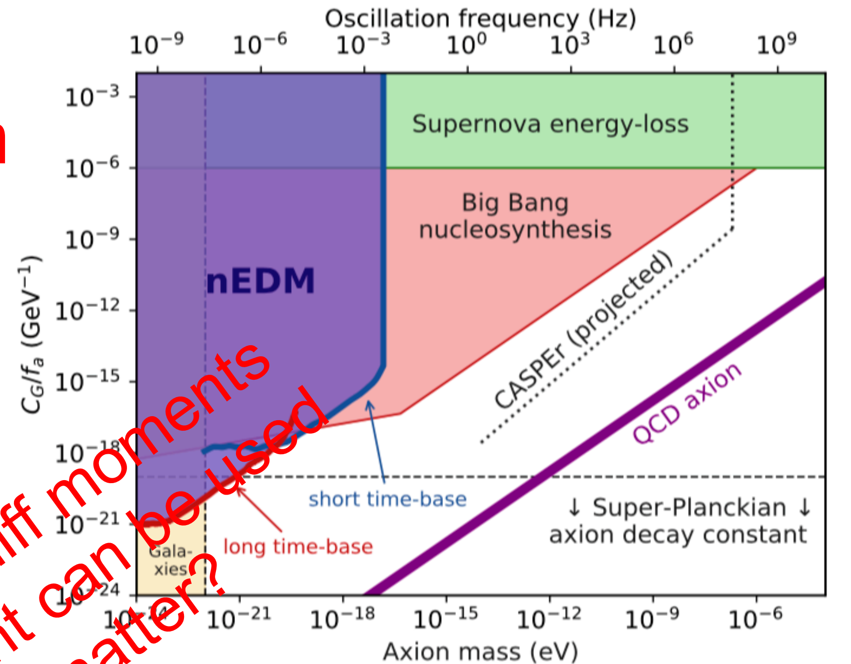


G. de Angelis 2017

EDM limiting axions

Axion-Gluon and Axion-Nucleon

Search for axion-like dark matter through nuclear spin precession in electric and magnetic fields C. Abel et al. 2017 arXiv:1708.06367v1 (2017)

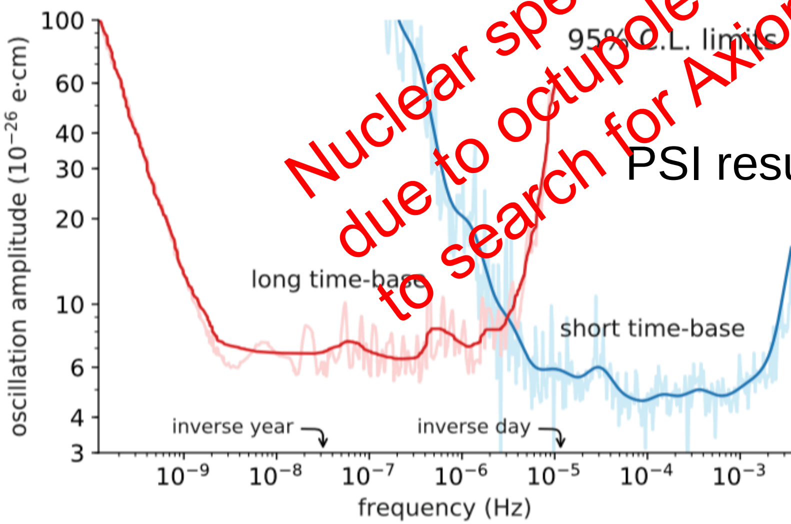


$$\mathcal{L}_{\rm int} = \frac{C_G}{f_a}\frac{g^2}{32\pi^2} a G^b_{\mu\nu}\tilde{G}^{b\mu\nu} - \frac{C_N}{2f_a}\partial_\mu a\ \bar{N}\gamma^\mu\gamma^5 N$$

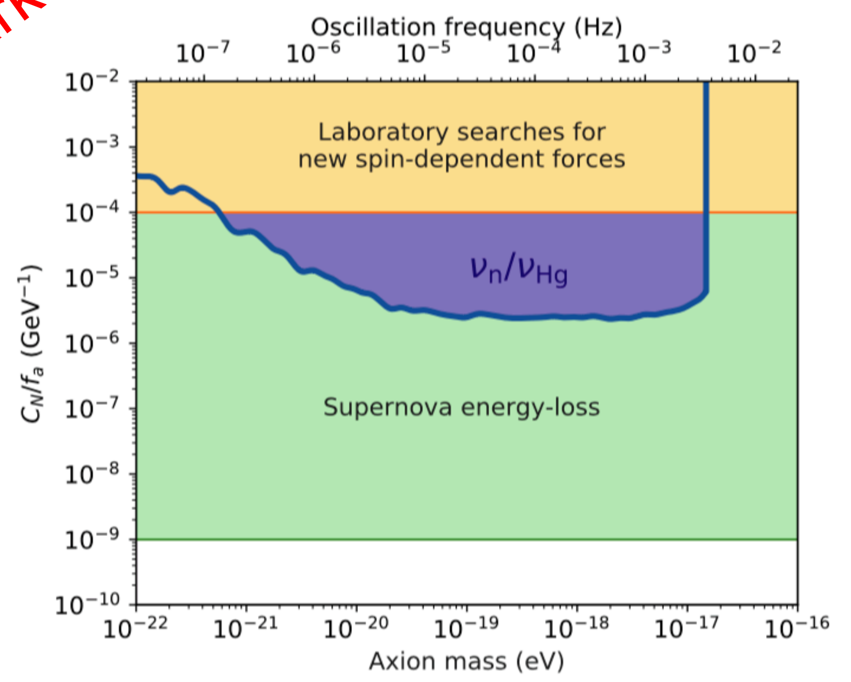
$$d_{\rm n}(t) \approx +2.4\times 10^{-16}\ \frac{C_G a_0}{f_a}\cos(m_a t)\ e\cdot{\rm cm}$$

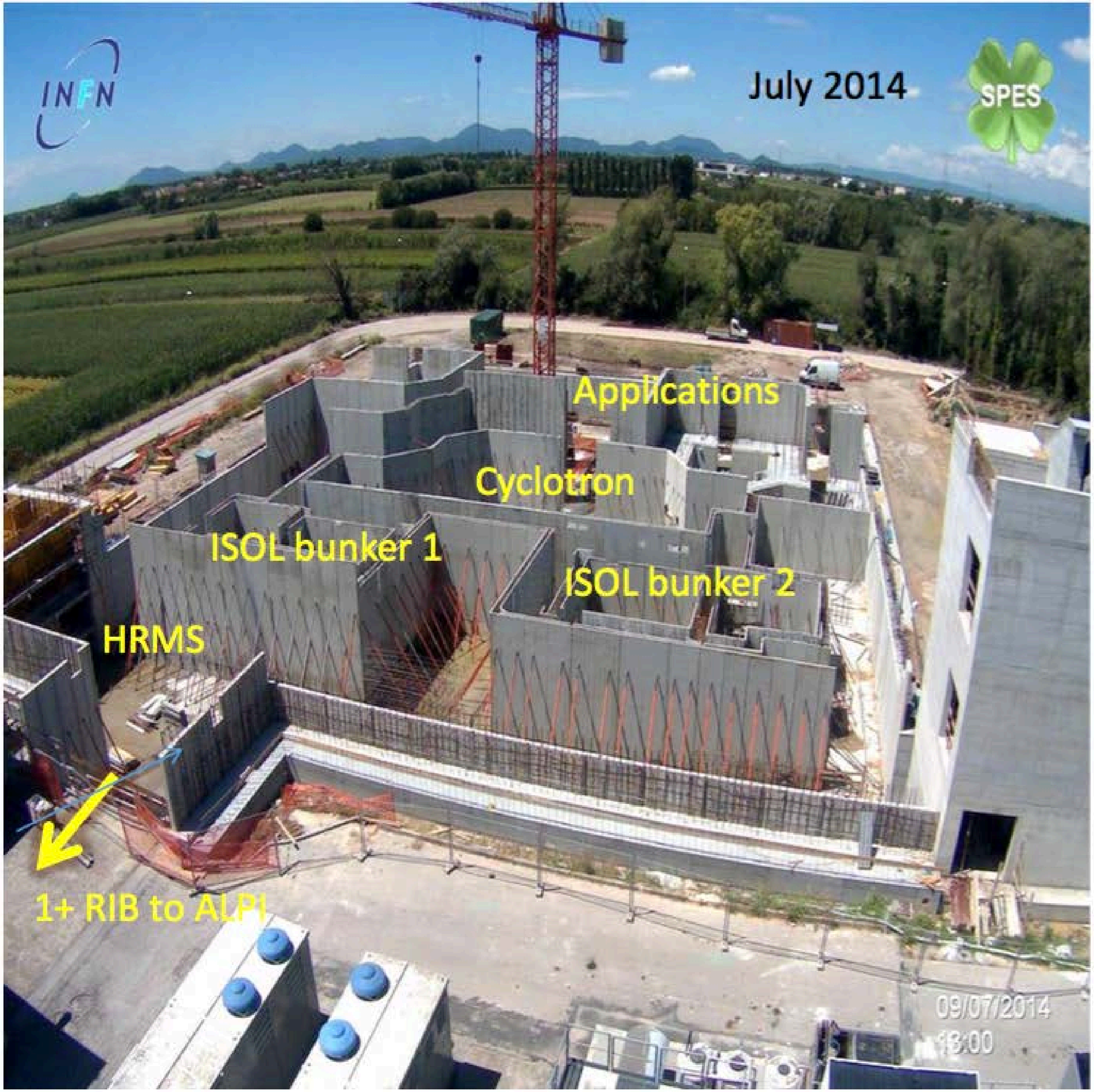
$$d_{\rm Hg}(t) \approx +1.3\times 10^{-19}\ \frac{C_G a_0}{f_a}\cos(m_a t)\ e\cdot{\rm cm}$$

Nuclear species with large schiff moments due to octupole enhancement can be used to search for Axion-like Dark matter?



PSI results





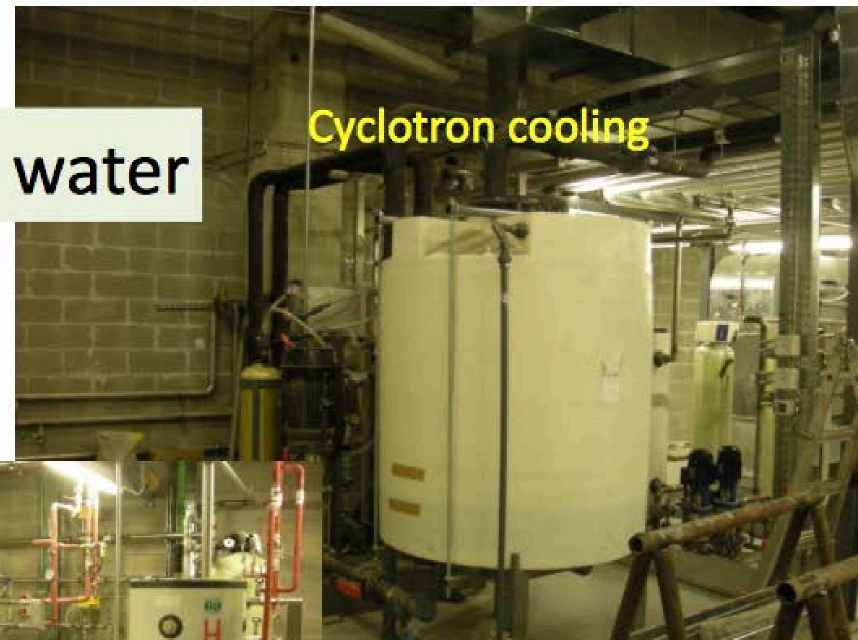
SPES building

50x60 m^2
-3 to +11 m height
24.000 m^3 of concrete
1.150 tons iron

3-4 m shielding wall thick

The SPES building 2016

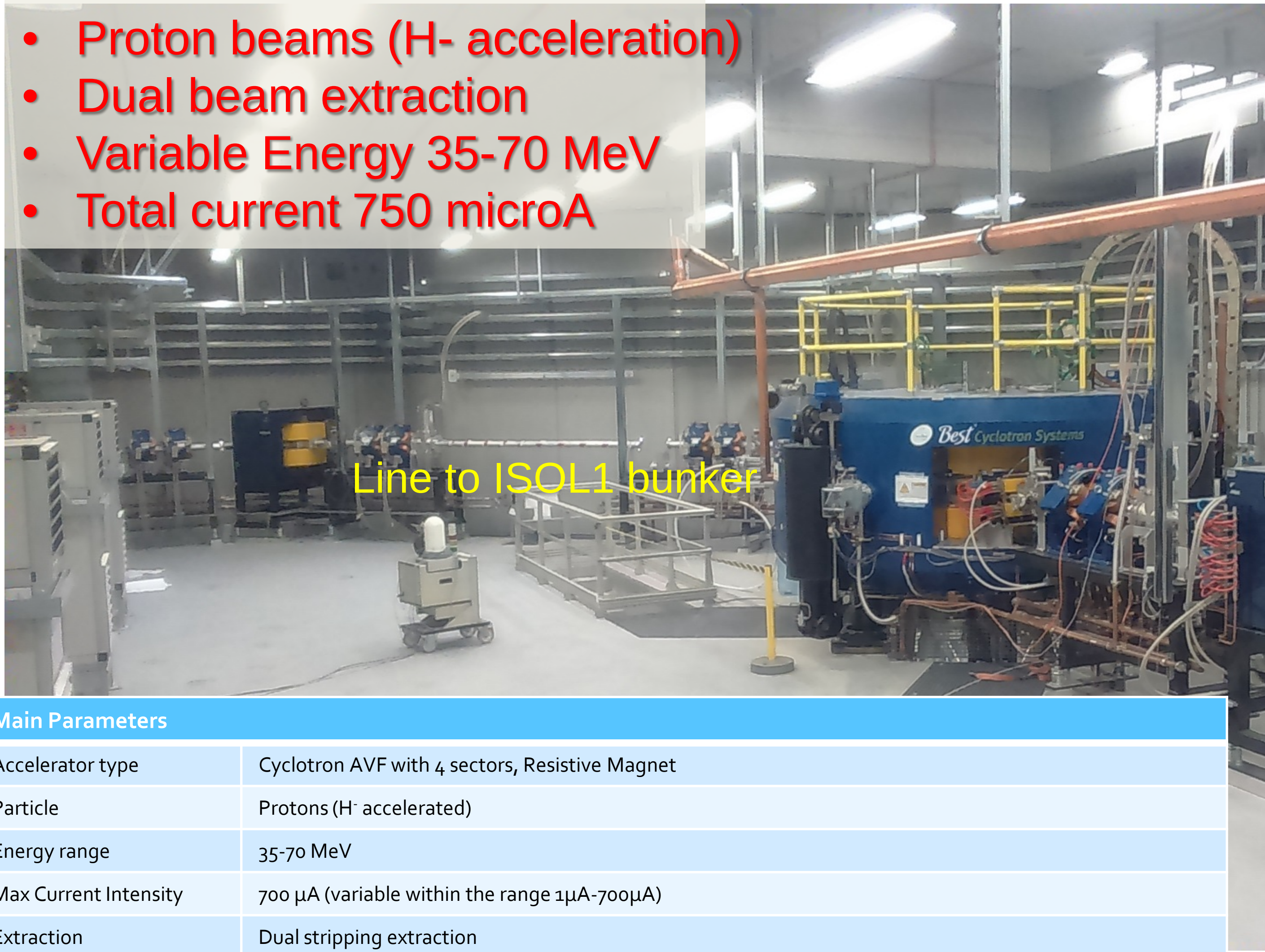
PLANTS: air and water



Moduls for cooling water

Cyclotron and beam lines

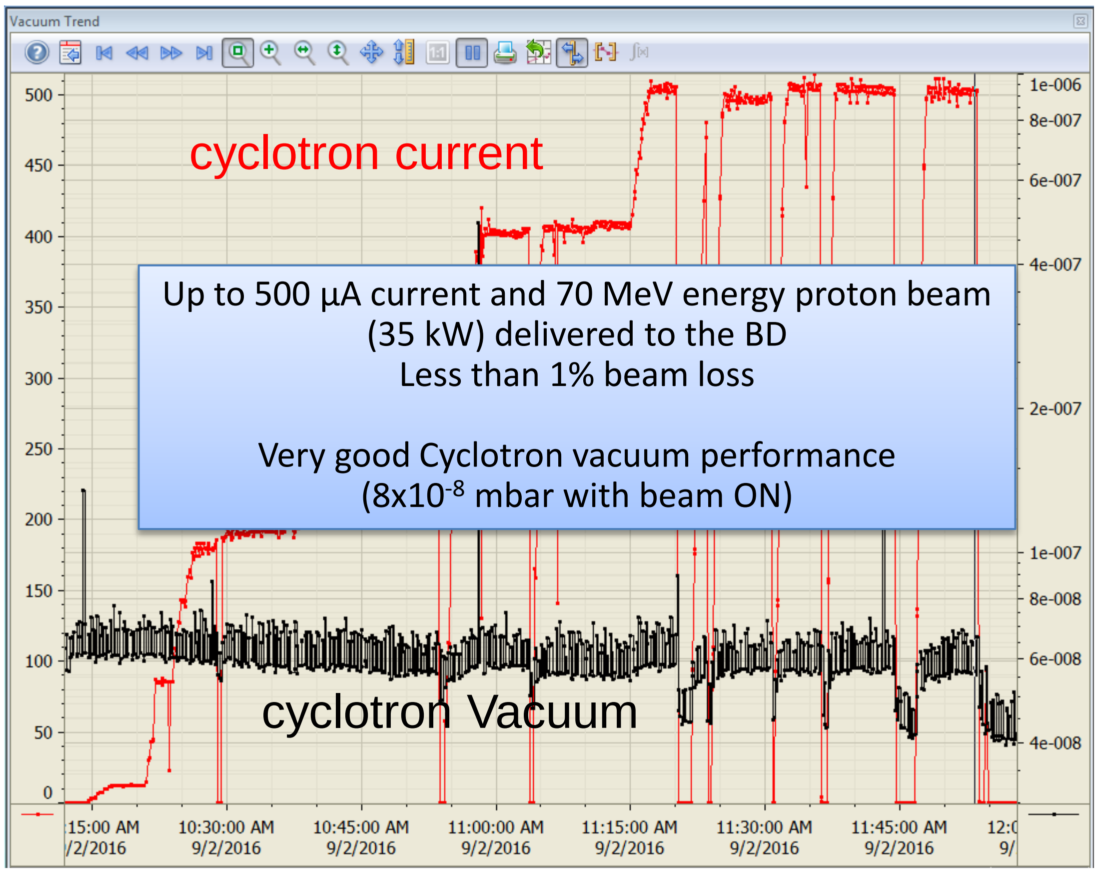
- Proton beams (H- acceleration)
- Dual beam extraction
- Variable Energy 35-70 MeV
- Total current 750 microA



Main Parameters	
Accelerator type	Cyclotron AVF with 4 sectors, Resistive Magnet
Particle	Protons (H^- accelerated)
Energy range	35-70 MeV
Max Current Intensity	700 μA (variable within the range 1μA-700μA)
Extraction	Dual stripping extraction
Max Magnetic Field	1.6 T (Bo = 1 T)
RF System	nr. 2 delta cavities; harmonic mode=4; f_{RF} =56 MHz; 70 kV peak voltage; 50 kW RF power (2 RF amplifiers)
Ion Source	Multi-cusp volume H^- source; I_{ext} =8mA; V_{ext}=40 kV; axial injection
Dimensions	Φ=4.5 m, h=2 m, W=190 tons

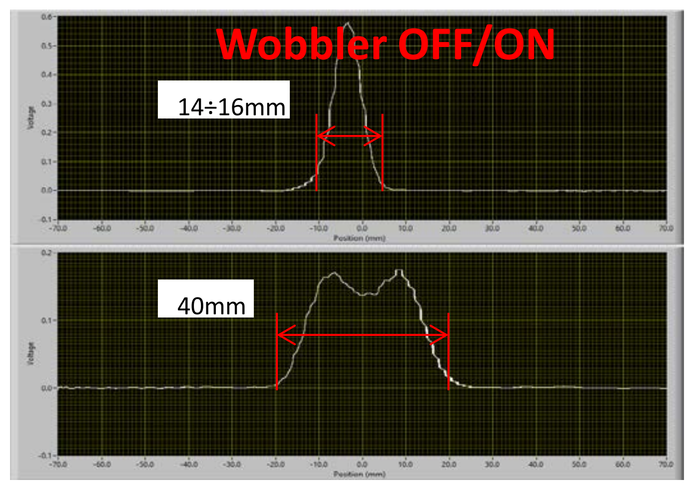
Cyclotron commissioning

- May 30th 2016 → dual extraction 70 MeV beam – 3 μA
- Sept 9th 2016 → acceleration 70 MeV beam – 500 μA
- Oct Nov 2016 → preliminary endurance test 250 μA, 40 MeV
- End Nov 2016 → source HV transformer brakes before to complete Site Acceptance Test
- June - July 2017 → endurance test completed
- September 2017 → cyclotron accepted

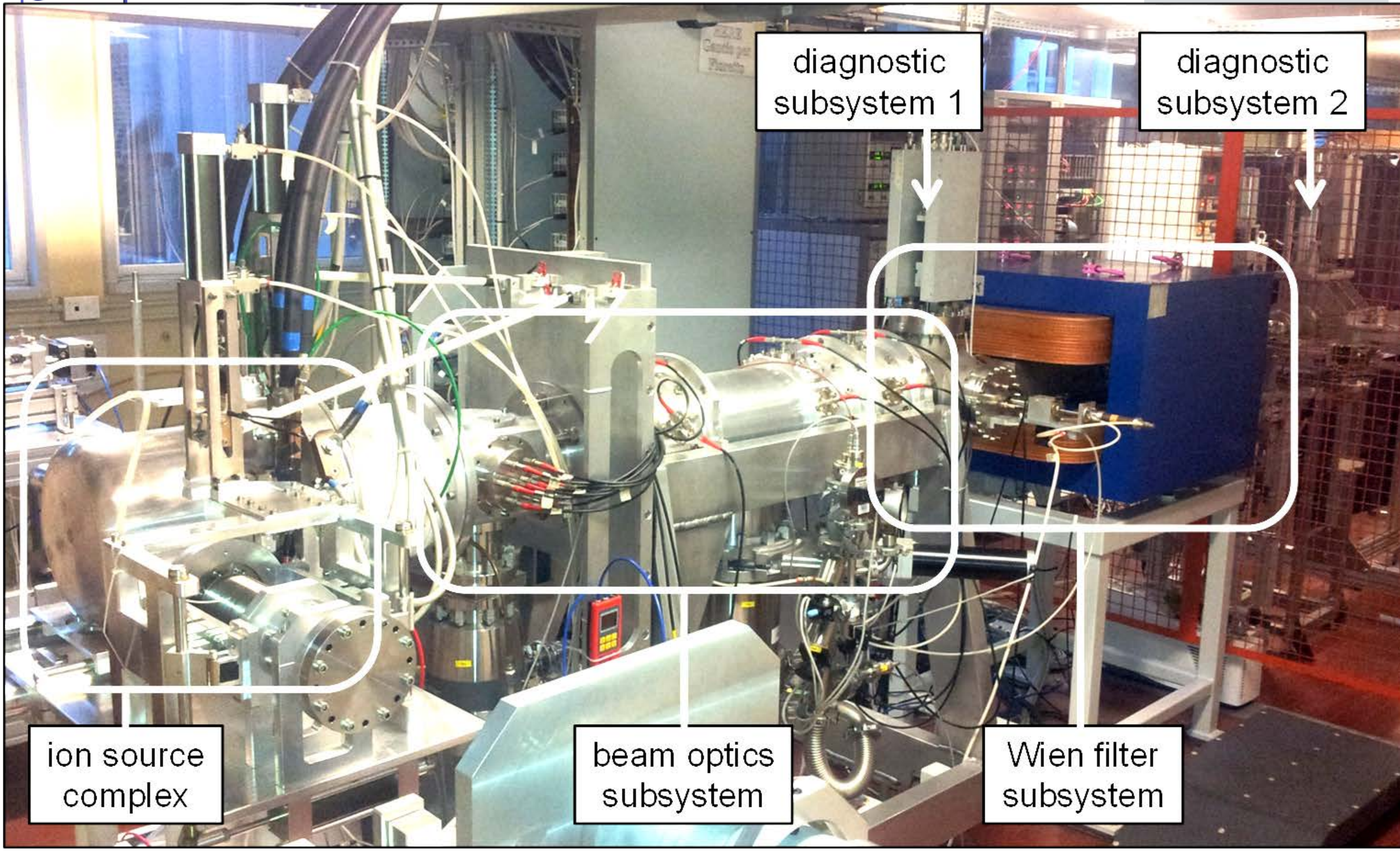


Up to 500 μA current and 70 MeV energy proton beam
(35 kW) delivered to the BD
Less than 1% beam loss

Very good Cyclotron vacuum performance
($8x10^{-8}$ mbar with beam ON)

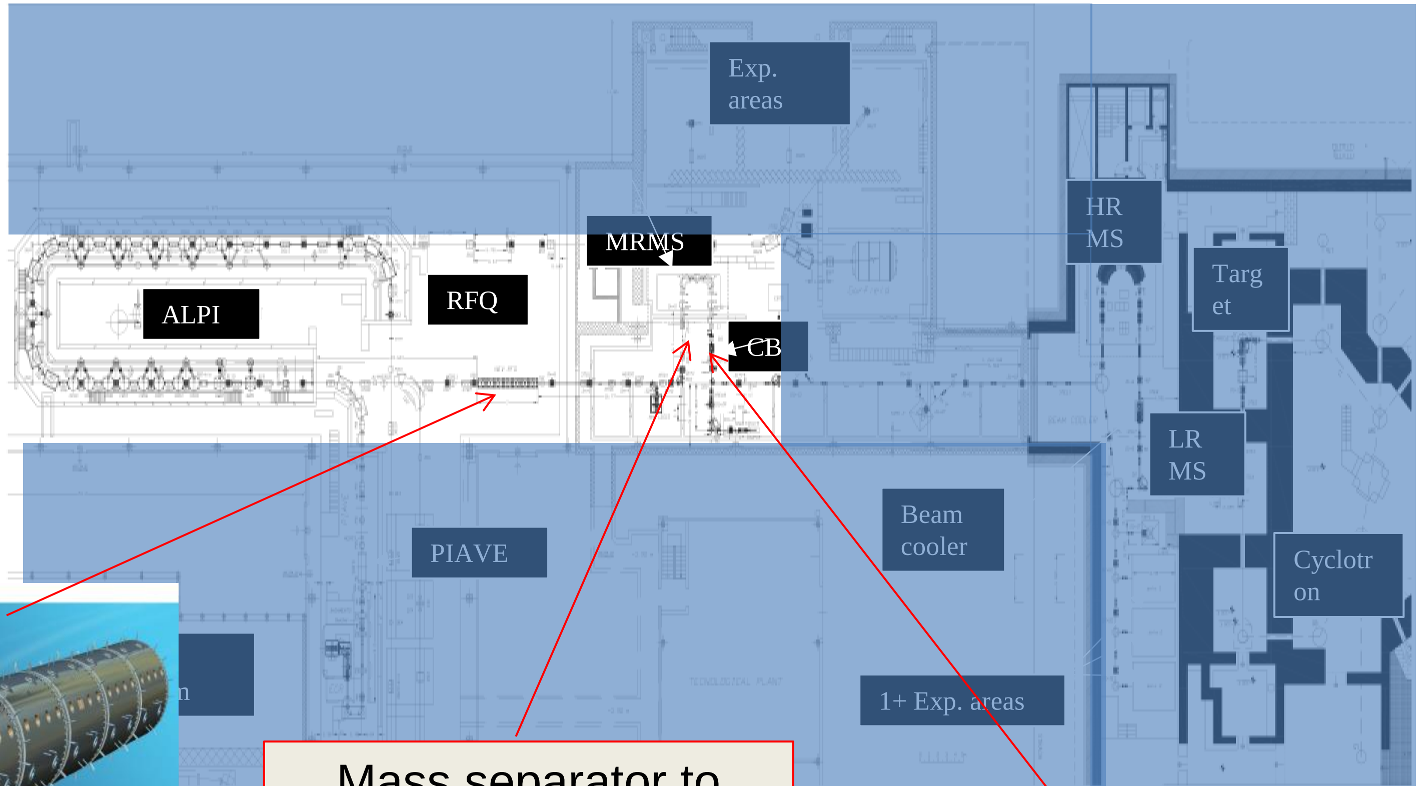


SPES ISOL system

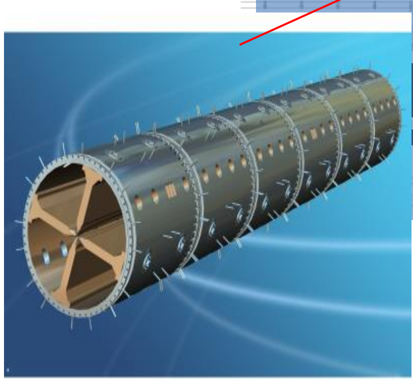


System under operation for source commissioning. (Following ISOLDE Design)
Final version updated for radiation hardness and maintenance is under construction.

n+ Beam transport and reacceleration

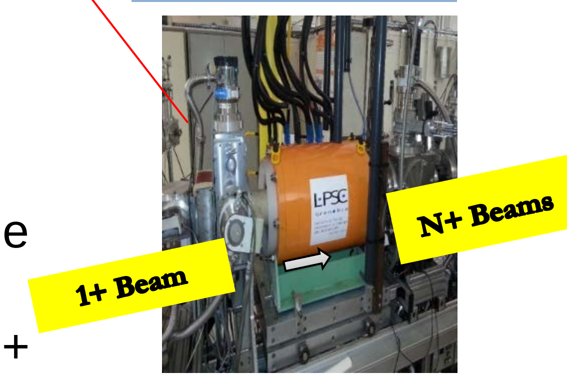


Mass separator to clean the beam from CB contaminants

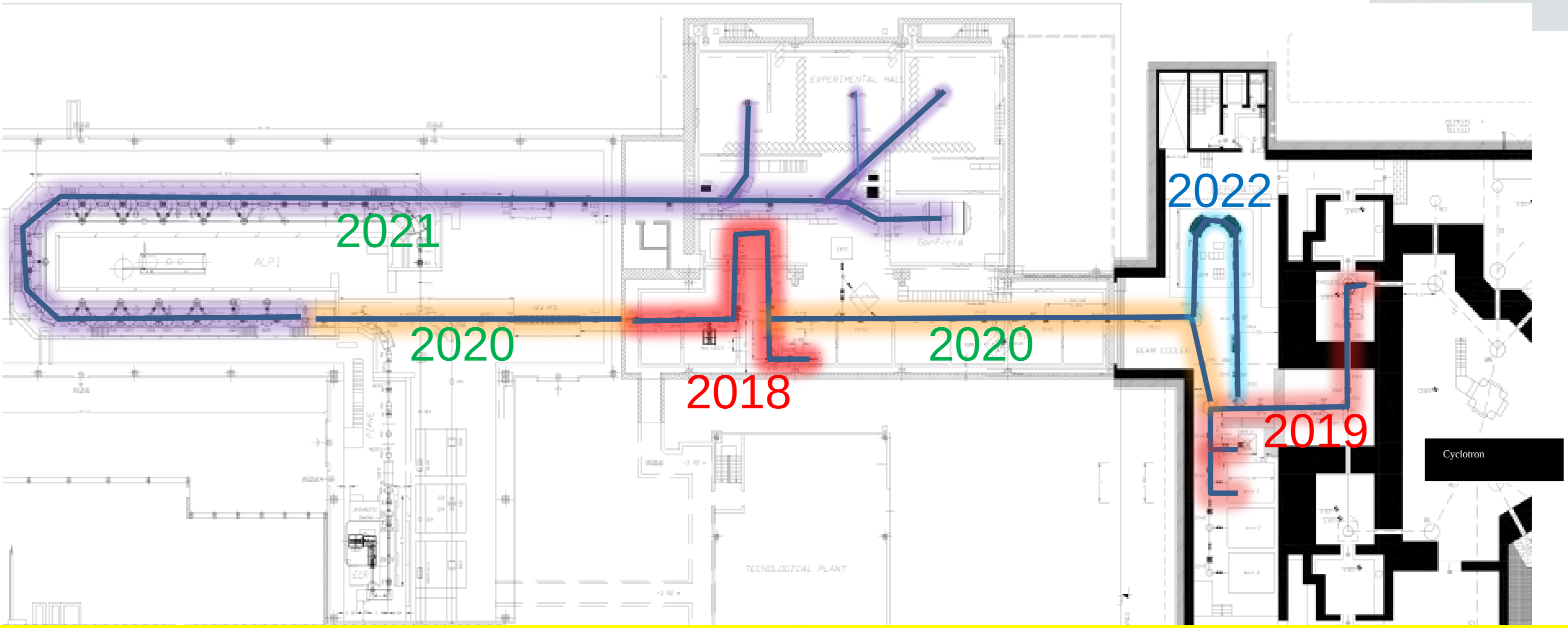


Pre-accelerator
RFQ (700 keV/n)

ECR_Charge Breeder
from 1+ to n+



Installation phases



1. installation of Charge Breeder and related mass separator: ready in 2018

2. installation of ISOL and 1+ beam line up to the tape station: ready in 2019

   Experiments with non-reaccelerated beams

3. Installation of RFQ and 1+ beam line up to Charge Breeder: ready 2020

4. Reaccelerated beams: ready in 2021

✓ High resolution mass selection: ready in 2022

Nuclei Matter

SPES RIB facility on the way (low energy beams in 2019)

Our current understanding of nuclei has benefited from technological improvements in experimental equipment and accelerators that have expanded the range of available isotopes and allowed experiments to be performed with only a small number of atoms. Concurrent advances in theoretical approaches and computational science have led to a more detailed understanding and pointed toward which nuclei and what phenomena to study.

Profound intersections

- Nuclear Structure
- Astrophysics
- Fundamental Symmetries

How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?

- Energy (fission, reactions, decays…)
- Security (stewardship, forensics, detection…)
- Isotopes (medicine, industry, defense, applied research…)

Thanks for Attention