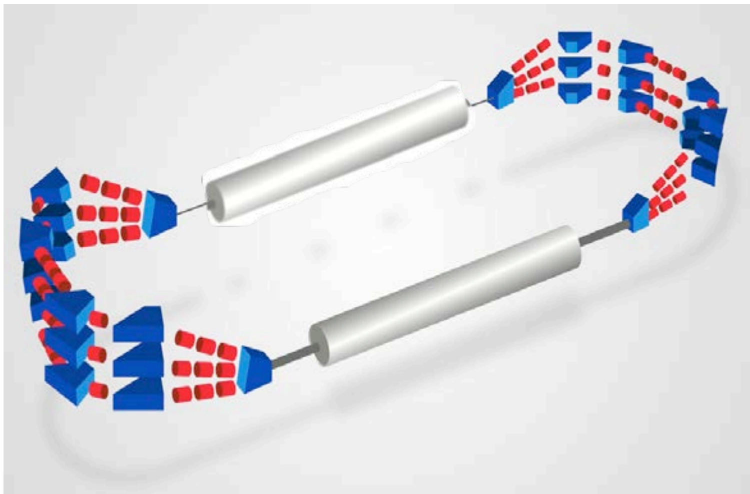
on possible nuclear-physics avenues offered by a Orsay-hosted 450-MeV PERLE version

David Verney, IPN Orsay

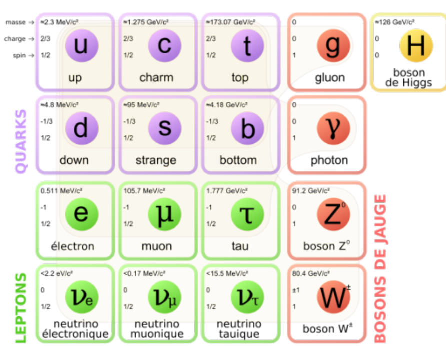


- Why seize the opportunity of the (possible) construction of an ERL prototype in Orsay to perform e-scattering off RIBs ?
    - The big picture
    - more detailed (realistic, sustainable) physics case :
      fission fragments ISOL-beams at Orsay (ALTO)
- tentative sketch of the project based on:
    - extrapolation from already available RIB from ALTO (FF: medium mass n-rich nuclei)
    - The aimed ERL machine

An unconventional (and somewhat provocative) introduction :
The untold legend of the human quest for ultimate components of matter

The outermost Aristotle's sphere
"The final cause, then, produces motion by being loved, but all other things move by being moved"
Aristotle Metaphysics 1072b4

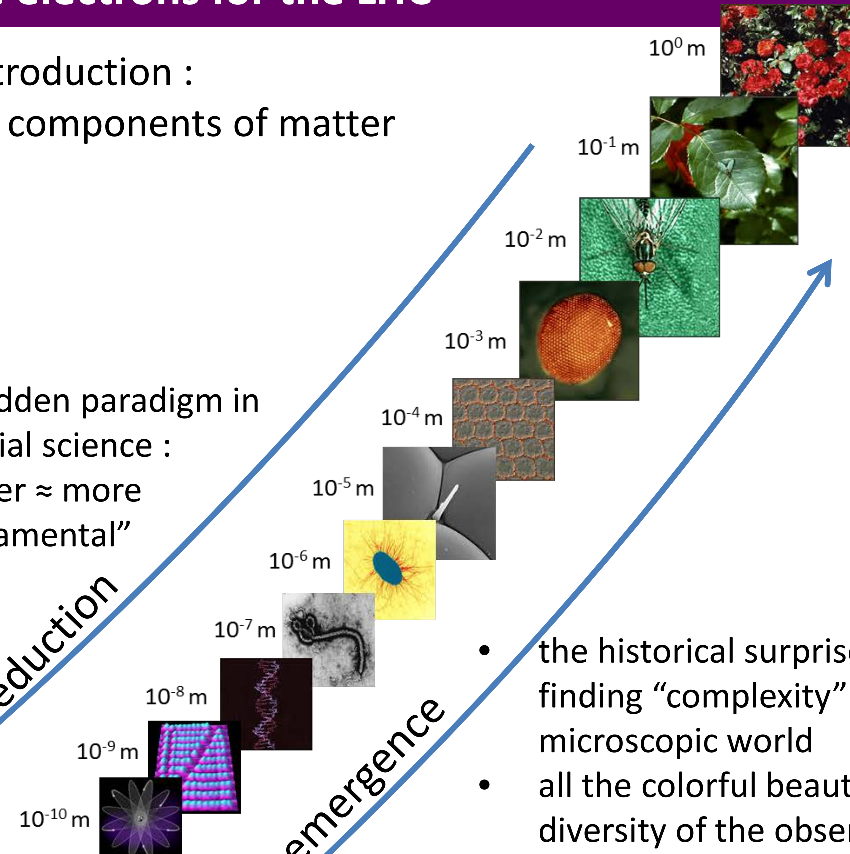
SU(3)×SU(2)×U(1)

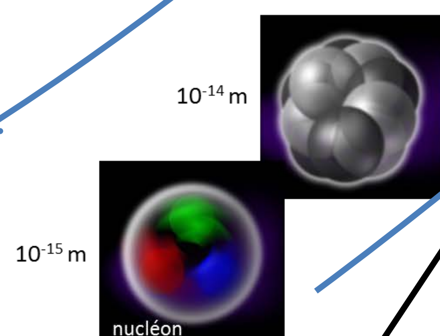


the hidden paradigm in material science :
smaller ≈ more "fundamental"

reduction

emergence





- the historical surprise of finding "complexity" in the microscopic world
- all the colorful beauty and diversity of the observable world is **not** due to elementary objects but to **medium effects**

some foolish people remained stuck at this reputed unessential level of organization of matter
why ?

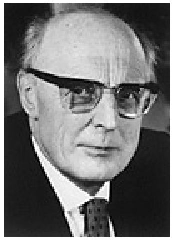
emergence
(presently addressed through effective theories)

The "single-particle" concept

Nobel price 1963

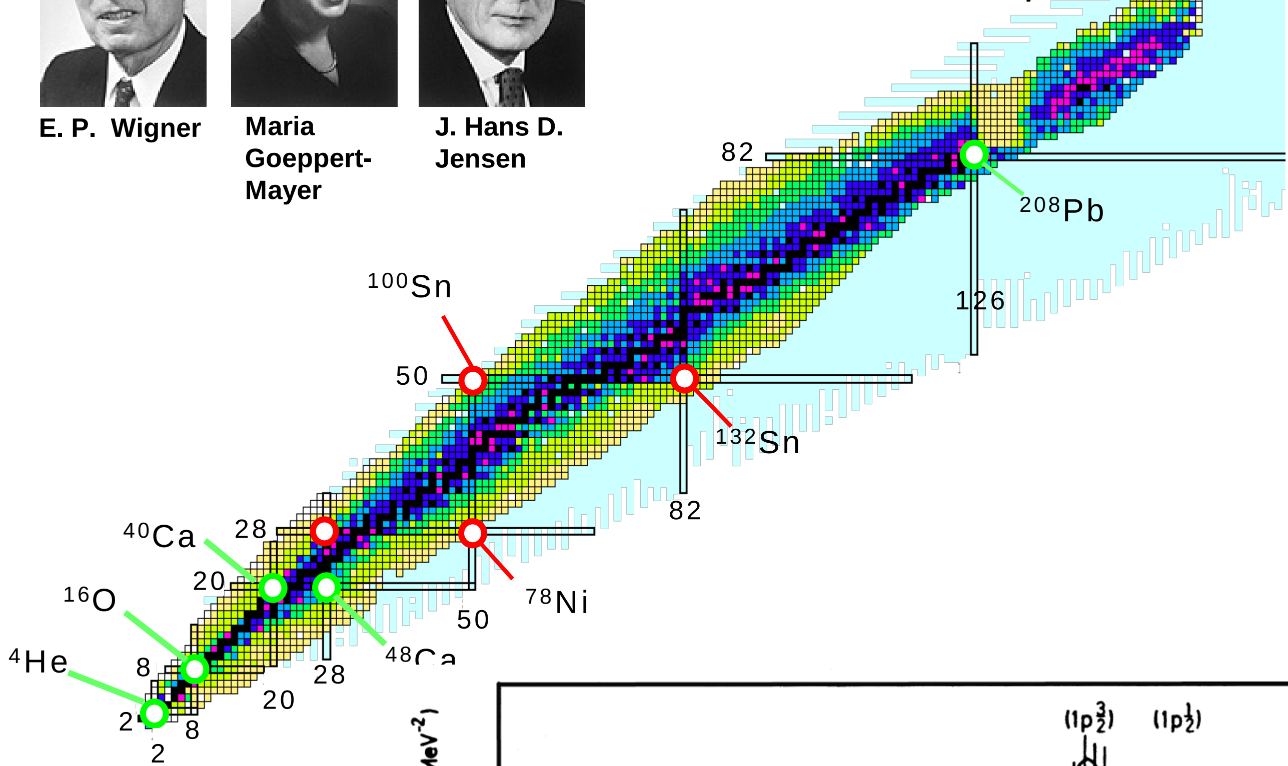
E. P. Wigner

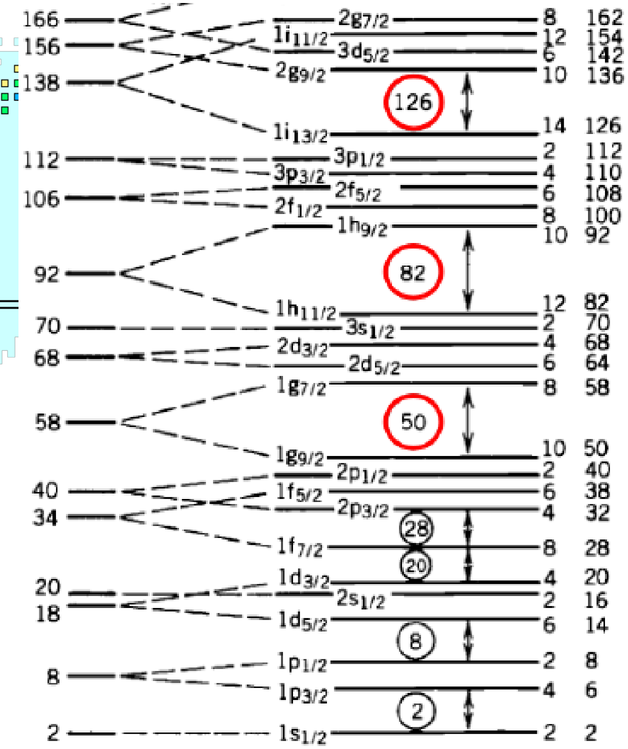
Maria Goeppert-Mayer

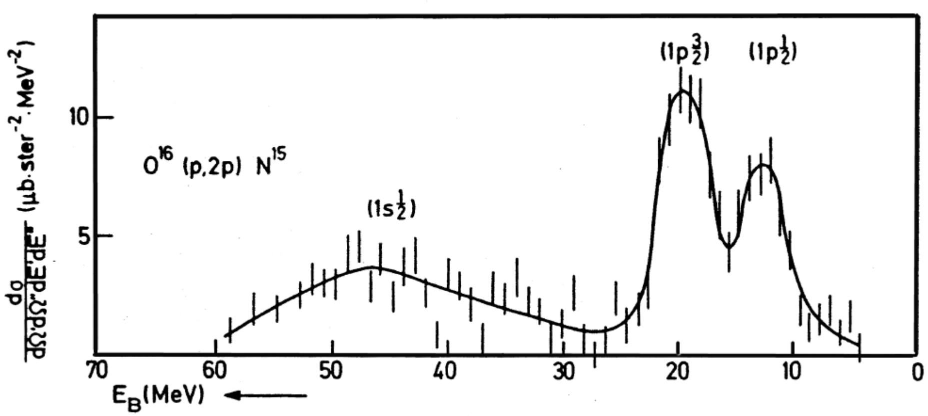


J. Hans D. Jensen

$$\mathcal{H}_{CM} = OH + \underbrace{U(r)(\vec{l}\cdot\vec{s})}_{V^{LS}}$$







T.A.J. Maris, P. Hillman, and H. Tyren, Nucl. Phys. 7 (1958) 1.

in parallel:

Nobel price 1961

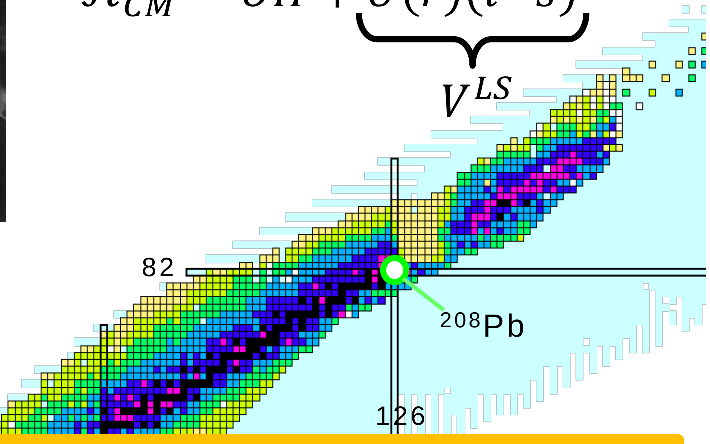
R. Hofstadter

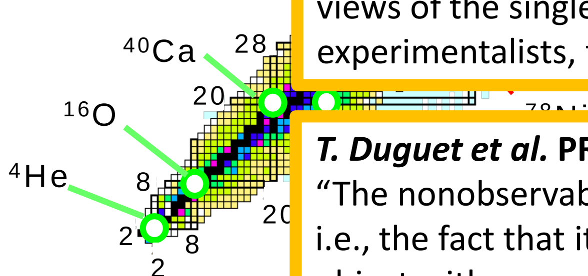
1953 : e on Au Stanford

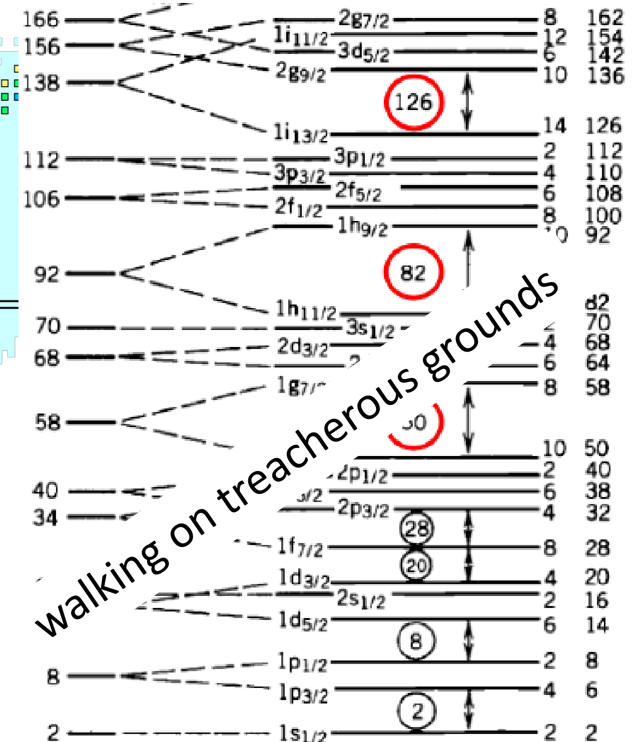
Nobel price 1963

E. P. Wigner — Maria Goeppert-Mayer — J. Hans D. Jensen

$$\mathcal{H}_{CM} = OH + \underbrace{U(r)(\vec{l}\cdot\vec{s})}_{V^{LS}}$$







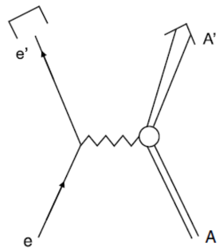
***M. Baranger NPA*149 (1970)**
“The purpose of this paper is to examine one particular definition which bridges the gap between two well-known views of the single-nucleon potential, one popular among experimentalists, the other among theorists. “

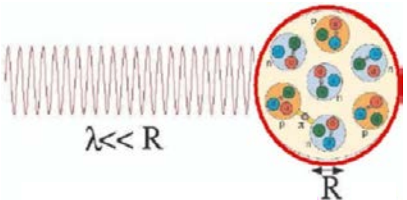
***T. Duguet et al.* PRC92 (2015)**
“The nonobservable nature of the nuclear shell structure, i.e., the fact that it constitutes an intrinsically theoretical object with no counterpart in the empirical world, must be recognized and assimilated.”

what has been missing in **nuclear structure** is **precision**:
glaring need for measured quantities which are as close as possible to observables (in the quantum mechanics sense)
$\rightarrow$ we need “clean probes”

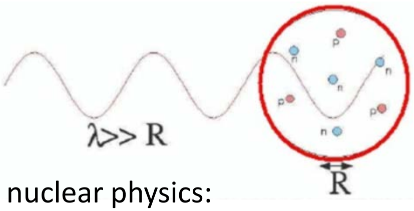
- ion manipulation with em fields: mass measurements
- interaction with the hyperfine field : laser spectroscopy, nuclear orientation$\rightarrow I^{(\pi)}, \mu, Q_s, \delta\langle r^2_c\rangle$
- γ-spectroscopy : lifetimes, B(Eλ), B(Mλ)
- e- scattering

e momentum transfer q $\approx 1/\lambda$





hadron physics:
structure of the nucleon



nuclear physics:
internal structure of the nucleus
E_e= 500 MeV $\rightarrow \approx$0.5 fm scale

contrary to hadron probe, the only unknown in the reaction is the nuclear part

A(e,e) elastic cross section

$$\left(\frac{d\sigma}{d\Omega}\right)_{eA\to eA} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{1}{1+\frac{2E}{M}\sin^2(\theta/2)} |F(\vec{q})|^2$$

point charge nucleus

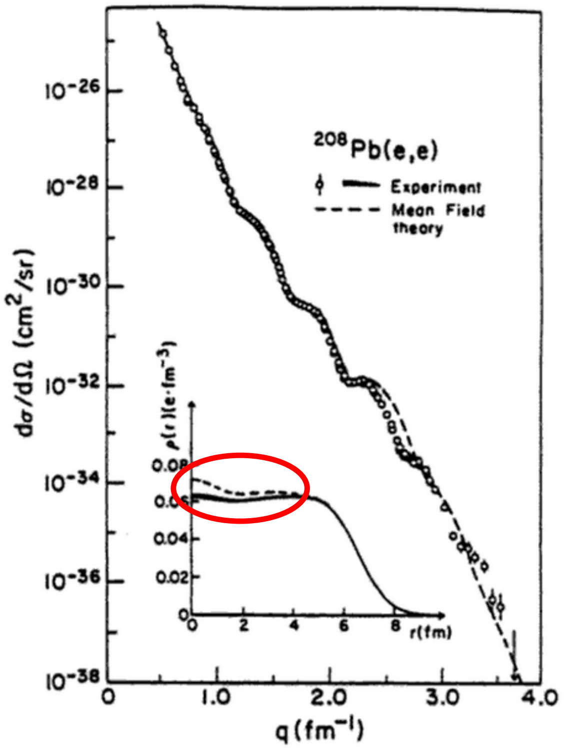
$$F(\vec{q}) = \frac{1}{Ze}\int \varrho(\vec{r}) e^{i\vec{q}\cdot\vec{r}} d^3r$$

form factor

Fourier transform

$$\varrho(\vec{r}) = \frac{Ze}{(2\pi)^3}\int F(\vec{q}) e^{-i\vec{q}\cdot\vec{r}} d^3q$$

charge distribution
“model independent”



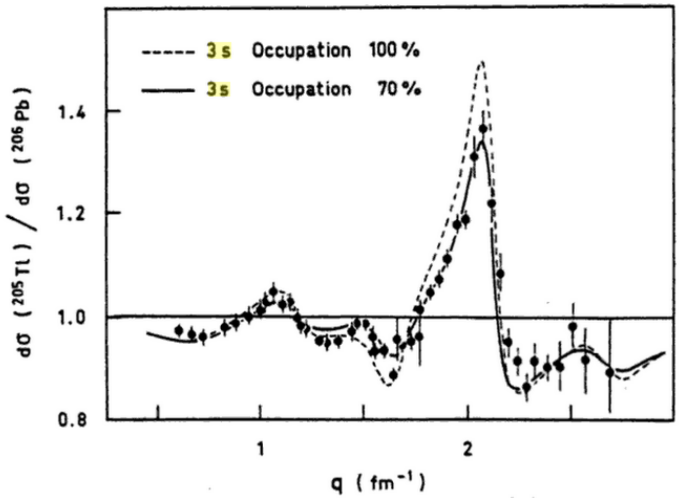
12 orders of magnitude !

B. Frois and Papanicolas
Ann. Rev. Nucl. Part. Sci 37 (1987)

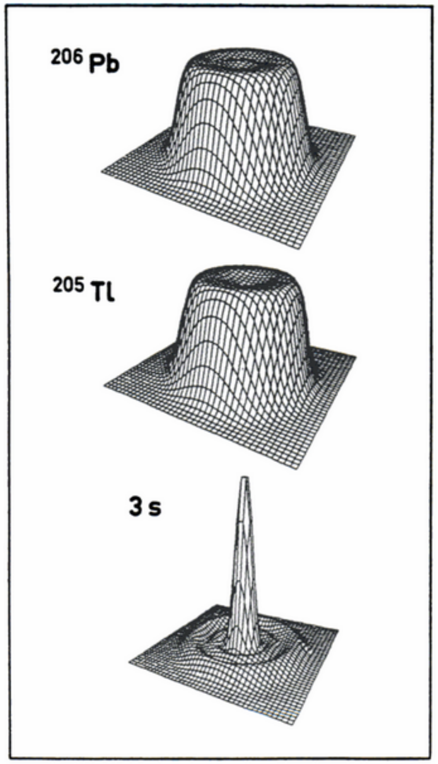
Dechargé and Gogny
PRC 81 (1980)

Cavedon, Frois, Goutte et al.
PRL 49 (1982)

etc…



First "picture" of a "single particle" evolving inside the nucleus



B. Frois et al
in Modern Topics in Electron Scattering (World Scientific 1991)

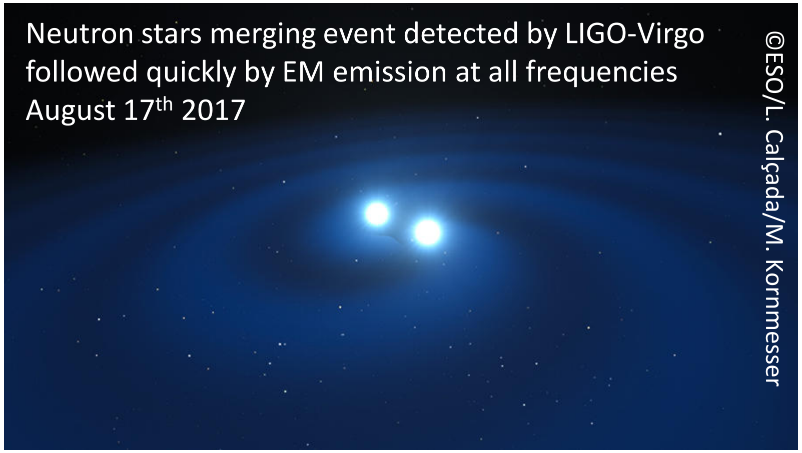
revealed **in medium effects**
(how far a "single particle" is from a free nucleon)

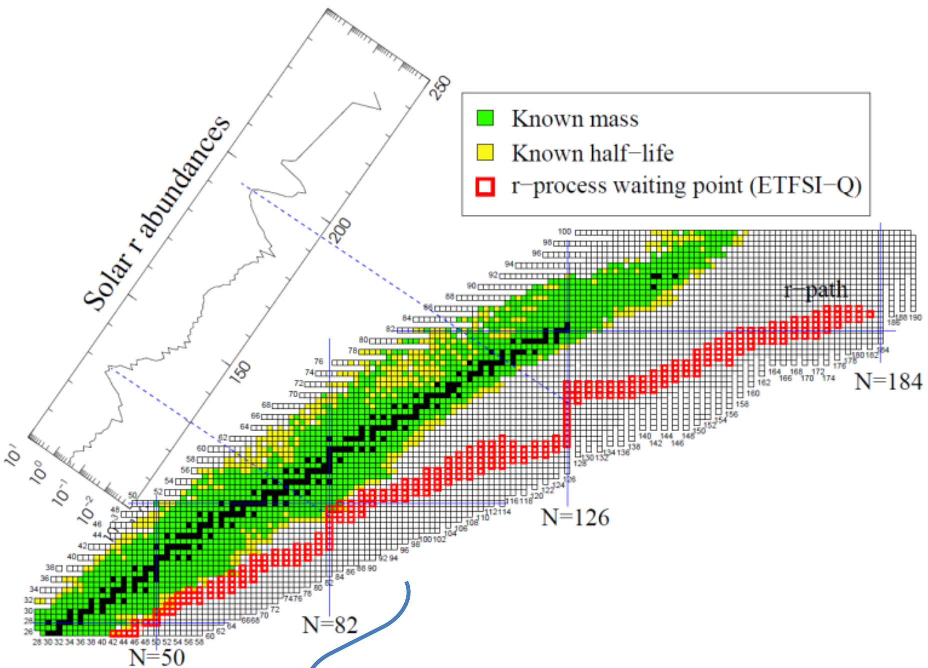
- part of the single-particle quenching has well understood origins: core (collective) couplings, many-body correlations

- short-range correlations, non-local part of the potential

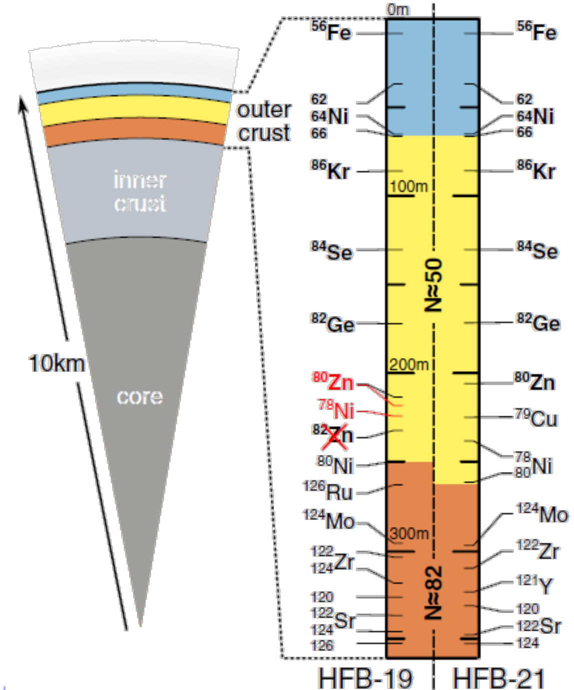
→ kinks, neutron skin and giant haloes formation ?

→ shell evolution ?





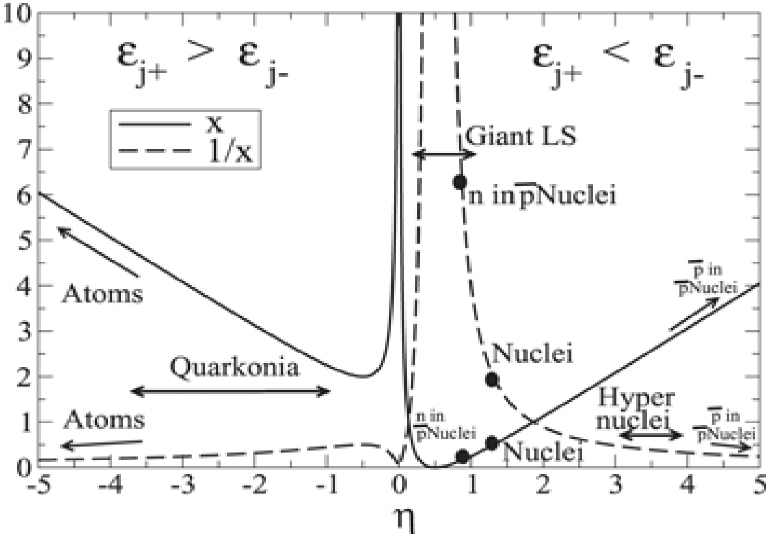
on earth
fission of actinides



Wolf et al. PRL 110 (2013)

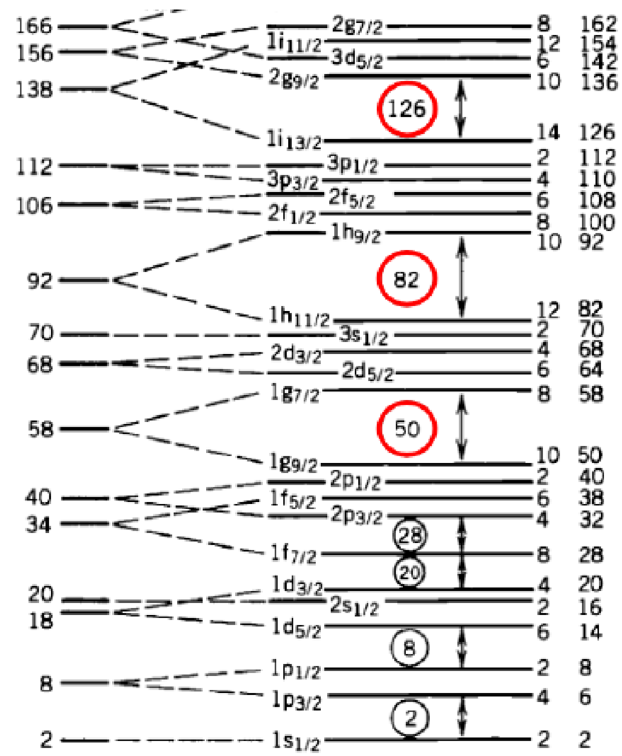
spin-orbit : universal effect for quantum systems made of particles having spin : atoms, nuclei, hyper-nuclei, quarkonia…
important role in condensed matter physics : cold atoms, spintronics, topological insulators...

J-P Ebran et al 2016 J. Phys. G: Nucl. Part. Phys. 43 085101



$$\eta \equiv \frac{m}{V-S}$$

$$1/x \equiv \frac{|\Delta\langle V^{SL}\rangle|}{\hbar\omega_0}$$



Dirac equation governing the single particle motion dynamics

$$\rightarrow \quad \boxed{V^{LS} = \frac{1}{2M^2(r)}\frac{1}{r}\frac{d}{dr}(V(r) - S(r))\vec{l}\cdot\vec{s}}$$

vector potential (short range repulsion) $\approx +350$ MeV

scalar potential (medium range attraction) ≈ -400 MeV

in atomic system:
$1/x \sim \alpha^2 \approx 10^{-4}$

nucleon mass ≈ 940 MeV

nucleon mass $\approx \Delta(r) = V(r) - S(r)$

QCD sum rules $\rightarrow$ an "emerging" property of QCD vector potential (short range repulsion) $\approx +350$ MeV

scalar potential (medium range attraction) ≈ -400 MeV

very large $\Delta(r) = V(r) - S(r)$

$\Updownarrow$

very small $\Sigma(r) = V(r) + S(r)$

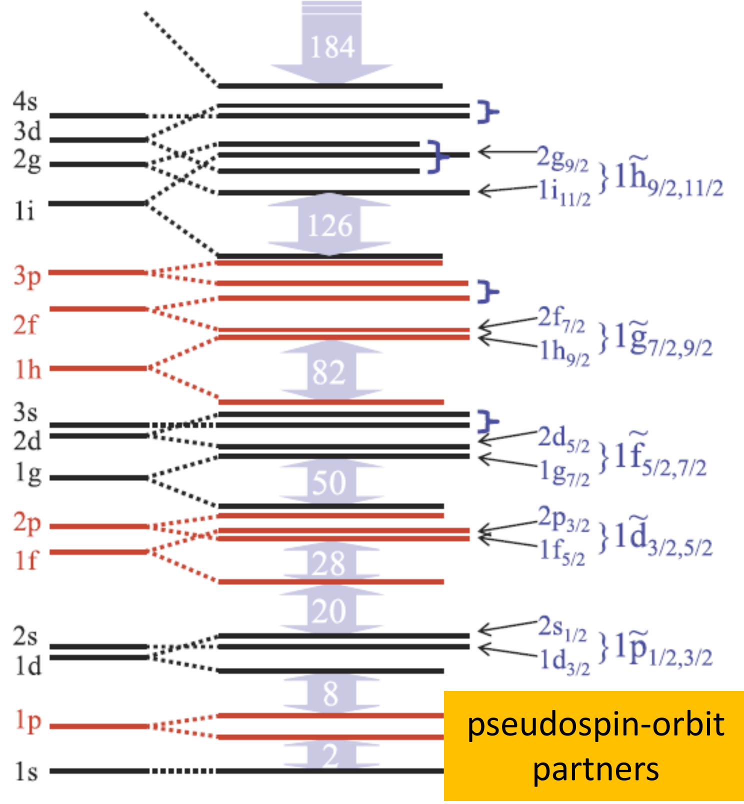
$\Downarrow$

approximate realization of the
pseudospin symmetry
(as a dynamical symmetry)

Hecht, Adler,
Nucl. Phys. A **137**, 129 (1969)
Arima, Harvey, Shimizu,
Phys. Lett. B **30**, 517 (1969)

$$(\tilde{n} = n-1, \tilde{\ell} = \ell + 1, \tilde{s} = s)$$

$$\left.\begin{array}{r}(n, \ell, j = \ell + \frac{1}{2}) \\ (n-1, \ell+2, j = \ell + \frac{3}{2})\end{array}\right\} (\tilde{j} = \tilde{\ell} \pm \tilde{s})$$



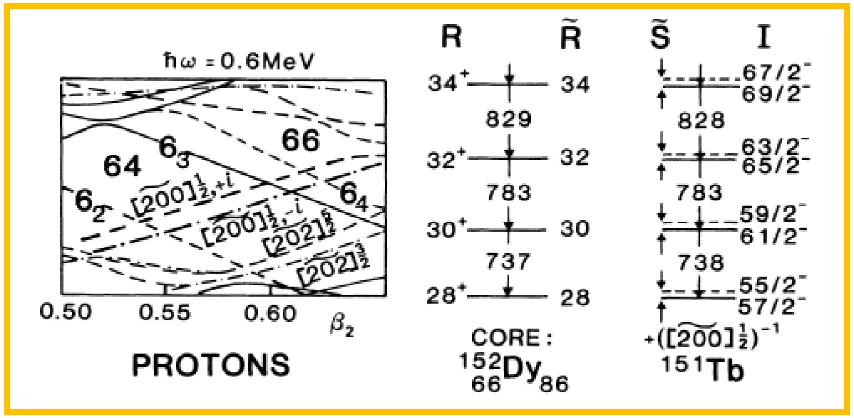
Liang et al. Phys. Rep. 570, 1 (2015)

$\Downarrow$

pseudo-SU(3) symmetry
for multi-nucleon wave functions

$\Updownarrow$

quadrupole collectivity

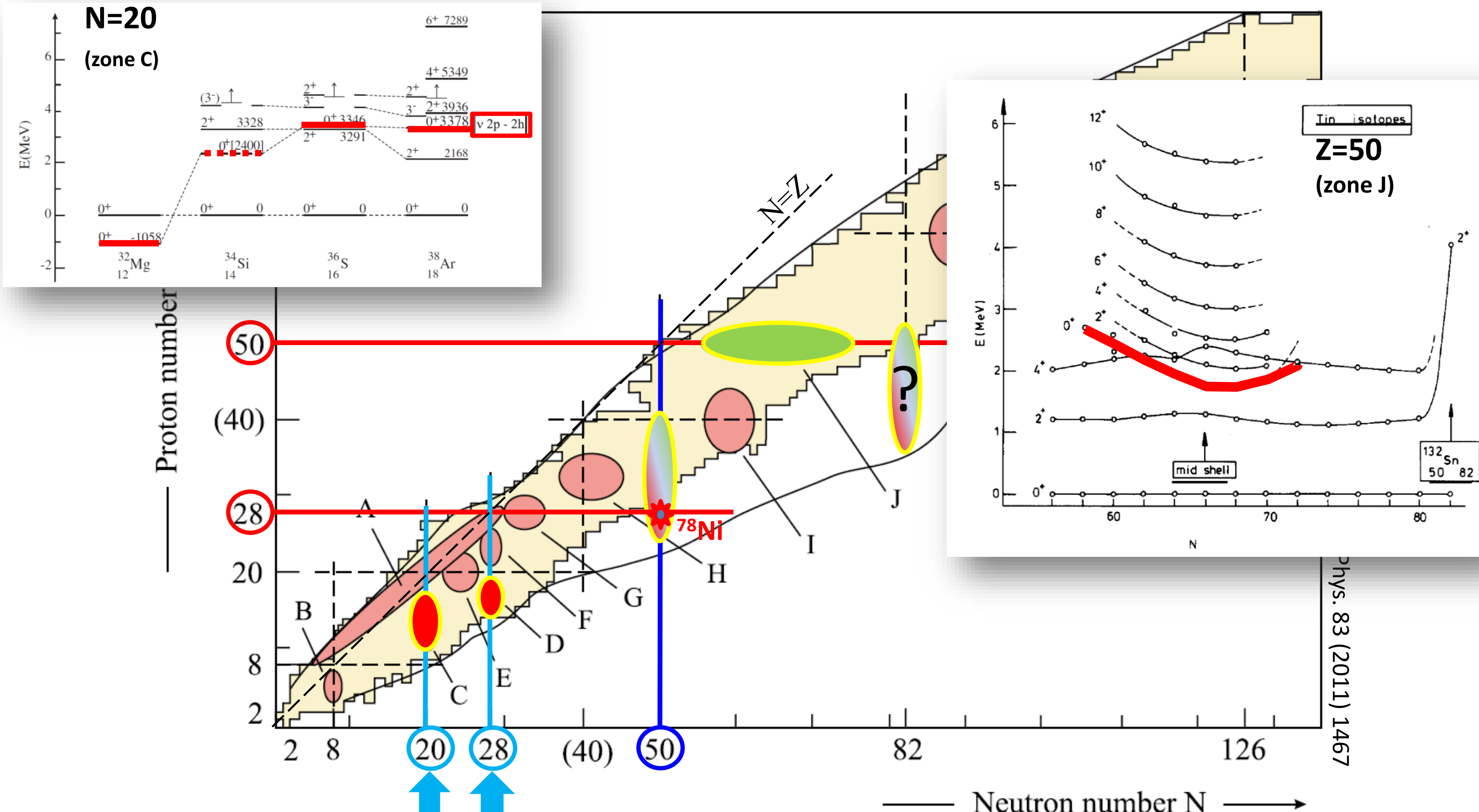


Nazarewicz et al., PRL**64**, 1654 (1990)

- superdeformed identical rotation bands
- superdeformed configurations
- quantized alignment
- pseudospin partner bands
- …
- exotic nuclei ?

SO magic numbers from a shape-coexistence point of view

"spherical magicity" and shape coexistence : two inseparable facets of the same deeper phenomenon ?



historical case N=20 (^{32}Mg region)
Klapisch PRL 31 118 (1973)
Thibault PRC 12 644 (1975)
Détraz PRC 19 164 (1979)

N=28 (^{42}Si region)
Bastin PRL 99 022503 (2007)

Spin-Orbit magic numbers ≈ the “r-process” magic numbers

nuclear spin-orbit:
2 sides of the same coin
(in a relativistic vision)

very large $\Delta(r) = V(r) - S(r)$

⇳

large SO splitting at the mean-field level

⇳

shell closures

very small $\Sigma(r) = V(r) + S(r)$

⇳

pseudospin symmetry

⇳

pseudo-SU(3) symmetry : quadrupole collectivity

shape coexistence aka “magicity evolution” far from stability

isospin asymmetry of the pseudo-spin symmetry
(isovector vector ρ-meson exchange, short range)

Fock term ≈ δ-meson exchange (isovector scalar)
[Ebran et al. PRC 94 024304 (2016)]

first experimental (indirect) hints are just becoming available (need precise probes)

A(e,e’) **inelastic** cross section

$$\frac{d\sigma}{d\Omega} = \sigma_p \eta \left[\sum_{\lambda=0}^{\infty} \frac{q_\mu^4}{q^4} |F_\lambda^C(q)|^2 + \left(\frac{q_\mu^2}{2q^2} + \tan^2\frac{\theta}{2}\right) \sum_{\lambda=1}^{\infty} \underbrace{\{|F_\lambda^E(q)|^2 + |F_\lambda^M(q)|^2\}}_{\text{transverse form factor}} \right]$$

point charge nucleus

recoil factor

longitudinal form factor

transverse form factor

$$\rho_\lambda(r) = \int \langle \psi_f \| \rho_{op}(\mathbf{r}) Y_\lambda(\hat{\mathbf{r}}) \| \psi_i \rangle \, d\hat{r}$$

charge transition density

$$J_{\lambda\lambda'}(r) = \frac{i}{c} \int \langle \psi_f \| \mathbf{J}_{op}(\mathbf{r}) \cdot \mathbf{Y}_{\lambda\lambda' 1}(\hat{\mathbf{r}}) \| \psi_i \rangle \, d\hat{r}$$

current transition density

$$B(\mathrm{E}\lambda) = \frac{2J_f+1}{2J_i+1} \left[\int_0^\infty \rho_\lambda(r) r^{\lambda+2} dr \right]^2 \qquad B(\mathrm{M}\lambda) = \frac{\lambda}{\lambda+1} \frac{2J_f+1}{2J_i+1} \left[\int_0^\infty J_{\lambda\lambda}(r) r^{\lambda+2} dr \right]^2$$

$\mu \approx F_M$ for $q \to 0$
(elastic at 180°)

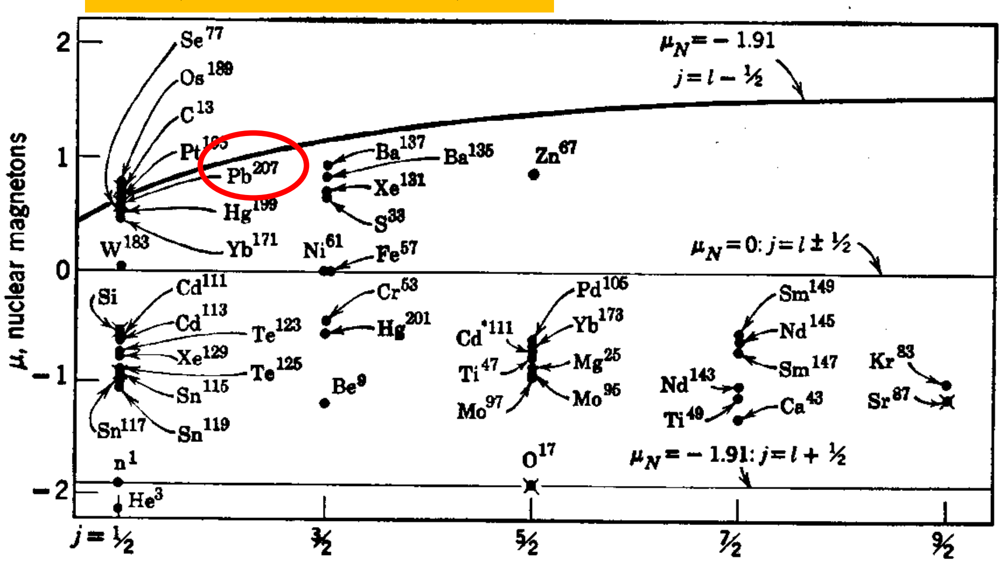
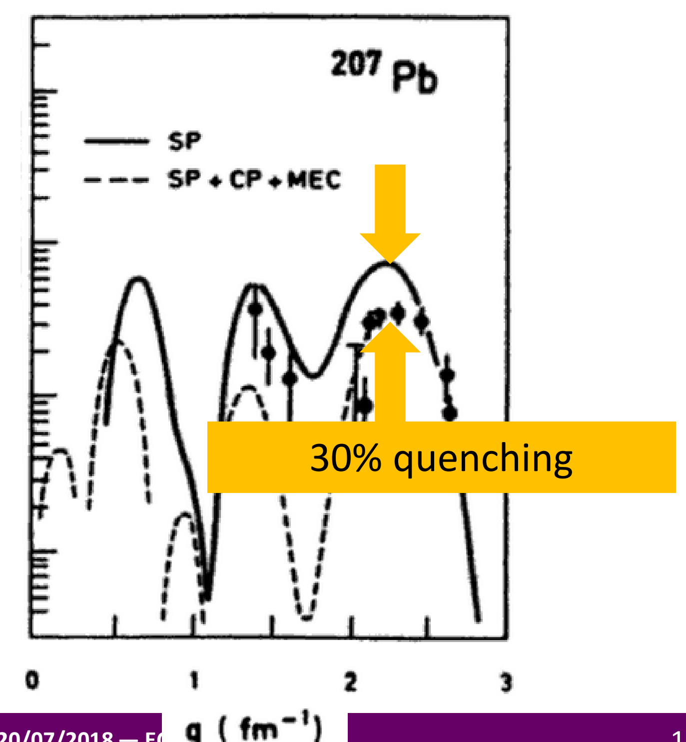
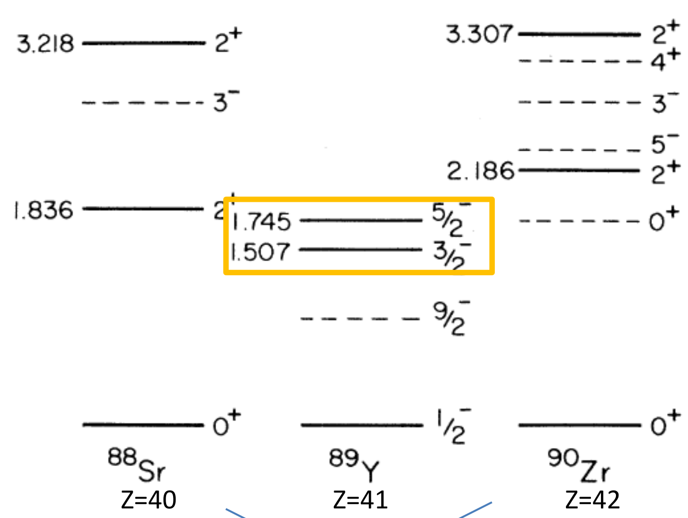


Fig. I.5. Magnetic moments of nuclei with odd N plotted against the spin.

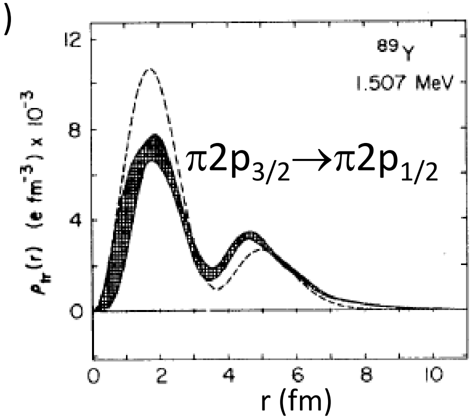


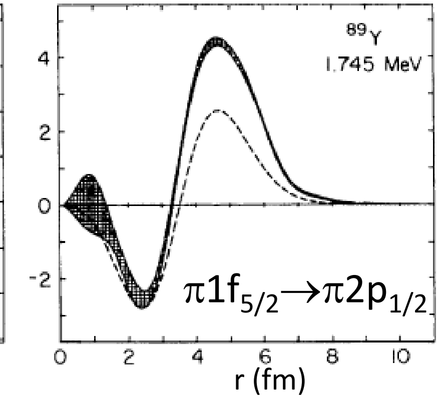
e-scattering as a precision spectroscopy tool

One example: N=50 isotones Schwentker et al. PRL 50 (1983)

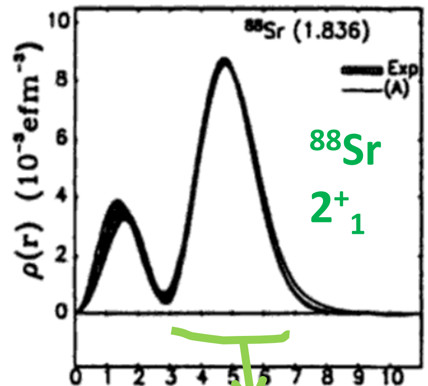


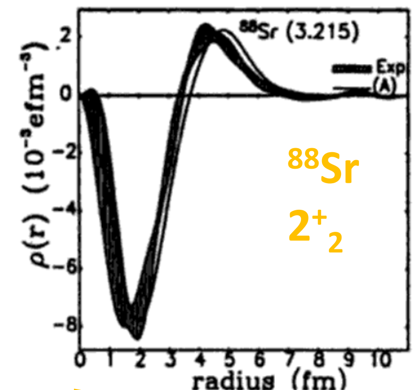
~~$[^{88}\mathrm{Sr};\, 2^+]\otimes\pi 2p_{1/2}$~~





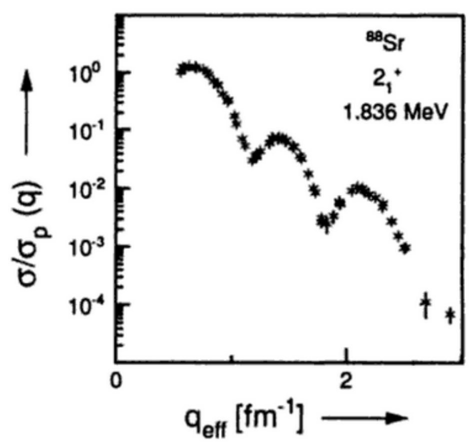
curve "A": the two 2+ are orthogonal linear combinations of $[2p_{3/2}^{-1}2p_{1/2}]_{2+}$ and $[1f_{5/2}^{-1}2p_{1/2}]_{2+}$

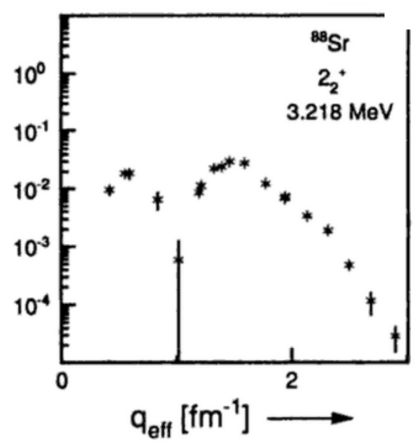




surface oscillation ("standard" collective state)

nuclear interior solicited

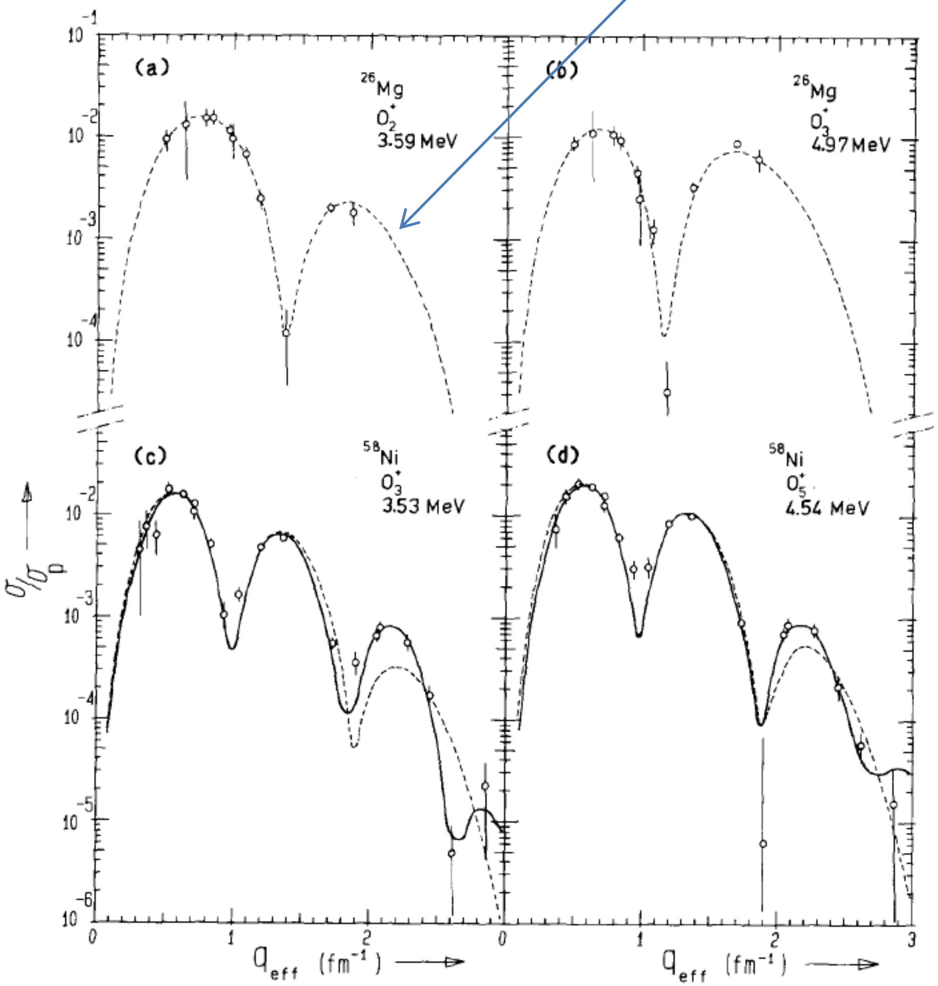




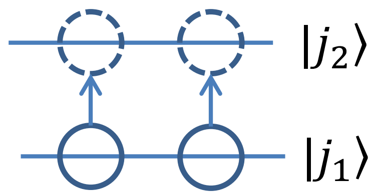
0^+ states and "intruder" configurations (shape coexistence)

only obtained when including $2\hbar\omega$ excitations (intruders)

looks like a C2 at low q



first moment of ρ_0(r) : $\mathrm{M(E0)} = \int \rho_0(r) r^4\, dr$



$|0^+{}_1\rangle = \mathrm{a}|j_1{}^2\rangle + \mathrm{b}|j_2{}^2\rangle$

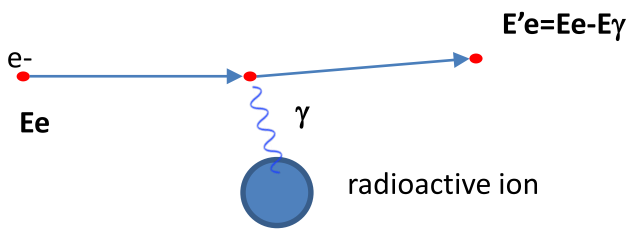
$|0^+{}_2\rangle = \mathrm{b}|j_1{}^2\rangle - \mathrm{a}|j_2{}^2\rangle$

$$\mathrm{M(E0)} = 2\mathrm{ab} \int \left\{ u^2{}_{j1} - u^2{}_{j2} \right\} r^4\, dr \approx \langle r^2\rangle_{j1} - \langle r^2\rangle_{j2}$$

$\rightarrow$ clear/"clean" signature of the s.p. ingredients of the intruder/coexisting structure not to mention :

- radius, diffusivity

- perfect coulomb excitation : forward electron scattering (no multi-step process)

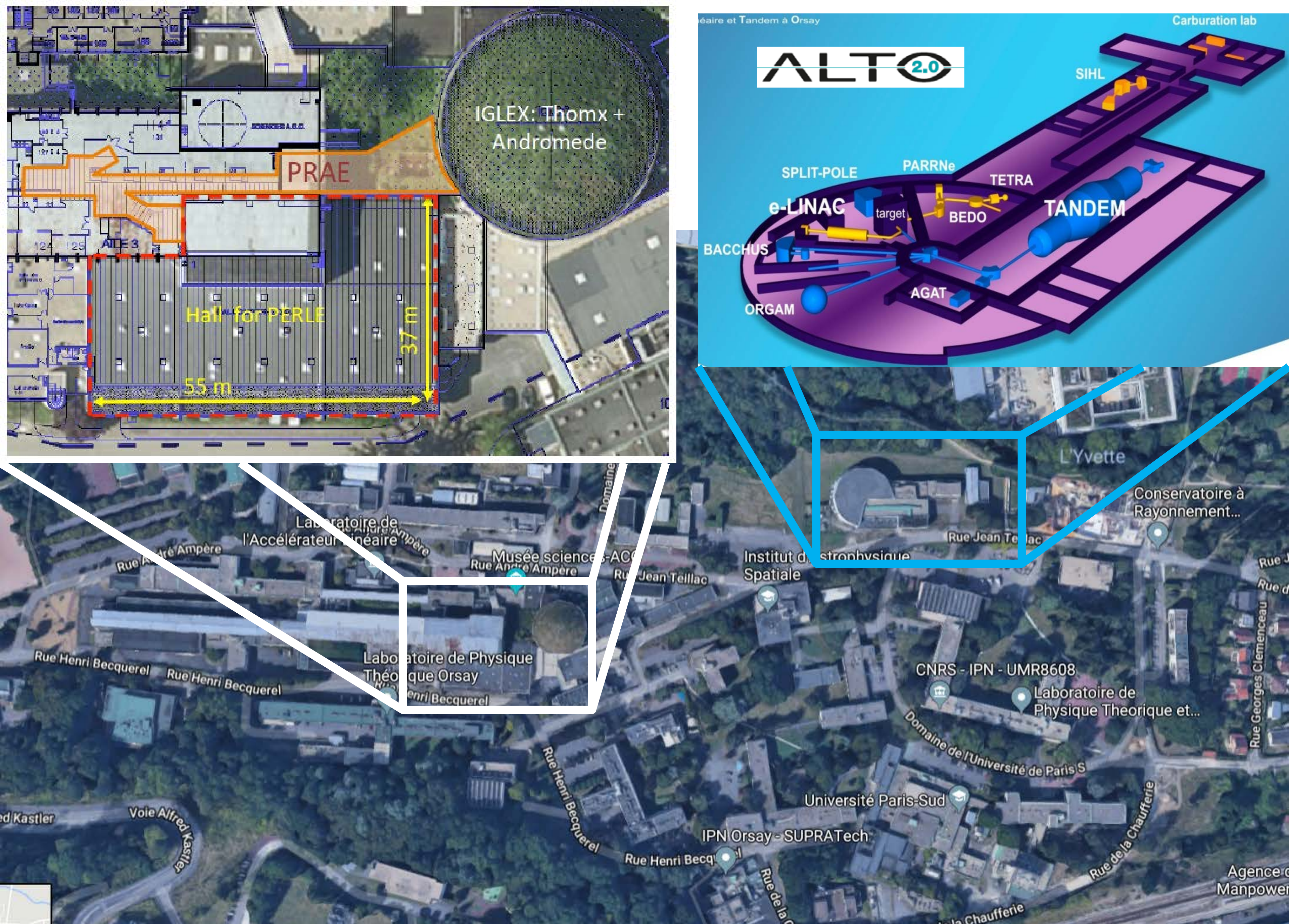


- "clean" excitation of 1p-1h configuration at high multipolarity

- Excitation of collective modes (PDR etc)

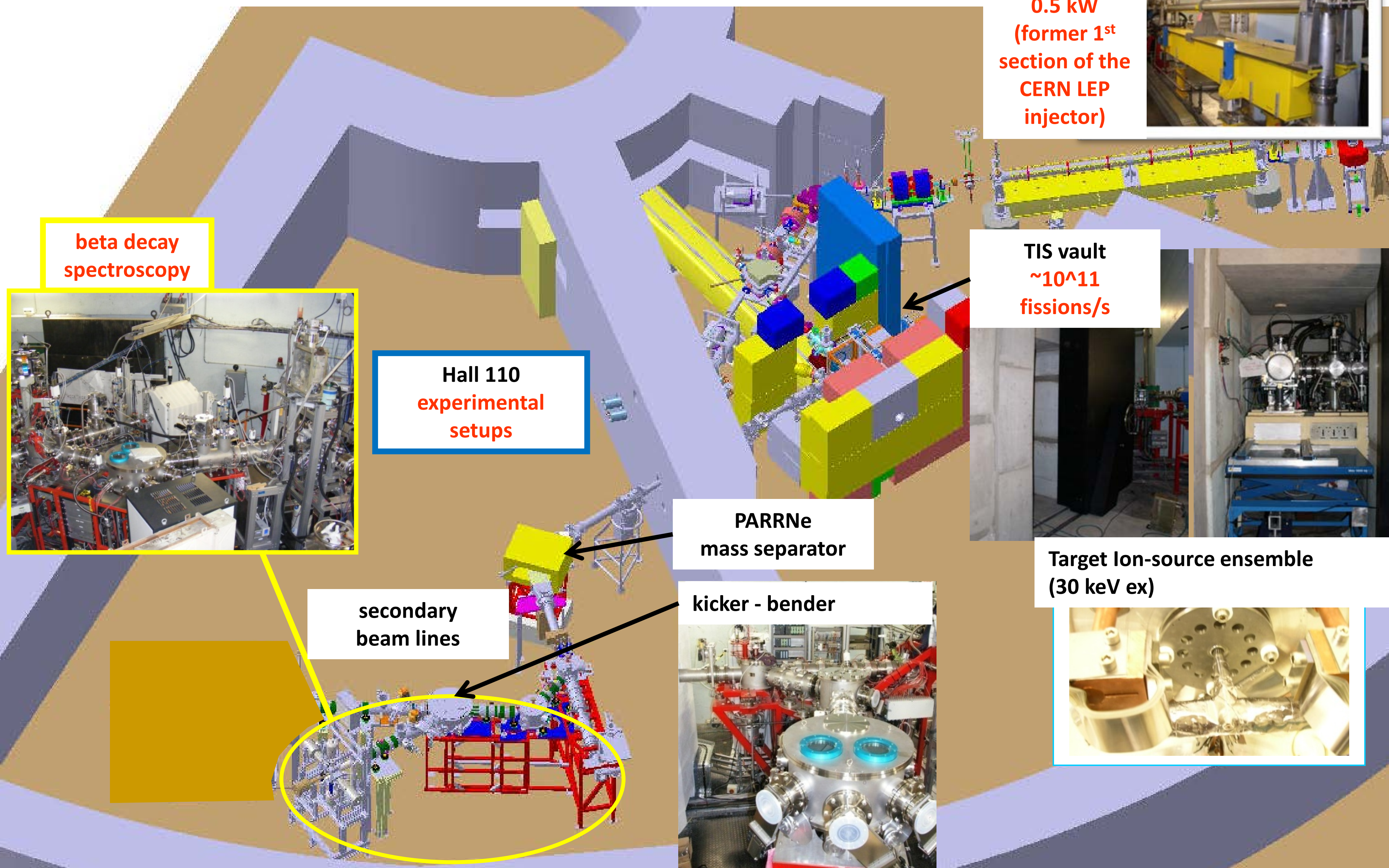
- fission studies (condition on electron energy would give precise information of the initial condition of the fissioning system)

The possible physics program spans exactly the physics interests of the vast majority of the low-energy nuclear physics community in Orsay-Saclay (and in France)
… **with a much more powerful probe**!

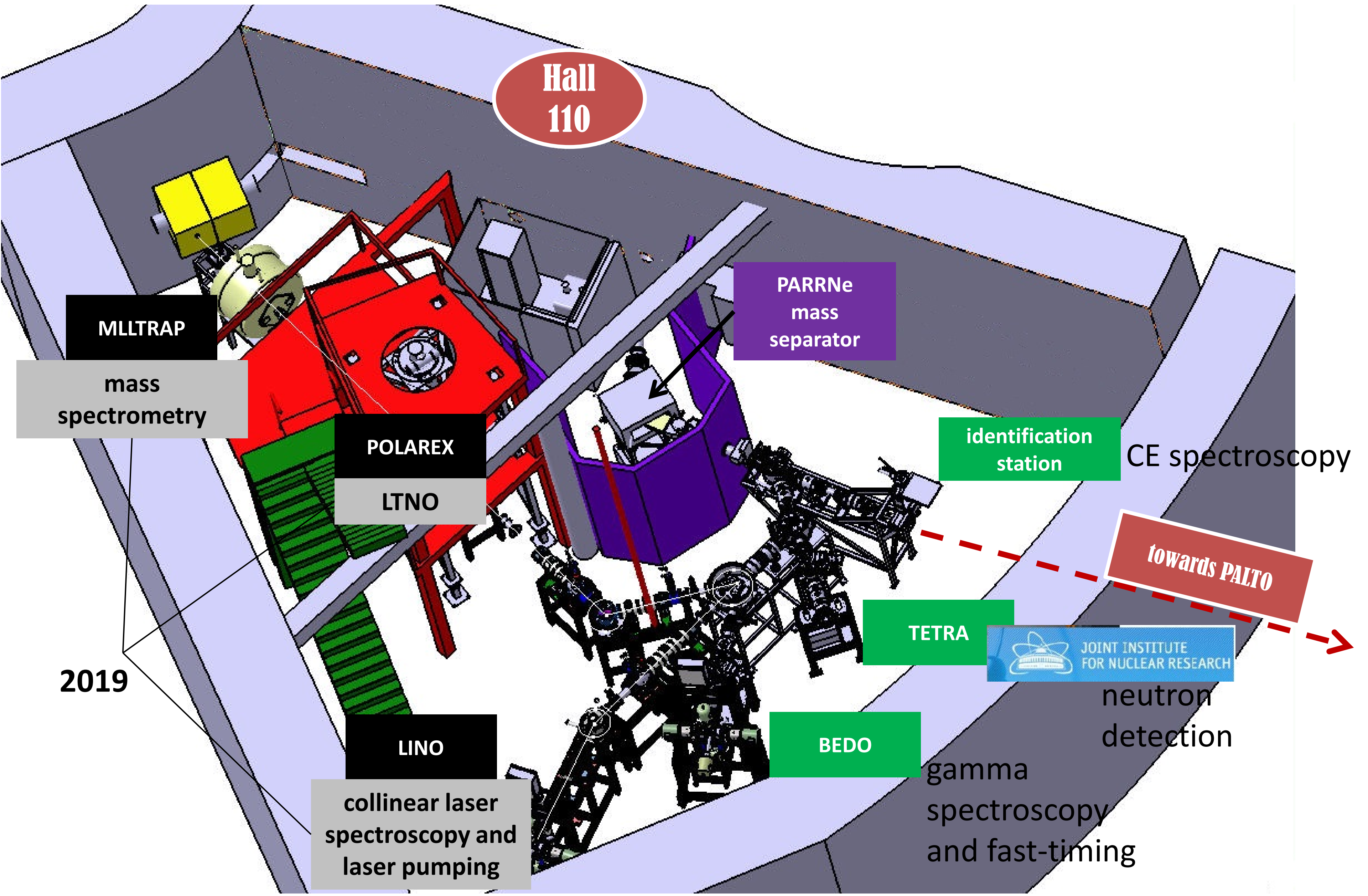

IGLEX: Thomx +
Andromede
PRAE
Hall for PERLE
37 m
55 m
ALTO 2.0
Carburation lab
SIHL
SPLIT-POLE
PARRNe
TETRA
e-LINAC
target
BEDO
TANDEM
BACCHUS
AGAT
ORGAM
L'Yvette
Conservatoire à
Rayonnement...
Rue Jean Teillac
Rue André Ampère
Musée sciences-ACC
Institut d'Astrophysique
Spatiale
Laboratoire de Physique
Théorique Orsay
Rue Henri Becquerel
CNRS - IPN - UMR8608
Laboratoire de
Physique Theorique et...
Domaine de l'Université de Paris S
Université Paris-Sud
IPN Orsay - SUPRATech
Voie Alfred Kastler
Rue de la Chaufferie
Agence
Manpower

Beams available today at ALTO – 0.5 kW primary e-beam

The first photofission-based ISOL facility operated in the world



The ISOL experimental hall



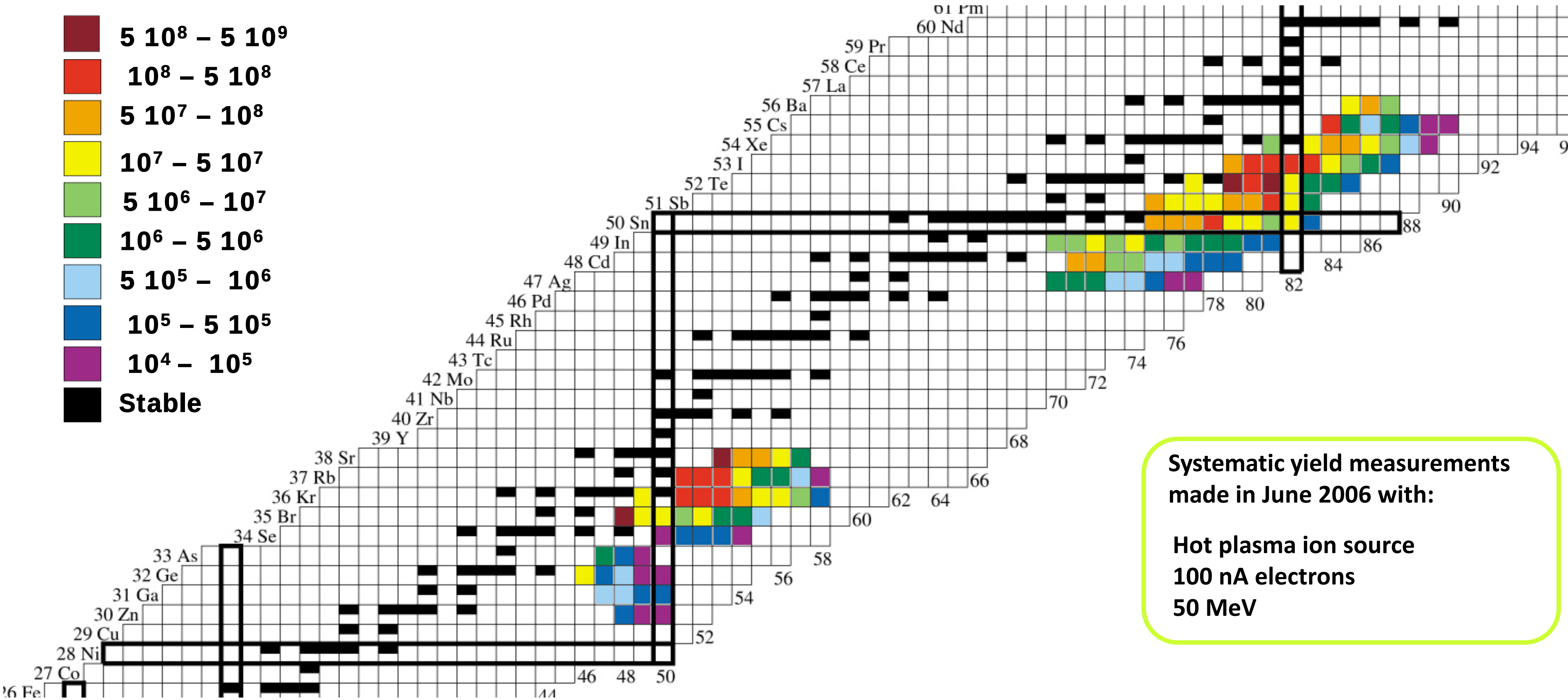
Beams available today at ALTO

Measured productions yields at the detection point
on line with the PARRNe mass separator
electrons -> gamma induced fission

nominal intensity:
10 μA ⇒~ 10^{11} fissions/s

Production pps / 10 μA e-

- $5\ 10^8 – 5\ 10^9$
- $10^8 – 5\ 10^8$
- $5\ 10^7 – 10^8$
- $10^7 – 5\ 10^7$
- $5\ 10^6 – 10^7$
- $10^6 – 5\ 10^6$
- $5\ 10^5 – 10^6$
- $10^5 – 5\ 10^5$
- $10^4 – 10^5$
- Stable

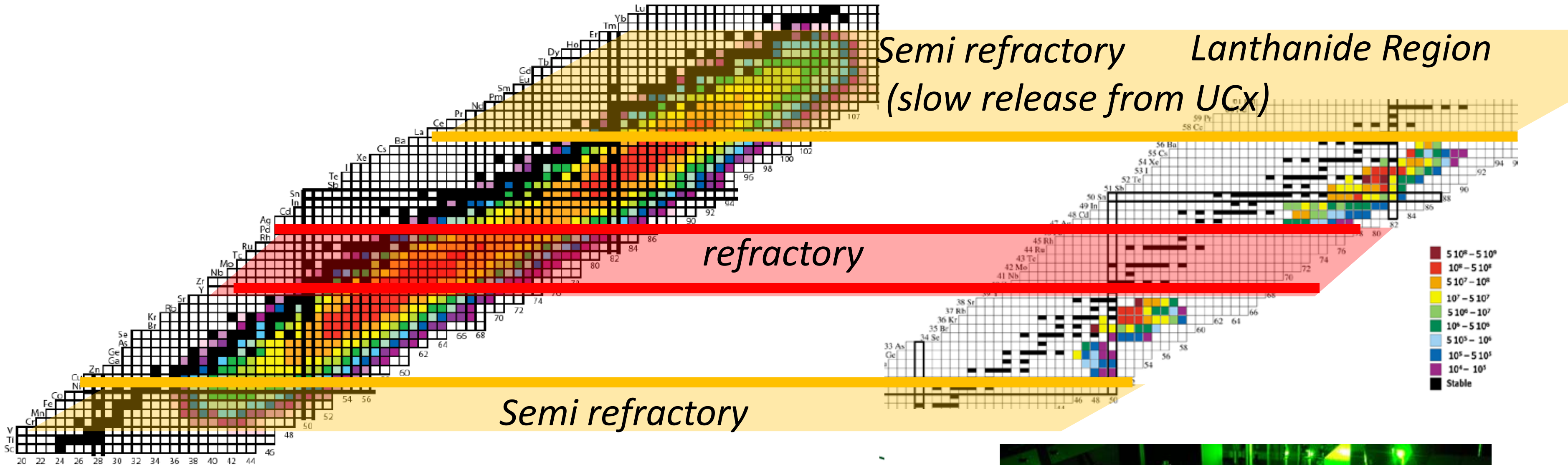


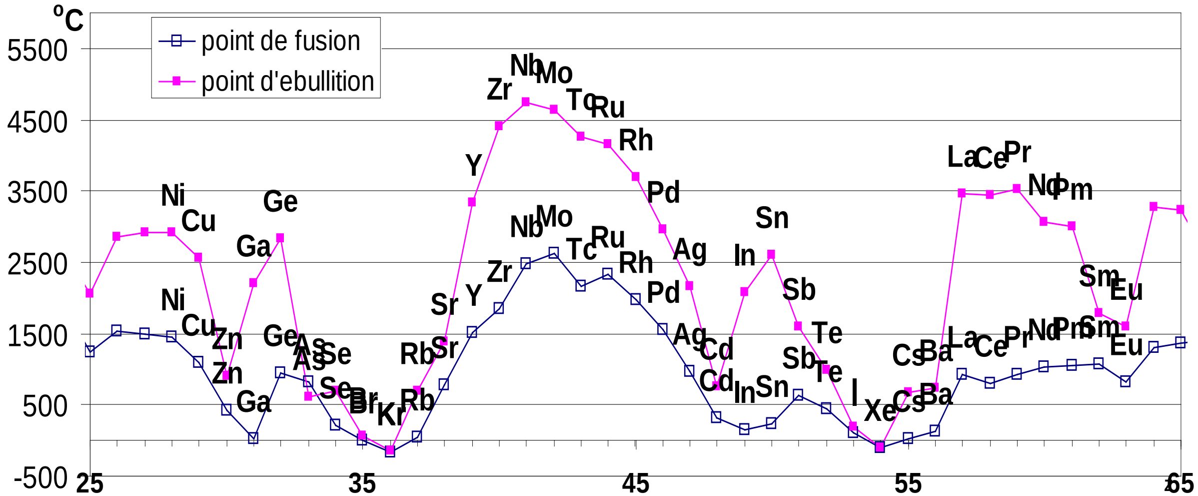
Systematic yield measurements made in June 2006 with:

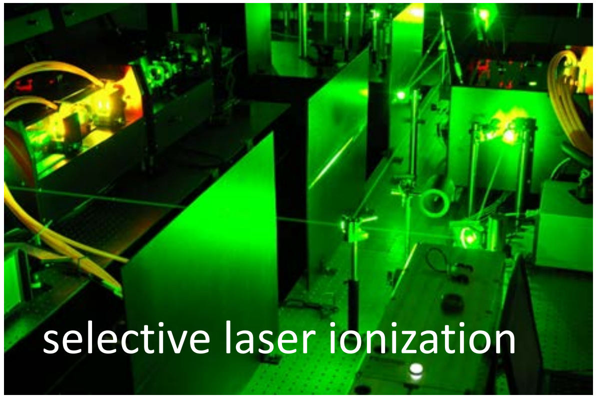
Hot plasma ion source
100 nA electrons
50 MeV

Beams available today at ALTO – 0.5 kW primary e-beam

RIB availability, intensity and purity within ISOL techniques



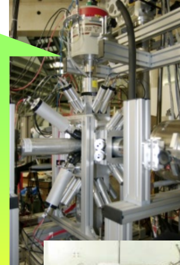
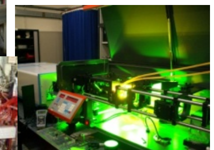


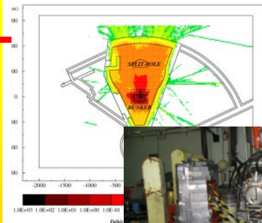


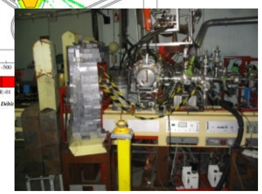
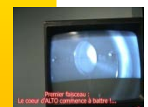
+ physicochemical optimization of the UCx matrix (nano-materials) (collaboration with ISOLDE)

+ in-target chemistry technique (fluorination) a long road …

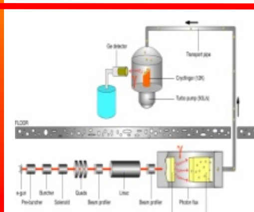
- 2013 — INAUGURATION
- BEDO commissioning
- 2012 — green light from French nuclear safety authorities
- asn AUTORITÉ DE SÛRETÉ NUCLÉAIRE
- 2011 — first laser ionized RIB
- 2010
- 2009–2010 — building of the low energy beam lines + laser ion source
- 2008–2009 — Commissioning : tests and radiation safety measurements
- TIS vault
- 2008 — 84Ga -> 84Ge β-decay
- 2007
- 2006 — UCx target on line with e-beam – production yields measurements
- First e-beam extracted
- 2004–2005 — RF system
- 2003 — construction of the LINAC bunker
- 2002 — arrival of the LINAC cavity from decommissioned LEP injector
- 2002 — 81Zn -> 81Ga β-decay
- 2001 — 83Ga -> 83Ge β-decay
- 2001 — exploratory photofission experiment at CERN
- 2000
- 1999
- 1998 — ISOL available at TANDEM
PARRNe mass-separator on line
- 1998 — initial idea of a R&D test bench for the SPIRAL2 project at the Orsay Tandem







The PERLE@Orsay project

PERLE is a high current, multi-turn ERL facility (900 MeV),

designed to study and validate main principles of the Large Hadron Electron Collider (LHeC: 60 GeV)

LHeC would use a 3-pass energy recovery, recirculating linac with 20 GeV per pass and a current of about 10 mA; the RF frequency would be 802 MHz

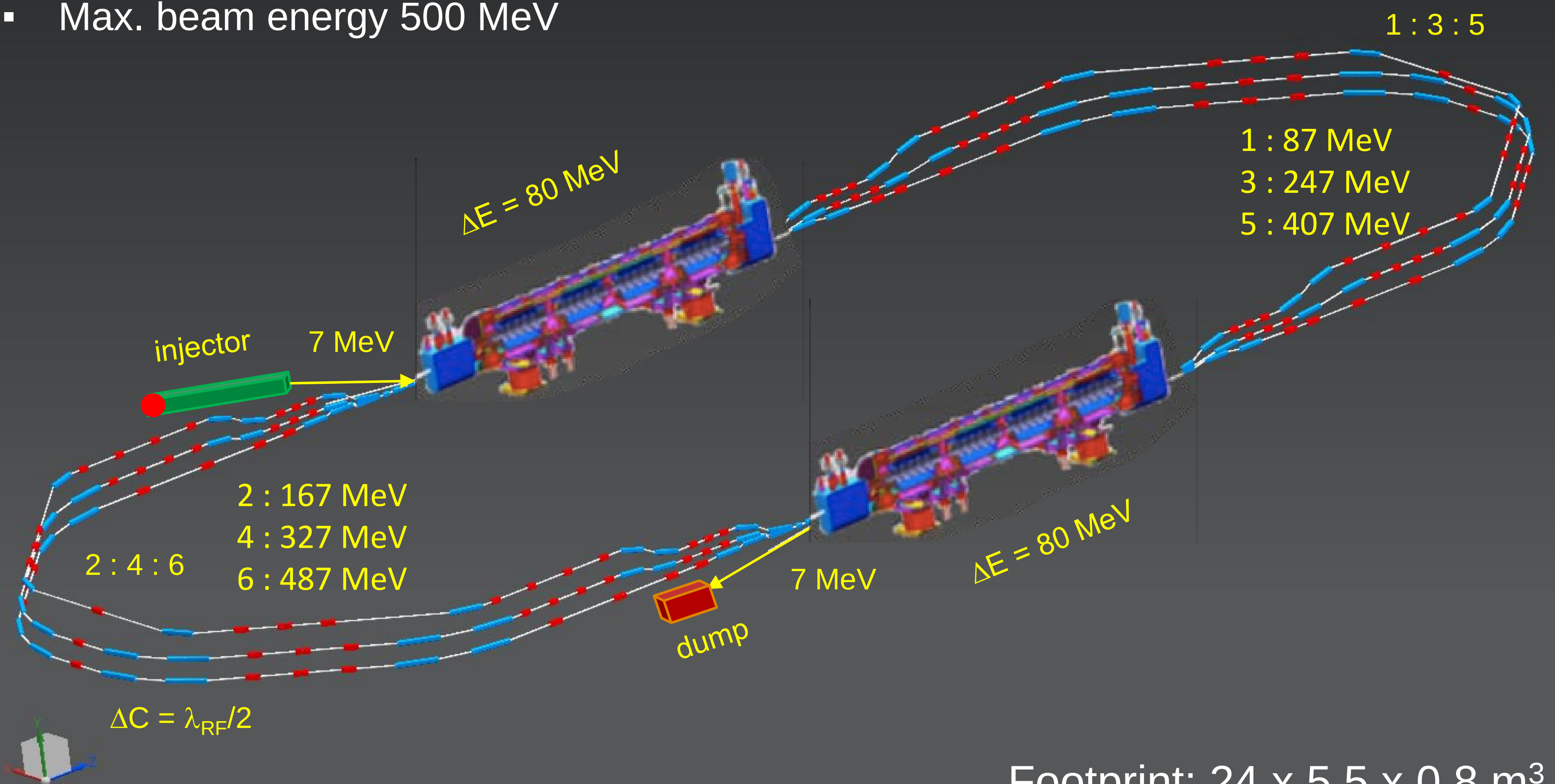
The Orsay realization of PERLE (called **PERLE@Orsay**) is a smaller version (500 MeV) with the same design challenges and the same beam parameters:

Target Parameter	**Unit**	**Value**
Injection energy	MeV	7
Electron beam energy	MeV	500
Normalised Emittance $\gamma\varepsilon_{x,y}$	mm mrad	6
Average beam current	mA	20
Bunch charge	pC	500
Bunch length	mm	3
Bunch spacing	ns	25
RF frequency	MHz	801.58
Duty factor		CW

Courtesy W. Kaabi (LAL Orsay)
(LHeC/FCC-eh and PERLE Workshop, 27-29 June 2018, Orsay, France)

The PERLE@Orsay configuration

- 2 Linacs (Four 5-Cell 801.58 MHz SC cavities)
- 3 turns (160 MeV/turn)
- Max. beam energy 500 MeV

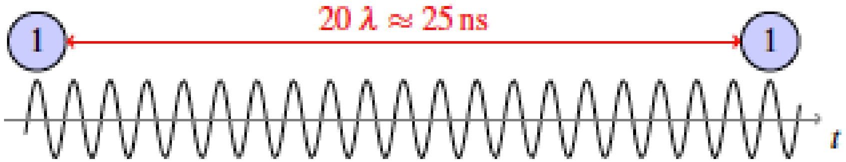


Footprint: 24 x 5.5 x 0.8 m^3

Courtesy W. Kaabi (LAL Orsay)
(LHeC/FCC-eh and PERLE Workshop, 27-29 June 2018, Orsay, France)

The PERLE@Orsay configuration

- Basic RF structure, without recirculation: Bunches are injected every 25 ns



801.58 MHz RF, 5-cell cavity:

λ = 37.40 cm

$L_c = 5\lambda/2 = 93.50$ cm

Grad = 21.4 MeV/m (20 MeV per cavity)

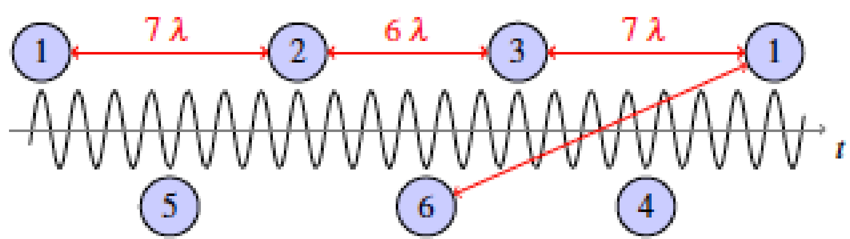
ΔE= 80 MeV per Cryo-module

- When recirculation occurs: bunches at different turns in the linacs:

→ Ovoid bunches in the same bucket

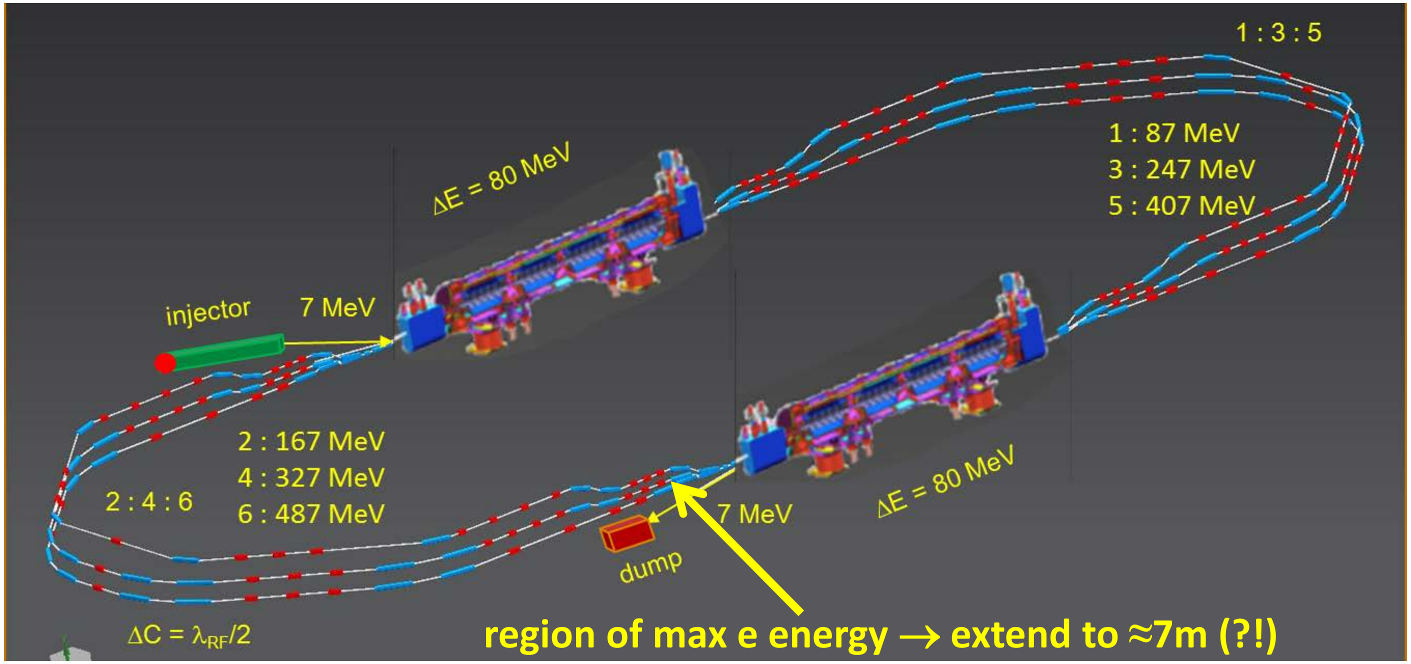
→ Recombination pattern adjusted by tuning returned arcs length of the required integer of λ.

Turn number	Total pathlength
1	$n \times 20\lambda + 7\lambda$
2	$n \times 20\lambda + 6\lambda$
3	$n \times 20\lambda + 3.5\lambda$



- o Maximize the distance between the lowest energy bunches (1 & 6): ovoid reducing the BBU threshold current due to the influence of HOMs kicks.
- o Achieve a nearly constant bunch spacing: minimize collective effects

injection of ALTO-like RIBS into the ERL



Largely inspired by the pioneering SCRIT example

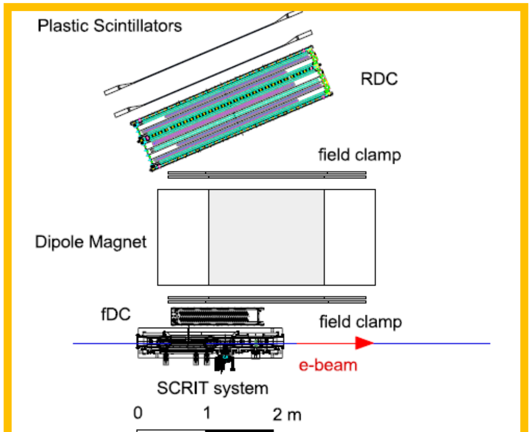
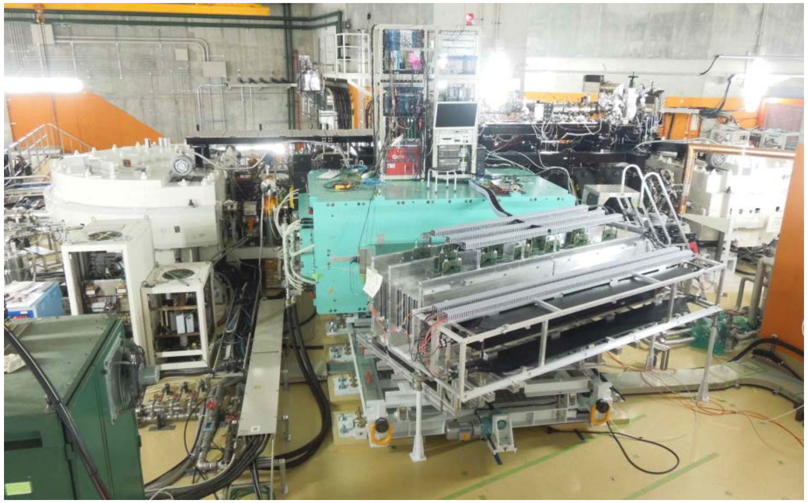


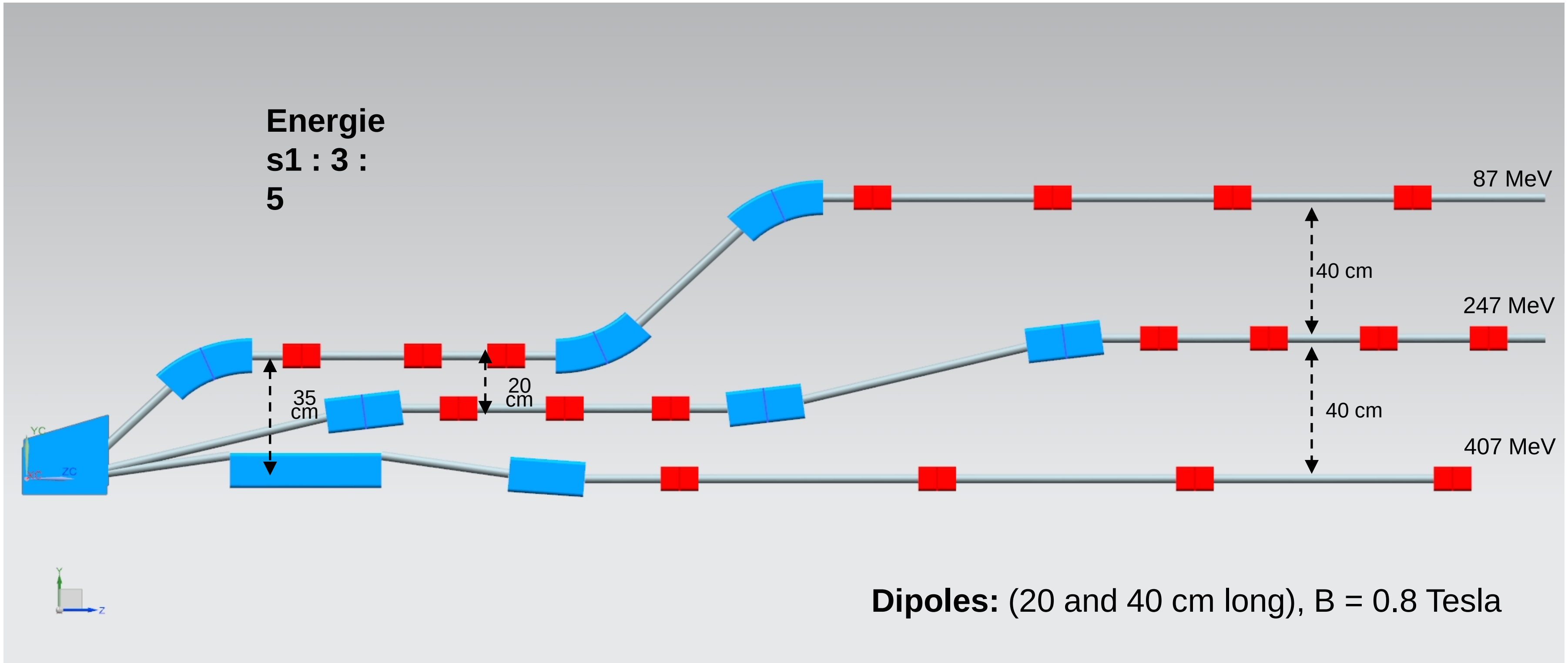
Figure 2. Schematic layout of detectors in WiSES.



T Ohnishi et al Phys. Scr. T166 (2015) 014071

The PERLE@Orsay configuration

Switchyard- Vertical Separation of Arcs (1, 3, 5):



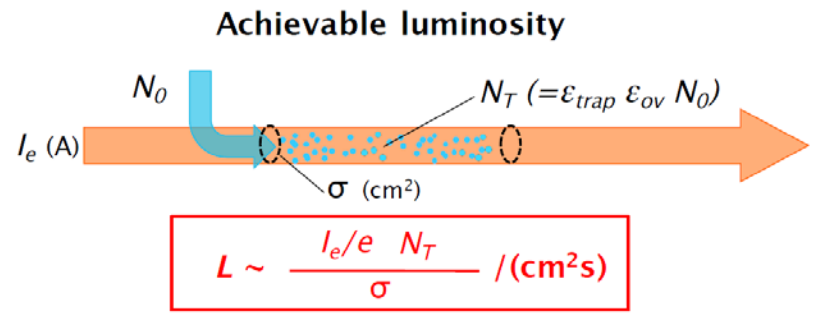
Courtesy W. Kaabi (LAL Orsay)
(LHeC/FCC-eh and PERLE Workshop, 27-29 June 2018, Orsay, France)

The DESTIN project

Chancé et al (CEA Saclay) **ETIC** project within GANIL-2025 (2015)
calculations within ERL hypothesis :

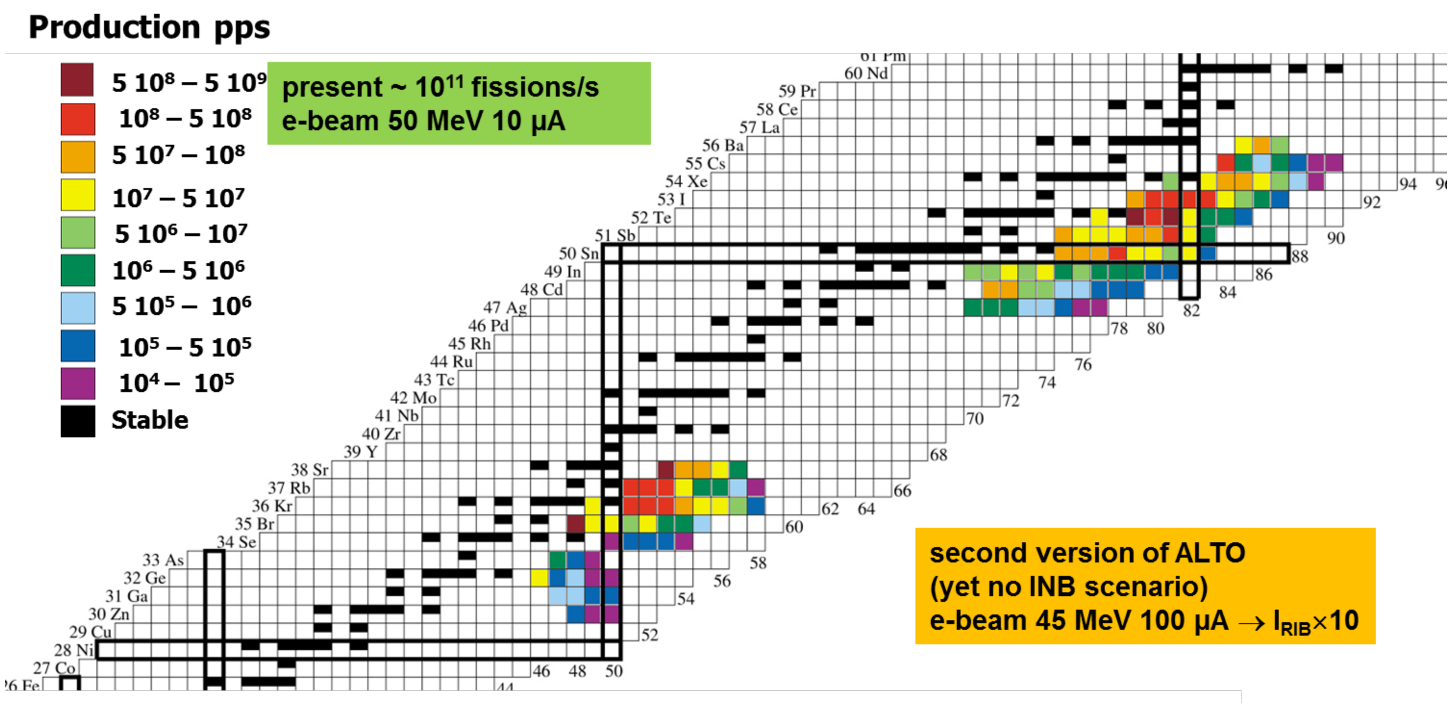
I_e=200 mA N_A=10^6 trapped ions: $\mathcal{L} \simeq 10^{29}$ should be achieved

based on
[A.N. Antonov et al., Nucl. Instr. and Meth. A **637** 60 (2011)] ELISE project GSI



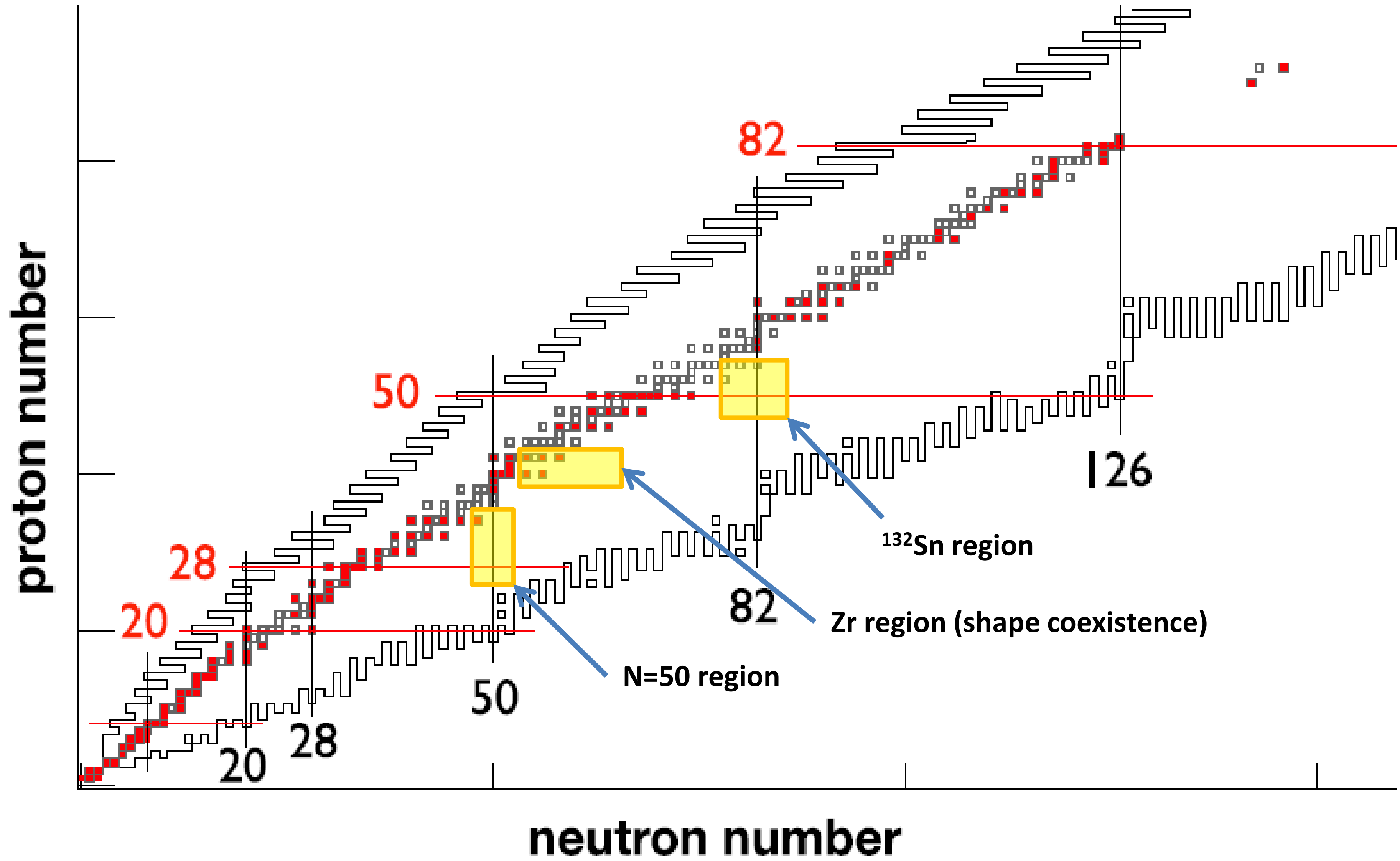
PERLE@Orsay : 20 mA $\rightarrow \mathcal{L} \simeq 10^{28}$ is *probably* achievable for a **10^6** trapped RI population **on the principle**

but the dynamical e-beam-RI coupling should be investigated : first time with a ERL time structure
e-beam instabilities ? impact on ERL operation ?

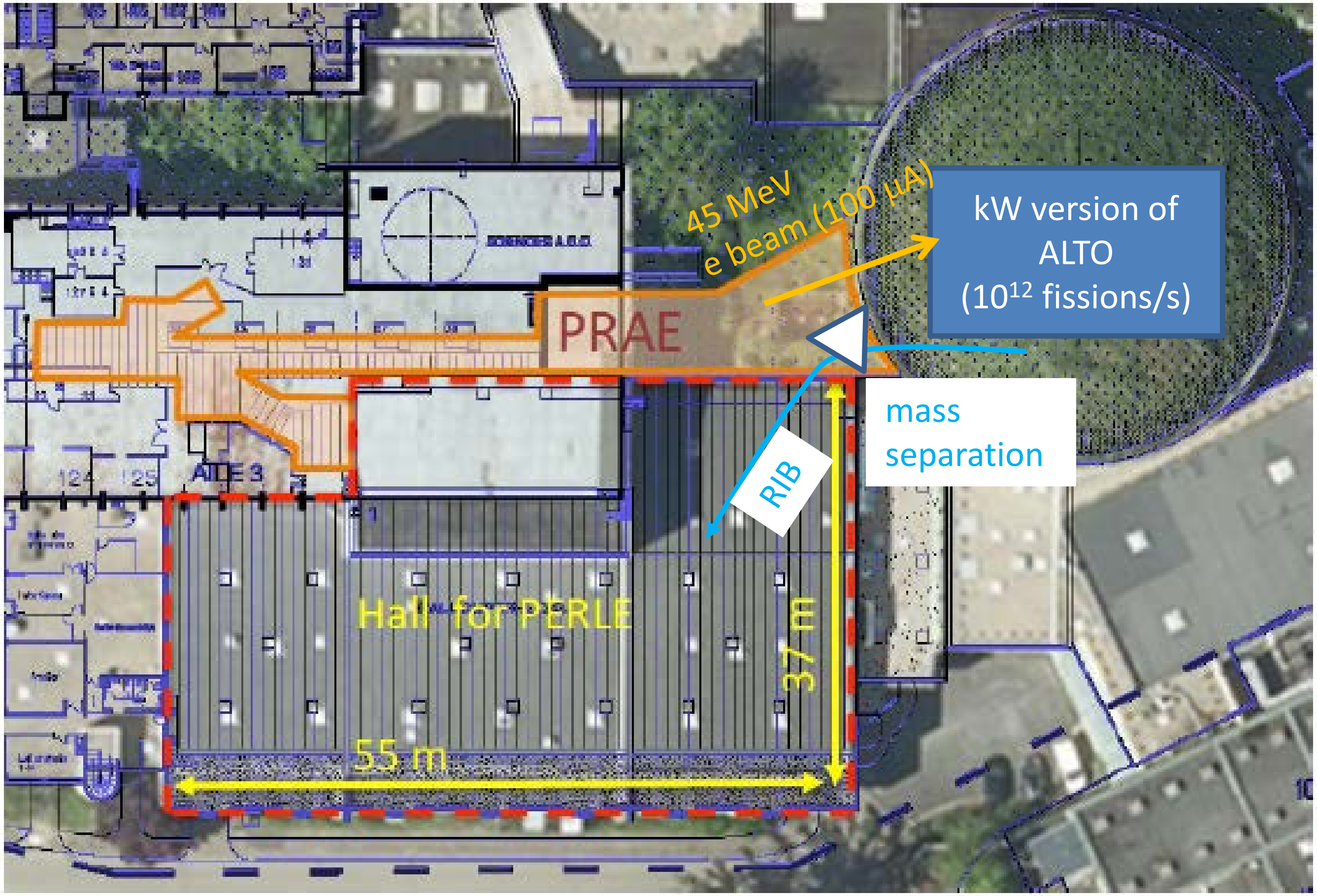


stable targets already used T. Suda, H. Simon [Progress in Particle and Nuclear Physics 96 (2017) 1]

radioactive targets envisioned with DESTIN

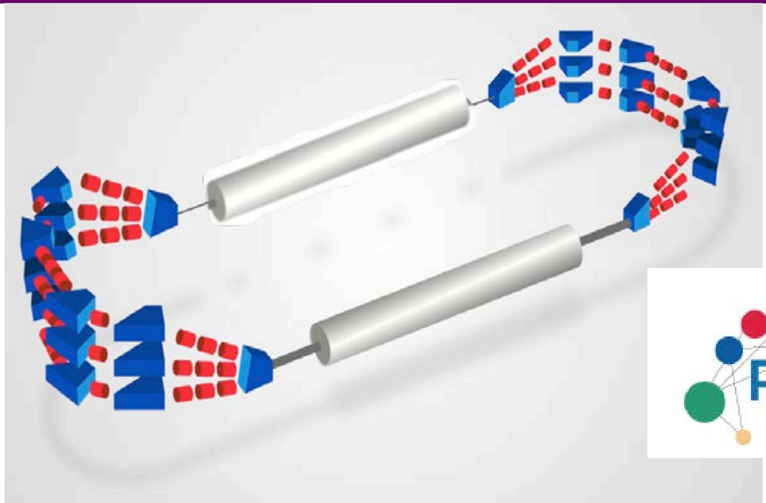


Possible layout for DESTIN



Conclusion & perspectives

the Orsay PERLE-based project DESTIN
[DEep STructure Investigation of (exotic) Nuclei]
is for the time being just in idea…



- to seize the opportunity of the construction of an ERL prototype on the Paris-Saclay University Campus to build an RI-e-scattering experimental setup (inspired by SCRIT)
  - site decision for PERLE within one year
  - requires to build/move/adapt the existing ALTO ISOL photofission facility in Orsay

- the aim:
  - demonstration setup : fixed radioactive target in ERL for the first time
    $\rightarrow$ towards a possible more ambitious ERL-based system ($\rightarrow \mathcal{L} \simeq \mathbf{10^{29}}$)
  - realize a sustainable, realistic physics program that would collect the interest of the LE nuclear physics community (local, national, international)
    (extension and deepening of the existing activity based on the em probe)