Nuclear physics in the era of radioactive ion beams

(matter at extremes)

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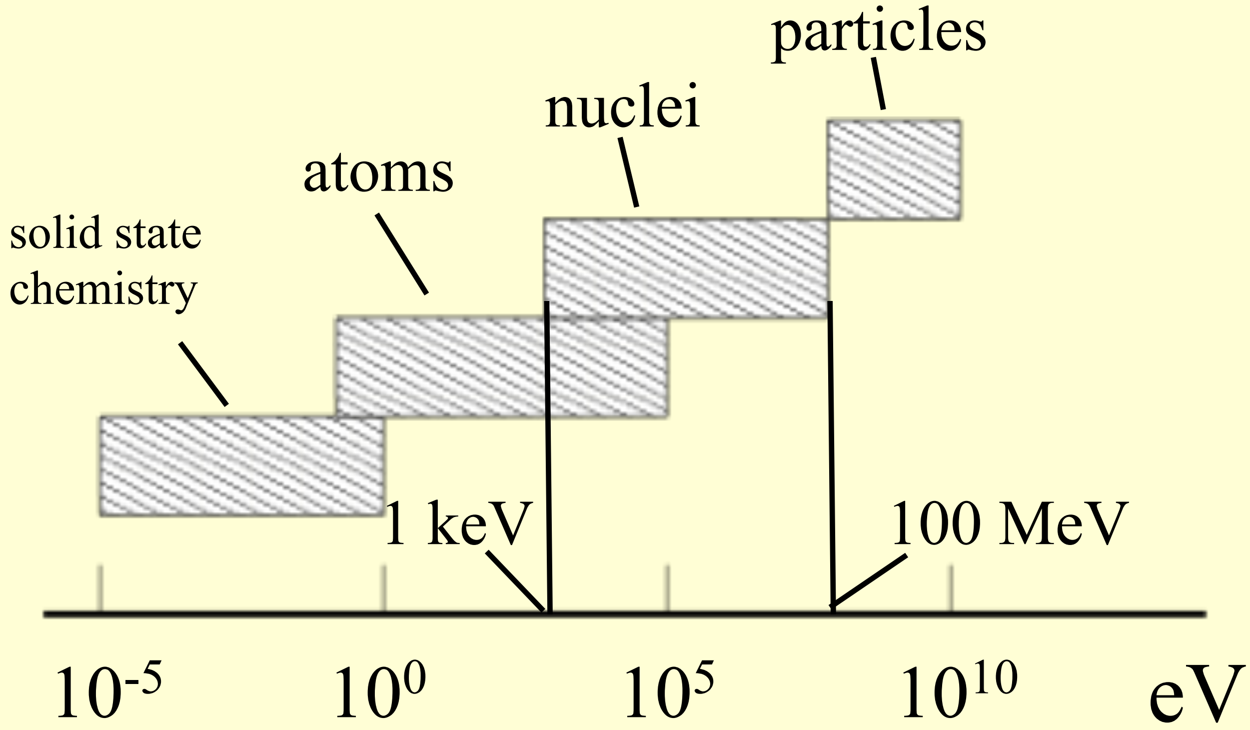
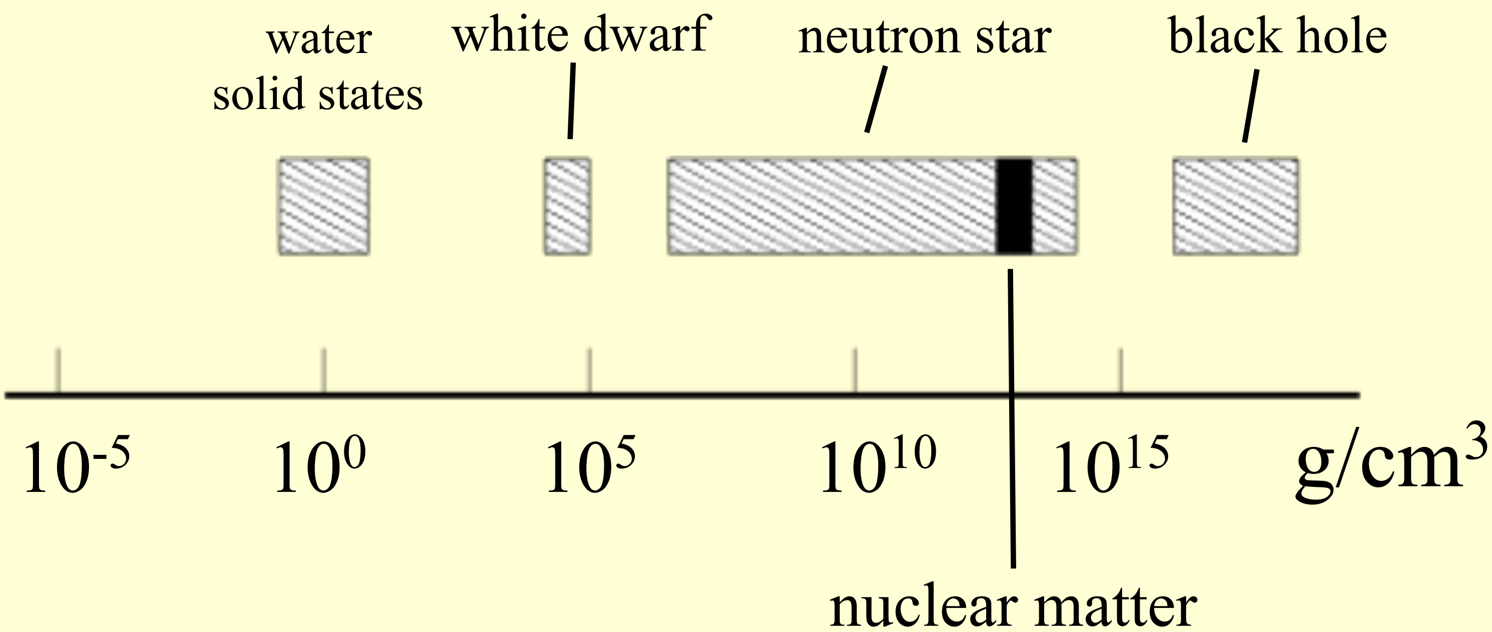
Scales

Energy scale



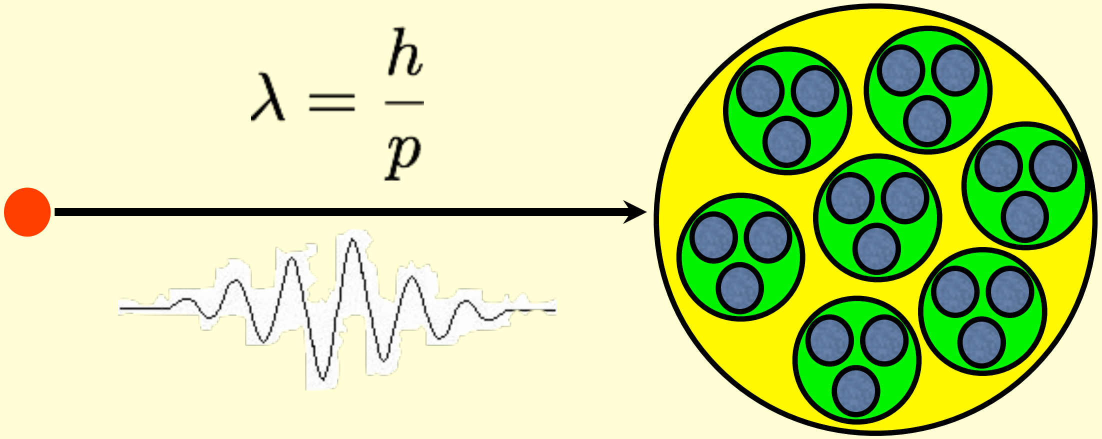
Scales

Density scale



How to probe (sub)nuclear matter?

$$\lambda = \frac{h}{p}$$



$$\Delta x \approx \lambda\!\!\!^{-} = \frac{\hbar c}{pc} = \frac{200\,\mathrm{MeV\,fm}}{pc}$$

$p = 10\,\mathrm{MeV/c}$ → $\Delta x \approx 20\,\mathrm{fm}$ Nucleus

$p = 100\,\mathrm{MeV/c}$ → $\Delta x \approx 2\,\mathrm{fm}$ Nucleons

$p = 1000\,\mathrm{MeV/c}$ → $\Delta x \approx 0.2\,\mathrm{fm}$ Quarks

Forces in nuclei

two protons, 1 fm apart

1. Strong interaction (QCD) scale: 1

   - responsible for nuclear binding
   - alpha decay, nuclear fission and fusion processes

2. Electromagnetic interaction scale: 0.01

   - correction to binding energies, N>Z for heavy nuclei
   - gamma decay of excited states

3. Weak interaction scale: 0.0000001

   - nuclear beta decay
   - mirror symmetry violation

4. Gravitational interaction scale: 10^{-36}

   - forget it!

Not only the effective strong force, but also e.m. and weak interactions play an important role in understanding nuclear physics!

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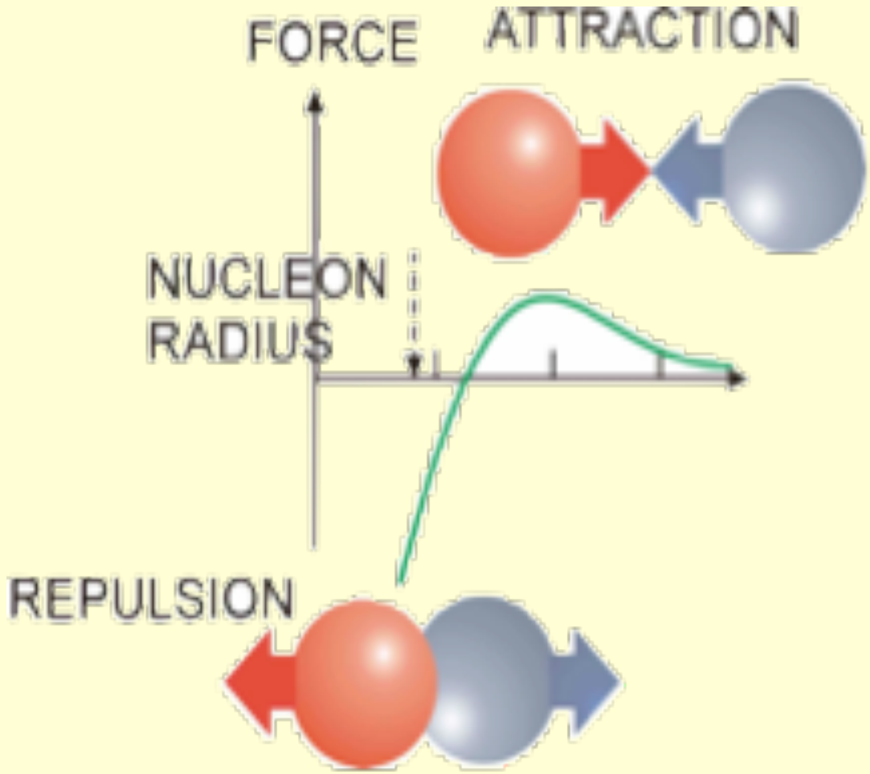
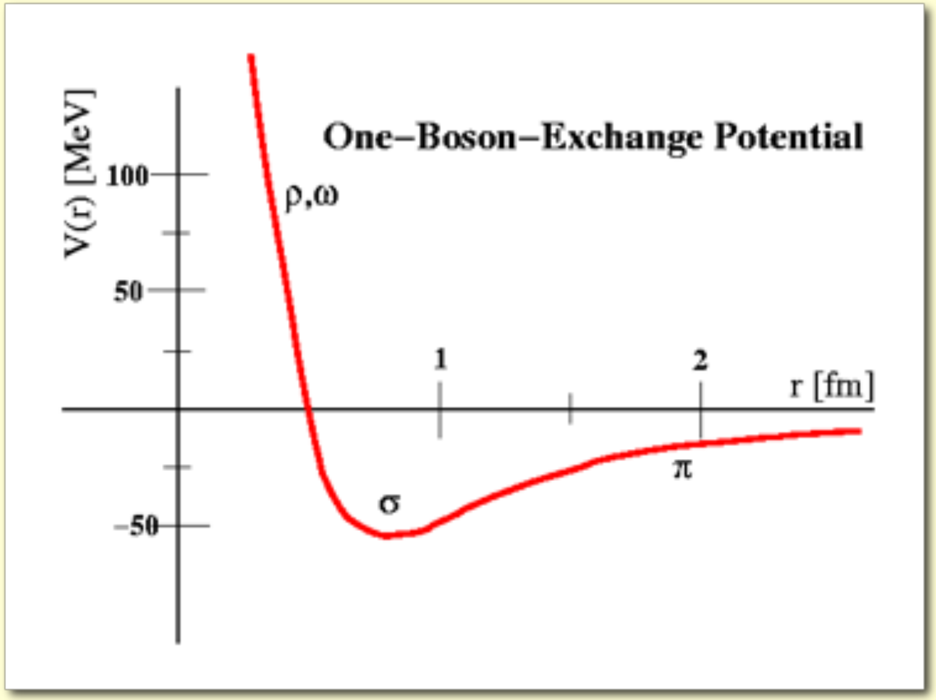
Nuclear potential (start with NN potential)





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NN potential, phenomenological structure

Most general two-body potential under those symmetries
(Okubo and Marshak, *Ann. Phys.* **4**, 166 (1958))

Central term

$$V_{NN} = V_0(r) + V_\sigma \sigma_1 \cdot \sigma_2 + V_\tau(r)\, \tau_1 \cdot \tau_2 + V_{\sigma\tau}(r)(\sigma_1 \cdot \sigma_2)(\tau_1 \cdot \tau_2)$$

$$+V_{LS}(r)\, \vec{L} \cdot \vec{S} + V_{LS\tau}(r)(\vec{L} \cdot \vec{S})(\tau_1 \cdot \tau_2)$$ ← Spin orbit

$$+V_T(r)\, S_{12} + V_{T\tau}(r)\, S_{12}(\tau_1 \cdot \tau_2)$$ ← Tensor

+higher terms in L and p

$$S_{12} = 3(\sigma_1 \cdot \vec{r})(\sigma_2 \cdot \vec{r})/r^2 - \sigma_1 \cdot \sigma_2$$

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The Yukawa theory of nuclear forces

S. Tomonaga, H. Yukawa, and S. Sakata in the 1950s.

From:

H. Yukawa, Proc. Phys. Math. Soc. Japan **17**, 48 (1935).

In analogy with the scalar potential of the electromagnetic field, a function $U(x, y, z, t)$ is introduced to describe the field between the neutron and the proton. This function will satisfy an equation similar to the wave equation for the electromagnetic potential.

Now the equation

$$\left\{\Delta - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right\} U = 0 \tag{1}$$

has only static solution with central symmetry $\frac{1}{r}$, except the additive and the multiplicative constants. The potential of force between the neutron and the proton should, however, not be of Coulomb type, but decrease more rapidly with distance. It can be expressed, for example, by

$$+ \text{ or } -g^2\frac{e^{-\lambda r}}{r}, \tag{2}$$

where g is a constant with the dimension of electric charge, i. e., cm.$^{\frac{3}{2}}$ sec.$^{-1}$ gr.$^{\frac{1}{2}}$ and λ with the dimention cm.$^{-1}$

Since this function is a static solution with central symmetry of the wave equation

$$\left\{\Delta - \frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \lambda^2\right\} U = 0, \tag{3}$$

let this equation be assumed to be the correct equation for U in vacuum. In the presence of the heavy particles, the U-field interacts with them and causes the transition from neutron state to proton state.

Effective potentials in nuclei

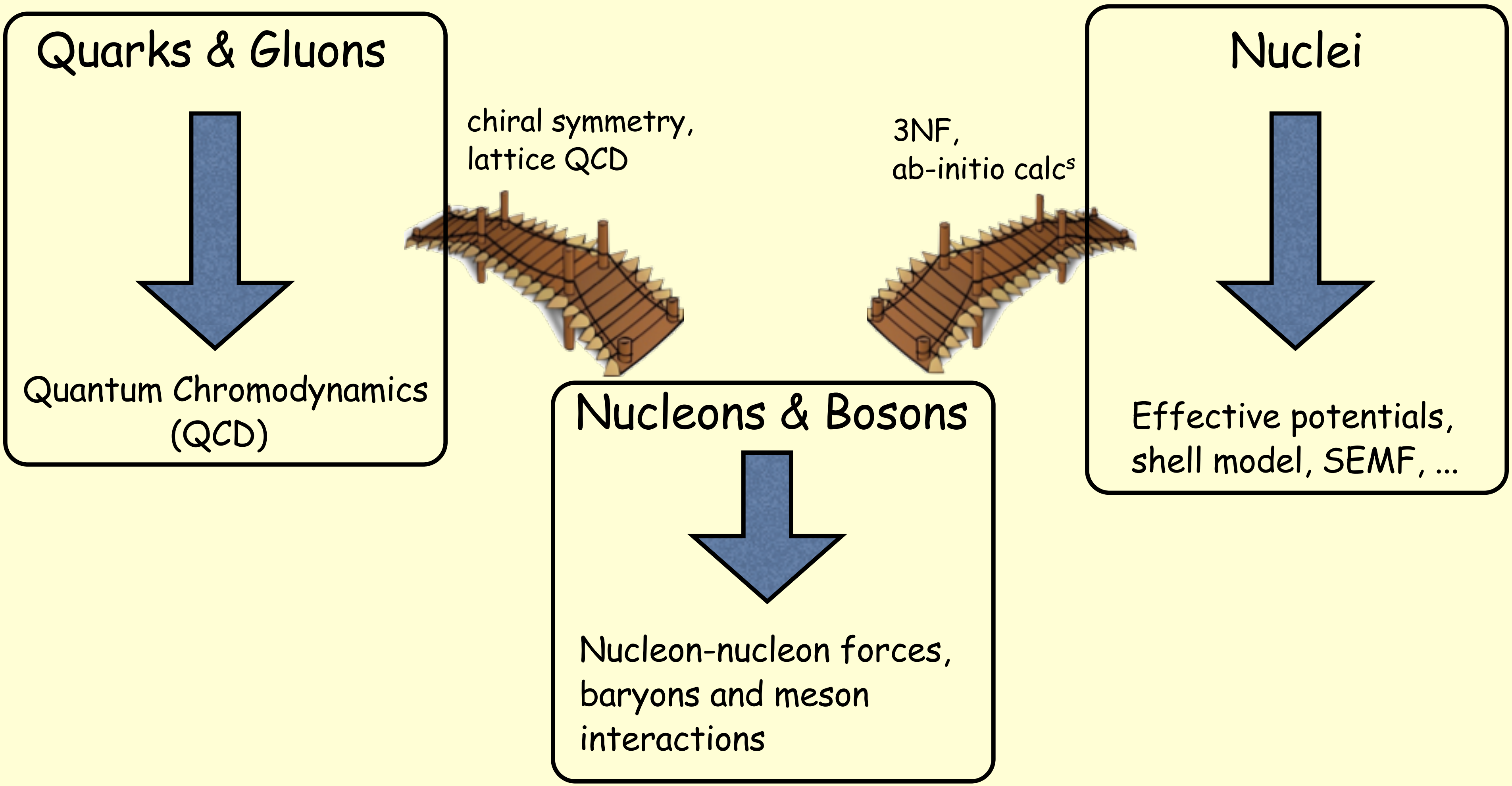
N-N potential

$$\hat{H} = \sum_{i=1}^{A} \frac{\hat{p}_i^2}{2m_i} + \sum_{i<j=1}^{A} V(\vec{r}_i, \vec{r}_j)$$

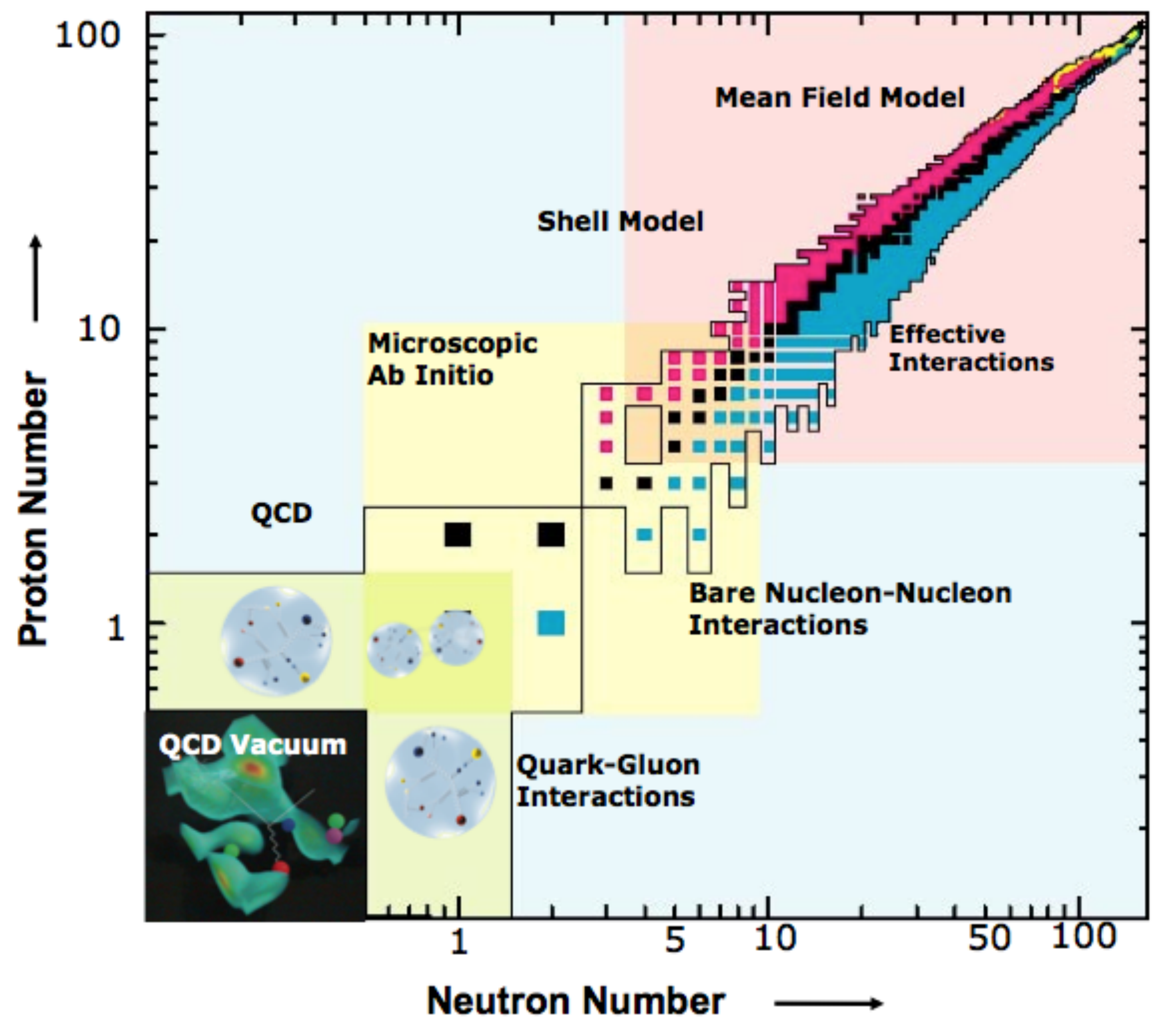
"name of the game"

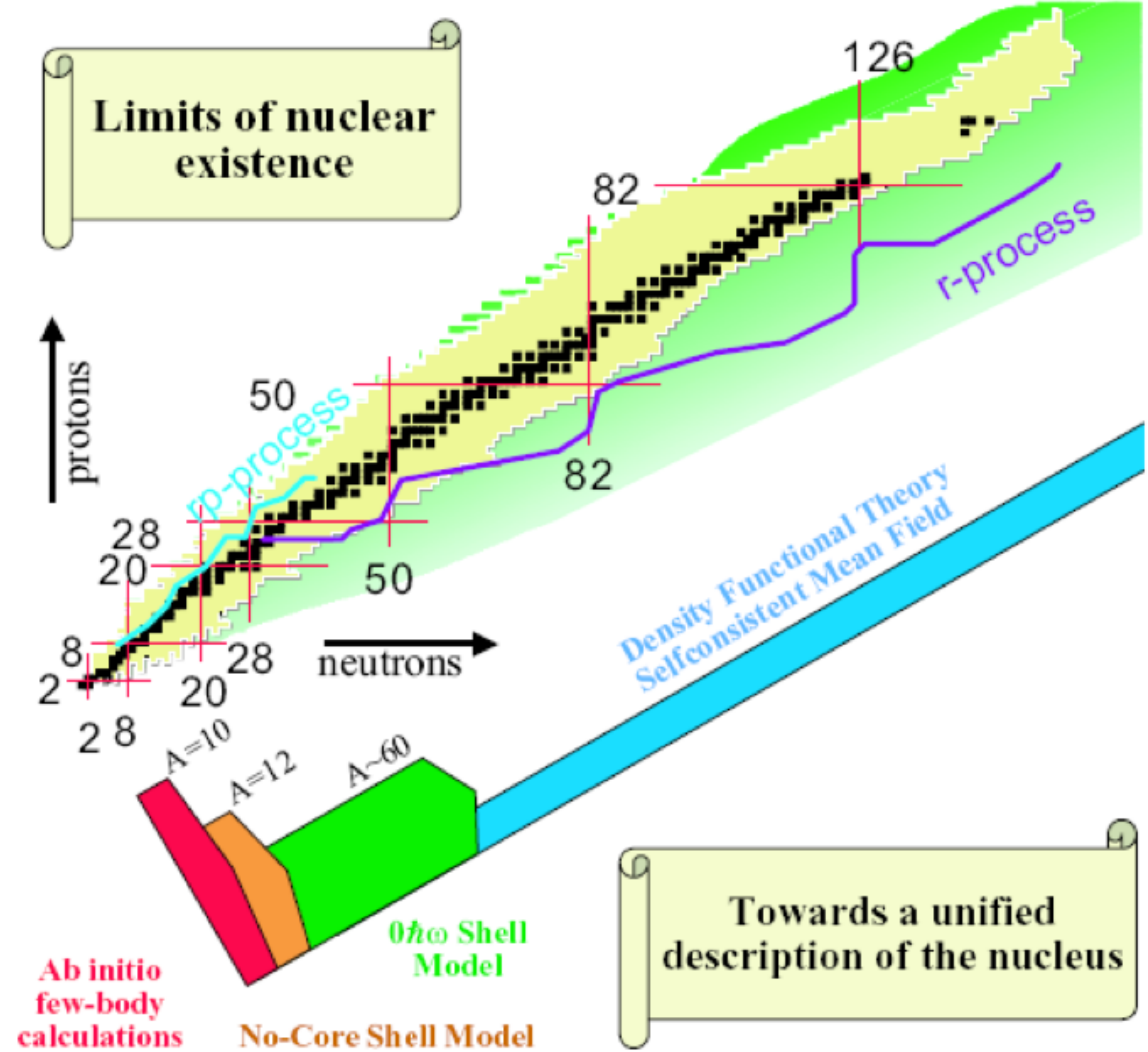
$$\hat{H} = \sum_{i=1}^{A} \left(\frac{\hat{p}_i^2}{2m_i} + U(\vec{r}_i) \right)$$

effective one-body potential


Quarks & Gluons
Quantum Chromodynamics (QCD)
chiral symmetry, lattice QCD
Nucleons & Bosons
Nucleon-nucleon forces, baryons and meson interactions
3NF, ab-initio calcs
Nuclei
Effective potentials, shell model, SEMF, ...

Nuclear Chart





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What to measure?

its weight

its size

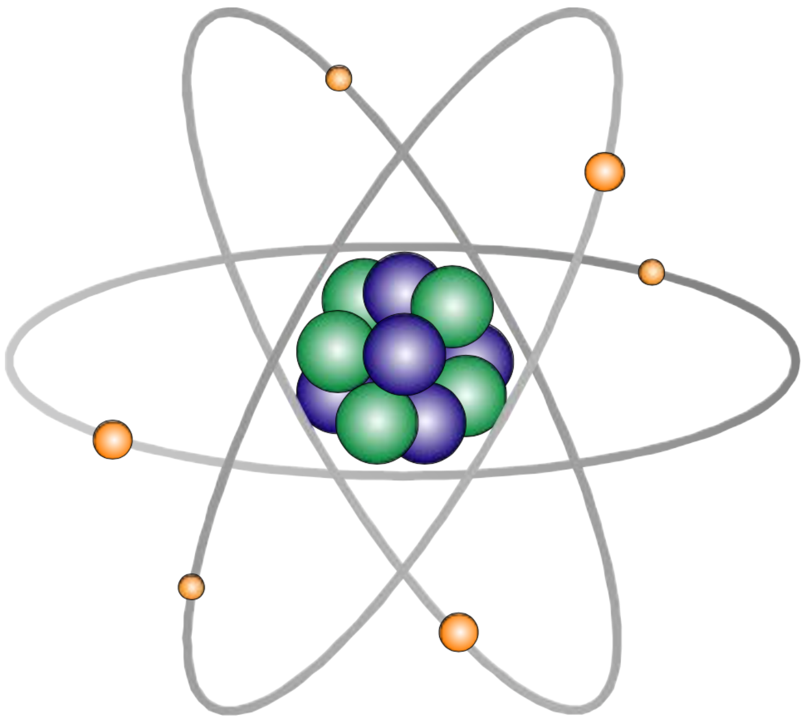
its life-time/decay

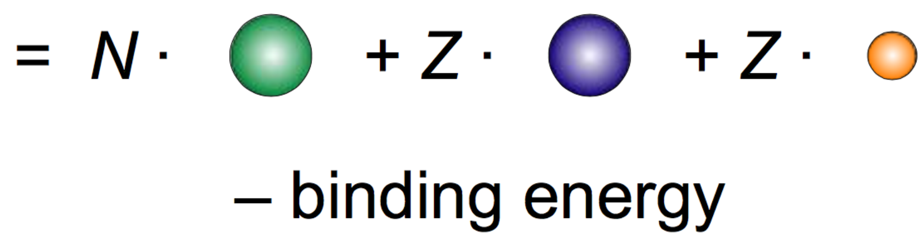
its shape

its e.m. properties

its mood (state)

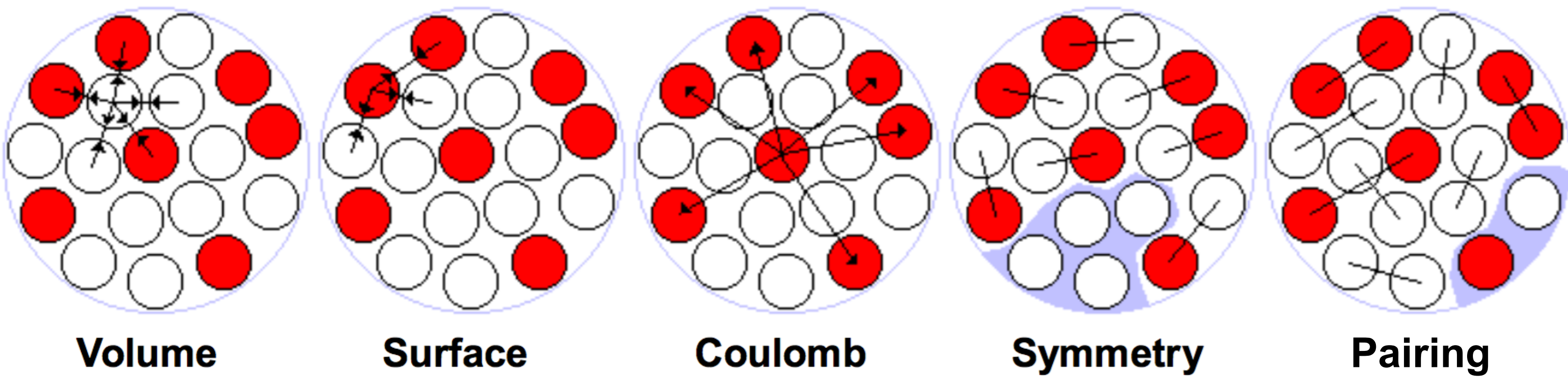
Masses determine the atomic and nuclear binding energies reflecting all forces in the atom/nucleus





$$M_{Atom} = N \bullet m_{neutron} + Z \bullet m_{proton} + Z \bullet m_{electron} - (B_{atom} + B_{nucleus})/c^2$$

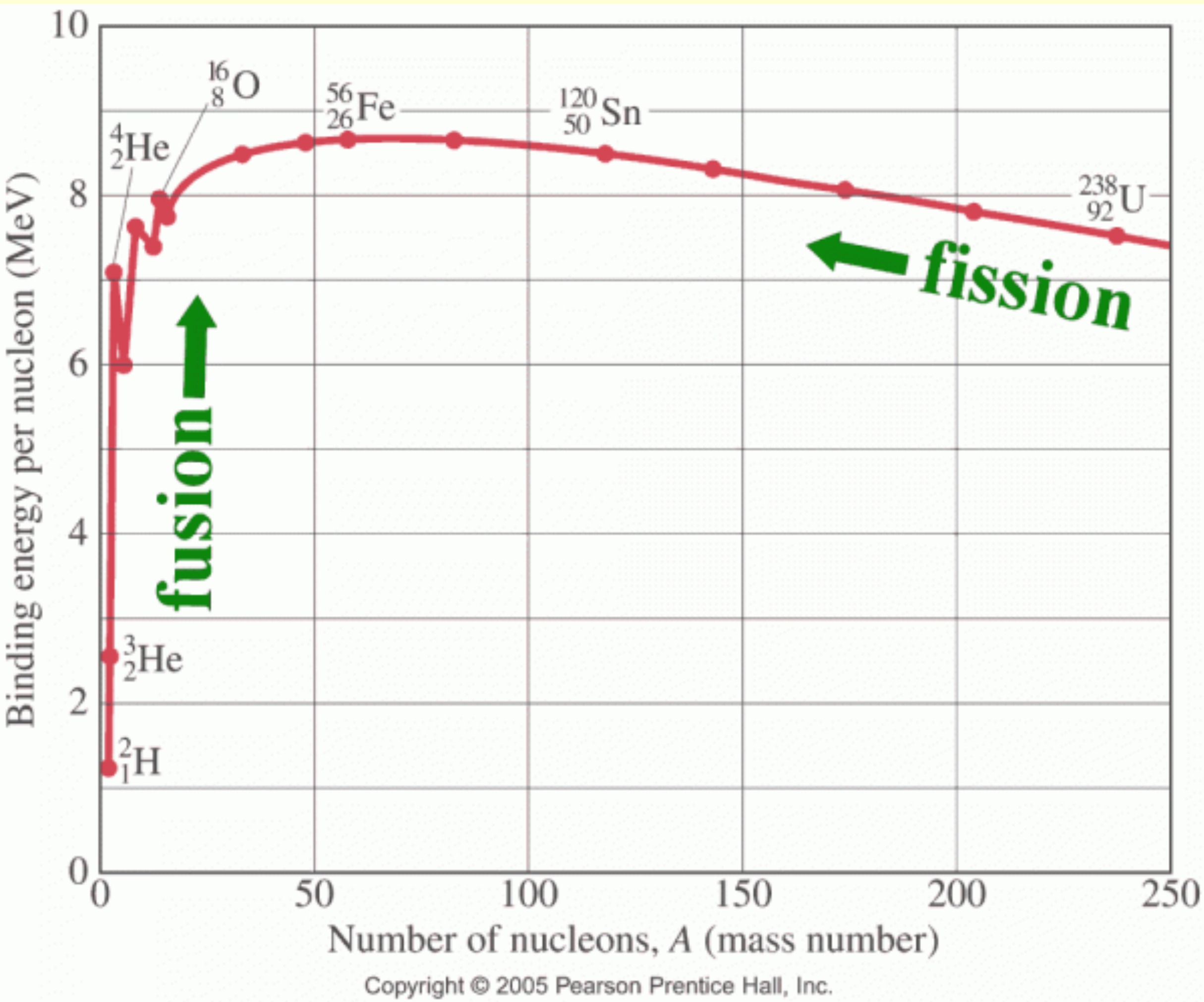
Empirical mass formula

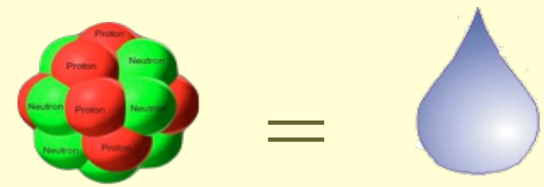


Liquid drop model

Semi-empirical mass formula
(Carl Friedrich von Weizsaecker, 1935)

$$E_B = a_V A - a_S A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_A \frac{(A-2Z)^2}{A} + \delta(A,Z)$$

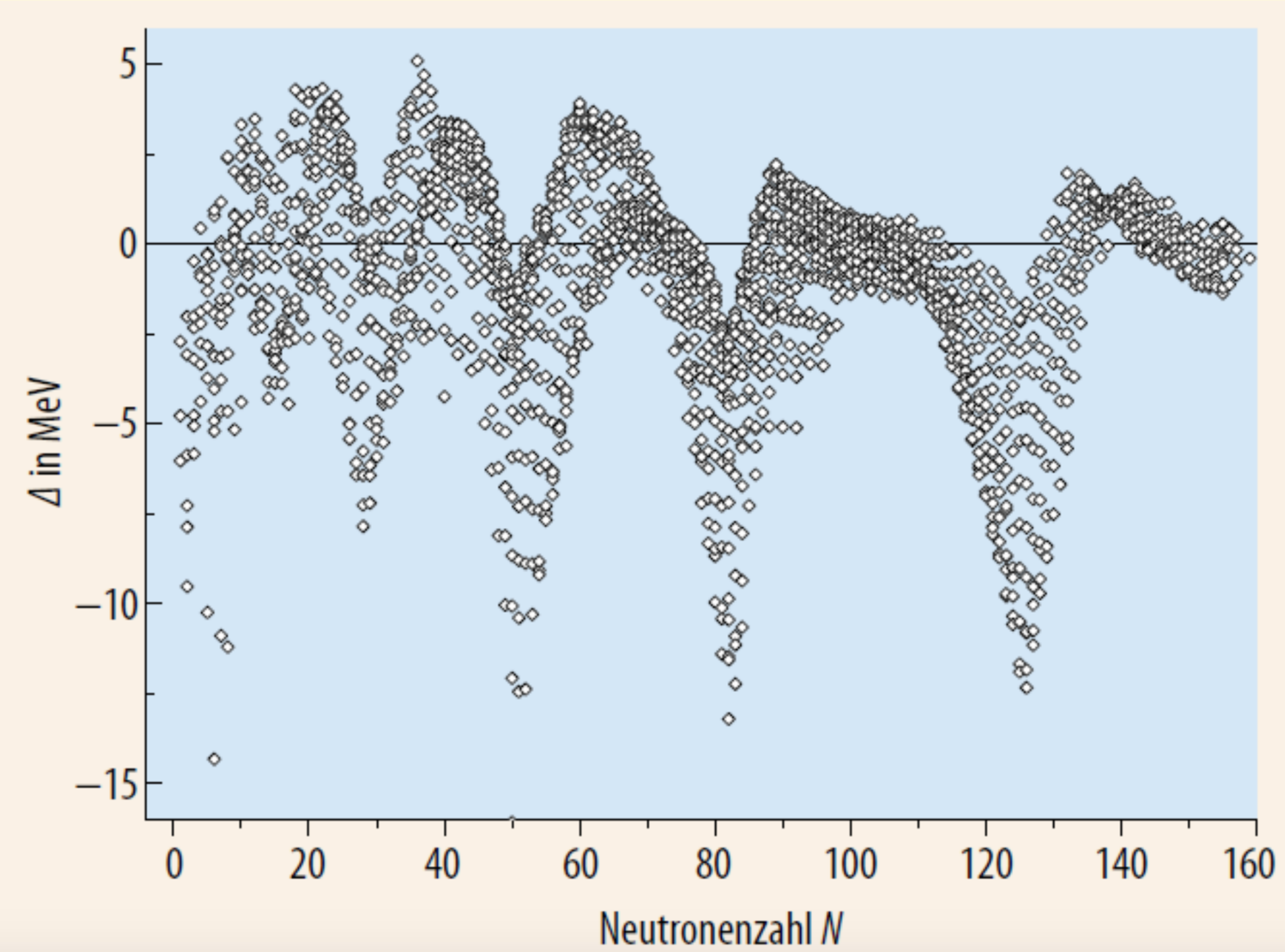




Liquid drop model provides a qualitative description of some of the bulk properties of the nucleus, such as the binding energy

But what about the “magic” numbers? Other models are needed, such as the shell model...

$M_{exp} - M_{emp}$



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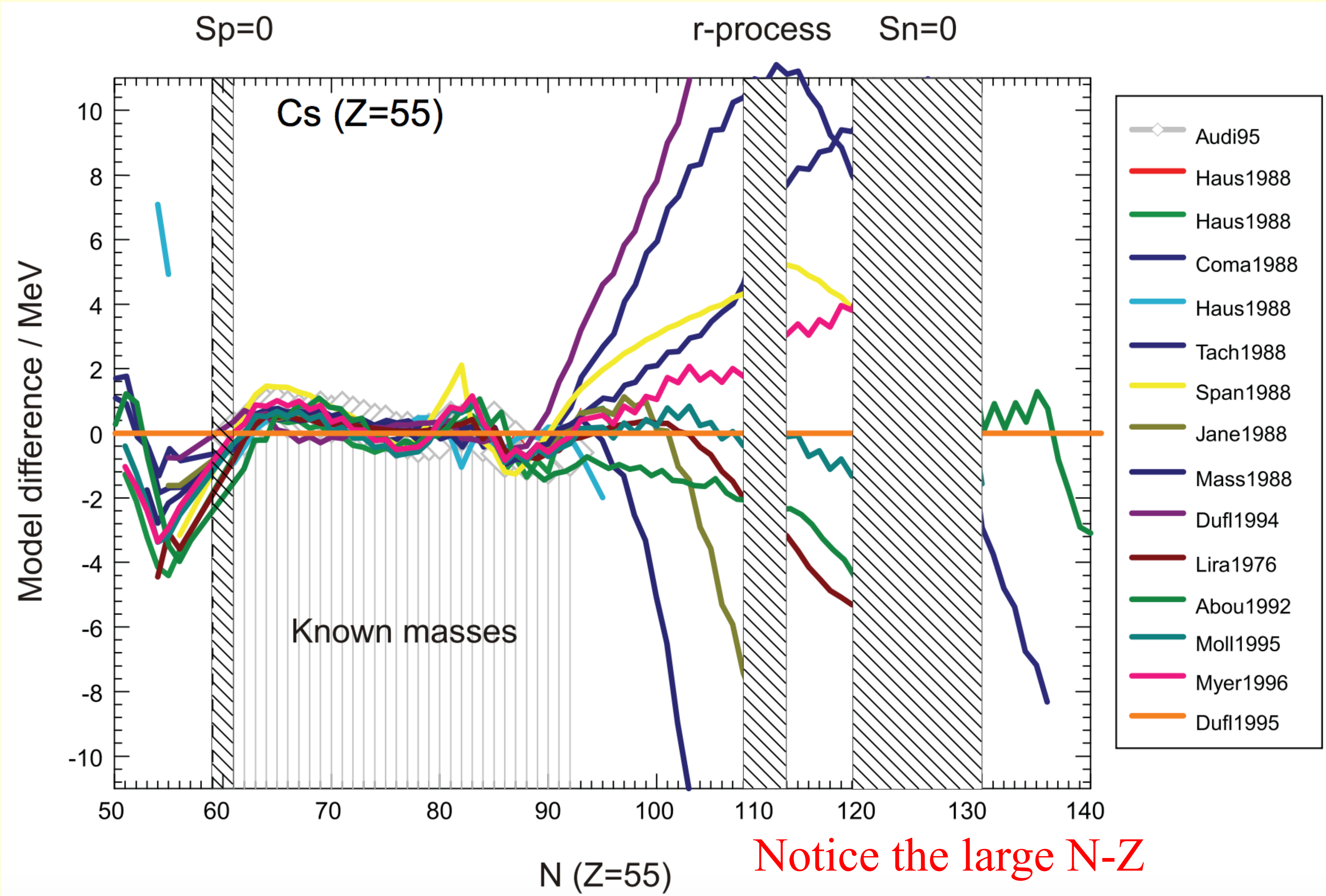
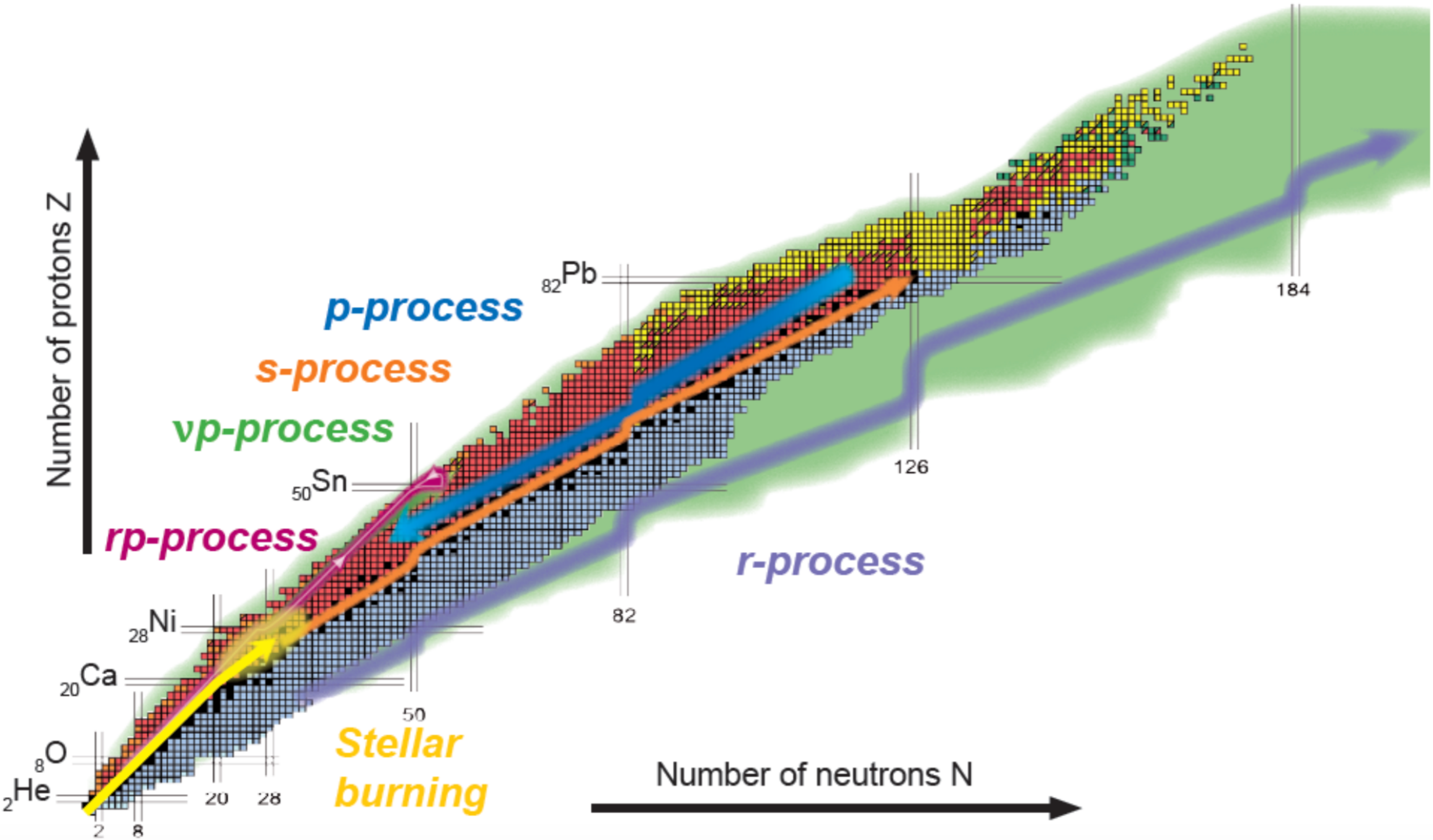
Model differences

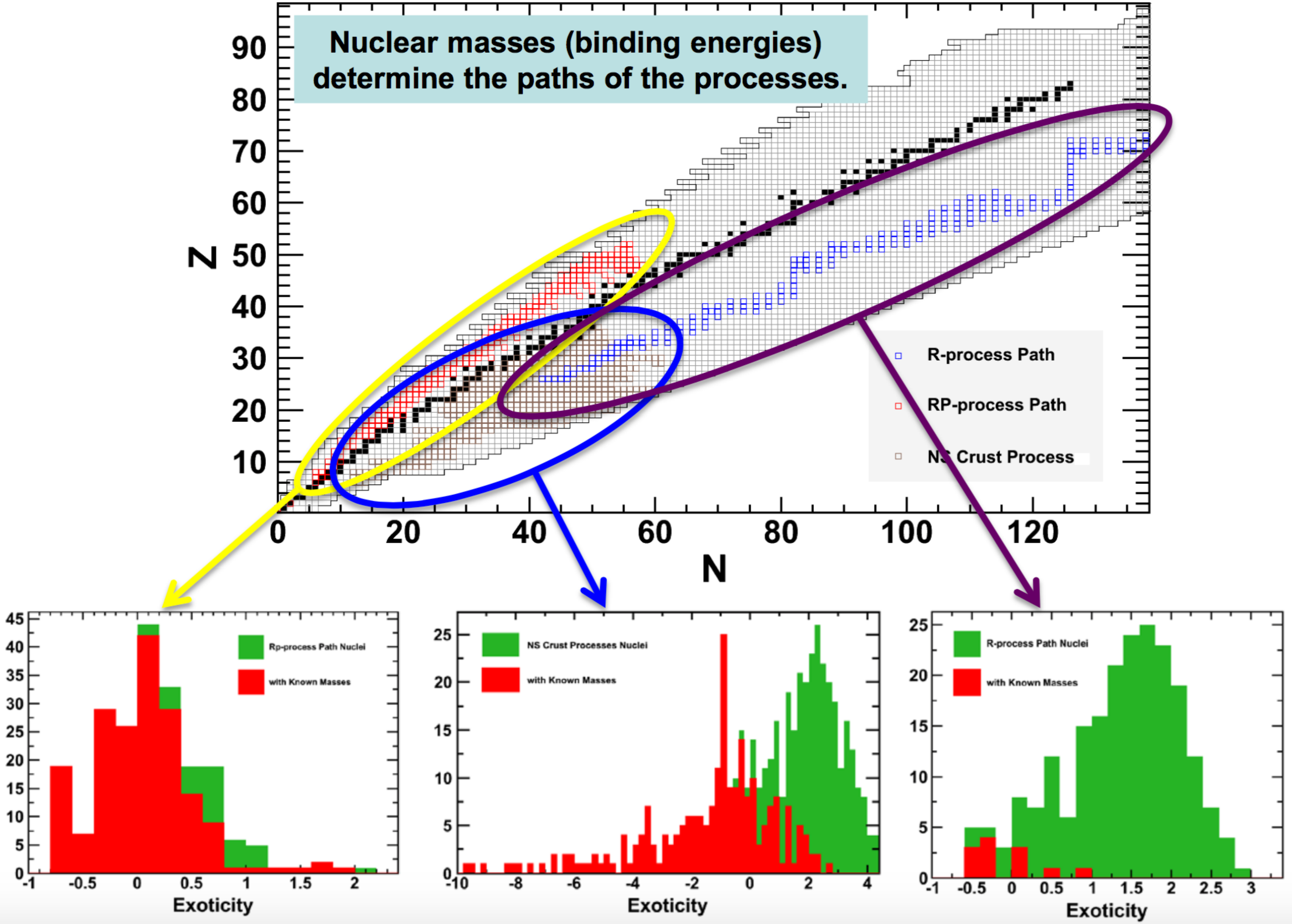


Notice the large N-Z

Nuclear and astrophysics meet

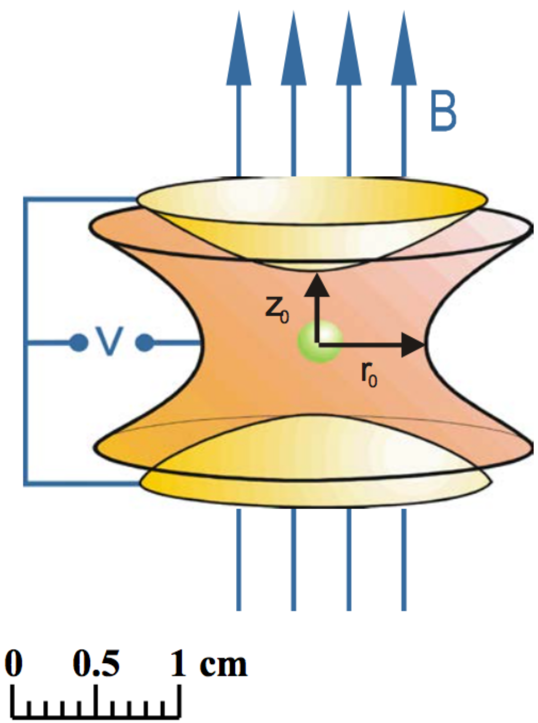


Mass spectrometry for nucleosynthesis

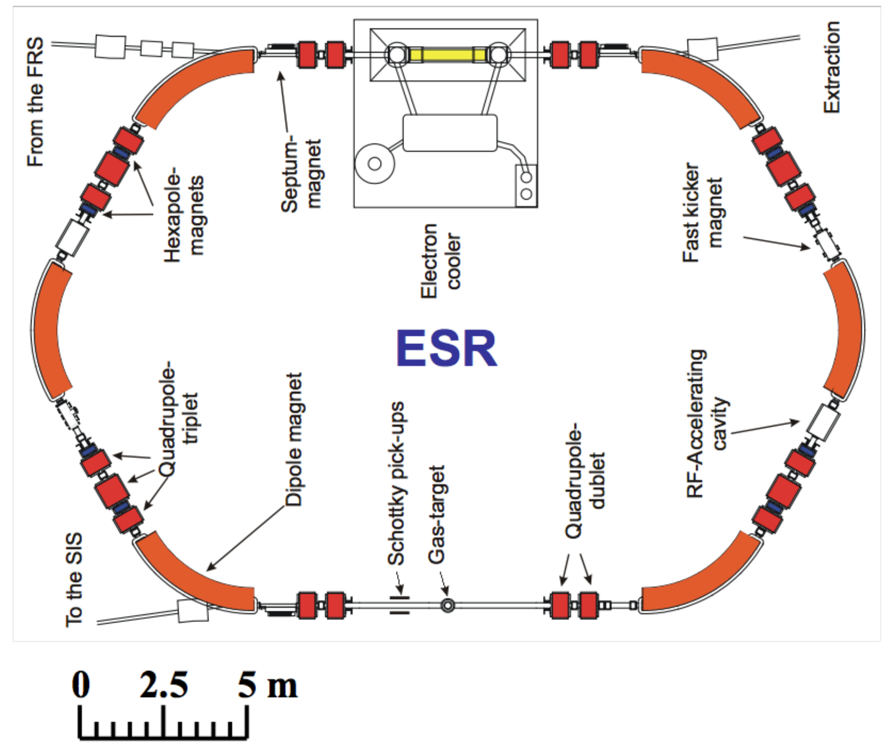


Mass-measurement techniques

Penning trap



Storage ring



Particles nearly at rest in space

✔ Ions cooled
✔ Single-ion sensitivity

Relativistic particles

✔ Long storage times
✔ High accuracies

Equation of motion in a Penning trap

plus Lorentz force:

$$\vec{F} = -e_0 \vec{\nabla}\phi(r) + \vec{v} \times \vec{B}$$

equation of motion:

$$\vec{F} = -e_0 \left(\vec{\nabla}\phi(r) + \vec{v} \times \vec{B}\right) + m\ddot{\vec{r}} = 0$$

axial oscillation

$$\frac{2e_0 U_0}{m d_0^2} \cdot z + m\ddot{z} = 0$$

$$\omega_z = \sqrt{\frac{2e_0 U_0}{m d_0^2}}$$

z or axial frequency

radial oscillation

substitution:

$$u = x + iy$$

$$\omega_c = \frac{e_0}{m} B$$

$$u(t) = u_0 e^{-i\omega t}$$

$$i\omega_c \dot{u} - \frac{\omega_z^2}{2} u + \dot{u} = 0$$

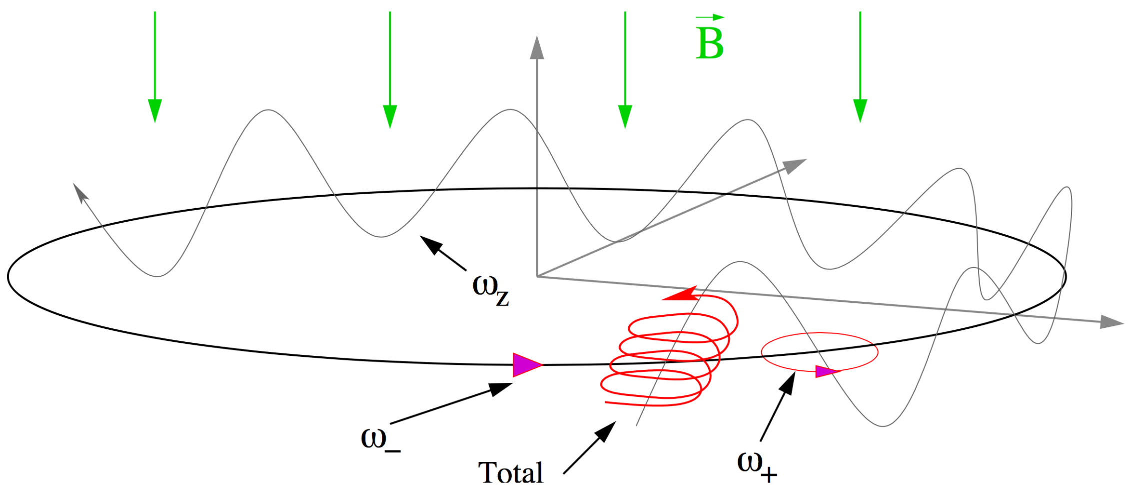
$$\omega_+ = \frac{\omega_c}{2} + \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

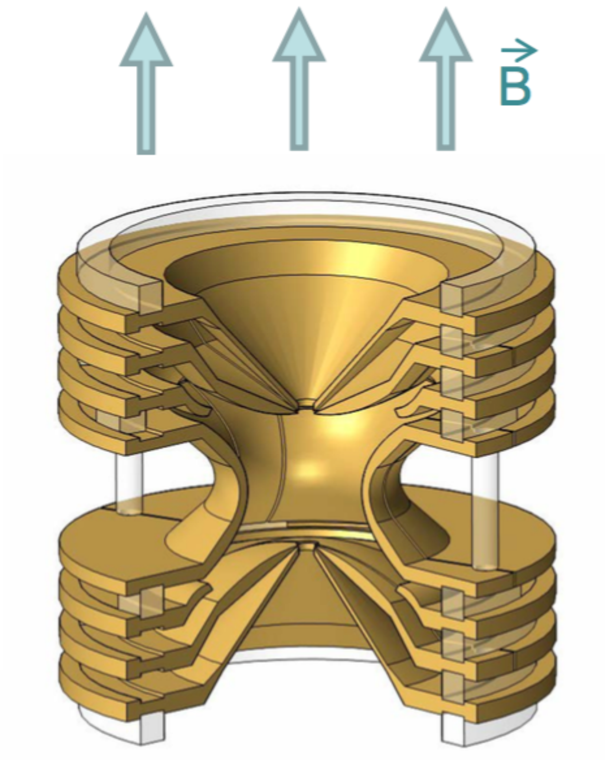
modified cyclotron frequency

$$\omega_- = \frac{\omega_c}{2} - \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

magnetron frequency

Penning trap at work





The free cyclotron frequency is inverse proportional to the mass of the ions!

$$\omega_c = qB/m$$

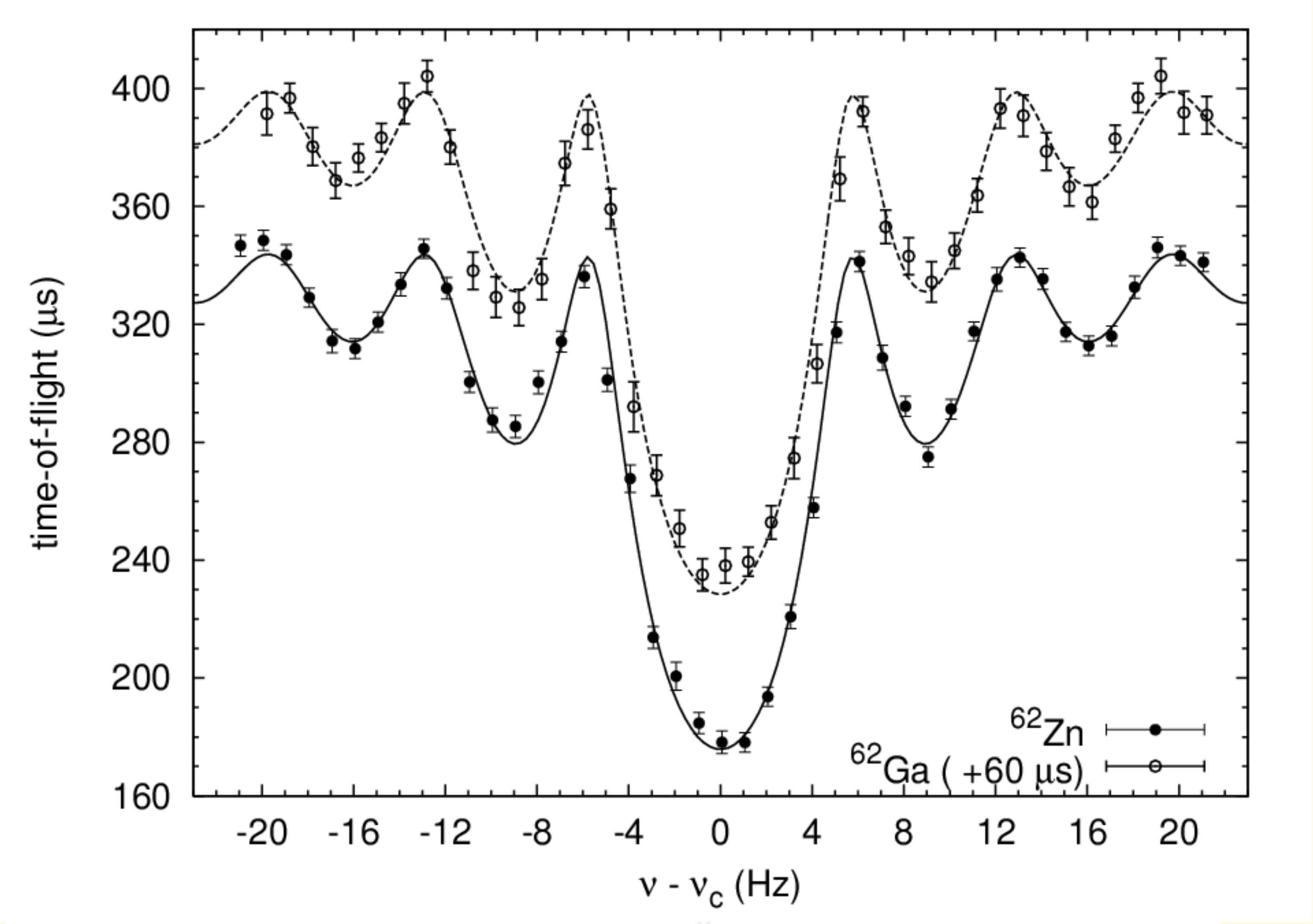
An ***invariance theorem*** saves the day:

$$\omega_c^2 = \omega_+^2 + \omega_-^2 + \omega_z^2$$

$$\omega_c = \omega_+ + \omega_-$$

L.S. Brown, G. Gabrielse, Rev. Mod. Phys. 58, 233 (1986).
K. Blaum, Phys. Rep. 425, 1 (2006).

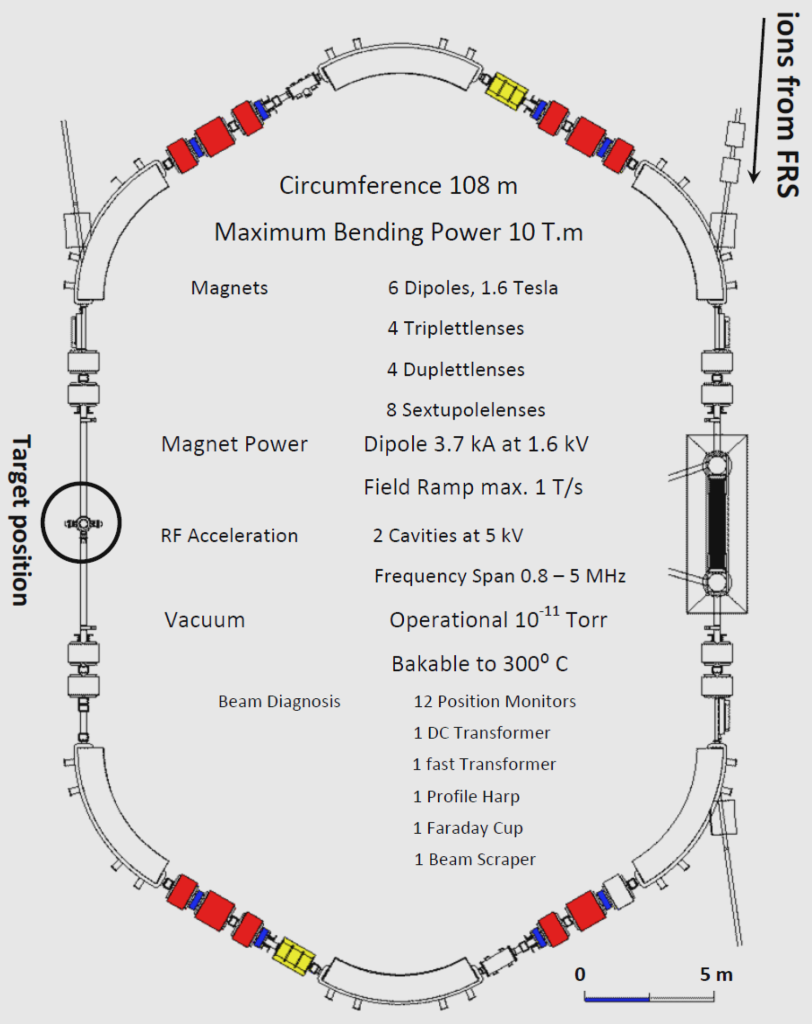
Penning trap measurement



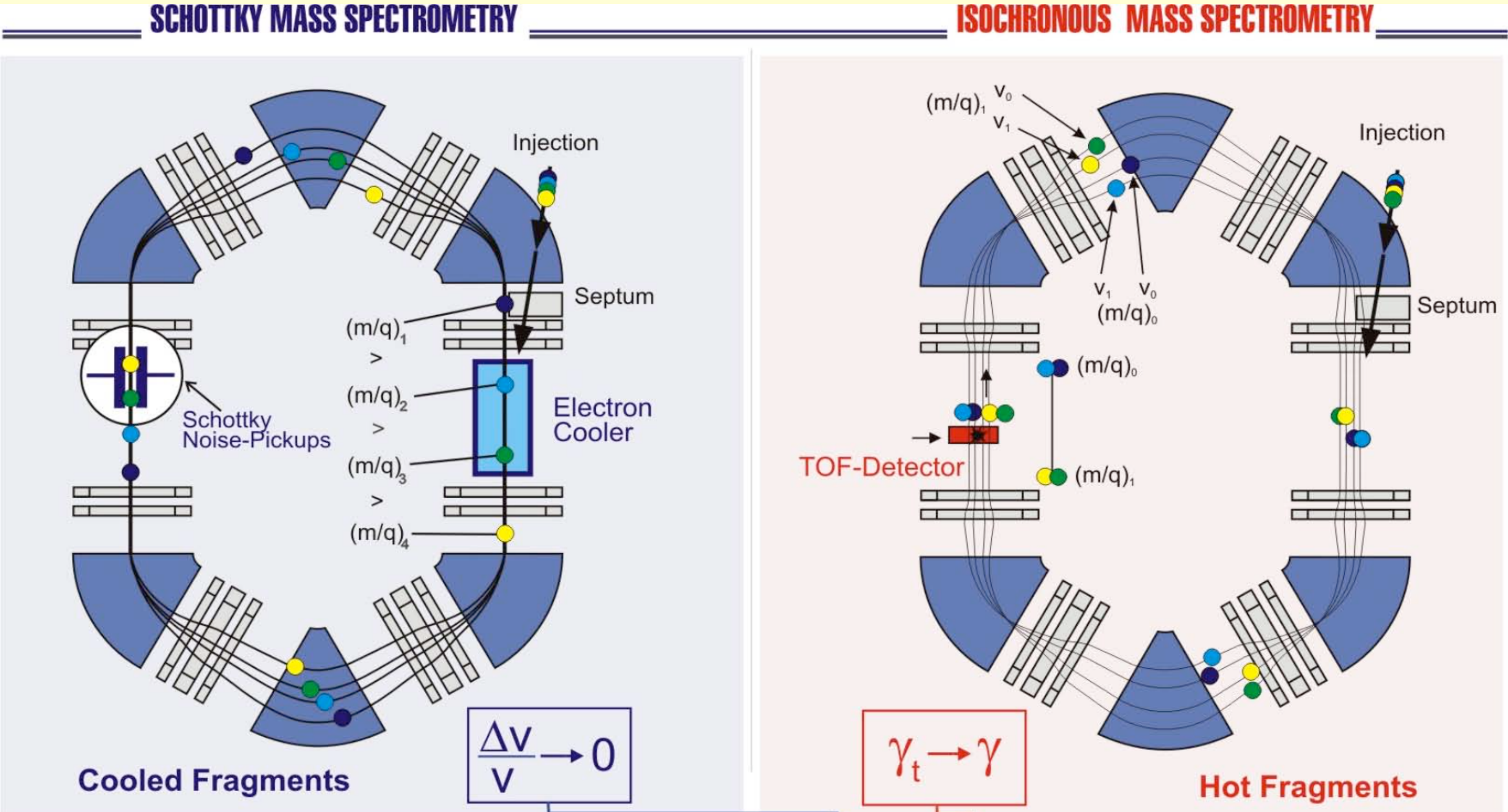
Mass measurement in a storage ring

$$\frac{\Delta t}{t} = -\frac{\Delta f}{f} = \frac{1}{\gamma_t^2} \cdot \frac{\Delta(m/q)}{m/q} + (\frac{\gamma^2}{\gamma_t^2} - 1) \cdot \frac{\Delta v}{v}$$

- Isochronous Mass Spectrometry $\gamma \rightarrow \gamma_t$
- Schottky Mass Spectrometry $\frac{\Delta v}{v} \rightarrow 0$



Mass measurement in a storage ring



Stochastic
+
Electron cooling

$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \frac{\Delta v}{v}\left(1-\frac{\gamma^2}{\gamma_t^2}\right)$$

Isochronous optics

ILIMA

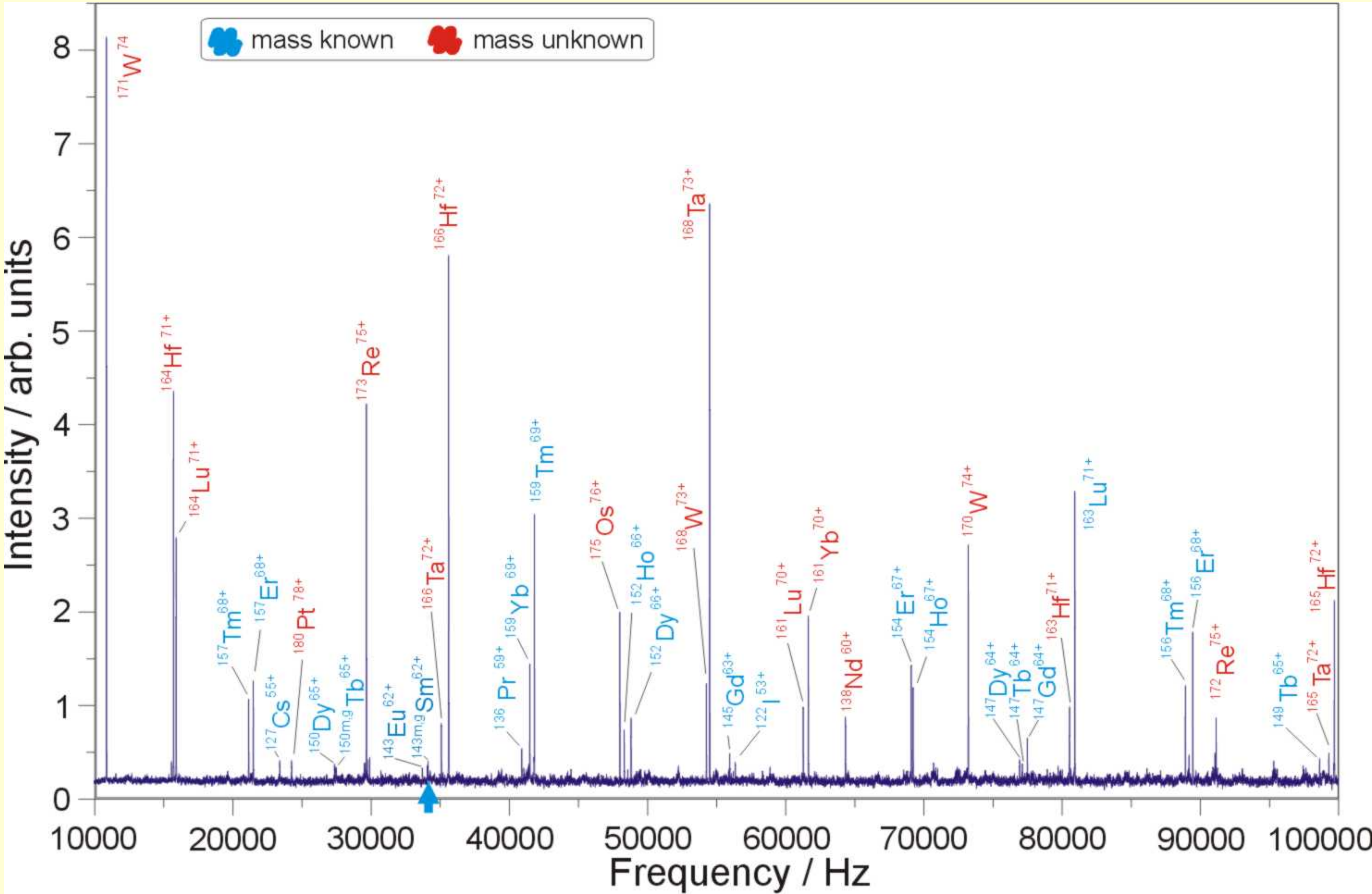
Using storage rings

Schottky Mass Spectrometry (with cooling): $T_{½} > 1$ s

Isochronous Mass Spectrometry: $T_{½} > 10$ μs

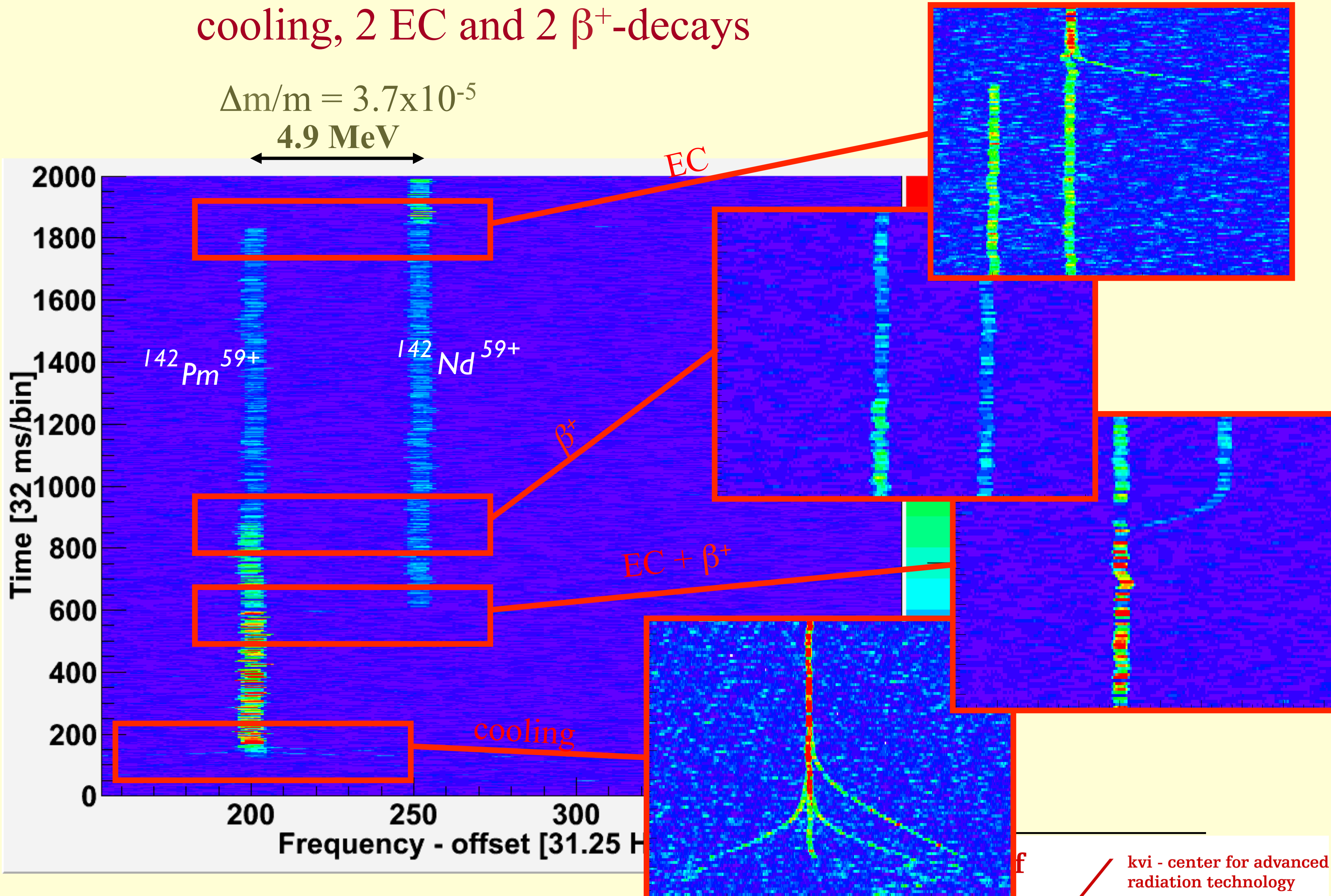
resolving power ~ 10^6
accuracy ~ 30 μu, i.e. ~ 30 keV

Schottky Mass Spectrometry



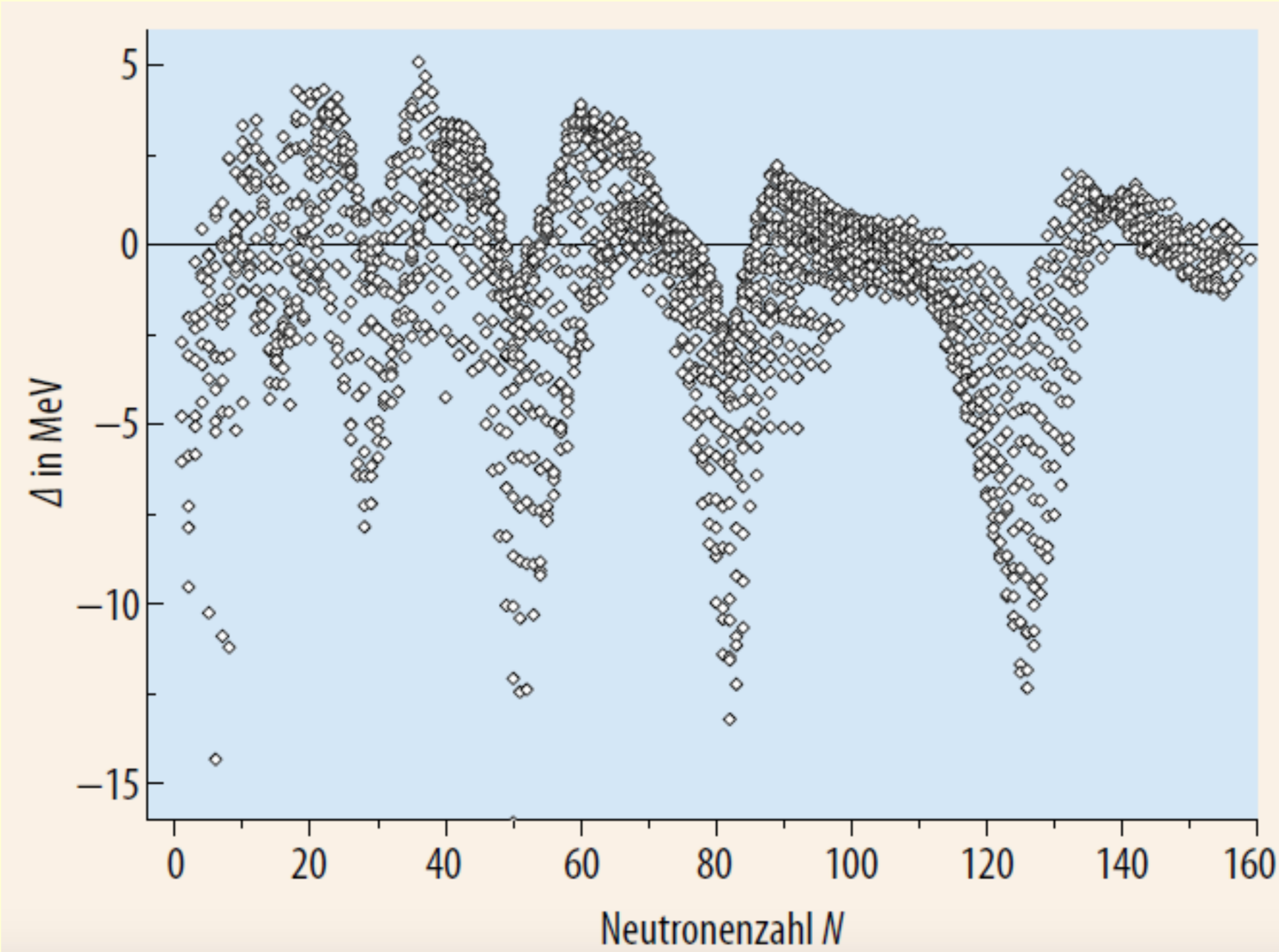
EC and decay in ESR

cooling, 2 EC and 2 β^+-decays



Shell structure of nuclei

$M_{exp} - M_{emp}$



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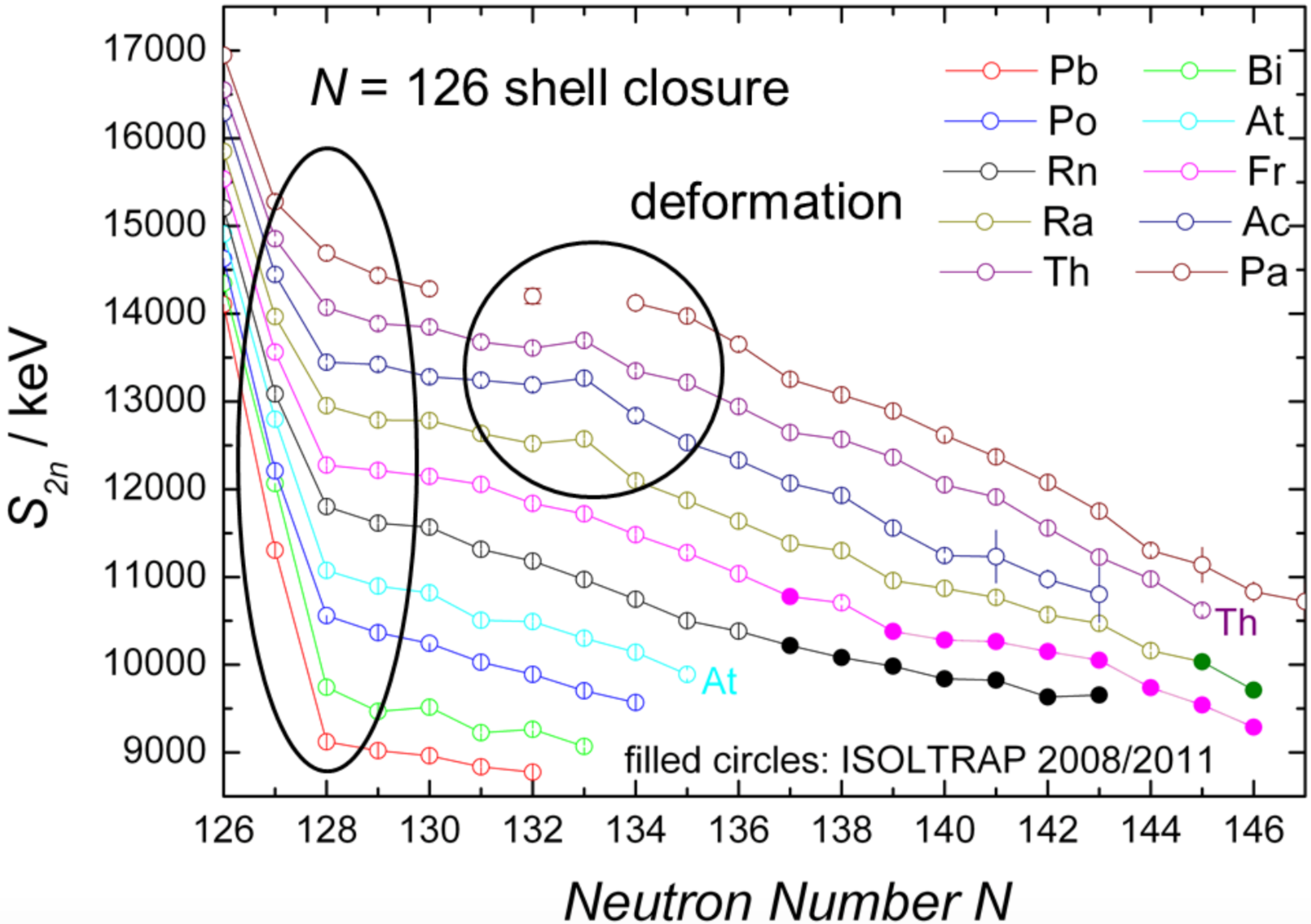
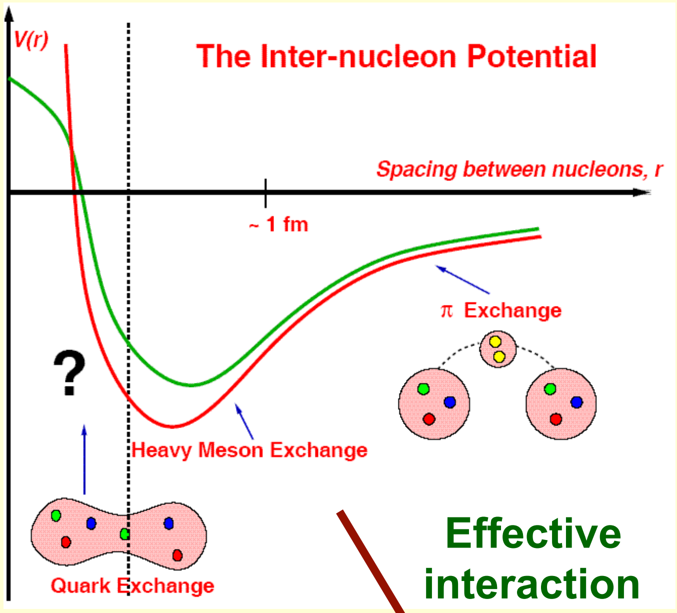
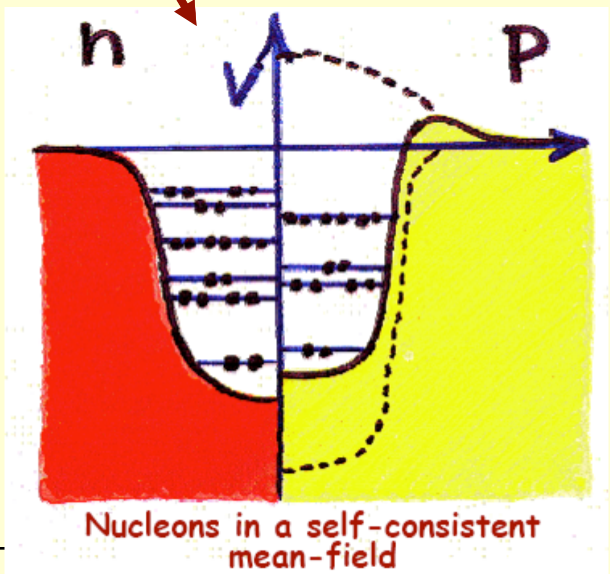
Two-neutron separation energies

$$S_{2n} = B_{nucl}(Z,N) - B_{nucl}(Z,N\text{-}2)$$



Mean-field model of nuclei

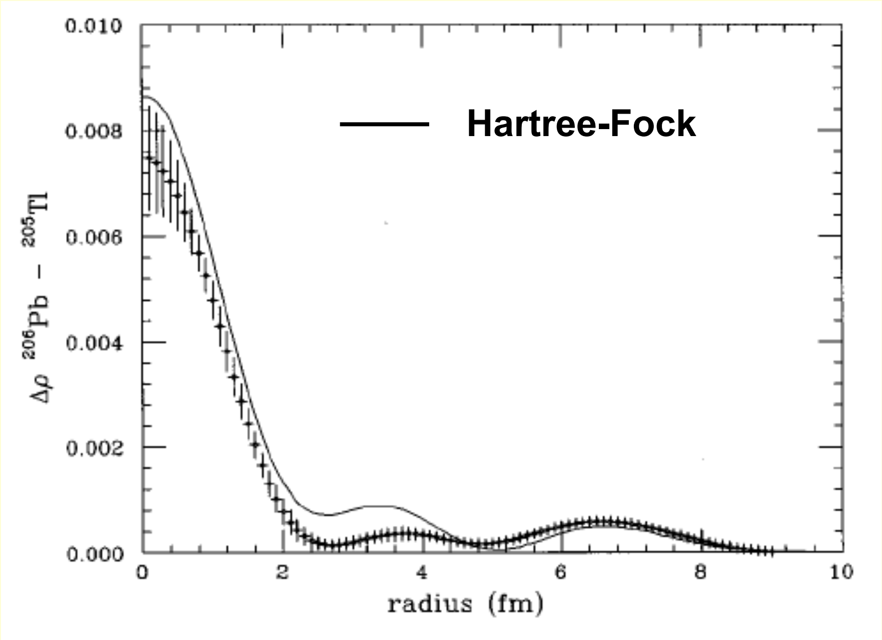




Ph. Chomaz

Validity of Mean Field Concept

J. Cavedon et al., Phys. Rev. Lett. 49 (1982) 978.

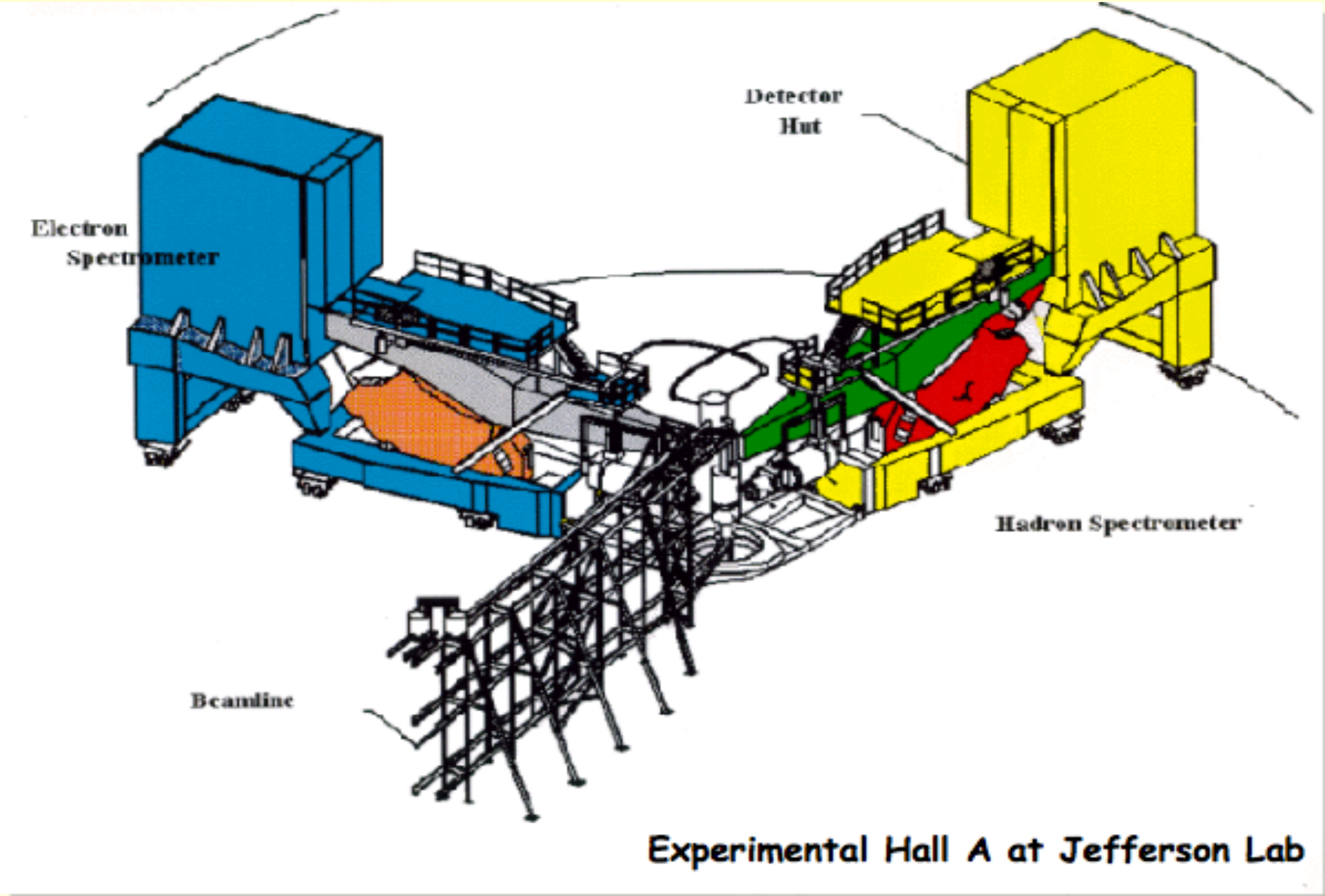


Electron Scattering

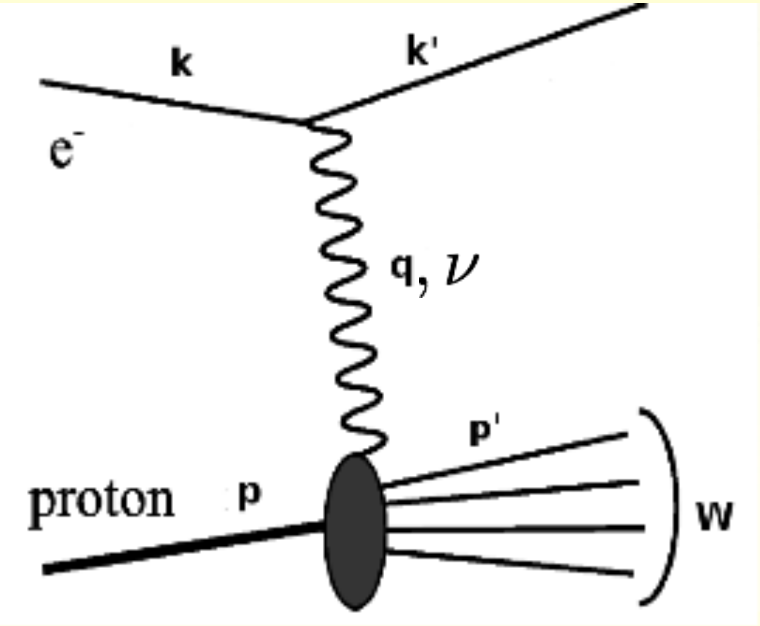
Charge density difference between ^{206}Pb and ^{205}Tl

^{206}Pb and ^{205}Tl differ in IPM by one 3s $_{1/2}$ proton

Coincidence electron measurements



Basic kinematics



k, k', p, p', q - 4-momenta of particles

ν - energy transfer

q - 4-momentum transfer

M - mass of proton p

W - invariant mass of p′

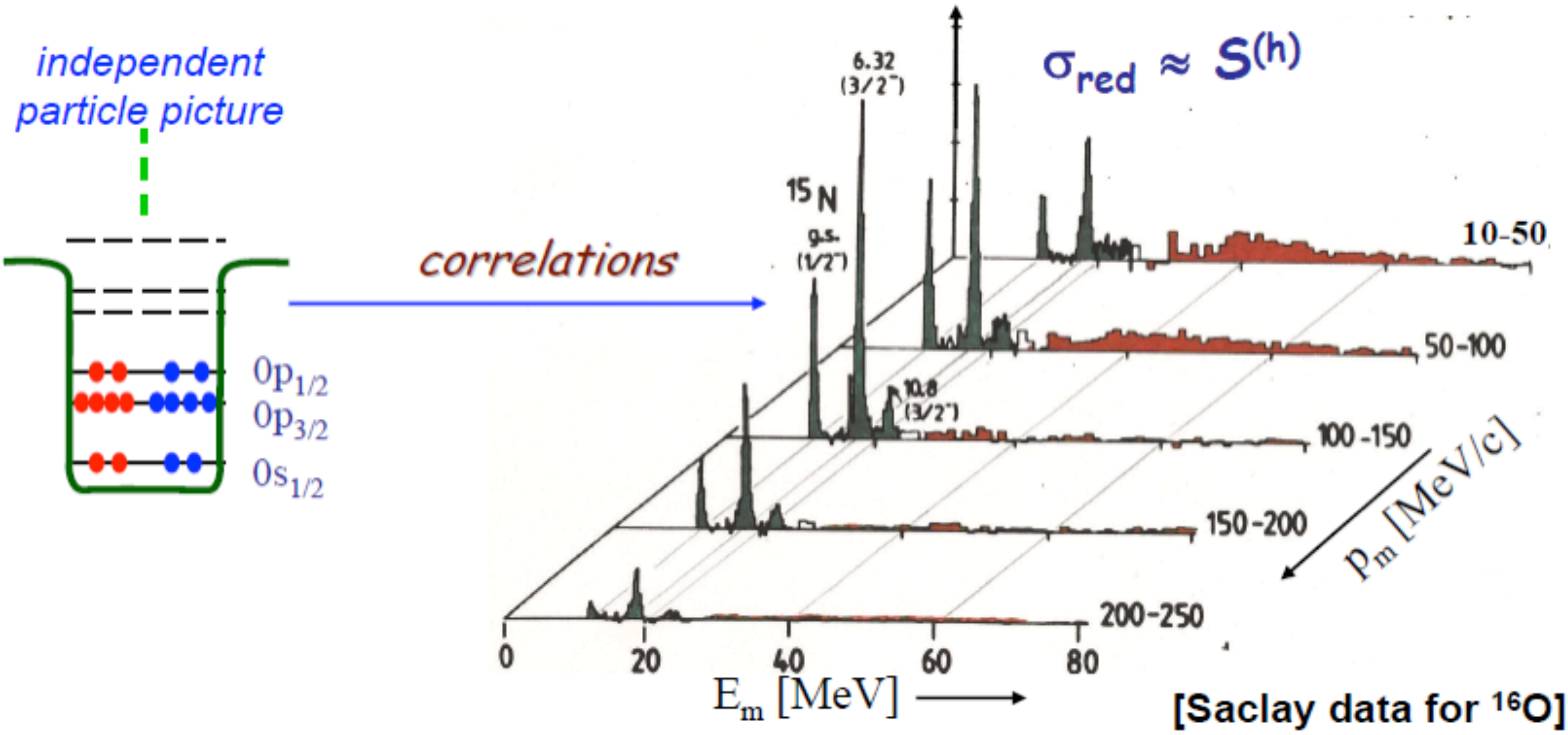
$$p' = p + q$$

$$p'^2 = (p+q)^2 = p^2 + 2pq + q^2$$

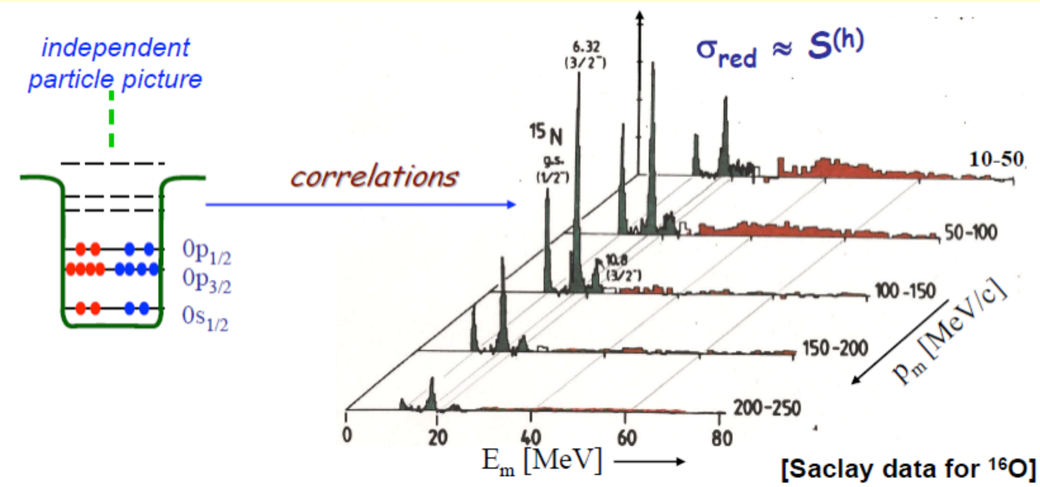
$p'^2 = W^2$, $p^2 = M^2$, $pq = M\nu$, $q^2 = -Q^2$

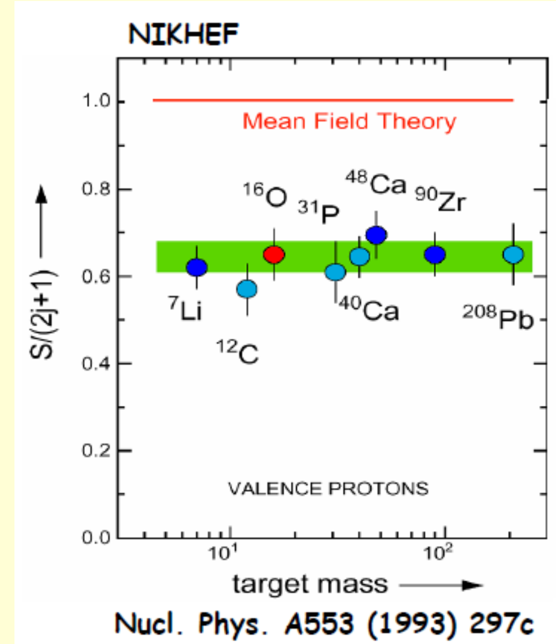
$$Q^2 = M^2 + 2M\nu - W^2$$

Single-particle structure



Single-particle structure





Deviation from the independent-particle picture:

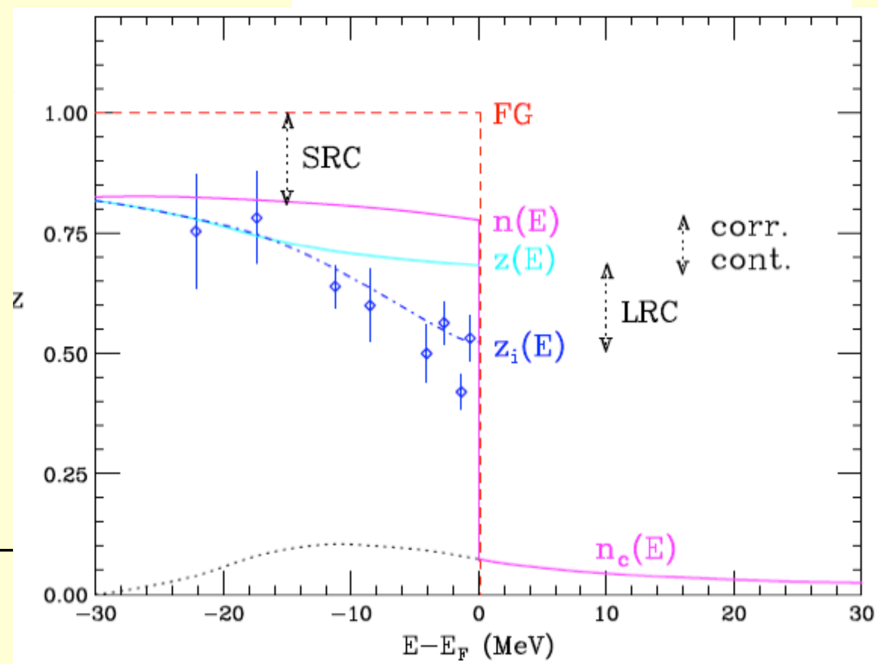
Correlations: Configuration mixing,

Coupling to collective phonons

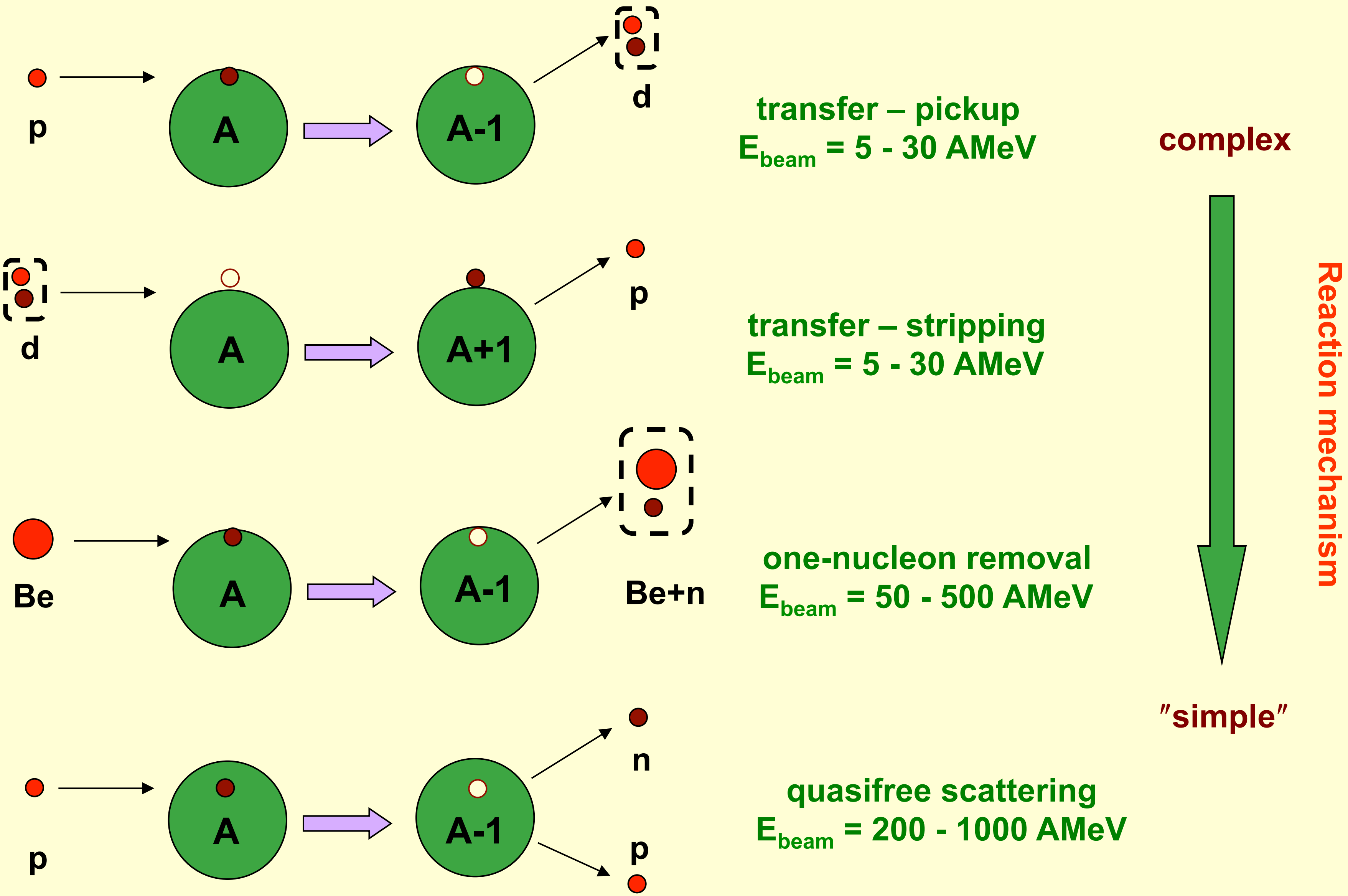
Short-range correlations → high momenta

→ reduced single-particle strength

(occupations, spectroscopic factors)



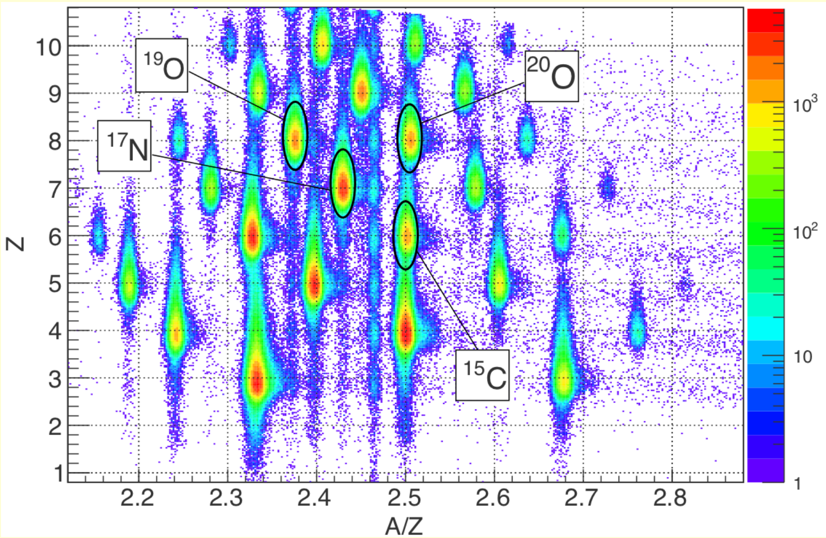
Direct reactions for (one-) nucleon removal



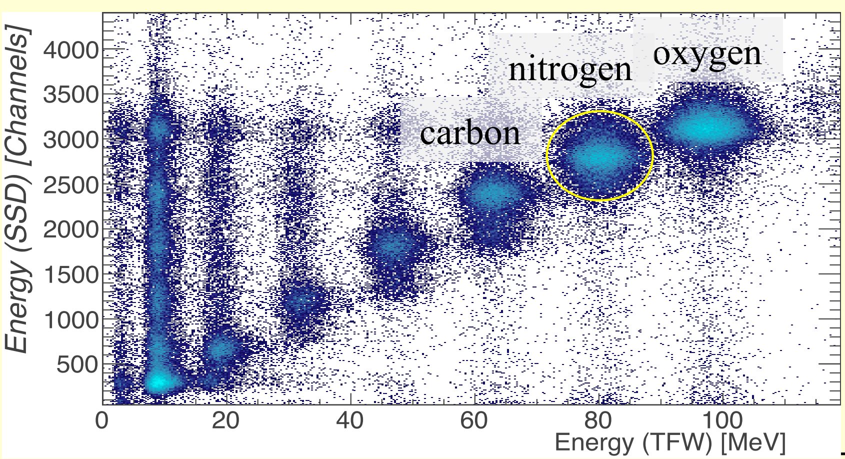
Quasi-free scattering

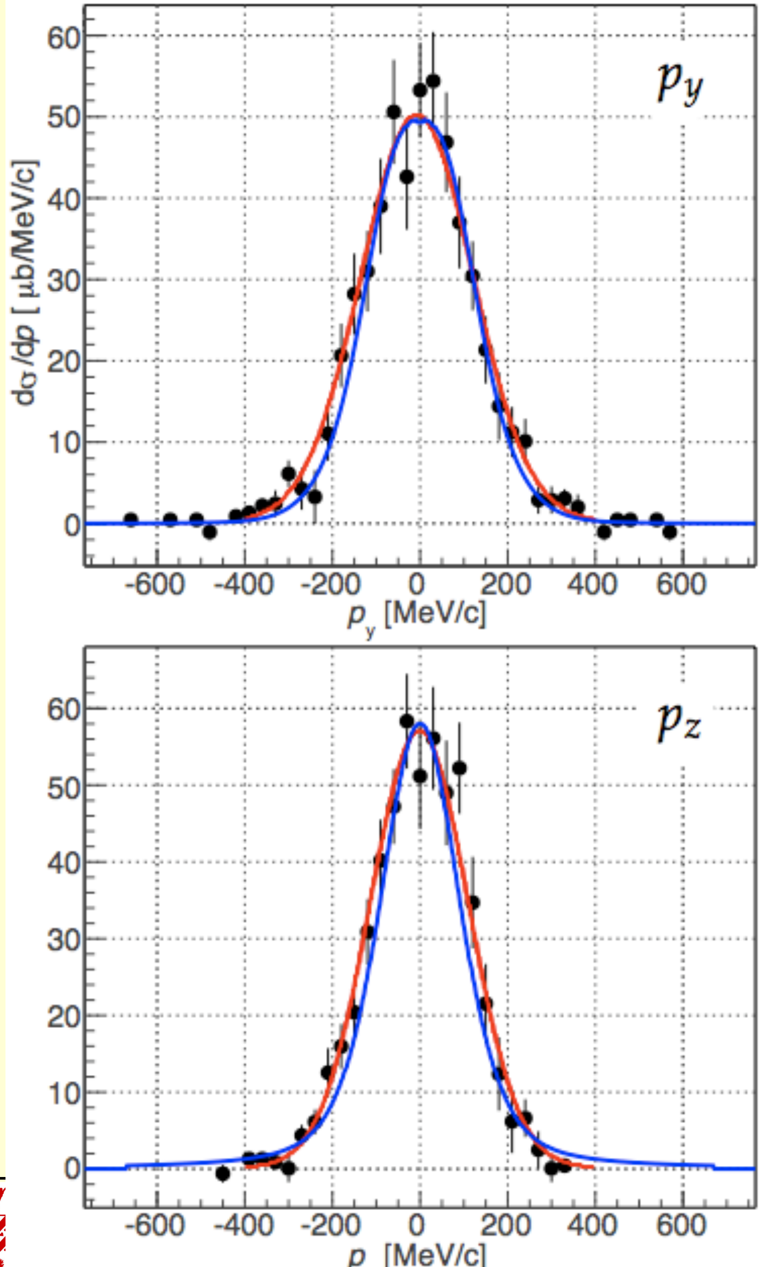
$p(^{20}O\ ,\ pp^{19}N)$

Incoming Particles



Outgoing Particles

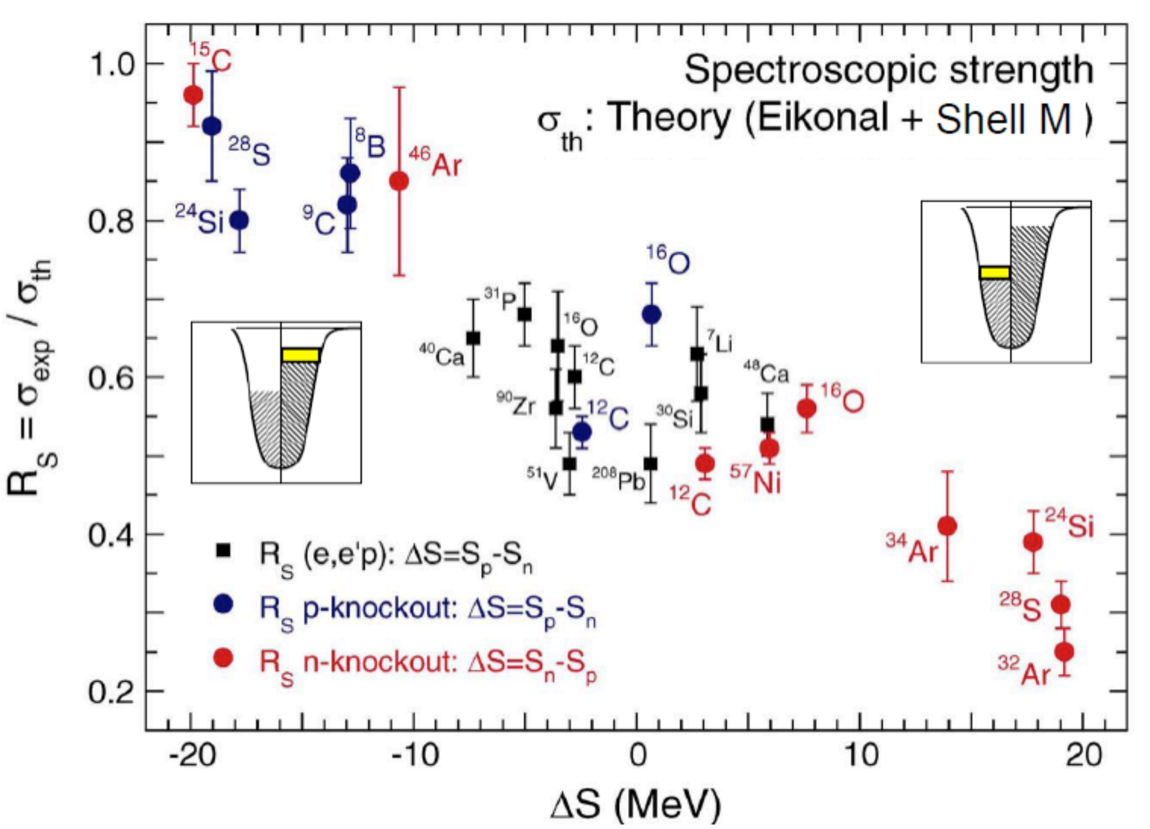




Spectroscopic factors for neutron-proton asymmetric nuclei

weakly bound nucleons

strongly bound nucleons



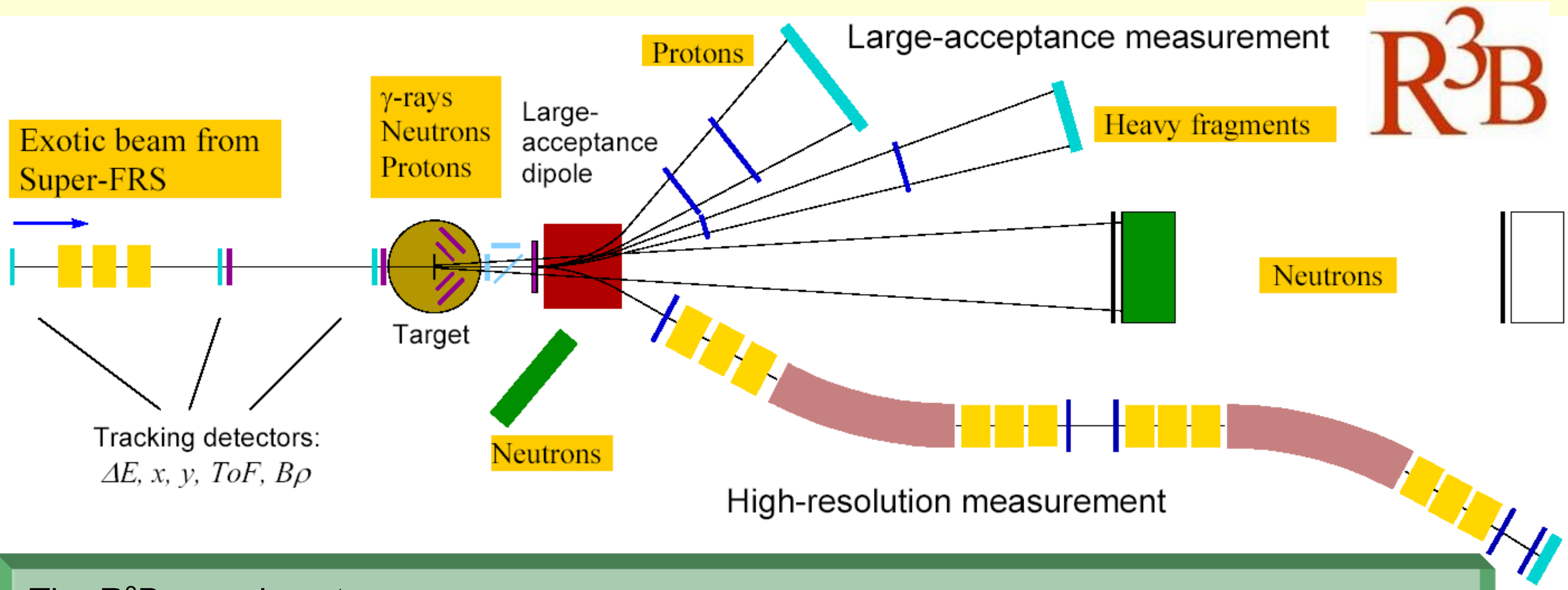
?

Origin unclear

isospin dependence of correlations ?

Figure from Alexandra Gade, Phys. Rev. C 77, 044306 (2008)

Reactions with Relativistic Radioactive Beams



The R^3B experiment:

- identification and beam "cooling" (tracking and momentum measurement, $\Delta p/p \sim 10^{-4}$)
- exclusive measurement of the final state:
  - identification and momentum analysis of fragments
    (large acceptance mode: $\Delta p/p \sim 10^{-3}$, high-resolution mode: $\Delta p/p \sim 10^{-4}$)
  - coincident measurement of neutrons, protons, gamma-rays, light recoil particles
- applicable to a wide class of reactions

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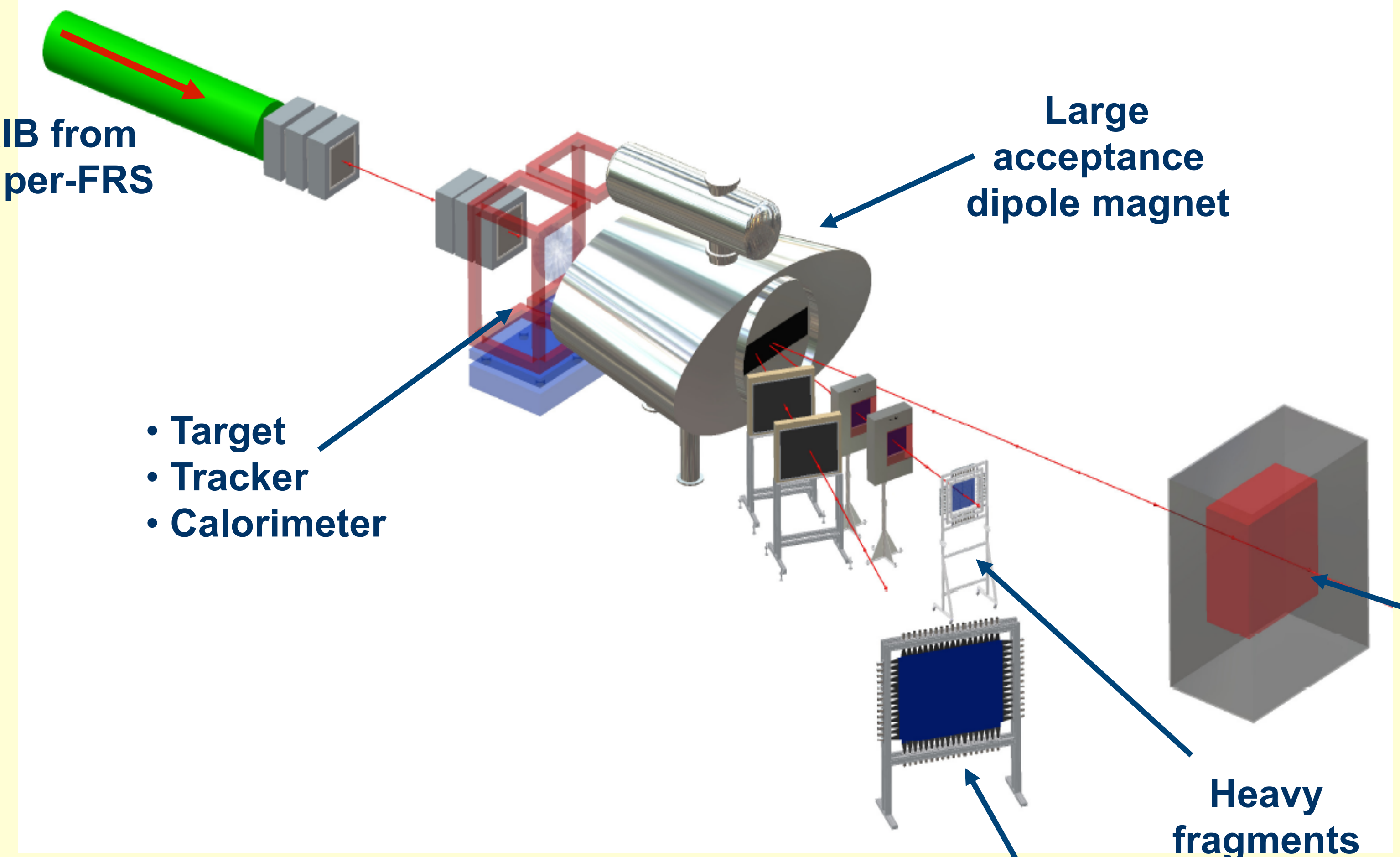
Reactions with Relativistic Radioactive Beams
R^3B



R3B Start version:
2014

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The Collective Response of the Nucleus: Giant Resonances

Electric giant resonances

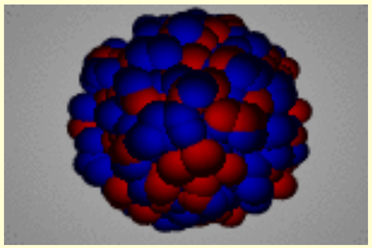
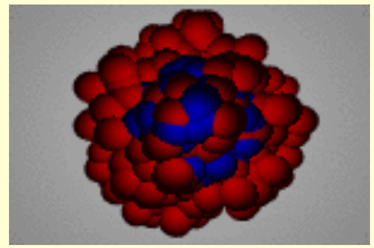
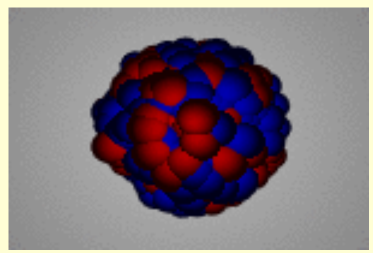
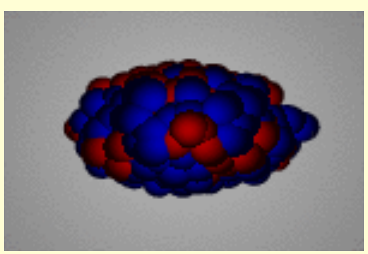
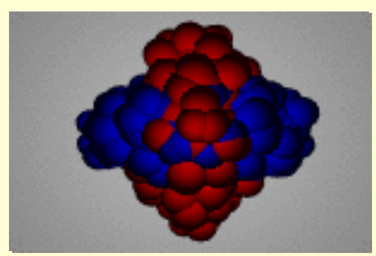
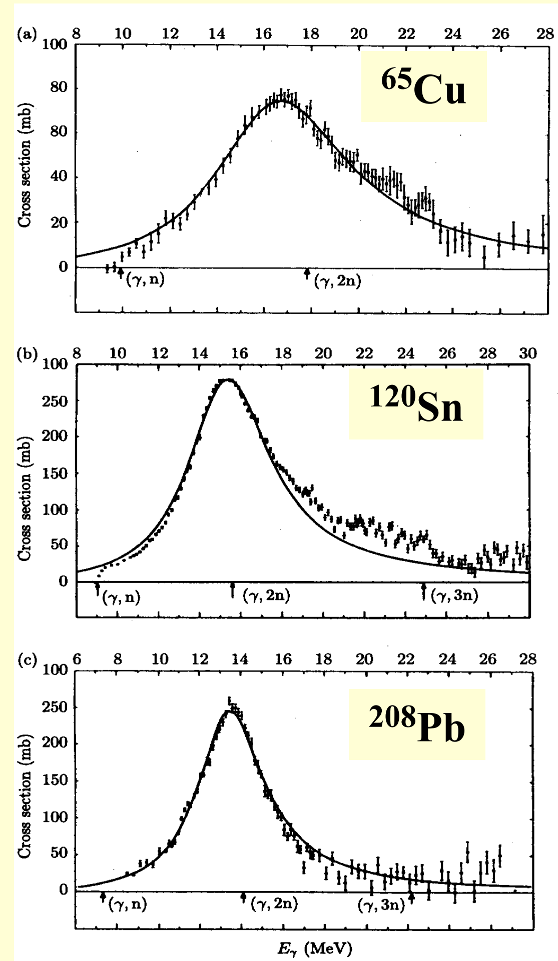
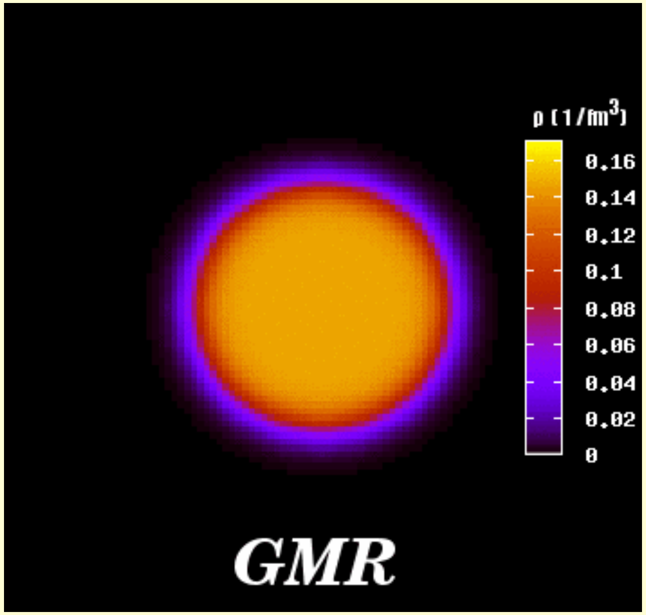
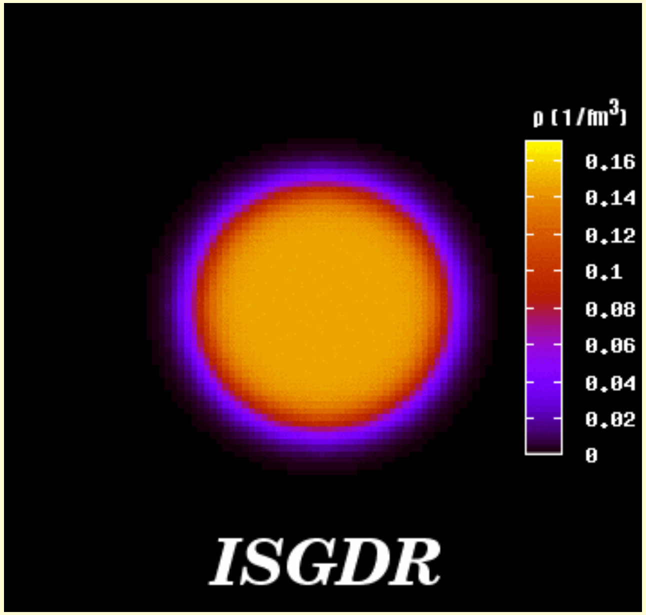
	Isoscalar	Isovector
Monopole (GMR)		
Dipole (GDR)		
Quadrupole (GQR)		

Photo-neutron cross sections

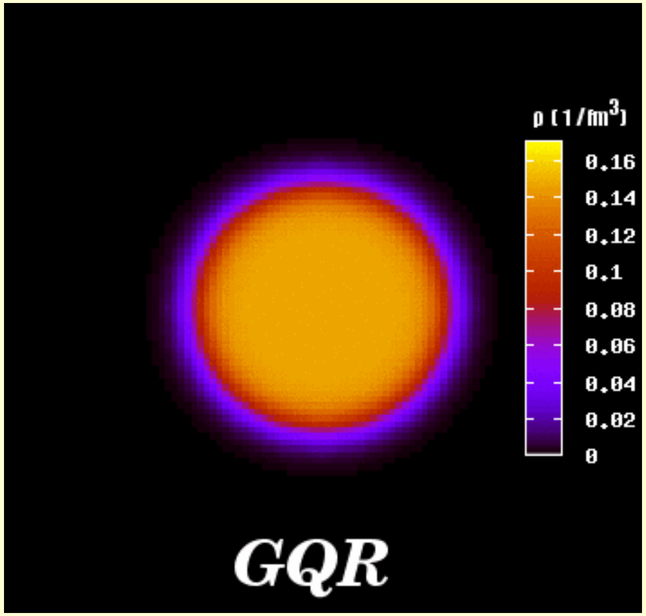
Berman and Fulz, Rev. Mod. Phys. 47 (1975) 47

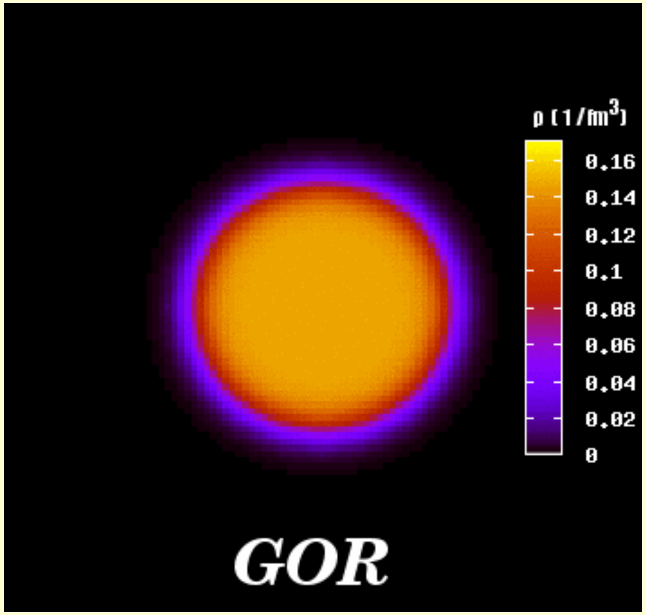



ρ (1/fm³)
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
GMR

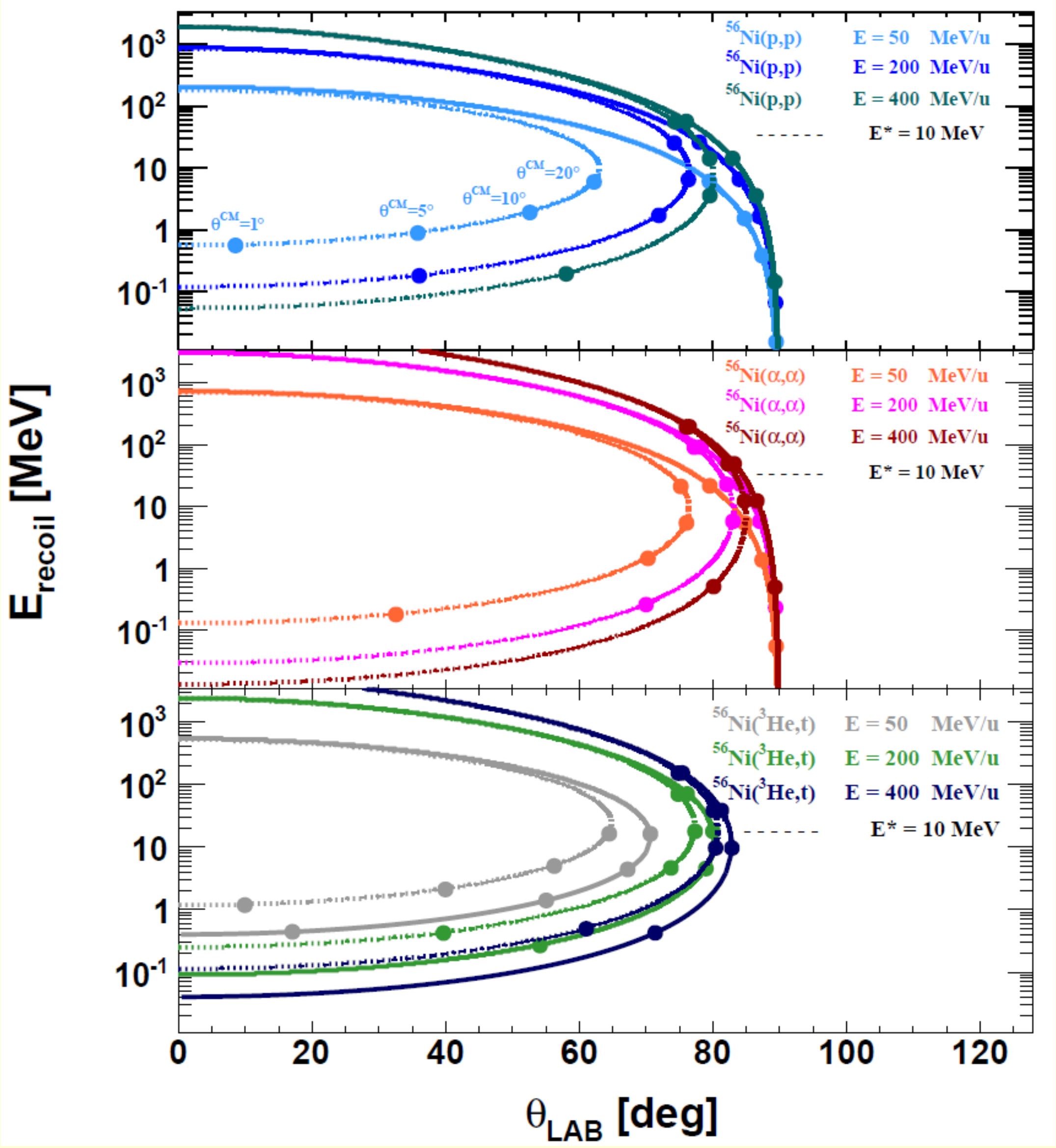

ρ (1/fm³)
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
ISGDR

M. Itoh

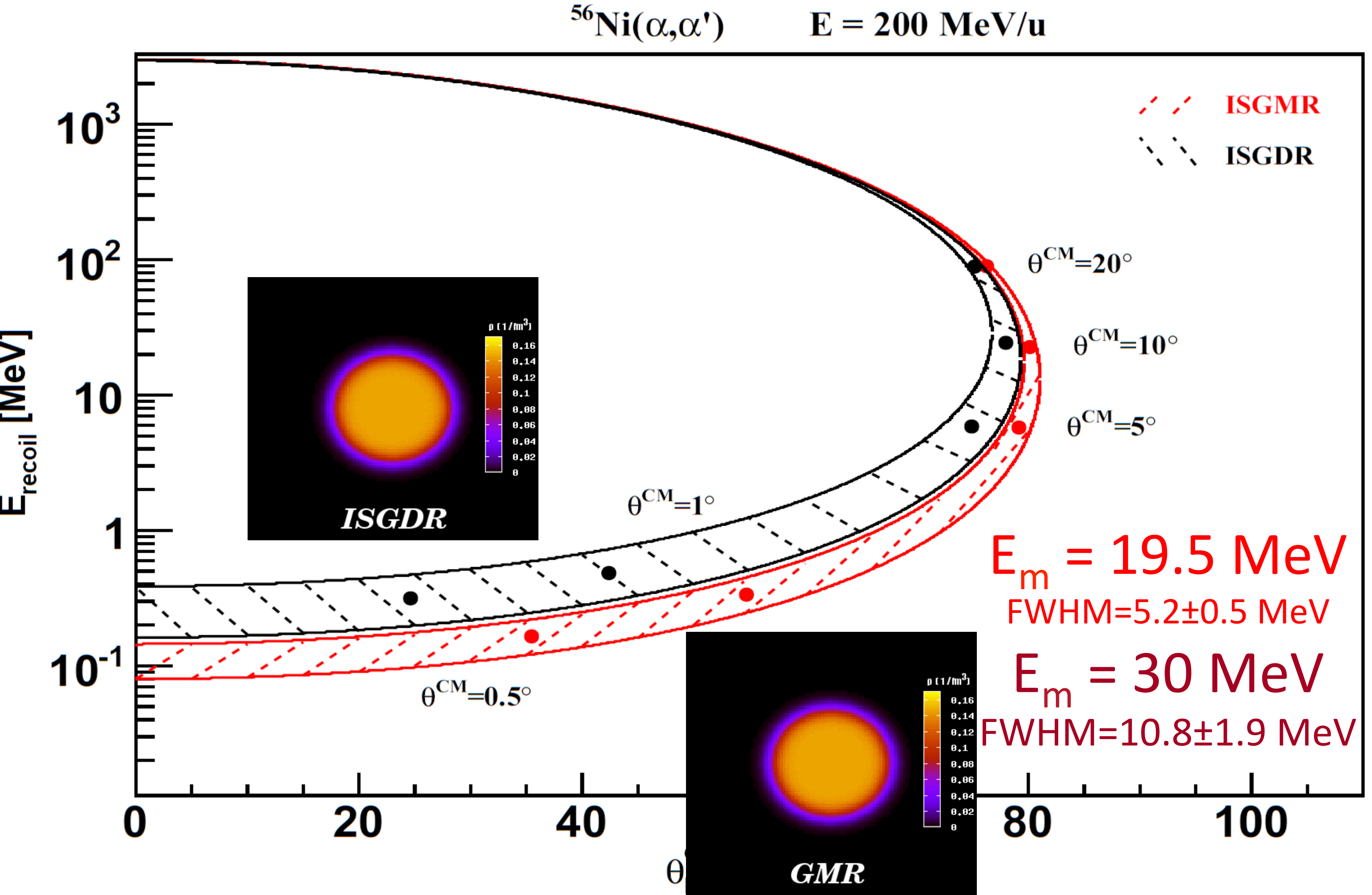

ρ (1/fm³)
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
GQR


ρ (1/fm³)
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
GOR

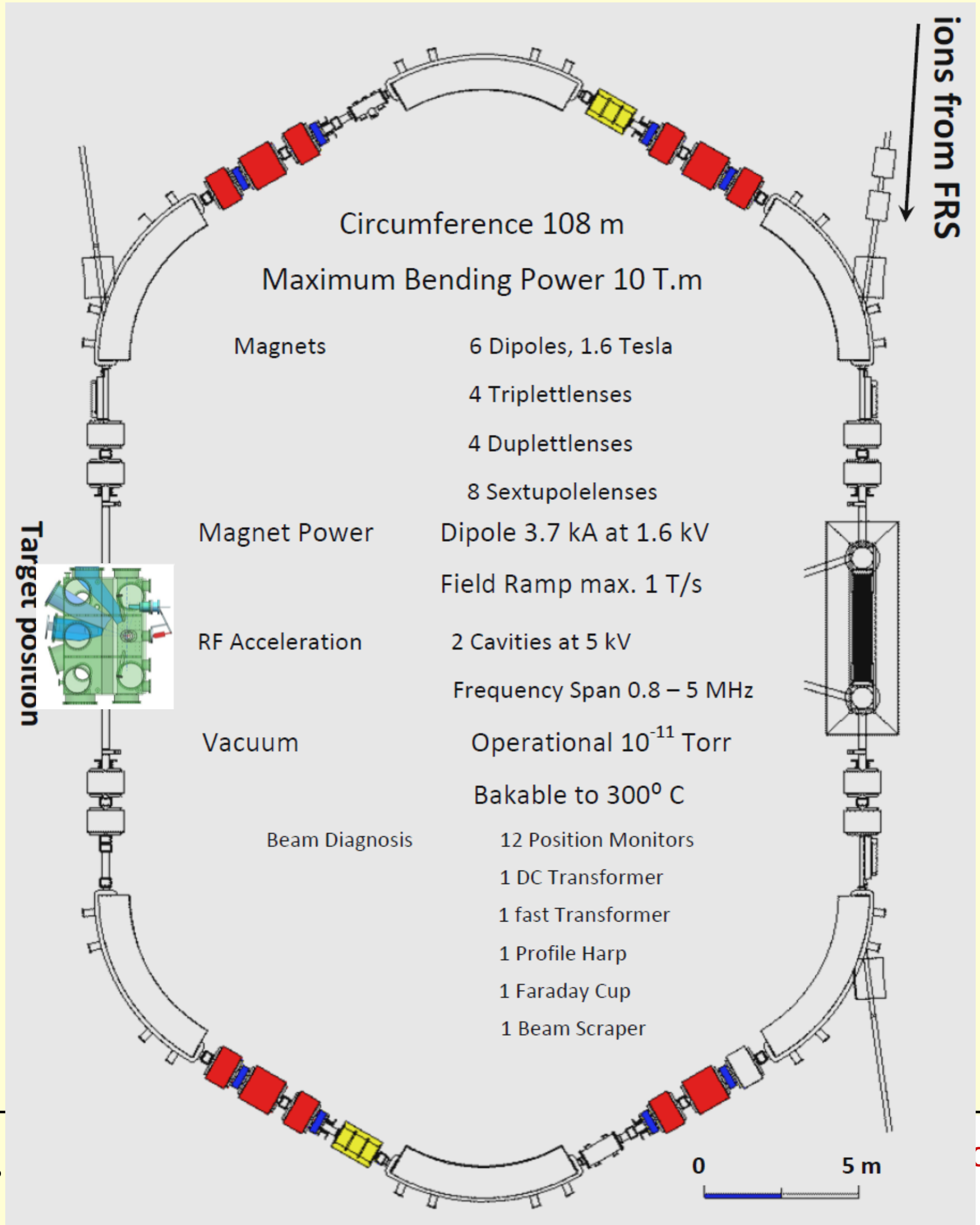
Kinematics for inverse reaction for ^{56}Ni



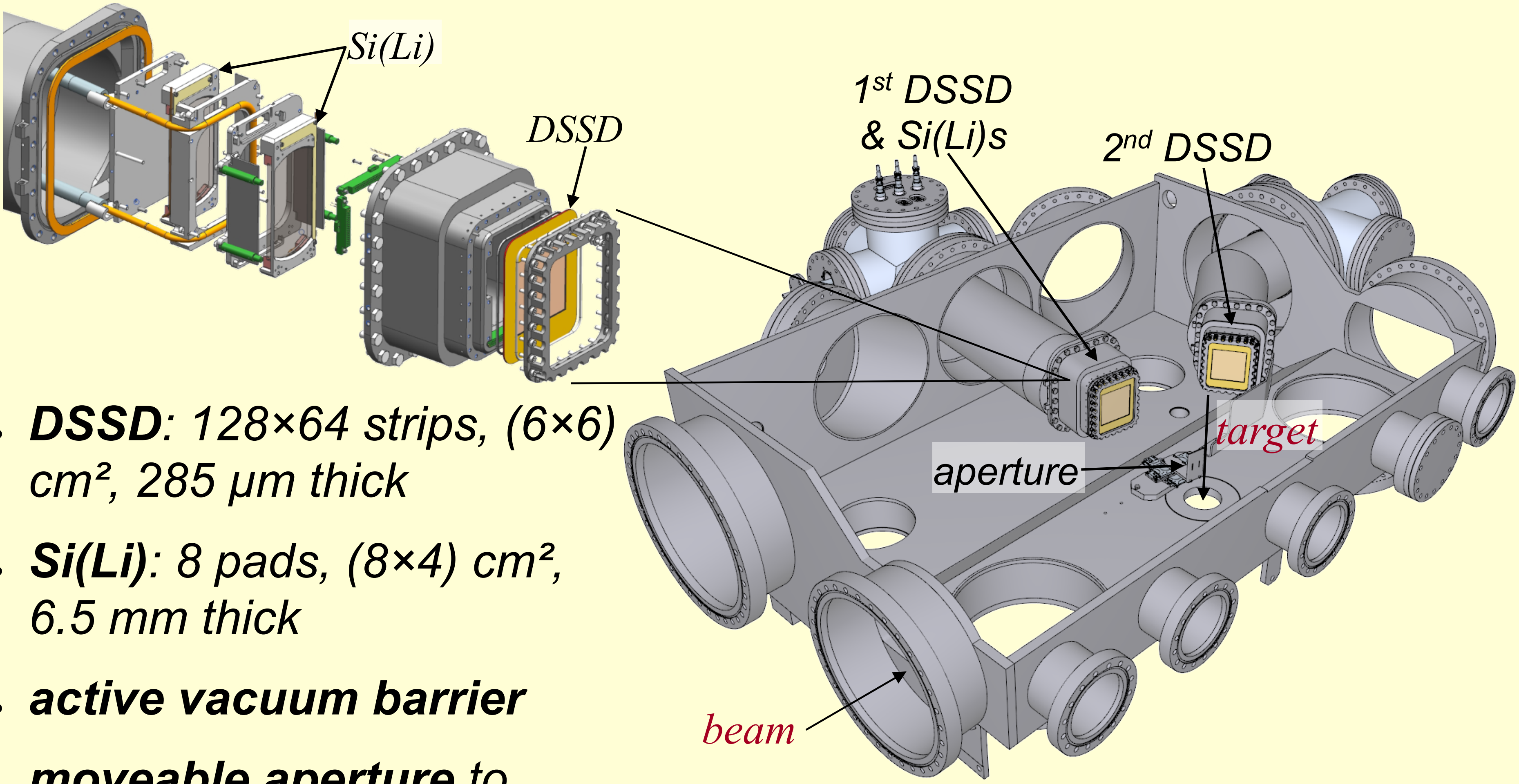
ISGMR/ISGDR channels in ^{56}Ni with (α,α')



Setup @ ESR


ions from FRS
Target position
Circumference 108 m
Maximum Bending Power 10 T.m
Magnets
6 Dipoles, 1.6 Tesla
4 Triplettlenses
4 Duplettlenses
8 Sextupolelenses
Magnet Power
Dipole 3.7 kA at 1.6 kV
Field Ramp max. 1 T/s
RF Acceleration
2 Cavities at 5 kV
Frequency Span 0.8 – 5 MHz
Vacuum
Operational 10^{-11} Torr
Bakable to 300⁰ C
Beam Diagnosis
12 Position Monitors
1 DC Transformer
1 fast Transformer
1 Profile Harp
1 Faraday Cup
1 Beam Scraper
0
5 m

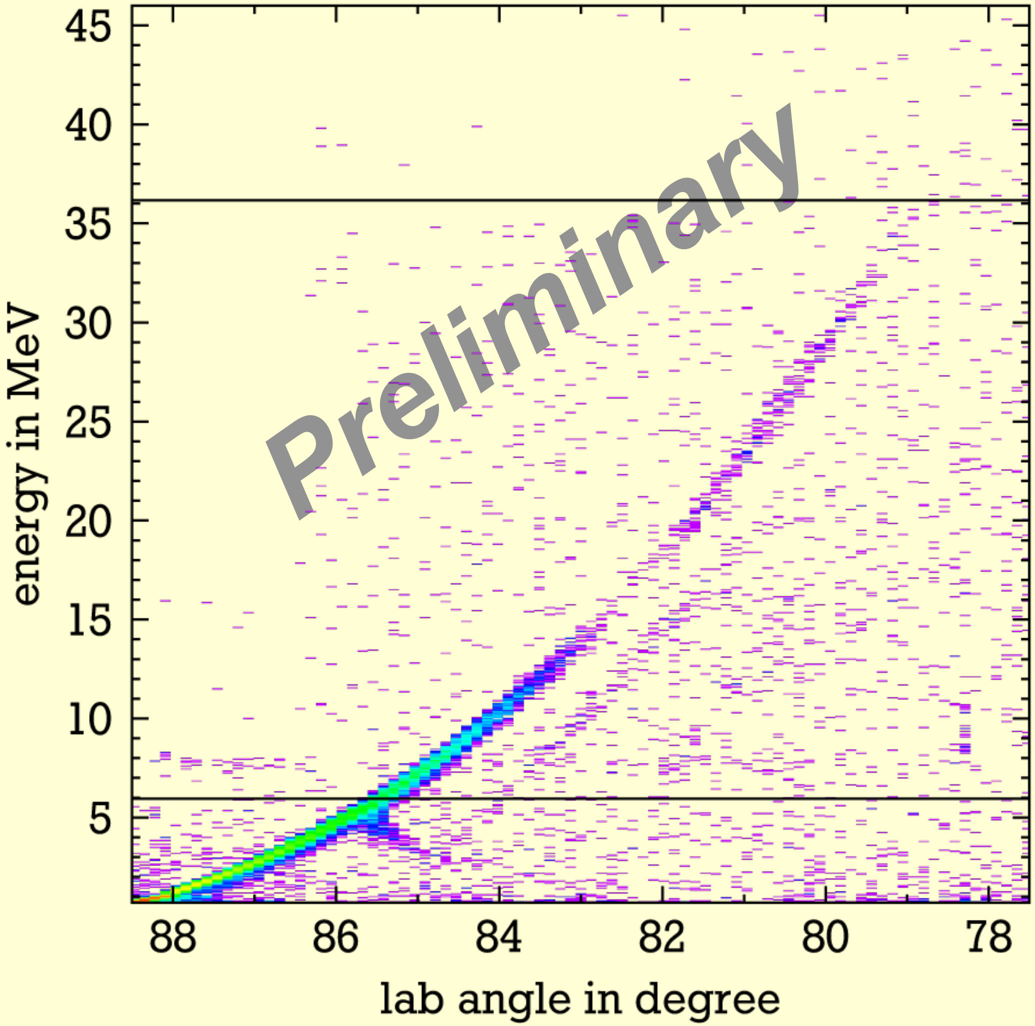
The new ESR Scattering chamber

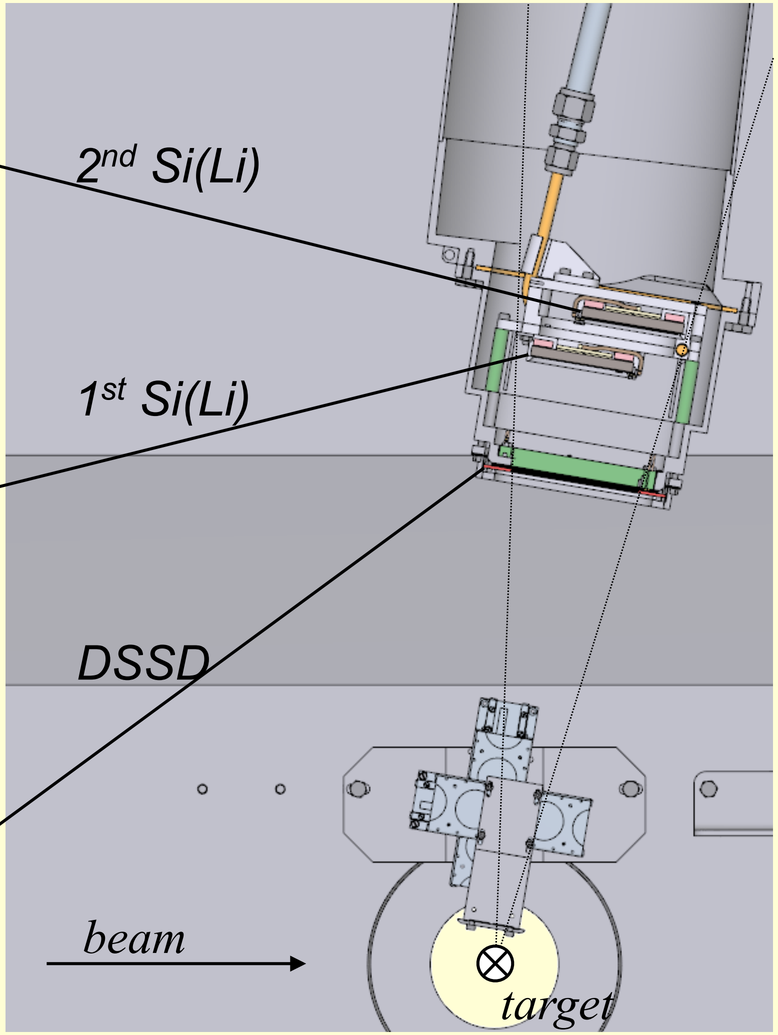


- ***DSSD***: *128×64 strips, (6×6) cm², 285 µm thick*
- ***Si(Li)***: *8 pads, (8×4) cm², 6.5 mm thick*
- ***active vacuum barrier***
- ***moveable aperture** to improve angular resolution*

First results with radioactive beam

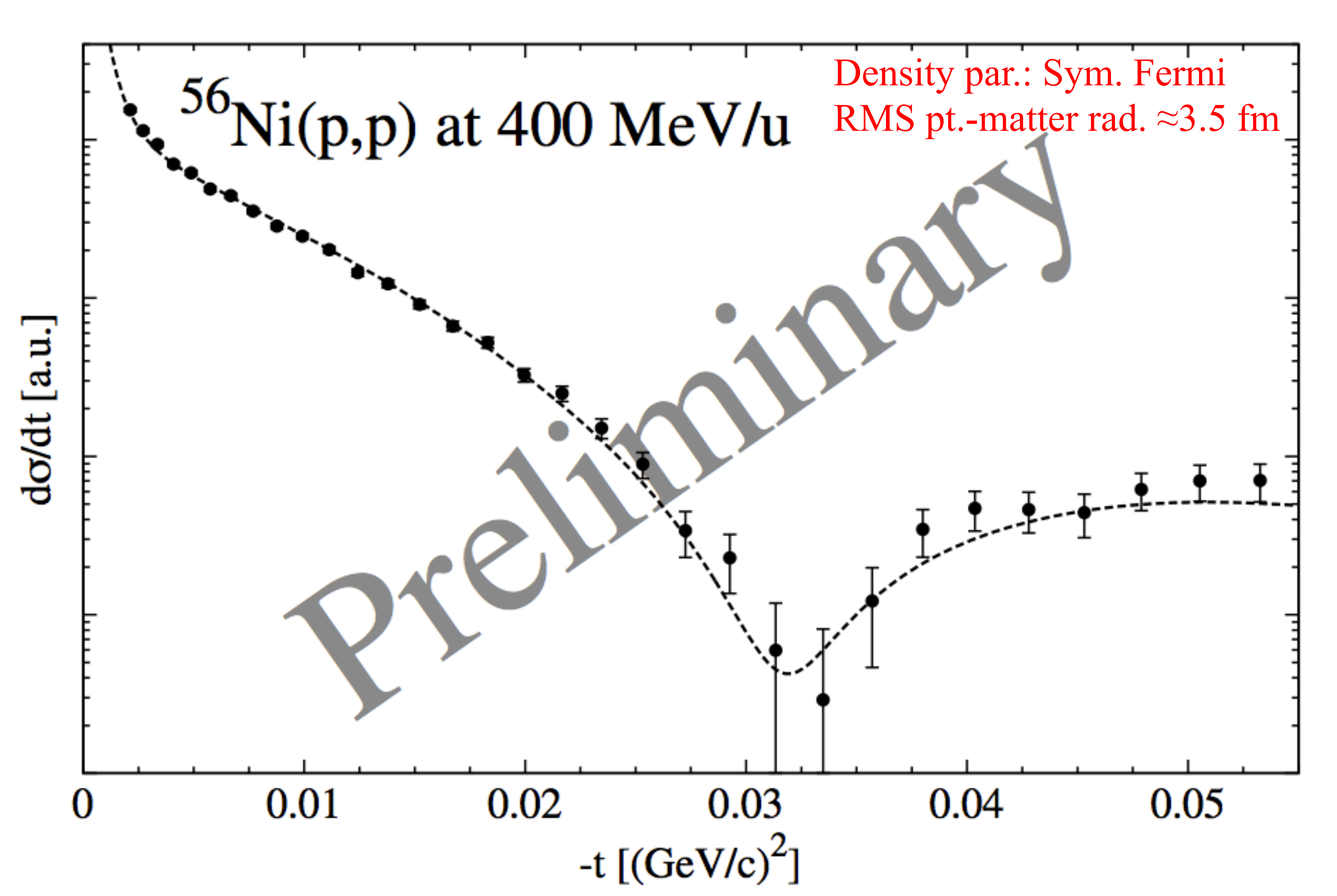
^{56}Ni(p,p), E = 400 MeV/u



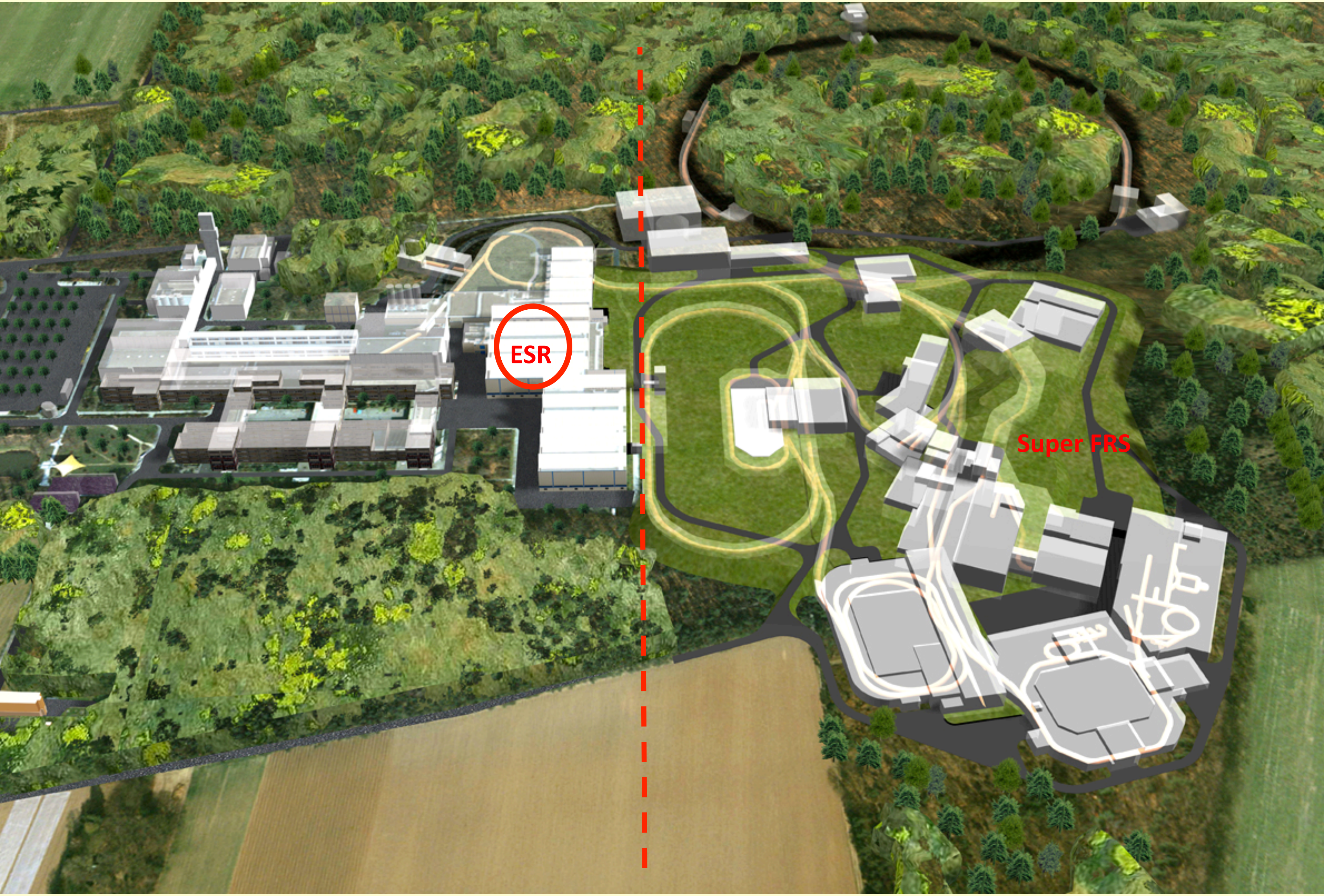


First results with radioactive beam

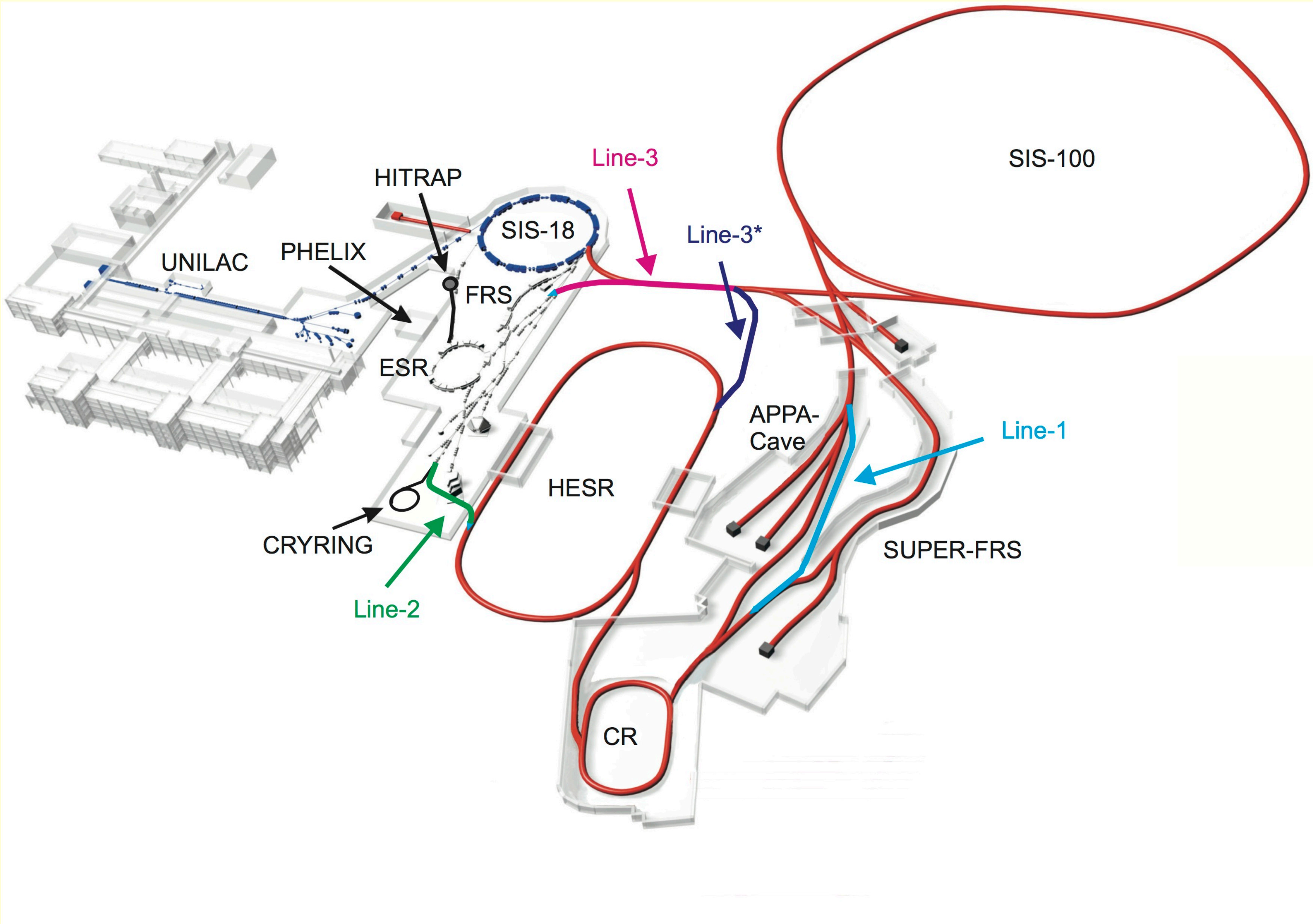
- Elastic p-scattering off ^{56}Ni (E105), M. von Schmid



for advanced
:hnology


ESR
Super FRS

GSI and FAIR overview



Improvements over the present

Primary beams:

- **Factor 100-1000 over present intensities**

Secondary beams:

- **Broad range of radioactive beams up to 1.5-2 GeV/u; factor of 10000 improvement in intensity with respect to the present facilities**

Conclusions and outlook

- Many unanswered questions will be addressed with the new generation facilities.
- Various aspects of nuclear matter (sizes, shapes, interactions, limits of stability etc. etc.) will be studied in the coming years.
- Understanding the structure of nuclei and the forces governing them will also give clues on how the stars are formed and evolve.
- Many laboratories capable of producing intense radioactive beams have come online or are in the process of building.
- State-of-the-art detection techniques are being developed to go to the extremes

Thank you!