Crossing bounds: From exotic nuclear systems to FAIR

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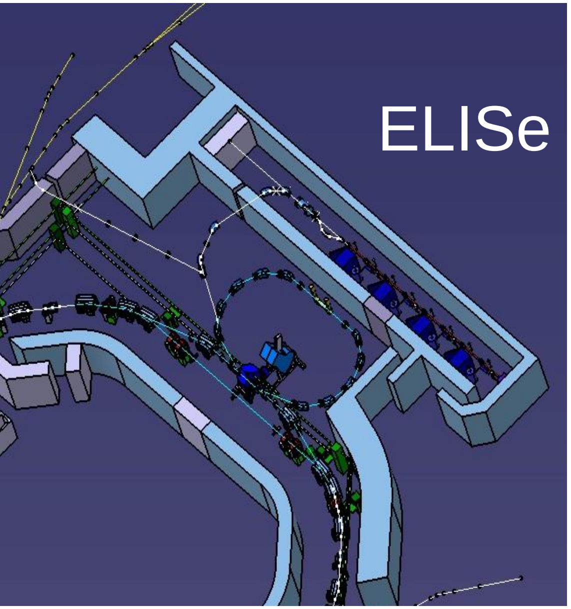
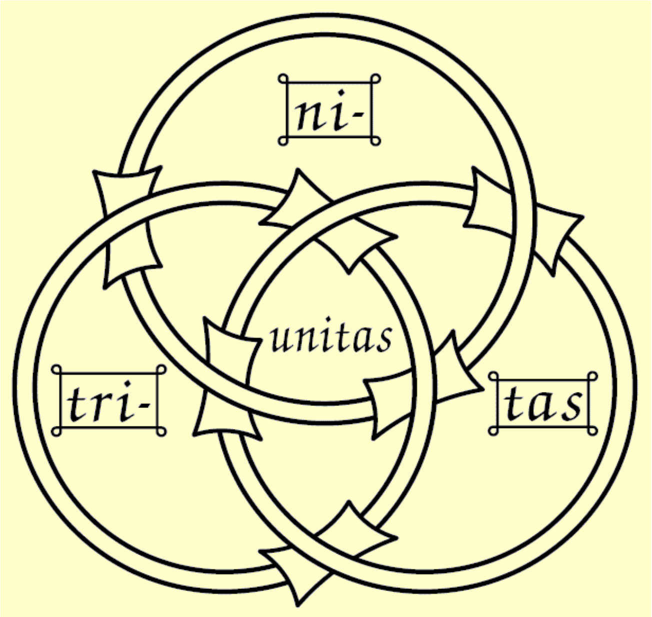
My main projects

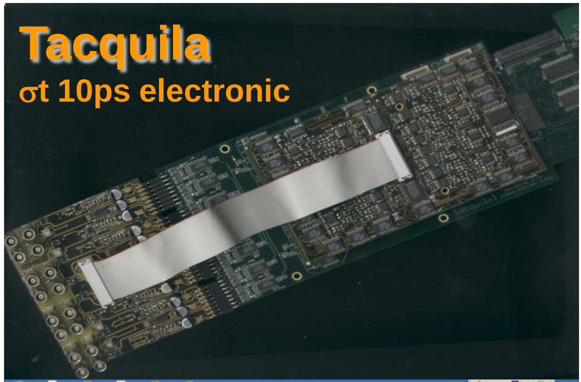
Electronics for NUSTAR/FAIR

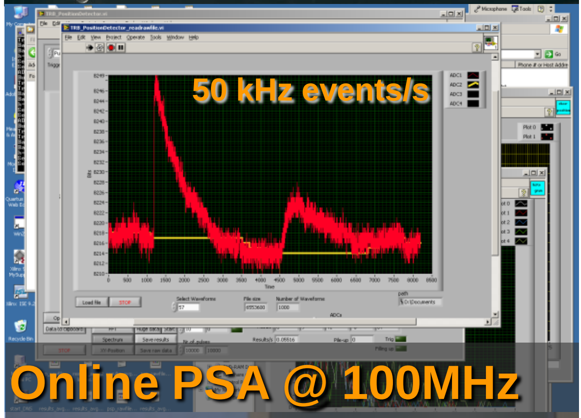


e$^-$ scattering
with radioactive beams



unstable
nuclear systems





Menu

1. NUSTAR: Nuclear Structure Astrophysics & Reactions
2. Halo Nuclei: Low density nuclear matter
3. Extremely neutron rich systems
4. EOS studies via nuclear excitations
5. The future is FAIR
6. Summary

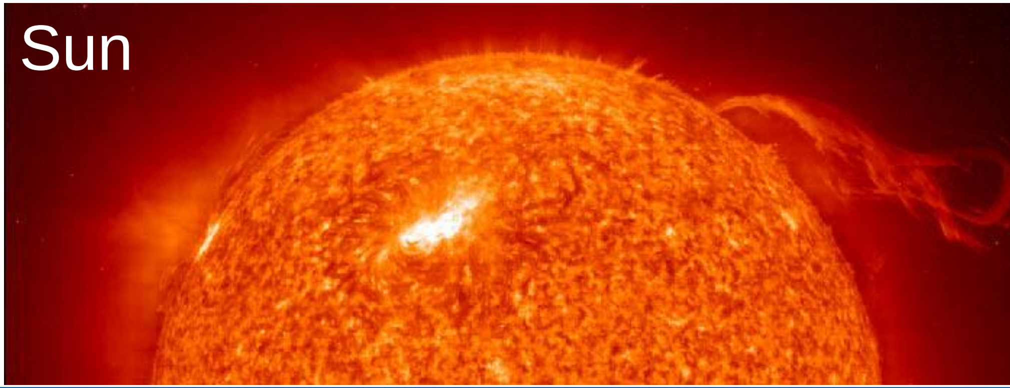
Stellar environments

What do we know ? And how ….

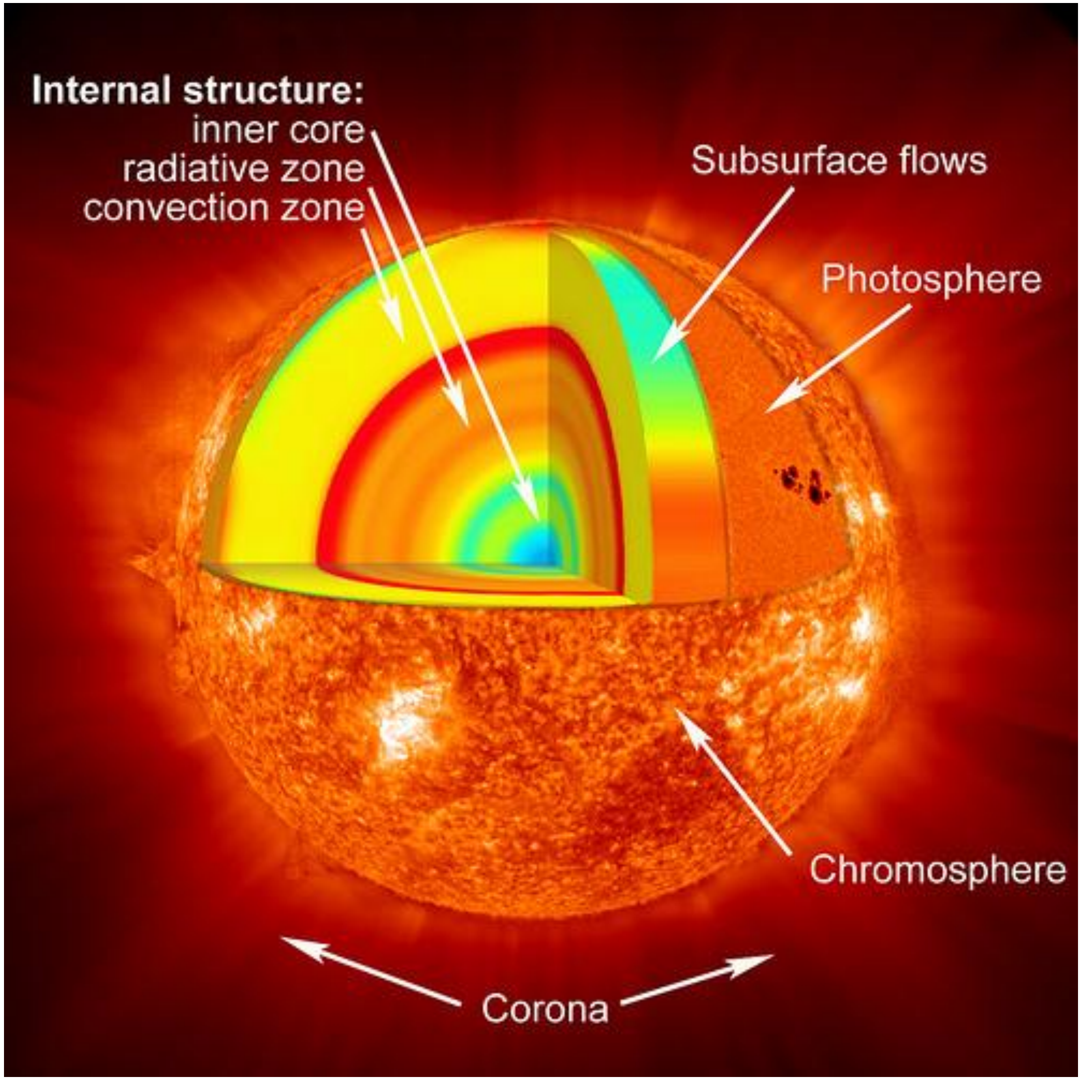
- Primary input to Astrophysics is the observations of (very) distant objects through astronomers

➔ indirect measurements

- At the first glance for we just look at rather hot surfaces of stars …



Thermodynamics defines the boundaries



… and that's what we want to know.

Start:
Basic properties:

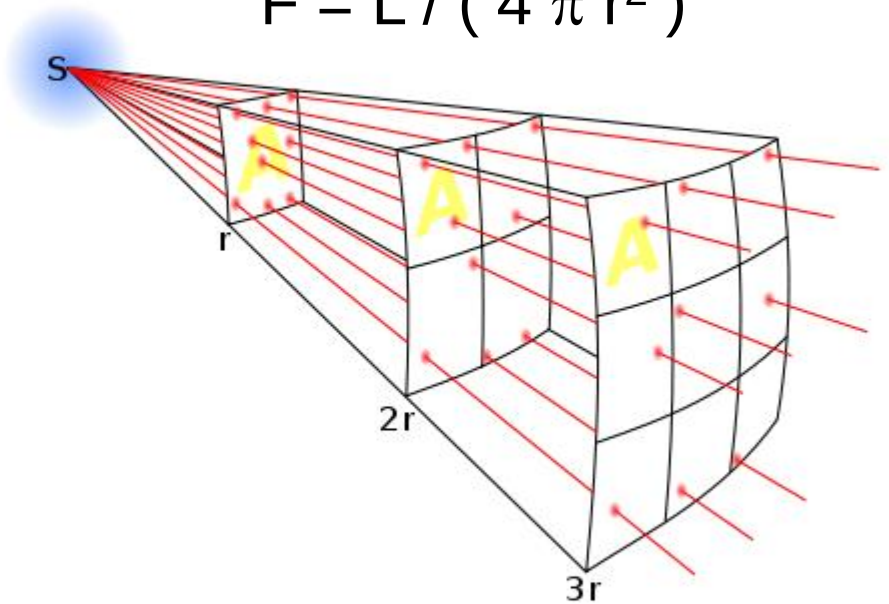
- Temperature
- Size

Observables:

- Apparent Magnitude
- Spectrum

Magnitude/Distance analysis (Inverse Square Law)

$F = L / (4 \pi r^2)$



Apparent magnitude and absolute magnitude (or luminosity) can only be related if distance is known !

Example: solar luminosity

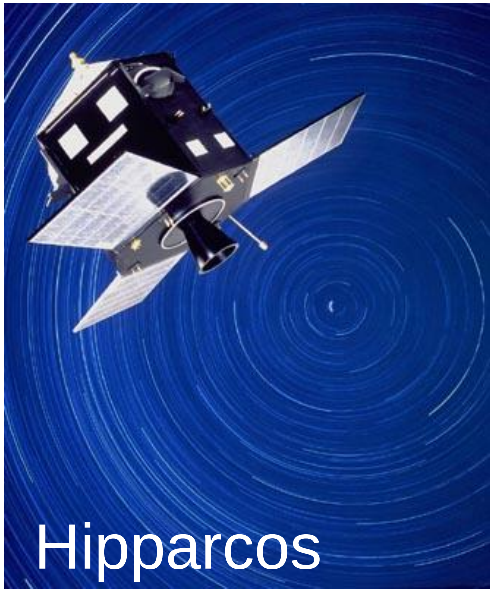
$L_{sol} = 3.846 \times 10^{26}$ W

@ 1AU flux is $F = 1365$ W m^{-2}

@ 10pc it is $F = 3.208 \times 10^{-10}$ W m^{-2}

➔ comparison is done at 10pc (absolute magnitude)

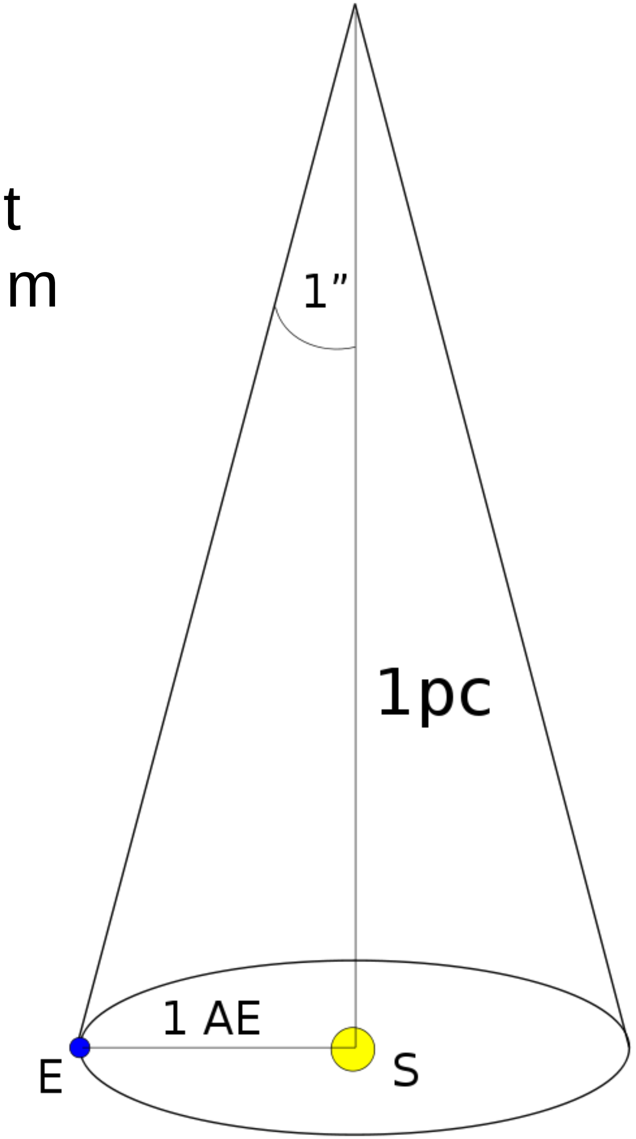
Magnitude/Distance analysis



E.g. direct method:

Parallax measurement

1pc = $3.086\ldots\ 10^{16}$ m
= 3.262… ly



***H**igh **P**recision **Par**allax **Co**llecting **S**atellite*

1989-1993

0.001“ reolution → 1% (30ly) 400 stars,
10% (300ly) 28000 stars

(Milky Way diameter: 100‘000 ly)

➔ indirect methods: red-shift, cepheids, SN

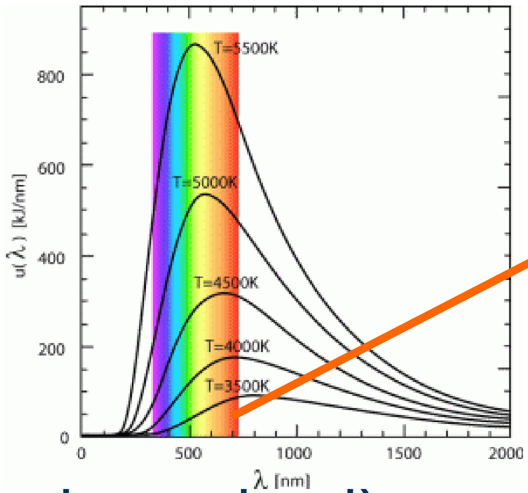
Spectral analysis (blackbody radiation)

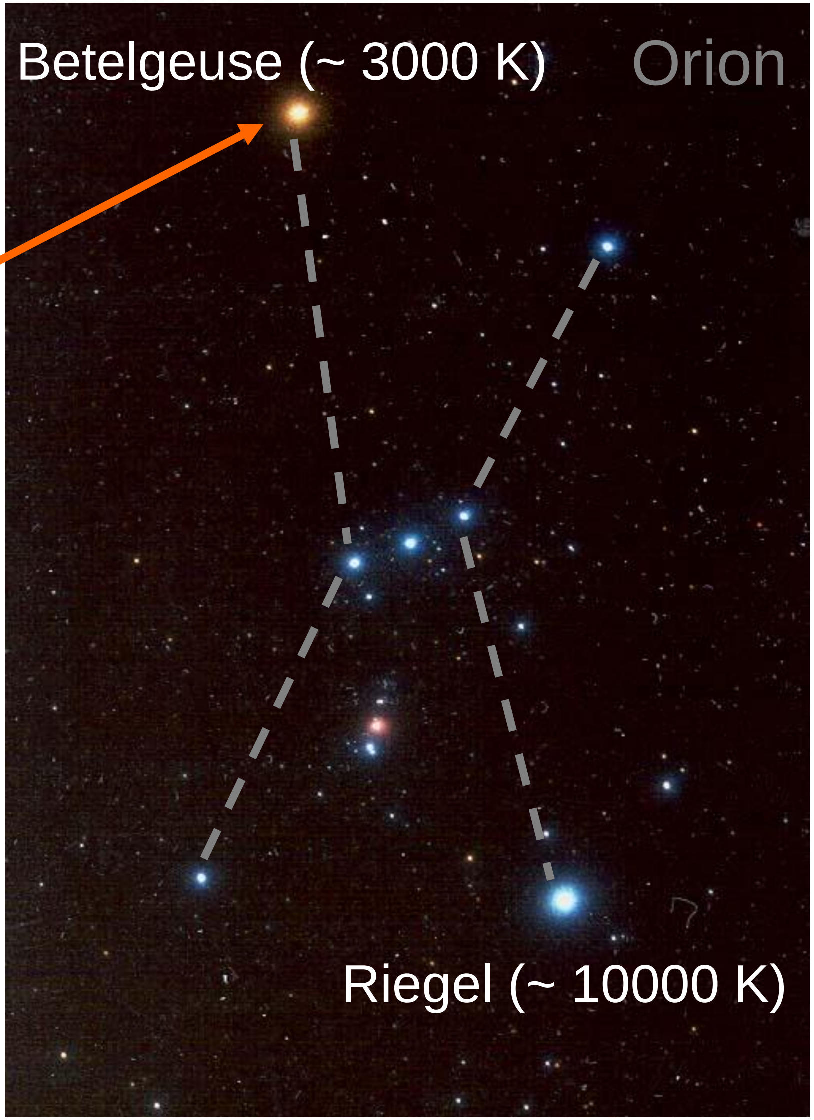
Wiens law

$\lambda_{max} T = 0.0029$ m K

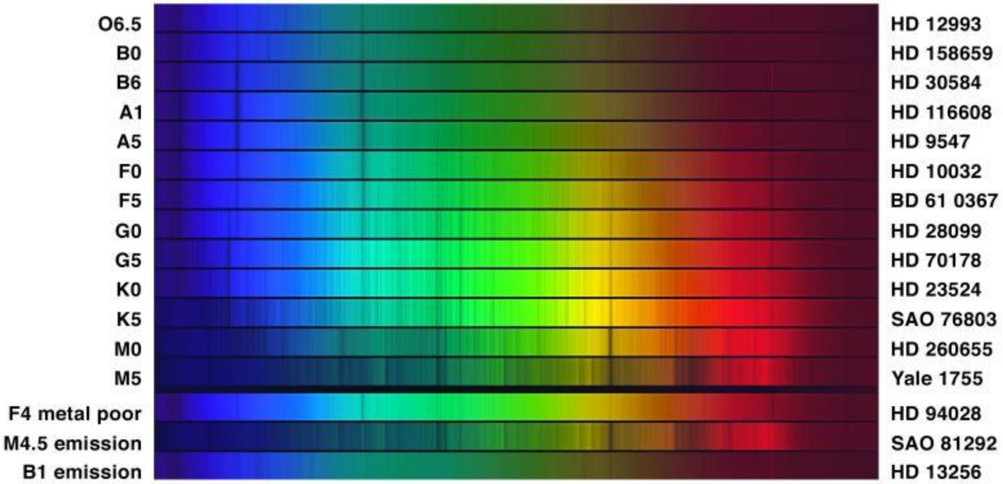
3000 K – 970 nm (IR)

10000K – 290 nm (UV)





and (wave length dependend) classification (+ absorption lines)



Spectral analysis (blackbody radiation)

and conditions how the light was emitted …

Stefan-Boltzmann eq.

(σ = 5.67… 10^{-8} W m^{-2} K^{-4})

$$L = 4\pi R^2 \sigma T^4$$

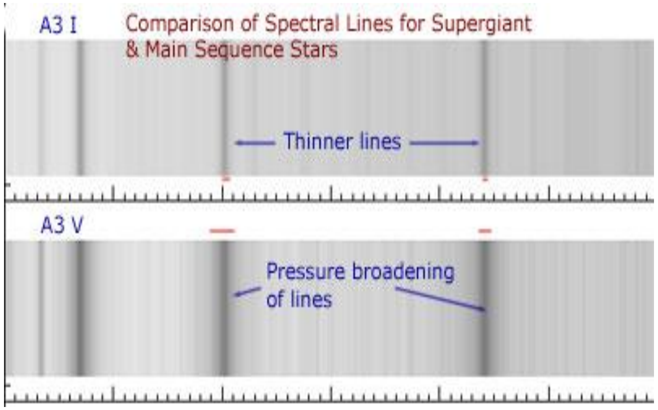
e.g. Sun T: 5777K

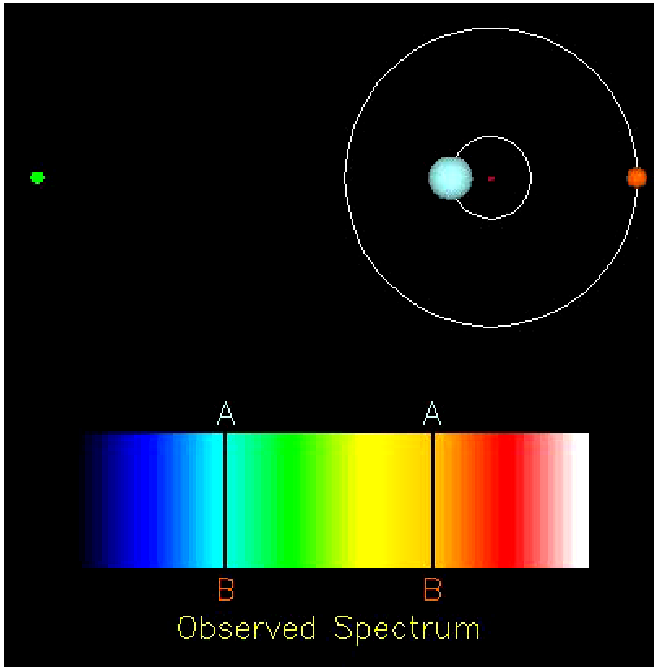
R: 0.6955 Mio km

→ L: 3.839 $\times 10^{26}$ W

➔ Model input

T, L, R from M, m, r & absorption



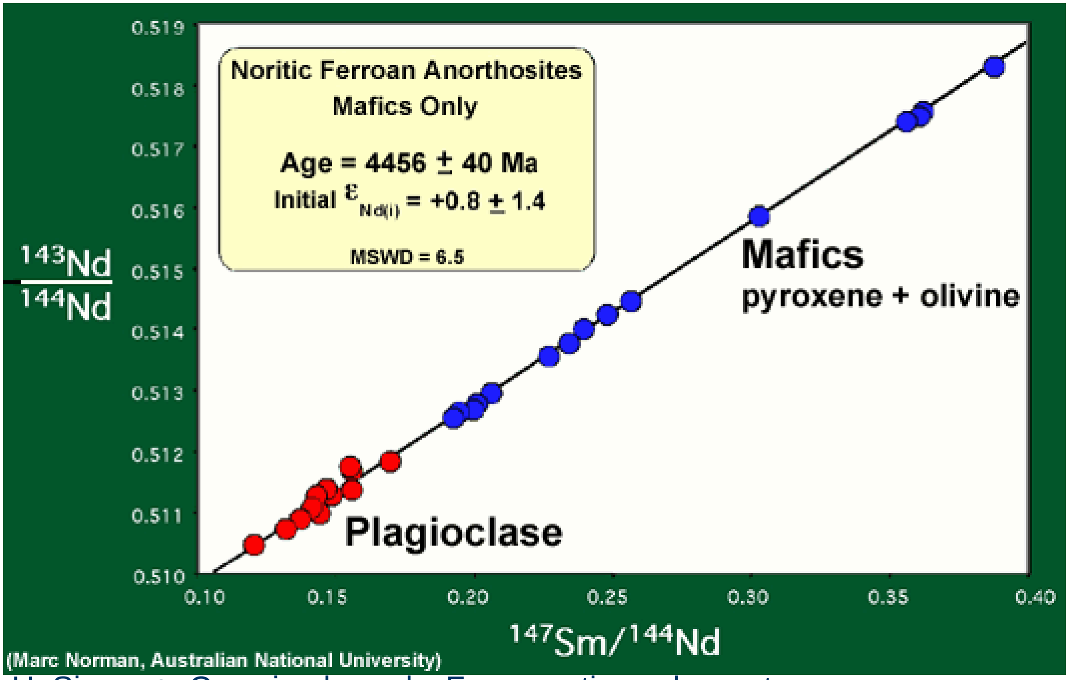


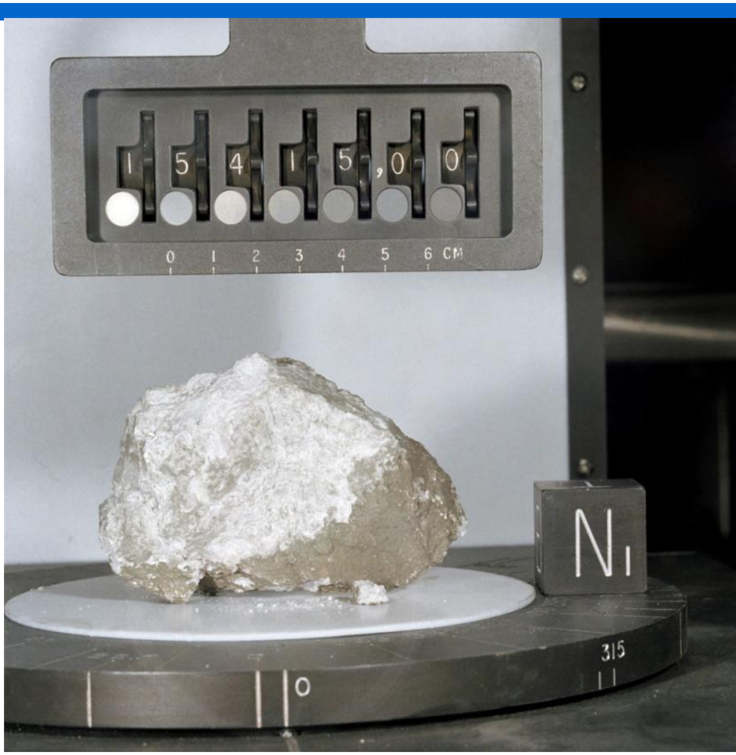
Lifetime measurements with radioisotopes

$^{147}Sm \xrightarrow{\alpha} {}^{143}Nd$, $T_{1/2}$:1.06 x 10^{11} y

^{144}Nd α decay, $T_{1/2}$:2.29 x 10^{15} y

➔ Moon surface is ~ 5 x 10^{9} y old

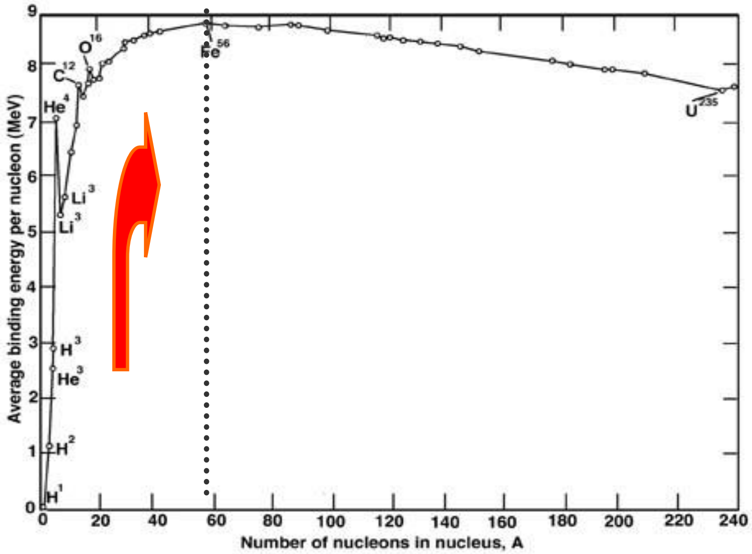




Appollo 15: “genesis rock”

… so the sun should be as old (at least) !

Consequences:



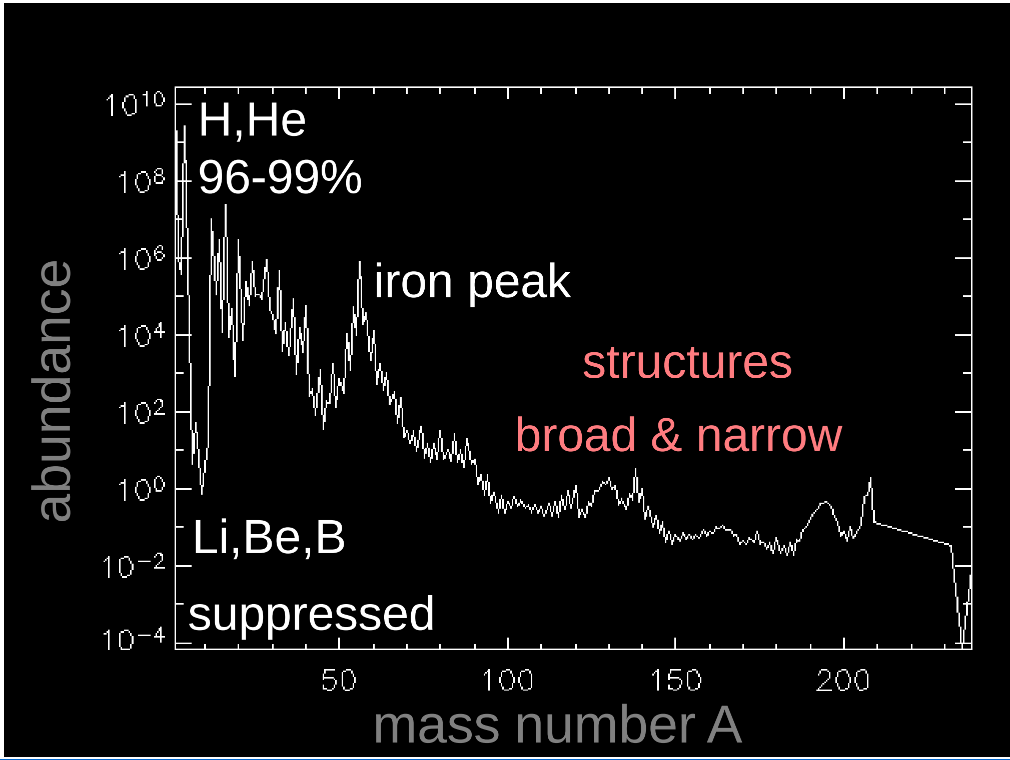
Stars use nuclear energy (fusion)

→ seed production up ~ A=56

→ 'slow' process

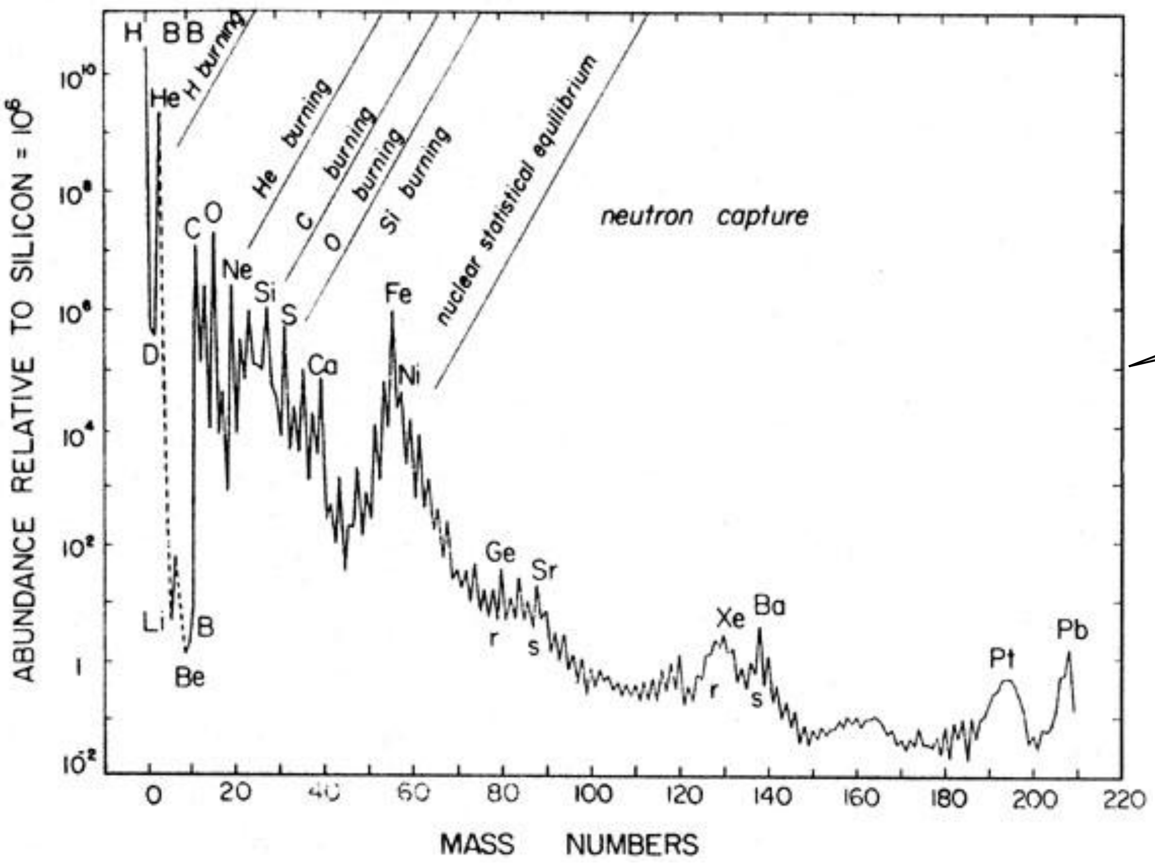
And how are heavier elements (A ≥ 56) produced ?

solar abundances



… predominantly via slow and rapid neutron capture

1. 2.→



Summary of the dominant processes

Why (and where) are radioactive beams involved ?

Examples:
1. pp (III) in the sun
2. r-process
3. n-star EOS

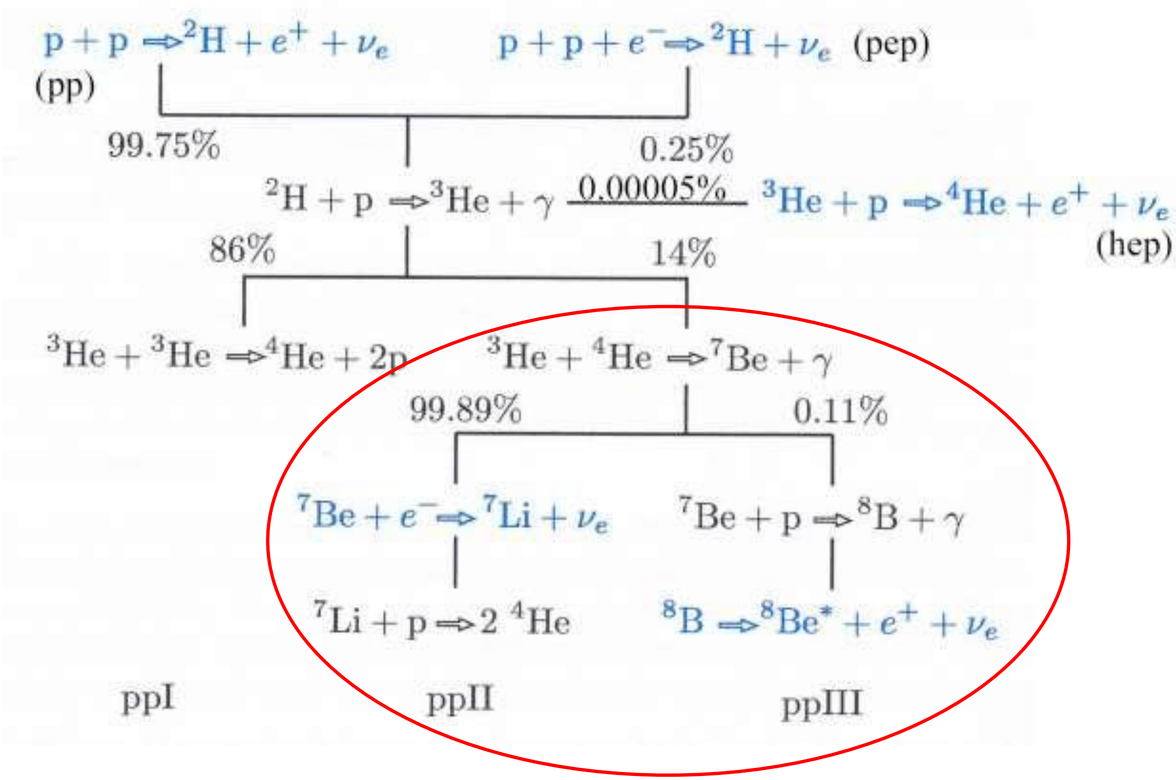
Tomography of the sun via neutrinos !

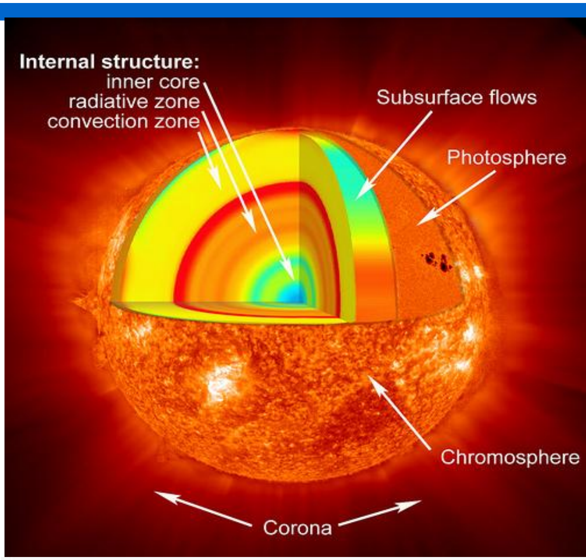
… and radioactive isotopes in the sun

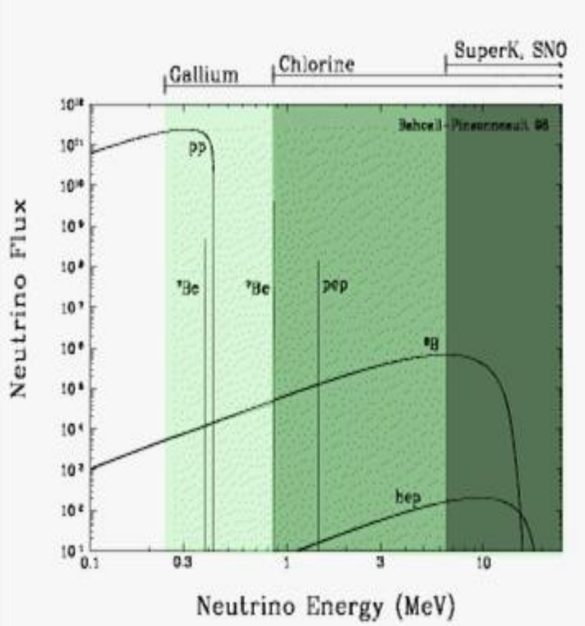
simple idea $4p \rightarrow {}^4He + 2e^+ + 2\nu$

$\Delta mc^2 = 26.73$ MeV

$Q_{eff} = \Delta mc^2 - E_\nu$ however:







$^{7}Be + p \rightarrow {}^{8}B + \gamma$ in the laboratory (direct measurement)

^{7}Be is unstable ($T_{1/2}$ = 53d)

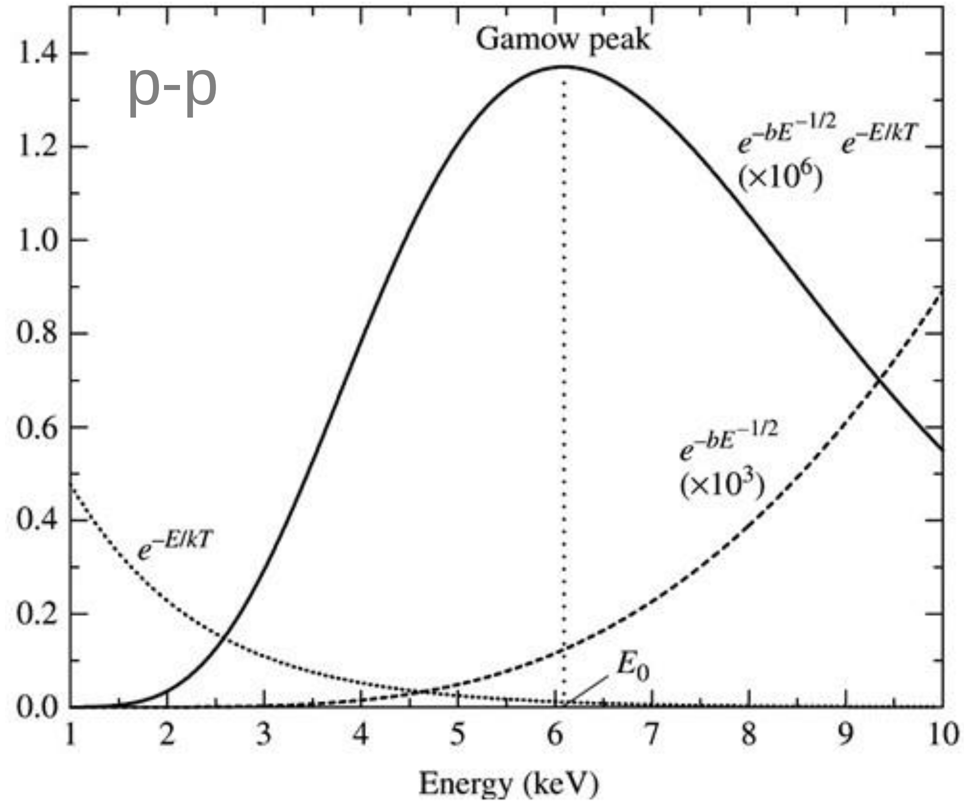
Temperature in the sun: ~ 15 Mio K
av. kin. energy $^{3}/_{2}$ kT = 8,6 · 10^{-5} eV/K * 1.5 · 10^{7} K = 1290 eV

➔ high energy tail of Boltzmann distribution
$\propto$ $e^{-E/kT}$

Coulomb repulsion
➔ tunneling through barrier
$\propto$ $e^{-b/\sqrt{E}}$

➔ low energy x-sec
(de Broglie wave length)
$\propto \pi (h/p)^2$ i.e. 1/E

Max.: $(bkT/2)^{2/3} = 1.22\,(Z_1^2 Z_2^2 \mu T_6^2)^{1/3}$ keV



➔ **Maximum $^{7}Be(p,\gamma)$ @ 18keV**,
very low energy on MeV scale !

LUNA (2009): **$^{3}He(\alpha, \gamma)^{7}Be$**
0.02 pb (2 events/m) @ 16keV
searching for a resonance
around 22keV (Gamov peak).

Possible way out …
Coulomb dissociation (CD)

Study inverse process (detailed balance)

^{8}B is unstable ($T_{1/2}$ = 0.77s)

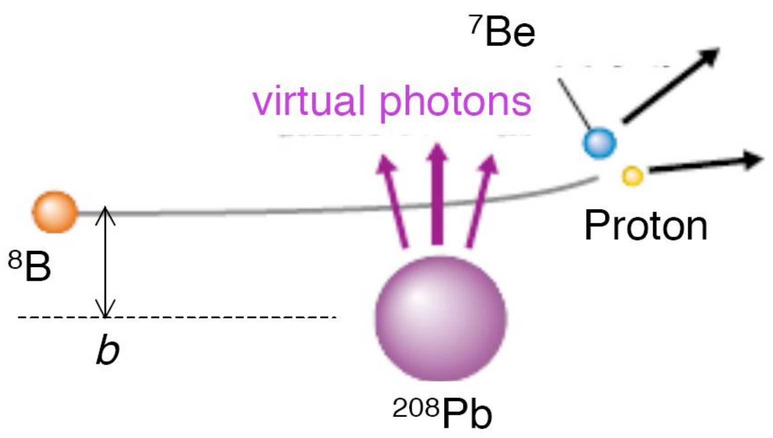
→ ^{8}B(γ,p) measure cross section σ_{CD} and relative energy ^{7}Be and p (starts at 0 threshold)

virtual photon theory

$$\frac{d\sigma_{CD}}{dE_\gamma} = \frac{1}{E_\gamma}\frac{dn}{dE_\gamma}\sigma_{(\gamma,p)}$$

↓ **detailed balance**

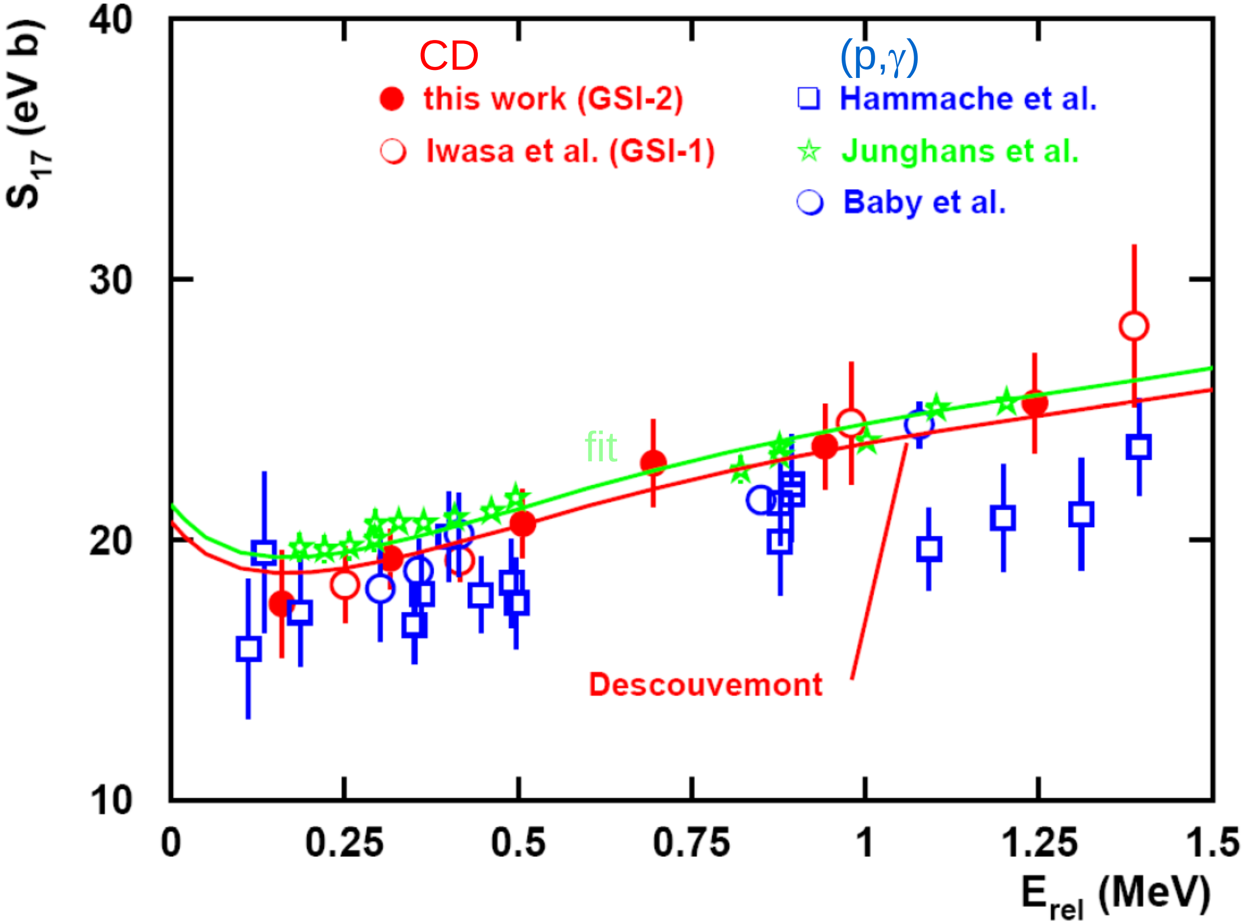
$$\sigma_{(\gamma,p)} = \frac{(2J_{7Be}+1)(2J_p+1)}{2(2J_{8B}+1)}\frac{k_{cm}^2}{k_\gamma^2}\sigma_{(p,\gamma)}$$



$k_\gamma = (E_{rel}+Q)/\hbar c$ $k_{cm}^2 = 2\mu E_{rel}/\hbar^2$ Q=138 keV

Both methods work … and deliver comparable results !

$\sigma(E) = S(E) / E\, e^{-b/\sqrt{E}}$ ➔ S(E) describes nuclear structure



Extrapolation
from 100keV
to relevant
low energy
still necessary !

resolution (CD)
vs.
rate (direct)

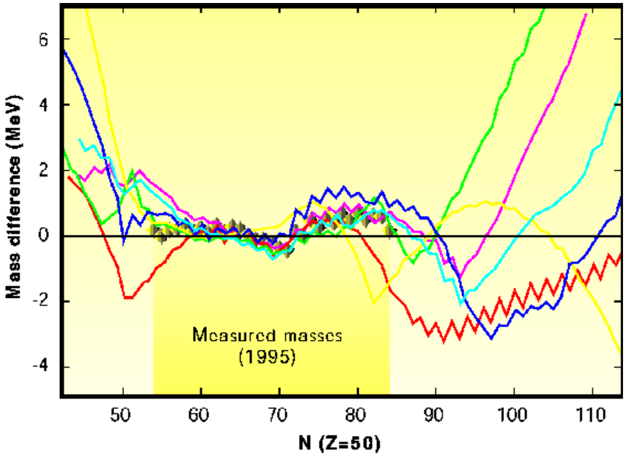
To be explained …

Radioactive Beam Studies:

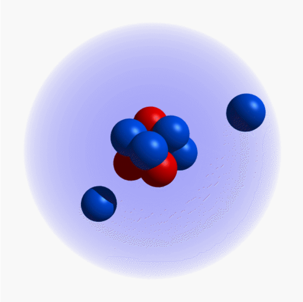
Specific (***x***, γ) reactions

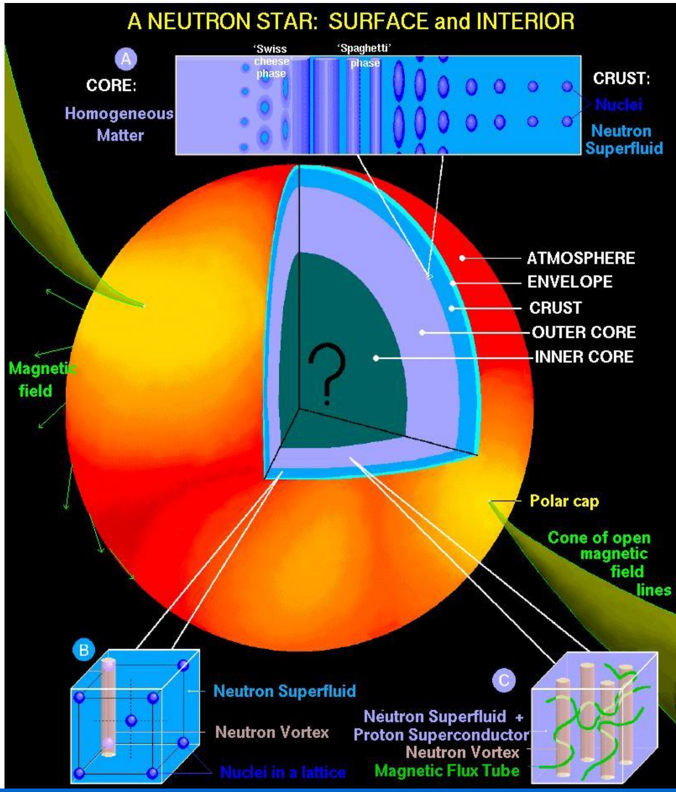
$^{4}He(2n,\gamma)^{6}He$, $^{7}Be(p,\gamma)^{8}B$, $^{14}C(n,\gamma)^{15}C$, $^{26}S(p,\gamma)^{27}P$, $^{15}O(2p,\gamma)^{17}Ne$, $^{31,32}Cl(p,\gamma)^{32,33}Ar$, …

Structure input for
extrapolation
of nuclear data

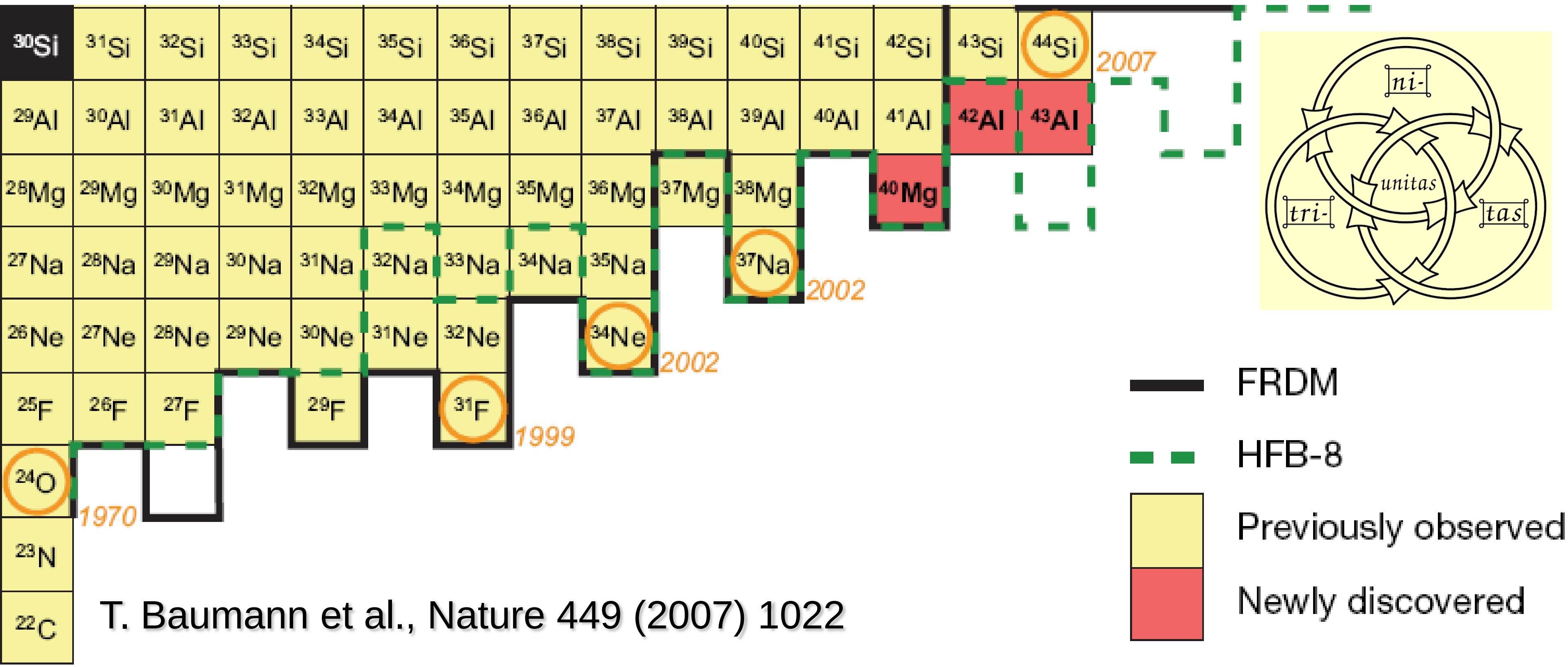


Neutron matter
very exotic systems,
^{x}n, $^{5,7}H$, $^{9,10}He$, $^{12,13}Li$, …
precise study asymmetry
EOS via excitations



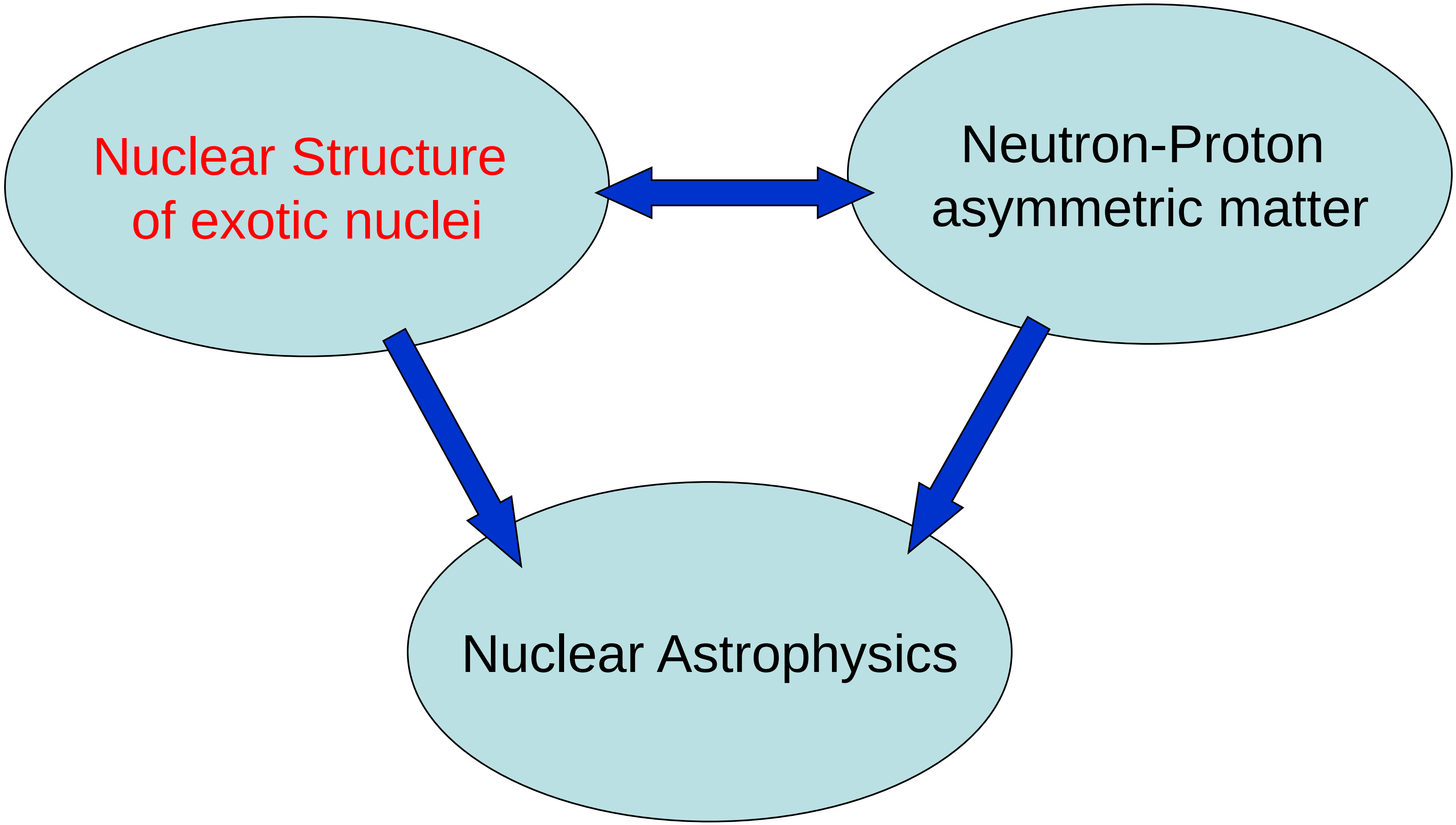


At the Outskirts: Three bodies find together



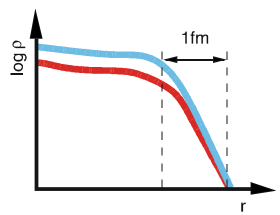
T. Baumann et al., Nature 449 (2007) 1022

Physics with radioactive beams

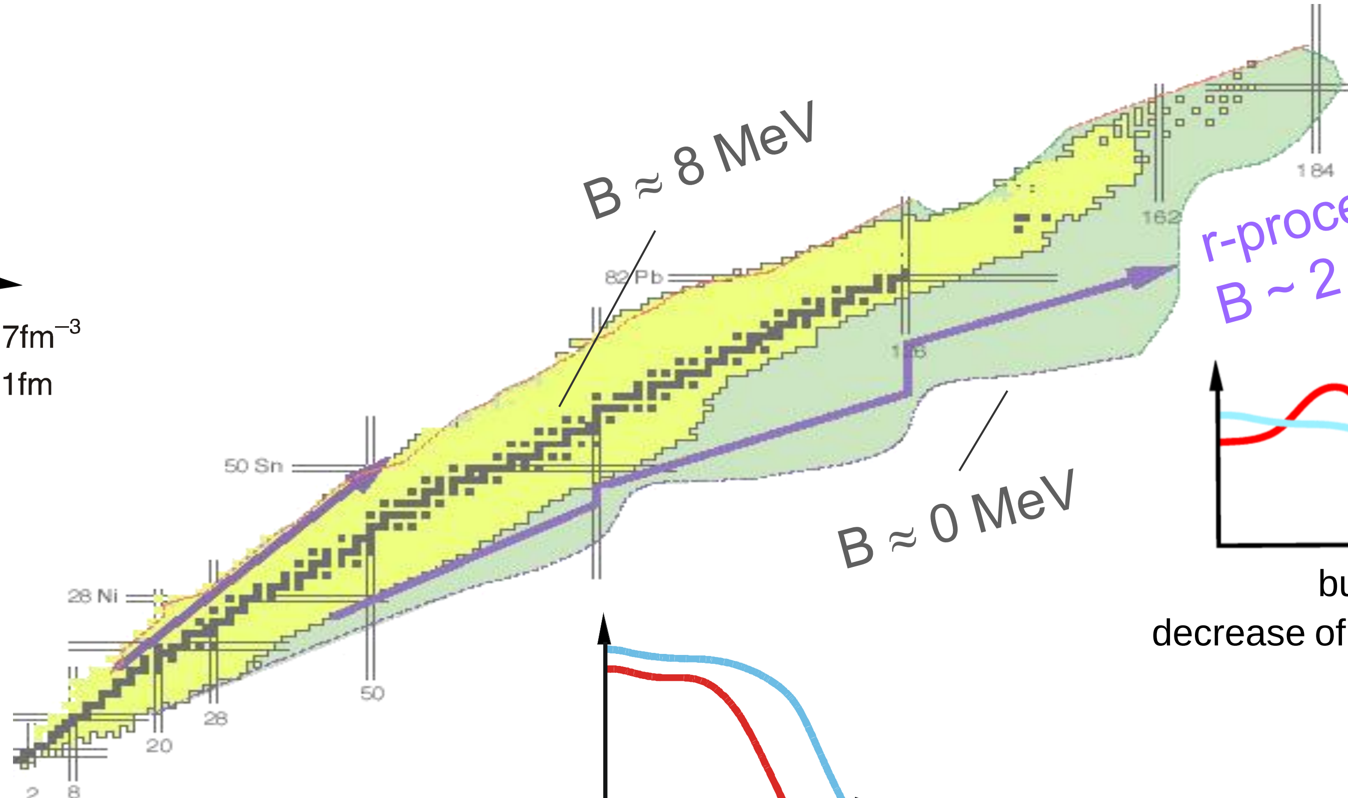


What‘s exotic in Exotic Nuclei

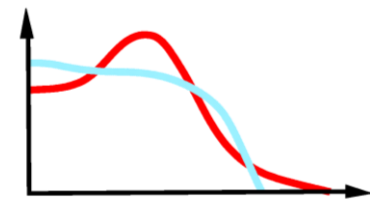
stable



$r_p = r_n, \quad \rho_0 = 0.17\text{fm}^{-3}$
$d_p = d_n = \text{const} \approx 1\text{fm}$

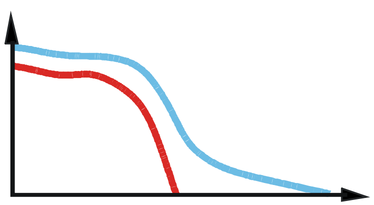


r-process path
$B \sim 2 - 3$ MeV



bubble
decrease of central density

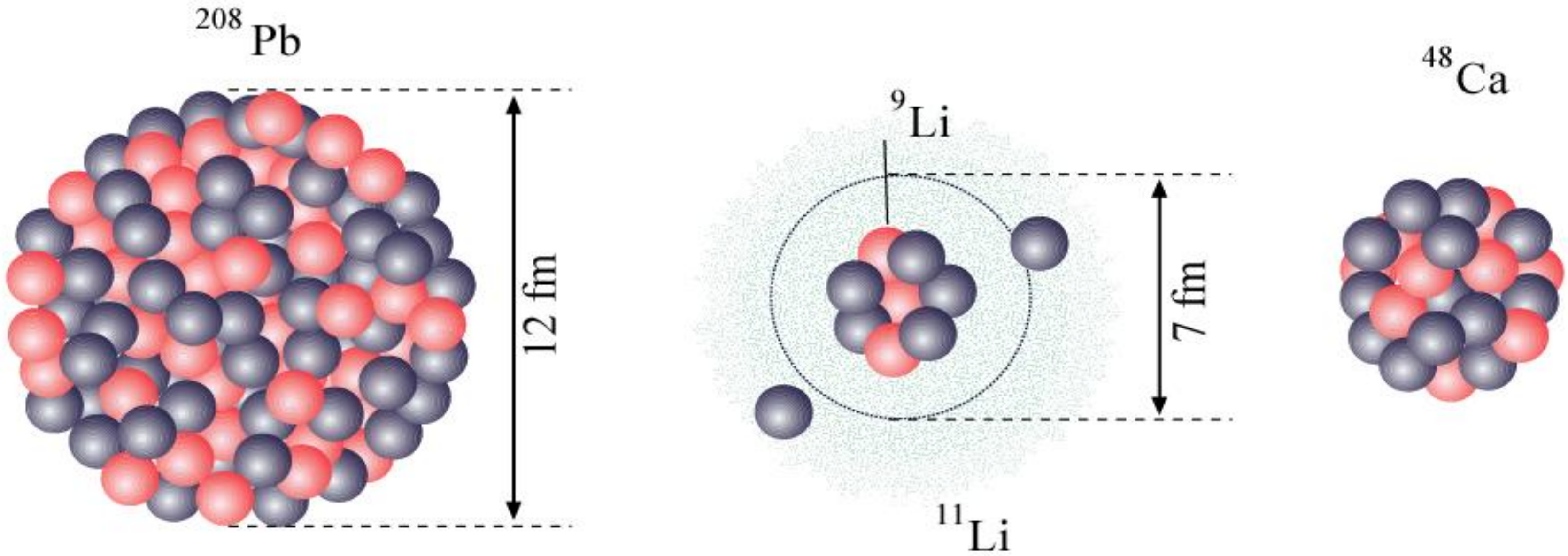
skin
$r_p \neq r_n$
$d_p = d_n$



halo
$r_p \neq r_n$
$d_p \neq d_n$

binding energies (B) of valence nucleons small
proton and neutron density distributions differ

Exotica: Haloes



The nuclear Halo

Threshold phenomenon resulting from a bound state close to the continuum

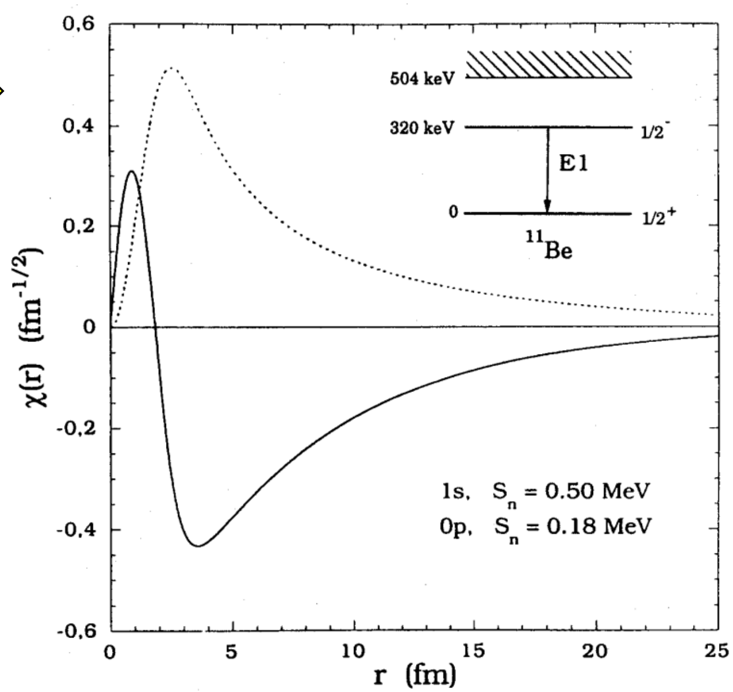
Low separation energy + short range of nuclear force allow tunnelling into the space surrounding the core

e.g. ^{11}Be

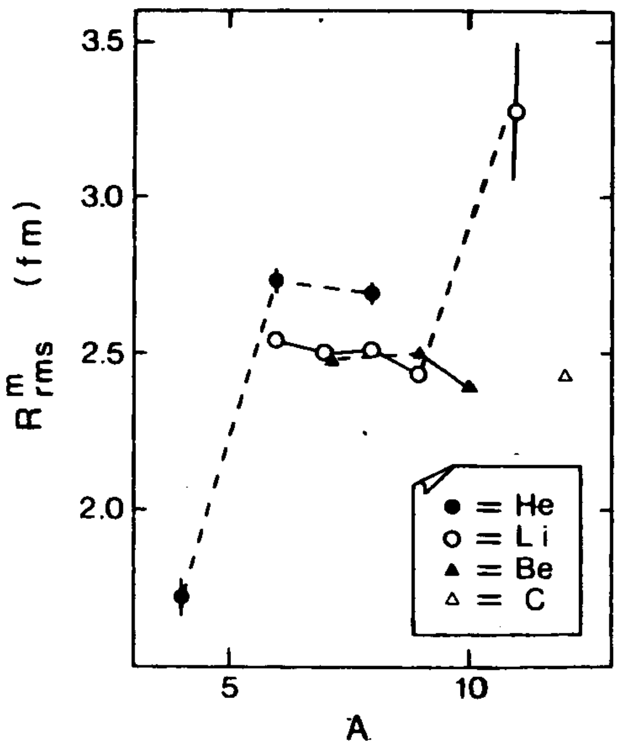
Spatially separated clusters

$$\psi(r) \rightarrow \frac{e^{-\kappa r}}{r}$$

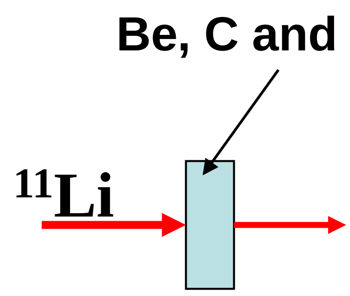
$$\kappa = \frac{\sqrt{2mS_n}}{\hbar}$$



Cross section reflects size (Tanihata 1985)



$$\sigma_I(p,t) = \pi[R_I(p) + R_I(t)]^2$$

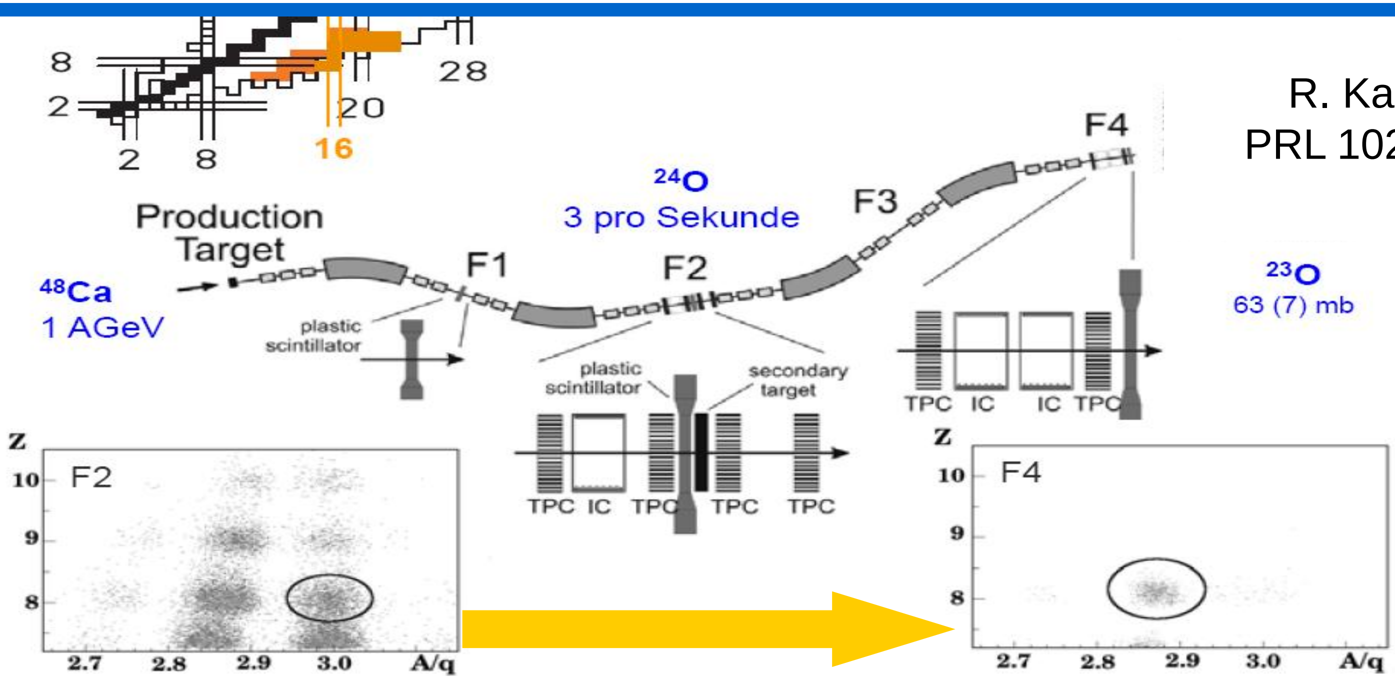


$$\sigma_I \Rightarrow \left\langle r^2_{matter} \right\rangle^{1/2}$$

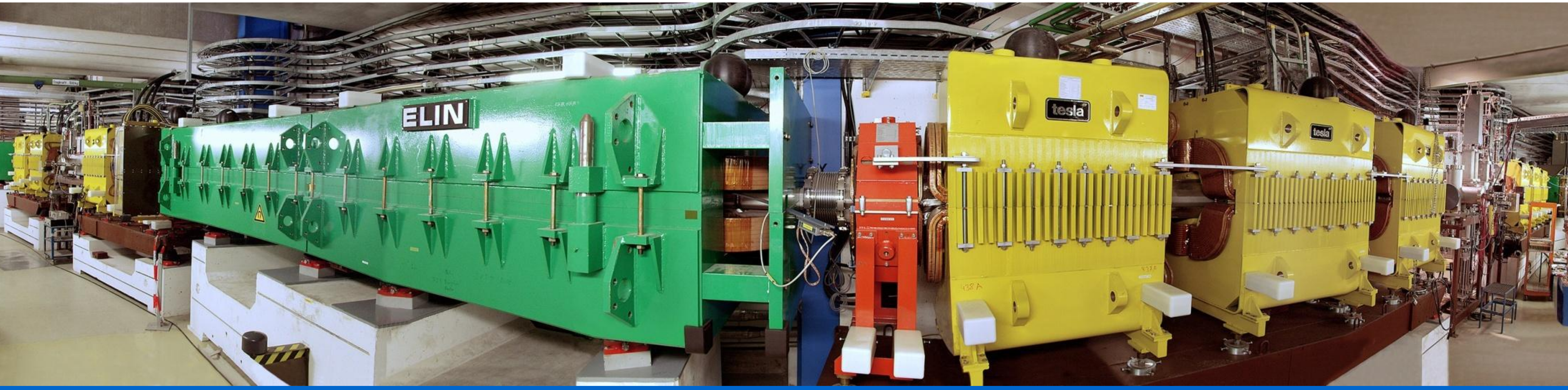
R(^{11}Li) = 3.10(14) fm

I. Tanihata et al., PRL 55 (1985) 2676

Transmission Experiment



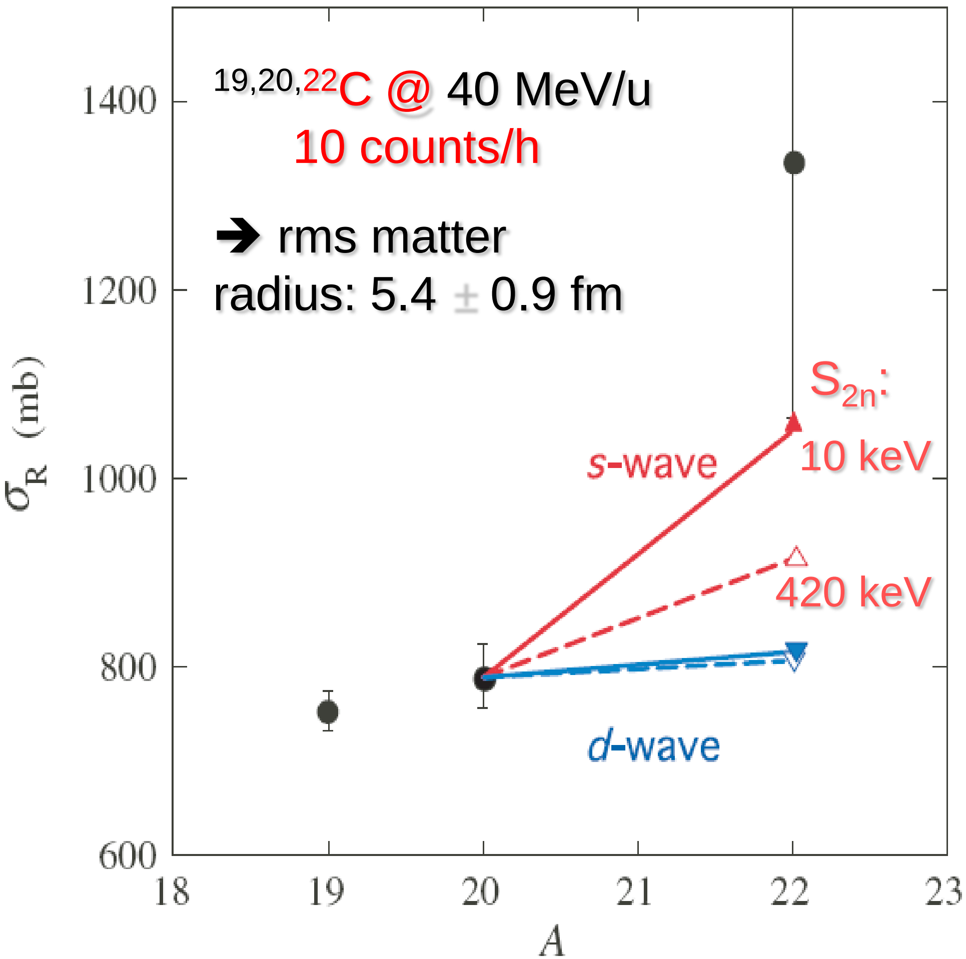
R. Kanungo et al.,
PRL 102(2009)152501

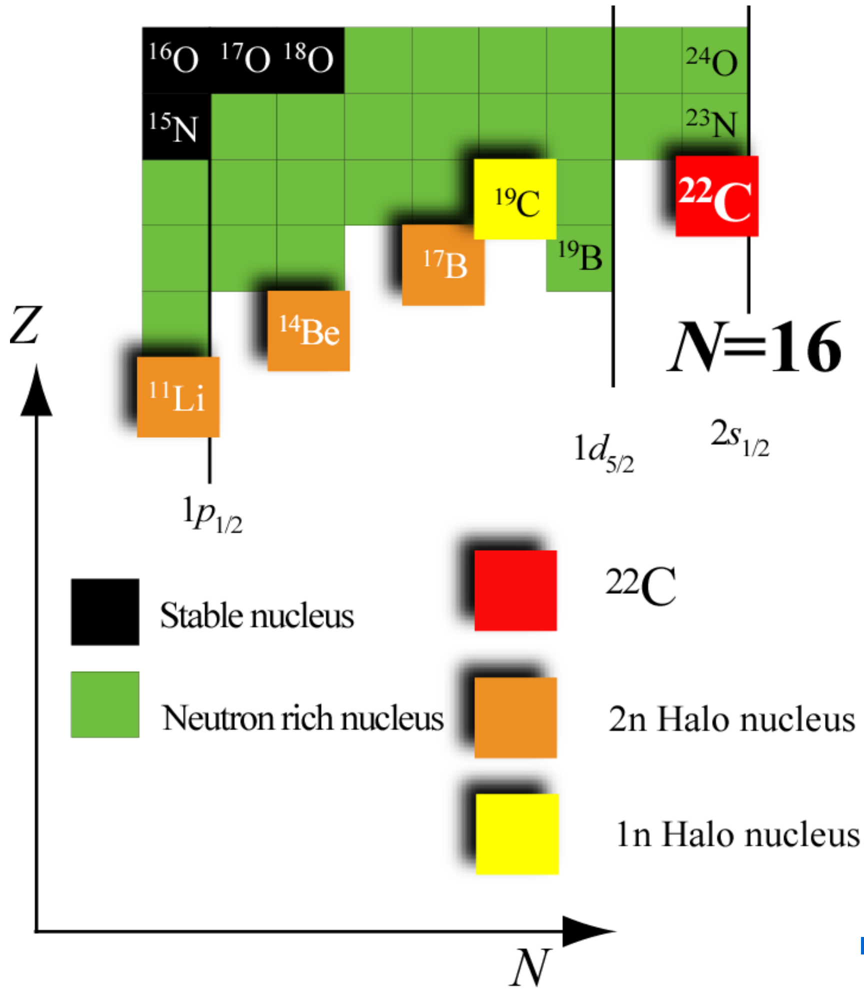


Observation of a Large Reaction Cross Section in the Drip-Line Nucleus ^{22}C

K. Tanaka,[1] T. Yamaguchi,[2] T. Suzuki,[2] T. Ohtsubo,[3] M. Fukuda,[4] D. Nishimura,[4] M. Takechi,[4,1] K. Ogata,[5] A. Ozawa,[6] T. Izumikawa,[7] T. Aiba,[3] N. Aoi,[1] H. Baba,[1] Y. Hashizume,[6] K. Inafuku,[8] N. Iwasa,[8] K. Kobayashi,[2] M. Komuro,[2] Y. Kondo,[9] T. Kubo,[1] M. Kurokawa,[1] T. Matsuyama,[3] S. Michimasa,[1,*] T. Motobayashi,[1] T. Nakabayashi,[9] S. Nakajima,[2] T. Nakamura,[9] H. Sakurai,[1] R. Shinoda,[2] M. Shinohara,[9] H. Suzuki,[10,6] E. Takeshita,[1,†] S. Takeuchi,[1] Y. Togano,[11] K. Yamada,[1] T. Yasuno,[6] and M. Yoshitake[2]

PRL 104 (2010) 062701



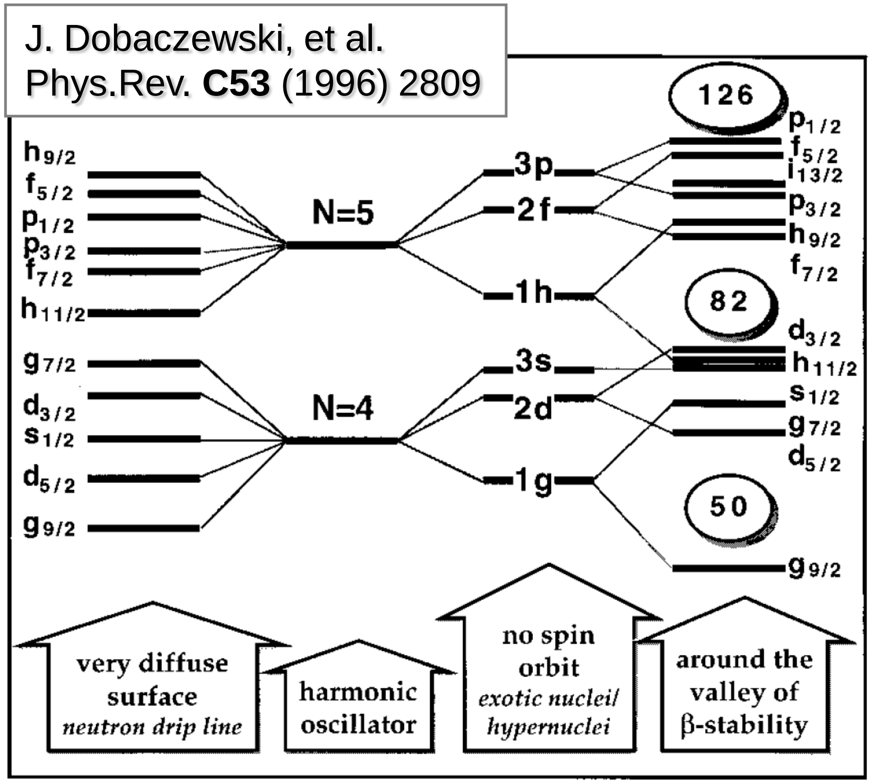


Shell reordering: Halo formation

Mean-field modifications

surface composed of diffuse neutron matter

derivative of mean field potential weaker and spin-orbit interaction reduced



Nucleon-nucleon interaction

$\sigma\sigma\tau\tau$ interaction :

coupling of p-n spin-orbit partners in partly occupied orbits

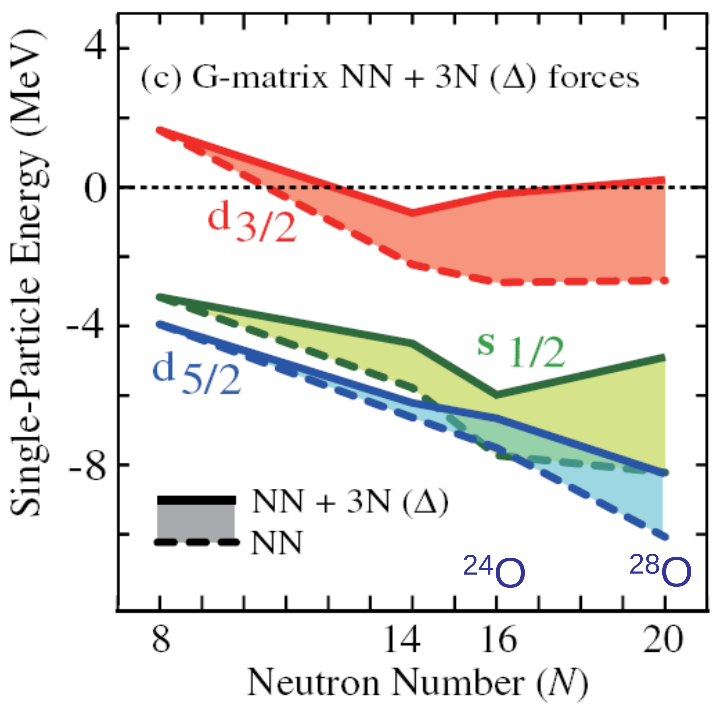
O: missing $\pi d_{5/2}$ do not bind $\nu d_{3/2}$ → N=16

T.Otsuka et al.,PRL**87** (2001) 082502

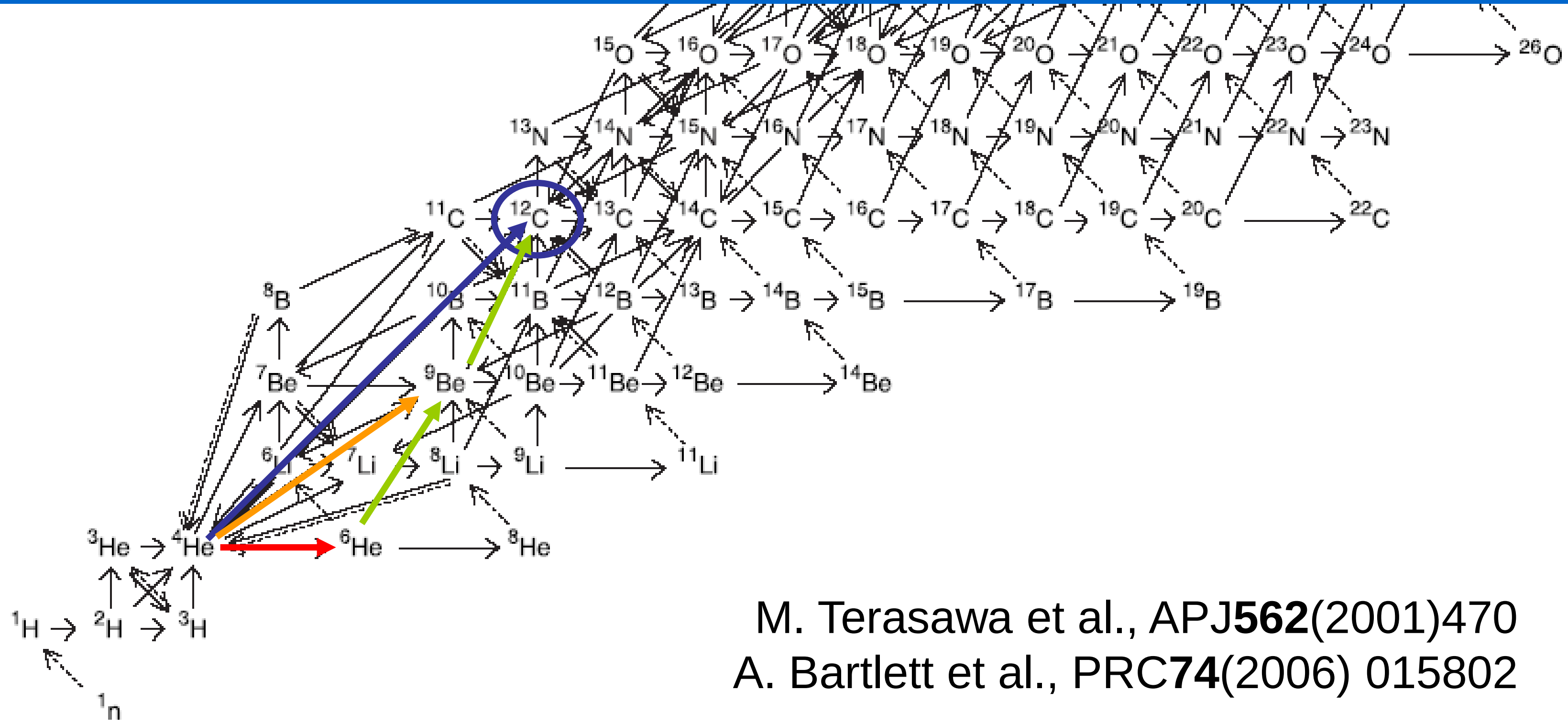
(tensor) PRL**95** (2005) 232502

Repulsive 3N force

T.Otsuka et al., PRL**105** (2010) 032501



Bridging the A=5,8 gaps for heavy element creation



M. Terasawa et al., APJ**562**(2001)470
A. Bartlett et al., PRC**74**(2006) 015802

- Bypass reactions to triple-α process — stellar burning
- ^{8}Be(n,γ)^{9}Be(α,n)^{12}C — e.g. core collapse supernovae
- ^{4}He(2n,γ)^{6}He(α,n)^{9}Be — possibly n-star mergers

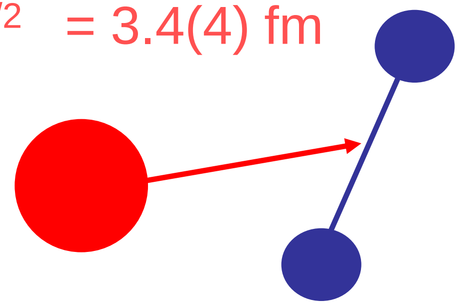
Continuum spectroscopy ($^{4}He(2n,\gamma)^{6}He$ backwards)

Coulomb dissociation:

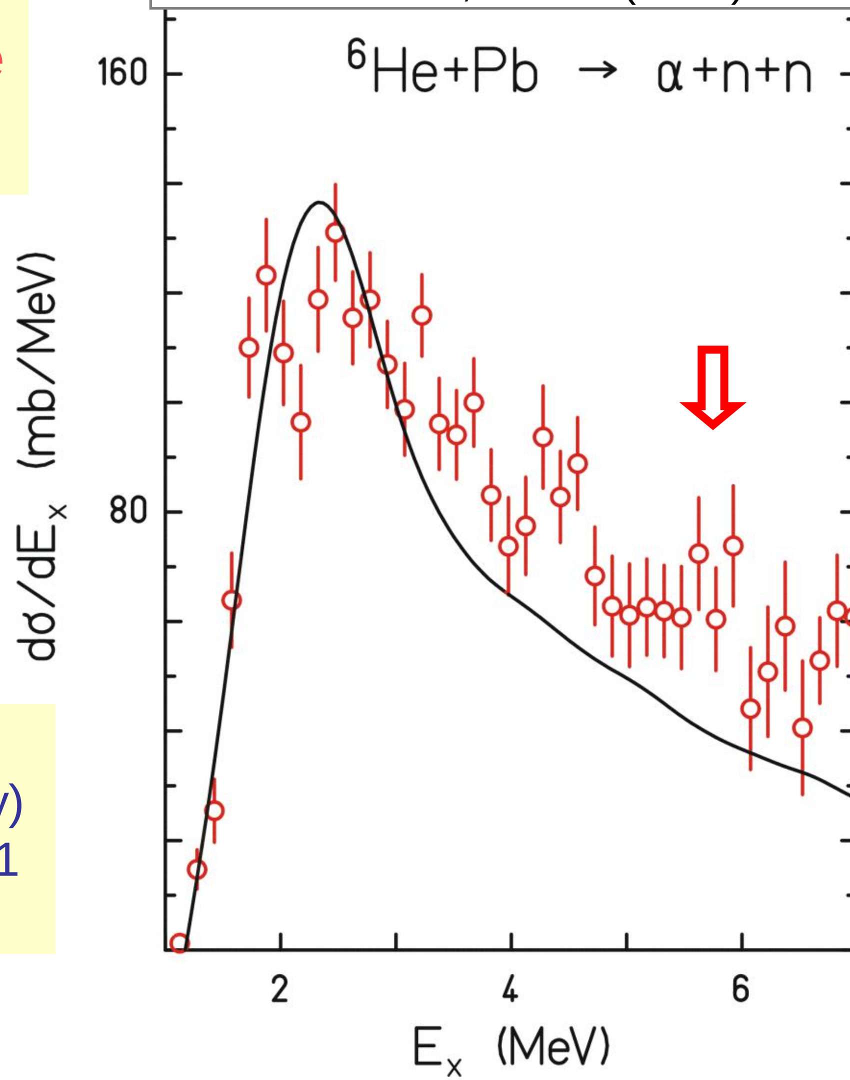
$E_x \leq 10$ MeV 100% cluster sumrule

$\Sigma B(E1) = 1.2(0.2)\ e^2fm^2$

$\langle r^2_{\alpha-nn}\rangle^{1/2} = 3.4(4)$ fm



T. Aumann et al., PRC**59**(1999)1252



$\langle r_c^2\rangle^{1/2}$ exp. = 2.016(72) fm

$\langle r_c^2\rangle^{1/2}$ exp. = 2.068(11) fm (laser spectroscopy)

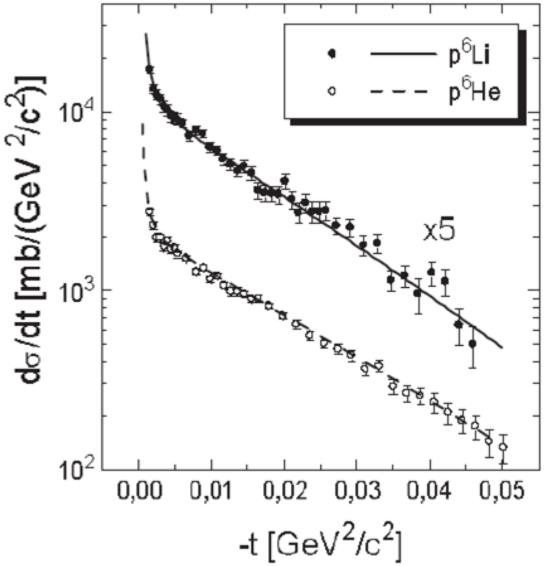
P. Mueller et al. PRL**99** (2007) 252501

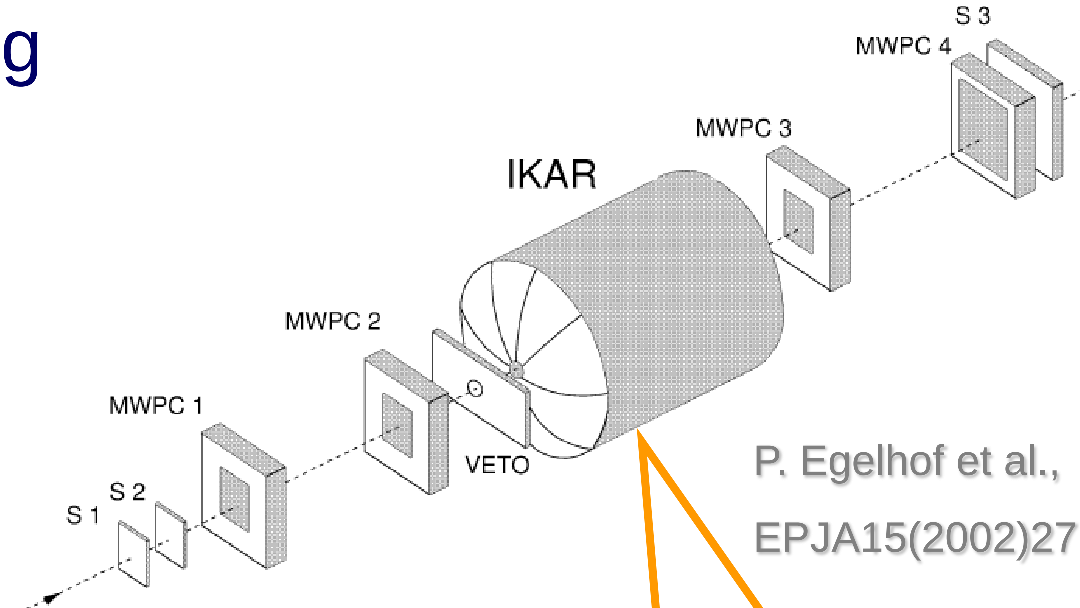
$\langle r_c^2\rangle^{1/2}$ theo. = 2.059 fm

B.V. Danilin et al., NPA632 (1998) 383

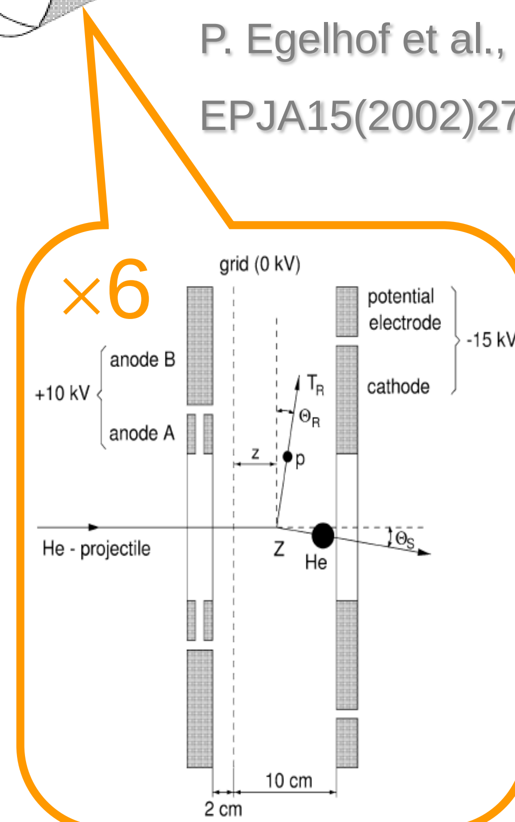
Elastic proton scattering

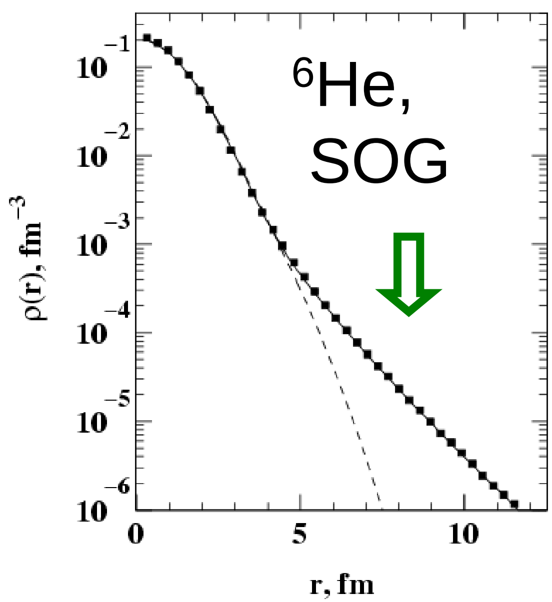
- inverse kinematics

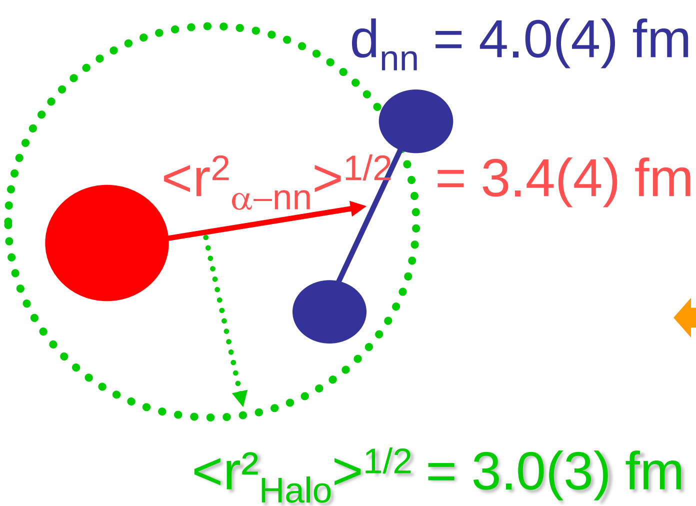




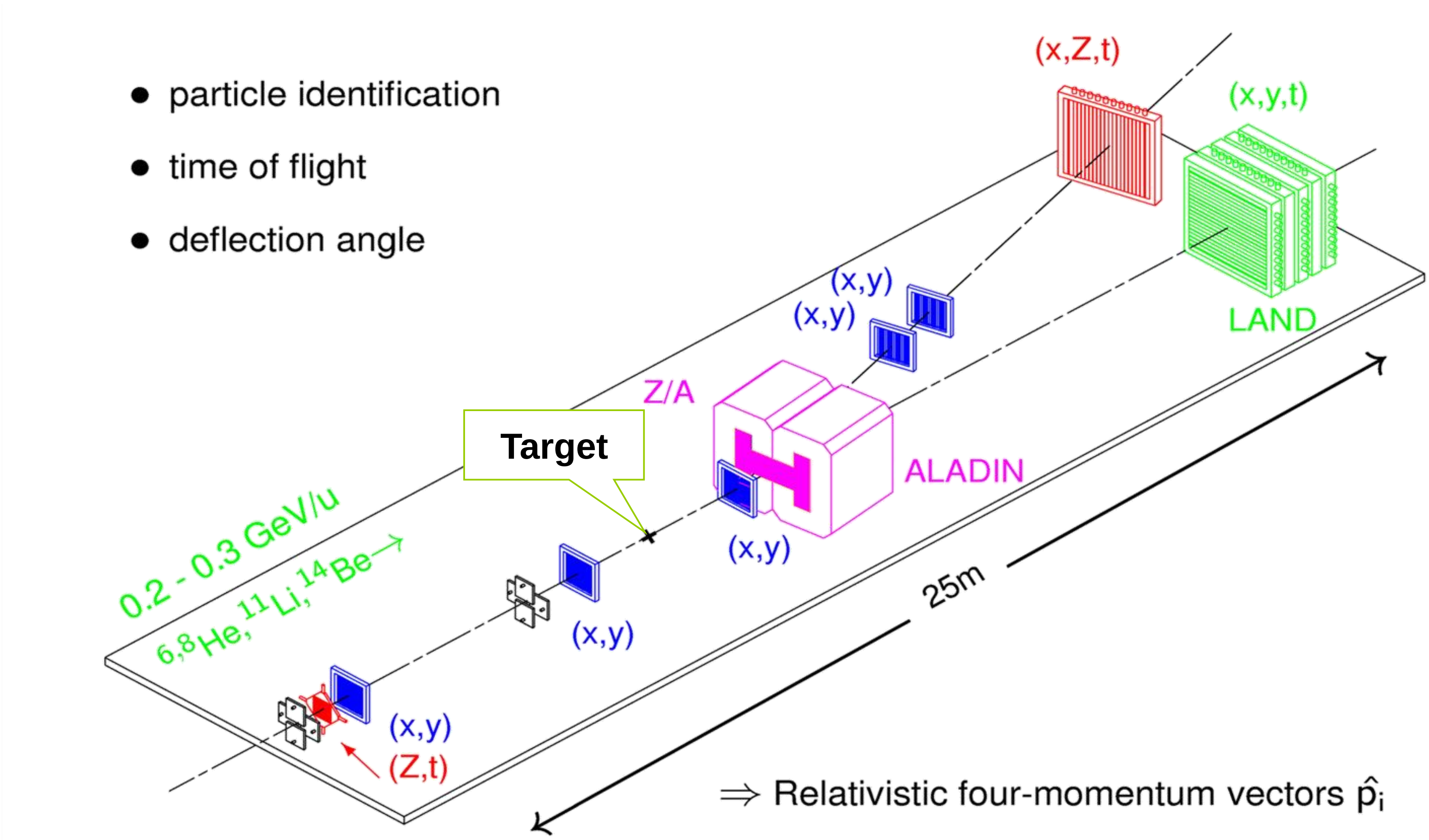
P. Egelhof et al., EPJA15(2002)27







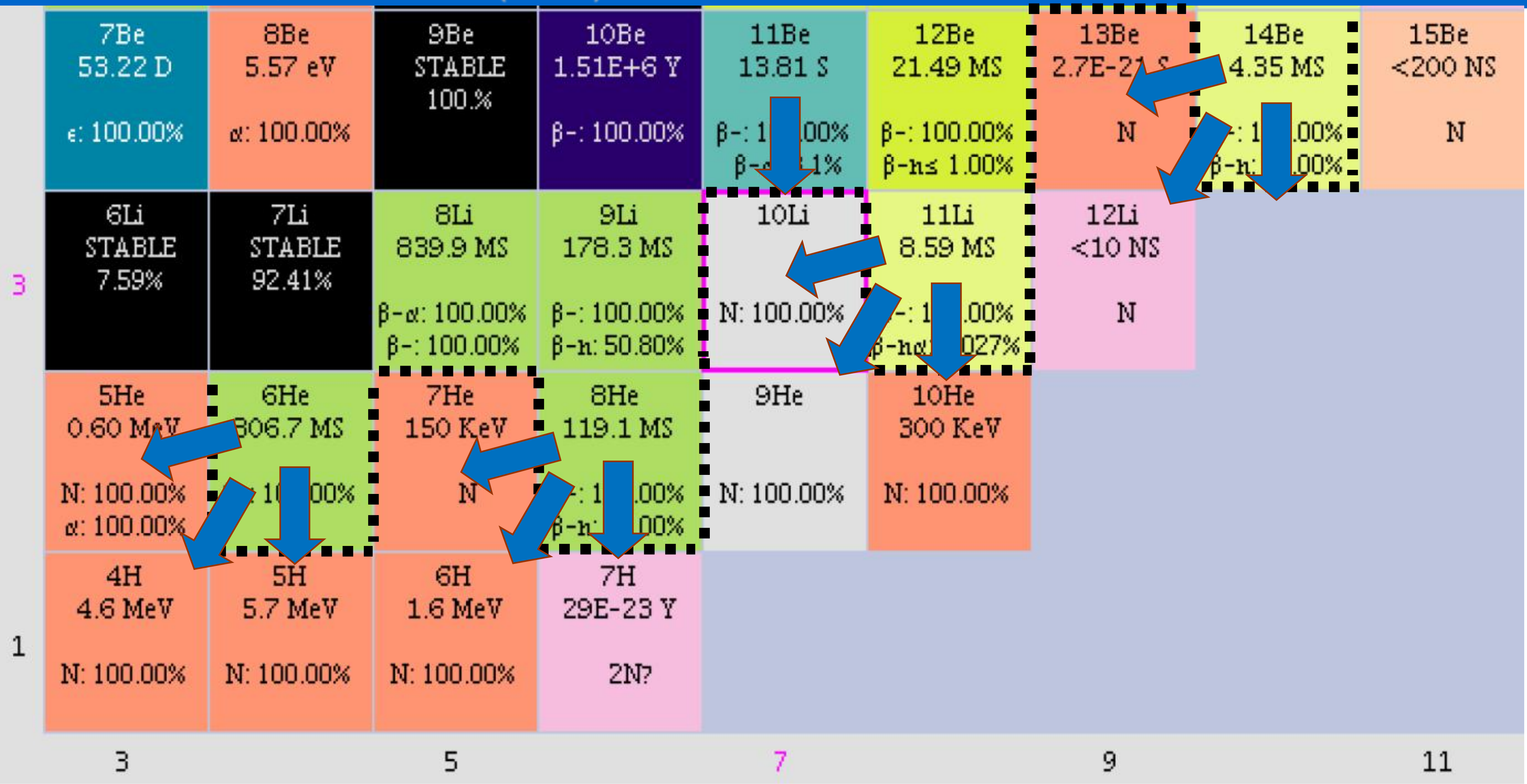
ALADIN-LAND Setup (kinematically complete)



Experimental Setup (less schematic)

Exotic structure across the dripline:

P.G. Hansen, Nature 328 (1987) 476



➔ **most exotic systems**

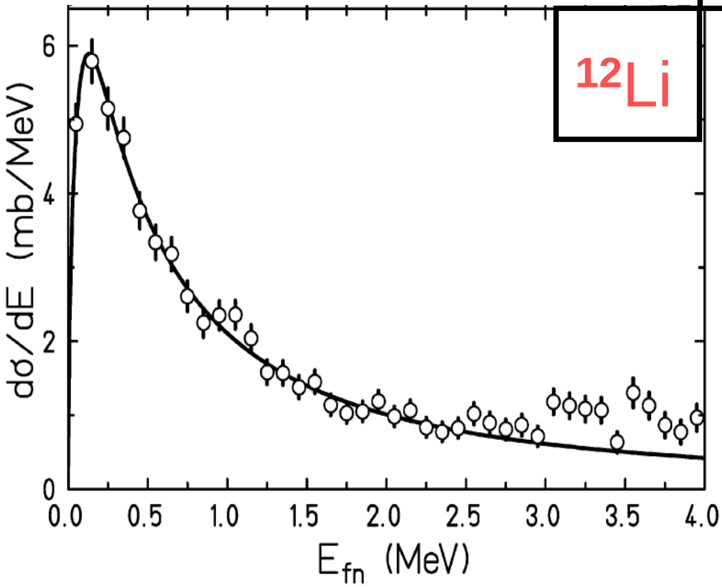
➔ **nearly unbiased & clean production !**

Exploring Unbound Lithium isotopes

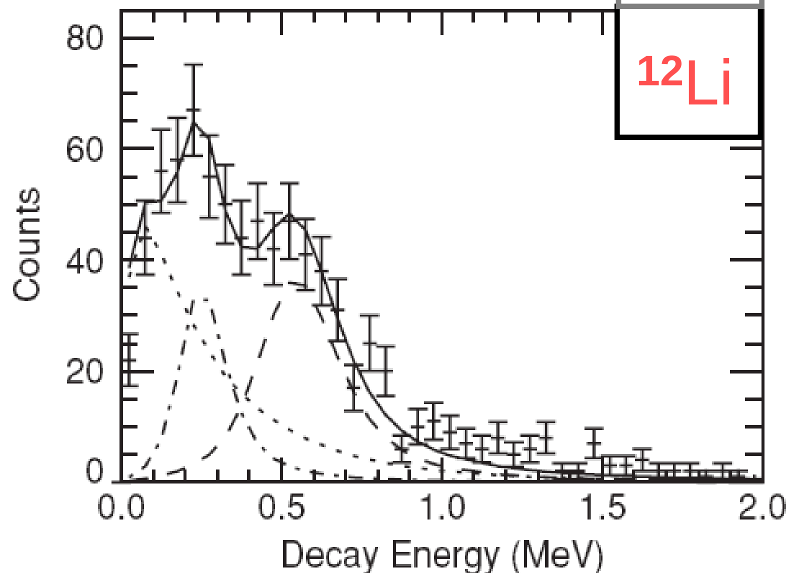
^{14}B

^{14}Be

^{12}Li

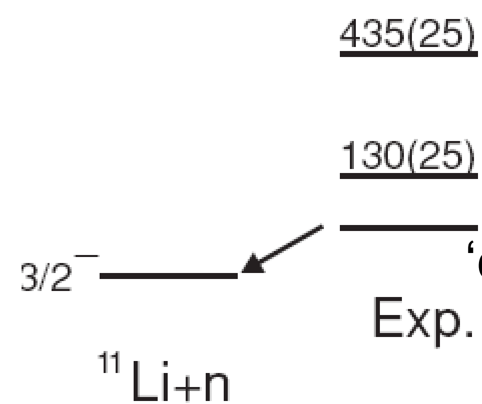


^{12}Li



a_s (fm)	S_n(MeV)
-13.7(1.6)	1.47(0.19)

Close to S_{2n} ^{14}Be



Y. Aksyutina et al., PL**B666** (2008) 430

C. Hall et al., PR**C81** (2010) 021302

Exploring Unbound Lithium isotopes

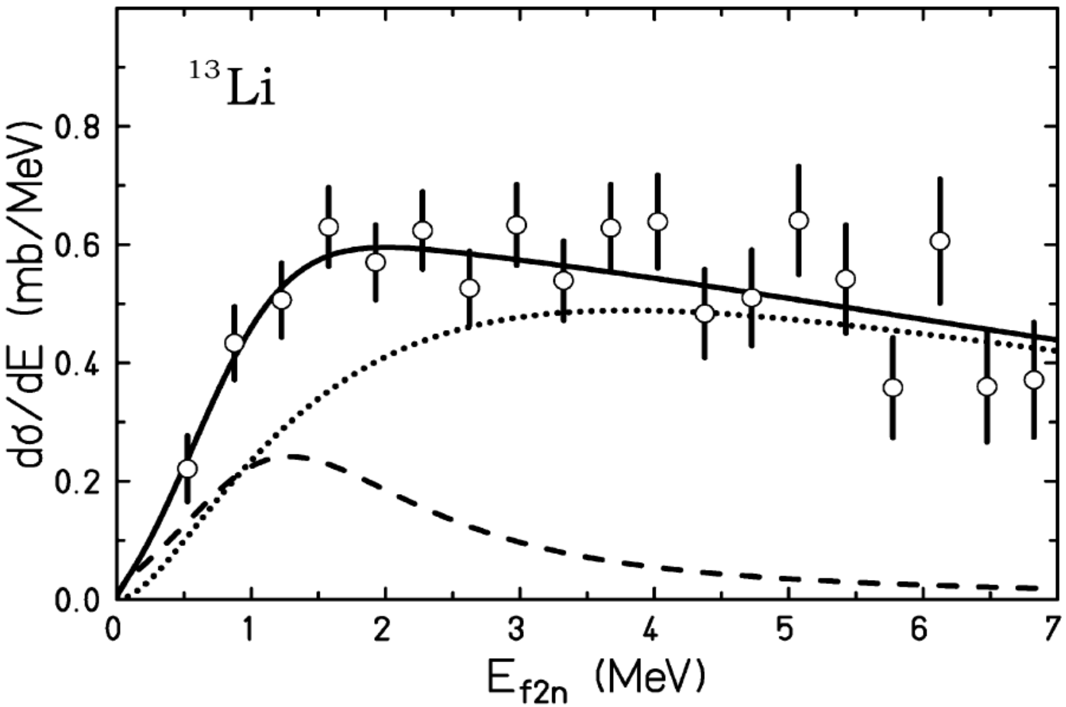
^{14}Be

^{13}Li

^{13}Li: ^{14}Be + p → ^{11}Li + n + n

$d\sigma/dE_{noFSI} \propto E^2/(2.21\ S_{2n} + E)^{7/2}$ $K_0=0$

C. Forssén, B. Jonson, M.V. Zhukov NP**A673** (2008) 143



Momentum transfer small, ^{11}Li core survives collision !

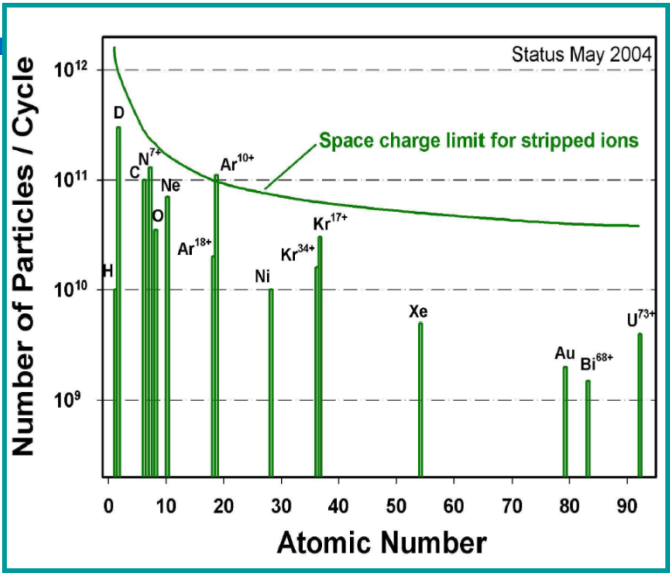
➔ ^{11}Li + 2n resonance picture

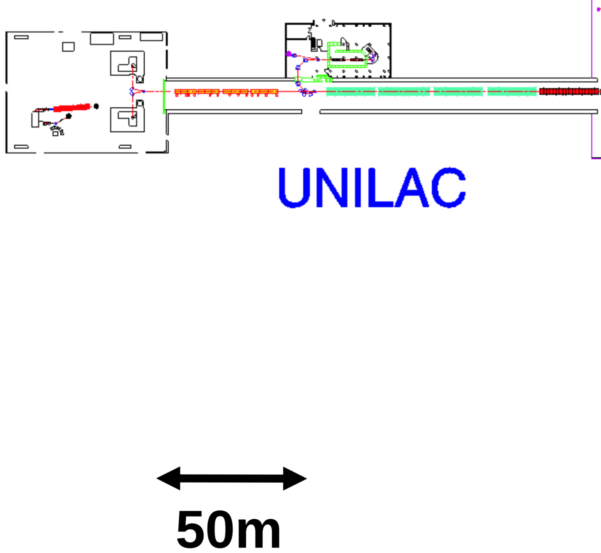
Evidence for existence at 1.47(31) MeV.

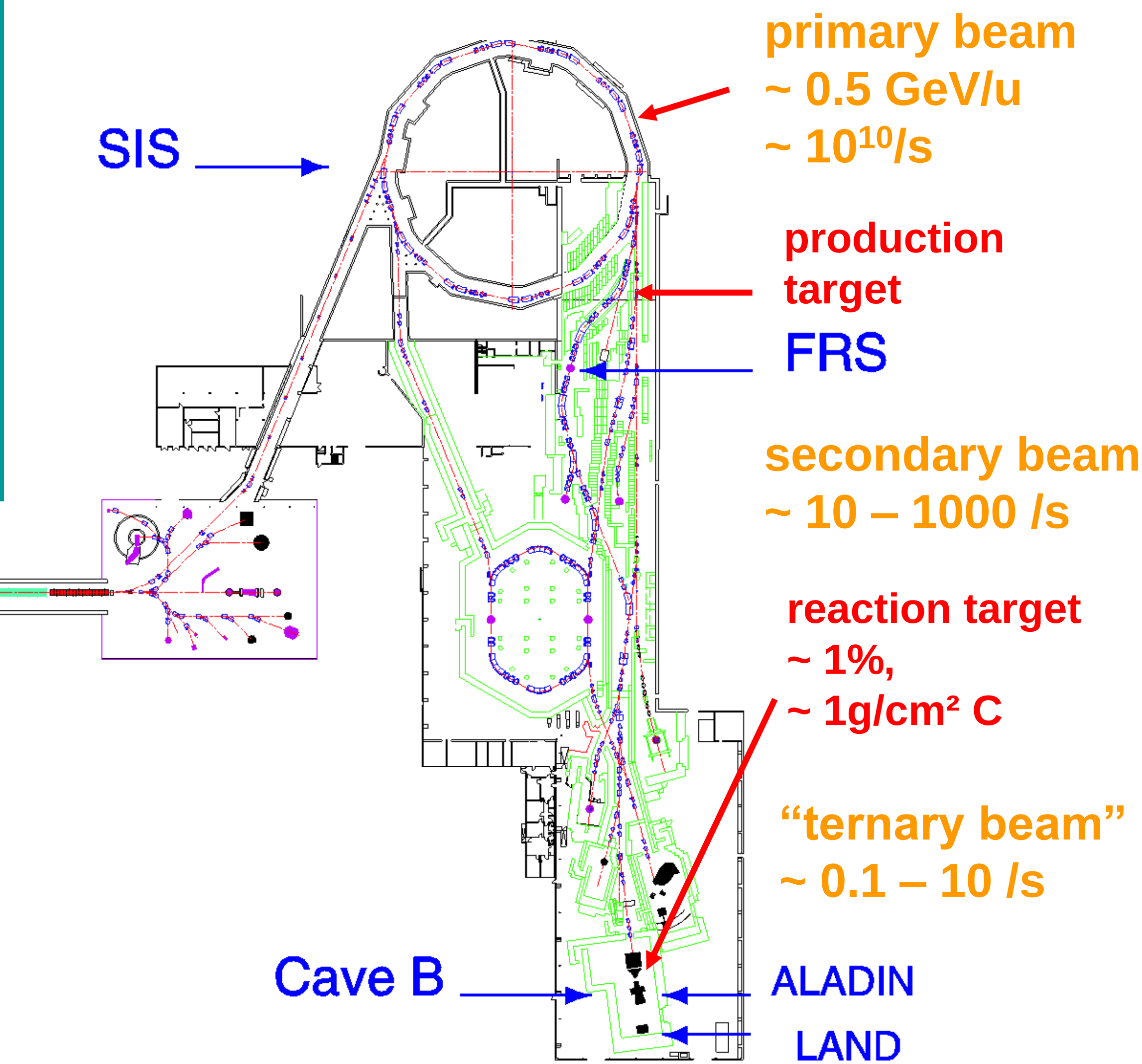
➔ Angular correlations …

Y. Aksyutina, H. Johansson et al., PL**B666** (2008) 430
H.T. Johansson, Y. Aksyutina, Nucl. Phys. **A847** (2010) 66

Intensities for detailed studies







Results and current limits …

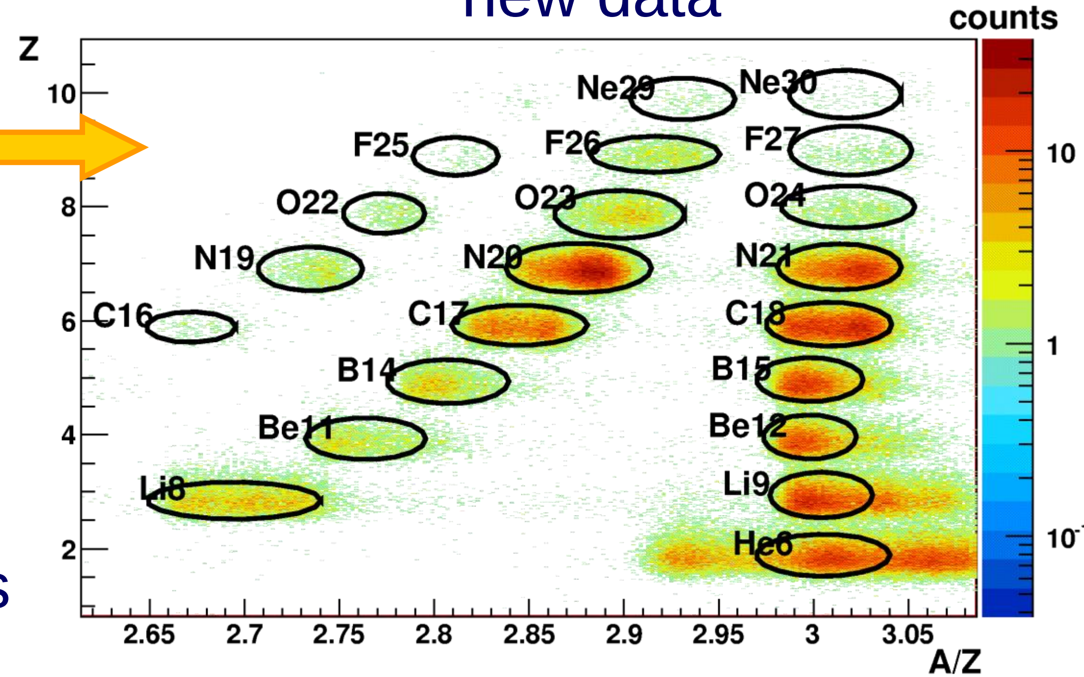
					14Be
		10Li	11Li	12Li	13Li
6He	7He	8He	9He	10He	first time !
5H					

- Comprehensive study of exotic unbound systems with extreme A/Z
- Structure information unveiled

25F	26F	27F
24O	25O	26O

- e.g. Unbound oxygen isotopes

new data



Results and current limits …

^{14}Be

^{10}Li	^{11}Li	^{12}Li	^{13}Li

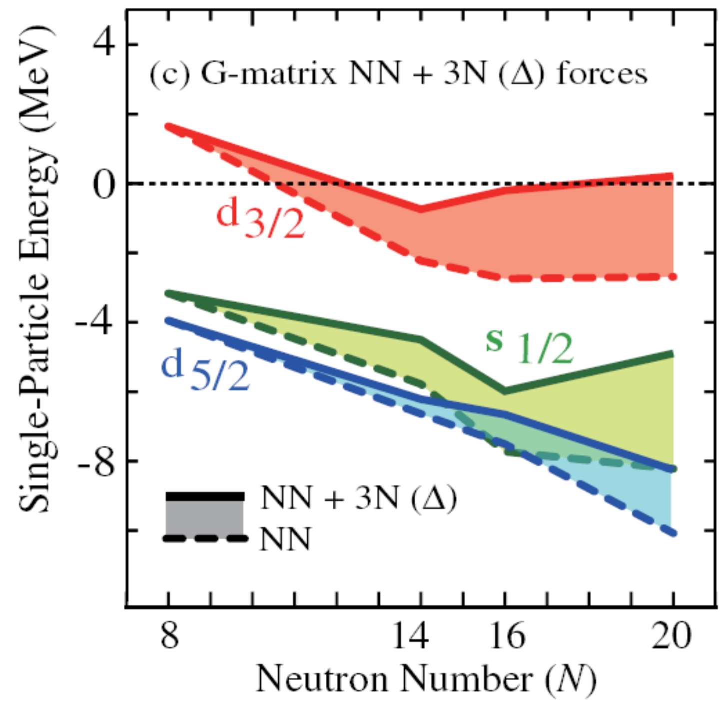
first time !

^{6}He	^{7}He	^{8}He	^{9}He	^{10}He

^{5}H

- Comprehensive study of exotic unbound systems with extreme A/Z
- Structure information unveiled

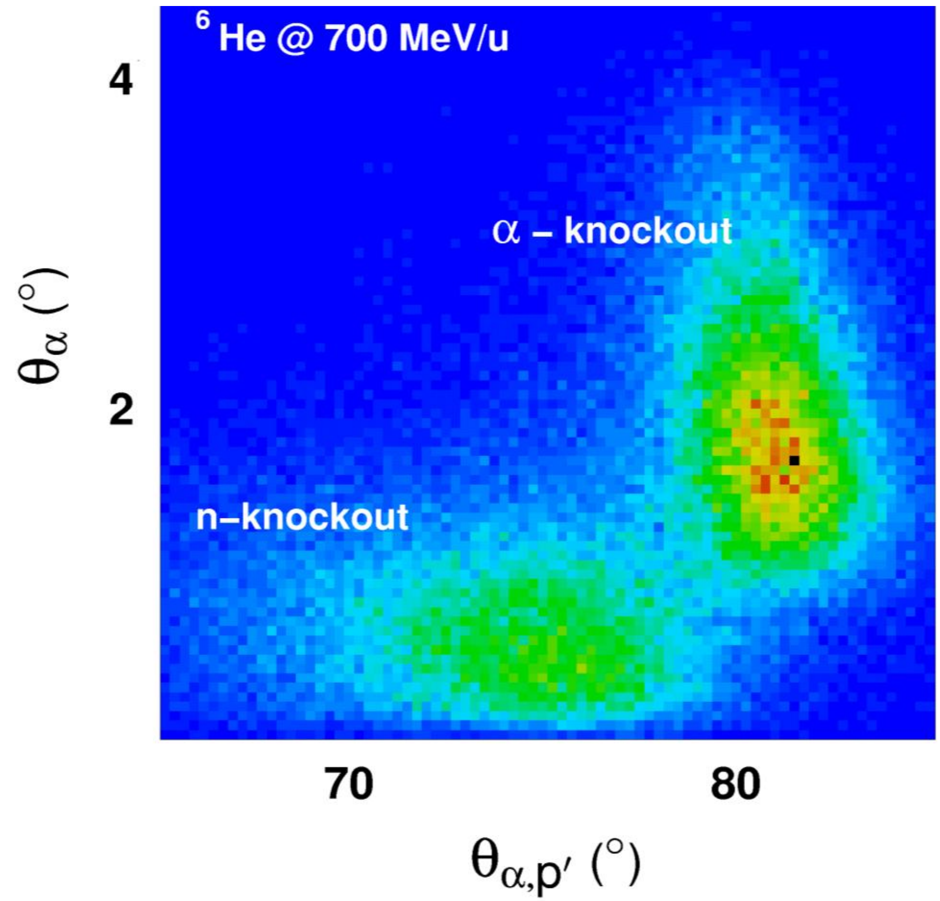
^{25}F	^{26}F	^{27}F
^{24}O	^{25}O	^{26}O



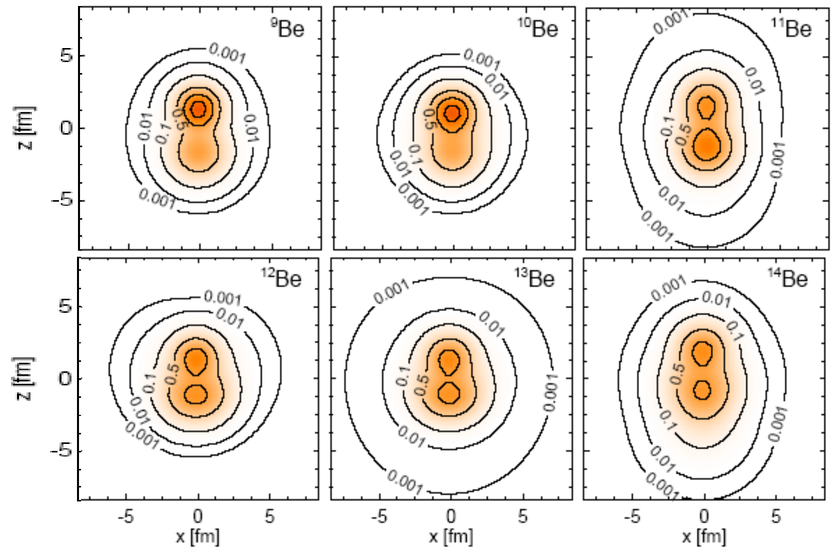
- e.g.
  Unbound oxygen isotopes

What next ? Target recoil detection !

L.V. Chulkov et al., Nucl. Phys. **A759**(2005)43



T. Neff et al., Nucl. Phys. **A752**(2005)321c



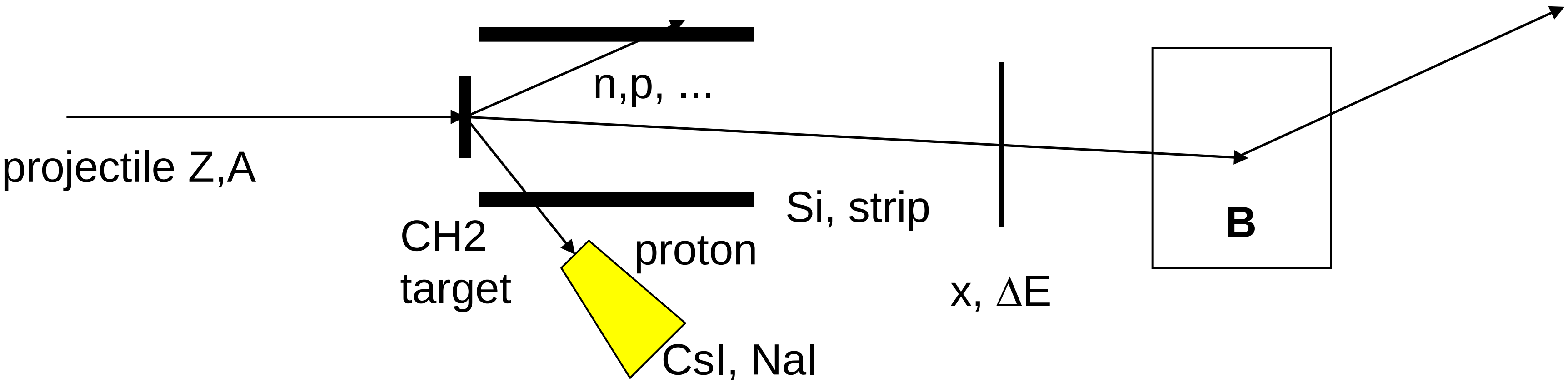
liquid hydrogen or CH_2 target
& recoil proton detection

Direct observation of kinematical correlations →

(i) (Cluster) spectroscopic factors
(p,2p),(p,pn),(p,px) inv. kinematics

(ii) clean production of **^{4}H, ^{7}H,…** via **α** knockout !

Quasi-free scattering in inverse kinematics



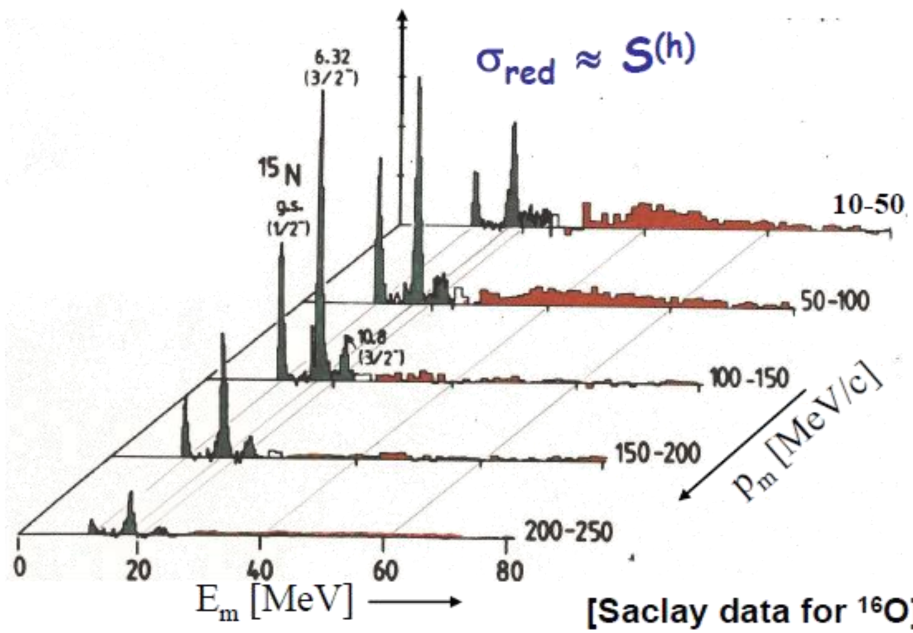
redundant experimental information:

- kinematical reconstruction from proton momenta
- plus gamma rays, recoil momentum, invariant mass

sensitivity not limited to surface

- → spectral functions
- → knockout from deeply bound states

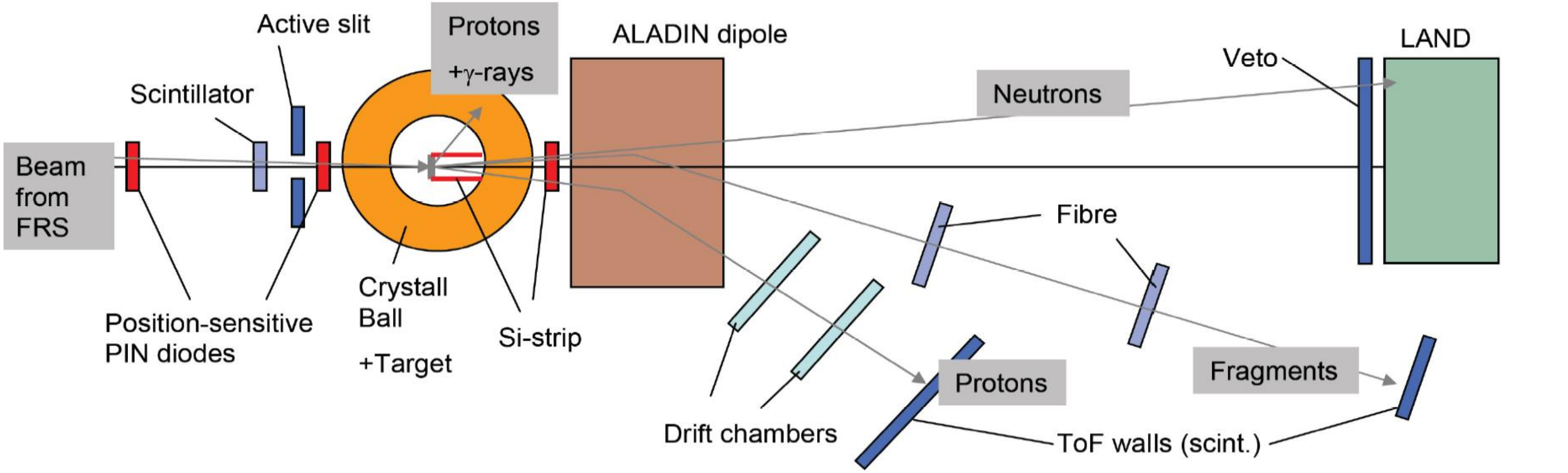
cluster knockout reactions

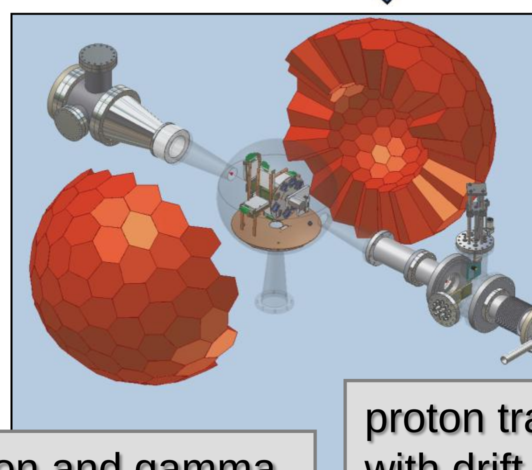


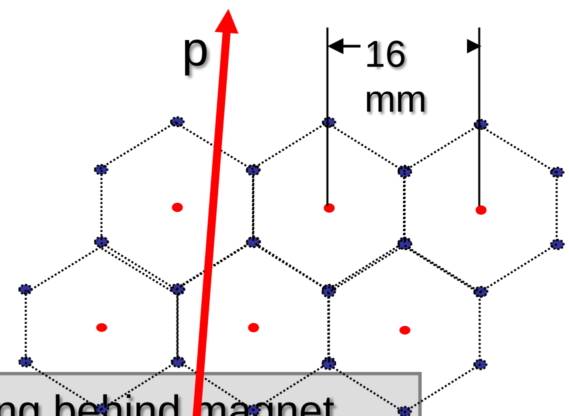
[Saclay data for ^{16}O]

New Experiments (Aug/Sep 2010)

R^3B/FAIR precursor: Setup at Cave C





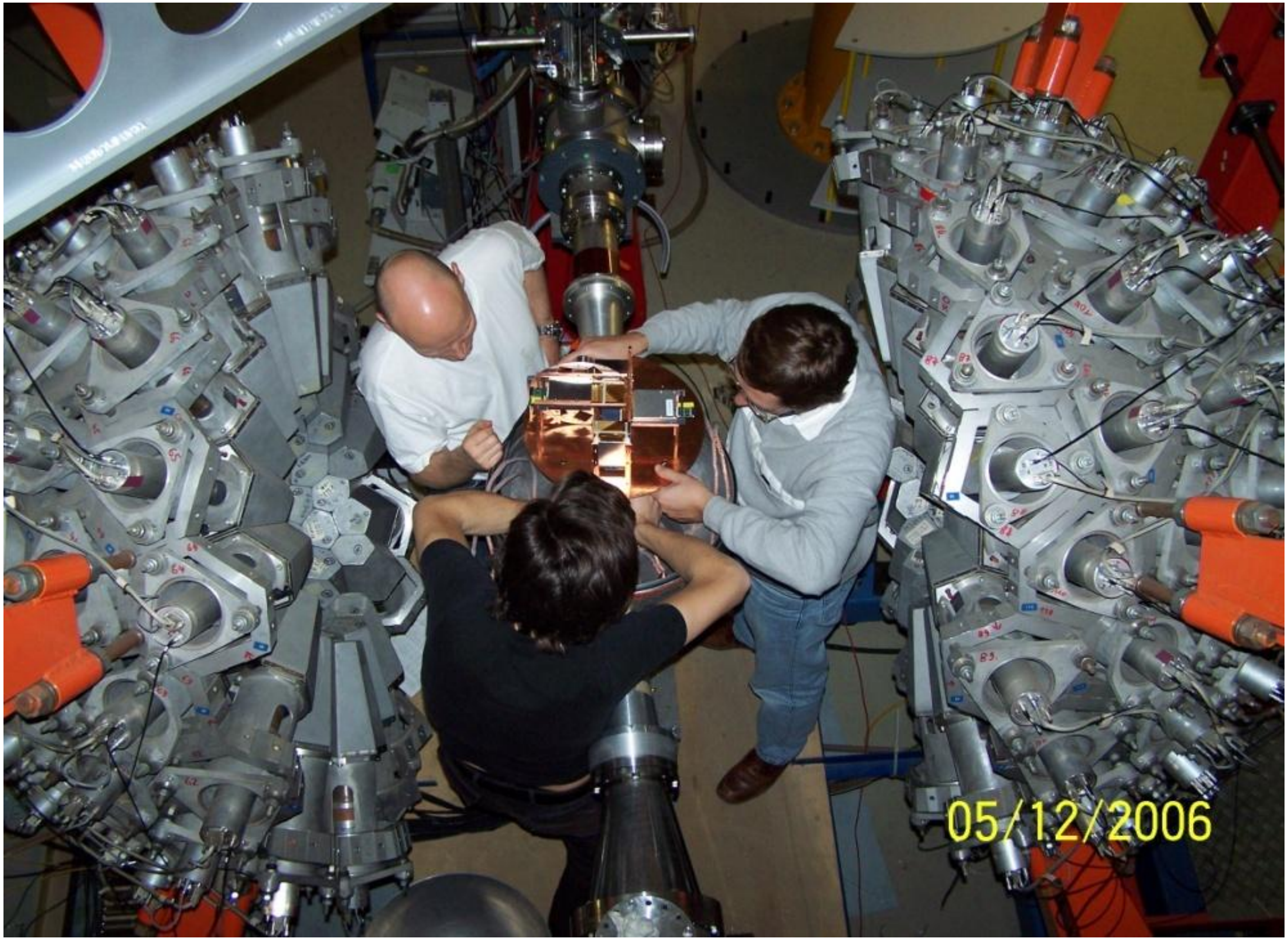


(p,2p) CH_2 target
Coulomb Diss. Pb

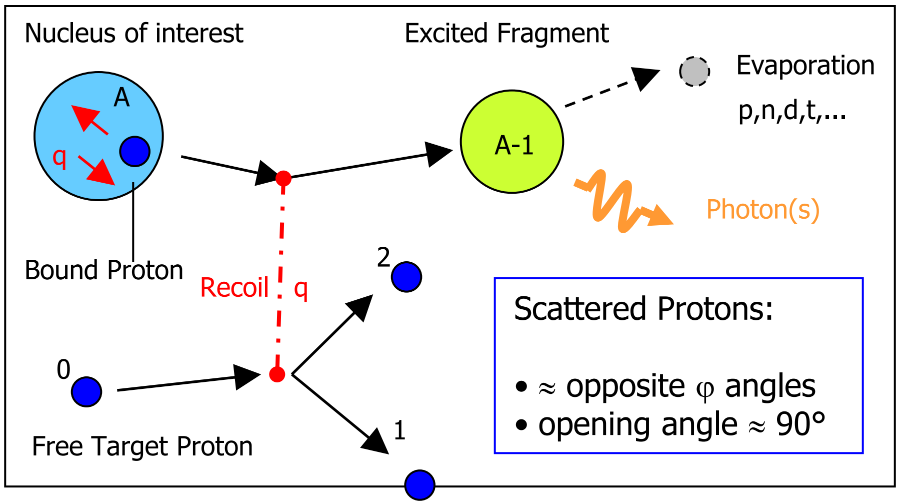
proton and gamma detection

proton tracking behind magnet with <u>drift chambers</u> (100×80 cm^2)
resolution ~200 μm

Experimental Setup (less schematic)



QFS with Exotic Nuclei: $^{17}Ne(p,2p)^{15}O+p$
The two-proton Halo (?) nucleus ^{17}Ne



Internal Momentum

$$q = -p_{A-1} = p_1 + p_2 - p_0$$

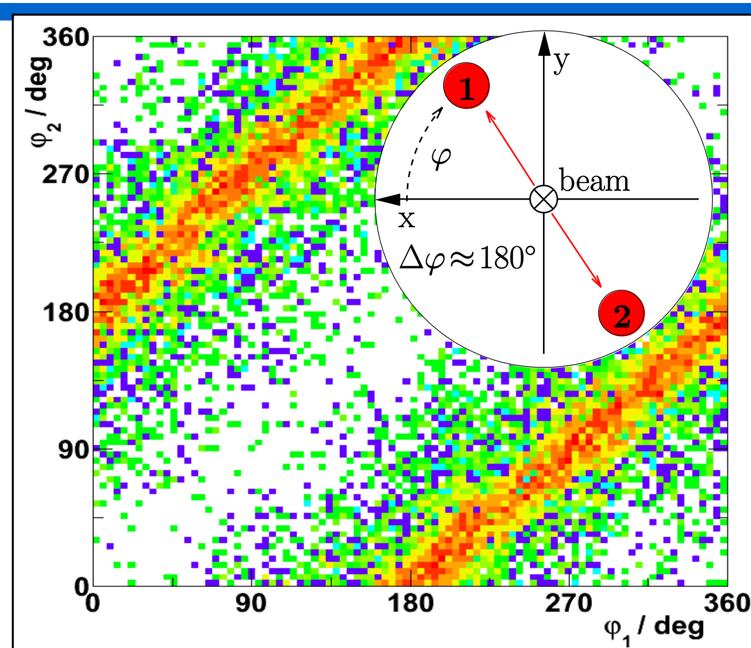
Separation Energy

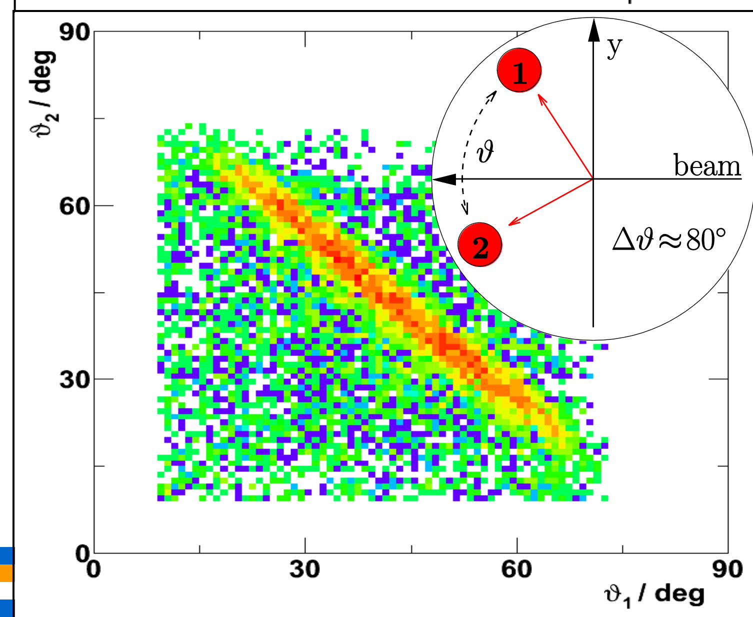
$$E_S = T_1 + T_2 + T_{A-1} - T_0$$

Pilot experiments with ^{12}C, ^{17}Ne and Ni isotopes already performed at the LAND-R3B setup are under analysis …

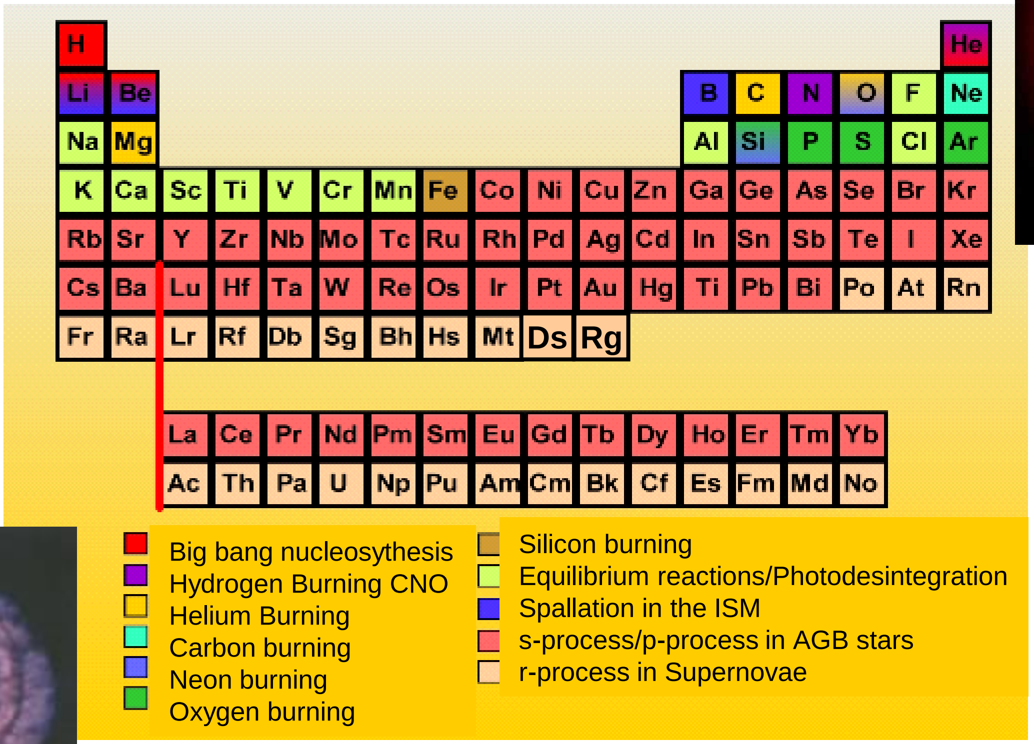
Angular Correlations measured with Si-strip detectors for $^{17}Ne(p,2p)^{15}O+p$

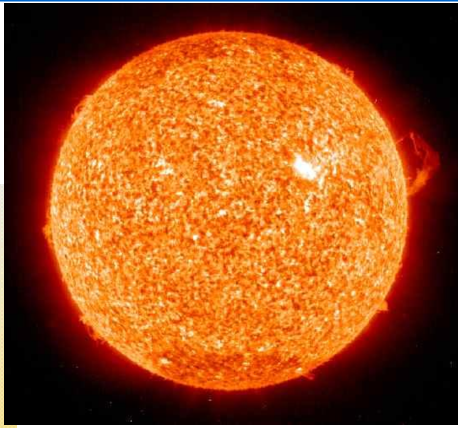
Δθ~180°, Δϕ~83° (sim. as for free pp scattering)





The origin of elements





Sun

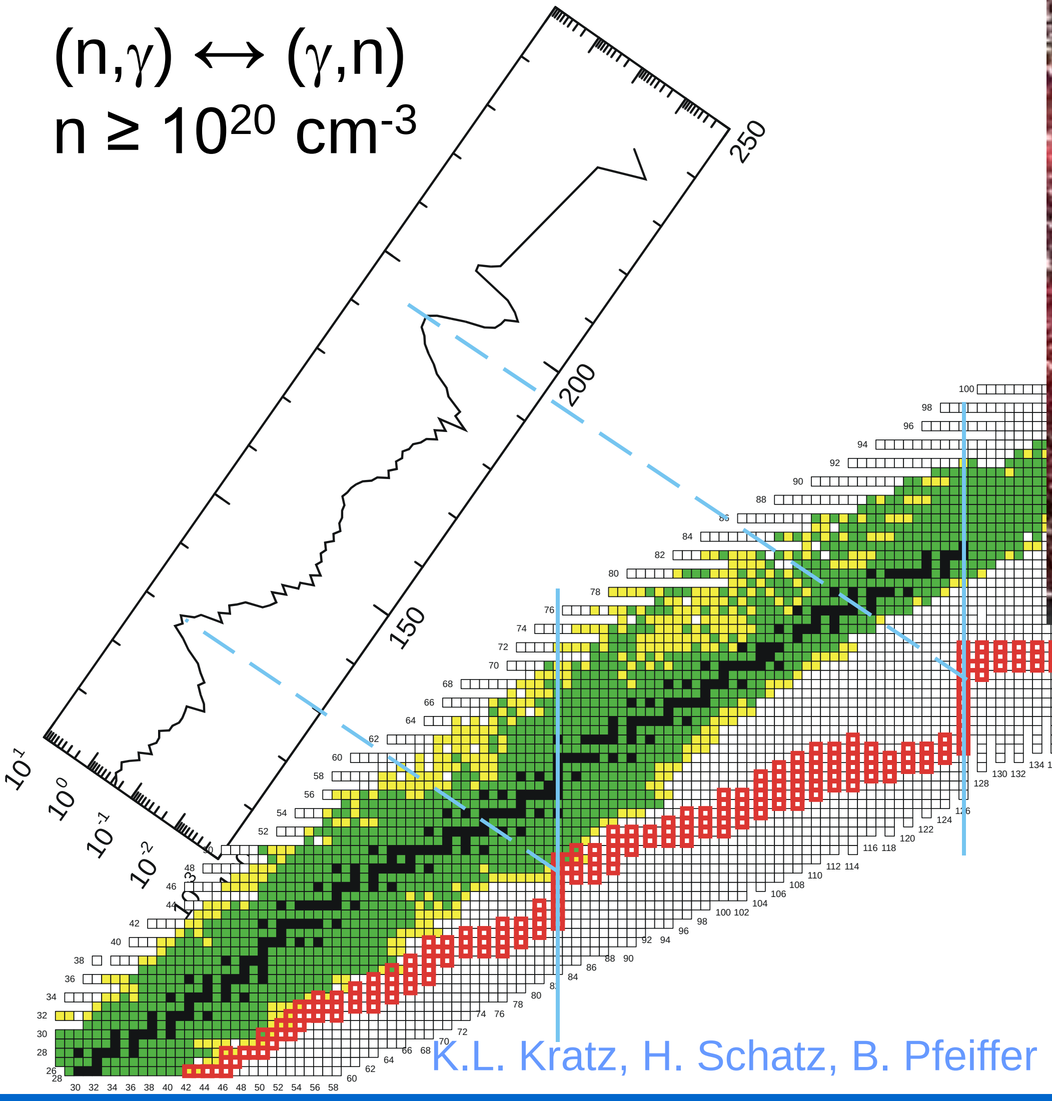
Eta Carinae

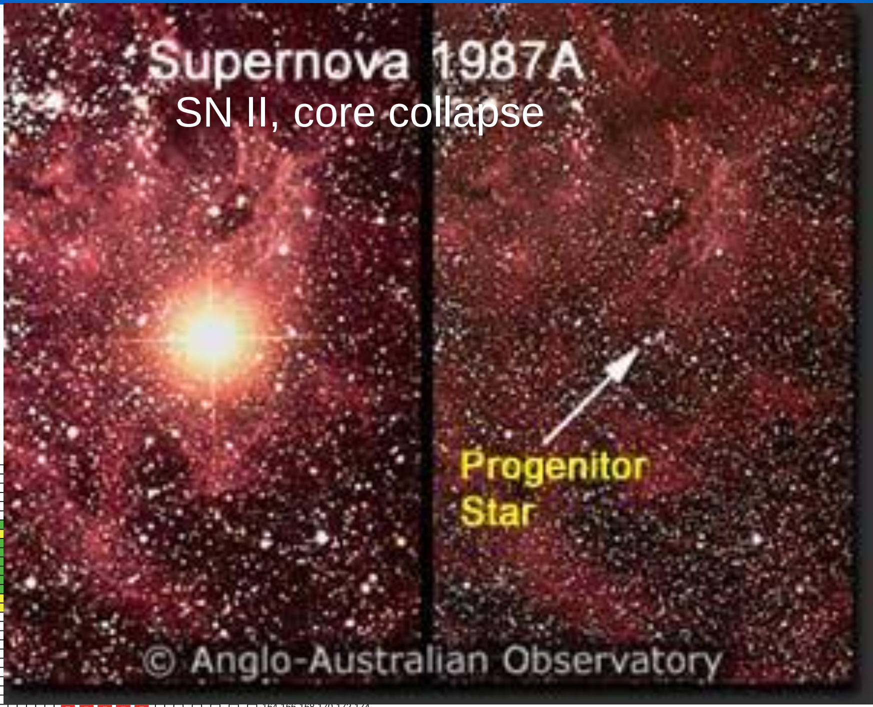
Nucleosynthesis (A ≥ 56)

e.g. r-process (~5x10^9 K)

(n,γ) ↔ (γ,n)

n ≥ 10^{20} cm^{-3}



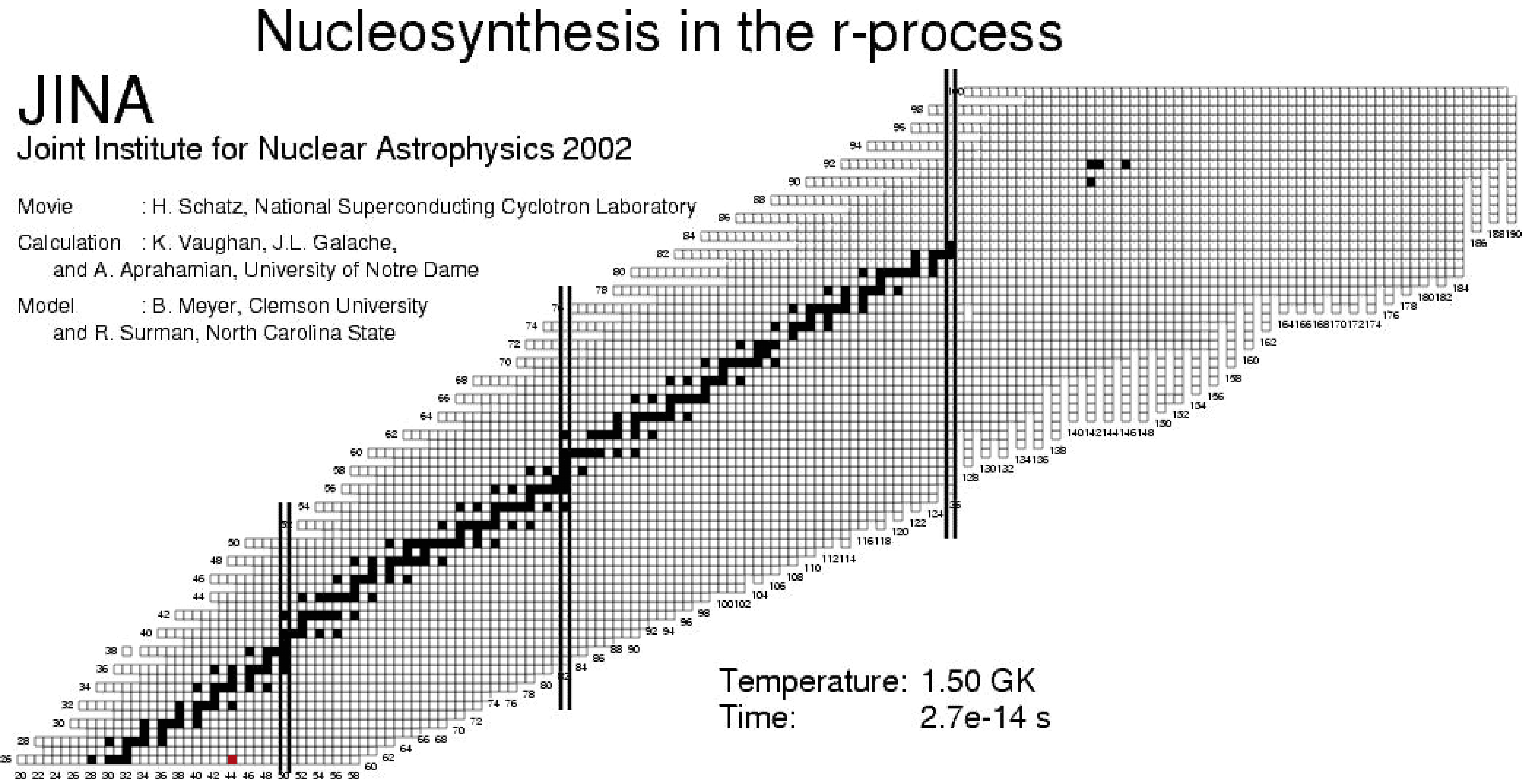


K.L. Kratz, H. Schatz, B. Pfeiffer

r-bumps explained, depend strongly on nuclear structure extrapolation !

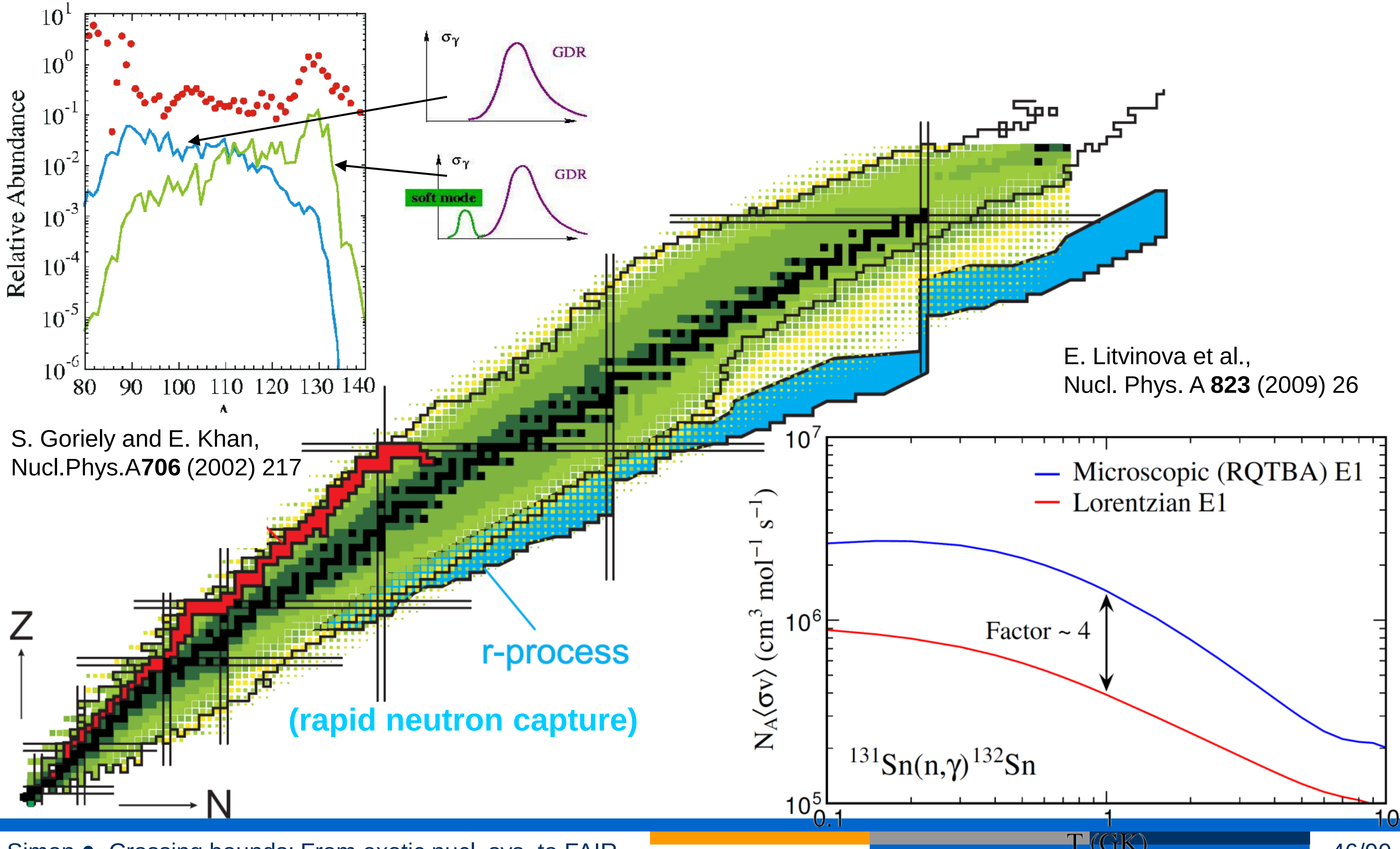
ETFSI-Q

Nucleosynthesis in the r-process (rapid neutron capture)



The dipole response of n-rich nuclei and the r-process

r-process abundance

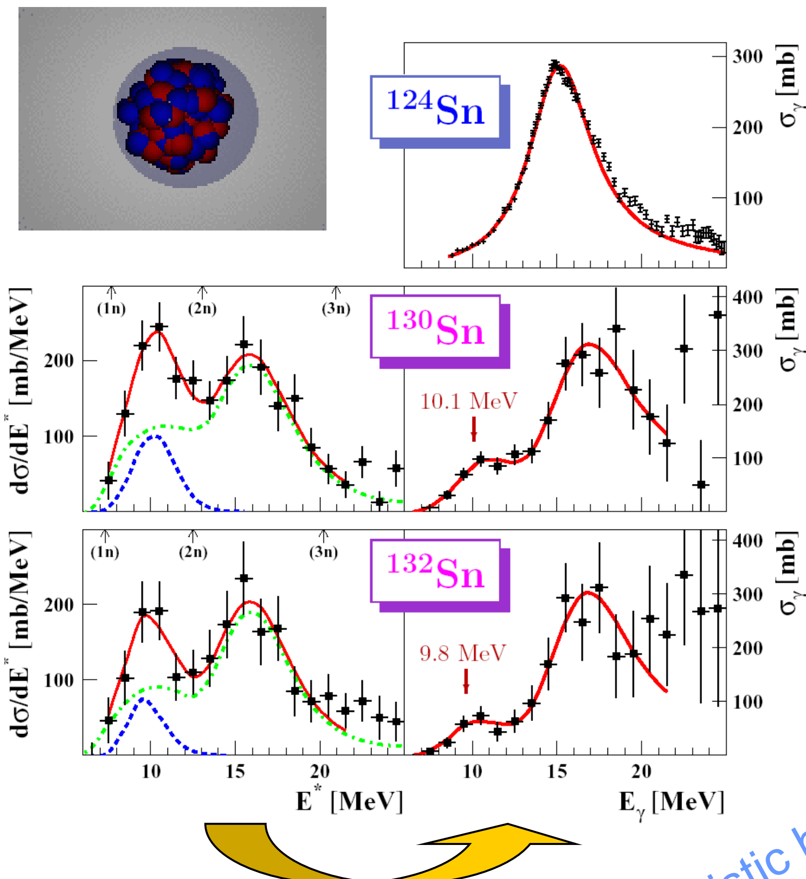


S. Goriely and E. Khan, Nucl.Phys.A**706** (2002) 217

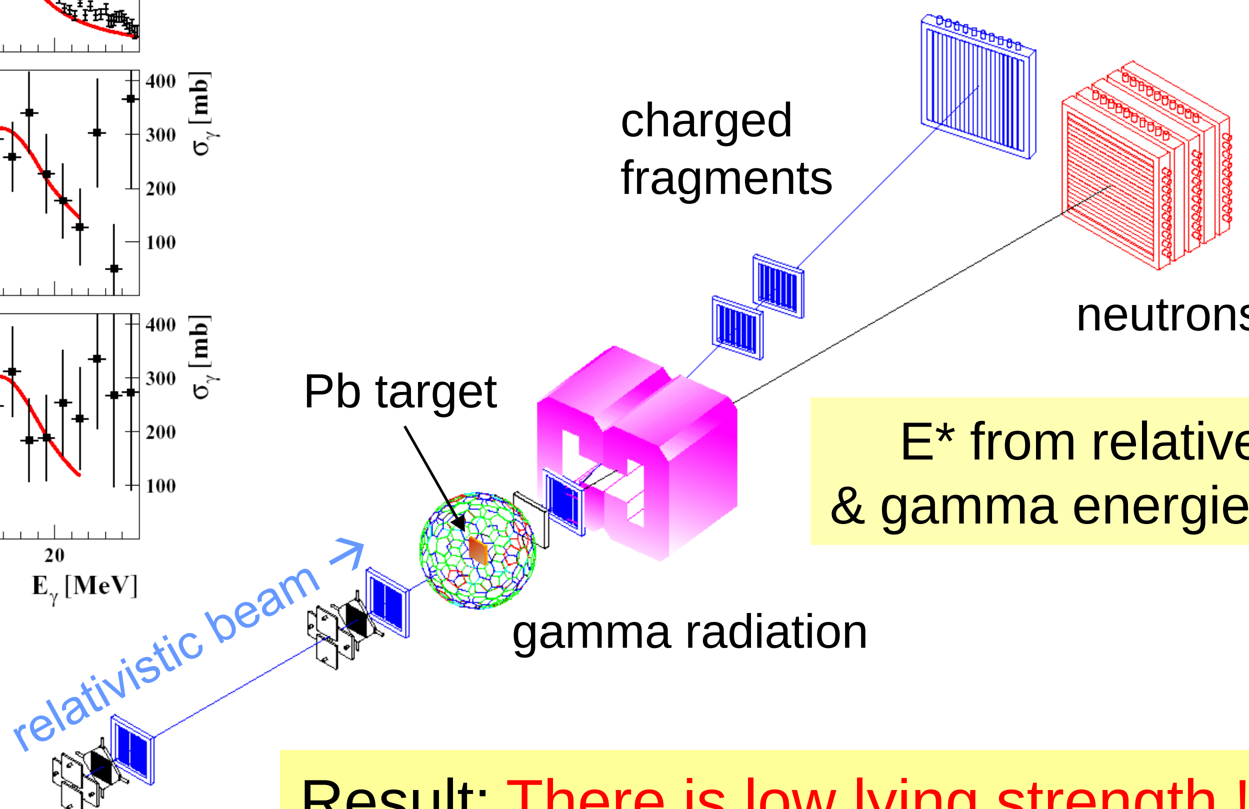
E. Litvinova et al., Nucl. Phys. A **823** (2009) 26

Studies of neutron-rich nuclei in the laboratory (survey)

Pygmy Resonances enhance (γ,n) via direct capture ?!



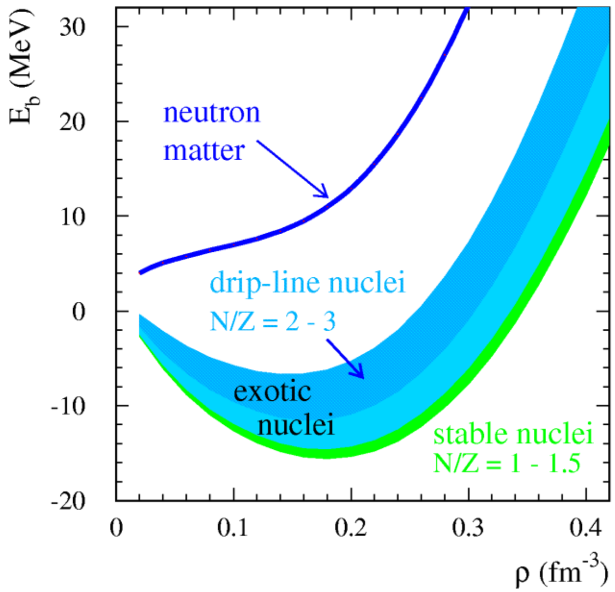
conversion
to photoabsorption

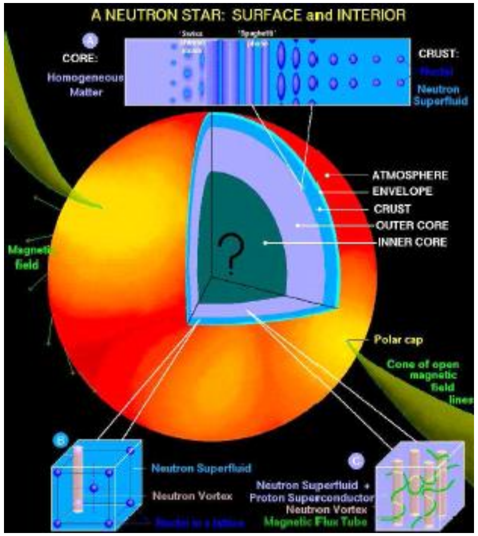


E* from relative
& gamma energies

Result: There is low lying strength !

Can we learn something on neutron matter?





Neutron Star

The nuclear equation of state:

dependence on n-p asymmetry and density

- symmetry energy and its density dependence close to saturation density

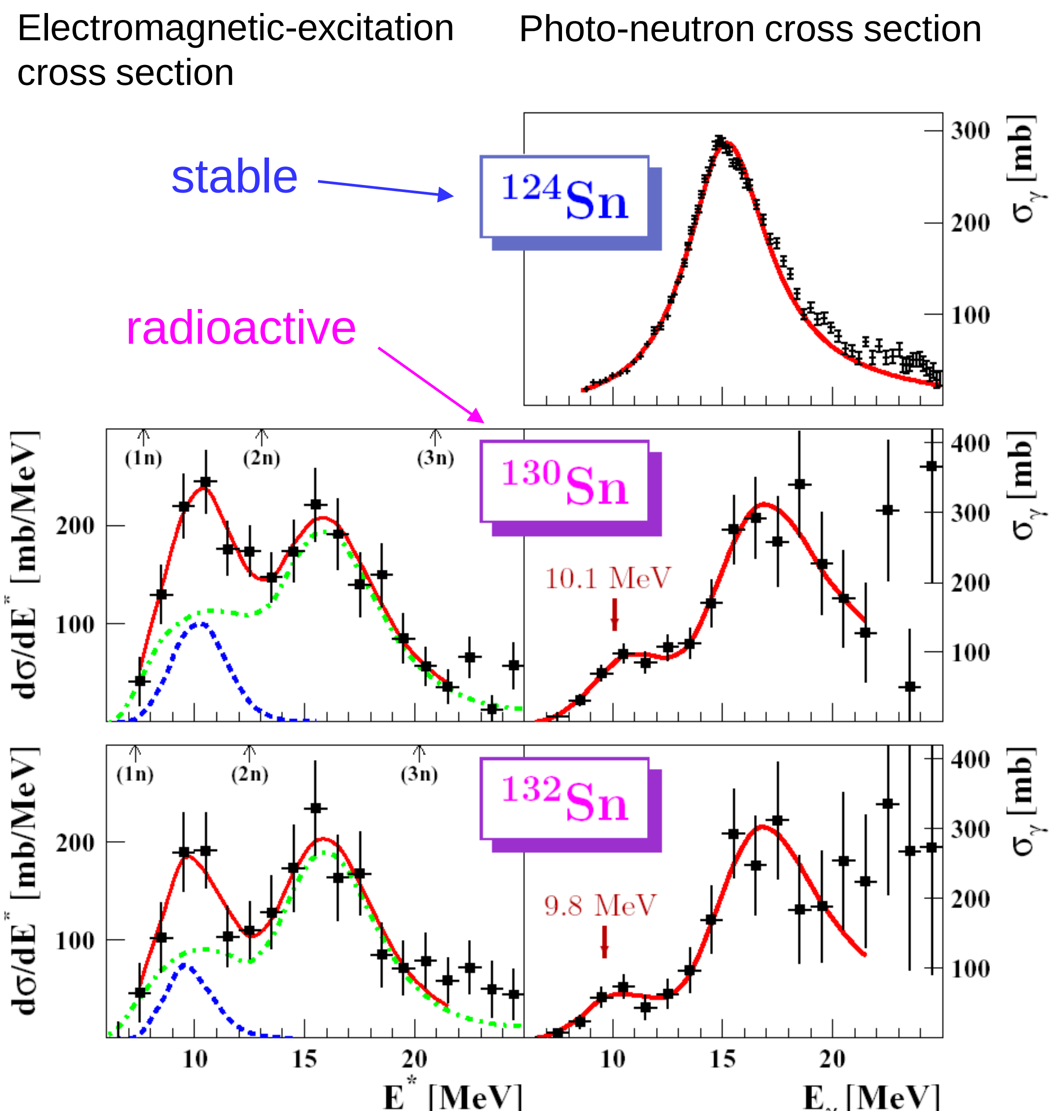
→ **properties of n-rich nuclei ?**

Dipole vibrations, neutron-skin thickness

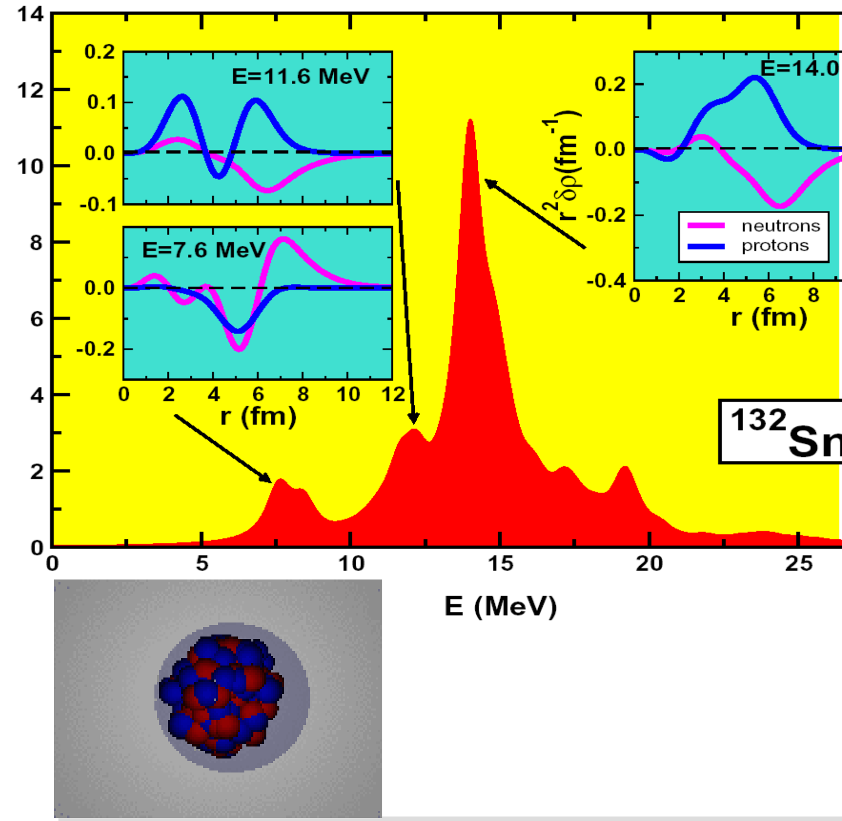
- symmetry energy at higher densities → reactions with n-rich nuclei (n-p flow)

Dipole-strength distributions in neutron-rich Sn isotopes

P. Ring et al.



P. Adrich et al., PRL 95 (2005) 132501



PDR

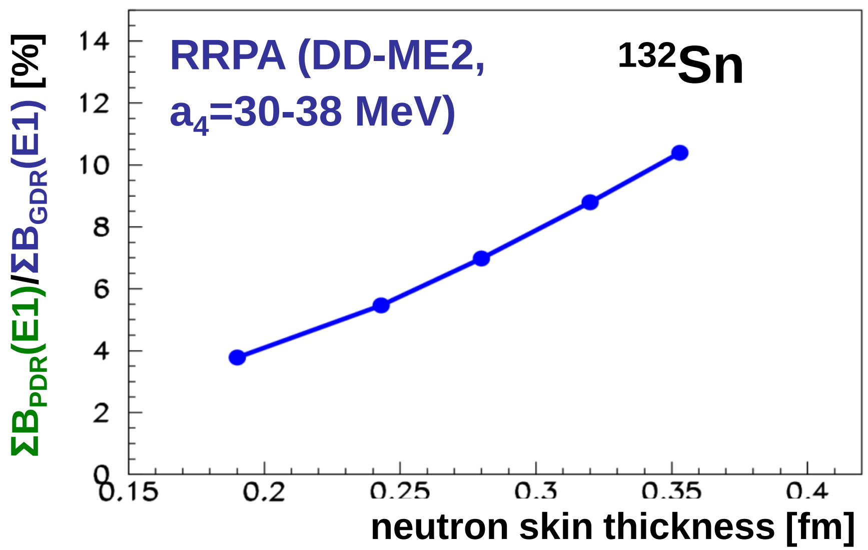
- located at 10 MeV
- exhausts a few % TRK sum rule
- in agreement with theory

GDR

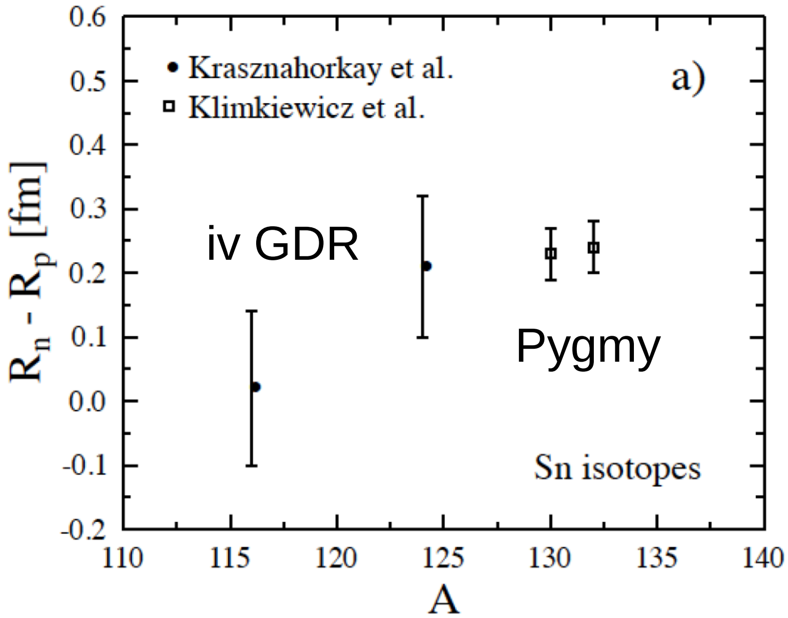
- no deviation from systematics

Pygmy dipole strength, Neutron Skin, and the Equation of State of neutron-rich Matter

Relation between dipole strength and n-skin thickness



n-skin thickness derived from dipole strength



"...,the pygmy dipole resonance may place important constraints on the neutron skin of heavy nuclei and, as a result, on the equation of state of neutron-rich matter."

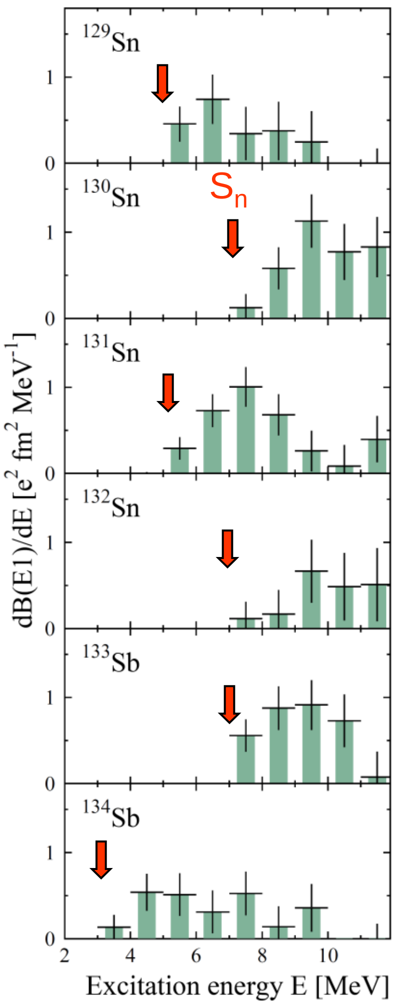
J. Piekarewicz, PRC 73 (2006) 044325

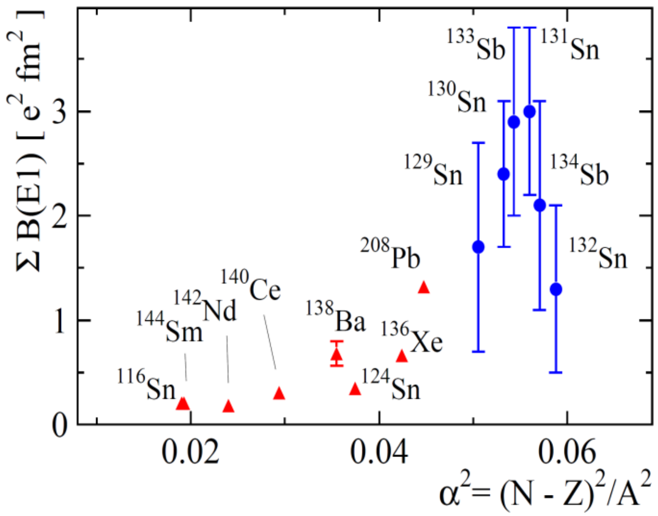
Constraints on EoS of neutron-rich matter derived from dipole strength of n-rich Sn isotopes

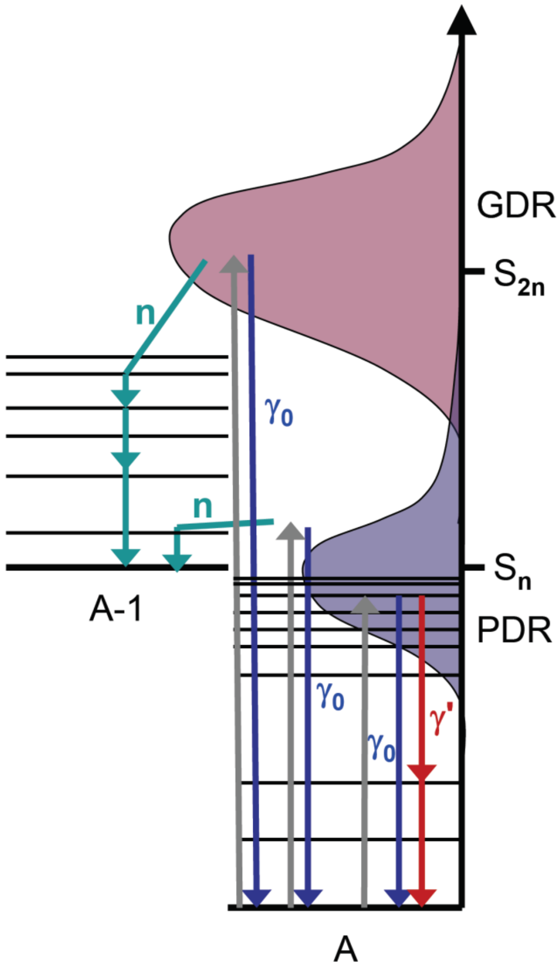
symmetry energy a_4 = 32.0 ± 1.8 MeV

pressure p_o = 2.3 ± 0.8 MeV/fm^3

Additional Information from γ spectroscopy



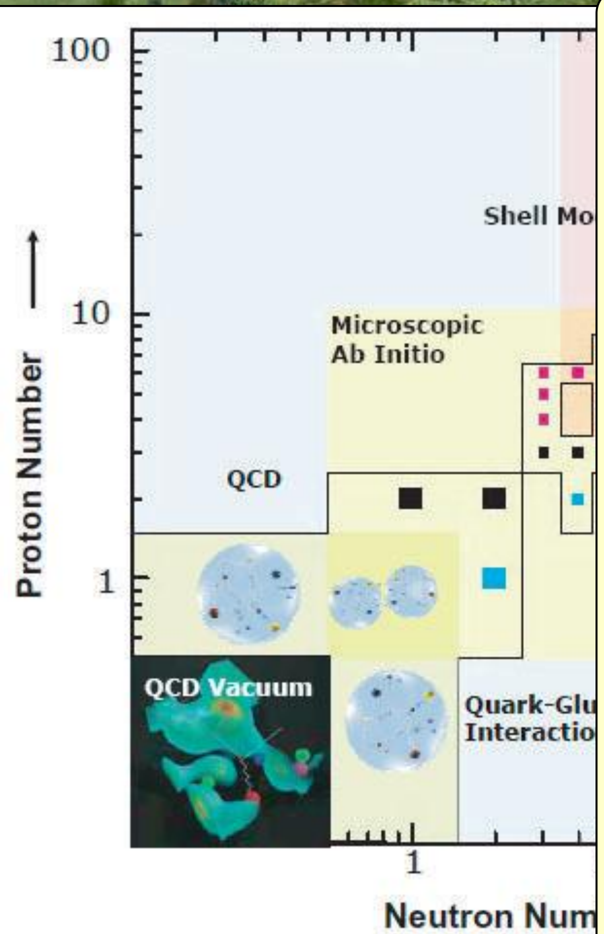




A. Klimkiewicz et al.,
*Phys. Rev. C **76** (2007) 051603(R)*

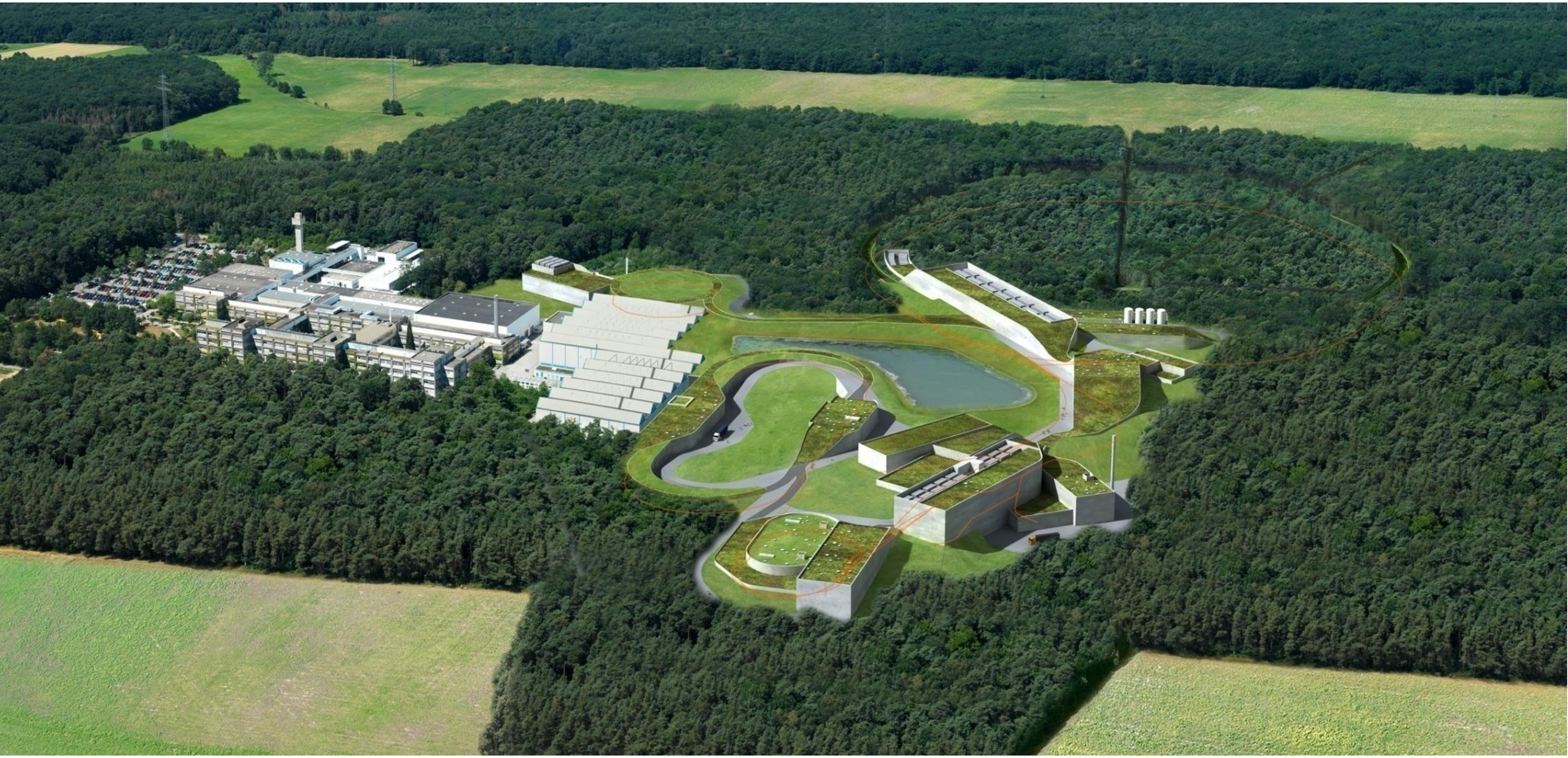
Intermittend Summary: Why do we study nuclear physics …

- Towards a Consistent Understanding of the Atomic Nucleus



- What are the limits for existence of nuclei?
  - Where are the proton and neutron drip lines situated?
  - Where does the nuclear chart end?
- How does the nuclear force depend on varying proton-to-neutron ratios?
  - What is the isospin dependence of the spin-orbit force?
  - How does shell structure change far away from stability?
- How to explain collective phenomena from individual motion?
  - What are the phases, relevant degrees of freedom, and symmetries of the nuclear many-body system?
- How are complex nuclei built from their basic constituents?
  - What is the effective nucleon-nucleon interaction?
  - How does QCD constrain its parameters?
- Which are the nuclei relevant for astrophysical processes and what are their properties?
  - What is the origin of the heavy elements?

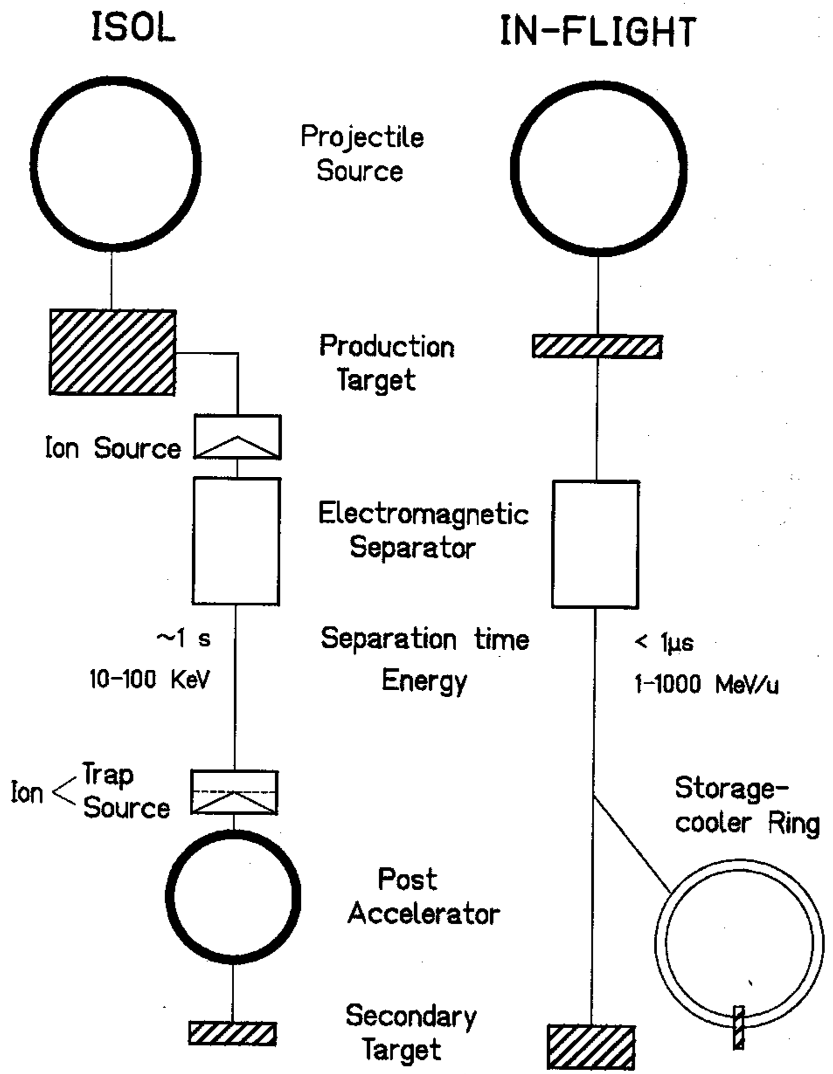
Preparing for FAIR ~2017/18



Intensity increase 3-4 orders of magnitude !

Production of radioactive beams: Methods

H. Geissel, G. Münzenberg, K. Riisager, Annu. Rev. Nucl. Part. Sci. 45 (1995) 163



ISOL:

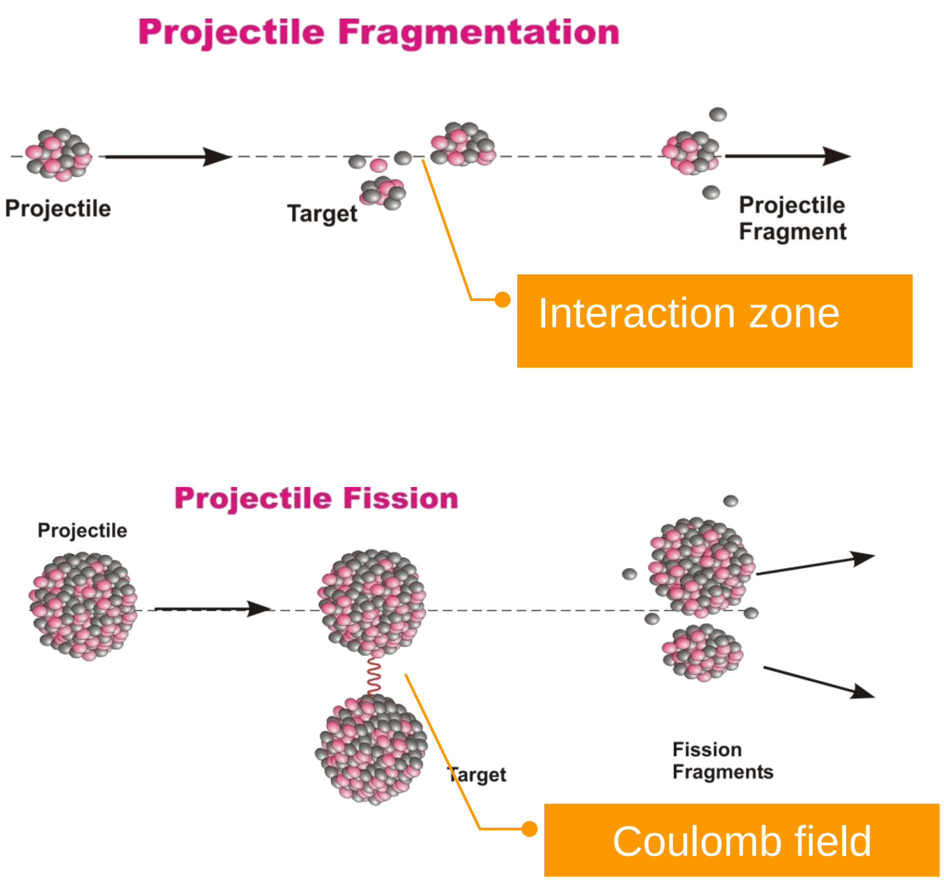
- spallation (~1 GeV protons)
- fission: p-induced, fast neutrons (d beam), slow neutrons (reactor), photons (e^- beam)
- fusion/evaporation, multi-nucleon transfer

IN-FLIGHT:

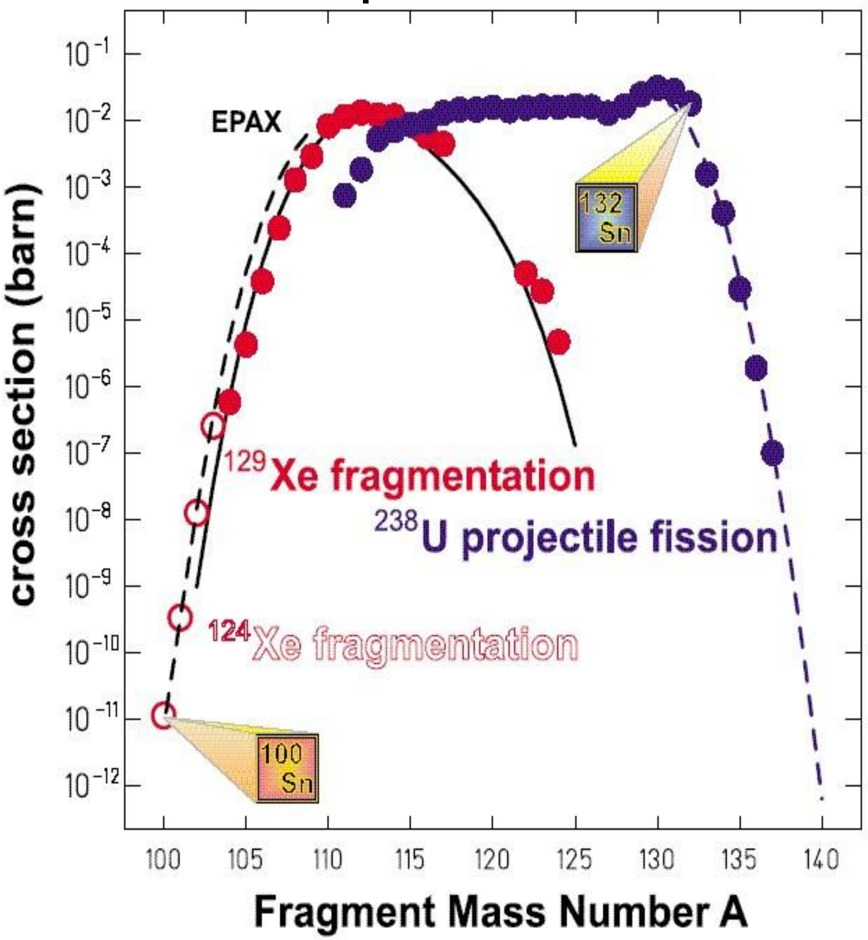
relativistic heavy ions (50 MeV/u – 1 GeV/u)

- fragmentation
- fission (elm. or nuclear induced)

RIBs produced by fragmentation or fission



Sn isotopes



(time of flight through FRS ~300ns)

Layout and Design parameters for the Super-FRS

Projectile:
- Elements p - U
- Energy up to 1.5 GeV/u
- Intensity up to 10^{12} /s (depending on element)
- DC or pulsed operation

Design Parameters:

$\varepsilon_x = \varepsilon_y =$ 40 π mm mrad

$\Phi_x =$ ± 40 mrad

$\Phi_y =$ ± 20 mrad

$\Delta P/P =$ ± 2.5 %

$B\rho$ = 2 - 20 Tm

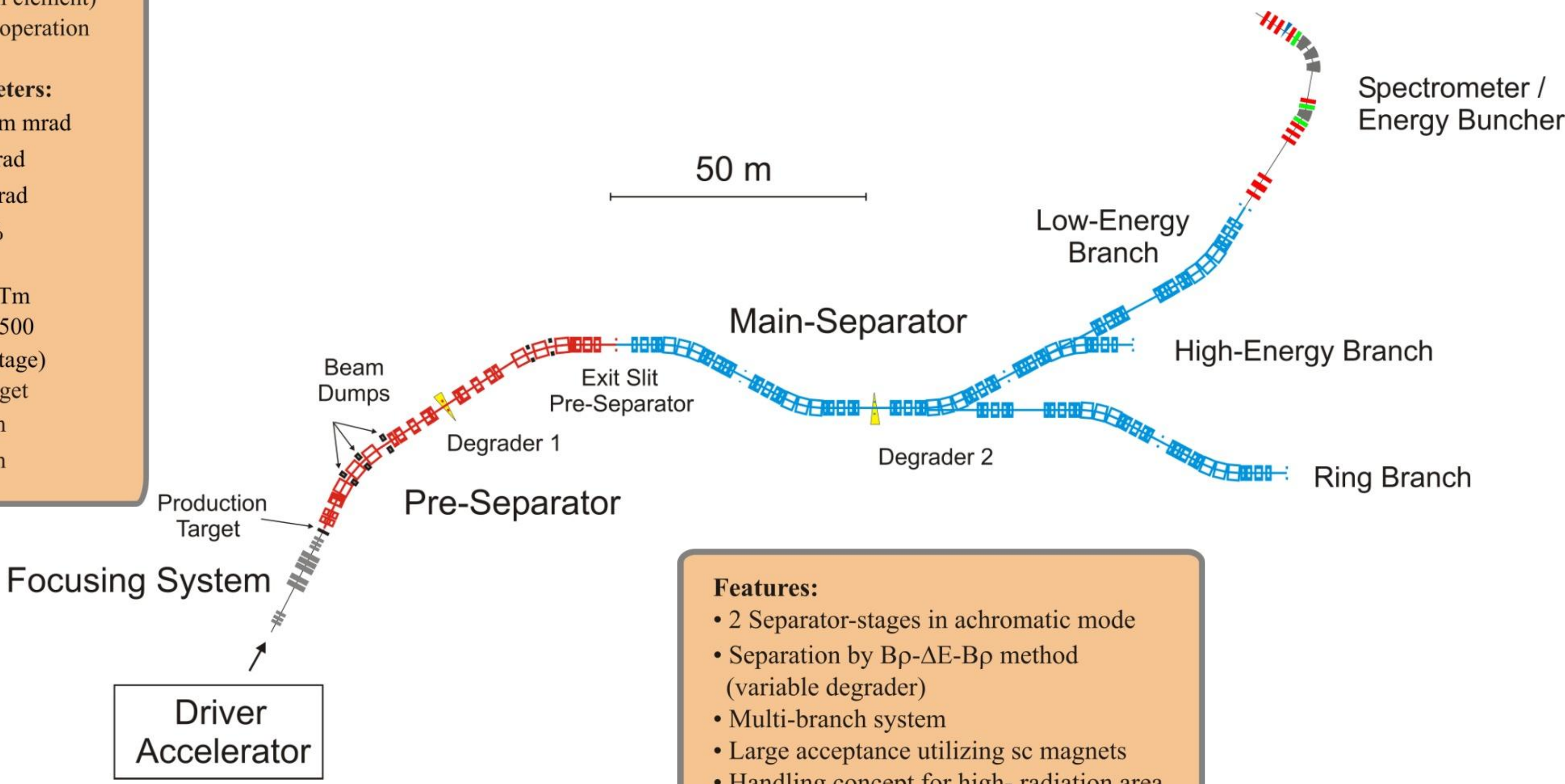
R_{ion} = 750 / 1500 (first / second stage)

Spot size on target

σ_x = 1.0 mm

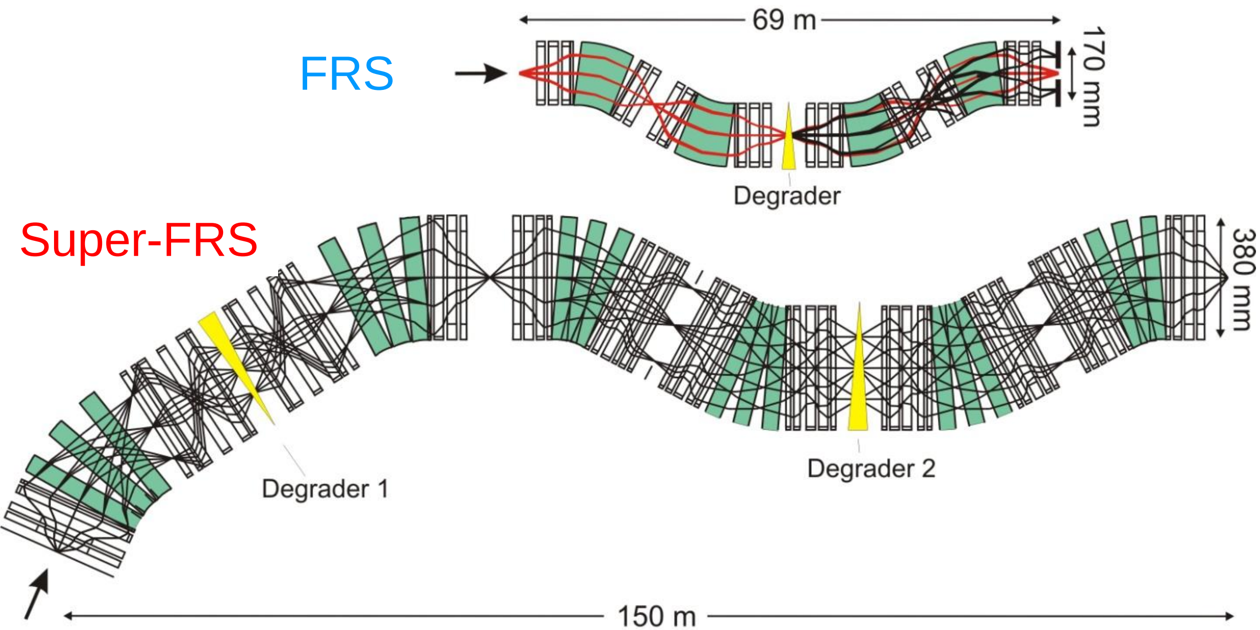
σ_y = 2.0 mm

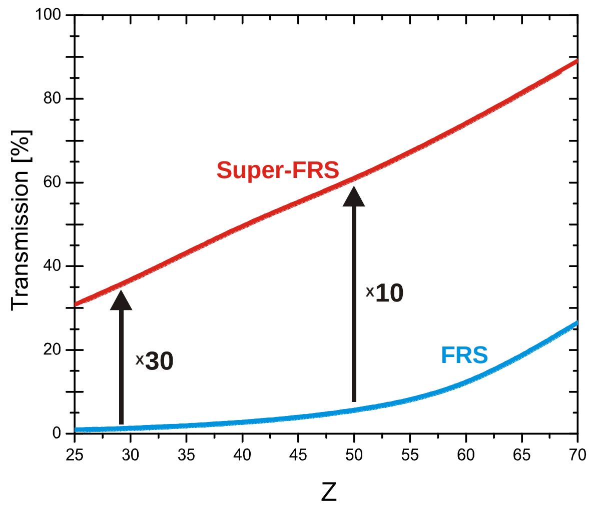
Goal: Larger Acceptance



Features:
- 2 Separator-stages in achromatic mode
- Separation by $B\rho$-ΔE-$B\rho$ method (variable degrader)
- Multi-branch system
- Large acceptance utilizing sc magnets
- Handling concept for high- radiation area

Comparison of FRS with Super-FRS, intensity gain

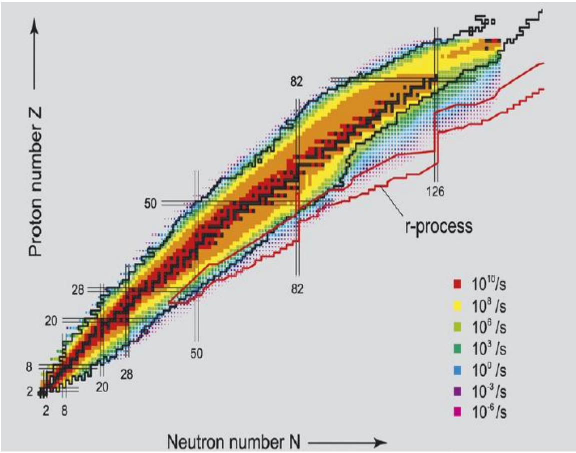




	$B\rho_{max}$	$\Delta p/p$	$\Delta\Phi_x$, $\Delta\Phi_y$	resolving power	gain factor ^{19}C	gain factor ^{132}Sn
FRS	18 Tm	1.0 %	±13, ±13 mrad	1500	1	1
Super-FRS	20 Tm	2.5 %	±40, ±20 mrad	1500	5	10
				including primary rate	250	20 000

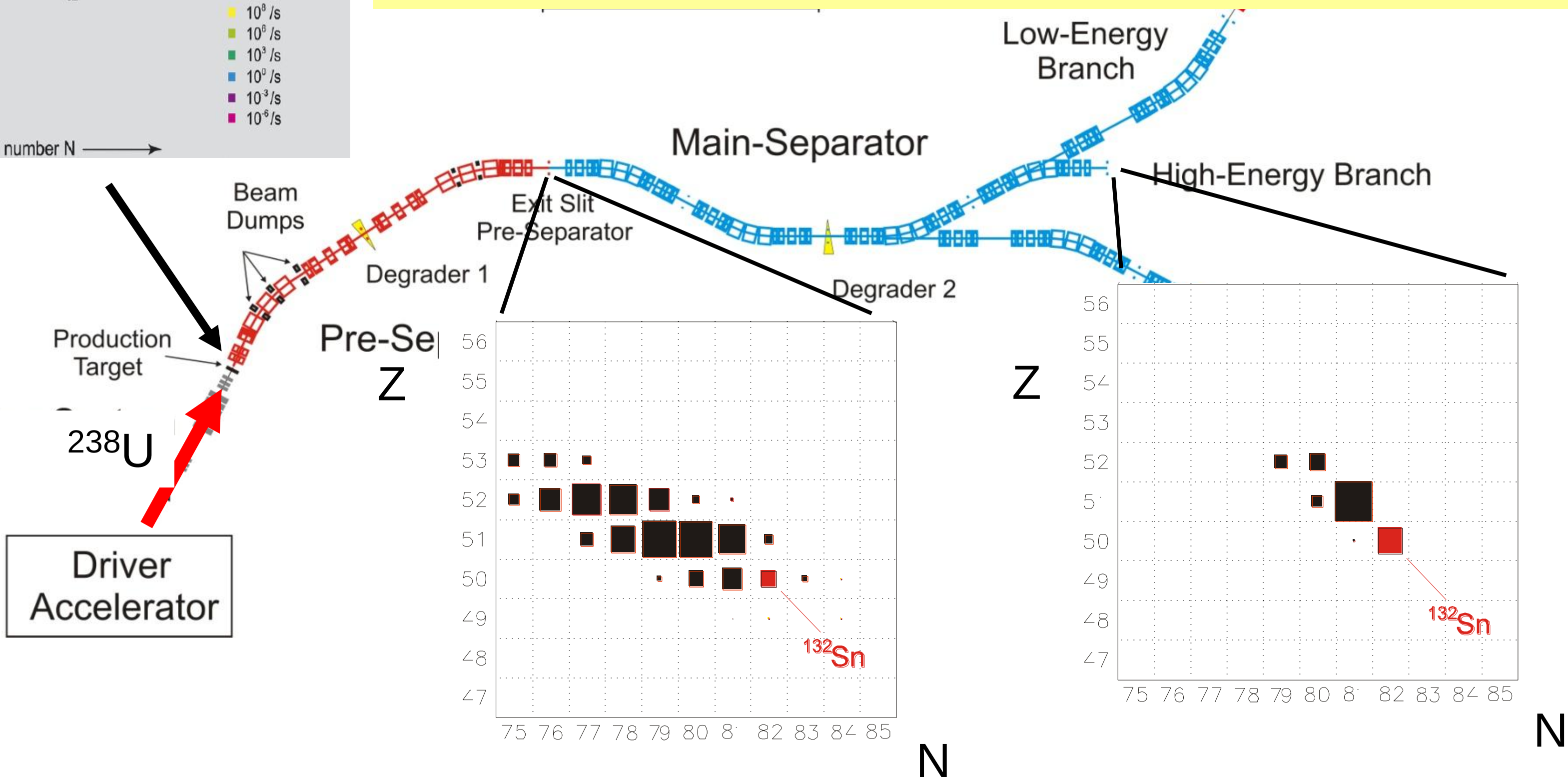
Separation Performance of the Super-FRS

1.1 A GeV ^{238}U on 4 g/cm^2 C target, two Al degraders d/R=0.3, d/R=0.7

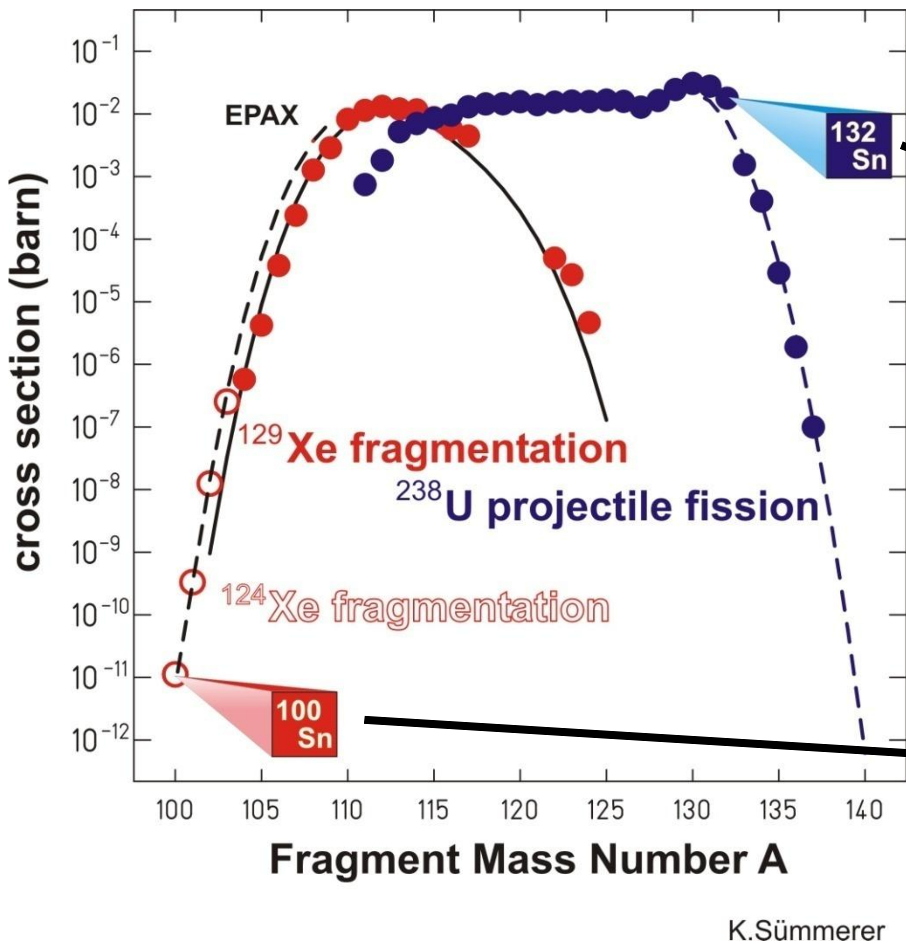


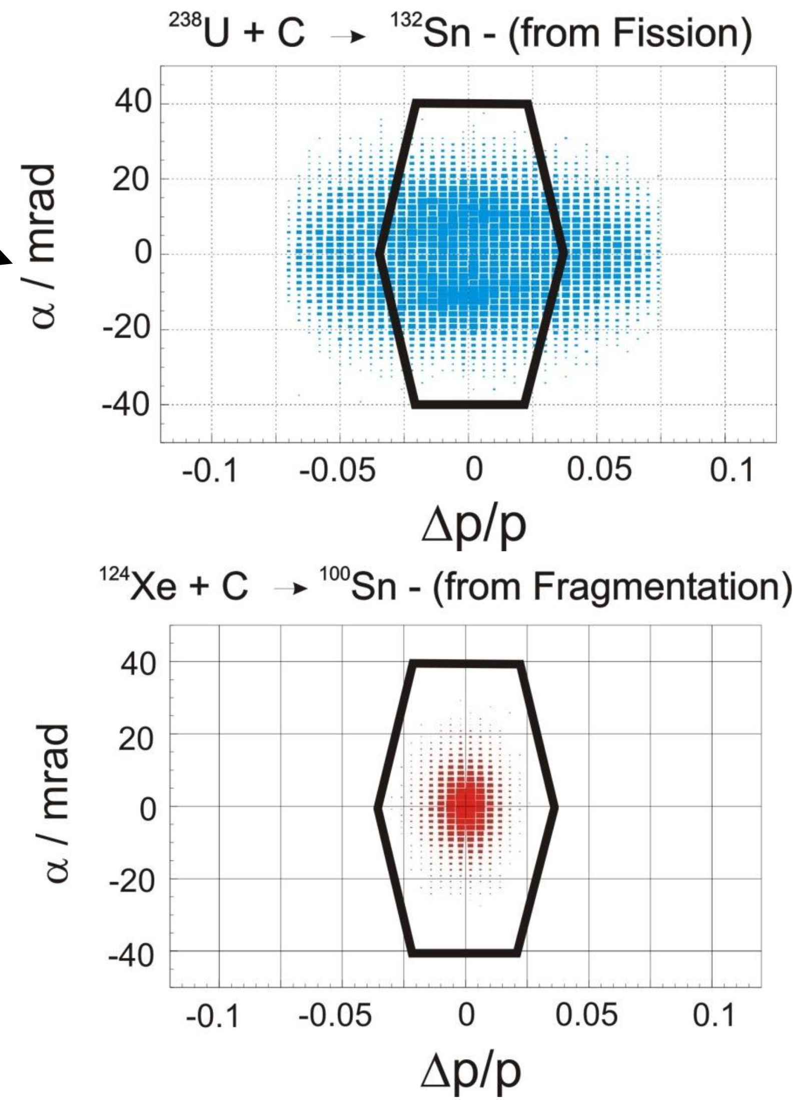
Features of two degrader stages

- Introduction of another separation cut in the A-Z plane
- Reduction of contaminants from fragments produced in the degrader
- Optimization of the fragment rate on detectors in the Main-Separator
- Possible usage of Pre- and Main-Separator for secondary reaction studies



Production of radioactive beams by fragmentation and fission





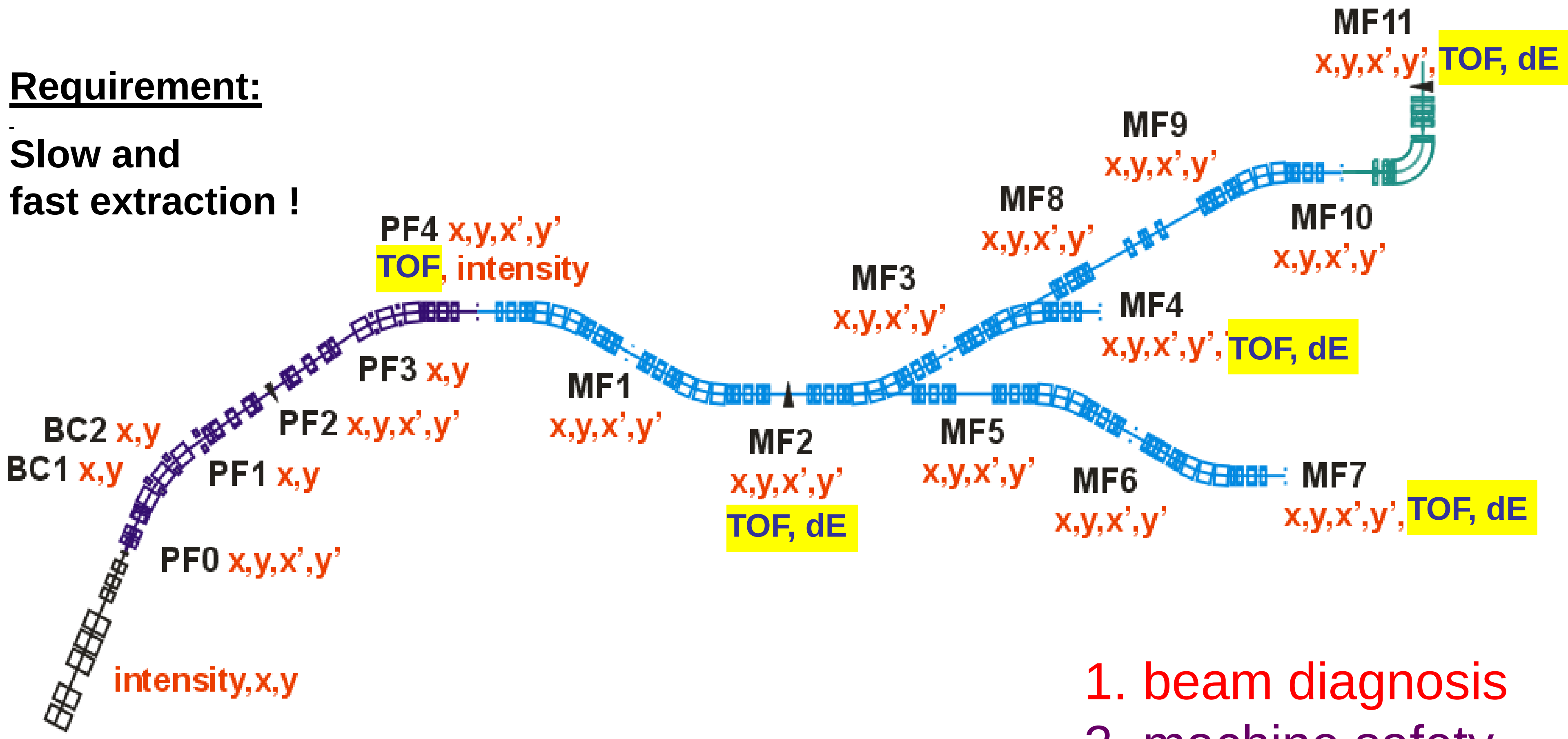
H. Geissel et al., NIMB204 (2003) 71

Detector Instrumentation of the SuperFRS

Requirement:

-

Slow and fast extraction !



1. beam diagnosis
2. machine safety
3. experiments

Bρ-ΔE-TOF method: Requirements

NO CHARGE STATES !

$B\rho = A/Z \cdot \beta \cdot \gamma$ → A/Z, P

$TOF = L/\beta$ ↗ ↘

$\Delta E \sim Z^2/\beta^2$ → Z

Pos res.	$\sigma \leq 1$ mm
Timing res.	σ: 50 ps
ΔE resolution	σ: 1-2 %

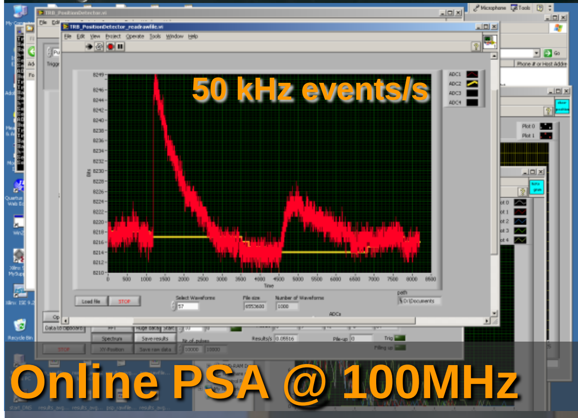
- Position: Wirechambers (single event readout)/Diamond
- ΔE: MUSIC/TEGIC
- TOF: Plastic/Diamond

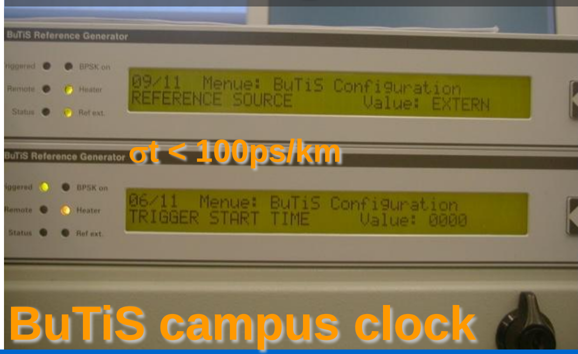
Fast sampling & timing techniques

- Challenge:
  - Beam identification at rates up to 1MHz.
  - ToF over km distance with sub-ns resolution.
  - ΔE resolution 2-3%

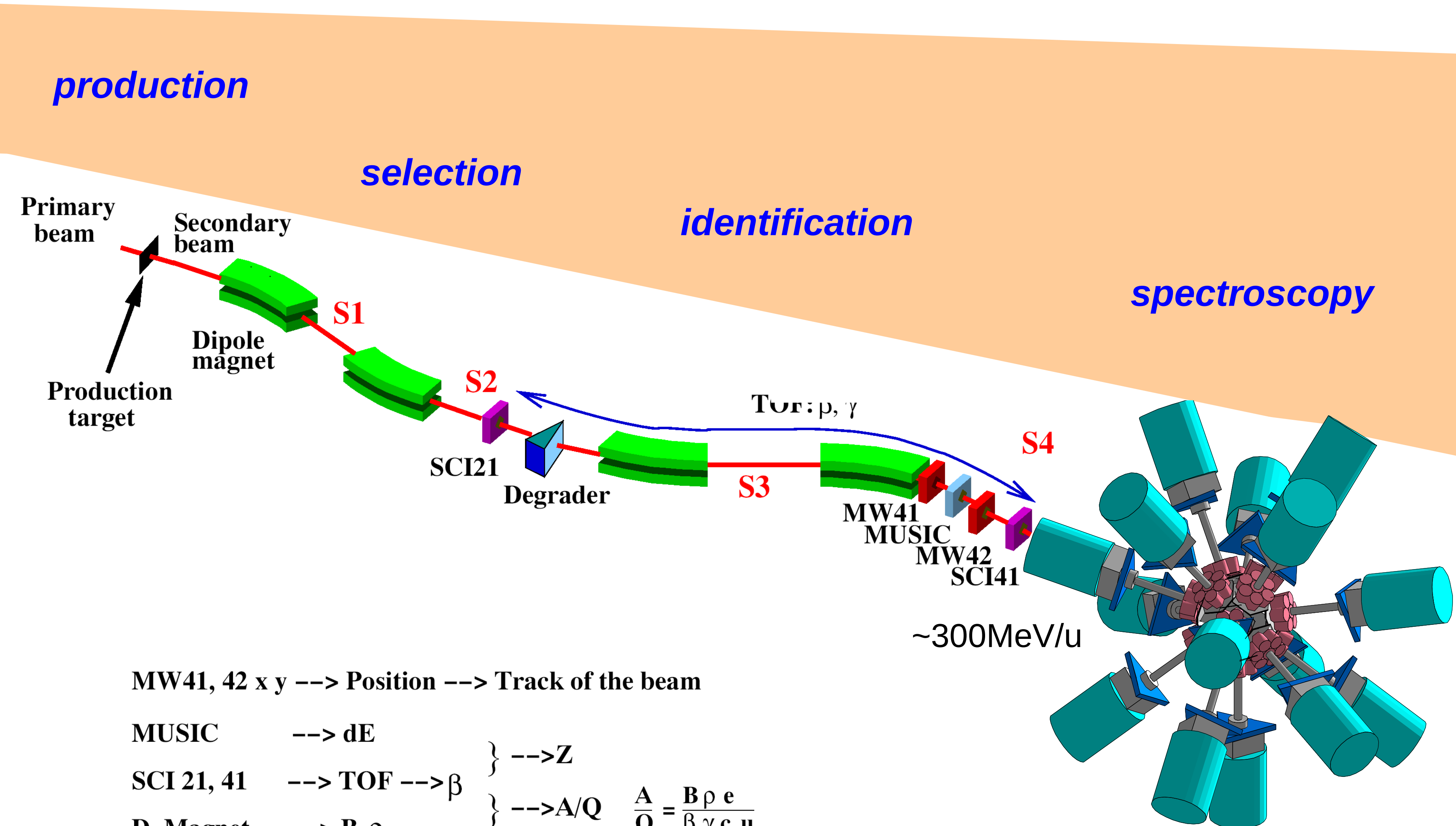
- Solution:
  - Fast sampling and FPGA based digital signal processing & pulse shape analysis.
  - Campus wide Time Distribution System based on FAIR BuTiS timing system.
  - TAC or DLL based Frontends.

- First studies using Tacquila@R³B/Cave-C.
- Digital Signal Processing (for PSP, MUSIC) in collaboration with KVI Groningen/JSI Lubljana





FRS & RISING ➔ Super-FRS HISPEC/DESPEC



MW41, 42 x y --> Position --> Track of the beam

MUSIC --> dE } -->Z

SCI 21, 41 --> TOF --> β

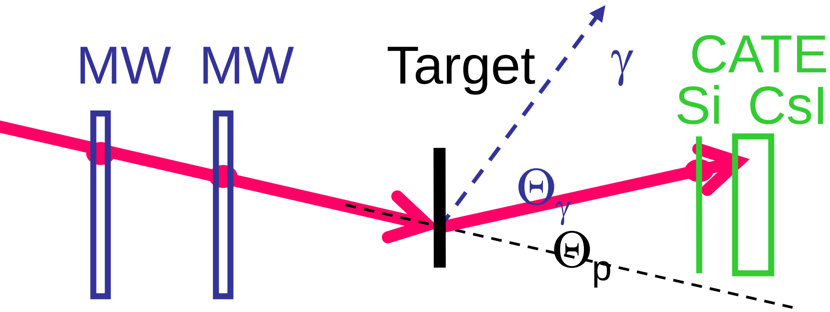
} -->A/Q $\frac{A}{Q} = \frac{B\rho e}{\beta\gamma c u}$

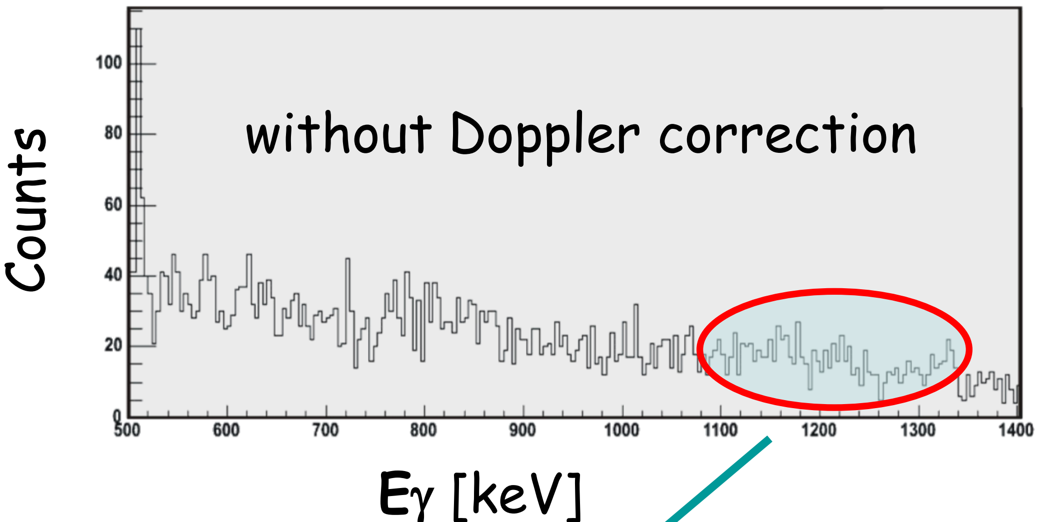
D. Magnet --> B ρ

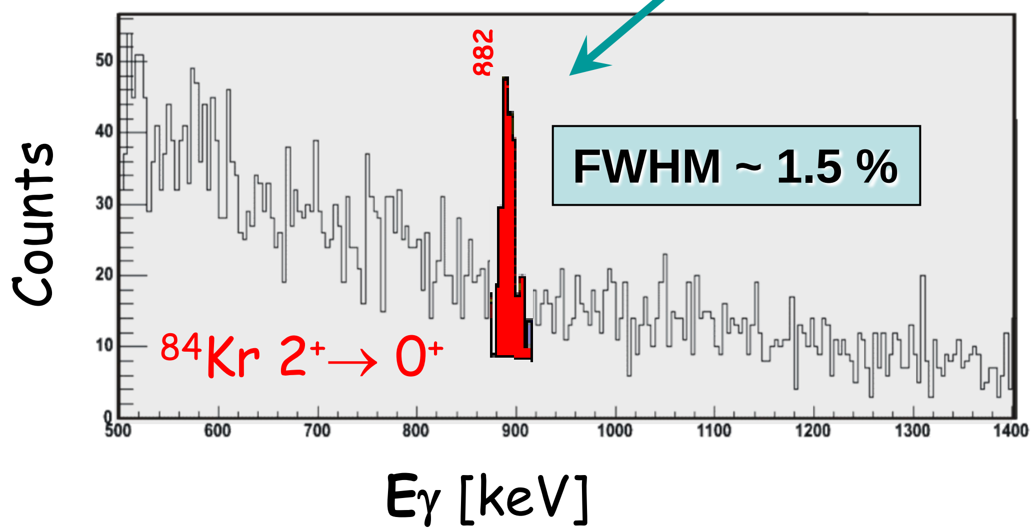
Coulomb excitation of a primary beam – ^{84}Kr

M. Gorska

^{84}Kr (113 AMeV) + Au (0.4 g/cm^{2})

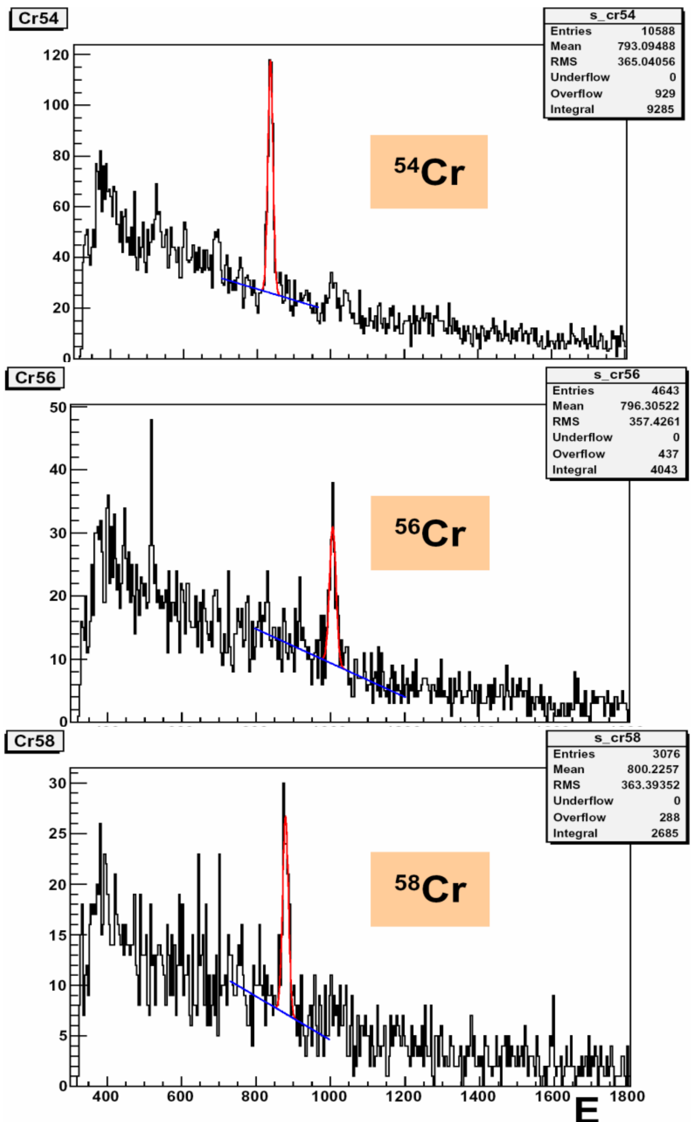






- **Particle identification before and after the target**
- **Forward scattering angle selection**
- **Fixed β= 0.4 value**
- **Event by event Doppler correction**

New Shell Structure: Cr isotopes



- B(E2) values for ^{56,58}Cr (lifetime/x-sec/energy)

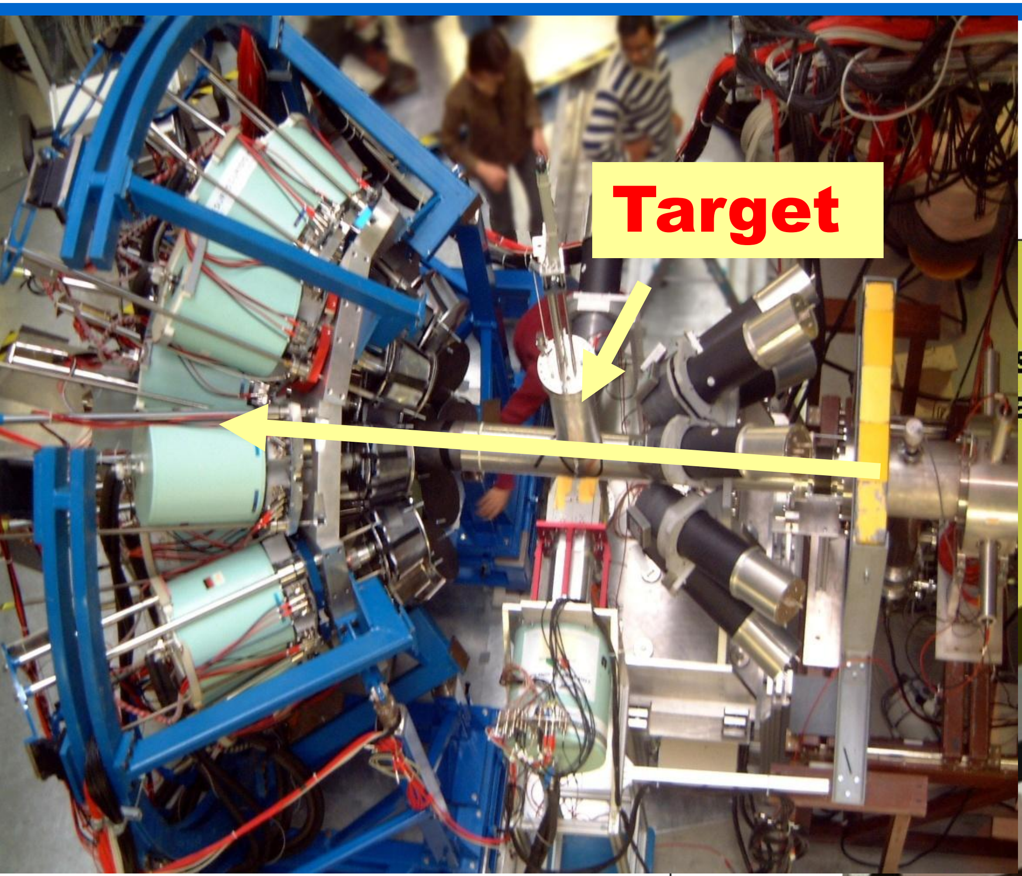
$$B(\mathrm{E2}, {}^{A}\mathrm{Cr}) = \frac{I_\gamma({}^{A}\mathrm{Cr})/N_{\mathrm{pro}}({}^{A}\mathrm{Cr})}{I_\gamma({}^{54}\mathrm{Cr})/N_{\mathrm{pro}}({}^{54}\mathrm{Cr})} B(\mathrm{E2}, {}^{54}\mathrm{Cr})$$

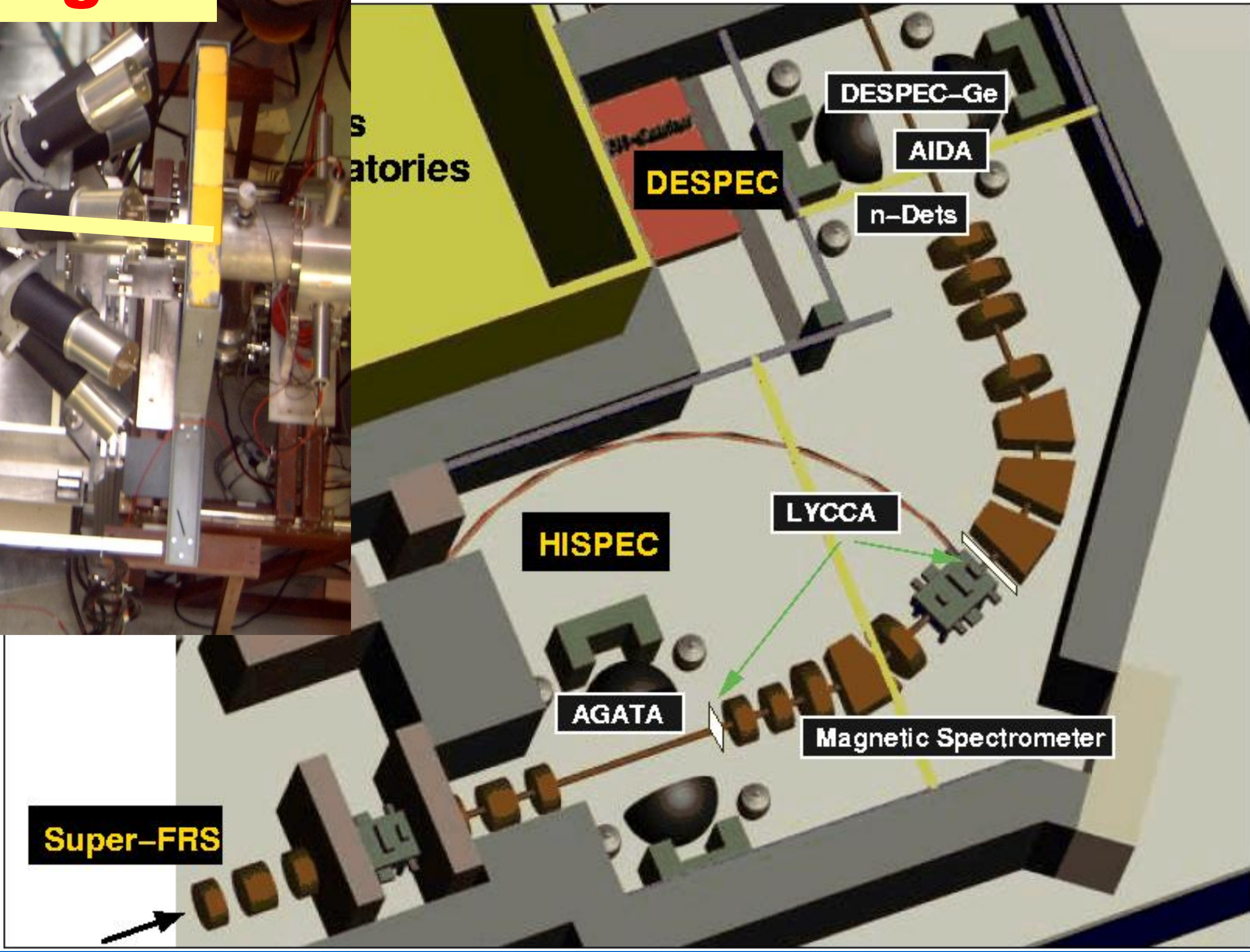
	E_γ [keV]	N_{ions}	I_γ eff.cor.	B(E2) [Wu]	B(E2) [Wu]
^{54}Cr	**835**	$3.0\cdot10^7$	21300	Normalisation	**14.6(6)**
^{56}Cr	**1006**	$1.5\cdot10^7$	6500	**8.7 (3.0)**	---
^{58}Cr	**880**	$1.0\cdot10^7$	7800	**14.8 (4.2)**	---

Indication for N=32 sub-shell closure

A. Bürger et al., Phys. Lett B622, 29 (2005)

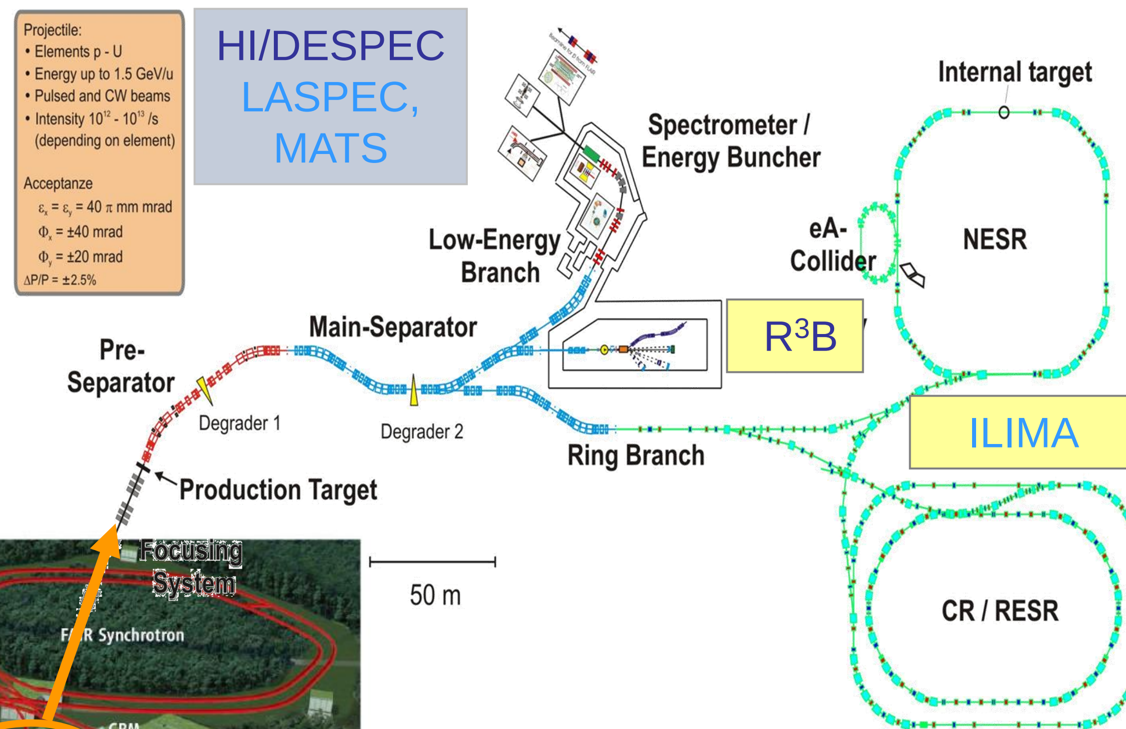
RISING → PRESPEC → HISPEC/DESPEC



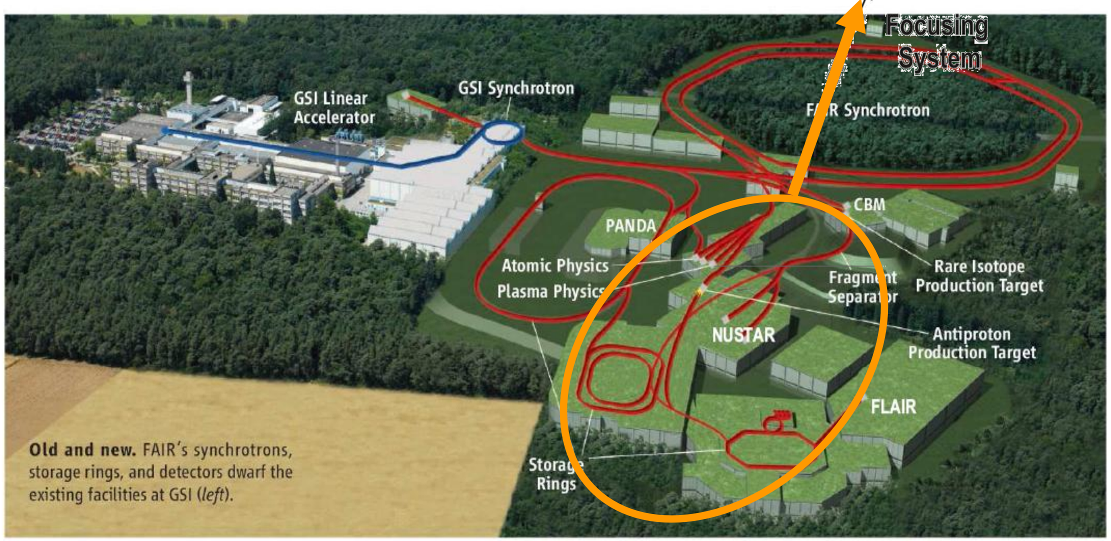


NUSTAR Experiments
(NUclear STructure Astrophysics and Reactions)

Exotic Nuclei
- Spectroscopy
- Reactions
- Mass/gs. prop.



schematic



Old and new. FAIR's synchrotrons, storage rings, and detectors dwarf the existing facilities at GSI (*left*).

2 NOVEMBER 2007 VOL 318 SCIENCE www.sciencemag.org

EXL	: hadron scattering
ELISe	: electron scattering
AIC	: antiproton scattering

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Exotic Nuclei
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- Reactions
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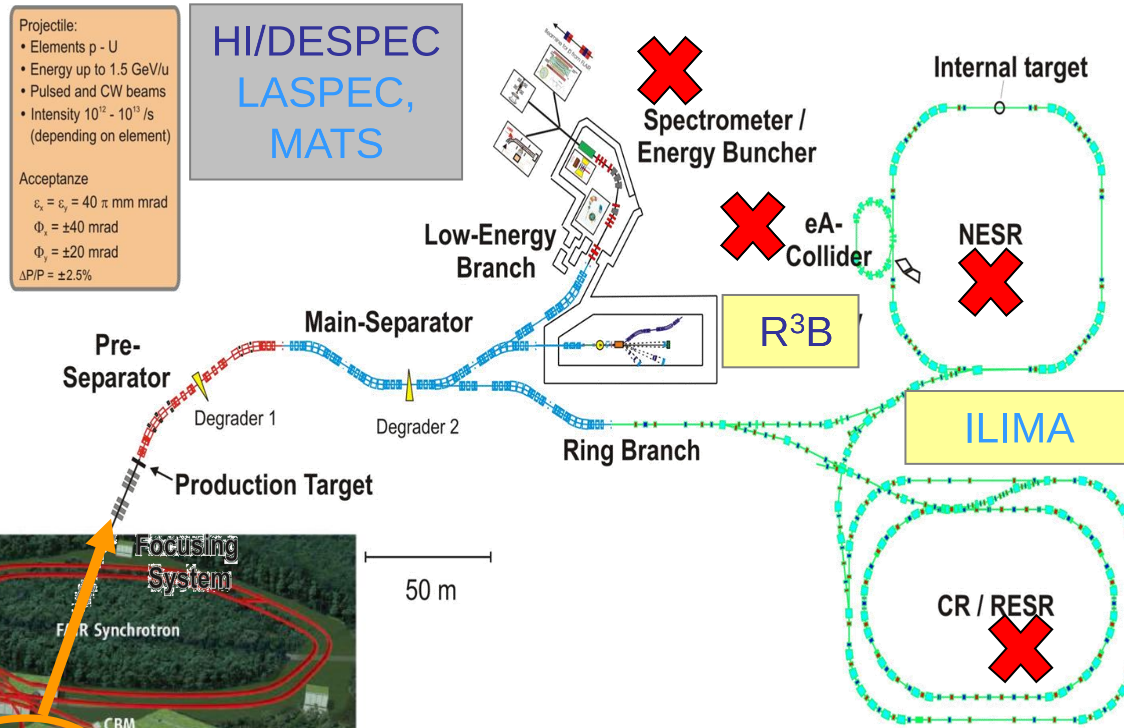

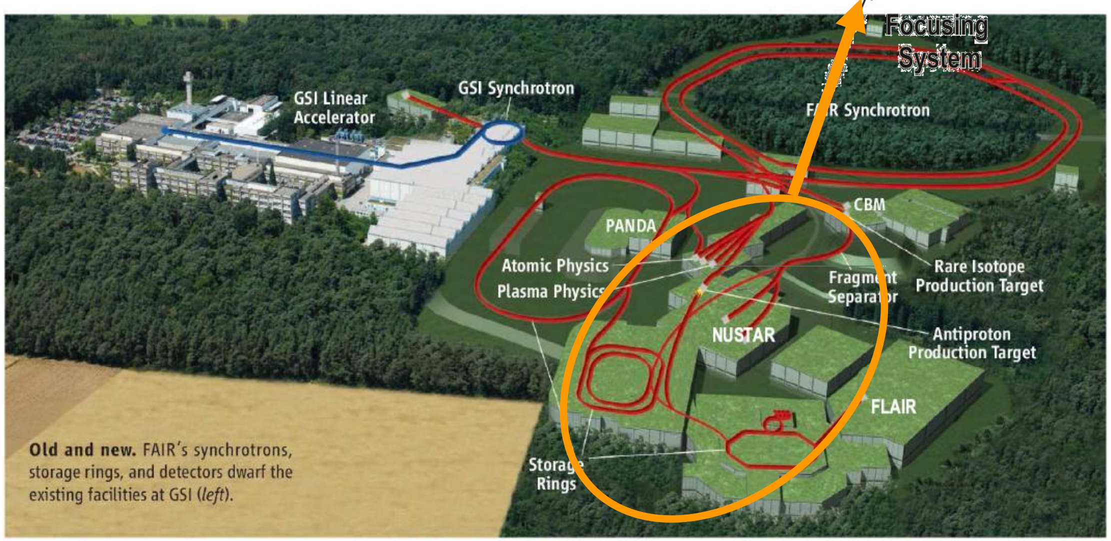

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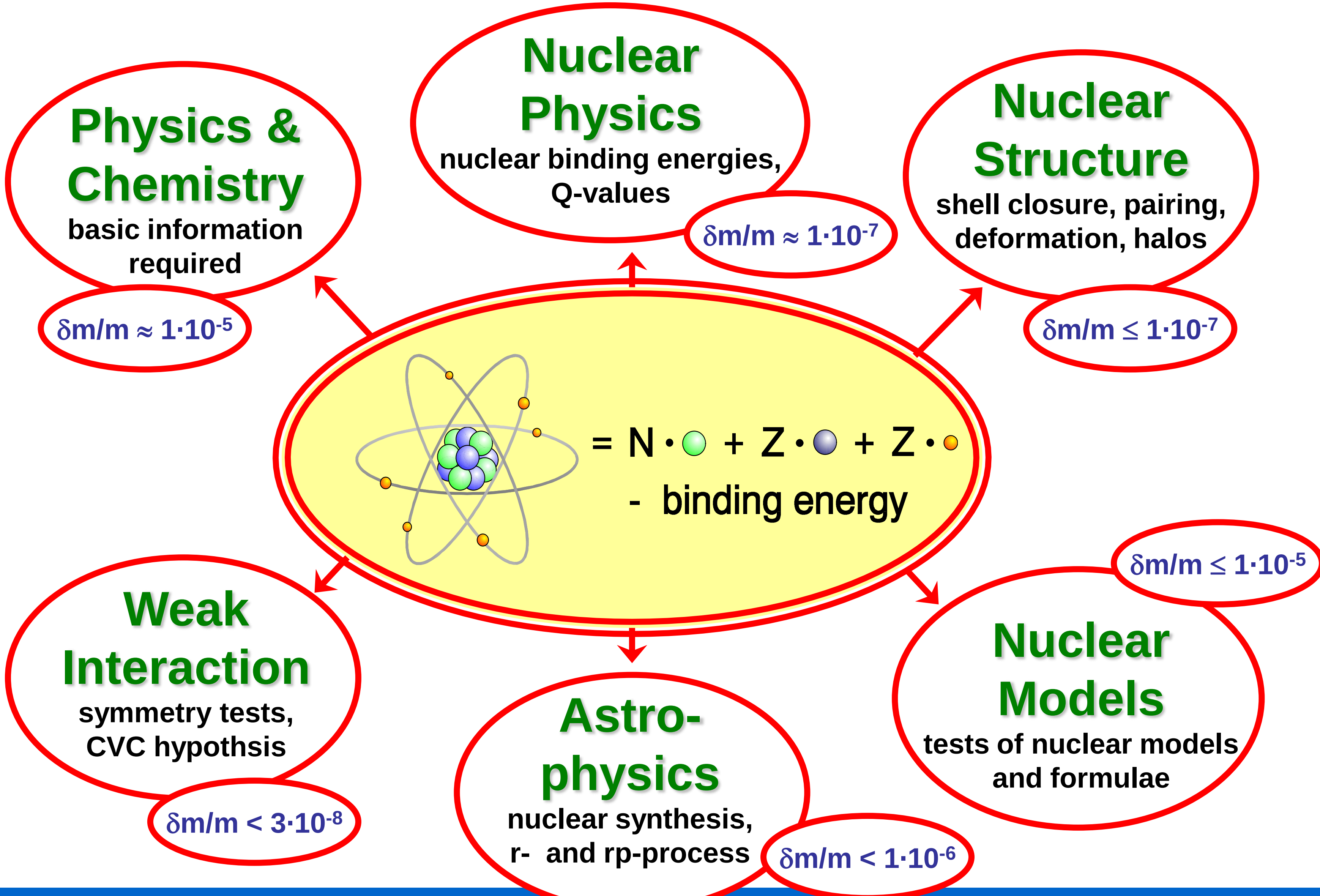
Mass: Fundamental Property of Nuclei

- Binding energies
  - Mass models
  - Shell structure
- Correlations
  - pairing
- Reaction phase space
  - Q-values
  - Reaction probabilities
- The reach of nuclei
  - Drip lines
- Nuclear astrophysics
  - Paths of nucleosynthesis
- Fundamental symmetries
- Metrology
- …..

Y. Litvinov

Importance of Atomic Masses



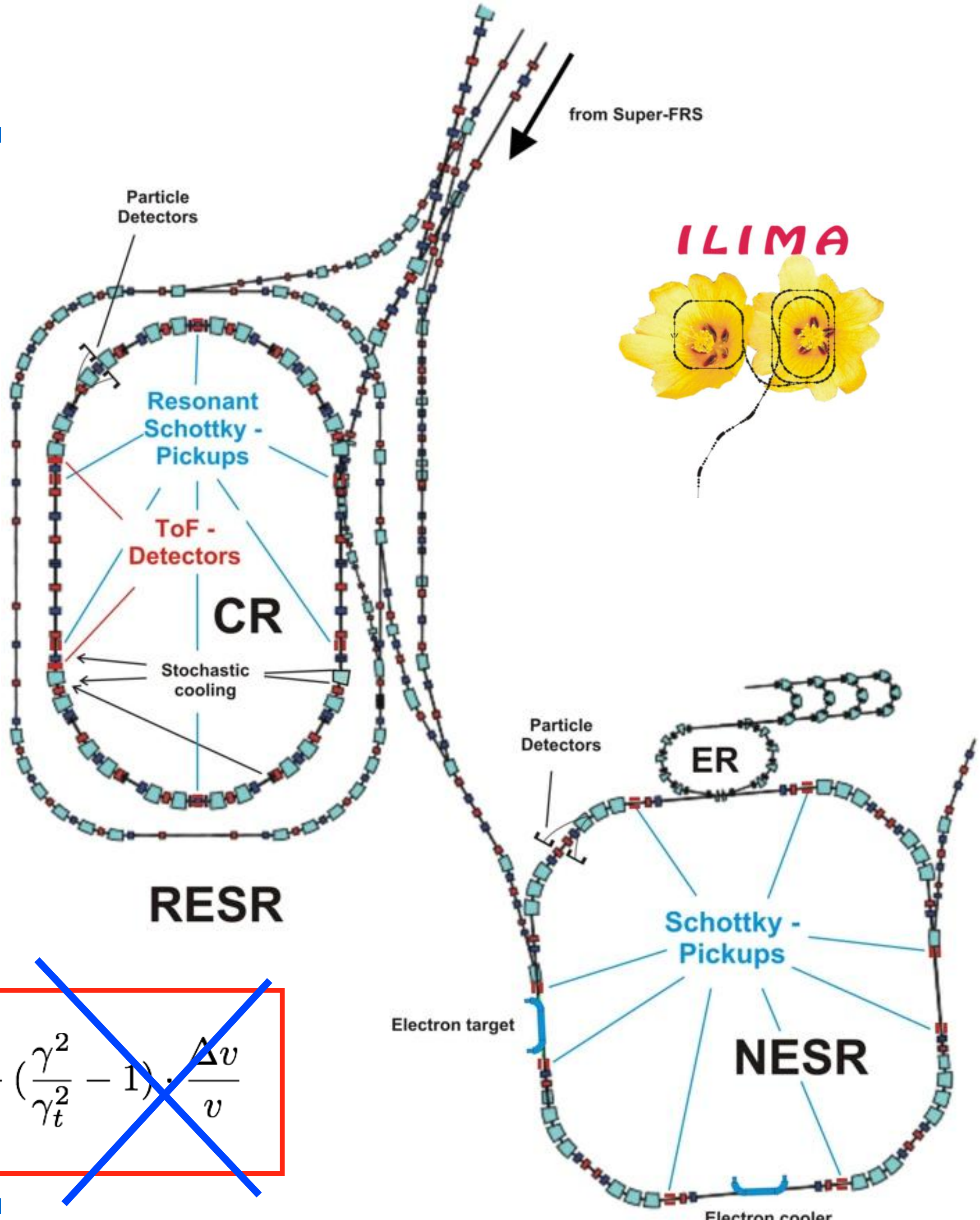
ILIMA: Set-Up

Isochronous Mass Spectrometry
in the CR

$$\gamma \rightarrow \gamma_t$$

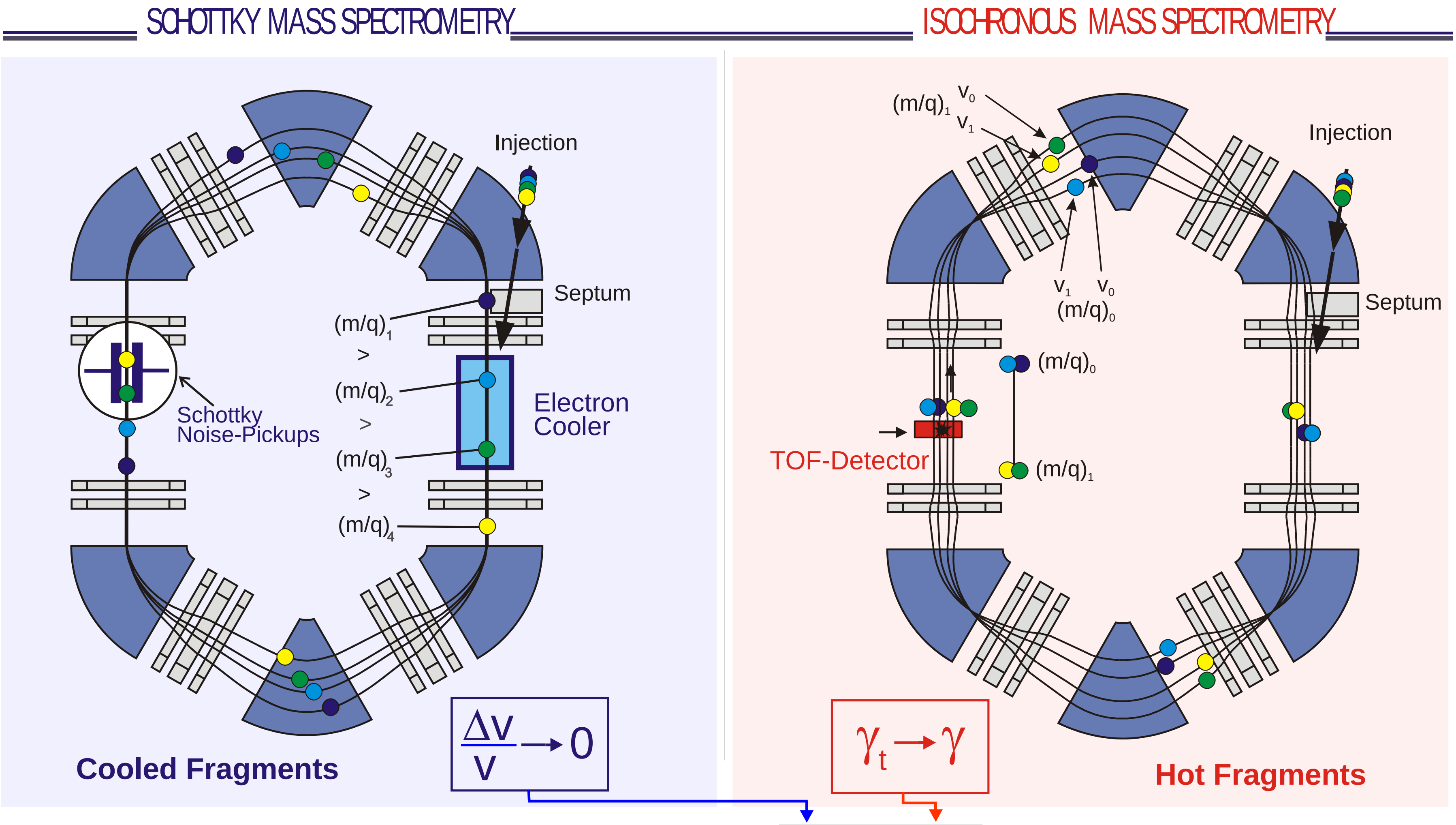
Schottky Mass Spectrometry
in the CR & NESR

$$\frac{\Delta v}{v} \rightarrow 0$$



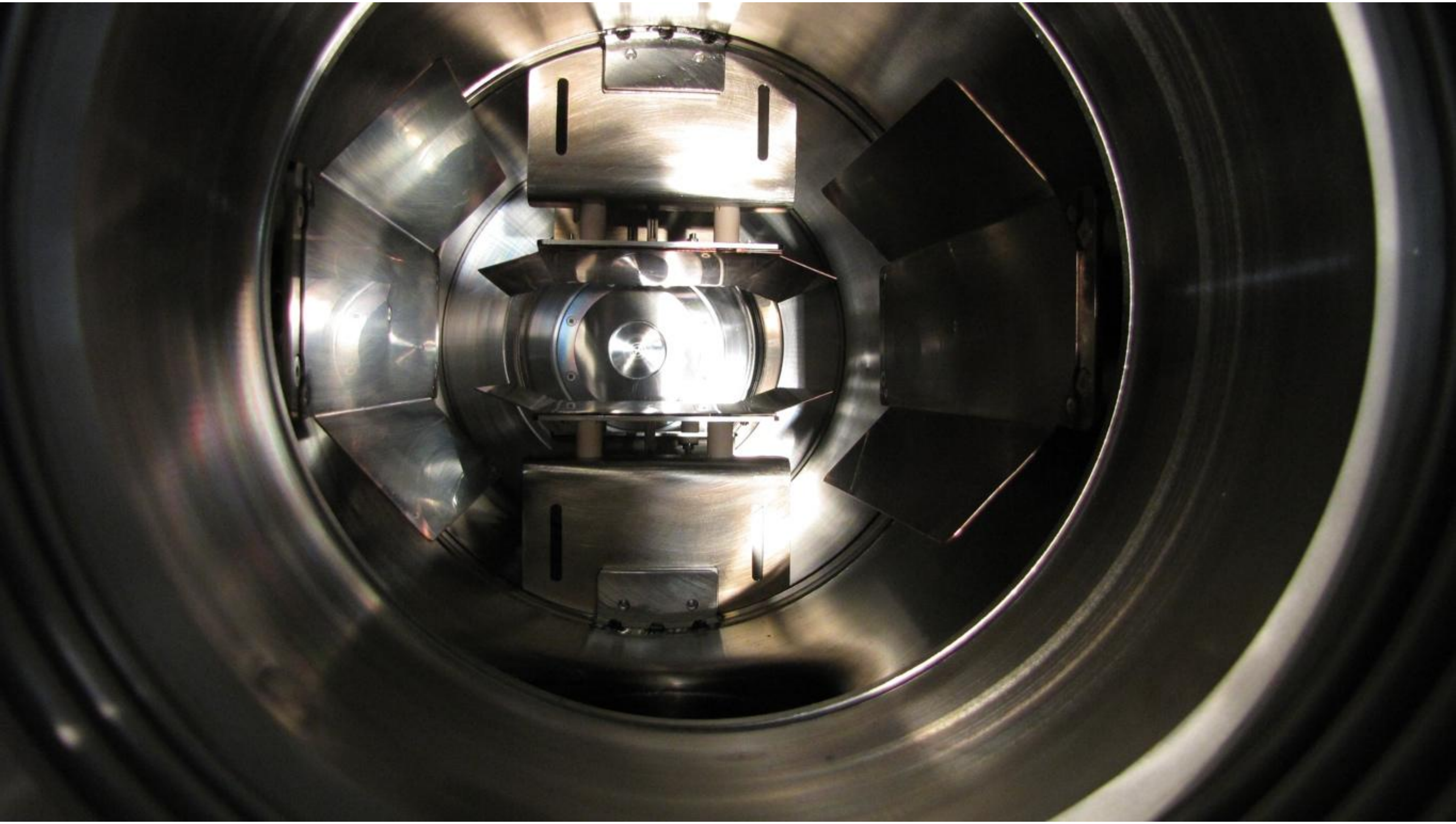
$$\frac{\Delta t}{t} = -\frac{\Delta f}{f} = \frac{1}{\gamma_t^2} \cdot \frac{\Delta(m/q)}{m/q} + (\frac{\gamma^2}{\gamma_t^2} - 1) \cdot \frac{\Delta v}{v}$$

SMS and IMS

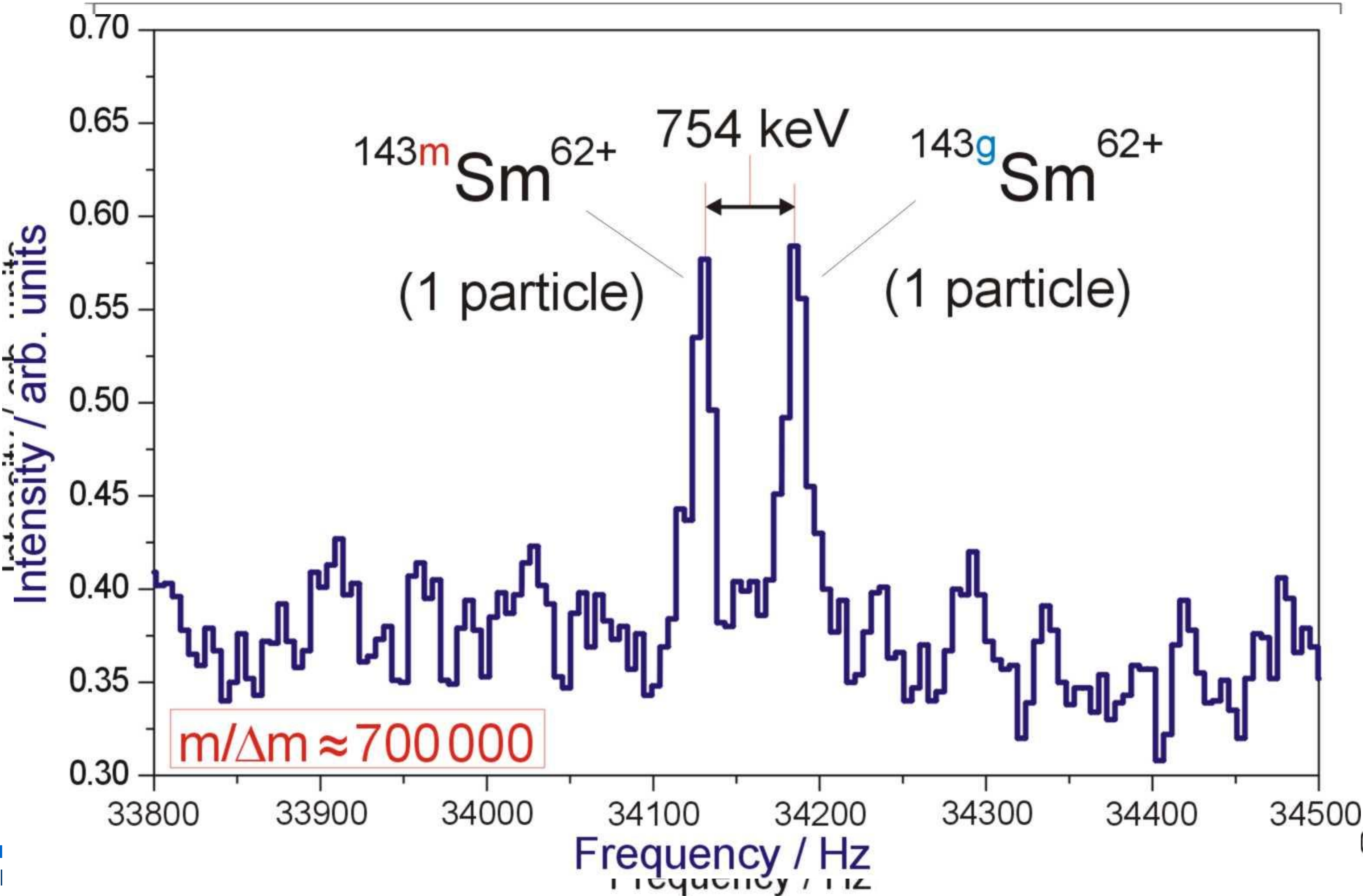


$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \frac{\Delta v}{v}\left(1-\frac{\gamma^2}{\gamma_t^2}\right)$$

Schottky Pick-Up in the ESR

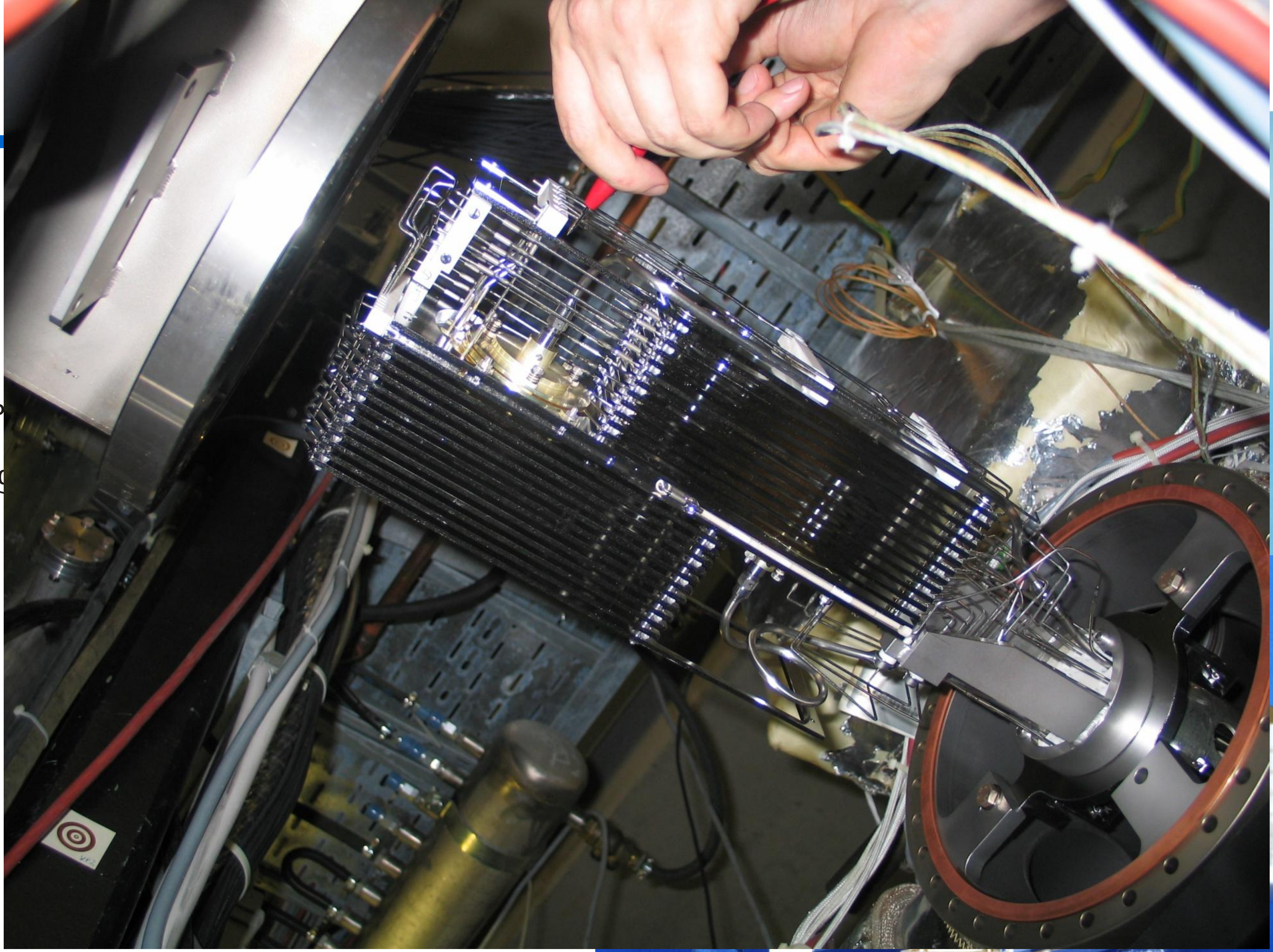


SMS: Broad Band Frequency Spectra

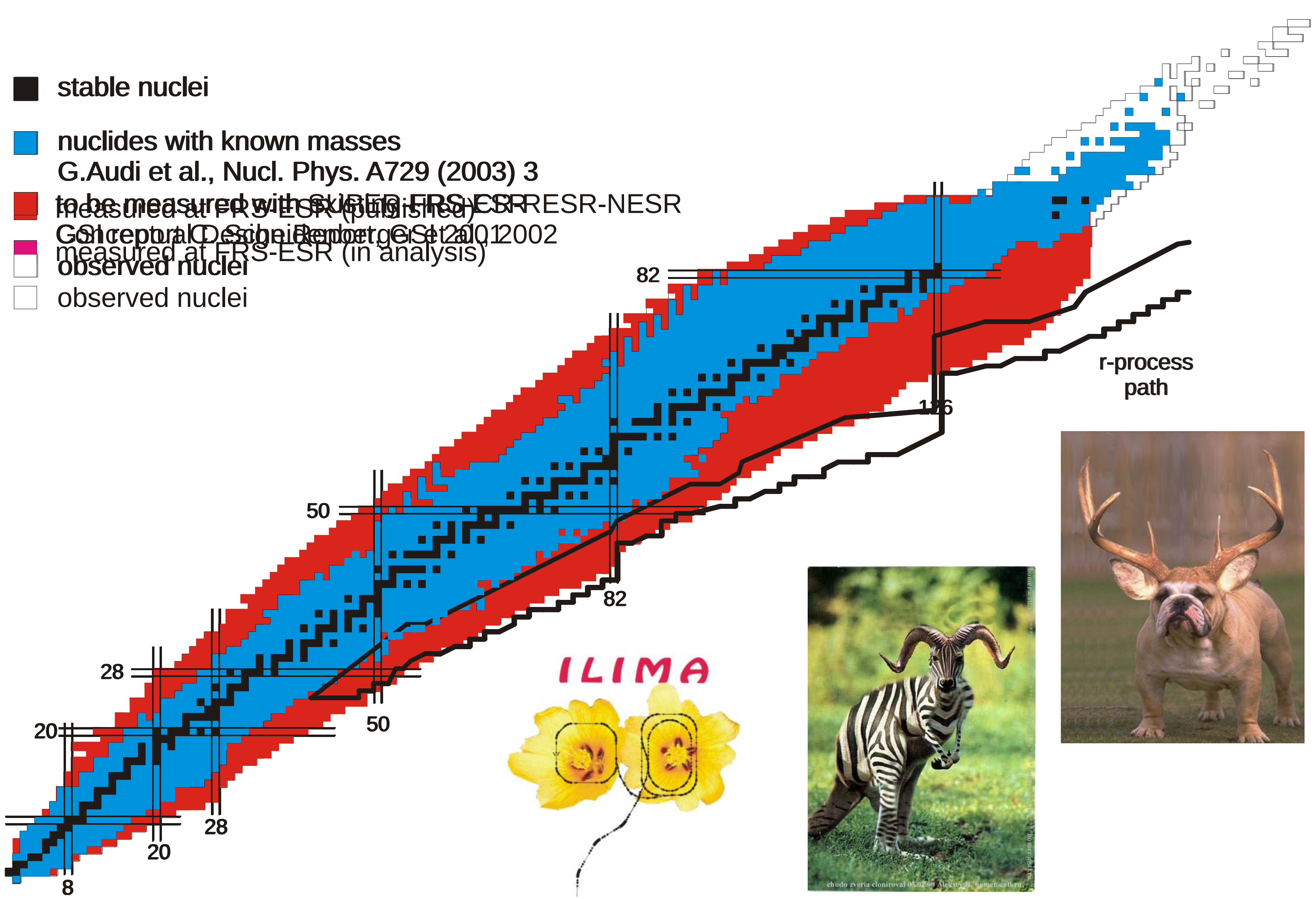


MCP

Anod



ILIMA: Masses and Halflives



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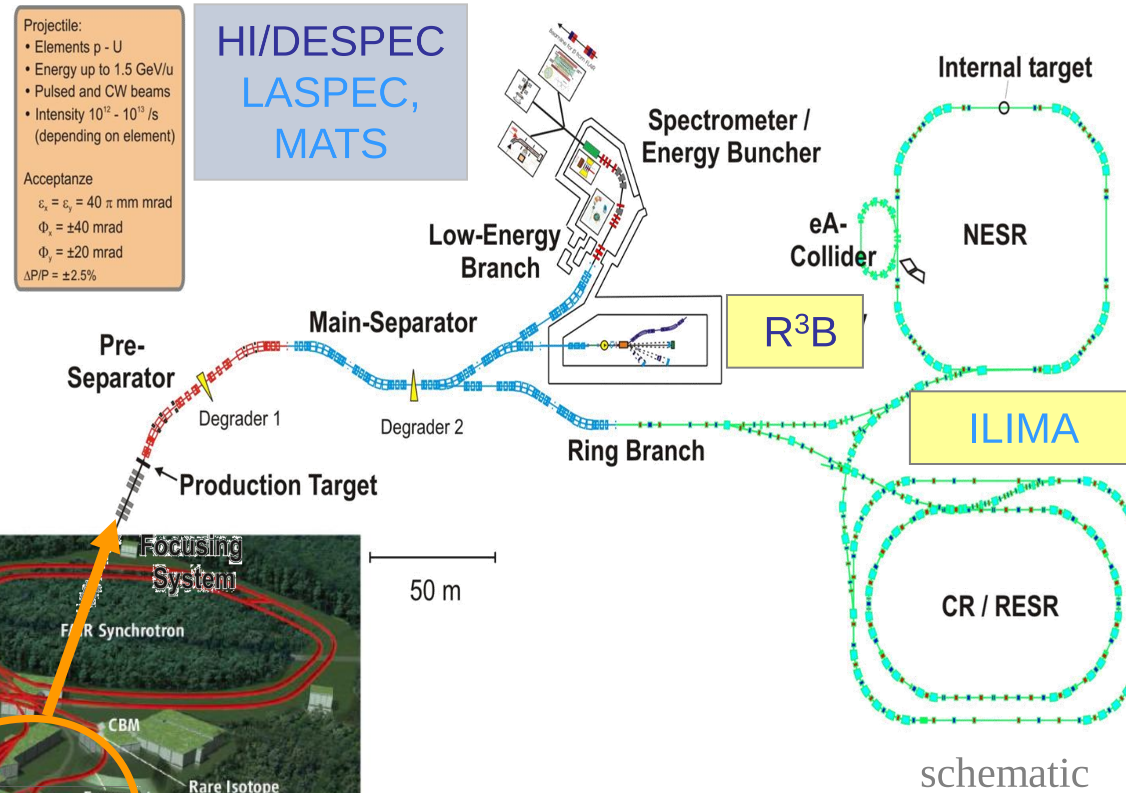
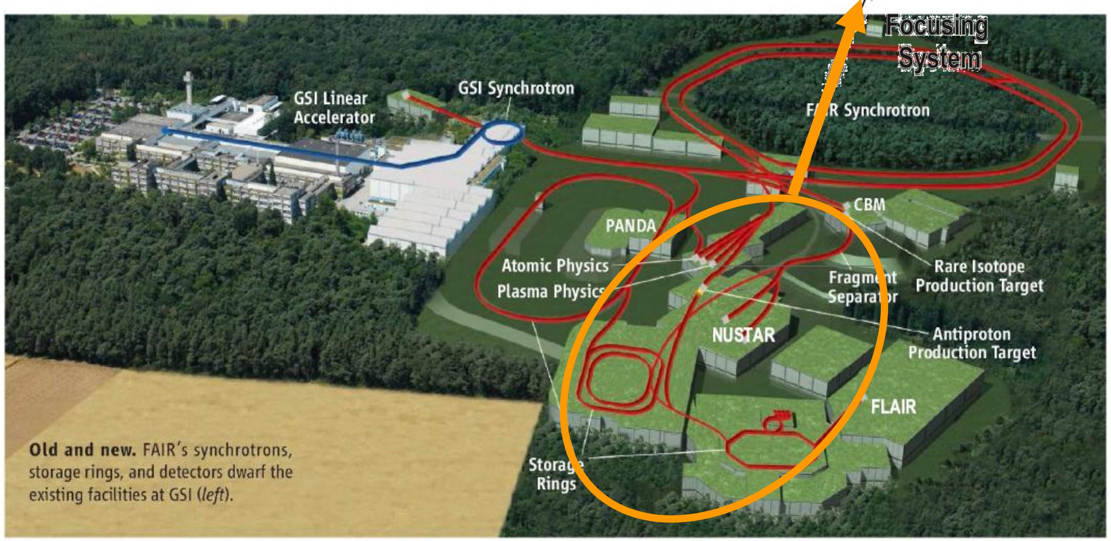
- Reactions
- Mass/gs. prop.





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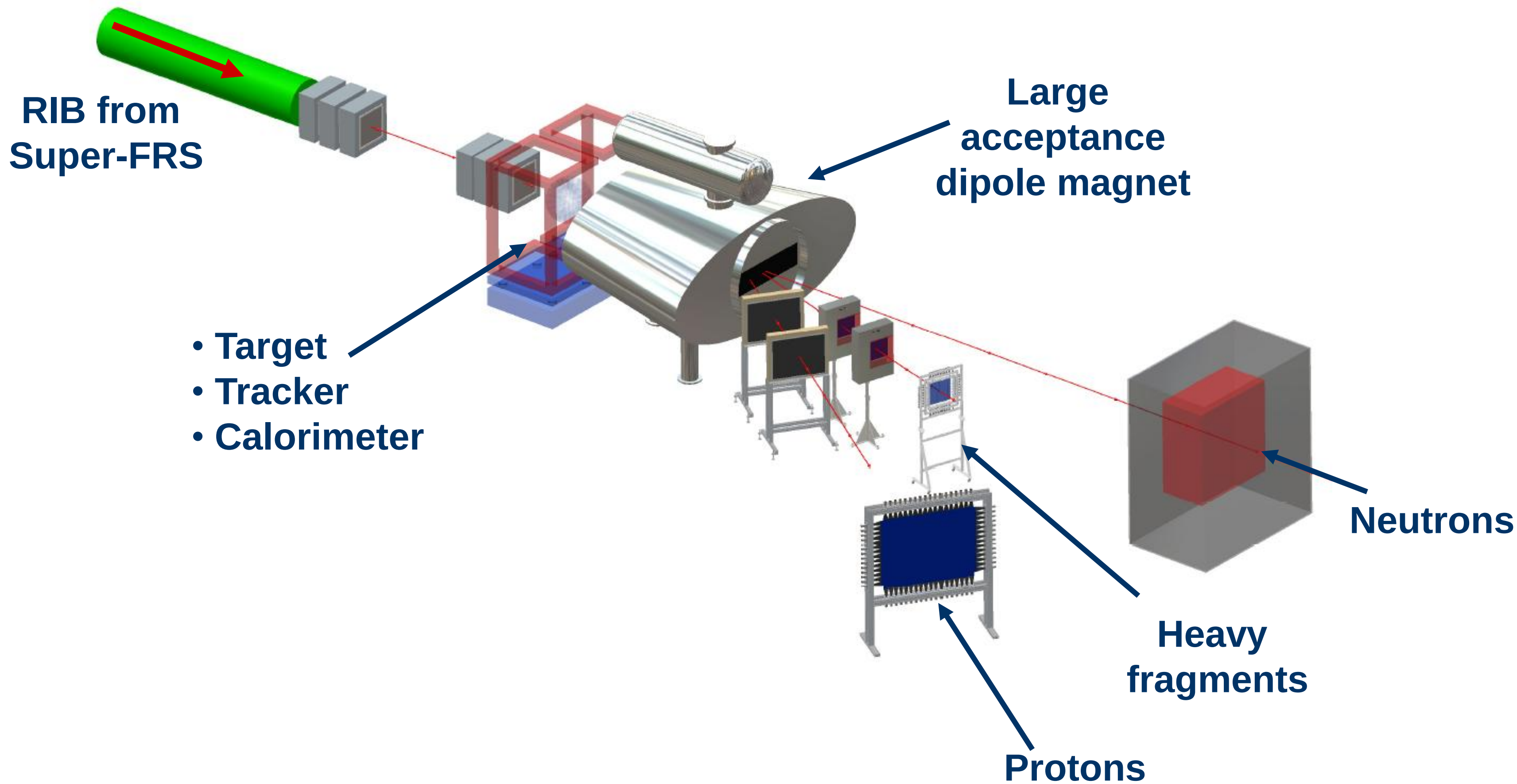
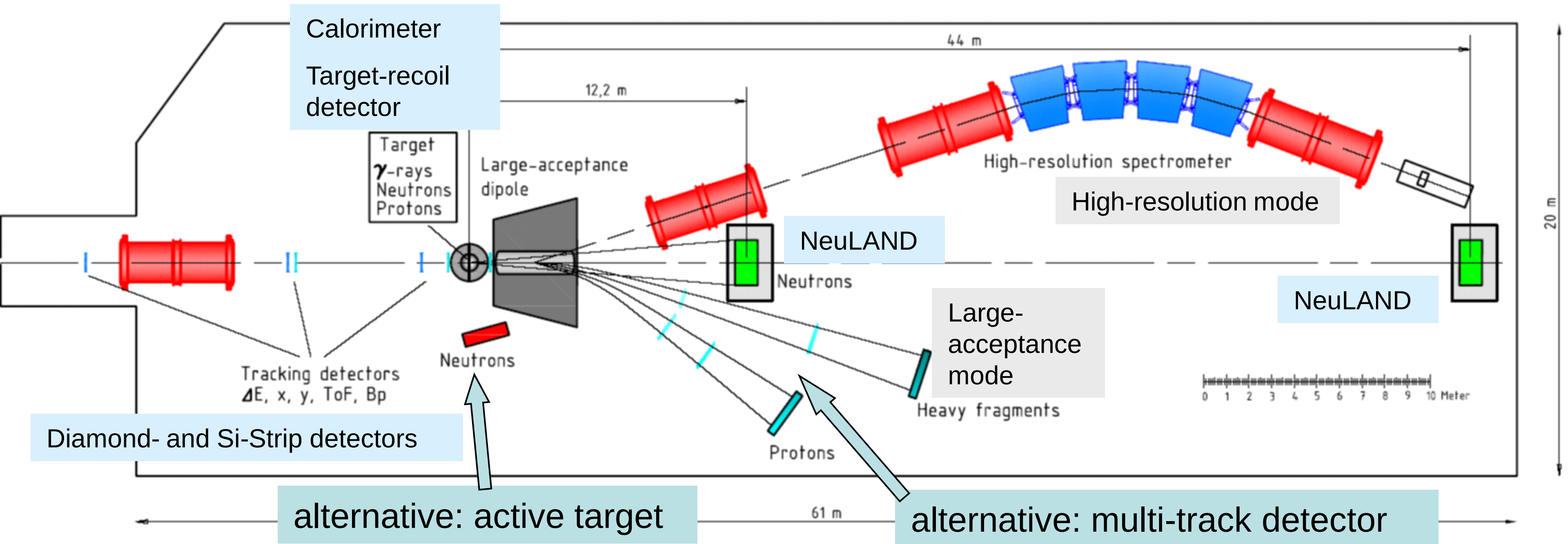
Reactions with Relativistic Radioactive Beams (2017/18)



Spokesperson: T. Aumann
http://www.gsi.de/fair/experiments/NUSTAR/R3b.html

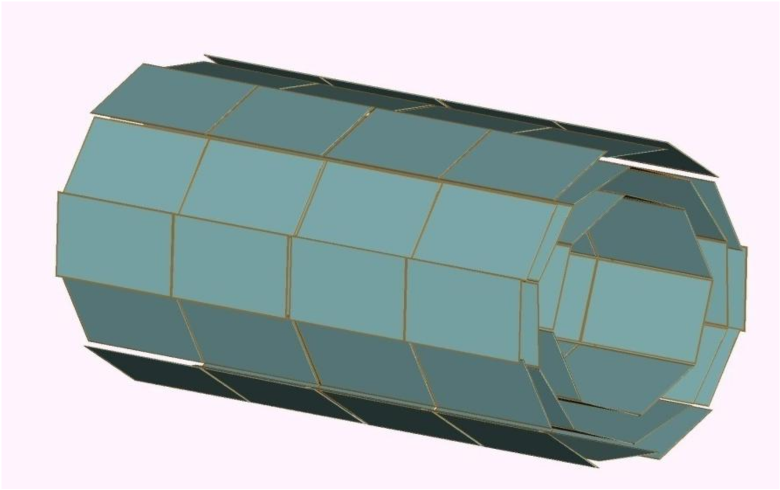
Reactions with Relativistic Radioactive Beams (full)



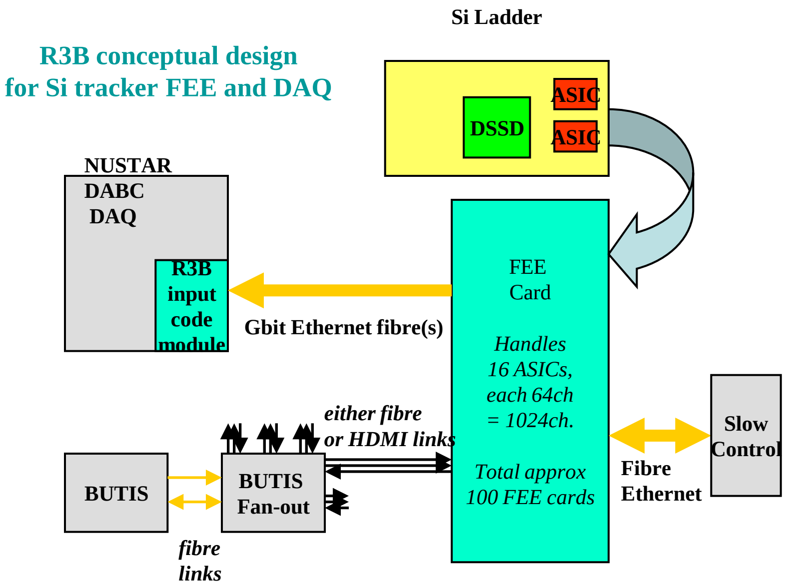
Kinematically complete measurement of reactions with high-energy secondary beams

- Nuclear Astrophysics
- Structure of exotic nuclei
- Neutron-rich matter

R3B Si Recoil Tracker



project started 1 April 2009
• Installation at R3B in 2013

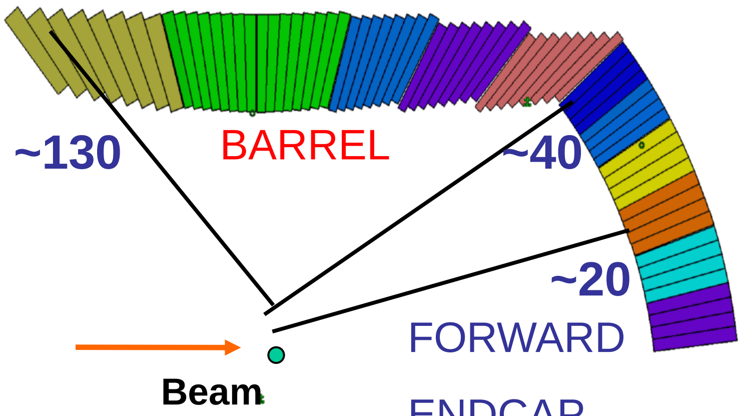


Tasks:

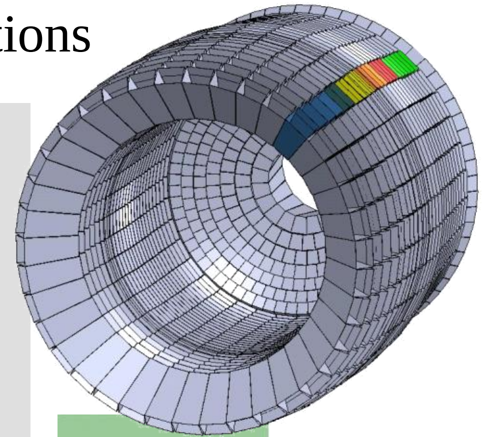
- Simulations of target-recoil detector
  - elastic, inelastic, quasifree …
- Si-microstrip prototype testing
  - micro-strip, MAPS …
- Si tracker mechanical design
- Mechanical integration of target-recoil detector sub-systems
  - with LH2 target and calorimeter
- FEE and DAQ
  - 100k channels, new ASIC design (low thresholds, self-triggering)
- Si-tracker construction, assembly and installation
  - Liverpool Semiconductor Centre (ATLAS, LHCb, etc)
- Si-ladder assembly testing

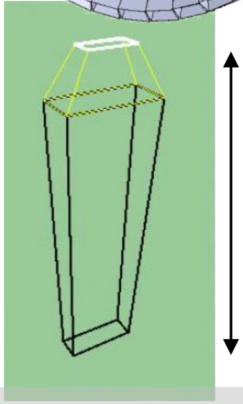
CALIFA CsI/phoswitch calorimeter

General design of the detector based on kinematical considerations



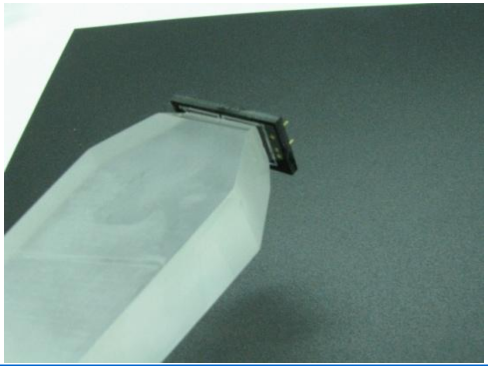
- "Egg" shape
- Highly segmented
- Thick detection volume
- Scintillation based
- performant photo-sensors



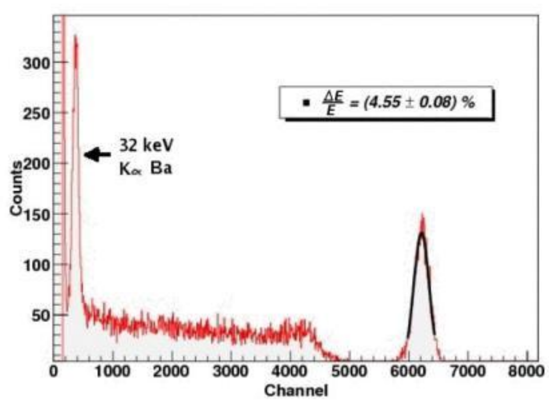


Crystal and photosensors

Barrel → CsI+APD



1cm^3 and 662 keV γ

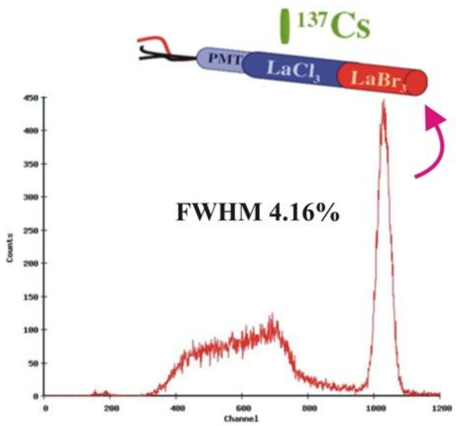


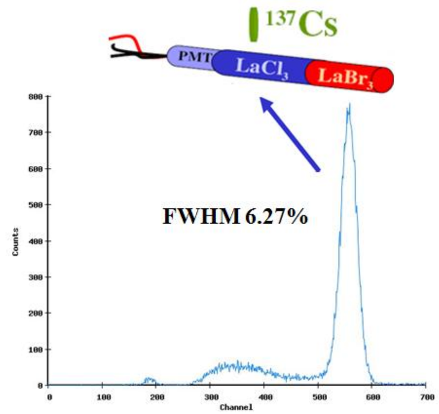
Real shape, 1MeV γ

→ $\Delta E/E \sim 5$ %

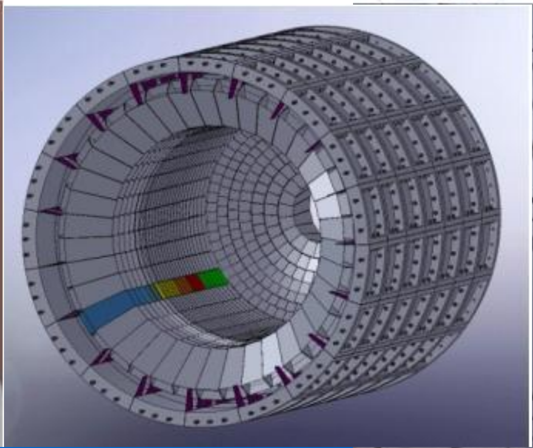
CALIFA forward endcap

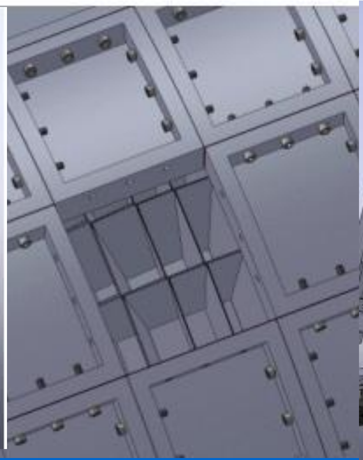
Phoswich solution is being investigated

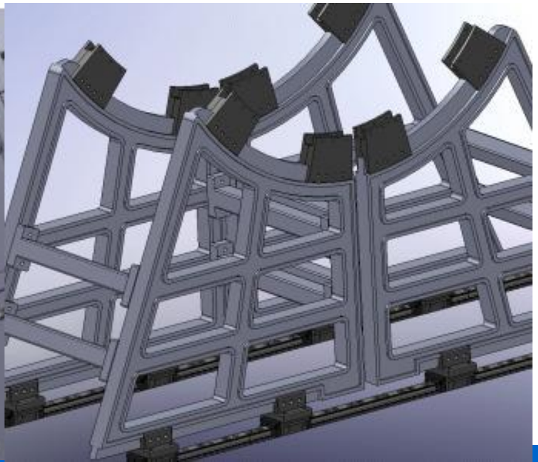




Engineering design and Mechanical structure → based on carbon fiber



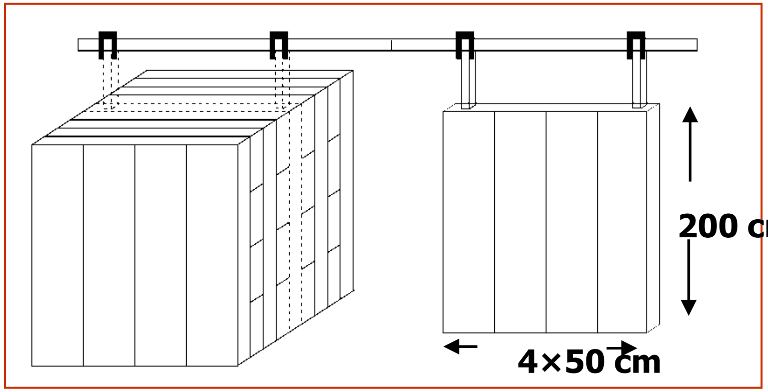




Neutron detector NeuLAND

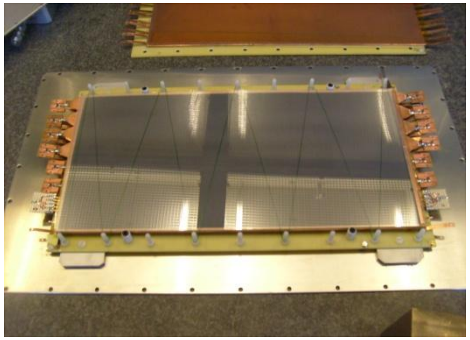
σ_t	< 100 ps
$\sigma_{x,y,z}$	≈ 1 cm
σ_{E^*}	20 keV
size	2 x 2 x 0.8 m^3
area	~ 140 m^2
# ch.	~ 10.000
weight	~ 15 t

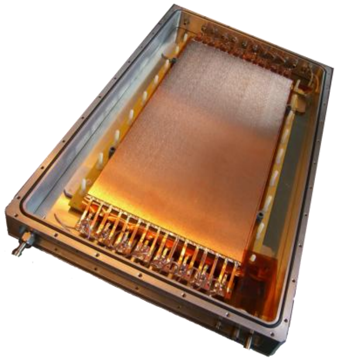
detection principle based
on
Resistive Plate Chambers
plus
iron converters

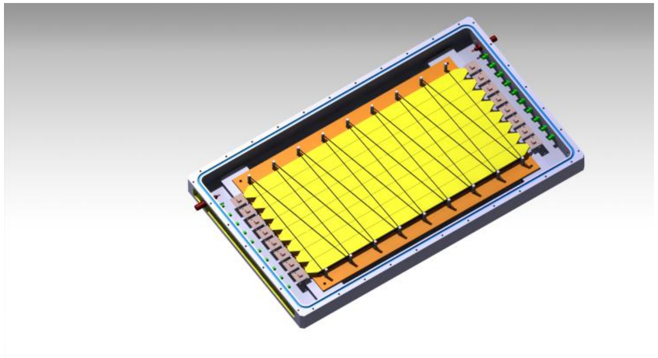


status:

- ✓ proof of principle: RPC excellent for slow protons
- ✓ prototypes with included converter as electrodes: efficiency of 99%, time resolution ~50 ps





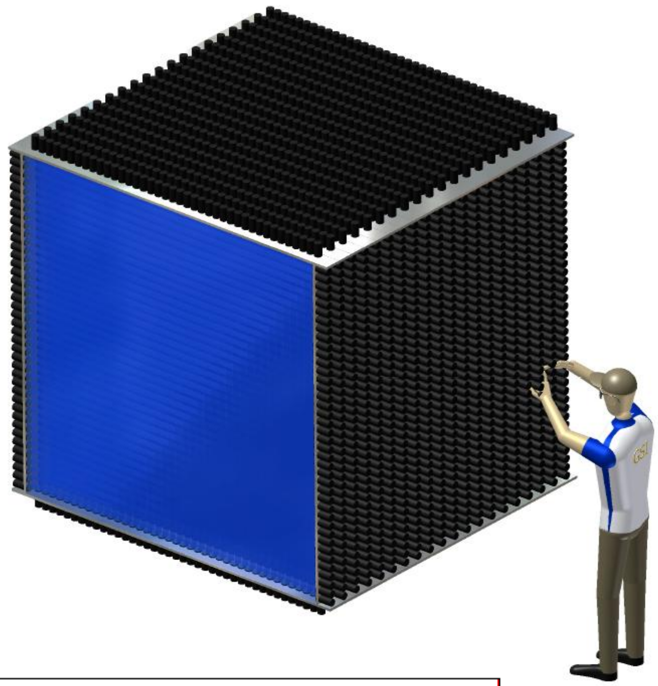


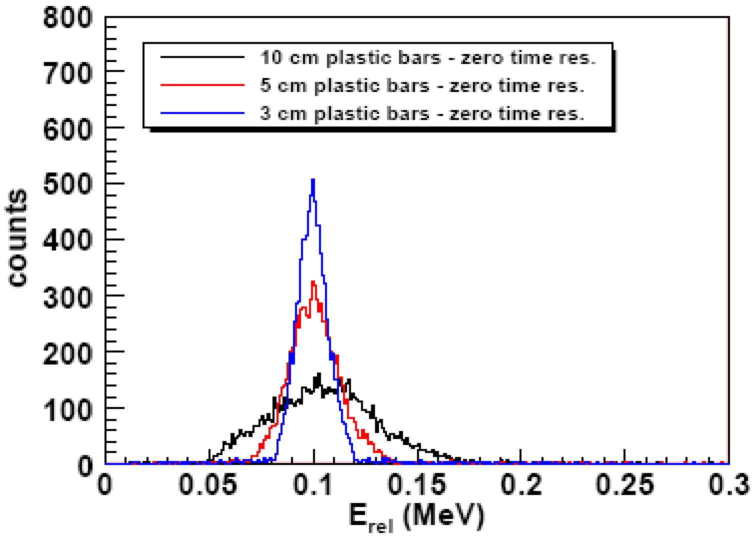
NeuLAND detector based on scintillators

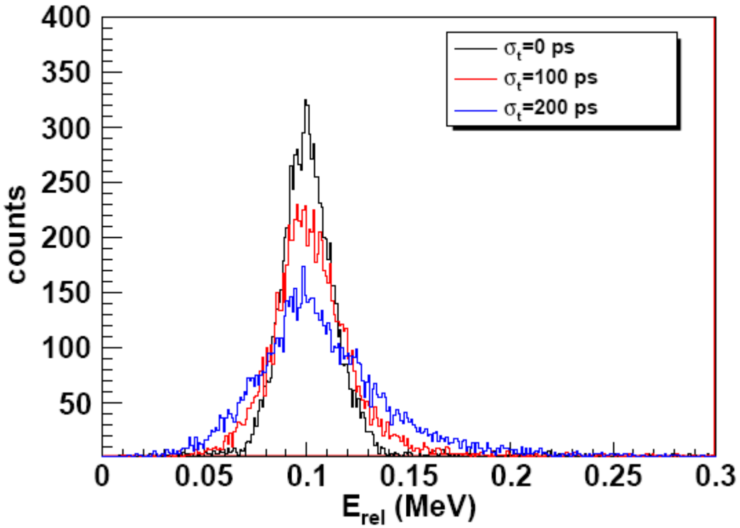
Simulation of alternative concept:

Studies with different bar size:
- bars of 5 x 5 cm
  (1600 bars and 3200 PMs)

- bars of 3 x 3 cm
  (4500 bars and 9000 PMs)







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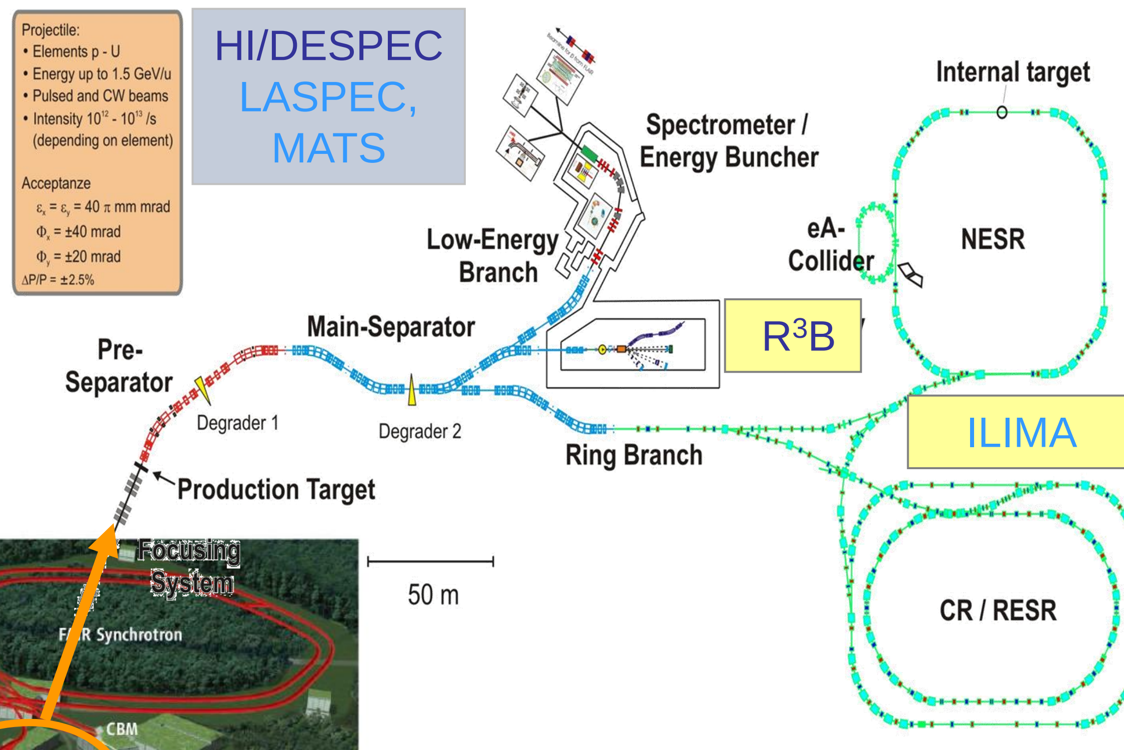
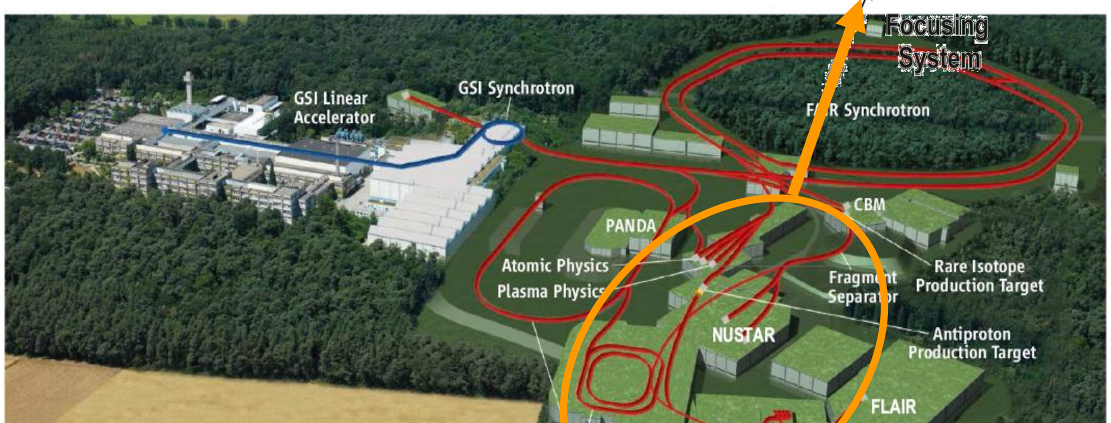


schematic



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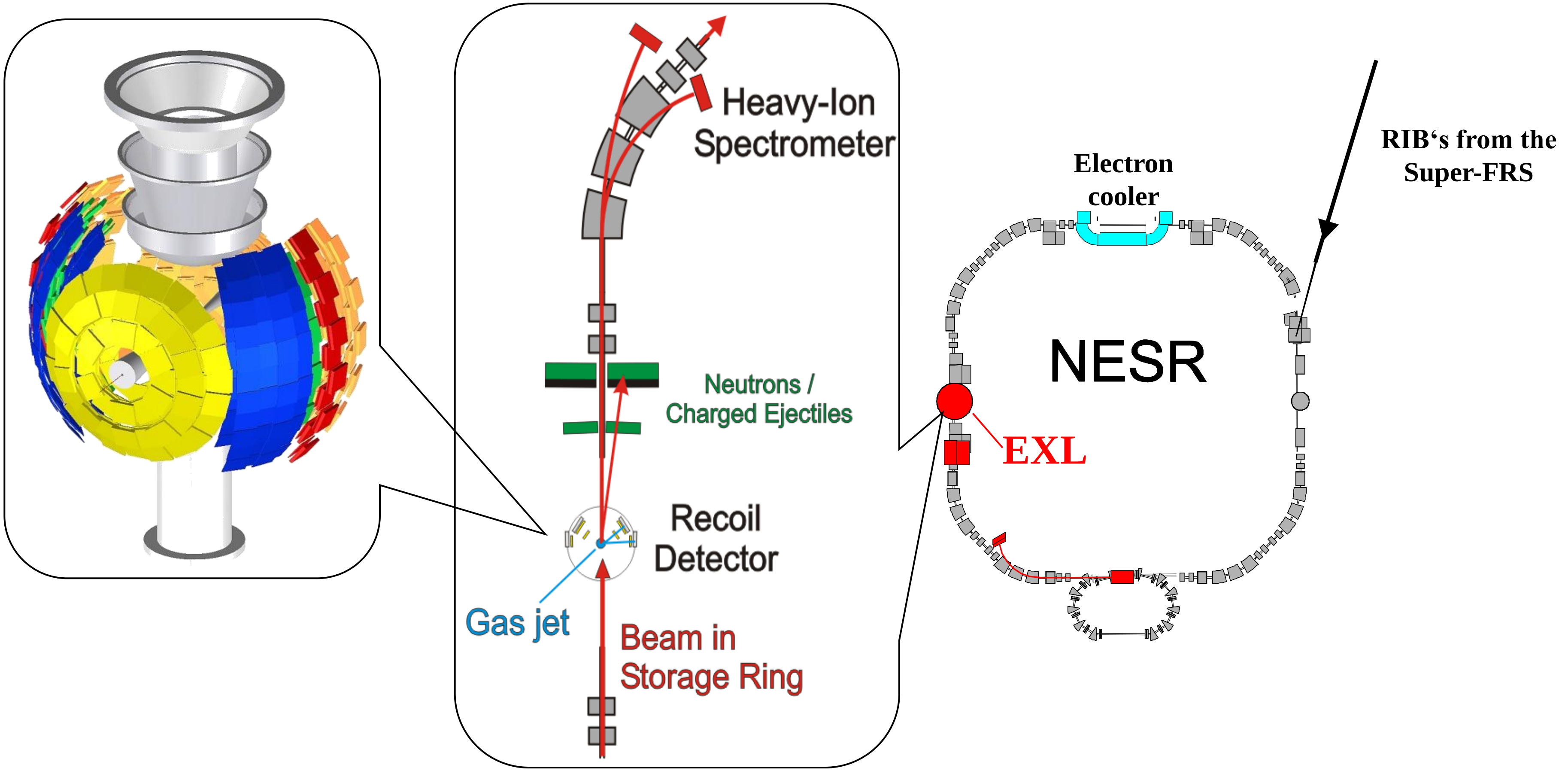
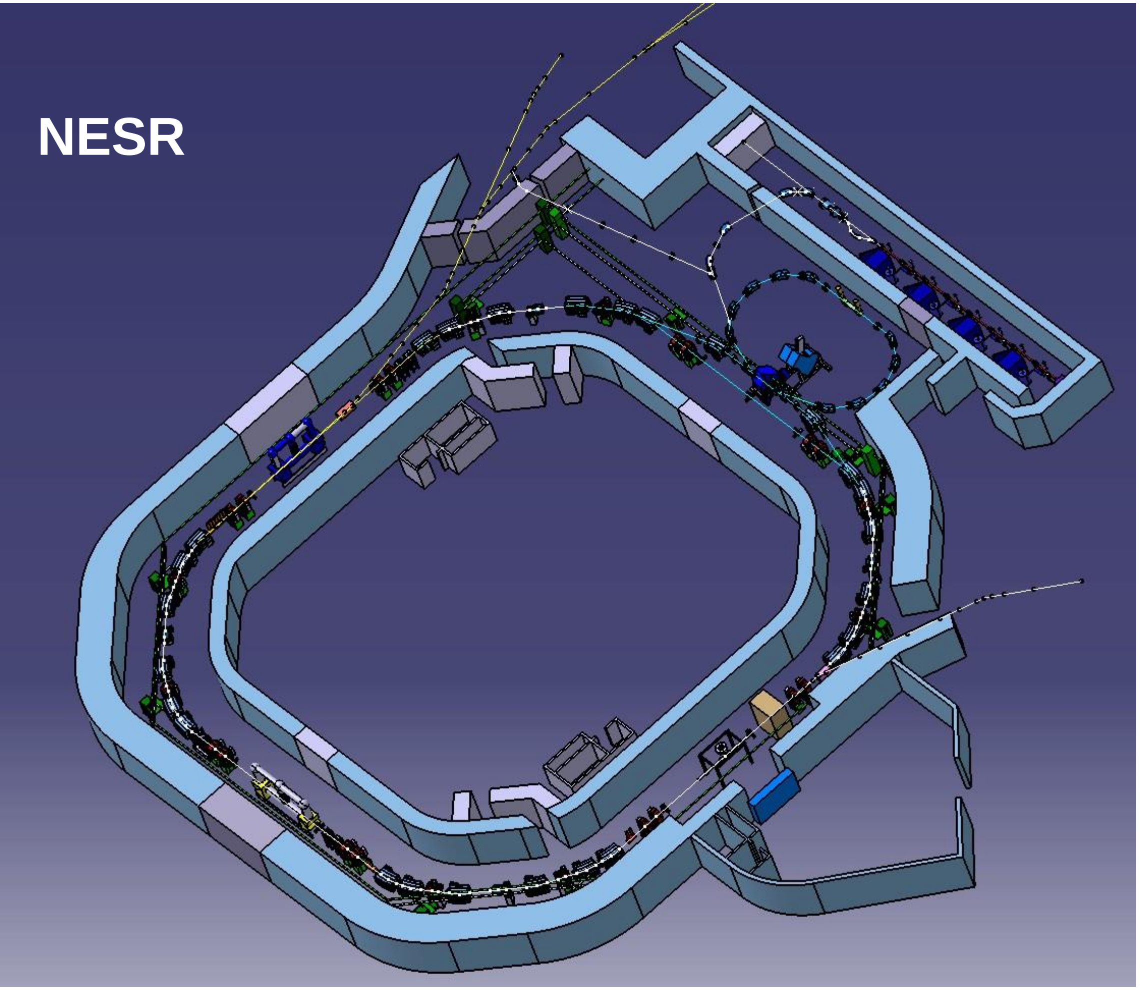
EXL: EXotic Nuclei Studied in Light-Ion Induced Reactions at the NESR Storage Ring



Realization of an RIB electron collider setup

The ELISe experiment



- 125-500 MeV electrons
- 200-740 MeV/u RIBs

➔ up to 1.5 GeV CM energy

- spectrometer setup at the interaction zone & detector system in ring arcs

- Part of the core facility

http://www.gsi.de/fair/reports/btr.html

AIC option:

- 30 MeV antiprotons

- detector system in ring arcs
- schottky probes

Why should one try to collide beams ?

- trying to get through the eye of the needle

• Target and scattered off particles can be detected
➔ excitation and de-excitation process is studied

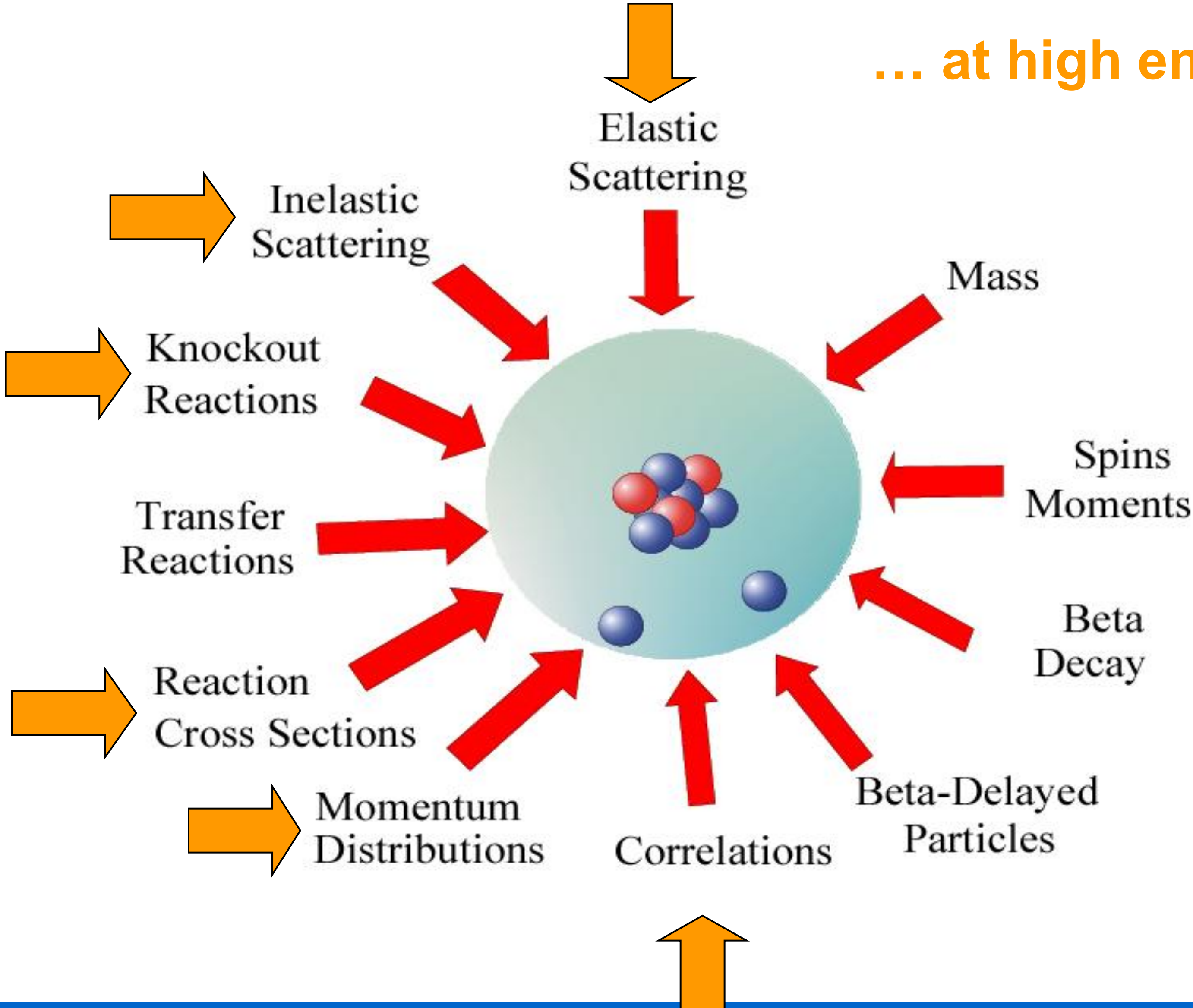
• ‘no target absorption’
➔ unhampered detection

• kinematical focusing
➔ solid angle
➔ Mott cross section enhanced (small angles)

• luminosity for unstable nuclei from a chemically non selective fragmentation facility
➔ 100µm x 100µm interaction area

Summary: there is no smoking gun …

… at high energies



FIN

Thanks to: T. Aumann, M. Gorska, Yu. Litvinov, …

Final Remarks

- FAIR offers unique opportunities

- The process of building has now been started
  in a first reduced version offering already a viable
  program for all four communities

  APPA CBM panda NUSTAR

- Stay tuned! New website: http://www.fair-center.eu/