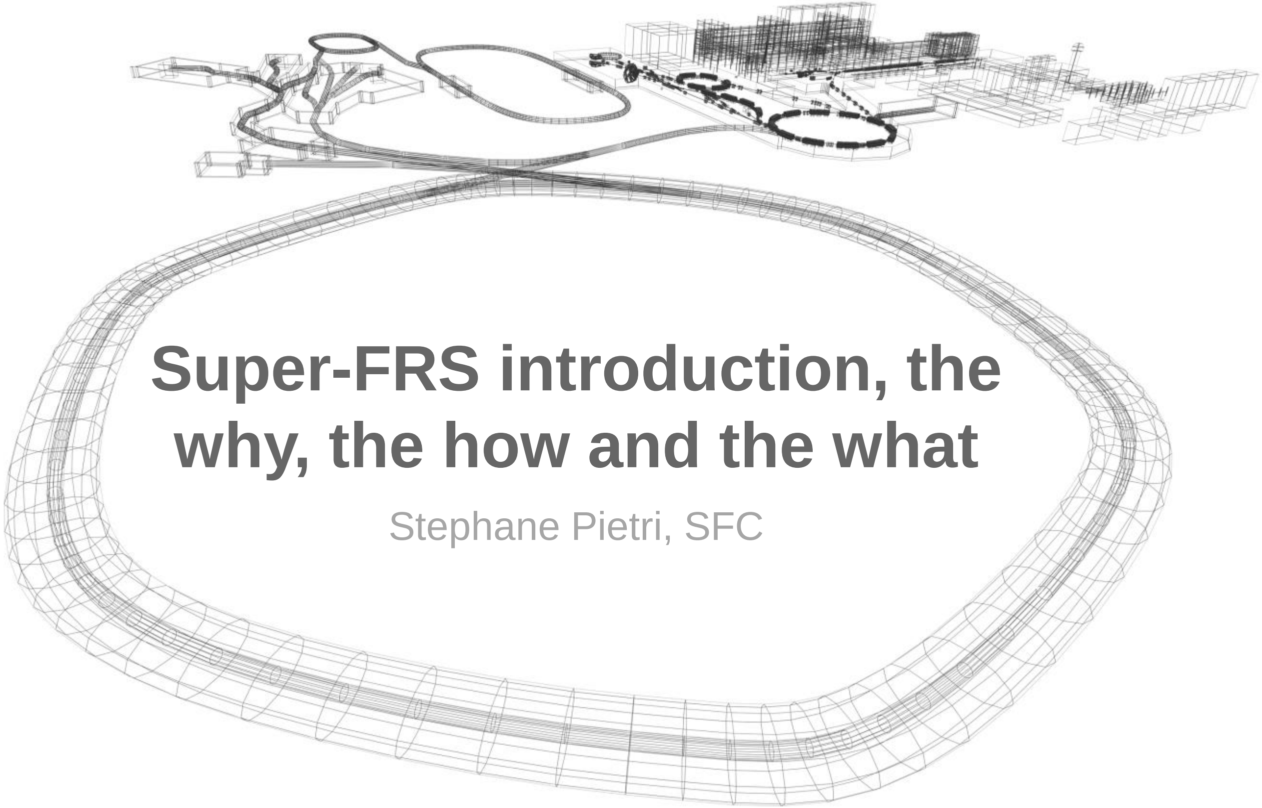
Super-FRS introduction, the why, the how and the what

Stephane Pietri, SFC



Layout

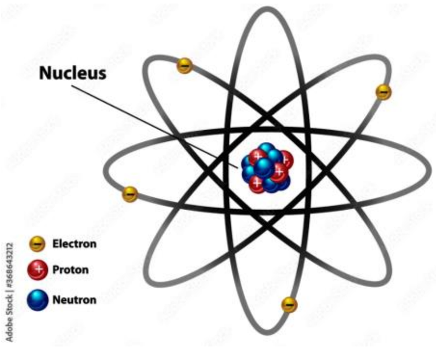
- Some physics introductions
  - nucleus
  - nuclear physics
  - decay – natural process
  - acceleration
  - reactions – “artificial” process
- Why study nuclear physics
  - cosmogenesis
  - LCDM model
  - neutrons and nuclei
  - r and s process path
  - where to look
- Super-FRS
  - objective
  - separation
  - degraders
  - identification
  - some interesting bits
  - how compare to the rest
- Selection of planned experiment
  - NUSTAR
  - DESPEC
  - HISPEC
  - Super-FRS EC
  - R3B

Layout

- Some physics introductions
  - nucleus
  - nuclear physics
  - decay – natural process
  - acceleration
  - reactions – “artificial” process
- Why study nuclear physics
  - cosmogenesis
  - LCDM model
  - neutrons and nuclei
  - r and s process path
  - where to look
- Super-FRS
  - objective
  - separation
  - degraders
  - identification
  - some interesting bits
  - how compare to the rest
- Selection of planned experiment
  - NUSTAR
  - DESPEC
  - HISPEC
  - Super-FRS EC
  - R3B

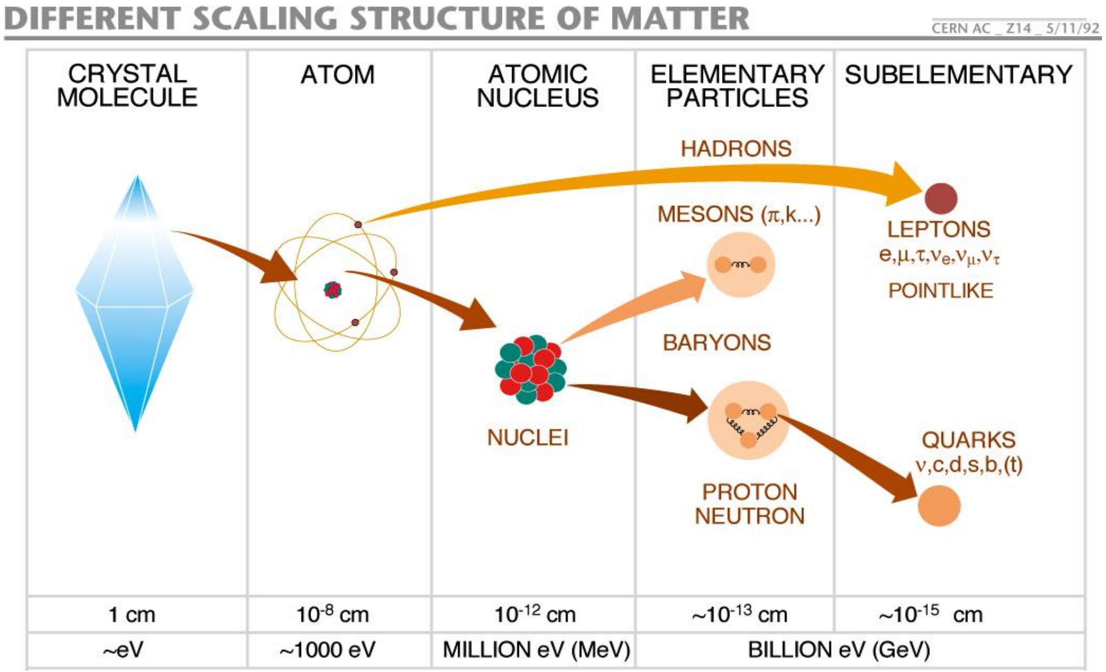
Some quick physics update

- nuclear physics, let's talk nucleus

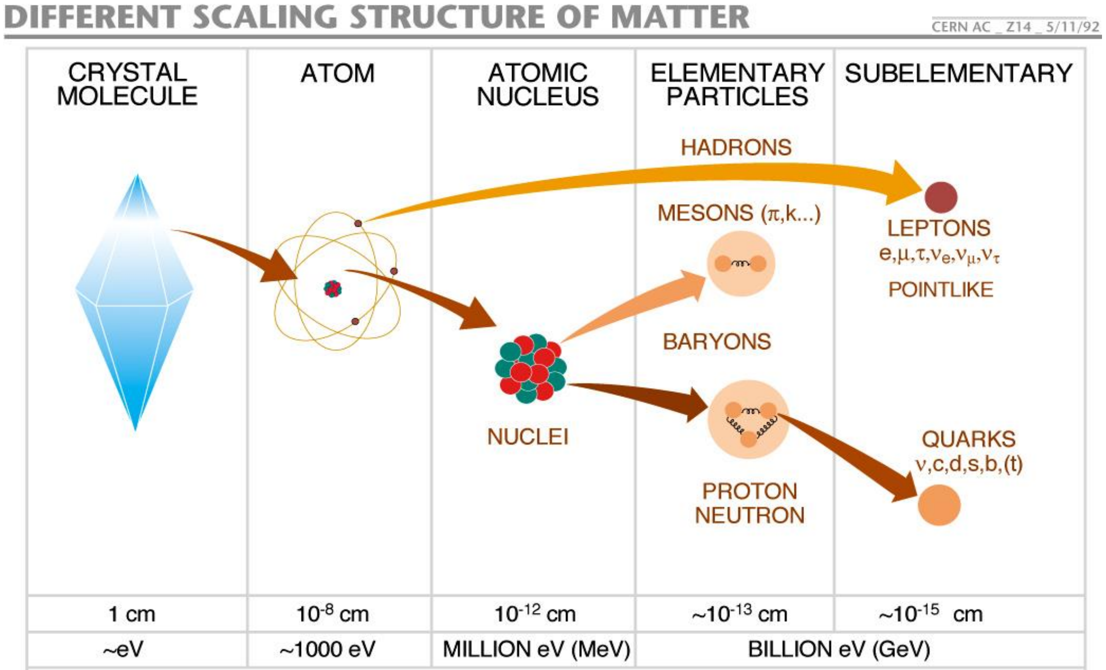


- nucleus: proton an neutrons
- ^{12}C or ^{14}C, element Z=6 , 6 protons, then 6 or 8 neutrons
- in nature usually comes with electrons (neutral charge)
- as many electrons as protons, but charge states $^{12}C^{2+}$
- nucleus are very small
  - ➔ quantum mechanics to describe them (energy quantified)

Nuclear physics, between atomic and hadronic physics



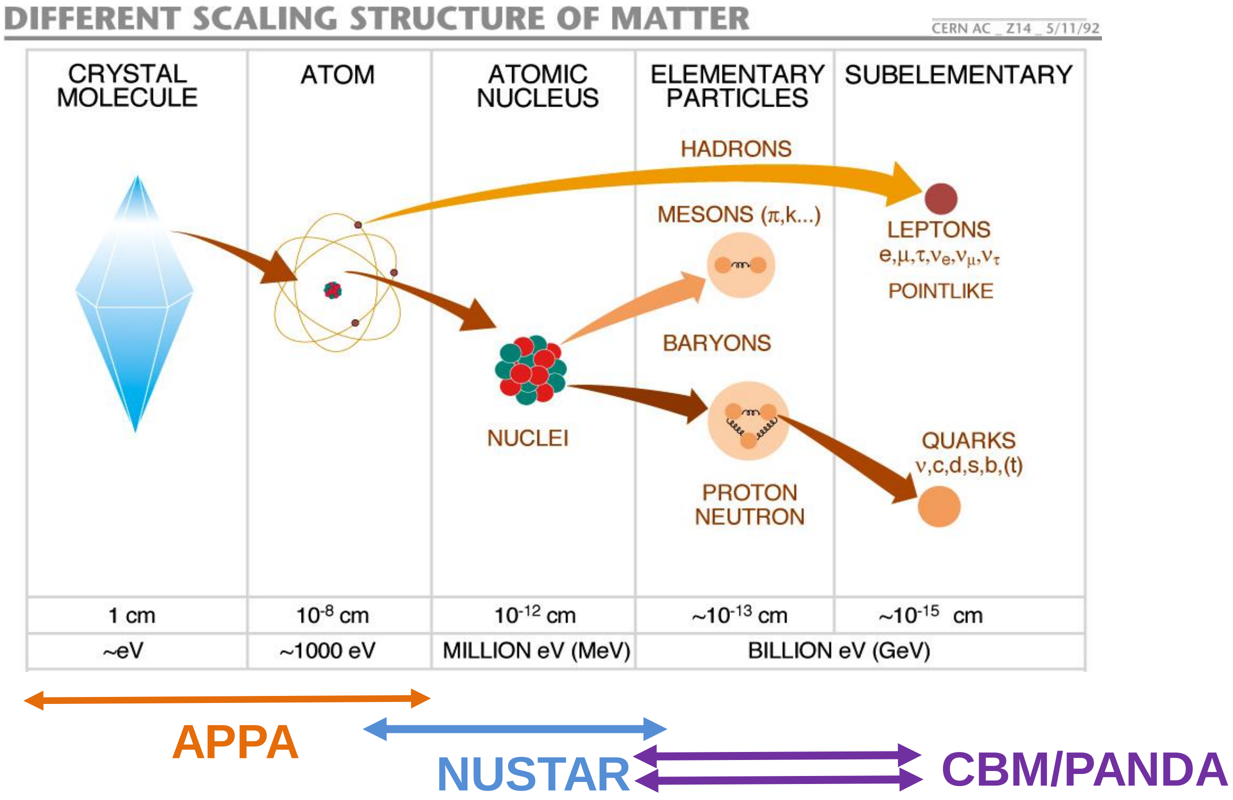
Nuclear physics, between atomic and hadronic physics



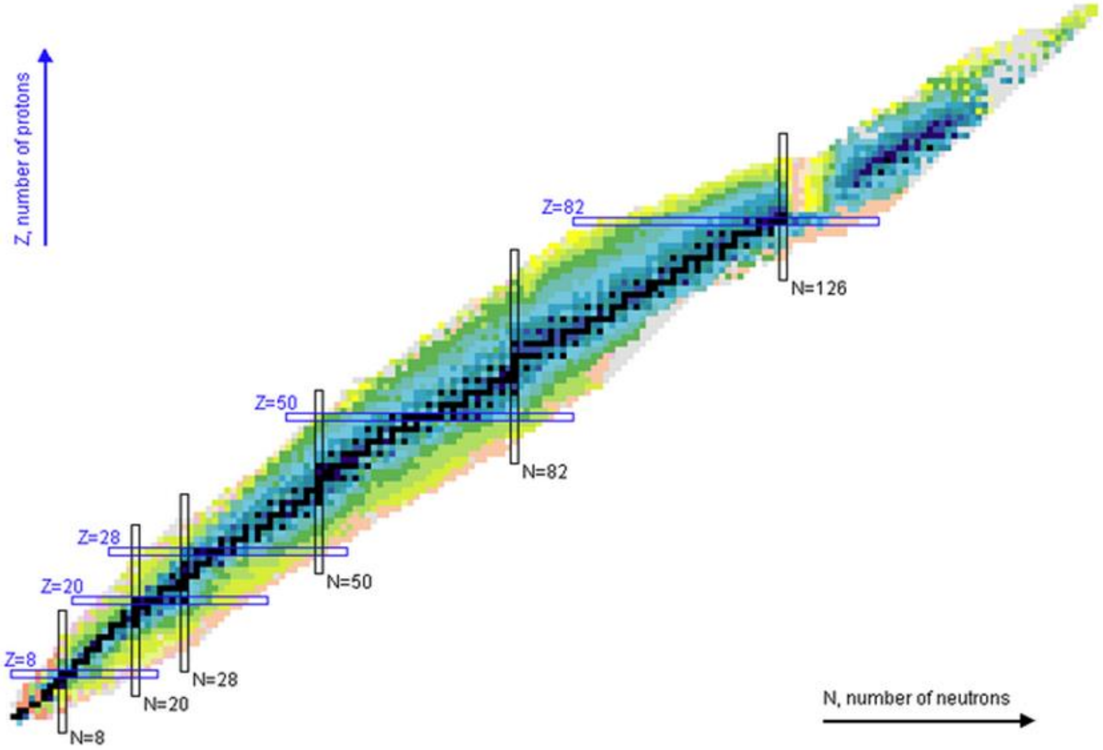
If the atom is Germany ➔ tables are the nuclei ➔ 99.9% of the mass is in the nuclei

Nuclear radius: 1.7 fm (H) to 11.7 fm (U) (1 fm = 1e-15 m)

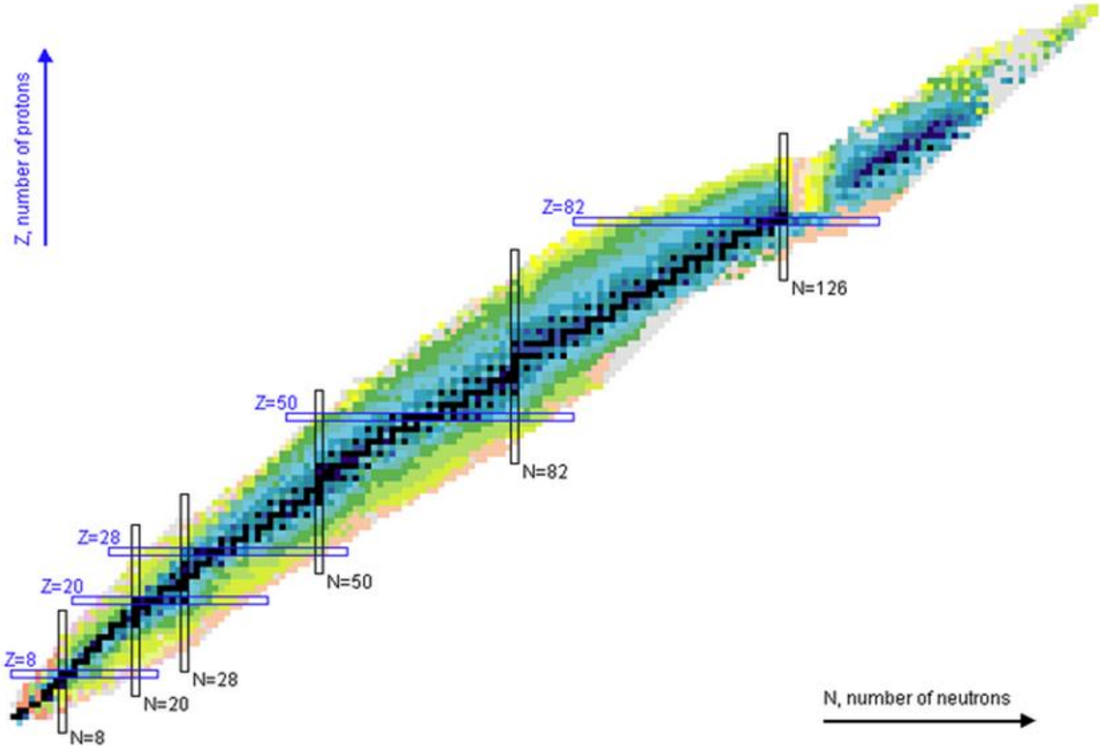
Physics at FAIR, universe in the lab

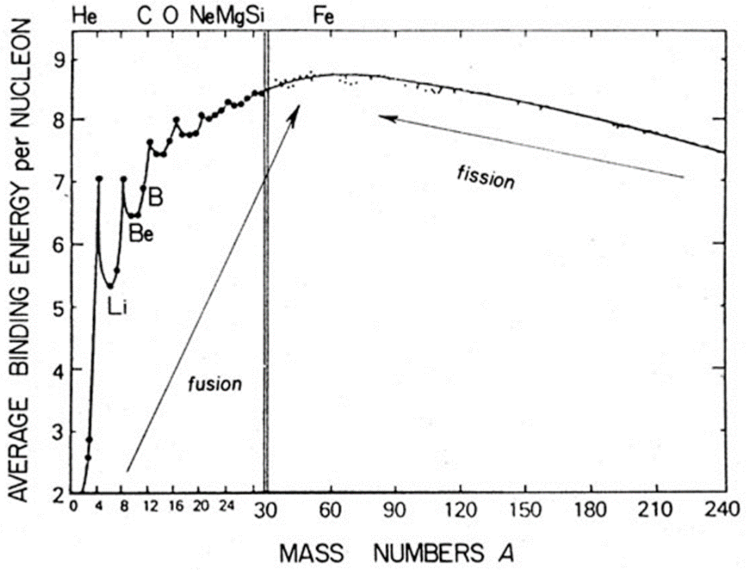


Nucleus existence



Nucleus existence



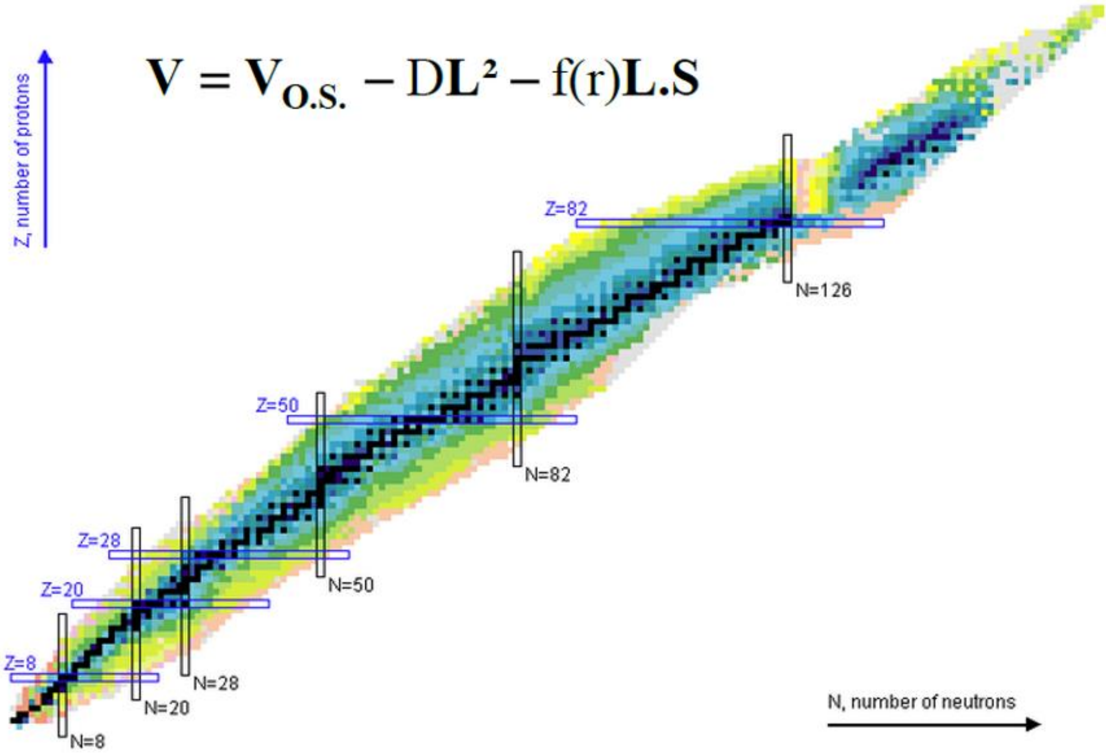


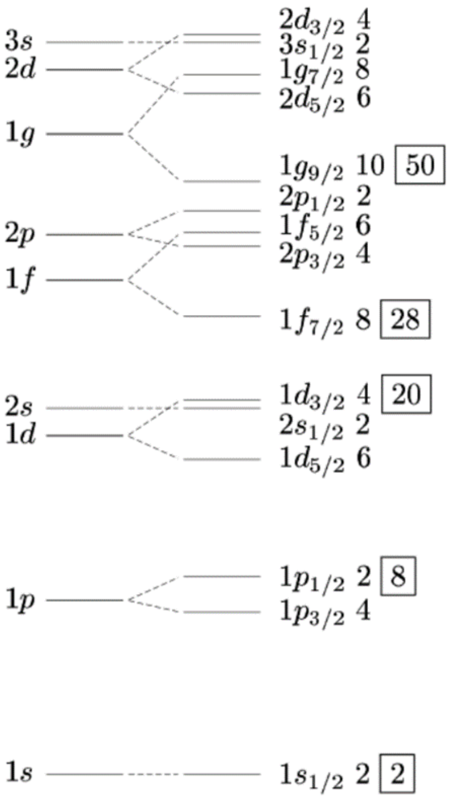
Binding energy, how stable

Second order correction on stability – shell model

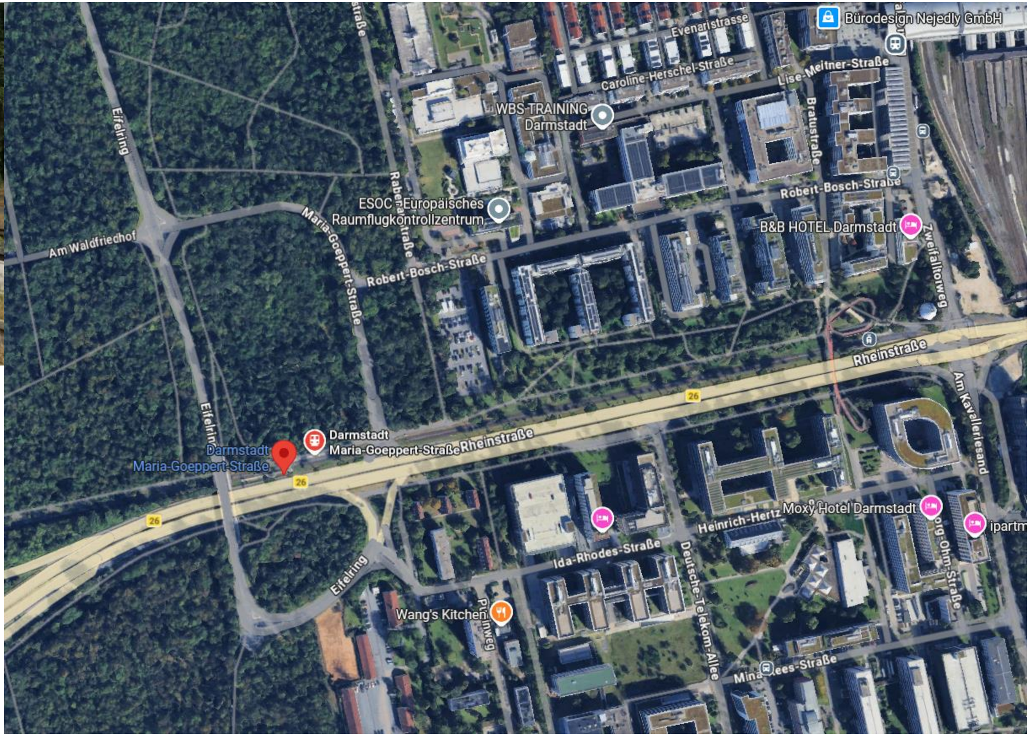
Shell model Maria Goepert-Mayer et al.

$$V = V_{O.S.} - DL^2 - f(r)L.S$$






Rheinstraße


Bürodesign Nejedly GmbH
Evenaristrasse
Caroline-Herschel-Straße
Lise-Meitner-Straße
WBS TRAINING Darmstadt
Eifelring
Bratustraße
Robert-Bosch-Straße
ESOC - Europäisches Raumflugkontrollzentrum
Maria-Goeppert-Straße
Am Waldfriedhof
B&B HOTEL Darmstadt
Zweifalltorweg
Rheinstraße
Am Kavalleriesand
Darmstadt Maria-Goeppert-Straße
Moxy Hotel Darmstadt
Heinrich-Hertz
Ida-Rhodes-Straße
Deutsche-Telekom-Allee
Wang's Kitchen
Mina-Rees-Straße
26

Radioactivity – decay properties

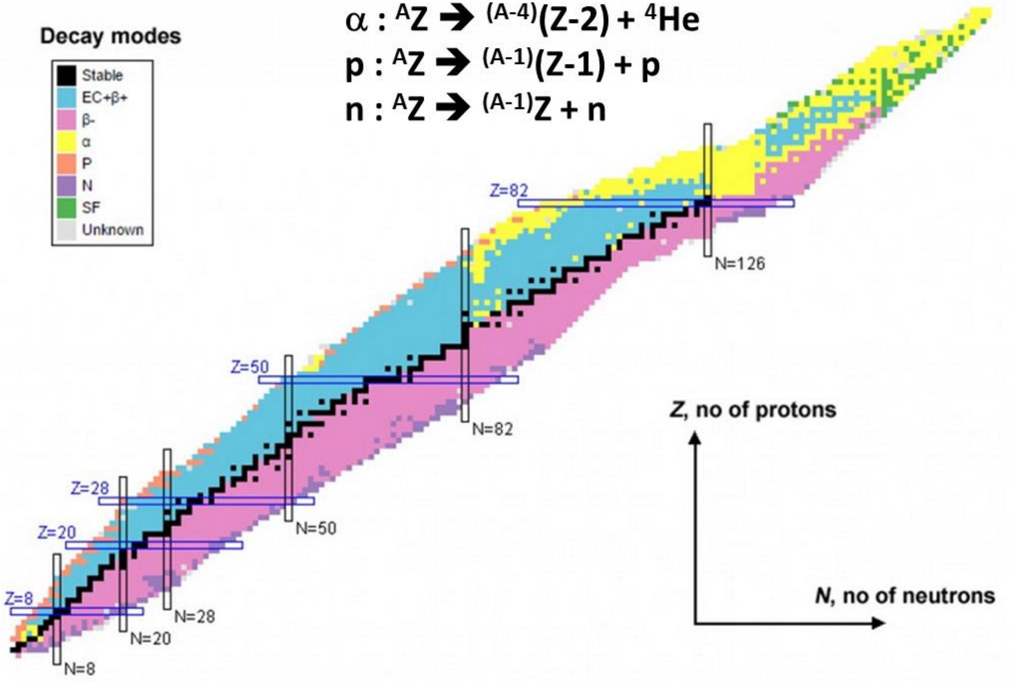
$\beta+: p \rightarrow n + e^{+} + \nu$

$\beta-: n \rightarrow p + e^{-} + \nu$

$\alpha : {}^{A}Z \rightarrow {}^{(A-4)}(Z-2) + {}^{4}He$

$p : {}^{A}Z \rightarrow {}^{(A-1)}(Z-1) + p$

$n : {}^{A}Z \rightarrow {}^{(A-1)}Z + n$



The table of nuclides (also known as a Segre chart). The key shows the atomic decay modes. The most important are stable atoms (black), alpha decay (yellow), beta minus decay (pink) and electron capture or beta plus decay (blue).

Radioactivity – decay properties

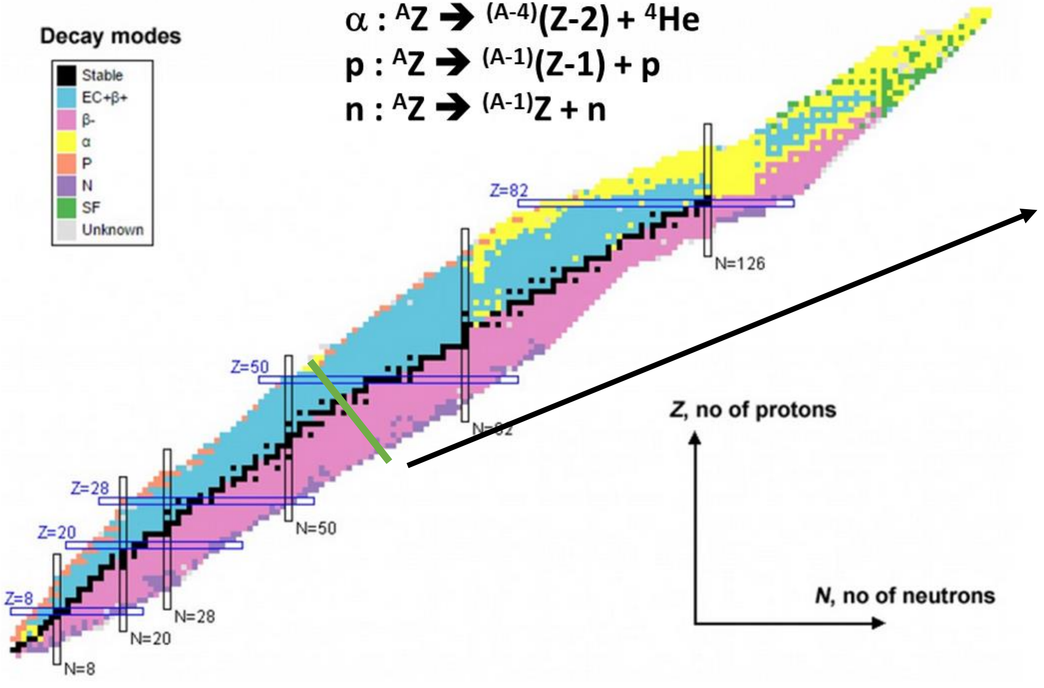
$\beta+: p \rightarrow n + e^+ + \nu$

$\beta-: n \rightarrow p + e^- + \nu$

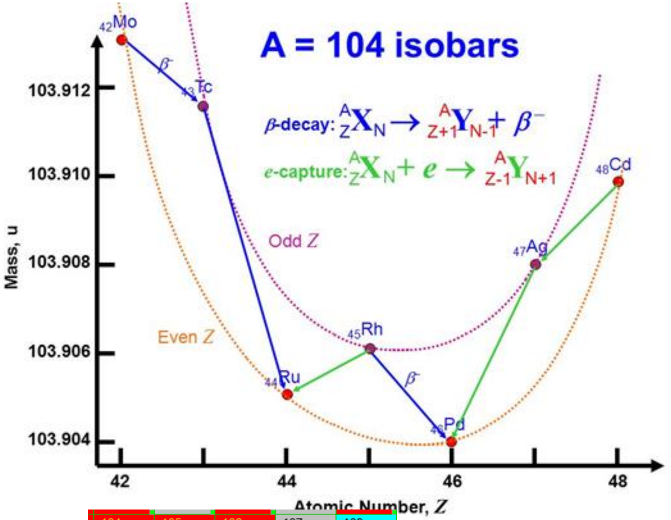
$\alpha: {}^{A}Z \rightarrow {}^{(A-4)}(Z-2) + {}^{4}He$

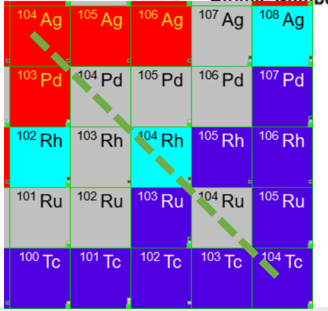
$p: {}^{A}Z \rightarrow {}^{(A-1)}(Z-1) + p$

$n: {}^{A}Z \rightarrow {}^{(A-1)}Z + n$



The table of nuclides (also known as a Segre chart). The key shows the atomic decay modes. The most important are stable atoms (black), alpha decay (yellow), beta minus decay (pink) and electron capture or beta plus decay (blue).

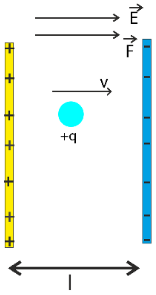




Maybe I want to do more : accelerate

Particle in electric field

F = q . **E**



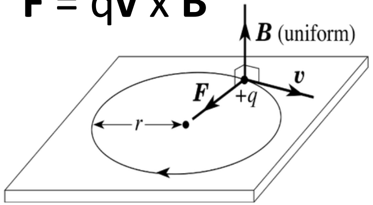
1 electron accelerate 1 V

➔ 1 eV of kinetic energy

➔ use to accelerate (or deflect)

Particle in magnetic field

F = q**v** x **B**



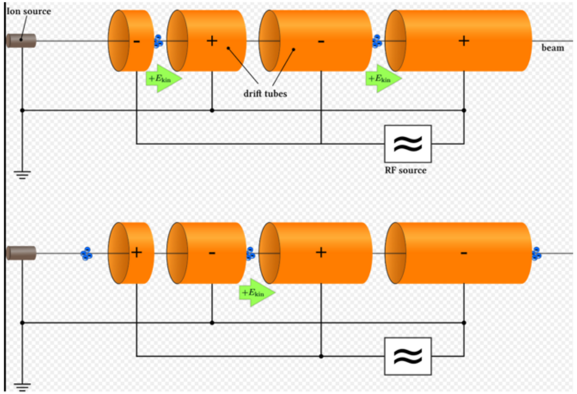
Bρ = v. m/q (Brho)

➔ **Bρ α (A/Q).βγ**

Accelerator – quick comment

Particle in accelerator: 1 eV ➔ energy for 1 electron for 1 V difference potential

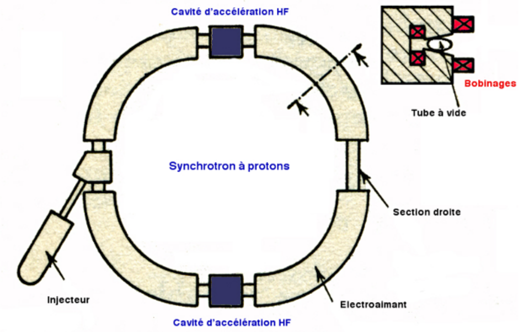
At GSI today: 2 main accelerator:
UNILAC (from 70s):



UNILAC: up to 15 MeV

Important U: all elements from H to U
➔ strength of GSI from 70s to 90s

SIS18, synchrotron: (Br up to 18 Tm)



Many revolutions: lots of acceleration

SIS18
➔~1 GeV (1000 MeV, 1e6 keV, 1e9 eV)

➔ need injector (stability of magnet at low current)

Some comments

Unilac: ~10 to 15 MeV.A ➔ 15% of the speed of light (limit of relativity)

SIS18: 1 GeV ➔ 88% of the speed of light ➔ need relativity for the equations of motion
300 MeV.A (LEB energy) ➔ 65% of the speed of light

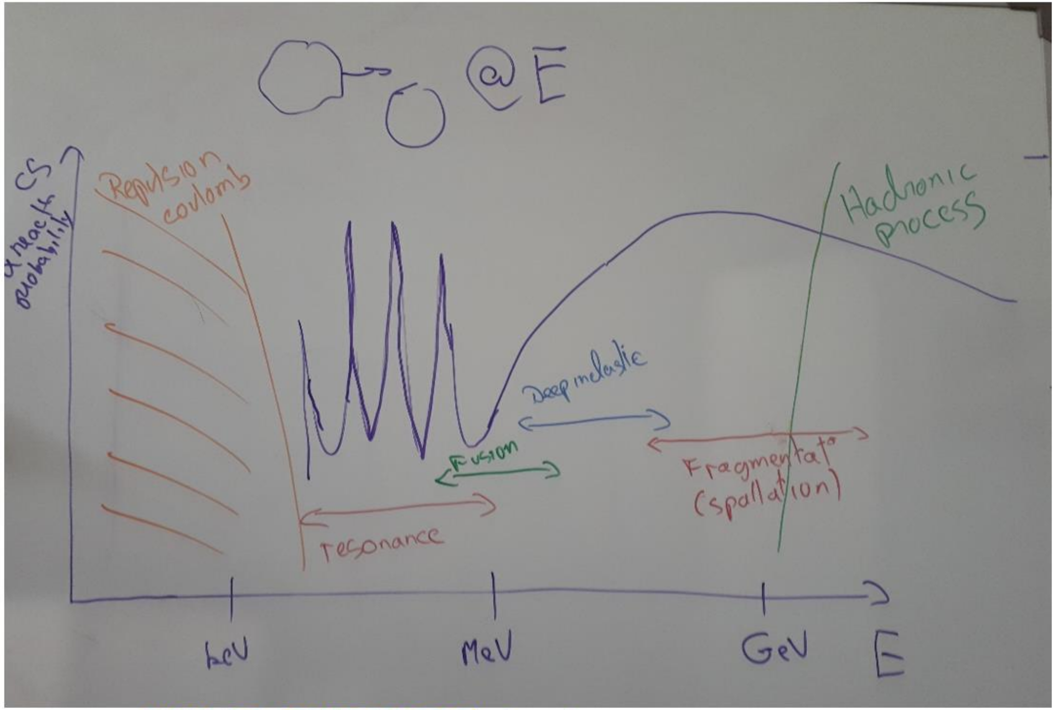
SIS100: 30 GeV protons ➔ 99,93% of speed of light

Note: signal speed in cable 66% speed of light (standard) to 87% (high quality)
speed of photons in a plastic or optical fiber 66-68% speed of light

➔ **this means the particle travel as fast as the signals they generate**

Speed of light 30 cm/ns ➔means synchronization of device in the ns or sub ns range

Nuclear reactions:



UNILAC (SHIP, TASCA) ⟷

⟷ SIS (SFRS/FRS/R3B/HISPEC)

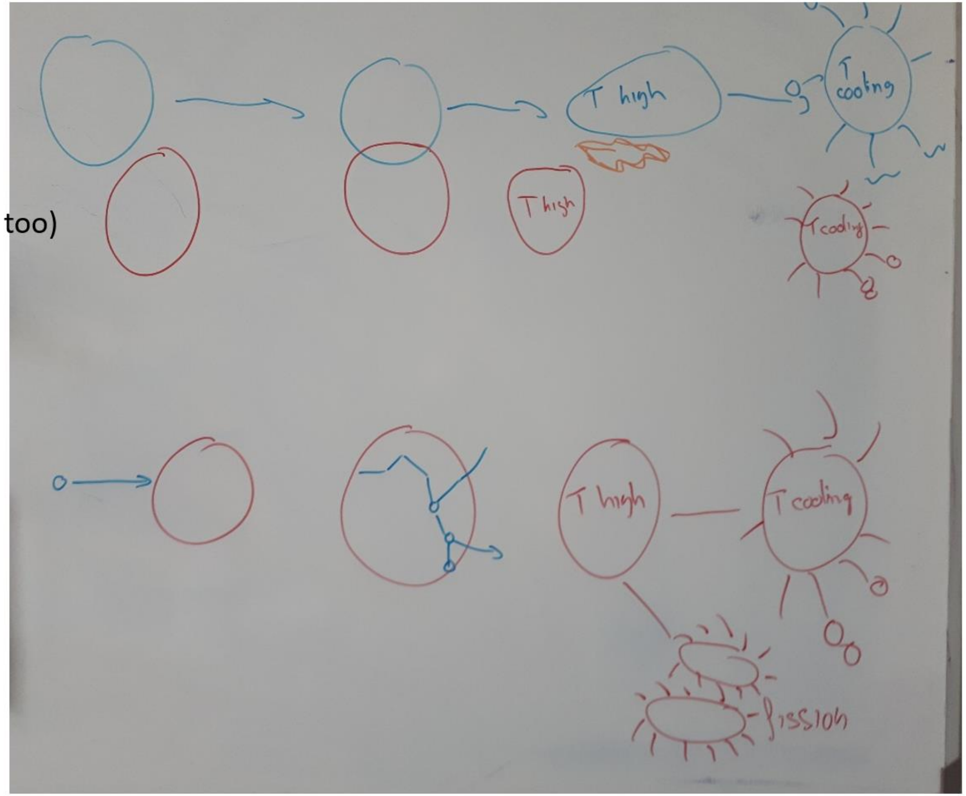
⟷ slowing down after FRS (gas cell)

Nuclear reactions high energy:

Abraison
ablaison

(can be with fission too)

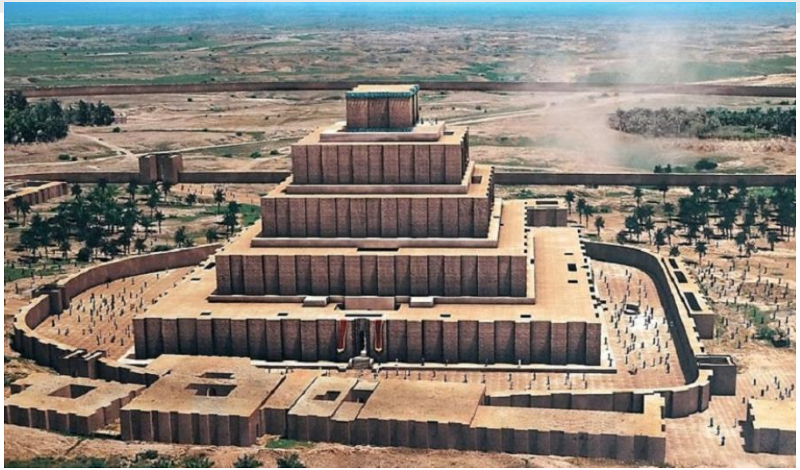
Spallation



Layout

- Some physics introductions
  - nucleus
  - nuclear physics
  - decay – natural process
  - acceleration
  - reactions – “artificial” process
- **Why study nuclear physics**
  - **cosmogenesis**
  - **LCDM model**
  - **neutrons and nuclei**
  - **r and s process path**
  - **where to look**
- Super-FRS
  - objective
  - separation
  - degraders
  - identification
  - some interesting bits
  - how compare to the rest
- Selection of planned experiment
  - NUSTAR
  - DESPEC
  - HISPEC
  - Super-FRS EC
  - R3B

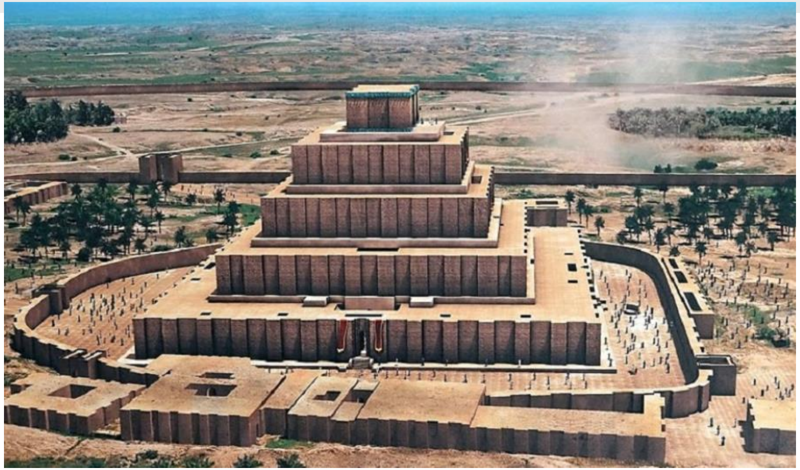
Build for their cosmology



Cosmology: explain how we came to be (not why)

All this looking at the stars (Babylonians had astronomical observations embedded in their “divine cosmology”)

Build for their cosmology

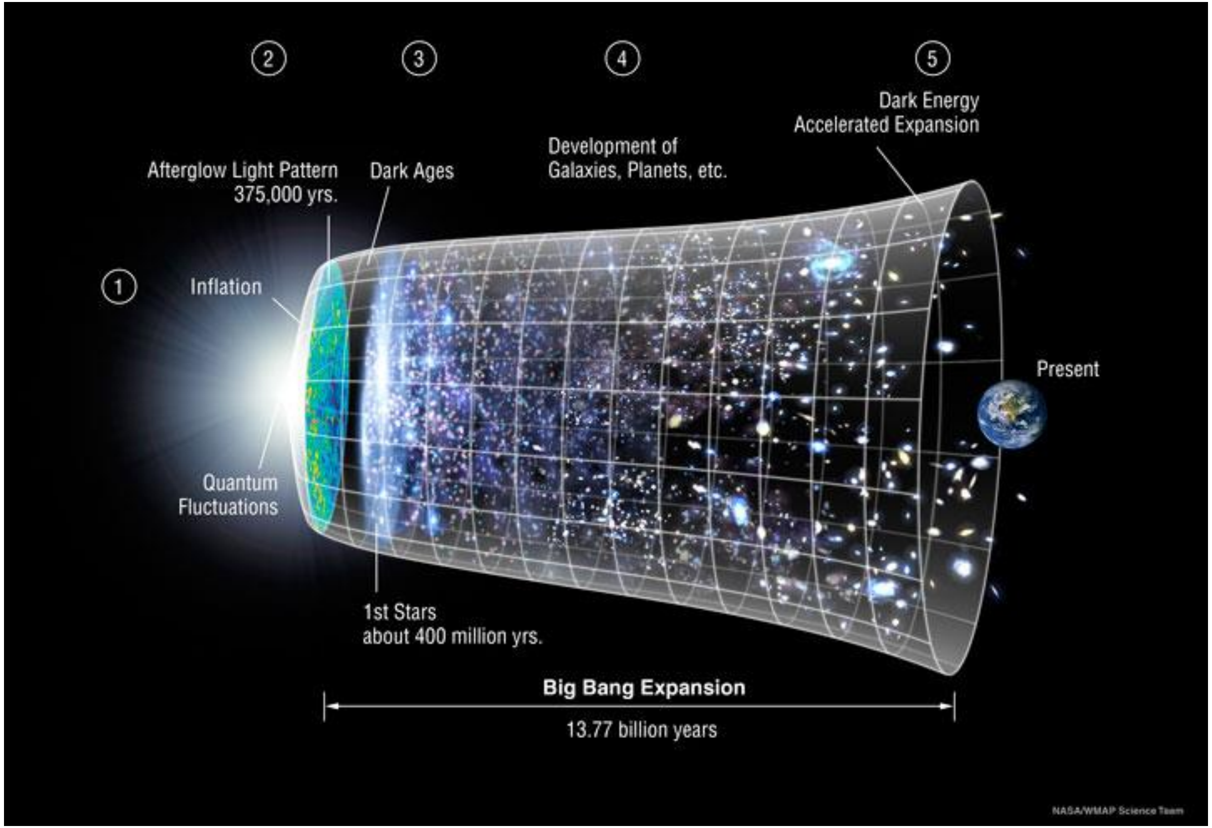


Cosmology: explain how we came to be (not why)

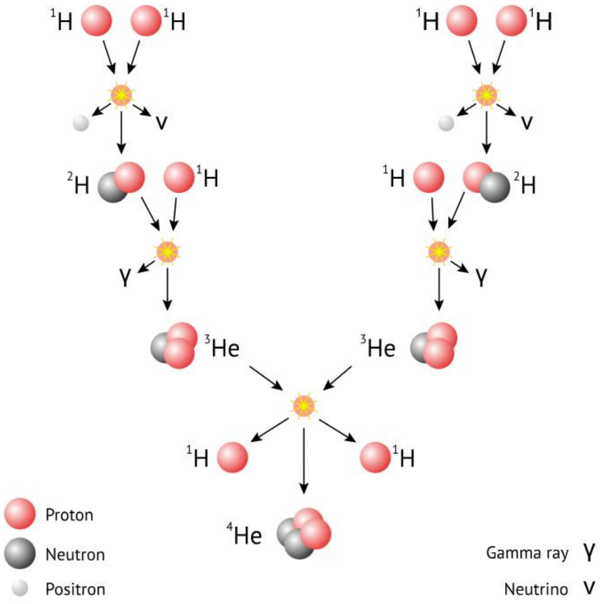
All this looking at the stars (Babylonians had astronomical observations embedded in their “divine cosmology”)
➔ since we improve our observation/measurement of the cosmos

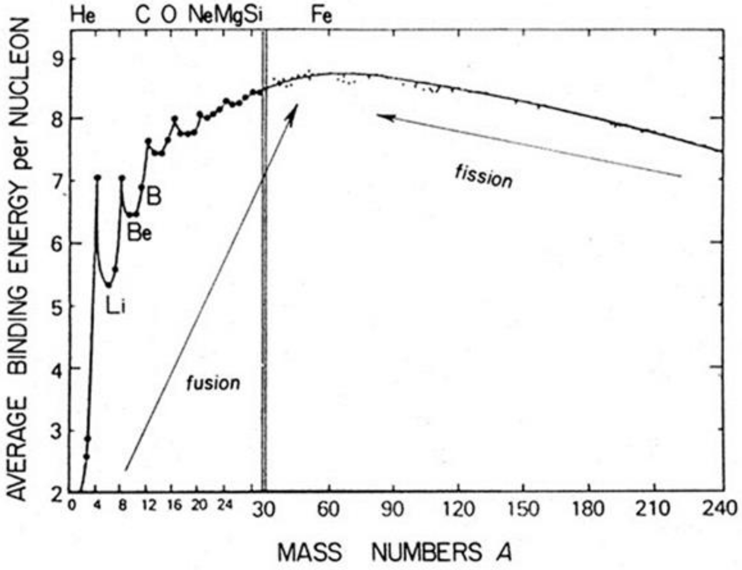
ΛCDM model – CDM for Cold Dark Matter

- Big bang
- Cool down
- Hadrons
- Gas
- Stars
- More stars
- Us



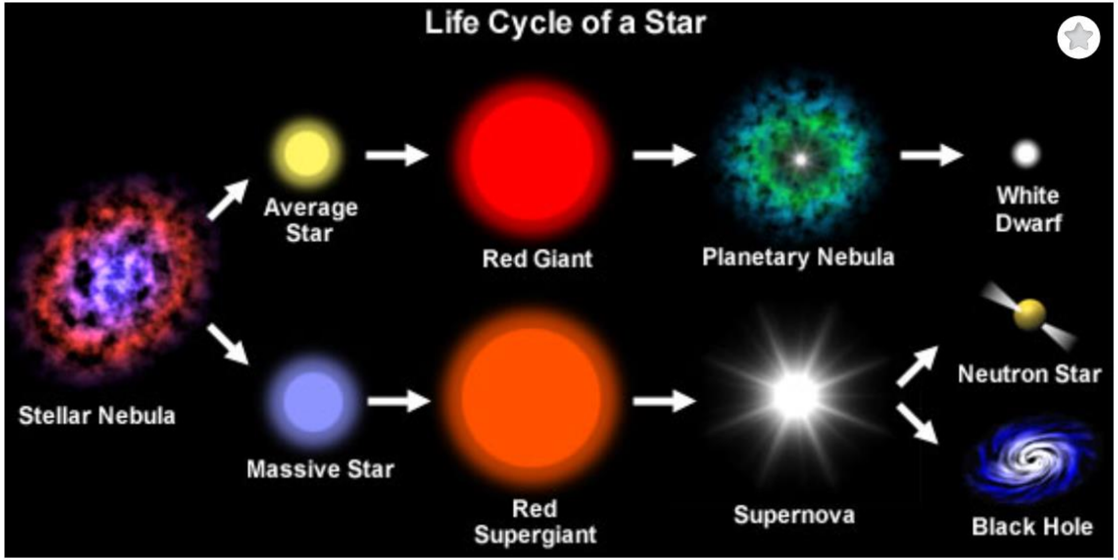
Gas + gravity : density to start fusion





Fe generation

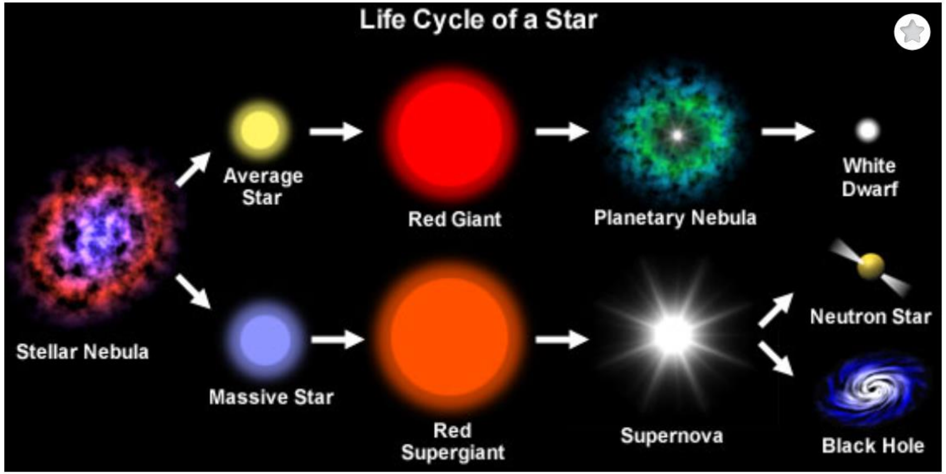
- Now no more things to burn



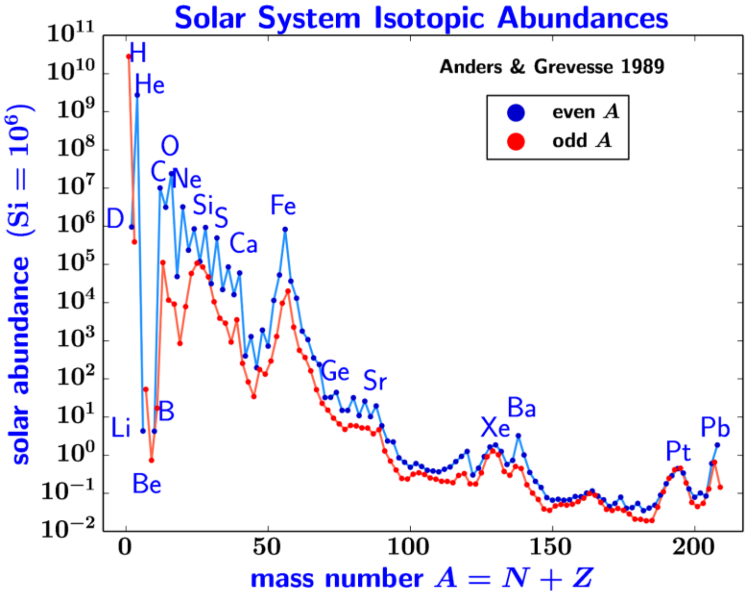
https://www.kiwico.com/

- if massive enough ➔ send Fe in the interstellar medium

Star - fusion



we burn up to Iron…

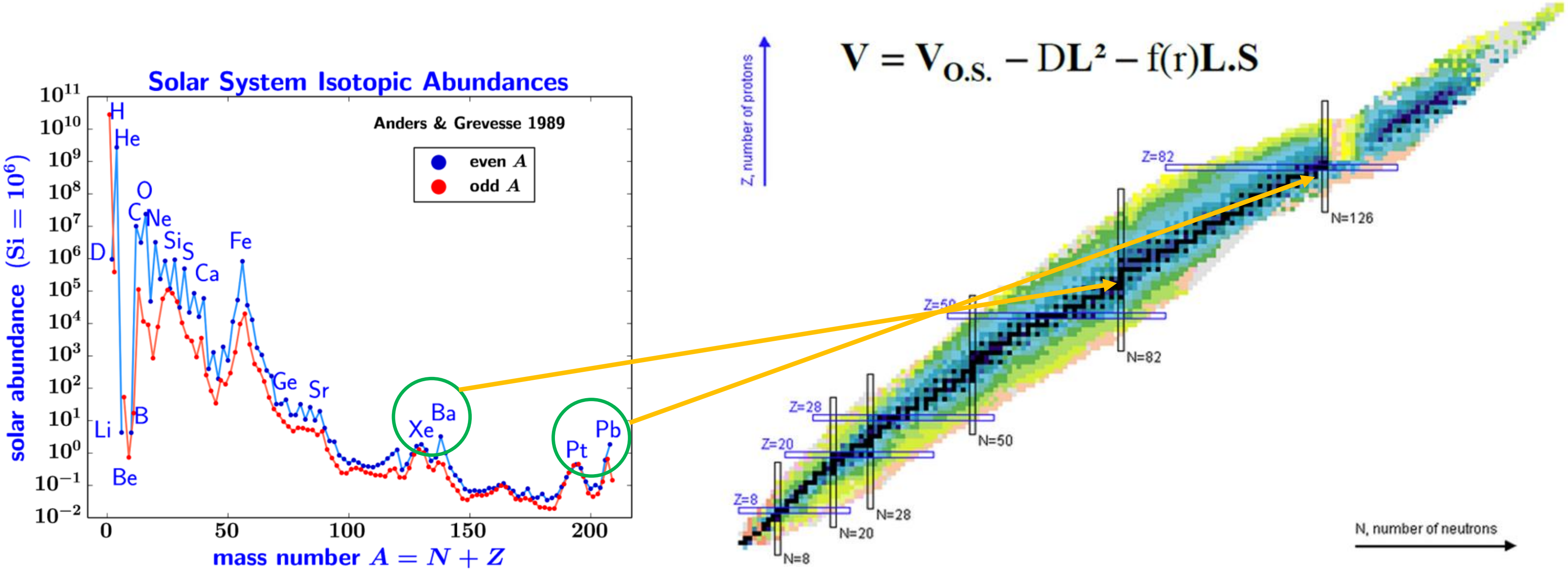


https://publish.illinois.edu/bdfields/files/2019/01/SolarIsoAbsOddEven.png

Seem to be linked to shell model

Shell model Maria Goepert-Mayer et al.

$$V = V_{O.S.} - DL^2 - f(r)L.S$$

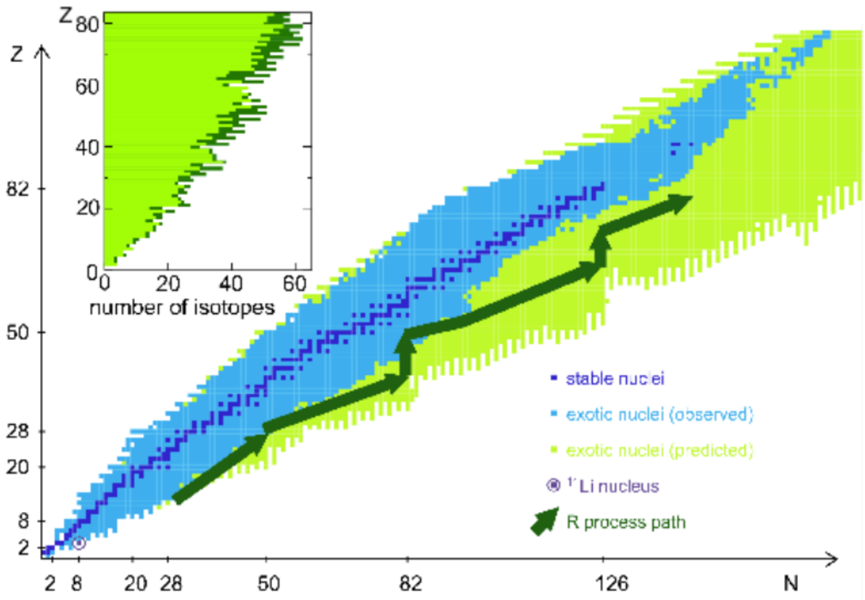


R – process path

In second generation starts, when explosive events, high neutron flux

➔ creation of heavy elements

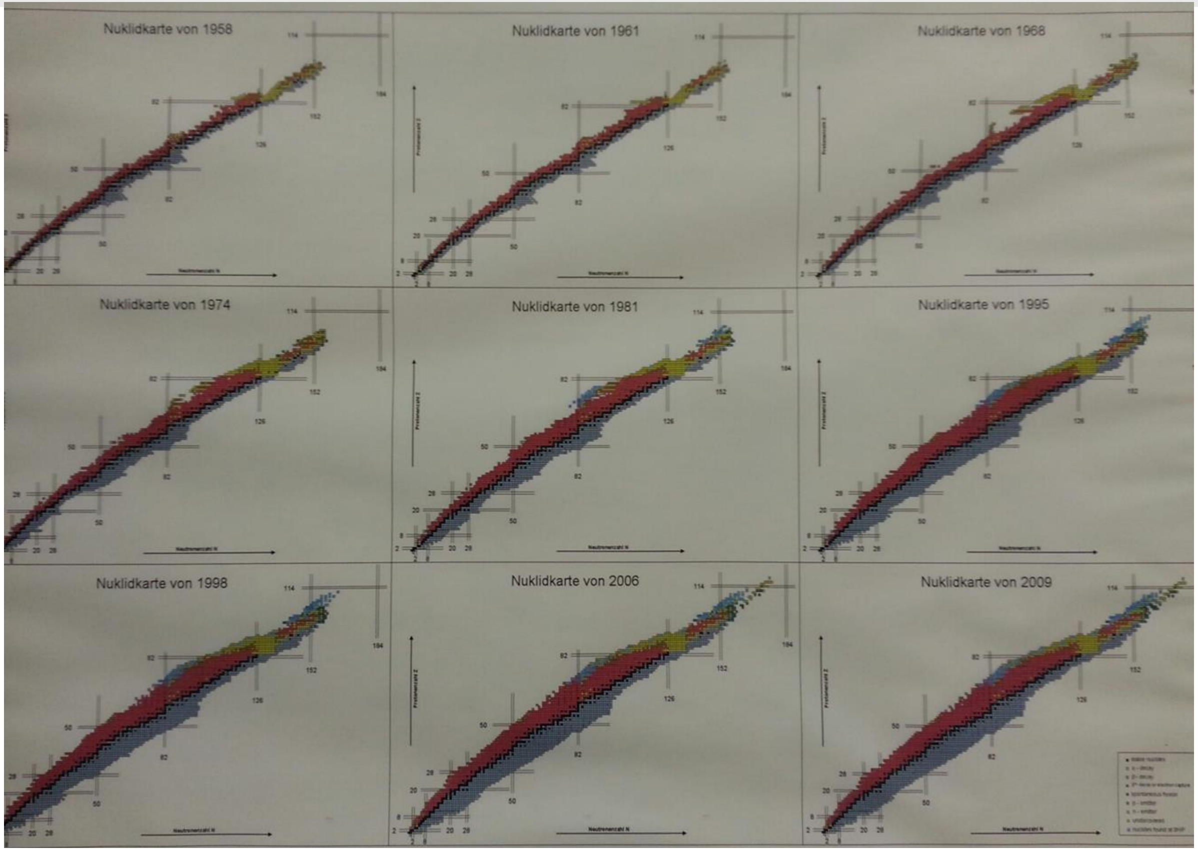
Evolution of shell structure in exotic nuclei - Otsuka, Takaharu *et al.* Rev.Mod.Phys. 92 (2020) no.1, 015002 arXiv:1805.06501 [nucl-th]

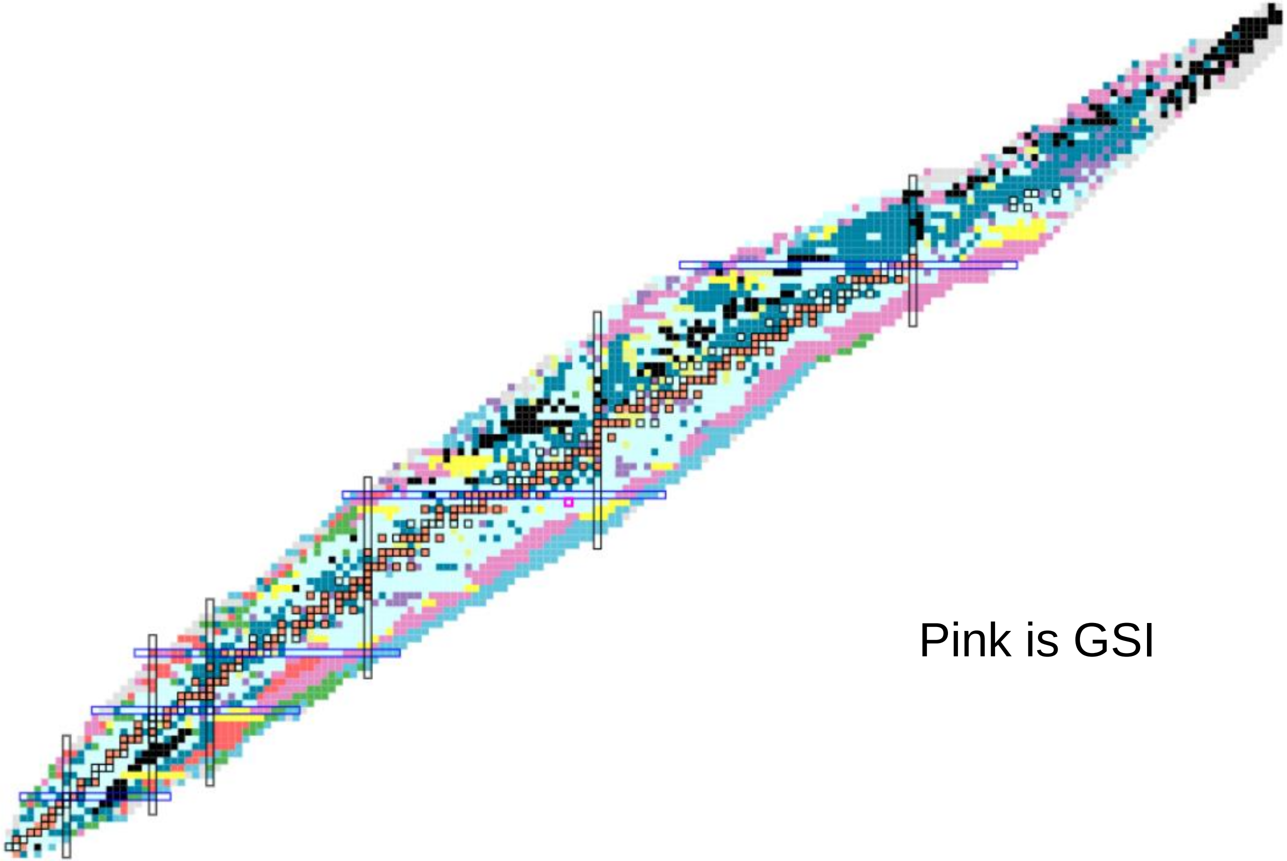


The nuclear chart as a function of ne
number, N and Z. Each nucleus is
specified by Z and N. Blue squares
Exotic nuclei experimentally observe
are shown by light-brown squares, w
squares denote those predicted by a
\cite{koura2005}. The ^{11}Li nucleus is
A possible path of the r process is i
by the green arrows. Inset: Number
exotic nuclei as a function of Z base
\cite{koura2005}. The light and dark
with two-neutron separation energy
respectively. Adapted from
\citet{otsuka_nobel,otsuka_nuppec}

Paths: competition between neutron capture and beta decay, needs mass and lifetimes

Nucleus production since the 50s





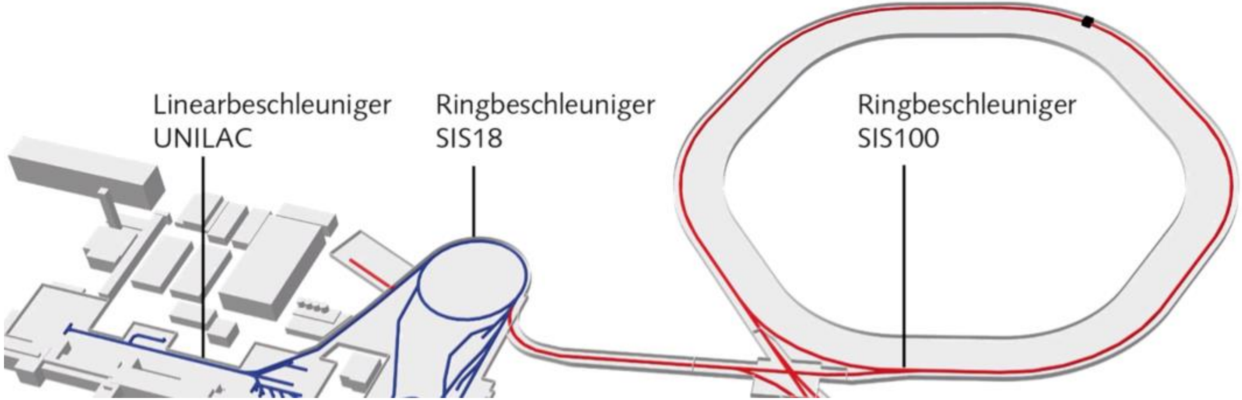
Pink is GSI

Layout

- Some physics introductions
  - nucleus
  - nuclear physics
  - decay – natural process
  - acceleration
  - reactions – “artificial” process
- Why study nuclear physics
  - cosmogenesis
  - LCDM model
  - neutrons and nuclei
  - r and s process path
  - where to look
- **Super-FRS**
  - **objective**
  - **separation**
  - **degraders**
  - **identification**
  - **some interesting bits**
  - **how compare to the rest**
- Selection of planned experiment
  - NUSTAR
  - DESPEC
  - HISPEC
  - Super-FRS EC
  - R3B

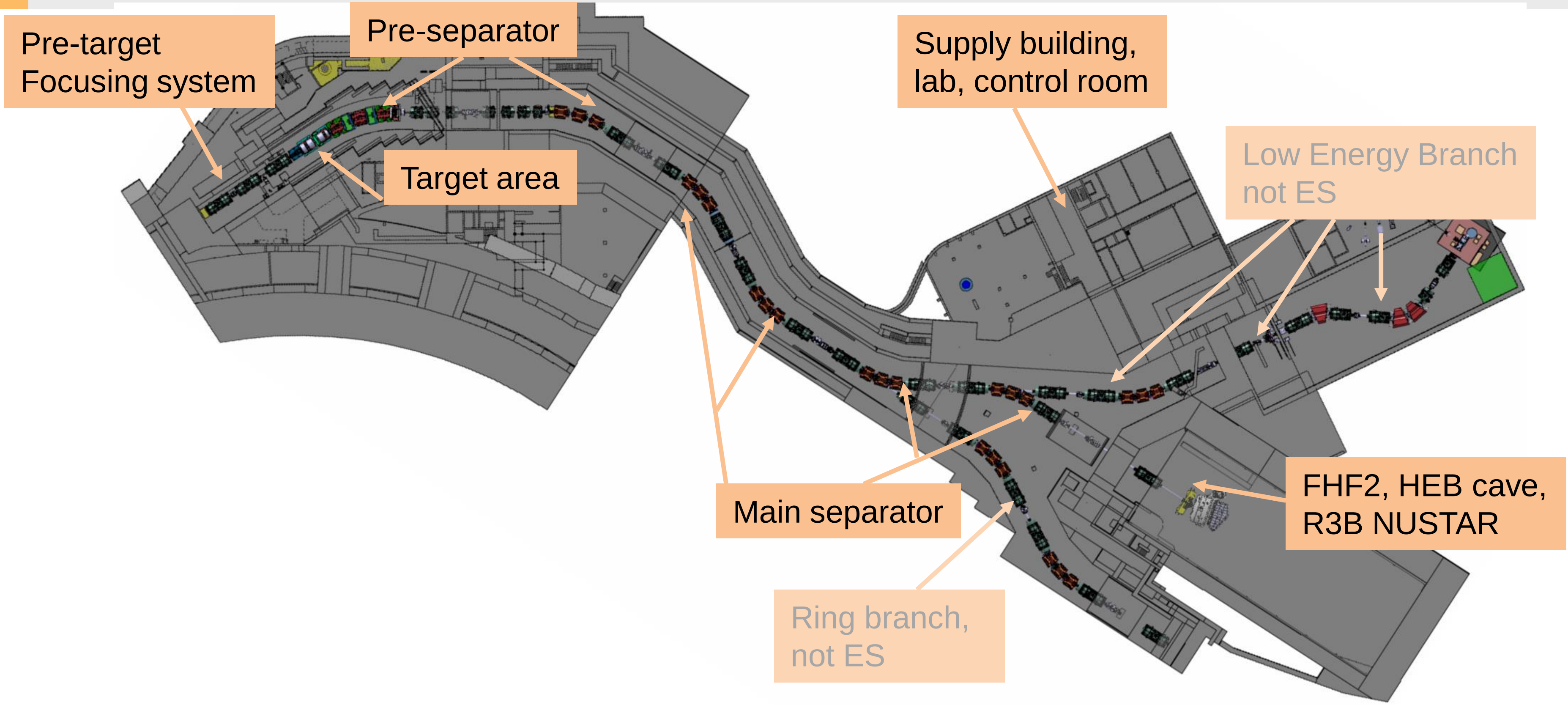
Why the Super-FRS

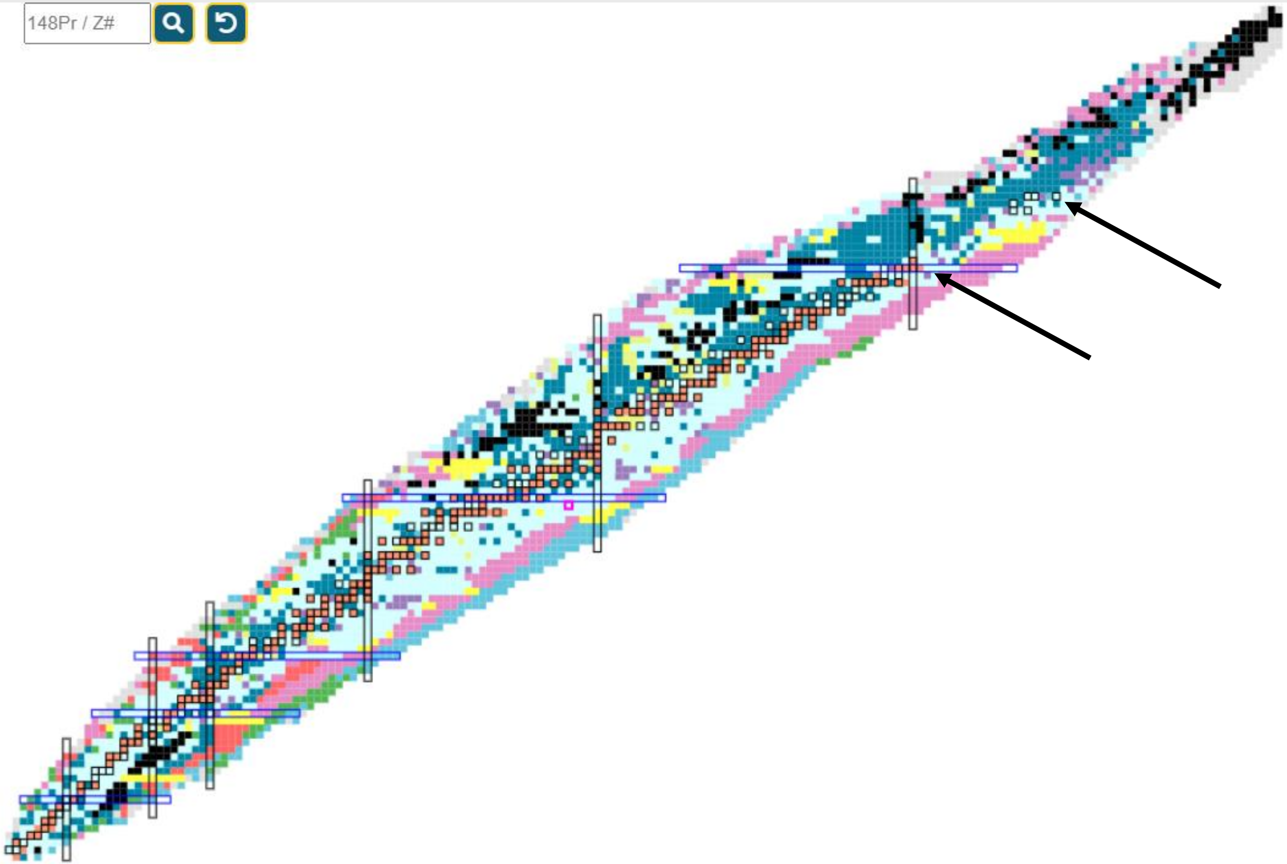
- Use of UNILAC (…) GSI can accelerate everything from H to U
- SIS18 ➔ allows high intensities, 1 GeV.U
- SIS100 ➔ allows either higher energies or higher intensities



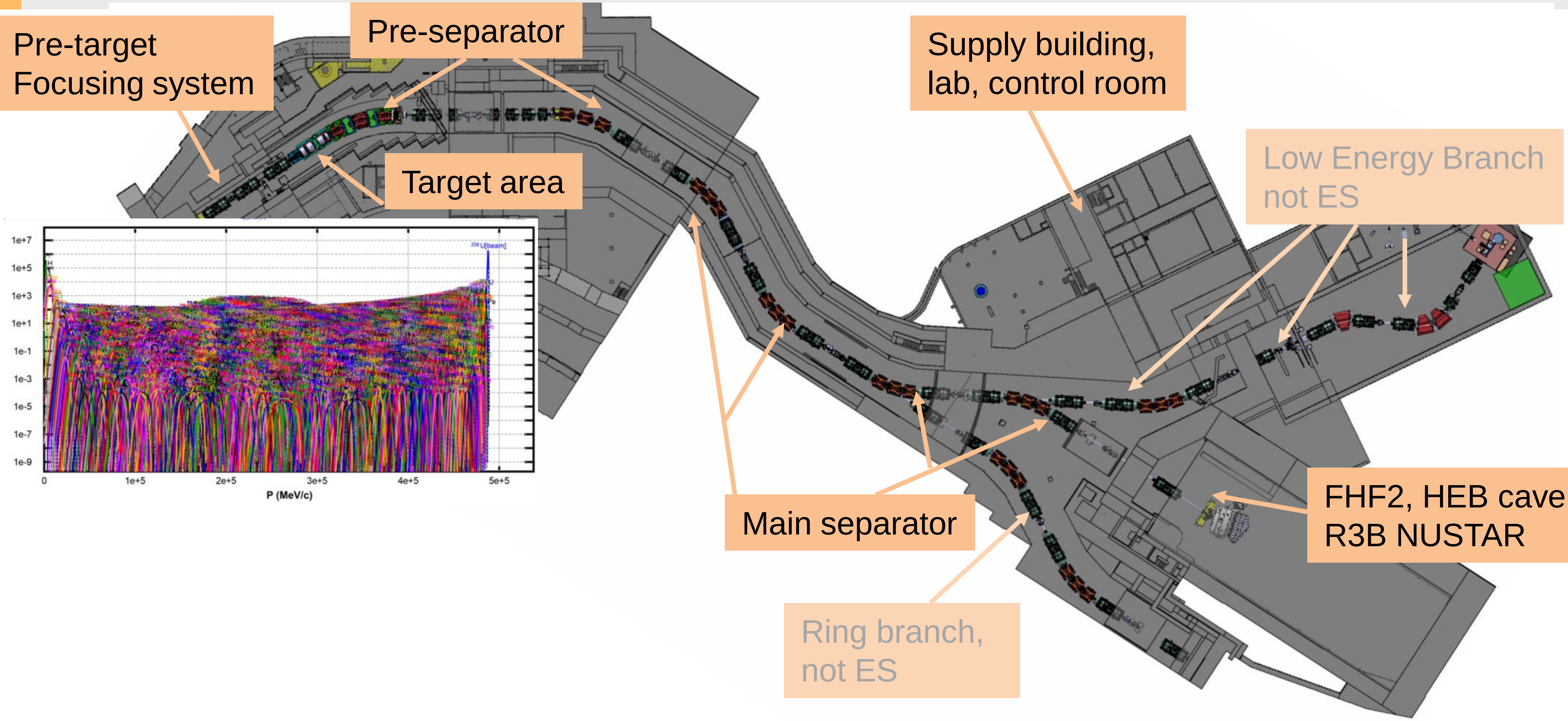
- $^{238}U^{73+}$ 18 Tm ➔1 GeV.U, 100 Tm ➔ 8.3 GeV.U, 2e10 p.p.spill in ring
- $^{238}U^{28+}$ 18 Tm ➔ 195 MeV.U, 100 Tm ➔ 2.7 GeV.U 2e11 p.p.spill in SIS18

Super-FRS – ^{238}U to ^{212}Pb (^{238}U+^{12}C ➔ ^{212}Pb @ 1.5 GeV.U)

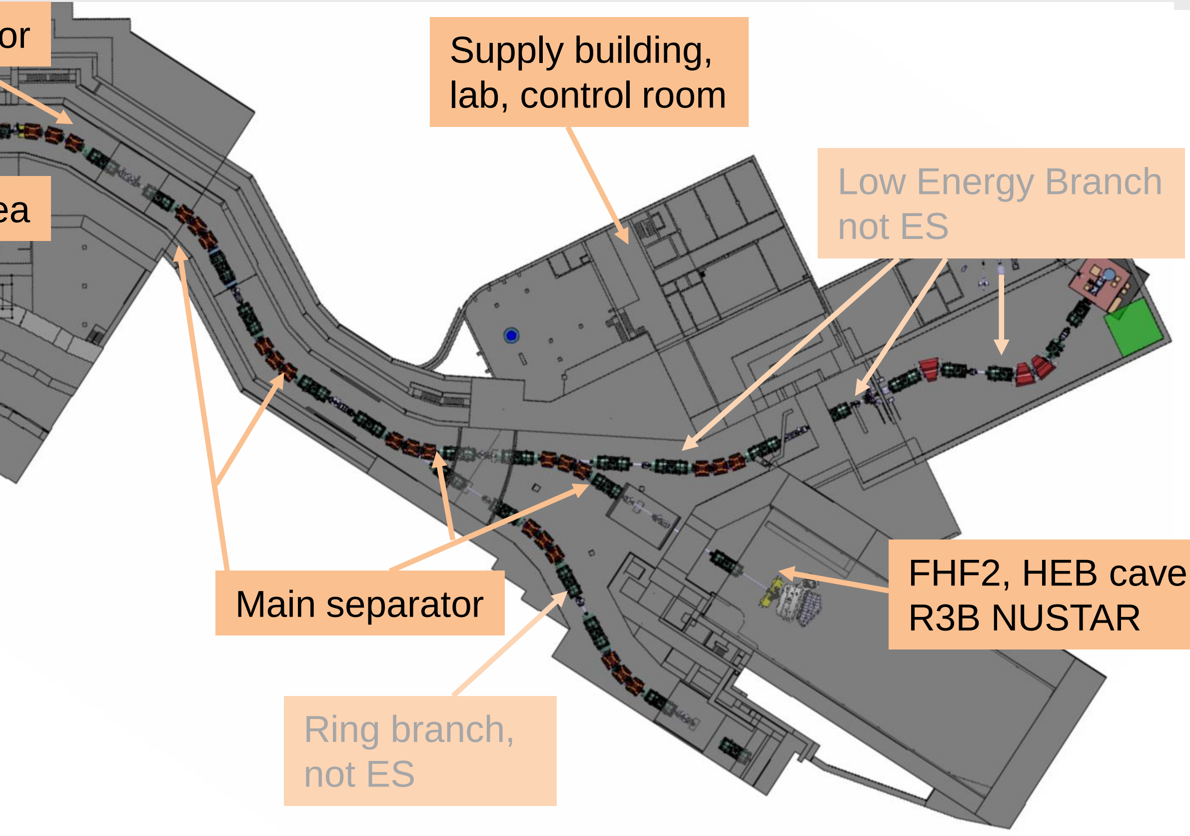


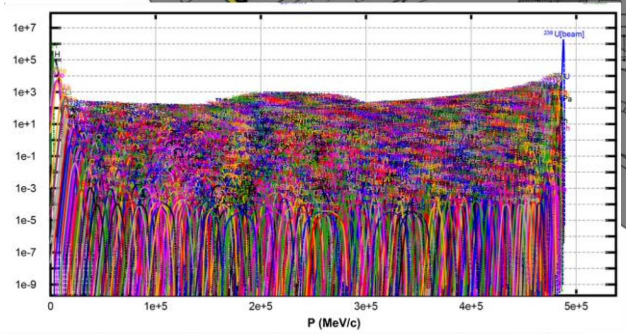

148Pr / Z#

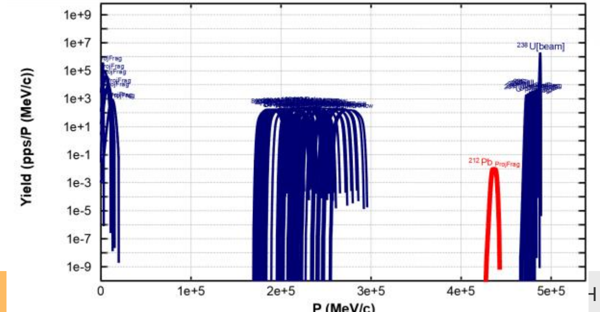
Super-FRS – general overview, changing ^{238}U to ^{212}Pb



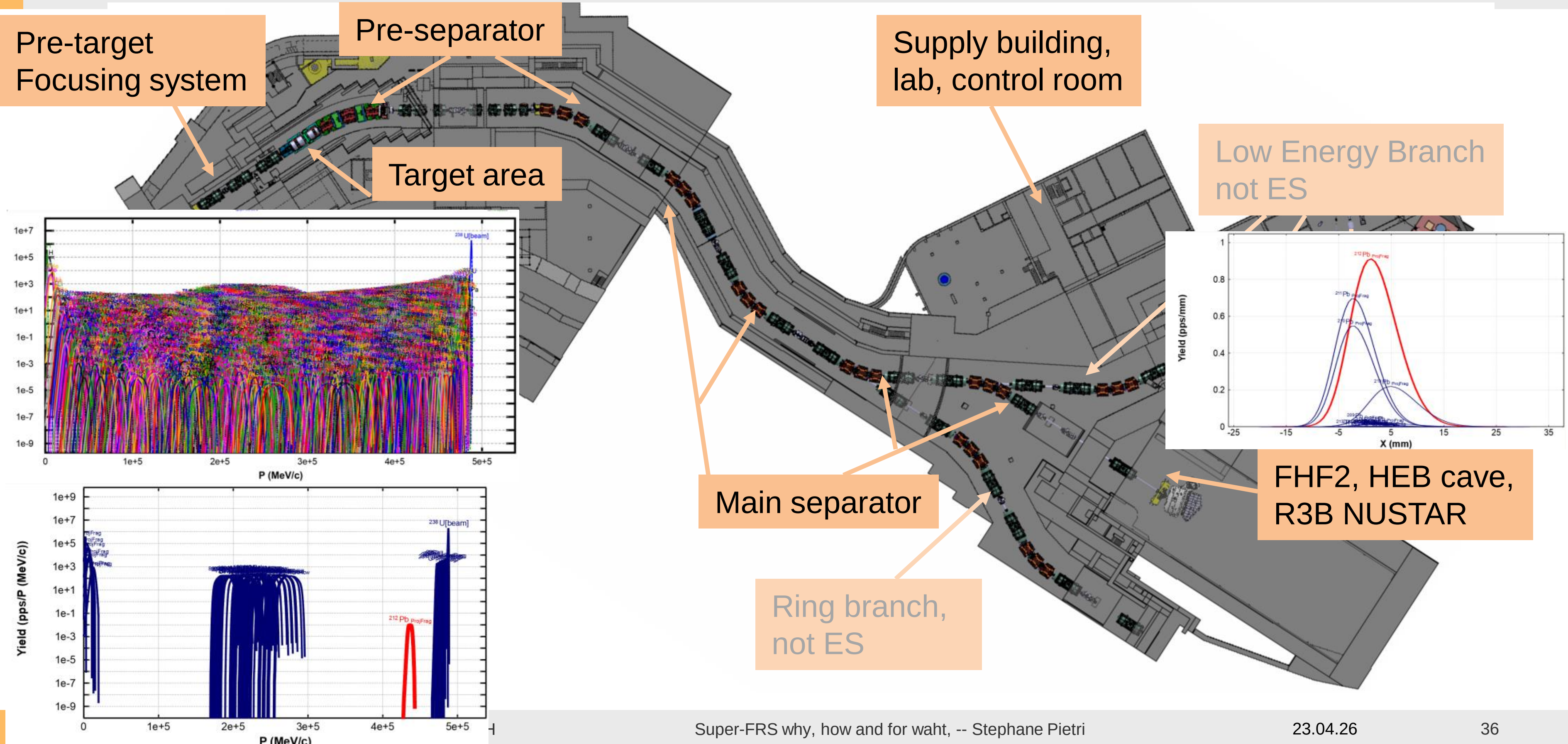
Super-FRS – general overview, changing ^{238}U to ^{212}Pb





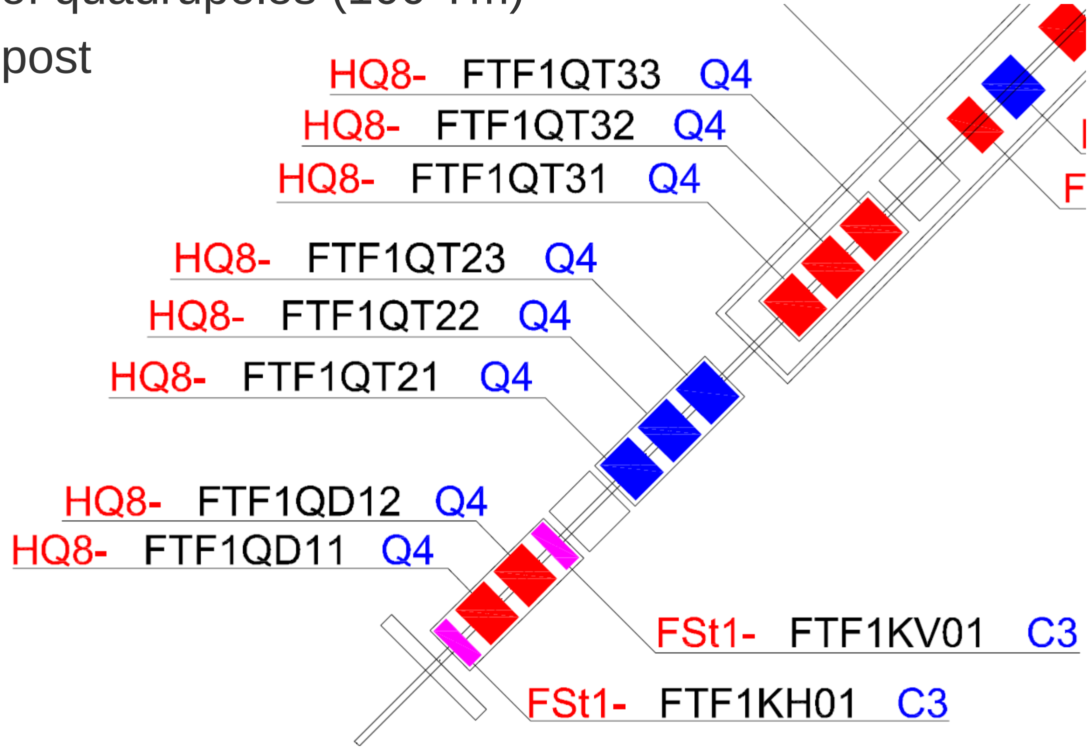


Super-FRS – general overview, changing ^{238}U to ^{212}Pb



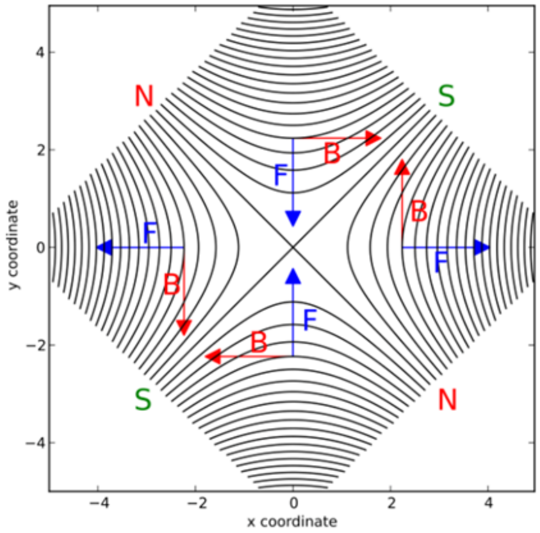
Beam come from SIS18/100 throught HEBT

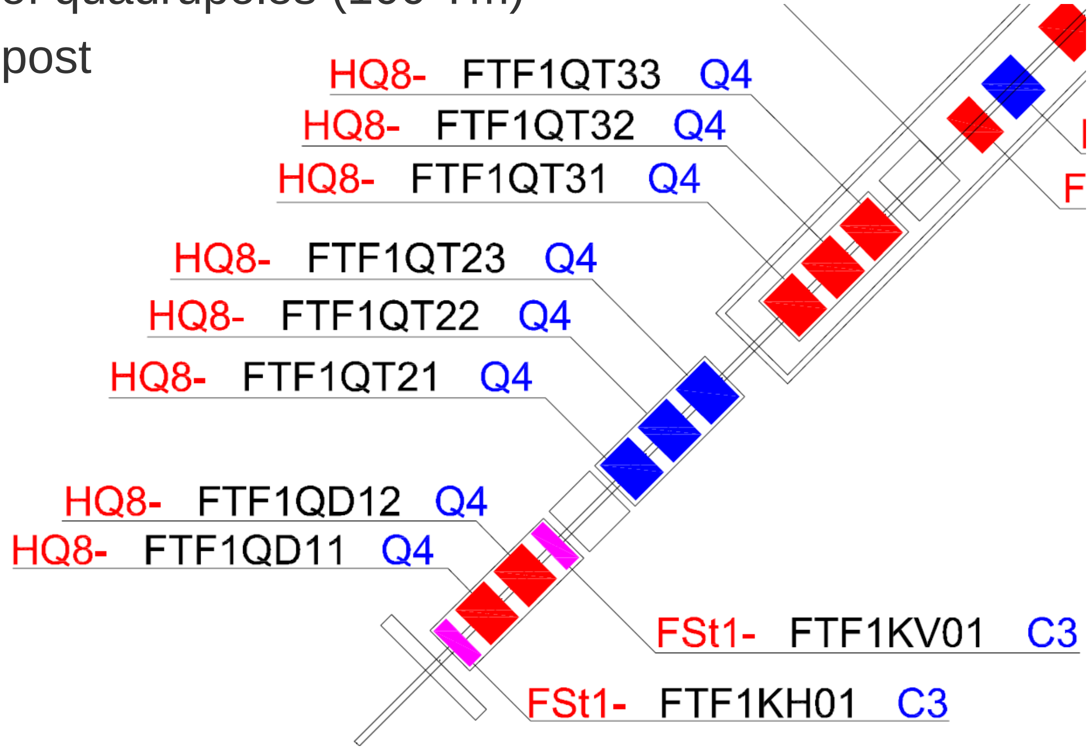
- First thing : focus ➔ series of quadrupoles (100 Tm)
- keep beam on target same post



Beam come from SIS18/100 throught HEBT

- First thing : focus ➔ series of quadrupoles (100 Tm)
- keep beam on target same post





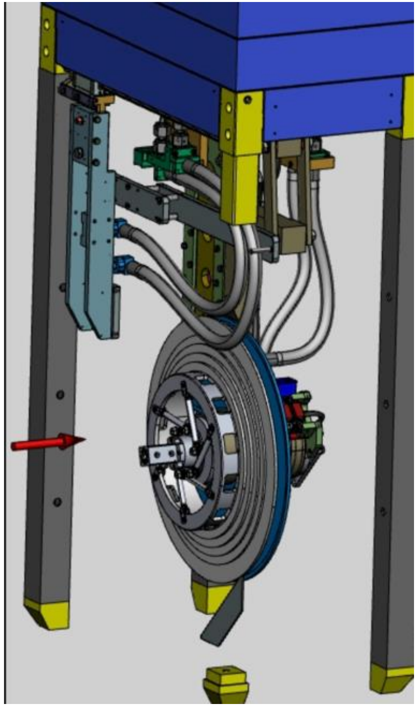
Andre.holzner GNU free license

Productions

- Target : nuclear reaction
- 1.10^{10} particle per second every 2 seconds of ^{238}U
- ➔ target 3 g/cm2 (13 mm) thick
- heat deposition: 380 W in beam on

- Probability to have nuclear reaction:

- Charge state



Charge state – or why we need 800+ MeV.U

- Nuclei in matter:
  - faster it goes more chance to loose electrons (>few 10 Mev.U)
  - more charged it is higher chance to capture electrons

➔ passing through matter creates an equilibrium of those two effects

  - @1500 MeV.U for Uranium in matter ➔ 73% $^{238}U^{92+}$, 25% $^{238}U^{91+}$, 2% $^{238}U^{90+}$… SIS100
  - @ 900 MeV.U, for Uranium in matter ➔ 46% $^{238}U^{92+}$, 43% $^{238}U^{91+}$, 9% $^{238}U^{90+}$…
  - @ 600 MeV.U, for Uranium in matter ➔ 21% $^{238}U^{92+}$, 49% $^{238}U^{91+}$, 28% $^{238}U^{90+}$…
  - @ 300 MeV.U, for Uranium in matter ➔ 10% $^{238}U^{92+}$, 17% $^{238}U^{91+}$, 70% $^{238}U^{90+}$…
  - @ 150 MeV.U, for Uranium in matter ➔ 0% $^{238}U^{92+}$, 10% $^{238}U^{91+}$, 73% $^{238}U^{90+}$…

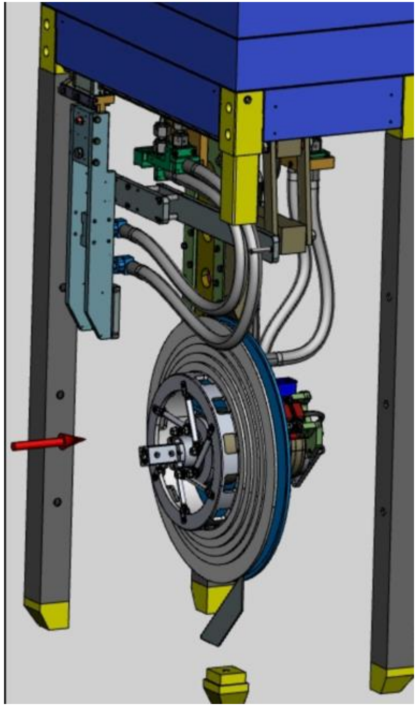
➔ for ^{212}Pb after target

  - @900 MeV.U for Pb in matter ➔ 71% $^{212}Pb^{82+}$, 25% $^{212}Pb^{81+}$, 2% $^{212}Pb^{80+}$…
  - @600 MeV.U for Pb in matter ➔ 49% $^{212}Pb^{82+}$, 42% $^{212}Pb^{81+}$, 8% $^{212}Pb^{80+}$…

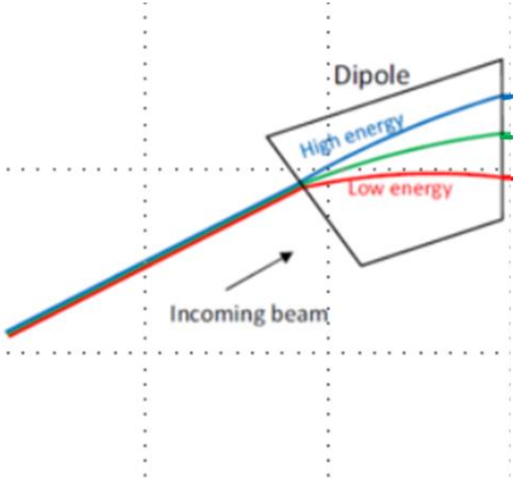
Productions

- Target : nuclear reaction
- 1.10^{10} particle per second ^{238}U (spill 1 s every 2 s)
- ➔ target 3 g/cm2 (13 mm) thick
- heat deposition: 380 W in beam on

- Probability to have nuclear reaction: 40%
- ➔ 60% of the beam stays ^{238}U (6e9 ppspill)
  - Fully stripped : 50% (3.10^{9} pps) $^{238}U^{92+}$
  - Charge state: 40% ($2.4\ 10^{9}$ pps) $^{238}U^{91+}$ and 10% ($0.6\ 10^{9}$ pps) $^{238}U^{90+}$
- $4.0\ 10^{9}$ fission and fragment fission produced
- At the target production of ^{212}Pb ➔ 161 particle per second!

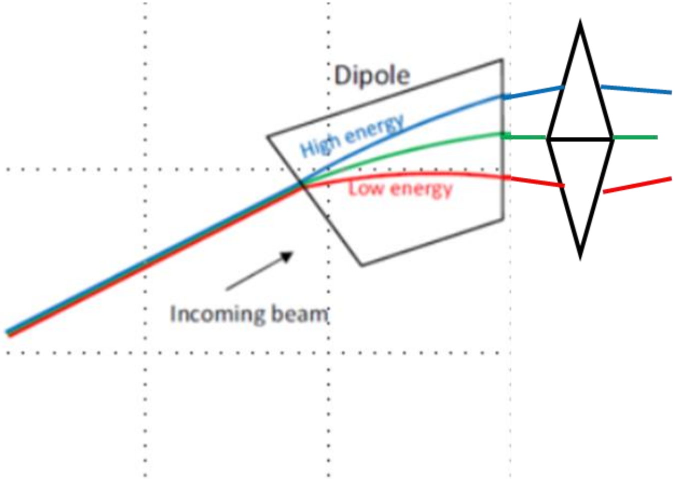


First dipole – Bρ selection



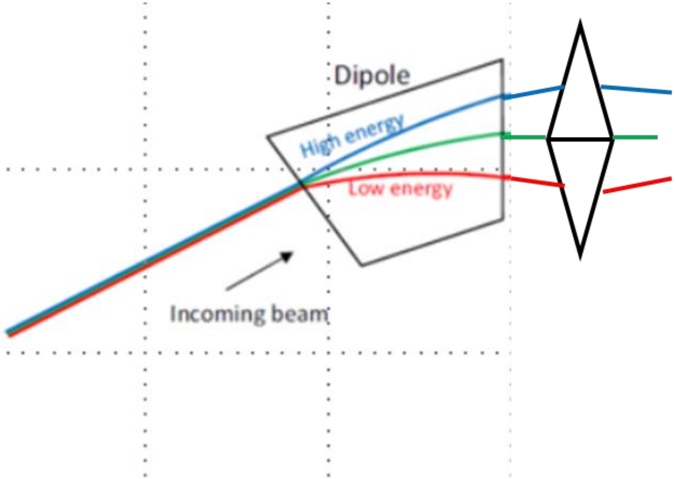
- $B\rho \propto (A/Q) . \beta\gamma$ ➔ dipole has an acceptance.
- My reaction will produce ^{212}Pb with a given momentum spread (0.6%)
- For fission ➔ (134Sn) it would be 3% spread

First dipole – Bρ selection



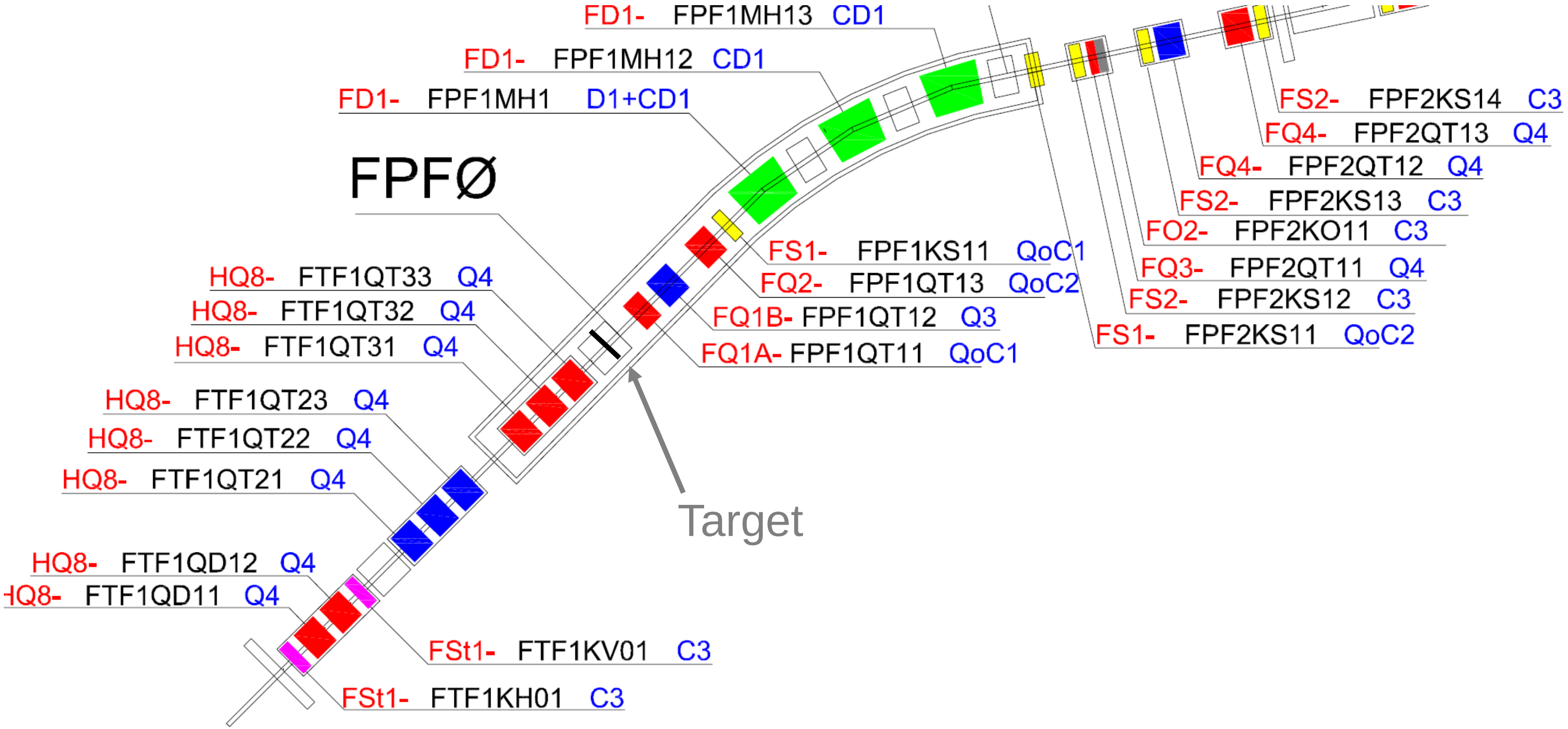
- $B\rho \propto (A/Q) \cdot \beta\gamma$ ➔ dipole has an acceptance.
- My reaction will produce ^{212}Pb with a given momentum spread (0.6%)
- For fission ➔ (^{134}Sn) it would be 3% spread

First dipole – Bρ selection



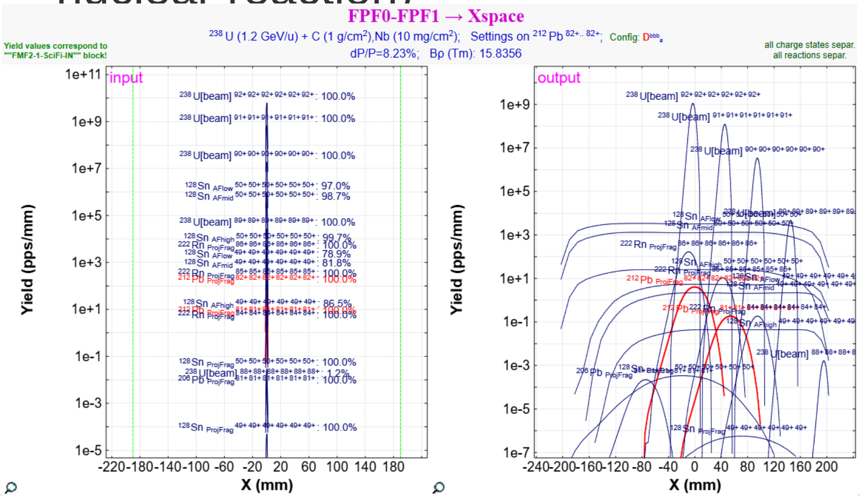
- Bρ α (A/Q) . βγ ➔ dipole has an acceptance.
- My reaction will produce ^{212}Pb with a given momentum spread (0.6%)
- For fission ➔ (^{134}Sn) it would be 3% spread
- ➔ but what about angle. (^{134}Sn +-20 mrad), ^{212}Pb +- 6 mrad

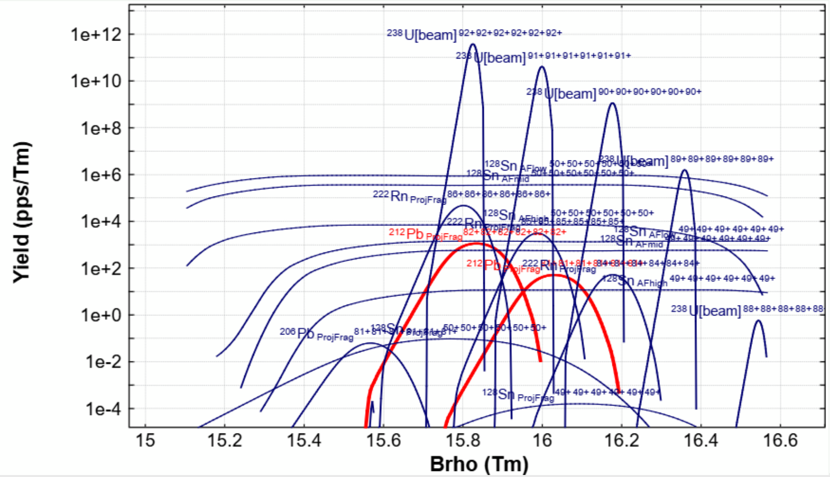
Super-FRS around the target



Dipole selection

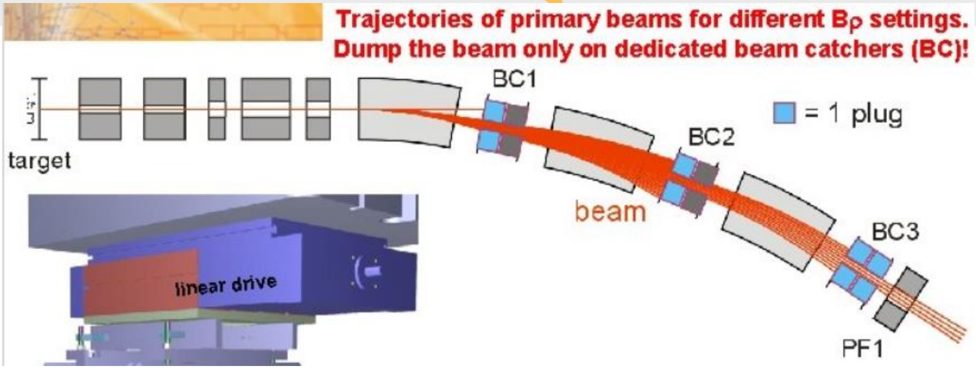
- Bρ α (A/Q) . βγ
- ➔ we want as big acceptance as possible
- ➔ we want as much selection as possible
- First dipole stage ➔ aim is to remove beam and charge state (and part of nuclear reaction)

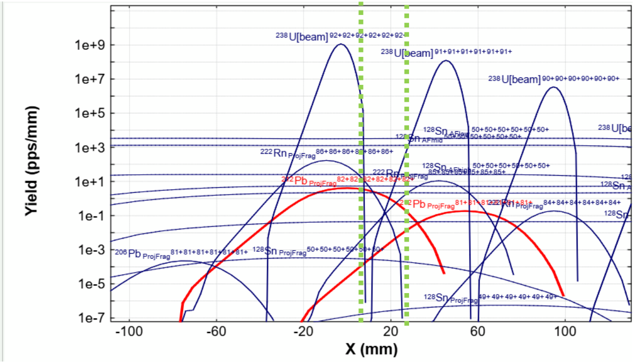


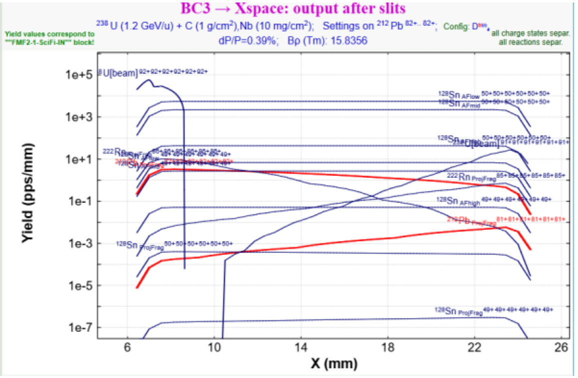


Slits and beam catchers

Intercept primary beam (and fragments) with beam catcher

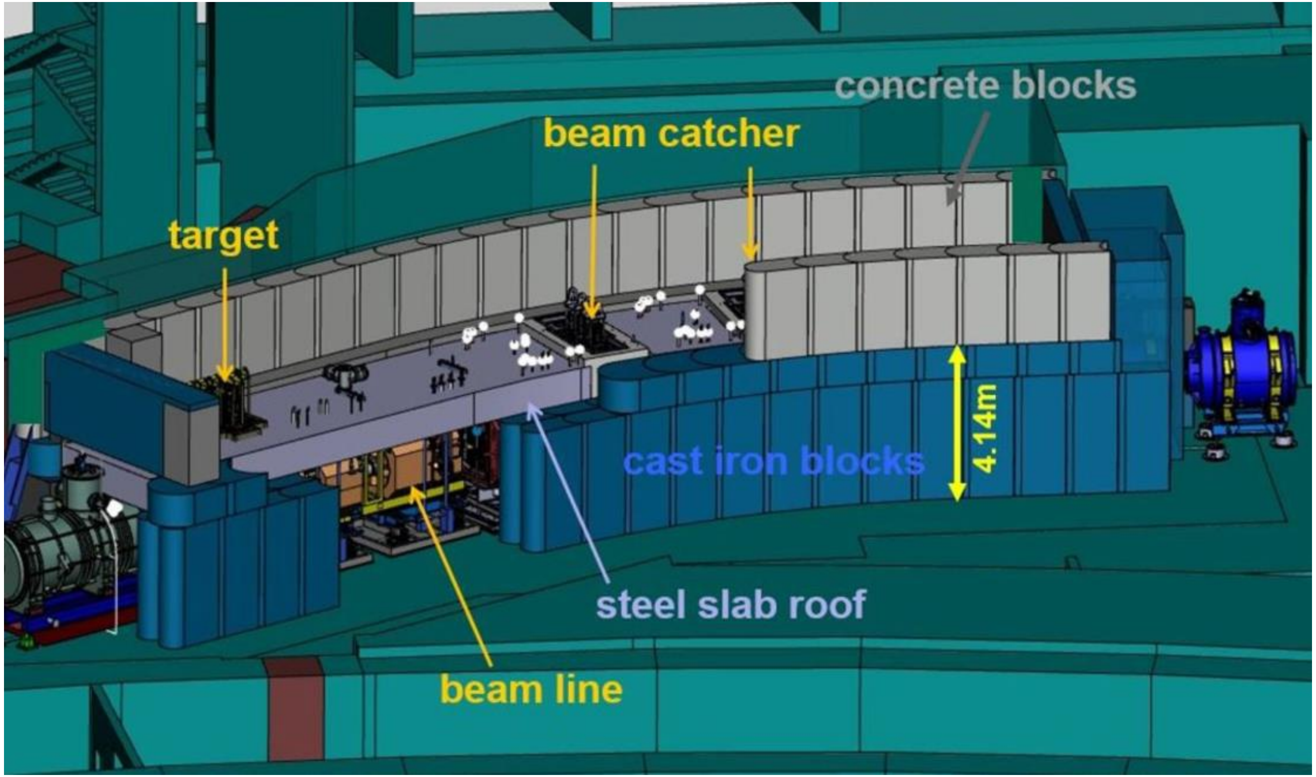






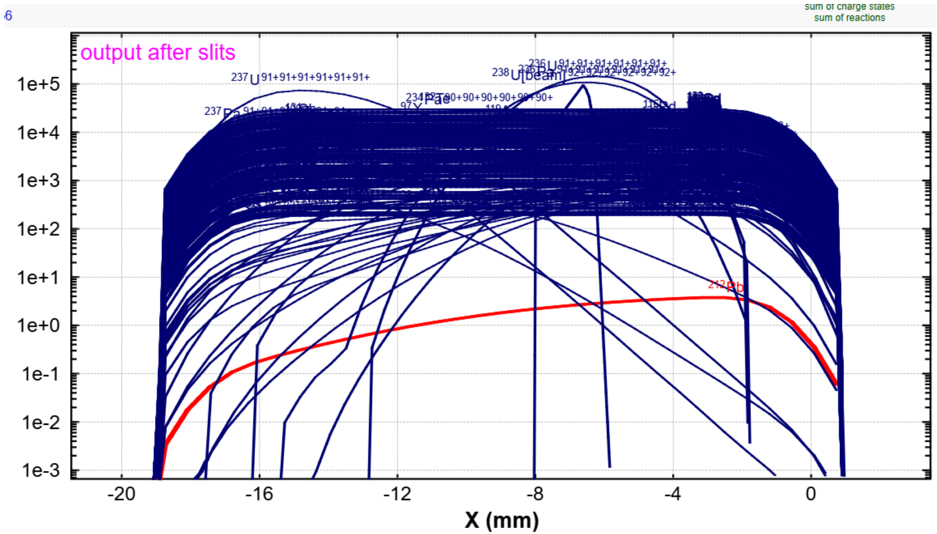
Between target and BC3, we pass from 1e10 pps to 3e7 pps ➔ reason NC magnets

This is why target is so much shielded



At this moment: selection Bρ

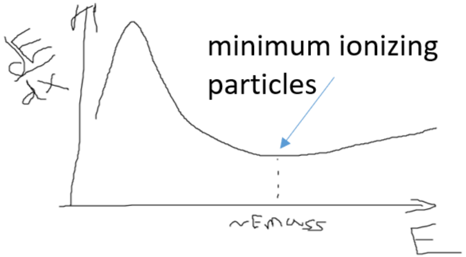
- Bρ very narrow (^{212}Pb worst case scenario)

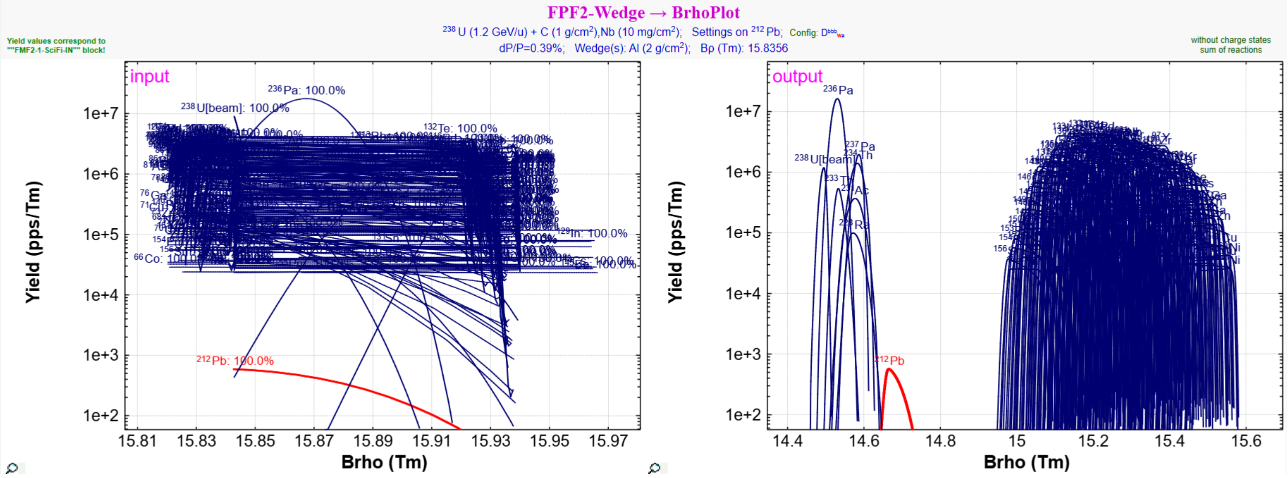


- More dipole will not help, we will redo the same selection

$B\rho$ – ΔE – $B\rho$ method

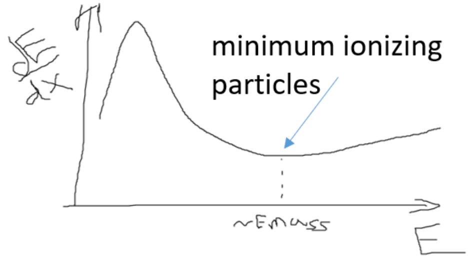
- most fragments are not ^{212}Pb, so if they pass through matter they slow down
- ➔ energy loss in matter α to $Z^2 . f(\beta)$, this means slowing down depends on element
- this means shift $B\rho$ distribution based on element number
- then we can re apply $B\rho$ selection next magnetic stage

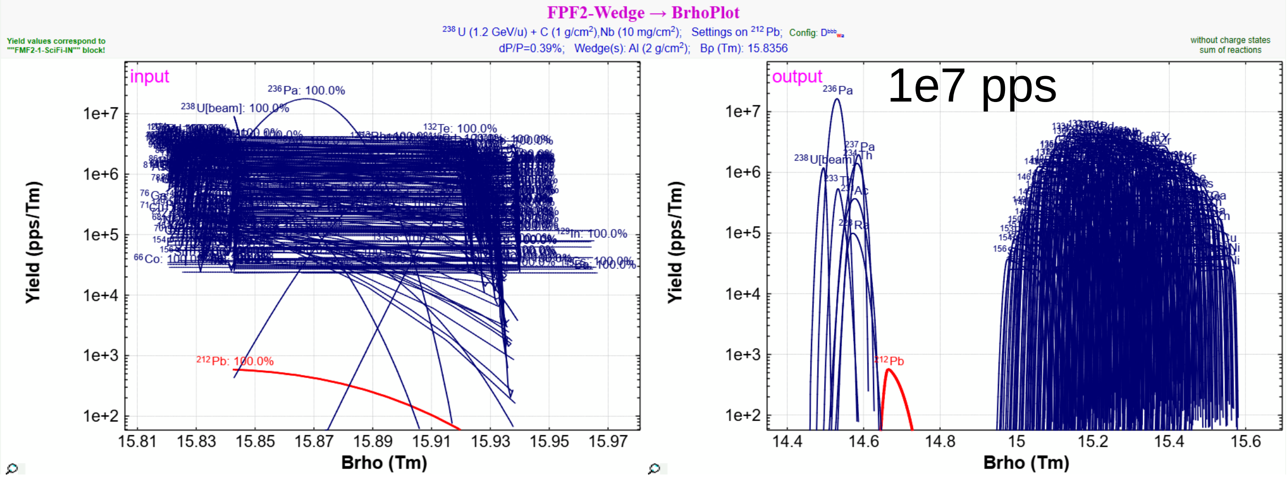




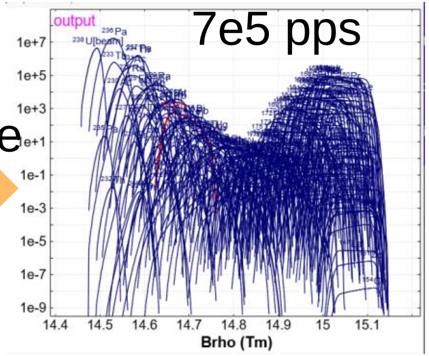
Bρ – ΔE – Bρ method

- most fragments are not ^{212}Pb, so if they pass through matter they slow down
- ➔ energy loss in matter α to Z^2 . f(β) , this means slowing down depends on element
- this means shift Bρ distribution based on element number
- then we can re apply Bρ selection next magnetic stage

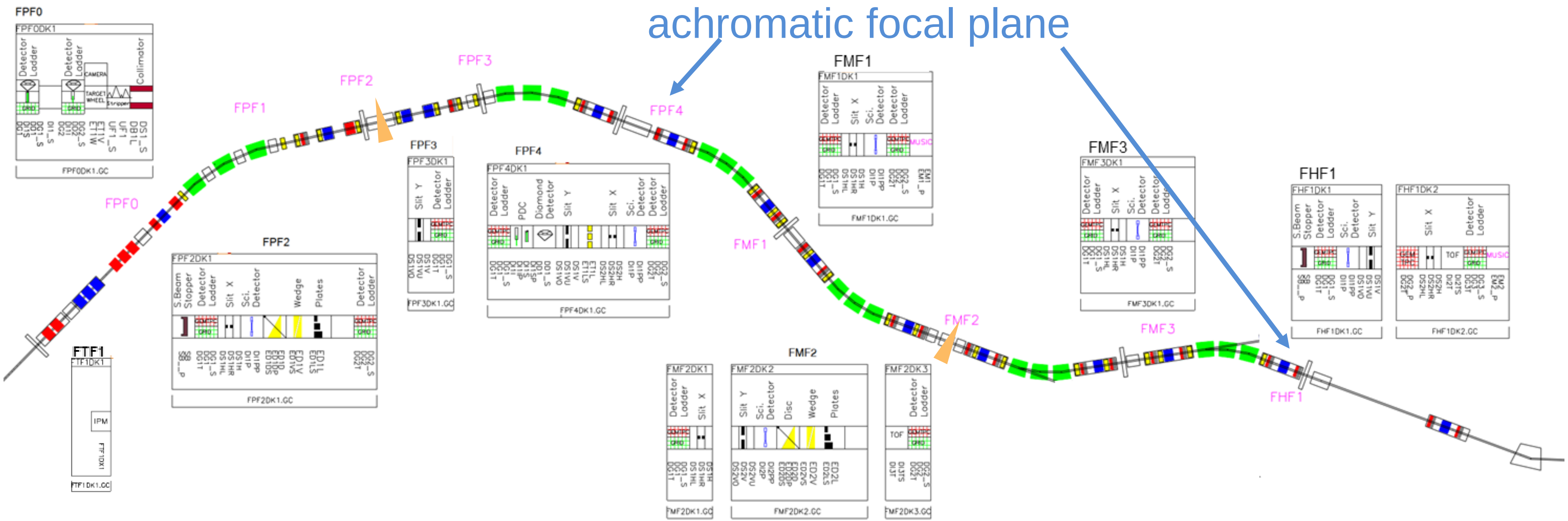




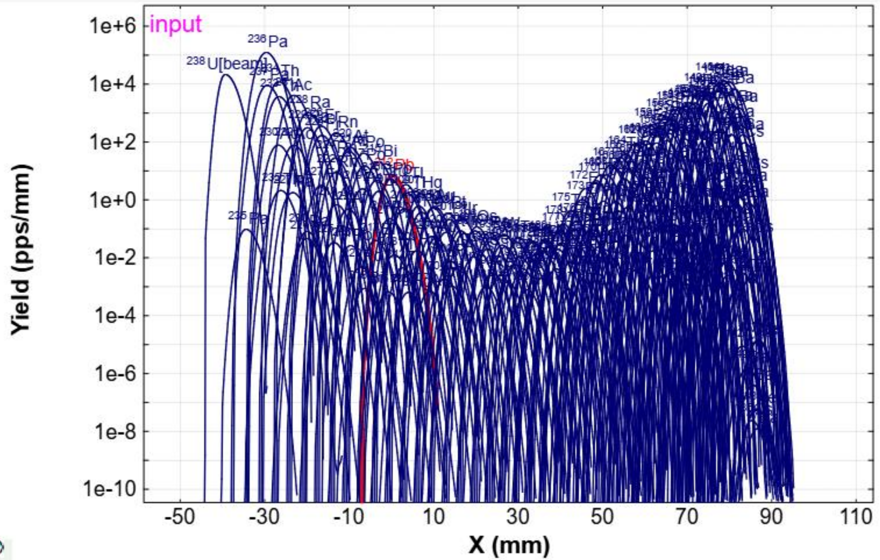
dipole



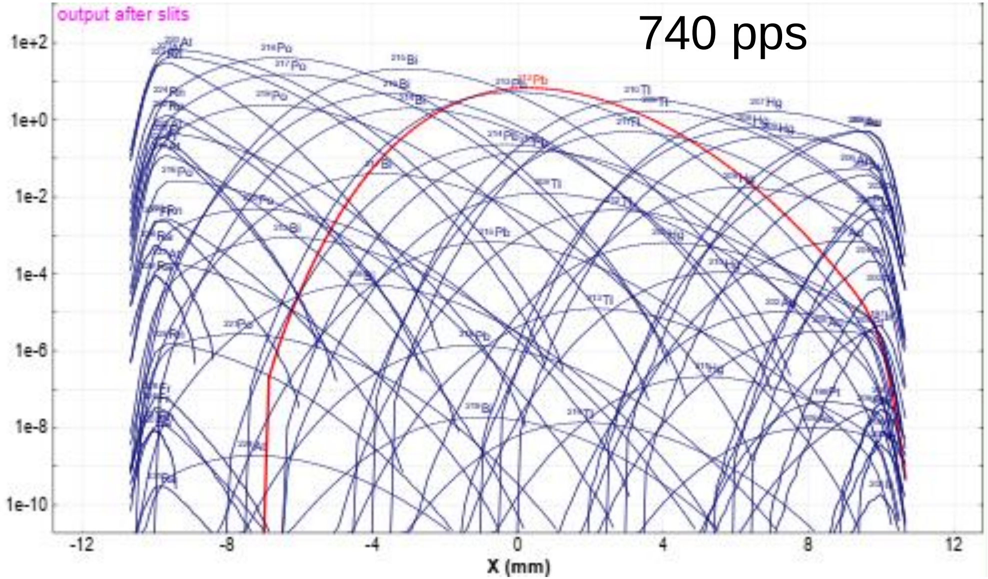
Wedges and achromatic planes



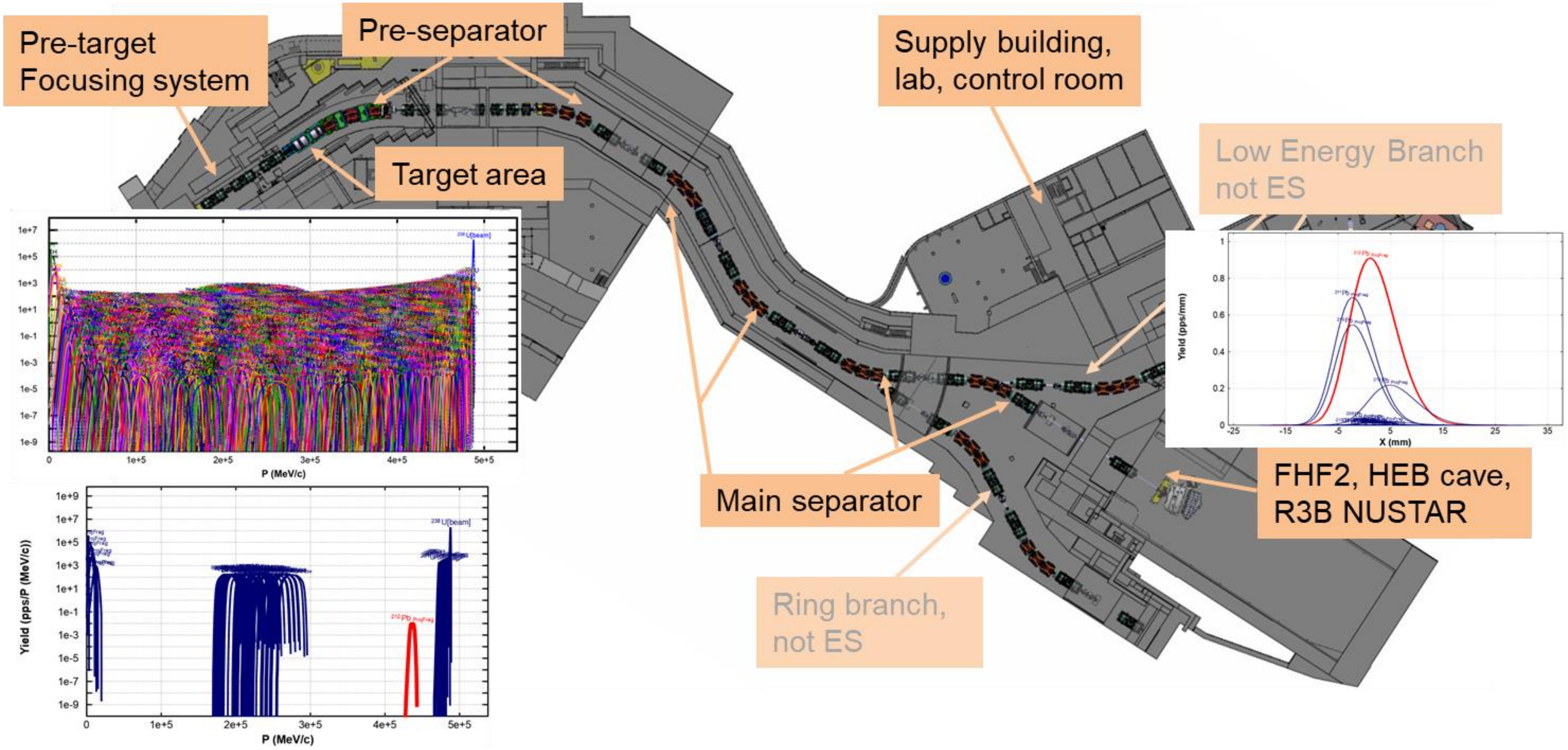
Achromatic focus ➔ better selection



740 pps

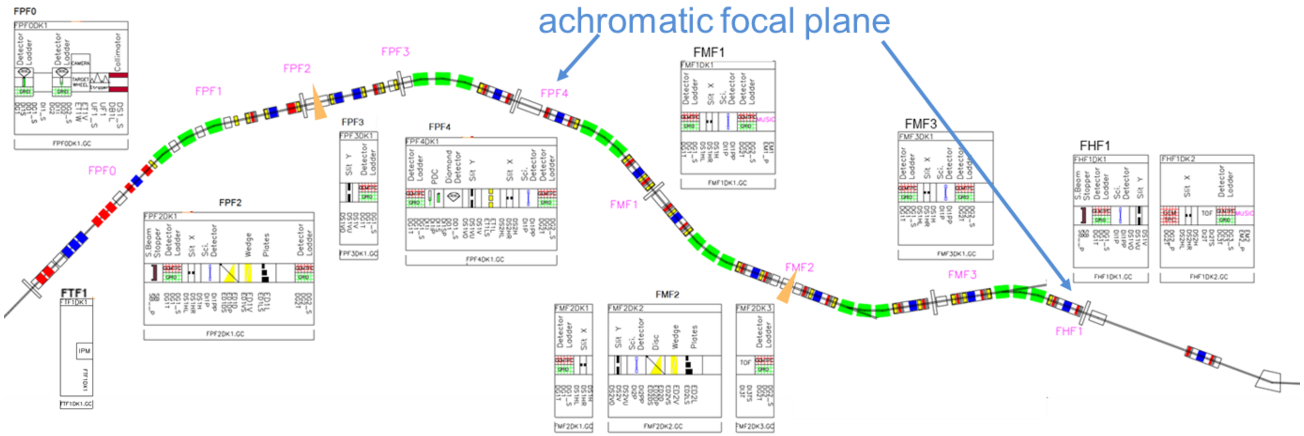


Super-FRS Bρ – ΔE – Bρ – ΔE – Bρ



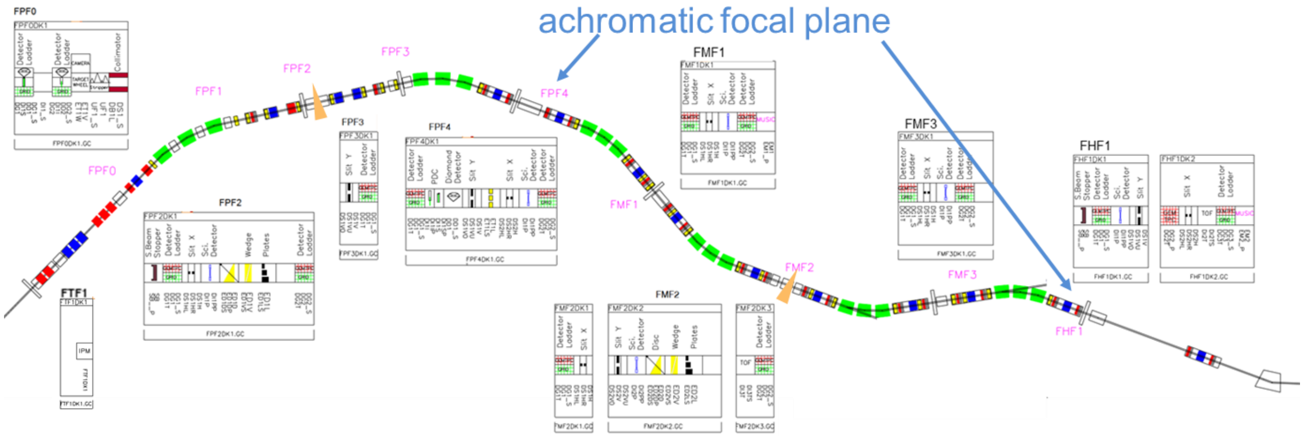
Identification

- Now we need $B\rho = C\,(A/Q)\beta\gamma = B\rho_0(1-(x_4-Mx_2)/D)$



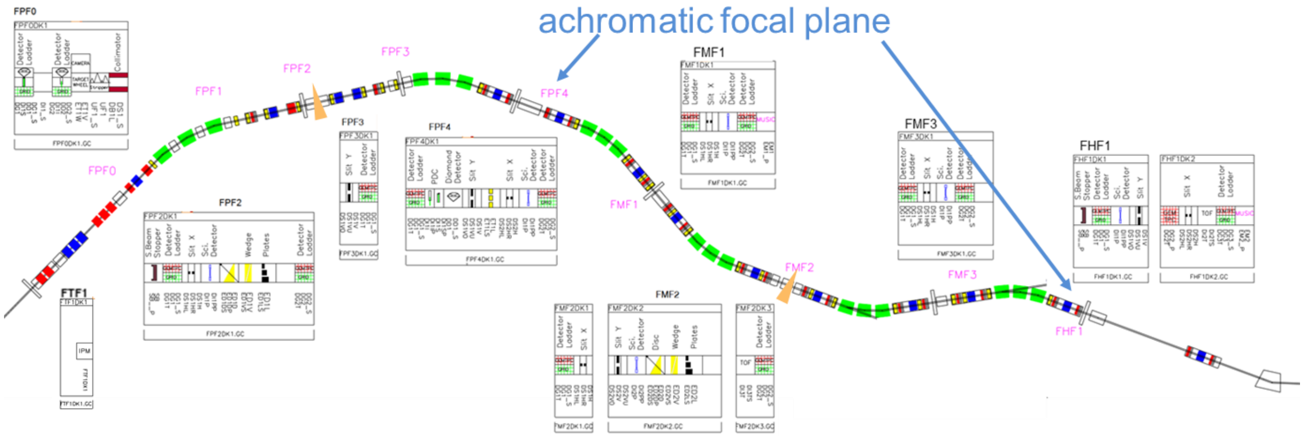
Identification

- Now we need $B\rho = C\,(A/Q)\beta\gamma = B\rho_0(1-(x_4-Mx_2)/D)$
- $B\rho_0$ ➔ comes from the magnet setting, M and D from the optic



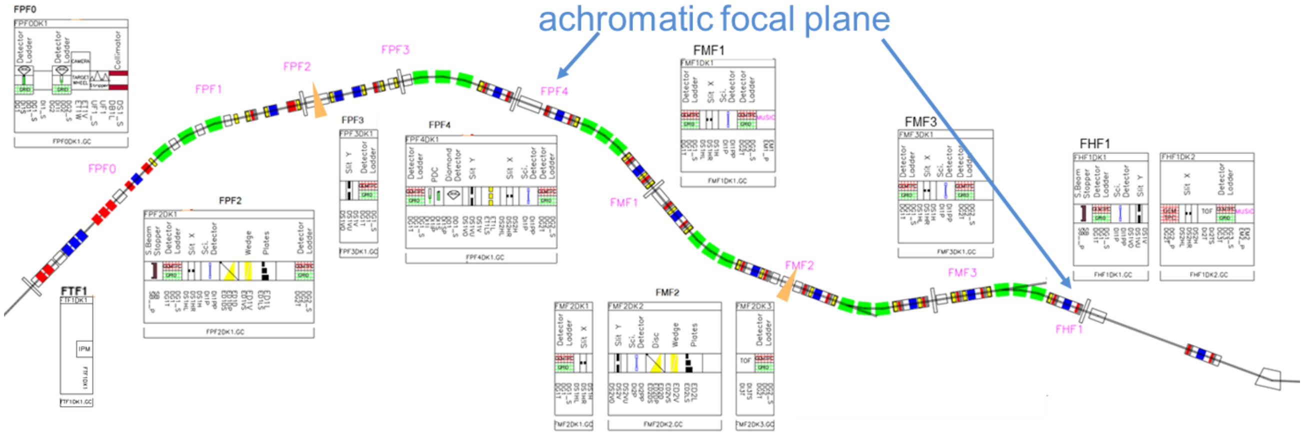
Identification

- Now we need $B\rho$ = C (A/Q)$\beta\gamma$ = $B\rho_0(1-(x_4-Mx_2)/D)$
- $B\rho_0$ → comes from the magnet setting, M and D from the optic
- x_2 and x_4 from the positions at FMF2 and FHF1 (SciFi or TPC)
- $\beta\gamma$ comes from the time of flight



Identification

- Now we need $B\rho$ = C (A/Q)$\beta\gamma$ = $B\rho_0(1-(x_4-Mx_2)/D)$
- $B\rho_0$ ➔ comes from the magnet setting, M and D from the optic
- x_2 and x_4 from the positions at FMF2 and FHF1 (SciFi or TPC)
- $\beta\gamma$ comes from the time of flight
- MUSIC determines Q ➔ A/Q and Q we know A



Charge state – or why we need 800+ MeV.U

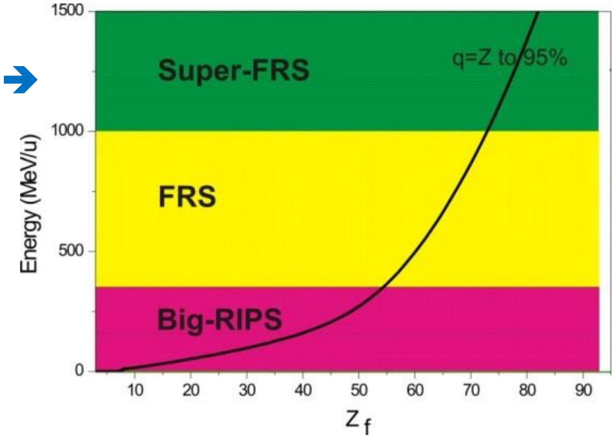
- Nuclei in matter:
  - faster it goes more chance to loose electrons (>few 10 Mev.U)
  - more charged it is higher chance to capture electrons

➔ passing through matter creates an equilibrium of those two effects
  - @1500 MeV.U for Uranium in matter ➔ 73% $^{238}U^{92+}$, 25% $^{238}U^{91+}$, 2% $^{238}U^{90+}$… SIS100
  - @ 900 MeV.U, for Uranium in matter ➔ 46% $^{238}U^{92+}$, 43% $^{238}U^{91+}$, 9% $^{238}U^{90+}$…
  - @ 600 MeV.U, for Uranium in matter ➔ 21% $^{238}U^{92+}$, 49% $^{238}U^{91+}$, 28% $^{238}U^{90+}$…
  - @ 300 MeV.U, for Uranium in matter ➔ 10% $^{238}U^{92+}$, 17% $^{238}U^{91+}$, 70% $^{238}U^{90+}$…
  - @ 150 MeV.U, for Uranium in matter ➔ 0% $^{238}U^{92+}$, 10% $^{238}U^{91+}$, 73% $^{238}U^{90+}$…

➔ for ^{212}Pb after target
  - @900 MeV.U for Pb in matter ➔ 71% $^{212}Pb^{82+}$, 25% $^{212}Pb^{81+}$, 2% $^{212}Pb^{80+}$…
  - @600 MeV.U for Pb in matter ➔ 49% $^{212}Pb^{82+}$, 42% $^{212}Pb^{81+}$, 8% $^{212}Pb^{80+}$…

Strength of Super-FRS, identification at high Z

When bare particle passes in matter probability to capture electron ➔ probability higher with Z and with low energy.



In flight identification is possible only
at FRS and Super-FRS for Z>65

This is why we use stripper foil between the musics:

If 10% to be miss identified in Z in a gas
➔ 2 music with stripper: 1% error

How do we compare

Production of New Isotopes Near the Heavy-element Nucleosynthesis Path

S. Pietri[a,*], H.A. Rösch-Kabadayı[a,b,c], J. Enders[b,c], T. Grahn[d,e], J.-P. Hucka[b,c], T. Kurtukian-Nieto[f,g], M. Luoma[d,e], A.M. Bruce[h],

and astrophysical models. The experiment therefore demonstrates that the FRS is competitive with modern facilities, making the impending arrival of the new separator Super-FRS [26] at FAIR an exciting prospect.

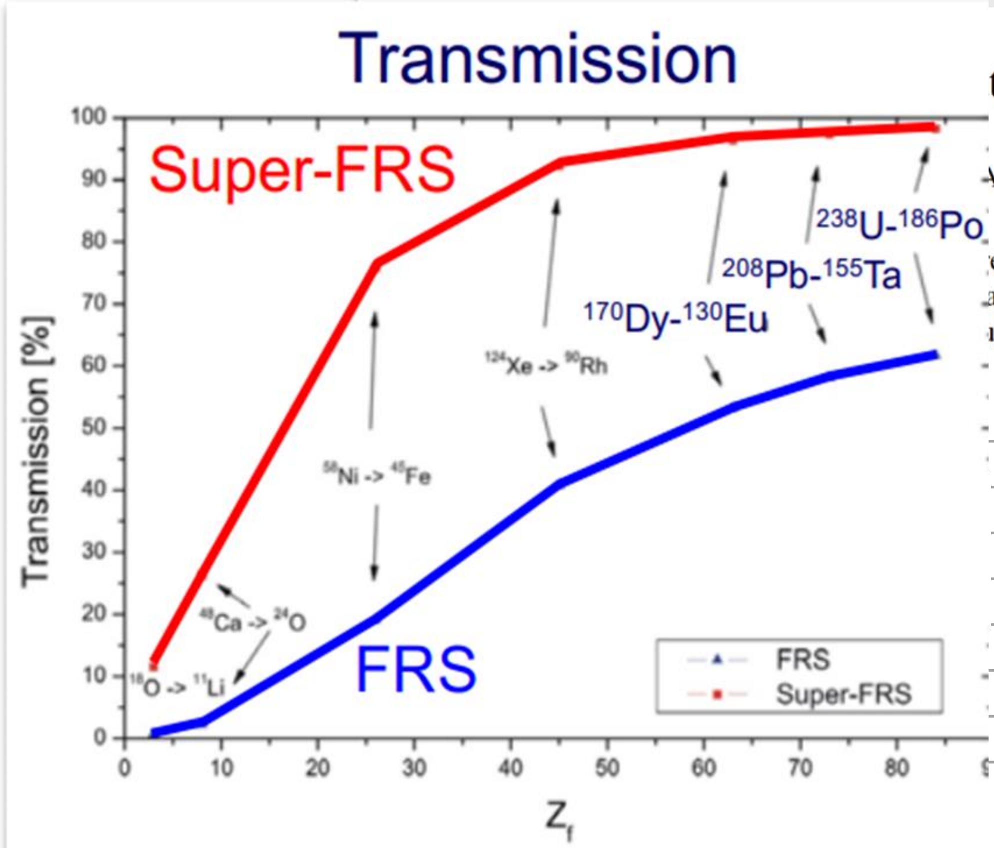
	FRS	SFRS
stage	2	3
Br Tm	18	20
dp/p	1%	2.5%
x ang mrad	7.5	40
y ang mrad	7.5	20
resolving P	1500	1500

How do we compare

Production of N... th

S. Pietri[a,*], H.A. Rösch-Kabadayı ... A.M. Bruce[h],

...efore demon-
...acilities, mak-
...per-FRS [26]



Layout

- Some physics introductions
  - nucleus
  - nuclear physics
  - decay – natural process
  - acceleration
  - reactions – “artificial” process
- Why study nuclear physics
  - cosmogenesis
  - LCDM model
  - neutrons and nuclei
  - r and s process path
  - where to look
- Super-FRS
  - objective
  - separation
  - degraders
  - identification
  - some interesting bits
  - how compare to the rest
- Selection of planned experiment
  - NUSTAR
  - DESPEC
  - HISPEC
  - Super-FRS EC
  - R3B

NUSTAR

@SIS – (S)FRS

HISPEC/DESPEC

High-Resolution in-flight Spectroscopy and Decay Spectroscopy

R3B

Reactions with relativistic radioactive beams

Super-FRS EC

Super-FRS Experiment Collaboration

@SIS – (S)FRS

ILIMA

Isomeric beams, lifetimes and masses

@UNILAC then @LEB

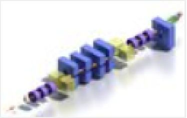
MATS

Precision measurements of very short-lived nuclei using an advanced trapping system

LaSpec

Laser spectroscopy

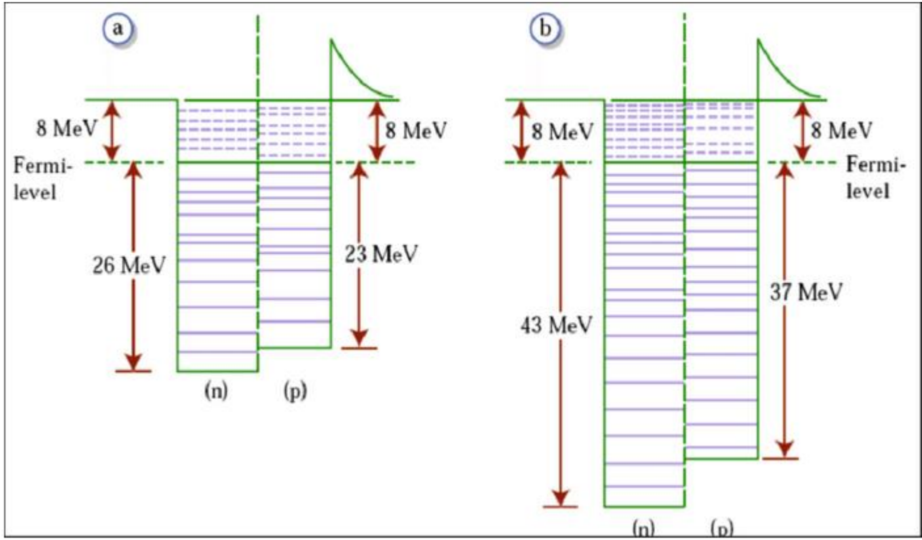
@UNILAC and future linac



SHE

Super-Heavy Element Research

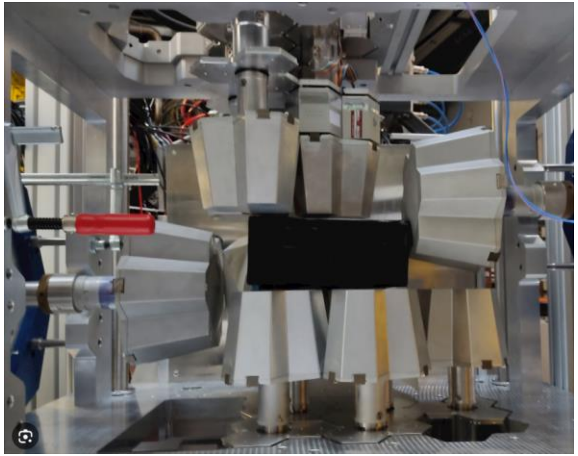
- To study structure : check how excitation happens
- first excited state ➔ usually decay by EM transition (gamma rays)
- Best detector ➔ Germanium (eff/res) or LaBr3 (speed)
- Ge need cooling (lN2)

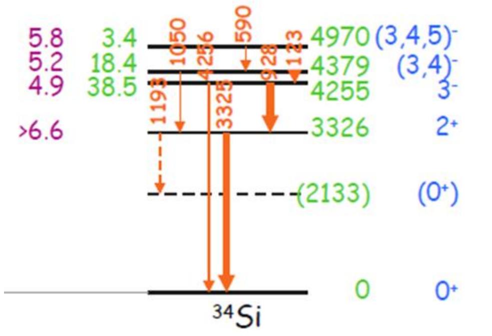


- for ES will be at FHF1

DESPEC

- Produce nucleus
- bring it to the end of the spectrometer
- measure its decay





From β decay ^{34}Al (in ^{36}S+Be@LISE)

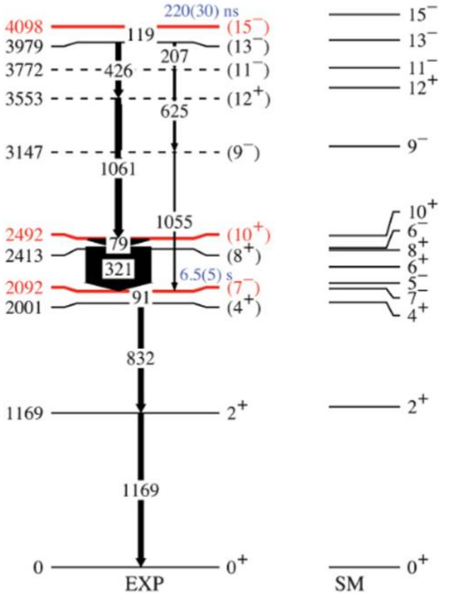


FIG. 3. (Color online) Comparison between the proposed excitation scheme of ^{128}Sn (EXP) with the results of shell-model calculations (SM).

Isomer ^{128}Sn, from ^{136}Xe+Be@FRS summer 2006 (A. Junclaus exp).

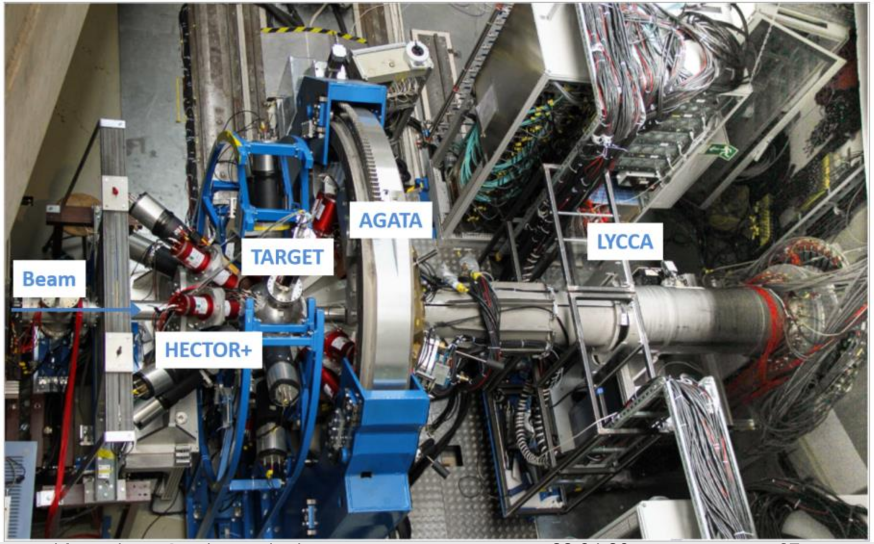
HISPEC – based on AGATA

- Excite the nuclei in front of high precision gamma detector (secondary target)
- Identify what comes out (COULEX or few nucleon removal)
- doppler correct the gamma rays

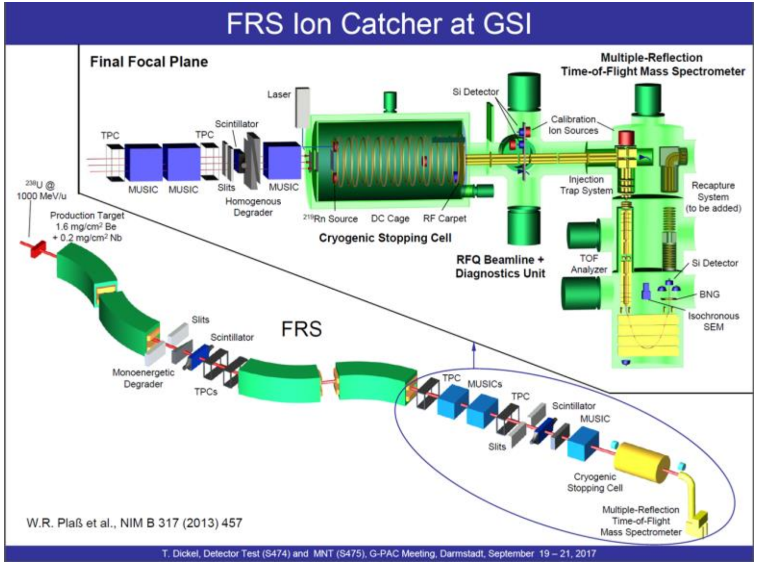
→ access to prompt gamma, not always reachable by decay

→ access to gamma lifetime →

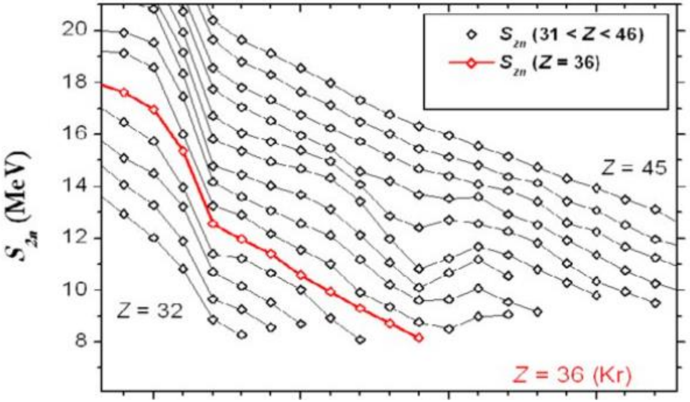
→ gives idea on nuclear shape (collectivity)



Super-FRS EC (one of many topics)



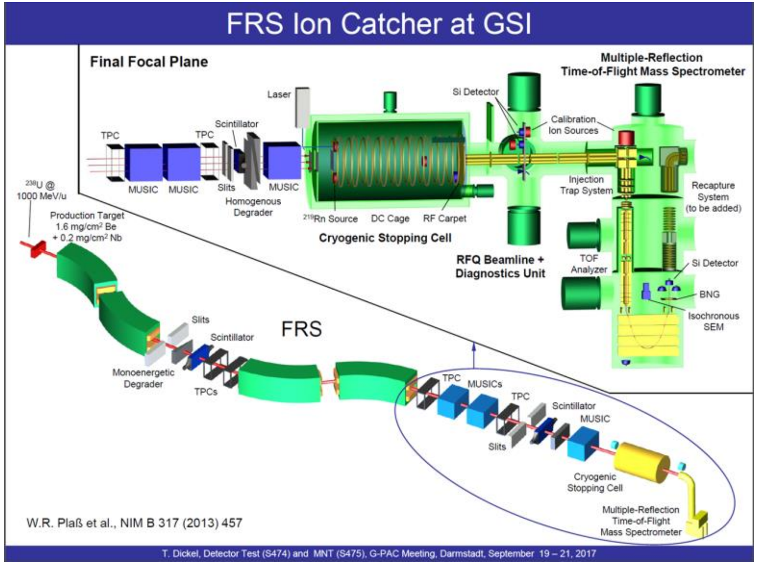
Mass give view of where binding energy changes



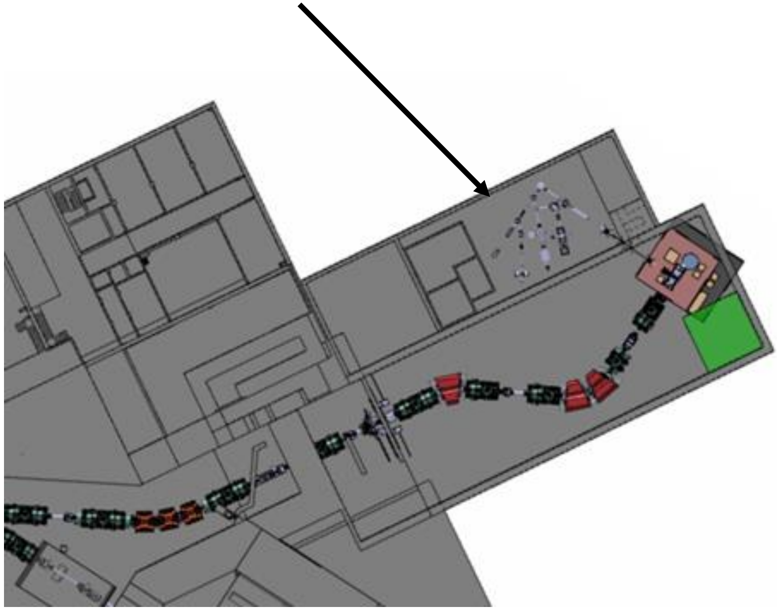
New IC one for Super-FRS
MR-TOF allows mass measurements

S Naimi, PhD Thesis
Universite Paris Diderot

Gas cell – as preparation for MATS and LASPEC

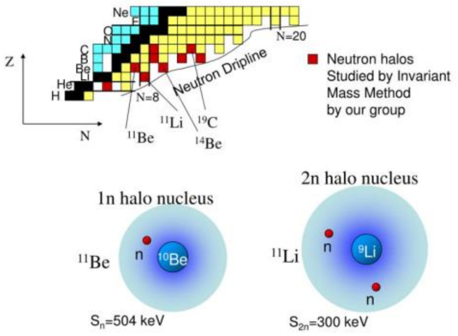


MATS and LASPEC measurments



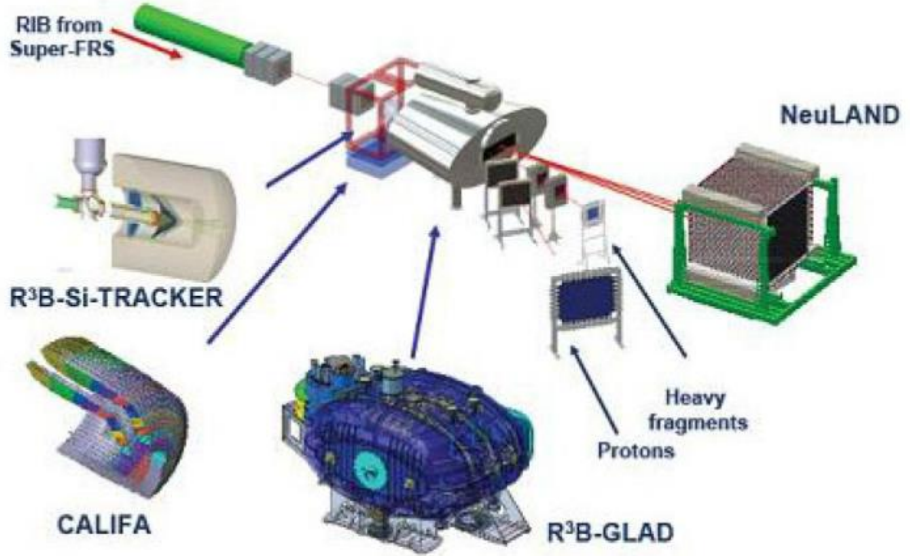
New IC one for Super-FRS
MR-TOF allows mass measurements

- Reactions at the end of Super-FRS (or FRS)
- Use GLAD to moment reconstruct products of reaction, trackers behind
- Use NeuLand to detect neutrons, CALIFA for prompt gamma/protons



Neutron skin

EOS of matter



… to answer how