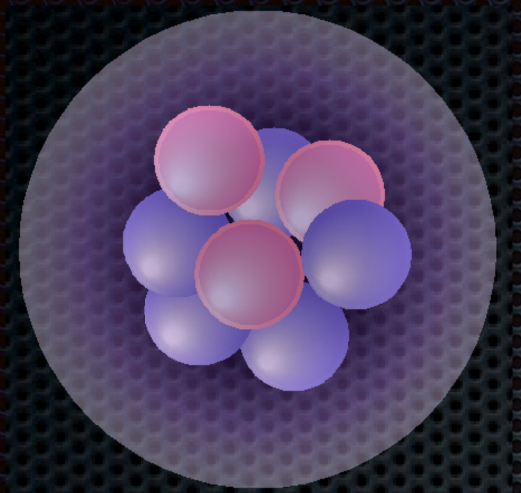
Study of the Properties of Atomic Nuclei with RI Beam

Maya Takechi, Niigata University

Atomic Nuclei



Nucleus

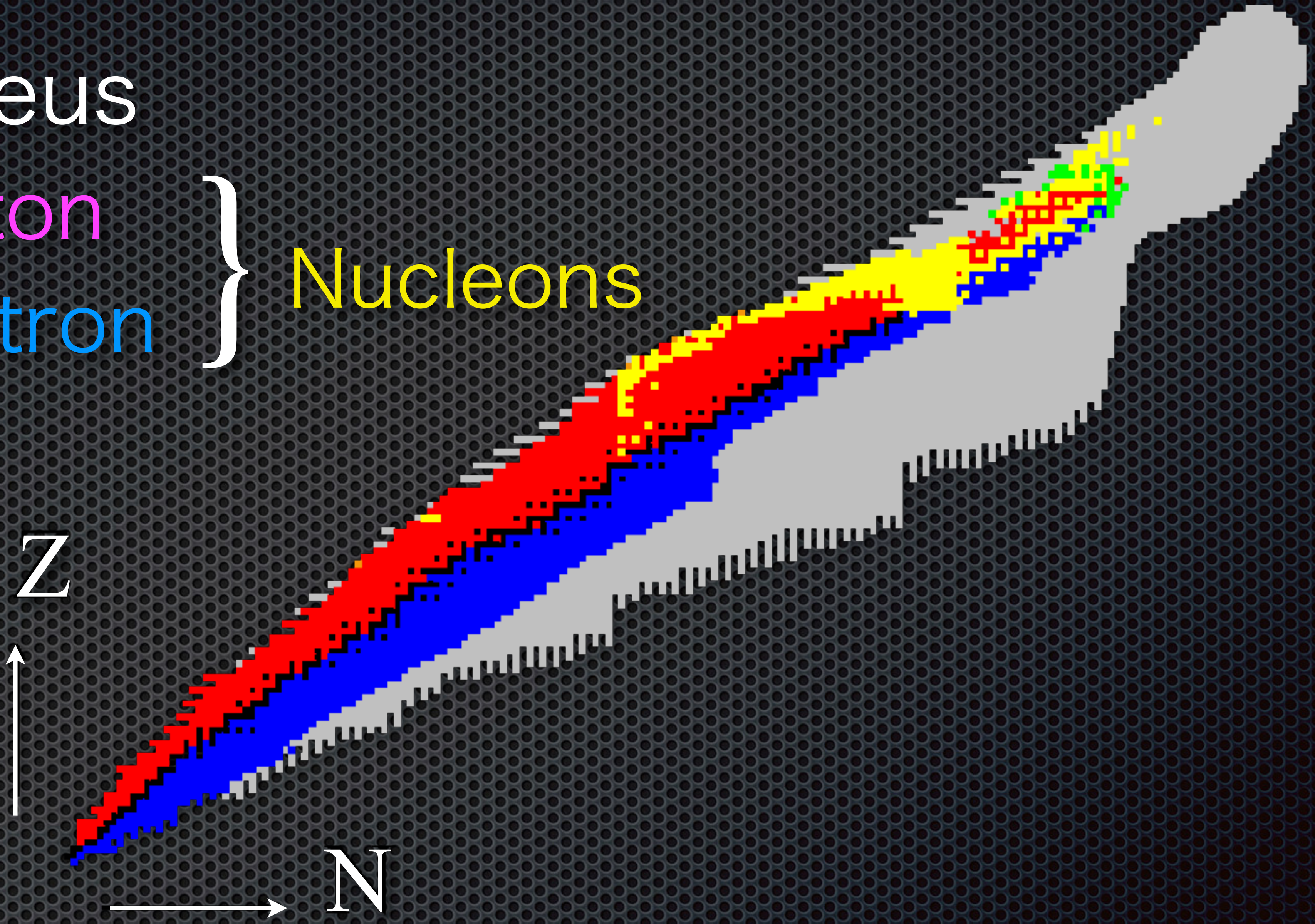
Proton
Neutron } Nucleons

Proton Number Z

Neutron Number N

Mass Number A

$A = N + Z$



Stable Nuclei ~300, Unstable Nuclei ~8000

Experimentally confirmed

Unstable Nuclei ~ 3000

Nuclear Property : Size, Density

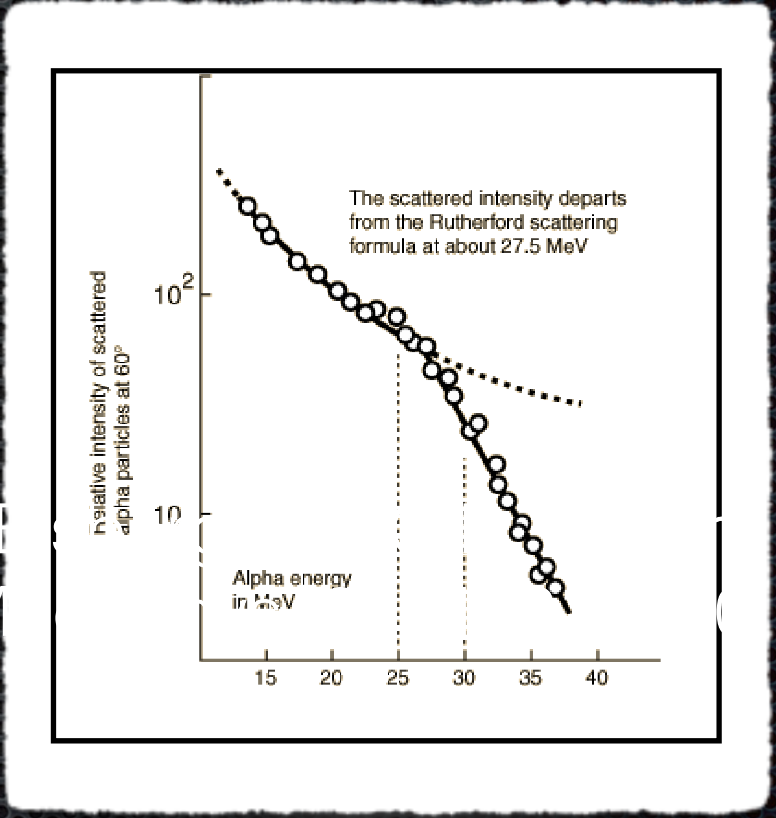
Known Properties from the Study of Stable Nuclei

Radius Alpha particle scattering on Stable Nuclei

Nuclear Radii ~ 1~10 fm

R.M. E

Rev. M



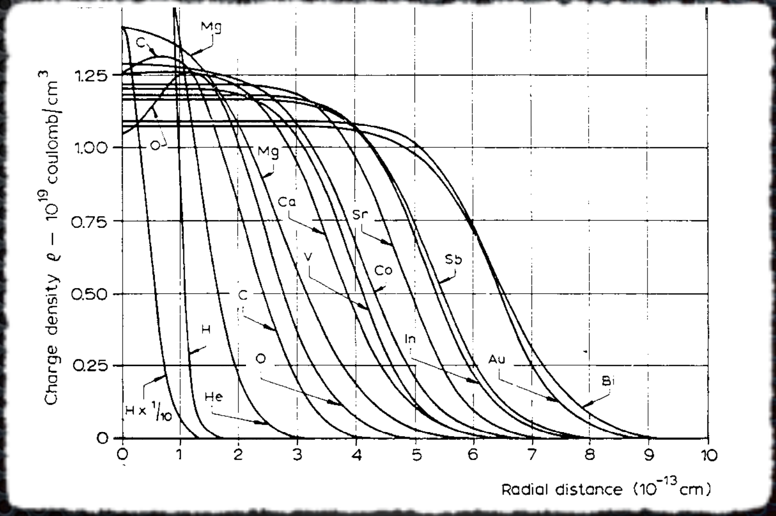
Electron Scattering

Nuclear radii follow the function of mass number

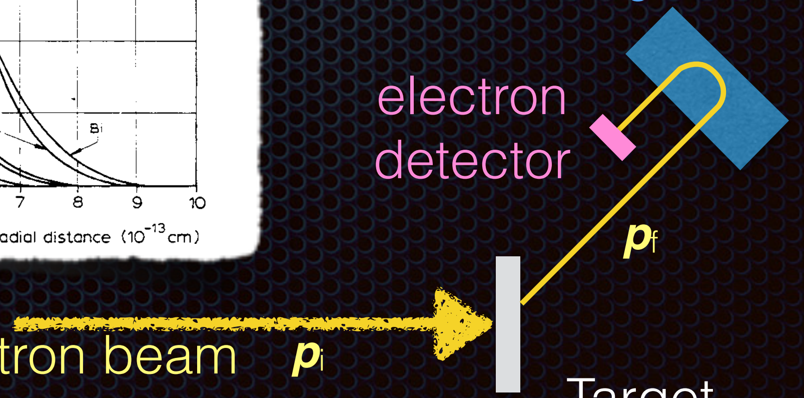
$R \propto r_0 * A^{1/3}$

Saturation Density

$m\,\rho_0 \approx 2.8 \times 10^{14}\ \mathrm{g \cdot cm^{-3}}$



R. Hofstadter Nobel Lecture



Nuclear Property : Mass, Binding Energy

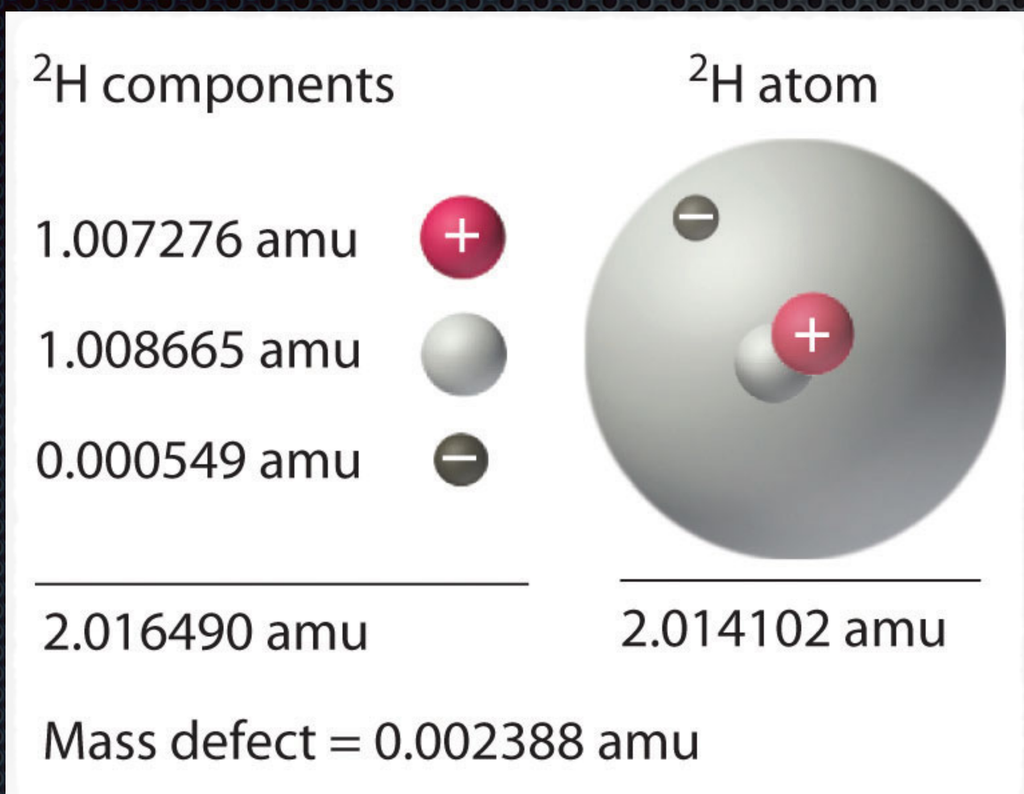
Ion source

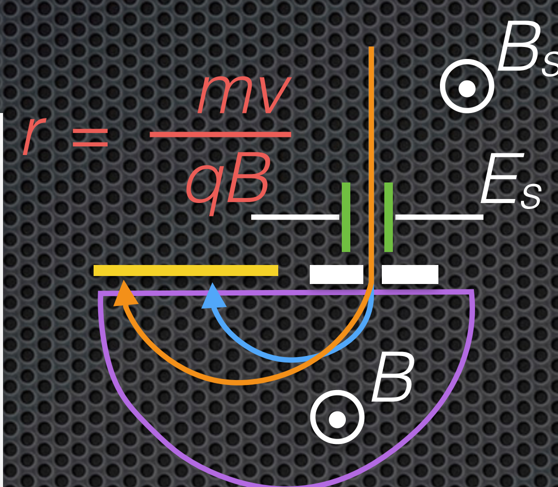
Known Properties from the Study of Stable Nuclei

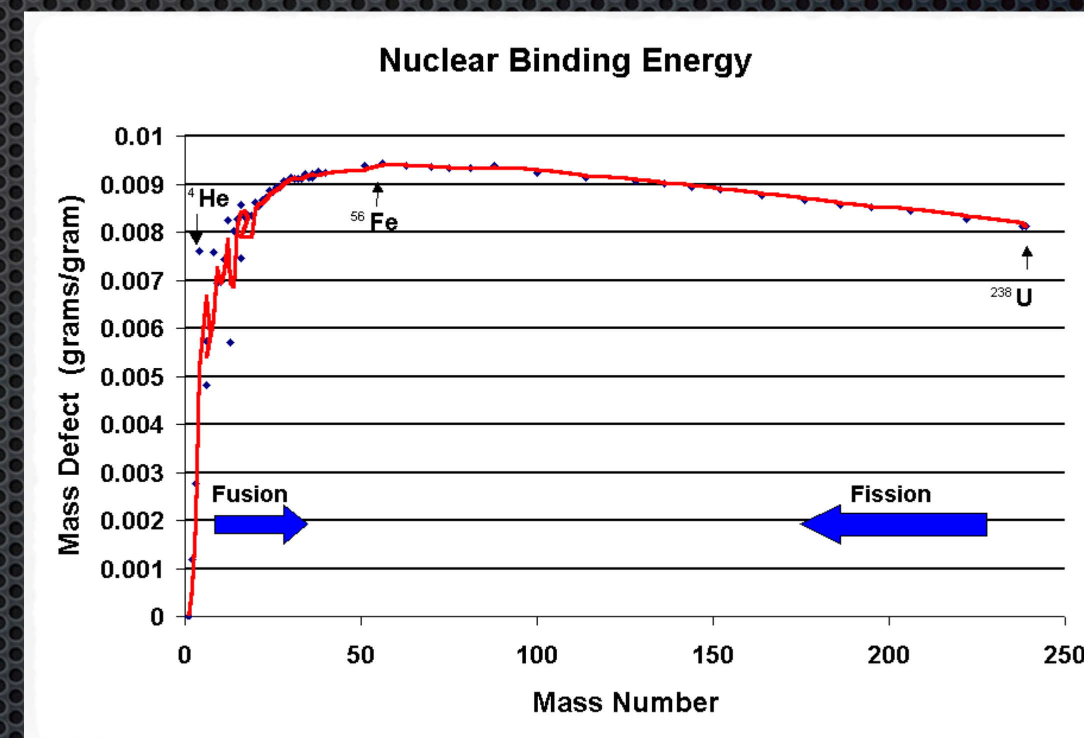
Mass Measurements by Mass spectrometer

Bainbridge Mass spectrograph (1930s)

Mass Defect







http://chemwiki.ucdavis.edu/

http://www.chem.fsu.edu/

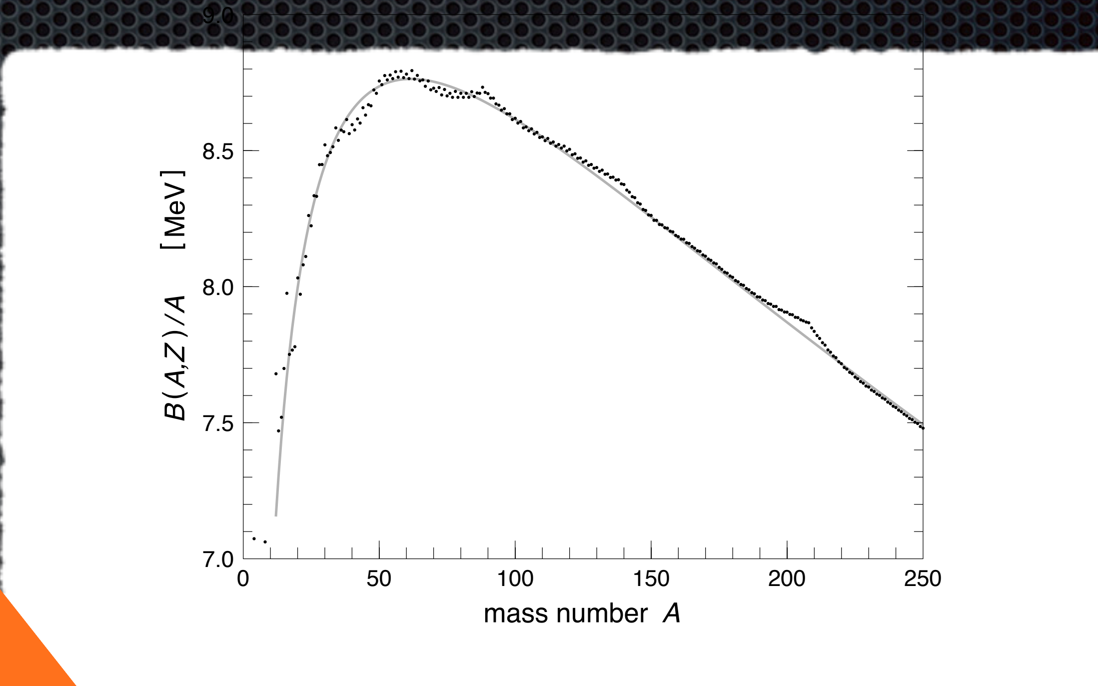
$$M(A, Z) = Z^*m_p + N^*m_n - B(A, Z)$$

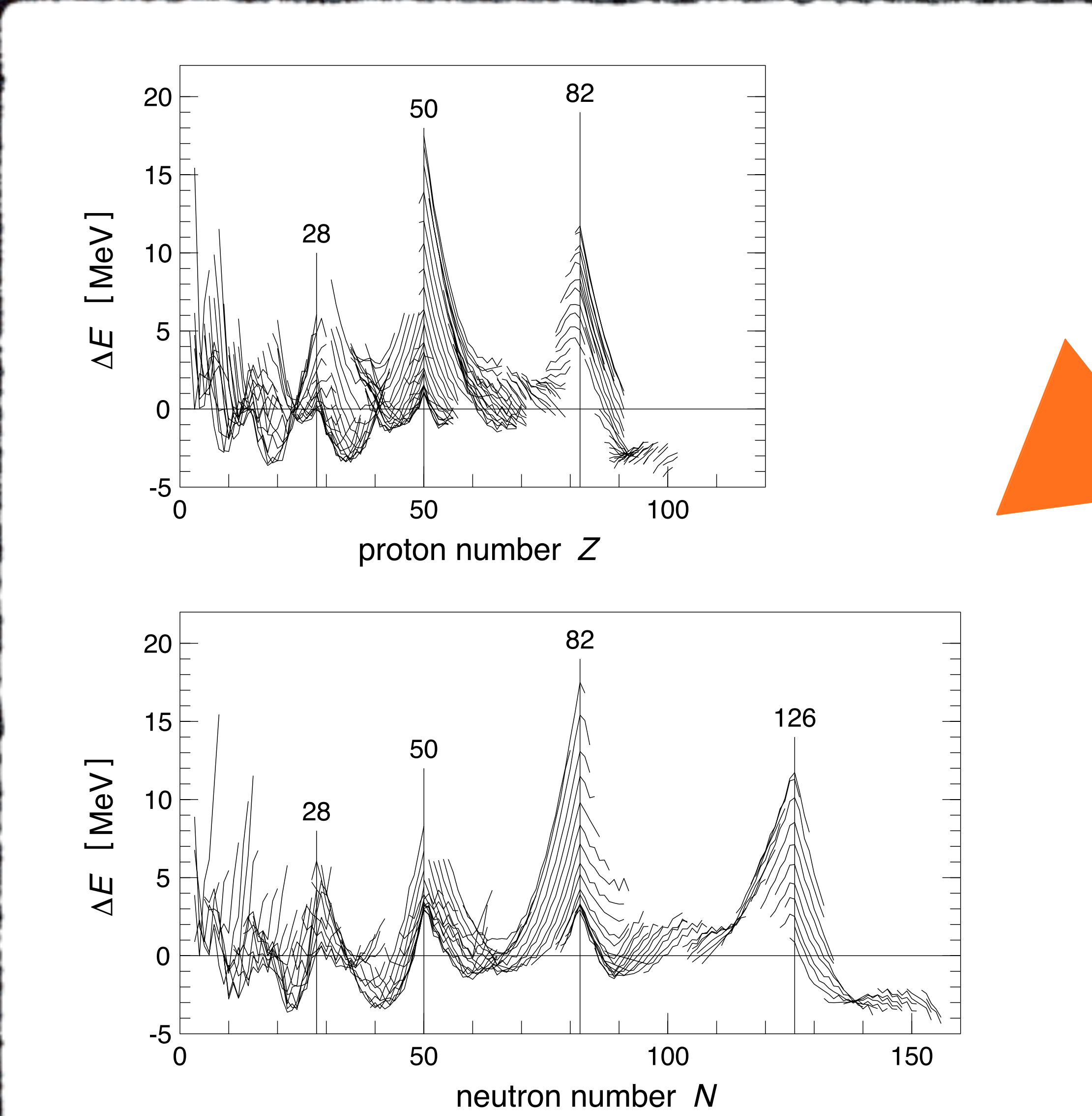
Binding Energy / nucleon
~8 MeV

Nuclear Structure : Magic Number

Figures are from the lecture note of Prof. K. Muto, Tokyo Institute of Technology

$$
\begin{aligned}
B(A,Z) &= b_{\mathrm{vol}}\,A && \text{体積エネルギー}\\
&- b_{\mathrm{surf}}\,A^{2/3} && \text{表面エネルギー}\\
&- b_{\mathrm{Coul}}\,\frac{Z^2}{A^{1/3}} && \text{Coulomb エネルギー}\\
&- b_{\mathrm{sym}}\,\frac{(A-2Z)^2}{A} && \text{対称エネルギー}\\
&- \Delta(A) && \text{対エネルギー}
\end{aligned}
$$





$$\Delta E = M_{\mathrm{Expt}} - B(A, Z)$$

Nuclei are more strongly bound when the number of constituent nucleons are certain magic numbers

N or Z = 8, 20, 28, 50, 82, 128

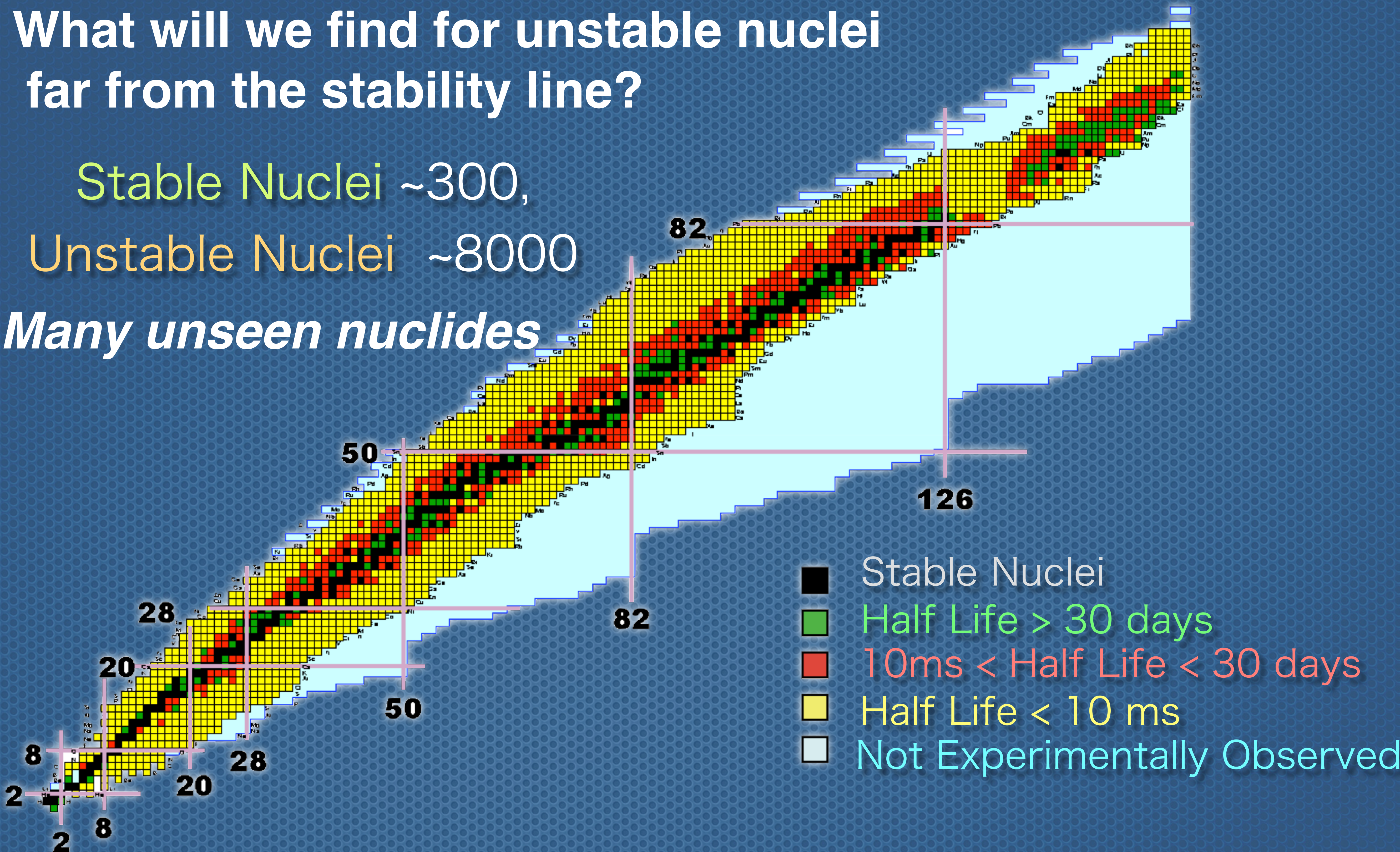
Closed Shell

What will we find for unstable nuclei far from the stability line?

Stable Nuclei ~300,

Unstable Nuclei ~8000

Many unseen nuclides



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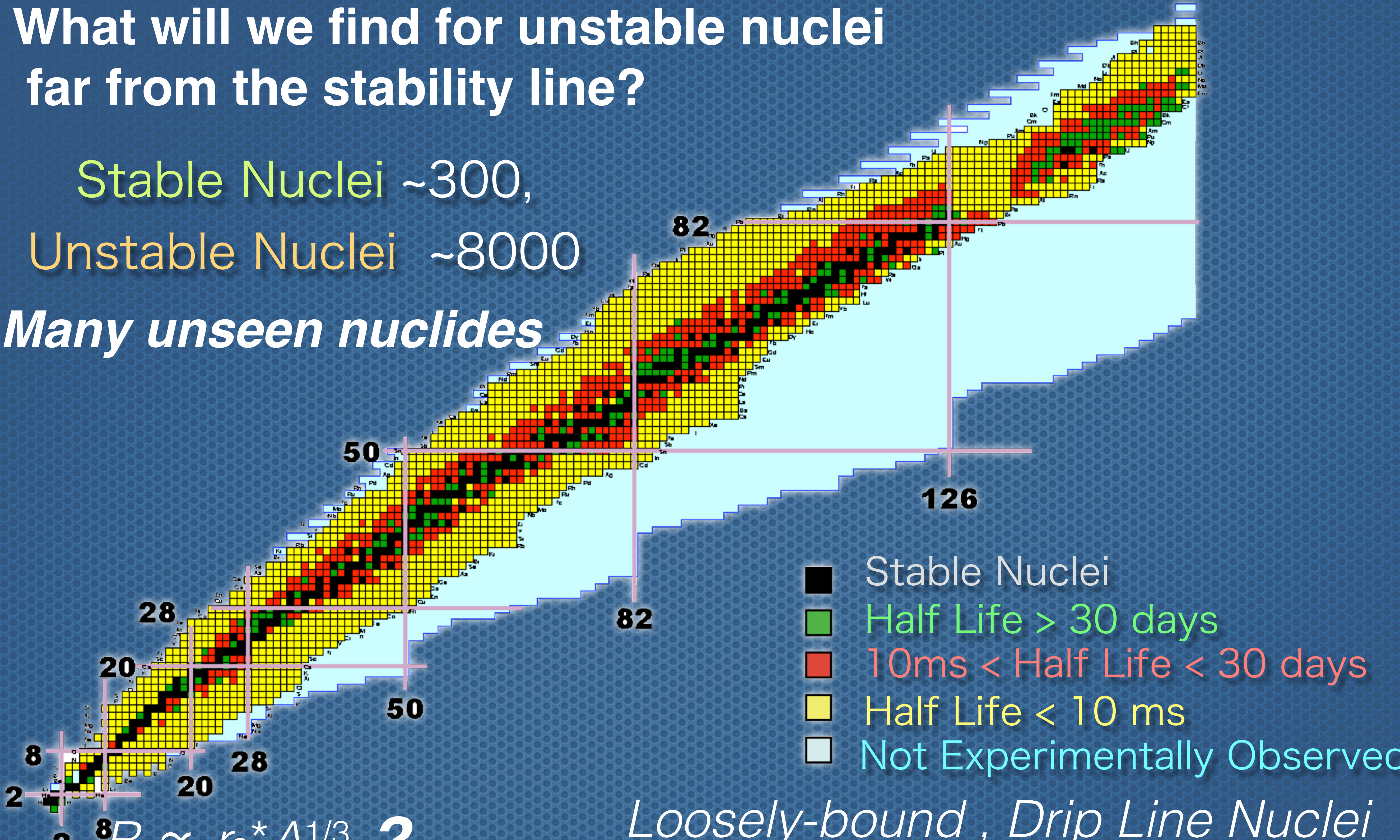


$R \propto r_0 {}^{*} A^{1/3}$ **?**

$m\,\rho_0 \approx 2.8 \times 10^{14}\ \mathrm{g \cdot cm^{-3}}$ **?**

Loosely-bound , Drip Line Nuclei

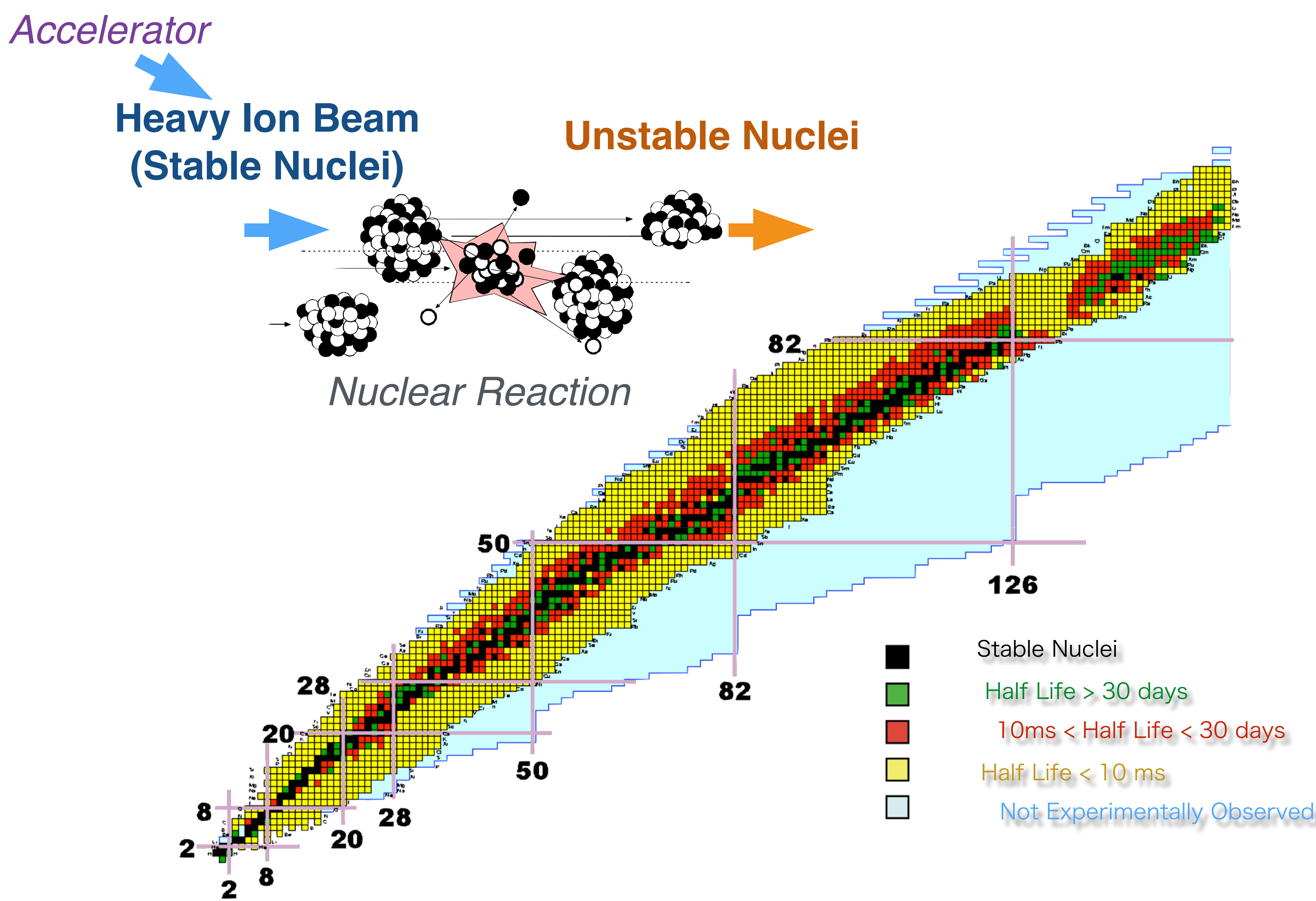
Weak Binding Energy

How is the structure **?**

Magic Number **?**

How can we study Unstable Nuclei?

Experimental Approach to Unstable Nuclei



Accellerator

What is the accelerator?

The machine which give certain kinetic energy to charged particles by accelerating and controlling them with the use of electro magnetic field.

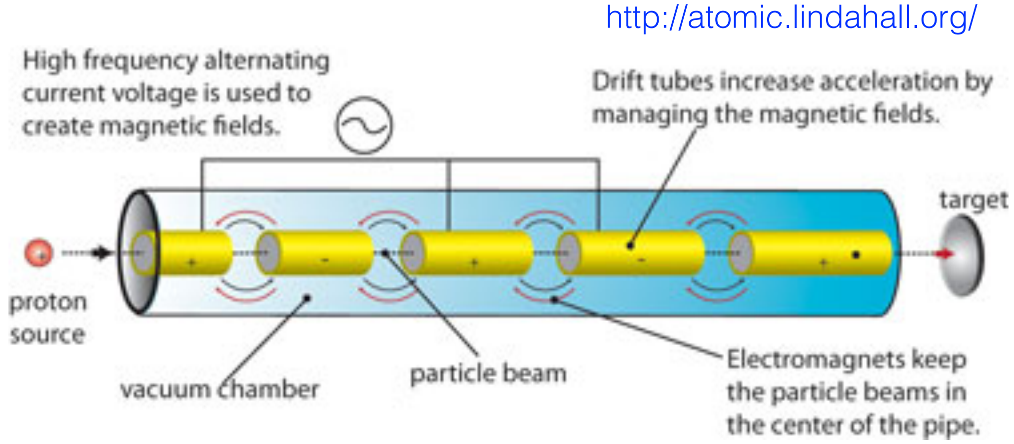
Unit of Energy

eV : Amount of energy gained by the charge of a single electron ($1.6*10^{-19}$) accelerated by an electric potential difference of 1V.

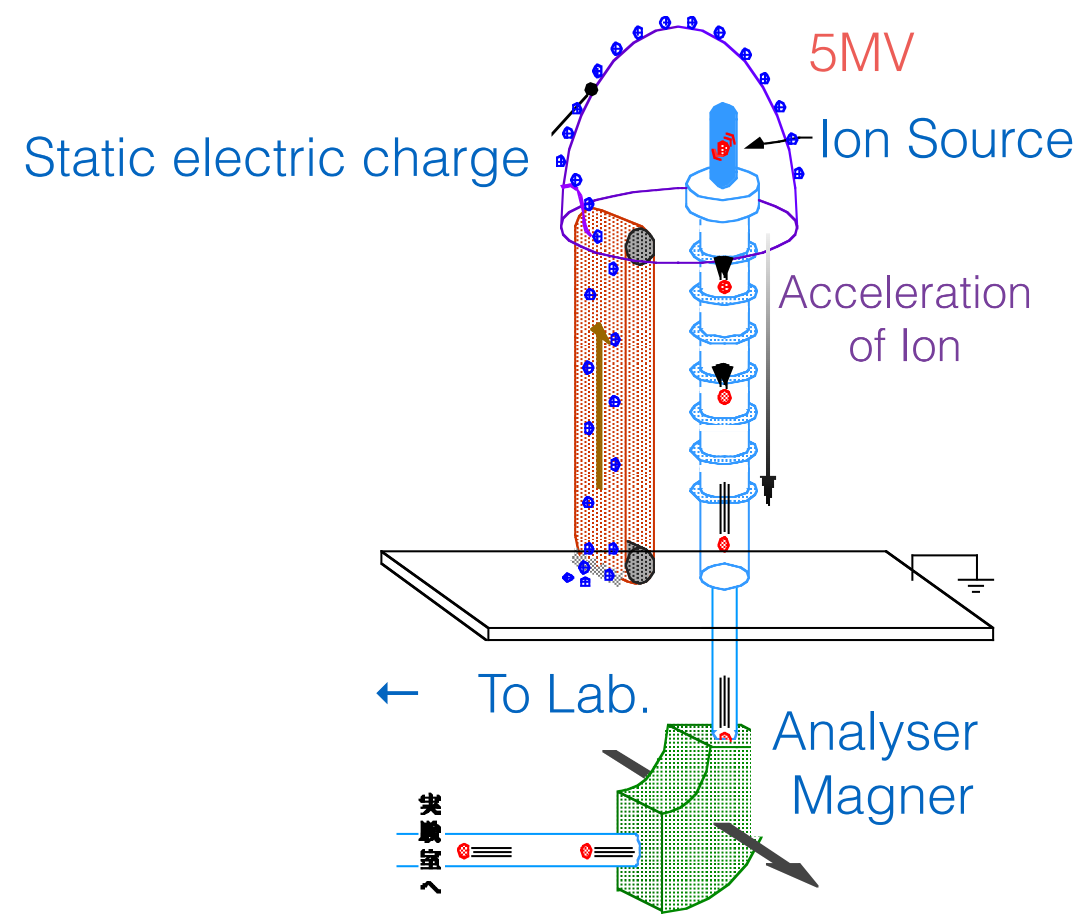
$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$$

- Electrostatic Accellerator
- Linear Accellerator

http://atomic.lindahall.org/



- Circular Accellerator



Van de Graaff

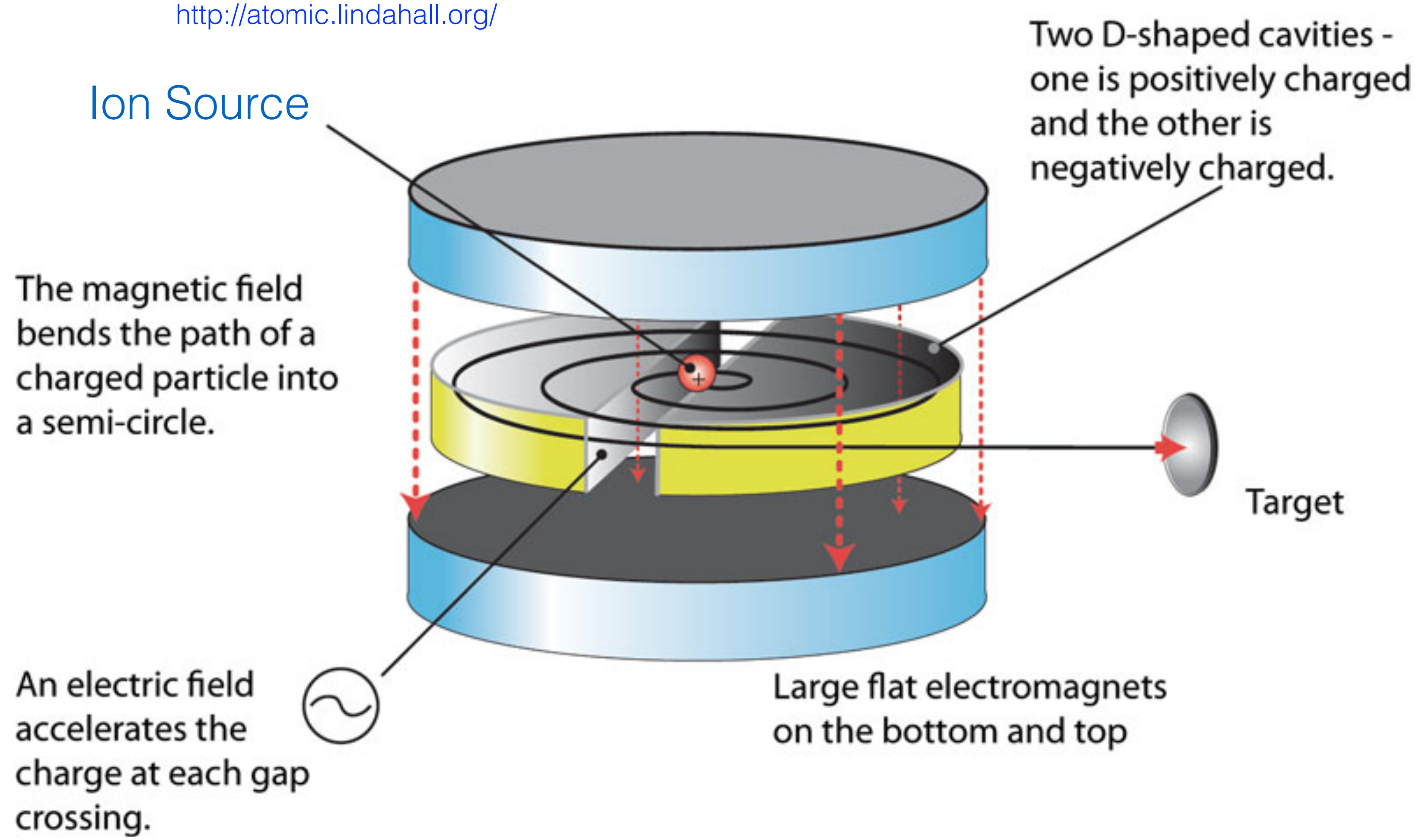
Circular Accellerator

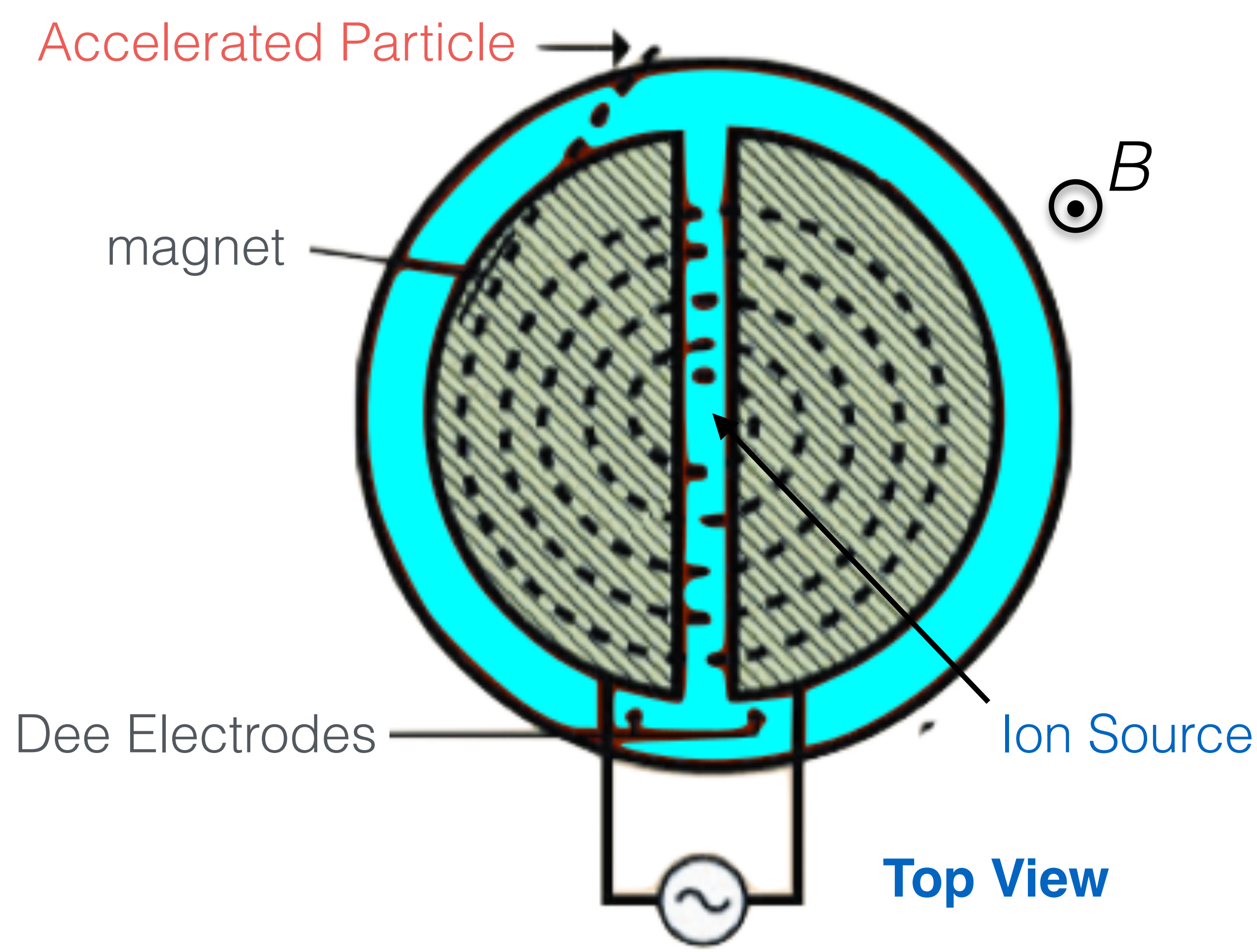
$$qvB = \frac{mv^2}{r}$$

$$r = \frac{mv}{qB}$$

$$T = \frac{2\pi m}{qB}$$

T is always constant, independent of particles velocity

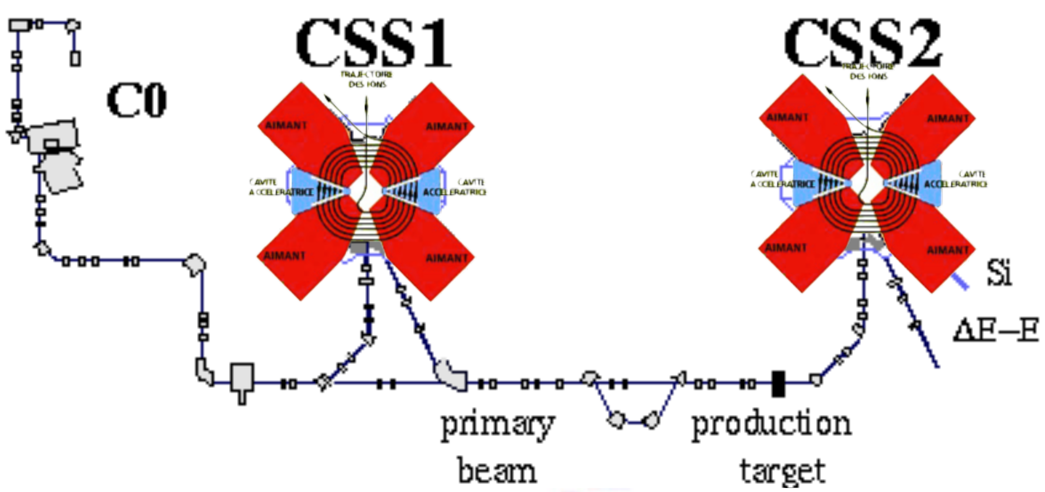


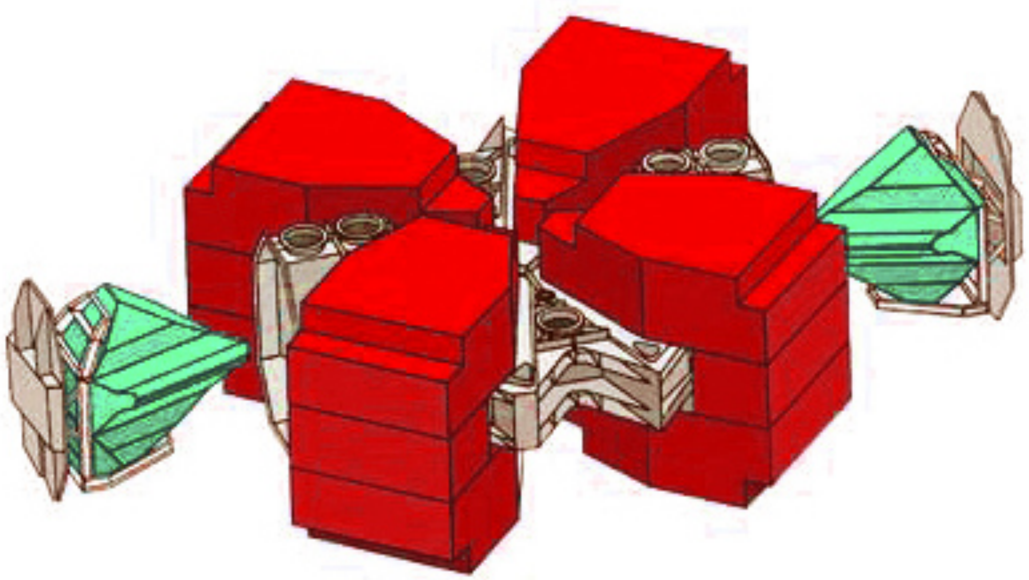


Cyclotron Facilities

NSCL K500, K1200 (USA)

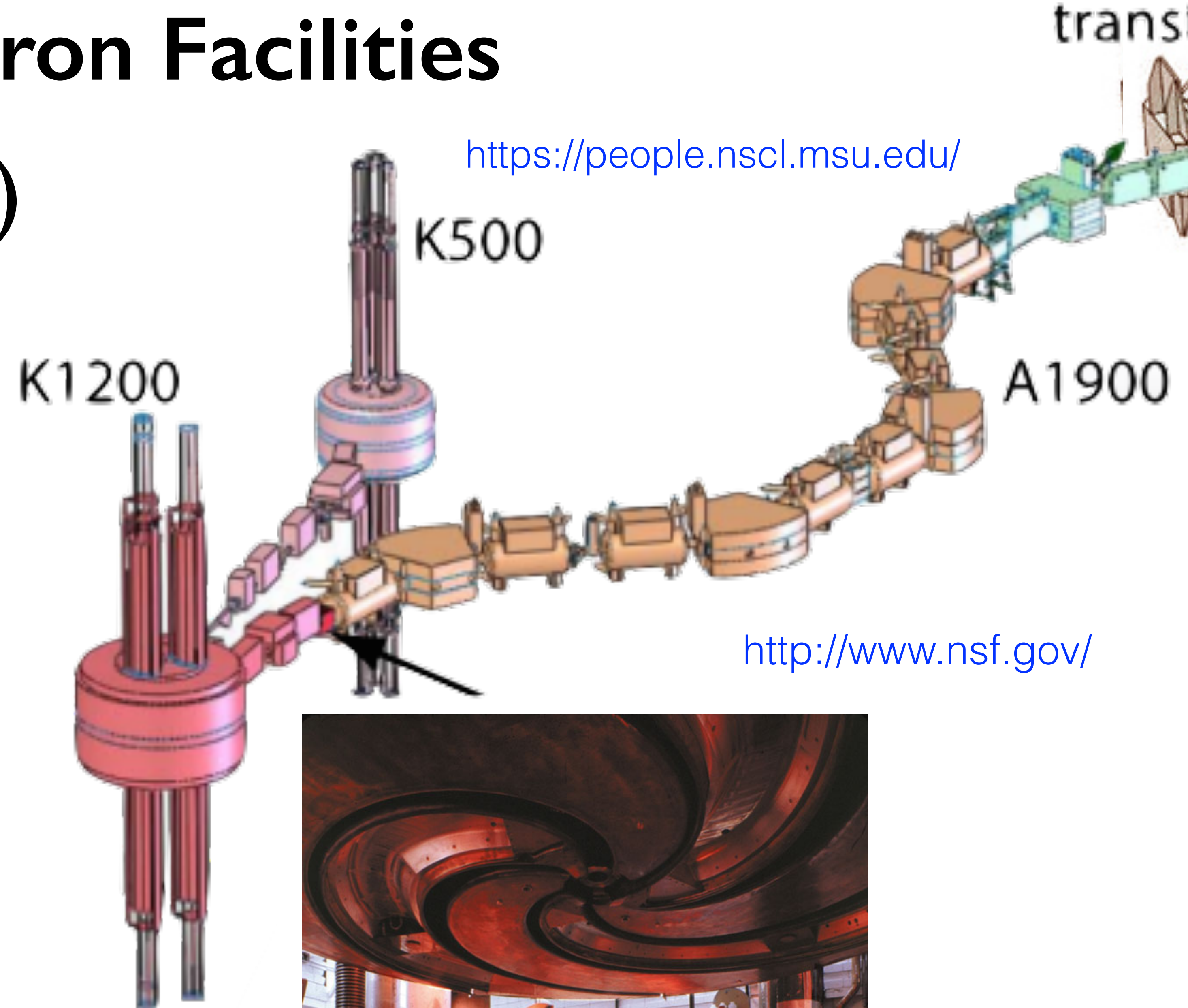
GANIL CSS1, CSS2



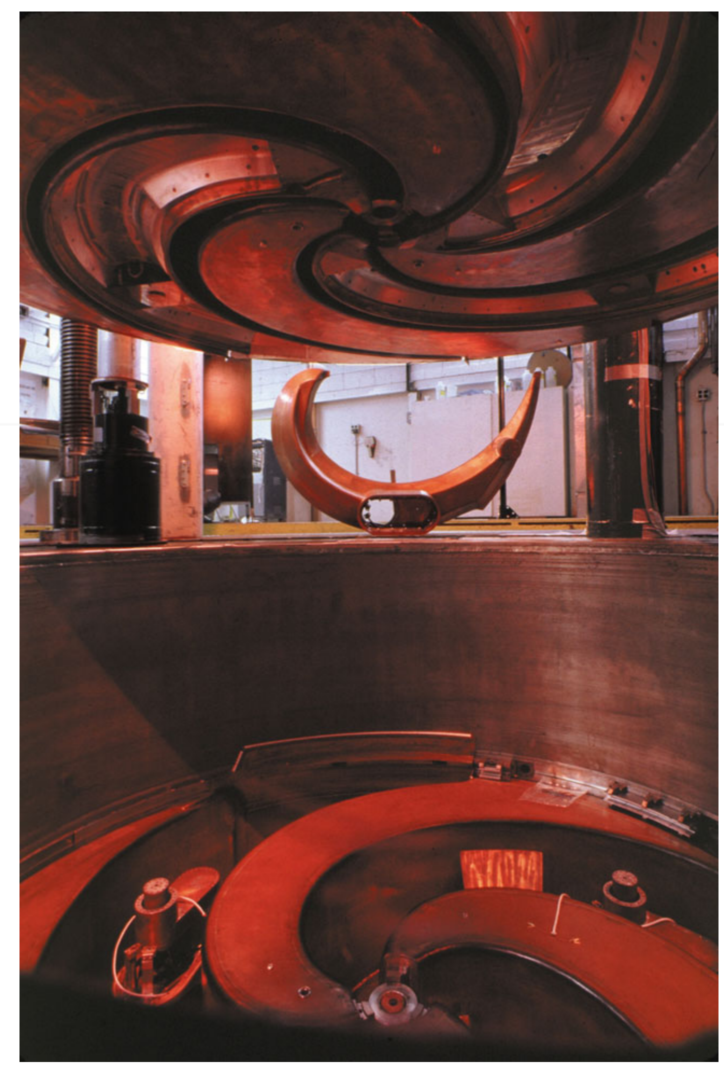


http://www.ganil-spiral2.eu/science-us/accelerator/css1-css2

https://people.nscl.msu.edu/



http://www.nsf.gov/

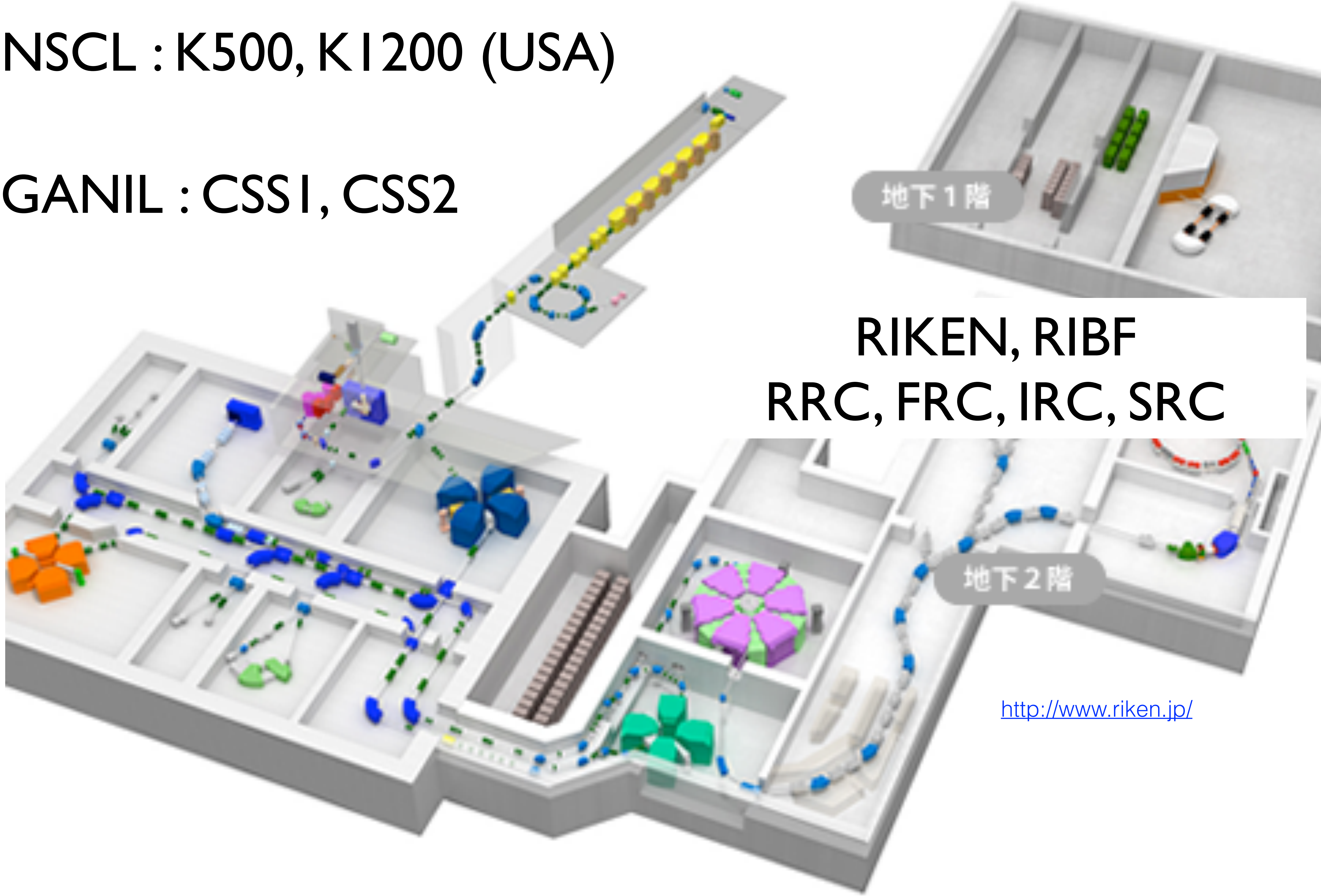


Cyclotron Facilities

NSCL : K500, K1200 (USA)

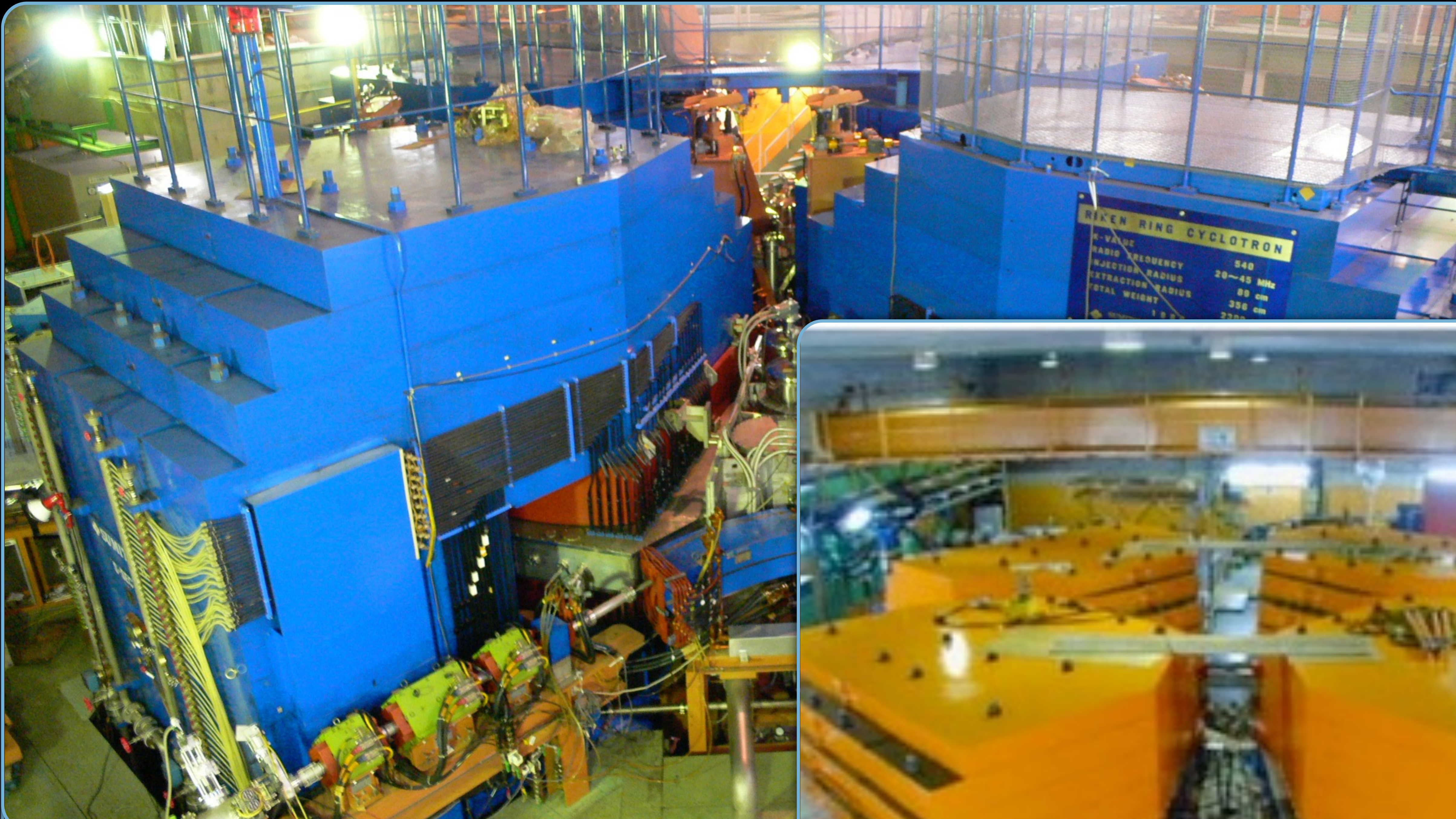
GANIL : CSS1, CSS2

RIKEN, RIBF
RRC, FRC, IRC, SRC



http://www.riken.jp/

http://www.riken.jp/



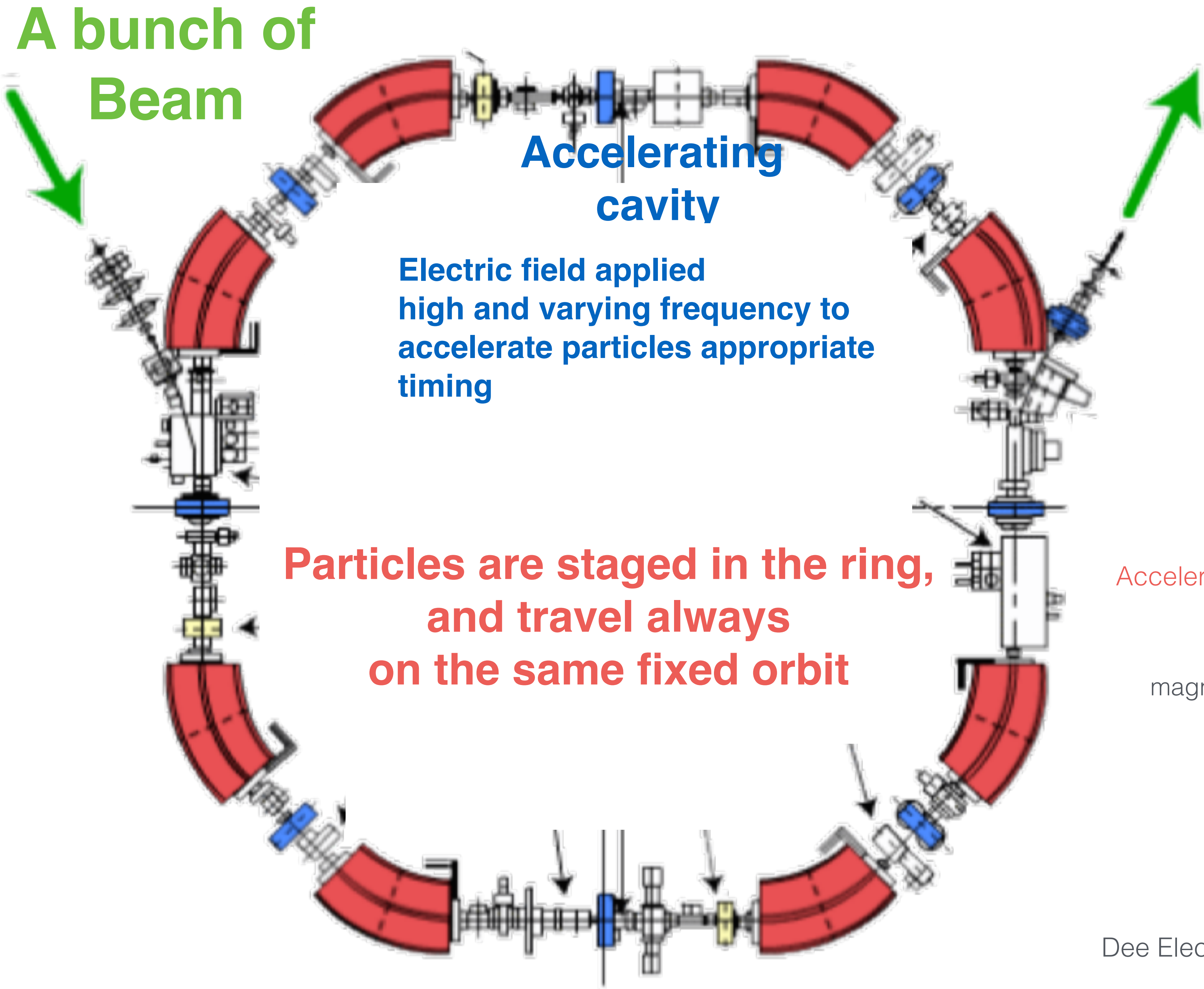
Synchrotron Accelerator

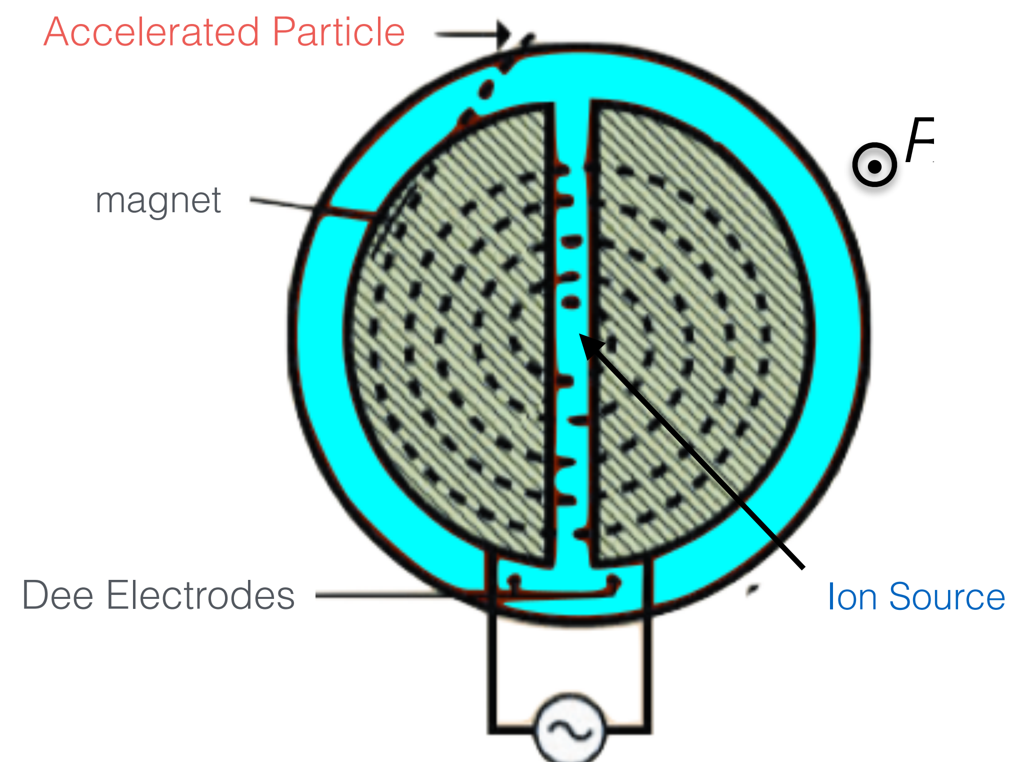
At relativistic energy

$$qvB = \frac{mv^2}{r}$$

$$T = \frac{2\pi m}{qB}$$

~~T is always constant, independent of particles velocity~~



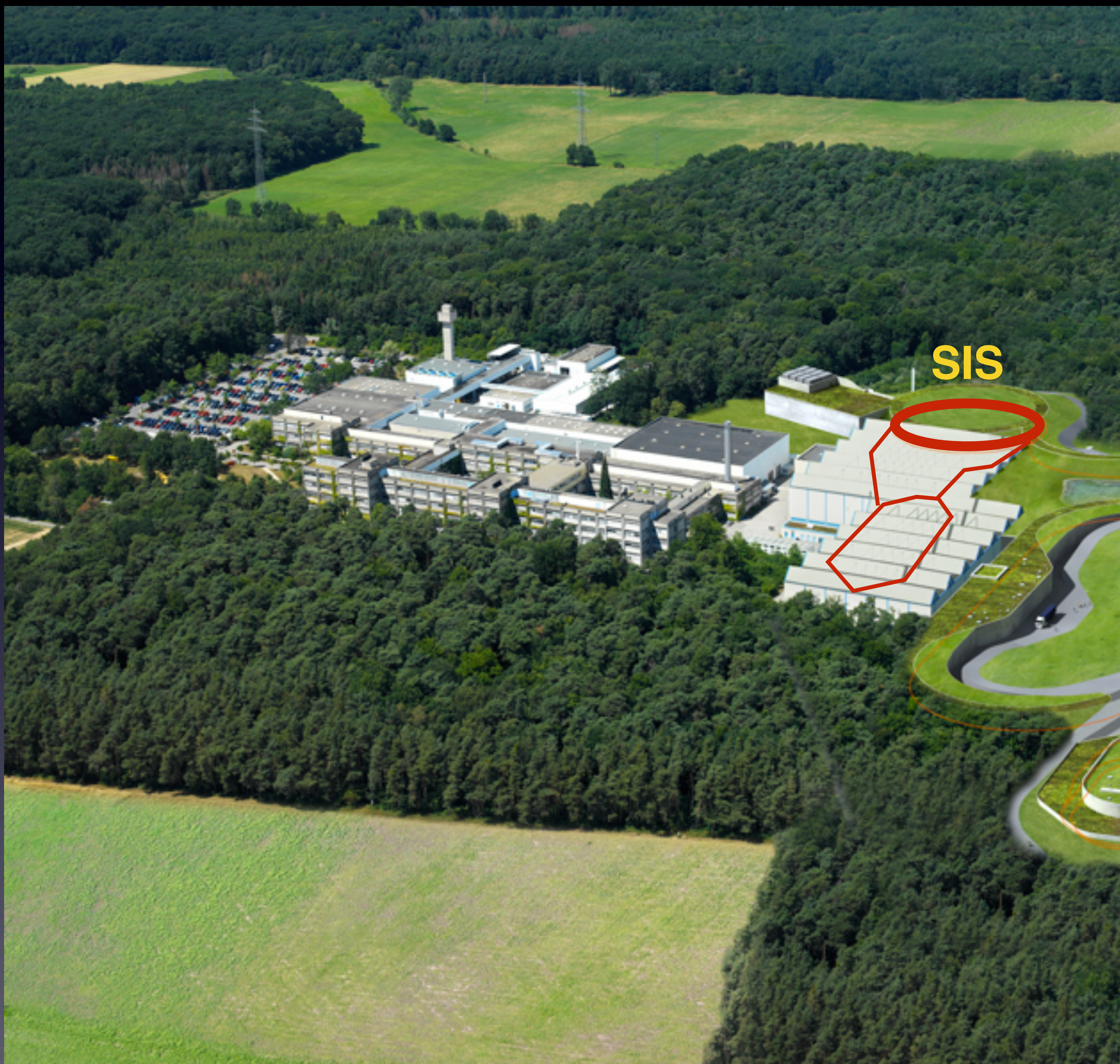


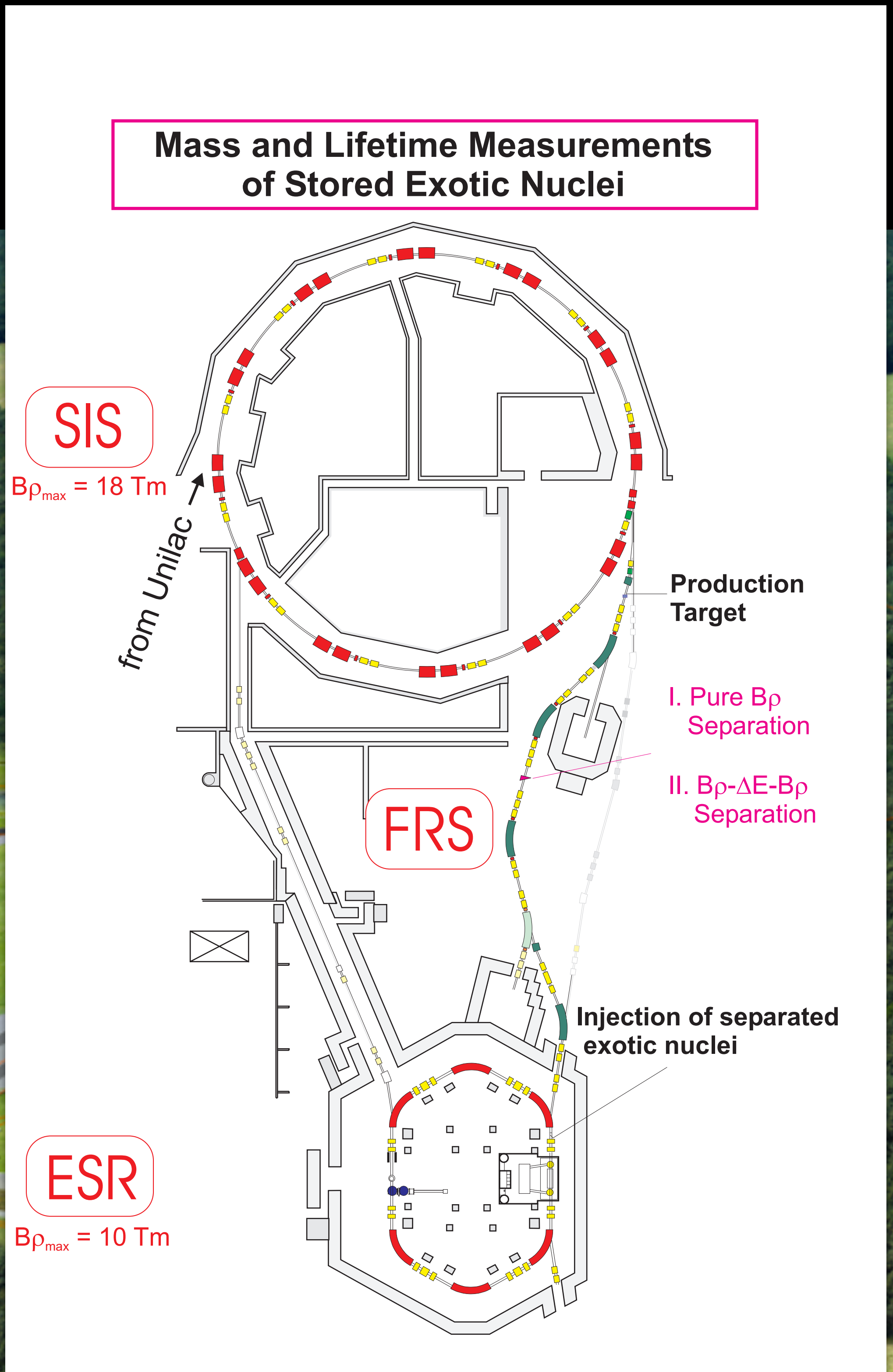
Cyclotron : Continuous Acceleration

Cyclotron : High **Intensity**

Synchrotron : High **Energy**

- GSI, SIS

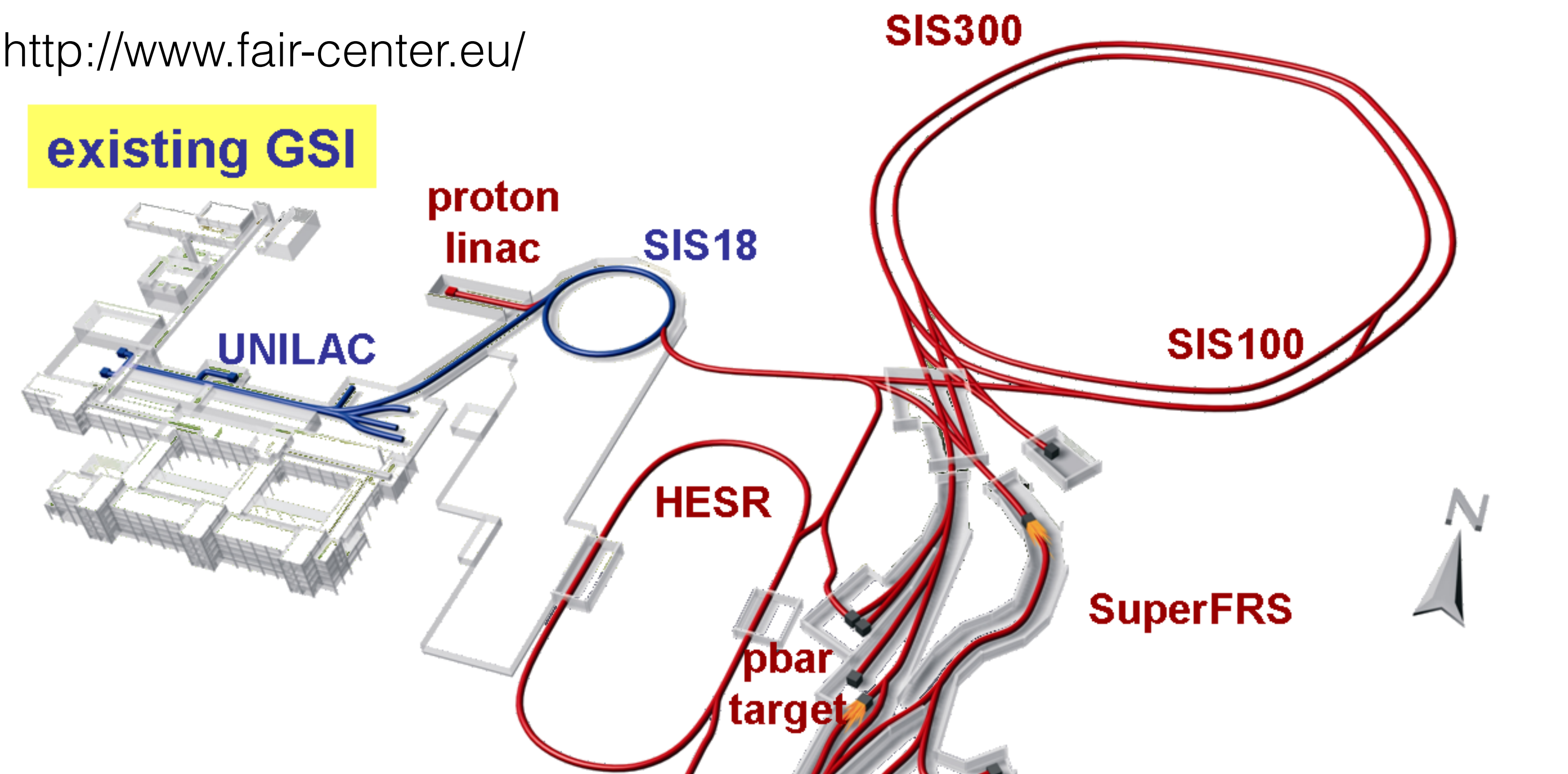




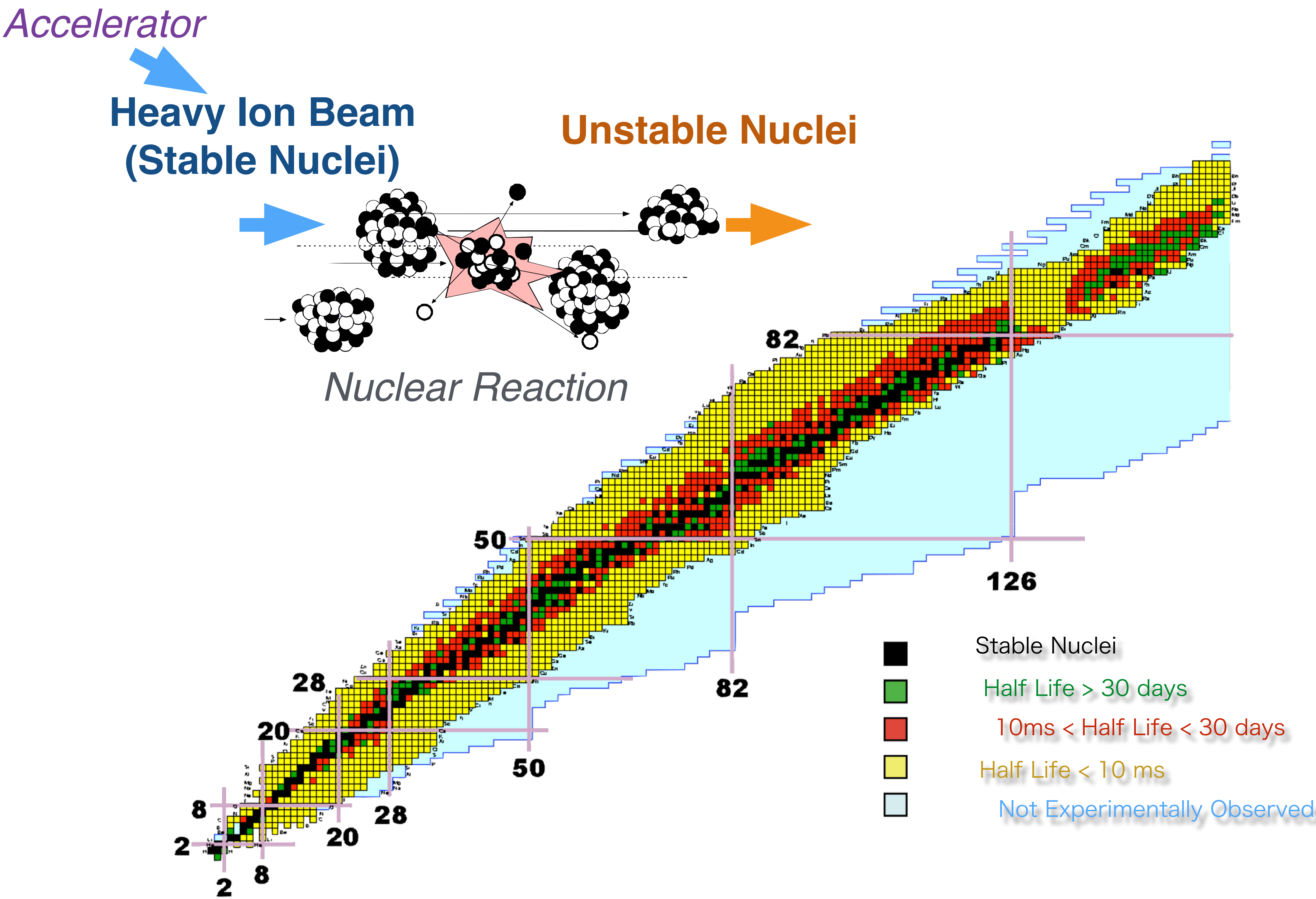
F. Bosch, Lect. Notes Phys. 651, 137 (2004)

- GSI, SIS and then SIS100, SIS300

http://www.fair-center.eu/



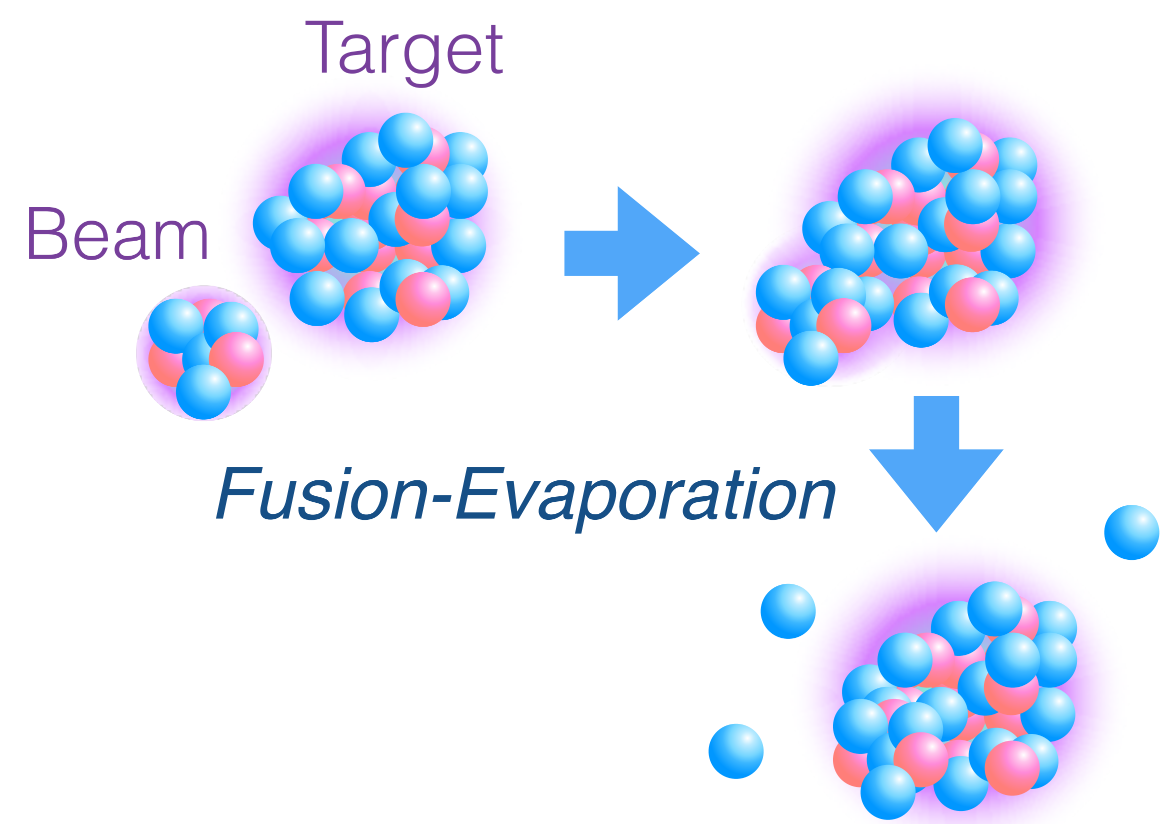
Experimental Approach to Unstable Nuclei



Production of Unstable Nuclei as Radioactive Isotope (RI) Beam

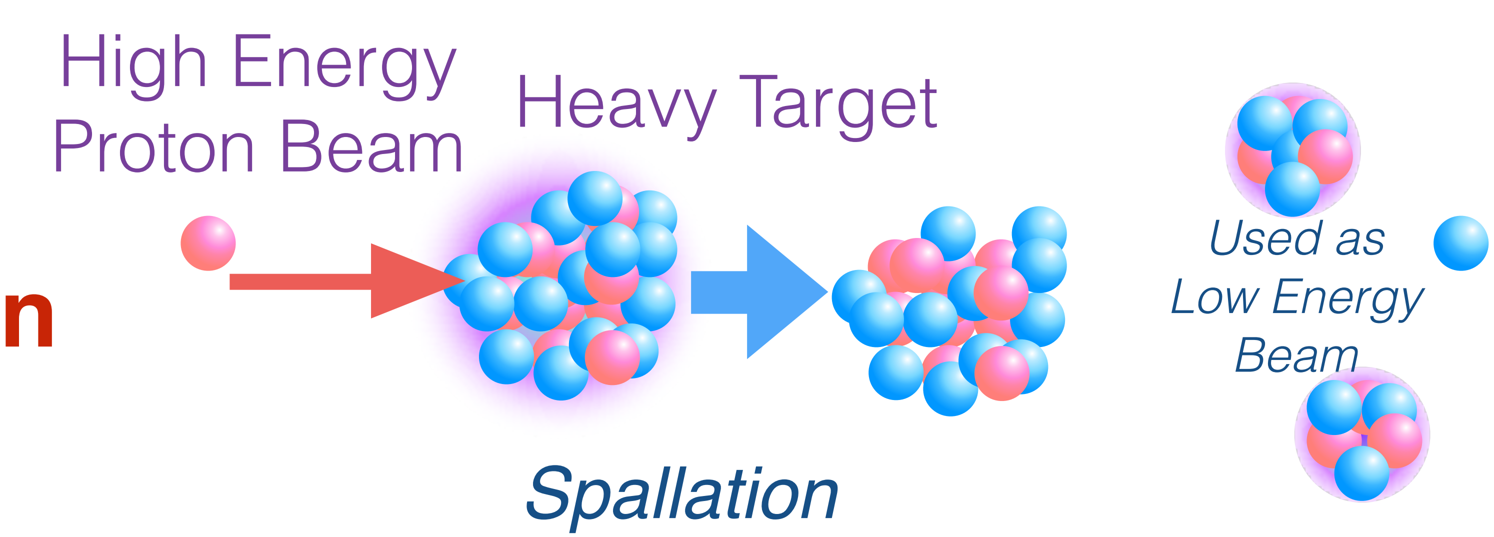
Production of Unstable Nuclei

- Fusion-evaporation
- Fission
- Transfer Reaction

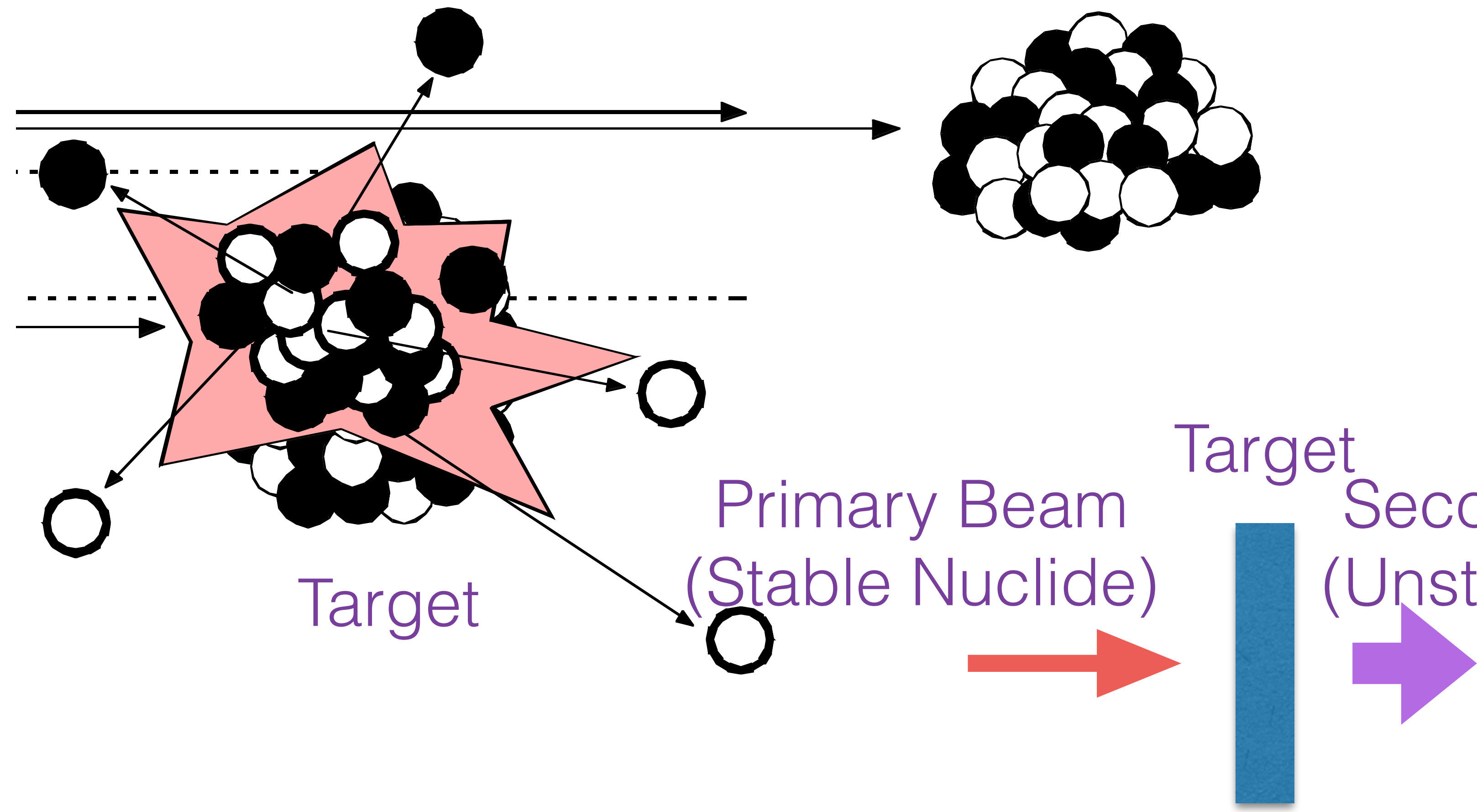


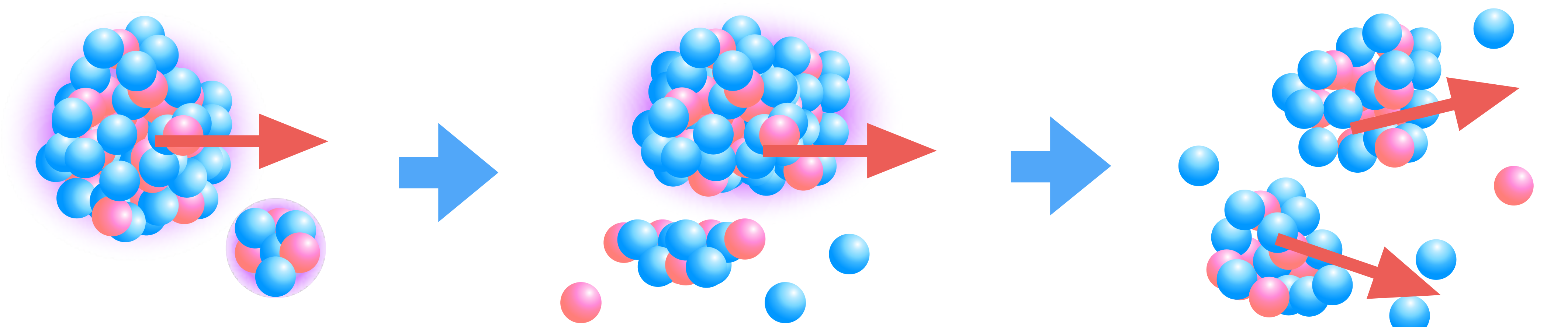
Production of **Unstable Nuclei Beam**

- Spallation → ISOL
- **Projectile Fragmentation**
- **Fission Ablation**



Projectile Fragmentation





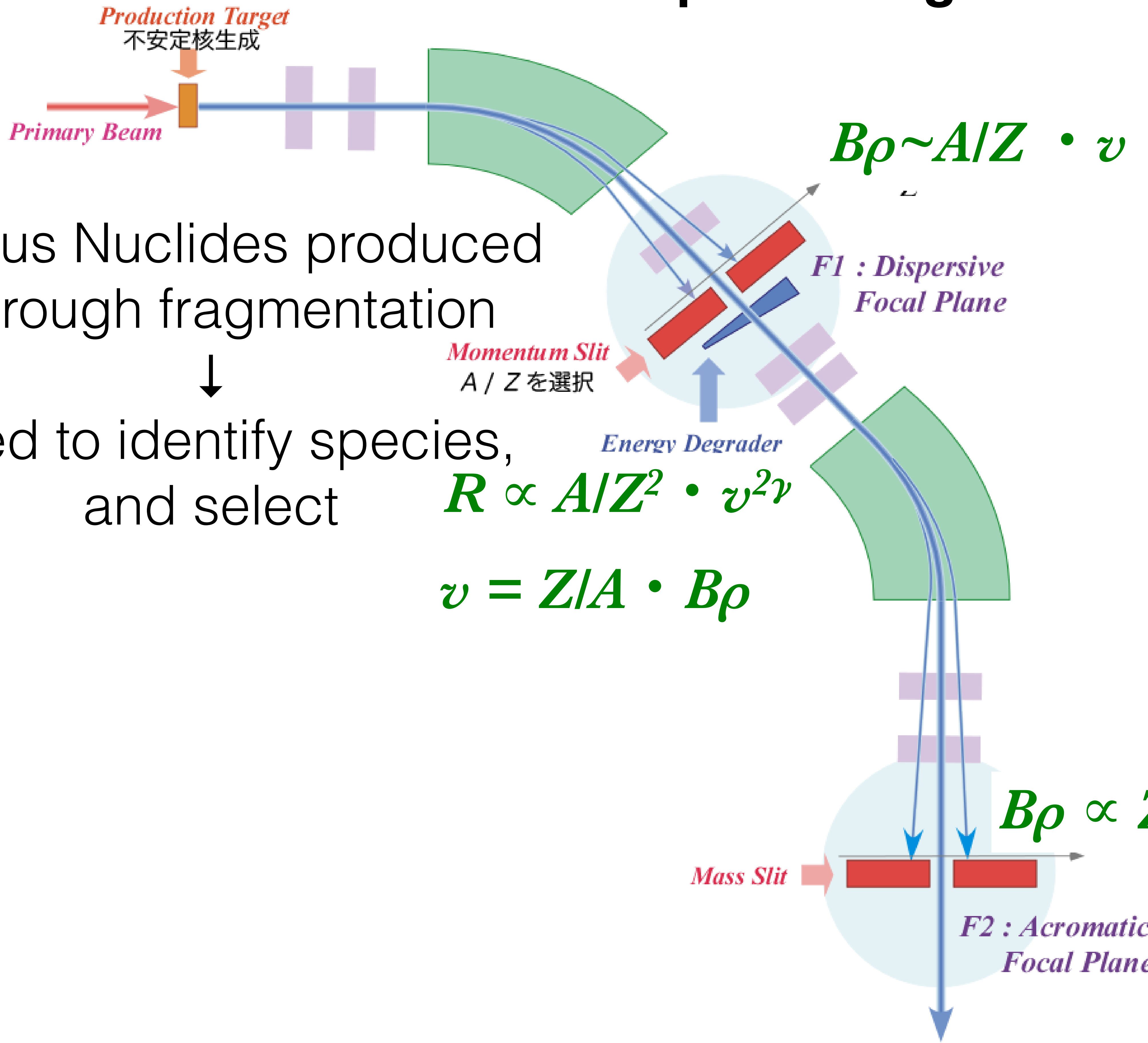
Fission Abrasion

Principle of Fragment Separator

Various Nuclides produced thorough fragmentation

↓

Need to identify species, and select



$B\rho \sim A/Z \cdot v$

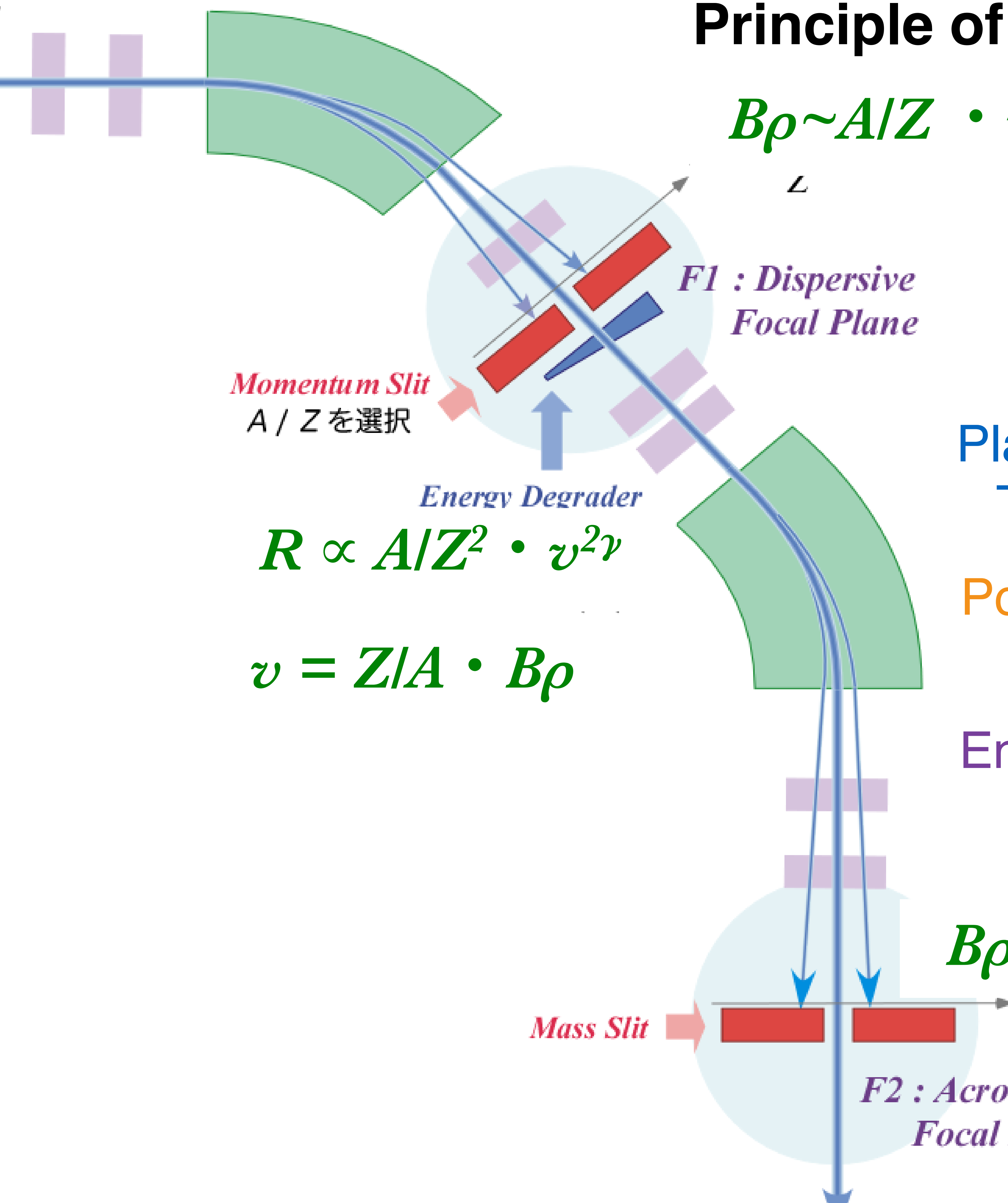
$R \propto A/Z^2 \cdot v^{2\gamma}$

$v = Z/A \cdot B\rho$

$B\rho \propto Z^{2\gamma-2} / A^{2\gamma-2}$

Principle of Fragment Separator

$$B\rho \sim A/Z \cdot v$$



$$R \propto A/Z^2 \cdot v^{2\gamma}$$

$$v = Z/A \cdot B\rho$$

For the more precise Particle Identification

Detectors

Plastic Scintillation Counter
Time Of Flight (TOF) : ***v***

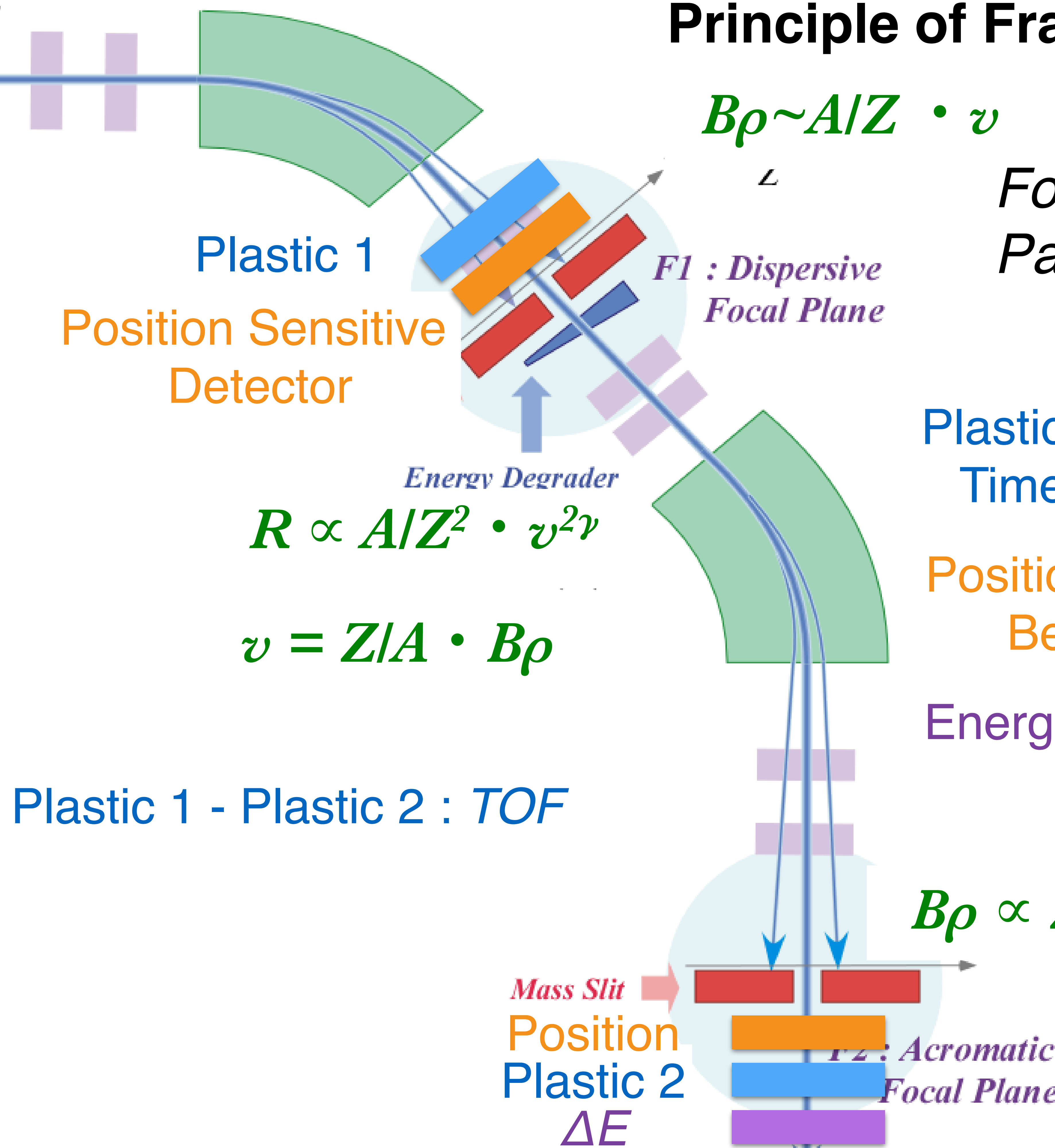
Position Sensitive Detector
Beam Position : ***Bρ***

Energy-Loss (ΔE) Detector

$$\Delta E \propto Z^2/v^2$$

$$B\rho \propto Z^{2\gamma-2} / A^{2\gamma-2}$$

Principle of Fragment Separator



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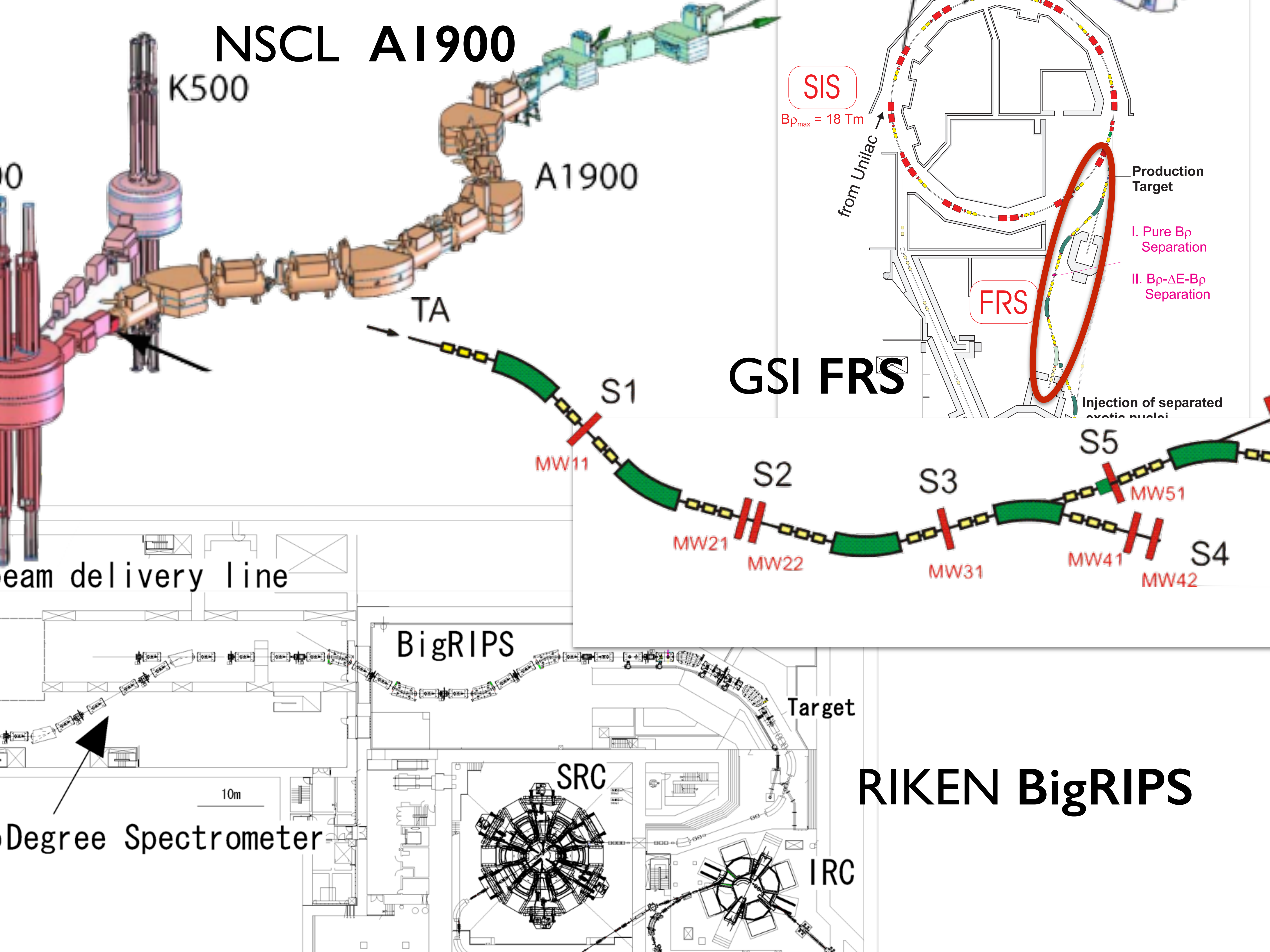
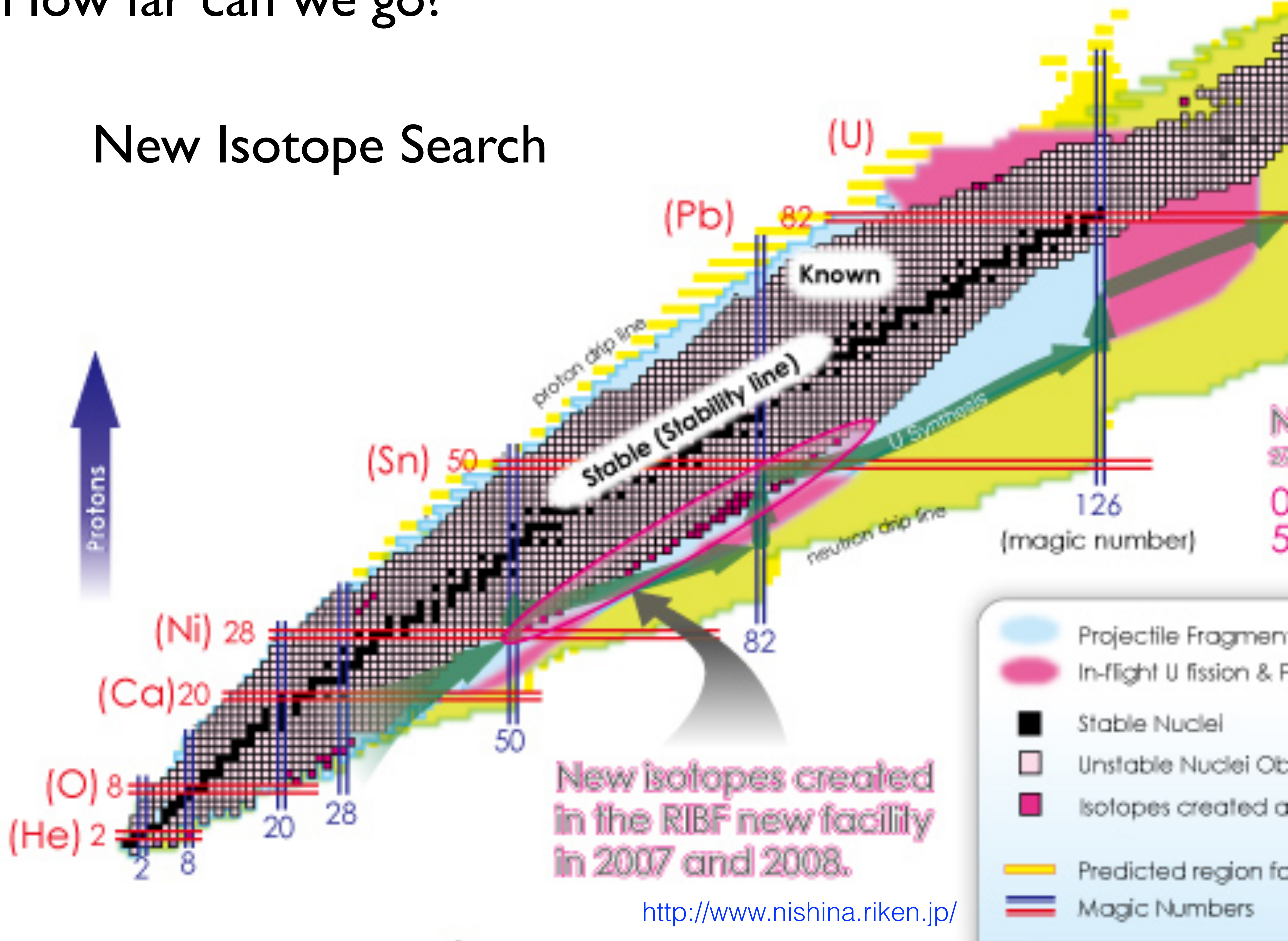

NSCL A1900
K500
A1900
TA
S1
MW11
S2
MW21
MW22
S3
MW31
S5
MW51
MW41
MW42
S4
SIS
Bρ$_{max}$ = 18 Tm
from Unilac
Production Target
I. Pure Bρ Separation
II. Bρ-ΔE-Bρ Separation
FRS
Injection of separated
GSI FRS
eam delivery line
BigRIPS
Target
10m
Degree Spectrometer
SRC
IRC
RIKEN BigRIPS

How far can we go?

New Isotope Search

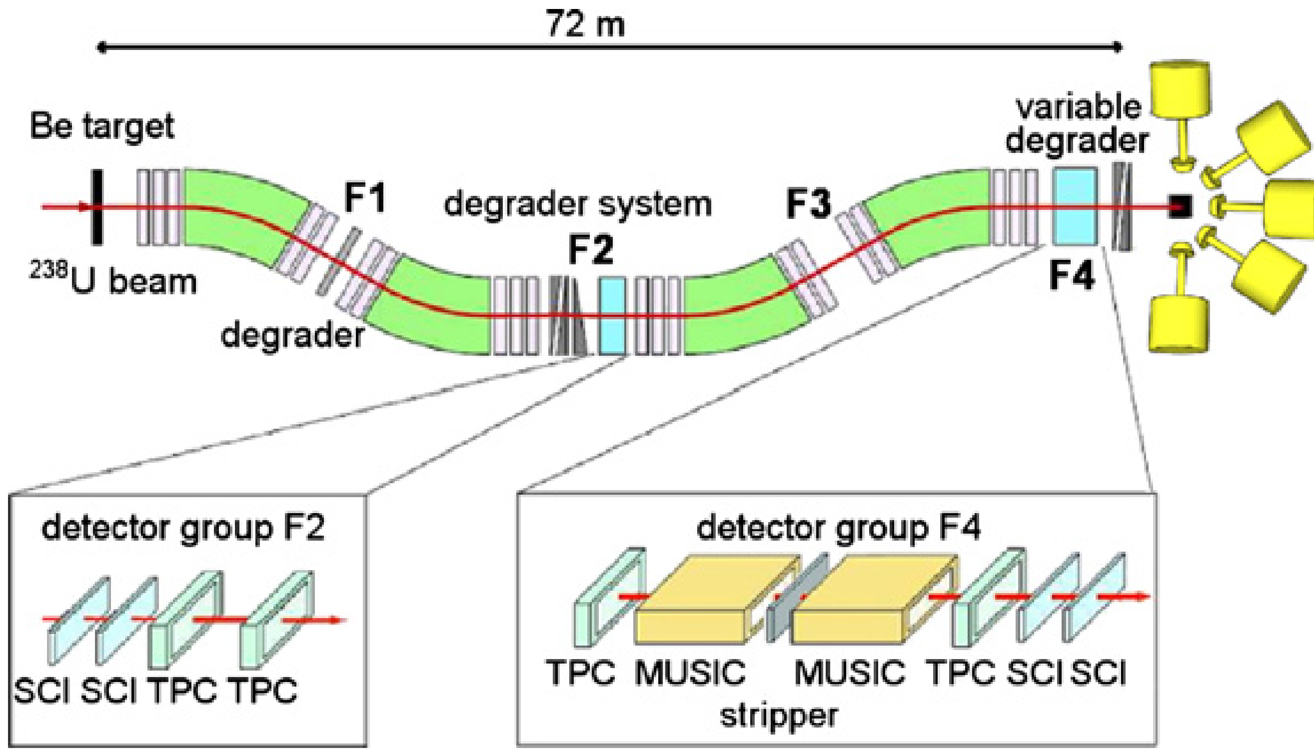


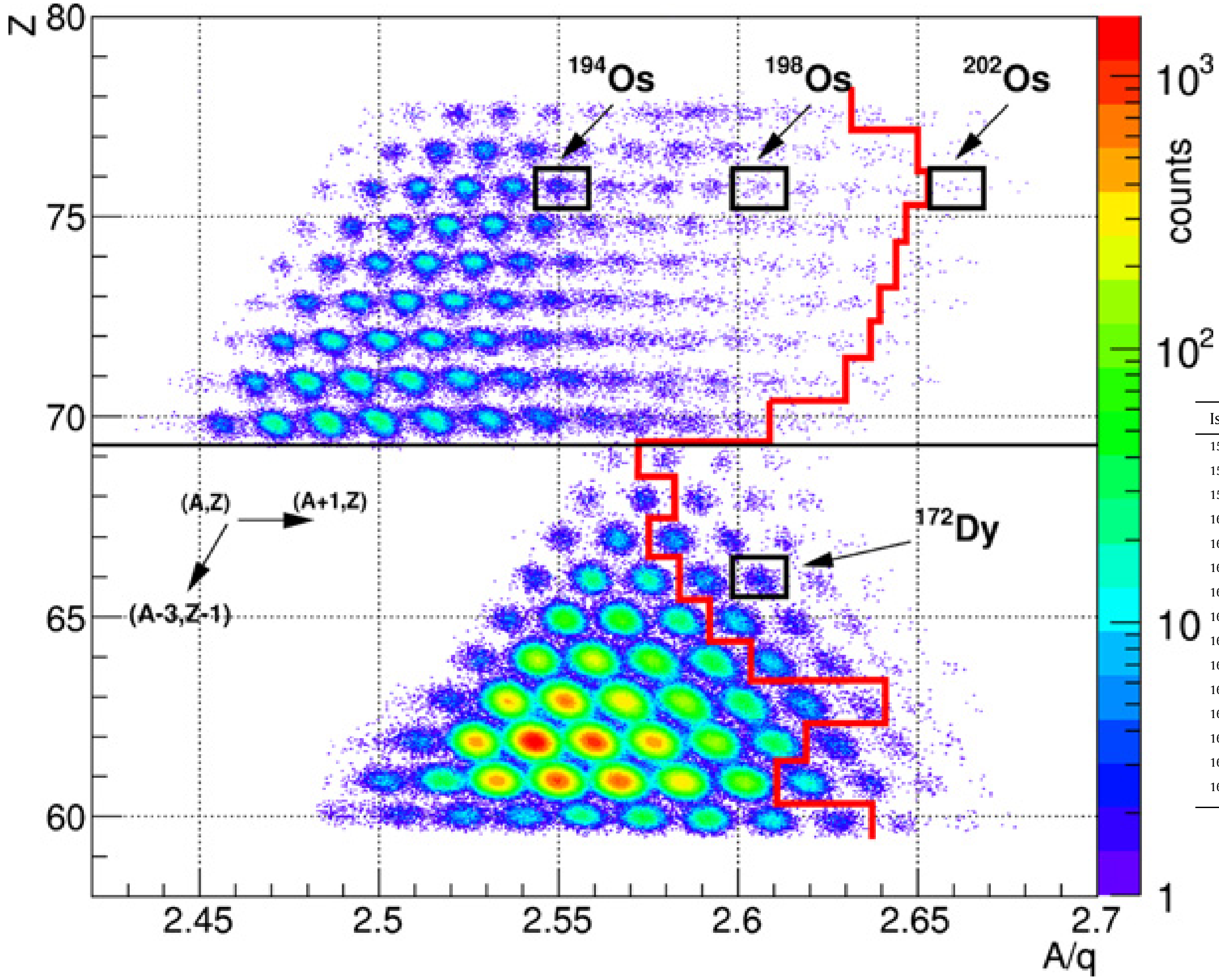
http://www.nishina.riken.jp/

Recent Works for New Isotope Search

J. Kurcewicz et al., Phys. Lett. **B 717** (2012) 371–375

GSI (2012)
^{238}U 1GeV/u on Be Target fission abrasion



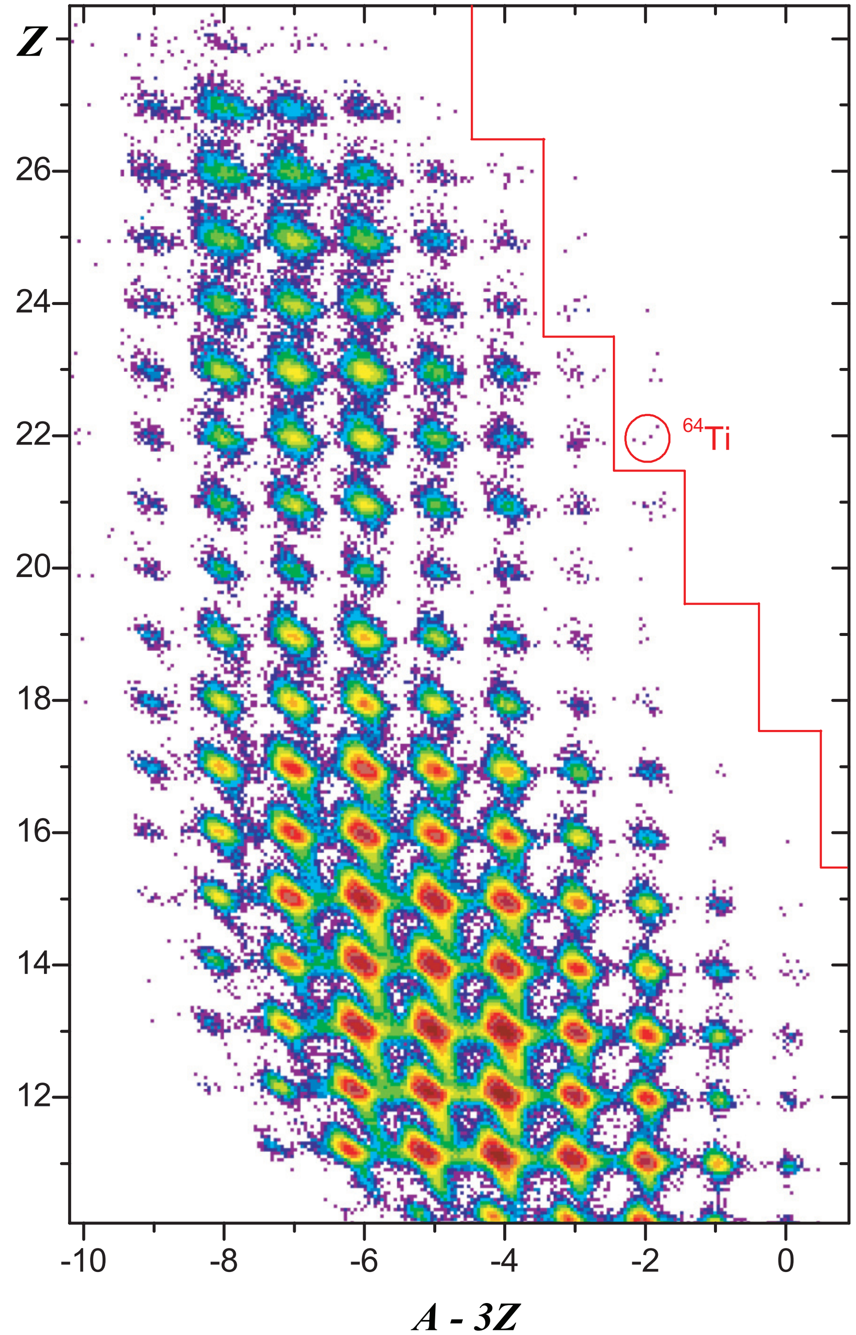


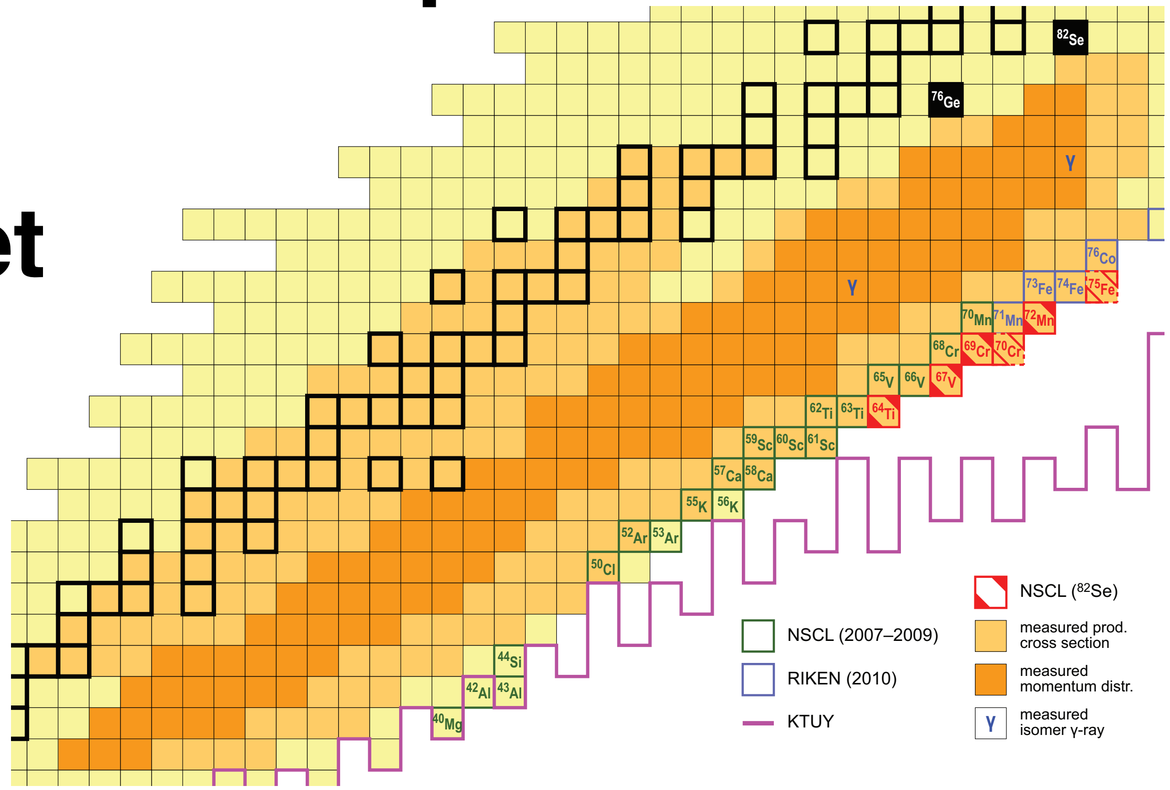
Isotope	σ (nb)	Isotope	σ (nb)	Isotope	σ (nb)	Isotope	σ (nb)
^{157}Nd*	980(40)	^{168}Gd	78(5)	^{176}Er	68(5)	^{188}Lu	0.010(3)
^{158}Nd*	201(11)	^{169}Gd	10.6(15)	^{177}Er	18(2)	^{190}Hf*	0.027(13)
^{159}Nd	39(4)	^{170}Gd	2.6(8)	^{178}Er	5.5(9)	^{193}Ta	0.017(5)
^{160}Nd	9.5(22)	^{169}Tb	751(28)	^{178}Tm*	24(3)	^{194}Ta	0.0037(19)
^{161}Nd	3.0(17)	^{170}Tb	99(6)	^{179}Tm	1.21(18)	^{195}W*	0.049(1)
^{160}Pm	518(36)	^{171}Tb	14(2)	^{180}Tm	4.5(9)	^{196}W	0.018(4)
^{161}Pm	161(9)	^{172}Tb	1.0(4)	^{181}Tm	0.6(3)	^{197}W	0.0034(17)
^{162}Pm	25(3)	^{171}Dy	441(18)	^{181}Yb*	2.3(3)	^{198}Re*	0.028(7)
^{163}Pm	4.5(15)	^{172}Dy	121(7)	^{182}Yb*	0.45(10)	^{199}Re	0.0076(27)
^{163}Sm	134(11)	^{173}Dy	18(2)	^{183}Yb	0.21(5)	^{202}Os	0.0044(20)
^{164}Sm	42(4)	^{174}Dy	1.9(6)	^{184}Yb	0.028(9)	^{203}Os	0.0025(18)
^{165}Sm	7.8(16)	^{173}Ho	341(15)	^{185}Yb	0.007(3)	^{205}Ir	0.003(2)
^{167}Eu	7.1(12)	^{174}Ho	98(6)	^{185}Lu*	0.22(7)	^{206}Pt	0.033(11)
^{168}Eu	2.0(8)	^{175}Ho	22(2)	^{186}Lu*	0.15(4)	^{207}Pt	0.008(3)
^{167}Gd	625(23)	^{176}Ho	2.2(6)	^{187}Lu	0.043(9)	^{208}Pt	0.0027(15)

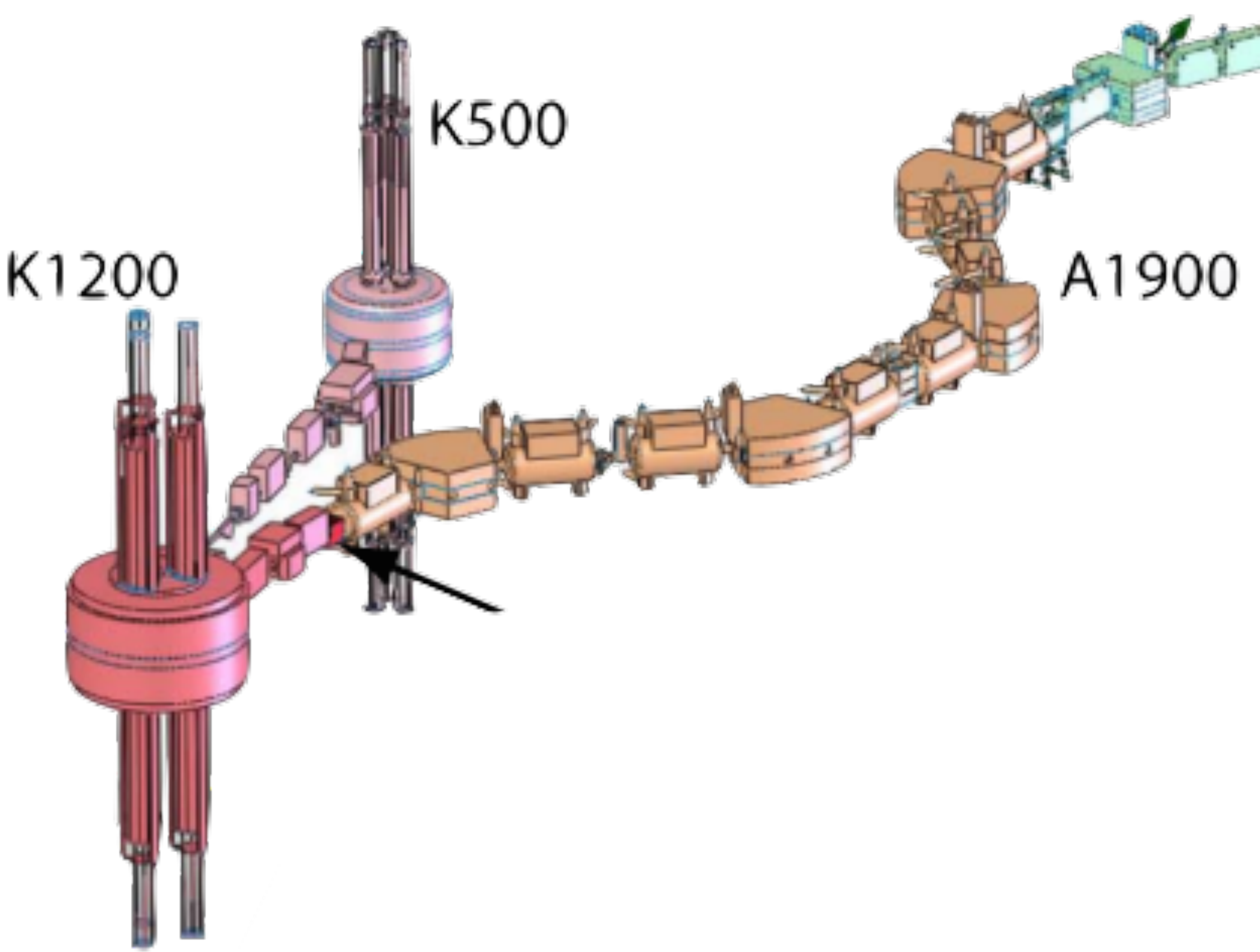
Recent Works for New Isotope Search

NSCL (2013)
^{82}Se 139 MeV/u on Be Target Projectile Fragmentation

O. B. Tarasov et al., Phys. Rev. C **87**, 054612 (2013)





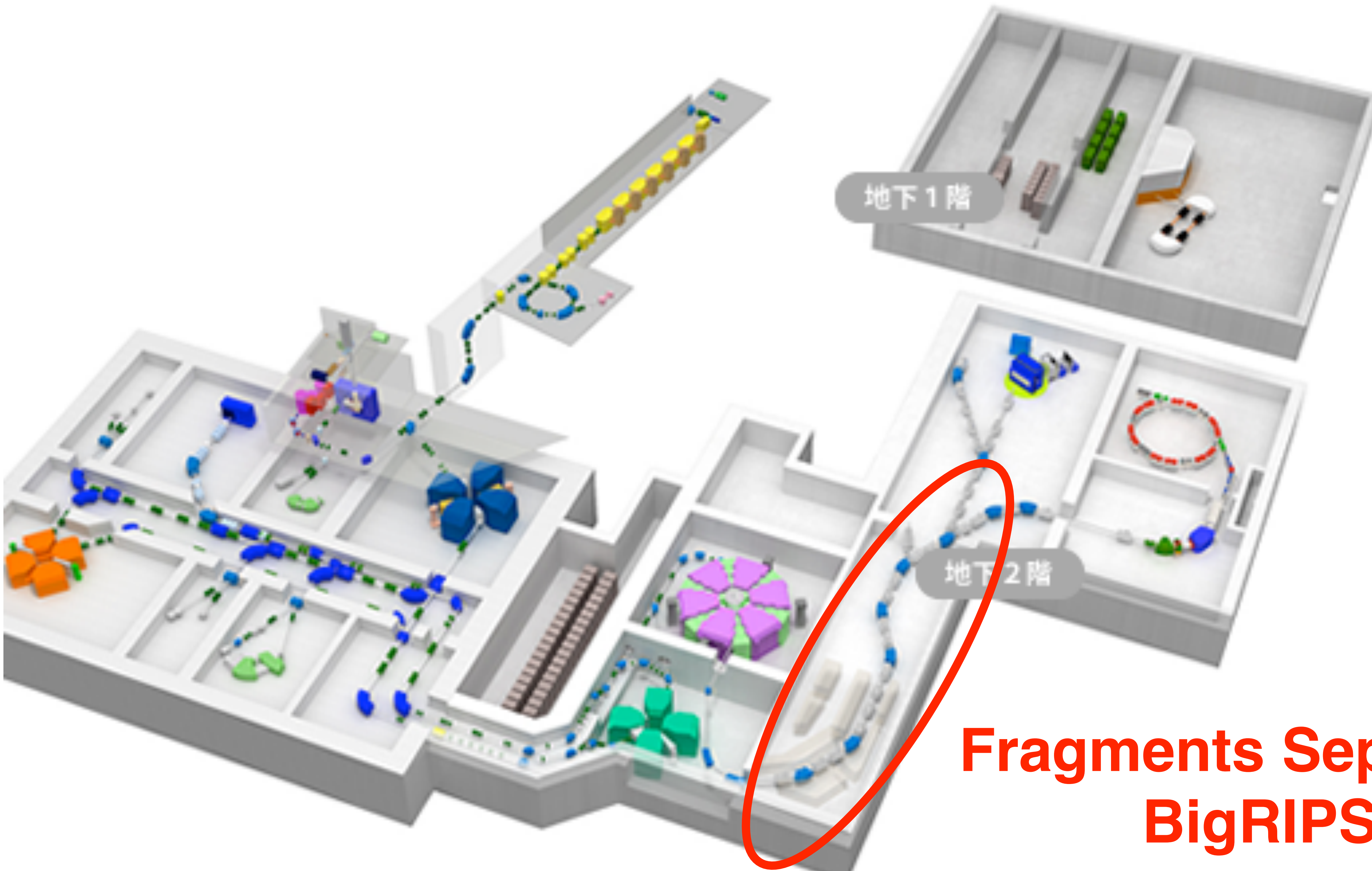


Recent Works for New Isotope Search

RIBF (2014)

^{238}U 345 MeV/u on Be Target

Fission Abrasion

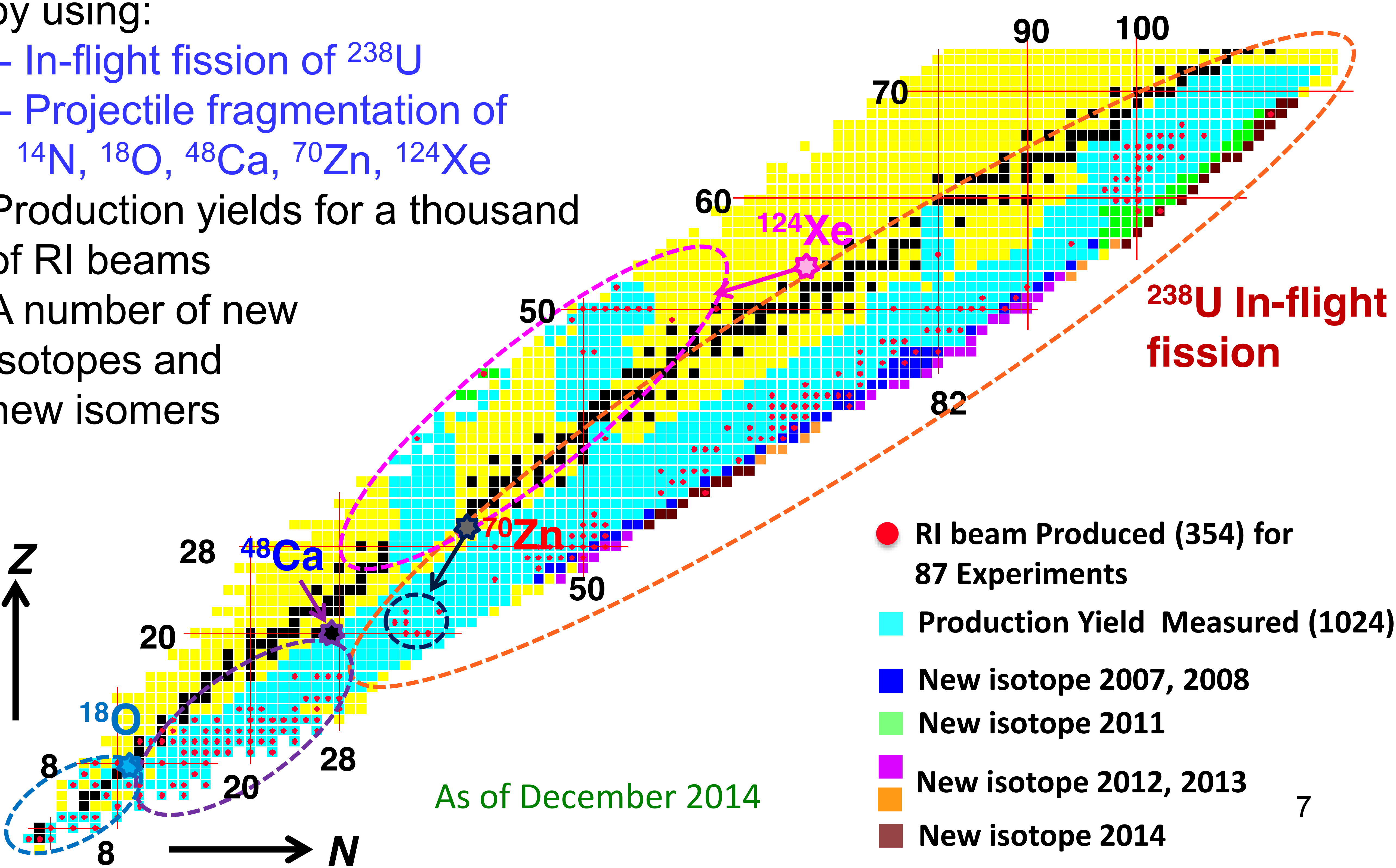


Fragments Separator BigRIPS

RI beams produced at BigRIPS (May 2007 – Dec. 2014)

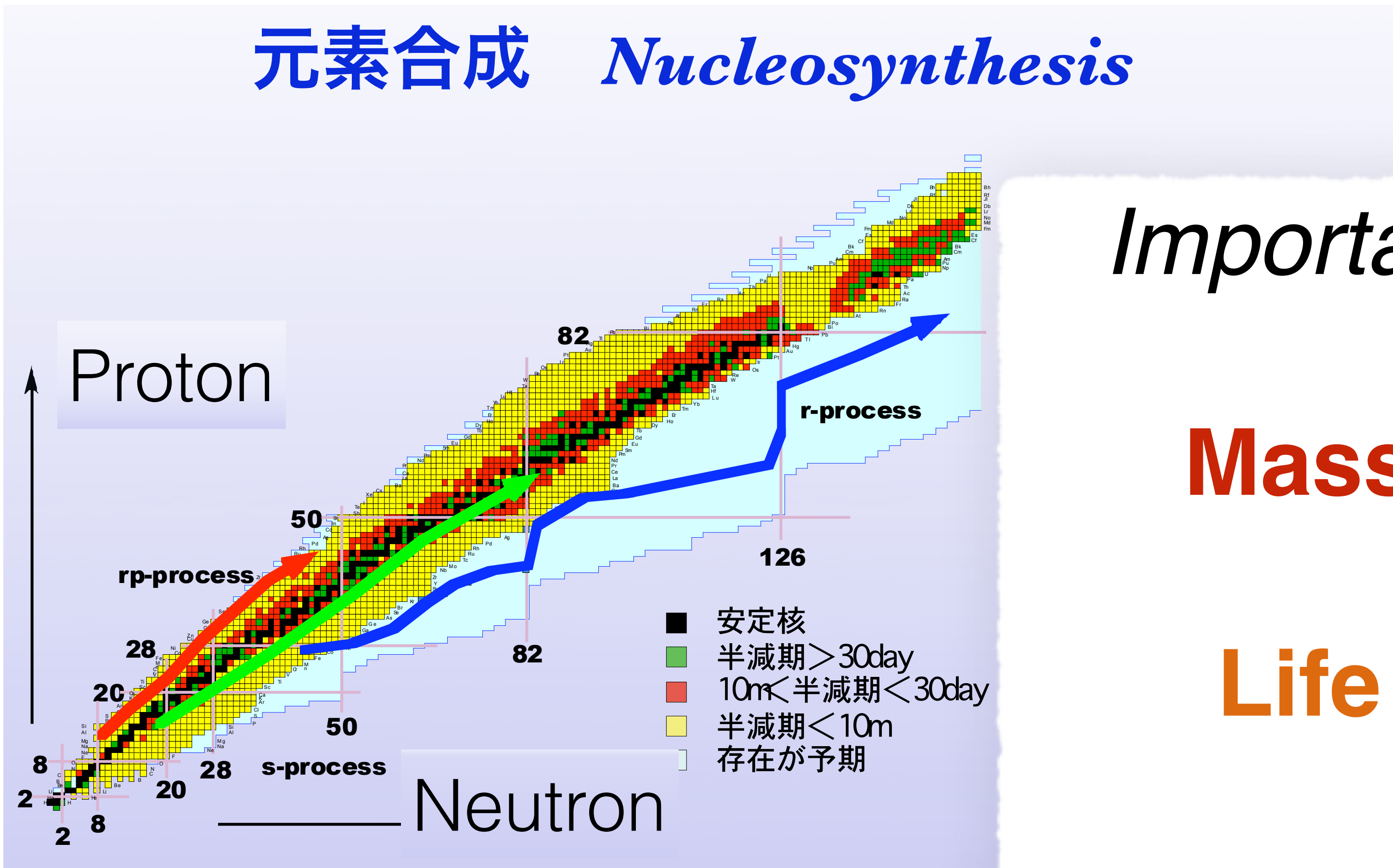
From presentation file of Prof. T. Kubo, RIKEN

- We have produced a total of 354 RI beams and delivered to 87 experiments.
- by using:
  - In-flight fission of ^{238}U
  - Projectile fragmentation of ^{14}N, ^{18}O, ^{48}Ca, ^{70}Zn, ^{124}Xe
- Production yields for a thousand of RI beams
- A number of new isotopes and new isomers



As of December 2014

Mass and Lifetime Measurements



Important

Mass

Life

σ(*n*-capture)

Mass Measurements of unstable nuclei

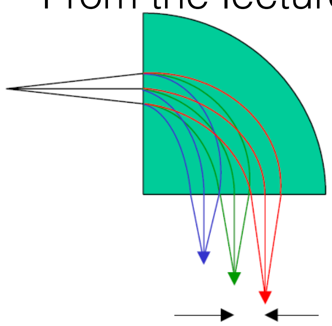
Lifetime of neutron-rich nuclei

Lifetime of bare nuclei ・・・ Re/Os clock

Direct MASS Measurements

Mass Spectrometer

From the lecture note of Prof. A. Gade, NSCL

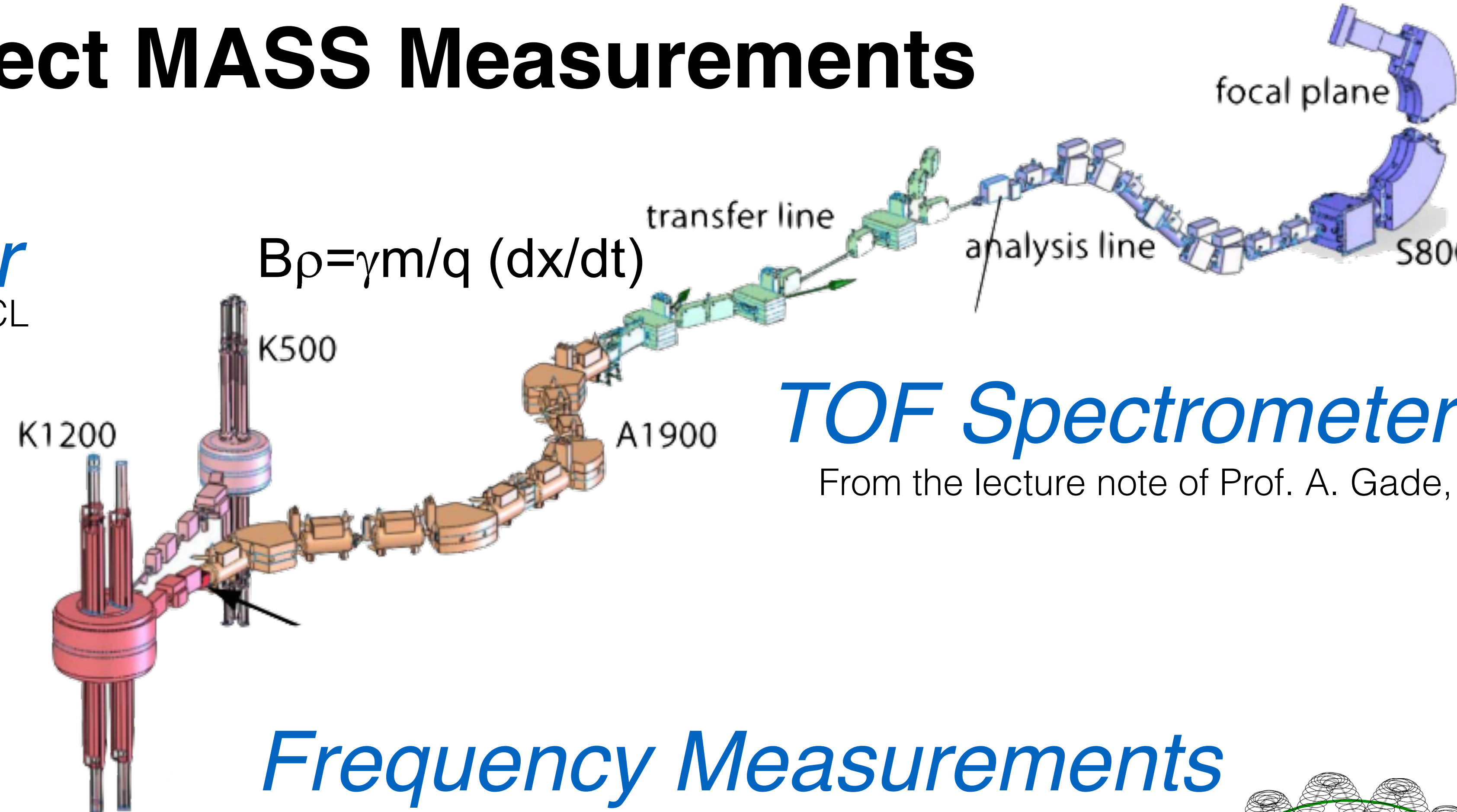


Mass separator (spectrograph, spectrometer)

Dispersion

$D = \Delta x \, m / \Delta m$

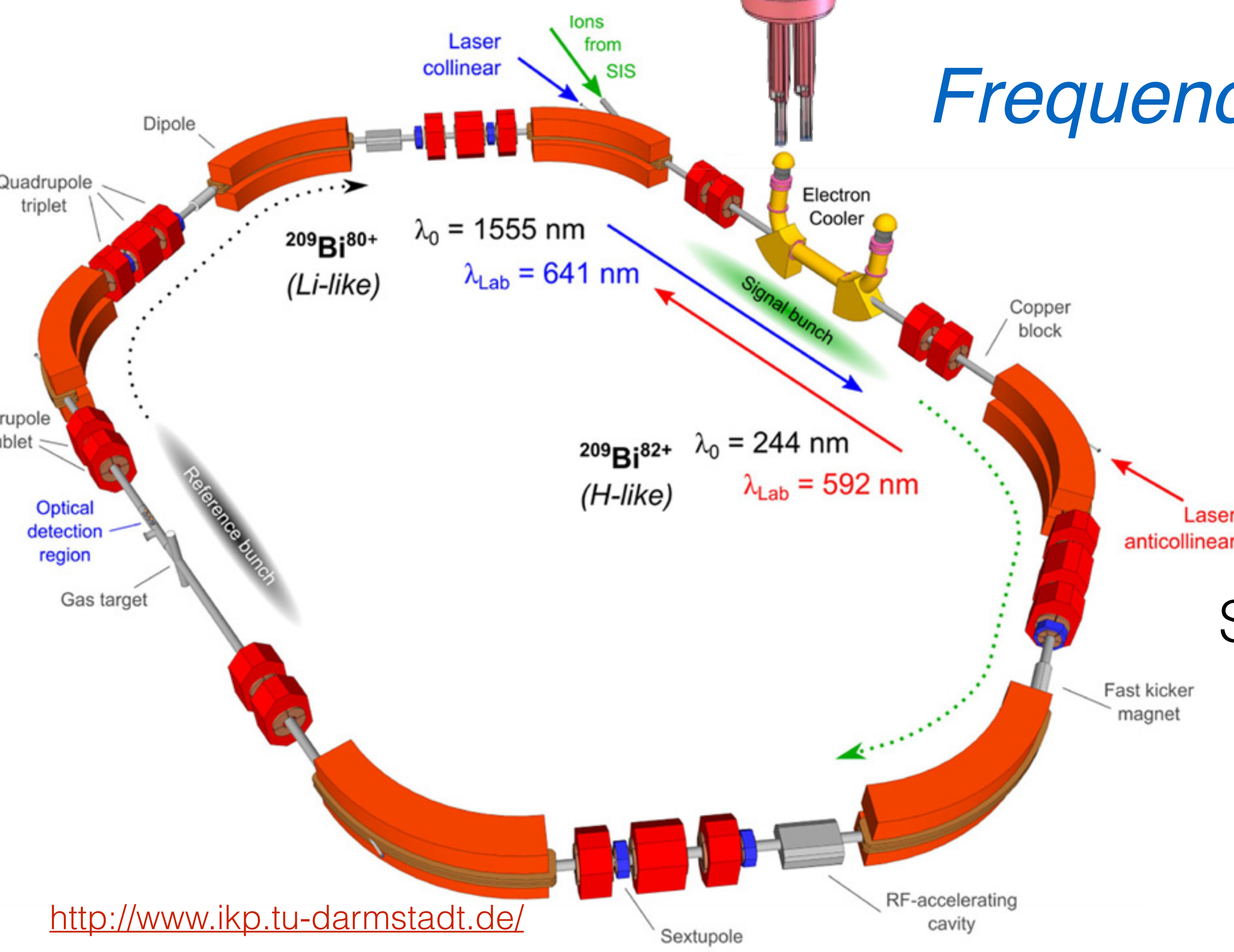
$B\rho = \gamma m/q \, (dx/dt)$



TOF Spectrometer

From the lecture note of Prof. A. Gade, NSCL

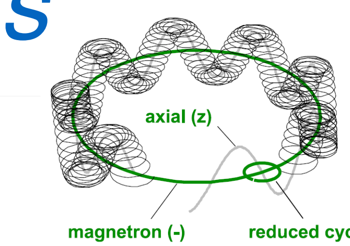
Frequency Measurements



Strage Ring

http://www.ikp.tu-darmstadt.de/

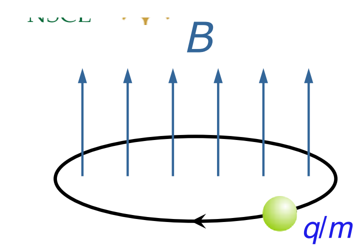
$$f_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$$

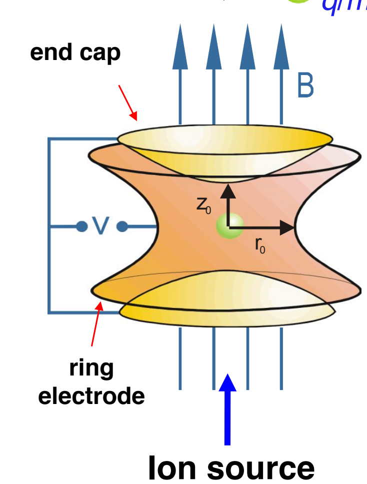


$$f_+ + f_- = f_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$$

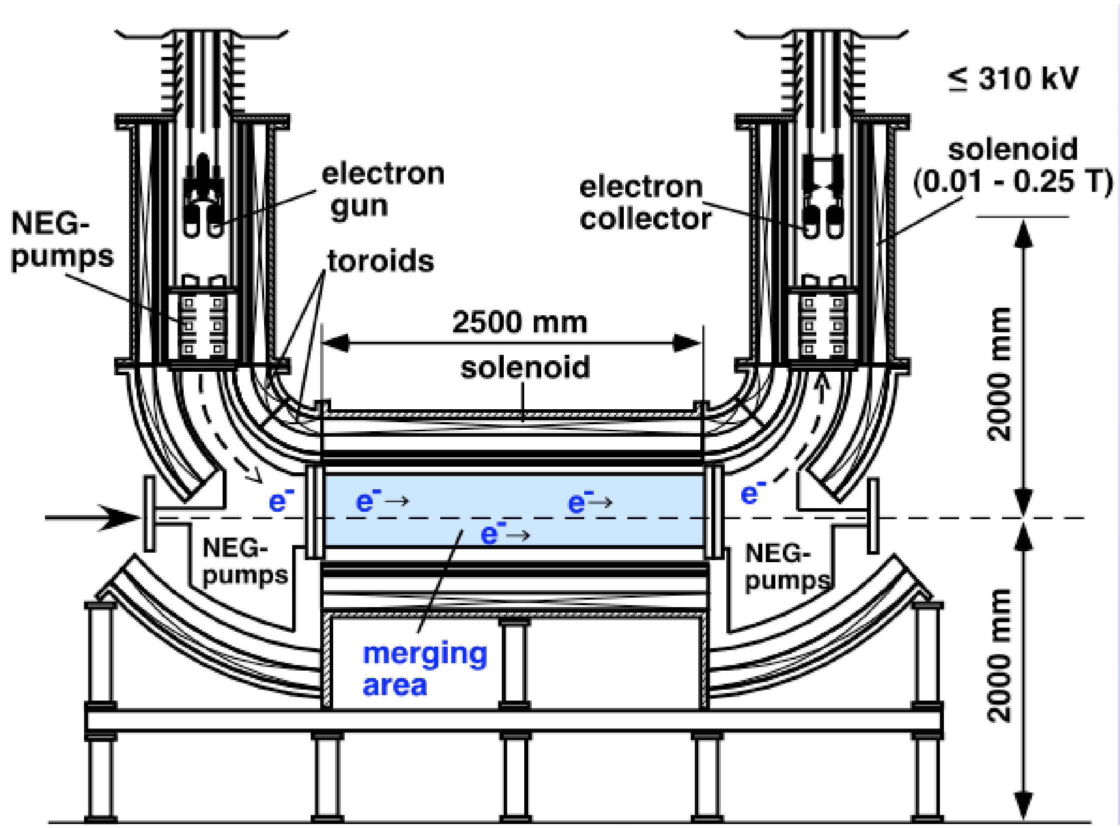
Penning Trap

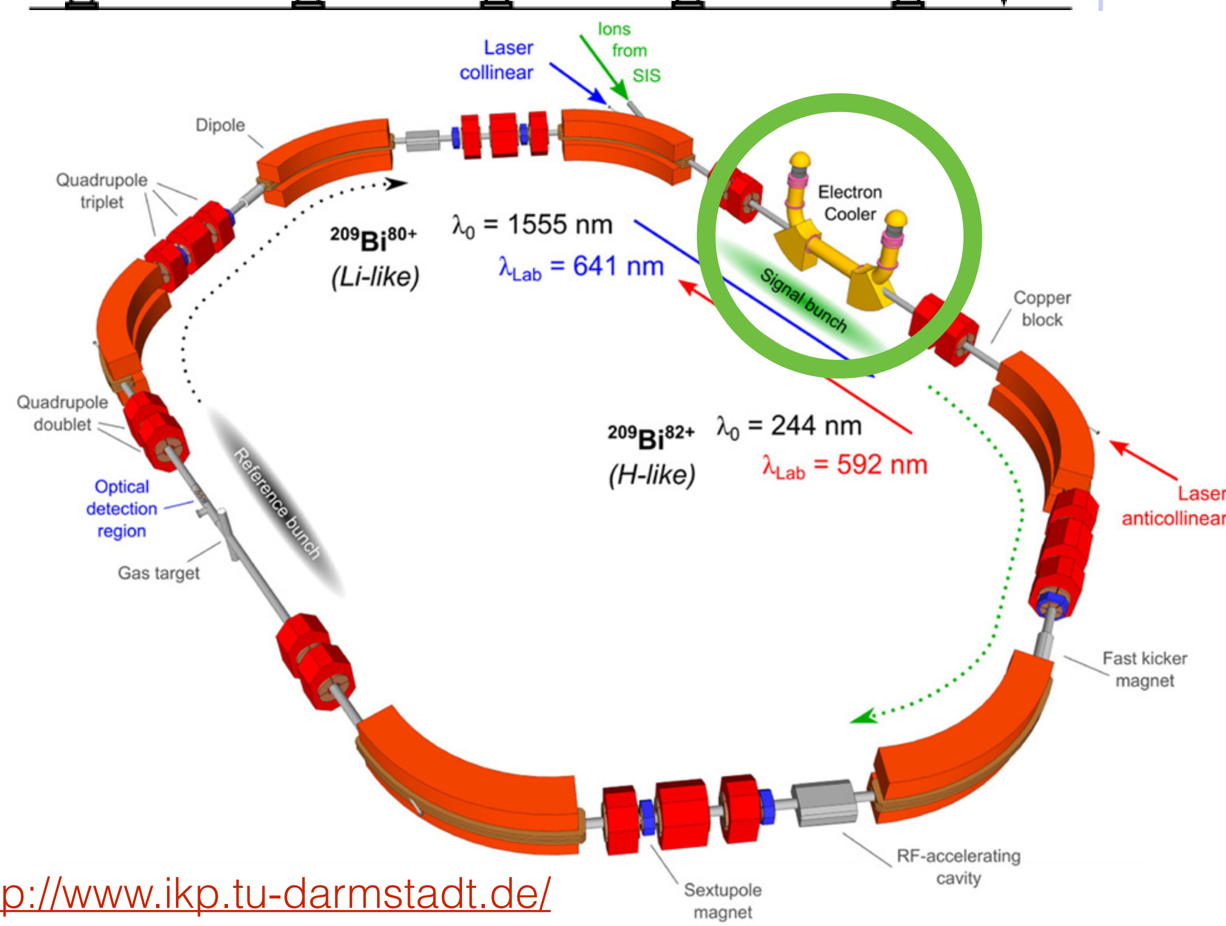
From the lecture note of Prof. A. Gade, NSCL

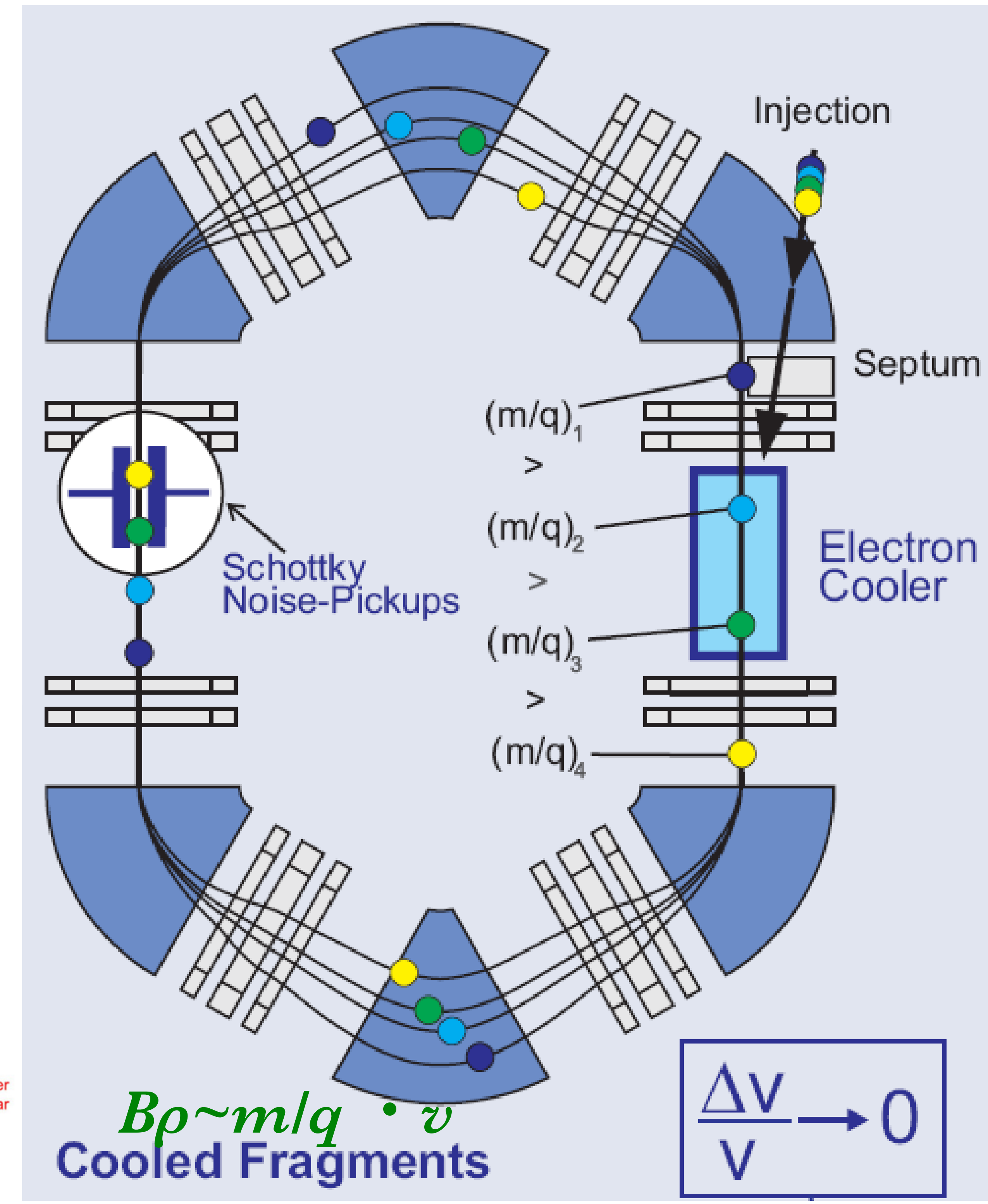




Mass Measurements with Experimental Storage Ring (ESR at GSI)





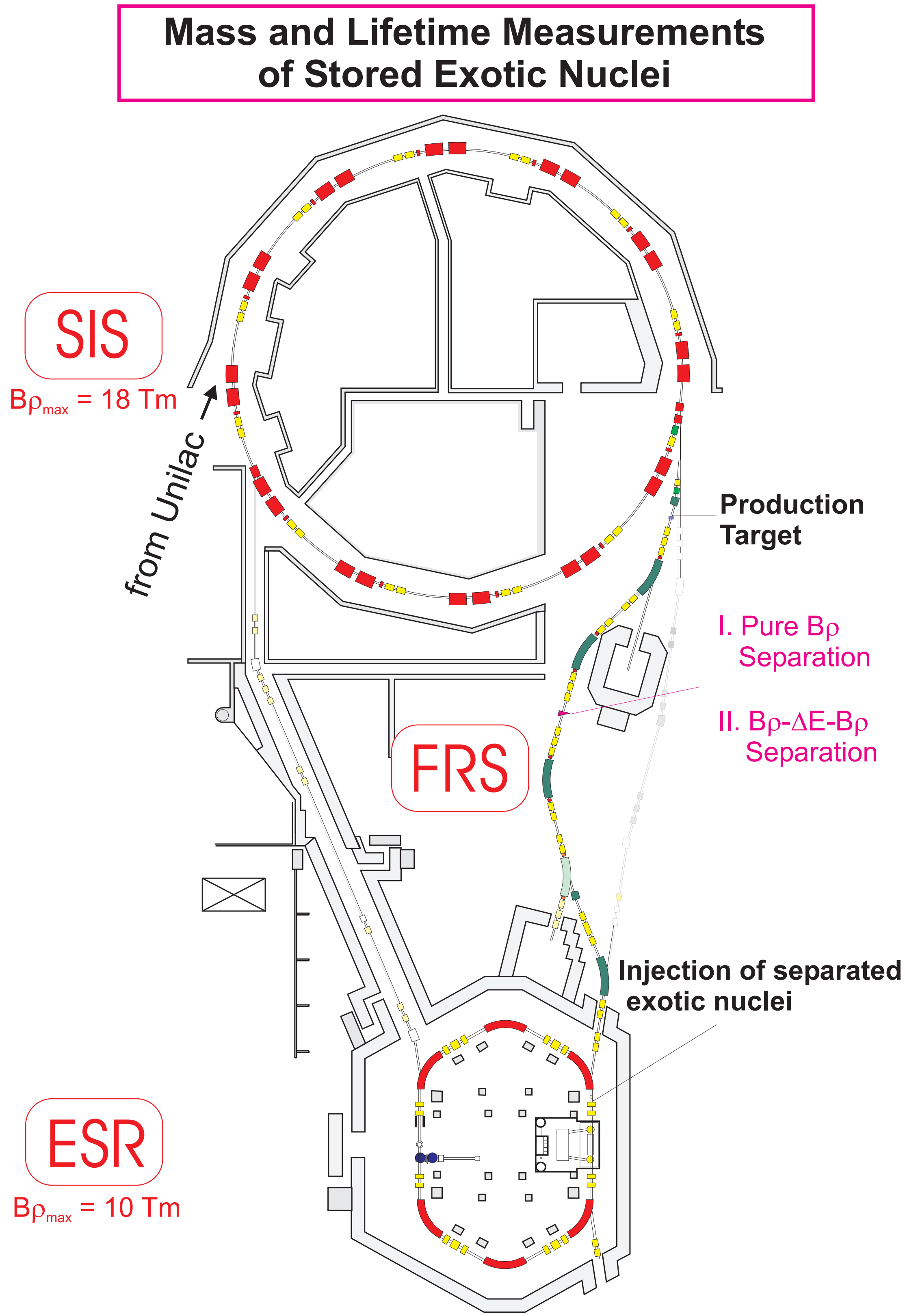


http://www.ikp.tu-darmstadt.de/

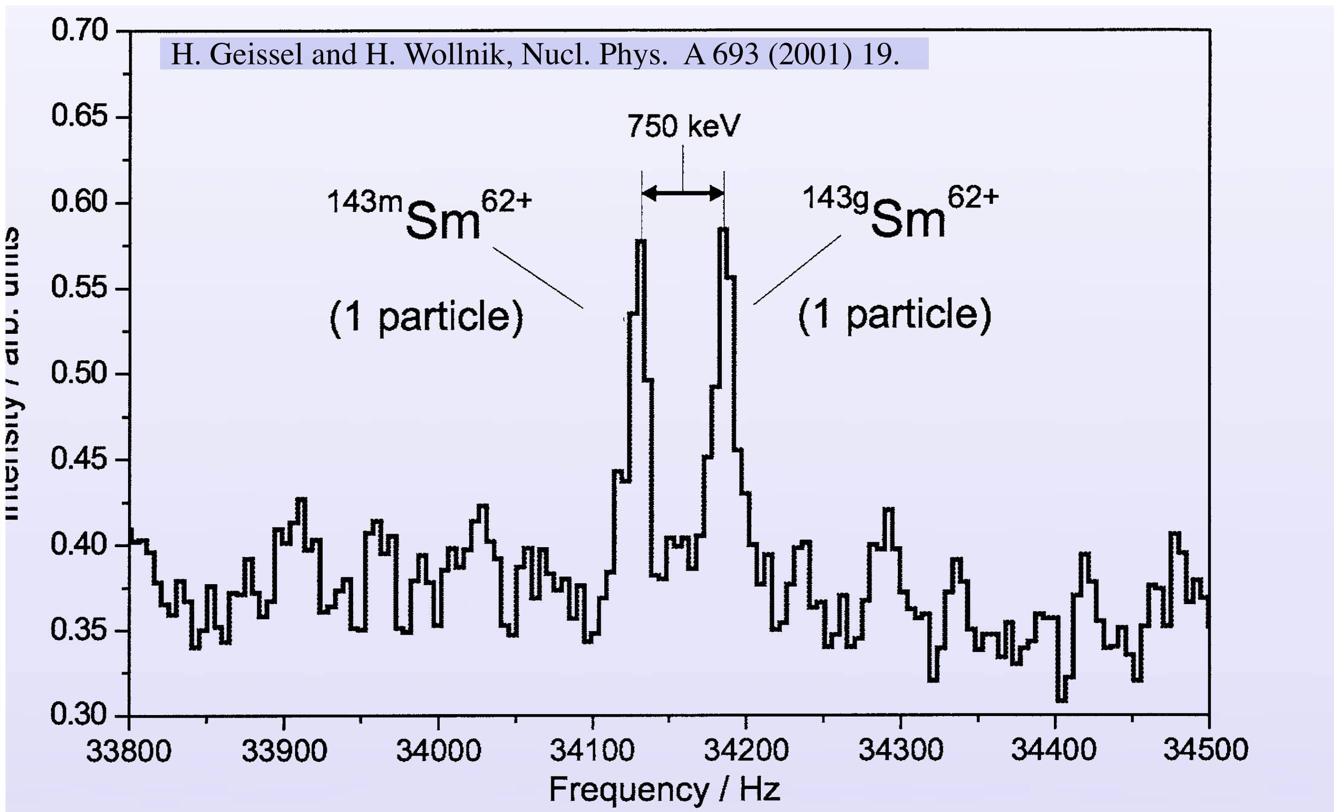
F. Bosch, Lect. Notes Phys. 651, 137 (2004)

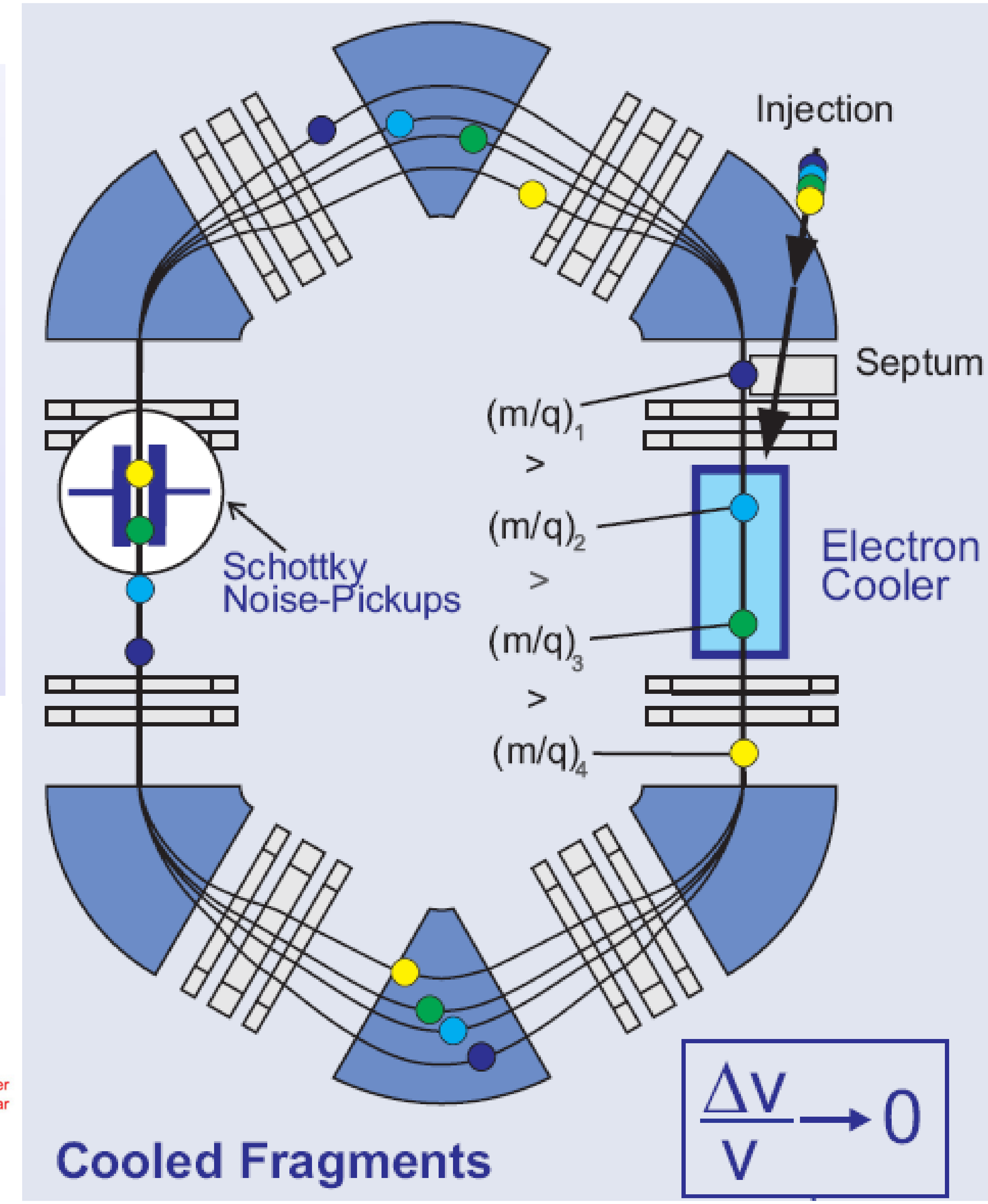
$T_{1/2} > 1s$

Mass Measurements with Strage Ring (ESR at GSI)

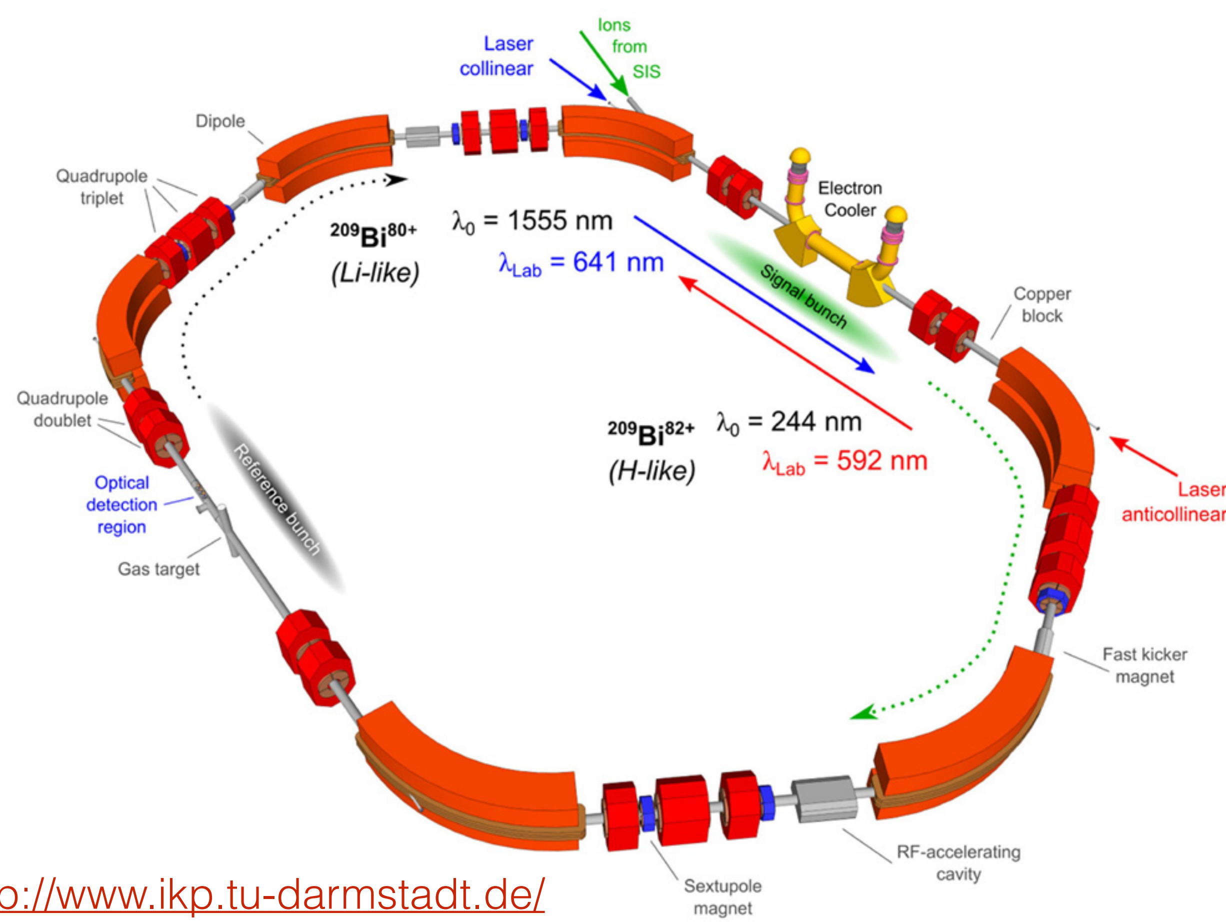


Mass Measurements with ESR





F. Bosch, Lect. Notes Phys. 651, 137 (2004)



http://www.ikp.tu-darmstadt.de/

$T_{1/2} > 1s$

Lifetime Measurements with ESR

ESR

Injection of **charge-stripped** Mother nucleus

Storage it until it decays into daughter nucleus

Decay

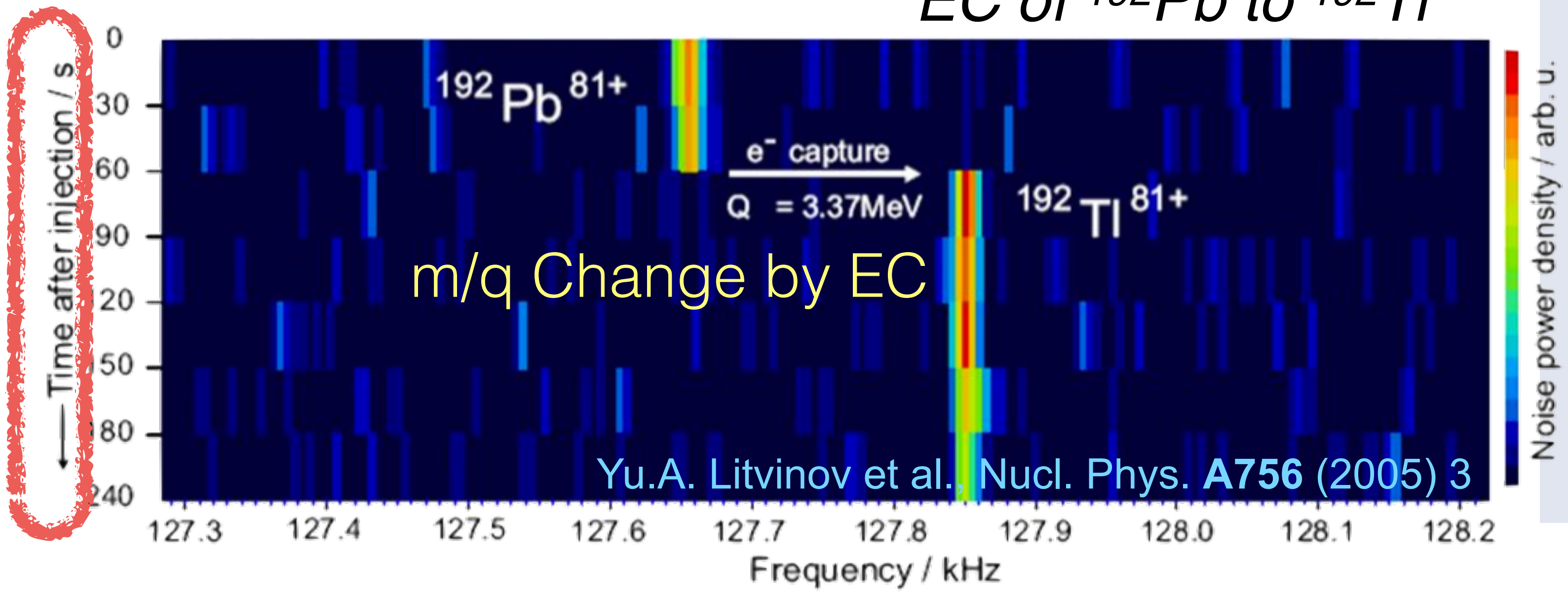
Sudden Change of frequency

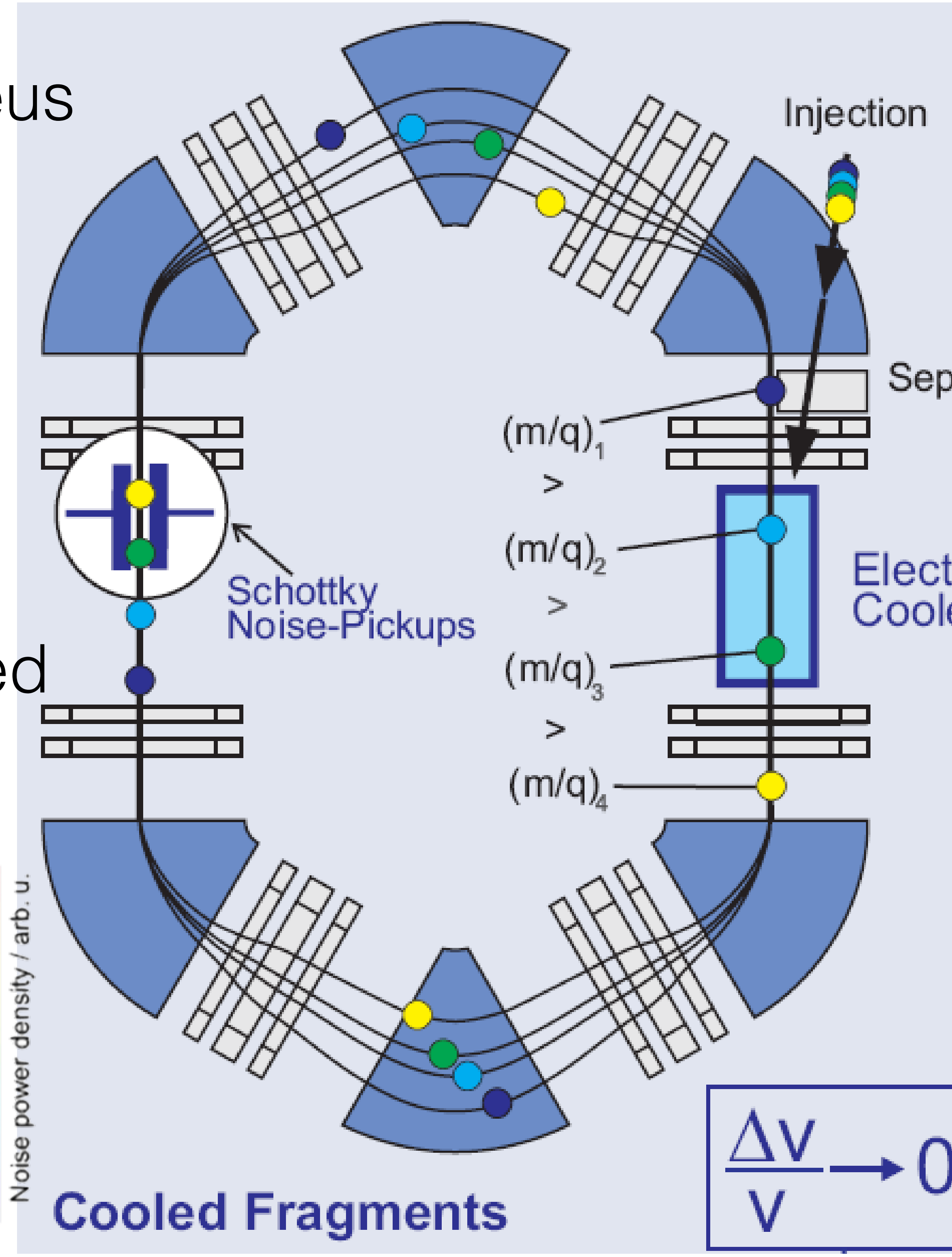
$m_{\mathrm{Mother}}/q \rightarrow m_{\mathrm{Daughter}}/q$

Time from injection to decay → recorded

Lifetime

EC of ^{192}Pb to ^{192}Tl





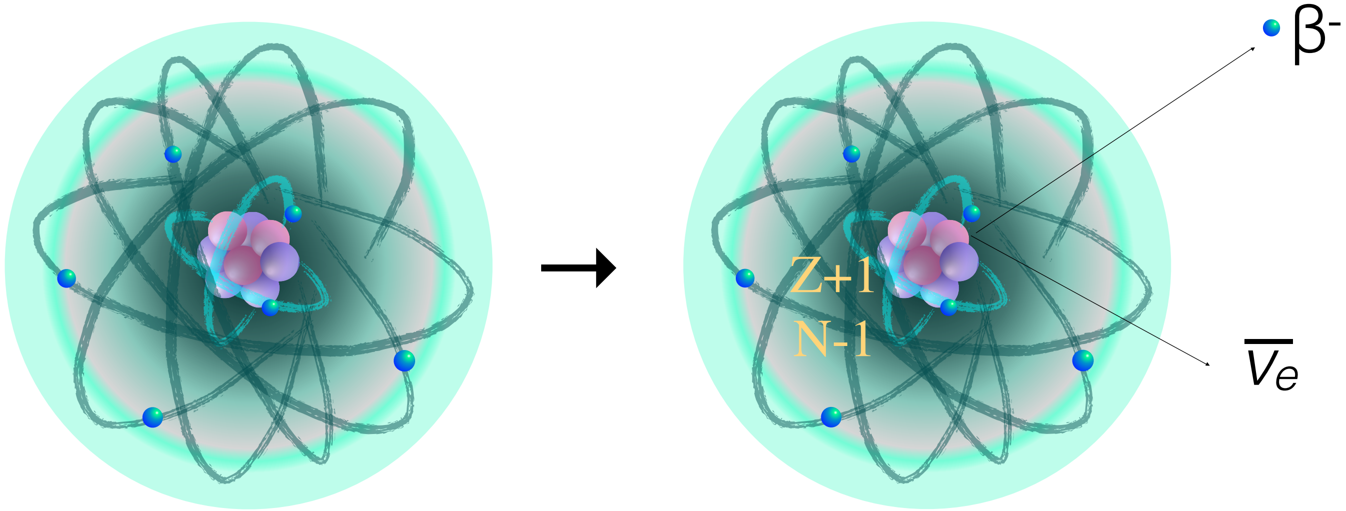
F. Bosch, Lect. Notes Phys. 651, 137 (2004)

Interesting Point :

Lifetime obtained using ESR = Lifetime of "Bare Nucleus"

Lifetime Measurements with ESR

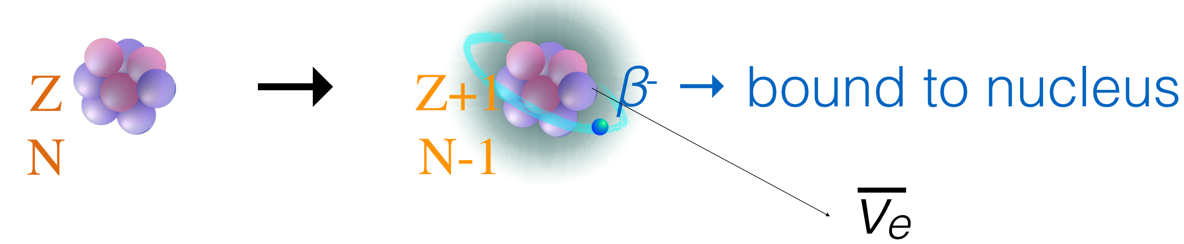
$n \rightarrow p + \beta^- + \overline{\nu}_e$



β^- decay : Nucleus in Atom

$n \rightarrow p + \beta^-$ (bound)+ $\overline{\nu}_e$

Bound-state β Decay



Bare Nucleus

"Eon Clock" for the age of Universe

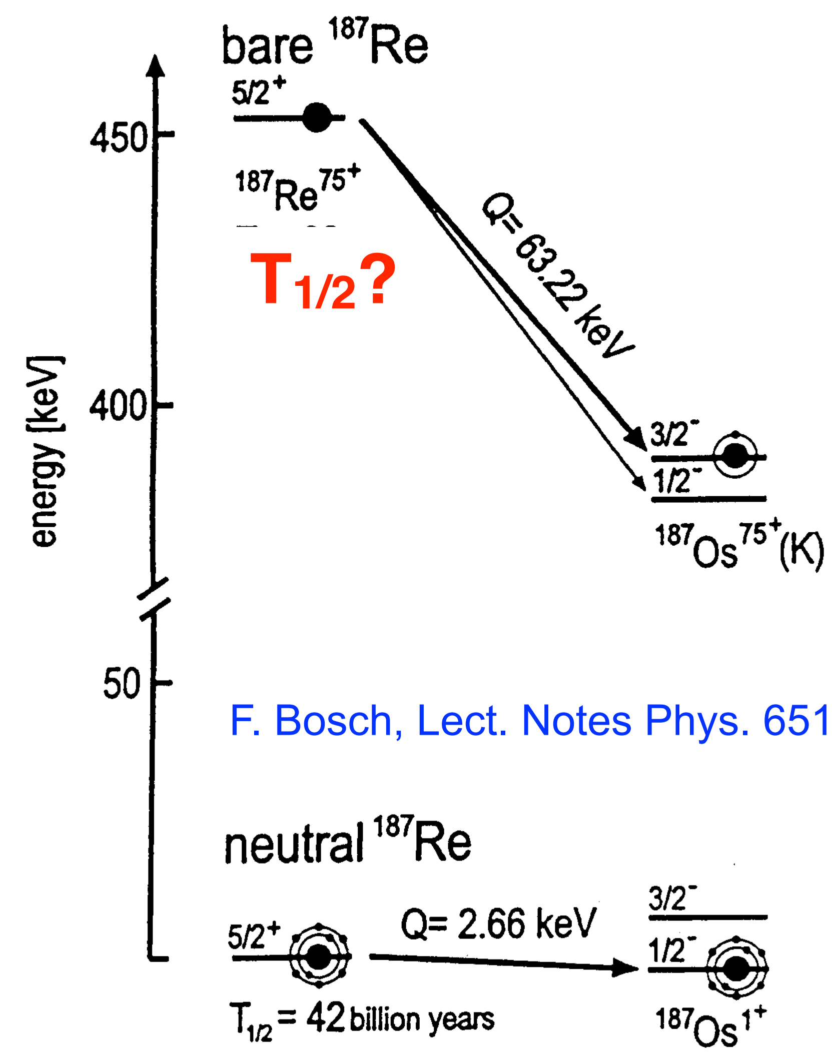
$^{187}\mathrm{Re}/^{187}\mathrm{Os}$ (β-decay; $T_{1/2} = 42 \text{ x } 10^9$ y)

In hot stellar plasma, ^{187}Re could be bare

Bound-state β Decay

Different Q value from electron binding energy and different $T_{1/2}$

How long is the $T_{1/2}$ of bare ^{187}Re?

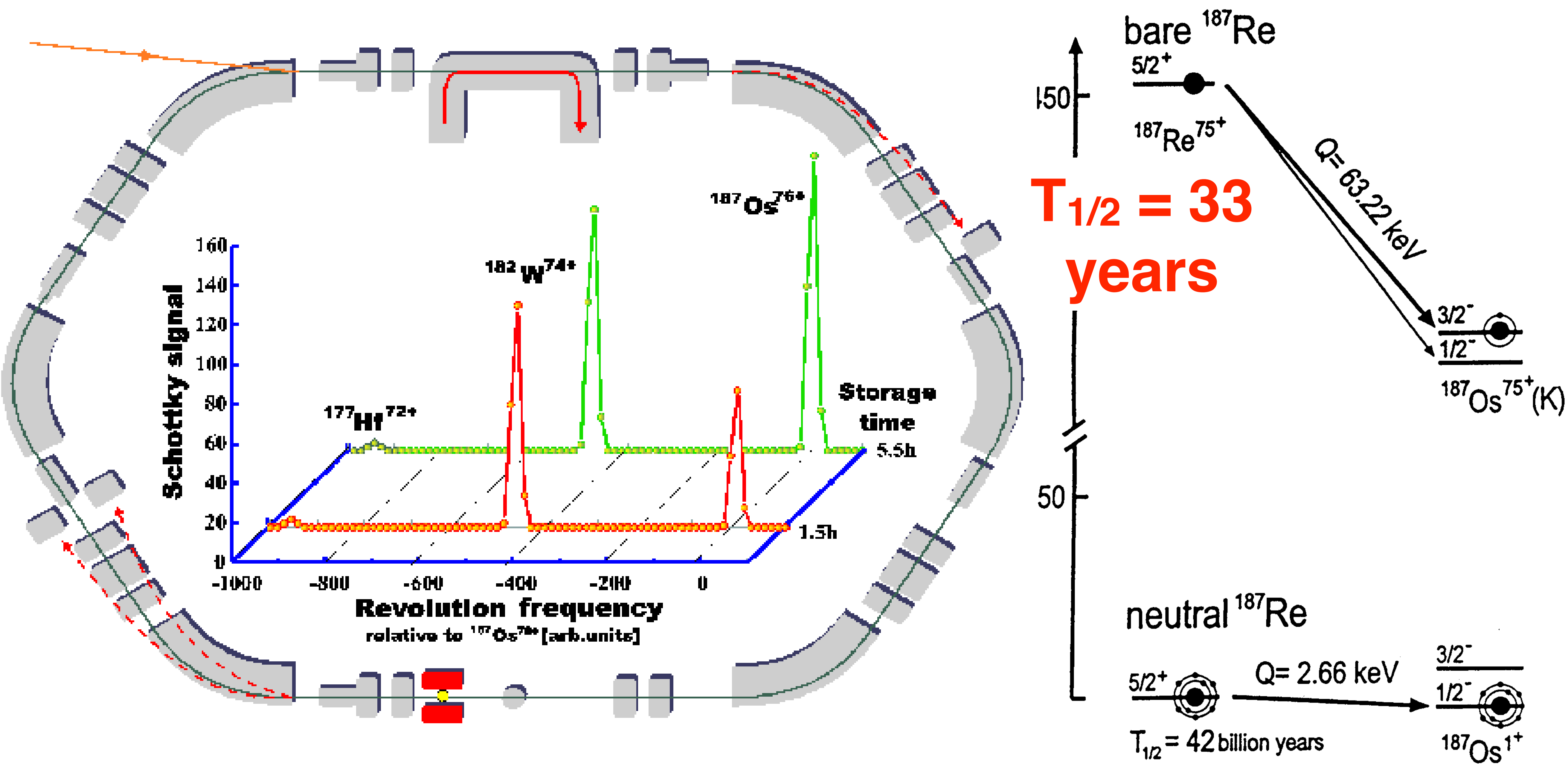


F. Bosch, Lect. Notes Phys. 651, 137 (2004)

Lifetime Measurements of ^{187}Re

F. Bosch, Lect. Notes Phys. 651, 137 (2004)

Beam : 400 MeV/u full-strip ^{187}Re Primary Beam from SIS



10^8 stored primary bare ^{187}Re ions, a few hundred ^{187}Os ions per hour were generated. From those numbers the impressively short half-life of 33 years for bare ^{187}Re has been determined.

Lifetime Measurements at RIBF

EURICA Project

Lifetime Measurements at RIBF

EURICA Project

PID tag : BigRIPS and ZDS

Beta-ray detection

WAS3ABi

・DSSSD

→ Tag the daughter which emits beta, from position information

・Measurements of beet-emitted time

→ **Lifetime**

Gamma-ray from Isomer and Daughter Nuclei

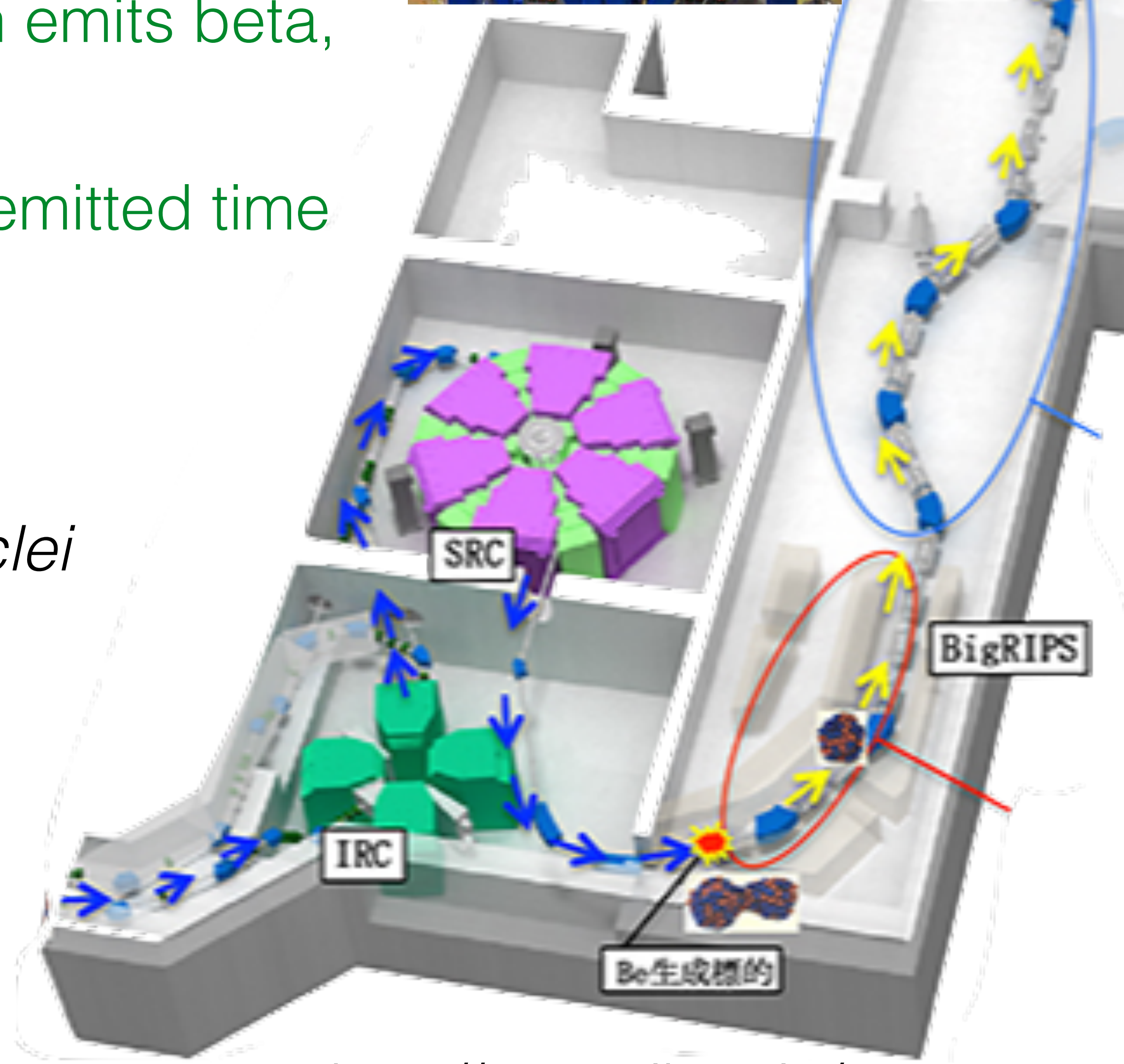
EURICA

・Isomer tag

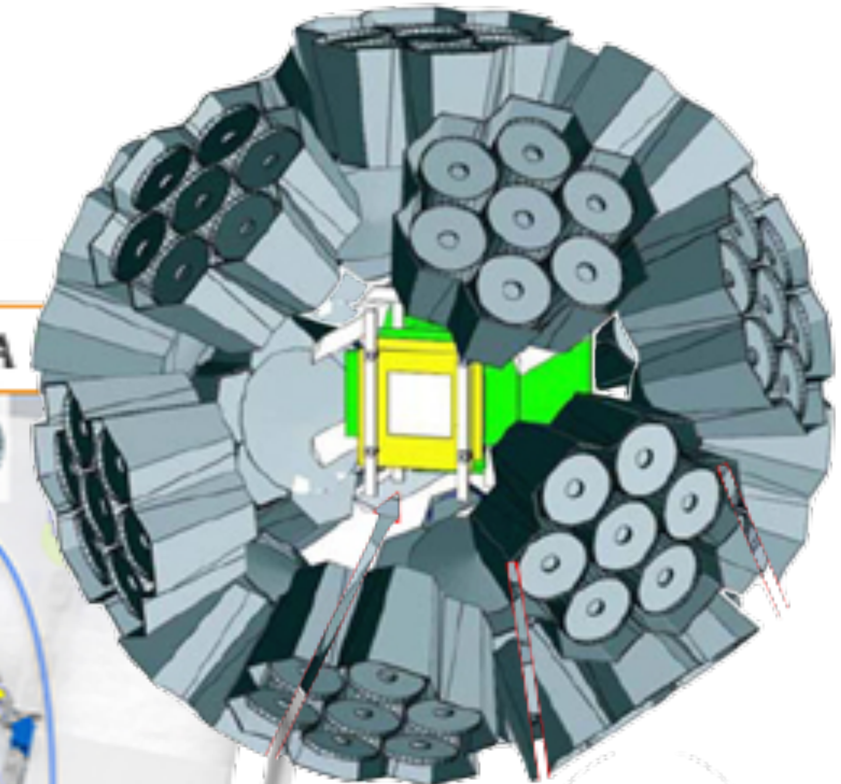
・β delayed gamma

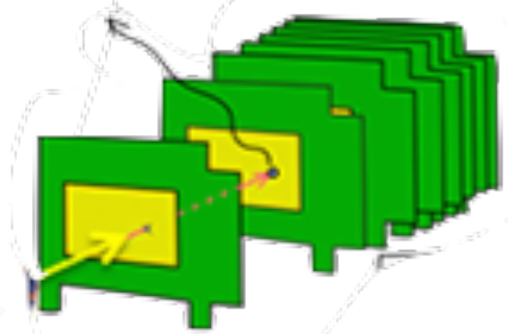
EURICA

(Euroball-RIKEN Cluster Array)



http://www.riken.jp/





WAS3ABi

(Wide range Active Silicon-Strip Stopper Arra
for Beta and ion detection)

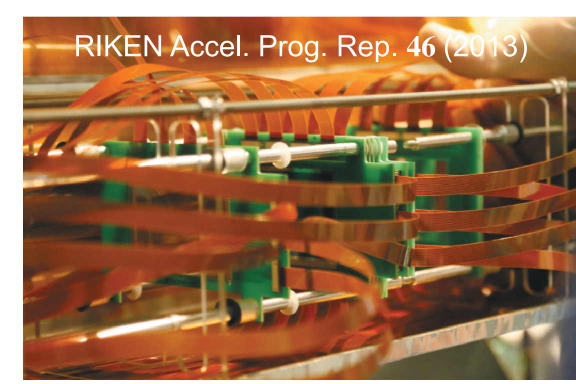


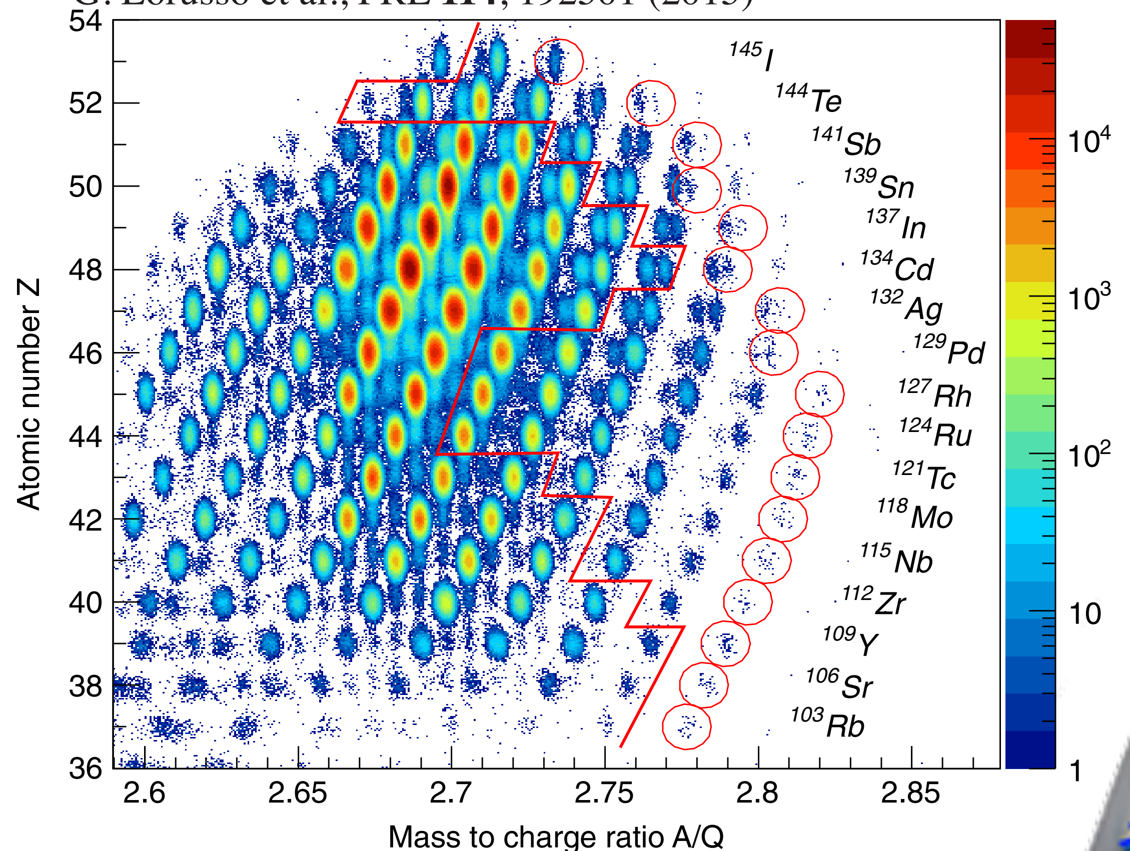
Fig. 1. Side view of WAS3ABi with eight DSSSDs. Aluminum rods were disconnected at the central position for the installation of the DSSSDs[4].

Lifetime Measurements at RIBF

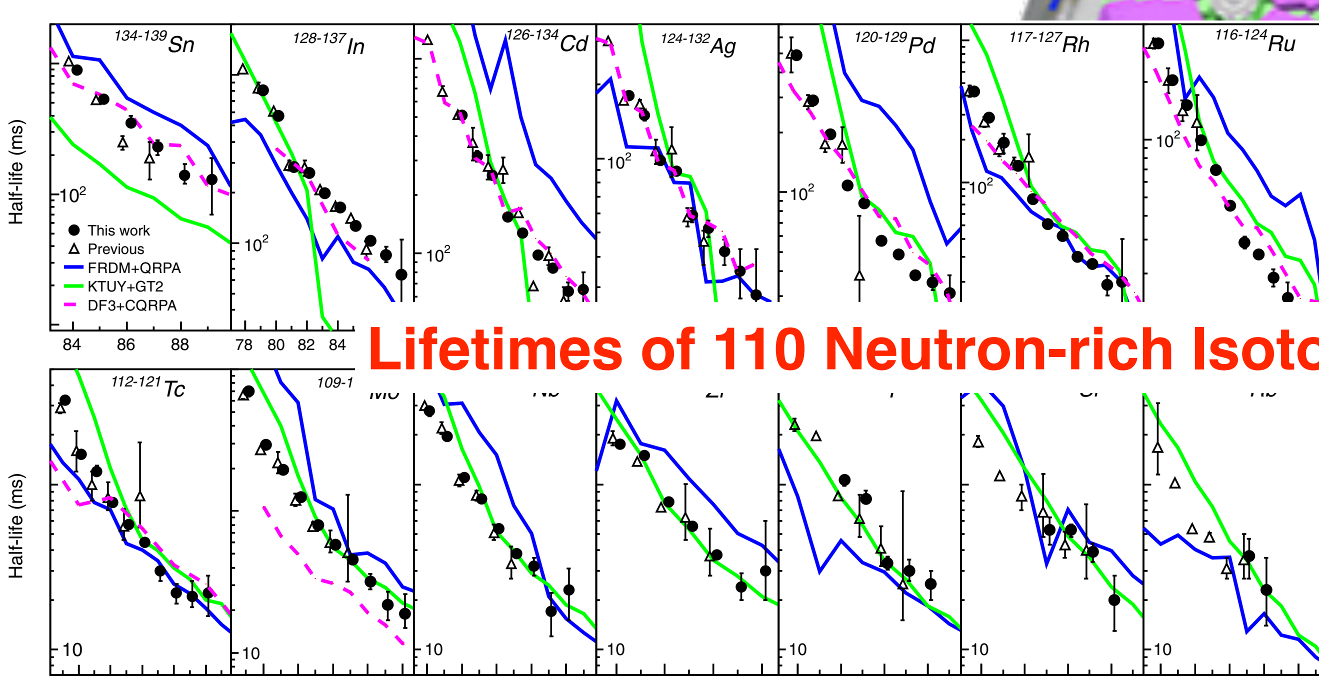
EURICA Project

Beams Implanted on WAS3ABi

G. Lorusso et al., PRL **114**, 192501 (2015)



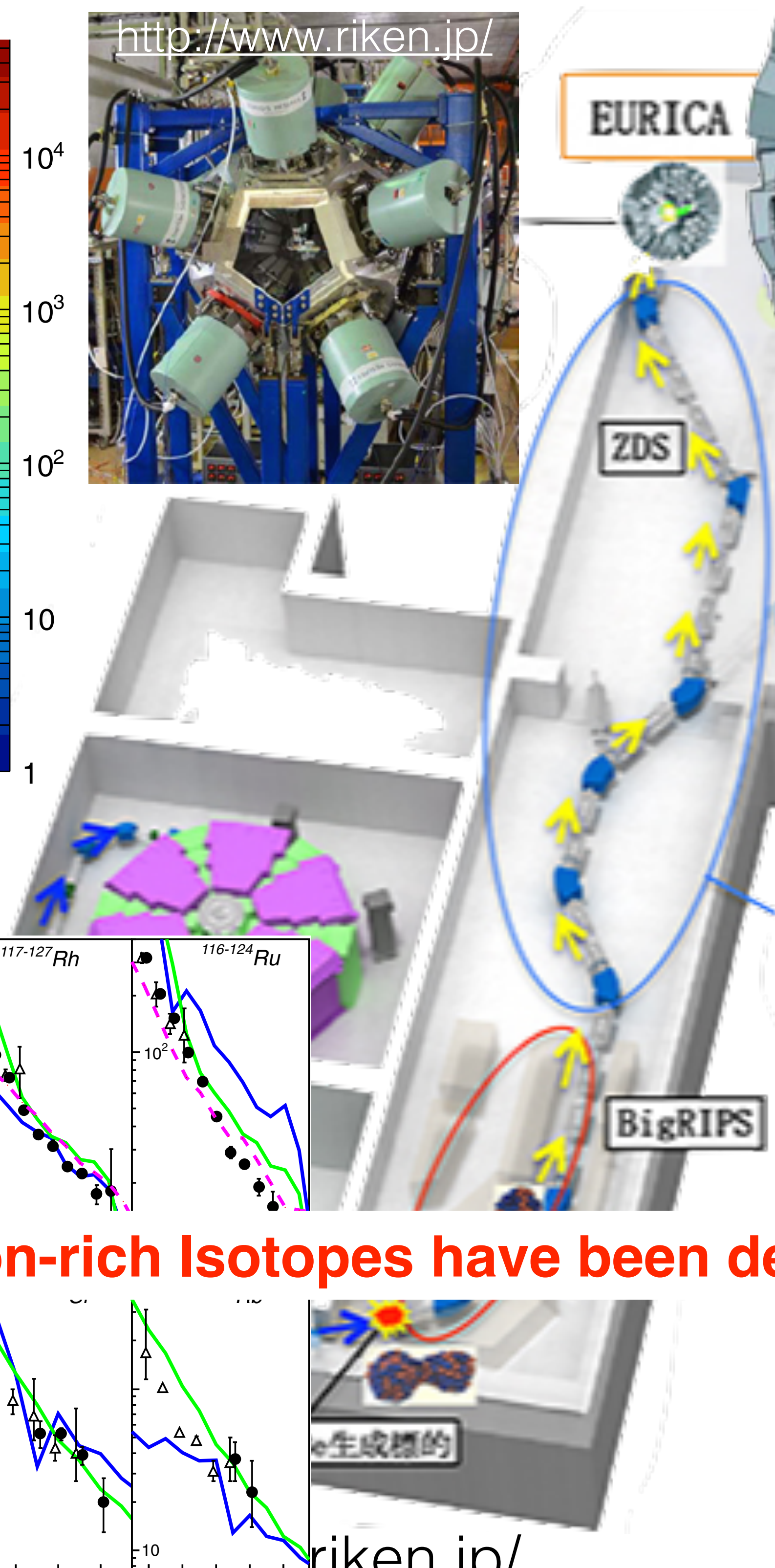
G. Lorusso et al., PRL **114**, 192501 (2015)

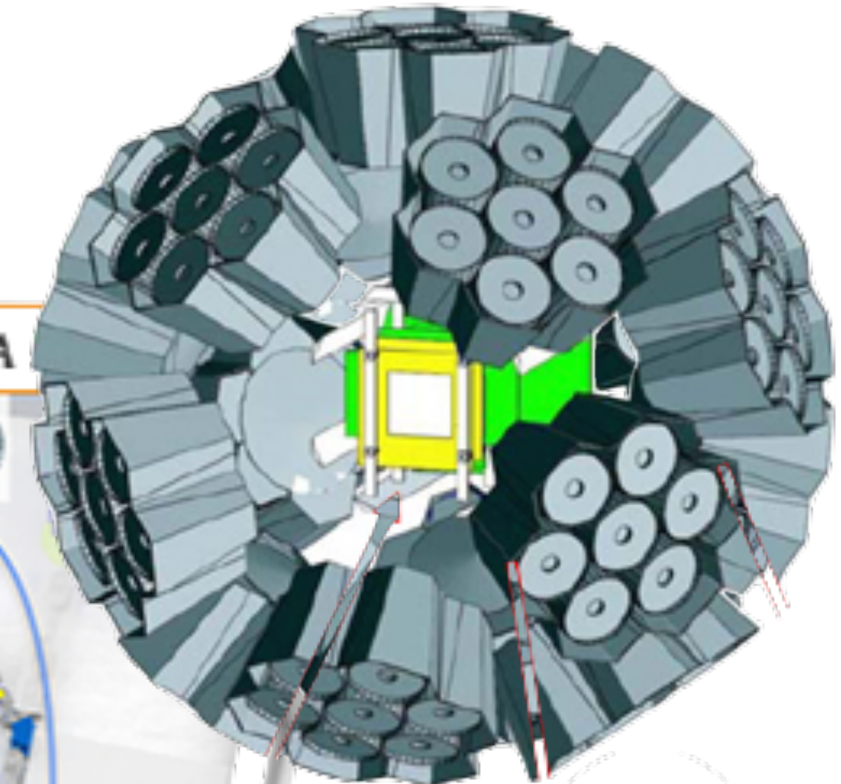


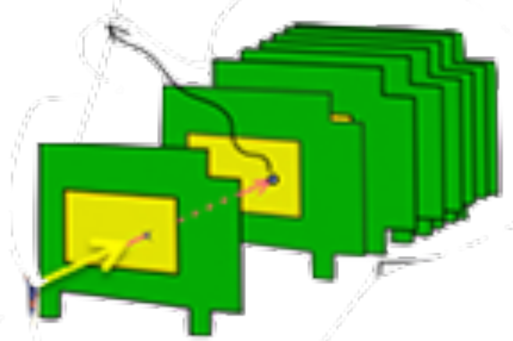
Lifetimes of 110 Neutron-rich Isotopes have been determined!

EURICA

(Euroball-RIKEN Cluster Array)







WAS3ABi

(Wide range Active Silicon-Strip Stopper Arra
for Beta and ion detection)

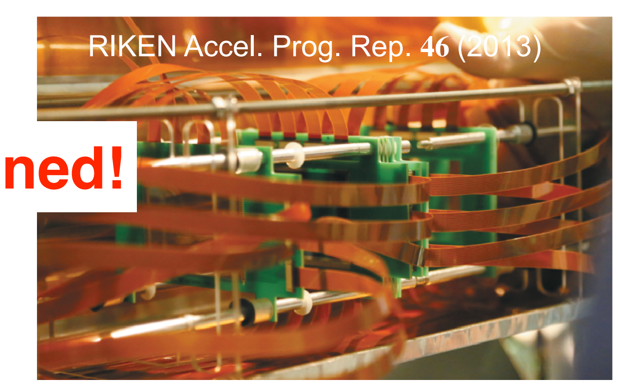


Fig. 1. Side view of WAS3ABi with eight DSSSDs. Aluminum rods were disconnected at the central position for the installation of the DSSSDs[4].

Nuclear Radii Measurements

Nuclear Radii Measurements

Stable Nuclei :

Electron Scattering Experiment

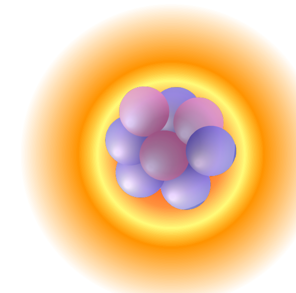
X-ray Measurements Muonic Atom

Unstable Nuclei :

Isotope shift Measurements

Charge Radii

Sensitive to the **Coulomb Potential** of Protons



Stable Nuclei or Unstable Nuclei

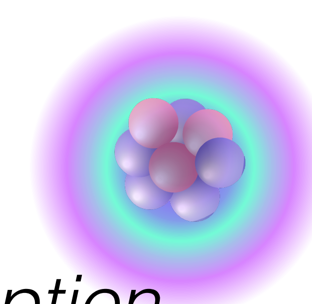
Nuclear Reaction

Elastic Scattering Cross Section

Total Reaction Cross Section

Matter Radii

Sensitive to the **Nuclear Potential** of Nucleons



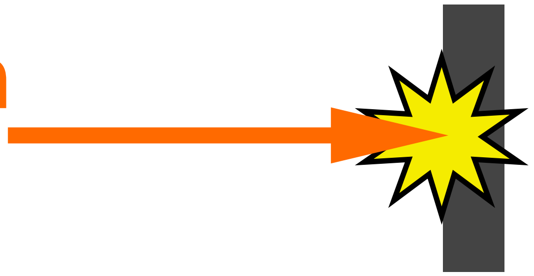
With some model assumption

Reaction Cross Section and Nuclear Size

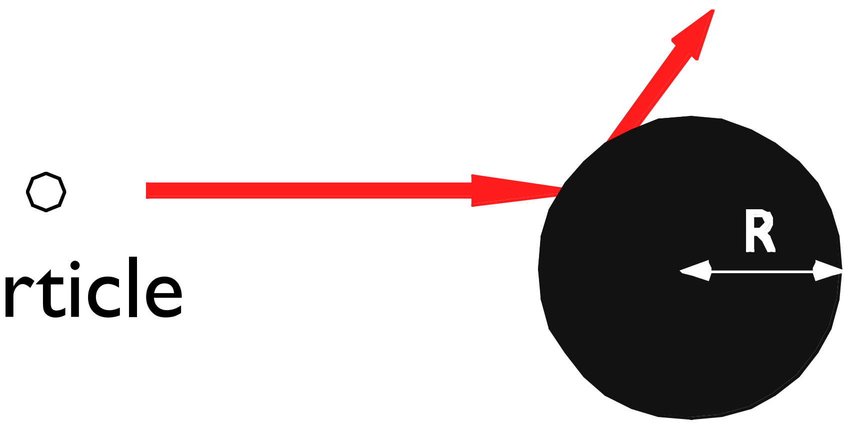
Reaction Cross Section ・・・Nuclear Reaction Probability

$\sigma_R = \sigma_{tot} - \sigma_{el}$

RI Beam



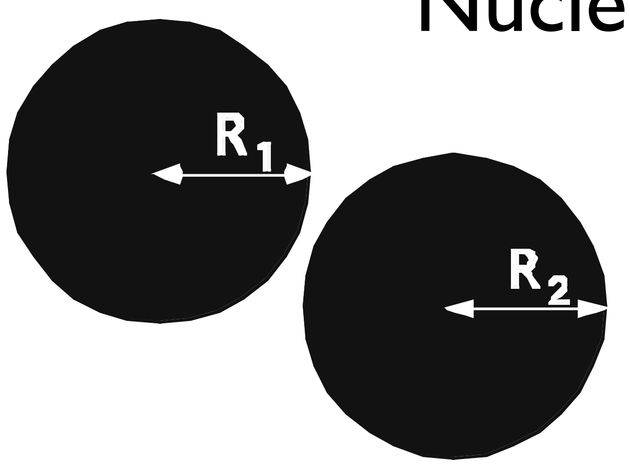
Experiment・・・Bombarding Target with RI Beam



Particle

Nucleus

$\sigma_R \propto \pi R^2$



$\sigma_R \propto \pi (R_1^2 + R_2^2)$

σ_R ・・・Size of Nuclei

Reaction Cross Section *Interaction Cross Section*

$\sigma_R = \sigma_{tot} - \sigma_{el}$ $\sigma_I = \sigma_R - \sigma_{inel}$ $\sigma_I \simeq \sigma_R$ at high energies

Glauber Model

$$\sigma_R = \int \mathrm{d}\boldsymbol{b}\left[1-\exp\left(-\int d^2\boldsymbol{r}\sum_{i,j}\sigma_{NN}(E)\,\rho_z^{P_i}(\boldsymbol{r})\,\rho_z^{T_j}(\boldsymbol{r}-\boldsymbol{b})\right)\right]$$

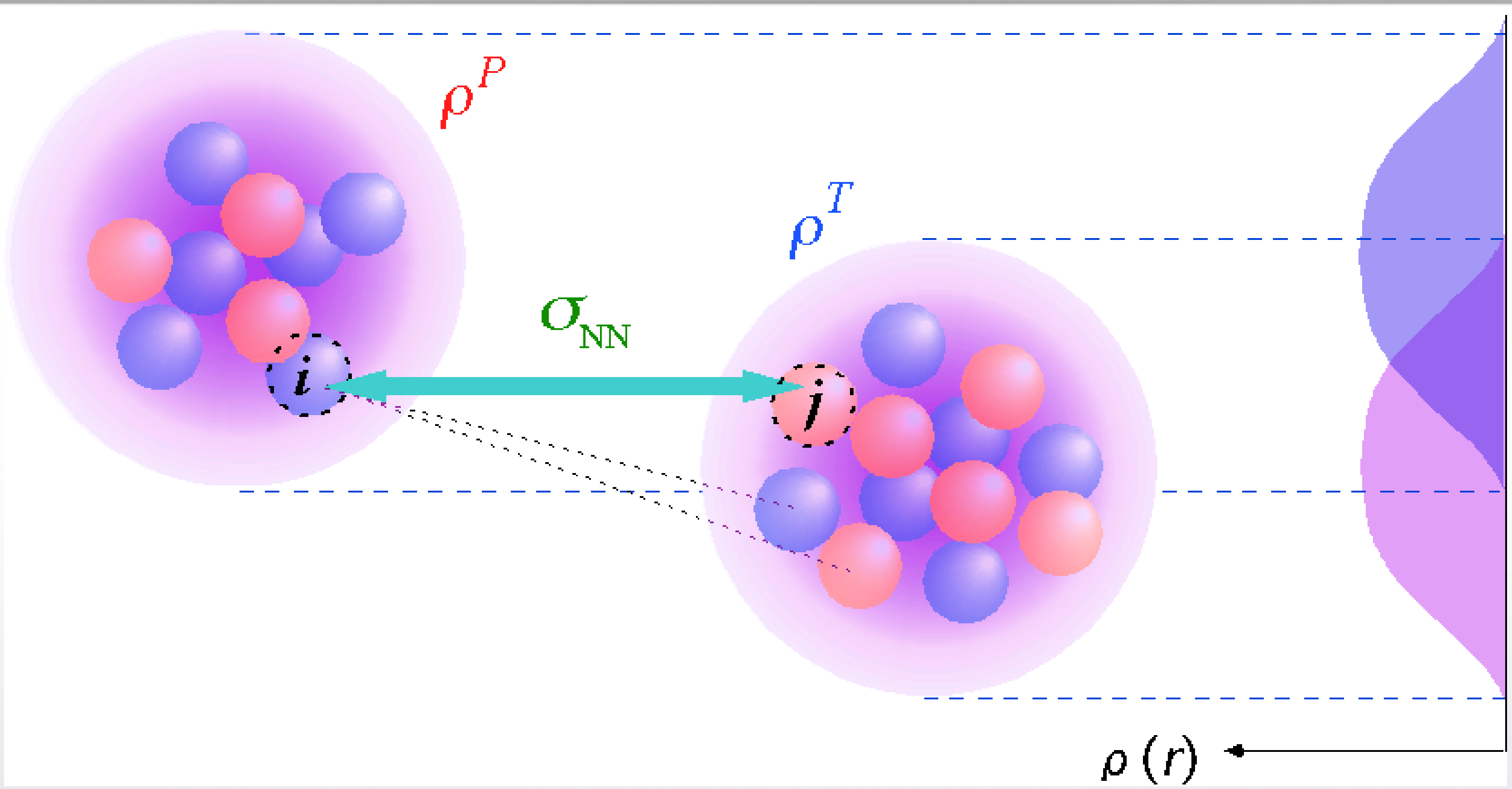
σ_{NN} Nucleon-Nucleon Total Cross Section

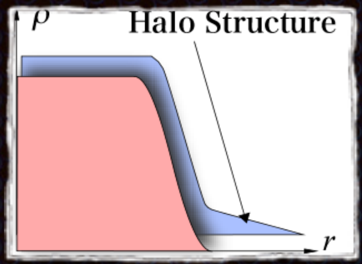
ρ^P Projectile Nucleon Density Distribution

ρ^T Target Nucleon Density Distribution

σ_I or σ_R ⟷ Nuclear Size

Glauber Calculation

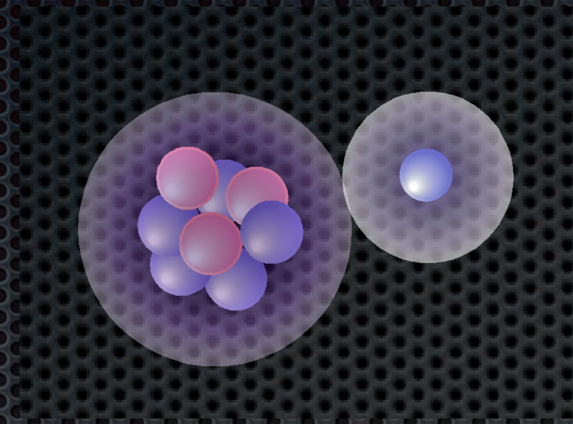


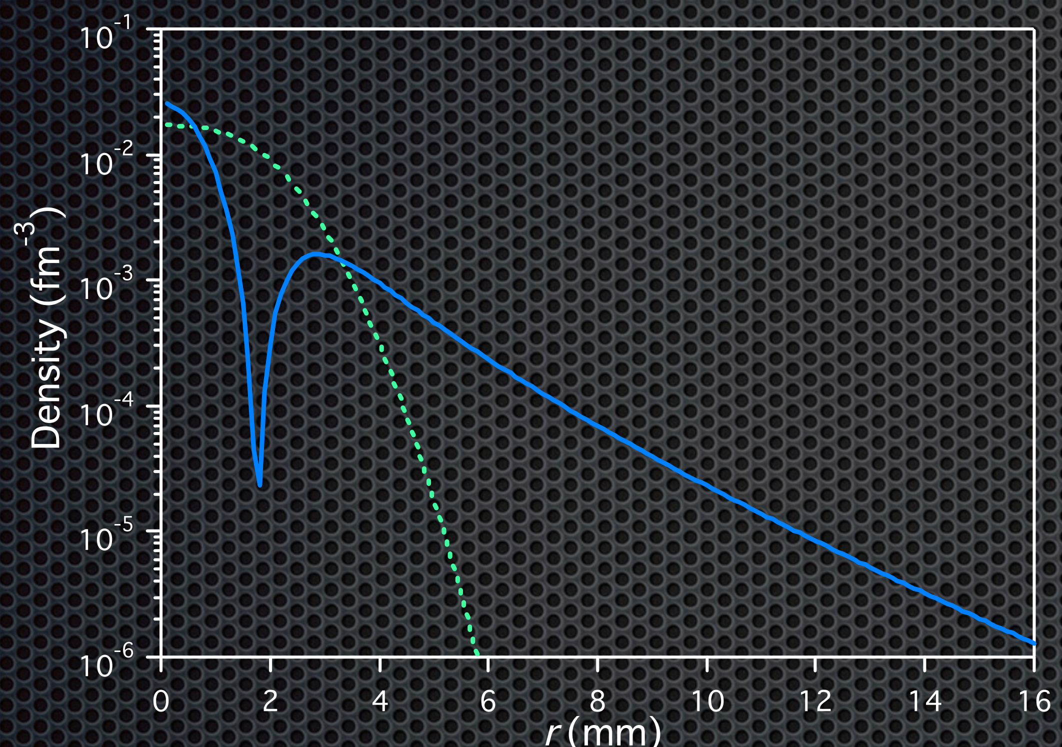


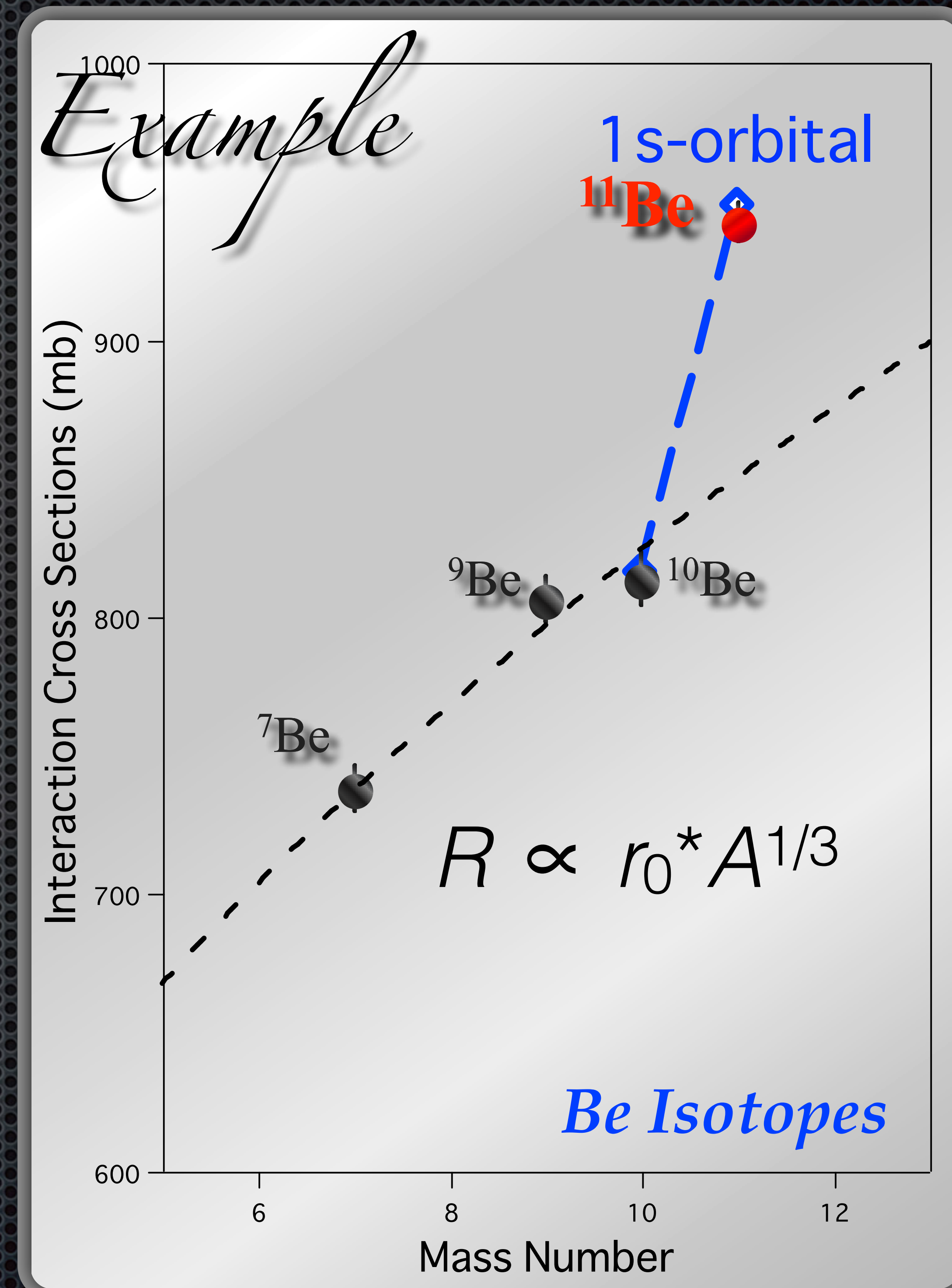
Nuclear Size and Halo Structure

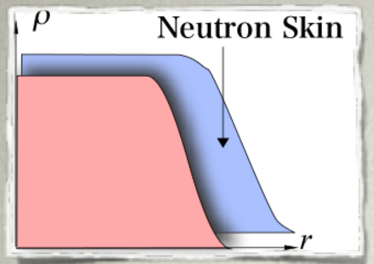
Neutron-Rich Nucleus ^{11}Be

$Z = 4, N = 7$







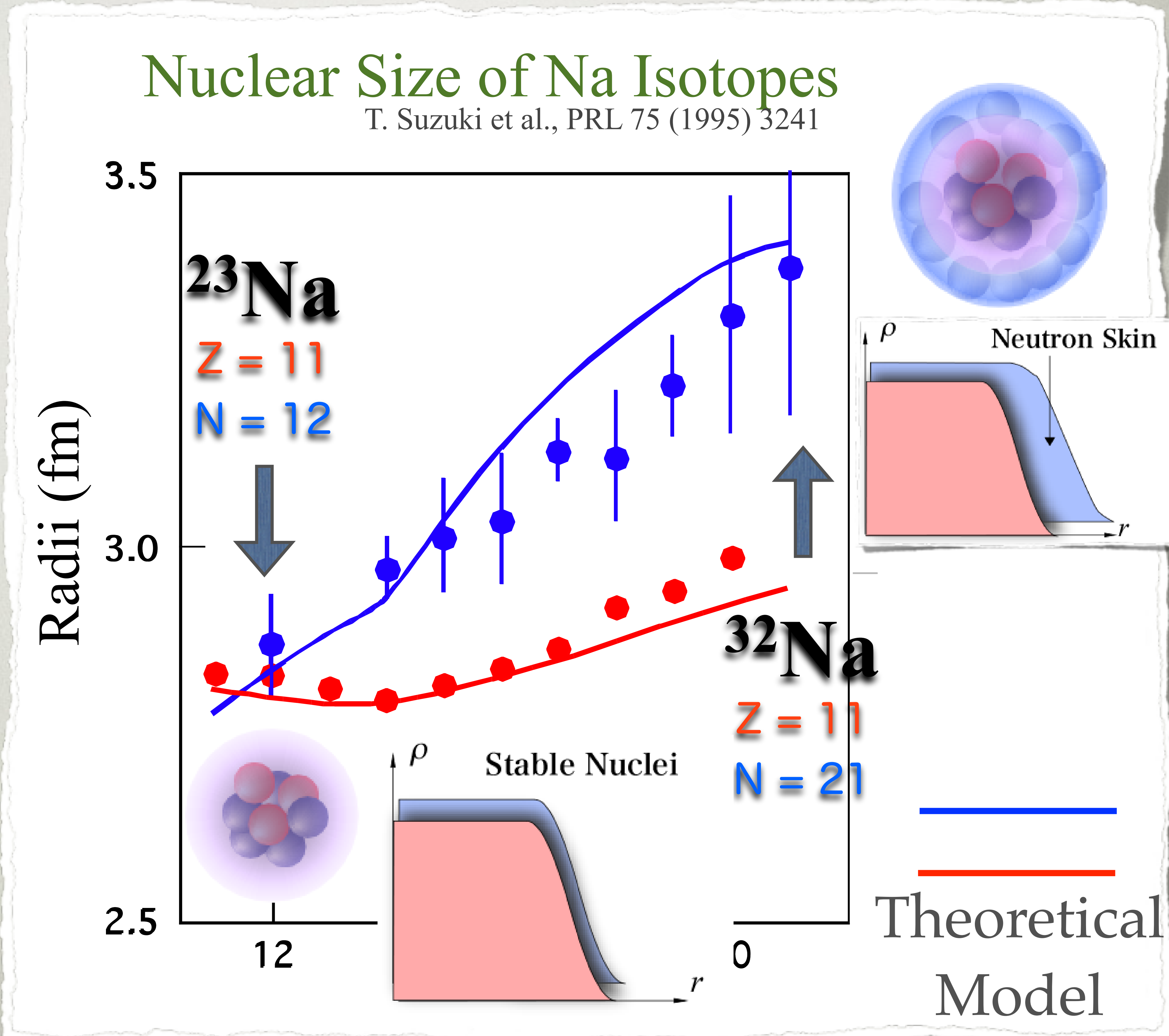


Nuclear Size and Skin formation

σ_I

Neutron Radii

Comparison with known Proton Radii
(Laser spectroscopy)

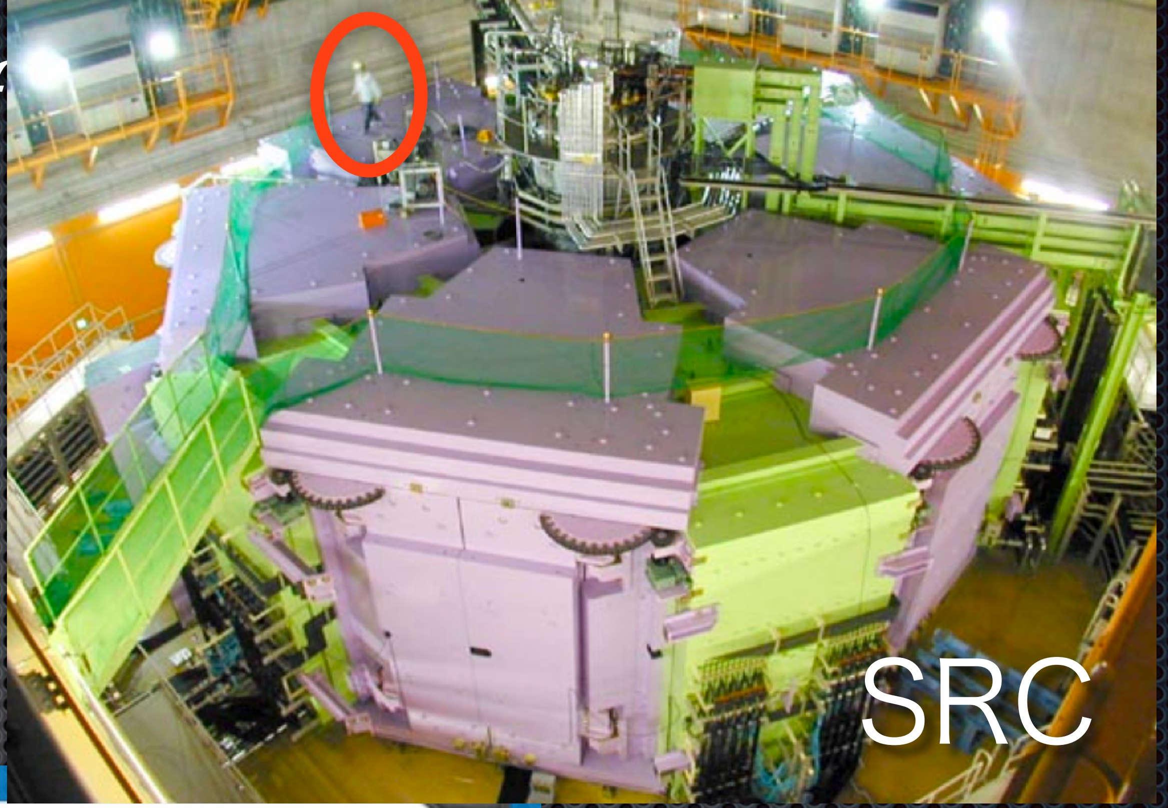


Experiment : Measurements of

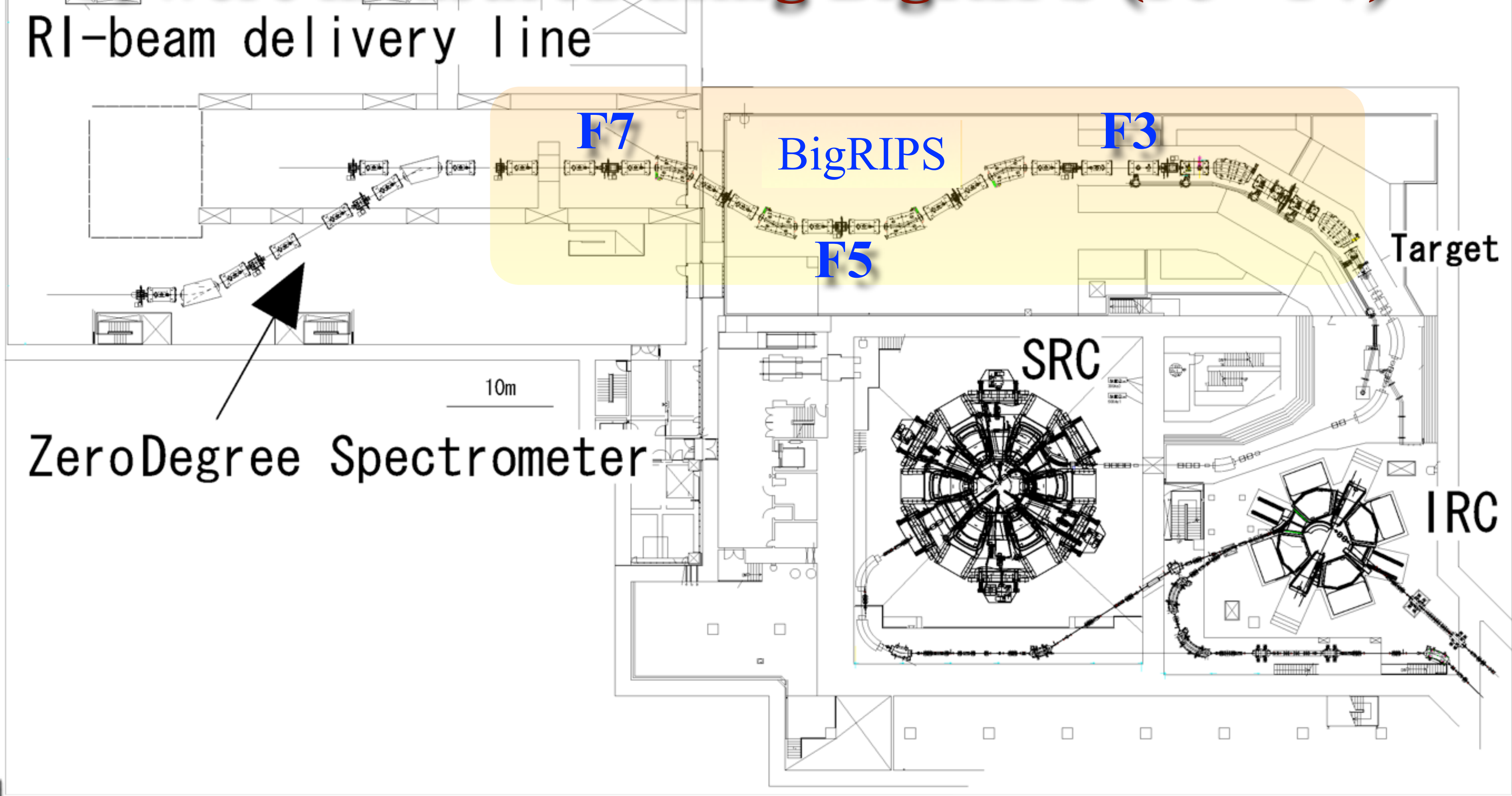
RIBF, RIKEN

Primary Beam ^{48}Ca

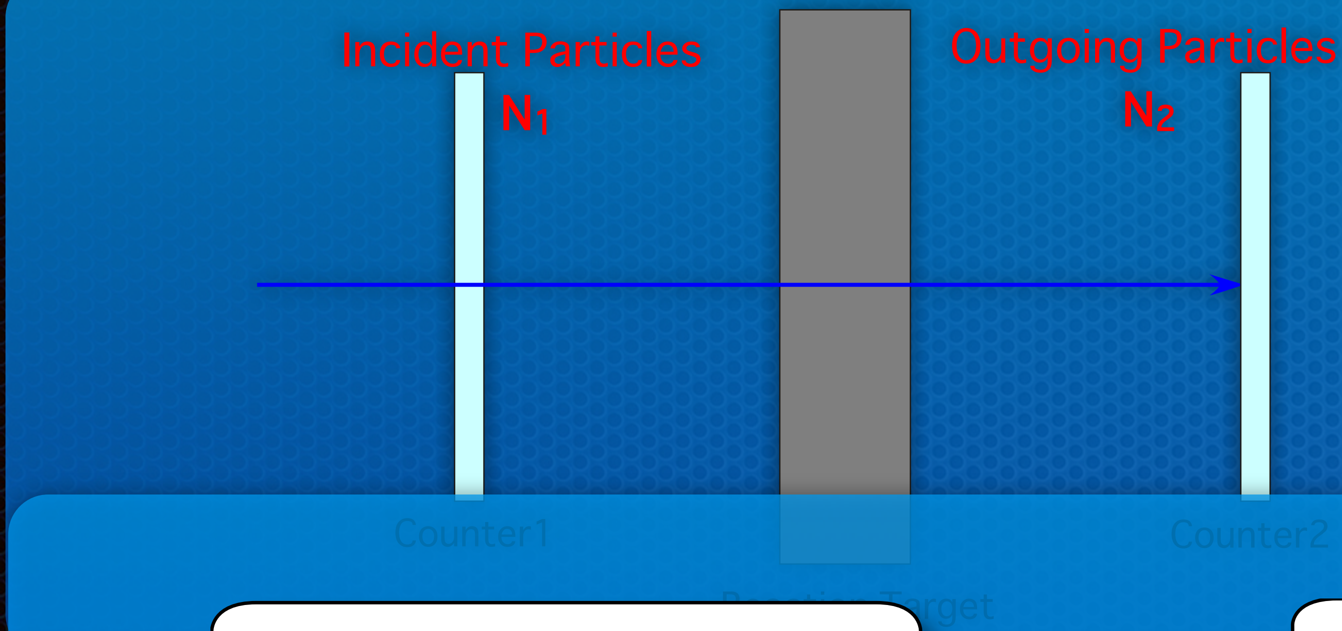
Secondary Beam $^{20\text{-}32}Ne$



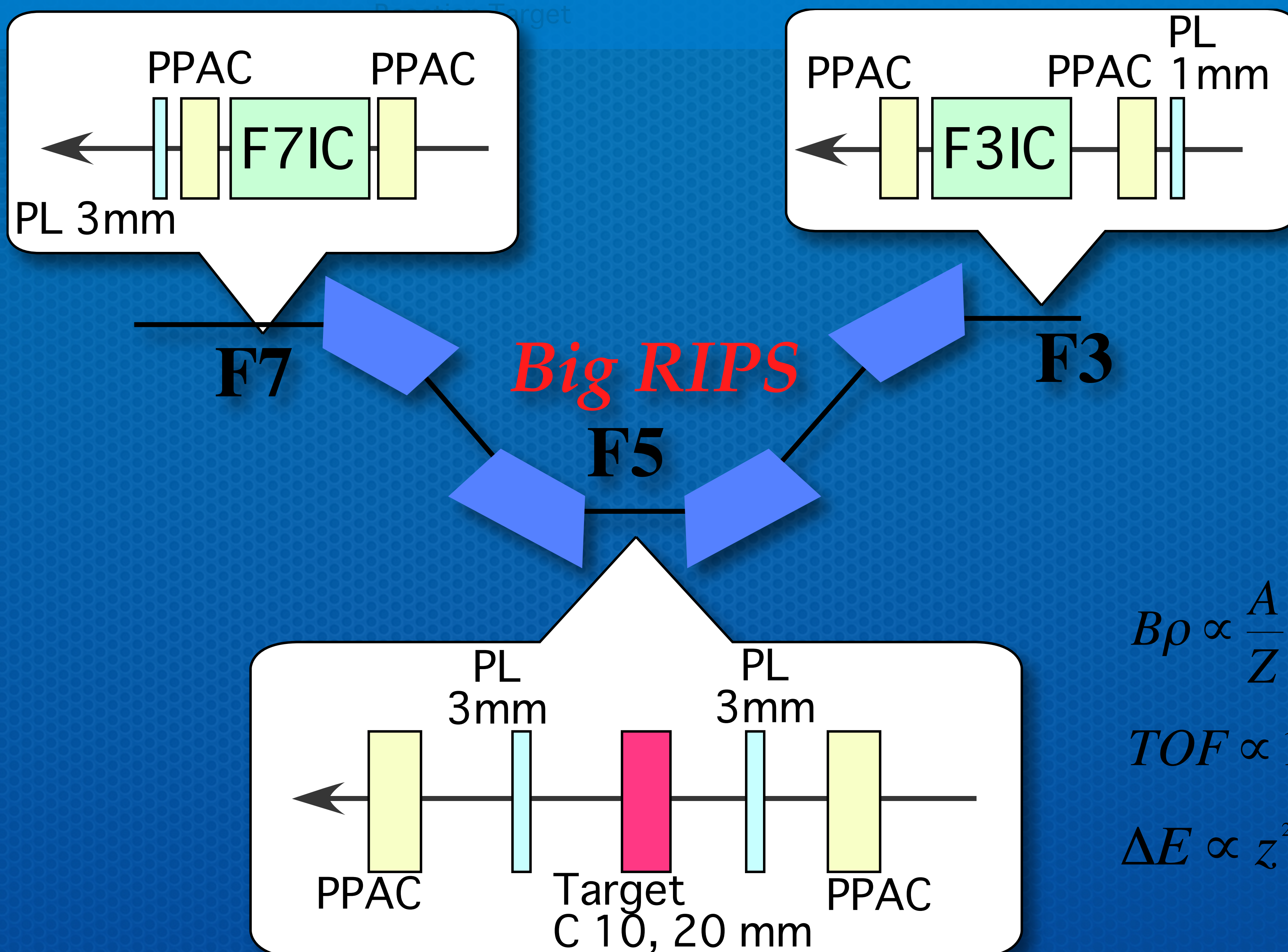
σ_I **were measured using BigRIPS (F3 - F7)**



Transmission Method



$$\sigma_R = -\frac{1}{t}\ln\left(\frac{N_2}{N_1}\right)$$



$$B\rho \propto \frac{A}{Z}\cdot v$$

$$TOF \propto 1/v$$

$$\Delta E \propto z^2 / v^2$$

Neutron Skin Formation in Ne Isotopes

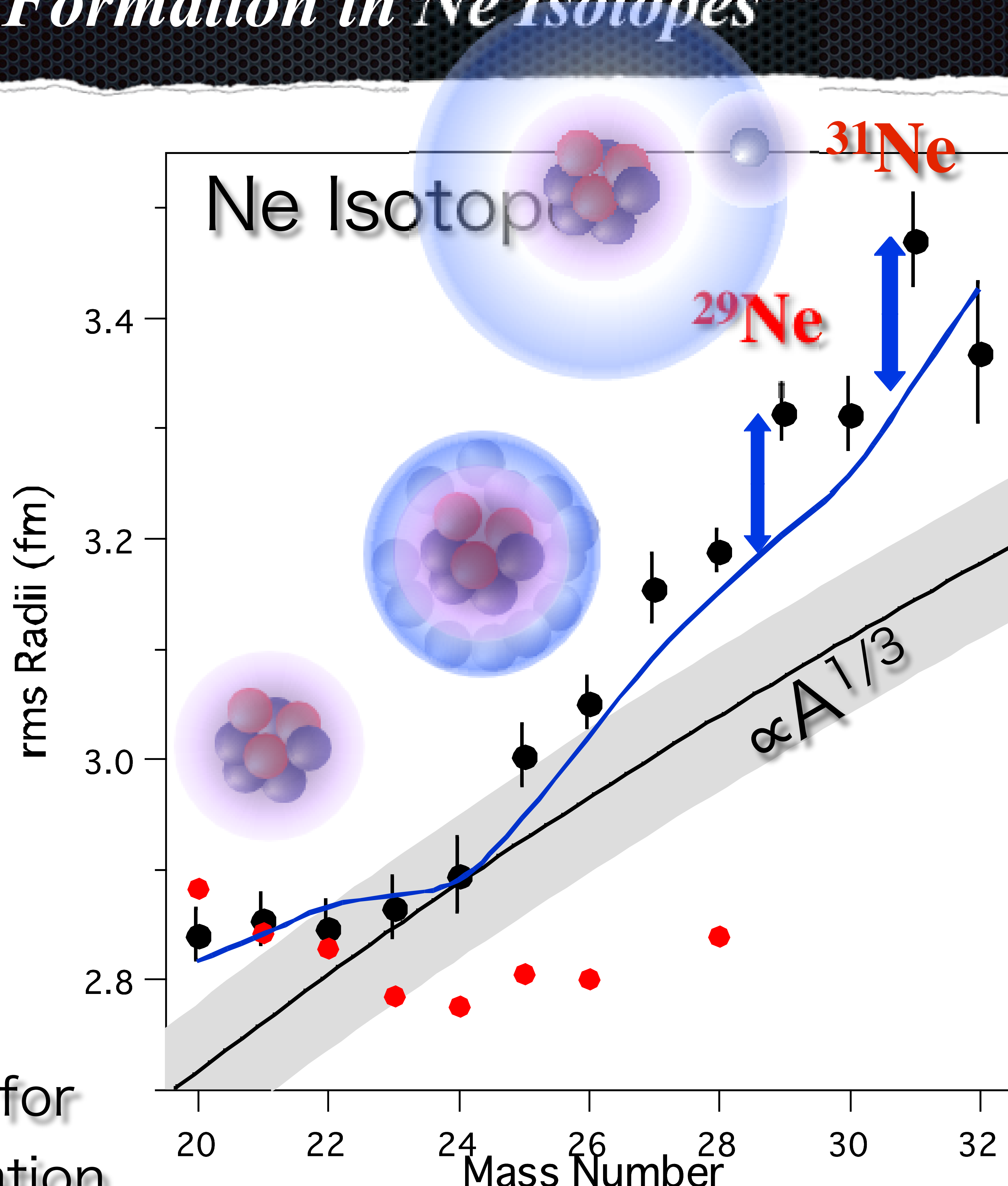
σ_I

Matter Radii

Comparison with known Proton Radii

(Laser spectroscopy)

Theoretical Model for Neutron Skin Formation



Near Future Experiment
Neutron Skin Determination for Ni isotope at RIBF

~ EOS for asymmetric nuclear matter ~

Study of Nuclear Matter from Symmetric to Asymmetric

Symmetric nuclear matter

- Saturation density ~0.17 fm^{-3}
- Energy per particle ~-16MeV
- Nearly incompressible

From Radii, Mass, Collective Excitation data for stable nuclei

Asymmetric nuclear matter

To describe the property of extreme matter

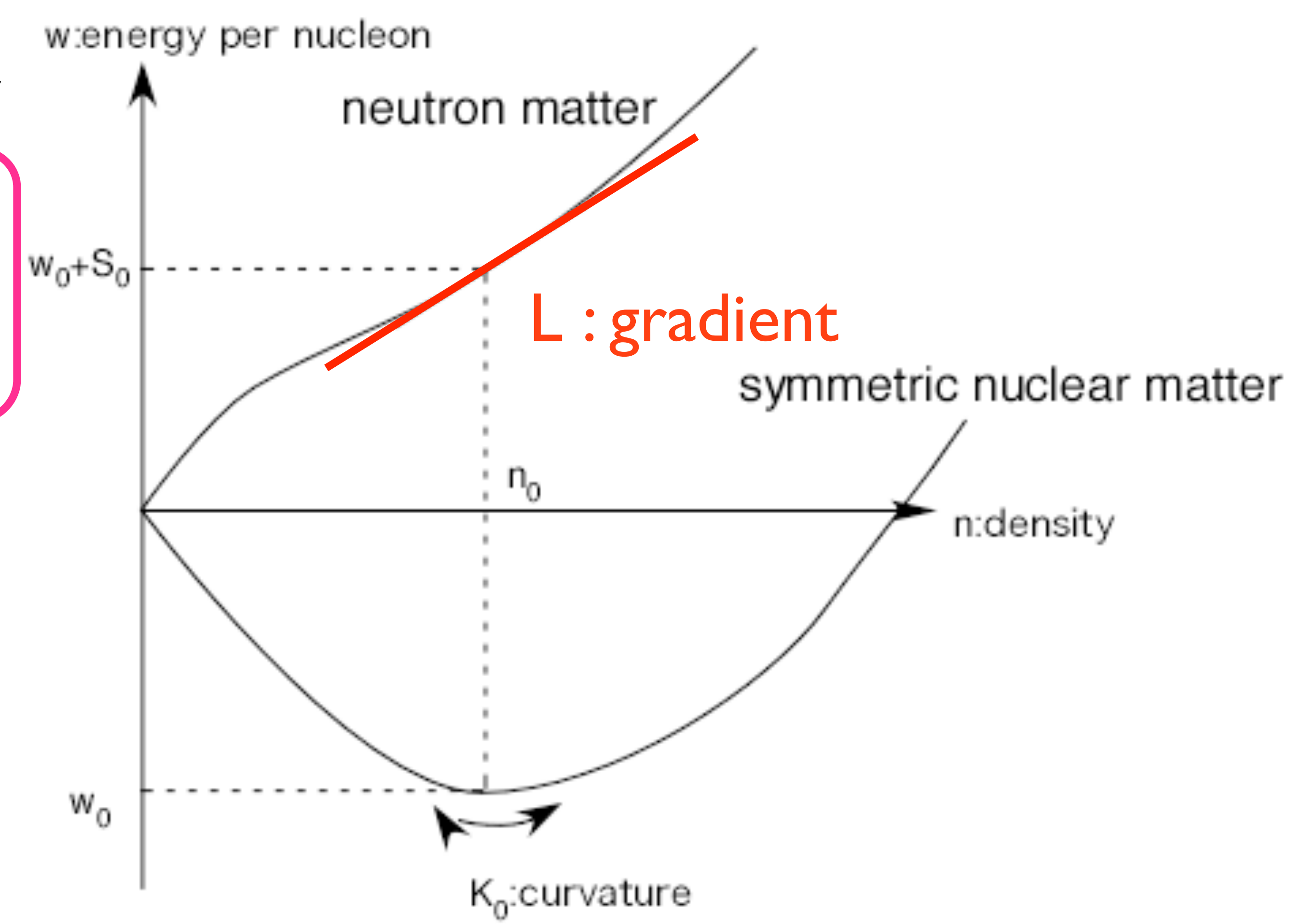
Neutron Star : Structure, Mass, Radius

Energy per nucleon of nearly symmetric nuclear matter

$$w(n,\delta) \backsimeq w_0 + \frac{K_0}{18n_0^2}(n-n_0)^2 + \delta^2\left[S_0 + \frac{L}{3n_0}(n-n_0)\right]$$

n_0 : saturation density, w_0 : saturation energy
K_0 : incompressibility, S_0 : symmetry energy at $n = n_0$
$\delta = (N - Z)/A$

L : Density derivative coefficient of symmetry energy



Kazuhiro Oyamatsu and Kei Iida Phys. Rev. C **81**, 054302 (2010)

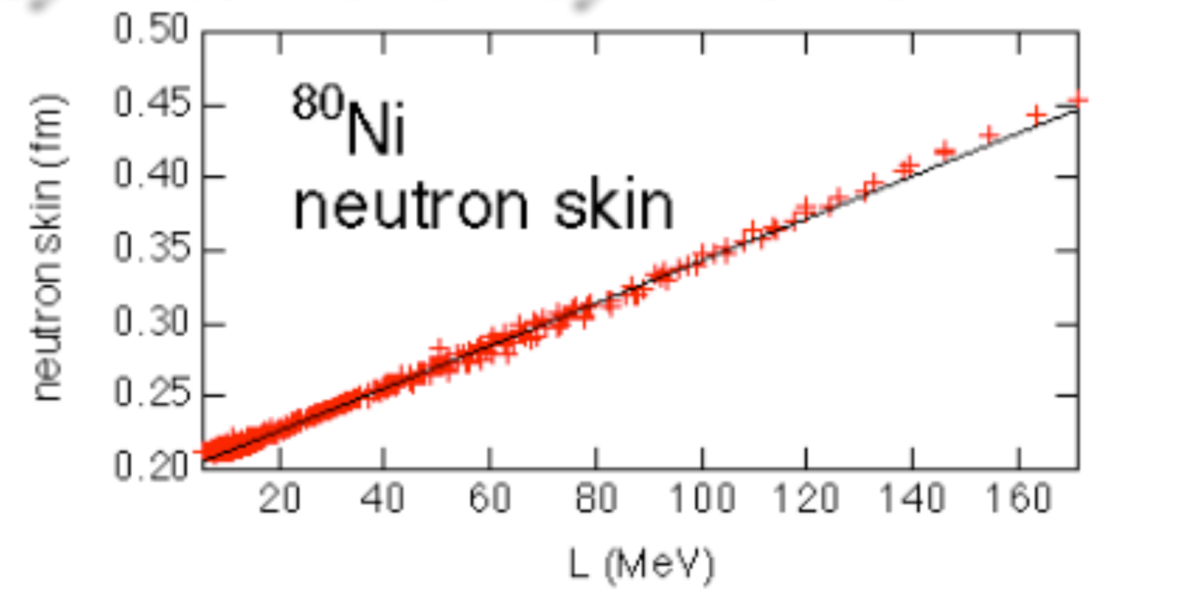
First key parameter L

Study of Nuclear Matter from Symmetric to Asymmetric

How to know L?

Information from atomic nuclei

Many theories indicate
strong correlation between neutron skin
thickness and L



Kazuhiro Oyamatsu and Kei Iida Phys. Rev. C **81**, 054302 (2010)

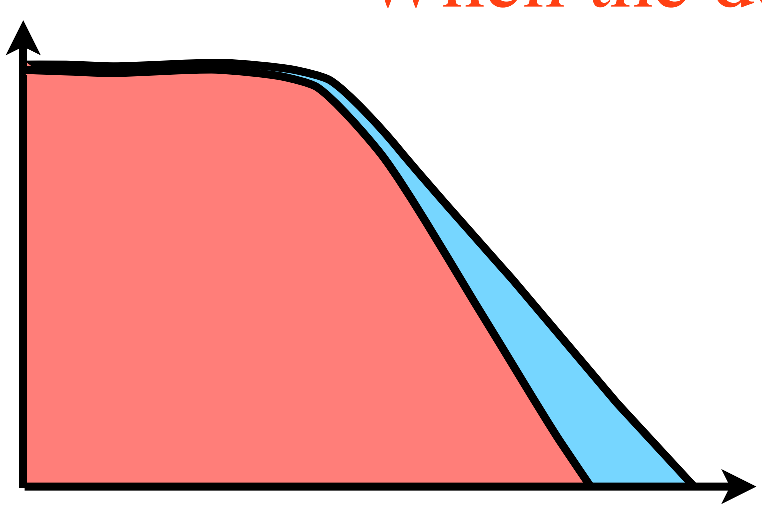
One Simple correlation **M. Centelles et al., PRL 102, 122502 (2009)**

EOS around N≃Z $$w(n,\delta) \backsimeq w_0 + \frac{K_0}{18n_0^2}(n-n_0)^2 + \delta^2\left[S_0 + \frac{L}{3n_0}(n-n_0)\right]$$

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

When the density of nuclear matter is around nuclear surface density

Symmetry term a_A ≃ symmetry term of EOS ~0.1 fm^{-3}

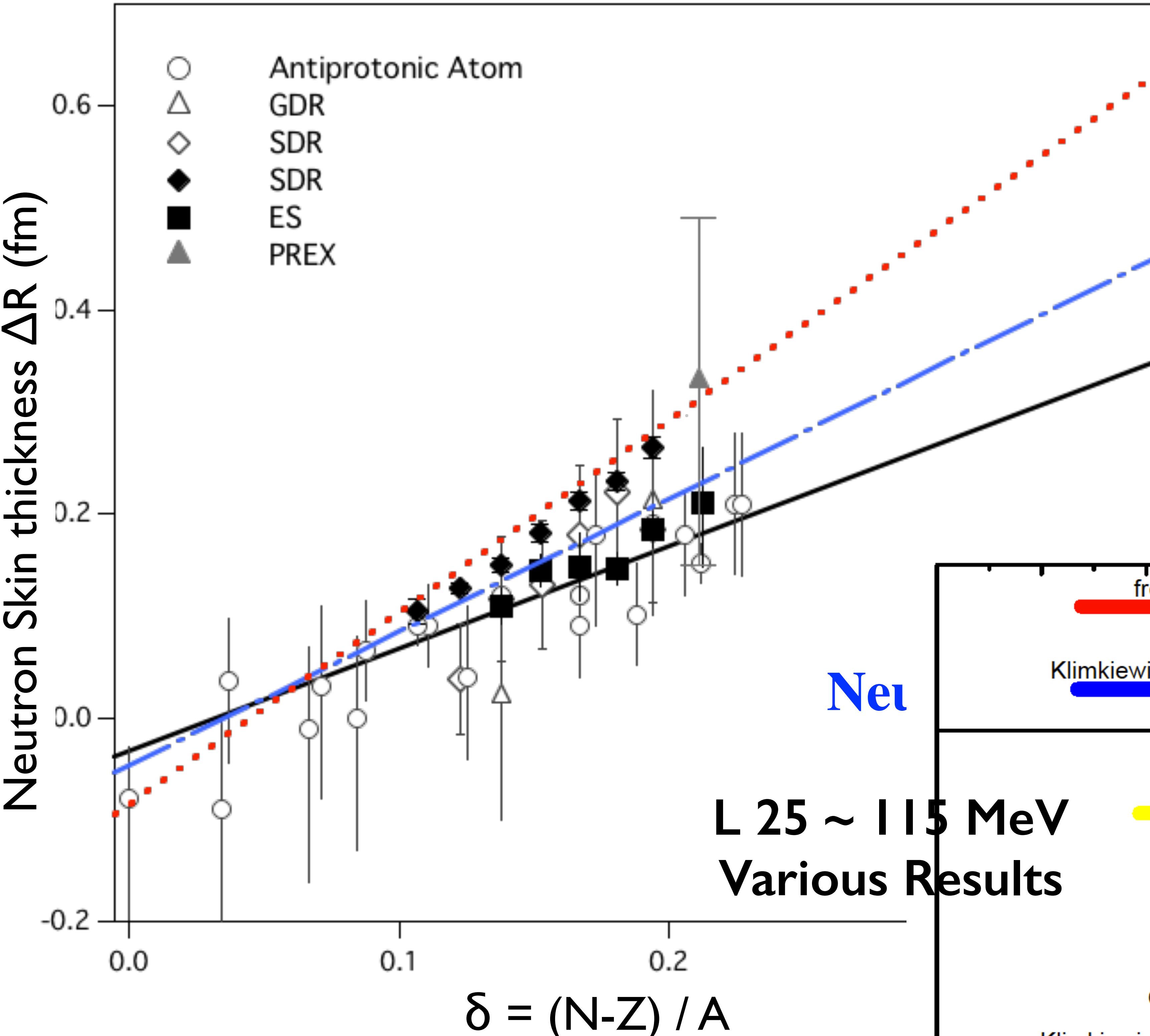


Neutron skin thickness $\Delta R \sim L \times \delta$ + *correction term*

$\delta = (N - Z)/A$, $A > 40$

Measurement of δ dependence of ΔR → L

Neutron Skin Measurements and Models

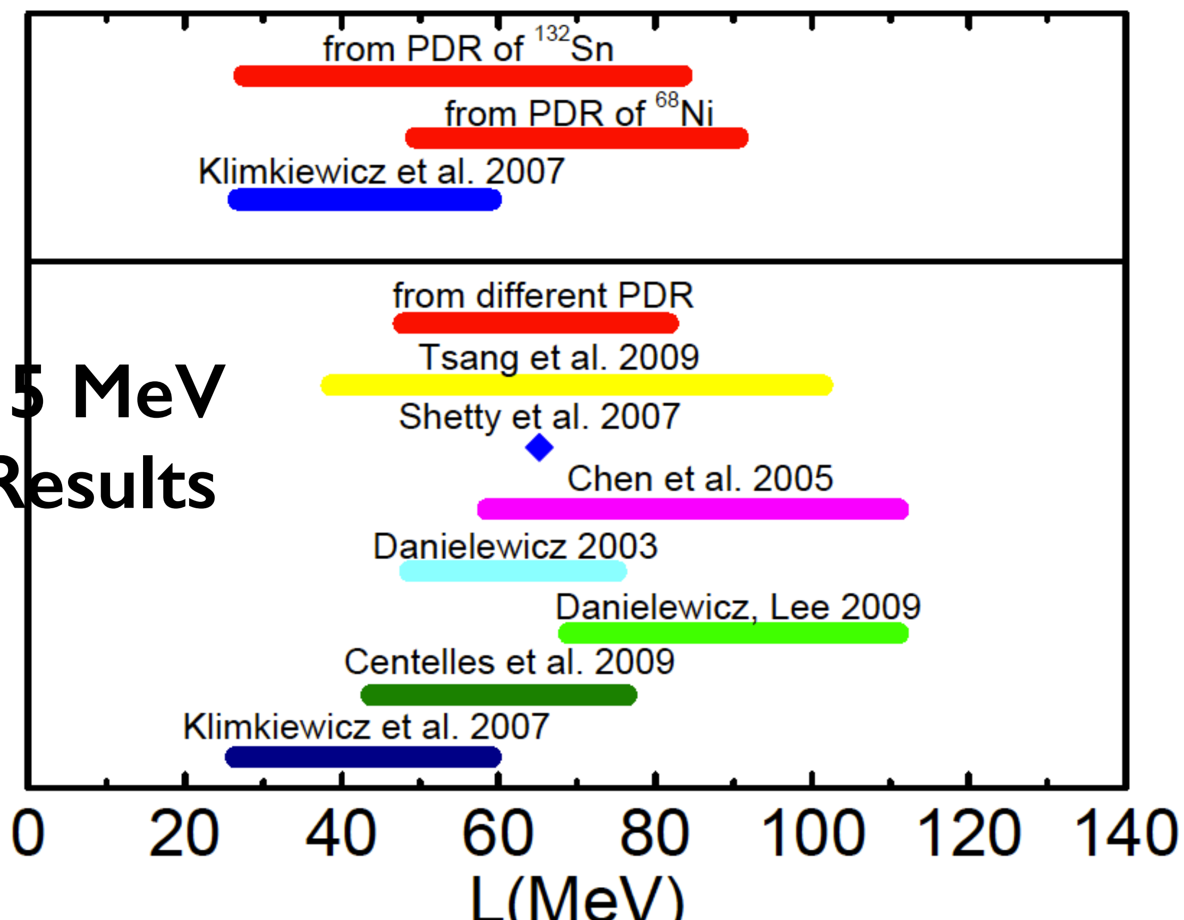


Prediction from NL3 interaction
Neutron Star $R_{1.4M\odot}$ 15km
M_{max} = 2.8 M⊙

FSUGold interaction
Neutron Star $R_{1.4M\odot}$ 13km
M_{max} = 1.7 M⊙

M. Centelles et al.,
Analysis of L using
Antiprotonic Atom Data
from A = 40 ~ 238

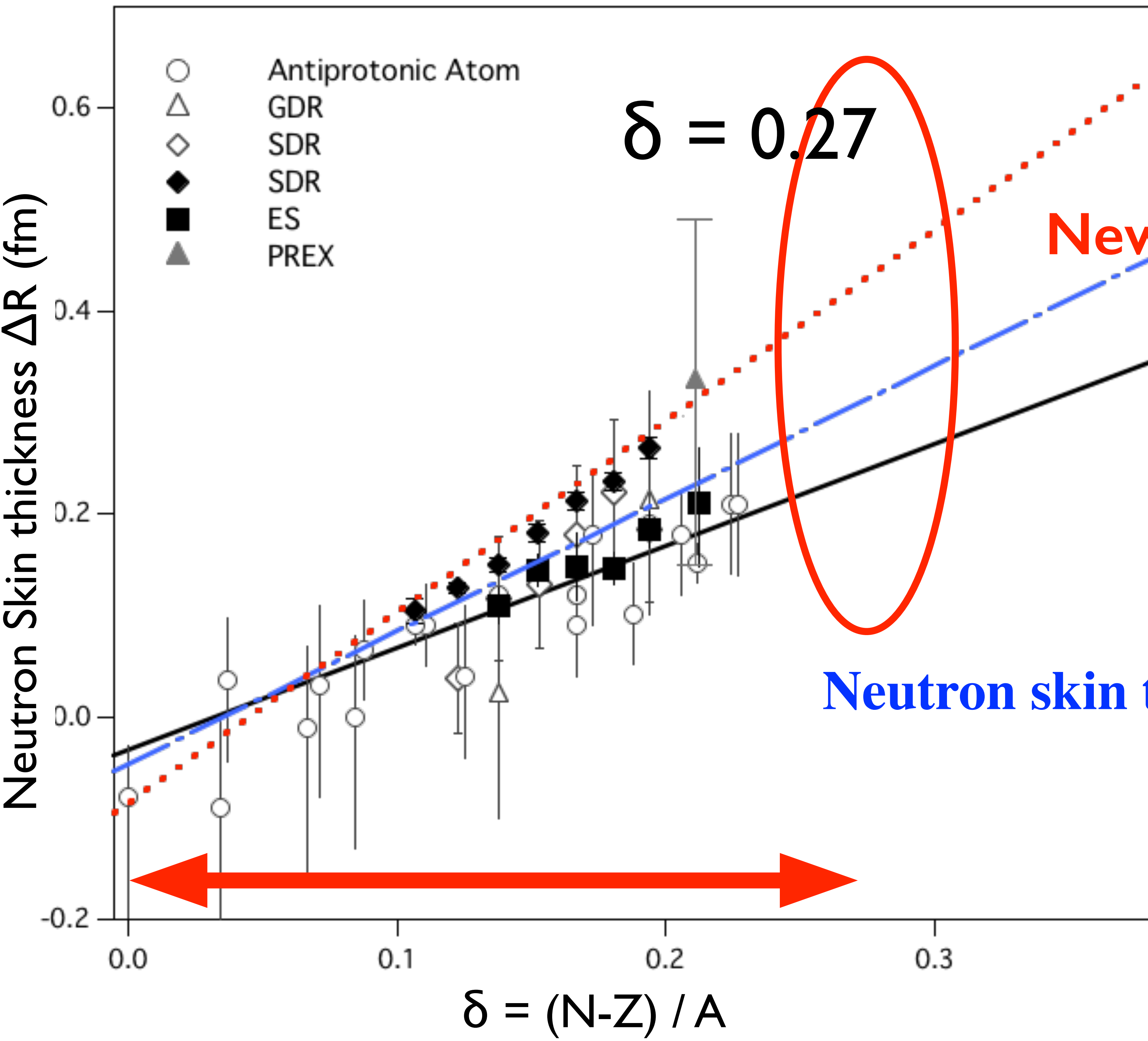
L 25 ~ 115 MeV
Various Results



Li-Gang Cao, H. Sagawa, G. Col'o
Nuclear Structure in China 2012 (2012) 33

Anti Protonic Atom : A. Trzcinska et al., Phys. Rev. Lett. **87** 082501 (2001).
GDR : A. Krasznahorkay et al., Nucl. Phys. A 567 521 (1994).
SDR : A. Krasznahorkay et al., Phys. Rev. Lett. 82, 3216 (1999).
SDR : A. Krasznahorkay et al., Nucl. Phys. A 731 224 (2004).
ES : S. Terashima et al., Phys. Rev. C 77 024317 (2008).
ES : J. Zenihiro et al., Phys. Rev. C 82 044611 (2010).

Neutron Skin Measurements and Models



New Measurements of ΔR
Ni isotopes from
^{56}Ni up to ^{77}Ni
δ = 0 ~ 0.27

Neutron skin thickness $\Delta R \sim L \times \delta$
$+$ *correction term*

$$\Delta R^2 = (A \cdot R_m{}^{\wedge 2} - Z \cdot R_p{}^{\wedge 2})/N$$

σ_I (Interaction cross section) → Matter Radius
σ_{CC} (Charge changing cross section) → Charge Radius