FRIB

Ecole Internationale Joliot Curie: New Avenues with Radioactive Ion Beams
Lecture 1

September, 2011

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U.S. DEPARTMENT OF
ENERGY
Office of Science

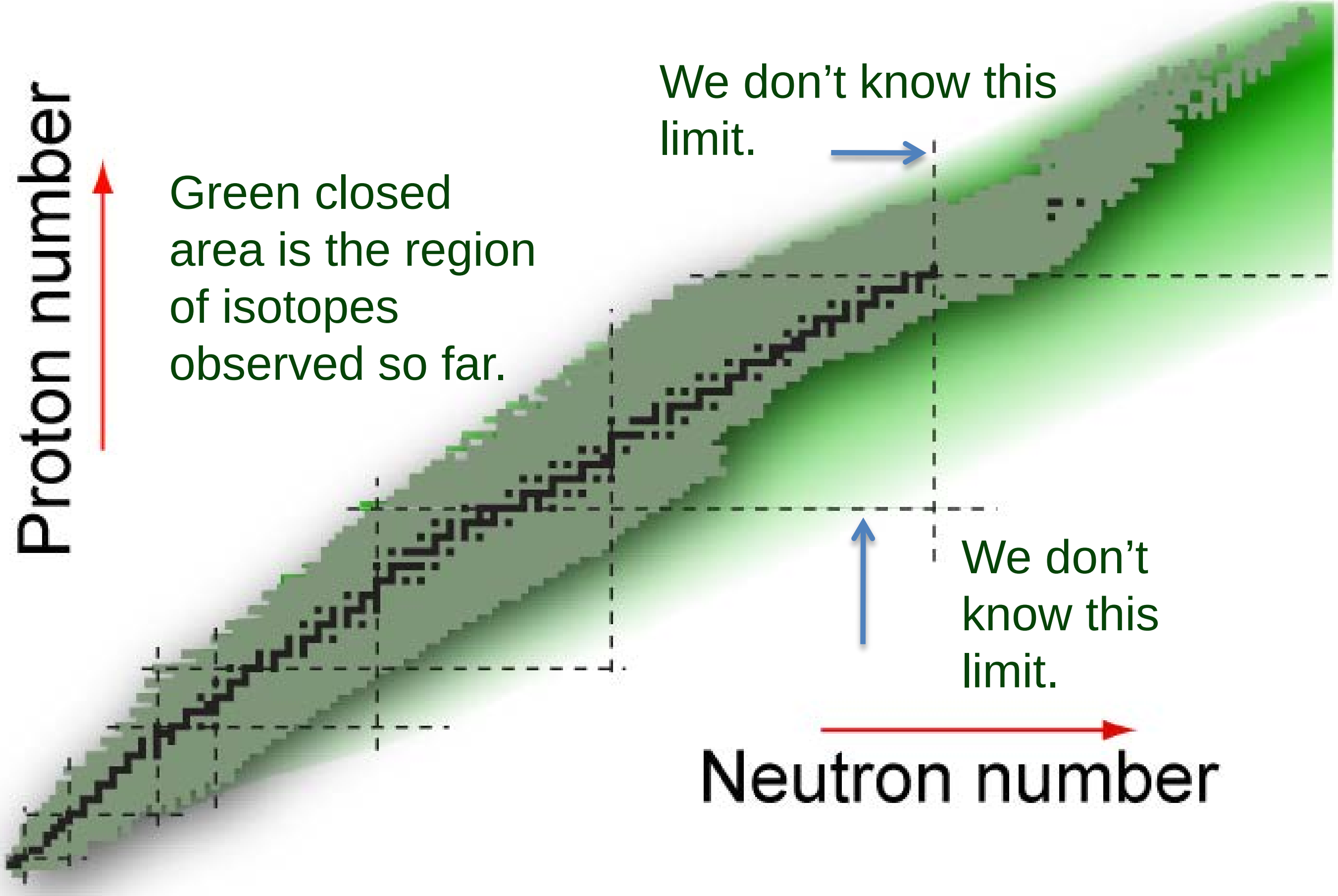
Outline of my two lectures

- The material will be an introduction, and motivation, for what you will hear in many of the following lectures (Lacroix, Harakeh, Poves, Papenbrock, Janssens, Schmidt, Flocard)
- Lecture 1: Search for the limits of nuclear binding and production of new isotopes
  - How many elements are possible?
  - How many isotopes of each element are possible?
  - History of the searches
  - Techniques and accelerator-based facilities to answer the previous two questions
- Lecture 2: Science with rare isotopes
  - Toward a comprehensive model of atomic nuclei and how they interact
  - Model the chemical history of the Universe and extreme astrophysical environments
  - Tests of Nature’s symmetries using the properties of nuclei
  - Use of unusual isotopes in other branches of science (applications)

It is important for you to ask questions.

The Nuclear Landscape

Roadmap: Chart of Nuclides (sometimes called a Segré Plot or Chart)



Green closed area is the region of isotopes observed so far.

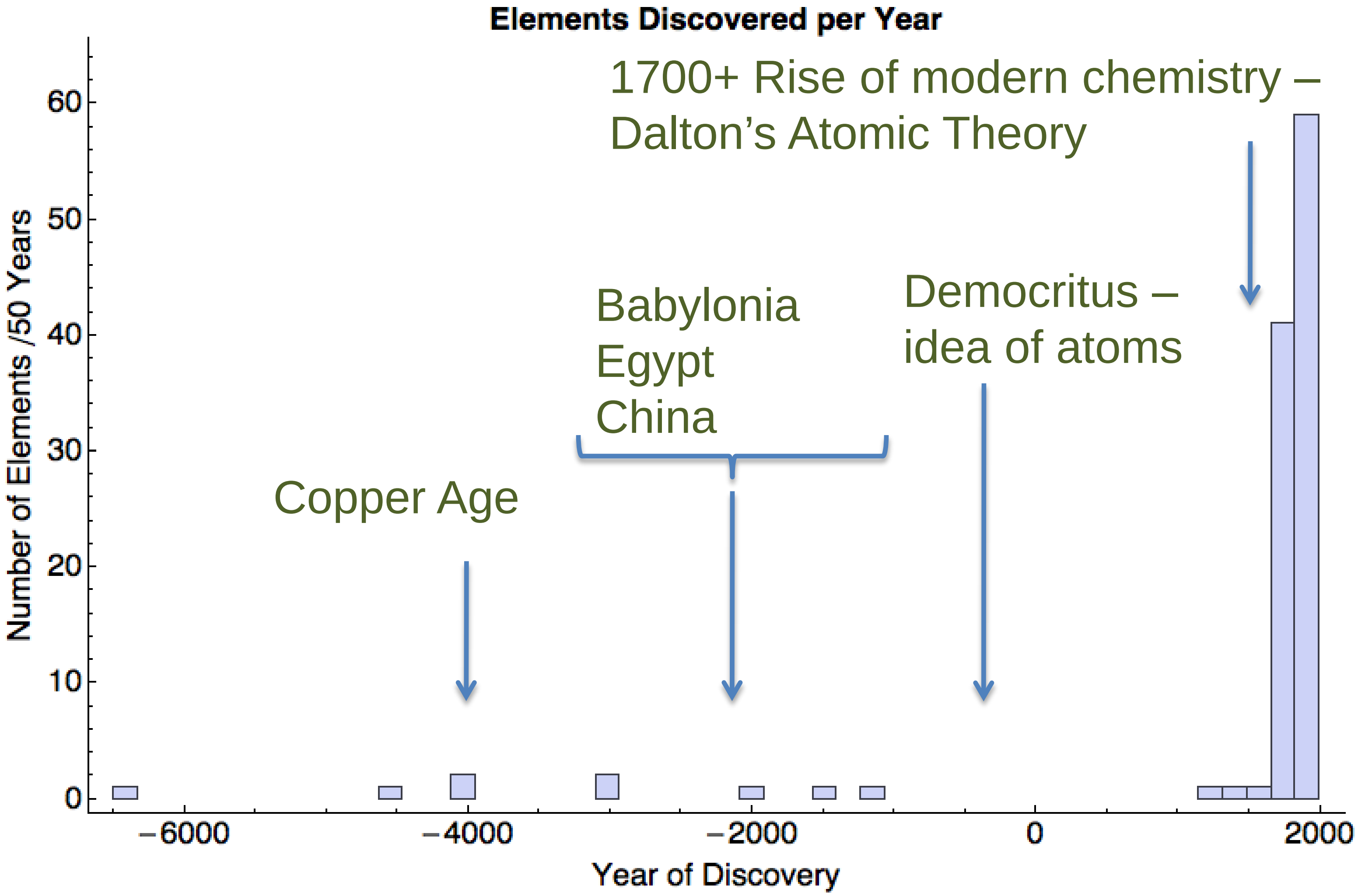
We don’t know this limit.

We don’t know this limit.

We don’t know this limit.

Black squares are the around 260 stable isotopes found in nature (> 1 Gy)

History of Element Discovery



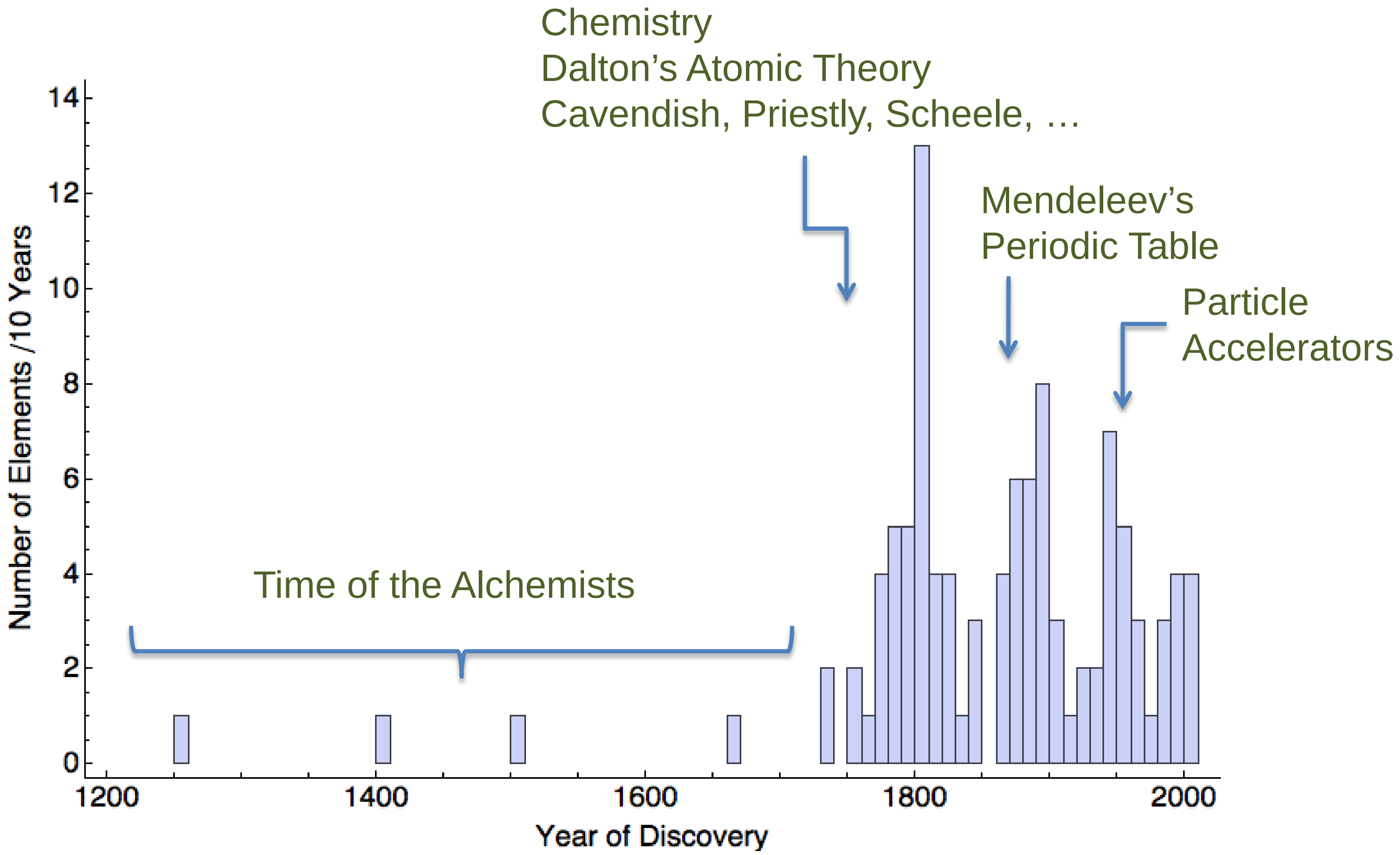
1700+ Rise of modern chemistry –
Dalton’s Atomic Theory

Babylonia
Egypt
China

Democritus –
idea of atoms

Copper Age

The history of element discovery 1200-2010



Chemistry
Dalton's Atomic Theory
Cavendish, Priestly, Scheele, …

Mendeleev's
Periodic Table

Particle
Accelerators

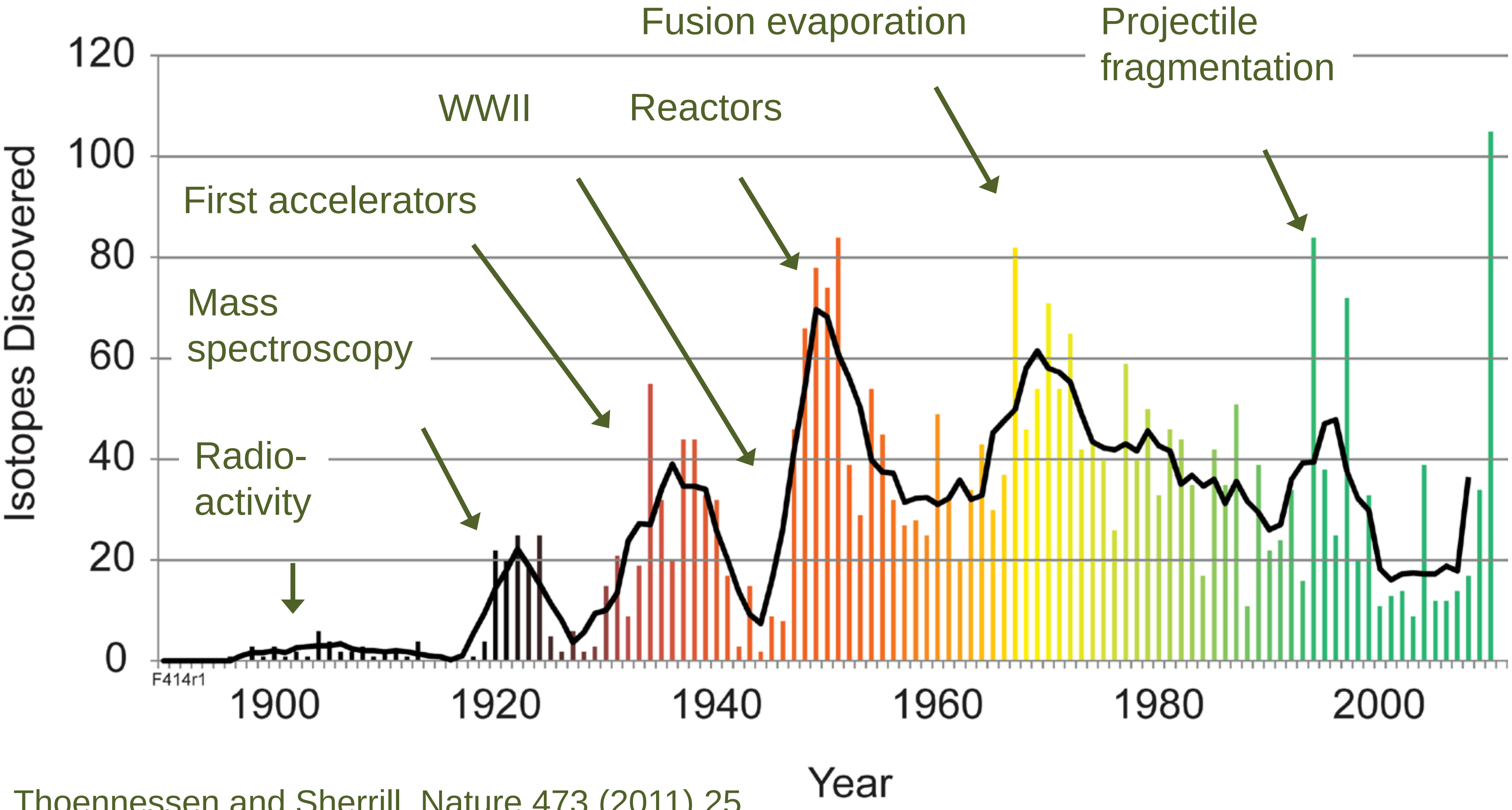
Time of the Alchemists

Discovery of Isotopes

- Fredrick Soddy – Credited with discovery of isotopes
  - With Rutherford he studied radioactive decay and developed a set of “Displacement Laws” that describe the transformation following decay
  - In 1910 he found t
    ay
    differed
  - He realized that at
    ms
    that he called isot
    n
    1913 showed the f
    pe.
  - "Put colloquially, th
    es.” –
    Soddy Nobel Prize
  - Won Nobel Prize i

- First artificial isot
  - The first artificial is
    re, 10
    Feb 1934) by bom
  - “We propose for the new radio isotopes formed by the transmutation of boron, magnesium and aluminum, the names radionitrogen, radiosilicon, radiophosphorus”
  - For this discovery, Curie and Joliot won the Nobel Prize in chemistry in 1935

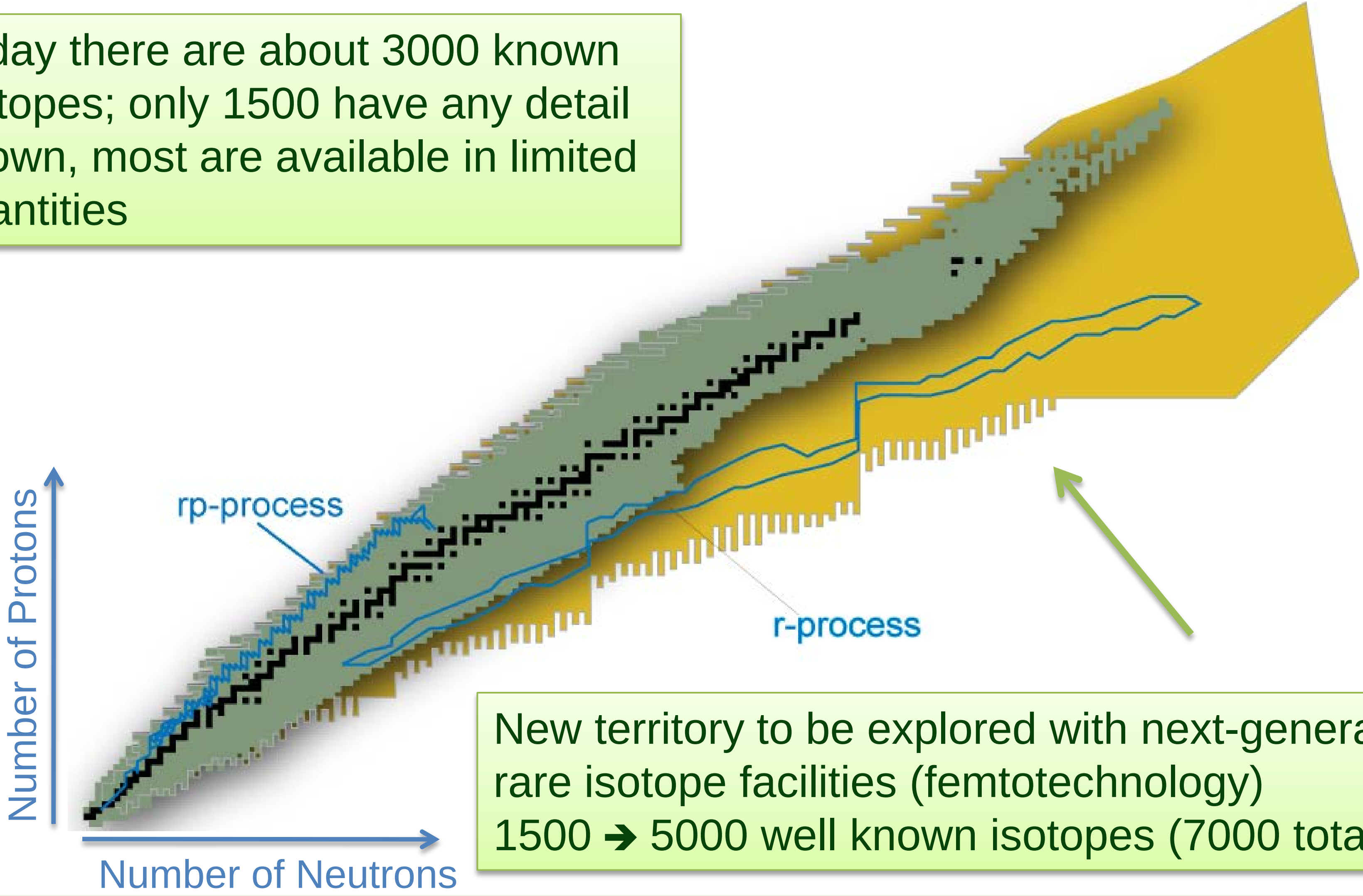
New isotope discoveries per year



Thoennessen and Sherrill, Nature 473 (2011) 25

Designer Isotope – Arbitrary Combination of Neutrons and Protons Desired by Research

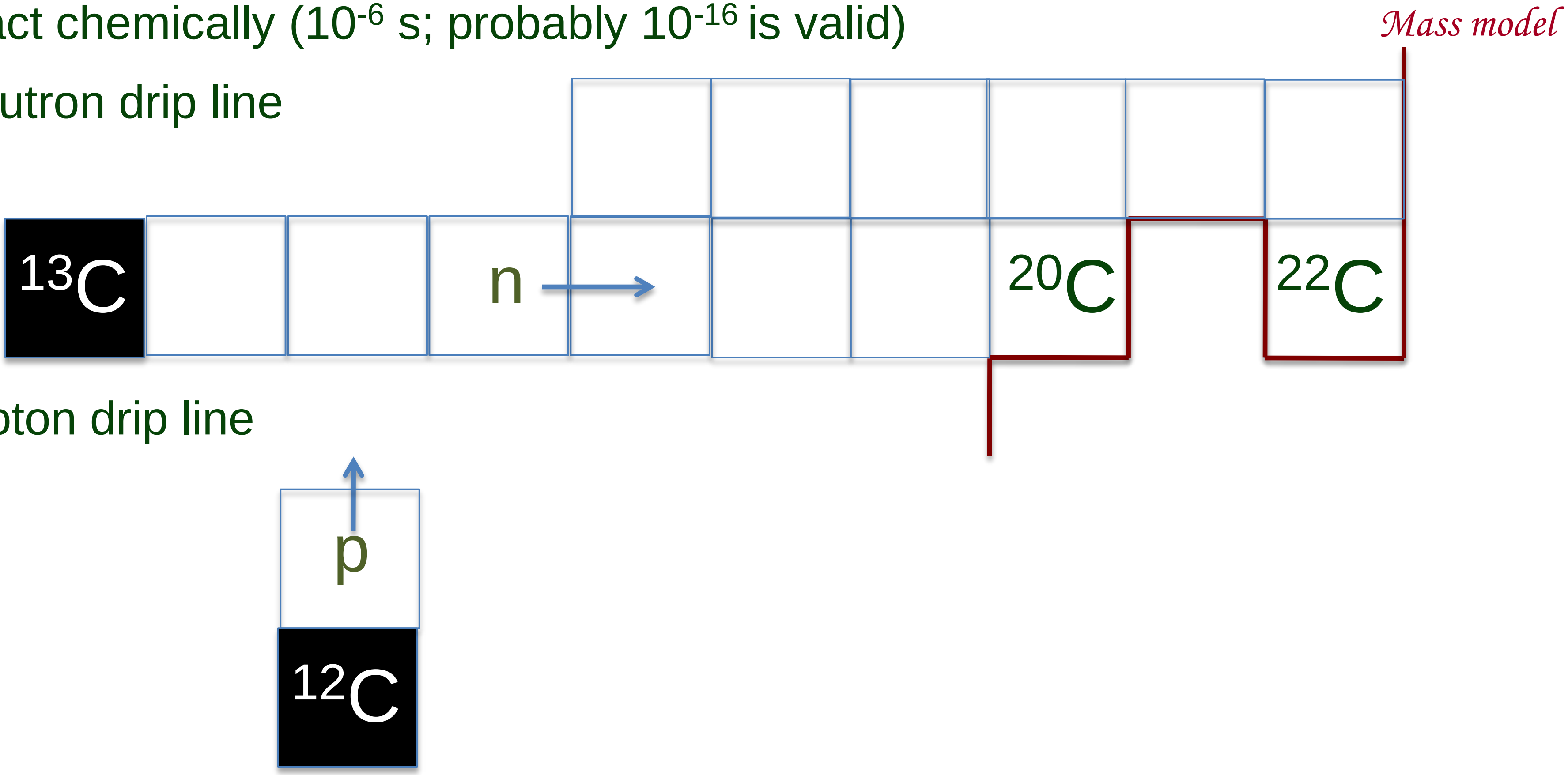
Today there are about 3000 known isotopes; only 1500 have any detail known, most are available in limited quantities



New territory to be explored with next-generation rare isotope facilities (femtotechnology)
1500 ➔ 5000 well known isotopes (7000 total?)

How many isotopes are possible?

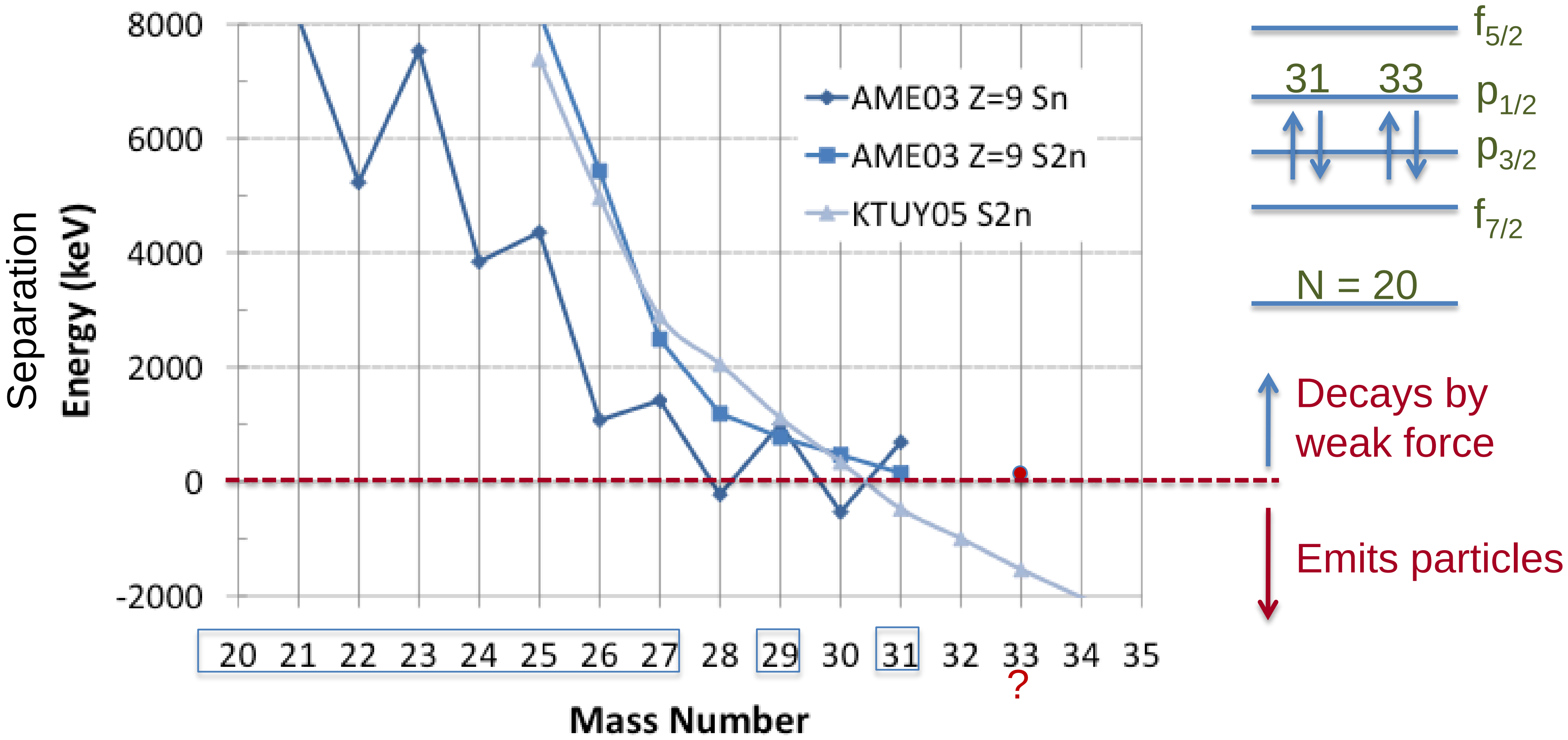
- Let's define "possible" as lasting long enough to make an atom that could react chemically (10^{-6} s; probably 10^{-16} is valid)
- Neutron drip line
- Proton drip line



- Heaviest elements – The claim for up to atomic number 118 has been made at Dubna (Oganessian et al.)

Systematics of Separation Energies: Fluorine

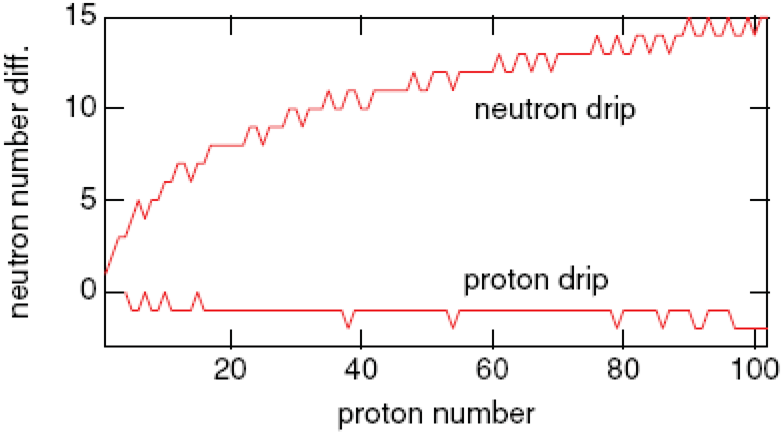
Separation energy is the energy required to remove 1 neutron (Sn) or 2 neutrons (S2n) – negative numbers say the neutron(s) is unbound



KTUY05 - Koura-Tachibana-Uno-Yamada, Prog Theor Phys 113 (2005) 305

Why are the drip lines interesting?

- Benchmark that all nuclear models can be measured against
- Sensitive to aspects of the nuclear force (see right)
- Along the drip lines the structure of nuclei is qualitatively different (Haloes and Skins – next lecture)
- New types of clustering, enhanced pairing, importance of the continuum (and relation to scattering), novel quantum states (Effimov states), study of nuclear interactions in a low density (or pure isospin) environment, etc.



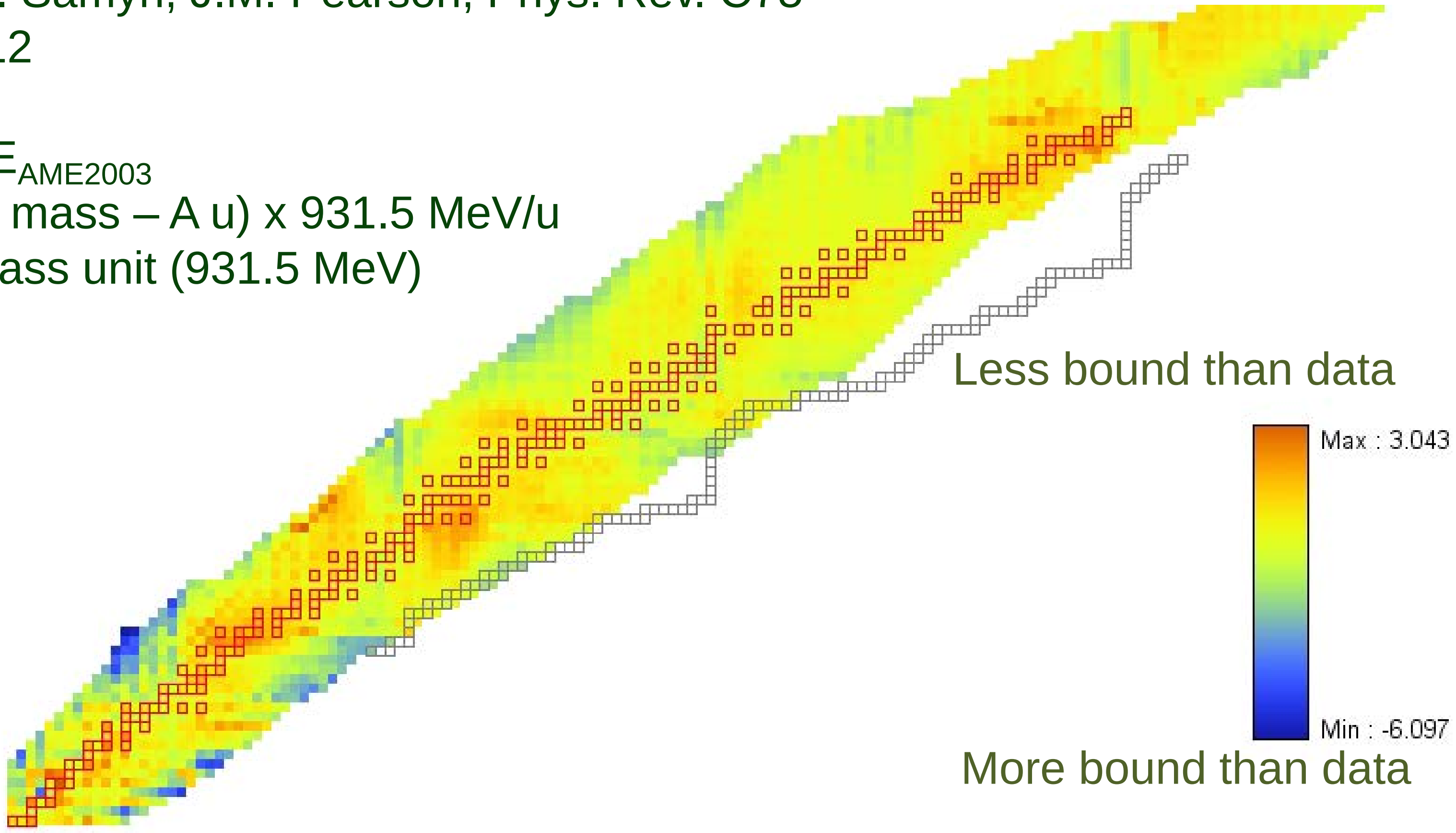
K Oyamatsu, K Iida, H Koura, Phy Rev C 82 (2010) 027301
Macroscopic model diff (high/low DD symmetry energy coefficient, L)

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

New Physics from Mass Model Comparison to Data

HFB-14: *Hartree-Fock-Bogoliubov w/delta pairing force*
S. Goriely, M. Samyn, J.M. Pearson, Phys. Rev. C75 (2007) 064312

$ME_{HFB14} - ME_{AME2003}$
ME = (Actual mass – A u) x 931.5 MeV/u
u = atomic mass unit (931.5 MeV)



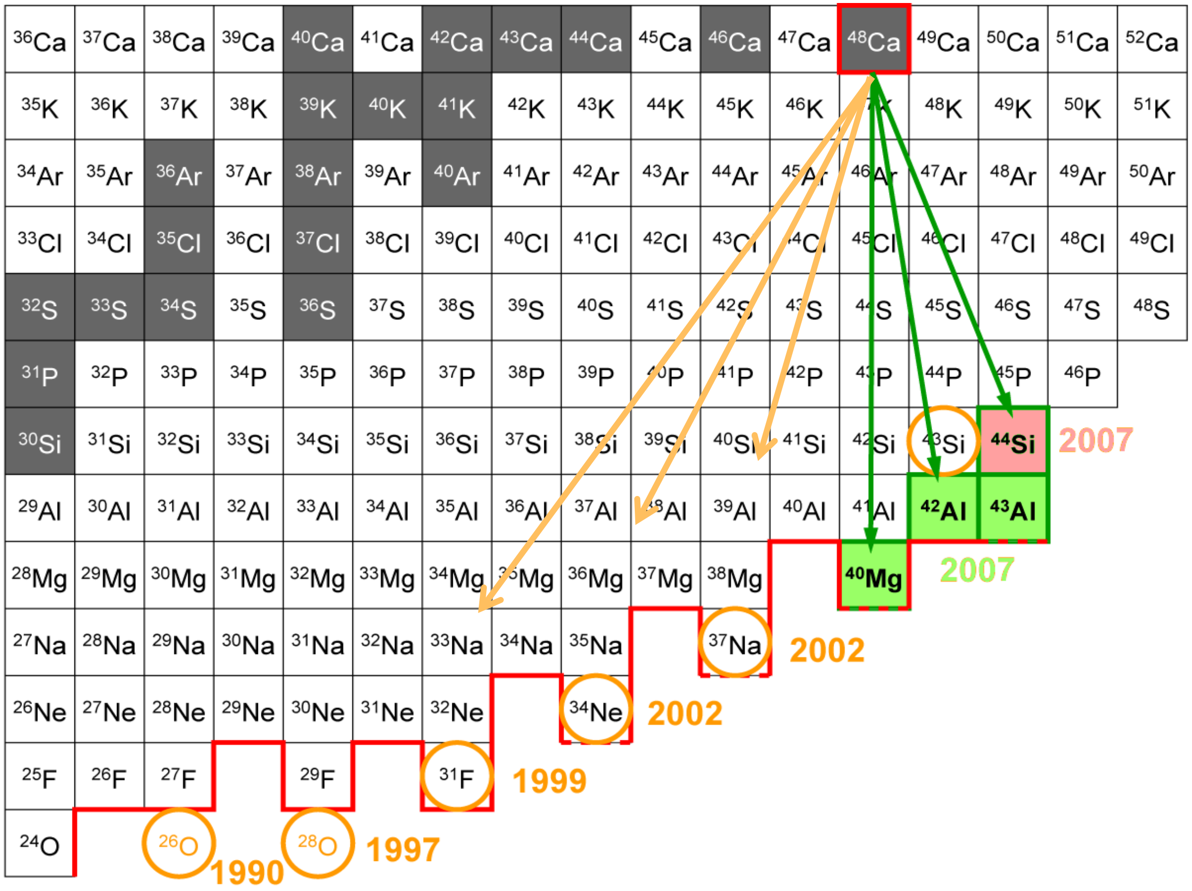
Less bound than data

More bound than data

www.nuclear masses.org

The Neutron Drip Line for low Z nuclei

- The location of the neutron drip line is only known up to Oxygen!
- No $^{25, 26}$O .. Guillemaud-Mueller, *et al. Phys. Rev. C41* (1990) 937
- H. Sakurai et al., PLB 448 (1999) 180
- ^{34}Ne & ^{37}Na .. Notani *et al.*, Phys. Lett. *B542* (2002) 49
- ^{44}Si .. Tarasov, *et al.* Phys. Rev. *C75* (07) 064613
- ^{40}Mg & ^{42}Al .. Baumann, *et al. Nature 449* (07) 1022

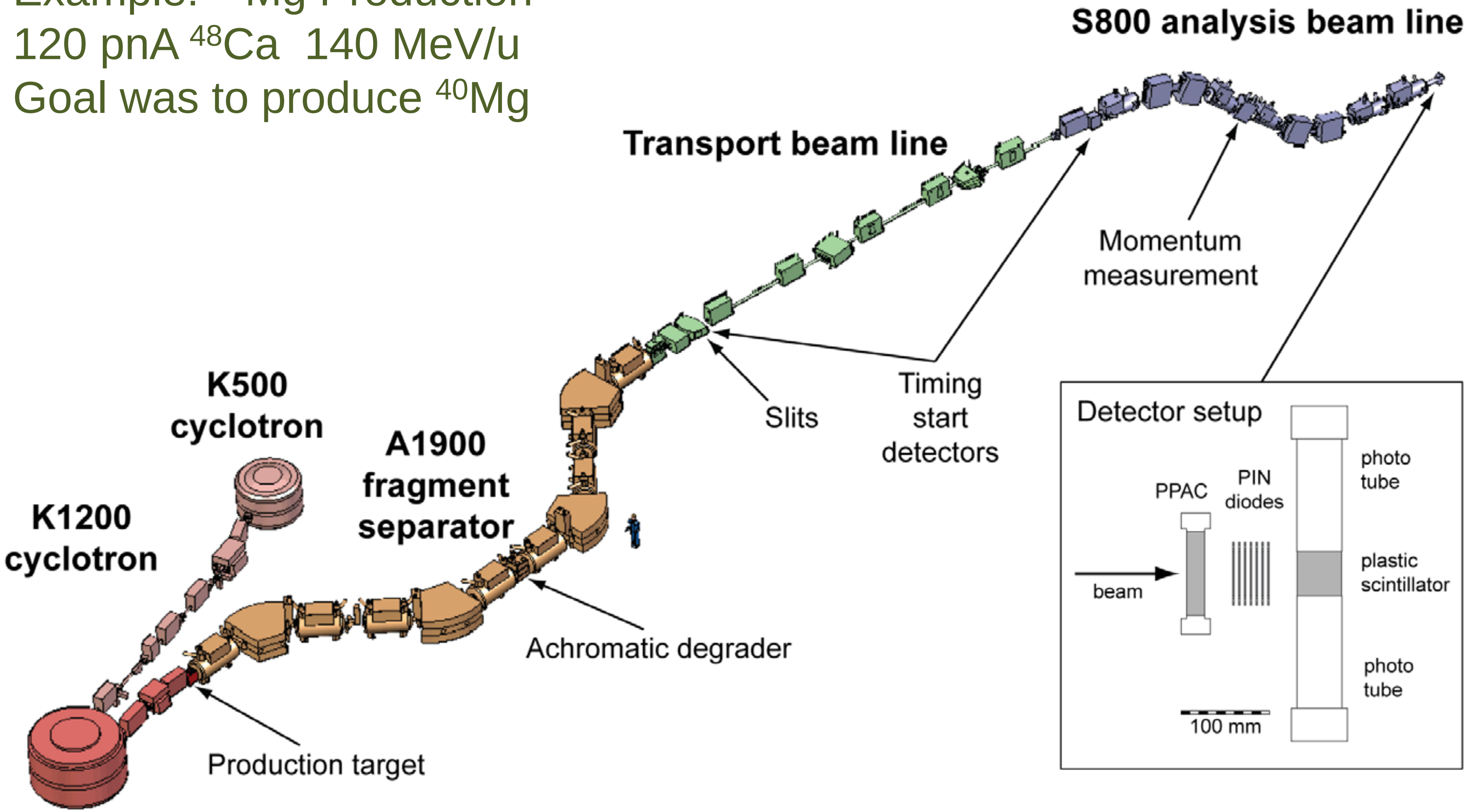


^{36}Ca	^{37}Ca	^{38}Ca	^{39}Ca	^{40}Ca	^{41}Ca	^{42}Ca	^{43}Ca	^{44}Ca	^{45}Ca	^{46}Ca	^{47}Ca	^{48}Ca	^{49}Ca	^{50}Ca	^{51}Ca	^{52}Ca
^{35}K	^{36}K	^{37}K	^{38}K	^{39}K	^{40}K	^{41}K	^{42}K	^{43}K	^{44}K	^{45}K	^{46}K	^{47}K	^{48}K	^{49}K	^{50}K	^{51}K
^{34}Ar	^{35}Ar	^{36}Ar	^{37}Ar	^{38}Ar	^{39}Ar	^{40}Ar	^{41}Ar	^{42}Ar	^{43}Ar	^{44}Ar	^{45}Ar	^{46}Ar	^{47}Ar	^{48}Ar	^{49}Ar	^{50}Ar
^{33}Cl	^{34}Cl	^{35}Cl	^{36}Cl	^{37}Cl	^{38}Cl	^{39}Cl	^{40}Cl	^{41}Cl	^{42}Cl	^{43}Cl	^{44}Cl	^{45}Cl	^{46}Cl	^{47}Cl	^{48}Cl	^{49}Cl
^{32}S	^{33}S	^{34}S	^{35}S	^{36}S	^{37}S	^{38}S	^{39}S	^{40}S	^{41}S	^{42}S	^{43}S	^{44}S	^{45}S	^{46}S	^{47}S	^{48}S
^{31}P	^{32}P	^{33}P	^{34}P	^{35}P	^{36}P	^{37}P	^{38}P	^{39}P	^{40}P	^{41}P	^{42}P	^{43}P	^{44}P	^{45}P	^{46}P	
^{30}Si	^{31}Si	^{32}Si	^{33}Si	^{34}Si	^{35}Si	^{36}Si	^{37}Si	^{38}Si	^{39}Si	^{40}Si	^{41}Si	^{42}Si	^{43}Si	**^{44}Si**		
^{29}Al	^{30}Al	^{31}Al	^{32}Al	^{33}Al	^{34}Al	^{35}Al	^{36}Al	^{37}Al	^{38}Al	^{39}Al	^{40}Al	^{41}Al	**^{42}Al**	**^{43}Al**		
^{28}Mg	^{29}Mg	^{30}Mg	^{31}Mg	^{32}Mg	^{33}Mg	^{34}Mg	^{35}Mg	^{36}Mg	^{37}Mg	^{38}Mg		**^{40}Mg**				
^{27}Na	^{28}Na	^{29}Na	^{30}Na	^{31}Na	^{32}Na	^{33}Na	^{34}Na	^{35}Na		^{37}Na						
^{26}Ne	^{27}Ne	^{28}Ne	^{29}Ne	^{30}Ne	^{31}Ne	^{32}Ne		^{34}Ne								
^{25}F	^{26}F	^{27}F		^{29}F		^{31}F										
^{24}O		^{26}O		^{28}O												

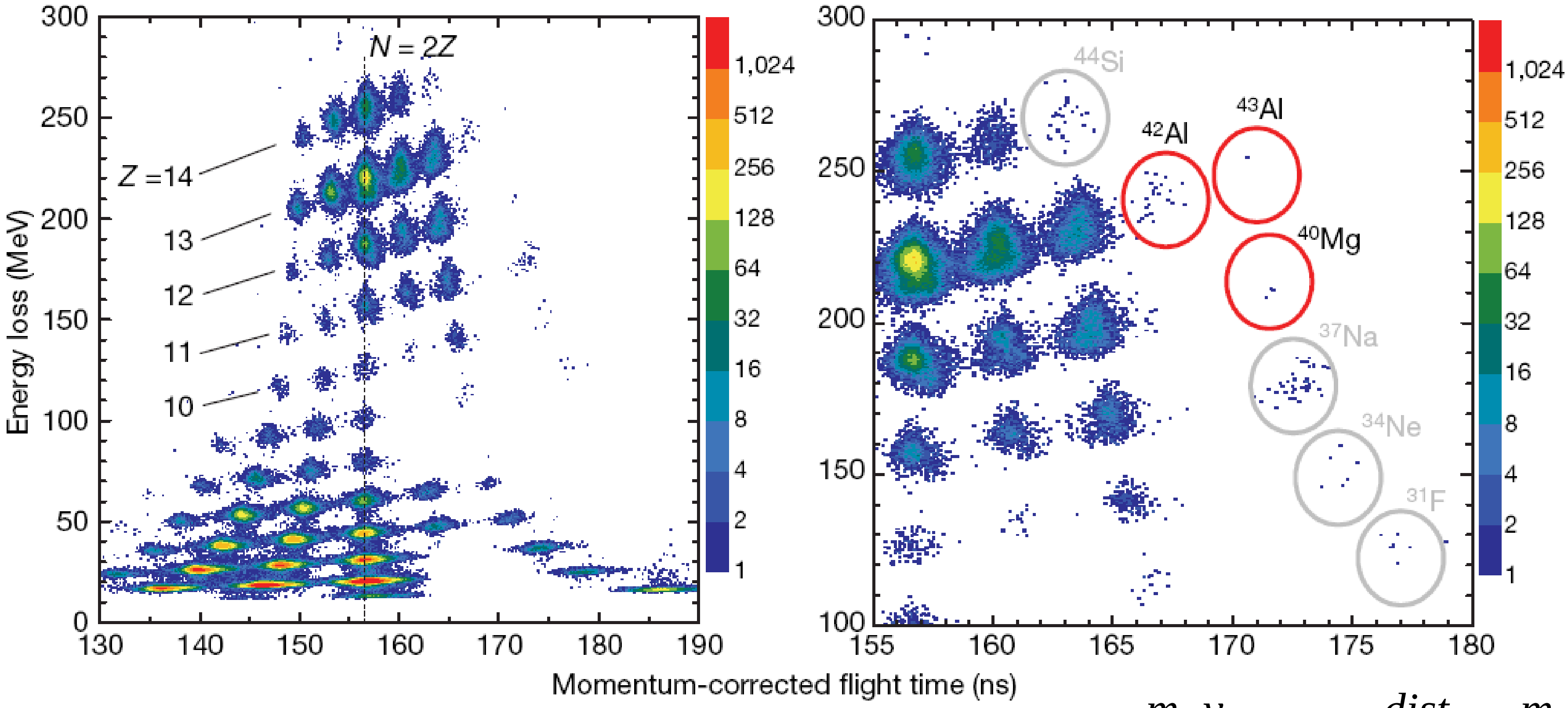
Production and Identification of Isotopes

Sometimes looking for 1 event from 10^{18} beam particles

Example: ^{40}Mg Production
120 pnA ^{48}Ca 140 MeV/u
Goal was to produce ^{40}Mg



First observation of ^{40}Mg



$$\rho = \frac{m\cdot v}{B\cdot q} \qquad tof = \frac{dist}{v} \rightarrow \frac{m}{q}$$

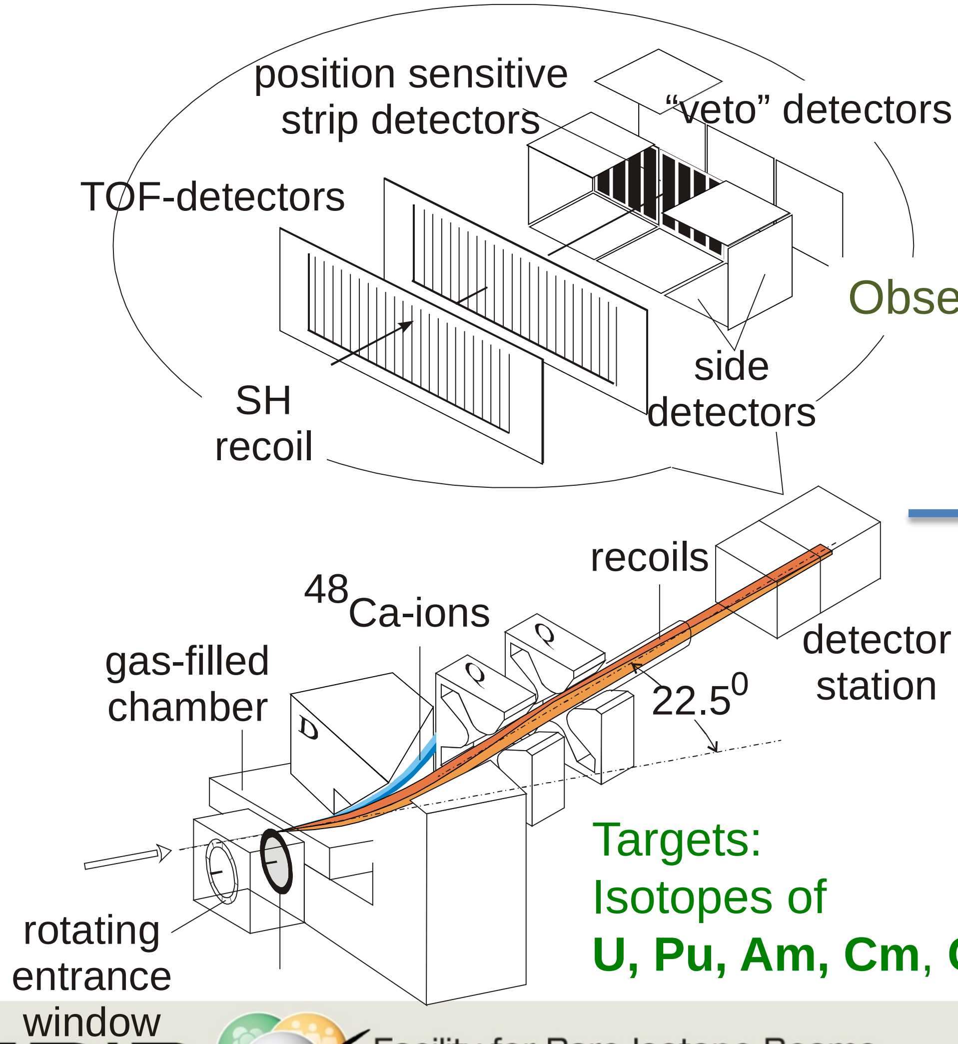
T. Baumann *et al.* , Nature **449**, 1022 (2007)

$$\Delta E\,(in\ material) \propto \frac{Z^2}{v^2}$$

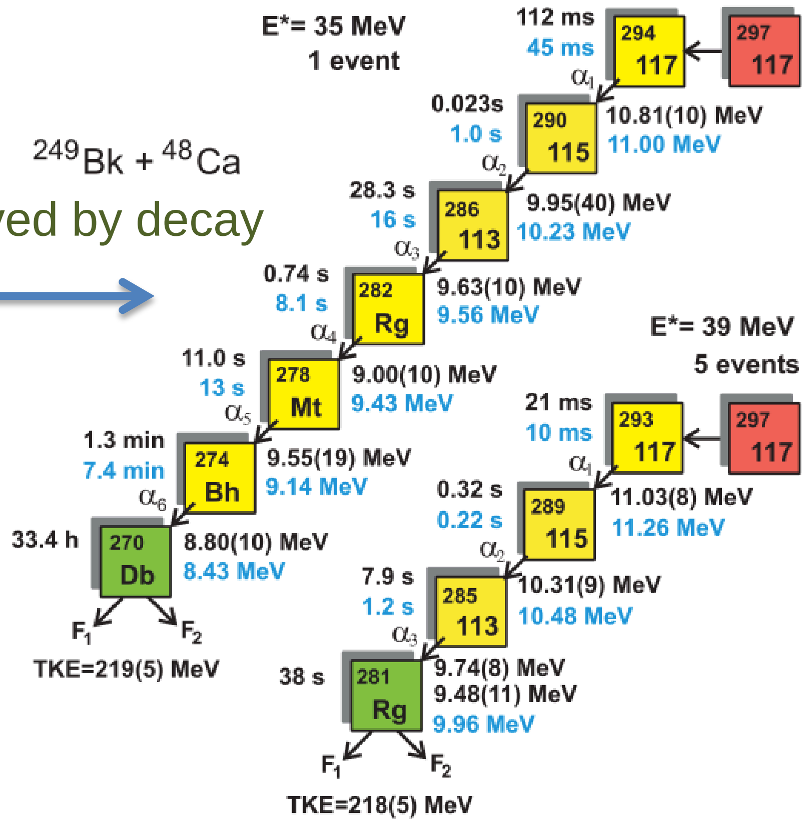
Identification of superheavy elements

- DUBNA (Yu Oganessian)

Yu. Ts. Ogannessian *et al.*, PRL 104, 142502 (2010)



Observed by decay



Targets:
Isotopes of
U, Pu, Am, Cm, Cf, and **Bk**

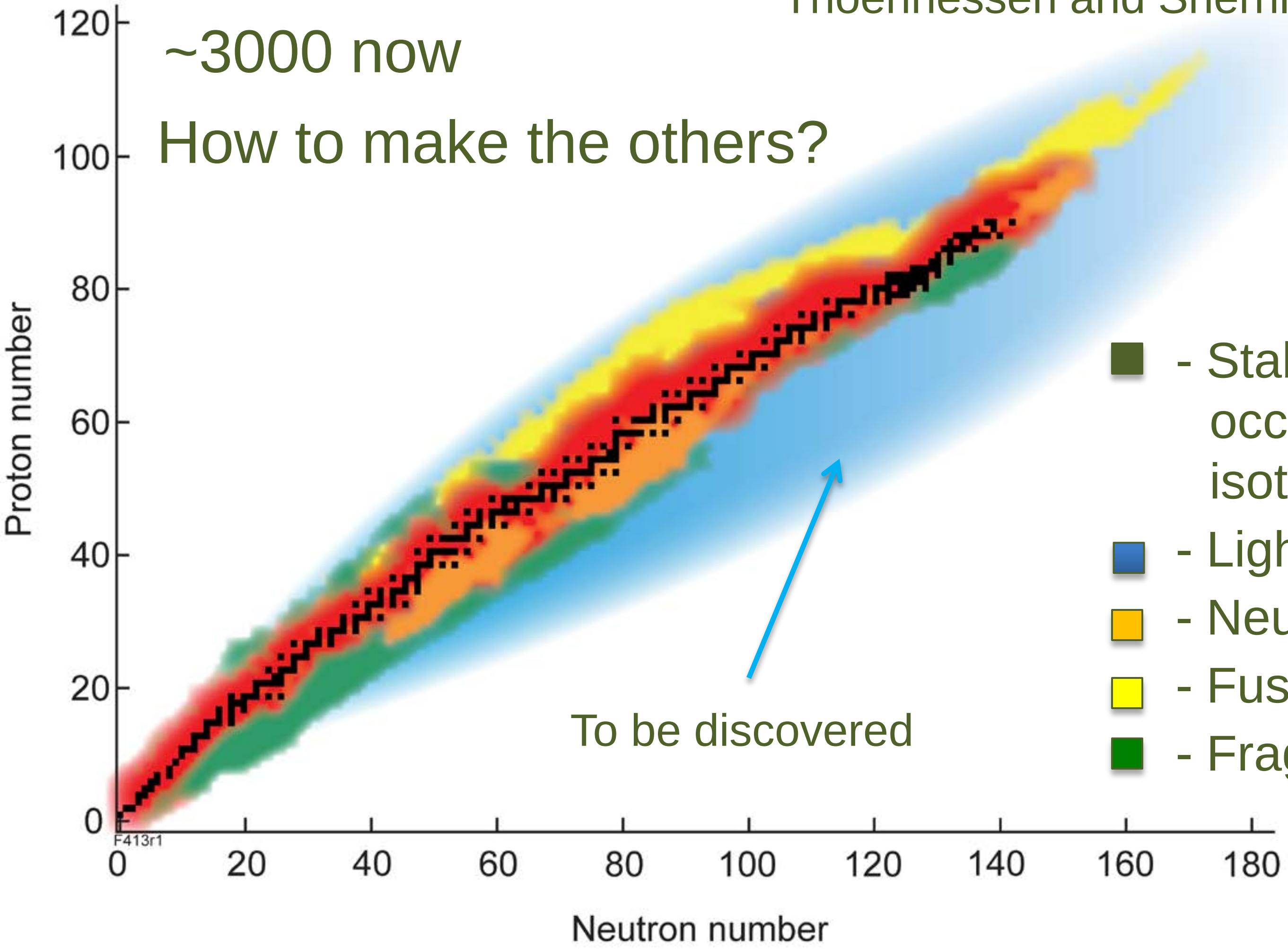
Rare Isotope Production Mechanisms

- There are a variety of nuclear reaction mechanisms used to add or remove nucleons (jargon)
- Spallation
- Fragmentation
- Coulomb fission (photo fission)
- Nuclear induced fission
- Light ion transfer
- Fusion-evaporation (cold, hot, incomplete, …)
- Fusion-Fission
- Deep Inelastic Transfer
- Charge Exchange

There is no best method. Many still have interesting physics question relevant to their application to produce rare isotopes.

How were the isotopes produced?

Thoennessen and Sherrill, Nature 473 (2011) 25



~3000 now

How to make the others?

To be discovered

- 🟫 - Stable and naturally occurring radioactive isotopes
- 🟦 - Light-particle reactions
- 🟧 - Neutron reactions
- 🟨 - Fusion-evaporation
- 🟩 - Fragmentation/spallation

Production Probability

- The probability of production of a fragment is related to its production cross section:

$$P = \frac{N(\tau)}{N_0} = \left(1 - e^{-\frac{\tau N_a \sigma}{A_t}}\right)$$

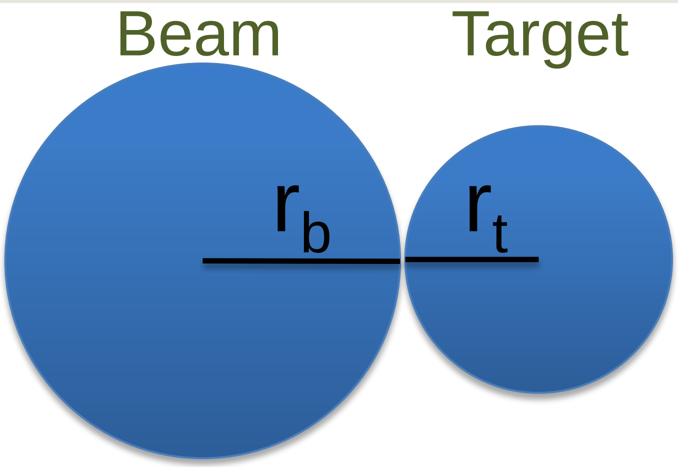
τ target thickness (g/cm^2)
N_a Avagodro’s number
A_t target mass number
σ production cross section

- For production cross sections of 1 mb and ^{9}Be target thickness of 1 g/cm^2 the production probability (and fragment rate) is high:

$$P = \frac{N(\tau)}{N_0} = \left(1 - e^{-\frac{1 \cdot 6.022\times10^{23} \cdot 1\times10^{-27}}{9}}\right) = 7\times10^{-5}$$

- Beam of 10^{14}/s beam would yield 7×10^{9} /s
- Note: Key is σ, τ, N_0

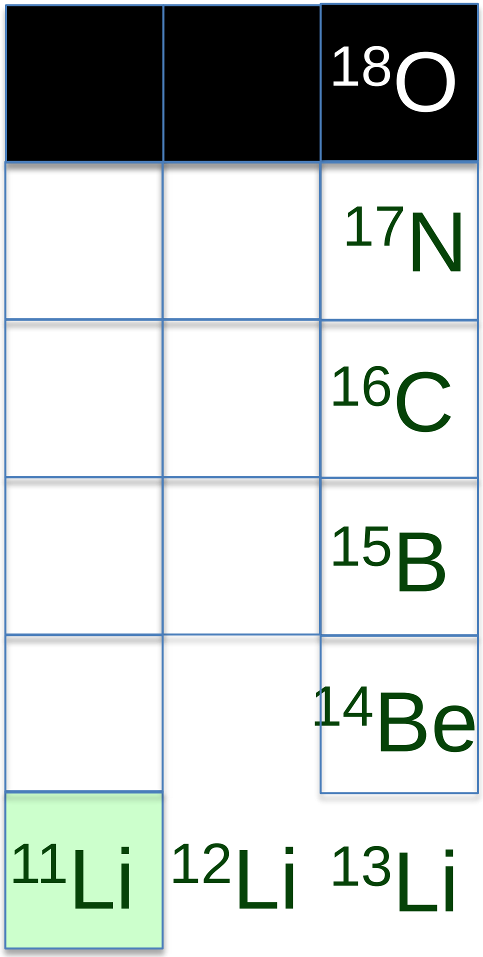
Cross Section for Production



$$\sigma = \pi \left(r_t + r_b \right)^2 \approx 600\ mb$$

Actual: ^{16}O + ^{12}C interaction cross section: 1000 mb (measured at 970 MeV/u)

Note: Above around 300 MeV/u the interaction length is shorter than the electronic stopping range of the ^{16}O so most beam particles can interact



One nucleon removal
Around 50 mb
(light nuclei)

P ≈ 5%

2n removal
5 mb
P = .5%

And so on
Rule of thumb
.1 x for each neutron removed

Production Mechanisms – High Energy

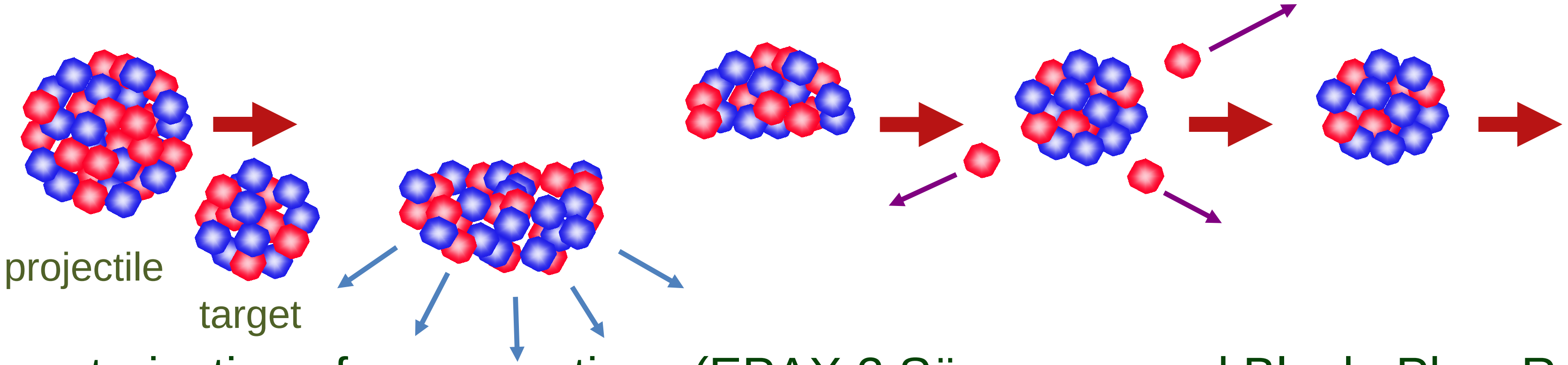
- Fragmentation (FRIB, RIBLL Lanzhou, NSCL, GSI, RIKEN, GANIL)
  - Projectile fragmentation of high energy (>50 MeV/A) heavy ions
  - Target fragmentation of a target with high energy protons or light HIs. In the heavy ion reaction mechanism community this would include *intermediate mass fragments*.
- Spallation (ISOLDE, TRIUMF-ISAC, EURISOL, SPES, …)
  - Name comes from spalling or cracking-off of target pieces.
  - One of the major ISOLDE mechanisms, e.g. ^{11}Li made from spallation of Uranium.
- Fission (HRIBF, ARIEL, ISAC, JYFL, BRIF,…)
  - There is a variety of ways to induce fission (photons, protons, neutrons (thermal, low, high energy)
  - The fissioning nuclei can be the target (HRIBF, ISAC) or the beam (GSI, NSCL, RIKEN, FAIR, FRIB).
- Coulomb Breakup (GSI)
  - At beam velocities of 1 GeV/n the equivalent photon flux as an ion passes a target is so high the GDR excitation cross section is many barns.

Spallation

From Wikimedia Commons: http://en.wikipedia.org/wiki/File:Spallation.gif

Fragmentation (Projectile)

- Pictorial model (above 50 MeV/u)



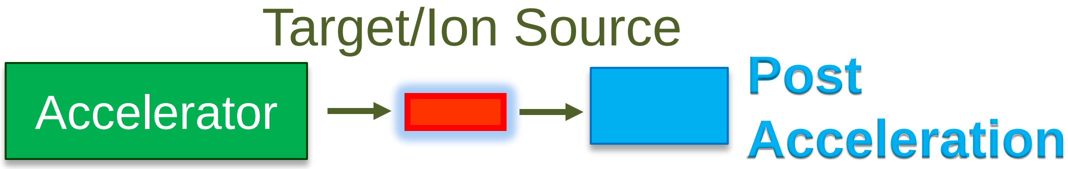
- Parameterization of cross sections (EPAX 2 Sümmerer and Blank, Phys.Rev. C61(2000)034607)
  - – Close related to Silverberg-Tso parameterization
  - – Parameters fit to experimental data (exponential form function of removed nucleons)
  - – Energy independent cross sections
  - – Production cross section does not depend on the target
- More detailed models (e.g. ABRABLA (K-H Schmidt *et al.* - See http://www-win.gsi.de/charms/)
- Internuclear Cascade

Production of Rare Isotopes by Projectile Fragmentation

- To produce a key nucleus like ^{122}Zr from ^{136}Xe, the production cross is estimated to be $2\text{x}10^{-18}$ b (2 attobarns, $2\text{x}10^{-46}$ m^2)
- Nevertheless with a ^{136}Xe beam of power 400 kW ($\cong 8\text{x}10^{13}$ ion/s) and modern separation techniques (fragment separators can select 1 out of 10^{18} produced), a few atoms per week can be made and studied
- For comparison: Element 117 production cross section was 1.3 (+1.5 -0.6) pb (Oganessian, Yu. Ts. et al. Phy Rev Lett 104 (2010) 142502)
- Few $\text{x}10^{-46}$ m^2 is on the order of 10 MeV neutrino elastic scattering cross sections

Rare Isotope Production Techniques

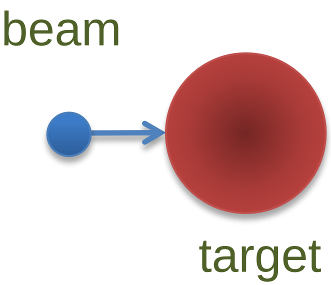
- Target spallation and fragmentation by light ions (ISOL – Isotope separation on line)



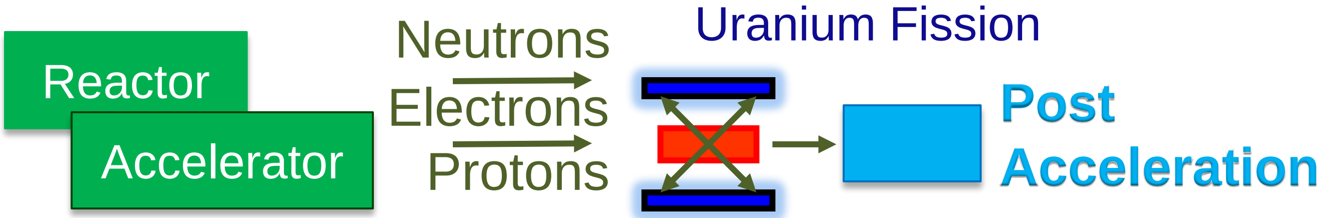
Target/Ion Source

Accelerator

Post Acceleration



- Photon or particle induced fission



Reactor

Accelerator

Neutrons

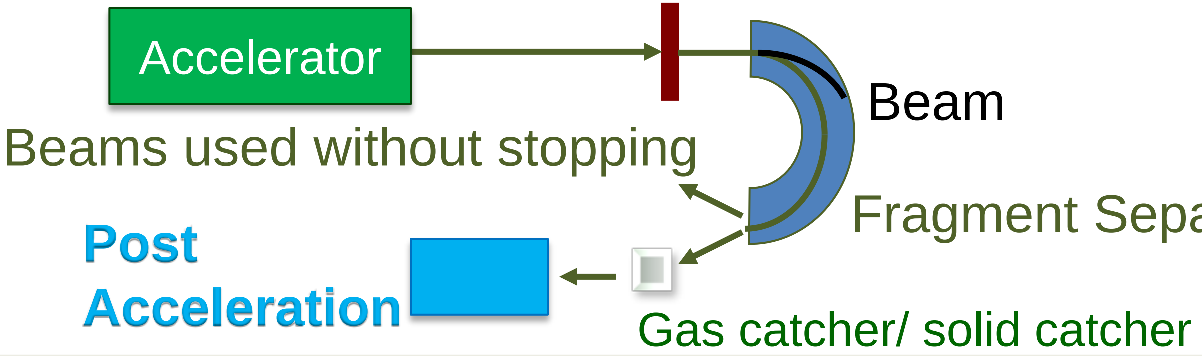
Electrons

Protons

Uranium Fission

Post Acceleration

- In-flight Separation following nucleon transfer, fusion, projectile fragmentation/fission



Accelerator

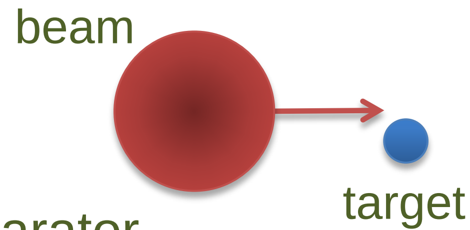
Beam

Beams used without stopping

Fragment Separator

Post Acceleration

Gas catcher/ solid catcher + ion source

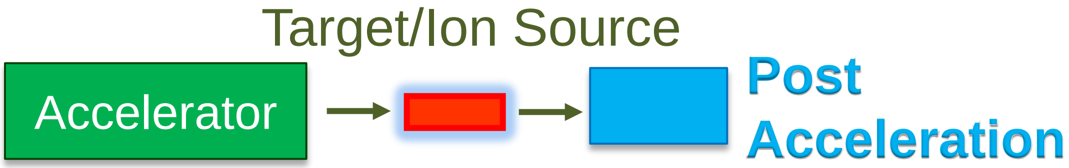


Accelerators

- The particle accelerator used for production is often called the "driver"
- Types
  - Cyclotron (NSCL, GANIL, TRIUMF (proton driver), HRIBF (proton driver), RIKEN RIBF)
  - Synchroton (GSI, FAIR-GSI)
  - LINAC (LINear ACcelerator) (FRIB, ATLAS - ANL
  - Others like FFAGs (Fixed-Field Alternating Gradient) are currently not used
- Main Parameters
  - Top Energy (e.g. FRIB will have 200 MeV/u uranium ions)
  - Particle range (TRIUMF cyclotron accelerates hydrogen, hence is used for spallation)
  - Intensity or Beam Power (e.g. 400 kW = $8 \times 6 \times 10^{12}$/s x 50GeV
  - Power = pμA x Beam Energy (GeV) (1pμA = 6×10^{12} /s)

Jargon

- ISOL

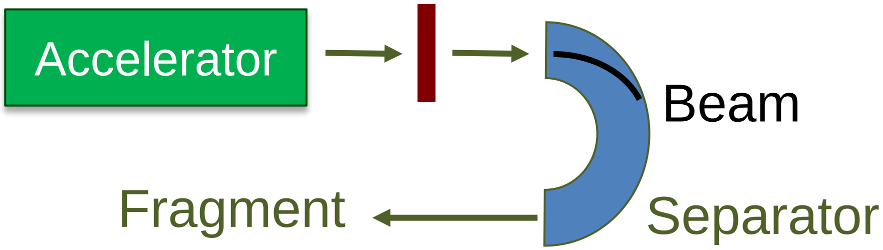


Target/Ion Source

Accelerator

Post Acceleration

- In-flight (projectile fragmentation is one production mechanism)



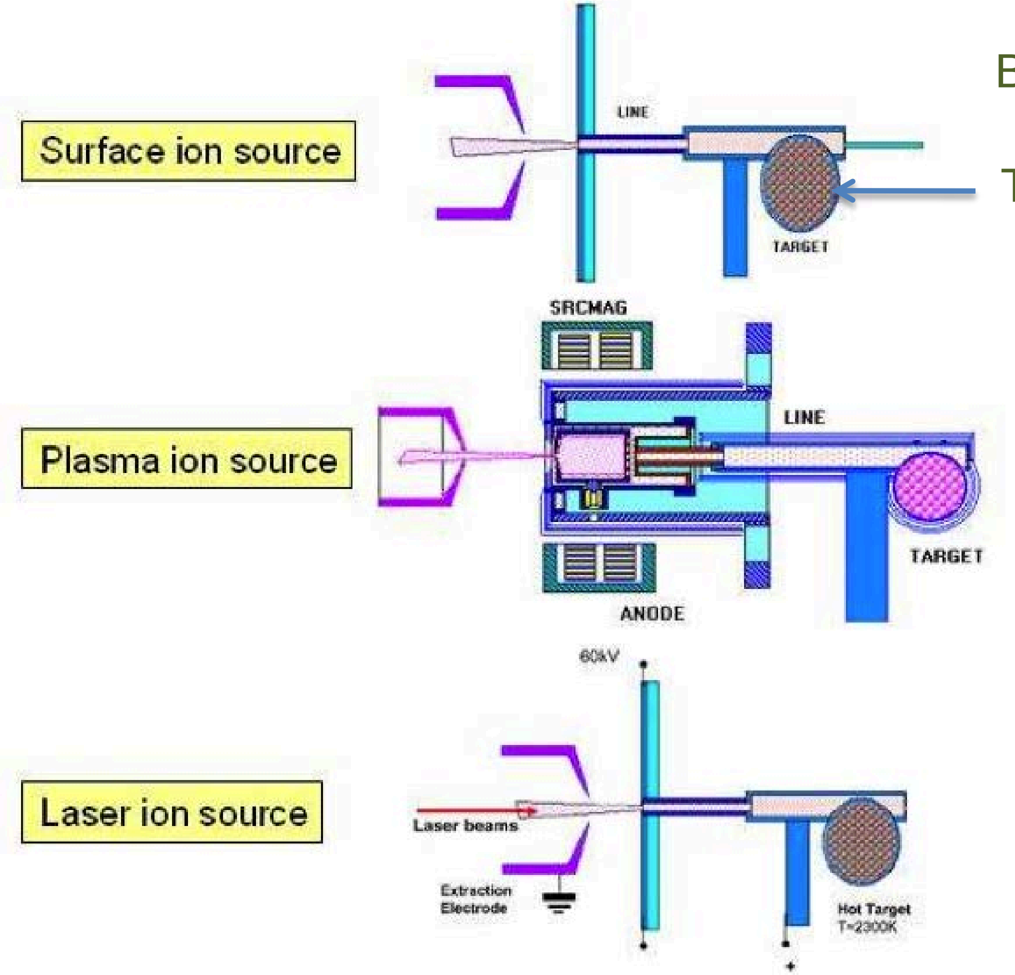
Accelerator

Beam

Fragment

Separator

Types of ISOL Ion Sources



Beam into page

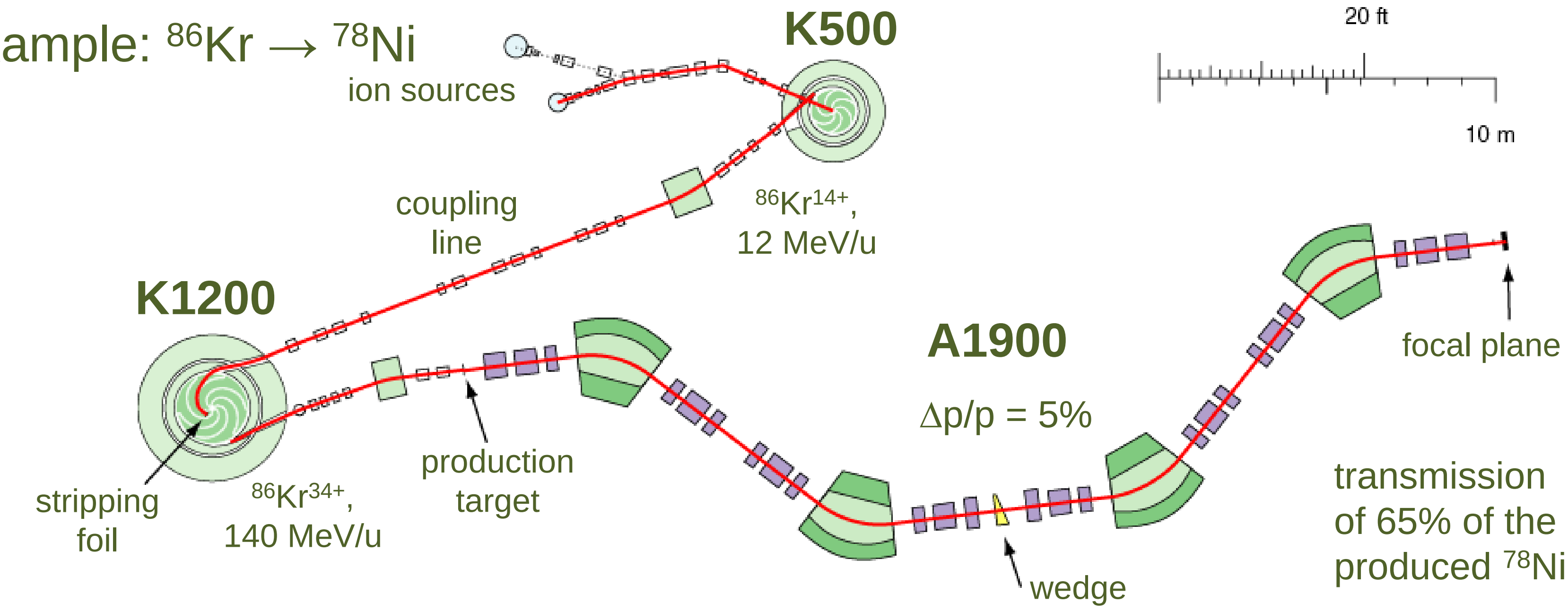
Target

P. Butler

In-Flight Production Example: NSCL’s CCF

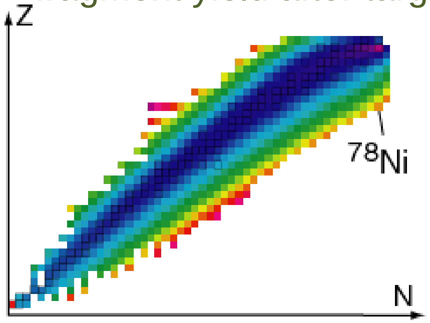
D.J. Morrissey, B.M. Sherrill, Philos. Trans. R. Soc. Lond. Ser. A. Math. Phys. Eng. Sci. 356 (1998) 1985.

Example: ^{86}Kr → ^{78}Ni

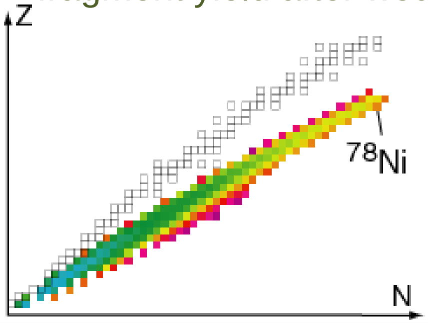


transmission of 65% of the produced ^{78}Ni

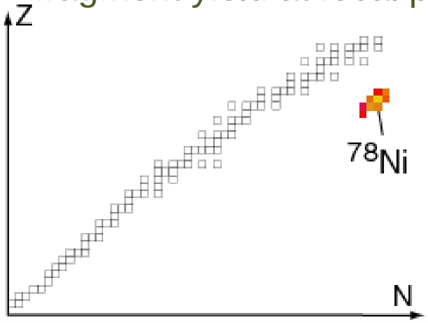
fragment yield after target



fragment yield after wedge



fragment yield at focal plane

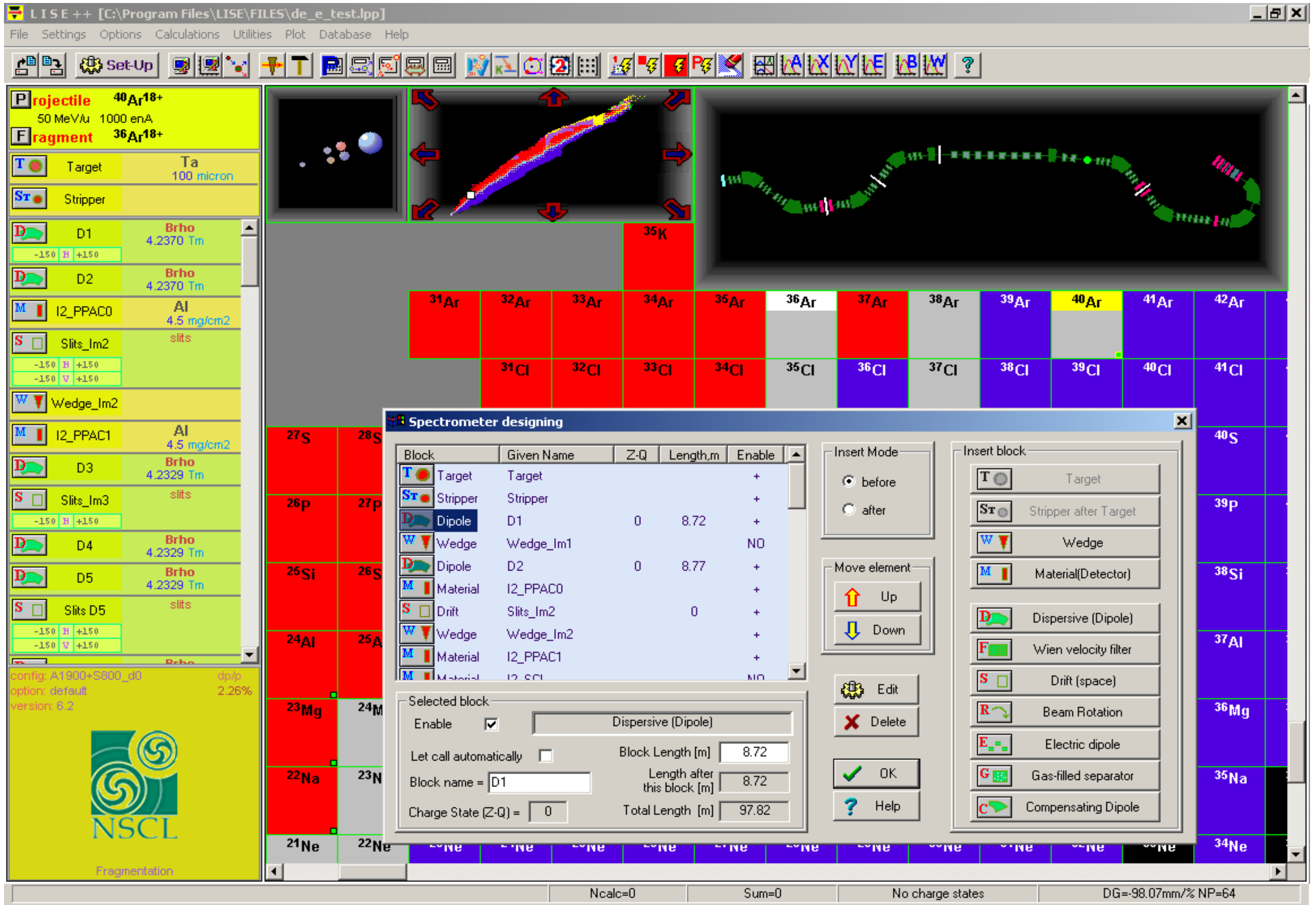


LISE++ Simulation Code

The code operates under Windows and provides a highly user-friendly interface.

See me at this school for a tutorial session

It can be downloaded from the following internet address:



L I S E ++ [C:\Program Files\LISE\FILES\de_e_test.lpp]

Projectile $^{40}Ar^{18+}$ 50 MeV/u 1000 enA
Fragment $^{36}Ar^{18+}$
Target: Ta 100 micron
Stripper
D1: Brho 4.2370 Tm; -150 H +150
D2: Brho 4.2370 Tm
I2_PPAC0: Al 4.5 mg/cm2
Slits_Im2: slits; -150 H +150; -150 V +150
Wedge_Im2
I2_PPAC1: Al 4.5 mg/cm2
D3: Brho 4.2329 Tm
Slits_Im3: slits; -150 H +150
D4: Brho 4.2329 Tm
D5: Brho 4.2329 Tm
Slits D5: slits; -150 H +150; -150 V +150
config: A1900+S800_d0
option: default
version: 6.2
dp/p 2.26%

Spectrometer designing

Block	Given Name	Z-Q	Length,m	Enable
Target	Target			+
Stripper	Stripper			+
Dipole	D1	0	8.72	+
Wedge	Wedge_Im1			NO
Dipole	D2	0	8.77	+
Material	I2_PPAC0			+
Drift	Slits_Im2		0	+
Wedge	Wedge_Im2			+
Material	I2_PPAC1			+

Insert Mode: ● before ○ after

Selected block
Enable ☑ Dispersive (Dipole)
Let call automatically ☐
Block name = D1
Charge State (Z-Q) = 0
Block Length [m] 8.72
Length after this block [m] 8.72
Total Length [m] 97.82

Ncalc=0 Sum=0 No charge states DG=-98.07mm/% NP=64

http://www.nscl.msu.edu/lise

O. Tarasov, D. Bazin *et al.*

Advantages/Disadvantages of ISOL/In-Flight

In-flight:
GSI
RIKEN
NSCL
FRIB
GANIL
ANL
RIBBAS …

- Provides beams with energy near that of the primary beam
  - For experiments that use high energy reaction mechanisms
  - Luminosity (intensity x target thickness) gain of 10,000
  - Individual ions can be identified
- Efficient, Fast (100 ns), chemically independent separation
- Production target is relatively simple

ISOL:
HRIBF
ISAC
SPIRAL
ISOLDE
SPES
EURIOSOL

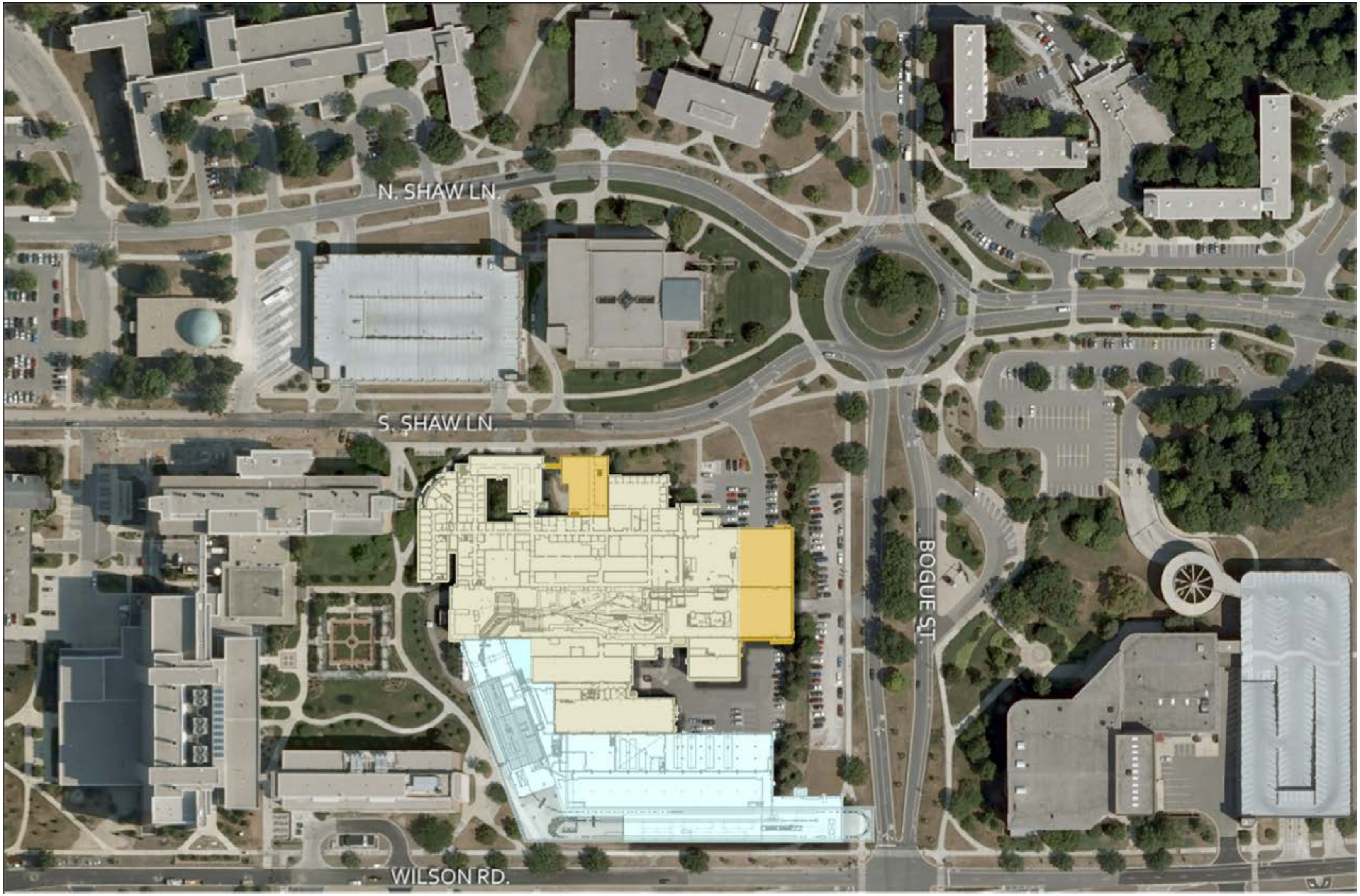
- Good Beam quality (π mm-mr vs. 30 π mm-mr transverse)
- Small beam energy spread for fusion studies
- Can use chemistry (or atomic physics) to limit the elements released
- 2-step targets provide a path to MW targets
- High beam intensity leads to 100x gain in secondary ions

400kW protons at 1 GeV is 2.4×10^{15} protons/s

The Five-Minute Rap Version

Rare Isotope Rap by Kate McAlpine (also did the LHC Rap)

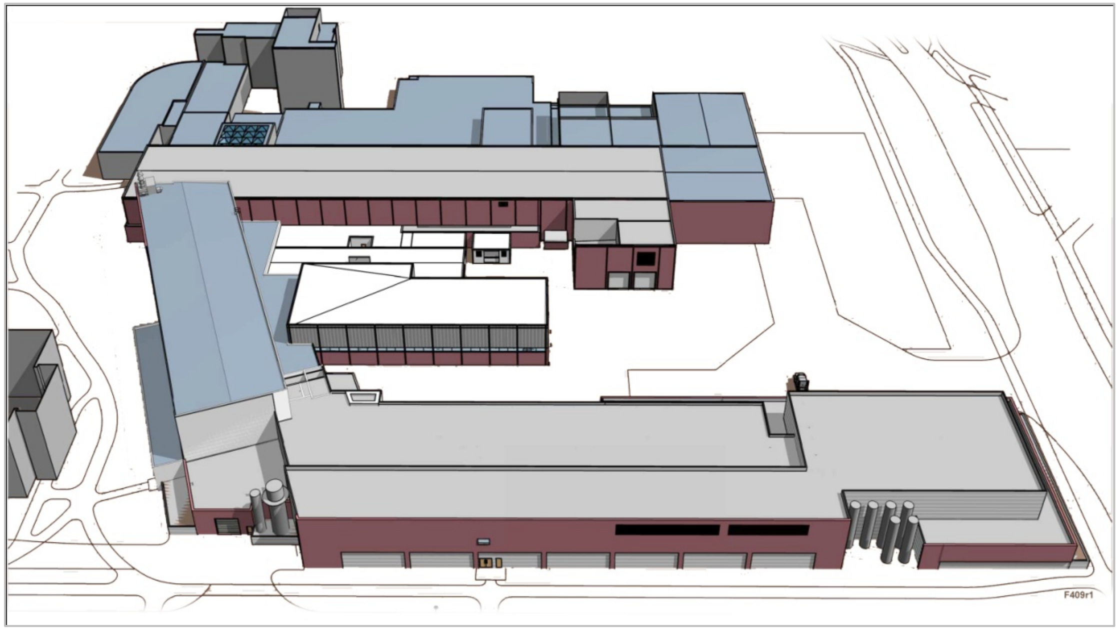
Facility for Rare Isotope Beams, FRIB - USA



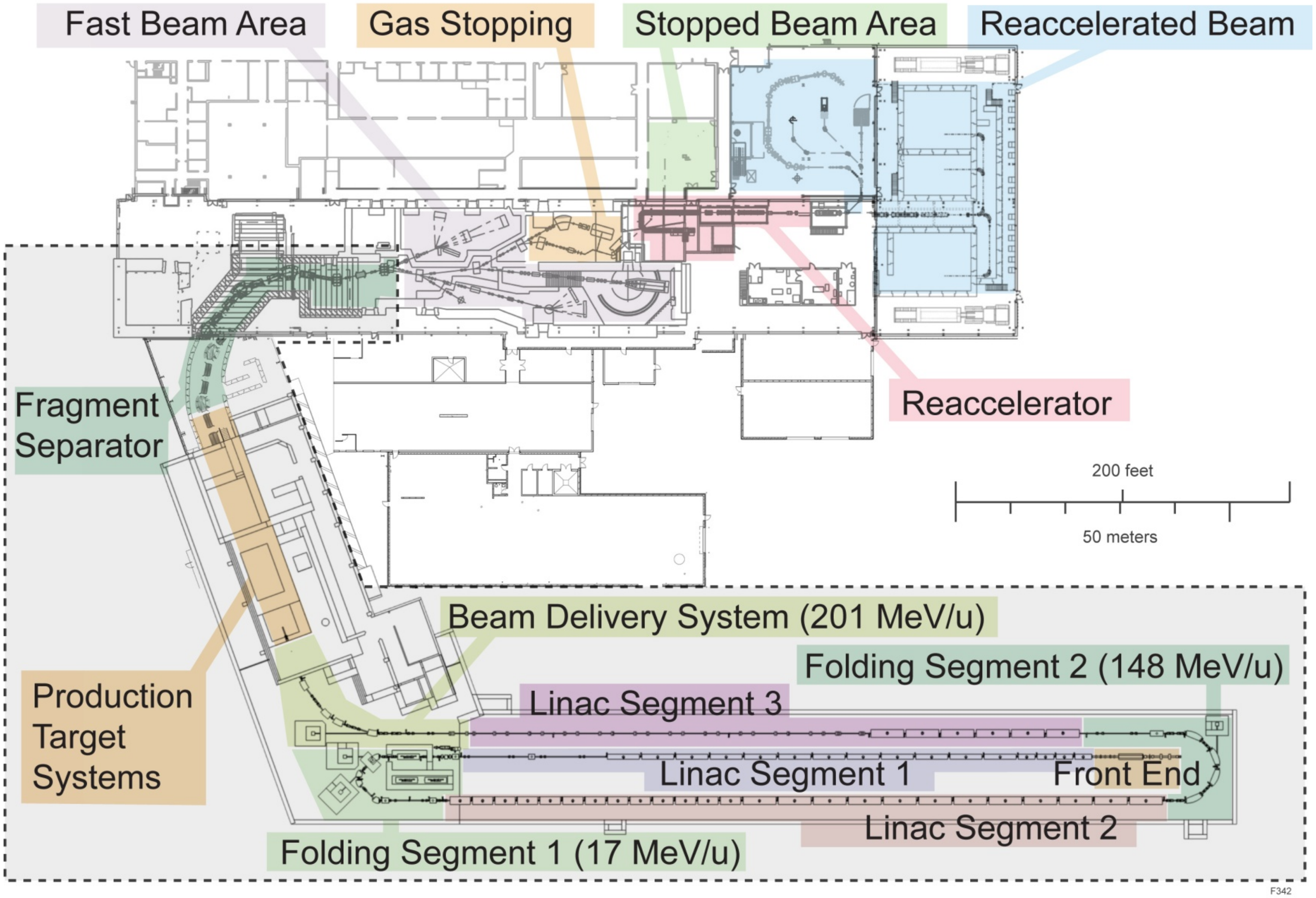
US Community's Major New Initiative – Facility for Rare Isotope Beams

- Laboratory Director Konrad Gelbke, Project Director Thomas Glasmacher
- Estimate of TPC $614.5M
- Project completion in 2020, managed for early completion in 2018
- Key features (unique)
  - 400 kW heavy ion beams
  - Efficient acceleration (multiple charge states)
  - Stopped and reaccelerated, separated beams
- Space for
  - Reaccelerated beams, uranium to 12 (15) MeV/u
  - Isotope harvesting

FRIB

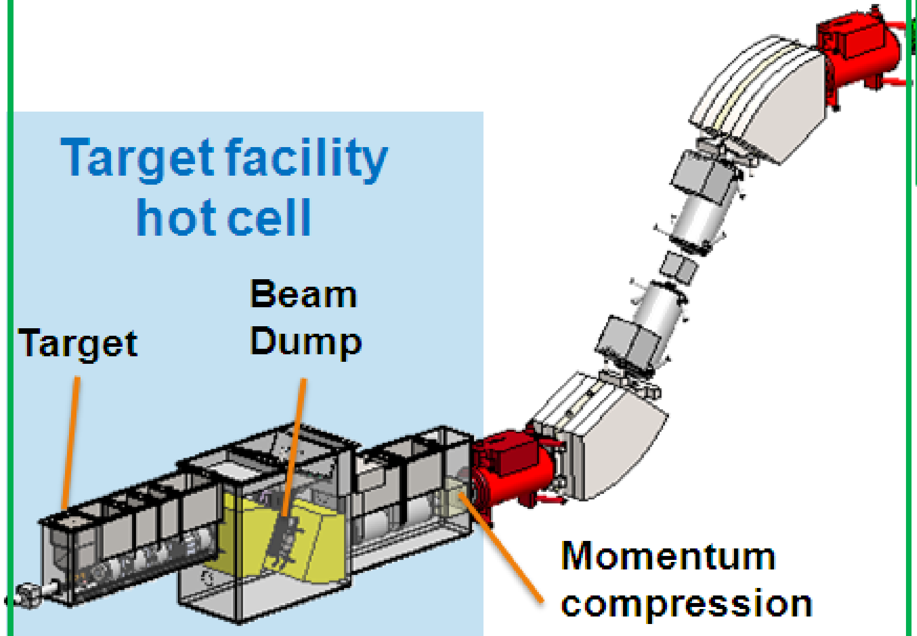


FRIB Facility Layout



FRIB Fragment Separator

Preseparator (Stage 1)



Target facility hot cell

Target

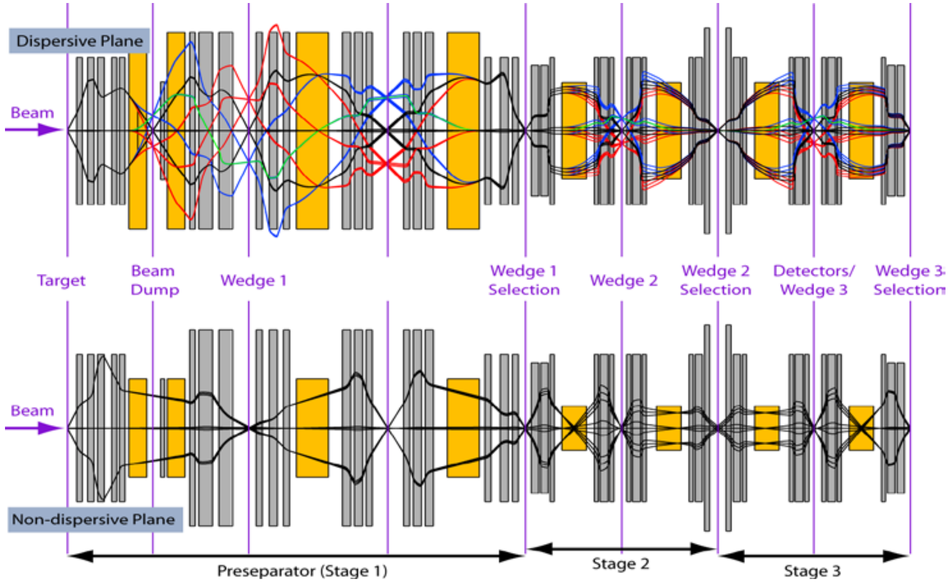
Beam Dump

Momentum compression wedge

Stages 2 and 3

86 m long

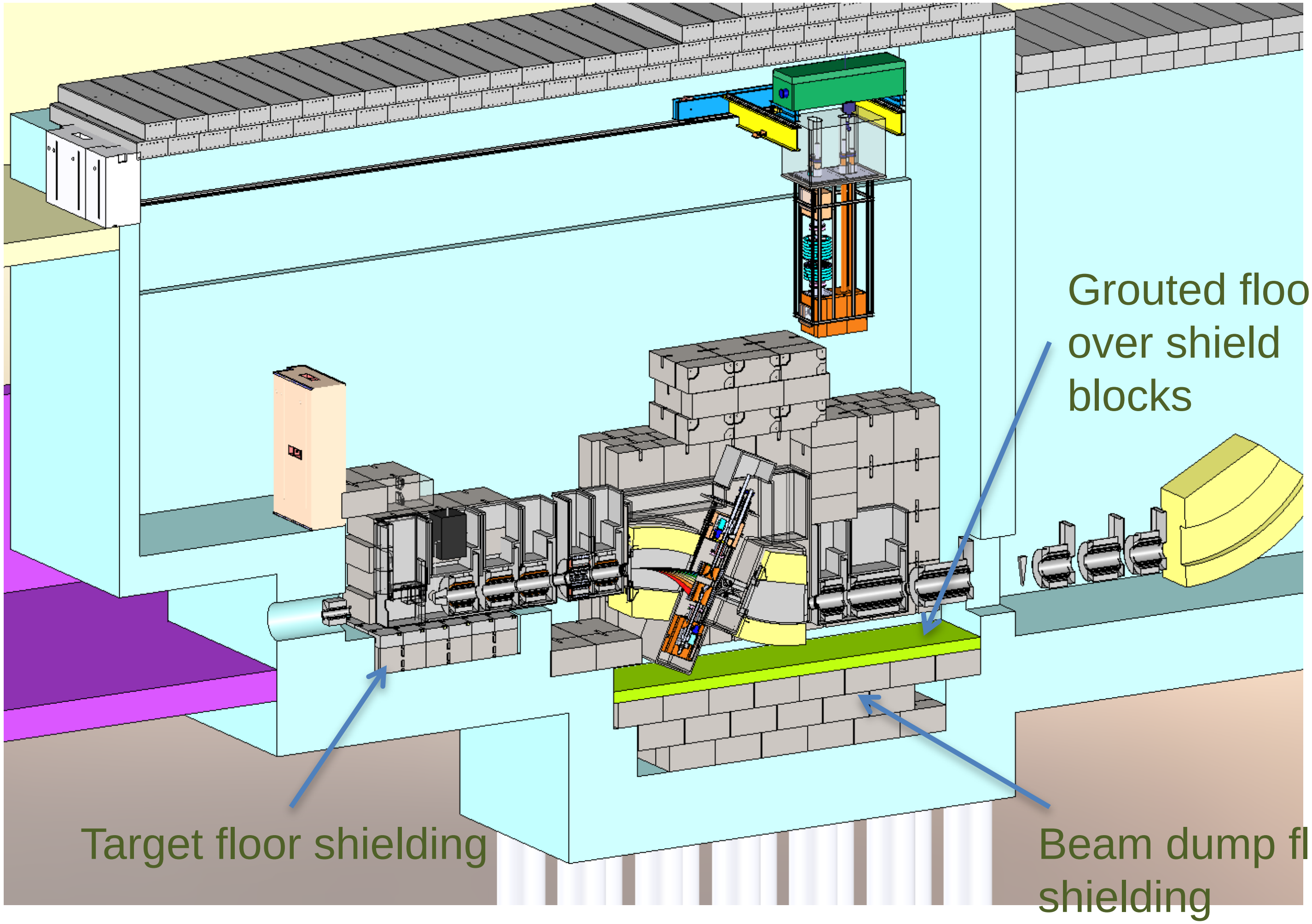
Use existing A1900 magnets



Target and beam dump capable to handle 400 kW beams

5th Order Ion Optical Design

Production Target and Beam Dump Area

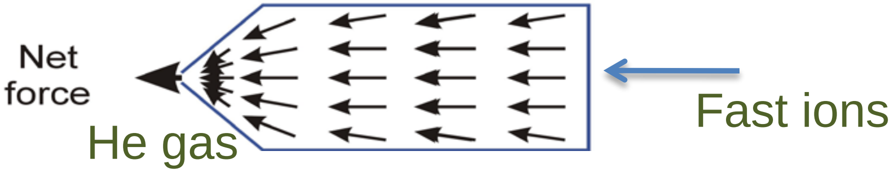


Grouted floor over shield blocks

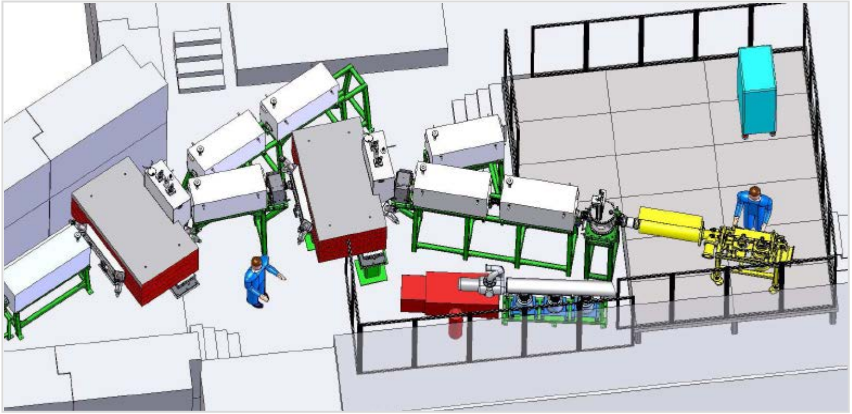
Target floor shielding

Beam dump floor shielding

Key FRIB component: Beam Stopping

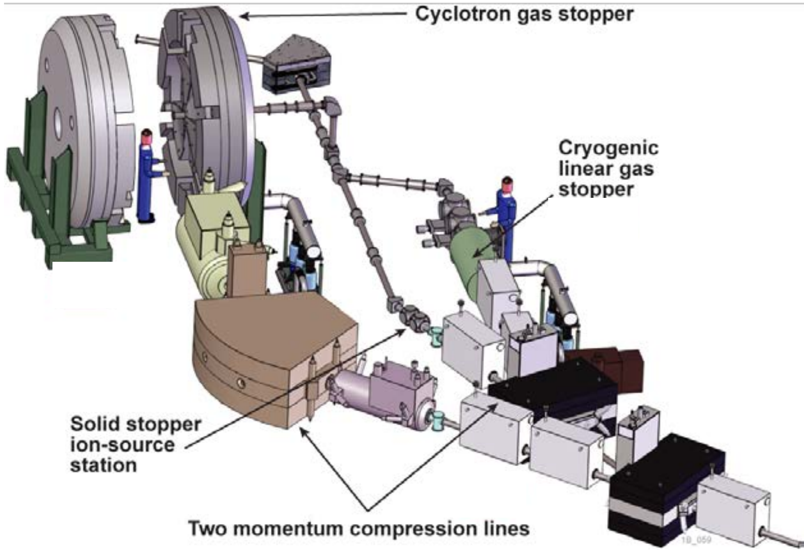


G. Savard, ANL, D. Morrissey NSCL LLN, GSI, et al.



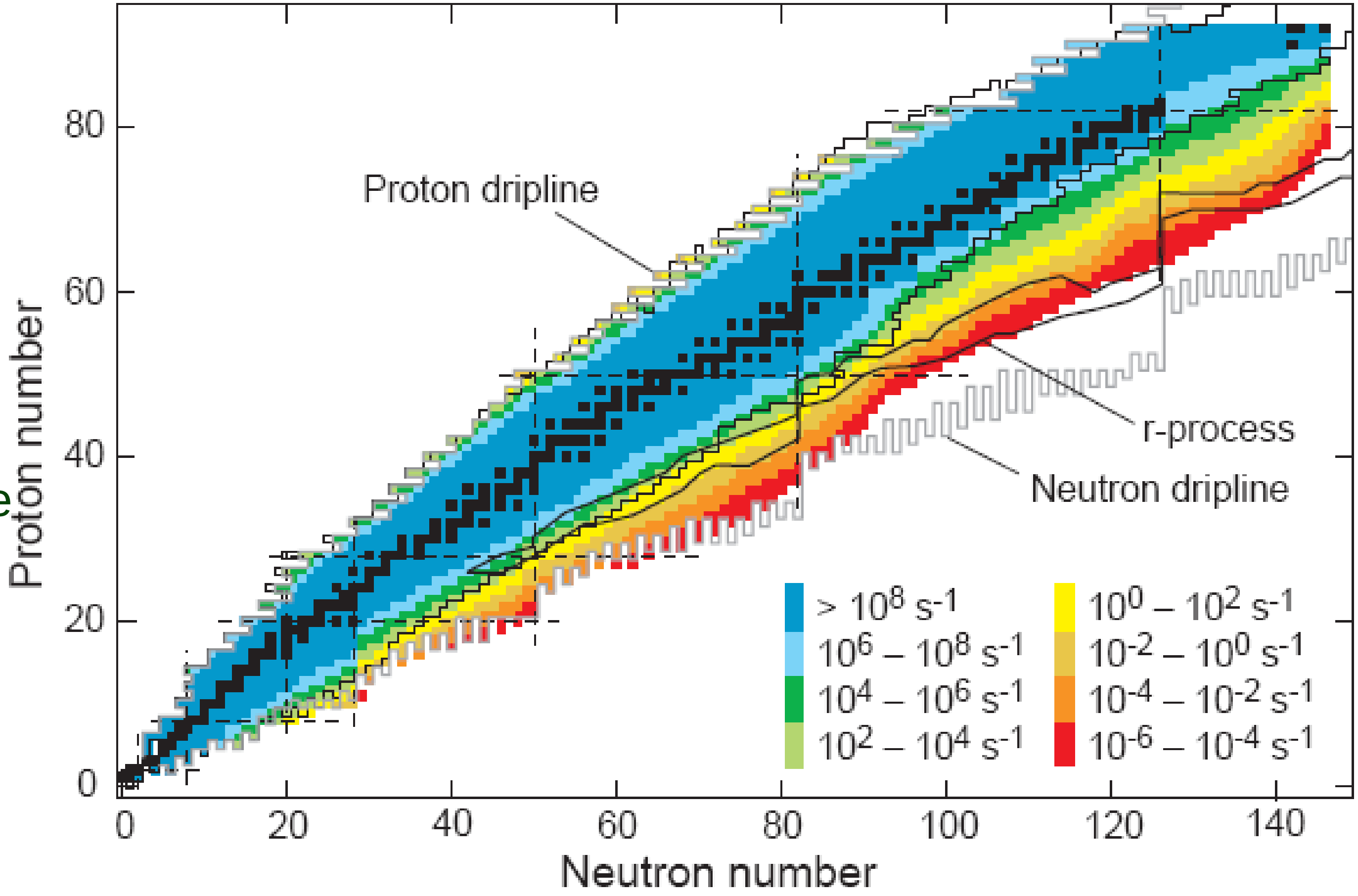
Beams for precision experiments at very low-energies or at rest and for reacceleration

- Cyclotron gas stopper
- Linear gas stopper
- Solid stopper (LLN (Belgium), KVI (Netherlands))



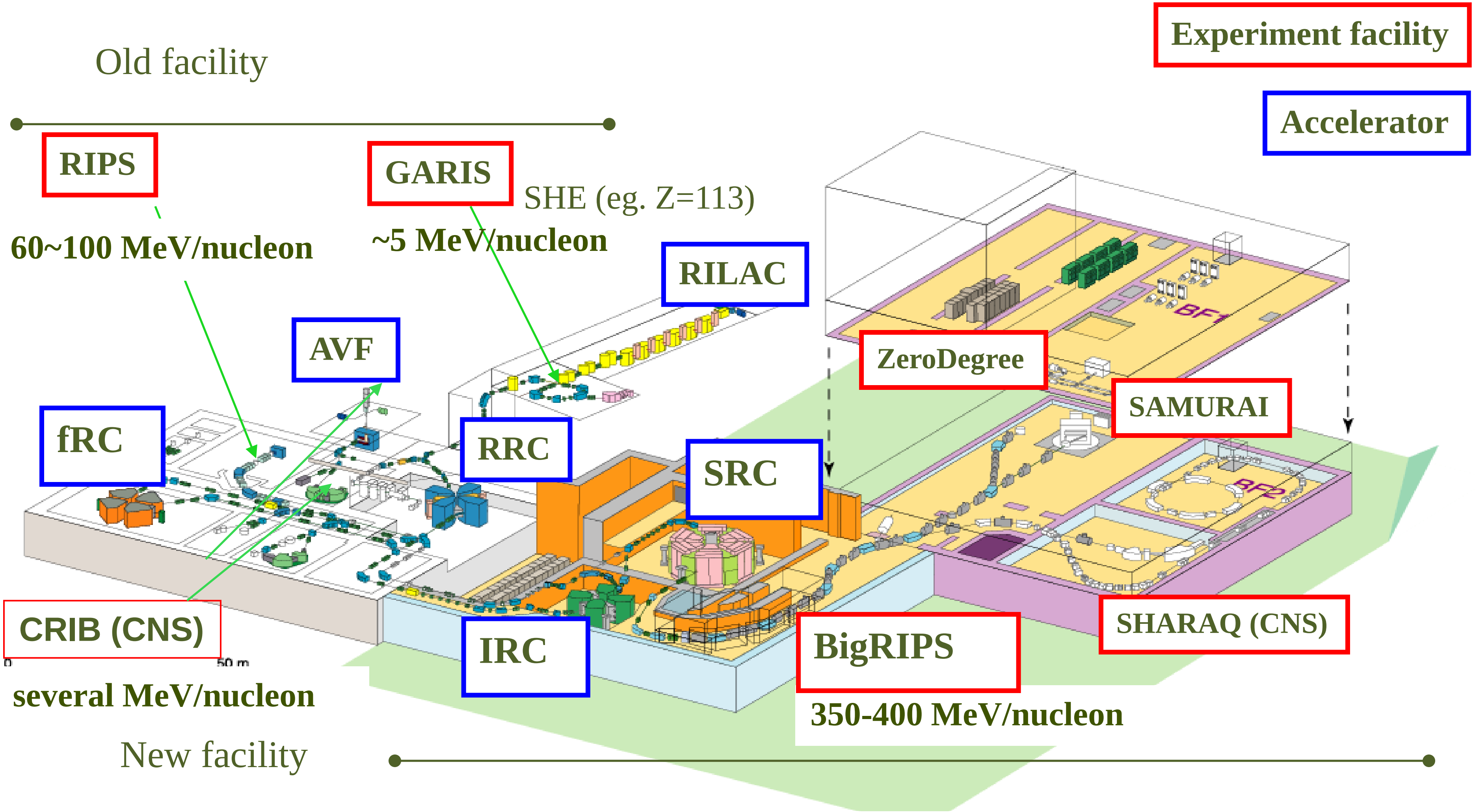
What New Nuclides Will Next Generation Facilities Produce?

- They will produce more than 1000 NEW isotopes at useful rates (4500 available for study)
- Theory is key to making the right measurements
- Exciting prospects for study of nuclei along the drip line to mass 120 (compared to 24)
- Production of most of the key nuclei for astrophysical modeling
- Harvesting of unusual isotopes for a wide range of applications



Rates are available at http://groups.nscl.msu.edu/frib/rates/

RIKEN RI Beam Factory (RIBF)



Experiment facility

Accelerator

Old facility

RIPS

60~100 MeV/nucleon

GARIS

SHE (eg. Z=113)

~5 MeV/nucleon

RILAC

AVF

fRC

RRC

SRC

ZeroDegree

SAMURAI

CRIB (CNS)

several MeV/nucleon

IRC

BigRIPS

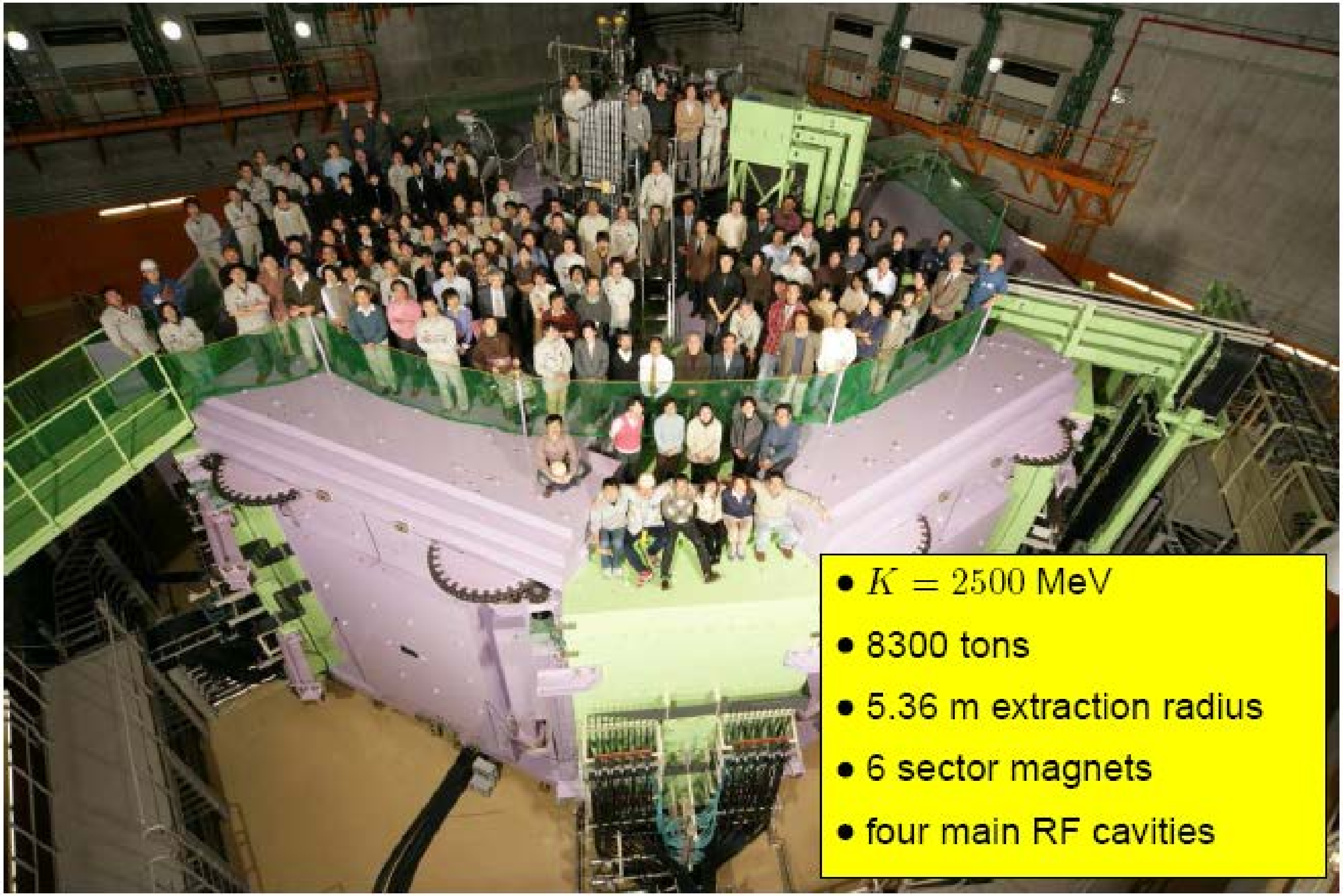
350-400 MeV/nucleon

SHARAQ (CNS)

New facility

Intense Heavy Ion beams (up to U) up to 345*A*MeV at SRC
Fast RI beams by projectile fragmentation and U-fission at BigRIPS
Operation since 2007

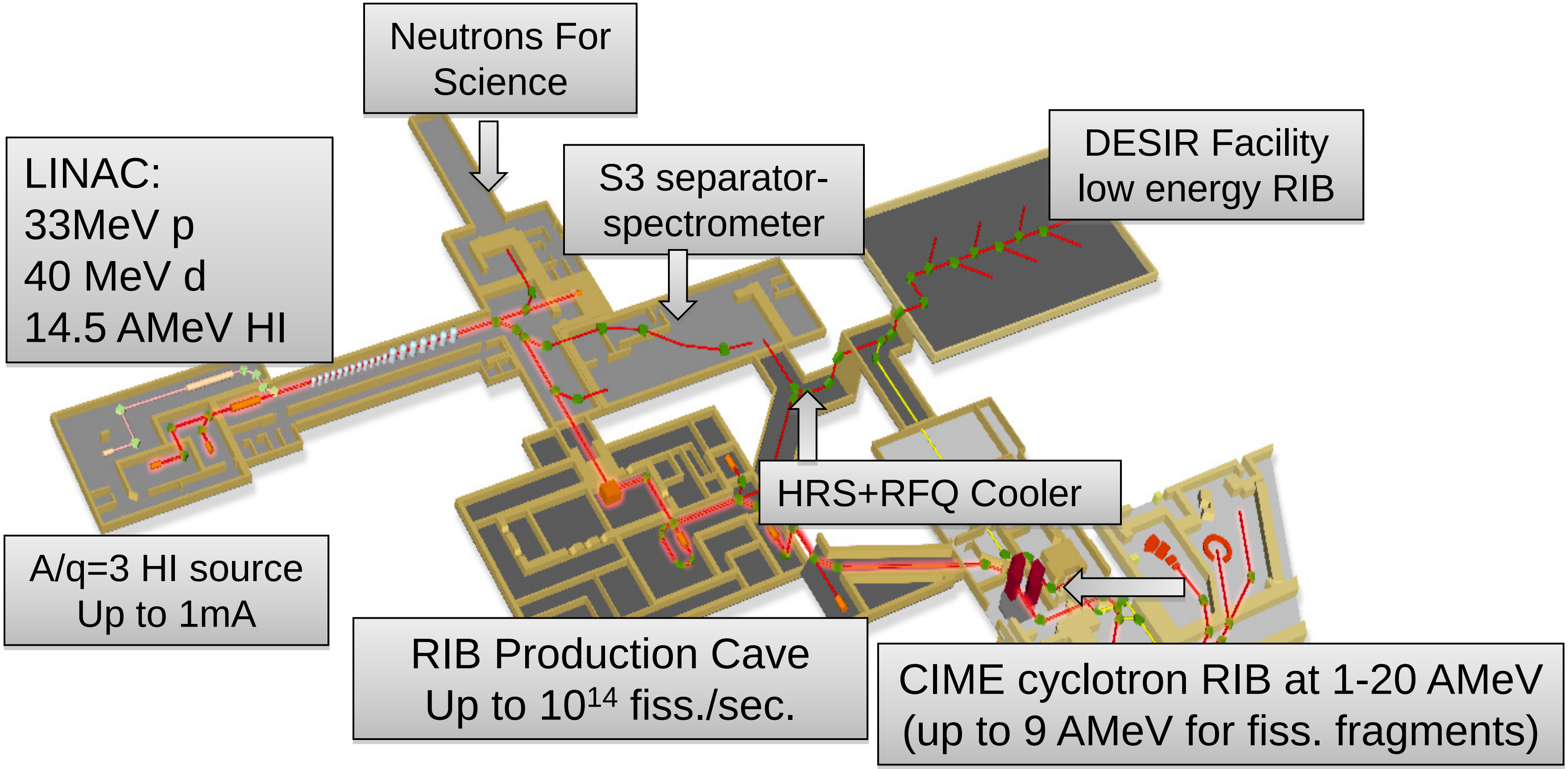
SRC: World Largest (Heaviest) Cyclotron



- $K = 2500$ MeV
- 8300 tons
- 5.36 m extraction radius
- 6 sector magnets
- four main RF cavities

Example of Other In-Target Production Facilities

- SPRIRAL2 – European Project Located at GANIL in France



Neutrons For Science

LINAC:
33MeV p
40 MeV d
14.5 AMeV HI

S3 separator-spectrometer

DESIR Facility low energy RIB

HRS+RFQ Cooler

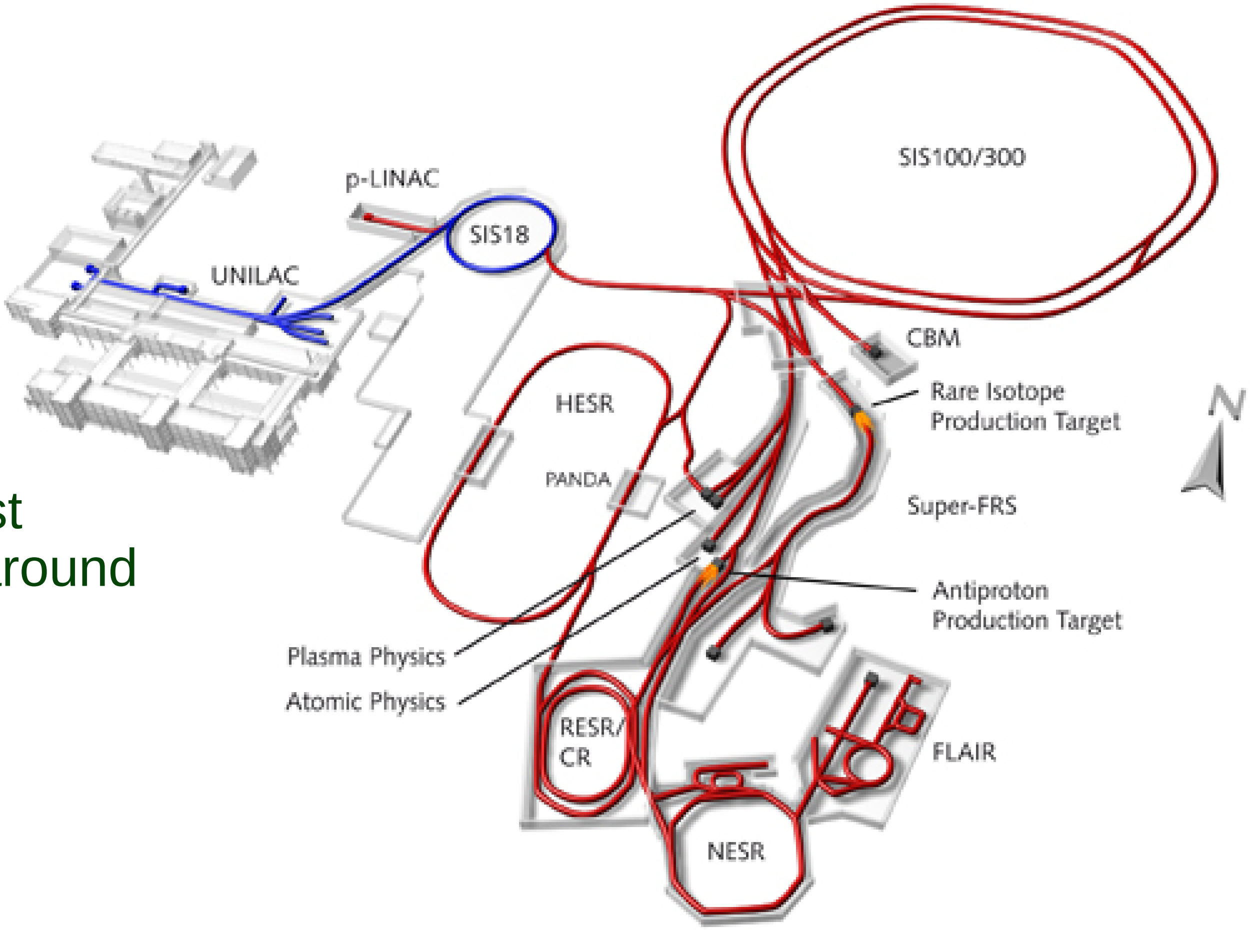
A/q=3 HI source
Up to 1mA

RIB Production Cave
Up to 10^{14} fiss./sec.

CIME cyclotron RIB at 1-20 AMeV
(up to 9 AMeV for fiss. fragments)

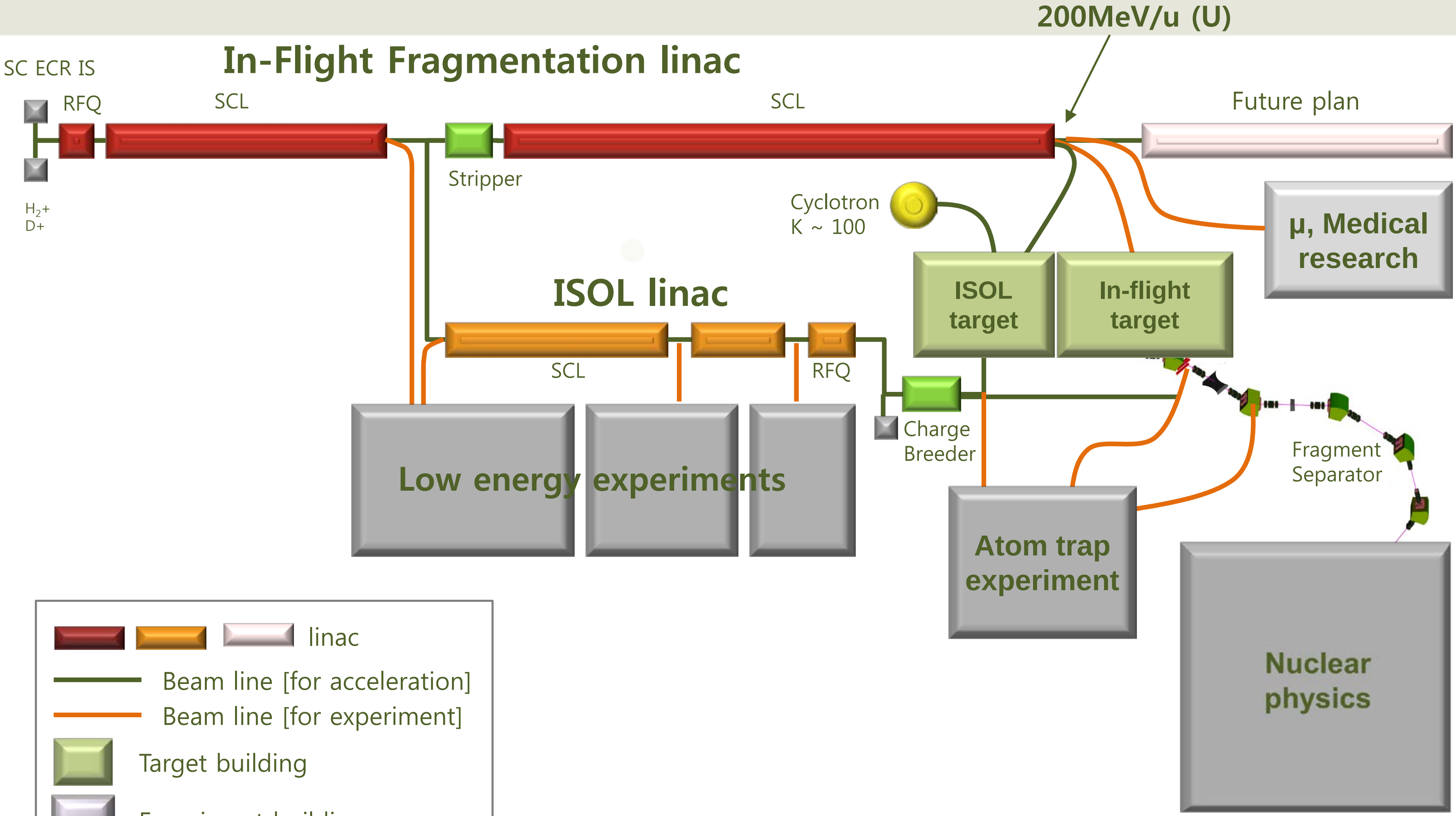
Facility for Antiproton and Ion Research

- Beams at 1.5 GeV/u
- 10^{12}/s Uranium
- Research
  - Compressed matter
  - Rare isotopes
  - Antiproton
  - Plasma
  - Atomic physics
- Completion of the first stages are planned around 2018



http://www.fair-center.de/index.php?id=1

KoRIA Schematic Layout



200MeV/u (U)

In-Flight Fragmentation linac

SC ECR IS

RFQ

SCL

SCL

Future plan

Stripper

H_2+
D+

Cyclotron
K ~ 100

μ, Medical research

ISOL linac

ISOL target

In-flight target

SCL

RFQ

Charge Breeder

Fragment Separator

Low energy experiments

Atom trap experiment

Nuclear physics

🟥 🟧 ⬜ linac

— Beam line [for acceleration]

— Beam line [for experiment]

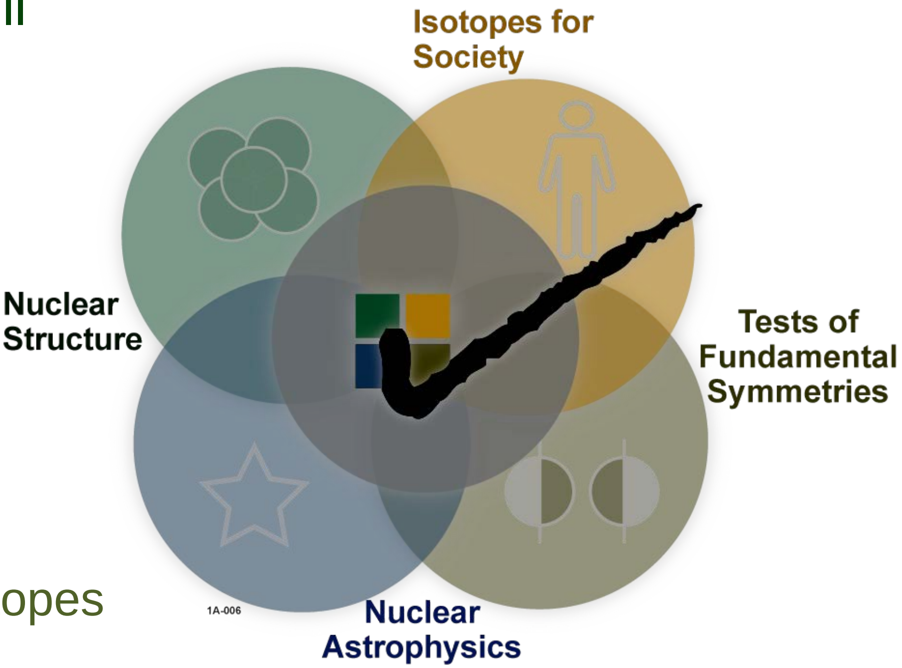
🟩 Target building

⬜ Experiment building

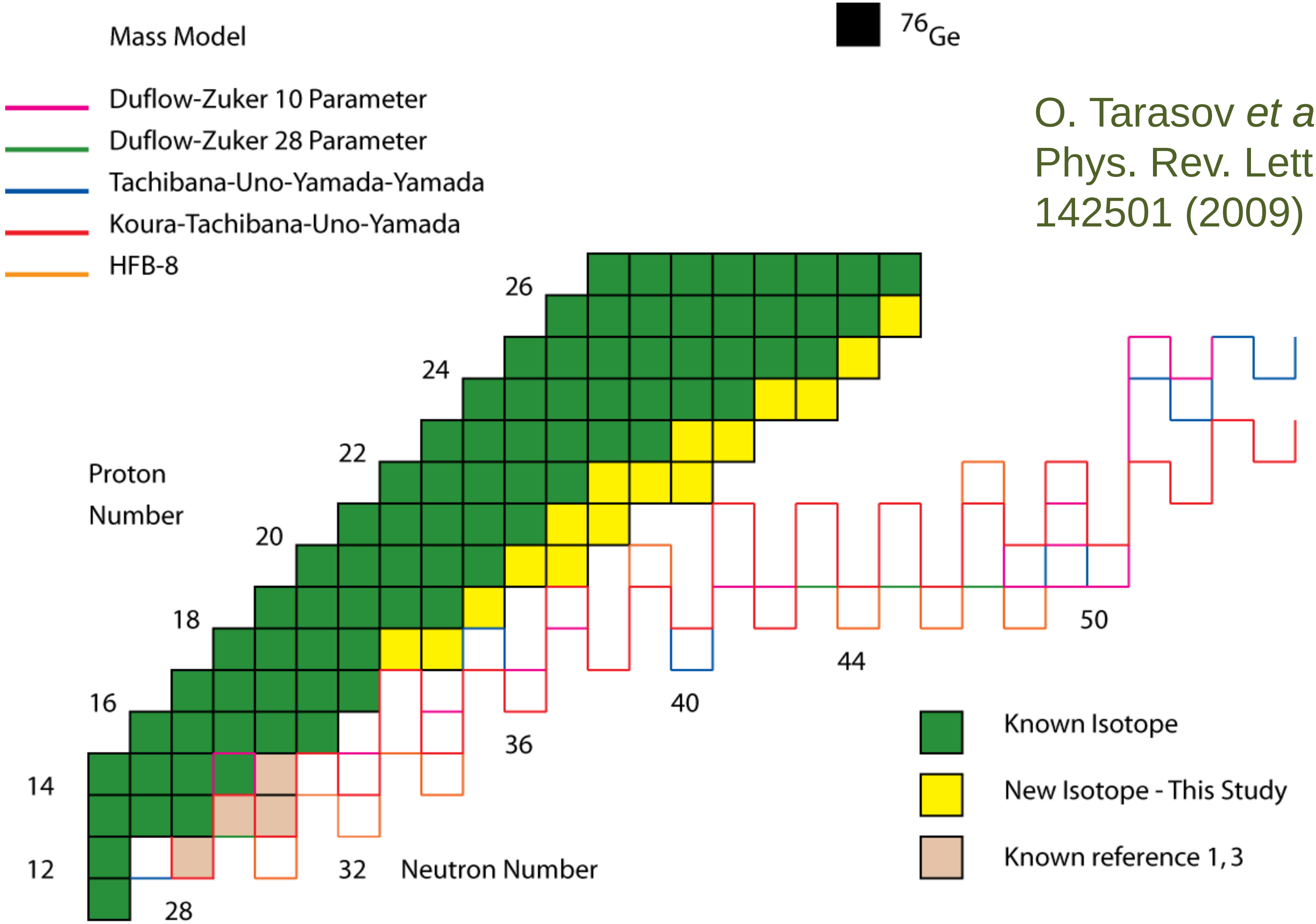
Seung Woo Hong

Summary

- We have entered the age of designer atoms – new tool for science
- Facilities world-wide (including FRIB) will allow production of a wide range of new designer isotopes (next lecture)
  - Necessary for the next steps in accurate modeling of atomic nuclei
  - Necessary for progress in astronomy (chemical history, mechanisms of stellar explosions)
  - Opportunities for the tests of fundamental symmetries
  - Important component of a future U.S. isotopes program
- There are significant challenges remaining in modeling and understanding the best production mechanism



Back to Exploring the Drip Lines



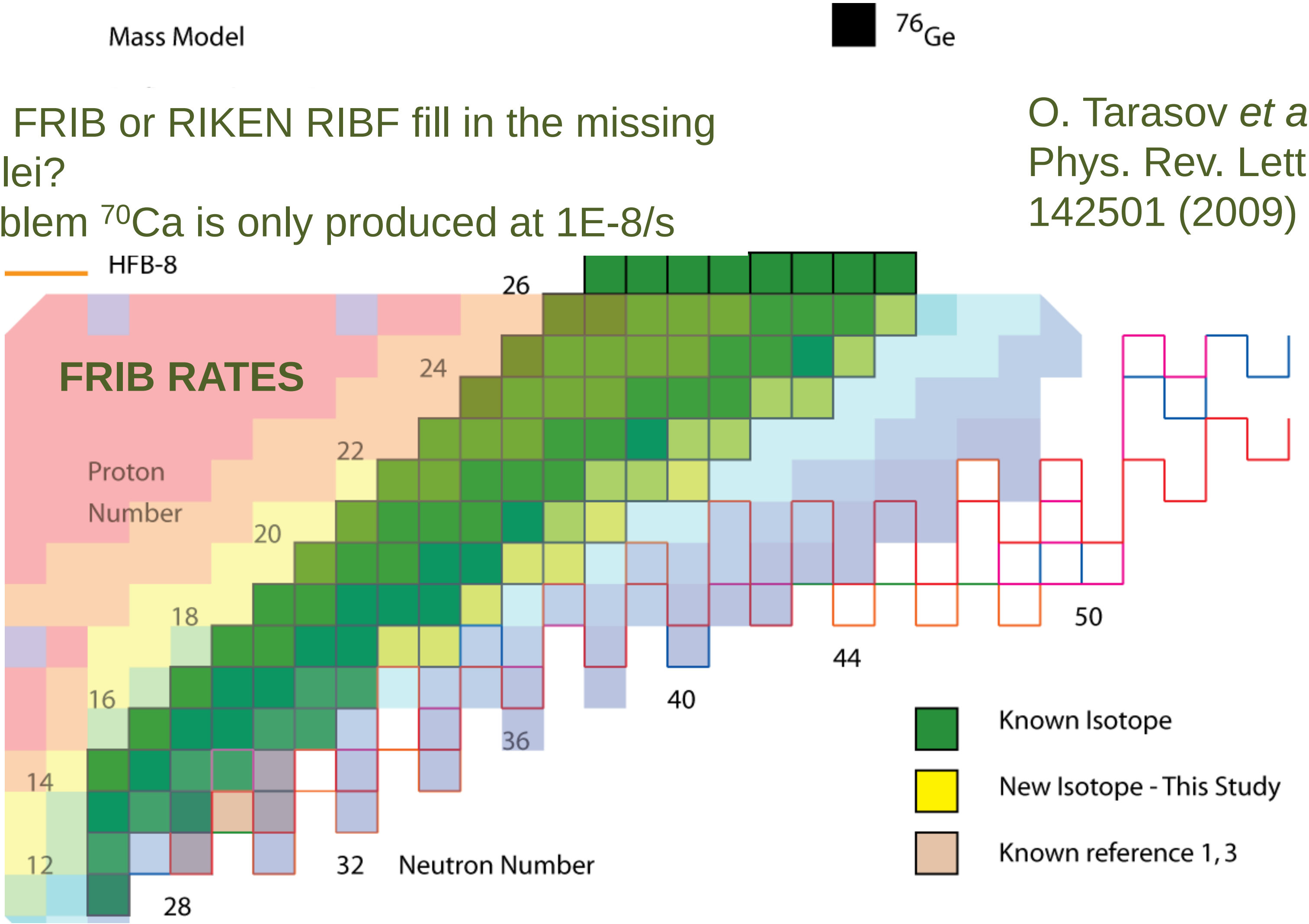
O. Tarasov *et al.*
Phys. Rev. Lett. 102, 142501 (2009)

Back to Exploring the Drip Lines

Will FRIB or RIKEN RIBF fill in the missing nuclei?
Problem ^{70}Ca is only produced at 1E-8/s

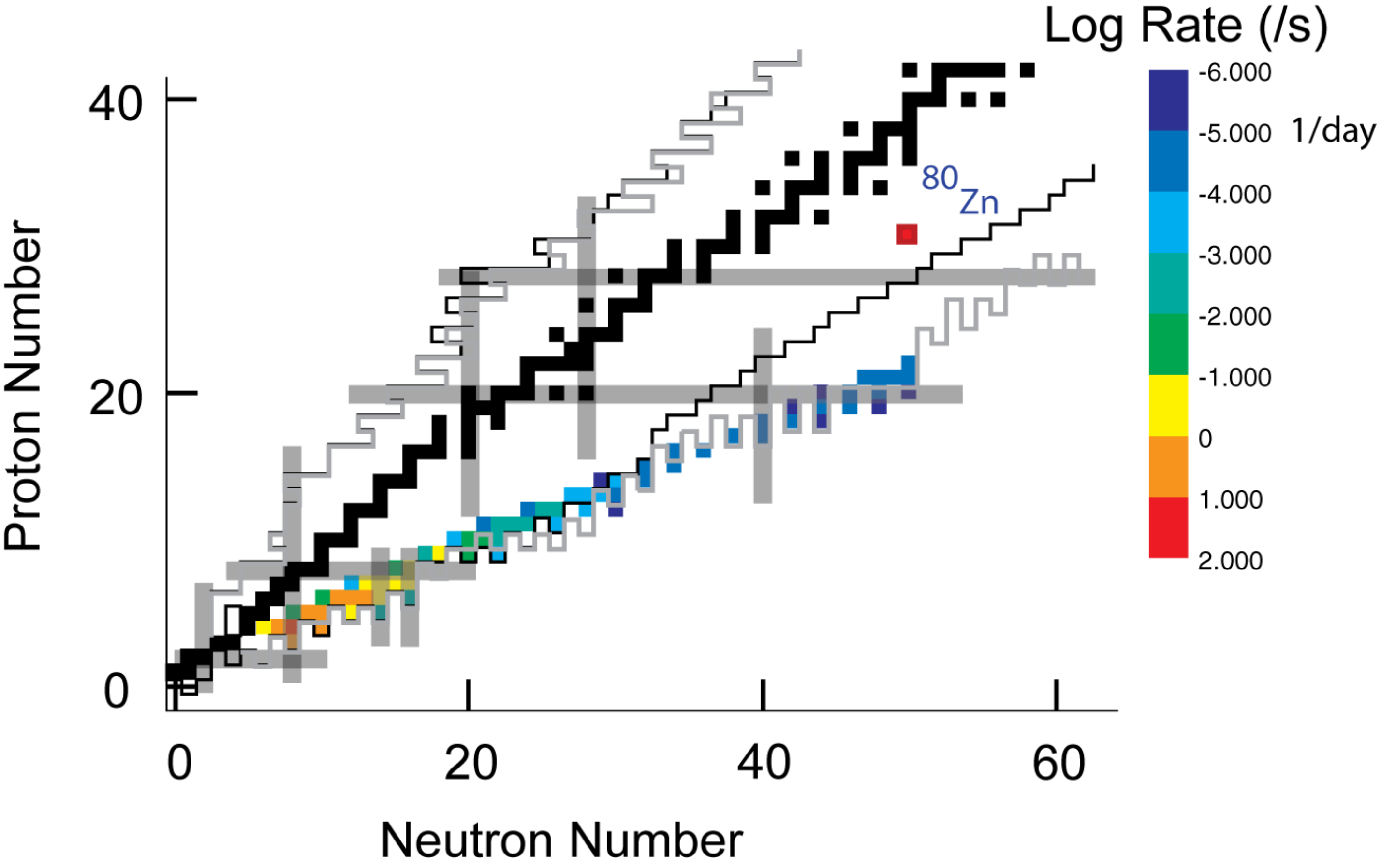
O. Tarasov *et al.*
Phys. Rev. Lett. 102, 142501 (2009)

FRIB RATES

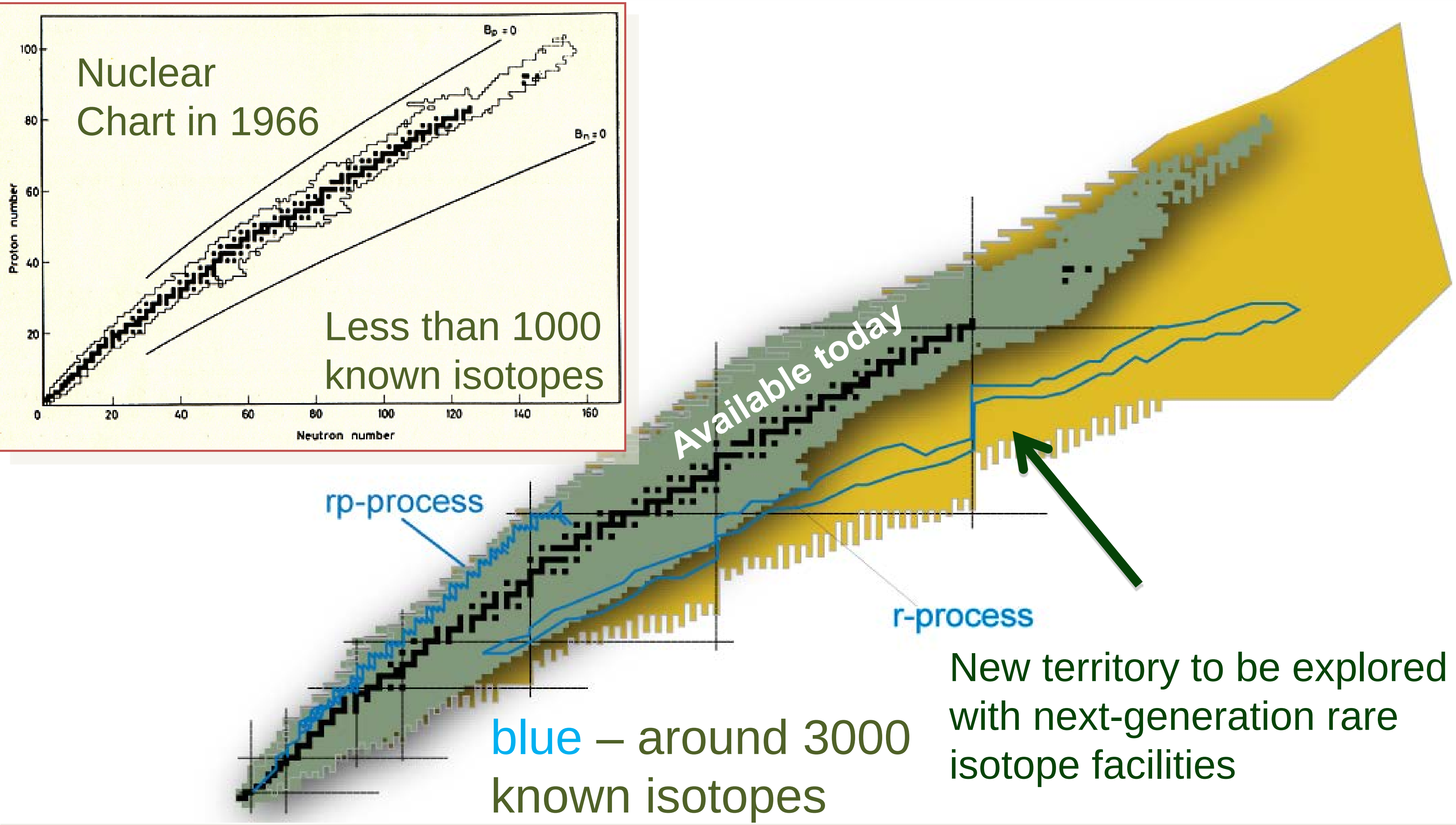


Future Prospects for Drip Line Study (upgraded FRIB with ISOL)

- Use proton induced fission of ^{238}U with 400 kW 600 MeV protons from FRIB
- ISOL Production of 5×10^8/s ^{80}Zn
- Acceleration to 160 MeV/u with the K1200 Cyclotron (200 MeV/u maximum energy)
- Production of nuclei along the drip line up to ^{70}Ca



The availability of rare isotopes over time



Nuclear Chart in 1966

Less than 1000 known isotopes

Available today

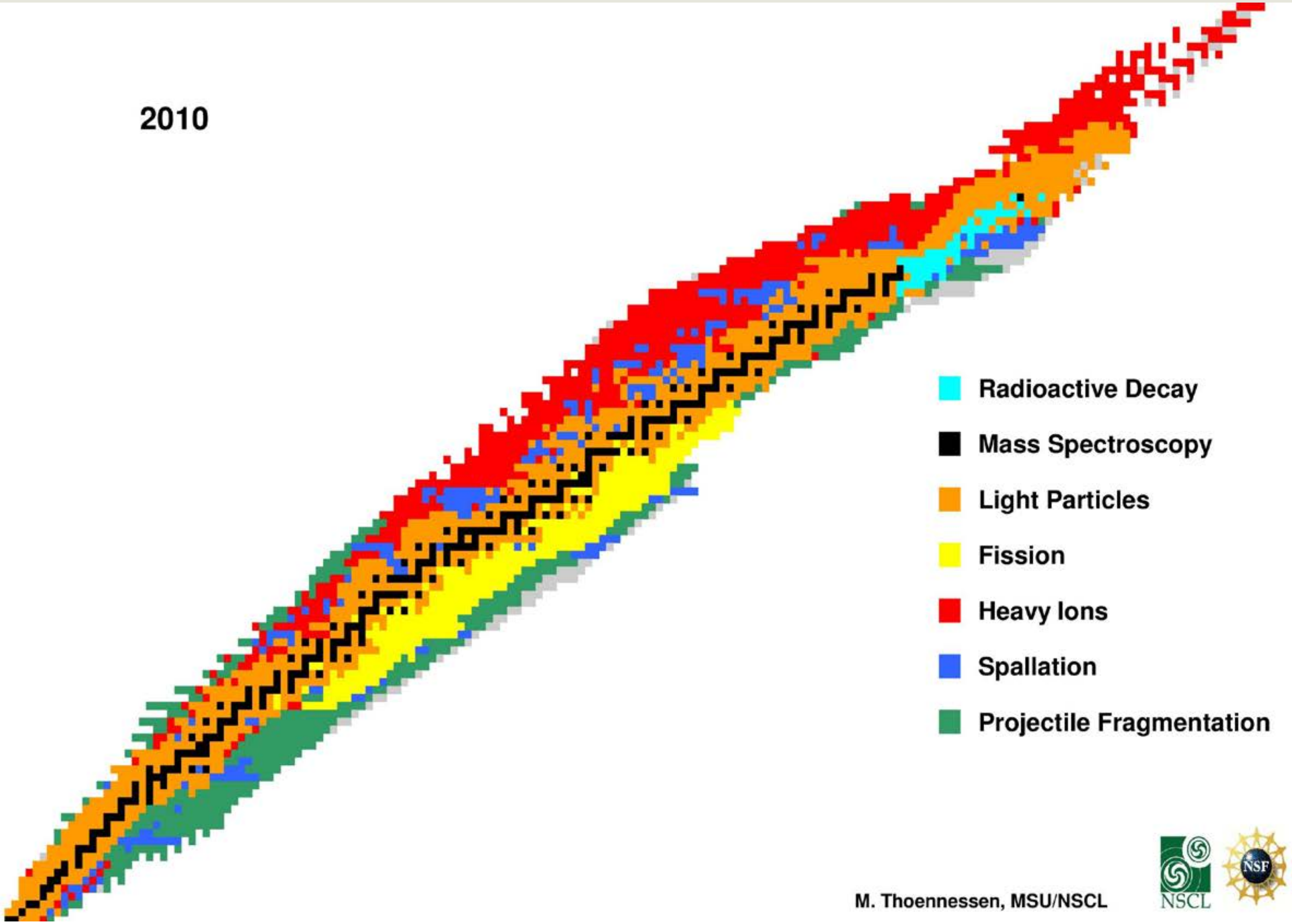
rp-process

r-process

blue – around 3000 known isotopes

New territory to be explored with next-generation rare isotope facilities

Method of discovery of the isotopes



M. Thoennessen, MSU/NSCL