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Superheavy Elements

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2026 Jun 23

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Outline

- Motivation & Background
  - History and status of heavy & superheavy element (SHE) production
  - Why are they interesting??
- SHE Recoil Separators
  - General methods & approaches
  - Current status of BGS
- Recent successes
  - Synthesis of ^{290}Lv (Z=116)
  - Mass Identification


Cat’s Eye Nebula

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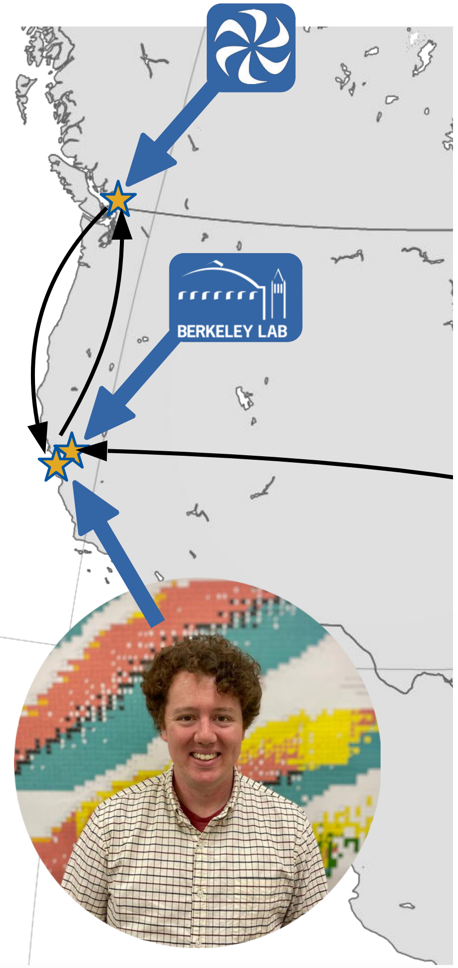
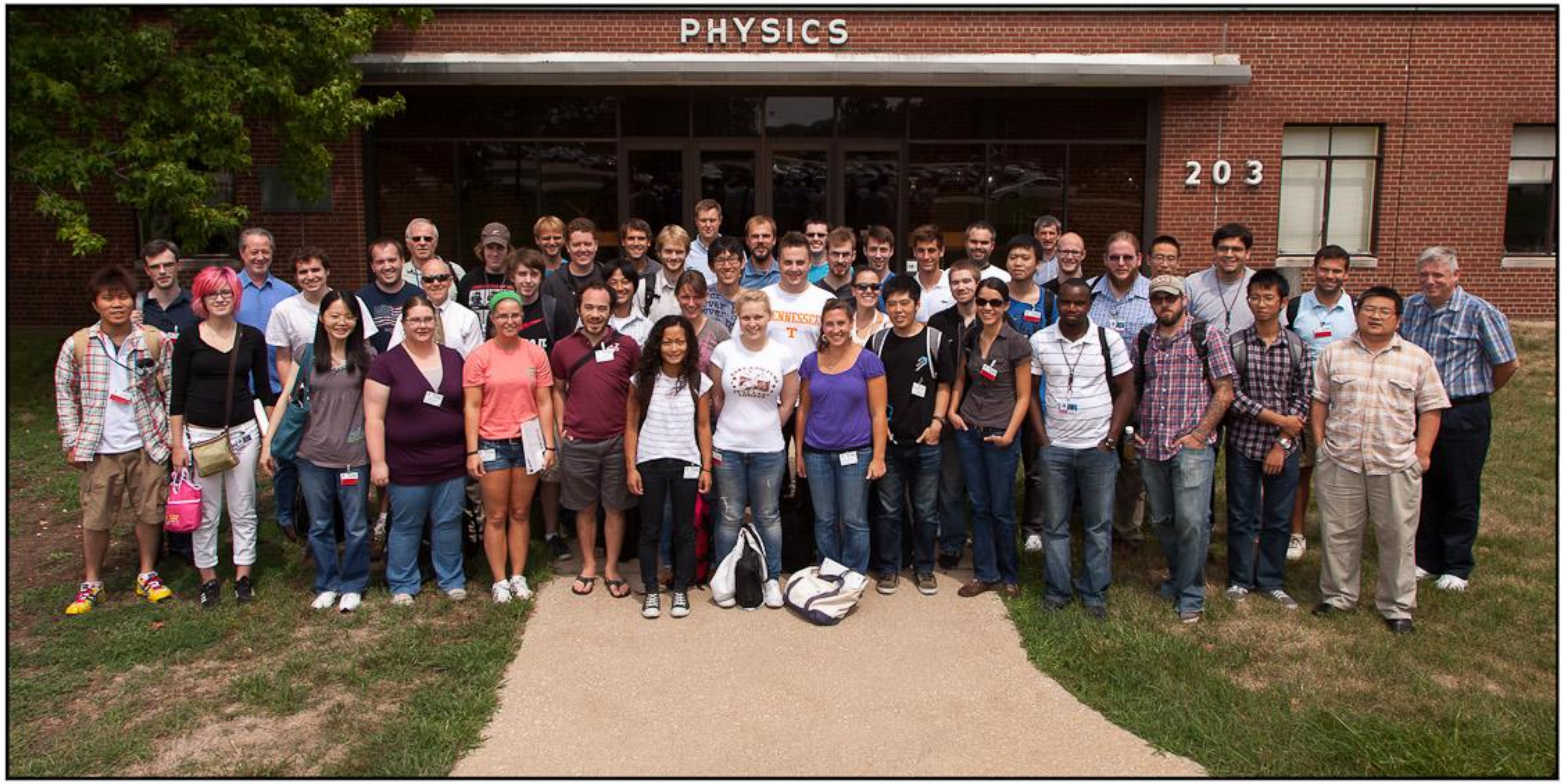
About Me

- Undergrad: Florida Atlantic U. (4 yrs)
  - First generation college student
  - No schooling / training in nuclear, but loved science, especially chem & physics
- Graduate: UC Berkeley (6.5 yrs)
  - Worked on super-heavy element reactions
  - EBSS 2012
- Post-doc: TRIUMF (2.5 yrs)
  - EMMA: nuclear structure & astrophysics
- Current: SJSU (6 yrs)
  - Teach nuclear chemistry and research targetry!
  - Goal: support student activity in nuclear science
  - Continue collaborating with the LBNL Heavy Elements group

About Me





E B S S 2 0 1 2

A U G U S T 5 - 1 0 , 2 0 1 2

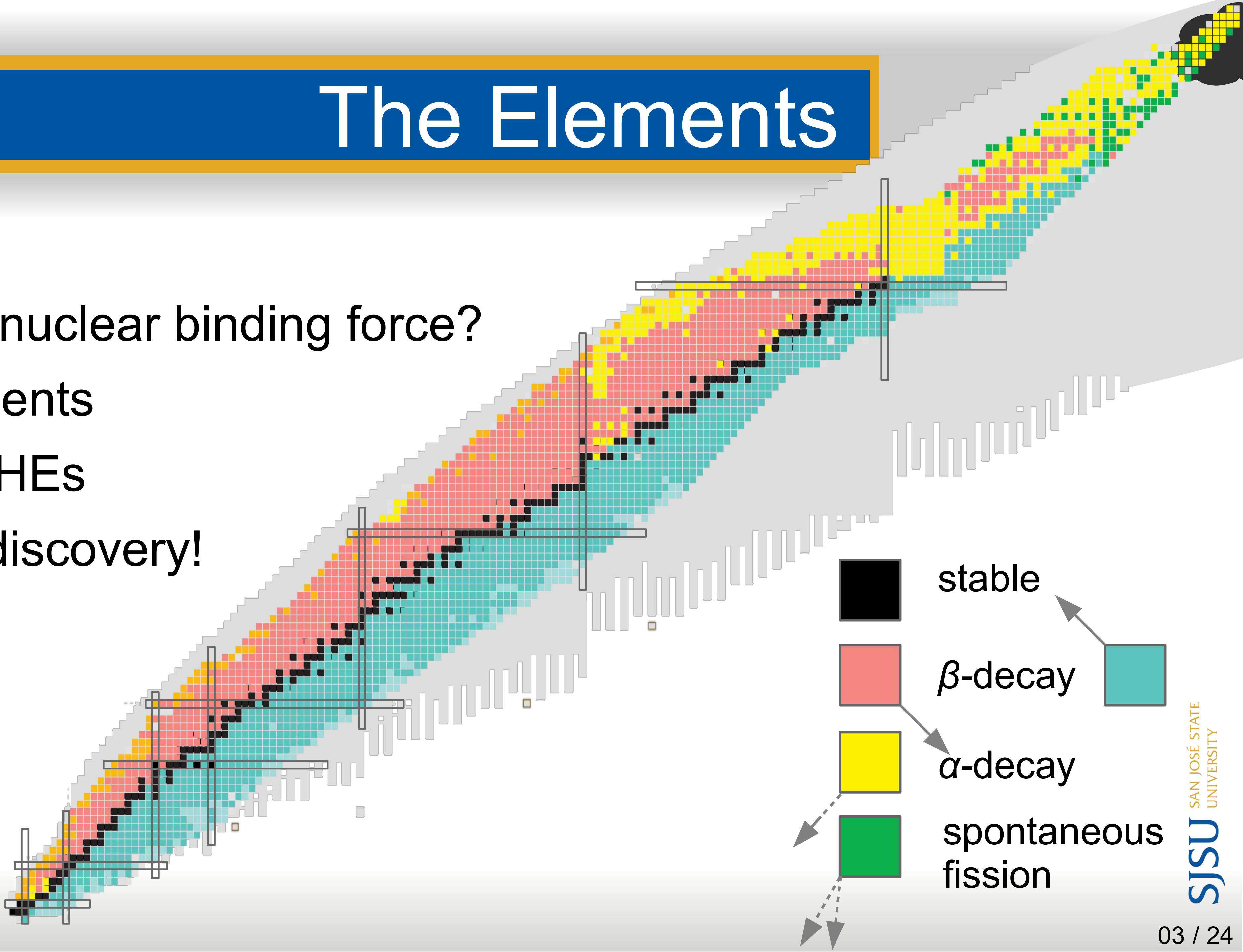
The Elements

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La>	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac*	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
			>	58 Ce	59 Pr	60 Nd	73 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
			*	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

The Elements

Motivations:

- Upper limits of nuclear binding force?
- Origins of elements
- Chemistry of SHEs
- Excitement of discovery!



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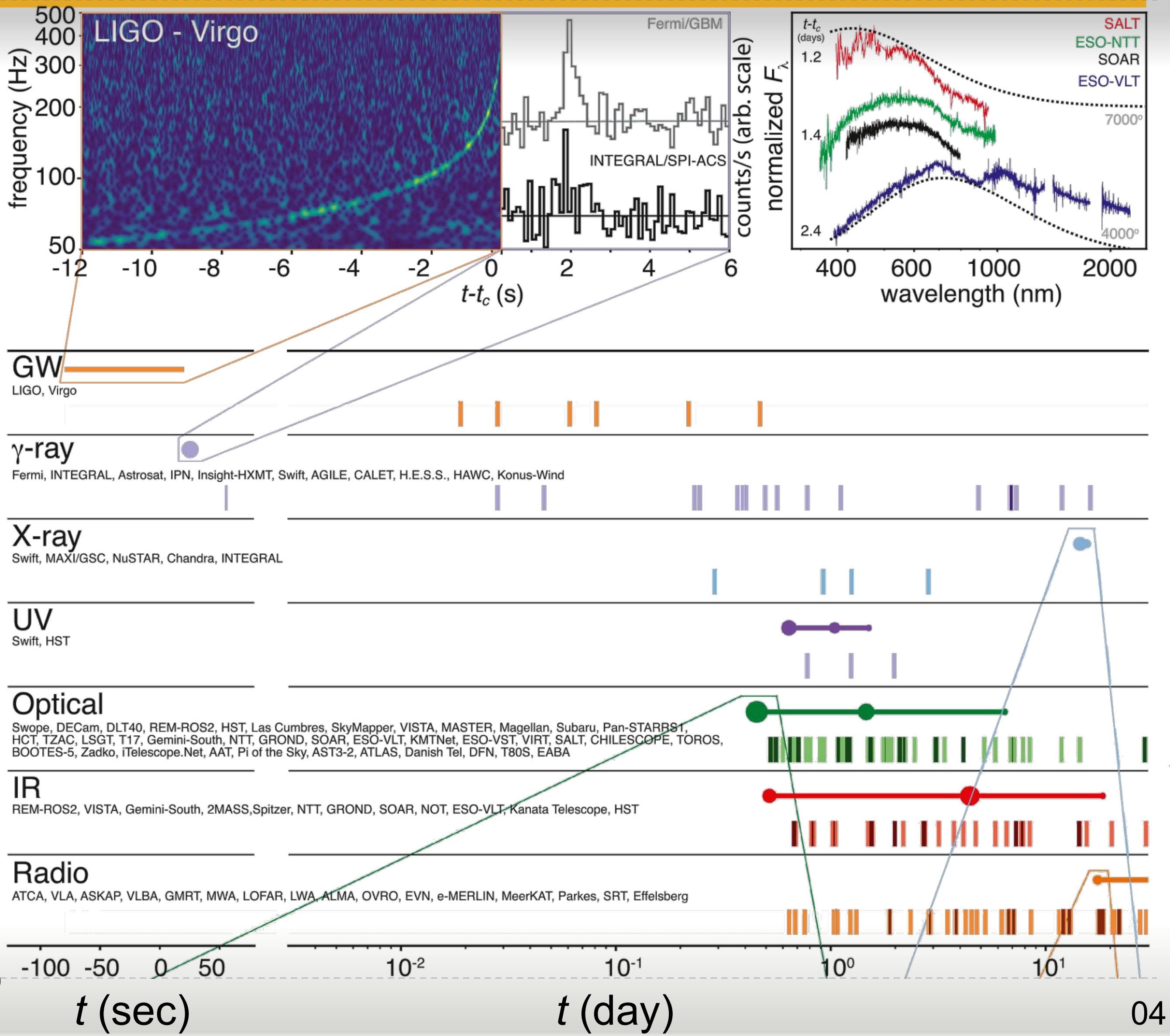
Origin of the elements

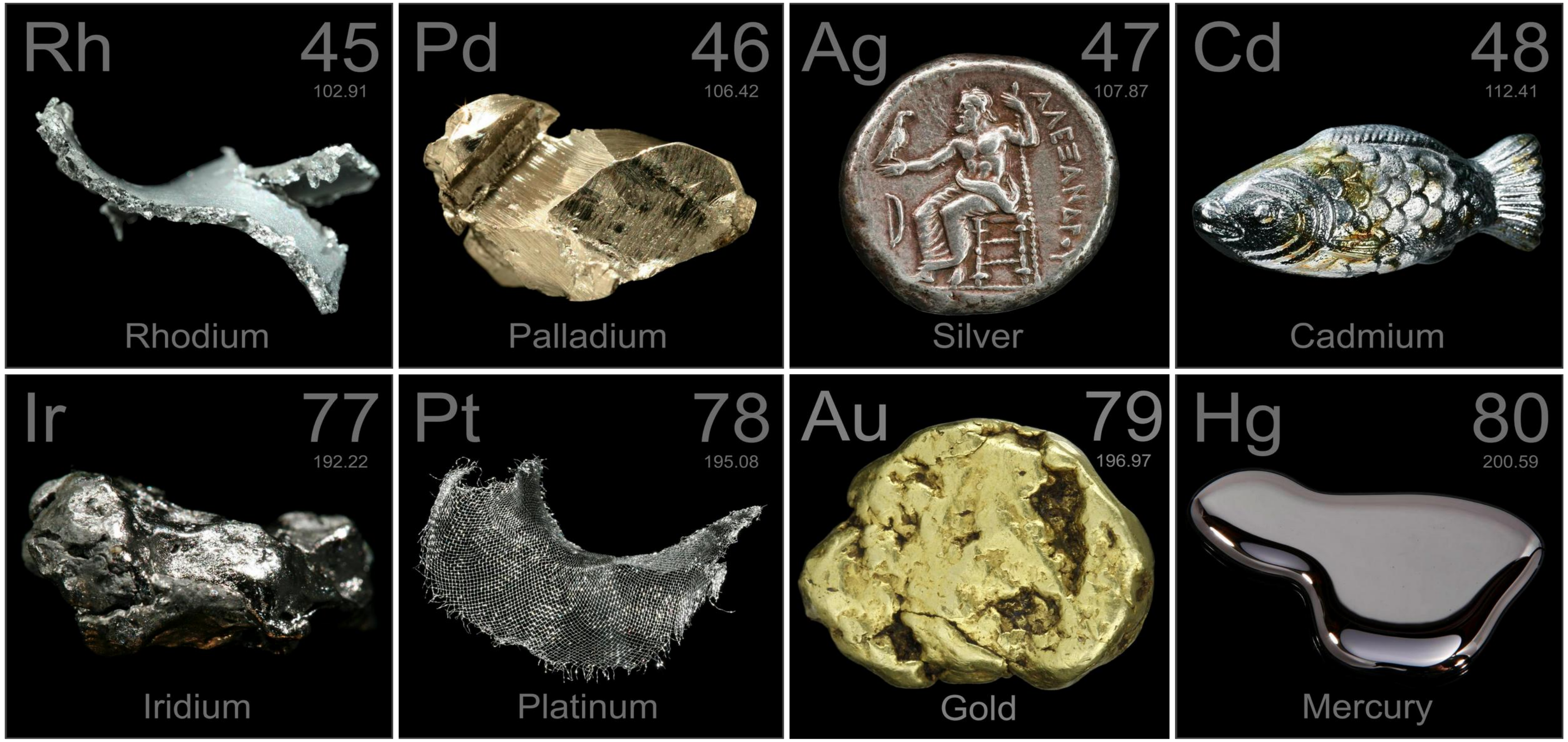
- Evidence for *r*-process in neutron star mergers
- Start of the "age of multimessenger astronomy!"
- To study these radioactive nuclei, they must first be produced in the lab



The Astrophysical Journal Letters,848:L12(59pp), 2017 October 20

Chemical Behaviors of SHEs

- SHE == breakdown in periodic trends?
  - Relativistic shifts in electronic orbitals



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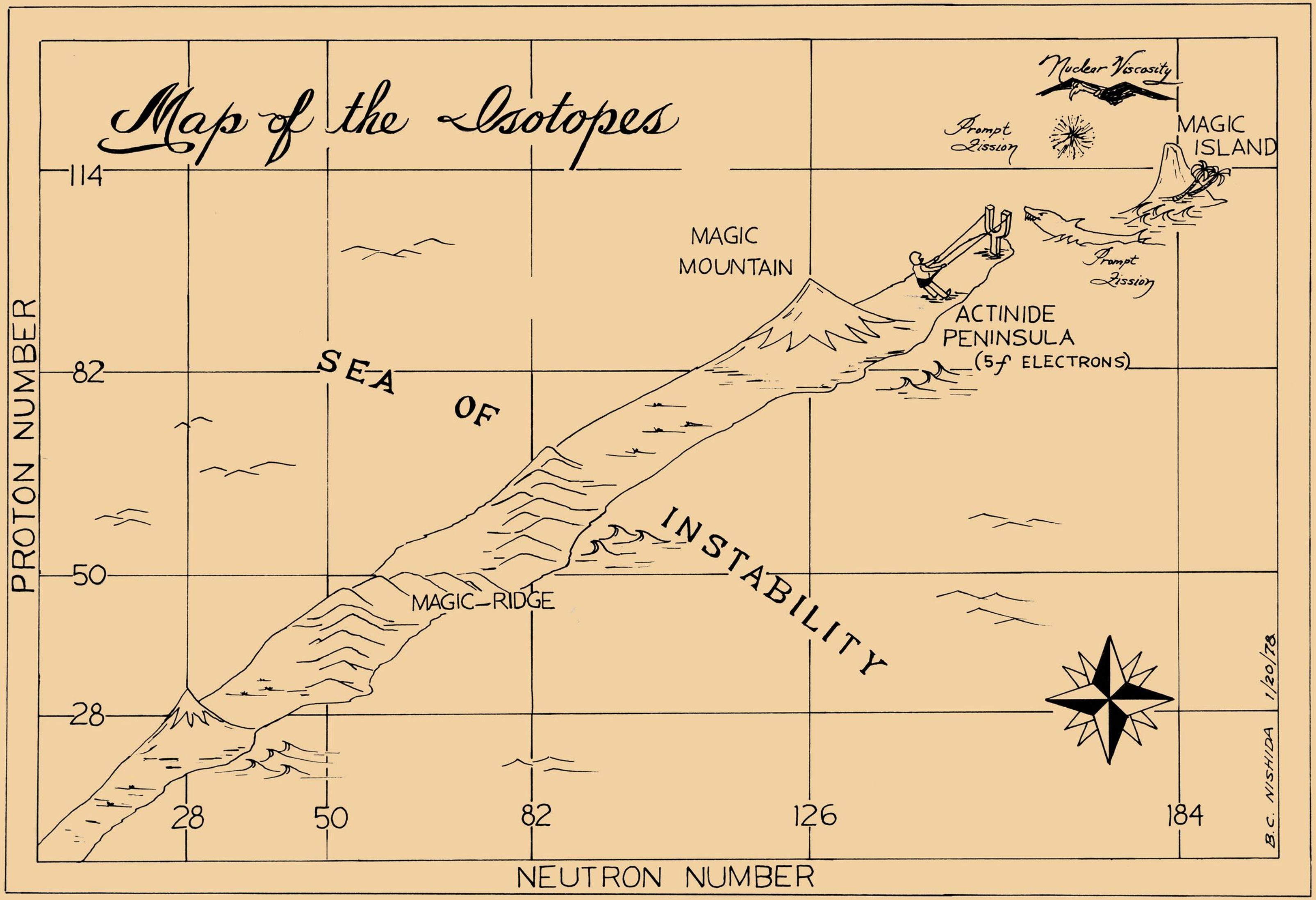
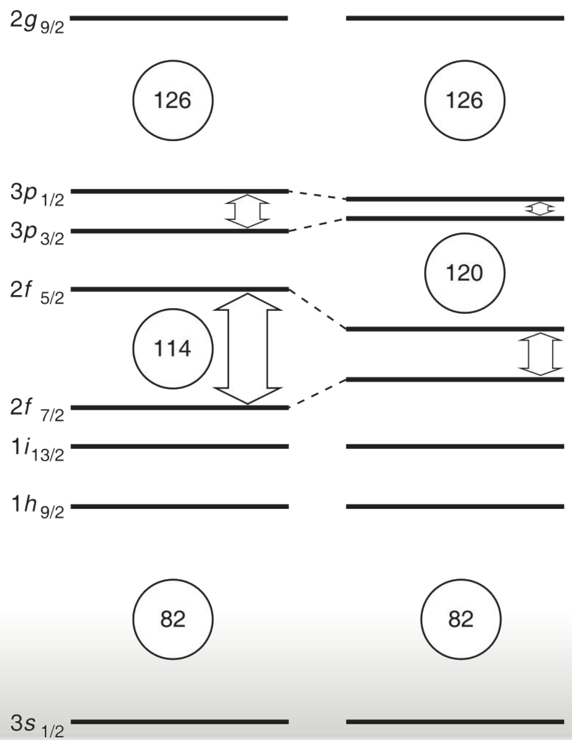
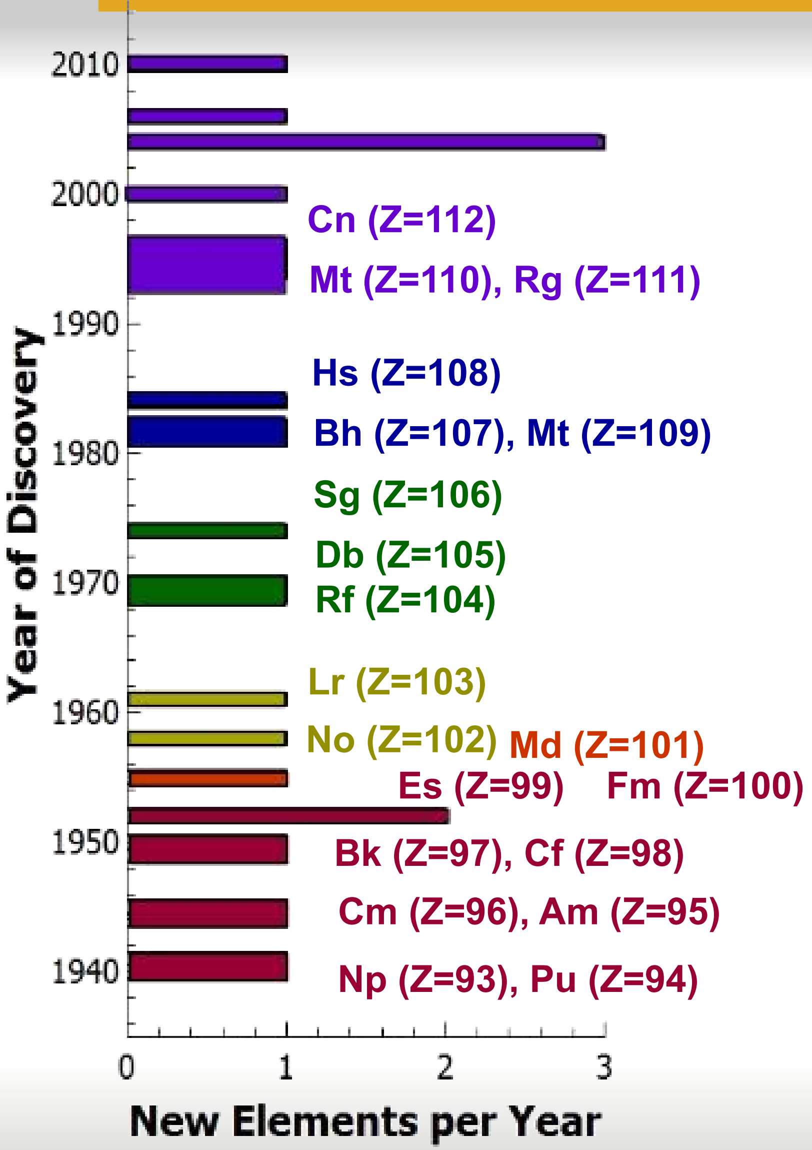
Historical Definition of “SHE”



- Search for _stability_
  - Pre-1967 picture
  - Need to “jump” from Rf → Fl , E120



Element Discovery



- IUPAC / IUPAP Definition:

  “The discovery of a chemical elements is the experimental demonstration beyond reasonable doubt, of the existence of a nuclide with atomic number Z not identified before, existing for at least 10^{-14} s.”

- Nomenclature:
  - Transuranic – element beyond uranium ($Z \geq 93$)
  - Transactinide – element beyond lawrencium ($Z \geq 104$)
  - Superheavy element – ...

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Element Discovery

- Six element discovered in past two decades
  - Z = 113 Nihonium (Nh): 2004 at RIKEN (1 atom in several months)
  - Z = 114 Flerovium (Fl): 1998 at JINR (2 atoms in 1 year)
  - Z = 115 Moscovium (Mc): 2003 at JINR (4 atoms in 1 month)
  - Z = 116 Livermorium (Lv): 2000 at JINR (3 atoms in 1 year)
  - Z = 117 Tennessine (Ts): 2010 at JINR (6 atoms in several months)
  - Z = 118 Oganesson (Og): 2002 at JINR (3 atoms in several months)

INTERNATIONAL UNION OF PURE AND APPLIED CHEMISTRY

For Release 8 June 2016

IUPAC is naming the four new elements nihonium, moscovium, tennessine, and oganesson

Following earlier reports that the claims for discovery of these elements have been fulfilled [1, 2], the discoverers have been invited to propose names and the following are now disclosed for public review:

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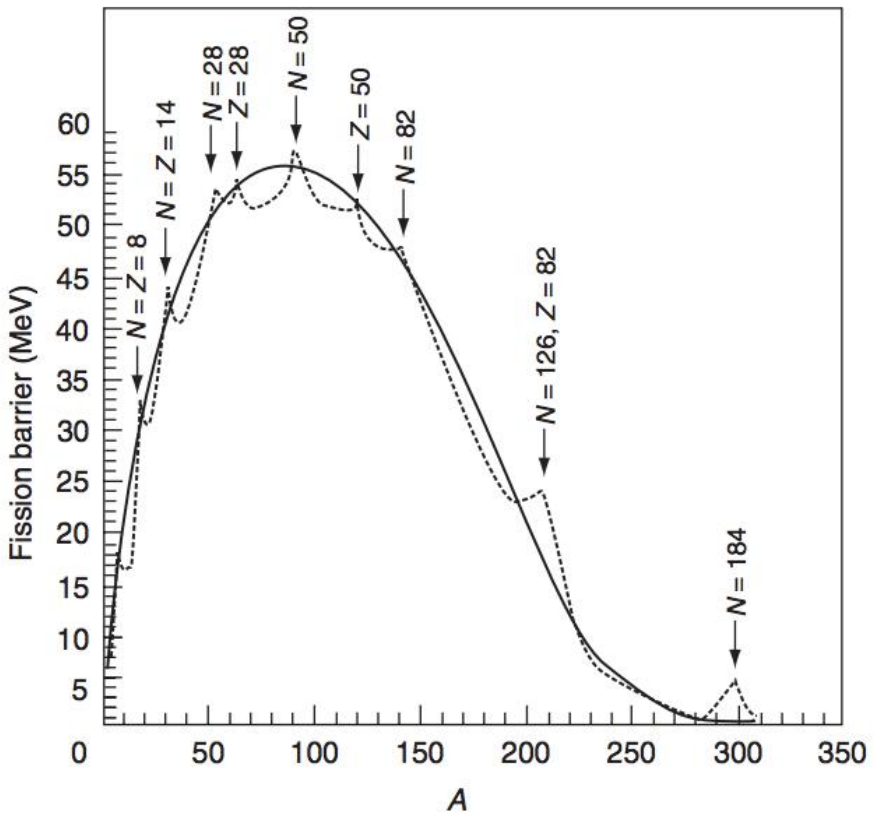
Stability of SHEs

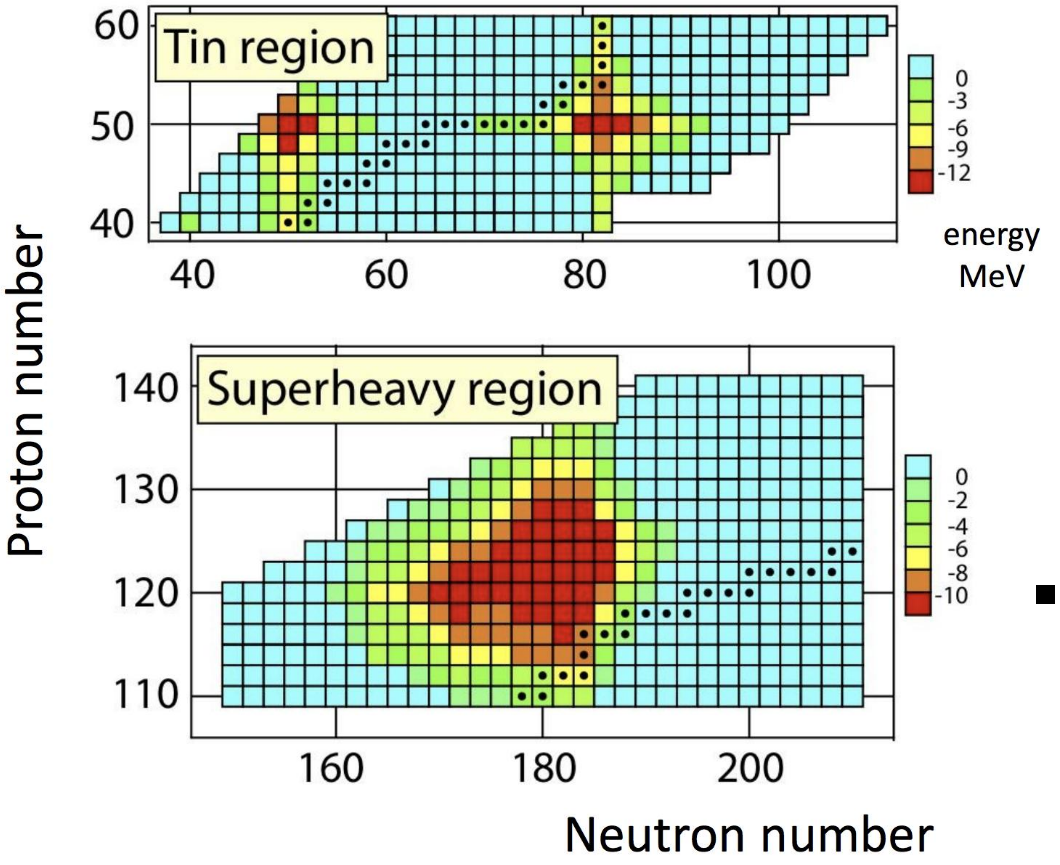


Fission-Barrier heights as a function of A. Smooth line calculated with semi-empirical mass formula and the dotted line illustrates the effects of nuclear structure.

- SHEs exist at edge of fission barriers
  - B_f drops rapidly for heavy nuclei due to increasing repulsive forces.
  - Favorable shell structure can increase a nucleus's resistance to fission.

- Modern SM calculations have diffuse shell stabilization
  - *Z* closure could be 114 – 120

Stability of SHEs



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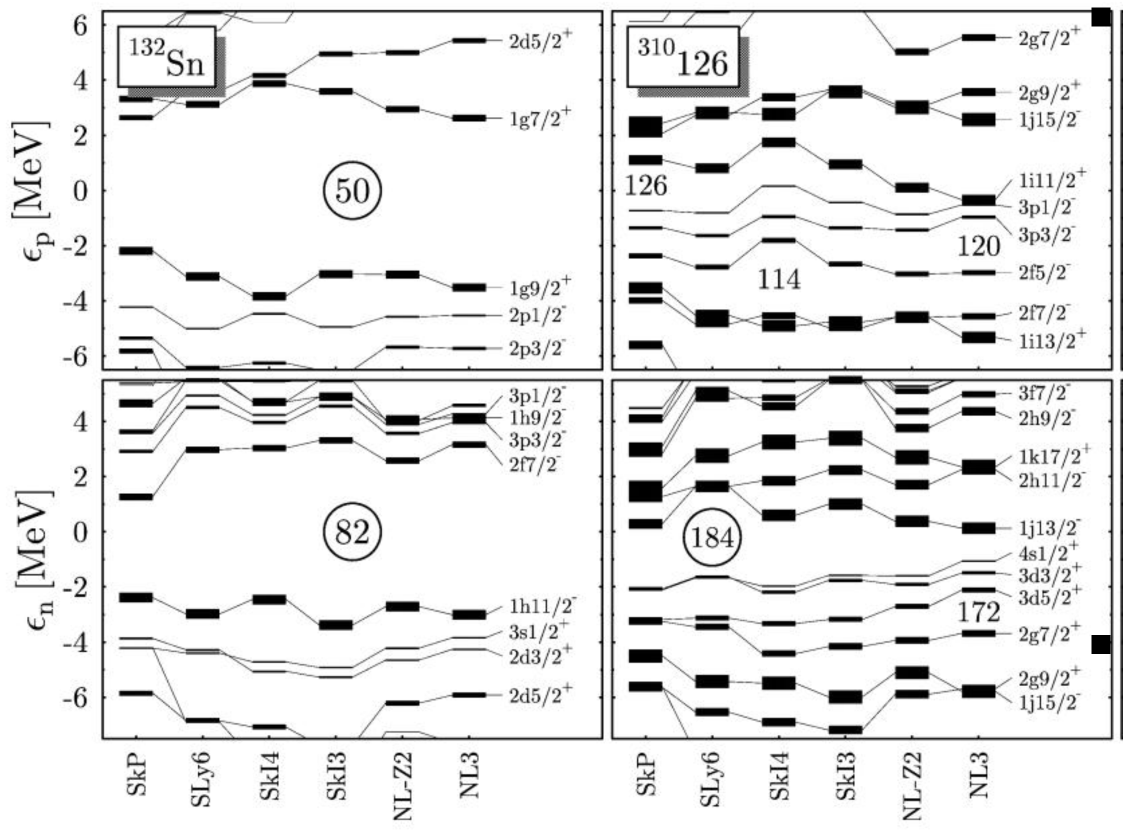
M. Bender et al., Phys. Lett. B 515, 42 (2001).

Stability of SHEs

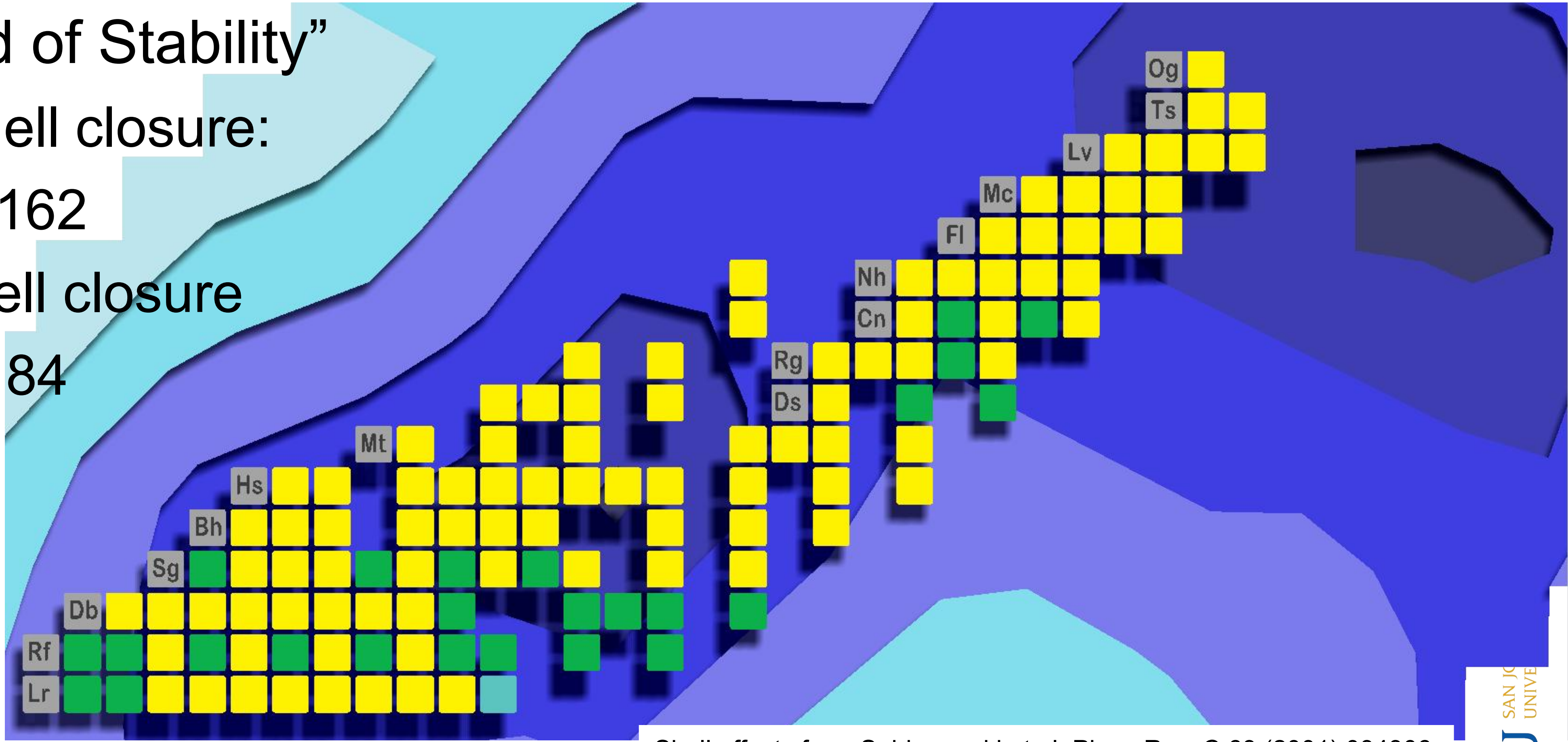


Calculated single-particle spectra for ^{132}Sn and $^{310}126$.
Energies are relative to the Fermi surface.

- SHEs exist at edge of fission barriers
  - B_f drops rapidly for heavy nuclei due to increasing repulsive forces.
  - Favorable shell structure can increase a nucleus's resistance to fission.
- Modern SM calculations have diffuse shell stabilization
  - *Z* closure could be 114 – 120

Modern SHEs

- Edge of "Island of Stability"
  - Deformed shell closure: $Z \sim 108$, $N \sim 162$
  - Spherical shell closure $Z \sim 114$, $N \sim 184$



Shell effects from Sobiczewski et al: Phys. Rev. C 63 (2001) 034306

Element Synthesis

- Techniques for element synthesis

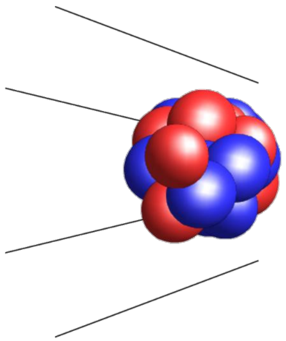
(1) Reactor-based

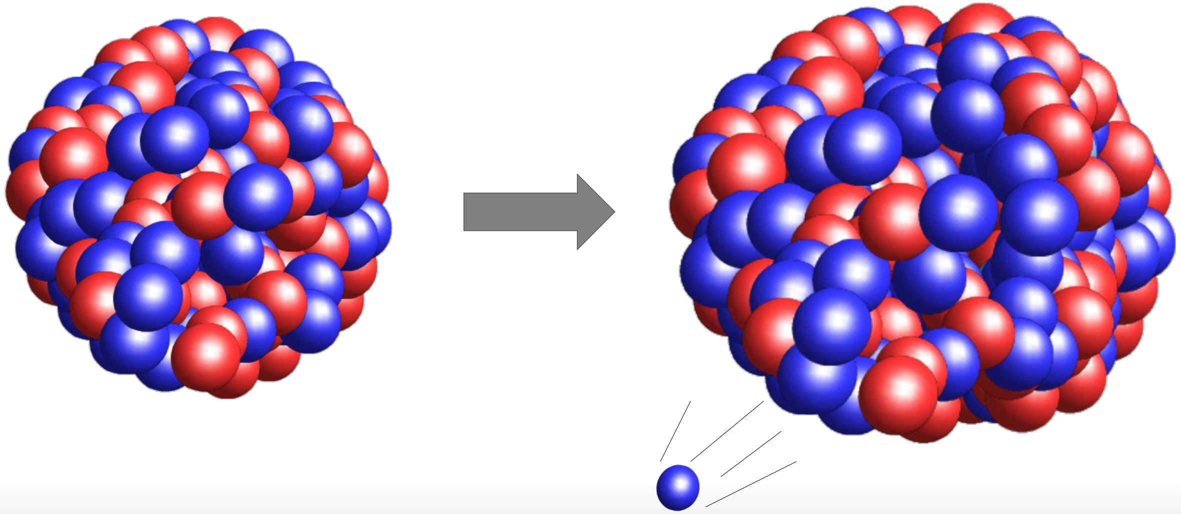
– *n* capture + β^- decay

– Similar to *s*-process

(2) Accelerator-based reactions

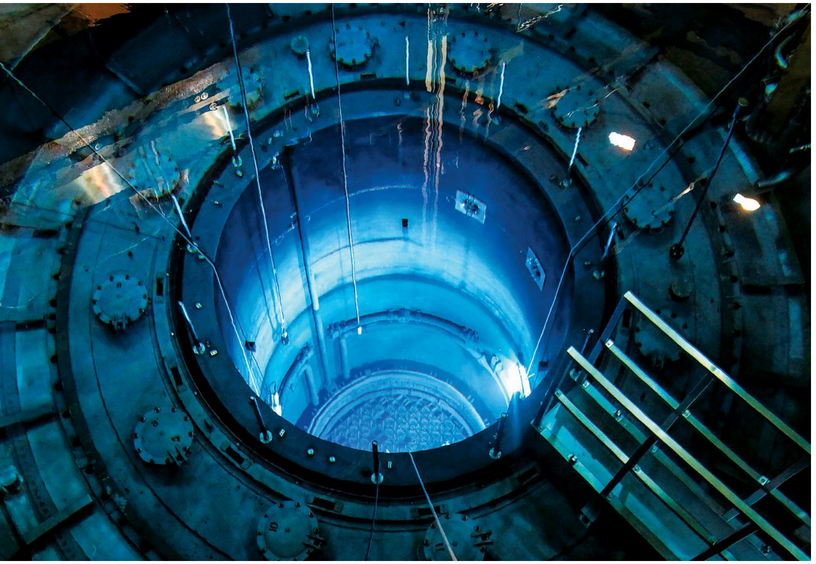
- Compound Nuclear
- Multi-nucleon transfer

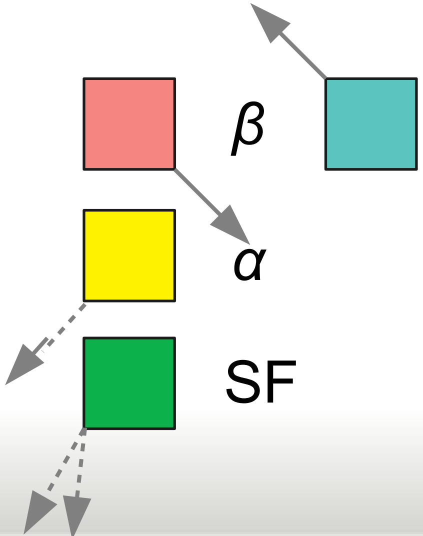


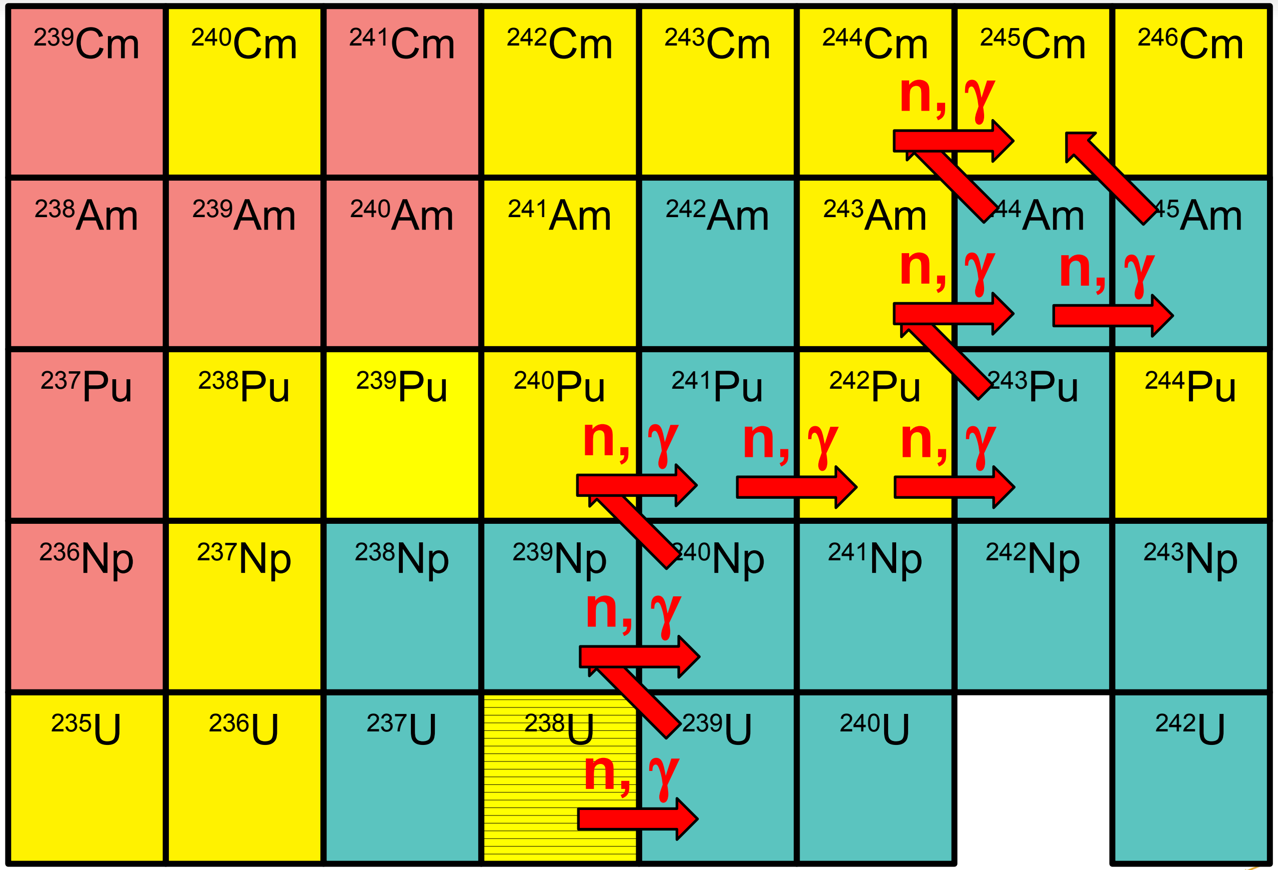


Heavy Element Production

- Reactor Breeding
  - Oldest technique, since 1940s
  - *n* capture must compete with decay kinetics

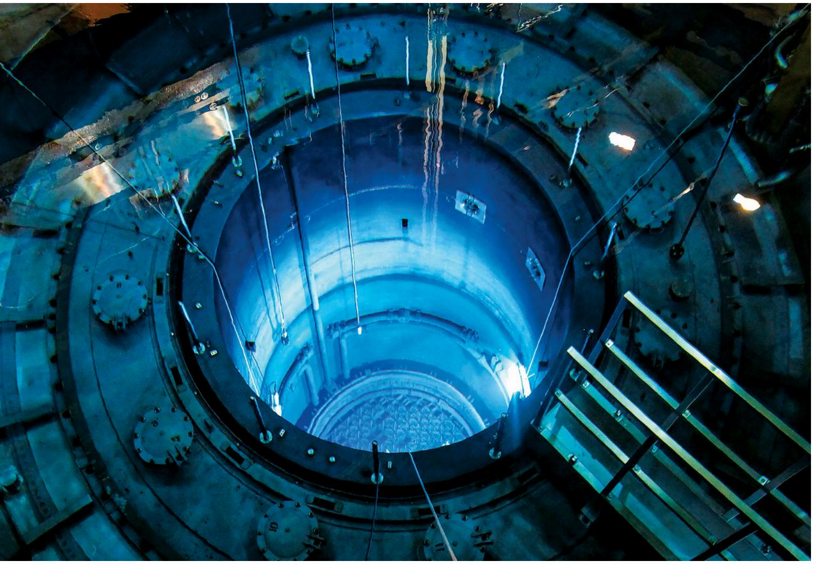


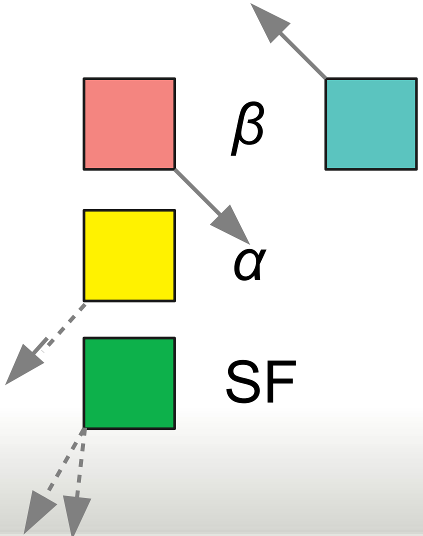


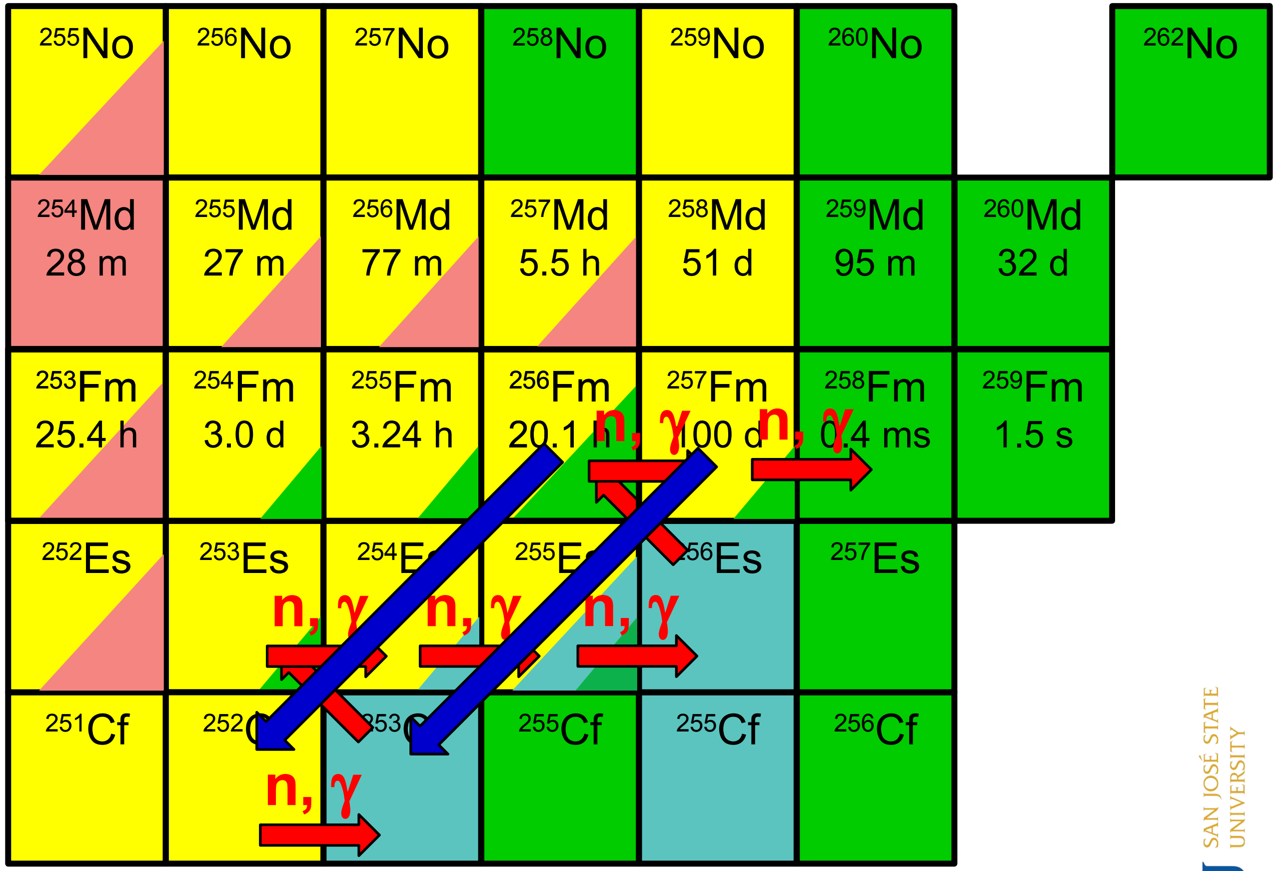


Heavy Element Production

- Fermium Gap
  - Fm decay rate stoo fast for reactors
  - Still possible in much high neutron fluxes, i.e in stellar explosion

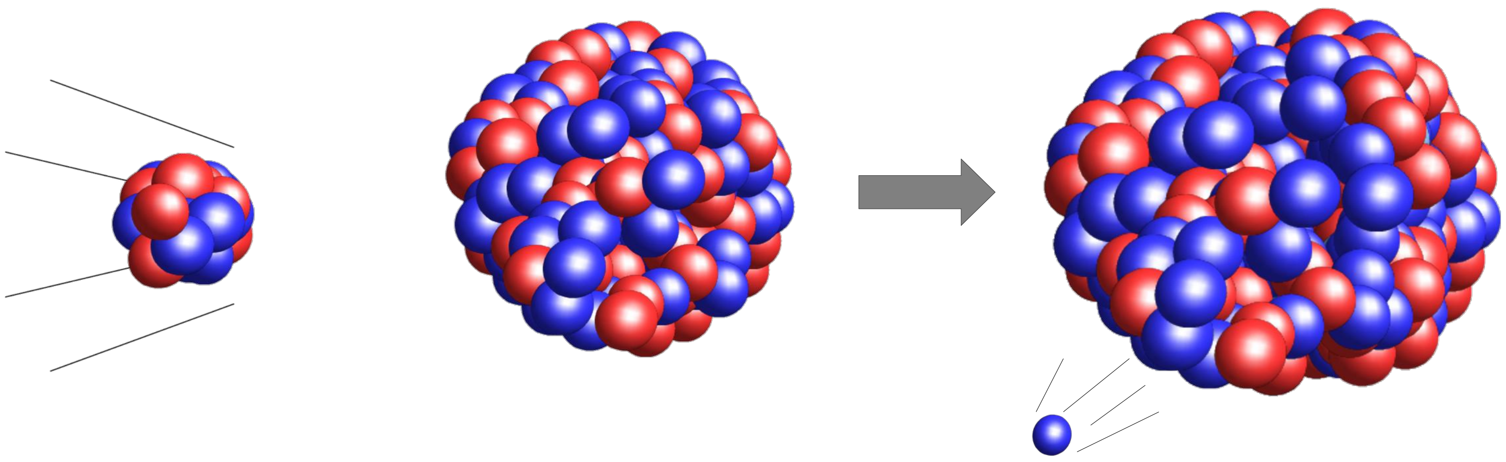






Compound Nuclear Reactions

- Fusion Evaporation
  - Light(er) ion beam on heavy(ier) target
  - Accelerated above Coloumb barrier
  - Post-fusion excitation dissipated via particle emission



Compound Nuclear Reactions

- Reaction Theory:
  - Three step process, depends on *E, Z, A*

Production cross section → $$\sigma_{EVR}(E_{c.m.}) = \sum_J \sigma_{cap}(E_{c.m.}, J) P_{CN}(E_{c.m.}, J) W_{sur}(E_{c.m.}, J)$$

Capture cross section — Probability of CN formation — Survival

Fusion Evaporation = (sticking) x (fusion) x (survival)

  - Survival: dissipating excitation energy without breaking apart

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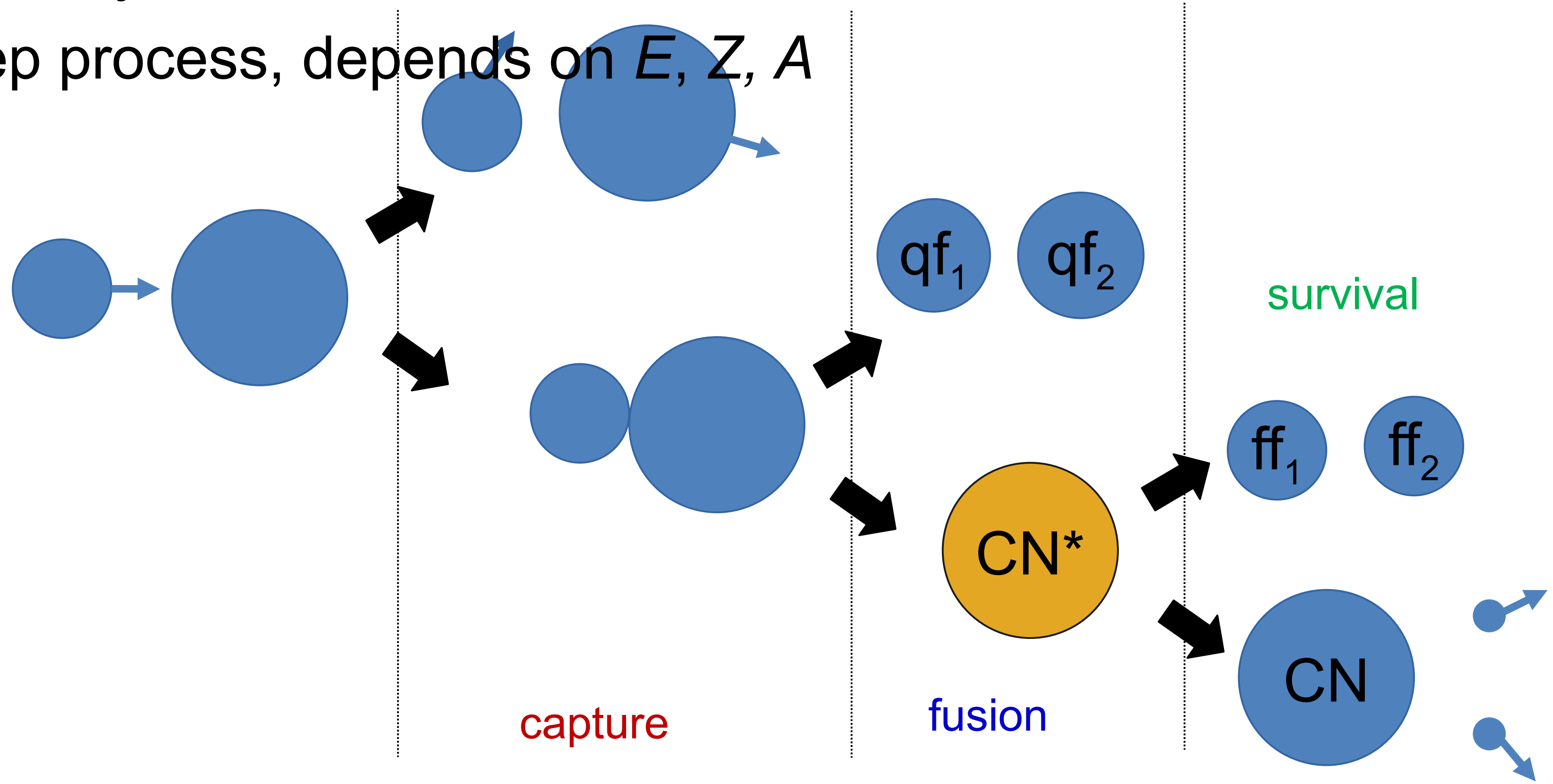
Compound Nuclear Reactions

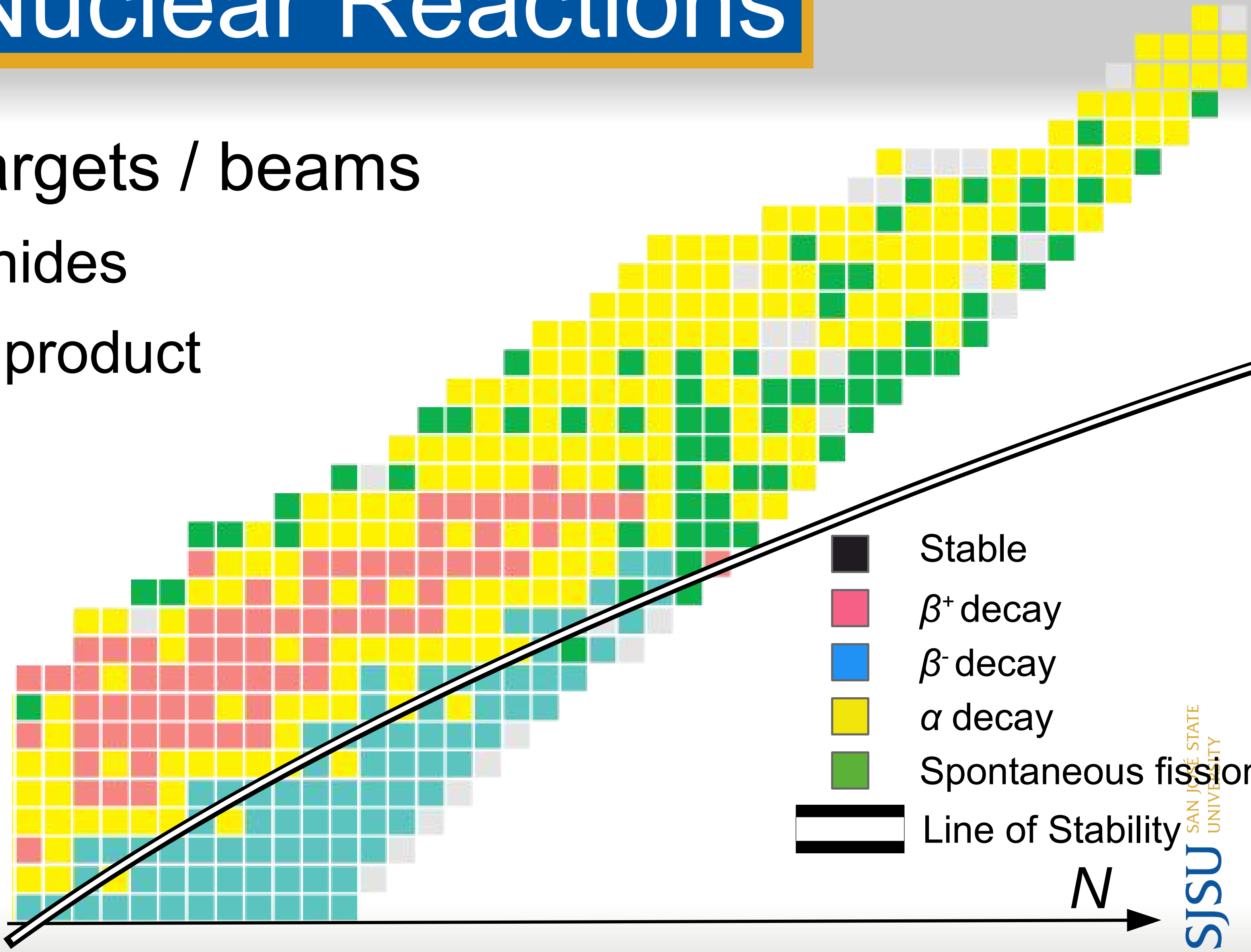
- Reaction Theory:
  - Three step process, depends on *E*, *Z*, *A*



  - Survival: dissipating excitation energy without breaking apart

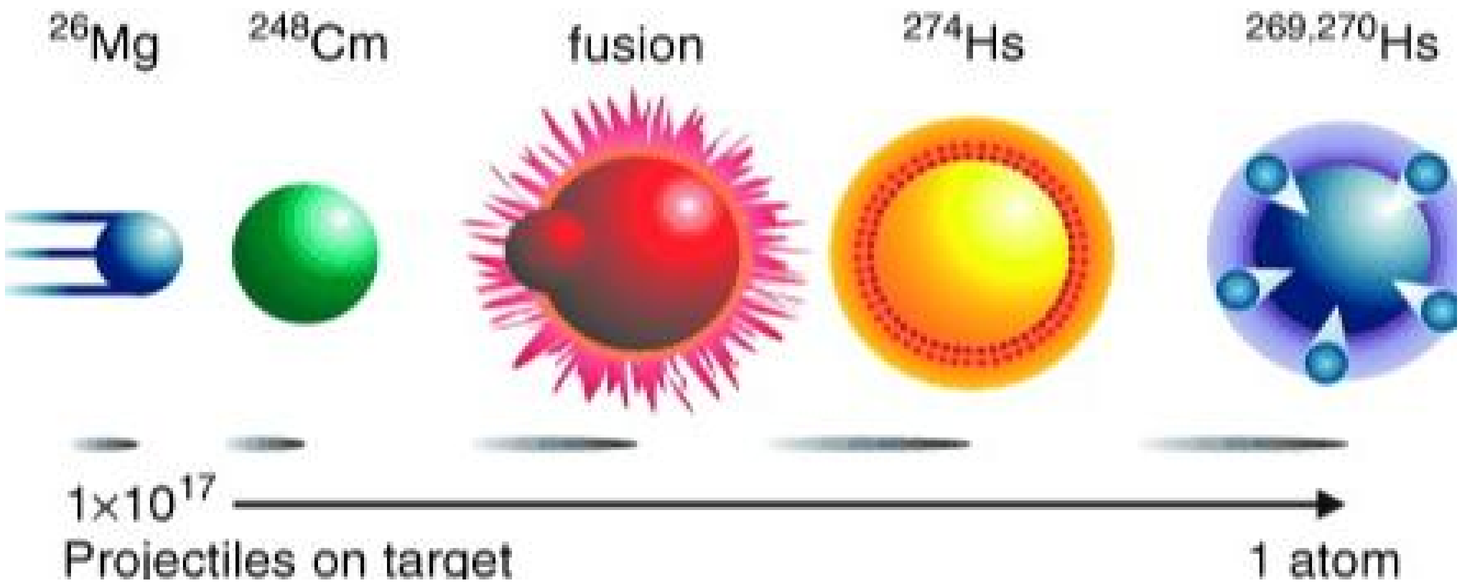
Compound Nuclear Reactions

- **<u>Need</u>** neutron-rich targets / beams
  - Targets: Pb / Bi, actinides
  - Beams: based upon product



Compound Nuclear Reactions

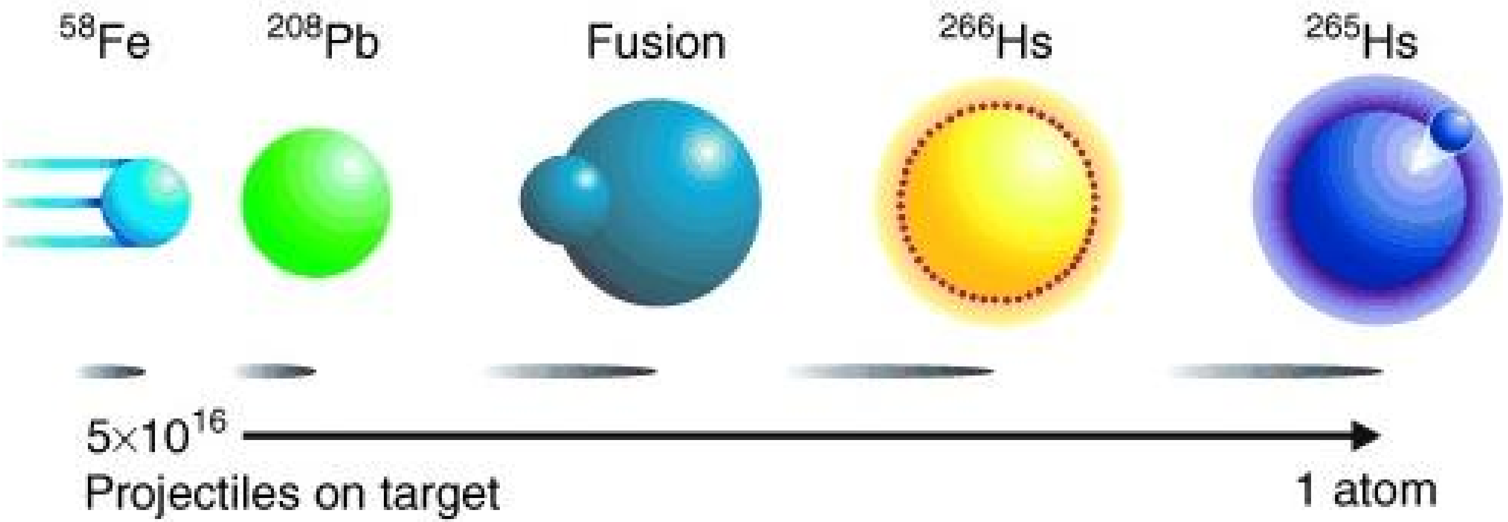
- "Hot" Fusion vs. "Cold" Fusion
  - Hot Fusion: actinides + light ion beam, higher CN excitation (*E**~40 MeV)
    - Take Advantage of greater *n* in actinides



^{248}Cm (^{26}Mg, 5*n*) ^{269}Hs

Compound Nuclear Reactions

- "Hot" Fusion vs. "Cold" Fusion
  - Hot Fusion: actinides + light ion beam, higher CN excitation (E^*~40 MeV)
  - Cold Fusion: Pb / Bi target + beam, lower CN excitation (E^*~10 MeV)
    - Take advantage of shell closure in target



^{208}Pb (^{58}Fe, 1*n*) ^{265}Hs

Compound Nuclear Reactions

- "Hot" Fusion vs. "Cold" Fusion
  - Hot Fusion: actinides + light ion beam, higher CN excitation (E^*~40 MeV)
  - Cold Fusion: Pb / Bi target + beam, lower CN excitation (E^*~10 MeV)

- "Lukewarm" Fusion
  - ^{48}Ca + actinides, CN excitation (E^*~ 20 -- 40 MeV)
    - Take advantage of highest neutron economy from beam + target,
    - Take advantage of doubly magic ^{48}Ca

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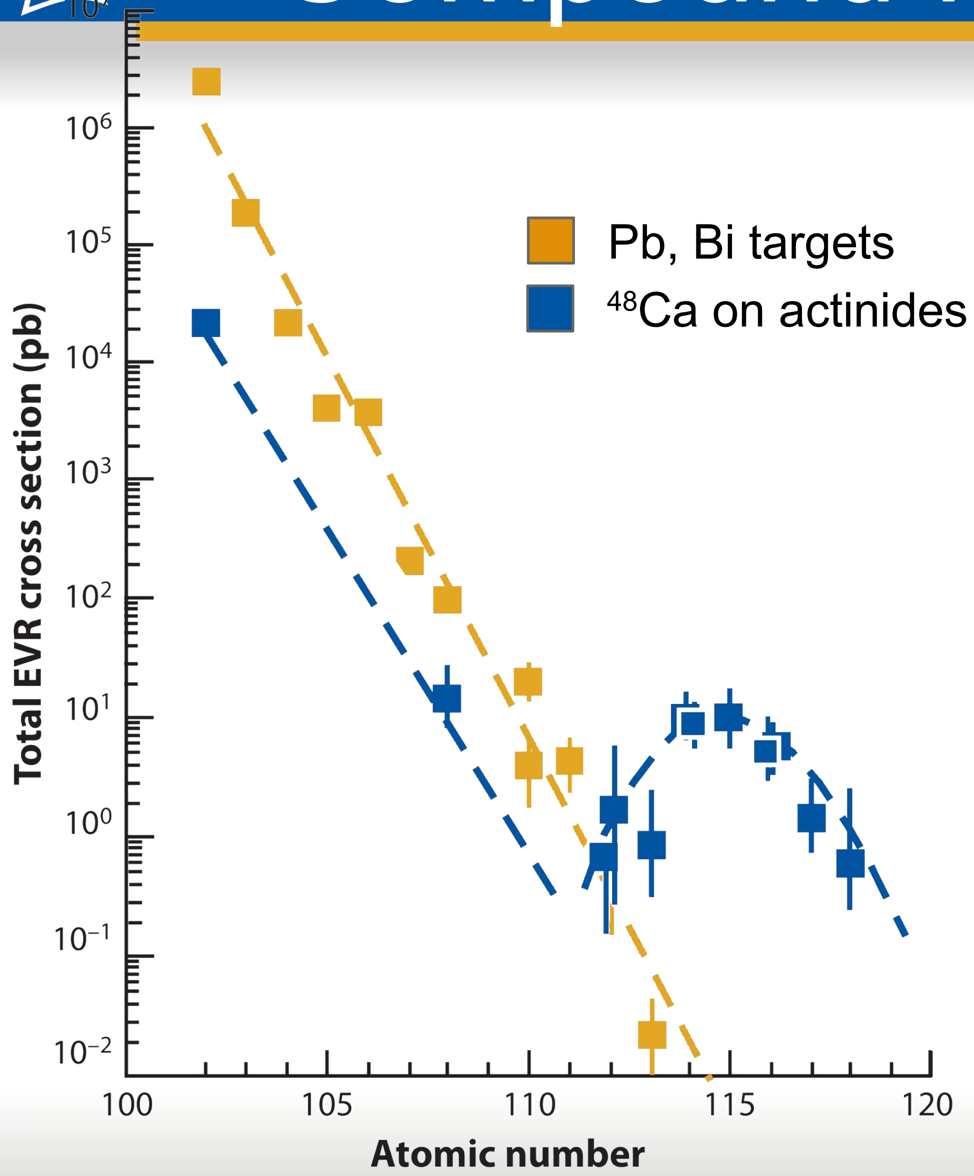
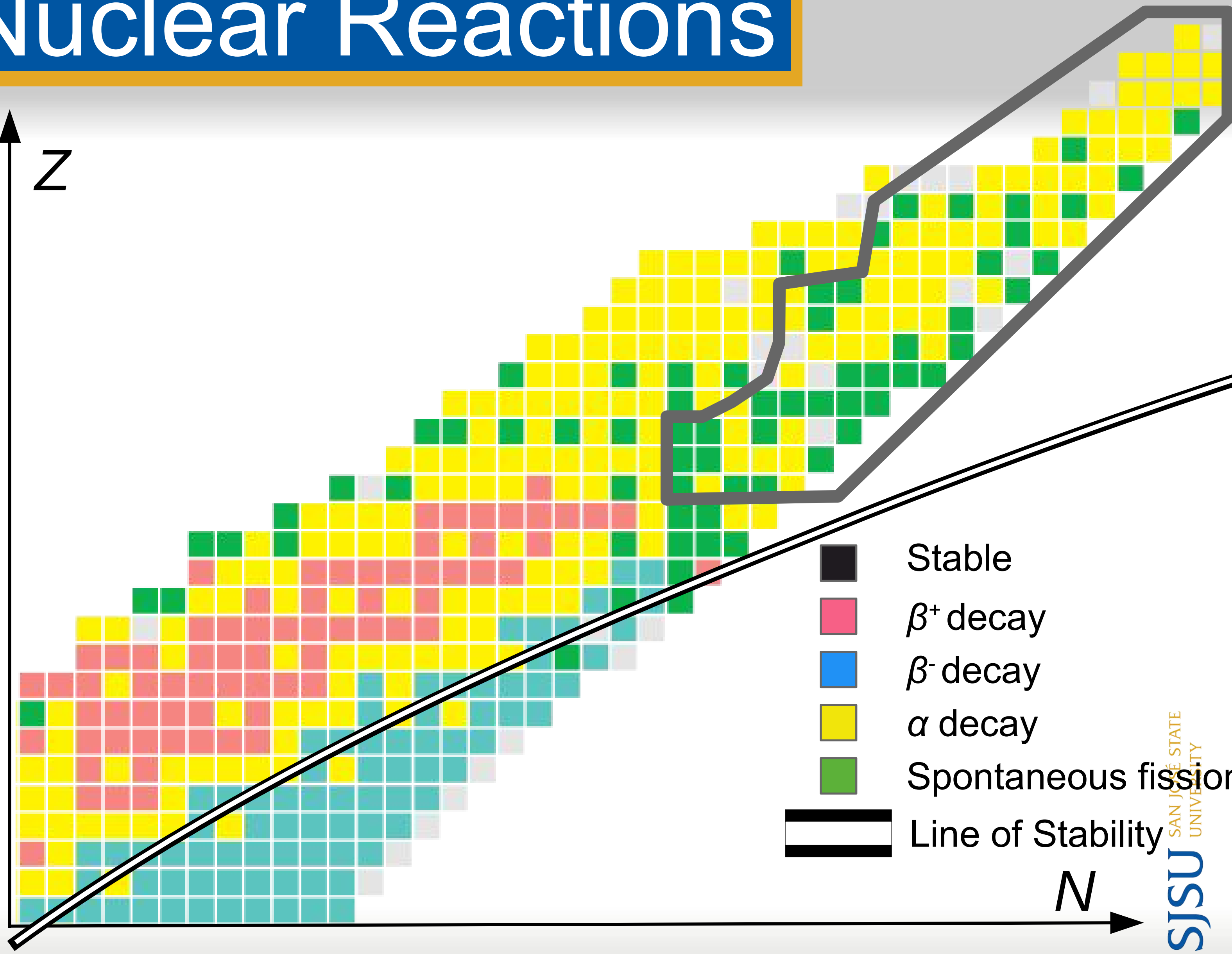
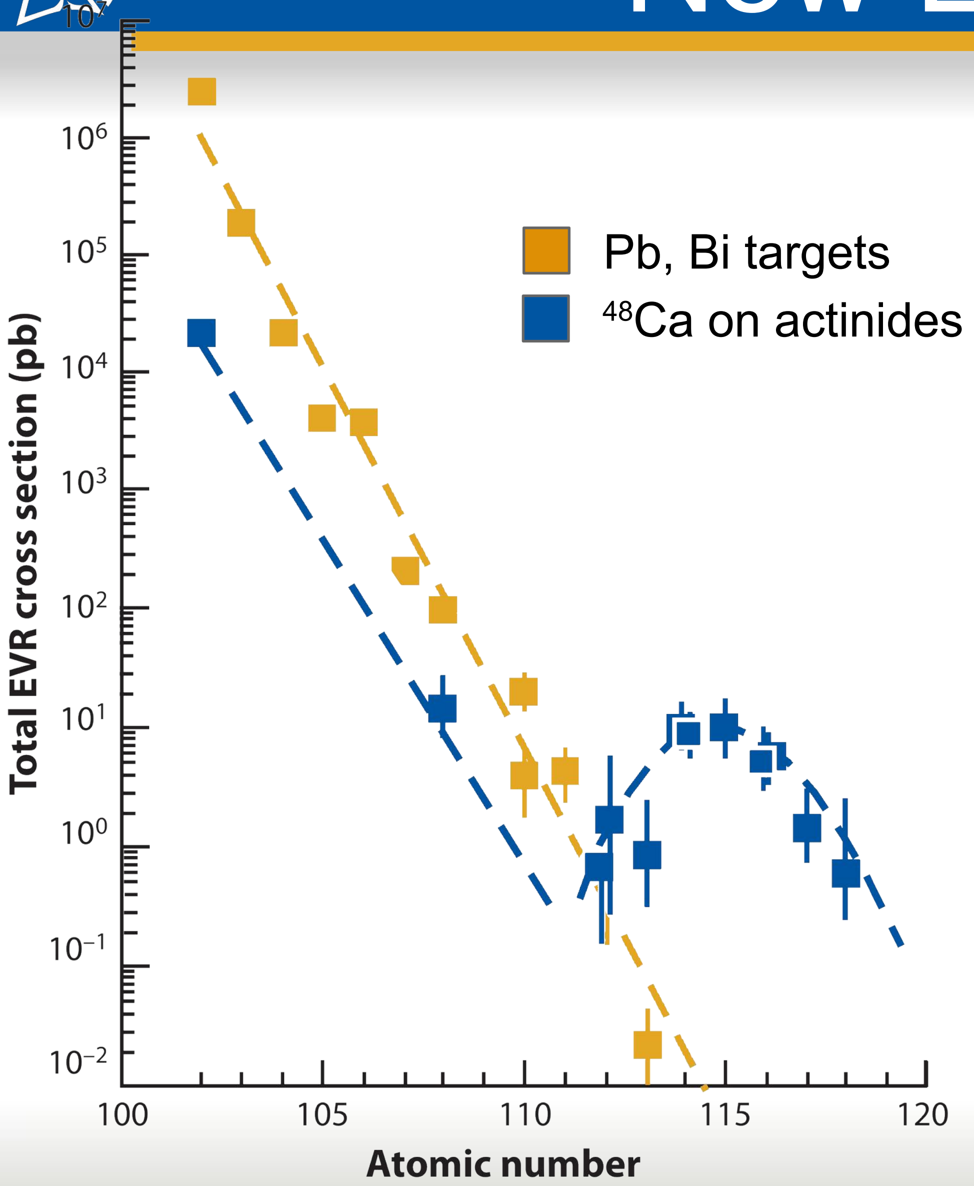
Compound Nuclear Reactions





New Element Synthesis



- Nuclei at the very bounds of stability
  - Low production cross sections
  - Short lived isotopes

102	103	104	105	109	115
^{254}No 55 s	^{255}Lr 22 s	^{257}Rf 4.7 s	^{258}Db 4 s	^{276}Mt 0.54 s	^{288}Mc 171 ms
1/s	10/min	1/min	1/hr	1/wk	1/day

- Og(Z=118) is heaviest synthesized element
  - ^{249}Cf (Z=98) + ^{48}Ca
  - Cannot get enough Es (Z = 99)

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Experimental Approach

- Low cross sections means high flux beams
  - Limited accelerator facilities focused on heaviest elements

- Dedicated recoil separators
  - Extremely low statistics, incredible background suppression needed

- Need right target, right beam & beam flux, and luck

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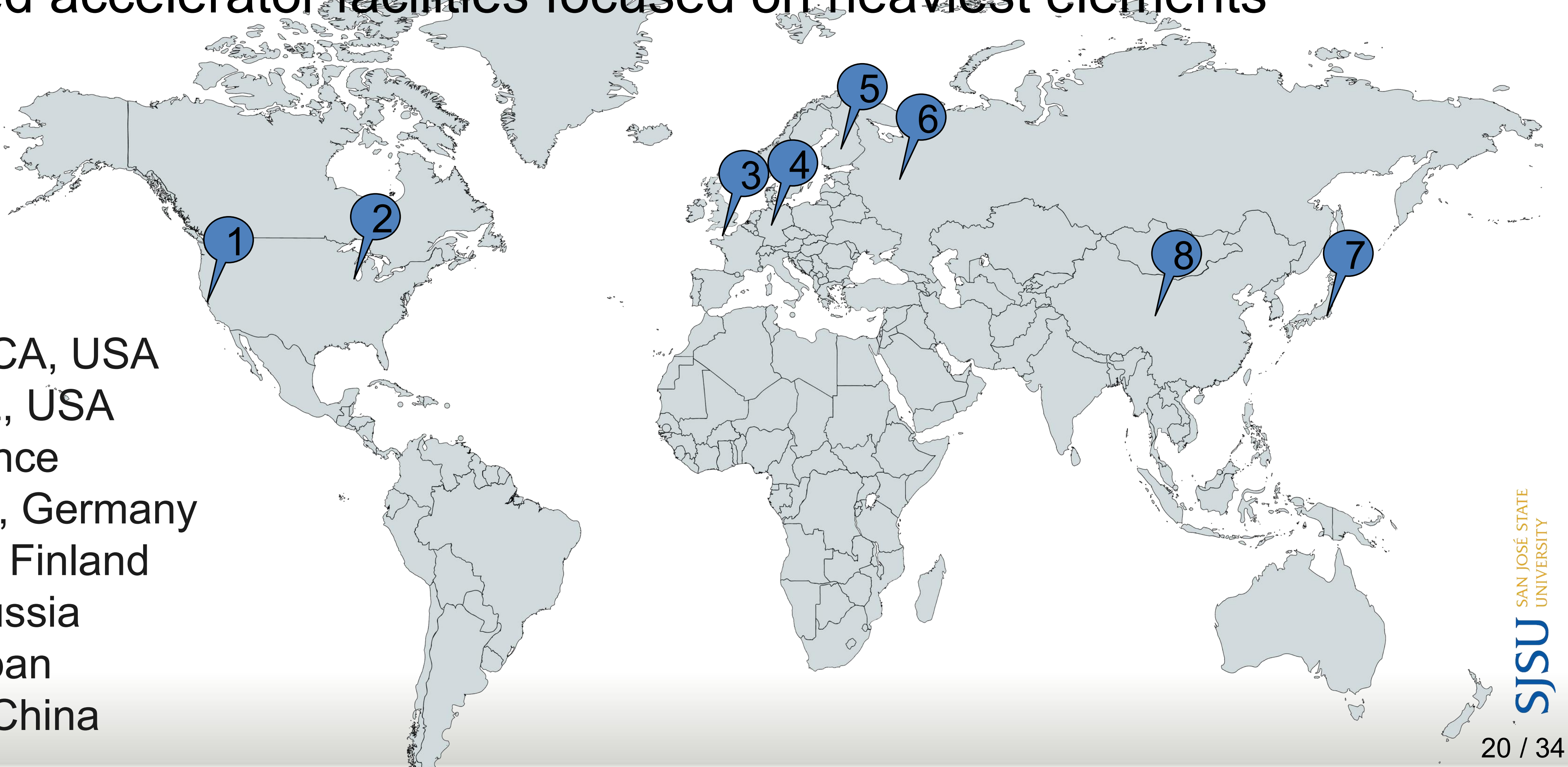
Experimental Approach

- Limited accelerator facilities focused on heaviest elements



1. Berkeley, CA, USA
2. Lemont, IL, USA
3. Caen, France
4. Darmstadt, Germany
5. Jyväskylä, Finland
6. Dubna, Russia
7. Tokyo, Japan
8. Lanzhou, China

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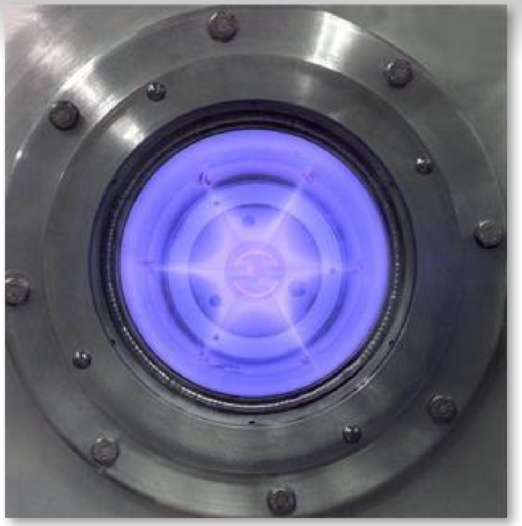
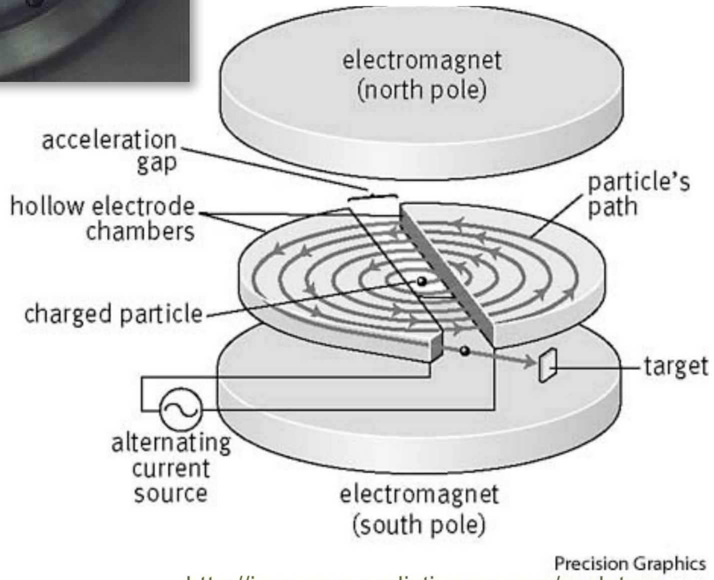
Ion sources & Accelerators

- Ion sources:

  Deliver highly charged plasmas to accelerators

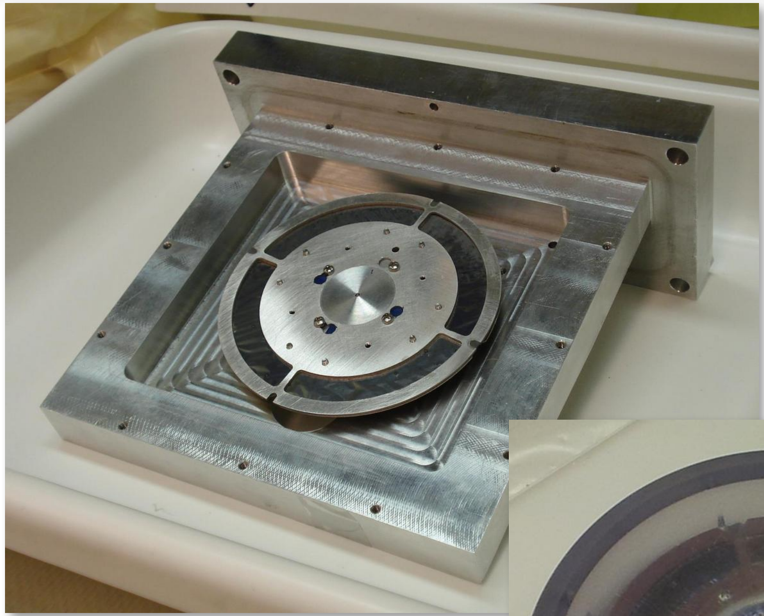


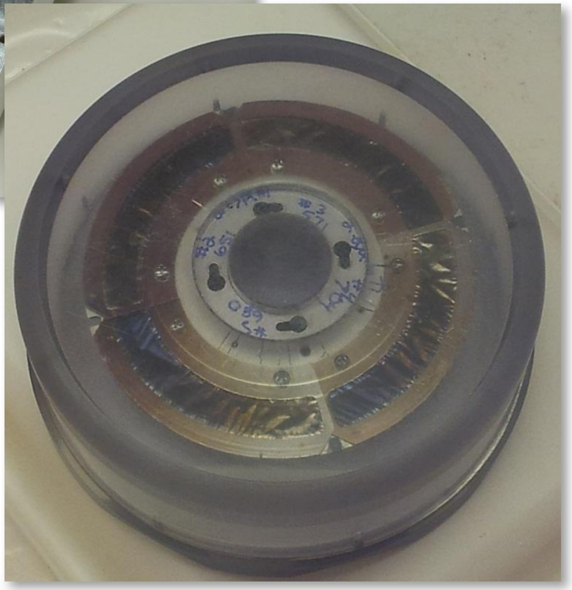


http://images.yourdictionary.com/cyclotron

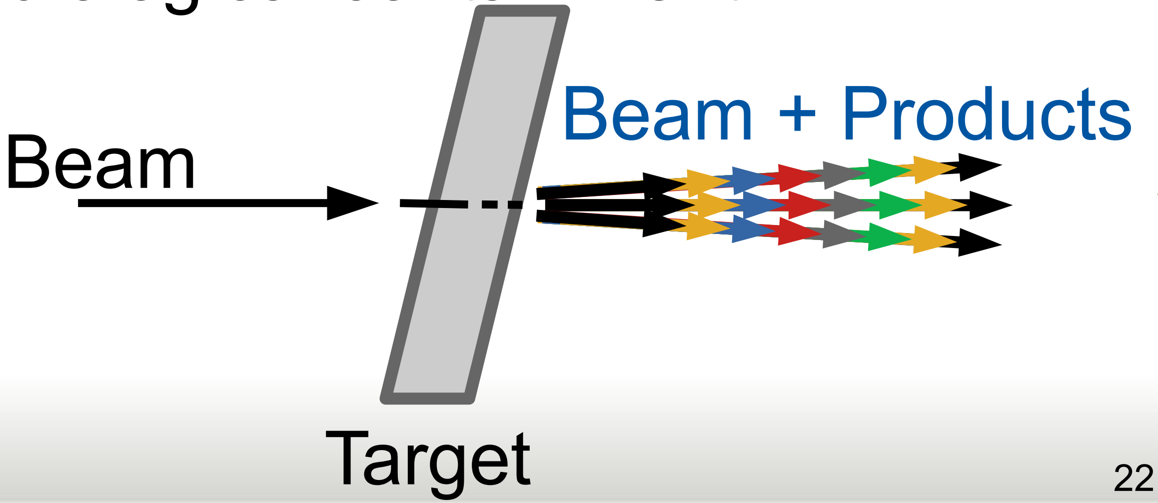
- Accelerators:
  - Transport ion beam to experimental facility
  - SHE prodution: linac, cyclotron

Targetry and Reaction Products





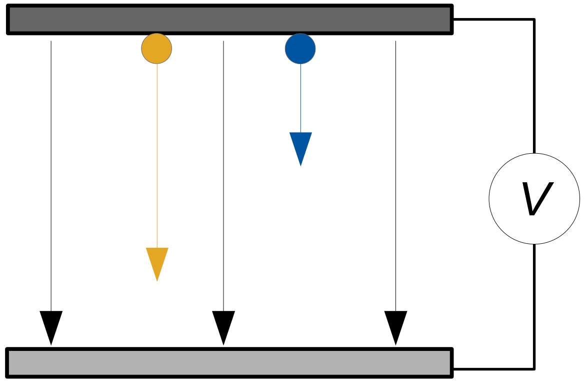
- Thickness ~500 μg/cm^2
  - Optimize energy loss
  - ~2000 nuclei for beam interactions
- High beam flux = rotating targets
  - Heat dissipation
- Actinide targets = additional radiological containment



Manipulating ions

- Electrostatics

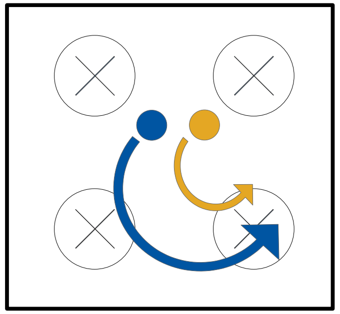
$$\vec{F}_{\vec{E}} = q \cdot \vec{\mathcal{E}}$$



$m_{●} = 2\, m_{●}$

- Magnetics

$$\vec{F}_{\vec{B}} = q\, \vec{v} \times \vec{\mathcal{B}}$$



● v_i = <very small>
q = +1

$\rho_{●} = \rho_{●}$

● v_i = <very small>
q = +1

$\rho_{●} = 2\, \rho_{●}$

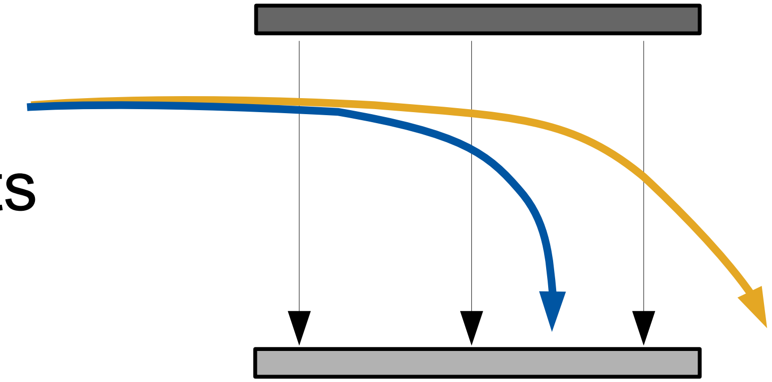
Recoil Separators

- In-flight separation of reaction products
- Purpose:
  - Product selection
  - Separates from beam, unwanted reaction products

- Electrostatic

$$\vec{F}_{\vec{E}} = q\vec{\mathcal{E}}$$

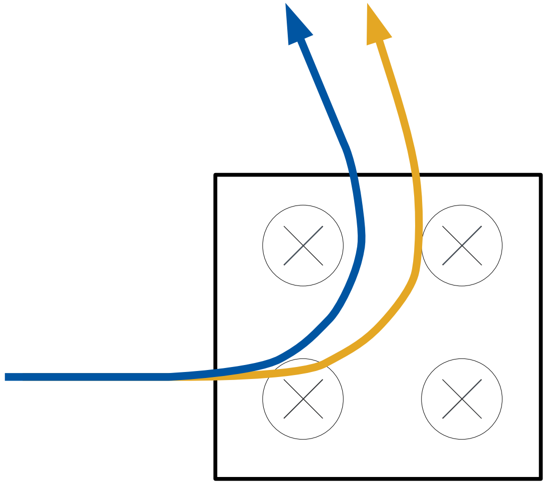
$$\mathcal{E}\rho = \frac{mv^2}{q} = \frac{2E}{q}$$



- Magnetic

$$\vec{F}_{\vec{B}} = q\vec{v}\times\vec{\mathcal{B}}$$

$$\mathcal{B}\rho = \frac{mv}{q} = \frac{p}{q}$$

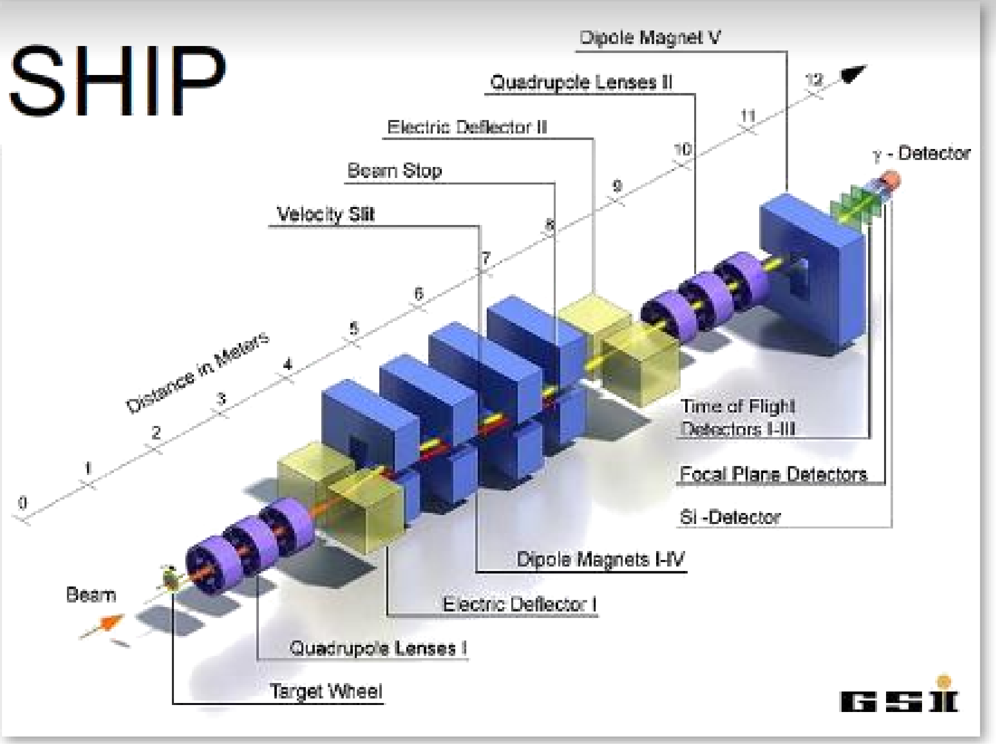


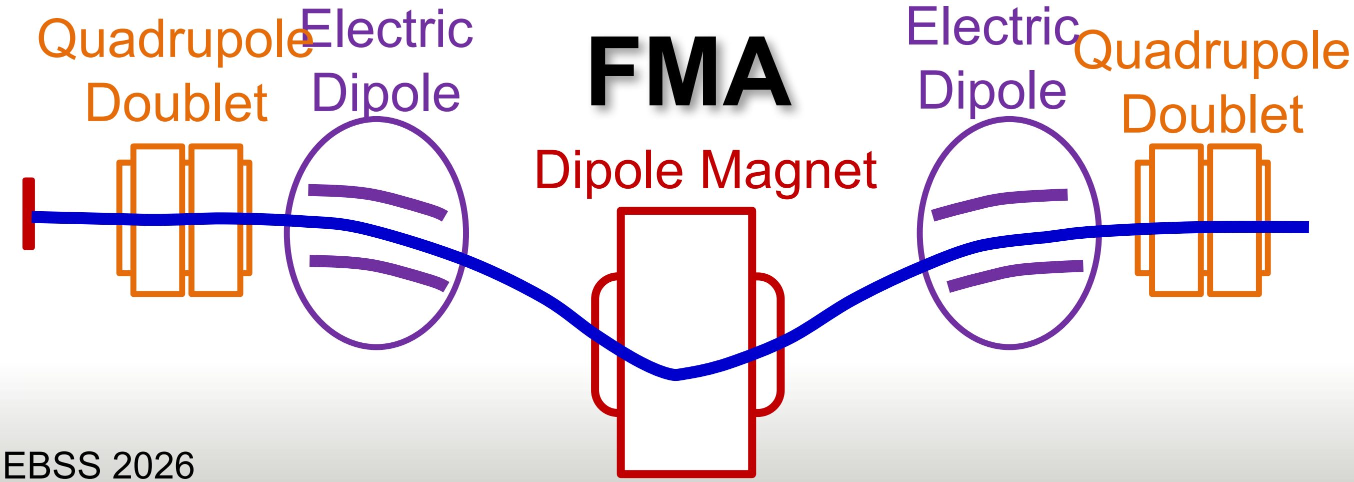
Vacuum Mode Separator

Standard Configuration:

- Quadrupole doublet (or triplet)
- Electric Dipole
- Magnetic Dipole
- Electric Dipole
- Quadrupole doublet (or triplet)

Examples: FMA, SHIP, SHELLS





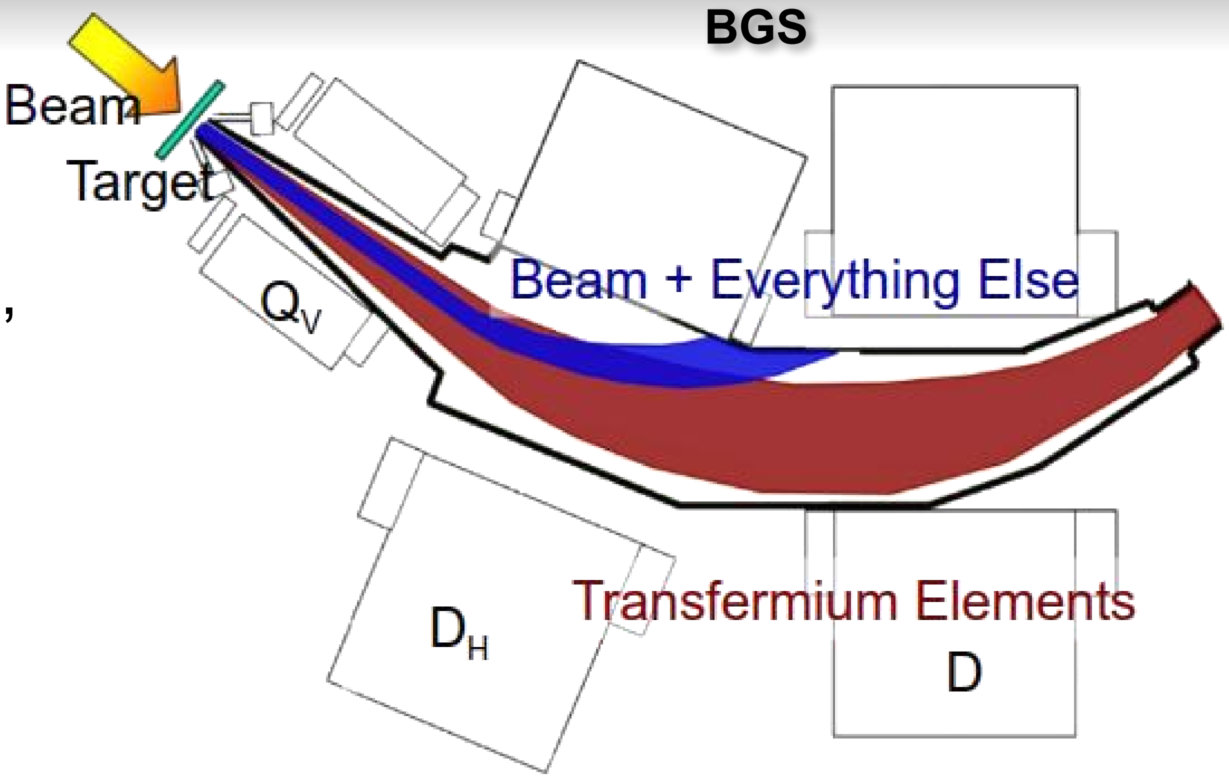
Velocity Filters:

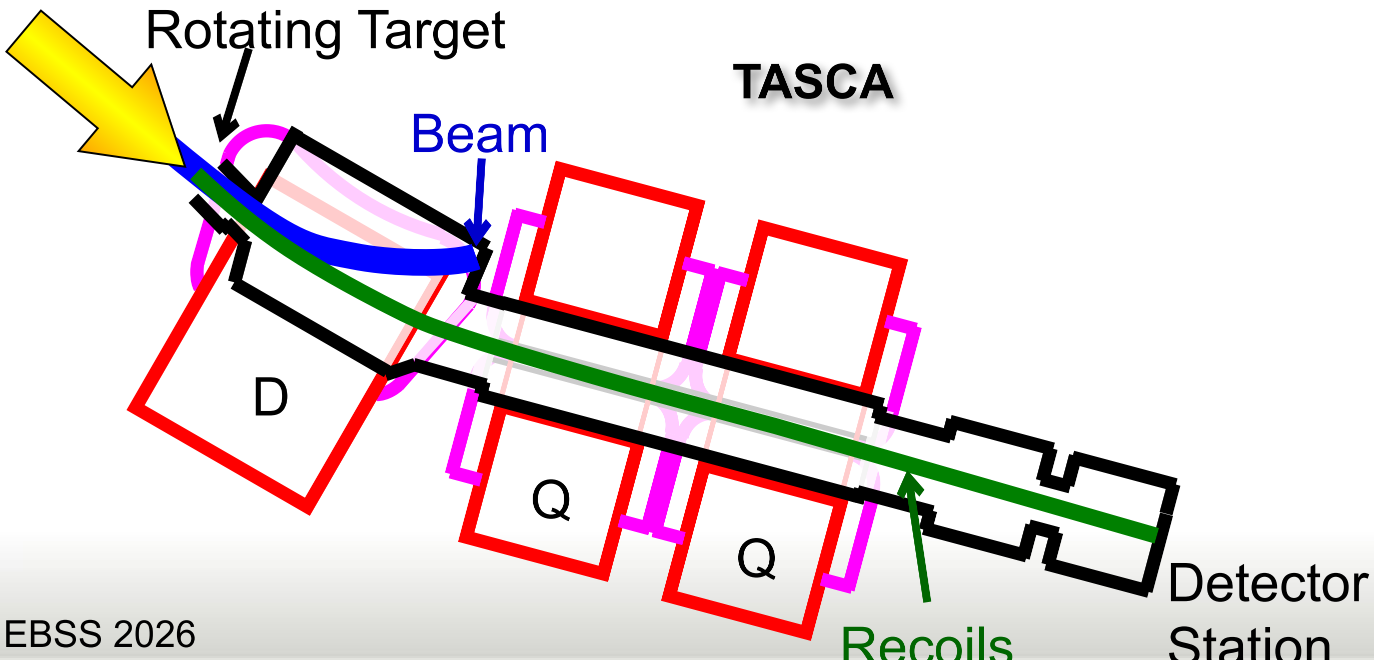
- Velocity of Beam and SHE are very different

Gas-filled Separators

Standard Configuration:
- Dipole
- Quadrupole doublet

Examples: DGFRS, GARIS(I-III), RITU, SASSY, TASCA

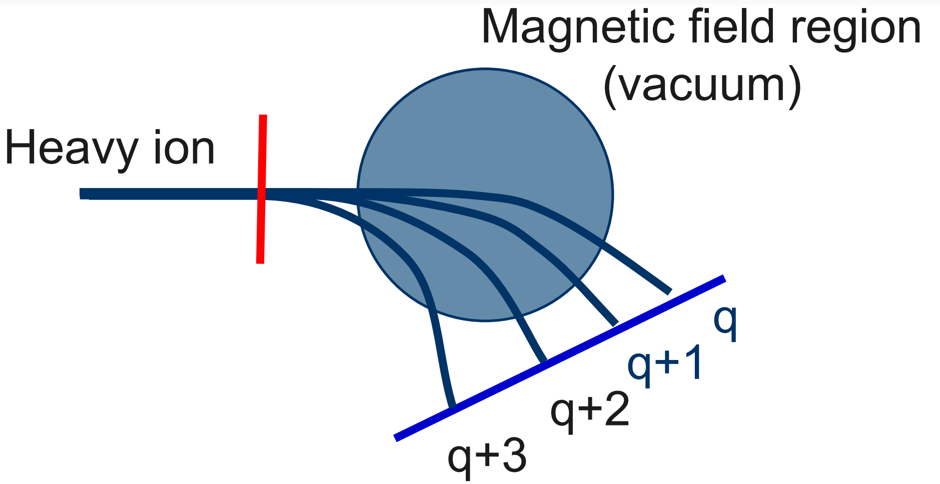


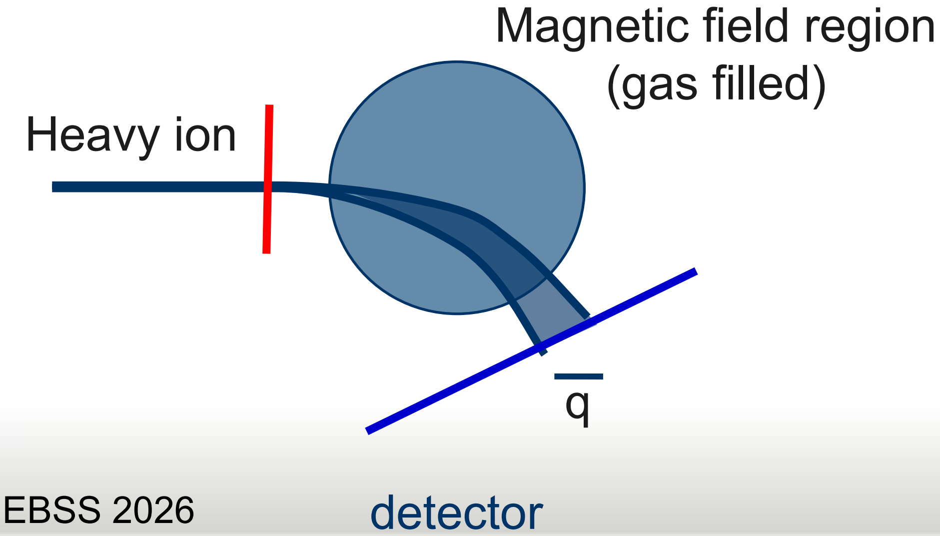


Other Configuration:
- Quadrupole
- Focusing dipole
- Dipole

Examples: BGS

Vacuum vs Gas-filled Separators





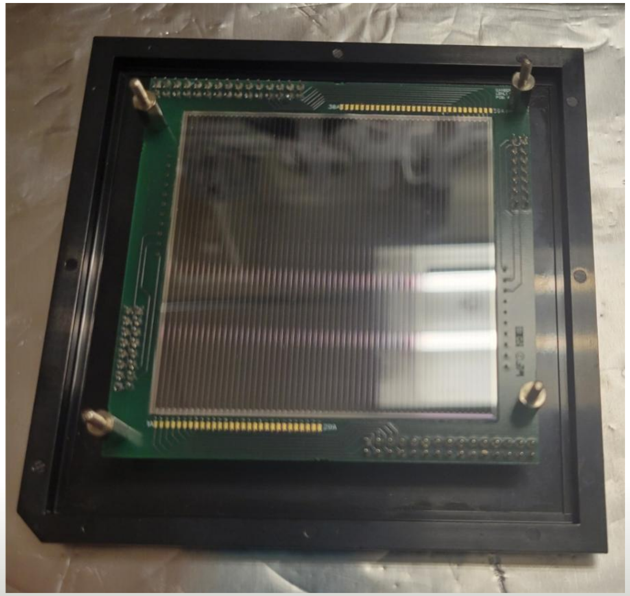
- Vacuum mode separators:
  - Higher mass resolution
- Gas-filled Separators:
  - Higher transmission efficiency

Vacuum vs Gas-filled Separators

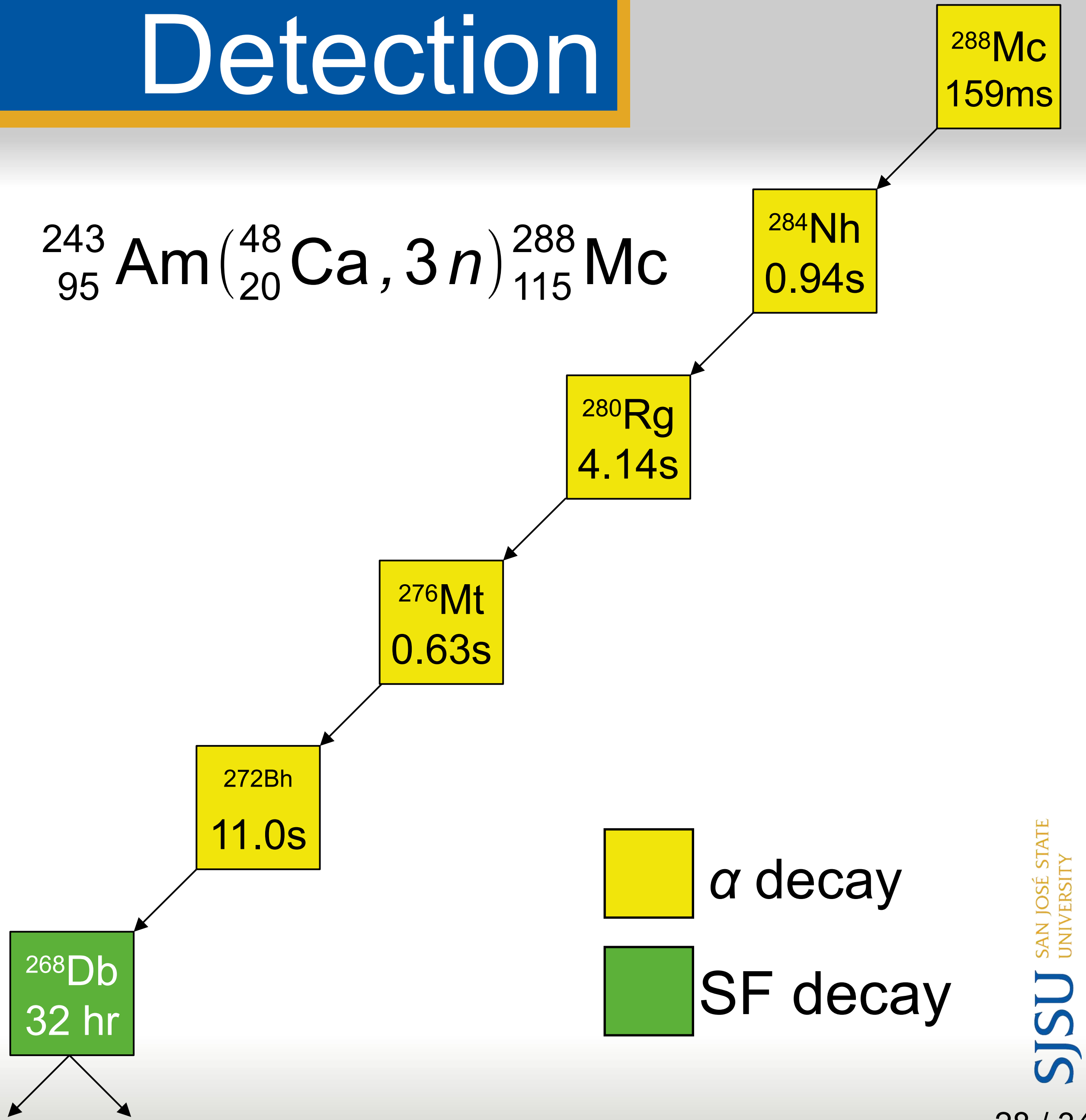
	Vacuum Separators	Gas-filled Separators
Examples	FMA, SHIP, VASSILISSA, etc	BGS, DGFRS, GARIS, RITU, TASCA, etc
Angular acceptance	Moderate (up to 16 msr)	Large (up to 45 msr)
Velocity acceptance	Moderate (up to ±25%)	Large (up to 100%)
Charge acceptance	Moderate (up to ±7%)	Large (up to 100%)
Efficiency: $^{48}Ca+^{208}Pb$	**Up to 30%**	**Up to 70%**
Mass resolution	Good (M/ΔM>200)	Poor (M/ΔM <30)

Detection

- Focal Plane Detection
  - Highly pixellated Si charged particle detectors
  - “Genetic Fingerprint” to distiguish from 1-2 kHz



$$^{243}_{95}\mathrm{Am}\left(^{48}_{20}\mathrm{Ca}, 3n\right)^{288}_{115}\mathrm{Mc}$$



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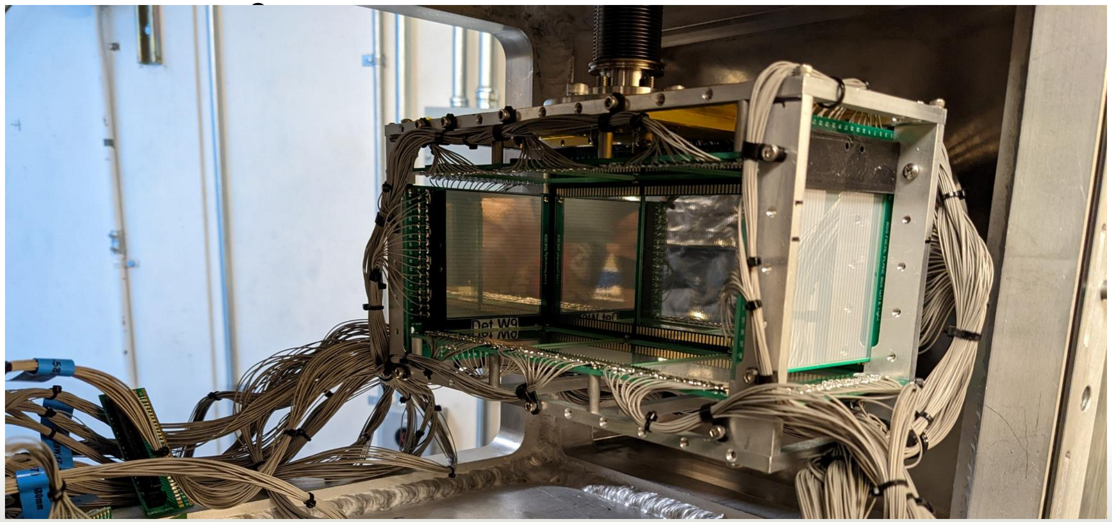

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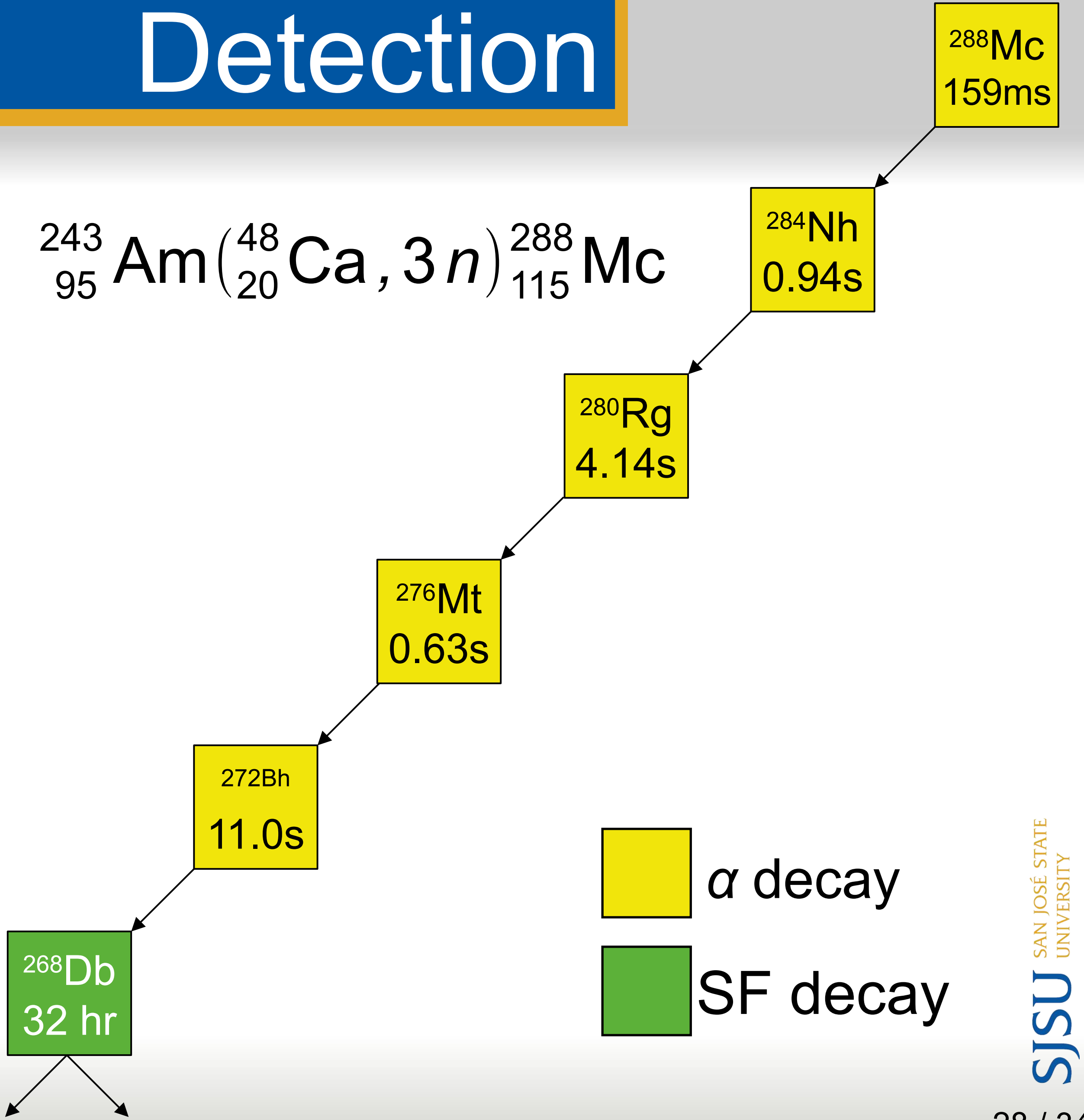
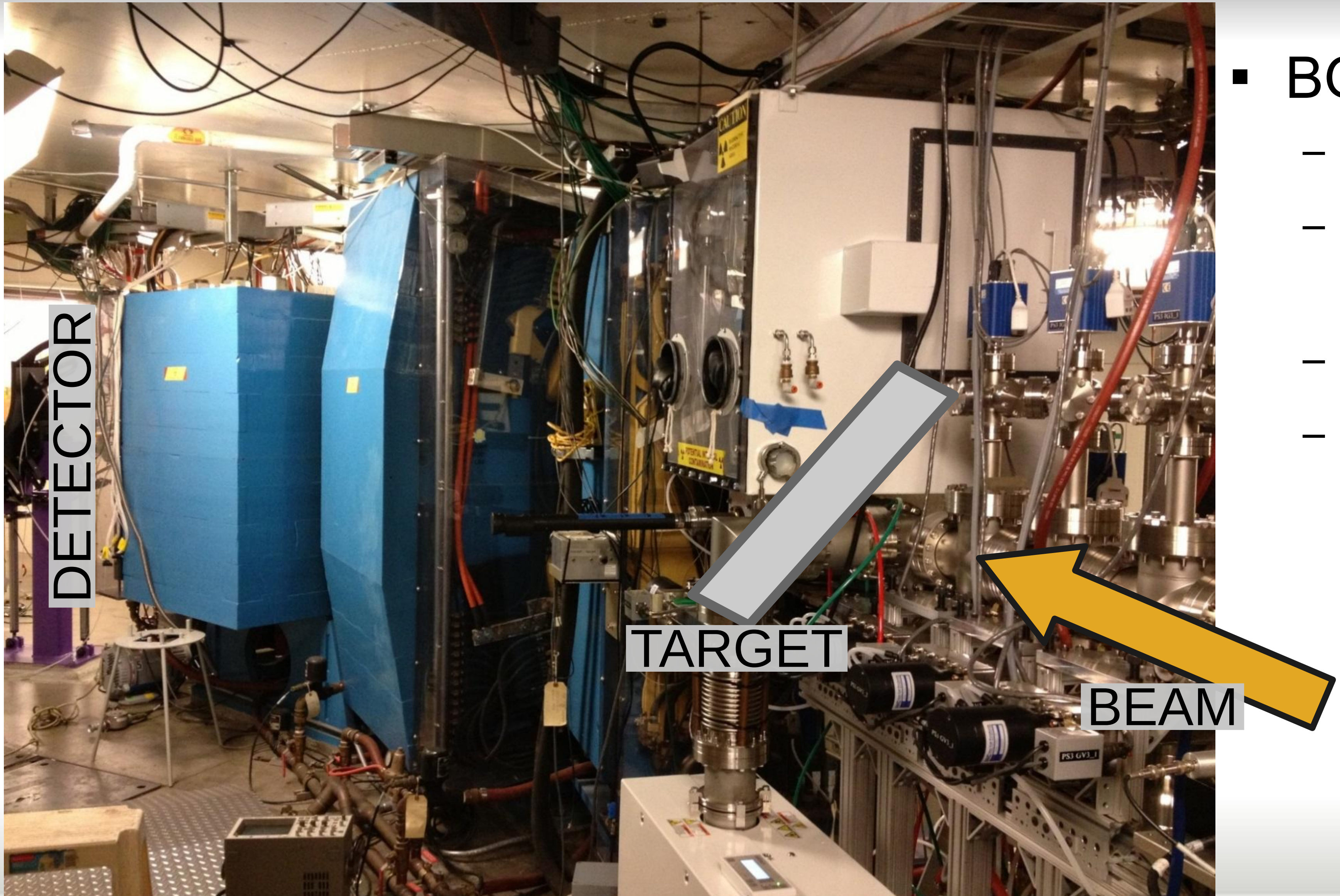


Current Efforts

- Production / Cross Section Measurements
- Chemistry of SHEs
  - Gas phase chemistry
  - Liquid phase chemistry
  - Thermal gradients
- Nuclear Structure
  - In-beam spectroscopy
  - Recoil – decay tagging on high spin isomers
- Mass Spectroscopy
  - High precision

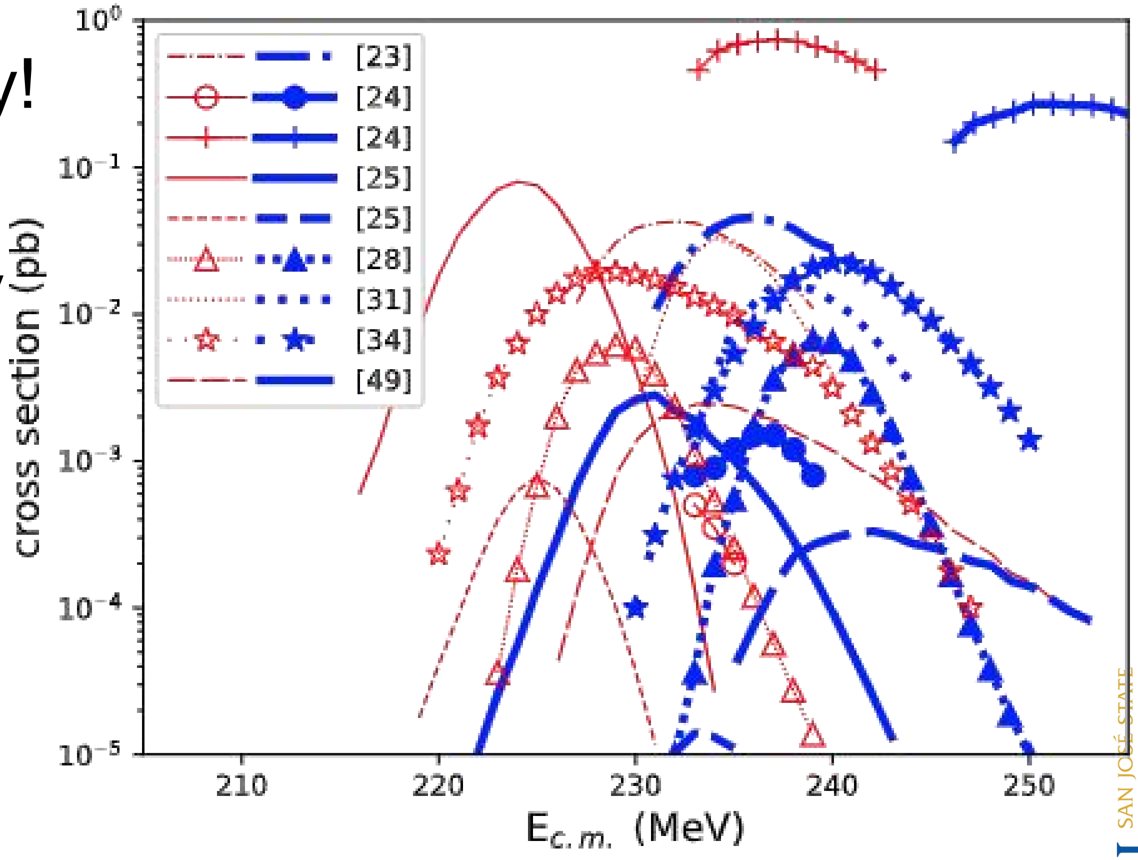
Berkeley Gas-filled Separator



- BGS
  - Differential pumping
  - Glovebox for radioactive targets
  - QDD arrangement
  - BGS Focal Plane Detection area

Going beyond ^{48}Ca

- Beam of ^{50}Ti is a promising next step
  - Been attempted before, need to verify!
- Experimental Plan: ^{244}Pu (^{50}Ti, 4n)^{290}Lv
  - ^{50}Ti: 6 x 10^{12} ions / sec
  - ^{244}Pu: ≈ 430 μg/cm^2



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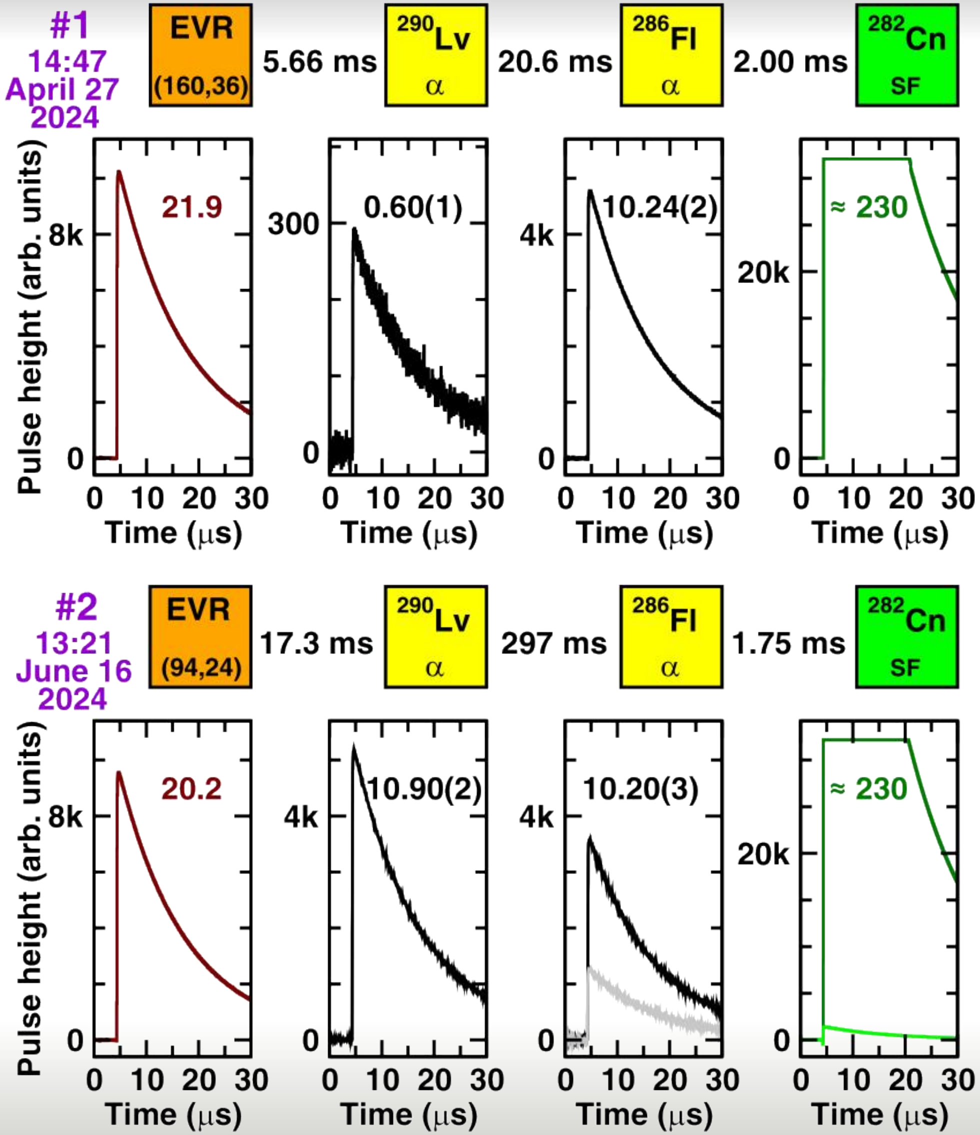
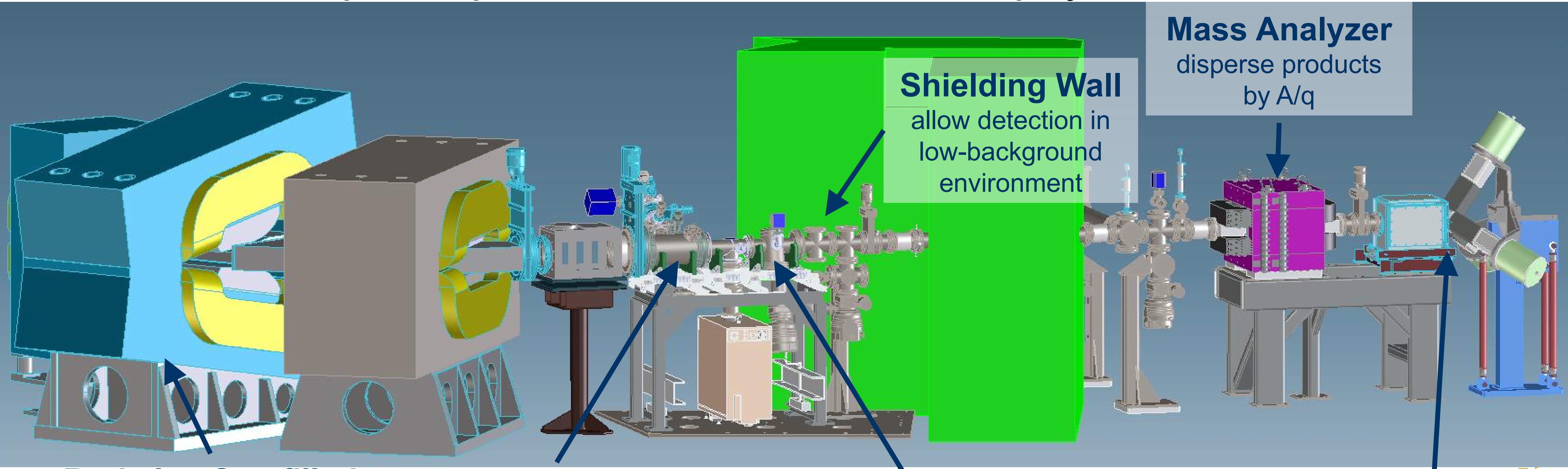
- Experimental Plan: ^{244}Pu (^{50}Ti, 4n)^{290}Lv
  - ^{50}Ti: 6 x 10^{12} ions / sec
  - ^{244}Pu: ≈ 430 μg/cm^2
- Results:
  - 22.1 days for 2 events!
  - E120 might be possible?!



BGS + FIONA

- BGS as a pre-separator for a whole host of physical measurments!



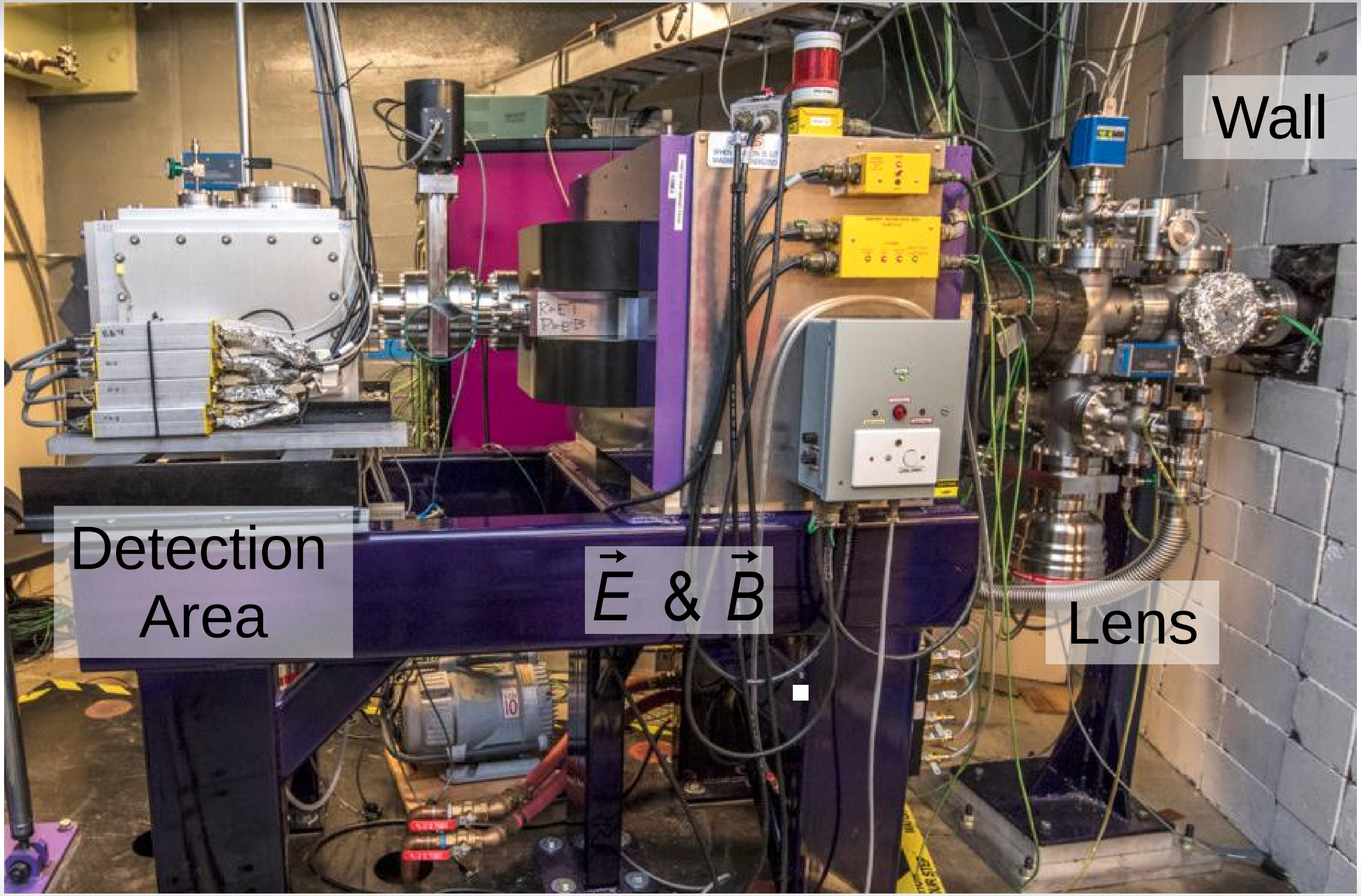
Berkeley Gas-filled Separator
Produce` and separate heavy element isotopes

RF Gas Catcher
Collect ions in He gas

RF Quadrupole Trap
bunch and cool ions, re-accelerate and transfer to mass analyzer

Detector Station
^{A}Z from α-decay
mass from x-position
lifetime from y-position

BGS + FIONA

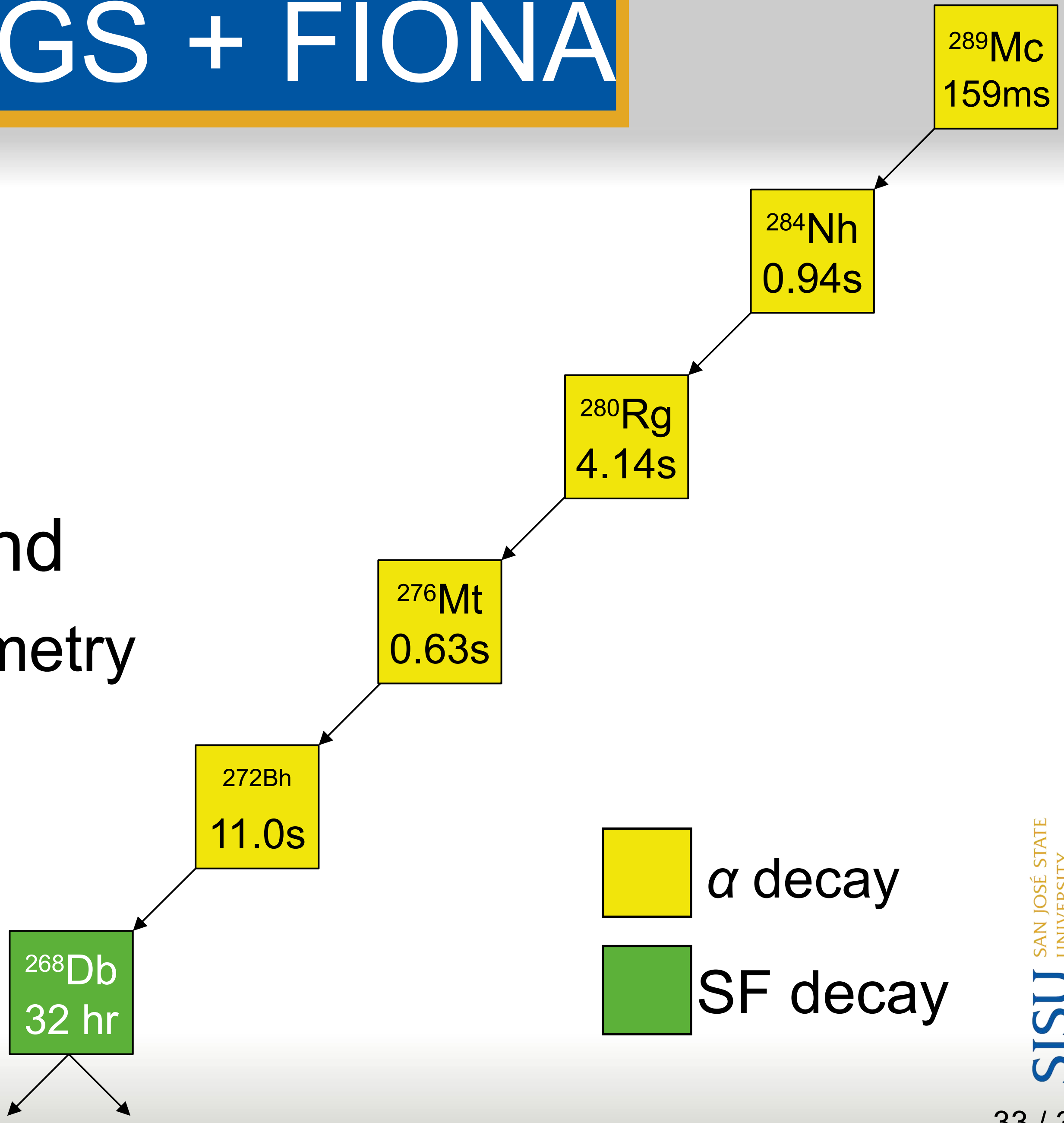


Experimental Setup:

- BGS:
  - 70% transmission
  - $\leq$ 1 μs transport time
- Thermalization:
  - 30% transmission
  - ~30 ms transport time
- FIONA
  - 90% transmission
  - 1 μs transport time

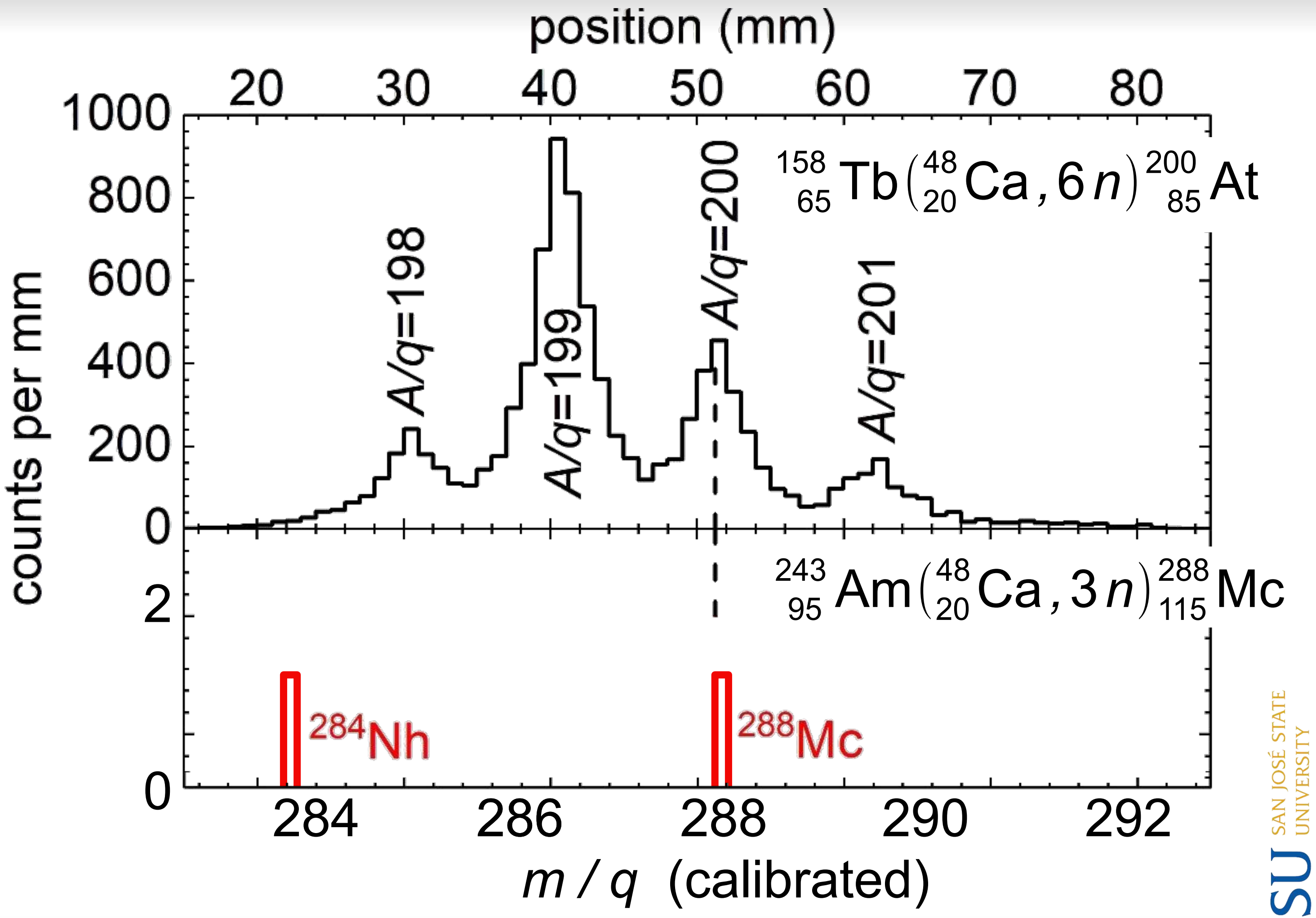
BGS + FIONA

- Headline experiment:
  - $^{243}_{95}\mathrm{Am}(^{48}_{20}\mathrm{Ca},3n)^{288}_{115}\mathrm{Mc}$
  - Detection via decay chain
- Huge reduction in background
  - Atom at a time mass spectrometry
  - Nuclear structure studies
  - Gamma, *X* ray spectroscopy
  - Fission studies



BGS + FIONA

- First direction mass determination of a superheavy element!
- Implications:
  - Mass model confirmed
  - Anchor 50+ isotopes



In Conclusion

- Why study the superheavies?
- How are they produced and studied?
  - Recoil Separators and production studies
- Heavy element science at 88” cyclotron
  - Verified synthesis of ^{290}Lv (Z=116) using ^{50}Ti
  - Mass Identification of SHEs with FIONA

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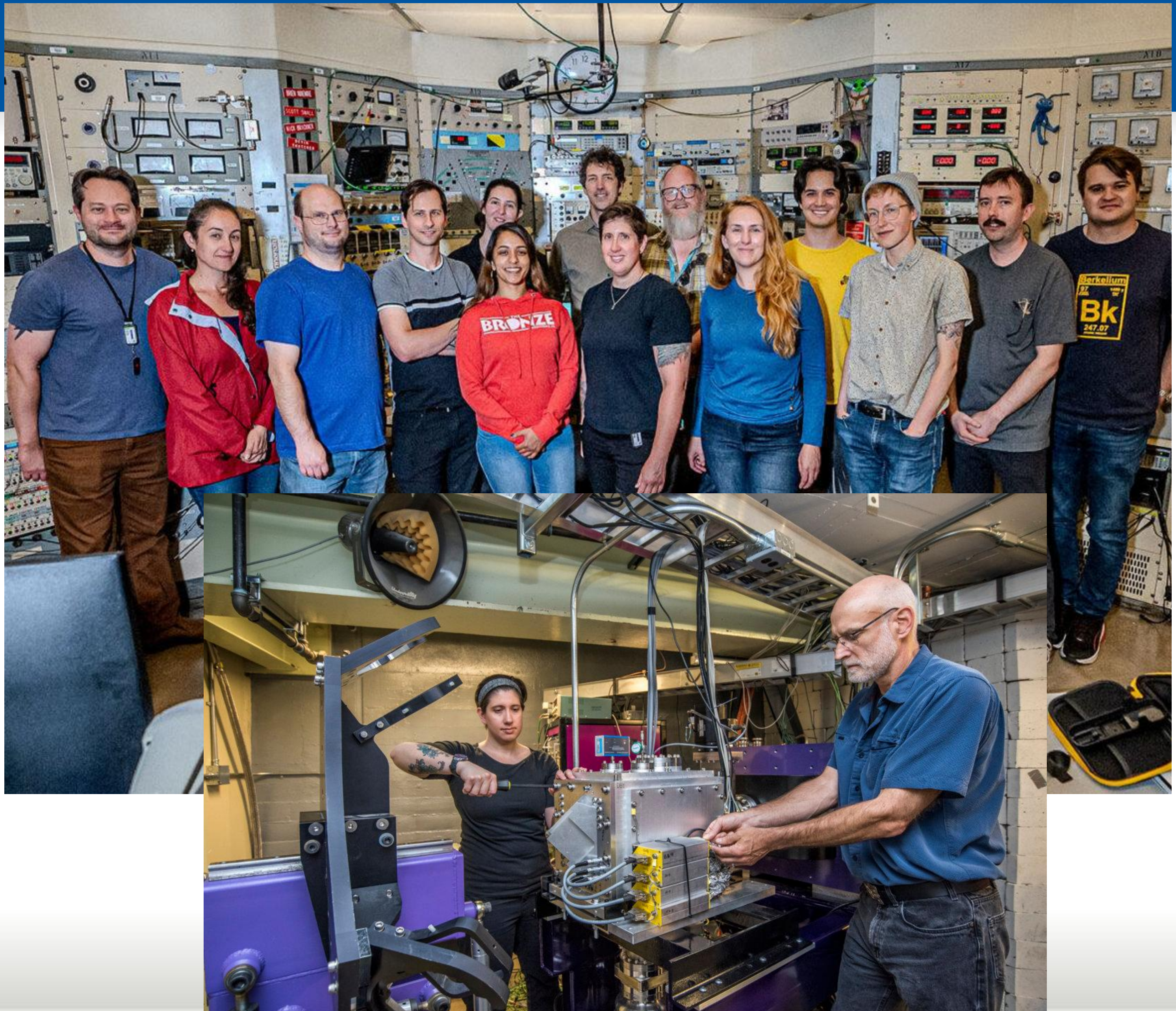

Thank you!

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