EXPERIMENTS WITH RADIOACTIVE BEAMS

D. Bazin
National Superconducting Cyclotron Laboratory
Michigan State University

Menu

Production methods

Types of experiments

Reaction experiments

Issues and solutions

Looking towards the future

Production methods

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  - Fragment stable target nuclei with high intensity light beam (usually protons)
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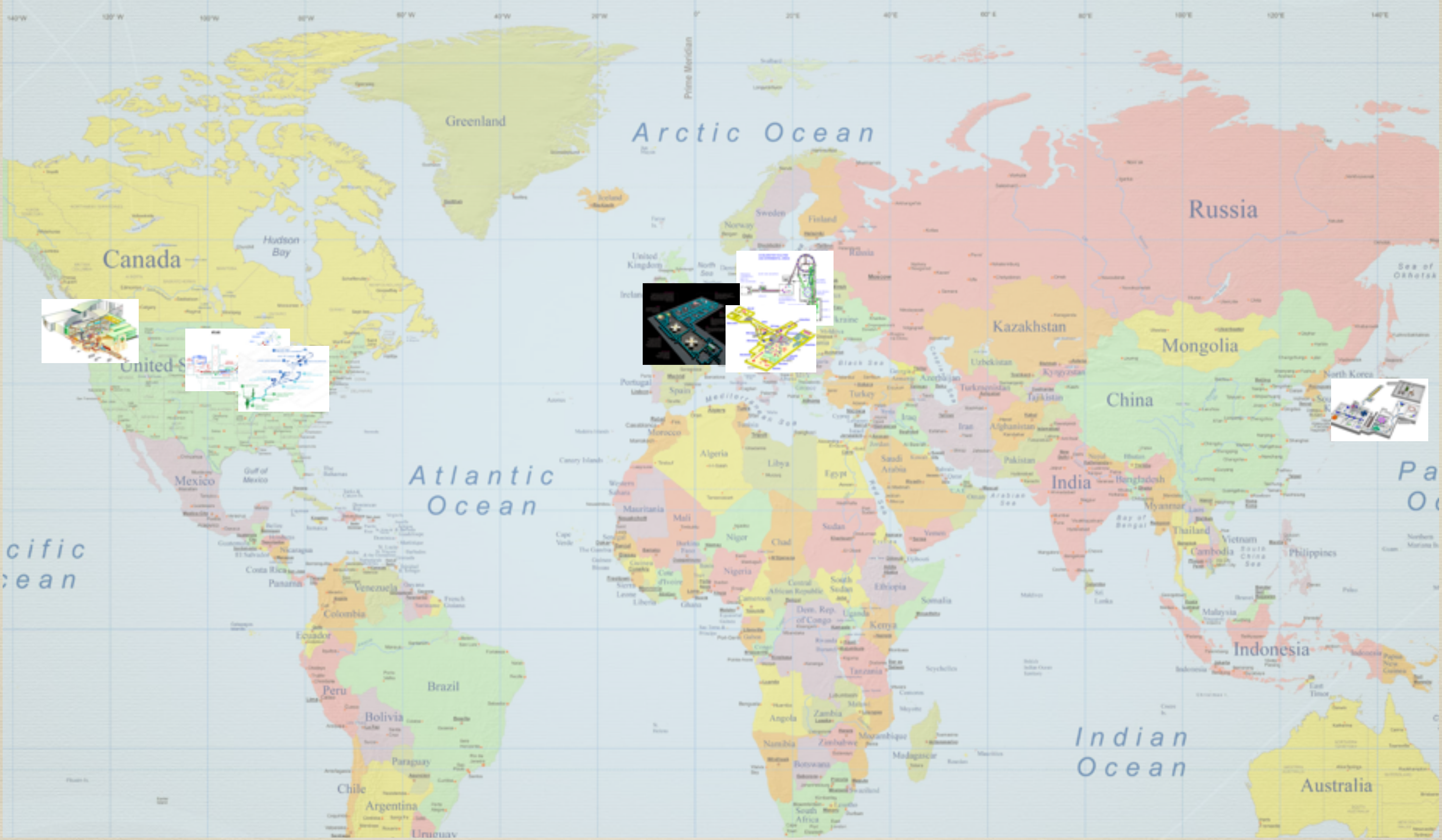
- Other methods
  - Transfer reactions, fission source, etc…

Main facilities in the world



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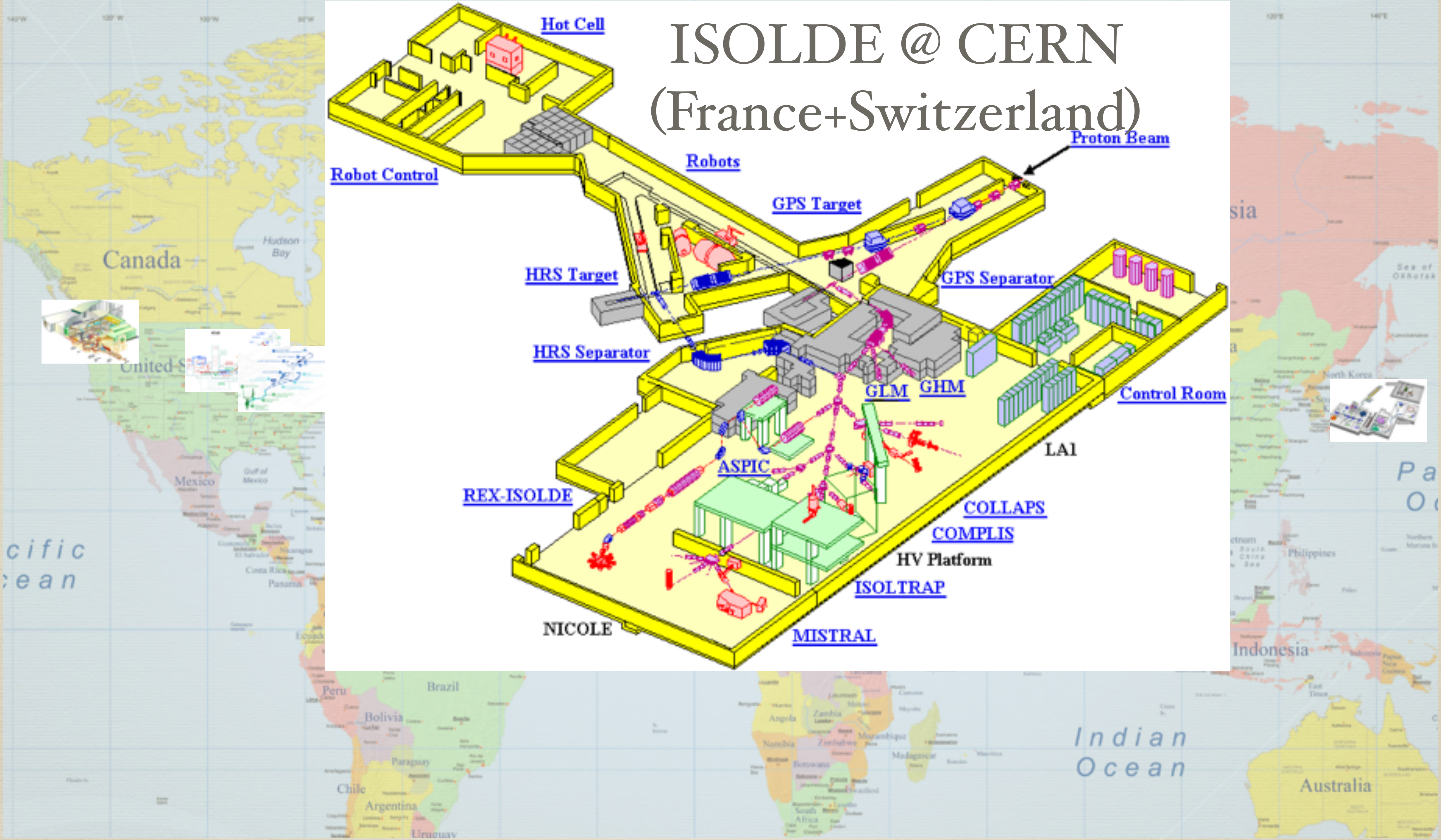

ISOLDE @ CERN (France+Switzerland)

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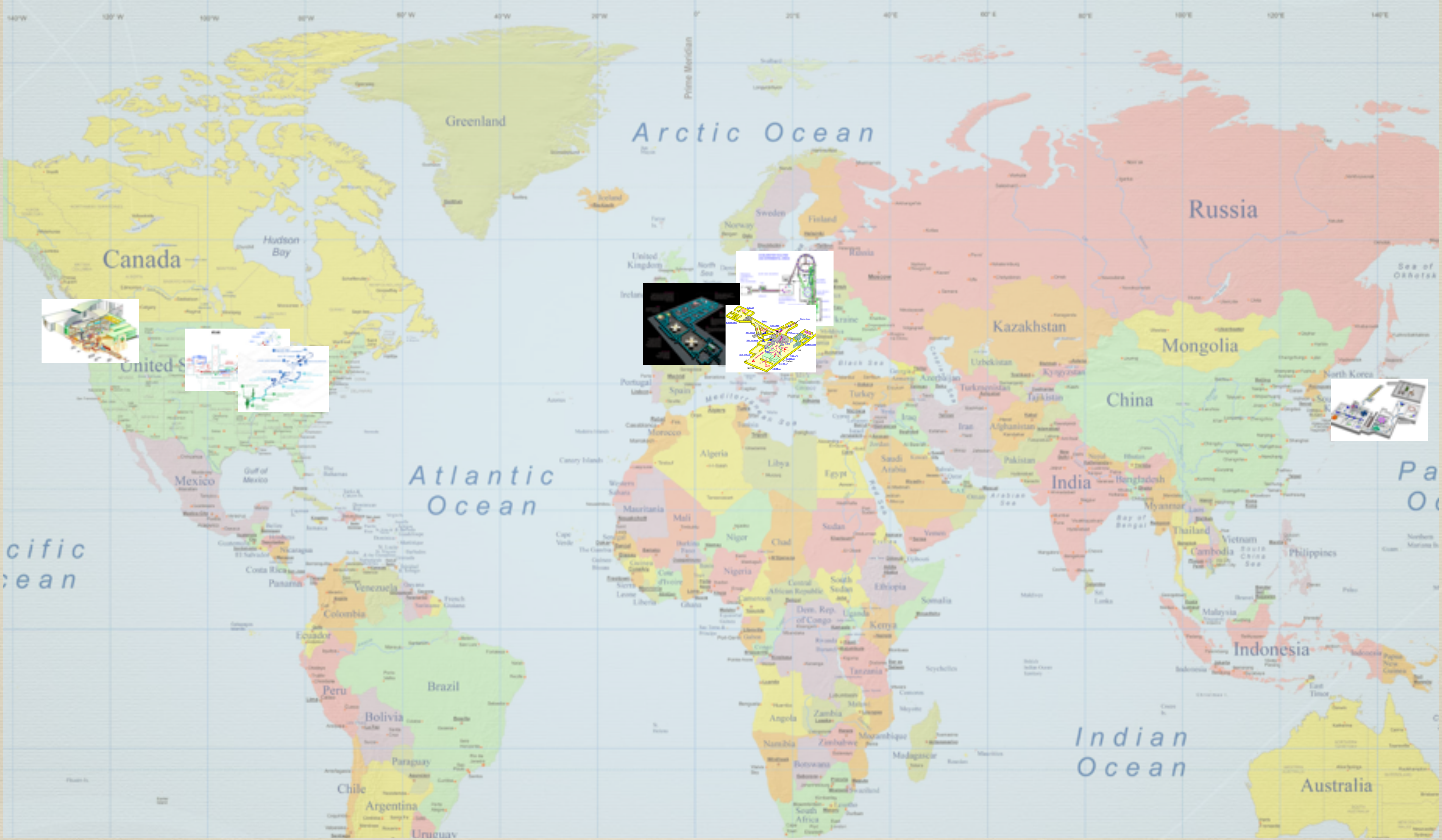

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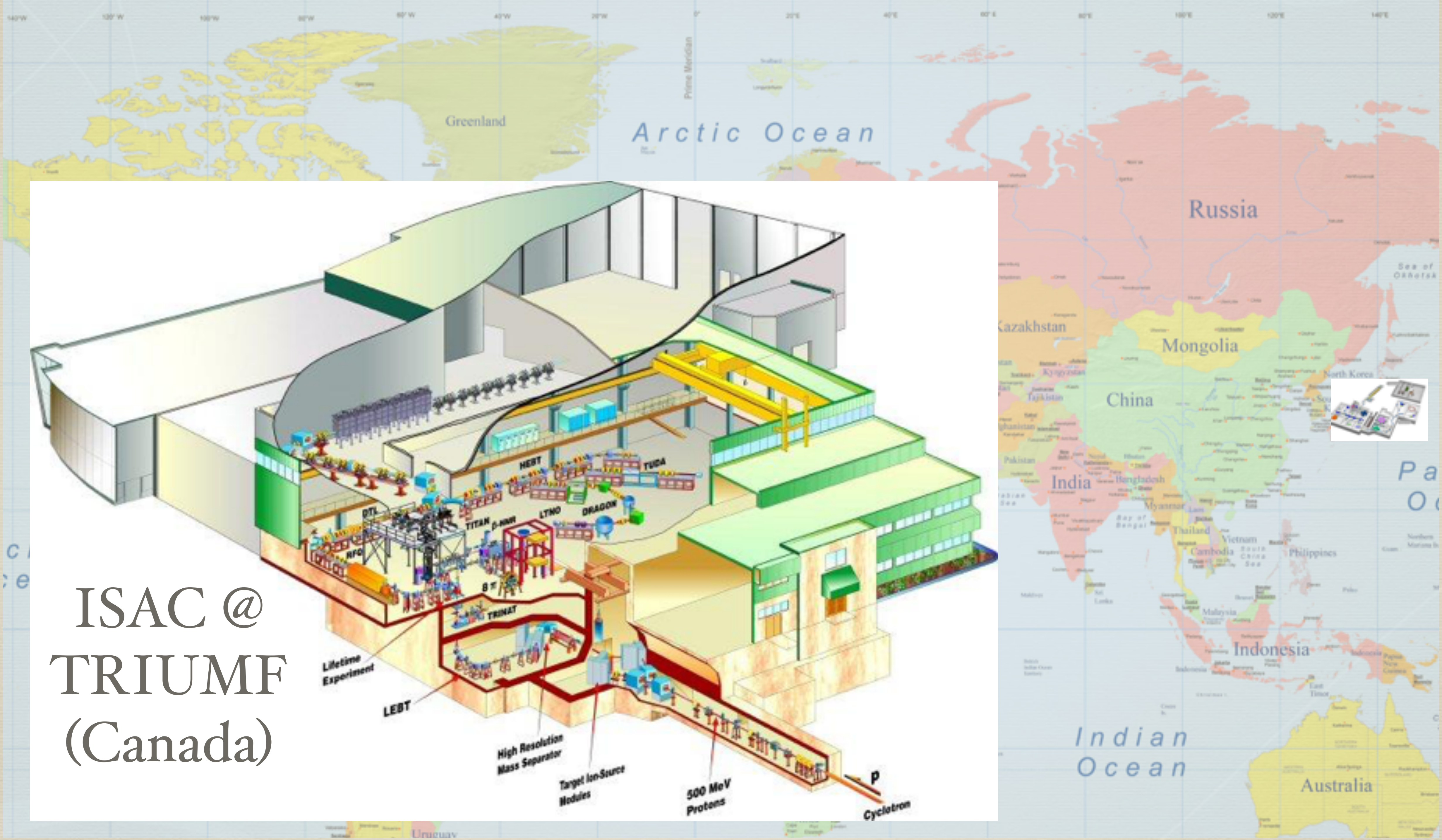

ISAC @ TRIUMF (Canada)

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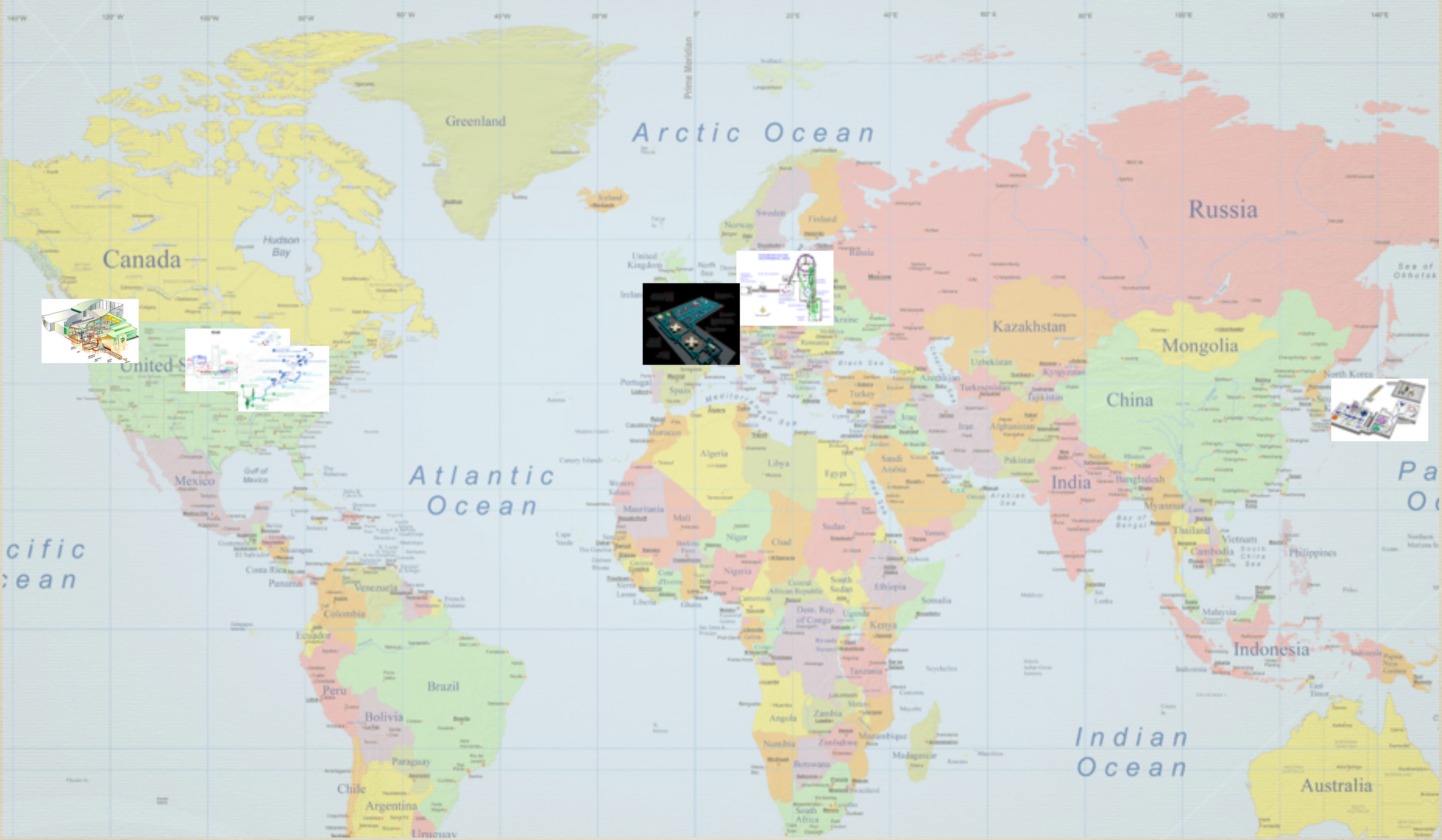

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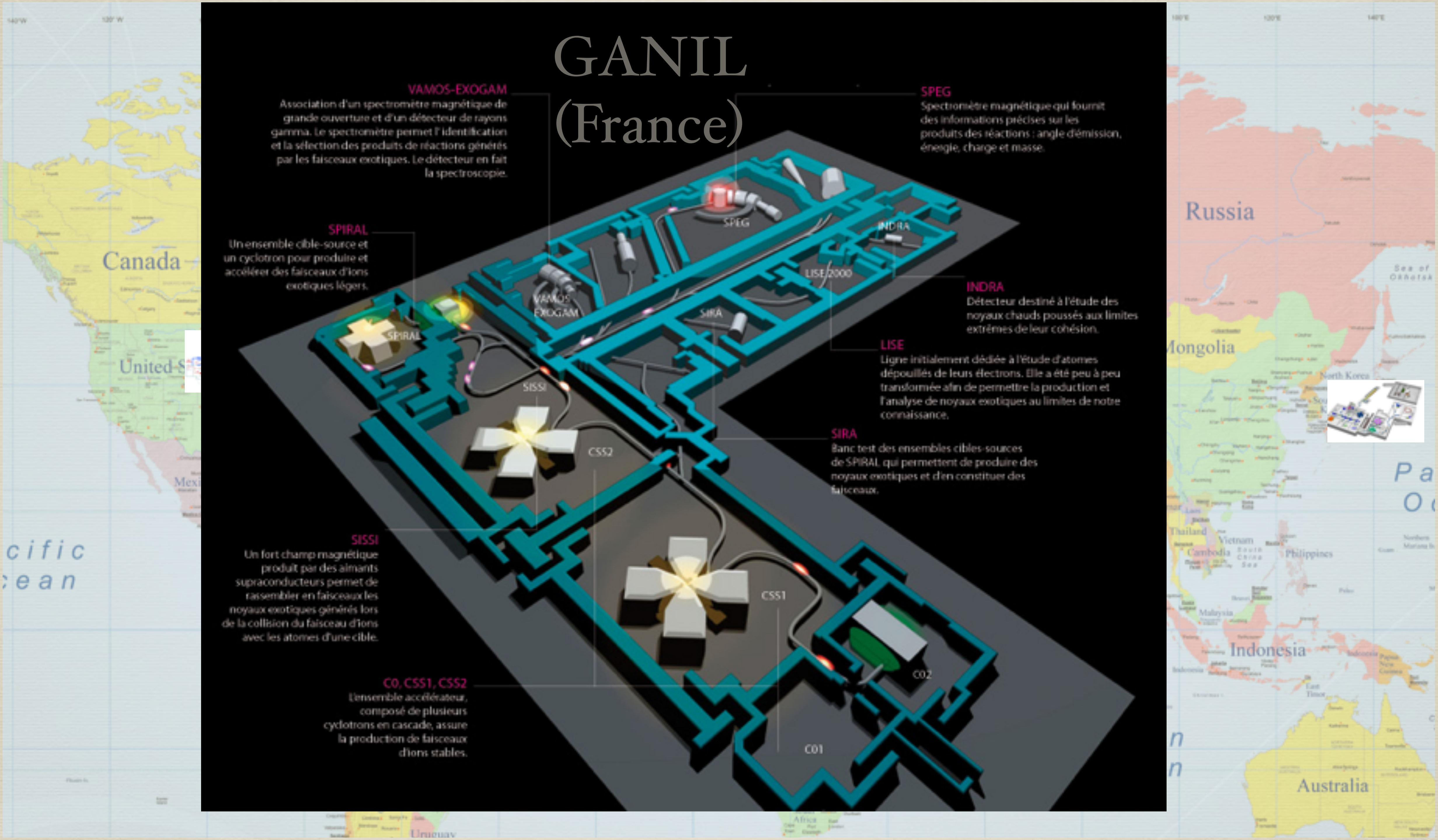

GANIL
(France)

VAMOS-EXOGAM
Association d'un spectromètre magnétique de grande ouverture et d'un détecteur de rayons gamma. Le spectromètre permet l' identification et la sélection des produits de réactions générés par les faisceaux exotiques. Le détecteur en fait la spectroscopie.

SPIRAL
Un ensemble cible-source et un cyclotron pour produire et accélérer des faisceaux d'ions exotiques légers.

SPEG
Spectromètre magnétique qui fournit des informations précises sur les produits des réactions : angle d'émission, énergie, charge et masse.

INDRA
Détecteur destiné à l'étude des noyaux chauds poussés aux limites extrêmes de leur cohésion.

LISE
Ligne initialement dédiée à l'étude d'atomes dépouillés de leurs électrons. Elle a été peu à peu transformée afin de permettre la production et l'analyse de noyaux exotiques au limites de notre connaissance.

SIRA
Banc test des ensembles cibles-sources de SPIRAL qui permettent de produire des noyaux exotiques et d'en constituer des faisceaux.

SISSI
Un fort champ magnétique produit par des aimants supraconducteurs permet de rassembler en faisceaux les noyaux exotiques générés lors de la collision du faisceau d'ions avec les atomes d'une cible.

C0, CSS1, CSS2
L'ensemble accélérateur, composé de plusieurs cyclotrons en cascade, assure la production de faisceaux d'ions stables.

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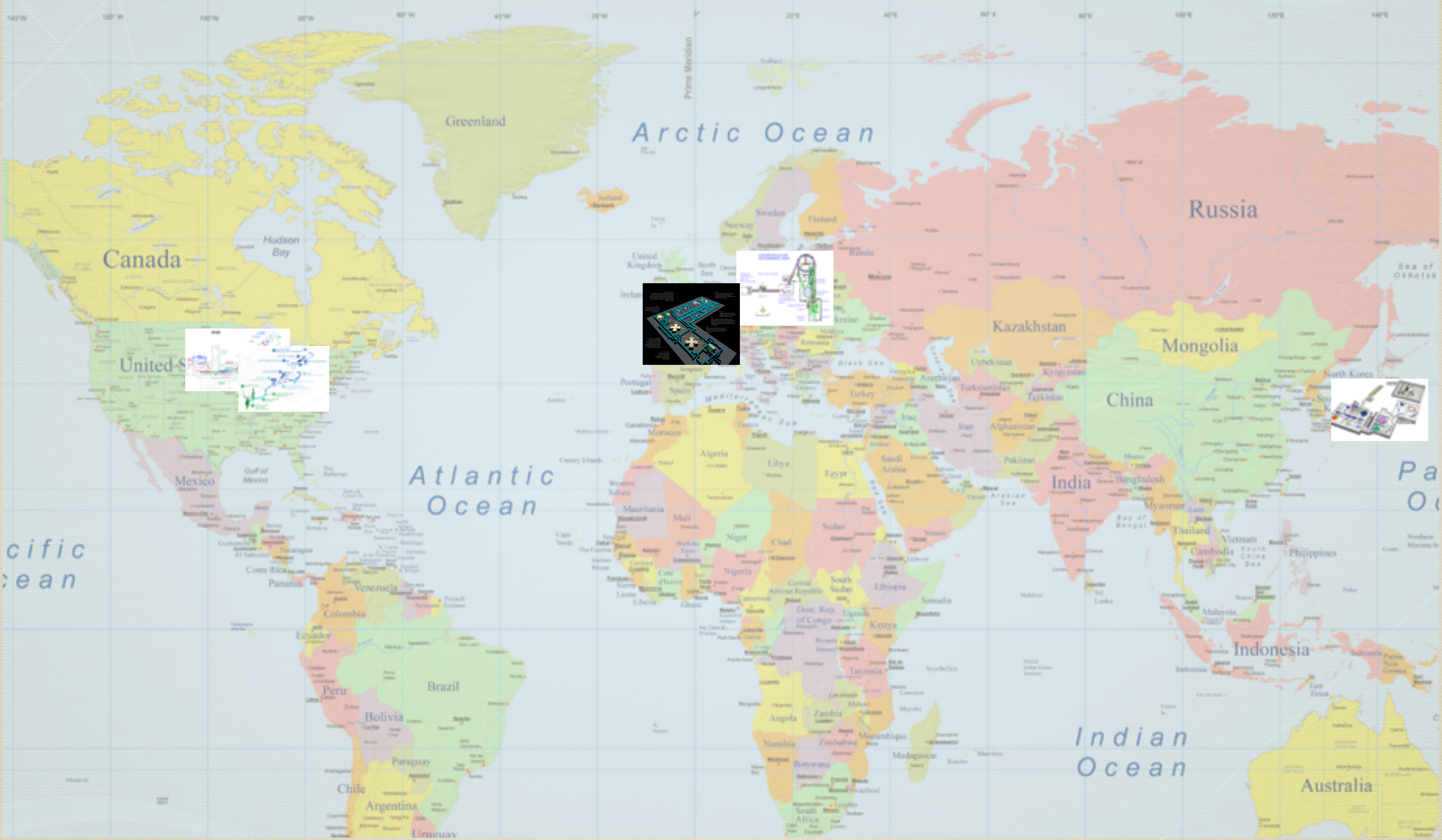

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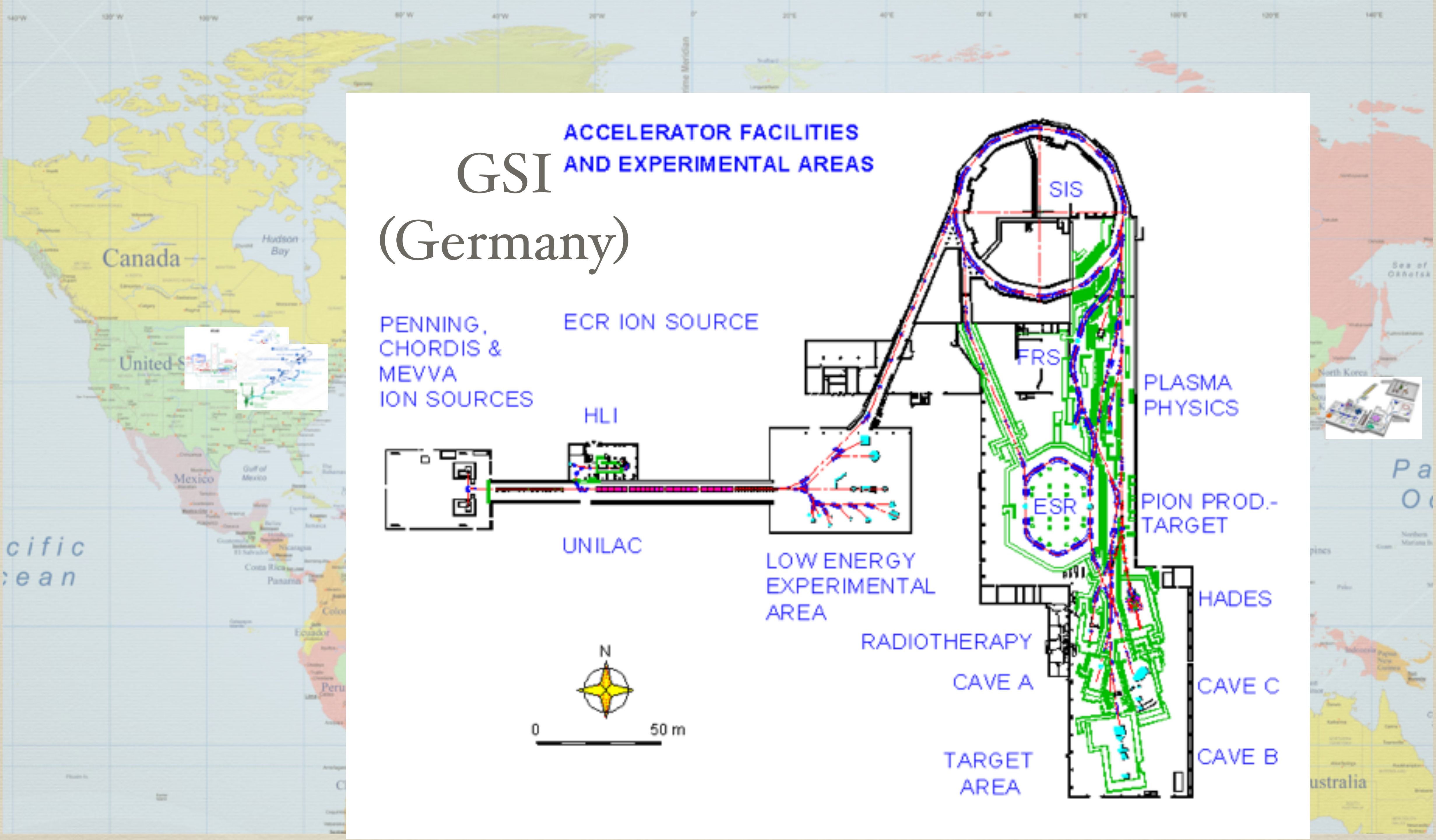

GSI
(Germany)

Main facilities in the world

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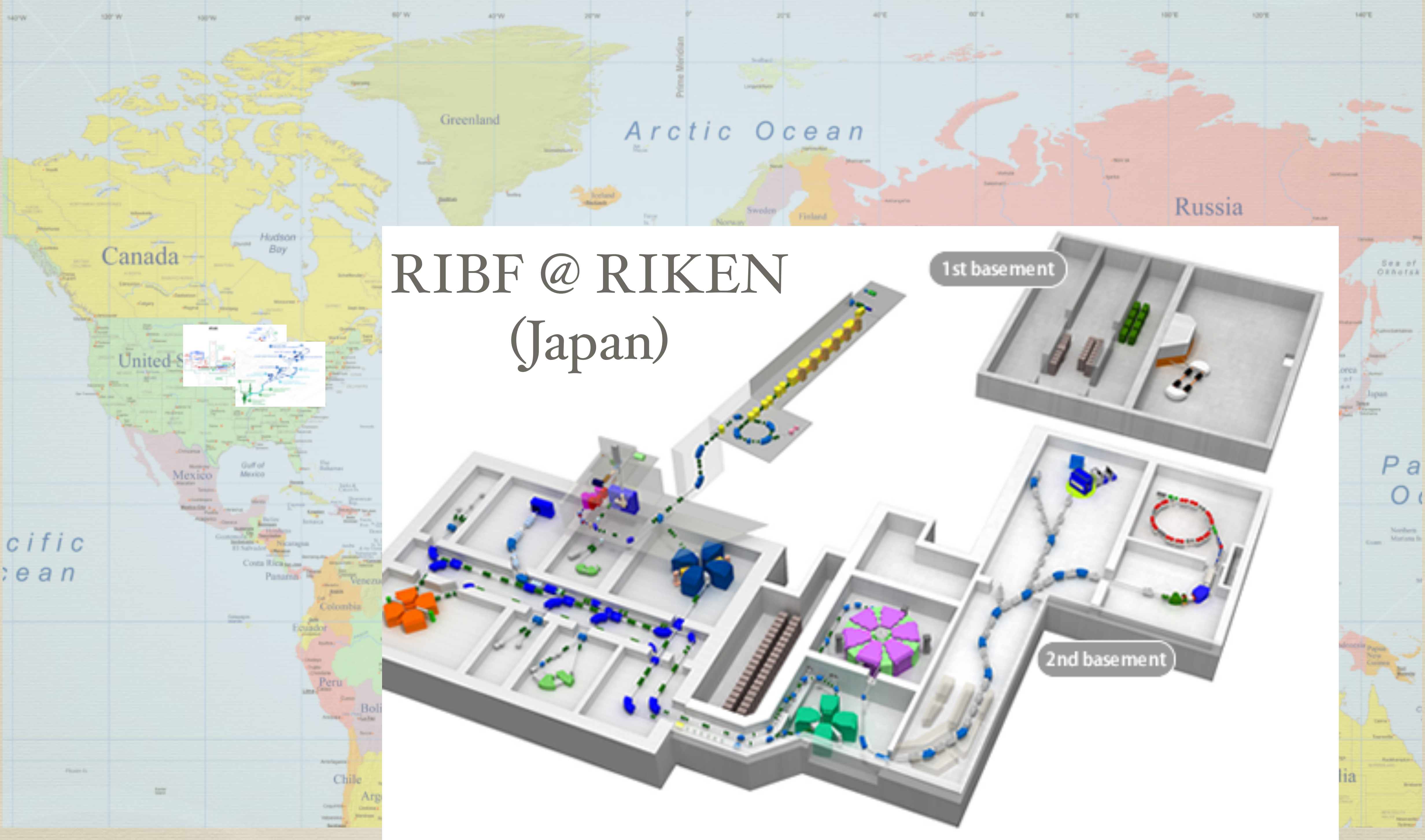

RIBF @ RIKEN
(Japan)

Main facilities in the world

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NSCL @ MSU
(USA)

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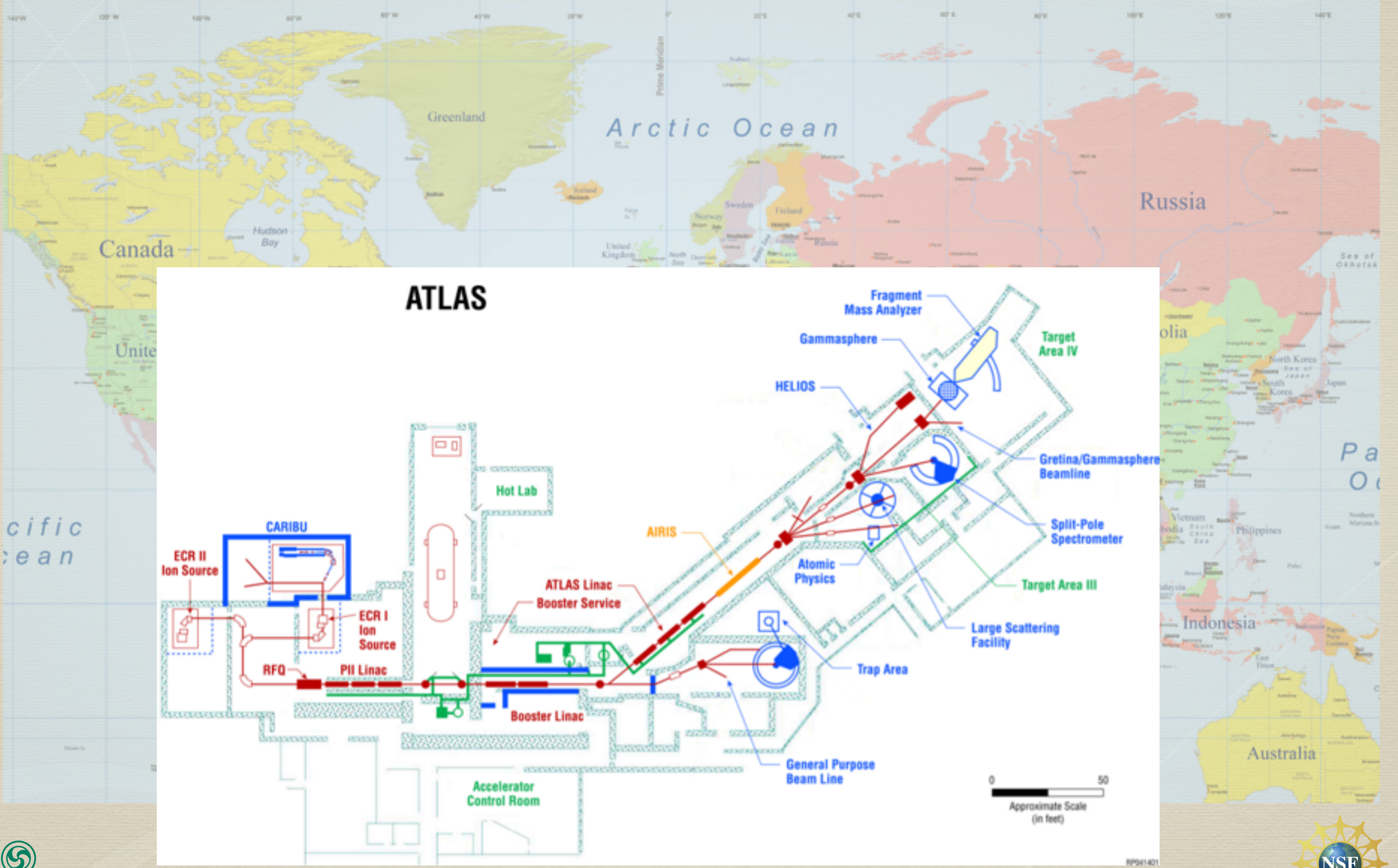

Main facilities in the world

Projectile fragmentation

- Randomly cut stable nuclei into fragments
  - High energy (50 - 1 GeV/u or more)
  - “Spectator” nucleons form projectile fragment
  - Projectile fragments carry most of momentum
  - High efficiency of collecting them at forward angles
  - Thick targets to increase probability of nuclear reaction

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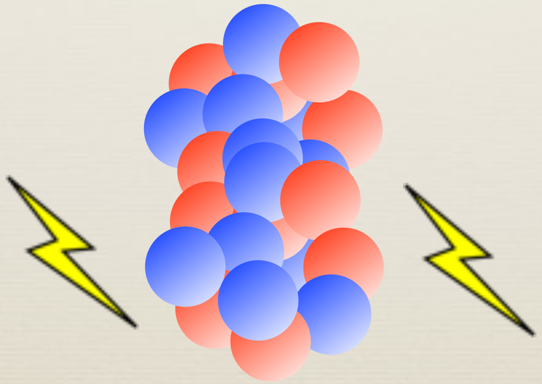

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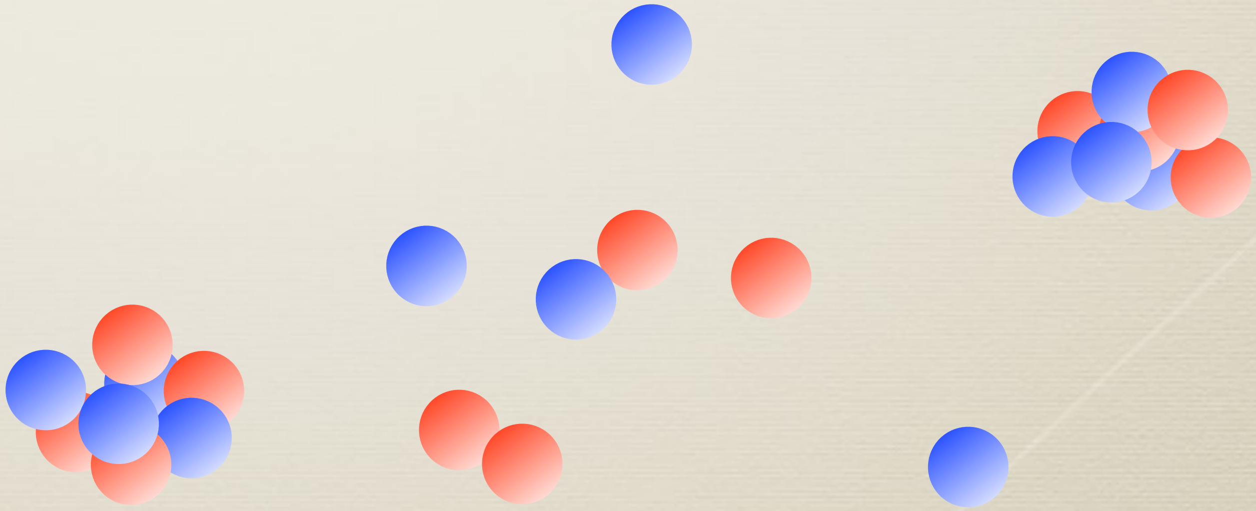
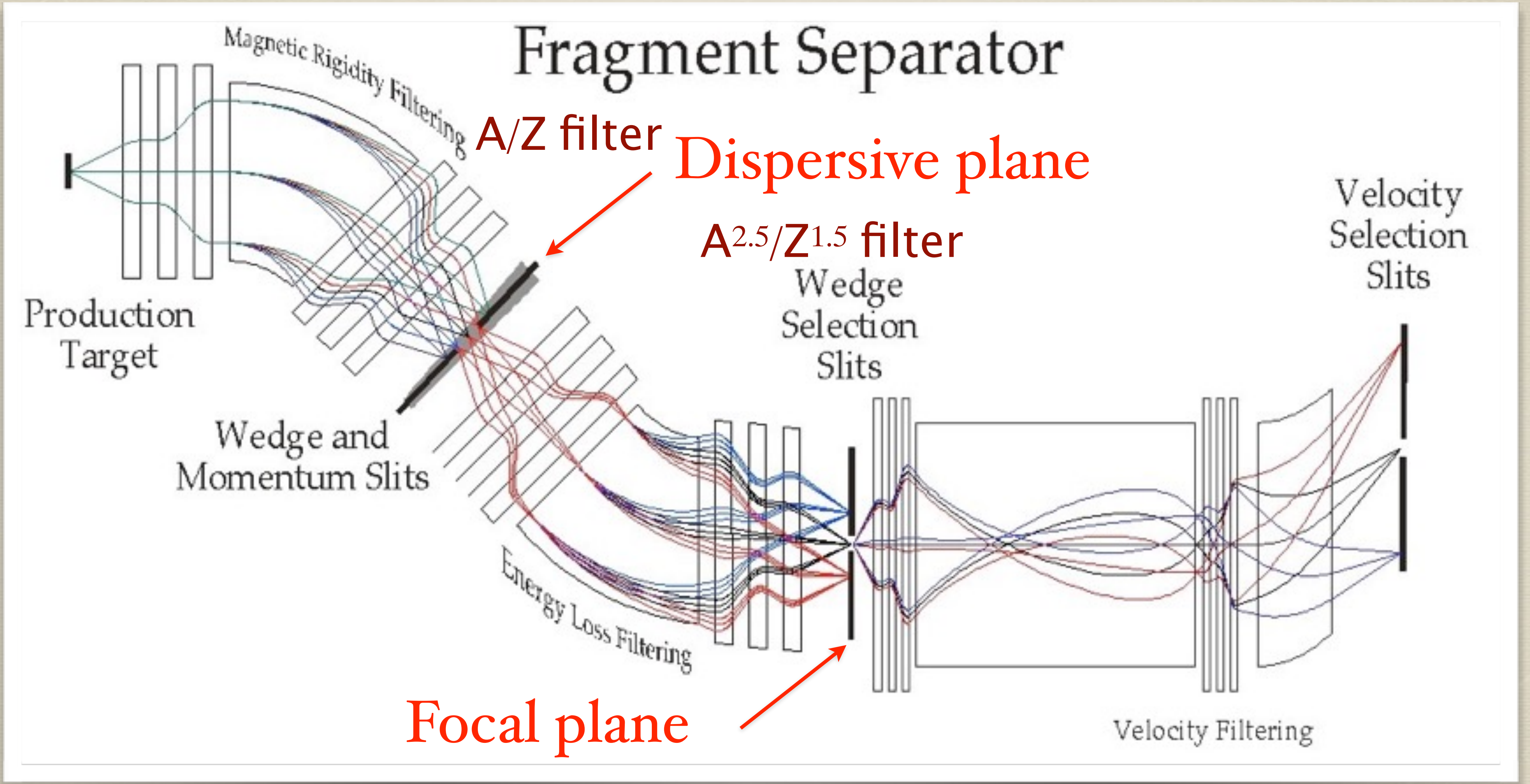
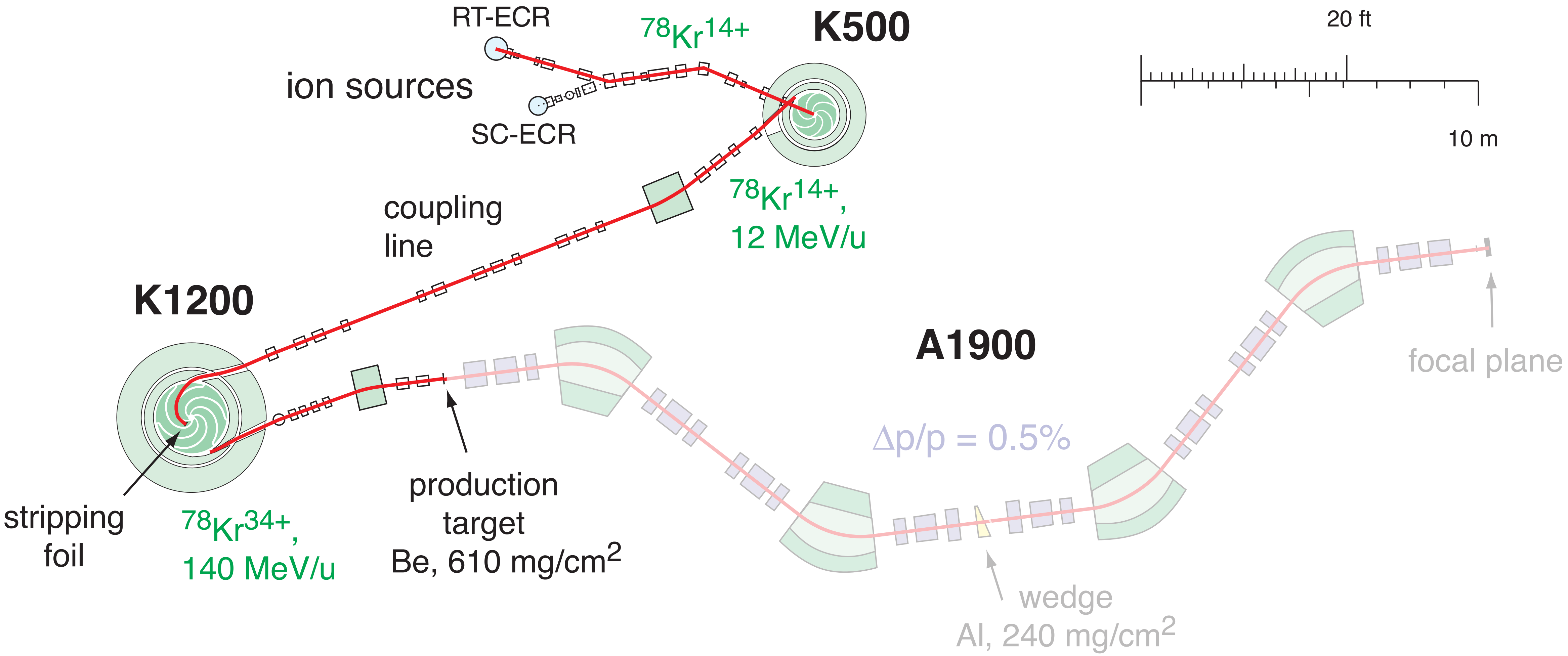


Fragment separator

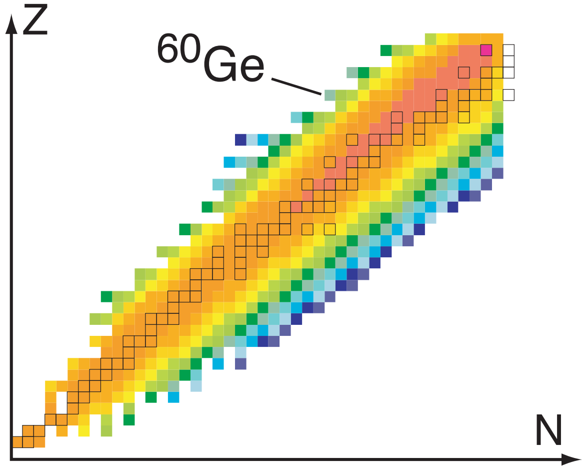


- Select forward focused fragments produced from projectile fragmentation reactions
- Use various selection criteria: magnetic rigidity (Bρ), energy loss (wedge), velocity (Wien filter, RF Separator)

Experimental Setup at the NSCL



fragment yield after target



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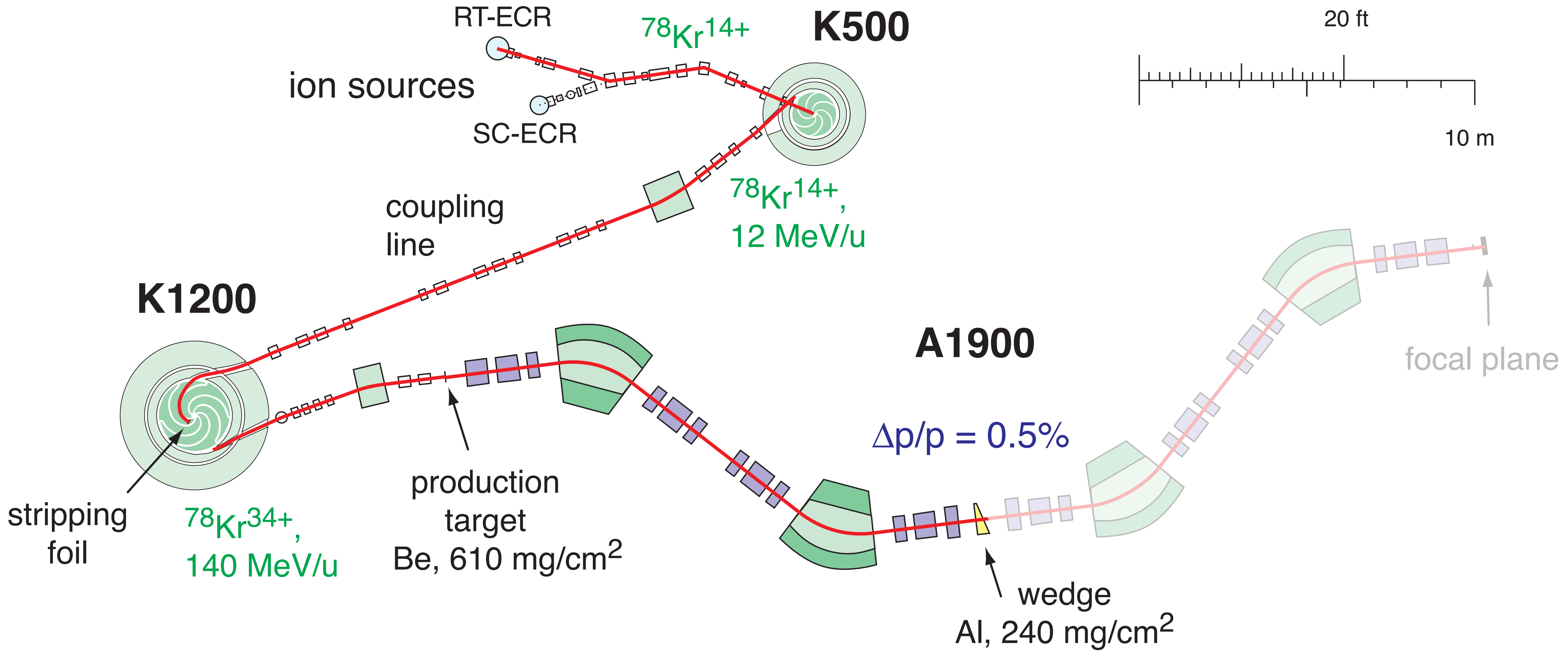

RT-ECR

ion sources

SC-ECR

$^{78}Kr^{14+}$

K500

20 ft

10 m

$^{78}Kr^{14+}$,
12 MeV/u

coupling
line

K1200

A1900

focal plane

$\Delta p/p = 0.5\%$

stripping
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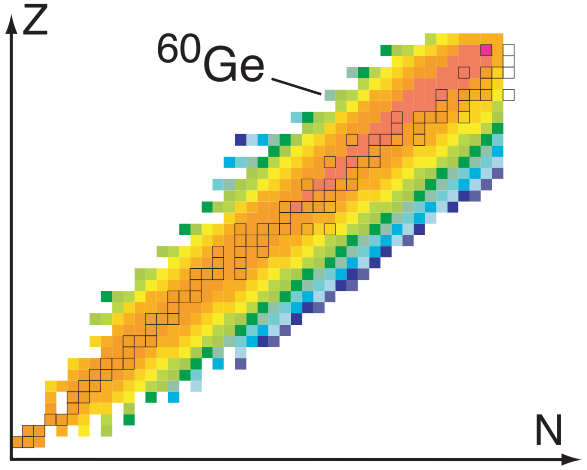

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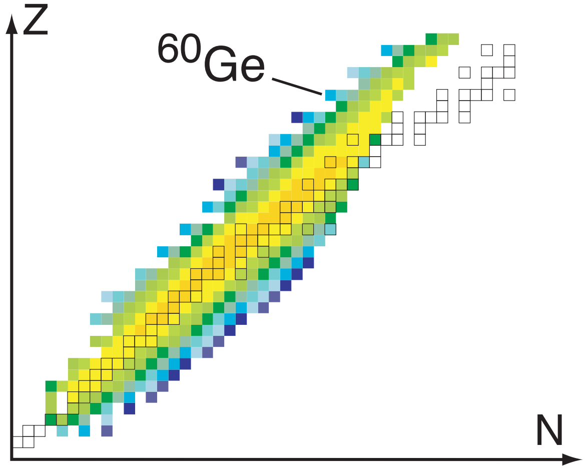

A/Z filter

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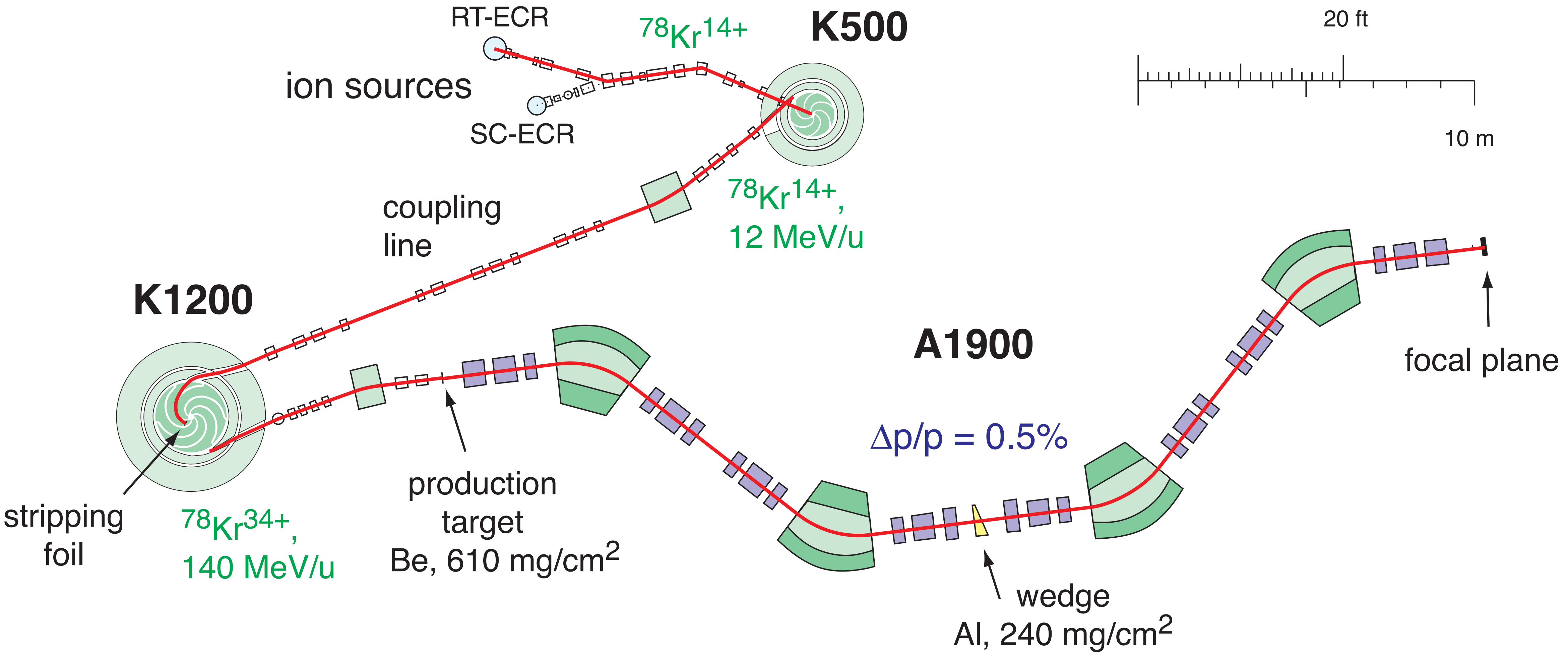

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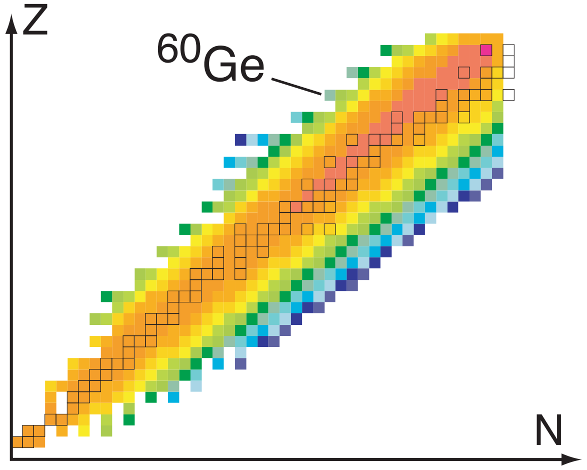

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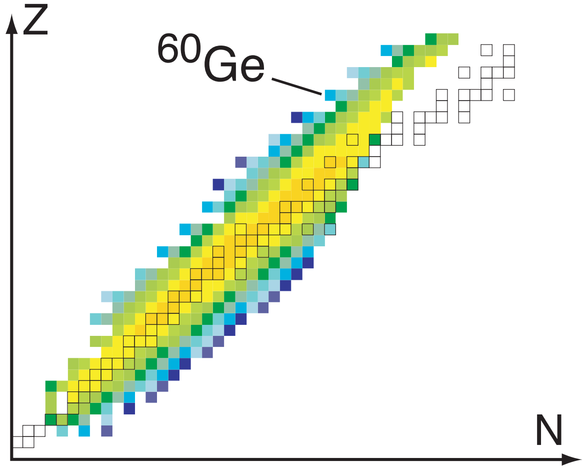
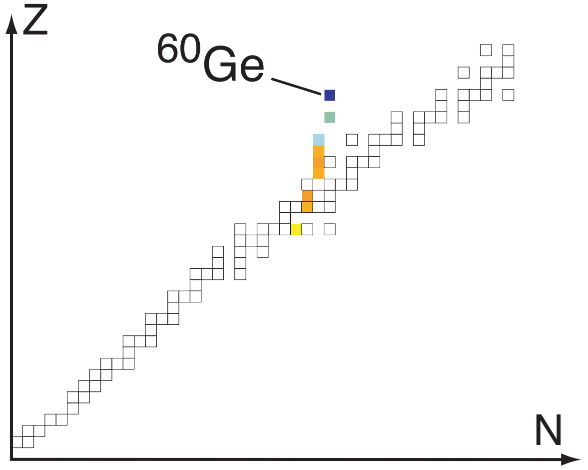


fragment yield at focal plane



A/Z ⊗ $A^{2.5}/Z^{1.5}$ filter

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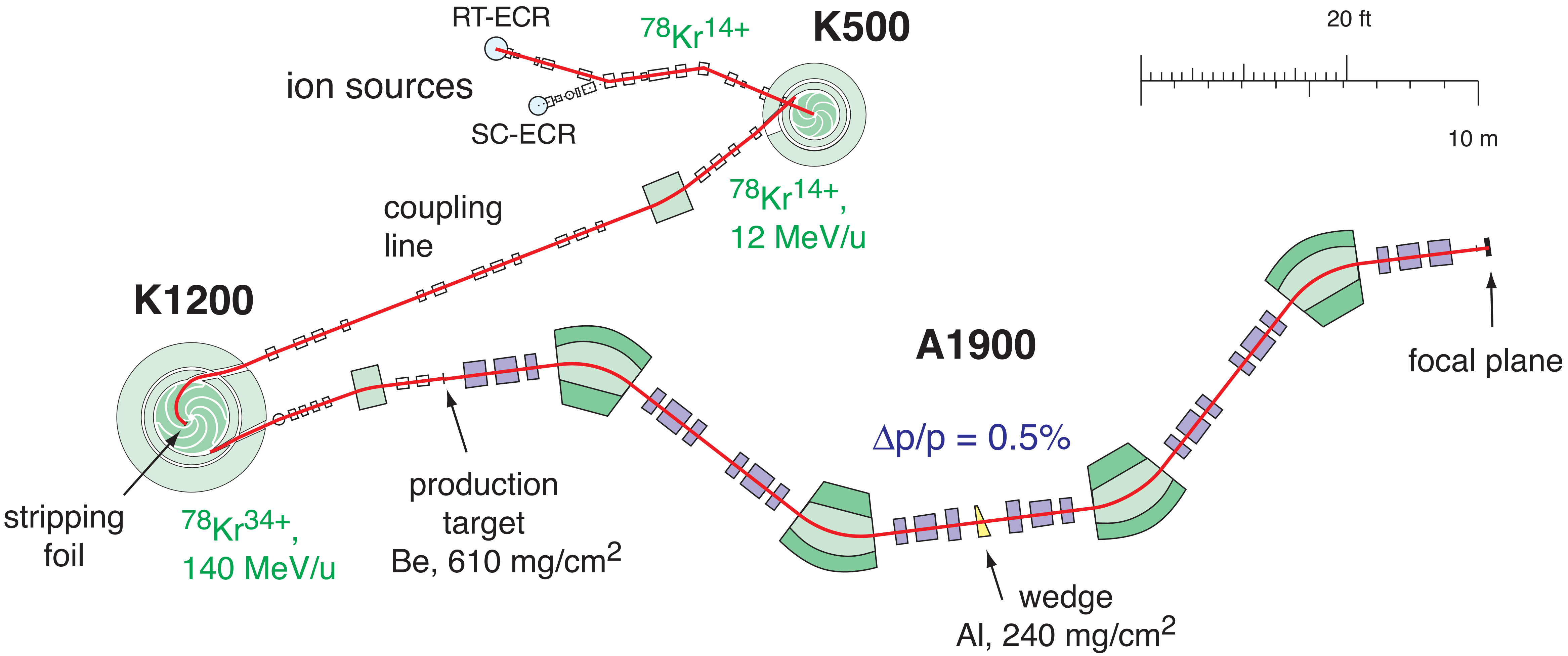

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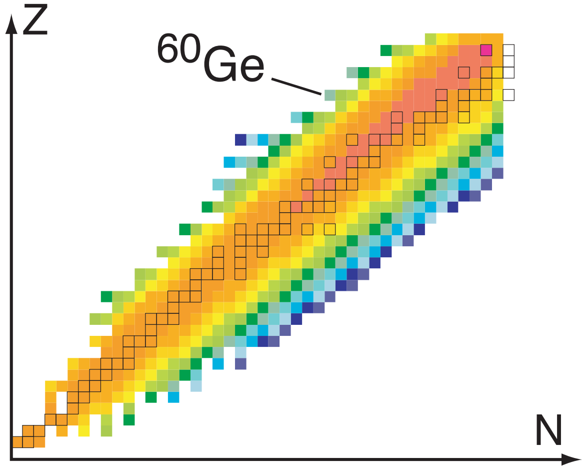

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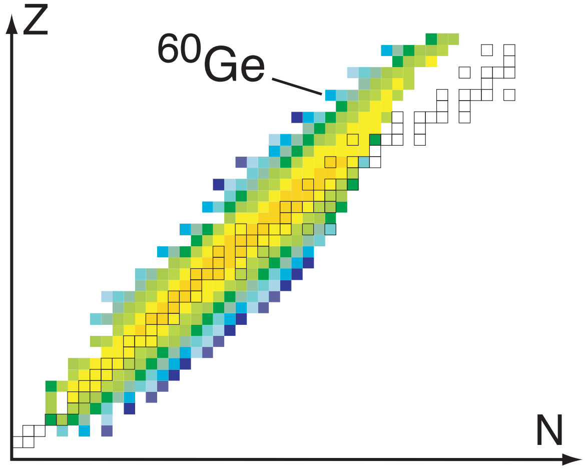

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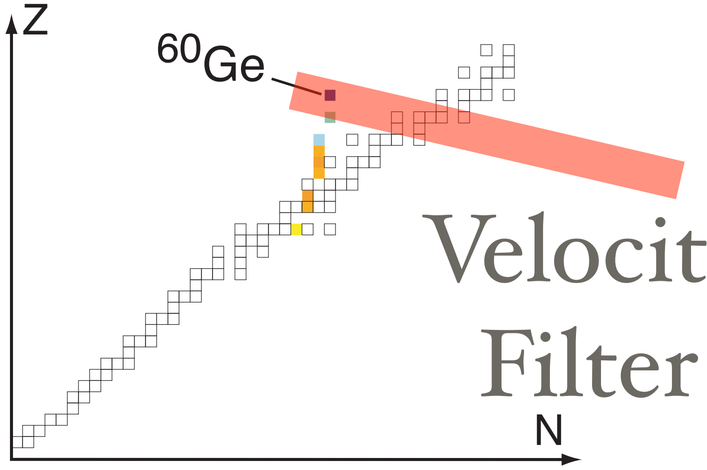

Velocity Filter

$A/Z \otimes A^{2.5}/Z^{1.5}$ filter

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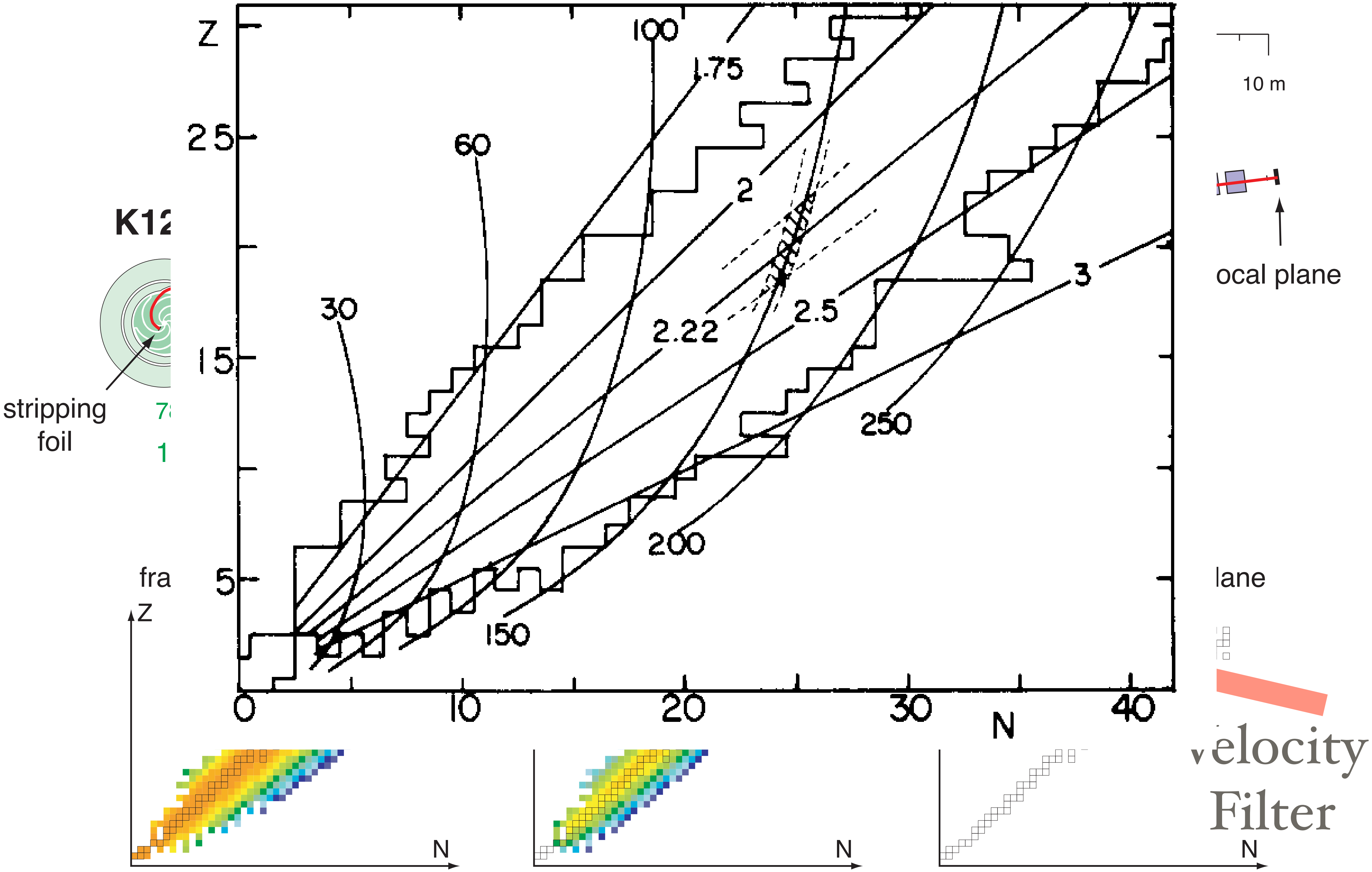

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  - Dynamical and statistical properties, but also (and in fact mostly) static properties

Nuclear reactions

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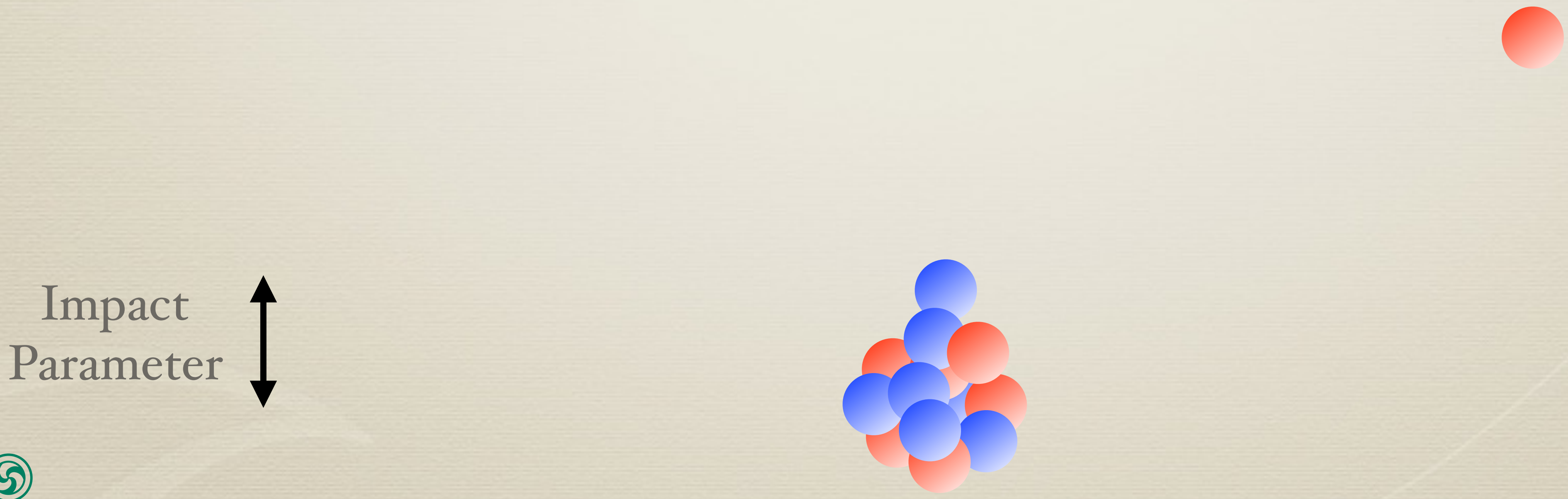

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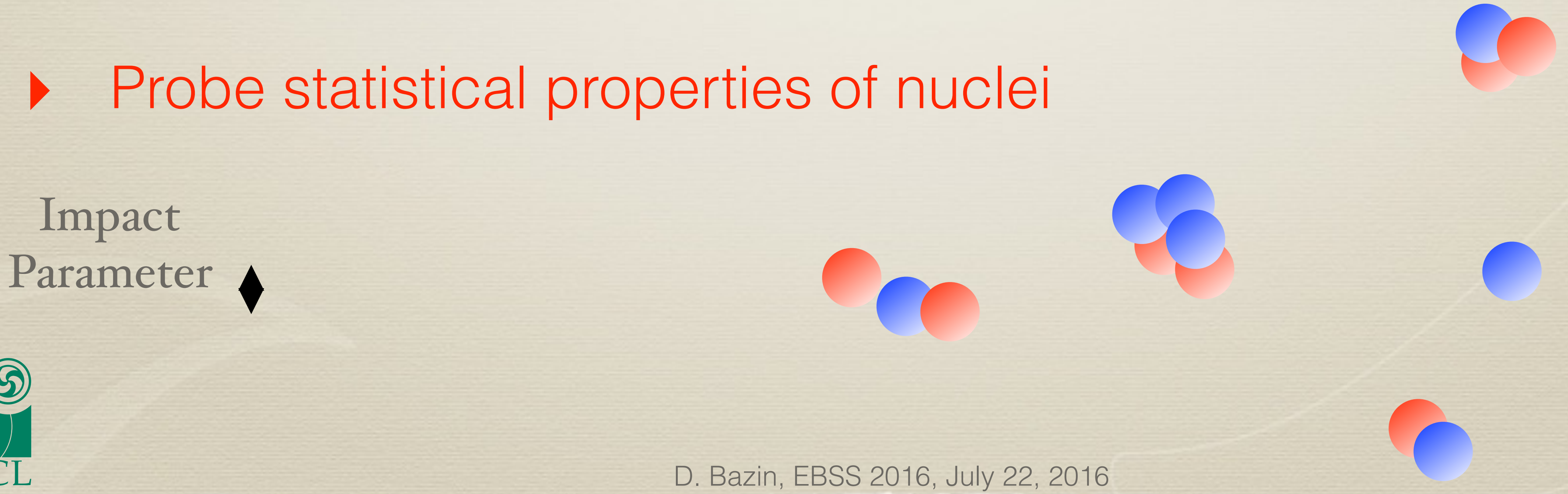

Direct reactions are tools

- … to study Nuclear Structure and Astrophysics

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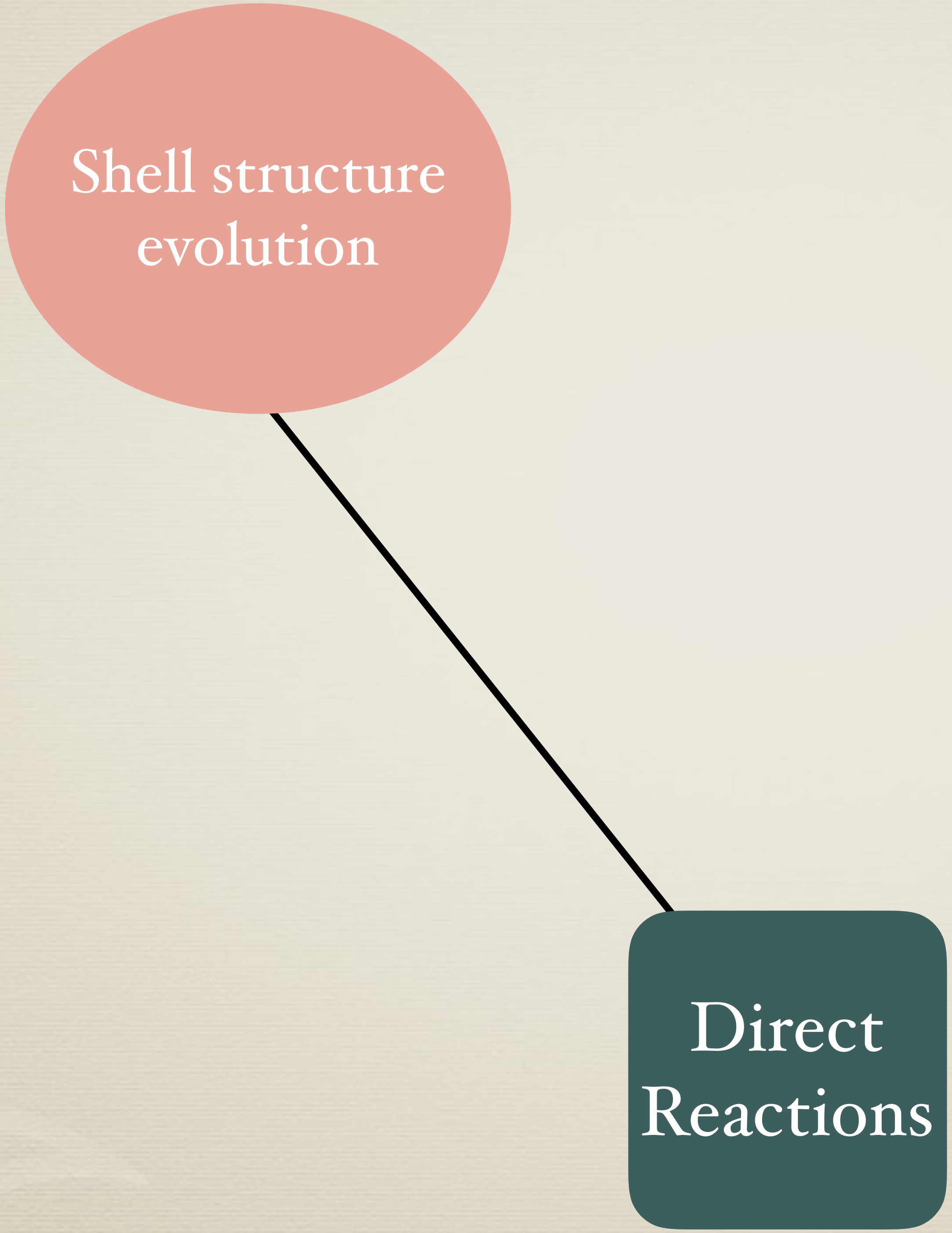

Shell structure evolution

Direct Reactions

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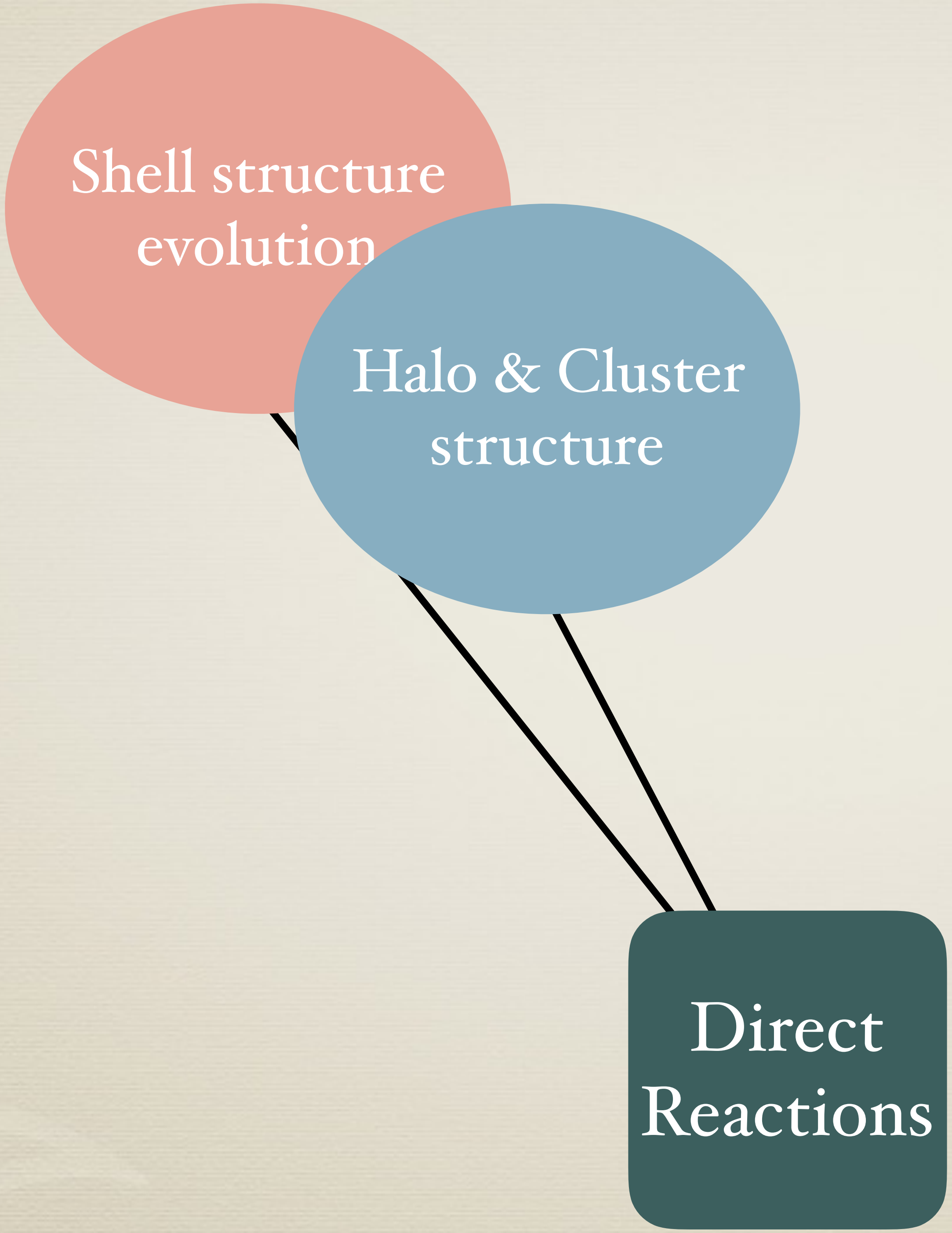

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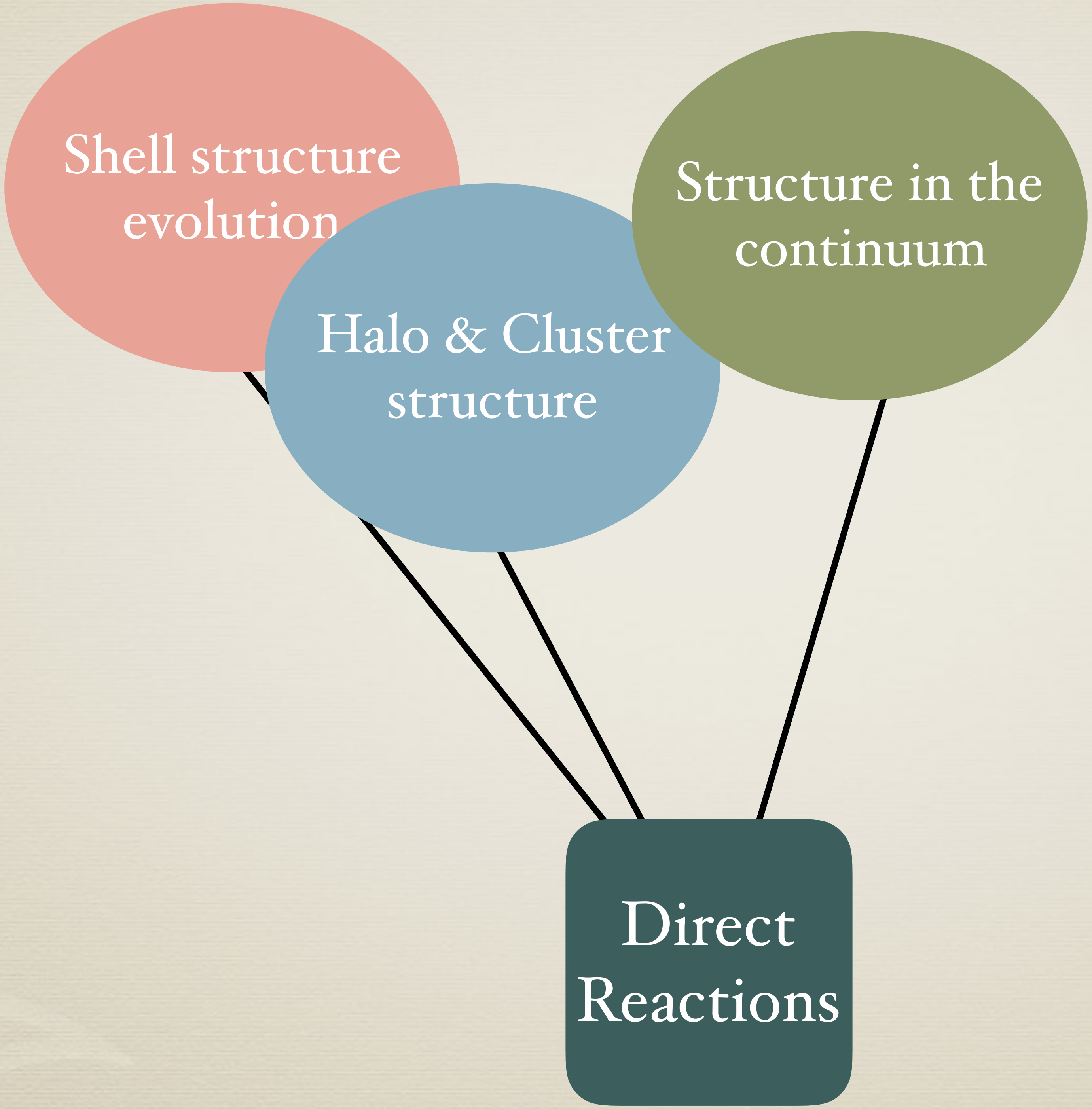

Shell structure evolution

Halo & Cluster structure

Structure in the continuum

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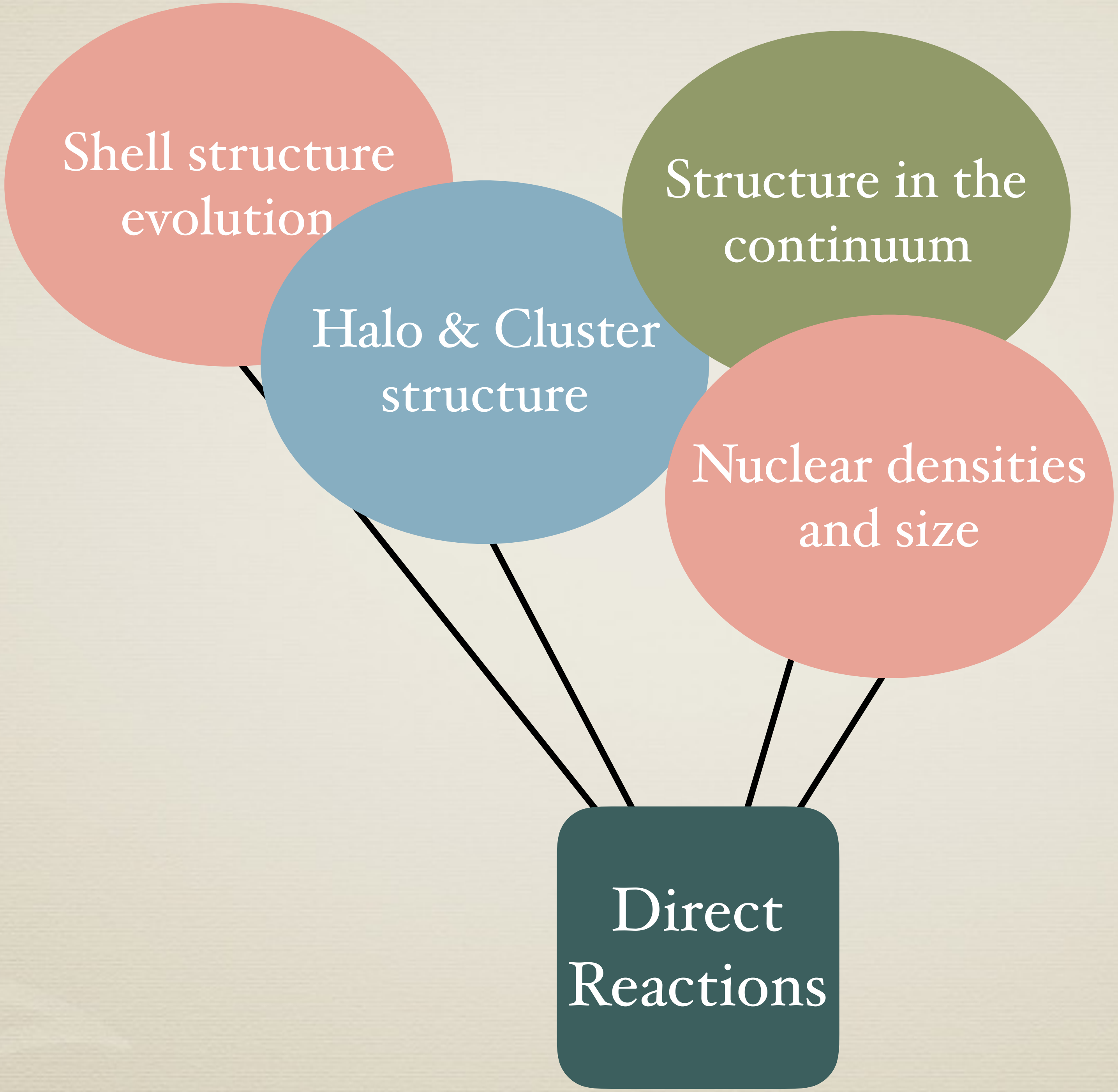

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Nuclear densities and size

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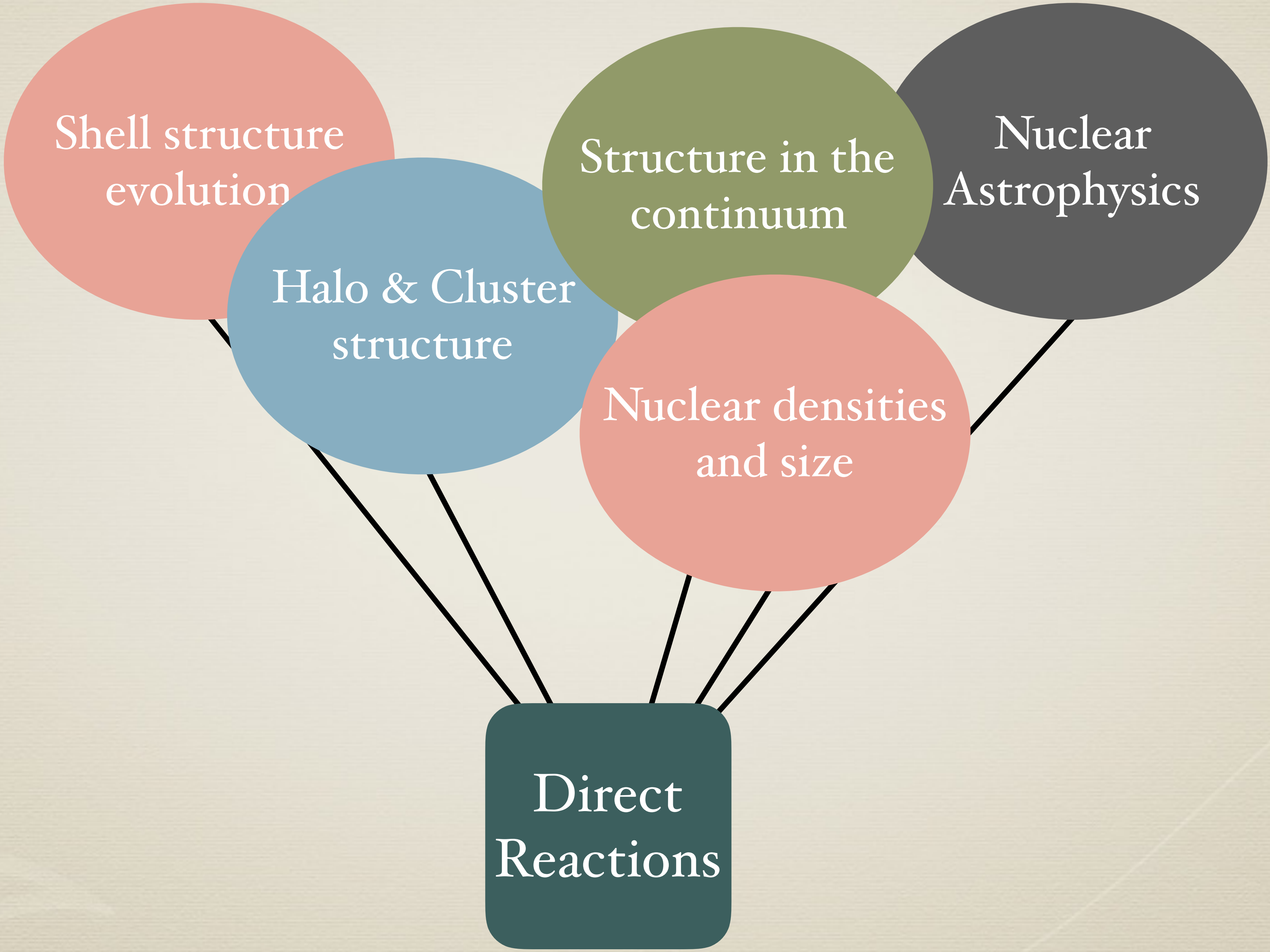

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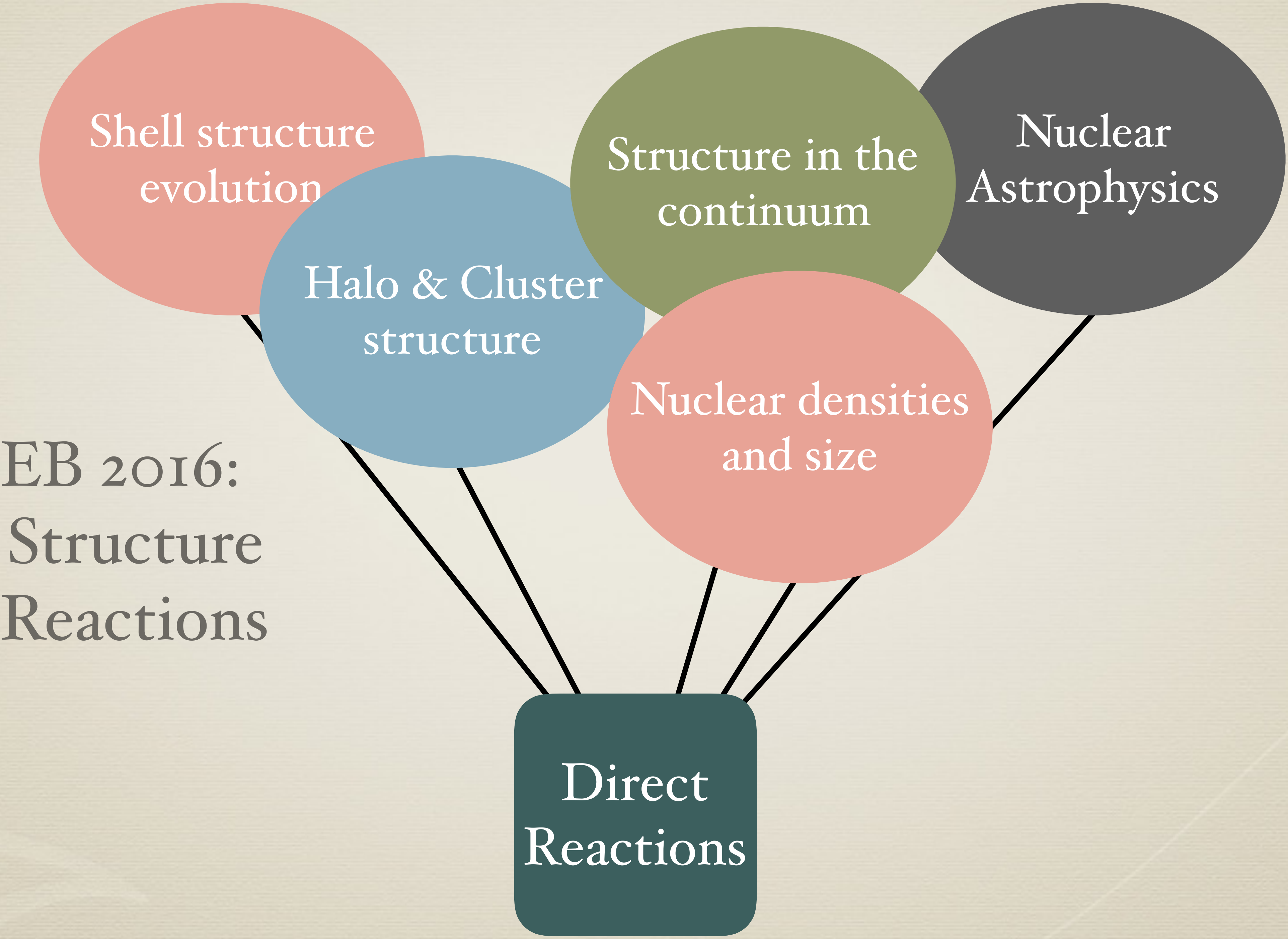

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DREB 2016:
75% Structure
25% Reactions

Not so simple…

- Pictures and words are necessary, but they confine and restrict the imagination

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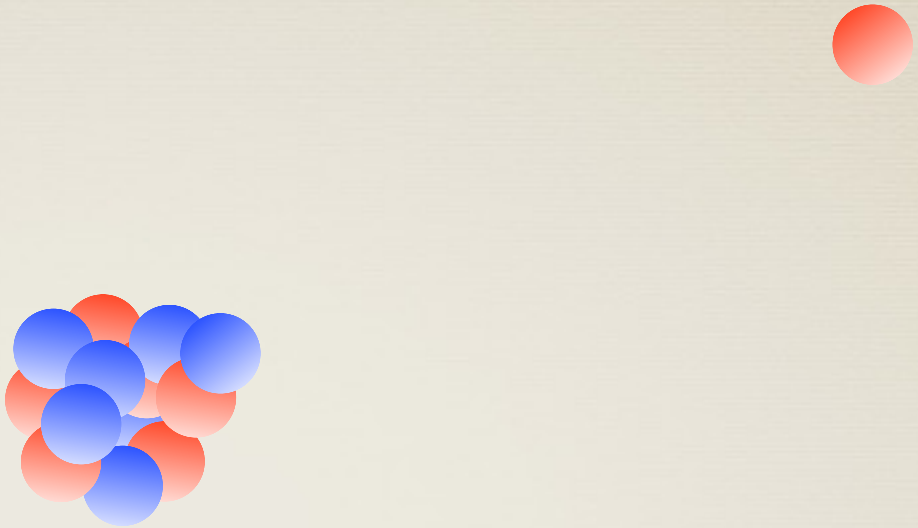

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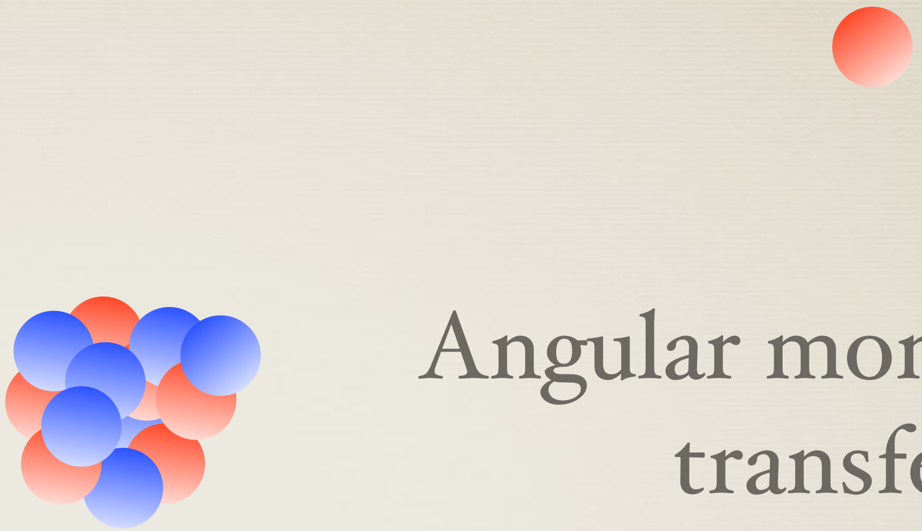

Angular momentum transfer

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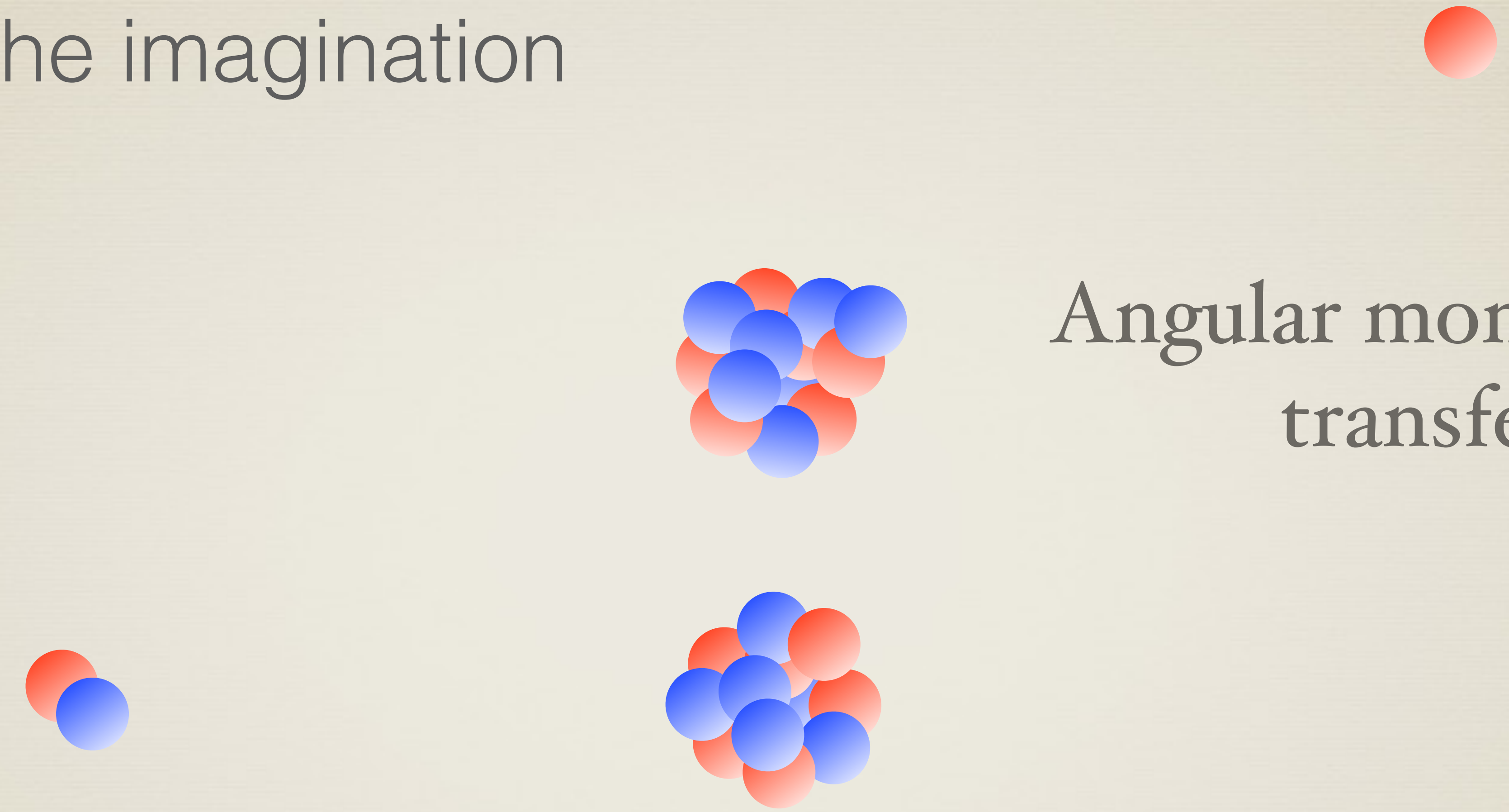

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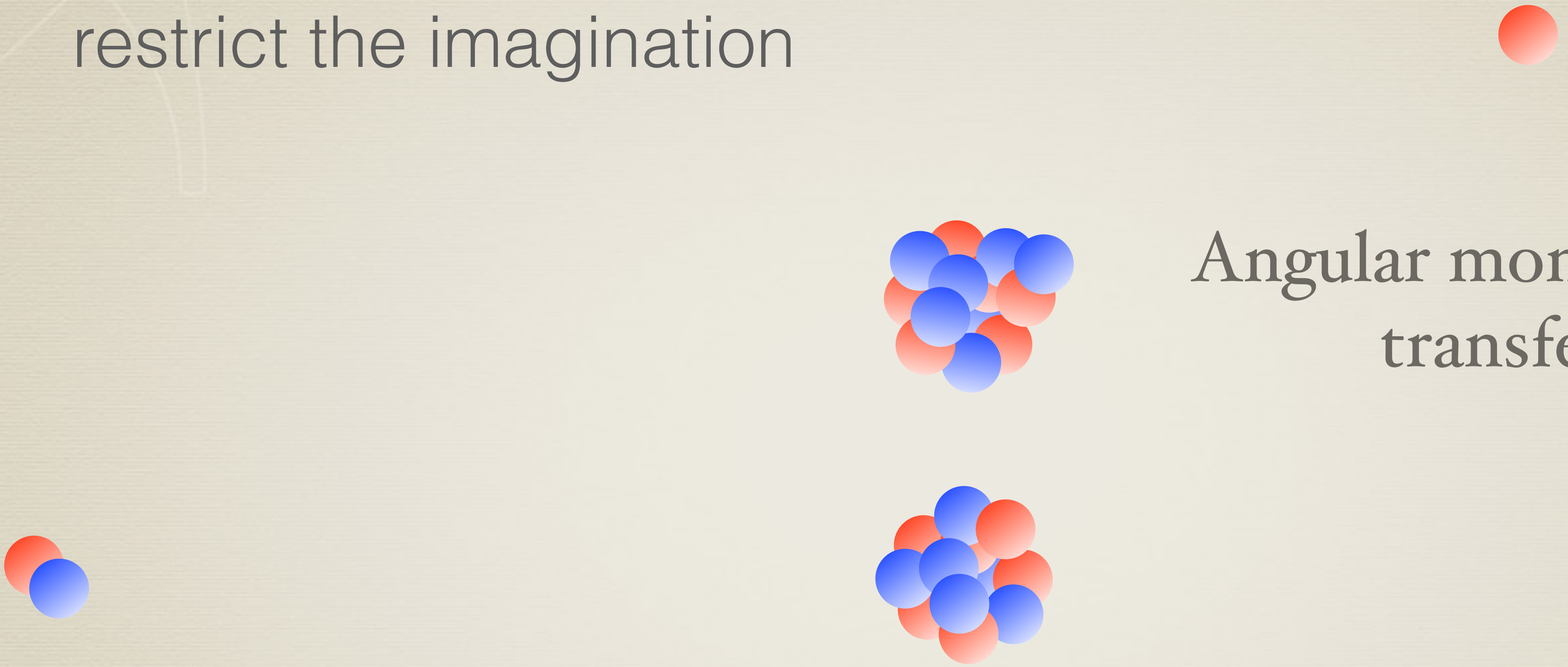

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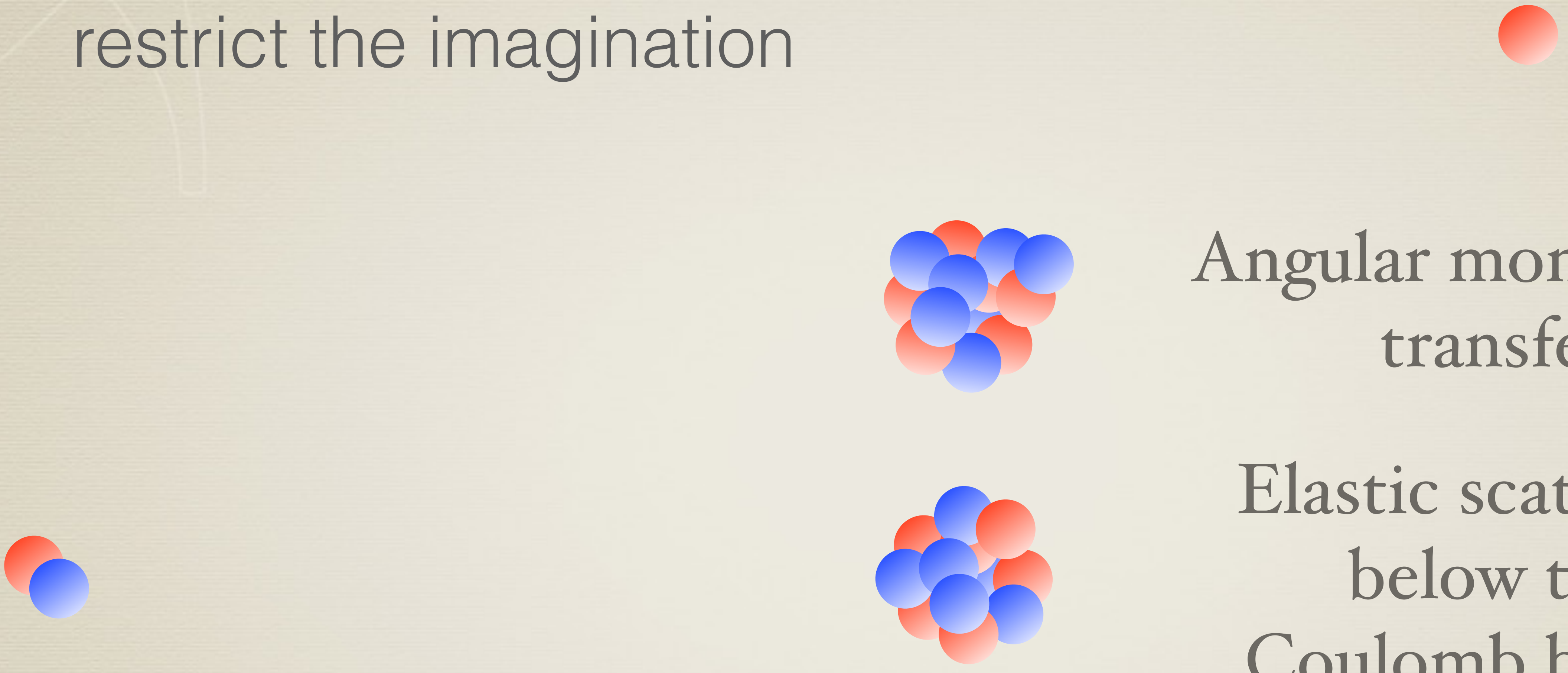

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Elastic scattering below the Coulomb barrier

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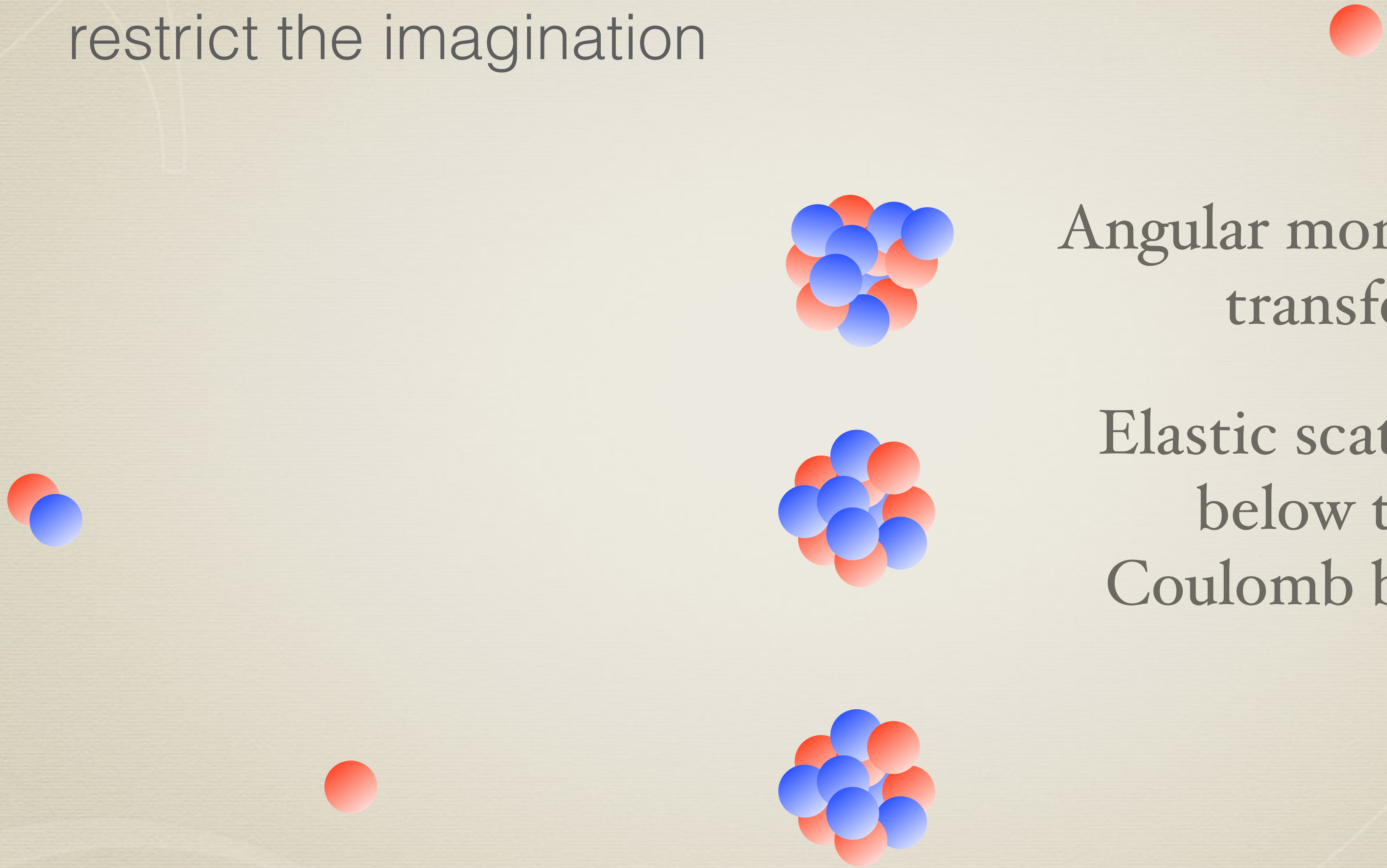

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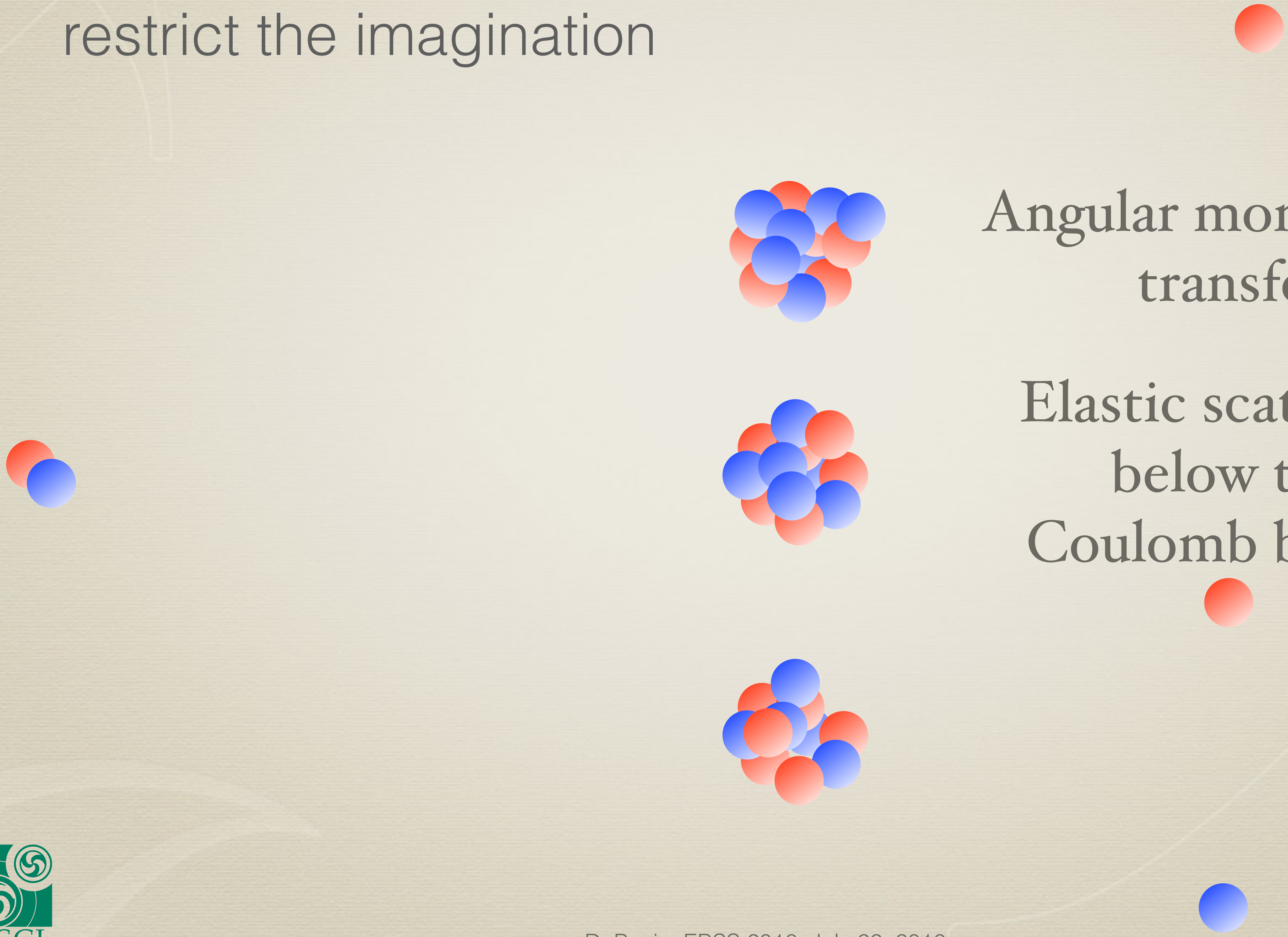

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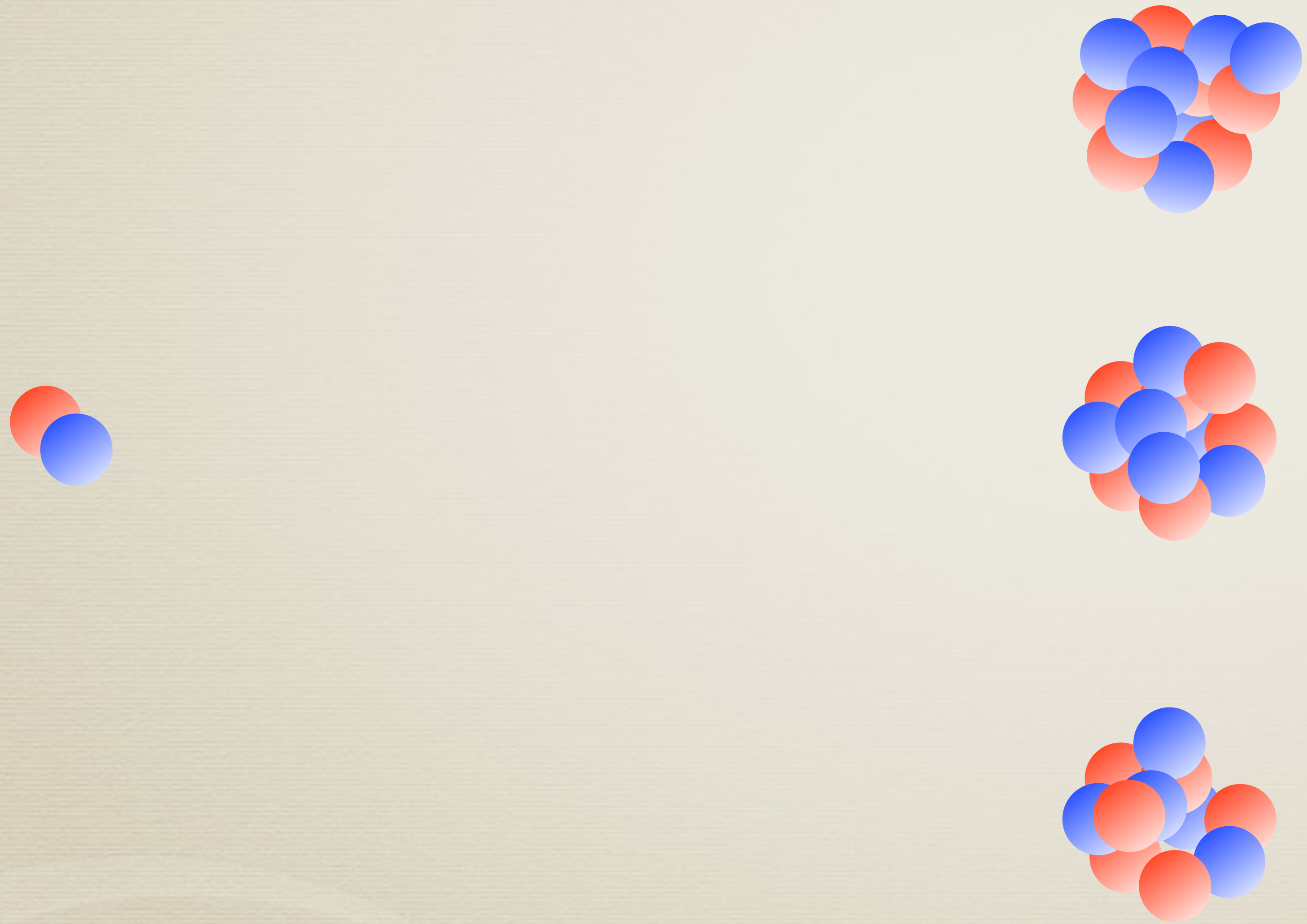

Angular momentum transfer

Elastic scattering below the Coulomb barrier

Quasi-free (p,pn) scattering

A large palette of tools

- Covering a very wide range of beam energies
  - From < 1 MeV/u up to >1 GeV/u

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Impact Parameter

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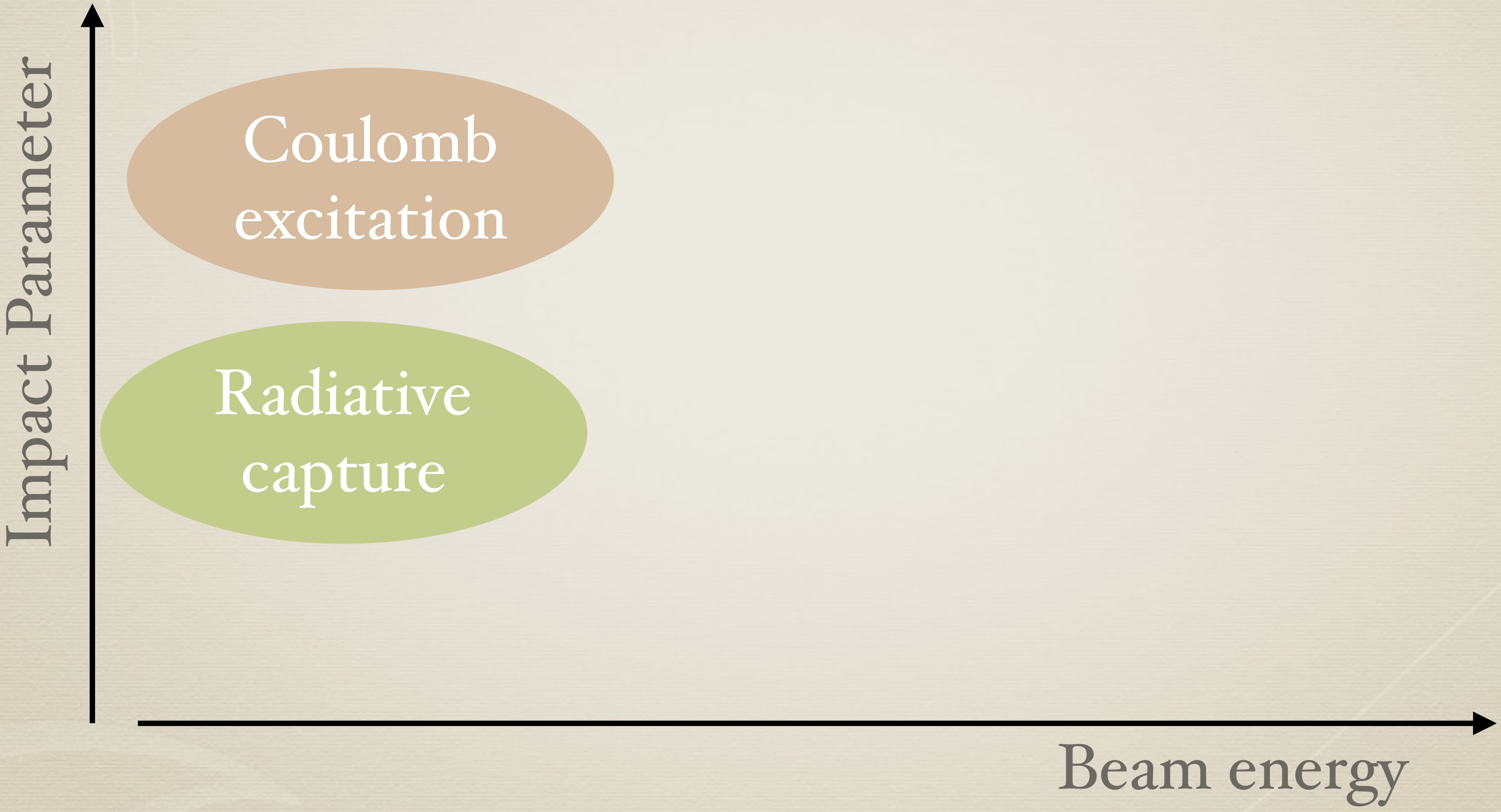

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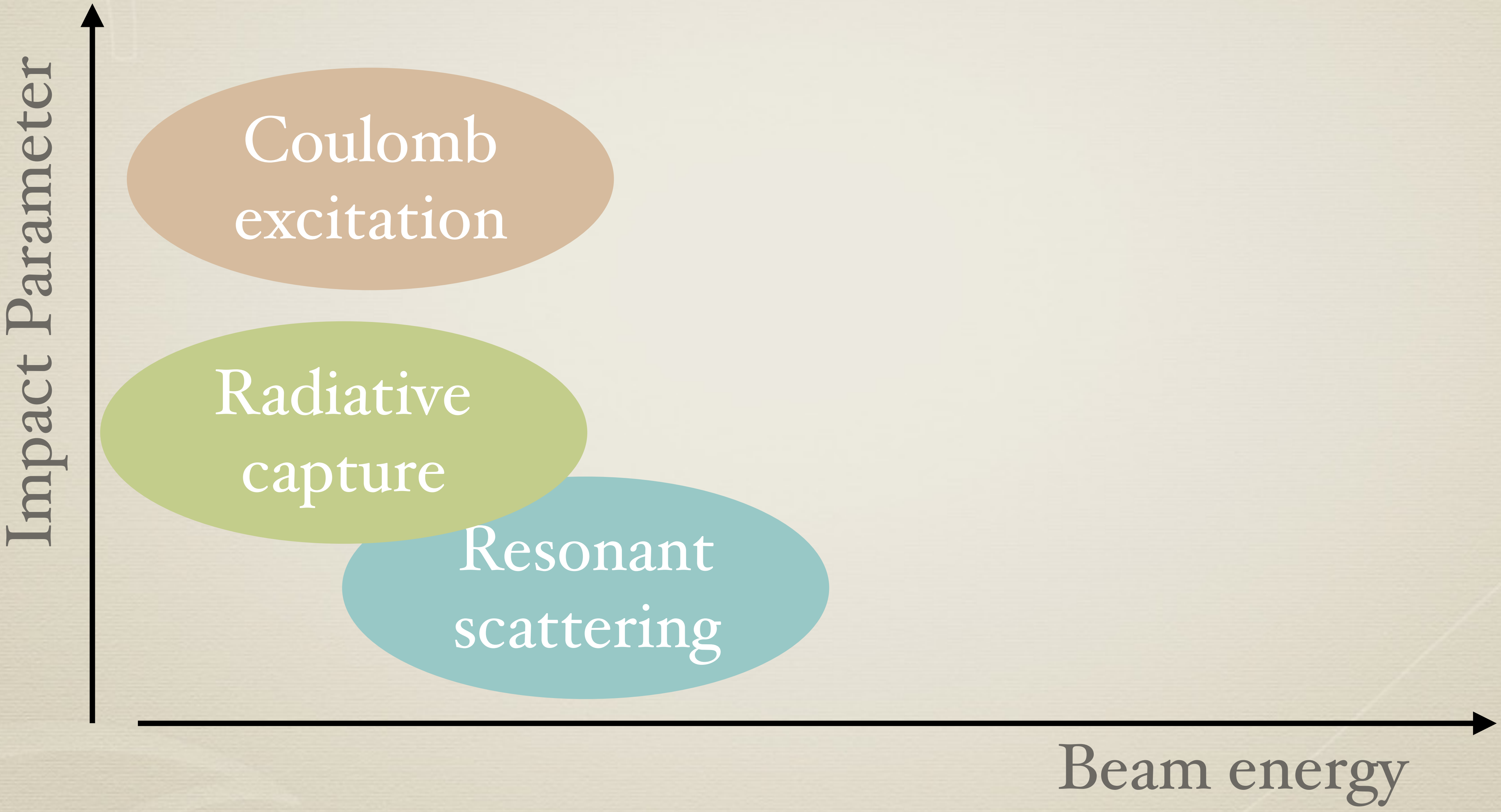

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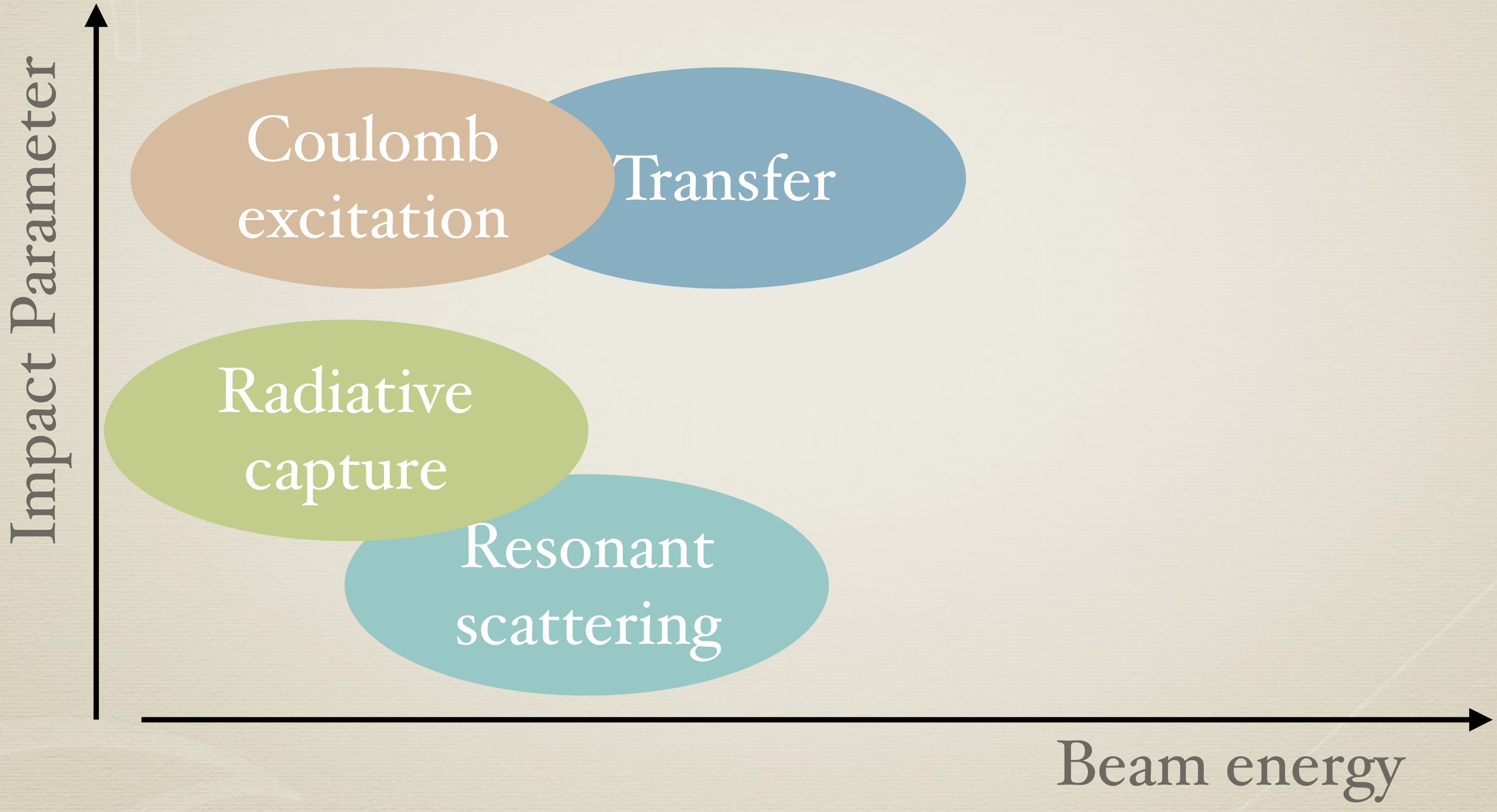

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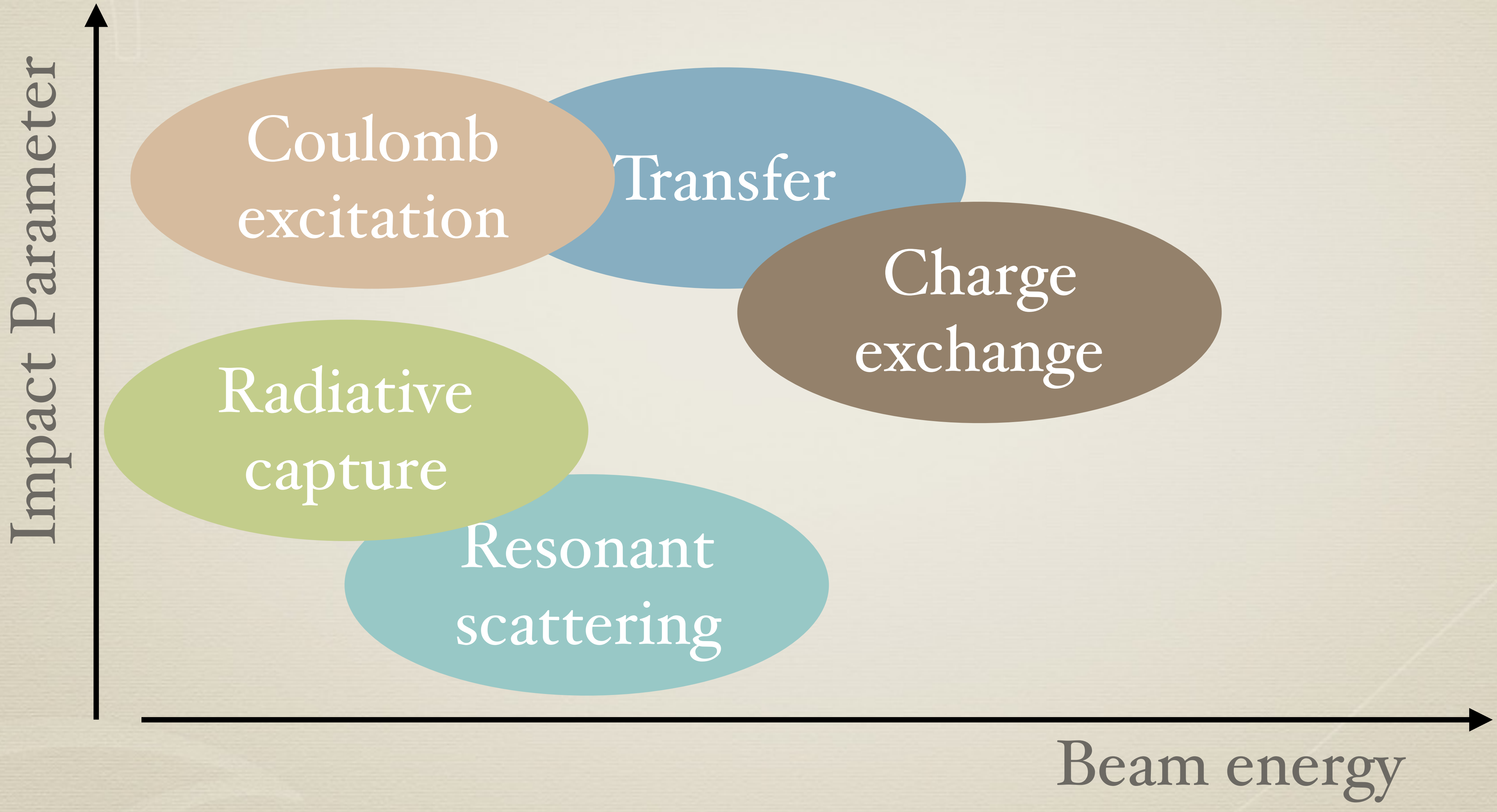

A large palette of tools

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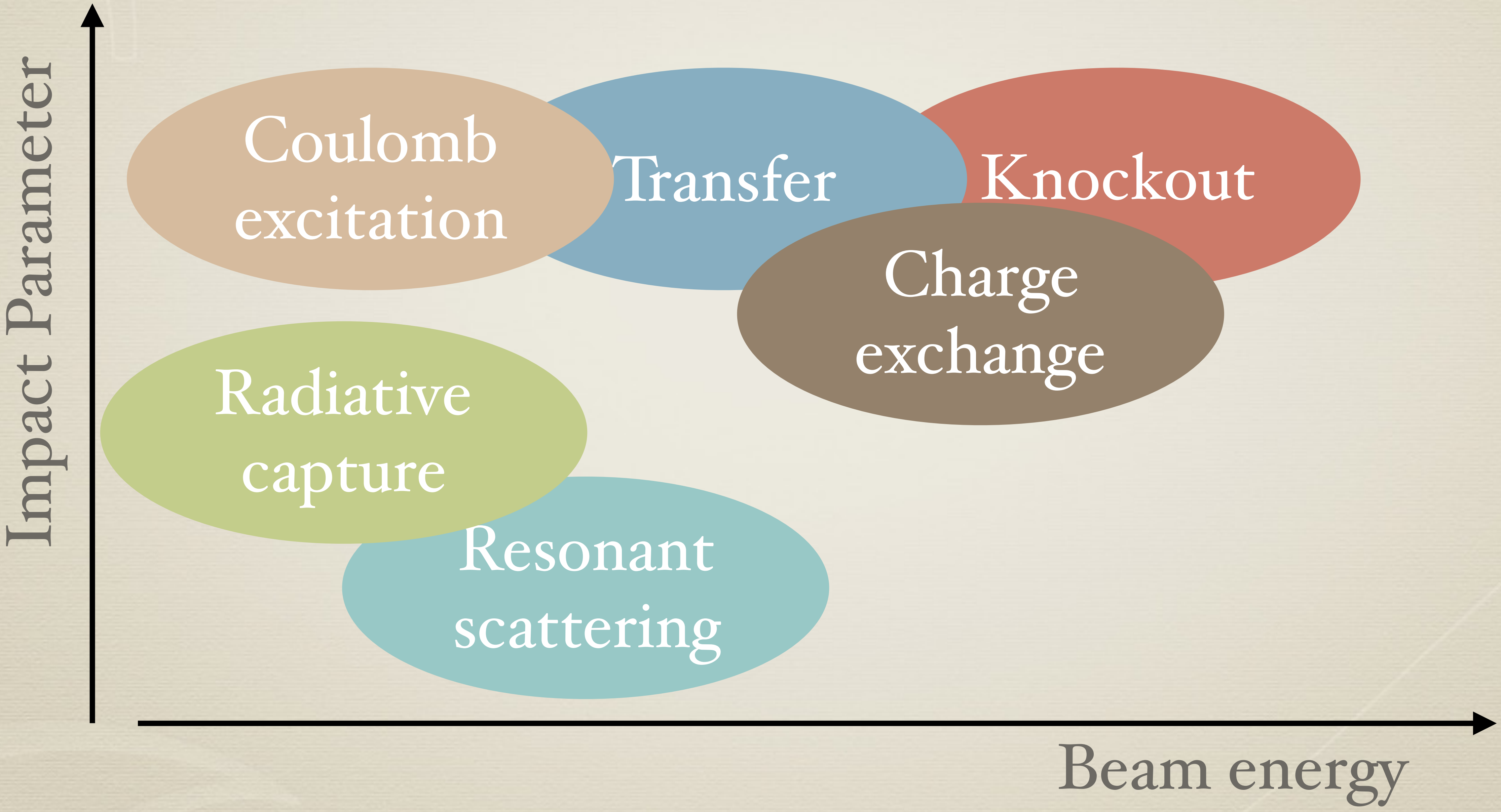

Impact Parameter

Coulomb excitation

Transfer

Knockout

Charge exchange

Radiative capture

Resonant scattering

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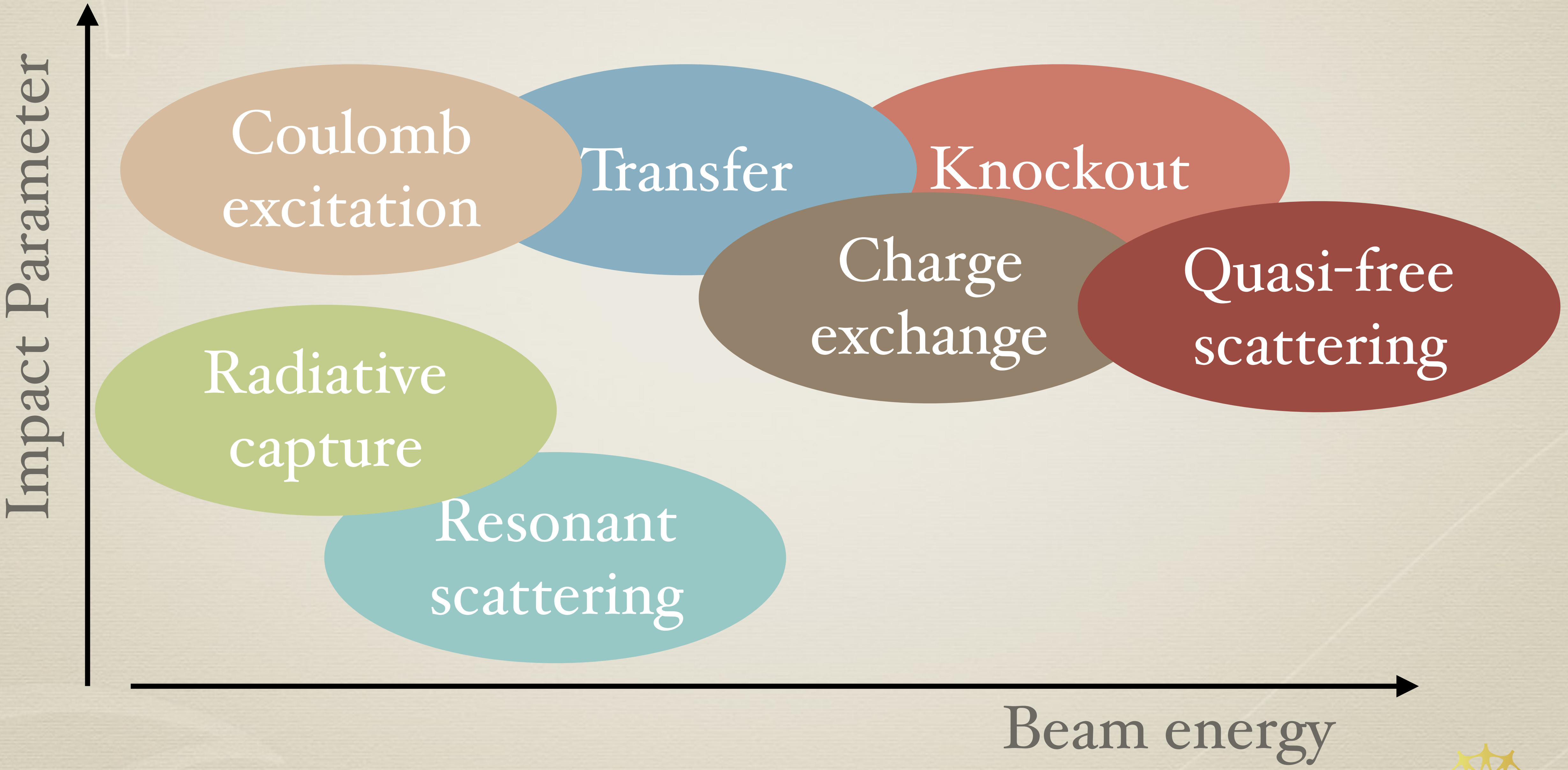

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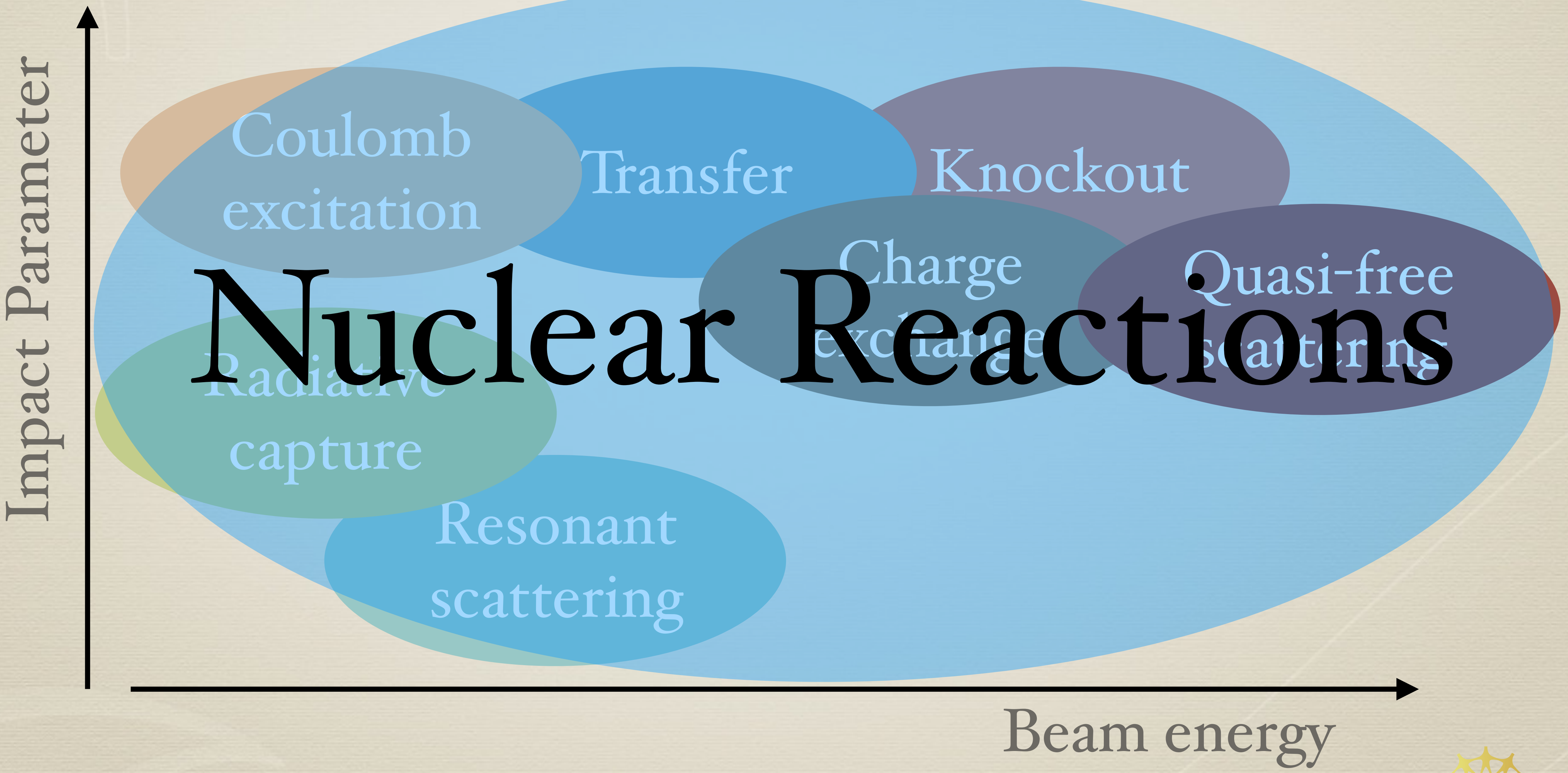

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Nuclear Reactions

Beam energy

Nuclear Physics Conundrum

- Using “simple” nuclear reaction to study nuclear structure

Observable:
cross section

Structure model:
spectroscopic factor

Reaction model:
single-particle
cross section

$$\sigma^{if} = \sum_{|J_f - J_i| \le j \le J_f + J_i} S_j^{if}\,\sigma_{sp}$$

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- One observable, two model inputs
- We want to extract valuable structure information
- Challenge: need valid reaction model!

The good early days…

- Use light nuclei (p, d, ^{4}He) on stable targets
  - Large beam intensities (10^{8} pps and more)
  - Simple detector setups (few detectors around target, or simple spectrometer)
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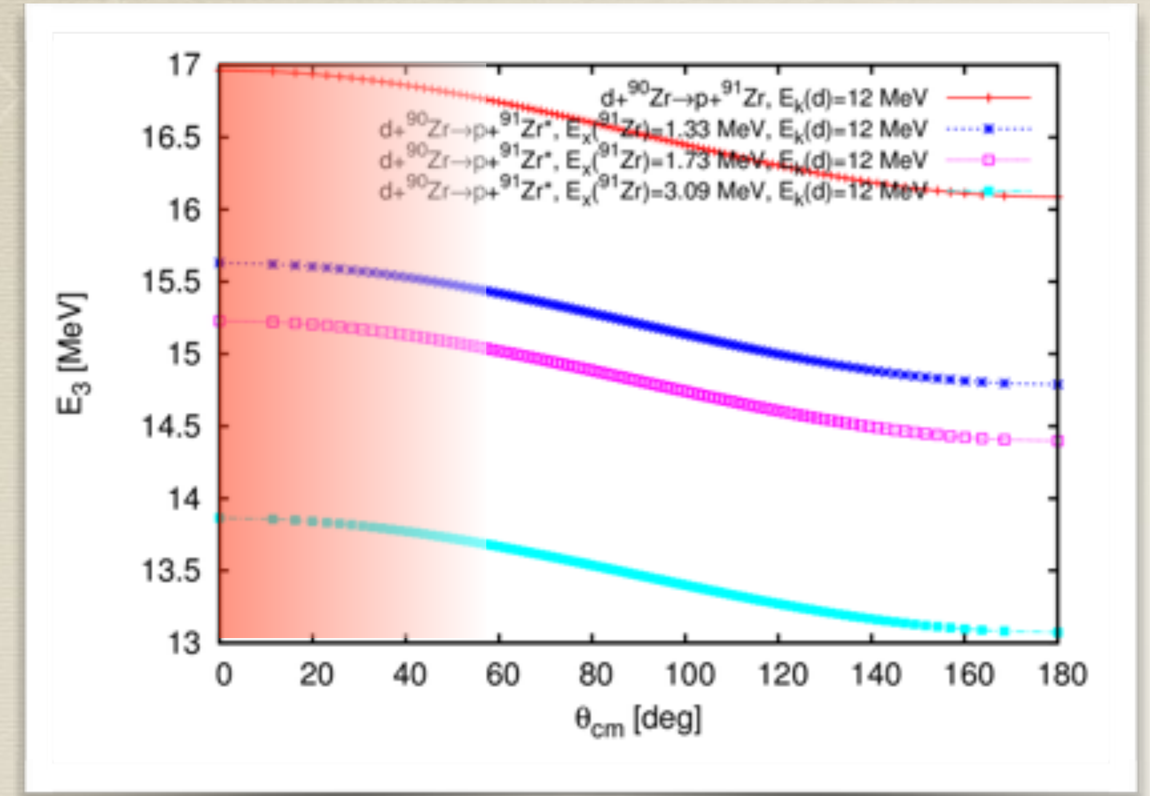
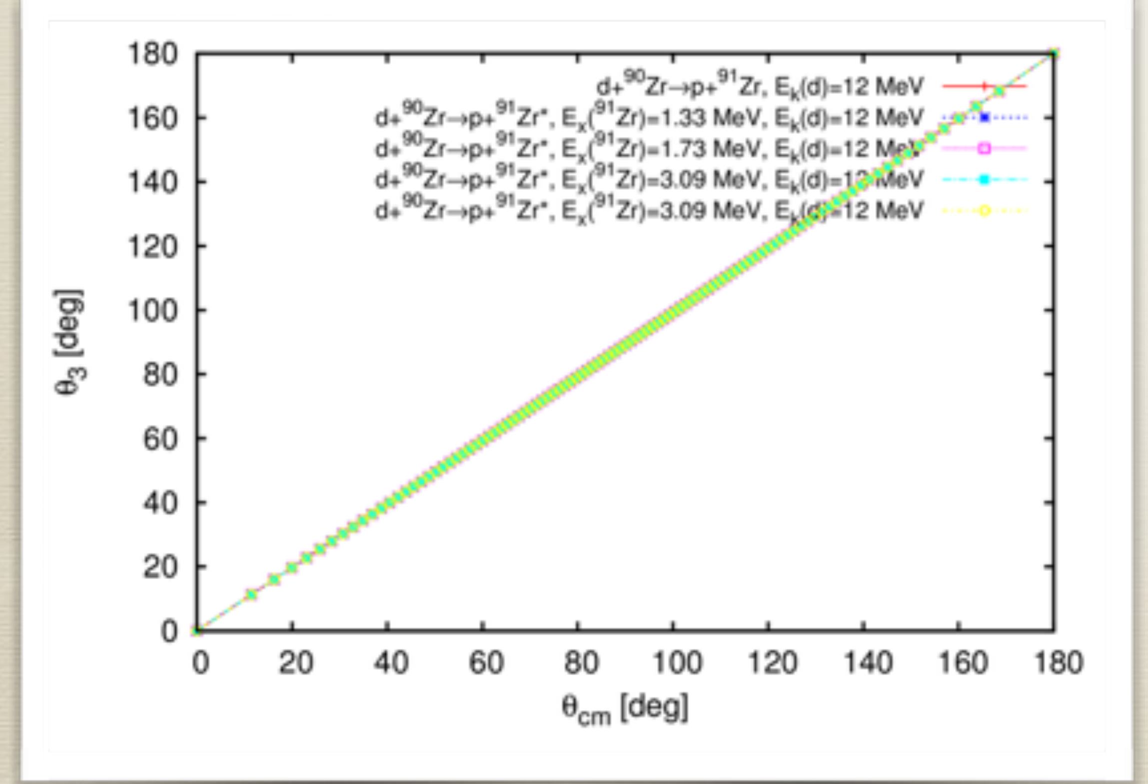
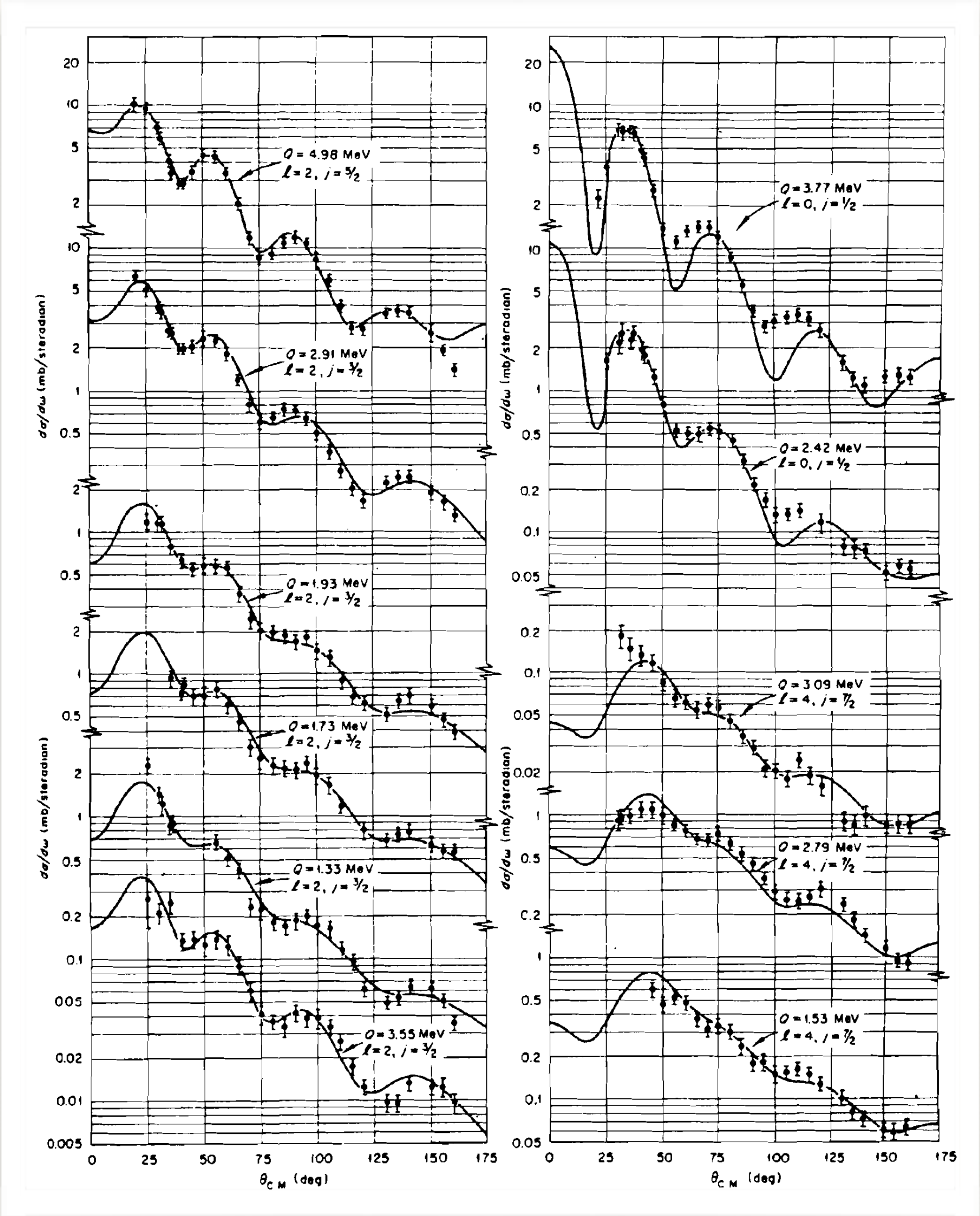
  - Detect the scattered particle emerging from target
- Use direct reactions to study static properties of nuclei
  - Populate levels in heavy residue → level scheme
  - Measure energy and angular distribution of scattered particle → spins and parities of states
  - Measure cross sections and compare to reaction calculations → spectroscopic factors

The ^{90}Zr(d,p)^{91}Zr reaction







^{90}Zr(d,p)^{91}Zr @ 6 MeV/u to 1g, 2d, 3s orbitals
H. Feshbach, Nuclear Reactions, Wiley & Sons (1992)

Issue n°1: inverse kinematics!

- (d,p) reaction in direct kinematics

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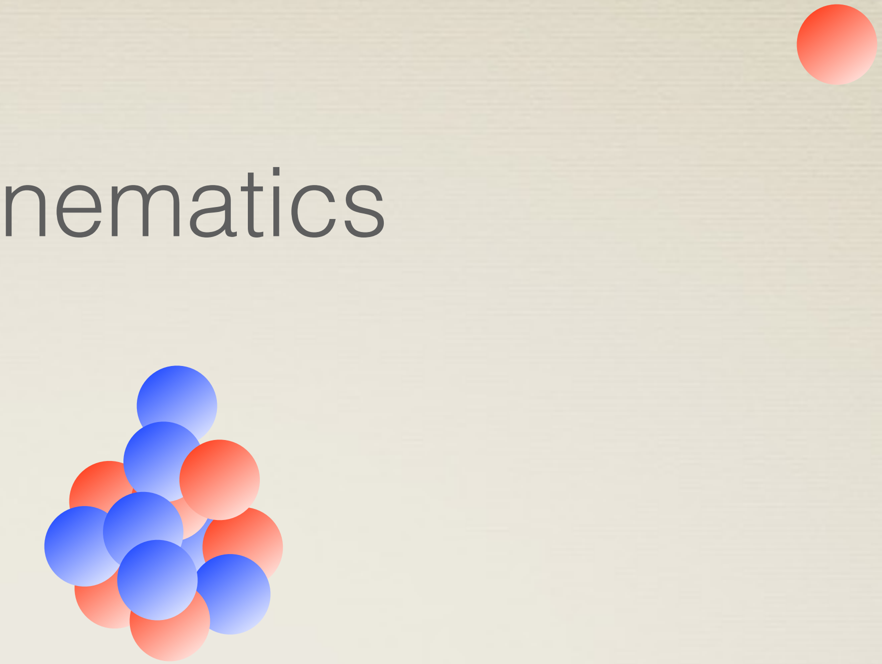
- (d,p) reaction in direct kinematics



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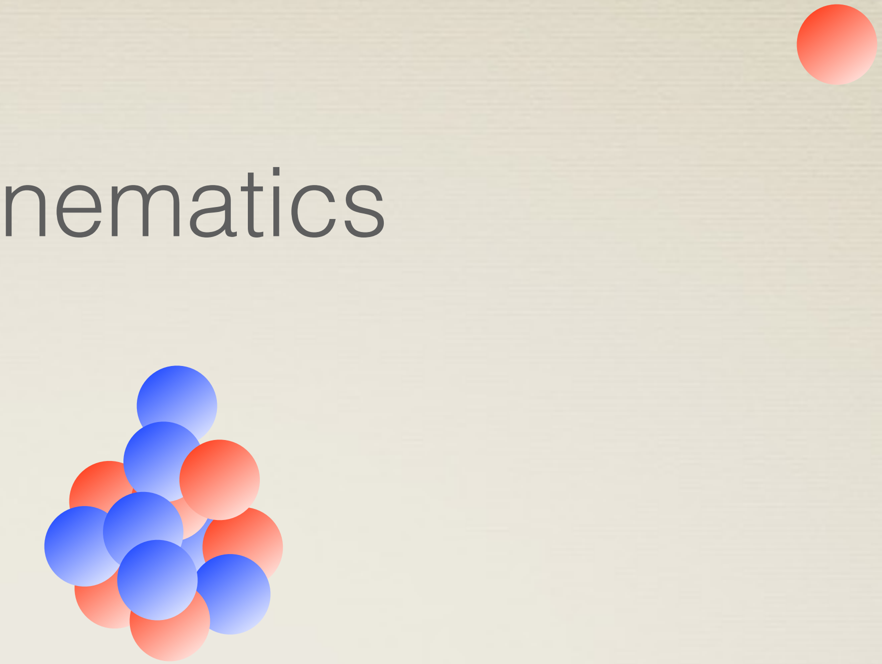

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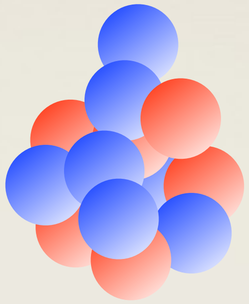

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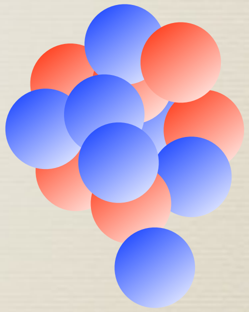
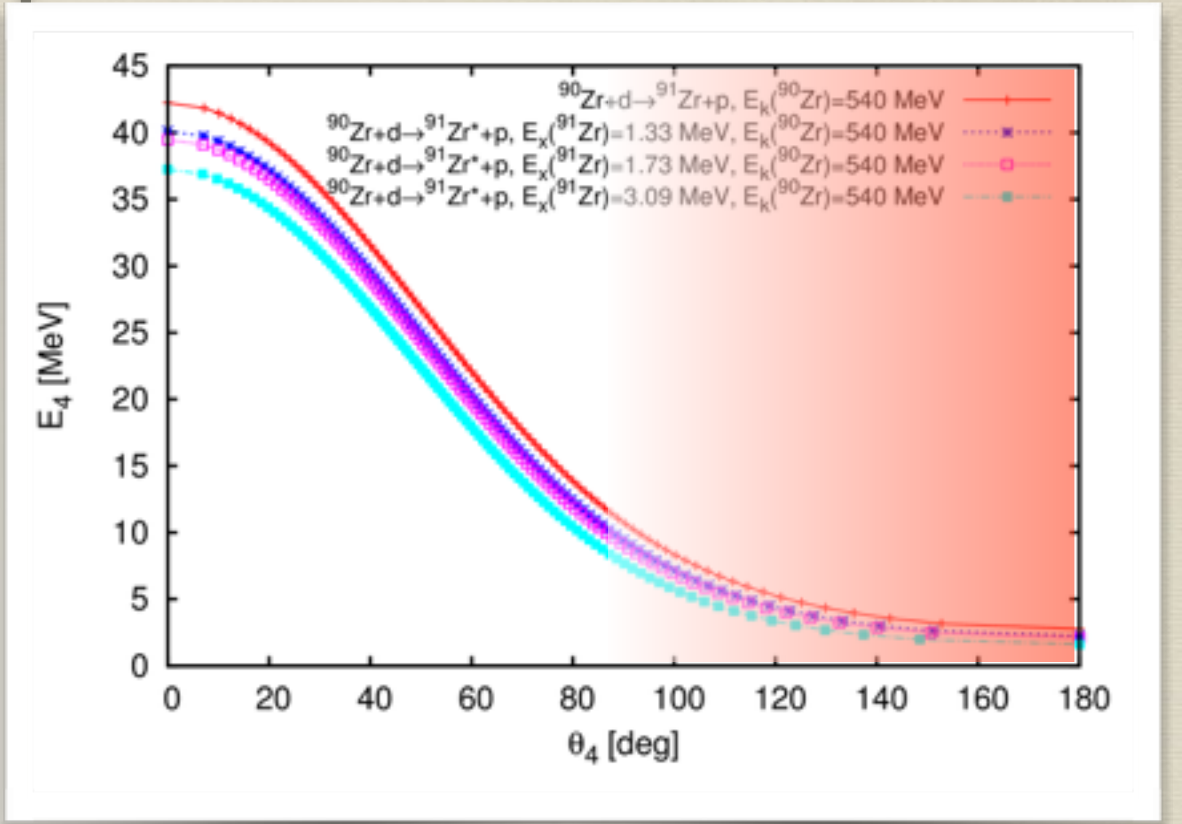
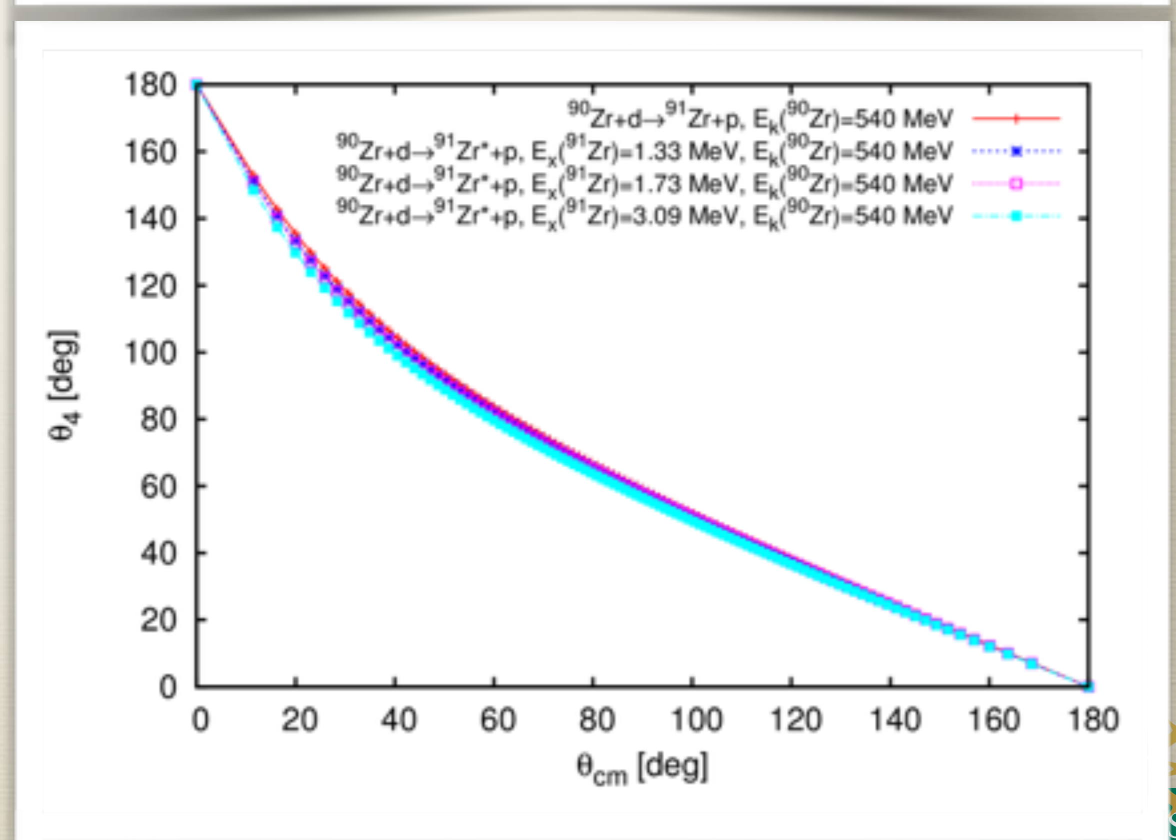


Backwards!

d(^{90}Zr, ^{91}Zr)p reaction

- What happened!





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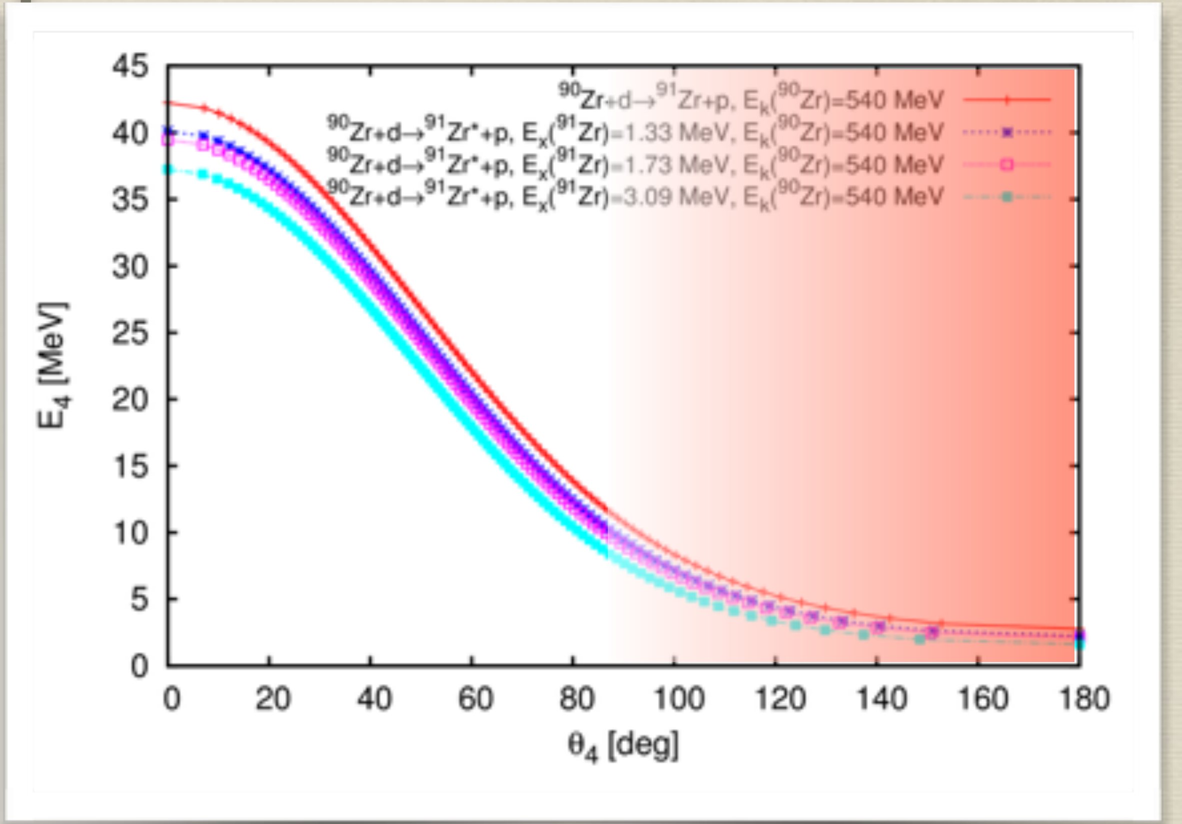

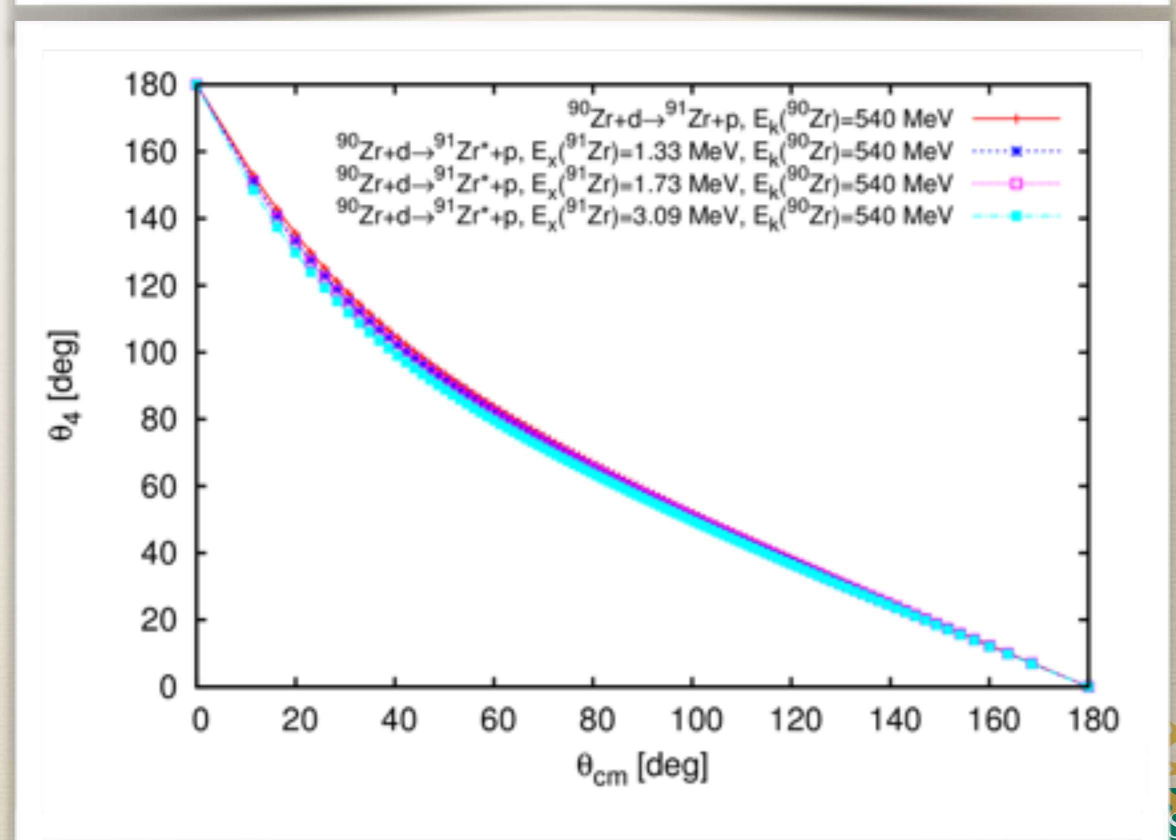

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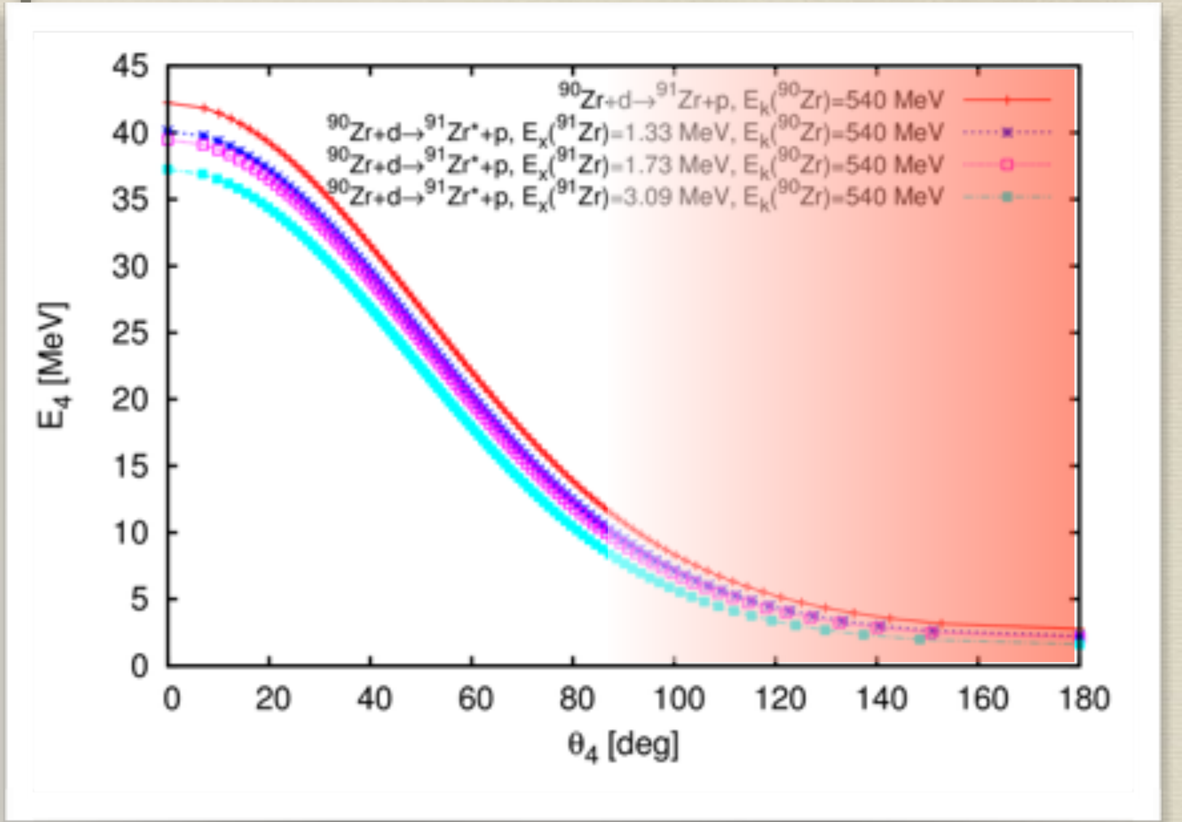

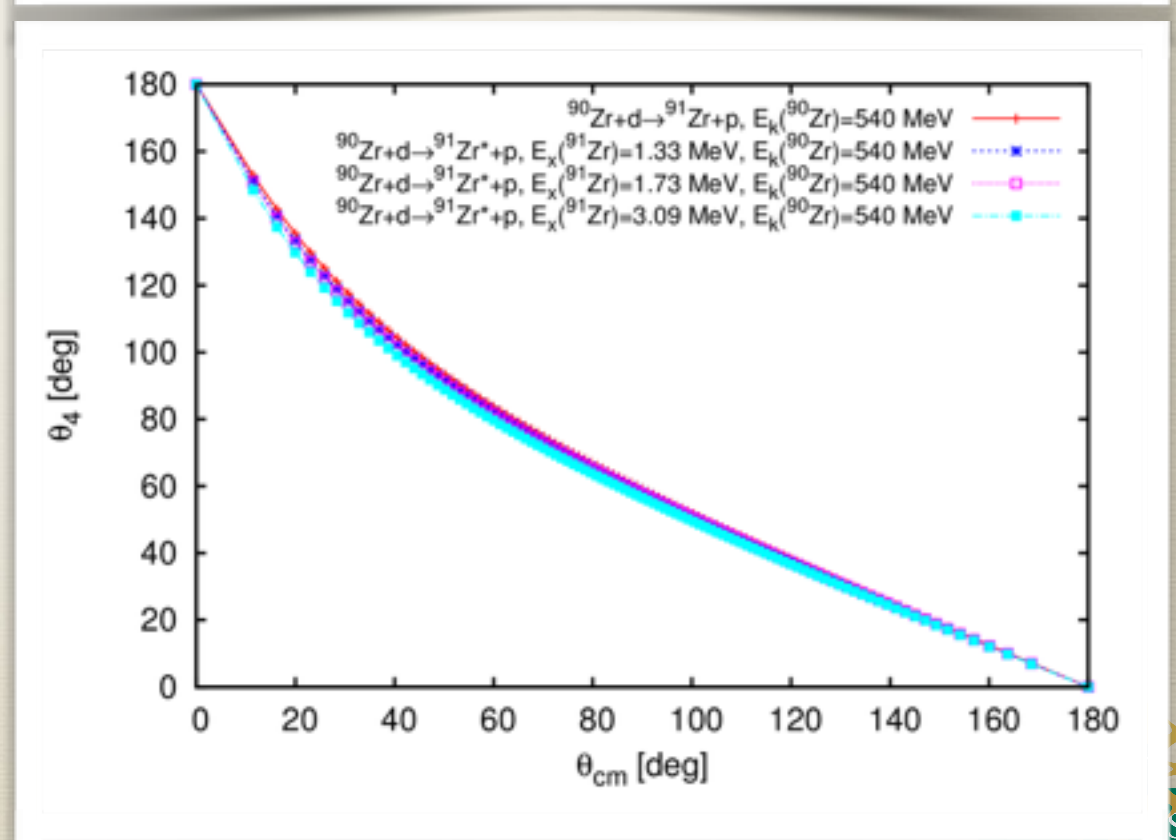

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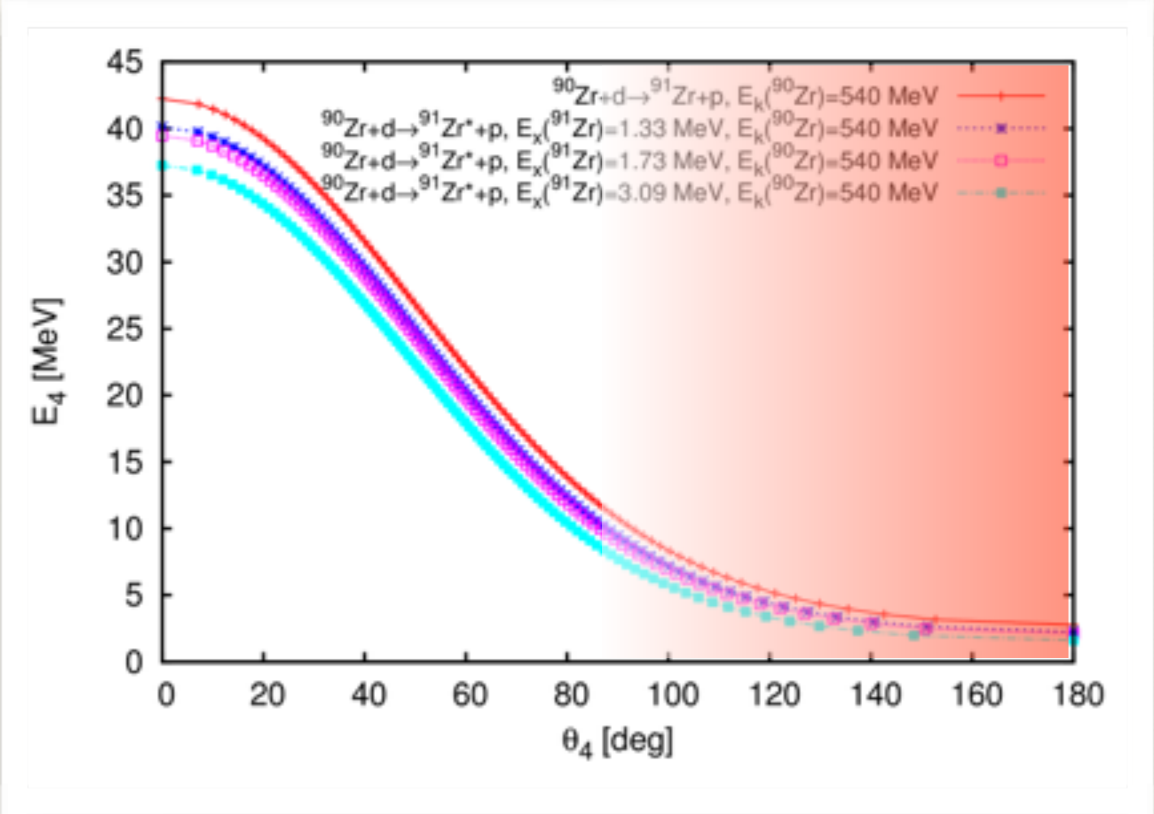

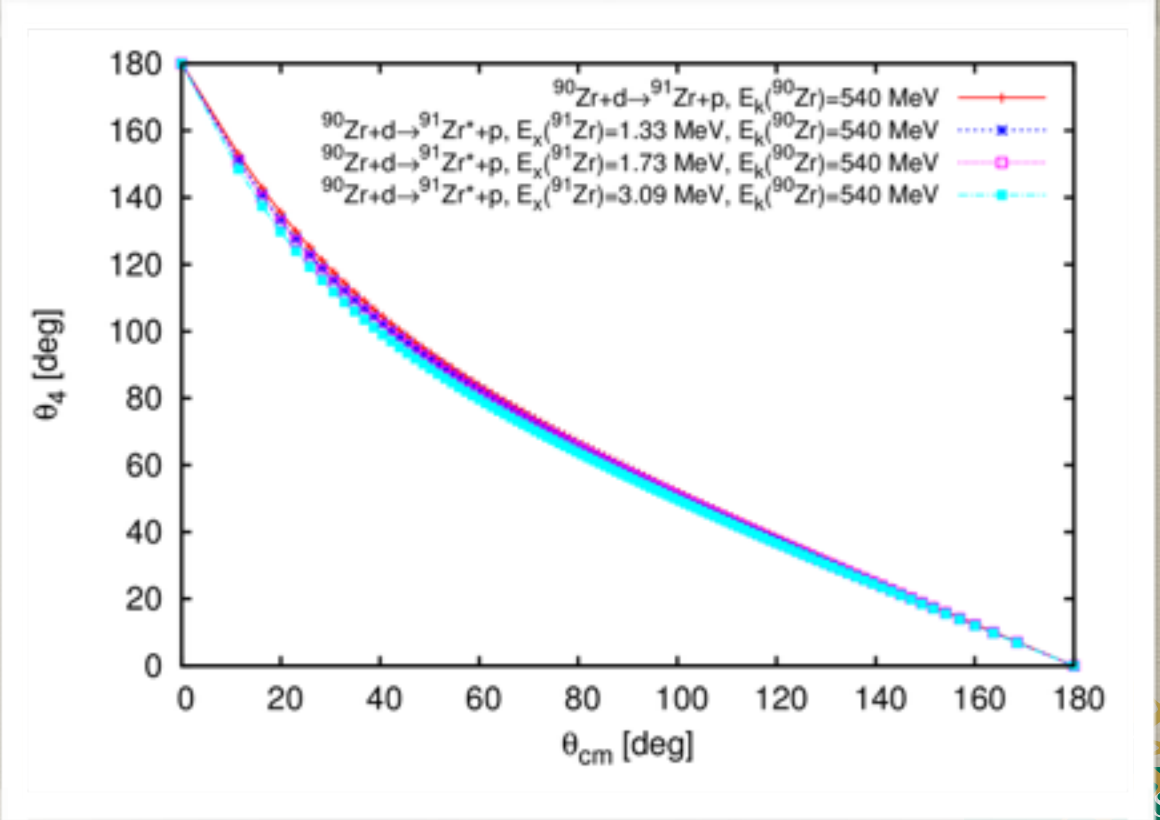

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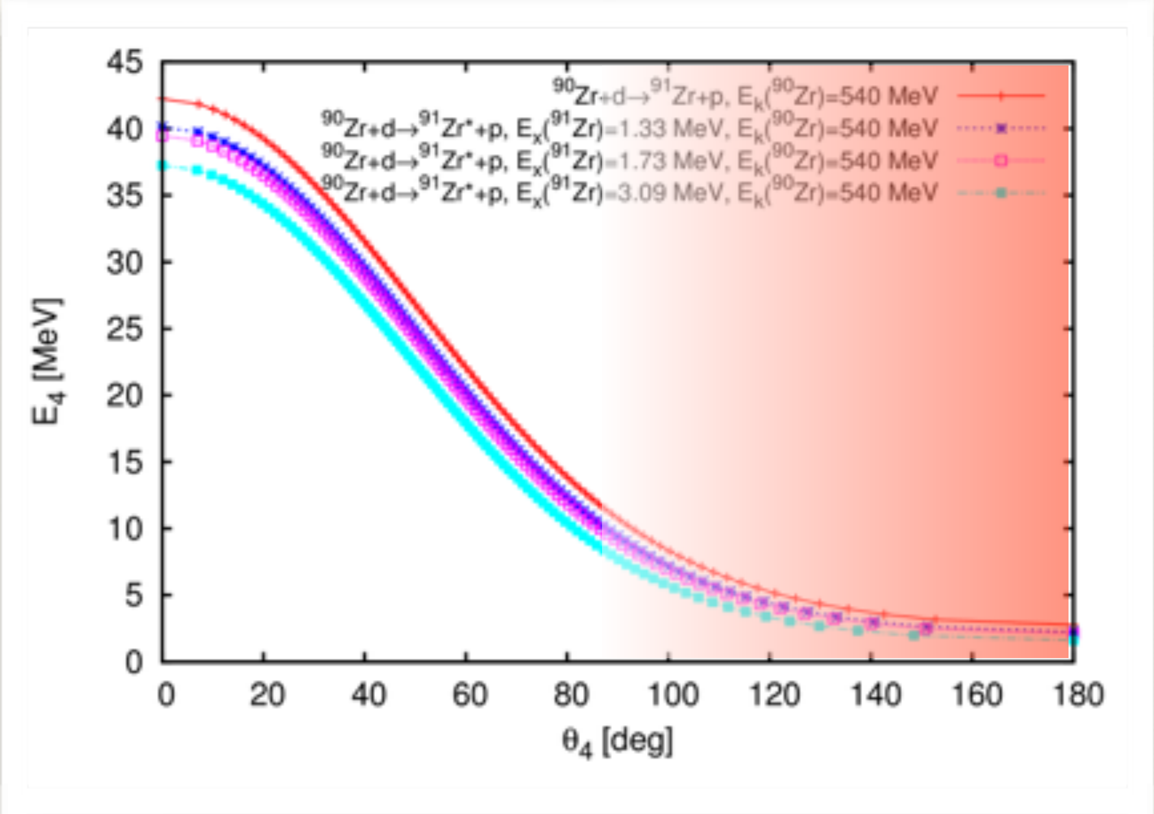

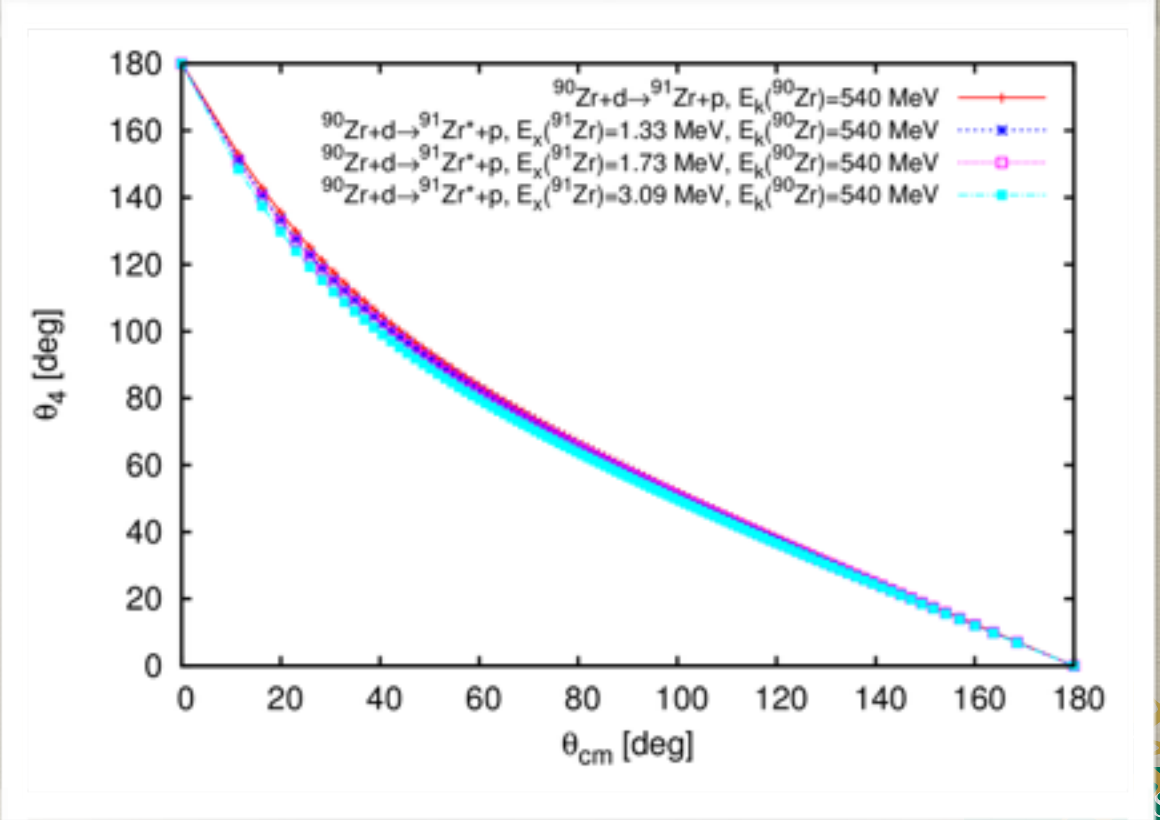

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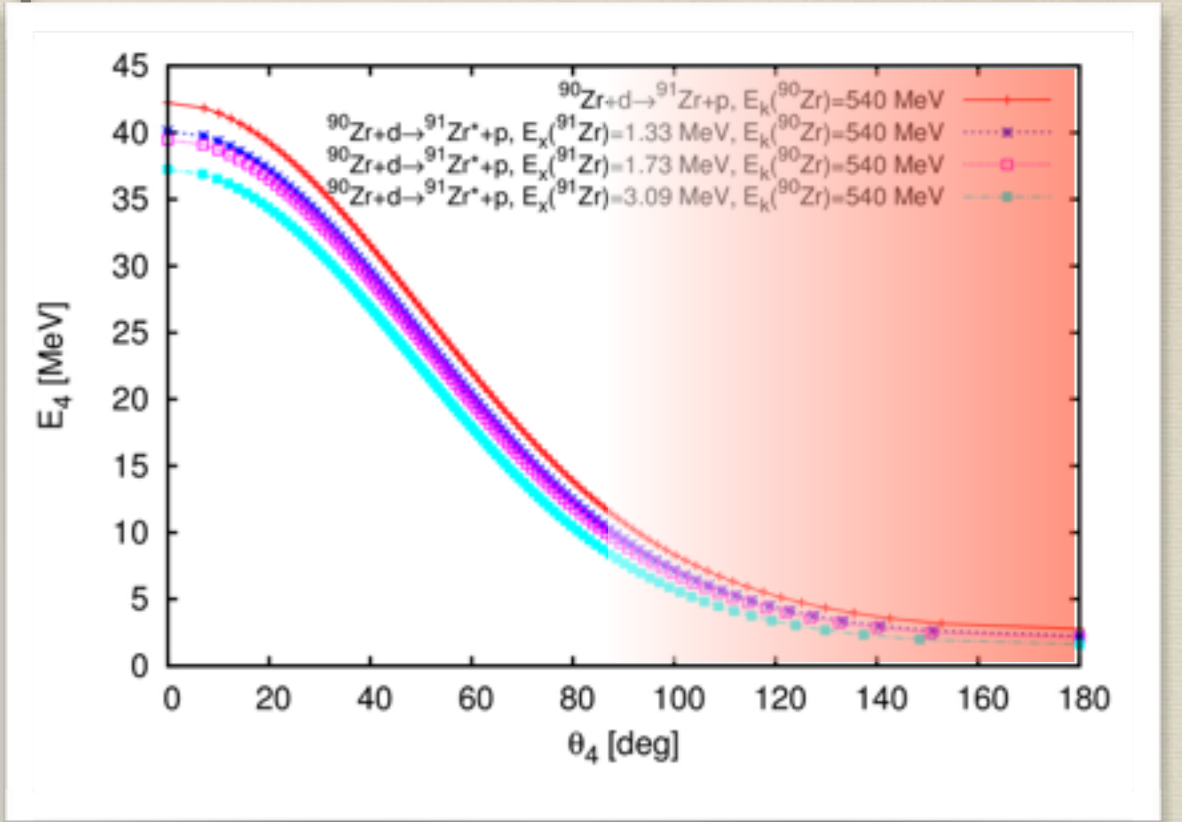
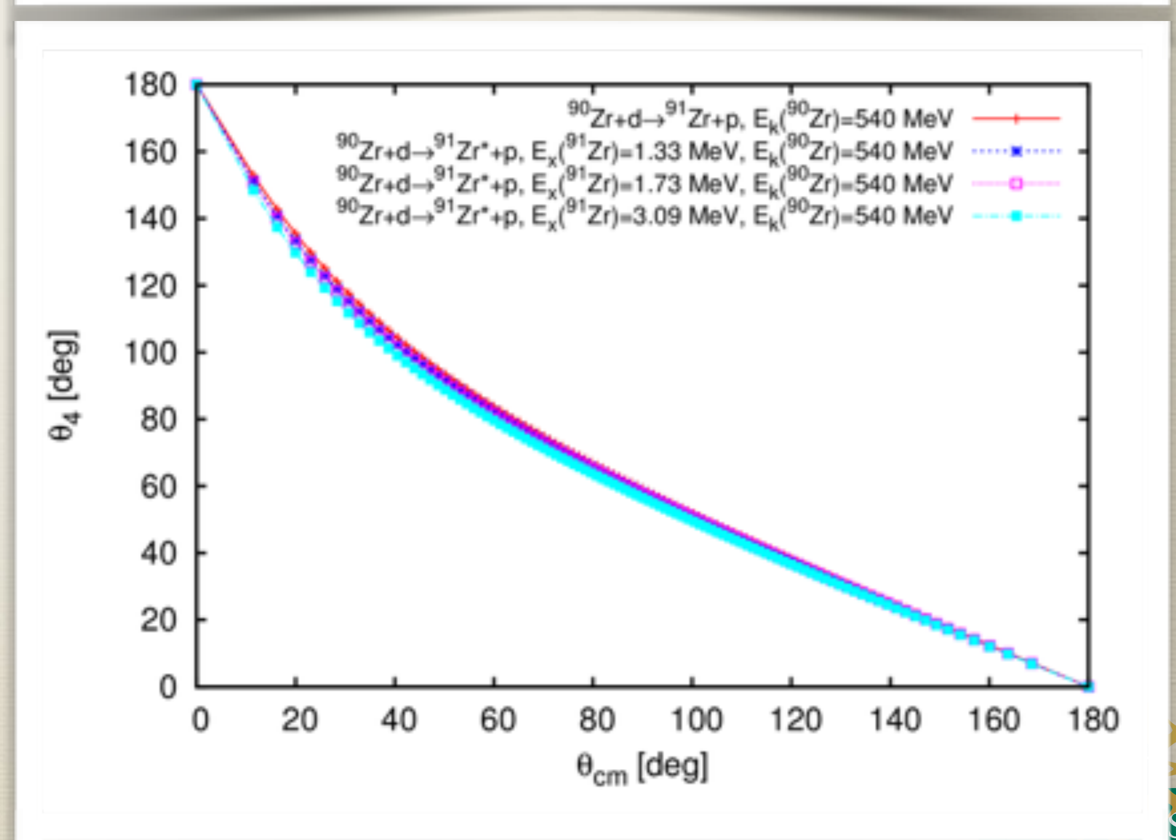
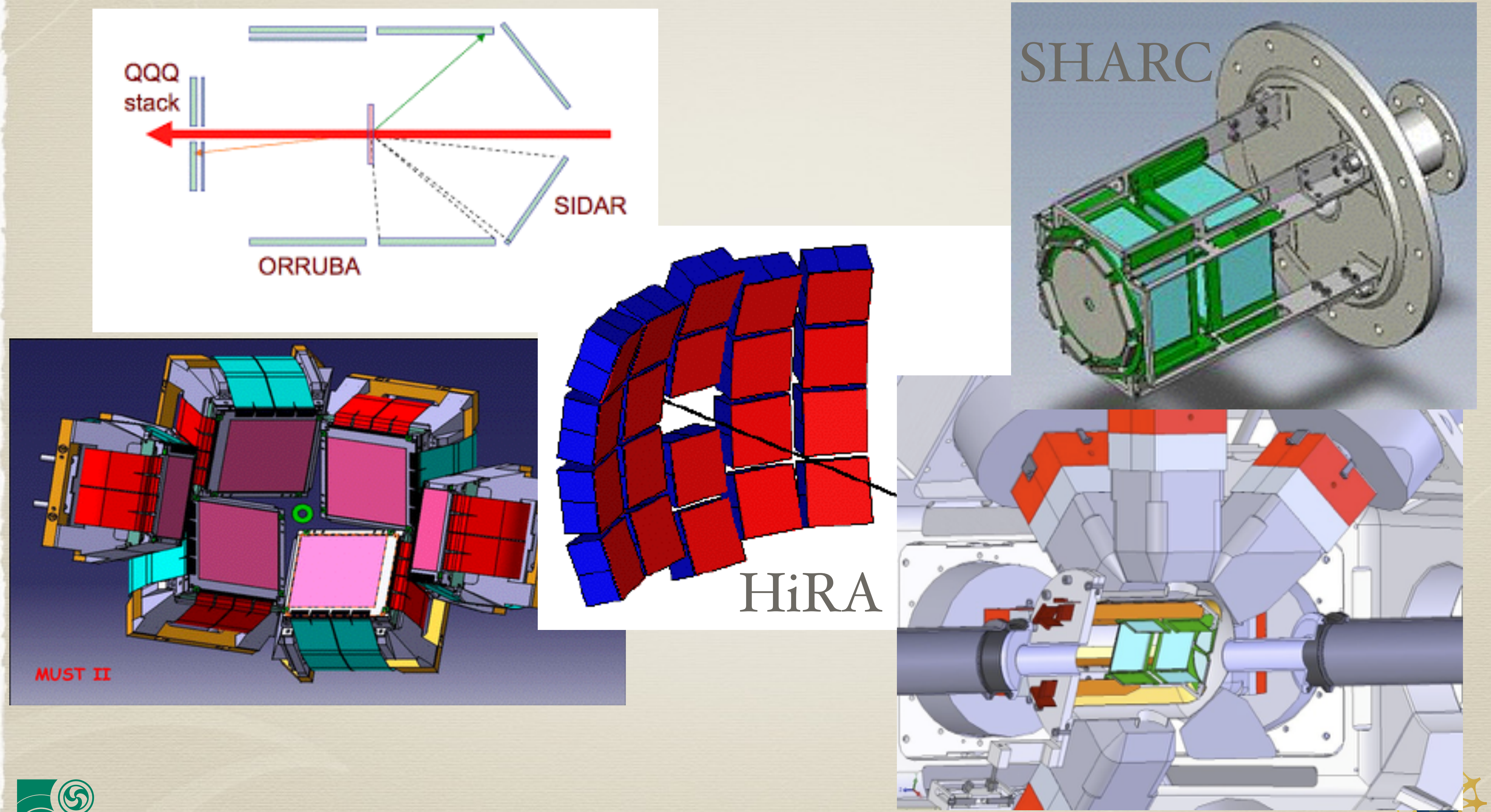
  - More difficult for proton to emerge from target
  - Proton energies much more dependent on scattering angle





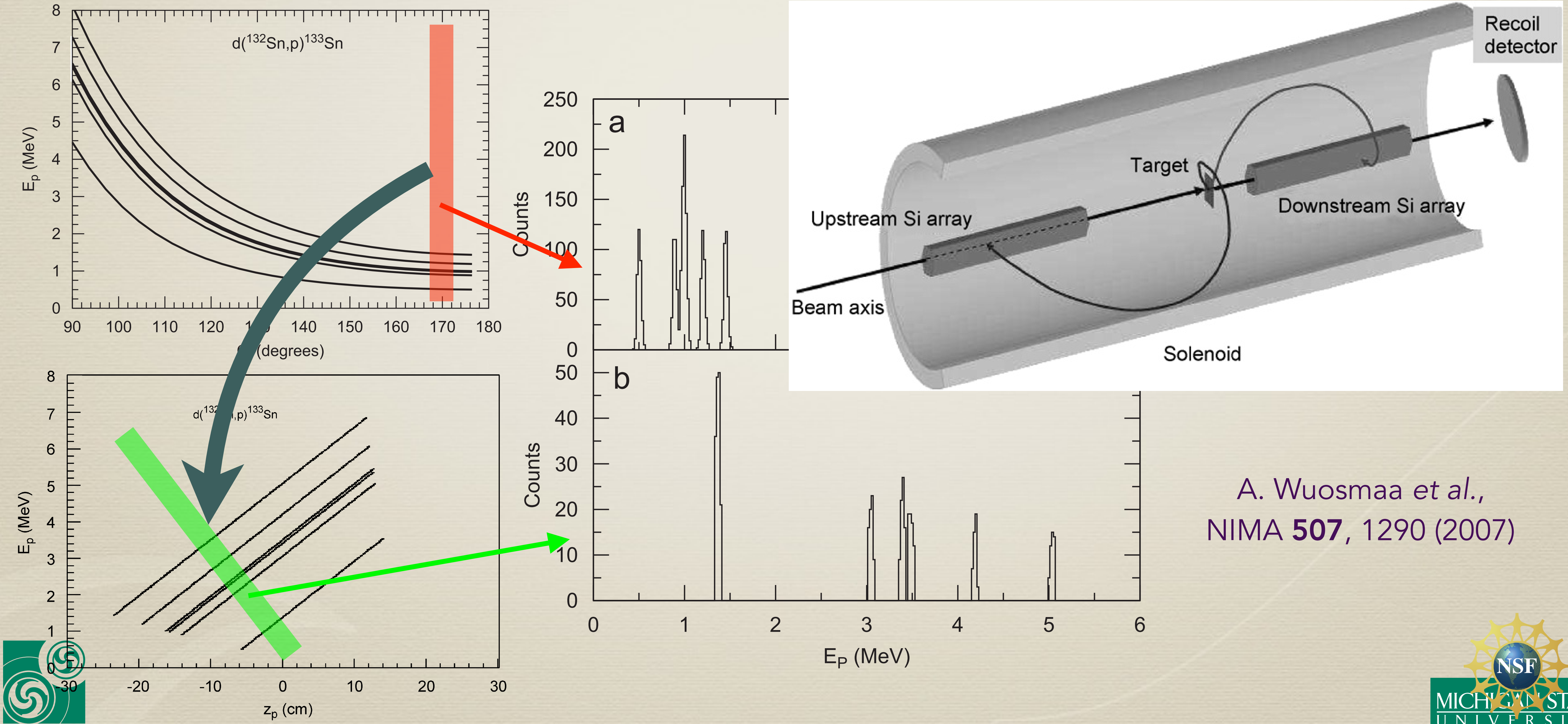
Solutions…

- Cover as much solid angle as possible



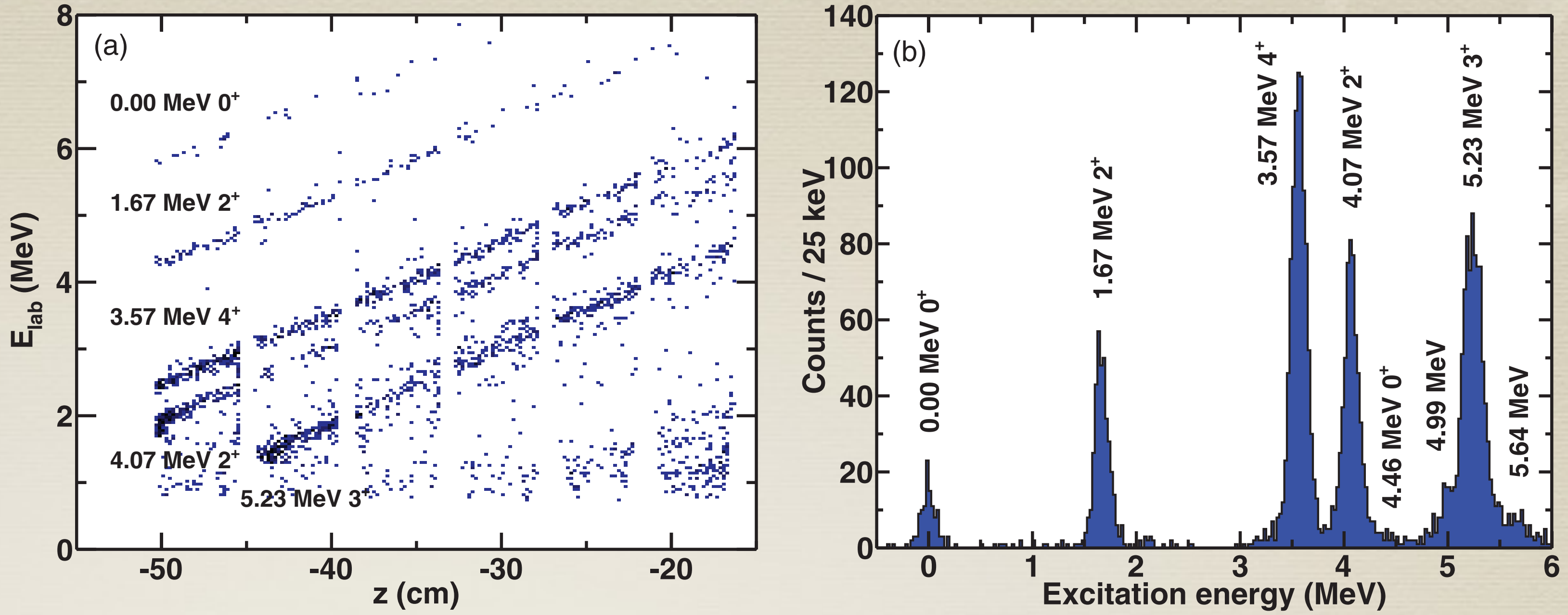
Helios: solving inverse kinematics

- Kinematic compression of energies
  - Solenoid spectrometer directly measures center-of-mass energies
  - Large angular acceptance within solenoid boundaries

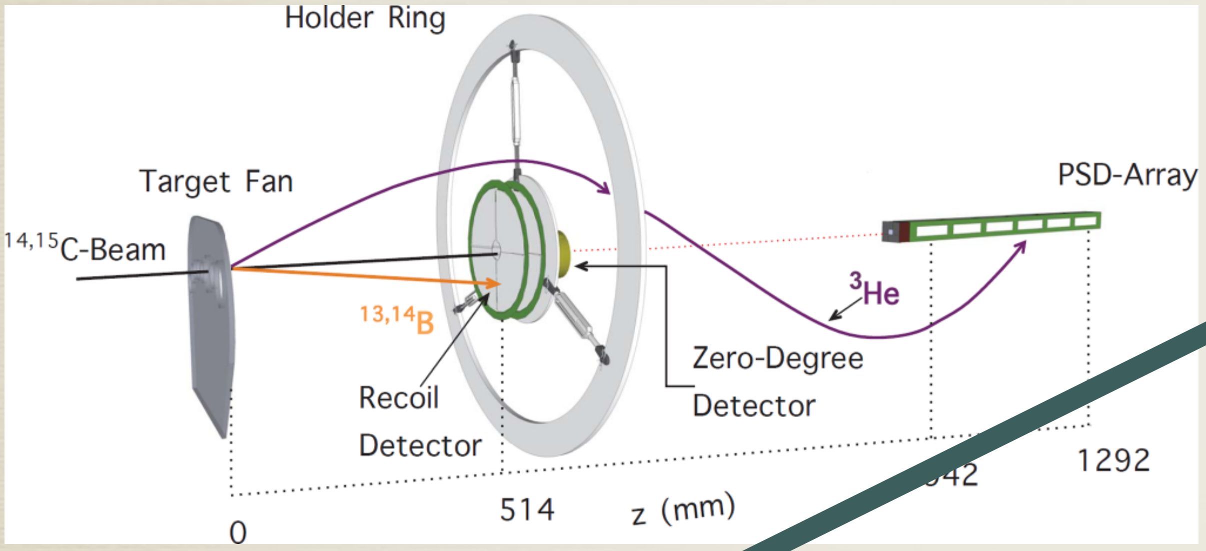


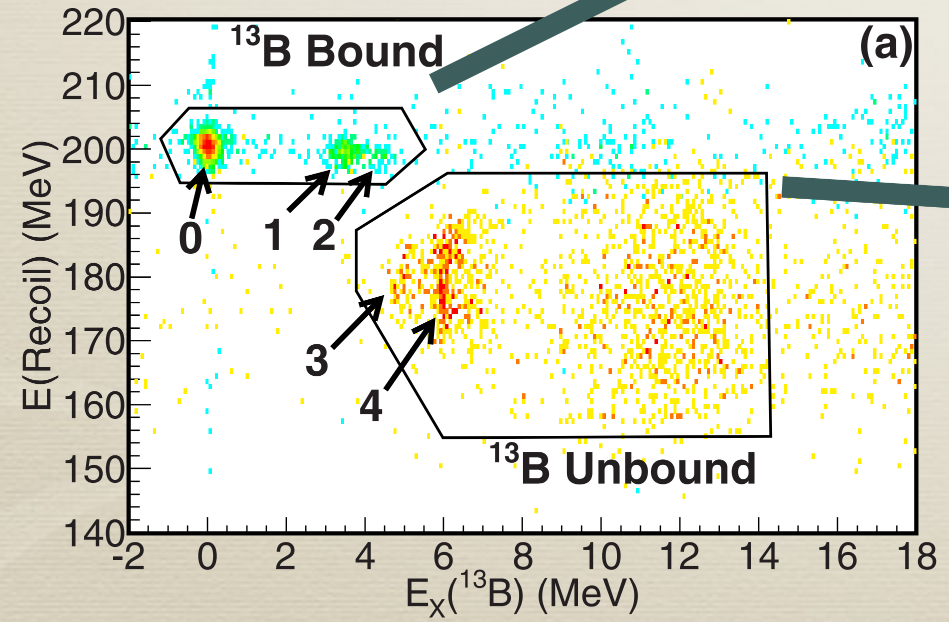
A. Wuosmaa *et al.*,
NIMA **507**, 1290 (2007)

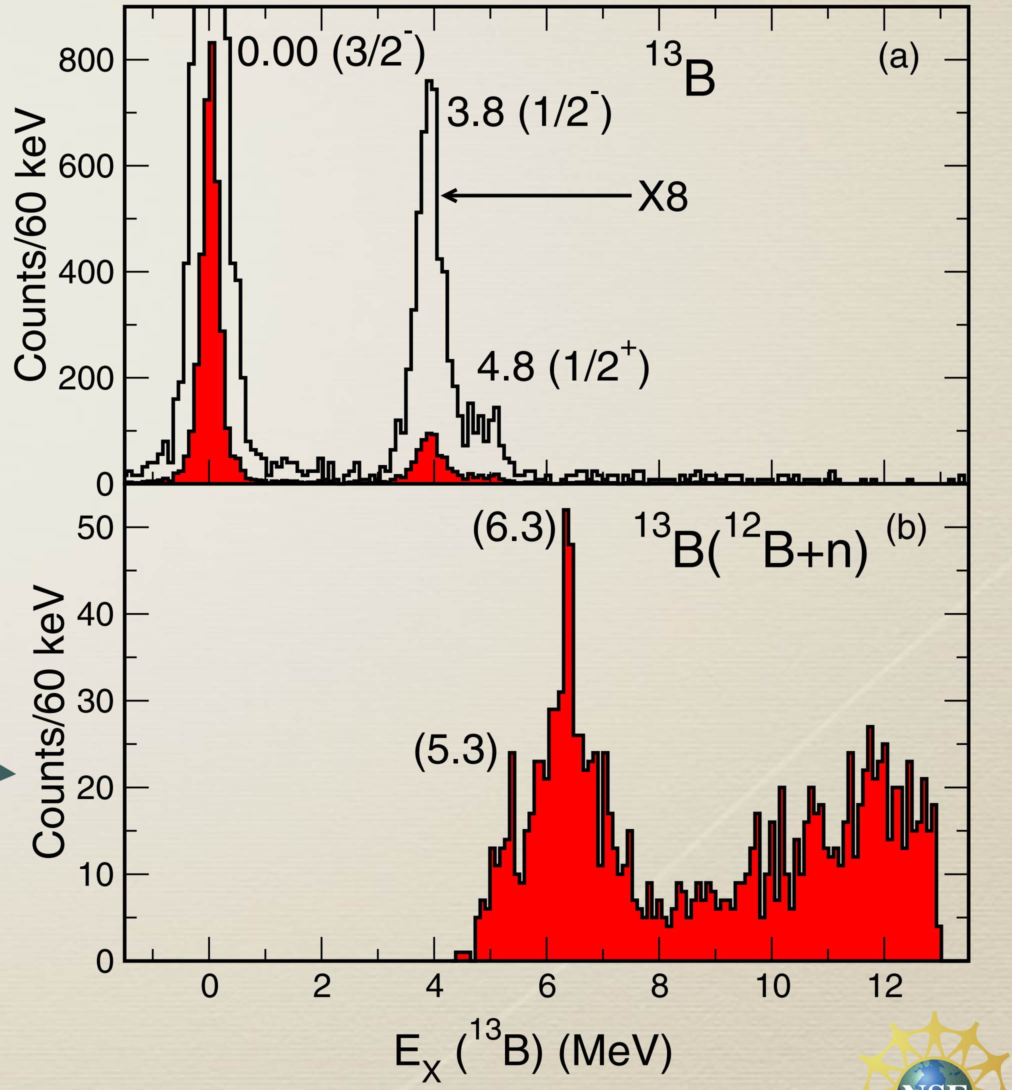
$^{19}O(d,p)^{20}O$



$^{14}C(d,{}^{3}He)^{13}B$







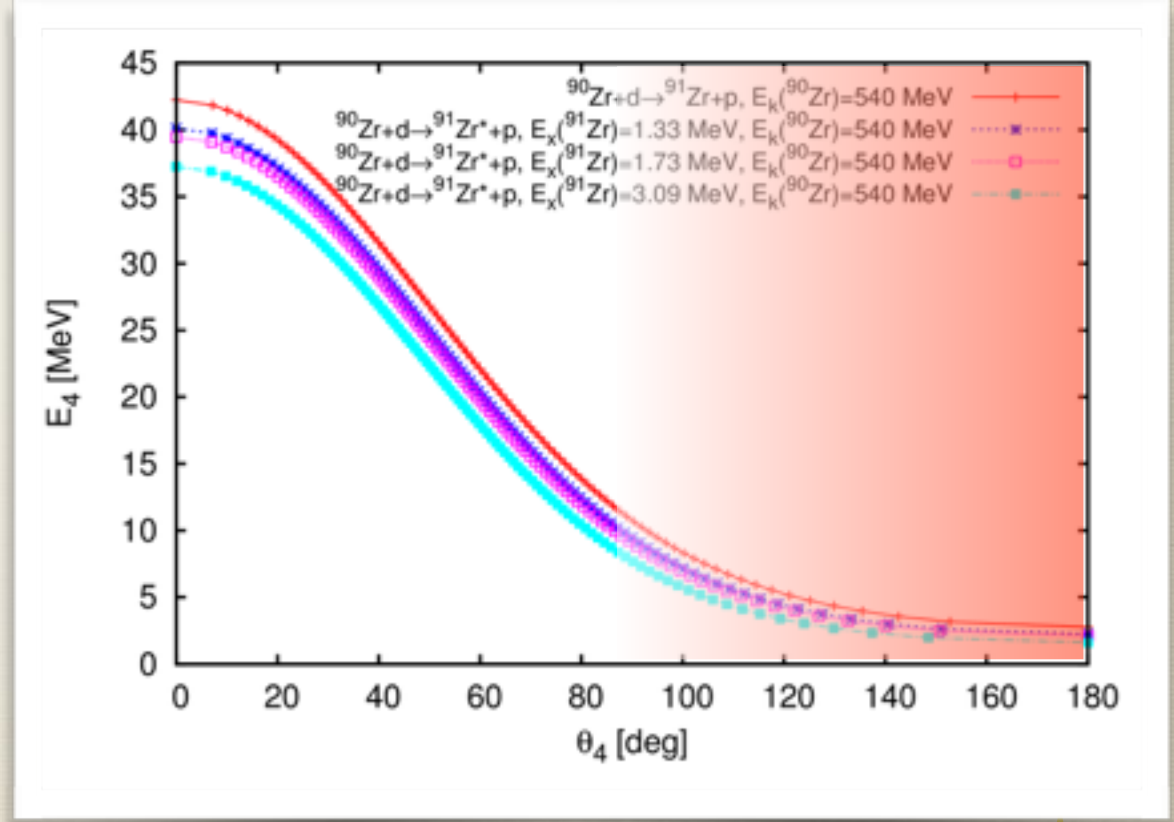
S. Bedoor *et al.*, PRC **93**, 044323 (2016)

Issue n°2: luminosity!

Event rate in detector $\frac{dR}{dt} = L\sigma_R$ Cross section

$L = \phi\varrho \boxed{l\varepsilon}$

beam flux
target density
target thickness
detector efficiency



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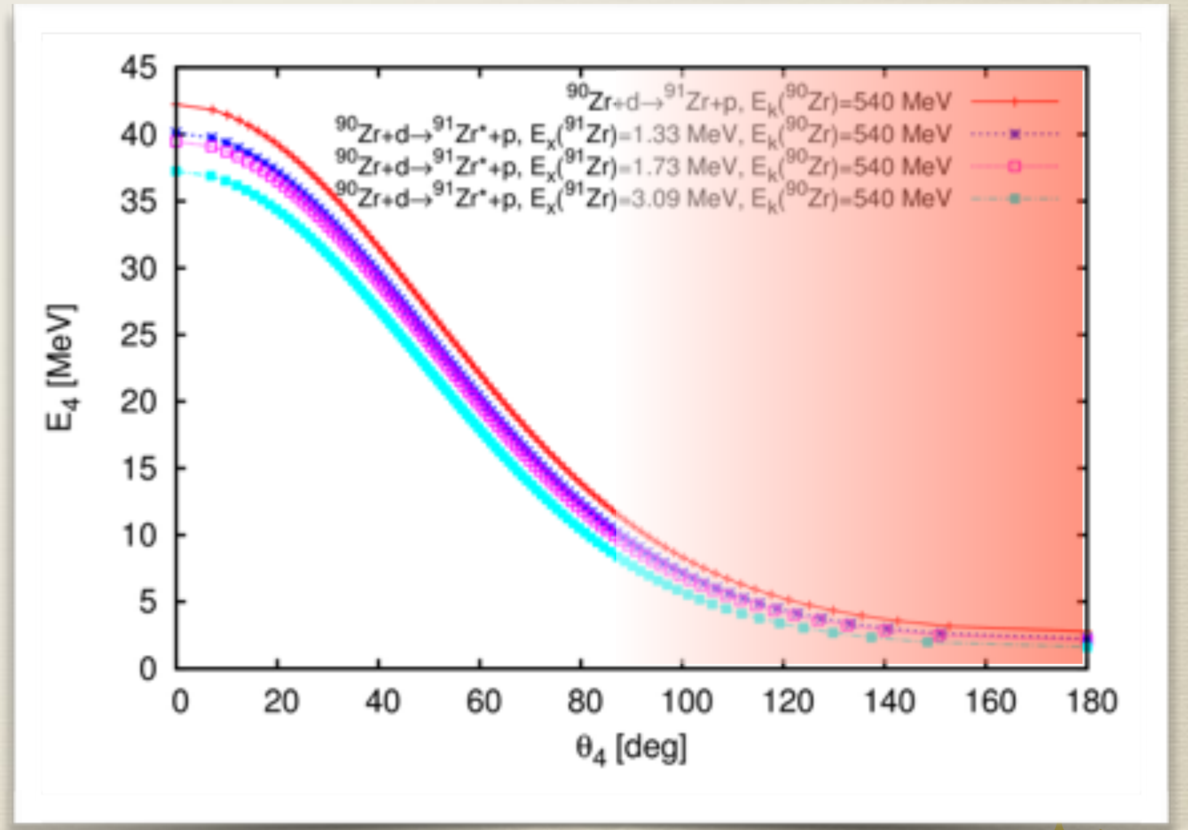

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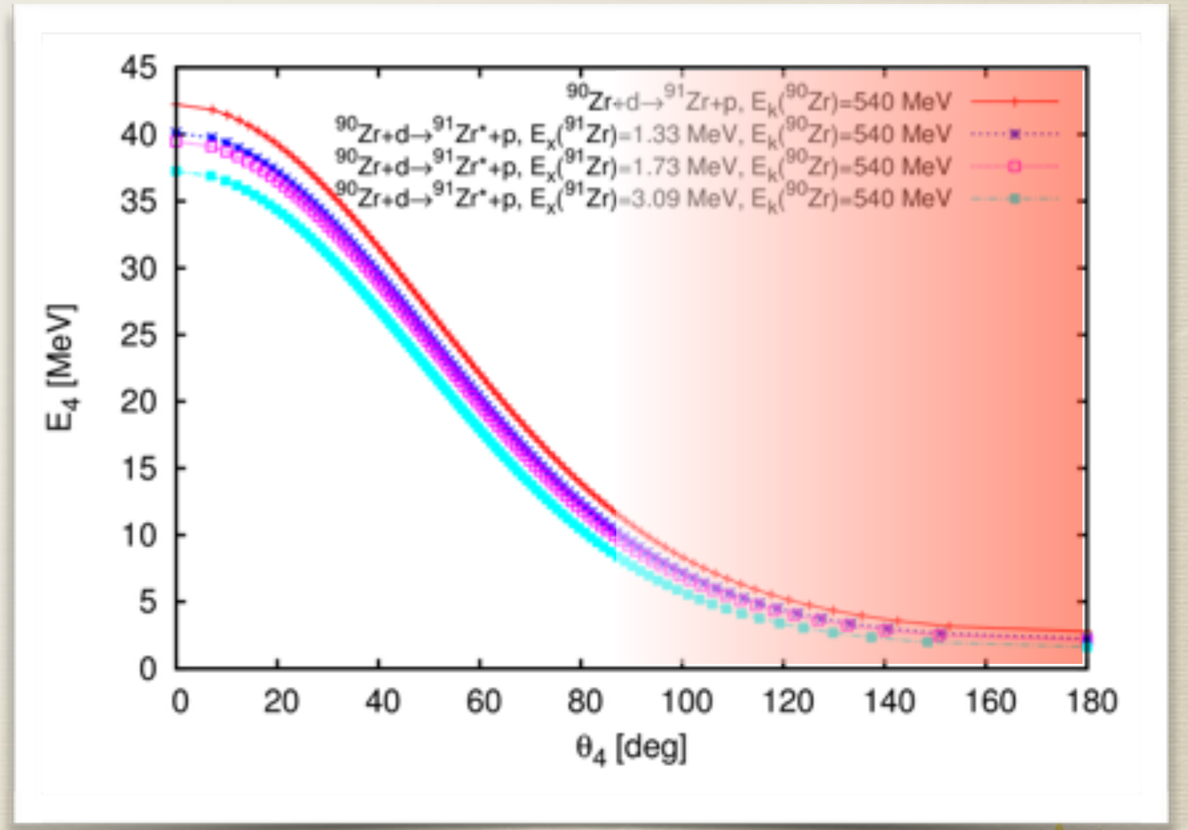
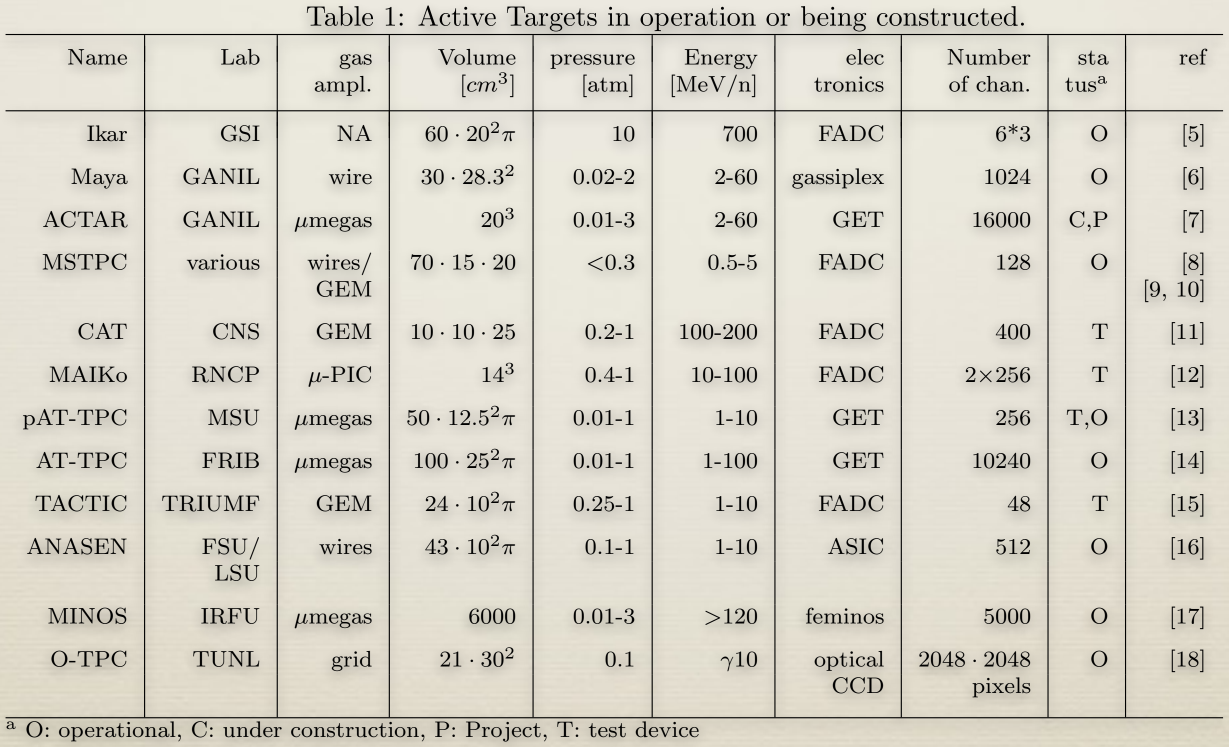
- Radioactive beams are weak
  - Intensities several orders of magnitude smaller than stable beams
  - New experimental techniques needed!



The rise of Active Targets

- Solving the “too thick target” problem
  - Active Target: target no longer inert material, but used also to detect particles and/or determine vertex position



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Ikar	GSI	NA	$60 \cdot 20^2\pi$	10	700	FADC	6*3	O	[5]
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CAT	CNS	GEM	$10 \cdot 10 \cdot 25$	0.2-1	100-200	FADC	400	T	[11]
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pAT-TPC	MSU	μmegas	$50 \cdot 12.5^2\pi$	0.01-1	1-10	GET	256	T,O	[13]
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O-TPC	TUNL	grid	$21 \cdot 30^2$	0.1	γ10	optical CCD	$2048 \cdot 2048$ pixels	O	[18]

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S. Beceiro-Novo *et al.*, PPNP **84**, 124 (2015)

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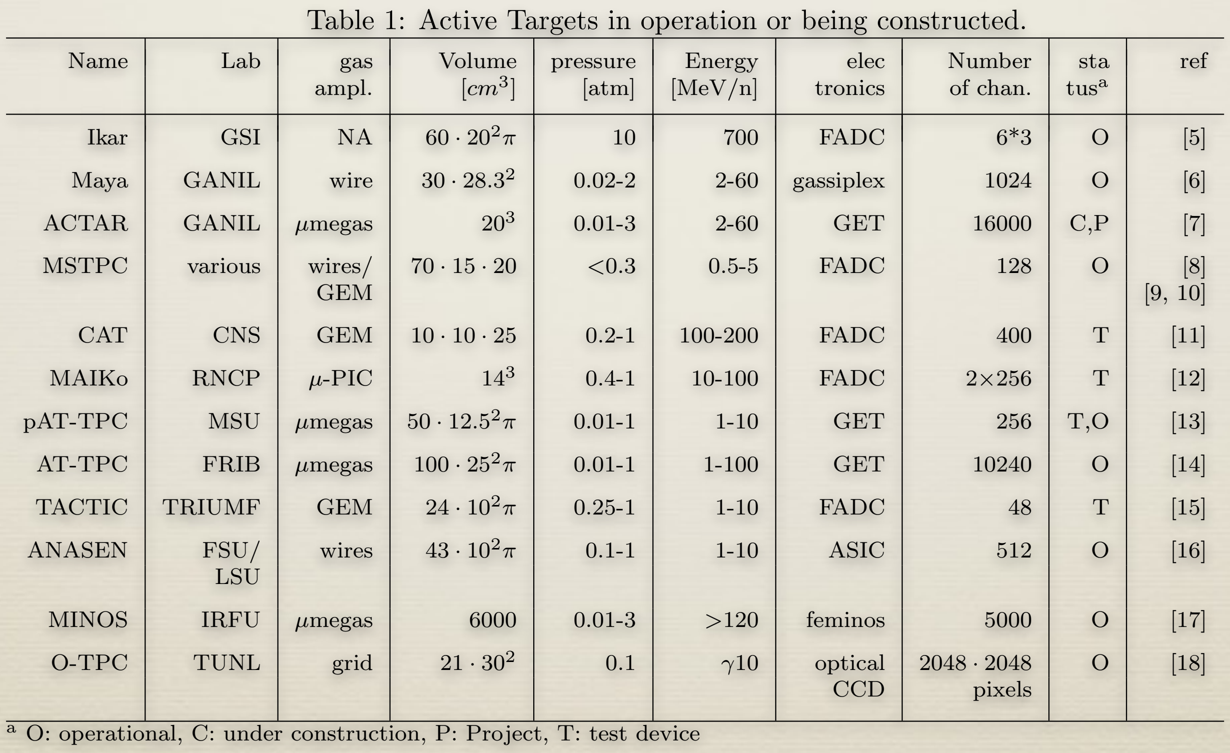

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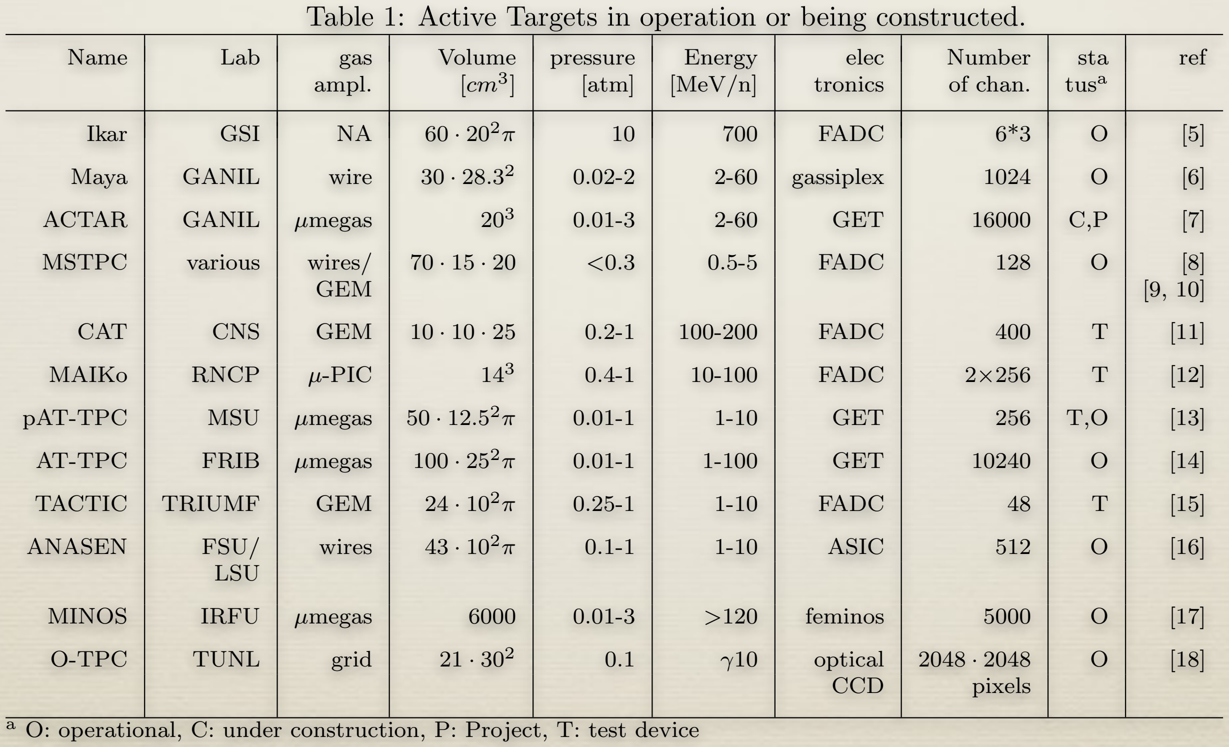

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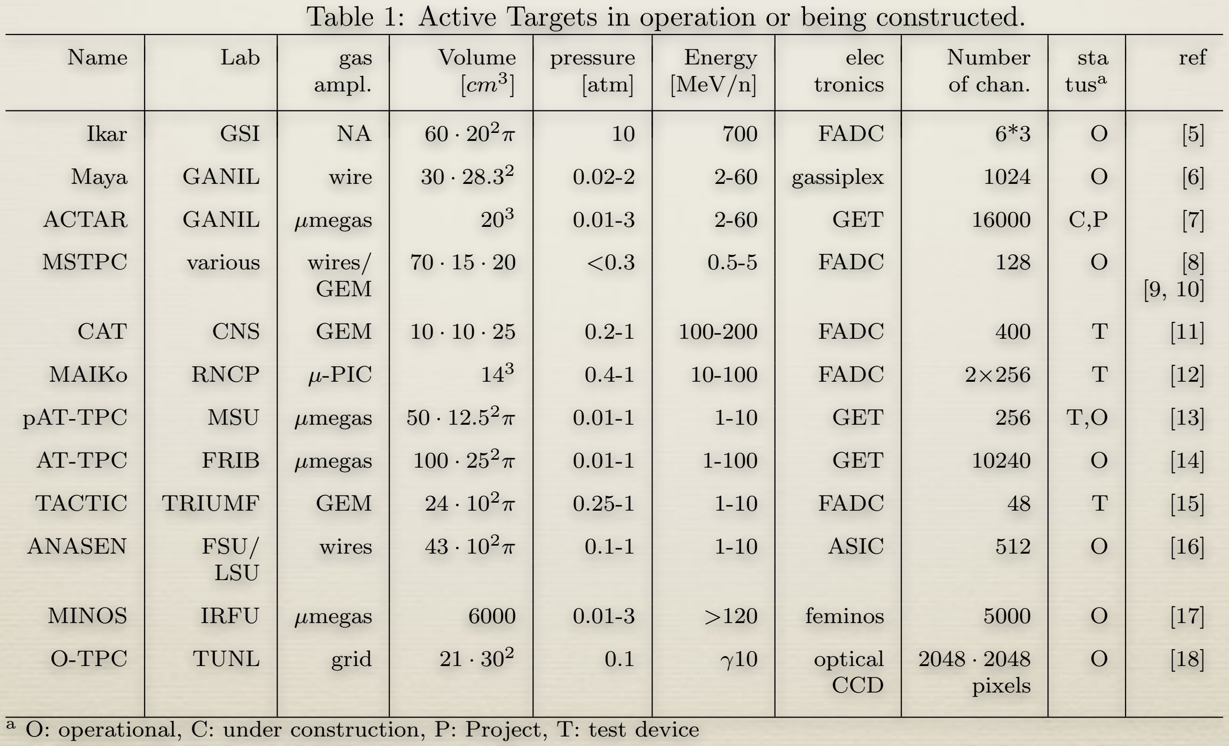

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MSTPC	various	wires/ GEM	$70 \cdot 15 \cdot 20$	<0.3	0.5-5	FADC	128	O	[8] [9, 10]
CAT	CNS	GEM	$10 \cdot 10 \cdot 25$	0.2-1	100-200	FADC	400	T	[11]
MAIKo	RNCP	μ-PIC	14^3	0.4-1	10-100	FADC	2×256	T	[12]
pAT-TPC	MSU	μmegas	$50 \cdot 12.5^2\pi$	0.01-1	1-10	GET	256	T,O	[13]
AT-TPC	FRIB	μmegas	$100 \cdot 25^2\pi$	0.01-1	1-100	GET	10240	O	[14]
TACTIC	TRIUMF	GEM	$24 \cdot 10^2\pi$	0.25-1	1-10	FADC	48	T	[15]
ANASEN	FSU/ LSU	wires	$43 \cdot 10^2\pi$	0.1-1	1-10	ASIC	512	O	[16]
MINOS	IRFU	μmegas	6000	0.01-3	>120	feminos	5000	O	[17]
O-TPC	TUNL	grid	$21 \cdot 30^2$	0.1	γ10	optical CCD	$2048 \cdot 2048$ pixels	O	[18]

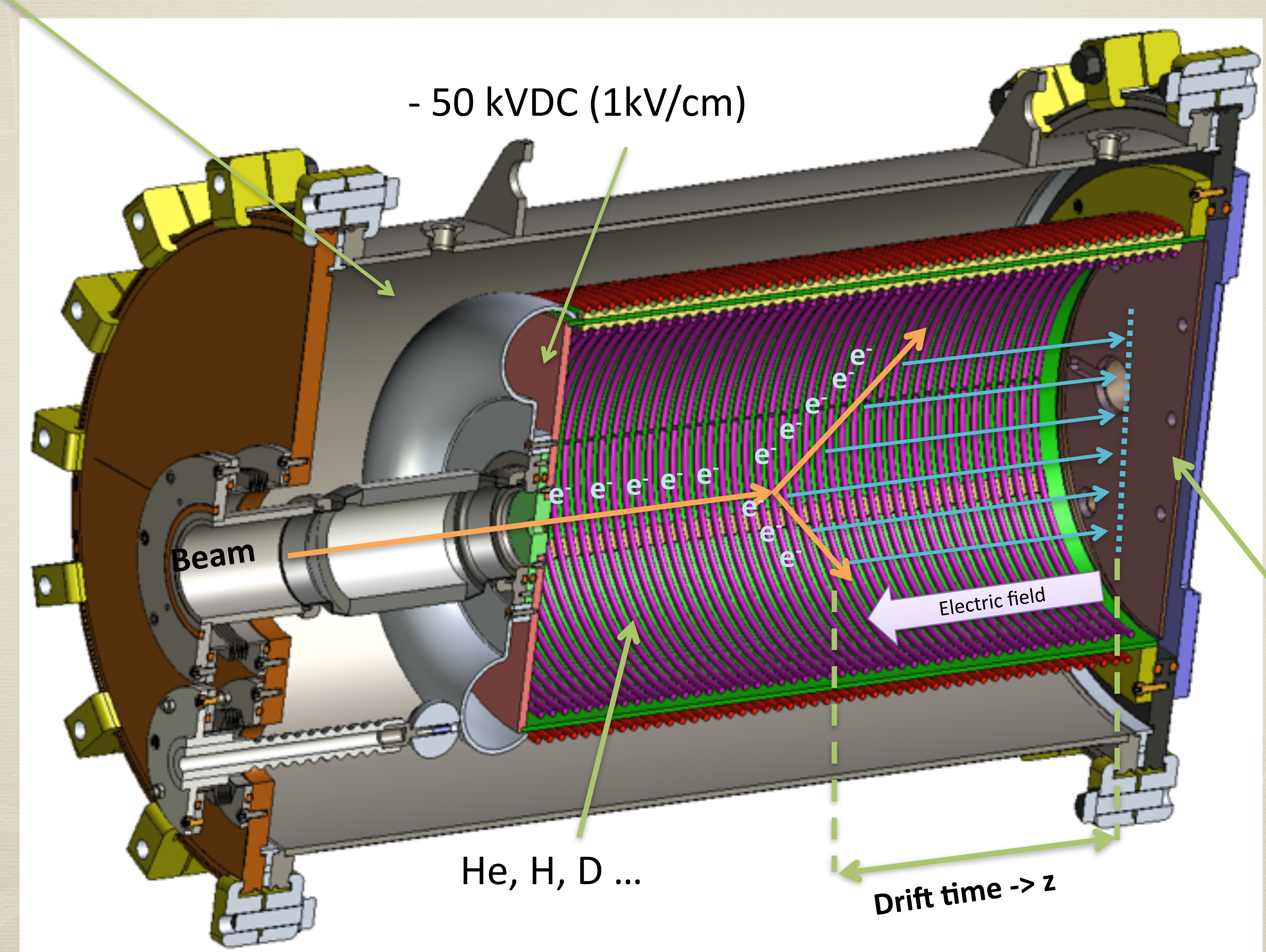
[a] O: operational, C: under construction, P: Project, T: test device

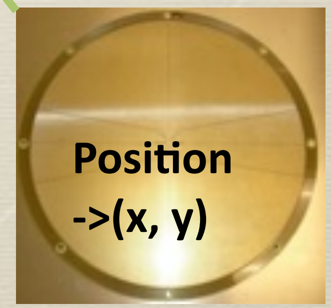
S. Beceiro-Novo *et al.*, PPNP **84**, 124 (2015)

Example: AT-TPC @ NSCL

Insulator gas volume

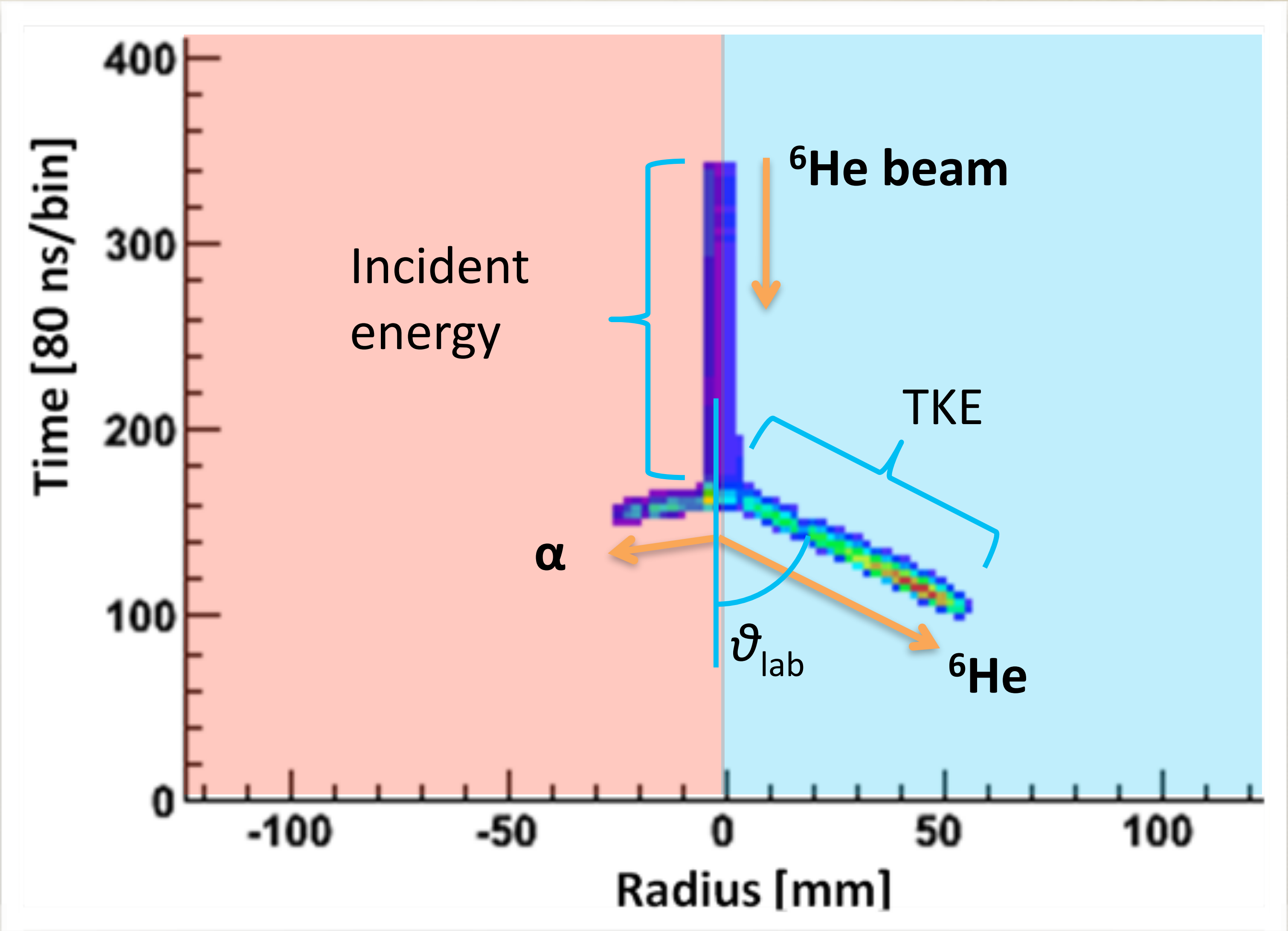
☐ N_2 gas 30 kV/cm x 6 cm = 180 kV



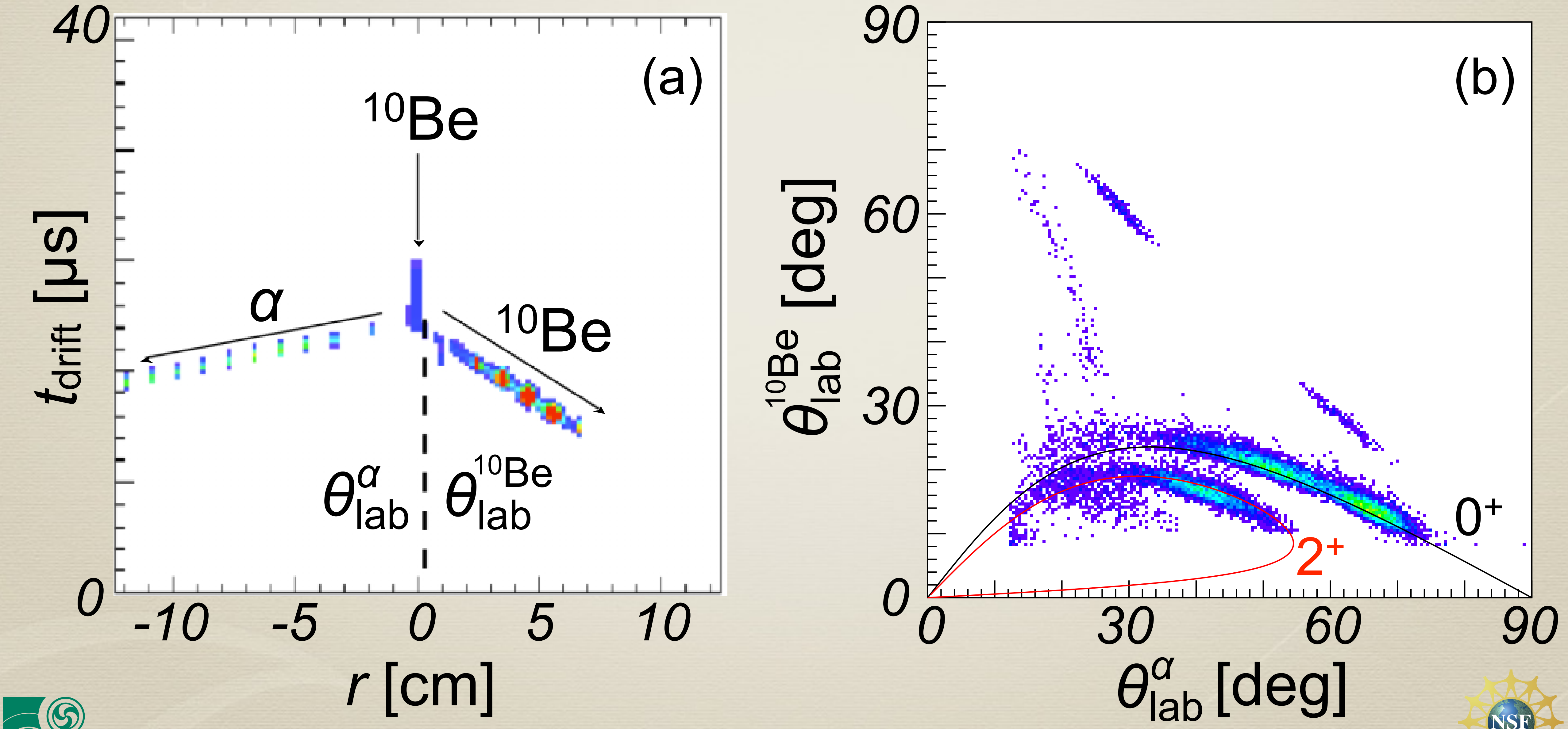


Tracking reactions inside target

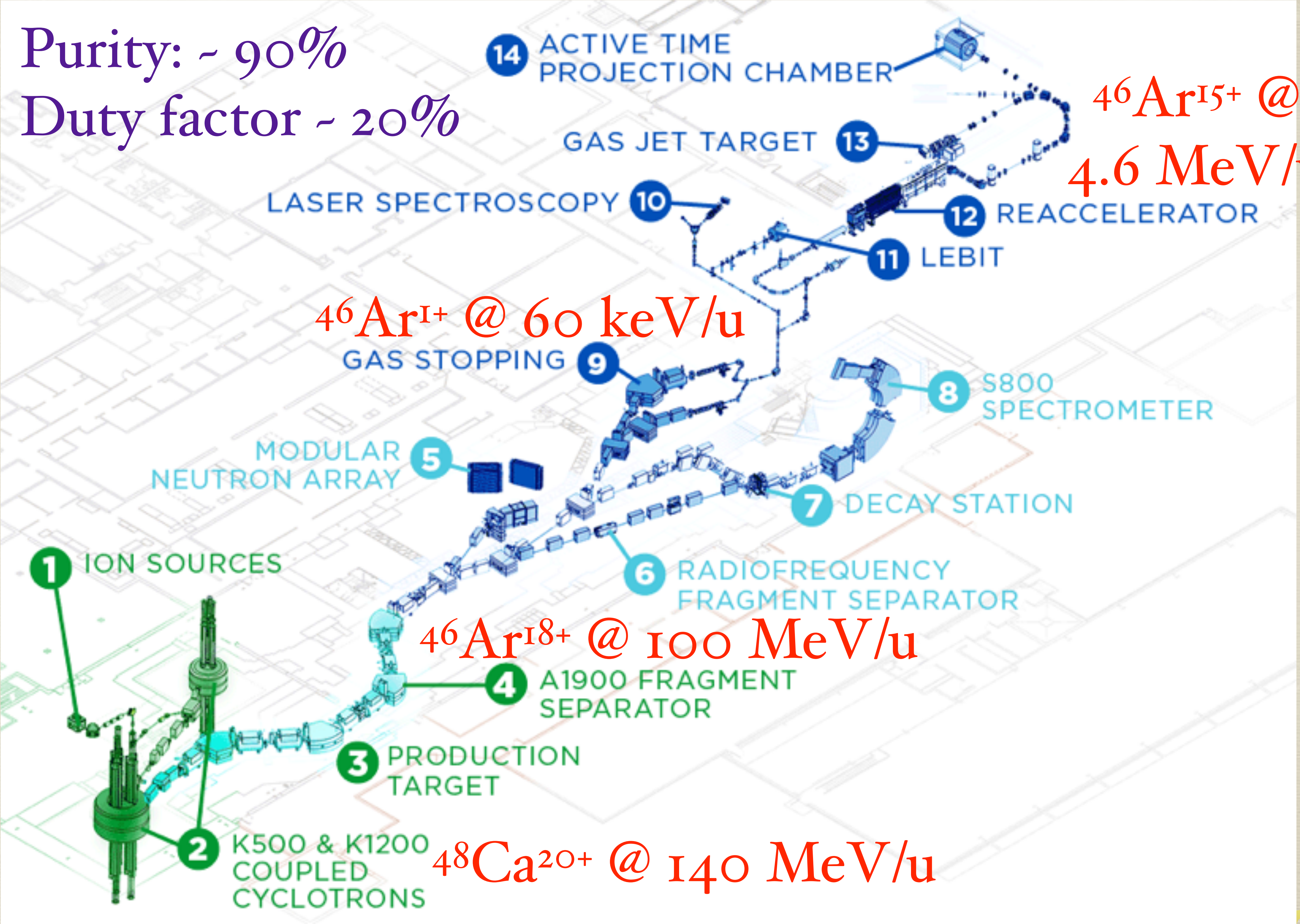
- ^{6}He+^{4}He elastic scattering
- Image of charged particle trajectories
- Beam slows down in gas
- Vertex location tells reaction energy
- Energy loss tells which particle is which
- Length and angle between scattered tracks follow kinematics



- ^{10}Be + ^{4}He elastic and inelastic scattering
- Dual gain trick to detect both scattered ^{4}He and ^{10}Be
- Clear separation between gs (0^+) and 1st excited state (2^+) at 3.37 MeV



Re-accelerated radioactive beam experiment



Purity: ~ 90%

Duty factor ~ 20%

^{46}Ar^{15+} @ 4.6 MeV/u

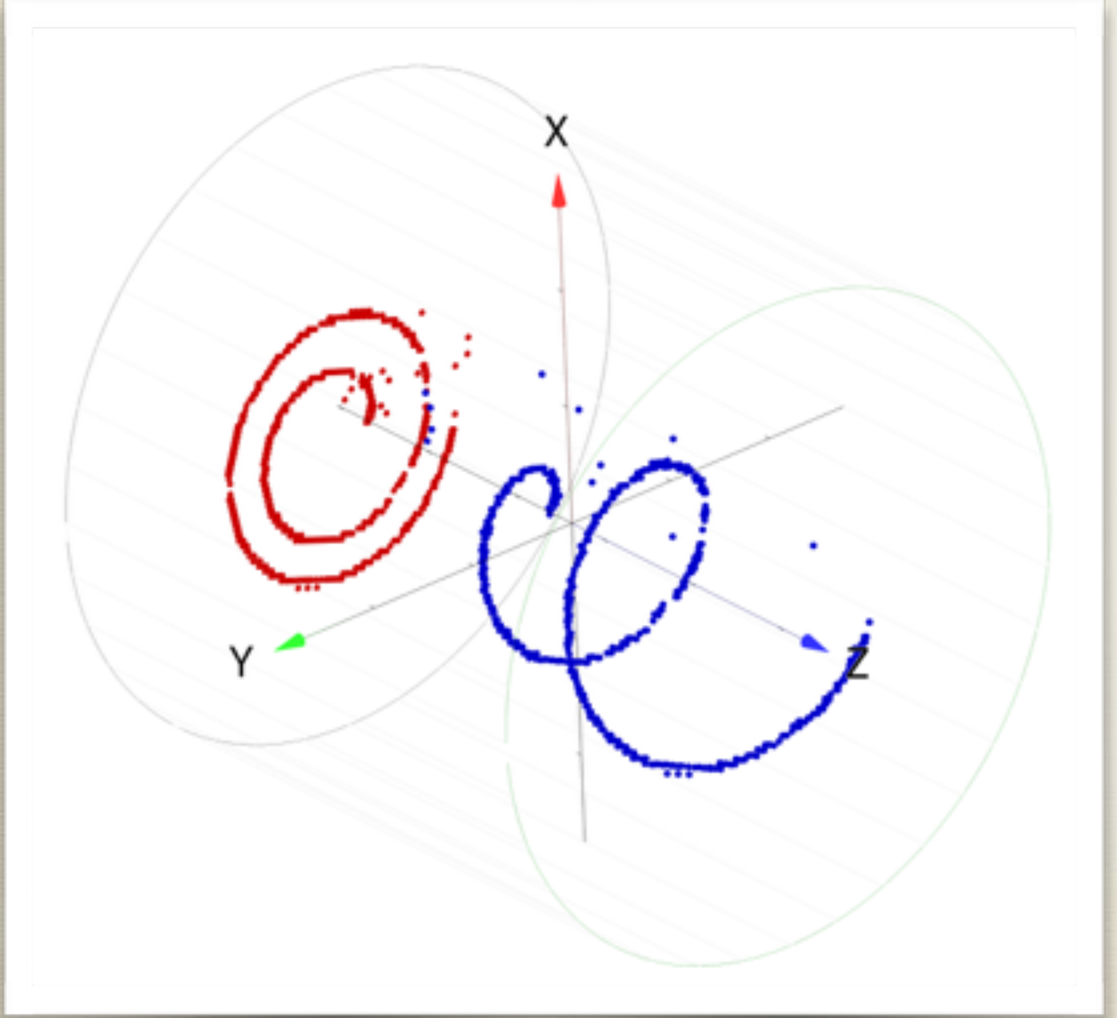
^{46}Ar^{1+} @ 60 keV/u

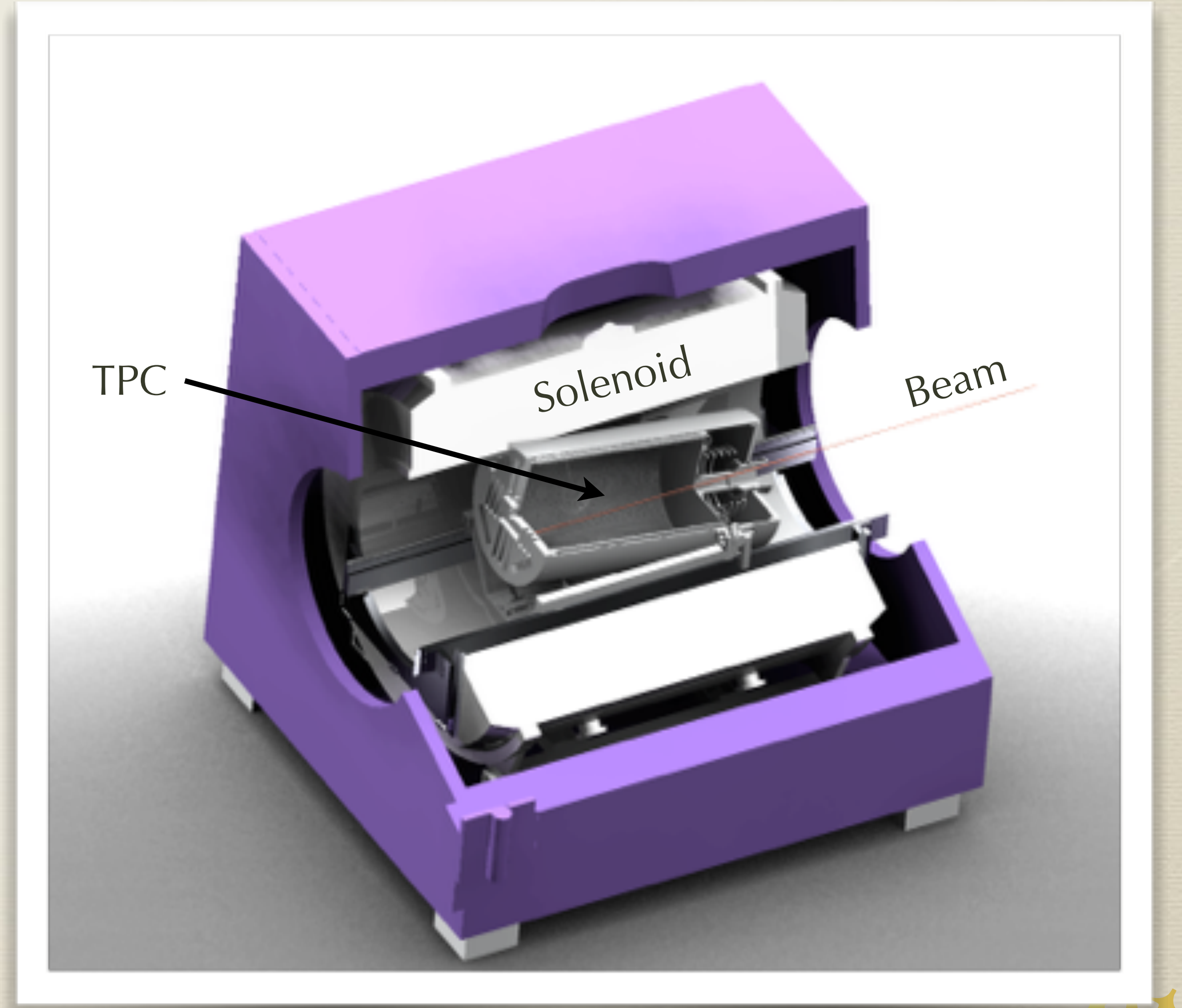
^{46}Ar^{18+} @ 100 MeV/u

^{48}Ca^{20+} @ 140 MeV/u

3D camera for nuclear reactions

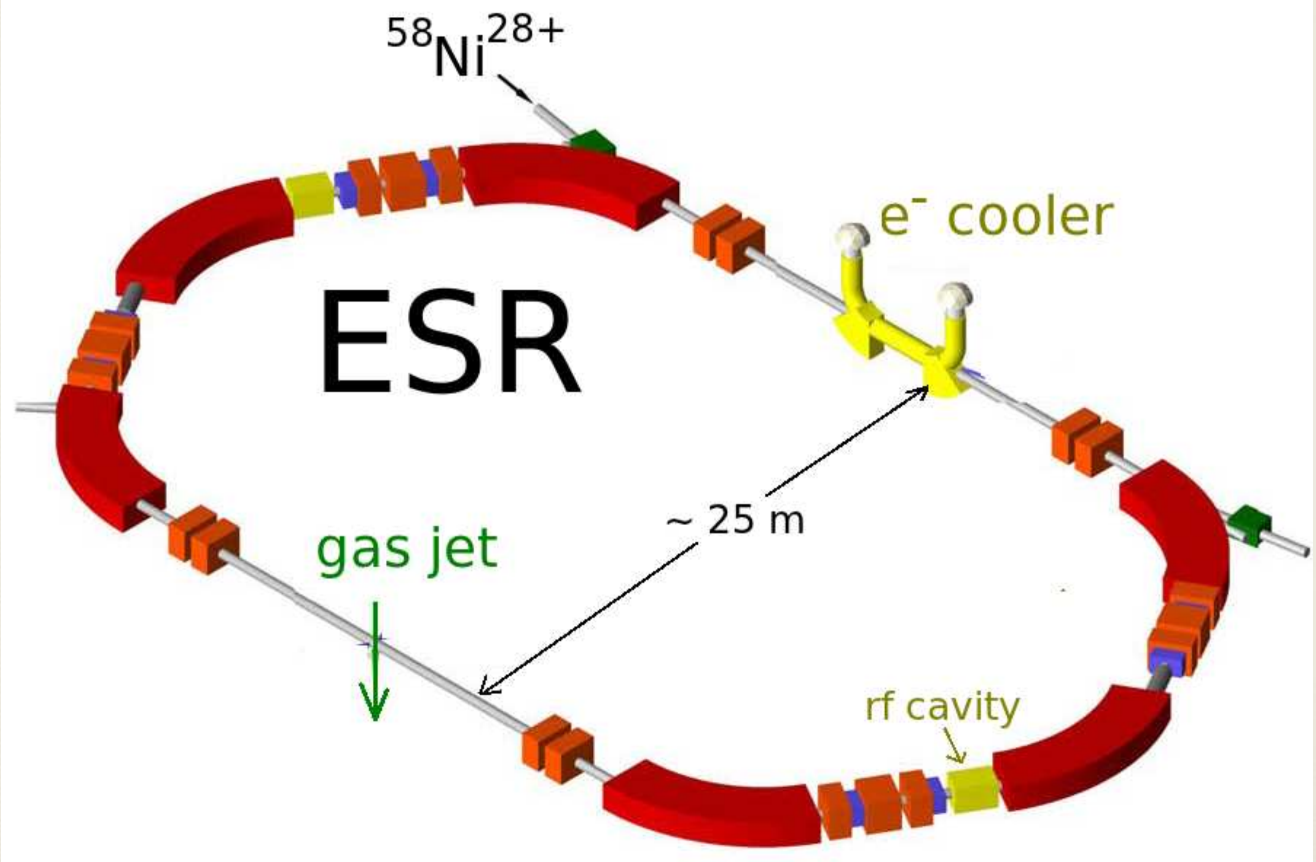
- Event from ^{46}Ar(p,p) elastic scattering at 4.6 MeV/u @ NSCL
- AT-TPC placed inside solenoidal magnetic field to curve trajectories
- 10,240 pads x 512 time samples = 5.2 Mpixels per event
- Expected energy resolution 50-100 keV





Stored beams at EXL

- Recirculate radioactive beam onto gas target
  - Luminosity boost by 10^5-10^6 on thin (gas) target



J. C. Zamora, Ph. D. thesis, 2016

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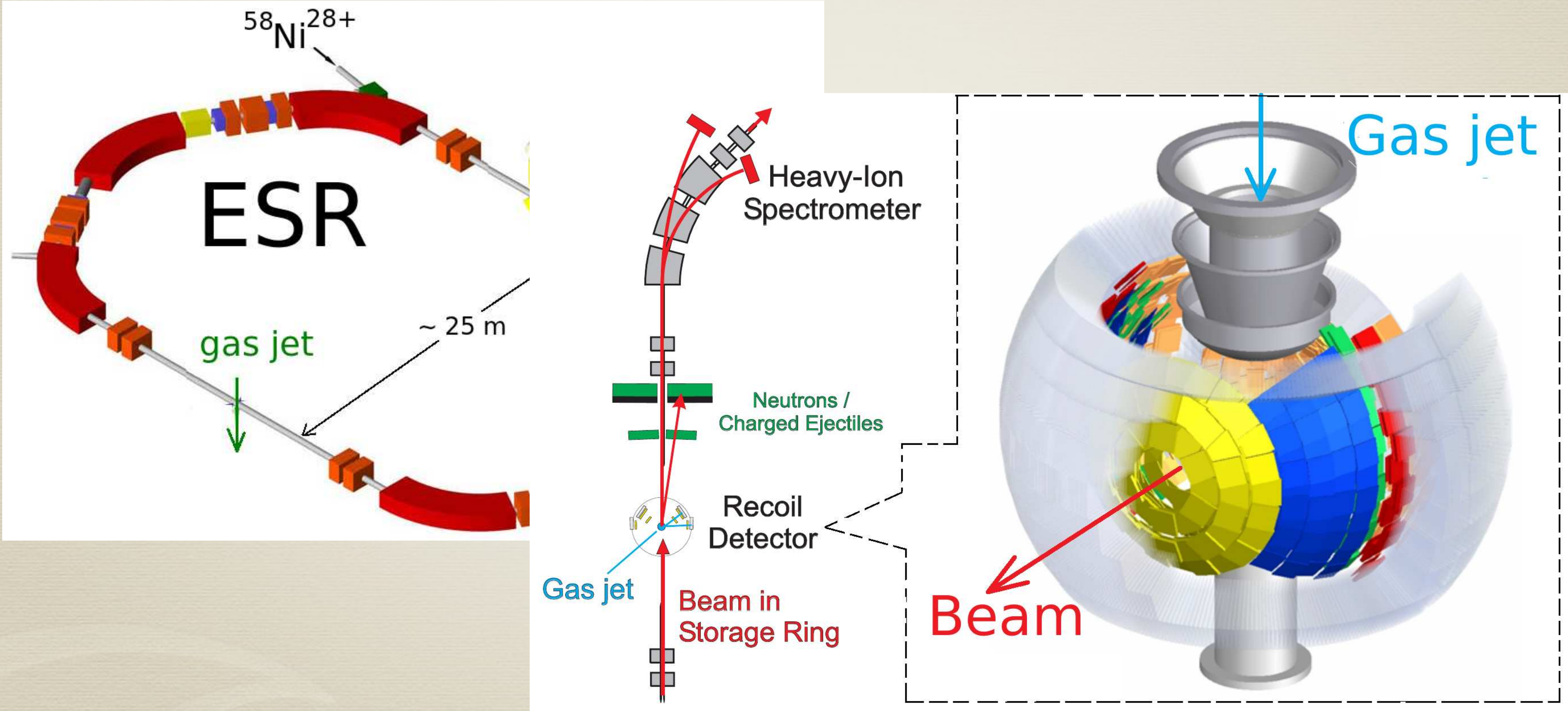
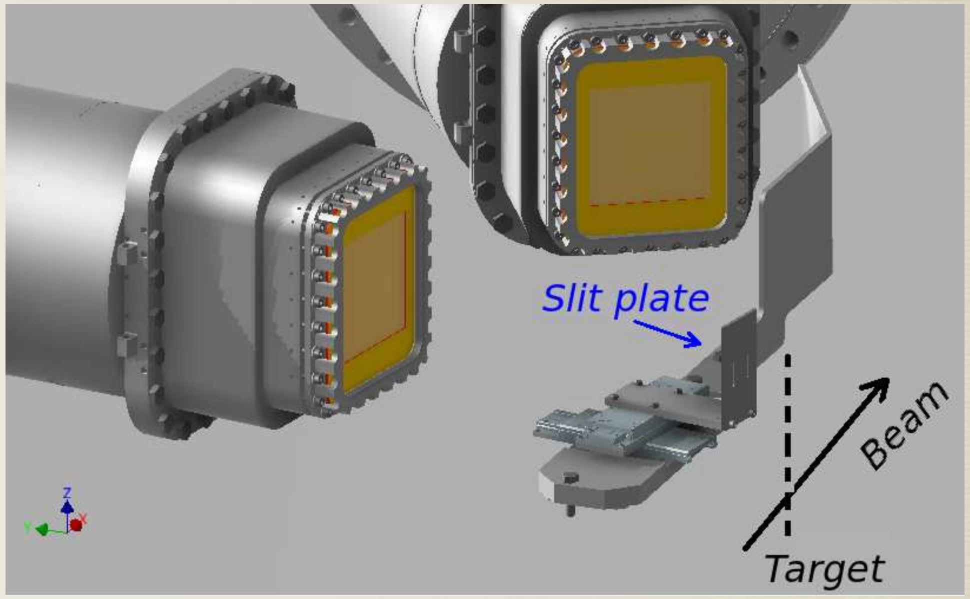


J. C. Zamora, Ph. D. thesis, 2016

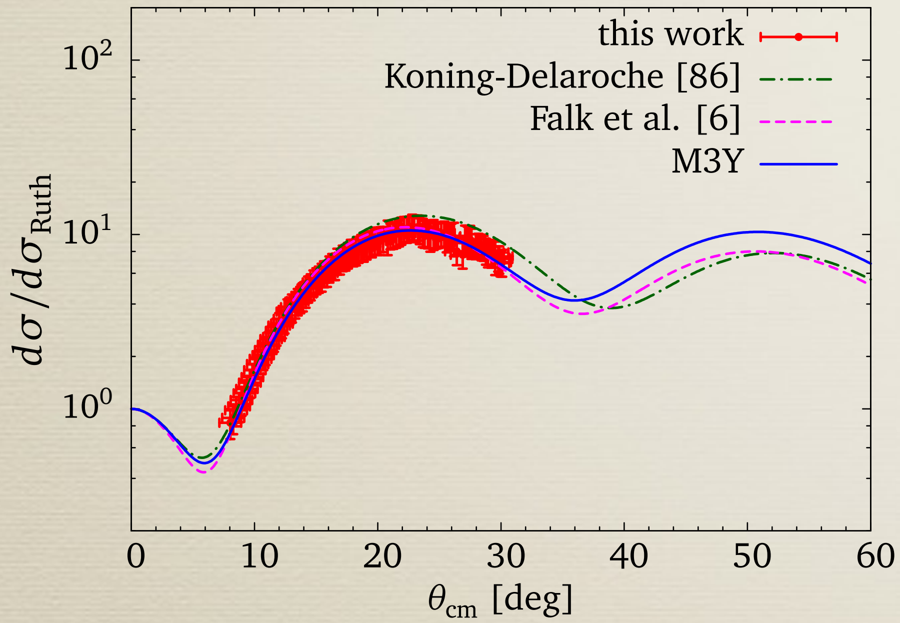
First results with stable beams

- Elastic and inelastic scattering of ^{20}Ne+p and ^{58}Ni+α
  - Luminosities from 6.10^{25} to 6.10^{27} cm^{-2}s^{-1} achieved
  - High vacuum environment
  - Emittance growth



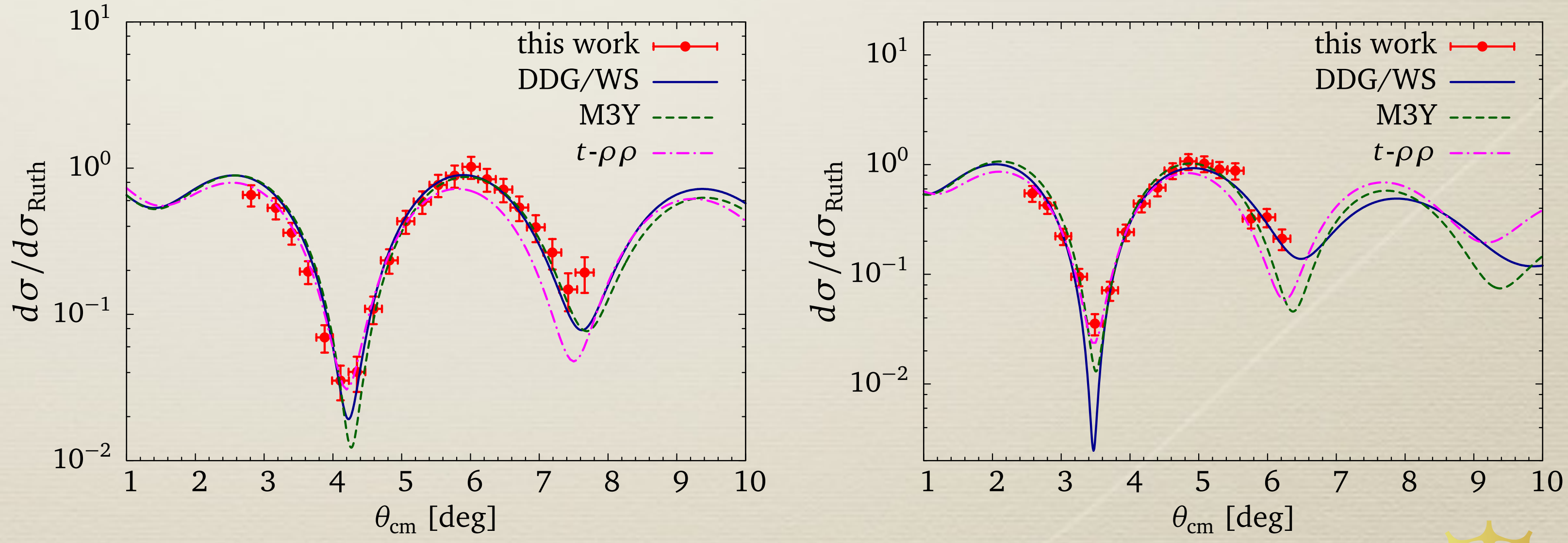
^{20}Ne+p

50 MeV/u



^{58}Ni+α

100 & 150 MeV/u



(a) 100 MeV/u.

(b) 150 MeV/u.

J. C. Zamora, Ph. D. thesis, 2016

Luminosity from fast beams

- In-beam γ-ray spectroscopy and invariant-mass spectroscopy

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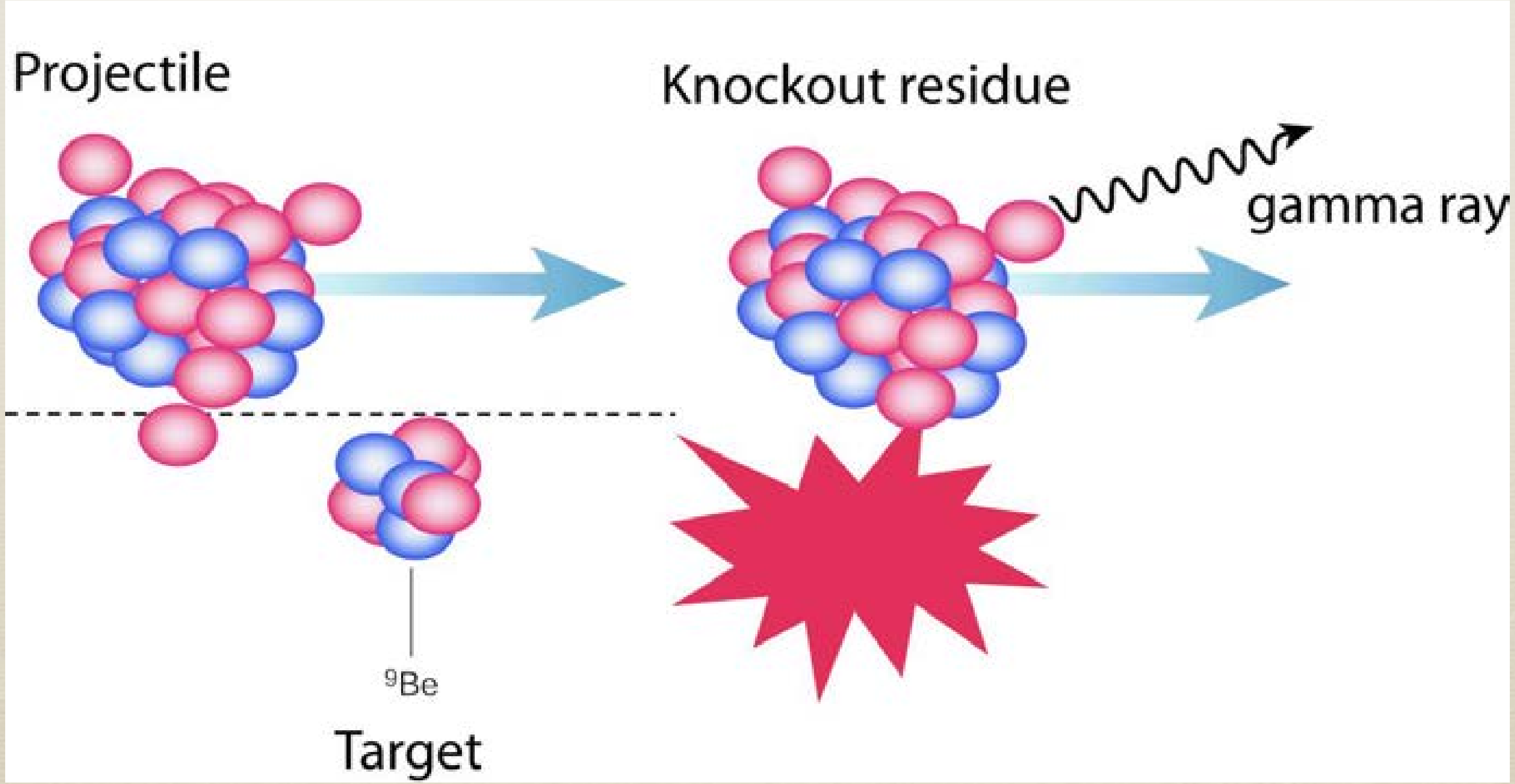
  - Use γ-ray tracking arrays with Doppler correction to measure de-excitation of fast moving residue: high resolution
  - For unbound states: long time-of-flight neutron arrays placed around 0° to reconstruct invariant mass
- Large number of devices are available and developing around the world

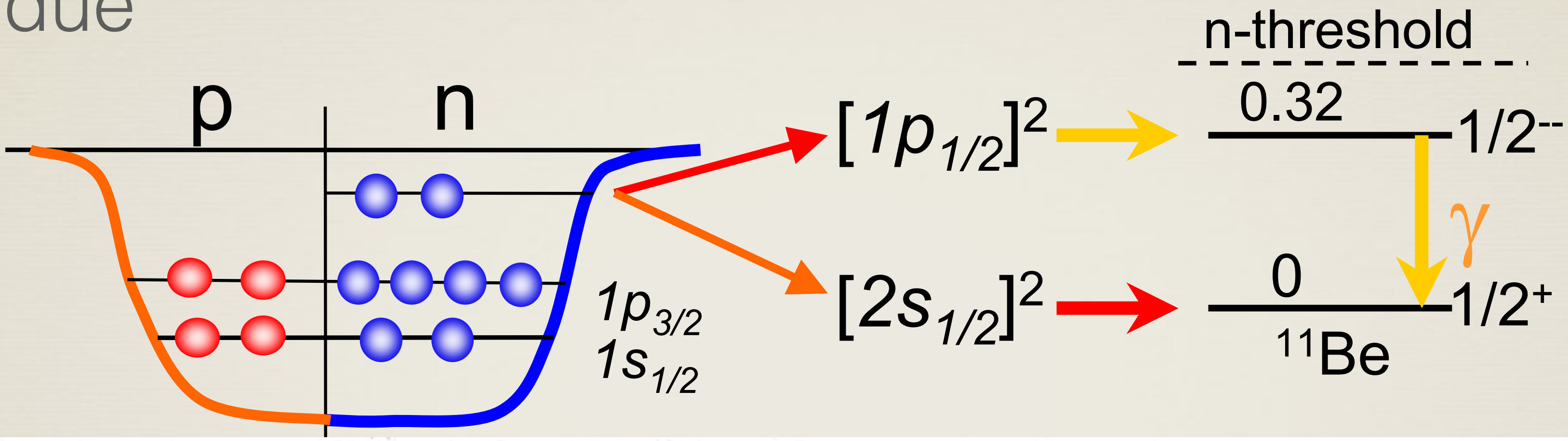
in-beam γ-ray spectroscopy

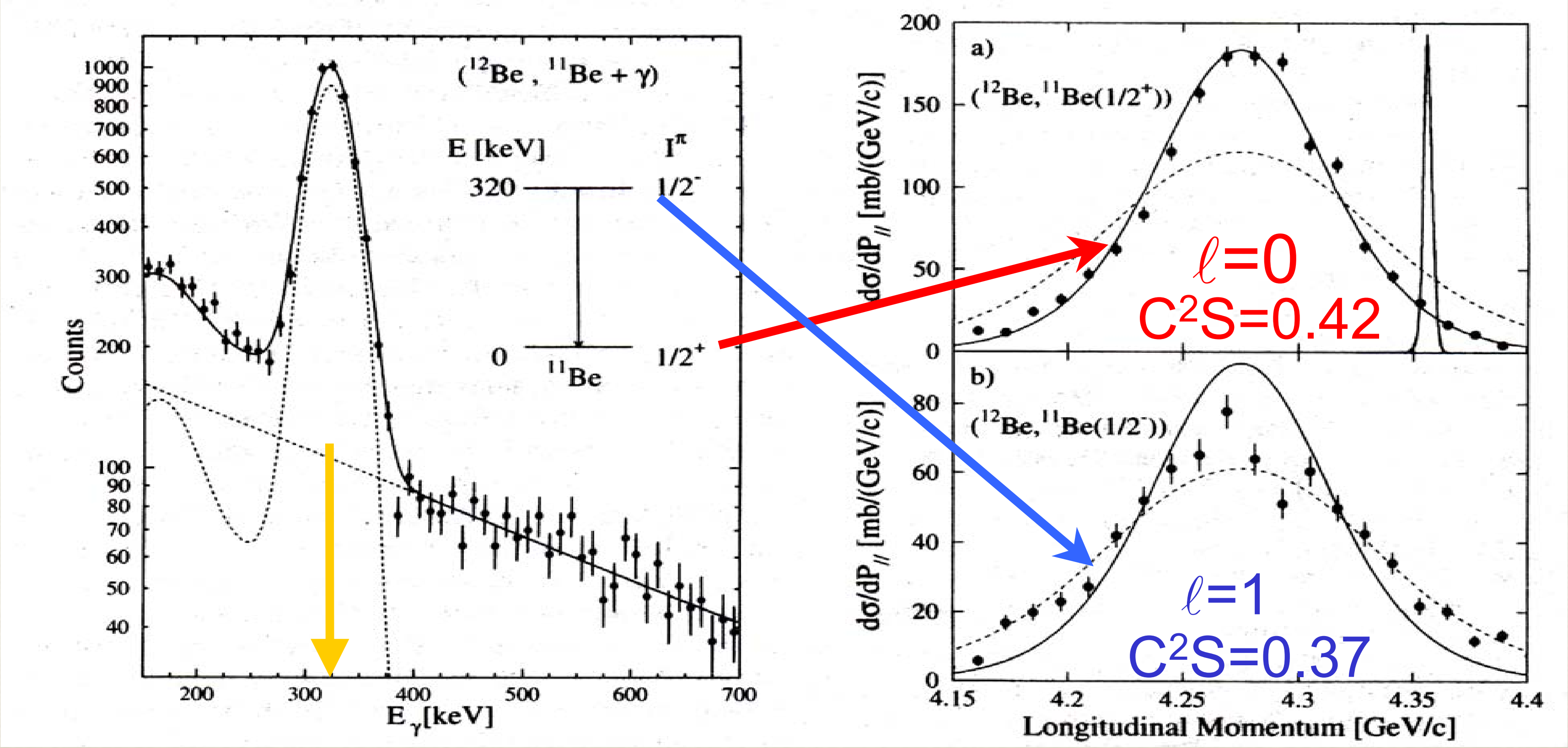
- Reactions with fast radioactive beam
  - Reaction residue loses one or a few nucleons
  - Only residue is collected and detected at forward angles
  - Thick targets can be used (luminosity!)
  - High efficiency array detects Doppler-shifted γ-ray from residue



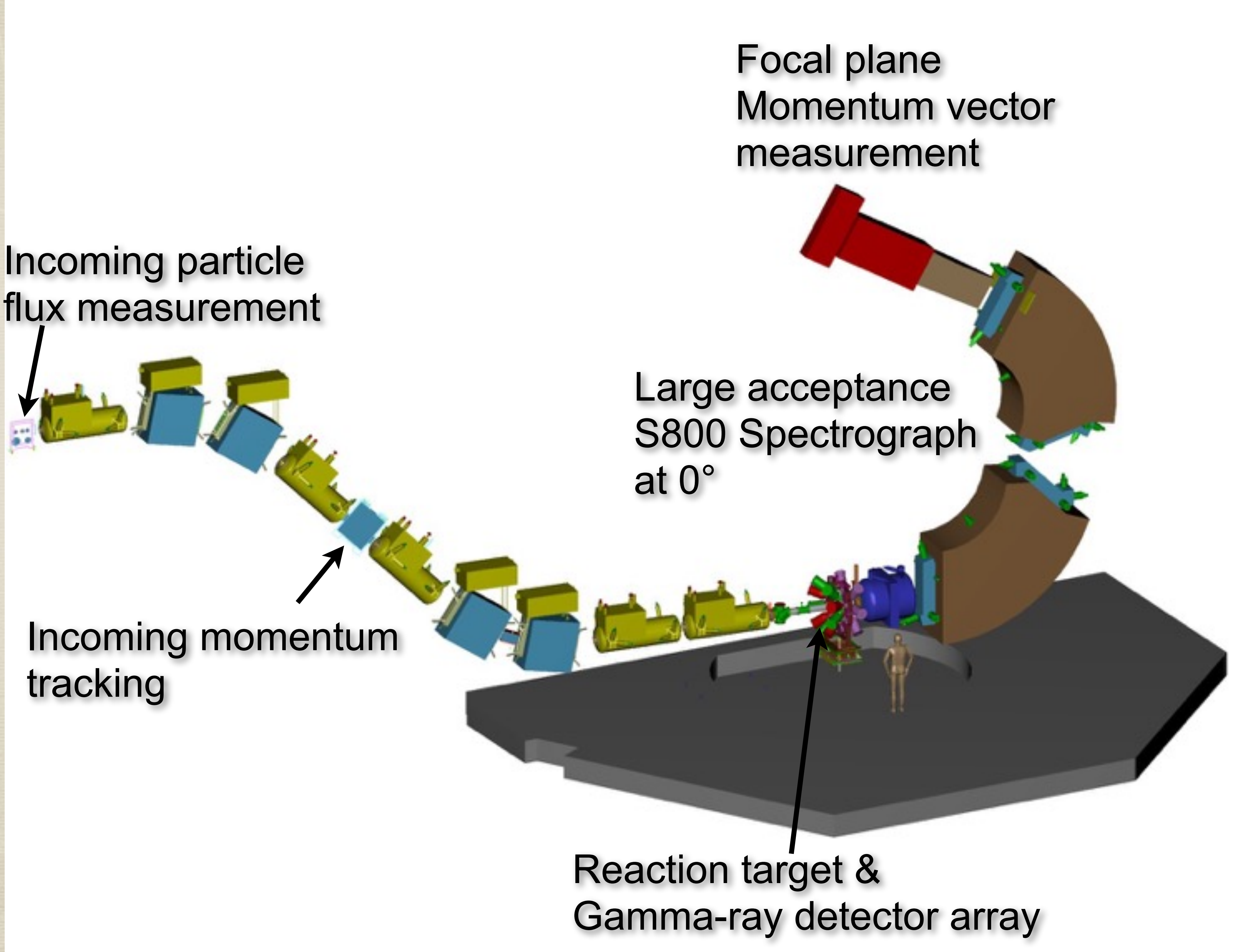
Knockout reactions

- Pillar of today's radioactive nuclei spectroscopy
  - Angular momentum of removed nucleon from parallel momentum of residue





S800 spectrograph + Gretina array



Focal plane
Momentum vector
measurement

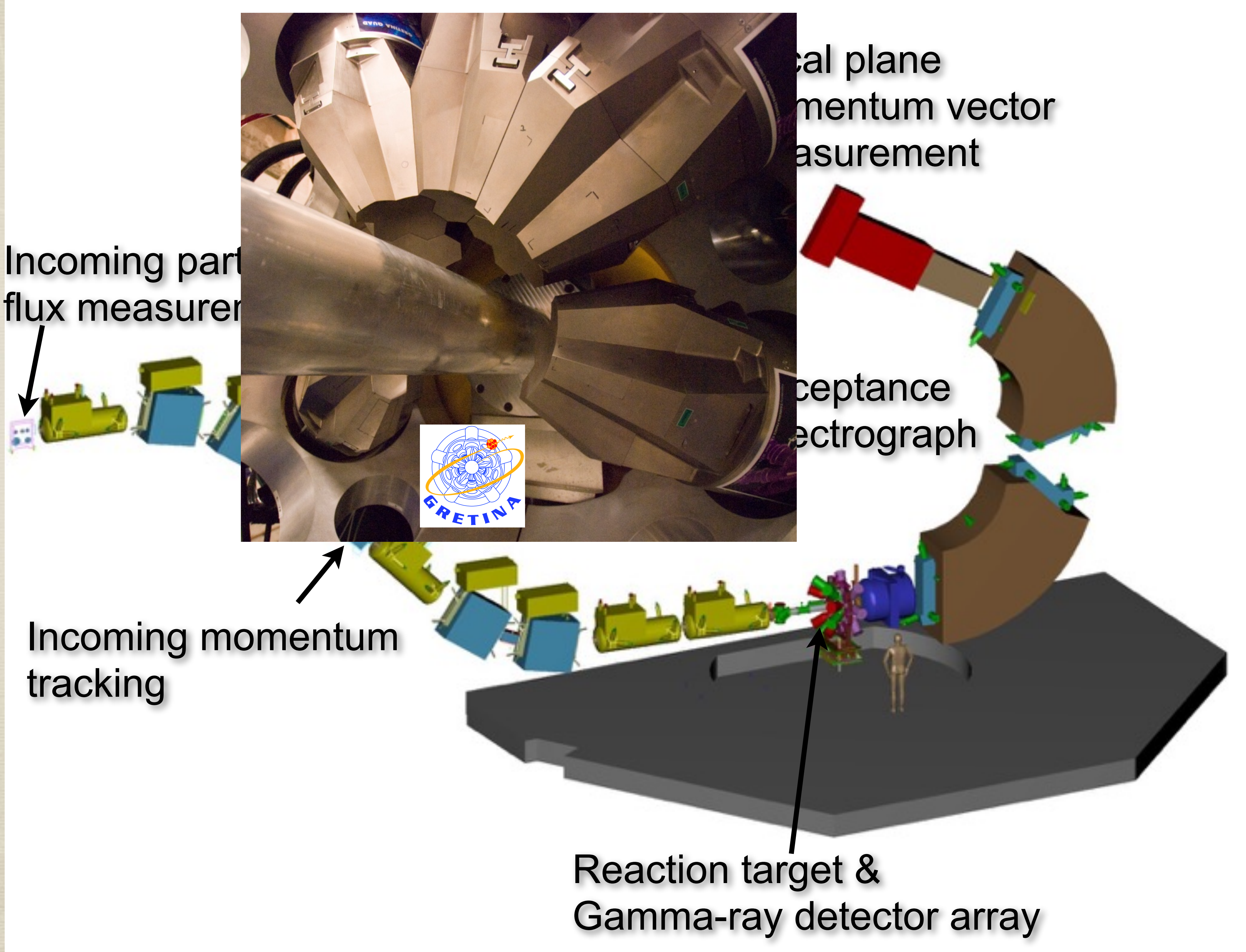
Incoming particle
flux measurement

Large acceptance
S800 Spectrograph
at 0°

Incoming momentum
tracking

Reaction target &
Gamma-ray detector array

S800 spectrograph + Gretina array



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Reaction target &
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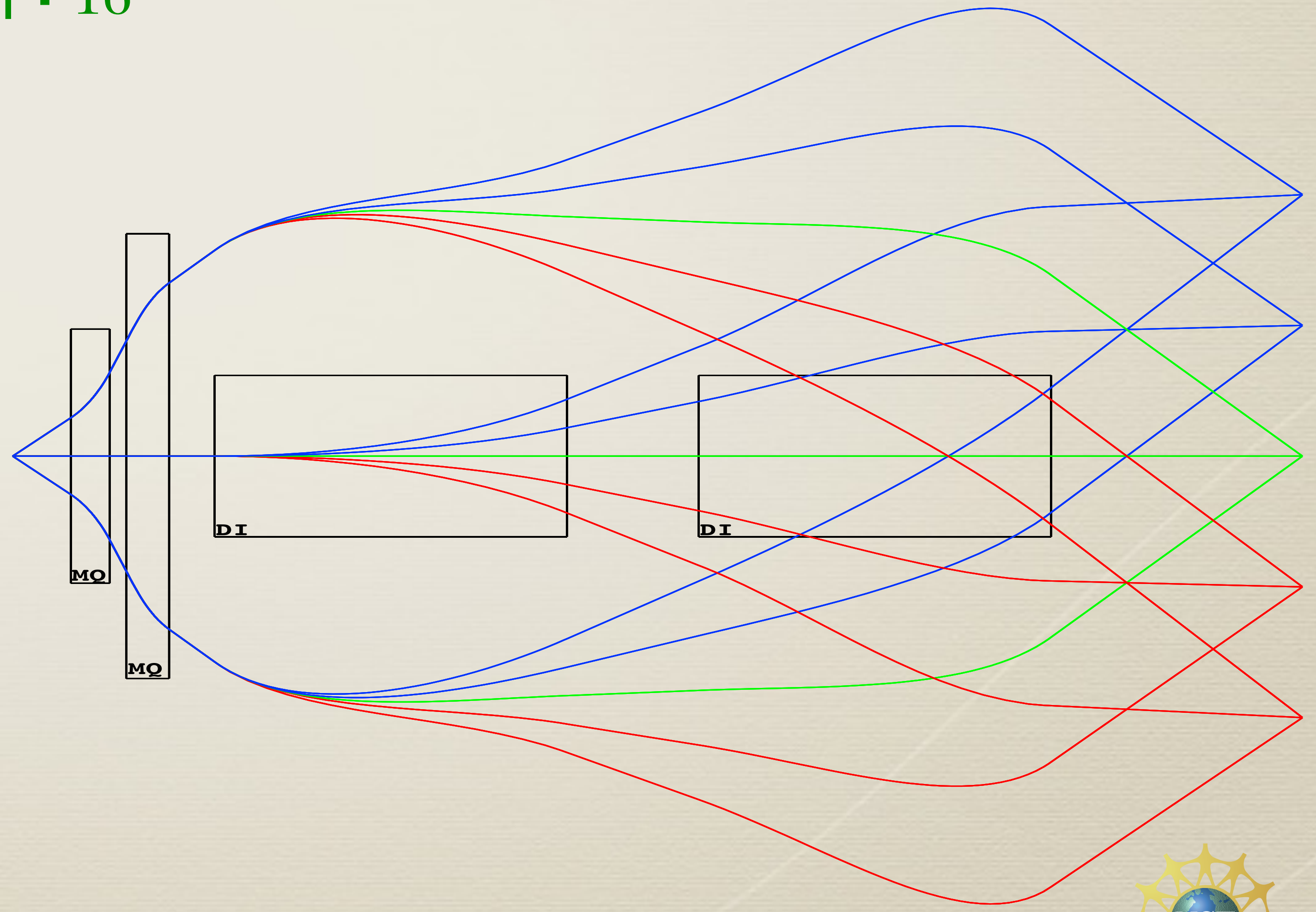
S800: “software” spectrograph

- Magnetic elements have fringe fields and imperfections
  - Optics are not perfect and deviate from 1st order (linear)
  - Deviations are called “high order aberrations”

$$x_f = x_i T_{11} + a_i T_{12} + d_i T_{16}$$

	x(m)	a(rad)	y(m)	b(rad)	l(m)	d(1)
xf	-0.893	-9.12e-06	0	0	0	-9.54
af	-0.727	-1.12	0	0	0	-0.172
yf	0	0	-0.59	-0.704	0	0
bf	0	0	1.33	-0.102	0	0
lf	6.78	10.7	0	0	1	-10.3
df	0	0	0	0	0	1



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$$x_f = x_i T_{11} + a_i T_{12} + d_i T_{16} + x_i a_i T_{112} + a_i d_i T_{126} + \ldots$$

	x(m)	a(rad)	y(m)	b(rad)	l(m)	d(1)
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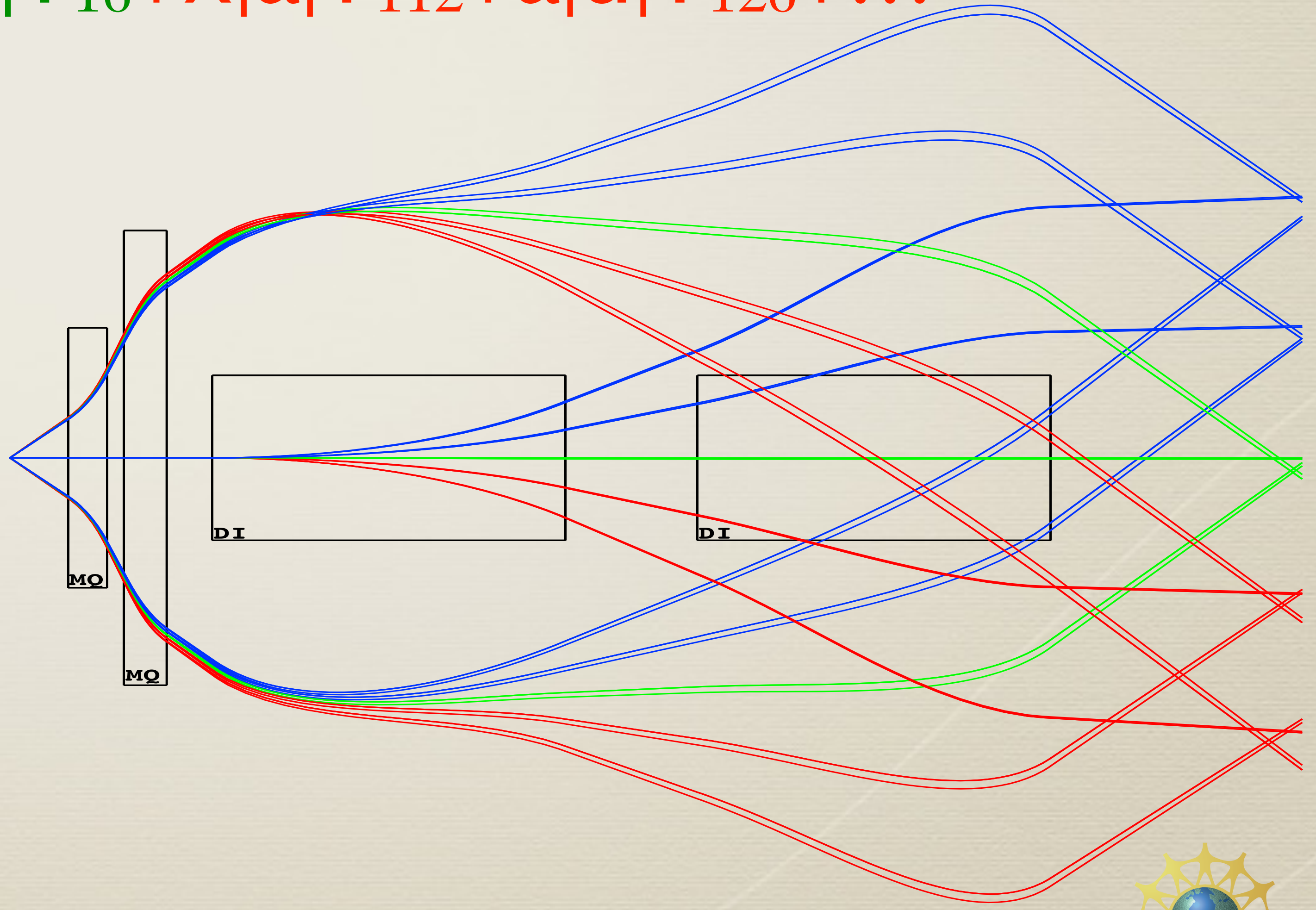


Trajectory reconstruction

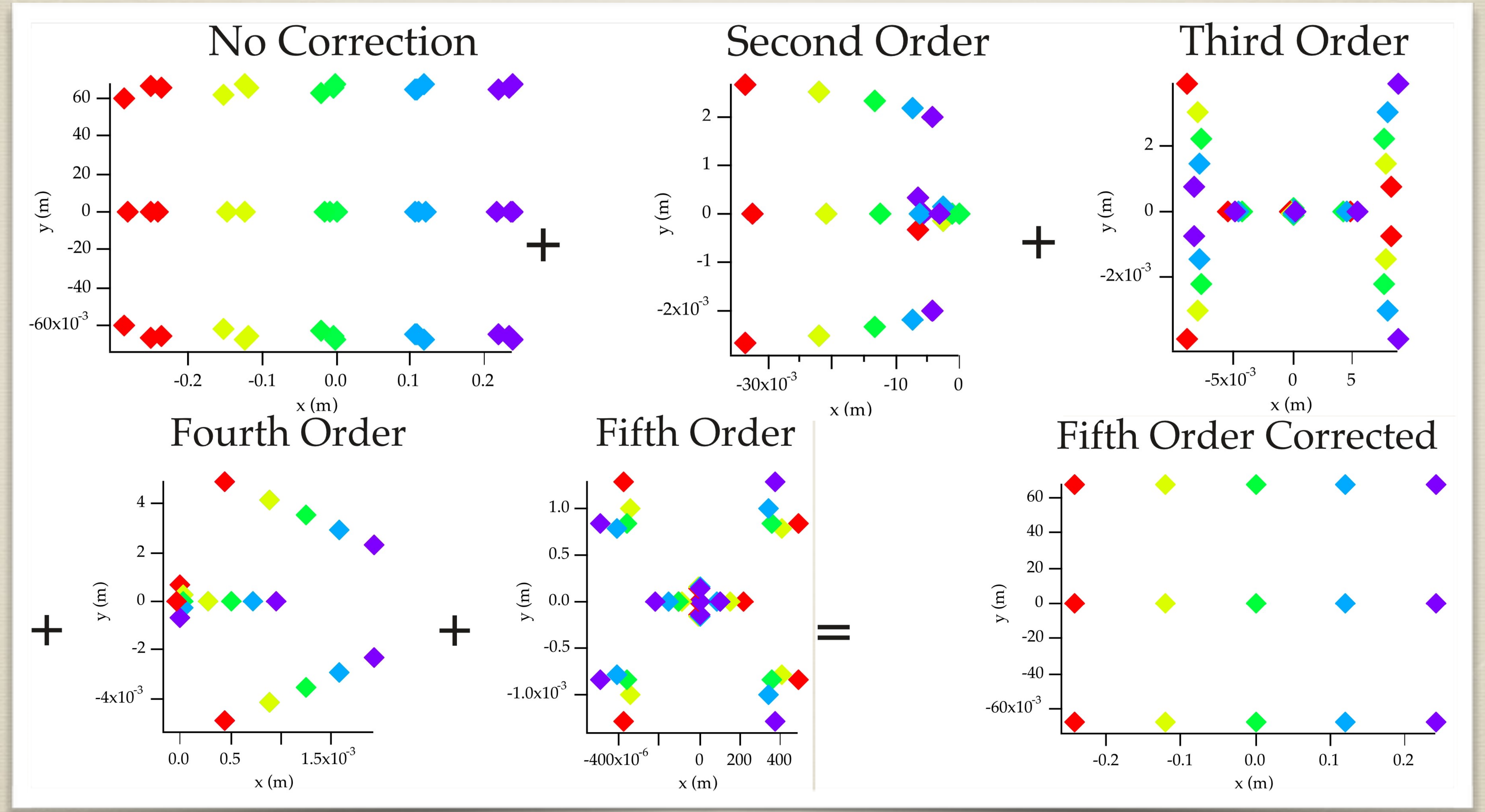
- Deduce parameters of particle at the target location from measurements at the focal plane
- Calculate 4x4 forward matrix up to order N (COSY infinity)
- Inverse forward matrix assuming $x_i=0$ to get d_i
- Apply inverse matrix (map) to data to extract energy and scattering angle at the target location

$$\begin{pmatrix} x_f \\ \theta_f \\ y_f \\ \phi_f \end{pmatrix} = S \begin{pmatrix} \delta_i \\ \theta_i \\ y_i \\ \phi_i \end{pmatrix} \quad \Rightarrow \quad \begin{pmatrix} \delta_i \\ \theta_i \\ y_i \\ \phi_i \end{pmatrix} = S^{-1} \begin{pmatrix} x_f \\ \theta_f \\ y_f \\ \phi_f \end{pmatrix}$$

$$(x_i = 0)$$

Aberration corrections

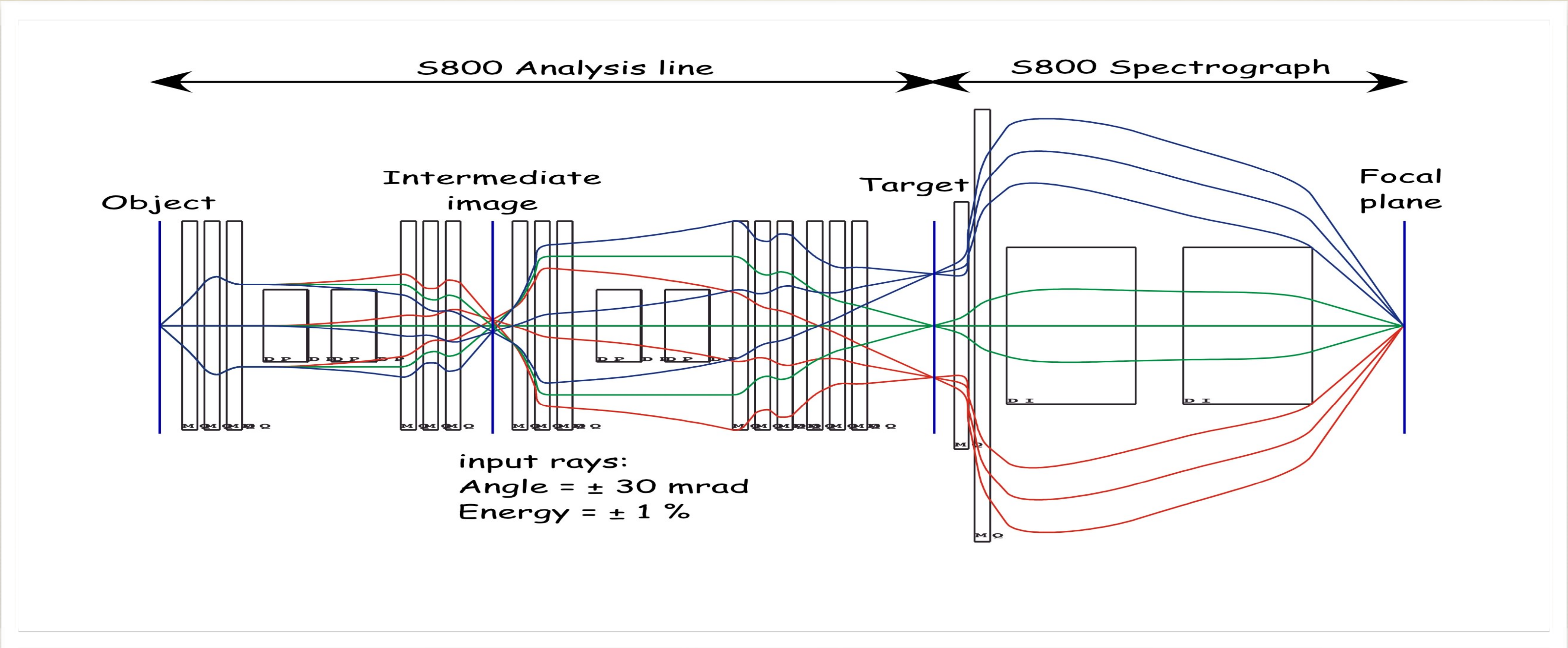
Initial grid: Δd=±5%, Δa=±60mrad, Δb=±90 mrad



Expected energy resolution for a 1mm beam spot size: 1 part in 5,000 (0.02%)

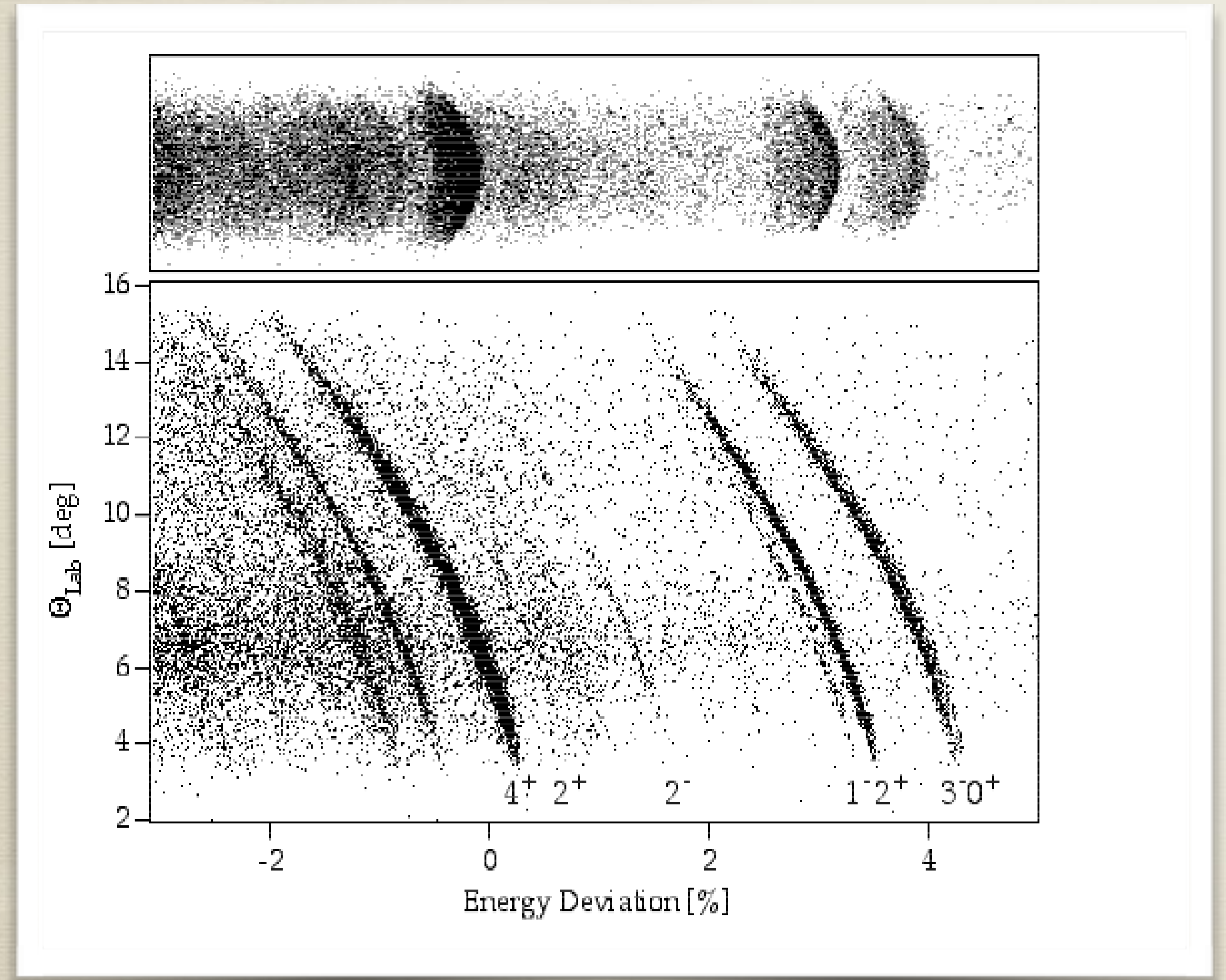
Dispersion matching

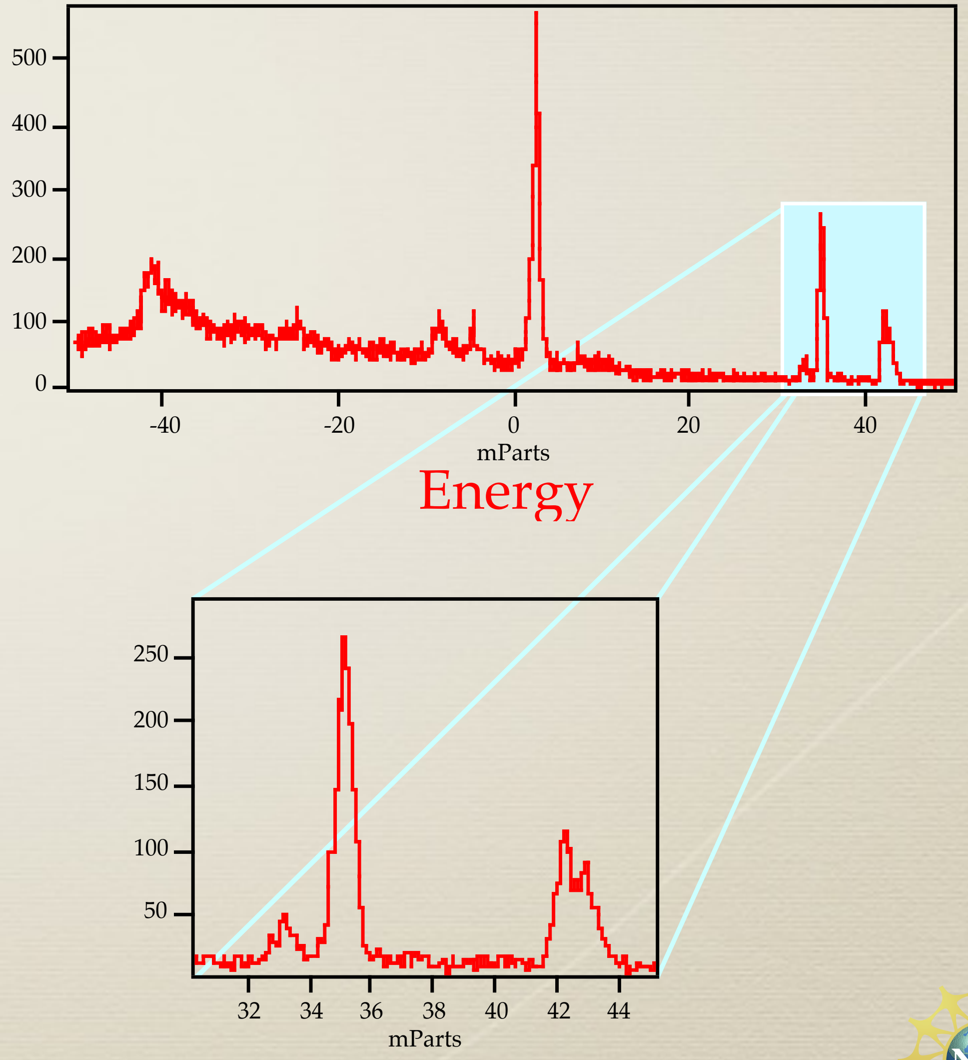
- Analysis line disperses the radioactive beam at target location
- Without target: all particles refocussed in focal plane
- Position at focal plane only depends on energy lost in target



Example

- Reaction: $^{12}C(^{7}Li,^{3}H)^{16}O$ at 19 MeV/u
  - Spectrograph rotated at 8°
  - Energy resolution of 1/1800 over full acceptance (20 msr)





Particle identification in S800

- How to identify the heavy residues collected in the S800
- Use time-of-flight and energy loss measurements
- Time-of-flight depends on velocity and trajectory length
- Energy loss depends on velocity
- Corrections are needed to recover resolution and achieve identification

	x(m)	a(rad)	y(m)	b(rad)	l(m)	d(1)
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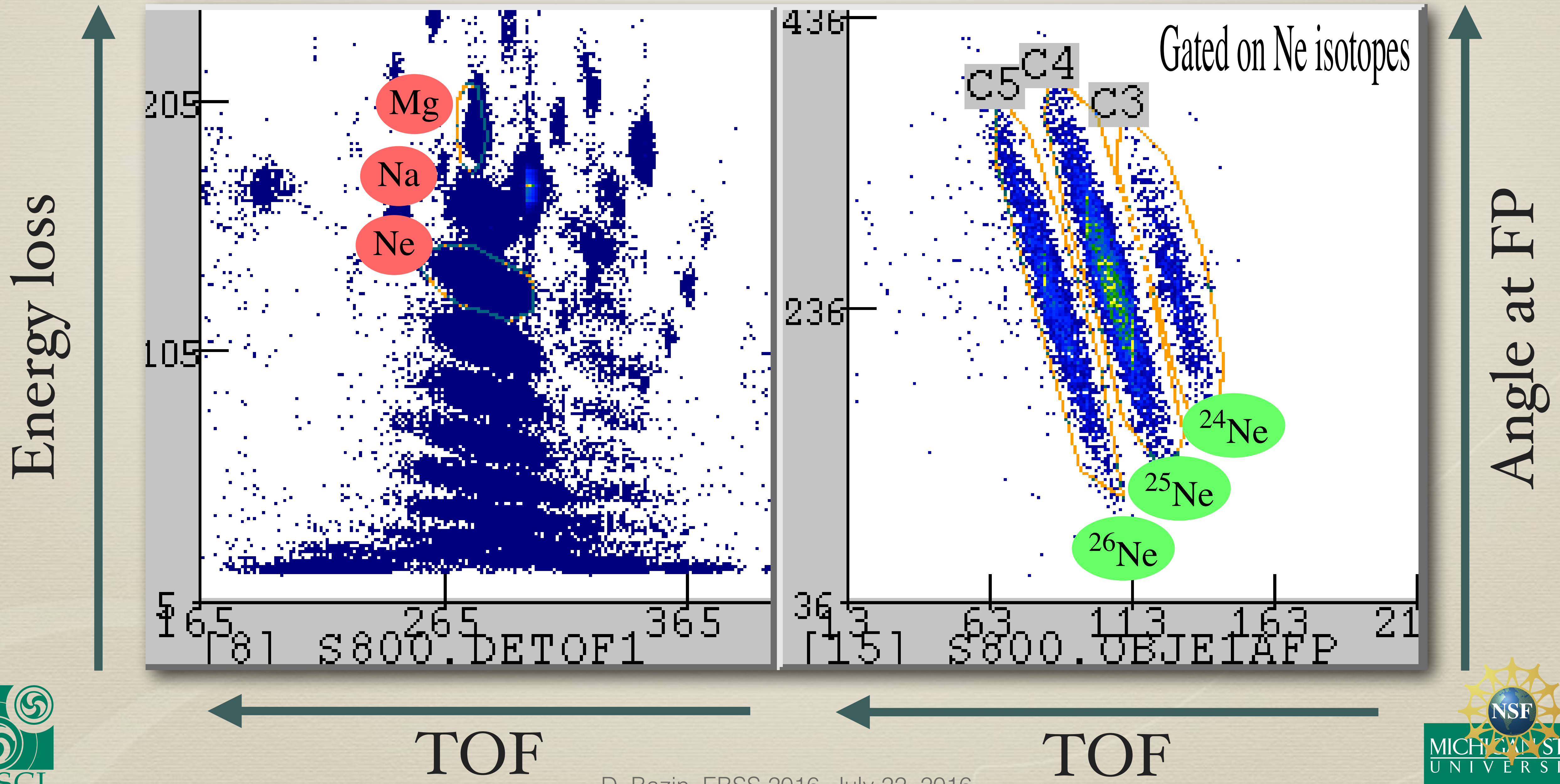
Example

- Angle at Focal Plane directly proportional to length of trajectory inside S800
- Without correction ^{26,25,24}Ne are not resolved

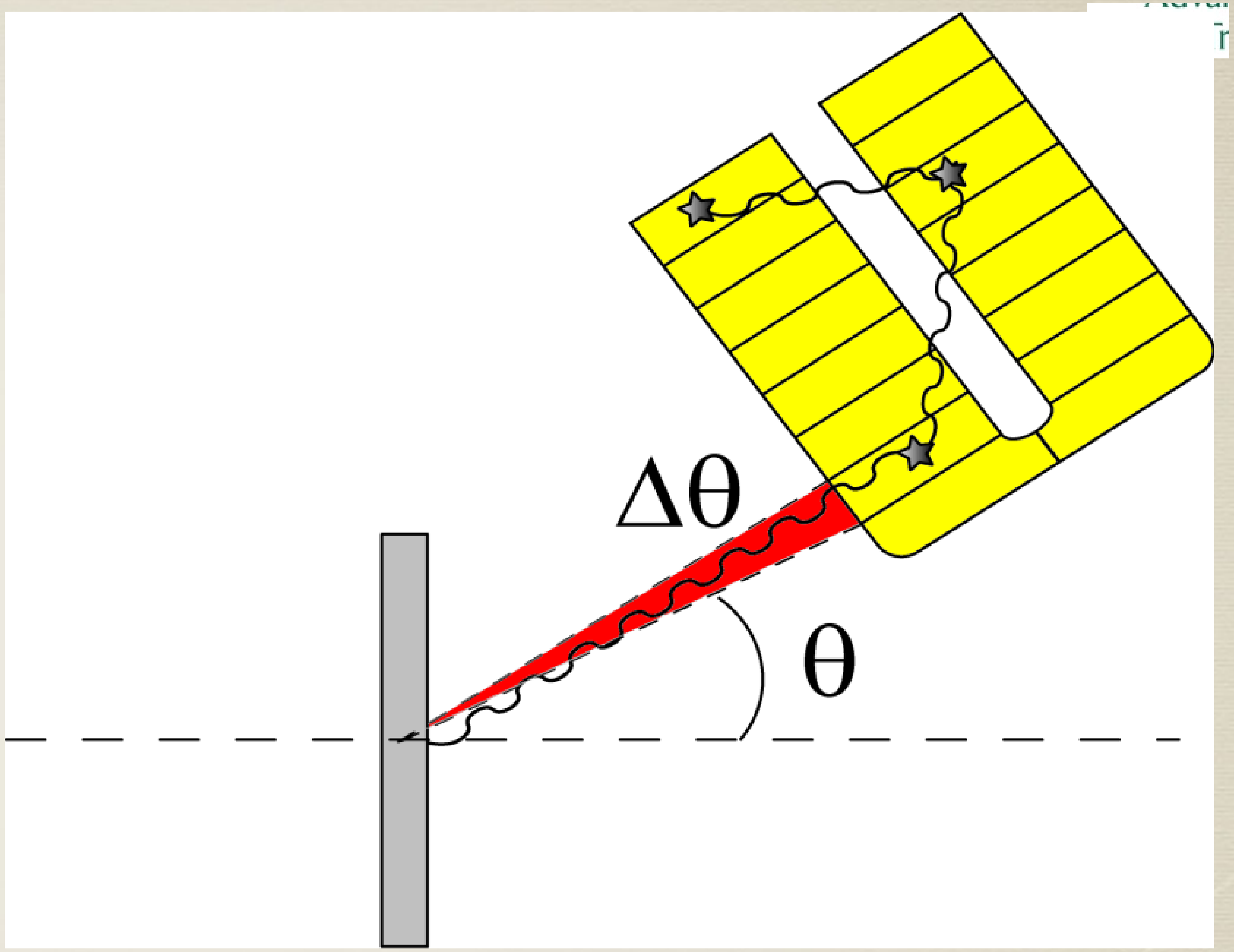


Doppler correction

$$E = E_0 \frac{\sqrt{1-\beta_0{}^2}}{1-\boldsymbol{\beta}_0 \cdot \mathbf{e}}$$

$$\boldsymbol{\beta}_0 \cdot \mathbf{e} = |\boldsymbol{\beta}_0| \cos\theta_0$$

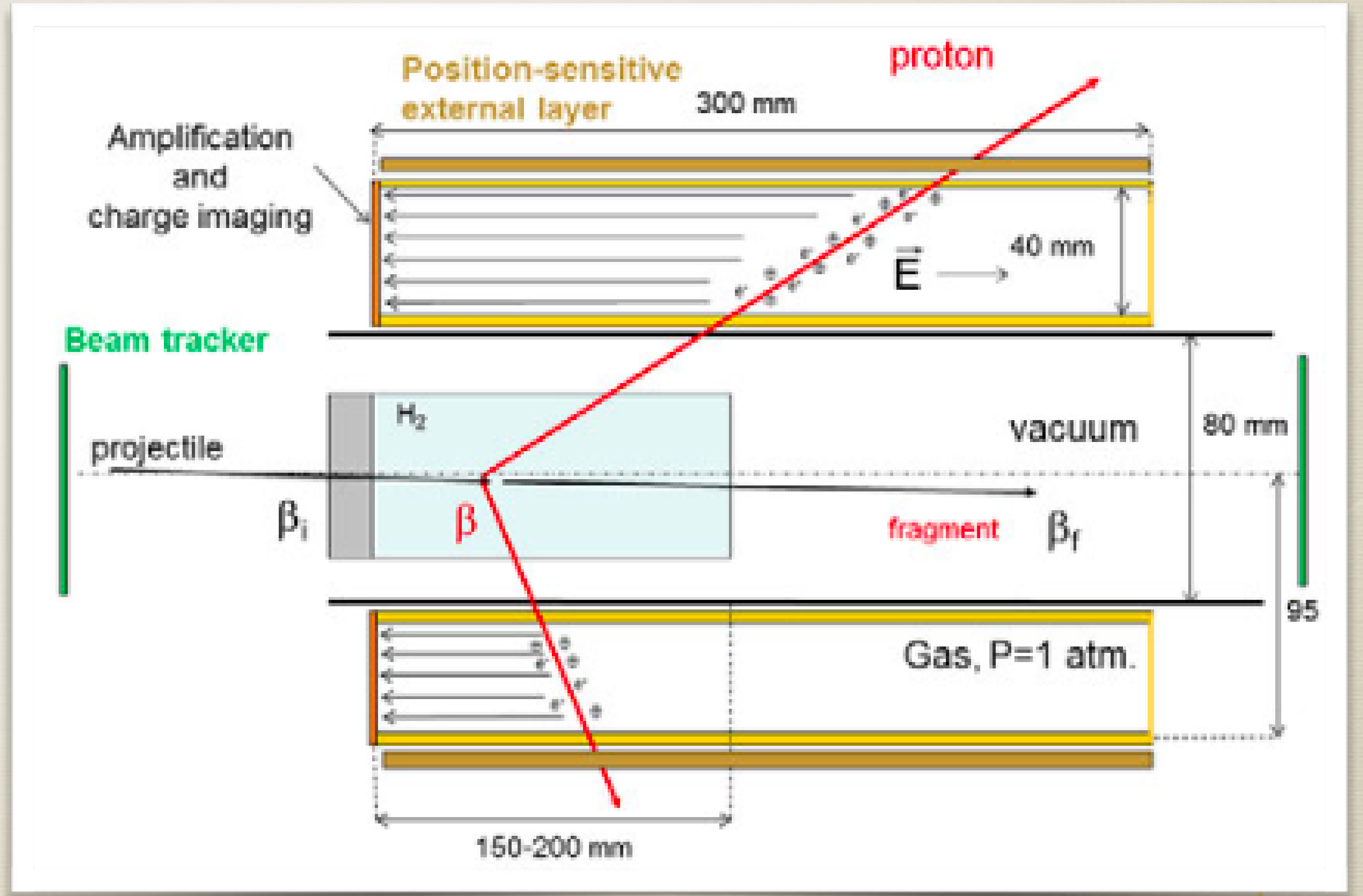
E_0	γ-ray energy in the source frame
E	γ-ray energy in the lab frame
$\boldsymbol{\beta}_0$	velocity of the source
θ_0	γ-ray angle of emission



- γ-ray energy directly related to velocity at the time of emission
- Resolution directly related to target thickness

Vertex tracker: MINOS design

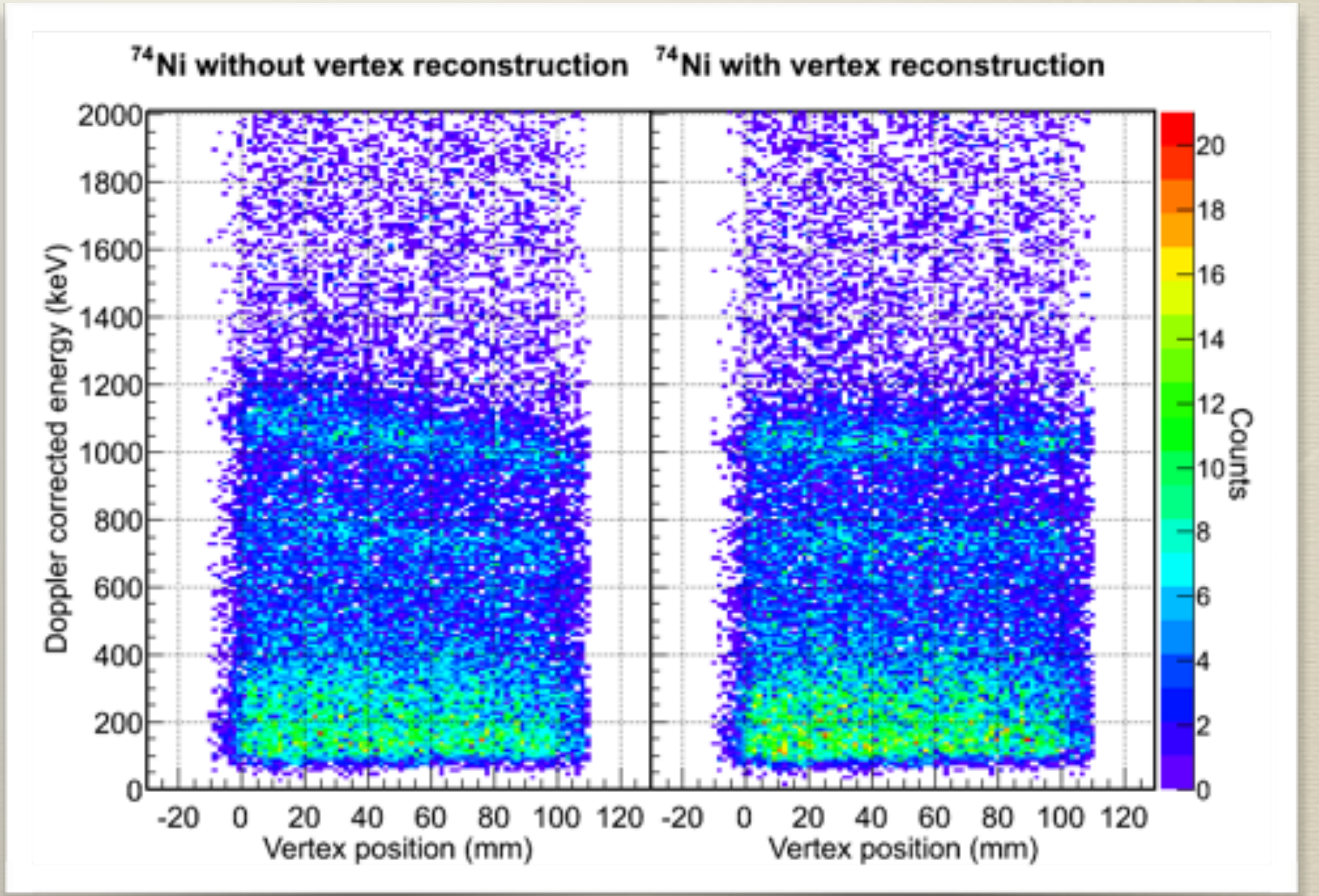
- In-beam γ-ray spectroscopy relies on Doppler correction
  - Both γ-ray angle and energy of reaction needed
  - Vertex tracker measures reaction location inside LH_2 volume
  - (p,2p) or (p,pn) reactions at 200-300 MeV/u
  - Protons can escape target



A. Obertelli et al., EPJA 50, 8 (2014)

MINOS performance

- Gains in luminosity and resolution
  - Luminosity increase by a factor 5 to 50
  - Resolution gain depends greatly on γ-ray array performance
  - γ-ray tracking Ge array resolution will result in sensitivity gains 100-200
- Present use @ RIBF/RIKEN
  - DALI2 NaI array (6-7%)
  - Example shows clear improvement with vertex determination



Courtesy of A. Obertelli

Take aways…

- Experiments with radioactive beams are challenging
    - Inverse kinematics makes life difficult at low energies, but can be exploited for high luminosity at high energies
    - Low beam intensities requires to design experiments with high efficiency to recover good luminosity

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- Radioactive beams are developing worldwide and need new experimental ideas and innovations to tackle its challenges
- Experimental developments foster new discoveries (and vice versa)

The fun begins tonight!

- You will perform a real in-beam γ-ray spectroscopy experiment!

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- Challenges:
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- Don’t worry, we will help you (a little…)