Nuclear Astrophysics Experiments:

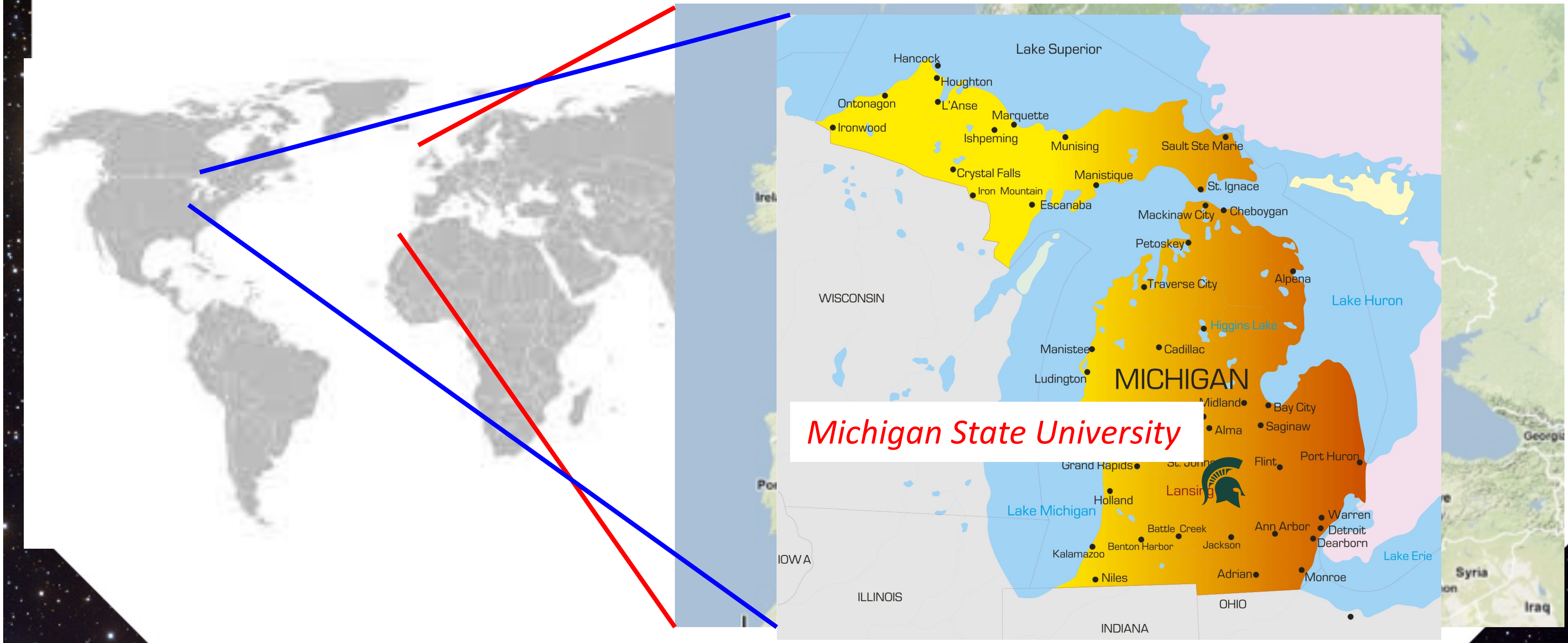
(in heavy element nucleosynthesis)

Artemis Spyrou

Michigan State University

Nice to meet you !

- From Cyprus
- Undergraduate studies: Physics - Thessaloniki, Greece
- Graduate School: Nuclear Physics – Athens, Greece
- Postdoc: Michigan State University
- Assistant Professor, Associate Professor, Associate Director for Education



Michigan State University

Nice to meet you !

In school: Competitive swimming

Grad school: snowboarding

Miki

Katerina

Fivo

Running

Baking

Overview – Lecture 1

- Heavy Element Nucleosynthesis
- Astrophysical processes above Fe that may or may not contribute
  - Neutron-capture processes (s,r,i)
  - Proton-capture processes (νp, rp)
  - Photodissociation processes (γ, p)
- Accelerator facilities

Overview – Lecture 2

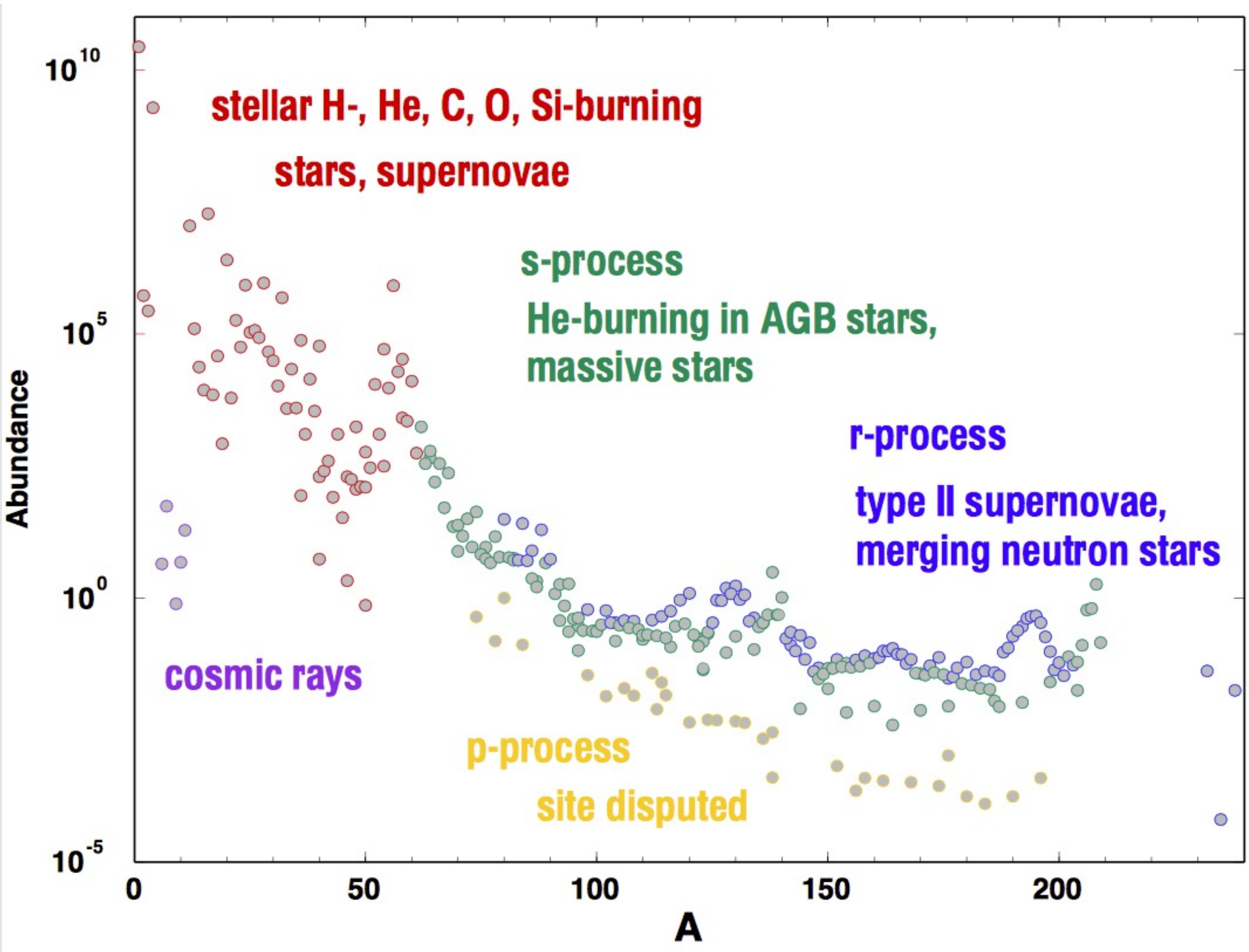
- Direct techniques for proton/alpha captures
  - Intro to non-resonant/statistical reactions
  - Regular Kinematics (Activation, Angular distributions, g-summing)
  - Inverse kinematics (Recoil separator, ring, γ-summing)
- Indirect techniques (~~resonance properties~~, statistical properties, time reverse)

Overview – Lecture 3

Nuclear Structure

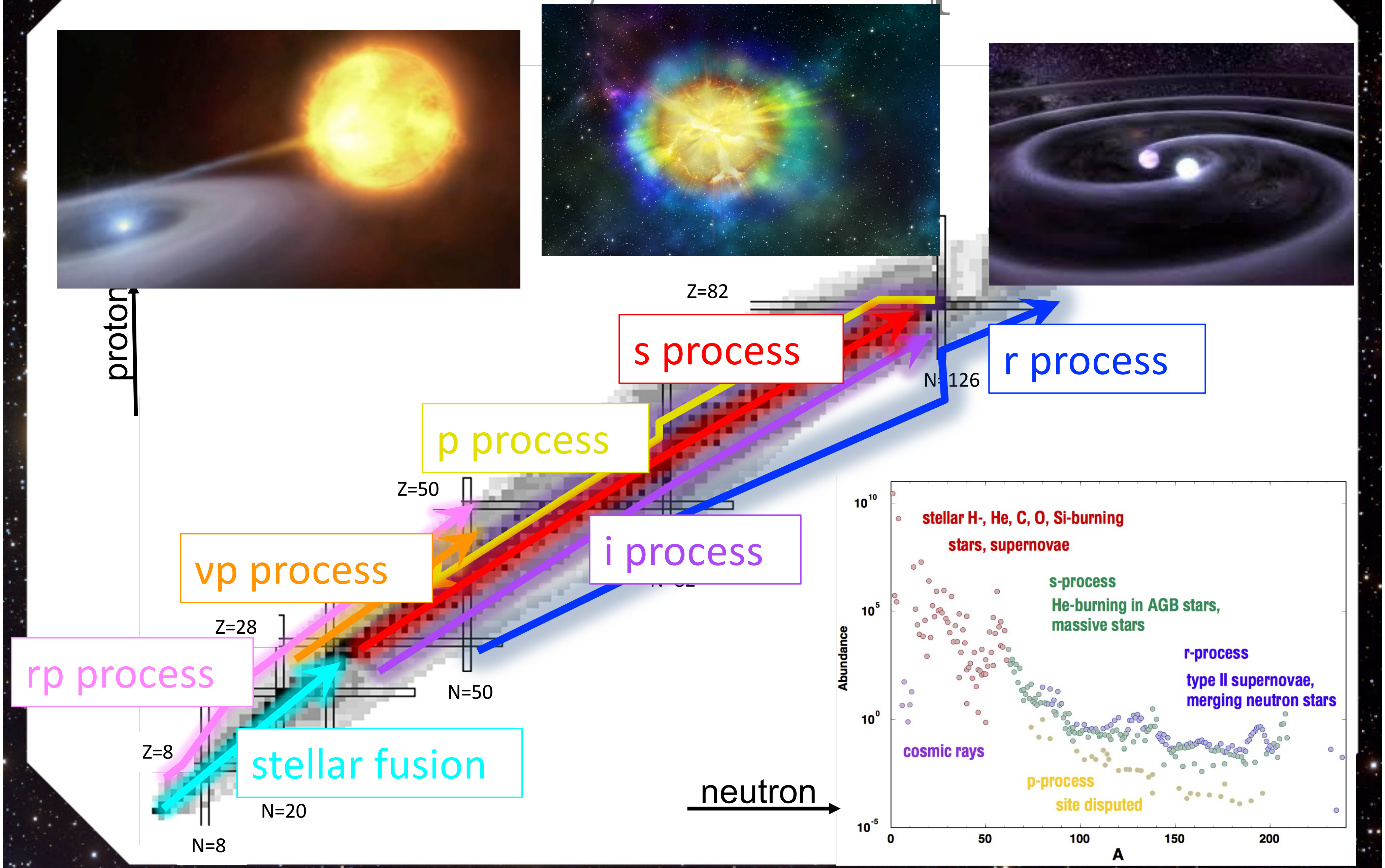
- Masses (time of flight, traps)
- Half lives
- Pn values (time of flight, thermalization, traps)
- Neutron-captures: Indirect techniques (surrogate, β-Oslo)

Abundances



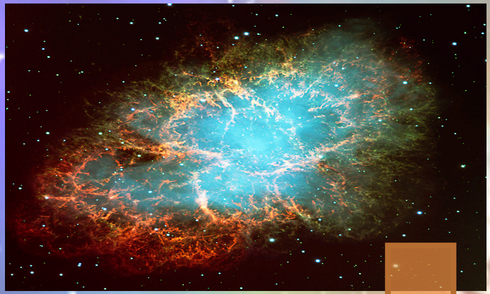
From M. Wiescher, JINA web

Nucleosynthesis paths

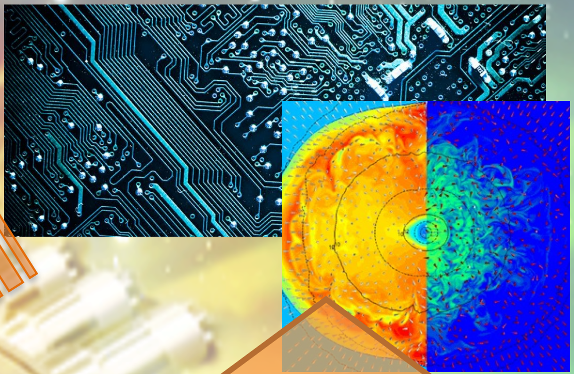


Nuclear Astrophysics

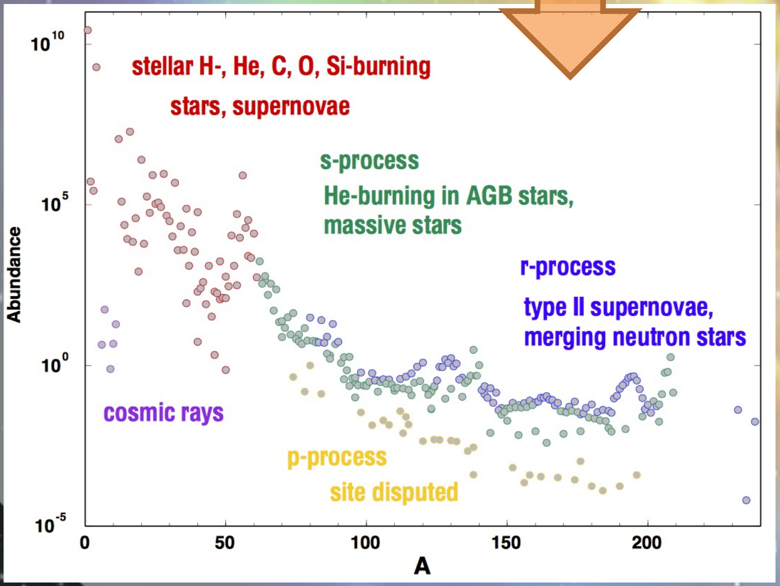
Observations

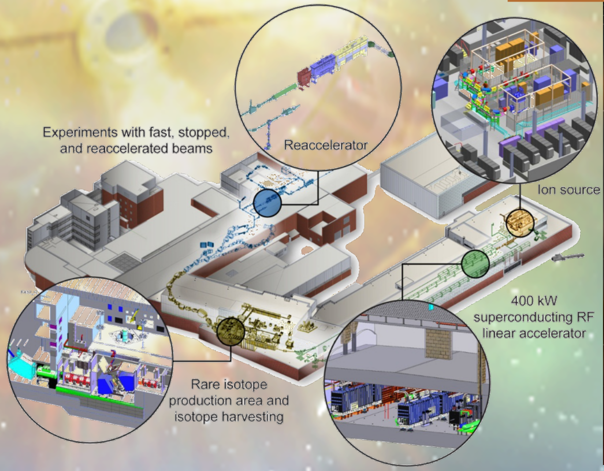


Models

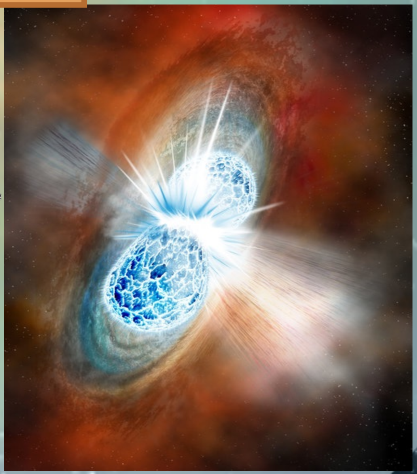


Input





Nuclear

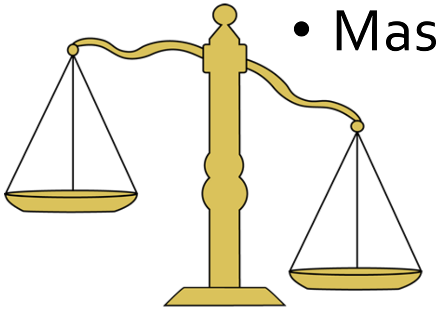


Astro

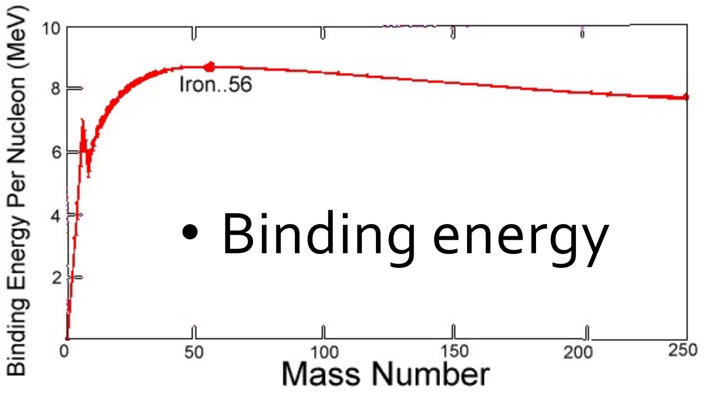
Figure Credit: Erin O'Donnel, NSCL

Nuclear input: What do we need?

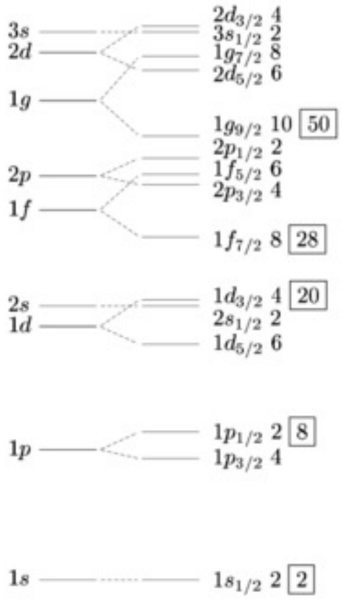
o Basic nuclear properties



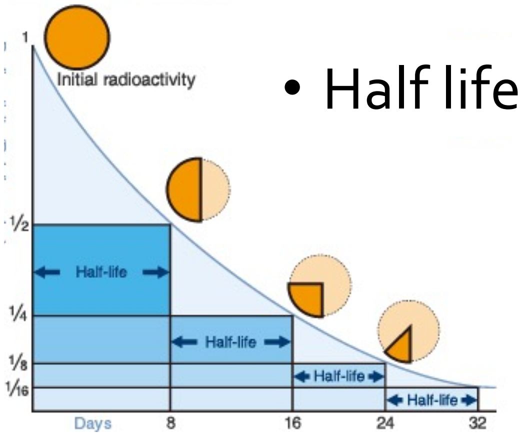
- Mass



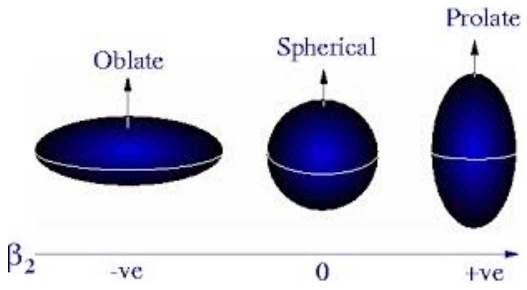
- Binding energy



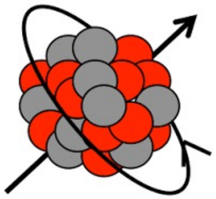
- Level structure



- Half life



- Nuclear radius/shape

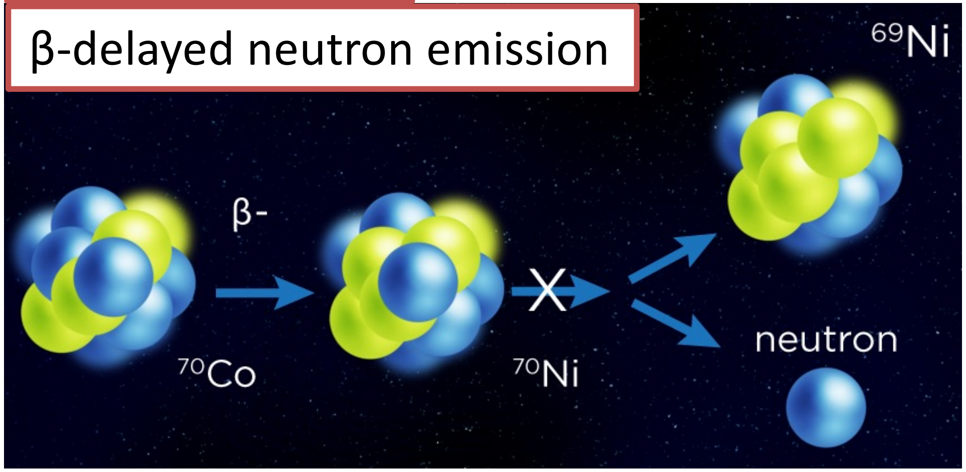


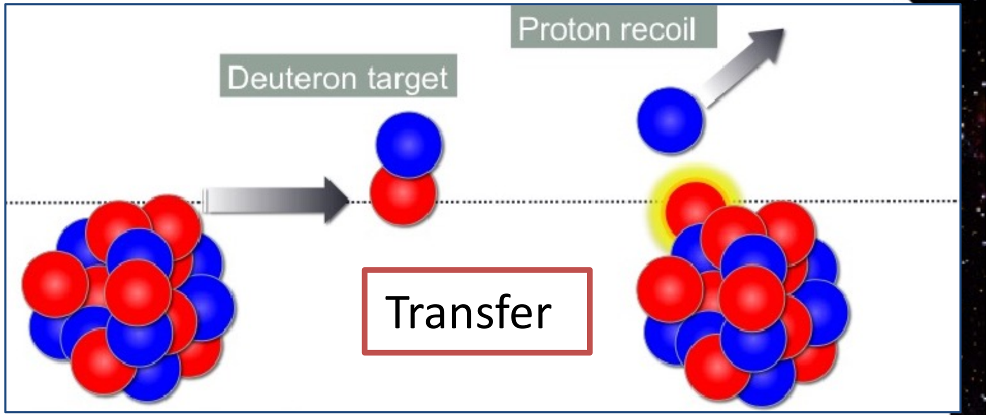
- Angular Momentum

Nuclear input: What do we need?

β-decay half-lives

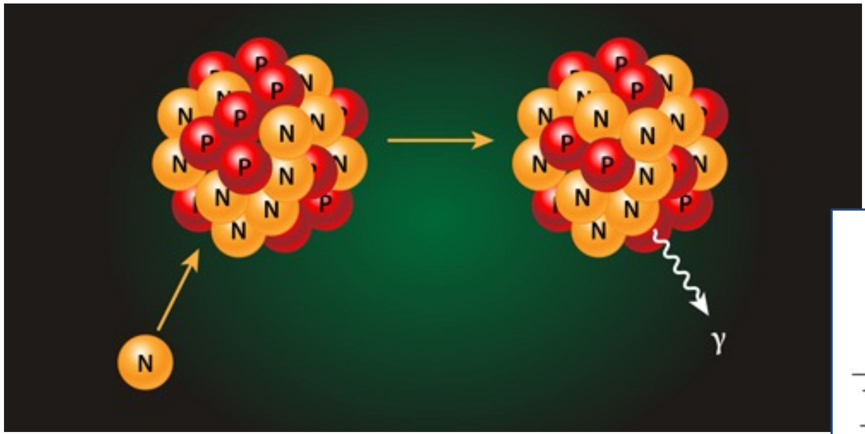
β-delayed neutron emission



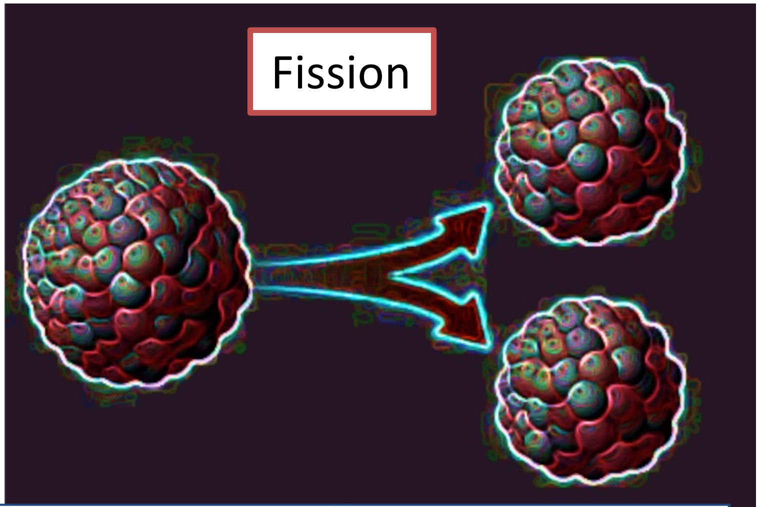


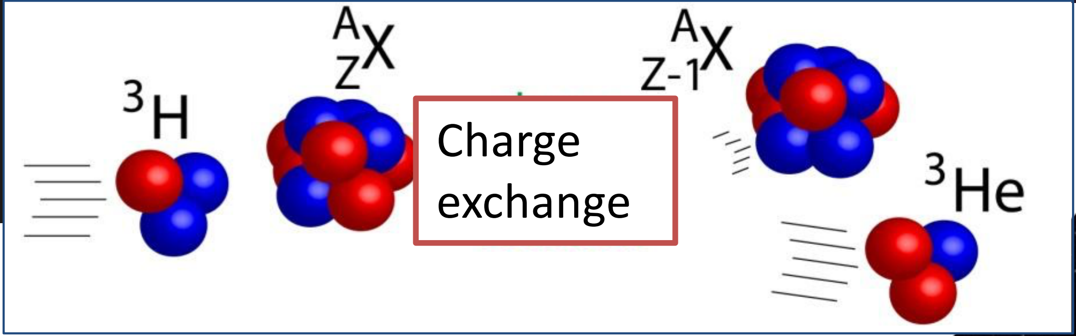
Transfer

Neutron/proton Captures



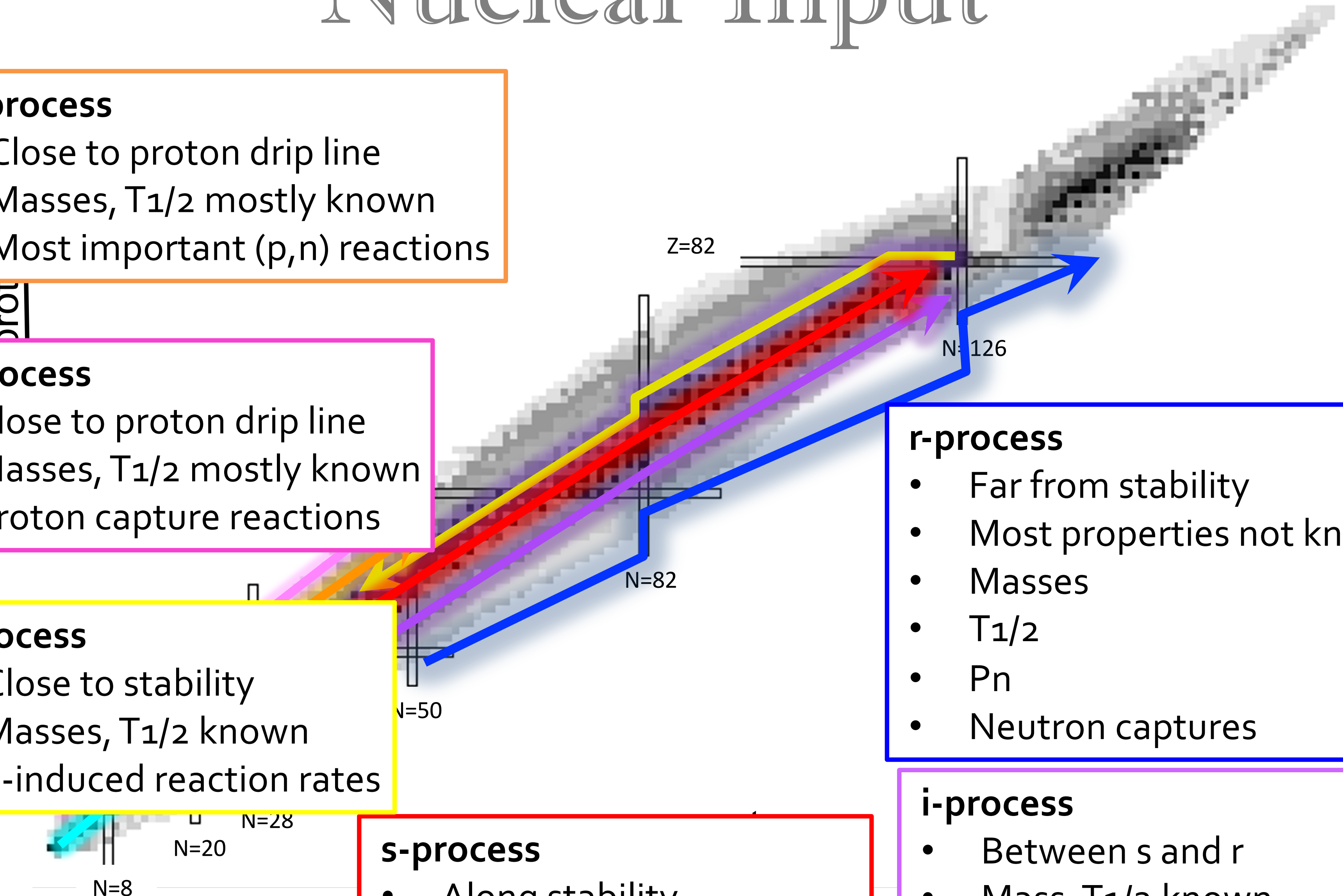
Fission





Charge exchange

Nuclear Input



νp-process
- Close to proton drip line
- Masses, T1/2 mostly known
- Most important (p,n) reactions

rp-process
- Close to proton drip line
- Masses, T1/2 mostly known
- Proton capture reactions

p-process
- Close to stability
- Masses, T1/2 known
- γ-induced reaction rates

s-process
- Along stability
- Most properties known
- Missing neutron captures

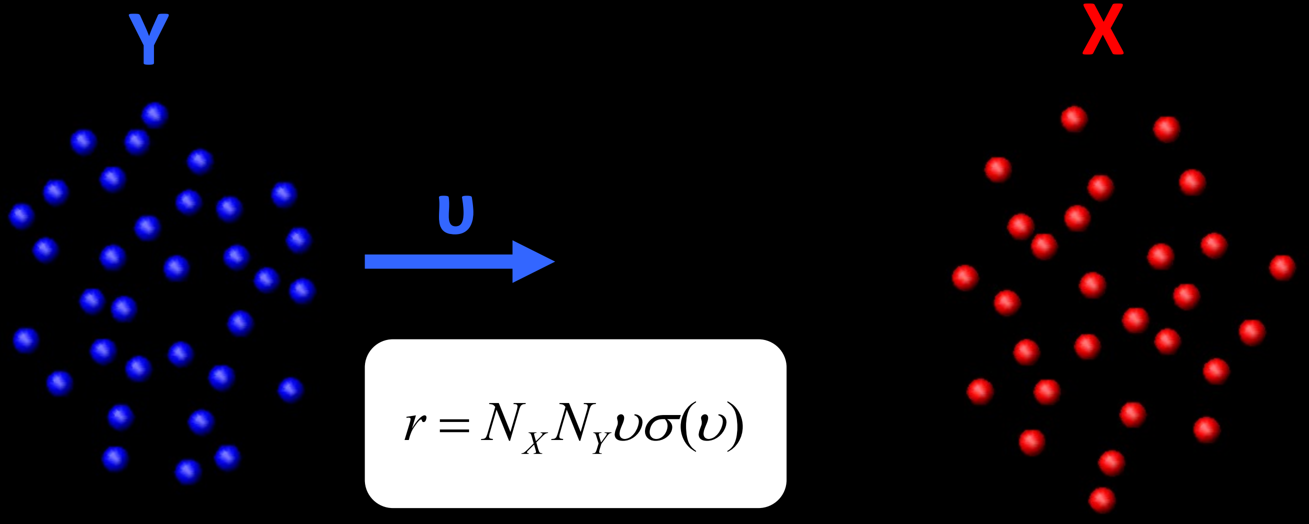
r-process
- Far from stability
- Most properties not known
- Masses
- T1/2
- Pn
- Neutron captures

i-process
- Between s and r
- Mass, T1/2 known
- Missing neutron captures

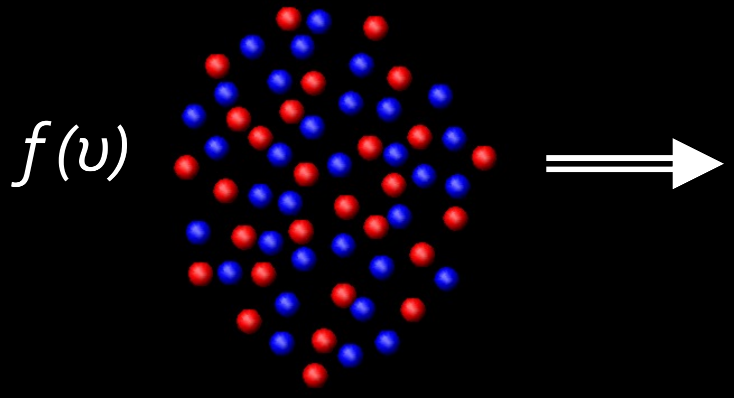
Nuclear Reactions in Stars

Main focus on capture reactions

Today focusing on reactions



$$r = N_X N_Y \upsilon \sigma(\upsilon)$$



$$r = N_X N_Y \int_0^\infty f(\upsilon)\sigma(\upsilon)\upsilon\, d\upsilon$$

r: *reaction rate*
N_x, N_y: *number of particles*
υ:*velocity*
σ(υ): *reaction cross section at υ*
f(υ): *velocity distribution*
<συ>: *reaction rate per particle pair*

$$\langle \sigma\upsilon \rangle = \frac{r}{N_X N_Y} = \int_0^\infty f(\upsilon)\sigma(\upsilon)\upsilon\, d\upsilon$$

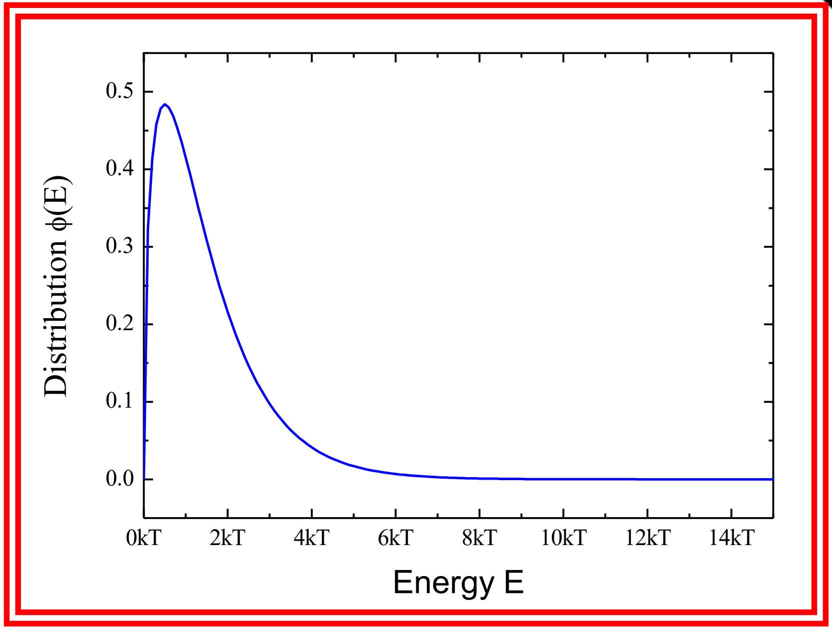
Rolfs and Rodney, “Cauldrons in the cosmos”

Maxwell – Boltzmann distribution

$$f(v) = 4\pi v^2 \left(\frac{m}{2\pi kT}\right)^{3/2} e^{\left(-\frac{mv^2}{2kT}\right)}$$

$$\Downarrow$$

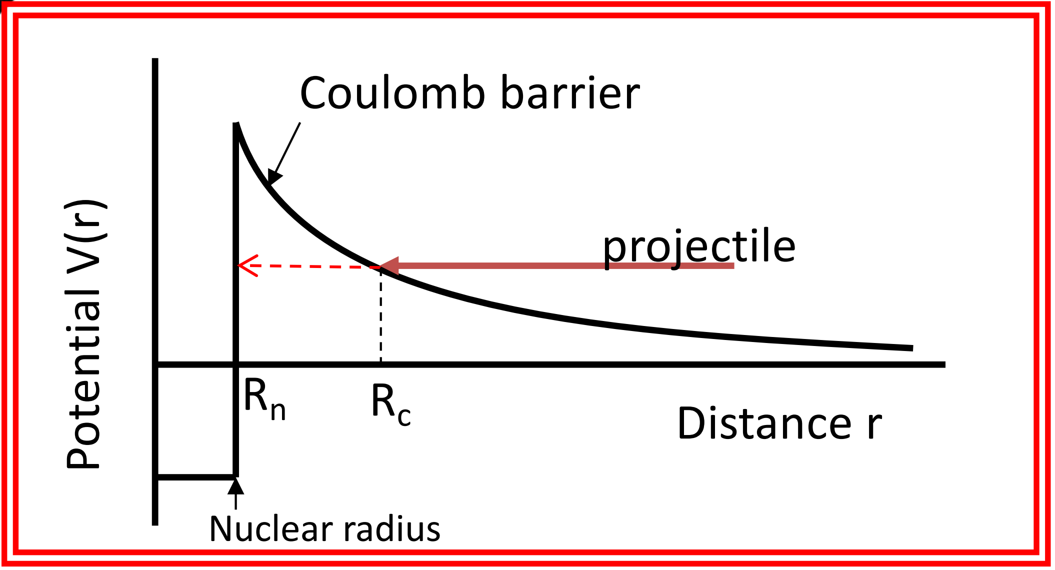
$$\phi(E) = \frac{2}{\sqrt{\pi}} \left(\frac{1}{kT}\right)^{3/2} E^{1/2} e^{\left(-\frac{E}{kT}\right)}$$



$$\boxed{\langle \sigma v \rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma(E) E e^{\left(-\frac{E}{kT}\right)} dE}$$

Rolfs and Rodney, “Cauldrons in the cosmos”

Tunnel Effect – S-factor



$$P = \frac{|\psi(R_n)|^2}{|\psi(R_c)|^2}$$

Tunneling probability -> increasing with energy

Cross section has two components:

1. Interaction between particles (pure nuclear)
2. The Coulomb force

$$\sigma(E) = \frac{1}{E} e^{(-2\pi\eta)} \boxed{S(E)}$$

Astrophysical S-factor

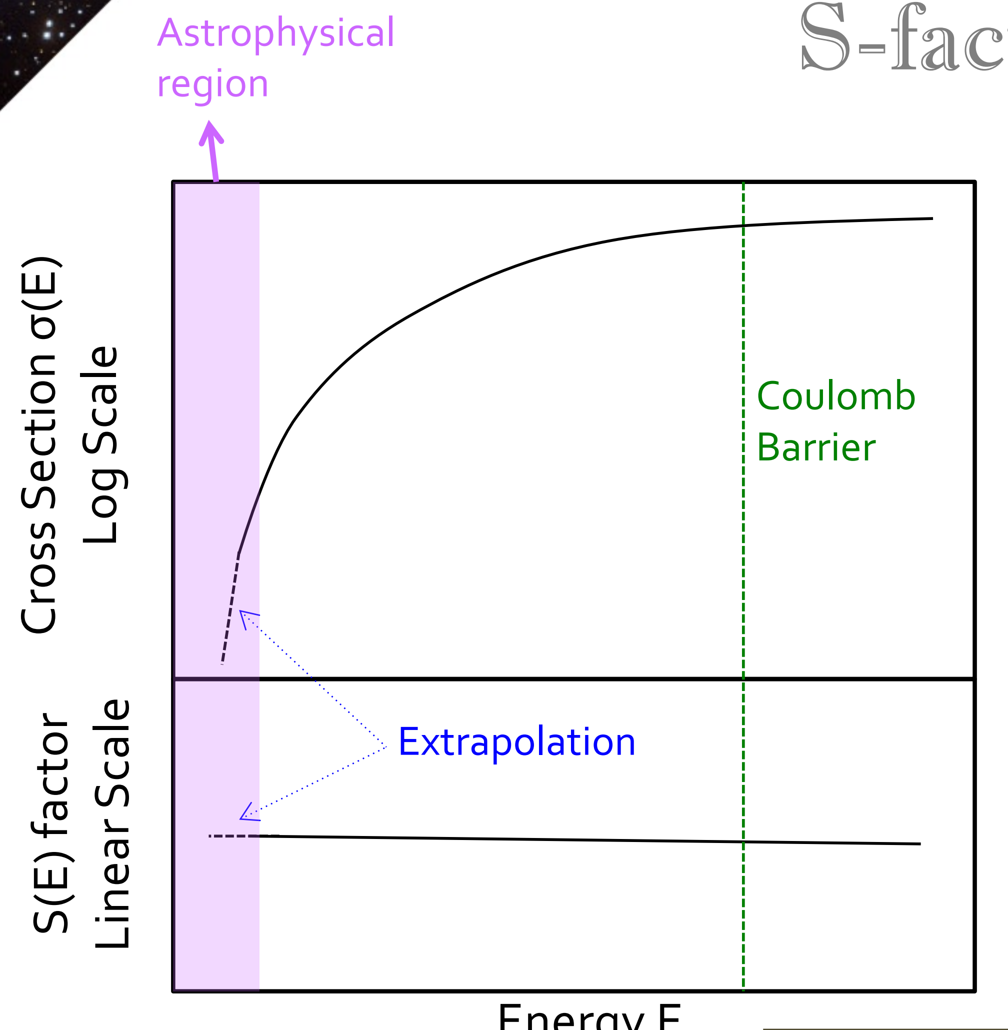
Contains all the pure nuclear properties

η: Sommerfeld parameter

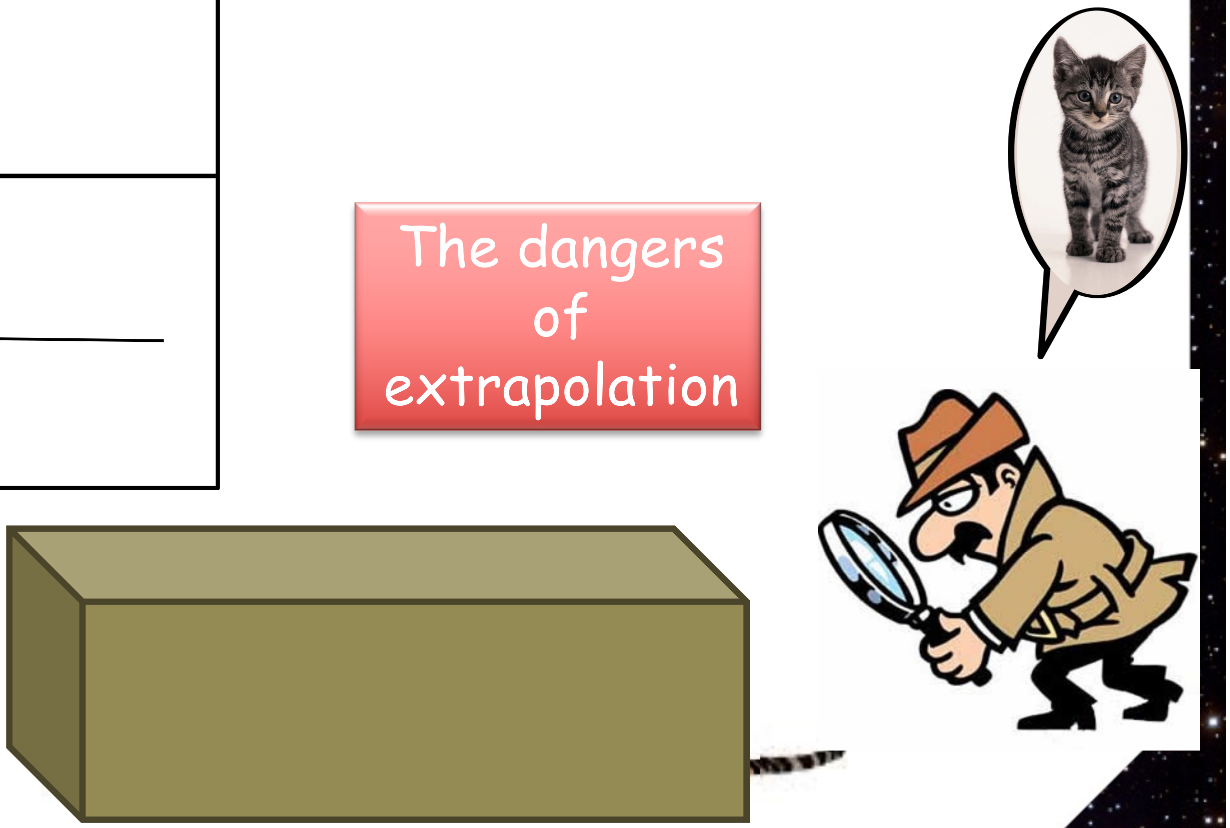
$$\boxed{\eta = \frac{Z_1 Z_2 e^2}{\hbar \upsilon}}$$

Rolfs and Rodney, “Cauldrons in the cosmos”

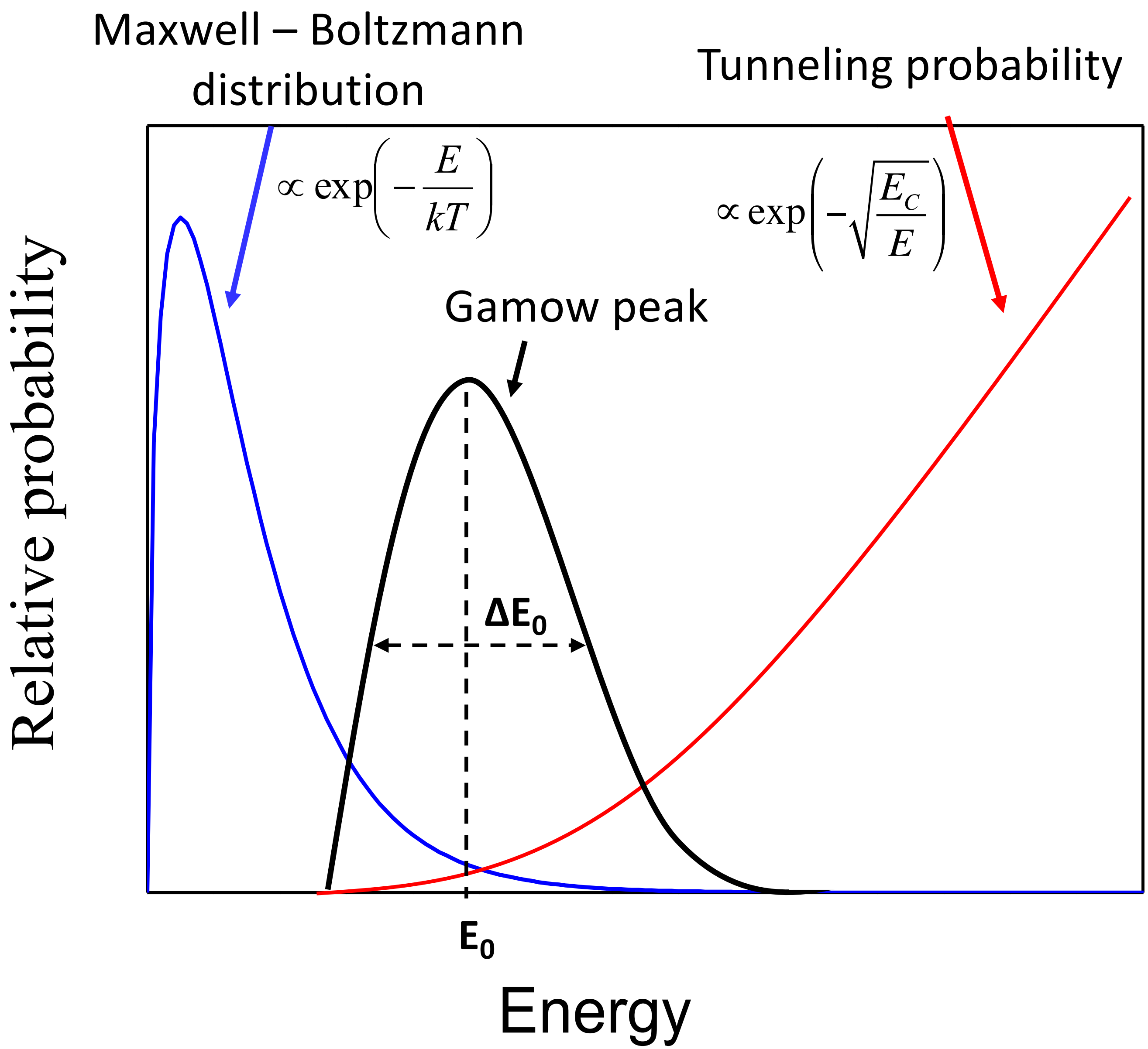
S-factor



The dangers of extrapolation



Gamow Window



Maxwell – Boltzmann distribution

$\propto \exp\left(-\frac{E}{kT}\right)$

Tunneling probability

$\propto \exp\left(-\sqrt{\frac{E_C}{E}}\right)$

Gamow peak

Gamow Window

- Charged particles

Standard approximation

$$E_0 = 0.12204(Z_1^2 Z_2^2 \mu T_9^2)^{1/3}$$

$$\Delta E_0 = 0.237(Z_1^2 Z_2^2 \mu T_9^5)^{1/6}$$

[in MeV]

Window: $\boxed{E_0 + \frac{\Delta E_0}{2}}$

p process: T= 1.8 – 3.3 GK
- ○ (p,γ): E_p= 1 – 5 MeV
- ○ (α,γ): E_α= 4 -12 MeV

rp process: T= 1.1 – 1.3 GK
- ○ (p,γ): E_p= 0.8 – 2 MeV

νp process: T= 1.5 – 3.0 GK
- ○ (p,γ): E_p= 1 – 4 MeV

- Neutrons

No Coulomb barrier, angular momentum

$$E_{eff} = 0.172 T_9 (\ell + \frac{1}{2})$$

$$\Delta E_{eff} = 0.194 T_9 \sqrt{\ell + \frac{1}{2}}$$

[in MeV]

Window: $\boxed{E_{eff} + \frac{\Delta E_{eff}}{2}}$

s process: T~ 0.3GK
- ○ (n,γ): E_n= 25 - 75 keV

i process: T= 0.1-0.3GK
- ○ (n,γ): E_p= 10 – 75 MeV

r process: T= 0.1 – 2.0 GK
- ○ (n,γ): E_p= 10 – 500 keV

Rauscher, PRC 81 (2010) 045807

Kadonis.org : Gamow Calculator

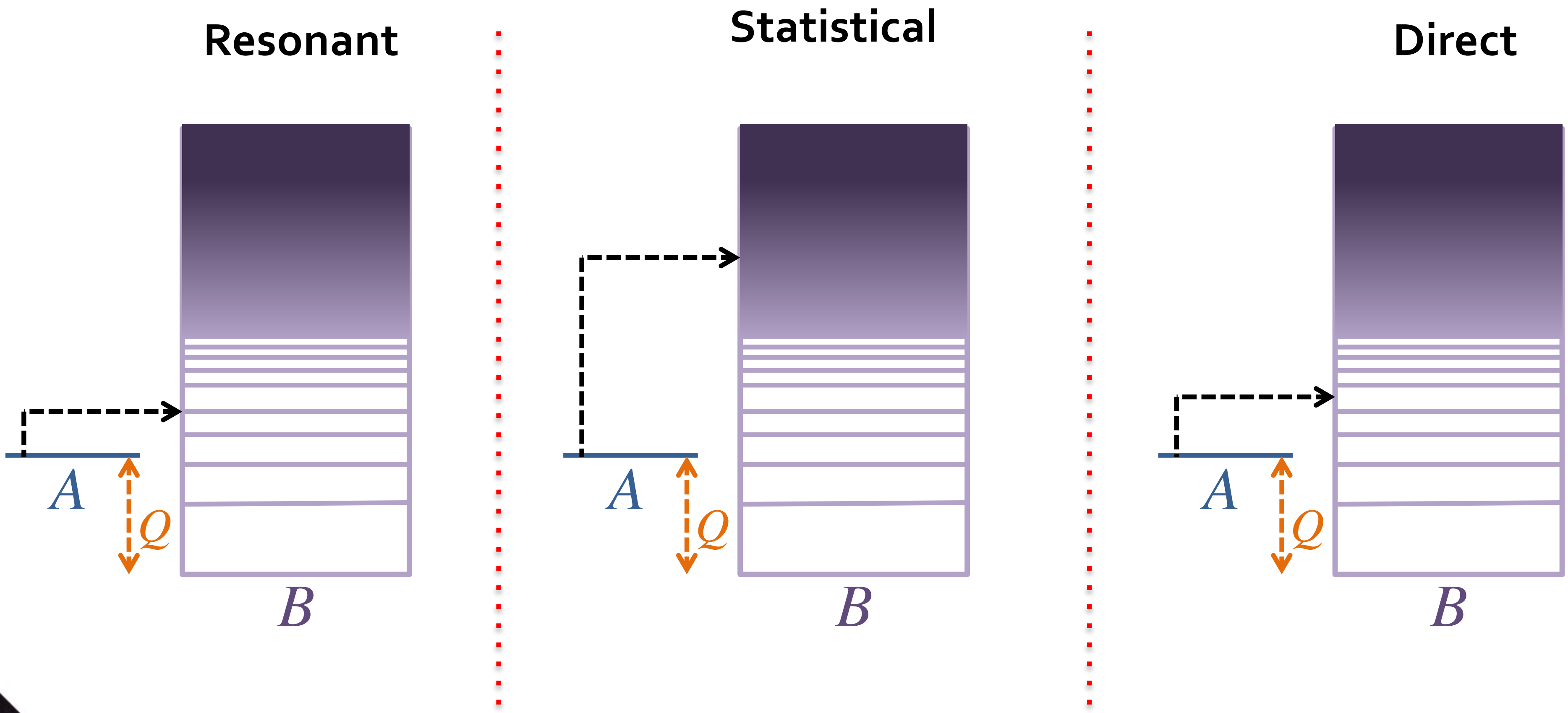
Nuclear input: What do we need?

- Nuclear reactions/Astrophysical reaction rates

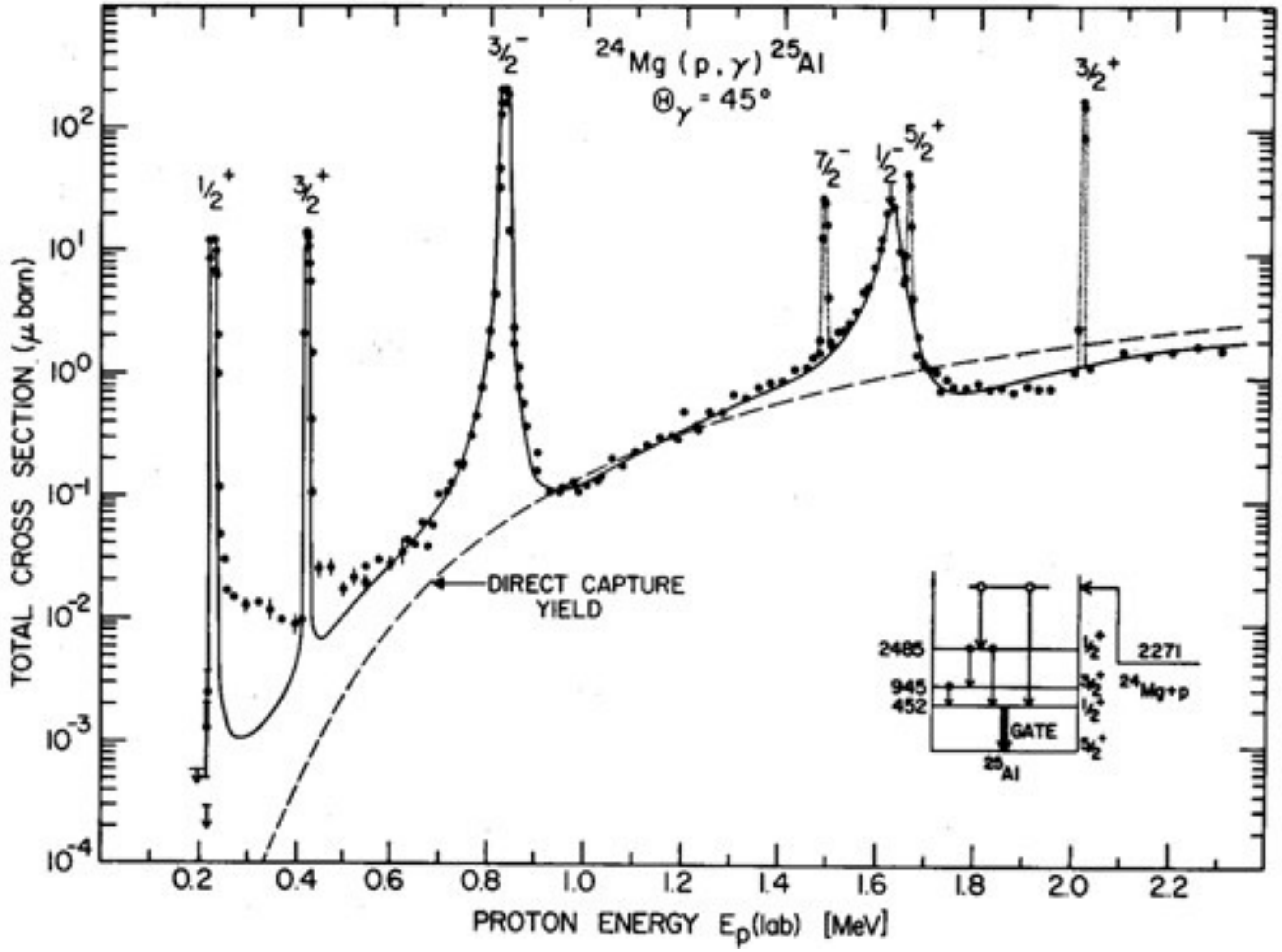
Incoming channel

$$a + A \rightarrow B^* \rightarrow B + \gamma$$

Radiative capture reactions



Example: ^{24}Mg(p,γ)^{25}Al



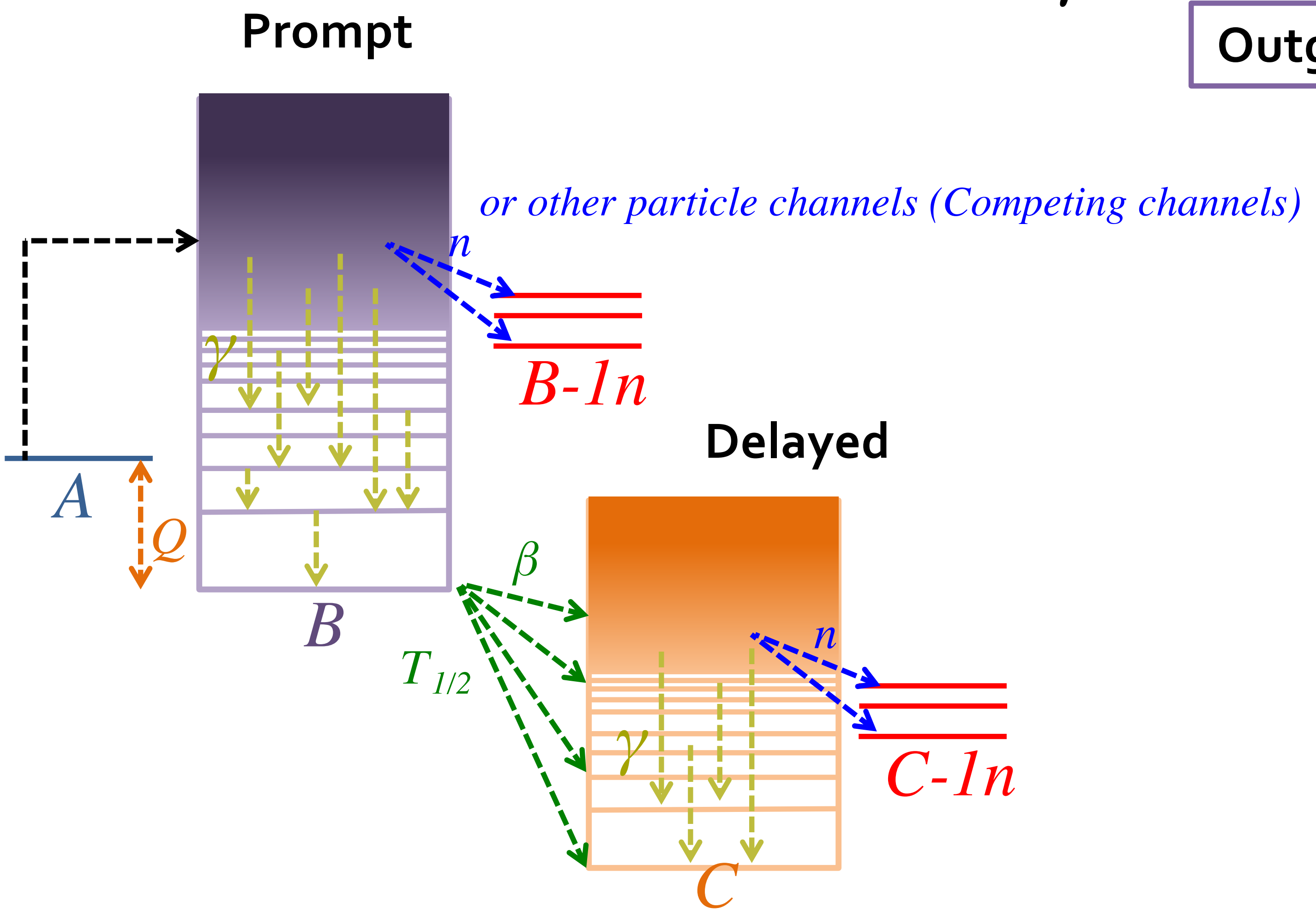
Marialuisa Aliotta, University of Edinburgh
11th Euro Summer School on Exotic Beams

Nuclear input: What do we need?

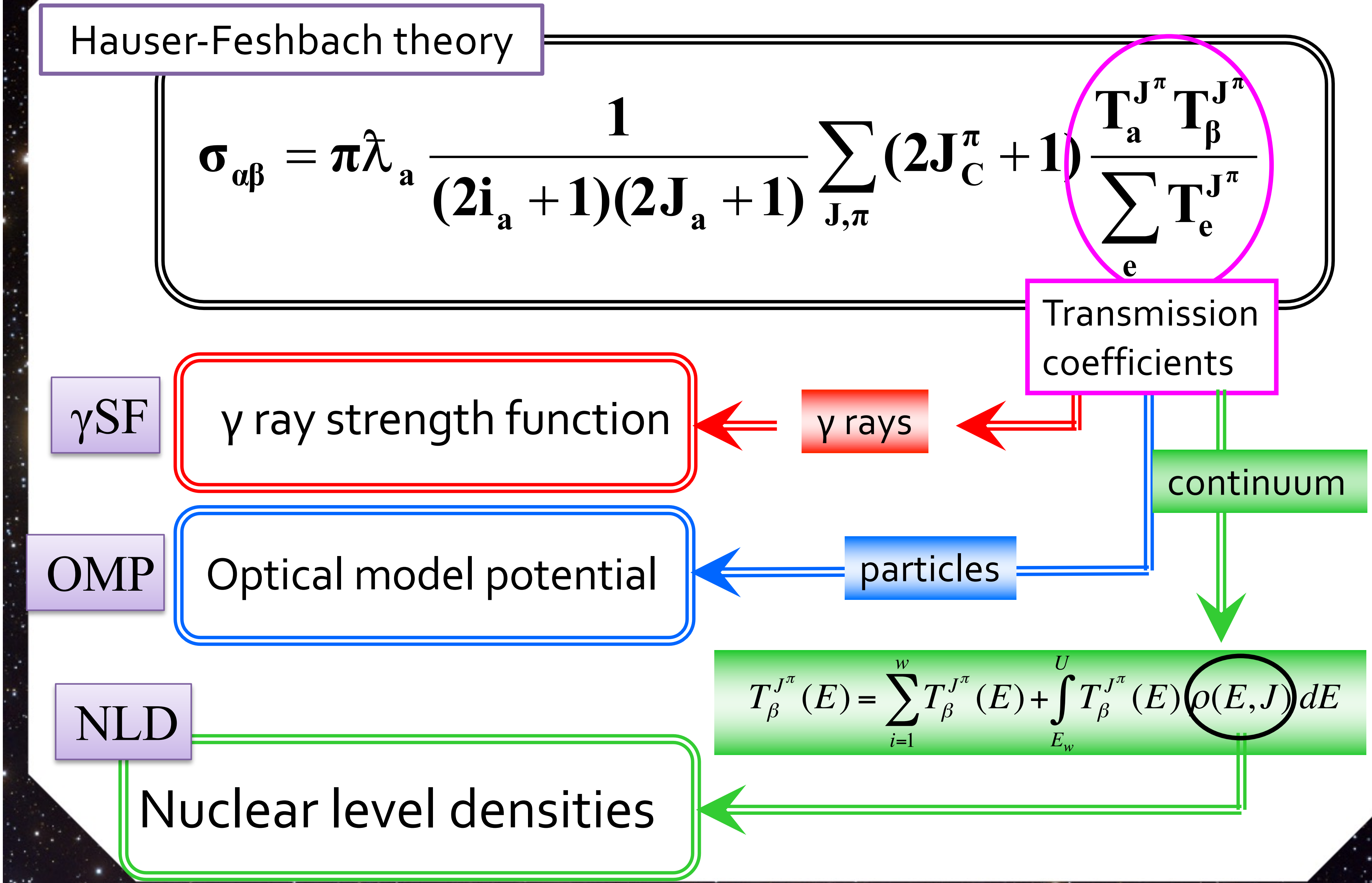
- Nuclear reactions/Astrophysical reaction rates

$$a + A \rightarrow B^{*} \rightarrow B + \gamma$$

Outgoing channel



Calculate: Cross Section



Hauser-Feshbach theory

$$\sigma_{\alpha\beta} = \pi \bar{\lambda}_a \frac{1}{(2i_a+1)(2J_a+1)} \sum_{J,\pi} (2J_C^\pi+1) \frac{T_a^{J^\pi} T_\beta^{J^\pi}}{\sum_e T_e^{J^\pi}}$$

Transmission coefficients

γ rays

continuum

particles

γSF

γ ray strength function

OMP

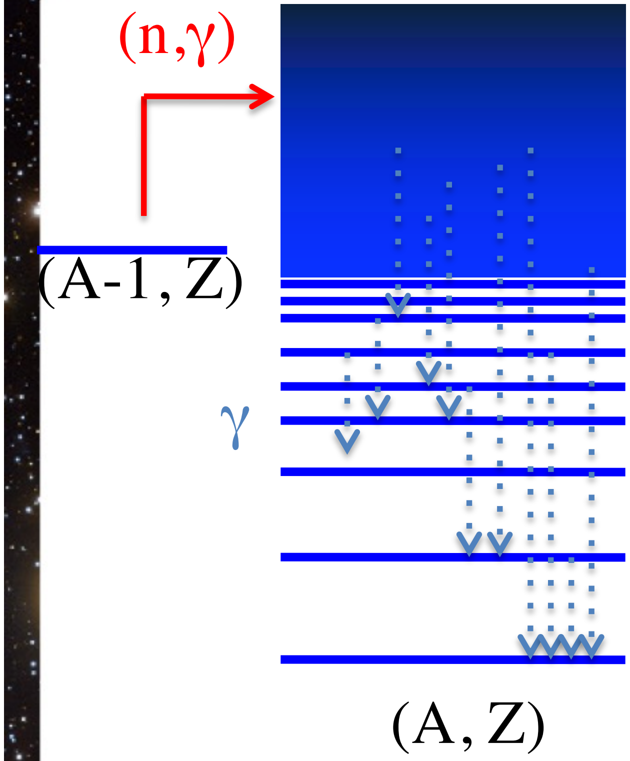
Optical model potential

$$T_\beta^{J^\pi}(E) = \sum_{i=1}^{w} T_\beta^{J^\pi}(E) + \int_{E_w}^{U} T_\beta^{J^\pi}(E)\,\rho(E,J)\,dE$$

NLD

Nuclear level densities

Calculate (n,γ) Cross Section



Hauser – Feshbach

- Nuclear Level Density

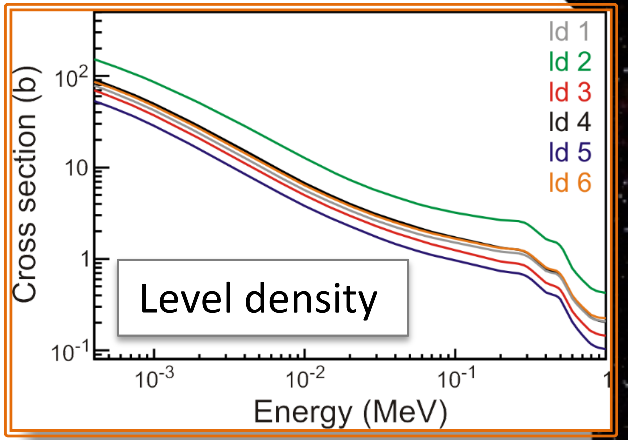
Constant T+Fermi gas, back-shifted Fermi gas, superfluid, microscopic

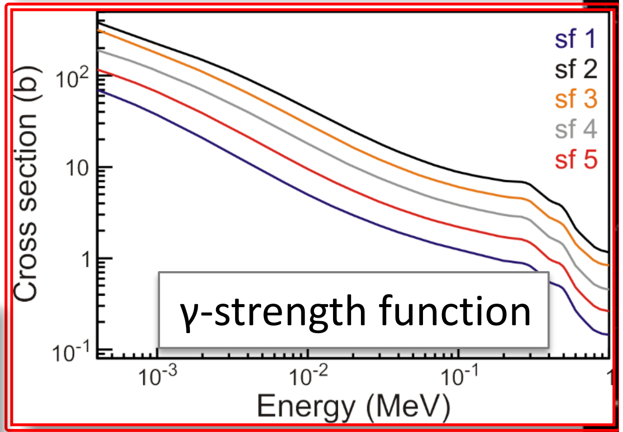
- γ-ray strength function

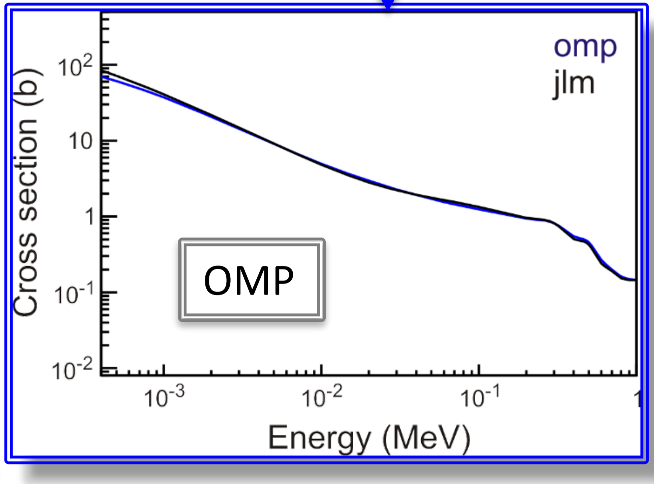
Generalized Lorentzian, Brink-Axel, various tables

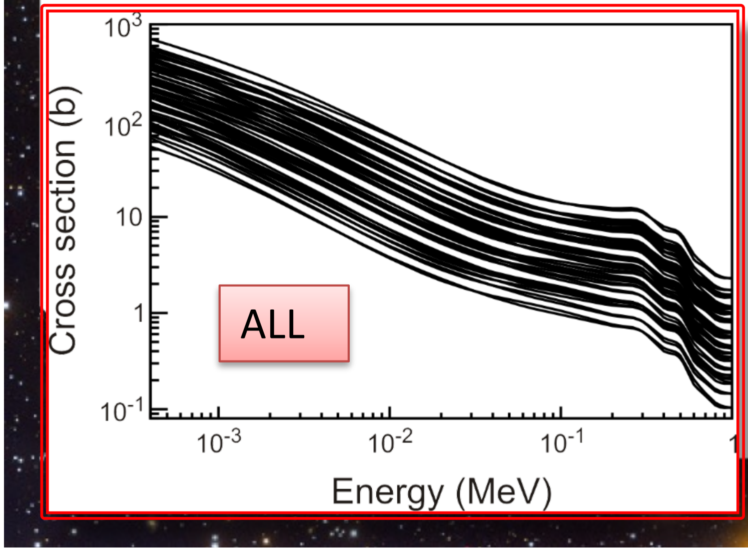
- Optical model potential

Phenomenological, Semi-microscopic





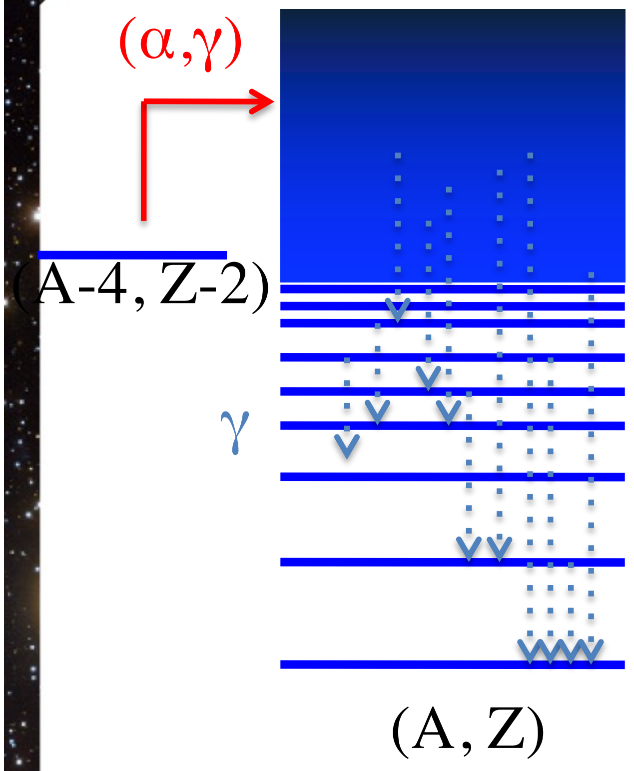




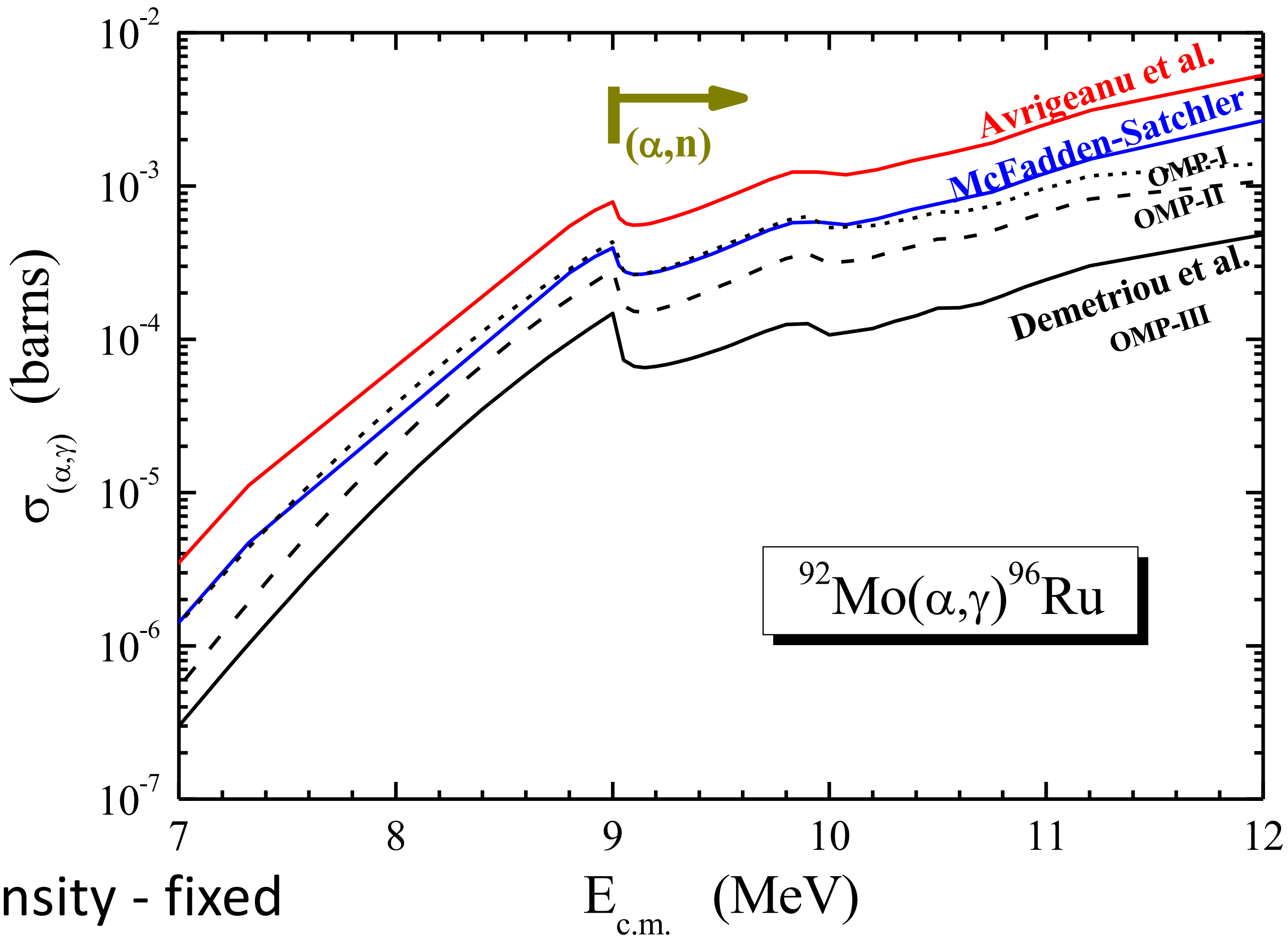
^{95}Sr(n,γ)^{96}Sr

TALYS

Calculate (α,γ) Cross Section



^{92}Mo(α,γ)^{96}Ru



- Nuclear Level Density - fixed
- γ-ray strength function – fixed
- α - Optical model potential - varying

In the Laboratory

- Yield of reaction: $Y = \dfrac{Number\ of\ reactions}{Number\ of\ beam\ particles}$
- Cross section: $\sigma = \dfrac{Yield\ of\ reaction}{Number\ of\ target\ particles} = \boxed{\dfrac{N_R}{N_b \cdot N_T}}$

To measure a cross section you need three things:

1. Number of target particles (N_T) !!!
2. Number of beam particles (N_b) !!!
3. Number of reactions (N_R) !!!

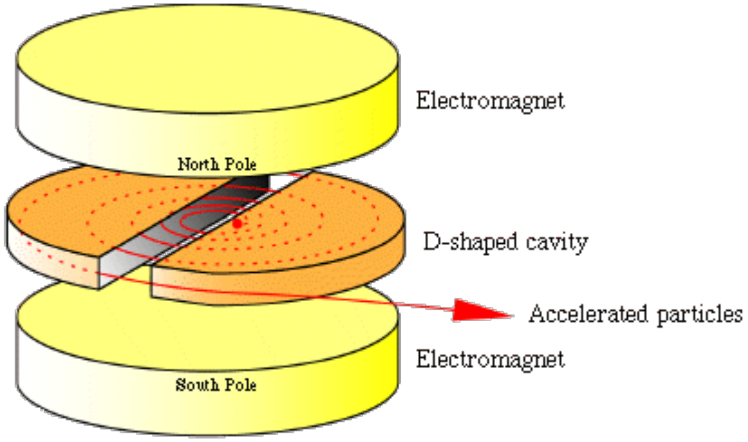
But first … you need a beam

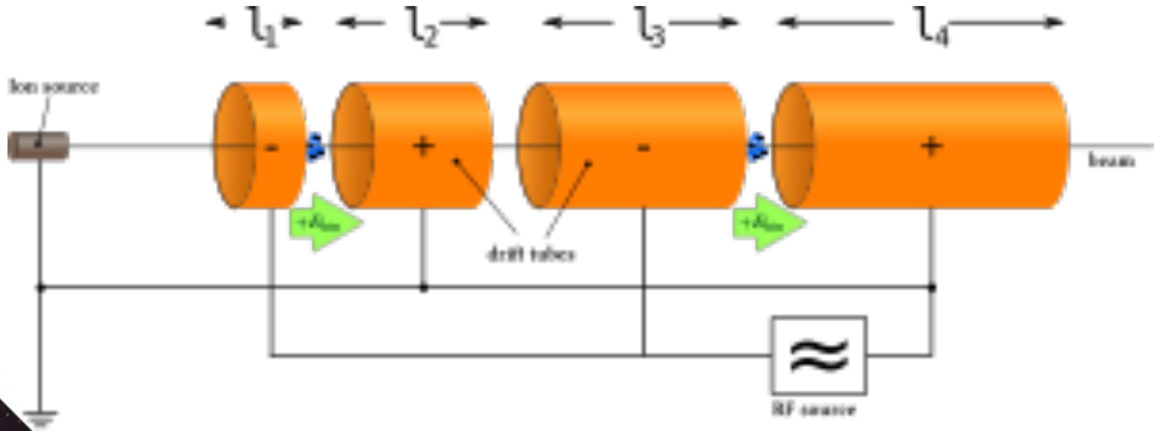
Accelerator Facilities

Facilities

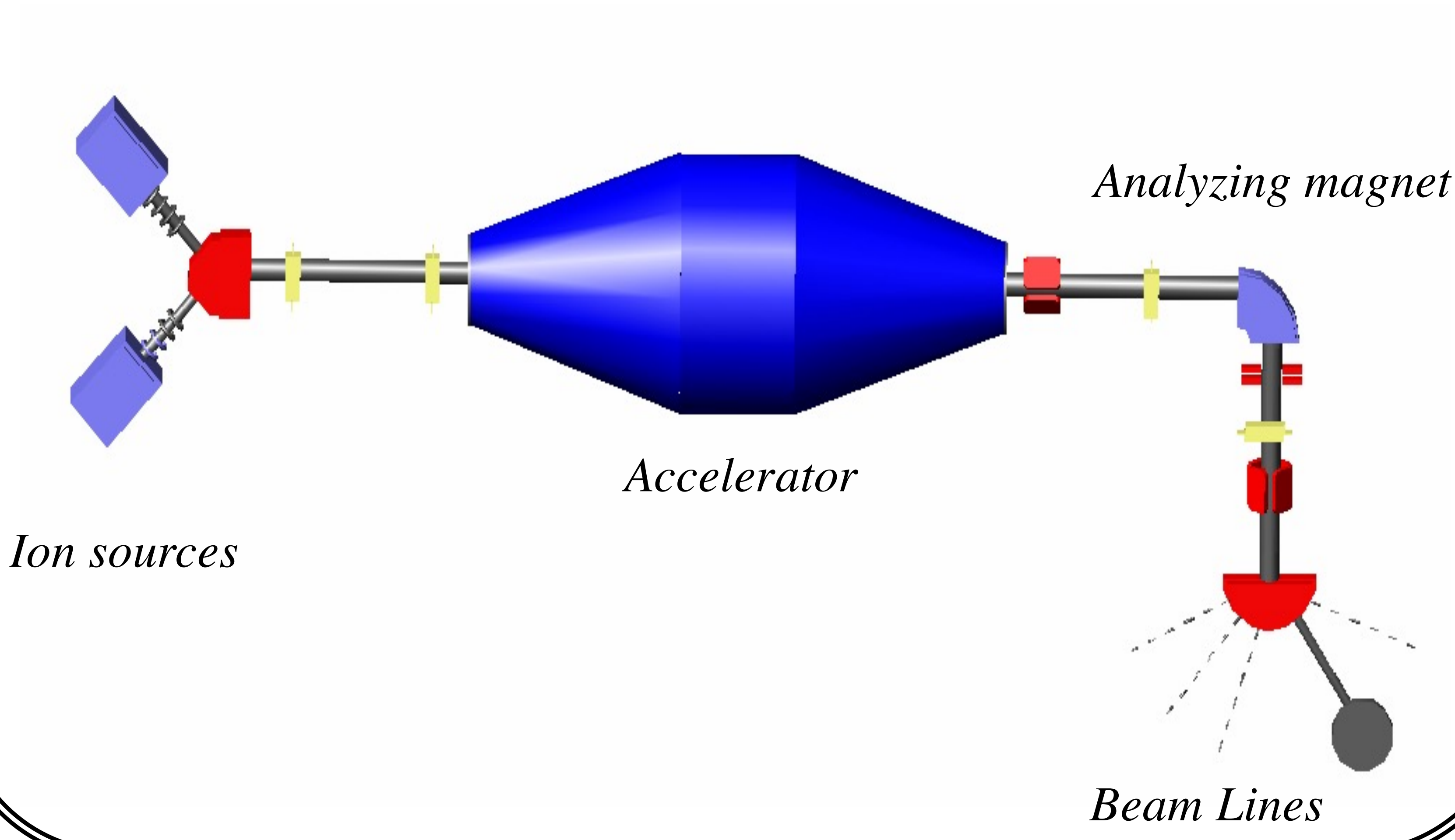
Stable beam facilities (Intro Physics)

- Van de Graaff (single-ended or tandem)
- Cyclotrons
- LINACS





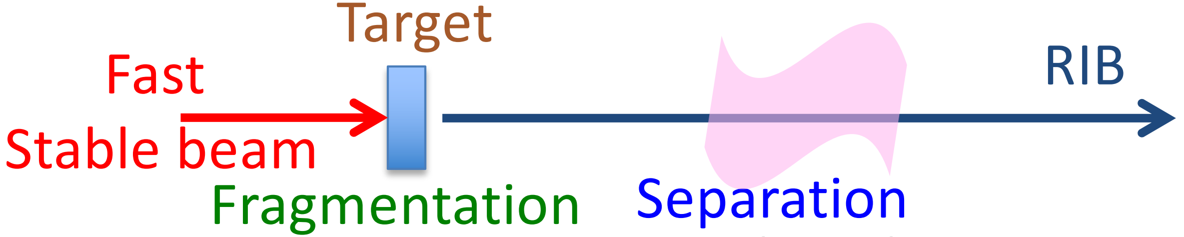
Basic Components



5MV tandem accelerator @ Institute of Nuclear Physics, "Demokritos", Athens, Greece

Radioactive Beams

- **Fragmentation**: NSCL/FRIB, GSI/FAIR, RIKEN, HIRFL …


Target

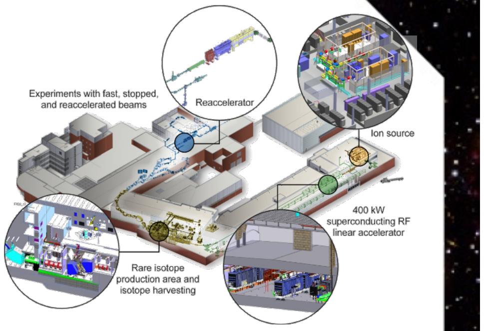
Fast

Stable beam

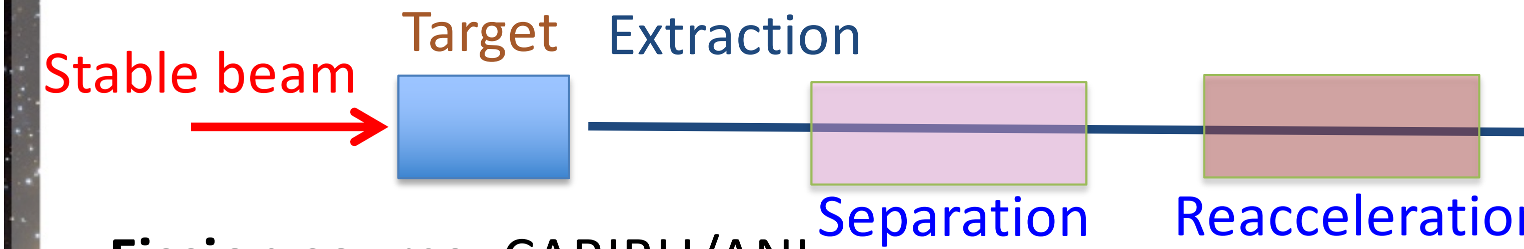
RIB

Fragmentation

Separation



- **Isotope Separation On-Line (ISOL)**: TRIUMF, SPIRAL, ISOLDE, …


Target

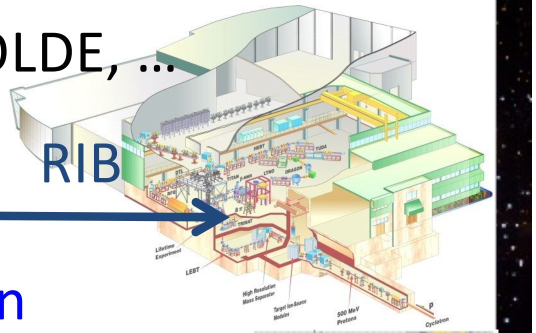
Extraction

Stable beam

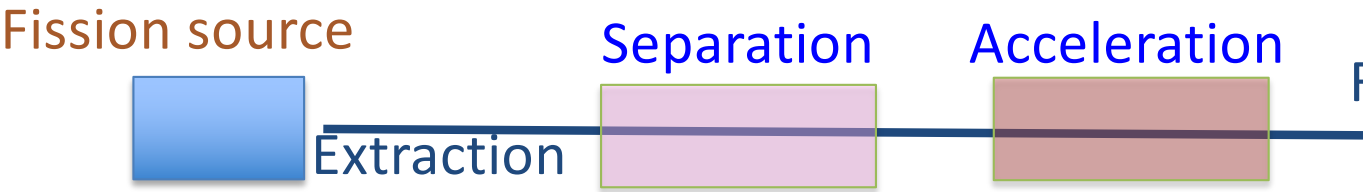
RIB

Separation

Reacceleration



- **Fission source**: CARIBU/ANL

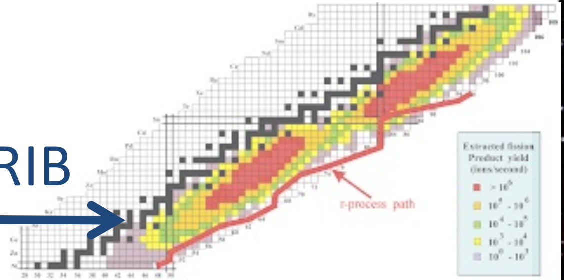

Fission source

Separation

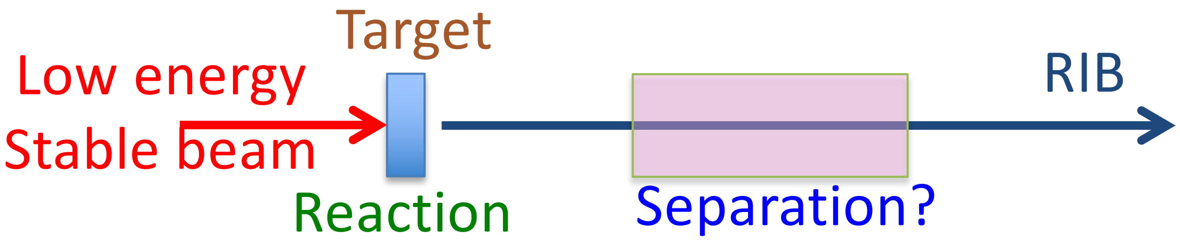
Acceleration

RIB

Extraction



- **Low energy reactions**: ANL, FSU, Texas A&M, Notre Dame, …


Target

Low energy

Stable beam

RIB

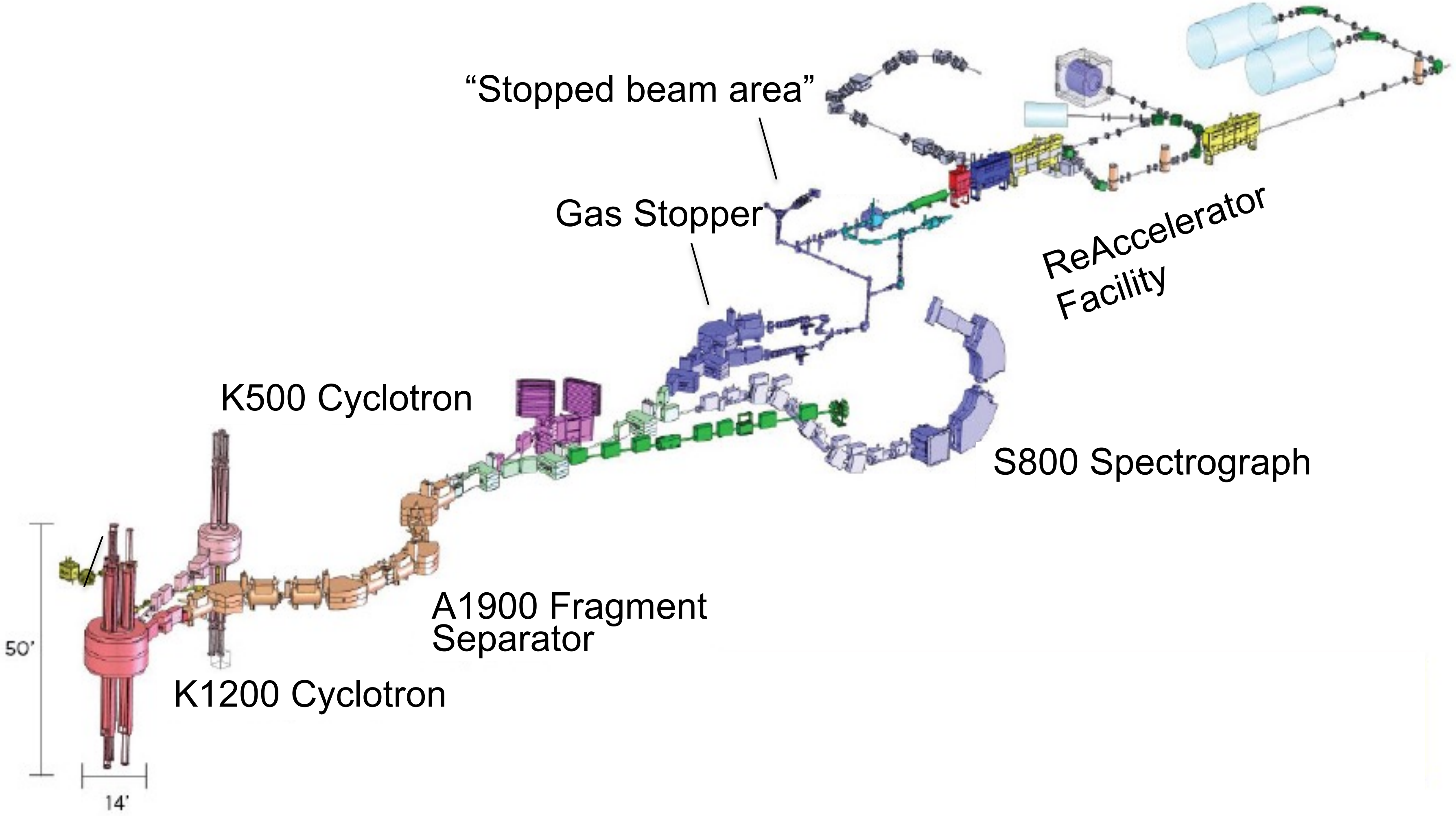
Reaction

Separation?

Artemis Spyrou, NIC 2021,

NSCL@MSU

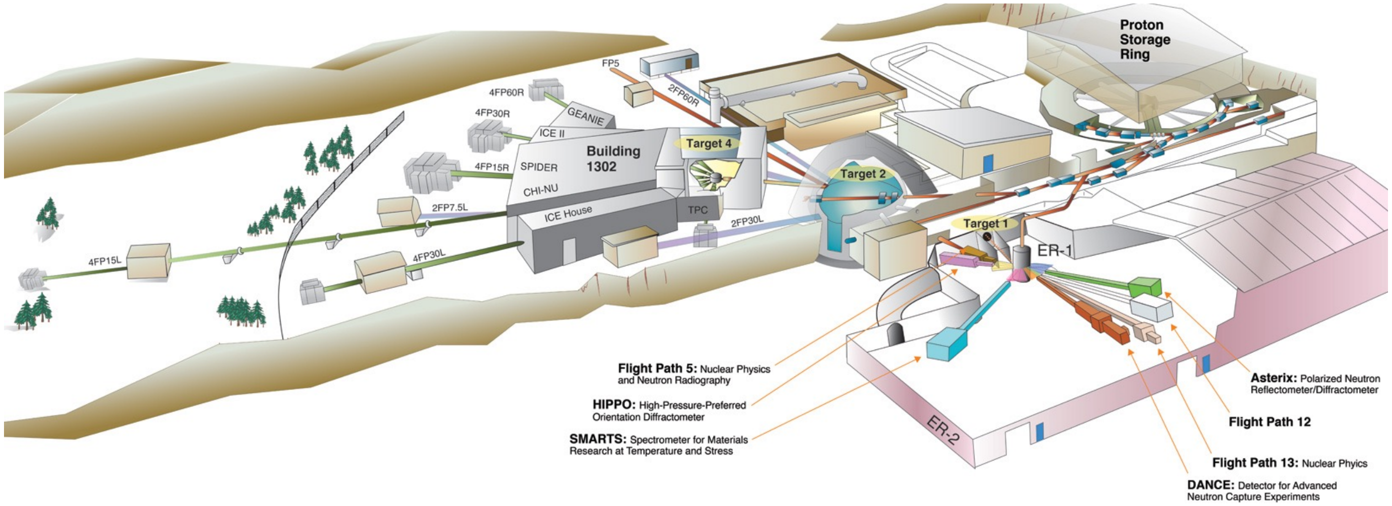
- **National Superconducting Cyclotron Laboratory**



Neutron Facilities

Time-of-Flight: e.g. nTOF@CERN, LANSCE@ Los Alamos, IRMM@Geel, Belgium, etc

- High energy protons on heavy target, broad energy distribution, pulsed beam.



Flight Path 5: Nuclear Physics and Neutron Radiography

HIPPO: High-Pressure-Preferred Orientation Diffractometer

SMARTS: Spectrometer for Materials Research at Temperature and Stress

Asterix: Polarized Neutron Reflectometer/Diffractometer

Flight Path 12

Flight Path 13: Nuclear Phyics

DANCE: Detector for Advanced Neutron Capture Experiments

Reaction-based, quasi-monoenergetic: Any low energy facility

- Reactions: $^{2}H(^{2}H,n)^{3}He$ – Q= 3.3 MeV - E_n= 2.5 MeV

  $^{3}H(^{2}H,n)^{4}He$ – Q= 17.6 MeV - E_n = 14.1 MeV

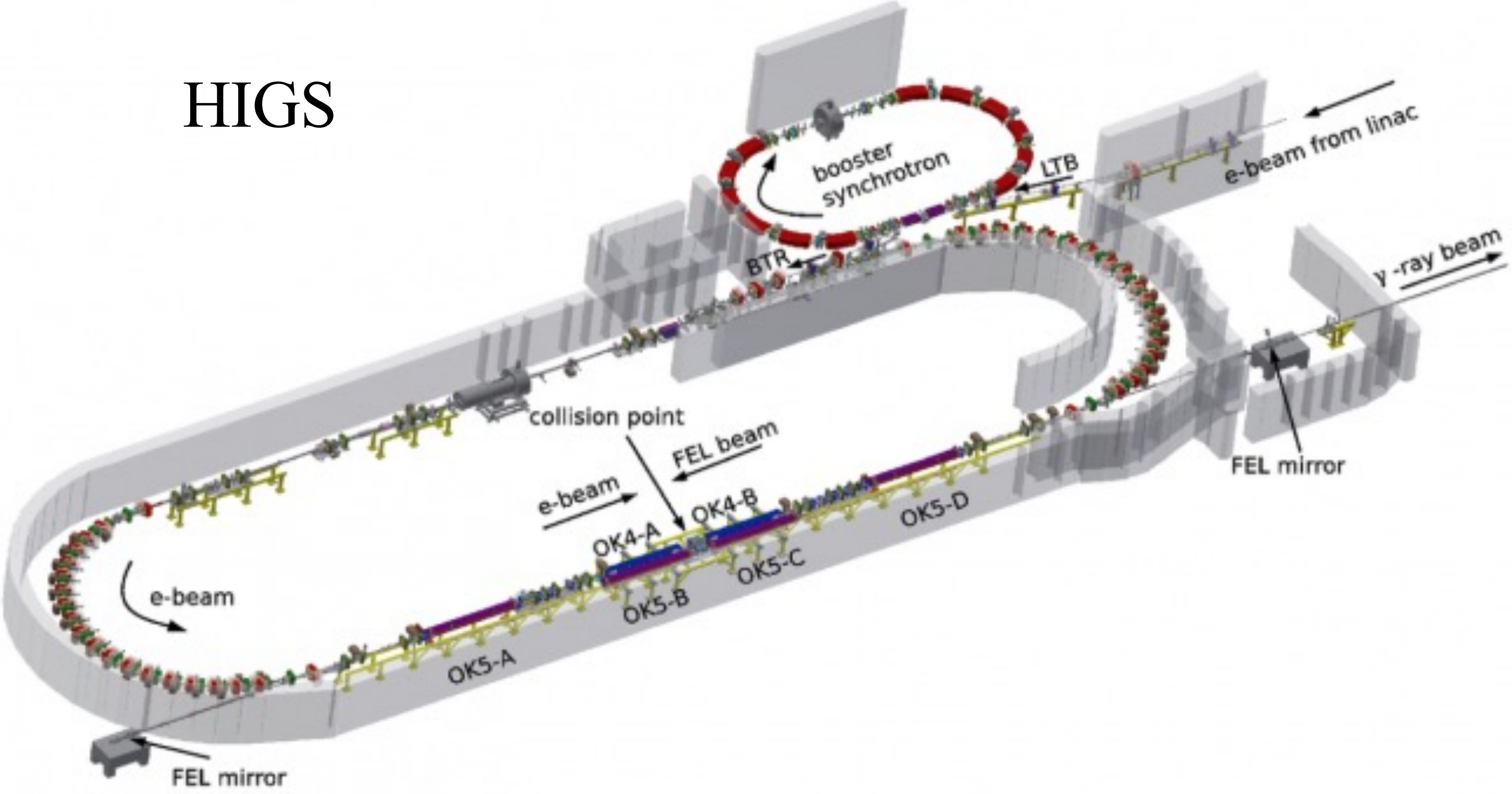
  $^{7}Li(p,n)^{7}Be$ – Q= - 1.64 MeV – E_n=? – How can you get 25 keV?

  …

γ-ray beam facilities

- Bremsstrahlung based (electron accelerators)
- Compton scattering e.g HIGS facility in North Carolina, LCS in Japan…)

HIGS



In the Laboratory

- Yield of reaction: $Y = \dfrac{Number\ of\ reactions}{Number\ of\ beam\ particles}$
- Cross section: $\sigma = \dfrac{Yield\ of\ reaction}{Number\ of\ target\ particles} = \boxed{\dfrac{N_R}{N_b \cdot N_T}}$

To measure a cross section you need three things:

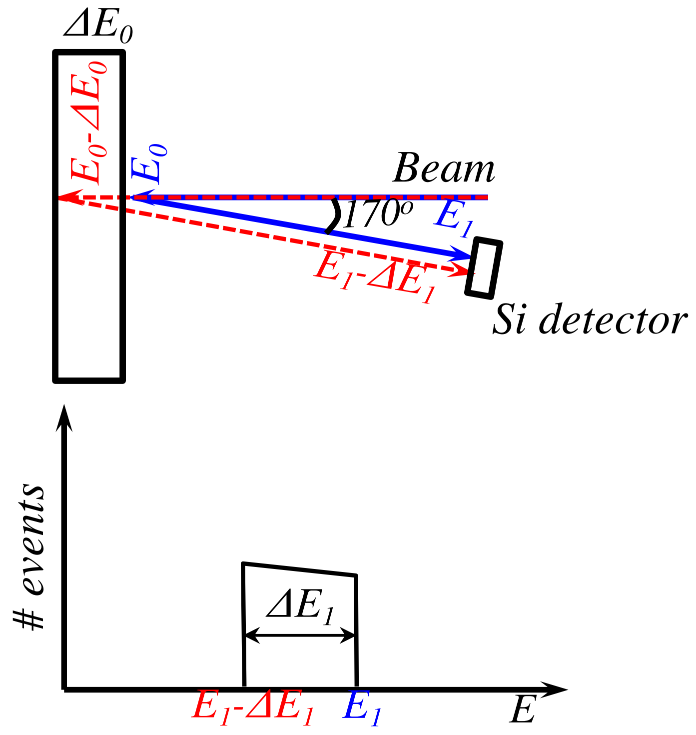
1. Number of target particles (N_T) !!!
2. Number of beam particles (N_b) !!!
3. Number of reactions (N_R) !!!

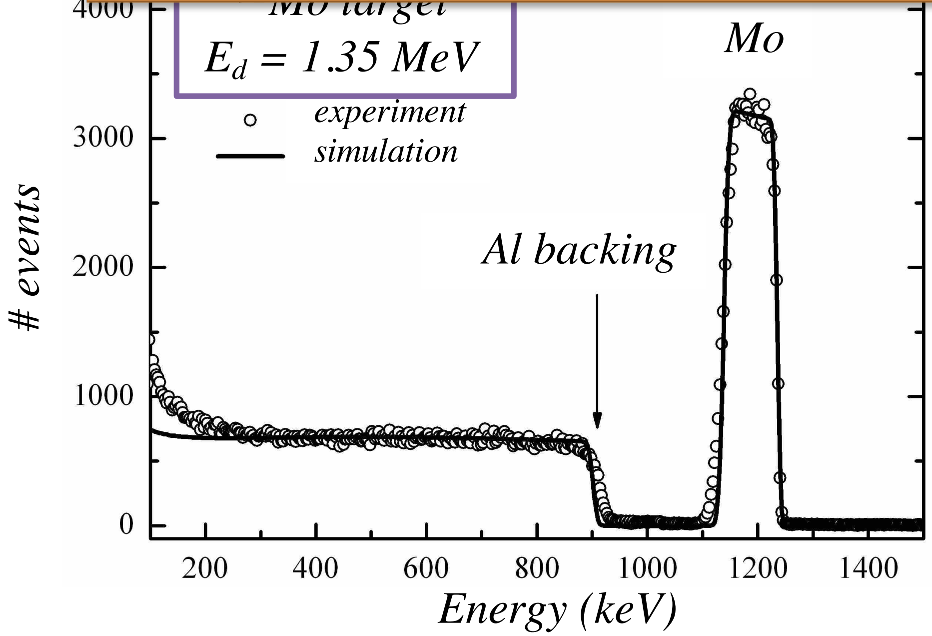
Number of target particles

1

What would happen if my backing material was Ta?

- Rutherford backscattering





$$N_T = \frac{N_A \xi}{A}$$

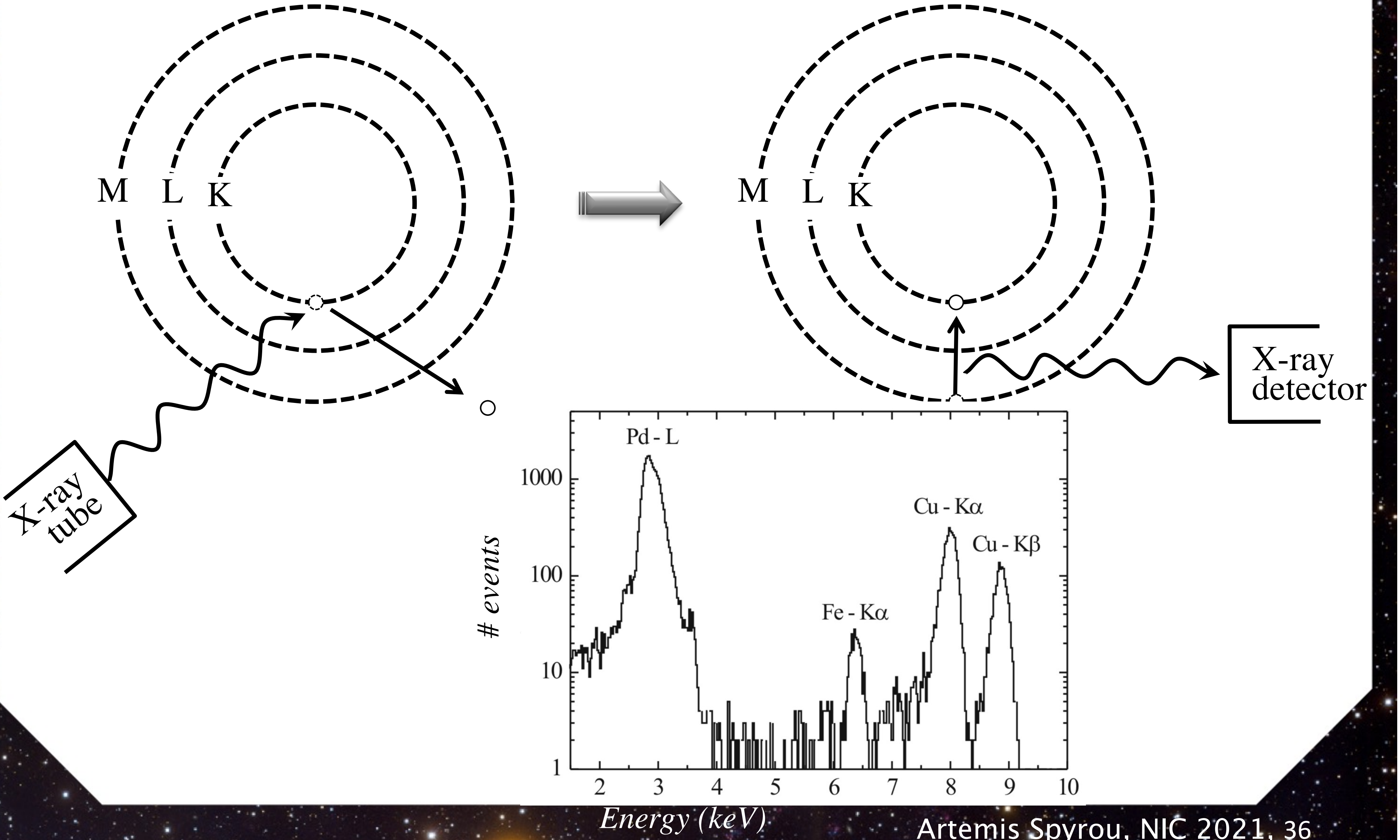
N_A: Avogadro number
A: Atomic mass
ξ: target thickness in g/cm²

- ○ Simulation with SIMNRA
- ○ Known detector geometry
- ○ Known cross section
- ○ Free parameter: target thickness/composition

Number of target particles

1

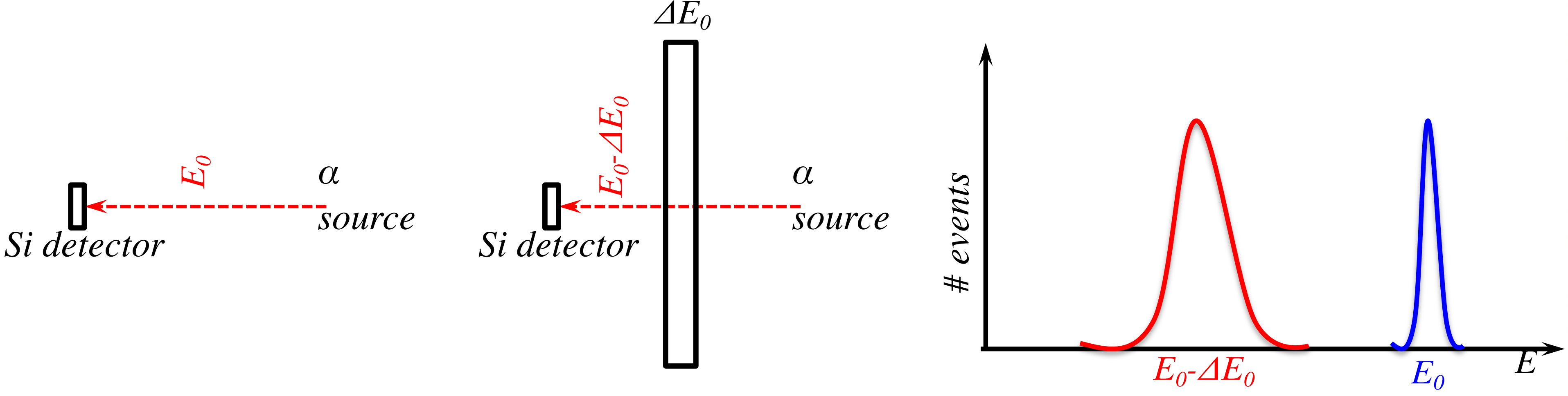
- X-ray Fluorescence (XRF)



Number of target particles

1

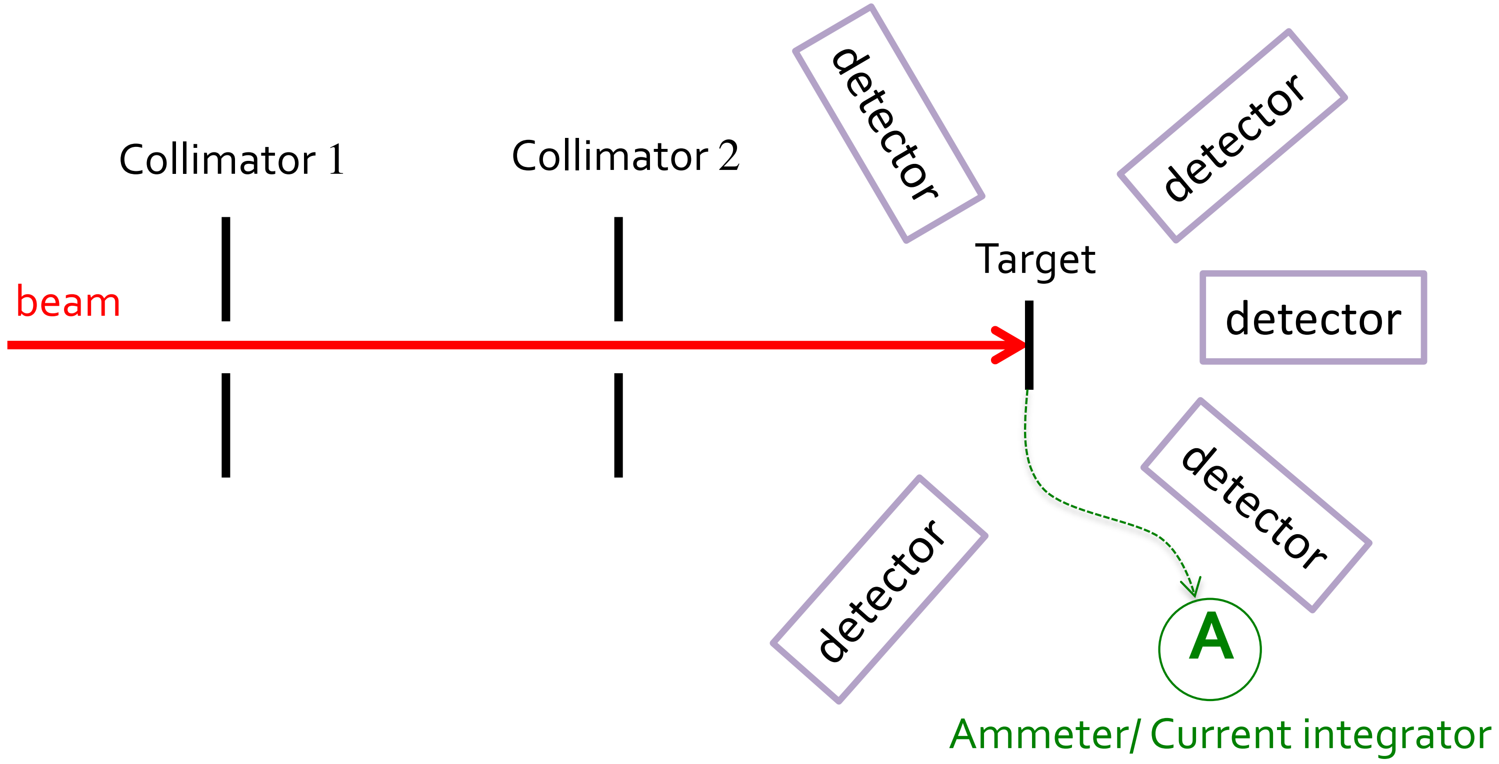
- Particle energy loss



- ○ Many other techniques like resonance measurement, use of spectrometer or recoil separator, use a reaction, etc
- ○ If radioactive sample: activity from decay

Number of beam particles

- High beam intensities: measure deposited charge



e.g. $^{1}H^{+}$ beam: each beam particle deposits 1.6×10^{-19} Cb (e^{-} charge)

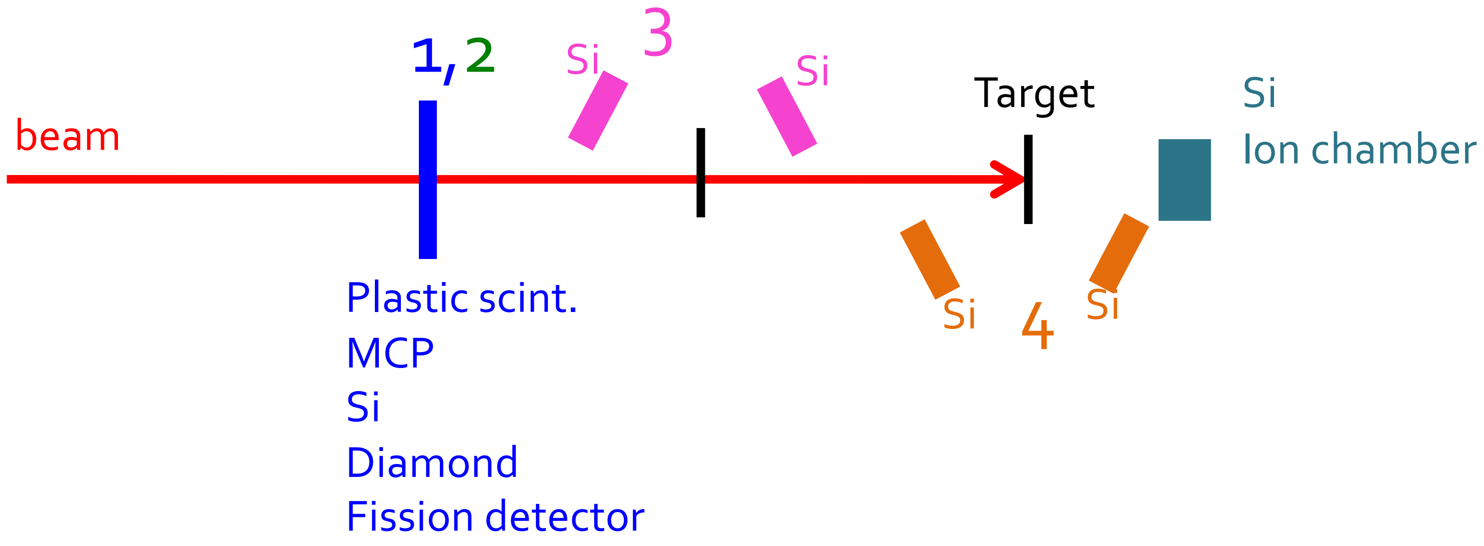
$^{84}Kr^{27+}$ beam: each beam particle deposits $27 \times 1.6 \times 10^{-19}$ Cb

Do you expect all ions to deposit one electrical charge?

Number of beam particles

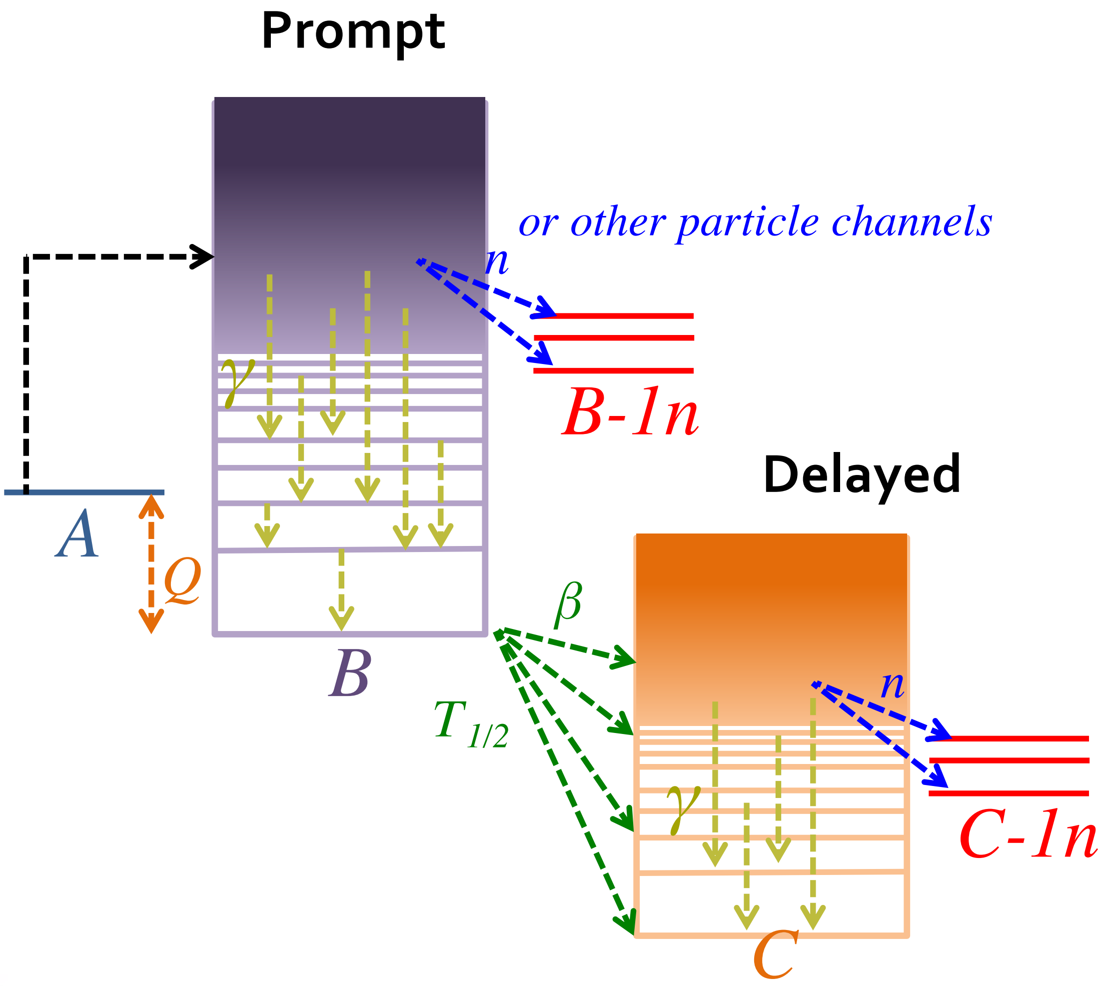
- **Low beam intensities: measure each particle in detector**

1. In beam detector upstream to measure continuously
2. In beam detector upstream to insert every so often
3. Scattering detector upstream
4. Detector looking at target scattering
5. Detector downstream after target
6. Activation (especially for neutrons)



Number of reactions

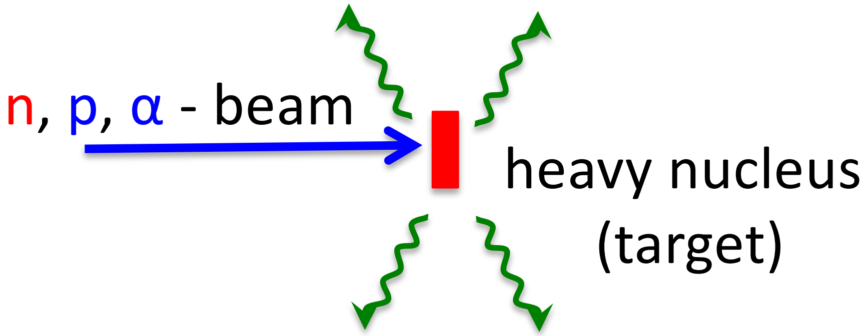
$$a + A \rightarrow b + B$$



- ○ Measure prompt γ rays
- ○ Measure emitted particles
- ○ Measure β-delayed γ rays
- ○ Measure the recoiling nucleus (inverse kinematics)
- ○ Measure emitted X-rays
- ○ Combination of the above

- ○ Know efficiency
- ○ Understand setup
- ○ Understand background
- ○ Estimate uncertainties

Regular kinematics



Facilities: Stable beam (ATOMKI, Athens, Notre Dame, Cologne, Florida State, nTOF, Los Alamos, Karlsruhe, etc)

Equipment: Gamma-ray detectors, X-ray detectors, charged particle detectors

Techniques: Activation, Angular distribution, Summing

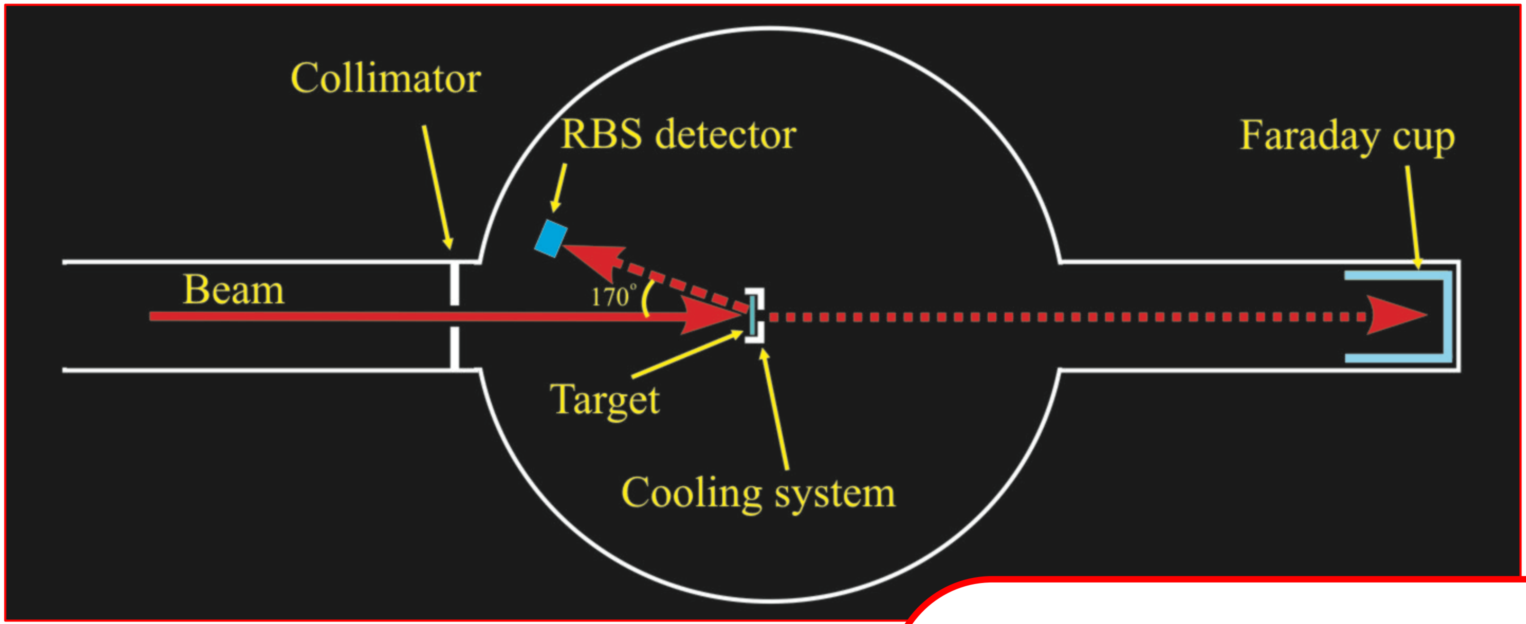
Advantages:

- High intensity stable beams
- Well developed techniques

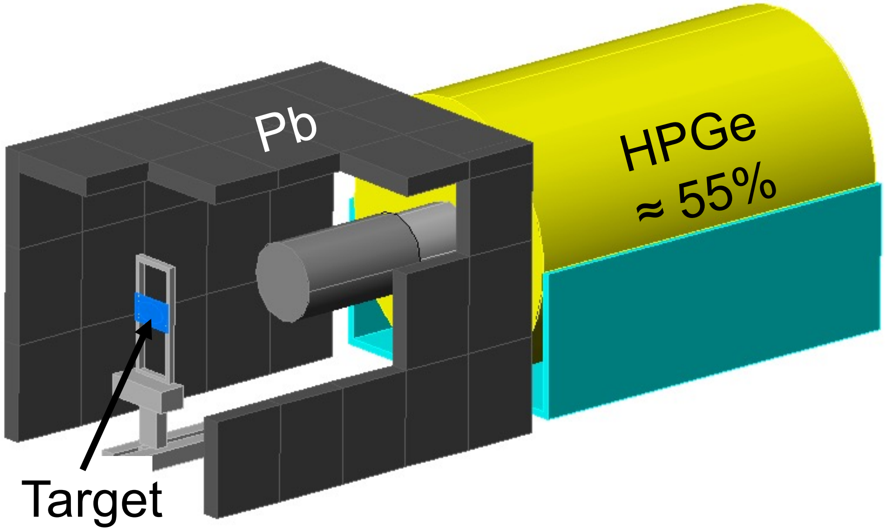
Disadvantages

- Not applicable for all targets, in particular radioactive nuclei

Activation

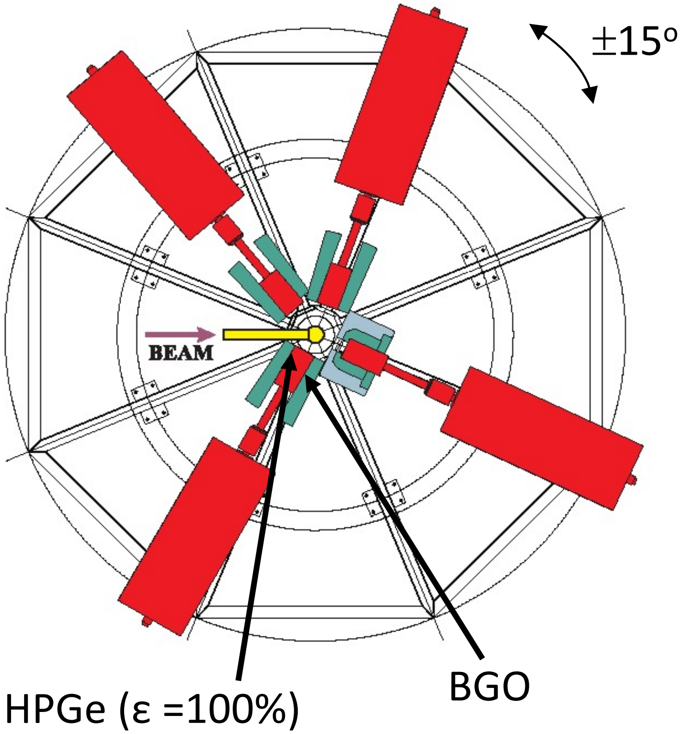


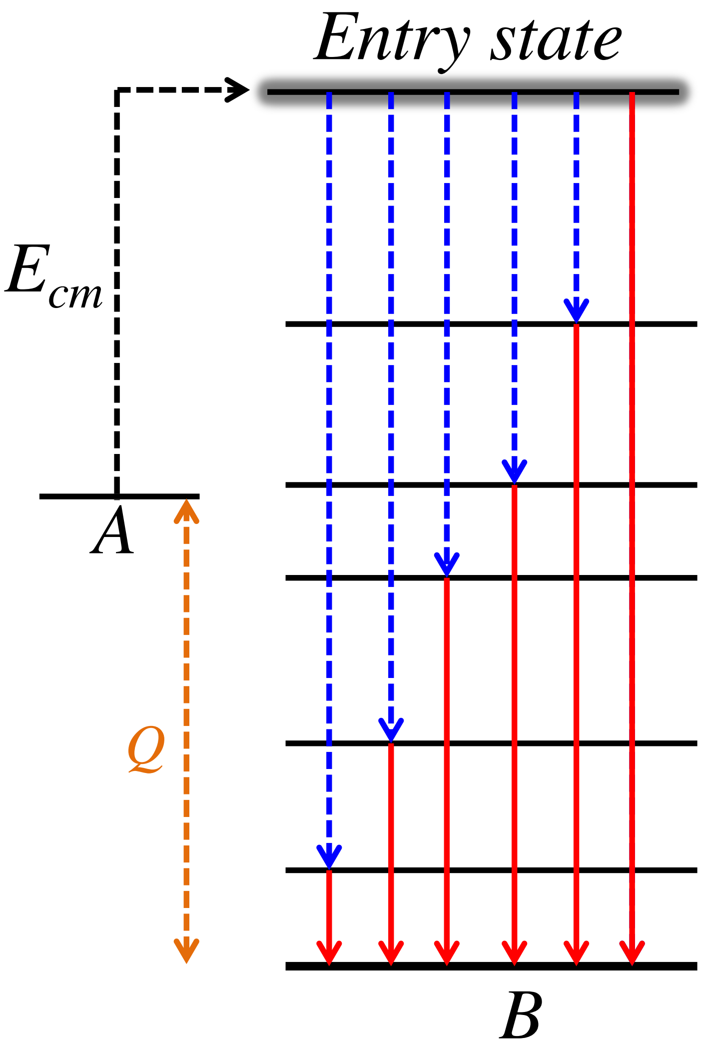
- Irradiate for time according to half life
- Monitor beam intensity
- After irradiation move sample to low background area, HPGe
- Detect β-delayed γ-rays



T. Sauter and F. Kappeler, Phys. Rev. C 55, 3127 (1997).

Angular Distributions

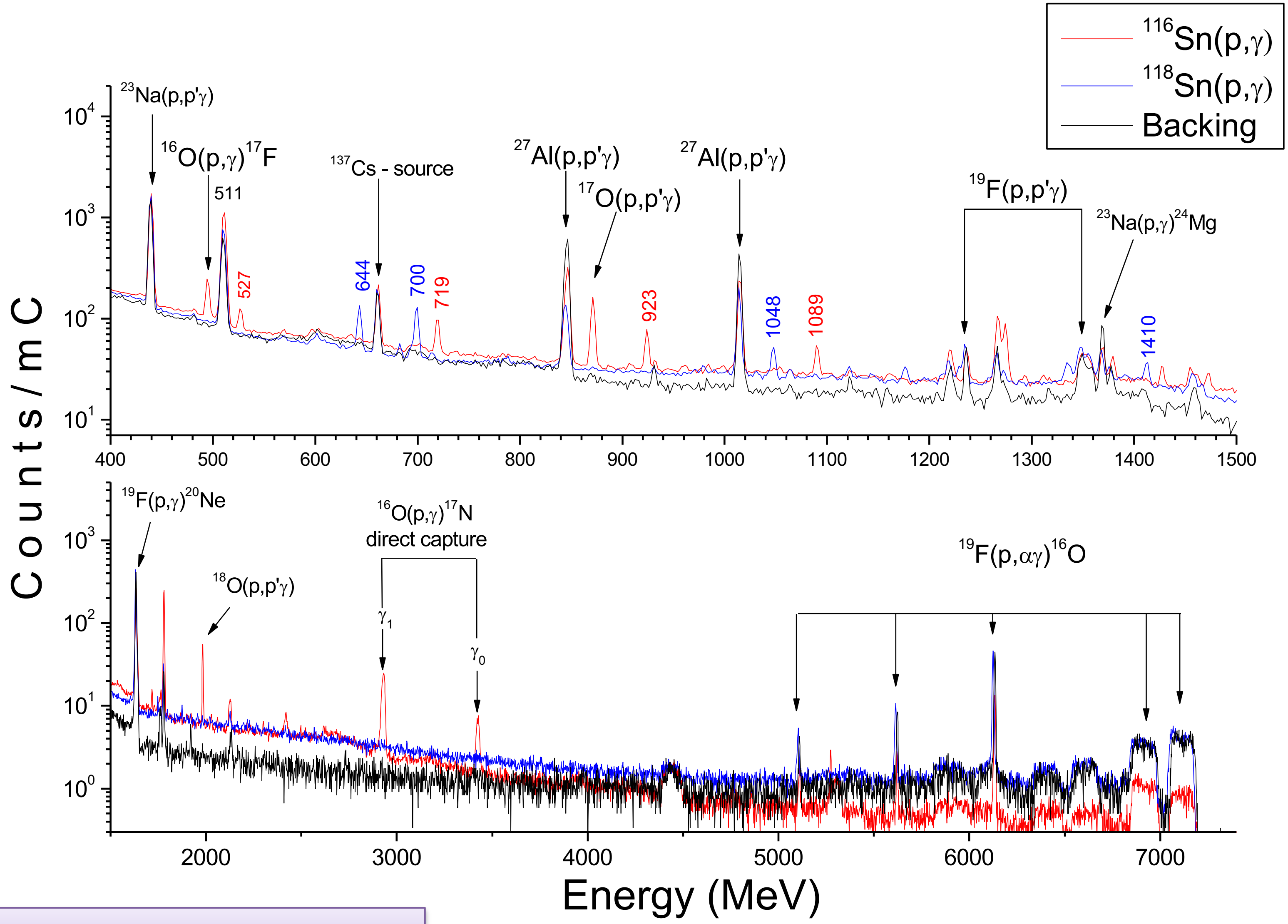




- In beam γ-ray detection
- Measure at many angles
- High resolution system (HPGe)
- Create angular distributions
- Extract reaction yield
- Extract cross sections

e.g. Galanopoulos, et al, PRC 67 (2003) 015801

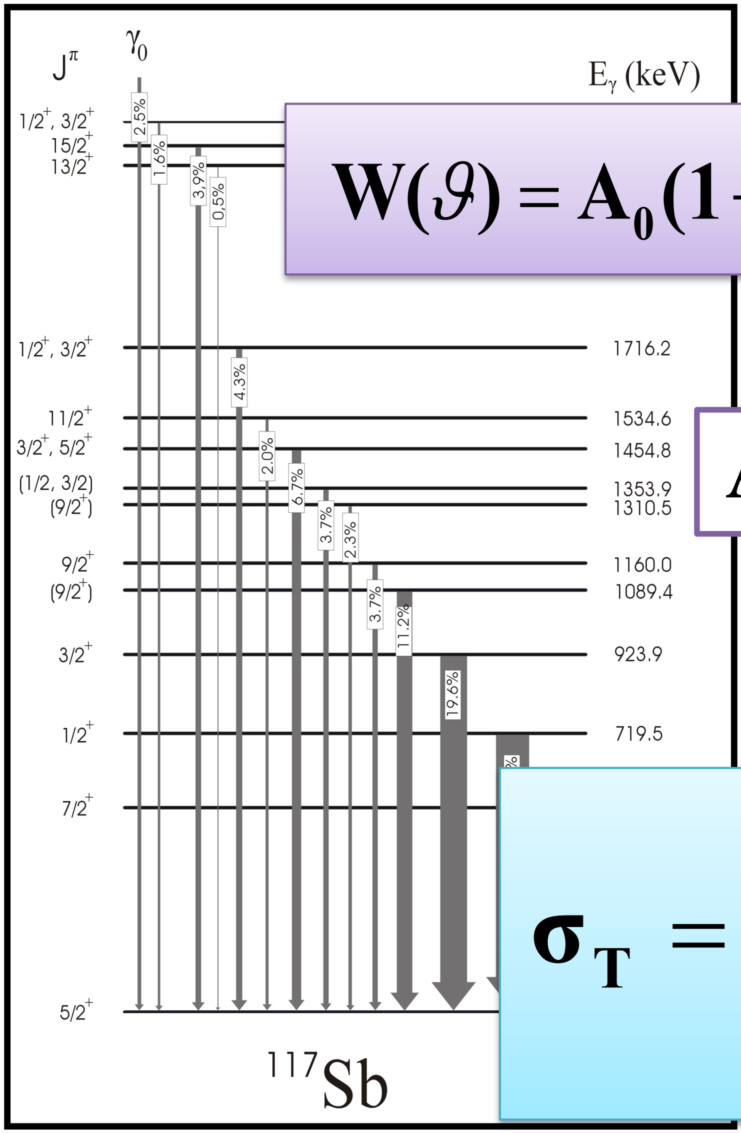
Angular Distributions



- ○ Sample spectrum

e.g. Galanopoulos, et al, PRC 67 (2003) 015801

Angular Distributions

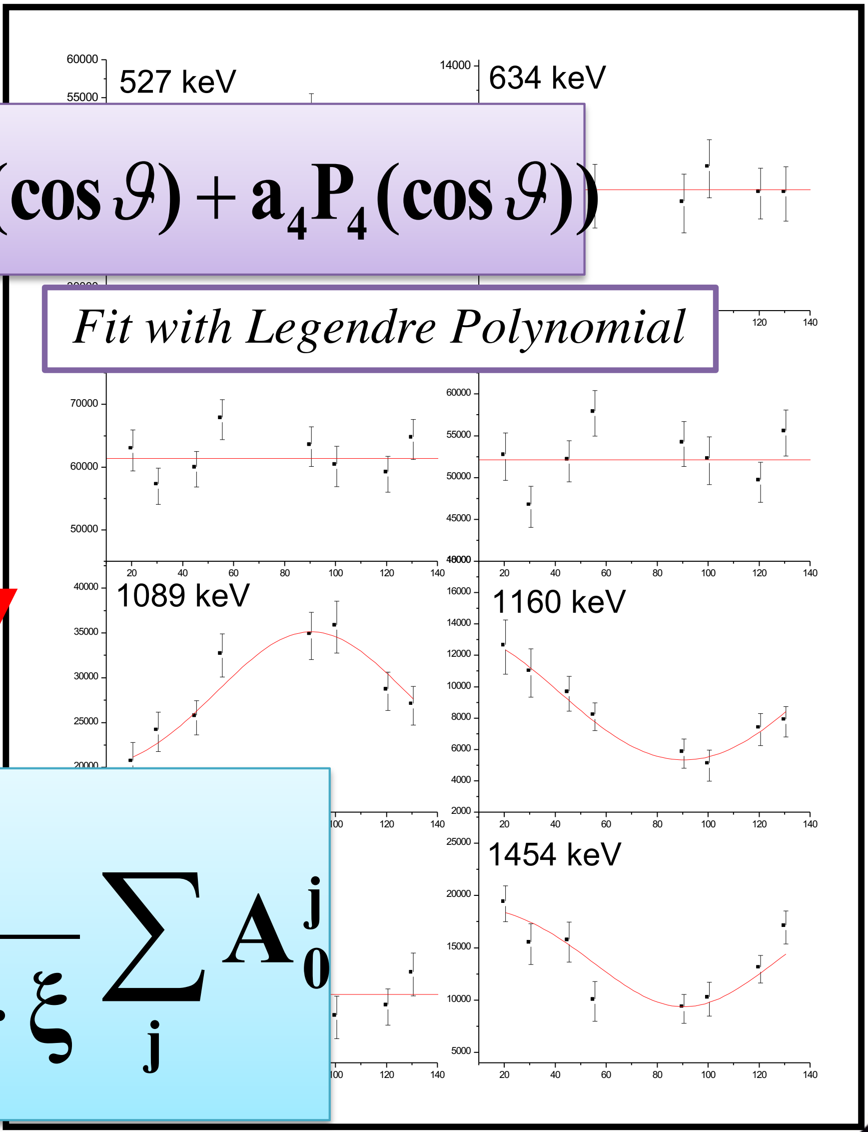


$$W(\vartheta) = A_0(1 + a_2P_2(\cos\vartheta) + a_4P_4(\cos\vartheta))$$

Fit with Legendre Polynomial

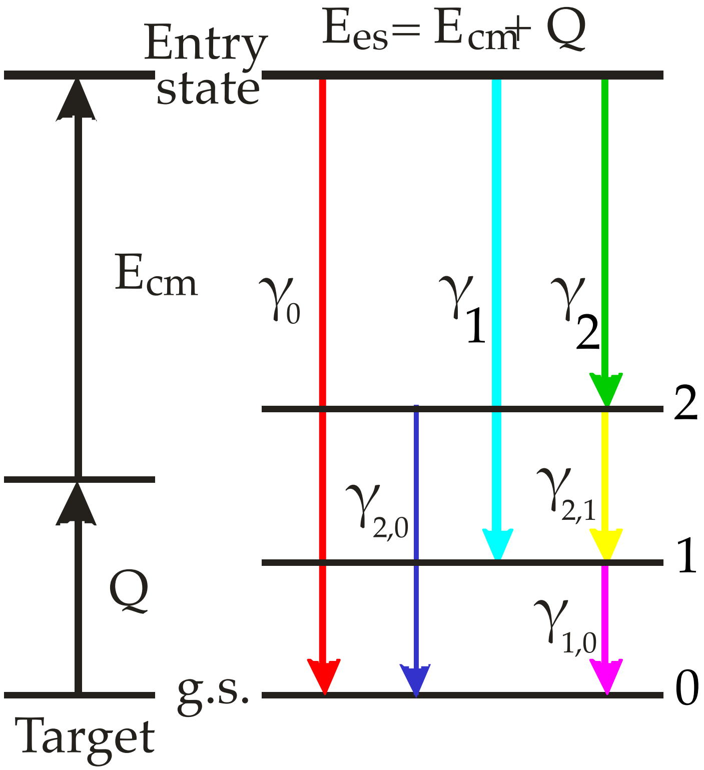
$$A_0$$

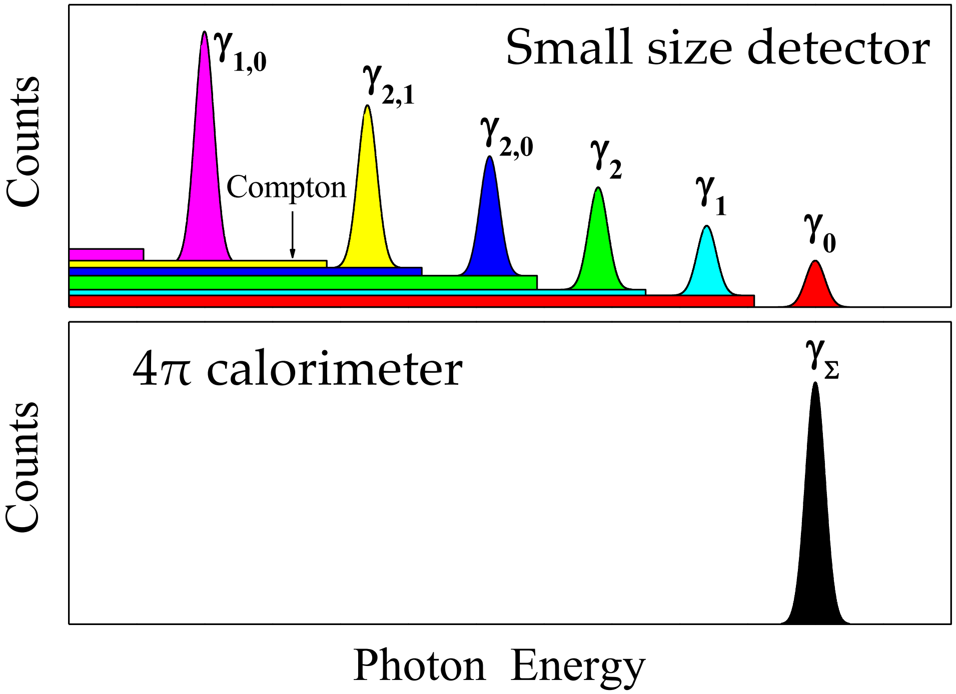
$$\sigma_T = \frac{A}{N_A \cdot \xi}\sum_j A_0^j$$



e.g. Galanopoulos, et al, PRC 67 (2003) 015801

Summing Technique

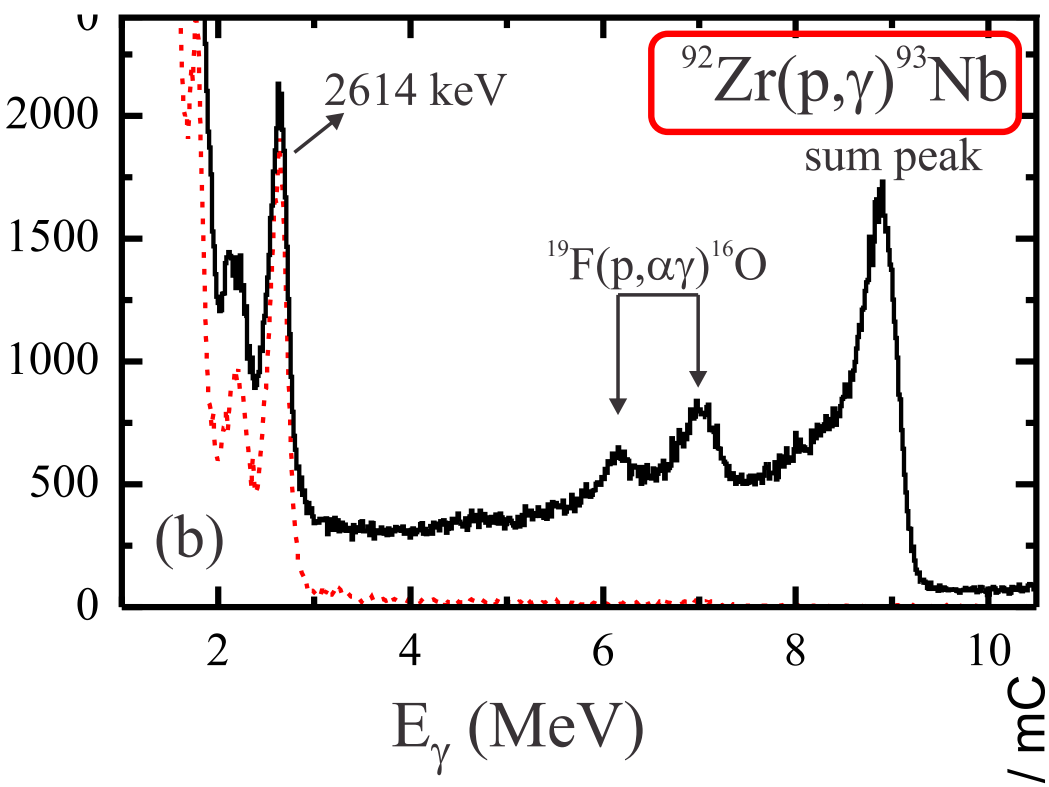


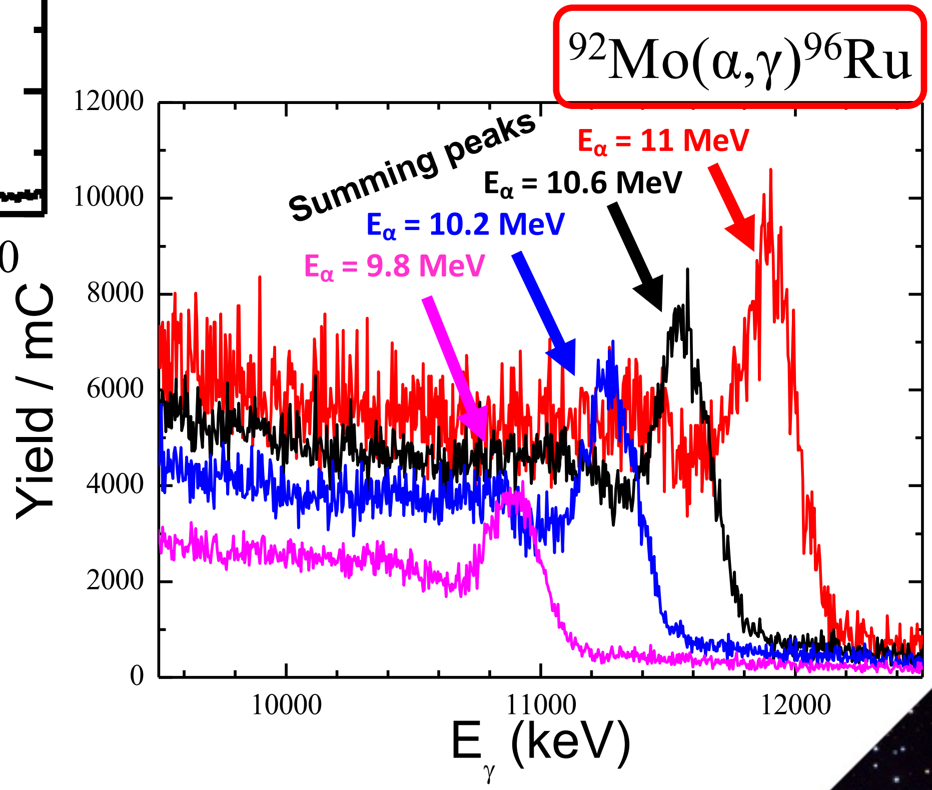


- In beam γ-ray detection
- Sum all energy in a cascade
- Need very high efficiency detector
- Need highly enriched samples
- Efficiency dependence on the γ-multiplicity
- Simple analysis

Spyrou et. al. PRC 76 (2007) 015802
Simon et. al. NIMA 703 (2013) 16

Summing Technique

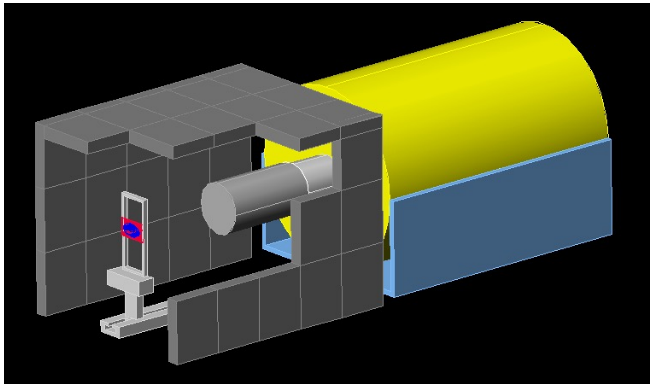




Spyrou et. al. PRC 76 (2007) 015802
Simon et. al. NIMA 703 (2013) 16

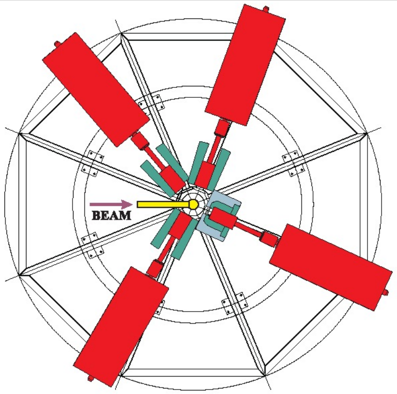
Comparison – Stable Beam

Activation technique - Off line



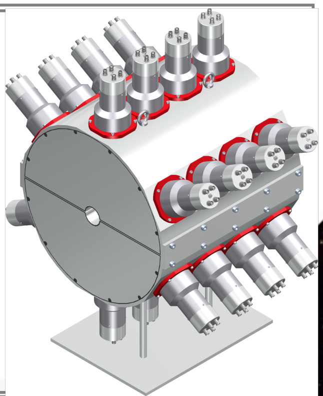
- Low energy γ-rays
- Small size HPGe
- Natural targets
- Suitable half-life

Angular Distributions – In beam



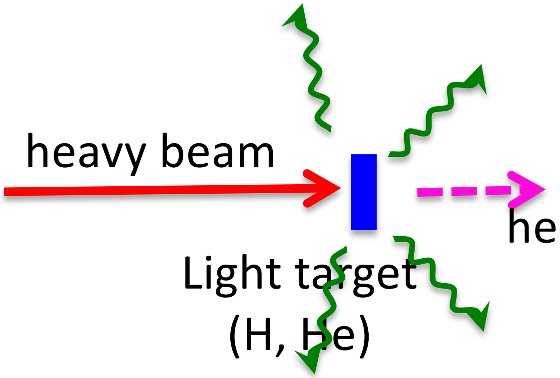
- Decay scheme information
- High volume HPGe detector
- Time-consuming data collection and analysis

Angle integrated measurements – In beam



- High efficiency
- Simple analysis procedure
- Limited spectroscopic information

Inverse kinematics



heavy beam

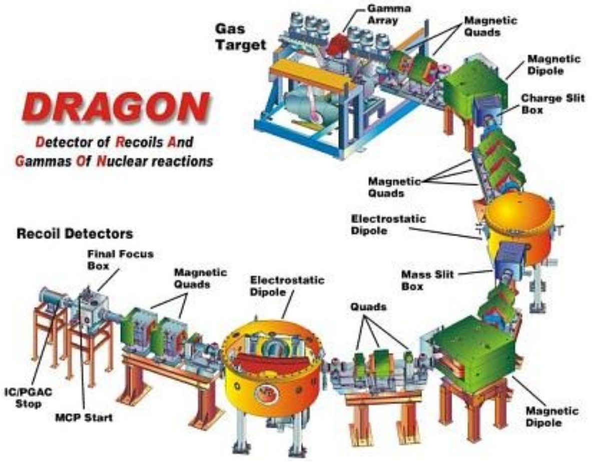
heavy recoil

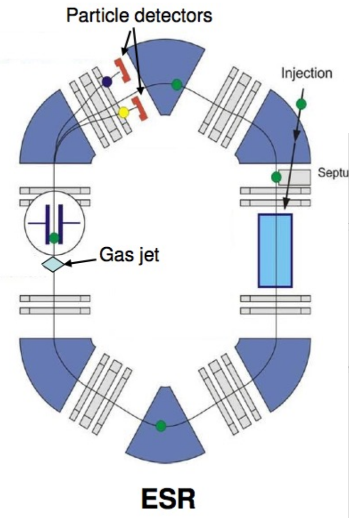
Light target
(H, He)

- ✓ recoil separators
- ✓ ring measurements
- ✓ γ-summing
- ✓ activation/implantation

Radioactive Beam Facilities: TRIUMF, MSU, GSI, GANIL, CERN, ANL?
Equipment: Dragon, SECAR, Storage ring, SuN, LISE, …

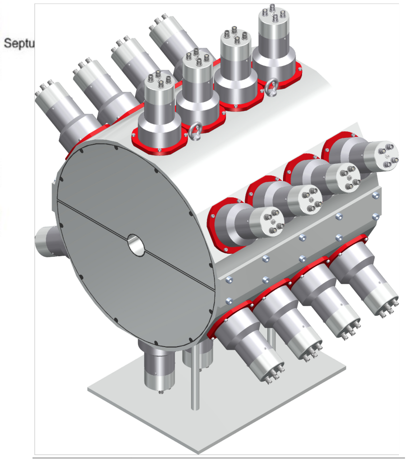
TRIUMF



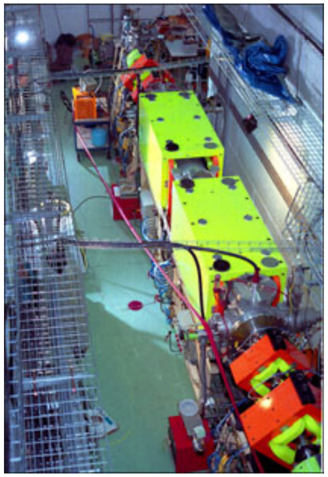


GSI

MSU



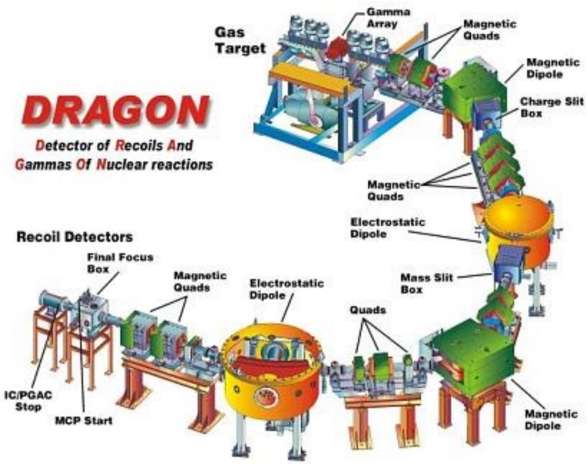
GANIL



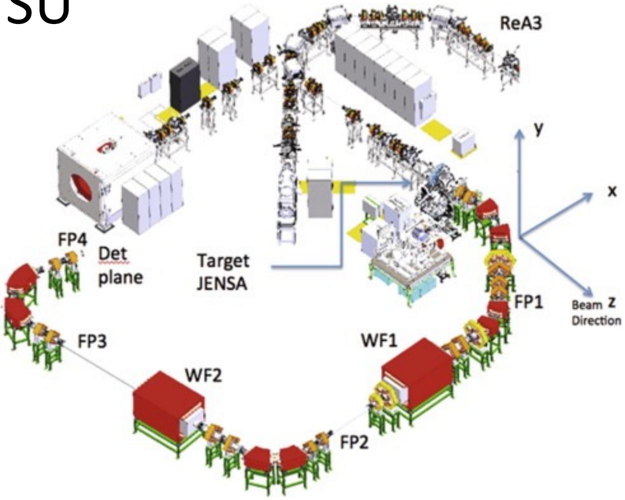
Recoil separators

- Mane different separators in operation or under construction
- So far only DRAGON @ TRIUMF has been used for heavy element nucleosynthesis experiments.

DRAGON @ TRIUMF



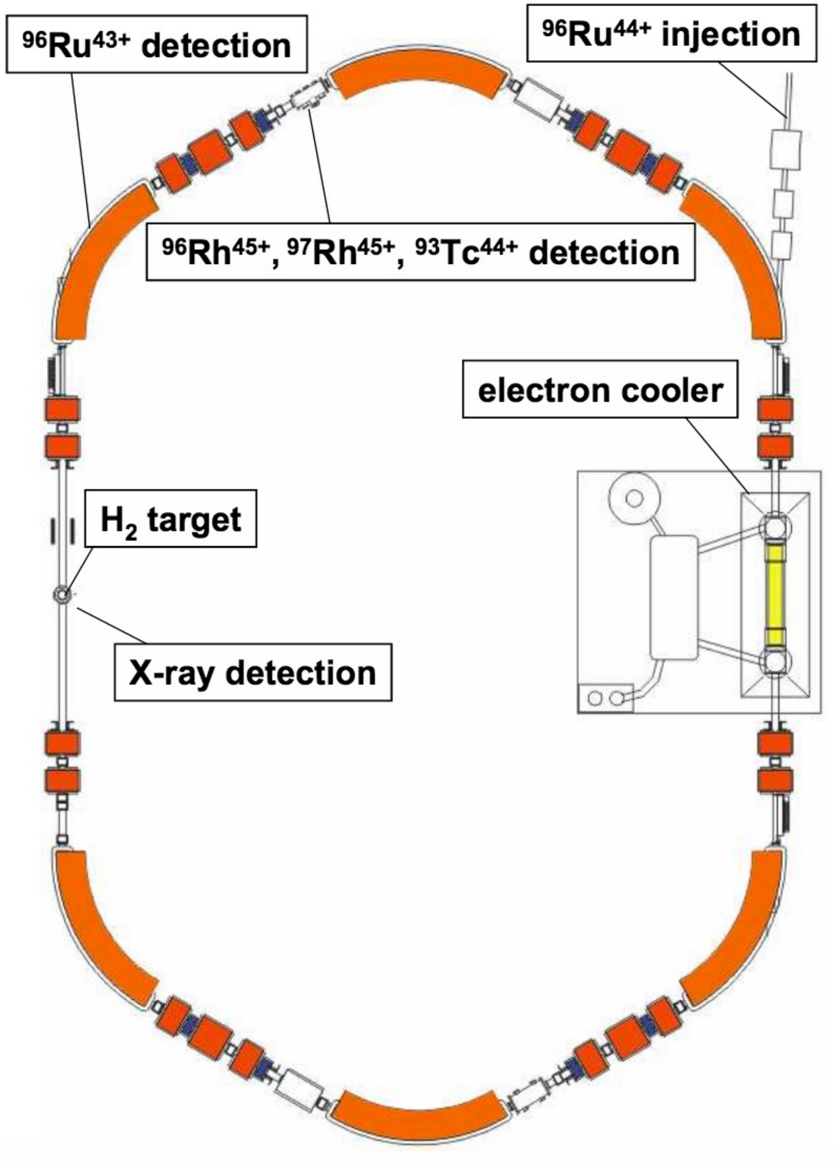
SECAR @ MSU

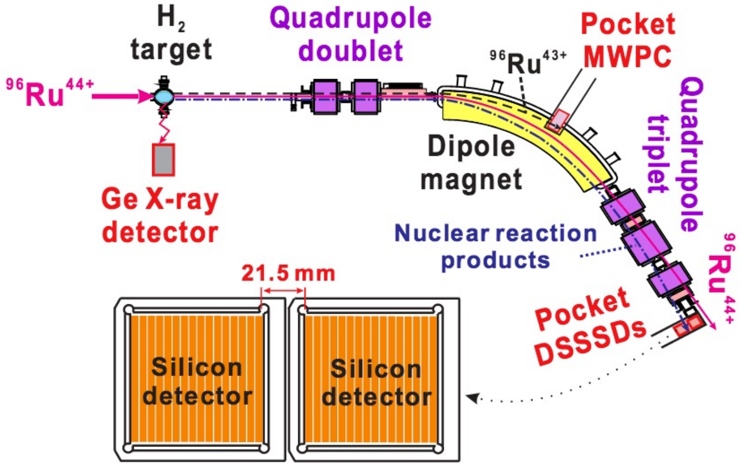


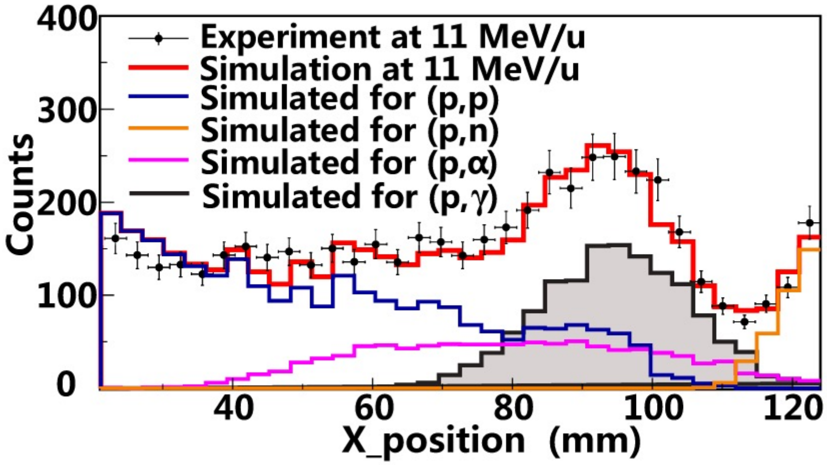
St. George @ Notre Dame

Storage rings

^{96}Ru(p,γ)^{97}Rh



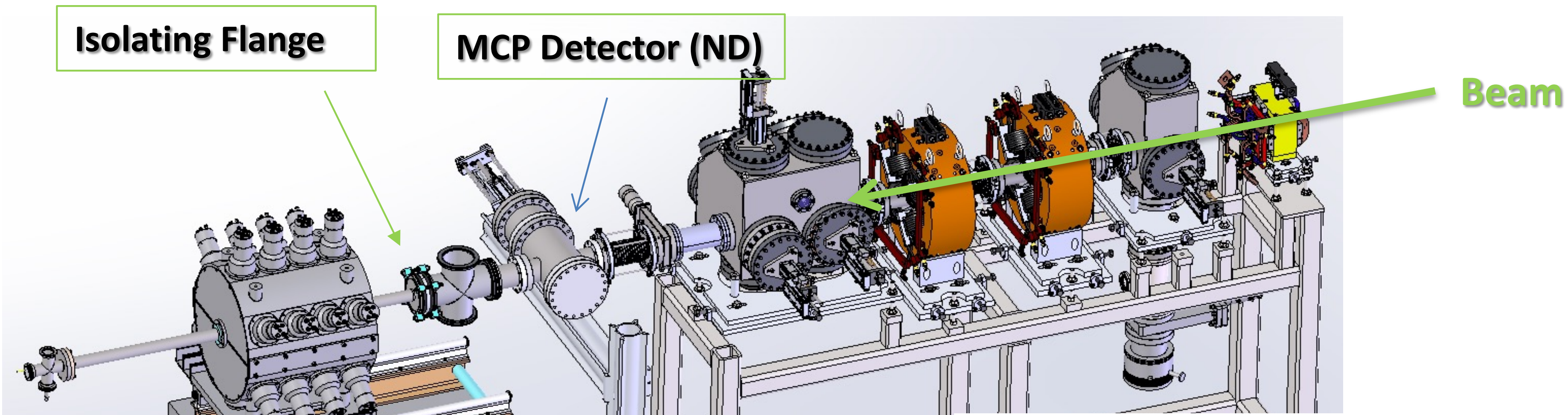




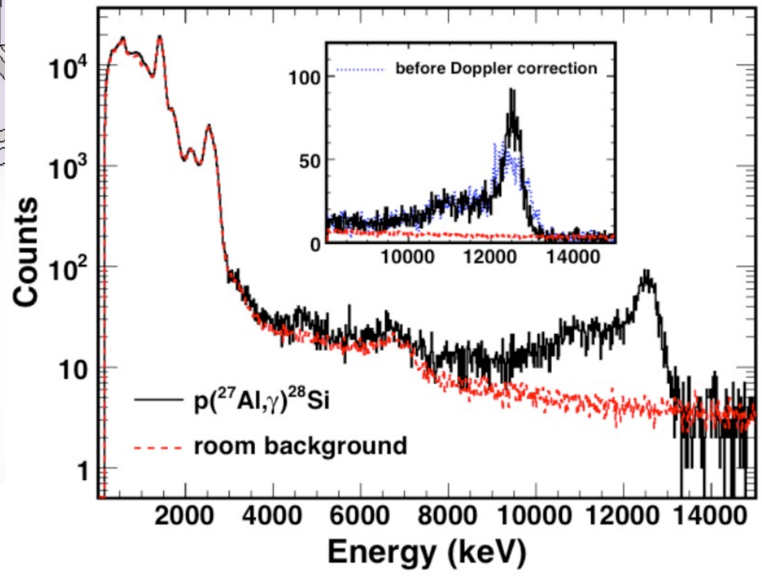
Mei, *et*. *al*. PRC 92 (2015) 035803

Summing in inverse kinematics

3



- Hydrogen gas target
- Heavy beam
- Doppler shift



S.J. Quinn, et al., Nucl. Instr. Meth. A 57, 62 (2014)

Indirect Measurements

Indirect Measurements

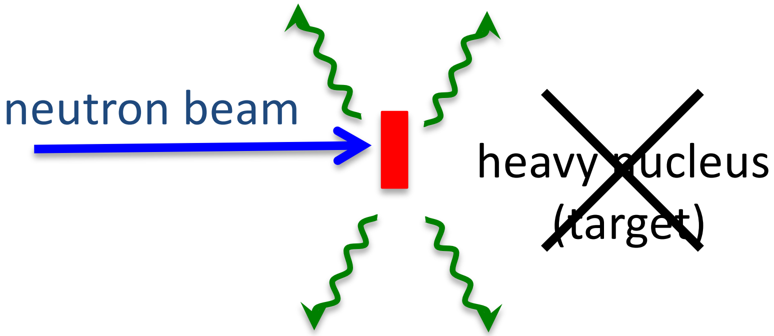
- Many measurements are hard or impossible to perform directly.
- Indirect approaches are useful for constraining reaction rates and providing input into the astrophysical calculations that would otherwise not be possible.

Some examples of indirect techniques

- Transfer reactions (d,n) and (d,p) for (p,γ) and (n,γ) reactions respectively
- β-decay feeding levels of interest and extracting branchings
- Various reaction studies to extract spins of levels
- Trojan Horse method for low-energy reaction rates
- Surrogate Method for (n,γ) reactions
- Oslo/β-Oslo for (n,γ) reaction studies
- Various reactions for extracting nuclear level density or γ-ray strength function
- Coulomb dissociation for γ-ray strength

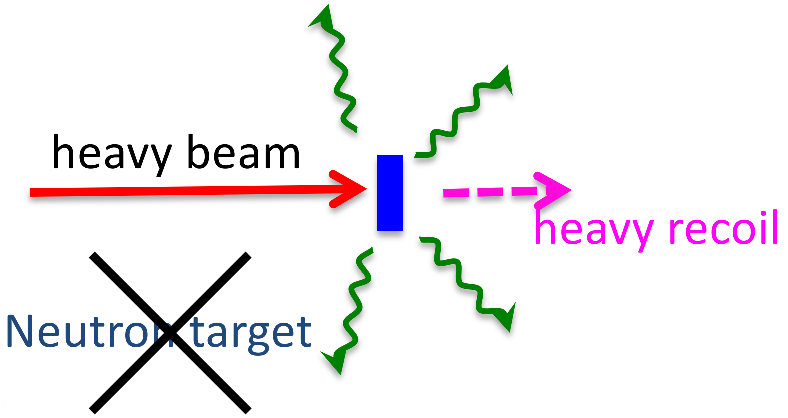
The trouble with neutron capture

○ Regular kinematics

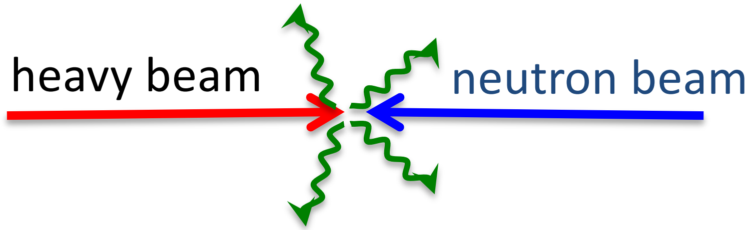


- Measuring Neutron Capture reactions on short-lived nuclei is at best challenging
- **Need indirect techniques**
- Surrogate technique (d,p)-(n,γ)
- Measure NLD, γSF
- Can also be applied to (p,γ) – why?

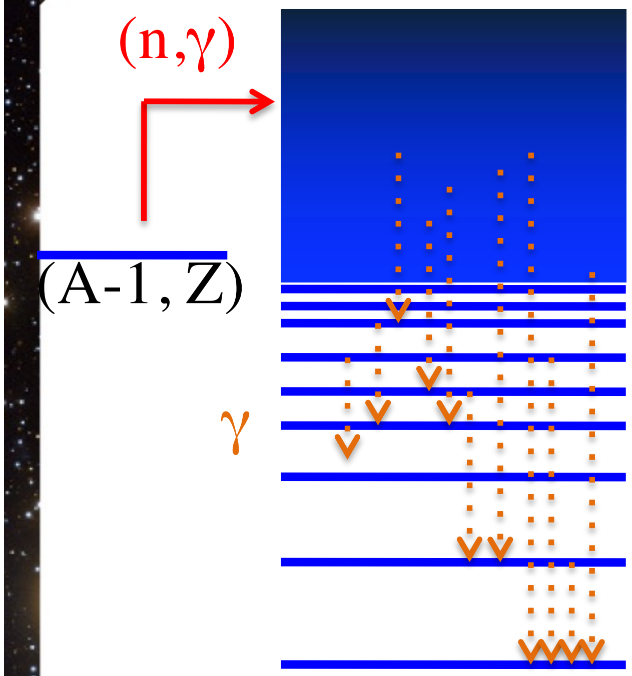
○ Inverse kinematics



○ Colliding beams ?

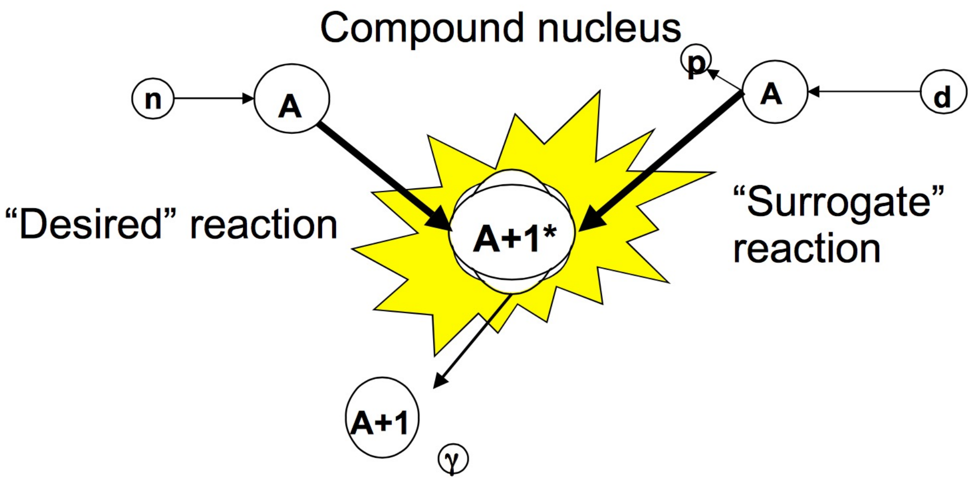


Surrogate technique



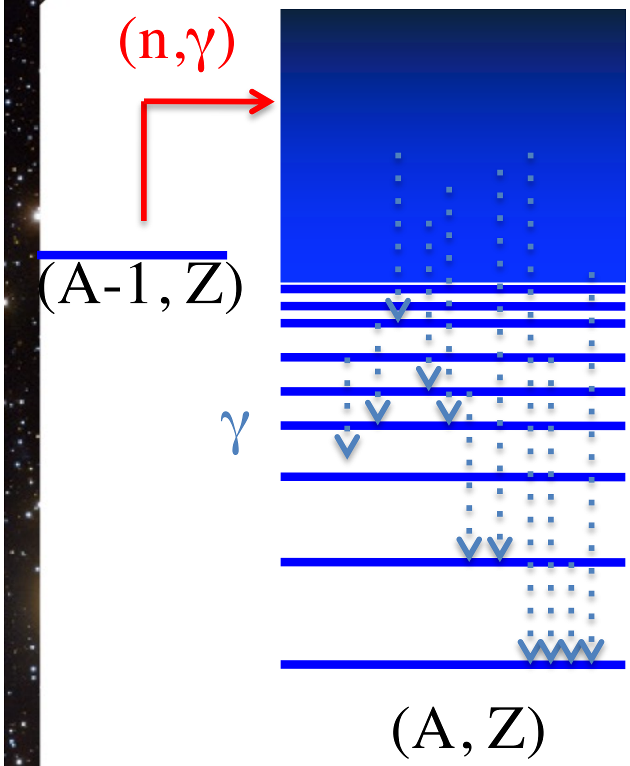
- Formation of compound nucleus (CN) independent of its decay
- Form same CN as (n,γ) via (d,p)
- Study its decay
- Inform the models
- Applicable in regular and inverse kinematics
- Applicable a few steps from stability

Validation: ^{95}Mo(n,γ)^{96}Mo
Significant progress during the last couple of years



A. Ratkiewicz, J. Cizewski, EPJ Web of Conferences 92 (2015) 02012

Calculate (n,γ) Cross Section



Hauser – Feshbach

- Nuclear Level Density

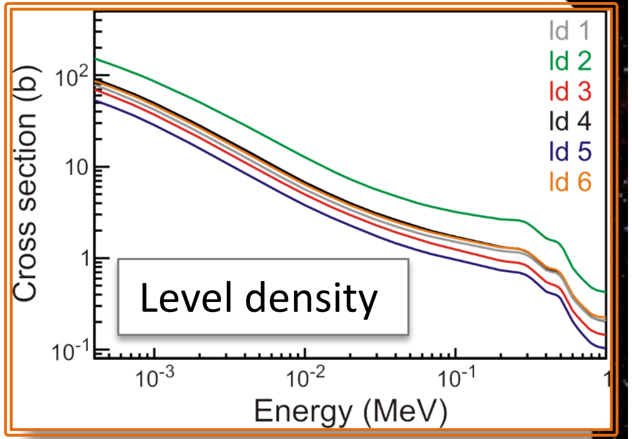
Constant T+Fermi gas, back-shifted Fermi gas, superfluid, microscopic

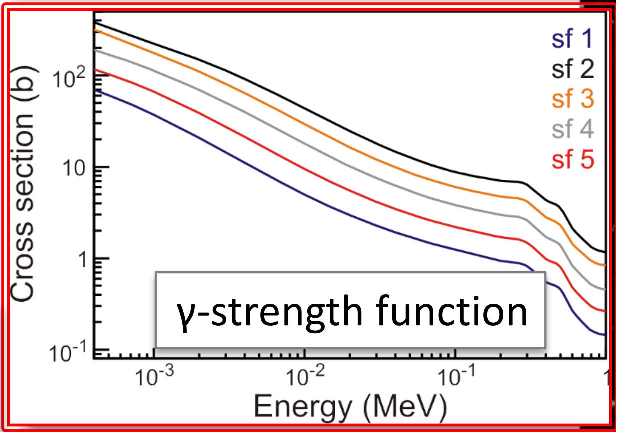
- γ-ray strength function

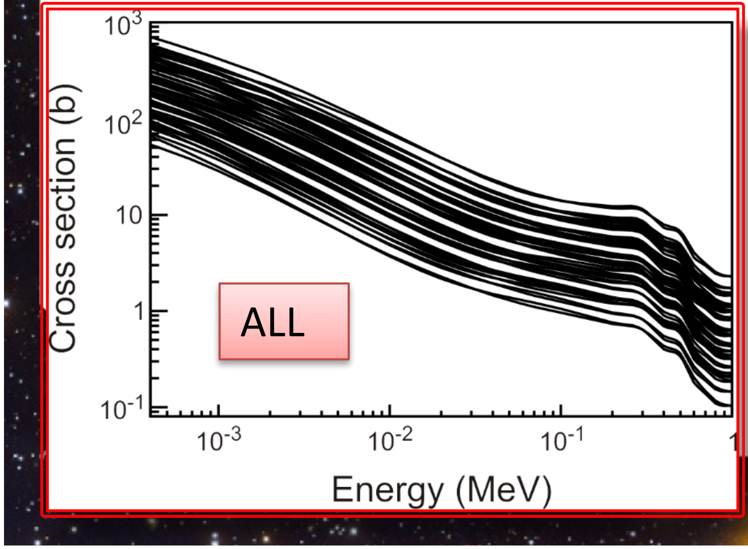
Generalized Lorentzian, Brink-Axel, various tables

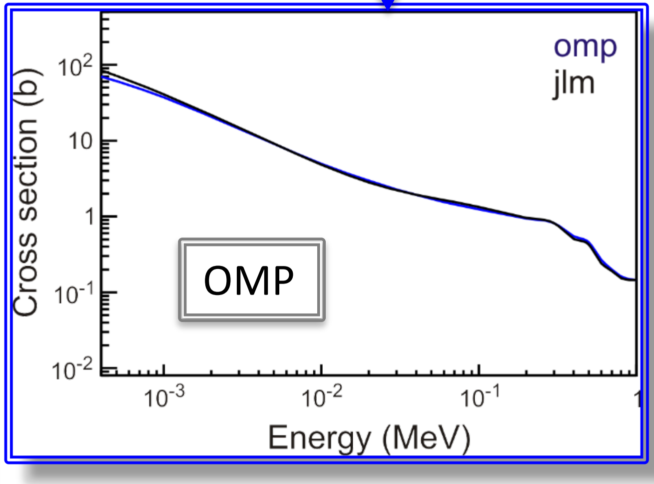
- Optical model potential

Phenomenological, Semi-microscopic







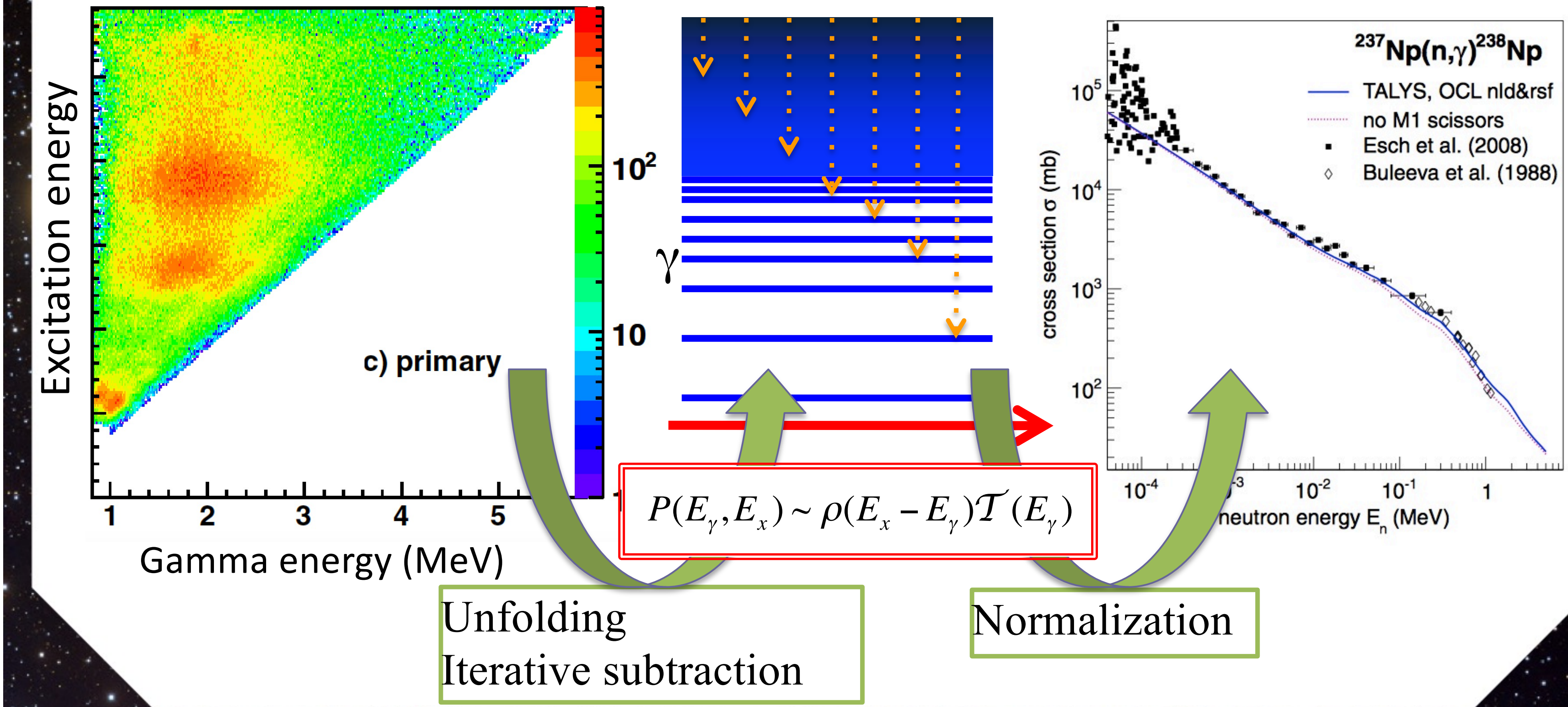


^{95}Sr(n,γ)^{96}Sr

TALYS

Traditional Oslo method

- Use reaction to populate the compound nucleus of interest
- Measure excitation energy and γ-ray energy
- Extract **level density** and **γ-ray strength function** (external normalizations)
- Calculate "semi-experimental" (n,γ) cross section
- Excellent agreement with measured (n,γ) reaction cross sections



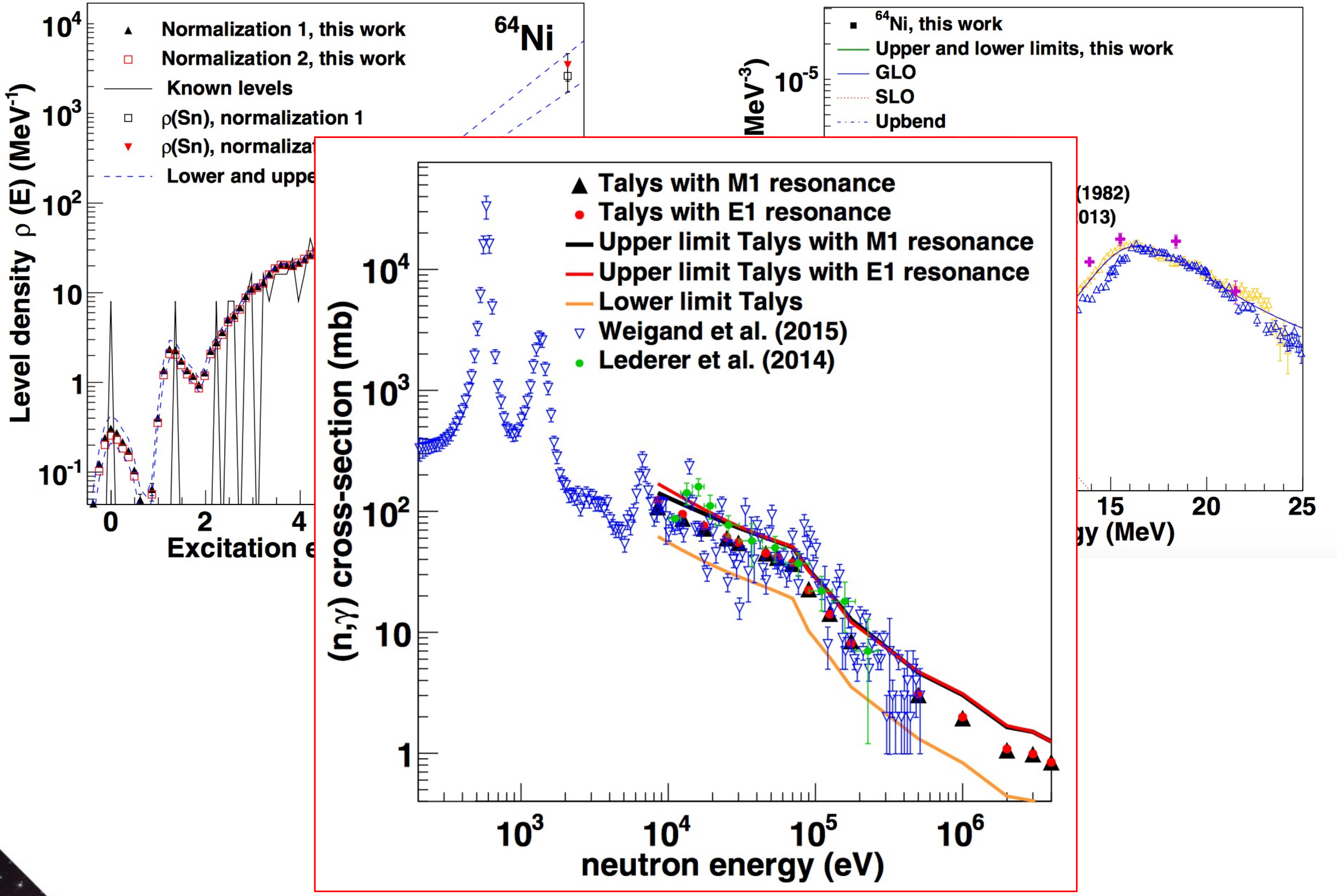
$$P(E_\gamma, E_x) \sim \rho(E_x - E_\gamma)\mathcal{T}(E_\gamma)$$

Unfolding
Iterative subtraction

Normalization

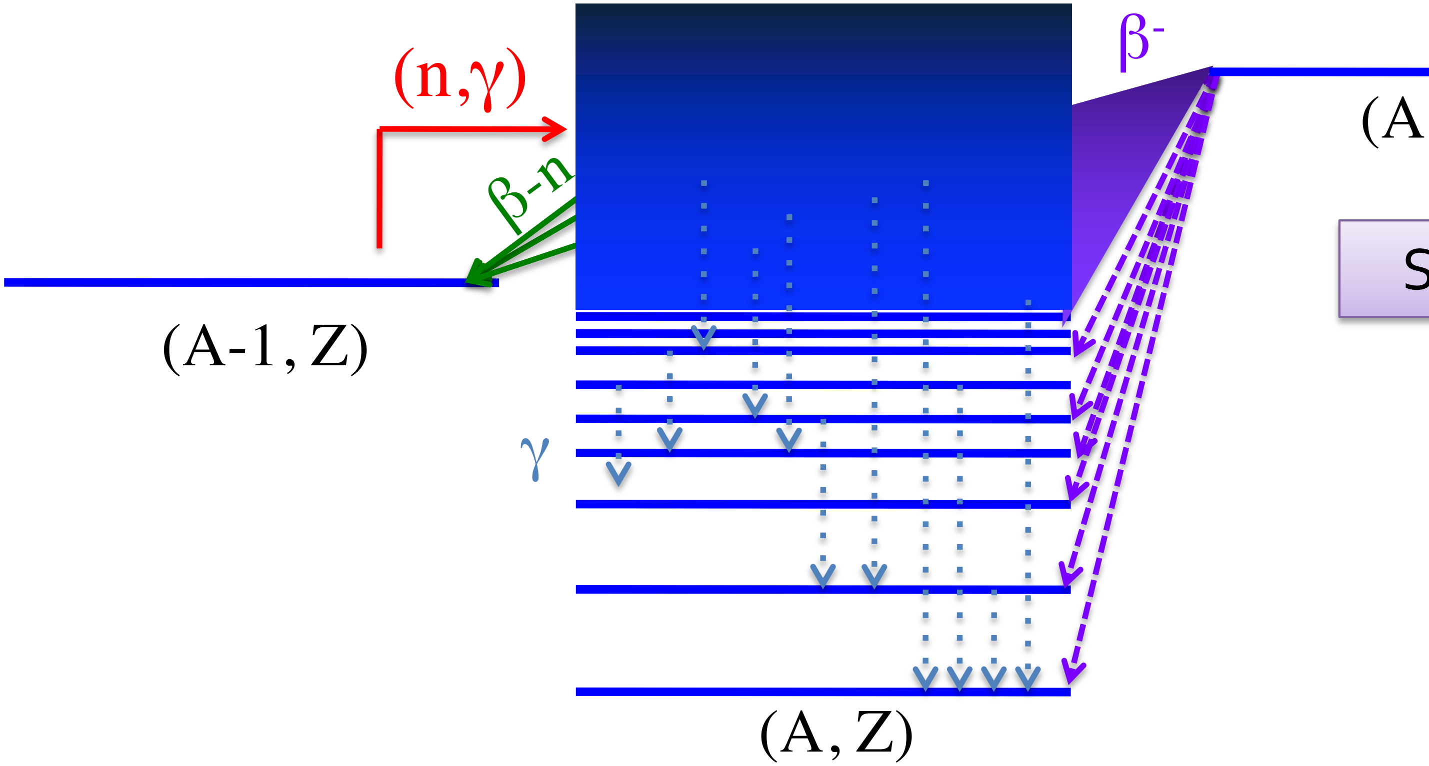
T.G. Tornyi, M. Guttormsen,et al., PRC2014

Example Oslo method

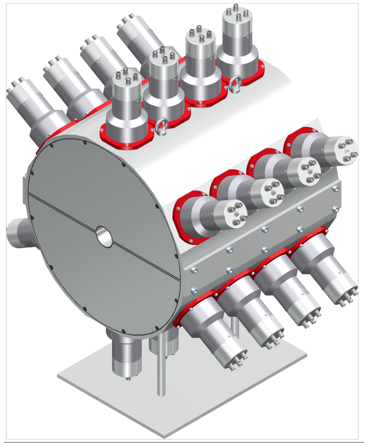


L. Crespo-Campo, et. al. PRC 94 (2016) 044321

β-Oslo



SuN @ MSU

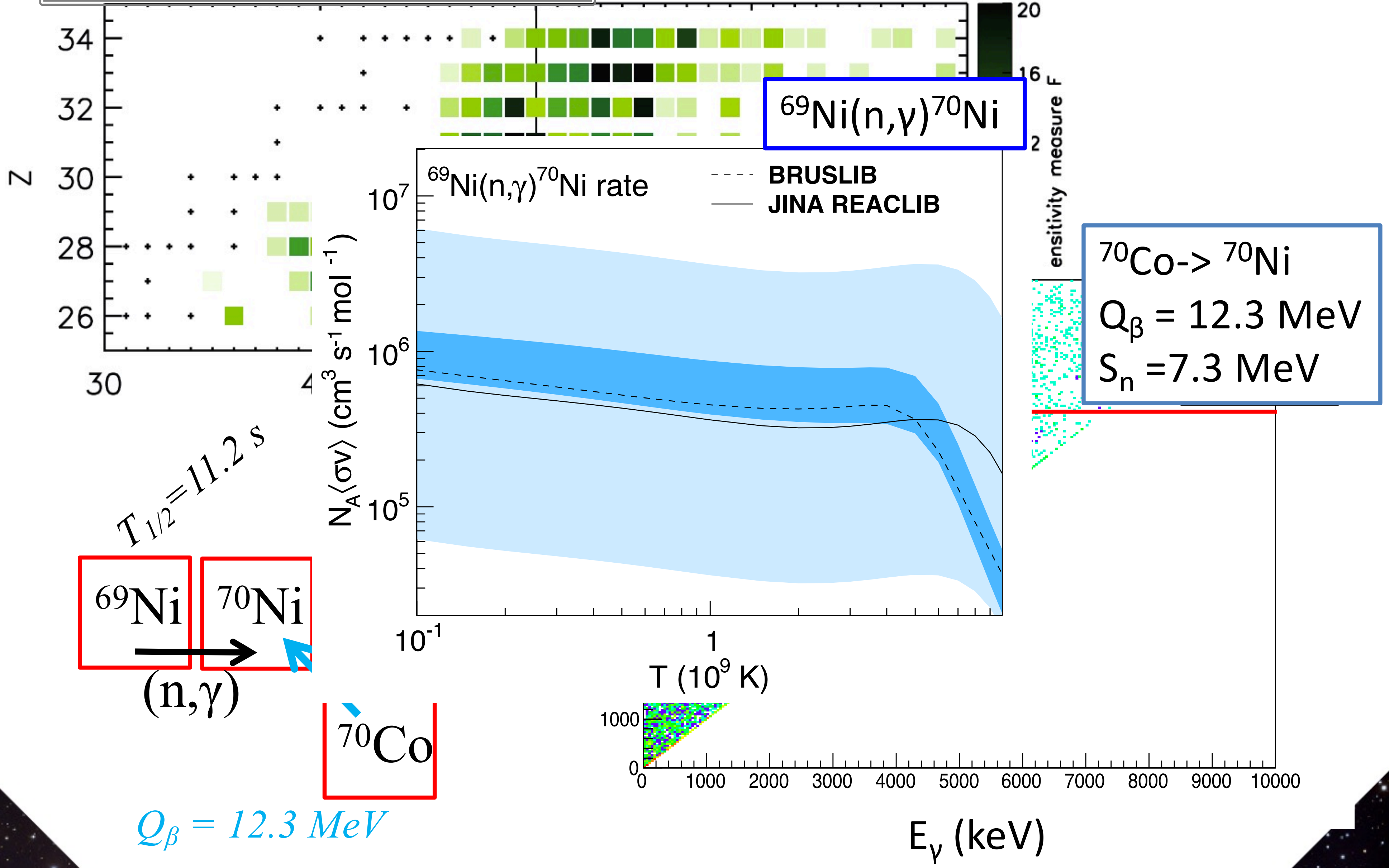


- Populate the compound nucleus via β-decay (large Q-value far from stability)
- Spin selectivity – correct for it
- Extract level density and γ-ray strength function
- Advantage: Can reach (n,γ) reactions with beam intensity down to 1 pps.

Spyrou, Liddick, Larsen, Guttormsen, et al. PRL2014

Example β-Oslo

R. Surman, et al., , AIP Advances 4, 041008 (2014)



^{69}Ni(n,γ)^{70}Ni

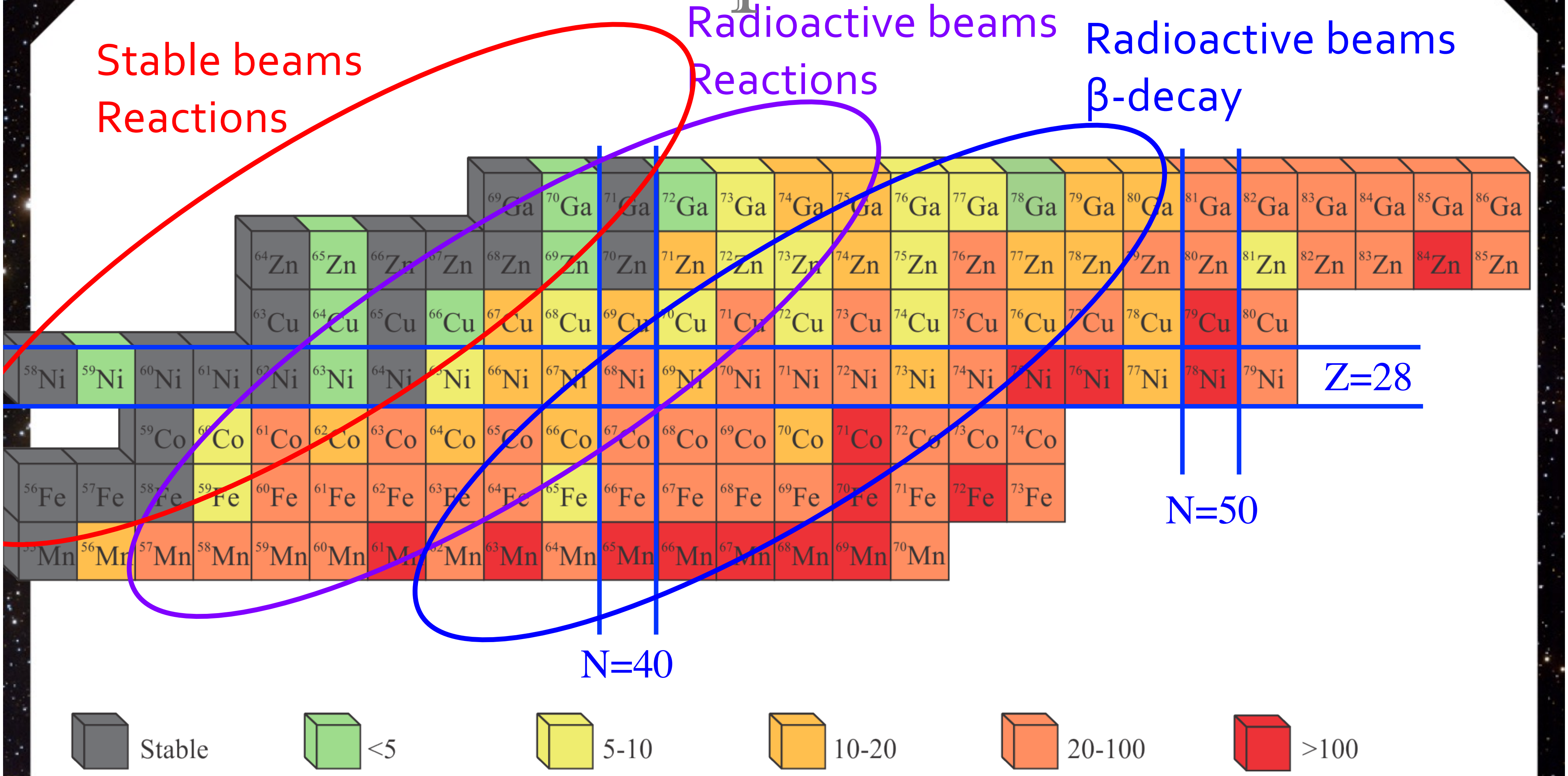
^{70}Co-> ^{70}Ni

Q_β = 12.3 MeV

S_n =7.3 MeV

Q_β = 12.3 MeV

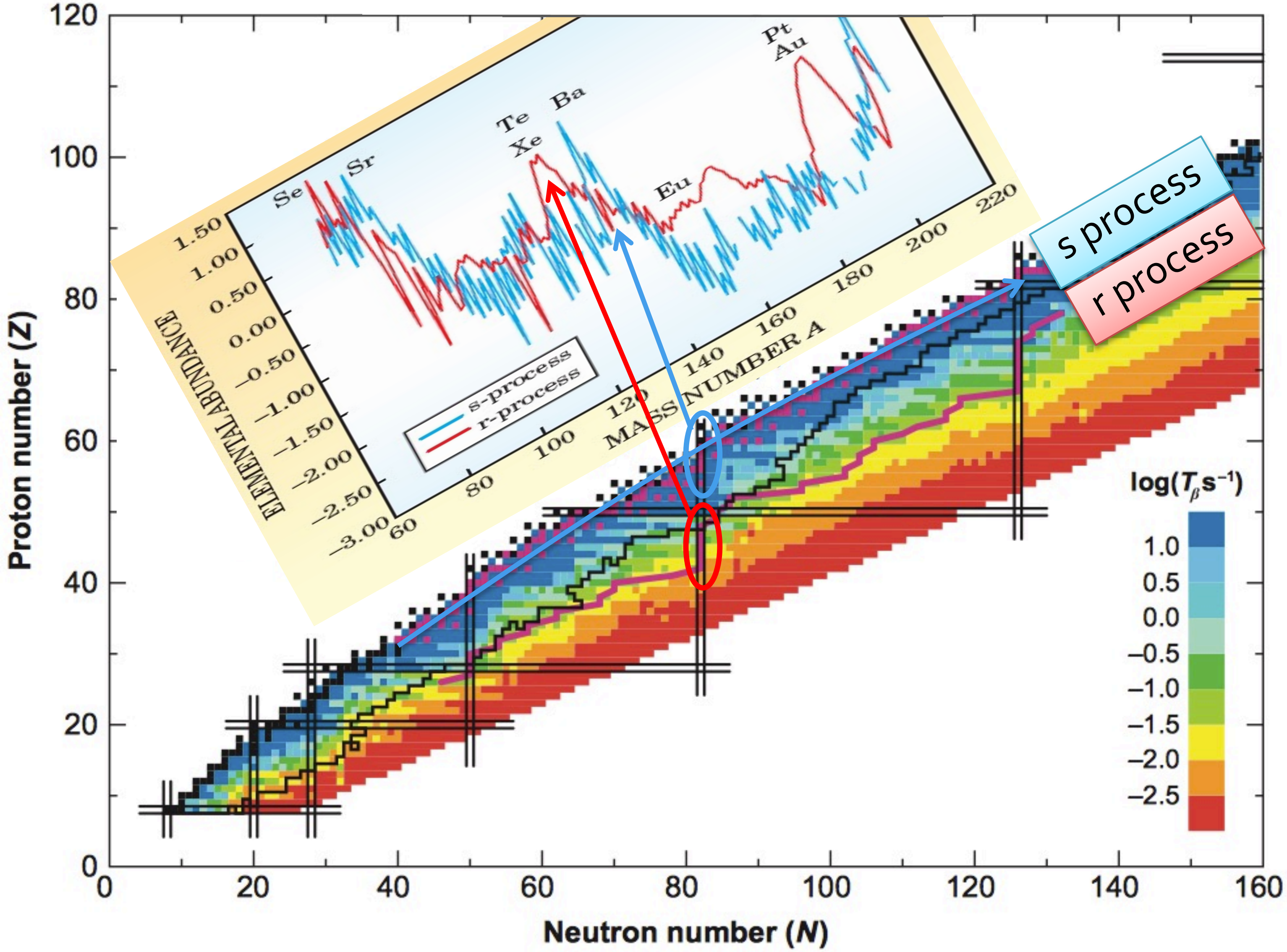
Neutron-Capture variation



- Variation of theoretical predictions using TALYS, changing NLD and γSF
- Predictions diverge moving away from stability

Nuclear Structure

s/r-process paths and abundances

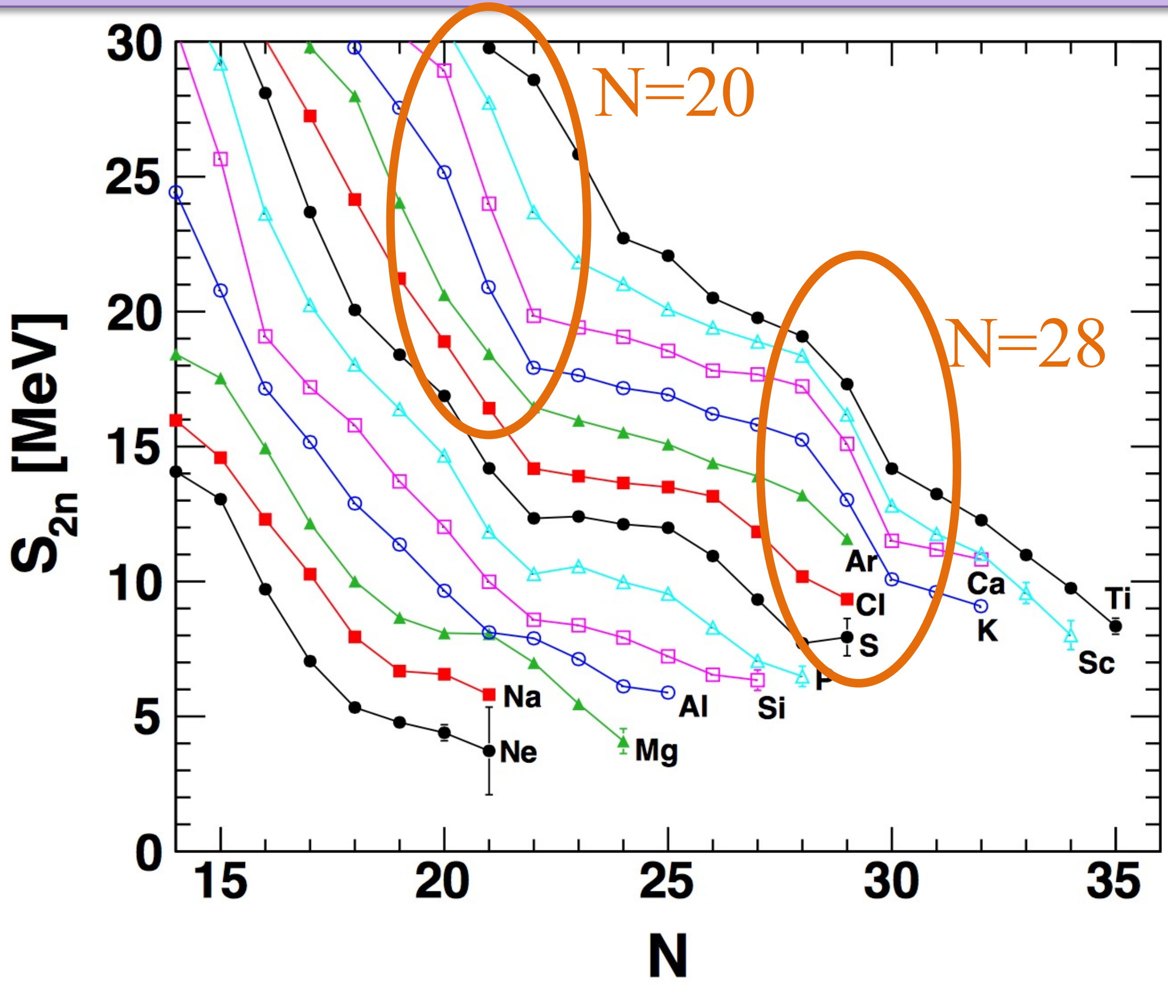


Sneden, C., Cowan, J. J., & Gallino, R., *Ann. Rev. Ast. Ap.* **46** (200

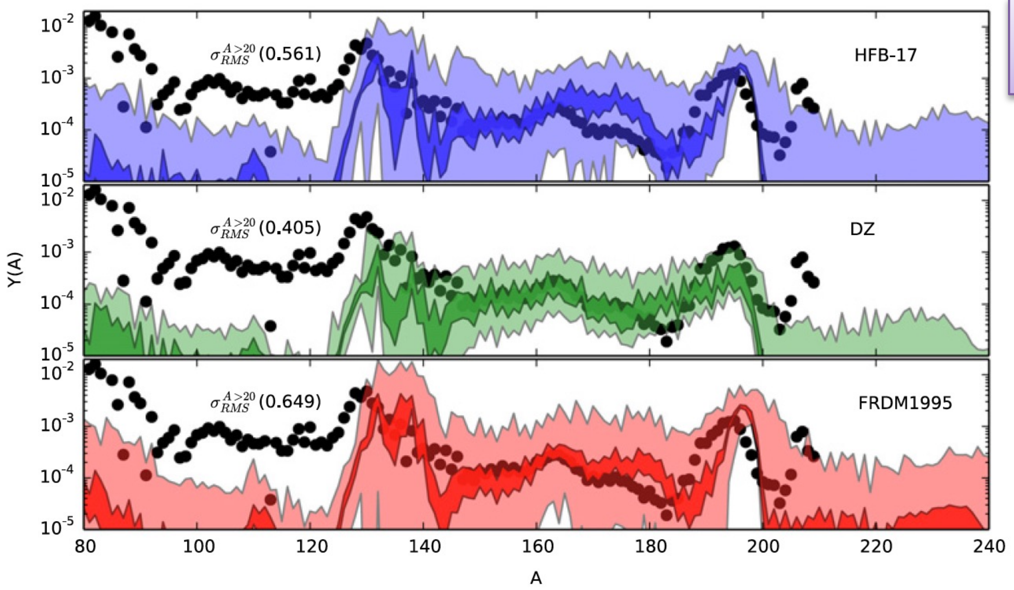
Cowan and Thielemann, Physics Today, 2004

Mass measurements

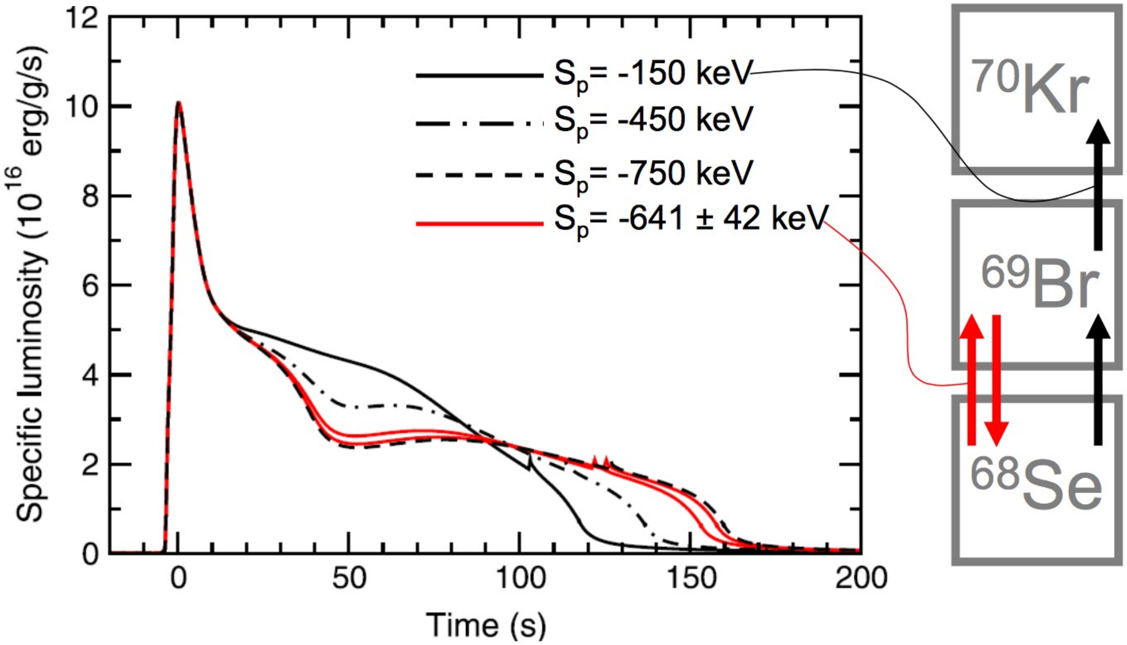
- Strong connection between nuclear mass (binding energy) and shell closures
- Two-neutron separation energies – example



Impact of mass to astrophysics



r-process abundances

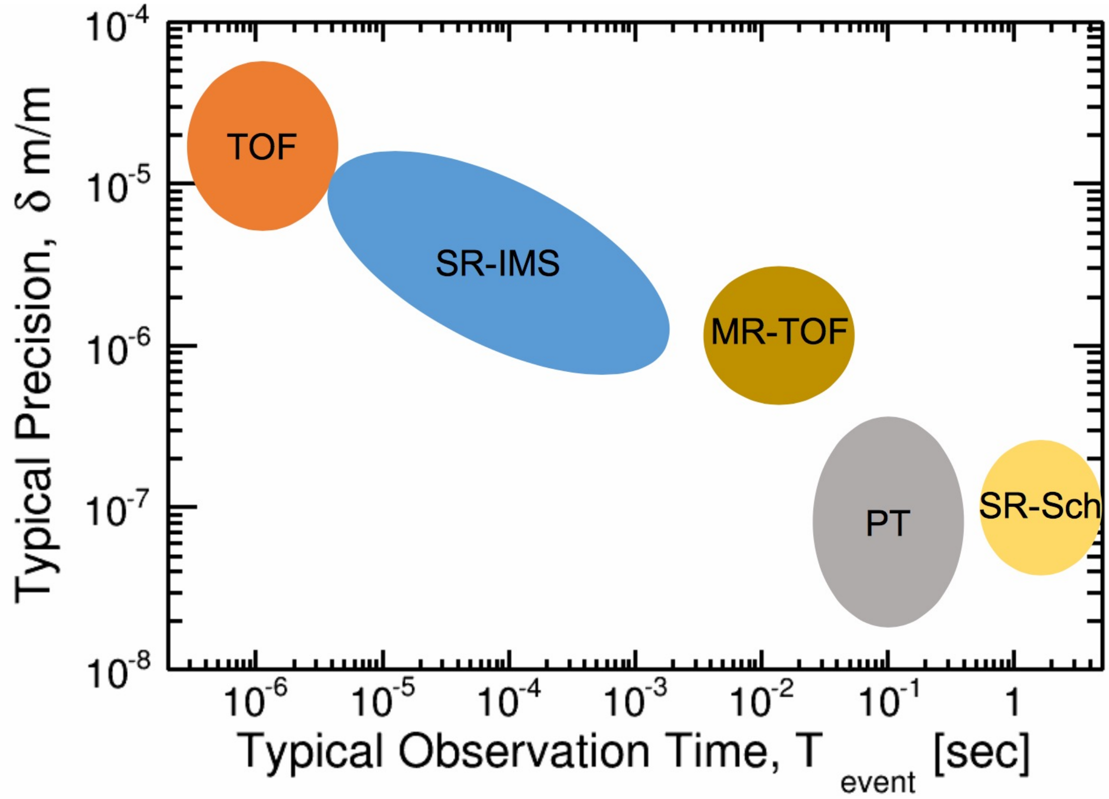


X-ray burst Luminosity

M. Mumpower, et. al. Prog. Nucl. Part. Phys. 86 (2016) 86.
M. del Santo et al., Physics Letters B 738, 453 (2014).

Mass measurements

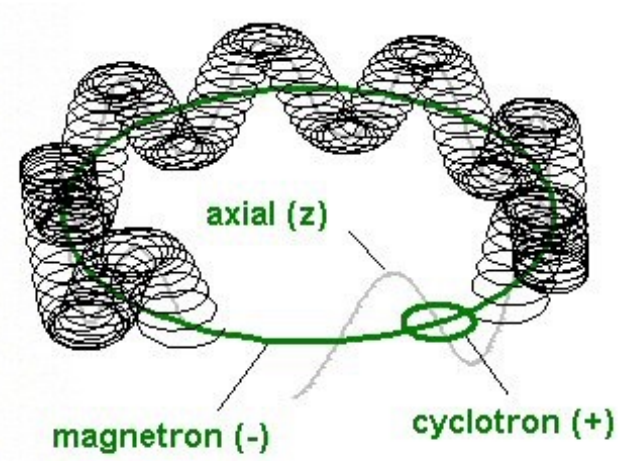
- Penning Traps (PT)
- Time-of-Flight (ToF)
- Multi-reflection ToF (MR ToF)
- Storage Rings – Schottky (SR-Sch)
- Storage Ring – Isochronous Mass Spectrometry (SR – IMS)



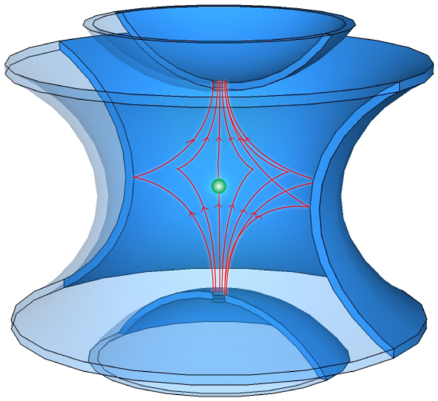
Z. Meisel, PhD thesis, MSU 2015

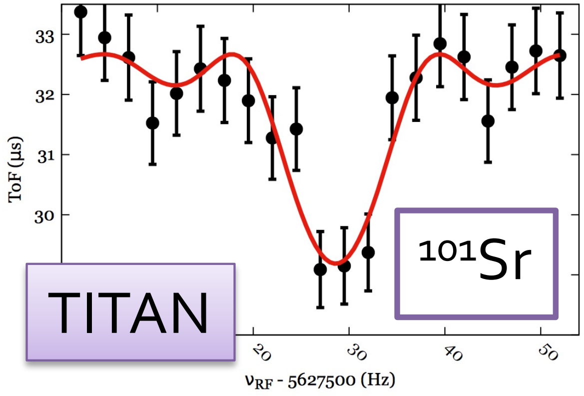
Penning Trap

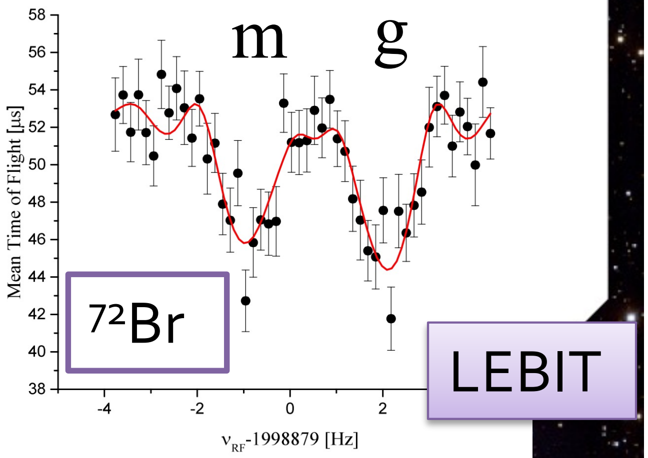
- Triple motion in penning trap
- Used for measuring the mass of nuclei with very large accuracy
- Confining particles in electric and magnetic fields



- Canadian Penning Trap @ANL
- LEBIT @ MSU
- ISOLTRAP @ ISOLDE, CERN
- TITAN @ TRIUMF
- JYFLTRAP@Jyvaskula
- SHIPTRAP@GSI



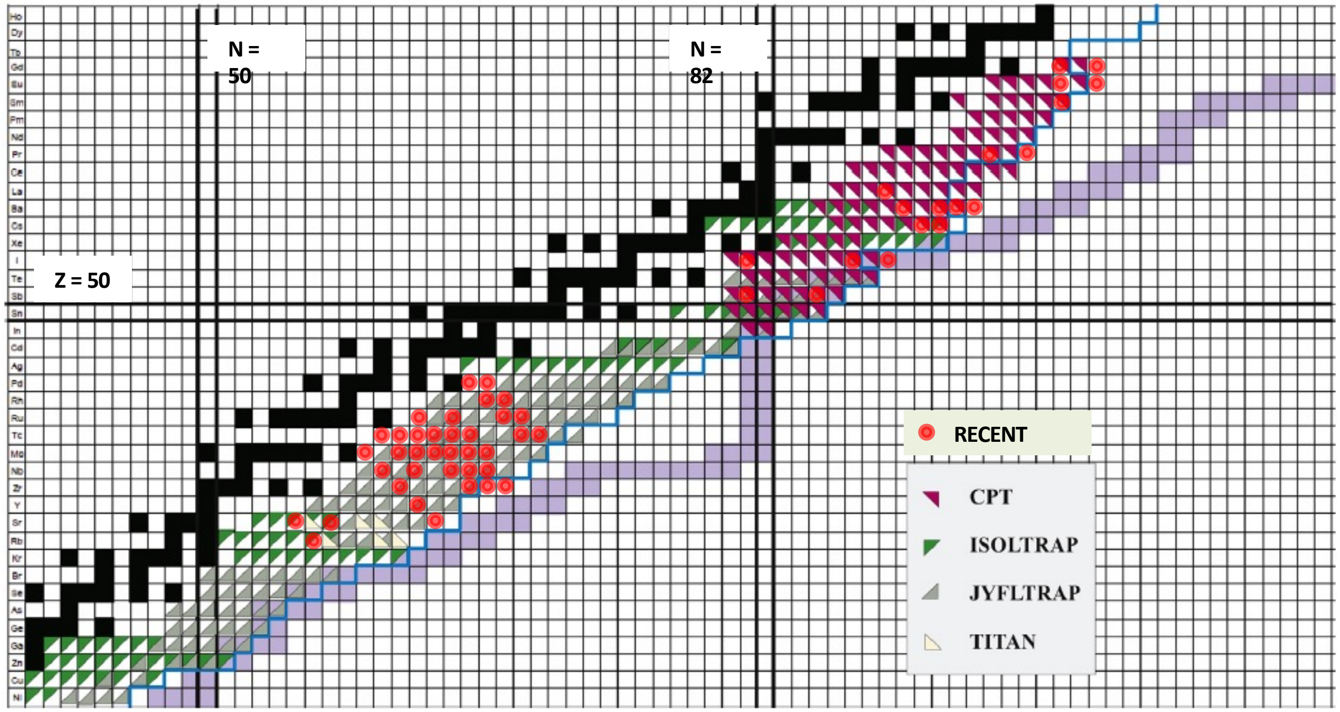




R. Klawitter, et. al. Phys. Rev. C 93 (2016) 045807
A. Valverde, et. al. Phys. Rev. C 91 (2015) 037301

Example results: Penning Trap

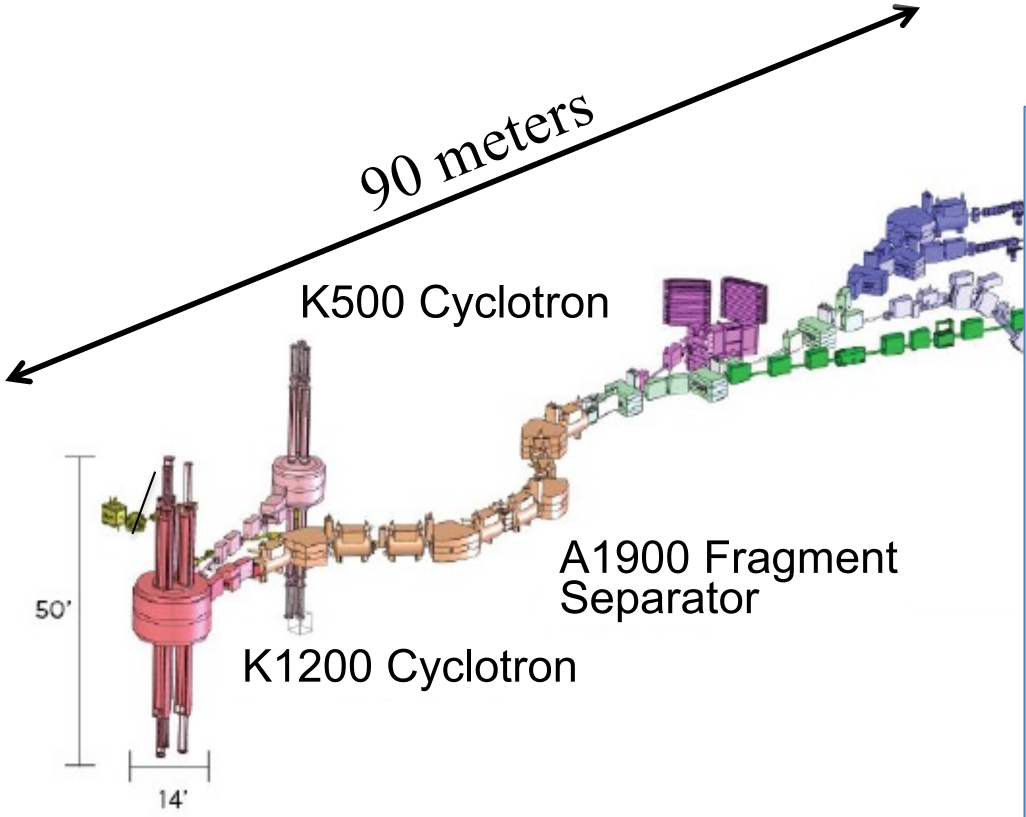
- Canadian Penning Trap @ANL
- Collaboration ANL + Notre Dame
- Impact on r-process calculations



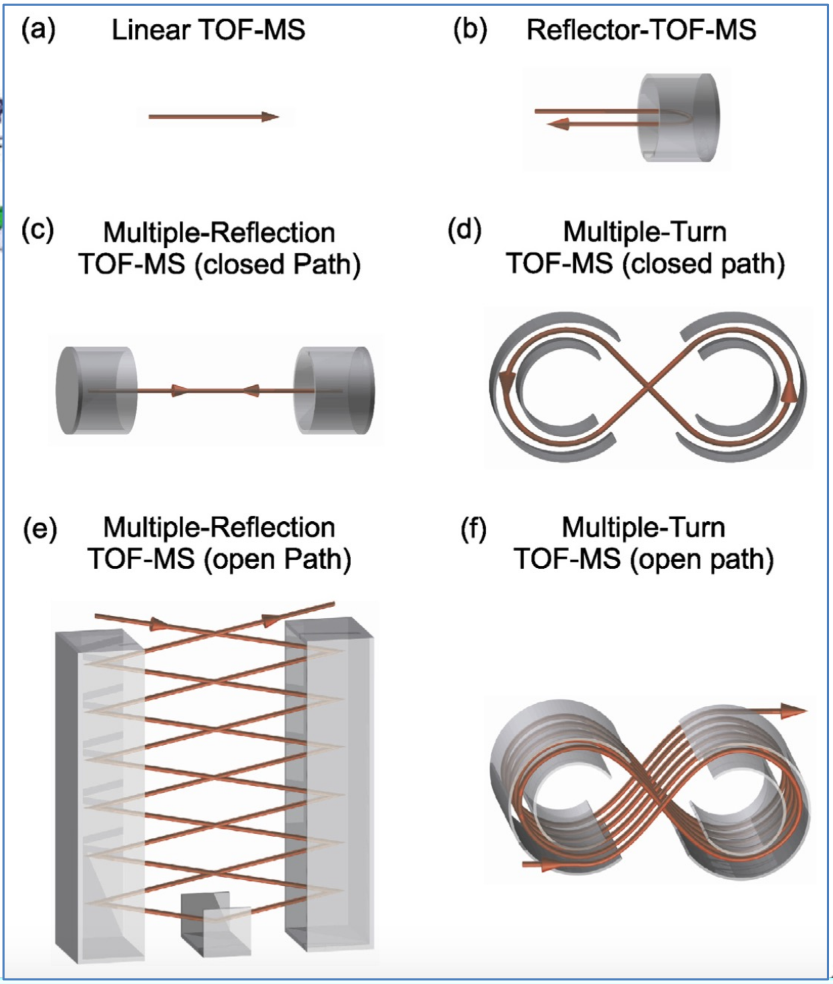
J. A. Clark and G. Savard, Int. J. Mass Spectrom. ***349-350****, 81 (2013).*

Time-of-Flight

- **National Superconducting Cyclotron Laboratory @ MSU**

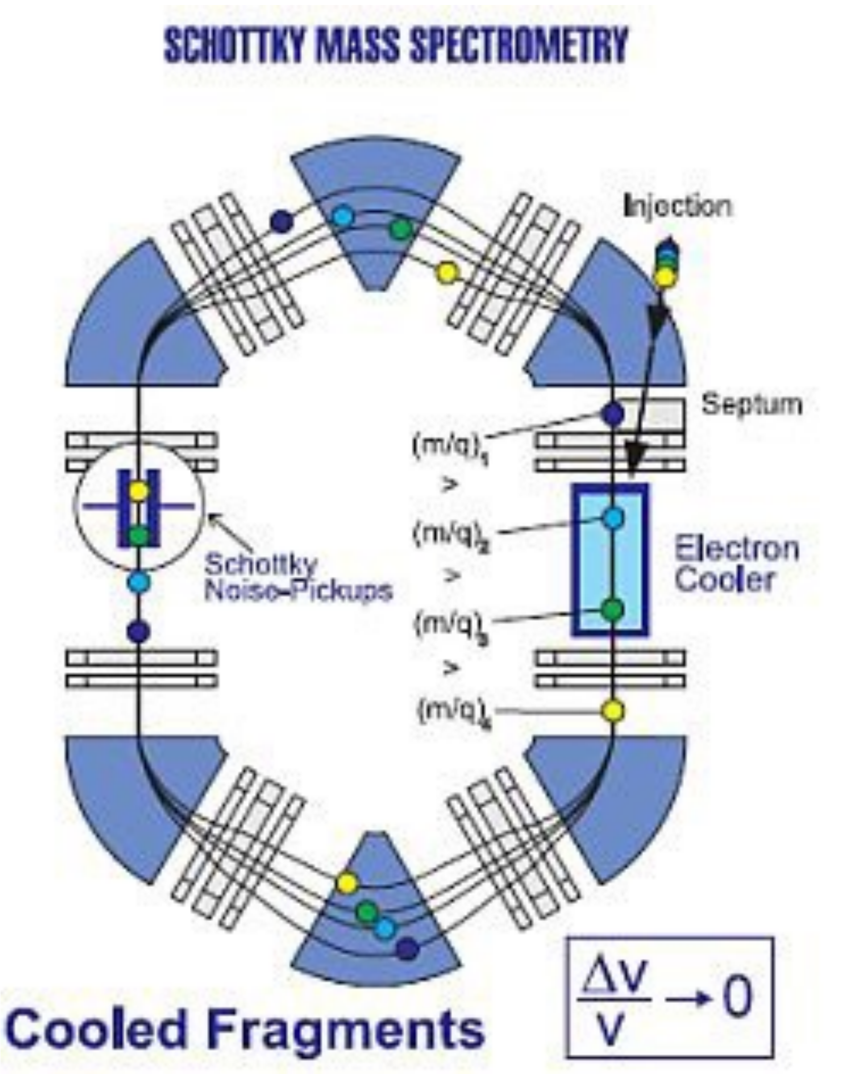


Z. Meisel, S. George, et. al. Prys. Rev. Lett. 114 (2015) 022501

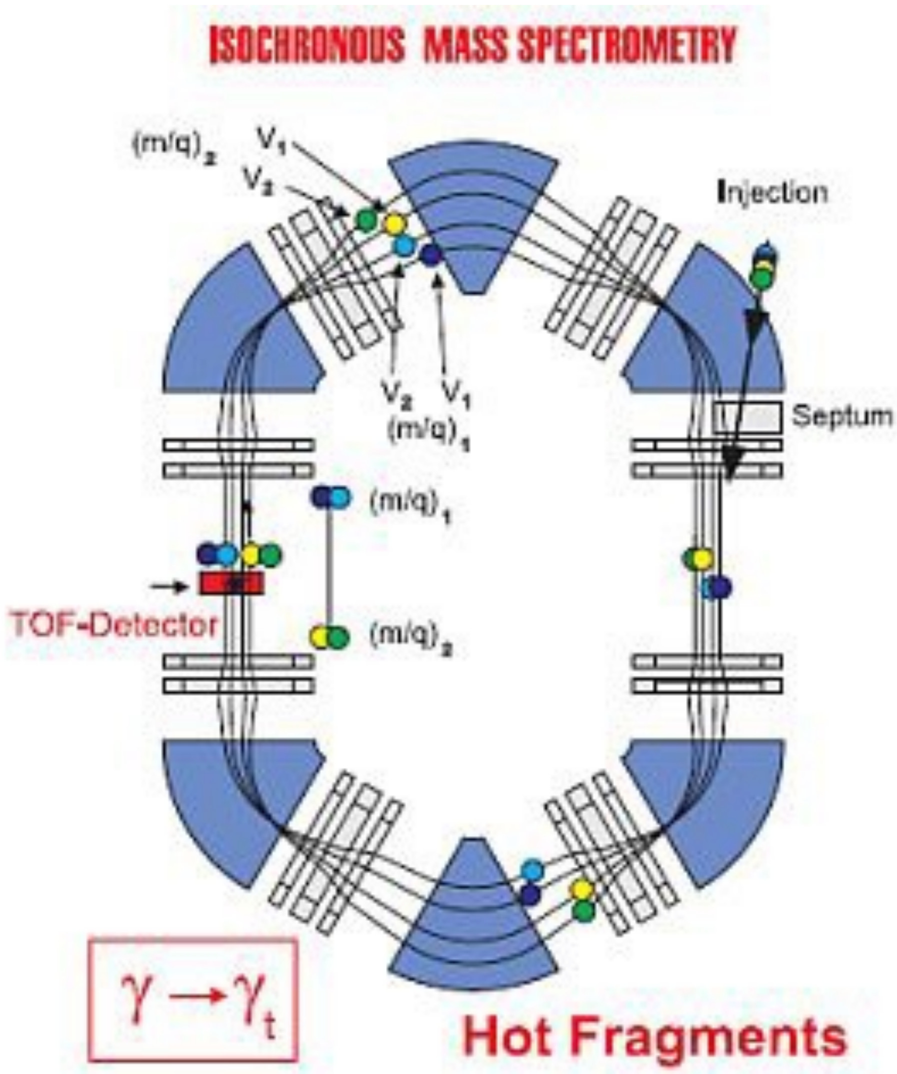


W. Plaβ et. al., Intern. J. of Mass Spectrom. 349 (2013) 134

Storage Rings



SCHOTTKY MASS SPECTROMETRY

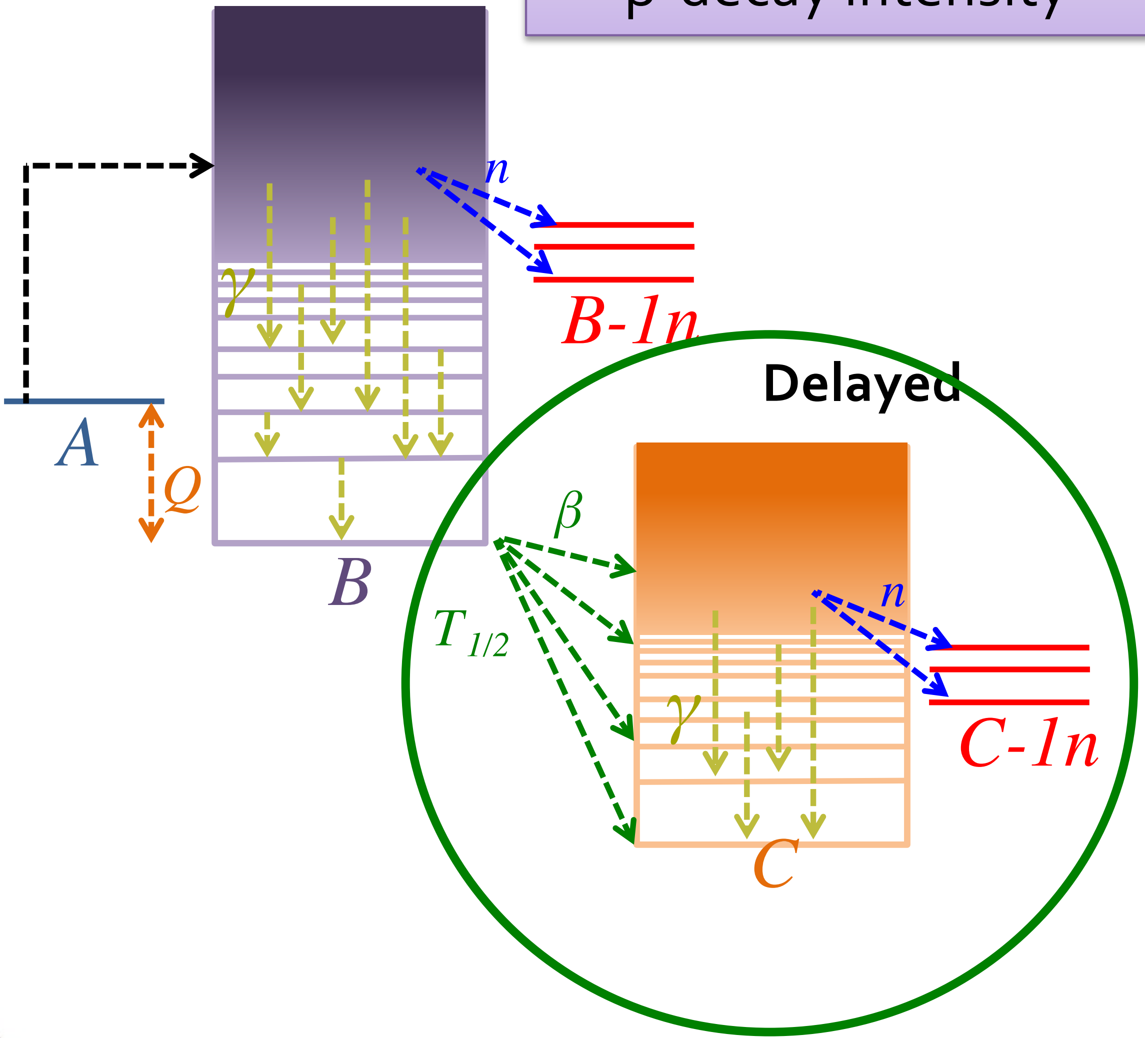


ISOCHRONOUS MASS SPECTROMETRY

www.gsi.de

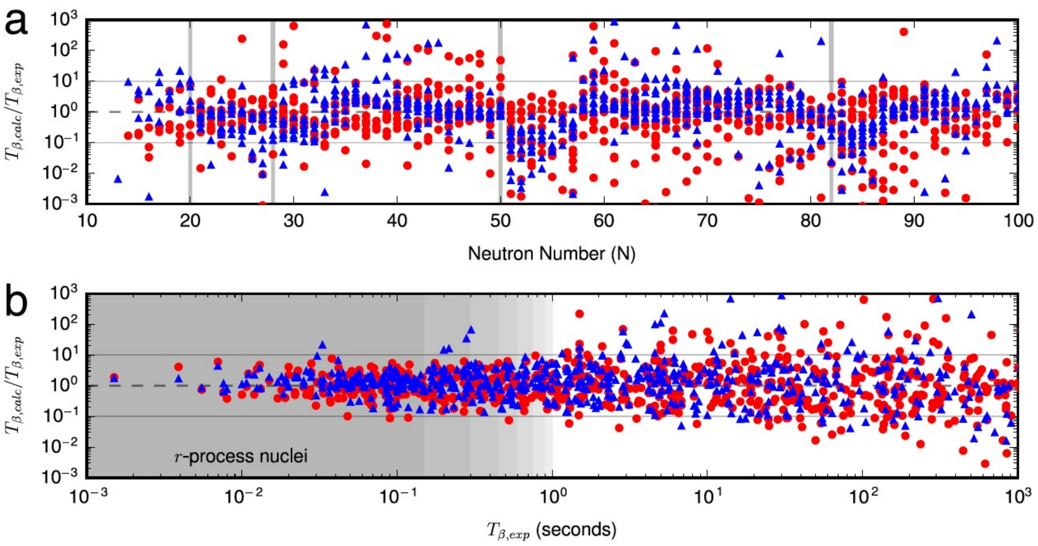
β decay properties

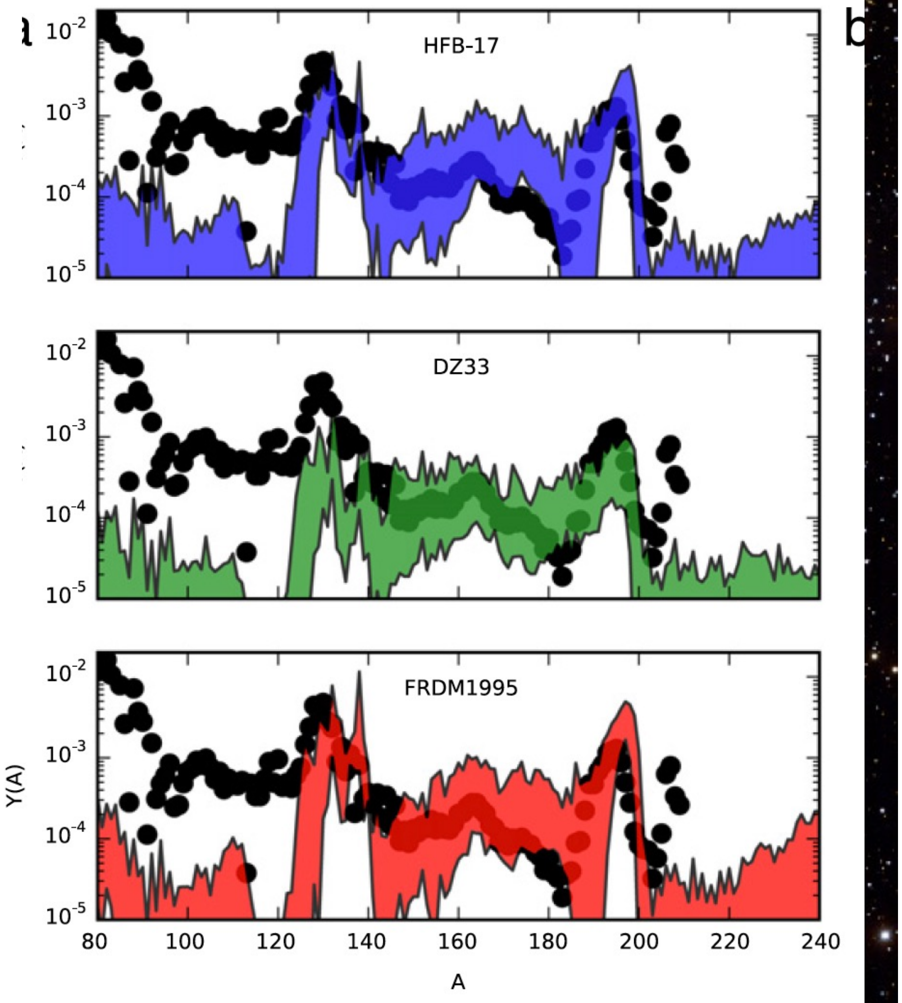
- Half life $T_{1/2}$
- β-delayed neutron emission probability P_n
- β-decay intensity



Half life

- Impact of half-lives on r-process

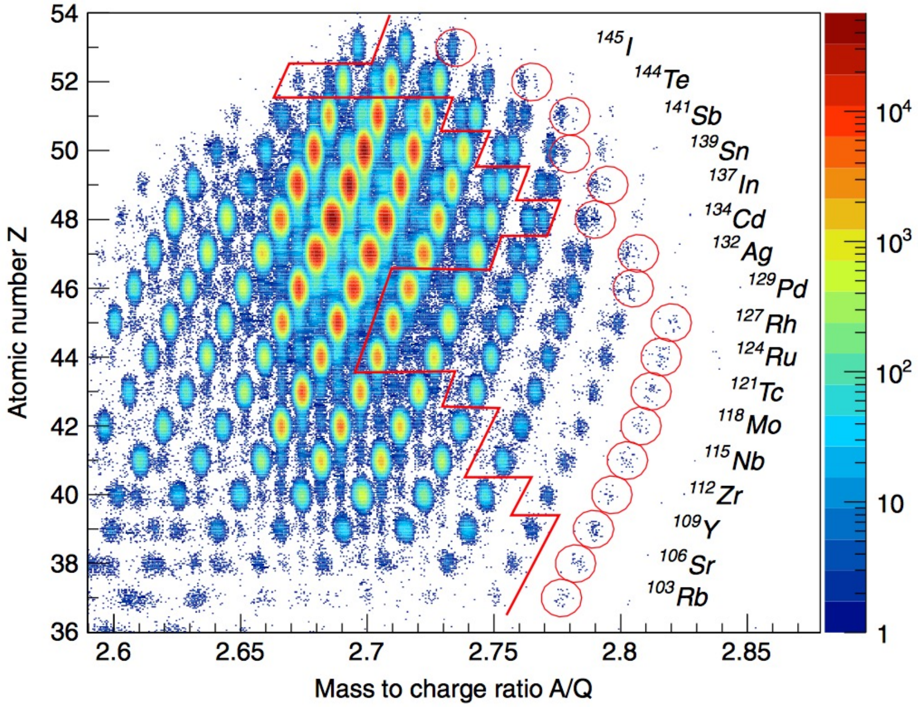


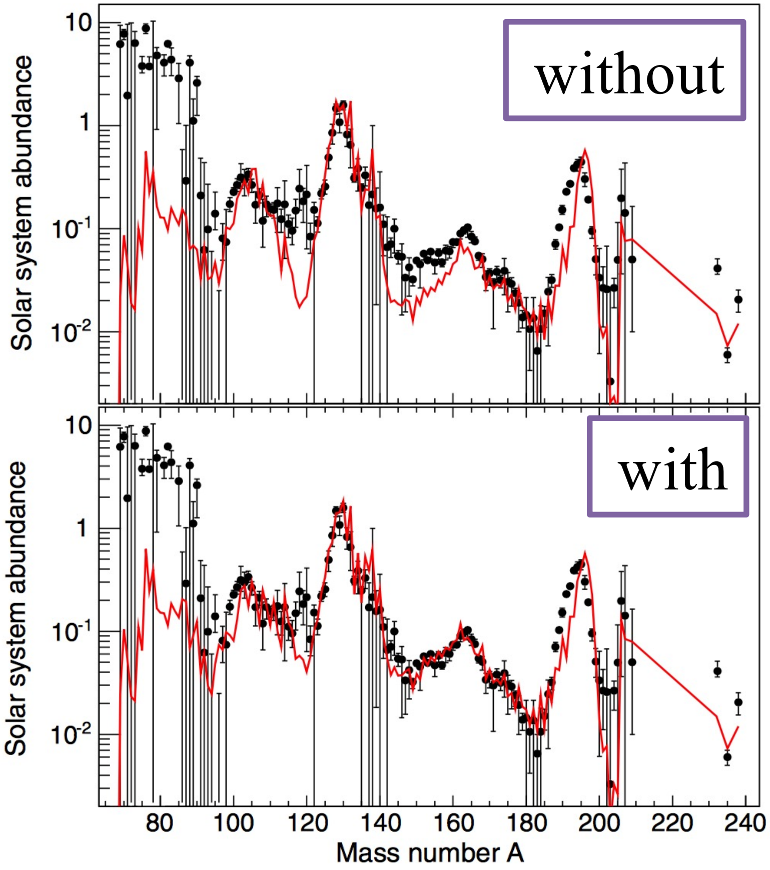


M. Mumpower, et. al. Prog. Nucl. Part. Phys. 86 (2016) 86.

Half life

- RIKEN recently completed a major upgrade
- Higher beam rates than other facilities
- Systematics of T1/2
- Impact on r process



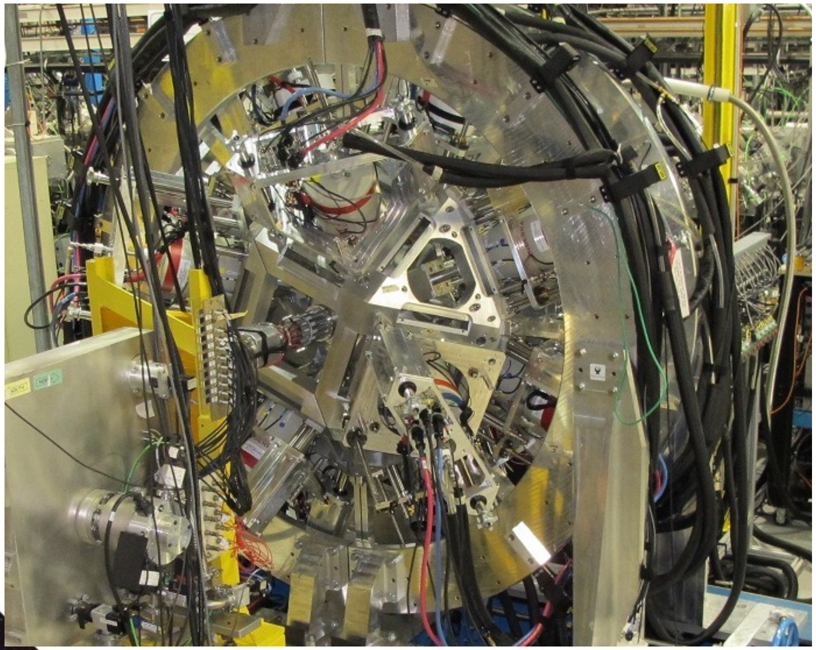


G. Lorusso, et. al. Phys. Rev. Lett. 114 (2015) 192501

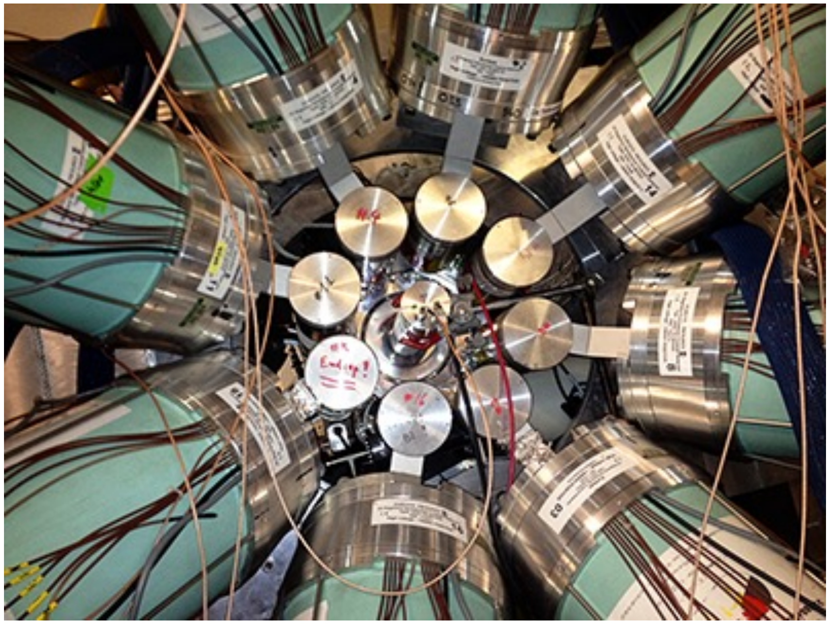
High resolution

- Mentioned that nuclear structure understanding is important for all astrophysical processes
- Many ways to study nuclear structure
- β decay is typically the first view of a nucleus (low beam intensity)
- High resolution measurements for the low lying level scheme

GRIFFIN @ TRIUMF

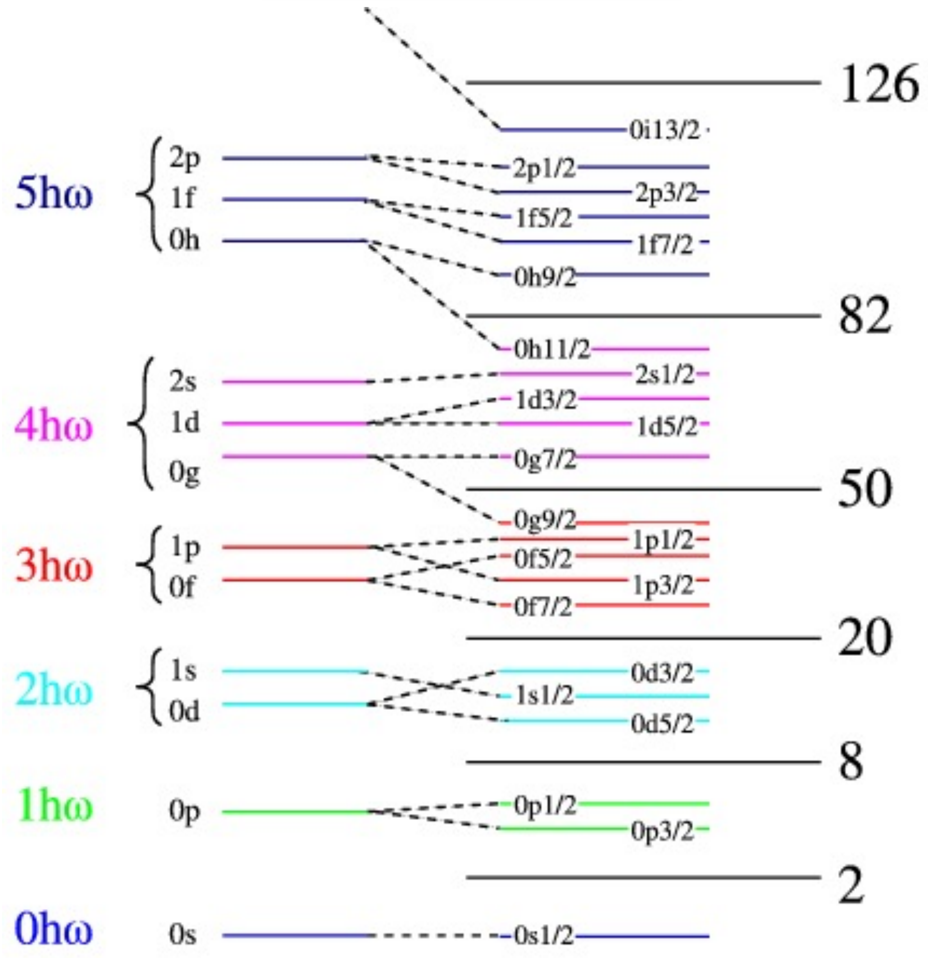


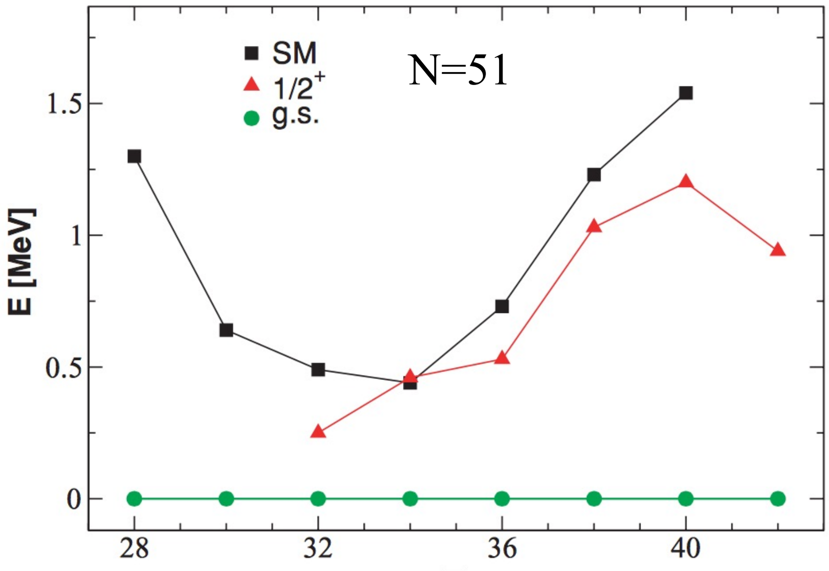
SeGA + BCS @ MSU



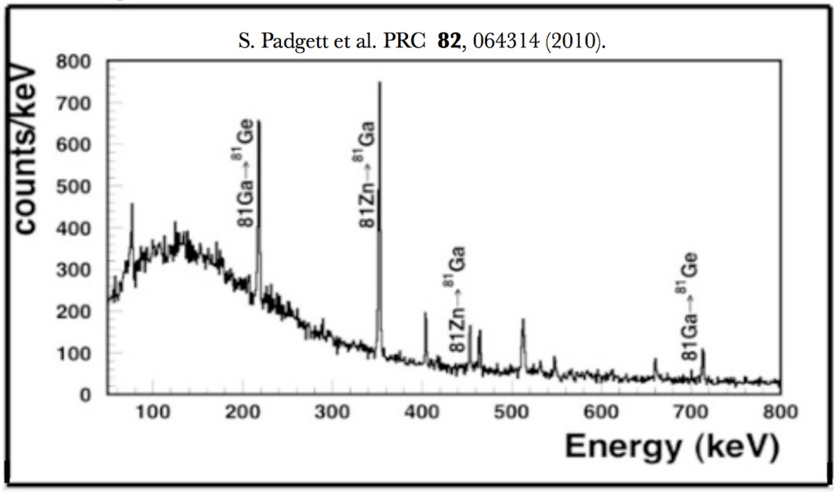
Evolution of Nuclear Structure

Shell model





HPGe Clovers @ ORNL



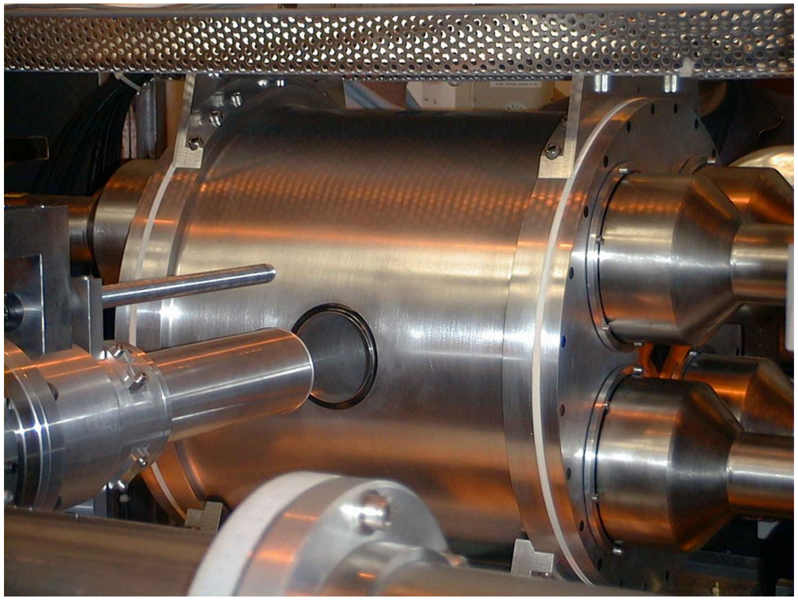
S. Padget, et. al. Phys. Rev. C 82 (2010) 064314

Why measure β-decay intensity?

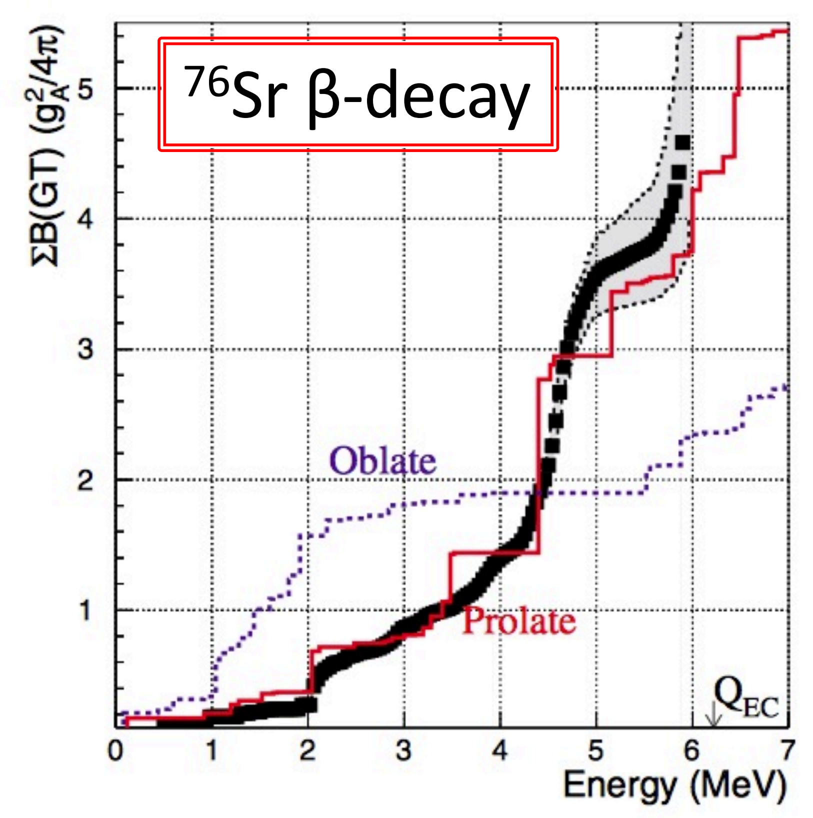
- Model constraints for better input in r-process calculations

(Cannot measure everything - we need to rely on model predictions)

- Nuclear structure information
  - $T_{1/2}$ sensitive to nuclear shape
  - Can get same $T_{1/2}$ for different shapes
  - β-decay strength: sensitive constraint



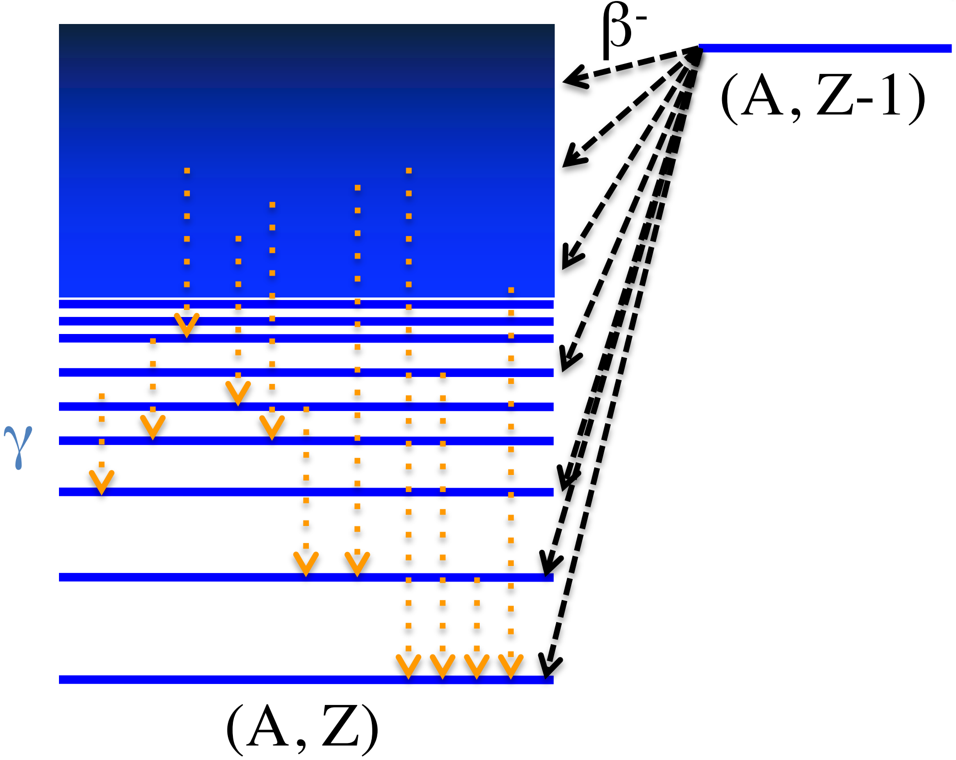
- Lucrecia @ CERN



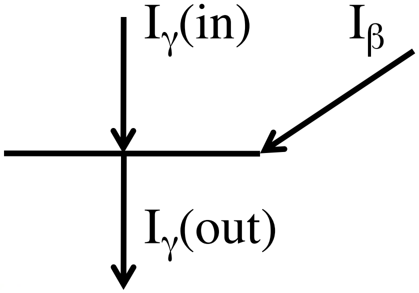
E. Nacher, *et al.*, *Phys. Rev. Lett.* 92 (2004) 232501.

Total Absorption Spectroscopy

John Milton's "Paradise Lost

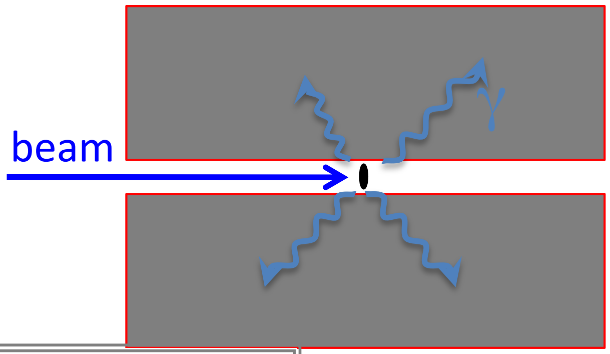


Small size – low efficiency detector



$$I_\beta = I_\gamma(\text{out}) - I_\gamma(\text{in})$$

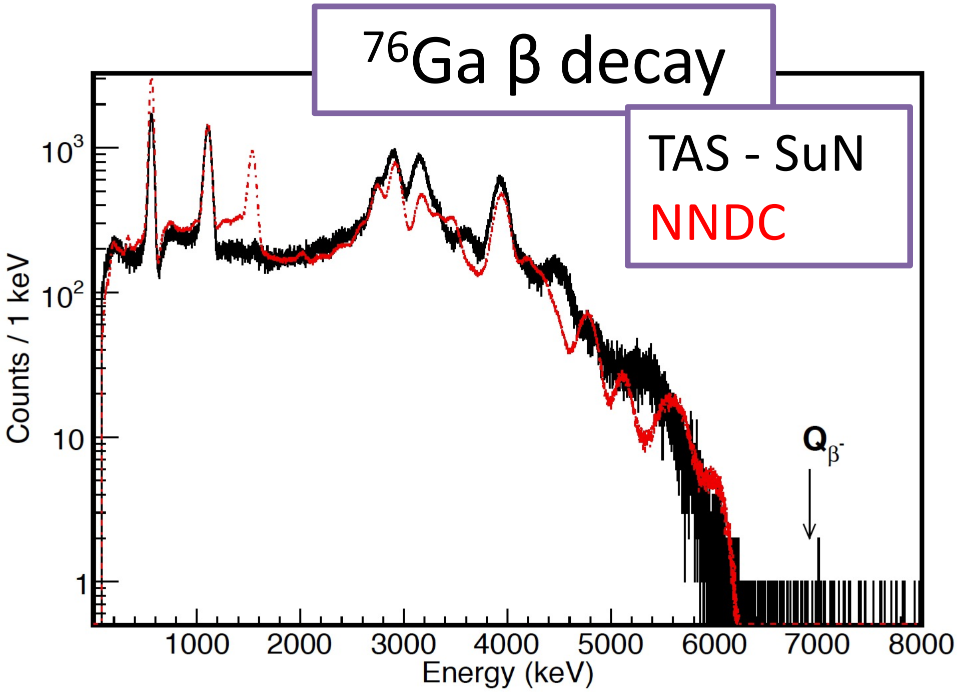
Large size - high efficiency detector



$$E_x = E_{\gamma 1} + E_{\gamma 2} + E_{\gamma 3} + E_{\gamma 4} + \ldots$$

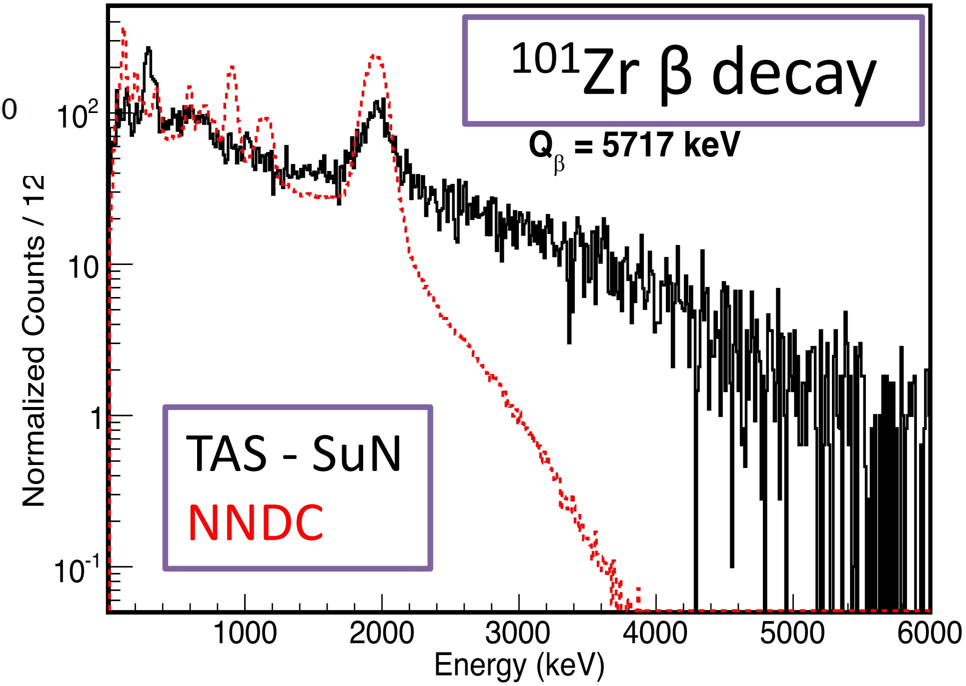
J.C. Hardy et al., Phys. Lett. B 71 (1977) 307.

The Pandemonium in Action



76Se	77Se	78Se	79Se	80Se
75As	76As	77As	78As	79As
74Ge	75Ge	76Ge	77Ge	78Ge
73Ga	74Ga	75Ga	76Ga	77Ga
72Zn	73Zn	74Zn	75Zn	76Zn

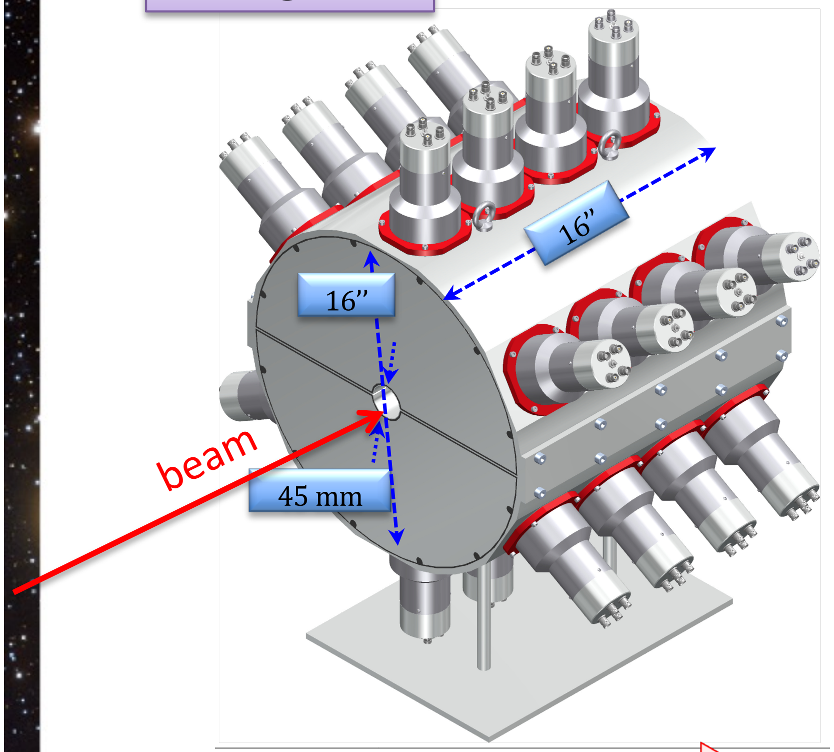
100Ru	101Ru	102Ru	103Ru	104Ru	105Ru
99Tc	100Tc	101Tc	102Tc	103Tc	104Tc
98Mo	99Mo	100Mo	101Mo	102Mo	103Mo
97Nb	98Nb	99Nb	100Nb	101Nb	102Nb
96Zr	97Zr	98Zr	99Zr	100Zr	101Zr

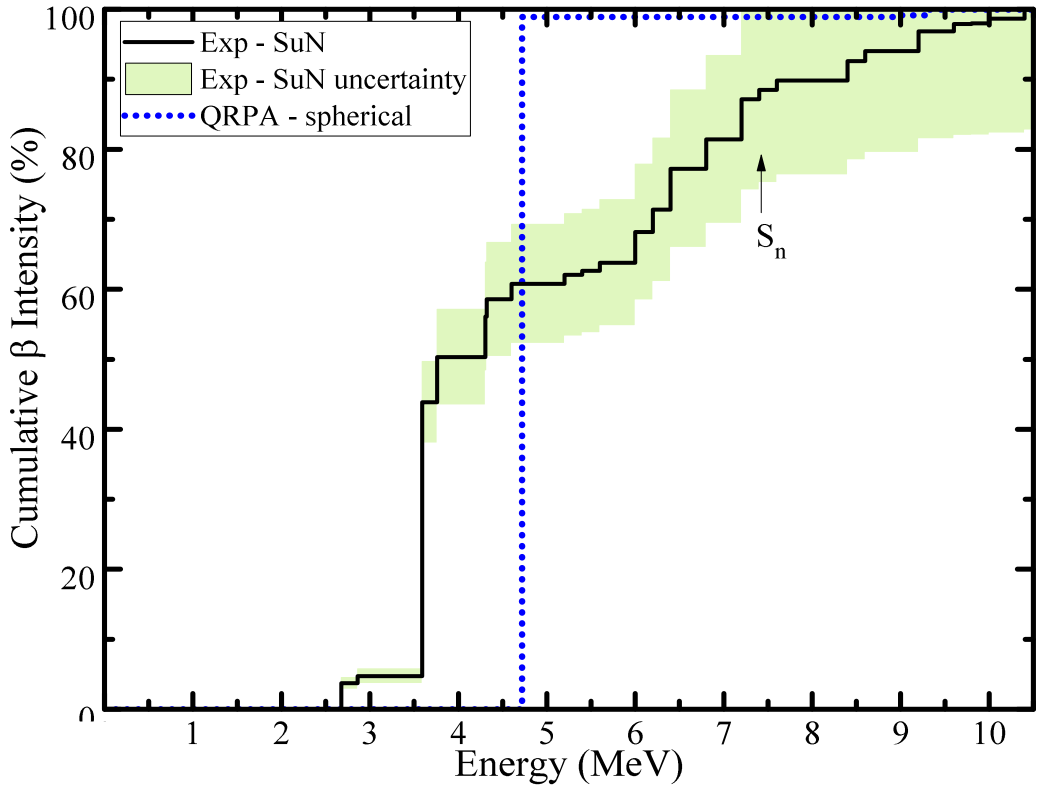


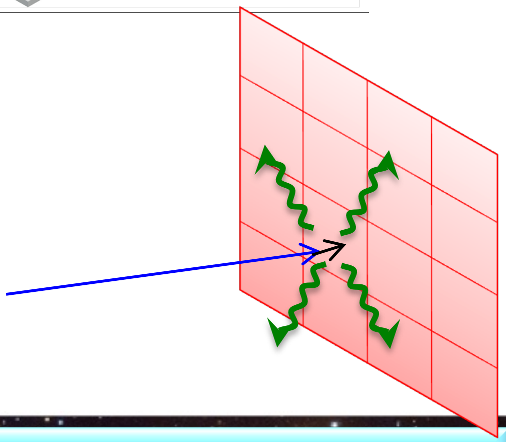
A. Dombos, et. al. PRC93 (2016) 064317

r-process example: ^{70}Co β-decay Intensity

SuN @ MSU



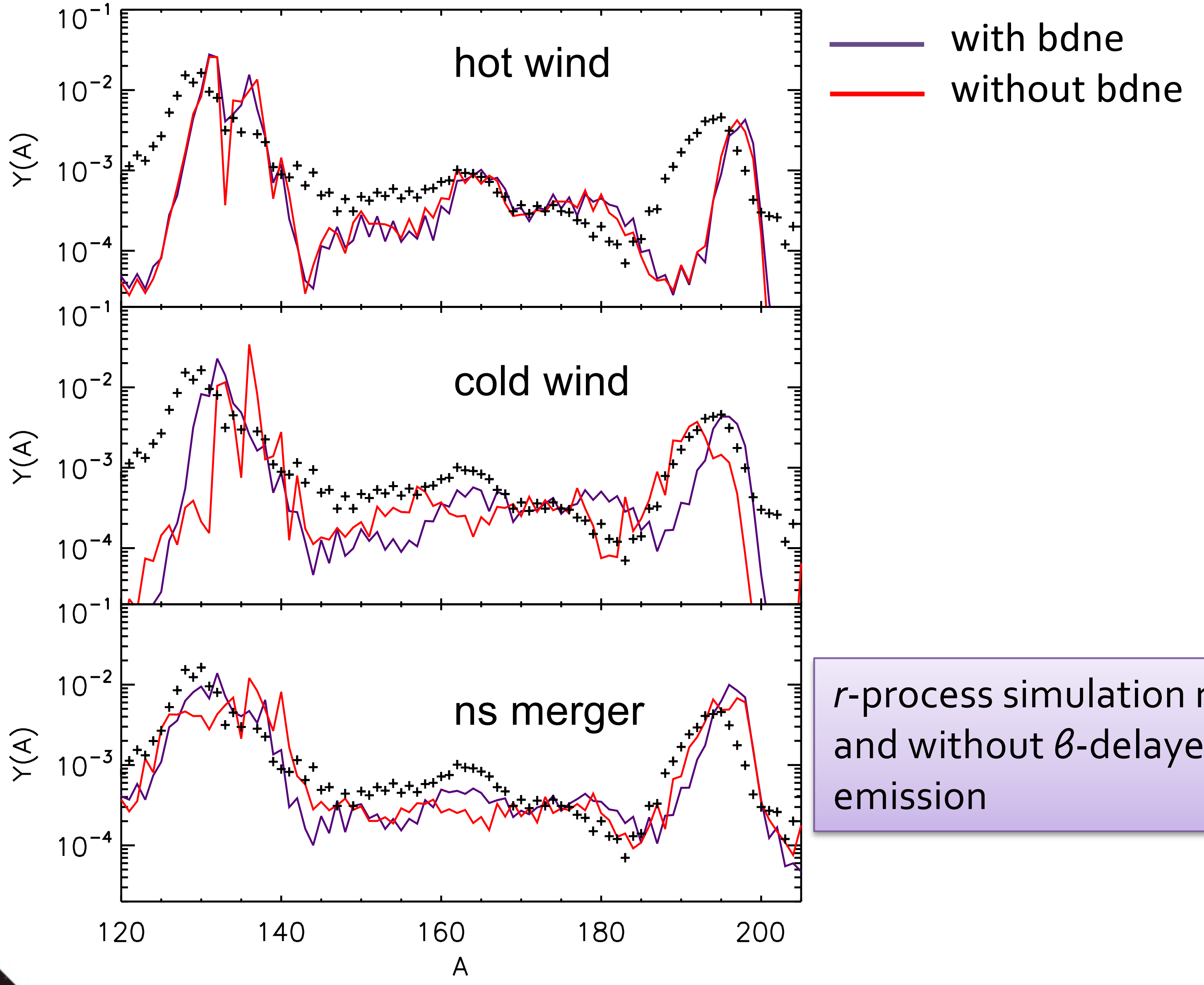




Double Sided Si Strip Detector
For ion and β detection

A. Spyrou, S.N. Liddick, et al. Phys. Rev. Lett. 117 (2016) 142701

Importance of P_n values



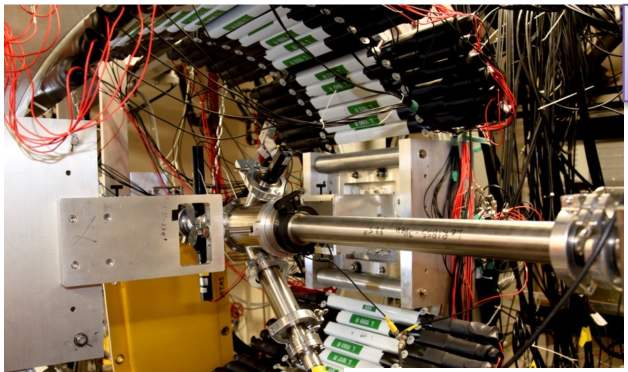
r-process simulation results with and without β-delayed neutron emission

R. Surman, et. al. JPS Conf. Proc. 6 (2015) 010010

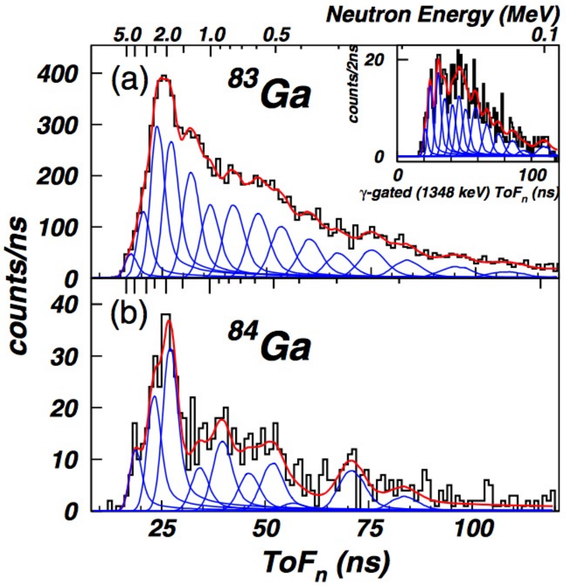
Measuring Pn values

- Integrated measurement - 3He counters (3Hen, NERO, BRIKEN)
- Time of flight – energy information (VANDLE, LENDA, DESCANT)
- New technique – Paul trap (@ ANL)

VANDLE @ ORNL



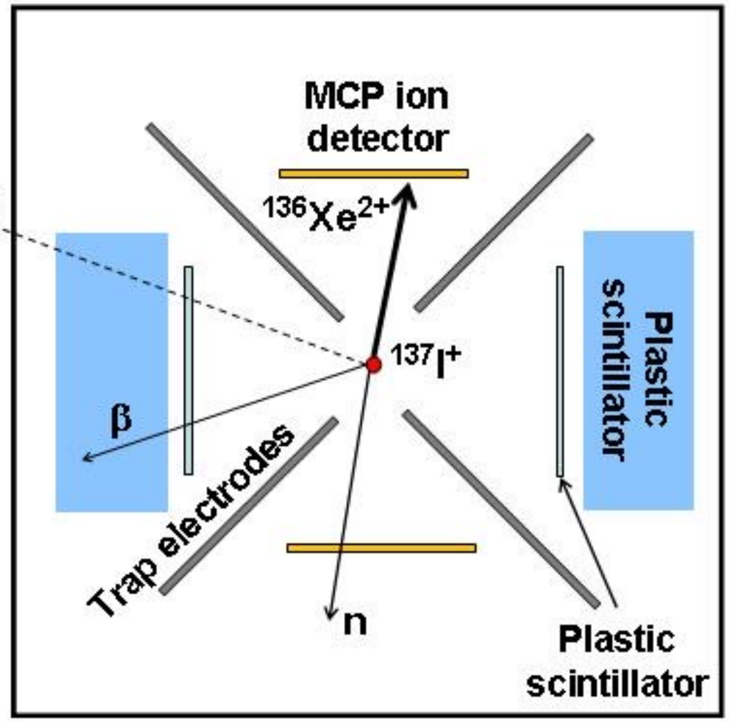
DESCANT @ TRIUMF

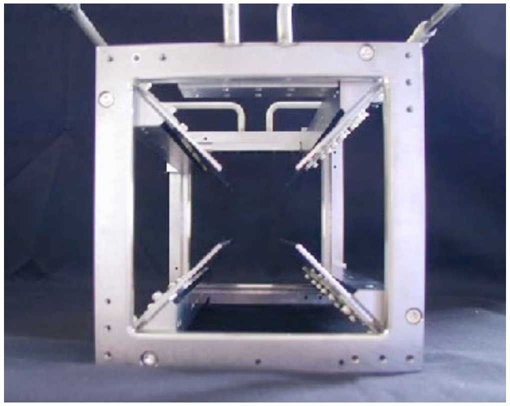


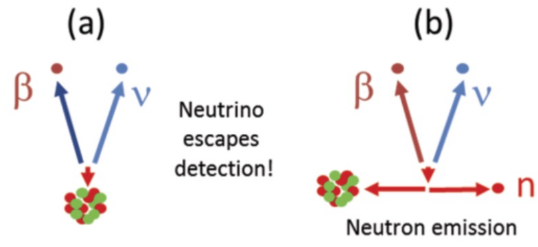
NERO @ MSU

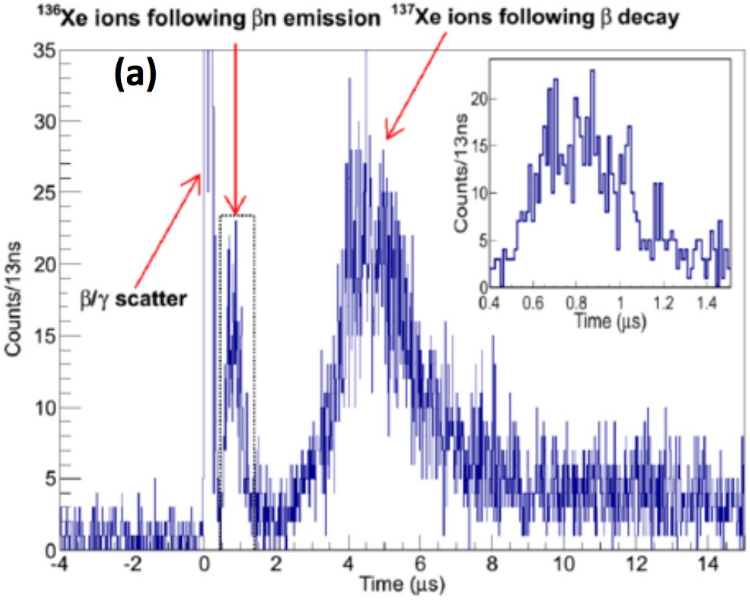
M. Madurga, et. al. Phys. Rev. Lett. 117 (2016) 092502

Paul trap









- Surround ion trap (Paul trap) with plastic scintillators (to detect β's) and MCPs (to detect decay recoils)
- Beta-delayed neutron decay measured without detecting neutron

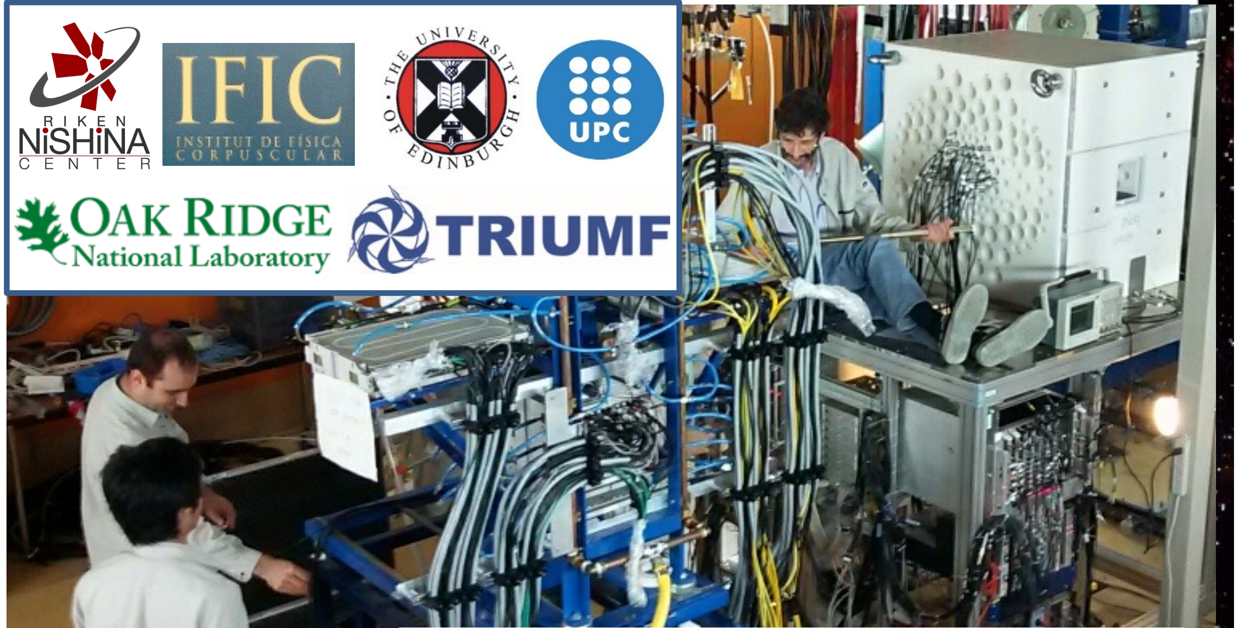
N. Scielzo, et. al., Nucl. Data Sheets 120 (2014) 70

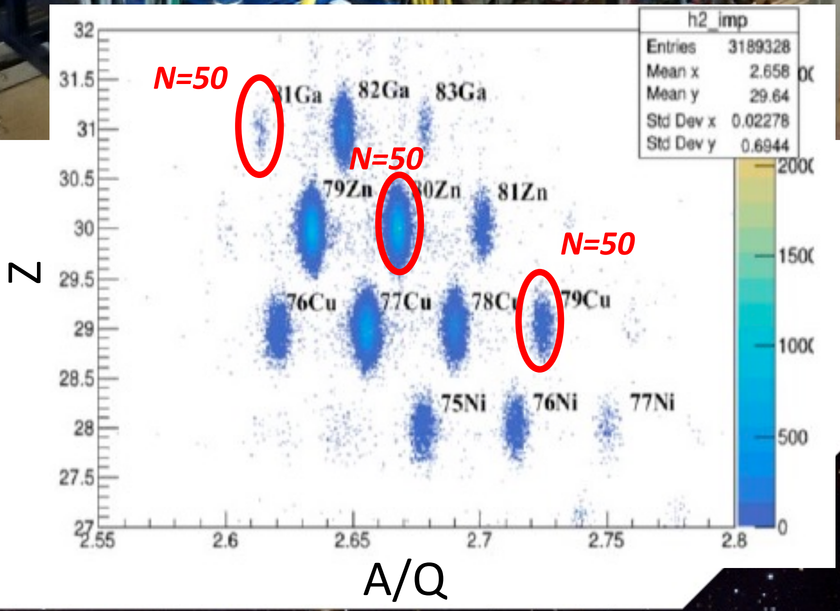
Example: Recent Pn measurements

- Installed at RIKEN Nishina Center in Wako/ Japan
- 148 ^{3}He-filled neutron counters from Germany, Japan, Spain, USA and 2 HPGe clovers (Oak Ridge)
- Implantation detector AIDA (Edinburg, Daresbury)
- First parasitic experiment – more to come 2017-2019

BRIKEN

- **Goal**: Measure >100 of the most exotic neutron-rich isotopes presently accessible





Summary

We covered A LOT of material but we didn't cover EVERYTHING. Here's some of what we didn't cover:

- Isomers
- Charge Exchange Reactions
- (p,n) reactions for νp process
- (α,n) reactions for neutron-star crusts
- Equation of State experiments
- Fission
- …

Overview

"We shape our tools and thereafter our tools shape us."

Marshall McLuhan