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Astrophysics – Critical Nuclear Physics

K. E. Rehm

Physics Division

Argonne National Laboratory

NIC-X School, Argonne, July 2008

J I N A

Atomic Physics

Gravitation

Particle Physics

Plasma Physics

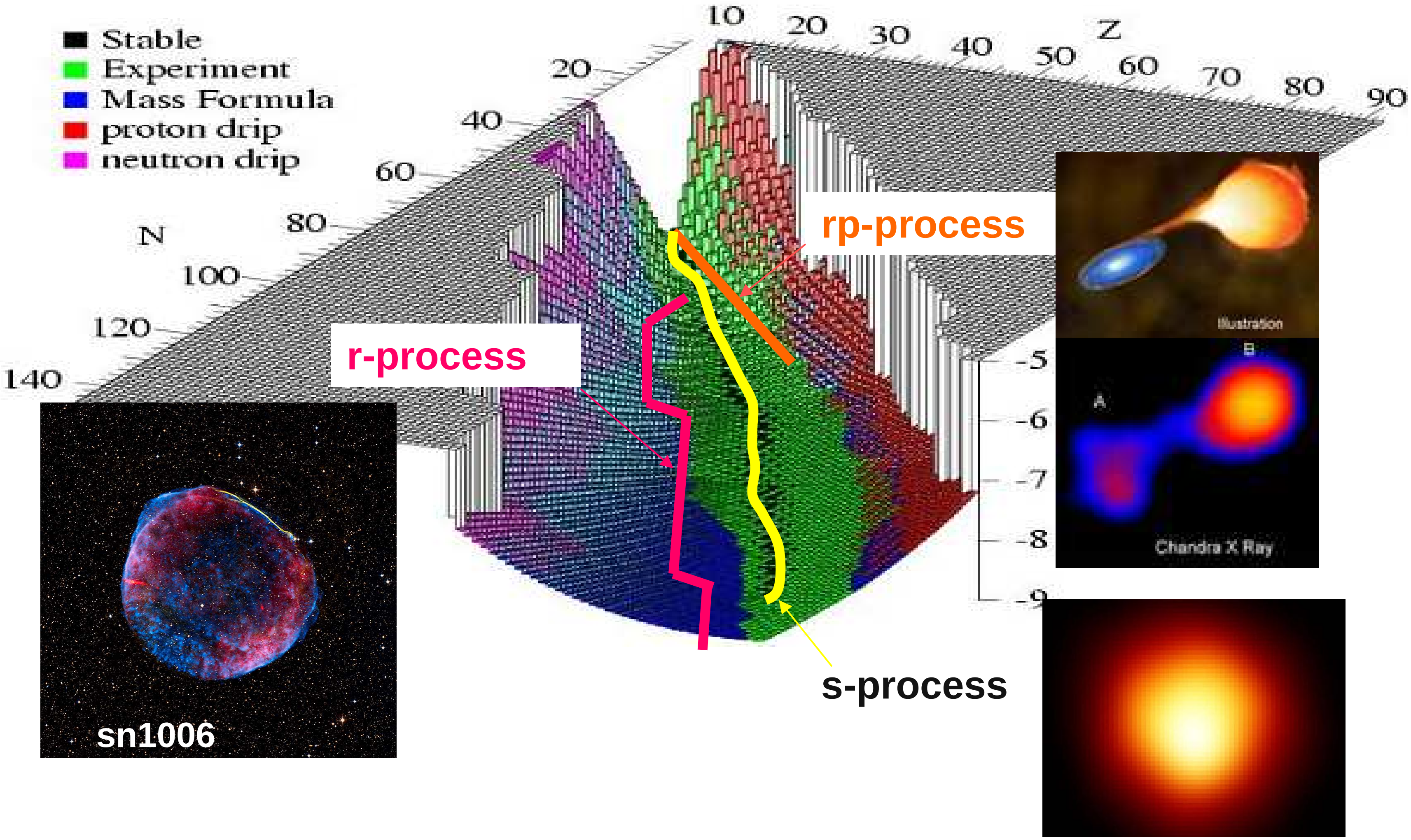
Astronomical Observations

Cosmology

Nuclear Physics

Neutrino Physics

Nuclei involved in Astrophysics

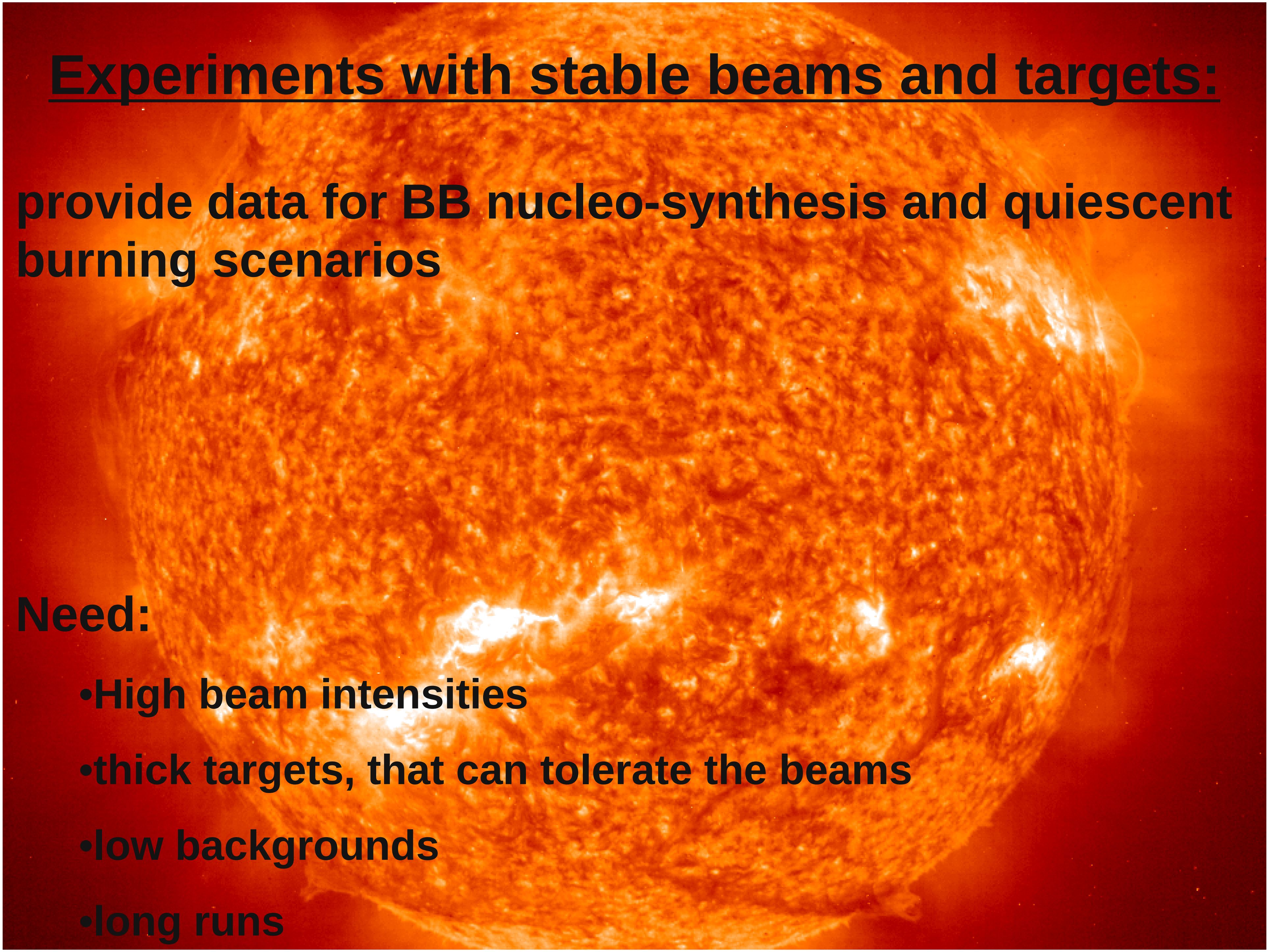


rp-process

r-process

s-process

sn1006

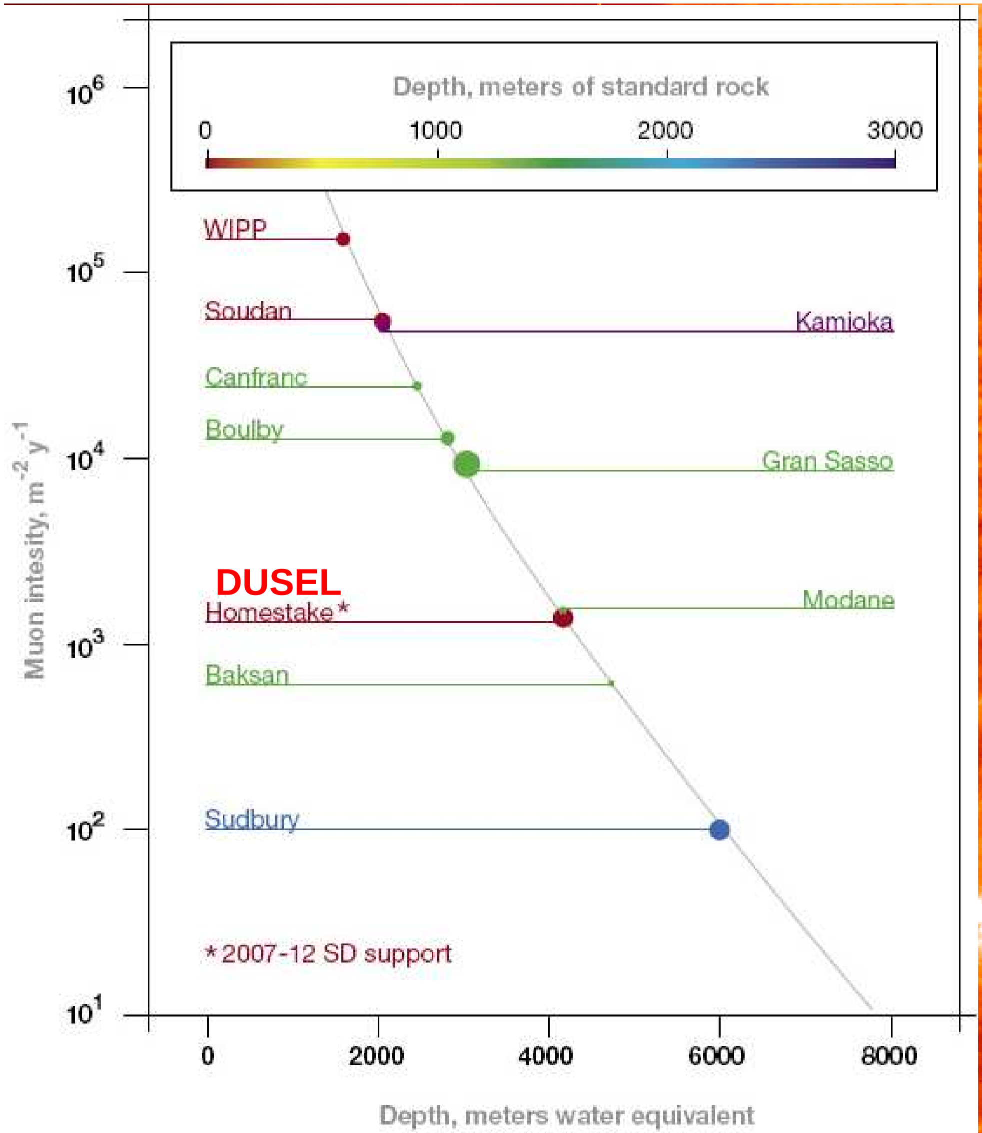


Experiments with stable beams and targets:

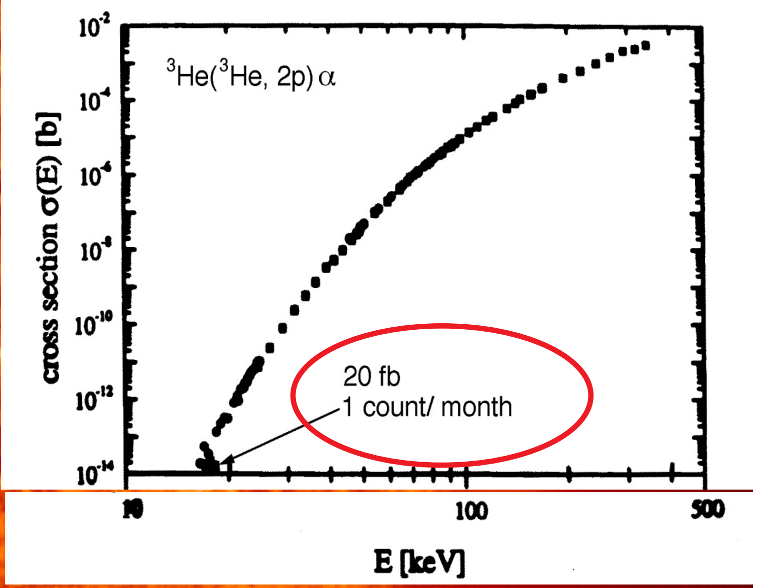
provide data for BB nucleo-synthesis and quiescent burning scenarios

Need:

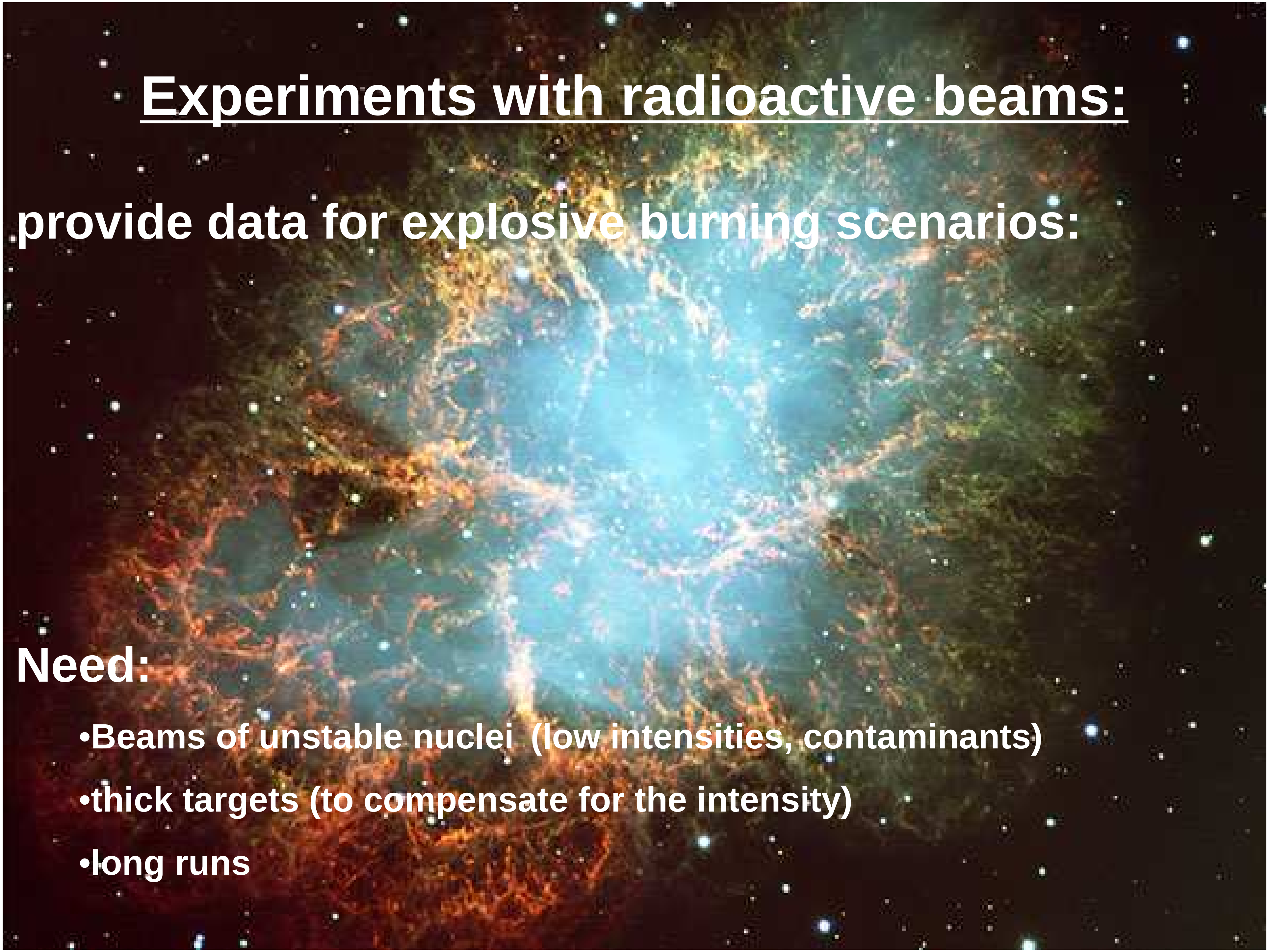
- **High beam intensities**
- **thick targets, that can tolerate the beams**
- **low backgrounds**
- **long runs**



LUNA Gran Sasso



See session 3: (C. Iliadis, G. Imbriani)

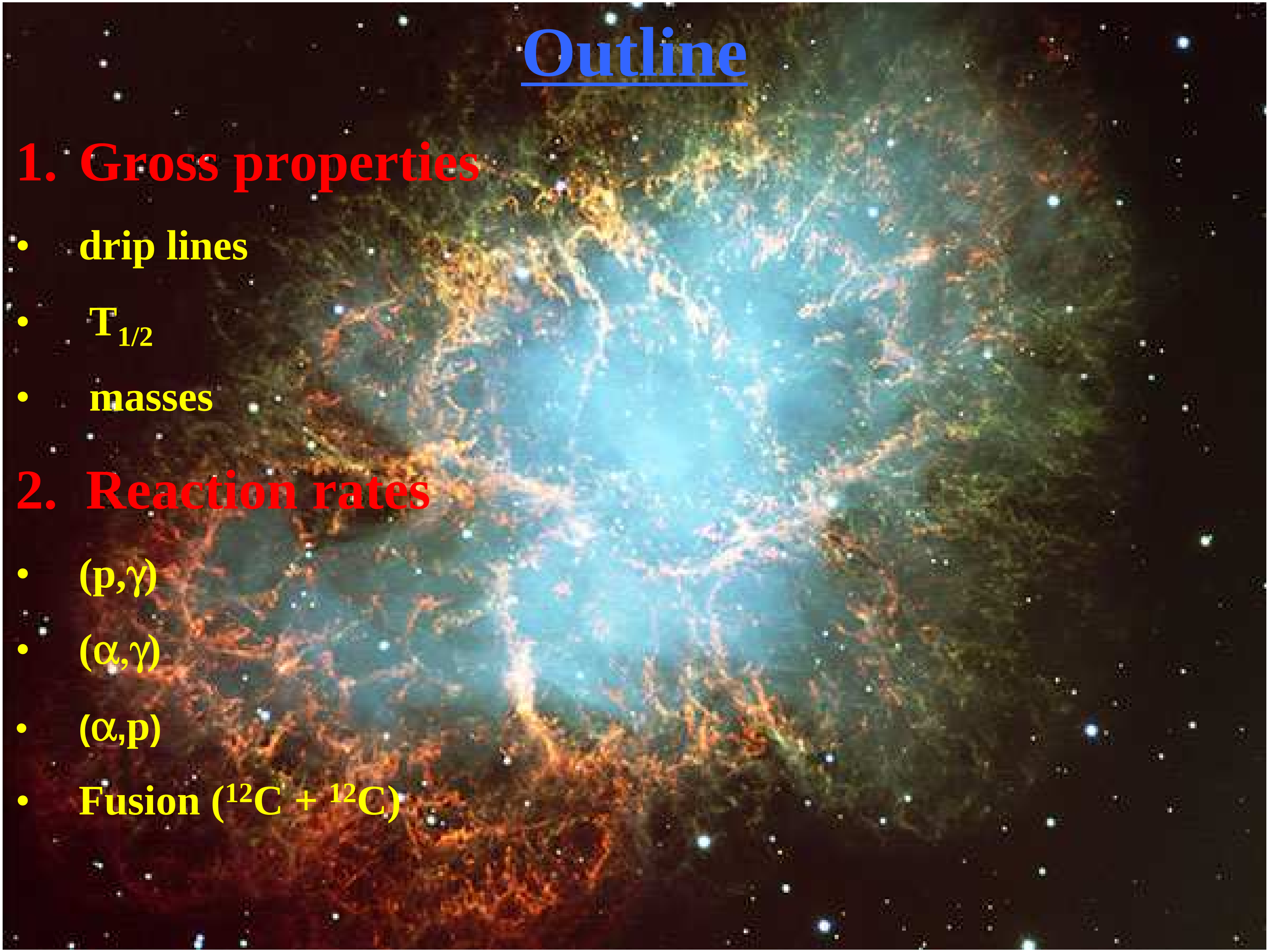


Experiments with radioactive beams:

provide data for explosive burning scenarios:

Need:

- Beams of unstable nuclei (low intensities, contaminants)
- thick targets (to compensate for the intensity)
- long runs



Outline

1. Gross properties

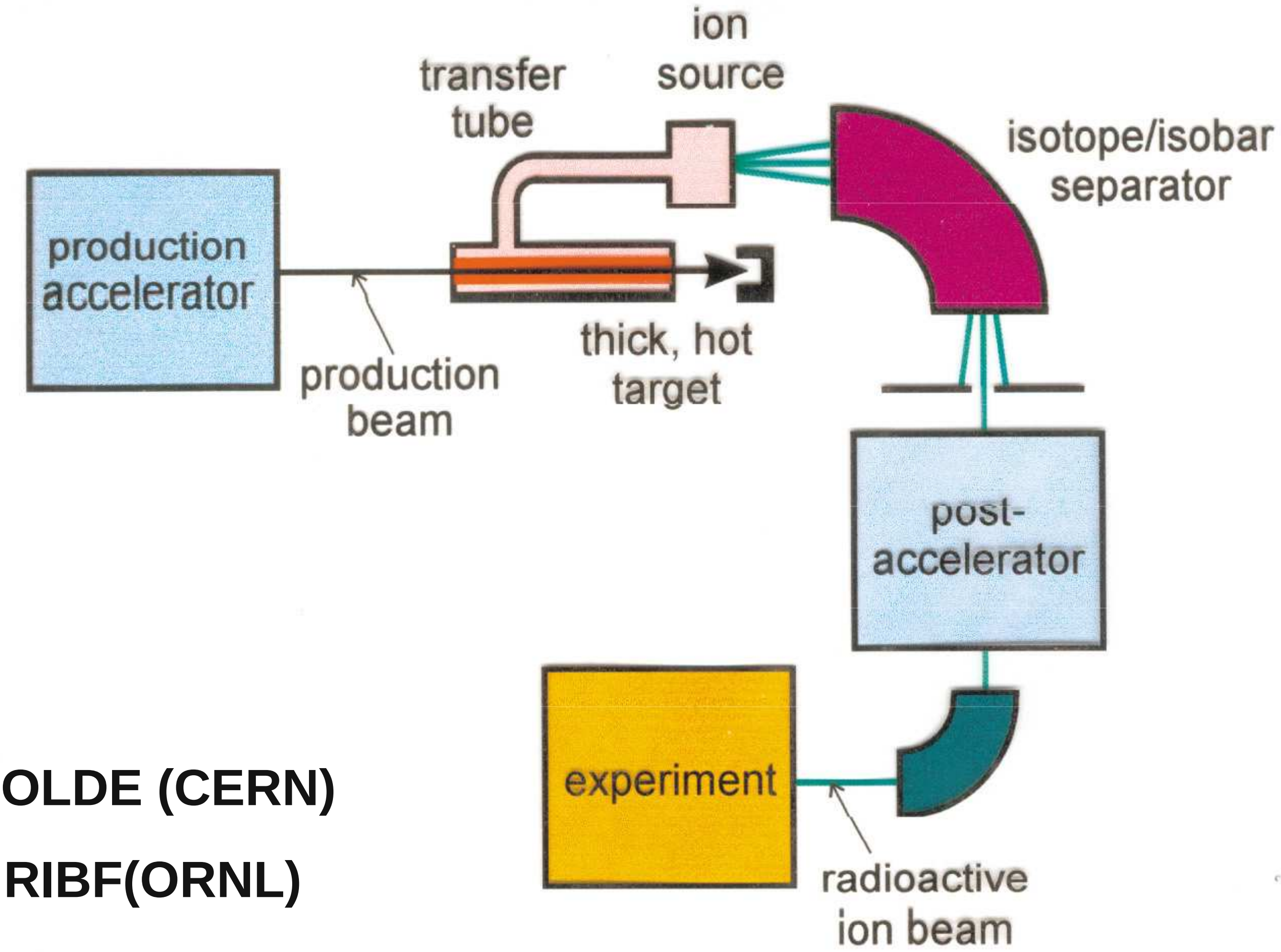
- **drip lines**
- **$T_{1/2}$**
- **masses**

2. Reaction rates

- **(p,γ)**
- **(α,γ)**
- **(α,p)**
- **Fusion ($^{12}C + ^{12}C$)**

Radioactive beam production:

Isotope Separation OnLine (ISOL)



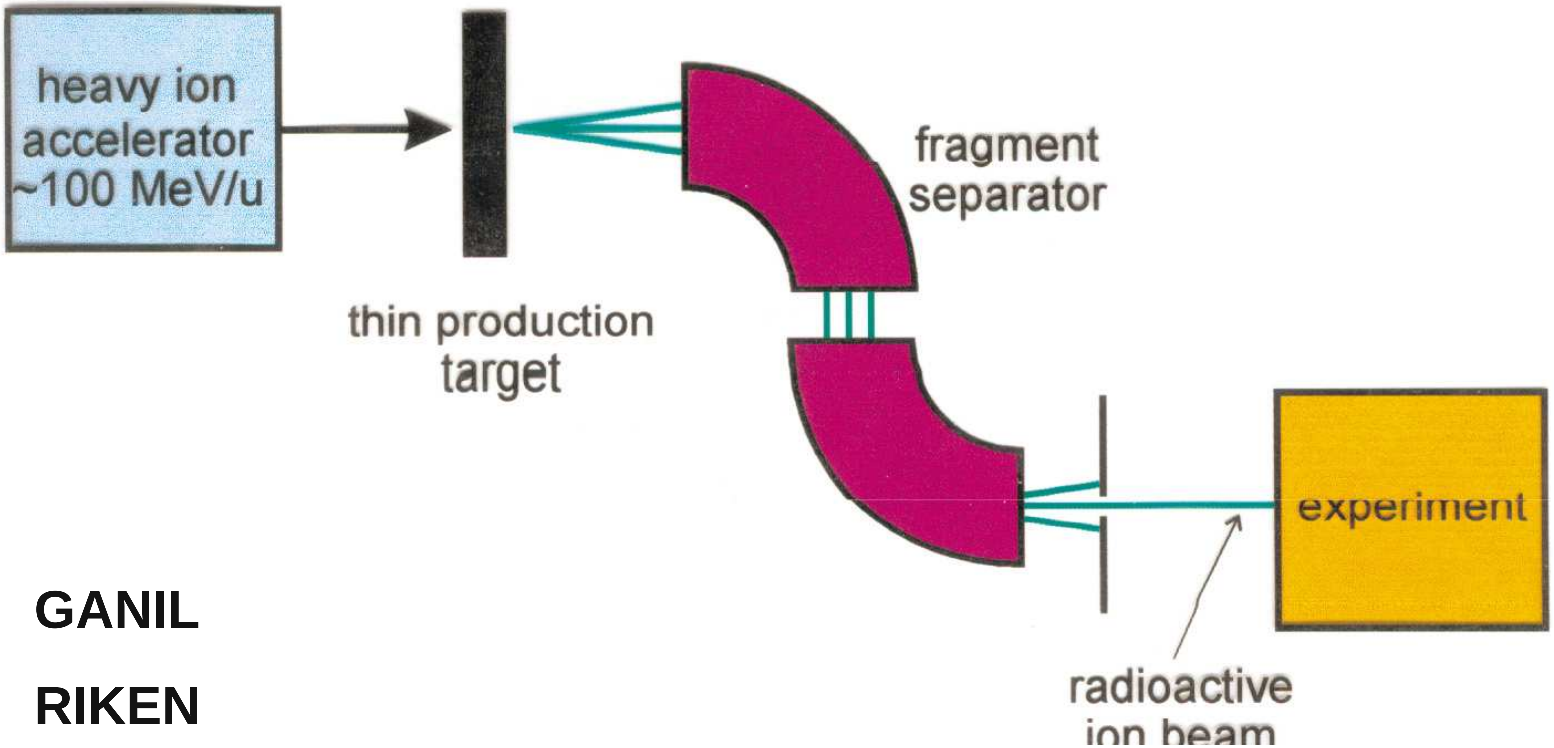
ISOLDE (CERN)

HIRIBF(ORNL)

ISAC(TRIUMF)

Radioactive beam production:

Fragmentation Technique



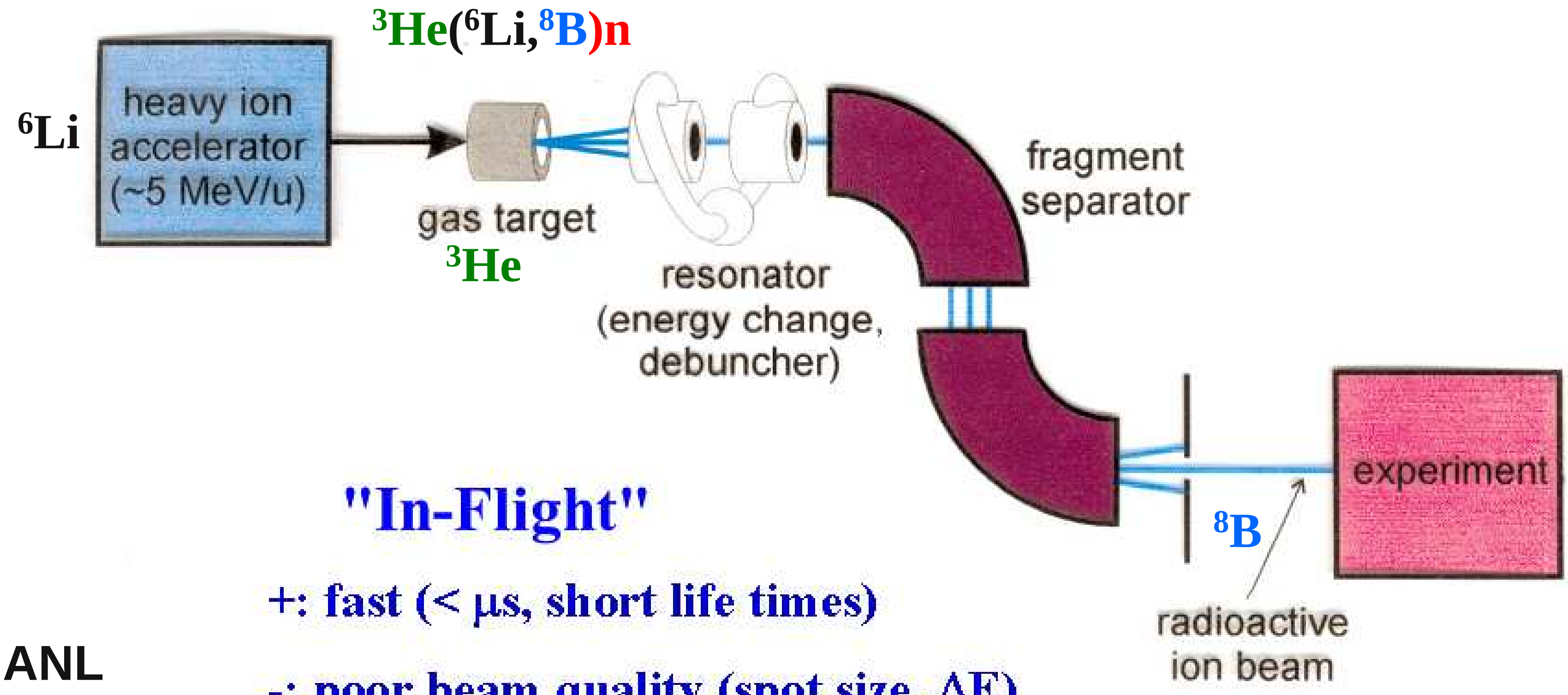
GANIL

RIKEN

GSI

NSCL

Radioactive beam production: In-Flight technique



"In-Flight"

+: fast (< μs, short life times)

-: poor beam quality (spot size, ΔE)

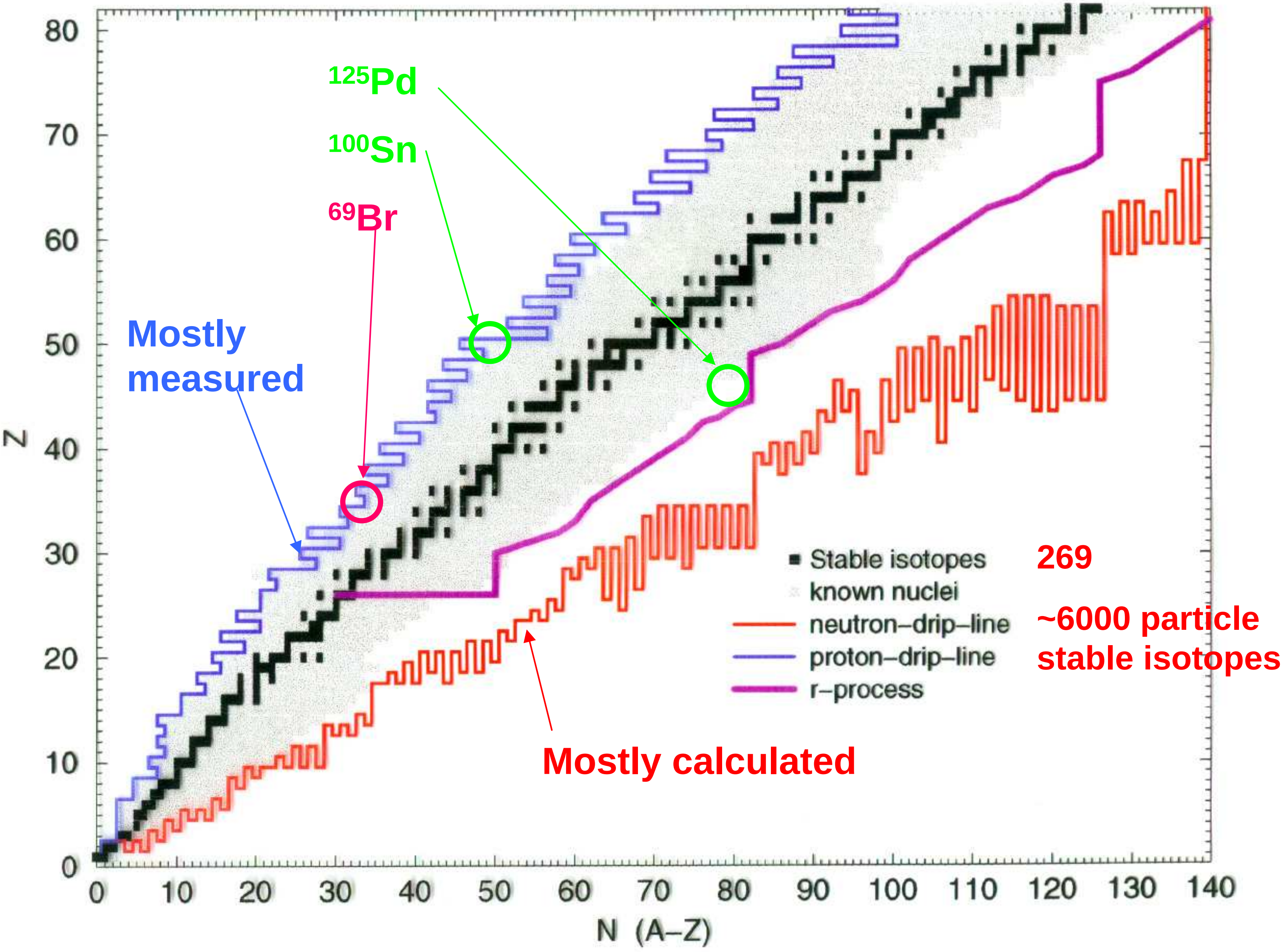
ANL

ND

CRIB

…

The Nuclear Landscape



$^{125}\mathrm{Pd}$

$^{100}\mathrm{Sn}$

$^{69}\mathrm{Br}$

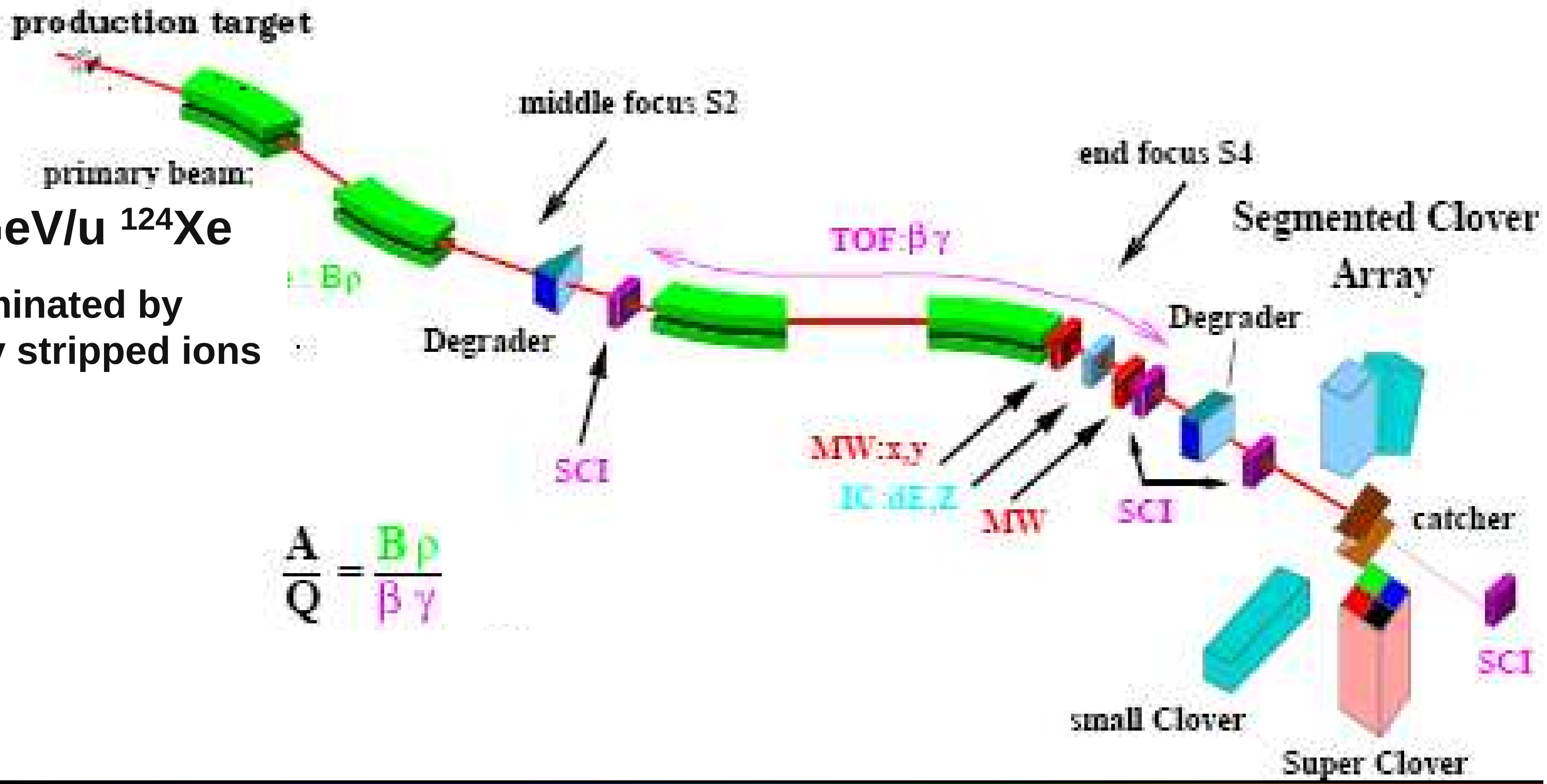
Mostly measured

269

~6000 particle stable isotopes

Mostly calculated

Radioactive beam production at GSI

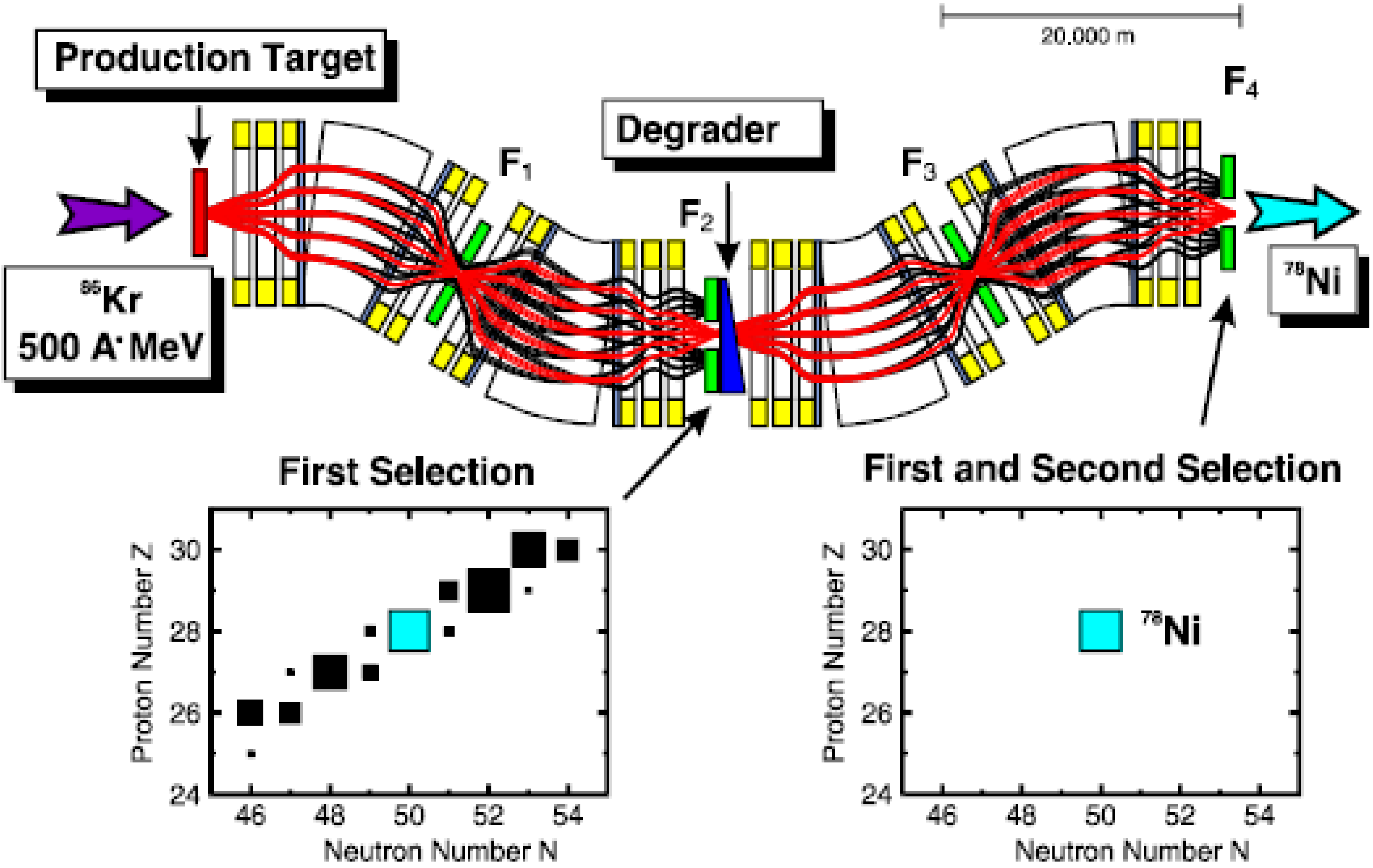


$$\frac{A}{Q} = \frac{B\rho}{\beta\gamma}$$

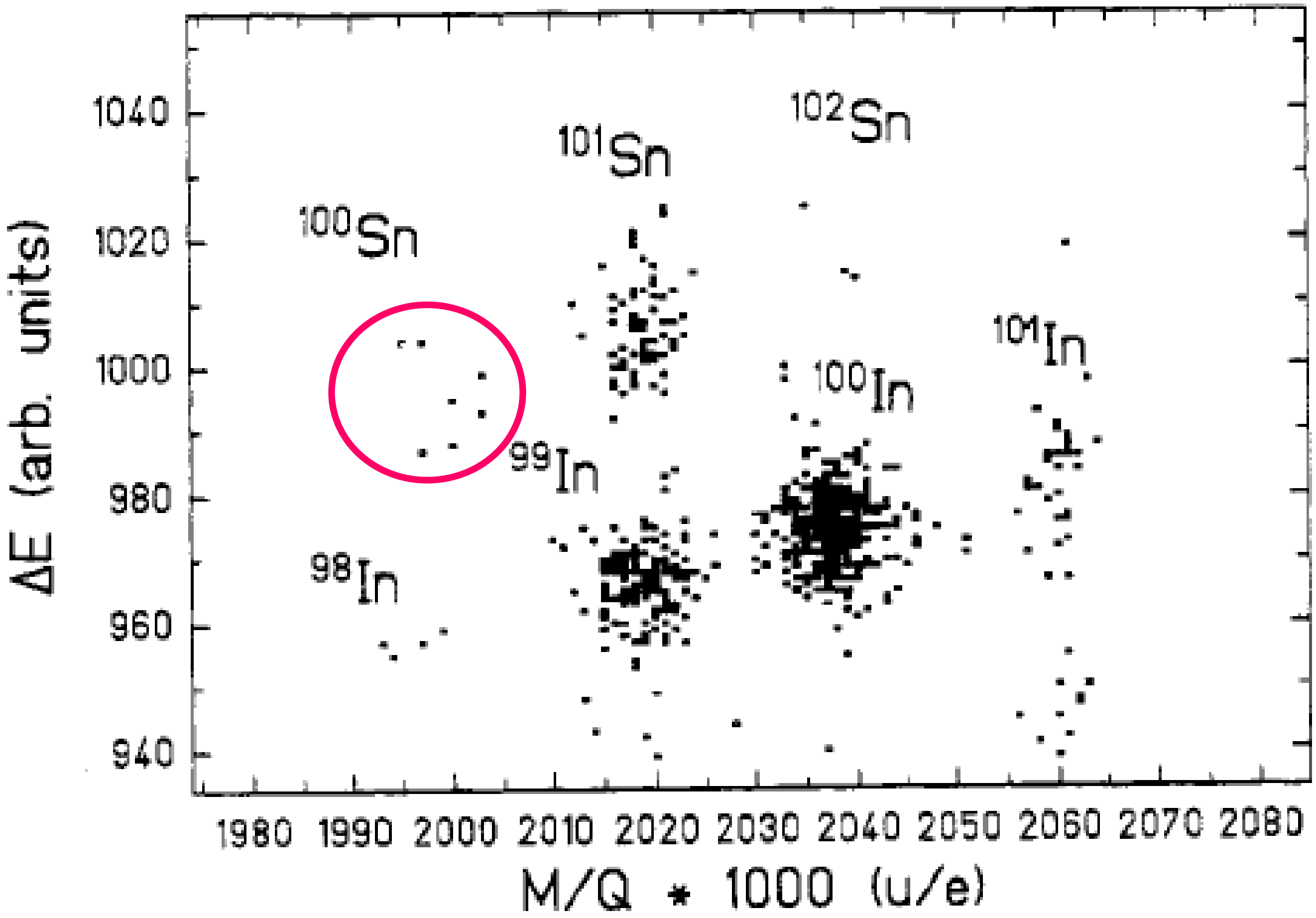
1 GeV/u ^{124}Xe

Dominated by fully stripped ions

$B\rho$ - ΔE - $B\rho$ Separation Method

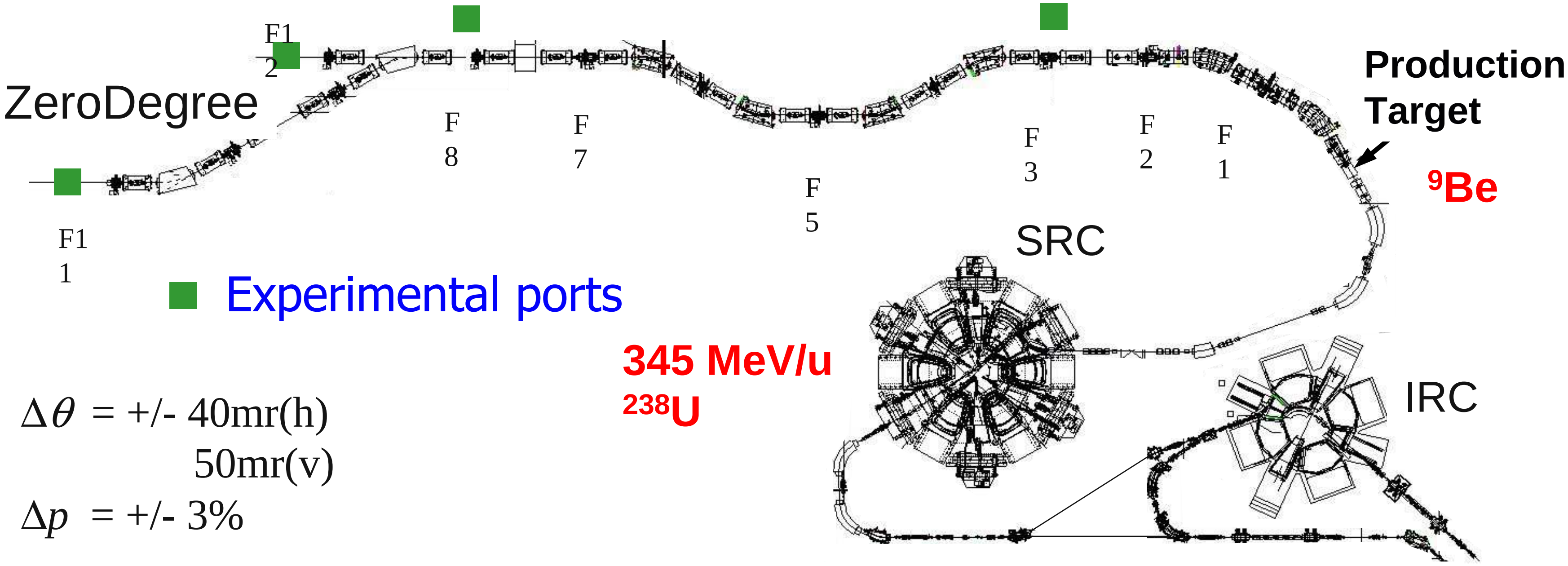


First detection of the N=Z nucleus ^{100}Sn



R. Schneider et al., Phys. Scr. T56, 67(1995)

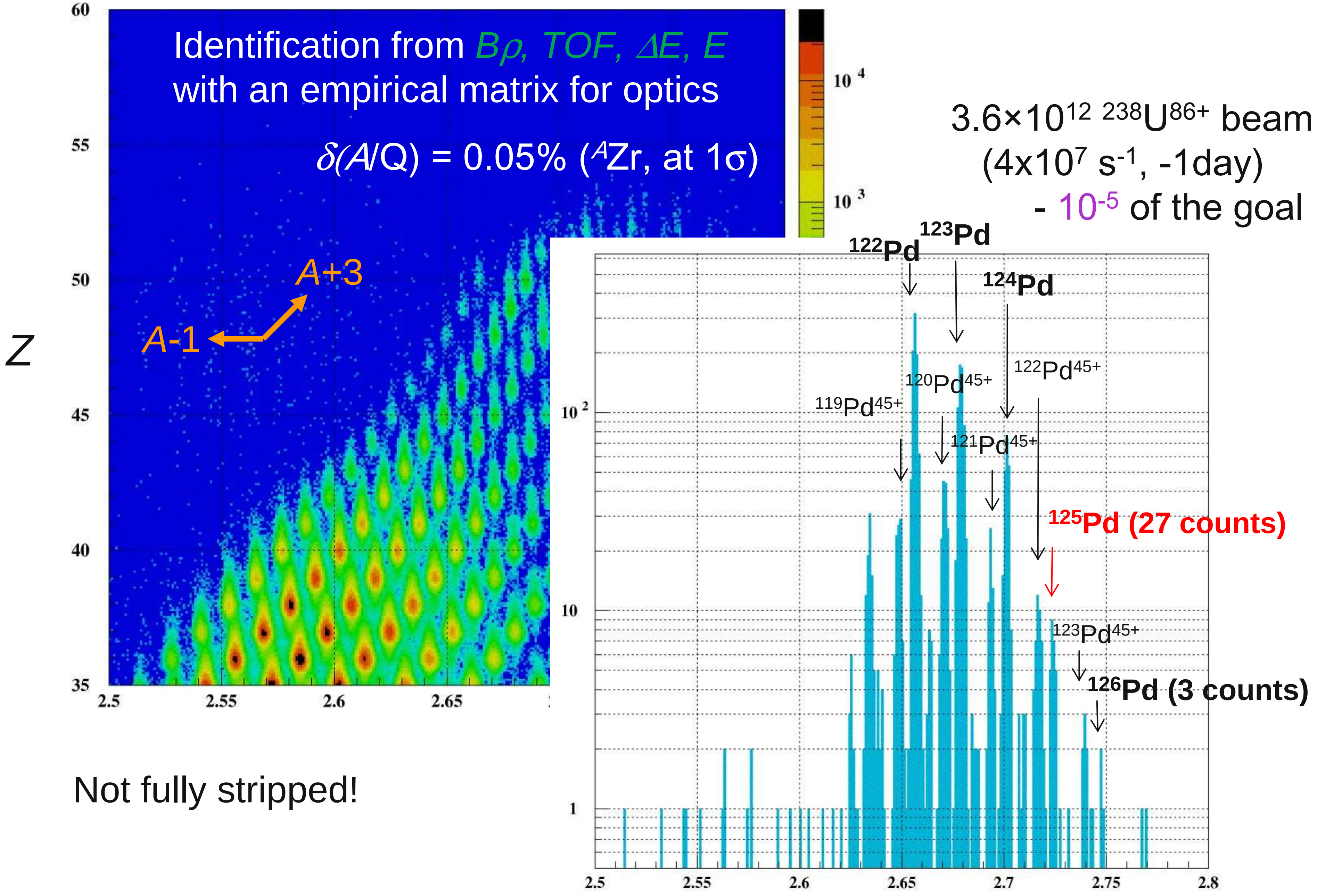
Radioactive beam production at RIKEN



🟩 Experimental ports

$\Delta\theta$ = +/- 40mr(h)
50mr(v)

Δp = +/- 3%



Identification from $B\rho$, TOF, ΔE, E
with an empirical matrix for optics

$\delta(A/Q) = 0.05\%$ (^{A}Zr, at 1σ)

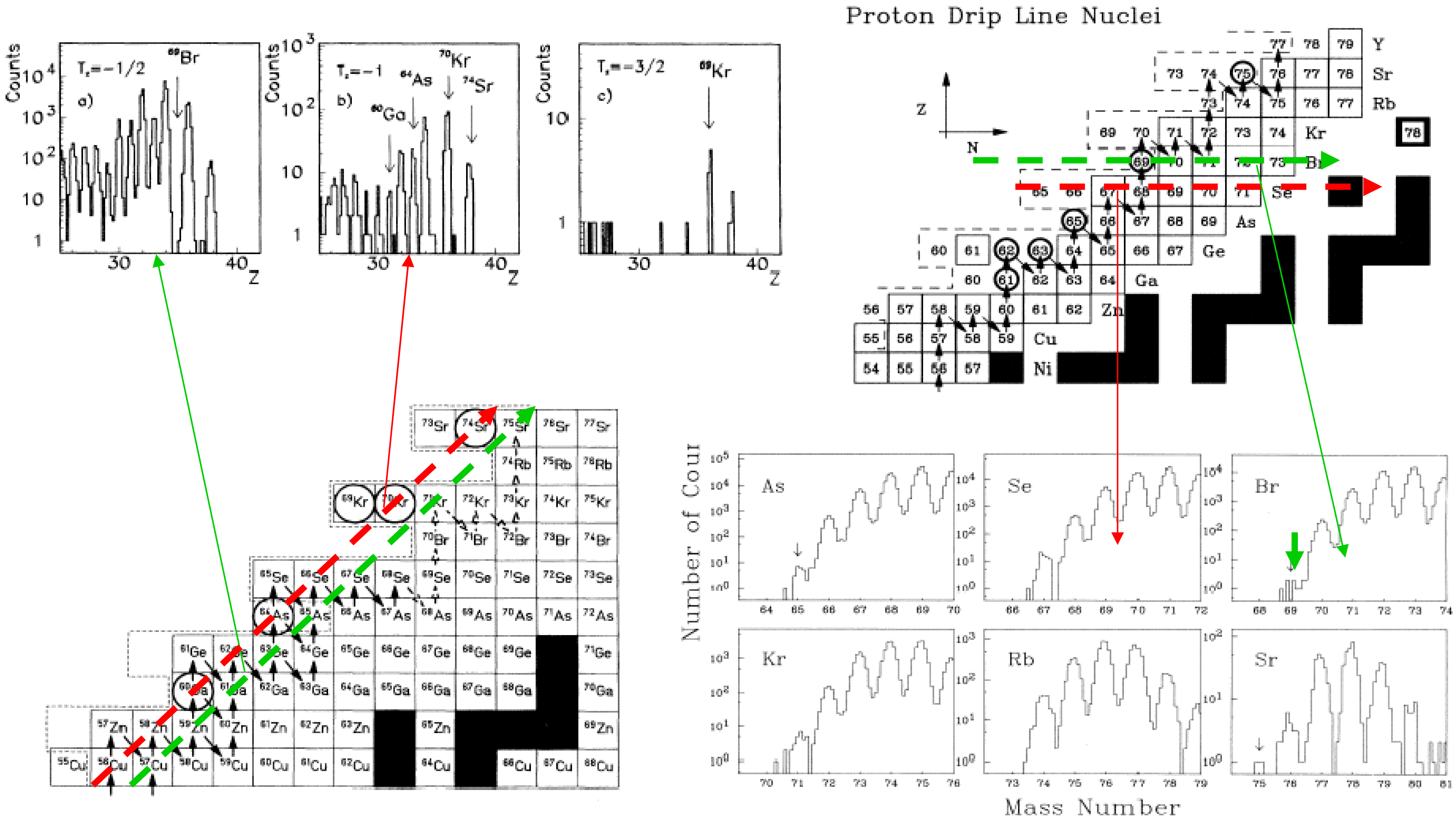
3.6×10^{12} $^{238}U^{86+}$ beam
($4\text{x}10^{7}$ s^{-1}, -1day)
- 10^{-5} of the goal

^{125}Pd (27 counts)

^{126}Pd (3 counts)

Not fully stripped!

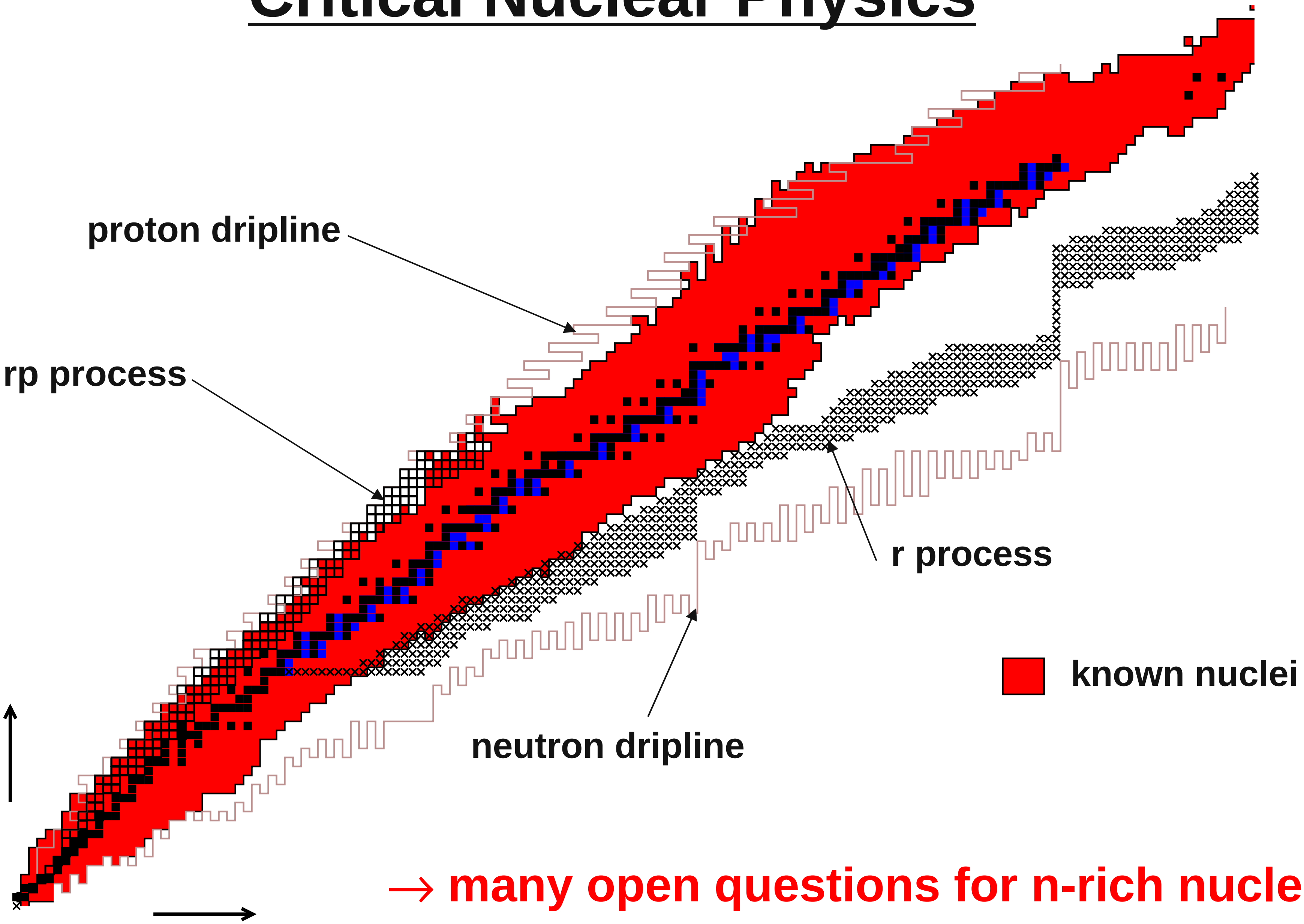
Caveat: Existence/non-existence: ^{69}Br



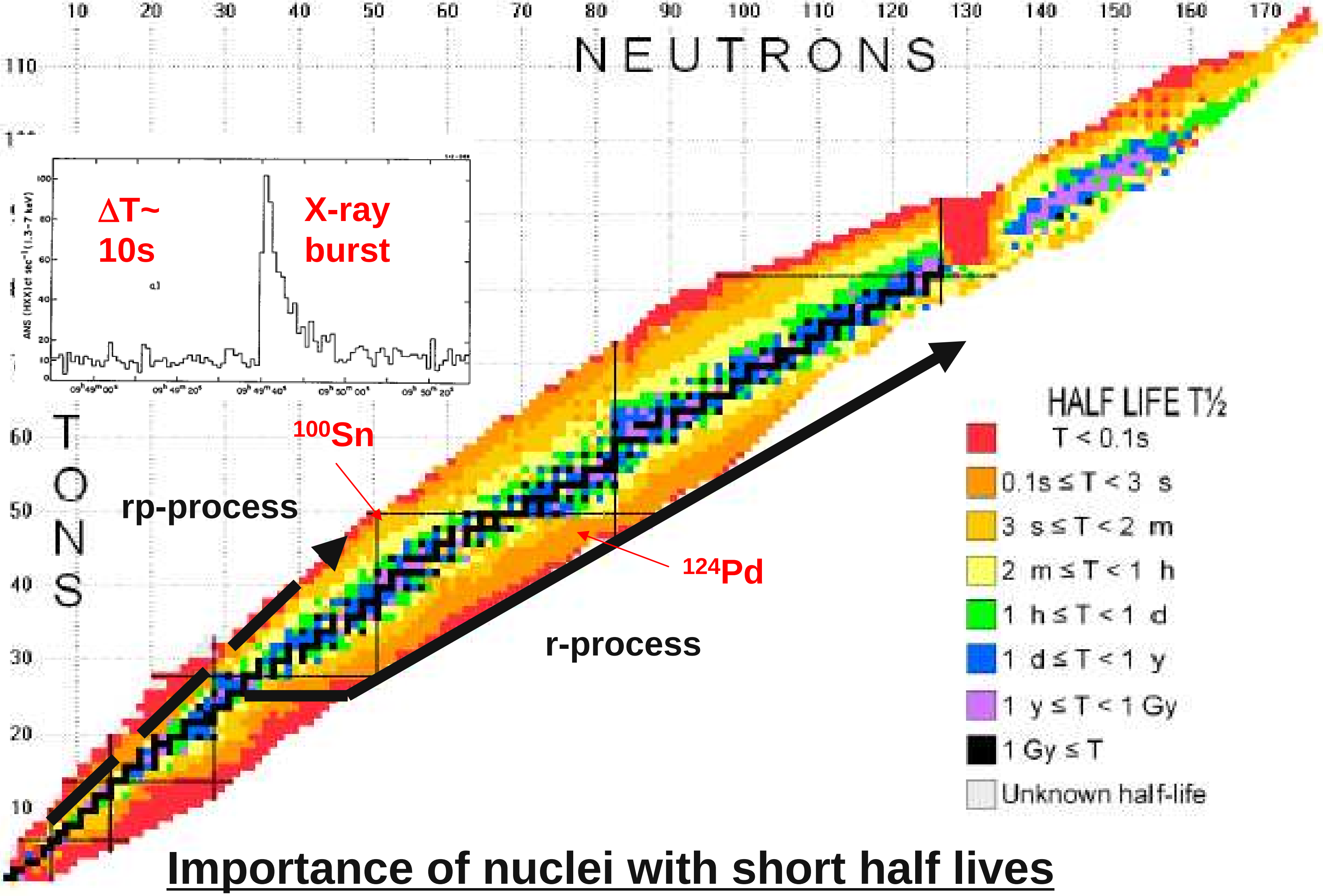
B. Blank et al. PRL 74,4611(1995)

M. F. Mohar et al, PRL66,1571(1991)

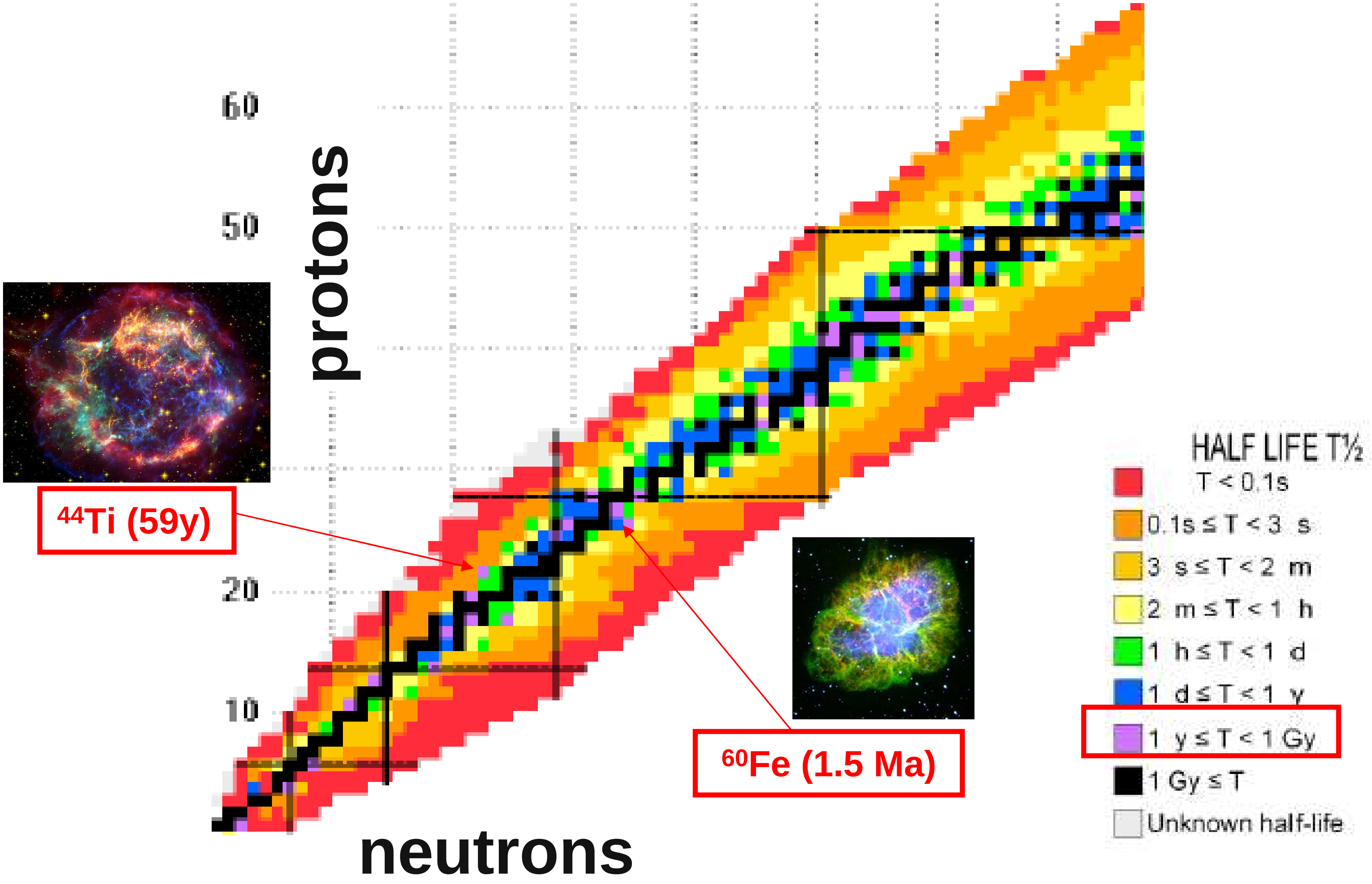
Critical Nuclear Physics



→ many open questions for n-rich nuclei



Importance of nuclei with short half lives



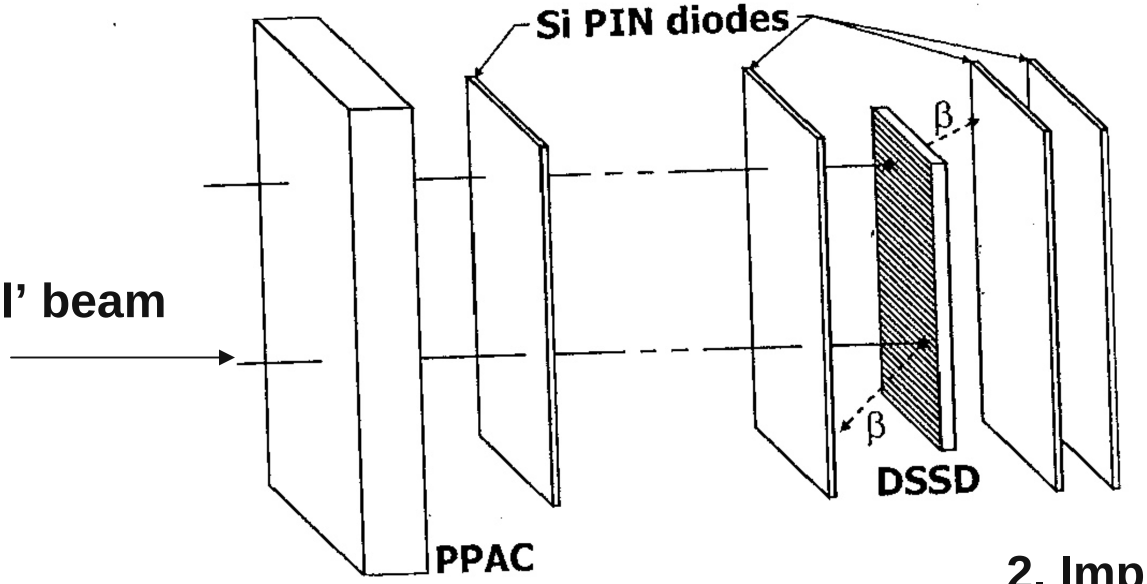
^{44}Ti (59y)

^{60}Fe (1.5 Ma)

Importance of nuclei with long half lives

Principle of Half-life Measurements

‘cocktail’ beam



2. Implantation

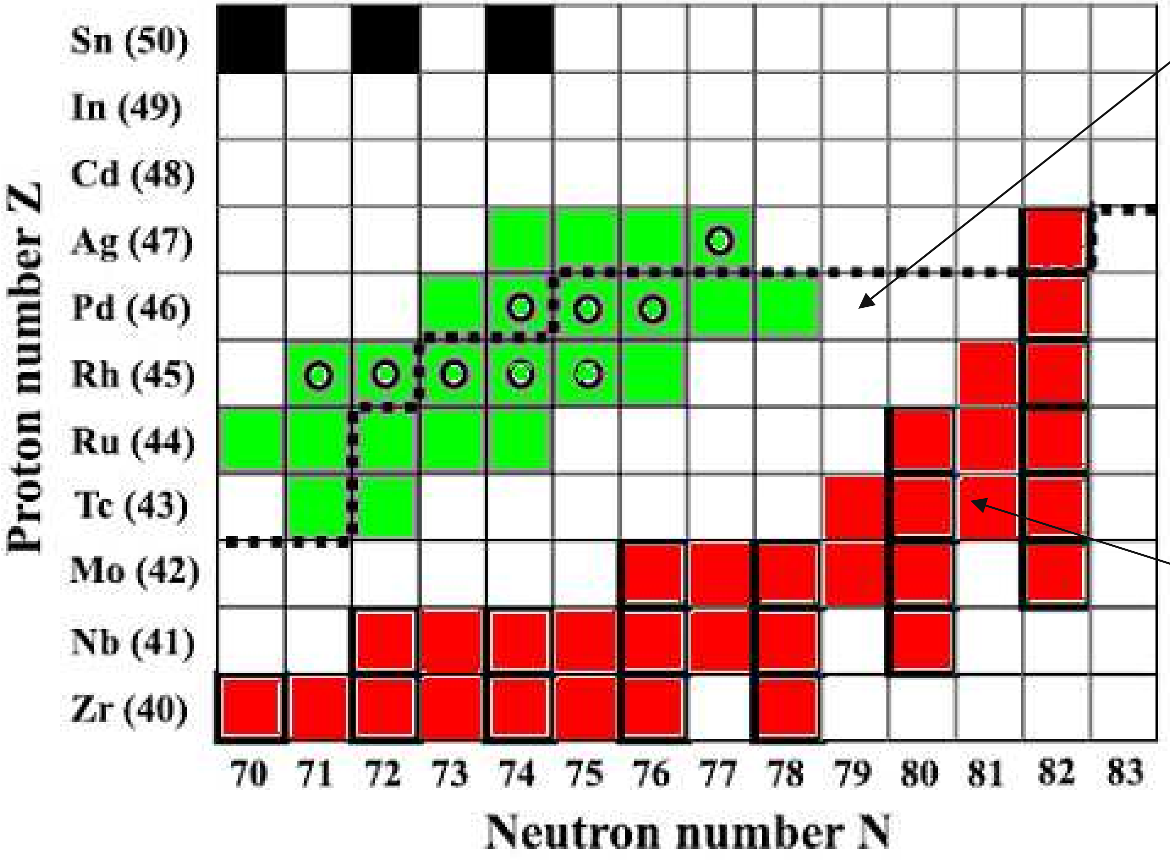
1. Particle identification
t=0

3. Detection of β-decay

$t = t_\beta$

J. J. Prisciandaro et al. NIMA 505, 140(2003)

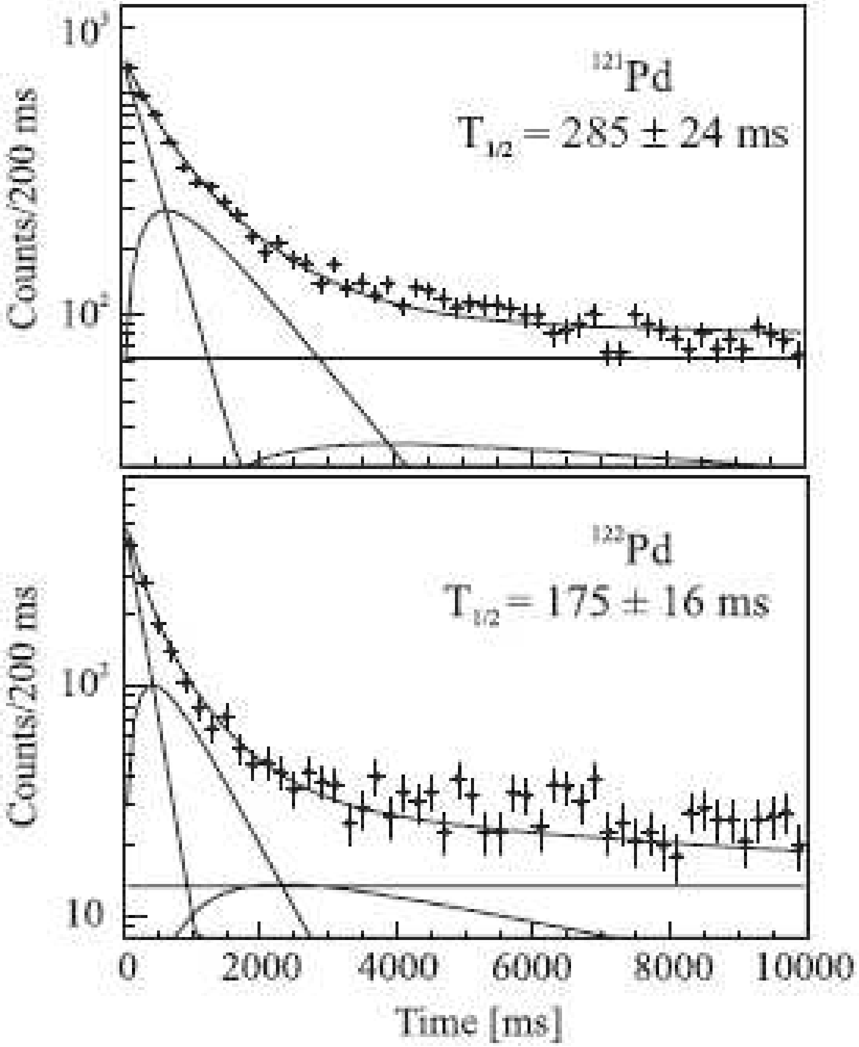
Example 2: n-rich Pd nuclei



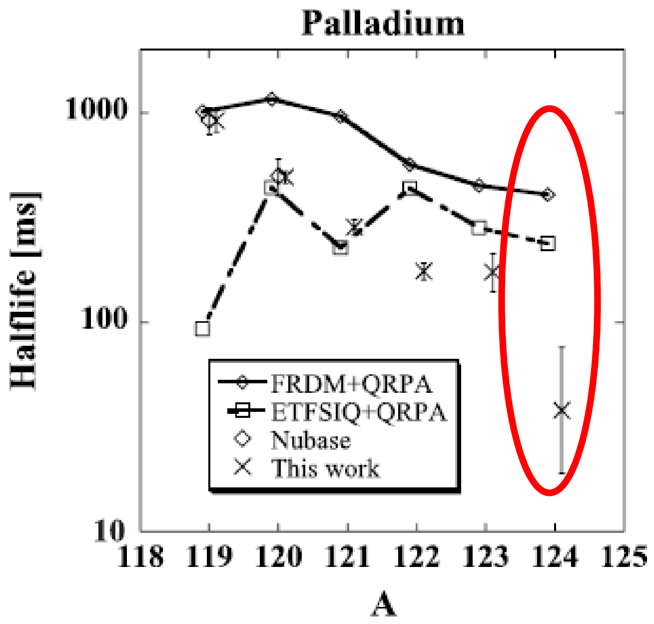
^{125}Pd
RIKEN

r-process
path

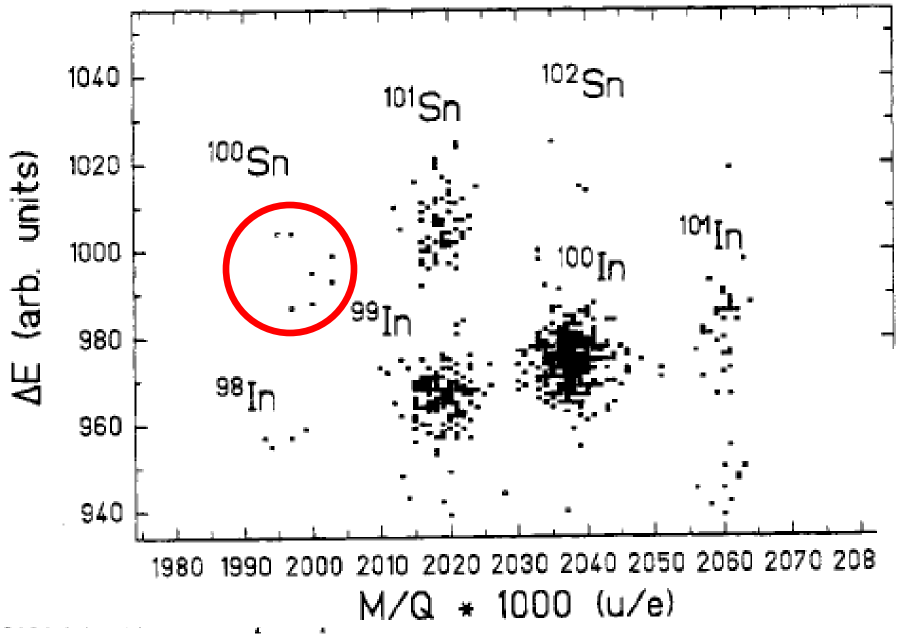
F. Montes et al. PRC73, 035801(2006)



	Events	$T_{1/2}$(ms)
^{120}Pd	8802	492(33)
^{121}Pd	11646	285(24)
^{122}Pd	2626	175(16)
^{123}Pd	293	174^{38}_{34}
^{124}Pd	30	38^{38}_{19}

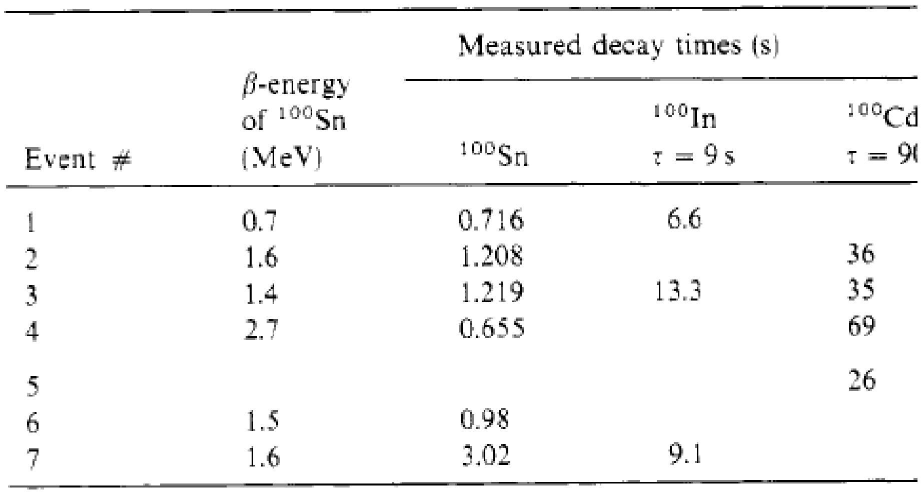


Example: ^{100}Sn $T_{1/2}$=0.94s

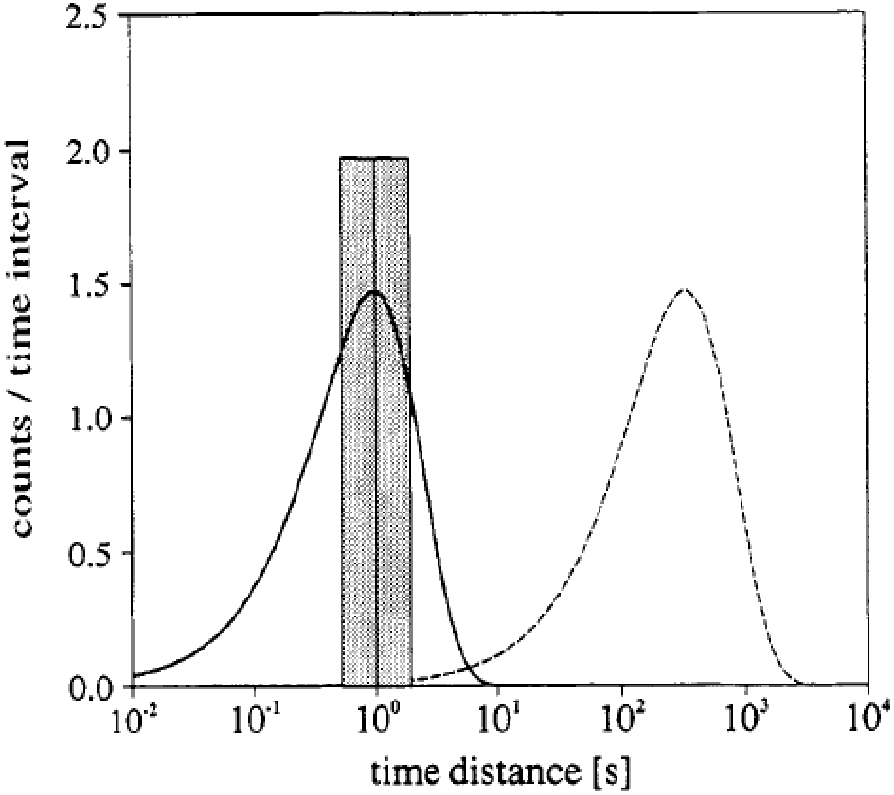


R. Schneider et al.

Phys. Scr. T56, 67 (1995)



		Measured decay times (s)		
Event #	β-energy of ^{100}Sn (MeV)	^{100}Sn	^{100}In $\tau = 9$ s	^{100}Cd $\tau = 9$
1	0.7	0.716	6.6	
2	1.6	1.208		36
3	1.4	1.219	13.3	35
4	2.7	0.655		69
5				26
6	1.5	0.98		
7	1.6	3.02	9.1	



Measurement of very long half lives: ^{60}Fe ($T_{1/2}$~1.5 Ma)

Principle:

1. Produce ^{60}Fe (e.g. in a beam stop of an accelerator) ($N \sim 10^{15}$ atoms).
2. Measure the activity of the sample.
3. Calculate (Roy and Kohman, Can. J. Phys. 35, 649(1957) or
4. Measure (Kutschera et al., NIMB5, 430(1984)) the number of atoms produced.
5. Use the relation $A(t)= \lambda N(t)$.

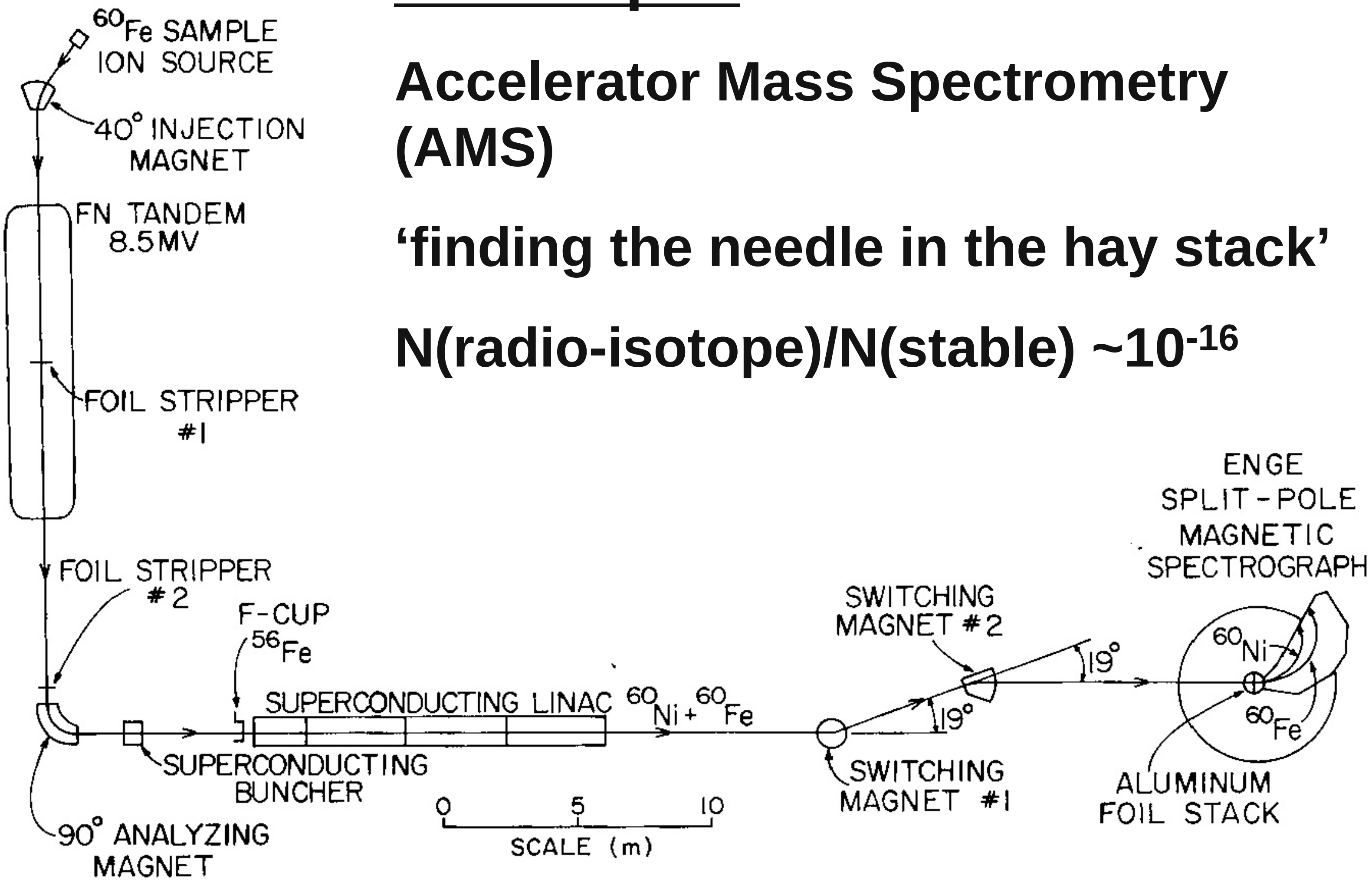
Measuring the number of atoms:

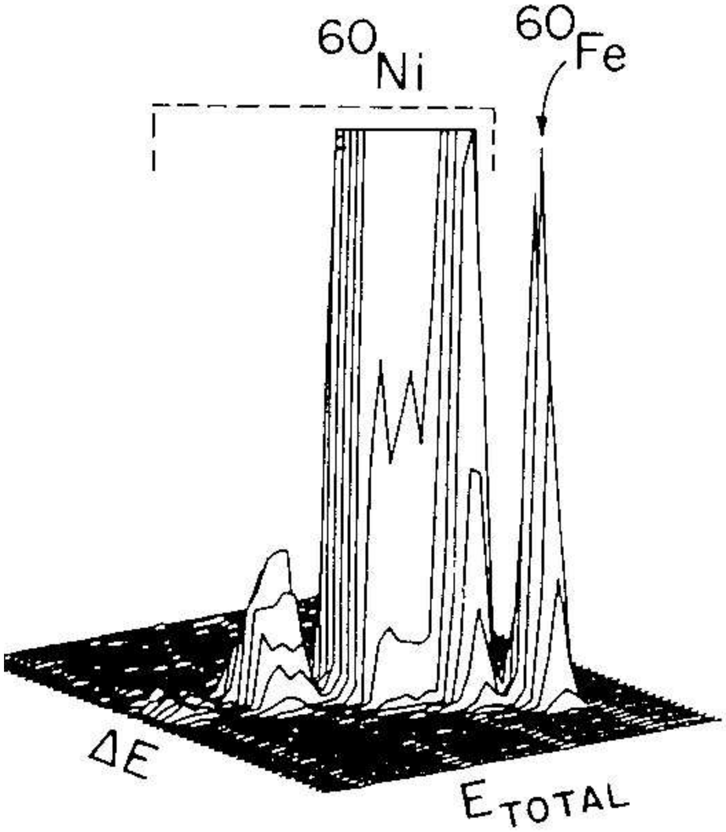
Technique:

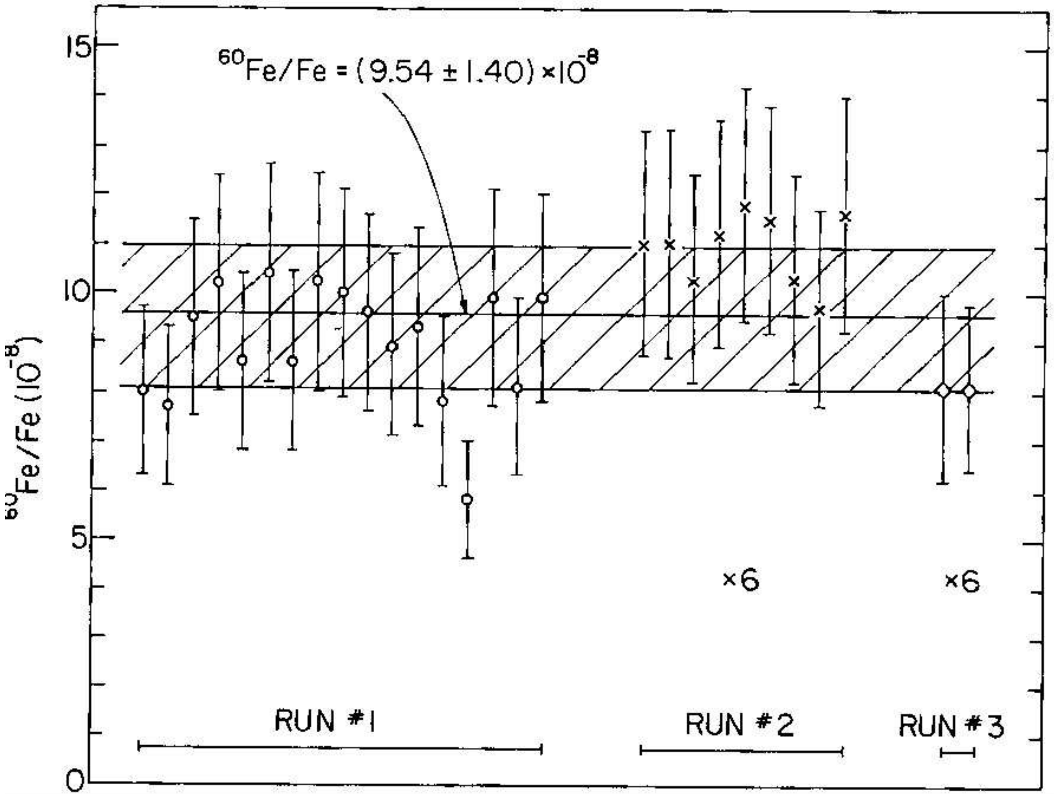
Accelerator Mass Spectrometry (AMS)

‘finding the needle in the hay stack’

N(radio-isotope)/N(stable) ~10^{-16}





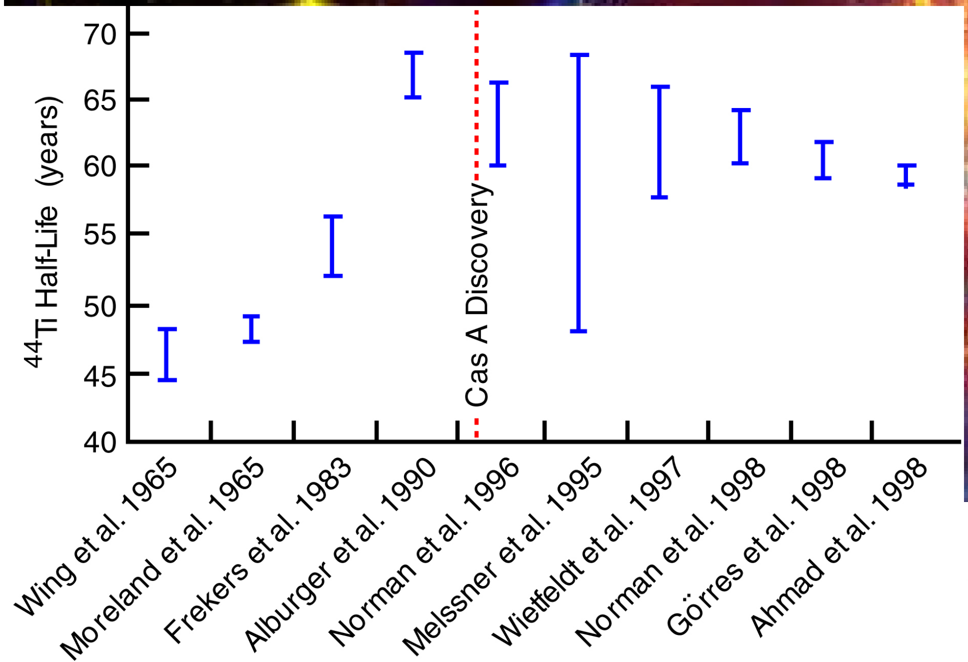


^{60}Fe and ^{60}Ni are detected in the ionization chamber of a magnetic spectrograph. E(Fe) ~ 300 MeV

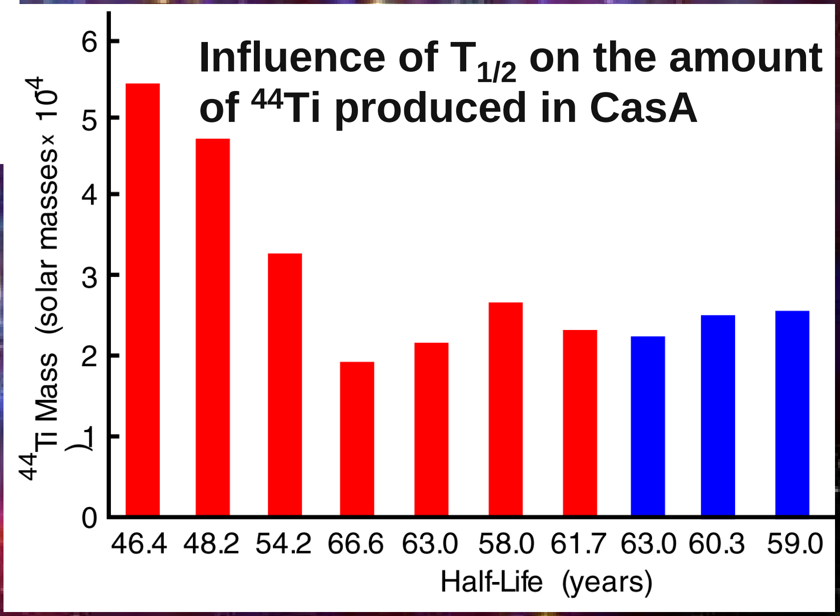
Absolute measurement! Check systematic errors.

$T_{1/2}(^{60}\text{Fe})$=1.5±0.27 Ma (was 0.3 Ma before)

Measurement of intermediate half-lifes: ^{44}Ti ($T_{1/2}$~60 years)

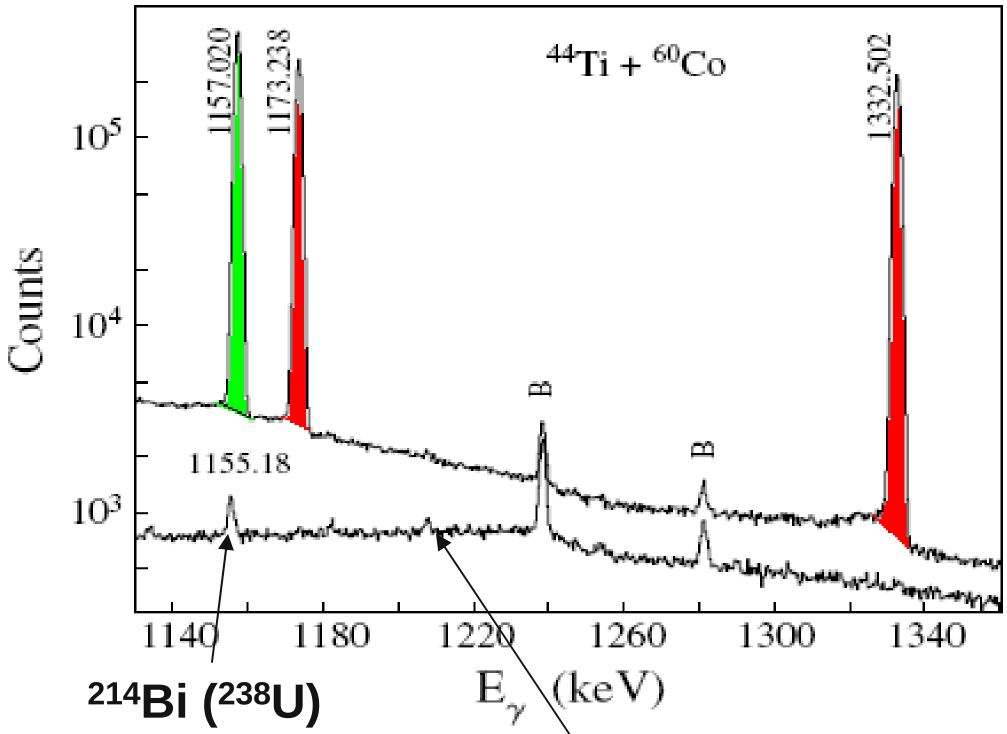


$T_{1/2}$(^{44}Ti) measurements


Influence of $T_{1/2}$ on the amount of ^{44}Ti produced in CasA

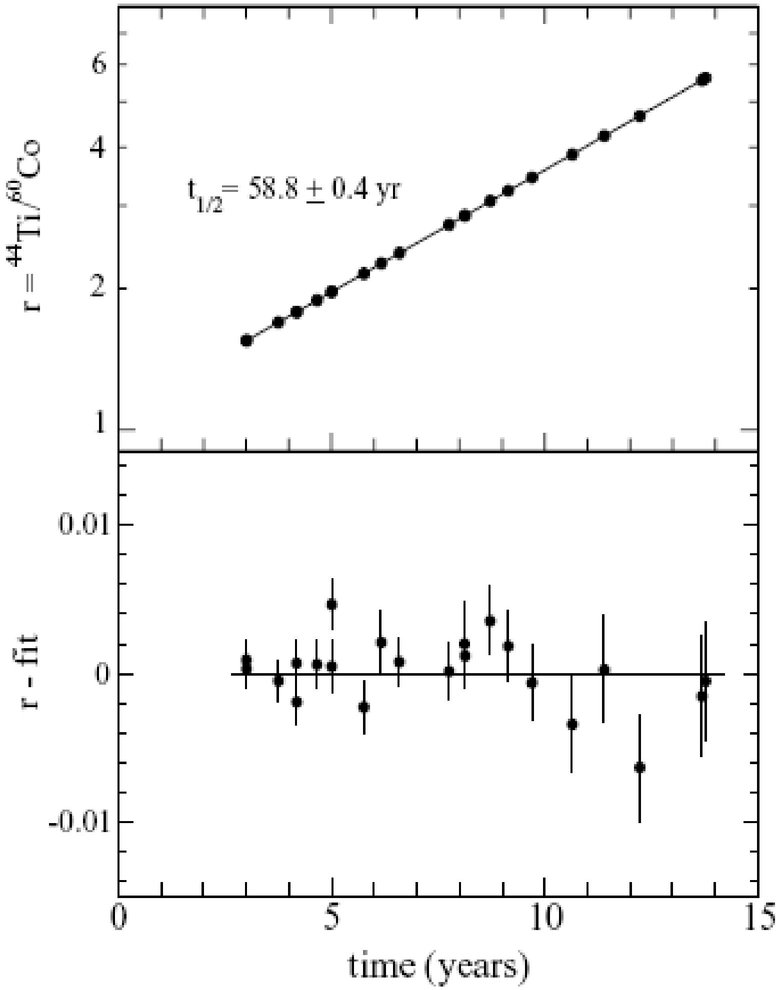
I. Ahmad et al. PRC74, 065803 (2006)

Relative measurement ^{44}Ti-^{60}Co



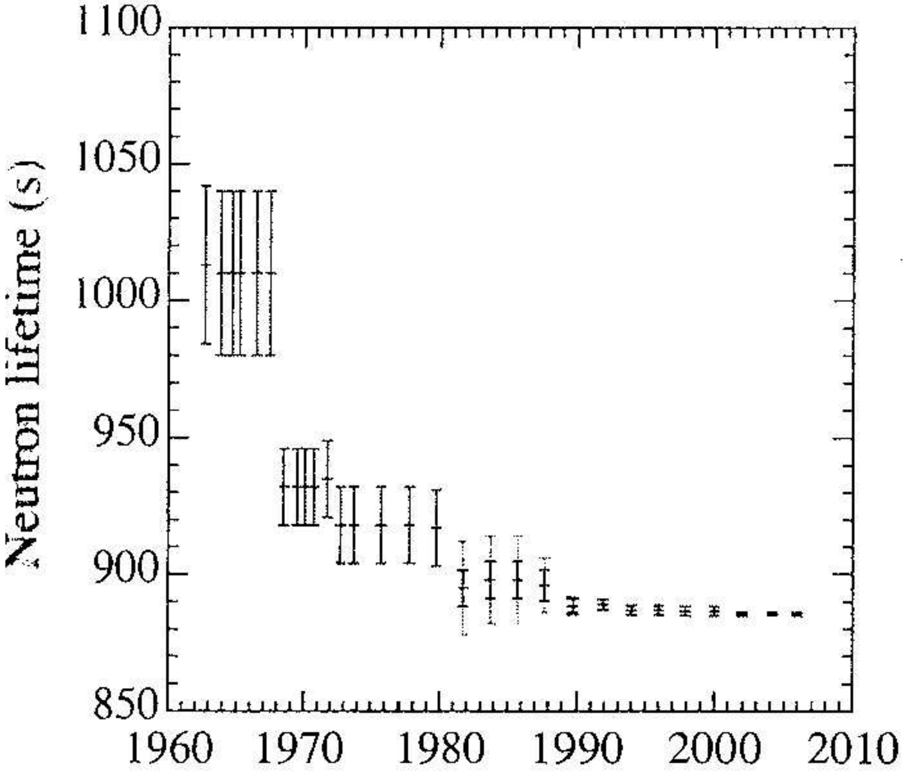
^{214}Bi (^{238}U)

Room background

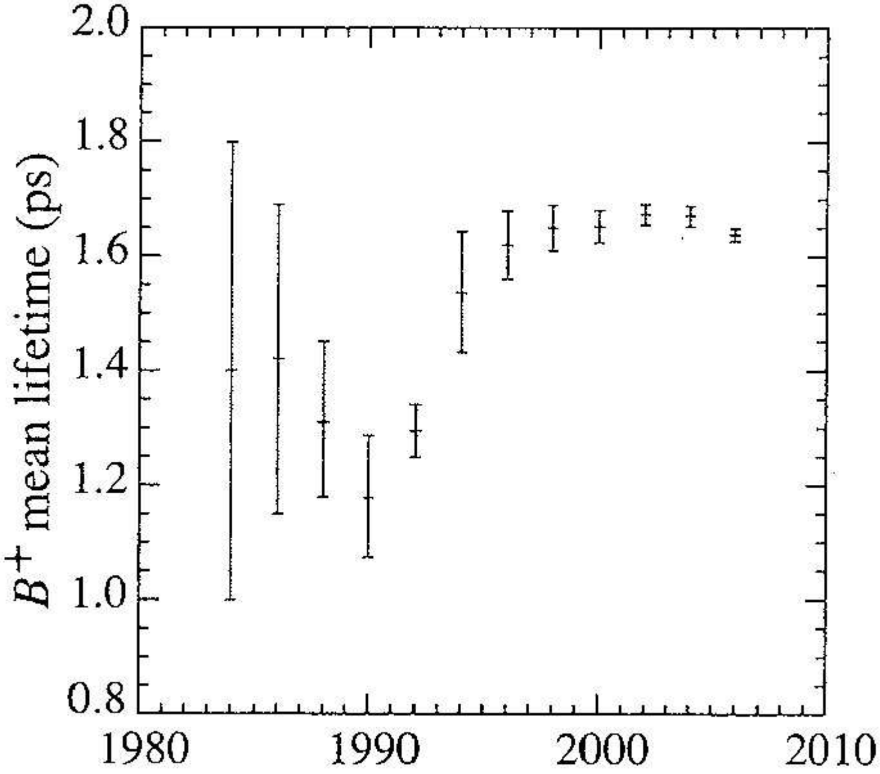


$T_{1/2}(^{44}\text{Ti})=58.8\pm0.4$ y

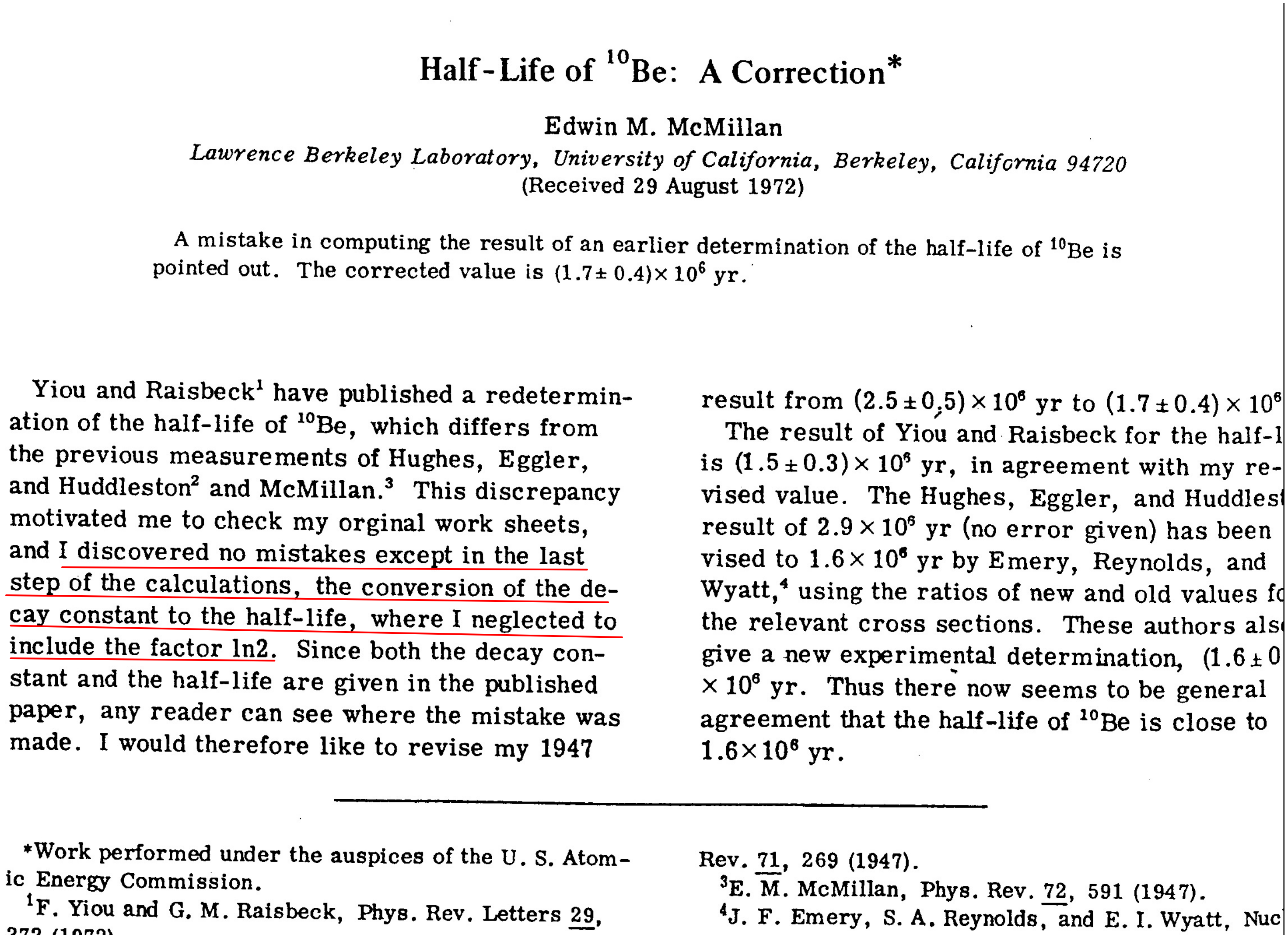
Caveat: beware of the systematic errors!



(from Particle Data Group)



The difference between half-life and mean life:



Half-Life of ^{10}Be: A Correction*

Edwin M. McMillan
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

(Received 29 August 1972)

A mistake in computing the result of an earlier determination of the half-life of ^{10}Be is pointed out. The corrected value is $(1.7 \pm 0.4) \times 10^6$ yr.

Yiou and Raisbeck[1] have published a redetermination of the half-life of ^{10}Be, which differs from the previous measurements of Hughes, Eggler, and Huddleston[2] and McMillan.[3] This discrepancy motivated me to check my orginal work sheets, and I discovered no mistakes except in the last step of the calculations, the conversion of the decay constant to the half-life, where I neglected to include the factor ln2. Since both the decay constant and the half-life are given in the published paper, any reader can see where the mistake was made. I would therefore like to revise my 1947 result from $(2.5 \pm 0.5) \times 10^6$ yr to $(1.7 \pm 0.4) \times 10^6$

The result of Yiou and Raisbeck for the half-l is $(1.5 \pm 0.3) \times 10^6$ yr, in agreement with my revised value. The Hughes, Eggler, and Huddles result of 2.9×10^6 yr (no error given) has been vised to 1.6×10^6 yr by Emery, Reynolds, and Wyatt,[4] using the ratios of new and old values f the relevant cross sections. These authors als give a new experimental determination, (1.6 ± 0 $\times 10^6$ yr. Thus there now seems to be general agreement that the half-life of ^{10}Be is close to 1.6×10^6 yr.

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*Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] F. Yiou and G. M. Raisbeck, Phys. Rev. Letters 29, 372 (1972).

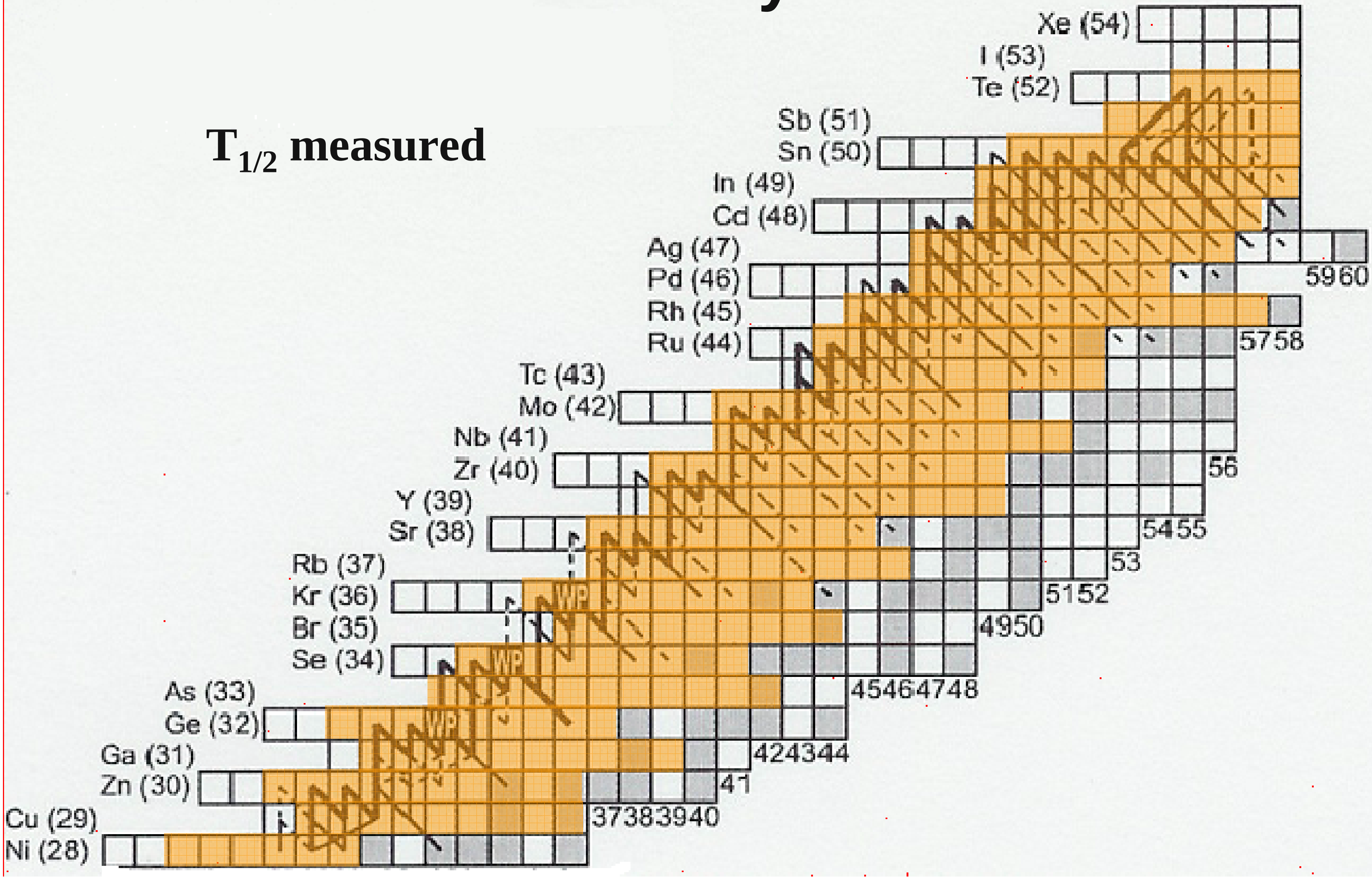
Rev. 71, 269 (1947).

[3] E. M. McMillan, Phys. Rev. 72, 591 (1947).

[4] J. F. Emery, S. A. Reynolds, and E. I. Wyatt, Nuc

Critical Nuclear Physics

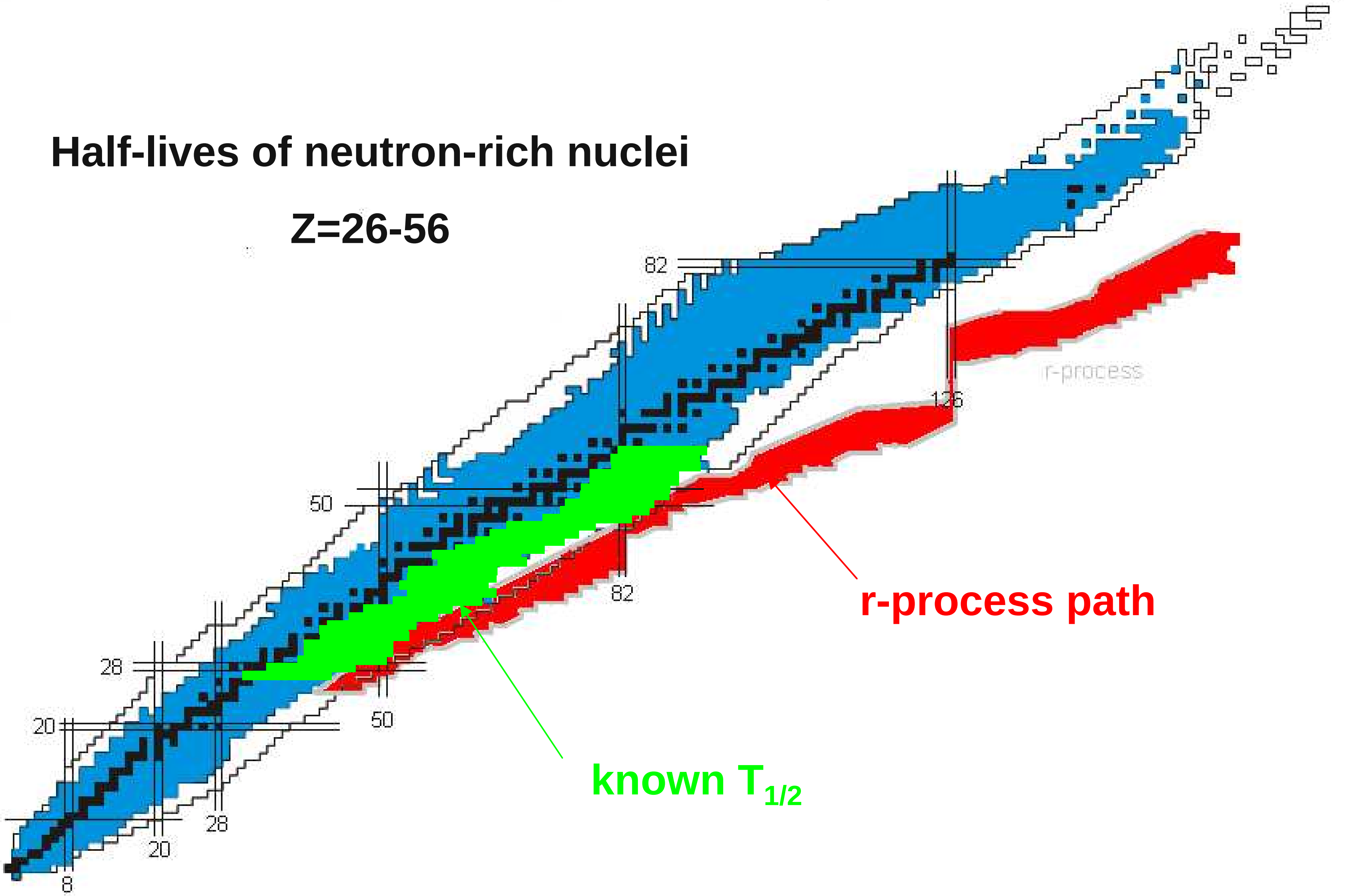
$T_{1/2}$ measured



Critical Nuclear Physics

Half-lives of neutron-rich nuclei

Z=26-56



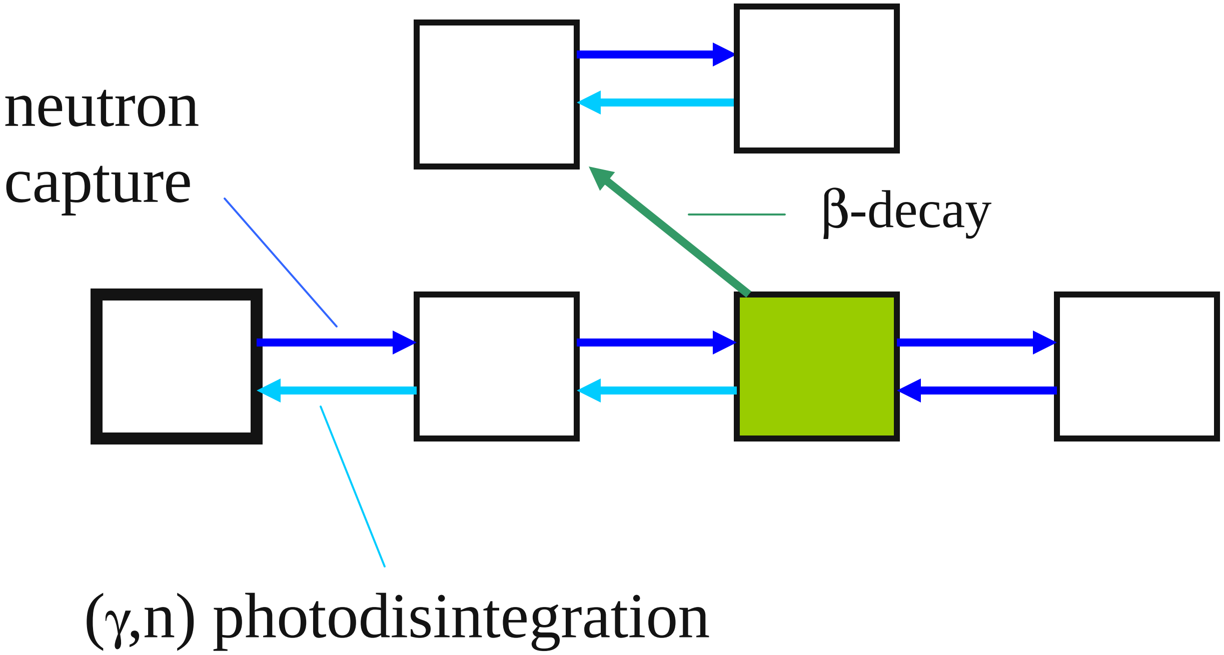
r-process path

known $T_{1/2}$

Mass Measurements

Why do we need masses?

- Needed to determine the driplines
- Needed to determine the half-lives
- Needed to determine the path of the r-process



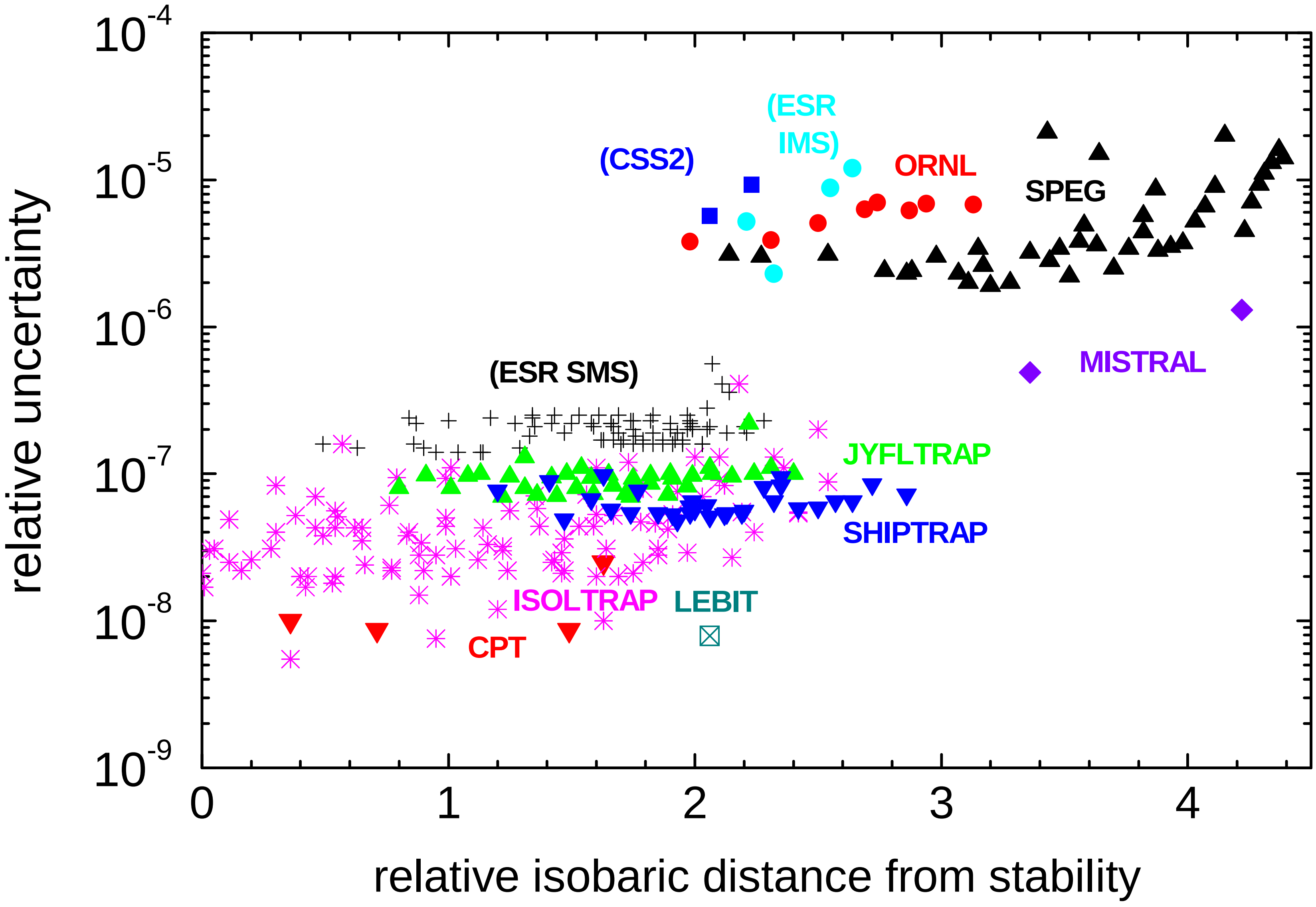
$$\frac{Y(Z,A+1)}{Y(Z,A)} = n_n \frac{G(Z,A+1)}{2G(Z,A)} \left[\frac{A+1}{A} \frac{2\pi\hbar^2}{m_u kT} \right]^{3/2} \exp(S_n / kT)$$

Saha equation

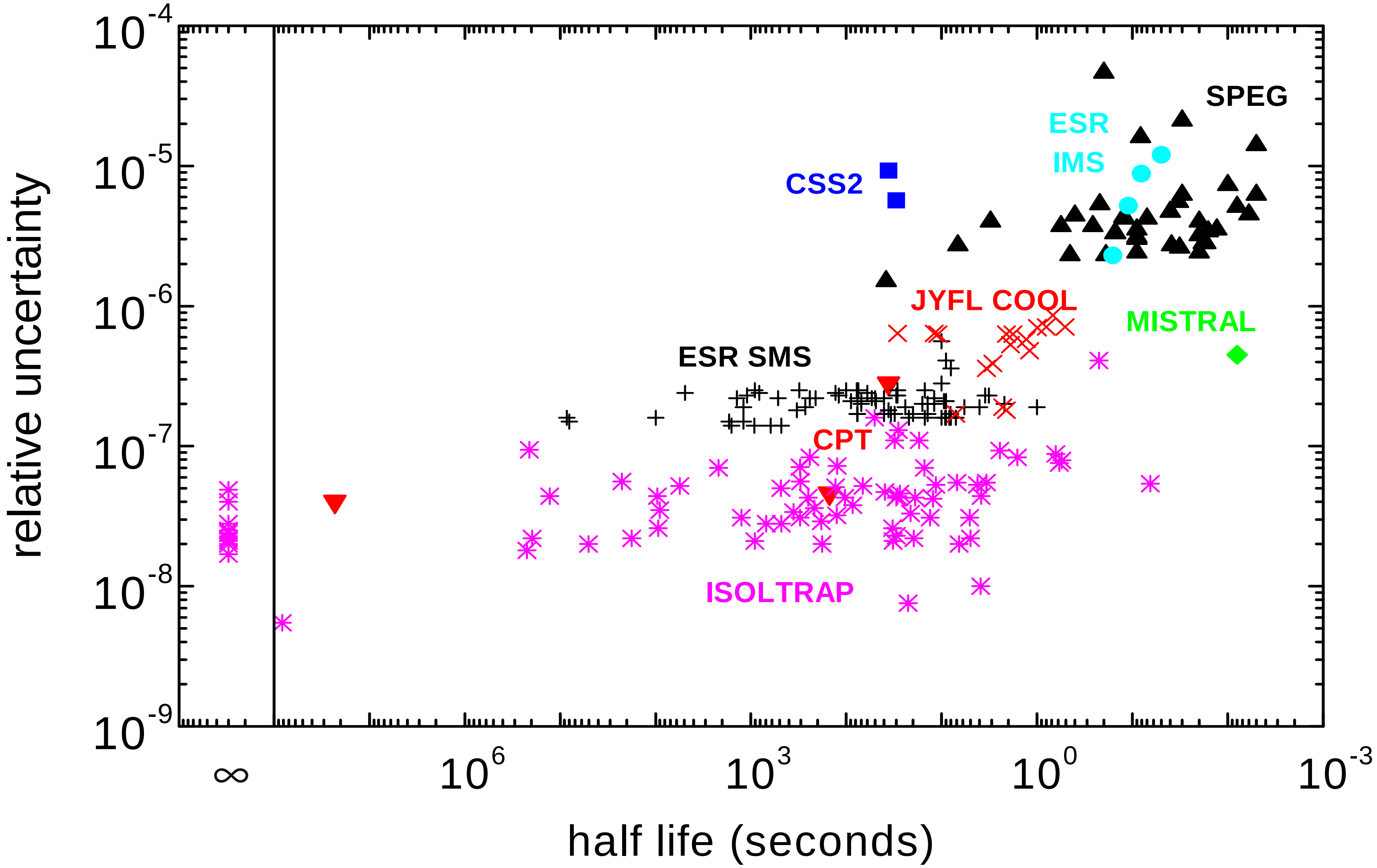
Techniques for mass measurements

- Reaction Q-values: A(a,b)B
- TOF + energy measurements: $E=m*s^2/t^2$
- Cyclotron resonance: $T_{cycl}*eB/2\pi=m/q$
- Storage rings

For details see
D. Lunney et al. RMP75, 1021(2003)

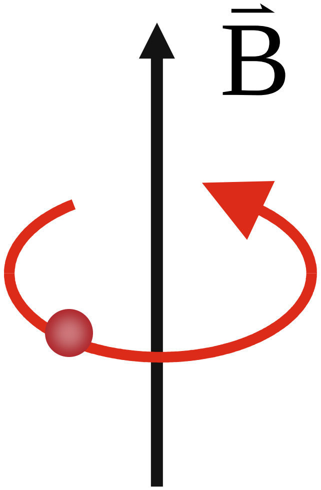


D. Lunney, Proc. Nuclei in the Cosmos IX, (2006)



See: Lunney, Pearson & Thibault, Rev. Mod. Phys. 75 (2003) 1021

How a Penning trap works -1

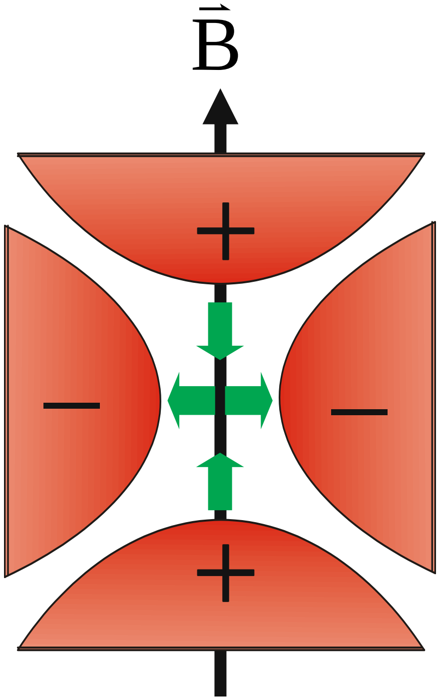


- constant axial magnetic field
- particle orbits in horizontal plane

$$\omega_c = \frac{qB}{m}$$

- free to escape axially

How a Penning trap works-2



Add an axial harmonic potential to confine particles:

$$V = \frac{V_o}{2d^2}(z^2 - \frac{r^2}{2})$$

Motion of ions in a Penning trap

Solve for equations of motion:

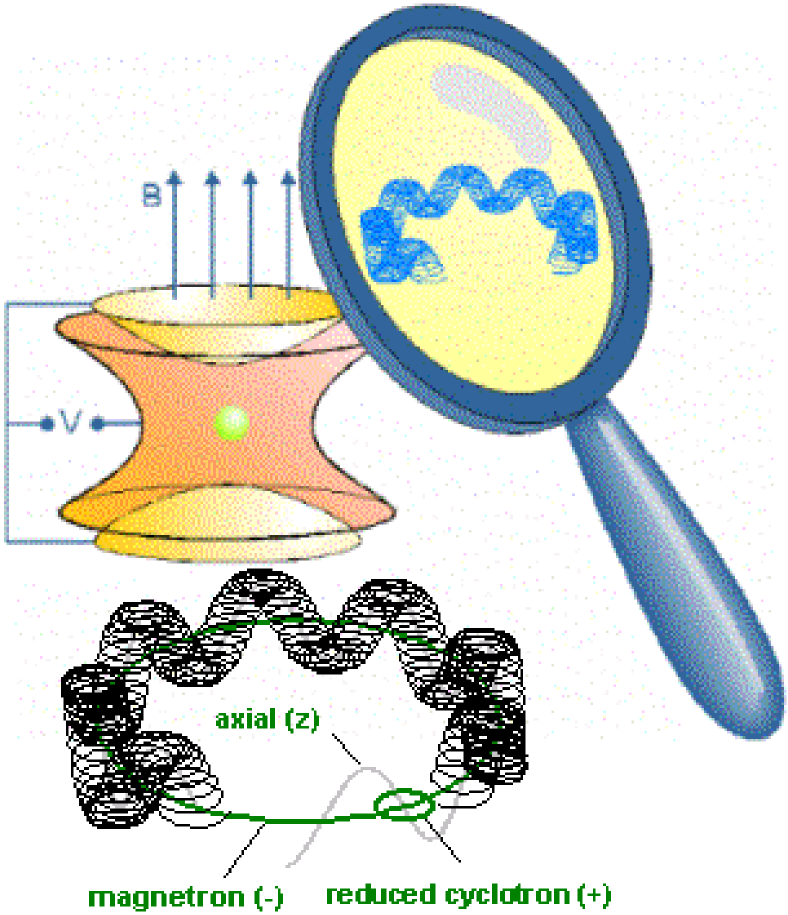
$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

Axial oscillations:

$$\omega_z = \sqrt{\frac{eV}{md^2}}$$

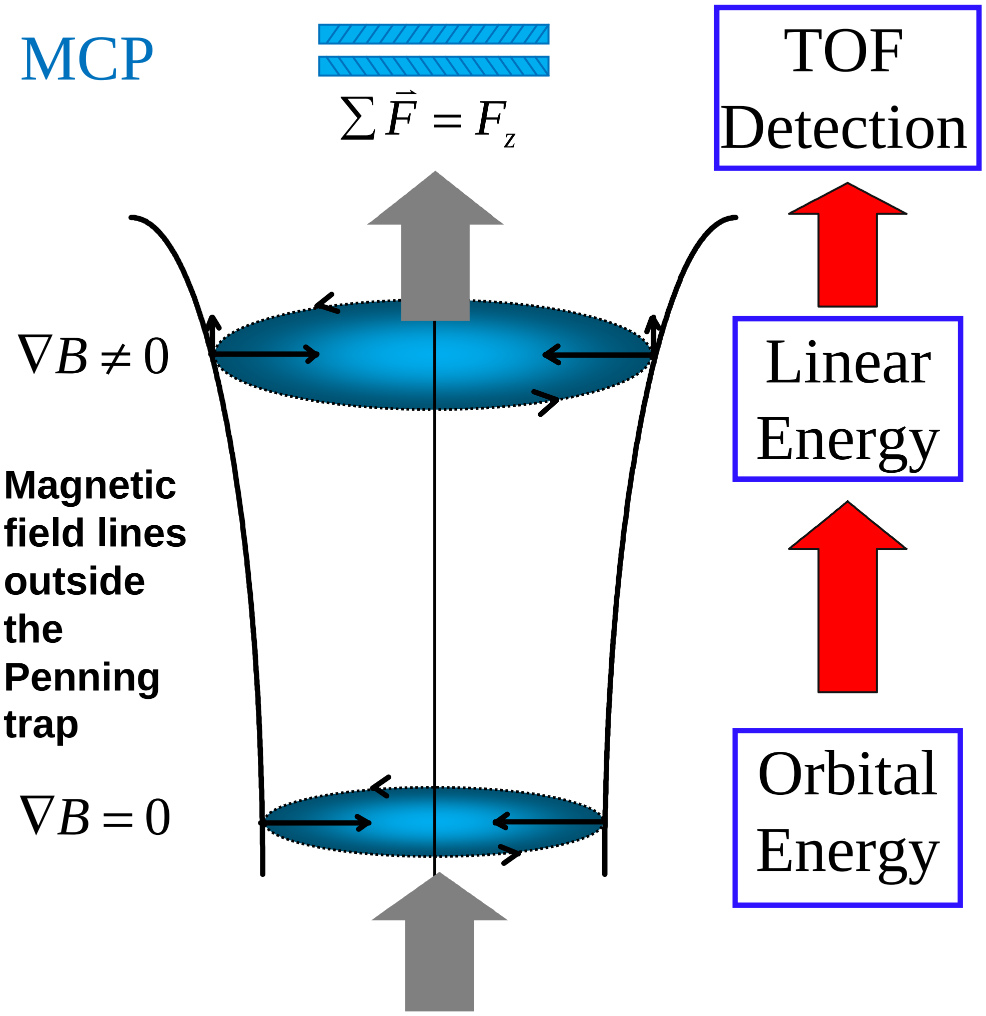
Radial motion:

$$\omega_\pm = \frac{\omega_c}{2} \pm \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$



picture from http://isoltrap.web.cern.ch/isoltrap/

Penning trap mass spectrometry



MCP

$\sum \vec{F} = F_z$

TOF Detection

$\nabla B \neq 0$

Linear Energy

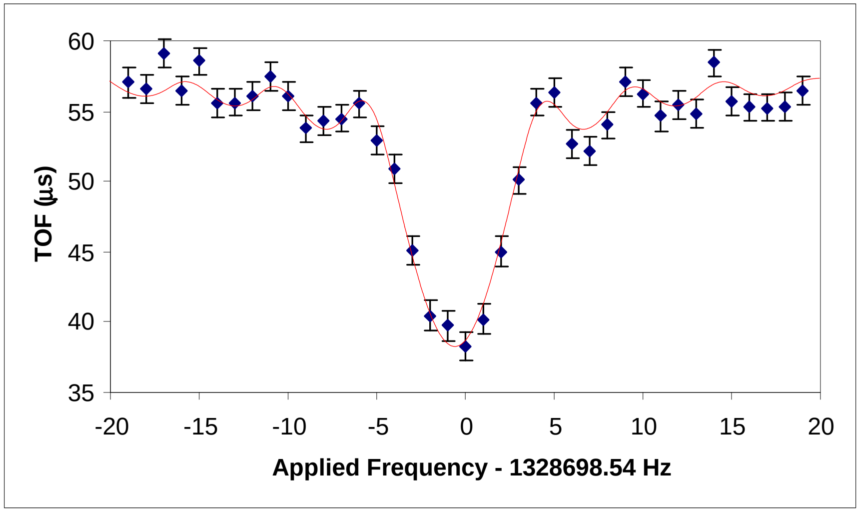
Magnetic field lines outside the Penning trap

$\nabla B = 0$

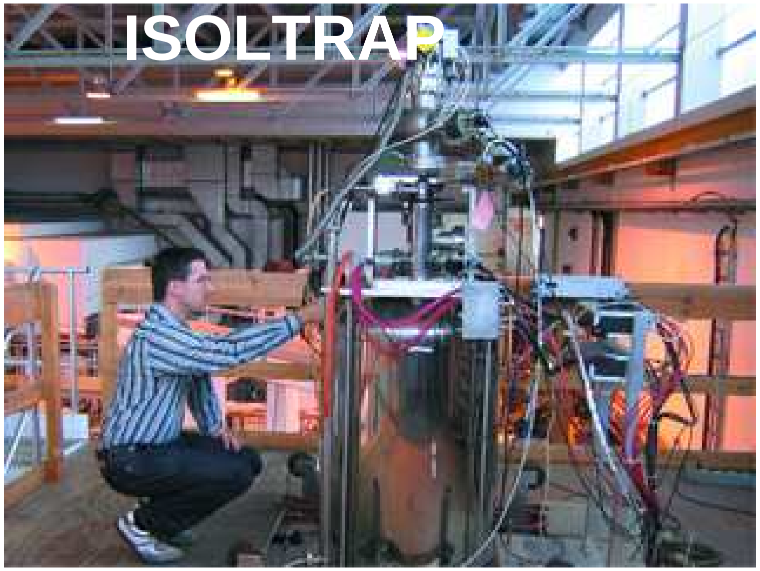
Orbital Energy

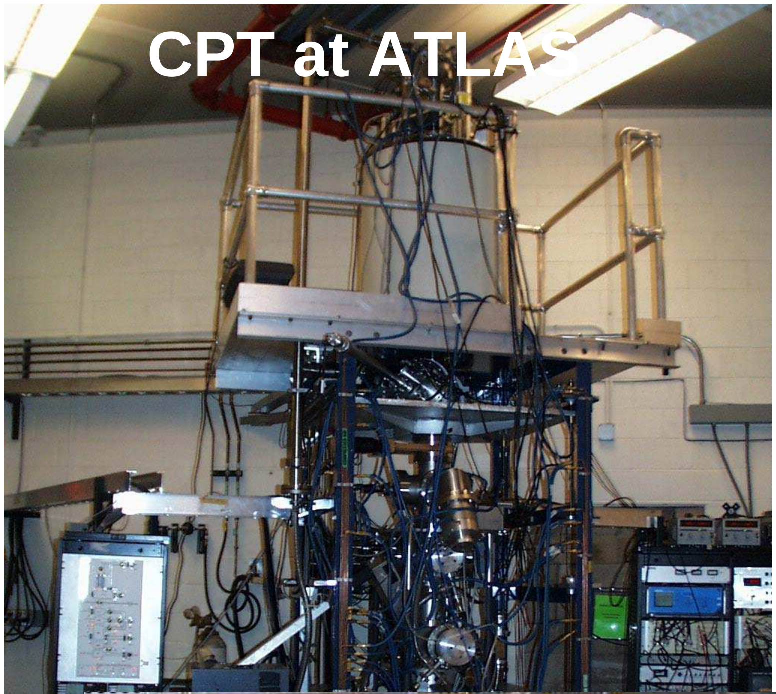
Ions from the Penning trap

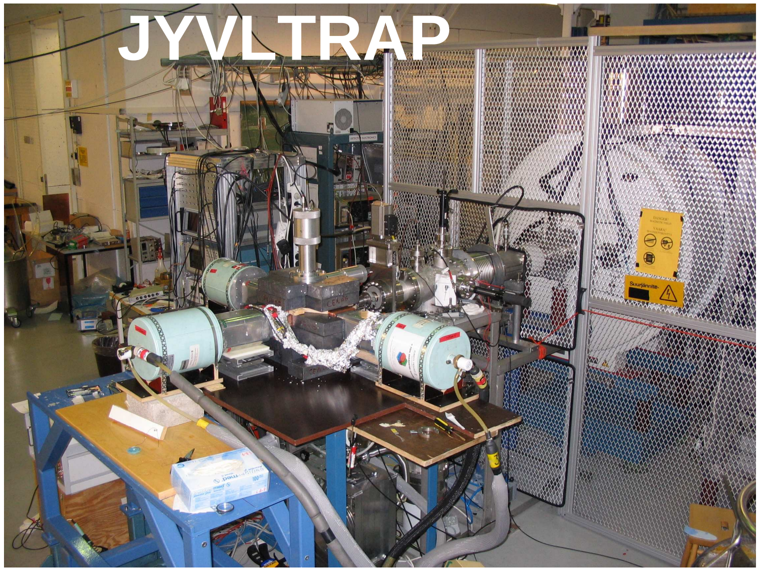
Sample TOF spectrum

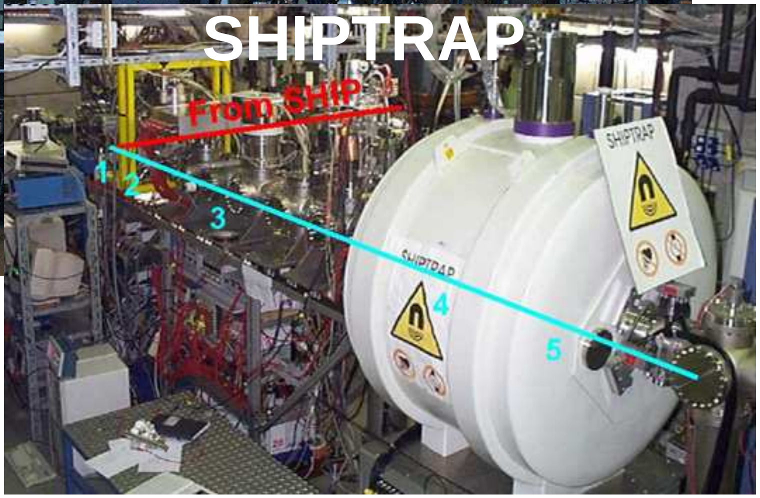


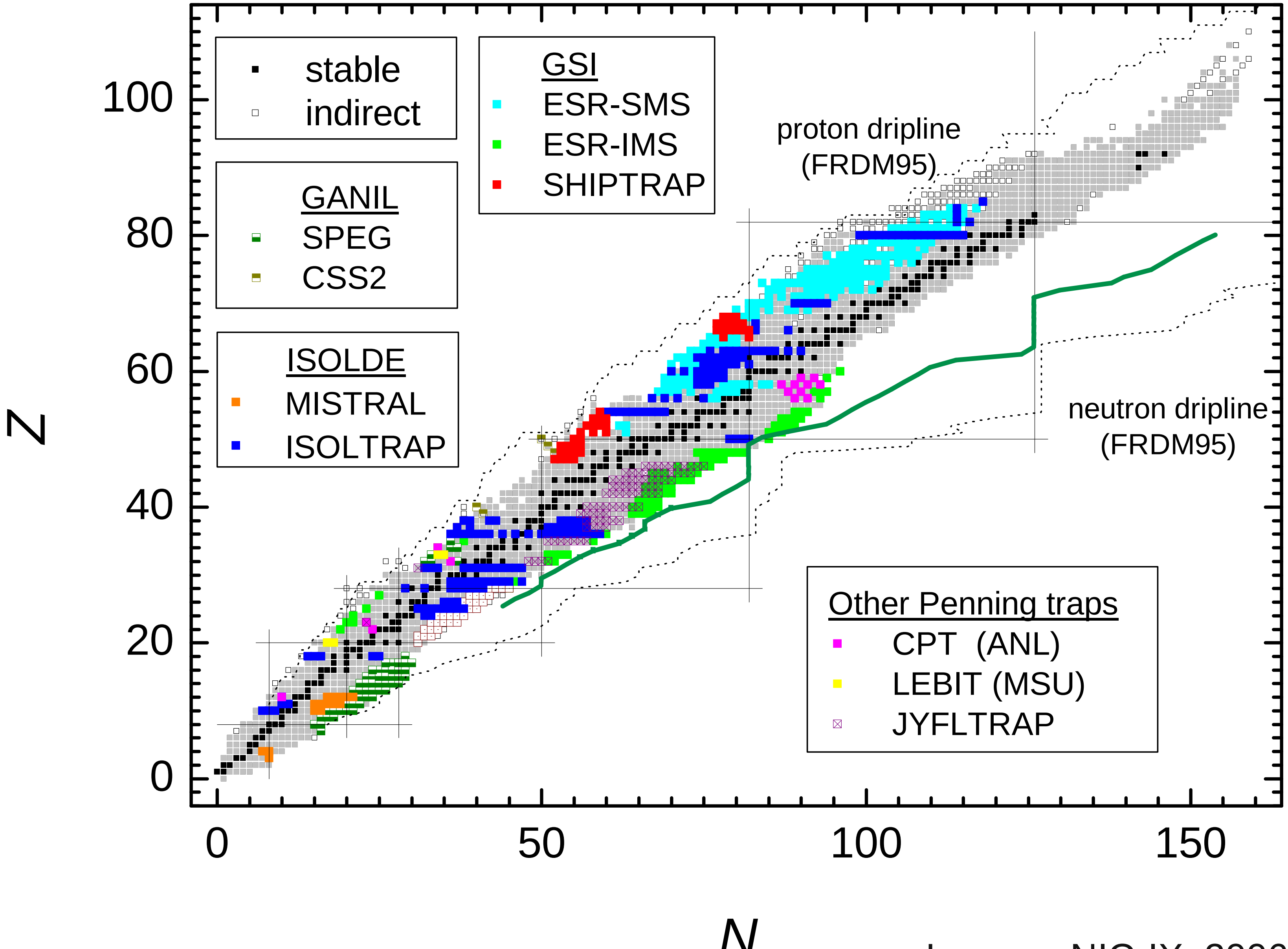
Penning traps


ISOLTRAP


CPT at ATLAS


JYVLTRAP


SHIPTRAP



Lunney, NIC-IX, 2006

PRL **96,** 042504 (2006) PHYSICAL REVIEW LETTERS week ending 3 FEBRUARY 2006

First Precision Mass Measurements of Refractory Fission Fragments

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(Received 15 April 2005; published 1 February 2006; corrected 7 February 2006)

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International Journal of Mass Spectrometry 251 (2006) 252–259

www.elsevier.com/locate/ijms

Studies of neutron-rich isotopes with the CPT mass spectrometer and the CARIBU project

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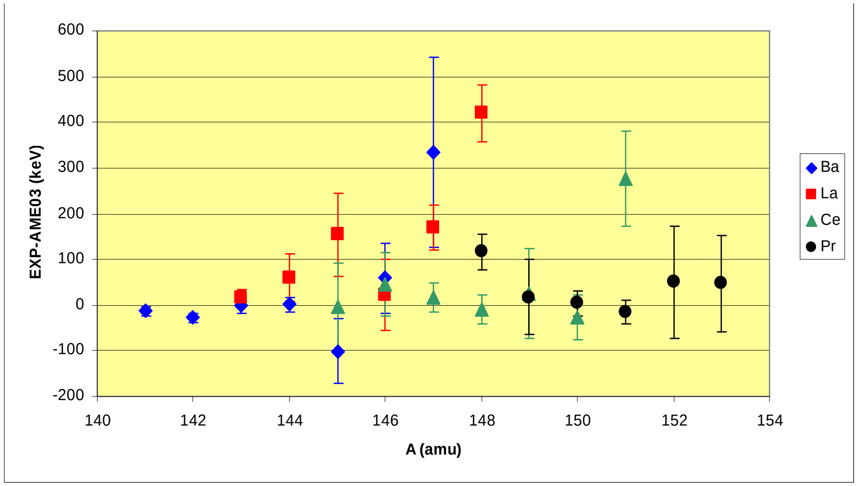
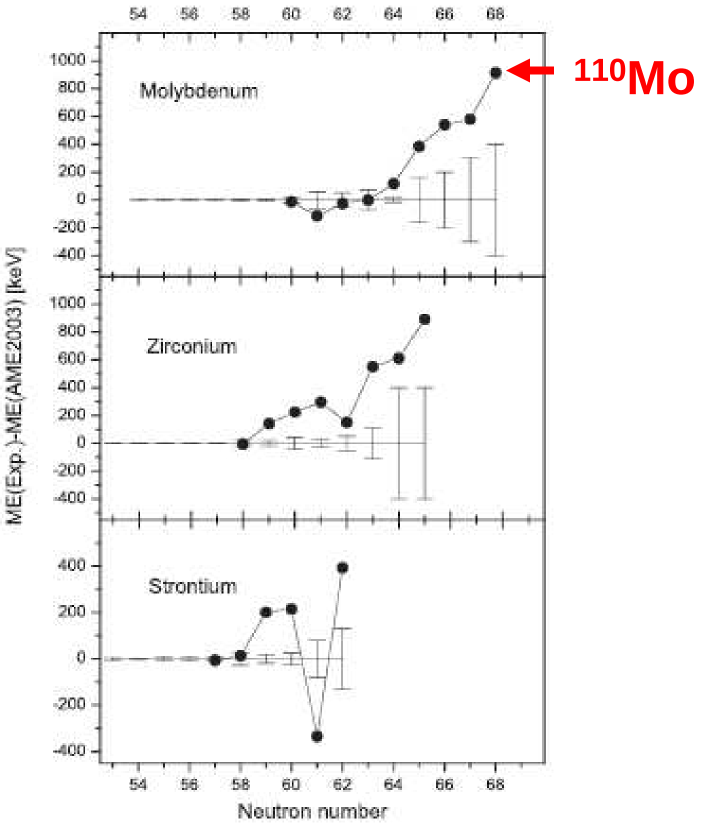
Received 2 January 2006; received in revised form 30 January 2006; accepted 31 January 2006

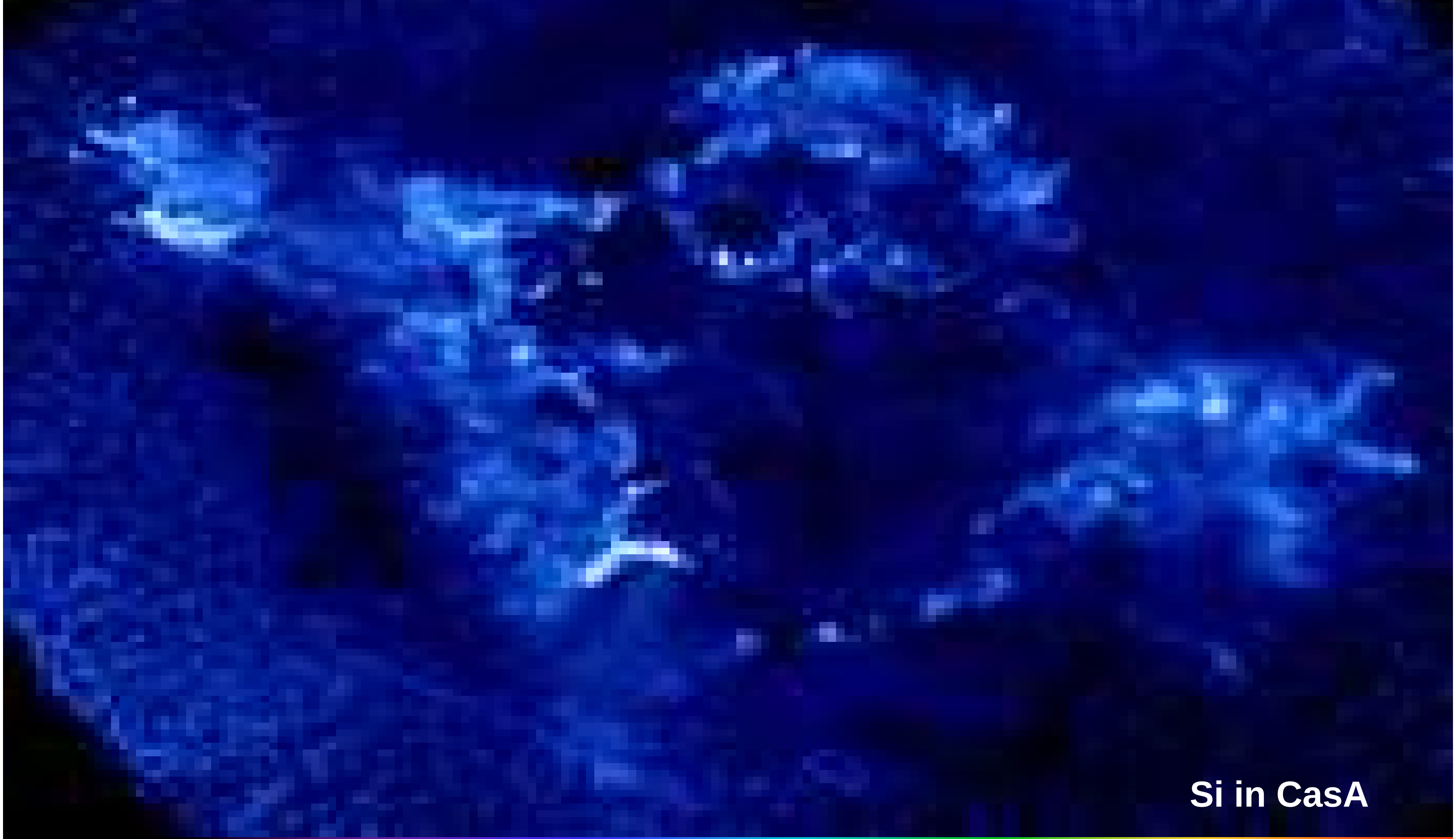




n-rich nuclei are less bound than expected by mass formulae

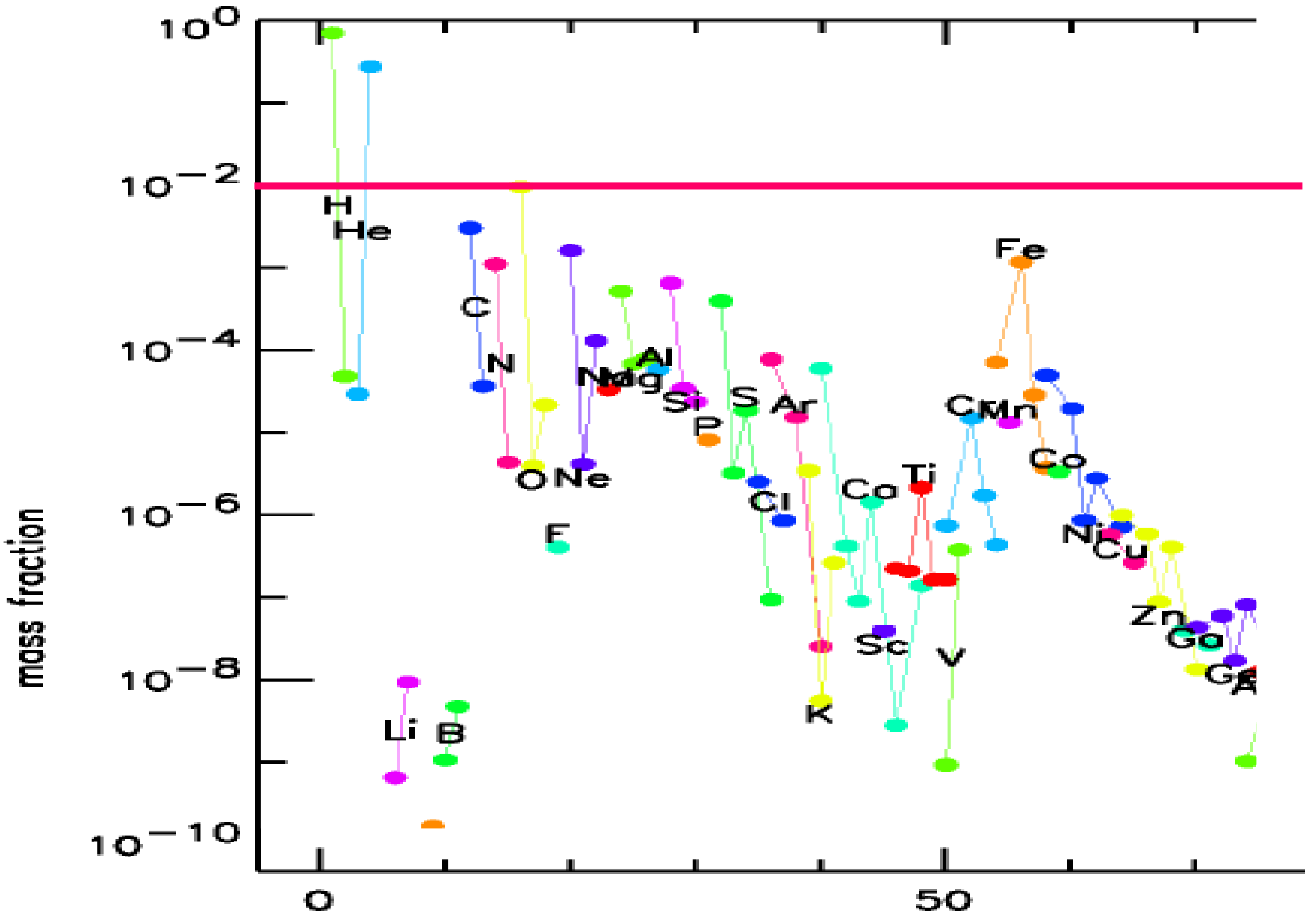
→ neutron drip line moves closer to the valley of stability

Reactions in Nuclear Astrophysics



Si in CasA

Stellar abundance pattern



Most reactions induced by:

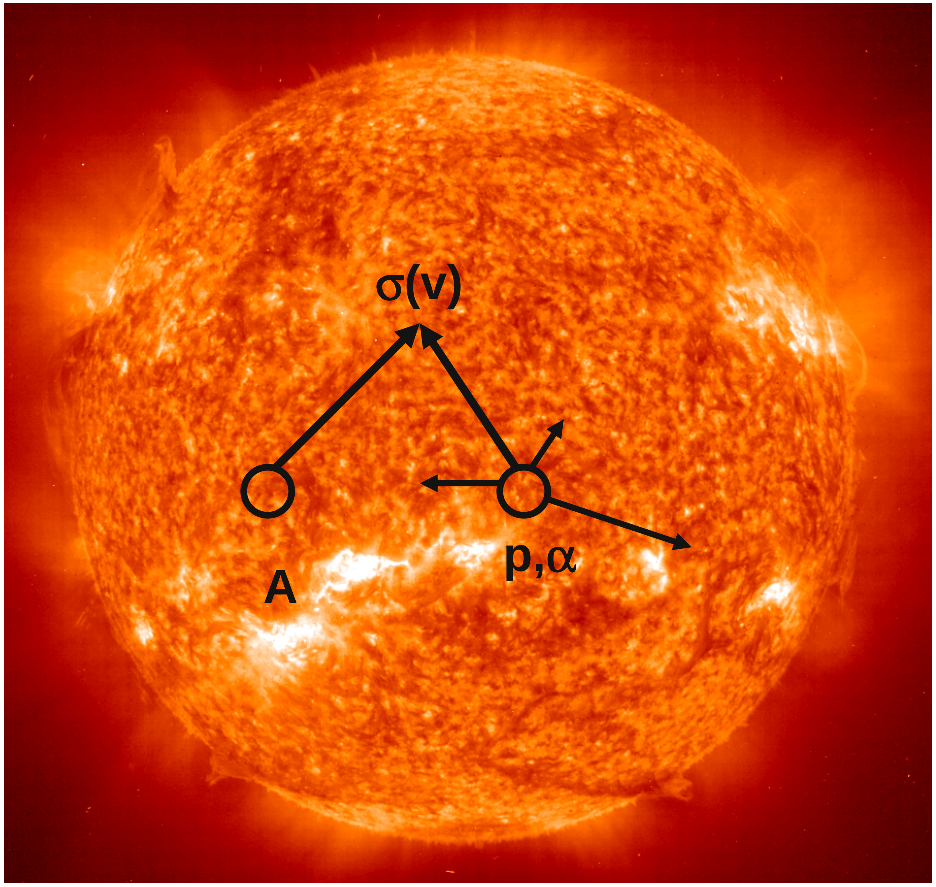
p,α

(^{16}O,^{12}C, n)

Critical reactions in nuclear astrophysics

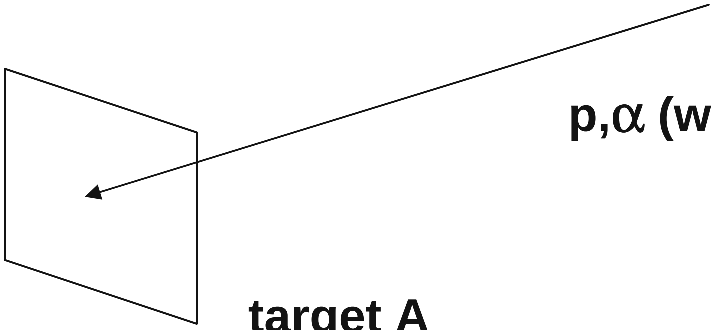
(p,γ)	(novae, rp-process)
(α,γ)	(red giants)
(α,p)	(rp-process)
^{12}C + ^{12}C fusion	(supernovae)
(n,γ)	(r-process, s-process), [session 9,10]
GT transitions	(supernovae), [session 5]
(α,n)	(s-process, red giants), [session 10]
(p,α)	(novae), [session 14]
(γ,p), (γ,n), (γ,α)	(p-process), [session 11]

In Nature:



v: Maxwellian distribution

In the laboratory:



p,α (with velocity v_o)

target A

$\sigma(v_o)$

Reactions between Charged Particles

(Astrophysical Reaction Rate)

Example: $^{12}C(p,\gamma)^{13}N$

N_c: ^{12}C particles/cm^3

N_p: protons/cm^3

v_o: relative velocity between C and p

Rate: $r = N_c \bullet N_p \bullet v_o \bullet \sigma_{p\gamma}(v_o)$ $\{cm^{-3}\ s^{-1}\}$

Plasma: velocity distribution $\phi(v)$

$v\sigma \rightarrow \langle v\sigma\rangle = \int \phi(v)\cdot v\cdot \sigma(v)\, dv$

($\langle v\sigma\rangle$ reaction rate per particle pair)

Particle densities N_i:

$\rho = N_i \mu$ μ= weight of a particle

$\rho = N_i A/N_A$ N_A: Avogadro's Number

$N_i = \rho N_A/A$

Or, for a multi-particle gas with X_i as a mass fraction:

$N_i = \rho N_A/A\ X_i$

In normal stellar matter (not in neutron stars)

$$\phi_i(v_i) = 4\pi v_i^2 \left(\frac{m}{2\pi kT}\right)^{3/2} \exp\left(-\frac{mv^2}{2kT}\right) \text{ (Maxwellian)}$$

$$\langle\sigma v\rangle = \iint \phi(v_1)\phi(v_2)\sigma(v_{rel})v_{rel}\, dv_1 dv_2$$

$v_1 = V + m_2/(m_1+m_2)v$ V : center-of-mass velocity

$v_2 = V - m_1/(m_1+m_2)v$ v : relative velocity ($v_1 - v_2$)

$$\langle\sigma v\rangle = \iint \Phi(V)\phi(v)\, v\, \sigma(v)\, dv\, dV$$

Where:

$\Phi(V)=4\pi V^2(M/(2\pi kT))^{3/2}\ \exp(- MV^2/(2kT))$

$M=m_1+m_2$

$\phi(v)=4\pi v^2(\mu/(2\pi kT))^{3/2}\ \exp(-\mu v^2/(2kT))$

$\mu=m_1m_2/(m_1+m_2)$

$<\sigma v>=\int \phi(v)v\sigma(v)dv$

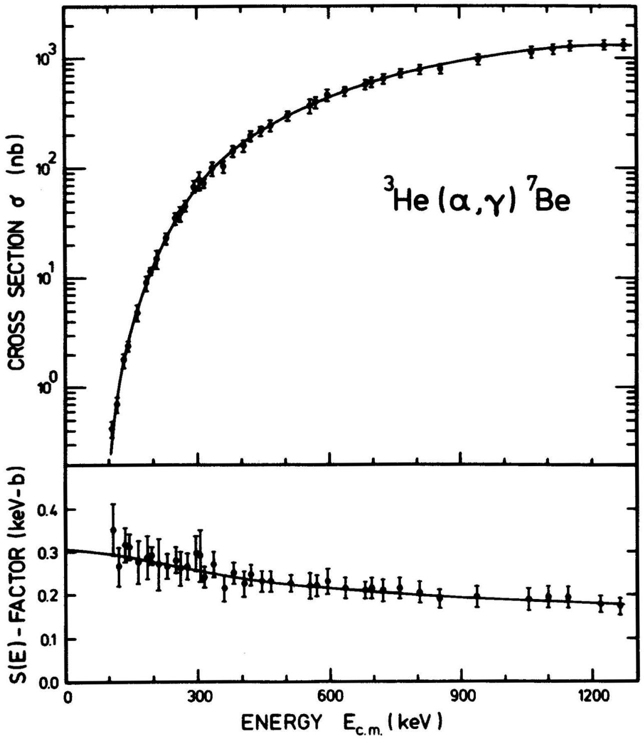
Because $\int\Phi(V)dV=1$

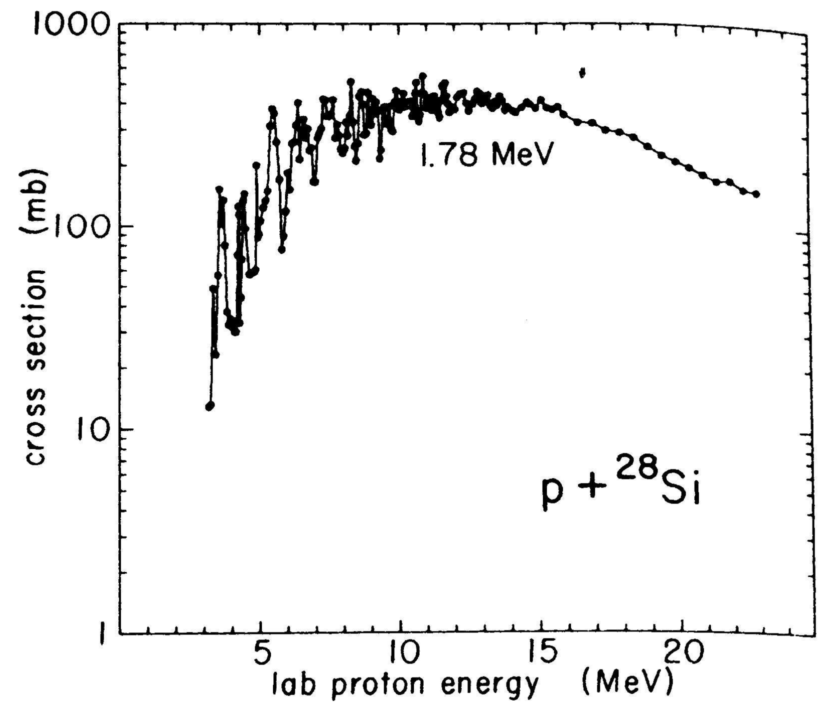
$$<\sigma v>=4\pi\left(\frac{\mu}{2\pi kT}\right)^{3/2}\int v^3\,\sigma(v)\,\exp\left(-\frac{\mu v^2}{2kT}\right)dv$$

or

$$\boxed{<\sigma v>=\left(\frac{8}{\pi\mu}\right)^{1/2}\left(\frac{1}{kT}\right)^{3/2}\int\sigma(E)\,E\,\exp\left(-\frac{E}{kT}\right)dE}$$

Need σ(E):





Non-resonant cross sections

resonant cross sections

To eliminate the strong energy dependence, one takes out the trivial factors : $e^{-2\pi\eta}/E$ and defines a new parameter S **(S-Factor)** which contains the ‘non-trivial’ energy dependence:

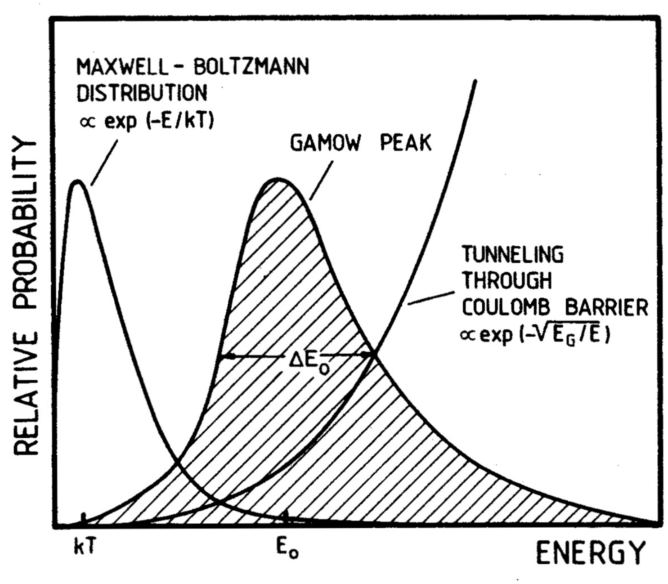
$$\sigma = S(E)/E\ e^{(-2\pi\eta)}$$

$$S(E) = \sigma\ E\ e^{(2\pi\eta)}$$

With S(E) one can rewrite $<\sigma v>$:

$$<\sigma v> = \left(\frac{8}{\pi\mu}\right)^{1/2} \left(\frac{1}{kT}\right)^{3/2} \int S(E) \exp(-E/kT - b/E^{1/2})\, dE$$

argument of the exponent:



Maximum of the argument at E_0:

$E_0=(bkT/2)^{2/3}$ with $b=(2\mu)^{1/2}\,\pi e^2 Z_1 Z_2/\hbar$

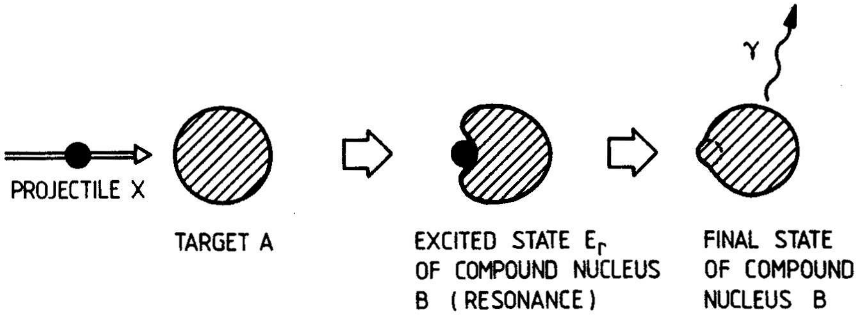
or

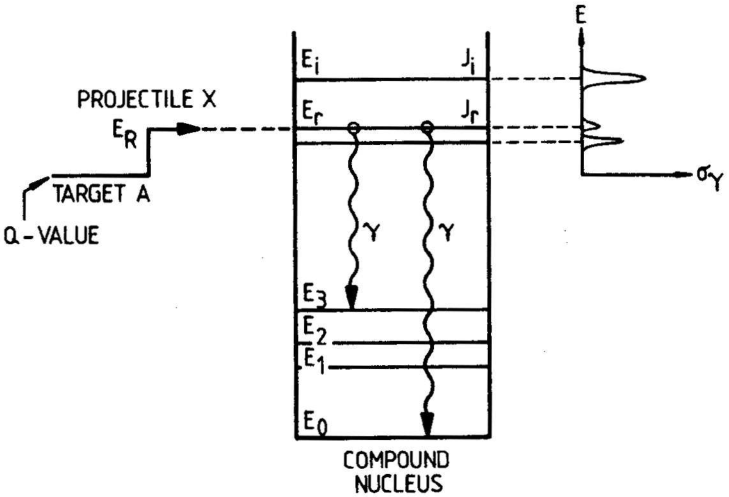
$$\boxed{E_0=1.22(\,Z_1^2 Z_2^2 \mu\, T_6^2)^{1/3}\ [\mathrm{keV}]}$$

Gamow peak

T_6: temperature in 10^6 K

Resonance Reactions





$\sigma_{\text{resonance}}$: Breit-Wigner shape

$$\boxed{\sigma_{i\to f} = \frac{\pi}{k^2}\,\frac{2J+1}{(2J_1+1)(2J_2+1)}\,\frac{\Gamma_i\Gamma_f}{(E-E_r)^2+(\Gamma/2)^2}}$$

J: spin of the resonance

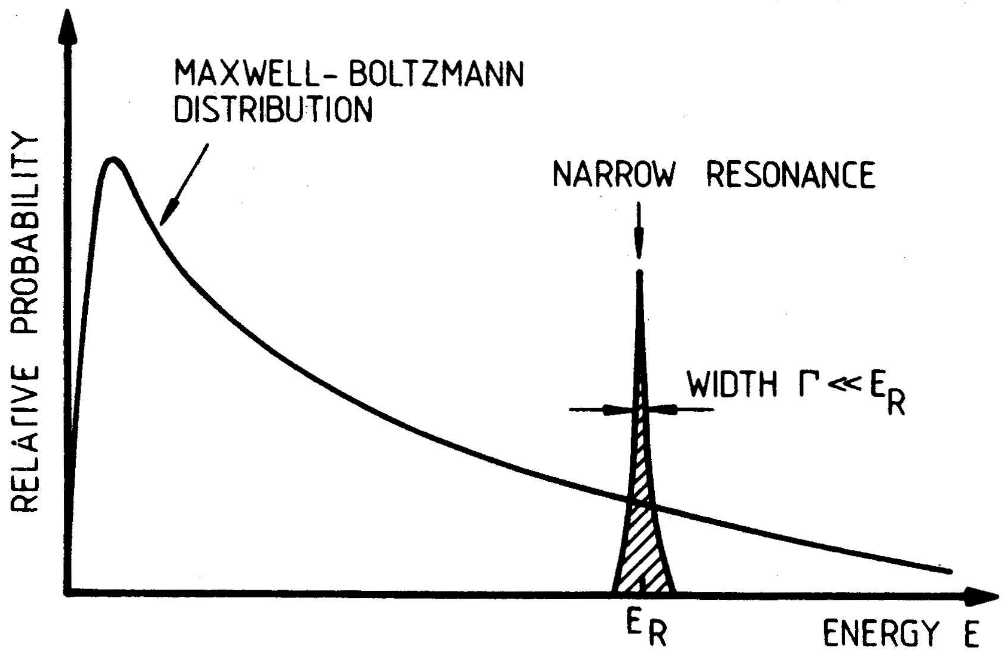
$J_{1,2}$: spin of the particles in the entrance channel

k: wave number

$\Gamma_{i,f}$: widths (decay probabilities) in the entrance or exit channel

E_r: resonance energy

Γ: total width ($\Gamma_i+\Gamma_f+..$)



$$<\sigma v> = \left(\frac{8}{\pi\mu}\right)^{1/2} \left(\frac{1}{kT}\right)^{3/2} \int \sigma_{BW}\, E\, \exp(-E/kT)\, dE$$

$$<\sigma v> = \left(\frac{8}{\pi\mu}\right)^{1/2} \left(\frac{1}{kT}\right)^{3/2} E_r \exp(-E_r/kT) \int \sigma_{BW}(E)\, dE$$

$$\int \sigma_{BW}(E)\, dE = \frac{\pi}{k^2}\ \omega\Gamma_i\Gamma_f\ \pi/(\Gamma/2)$$

$$= 2\pi^2/k^2\ \frac{\omega\,\Gamma_i\Gamma_f}{\Gamma} =$$

$$= 2\pi^2/k^2\ \omega\gamma$$

$\omega\gamma$: resonance strength

$$<\sigma v> = \left(\frac{2\pi}{\mu kT}\right)^{3/2} \hbar^2\, \omega\gamma\, \exp(-E_r/kT)$$

For several non-overlapping resonances:

$$\boxed{<\sigma v> = \left(\frac{2\pi}{\mu kT}\right)^{3/2} \hbar^2 \sum \omega\gamma_i\, \exp(-E_i/kT)}$$

High rates for:

1. Large $\omega\gamma$
2. low resonance energies E_i

(p,γ) reactions

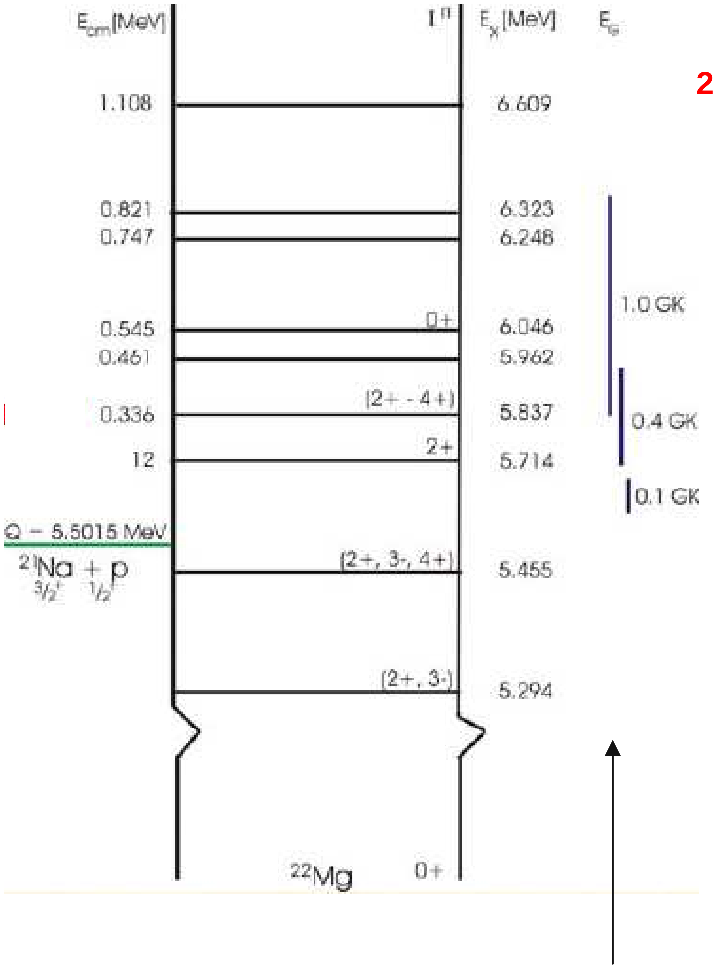
- Center of activities with radioactive beams
- Mainly resonant
- Example $^{21}Na(p,\gamma)^{22}Mg$ (TRIUMF)

S. Bishop et al. PRL90, 162501(2003)

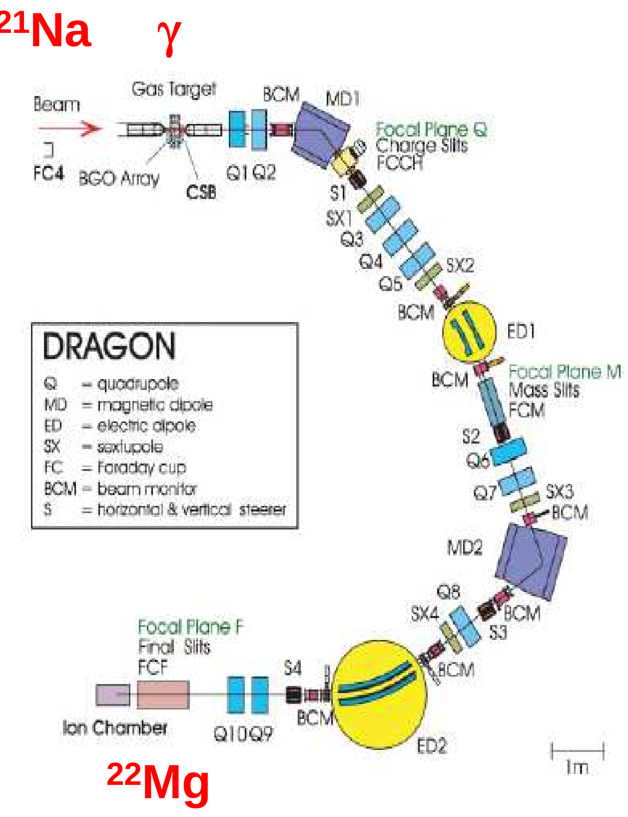
J. d’Auria et al. PRC69, 065803(2004)

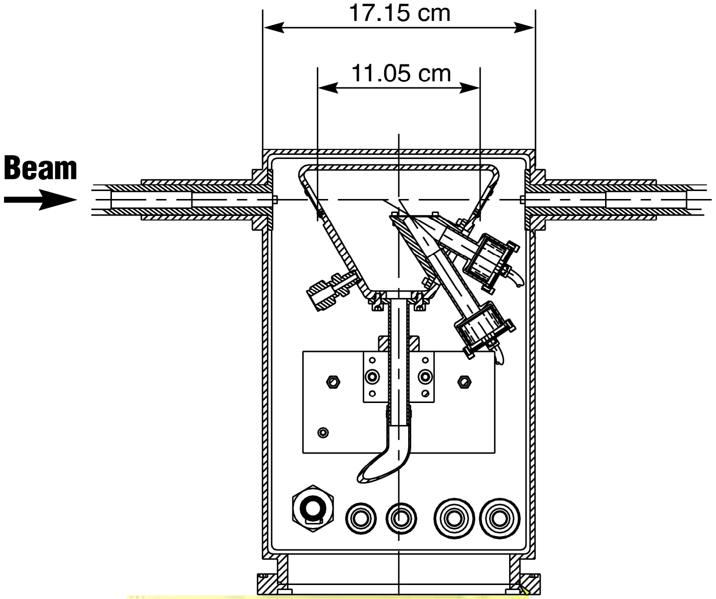
Need 200-500 keV ^{21}Na ($T_{1/2}$=22.8 s) beams and hydrogen gas target

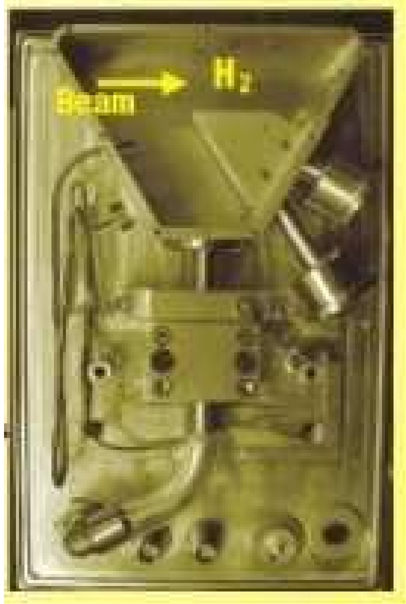
Reaction studied as: p(^{21}Na,^{22}Mg)γ

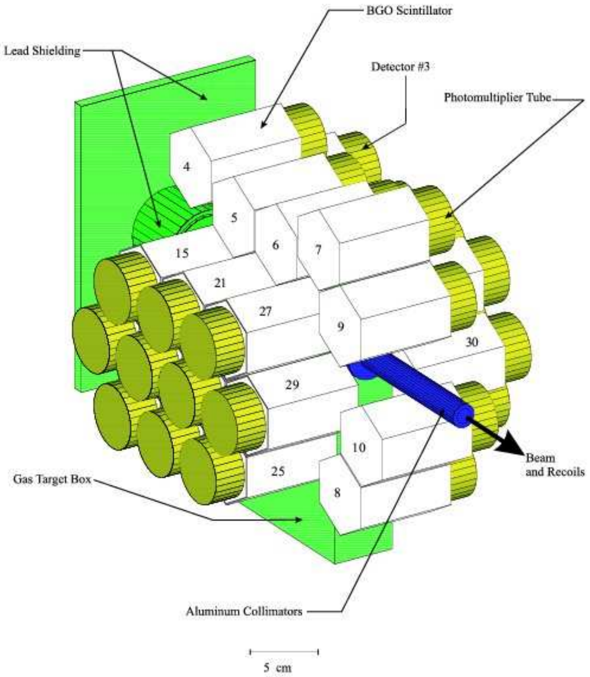


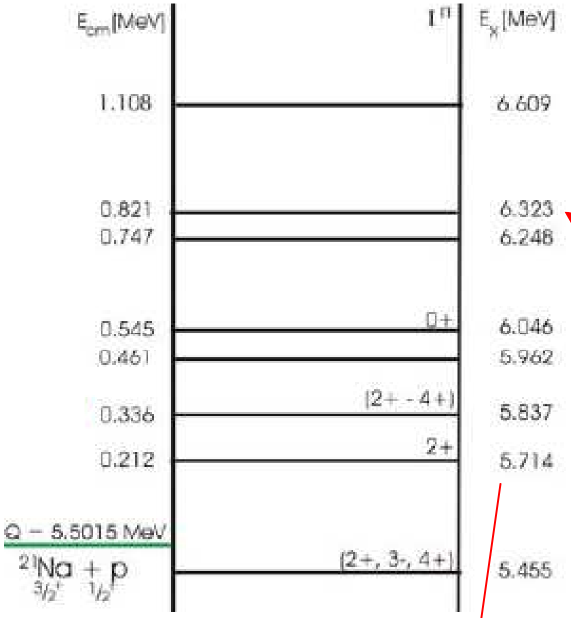
“Gamow” windows

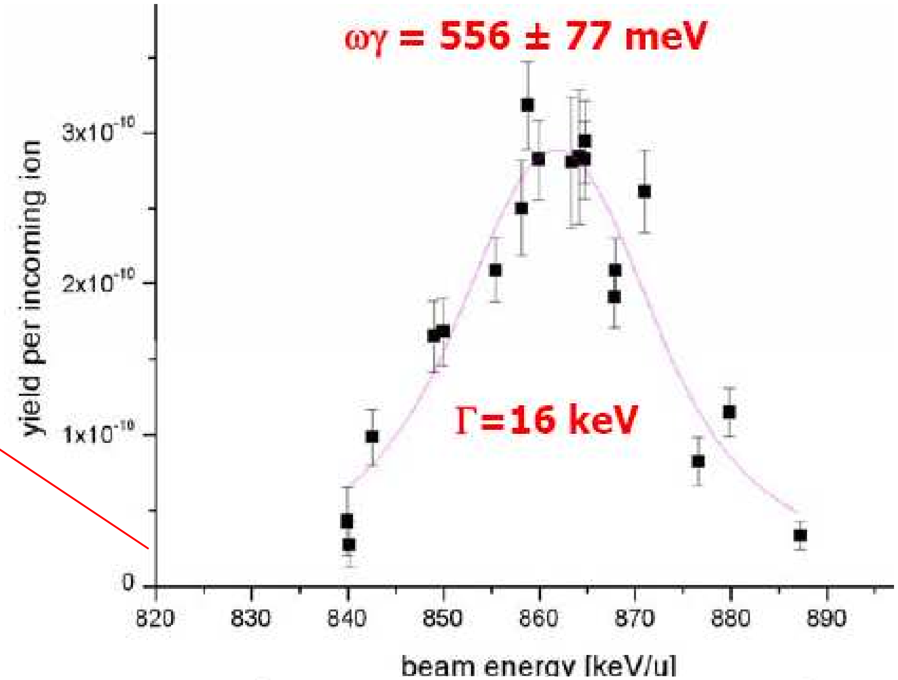



17.15 cm
11.05 cm
Beam


Beam
H$_2$

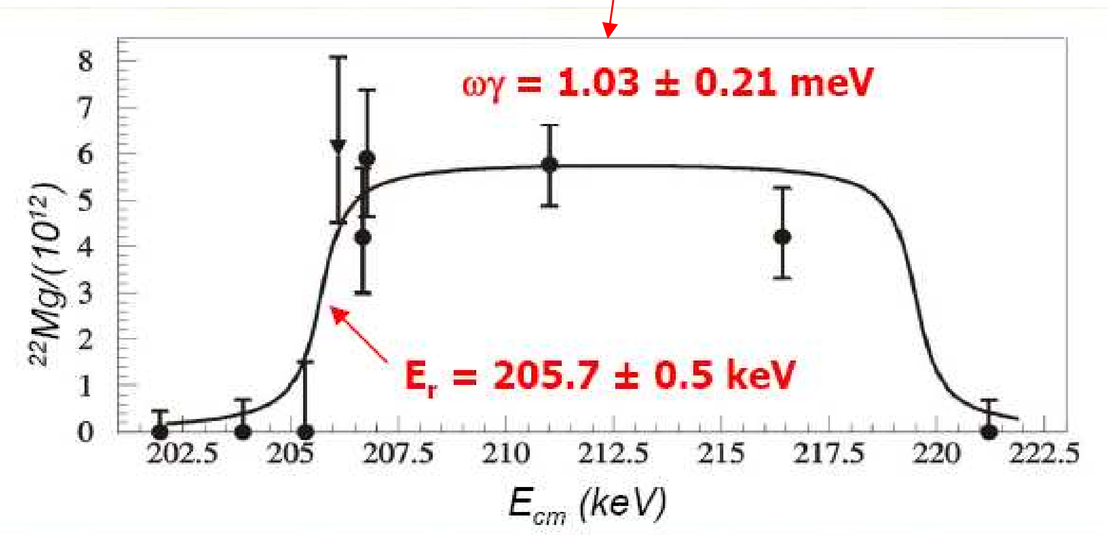

BGO Scintillator
Lead Shielding
Detector #3
Photomultiplier Tube
4
5
6
7
15
21
27
9
30
29
10
25
8
Beam
and Recoils
Gas Target Box
Aluminum Collimators
5 cm





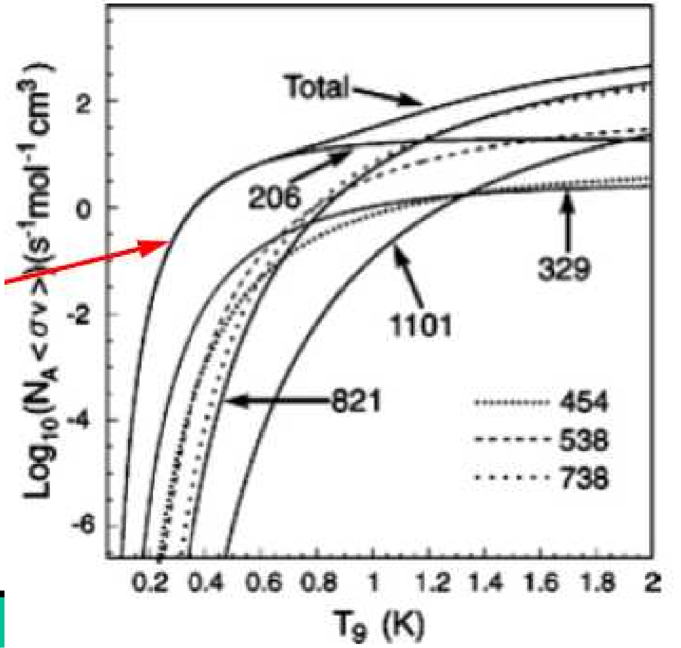
ωγ = 556 ± 77 meV

Γ=16 keV

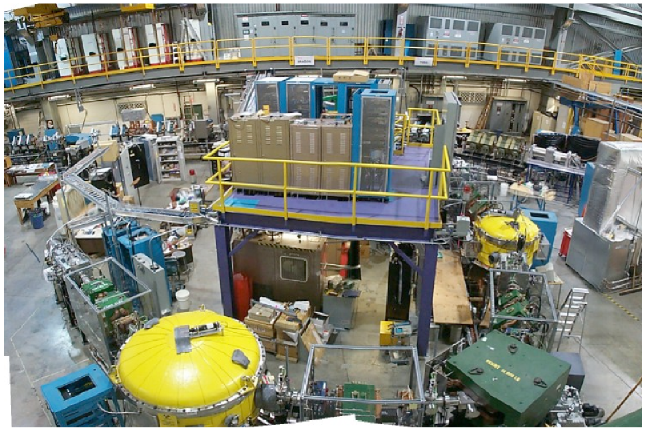


ωγ = 1.03 ± 0.21 meV

E_r = 205.7 ± 0.5 keV

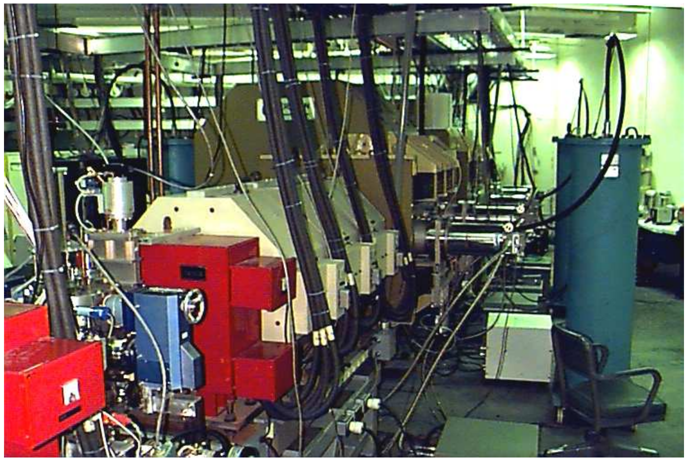


Other Recoil Separators for Astrophysics



DRAGON at TRIUMF ISAC

Used to measure $^{21}Na(p,\gamma)^{22}Mg$



DRS at ORNL HRIBF

Used to measure $^{18}F(d,p)^{19}F$

ARES at Louvain-la-Neuve

Used to measure $^{19}Ne(p,\gamma)^{20}Na$

FMA at ANL ATLAS

Used to measure $^{18}F(p,\gamma)^{19}Ne$

- (p,γ) reaction with stable nuclei: many examples, cross sections typically ~μb

- with radioactive beams studied so far:

$^{7}Be(p,\gamma)$, $^{13}N(p,\gamma)$, $^{17}F(p,\gamma)$, $^{21}Na(p,\gamma)$, $^{26}Al(p,\gamma)$

- need beam intensities > 10^{8} /s, which is difficult for radioactive beams

→use indirect techniques

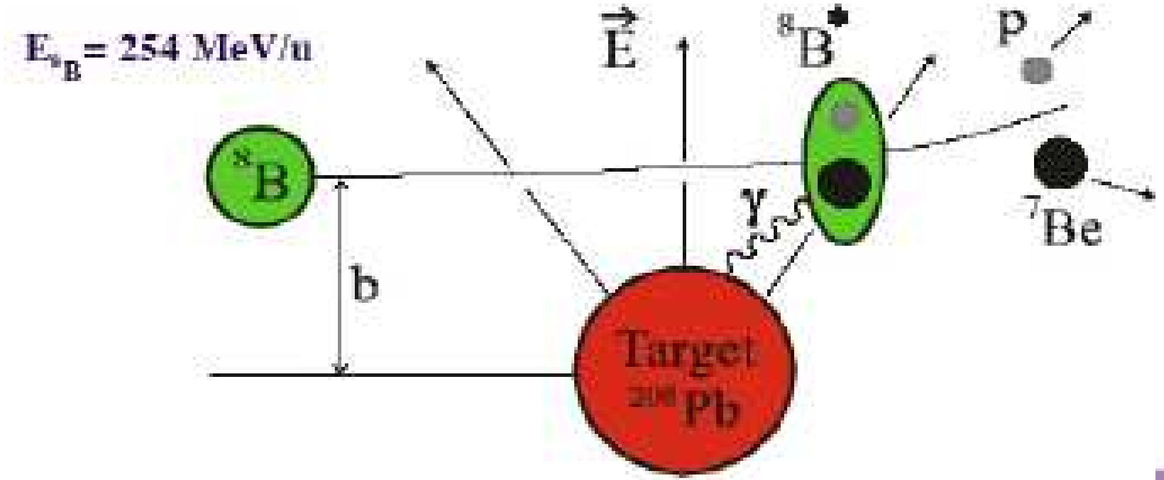
Indirect techniques for (p,γ) reactions:

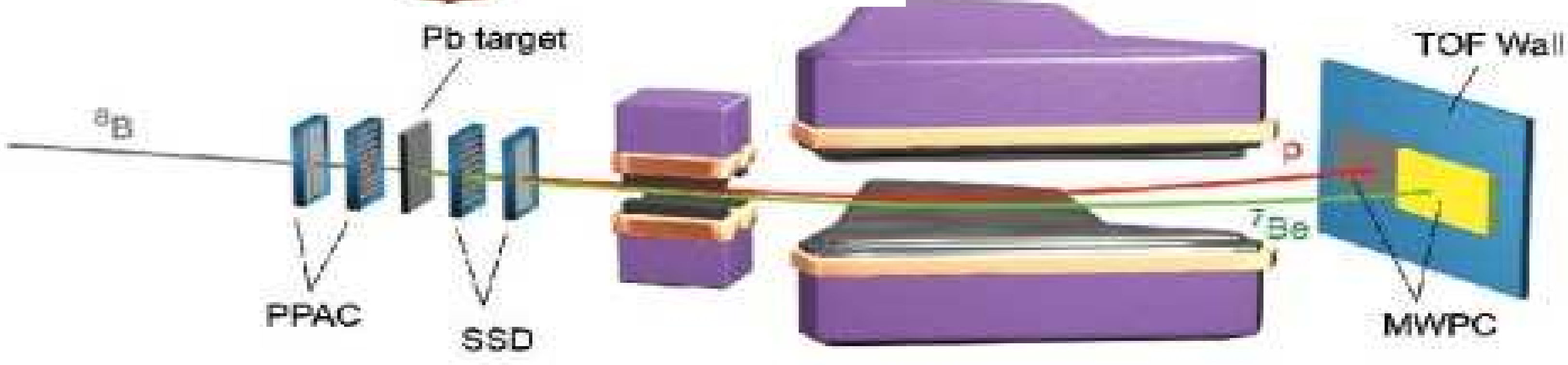
$$\boxed{\sigma_{p\rightarrow\gamma} \quad \frac{\pi}{k^2}\,\frac{2J+1}{(2J_1+1)(2J_2+1)}\,\frac{\Gamma_p\,\Gamma_\gamma}{(E-E_r)^2+(\Gamma/2)^2}}$$

1. Determine E_r (e.g. via transfer reactions)
2. Determine J (e.g. via angular distributions)
3. Determine Γ_γ (e.g. via a γ lifetime measurement)
4. Determine Γ_p (e.g. via elastic scattering)

Other Indirect Techniques:

- <u>Coulomb dissociation:</u> ($^8B(\gamma,p)^7Be$ is the time-inverse reaction of $^7Be(p,\gamma)^8B$)





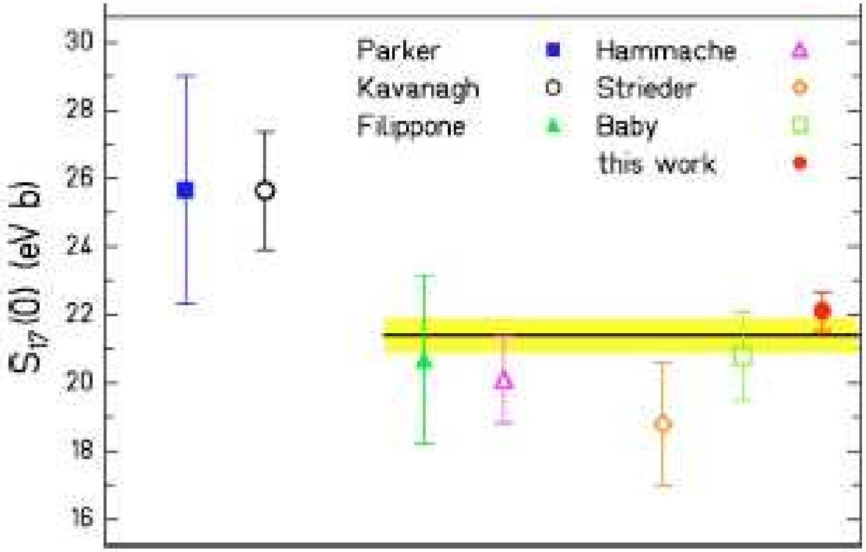
$^{7}\mathrm{Be}(p,\gamma)^{8}\mathrm{B}$

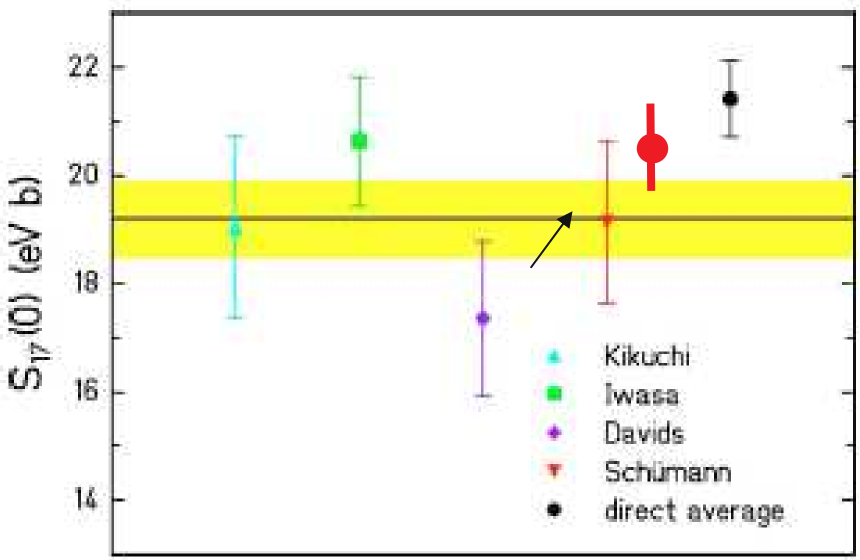
Direct measurement

$S_{17}(0)=22.1\pm0.6\pm0.6$ eVb

Indirect measurement

$S_{17}(0)=20.6\pm0.8\pm1.2$ eVb





Junghans et al. PRC68, 065803(2003)

Schümann et al. PRC73, 015806(2006)

Other Indirect techniques:

1. **Transfer Reactions (Asymptotic Normalization Coefficients, ANC)** **(A. Mukhamedzanov et al. PRC56, 1302(1997)**
2. **γ-spectroscopy following fusion reactions** **(D. Jenkins et al. PRL 92, 031101 (2004)**
3. **γ-spectroscopy following knockout reactions** **(R. Clement et al., PRL 92 172502, (2004))**
4. **(^{3}He,d) reactions** **(C. L. Jiang et al., subm. to PRC)**

(α,γ) Reactions

cross sections ~ 1/100 $\sigma(p,\gamma)$

Important examples:

$\alpha+\alpha+\alpha\rightarrow{}^{12}C$	bridging the mass 8 gap
$^{12}C(\alpha,\gamma)^{16}O$	‘most important reaction in Nuclear Astrophysics’
$^{15}O(\alpha,\gamma)^{19}Ne$	breakout from the hot CNO cycle
$^{40}Ca(\alpha,\gamma)^{44}Ti$	production of the gamma tracer ^{44}Ti

Direct measurements of ^{40}Ca(α,γ)^{44}Ti (amount of ^{44}Ti in CasA SN remnant)

- **1977: high intensity ^{4}He beams + ^{40}Ca target, γ detection**
- (E. Coopermann et al., Nucl. Phys. A284, 163 (1977))
- **Target deterioration**
- **Detection efficiency**
- **Background**

New approaches (^{40}Ca beam and ^{4}He target):

- **Accelerator mass spectrometry**

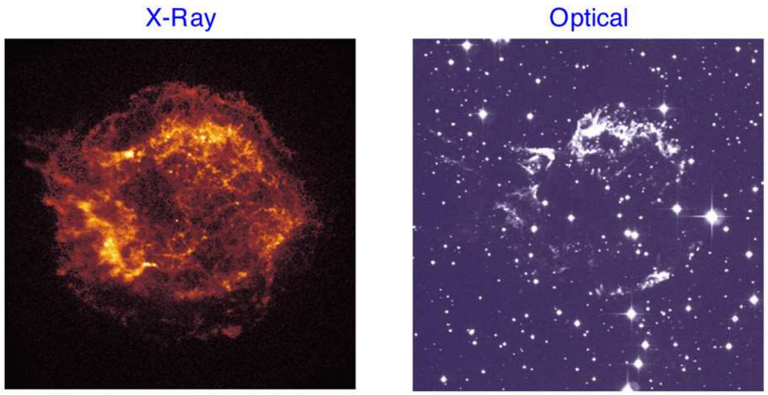
(H. Nassar et al., PRL96, 041102(2006)

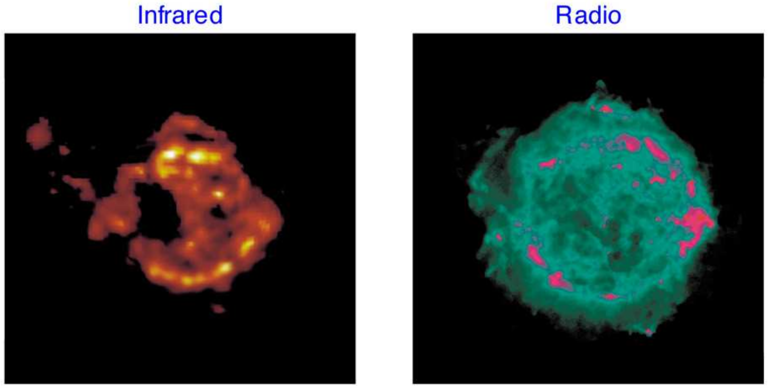
- **Measurements in inverse kinematics**

(C. Vockenhuber et al., PRC76, 035801(2007))

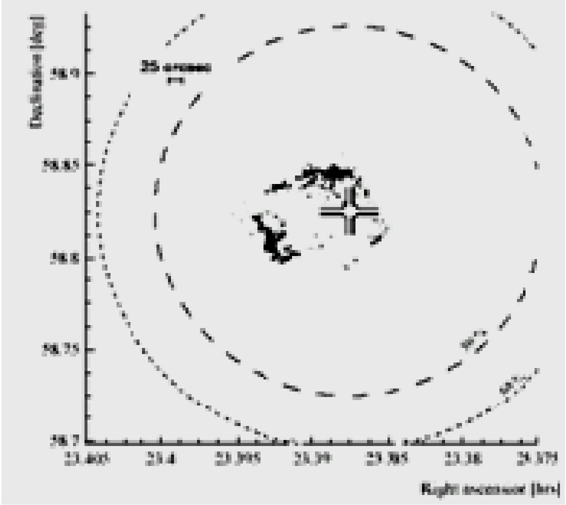

Cas A (x 30)
1.157 MeV ^{44}Ti
γ source (x 1)

CASSIOPEIA A

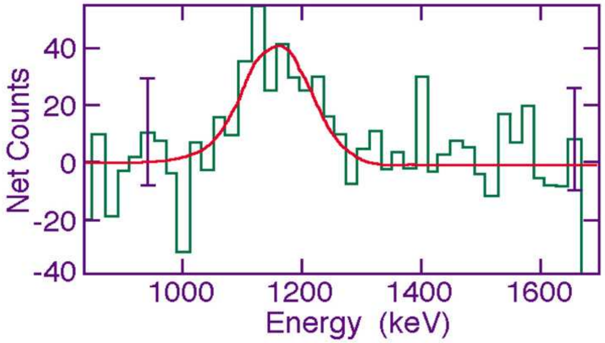

X-Ray
Optical

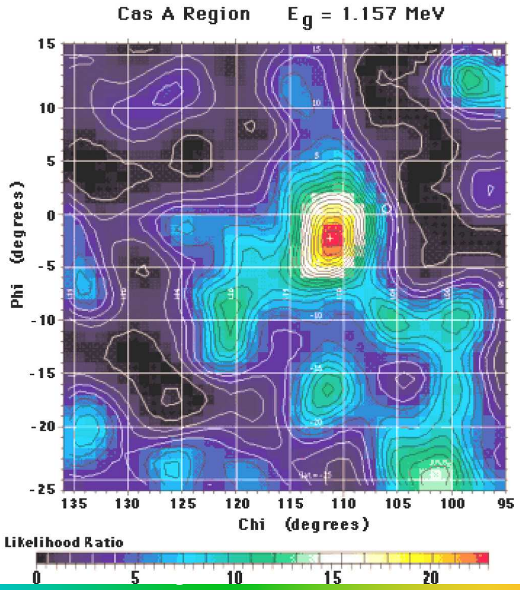

Infrared
Radio

TeV γ-rays



^{44}Ti Signal from COMPTEL





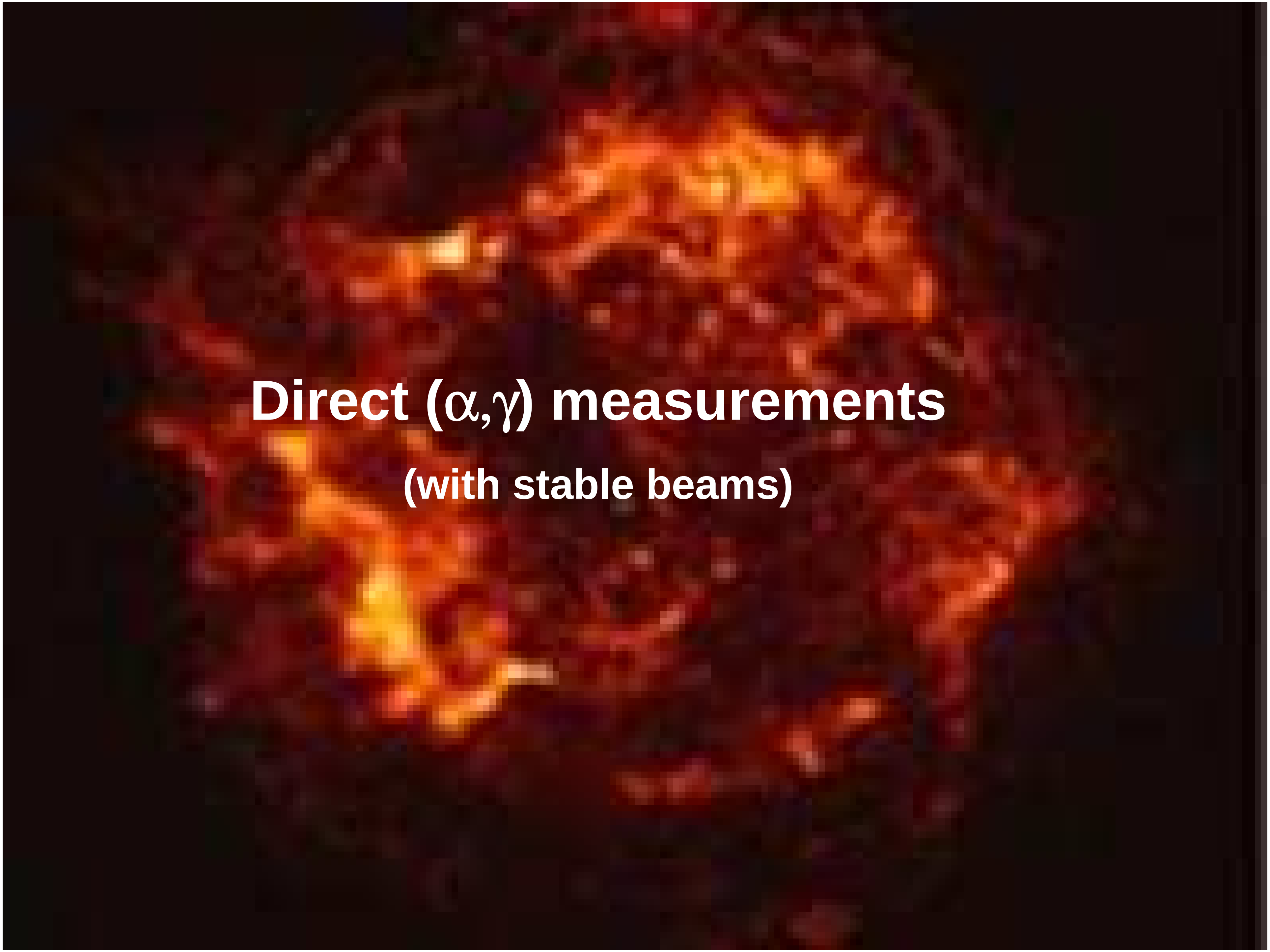
^{44}Ti (59 y)
1.157 keV

Problems with ^{44}Ti signal

- **Amount of ^{44}Ti measured in Cas A:** **160±60 $\mu M_{\odot}$ (3x10^{26} kg)**
- **Amount of ^{44}Ti <u>calculated</u>:** **20 - 80 $\mu M_{\odot}$**

(for comparison: mass of the earth ~ 6x10^{24} kg)

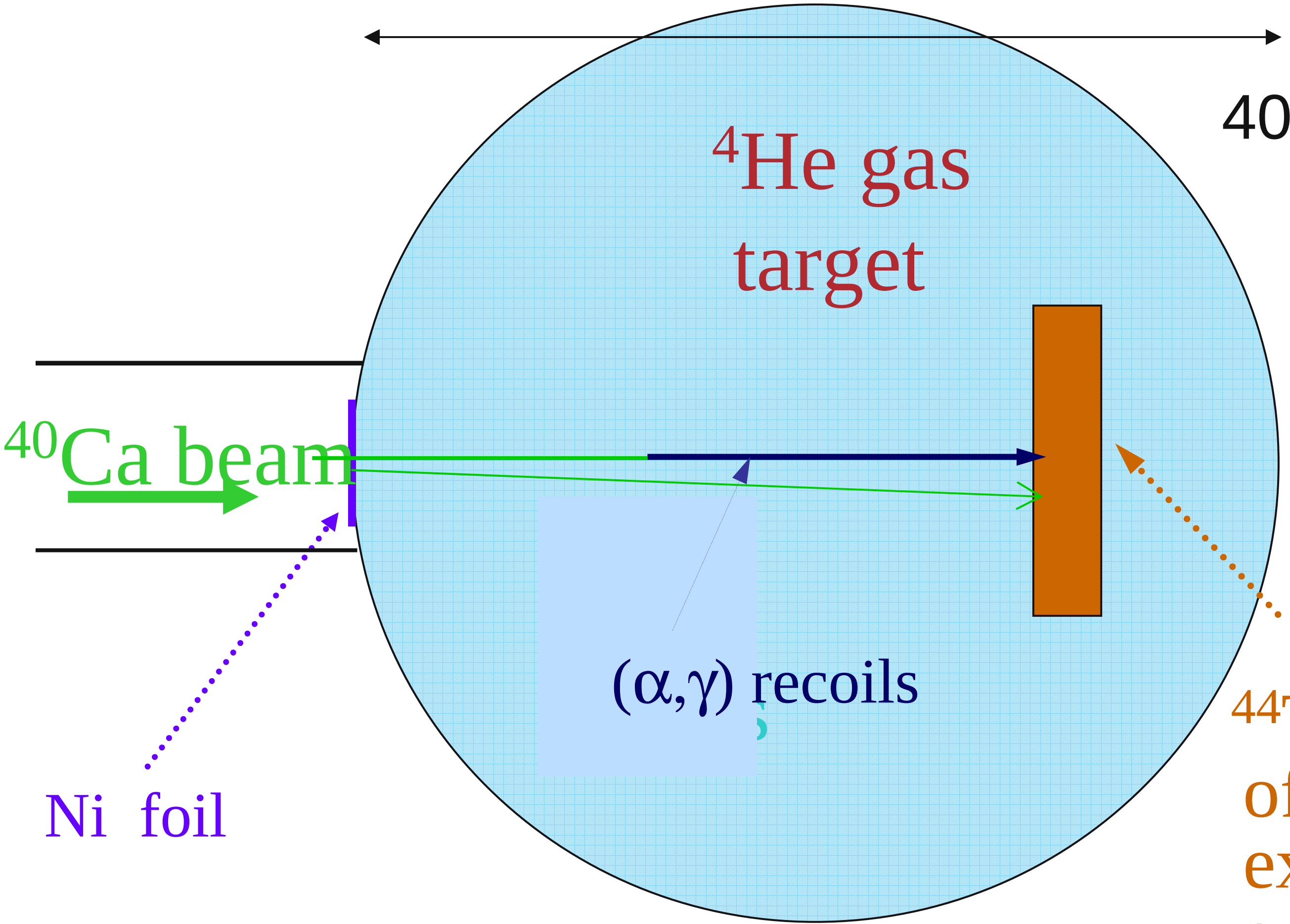
Mn 1246° 2061° +2+3+4+7 54.938049 0.000031%	Mn44	Mn45	Mn46 41 ms ECp	Mn47 100 ms ECp	Mn48 158.1 ms 4+ ECp,ECα,...	Mn49 382 ms 5/2- EC	Mn50 283.88 ms 0+ * EC	Mn51 46.2 m 5/2- EC	Mn52 5.591 d 6+ * EC	Mn53 3.74E+6 y 7/2- EC
Cr42	Cr43 21 ms (3/2+) ECp,ECα,...	Cr44 53 ms 0+ ECp	Cr45 50 ms ECp	Cr46 0.26 s 0+ EC	Cr47 500 ms 3/2- EC	Cr48 21.56 h 0+ EC	Cr49 42.3 m 5/2-	Cr50 1.8E+17 y 0+ ECEC 4.345	Cr51 27.702 d 7/2- EC	Cr52 0+ 83.789
V41	V42	V43 800 ms (7/2-) EC	V44 90 ms (2+) * ECα	V45 547 ms 7/2- EC	EC	V47 32.6 m /2- EC	V48 15.9735 d 4+ EC	V49 330 d 7/2-	V50 1.4E+17 y 6+ EC,β^- 0.250	V51 7/2- 99.750
Ti40 50 ms 0+ EC	Ti41 80 ms 3/2+ ECp	Ti42 199 ms 0+ EC	Ti43 509 ms 7/2- EC	Ti44 63 y 0+ EC	Ti45 184.8 m 7/2- EC	Ti46 0+ 8.0	Ti47 5/2- 7.3	Ti48 0+ 73.8	Ti49 7/2- 5.5	Ti50 0+ 5.4
Sc39 (7/2-)	Sc40 182.3 ms 4- ECp,ECα,...	Sc41 596.3 ms 7/2- EC	Sc42 681.3 ms + * EC	Sc43 3.891 h 7/2- EC	Sc44 3.927 h 2+ * EC	Sc45 7/2- * 100	Sc46 83.79 d 4+ * β^-	Sc47 3.3492 d 7/2- β^-	Sc48 43.67 h 6+ β^-	Sc49 57.2 m 7/2- β^-
Ca38 440 ms 0+ EC	Ca39 859.6 ms 3/2+ EC	Ca40 0+ 96.941	Ca41 1.03E+5 y 7/2- EC	Ca42 0+ 0.647	Ca43 7/2- 0.135	Ca44 0+ 2.086	Ca45 162.61 d 7/2- β^-	Ca46 0+ 0.004	Ca47 4.536 d 7/2- β^-	Ca48 6E+18 y 0+ β^-,$\beta^-\beta^-$ 0.187
K37 1.226 s 3/2+ EC	K38 7.636 m 3+ * EC	K39 3/2+ 93.2581	K40 1.277E+9 y 4- EC,β^- 0.0117	K41 3/2+ 6.7302	K42 12.360 h 2- β^-	K43 22.3 h 3/2+ β^-	K44 22.13 m 2- β^-	K45 17.3 m 3/2+ β^-	K46 105 s (2-) β^-	K47 17.50 s 1/2+ β^-
Ar36 0+ 0.337	Ar37 35.04 d 3/2+ EC	Ar38 0+ 0.063	Ar39 269 y 7/2- β^-	Ar40 0+ 99.600	Ar41 109.34 m 7/2- β^-	Ar42 32.9 y 0+ β^-	Ar43 5.37 m (3/2,5/2) β^-	Ar44 11.87 m 0+ β^-	Ar45 21.48 s β^-	Ar46 8.4 s 0+ β^-



Direct (α,γ) measurements

(with stable beams)

Experimental setup for the $^{40}Ca(\alpha,\gamma)^{44}Ti$ experiment :



40 cm

^{4}He gas target

^{40}Ca beam

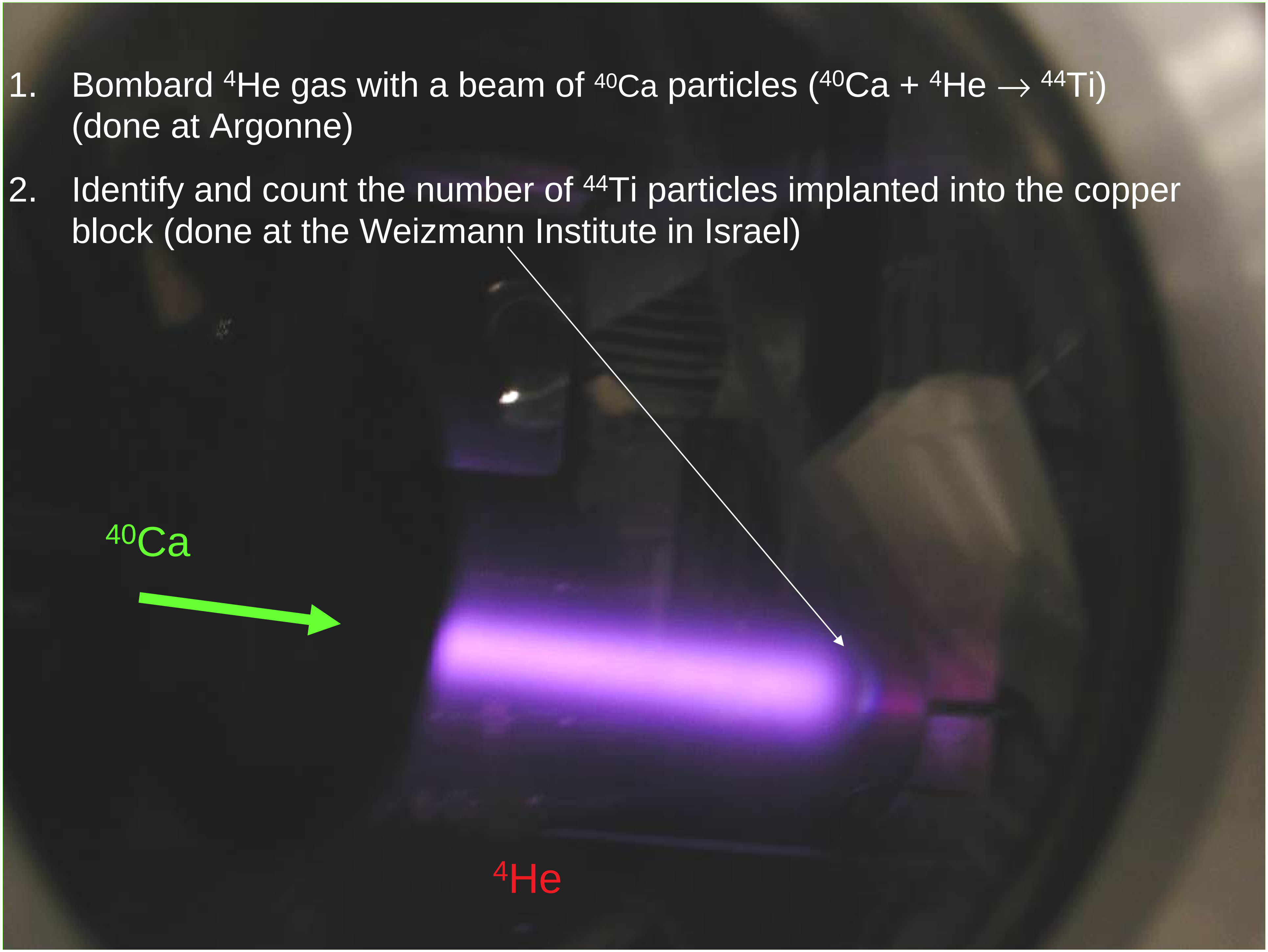
(α,γ) recoils

Ni foil

catcher : ^{44}Ti (0.0004 Bq) off-line extraction and counting of atoms

Energy-integrated measurement!

1. Bombard ^{4}He gas with a beam of ^{40}Ca particles ($^{40}Ca + ^{4}He \rightarrow ^{44}Ti$) (done at Argonne)
2. Identify and count the number of ^{44}Ti particles implanted into the copper block (done at the Weizmann Institute in Israel)



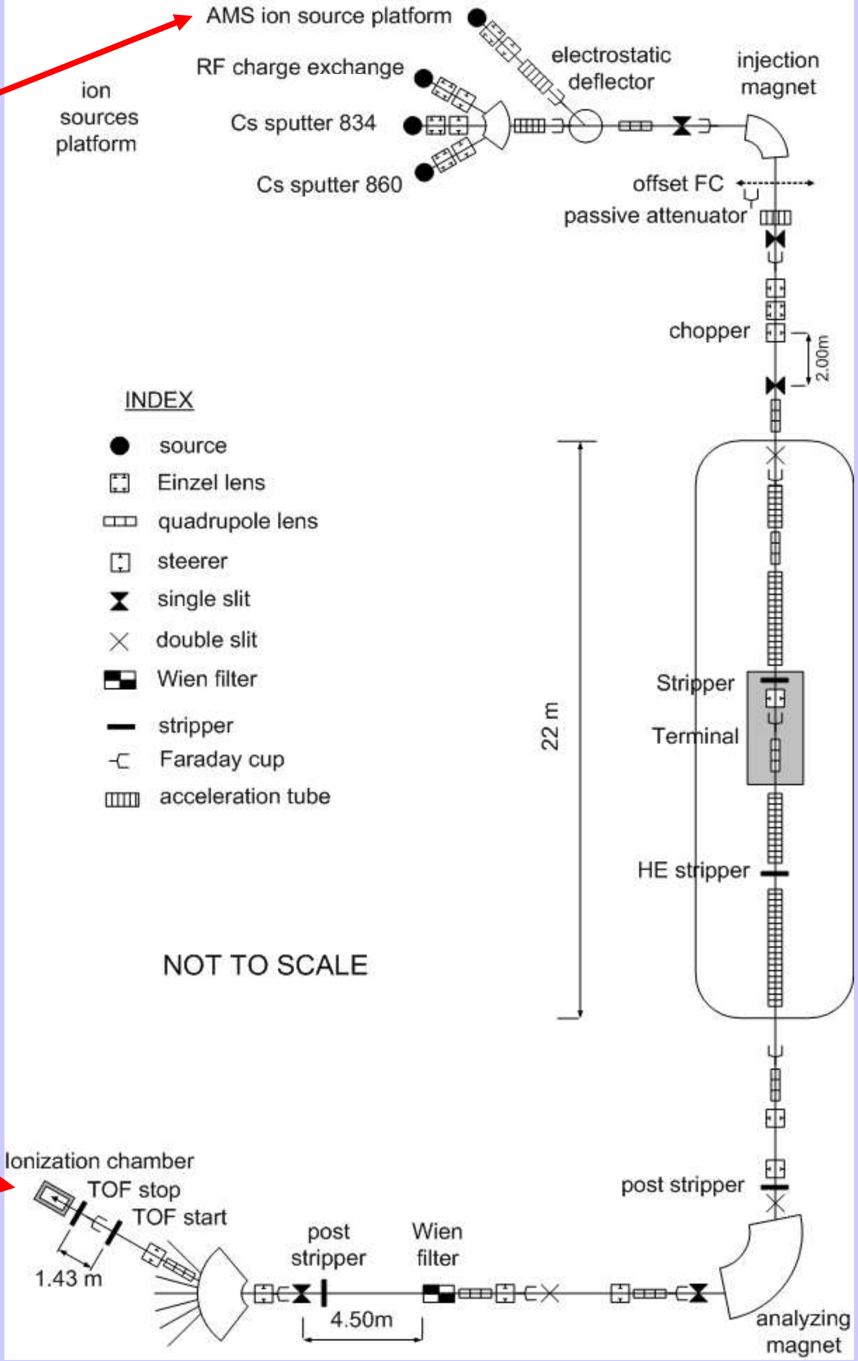
ion source

$^{(44+nat)}TiO_2 \rightarrow {}^{44,46}Ti^-$

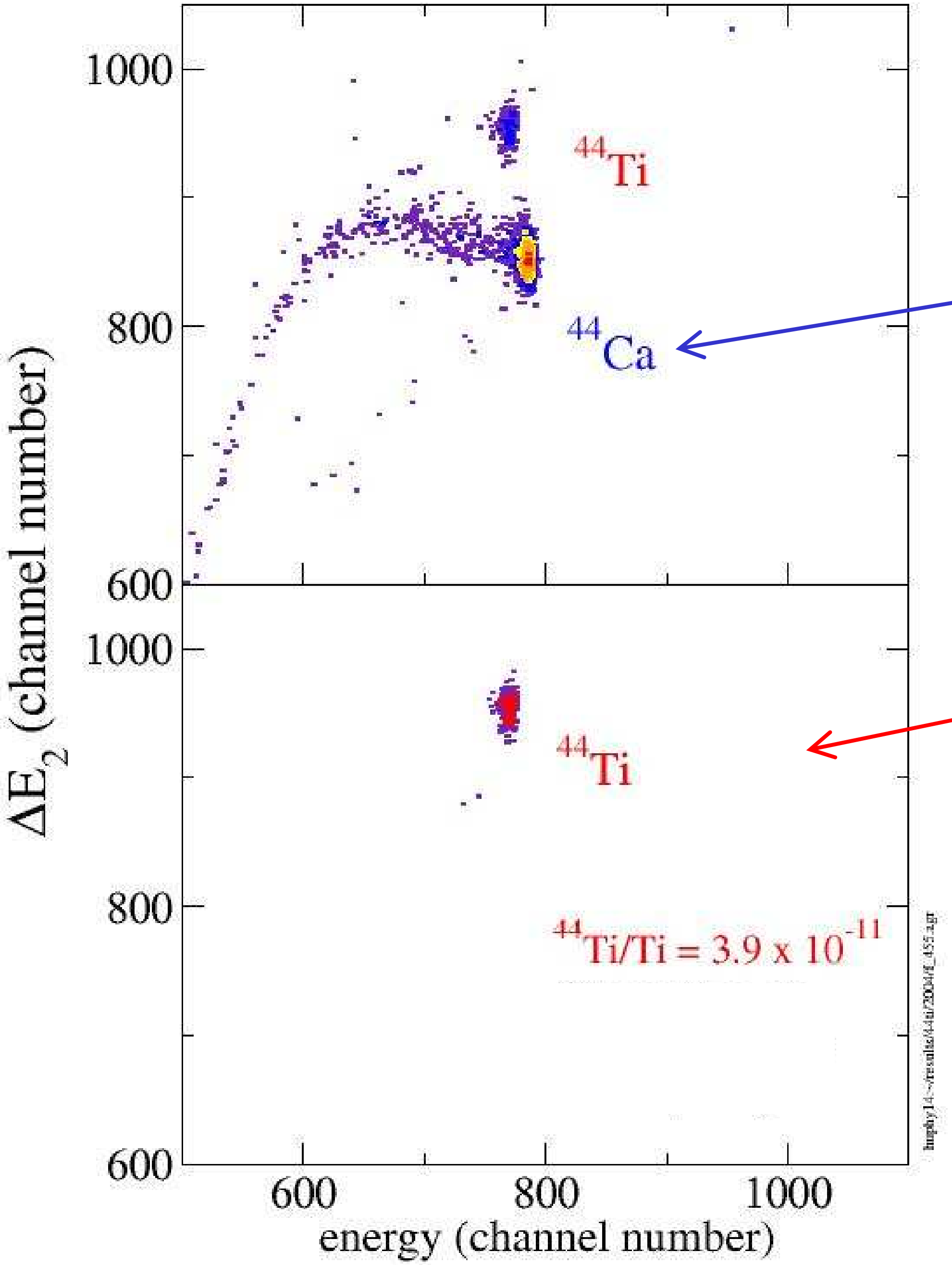
14UD Pelletron
Weizmann Institute
of Science, Rehovot

AMS : mass spectrometry
at high energy : 130 MeV

analysis and detection:
^{44}Ti, ^{46}Ti



tandem
accelerator

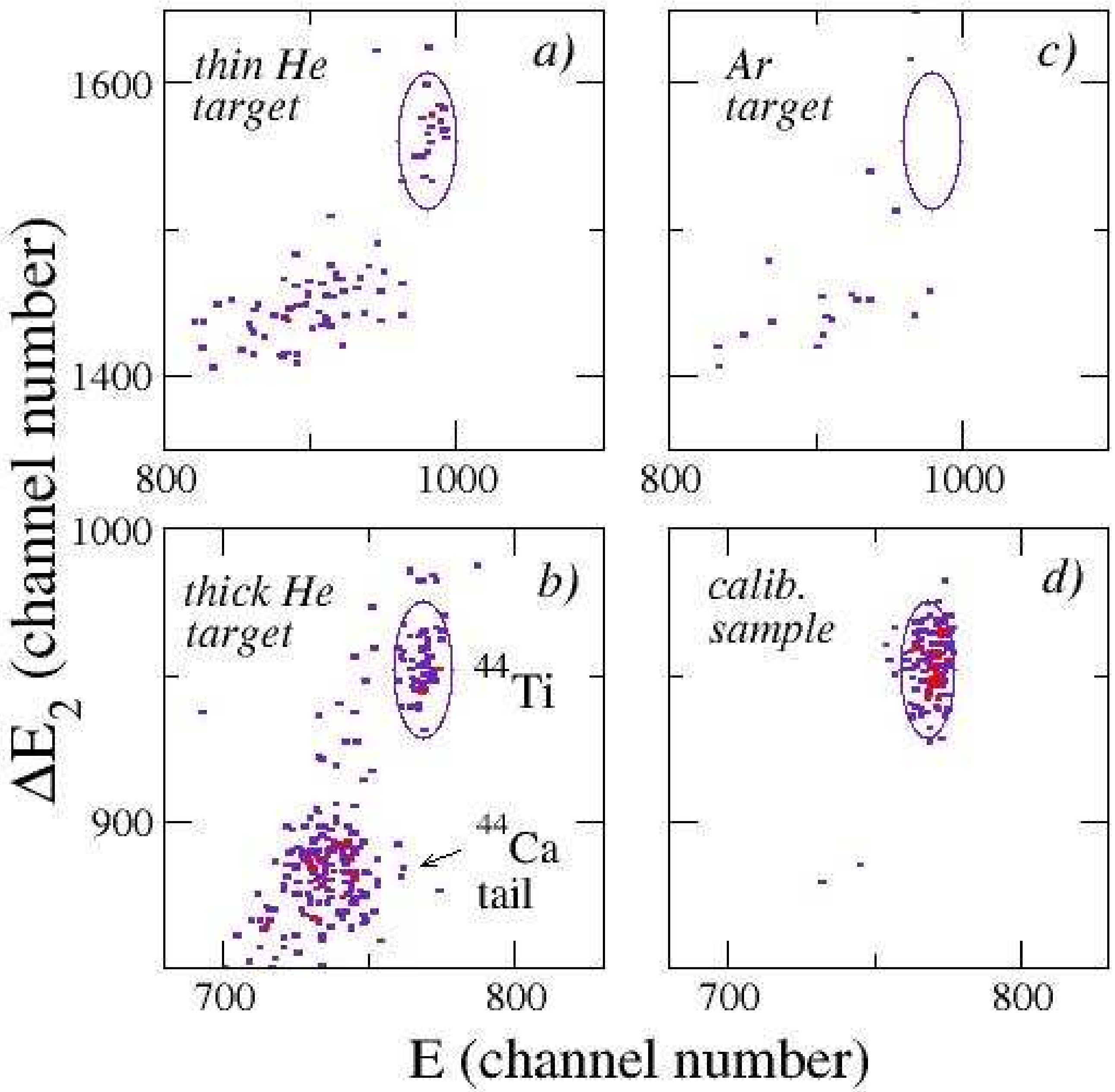


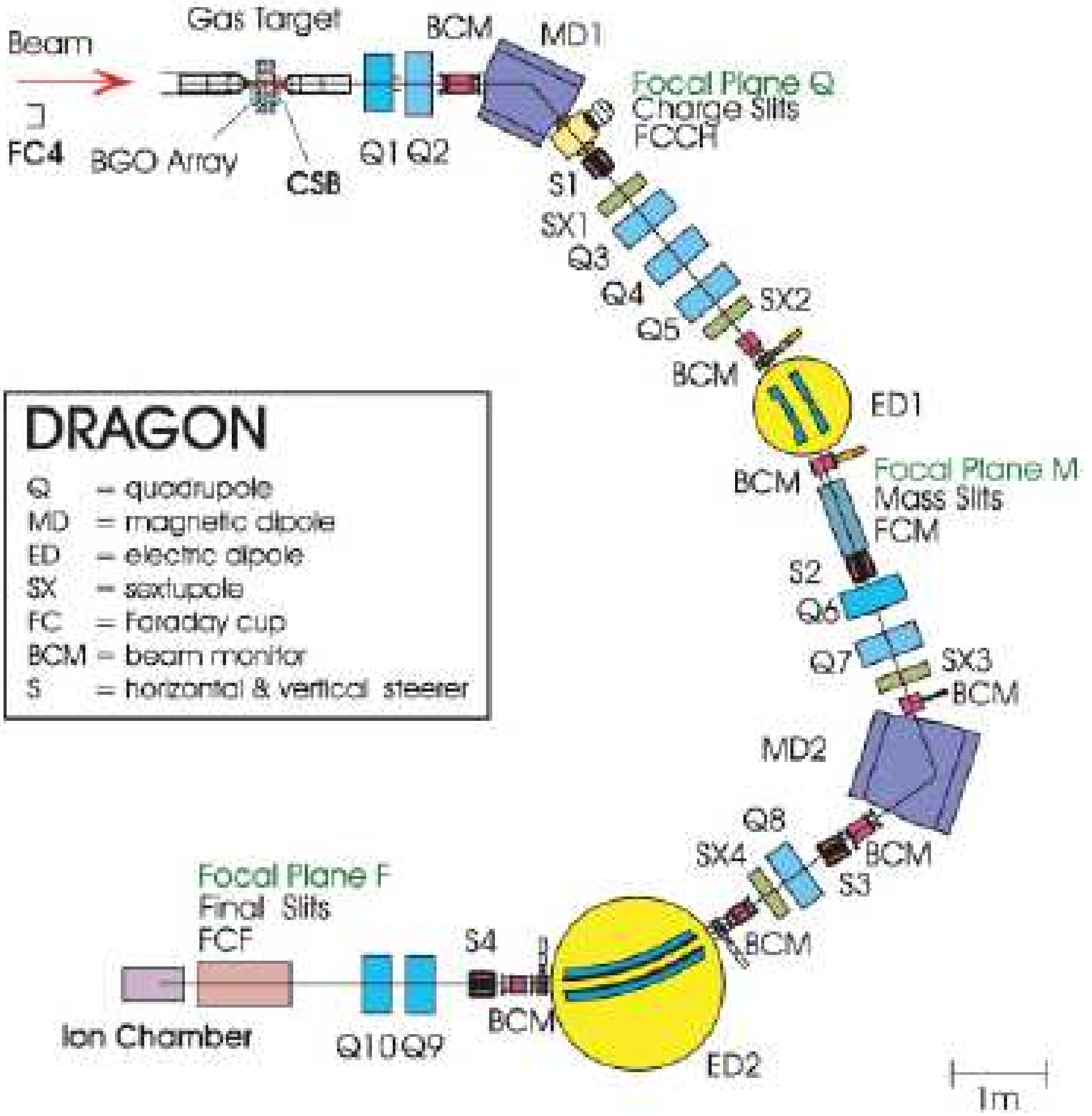
chemical
impurity

filtered
by additional
ΔE signals

^{4}He (^{40}Ca,^{44}Ti) γ

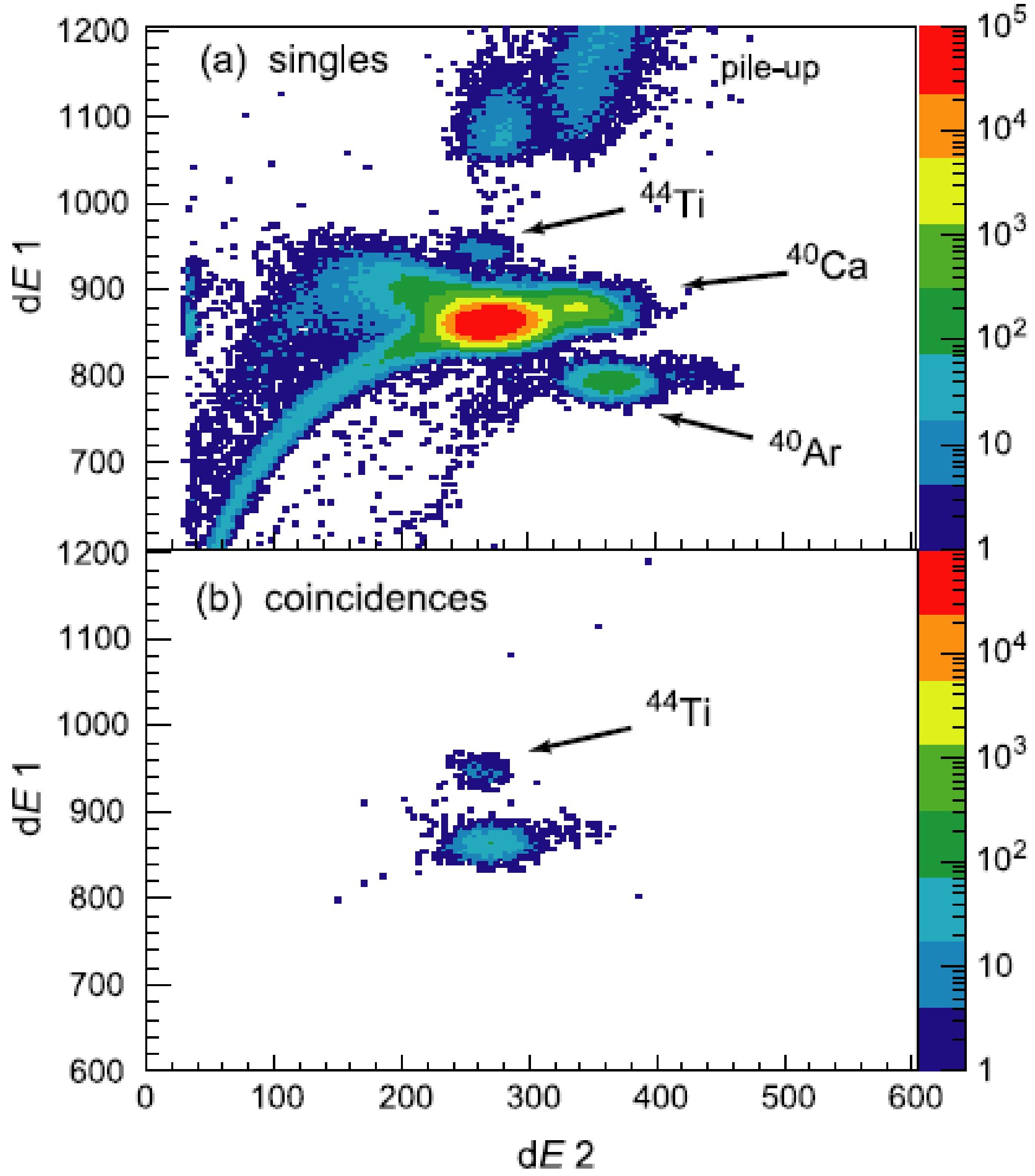
E_{cm}= 0.6 – 1.2 MeV/u

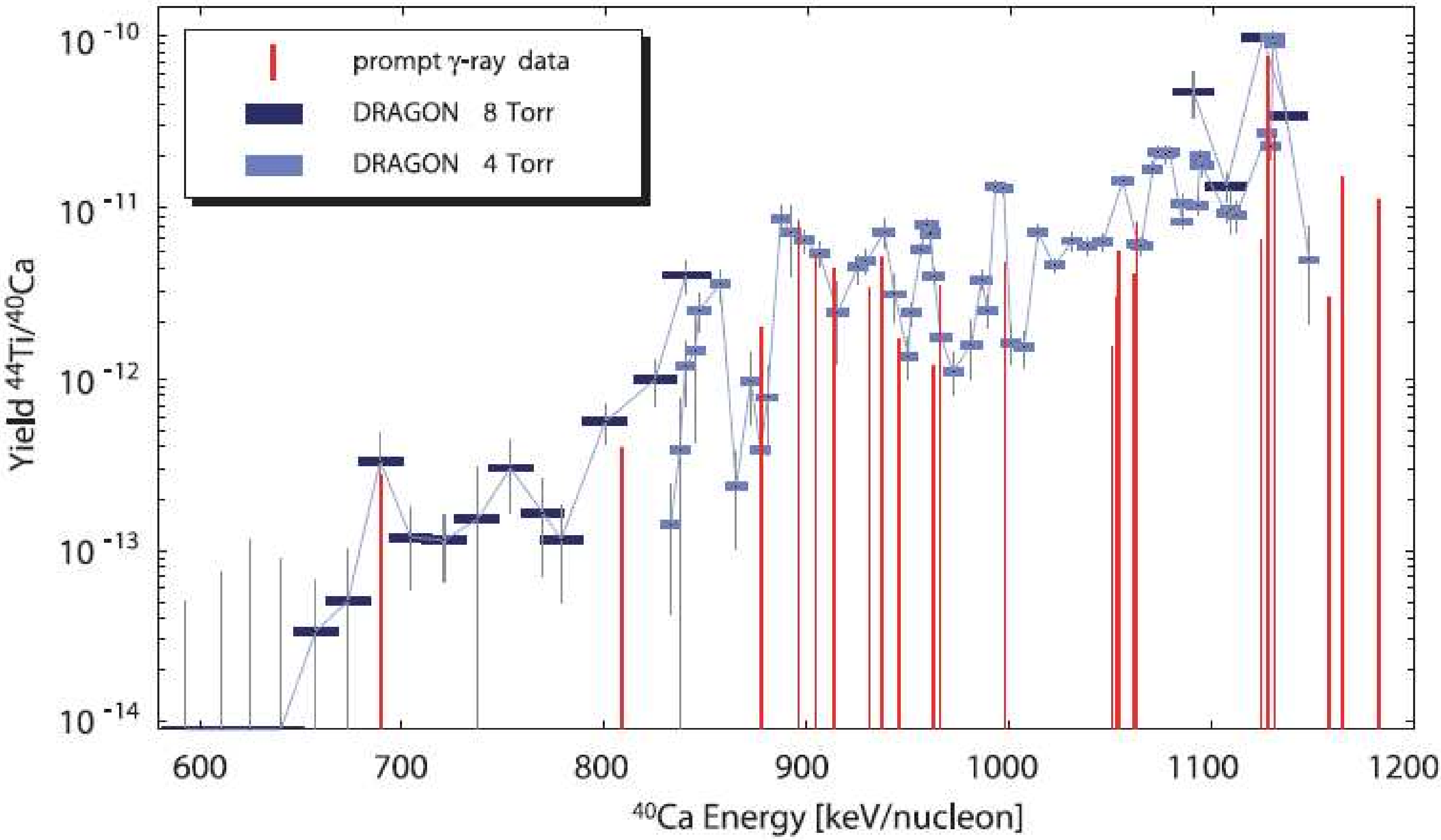


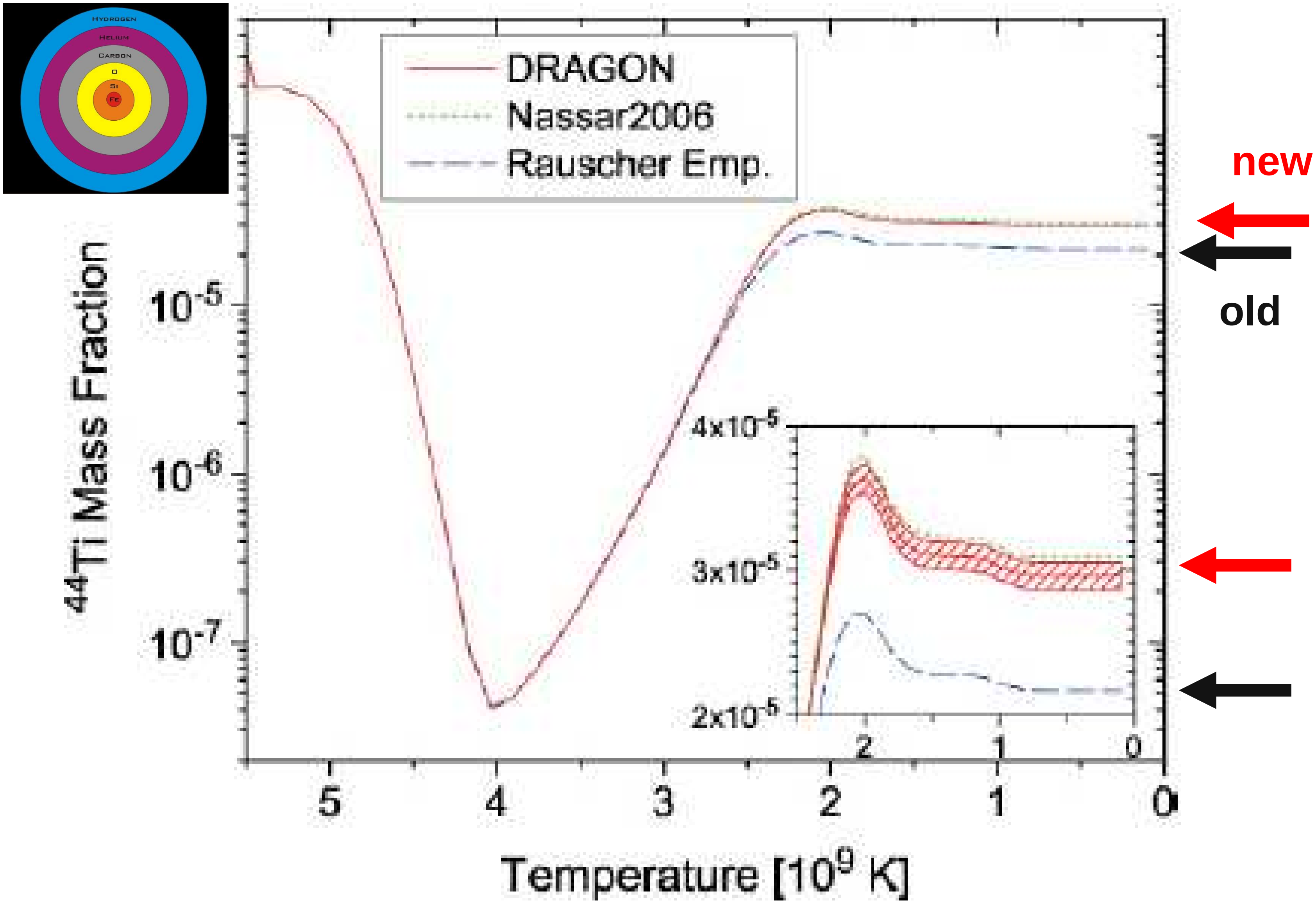


DRAGON

Q = quadrupole
MD = magnetic dipole
ED = electric dipole
SX = sextupole
FC = Faraday cup
BCM = beam monitor
S = horizontal & vertical steerer


(a) singles
pile-up
^{44}Ti
^{40}Ca
^{40}Ar
(b) coincidences
^{44}Ti
dE 1
dE 1
dE 2
1200
1100
1000
900
800
700
1200
1100
1000
900
800
700
600
0
100
200
300
400
500
600
10^5
10^4
10^3
10^2
10
1
10^4
10^3
10^2
10
1


prompt γ-ray data
DRAGON 8 Torr
DRAGON 4 Torr
10 -10
10 -11
10 -12
10 -13
10 -14
Yield 44Ti/40Ca
600
700
800
900
1000
1100
1200
40Ca Energy [keV/nucleon]


Hydrogen
Helium
Carbon
O
Si
Fe
DRAGON
Nassar2006
Rauscher Emp.
^{44}Ti Mass Fraction
10^{-5}
10^{-6}
10^{-7}
5
4
3
2
1
0
Temperature [10^9 K]
4×10^{-5}
3×10^{-5}
2×10^{-5}
2
1
0
new
old

(time)

Indirect (α,γ) measurements

$$\sigma(\alpha,\gamma) = \frac{\pi}{k^2}\frac{2J+1}{(2J_1+1)(2J_2+1)}\frac{\Gamma_a\,\Gamma_\gamma}{(E-E_r)^2+(\Gamma/2)^2}$$

for $^{15}O(\alpha,\gamma)^{19}Ne$:

E_r ✓

J ✓

Need: Γ_γ (from T_γ)

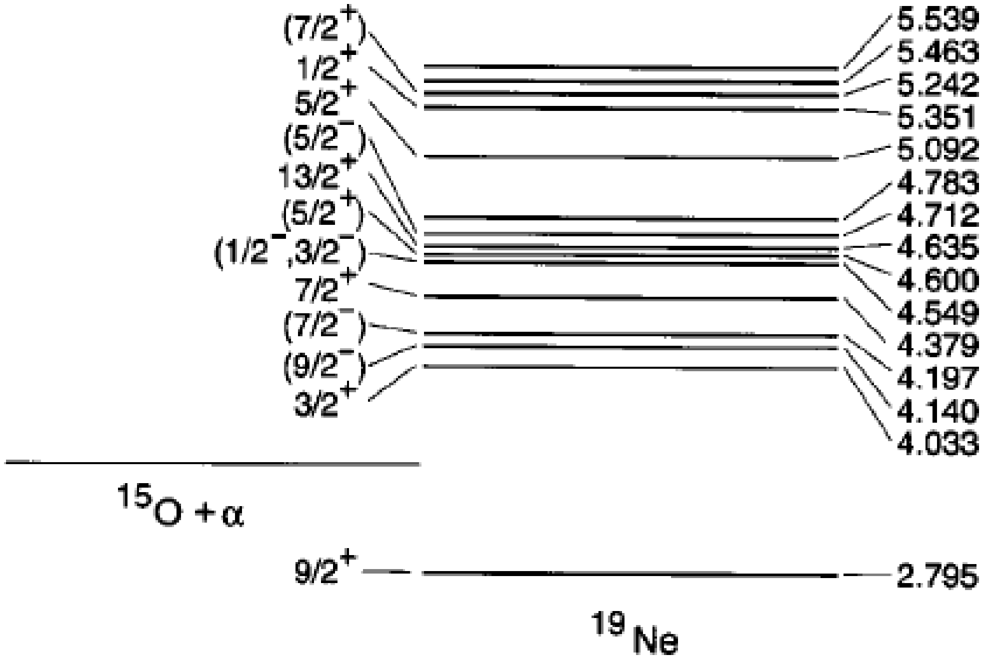
$\Gamma_\alpha/\Gamma_\gamma$

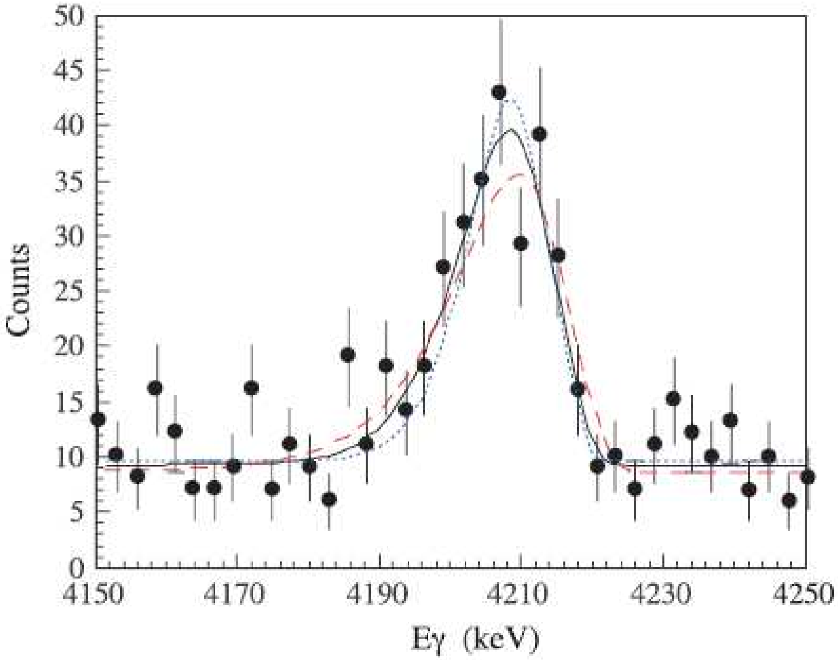
$T_{1/2}$ measurements in ^{19}Ne (Γ_γ(4.033 MeV))

W. P. Tan et al., PRC, 72, 041302(2005)

R. Kanungo et al., PRC74, 045803(2006)

S. Mythili et al., PRC 77,035803(2008)

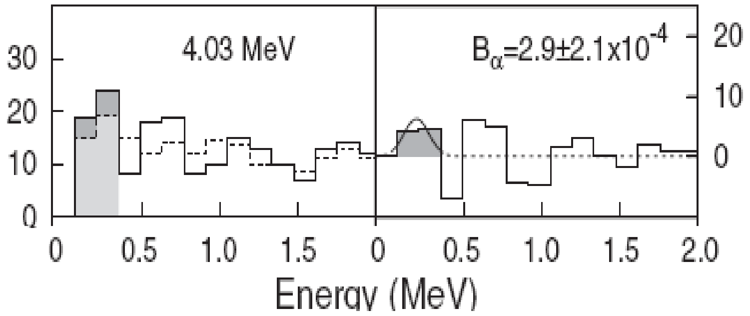




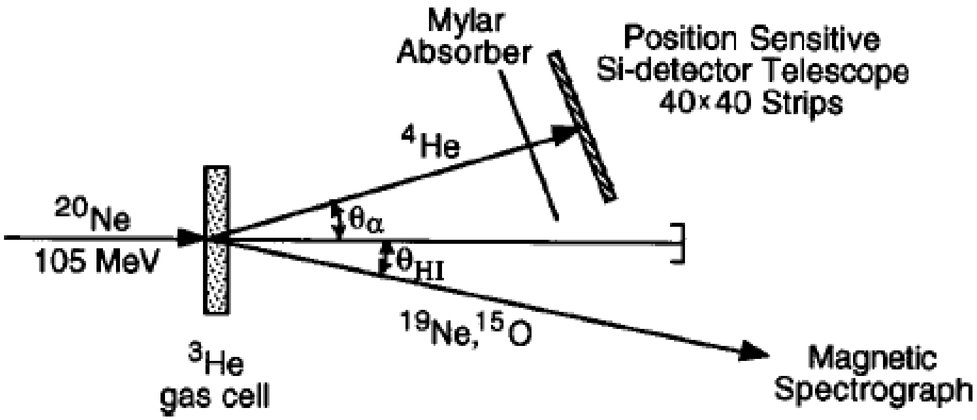
$\tau = 11^{+4}_{-3}$ fs

$(\Delta x \sim 3\mu)$

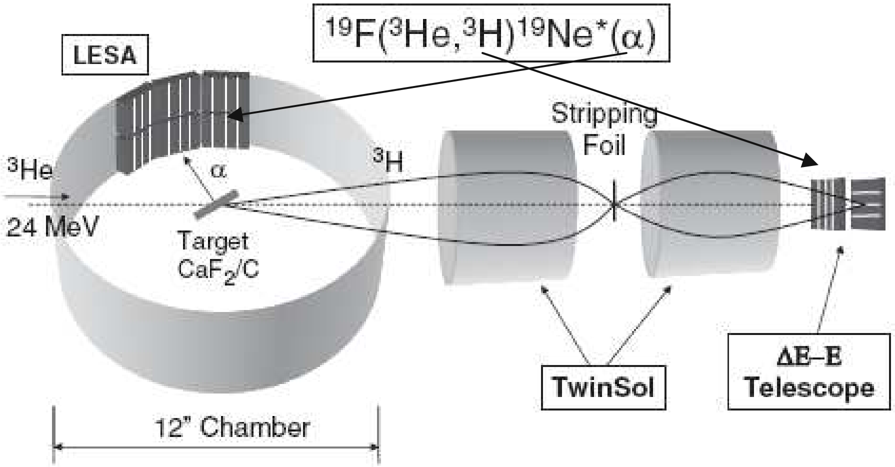
Need measurement of Γ_α or $\Gamma_\alpha/\Gamma_\gamma$



^{3}He(^{20}Ne,t)^{19}Ne→^{15}O + α

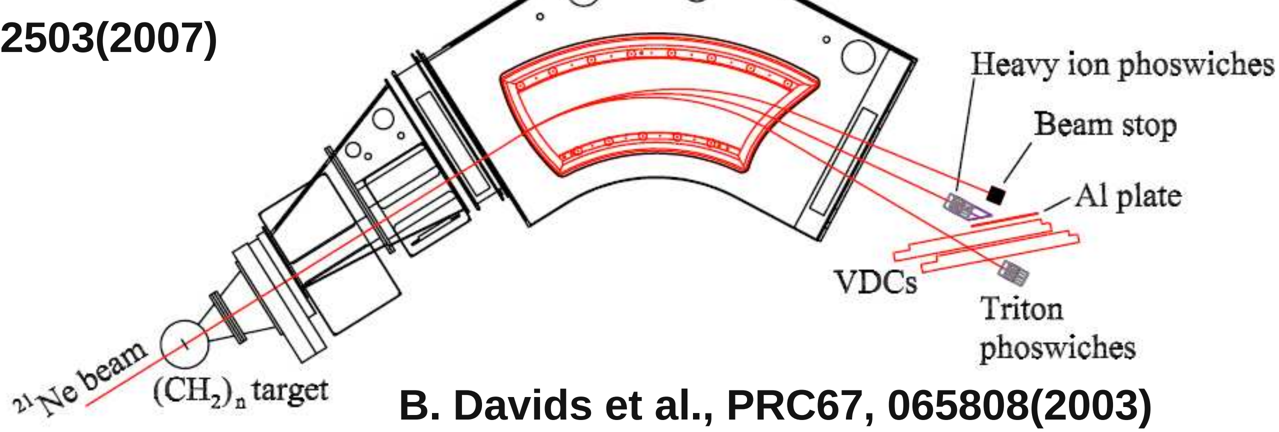


K.E. Rehm et al., PRC67, 065809(2003)



W. P. Tan et al., PRL98, 242503(2007)

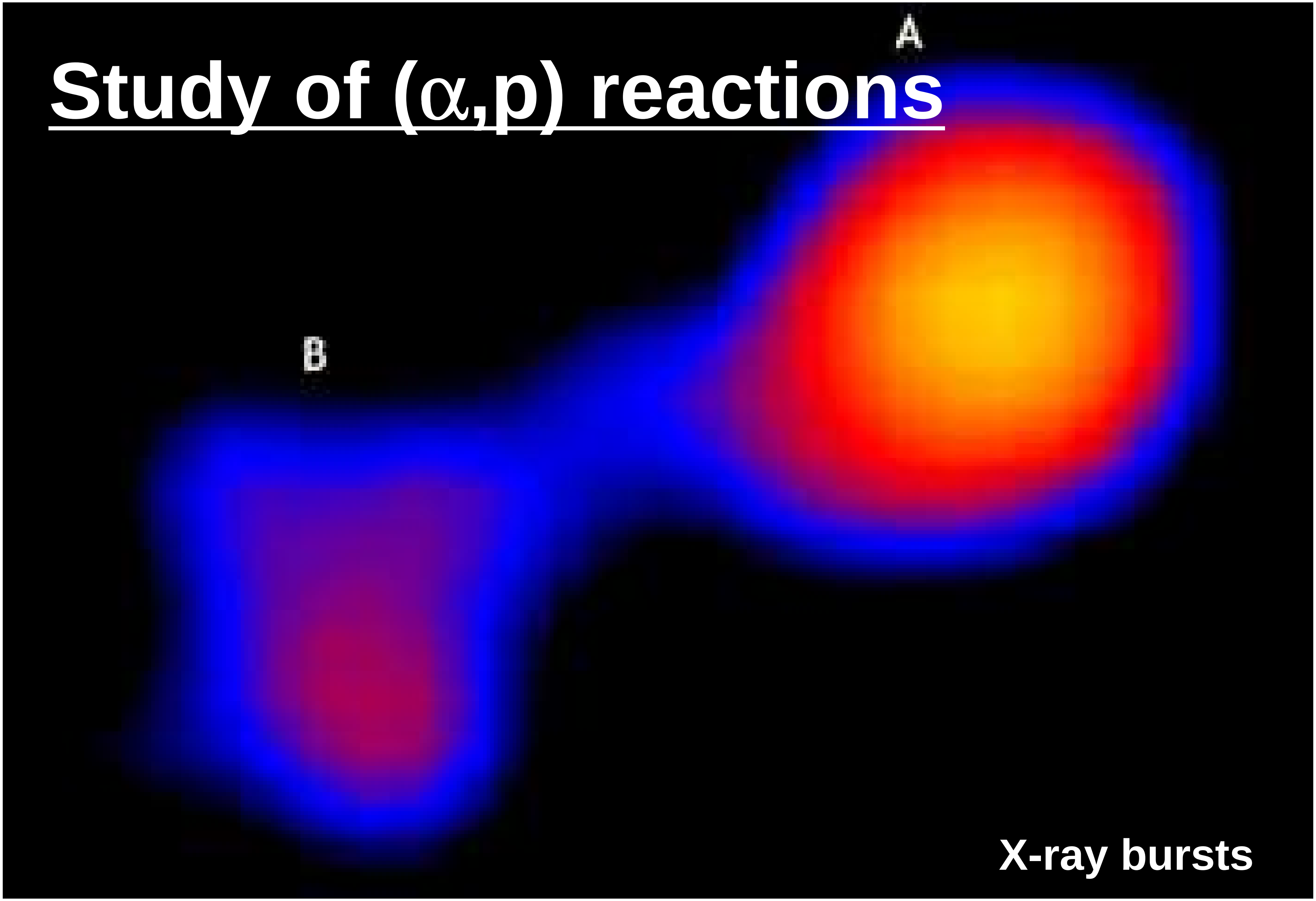
$$\boxed{\Gamma_\alpha/\Gamma_\gamma < 4x10^{-4}}$$



p(^{21}Ne,t)^{19}Ne→^{15}O + α

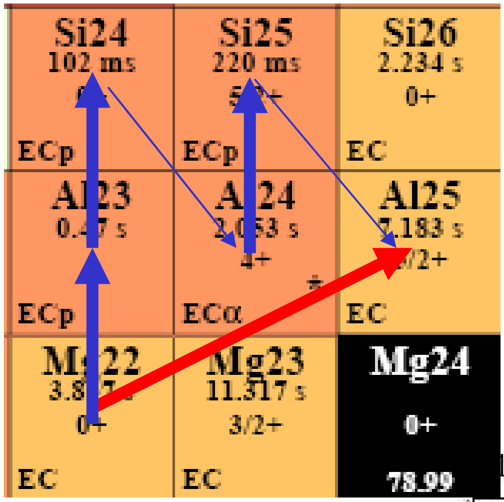
B. Davids et al., PRC67, 065808(2003)

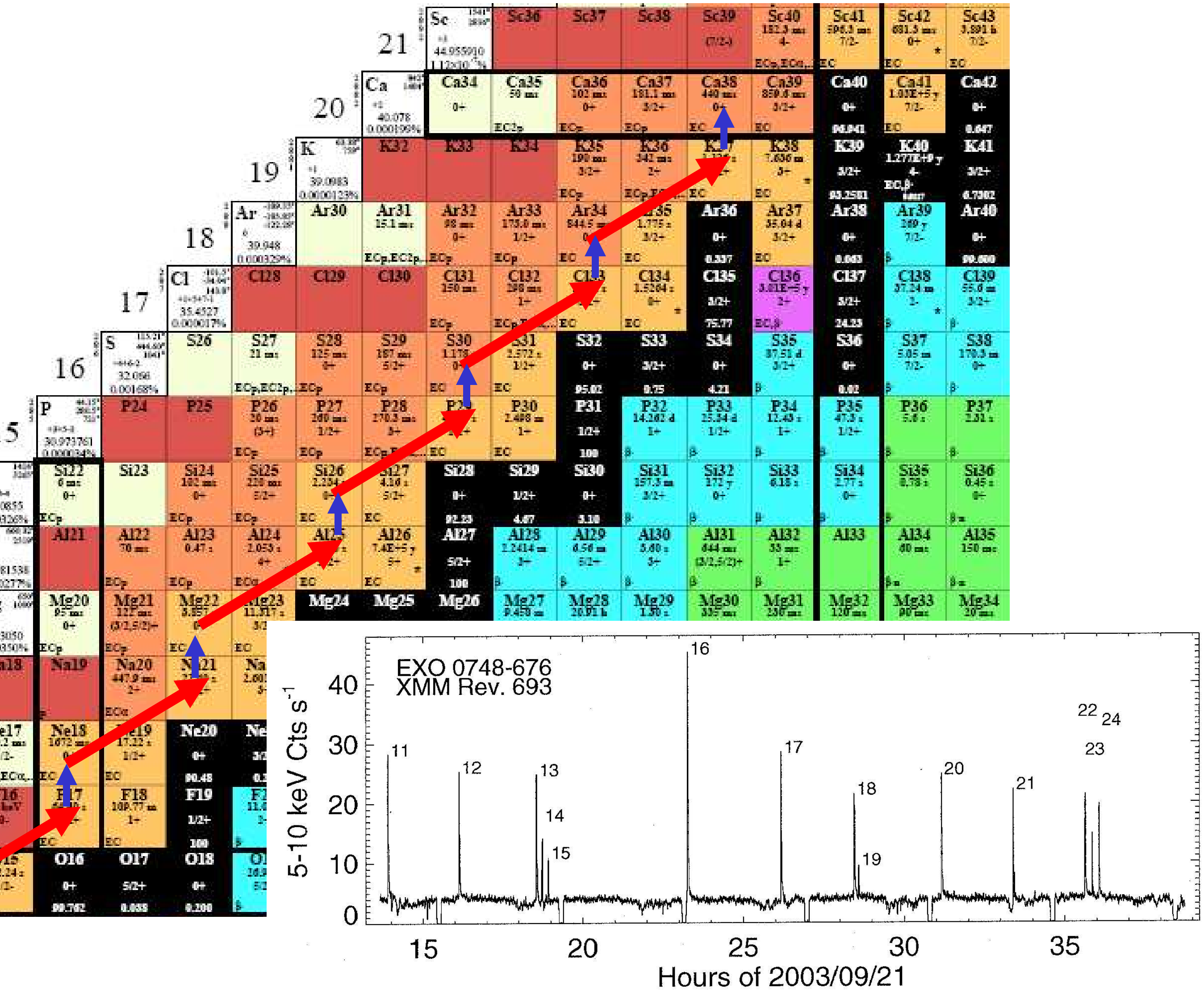
Study of (α,p) reactions



X-ray bursts

The (α,p) reaction in the (rp) process



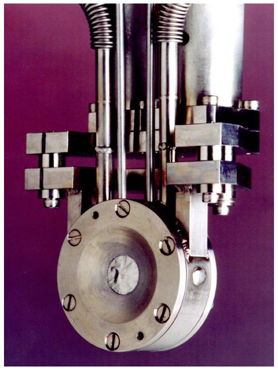


1 (α,p) =

3 (p,γ) +
2 β dec.

But, need ^{4}He,
Coulomb Barrier

Direct measurement of ^{44}Ti(α,p)^{47}V in inverse kinematics

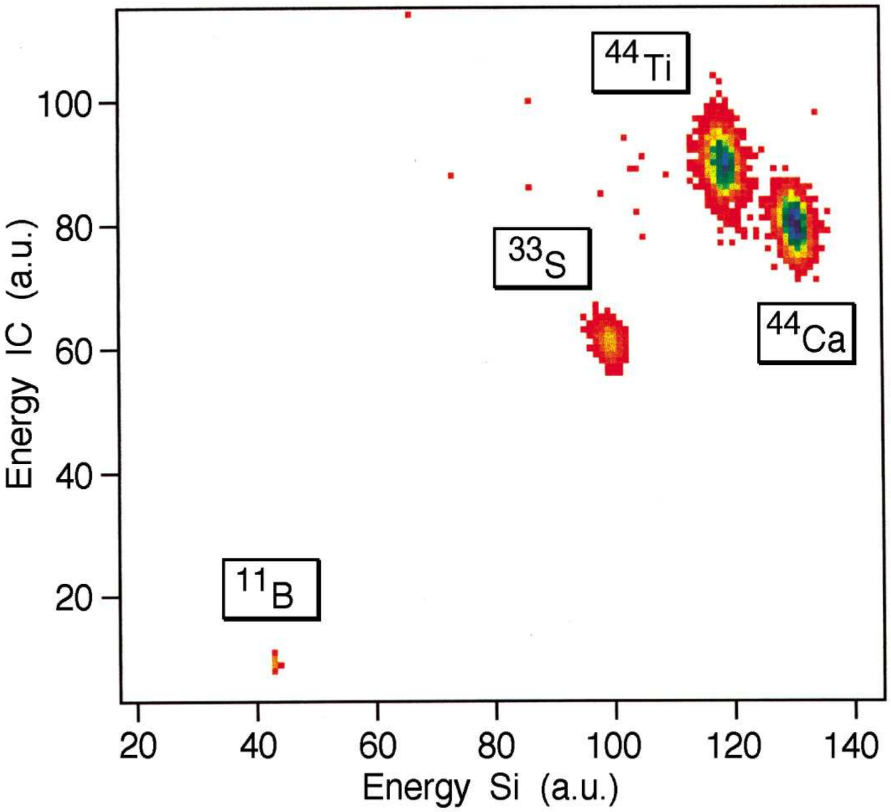


^{4}He target

A. Sonzogni et al., PRL84, 1651(2000)

Beam contaminants at ATLAS(^{44}Ti)

(measure $^{44}Ti(\alpha,p)^{47}V$ and $^{44}Ca(\alpha,p)^{47}Sc$)



$$\frac{\Delta m}{m}\,(^{44}Ti - {}^{44}Ca) = 1.1 \times 10^{-4}$$

Beam Contaminants: $^{44}Ca^{8+}$

$^{33}S^{6+}$

($^{22}Ne^{4+}$)

$^{11}B^{2+}$

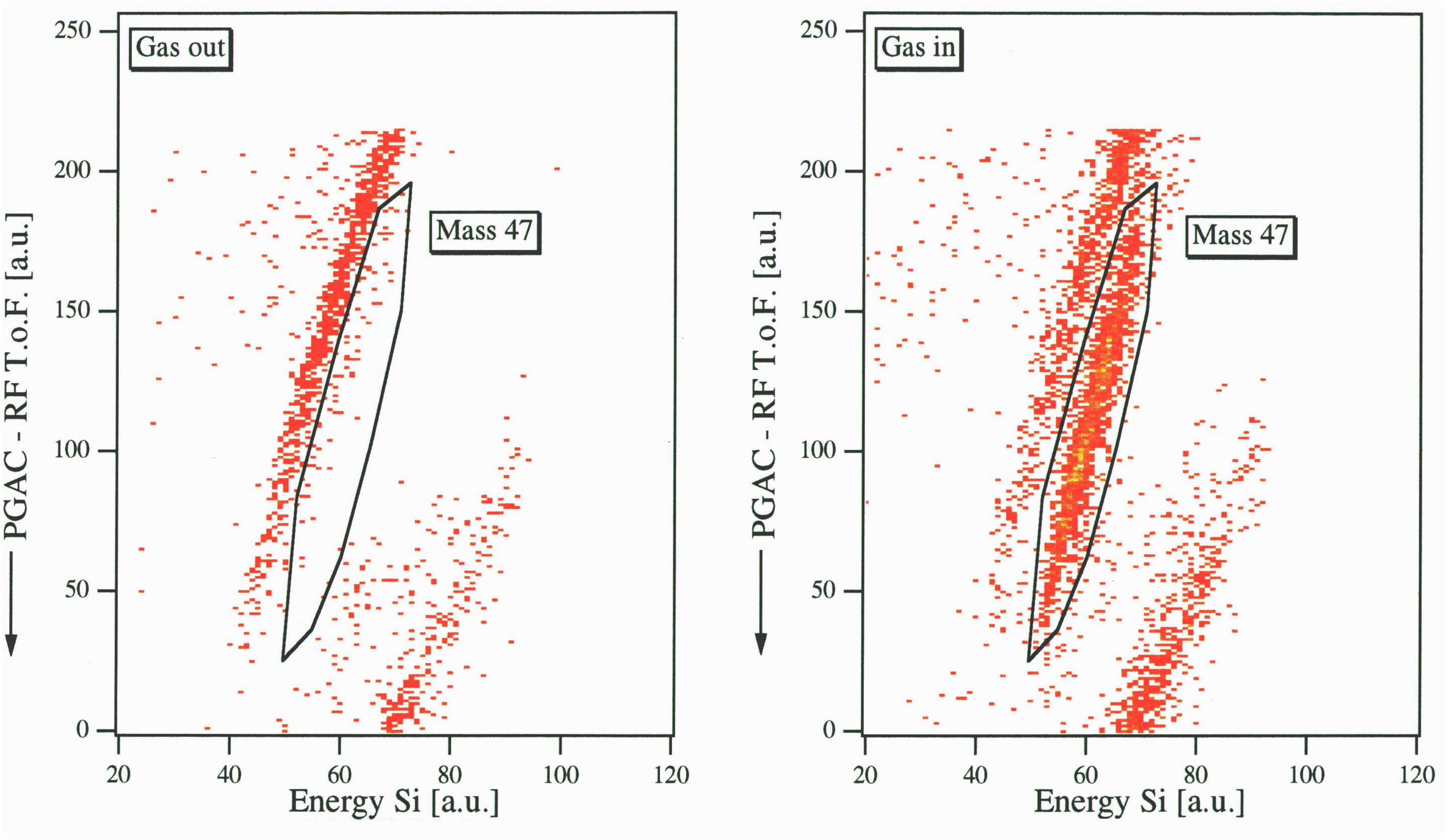
Injected mass: $^{44}TiO^-$ (mass 60)

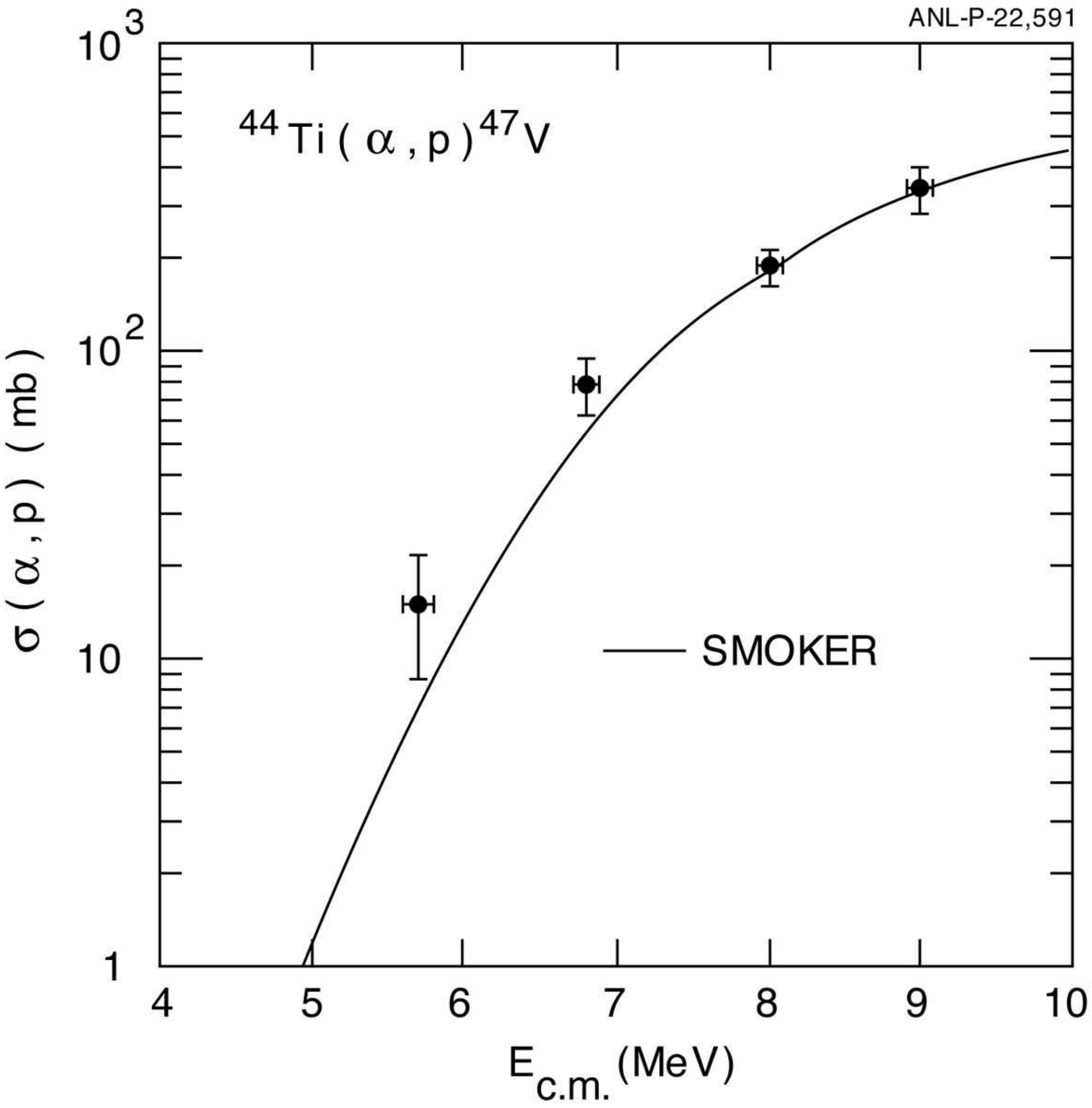
$^{44}CaO^-$

$^{33}SC_xH_y$(?)

$^{11}B_xC_yH_z$ (?)

$^{4}He(^{44}Ti,^{47}V)p$ or $^{4}He(^{44}Ca,^{47}Sc)p$

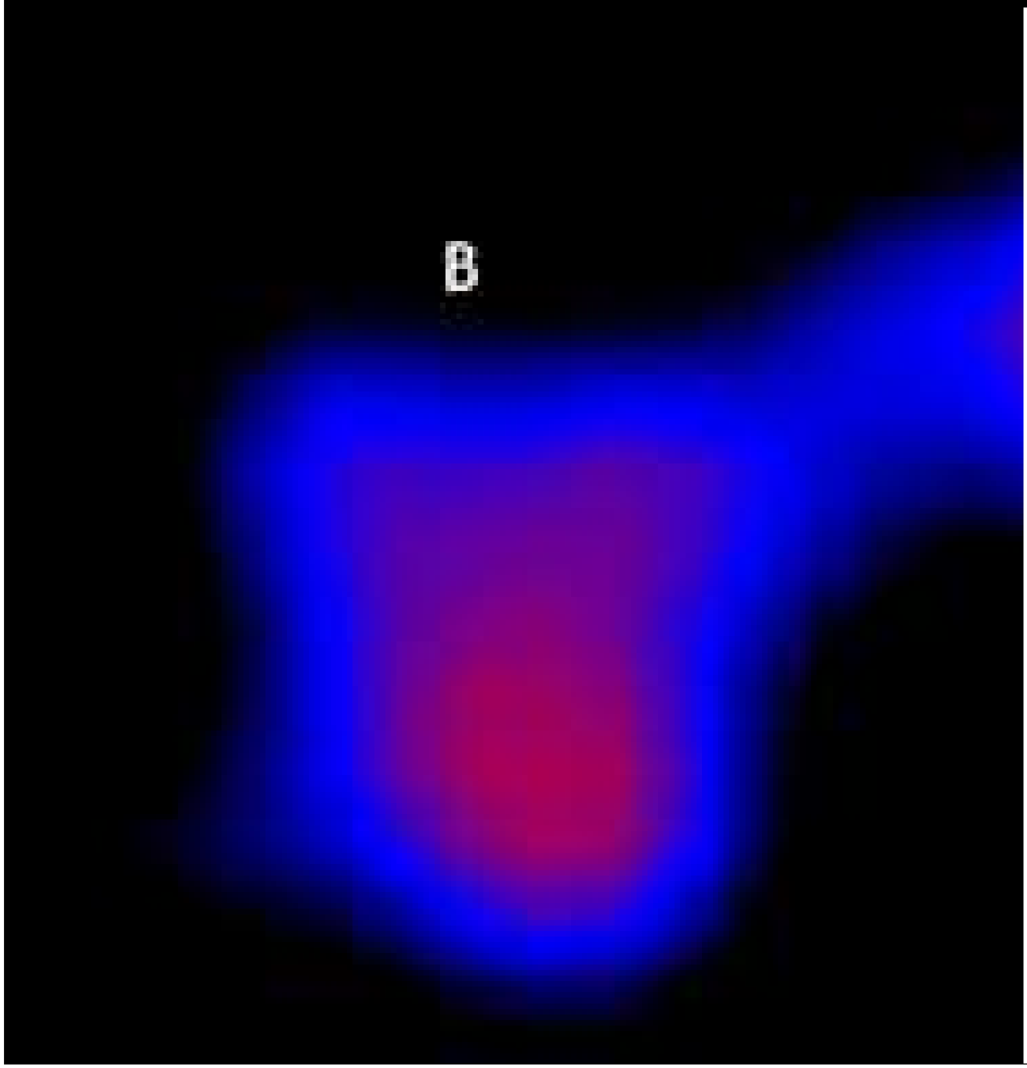


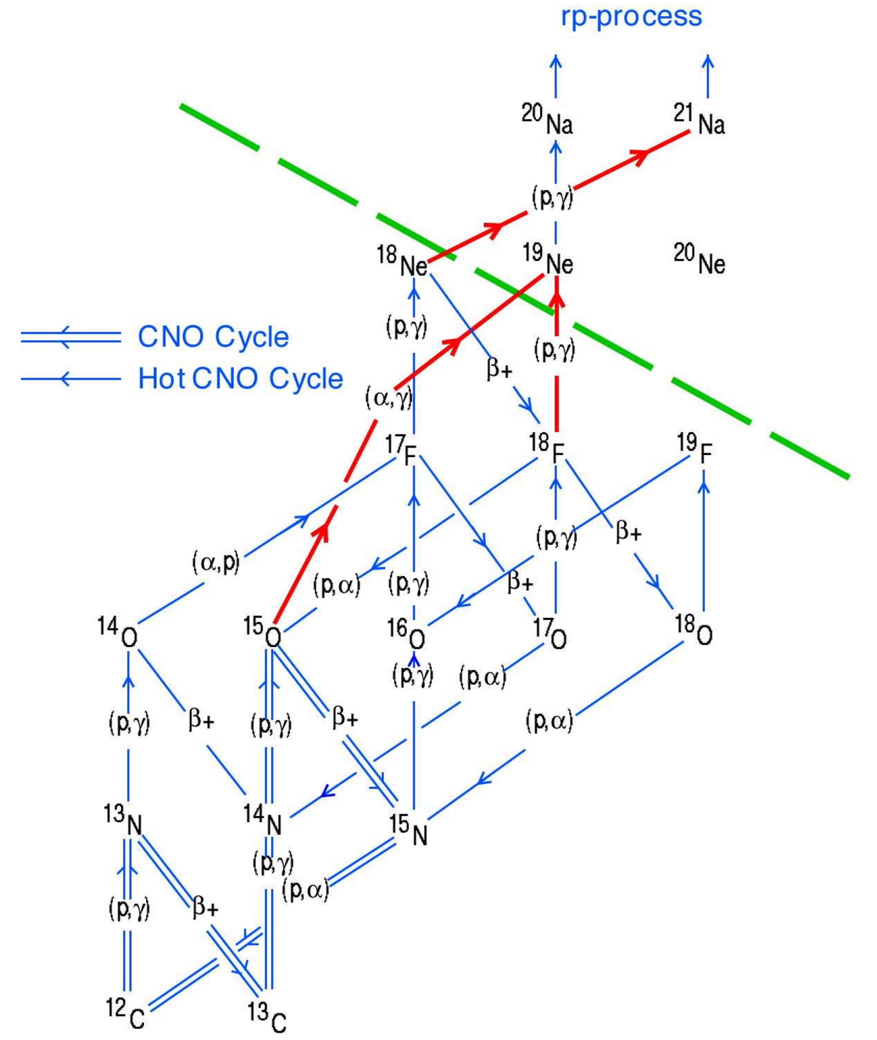


A. Sonzogni et al., PRL84, 1651(2000)

The ^{18}Ne(α,p) reaction:

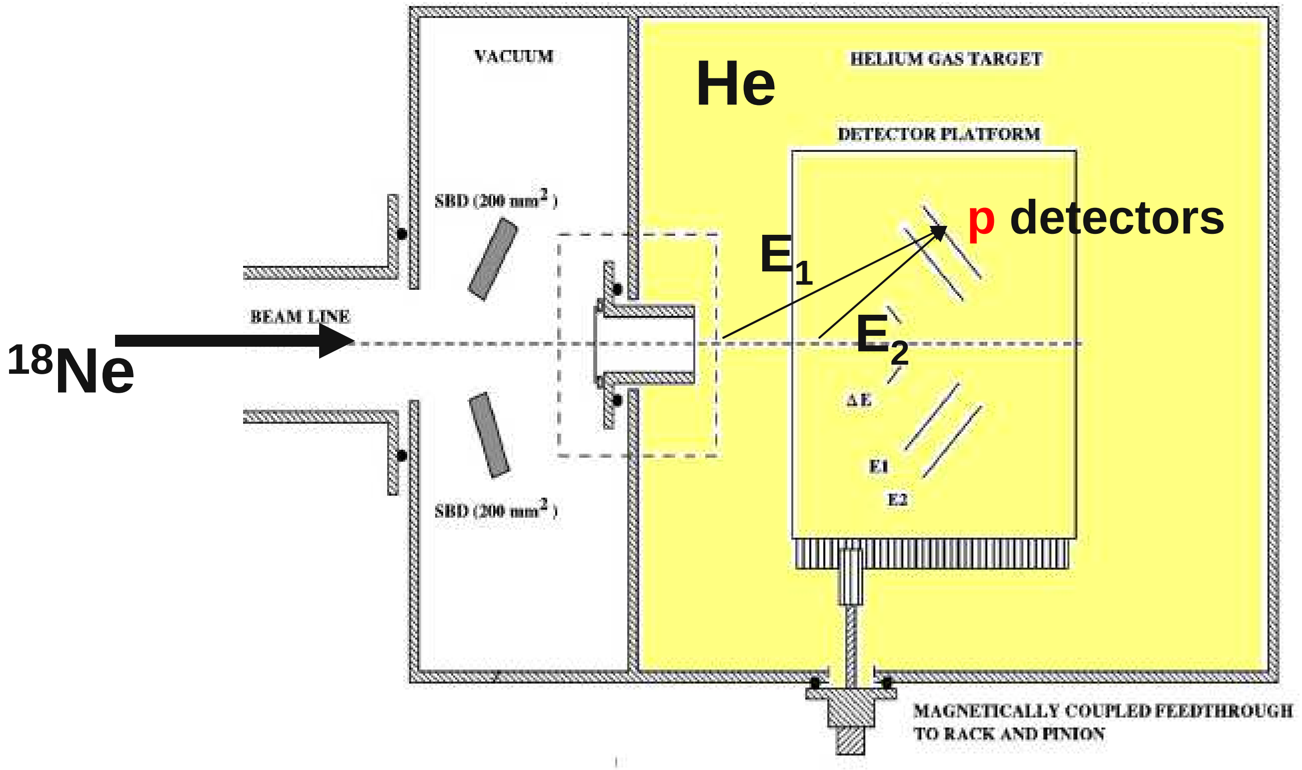
breakout from the hot CNO cycle





Direct measurement of ^{18}Ne(α,p)^{21}Na:

For recoil separator would need a large acceptance



- **Efficiencies**
- **Transitions to excited states**
- **Limited to higher energies**

W. Bradfield-Smith et al., PRC59, 3402(1999)
D. Groombridge et al. PRC66,055802(2002)

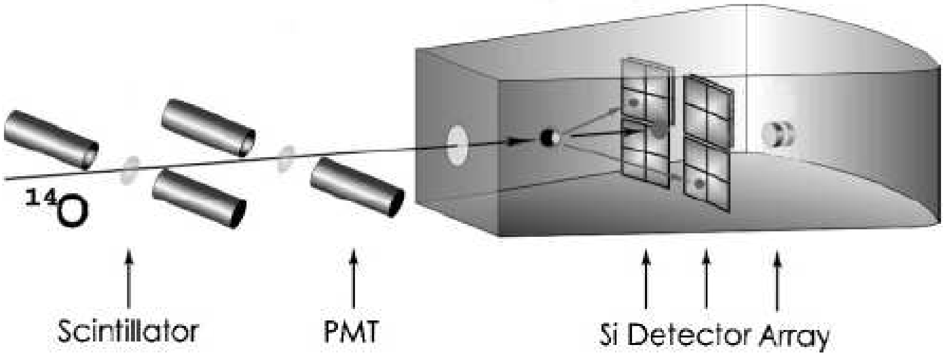
Indirect methods (α,p):

Inverse reactions:

^{21}Na(p,α)^{18}Ne, see: S. Sinha et al., BAPS 2004 2004 and to be publ.

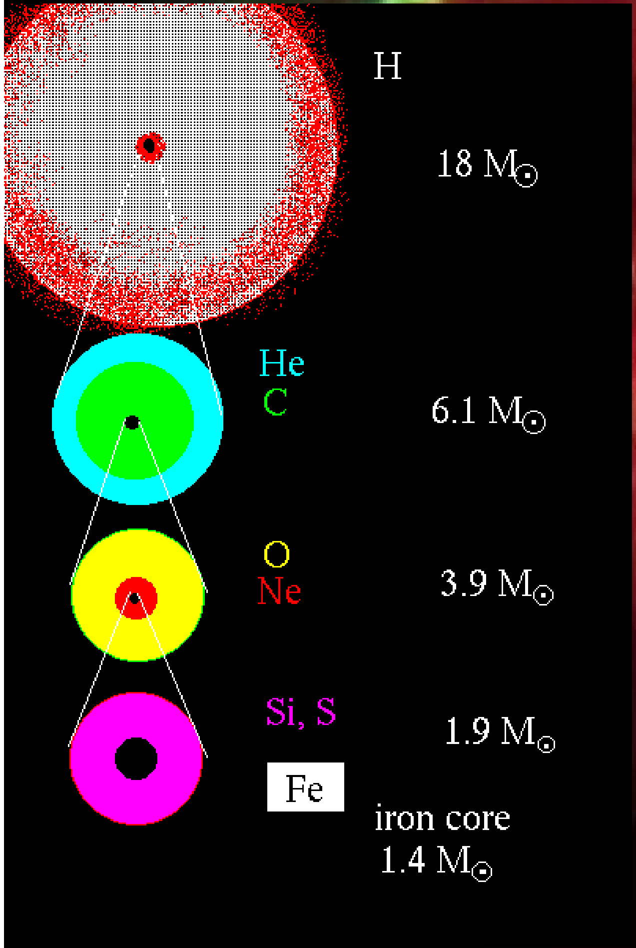
Thick target technique:

C. B. Fu et al. PRC76, 0212603(2007)



Fusion reactions in nuclear astrophysics

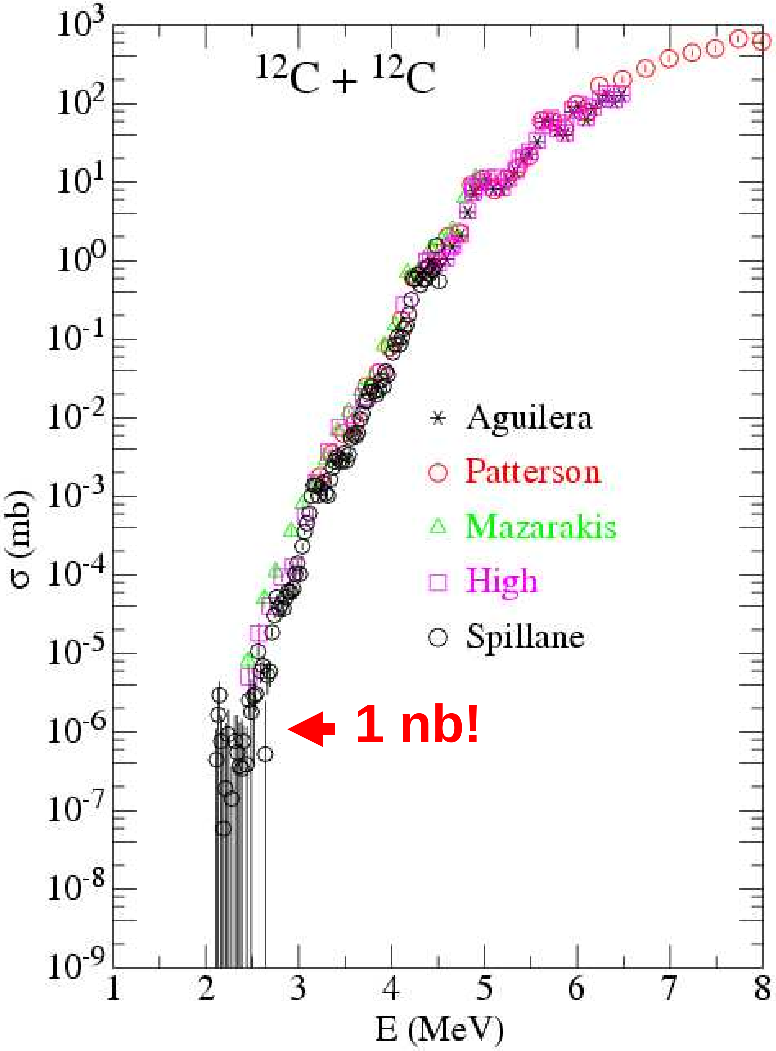
Carbon burning



Hydrogen burning	10^7y
Helium burning	10^6y
Carbon burning	10^3y
Si burning	1d

How to extrapolate towards lower energies

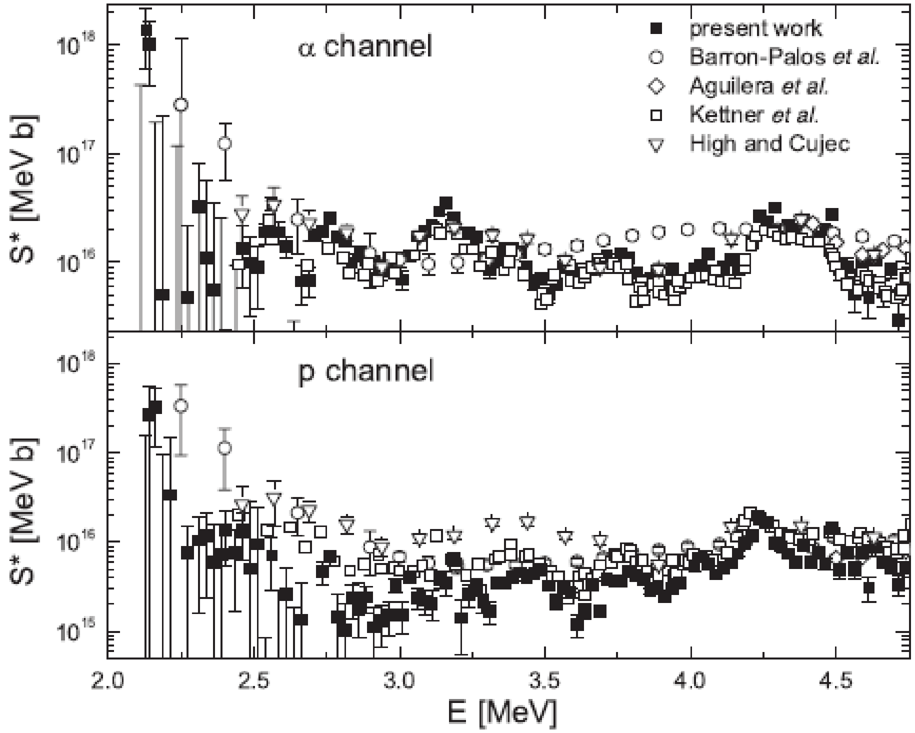
Example: ^{12}C + ^{12}C fusion



1 nb!

$$^{12}C(^{12}C,p)^{23}Na \quad Q = 2.240\,MeV$$

$$^{12}C(^{12}C,\alpha)^{20}Ne \quad Q = 4.617\,MeV$$



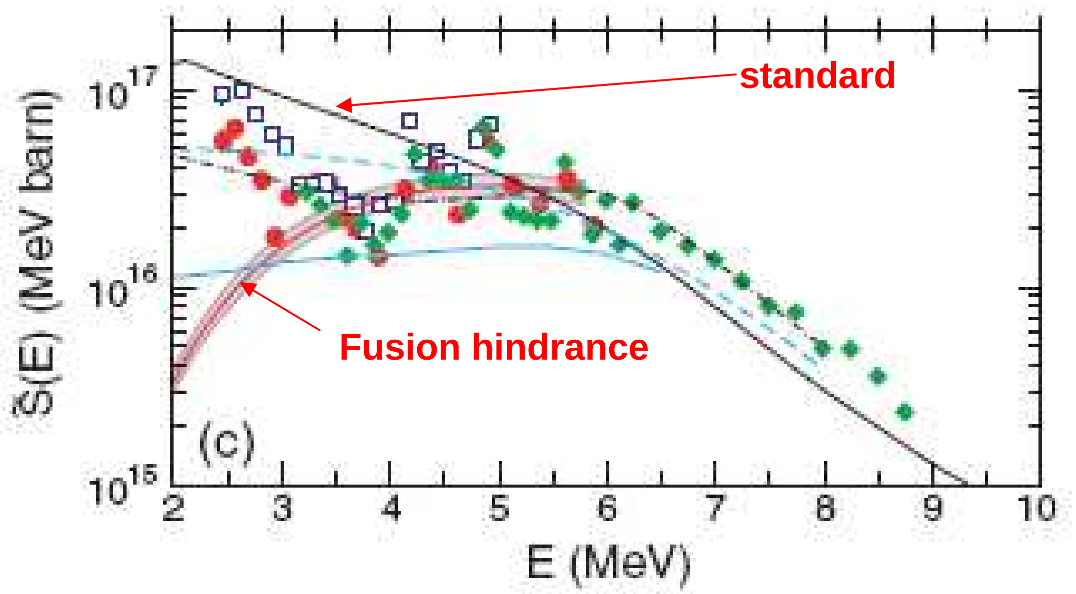
T. Spillane et al., PRL98, 122501(2007)

Problems:

- Cross sections are in the pb range
- Data from various groups don't agree
- There can be resonances at low E
- How to extrapolate (fusion hindrance)

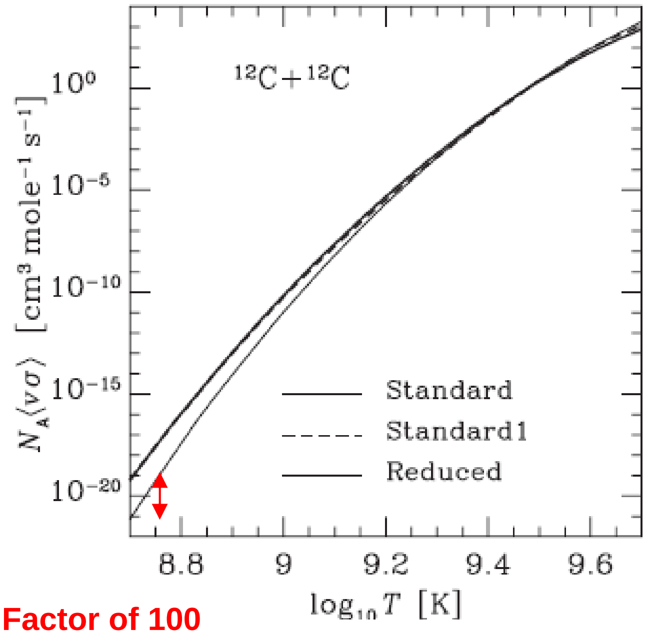
C. L. Jiang et al., PRC 75, 015803(2007)

L. R. Gasques et al., PRC76, 035802(2007)



standard

Fusion hindrance



Factor of 100
different rates!

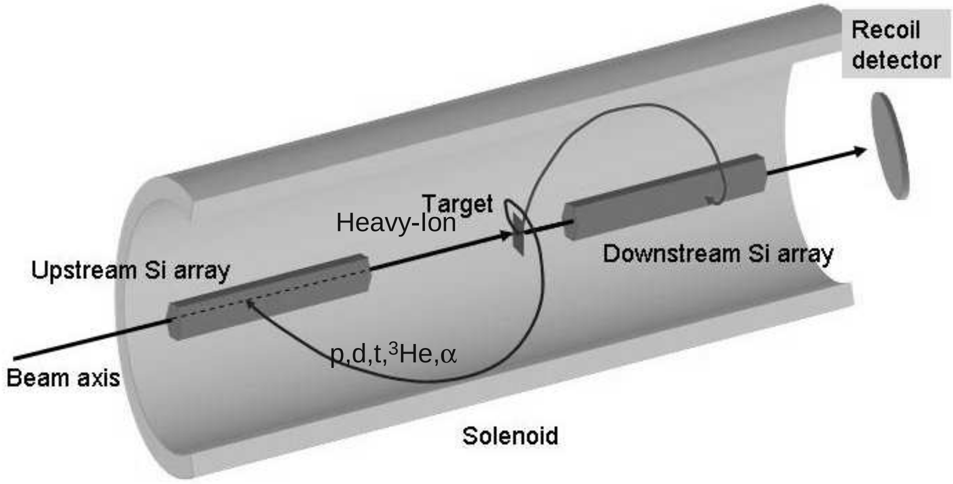
Need experimental data!

A new technique for particle detection in inverse kinematics

Measured quantities	
Flight time:	$T_{flight}=T_{cyc}$
Position:	z
Energy:	E_{lab}

Derived quantities	
Part. ID:	m/q
Energy:	E_{cm}
Angle:	θ_{cm}

Field: 5 Tesla	
Particle	**T_{cyc} (ns)**
p	**13.1**
d,α	**26.2**
t	**39.4**
^{3}He	**19.7**

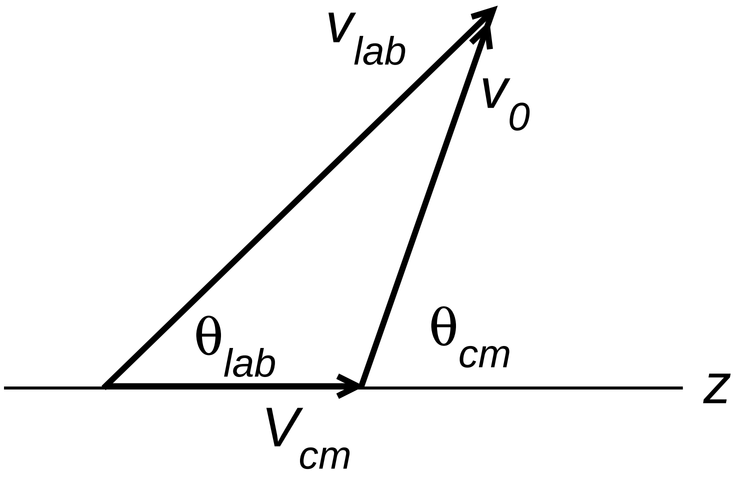


$$\frac{m}{q} = \frac{eB}{2\pi} \times T_{flight}$$

$$E_{cm} = E_{lab} + \tfrac{1}{2} m V_{cm}^2 - \frac{V_{cm} qeB}{2\pi} z$$

$$\theta_{cm} = \arccos\left(\frac{1}{2\pi} \frac{qeBz - 2\pi m V_{cm}}{\sqrt{2mE_{lab} + m^2 V_{cm}^2 - mV_{cm} qeBz/\pi}} \right)$$

Simple kinematics



$$z = v_{\parallel} T_{cyc} = (V_{cm} + v_0 \cos\theta_{cm}) T_{cyc}$$

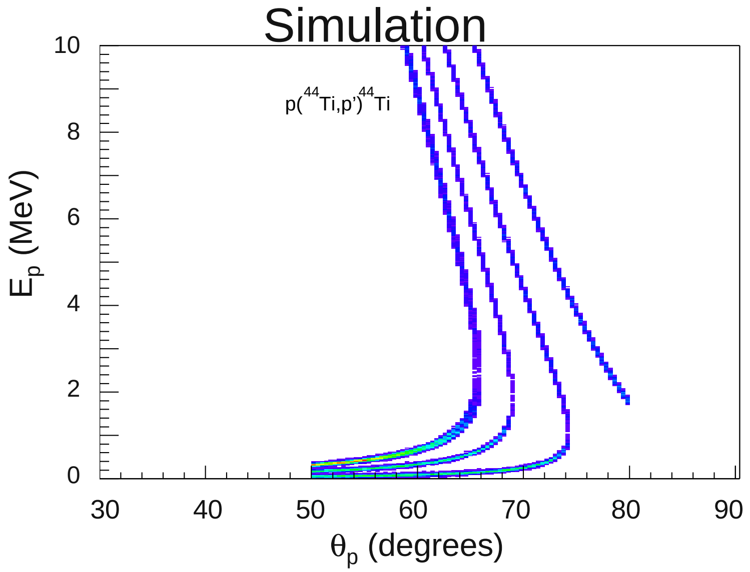
$$\Rightarrow v_0 \cos\theta_{cm} = \frac{z}{T_{cyc}} - V_{cm}$$

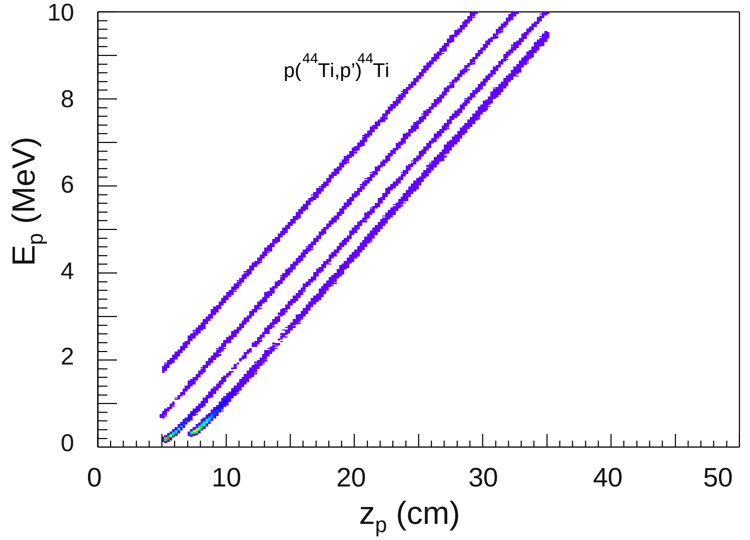
$$E_{lab} = \frac{m}{2}\left[v_{\parallel}^{2} + v_{|}^{2}\right] = \frac{m}{2}\left[(v_0 \cos\theta_{cm} + V_{cm})^2 + v_0^{2} \sin^2\theta_{cm}\right]$$

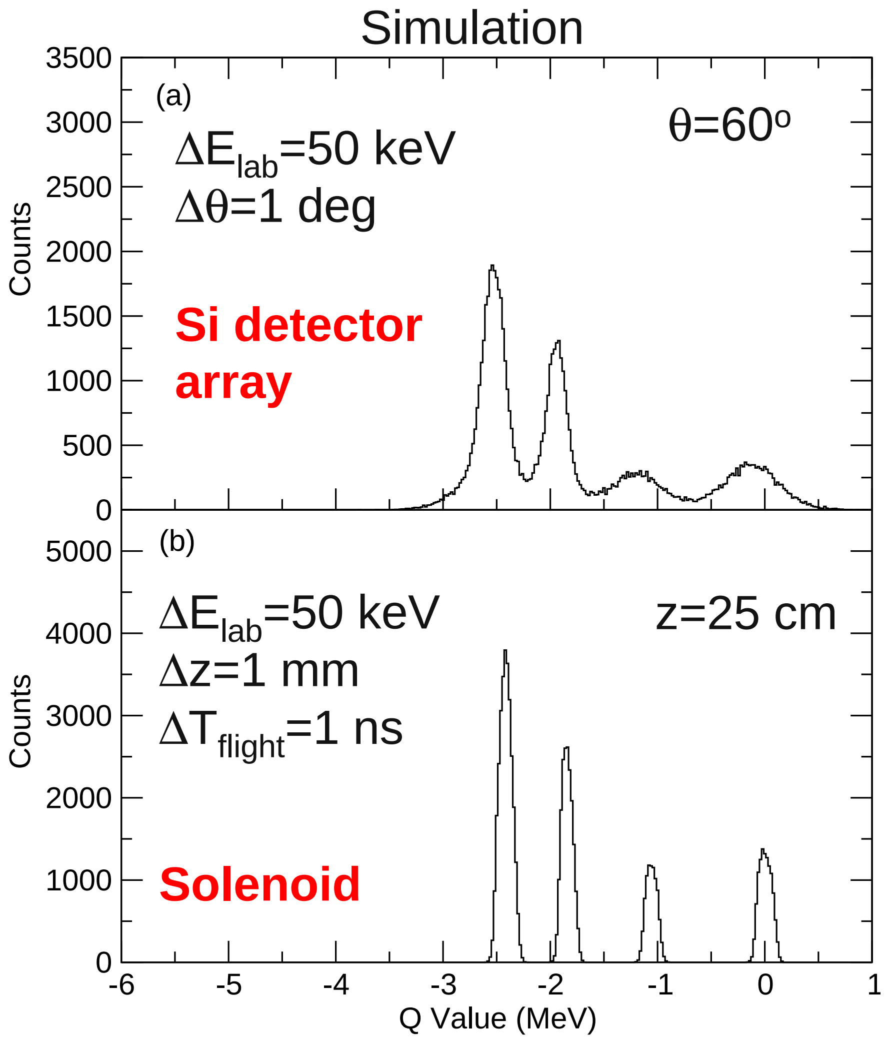
$$= \frac{m}{2}\left[v_0^{2} \cos^2\theta_{cm} + V_{cm}^2 + 2 v_0 V_{cm} \cos\theta_{cm} + v_0^{2} \sin^2\theta_{cm}\right]$$

$$= E_{cm} - \frac{m}{2} V_{cm}^2 + \frac{m V_{cm} z}{T_{cyc}}$$

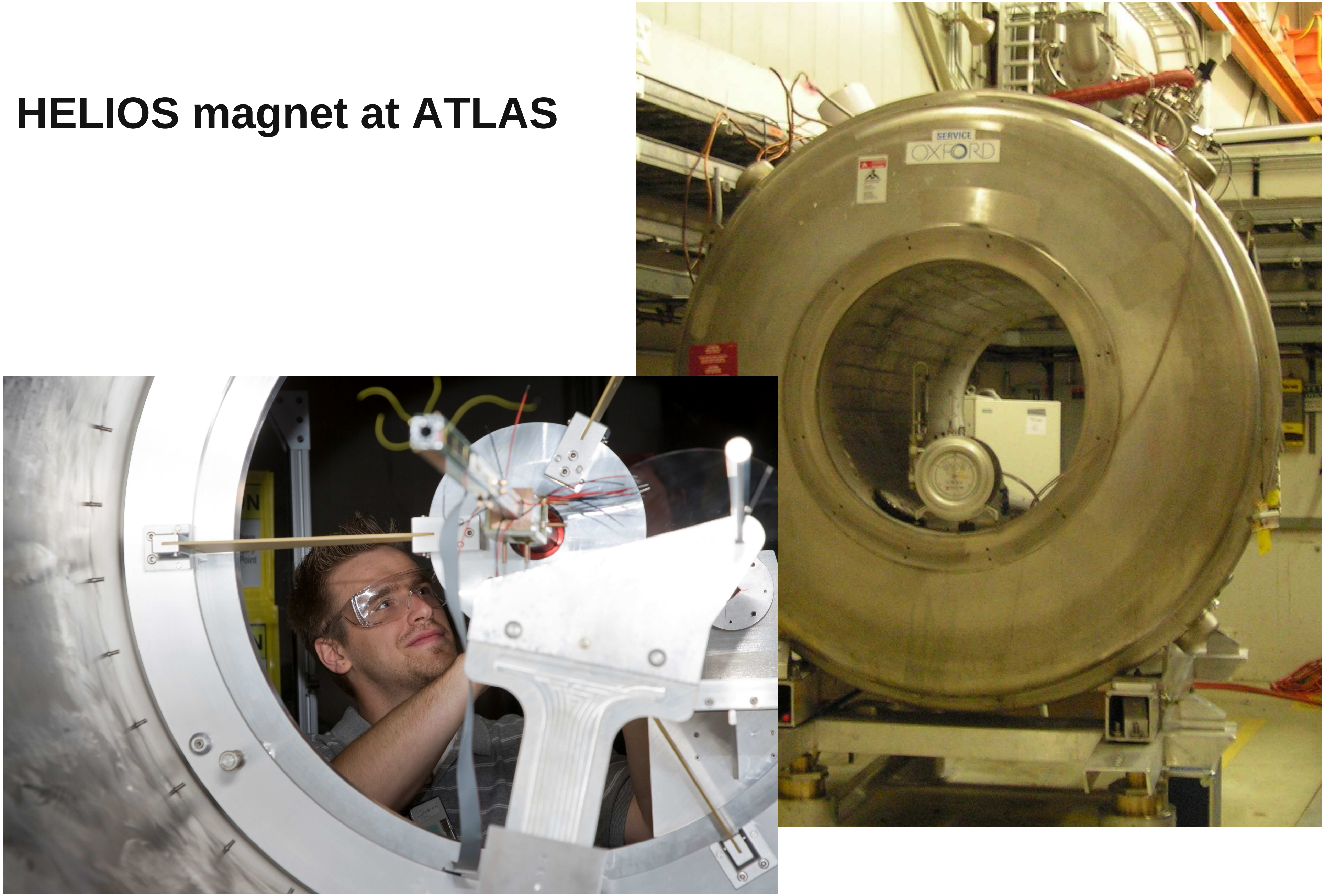
p(^{44}Ti,p')^{44}Ti kinematics







HELIOS magnet at ATLAS



Advantages of Solenoid Spectrometer

- *Automatic particle identification*
- *Excellent center-of-mass energy resolution*
- *High detection efficieny*
- *Simple detector and electronics - few channels*
- *Excellent center-of-mass angle resolution*