RIB in experimental Nuclear Astrophysics

Lucio Gialanella
Dipartimento di Matematica e Fisica
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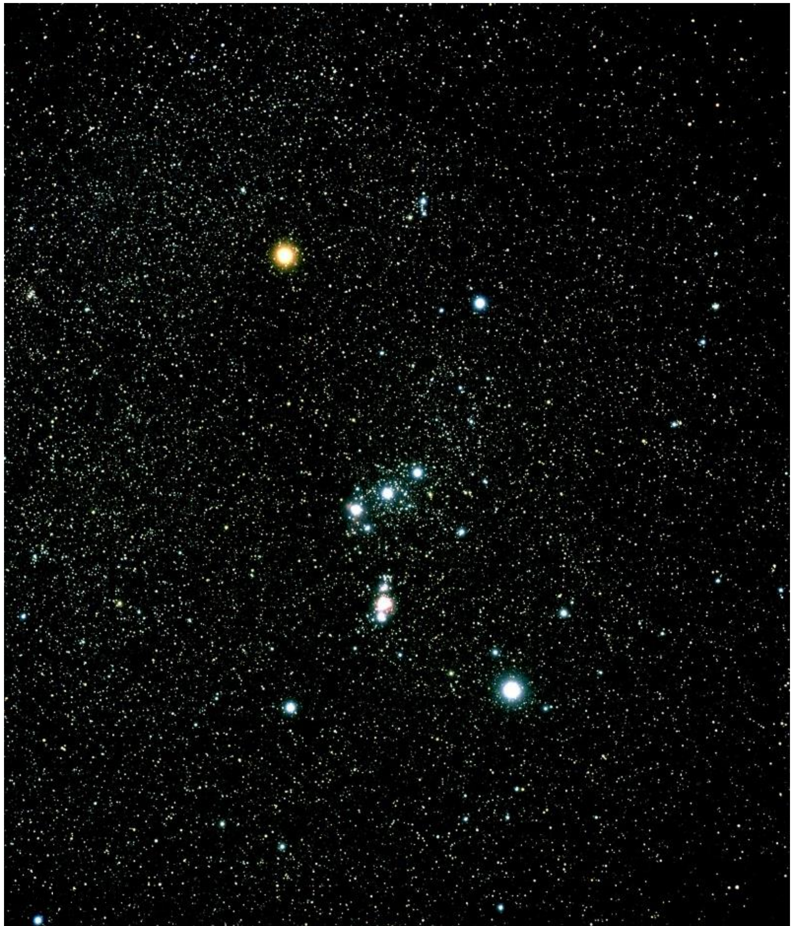
Naples, Italy

1. What is nuclear astrophysics?



RIB in experimental Nuclear Astrophysics

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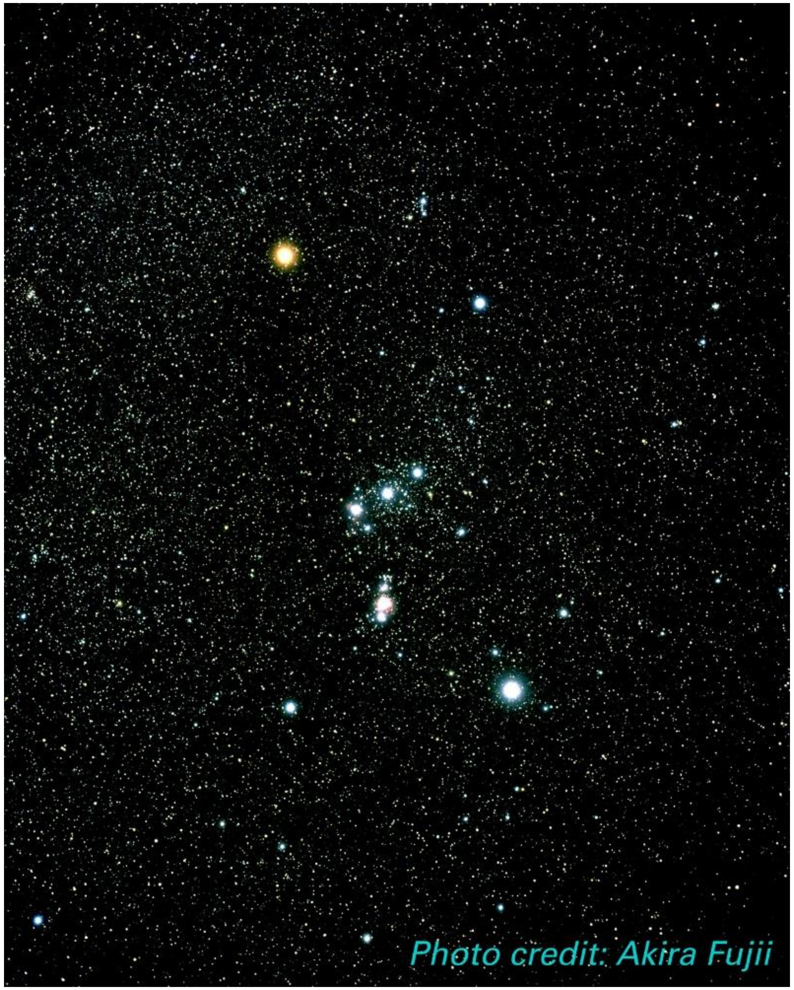
1. <u>What is nuclear astrophysics?</u>

Why stars shine?

What are the stars made of?

Are stars moving or changing?



1 - Source of stellar energy: gravitational

- The virial theorem describes enegetically the gravitational contraction:

$K=-1/2\ U_g$

K internal energy

Ug= gravitational potential energy

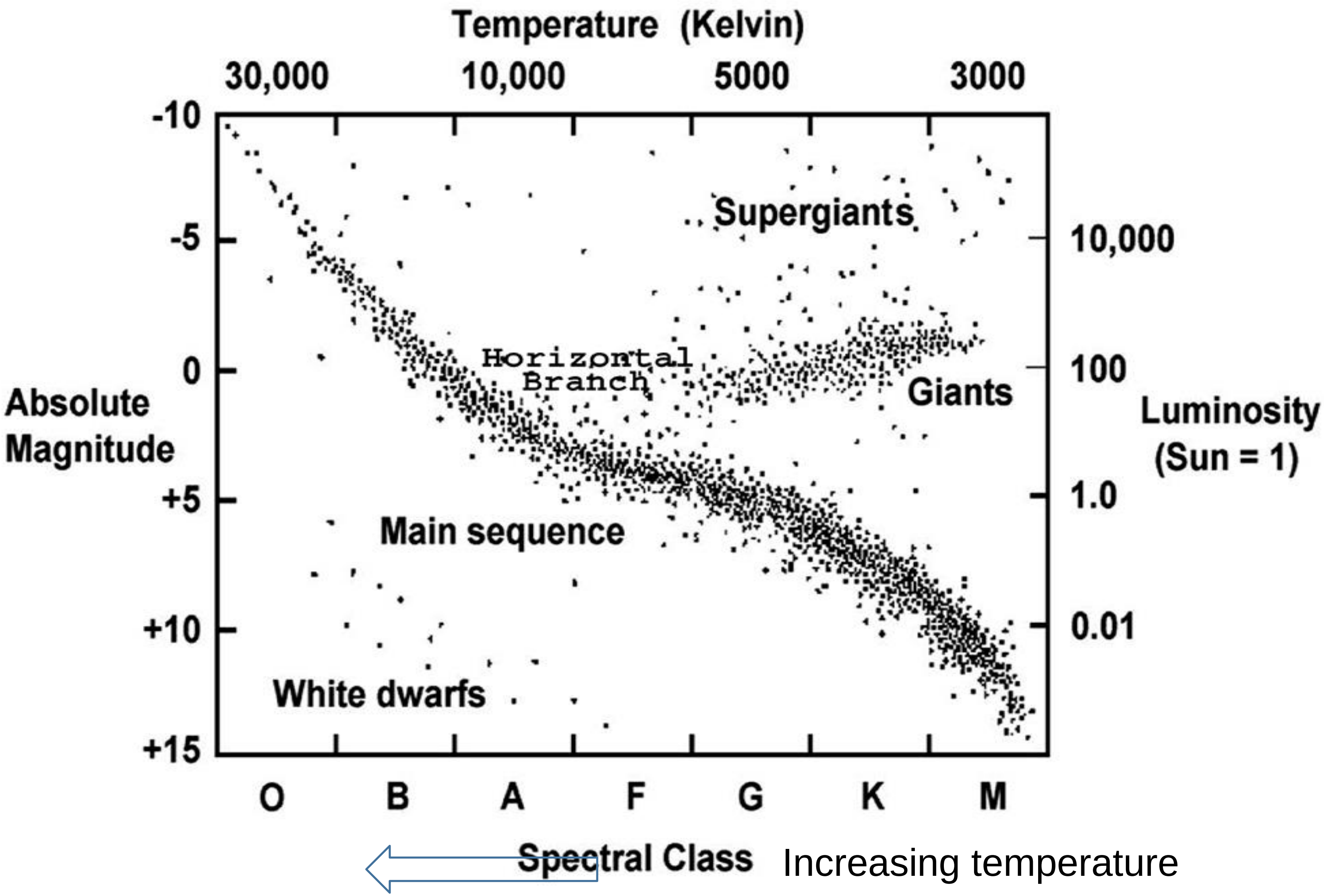
For the Sun:

$U_g \sim 3G\ M^2/(5R) \sim 4\cdot 10^{-10}\ (2 \cdot 10^{30})^2 / (7 \cdot 10^8)\ J \sim 2 \cdot 10^{42}\ J$

$L \sim 1.3 \cdot 10^3\ 4\pi/DW \sim 3.8 \cdot 10^{26}\ J/s$

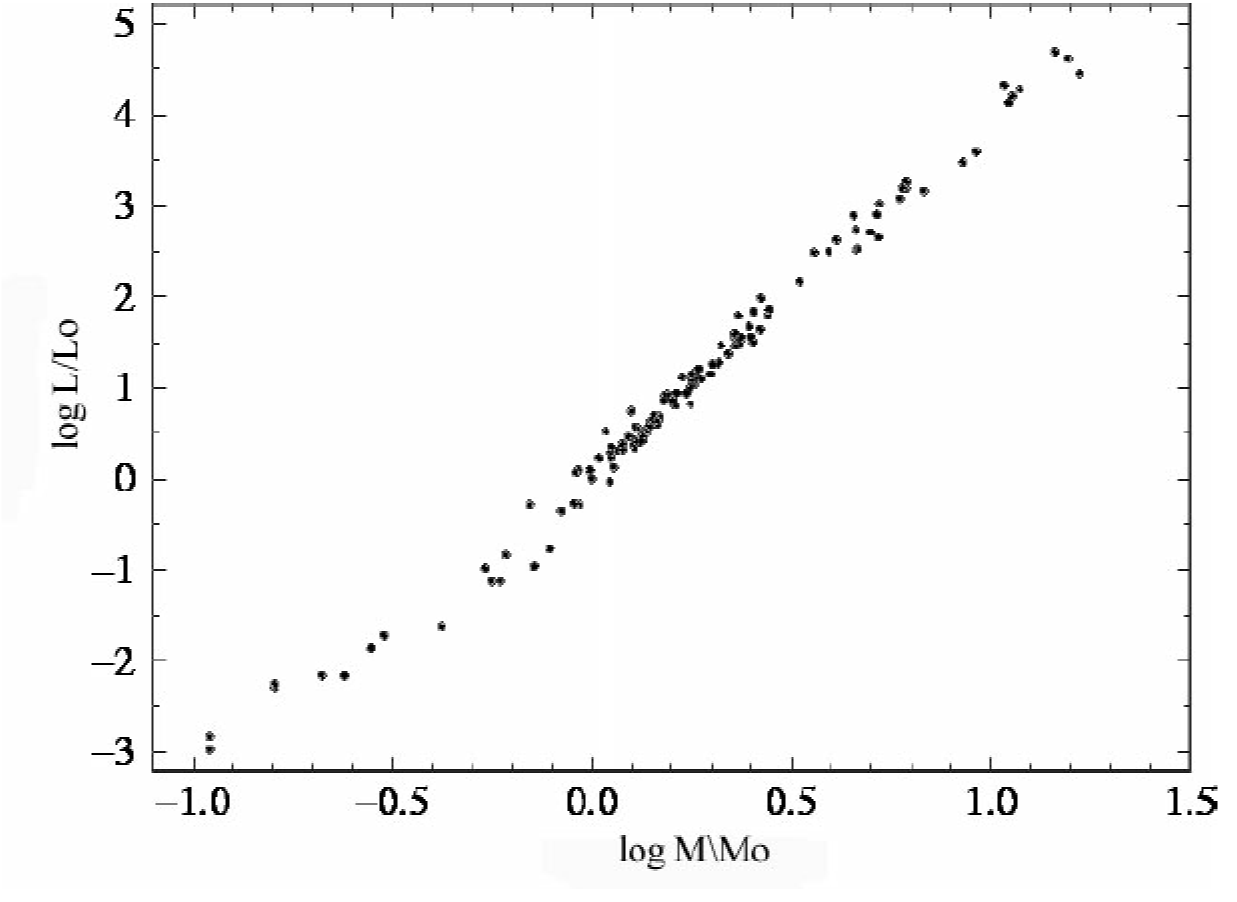
$U_g/(2L) \sim 2.5 \cdot 10^{15}\ s \sim 30\ My$ (Kelvin-Helmholtz)

So, gravitation can account for a lifetime of the order of 10 My, consistent with the (wrong) estimate of Earth’s age (Lord Kelvin’s estimate)



Credit: http://chandra.harvard.edu/graphics/edu/formal/variable_stars/HR_diagram.jpg

Luminosity mass relation in MS



V. Castellani „Astrofisica stellare“ Zanichelli, 1985

Stellar quiescent burning

hydrostatic equilibrium

heat transport

mass continuity

energy conservation

follow by a later boat. A. C. D. Crommelin.

The Sources of Stellar Energy.

Whence comes the store of energy which is continually radiated into space by the Sun and stars? The answer usually given is that by the gradual shrinkage of the star great quantities of gravitational energy are converted into heat, which replaces the

The Observatory, Vol. 42, p. 371-376 (1919)

2. Source of stellar energy: nuclear

- Nuclear binding energy per nucleon is BE~ 8MeV

$U_n = 1.9\cdot10^{30}/1.6\cdot10^{-27}\ \ 8\ 1.6\cdot10^{-13}$ J ~ $1.5\cdot10^{45}$ J

U_n/L ~ 100 Gy

But $kT \ll U_c$

$U_c=1.44\ Z_1Z_2\ /(R_1+R_2+R_n)$ MeV ~ $Z_1Z_2\ /(A_1^{1/3}+A_2^{1/3})$ MeV

p+p in the Sun

U_c ~ 0.7 MeV $\qquad$ kT ~ $8.6\ 10^{-5}\ \ 1\ 10^{7}$ eV ~ 1 keV

Zur Quantentheorie des Atomkernes.

Von **G. Gamow**, z. Zt. in Göttingen.

Mit 5 Abbildungen. (Eingegangen am 2. August 1928.)

Es wird der Versuch gemacht, die Prozesse der α-Ausstrahlung auf Grund d Wellenmechanik näher zu untersuchen und den experimentell festgestellten Z sammenhang zwischen Zerfallskonstante und Energie der α-Partikel theoretisch z erhalten.

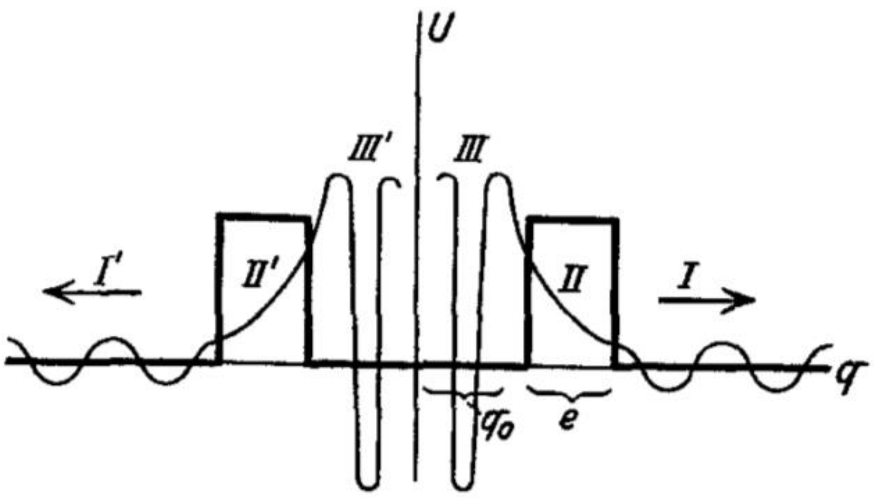


Fig. 3.

PHYSICAL REVIEW

Energy Production in Stars*

H. A. BETHE
Cornell University, Ithaca, New York

(Received September 7, 1938)

§6. TRIPLE COLLISIONS OF ALPHA-PARTICLES

In the preceding section, we have shown that collisions with protons alone lead practically always to the formation of α-particles. In order that heavier nuclei be formed, use must therefore certainly be made of the α-particles themselves. However, collisions of an α-particle with one other particle, proton or alpha, do not lead to stable nuclei. Therefore we must assume triple collisions, of which three types are conceivable:

$$He^4+2H=Be^6, \tag{31}$$

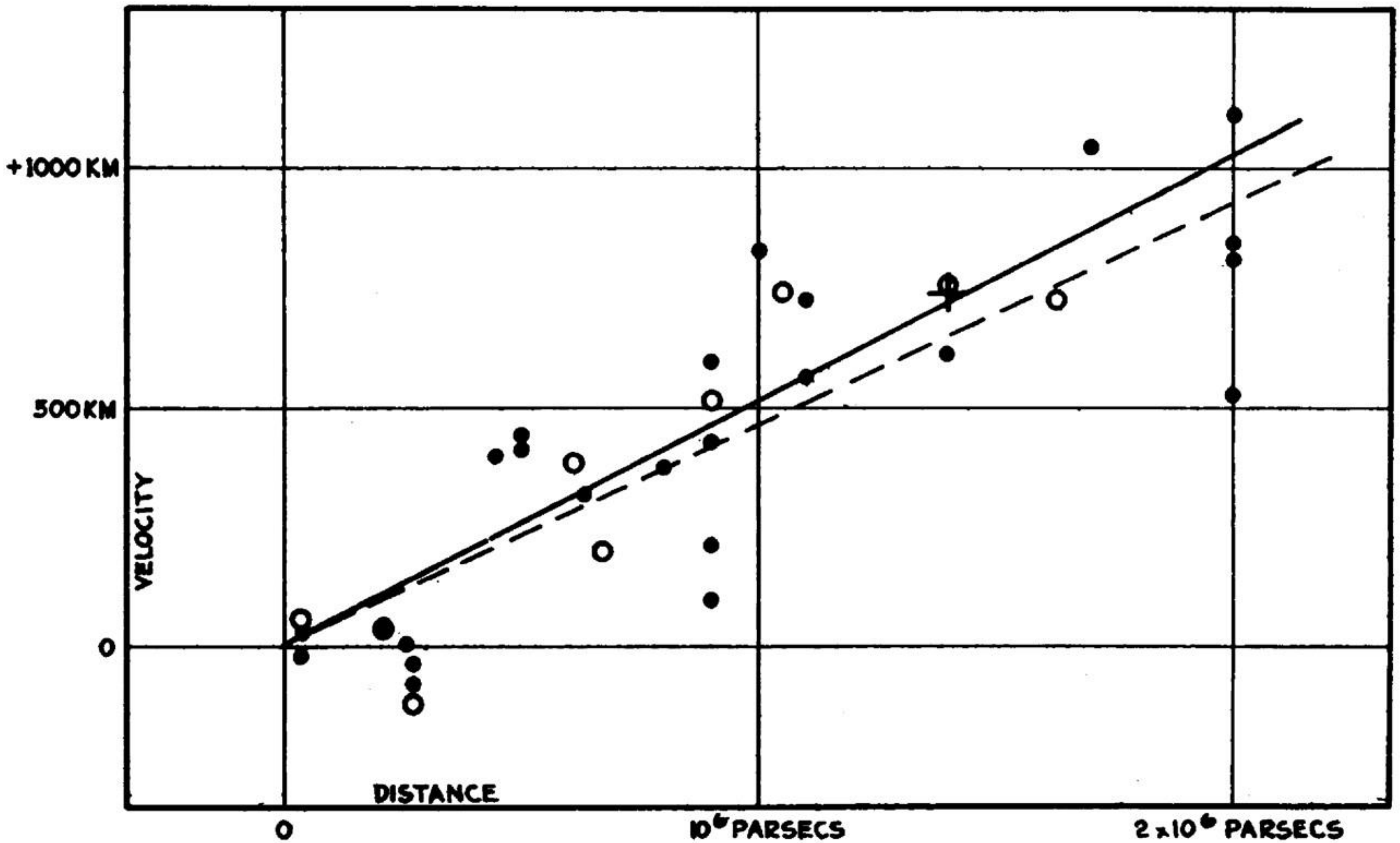
$$2He^4+H=B^9, \tag{32}$$

$$3He^4=C^{12}. \tag{33}$$

The considerations of the last two sections show that there is no way in which nuclei heavier than helium can be produced permanently in the interior of stars under present conditions.

Mass gap A=5, 8

Velocity-Distance Relation among Extra-Galactic Nebulae.



Edwin Hubble PNAS 1929;15:168-173

Hubble&Humason ApJ 1931

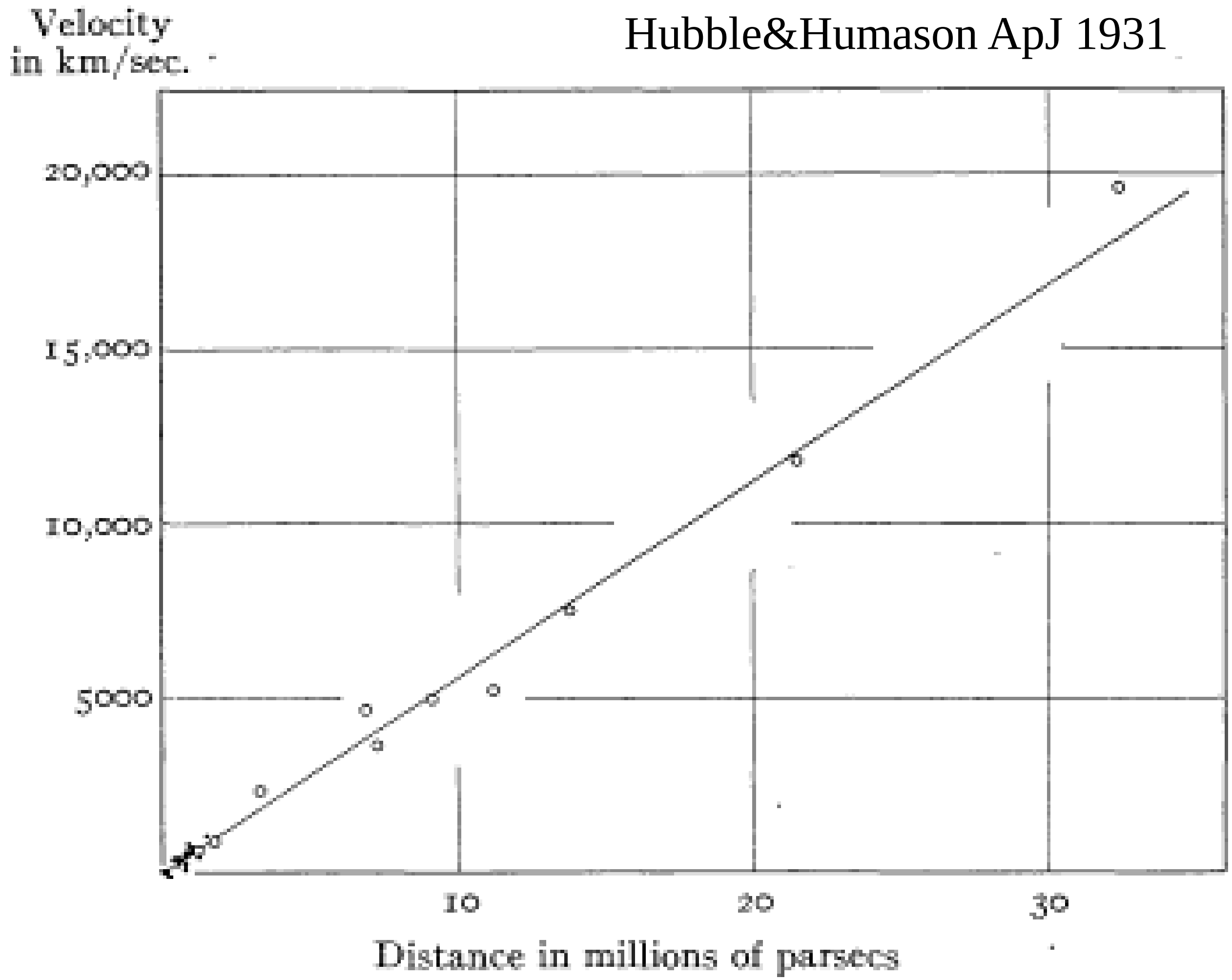


FIG. 5.—The velocity-distance relation. The circles represent mean values for clusters or groups of nebulae. The dots near the origin represent individual nebulae, which, together with the groups indicated by the lowest two circles, were used in the first formulation of the velocity-distance relation.

Hubble's law (1929)

1 Mpc=3.1 10^{19} km H^{-1}=13.8 Gy

V=Hd con H=71±7 km s^{-1} Mpc^{-1}

Big Bang Nucleosynthesis

The Origin of Chemical Elements

R. A. Alpher*
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland

AND

H. Bethe
Cornell University, Ithaca, New York

AND

G. Gamow
The George Washington University, Washington, D. C.
February 18, 1948

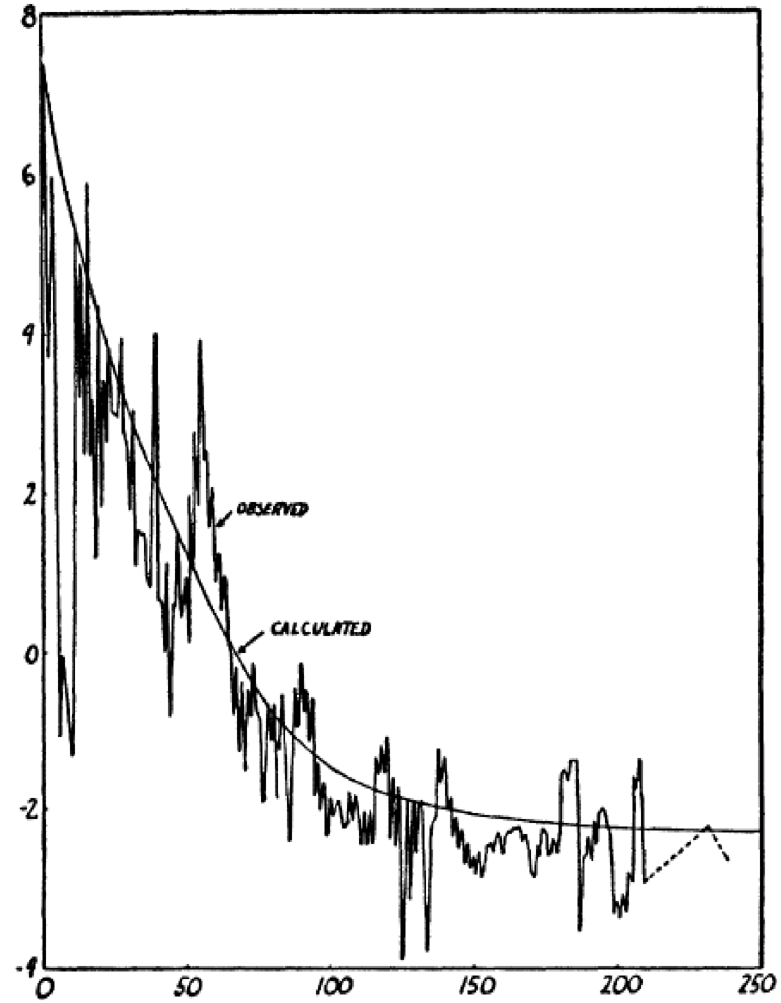


Fig. 1.

Log of relative abundance

Atomic weight

But there was no way to ovecome the gap at A=5, 8

REVIEWS OF
MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

Kellogg Radiation Laboratory, California Institute of Technology, and
Mount Wilson and Palomar Observatories, Carnegie Institution of Washington,
California Institute of Technology, Pasadena, California

but stellar nucleosynthesis alone cannot account for the abundances of light elements

Big Bang Nucleosynthesis revised

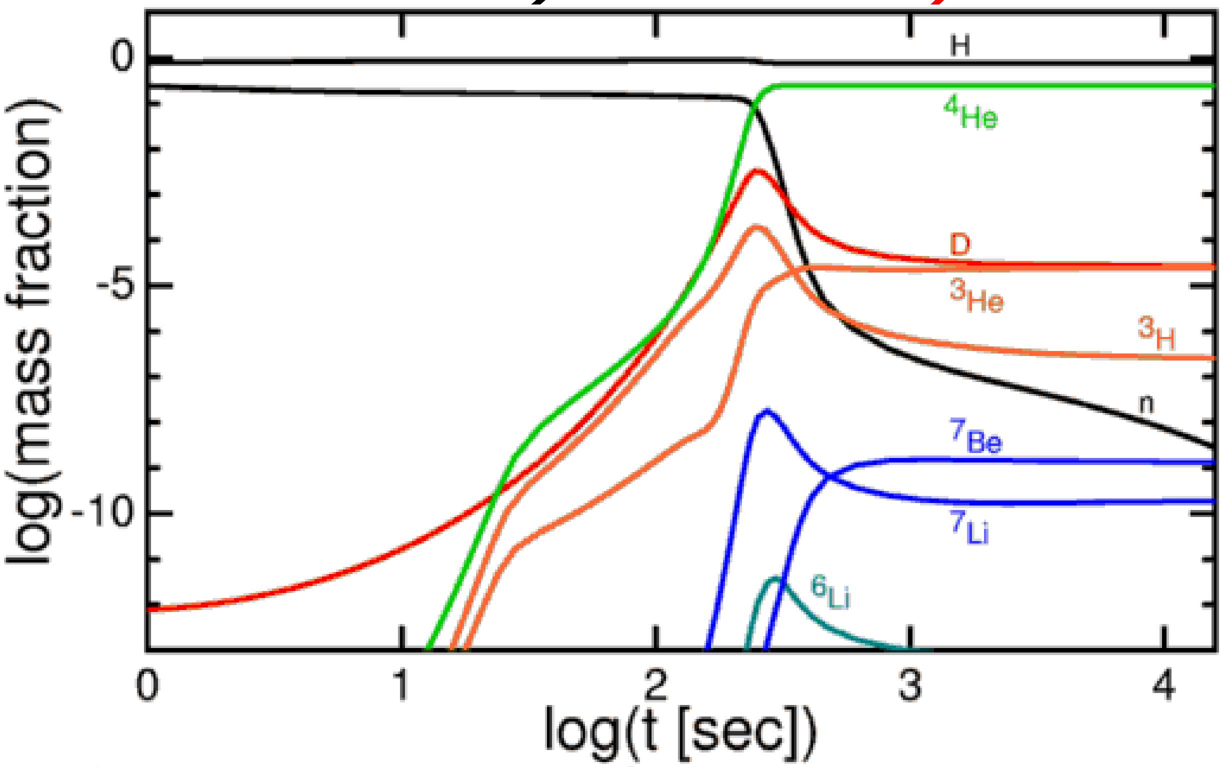
$p + e^- \longleftrightarrow n + \nu$

$n + e^+ \longleftrightarrow p + \bar{\nu}$

$n \longrightarrow p + e^- + \bar{\nu}$

τ=894±5 s

$p + n \longleftrightarrow d + \gamma$



$d + n \longrightarrow H^3 + \gamma$

$H^3 + p \longrightarrow He^4 + \gamma$

$d + p \longrightarrow He^3 + \gamma$

$He^3 + n \longrightarrow He^4 + \gamma$

$d + d \longrightarrow He^3 + n$

$d + d \longrightarrow H^3 + p$

$H^3 + d \longrightarrow He^4 + n$

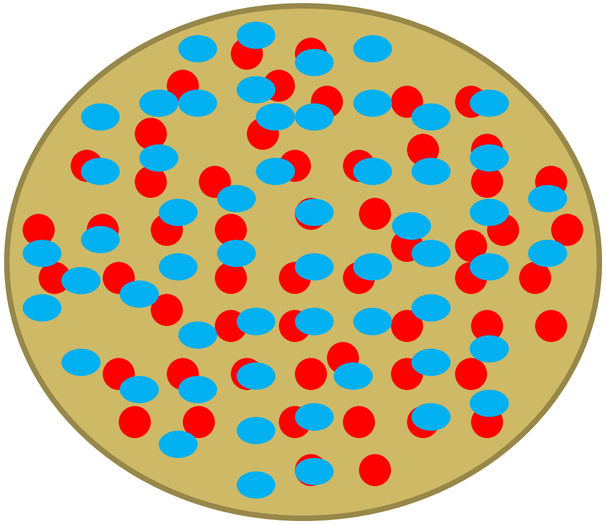
$He^3 + d \longrightarrow He^4 + p$

$d + d \longrightarrow He^4 + \gamma$

http://www.astro.ucla.edu/~wright/BBNS.html

Nuclear reactions in stars

$X + a$



if v is the relative velocity

$$Y = N_a N_X \sigma v$$

since v has a distribution P(v)

$$Y = \int_0^\infty N_a N_X \sigma P(v) v dv = N_a N_X \langle \sigma v \rangle$$

P(v) -> Maxwell Boltzmann distribution

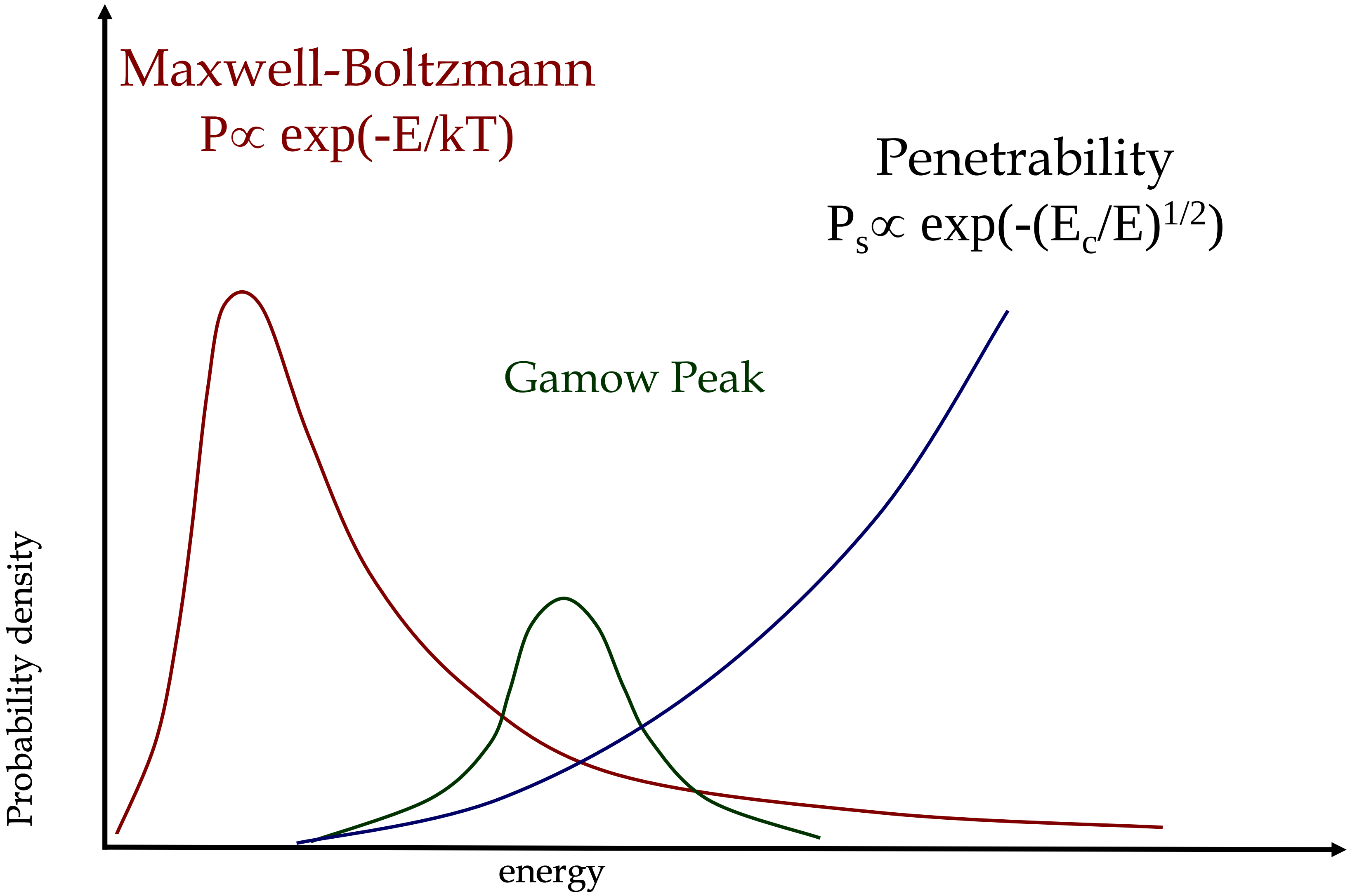
$$< \sigma v >= \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma(E) E \exp\left[-\frac{E}{kT}\right] dE$$

$$N_a N_X < \sigma v >= Y$$

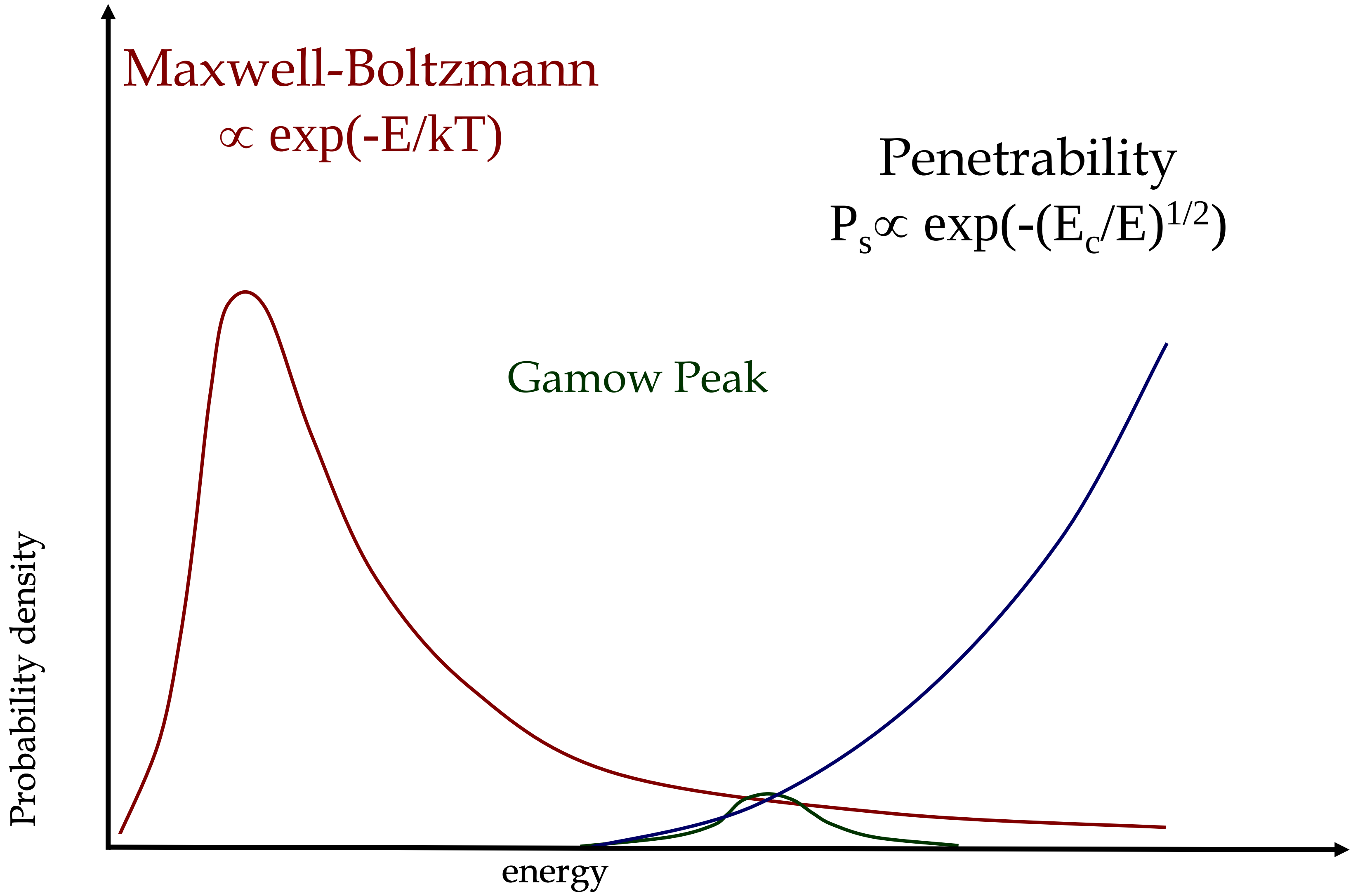
$$\frac{dN_X}{dt} = -\frac{N_a < \sigma v >}{Y} \cdot N_X = -\lambda_{X,a} N_x$$

$$\tau_{X,a} = \frac{1}{\lambda_{X,a}}$$

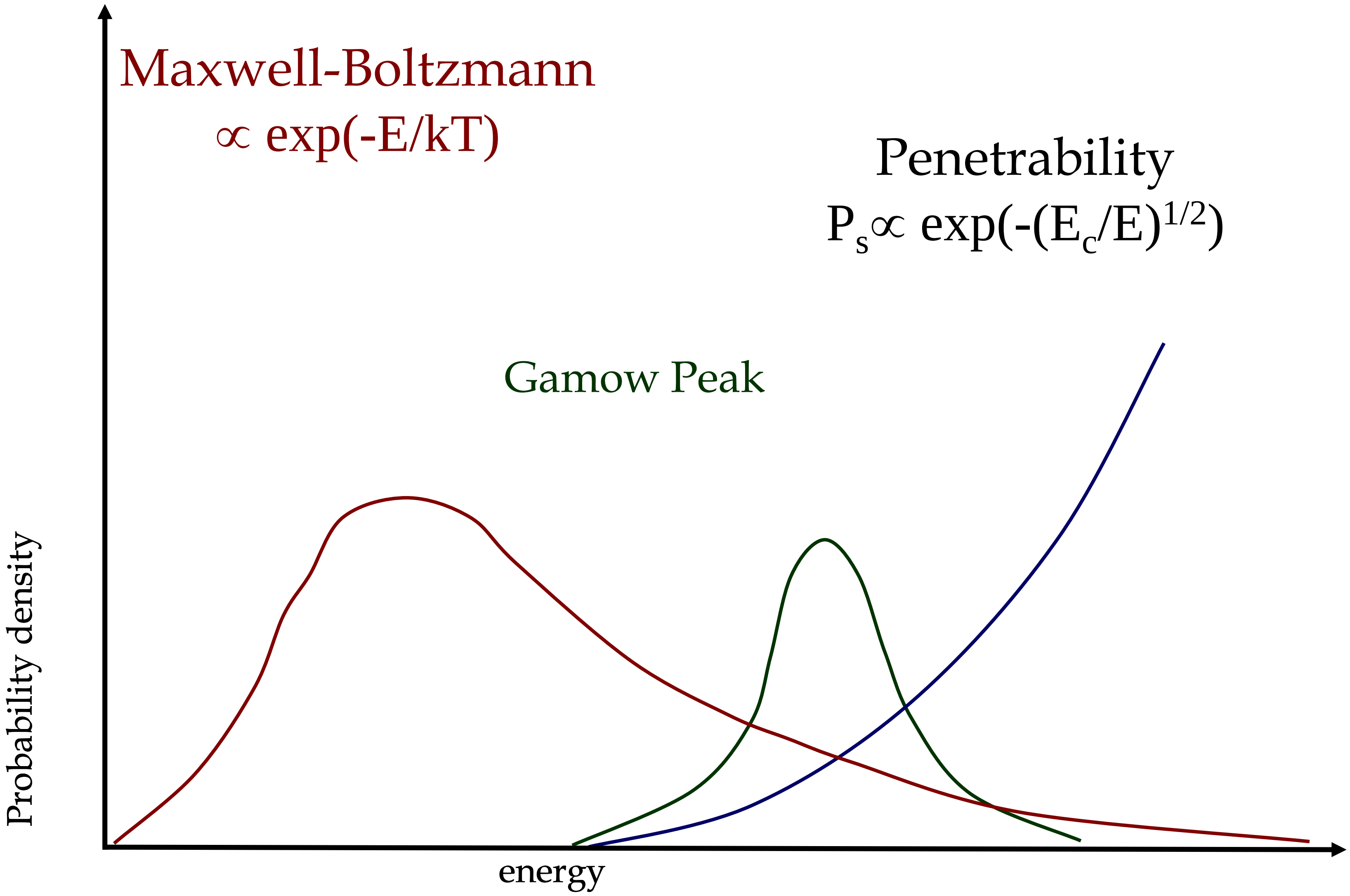
P(v) -> Maxwell Boltzmann distribution
e.g. p+p



Same temperature but larger coulomb barrier



Same Coulomb barrier but higher temperature



Since σ is dominated by the penetrability of the coulomb barrier, it is usual to factorize it out and define the S factor

$$\sigma(E) = \frac{S(E)}{E} \cdot P_s(E)$$

So, $E_0 = f(Z_1, Z_2, T)$: that is the reason for separate, subsequent burnings

Sun : $T_6 = 15$

Reaction	E_0(keV)	Integral
p+p	5.9	$7\ 10^{-6}$
$^4He+^{12}C$	56	$5.9\ 10^{-56}$
$^{16}O+^{16}O$	237	$2.5\ 10^{-237}$

H burning (T_6 10-60)

pp chain

$p + p \rightarrow {}^2H + e^+ + \nu$ **[0.27 MeV]** $p + e^- + p \rightarrow {}^2H + \nu$ **[1.44 MeV]**

99.75% 0.25%

${}^2H + p \rightarrow {}^3He + \gamma$

86% 14% $2 \cdot 10^{-5}$%

${}^3He + {}^3He \rightarrow$ **${}^4He$** $+ 2p$ ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$ ${}^3He + p \rightarrow {}^4He + e^+ + \nu$

99.89% 0.11%

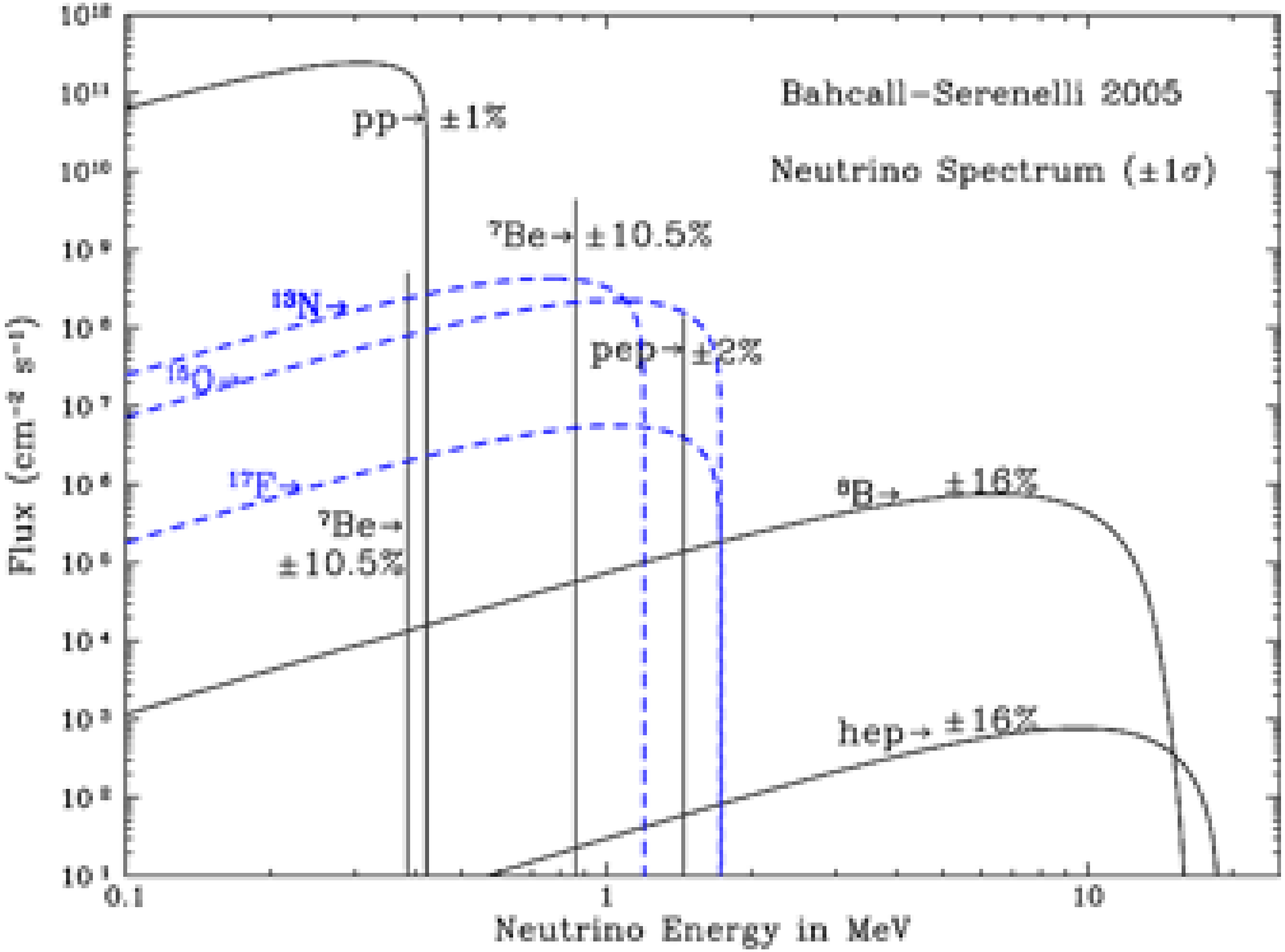
${}^7Be + e^- \rightarrow {}^7Li + \nu$ **[0.81 MeV]** ${}^7Be + p \rightarrow {}^8B + \gamma$

${}^7Li + p \rightarrow {}^8Be$ ${}^8B \rightarrow {}^8Be + e^+ + \nu$ **[6.80 MeV]**

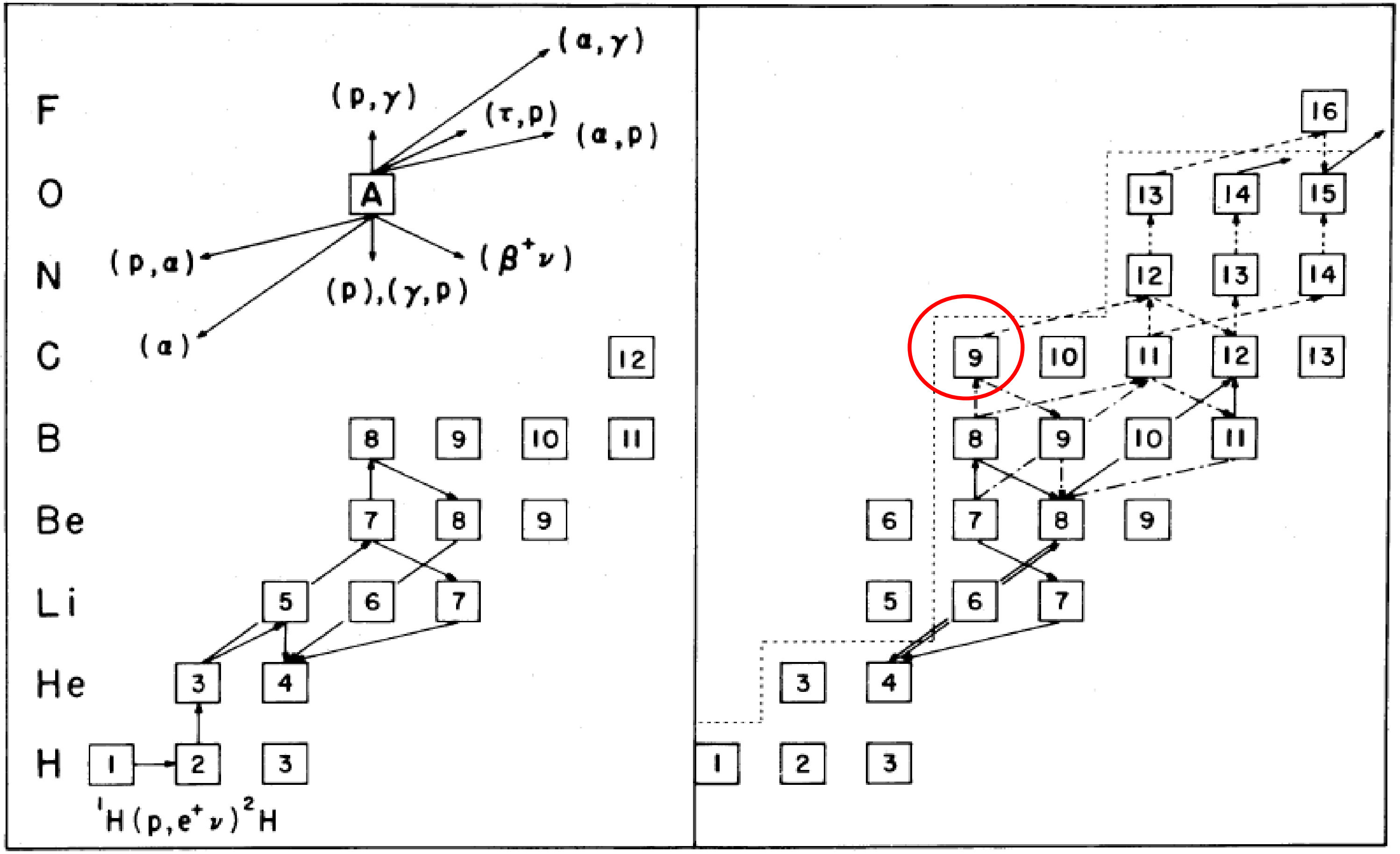
${}^8Be \rightarrow 2$ **${}^4He$** ${}^8Be \rightarrow 2$ **${}^4He$**

CHAIN I	CHAIN II	CHAIN III	CHAIN IV
Q_{eff} = 26.20 MeV	Q_{eff} = 25.66 MeV	Q_{eff} = 19.67 MeV	Q_{eff} = 16.84 MeV

Solar neutrino energy spectrum



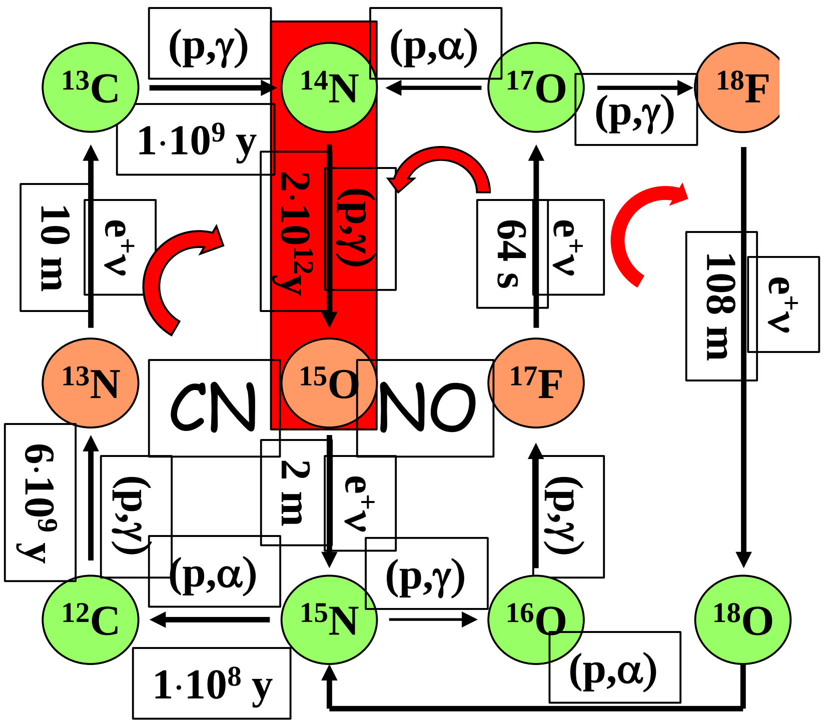
HOT PROTON-PROTON CHAINS

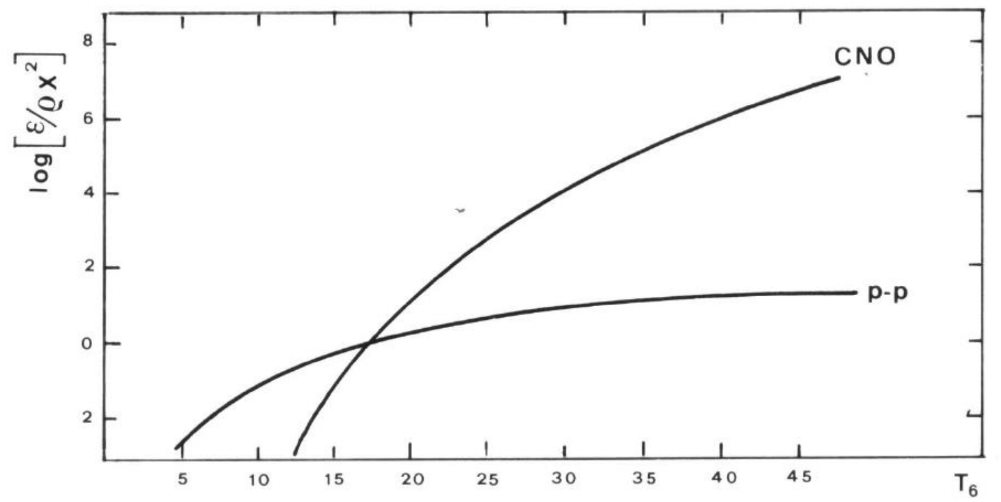


M. Wiescher et al, ApJ 1989

Hydrogen burning at high temperature and metallicity

CNO bi-cycle

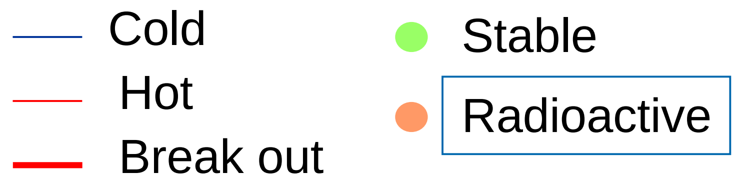




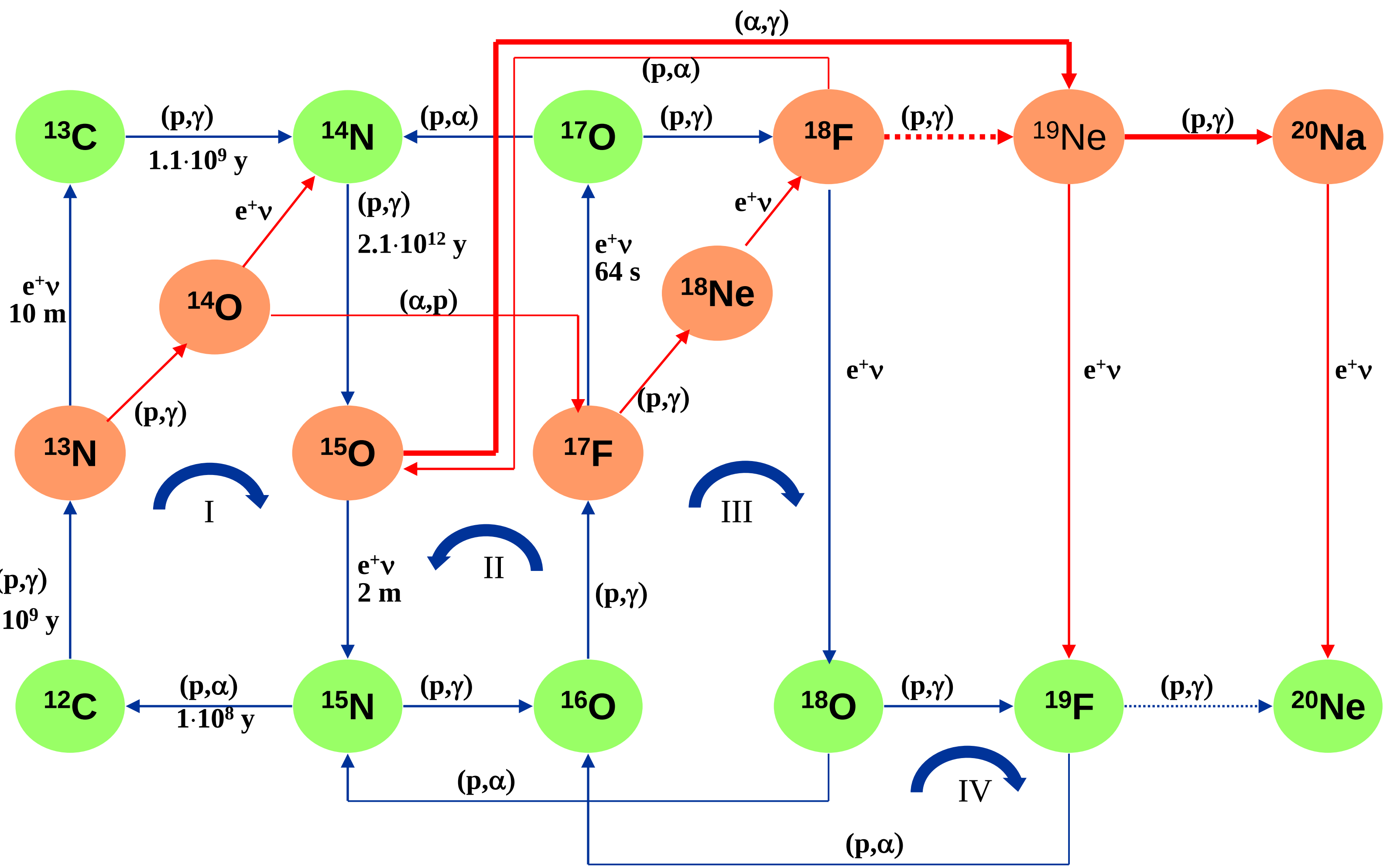
Result:
- H burning
- Enrichment in ^{14}N

CN	NO
Q_{eff} = 26.02 MeV	Q_{eff} = 25.73 MeV

Hot CNO (T_9~0.1)

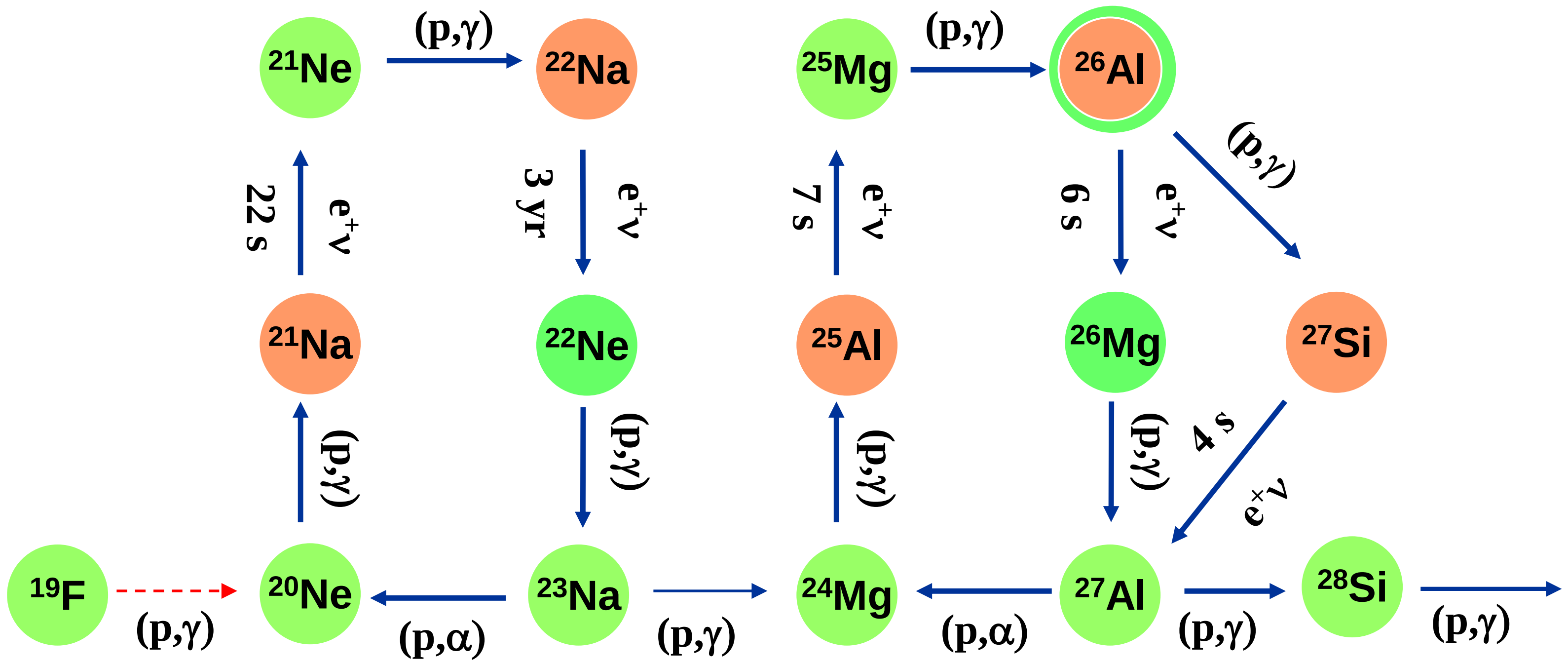


Cold
Hot
Break out
Stable
Radioactive



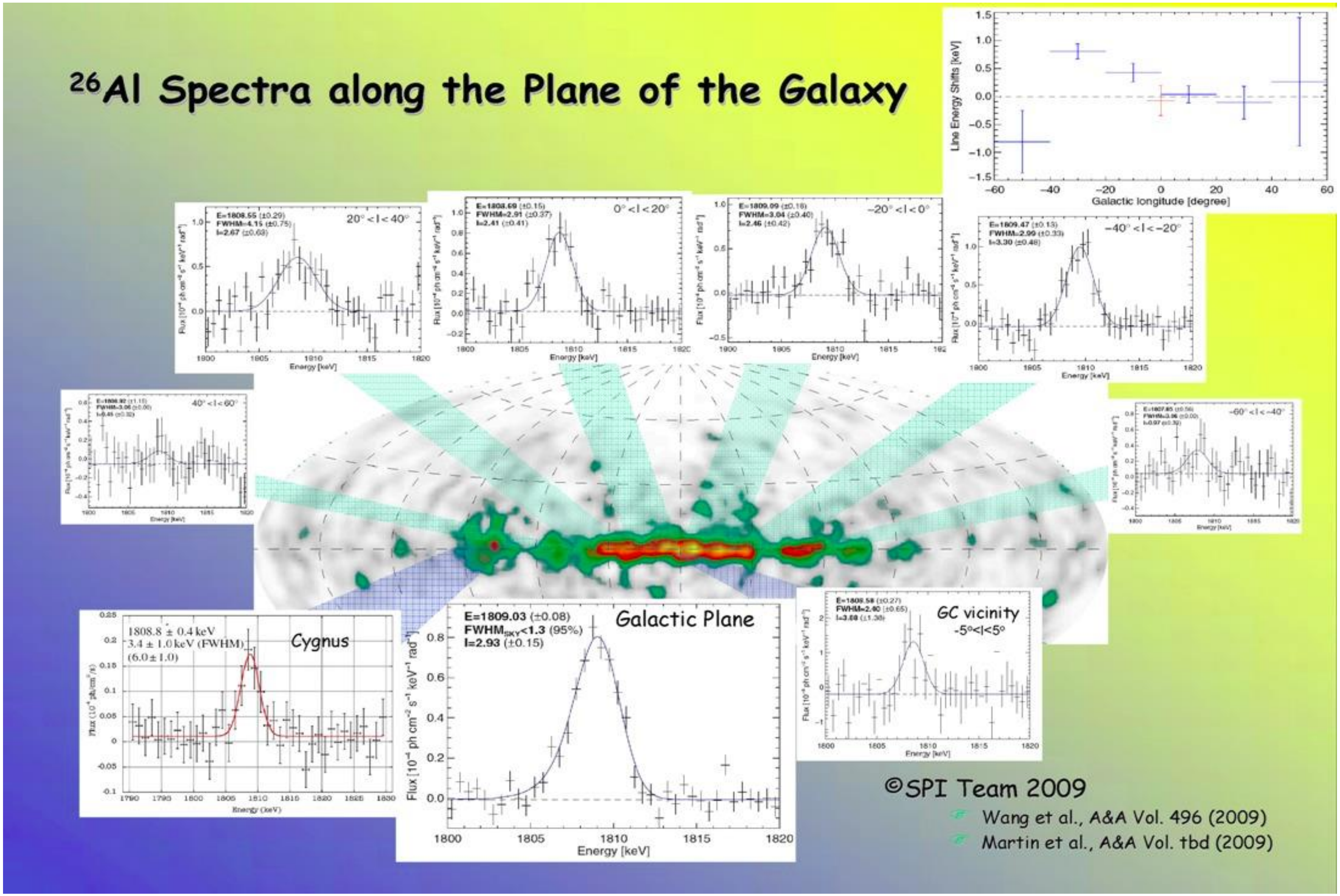
13C
14N
17O
18F
19Ne
20Na
14O
18Ne
13N
15O
17F
12C
15N
16O
18O
19F
20Ne
(p,γ)
1.1·10⁹ y
(p,α)
(p,γ)
(p,γ)
(p,γ)
(α,γ)
(p,α)
e⁺ν
(p,γ)
2.1·10¹² y
e⁺ν
64 s
e⁺ν
e⁺ν
10 m
(α,p)
(p,γ)
(p,γ)
e⁺ν
e⁺ν
e⁺ν
I
II
III
IV
e⁺ν
2 m
(p,γ)
6·10⁹ y
(p,γ)
(p,α)
1·10⁸ y
(p,γ)
(p,γ)
(p,γ)
(p,α)
(p,α)

Hot NeNa and MgAl cycles ($T_9 \sim 0.1$)

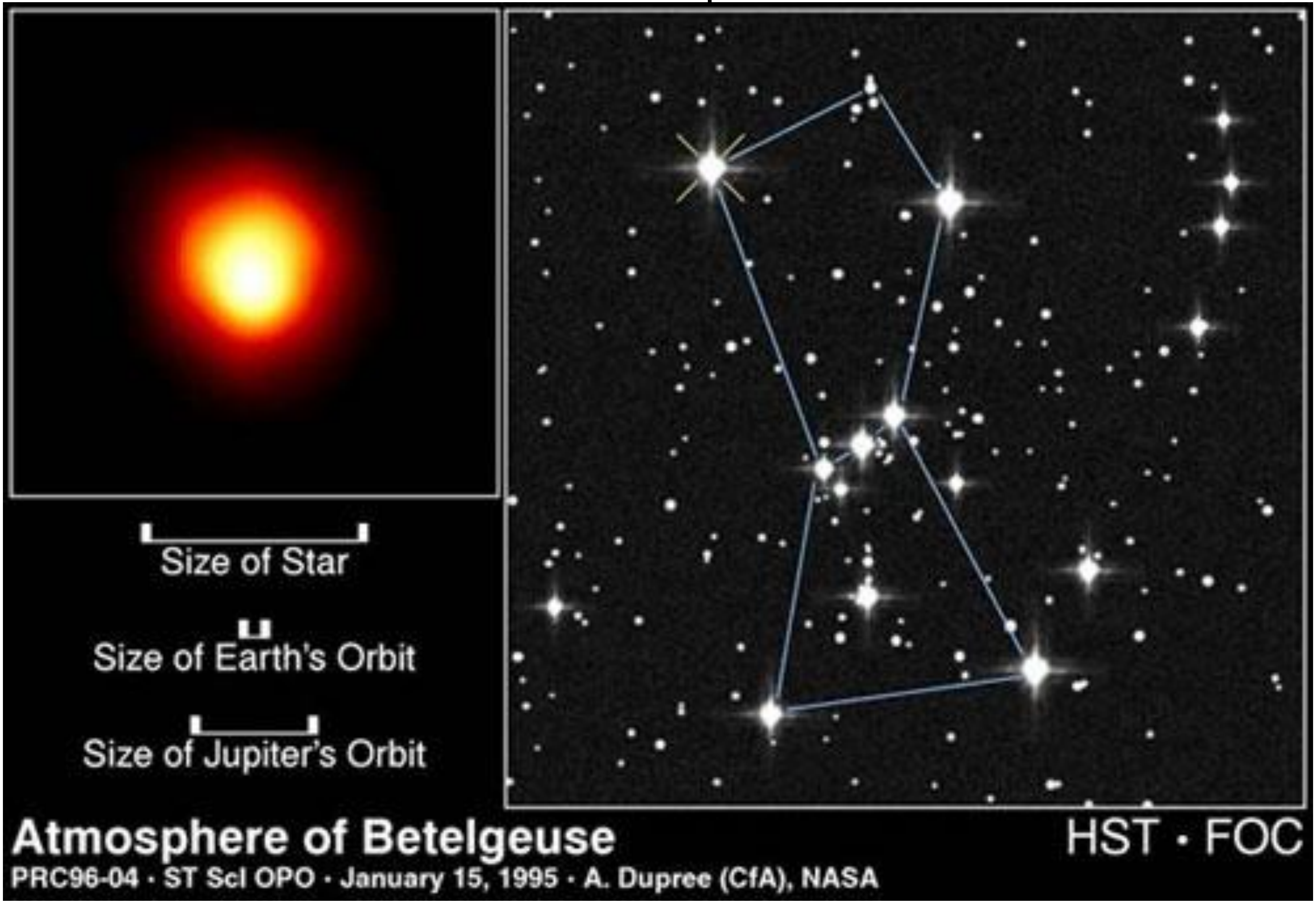


+ other paths (e.g. ^{21}Na(p,γ)^{22}Mg, ^{22}Mg(p,γ) ^{23}Al, ^{23}Mg(p,γ) ^{24}Al ->^{24}Mg)

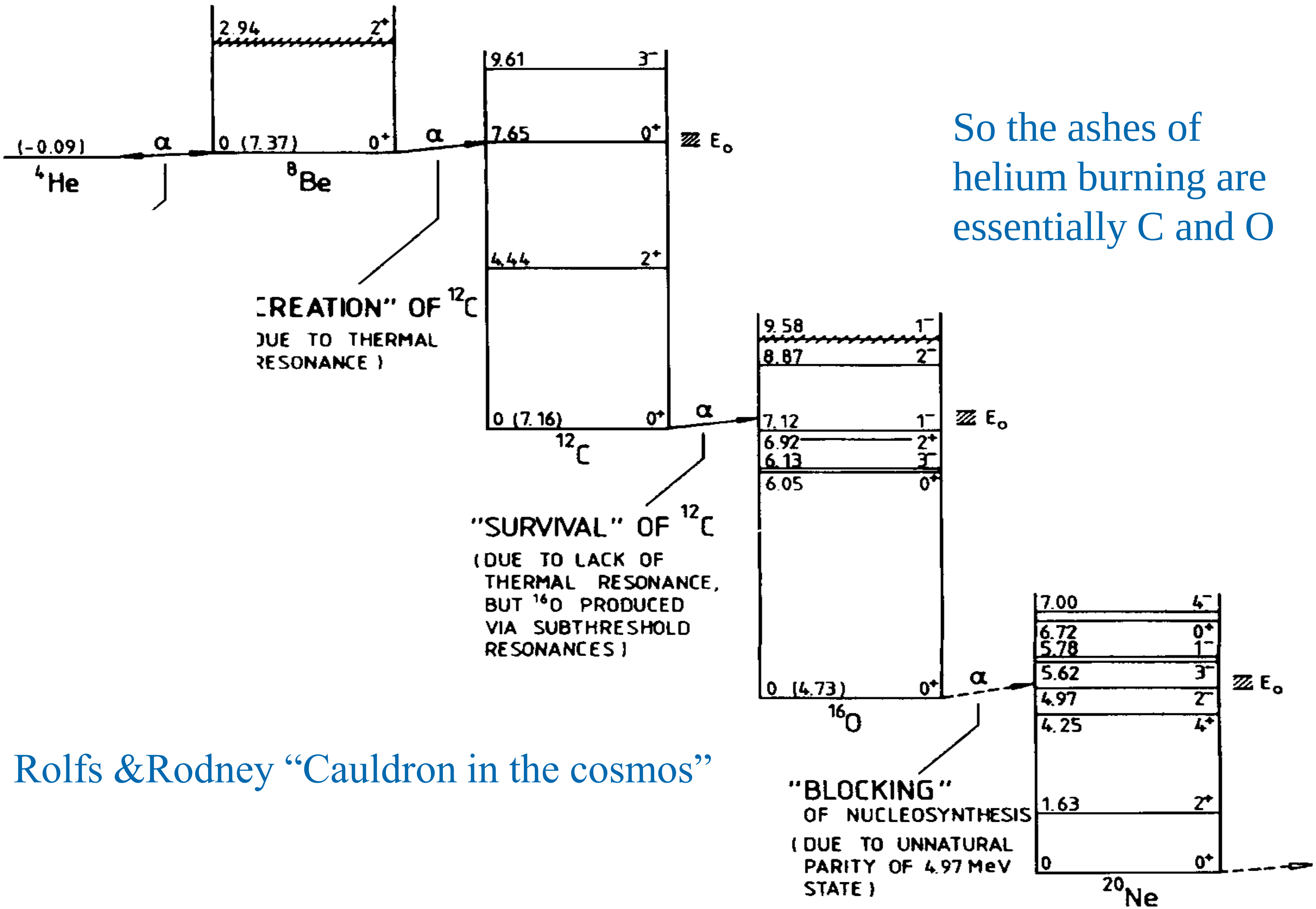
26Al Comptel-Integral/SPI



After Hydrogen exhaustion, core contracts and star expands



Helium burning T_9~0.1-0.3



So the ashes of helium burning are essentially C and O

Rolfs &Rodney "Cauldron in the cosmos"

PHYSICAL REVIEW D, VOLUME 61, 017301

Triple-alpha process and the anthropically allowed values of the weak scale

Tesla E. Jeltema and Marc Sher
Nuclear and Particle Theory Group, Physics Department, College of William and Mary, Williamsburg, Virginia 23187
(Received 27 May 1999; published 29 November 1999)

Stellar Production Rates of Carbon and Its Abundance in the Universe

H. Oberhummer,[1]* A. Csótó,[2] H. Schlattl[3]

The bulk of the carbon in our universe is produced in the triple-alpha process in helium-burning red giant stars. We calculated the change of the triple-alpha reaction rate in a microscopic 12-nucleon model of the ^{12}C nucleus and looked for the effects of minimal variations of the strengths of the underlying interactions. Stellar model calculations were performed with the alternative reaction rates. Here, we show that outside a narrow window of 0.5 and 4% of the values of the strong and Coulomb forces, respectively, the stellar production of carbon or oxygen is reduced by factors of 30 to 1000.

Advanced burnings

Carbon (T_9 ~0.6-0.9)

$^{12}C+^{12}C$ → $^{20}Ne+\alpha$ + 4.6 MeV

$^{12}C+^{12}C$ → $^{23}Na+p$ + 2.2 MeV

$^{12}C+^{12}C$ → $^{23}Mg+n$ - 2.6 MeV

Neon(T9 ~ 1.2-1.7)

$^{20}Ne+\gamma$ (4.7 MeV)->$^{16}O+a$;

$^{20}Ne+\alpha$->^{24}Mg+4.6 MeV

→ $^{20}Ne+^{20}Ne$->$^{16}O+^{24}Mg$

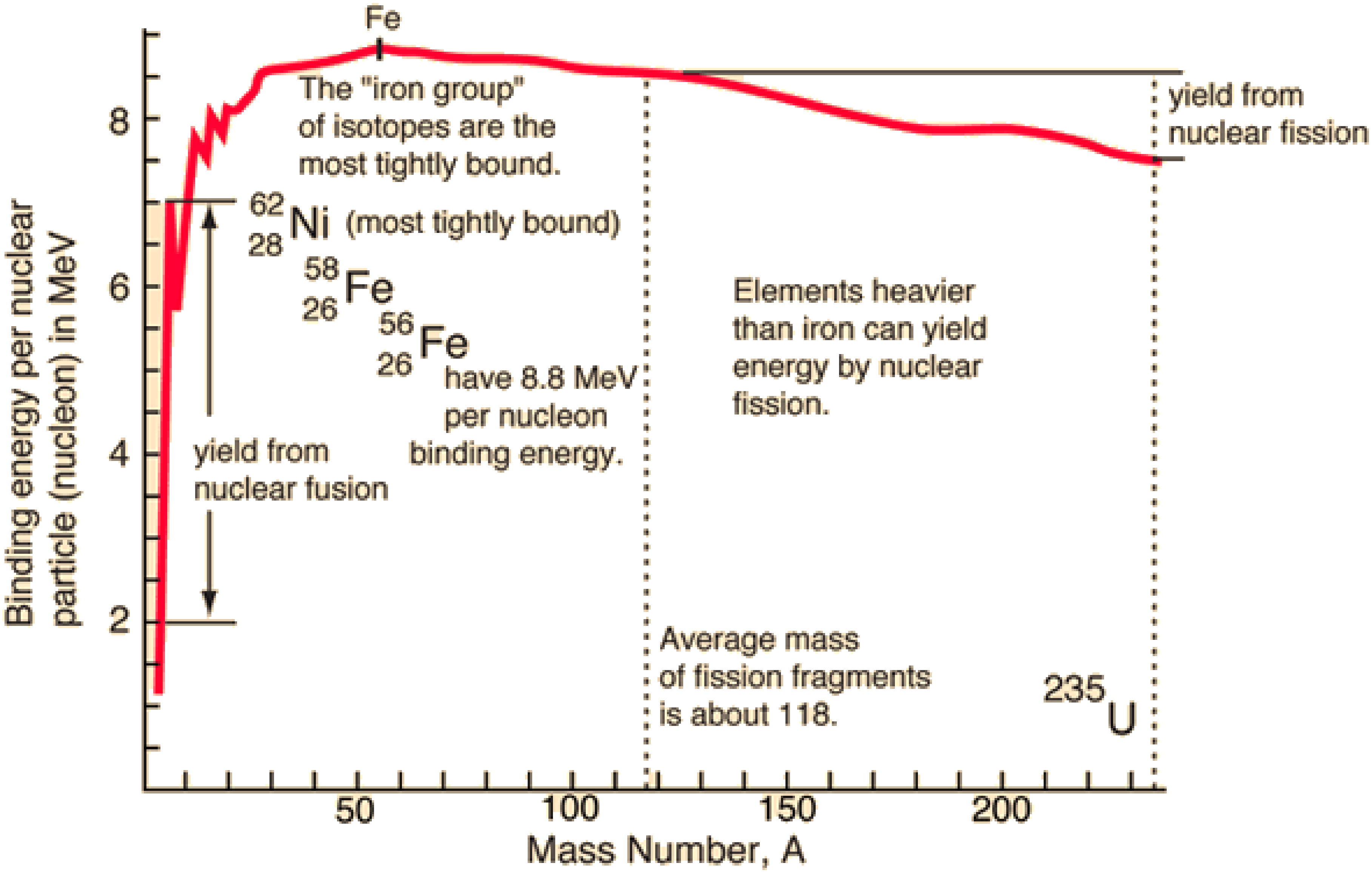
Oxygen ($T_9 \sim 1.4-2.3$)

$^{16}O + ^{16}O \rightarrow$

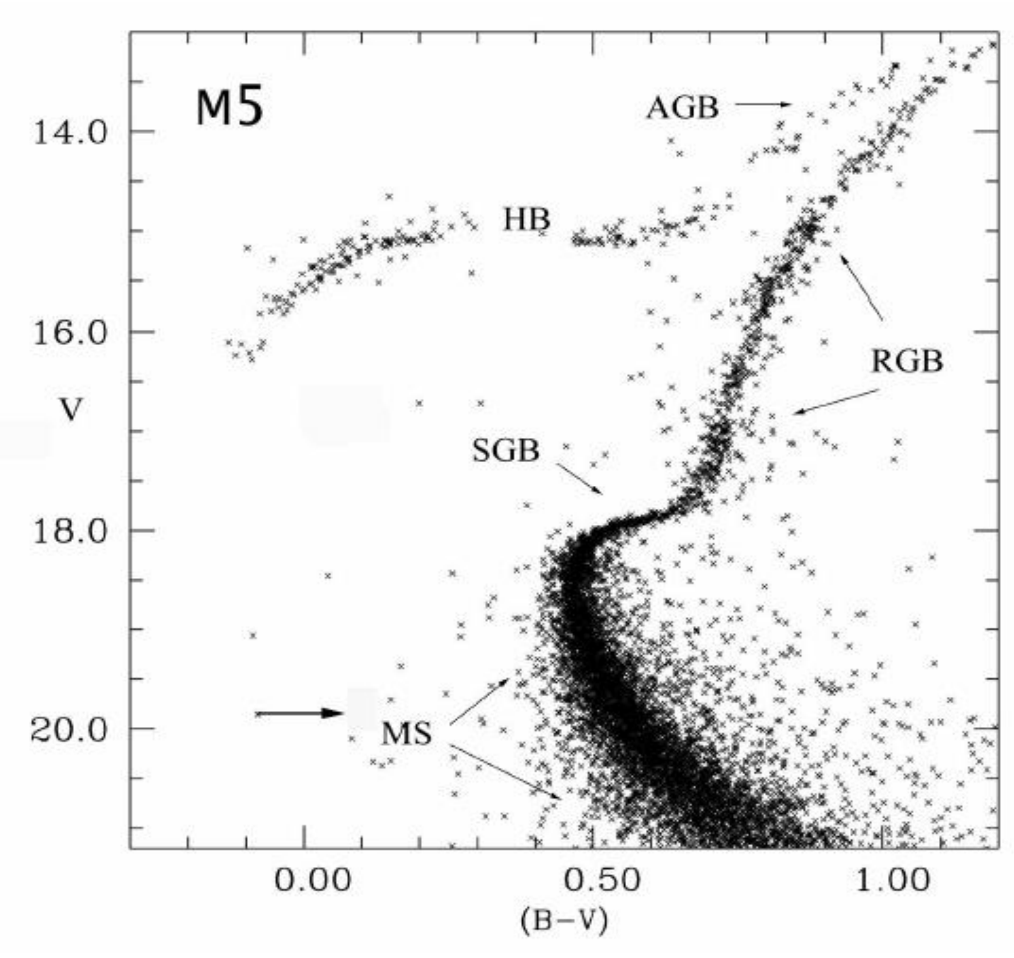
- $^{28}Si + \alpha + 9.6$ MeV
- $^{31}P + p + 7.7$ MeV
- $^{31}S + n + 1.5$ MeV
- $^{30}Si + 2p + 0.38$ MeV
- $^{30}P + d - 2.4$ MeV

Silicon ($T_9 \sim 2.7-4.0$)

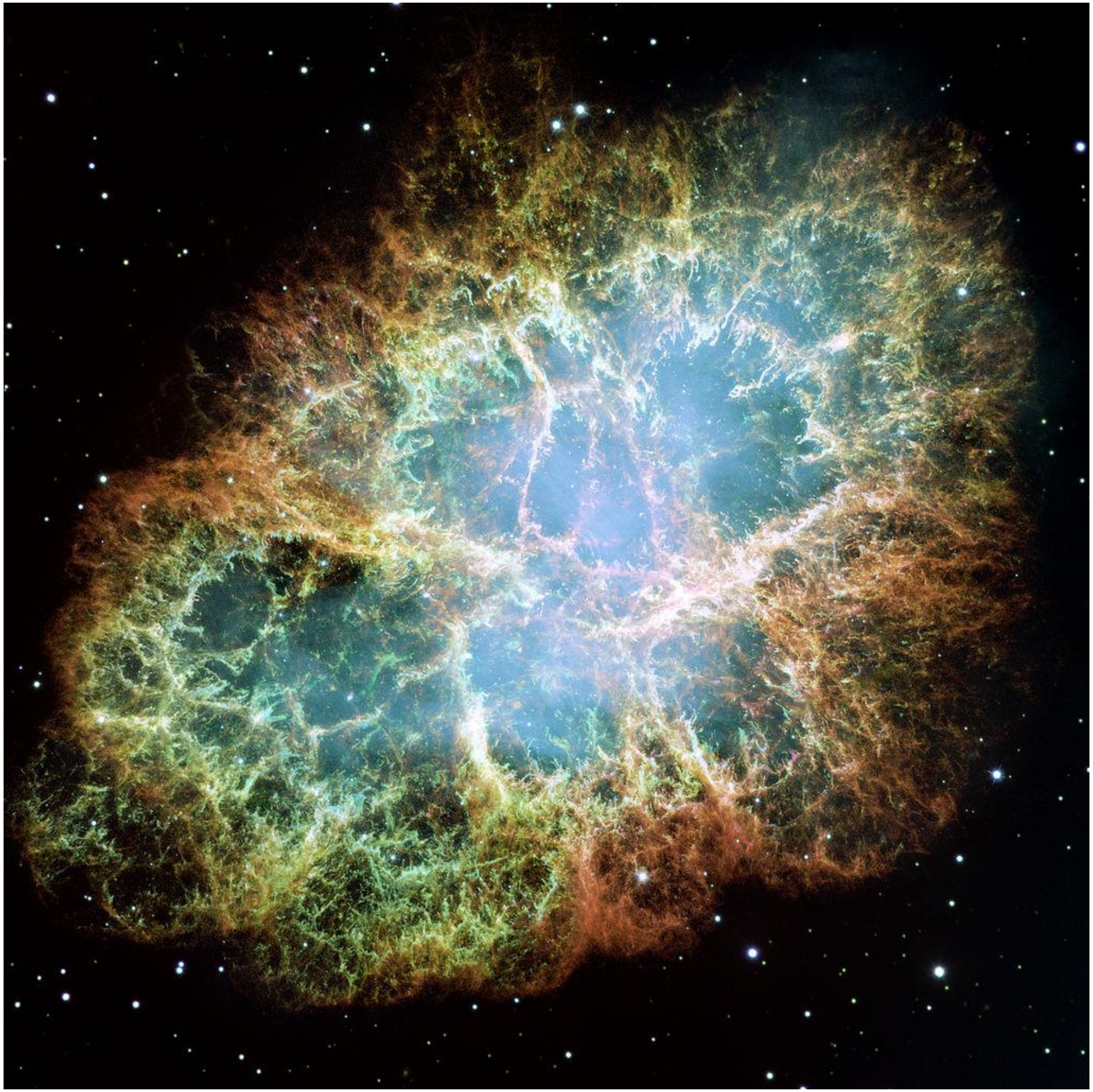
$^{28}Si + \gamma \rightarrow \begin{matrix} \alpha \\ p \\ n \end{matrix} + A \rightarrow \begin{matrix} ^{54,56}Fe \\ ^{58}Ni \end{matrix}$



http://hyperphysics.phy-astr.gsu.edu/hbase/nucene/nucbin.html



V. Castellani „Astrofisica stellare“ Zanichelli, 1985



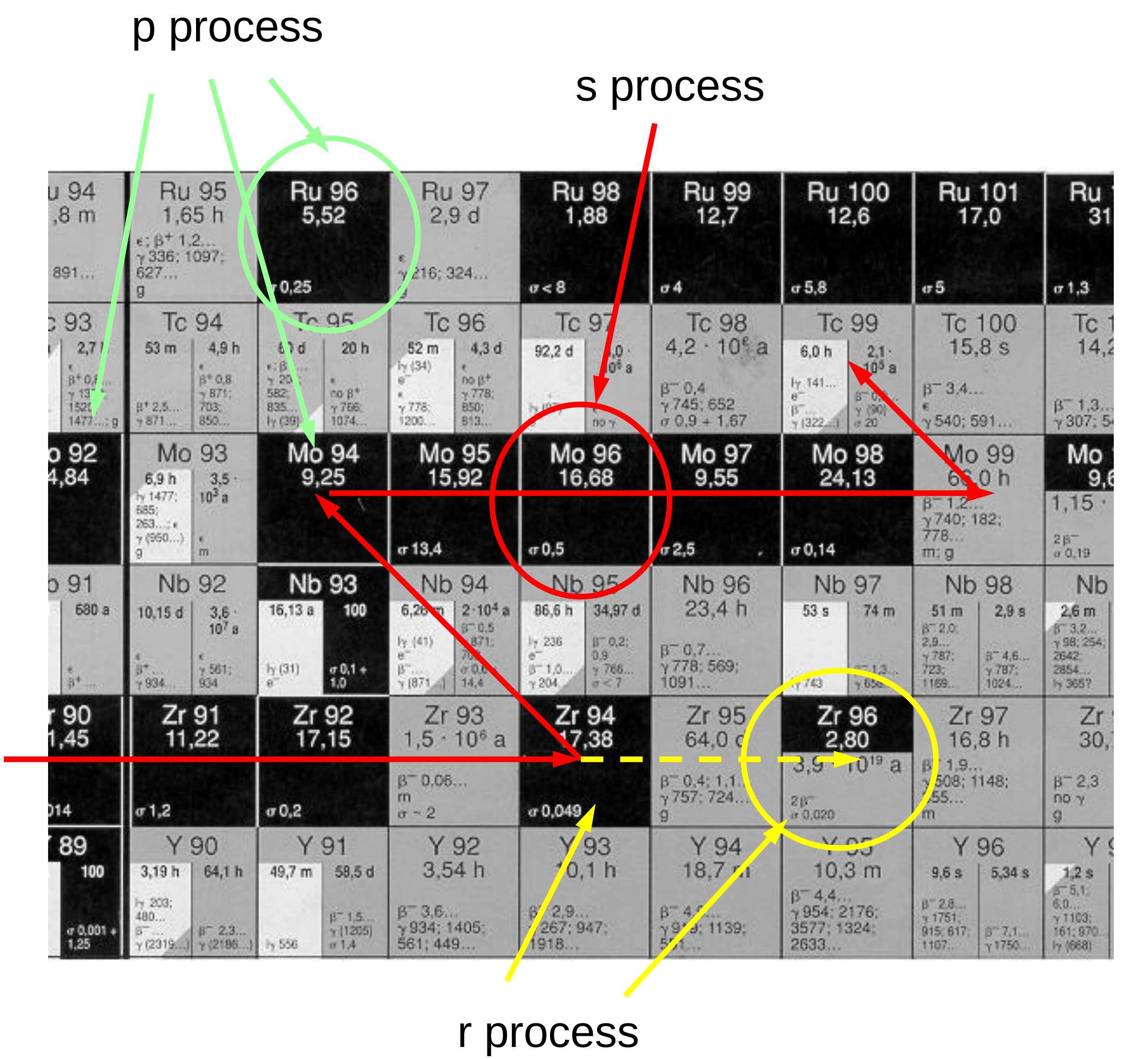
HST- NASA, ESA, "Crab Nebula" J. Hester and A. Loll (Arizona State University)

Evolutionary Stages of a 25-$M_\odot$ Star

Stage	Core Temperature [K]	Core Density [kg/m³]	Duration of Stage
Hydrogen burning	4×10^7	5×10^3	7×10^6 years
Helium burning	2×10^8	7×10^5	7×10^5 years
Carbon burning	6×10^8	2×10^8	600 years
Neon burning	1.2×10^9	4×10^9	1 year
Oxygen burning	1.5×10^9	10^{10}	6 months
Silicon burning	2.7×10^9	3×10^{10}	1 day
Core collapse	5.4×10^9	3×10^{12}	3 second
Core bounce	2.3×10^{10}	4×10^{15}	milliseconds
Explosion (supernova)	$\sim 10^9$	varies	10 seconds

http://www.physics.byu.edu/faculty/christensen

s, r, and p processes



s process

- low neutron density $\rho_n \sim 10^{7-8}$ n/cm^3
- seed from advanced burnings
- neutron sources in burning shells with dredge up :

$^{12}C(p,\gamma)^{13}N(\beta^+\nu)^{13}C(\alpha,n)^{16}O$

$^{14}N(\alpha,\gamma)^{18}F(\beta^+\nu)^{18}O(\alpha,\gamma)^{22}Ne(\alpha,n)^{25}Mg$

- neutron traps, p.e. ^{14}N
- nucleosintesis close to the valley of stability up to A~208

$\tau_n(A) > \tau_\beta(A)$

r-process

- high neutron density $\rho_n \sim 10^{20}$ n/cm^3
- yields depend somwhat on seed nuclei fron advanced burning
- neutron sources: SNII, neutron-star mergers, neutrino-driven winds following core collapse
- $\tau_n(A) << \tau_\beta(A)$,except that at shell closures
- It stops for spontaneous or induced fission at A□~260
- Lot of exotic nuclear physics (halflives, masses, fusion barriers for neutron rich nuclei)

p and rp processes

- production of proton rich nuclei
- rp process via (p,γ) in hot cycles (CNO, NeNa, MgAl) in Novae
- r process via (γ,n) at higher temperatures in SN1, SNII (halflives, masses)

Nucleosynthesis in the r-process

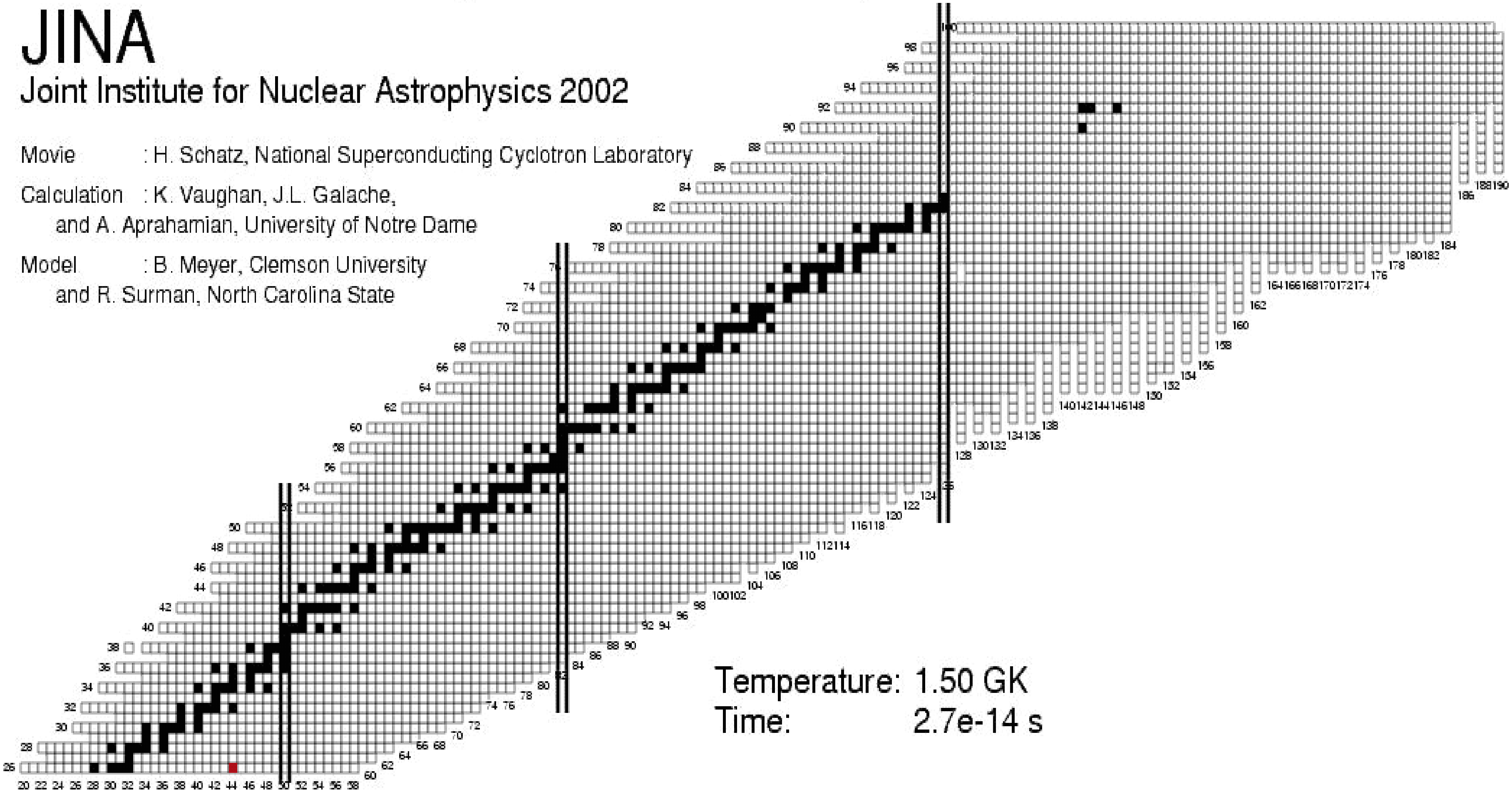
JINA

Joint Institute for Nuclear Astrophysics 2002

Movie : H. Schatz, National Superconducting Cyclotron Laboratory

Calculation : K. Vaughan, J.L. Galache, and A. Aprahamian, University of Notre Dame

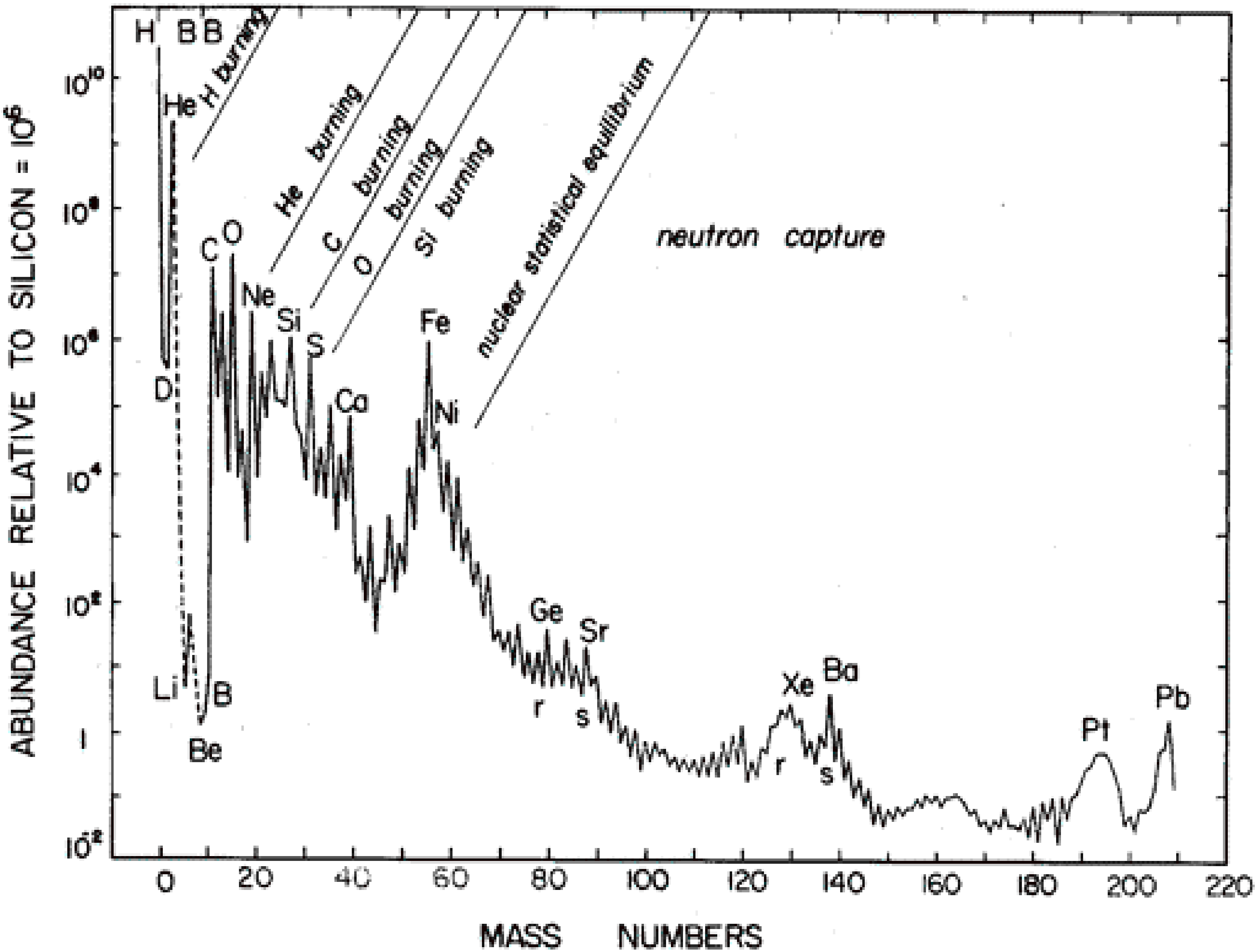
Model : B. Meyer, Clemson University and R. Surman, North Carolina State



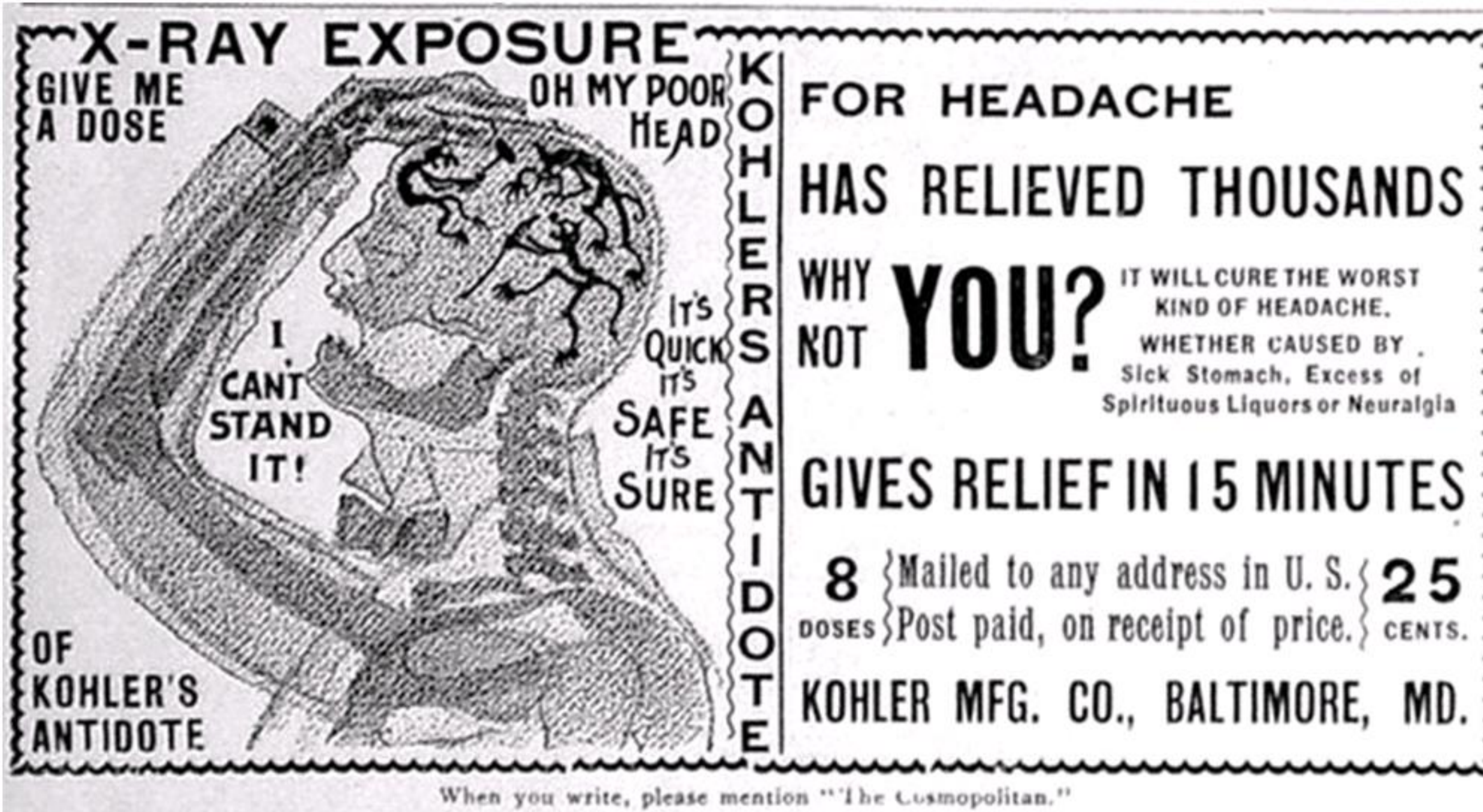
A key feature of r-process: nice movies

http://compact-merger.astro.su.se/movies.html

httpcompact-merger.astro.su.semovies.html.avi

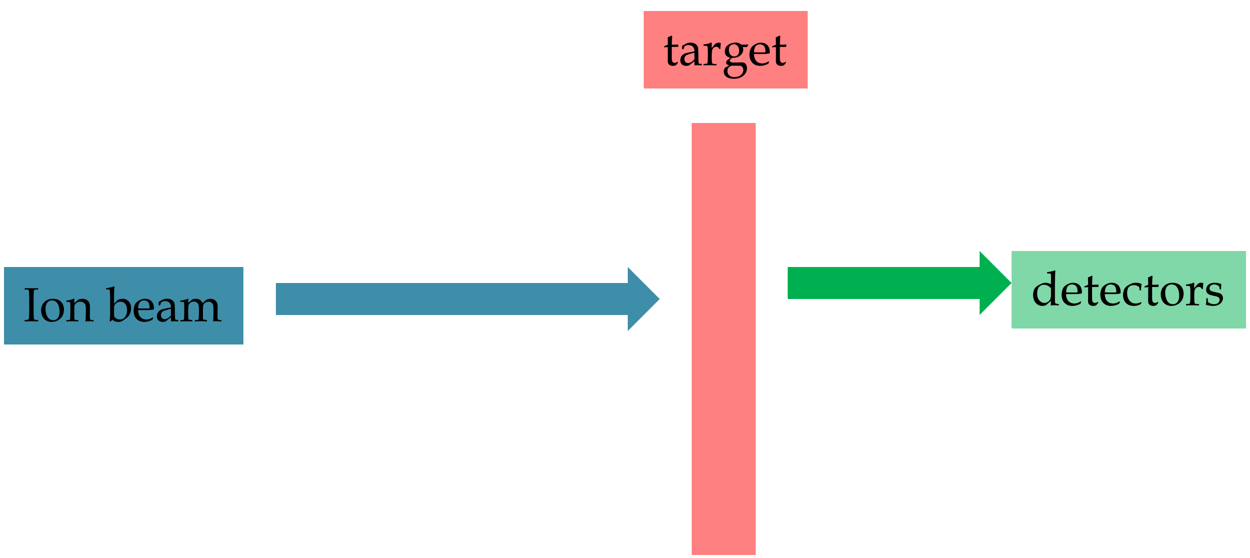


H
BB
H burning
He
He burning
C burning
O burning
Si burning
nuclear statistical equilibrium
neutron capture
C
O
Ne
Si
S
Ca
Fe
Ni
D
Li
B
Be
Ge
Sr
r
s
Xe
Ba
Pt
Pb
ABUNDANCE RELATIVE TO SILICON = 10^6
10^{10}
10^8
10^6
10^4
10^2
1
10^{-2}
0
20
40
60
80
100
120
140
160
180
200
220
MASS NUMBERS


X-RAY EXPOSURE
GIVE ME A DOSE
OH MY POOR HEAD
I CANT STAND IT!
IT'S QUICK IT'S SAFE IT'S SURE
OF KOHLER'S ANTIDOTE
KOHLERS ANTIDOTE
FOR HEADACHE
HAS RELIEVED THOUSANDS
WHY NOT YOU?
IT WILL CURE THE WORST KIND OF HEADACHE.
WHETHER CAUSED BY Sick Stomach, Excess of Spirituous Liquors or Neuralgia
GIVES RELIEF IN 15 MINUTES
8 DOSES
Mailed to any address in U. S. Post paid, on receipt of price.
25 CENTS.
KOHLER MFG. CO., BALTIMORE, MD.
When you write, please mention "The Cosmopolitan."

Nuclear reactions in the laboratory

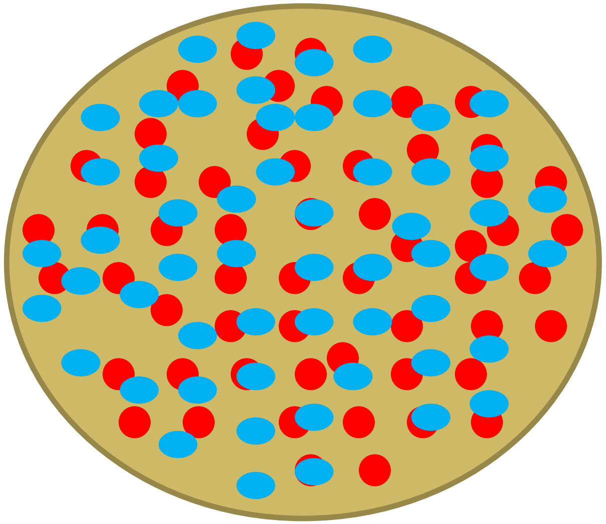
X(a,b)Y

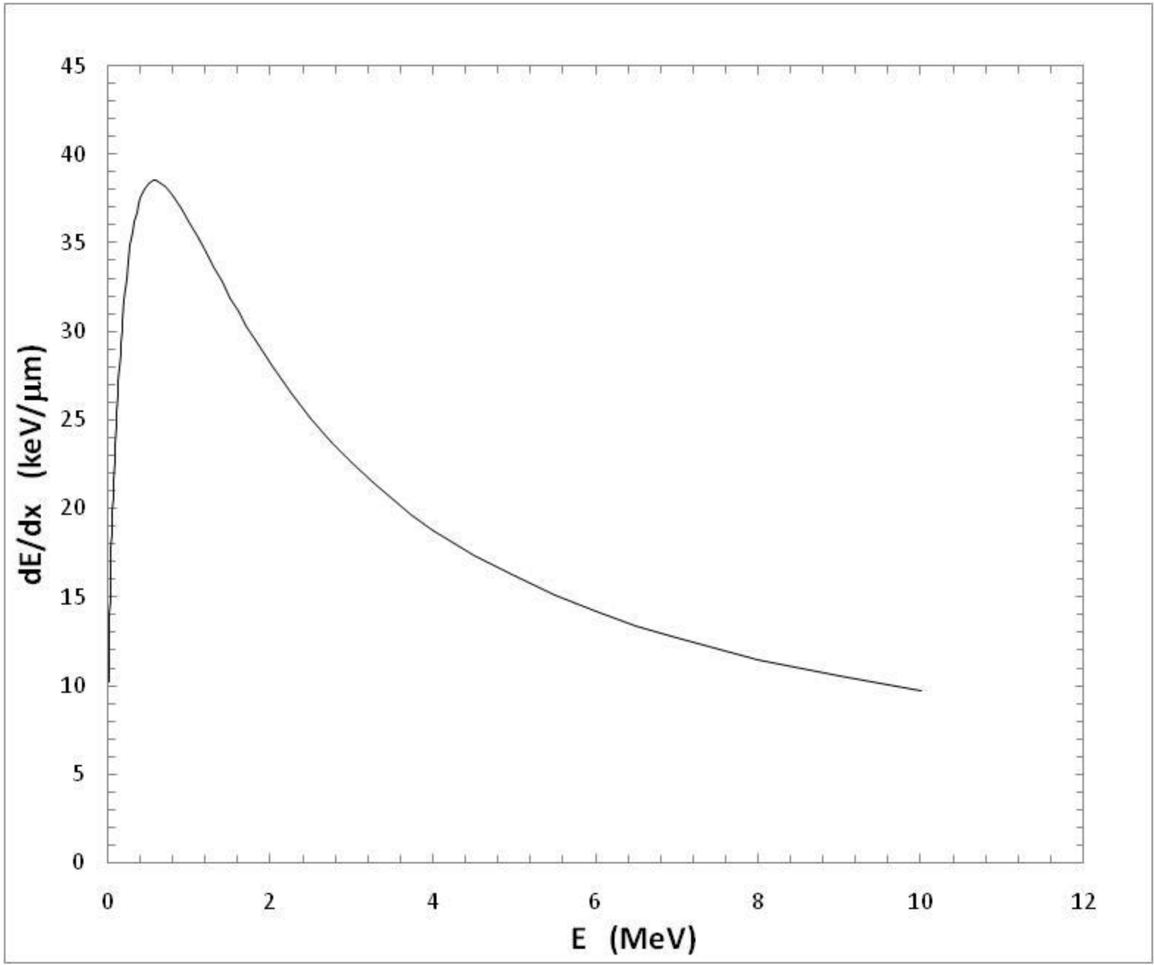


Reaction yield

$$Y = \frac{N_t \sigma}{F} \cdot N_p$$

NOTE: σ depend on E, and E is not constant through the target

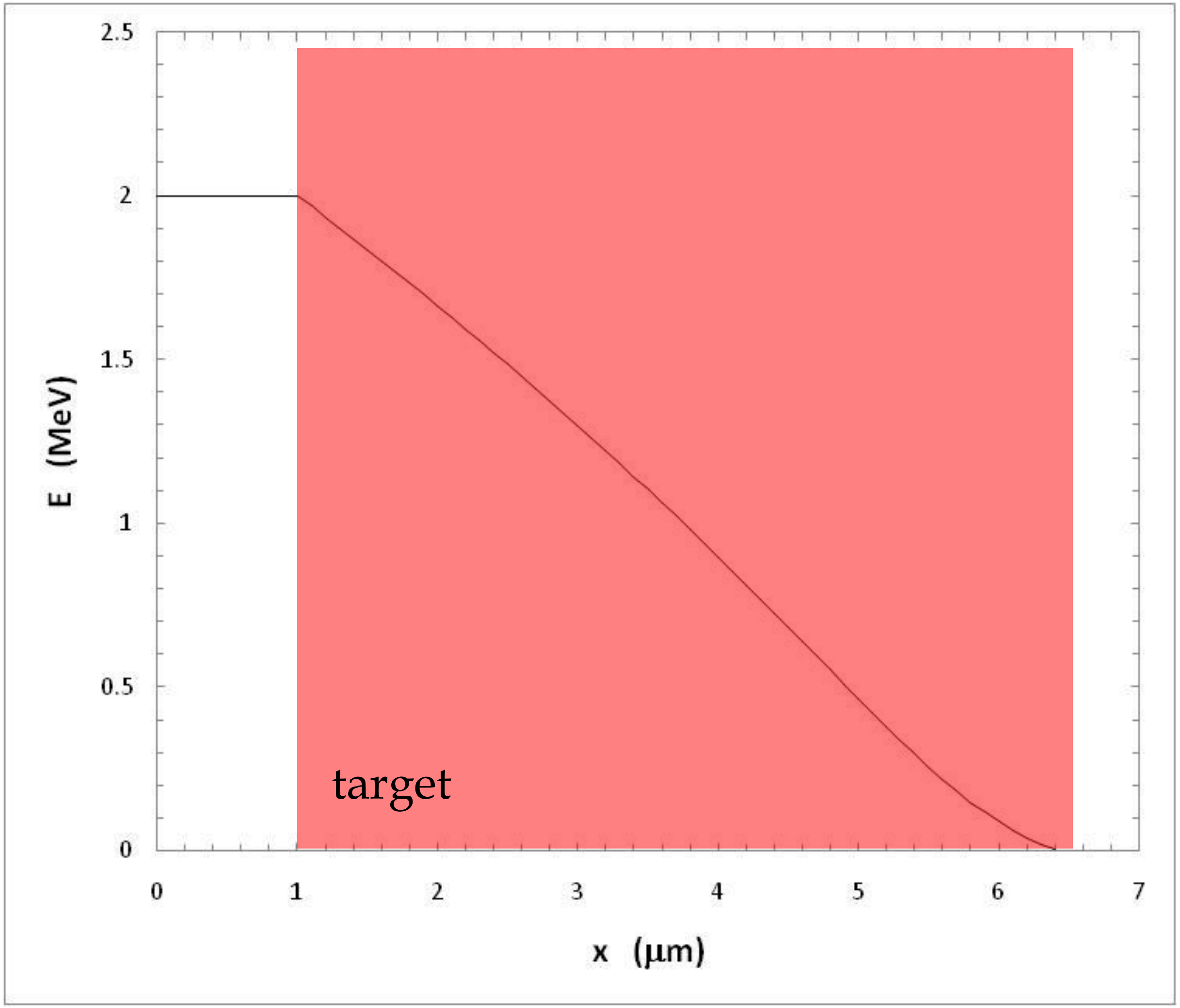




α particles in C
SRIM calulation
www.srim.org

$$E(x) = E_0 - \int_{x_0}^{x} \frac{dE}{dx'}\, dx'$$

α particles in C
SRIM calulation

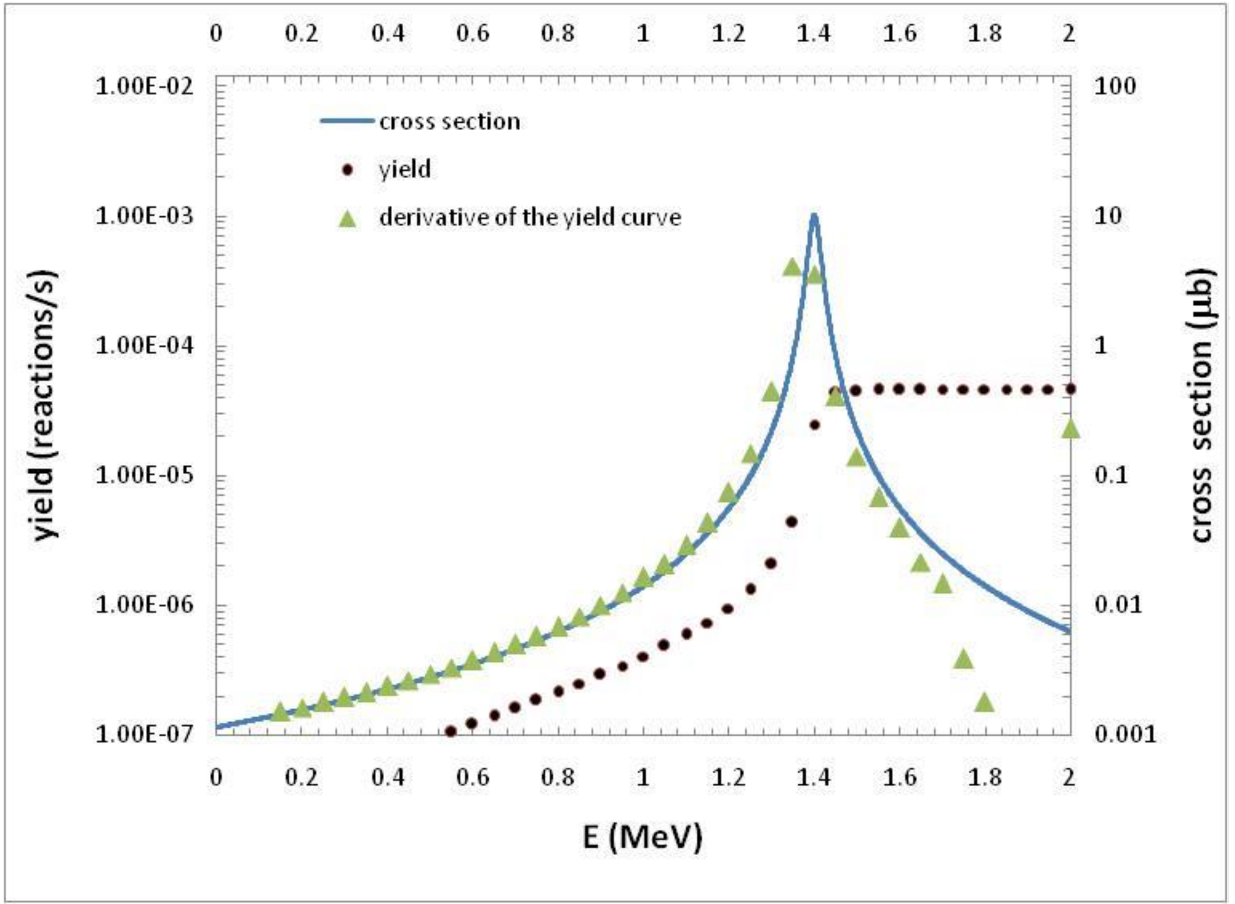


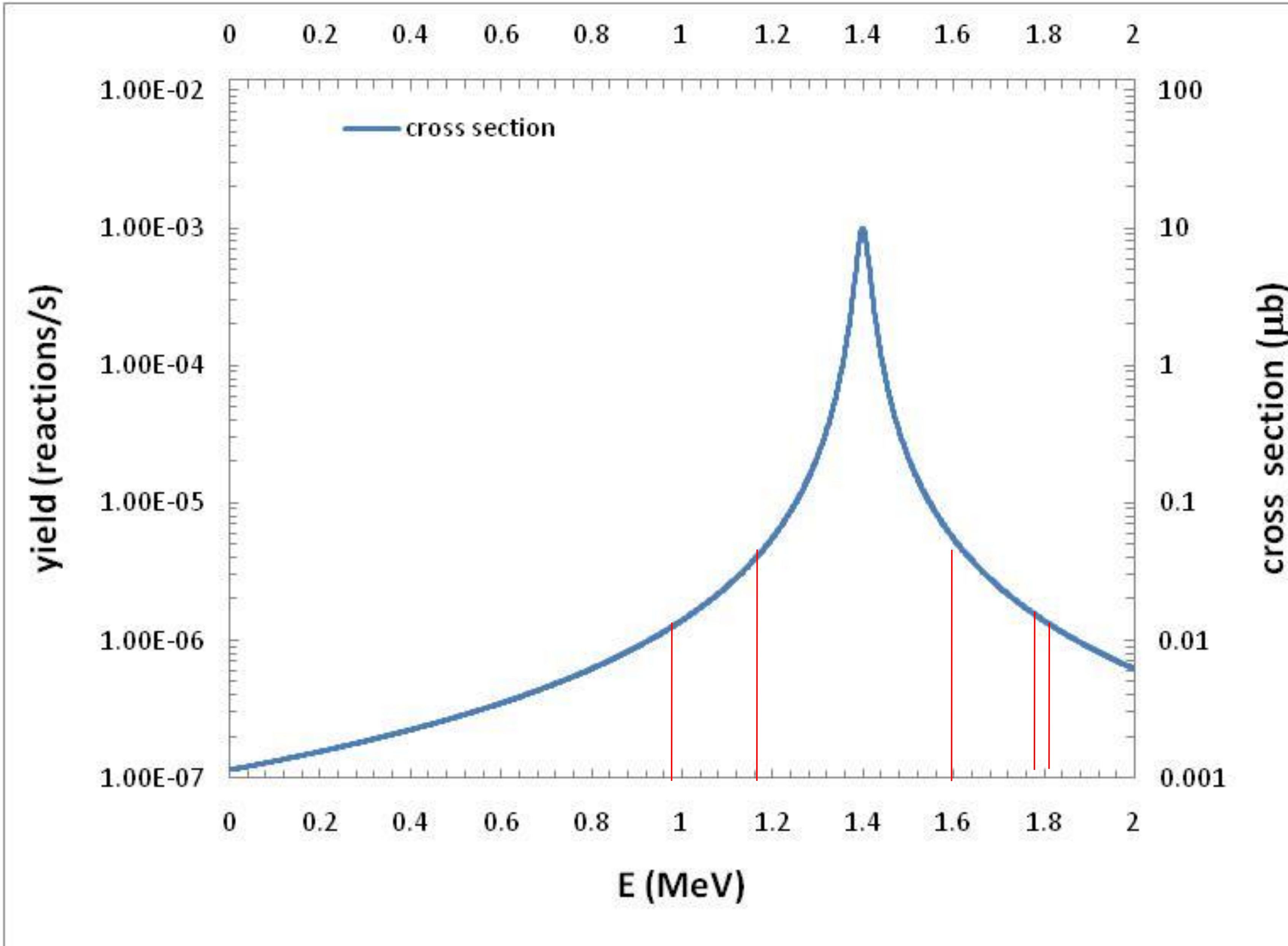
$$Y = \int_{x_0}^{x_1} N_p \frac{n_t \sigma(E)}{F} F dx = \int_{E_1}^{E_0} N_p n_t \sigma(E) \frac{1}{\frac{dE}{dx}} dE$$

Case of a single resonance

E_r=1.4 MeV
Γ=30 keV

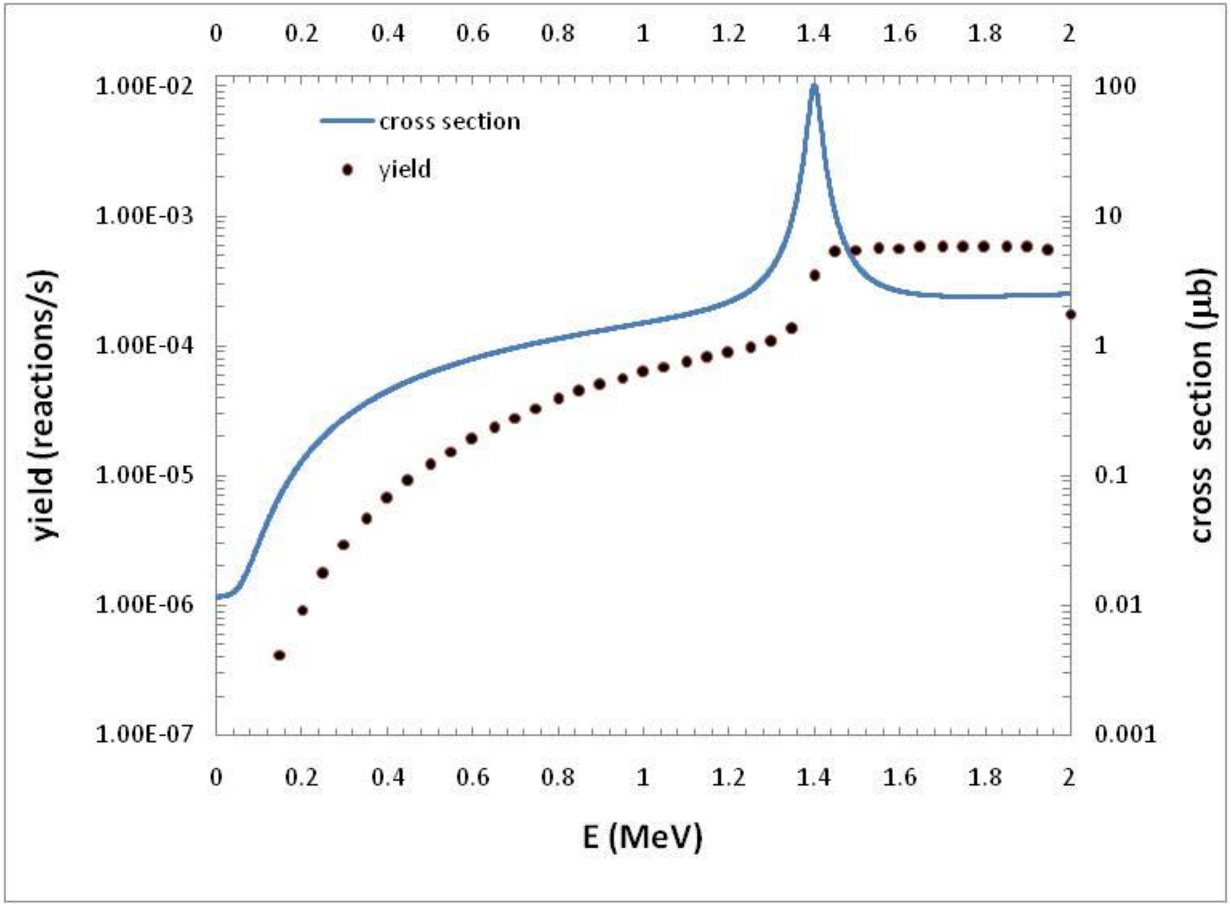
ΔE_t=3 to 680 keV)





cross section
yield (reactions/s)
cross section (μb)
E (MeV)
1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
100
10
1
0.1
0.01
0.001
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

resonant+not resonant



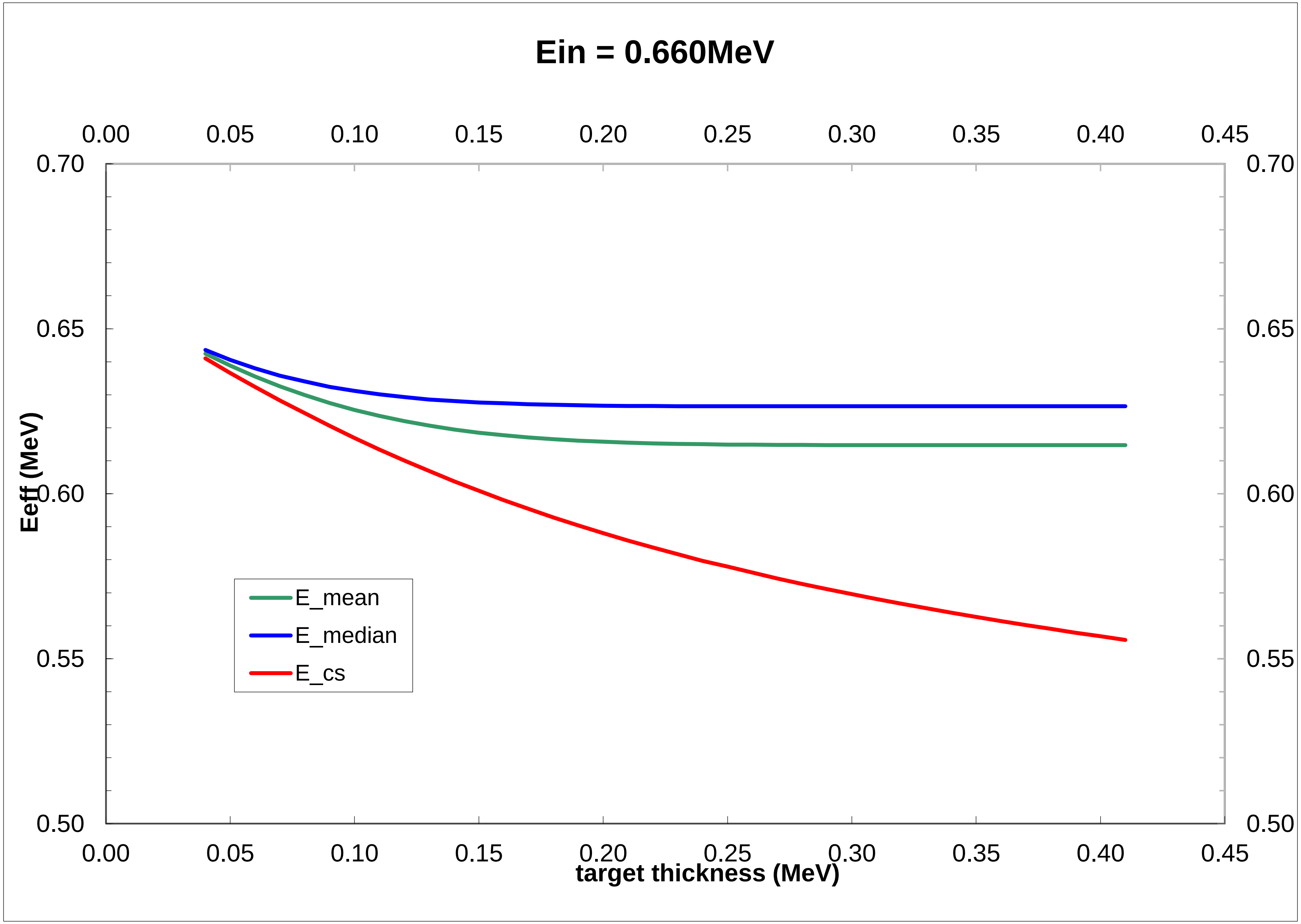
Effective energy for the cross section extracted from a yield
There are 3 recipes found in the literature

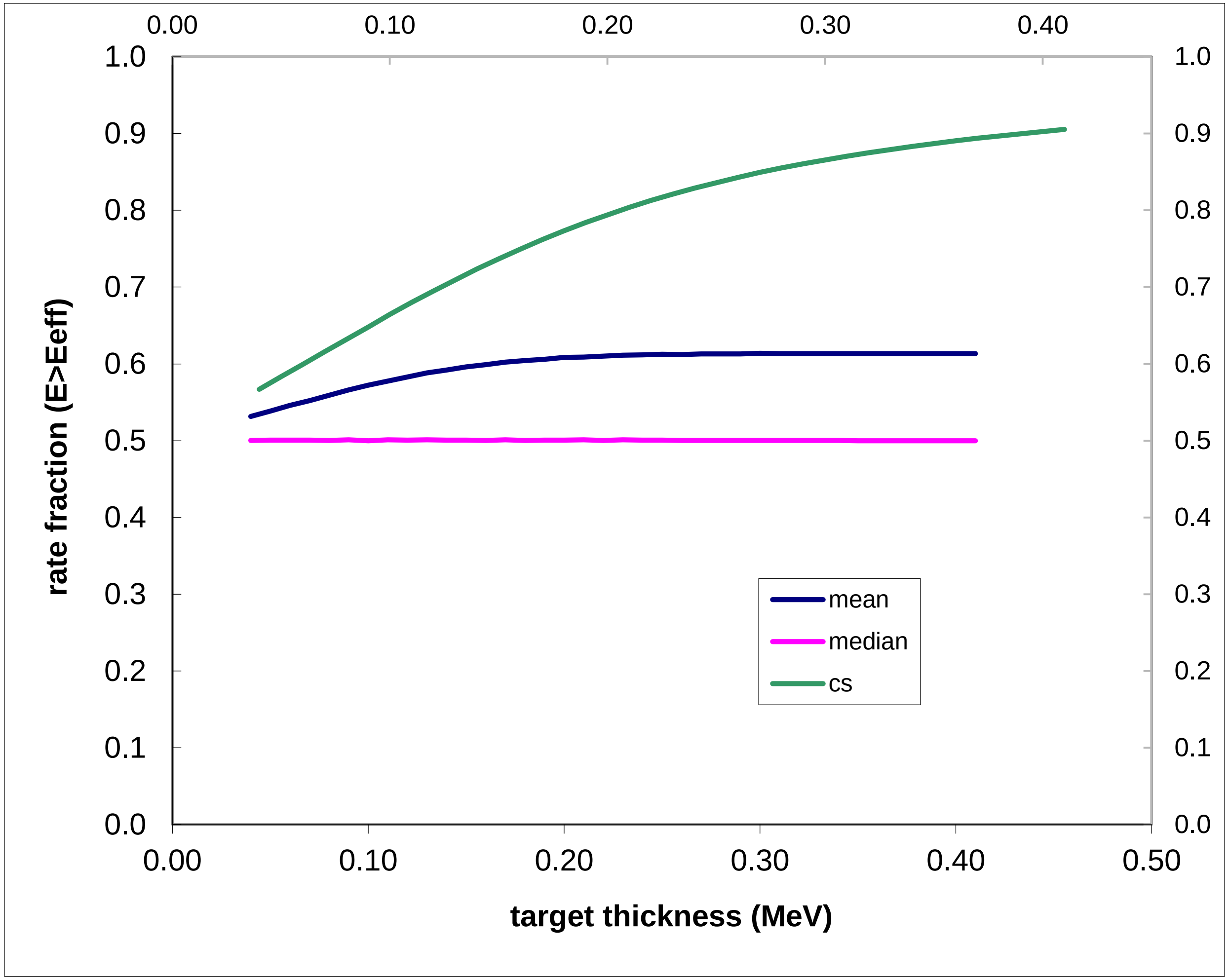
1
$$\int_{E_0-\Delta E}^{E_{eff}} \sigma(E)dE = \frac{1}{2}\int_{E_0-\Delta E}^{E_0} \sigma(E)dE$$

2
$$E_{eff} = \frac{\int_{E_0-\Delta E}^{E_0} \sigma(E)EdE}{\int_{E_0-\Delta E}^{E_0} \sigma(E)dE}$$

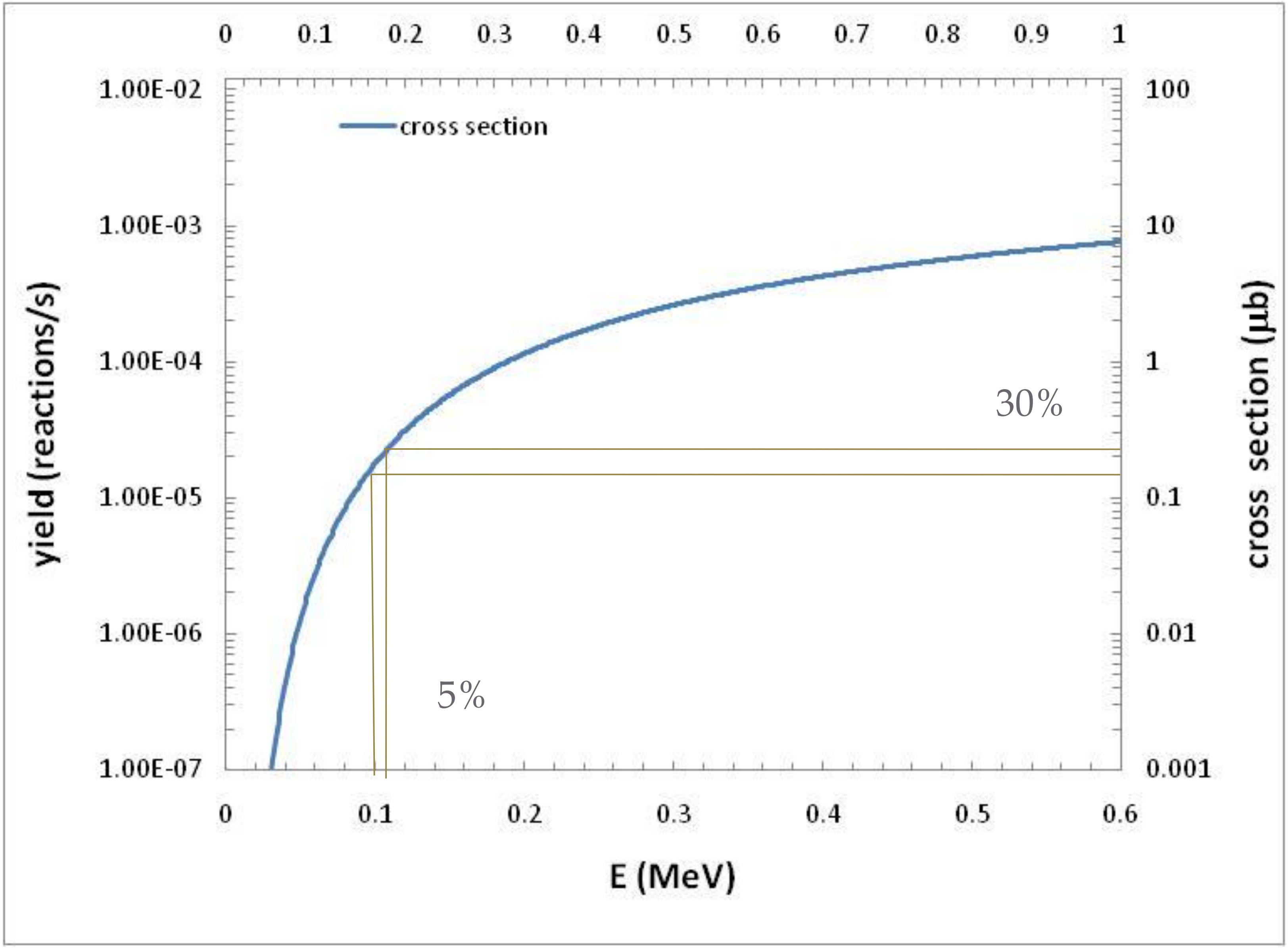
3
$$\frac{N_r}{N_p N_t} = \frac{\int_{E_0-\Delta E}^{E_0} \sigma(E)dE}{\Delta E} = \sigma_{eff}$$

$$\sigma(E_{eff}) = \sigma_{eff}$$


Ein = 0.660MeV
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.70
0.65
0.60
0.55
0.50
Eeff (MeV)
E_mean
E_median
E_cs
target thickness (MeV)



0.00
0.10
0.20
0.30
0.40
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
rate fraction (E>Eeff)
mean
median
cs
0.00
0.10
0.20
0.30
0.40
0.50
target thickness (MeV)



0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
cross section
yield (reactions/s)
1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
cross section (µb)
100
10
1
0.1
0.01
0.001
30%
5%
0
0.1
0.2
0.3
0.4
0.5
0.6
E (MeV)

Experimental determination of reaction cross sections

Direct methods:

very low cross sections -> low counting rates
measure outside Gamow window -> extrapolation (reaction mechanism
cosmic radiation + nat. roombckg
Beam/target induced bckg

For RIB: low beam intensity

key improvements:

- Beams (obvious)
- Targets
- Detectors

Radiative captures reactions

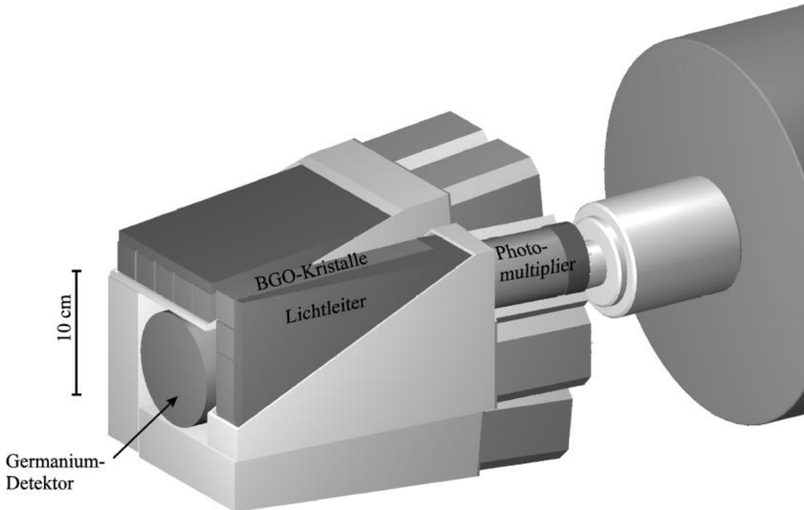
No direct natural background

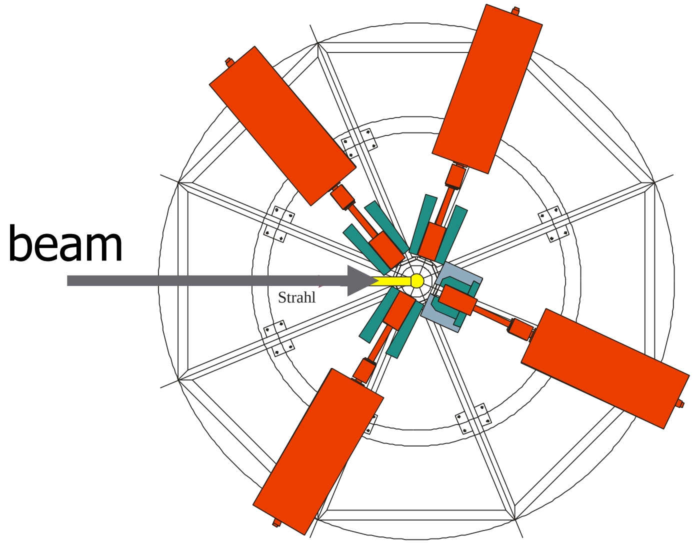
X(α,γ)Y

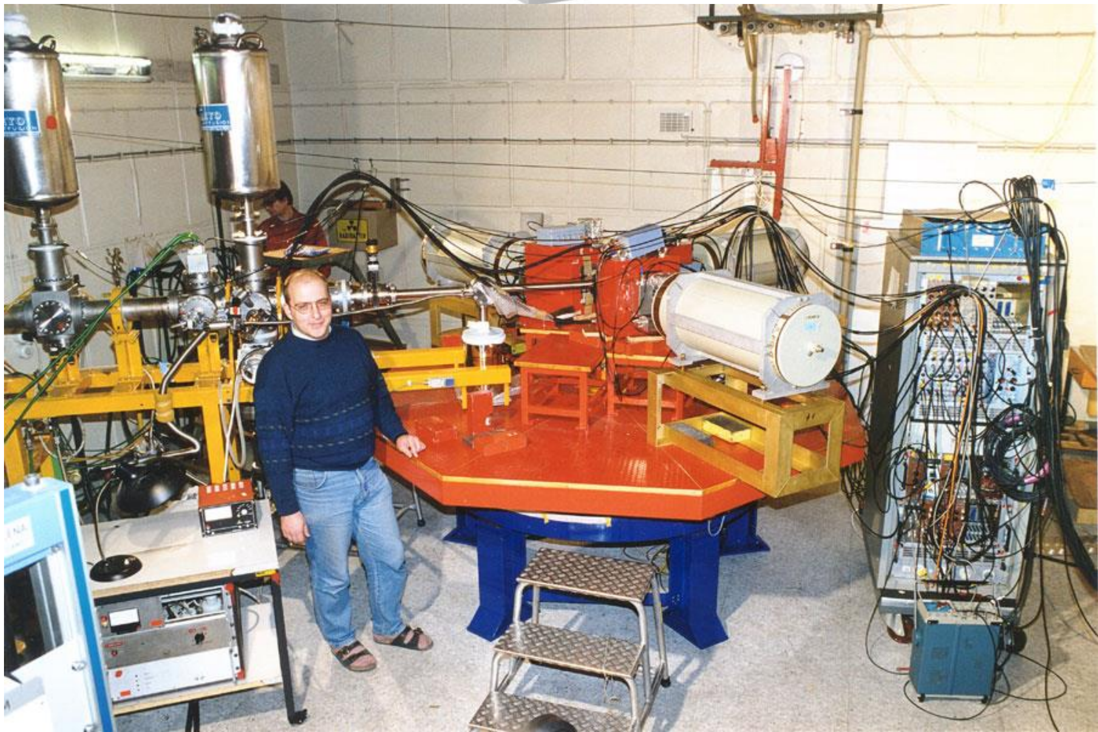
Cosmic background
Natural radioactivity

$^{12}C(^4He,\gamma)\,^{16}O$ Stuttgart

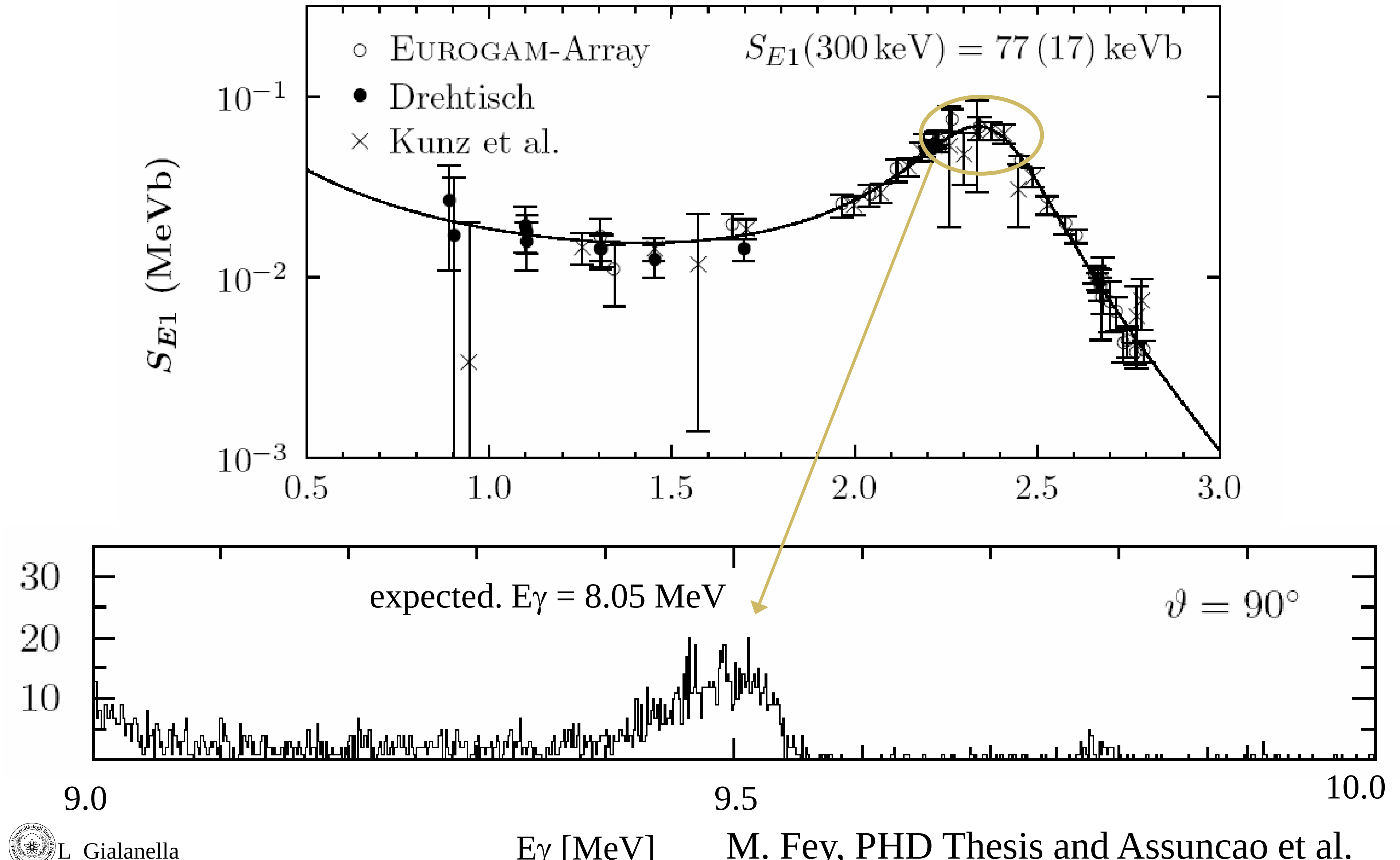
- ^4He beam on ^{12}C solid target
- Targets: (low-energy) ion beam implantation
    - $^{12}C/^{13}C$ separation of accelerated ions
- Array of Ge detectors
    - Eurogam
    - Ge surrounded by BGO crystals (active shielding)
        - Compton suppression
        - Cosmic ray suppression





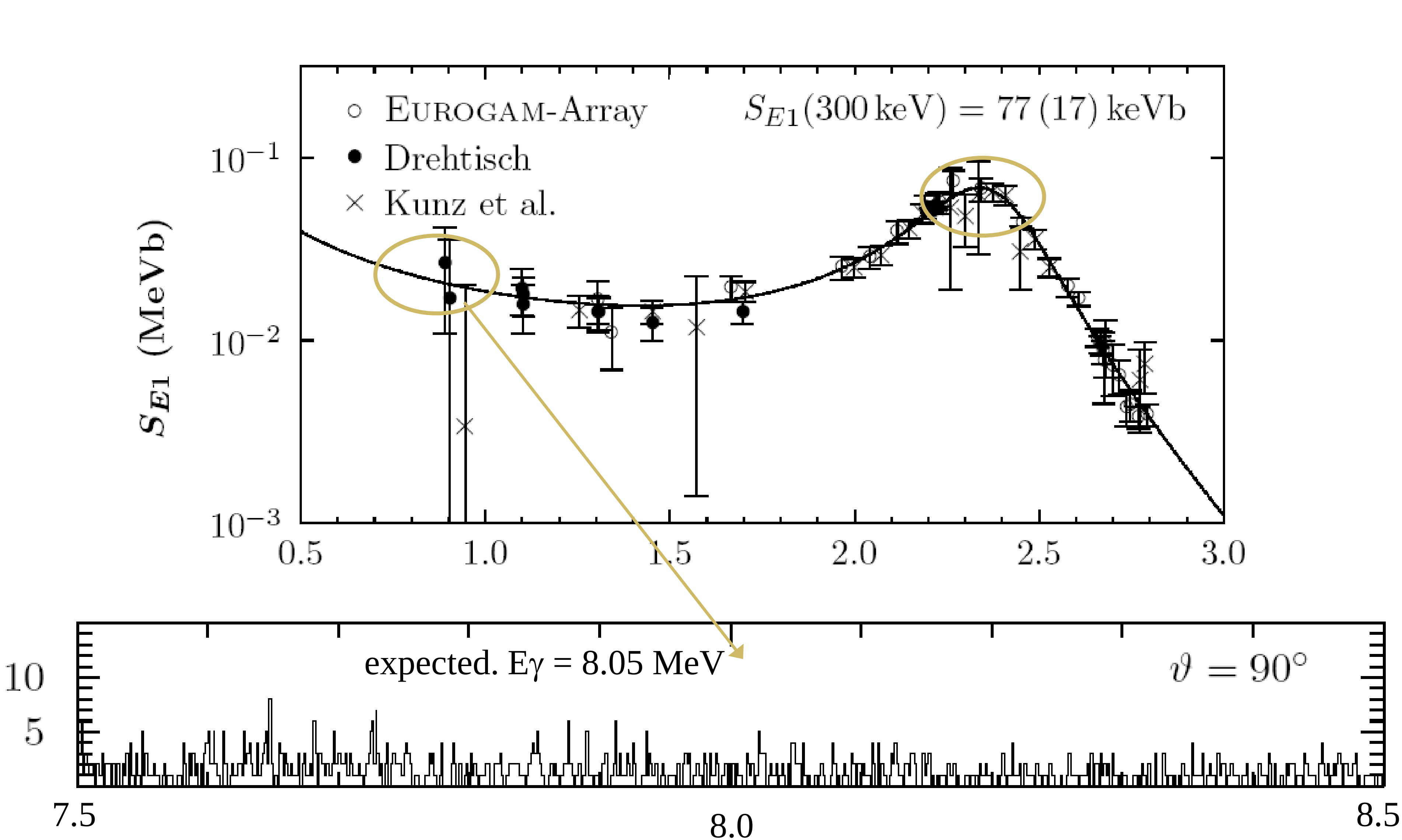


Stuttgart-Eurogam



M. Fey, PHD Thesis and Assuncao et al.

Stuttgart-Eurogam

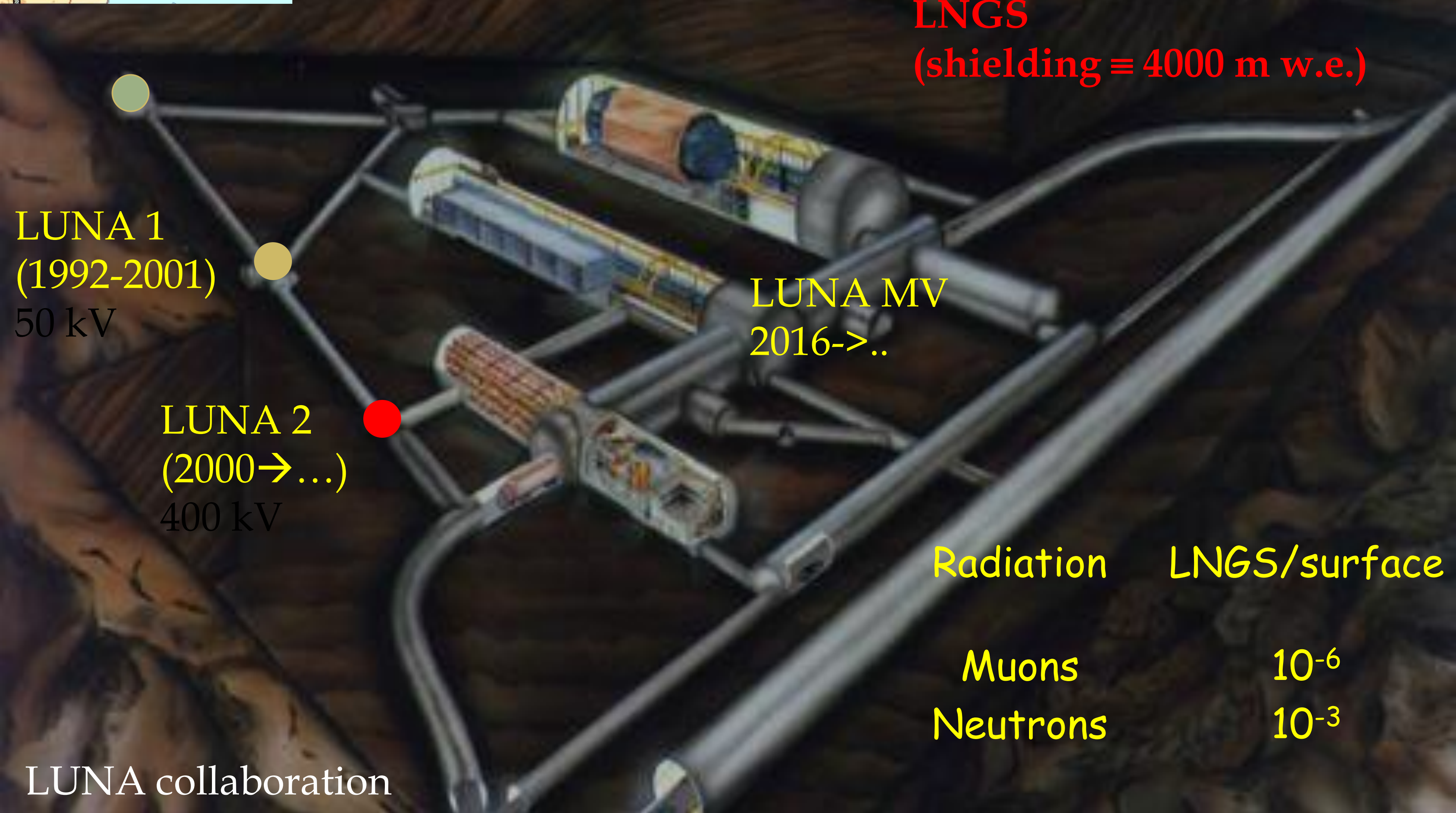


L Gialanella

Eγ [MeV]

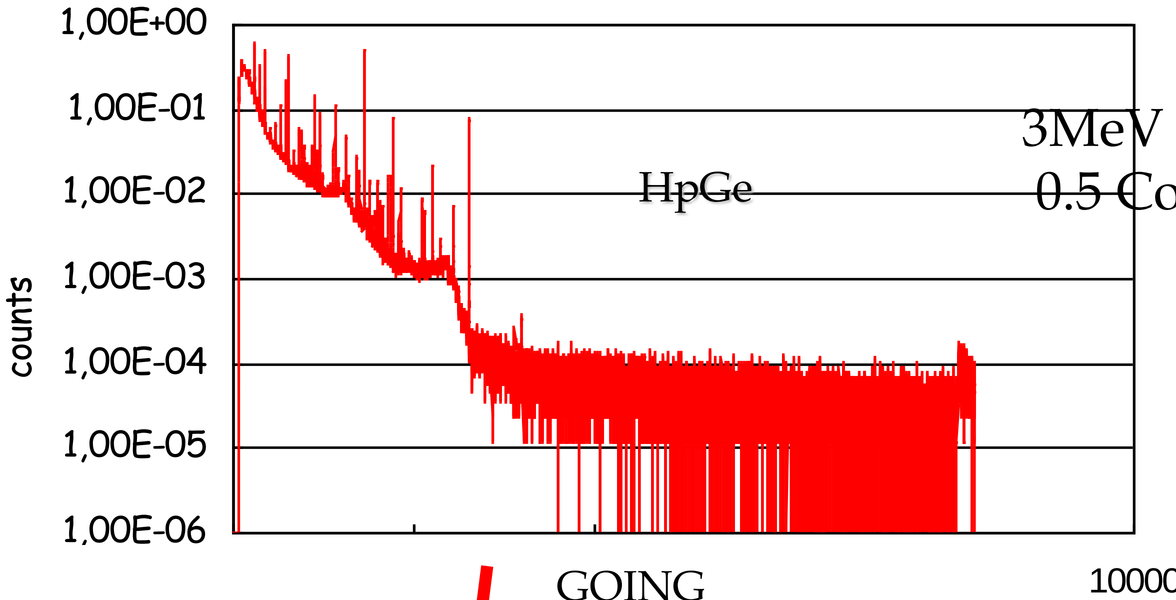
M. Fey, PHD Thesis and Assuncao et al.

Laboratory for Underground Nuclear Astrophysics



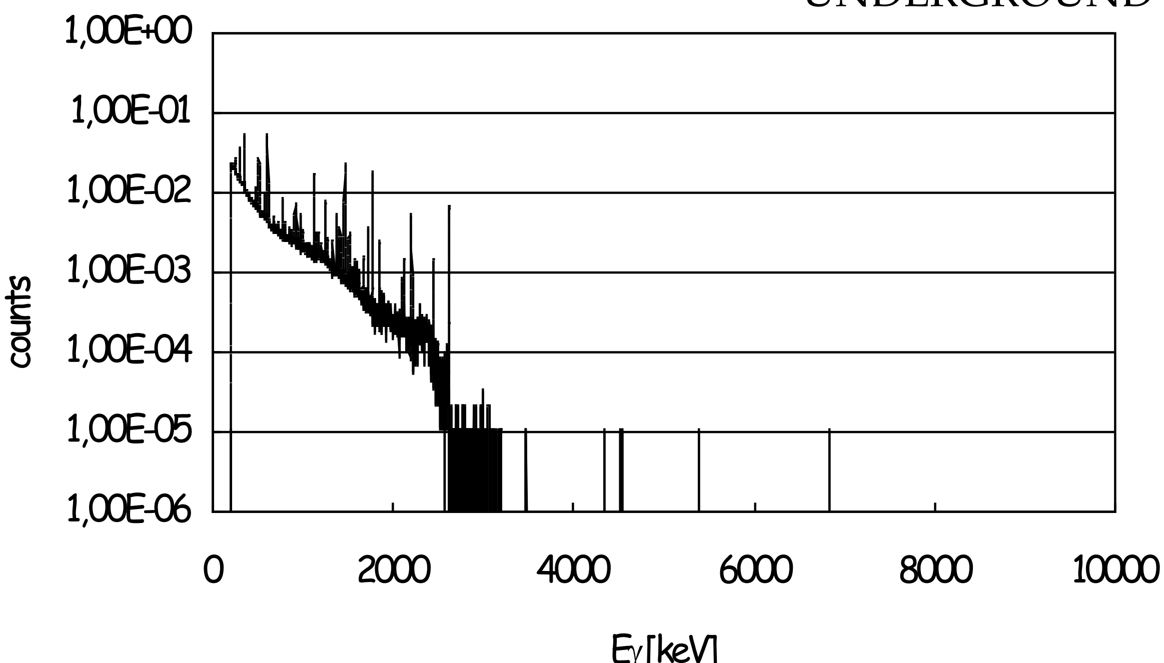
Radiation	LNGS/surface
Muons	10^{-6}
Neutrons	10^{-3}

LUNA collaboration



3MeV < Eγ < 8MeV:
0.5 Counts/s

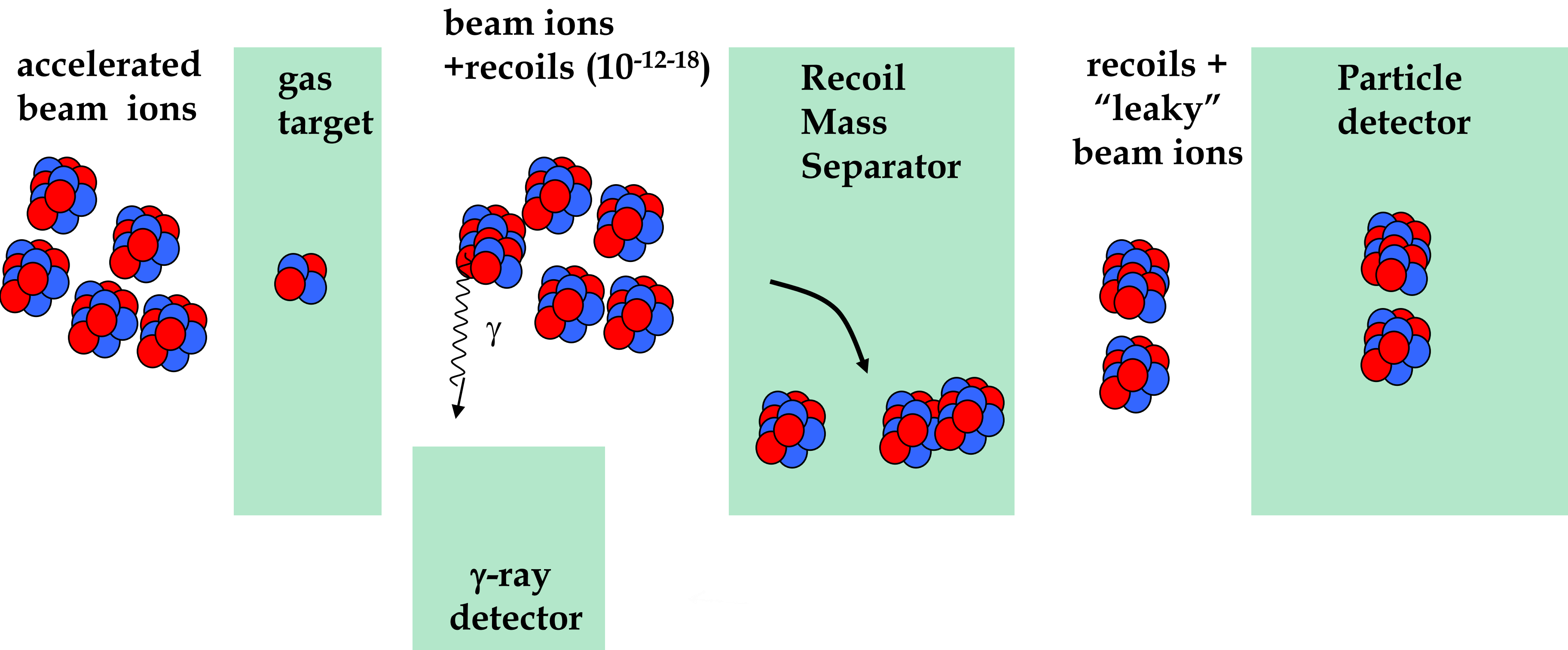
GOING
UNDERGROUND



3MeV < Eγ < 8MeV
0.0002 Counts/s

courtesy LUNA collaboration

RMS : working principle



$$N_{recoils} = N_{projectiles} \times n_{target} \times \sigma \times T_{ERNA} \times \Phi_q \times \varepsilon_{part}$$

$$N_{gamma} = N_{recoils} \times \varepsilon_\gamma$$

Recoil Separators

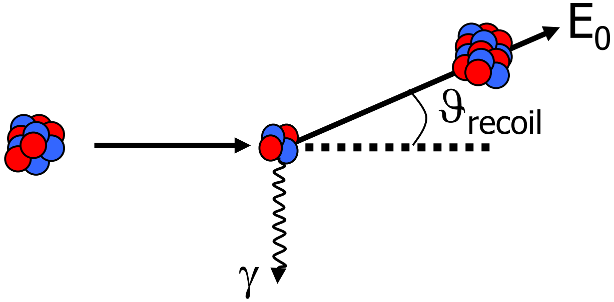
basic principles

Angular and energy broadening by γ-ray emission

$$p_\gamma = E_\gamma / c$$

$\vartheta_\gamma = 90°$

Full angular broadening



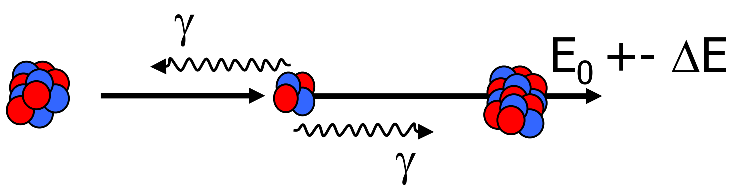
$$\vartheta_{recoil} \approx \tan^{-1}(\Delta p/p) = \tan^{-1}\left(\frac{E\gamma/c}{p_{recoil}}\right)$$

$\vartheta\gamma_{max} = 26\text{mrad}$

-> ø52 mm after 1 m !

$\vartheta_\gamma = 0° / 180°$

Full energy broadening

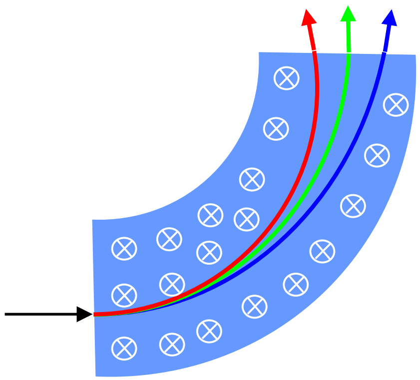


$$\Delta E/E_0 \approx 2\,\Delta p/p = 2\,\frac{E\gamma/c}{p_{recoil}}$$

$\Delta E \sim \pm 185$ keV

$E0 = 3.6$ MeV

Recoil Separators
basic separation principles

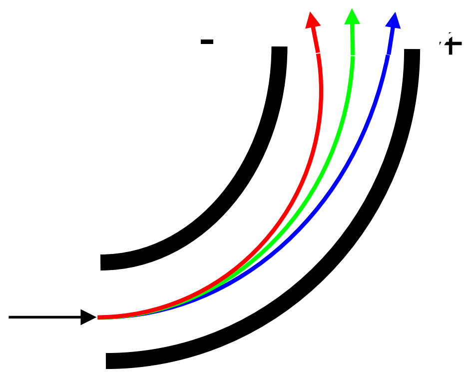


magnetic dipole

$$F_z = F_L$$

$$\frac{P}{q} = r \times B$$

Momentum filter

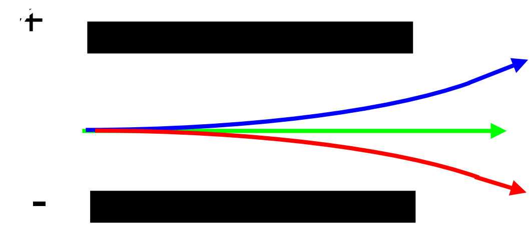


electric dipole

$$F_z = F_e$$

$$\frac{E}{q} = \frac{r \times U}{2 \times d}$$

Energy filter



Wien filter

$$|F_e| = |F_L|$$

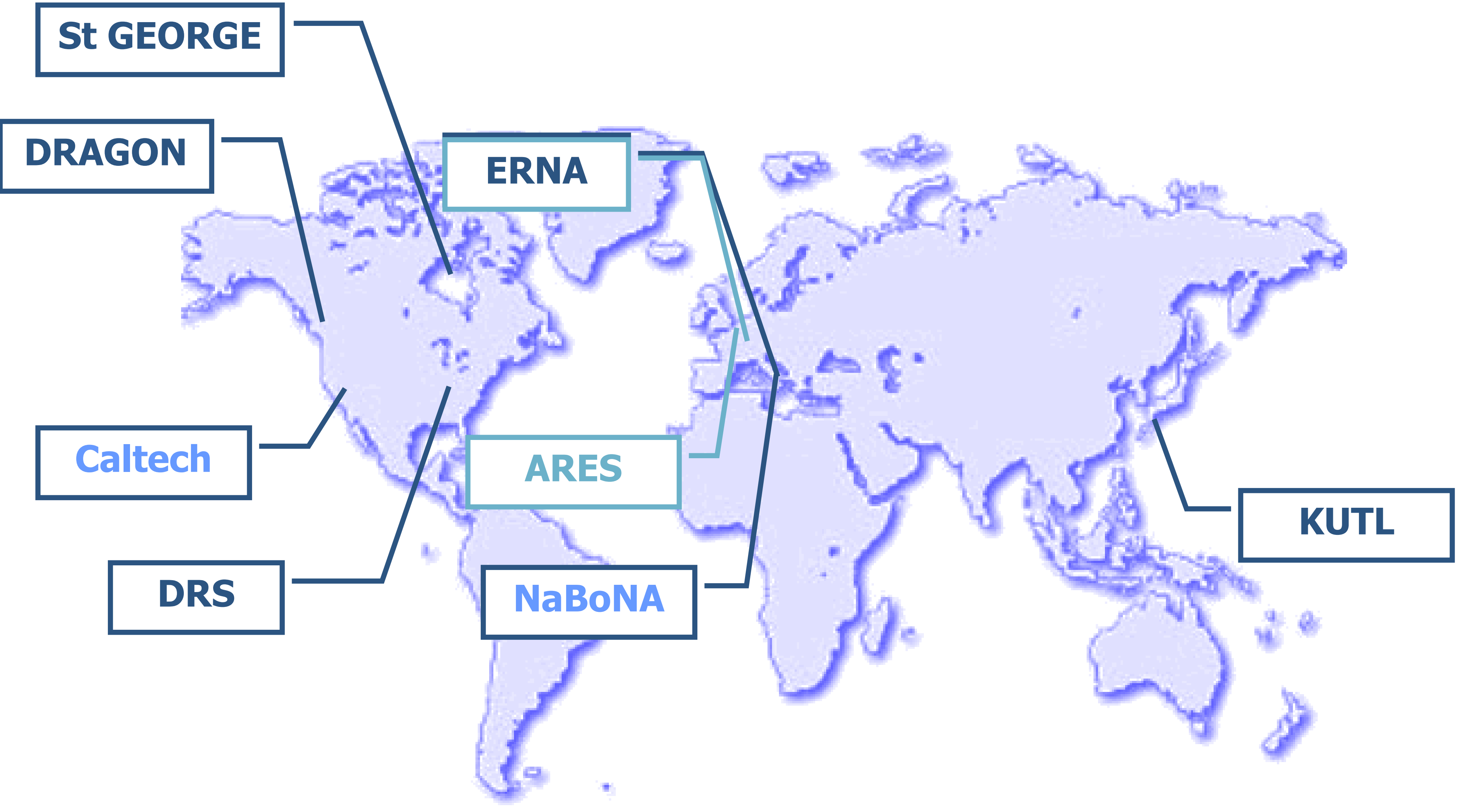
$$v = \frac{U}{B \times d}$$

Velocity filter

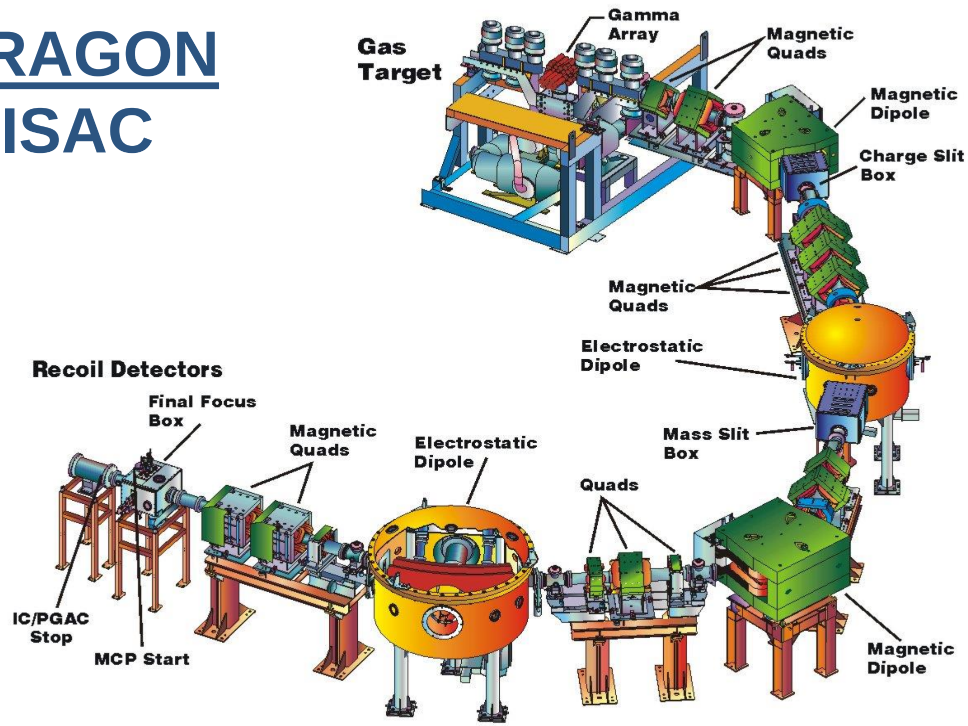
Charge insensitive for v=v0
Variable analyzing power

Combine to $\frac{m}{q}$ filtering

RMS for Nuclear Astrophysics



DRAGON
ISAC

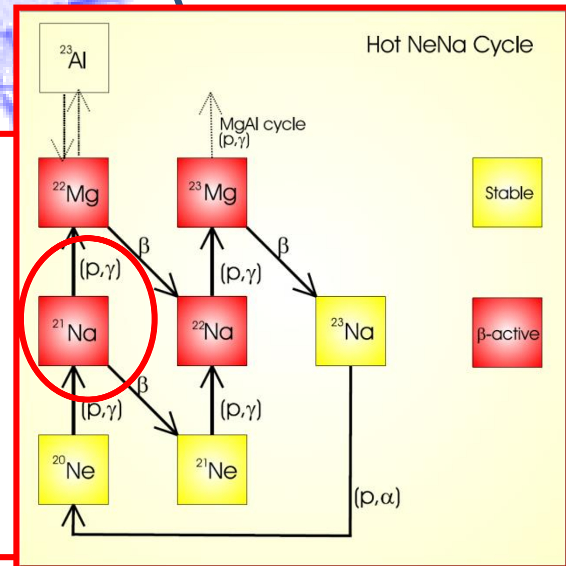


DRAGO

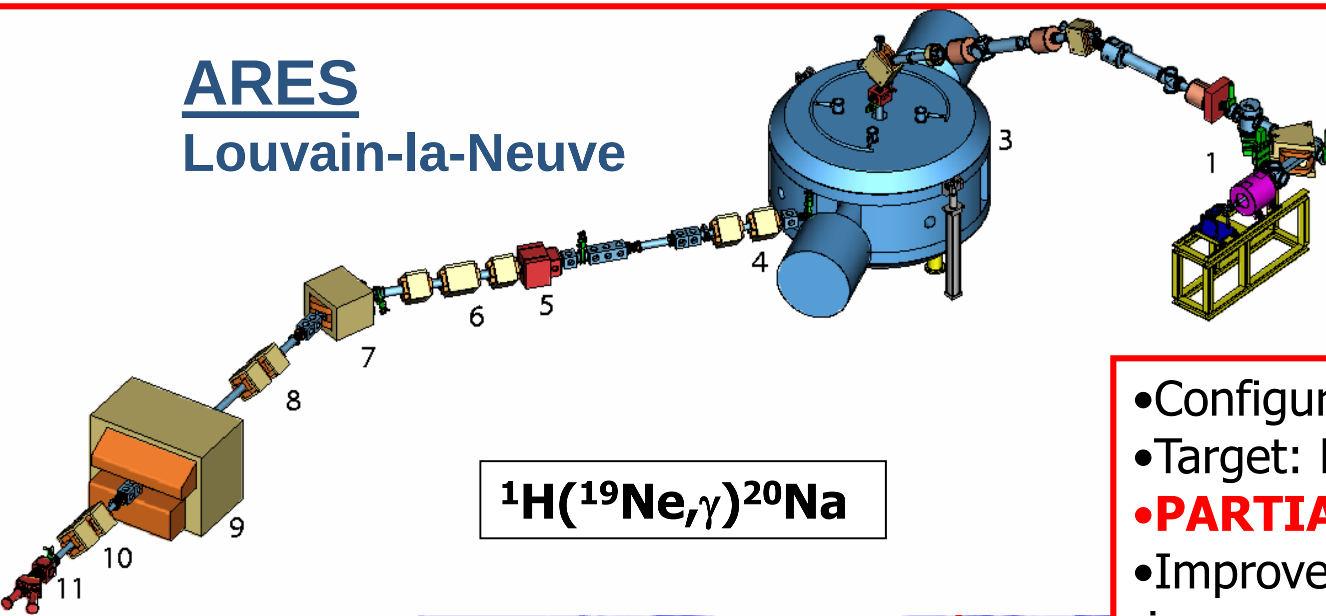
Calt

DRS

- Configuration: M-E-M-E
- radioactive ion beams
- differentially pumped gas target
- Acceptances 18mrad (?)
- Assumption of **FULL acceptances**

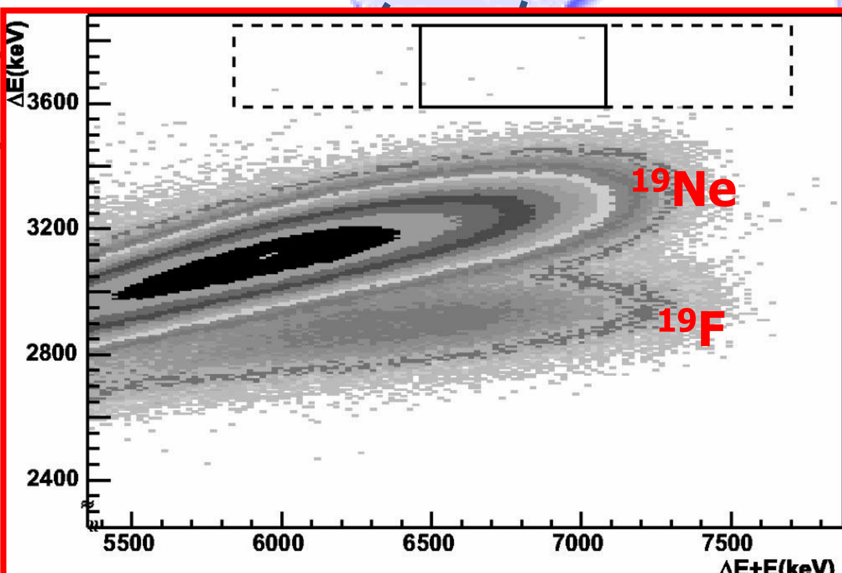


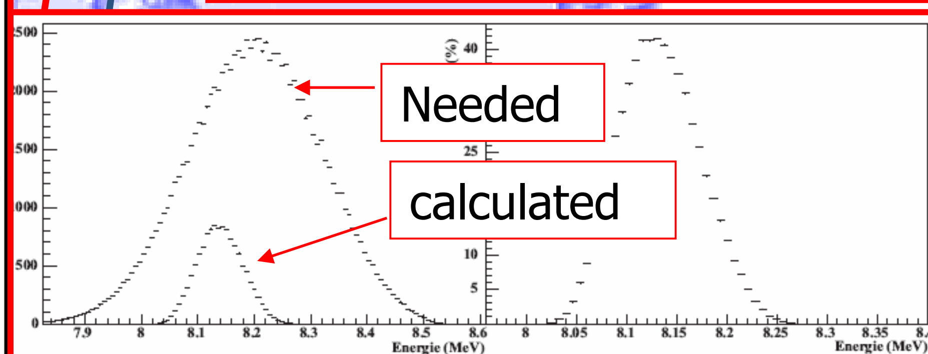
ARES
Louvain-la-Neuve



$^{1}H(^{19}Ne,\gamma)^{20}Na$

- Configuration: M-W
- Target: H containing foil
- **PARTIAL ACCEPTANCES**
- Improvements planned to increase suppression (add. Magnet)





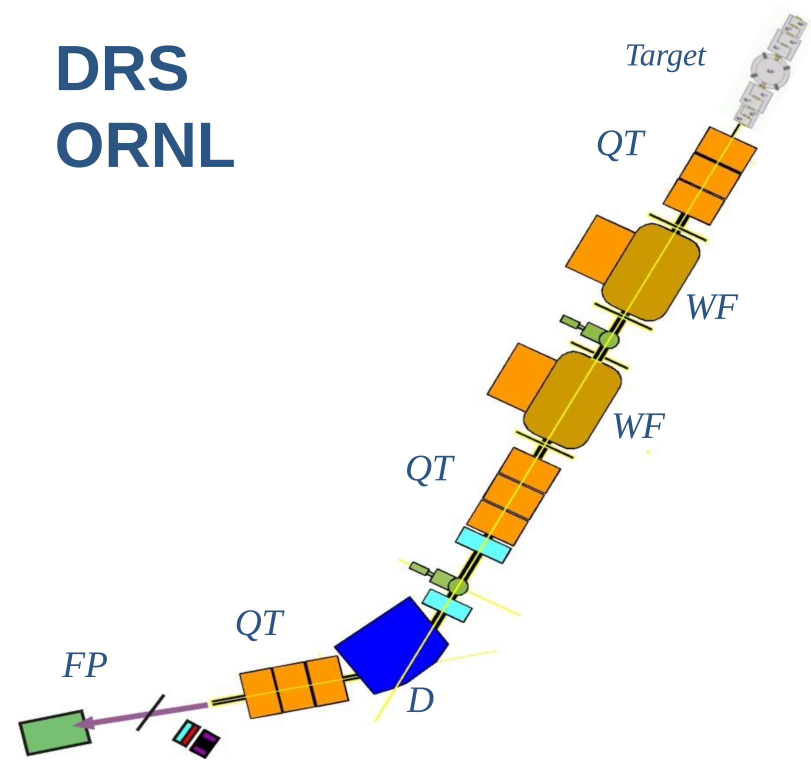
Calculated acceptance vs reaction kinematics

Courtesy of M. Couder, Notre Dame

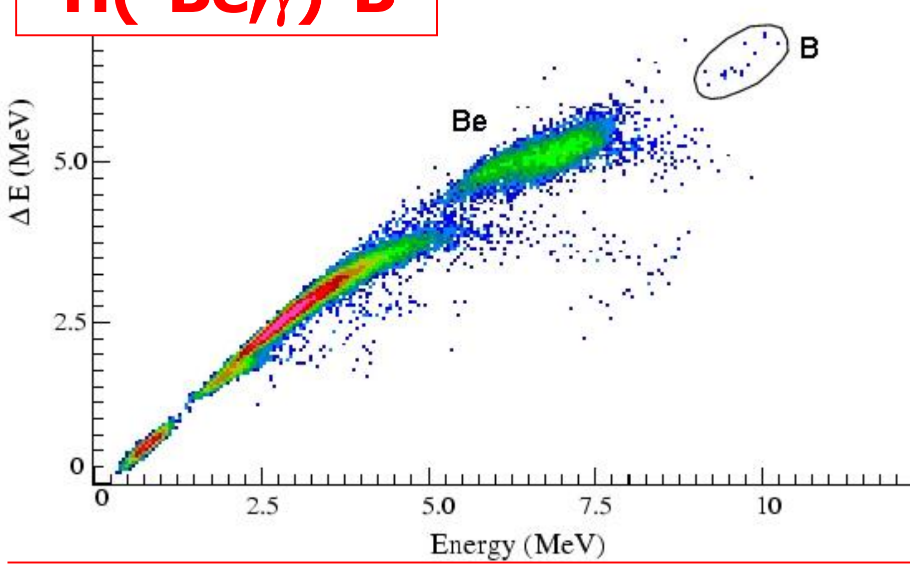
DRAGON

ERNA

DRS ORNL



$^{1}H(^{7}Be,\gamma)^{8}B$

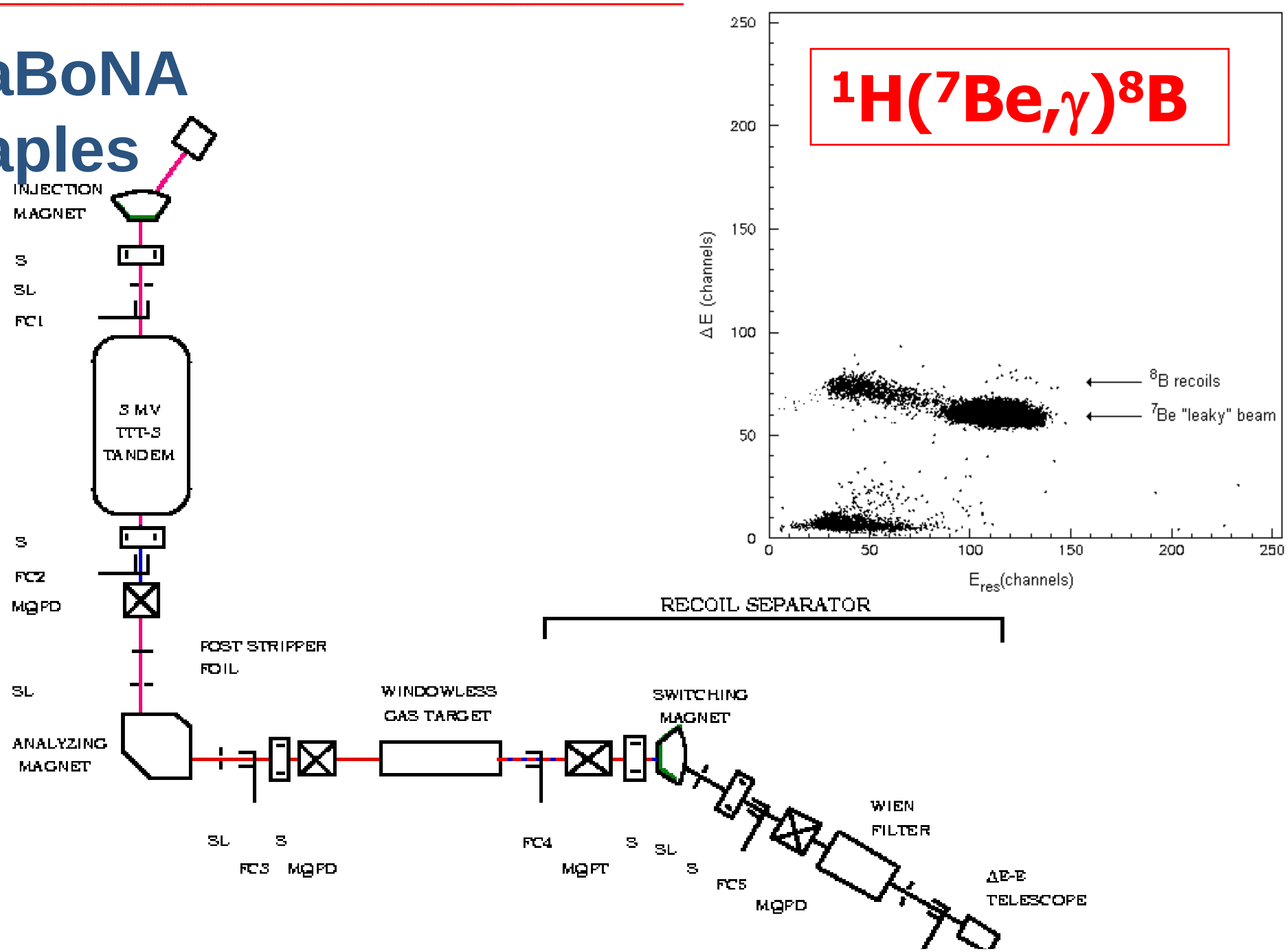


- Configuration: W-W-M
- Acceptances angle +-45 mrad
  energy +-5%

- H-Gastarget

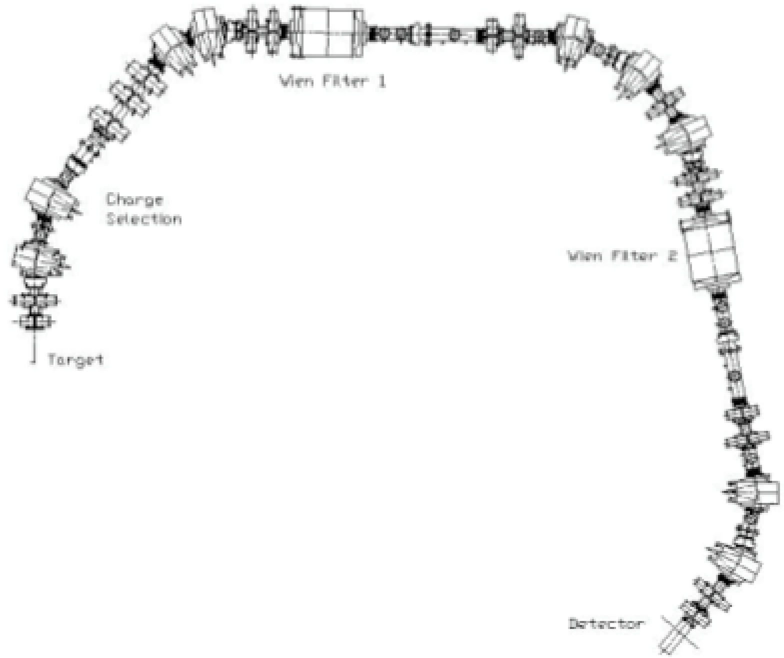
(differentially pumped, windowless)

NaBoNA Naples

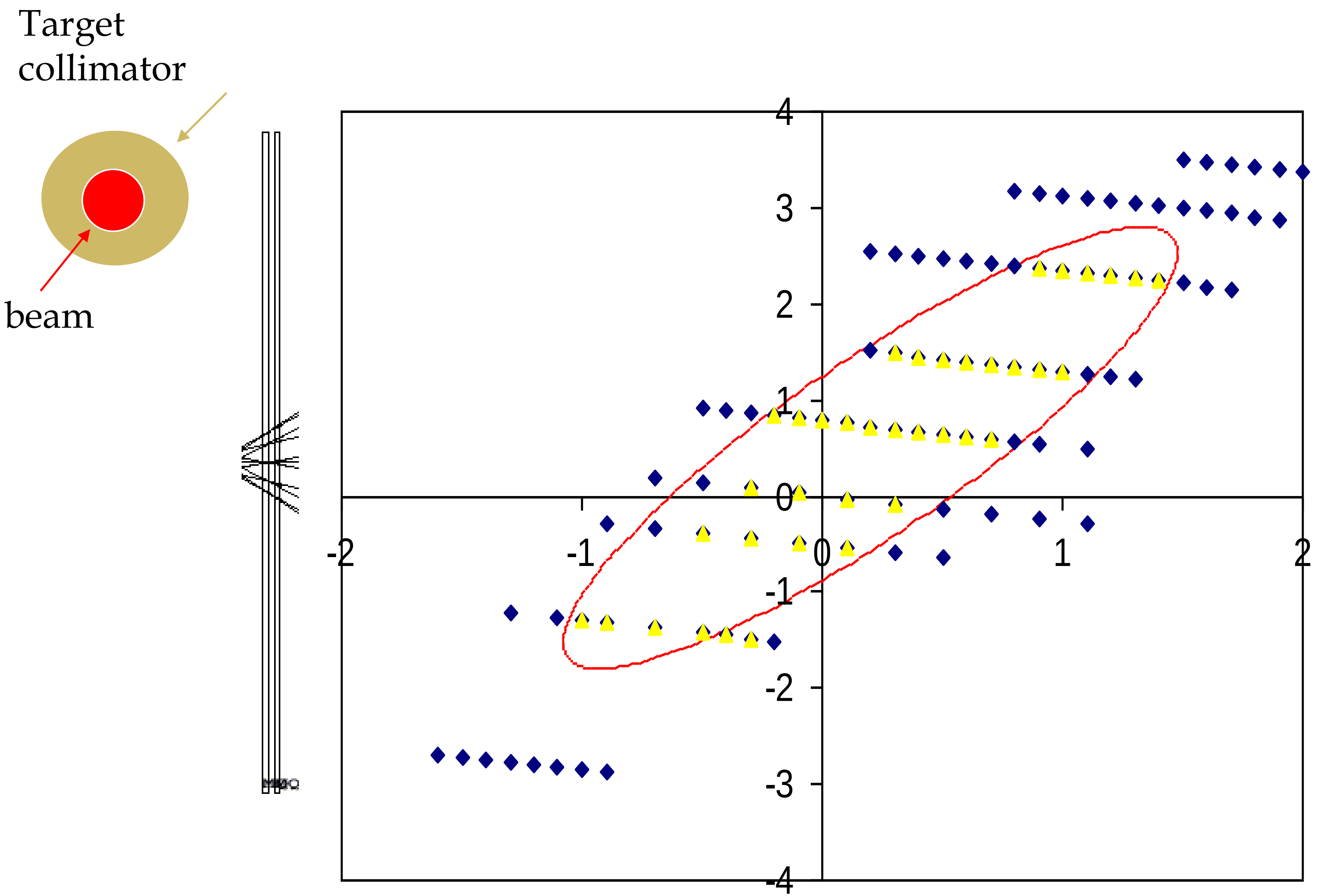


NaBoNA -> Precursor of ERNA

Next to come: SECAR at FRIB



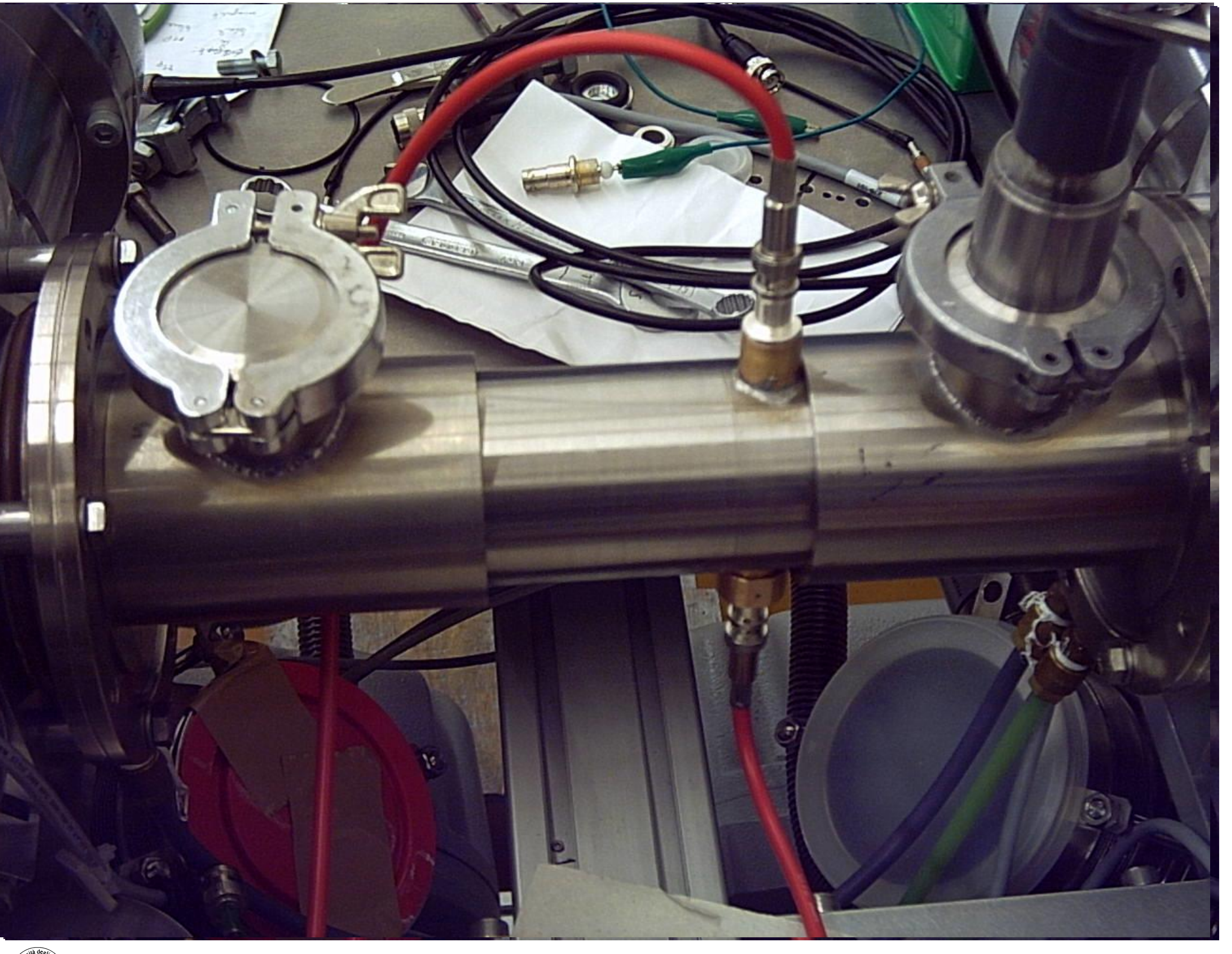
Small beam emittance



Angular acceptance along the gas target

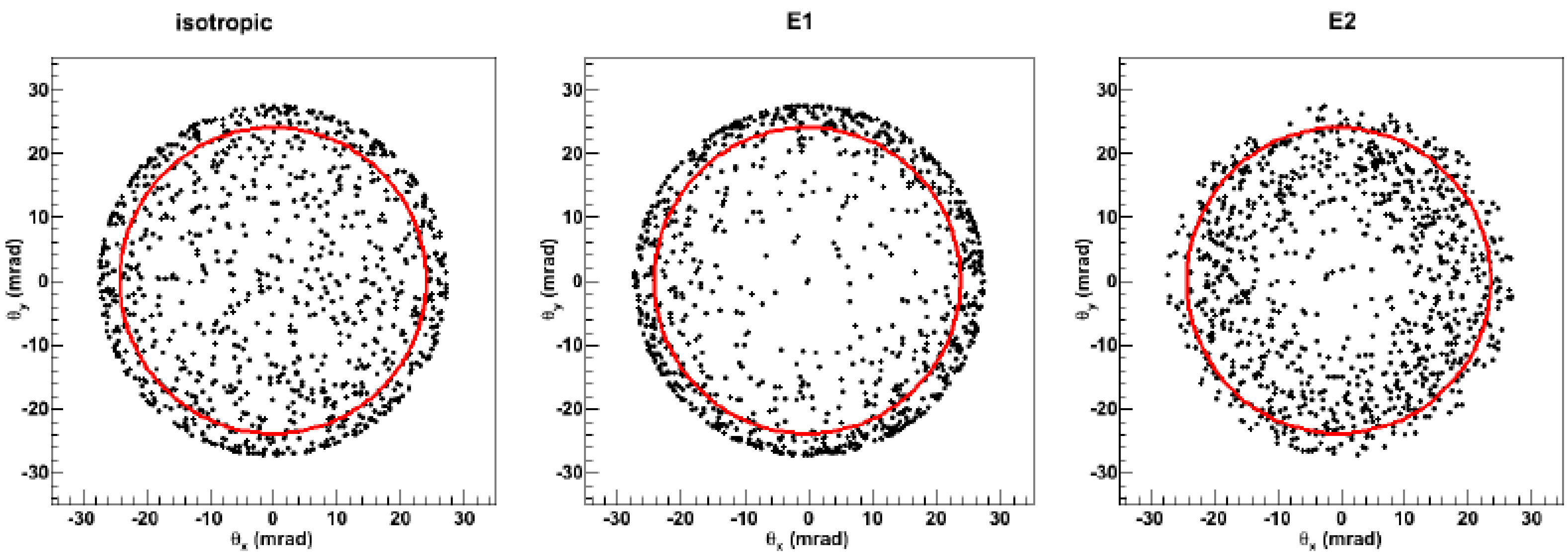
Energy acceptance

Change beam energy



Why is acceptance so important? An example: $^{12}C(\alpha,\gamma)^{16}O$ at E_{cm}=1 MeV

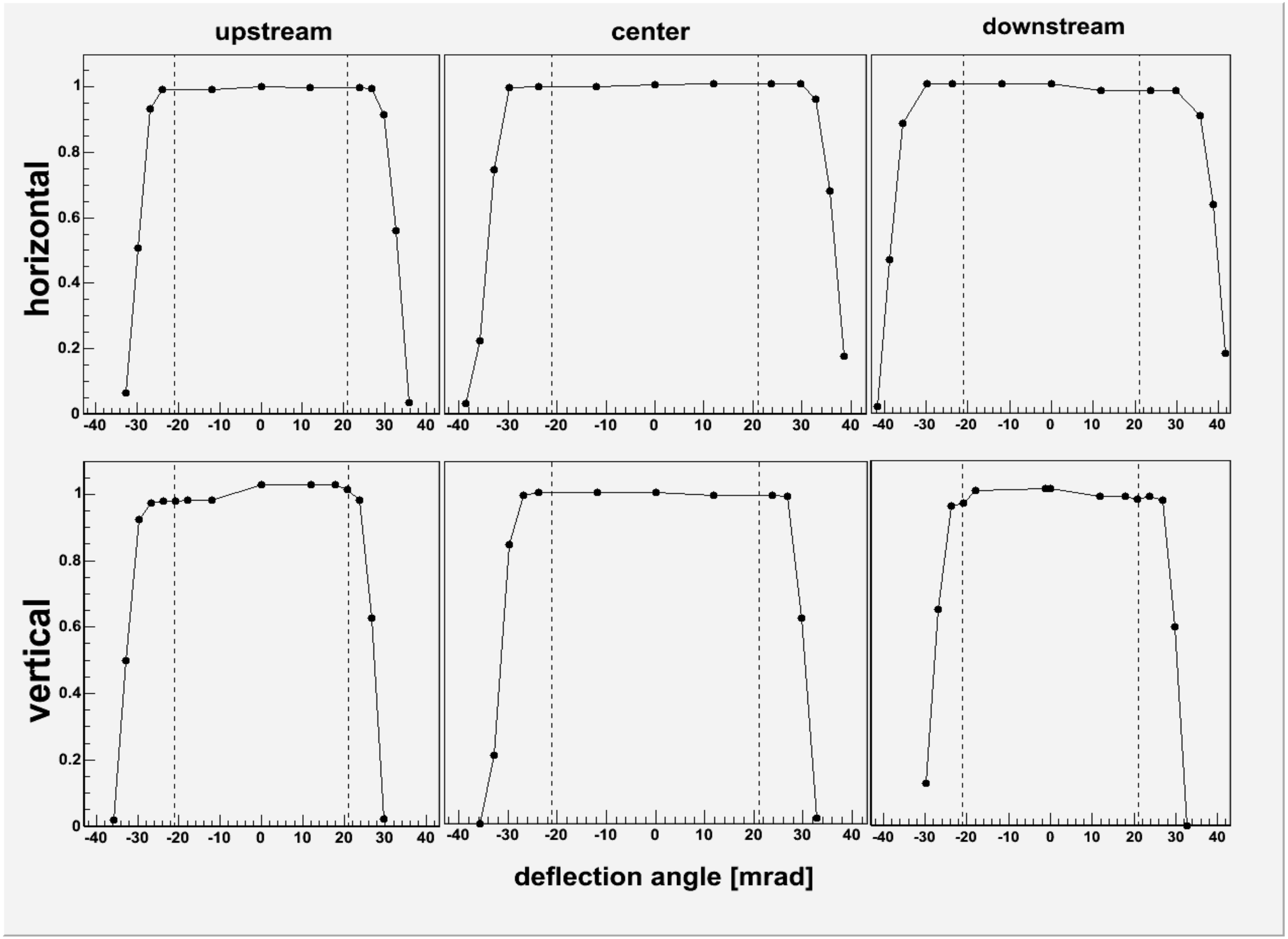
Required acceptance:27 mrad
Actual acceptance: 24 mrad



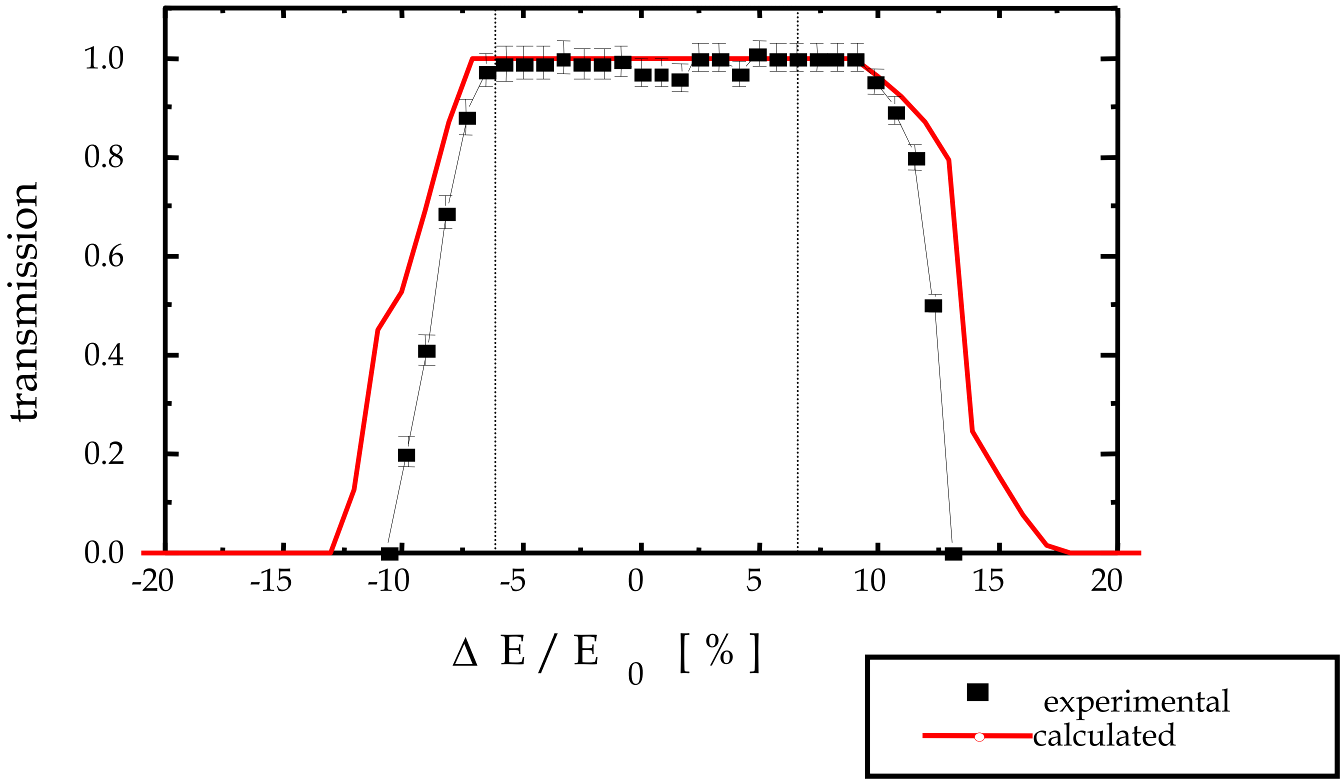
Recoils	47%	66%	23%
Loss	(beam and target effects not included)		

L. G. and D. Schuermann *ENA VI* – POS 2011

Angular acceptance - experimental

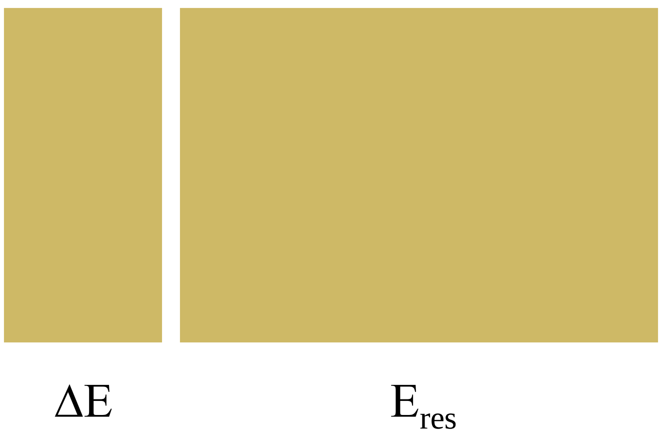


Energy acceptance - experimental



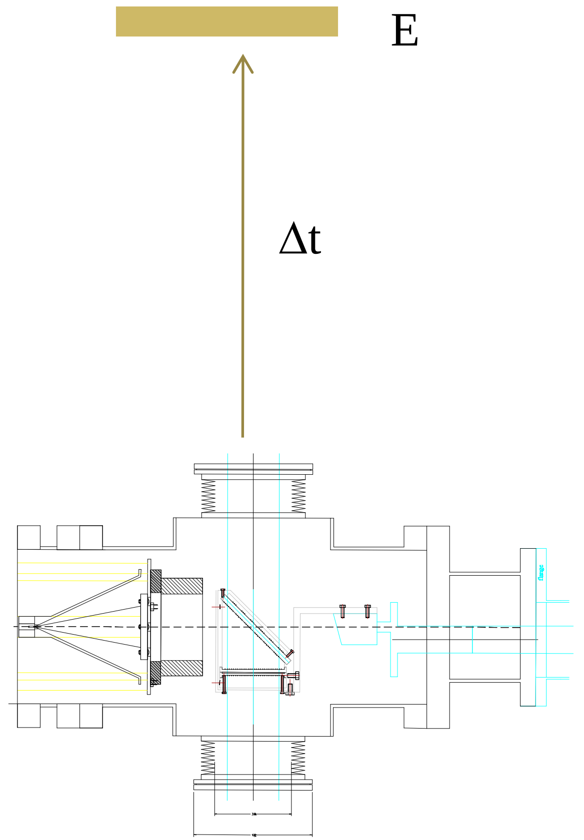
Recoil detection and identificationz

Charge identification



$$\Delta E \cdot E \propto MZ^2$$

Mass identification



$$\Delta t = L\,(m/2E)^{1/2}$$

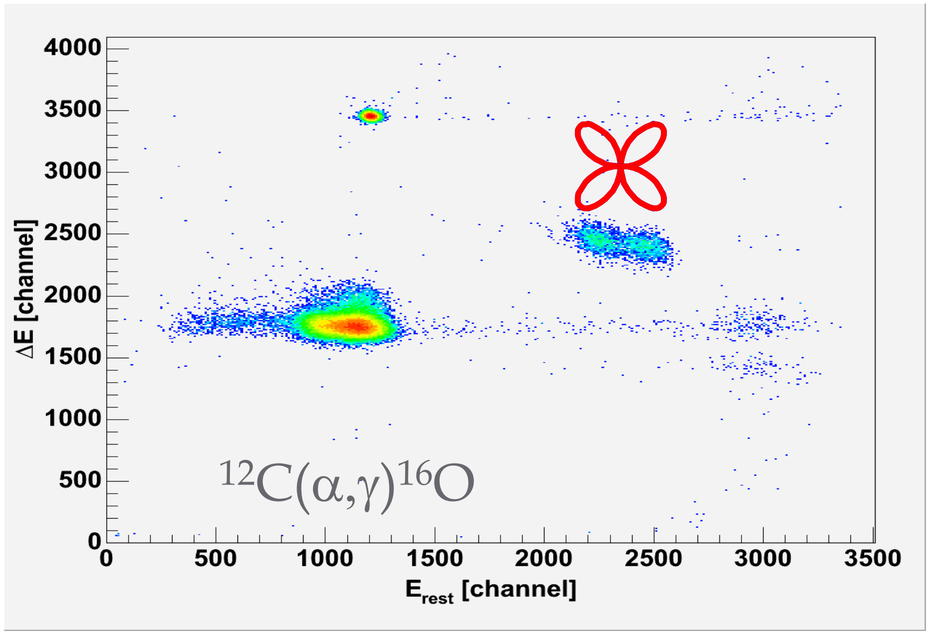
Recoil detection

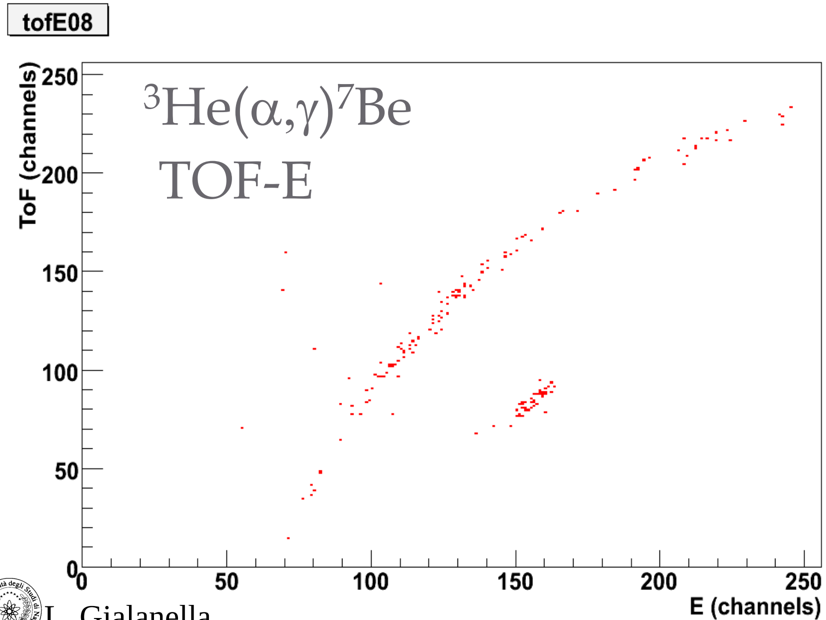
<u>Full acceptance</u>

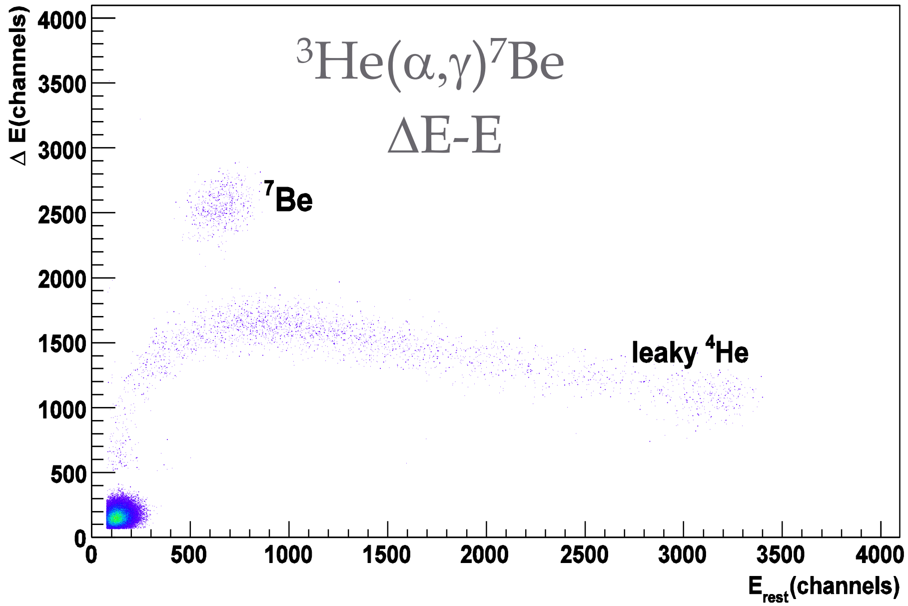
<u>Suppression</u>

Separator: 10^{-10}-10^{-11}

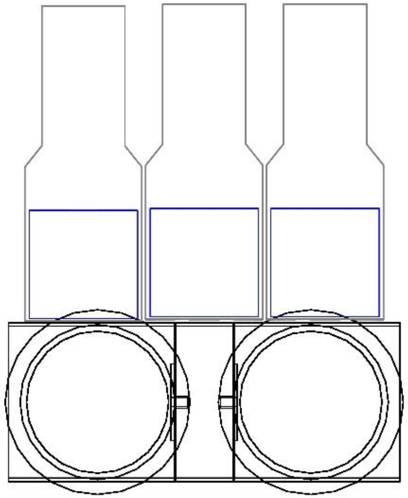
Detector : 10^{-3}-10^{-6}



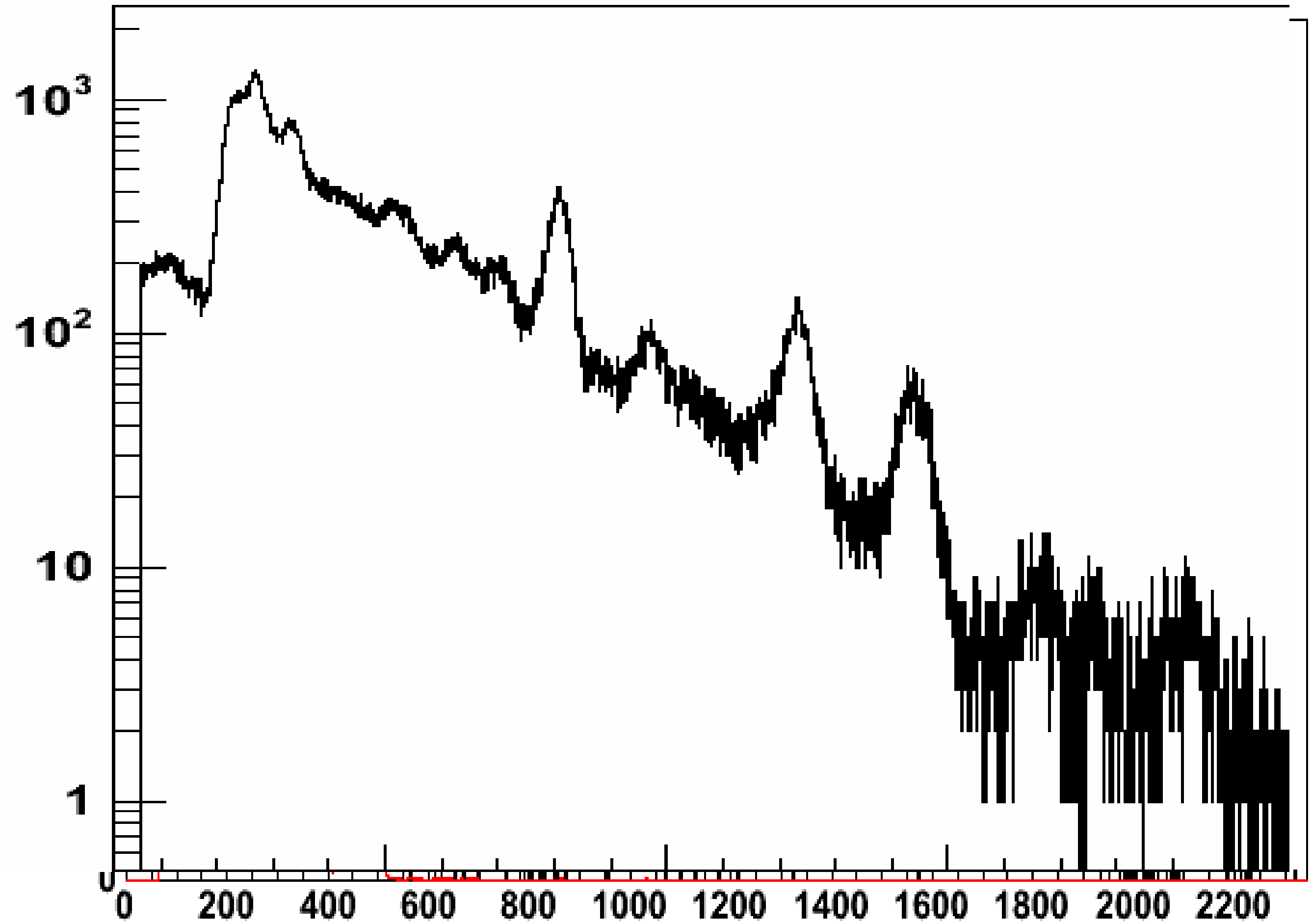


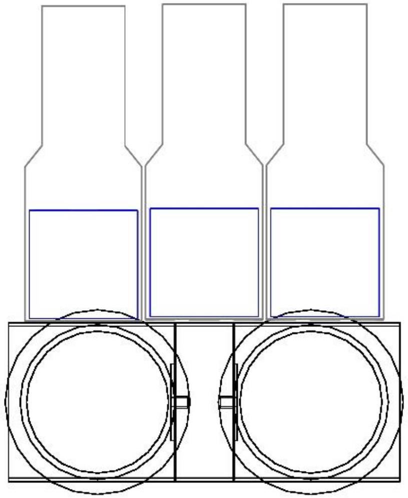


L. Gialanella

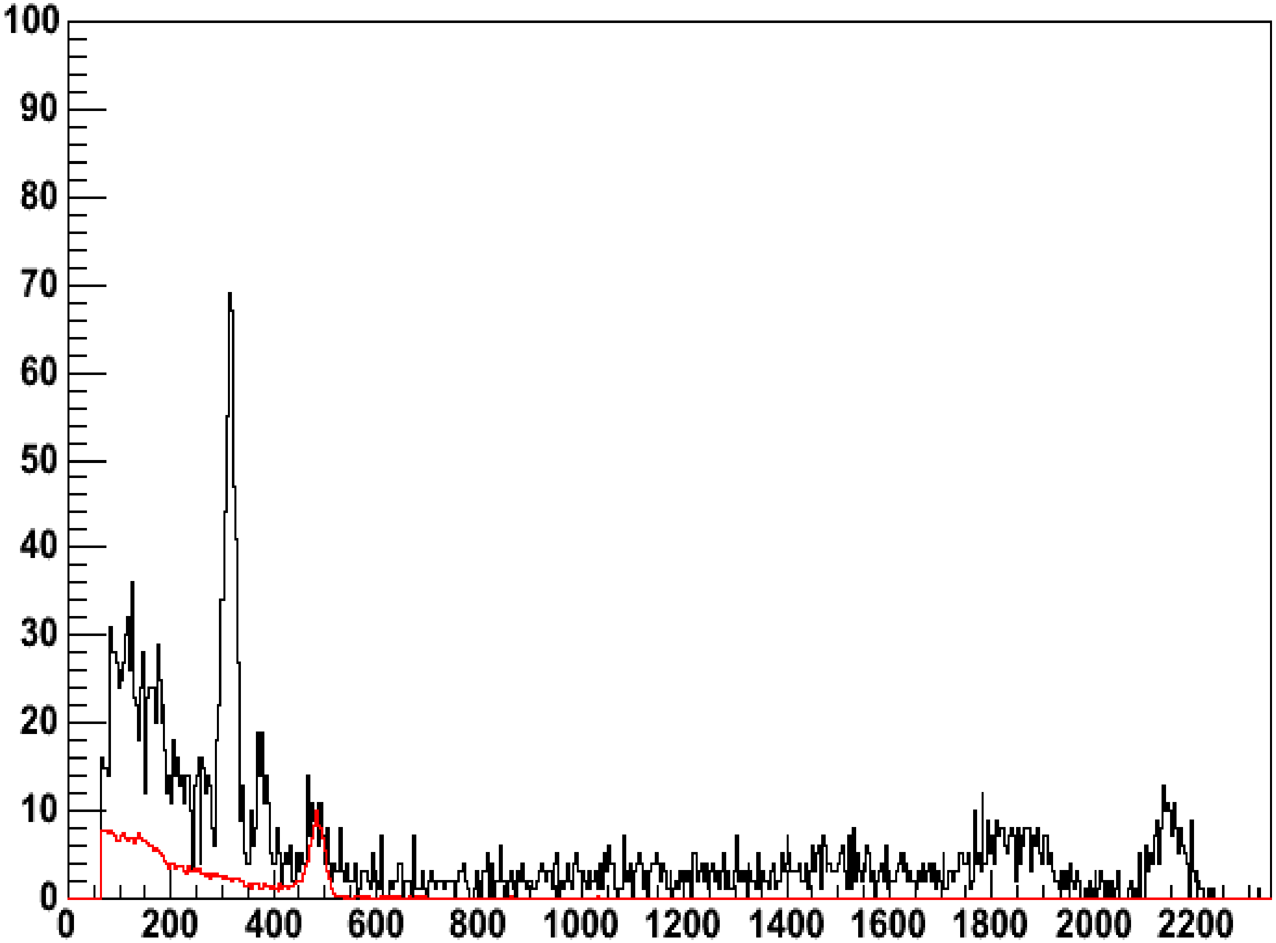


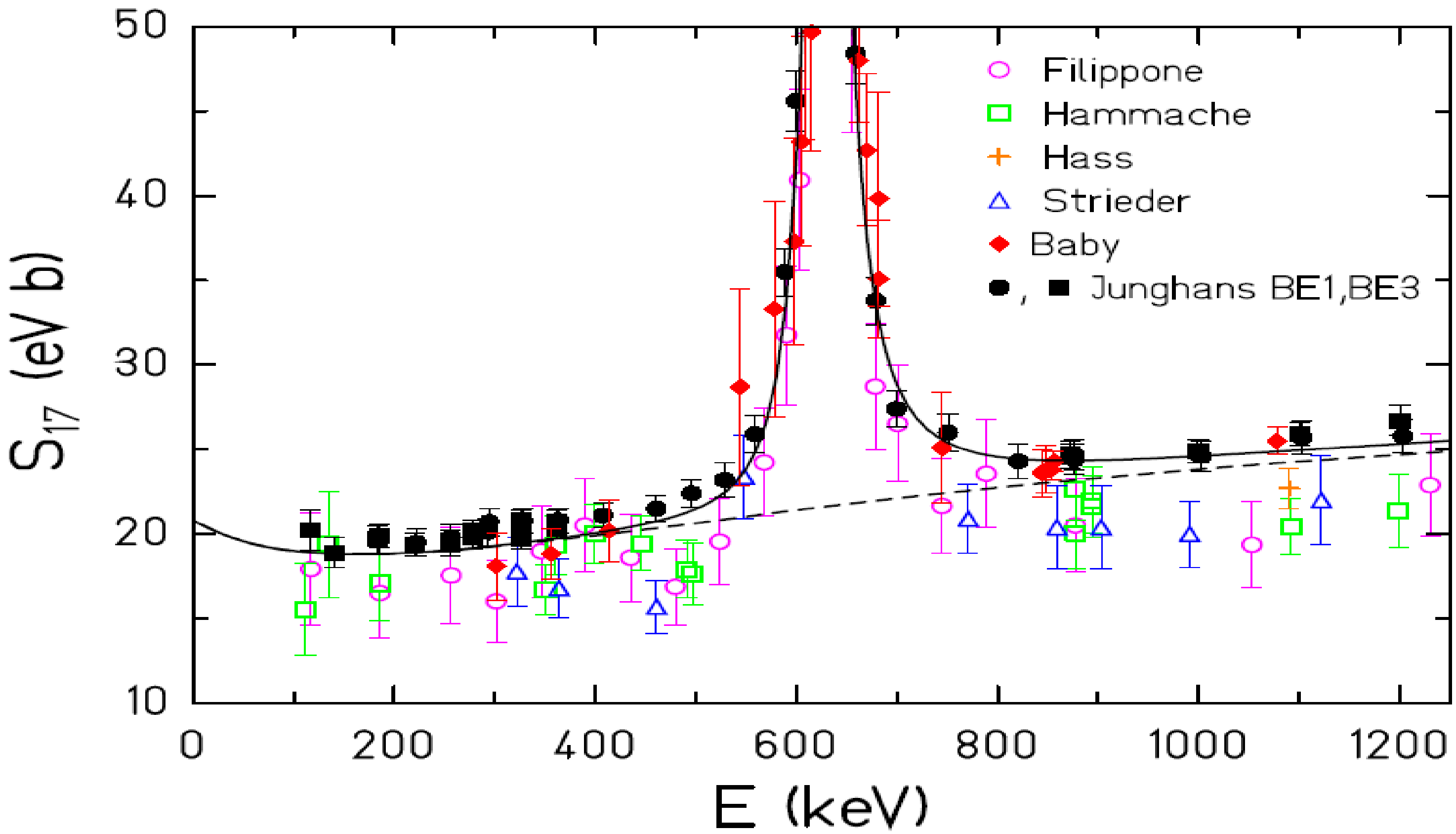
$^{3}He(\alpha,\gamma)^{7}Be$ – γ measurements





$^{3}He(\alpha,\gamma)^{7}Be$ – γ measurements



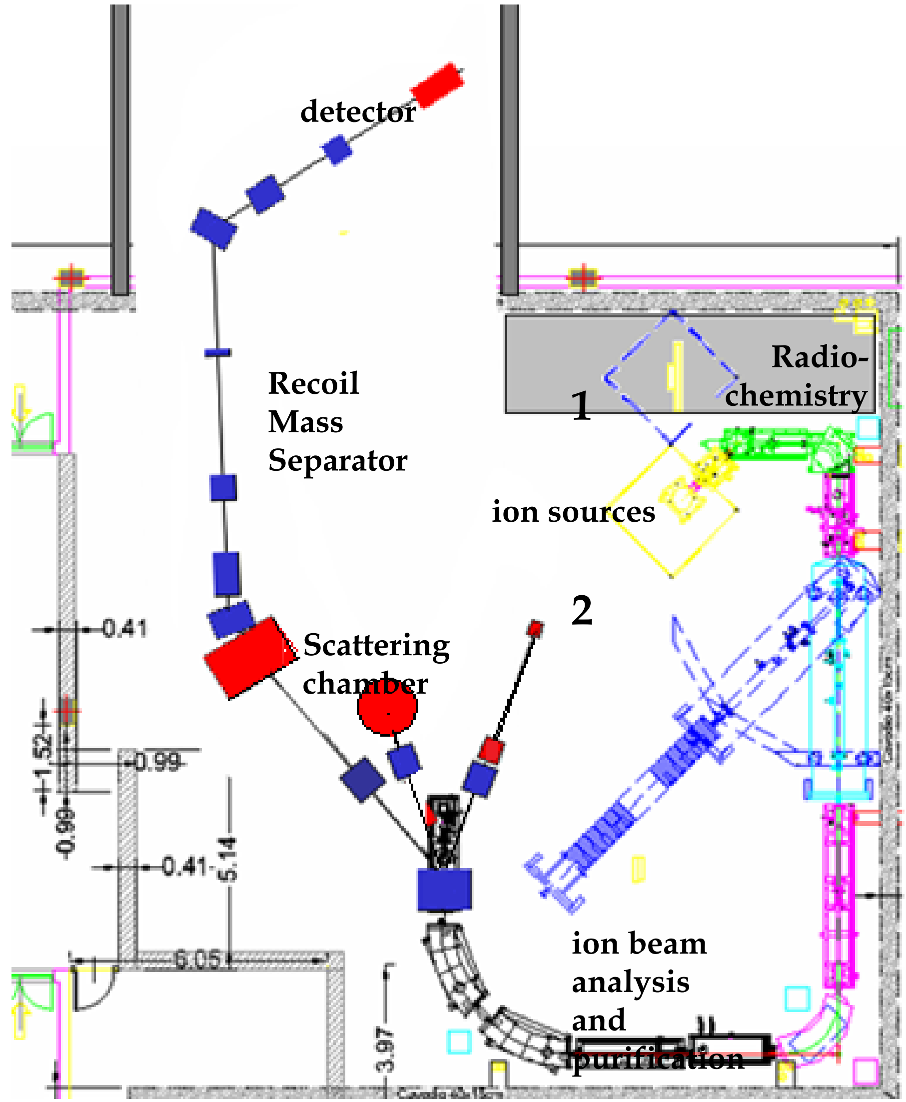


$$S_{17}(0) = 20.8 \pm 0.7(\mathrm{expt}) \pm 1.4(\mathrm{theor}) \ \ \mathrm{eV\ b.}$$

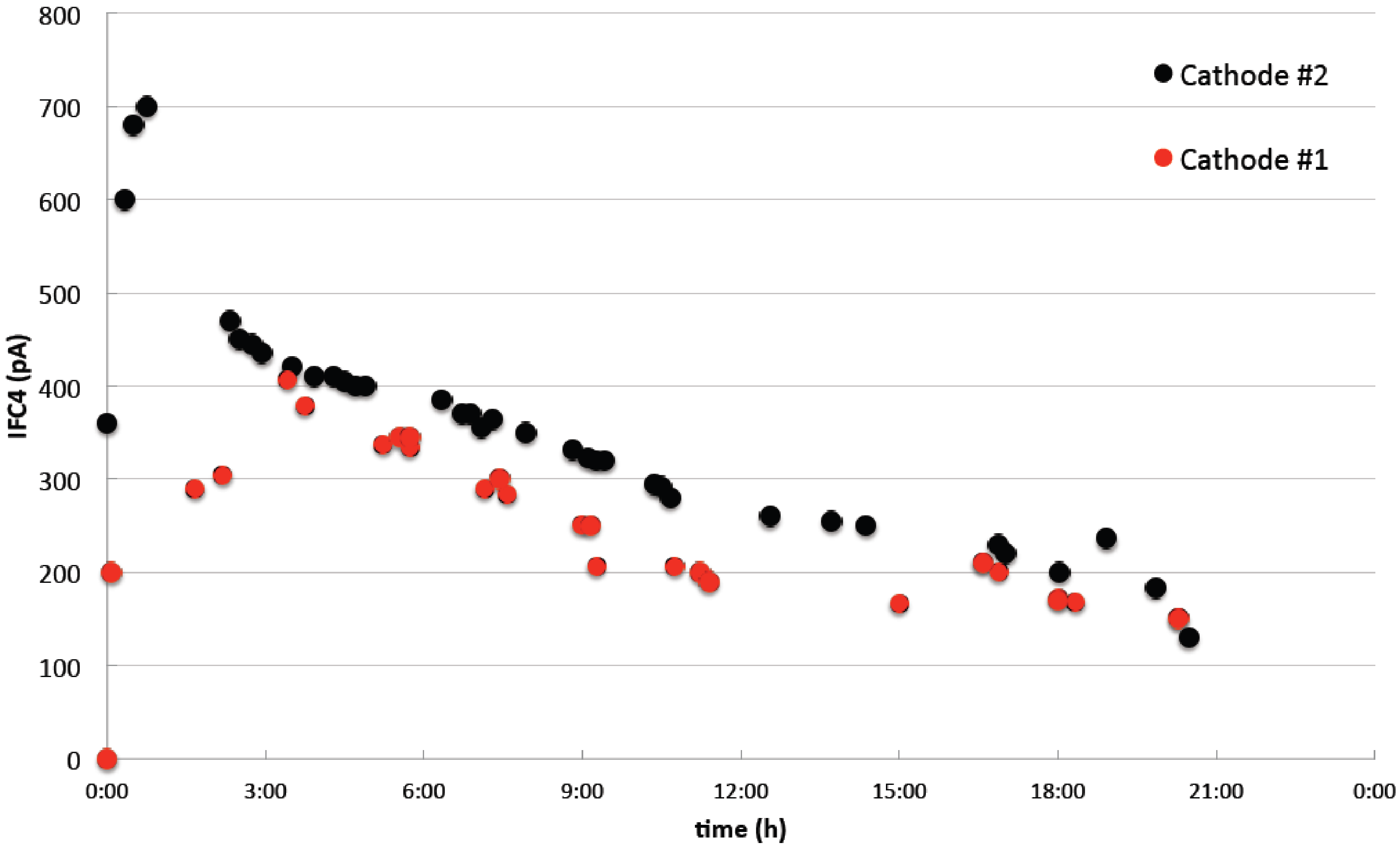
Adelberger et al 2011

ERNA at CIRCE, Caserta, Italy

- High intensity ion beams
- Medium lived RIB
- Applied physics
- Basic research
- Service

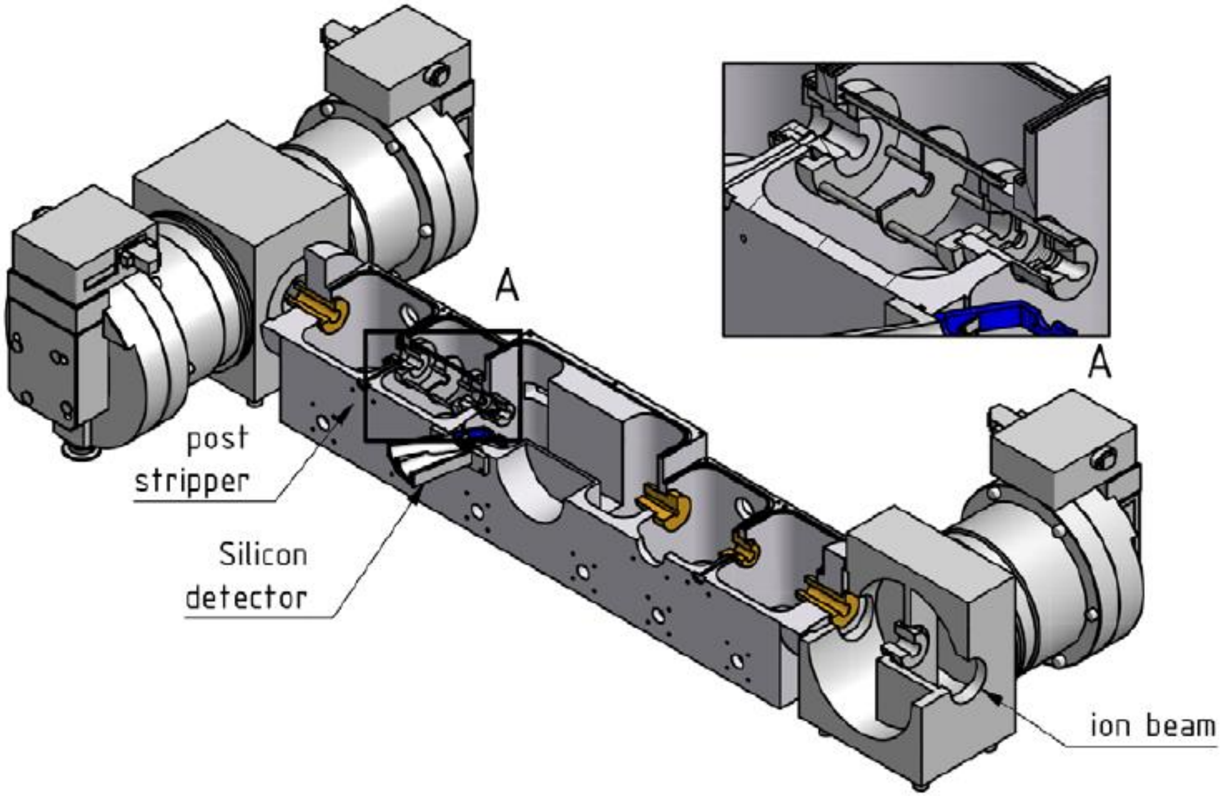


^{7}Be beam current vs time



Hydrogen gas target

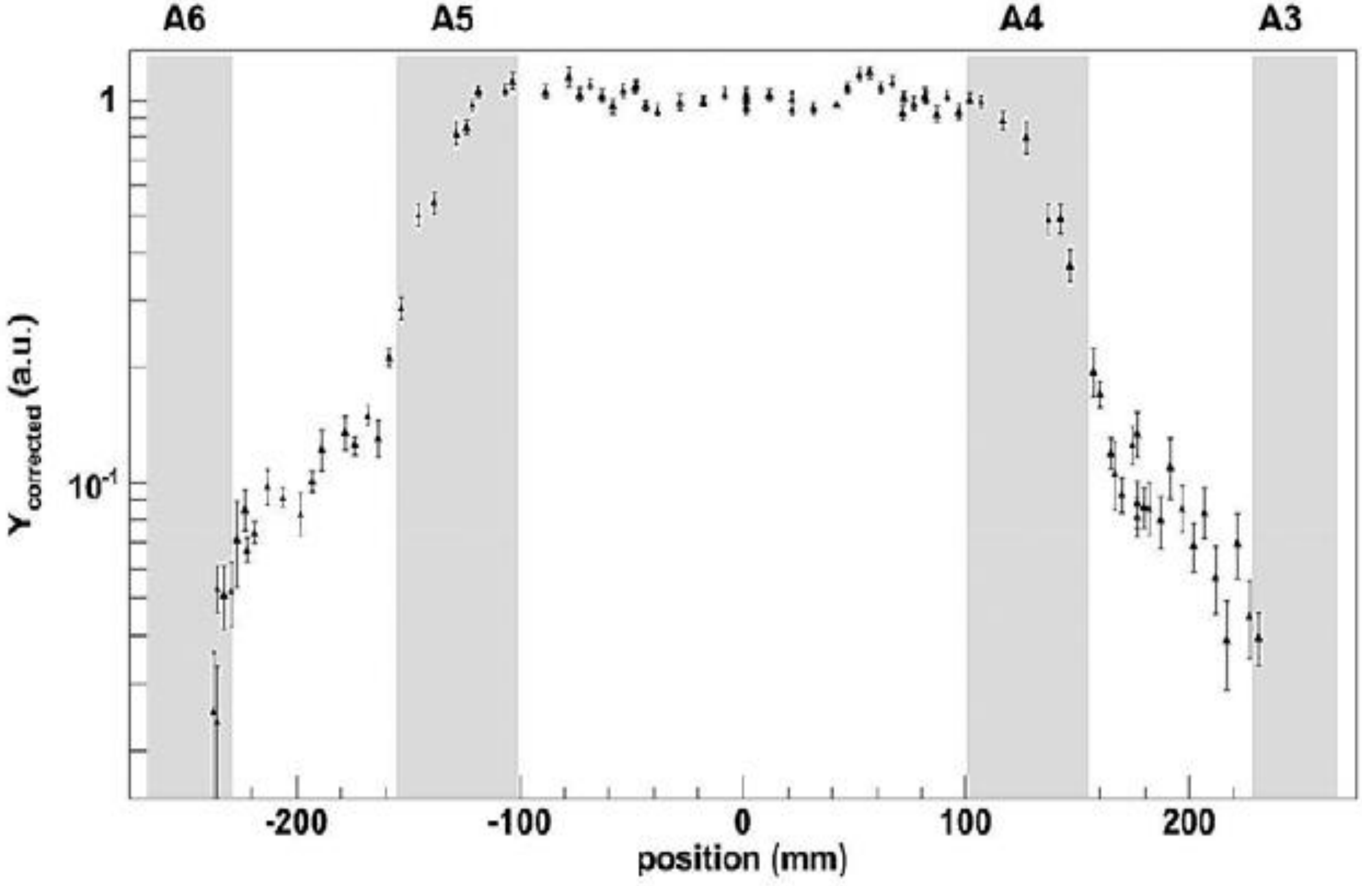
Eur. Phys. J. A (2013) **49**: 80

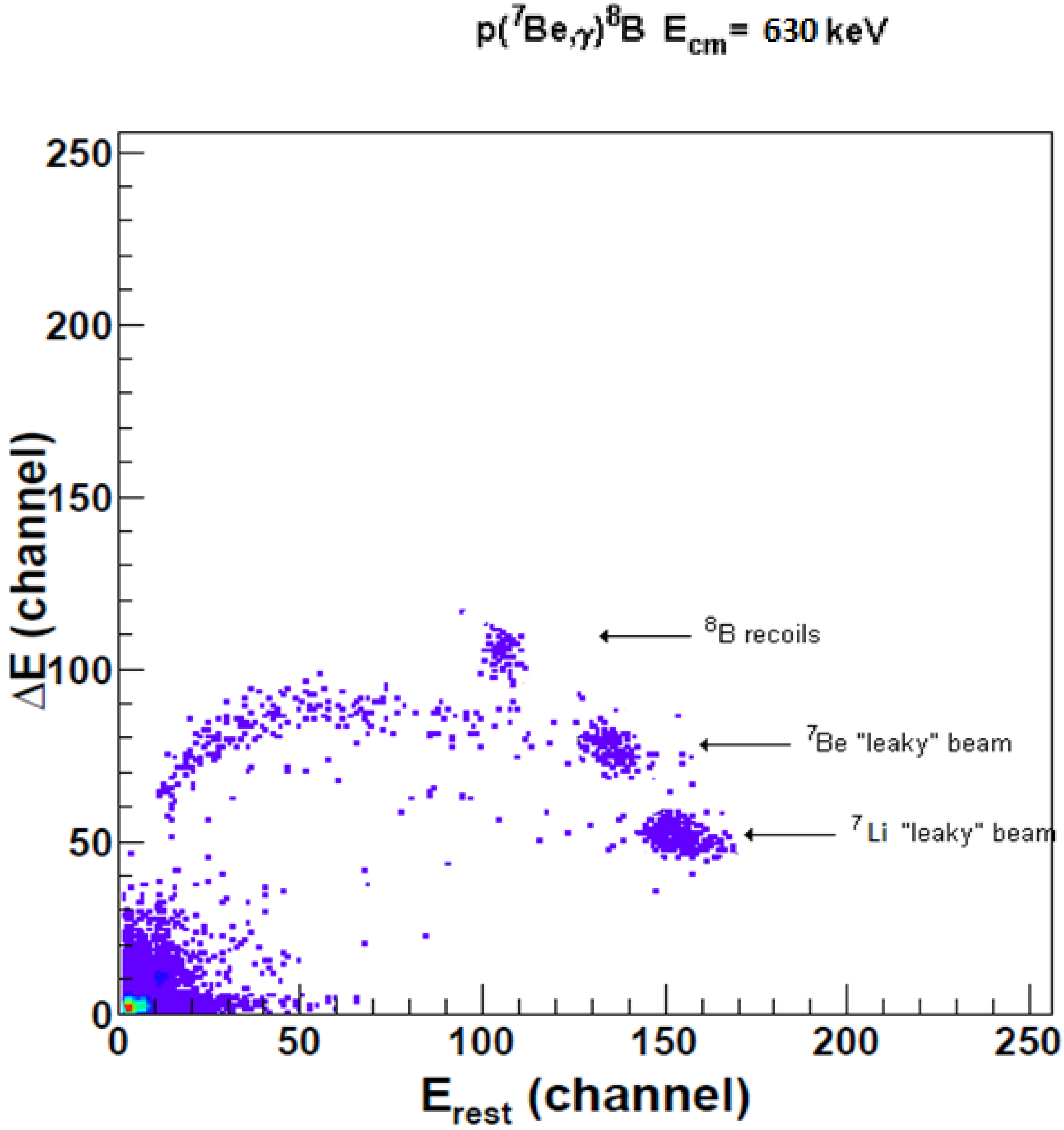


Hydrogen gas target profile

Eur. Phys. J. A (2013) 49: 80

0.7-1.0 10^{19} at/cm^2





^{7}Be beam:
10^{9} p/s
(up to 10^{10} p/s)

Five energies
600-800 KeV
>10% statistics

Outlook

RIB are an essential tool in Nuclear Astrophysics:

• r-process: half lives, neutron capture far from stability, surrogate reactions

• explosive burnings (novae, supernovae Type I, Xray burst)
p-rich nuclei, low energy

Key experimental issues are:

- beam intensity
- detection apparatuses

I did not present indirect methods, that provide very important information (e.g. Coulomb excitation, TMH, transfer reactions, and others)

A final remark: new large scale facilities for RIB are promisingly growing, but stable beams and small facilities are very important in this field.

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- Very important: all original works

One-day SPES Workshop “ Nuclear astrophysics at SPES
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