The 2nd RISP Intensive Program on
“Rare Isotope Physics”

July 7, 2017

Nuclear Astrophysics
Lecture #1

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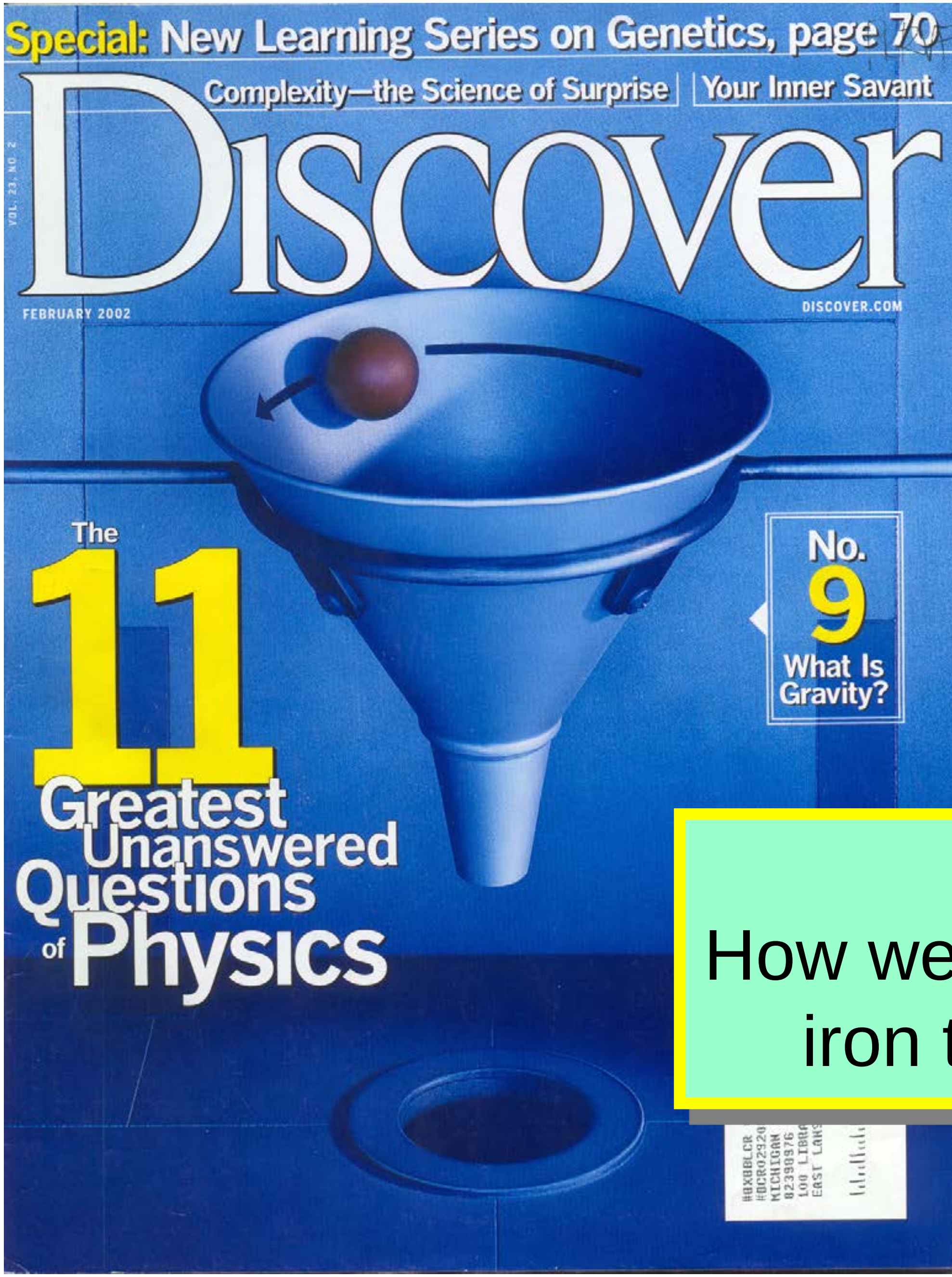
Outline

- Lecture #1: Introduction of Nuclear Astrophysics
  - Historical background
  - Theoretical/Experimental considerations
  - Nuclear reactions in the Sun
  - Experiments using stable beams
- Lecture #2: Nuclear Astrophysics Experiments using Radioactive Ion Beams I
  - Why RIB?
  - Hydrogen burnings, HCNO, rp-process, r-process
  - Experiments at RIKEN & CNS
  - Prospect for the Korea RI Accelerator

Nuclear Astrophysics

- Addresses some of the most compelling questions in nature
  - The origins of the elements
  - How does the sun shine for so many years?
  - What is the total density of matter in the universe?
  - How did the stars, galaxies evolve?
- Require a considerable amount of nuclear physics information as input
  - Mostly based on theoretical models or extrapolations
- More complete and precise nuclear physics measurements are needed



Based on National Academy of Science Report

[Committee for the Physics of the Universe (CPU)]

Question 3

How were the elements from iron to uranium made ?

~90 Years of Nuclear Astrophysics

A Story of Success

1928 Gamow-Factor
George Gamow

1931 Stellar Structure & Theory of White Dwarfs
Subramanyan Chandrasekhar

1938 CNO Cycle - C. F. von Weizsacker
CNO Cycle, pp Chain - Hans Bethe

1957 Nucleosynthesis of Elements in Stars
Margaret &Geoffrey Burbidge, William Fowler and Fred Hoyle = B^2FH

The 0+ 2^{nd} Excited State in ^{12}C Measured at 7.65 MeV in 1957

1967 Nobel Prize: Hans Bethe

Reactions in the Sun: pp chain

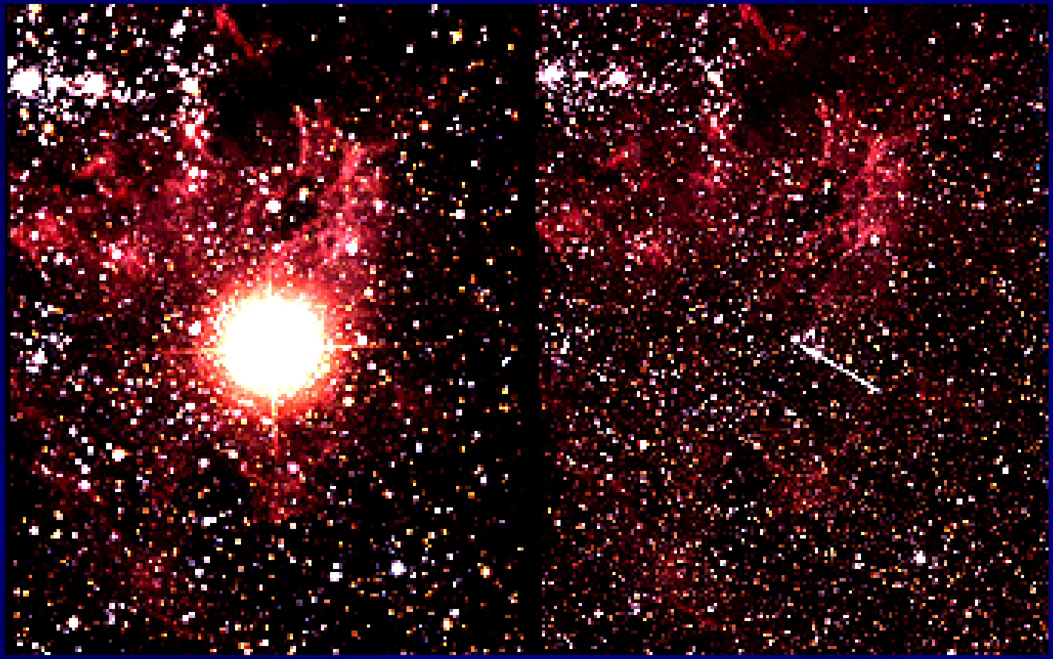
Solar Neutrino Problem: $^{7}Be(p,g)$

1983 Nobel Prize: William Fowler
Subramanyan Chandrasekhar

2002 Nobel Prize for Neutrino Detection
Raymond Davis & Masatoshi Koshiba
X-ray Astronomy - Riccardo Giacconi

2015 Nobel Prize for Neutrino oscillation
Takaaki Kajita & Arthur McDonald

Experimental Nuclear Astrophysics



Nuclear reactions in stars

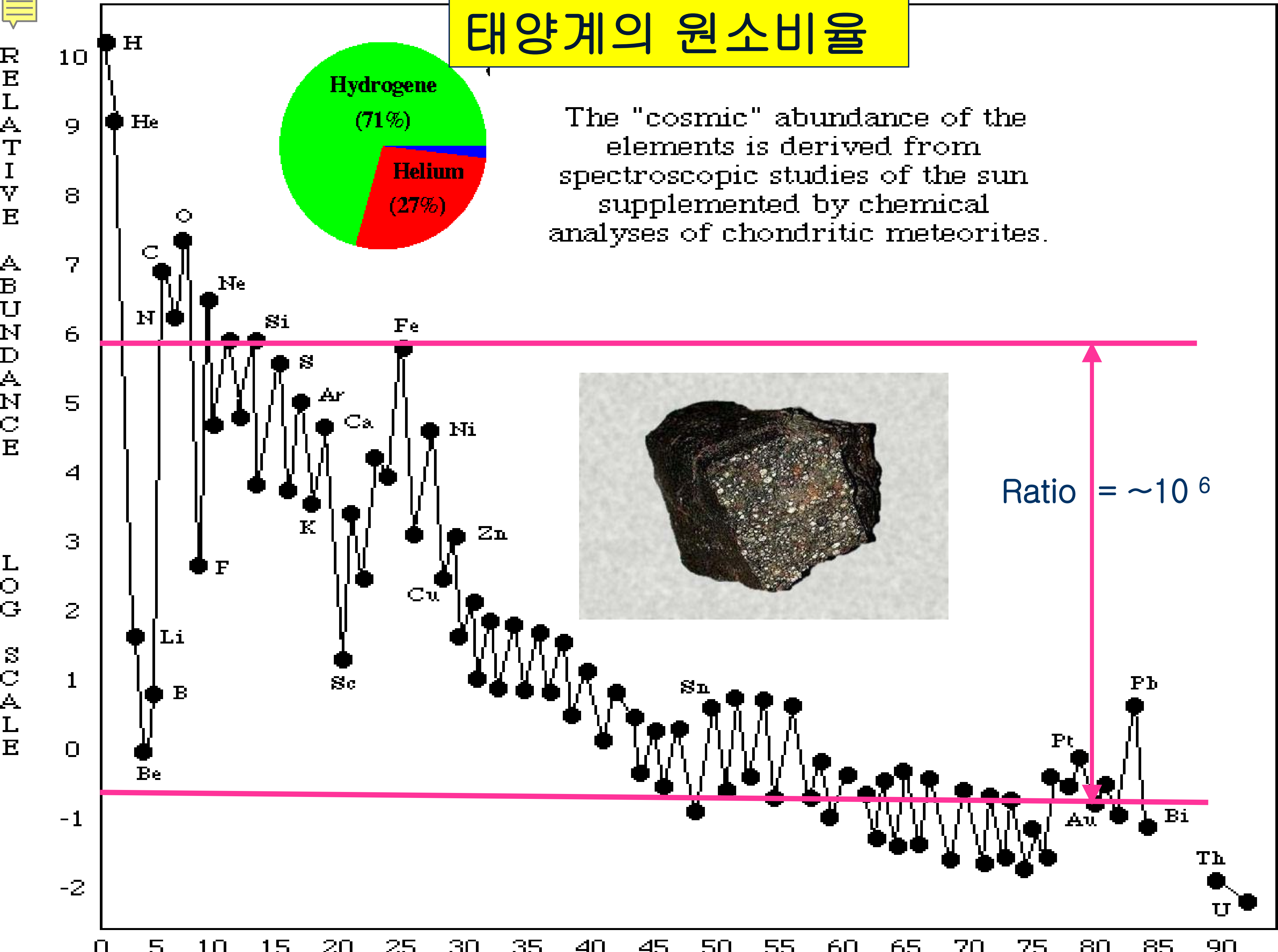
→ **produce energy**

→ **generate the elements**

Experimental Nuclear Astrophysics

- We try to observe nuclear reaction processes from
  - Heat from stars
    - probes only surface
  - Abundances of elements
  - Neutrino's from stars
    - probes interior of star
  - Lab studies of reaction cross-sections
    - Experimental nuclear physics

태양계의 원소비율



RELATIVE ABUNDANCE LOG SCALE
Hydrogene (71%)
Helium (27%)
The "cosmic" abundance of the elements is derived from spectroscopic studies of the sun supplemented by chemical analyses of chondritic meteorites.
Ratio = ~10 6
H
He
Li
Be
B
C
N
O
F
Ne
Si
S
Ar
K
Ca
Sc
Fe
Ni
Cu
Zn
Sn
Pt
Au
Pb
Bi
Th
U
10
9
8
7
6
5
4
3
2
1
0
-1
-2
0
5
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15
20
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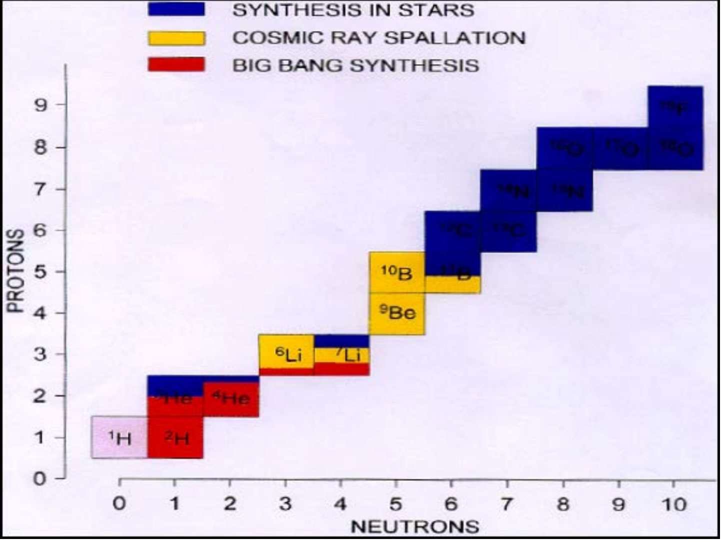
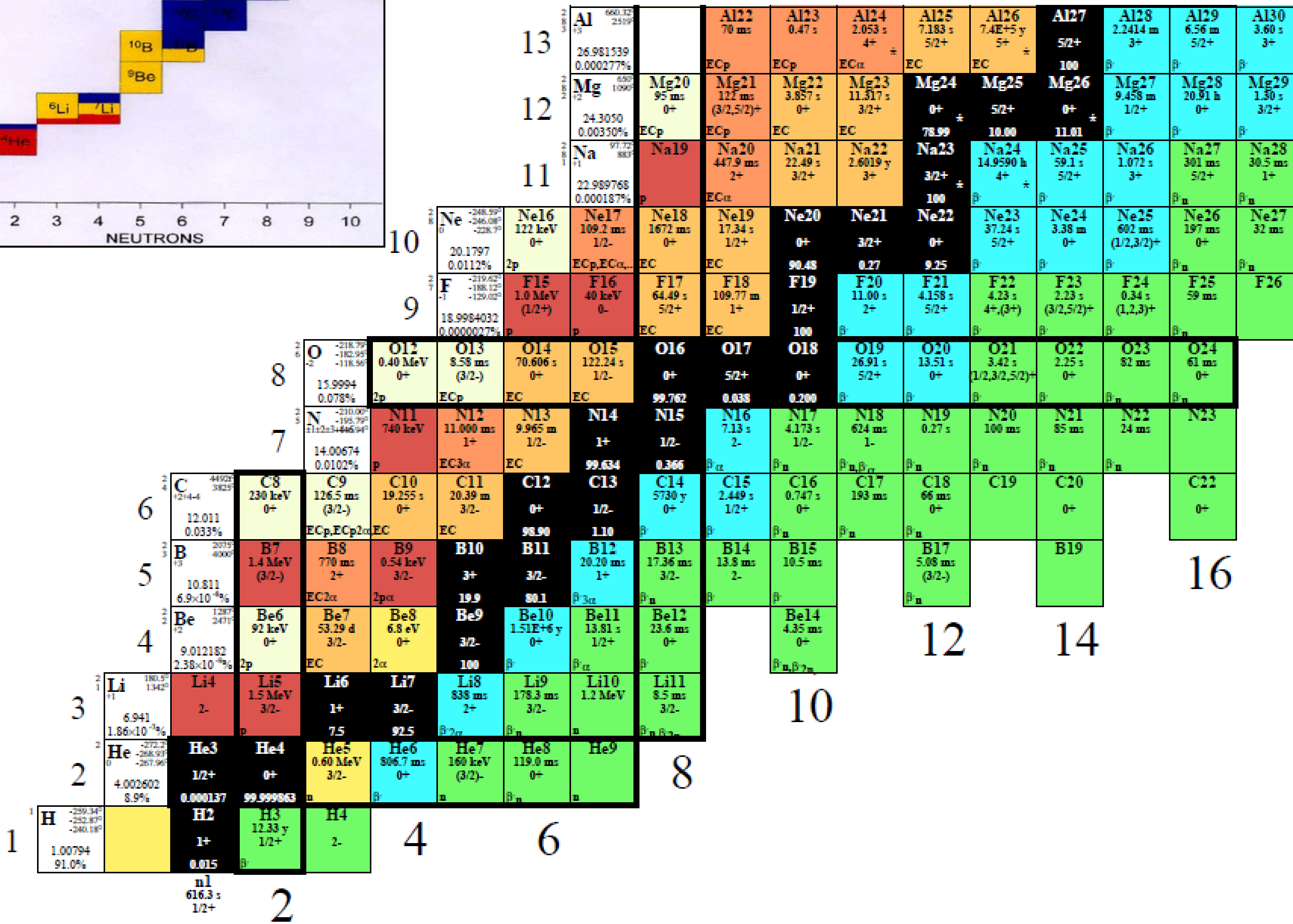
35
40
45
50
55
60
65
70
75
80
85
90


SYNTHESIS IN STARS
COSMIC RAY SPALLATION
BIG BANG SYNTHESIS
PROTONS
NEUTRONS
0
1
2
3
4
5
6
7
8
9
10
¹H
²H
⁴He
⁶Li
⁷Li
⁹Be
¹⁰B


1
2
3
4
5
6
7
8
9
10
11
12
13
H
1.00794
91.0%
He
4.002602
8.9%
Li
6.941
Be
9.012182
B
10.811
C
12.011
0.033%
N
14.00674
0.0102%
O
15.9994
0.078%
F
18.9984032
Ne
20.1797
0.0112%
Na
22.989768
Mg
24.3050
0.00350%
Al
26.981539
n1
616.3 s
H2
H3
12.33 y
H4
He3
He4
He5
He6
He7
He8
He9
Li4
Li5
Li6
Li7
Li8
Li9
Li10
Li11
Be6
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B10
B11
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B13
B14
B15
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B19
C8
C9
C10
C11
C12
C13
C14
5730 y
C15
C16
C17
C18
C19
C20
C22
N11
N12
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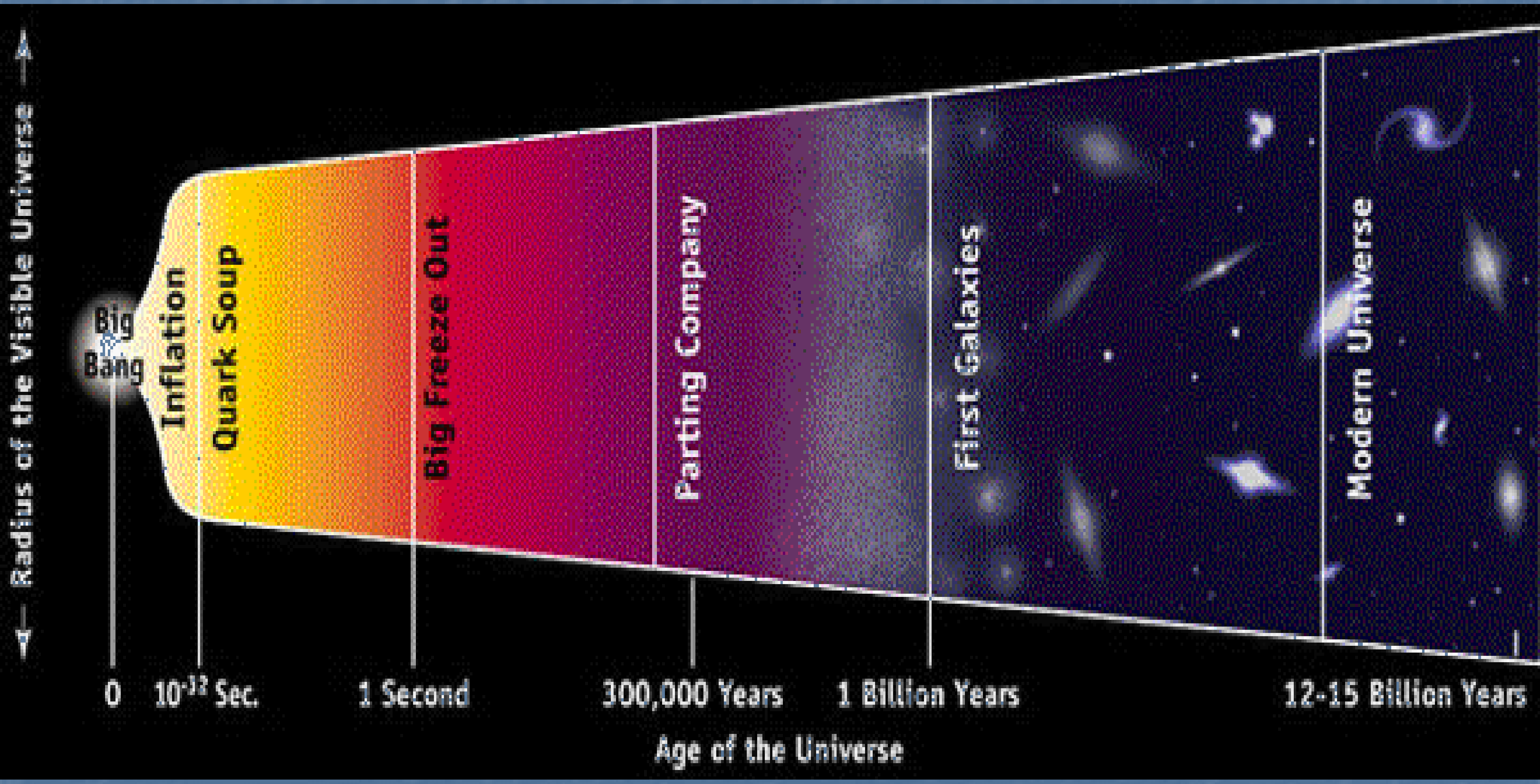
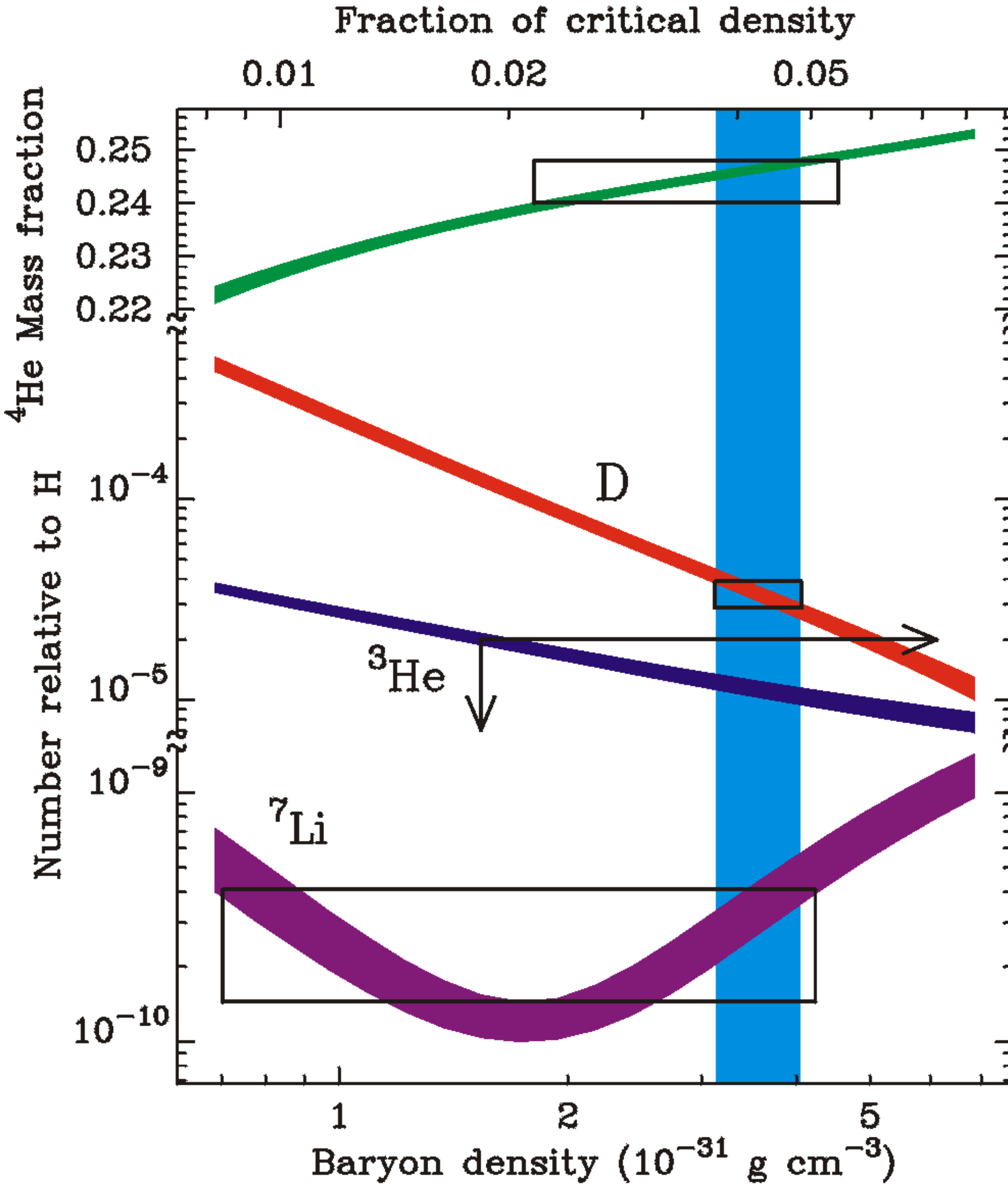
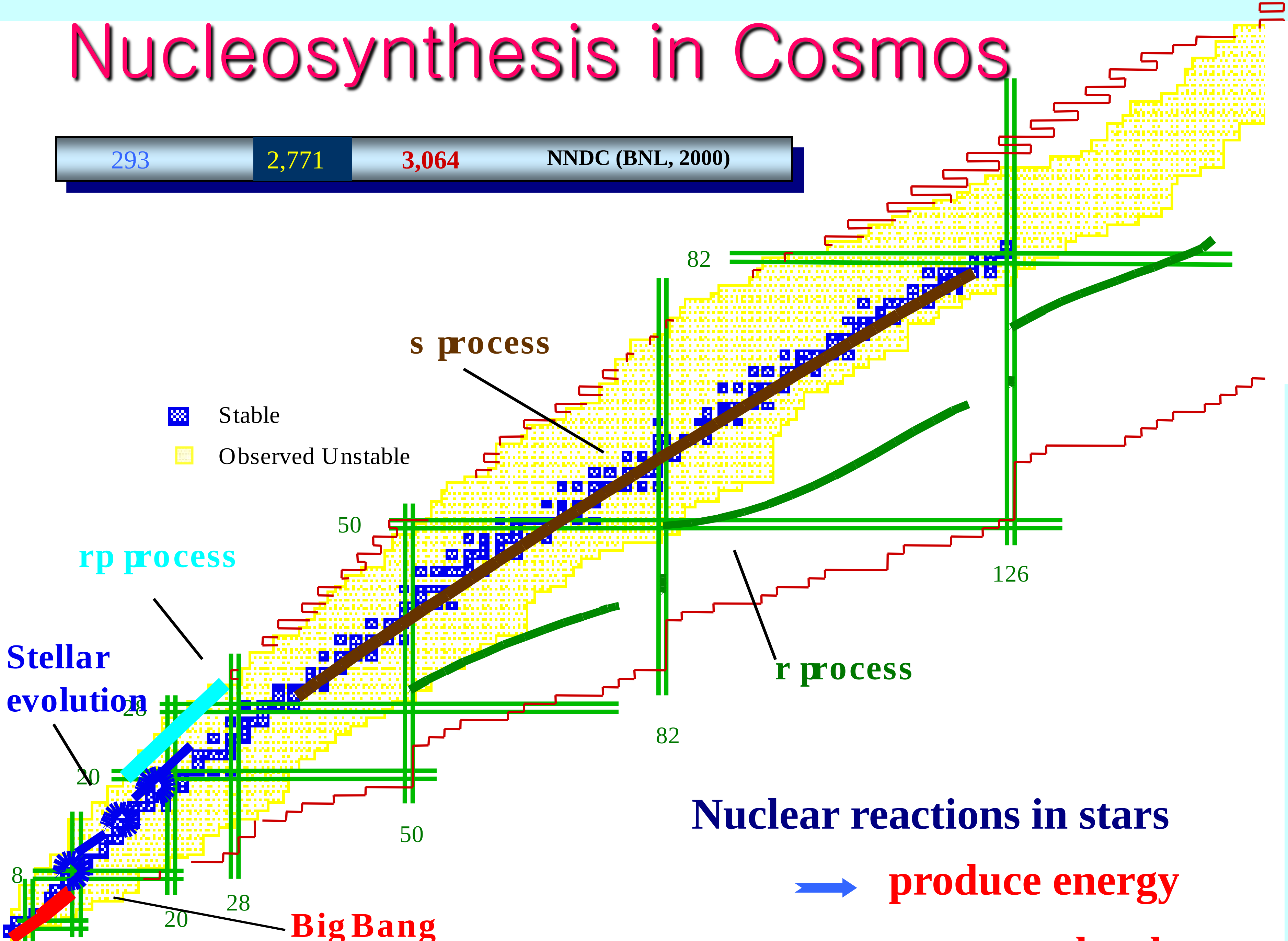

Radius of the Visible Universe
Big Bang
Inflation
Quark Soup
Big Freeze Out
Parting Company
First Galaxies
Modern Universe
0
10-32 Sec.
1 Second
300,000 Years
1 Billion Years
12-15 Billion Years
Age of the Universe

Figure taken from APS poster by Burles, Nollett & Turner



Question：What is the ratio of neutron over proton, n/p?

Nucleosynthesis in Cosmos



Nuclear reactions in stars

➡ **produce energy**

➡ **generate the elements**

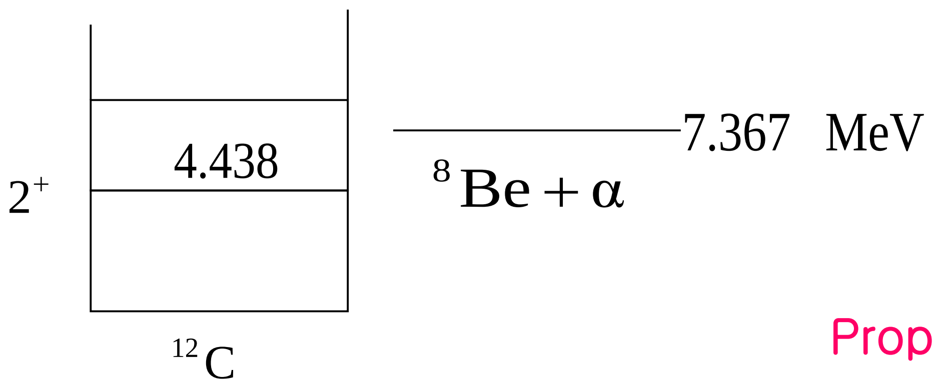
$$\mathrm{H},\ {}^{4}\mathrm{He},\ {}^{3}\mathrm{He},\ \mathrm{Li}\ \ -\ \ \text{Big Bang}$$

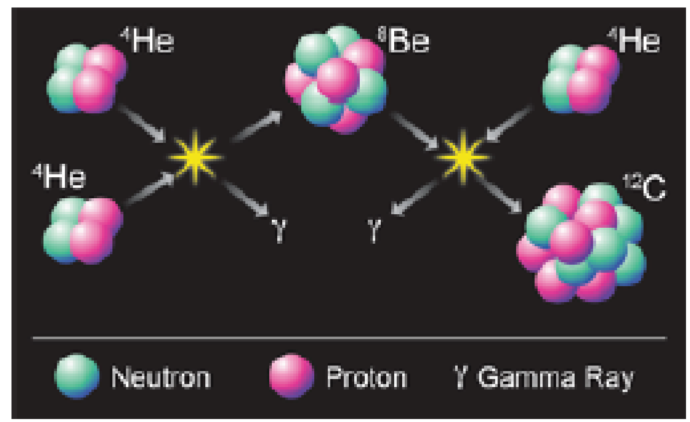
$${}^{4}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{8}\mathrm{Be} \rightarrow \alpha\text{-decay}$$

< Hoyle in 1953 >

$3\alpha \rightarrow {}^{12}\mathrm{C}$ Is insufficient to explain the observed abundance

$${}^{8}\mathrm{Be} + \alpha \rightarrow {}^{12}\mathrm{C} + \gamma$$





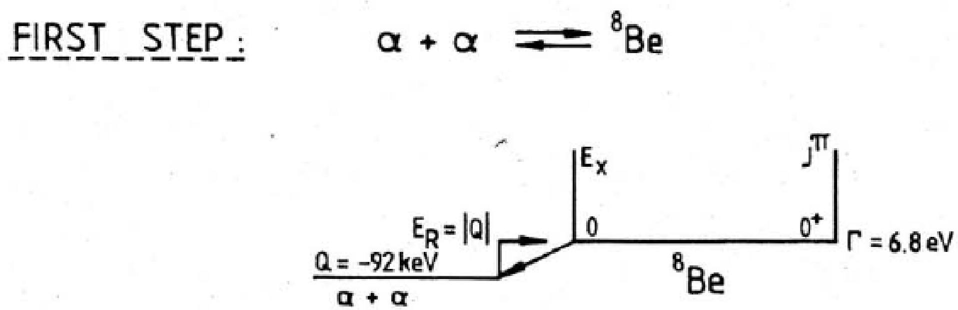
Proposed O^{+} at 7.68 MeV in 1953

Measured at 7.65 MeV in 1957

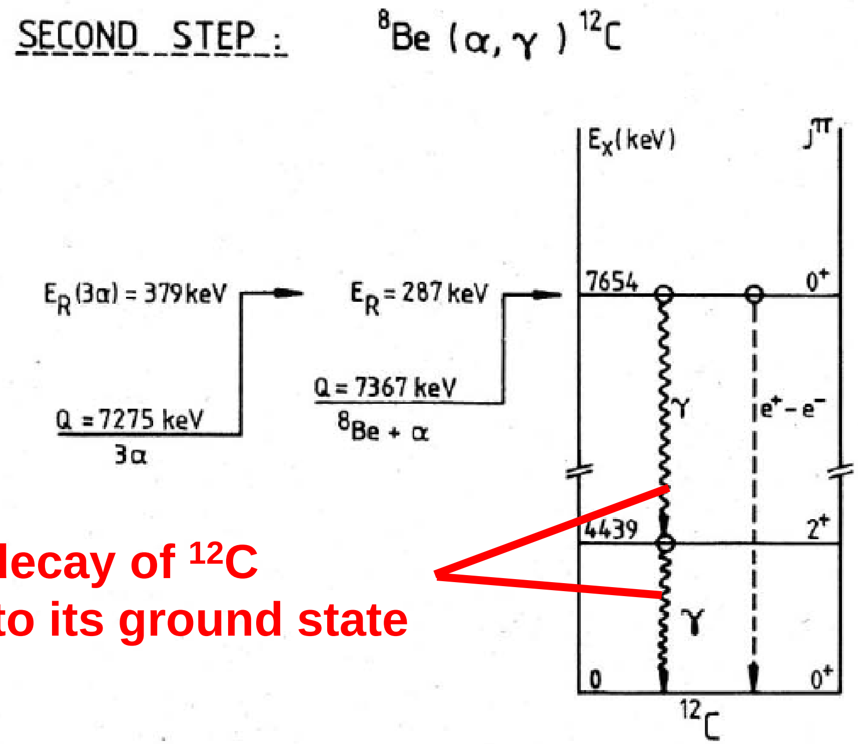
→ removed the major roadblock for the theory that elements are made in stars

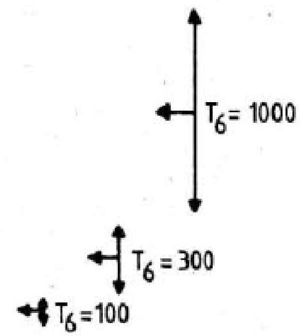
→ Nobel Prize in Physics 1983 for Willy Fowler

Third step completes the reaction:



Note: ^{8}Be ground state is a 92 keV resonance for the $\alpha+\alpha$ reaction





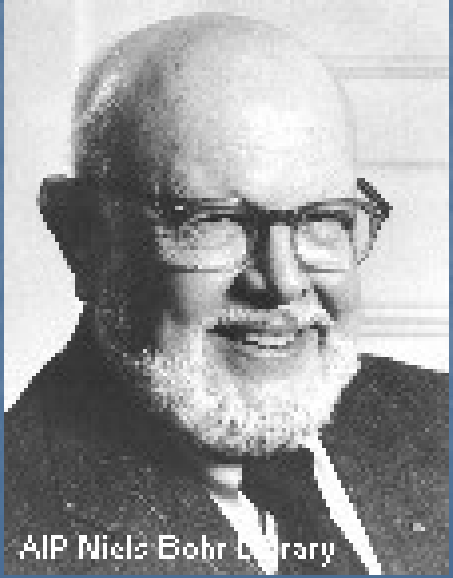
γ decay of ^{12}C into its ground state

Note:
$\Gamma_\alpha/\Gamma_\gamma > 10^3$
so γ-decay is very rare !

From H. Schatz @MSU

“ It is a remarkable fact that humans, on the basis of experiments and measurements carried out in the lab, are able to understand the universe in the early stages of its evolution, even during the first three minutes of its existence.”

Fowler (Nobel prize 1983)



Nucleosynthetic reactions are typically dominated by Coulomb barriers

$$E_B = \frac{Z_1 Z_2 e^2}{R} = \frac{1.44 Z_1 Z_2}{R(fm)} \; MeV$$

$$E_T \approx kT = 8.62\times10^{-8} T \; keV$$

$T \approx 10^8 \; K$	$E_T \approx 10$ keV
$d + p \rightarrow {}^3He + \gamma$	$E_B \approx 400$ keV
${}^{17}F + p \rightarrow {}^{18}Ne + \gamma$	$E_B \approx 2.52$ MeV
${}^{14}O + \alpha \rightarrow {}^{18}Ne + \gamma$	$E_B \approx 4.00$ MeV

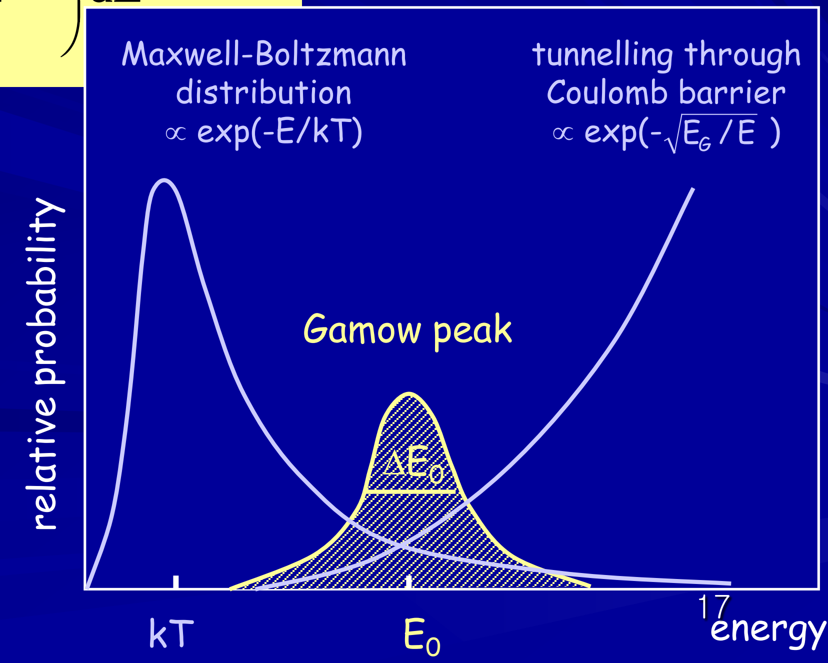
Thermonuclear reactions in stars

$$S(E) \equiv \sigma(E) E \exp\left(\frac{2\pi Z_1 Z_2 e^2}{\hbar v}\right)$$

$$\lambda = \langle \sigma v \rangle = \int_0^\infty \sigma(E) v(E) \Psi(E) dE$$

$$= \int_0^\infty \frac{S(E)}{E} \exp(-bE^{-1/2}) \sqrt{\frac{2E}{\mu}} \frac{2}{\sqrt{\pi}} \frac{E}{kT} \exp\left(-\frac{E}{kT}\right) \frac{dE}{(kTE)^{1/2}}$$

$$= \left(\frac{8}{\mu\pi}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \frac{S(E)}{E} \exp\left(-\frac{E}{kT} - bE^{-1/2}\right) dE$$



With above definition of cross section:

$$\langle\sigma v\rangle_{12} = \left(\frac{8}{\pi\mu_{12}}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty S(E)\,\exp\left[-\frac{E}{kT} - \frac{b}{E^{1/2}}\right] dE \qquad b = \sqrt{2\mu}\,\frac{\pi Z_1 Z_2 e^2}{\hbar}$$

$S(E)$ varies smoothly with energy

$f(E) = \exp\left[-\frac{E}{kT} - \frac{b}{E^{1/2}}\right]$ governs energy dependence

MAXIMUM reaction rate:

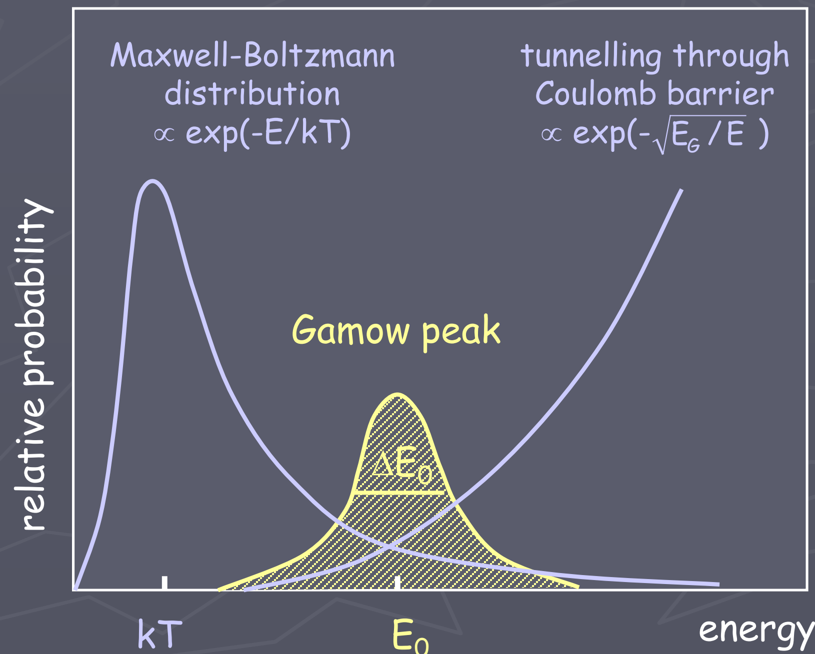
$$\frac{df(E)}{dE} = 0 \quad \Rightarrow \quad E_0 = \left(\frac{bkT}{2}\right)^{2/3}$$

$\Delta E_0 < E_0$

only small energy range contributes to reaction rate

$\Downarrow$

OK to set $S(E) \sim S(E_0)$ = const.



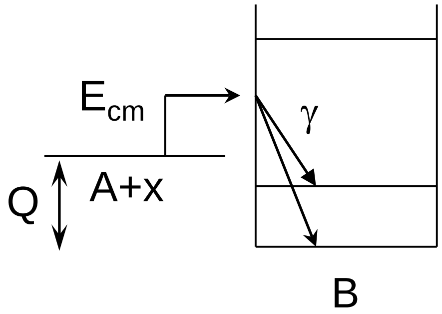
From: Second European Summer School on Experimental Nuclear Astrophysics

I. direct process

one-step process

direct transition into a bound state

example: radiative capture $A(x,\gamma)B$



$$\sigma_\gamma \propto \left| \langle B | H_\gamma | A + x \rangle \right|^2$$

H_γ = electromagnetic operator describing the transition

- reaction cross section proportional to single matrix element
- can occur at all projectile energies
- smooth energy dependence of cross section

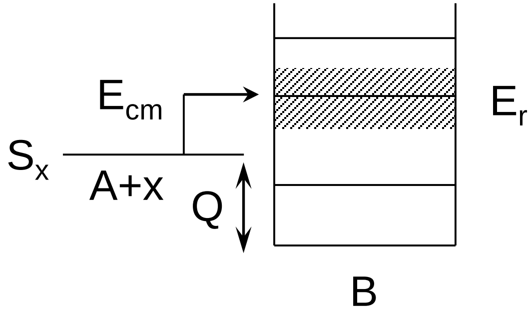
other direct processes: stripping, pickup, charge exchange, Coulomb excitation

II. resonant process

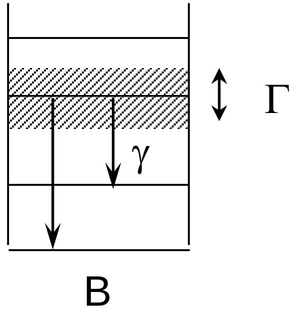
two-step process

example: **resonant radiative capture A(x,γ)B**

1. Compound nucleus formation
(in an unbound state)



2. Compound nucleus decay
(to lower excited states)



$$\sigma_\gamma \propto \underbrace{\left|\langle E_f | H_\gamma | E_r \rangle\right|^2}_{\text{compound decay}} \; \underbrace{\left|\langle E_r | H_B | A + x \rangle\right|^2}_{\text{compound formation}}$$

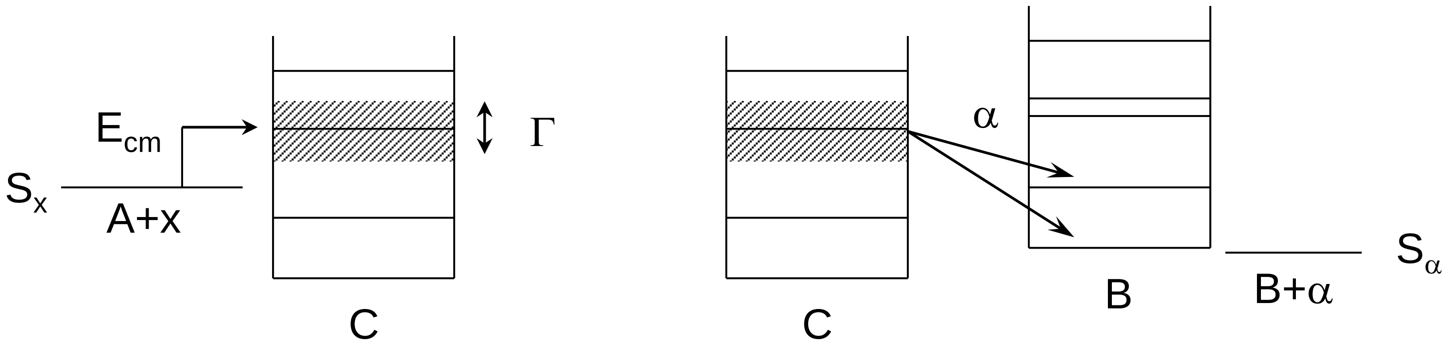
compound decay probability $\propto \Gamma_\gamma$ compound formation probability $\propto \Gamma_x$

- reaction cross section proportional to two matrix elements
- only occurs at energies $E_{cm} \sim E_r - Q$
- strong energy dependence of cross section

N. B. energy in entrance channel ($Q+E_{cm}$) has to match excitation energy E_r of resonant state, however all excited states have a width $\Rightarrow$ there is always some cross section through tails example: **resonant reaction A(x,α)B**

1. Compound nucleus formation (in an unbound state)

2. Compound nucleus decay (by particle emission)



$$\sigma_\gamma \propto \left|\langle B+\alpha|H_\alpha|E_r\rangle\right|^2 \left|\langle E_r|H_x|A+x\rangle\right|^2$$

compound decay probability $\propto \Gamma_\alpha$

compound formation probability $\propto \Gamma_x$

N. B. energy in entrance channel (S_x+E_{cm}) has to match excitation energy E_r of resonant state, however all excited states have a width $\Rightarrow$ there is always some cross section through tails example: direct capture $A + x \rightarrow B + \gamma$

$$\sigma = \pi \lambda_x^2 \left| \langle B | H | x + A \rangle \right|^2 P_\ell(E)$$

"geometrical factor"
de Broglie wavelength of projectile

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2mE}}$$

matrix element
contains nuclear properties of interaction

penetrability/transmission probability for projectile to reach target for interaction depends on projectile's angular momentum ℓ and energy E

$$\sigma = \frac{1}{E} \cdot P_\ell(E) \cdot S(E)$$

σ = (strong energy dependence) x (weak energy dependence)

S(E) = astrophysical factor contains nuclear physics of reaction
+ can be easily: graphed, fitted, extrapolated (if needed)

need expression for $P_\ell(E)$

factors affecting transmission probability:

- Coulomb barrier (for charged particles only)
- centrifugal barrier (both for neutrons and charged particles)

for a single isolated resonance:

resonant cross section given by **Breit-Wigner expression**

$$\sigma(E) = \pi \lambda\!\!\!^{-2} \frac{2J+1}{(2J_1+1)(2J_T+1)} \frac{\Gamma_1 \Gamma_2}{(E-E_r)^2 + (\Gamma/2)^2}$$

for reaction: 1 + T → C → F + 2

geometrical factor $\propto 1/E$

spin factor ω

- J = spin of CN's state
- J_1 = spin of projectile
- J_T = spin of target

strongly energy-dependent term

Γ_1 = partial width for decay via emission of particle 1
= probability of compound formation via entrance channel

Γ_2 = partial width for decay via emission of particle 2
= probability of compound decay via exit channel

Γ = total width of compound's excited state
$= \Gamma_1 + \Gamma_2 + \Gamma_\gamma + \ldots$

E_r = resonance energy

what about penetrability considerations? $\Rightarrow$ look for energy dependence in partial widths!

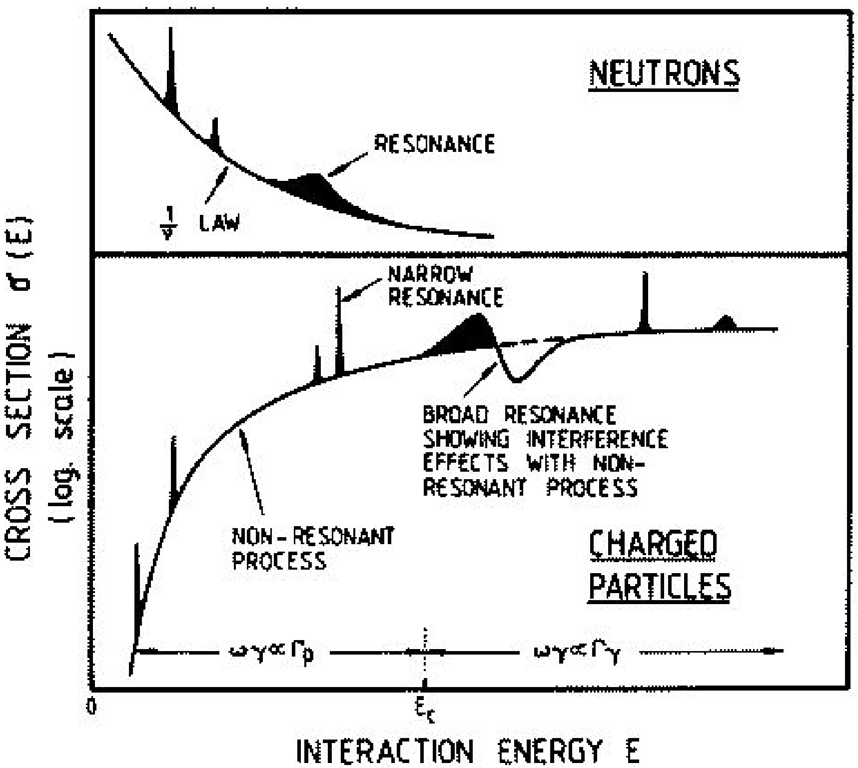
partial widths are NOT constant but energy dependent!

stellar reaction rate of nuclear reaction determined by the sum of contributions due to

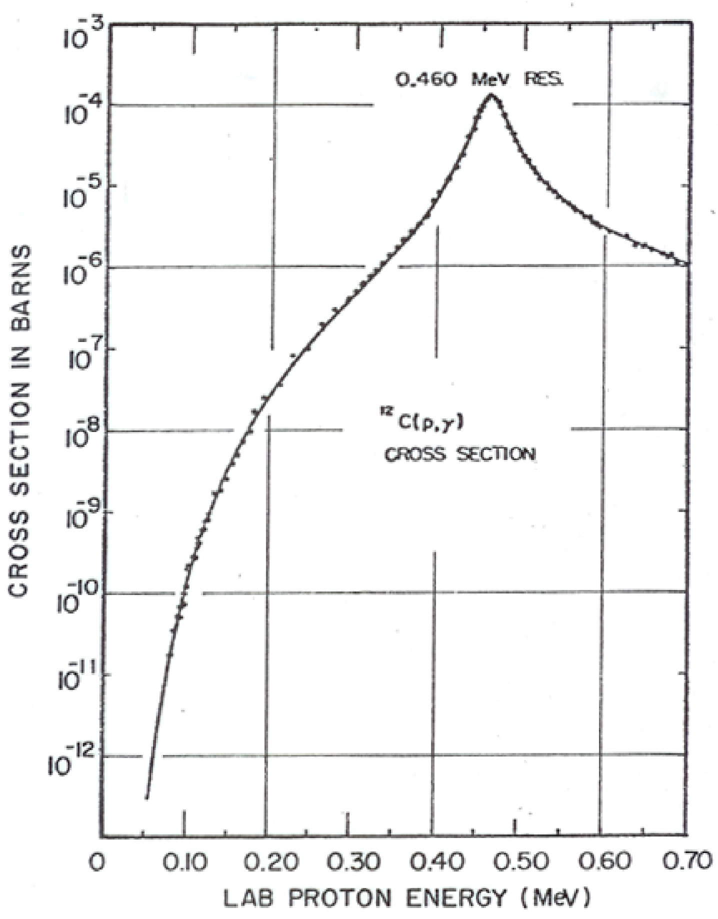
- direct transitions to the various bound states
- all narrow resonances in the relevant energy window
- broad resonances (tails) e.g. from higher lying resonances
- any interference term

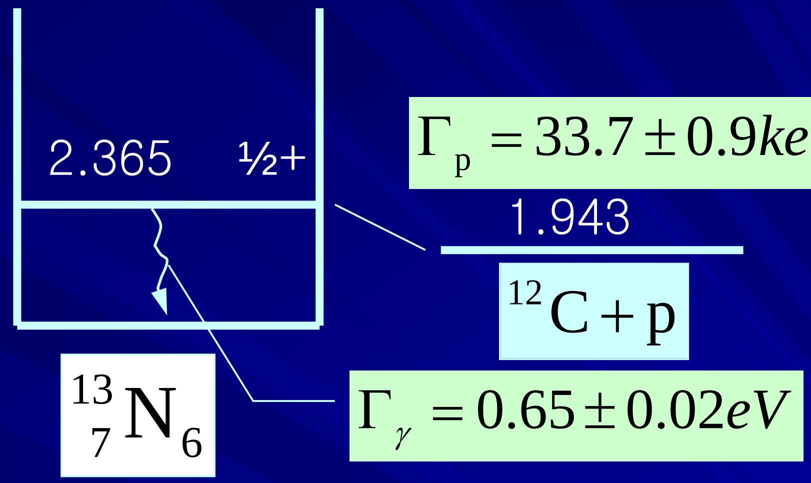
total rate

$$\langle\sigma v\rangle = \sum_i \langle\sigma v\rangle_{DCi} + \sum_i \langle\sigma v\rangle_{Ri} + \langle\sigma v\rangle_{tails} + \langle\sigma v\rangle_{int\,erference}$$



Rolls & Rodney
Cauldrons in the Cosmos, 1988

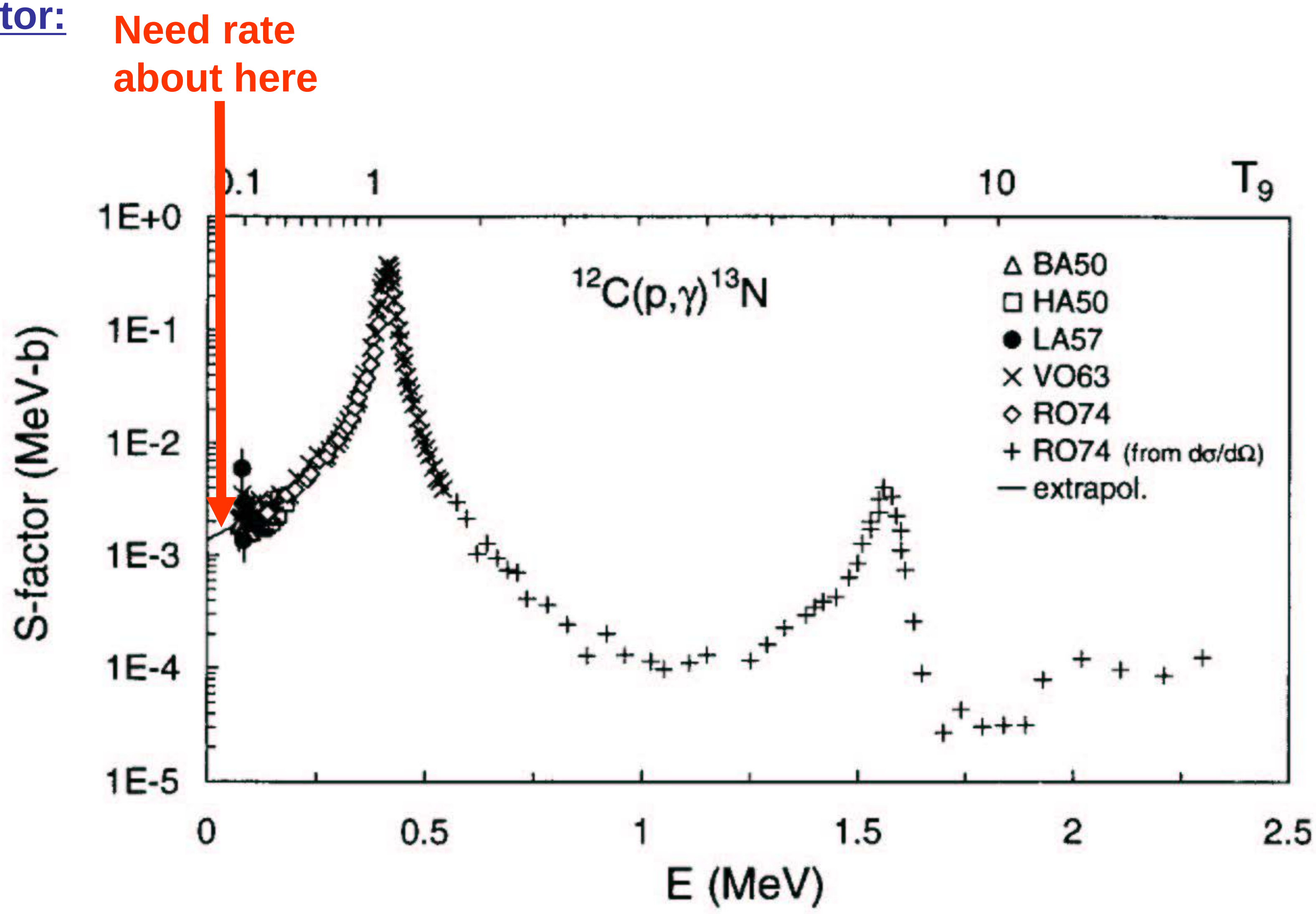




Breit-Wignor

$$\sigma \propto \frac{(2J+1)}{(2j_p+1)(2j_T+1)} \frac{\Gamma_p \Gamma_\gamma}{\left(E\text{-}E_\gamma\right)^2 + \left(\Gamma/2\right)^2}$$

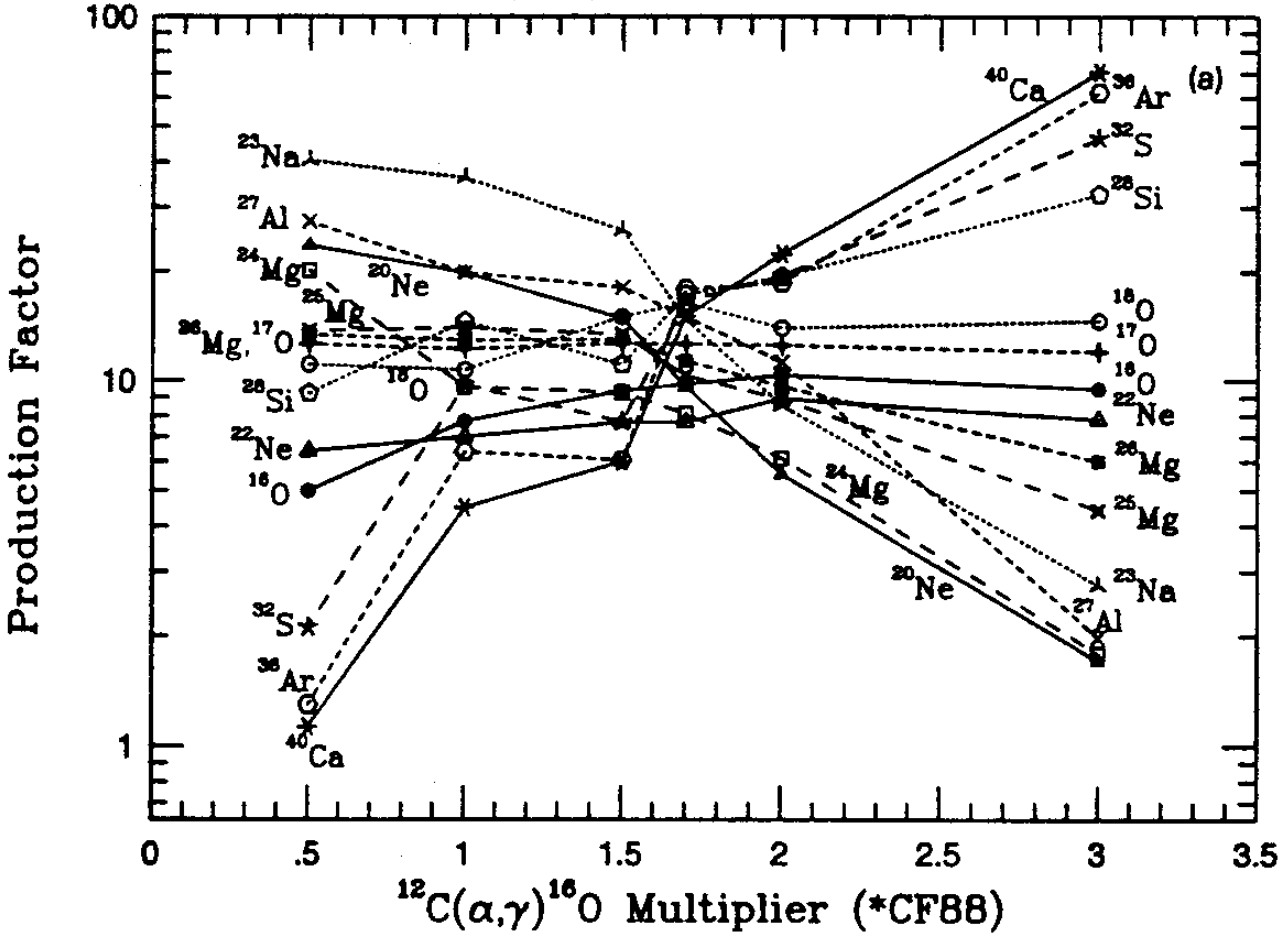
S-Factor:



From the **NACRE compilation** of charged particle induced reaction rates on stable nuclei from H to Si (Angulo et al. Nucl. Phys. A 656 (1999) 3

Massive star nucleosynthesis model as a function of $^{12}C(\alpha,\gamma)$ rate

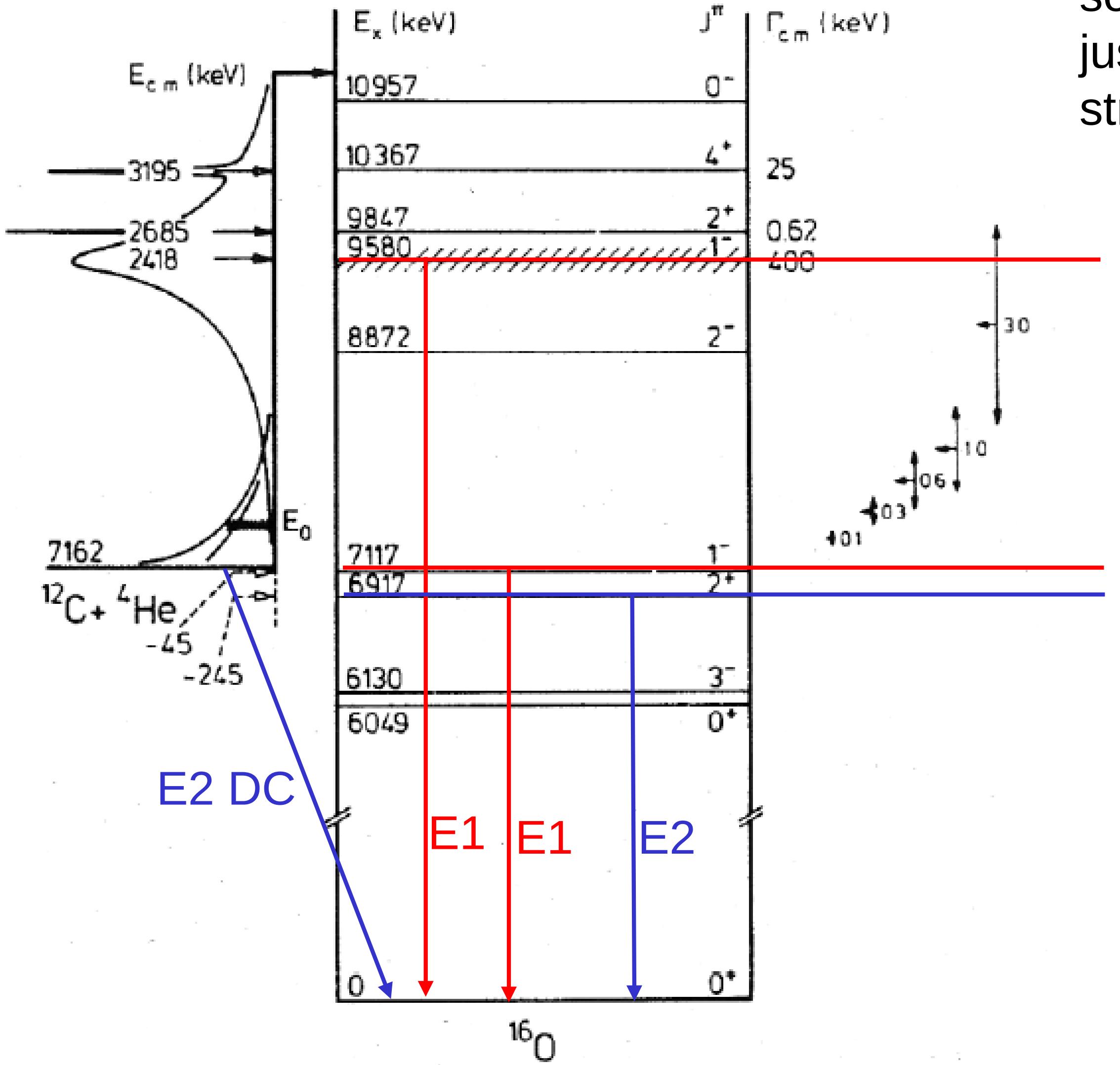
Weaver and Woosley Phys Rep 227 (1993) 65



- This demonstrates the sensitivity
- One could deduce a preference for a total S(300) of ~120-220
  (But of course we cannot be sure that the astrophysical model is right)

From H. Schatz @MSU

some tails of resonances just make the reaction strong enough …



complications:

- very low cross section makes direct measurement impossible
- subthreshold resonances cannot be measured at resonance energy
- Interference between the E1 and the E2 components

From H. Schatz @MSU

Therefore:

Uncertainty in the $^{12}C(\alpha,\gamma)$ rate is the single most important nuclear physics uncertainty in astrophysics

Affects:
- C/O ration → further stellar evolution (C-burning or O-burning ?)
- iron (and other) core sizes (outcome of SN explosion)
- Nucleosynthesis (see next slide)

Some current results for S(300 keV):

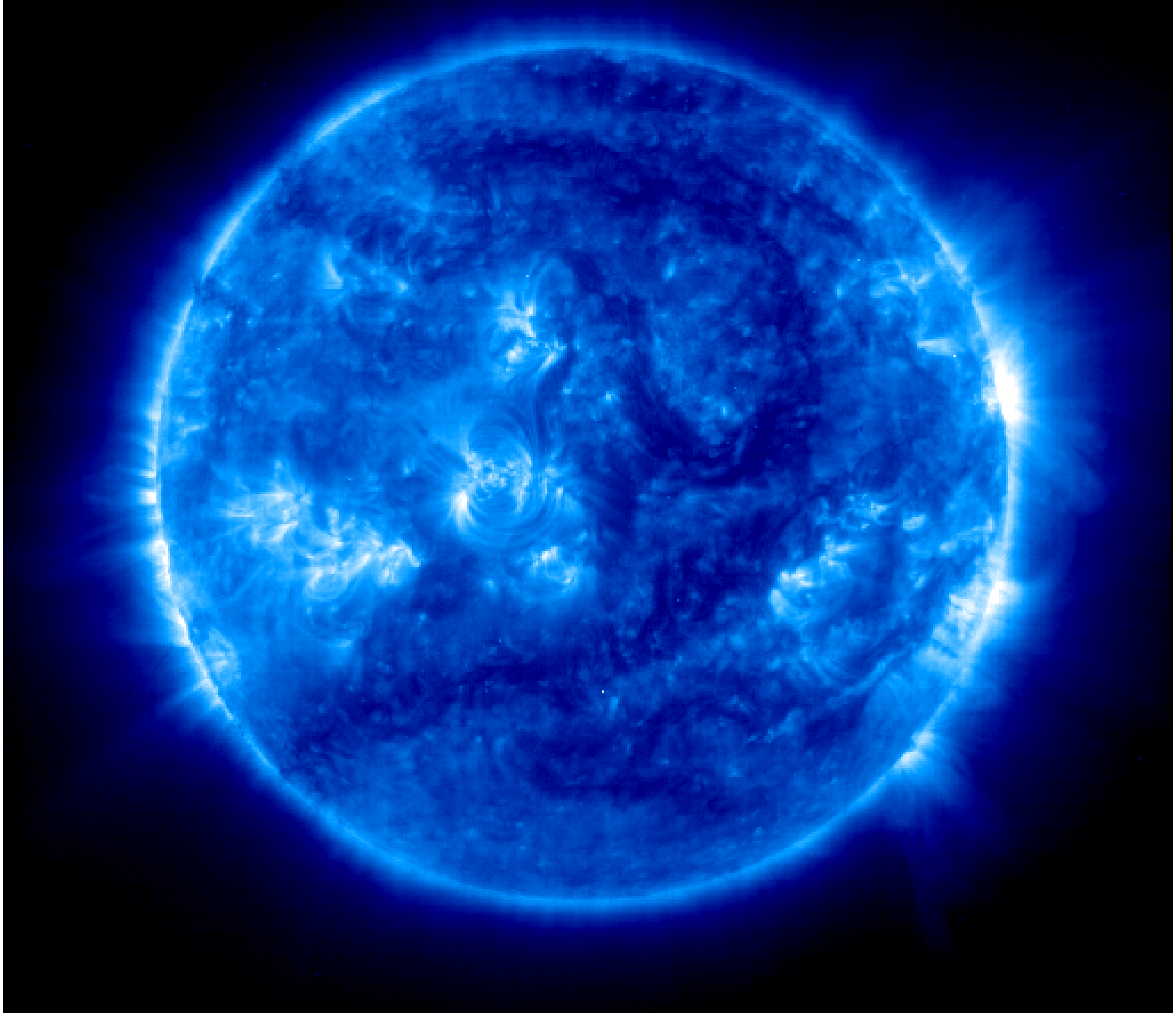
S_{E2}=53+13-18 keV b (Tischhauser et al. PRL88(2002)2501

S_{E1}=79+21-21 keV b (Azuma et al. PRC50 (1994) 1194)

But others range among groups larger !

From H. Schatz @MSU

Nuclear Reactions in the Sun



SOHO, 171A Fe emission line

The ppI chain

Step 1: ~~$p + p \longrightarrow {}^{2}He$~~

$p + p \longrightarrow d + e^{+} + \nu_e$

^{2}He is unstable

Step 2: $d + p \longrightarrow {}^{3}He$

~~$d + d \longrightarrow {}^{4}He$~~

d abundance is too low

Step 3: ~~${}^{3}He + p \longrightarrow {}^{4}Li$~~

~~${}^{3}He + d \longrightarrow {}^{4}He + n$~~

${}^{3}He + {}^{3}He \longrightarrow {}^{4}He + 2p$

^{4}Li is unstable

d abundance is too low

d+d not going because Y_d is small as d+p leads to rapid destruction

$^{3}He+^{3}He$ goes because Y_{3He} gets large as there is no other rapid destruction

proton-proton chain

proton-proton chain

$p + p \rightarrow d + e^+ + \nu$

$p + d \rightarrow {}^3He + \gamma$

86% | 14%

86%:

${}^3He + {}^3He \rightarrow {}^4He + 2p$

PP-I

$Q_{eff} = 26.20$ MeV

14%:

${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

99.7% | 0.3%

99.7%:

${}^7Be + e^- \rightarrow {}^7Li + \nu$

${}^7Li + p \rightarrow 2\,{}^4He$

PP-II

$Q_{eff} = 25.66$ MeV

0.3%:

${}^7Be + p \rightarrow {}^8B + \gamma$

${}^8B \rightarrow {}^8Be + e^+ + \nu$

$\downarrow$

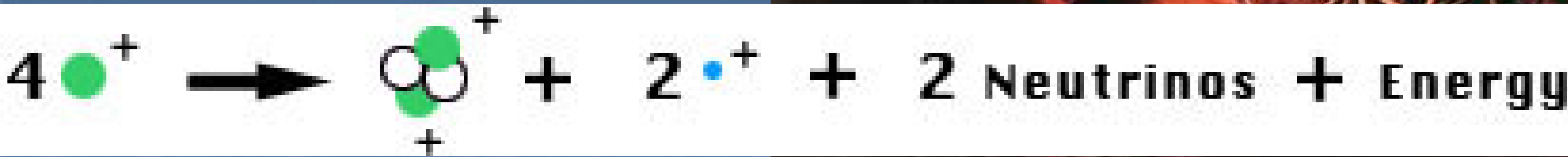
$2\,{}^4He$

PP-III

$Q_{eff} = 19.17$ MeV

net result: $4p \rightarrow {}^4He + 2e^+ + 2\nu + Q_{eff}$

From M. Aliotta

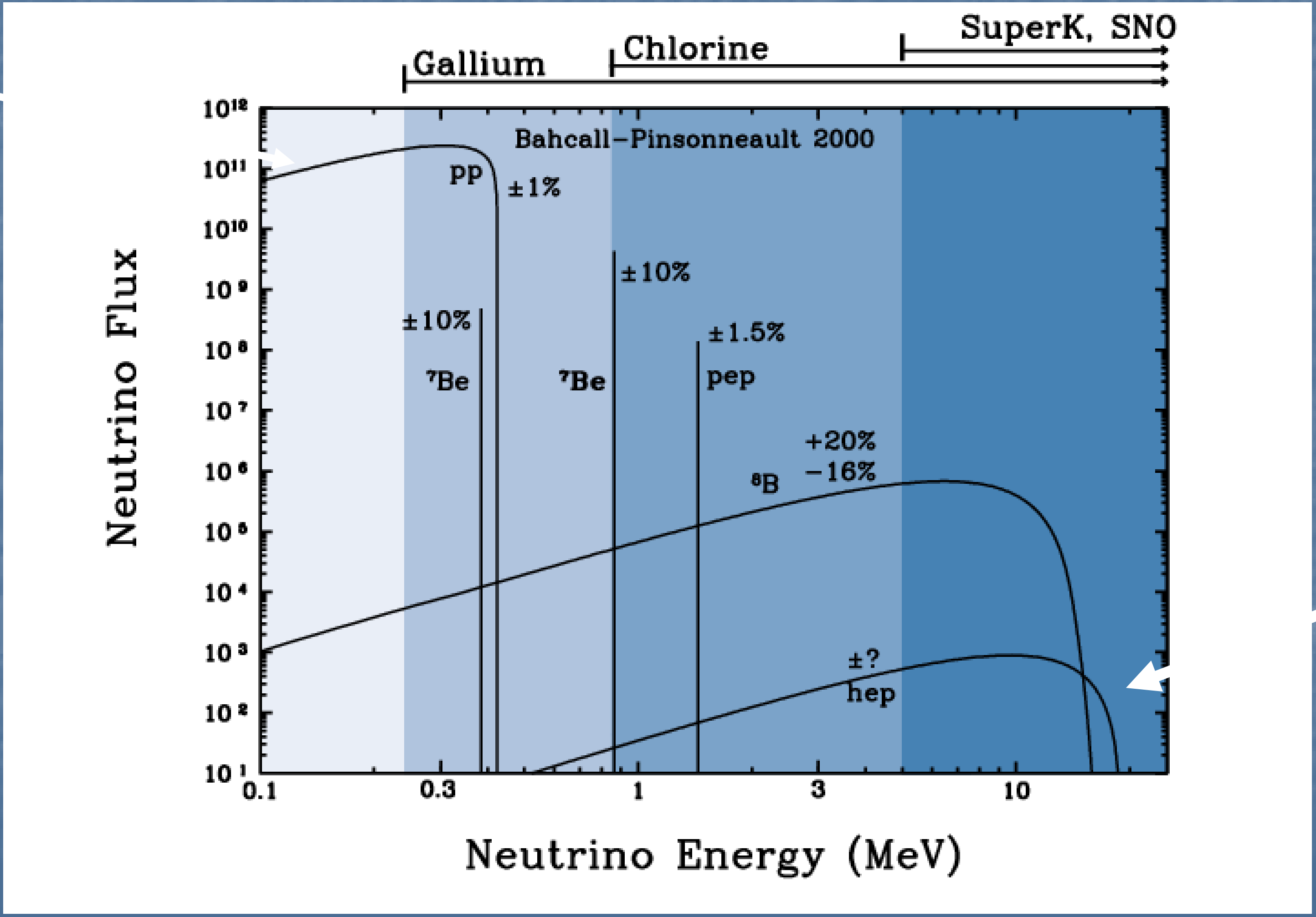


Question : solar constant 0.033 cal/sec/cm^2

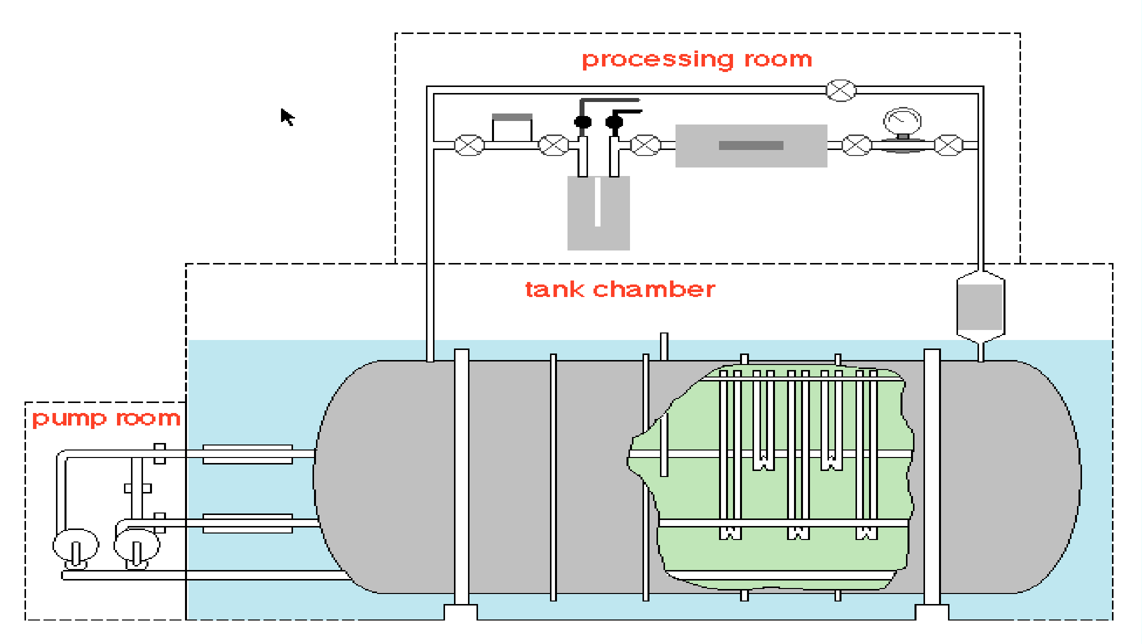
What is the number of protons consumed in the sun so far?

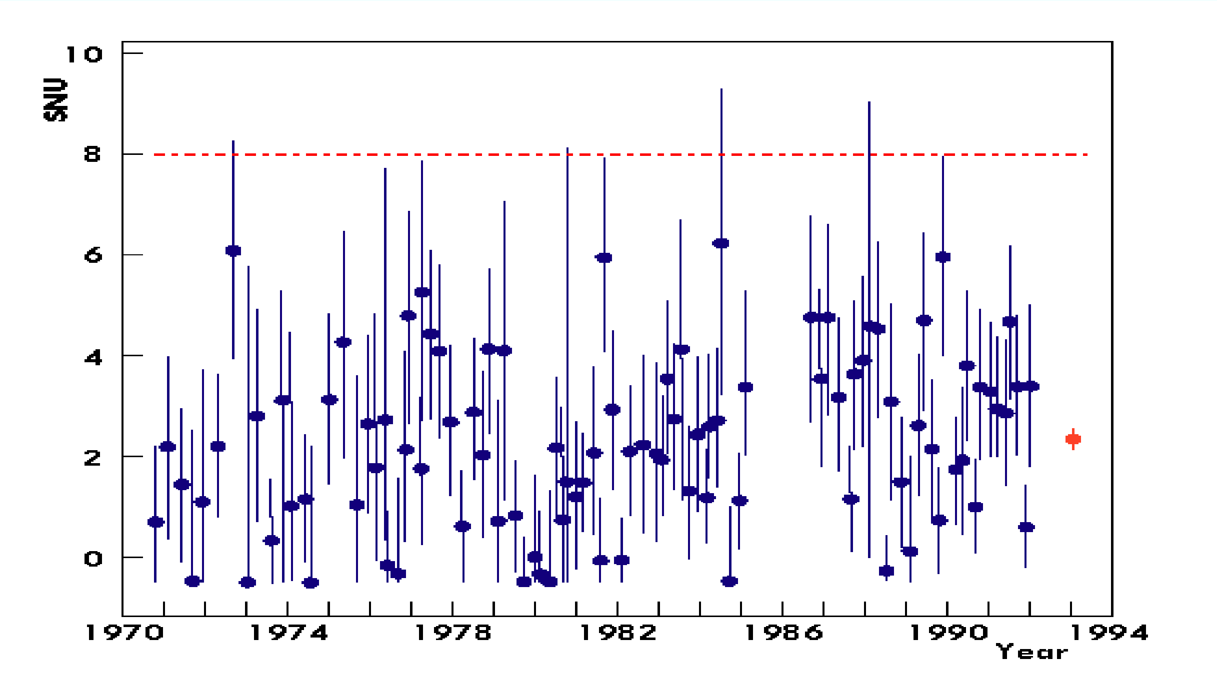
Solar Neutrino Spectrum

pp



hep





http://wwwlapp.in2p3.fr/neutrinos

First experimental detection of solar neutrinos:

- **1964** John Bahcall and Ray Davis have the idea to detect solar neutrinos using the reaction:

$$^{37}Cl + \nu_e \longrightarrow {}^{37}Ar + e^-$$

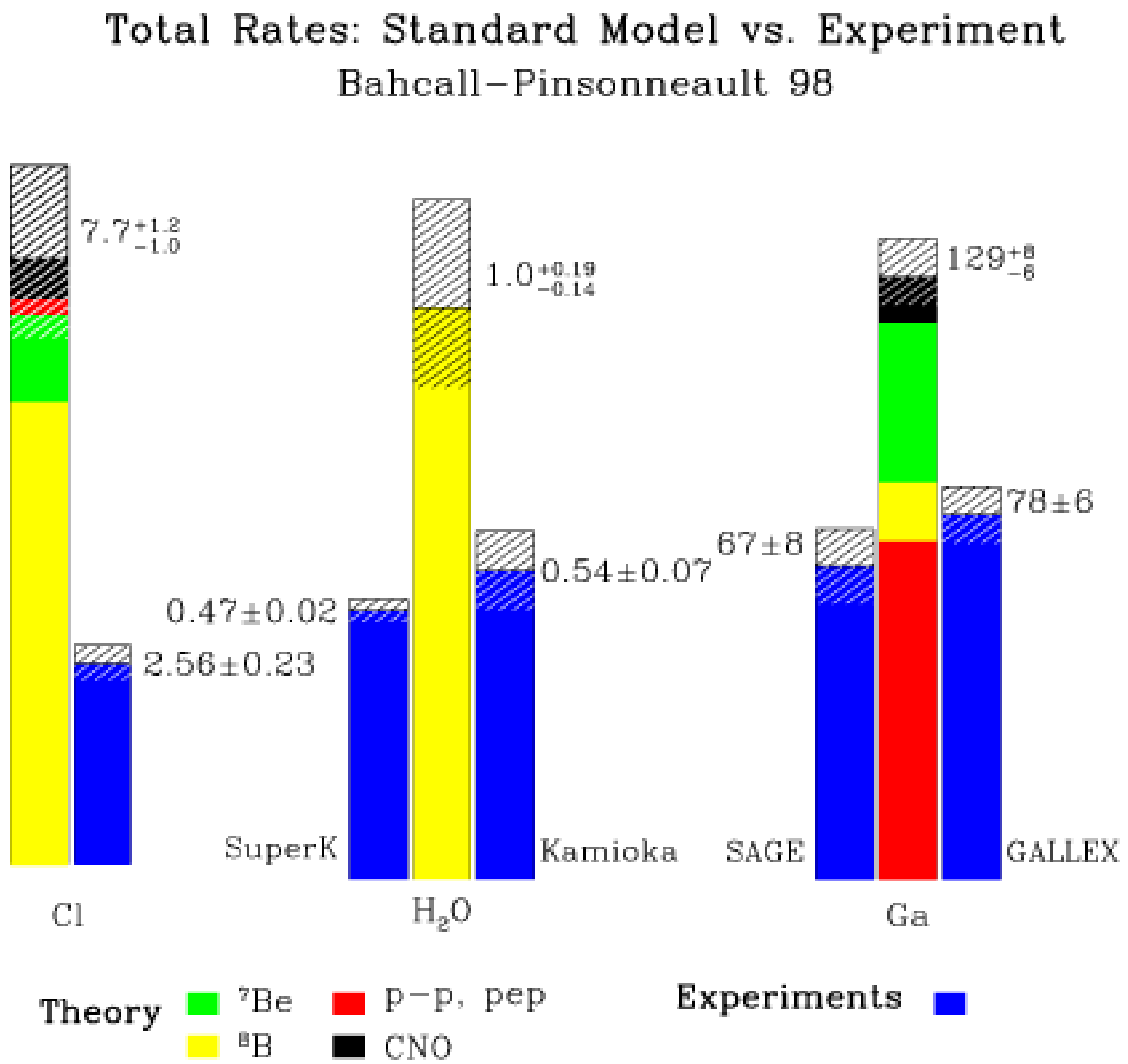
- **1967** **Homestake experiment starts taking data**
  - 100,000 Gallons of cleaning fluid in a tank 4850 feet underground
  - ^{37}Ar extracted chemically every few months (single atoms !) and decay counted in counting station (35 days half-life)
  - event rate: ~1 neutrino capture per day !
- **1968** **First results: only 34% of predicted neutrino flux !**

solar neutrino problem is born - for next 20 years no other detector !

Neutrino production in solar core ~ T^{25}

$\longrightarrow$ **nuclear energy source of sun directly and unambiguously confirmed**

$\longrightarrow$ **solar models precise enough so that deficit points to serious problem**



Total Rates: Standard Model vs. Experiment
Bahcall-Pinsonneault 98
7.7 +1.2 −1.0
2.56±0.23
Cl
1.0 +0.19 −0.14
0.47±0.02
0.54±0.07
SuperK
Kamioka
H2O
129 +8 −6
67±8
78±6
SAGE
GALLEX
Ga
Theory
7Be
8B
p−p, pep
CNO
Experiments

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

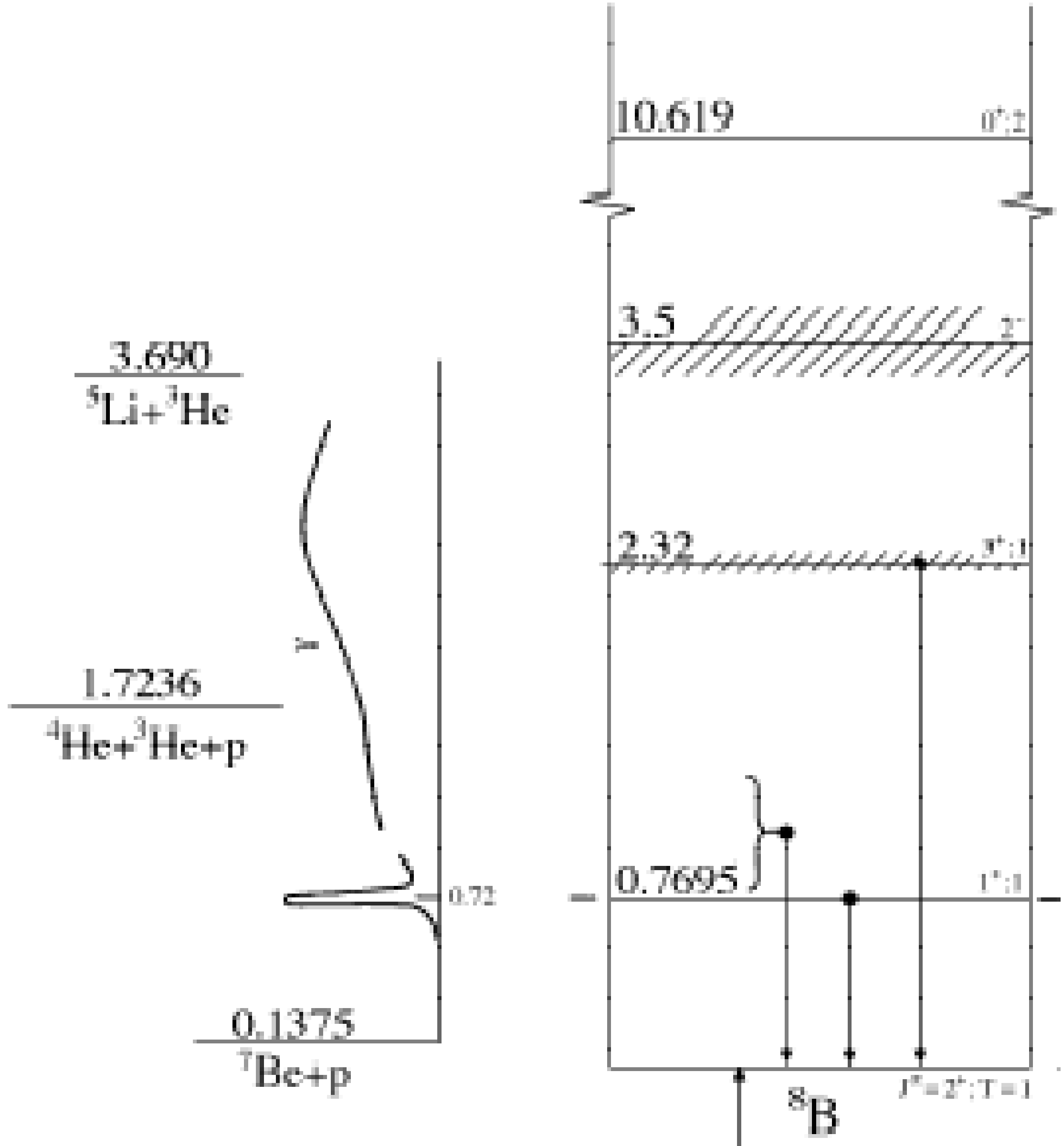
Levels and γ-ray branchings:

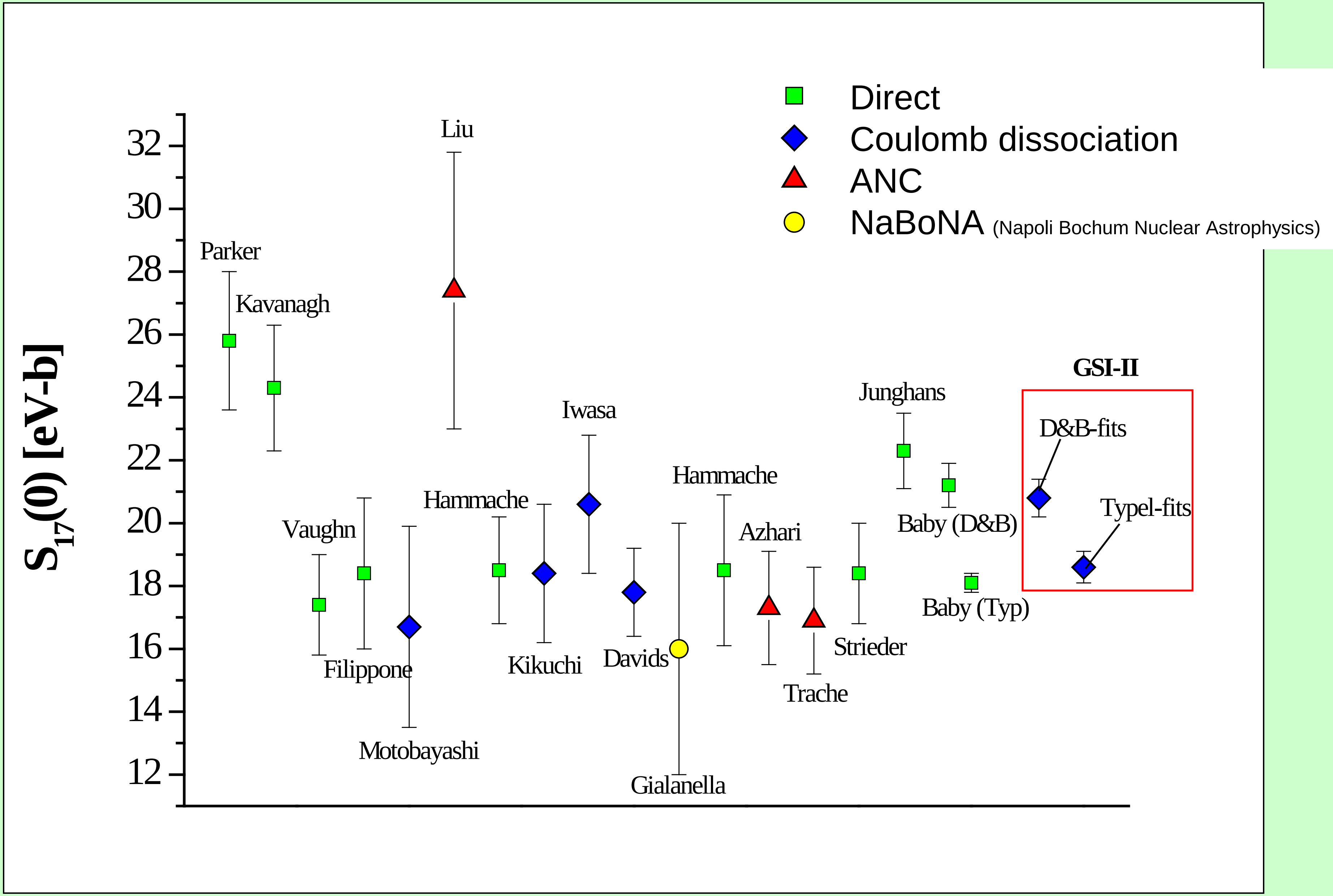
0, 2^+, 770 *3* ms, *[ABCDEFGH]*, T=1,
%EC+%β^+=100, %EC2α=100,
μ=1.0355 *3*

774 *6*, Γ=37 *5* keV, *[ABCEGH]*
γ_0 *774* M1

2320 *30*, 3^+, Γ=350 *40* keV, *[CGH]*, T=1

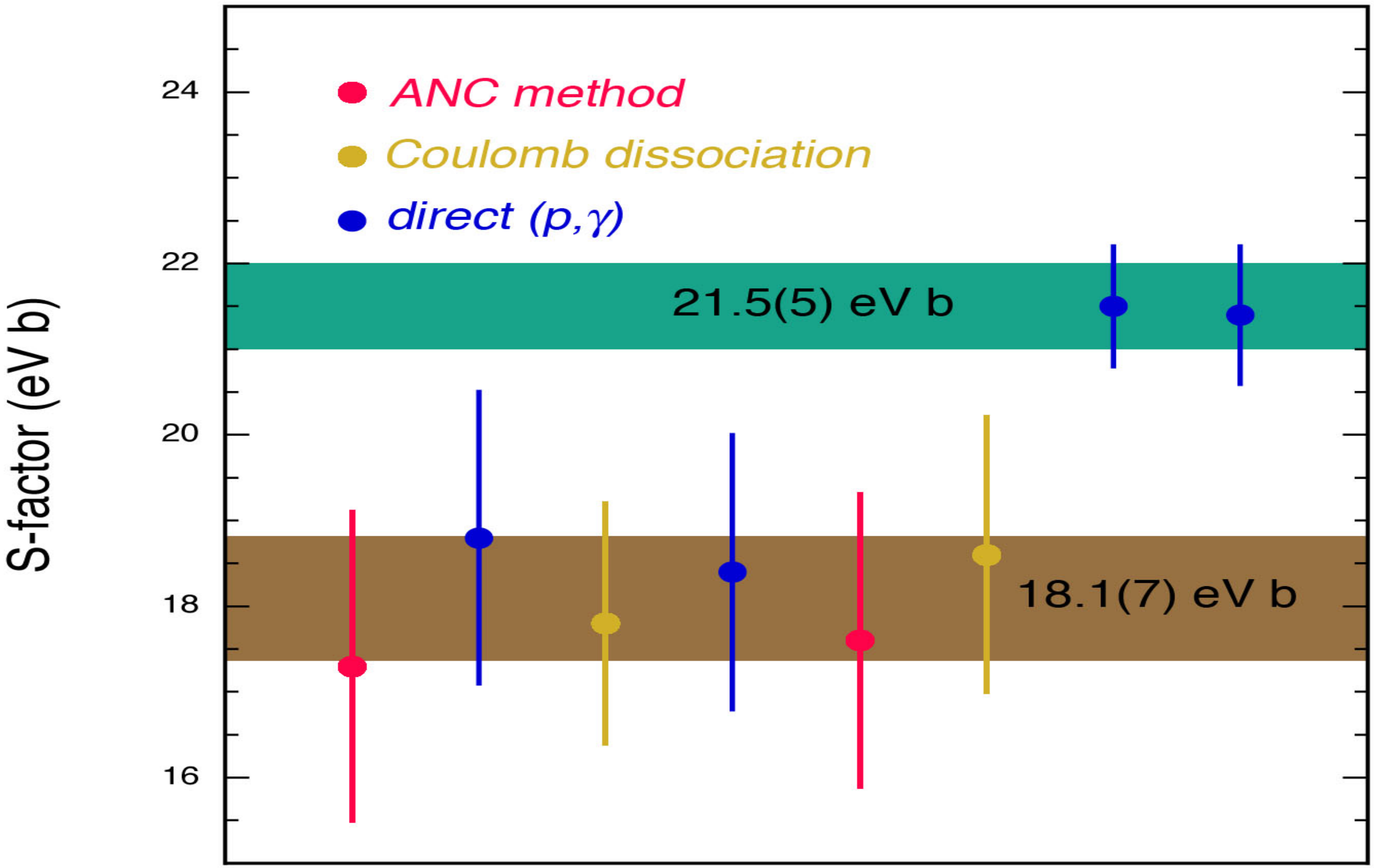
10619 *9*, 0^+, Γ<60 keV, *[H]*, T=2





From L. Gialanella @ INFN

$^7Be(p,\gamma)^8B$, 2001 - present



Solar fusion cross sections II: the pp chain and CNO cycles

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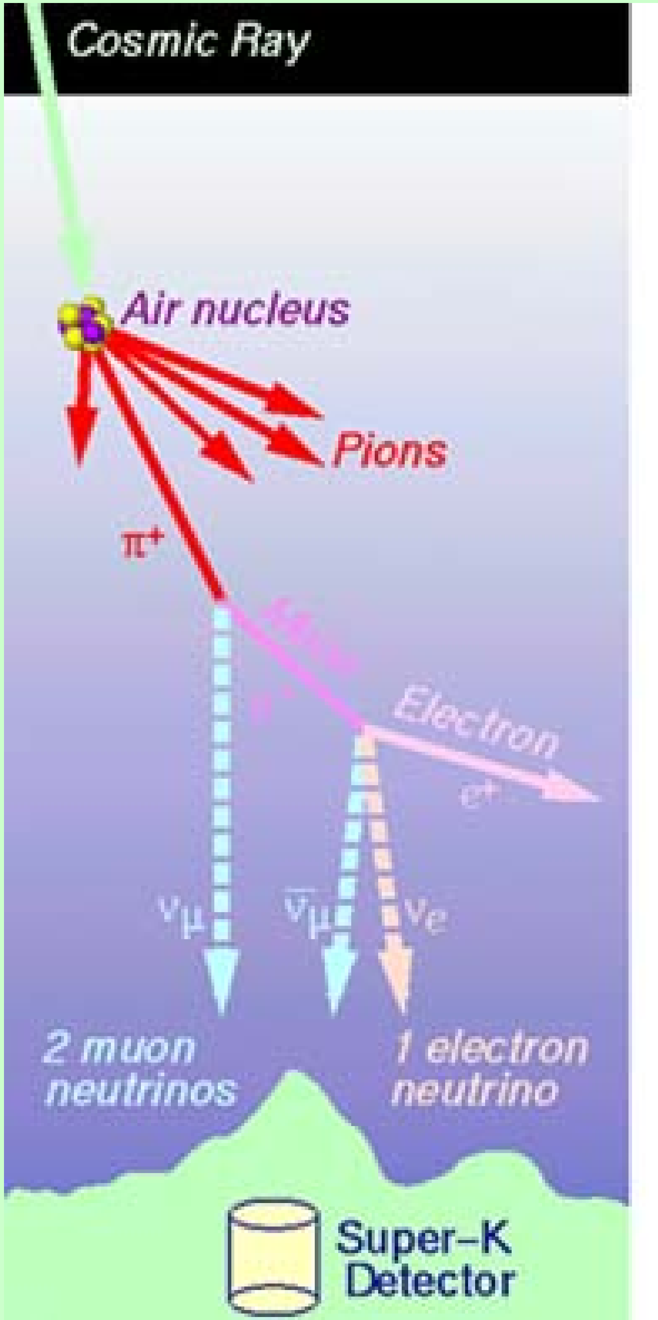
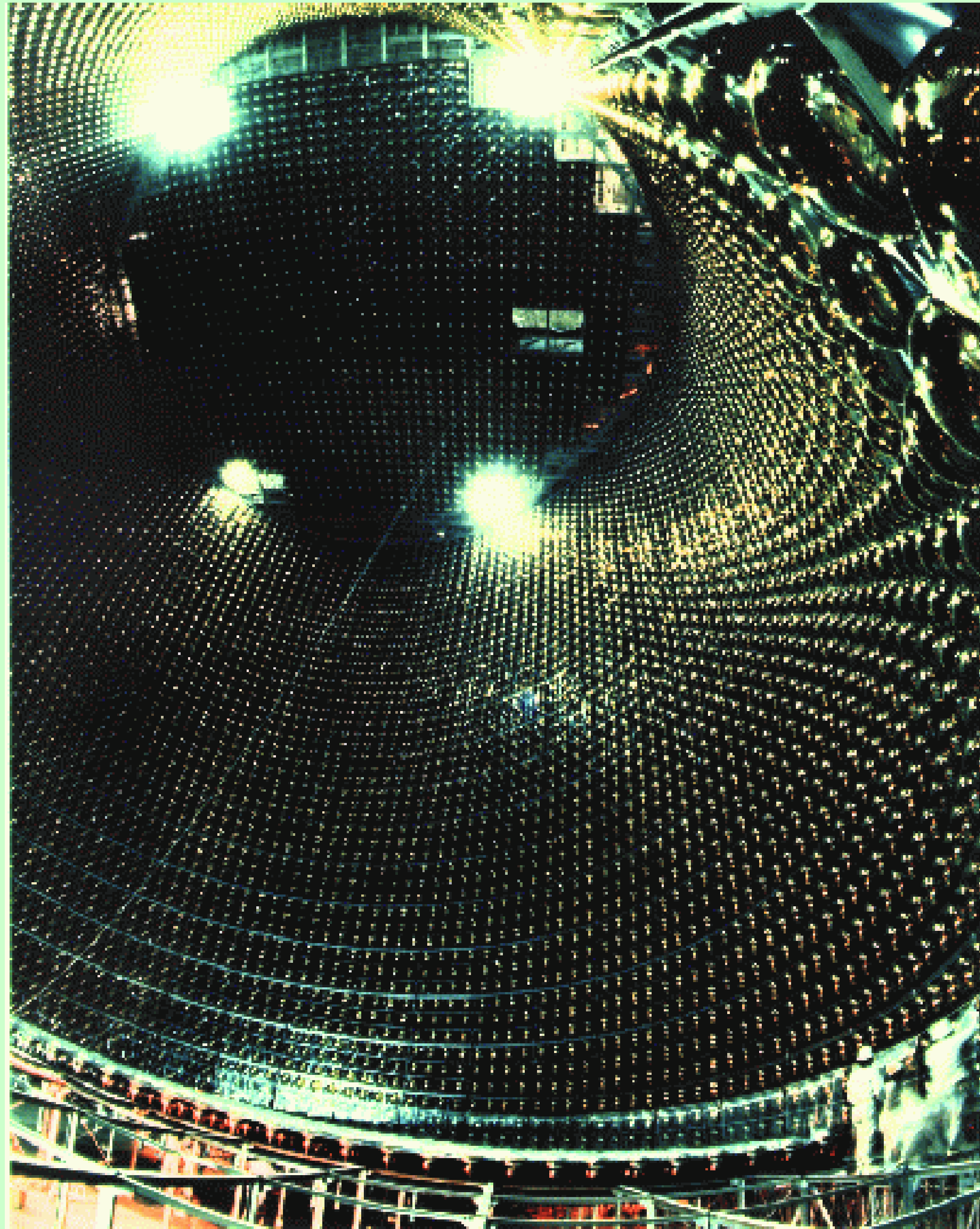
R. Cyburt

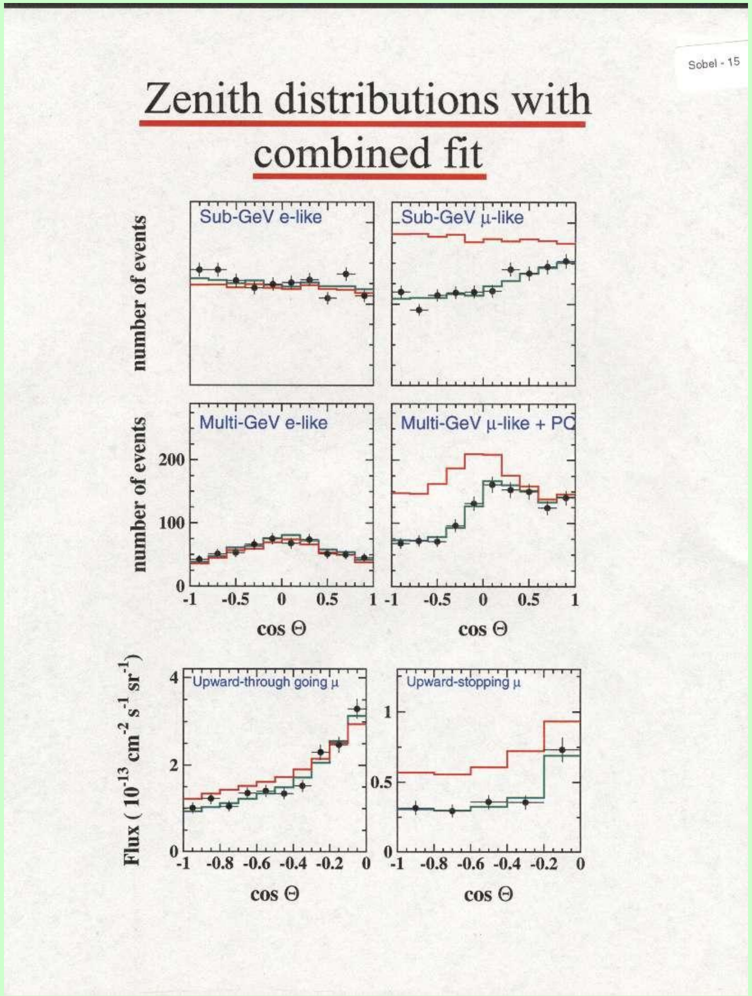
JINA and National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824 USA


Cosmic Ray
Air nucleus
Pions
π^+
Electron
e^+
ν_μ
$\bar{\nu}_\mu$
ν_e
2 muon neutrinos
1 electron neutrino
Super–K Detector



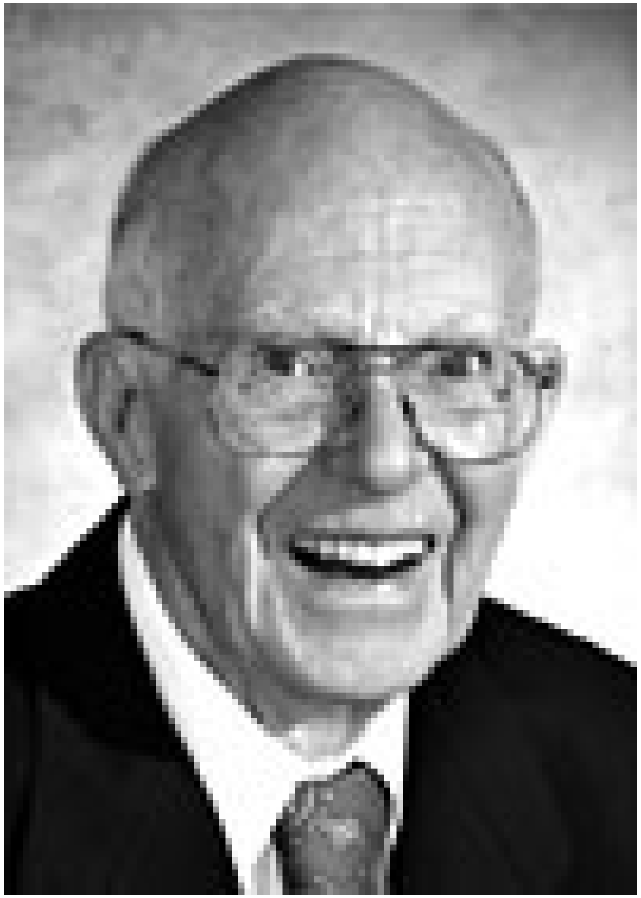
Atmospheric neutrinos

Super-Kamiokande

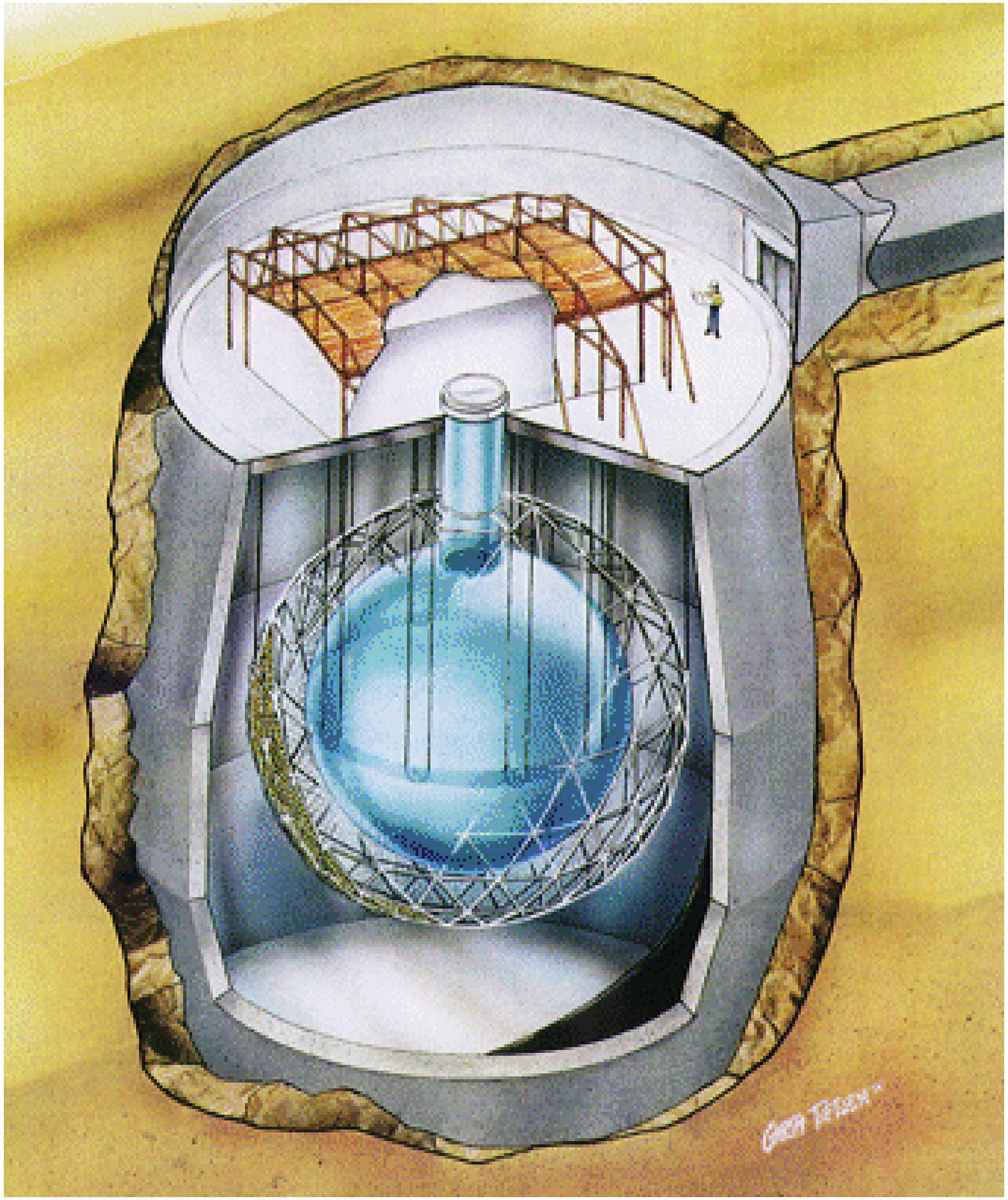


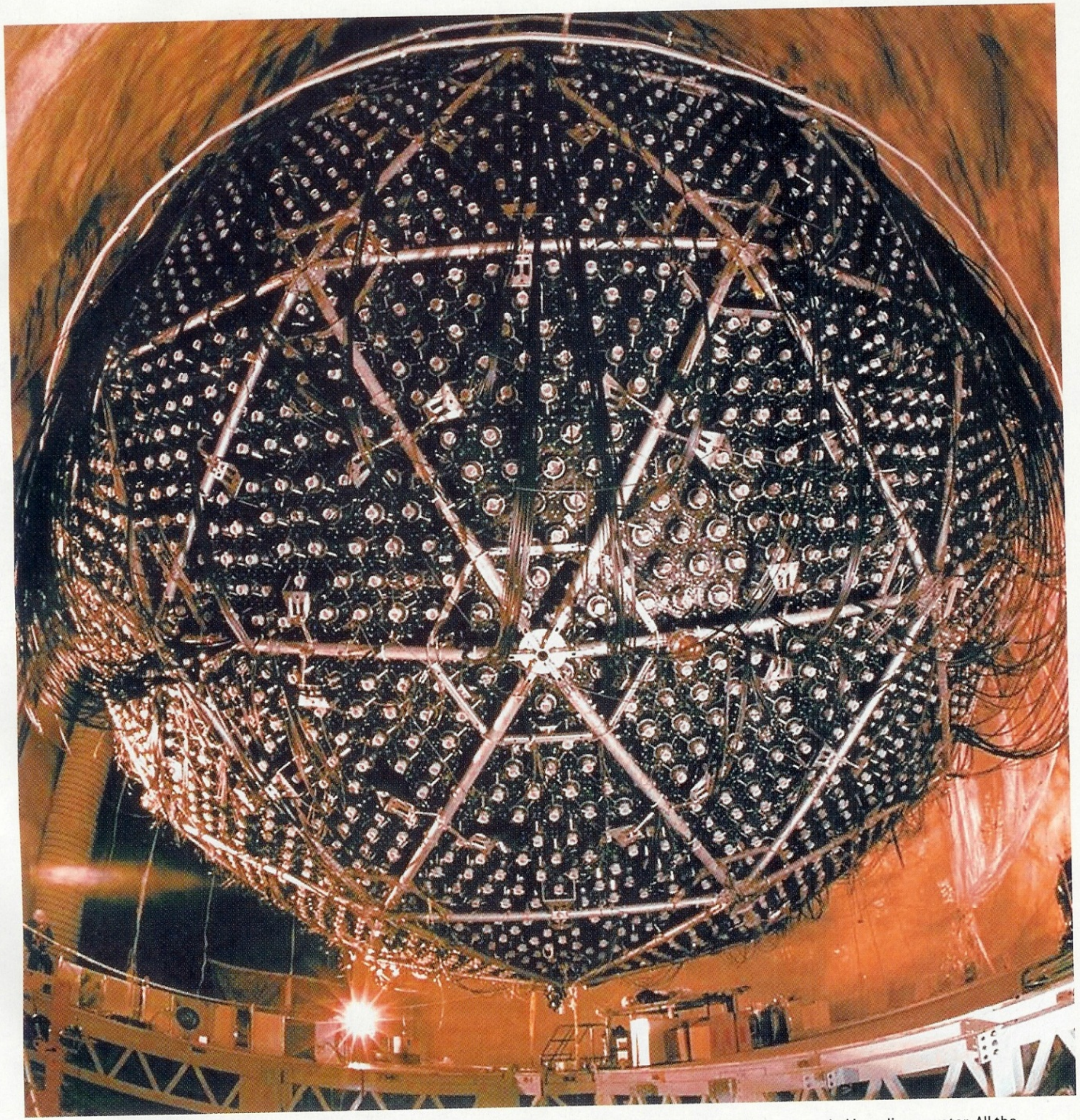
The Nobel Prize in Physics 2002

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

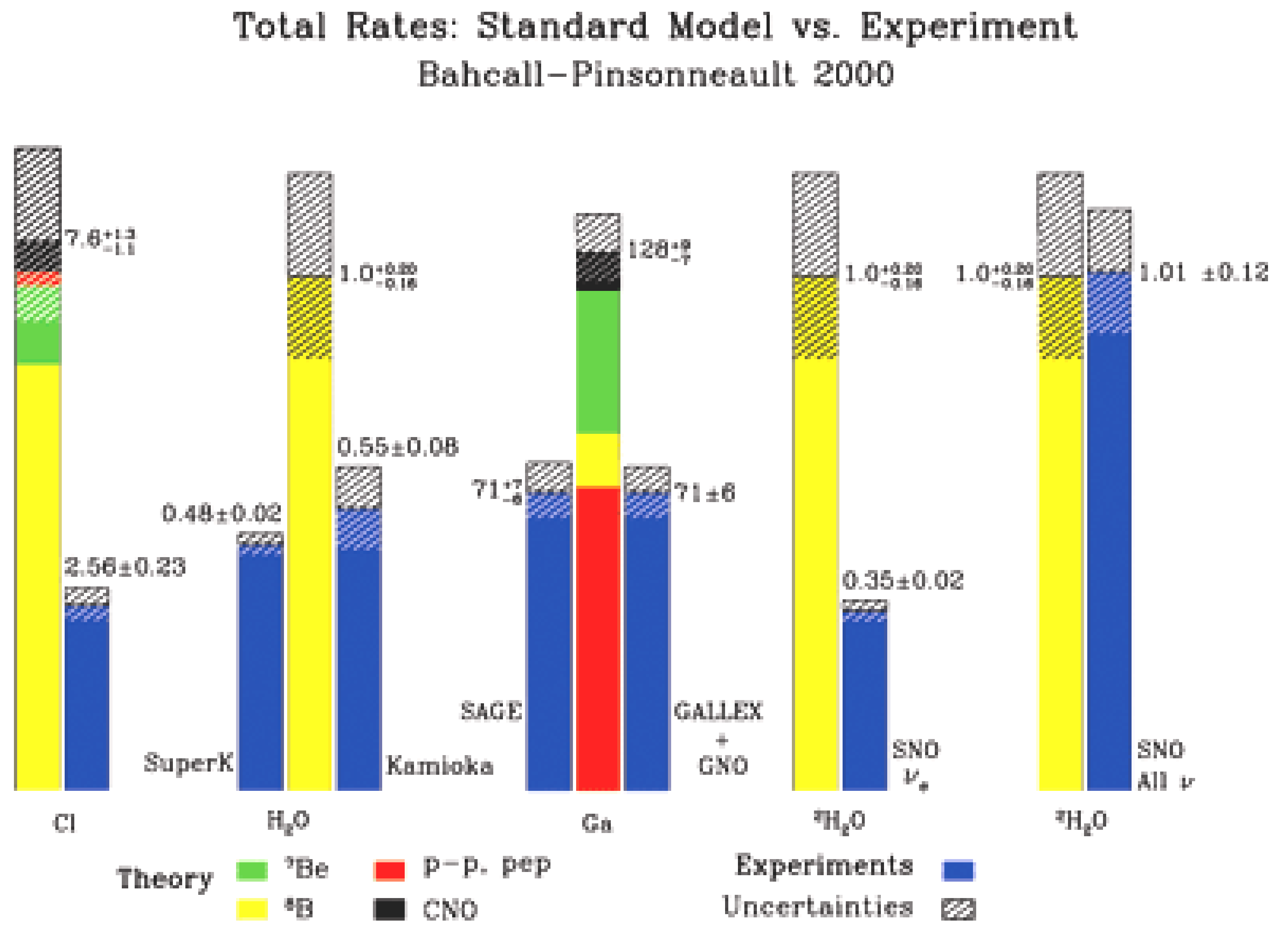


Sudbury Neutrino Observatory



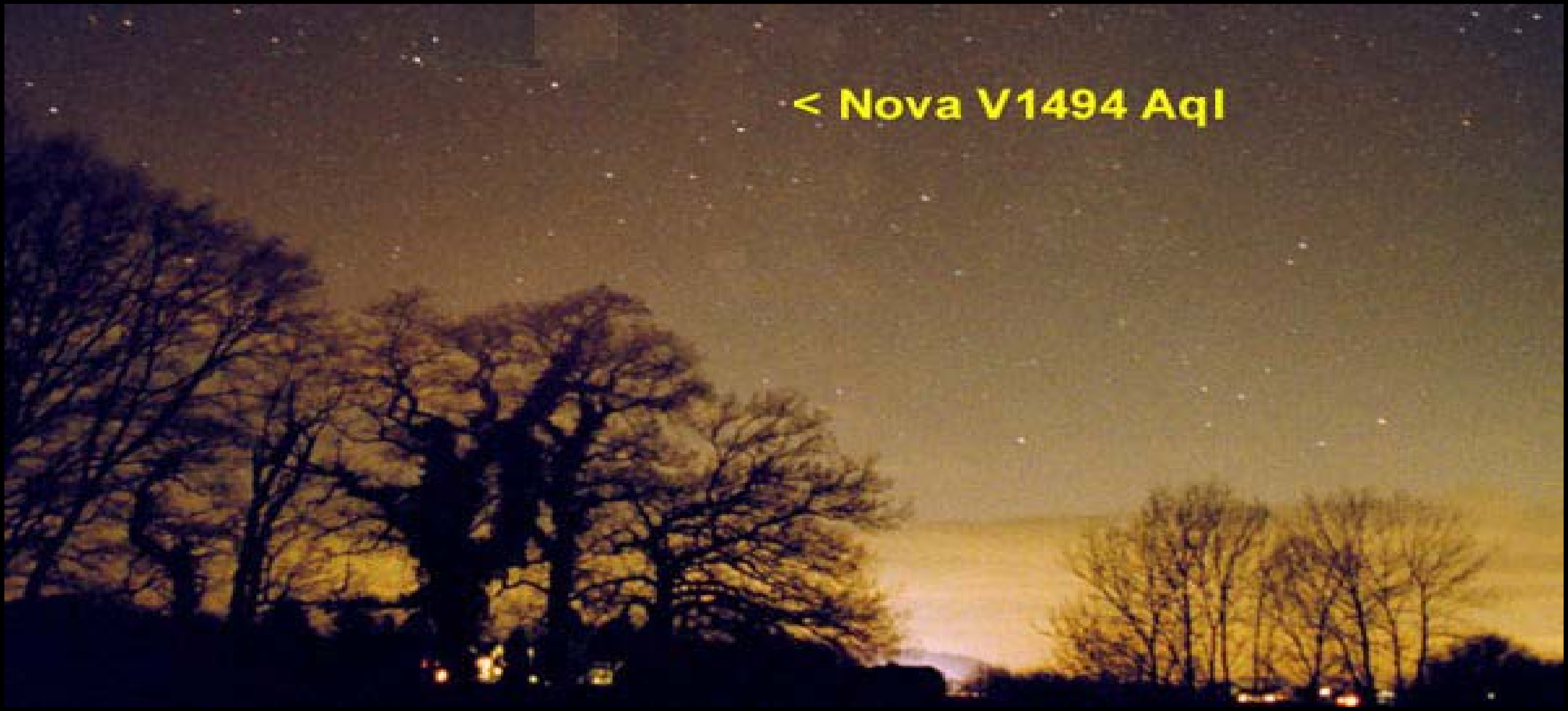


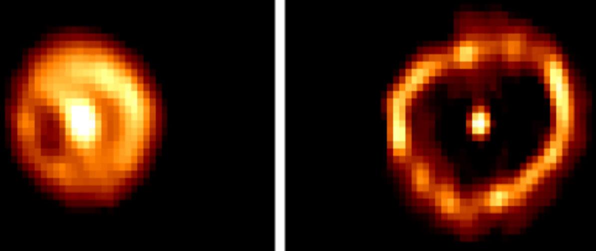
PHOTOMULTIPLIER TUBES—more than 9,500 of them—on a geodesic sphere 18 meters in diameter act as the eyes of the Sudbury Neutrino Observatory. The tubes surround and monitor a 12-meter-diameter acrylic sphere that contains 1,000 tons of heavy water. Each tube can detect a single photon of light. The entire assembly is suspended in ordinary water. All the materials that make up the detector must be extraordinarily free of natural traces of radioactive elements to avoid overwhelming the tubes with false solar neutrino counts.



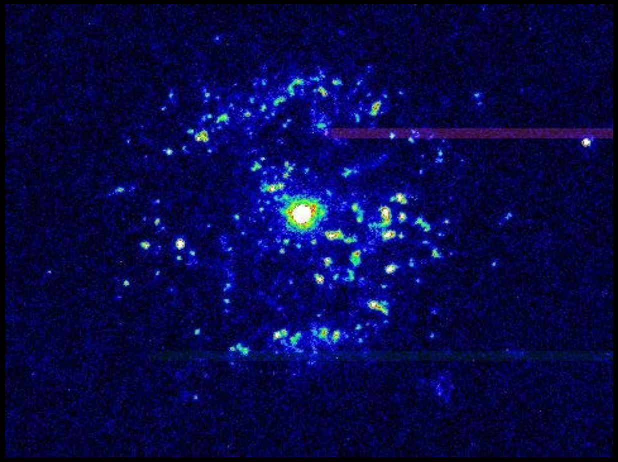
Total Rates: Standard Model vs. Experiment
Bahcall-Pinsonneault 2000
7.6 +1.3 −1.1
2.56±0.23
0.48±0.02
1.0 +0.20 −0.16
0.55±0.08
SuperK
Kamioka
128 +9 −7
71 +7 −6
71±6
SAGE
GALLEX + GNO
1.0 +0.20 −0.16
0.35±0.02
SNO νe
1.0 +0.20 −0.16
1.01 ±0.12
SNO All ν
Cl
H2O
Ga
2H2O
2H2O
Theory
7Be
8B
p-p, pep
CNO
Experiments
Uncertainties

Nova observations

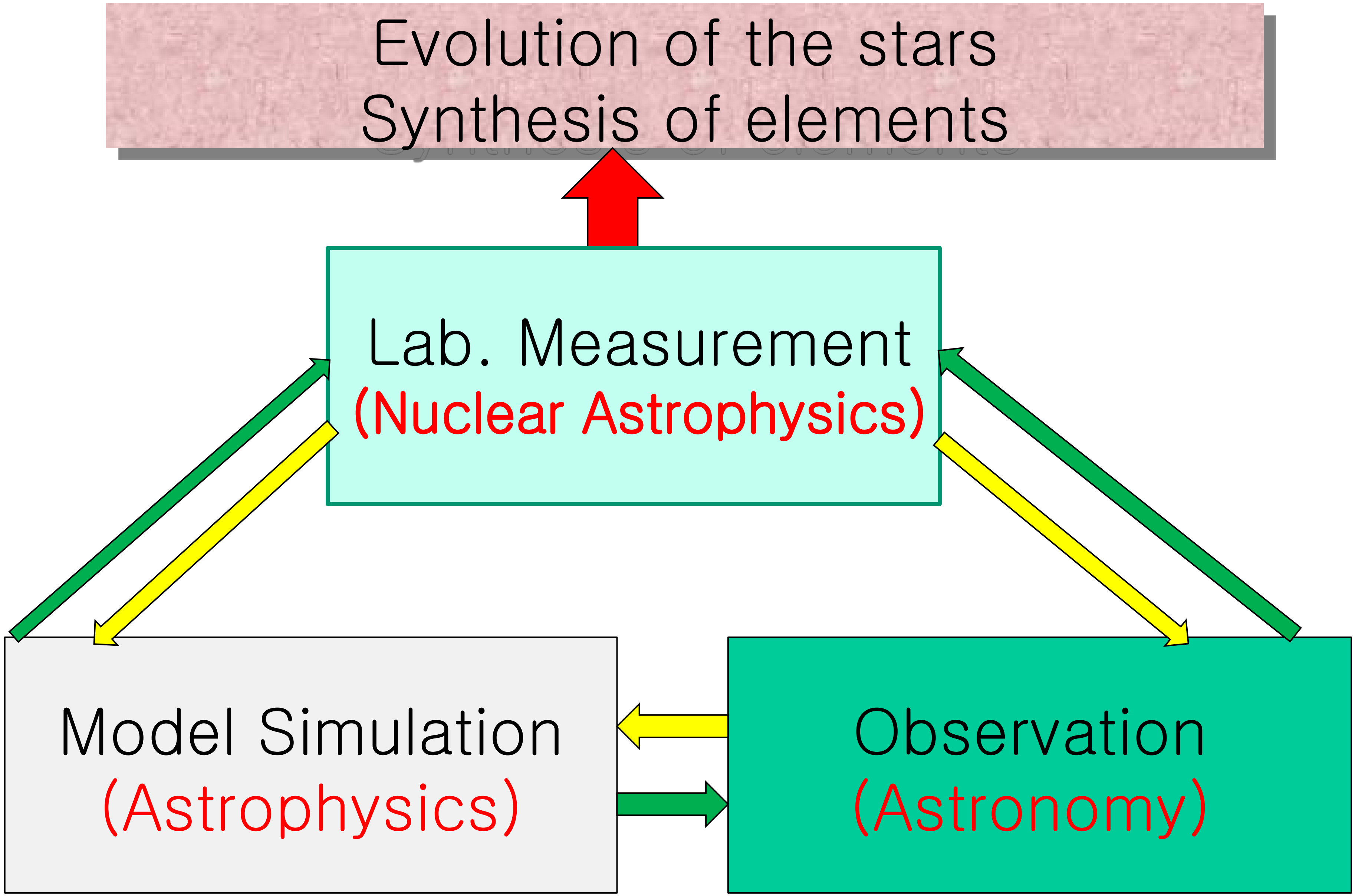




Nova Cygni



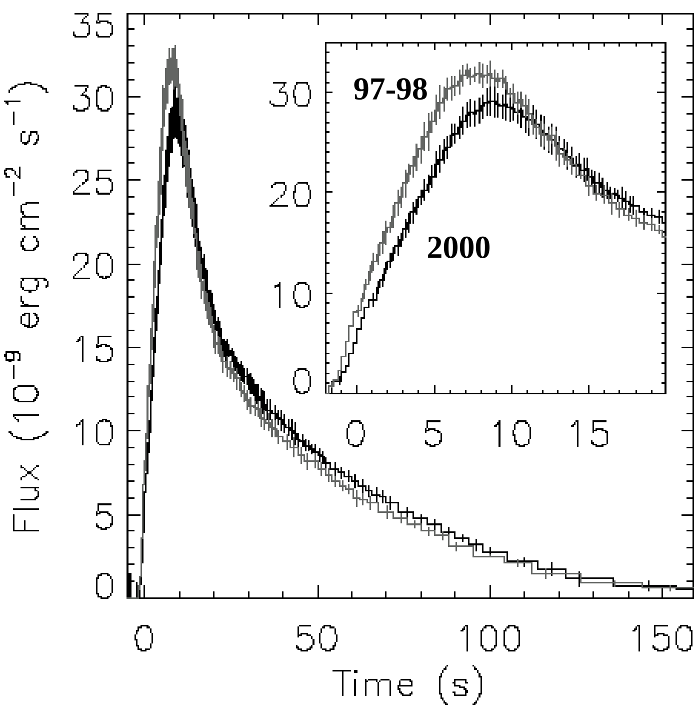
Nova Persei


Evolution of the stars
Synthesis of elements
Lab. Measurement
(Nuclear Astrophysics)
Model Simulation
(Astrophysics)
Observation
(Astronomy)

Another example: observation – model – nuclear astrophysics

Precision X-ray observations

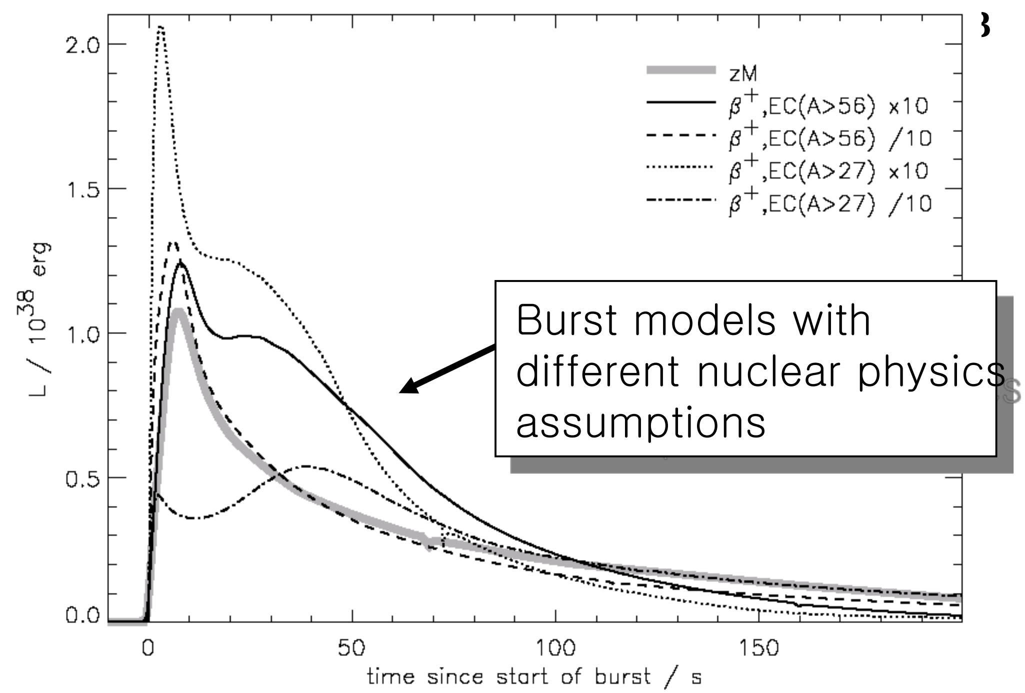
(NASA's RXTE)



→ GS 1826-24 burst shape changes !

(Galloway 2003 astro/ph 0308122)

Uncertain models due to nuclear physics



Woosley et al. 2003 astro/ph 0307425

- Need much more precise nuclear data to make full use of high quality observational data

From Schatz

The origin of galactic ^{26}Al

- Long-standing mystery in nuclear astrophysics:

  provides important clues to the chemical evolution of our galaxy

- ^{26}Al (ground state) decay:

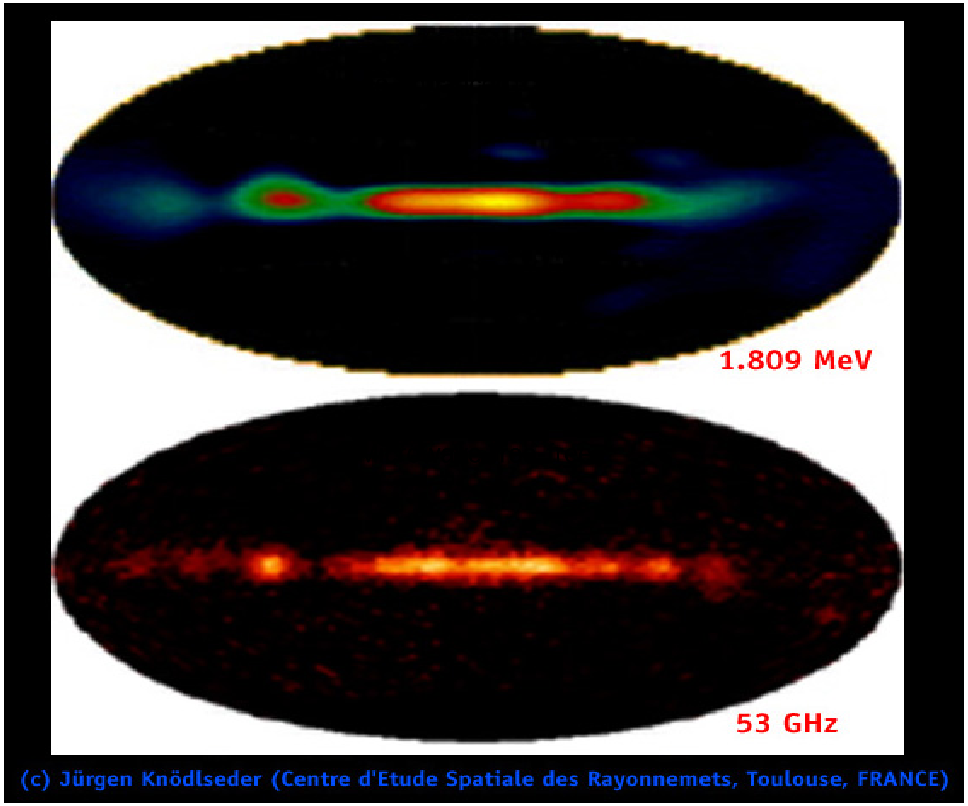
  $T_{1/2}$ = 0.7 million years

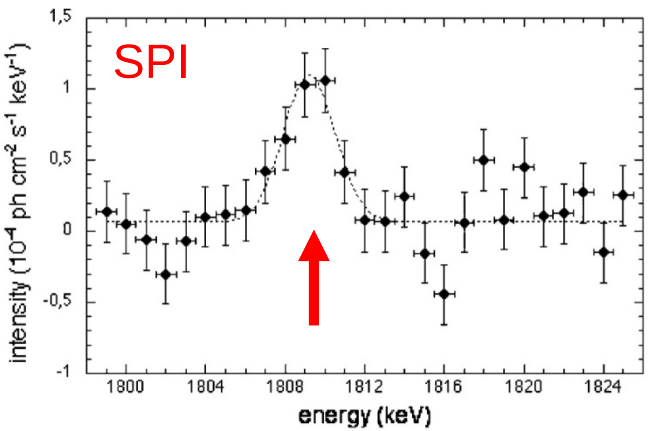
  1.809 MeV γ-ray

- Contexts: Gamma ray astronomy and presolar meteoritics

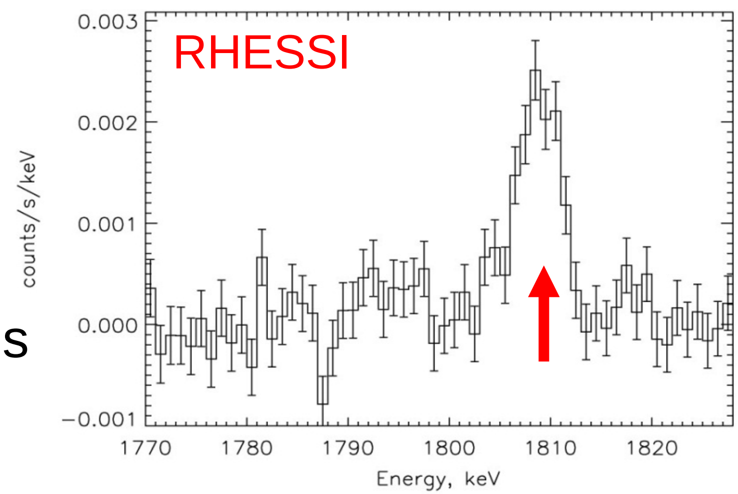
From Alan Chen @ McMaster

Galactic ^{26}Al and gamma ray astronomy





J. Knödlseder, New Ast. Rev. (2004)



D.M. Smith, Ap J Lett. (2003)

- Evidence for recent stellar nucleosynthesis
- ~ 3 solar masses of ^{26}Al
- ^{26}Al / ^{27}Al ~ 10^{-7}

(R. Diehl et al., Nature 2006)

From Alan Chen @ McMaster

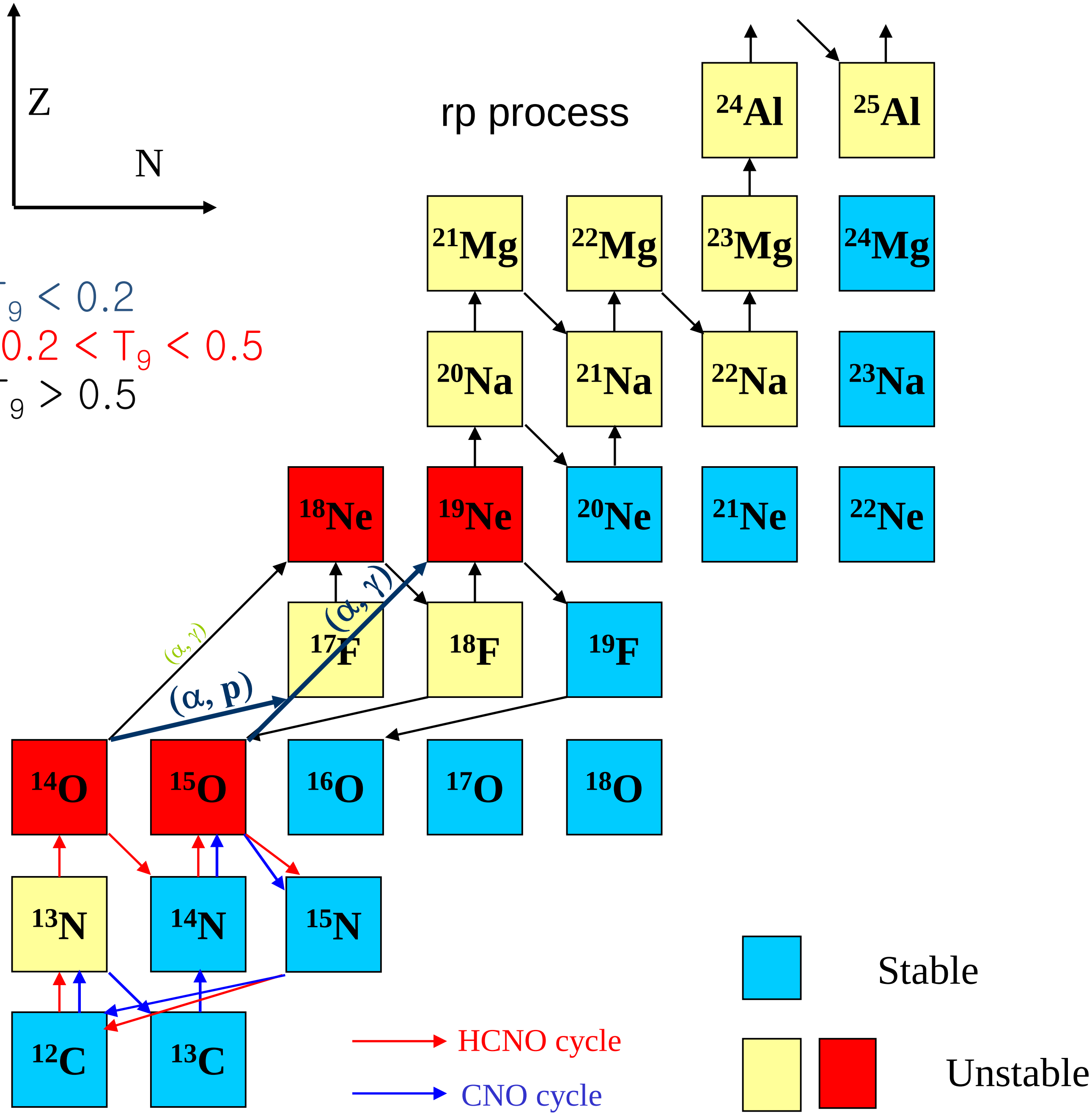
Stellar sources of galactic ^{26}Al?

- Stellar production sites?
  - Gamma ray map favors massive stars
    - Core collapse supernovae
    - Wolf-Rayet stars
  - Contributions from other sources can be significant
    - Nova explosions
    - AGB stars
- Novae: ^{26}Al production in explosive hydrogen burning
- Important reactions: $^{26}Al(p,\gamma)^{27}Si$, $^{25}Al(p,\gamma)^{26}Si$

CNO cycle : $T_9 < 0.2$

HCNO cycle: $0.2 < T_9 < 0.5$

rp process : $T_9 > 0.5$



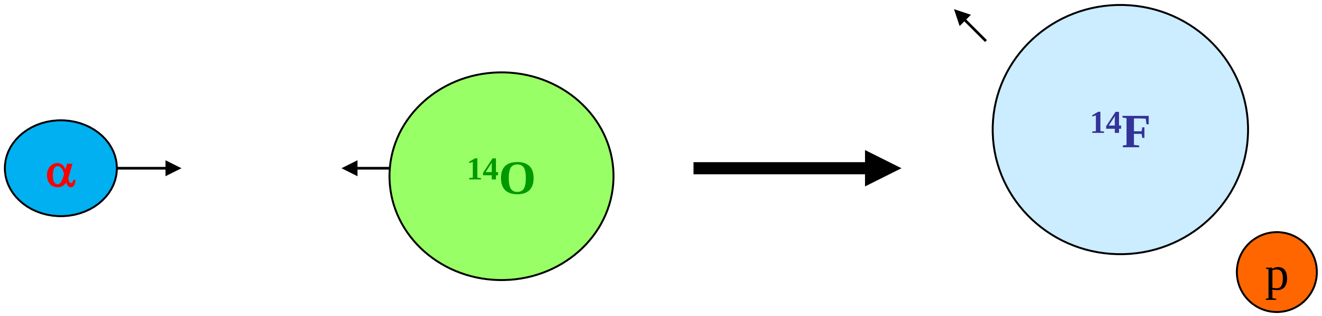
Studies on ^{18}Ne using stable beams and targets

- $^{19}F(p,t)^{18}Ne$
  @ Princeton, IUCF, INS(CNS)
- $^{16}O(^{3}He,n)^{18}Ne$
  @Univ. of Washington
- $^{12}C(^{12}C,^{6}He)^{18}Ne$
  @Yale Univ.

Nuclear Reactions

$$^{14}O + \alpha \ \text{->} \ ^{17}F + p$$

Notation



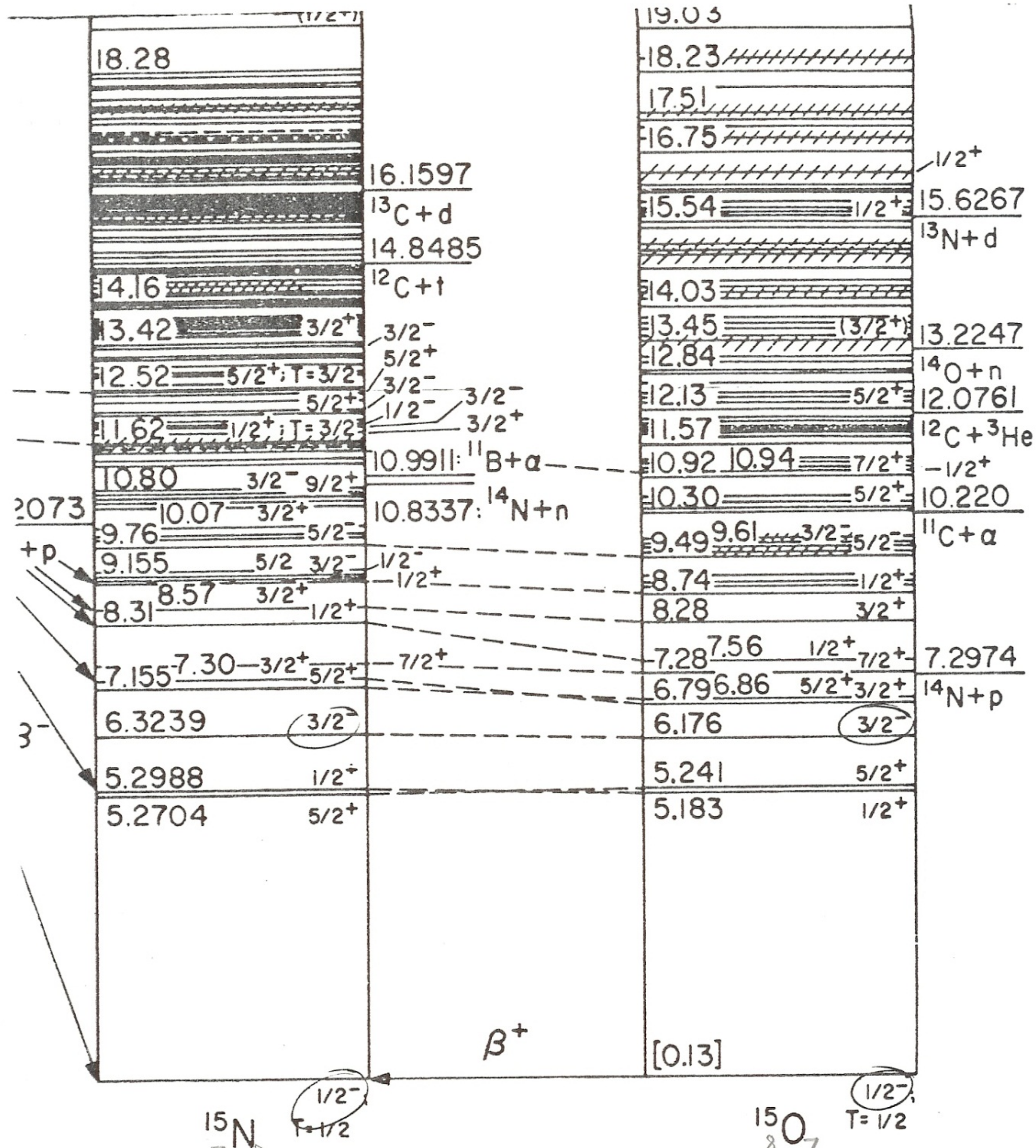
$$^{14}O(\alpha,p)^{17}F$$

The heavier “target” nucleus (Lab: target)

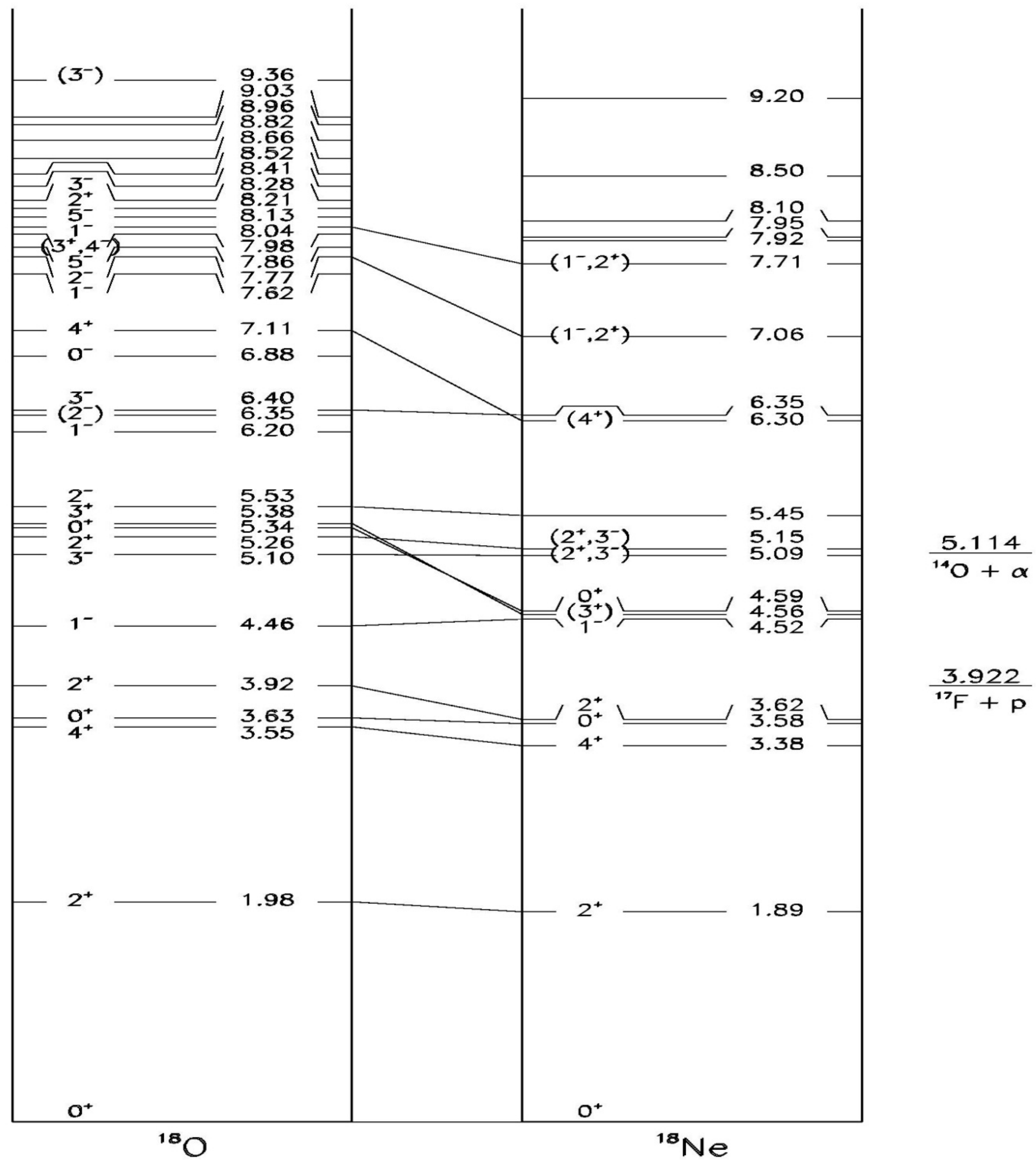
the lighter “incoming projectile” (Lab: beam)

the lighter “outgoing particle” (Lab: residual of beam)

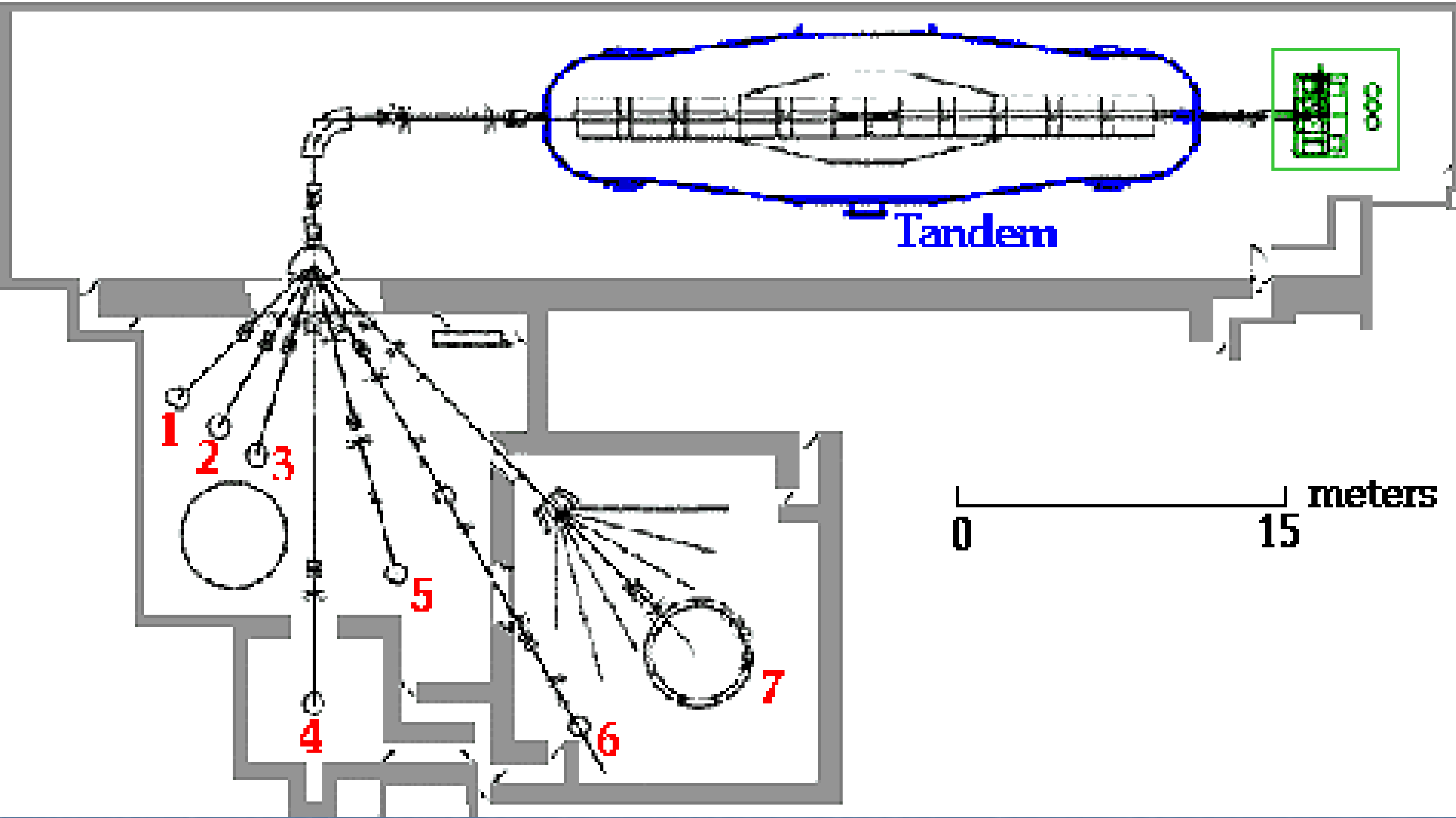
the heavier “residual” nucleus (Lab: residual of target)

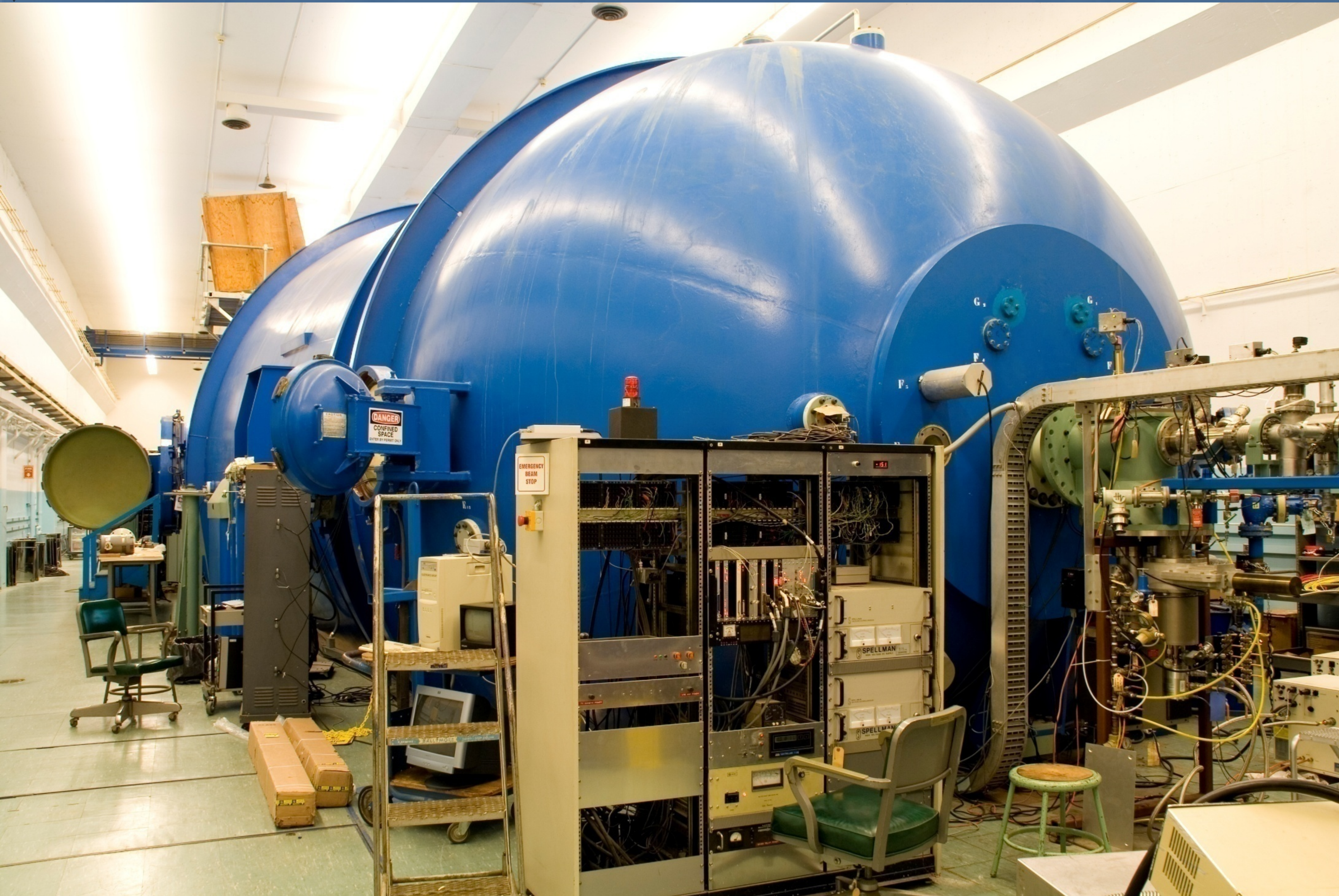


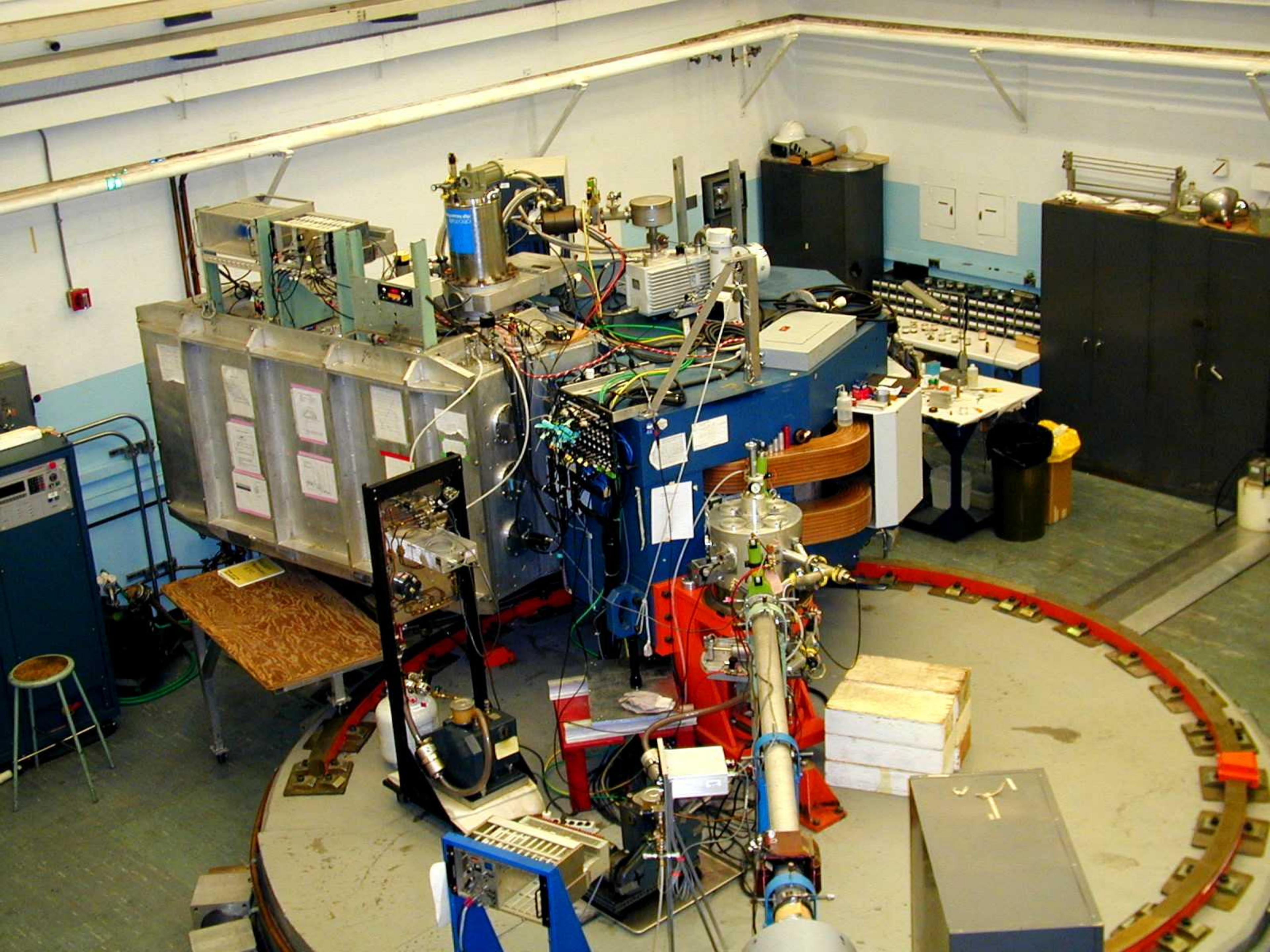
A = 15. For notation see fig. 4.



(3−) 9.36
9.03
8.96
8.82
8.66
8.52
8.41
3− 8.28
2+ 8.21
5− 8.13
1− 8.04
(3+,4−) 7.98
5− 7.86
2− 7.77
1− 7.62
4+ 7.11
0− 6.88
3− 6.40
(2−) 6.35
1− 6.20
2− 5.53
3+ 5.38
0+ 5.34
2+ 5.26
3− 5.10
1− 4.46
2+ 3.92
0+ 3.63
4+ 3.55
2+ 1.98
0+
18O
9.20
8.50
8.10
7.95
7.92
(1−,2+) 7.71
(1−,2+) 7.06
6.35
(4+) 6.30
5.45
(2+,3−) 5.15
(2+,3−) 5.09
0+ 4.59
(3+) 4.56
1− 4.52
2+ 3.62
0+ 3.58
4+ 3.38
2+ 1.89
0+
18Ne
5.114
14O + α
3.922
17F + p

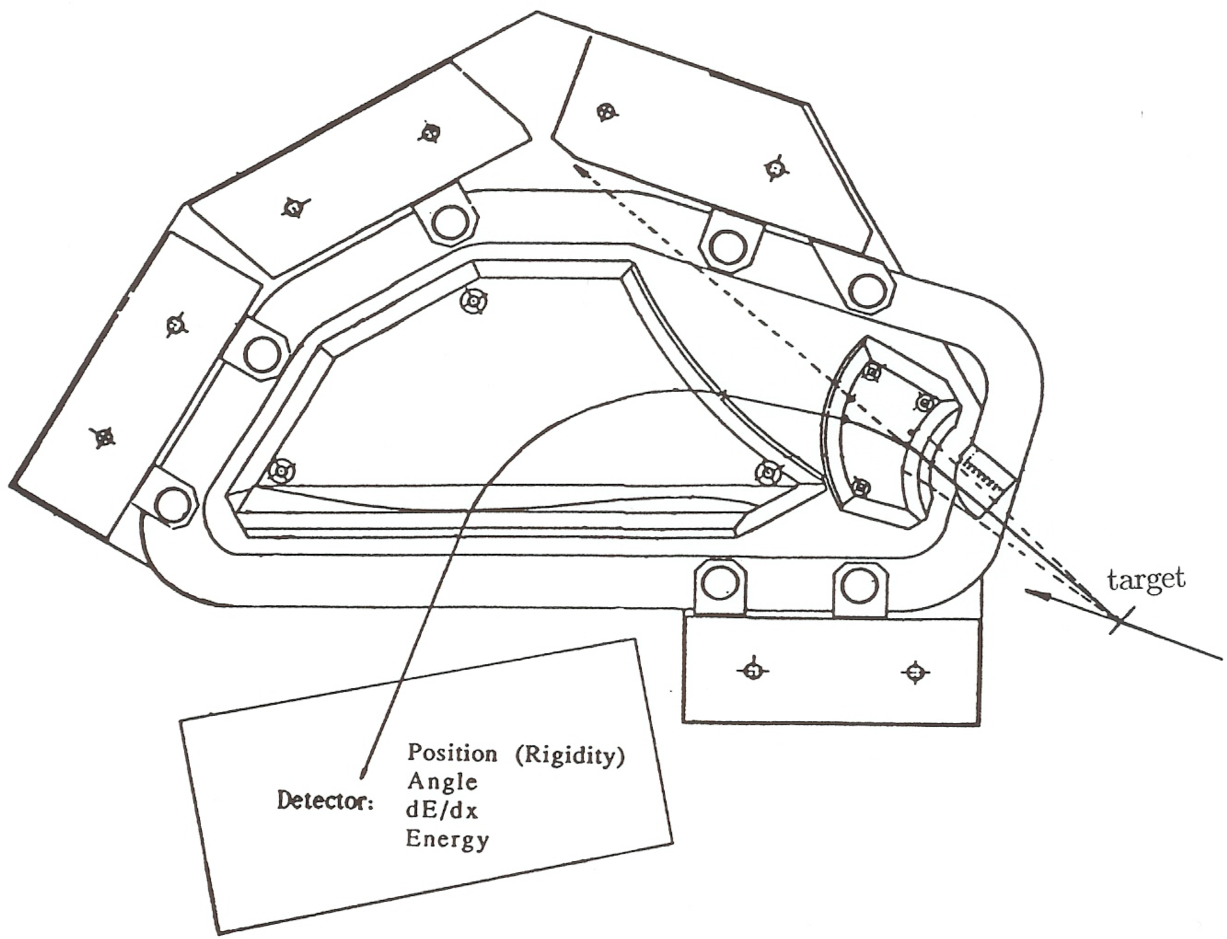

Tandem
1
2
3
4
5
6
7
0
15
meters

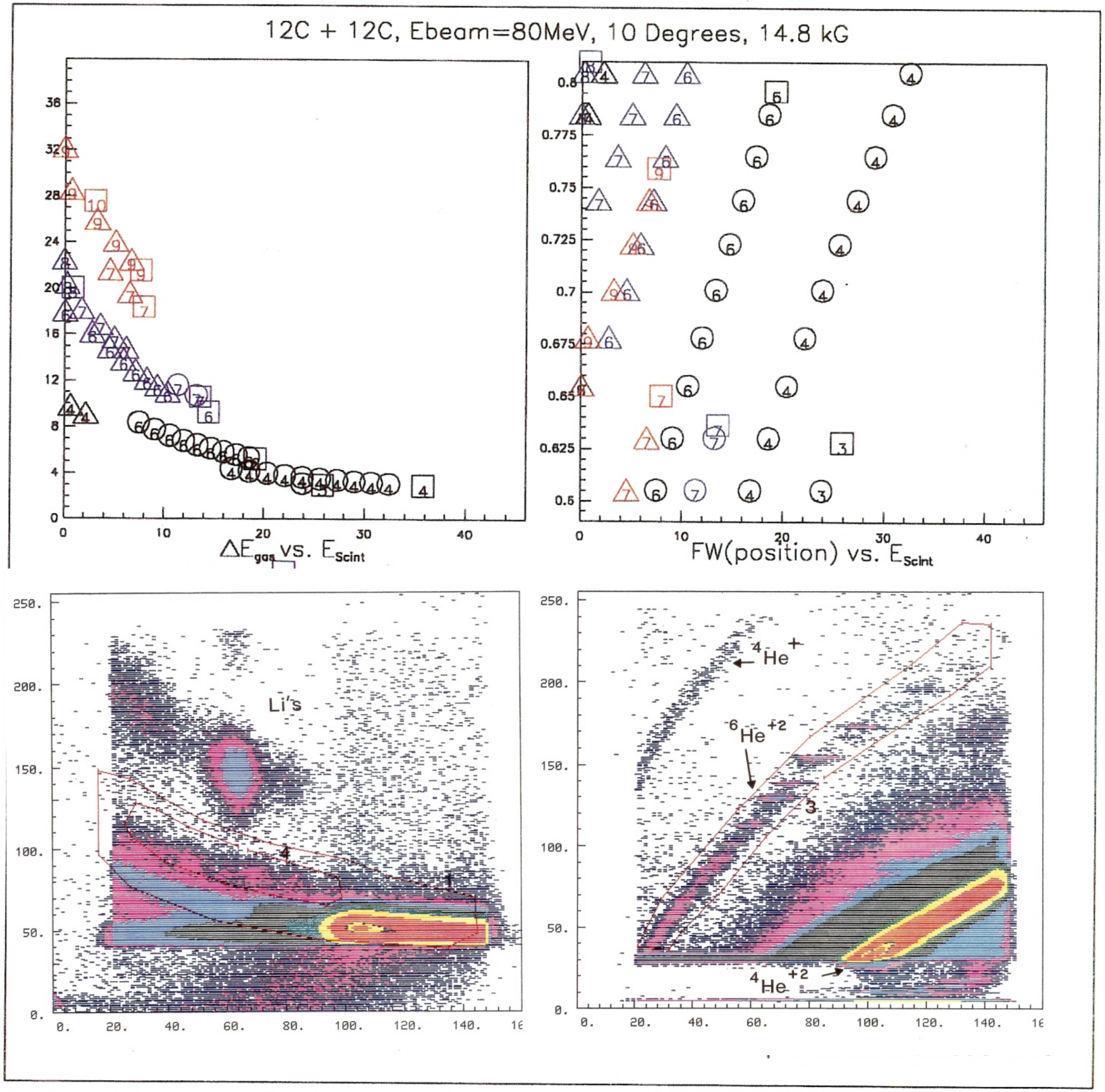

DANGER
CONFINED SPACE
EMERGENCY BEAM STOP
SPELLMAN
SPELLMAN

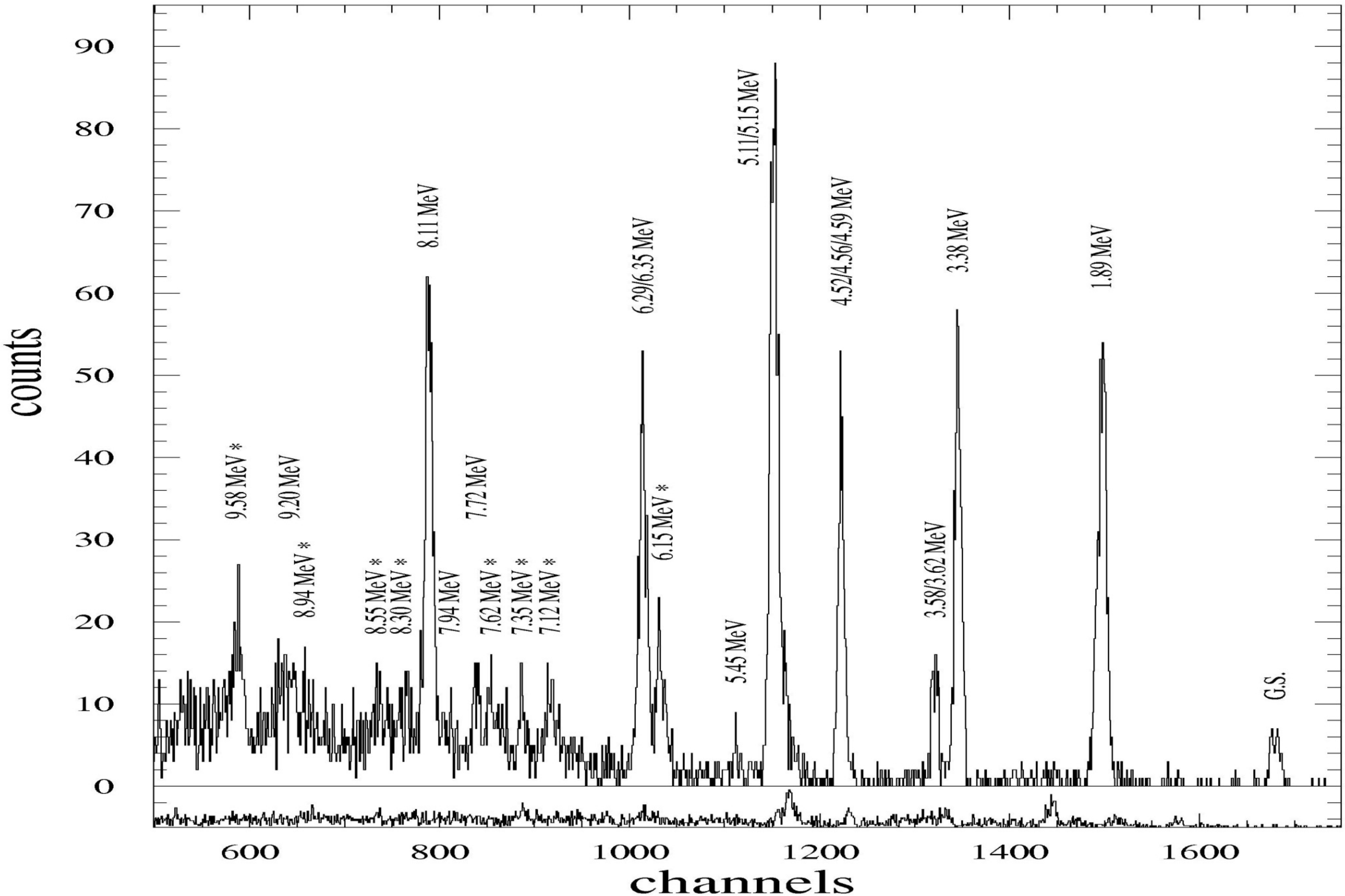


Performance Characteristics of the Yale Split-Pole Spectrograph

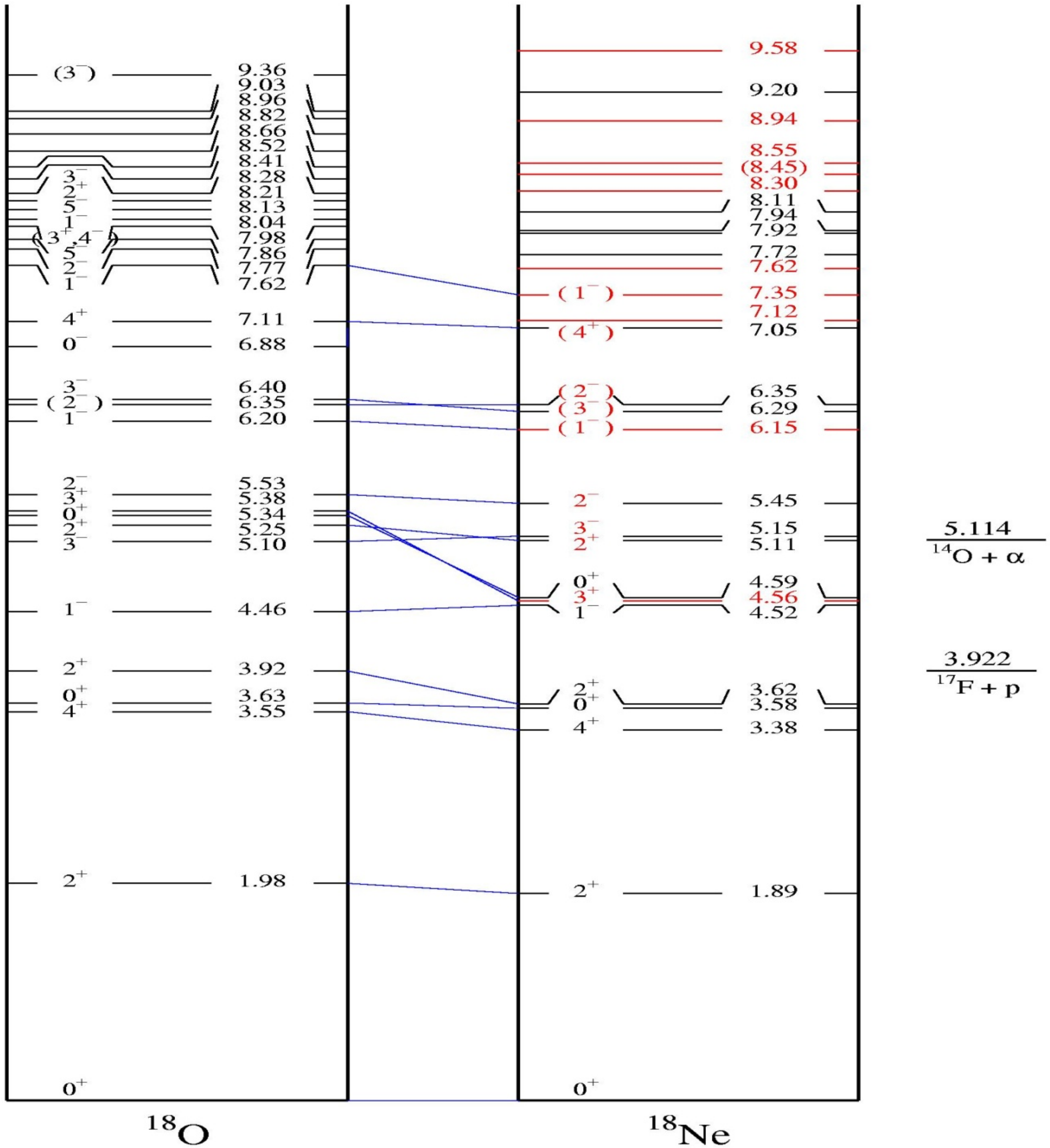
Solid Angle:	160 mrad x 80 mrad = 12.8 msr
Orbit radii at full solid angle:	51.1 cm to 92.0 cm
First order resolution for 1mm target splot:	
	$\Delta p/p = 1/4290$ for $\rho = 92$ cm
The momentum range:	$P_{max}/P_{min} = 1.80$
Maximum field strength:	B = 16.3 kG
Magnifications:	$M_x = 0.39$, $M_y = 2.9$




12C + 12C, Ebeam=80MeV, 10 Degrees, 14.8 kG
ΔE_gas vs. E_Scint
FW(position) vs. E_Scint
Li's
4He+
6He+2
4He+2



counts
channels
0
10
20
30
40
50
60
70
80
90
600
800
1000
1200
1400
1600
9.58 MeV *
9.20 MeV
8.94 MeV *
8.55 MeV *
8.30 MeV *
8.11 MeV
7.94 MeV
7.72 MeV
7.62 MeV *
7.35 MeV *
7.12 MeV *
6.29/6.35 MeV
6.15 MeV *
5.45 MeV
5.11/5.15 MeV
4.52/4.56/4.59 MeV
3.58/3.62 MeV
3.38 MeV
1.89 MeV
G.S.



(3⁻) 9.36
9.03
8.96
8.82
8.66
8.52
8.41
3⁻ 8.28
2⁺ 8.21
5⁻ 8.13
1⁻ 8.04
(3⁺,4⁻) 7.98
5⁻ 7.86
2⁻ 7.77
1⁻ 7.62
4⁺ 7.11
0⁻ 6.88
3⁻ 6.40
(2⁻) 6.35
1⁻ 6.20
2⁻ 5.53
3⁺ 5.38
0⁺ 5.34
2⁺ 5.25
3⁻ 5.10
1⁻ 4.46
2⁺ 3.92
0⁺ 3.63
4⁺ 3.55
2⁺ 1.98
0⁺
18O
9.58
9.20
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(8.45)
8.30
8.11
7.94
7.92
7.72
7.62
(1⁻) 7.35
7.12
(4⁺) 7.05
(2⁻) 6.35
(3⁻) 6.29
(1⁻) 6.15
2⁻ 5.45
3⁻ 5.15
2⁺ 5.11
0⁺ 4.59
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1⁻ 4.52
2⁺ 3.62
0⁺ 3.58
4⁺ 3.38
2⁺ 1.89
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18Ne
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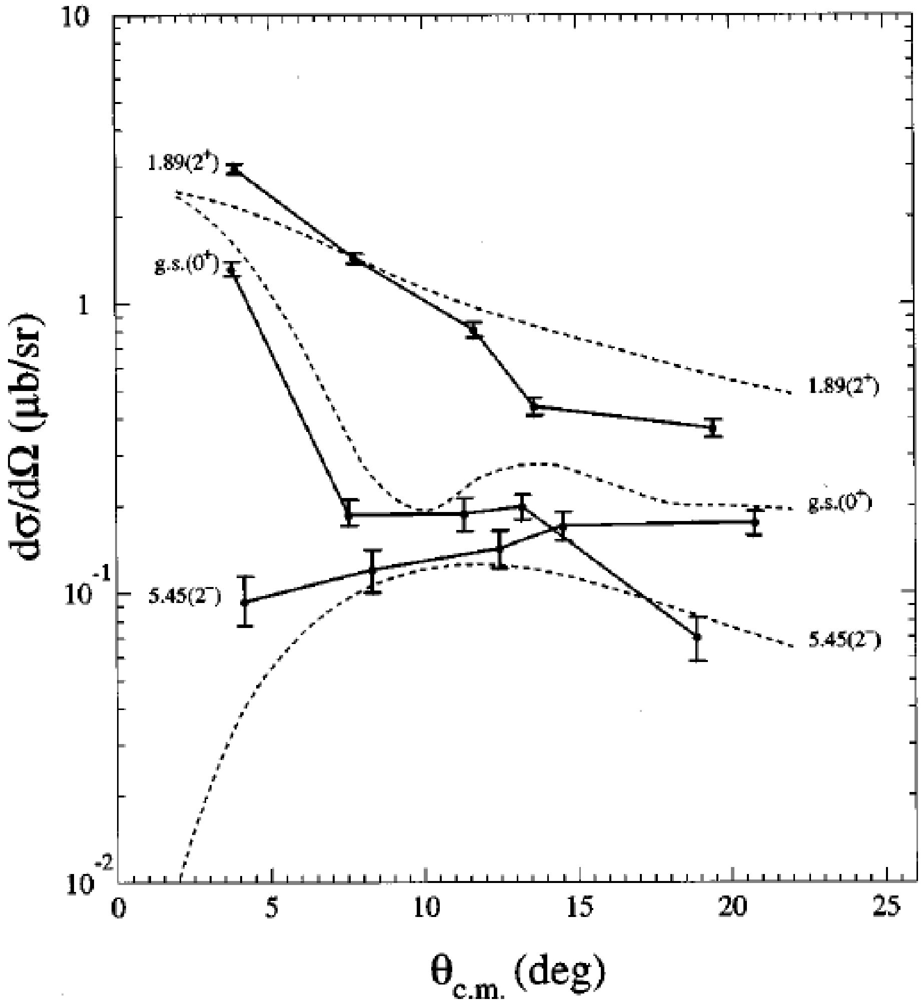

FIG. 8. Absolute Hauser-Feshbach statistical-model calculations compared to experimental angular distributions for ^{18}Ne states populated in the ^{12}C(^{12}C,^{6}He)^{18}Ne reaction at $E_{\mathrm{lab}} = 80.0$ MeV. The solid lines indicate experimental values; the dashed lines are model calculations.

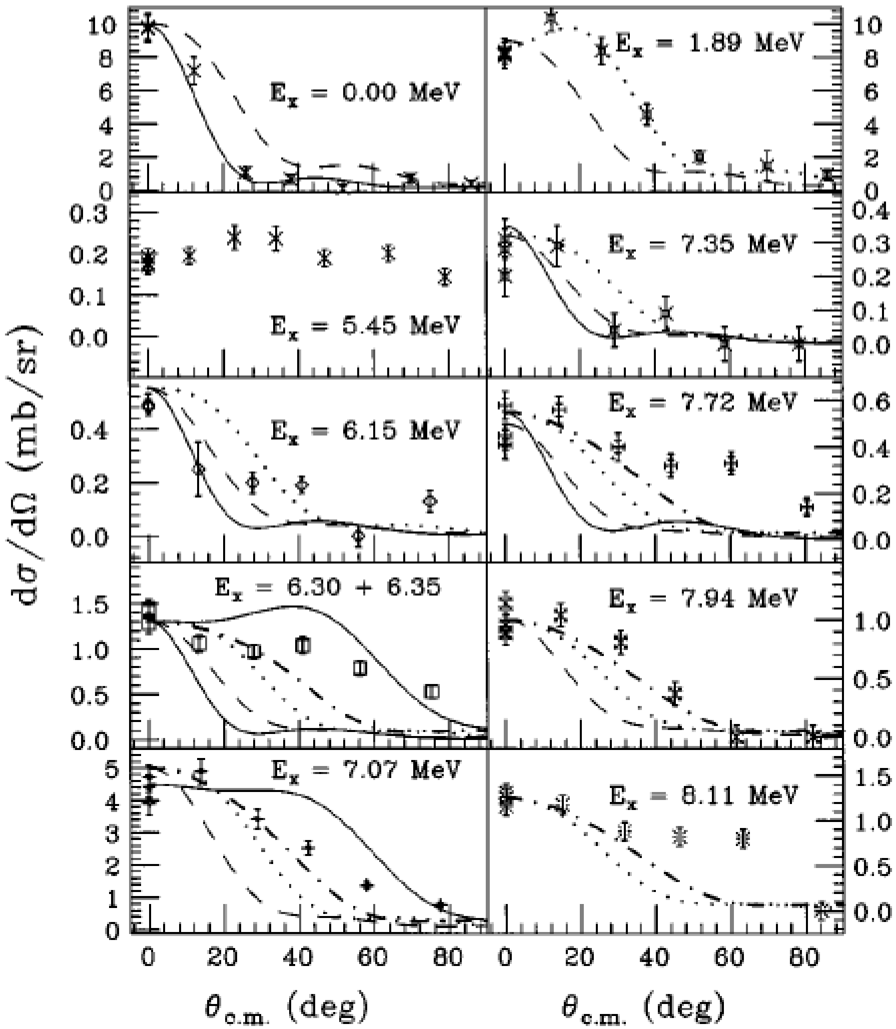

FIG. 5. $^{16}O(^{3}He,n)$ angular distributions taken at $E_{^3He}=14.5$ MeV. The lines show DWBA calculations for different values of the transferred orbital angular momentum; solid line, $L=0$; dashed line, $L=1$; dotted line, $L=2$; dot-dashed line, $L=3$; solid line, $L=4$.

Books

- C.E. Rolfs and W.S. Rodney *Cauldrons in the Cosmos*
- The University of Chicago Press, 1988 (…the “Bible”)

- D.D. Clayton *Principles of stellar evolution and nucleosynthesis*
- The University of Chicago Press, 1983

- W.D. Arnett and J.W. Truran *Nucleosynthesis*
- The University of Chicago Press, 1968

- J. Audouze and S. Vauclair *An introduction to Nuclear Astrophysics*
- D. Reidel Publishing Company, Dordrecth, 1980

- E. Böhm-Vitense *Introduction to Stellar Astrophysics, vol. 3*
- Cambridge University Press, 1992