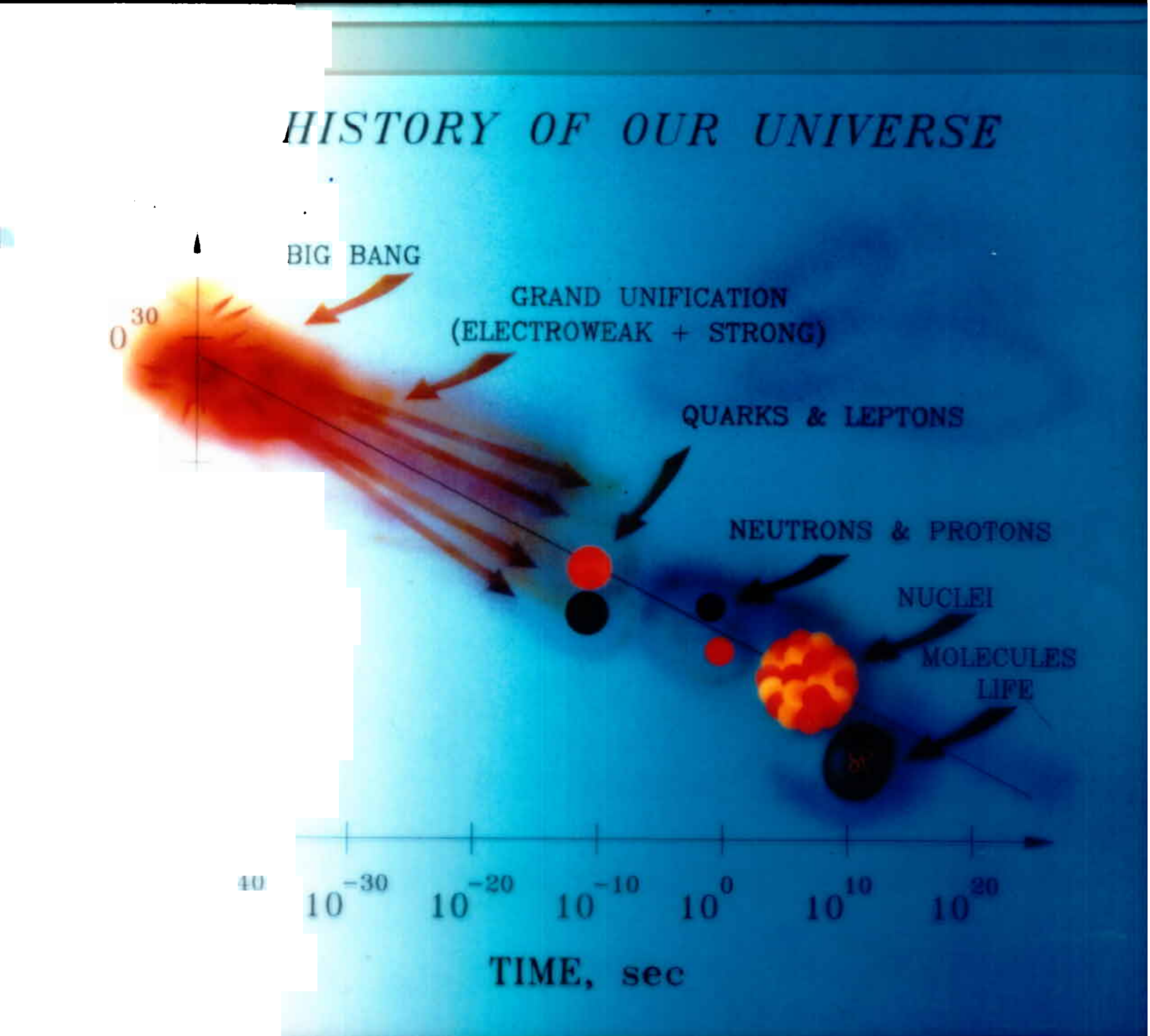
St. John's Public Lecture, The Pacific Institute of Theoretical Physics, Feb. 25, 2009

# The Evolution of Stars and the Creation of the Elements

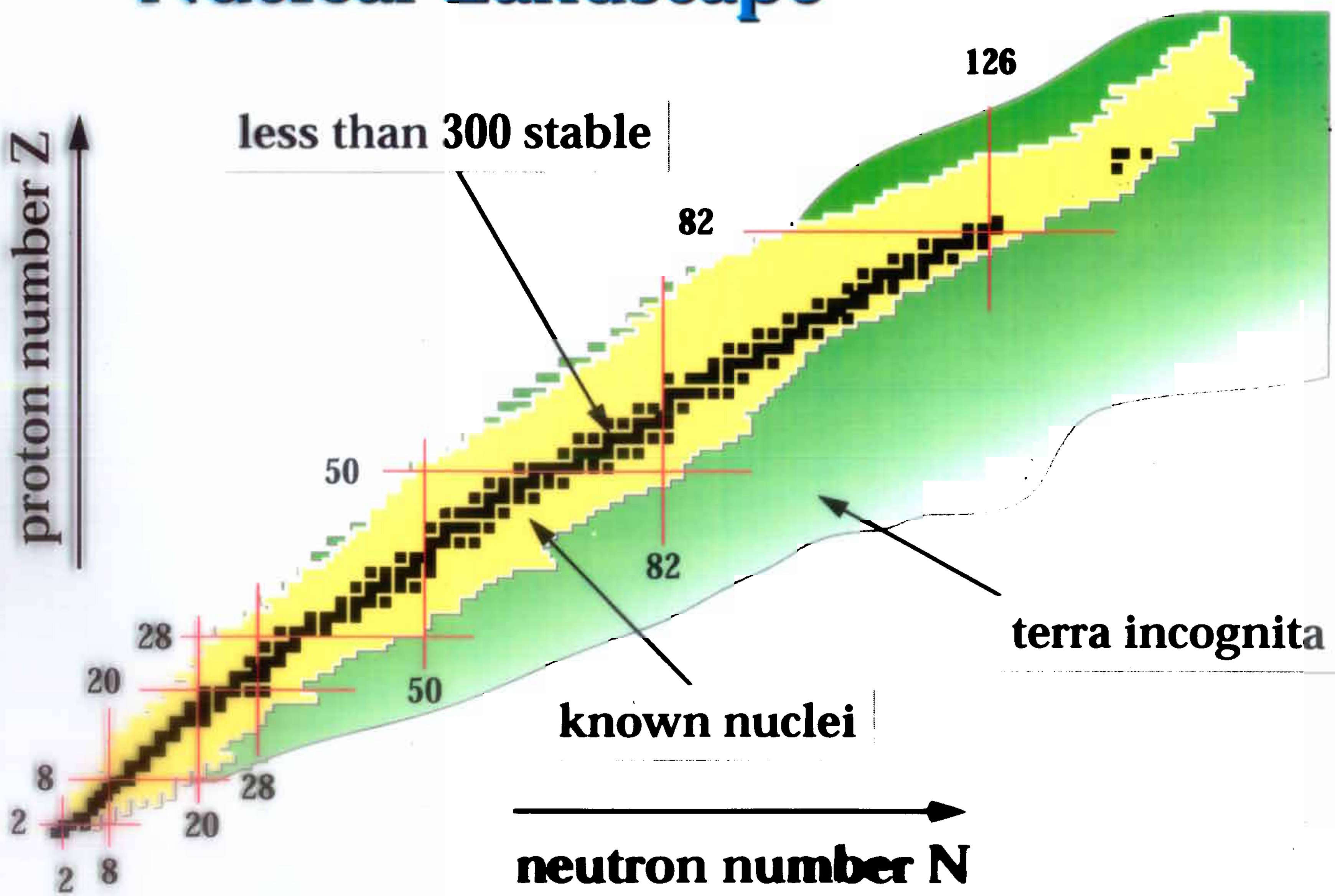
1. Introduction: The Nuclear Landscape

2. The Evolution of Stars

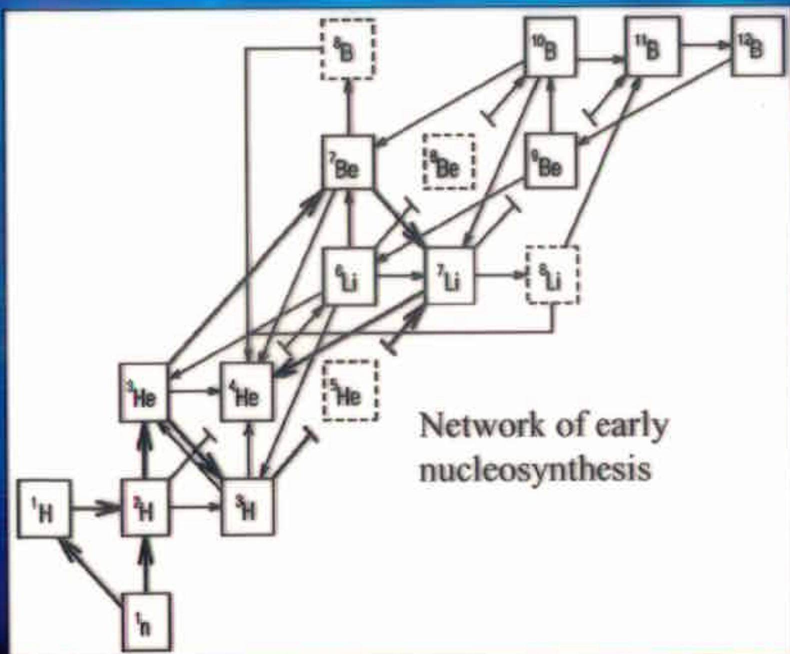
3. TRIUMF's New World-Leading Radioactive Beam Facility


HISTORY OF OUR UNIVERSE
BIG BANG
GRAND UNIFICATION
(ELECTROWEAK + STRONG)
QUARKS & LEPTONS
NEUTRONS & PROTONS
NUCLEI
MOLECULES
LIFE
$10^{-30}$ $10^{-20}$ $10^{-10}$ $10^{0}$ $10^{10}$ $10^{20}$
TIME, sec

# Nuclear Landscape



# Big Bang Nucleosynthesis




Astrophysics Theory Group – Ohio State University

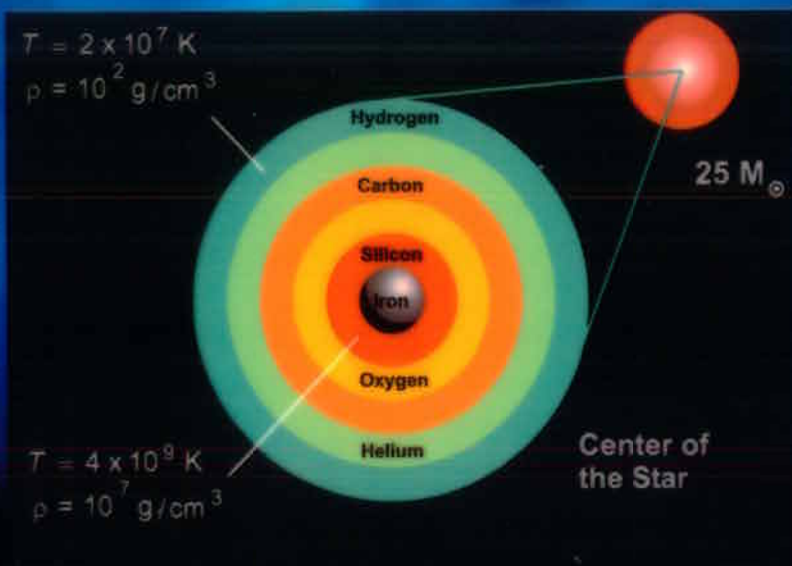
n/p ratio fixed by thermal equilibrium constraints at ~ 1/7

- n and p starting point
- Deuteron has low binding energy – so has to wait for cooler conditions to survive
- Once d formed can proton and neutron capture to $\alpha$-particles and heavier nuclei
- All neutrons decay to protons or are incorporated into $^4He$
- Reaction rates above this mass are small, so only trace amounts of Lithium etc, survive

# Stellar nucleosynthesis

- Series of burning phases occurs in which the ashes of the previous phase becomes the fuel for the next phase:
- Hydrogen burning via pp chain → Helium
- Helium burning via triple-alpha process

$$^{4}He + ^{4}He \rightarrow ^{8}Be^{*} + \gamma$$
$$^{4}He + ^{8}Be^{*} \rightarrow ^{12}C + \gamma$$

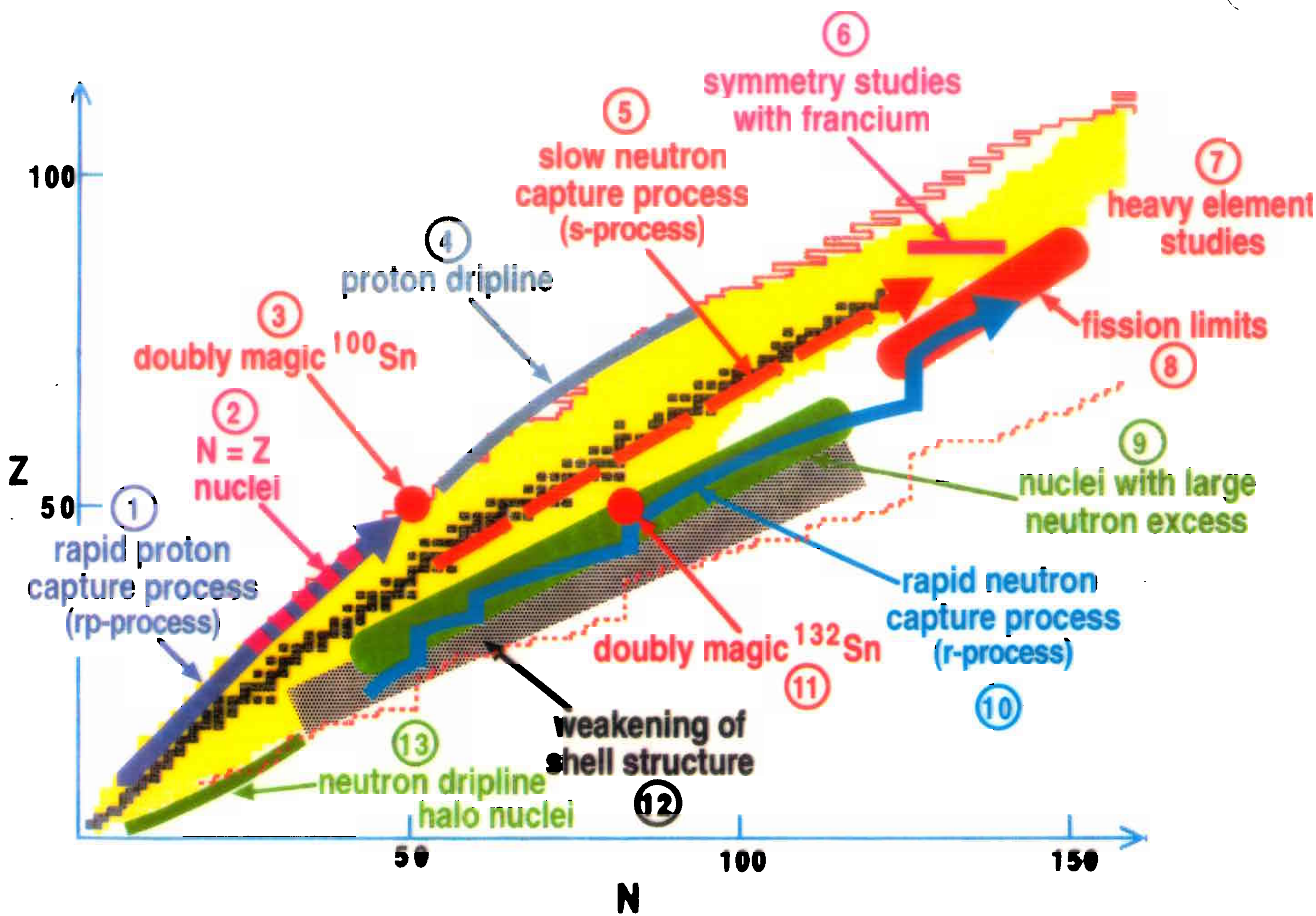


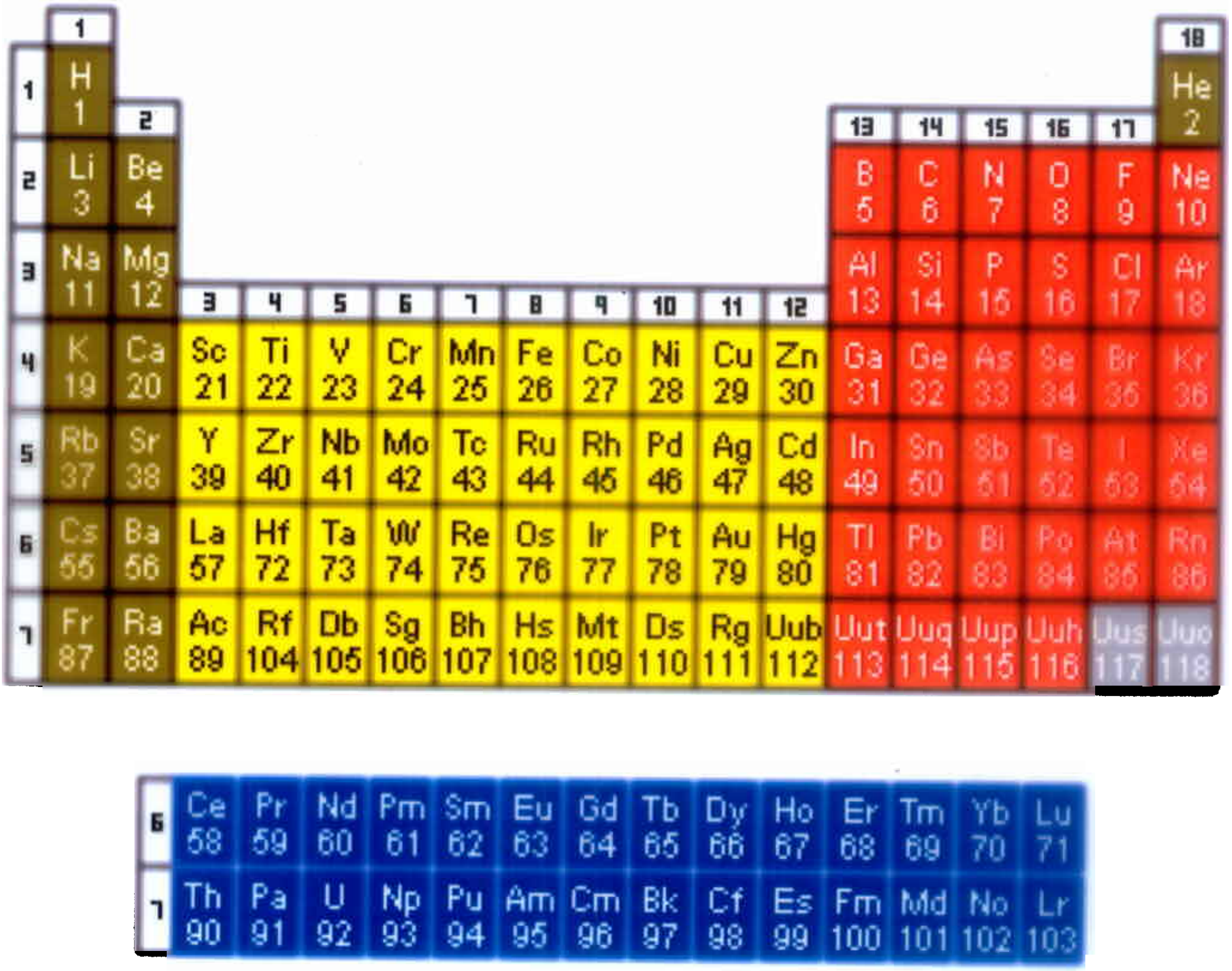
Center of 25 Solar Mass Star Late in its Life

Series of burning phases up to Iron:

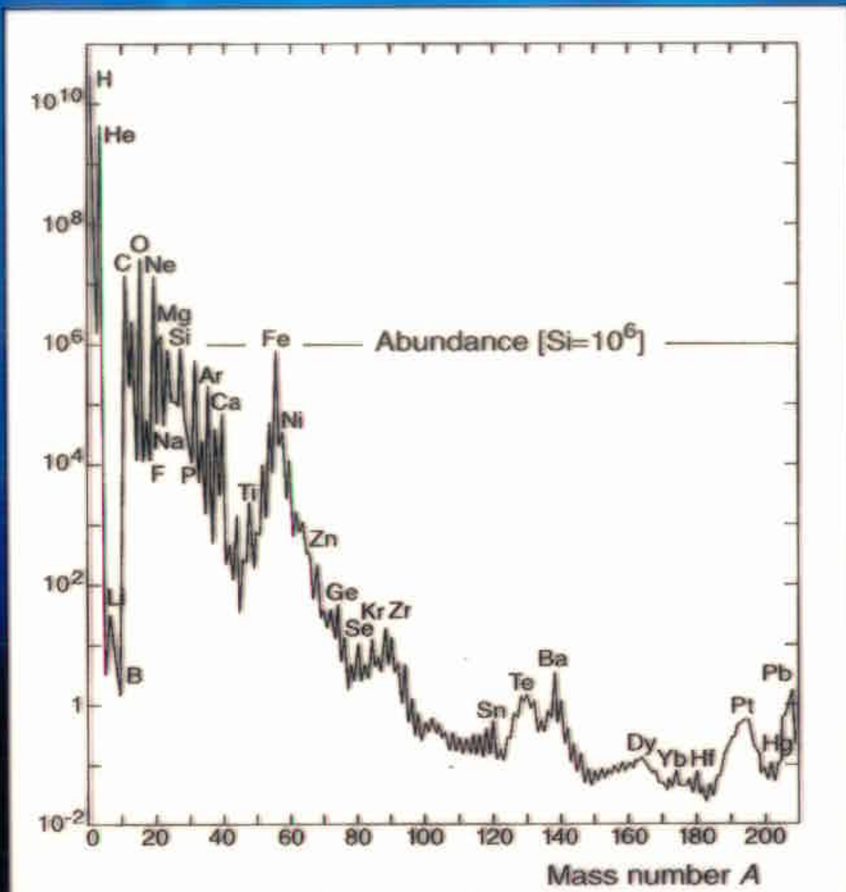
$$^{12}C + ^{4}He \rightarrow ^{16}O + \gamma$$
$$^{16}O + ^{12}C \rightarrow ^{28}Si + \gamma$$
$$^{28}Si + ^{28}Si \rightarrow ^{54}Fe + \gamma$$

Iron is the endpoint of this 'normal' nucleosynthesis since it is in close but unbridgeable proximity to $^{62}Ni$, the most tightly bound nucleus, beyond that, reactions would be endothermic.


1 rapid proton capture process (rp-process)
2 N = Z nuclei
3 doubly magic $^{100}$Sn
4 proton dripline
5 slow neutron capture process (s-process)
6 symmetry studies with francium
7 heavy element studies
8 fission limits
9 nuclei with large neutron excess
10 rapid neutron capture process (r-process)
11 doubly magic $^{132}$Sn
12 weakening of shell structure
13 neutron dripline halo nuclei
Z
100
50
N
50
100
150


1 18
1 H 1 2 He 2
13 14 15 16 17
2 Li 3 Be 4 B 5 C 6 N 7 O 8 F 9 Ne 10
3 Na 11 Mg 12 3 4 5 6 7 8 9 10 11 12 Al 13 Si 14 P 15 S 16 Cl 17 Ar 18
4 K 19 Ca 20 Sc 21 Ti 22 V 23 Cr 24 Mn 25 Fe 26 Co 27 Ni 28 Cu 29 Zn 30 Ga 31 Ge 32 As 33 Se 34 Br 35 Kr 36
5 Rb 37 Sr 38 Y 39 Zr 40 Nb 41 Mo 42 Tc 43 Ru 44 Rh 45 Pd 46 Ag 47 Cd 48 In 49 Sn 50 Sb 51 Te 52 I 53 Xe 54
6 Cs 55 Ba 56 La 57 Hf 72 Ta 73 W 74 Re 75 Os 76 Ir 77 Pt 78 Au 79 Hg 80 Tl 81 Pb 82 Bi 83 Po 84 At 85 Rn 86
7 Fr 87 Ra 88 Ac 89 Rf 104 Db 105 Sg 106 Bh 107 Hs 108 Mt 109 Ds 110 Rg 111 Uub 112 Uut 113 Uuq 114 Uup 115 Uuh 116 Uus 117 Uuo 118
6 Ce 58 Pr 59 Nd 60 Pm 61 Sm 62 Eu 63 Gd 64 Tb 65 Dy 66 Ho 67 Er 68 Tm 69 Yb 70 Lu 71
7 Th 90 Pa 91 U 92 Np 93 Pu 94 Am 95 Cm 96 Bk 97 Cf 98 Es 99 Fm 100 Md 101 No 102 Lr 103

# Nuclear Astrophysics: aims & requisites - abundances of atomic elements




- Abundances of atomic elements measured from: meteorites, solar spectra.
- Solar system considered typical.
- Aim to understand history of nucleosynthesis of this material.

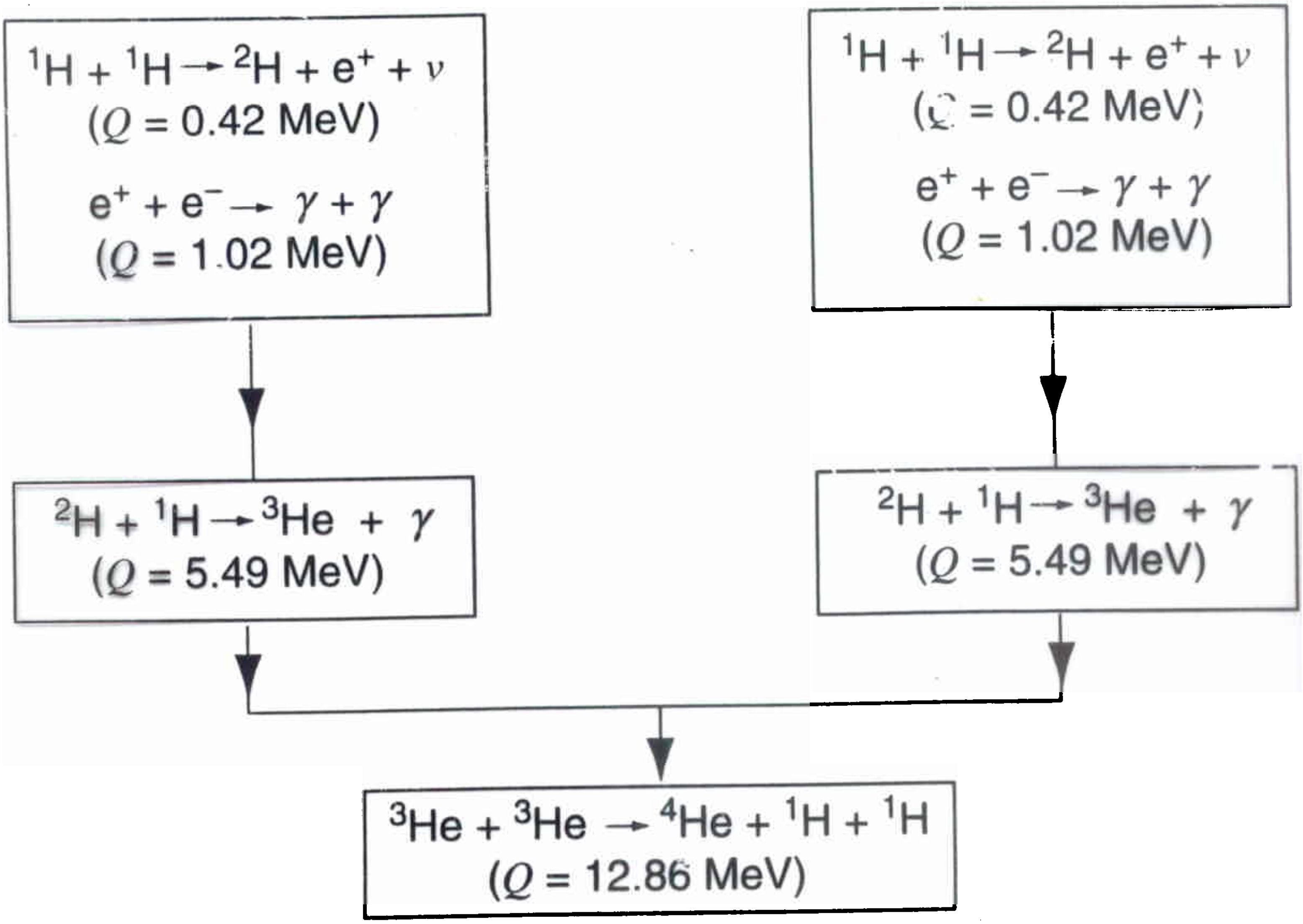
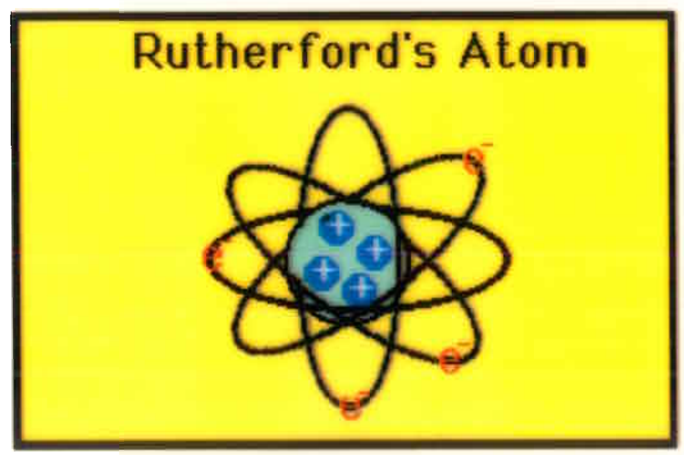



**FIGURE 51-10.** The proton–proton cycle that primarily ac-

# Ernest Rutherford (1871-1937)

- ***McGill (1898-1907)***
  - Elucidation of radioactivity
- Manchester (1907-1919)
  - The nuclear atom
- Cambridge (1919-1937)
  - The nucleus – neutrons and protons

*Rutherford at McGill*



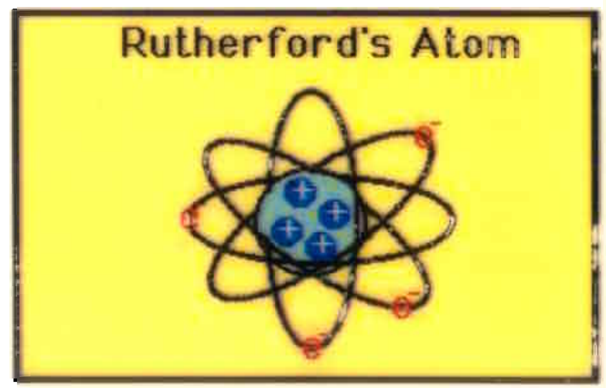
[redacted]

# Ernest Rutherford (1871-1937)

- Nobel Prize in Chemistry (1908)
- Unravelled mystery of *radioactivity* at McGill University (Montreal, 1898-1907)
  - Exponential decay law
  - Existence of *isotopes*
  - Details of uranium and thorium decay chains
  - Nature of *alpha, beta, gamma* radiation
  - Age of the earth
- With Geiger, elucidated nuclear atom (1912)
  - At Manchester, bombarded gold foils with alphas
- The neutron and nuclear physics
- Impact on Canada


[redacted]

*Rutherford at McGill*



## RADIOACTIVE DECAY

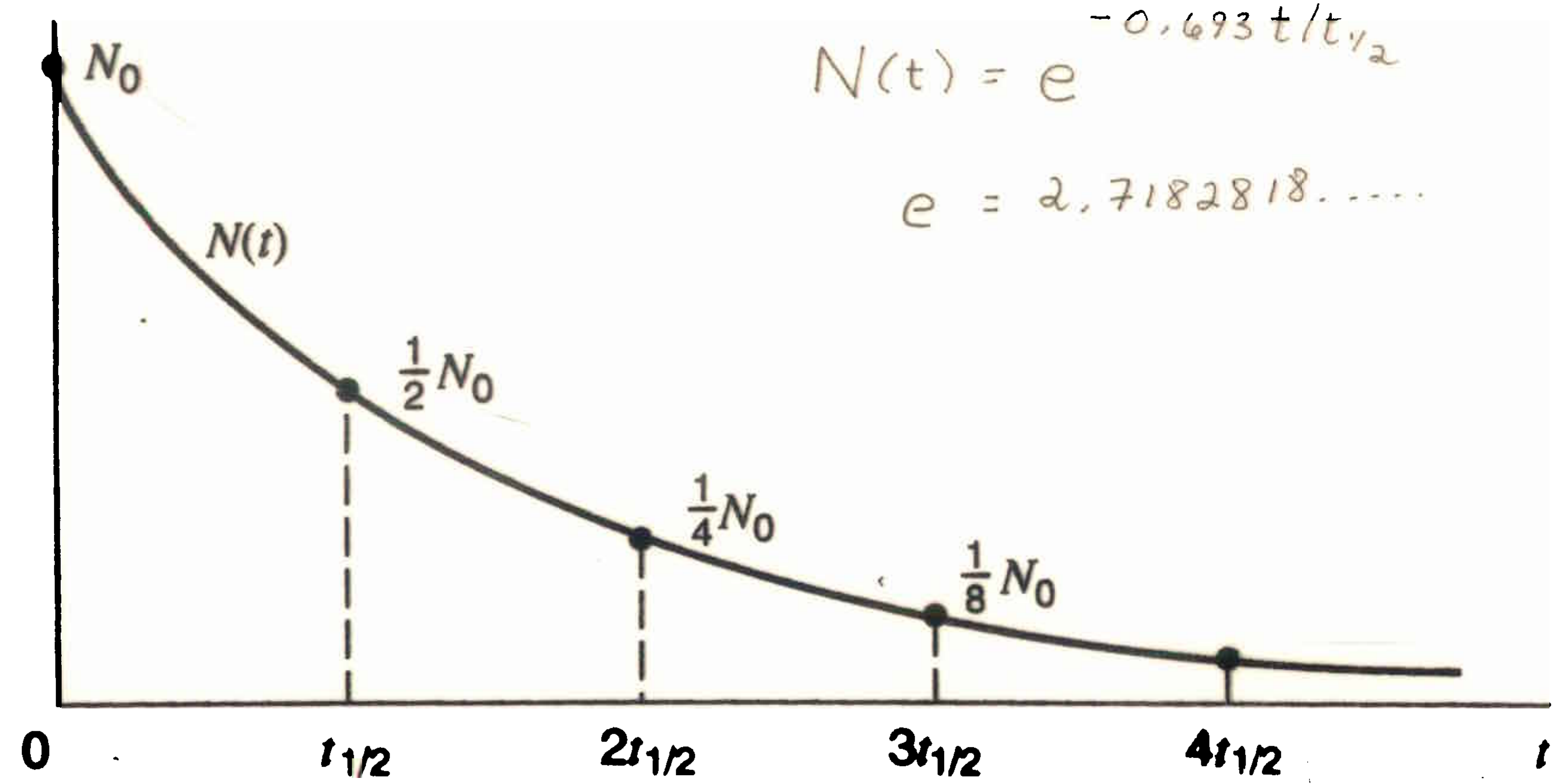
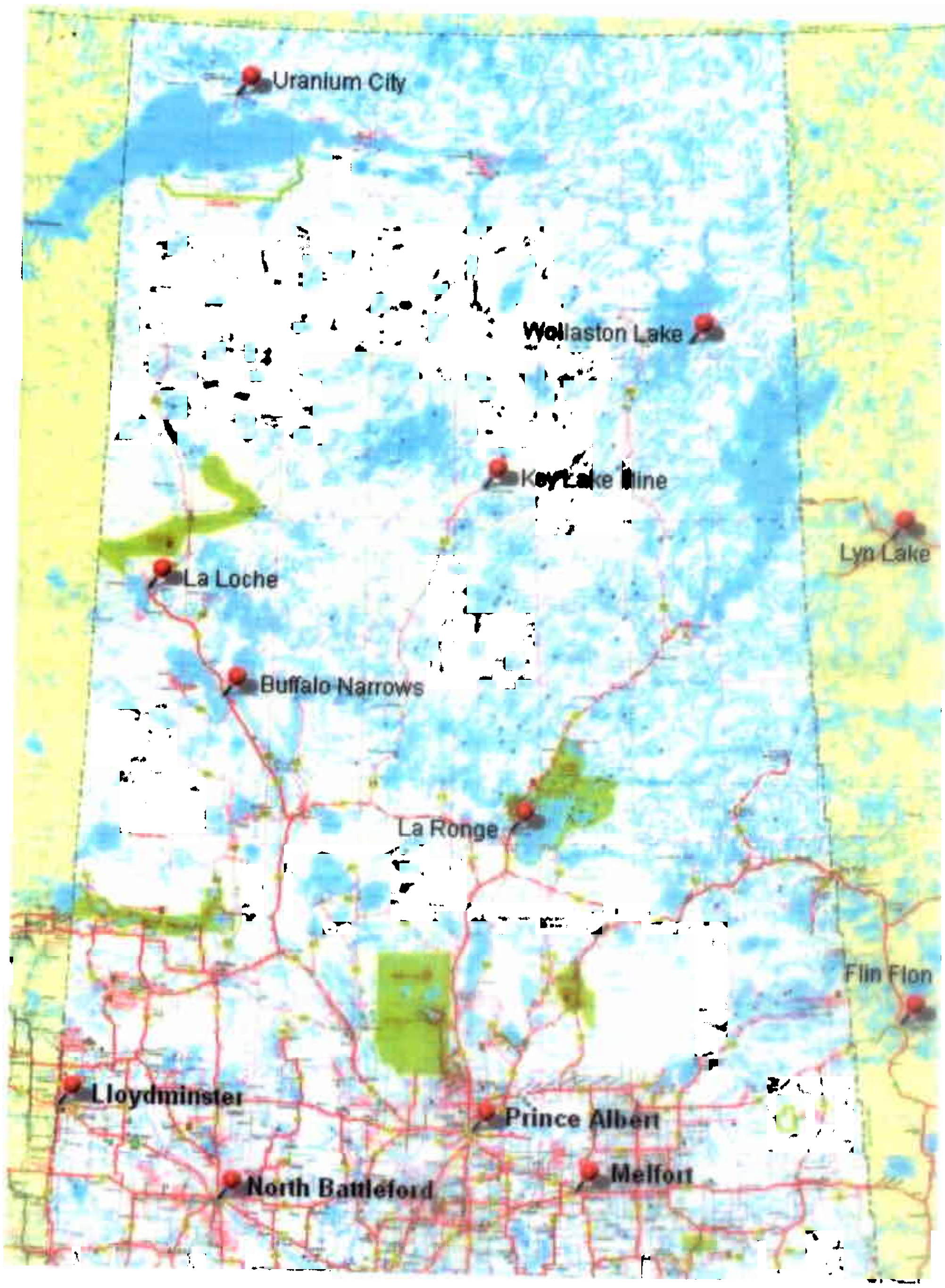



**FIGURE 50-7.** The exponential decrease in the number of radioactive nuclei and their decay rate.

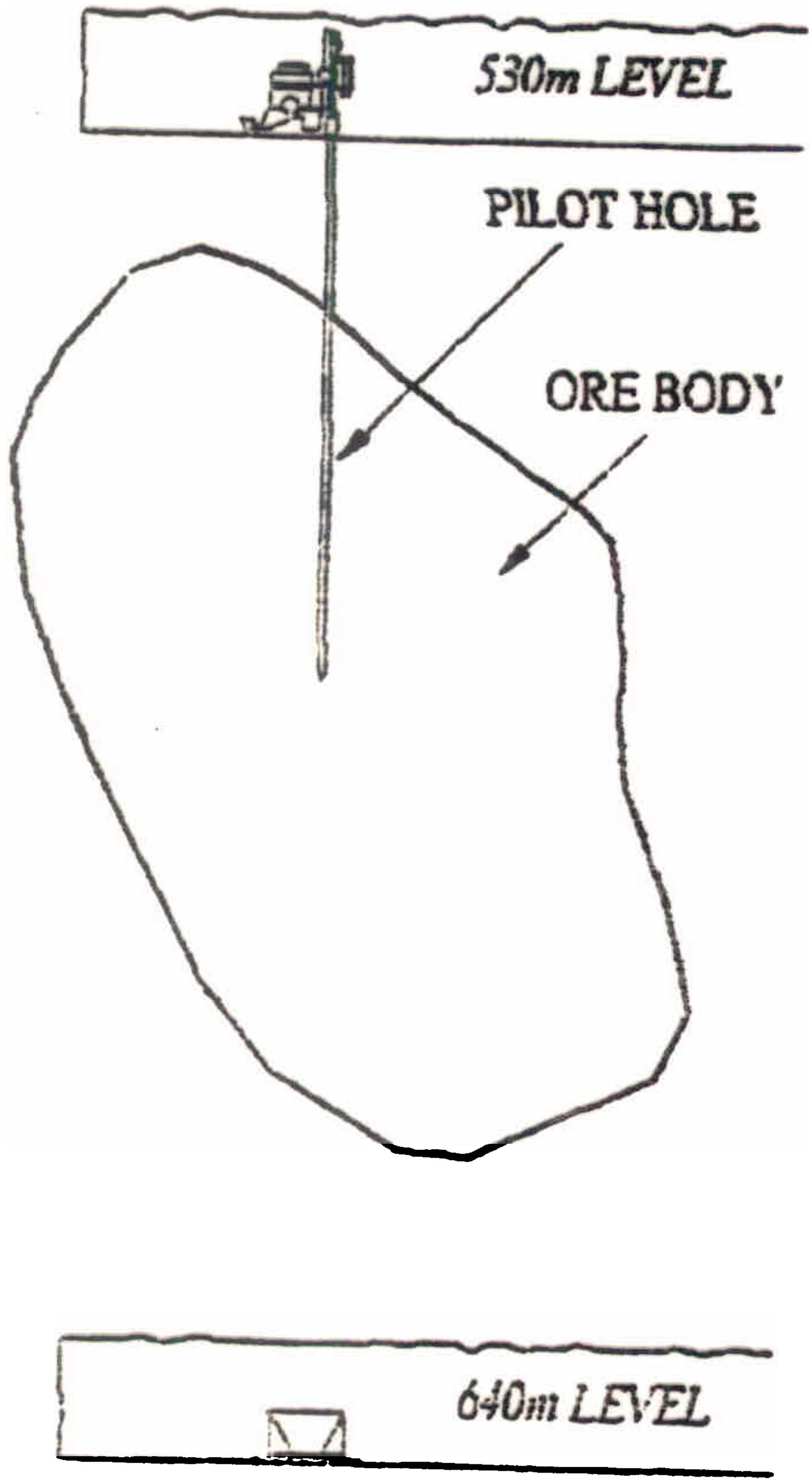
## URANIUM 238 (U238) RADIOACTIVE DECAY

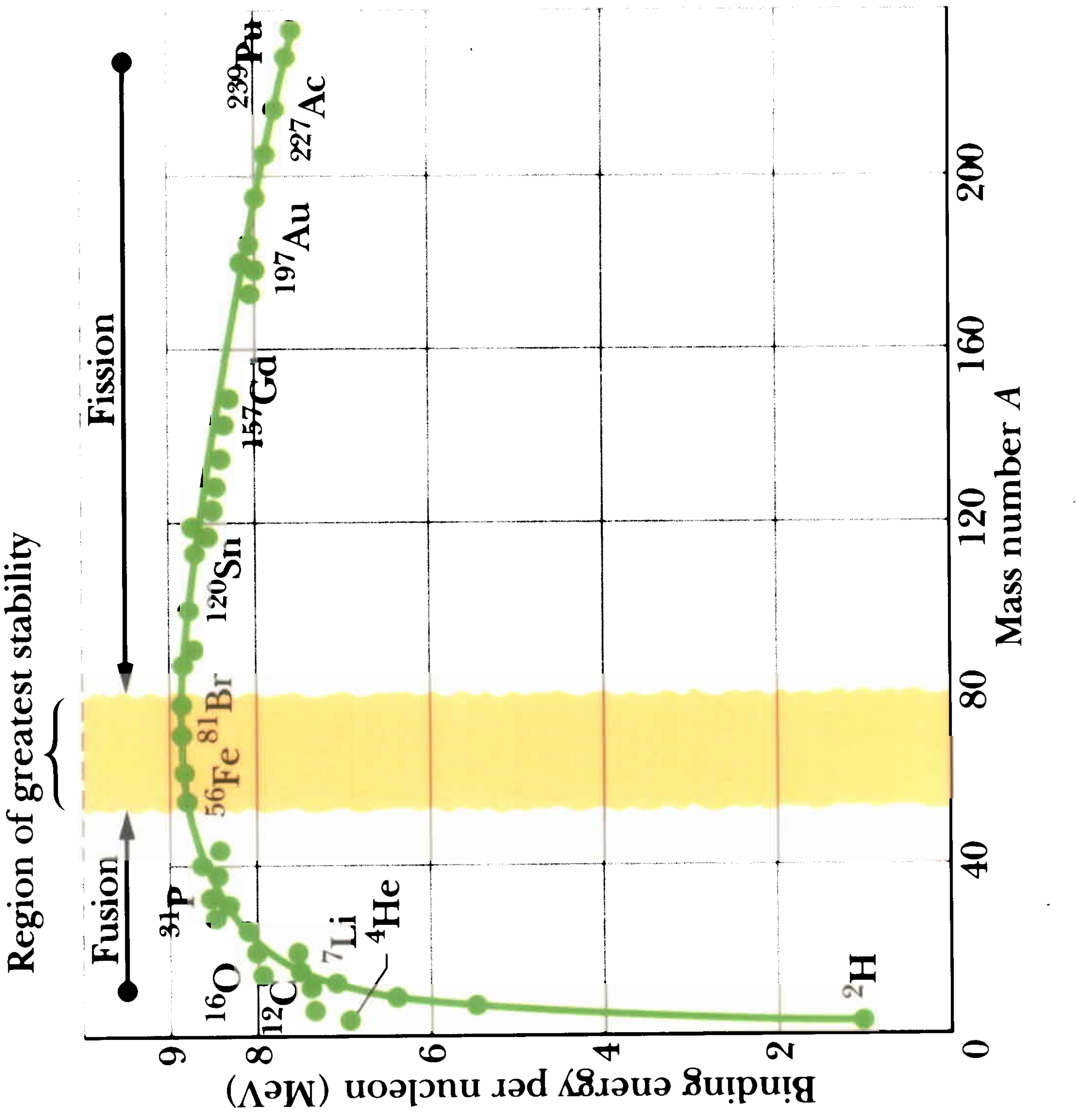
| type of radiation | nuclide | half-life |
|---|---|---|
| | uranium—238 | 4.5 x10$^{9}$ years |
| α | | |
| | thorium—234 | 24.5 days |
| β | | |
| | protactinium—234 | 1.14 minutes |
| β | | |
| | uranium—234 | 2.33 x10$^{5}$ years |
| α | | |
| | thorium—230 | 8.3 x10$^{4}$ years |
| α | | |
| | radium—226 | 1590 years |
| α | | |
| | radon—222 | 3.825 days |
| α | | |
| | polonium—218 | 3.05 minutes |
| α | | |
| | lead—214 | 26.8 minutes |
| β | | |
| | bismuth—214 | 19.7 minutes |
| β | | |
| | polonium—214 | 1.5 x10$^{-4}$ seconds |
| α | | |
| | lead—210 | 22 years |
| β | | |
| | bismuth—210 | 5 days |
| β | | |
| | polonium—210 | 140 days |
| α | | |
| | lead—206 | stable |

er Reference


Uranium City
Wollaston Lake
Key Lake Mine
Lyn Lake
La Loche
Buffalo Narrows
La Ronge
Flin Flon
Lloydminster
Prince Albert
North Battleford
Melfort

# DRILL PILOT HOLE TO 640m LEVEL





Region of greatest stability
Fusion
Fission
Binding energy per nucleon (MeV)
Mass number A
0
2
4
6
8
9
40
80
120
160
200
2H
4He
7Li
12C
16O
31P
56Fe
81Br
120Sn
157Gd
197Au
227Ac
239Pu




FIGURE 47-6

# Arthur Stanley Eddington

**"If you do not believe that the elements are created inside the hot interior of stars, I urge you to go seek a hotter place."**

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*

"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

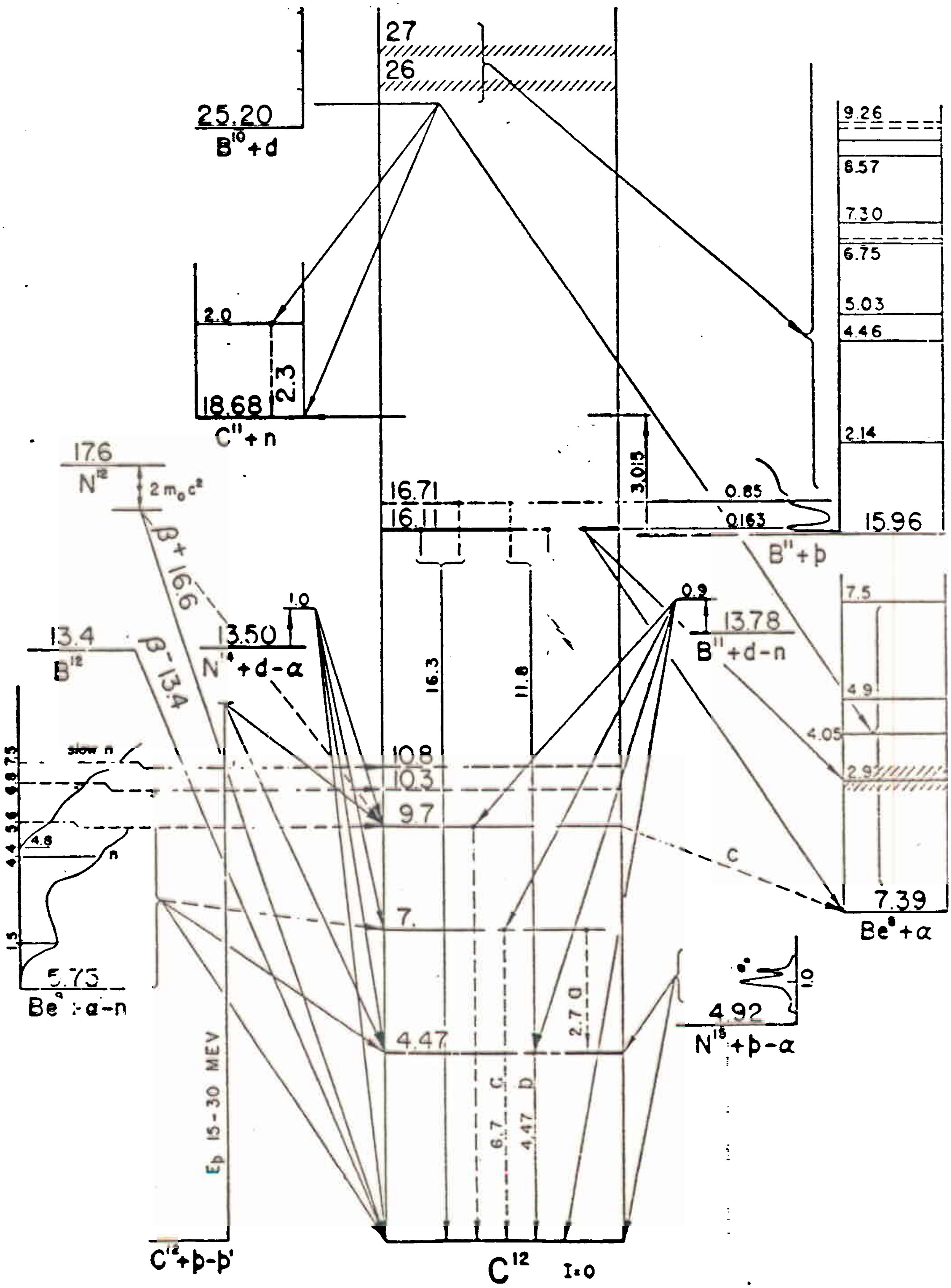
"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)

# Sir Fred Hoyle

## OSETI III Keynoter

- Chandra Wickramasinghe
- School of Maths Space Science Homepage
- Cardiff Astrophysics Blue Preprints
- Sir Fred Hoyle on Cardiff Web Site
- Books
- Chandra Wickramasinghe on this Web Site
- Cosmic Ancestry Web Site

**Sir Fred Hoyle, a world-renowned astronomer, is acknowledged to be one of the most creative scientists of the 20th century. He has held the position of Plumian Professor of Astronomy at Cambridge University, and was also the founder of the Institute of Astronomy at Cambridge. He is currently an Honorary Fellow of both Emmanuel College and St. John's College Cambridge and an Honorary Professor at Cardiff University of Wales. He is best known for his seminal contributions to the theory of the structure of stars and on the origin of the chemical elements in stars. He is a joint proponent of the Steady-State model of the Universe, and in collaboration with Chandra Wickramasinghe he has pioneered the modern theory of panspermia. Amongst the numerous awards and distinctions bestowed on him are the UN Kalinga Prize, 1968, the Royal Medal of the Royal Society and the Gold Medal of the Royal Astronomical Society. In 1997 he was awarded the highly prestigious Crafoord Prize by the the Swedish Academy in recognition of outstanding basic research in fields not covered by the Nobel prize. He is a Fellow of the Royal Society and a**



27
26
25.20
B10+d
9.26
8.57
7.30
6.75
5.03
4.46
2.0
2.3
18.68
C11+n
2.14
17.6
N12
2 m0c2
3.015
16.71
16.11
0.85
0.163
15.96
B11+p
β+ 16.6
1.0
13.50
N14+d-α
0.9
13.78
B11+d-n
7.5
13.4
B12
β- 13.4
16.3
11.8
4.9
4.05
slow n
10.8
10.3
2.9
9.7
4.8
n
c
7.
7.39
Be8+α
1.5
5.75
Be9+α-n
2.7 a
4.92
N15+p-α
1.0
4.47
Ep 15-30 MEV
6.7
4.47
C
D
C12+p-p'
C12
I=0

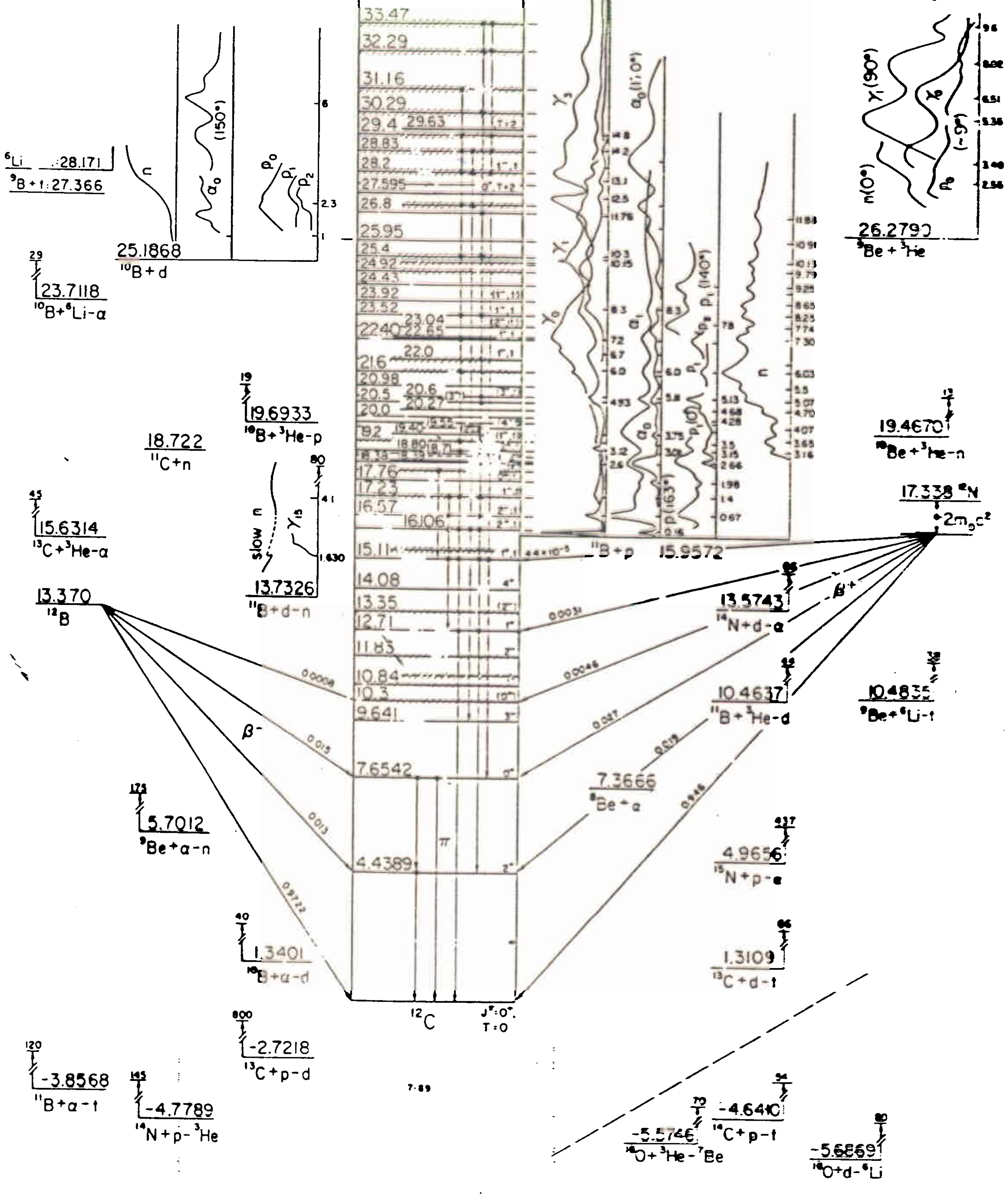
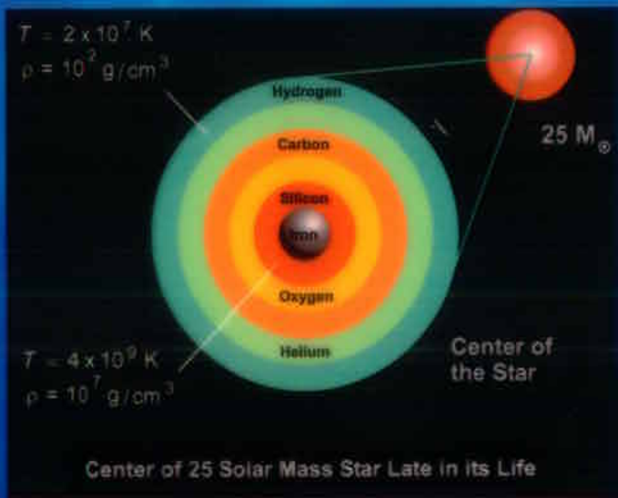


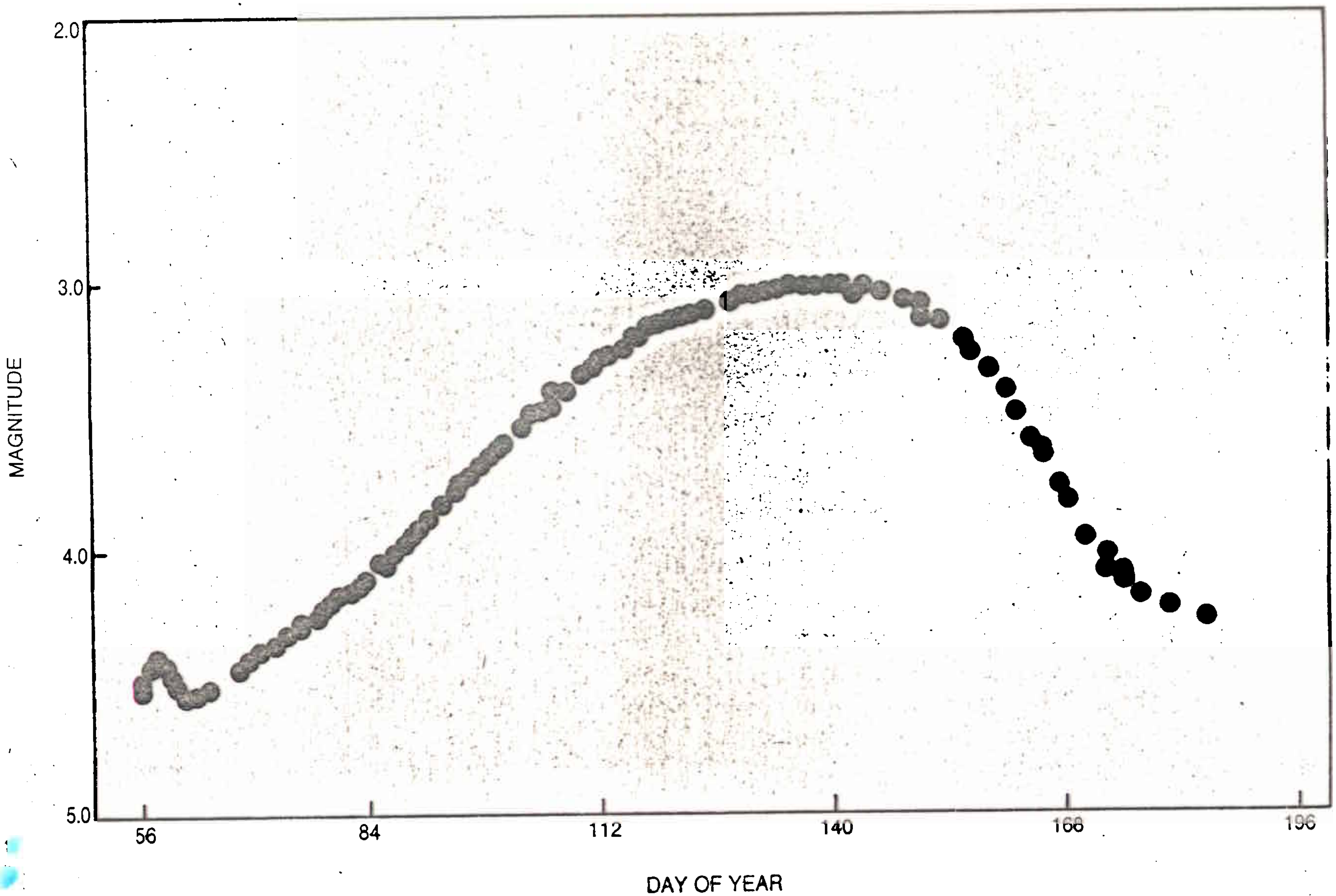
Fig. 7. Energy levels of $^{12}$C: for notation see fig. 2.

*Electromagnetic transitions*: (Ci 84a, Er 84b, Lo 84d, Mo 84d, Va 84, Ar 85b, Ca 85i, Gr 85f, An 86d, Ch 86o, Ke 86c, Sa 86ll, Vo 86i, Ca 87d, Er 87d, Ra 87, St 87d, Va 89b)

# Supernovae (Type II)




- High mass young star evolves 'onion skin' layers of ashes from nuclear burning.
- Fe endpoint.
- Photodisintegration reactions occur – energy lost through neutrinos – compensated by gravitational collapse.
- Core collapses until becomes neutron degenerate.
- Falling matter bounces off solid neutron core, producing shock front which initiates high temperatures and explodes entire envelope.



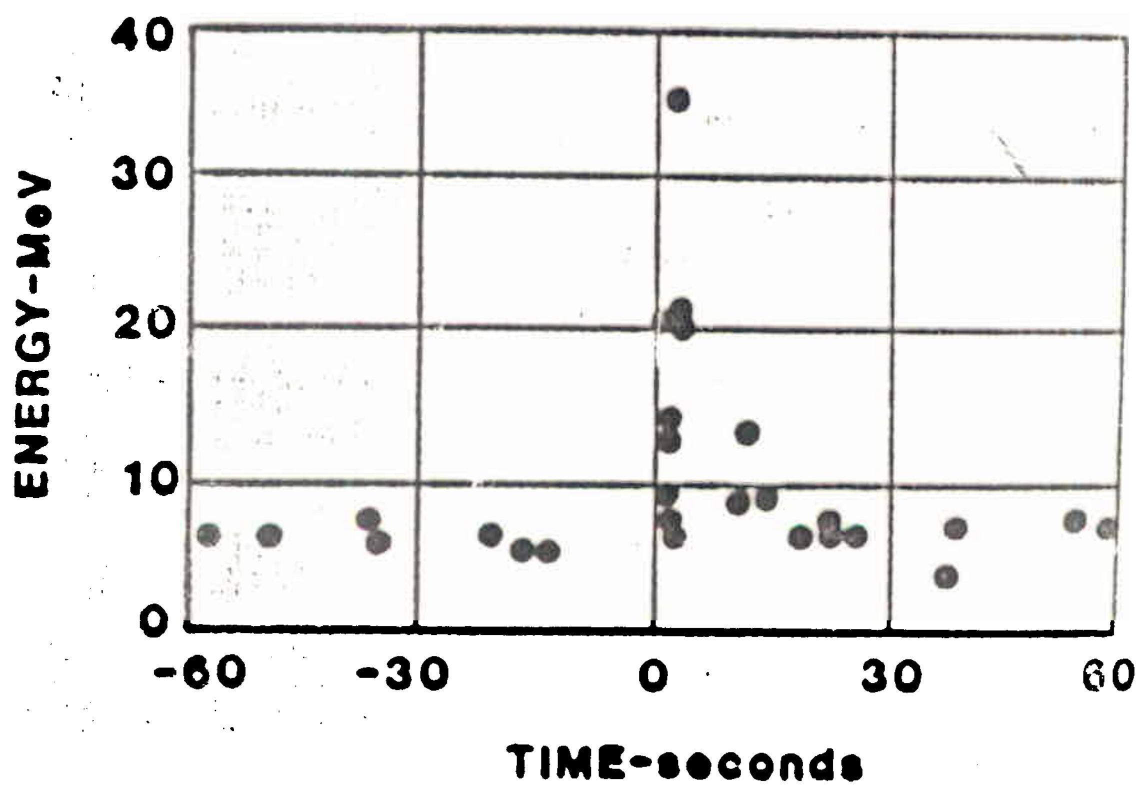

**Light curve** of SN1987a, obtained with the optical star sensor on the International Ultraviolet Explorer satellite between 24 February and 2 July 1987 (day 183). The intensity is given in magnitudes, a logarithmic scale in which an increase of 2.5 magnitudes corresponds to a factor-of-10 loss in brightness. (Courtesy of George Sonneborn and Robert Kirshner.)

Figure 2

# SN 1987 a

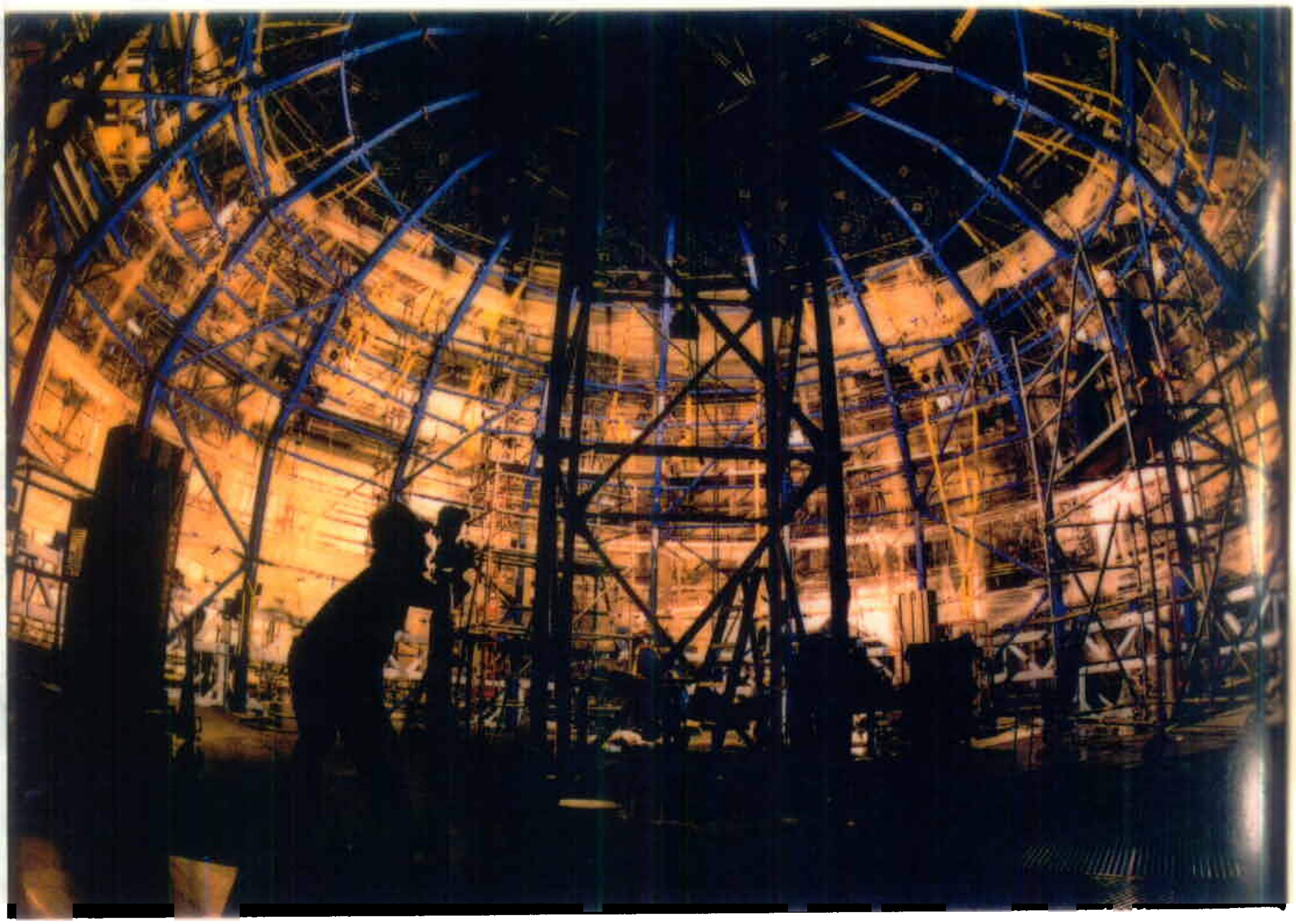
## (23 February 1987, LMC)

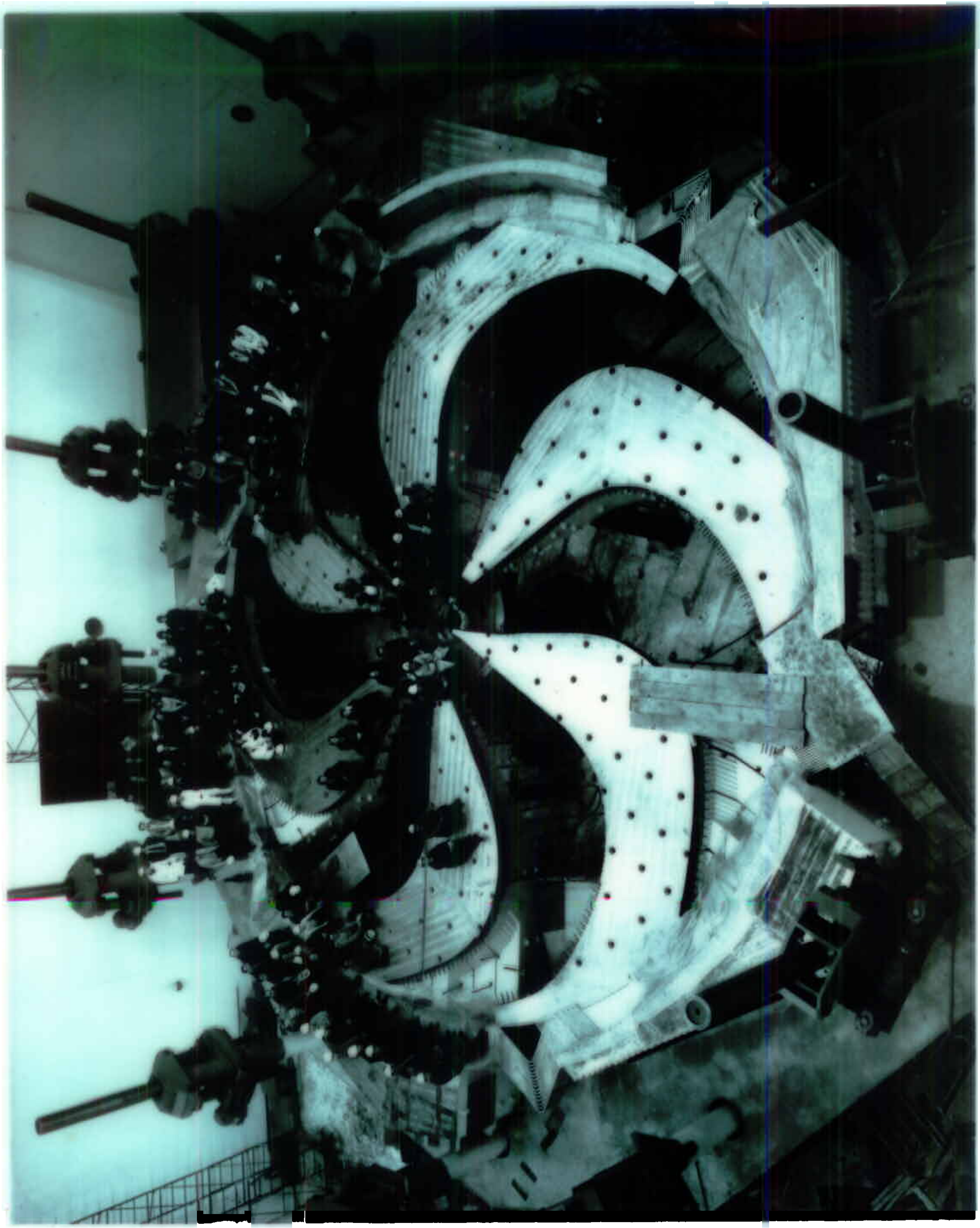
### NEUTRINOS



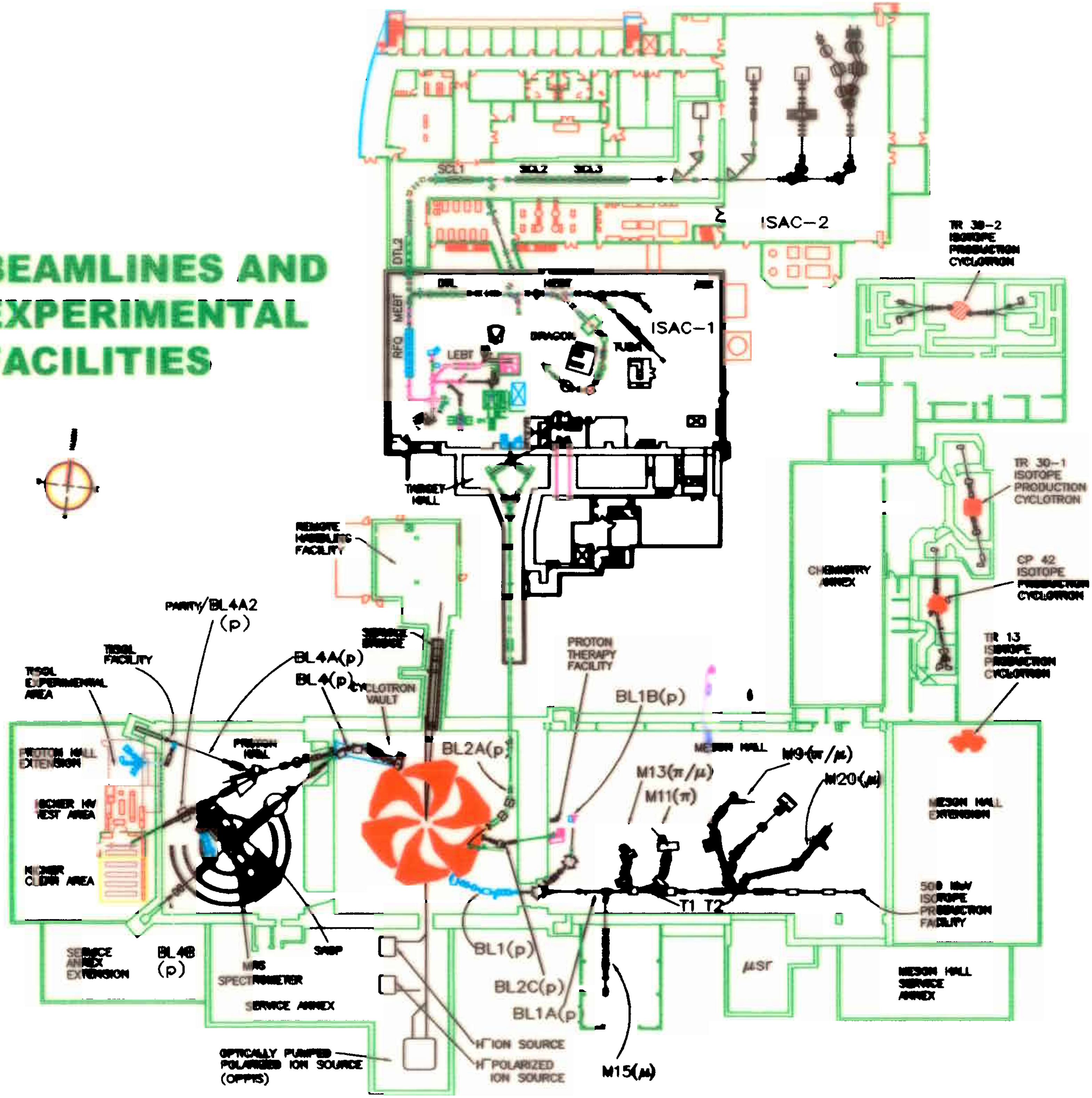
HOYLE:

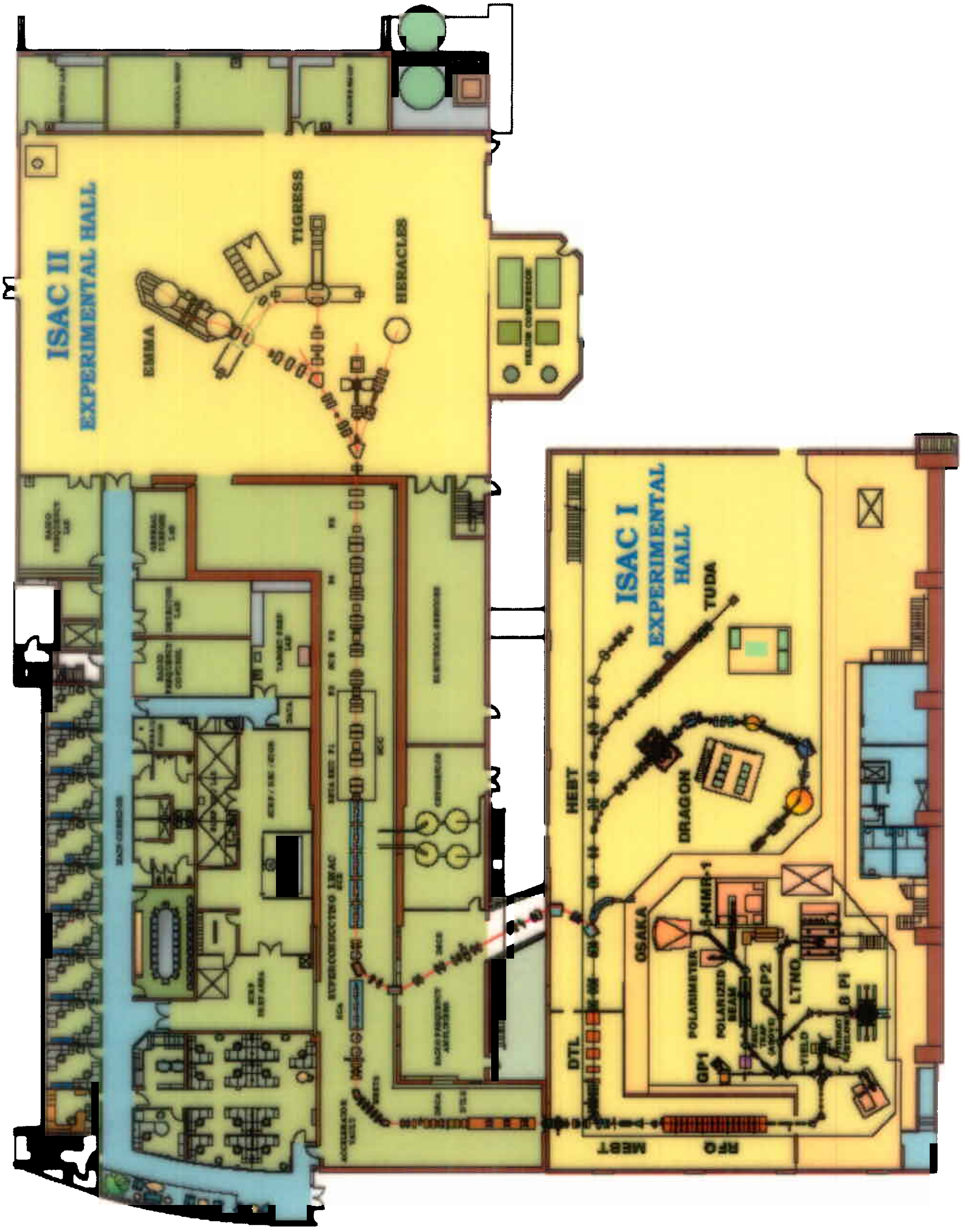
*"The universe is a put-up job."*





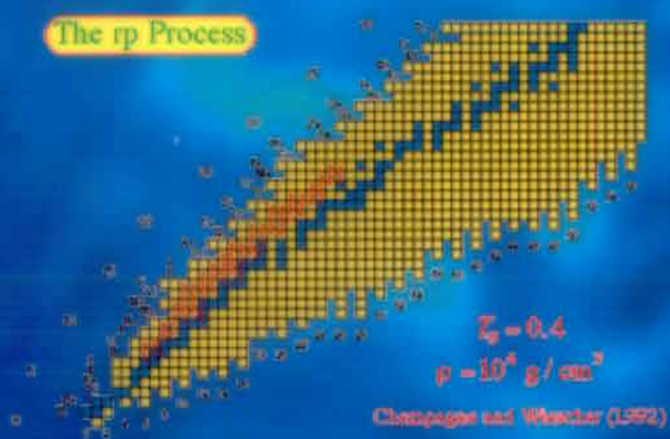
# BEAMLINES AND EXPERIMENTAL FACILITIES

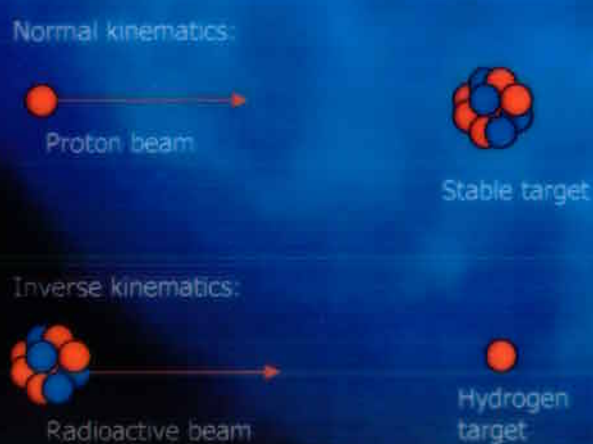



ISAC II
EXPERIMENTAL HALL
TIGRESS
HERACLES
EMMA
ISAC I
EXPERIMENTAL HALL
TUDA
DRAGON
HEBT
DTL
MEBT
RFQ
OSAKA
POLARIMETER
POLARIZED BEAM
GP1
GP2
LTNO
β-NMR-1

# ISAC-II

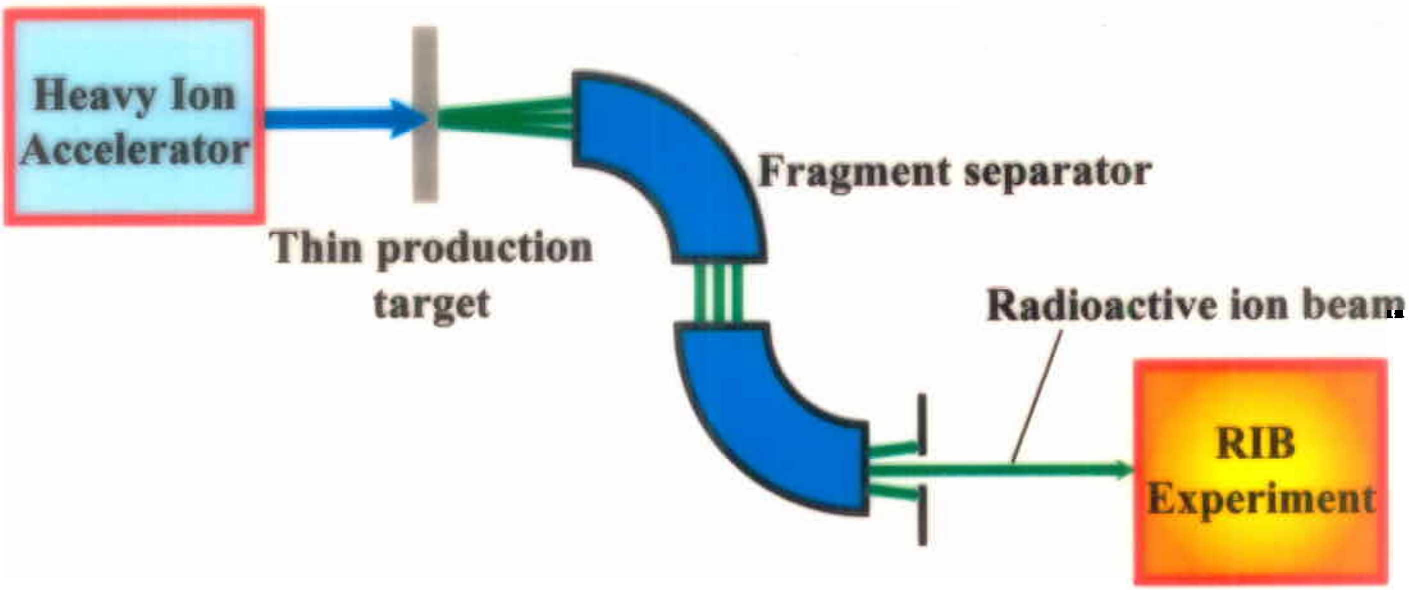
# The need for radioactive beams



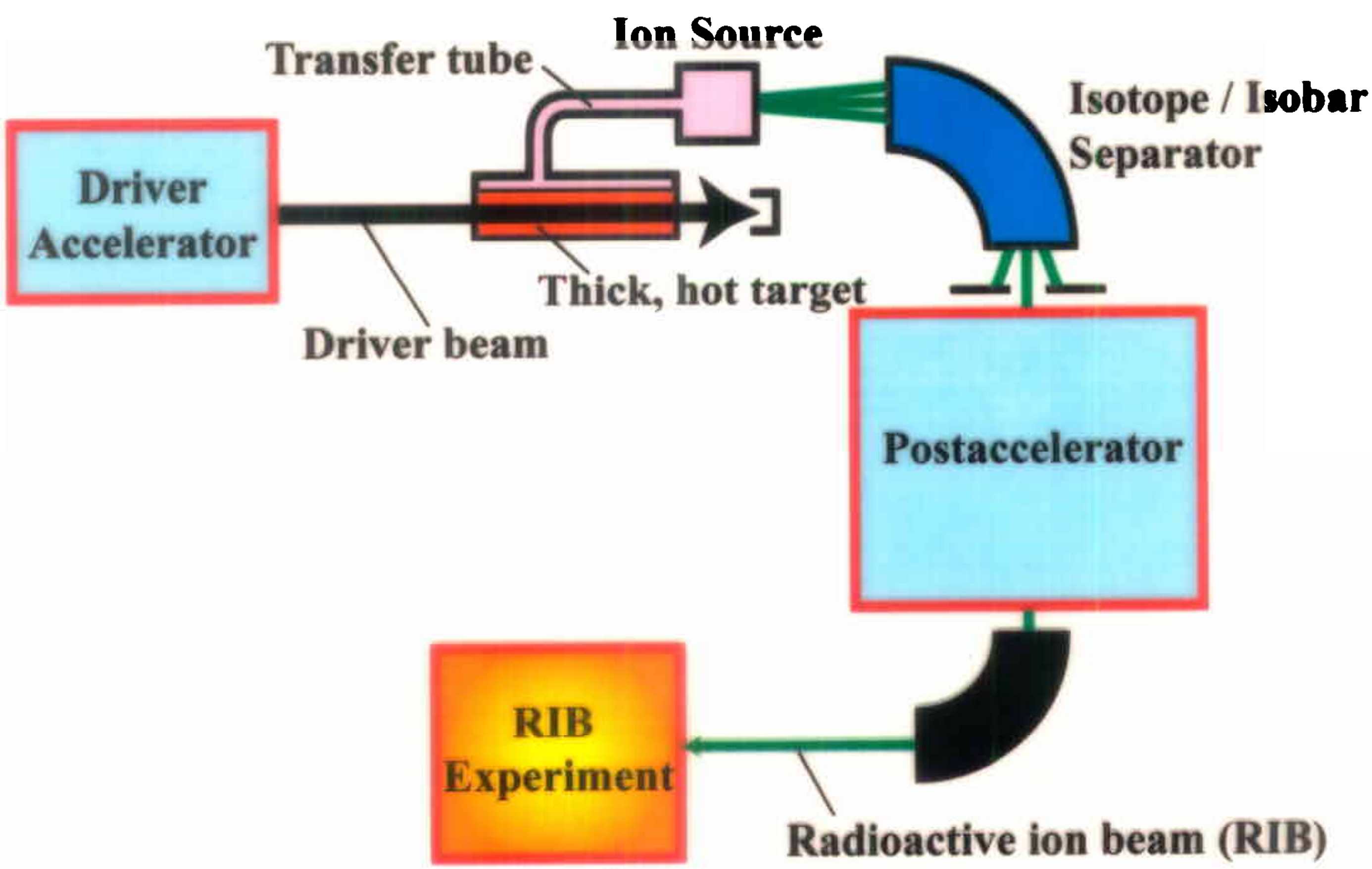




- Most of the reactions important to the rp process involve radioactive nuclei with short half-lives
- For reactions involving stable isotopes, can either use statistical approach (estimate) or perform direct experiments with stable targets in 'normal' kinematics
- Because of binding energy – further from stability means individual resonances count – no statistical estimates!
- Cannot construct targets with half-lives shorter than seconds
- Therefore, need inverse kinematics, with radioactive beam

# Projectile Fragmentation




# ISOL



# CURRENT RARE ISOTOPE FACILITIES

- ATLAS (ARGONNE)
- GANIL (FRANCE)
- ISAC (CANADA)
- HRIBF (OAK RIDGE)
- ISOLDE (CERN)
- RIKEN (JAPAN)

# The Big Questions

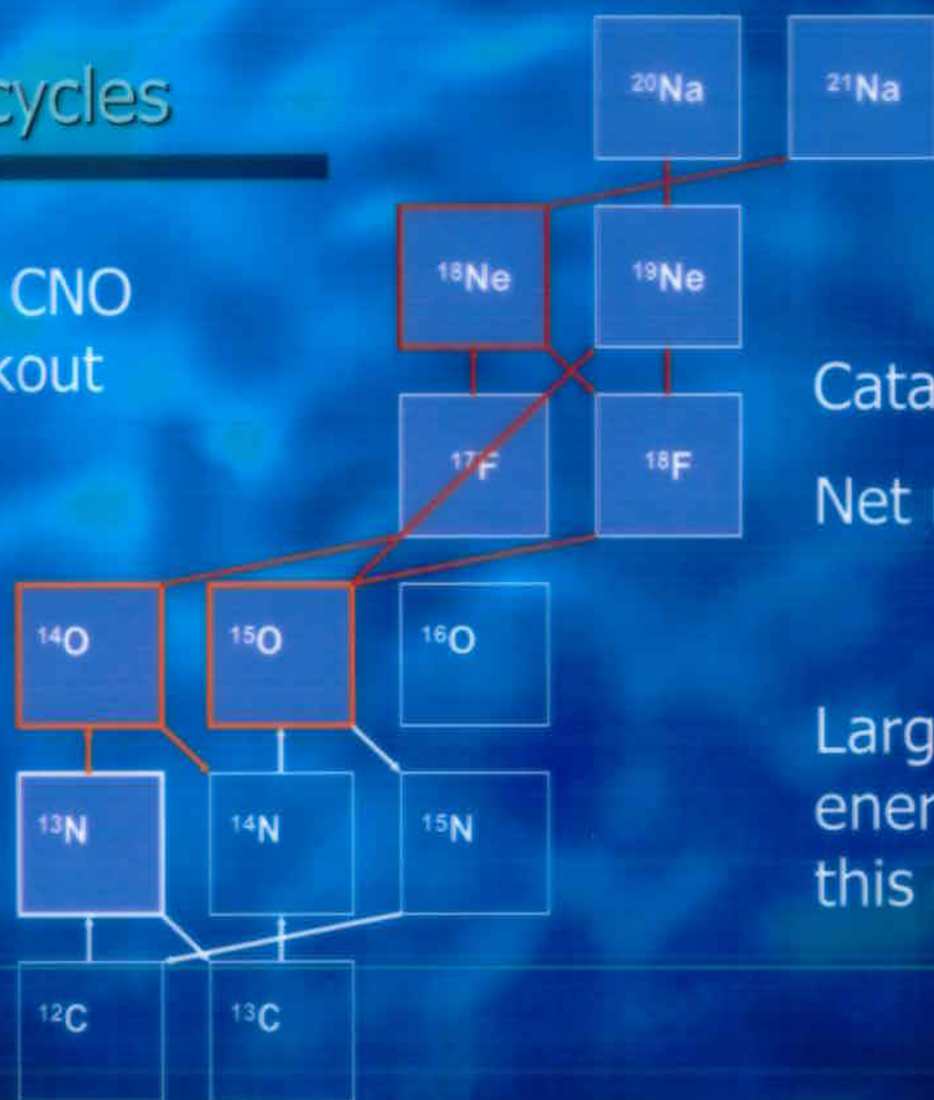
- How and where were the chemical elements produced?
- What role do nuclei play in the liberation of energy in stars?
- How are nuclear properties related to astronomical observables such as the solar neutrino flux, gamma rays emitted by astrophysical sources, and the light curves of nova, supernovae, and X-ray bursts?

# THE MAJOR ASTROPHYSICAL ISSUES

- What is the origin of the heavy elements?
- How do stars explode?
- What is the nature of dense nuclear matter in neutron stars?

# Burning cycles

CNO, hot CNO
and breakout



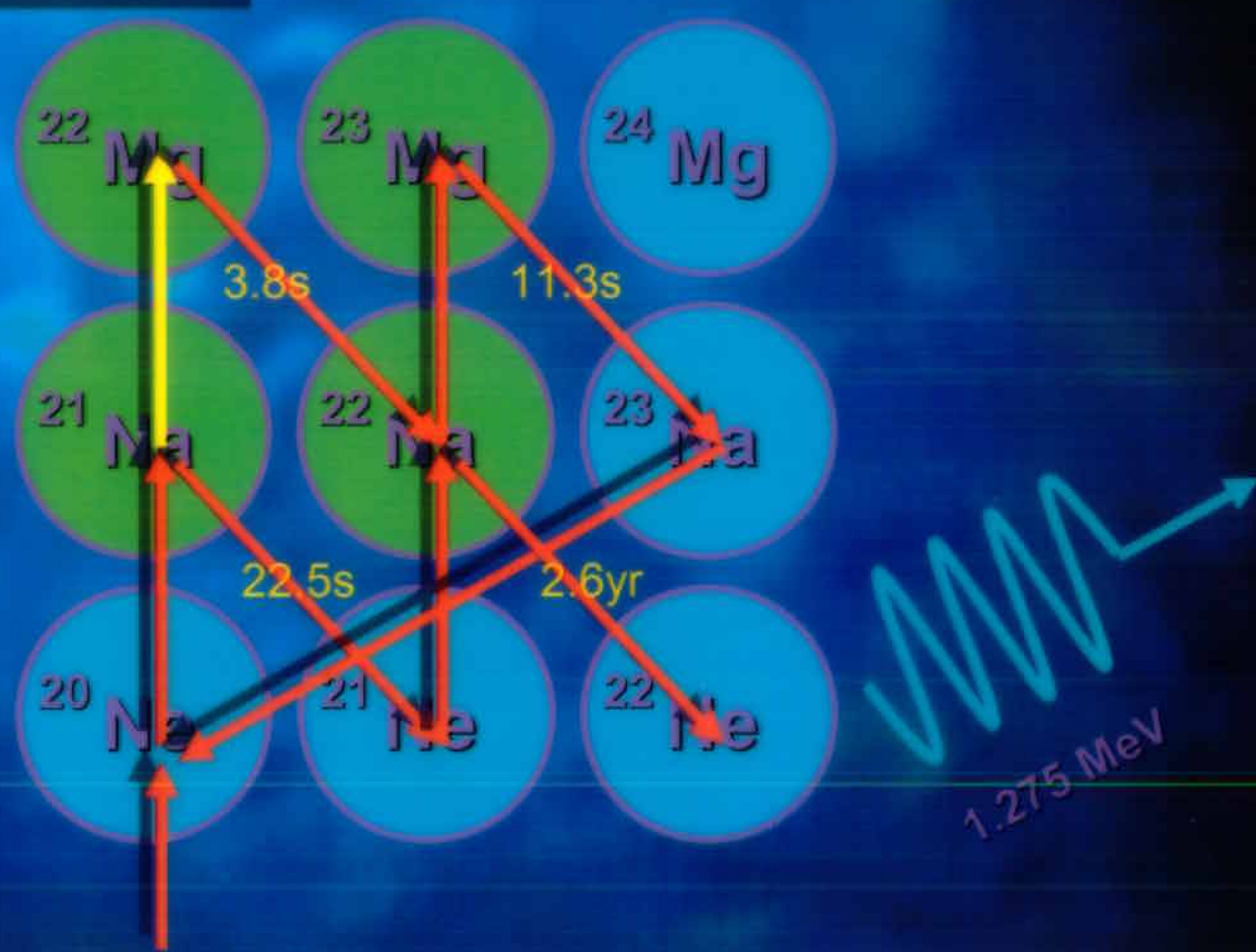

Catalytic H-burning

Net result: Helium

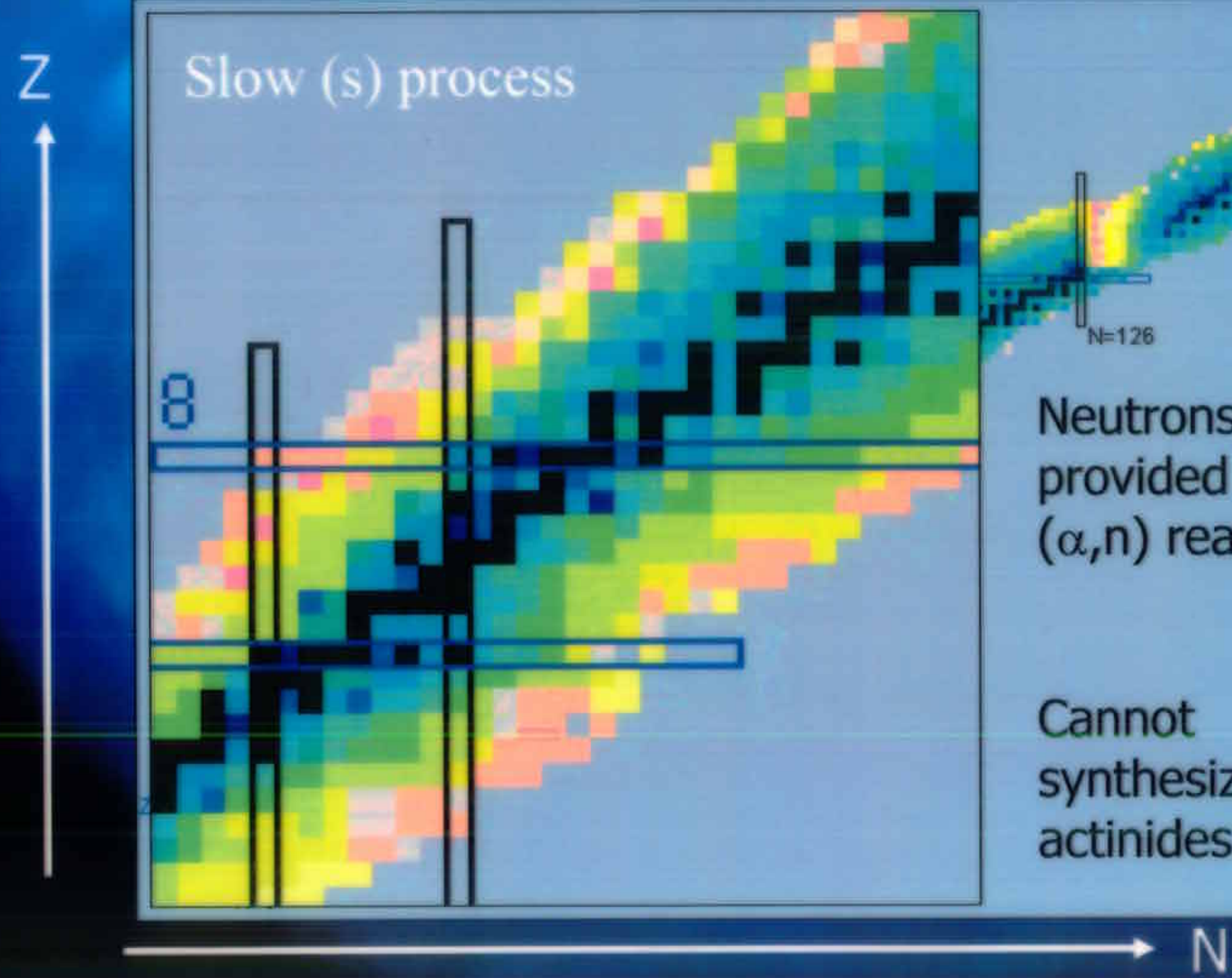
Large amount of energy liberated in this cycle.

# Burning cycles

NeNa
cycle



# Where do the rest of the nuclides come from?




Neutrons provided by ($\alpha$,n) reactions

Cannot synthesize actinides

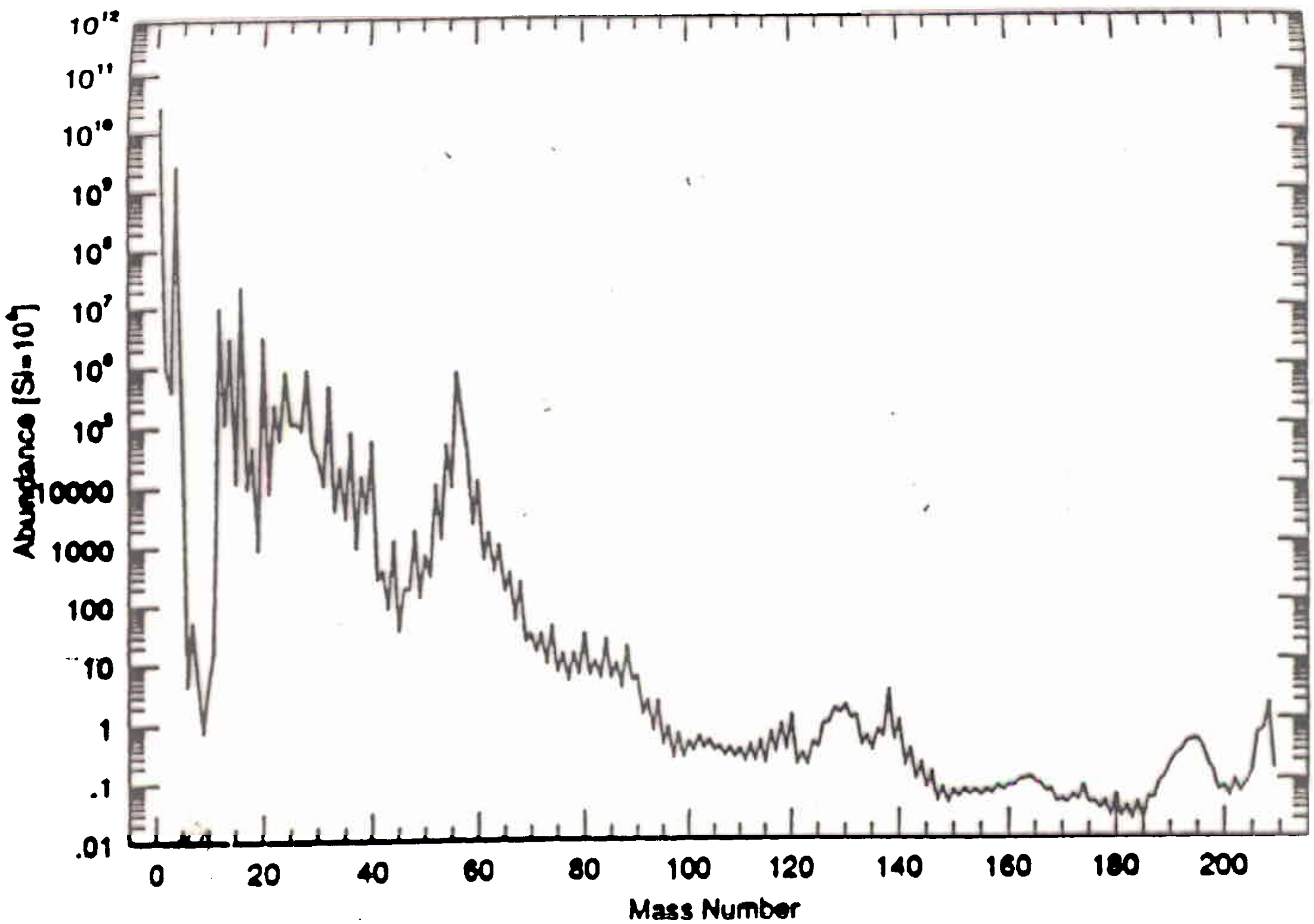
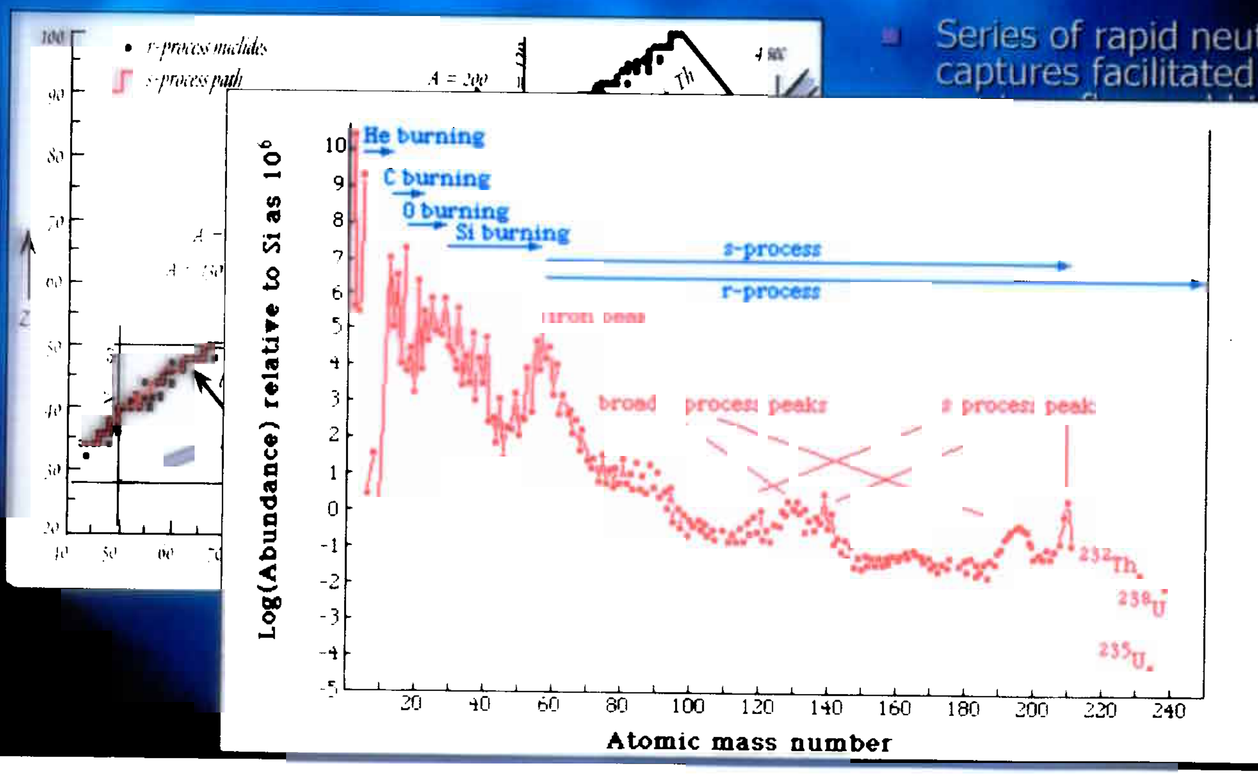



Fig. 1.1. **Solar abundances.** Elemental abundances (by number), as observed in the solar system, versus mass number of the elements (from Ref. 1).

# Rapid neutron (r) process




- Series of rapid neutron captures facilitated by high ...h ...ve
- ...ed here ...ity –
- ...on (Q- ...cay half- nucle...

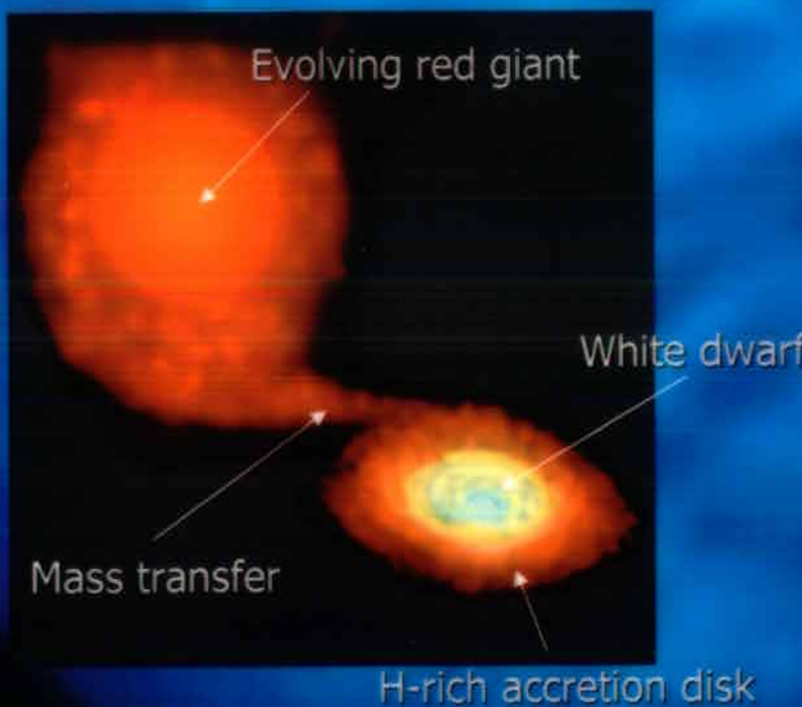
# HOW DO STARS EXPLODE?

- Core Collapse Supernovae
- Thermonuclear (Type 1a) Supernovae
- Novae
- X-Ray Bursts

# Sources of gamma rays:

- Supernovae: $^{56}Ni$, $^{57}Ni$, $^{44}Ti$ (IIa) , $^{60}Co$, $^{26}Al$
- O-Ne Novae: $^{22}Na$, $^{26}Al$, $^{13}N$, $^{18}F$,
- C-O Novae: $^{7}Be$,

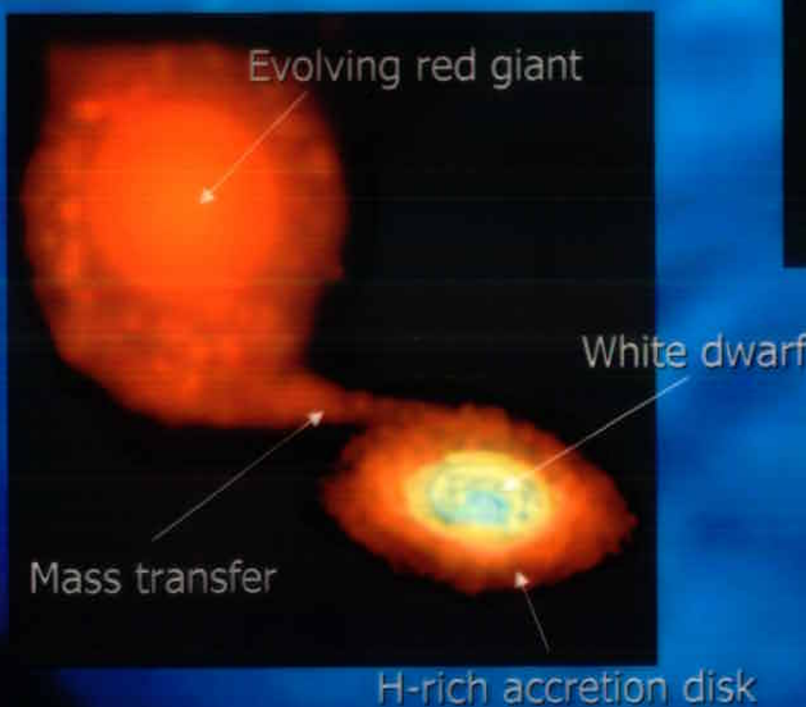
# Novae



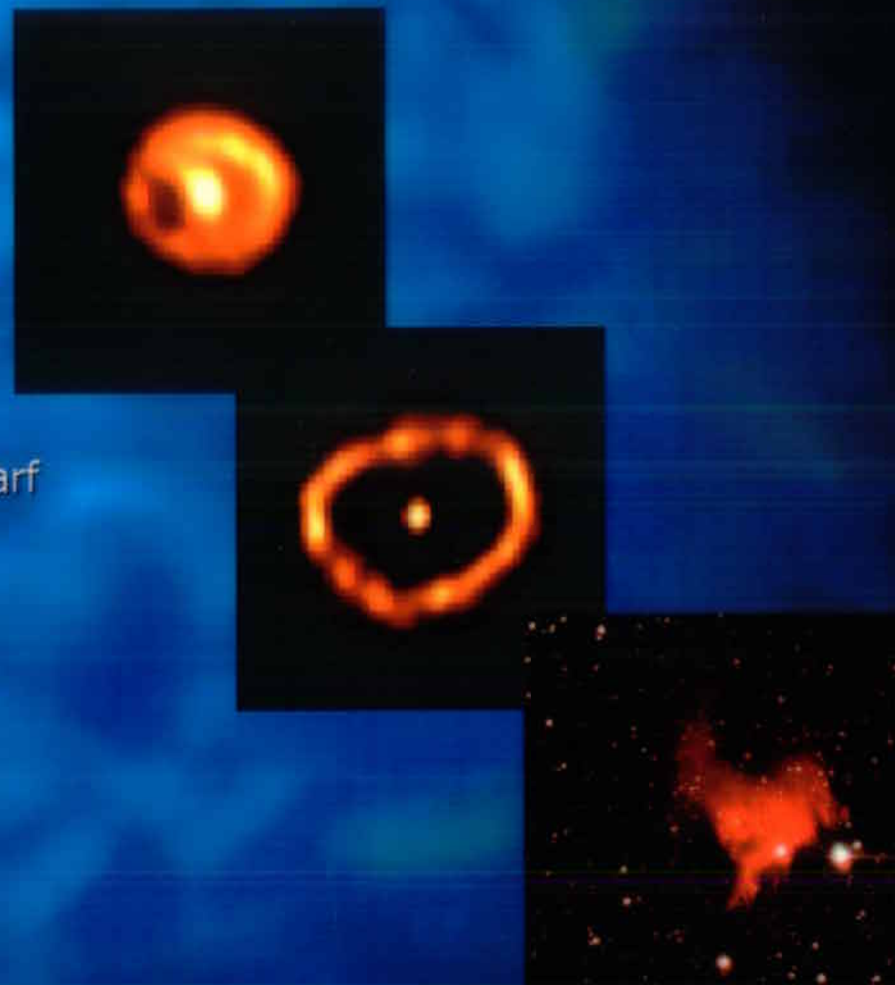

Artist's impression of an accreting white dwarf binary system

- Binary system where one star evolves faster than the companion – becomes white dwarf
- Companion enters red giant stage, expands to fill envelope of gravitational equipotential (Roche Lobe)
- H-rich material transferred into orbit around WD – accretion, heating, nuclear reactions & synthesis
- Gas becomes degenerate – $\rho$ increases but envelope can't expand – gas becomes opaque to own radiation causing sudden lifting of degeneracy – rapid expansion & ejection of material
- Typical T: ~0.01 – 0.3 GK
- Typical t ~ 100's days

# Novae

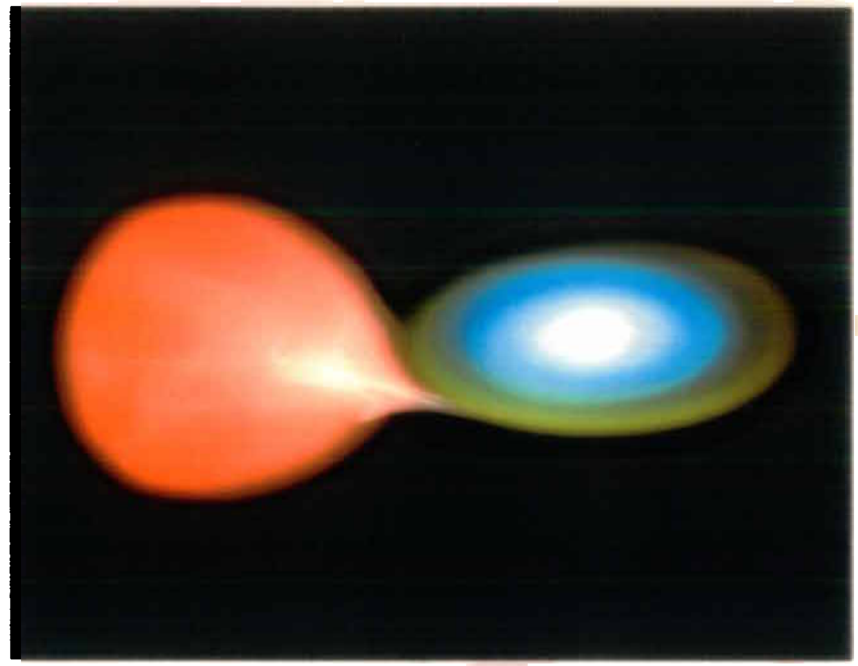



Artist's impression of an accreting white dwarf binary system



# Type I X-Ray Bursts

- Neutron star in a binary star system accretes H- and He-rich matter from its stellar companion
- Matter heated as it falls onto surface
- Thermonuclear runaway burns accreted fuel in repeated explosive bursts
- Brightest in x-rays
- X-ray light curves very precisely measured



# $^{44}$Ti: An Astrophysical $\gamma$ Ray Emitter

- Laboratory half-life of $60.0 \pm 1.0$ years
- Produced in core-collapse supernovae
  - Indication of relatively recent supernovae
  - Detected in Cas A, Vela supernova remnants
- Understanding of production requires reliable rate of $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction as shown in a comprehensive theoretical study of rates by The, Clayton, Meyer et al. 1998 (Clemson)