中国原子能科学研究院
China Institute of Atomic Energy

天体演化过程涉及的重要核数据

Important nuclear data in astrophysical evolution

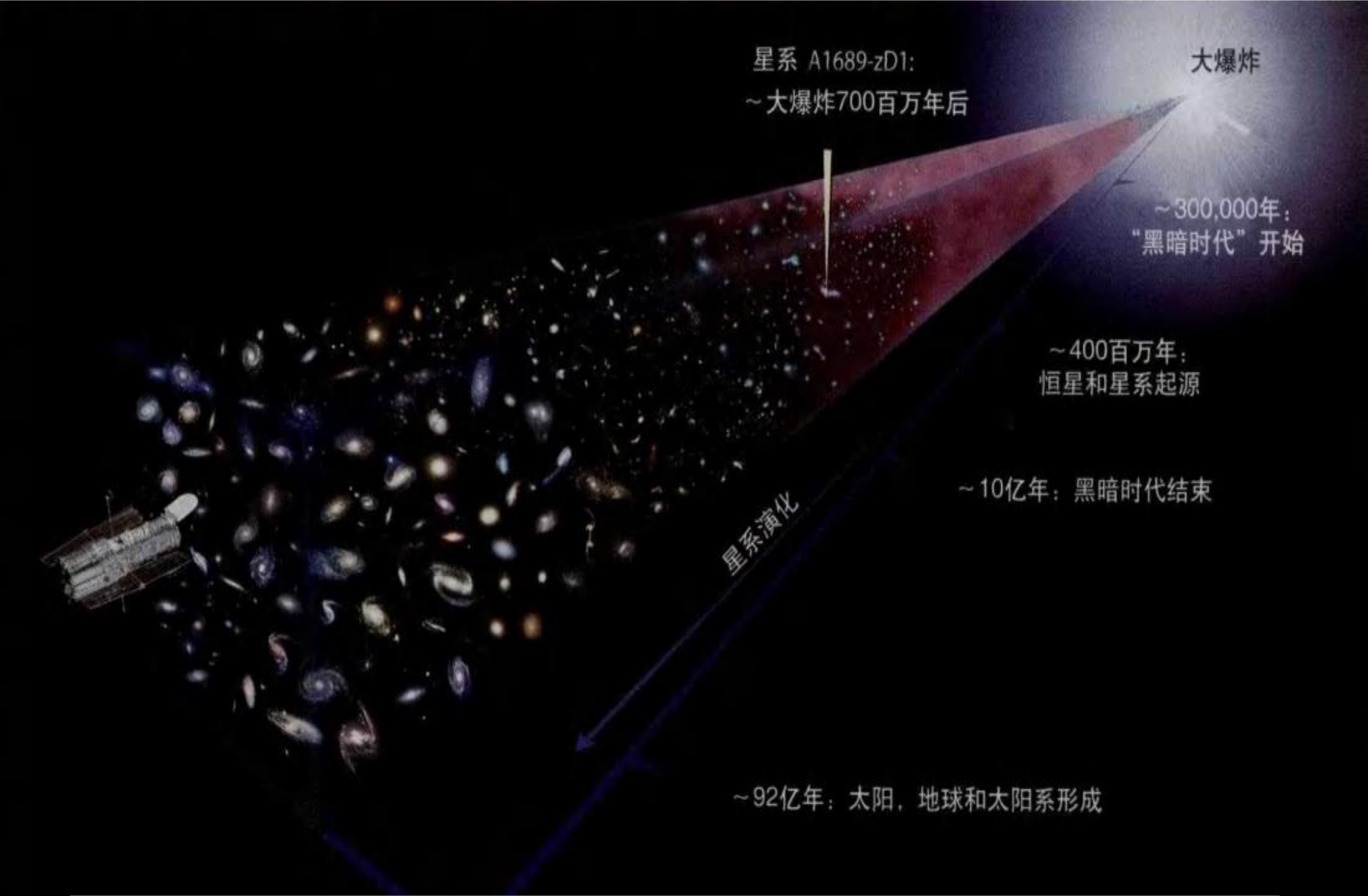
2020年CSNS反角白光中子源用户研讨会

李志宏

2020年8月10日

报告内容

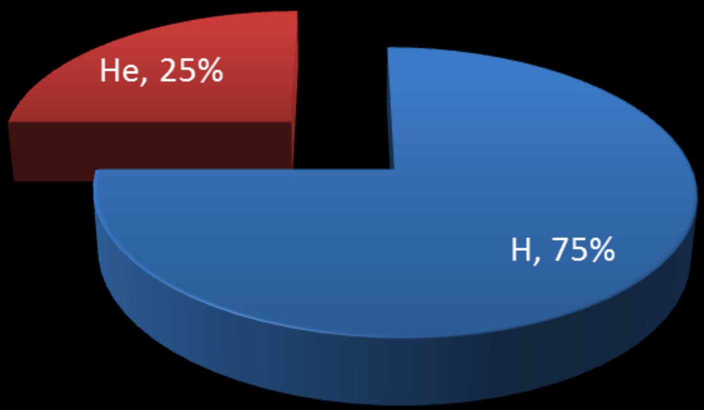
- 天体演化涉及的几个重要核过程
- 对应核过程涉及的重要核数据
  - 大爆炸核合成
  - 恒星核燃烧过程
  - 爆发性恒星核合成过程
  - 宇宙射线诱发的核过程
- 散列中子源上可以开展的天体核反应研究
- 报告总结


星系 A1689-zD1:
~大爆炸700百万年后
大爆炸
~300,000年：
"黑暗时代"开始
~400百万年：
恒星和星系起源
~10亿年：黑暗时代结束
星系演化
~92亿年：太阳，地球和太阳系形成

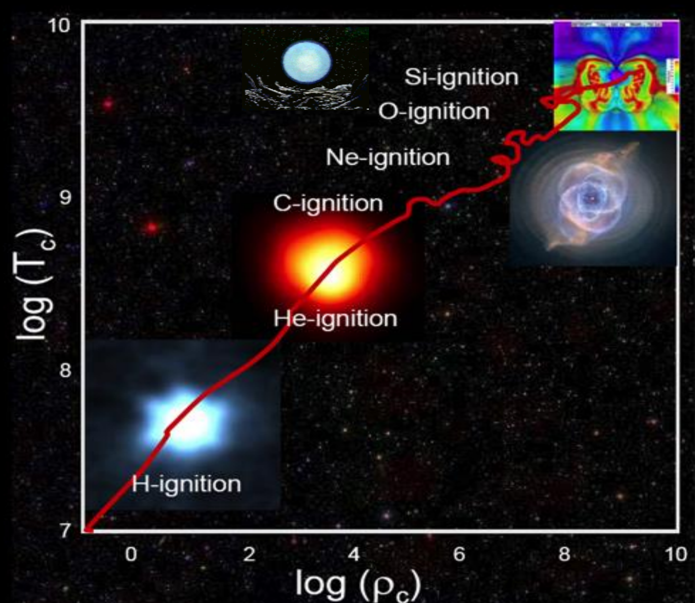
核过程：宇宙中的"炼金术"

宇宙演化与人体元素

Others (^2H,^3He,^6Li,^7Li)<0.00001



The big bang



The cosmos is within us. We are made of star-stuff (Carl Sagan）

Human Body Ingredients

The four ingredients below are essential parts of the body's protein, carbohydrate and fat architecture.

O
OXYGEN
65.0%
Critical to the conversion of food into energy.

C
CARBON
18.5%
The so-called backbone of the building blocks of the body and a key part of other important compounds, such as testosterone and estrogen.

H
HYDROGEN
9.5%
Helps transport nutrients, remove wastes and regulate body temperature. Also plays an important role in energy production.

N
NITROGEN
3.3%
Found in amino acids, the building blocks of proteins; an essential part of the nucleic acids that constitute DNA.

(Percentage of body weight. Source: *Biology*, Campbell and Reece, eighth edition.)

Other Key Elements

Calcium 1.5%
Lends rigidity and strength to bones and teeth; also important for the functioning of nerves and muscles, and for blood clotting.

Phosphorus 1.0%
Needed for building and maintaining bones and teeth; also found in the molecule ATP (adenosine triphosphate), which provides energy that drives chemical reactions in cells.

Potassium 0.4%
Important for electrical signaling in nerves and maintaining the balance of water in the body.

Sulfur 0.3%
Found in cartilage, insulin (the hormone that enables the body to use sugar), breast milk, proteins that play a role in the immune system, and keratin, a substance in skin, hair and nails.

Chlorine 0.2%
Needed by nerves to function properly; also helps produce gastric juices.

Sodium 0.2%
Plays a critical role in nerves' electrical signaling; also helps regulate the amount of water in the body.

Magnesium 0.1%
Plays an important role in the structure of the skeleton and muscles; also found in molecules that help enzymes use ATP to supply energy for chemical reactions in cells.

Iodine (trace amount)
Part of an essential hormone produced by the thyroid gland; regulates metabolism.

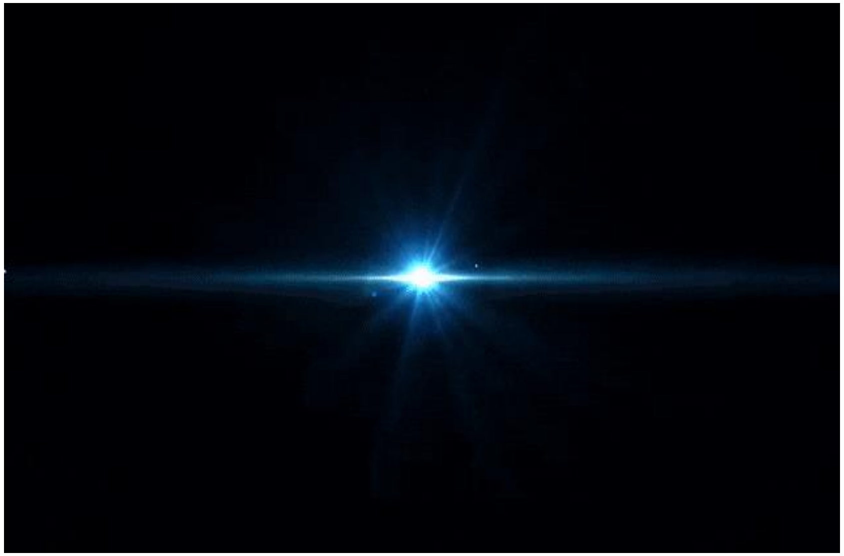
Iron (trace amount)
Part of hemoglobin, which carries oxygen in red blood cells.

Zinc (trace amount)
Forms part of some enzymes involved in digestion.

天体演化涉及的重要核过程

- 大爆炸原初核合成
- 平稳的恒星核燃烧阶段
  - 氢燃烧、氦燃烧
  - s-过程
- 爆发性的恒星核燃烧阶段
  - 剧烈的核燃烧过程
  - r-过程、p-过程
  - 高温CNO循环等
- 宇宙线核合成

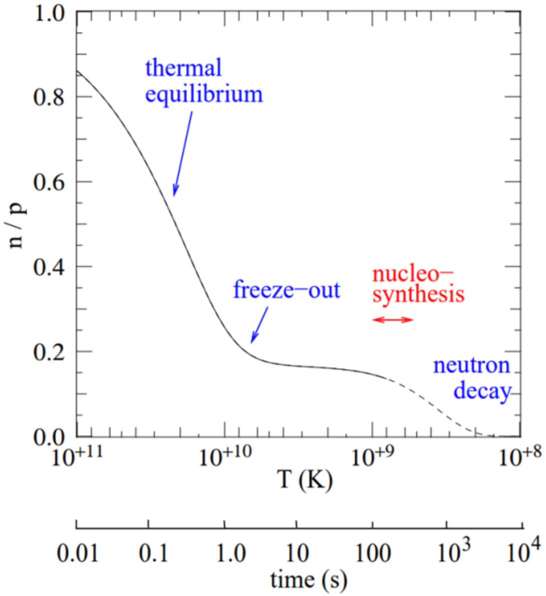
大爆炸原初核合成

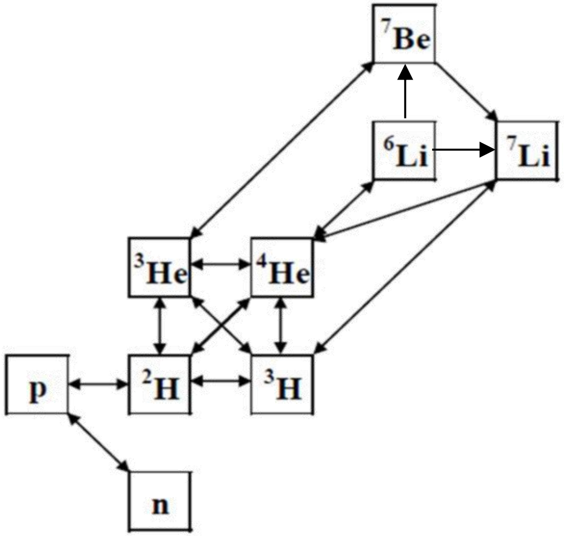


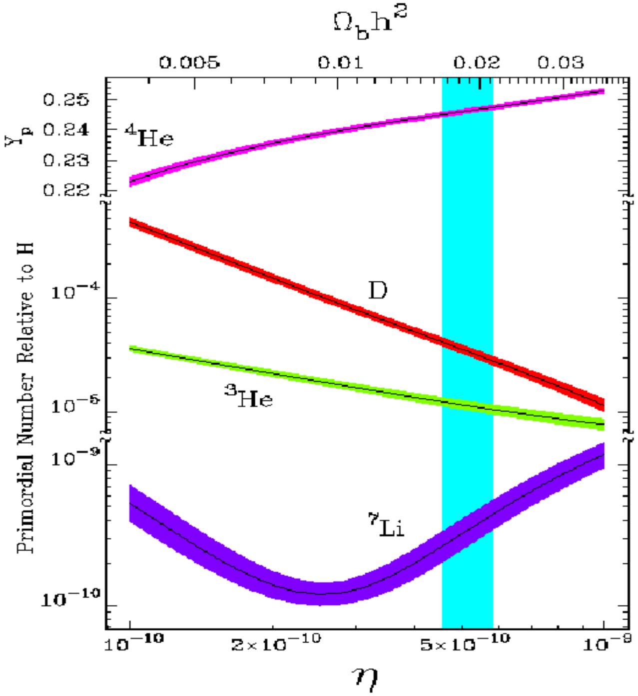
$$\frac{n_n}{n_p} \approx \exp\left(-\frac{(m_n - m_p)\,c^2}{k\,T}\right)$$

$$X_p \equiv \frac{\text{mass in H}}{\text{total mass}} = \frac{N_p - N_n}{N_p + N_n} = \frac{6}{8} = 0.75$$

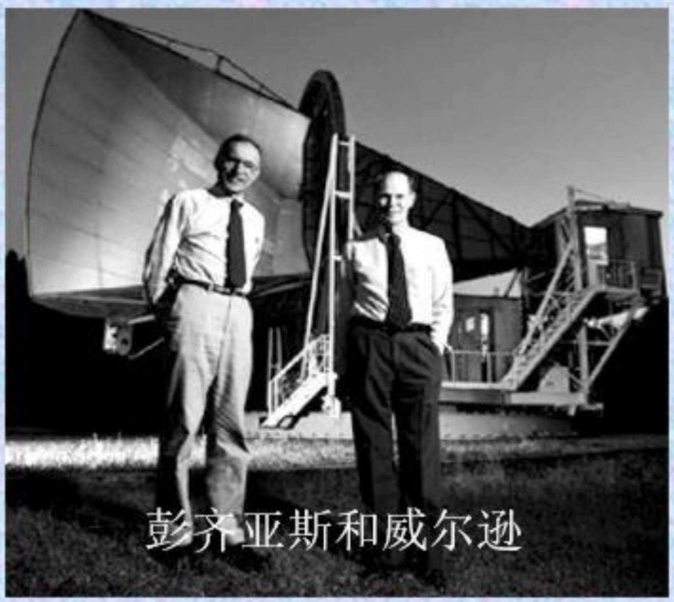
$$Y_p \equiv \frac{\text{mass in He}}{\text{total mass}} = \frac{2N_n}{N_p + N_n} = \frac{2}{8} = 0.25$$

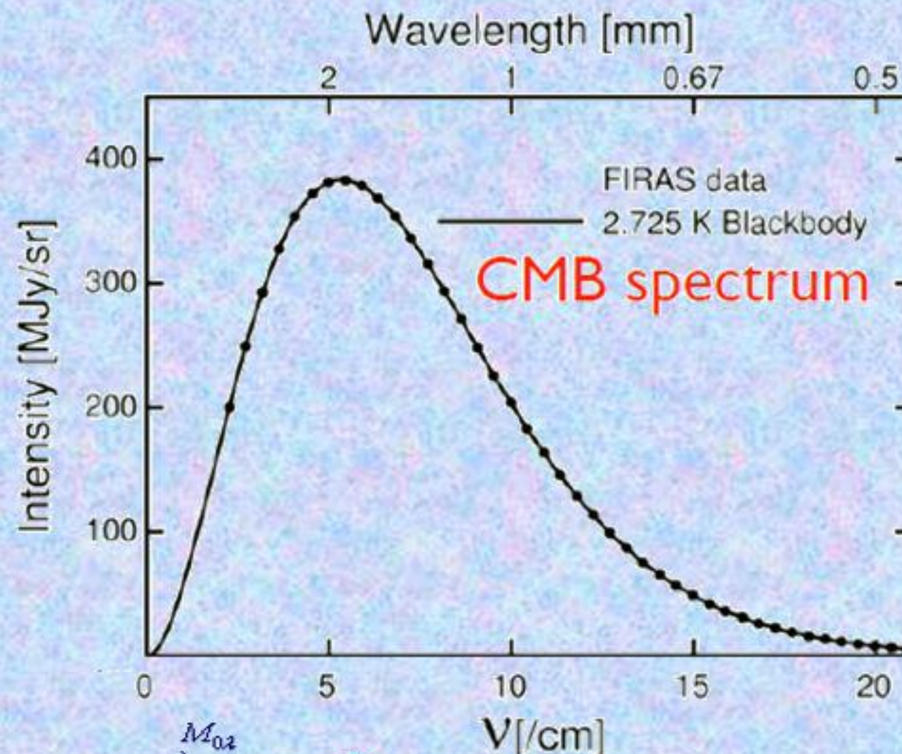


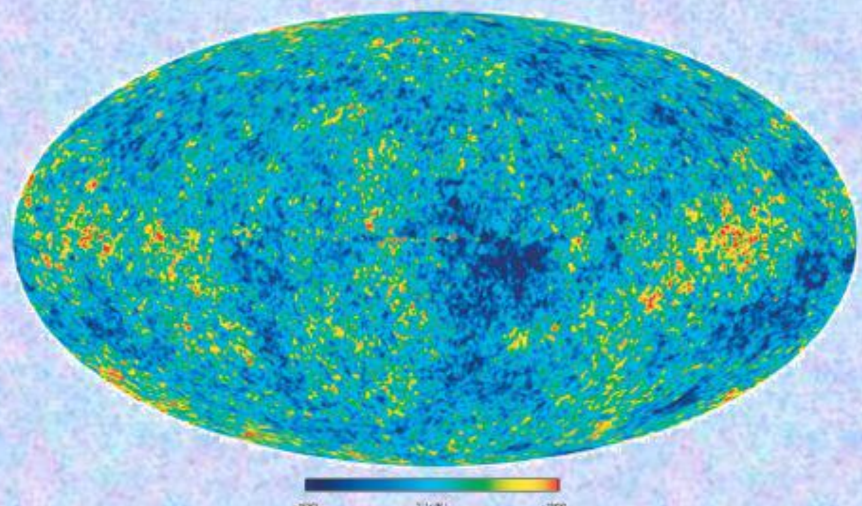




微波背景辐射







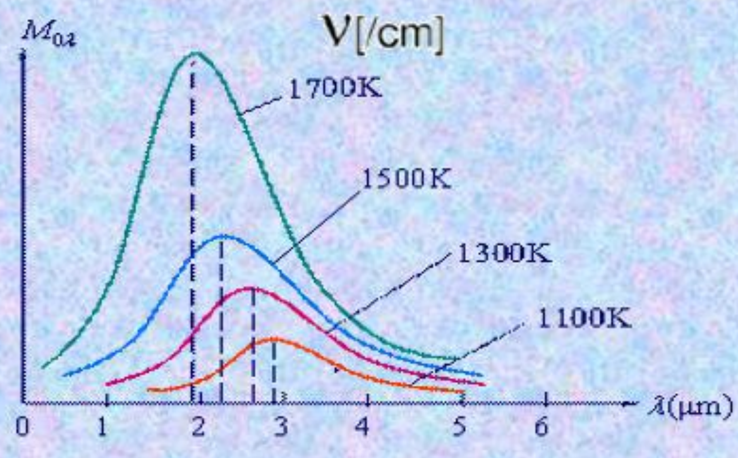
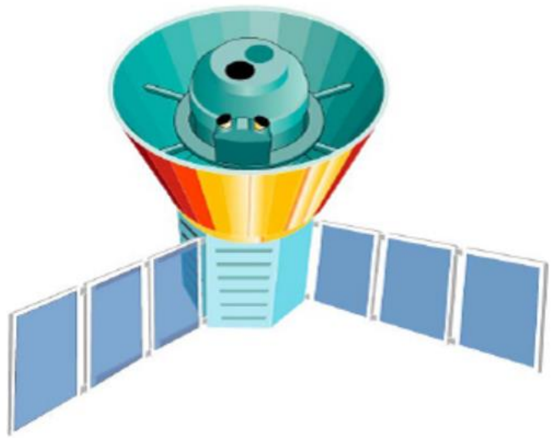
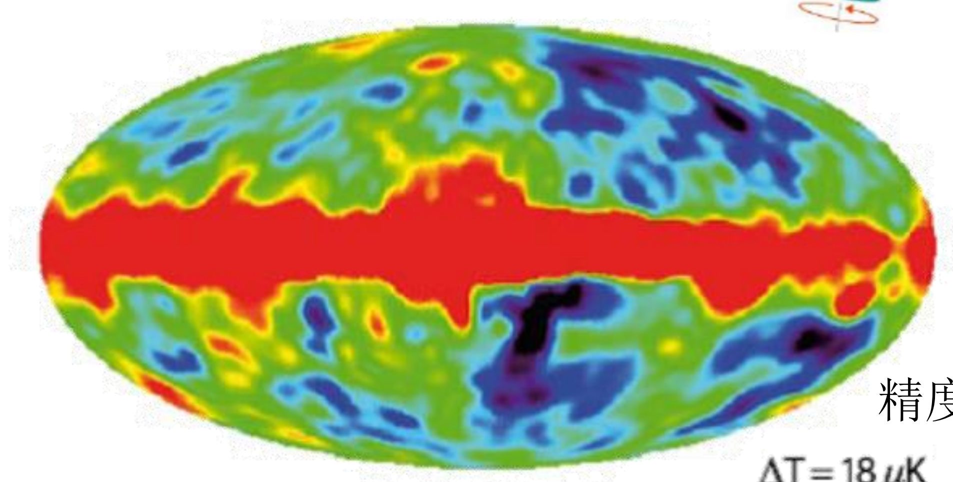


图20.2　不同温度下黑体辐射实验曲线

2006年诺贝尔物理学奖



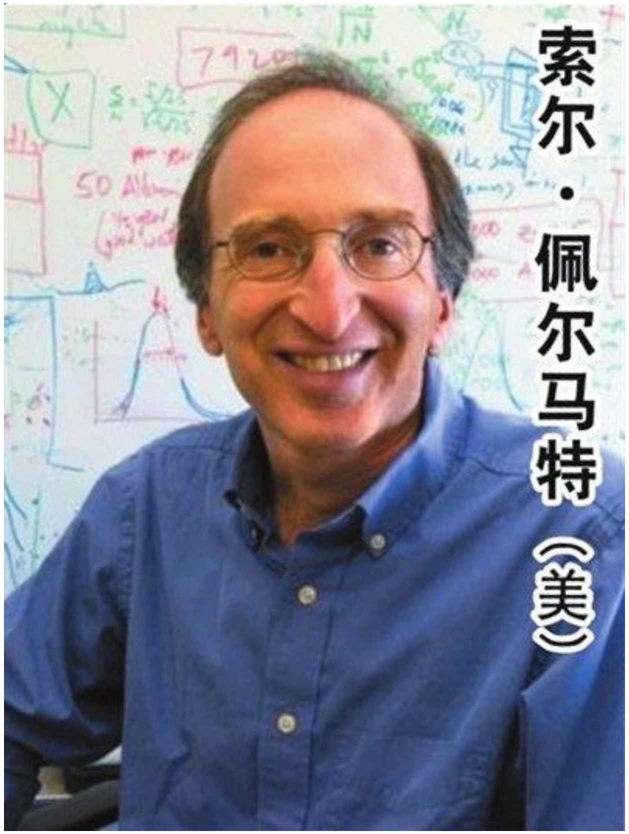
COBE



精度：10^{-5}

获奖原因：宇宙微波背景辐射的黑体形式和各向异性

2011年诺贝尔物理学奖

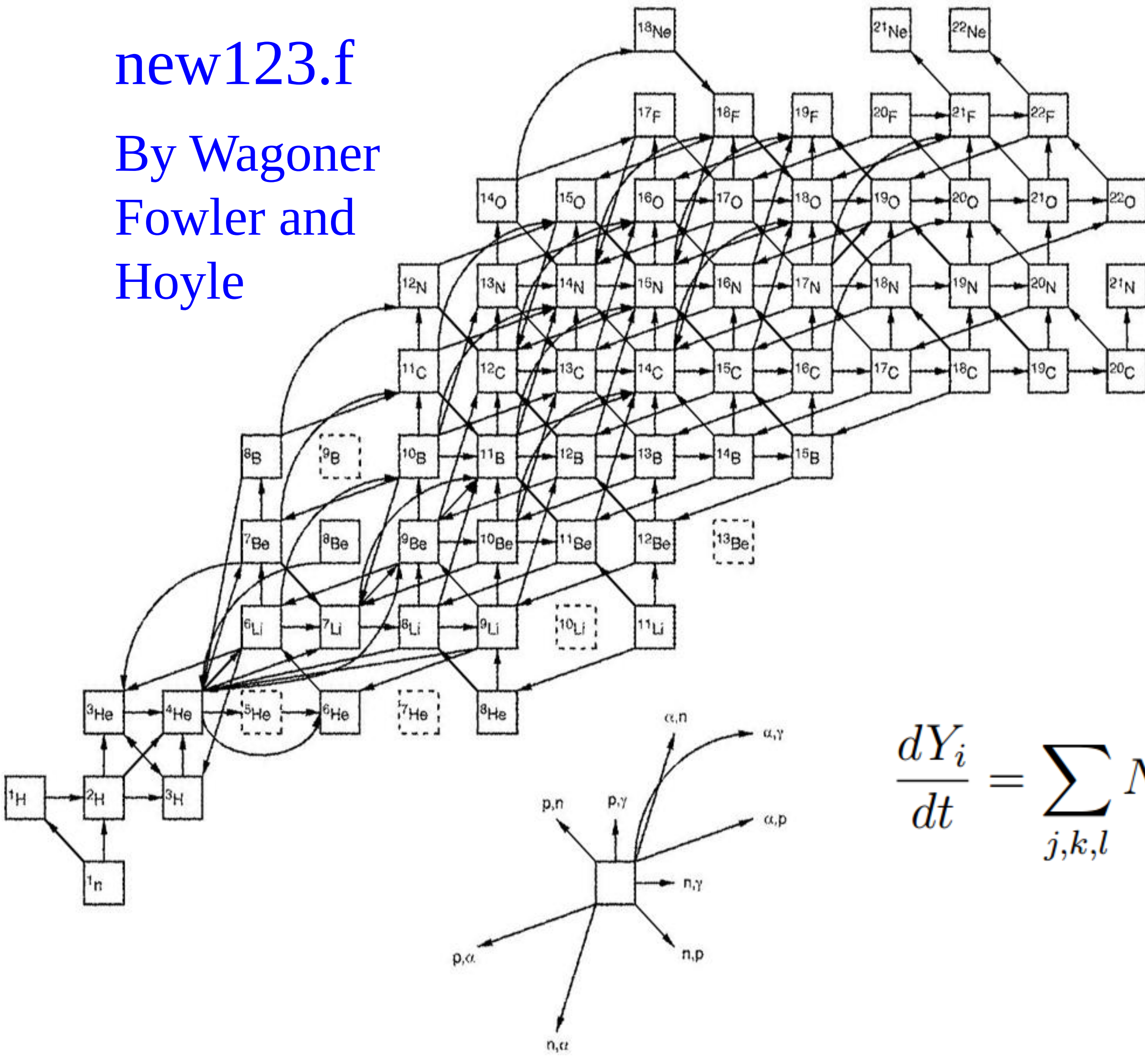


获奖原因：通过观测遥远超新星发现宇宙的加速膨胀

大爆炸核合成的网络计算

new123.f

By Wagoner Fowler and Hoyle



$$\frac{1}{R}\frac{dR}{dt}=\sqrt{\frac{8\pi G}{3}\rho-\frac{k}{R^2}+\frac{\Lambda}{3}}$$

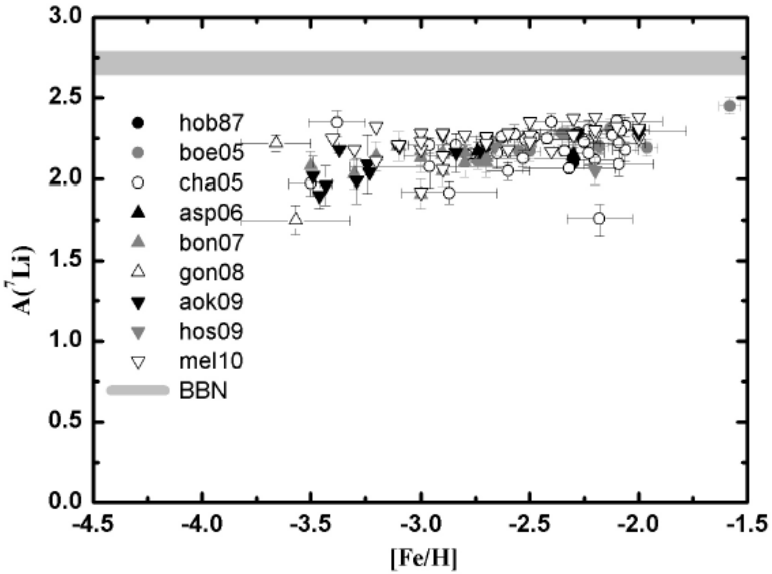
$$\frac{1}{n_b}\frac{dn_b}{dt}=-3\frac{1}{R}\frac{dR}{dt}$$

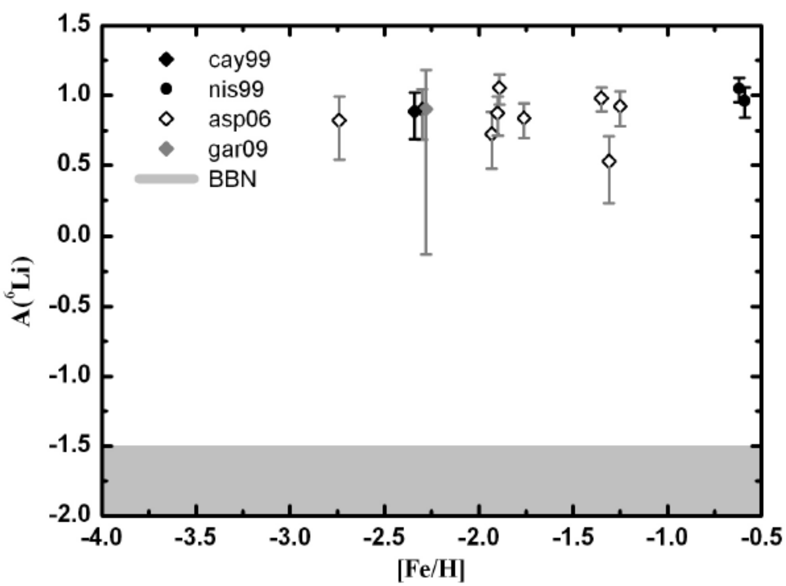
$$L\left(\frac{m_e}{T},\phi_e\right)=\frac{n_b q_b}{T^3}$$

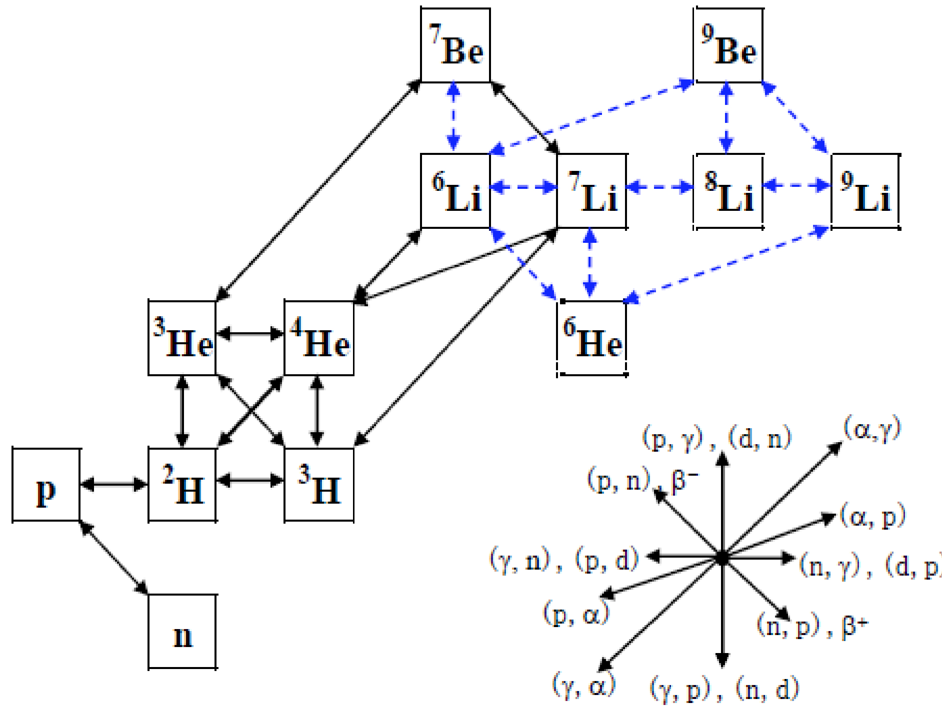
$$\frac{d\rho}{dt}=-3H(\rho+p)$$

$$\frac{dY_i}{dt}=\sum_{j,k,l}N_i\left(-\frac{Y_i^{N_i}Y_j^{N_j}}{N_i!N_j!}[ij]_k+\frac{Y_l^{N_l}Y_k^{N_k}}{N_l!N_k!}[lk]_j\right)$$

锂丰度的疑难

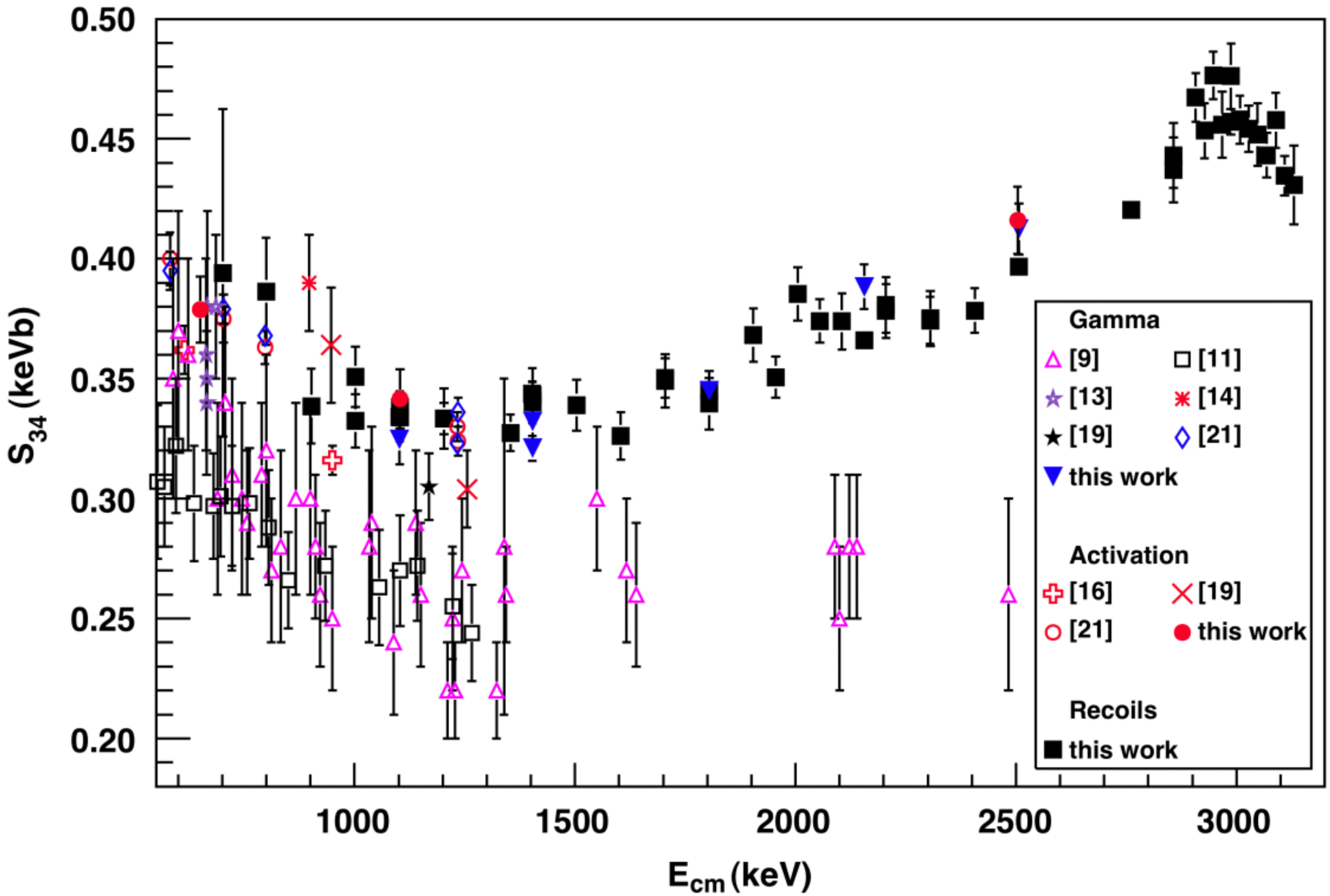






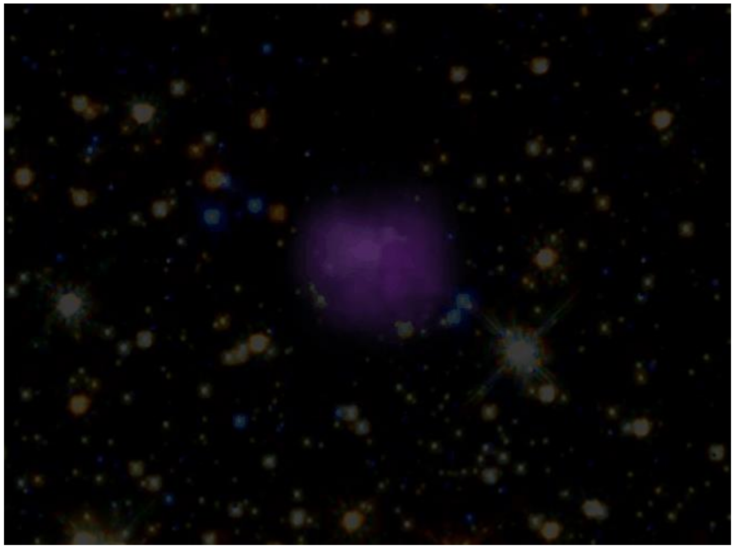
^{6}Li(p,γ)^{7}Be，^{7}Be(d,τ)^{6}Li，^{6}Li(n,γ)^{7}Li
^{6}Li(d,p)^{7}Li，^{6}Li(α,p)^{9}Be，^{6}He(p,n)^{6}Li
^{6}He(d,n)^{7}Li，^{6}He(p,γ)^{7}Li，Li(d,p)^{8}Li
^{7}Li(n,γ)^{8}Li，Li(d,p)^{9}Li，^{8}Li(n,γ)^{9}Li
^{8}Li(p,d)^{7}Li，^{8}Li(p,t)^{6}Li，^{8}Li(p,γ)^{9}Be

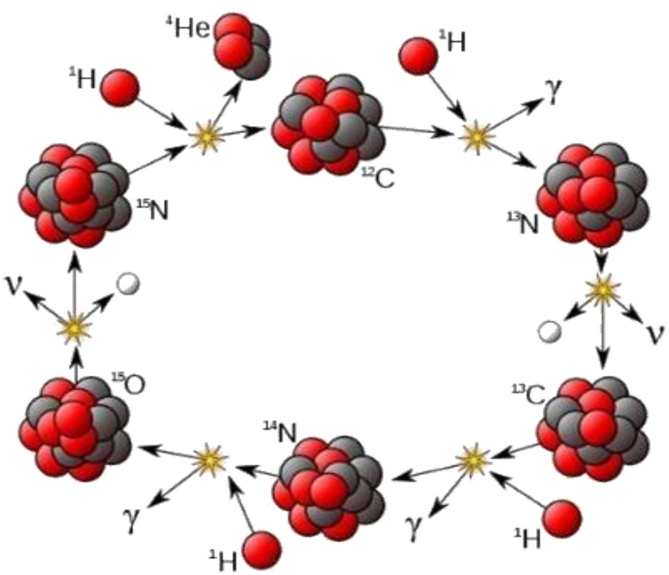
$^{3}He(\alpha,\gamma)^{7}Be$ in BBN

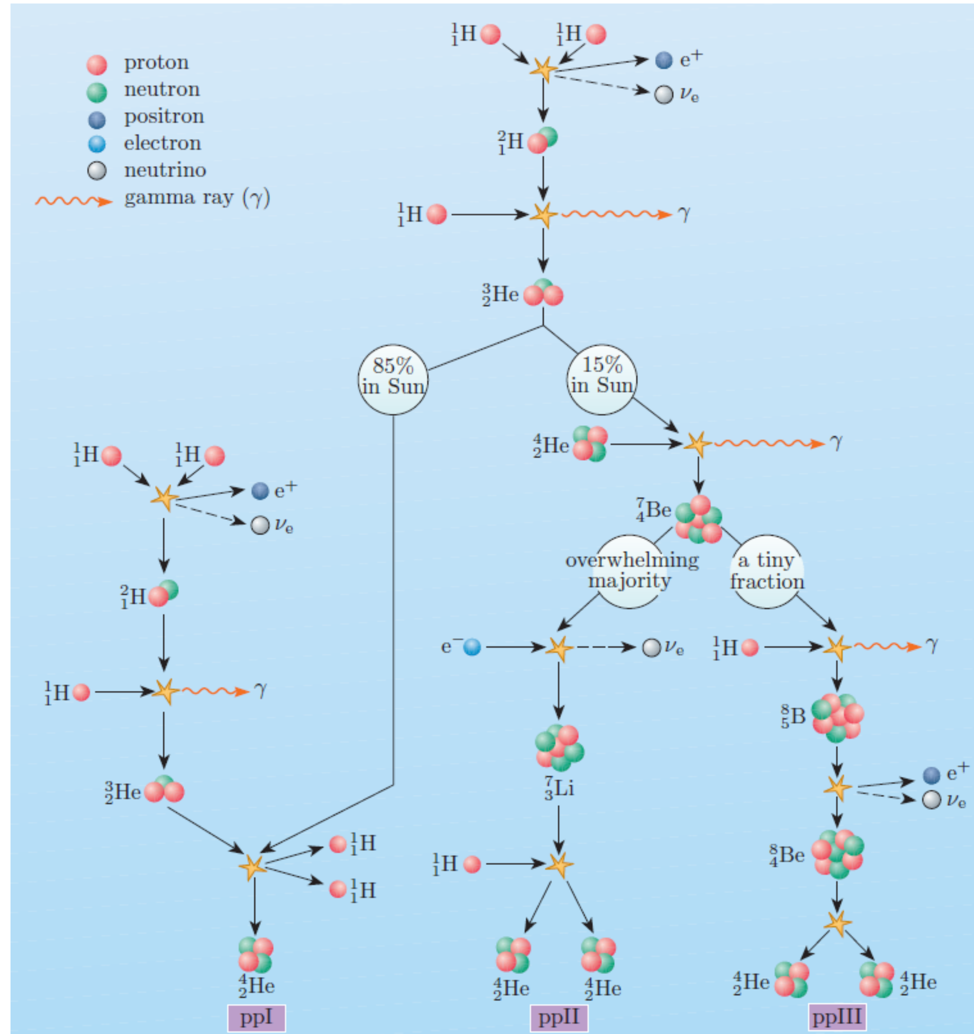


Di Leva *et al*. PRL **102** 232502 (2009)

平稳的恒星核燃烧过程





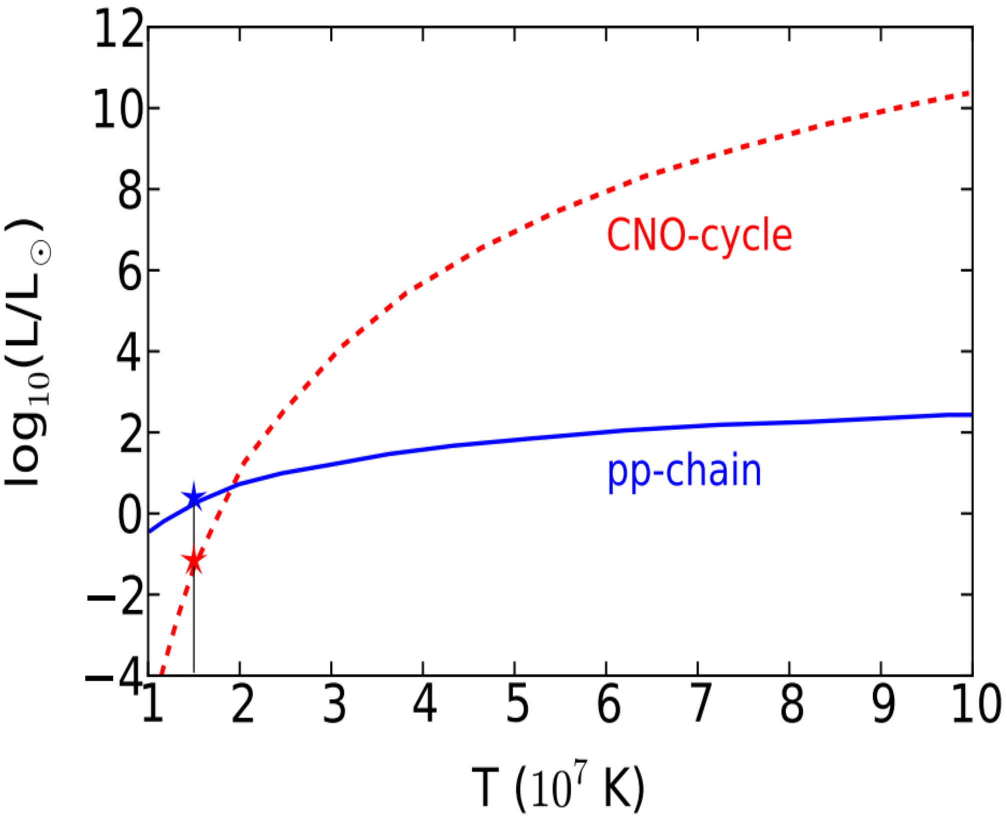


pp-chain

恒星的能源

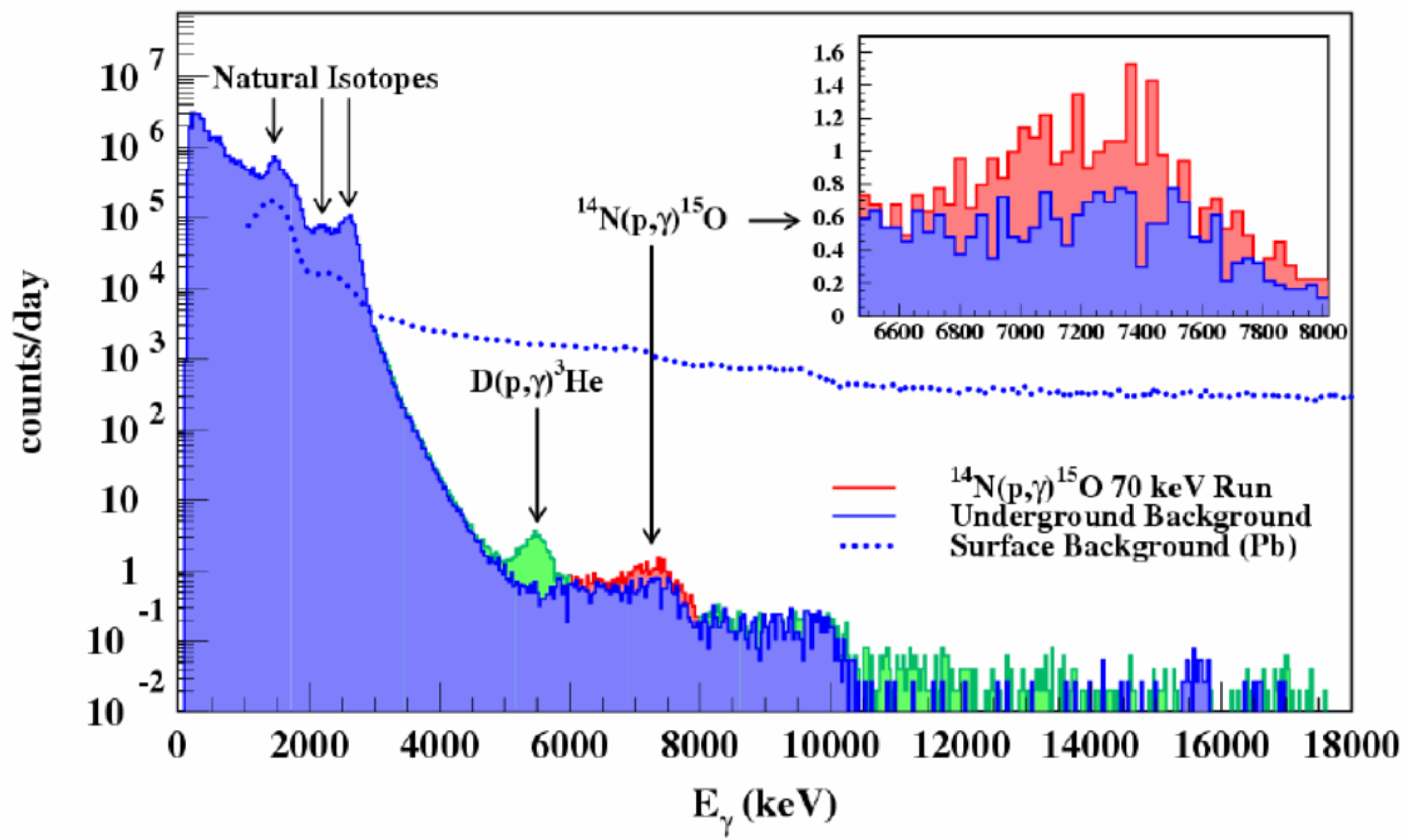
$$\varepsilon_{\mathrm{PPI}} = \frac{2.4\times10^{4}\,\rho X^{2} e^{\frac{-3.38}{T_9^{1/3}}}}{T_9^{2/3}}$$

$$\varepsilon_{\mathrm{CNO}} = \frac{4.4\times10^{25}\,\rho X Z e^{\frac{-15.2}{T_9^{1/3}}}}{T_9^{2/3}}$$



氢燃烧是恒星的主要能源。当恒星的质量变大时CNO循环会逐渐取代pp反应链成为恒星的主要能量来源。恒星的寿命由这一阶段的核过程持续时间控制

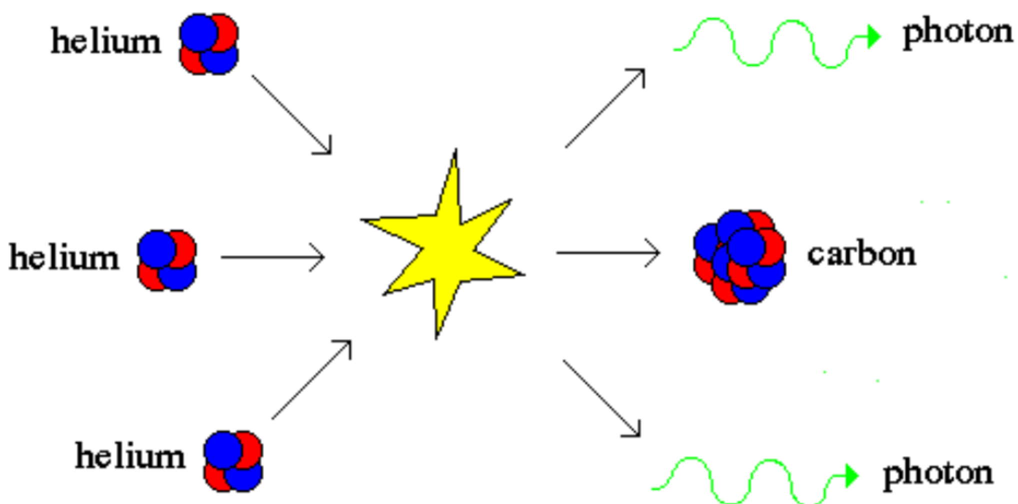
$^{14}N(p,\gamma)^{15}O$反应



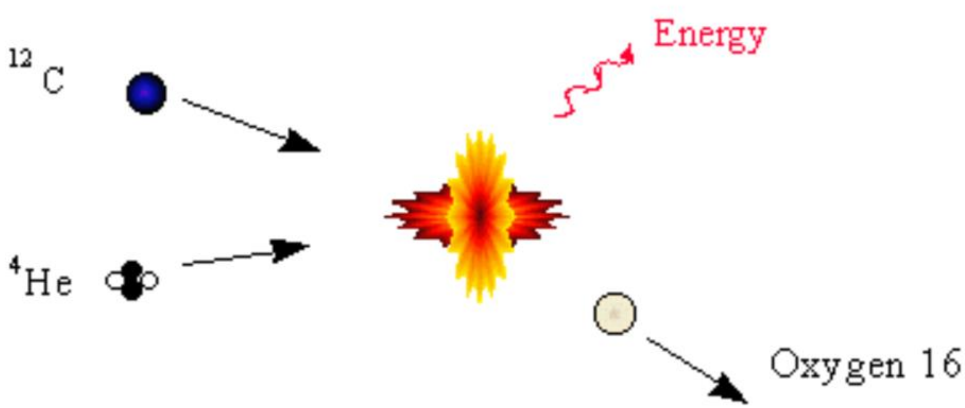
氦燃烧过程

$${}^{4}He_2 + {}^{4}He_2 + {}^{4}He_2 \longrightarrow {}^{12}C_6 + \gamma + \gamma$$

3α反应



${}^{12}C(\alpha, \gamma){}^{16}O$反应



3α过程

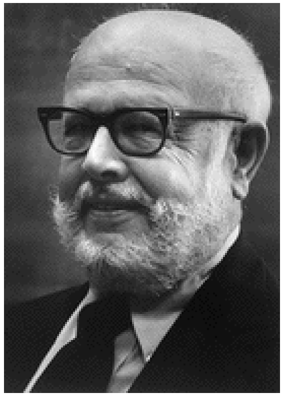
α+α ⇄ ^{8}Be (τ≈2.6 10^{-16} s)　　^{8}Be + α ⇄ ^{12}C*(7.7 MeV)

$$<\alpha\alpha\alpha> = 6\cdot 3^{3/2}\left(\frac{2\pi\hbar^2}{m_{4He}kT}\right)^3 \frac{\Gamma_\gamma}{\hbar} e^{-Q/kT}$$

$$Q/c^2 = m_{12C(7.7)} - 3m_\alpha$$

$$\varepsilon_{3\alpha} \approx 23.1\times\rho^2 X_\alpha^3\left(\frac{T}{2\cdot 10^8\,\mathrm{K}}\right)^{18.5}(\mathrm{erg/g/s})$$

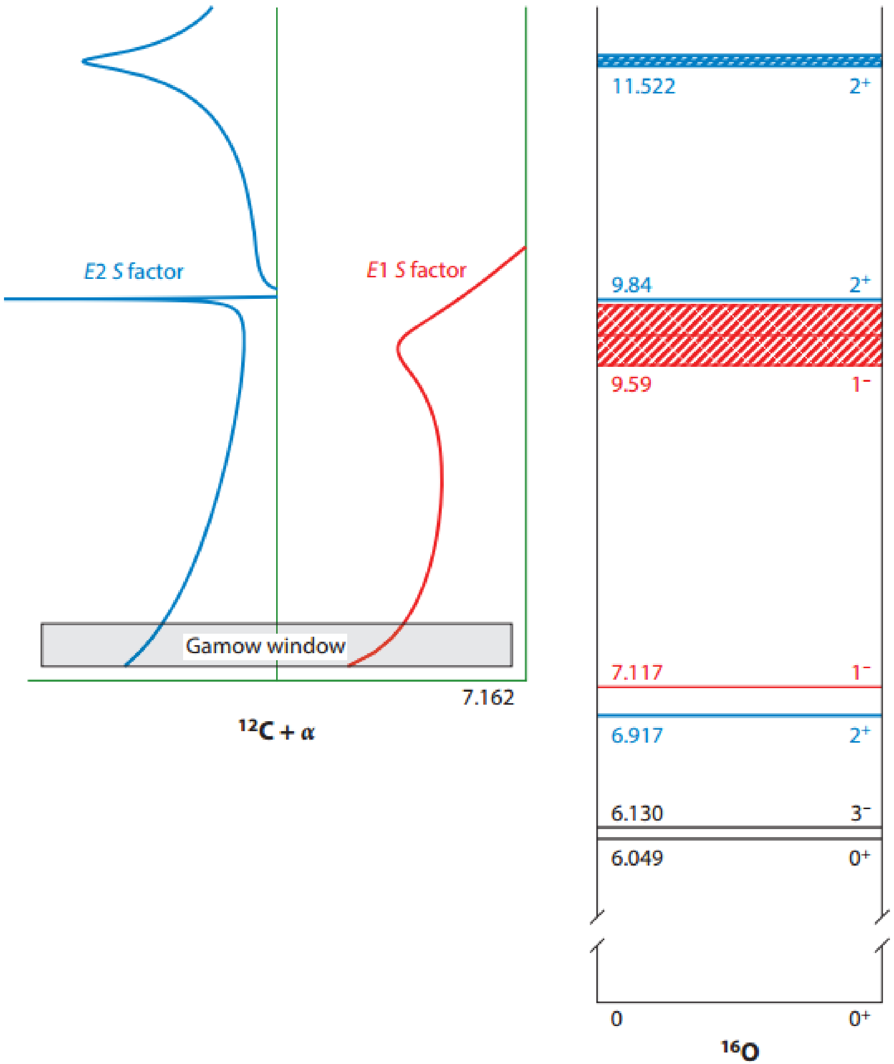
Hoyle state

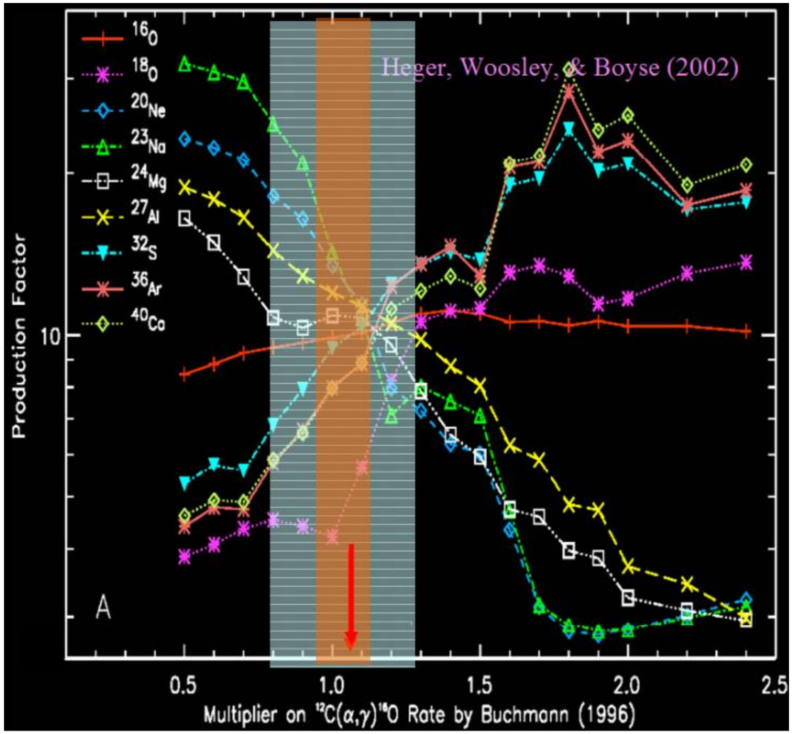


^{11}B(d,p)^{12}B*

1983 Nobel prize
实验核天体物理诞生！

$^{12}C(\alpha,\gamma)^{16}O$反应



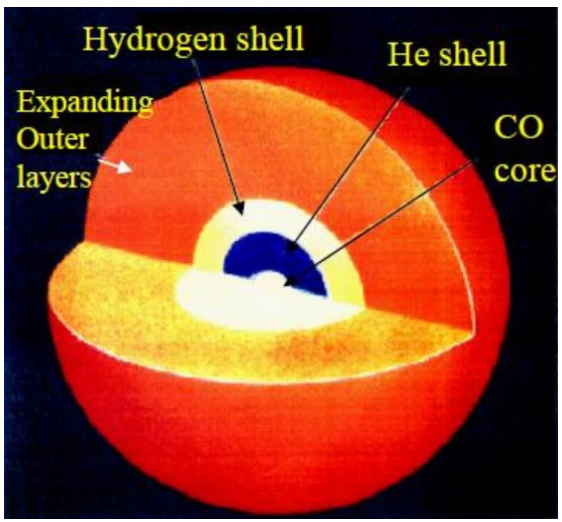


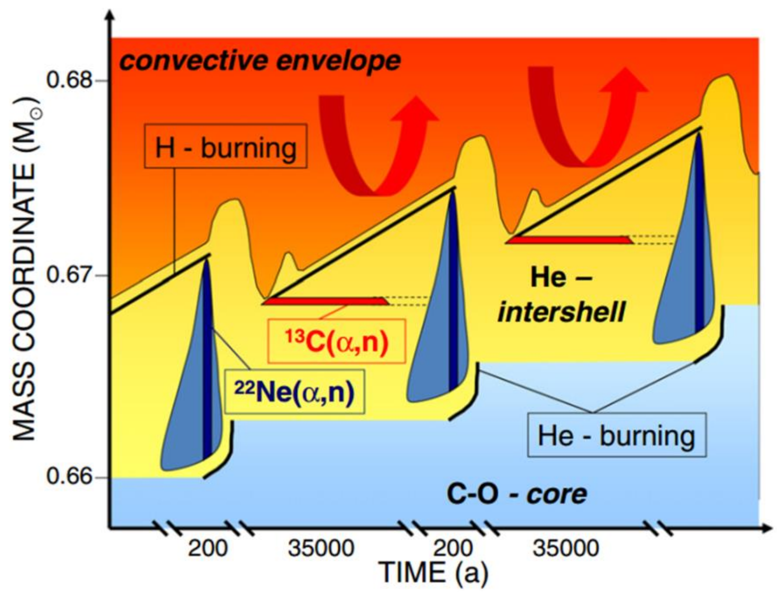
核天体物理中最重要的科学问题是确定氦燃烧过程中所决定的碳氧比. W. Fowler, Nobel lecture, 1983

核天体物理的圣杯反应

s-过程的中子源反应

$^{13}C(\alpha,n)^{16}O$：TP-AGB阶段的重要中子源，发生的温度条件是~$9T_7$-$2.7T_8$的低质量恒星(1.5-3$M_\odot$), 主要合成A~(90-209)核素。**$^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C(\alpha,n)^{16}O$**



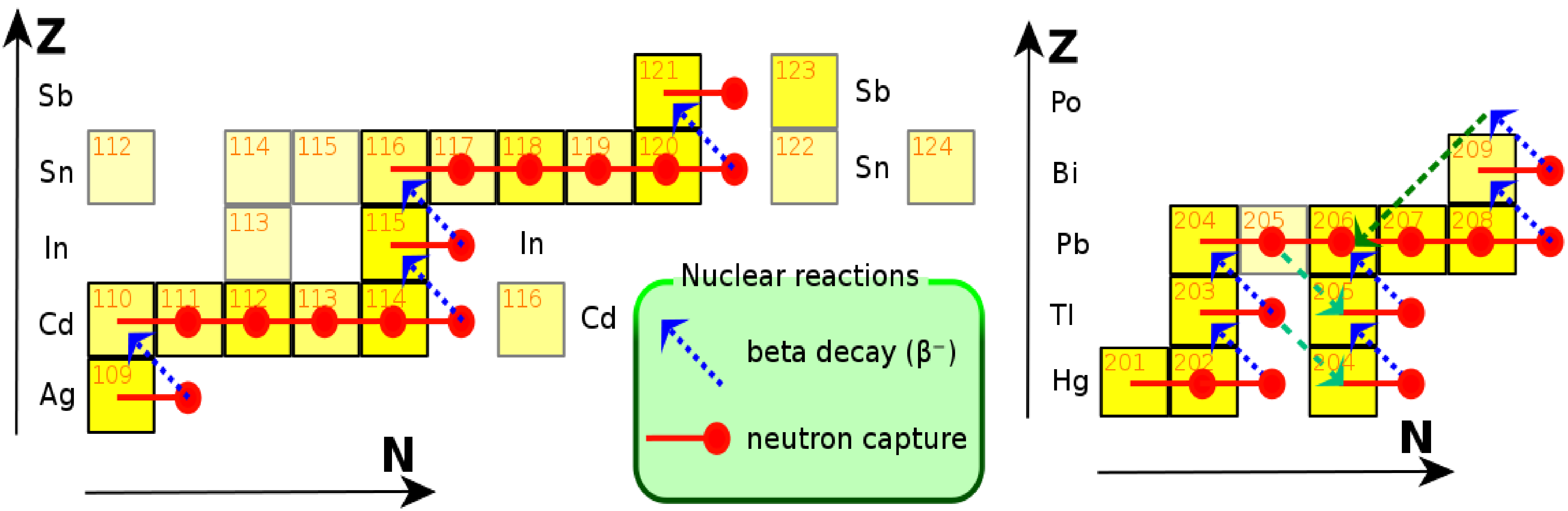


$^{22}Ne(\alpha,n)^{25}Mg$: 另一个中子源，发生的条件为温度 ~2.2-$3.5T_8$ 的大质量恒星M>8$M_\odot$。弱s过程，产生质量56−90的核素。

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

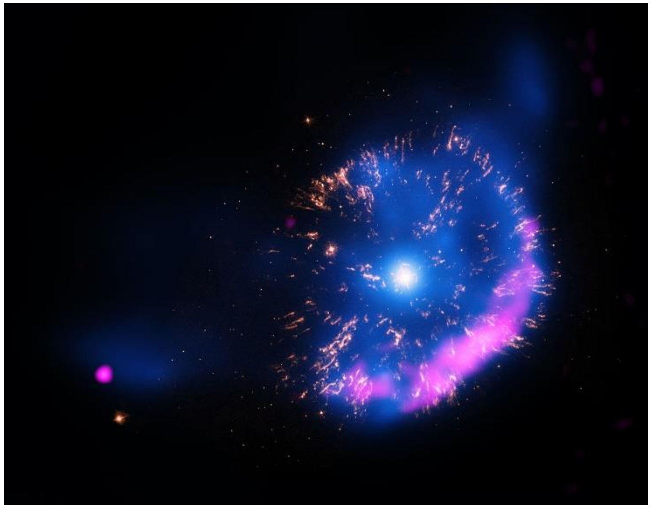
s-过程的特点

- 发生在氦燃烧阶段, 中子由$^{13}C(a, n)^{16}O$等反应现场产生
- 原子核增加中子的速度很慢, 过程中产生的不稳定核有足够的时间衰变
- 元素演化的路径位于原子核的稳定线附近
- s-过程不能远离稳定线的核素

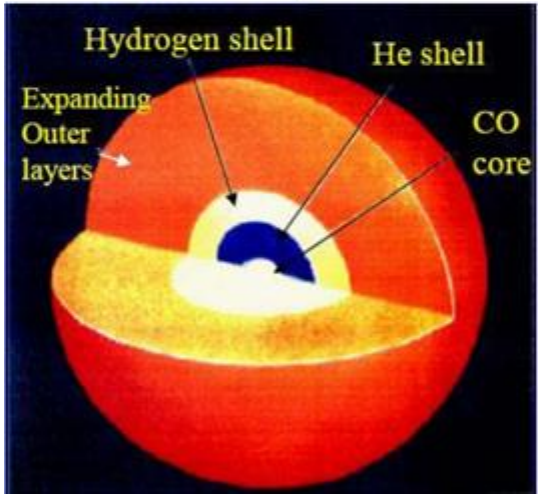


s-过程发生的场所

Wolf–Rayet star



Nova（T_9>0.1）



AGB star (T_9~0.05)

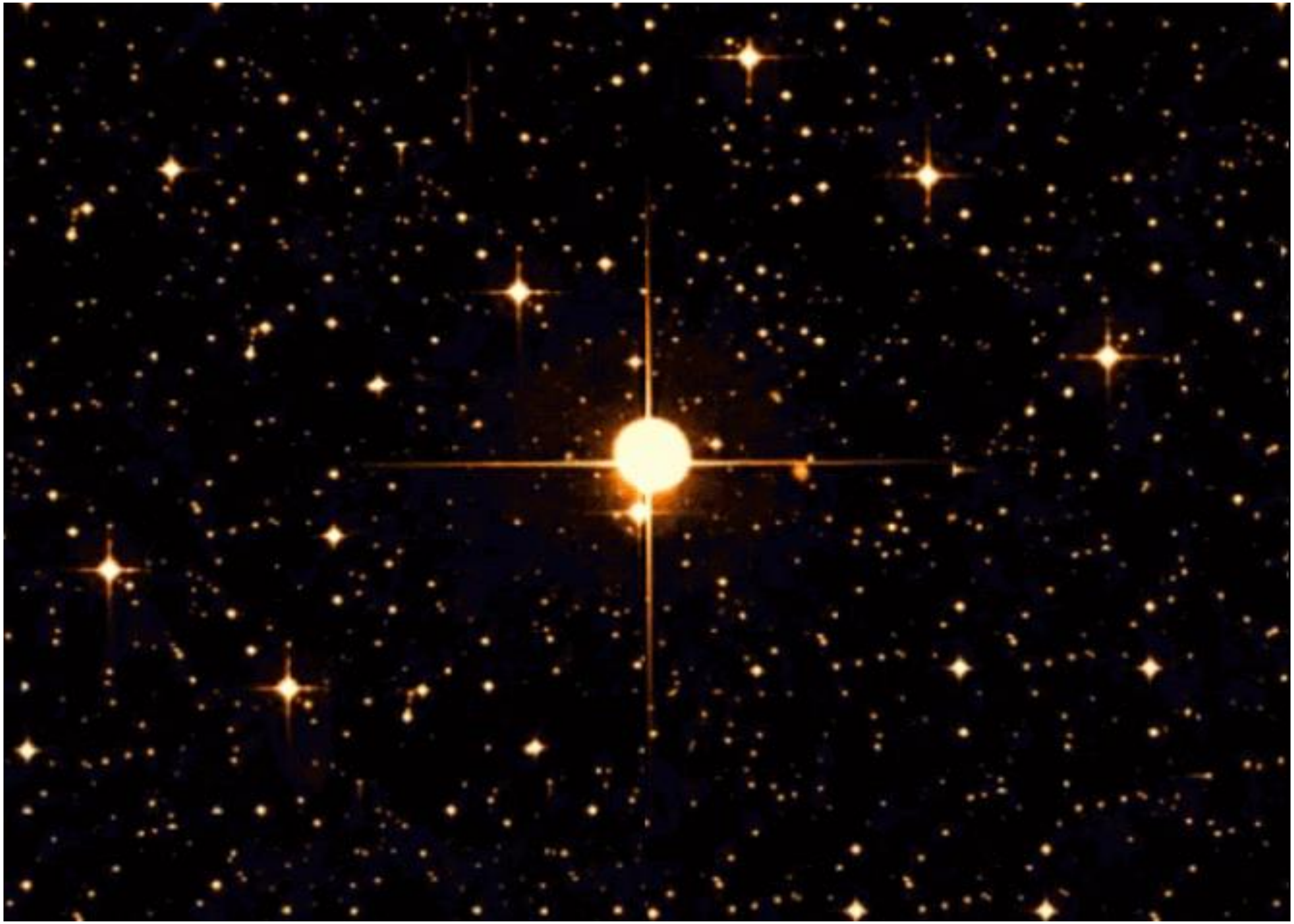
$$\tau_n \sim \frac{1}{n_n \sigma v} \sim \frac{3\times 10^{16} - 3\times 10^{17}}{n_n}\ \mathrm{s}.$$

时间尺度：10^2-10^6年

n_n~$10^{7\text{-}8}$/cm^3

核过程沿着β稳定线行进

大质量恒星的演化



碳、氖、氧燃烧

1. Carbon ~ 10^9 K

$^{12}C+^{12}C \rightarrow {}^{23}Na+p$

$\rightarrow {}^{20}Ne+\alpha$

$^{23}Na(p,\alpha)^{20}Ne$;

$^{20}Ne, ^{23}Na+ p,\alpha \rightarrow {}^{24\text{-}26}Mg$; ^{27}Al;….

2. Neon ~ 2×10^9 K

$^{20}Ne+\gamma \rightarrow {}^{16}O+\alpha$

$^{20}Ne+\alpha \rightarrow {}^{24}Mg$

$^{24}Mg(\alpha,\gamma)^{28}Si$; $^{25}Mg(\alpha,n)^{28}Si$;

$^{26}Mg(\alpha,n)^{29}Si$; $^{26}Mg(\alpha,\gamma)^{30}Si$; $^{27}Al(\alpha,p)^{30}Si$;

$^{30}Si(p,\gamma)^{31}P$

3. Oxygen ~ 3×10^9 K

$^{16}O+^{16}O \rightarrow {}^{28}Si+\alpha$

$\rightarrow {}^{31}P+p$

$\rightarrow {}^{31}S+n$

$\rightarrow {}^{28}Si$; ^{32}S

e过程

温度到达 4×10^9 K, ^{28}Si 的光致分裂导致硅分解:

$^{28}\text{Si}(\gamma,\text{p})^{27}\text{Al}$, $^{28}\text{Si}(\gamma,\alpha)^{24}\text{Mg}$,

一些弱束缚的核也开始分解:

Al, Mg, Ne, O $\rightarrow$ p, α, n

自由的中子、质子、α粒子被原子核俘获、释放，导致核统计平衡

$(\gamma,\text{p})\approx(\text{p},\gamma)$, $(\gamma,\alpha)\approx(\alpha,\gamma)$, $(\gamma,\text{n})\approx(\text{n},\gamma)$, $(\text{p},\text{n})\approx(\text{n},\text{p})$,..

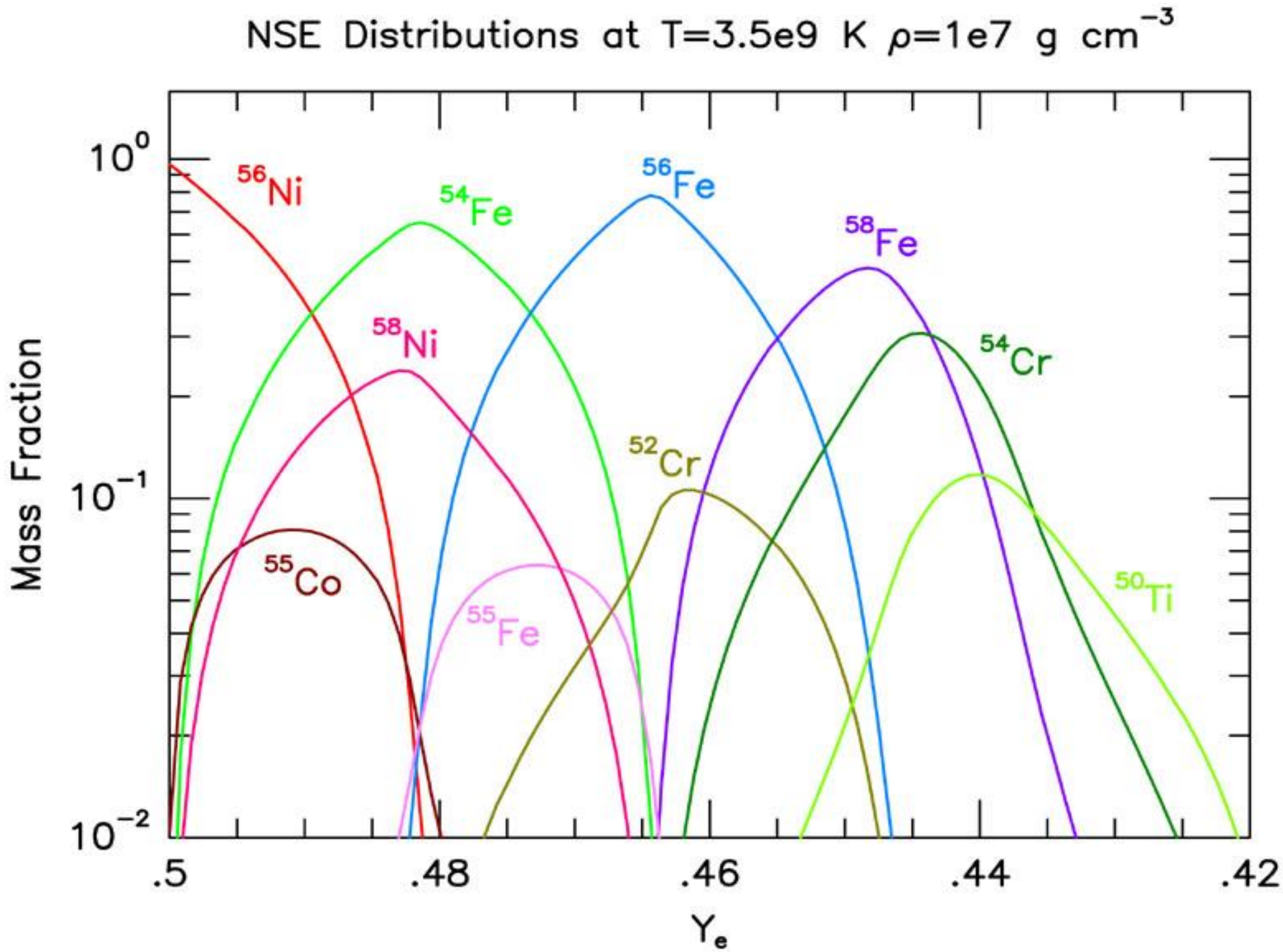
最终形成结合紧密的Fe、Ni峰

峰的分布由温度、环境的中子/质子比例、结合能决定

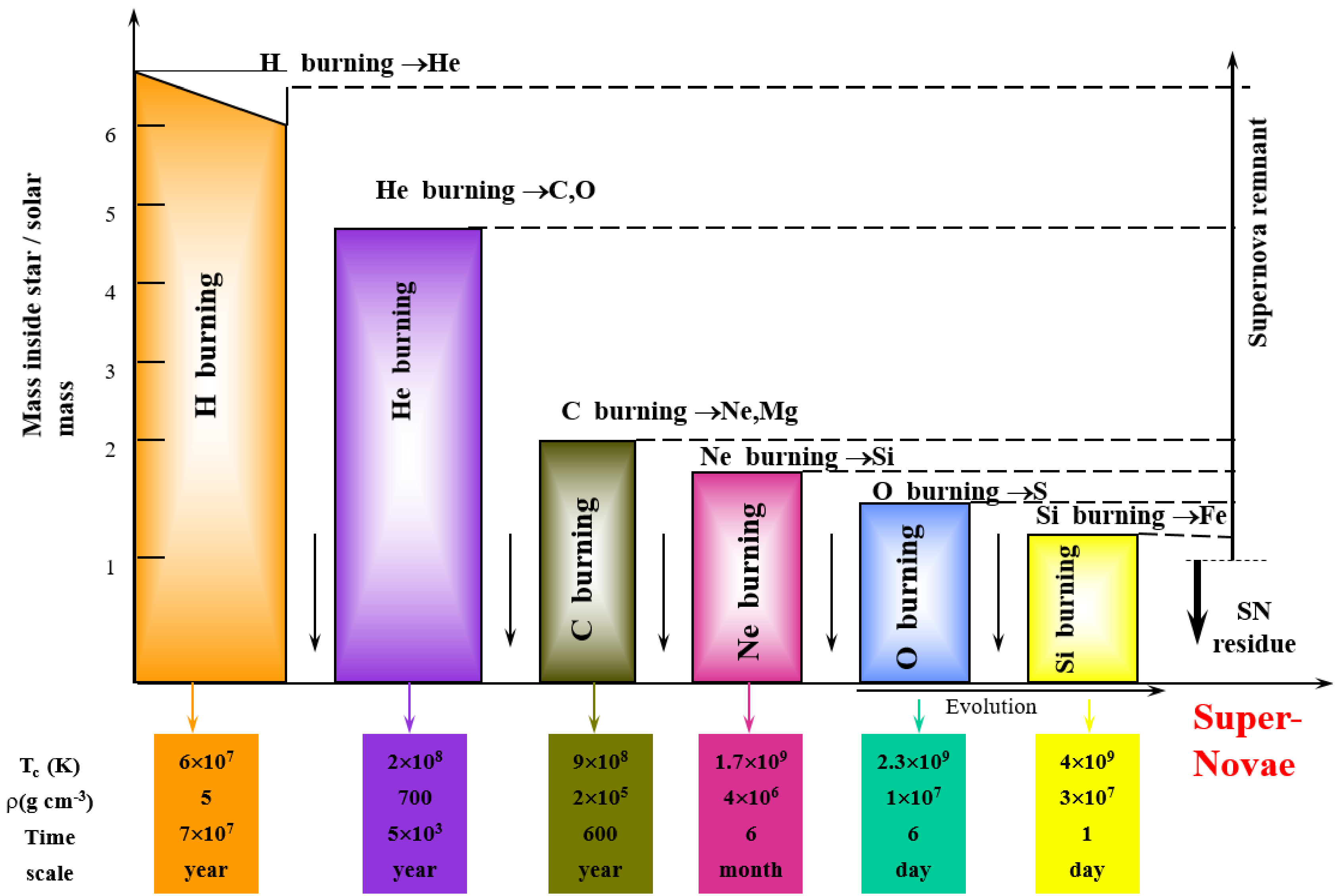
$$Z\cdot\mu_p+N\cdot\mu_n=\mu_{(\text{Z,N})} \qquad \mu=mc^2+kT\ln\left[\frac{n}{g}\left(\frac{h^2}{2\pi\, mkT}\right)^{3/2}\right]$$

$$Y(Z,N)=Y_p^Z Y_n^N G(Z,N)(\rho N_A)^{A-1}\frac{A^{3/2}}{2^A}\left(\frac{2\pi\hbar^2}{m_u kT}\right)^{\frac{3}{2}(A-1)} \mathrm{e}^{B(Z,N)/kT}$$

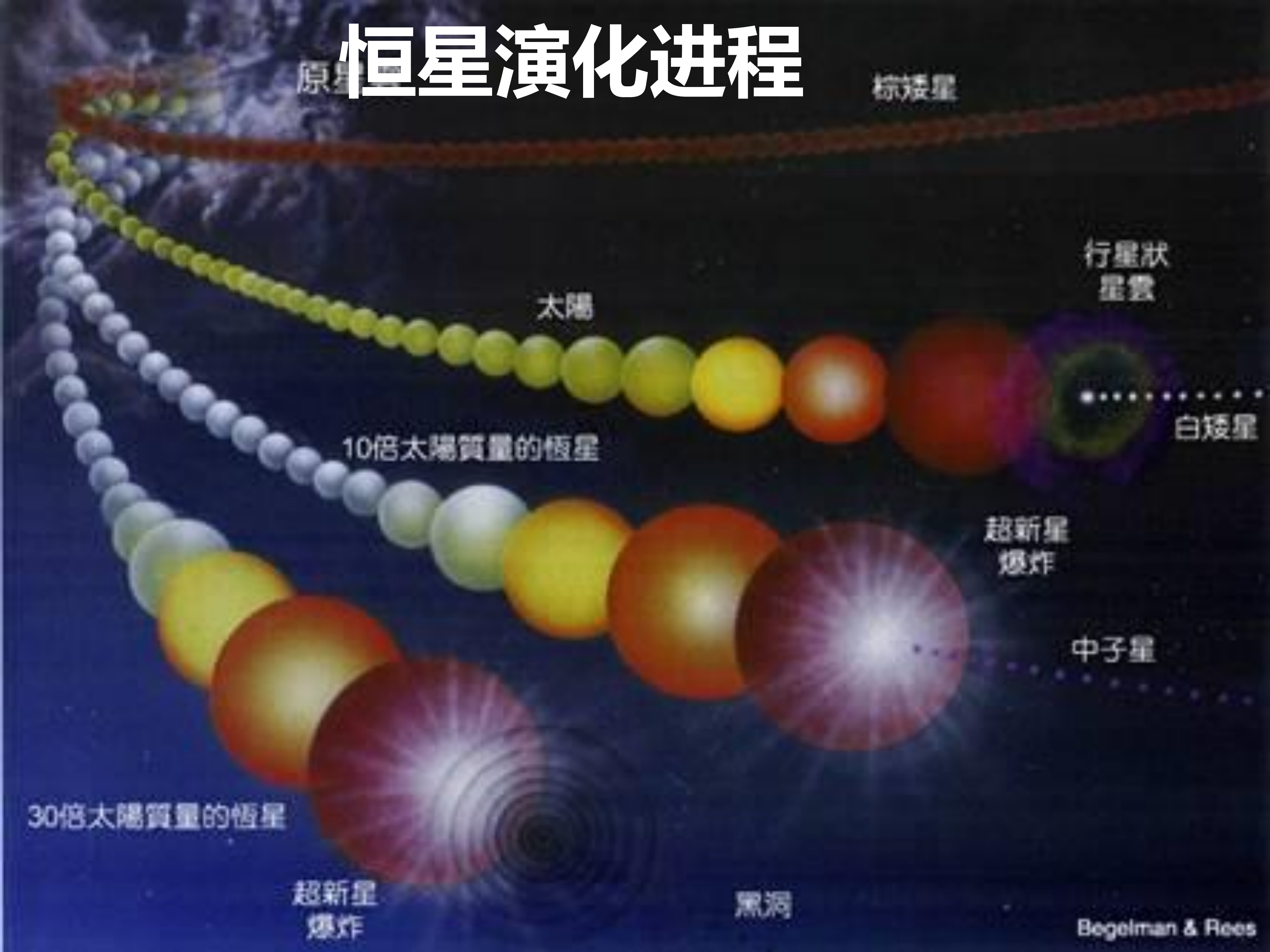
核统计平衡时的元素分布



25倍太阳质量的恒星演化过程



恒星演化进程

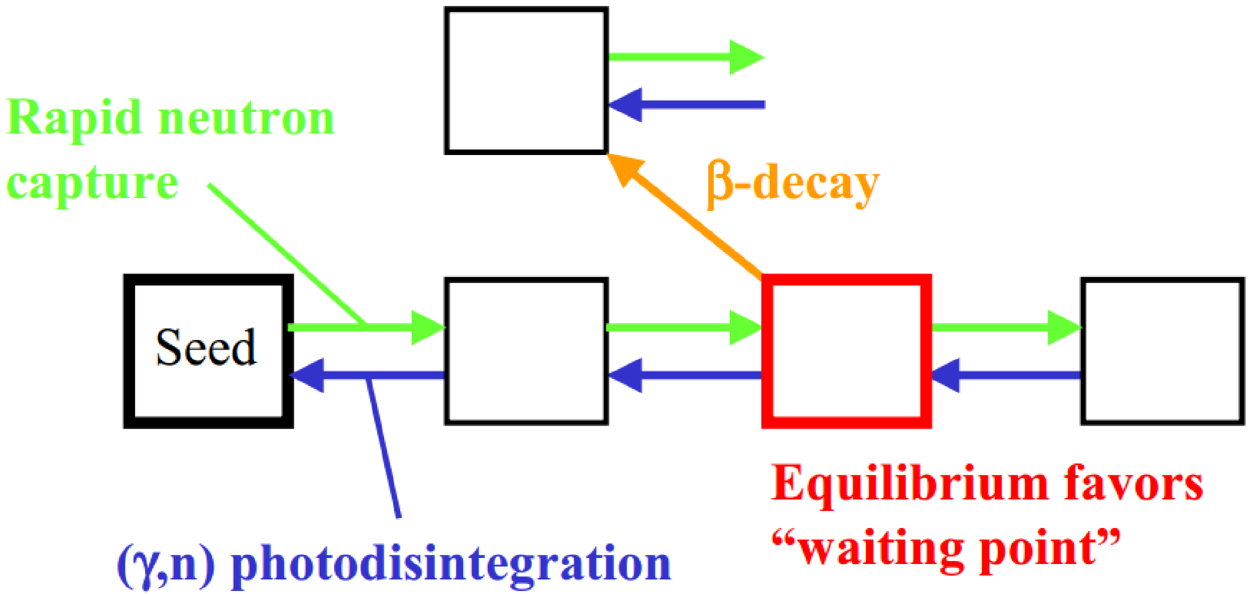

棕矮星
行星狀
星雲
太陽
白矮星
10倍太陽質量的恆星
超新星
爆炸
中子星
30倍太陽質量的恆星
超新星
爆炸
黑洞
Begelman & Rees

恒星爆炸过程

冲击波：中子、质子、中微子引发的核反应

r-过程模式

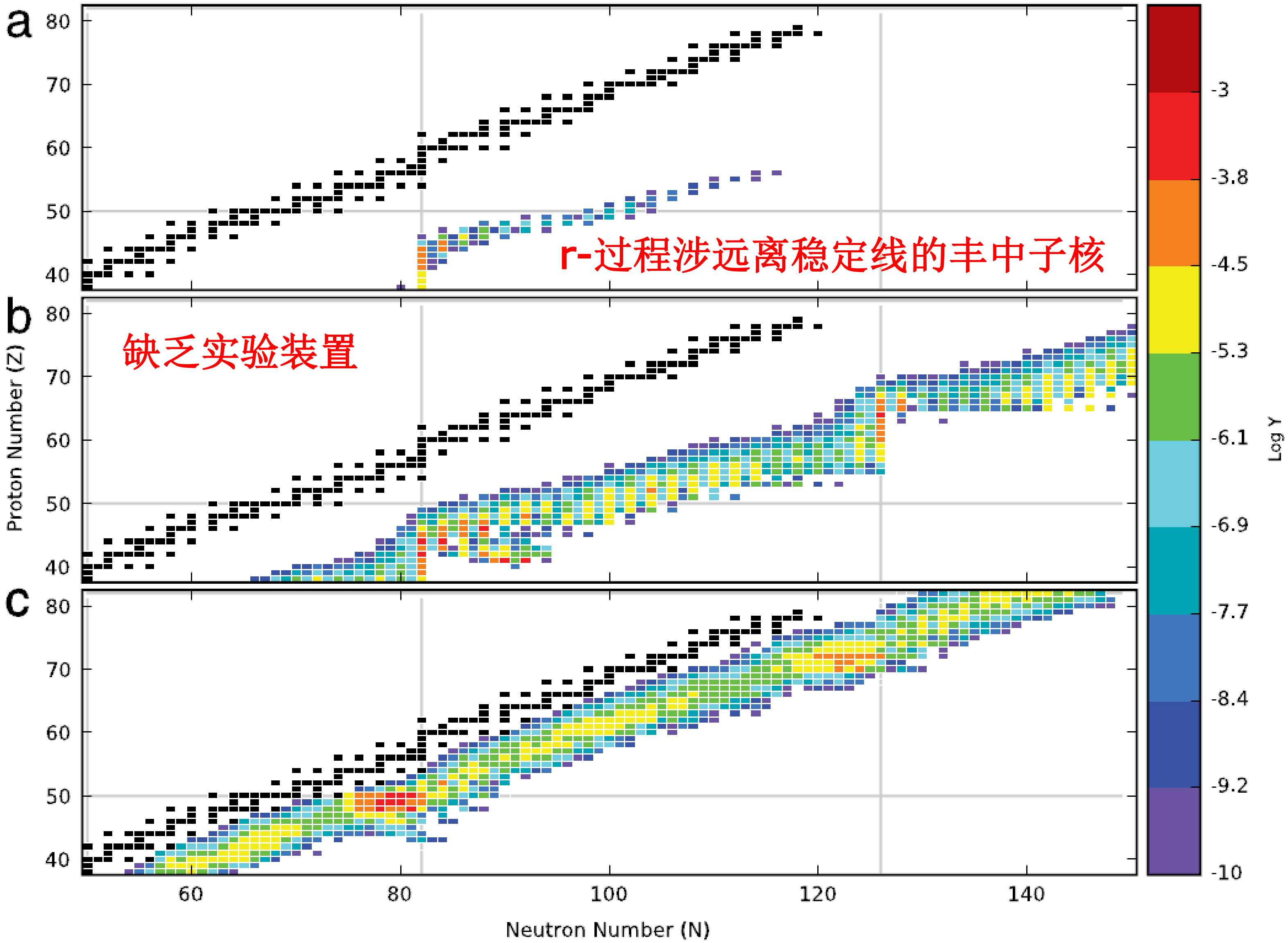
10-100 g/cm^3 neutrons →neutron capture timescale: ~ 0.2 μs



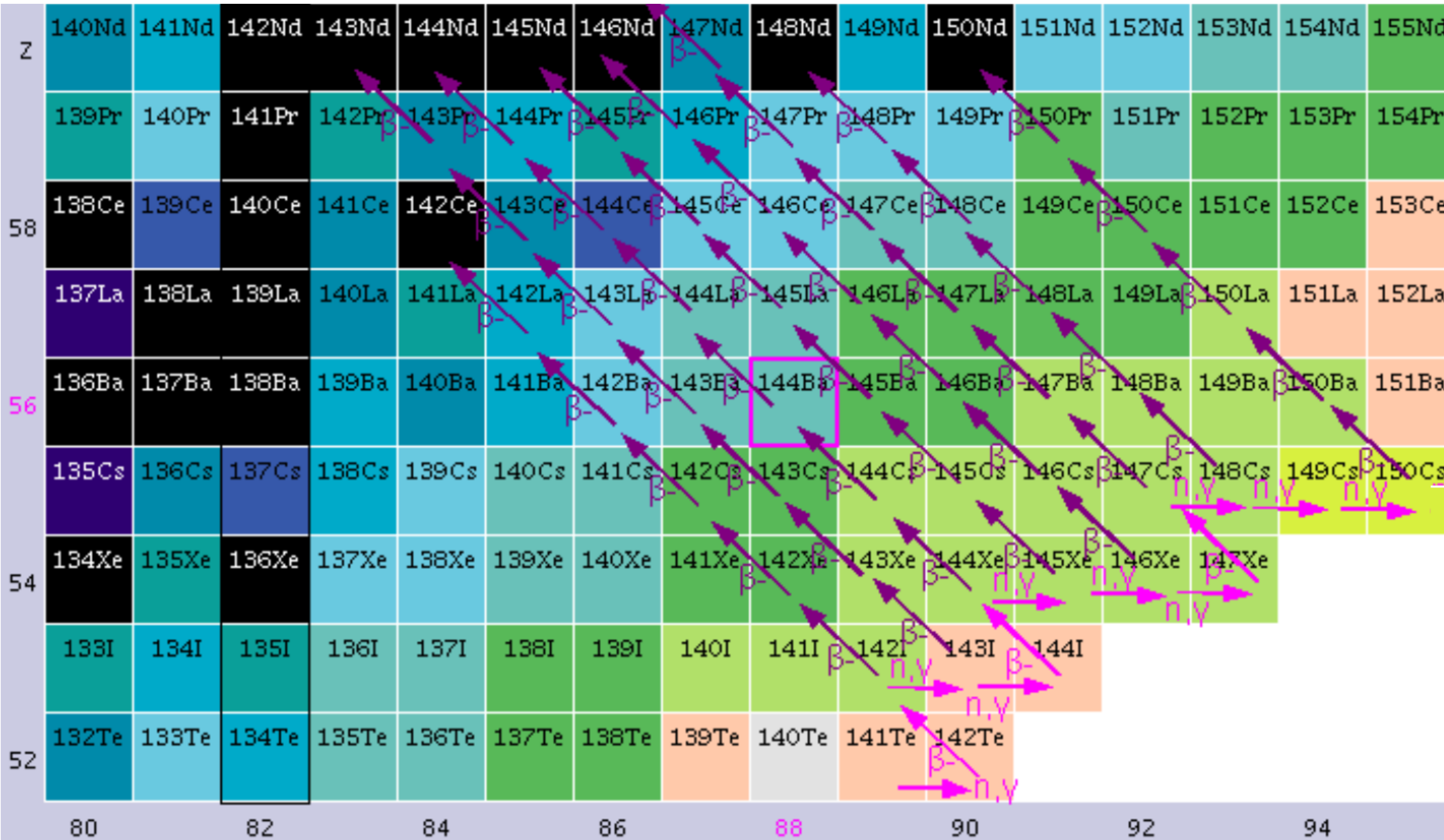
Location of path: $S_n = T_9/5.04 \times (34.08 + 1.5 \log T_9 - 1.5 \log n_n) = 2\text{-}4$ MeV

偶A核、幻数核、短半衰期的核是候选的等待点核

r–过程路径远离稳定线


a
b
c
r-过程涉远离稳定线的丰中子核
缺乏实验装置
Proton Number (Z)
Neutron Number (N)
Log Y
80
70
60
50
40
60
80
100
120
140
-3
-3.8
-4.5
-5.3
-6.1
-6.9
-7.7
-8.4
-9.2
-10

纯r-过程和纯s-过程核素



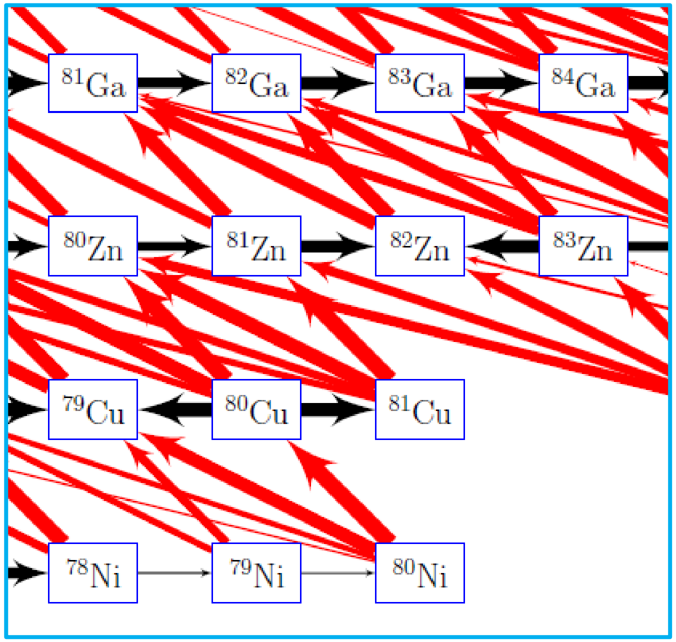
爆发性核合成的网络方程

生成

$$\frac{dN(Z,A)}{dt} = N(Z,A-1)\lambda_{n\gamma}^{Z,A-1} + N(Z,A+1)\lambda_{\gamma n}^{Z,A+1}$$
$$+ N(Z-1,A)\lambda_{\beta 0}^{Z-1,A} + \sum_k N(Z-1,A+k)\lambda_{\beta k n}^{Z-1,A+k}$$
$$+ N(Z+2,A+4)\lambda_{\alpha}^{Z+2,A+4}$$
$$- N(Z,A)[\lambda_{n\gamma}^{Z,A} + \lambda_{\gamma n}^{Z,A} + \lambda_{\beta}^{Z,A}]$$
$$- N(Z,A)[\lambda_{f}^{Z,A} + \lambda_{nf}^{Z,A} + \lambda_{\alpha}^{Z,A}]$$
$$+ \sum_f q_{Z_f,A_f}(Z,A)\lambda_f^{Z_f,A_f} N(Z_f,A_f)$$
$$+ \sum_f q^{\beta}_{Z_f,A_f}(Z,A)\lambda_{\beta f}^{Z_f-1,A_f} N(Z_f-1,A_f)$$
$$+ \sum_f q^{n}_{Z_f,A_f}(Z,A)\lambda_{nf}^{Z_f,A_f-1} N(Z_f,A_f-1)$$
$$+ \cdots,$$

消灭

其他带电粒子反应



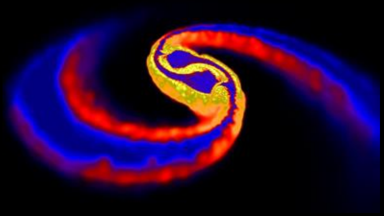
包括各种反应、衰变、裂变过程

温度高-激发态有重要贡献

时标短-衰变、中微子有重要贡献

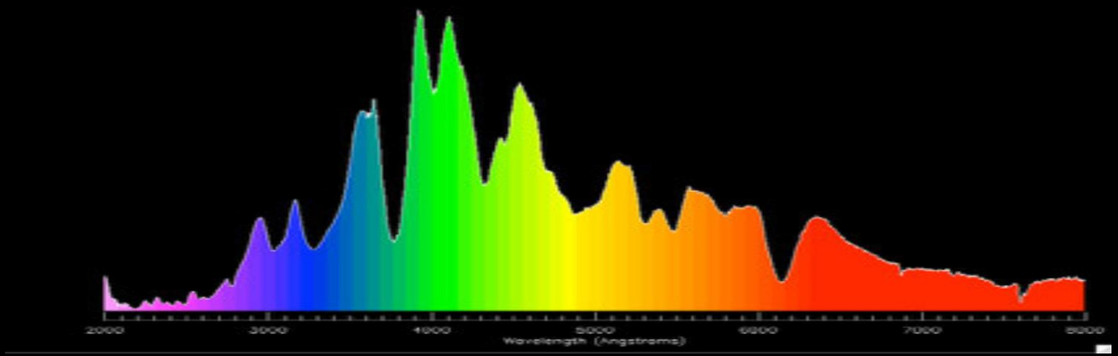
中子星并合过程

两体演化
10^6-10^9年



两体并合
毫秒-秒

辐射传输
数日

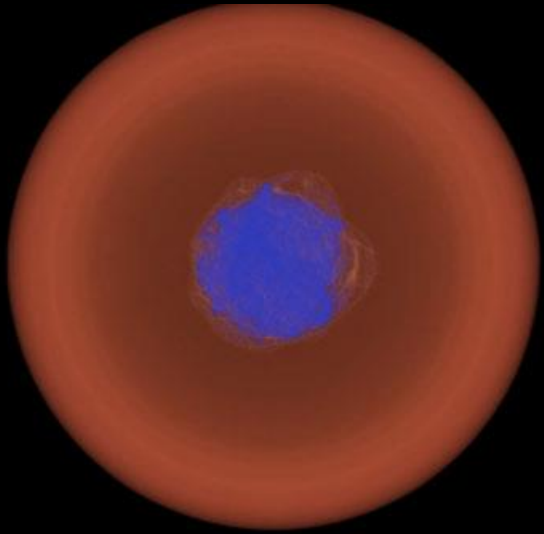


gamma-ray
x-ray
optical
radio

两种r-过程场所的比较

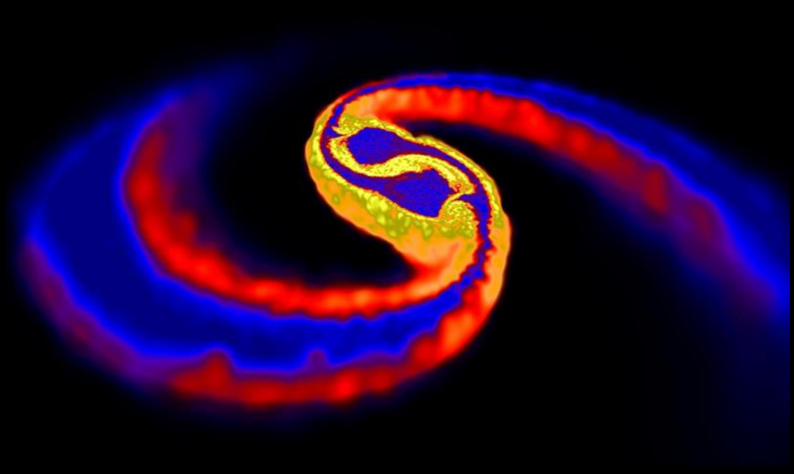
$n_e = N_p/(n_n+n_p) < 0.5$

core-collapse supernovae



中微子风驱动，质量小10^{-6}-10^{-5} $M_\odot$
亮度大，r-过程的纯低

neutron star merger

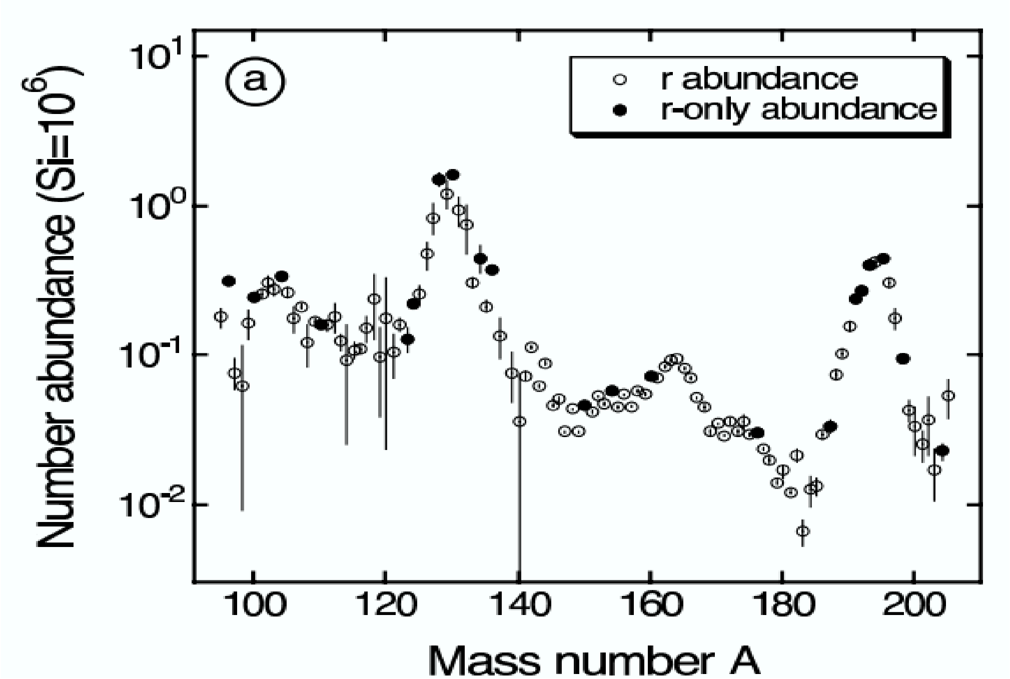


动力学抛射，盘风，10^{-4}-10^{-2} $M_\odot$
亮度暗，r-过程的纯度高

T =1-2 GK， n_n~10^{24} /cm^3　时间尺度：< 1 s

r-过程核的丰度

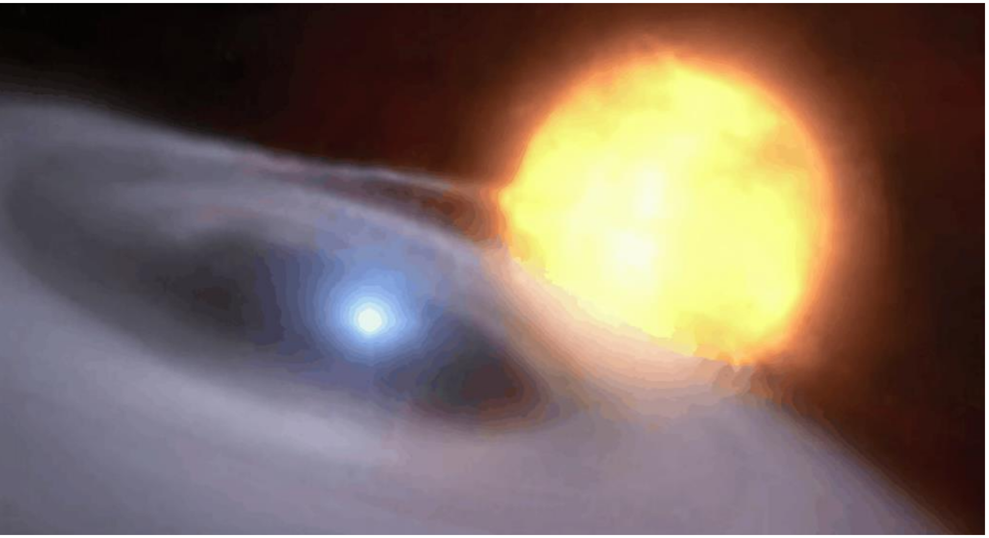
$$N_r(A,Z) = N_\odot(A,Z) - N_s(A,Z) = N_\odot(A,Z) - \frac{\langle\sigma\rangle_{A,Z} N_s(A,Z)}{\langle\sigma\rangle_{A,Z}}$$

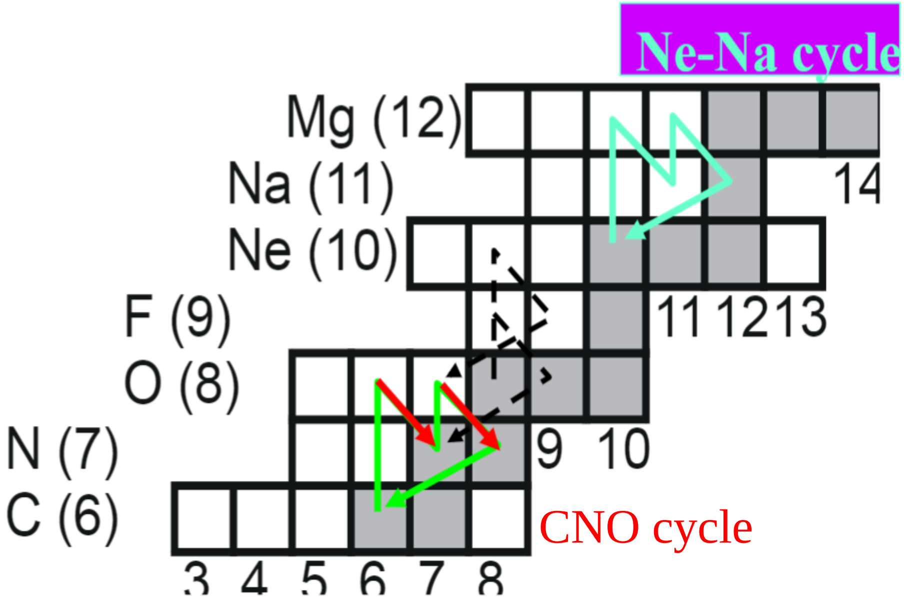


$$\frac{dN(Z,A)}{dt} = -N_n N(Z,A)\langle\sigma v\rangle_{Z,A} + N(Z,A+1)\lambda_\gamma(Z,A+1)$$

$$\frac{N(Z,A+1)}{N(Z,A)} = N_n \left(\frac{h^2}{2\pi m_{An} kT}\right)^{3/2} \frac{(2j_{Z,A+1}+1)}{(2j_{Z,A}+1)(2j_n+1)} \frac{G^{norm}_{Z,A+1}}{G^{norm}_{Z,A}} e^{Q_{n\gamma}/kT}$$

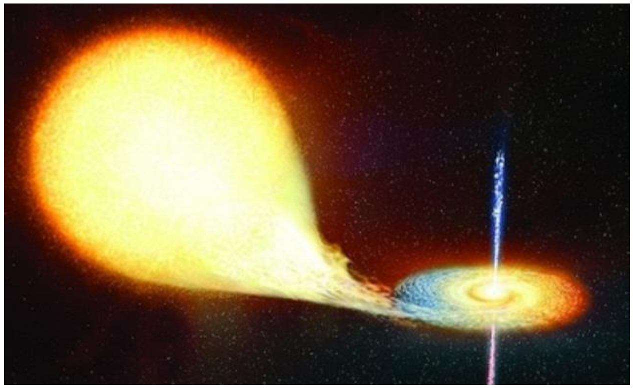
双星吸积引发的核合成

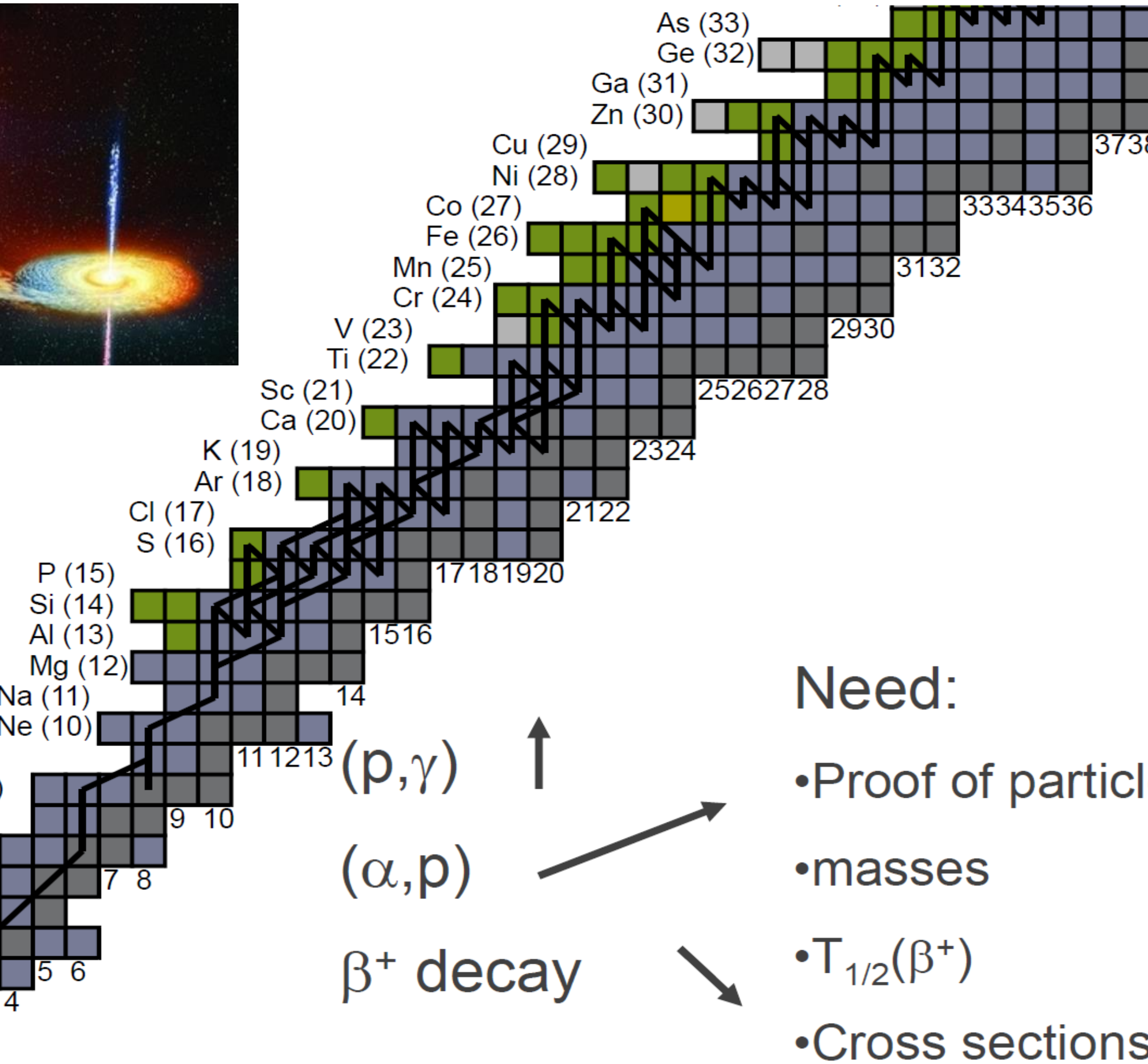




致密星为白矮星时，CO被吸积加热到一定的程度，会诱发热CNO循环反应。（新星）

快速质子俘获(rp-)过程

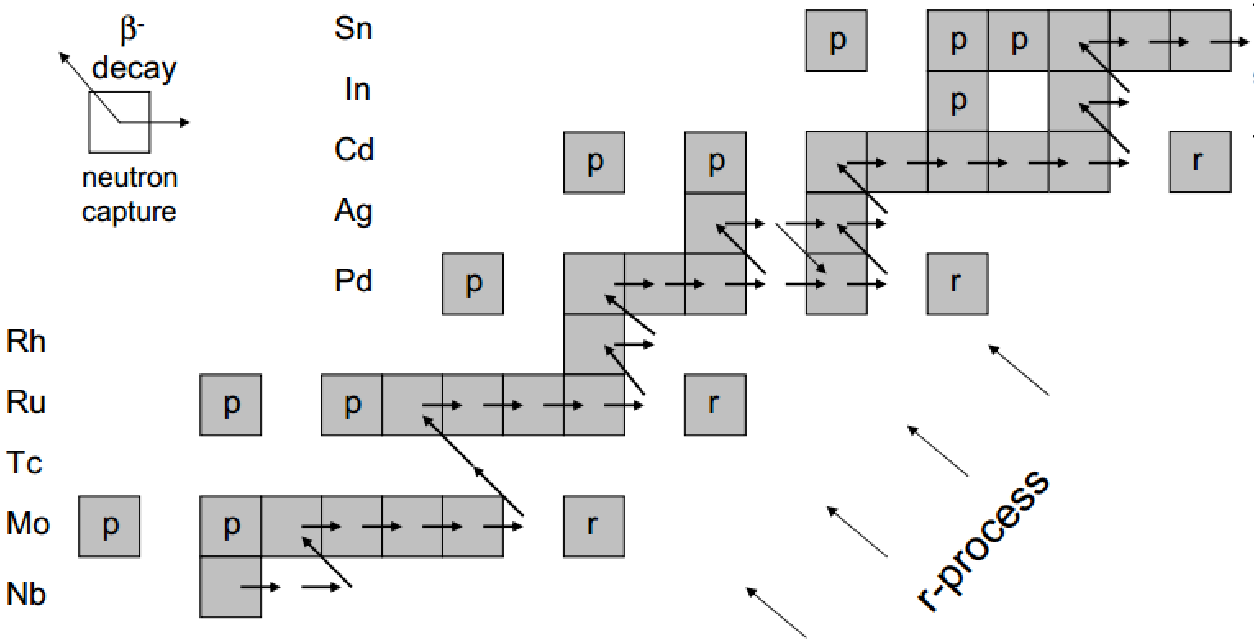




Need:

- Proof of particle stability
- masses
- $T_{1/2}(\beta^+)$
- Cross sections

p-process



^{74}Se – ^{196}Hg

时标：~1 s

Type II supernova

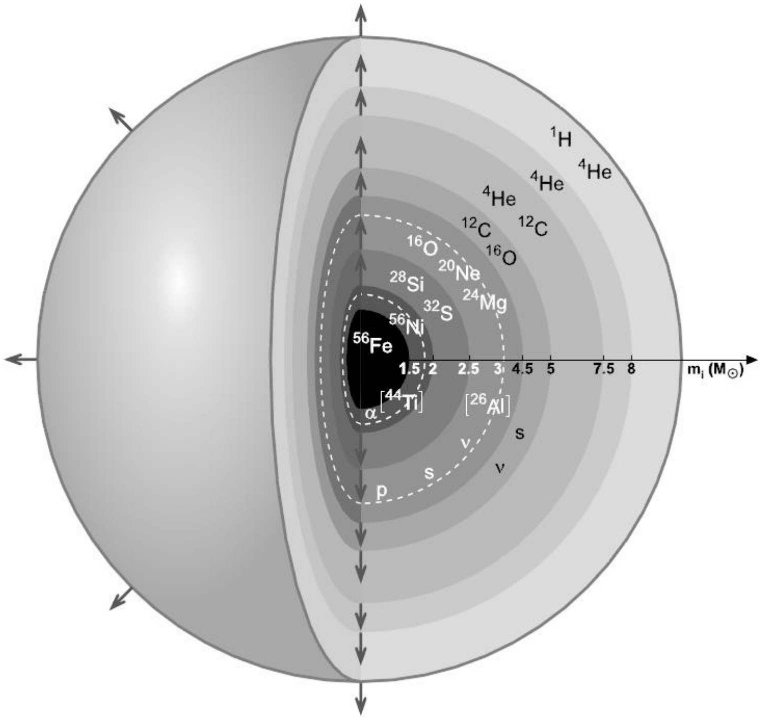
T~2-3 GK

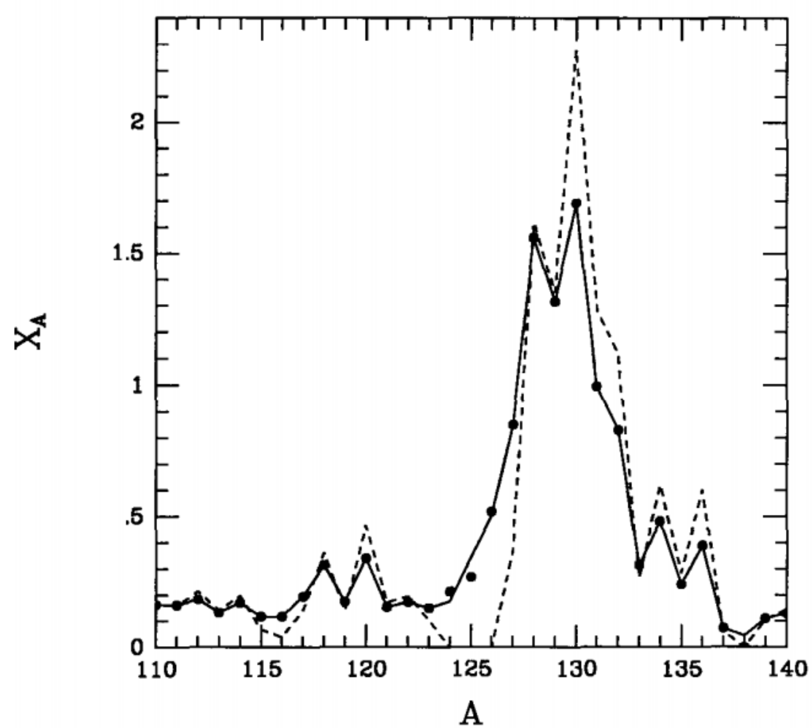
(γ,p),(γ,α),rp-,ν-process

Nucleus	Z	Solar system abundance (Si = 10^6)	Isotopic abundance (%)
^{113}In	49	$7.9 \cdot 10^{-3}$	4.3
^{112}Sn	50	$3.72 \cdot 10^{-2}$	0.97
^{114}Sn	50	$2.52 \cdot 10^{-2}$	0.66
^{115}Sn	50	$1.29 \cdot 10^{-2}$	0.34
^{120}Te	52	$4.3 \cdot 10^{-3}$	0.09
^{124}Xe	54	$5.71 \cdot 10^{-3}$	0.12
^{126}Xe	54	$5.09 \cdot 10^{-3}$	0.11
^{130}Ba	56	$4.76 \cdot 10^{-3}$	0.11
^{132}Ba	56	$4.53 \cdot 10^{-3}$	0.1
^{138}La	57	$4.09 \cdot 10^{-4}$	0.09
^{136}Ce	58	$2.16 \cdot 10^{-3}$	0.19
^{138}Ce	58	$2.84 \cdot 10^{-3}$	0.25
^{144}Sm	62	$8.0 \cdot 10^{-3}$	3.1
^{152}Gd	64	$6.6 \cdot 10^{-4}$	0.2
^{156}Dy	66	$2.21 \cdot 10^{-4}$	0.06
^{158}Dy	66	$3.78 \cdot 10^{-4}$	0.10
^{162}Er	68	$3.51 \cdot 10^{-4}$	0.14
^{164}Er	68	$4.04 \cdot 10^{-3}$	1.61
^{168}Yb	70	$3.22 \cdot 10^{-4}$	0.13
^{174}Hf	72	$2.49 \cdot 10^{-4}$	0.16
^{180}Ta	73	$2.48 \cdot 10^{-6}$	0.01
^{180}W	74	$1.73 \cdot 10^{-4}$	0.13
^{184}Os	76	$1.22 \cdot 10^{-4}$	0.02
^{190}Pt	78	$1.7 \cdot 10^{-4}$	0.01
^{196}Hg	80	$5.2 \cdot 10^{-4}$	0.15

35 nuclei

中微子引发的核反应





$$\phi \sim \frac{4 \cdot 10^{57}}{4\pi(20000\mathrm{km})^2} \sim 10^{38} \quad \mathrm{cm}^{-2}$$

$$^{20}\mathrm{Ne}(\nu,\nu')^{20}\mathrm{Ne}^* \rightarrow ^{19}\mathrm{Ne} + n \rightarrow ^{19}\mathrm{F} + e^+ + \nu_e + n$$

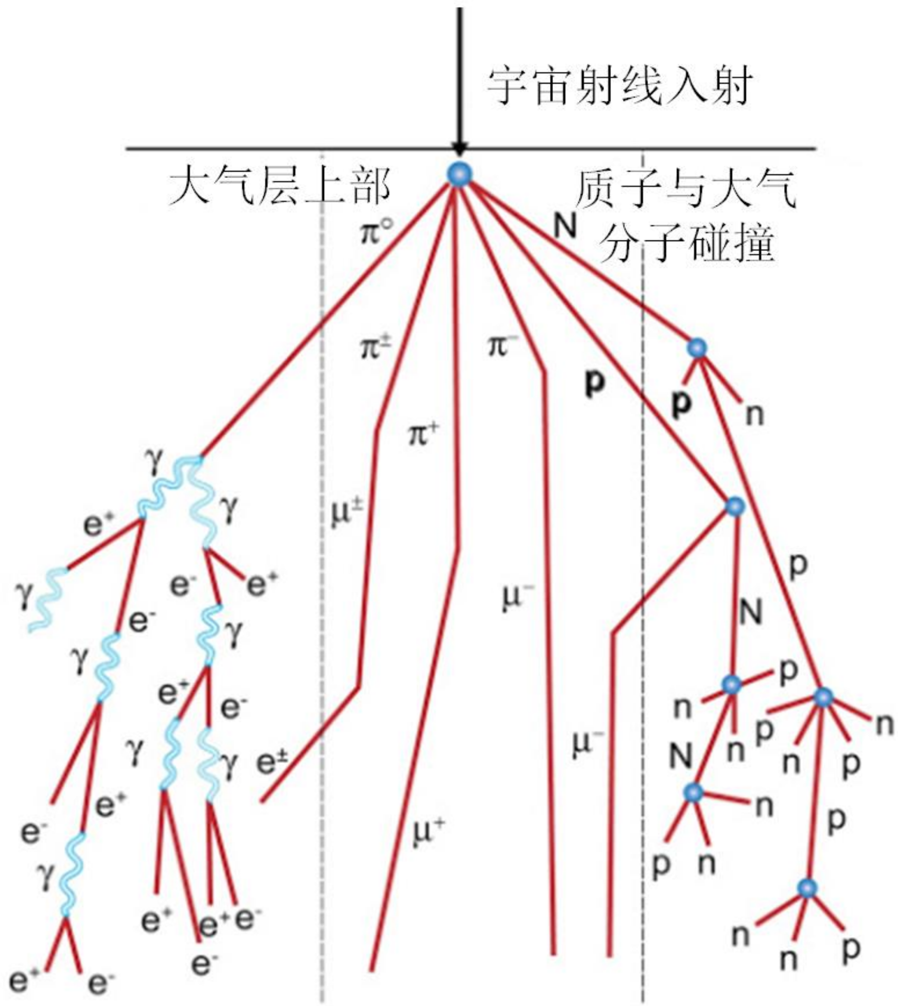
$$^{20}\mathrm{Ne}(\nu,\nu')^{20}\mathrm{Ne}^* \rightarrow ^{19}\mathrm{F} + p$$

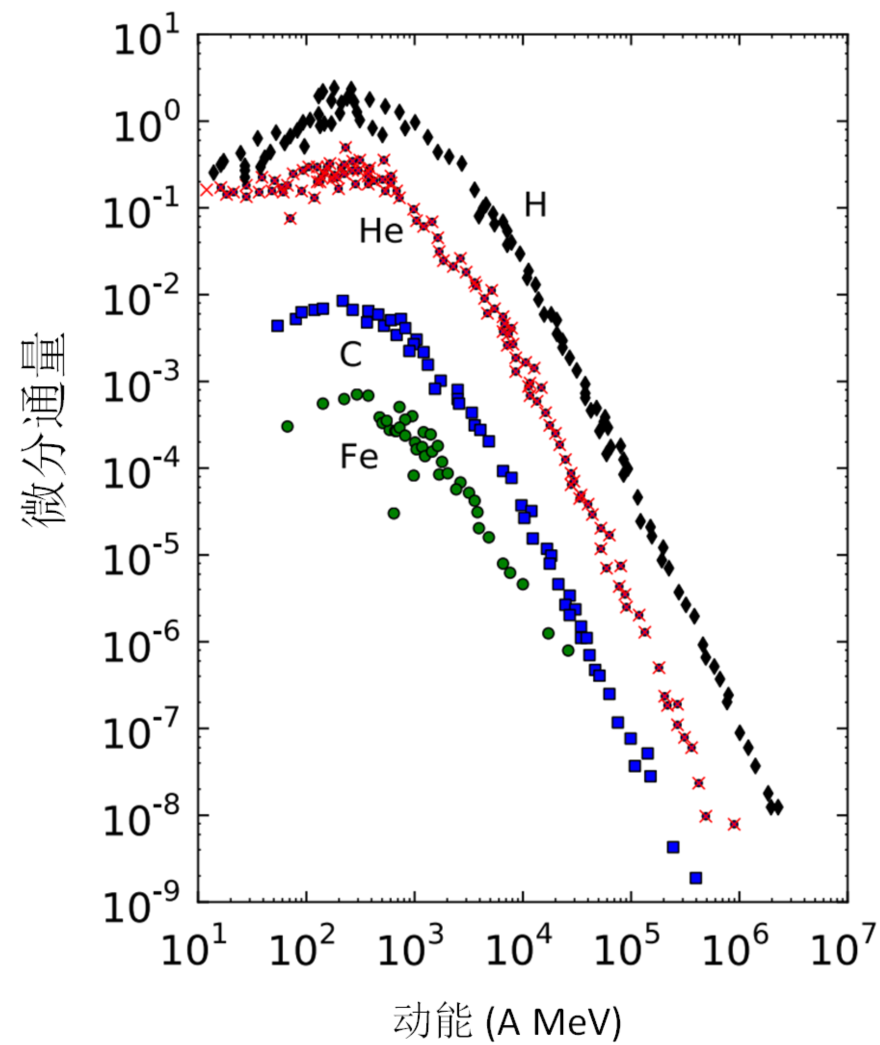
$$\frac{^{19}\mathrm{F}}{^{20}\mathrm{Ne}} = \frac{1}{3100} \longrightarrow \frac{1}{300}$$

是否考虑中微子效应的丰度差别

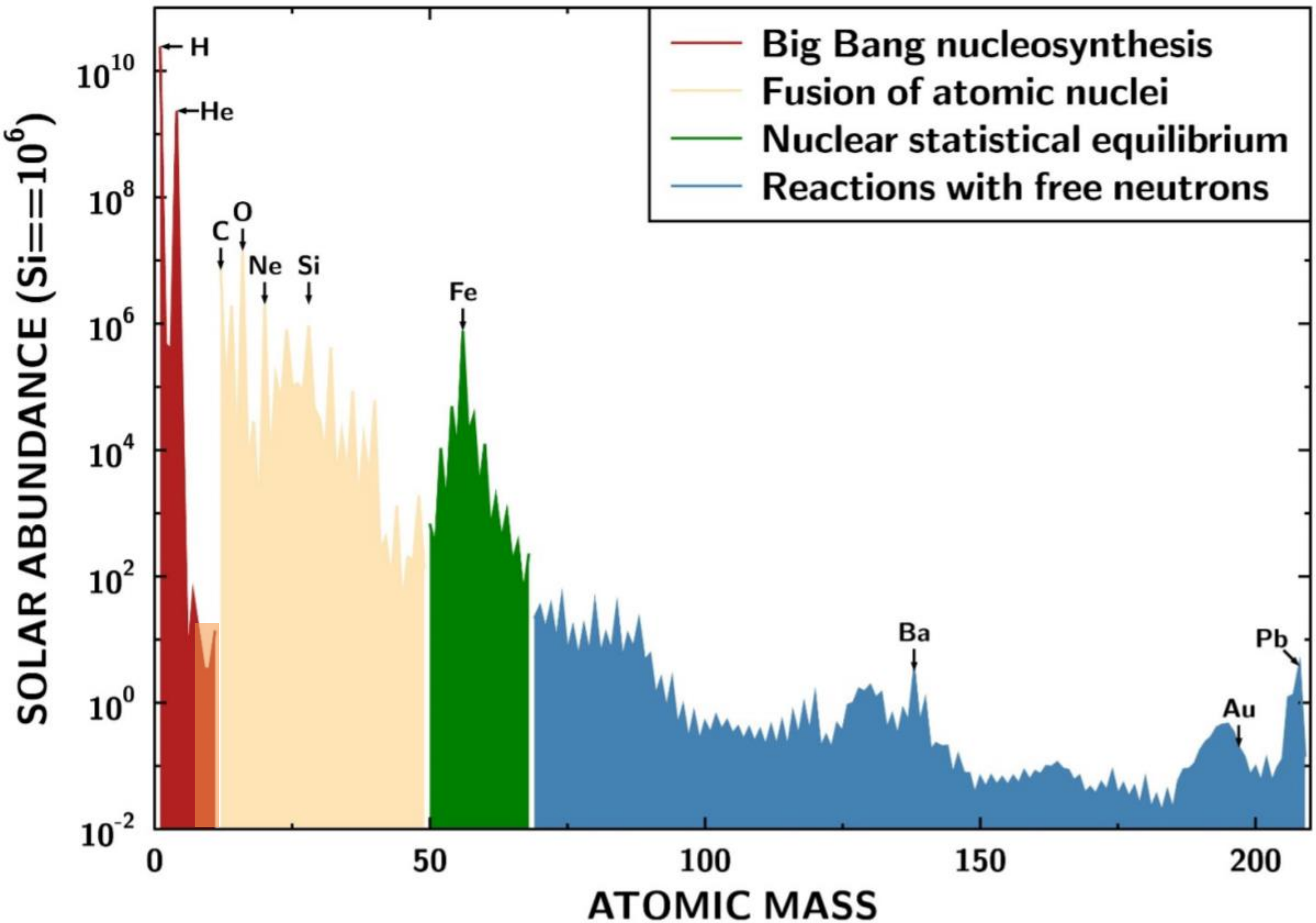
中微子的冲击波能够调节恒星物质的中子/质子比例，从而影响最终核素丰度。

宇宙射线诱发的核过程



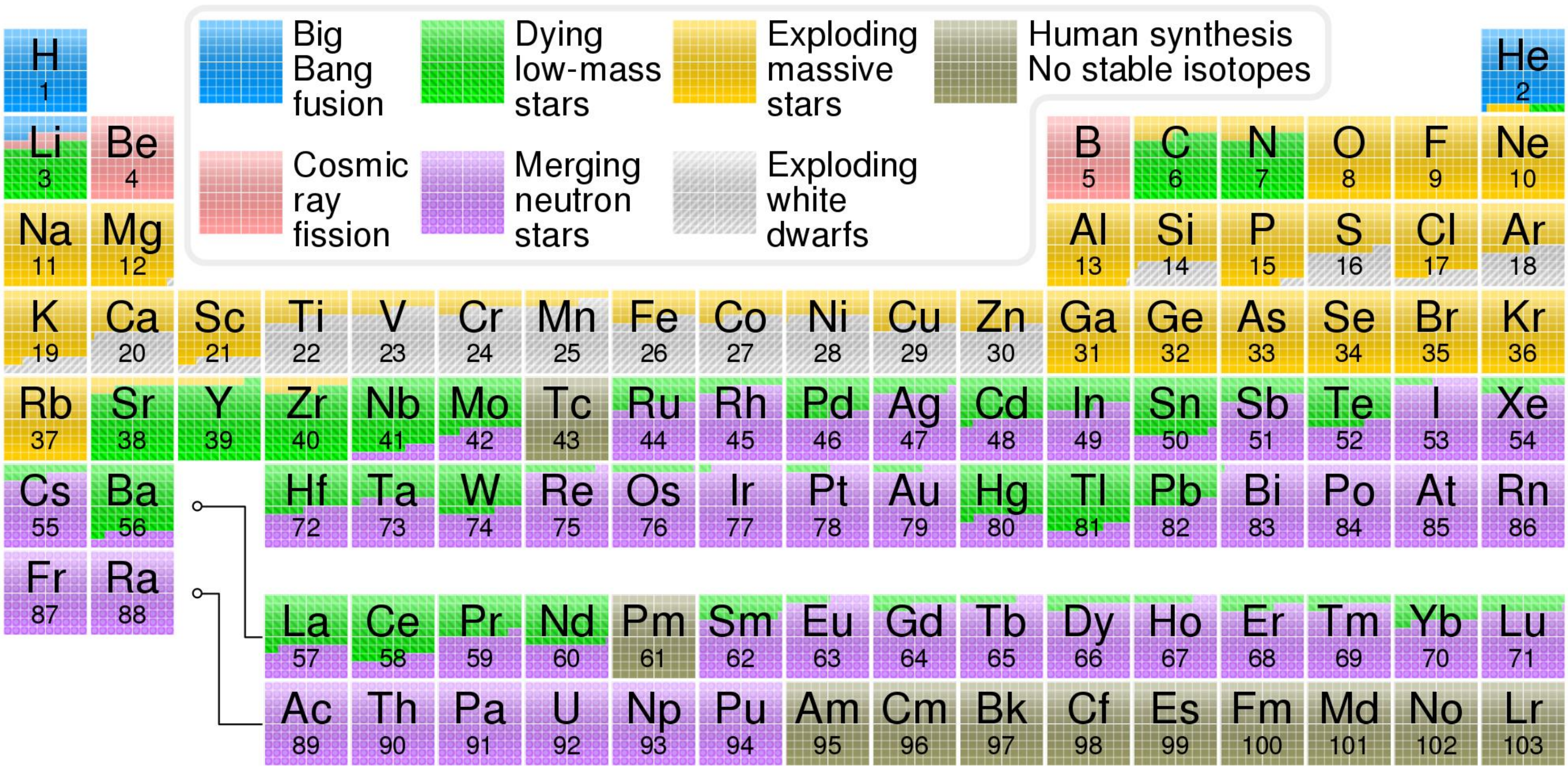


元素的丰度&起源

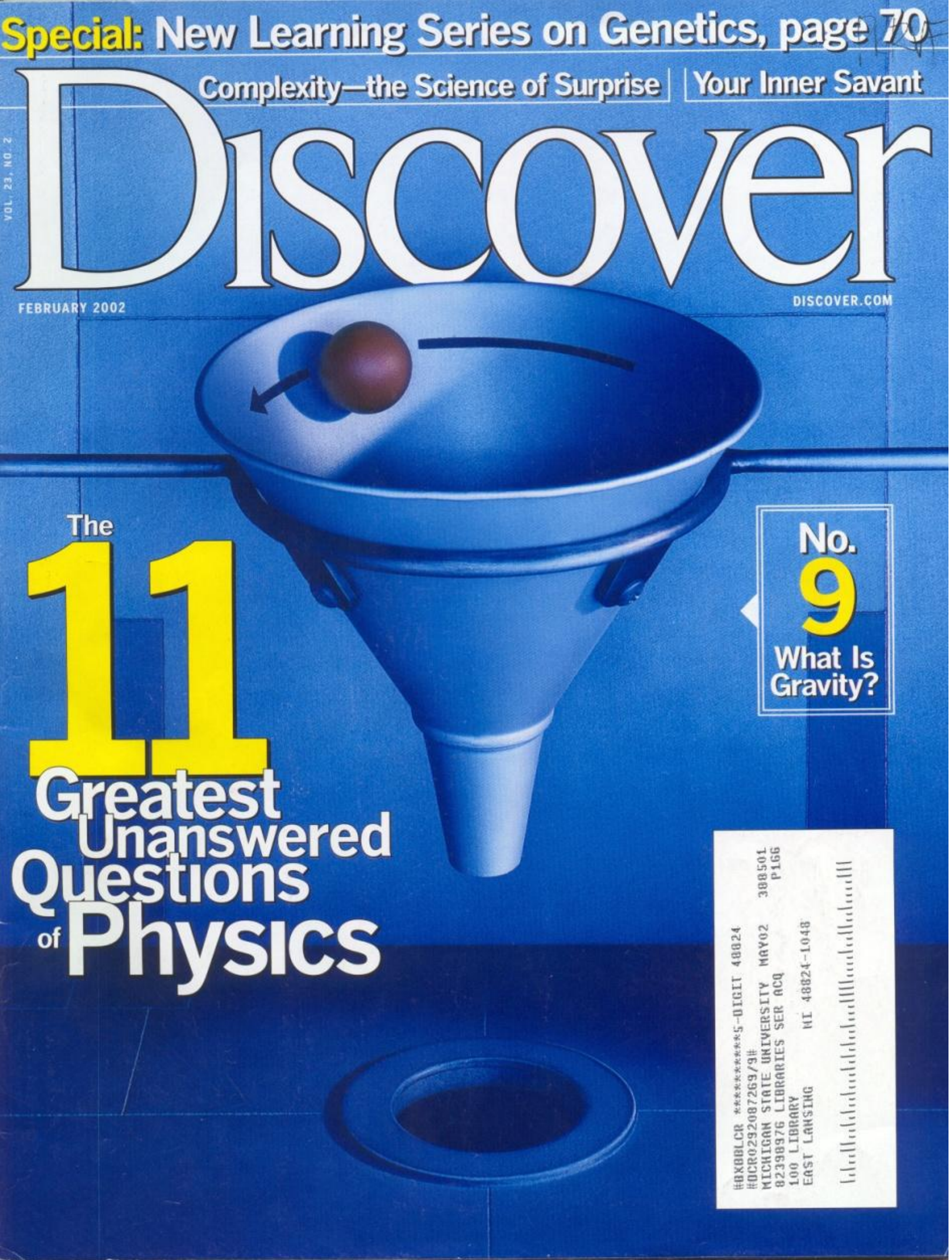


Big Bang nucleosynthesis
Fusion of atomic nuclei
Nuclear statistical equilibrium
Reactions with free neutrons
SOLAR ABUNDANCE (Si==10^6)
10^10
10^8
10^6
10^4
10^2
10^0
10^-2
H
He
C
O
Ne
Si
Fe
Ba
Au
Pb
0
50
100
150
200
ATOMIC MASS

宇宙中元素的起源



Big Bang fusion
Dying low-mass stars
Exploding massive stars
Human synthesis No stable isotopes
Cosmic ray fission
Merging neutron stars
Exploding white dwarfs
H 1
He 2
Li 3
Be 4
B 5
C 6
N 7
O 8
F 9
Ne 10
Na 11
Mg 12
Al 13
Si 14
P 15
S 16
Cl 17
Ar 18
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
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
Cs 55
Ba 56
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
Fr 87
Ra 88
La 57
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
Ac 89
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

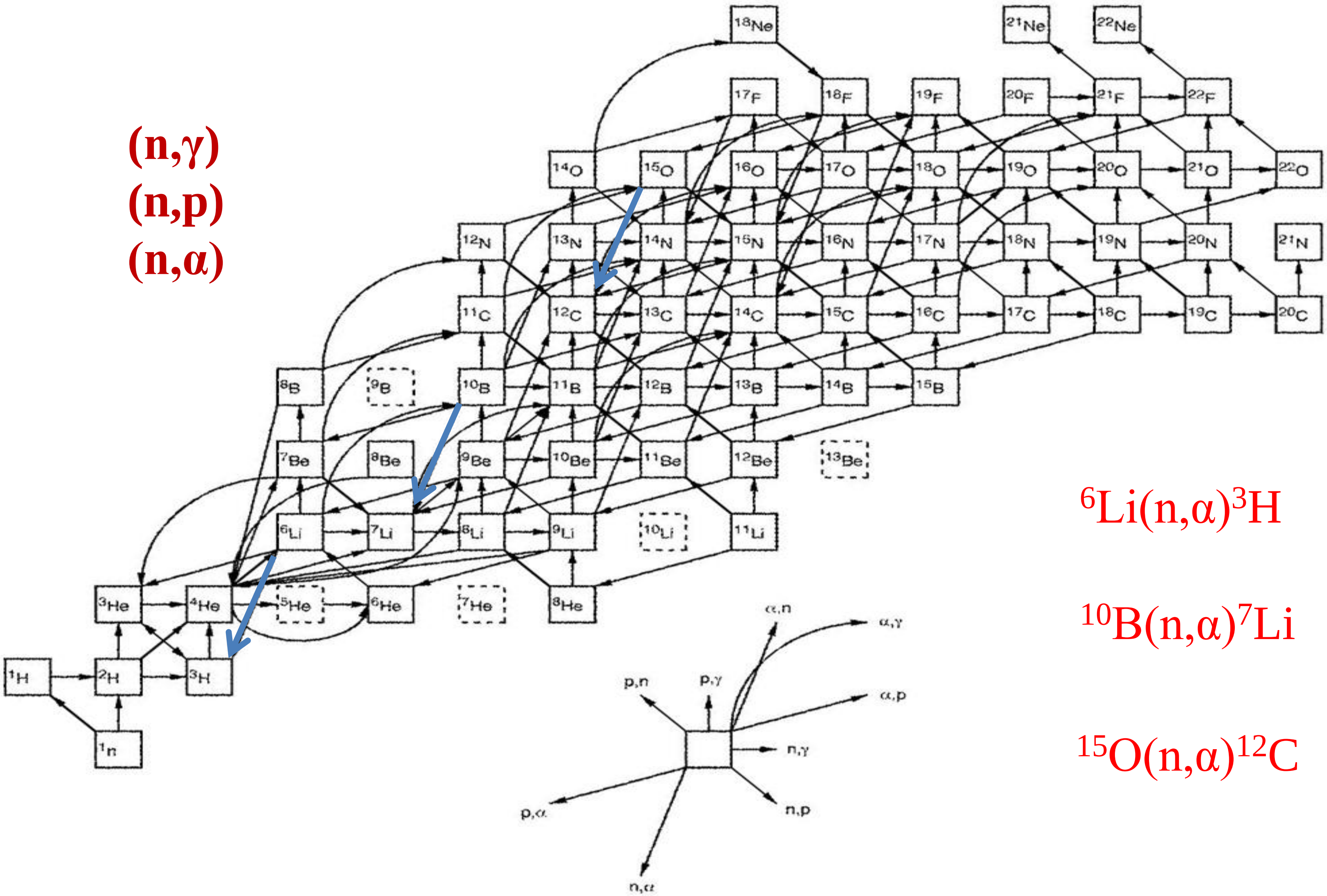


11重大未解的物理学问题

- **What is dark matter?**
- **What is dark energy?**
- **How were the heavy elements from iron to uranium made?**
- **Do neutrinos have mass (and how much)?**
- **Where do ultra-energy particles come from?**
- **Is a new theory of light and matter needed to explain what happens at very high temperature?**
- **Are there new states of matter at ultrahigh temperatures and densities?**
- **Are protons unstable?**
- **What is gravity?**
- **Are there additional dimensions?**
- **How did the Universe begin?**

大爆炸核合成相关的中子核反应

(n,γ)
(n,p)
(n,α)

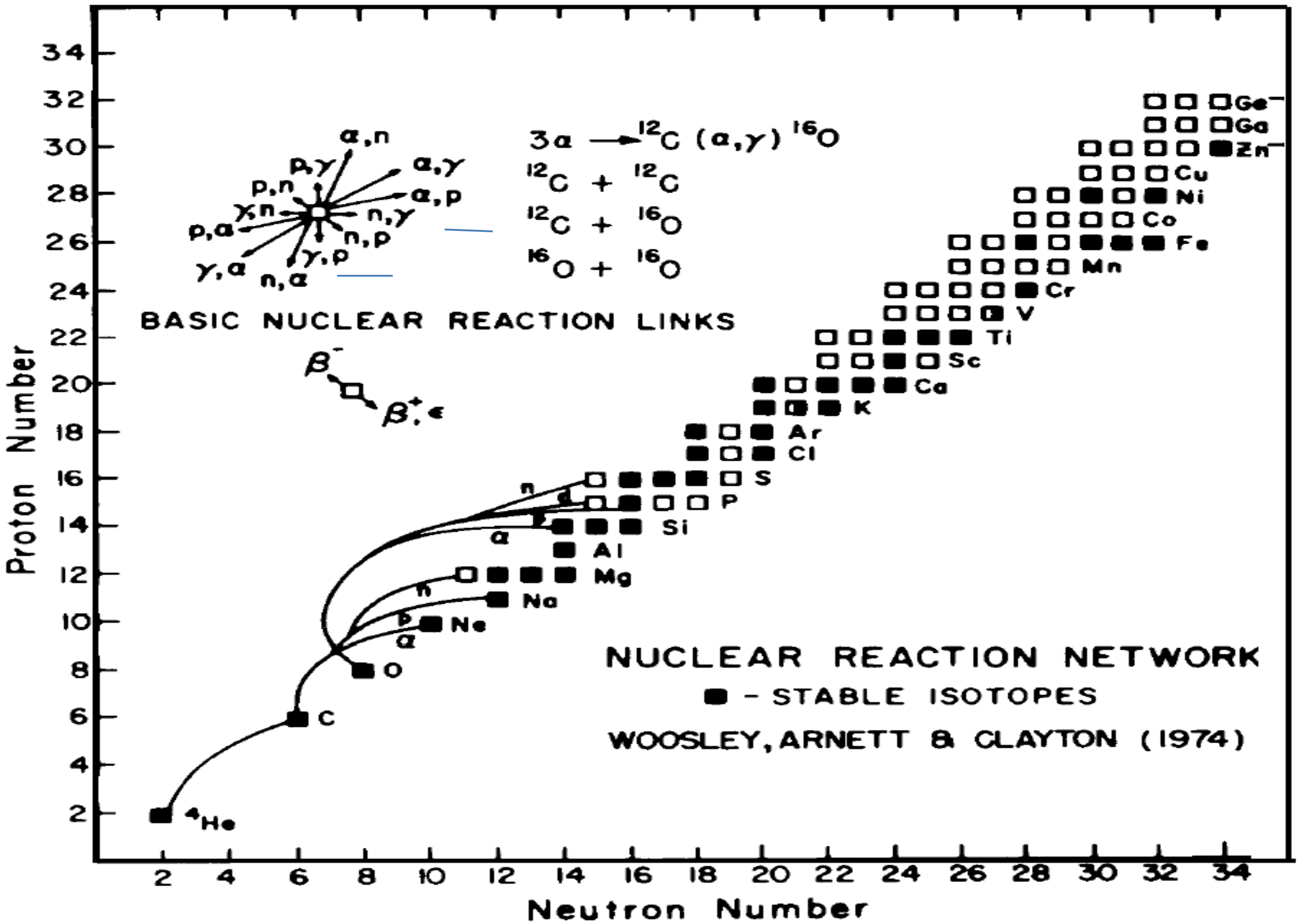


$^{6}Li(n,\alpha)^{3}H$

$^{10}B(n,\alpha)^{7}Li$

$^{15}O(n,\alpha)^{12}C$

恒星核燃烧涉及的中子核反应



^{14}N(n, p)^{14}C

^{17}O(n, p)^{17}N

^{17}O(n, α)^{14}C

^{26}Al(n, α)^{23}Na

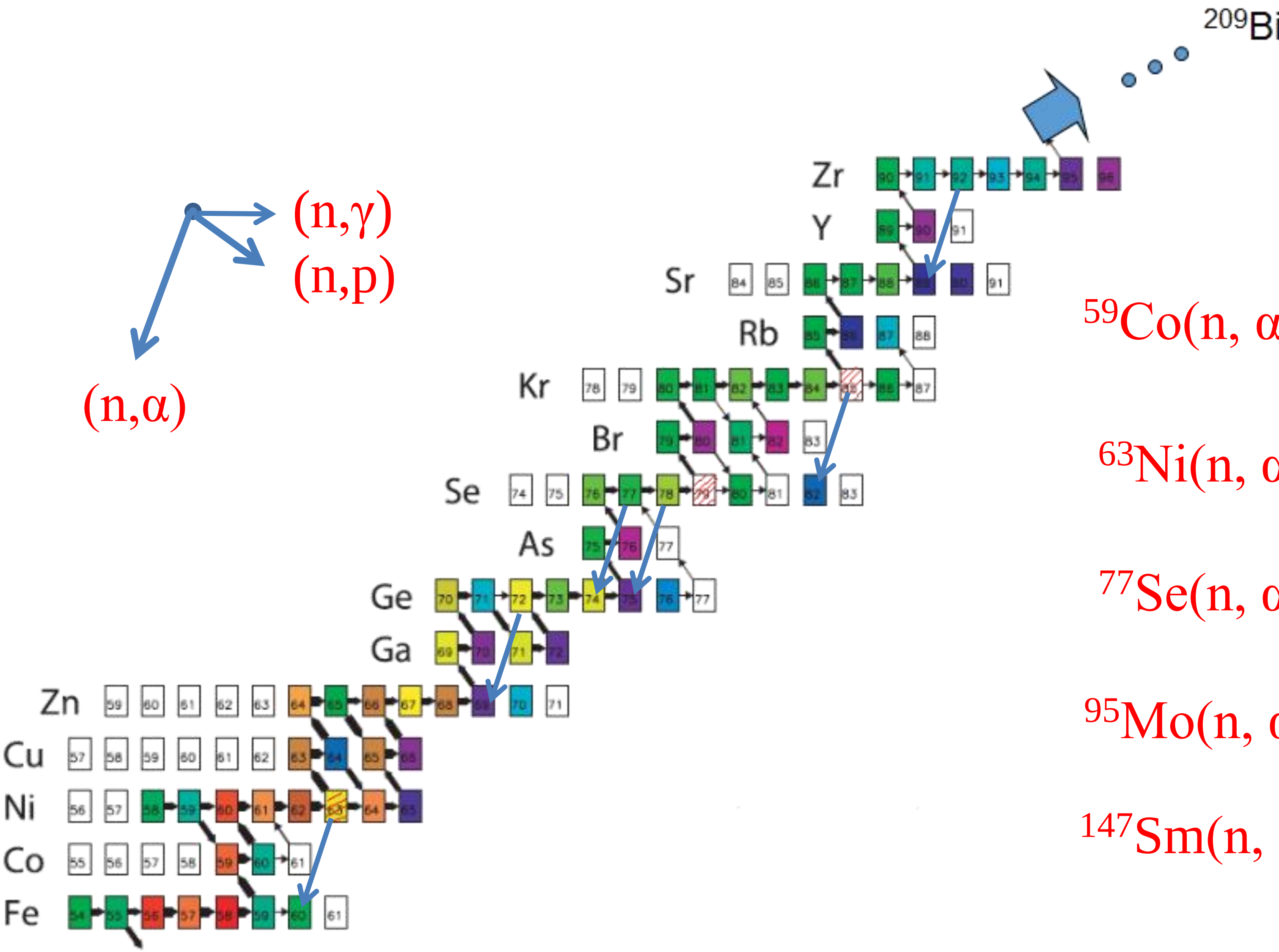
^{33}S(n, α)^{30}Si

^{36}Cl(n, α)^{33}P

^{33}Sr(n,α)^{30}Si

Fowler给出的元素合成网络

s - 过程涉及的中子核反应



^{59}Co(n, α)^{56}Mn

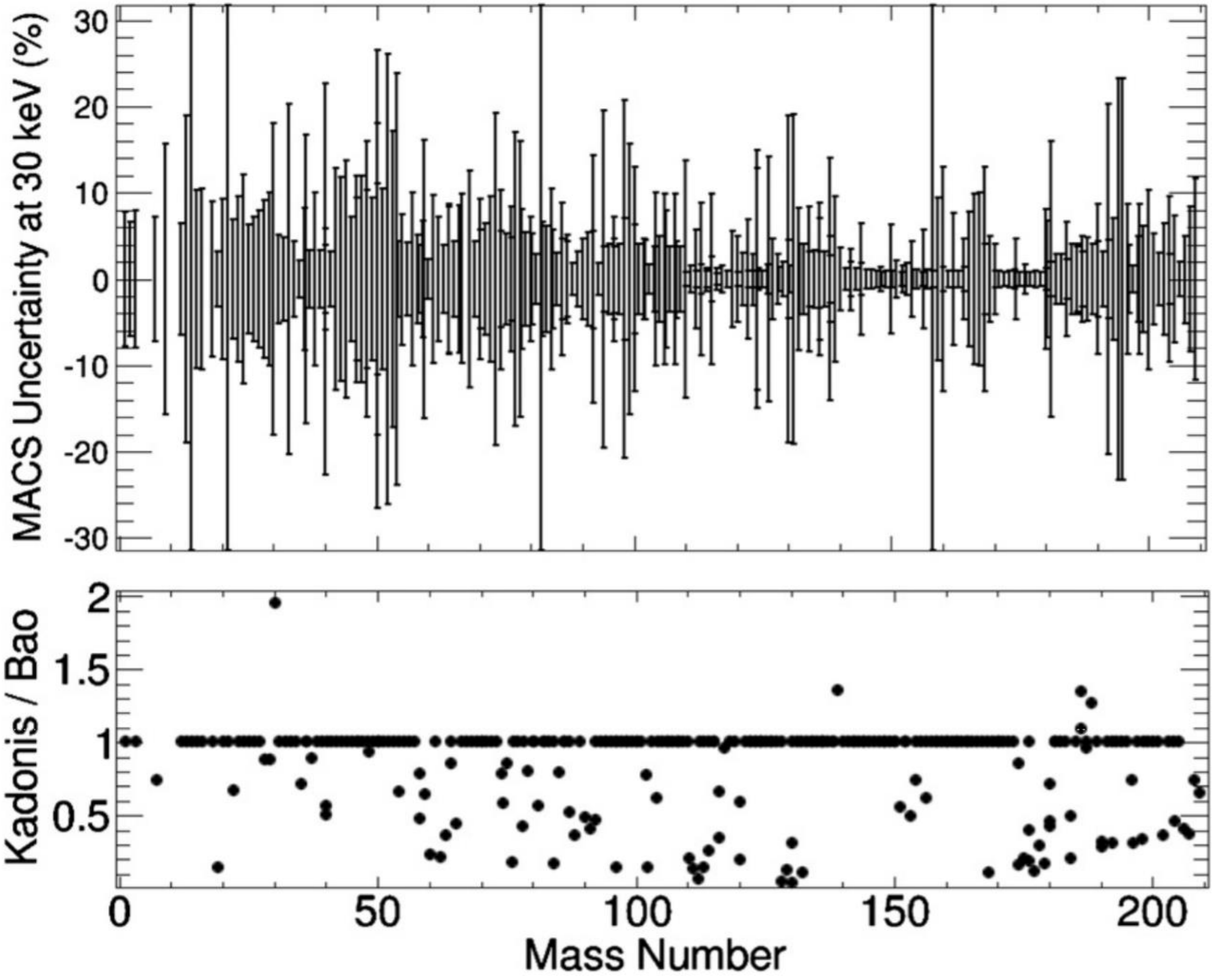
^{63}Ni(n, α)^{60}Fe

^{77}Se(n, α)^{74}Ge

^{95}Mo(n, α)^{92}Zr

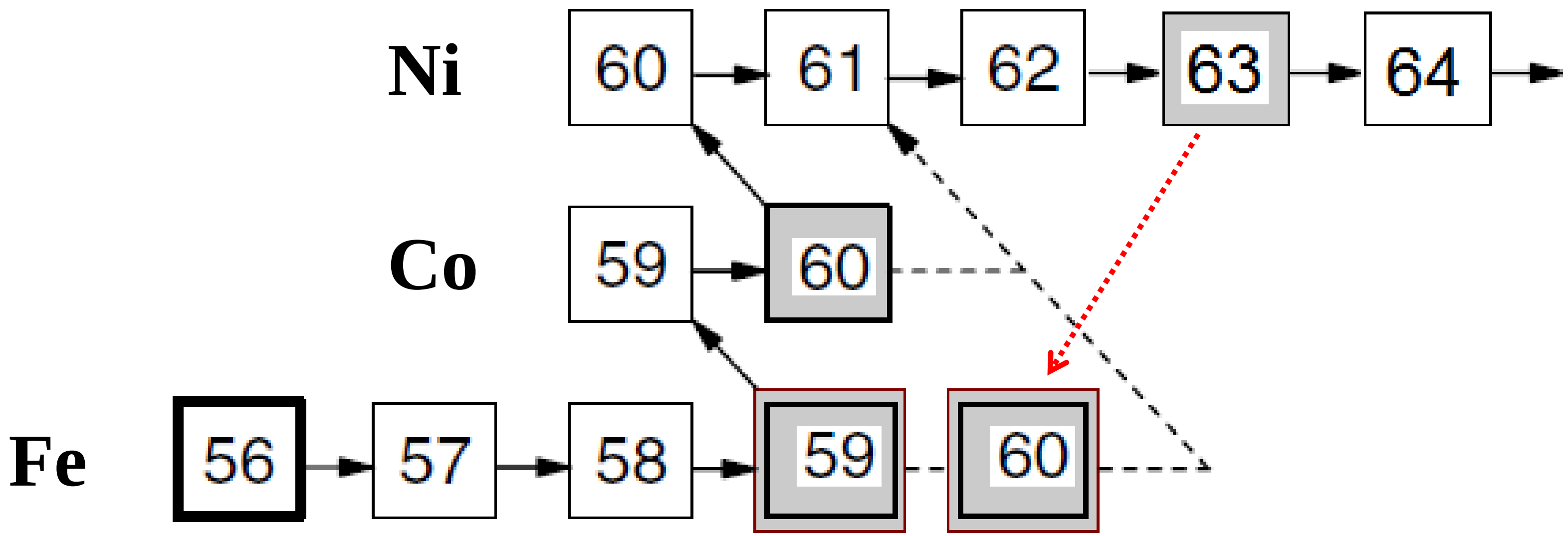
^{147}Sm(n, α)^{144}Nd

(n,γ)截面的不确定性



R Reifarth et al. J. Phys. G: Nucl. Part. Phys. 41 (2014) 053101

天体^{60}Fe的核合成路径



核素	^{59}Fe	^{60}Fe	^{60}Co	^{63}Ni
寿命	44 d	1.5×10^{6} a	5 a	100 a

^{63}Ni + n → ^{64}Ni* → ^{60}Fe + ^{4}He + 1.544MeV

^{64}Ni中子发射阈：9.658 MeV

^{64}Ni α发射阈：8.114 MeV

报告总结

- 天体演化过程中的四个重要的核过程
- 与这些核过程相关的重要核数据
  - 大爆炸原初核合成
  - 平稳的恒星核燃烧过程
  - 爆发性的恒星核过程
  - 宇宙线核合成过程
- CSNS反角白光中子源上能够开展的核天体物理研究工作

预祝反角白光中子源取得丰富的研究成果！

Thank You！

李志宏
中国原子能科学研究院
zhli@ciae.ac.cn
zhhli@foxmail.com