天体核网络方程

陈永寿

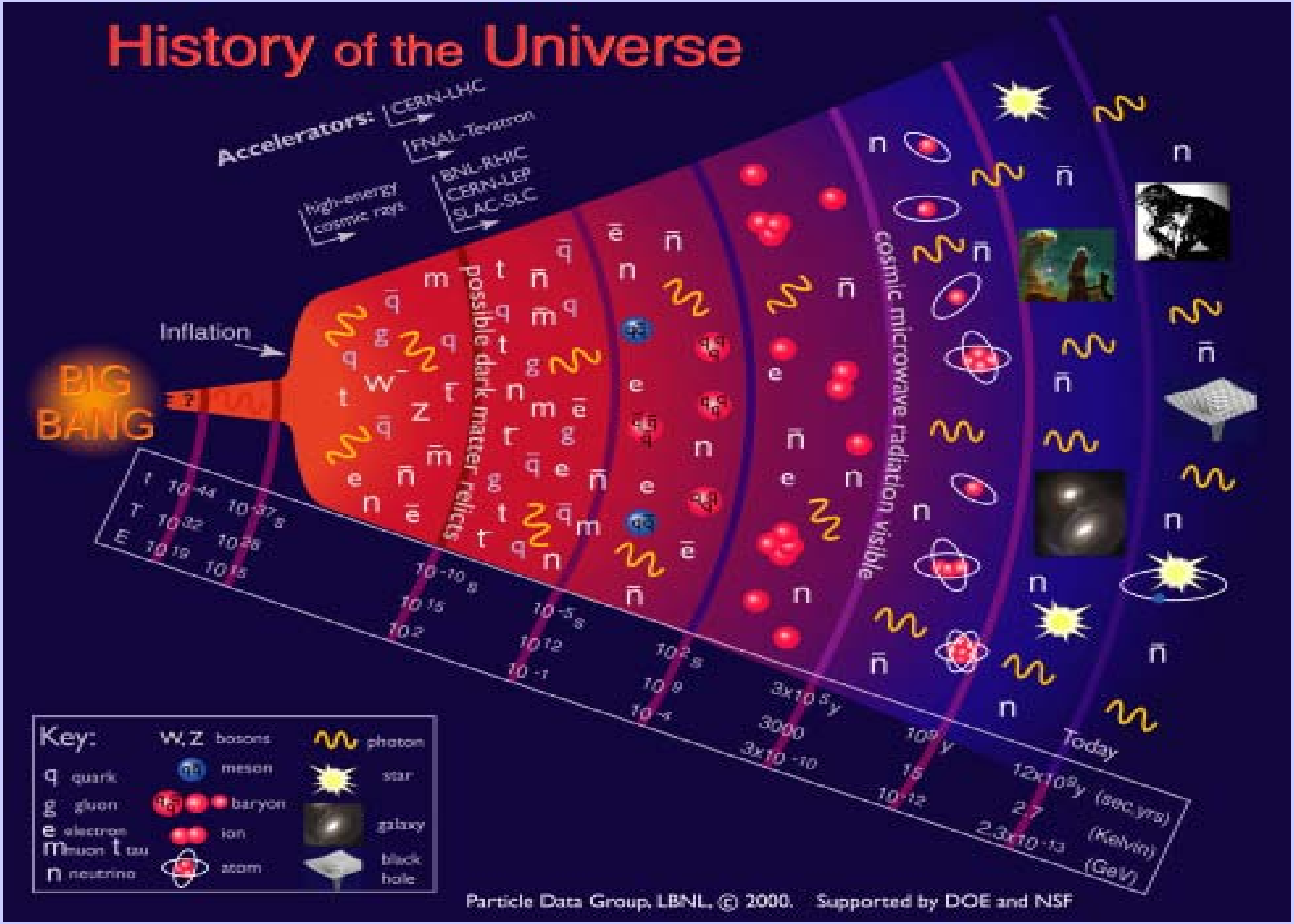
创新群体项目研讨会

夏门, 2011.10.13-14.

- **Introduction**
- **Newtwork and reaction rates**
- **Li-overproduction problem**
- **Planning**

Introduction

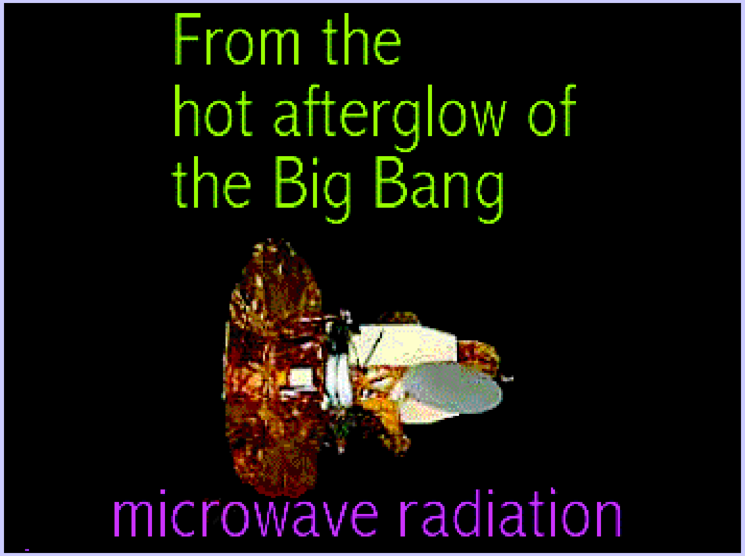
Evolution of the Universe

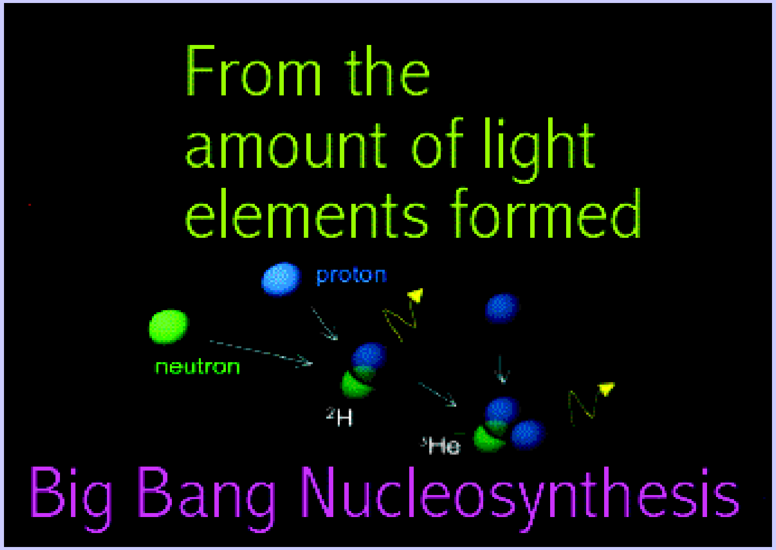


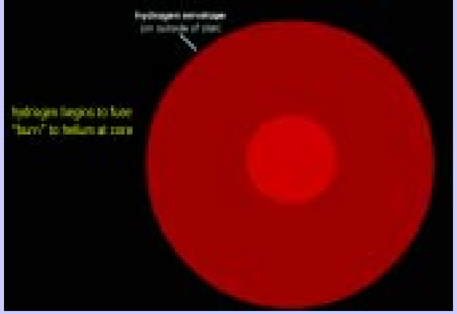
Three cosmology probes

They are complementary

Probing very different times after BB:
millions to billions years
380000 years
3 minutes



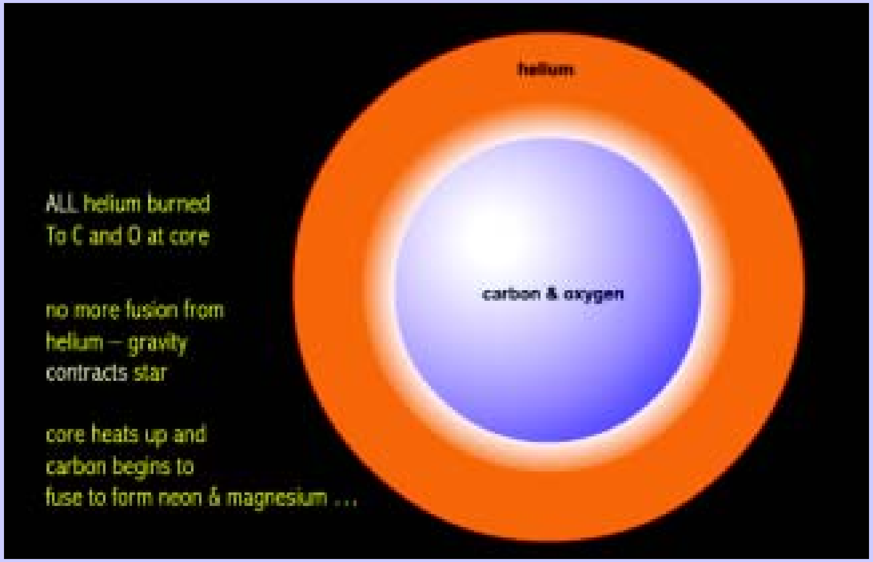


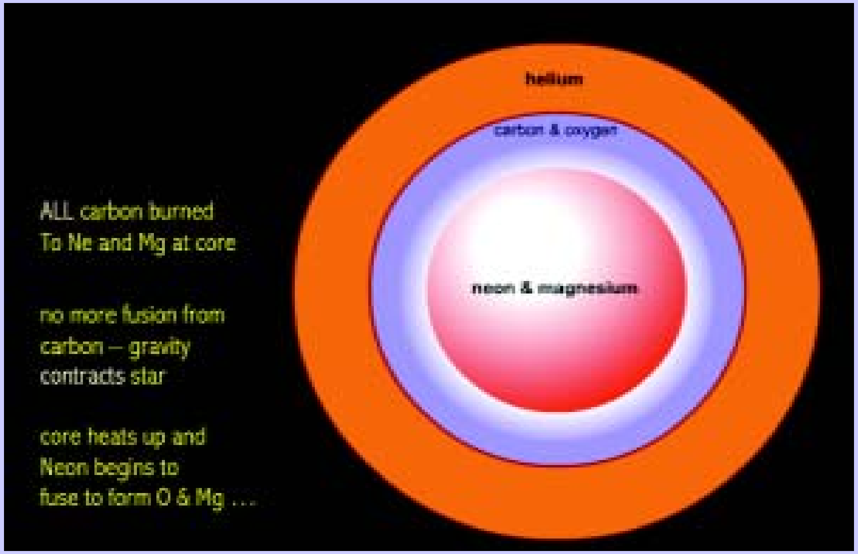


Stellar burning stages
Nuclear reaction drives the evolution stars

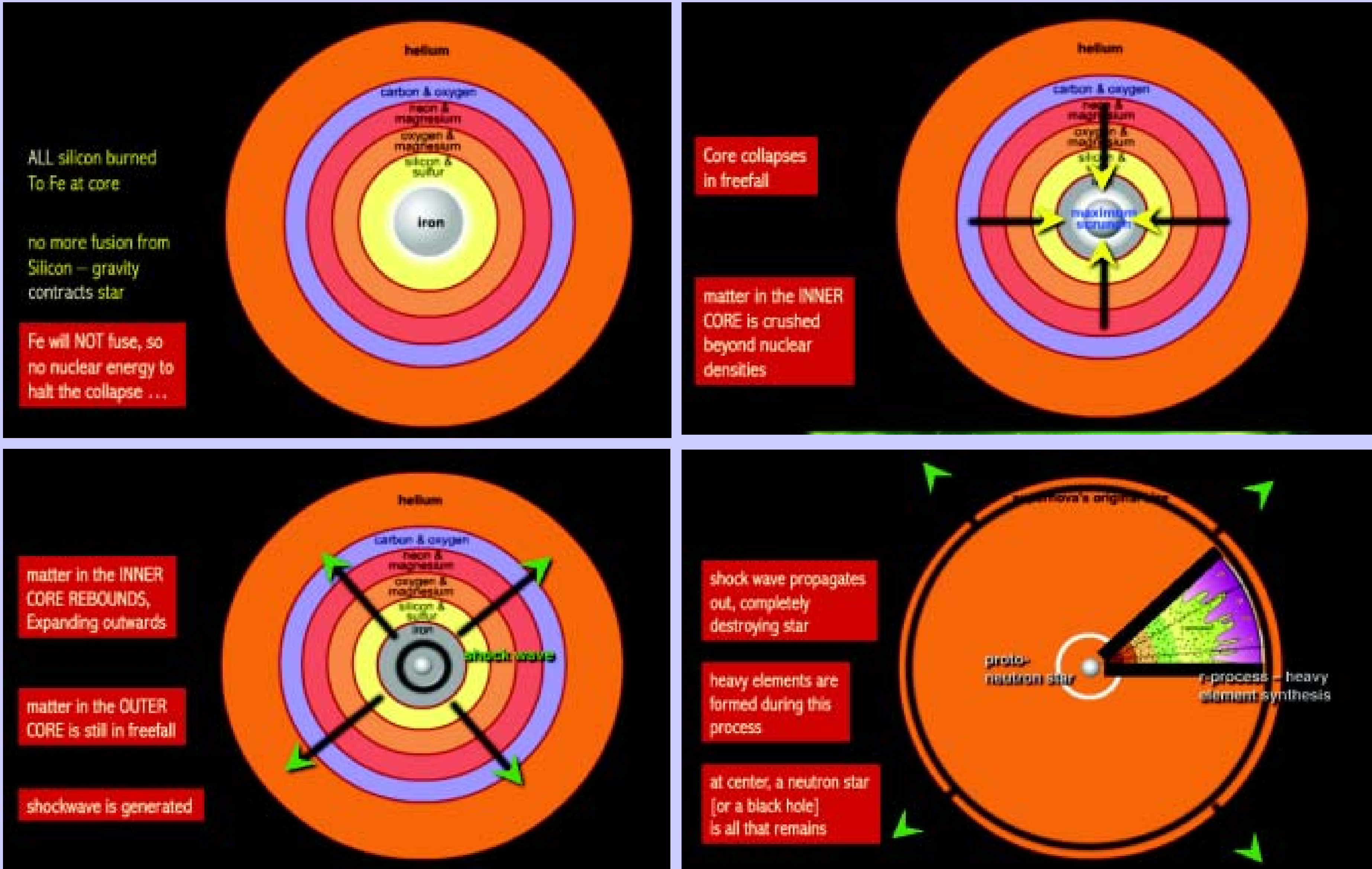
All hydrogen fuel burned to helium at core
No more fusion from hydrogen – gravity contracts star
Core heats up and helium begins to fuse to form carbon and oxygen

All helium burned to C and O at core
No more fusion from helium- gravity contracts star
Core heats up and C begins to fuse to form neon and magnesium…

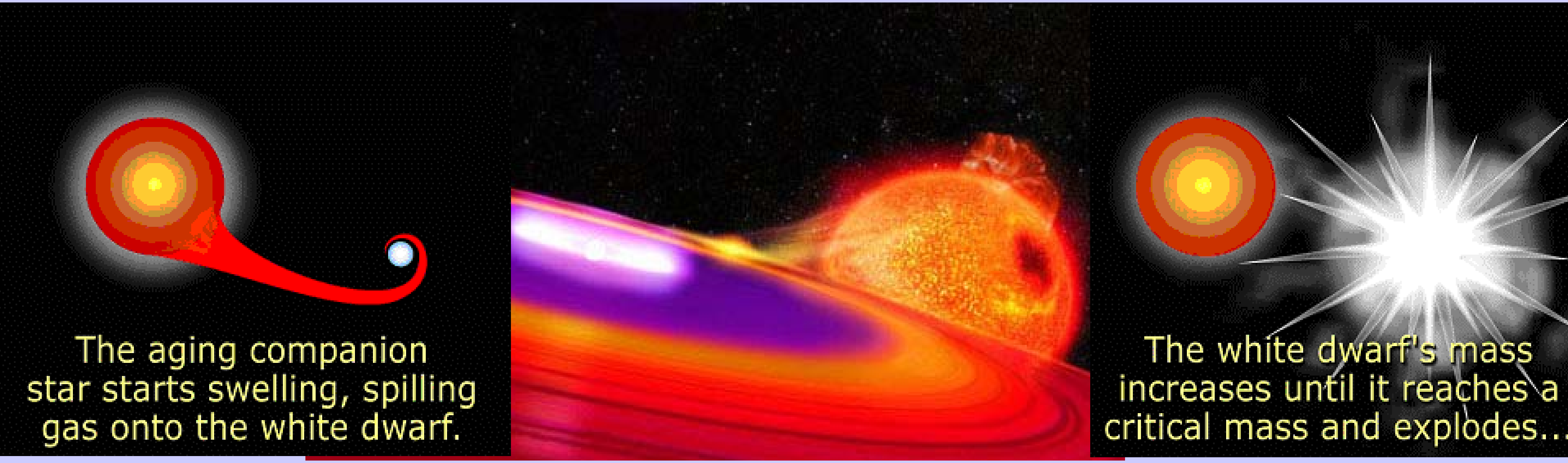




The death of stellar - Supernova



1a Type Supernovae



Accreting matter

Nuclear Burning rp

Explosion

天体核反应网络方程的特点

恒星演化的各个阶段的天体物理环境决定了特定的网络方程。（核反应的数量和类型）

宇宙中爆发性事的天体物理环境决定了特定的网络方程。

天体演化模型以及核物理输入的发展，网络方程相应发展。

Network
and
reaction rates

The reaction network
--- a set of differential equations

$$\frac{dY_i}{dt} = \sum_j N^i_j \lambda_j Y_j + \sum_{j,k} N^i_{j,k} \rho N_A < \sigma V >_{jk,i} Y_j Y_k$$
$$+ \sum_{j,k,l} N^i_{j,k,l} \rho^2 N_A{}^2 < \sigma V >_{jkl,i} Y_j Y_k Y_l$$

$Y_i = n_i / \rho N_A$ ***The nuclear abundance***

N_A ***Avagadro constant number***

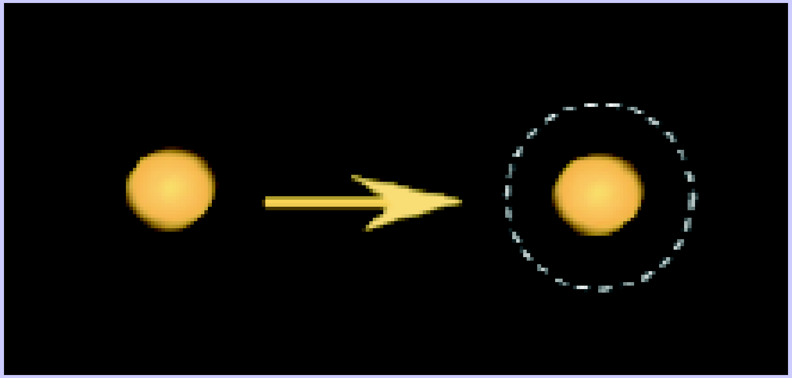
ρ ***The density***

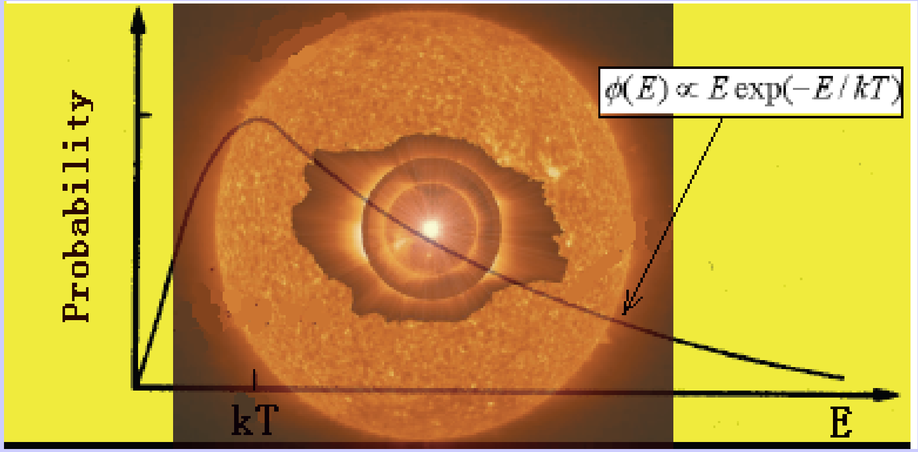
n_i ***The number density of species 'i'***

Definition of Reaction Rate

A reaction rate is defined to describe the rate of interaction of two types of nuclei in a star .
Reaction rate combine the INDIVIDUAL and ENSEMBLE behavior of nuclei in a star

INDIVIDUAL: interaction of any two particular nuclei depends on their relative velocity or relative energy

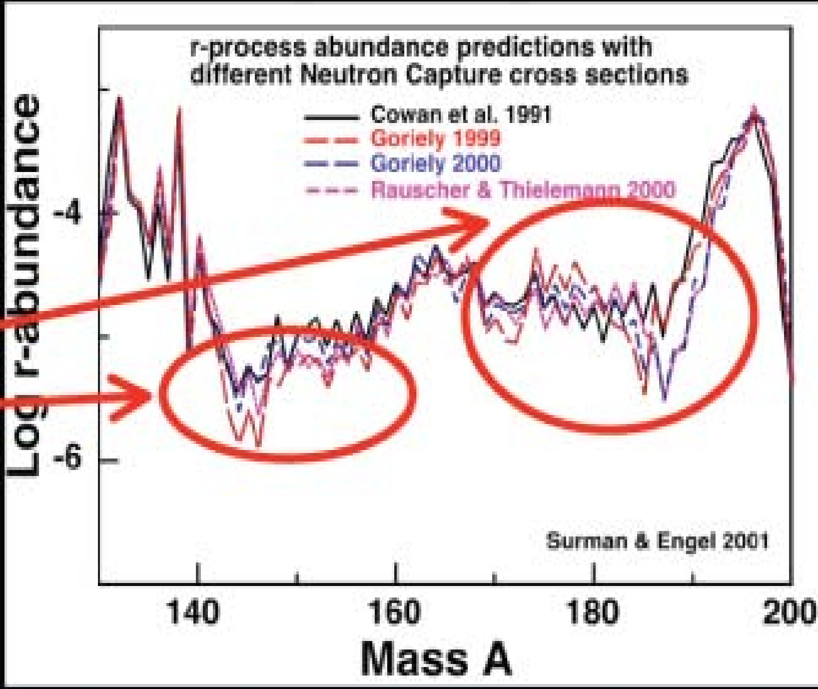


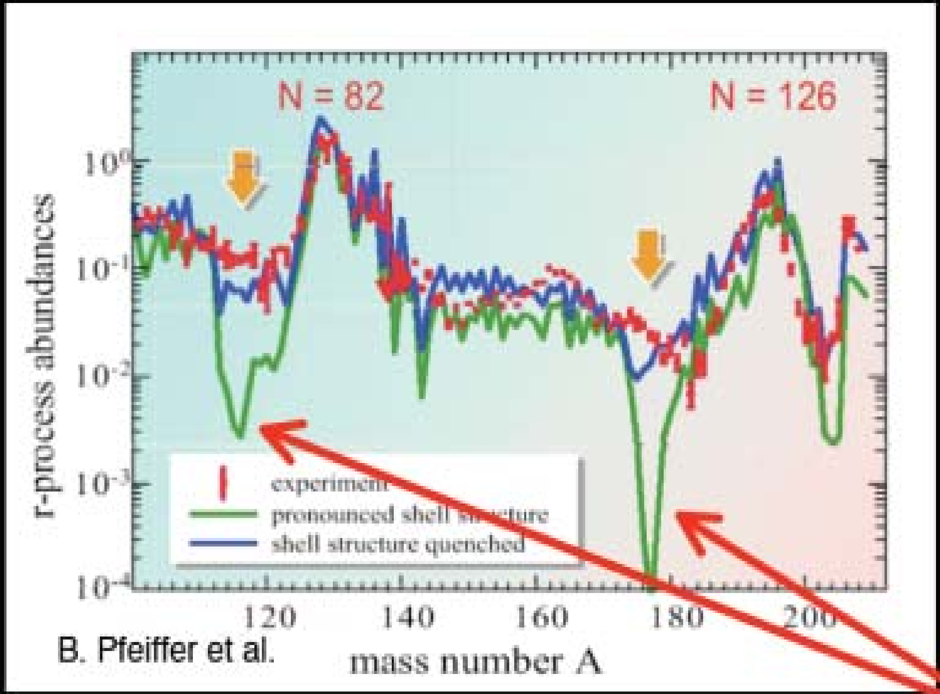


ENSEMBLE: pairs of nuclei have a wide range of relative energies in a star – characterized by the temperature of the system

sensitivity to nuclear physics - core collapse supernovae

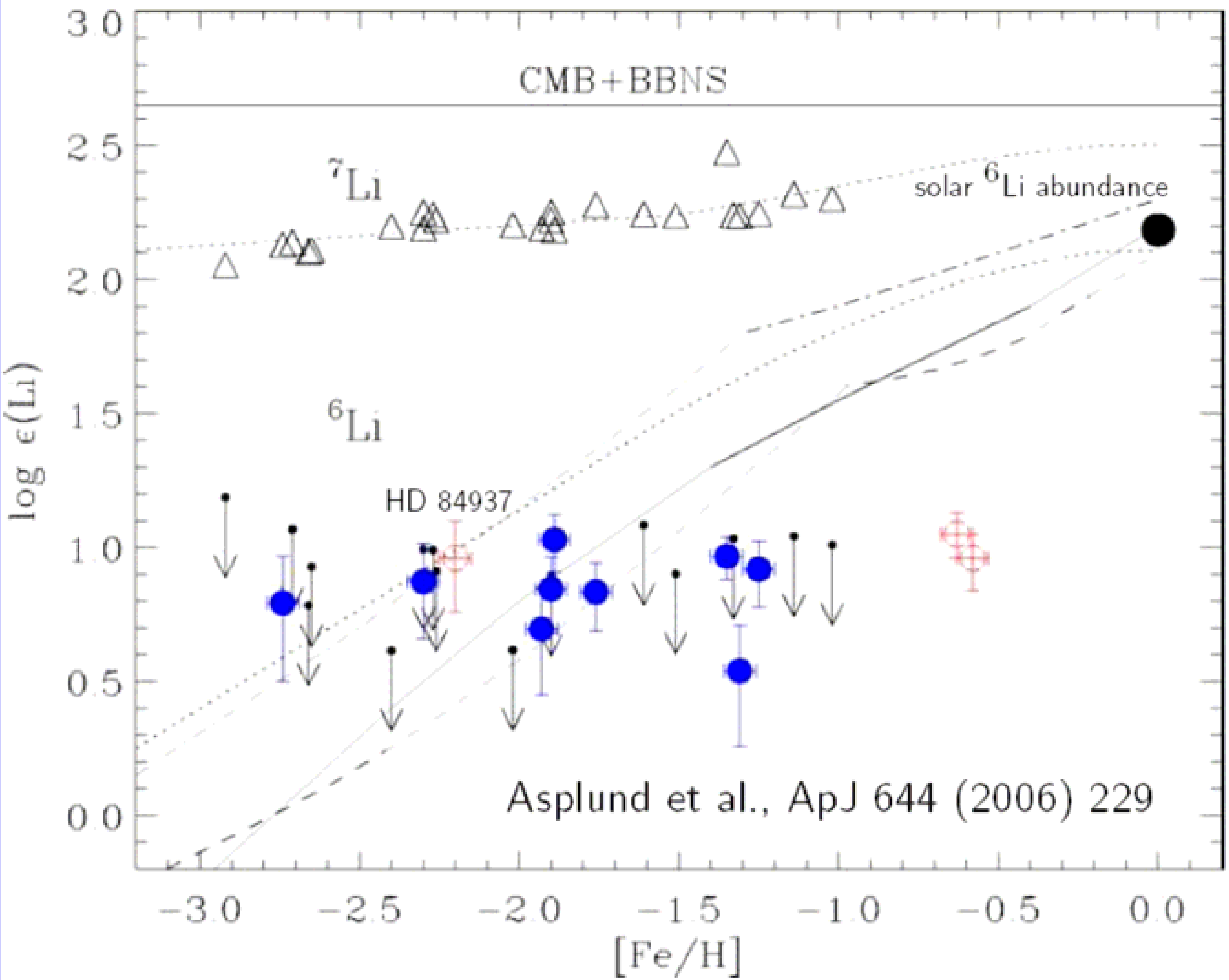
- **Neutron capture cross sections**, especially near ***closed neutron shells*** - can change abundances by **factor of ~10**





- **Nuclear structure information** - masses, lifetimes, neutron separation energies, shell structure … can change abundances by orders of magnitude

^{6}Li-overproduction problem



CMB+BBNS
^{7}Li
solar ^{6}Li abundance
^{6}Li
HD 84937
Asplund et al., ApJ 644 (2006) 229
log ε(Li)
[Fe/H]
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−3.0
−2.5
−2.0
−1.5
−1.0
−0.5
0.0

Cosmological Lithium Problem

Li-abundances Observed in metal-poor halo stars are in disagreement with the standard BBN

Simulation of BBN
with the baryon–to-photon ratio η fixed by WMAP

♦ **Observed ^{7}Li abundance is about a factor of 3 smaller than the prediction of standard model.**

♦ **Observed abundance of ^{6}Li is 1000 times larger than the prediction of standard model.**

问题出自： 核物理？天文观测？其它？

The set of differential equations for BBN

$$\frac{\dot{R}}{R} = H = \sqrt{\frac{8\pi G_N \rho}{3}}$$

$$\frac{\dot{n}_B}{n_B} = -3H$$

$$\dot{\rho} = -3H(\rho + p)$$

$$\rho = \rho_B + \rho_\gamma + \rho_e + \rho_\nu$$

$$\frac{dY_i}{dt} = \sum_j N^i_j \lambda_j Y_j + \sum_{j,k} N^i_{j,k} \rho_B N_A < \sigma V >_{jk,i} Y_j Y_k$$

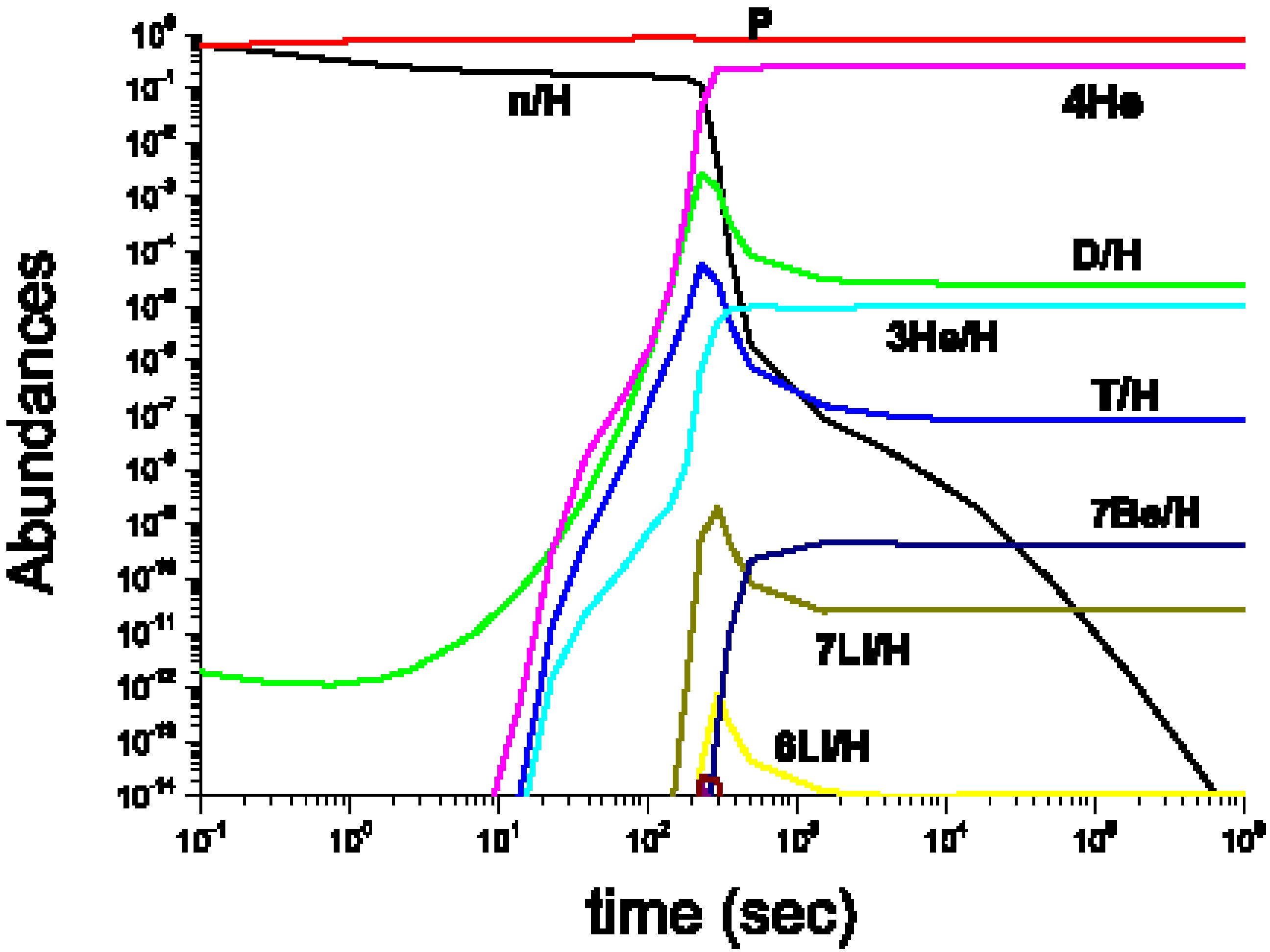
$$+ \sum_{j,k,l} N^i_{j,k,l} \rho_B{}^2 N_A{}^2 < \sigma V >_{jkl,i} Y_j Y_k Y_l$$

$$n_B \sum_i Z_i X_i = n_{e^-} - n_{e^+} \equiv L(\frac{m_e}{T}, \phi_e)$$

$$(\frac{\partial}{\partial t} - H|p|\frac{\partial}{\partial |p|}) f_{\nu_\alpha}(|p|,t) = I_{\nu_\alpha}[f_{\nu_e}, f_{\bar{\nu}_e}, f_{\nu_x}, f_{\bar{\nu}_x}, f_{e^-}, f_{e^+}]$$

BBN simulation 侯素青

with largest network and upgraded reaction rates (including CIAE rates of $^8Li(n,g)^9Li$,….)

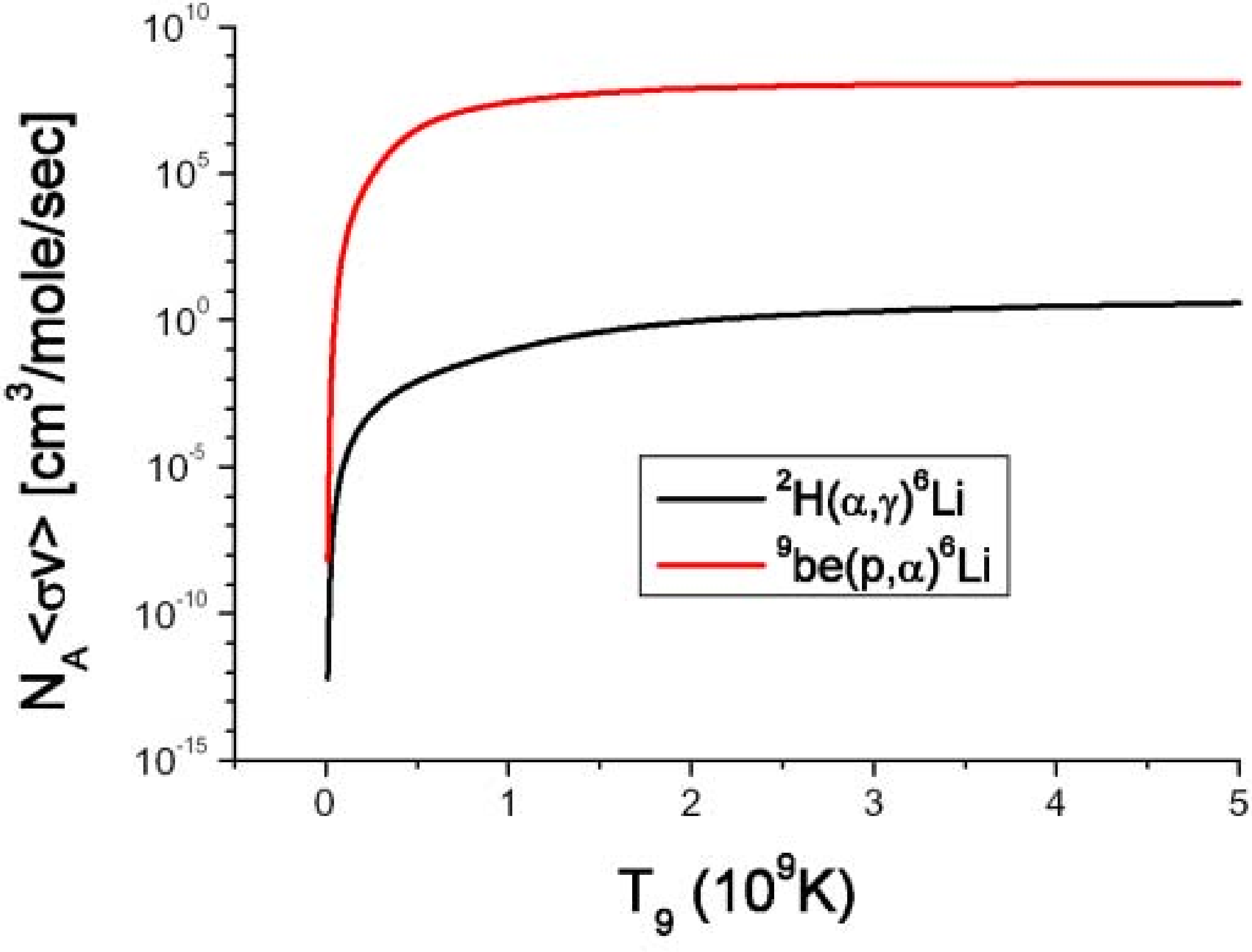


Reactions for creation and destruction of ^{6}Li

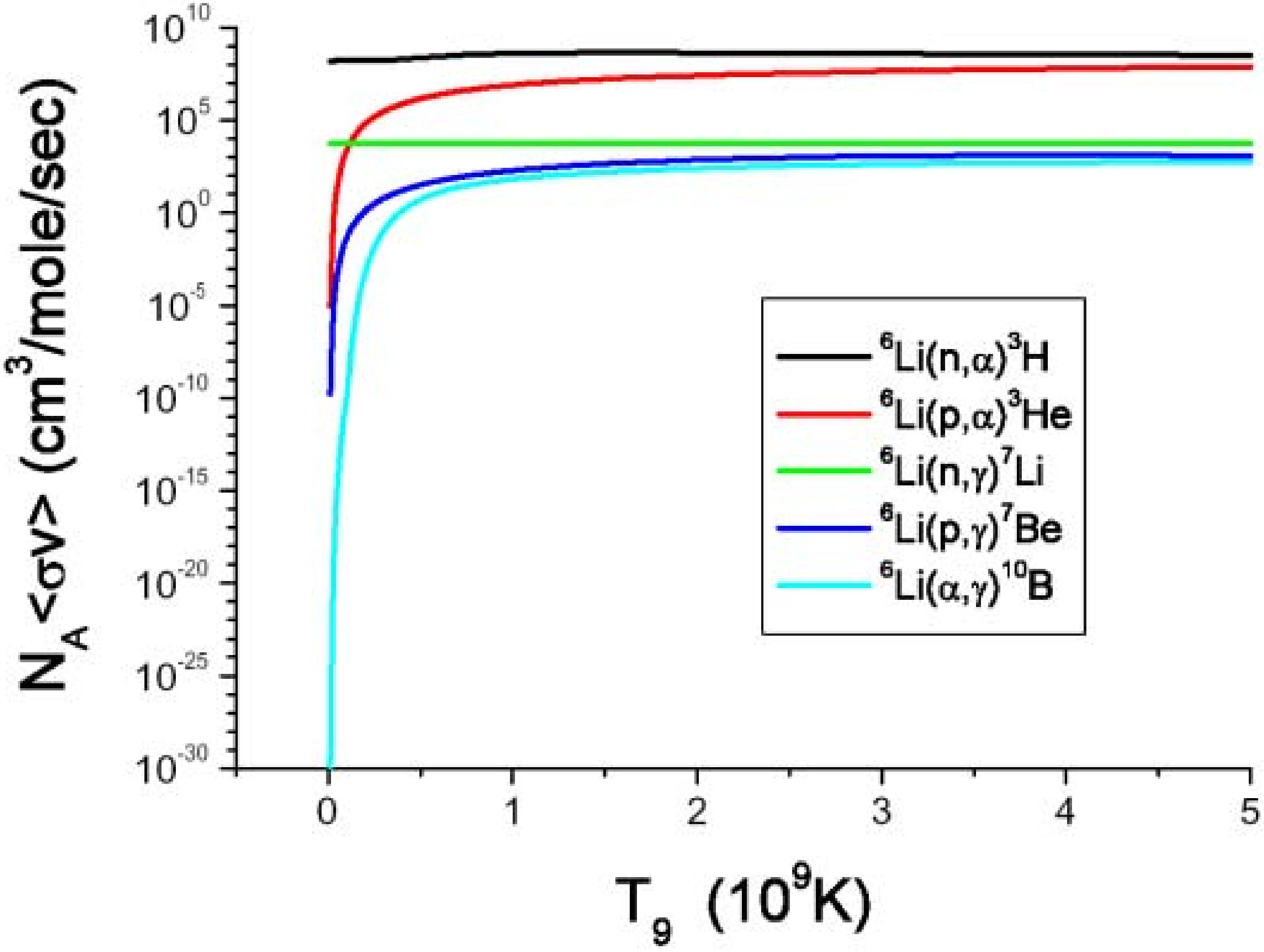
Table 1 Reactions for creation and destruction of ^{6}Li in the present network.

Creation of ^{6}Li	Destruction of ^{6}Li
$^2\mathrm{H}(\alpha,\gamma)^6\mathrm{Li}$	$^6\mathrm{Li}(n,\gamma)^7\mathrm{Li}$
$^9\mathrm{Be}(p,\alpha)^6\mathrm{Li}$	$^6\mathrm{Li}(n,\alpha)^3\mathrm{H}$
	$^6\mathrm{Li}(p,\gamma)^7\mathrm{Be}$
	$^6\mathrm{Li}(p,\alpha)^3\mathrm{He}$
	$^6\mathrm{Li}(\alpha,\gamma)^{10}\mathrm{B}$

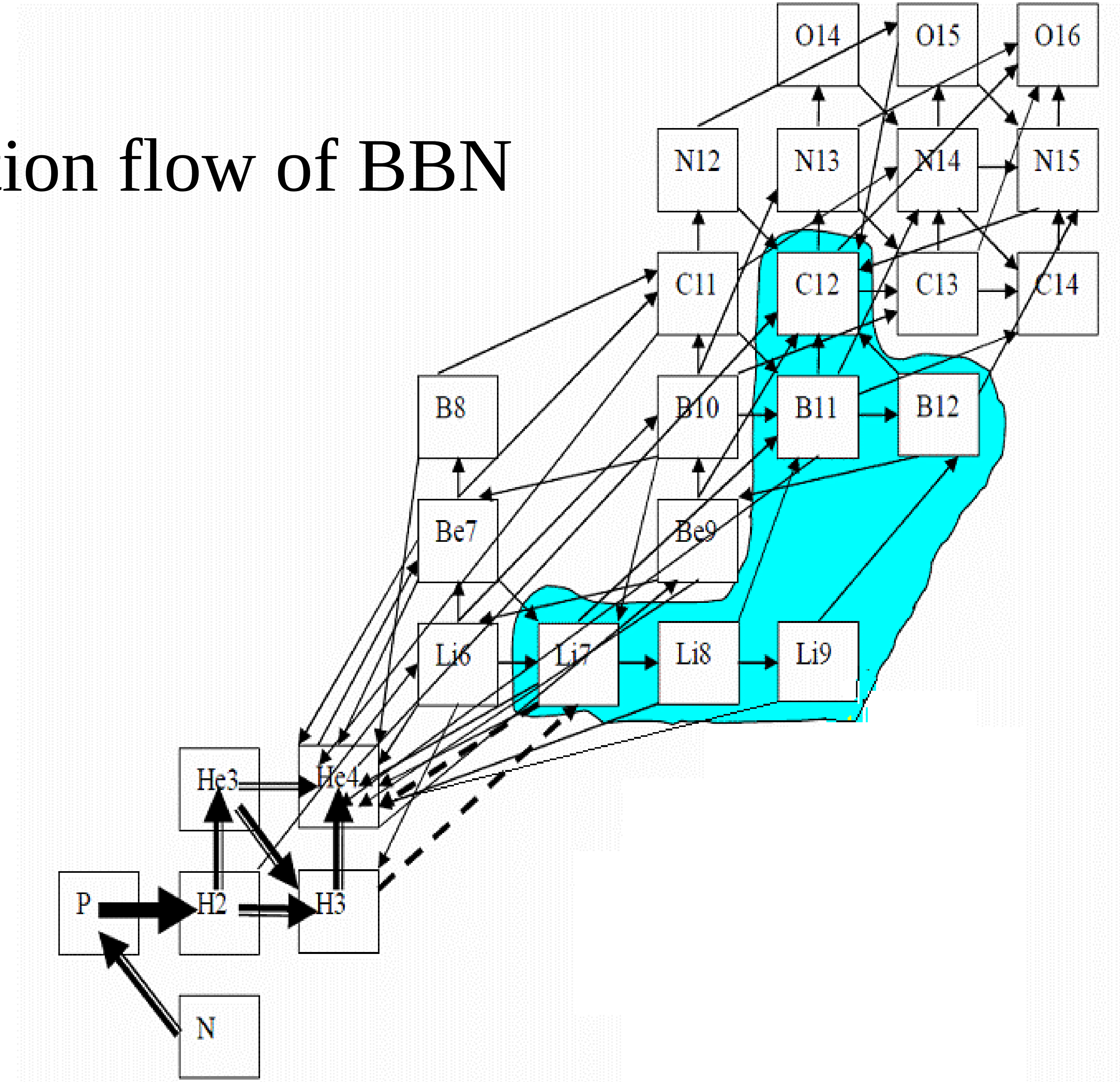
Rates of ^{6}Li - creation reactions



Rates of ^{6}Li - destruction reactions



Reaction flow of BBN



3 key reactions for the ^{6}Li – problem

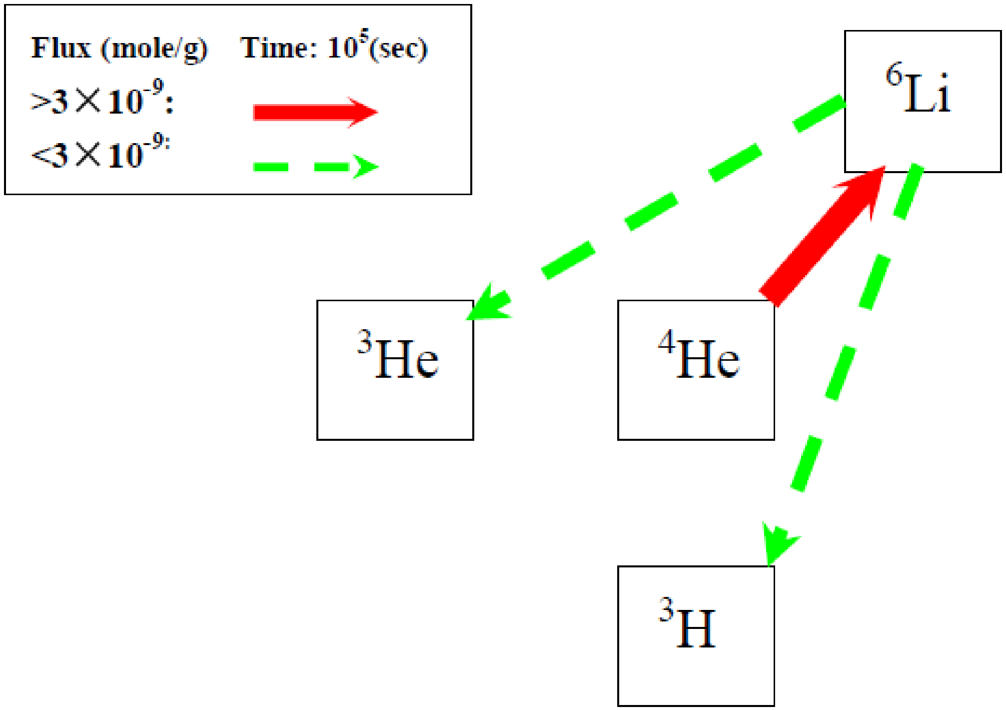


Figure 3: The fluxes calculated for three most important reactions to ^{6}Li production.

Reaction	Flux:
^{6}Li(n,α)^{3}H	2.42762E-09
^{6}Li(p,^{3}He)^{4}He	1.71925E-09
^{2}H(α,g)^{6}Li	4.14757E-09
all of other channels of ^{6}Li	<1E-14

Table 2: The values of fluxes of individual reactions of ^{6}Li

BBN 反应流计算结果表明：只有三个核反应最重要，它们完全决定了原初核合成的 ^{6}Li丰度。

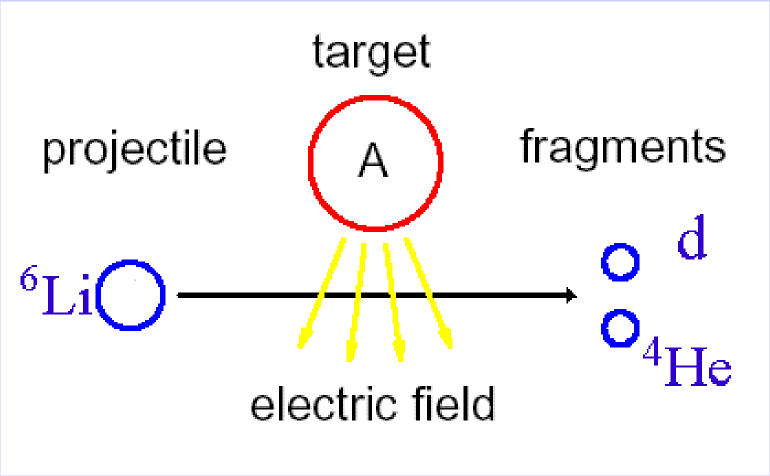
正是这3个核反应决定了^{6}Li丰度为10^{-13} （而观测值是10^{-10}）。

4.14757-2.42762-1.71925 =0.0007

初步结论：
^{6}Li超丰问题不大
可能是由于核物
理本身出了问题。

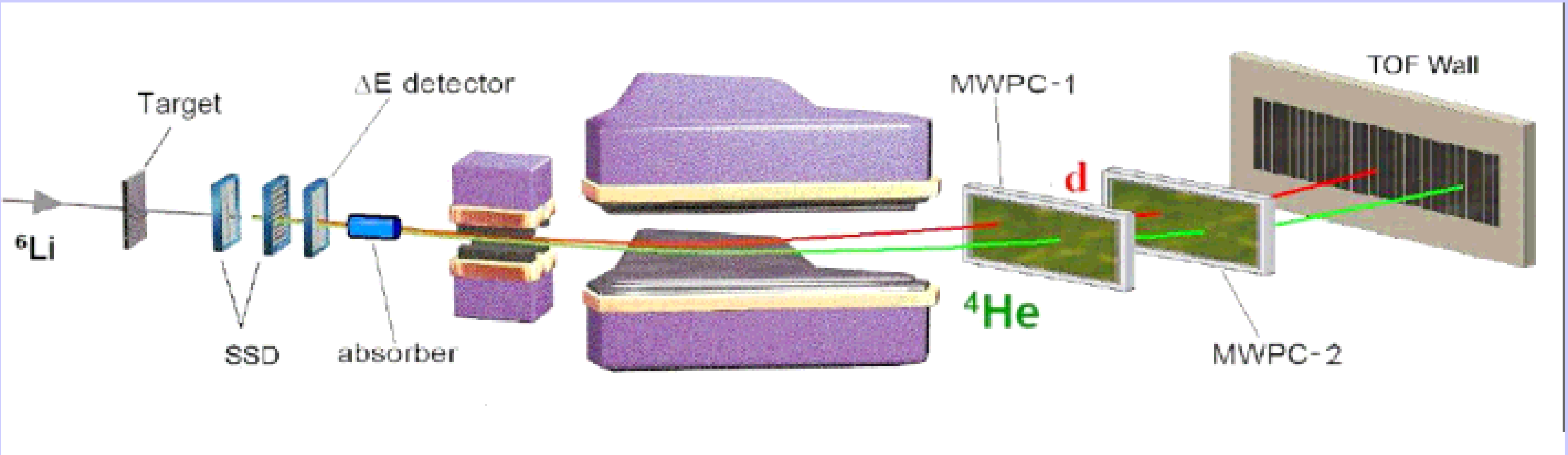
^{6}Li Breakup in Coulomb Dissociation

New GSI experiment with 150 A MeV ^{6}Li on Pb target



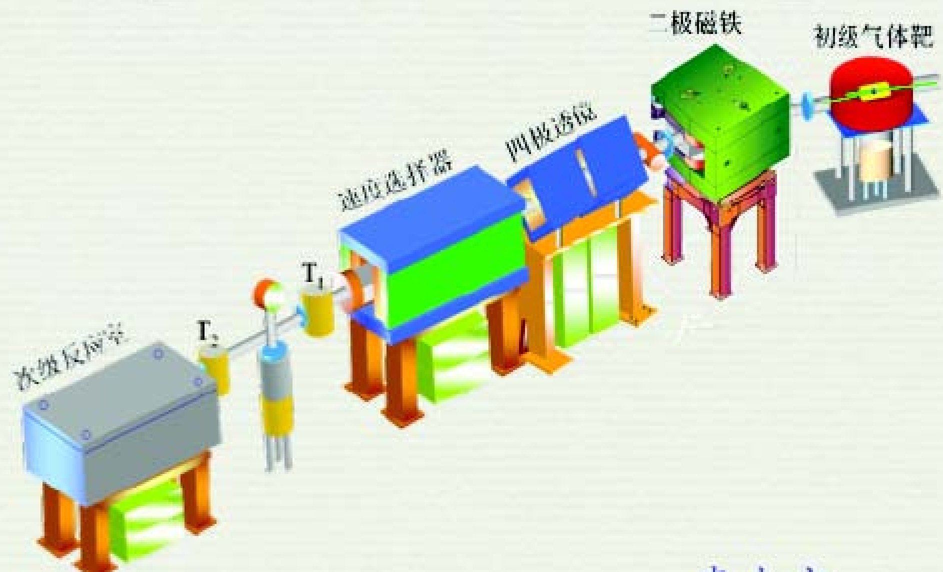
Stefan Typel, GSI
7th ANL/INT/JINA/MSU Annual FRIB workshop Interfaces between nuclear structure & reactions
August 8-12, 2011

^{6}Li + A → d + ^{4}He + A   d + ^{4}He → ^{6}Li



在串列加速器上完成的核反应测量

- $^{7}Li(^{6}Li,^{7}Li)^{6}Li \Rightarrow {}^{6}Li(n,\gamma)^{7}Li$
- $^{6}He(d,n)^{7}Li \Rightarrow {}^{6}He(p,\gamma)^{7}Li$
- $^{13}C(^{6}Li,^{7}Be)^{12}B \Rightarrow {}^{6}Li(p,\gamma)^{7}Be$
- $^{13}C(^{7}Li,^{8}Li)^{12}C \Rightarrow {}^{7}Li(n,\gamma)^{8}Li$
- $^{8}Li(d,p)^{9}Li \Rightarrow {}^{8}Li(n,\gamma)^{9}Li$
- $^{8}Li(d,n)^{9}Be \Rightarrow {}^{8}Li(p,\gamma)^{9}Be$
- $^{13}C(^{9}Be,^{8}Li)^{14}N \Rightarrow {}^{8}Li(p,\gamma)^{9}Be$
- $^{8}Li(p,d)^{7}Li, {}^{6}He(p,n)^{6}Li, {}^{8}Li(p,t)^{6}Li$



CIAE-^{6}Li问题下一步计划

^{4}He(nn,γ)^{6}He 反应激发函数

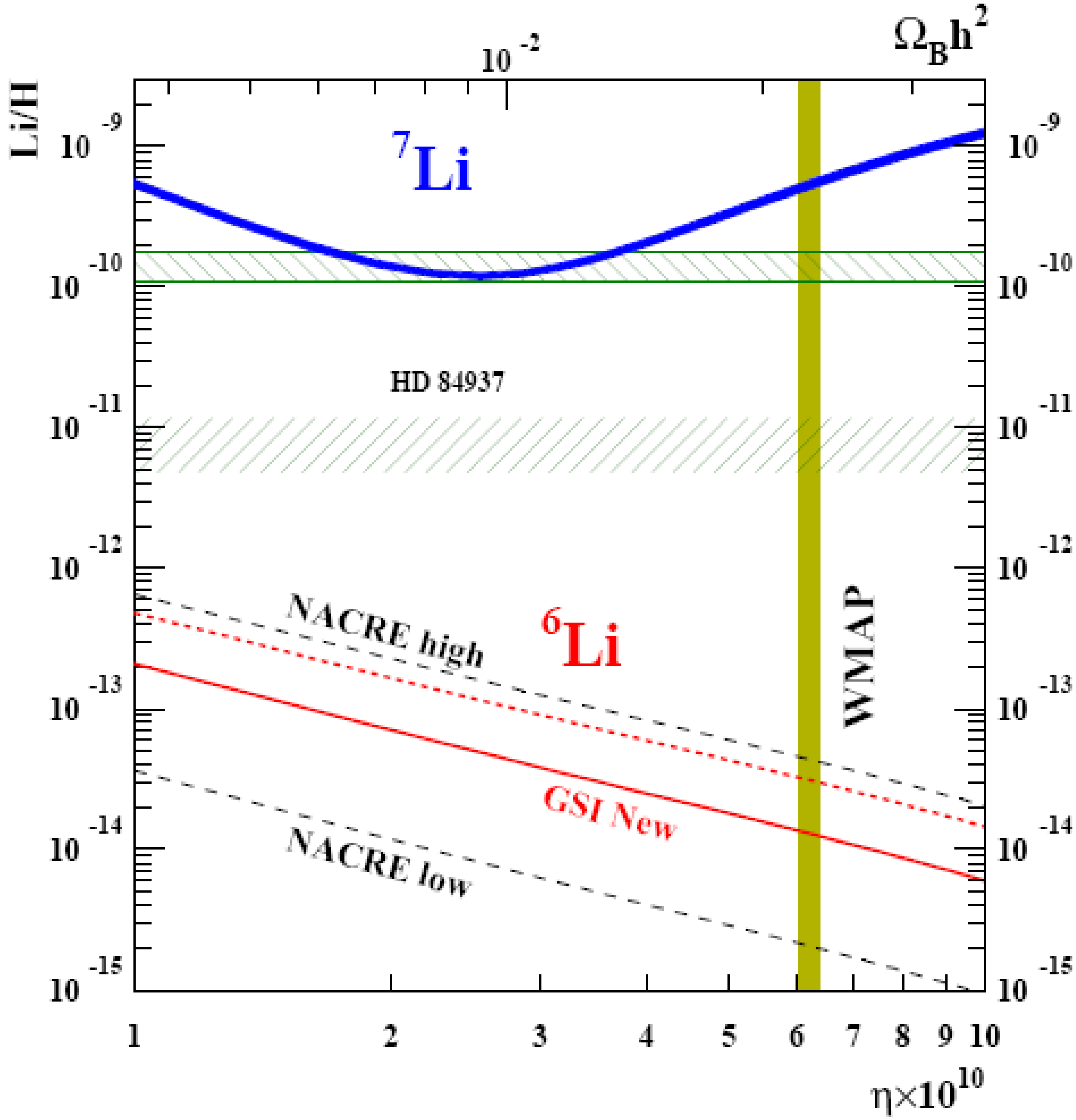
^{4}He(np,γ)^{6}Li 反应激发函数

^{7}Be(d,^{3}He)^{6}Li 反应激发函数

^{9}Li(p,α)^{6}He 反应激发函数

^{2}H(α,γ)^{6}Li 反应还有较大不确定性

CIAE的系统实验测量，将使**Li-**难题研究提高到一个新的层面，使我们有一定发言权。



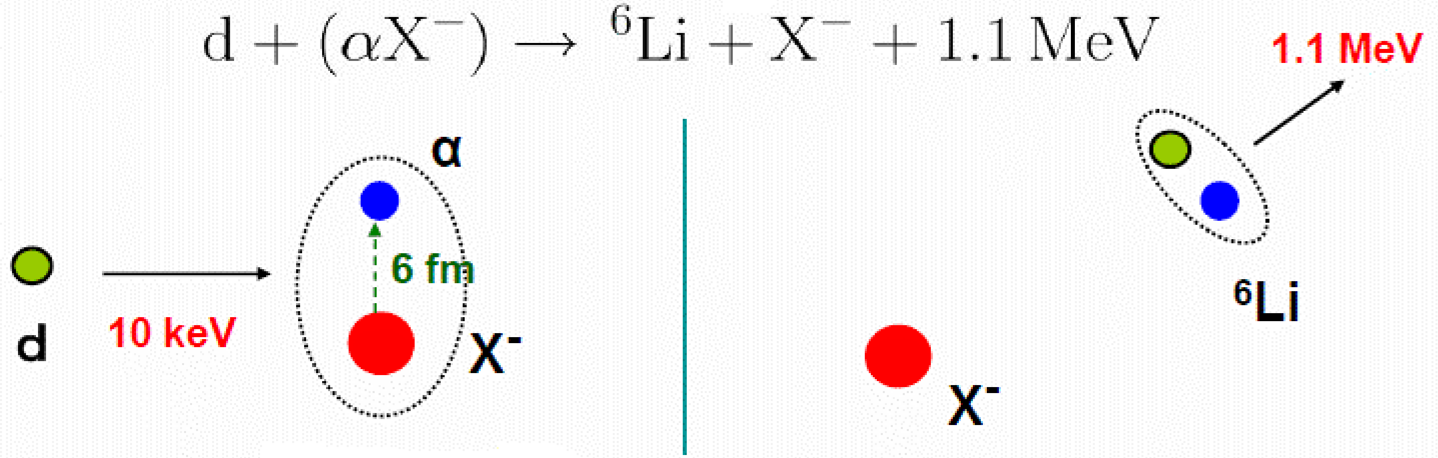
$\Omega_B h^2$
10^{-2}
Li/H
^{7}Li
HD 84937
^{6}Li
NACRE high
GSI New
NACRE low
WMAP
$\eta \times 10^{10}$

Particle physics catalysis of thermal BBN

M. Pospelov, axiV:hep-ph/0605215v4 15 Mar 2007 , (PRL June 2007)

According to the super- symmetry theory
X^- particle, negative charged, massive, lifetime long enough to survive until BBN time ,
for example, 50 GeV , 1600 seconds

$$d + (\alpha X^-) \rightarrow {}^6\mathrm{Li} + X^- + 1.1\,\mathrm{MeV}$$



$$\sigma(\ d + (X^-\alpha) \rightarrow {}^6\mathrm{Li} + X^-\ ) \sim 10^8 \times \sigma(\ d + \alpha \rightarrow {}^6\mathrm{Li} + \gamma\ )$$

planning

A .development of theory

1. Networks for selected astrophysical models
   Advanced nuclear data base of rates.
2. Nuclear theoretical models.
   Capture reaction theory (ANC)
   Shell model
   Spectroscopic factor
   beta-decay theory
   Nuclear mass theory

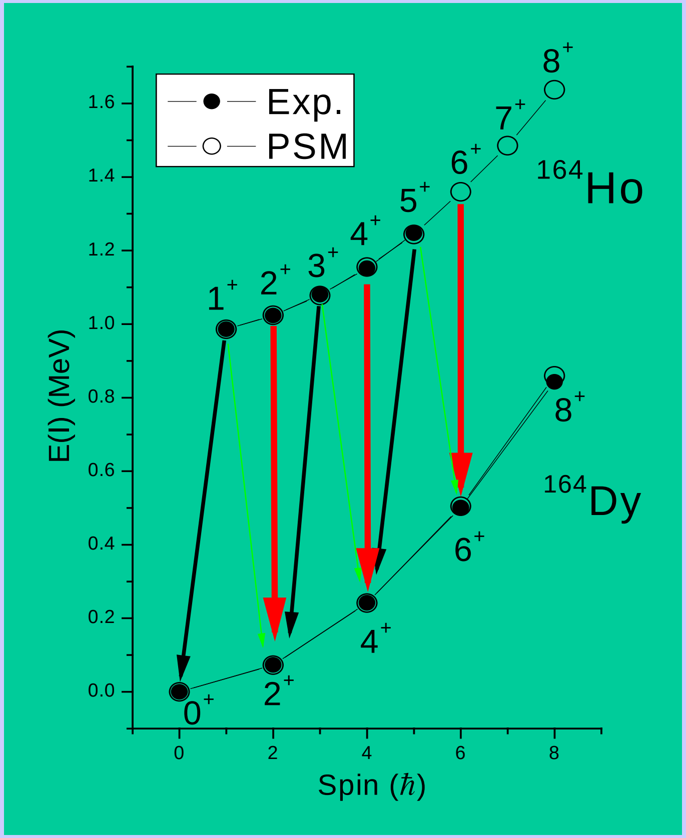
Neutron capture elements
in low-metallicity Galactic halo stars

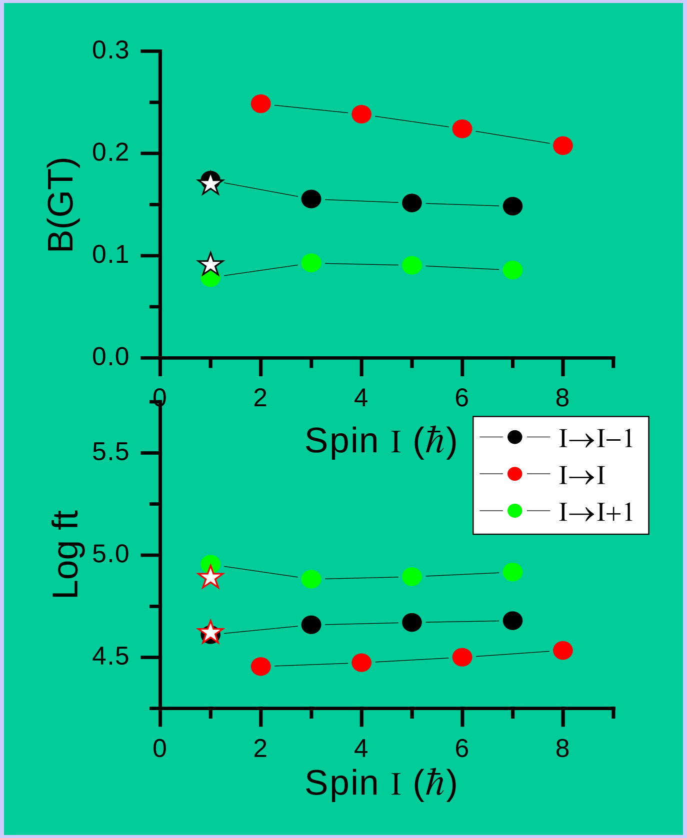
结合天文台观测研究

早期银河系核合成的时间、性质和天体物理环境

β-衰变理论

激发态间的Gamow-Teller 跃迁





Z.C. Gao et al., Phys. Rev. C74, 054303 (2006)

人才培养

通过几年或十年左右的努力，培养出一支较高学术水准的核天体物理科学研究队伍（实验和理论）。

这是一项有挑战性的艰巨工作。

Remark

现代宇宙学主要有三个探针：宇宙微波背景辐射、星体运动观测（1a型超新星）和宇宙大爆炸原初核合成。宇宙微波背景辐射的发现，微波背景辐射黑体谱和各向异性的发现是现代宇宙学的里程碑成就。宇宙加速膨胀的发现预示着什么事情都可能发生。大爆炸核合成的探索，试图从微观与宏观统一的角度看宇宙，是重要的科学方法论，我们有理由寄望宇宙学的新突破。

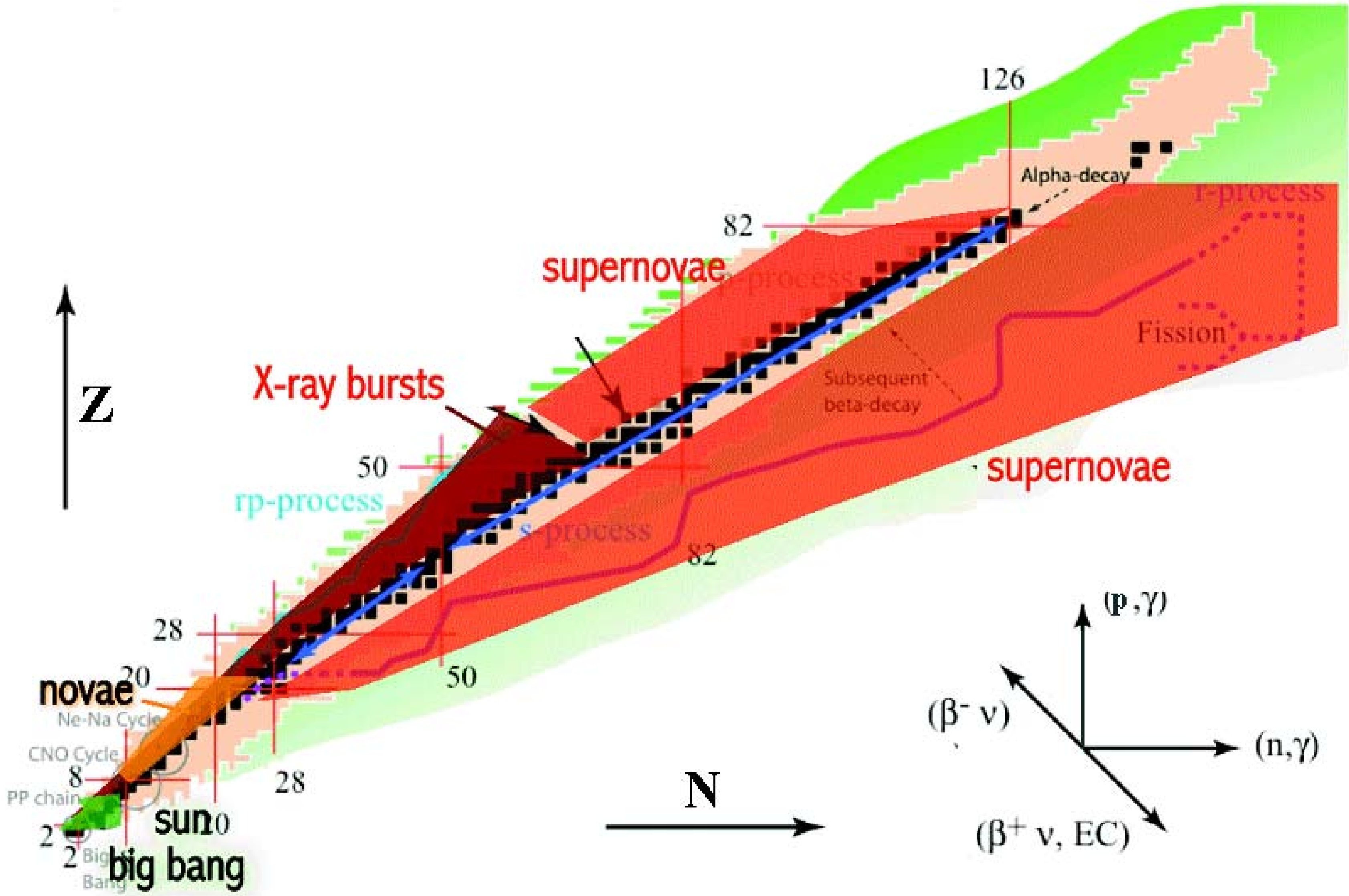
整体统一观

现在对科学的最大的挑战，已不仅是那些已知的物质。因为在我们知道的物质之外，还有暗物质、暗能量。所以　我们要立足新的基础科学前沿，一定要将小的与大的联系　起来，这个方法可称为“整体统一”。我认为，“整体统一”　的科学方法，应该是21世纪最重要的科学方法。

李政道

Thank you

天体核过程的路径



126
Alpha-decay
82
supernovae
X-ray bursts
Subsequent
beta-decay
Fission
50
rp-process
s-process
supernovae
82
28
20
novae
Ne-Na Cycle
50
CNO Cycle
8
28
PP chain
sun
2
0
2
big bang
Z
N
(p,γ)
(β⁻ ν)
(n,γ)
(β⁺ ν, EC)

Neutron capture elements
in low-metallicity Galactic halo stars

1、元素丰度随金属丰度的变化
Ge/H vs Fe/H

2、元素丰度比随金属丰度的变化
La/Eu vs Fe/H，Hf/Eu vs Fe/H
Mg/Fe vs Fe/H， Eu/Fe vs Fe/H

3、元素丰度比随的元素丰度比变化
Ba/Sr vs Ba/Fe

4、同一颗恒星中的中子俘获元素丰度

Log (x) vs A

5、中子俘获元素奇偶同位素比

Fraction of odd Ba vs Ba/H

Fraction of odd Ba vs Eu/Ba

Fraction of odd Ba vs Eu/Fe

Theoretical tasks:

Pure r-process

Pure s-Process

Mixed r- & s- process