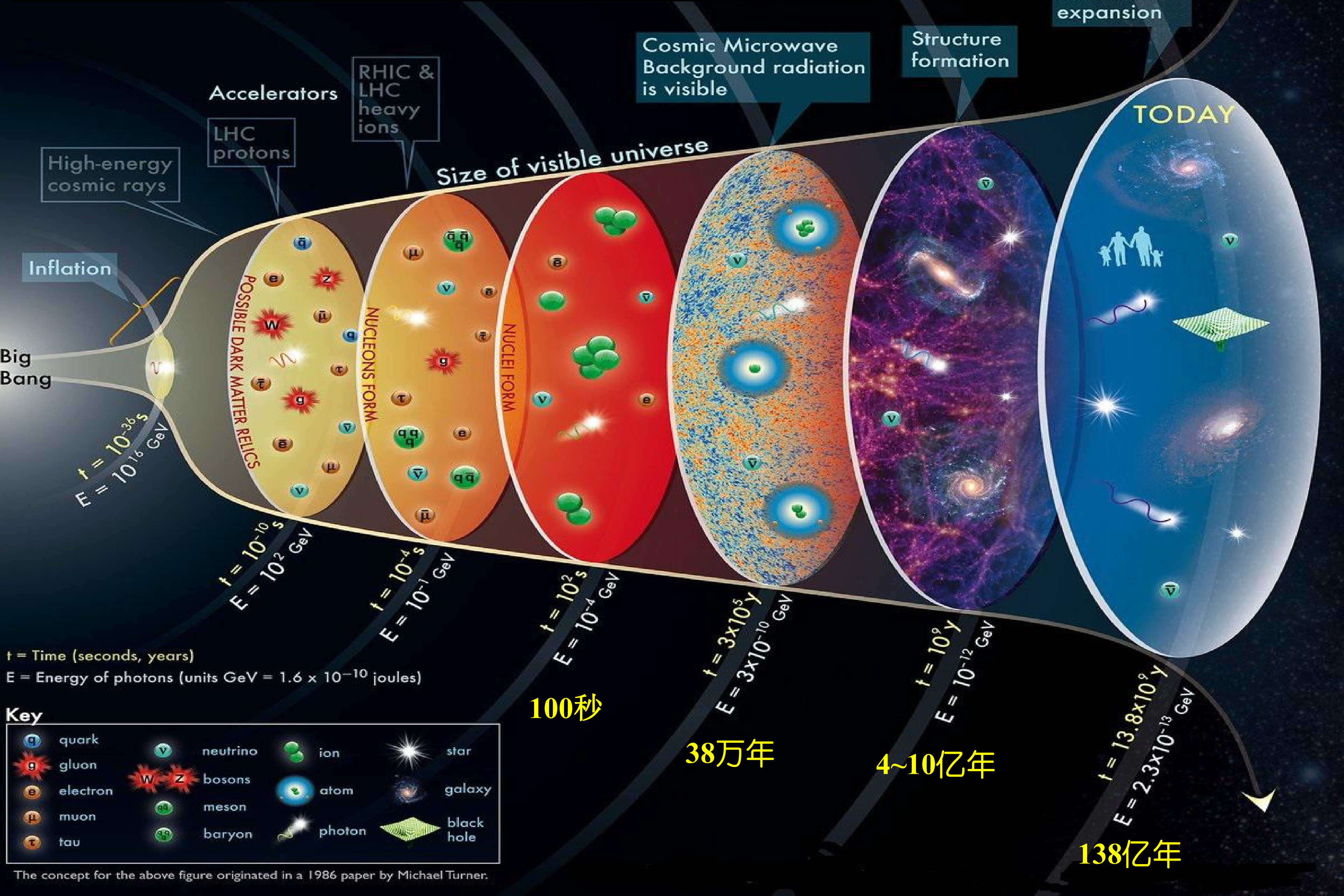
核天体物理

宇宙大爆炸锂问题

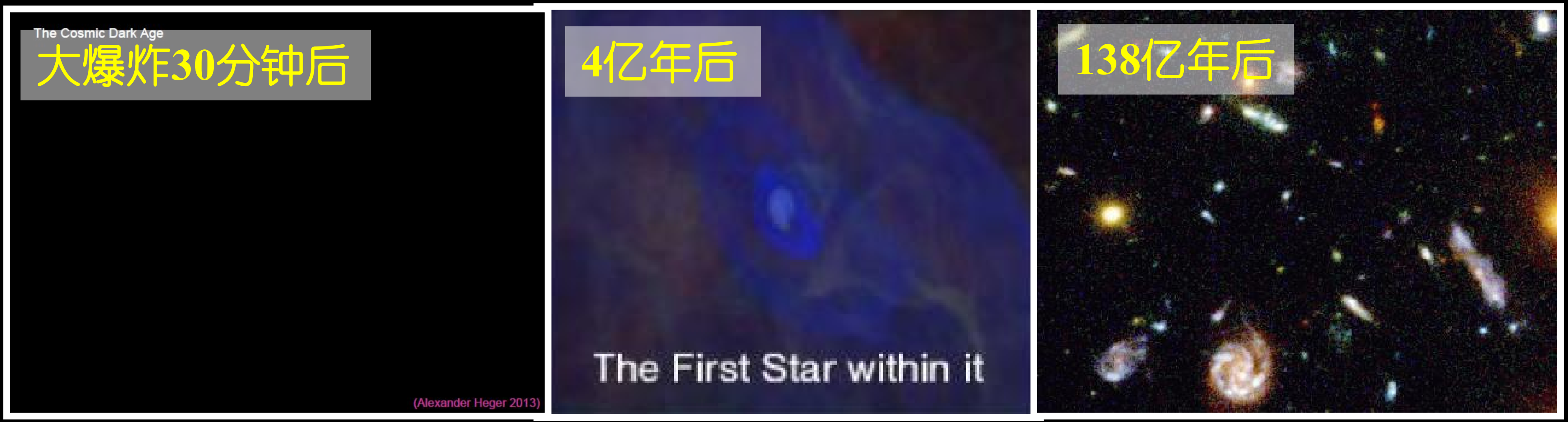
何建军

核科学与技术学院
北京师范大学

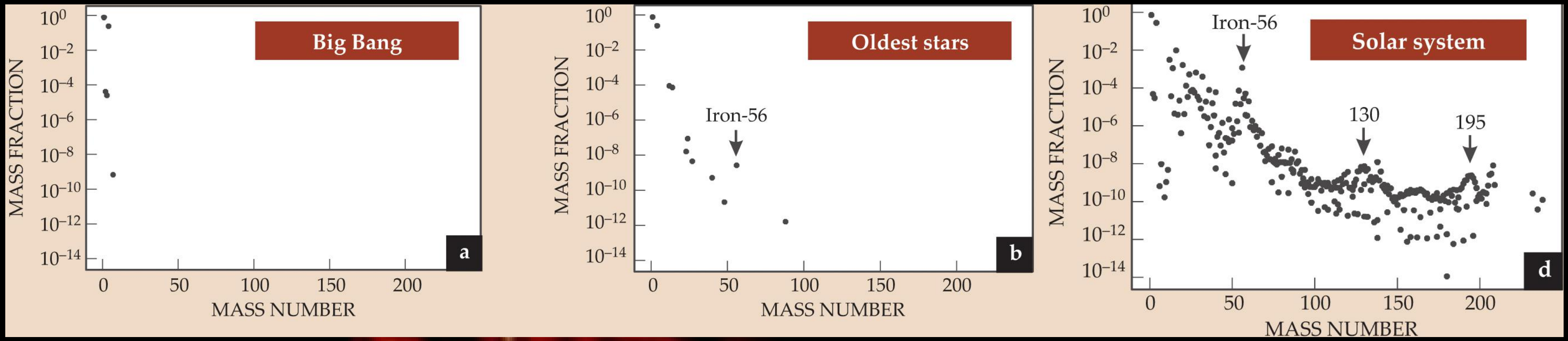
宇宙演化简史


Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
$t = 10^{-36}$ s
$E = 10^{16}$ GeV
$t = 10^{-10}$ s
$E = 10^{2}$ GeV
$t = 10^{-4}$ s
$E = 10^{-1}$ GeV
$t = 10^{2}$ s
$E = 10^{-4}$ GeV
$t = 3x10^{5}$ y
$E = 3x10^{-10}$ GeV
$t = 10^{9}$ y
$E = 10^{-12}$ GeV
$t = 13.8x10^{9}$ y
$E = 2.3x10^{-13}$ GeV
100秒
38万年
4~10亿年
138亿年
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^{-10} joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.

关键科学问题：元素起源

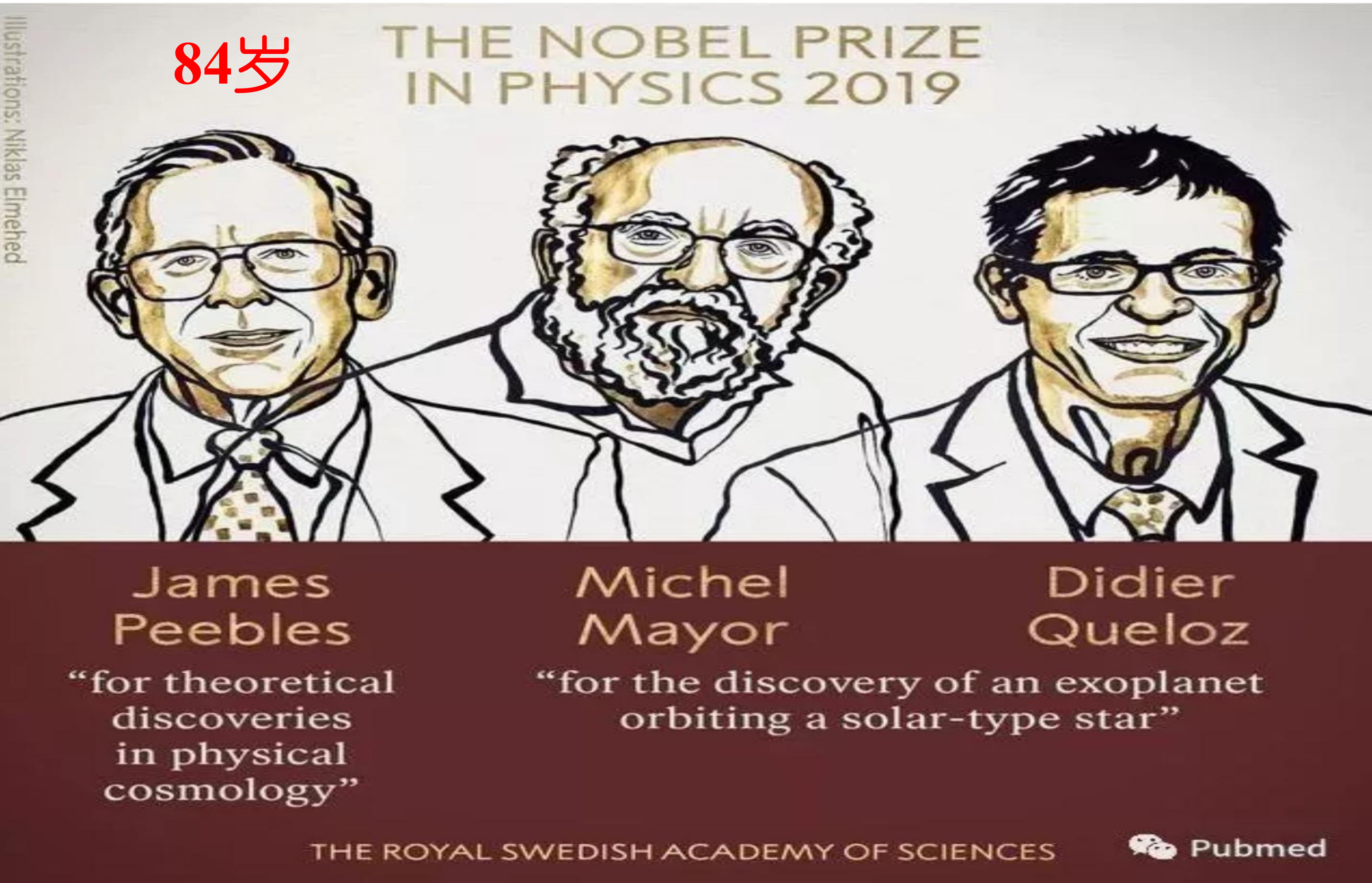


时间



我们都来自于星际尘埃（萨根）

宇宙微波背景辐射



84岁
Illustrations: Niklas Elmehed
THE NOBEL PRIZE
IN PHYSICS 2019
James
Peebles
"for theoretical
discoveries
in physical
cosmology"
Michel
Mayor
Didier
Queloz
"for the discovery of an exoplanet
orbiting a solar-type star"
THE ROYAL SWEDISH ACADEMY OF SCIENCES
Pubmed

宇宙微波背景辐射的发现

1965年：美国贝尔实验室

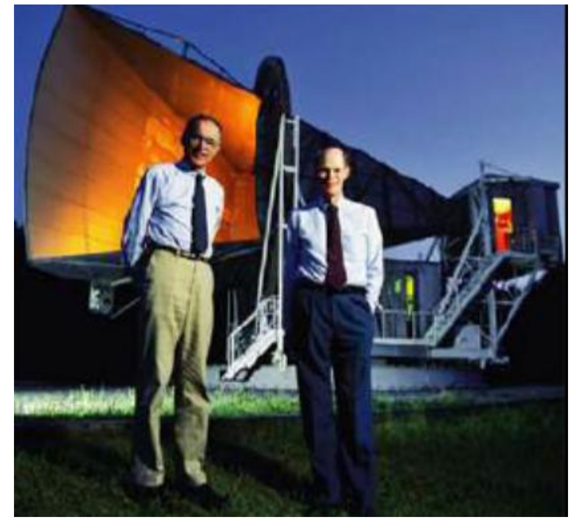
天体物理杂志：Astrophysical Journal

COSMIC BLACK-BODY RADIATION*

One of the basic problems of cosmology is the singularity characteristic of the familiar cosmological solutions of Einstein's field equations. Also puzzling is the presence of matter in excess over antimatter in the universe, for baryons and leptons are thought to be conserved. Thus, in the framework of conventional theory we cannot understand the origin of matter or of the universe. We can distinguish three main attempts to deal with these problems.

R. H. Dicke
P. J. E. Peebles
P. G. Roll
D. T. Wilkinson

May 7, 1965
Palmer Physical Laboratory
Princeton, New Jersey



诺奖（1978年）

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and

600字的论文

A. A. Penzias
R. W. Wilson

May 13, 1965
Bell Telephone Laboratories, Inc
Crawford Hill, Holmdel, New Jersey

彭齐亚斯

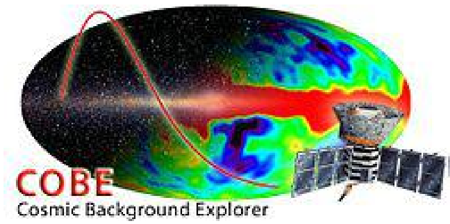
R·威尔逊

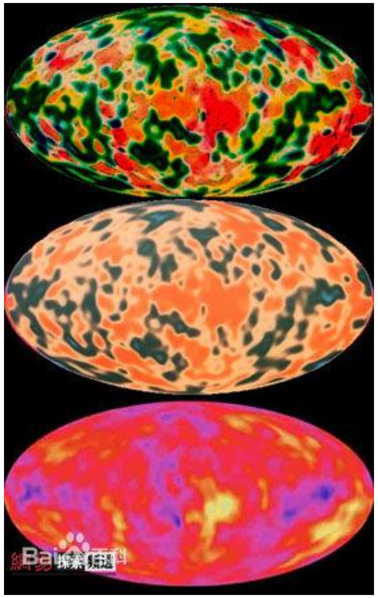
宇宙微波背景辐射卫星观测

1989年11月： 美国NASA发射COBE卫星(Cosmic Background Explorer)升空。马瑟和斯穆特领导的研究团队首次完成了对宇宙微波背景辐射的太空观测研究。发现宇宙微波背景辐射与黑体辐射非常吻合(2.726±0.010K)，从而为大爆炸理论提供了进一步支持。另外，发现宇宙微波背景辐射在不同方向上温度有着极其微小的差异(百万分之六)，所谓的各向异性。

根据宇宙学中的暴涨理论，这个温度涨落起源于宇宙在形成初期极小尺度上的量子涨落，它随着宇宙的暴涨而放大到宇宙学的尺度上，并且正是由于温度的涨落，造成宇宙中物质分布的不均匀性，最终得以形成诸如星系团等的一类大尺度结构。如果没有这样一种机制，那么今天的宇宙很可能完全不是现在这个样子，其中的物质也许像淤泥一样均匀分布。

基于COBE卫星的工作，使宇宙学进入了“精确研究”时代，是人类在宇宙学道路中的里程碑。





诺奖（2006年）

马瑟

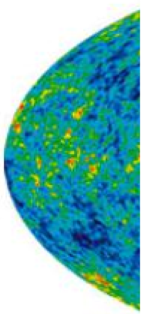
斯穆特

宇宙微波背景辐射

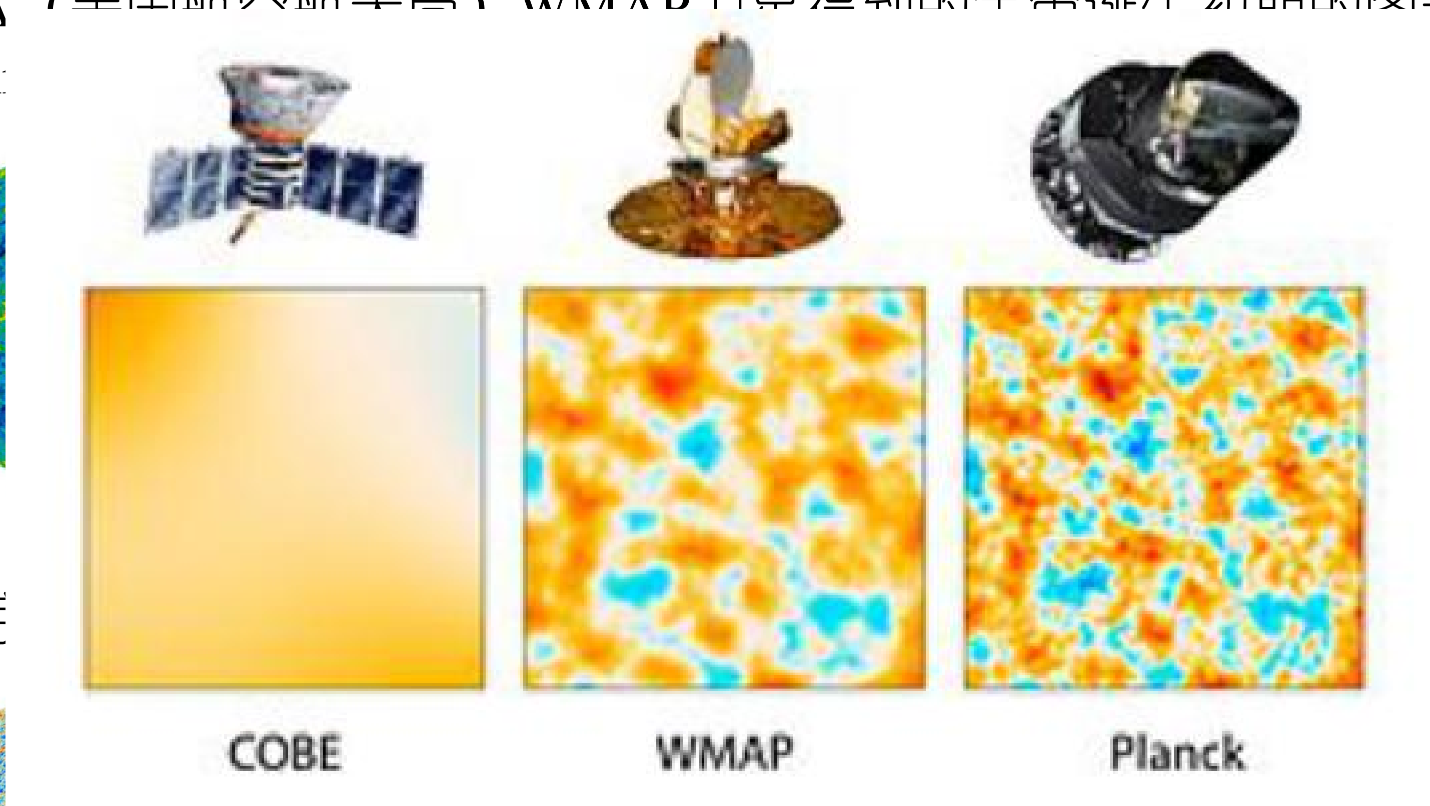
卫星观测

NASA（美国航空航天局）WMAP卫星得到的宇宙诞生初期的图景

(Wilk ... ，2001年)



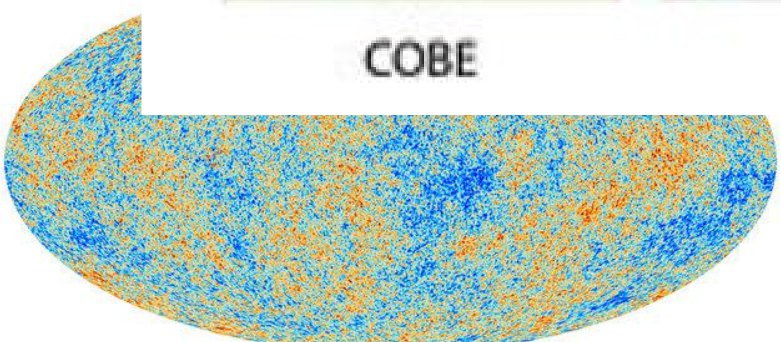
2009年)



ESA

到的宇

课



（2015）

	暗物质	普通物质	暗能量
WMAP	22.7%	4.5%	72.8%
PLANCK	26.8%	4.9%	68.3%

宇宙大爆炸模型

- **1929年：** 哈勃发现大多数星系都存在红移现象，建立了哈勃定律，被认为是宇宙膨胀的有力证据[PNAS15(1929)168]。
- **1932年：** 勒梅特提出现代大爆炸理论。认为宇宙开始于一个小的原始“超原子”的灾变性爆炸[Pop. Sci.]。
- **1946年：** 伽莫夫第一次将广义相对论融入到宇宙理论中，提出了热大爆炸宇宙学模型。发表了一篇关于元素合成的论文，成为大爆炸理论的基础性论文[PR70(1946)572]。
- **1949年：** 霍伊尔在BBC的一次广播节目中首先使用“大爆炸”一词，本意是嘲笑大爆炸模型。在他看来，大爆炸模型最初的“奇点”难以令人接受。
- **1967年：** 瓦格纳、福勒和霍伊尔首次对大爆炸核合成进行了网络方程计算[ApJ148(1967)3]

宇宙大爆炸原初核合成

- **1946-1950: αβγ提出通过核反应解释宇宙中元素丰度**

PHYSICAL REVIEW VOLUME 73, NUMBER 7 APRIL 1, 1948

Letters to the Editor

PUBLICATION of brief reports of important discoveries in physics may be secured by addressing them to this department. The closing date for this department is five weeks prior to the date of issue. No proof will be sent to the authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents. Communications should not exceed 600 words in length.

The Origin of Chemical Elements

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

AND

H. BETHE
Cornell University, Ithaca, New York

AND

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

We may remark at first that the building-up process was apparently completed when the temperature of the neutron gas was still rather high, since otherwise the observed abundances would have been strongly affected by the resonances in the region of the slow neutrons. According to Hughes,[2] the neutron capture cross sections of various elements (for neutron energies of about 1 Mev) increase exponentially with atomic number halfway up the periodic system, remaining approximately constant for heavier elements.

Using these cross sections, one finds by integrating Eqs. (1) as shown in Fig. 1 that the relative abundances of various nuclear species decrease rapidly for the lighter elements and remain approximately constant for the elements heavier than silver. In order to fit the calculated curve with the observed abundances[3] it is necessary to assume the integral of $\rho_n dt$ during the building-up period is equal to 5×10^4 g sec./cm^3.

On the other hand, according to the relativistic theory of the expanding universe[4] the density dependence on time is given by $\rho \cong 10^6/t^2$. Since the integral of this expression

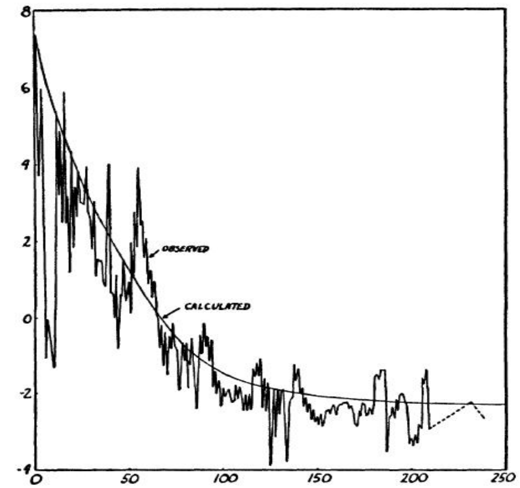
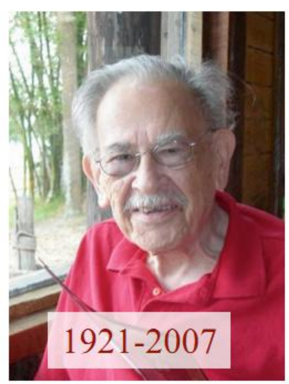
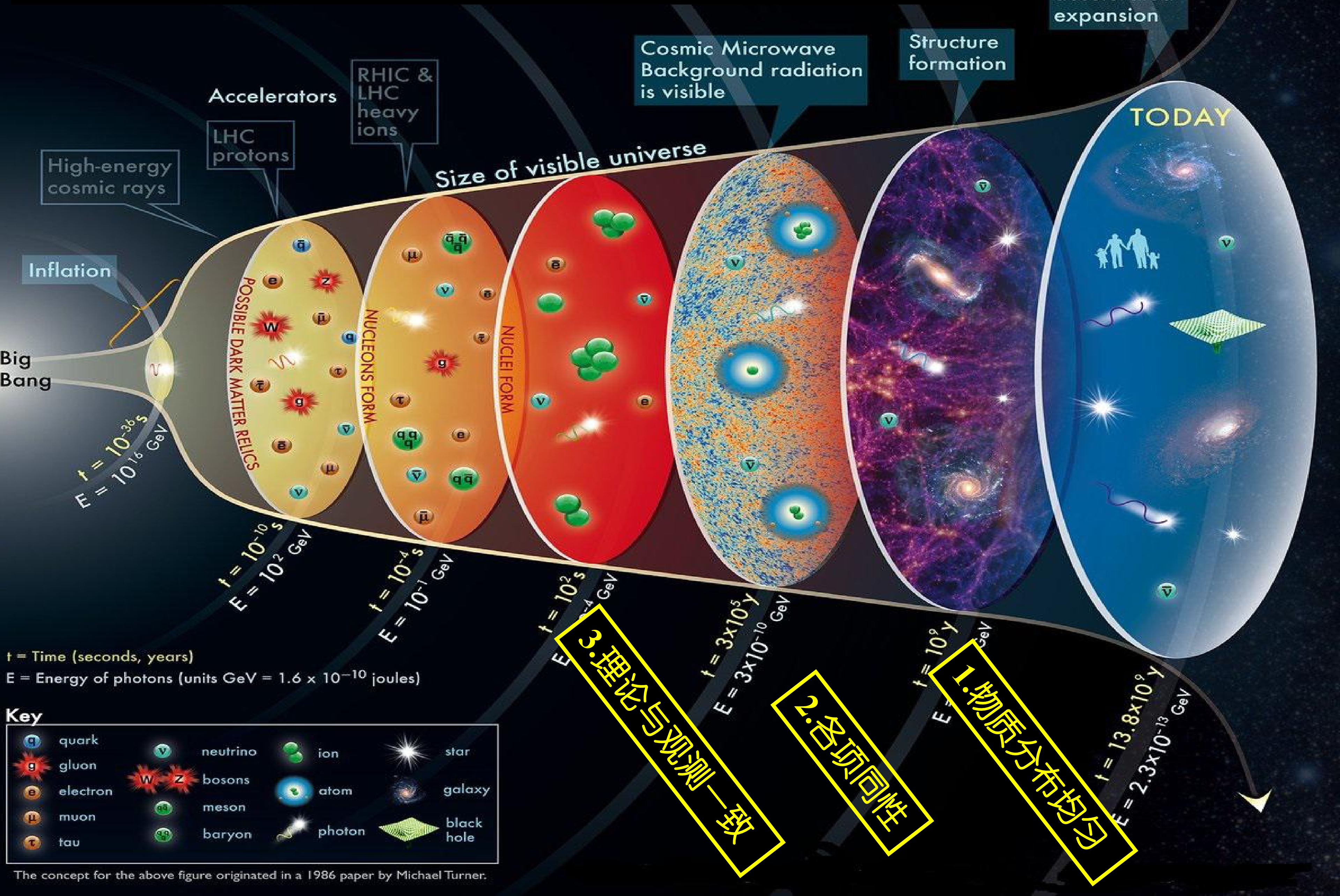


FIG. 1.
Log of relative abundance
Atomic weight



R.A. Alpher, H. Bethe and G. Gamow
"The Origin of Chemical Elements," Physical Review, 73, Issue 7, (1948), 803-804.

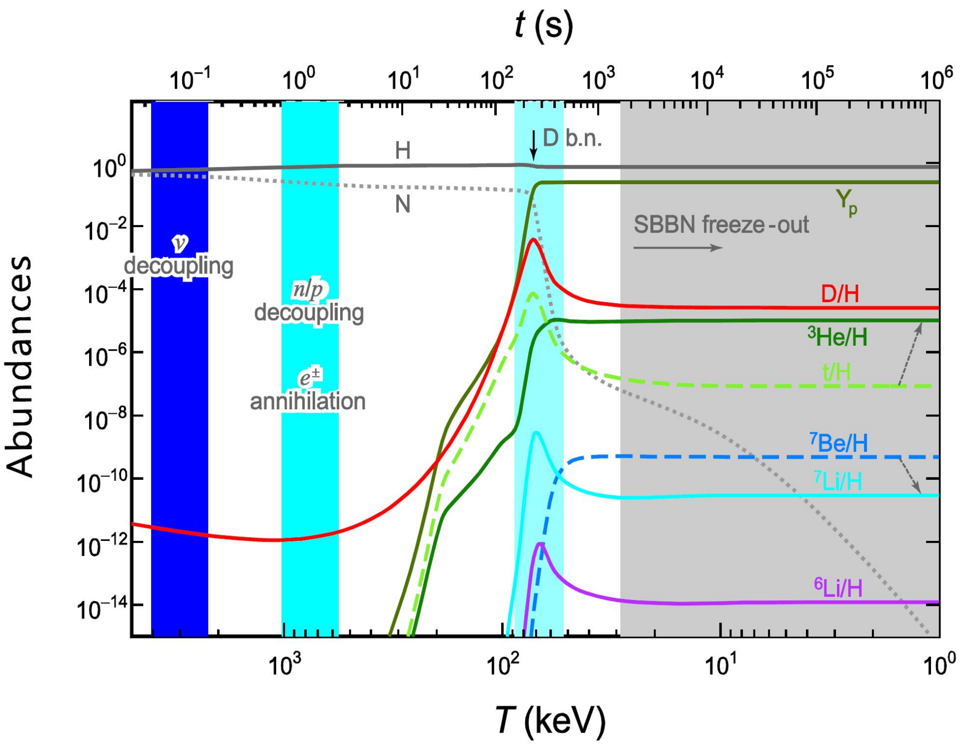
宇宙大爆炸模型的证据



The concept for the above figure originated in a 1986 paper by Michael Turner.

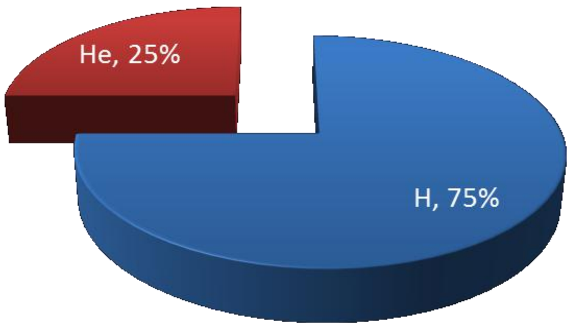
大爆炸模型的证据之一

宇宙大爆炸原初核合成(BBN)



- T > 1 MeV： n, p通过弱作用处于平衡
- T ≈ 1 MeV： n, p退耦， 脱离平衡
- T ≈ 0.1 MeV： 核合成开始有效进行
- T < 0.03 MeV： 核合成过程基本结束

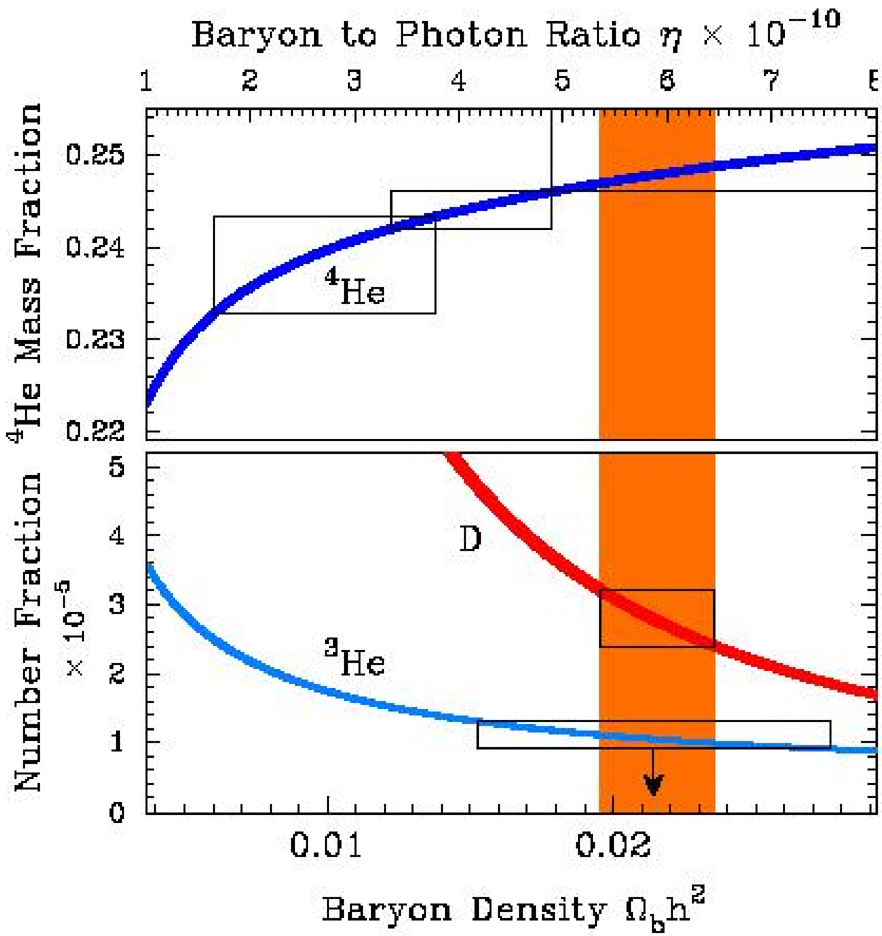
大爆炸30分钟后



其它 (^{2}H,^{3}He,^{6}Li,^{7}Li)<0.00001

M. Pospelov & J. Pradler, Big bang nucleosynthesis as a probe of new physics
Ann. Rev. Nucl. Part. Sci. 60 (2010) 539

大爆炸模型的证据之一



D, ^{4}He, ^{3}He 核素丰度天文观测值和BBN理论预测值基本一致！

大爆炸模型的证据之一

1967年，Wagoner, Fowler & Hoyle: 首次对大爆炸核合成进行了细致的网络方程计算

THE ASTROPHYSICAL JOURNAL, Vol. **148**, April 1967

ON THE SYNTHESIS OF ELEMENTS AT VERY HIGH TEMPERATURES*

ROBERT V. WAGONER, WILLIAM A. FOWLER, AND F. HOYLE
California Institute of Technology, Pasadena, California, and Cambridge University
Received September 1, 1966

BBN 微分方程组

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

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

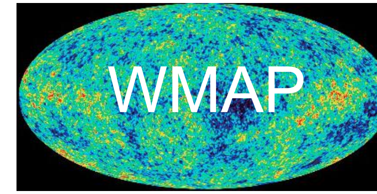
$$\dot{\rho}=-3H\left(\rho+p\right)$$

$$L\left(\frac{m_e}{T},\phi_e\right)=\frac{n_B}{T^3}\sum_j Z_j Y_j$$

$$\dot{Y}_i=\sum_{j,k,l}N_i\left(\Gamma_{kl\to ij}\frac{Y_l^{N_l}Y_k^{N_k}}{N_l!N_k!}-\Gamma_{ij\to kl}\frac{Y_i^{N_i}Y_j^{N_j}}{N_i!N_j!}\right)$$

R	尺度因子
n_B	重子数密度
ρ	总能量密度
p	压强
Z_i	电荷数
ϕ_e	电子化学势
Y_i	核素i的丰度
Γ	反应率

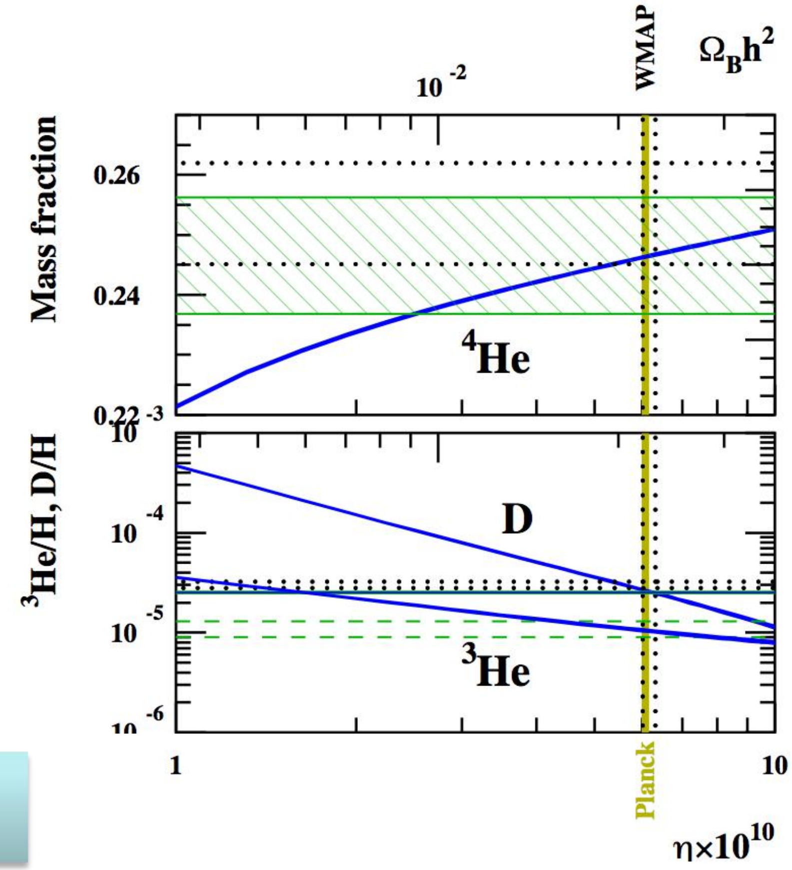
宇宙锂问题



- 最新核反应率
- 最新观测数据

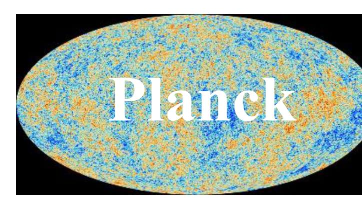
$\Omega_B h^2$ *[WMAP: Komatsu+ 2011; Planck: Ade+ 2013]*

- ^{4}He *[Aver+ 2011; 2013]*
- D *[Olive+ 2012; Cooke+ 2013]*
- ^{3}He *[Bania et al. (2002)]*
- ^{7}Li *[Sbordone+ 2010]*



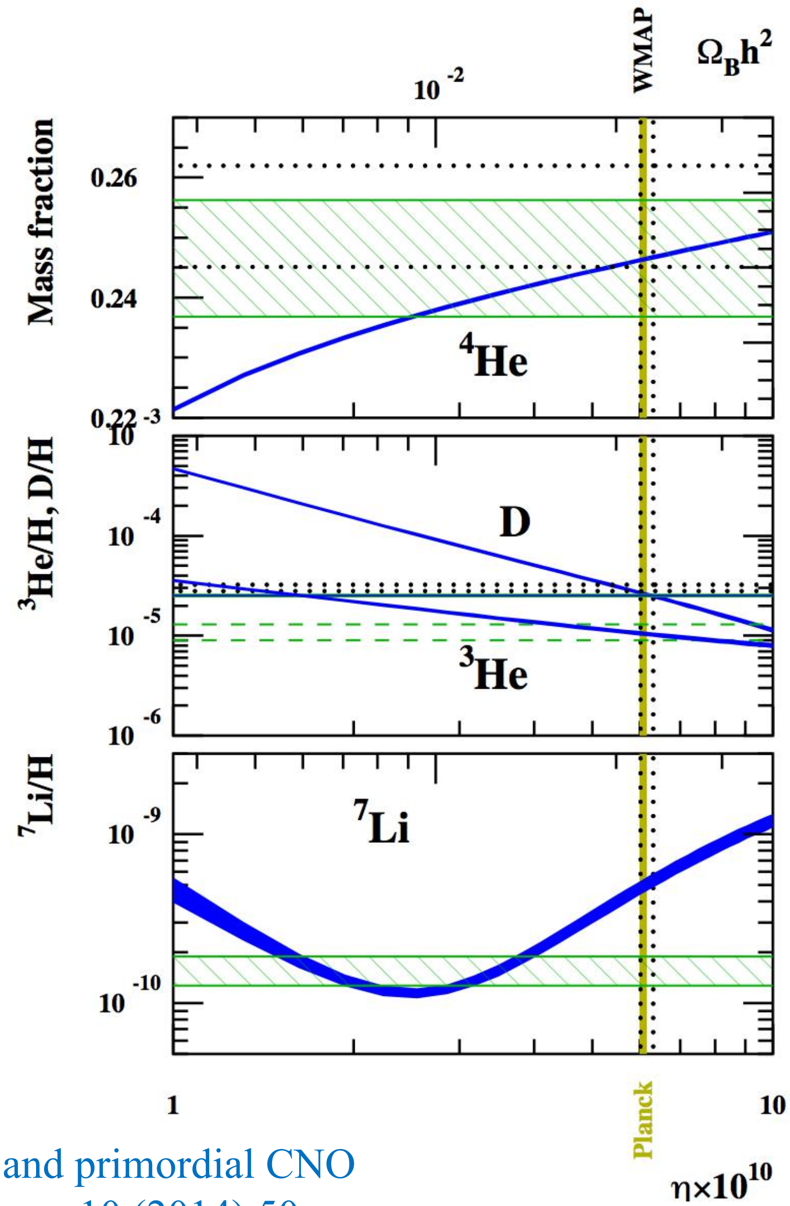
➢ ^{4}He, D和^{3}He符合得较好

A. Coc et al., Standard big bang nucleosynthesis and primordial CNO abundances after Planck. J. Cosmo. Astropart. Phys., 10 (2014) 50



宇宙锂问题

^{7}Li丰度存在3~4倍差异
(Cosmological Lithium Problem)



A. Coc et al., Standard big bang nucleosynthesis and primordial CNO abundances after Planck. J. Cosmo. Astropart. Phys., 10 (2014) 50

宇宙锂问题

事件回顾

2001年6月：

NASA发射了威尔金森微波各向异性探测器WMAP

2003年2月：

发布了宇宙诞生初期的图像以及一系列物理成果，即First-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations，简称WMAP1。WMAP的测量结果为

$\Omega_b h^2=0.024\pm0.001$，结合其他天文观测数据，得到的最佳拟合结果为

$\Omega_b h^2=0.0224\pm0.0009$，对应的重子与光子的比值为：$\eta=(6.1^{+0.3}_{-0.2})\times10^{-10}$

(η是一个非常小的量，为了方便，人们通常定义一个比较大的量，即$\eta_{10}=\eta\times10^{10}$)

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 148:175–194, 2003 September

FIRST-YEAR *WILKINSON MICROWAVE ANISOTROPY PROBE* (*WMAP*)[1] OBSERVATIONS: DETERMINATION OF COSMOLOGICAL PARAMETERS

D. N. SPERGEL,[2] L. VERDE,[2,3] H. V. PEIRIS,[2] E. KOMATSU,[2] M. R. NOLTA,[4] C. L. BENNETT,[5] M. HALPERN,[6] G. HINSHAW,[5] N. JAROSIK,[4] A. KOGUT,[5] M. LIMON,[5,7] S. S. MEYER,[8] L. PAGE,[4] G. S. TUCKER,[5,7,9] J. L. WEILAND,[10] E. WOLLACK,[5] AND E. L. WRIGHT[11]

Received 2003 February 11; accepted 2003 May 20

宇宙锂问题

事件回顾

2003年3月：
基于WMAP精确数据，Cyburt等人进行了BBN核合成计算，发现预言的^{7}Li丰度比天文观测值高2~3倍，也就是后来人们常说的锂问题或者宇宙锂问题。

ELSEVIER

Available online at www.sciencedirect.com
SCIENCE DIRECT

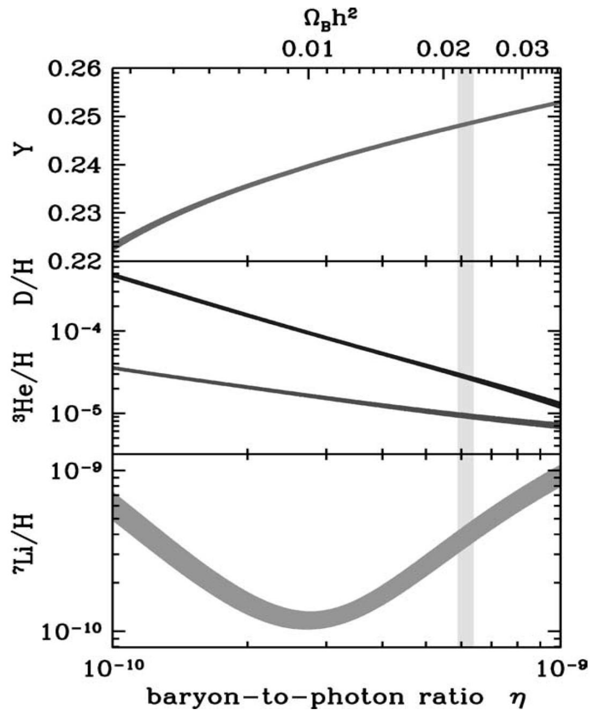
Physics Letters B 567 (2003) 227–234

Primordial nucleosynthesis in light of WMAP

Richard H. Cyburt [a], Brian D. Fields [b], Keith A. Olive [c]

[a] *Department of Physics, University of Illinois, Urbana, IL 61801, USA*
[b] *Center for Theoretical Astrophysics, Department of Astronomy, University of Illinois, Urbana, IL 61801, USA*
[c] *William I. Fine Theoretical Physics Institute, University of Minnesota, Minneapolis, MN 55455, USA*

Received 4 March 2003; received in revised form 4 June 2003; accepted 17 June 2003



宇宙锂问题

事件回顾

2003年7月：
基于WMAP精确数据，Coc等人进行了BBN核合成计算。

THE ASTROPHYSICAL JOURNAL, 600:544–552, 2004 January 10

UPDATED BIG BANG NUCLEOSYNTHESIS COMPARED WITH *WILKINSON MICROWAVE ANISOTROPY PROBE* OBSERVATIONS AND THE ABUNDANCE OF LIGHT ELEMENTS

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Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, IN2P3-CNRS and Université Paris Sud, Bâtiment 104, F-91405 Orsay Campus, France

ELISABETH VANGIONI-FLAM
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PIERRE DESCOUVEMONT AND ABDERRAHIM ADAHCHOUR[1]
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AND

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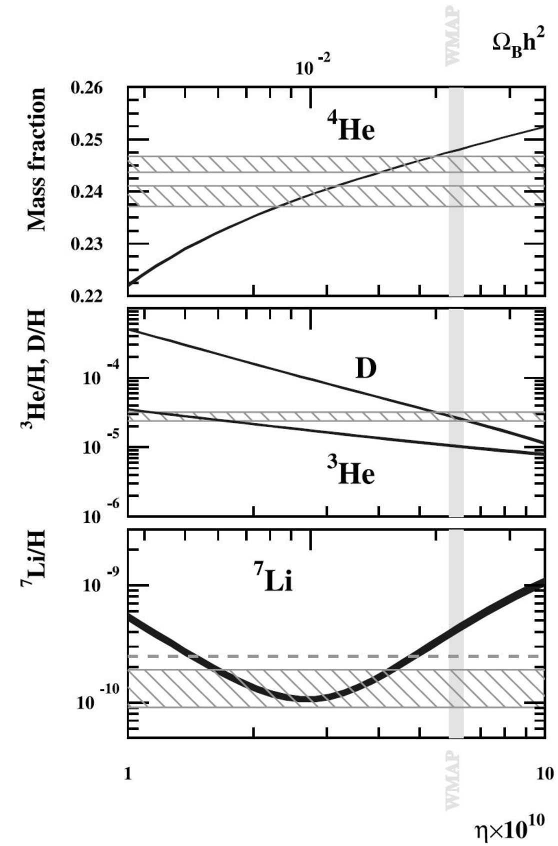
Received 2003 July 23; accepted 2003 September 24



宇宙锂问题

事件回顾

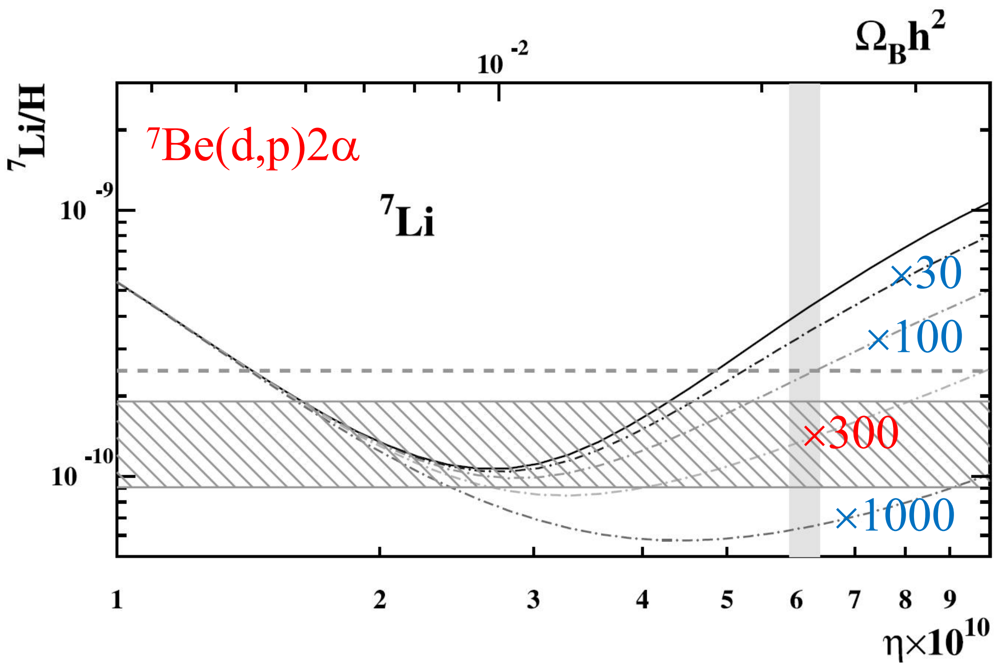
2003年7月：

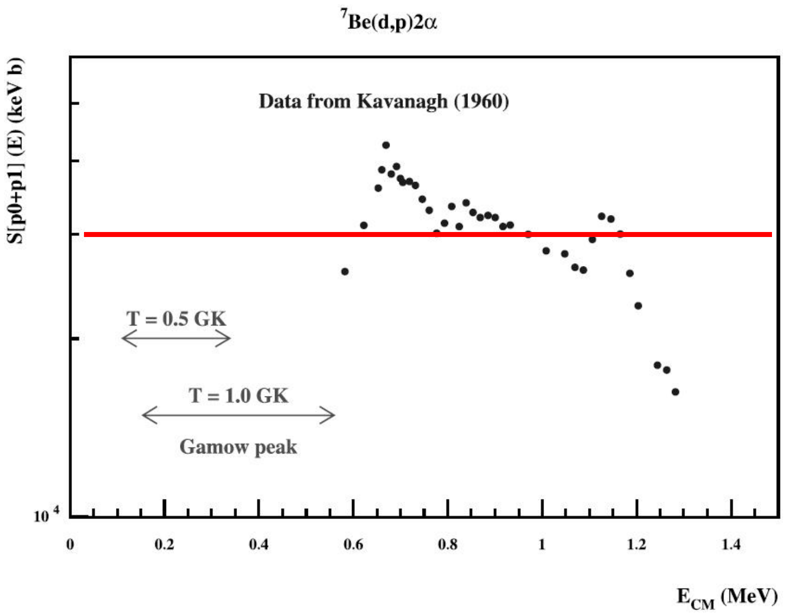
基于WMAP精确数据，Coc等人进行了BBN核合成计算。

并提出了解决锂问题的一个核物理实验方案

$^7Be(d,p)2\alpha$反应

CF88: $S = 100$ MeV·b





宇宙锂问题

事件回顾

2005年4月：

Angulo等人进行计算d(^{7}Be,p)2α 实验。

认为这个反应无法解决锂问题！

THE ASTROPHYSICAL JOURNAL, 630:L105–L108, 2005 September 10

THE ^{7}Be(d, p)2α CROSS SECTION AT BIG BANG ENERGIES AND THE PRIMORDIAL ^{7}Li ABUNDANCE

C. ANGULO, E. CASAREJOS, M. COUDER,[1] P. DEMARET, P. LELEUX,[2] AND F. VANDERBIST
Centre de Recherches du Cyclotron and Institut de Physique Nucléaire, Université catholique de Louvain, Chemin du Cyclotron 2, B-1348 Louvain-la-Neuve, Belgium; angulo@cyc.ucl.ac.be
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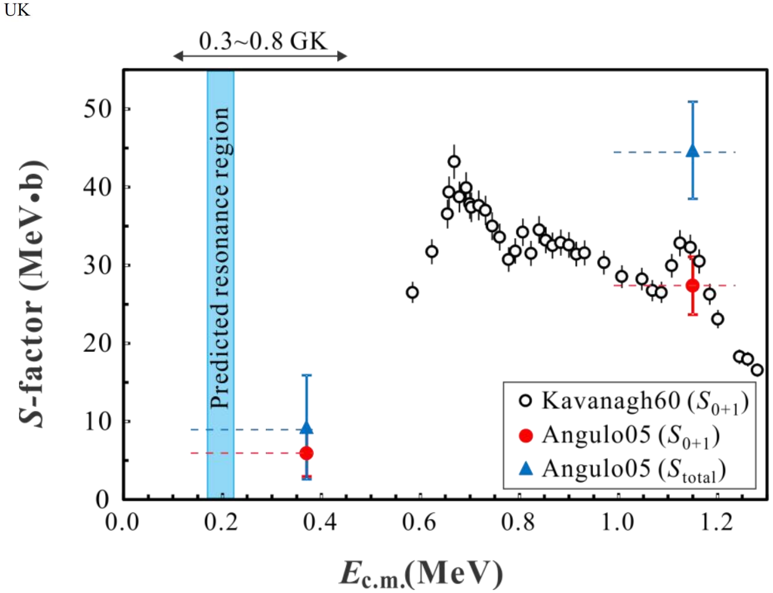
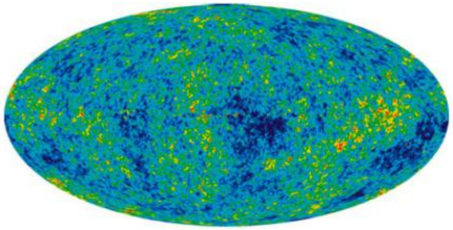


宇宙锂问题

WMAP(2001) *v.s.* Planck(2009)

WMAP (NASA)



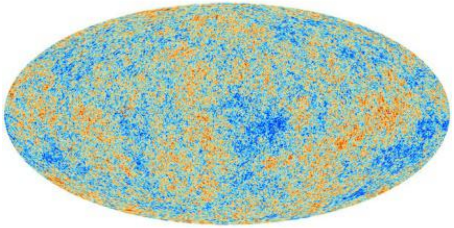
WMAP1 (2003)

$\Omega_b h^2 = 0.024 \pm 0.001$ (精度~4%), $\eta_{10} = 6.1^{+0.3}_{-0.2}$

WMAP9 (2013)

$\Omega_b h^2 = 0.02264 \pm 0.0005$ (精度~2.2%), $\eta_{10} = 6.19 \pm 0.14$

Planck (ESA)



Planck2013

$\Omega_b h^2 = 0.02205 \pm 0.00028$ (精度~1.3%)

WMAP9 (2013)

$\Omega_b h^2 = 0.02240 \pm 0.0001$ (精度~0.5%)

Planck的结果比WMAP的小~1.1%，精度更高！

可能的解决方案

- **天体物理解：** 天文观测结果解释有误？
  - 晕星存在锂消耗机理
  - 观测目标不合适

- **核物理解：** 核反应数据有误或不完整？
  - 重复检验控制^{7}Li产额的关键反应
  - ^{7}Be的次要消耗反应是否存在重要的共振

- **非标准模型解：** 理论不正确或不完善？
  - 标准粒子物理模型外
  - 标准宇宙模型不正确

可能的解决方案

相关文章发表：

Nature: 2篇，Rev. Mod. Phys.：1篇，PRL: 6篇

ApJ：20余篇，PRC&PRD：几十篇

Vol 442|10 August 2006|doi:10.1038/nature05011 nature

LETTERS

A probable stellar solution to the cosmological lithium discrepancy

A. J. Korn[1], F. Grundahl[2], O. Richard[3], P. S. Barklem[1], L. Mashonkina[4], R. Collet[1], N. Piskunov[1] & B. Gustafsson[1]

LETTER

doi:10.1038/nature11407

Observation of interstellar lithium in the low-metallicity Small Magellanic Cloud

J. Christopher Howk[1], Nicolas Lehner[1], Brian D. Fields[2,3] & Grant J. Mathews[1]

综述：何建军, 宇宙大爆炸锂问题，《科学通报》，(2020)

天体物理反应率

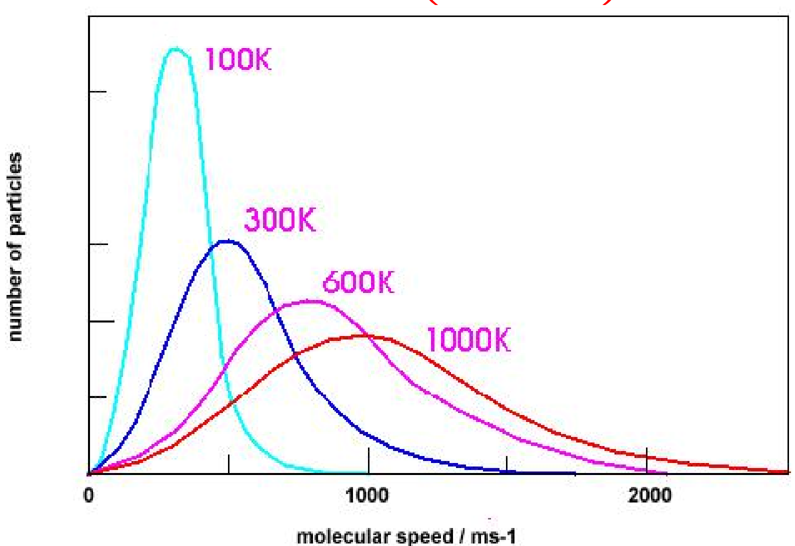
BBN网络方程输入量：核反应率

核反应率的定义：

$$<\sigma v> = \int_0^{\infty} \Phi(v) v \sigma(v) dv$$

理想气体！

$$\Phi(v) = 4\pi v^2 \left(\frac{m}{2\pi kT} \right)^{3/2} e^{-\frac{mv^2}{2kT}}$$



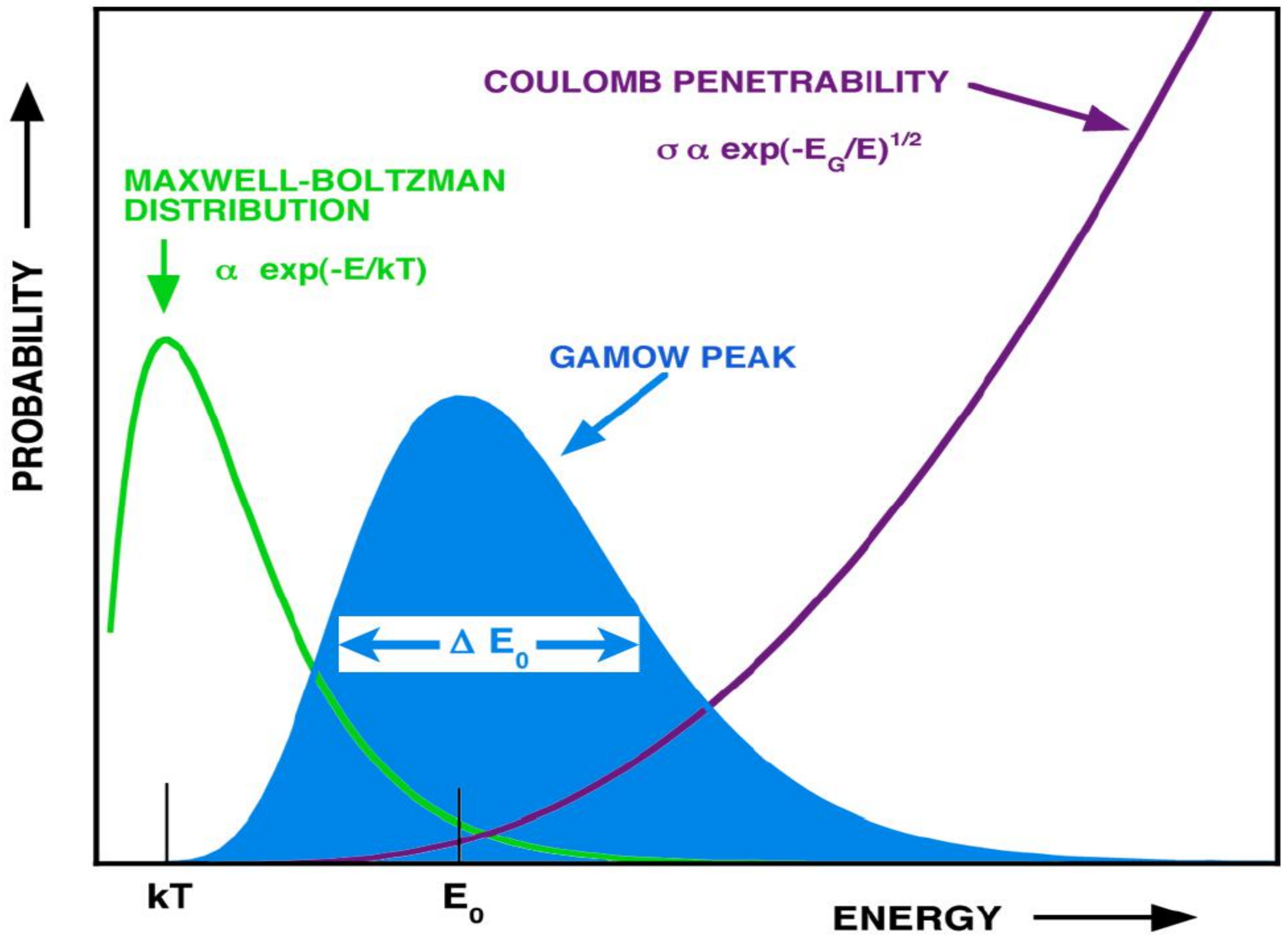
麦克斯韦 (1831-1879)

玻尔兹曼(1844-1906)

教科书：对于天体等离子体环境下的原子核，通常人们认为其满足麦克斯韦-玻尔兹曼速度分布率（这里简称MB分布）。

核反应率

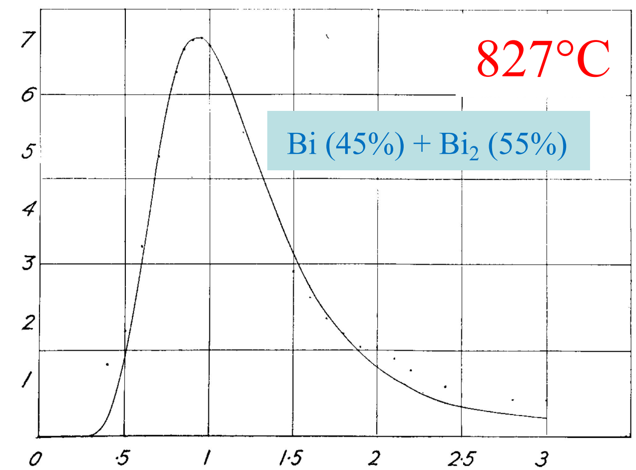
$$N_A\langle\sigma v\rangle = N_A\left(\frac{8}{\pi\mu}\right)^{\frac{1}{2}}\left(\frac{1}{kT}\right)^{\frac{3}{2}}\int_0^{\infty}\sigma(E)Ee^{-E/kT}dE$$

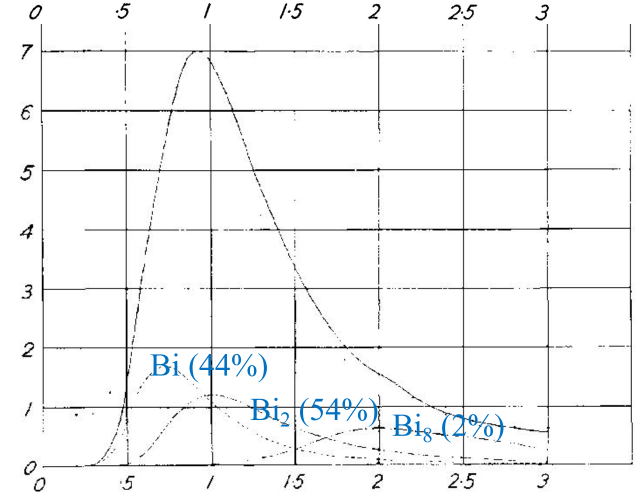


麦克斯韦速度分布率的验证

1920年之后，由于真空技术发展到了一定水平，著名德国物理学家斯特恩用银蒸气分子束实验获得银分子有着确定速度分布的信息，但未能给出定量结果。随后，加州大学物理系主任霍尔、蔡特曼等人作了技术改进，验证结果仍不尽如人意。

1934年我国物理学家葛正权在加州大学测定了铋蒸汽的速率分布，国际上公认他首先以精确的实验数据证明了该定律。然而，他在自己的论文中也分析了存在的误差，还需要进一步的改进。(C.C. Ko, J. Franklin Inst. 217(1934)173)





ELSEVIER

Journal of the Franklin Institute

Volume 217, Issue 2, February 1934, Pages 173-199

The heat of dissociation of Bi_2 determined by the method of molecular beams

Cheng Chuan Ko Ph.D.

精确实验验证

1955年美国哥伦比亚大学的密勒和库什以更高的分辨率，更强的分子射束和螺旋槽速度选择器，测量了钾和铊蒸气分子的速率分布（Miller & Kusch, Phys. Rev. 99(1955)1314）

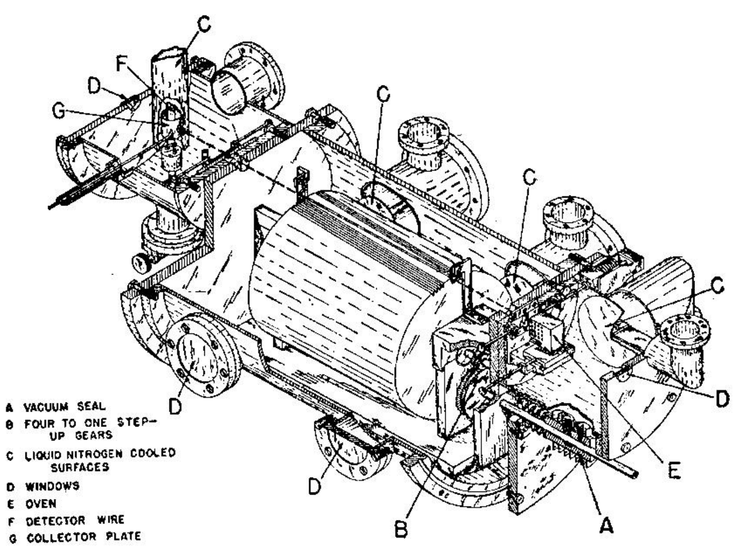


FIG. 2. Schematic diagram of the apparatus designed to measure velocity distributions.

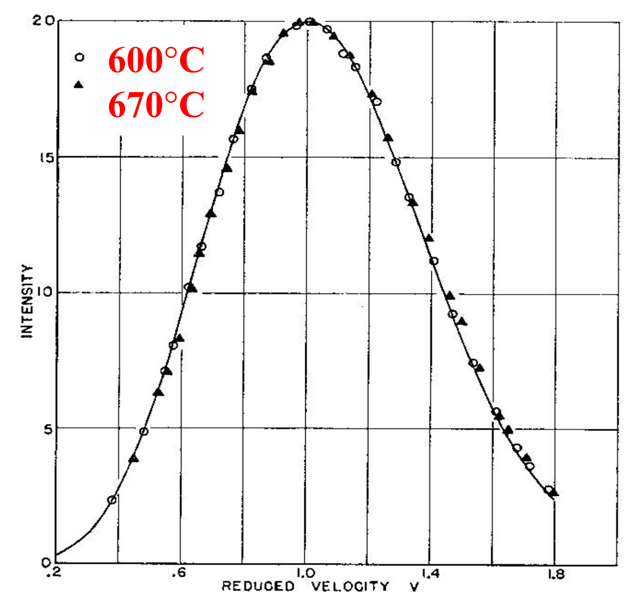


FIG. 5. Typical thallium velocity distributions. The data were taken with thin oven slits at vapor pressures given in Table II.

在BBN极端天体环境下，经典的MB分布还适用吗？

太阳中微子丢失之谜！

P. GALEOTTI
E. LOVERA

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Received January 22, 1974.

1 Brandi, E., and Jaschek, M., *Publ. astr. Soc. Pacif.*, **82**, 847 (1970).
2 Adelman, S., *Astrophys. J. Suppl. Ser.*, **26**, 226 (1973).
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4 Seeger, P. A., Fowler, W. A., and Clayton, D.D., *Astrophys. J. Suppl. Ser.*, **11**, 121 (1965).
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6 Guthrie, B. N. G., *Observatory*, **89**, 224 (1969).
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8 Havnes, O., and Conti, P. S., *Astr. Astrophys.*, **14**, 1 (1971).

Maxwellian relative energies and solar neutrinos

THE solar neutrino discrepancy is now regarded[1,2] as very serious. The general attitude is that the Sun is trying to tell us something but no one is quite sure what. I wish in this note to add to the list of possible *ad hoc* explanations; namely that the scarcity of ^{8}B neutrinos reflects a departure of the distribution of relative kinetic energies from the Maxwellian distribution. I have not been able to calculate a cause of the indicated depletion of the high energy tail of relative energies, so this explanation must be limited to the associated effect.

a good approximation.

Nonetheless we should perhaps be cautious, because the thermonuclear reactions involve improbable high energy fluctuations. For example, in a recent model[4] of the solar centre having $T_c = 14.9 \times 10^6$ K the most effective[3] energy E_o for the pp reaction is E_o (pp) $= 4.58\ kT$, and the reaction ^{3}He (α, γ) ^{7}Be leading to production of ^{8}B involves pairs whose average relative energy is E_o (3, 4) $= 17.4\ kT$ — very far out on the tail of the distribution. The power for the Sun comes from energies of a few kT, whereas the neutrinos come from nearly 20 kT; that causes the ^{8}B neutrino flux to be strongly modified if the high energy tail of the two-particle distribution is depleted.

To illustrate these effects I have recalculated the Sun assuming all Maxwellian distributions are multiplied by the same factor $\exp f(E)$, where $f(E)$ is a slowly varying function of energy. I find that the ^{8}B flux from the Sun depends on d^2f/dE^2: if $d^2f/dE^2 < 0$, the ^{8}B flux is reduced and if $d^2f/dE^2 > 0$ it is increased. The findings are most easily discussed by expanding $f(E)$ in Taylor series as $f(E) = \beta_o - \beta_1 E - \beta_2 E^2 + \ldots$ and ignoring higher terms as having negligible importance near E_o. The constant β_o is set by requiring that the distribution function remain normalised, and is a function of β_1 and β_2.

The β_1 term has no physical effect although it might seem to have, since it does seem at first glance to reduce the high energy tail. This would be true at fixed T, but to maintain the Sun's luminosity at its known value, its central temperature would have to be increased sufficiently to counteract the effect of β_1 on the solar power. This increase in T raises the ^{8}B neutrino flux back to exactly the value it had for $\beta_1 = 0$. Thus β_1 may be ignored as having no effect. For the ^{8}B neutrinos to be reduced in a Sun of fixed luminosity, the deviation from Maxwellian must decrease faster than $\exp(-\beta_1 E)$ between E_o (pp) and E_o (3, 4); that is, d^2f/dE^2 must be negative.

Suppose then that $f(E) \approx \beta_o - \beta_2 E^2$ and imagine that β_2 is a small number so that no great violence is done to the distribution. It is convenient to think of $\beta_2 E^2$ as being $\delta(E/kT)^2$, where $\delta = \beta_2 (kT)^2$ is a smallness parameter for the deviation. My calculations show that values in the range $5 \times 10^{-3} < \delta < 10^{-2}$ are adequate to suppress the neutrino flux to Davis's limit[1]. Values of δ in this range would mean that the deficiency in the distribution function is only a few per cent at a few kT, and at $E = 10\ kT$ the rate of change of the distribution function with energy due to the β_2 term is still only 10% of the Maxwellian rate of change. These values of δ entail negligible corrections to the equation of state but large corrections to the ^{8}B neutrino flux.

Using the same[4] unperturbed model of the solar centre, I find that the ratio of PPI completions to PPII + III is

$$[\mathrm{PPI}/(\mathrm{PPII+III})] \approx 10.36 \exp(117\delta) - 0.25 \qquad (1)$$

and is 10.11 for the unperturbed model. I also calculate that the ^{8}B neutrino flux stands in relation to the unperturbed flux as

$$\frac{\Phi_\nu(^8\mathrm{B}, \delta)}{\Phi_\nu(^8\mathrm{B}, \delta=0)} \approx 10^{-100\,\delta} \qquad (2)$$

For the two values $\Phi = 5 \times 10^{-3}$ and 10^{-2}, the ^{8}B neutrino flux is reduced by factors of 3 and 10 respectively. The flux of

many-body physics involved, so I write in the hope of more authoritative treatment from others.

I thank many colleagues who have urged me to publish this abbreviated account of a more detailed paper I circulated privately in 1971. This research was supported in part by the National Science Foundation.

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Received February 11, 1974.

1 Davis, R., jun. and Evans, J. C., *Proc. XIII int. Conf. Cosmic Rays* (Denver 1973).
2 Bahcall, J. N., *Astr. J.*, **76**, 283 (1971).
3 Clayton, D. D., *Principles of Stellar Evolution and Nucleosynthesis* chapter 4. (McGraw Hill, New York, 1968).
4 Bahcall, J. N., Bahcall, N. A., and Ulrich, R. K., *Astrophys. J.*, **156**, 559 (1969).

My calculations show that values in the range $5\times10^{-3} < \delta < 10^{-2}$ are adequate to suppress the neutrino flux to Davis's limit.

故事从这里开始

侯素青：
2011年到兰州近物所参加工作
2012年考取兰州近物所博士生

非广延熵(Tsallis熵)

C. Tsallis (1946-)

巴西籍著名物理学家

1988年提出了著名的Tsallis熵和Tsallis统计

$$S_q = k_B \sum_{i=1}^{W} p_i \ln_q \frac{1}{p_i} = k_B \frac{1-\sum_{i=1}^{W} p_i^q}{q-1}$$

$$\frac{x^{1-q}-1}{1-q} \equiv \ln_q x$$

$$\frac{S_q(A+B)}{k_B} = \frac{S_q(A)}{k_B} + \frac{S_q(B)}{k_B} + (1-q)\frac{S_q(A)}{k_B}\frac{S_q(B)}{k_B}$$

应用于

- 物理
- 化学
- 网络
- 经济学
- 计算机
- 生物学

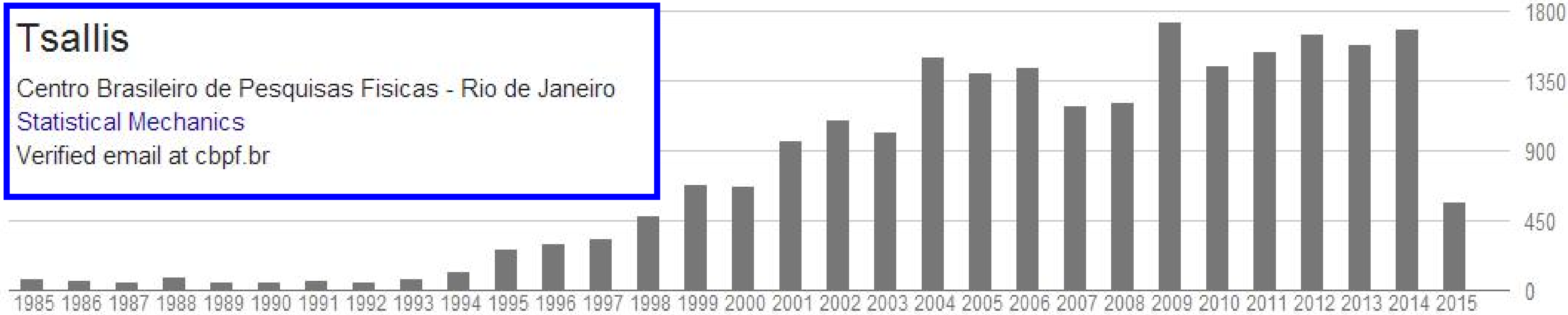
非广延分布的应用

- 自引力系统：
  Du, Europhys.Lett. 2004;
  Taruya et al, PRL 2003;
  Chavanis, A&A. 2003; 2002
- **Antonov** 问题：
  Taruya et al, MNRAS 2005
- 太阳中微子问题：
  Quarati et al, PLA 2005;
  Phys. A 2004; 2003;
  Haubold et al, Phys. A 2004;
  Clayton, Nature,1974; ApJ 1975.
- 等离子体中的非麦克斯韦分布：
  Du, PLA 2004;
  Leubner, ApJ 2004;
  Silva et al, PRE 2000, Phys. A 2005
- 恒星：
  Du, EPL 2006; New Astron. 2006
- 黑洞：
  Oliveira et al, PRD 2005
- 暗物质暗能量：
  Leubner, ApJ 2005; Beck, Phys. A 2004;
  Hansen et al, New Astron. 2005;
  Matos et al, Gen. Relativ. Gravit. 2005
- 星系簇团：
  Quarati et al, Astrophys. Lett. Comm. 1998;
  Hansen, New Astron. 2005
- 背景辐射的温度震荡：
  A. Bernui et al, EPL 2007

每年引用数

Tsallis

Centro Brasileiro de Pesquisas Fisicas - Rio de Janeiro
Statistical Mechanics
Verified email at cbpf.br



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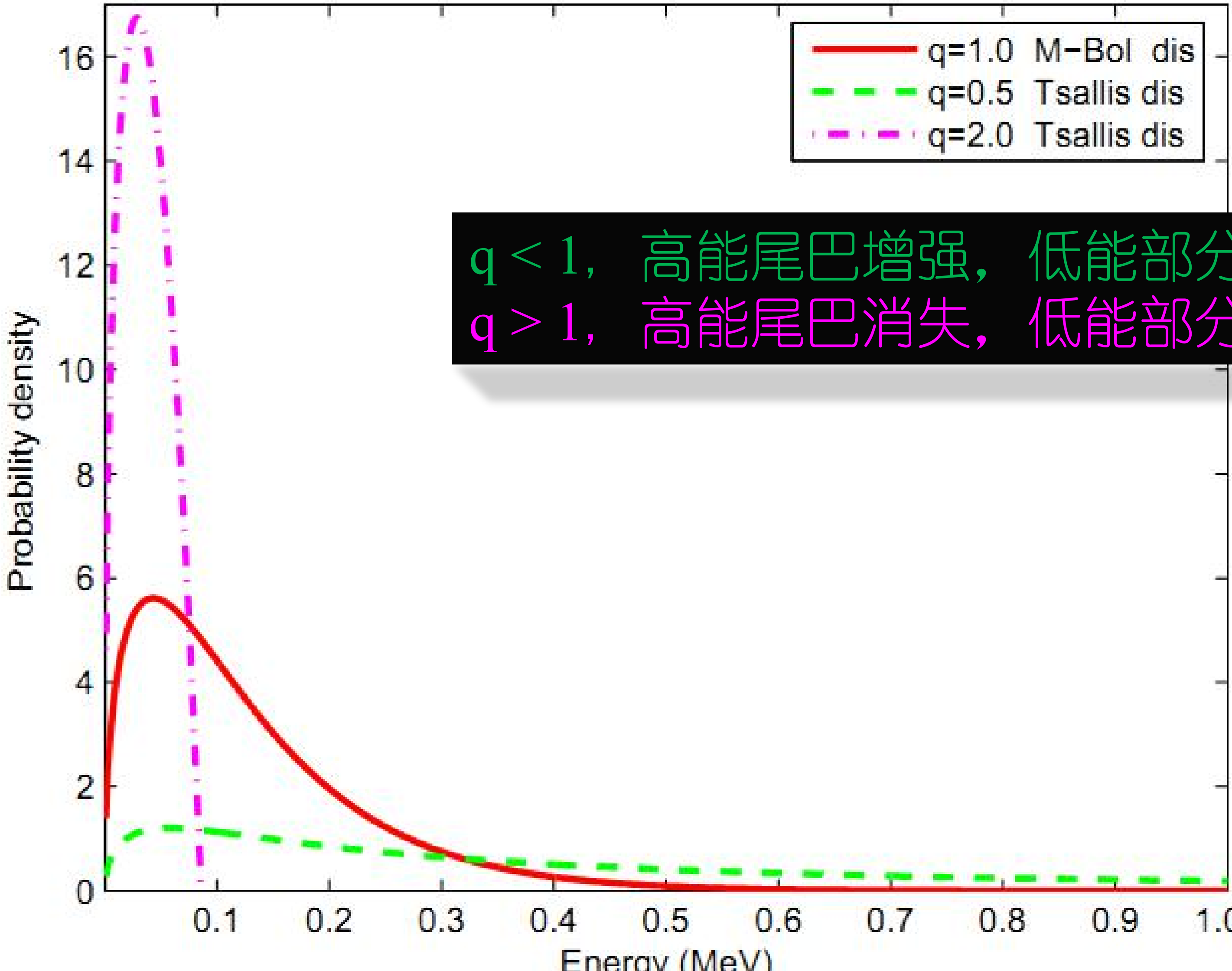
The role of constraints within generalized non C Tsallis, RS Mendes, AR Plastino Physica A: Statistical Mechanics and its Applications	1115	1998
Introduction to nonextensive statistical mecha C Tsallis Springer	946	2009
Generalized statistical mechanics: connectio EMF Curado, C Tsallis Journal of Physics A: Mathematical and General 24 (	860	1991
Nonextensive statistics: theoretical, experime evidences and connections C Tsallis Brazilian Journal of Physics 29 (1), 1-35	664	1999
Nonextensive entropy-Interdisciplinary applications M Gell-Mann, C Tsallis Nonextensive Entropy-Interdisciplinary Applications, by Edited by Murray ...	650	2004

非广延分布

$$f_q(E) = 2C_q \left(\frac{E}{\pi (k_B T)^3} \right)^{1/2} [1 - (q-1)\frac{E}{k_B \mathrm{T}}]^{1/(q-1)}$$

$$\xrightarrow{\mathrm{q} \to 1} f(E) = 2 \left(\frac{E}{\pi (k_B T)^3} \right)^{1/2} \exp\left(-\frac{E}{k_B \mathrm{T}} \right)$$

非广延分布的特征



$q < 1$，高能尾巴增强，低能部分减弱
$q > 1$，高能尾巴消失，低能部分增强

BBN反应列表

(1) $n \rightarrow p$	(18) $^{1}H(n, \gamma)^{2}H$
(2) $^{3}H \rightarrow {}^{3}He$	(19) $^{3}He(n, p)^{3}H$
(3) $^{8}Li \rightarrow 2\,{}^{4}He$	(20) $^{7}Be(n, p)^{7}Li$
(4) $^{6}He \rightarrow {}^{6}Li$	(21) $^{7}Li(p, \alpha)^{4}He$
(5) $^{6}Li(n, \gamma)^{7}Li$	(22) $^{2}H(p, \gamma)^{3}He$
(6) $^{2}H(n, \gamma)^{3}H$	(23) $^{3}H(\alpha, \gamma)^{7}Li$
(7) $^{6}Li(p, \gamma)^{7}Be$	(24) $^{3}He(\alpha, \gamma)^{7}Be$
(8) $^{6}Li(n, \alpha)^{3}H$	(25) $^{2}H(d, n)^{3}He$
(9) $^{3}He(n, \gamma)^{4}He$	(26) $^{2}H(d, p)^{3}H$
(10) $^{3}He(^{3}He, 2p)^{4}He$	(27) $^{3}H(d, n)^{4}He$
(11) $^{7}Li(n, \gamma)^{8}Li$	(28) $^{3}He(d, p)^{4}He$
(12) $^{9}Be(p, \alpha)^{6}Li$	(29) $^{7}Be(d, p)2\,{}^{4}He$
(13) $2\,{}^{4}He(n, \gamma)^{9}Be$	(30) $^{7}Li(d, n)2\,{}^{4}He$
(14) $^{8}Li(p, n)2\,{}^{4}He$	(31) $^{3}H(p, \gamma)^{4}He$
(15) $^{9}Be(p, d)2\,{}^{4}He$	(32) $^{6}Li(p, \alpha)^{3}He$
(16) $^{8}Li(n, \gamma)^{9}Li$	(33) $^{7}Be(n, \alpha)^{4}He$
(17) $^{9}Li(p, \alpha)^{6}He$	(34) $^{2}H(\alpha, \gamma)^{6}Li$

红色：最重要
蓝色：次重要
黑色：不重要

共计17个反应
+1个中子衰变

“致命”一击

The Astrophysical Journal, 767:67 (11pp), 2013 April 10 doi:10.1088/

BIG BANG NUCLEOSYNTHESIS WITH A NON-MAXWELLIAN DISTRIBUTION

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Received 2012 May 17; accepted 2013 February 13; published 2013 March 25

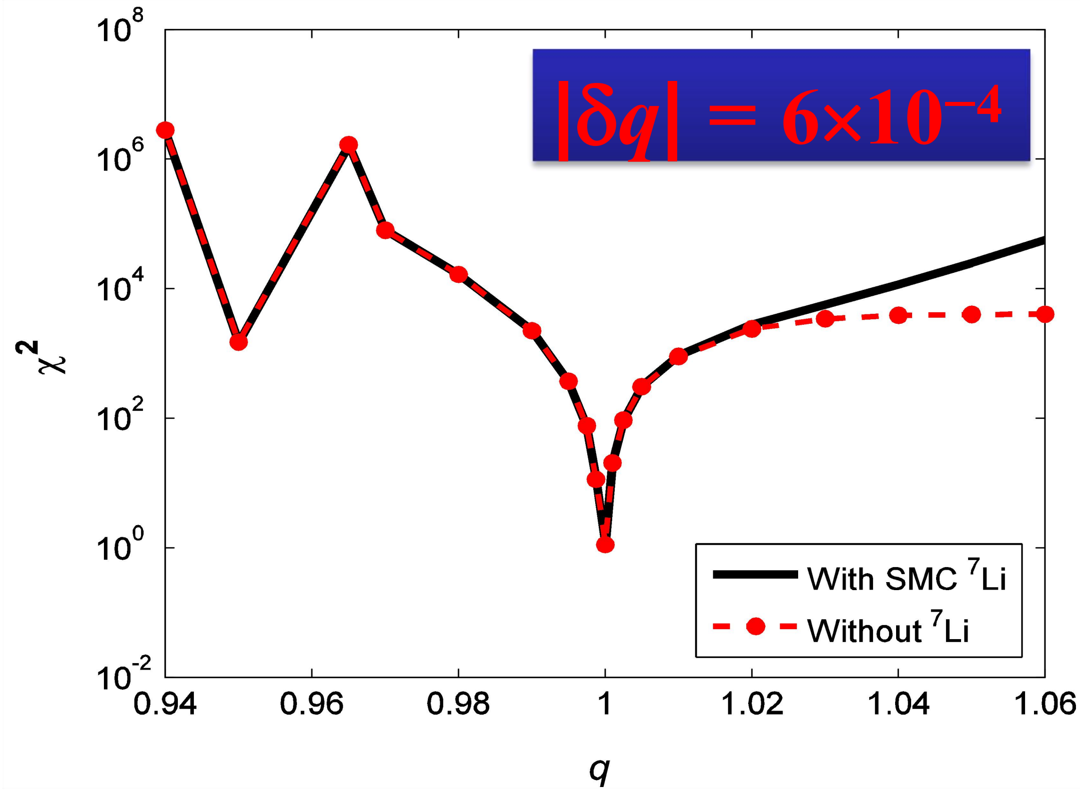
ABSTRACT

The abundances of light elements based on the big bang nucleosynthesis model are calculated using the Tsallis non-extensive statistics. The impact of the variation of the non-extensive parameter q from the unity value is compared to observations and to the abundance yields from the standard big bang model. We find large differences between the reaction rates and the abundance of light elements calculated with the extensive and the non-extensive statistics. We found that the observations are consistent with a non-extensive parameter $q = 1^{+0.05}_{-0.12}$, indicating that a large deviation from the Boltzmann–Gibbs statistics ($q = 1$) is highly unlikely.

该工作存在一些问题，具体表现为：

- 对反应率的计算进行了近似，与精确值存在较大差异
- **BBN**计算存在问题
- 归一系数存在问题

第1次搜索结果

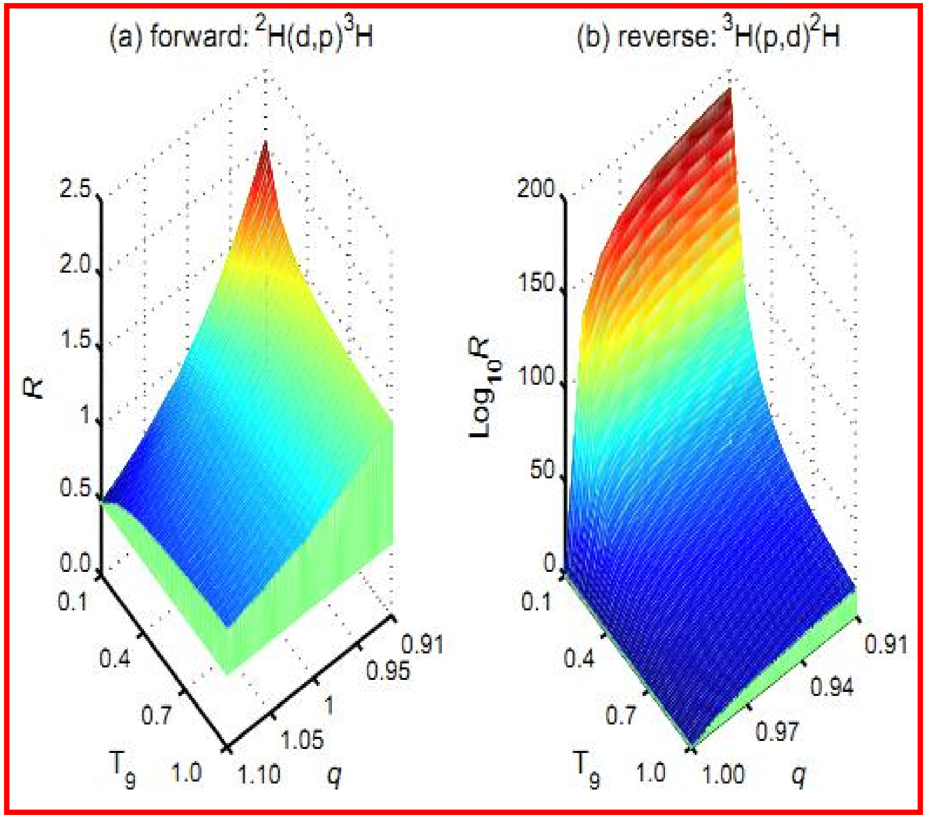


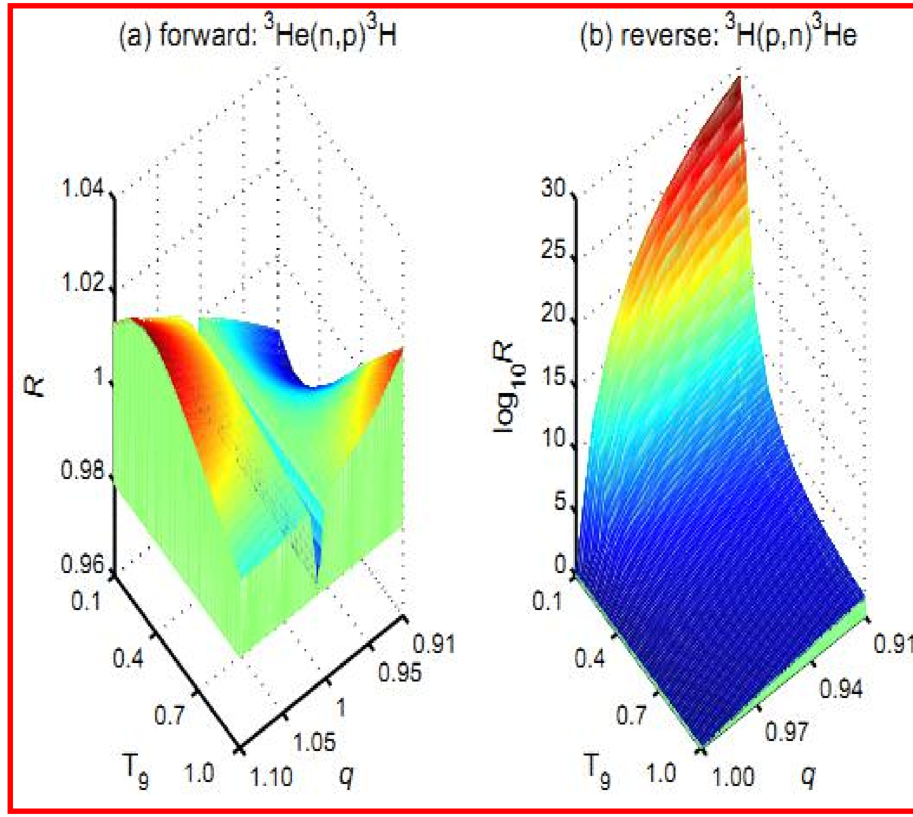
Bertulani *et al.*,
$\delta q = ^{+0.05}_{-0.12}$

被美国Astrophysical Journal拒稿!

问题：正反应运用**Tsallis**分布，为什么逆反应用**MB**分布？

参数q对反应率的影响





以带电粒子反应$^2H(d,p)^3H$为例，非广延分布下的反应率与玻尔兹曼分布下的反应率比值随温度和非广延参数q的变化（左边为正反应，右边为逆反应）

以中子反应$^3He(n,p)^3H$为例，非广延分布下的反应率与玻尔兹曼分布下的反应率比值随温度和非广延参数q的变化（左边为正反应，右边为逆反应）

BBN程序的验证

Table 2

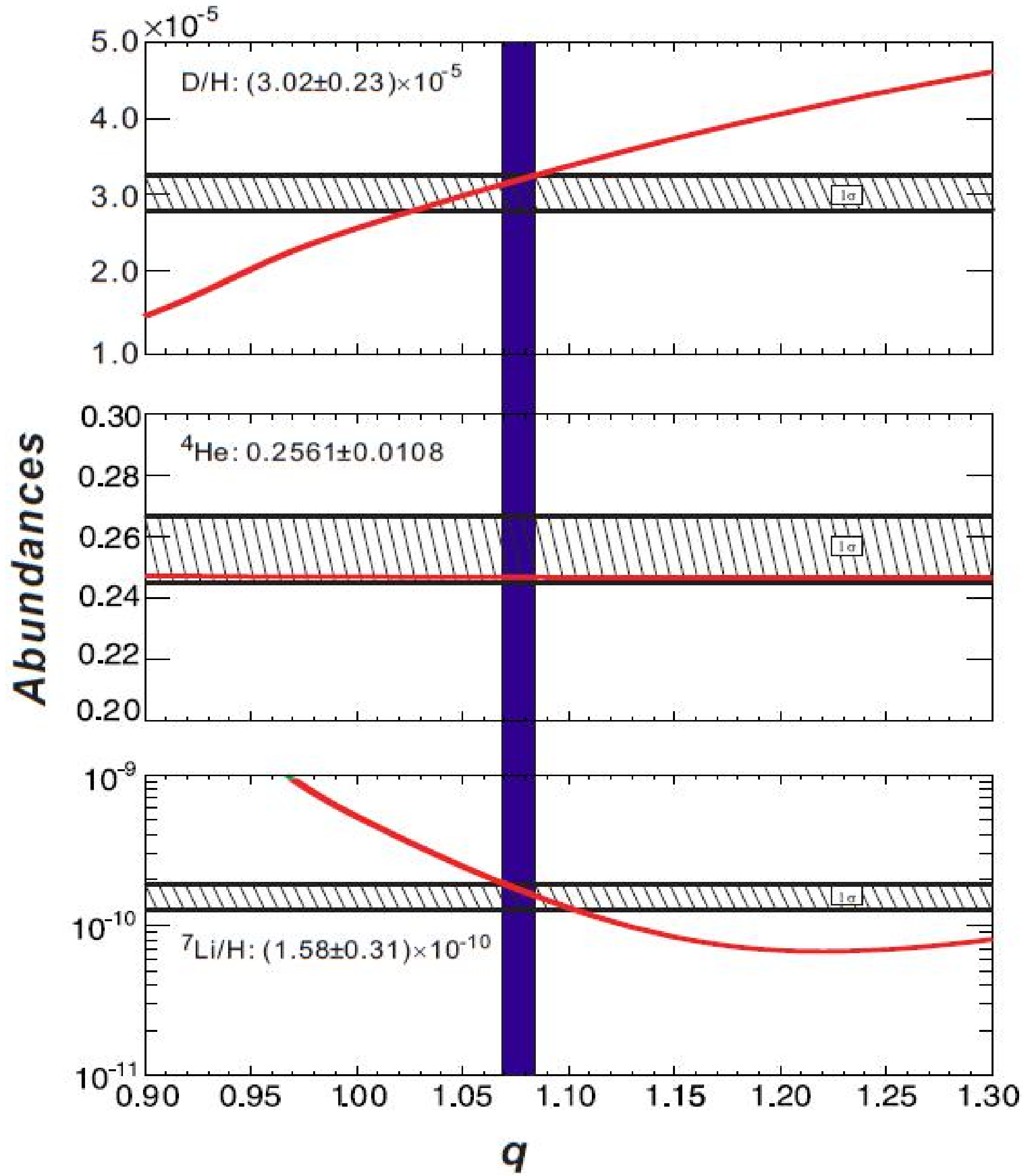
The Predicted Abundances for the BBN Primordial Light Elements[a]

Nuclide	Coc et al. (2012) ($q = 1$)	Cyburt et al. (2016) ($q = 1$)	Bertulani et al. (2013) ($q = 1$)	This work $q = 1$	This work $q = 1.069 \sim 1.082$	Observation
^{4}He	0.2476	0.2470	0.249	0.247	0.2469	0.2561 ± 0.0108 (Aver et al. 2010)
D/H($\times 10^{-5}$)	2.59	2.58	2.62	2.57	$3.14 \sim 3.25$	3.02 ± 0.23 (Olive et al. 2012)
^{3}He/H($\times 10^{-5}$)	1.04	1.00	0.98	1.04	$1.46 \sim 1.50$	1.1 ± 0.2 (Bania et al. 2002)
^{7}Li/H($\times 10^{-10}$)	5.24	4.65	4.39	5.23	$1.62 \sim 1.90$	1.58 ± 0.31 (Sbordone et al. 2010)

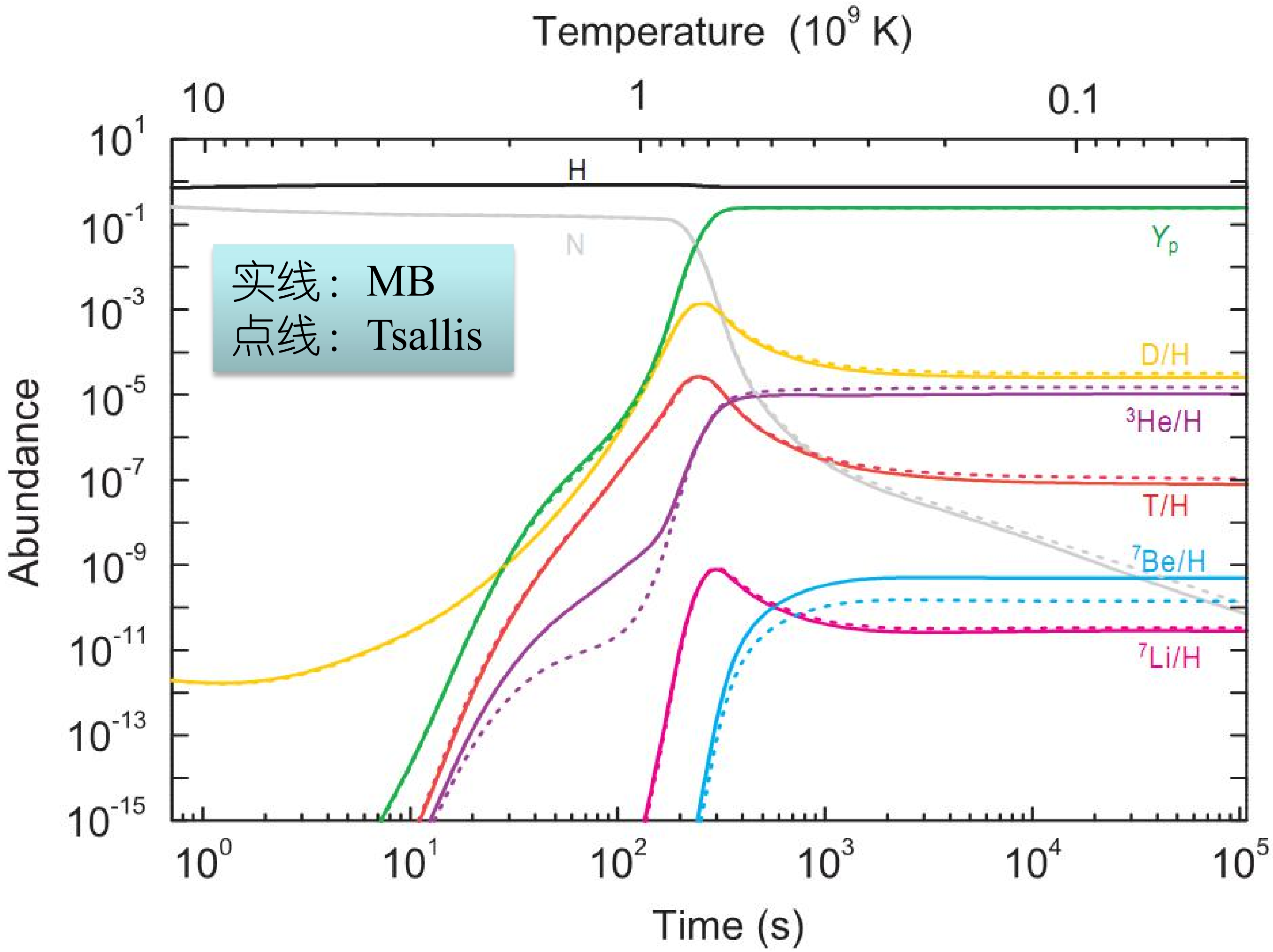
(a) The observational data are listed for comparison.

第2次搜索结果

在$1.069 < q < 1.082$时：
BBN的理论预言值与
天文观测值完全符合！

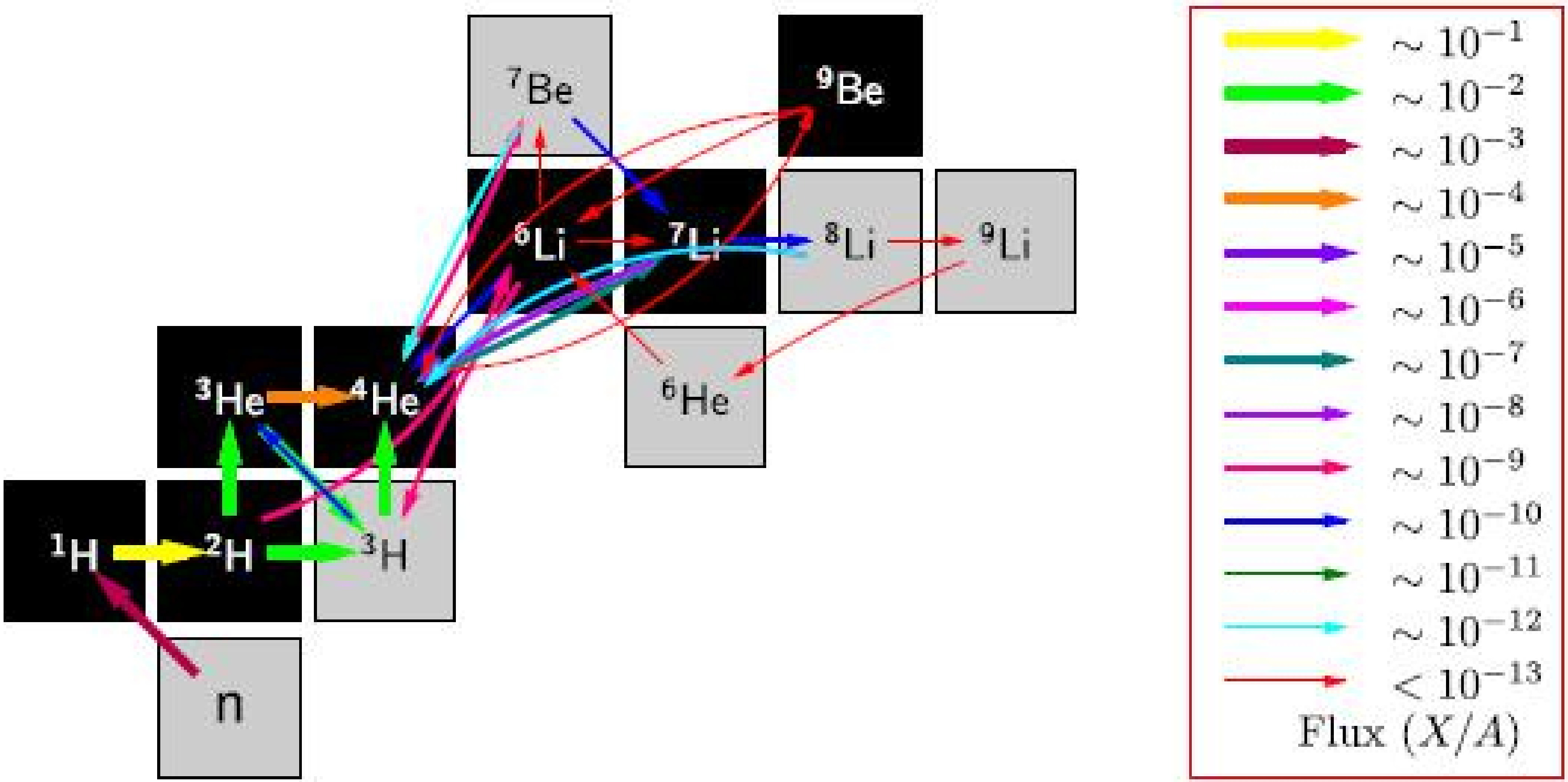


原初丰度随时间&温度演化

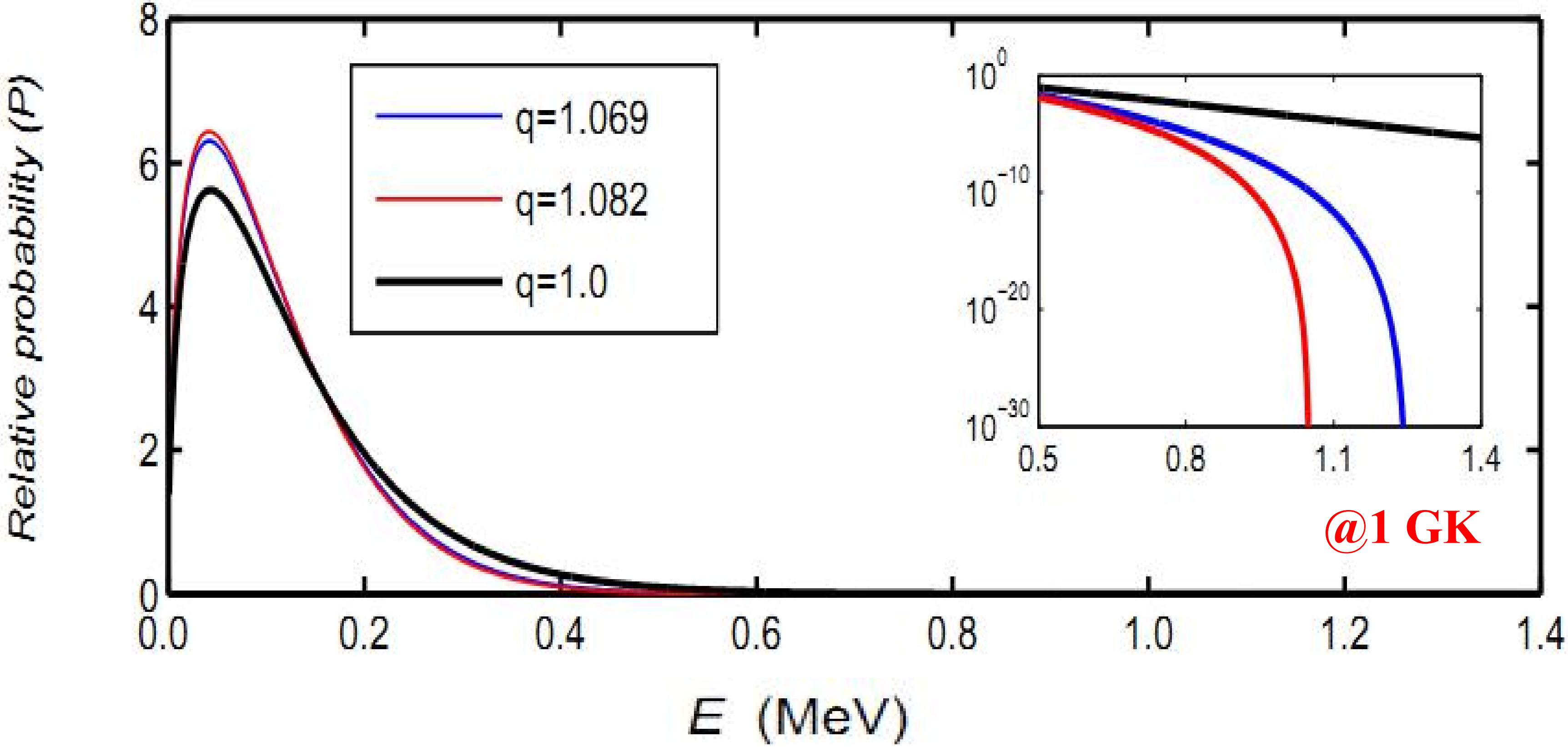


时间约180秒(即3分钟)时，核合成开始有效进行

涉及的主要反应流(Tsallis分布)



经典MB *v.s.* 广延Tsallis



文章发表

The Astrophysical Journal, 834:165 (5pp), 2017 January 10

doi:10.3847/1538-4357/834/2/165

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NON-EXTENSIVE STATISTICS TO THE COSMOLOGICAL LITHIUM PROBLEM

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审稿意见

dieter.hartmann@aas.org 2016/11/26 2:

收件人: 何建军NAOC;

抄送: dieter.hartmann@aas.org;

ApJ - AAS03189 Decision Letter

-

Dear Prof. He,

I am happy to report that the above paper is accepted for publication in The Astrophysical Journal without revision.

I am attaching the final report with this letter.

Correspondence concerning the logistical aspects of publishing this manuscript should be directed to journals.manager@aas.org. If you have any additional questions concerning the scientific content, please direct them to me.

Congratulations and best wishes:
Dieter H. Hartmann
AAS Scientific Editor
dieter.hartmann@aas.org

Referee Report

This is a very important and most interesting paper, presenting a simple but highly plausible solution to the Lithium Problem. The idea is to abandon the assumption that the lithium was created in exact thermodynamic equilibrium, and replace the Maxwell- Boltzman distribution with the corresponding distribution from Tsallis non-extensive statistics, which has found applications in a very wide range of problems. This approach provides an additional parameter q which is determined by the observations. The authors find an excellent fit to the observations with the parameter 1.069 <= q <= 1.082. This value of q is very close to the value q = 1 assumed for the Maxwell-Boltzman distribution function, implying that only very small deviations from thermodynamic equilibrium are required. The authors find excellent agreement between the predicted and observed primordial abundances of deuterium, helium and lithium. The authors also give a possibility argument based on the fact that nuclear reaction cross-sections favor the most energetic nuclei, which tends to diminish the distributions in the highest energies, while ambient electrons and photons restore the distributions to equilibrium slightly.

I strongly recommend publication of this paper.

美国天文学会亮点官网介绍

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Fixing the Big Bang Theory's Lithium Problem

3

By Susanna Kohler on 15 February 2017 FEATURES

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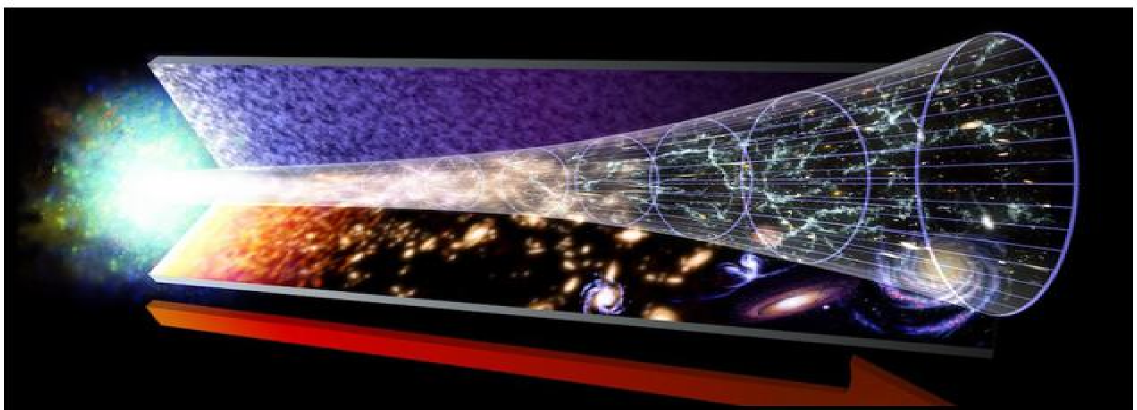

Artist's representation of the evolution of the universe, with time flowing to the right in the direction of the arrow. The Big Bang theory is the most widely accepted cosmological model of the universe, but it still contains a few puzzles. [NASA]

How did our universe come into being? The Big Bang theory is a widely accepted and highly successful cosmological model of the universe, but it does introduce one puzzle: the "cosmological lithium problem." Have scientists now found a solution?

Too Much Lithium

In the Big Bang theory, the universe expanded rapidly from a very high-density and high-temperature

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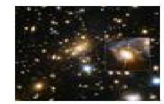
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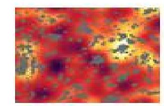
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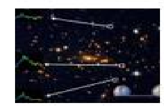
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央视报道

近代物理所等在大爆炸锂丰度问题研究中取得新的进展

小 结

- 探索在标准模型框架下解决宇宙锂问题的新方法，找到了一个可能的解决方案
- 探究非广延分布的深层次物理意义
- 开展该分布在其他天体模型中的应用
- 实验验证（强激光装置）？

展　望

多学科交叉融合

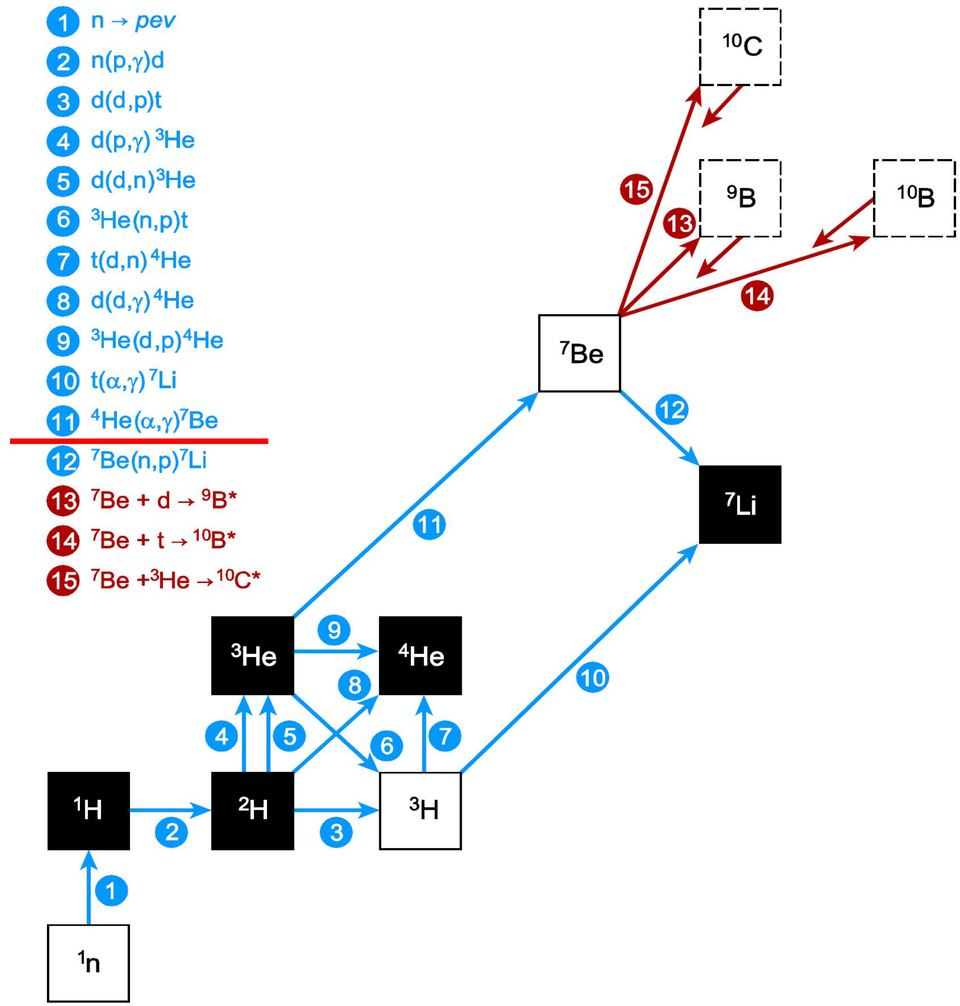
核物理

天体理论

天文观测

展 望

可能的核物理
解决方案

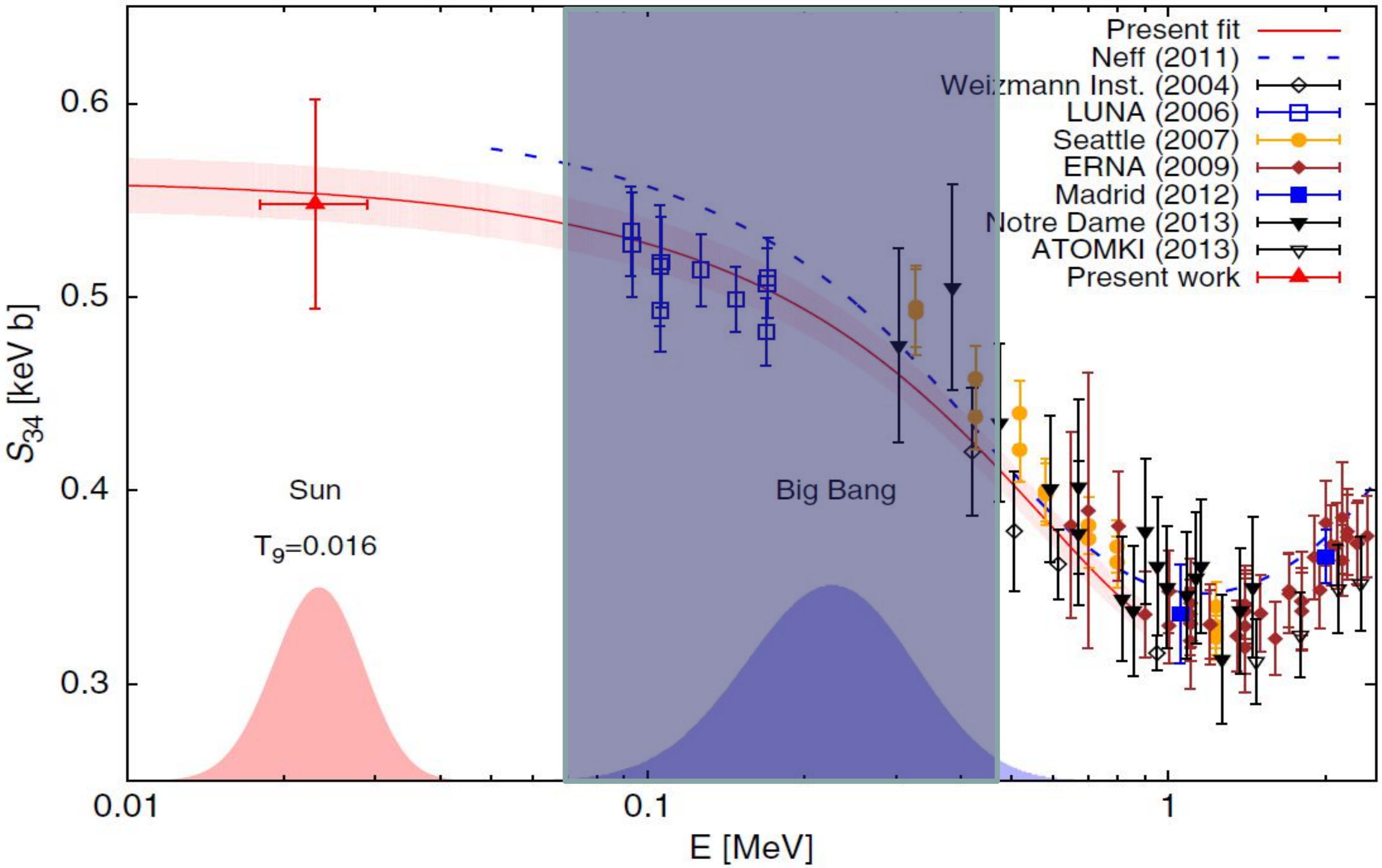


B.D. Fields, The primordial lithium problem, Ann. Rev. Nucl. Part. Sci. 61 (2001) 47
何建军，宇宙大爆炸锂问题，科学通报，卷65（35）：4047

展 望

核物理解

$^{3}He(\alpha, \gamma)^{7}Be$反应



低能区只有LUNA一家实验数据!

展 望

核物理解

理论预言:

N. Chakraborty, B.D. Fields and K.A. Olive

Phys. Rev. D 83 (2011) 063006

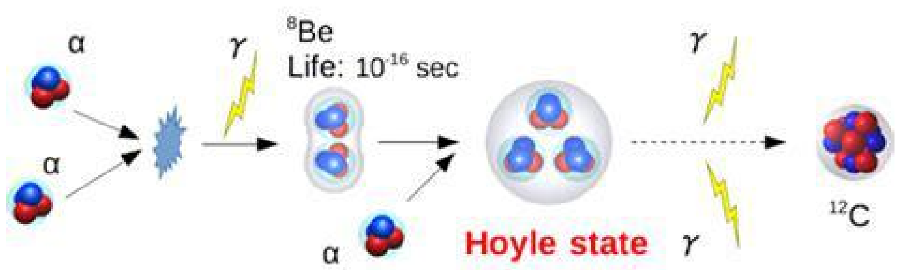
共振特性:

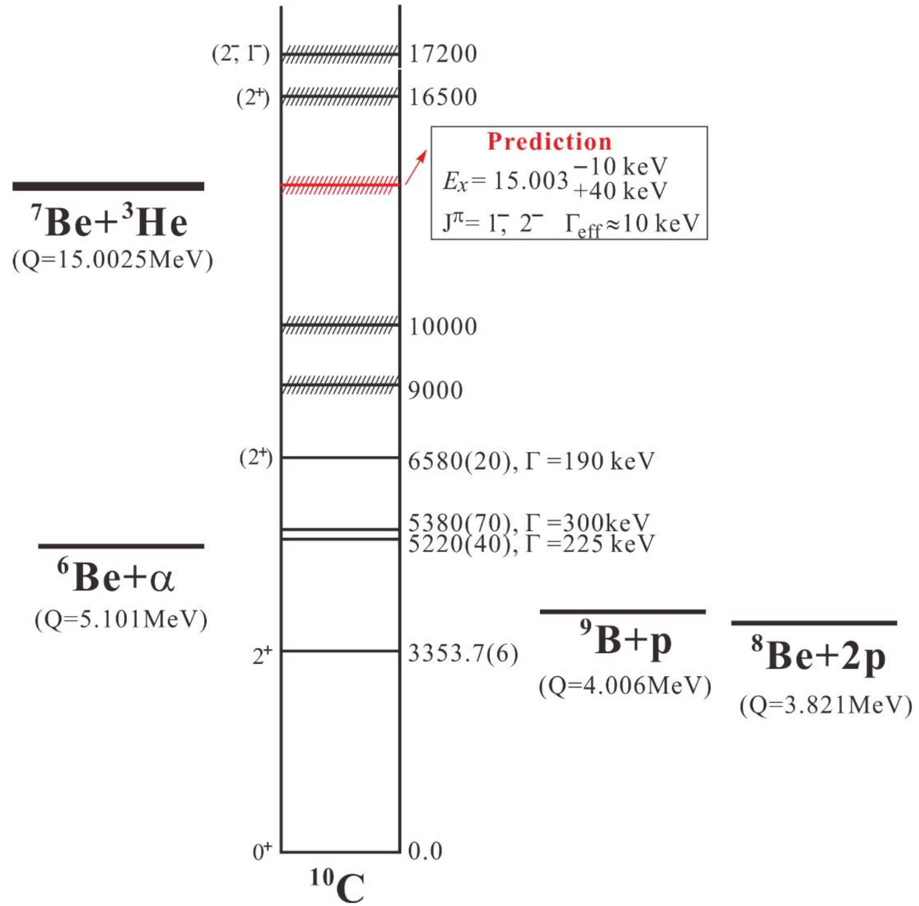
E_R : –10 ~ 40 keV

J^{π} : 1^- or 2^-

Γ_{eff} : ~ 10 keV

'Hoyle'-like





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核物理解

相关实验1:

F. Hammache *et al.*, Phys. Rev. C 88 (2013) 062802R

装置:

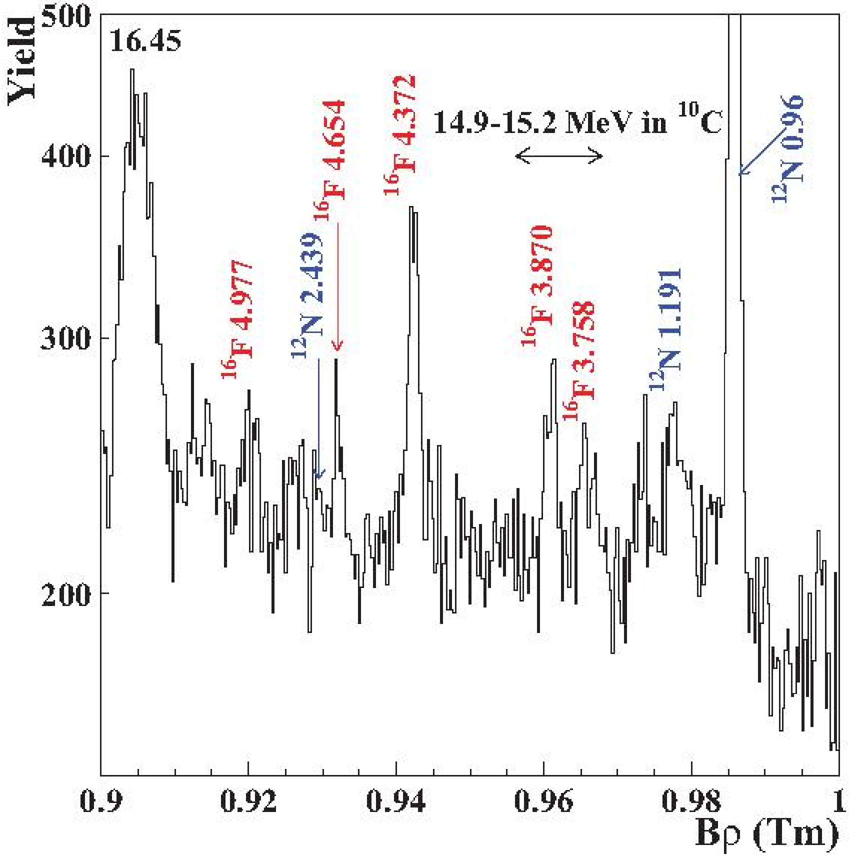
Orsay-ALTO, France

实验:

$^{10}B(^{3}He, t)^{10}C$

能量分辨:

~ 37 keV



Triton Bρ spectrum in $^{10}B+^{3}He$ experiment

展 望

核物理解

相关实验2:

W. Benenson *et al.*, Nucl. Phys. A 97 (1967) 510

装置:

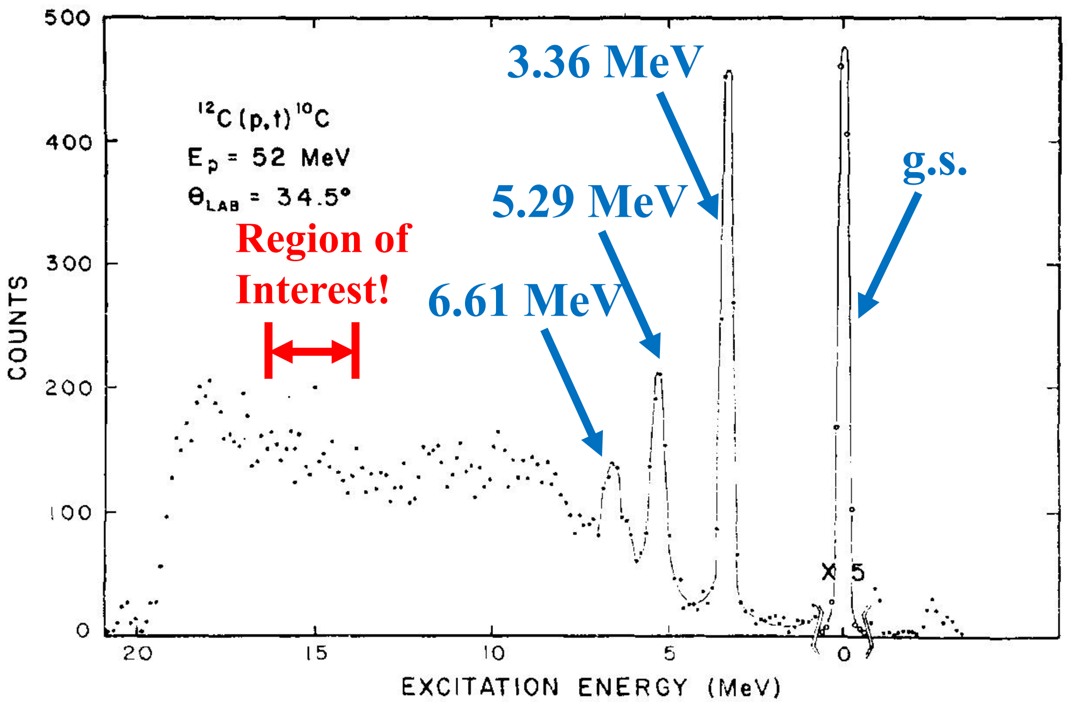
Michigan State University Cyclotron

实验:

$^{12}C(p, t)^{10}C$

能量分辨:

~ 145 keV



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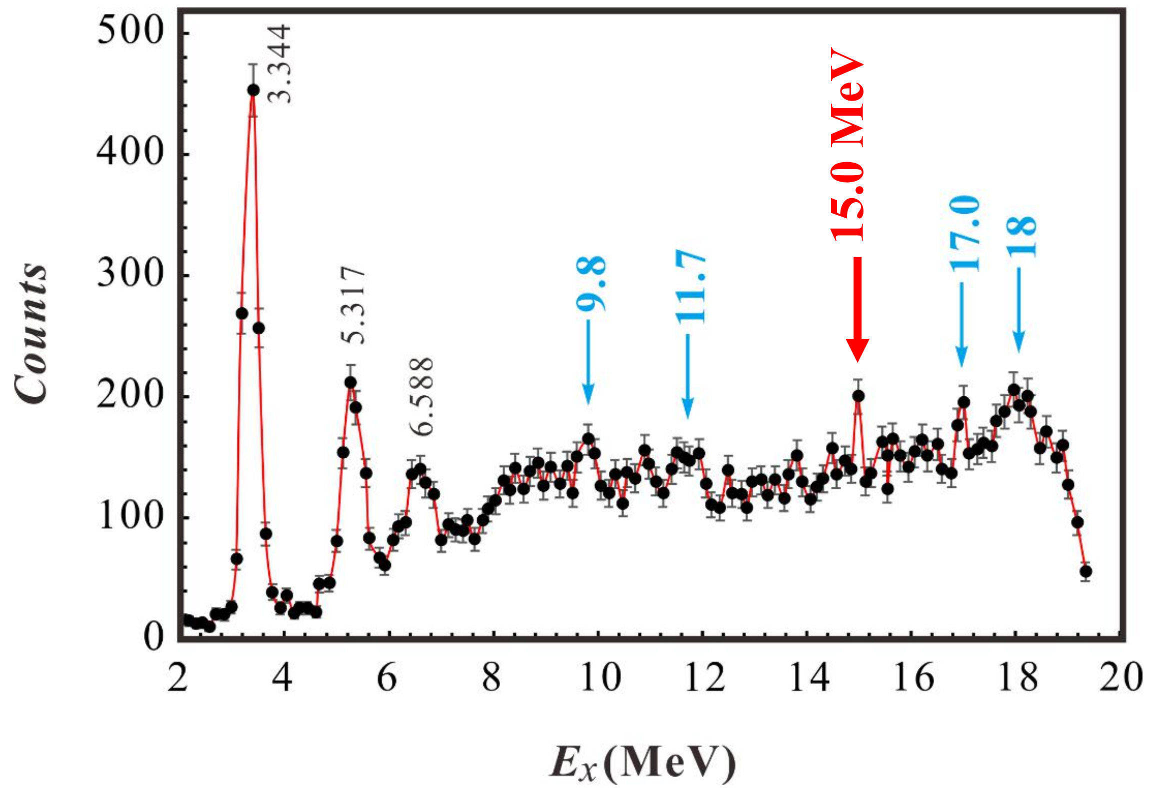
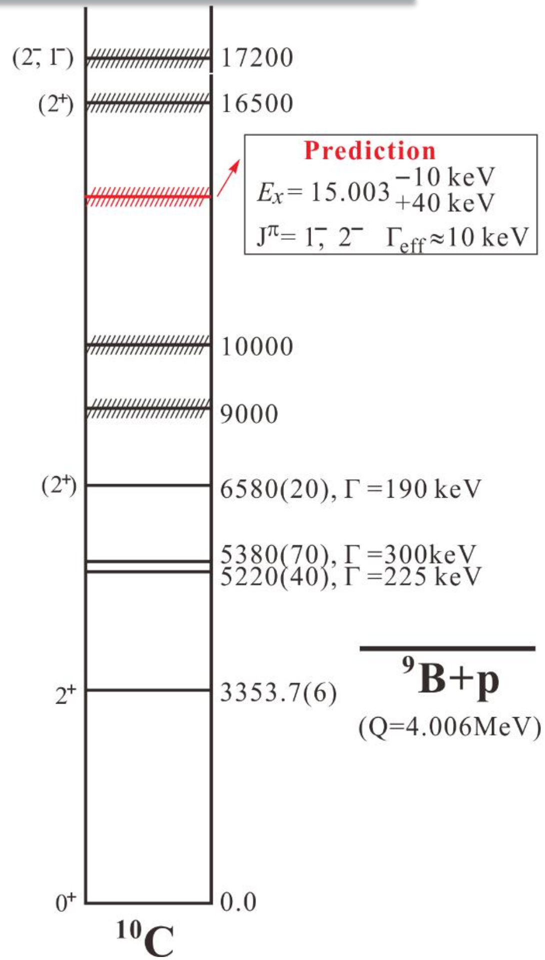
核物理理解

相关实验2:

W. Benenson *et al.*, Nucl. Phys. A 97 (1967) 510





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核物理解

相关实验3:

M. Yasue et al., J. Phys. Soc. Japan, 42 (1977) 367

装置:

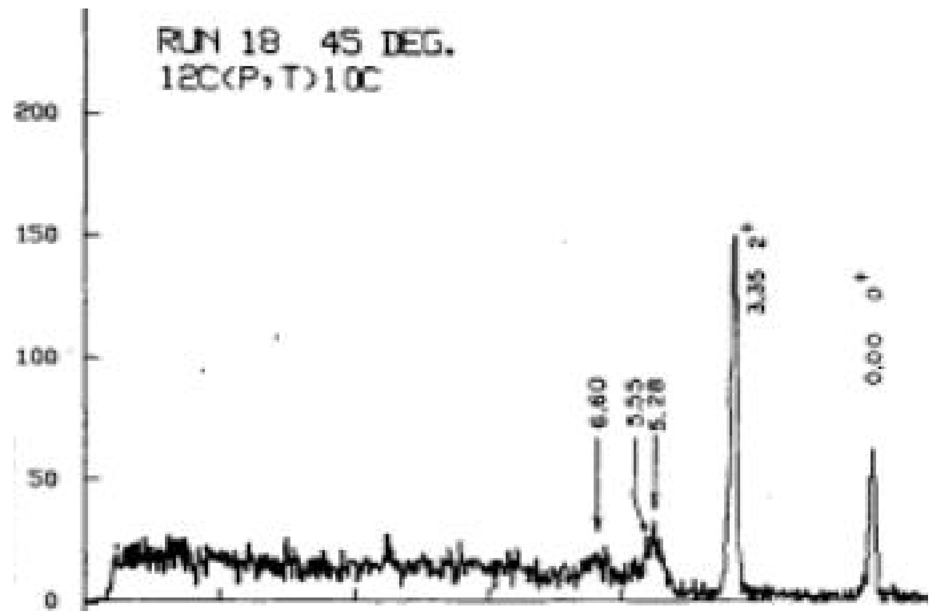
日本，东京大学INS synchrocyclotron

实验:

$^{12}C(p, t)^{10}C$, E_p=51.9 MeV

能量分辨:

~ 140 keV



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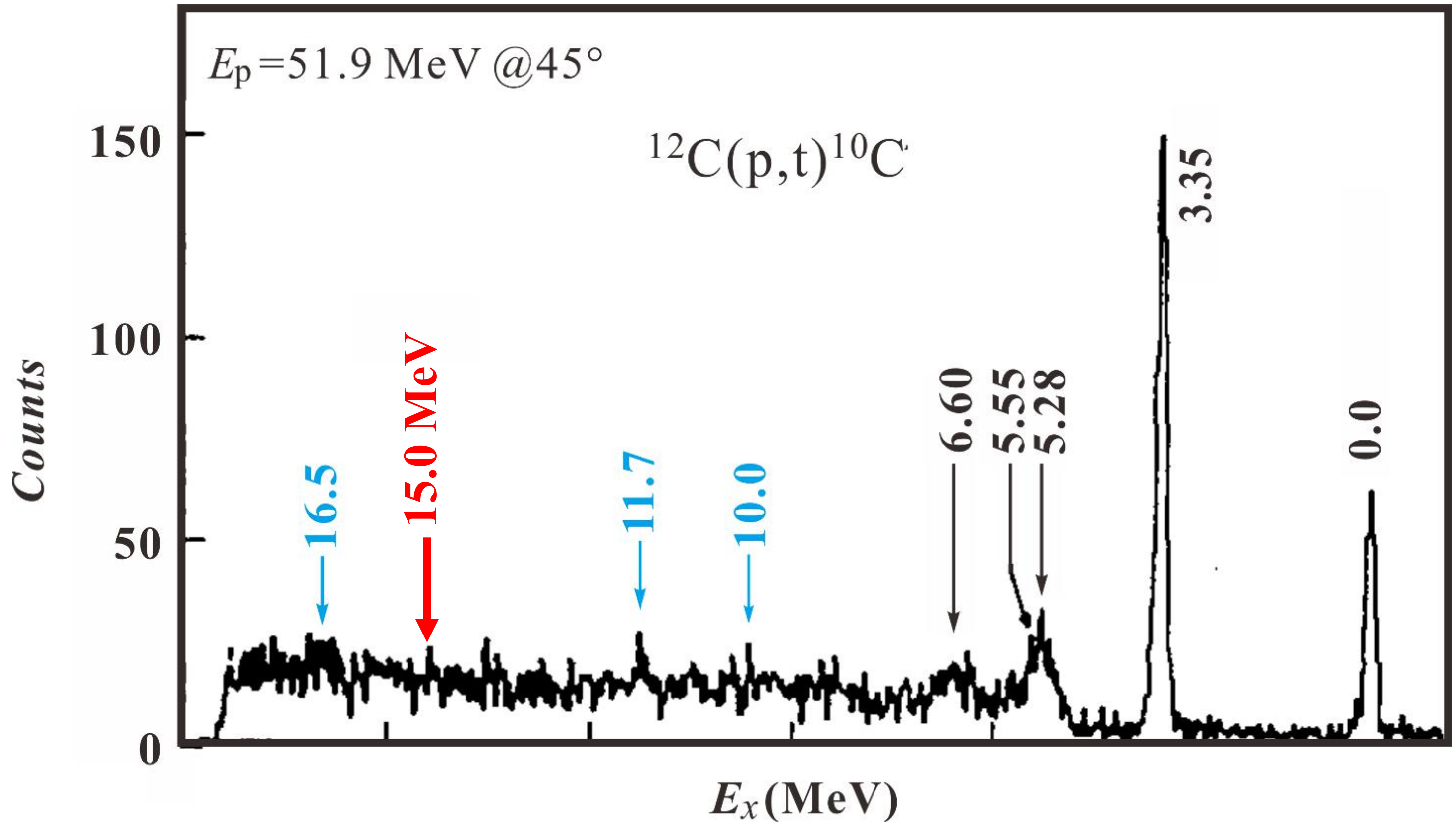
核物理解

相关实验3:

M. Yasue et al., J. Phys. Soc. Japan, 42 (1977) 367



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核物理解

实验提案 (proposal):

装置：

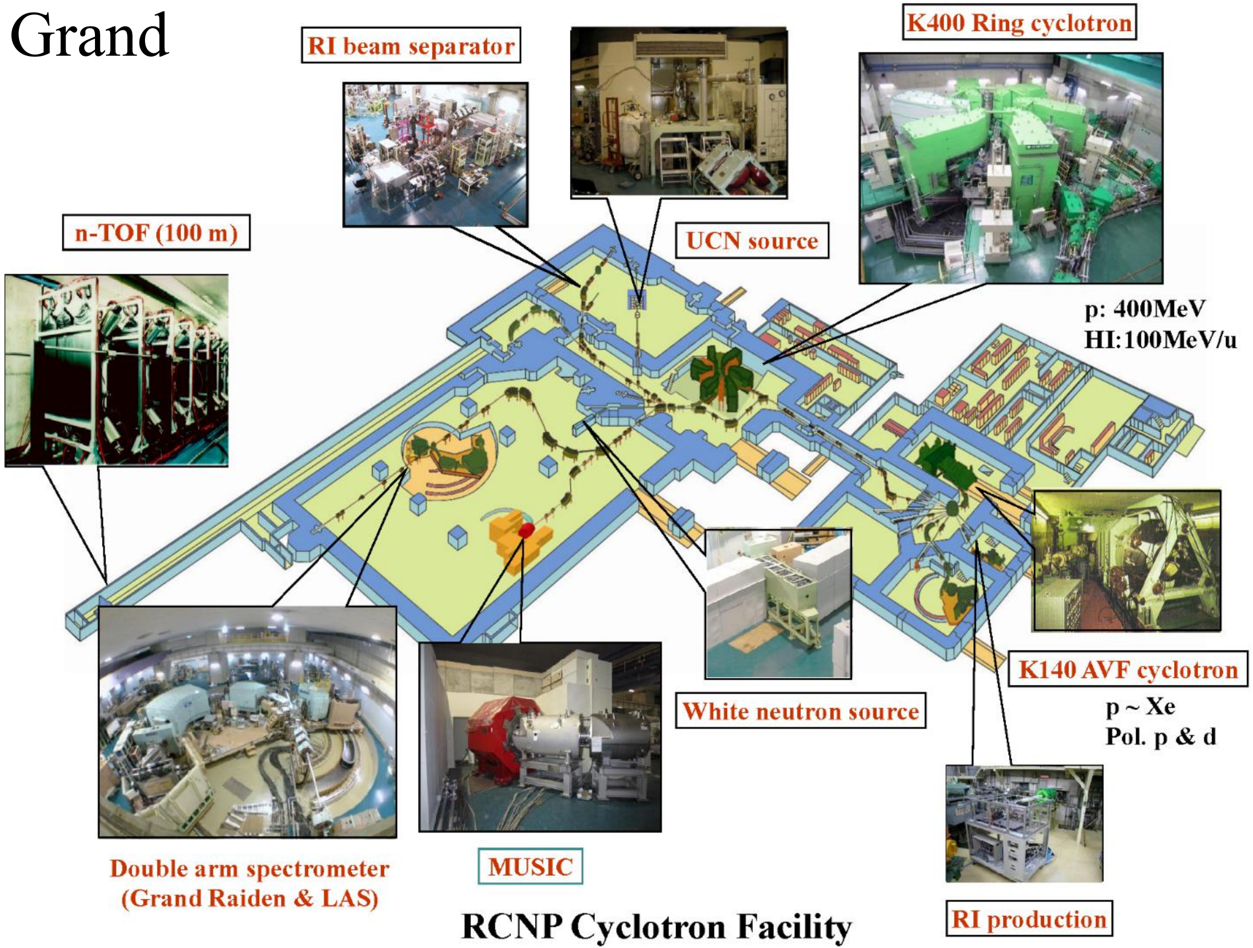
日本大阪大学RCNP Grand Raiden Spectrometer

实验:

$^{12}C(p, t)^{10}C$

能量分辨:

~ 10 keV (目标)



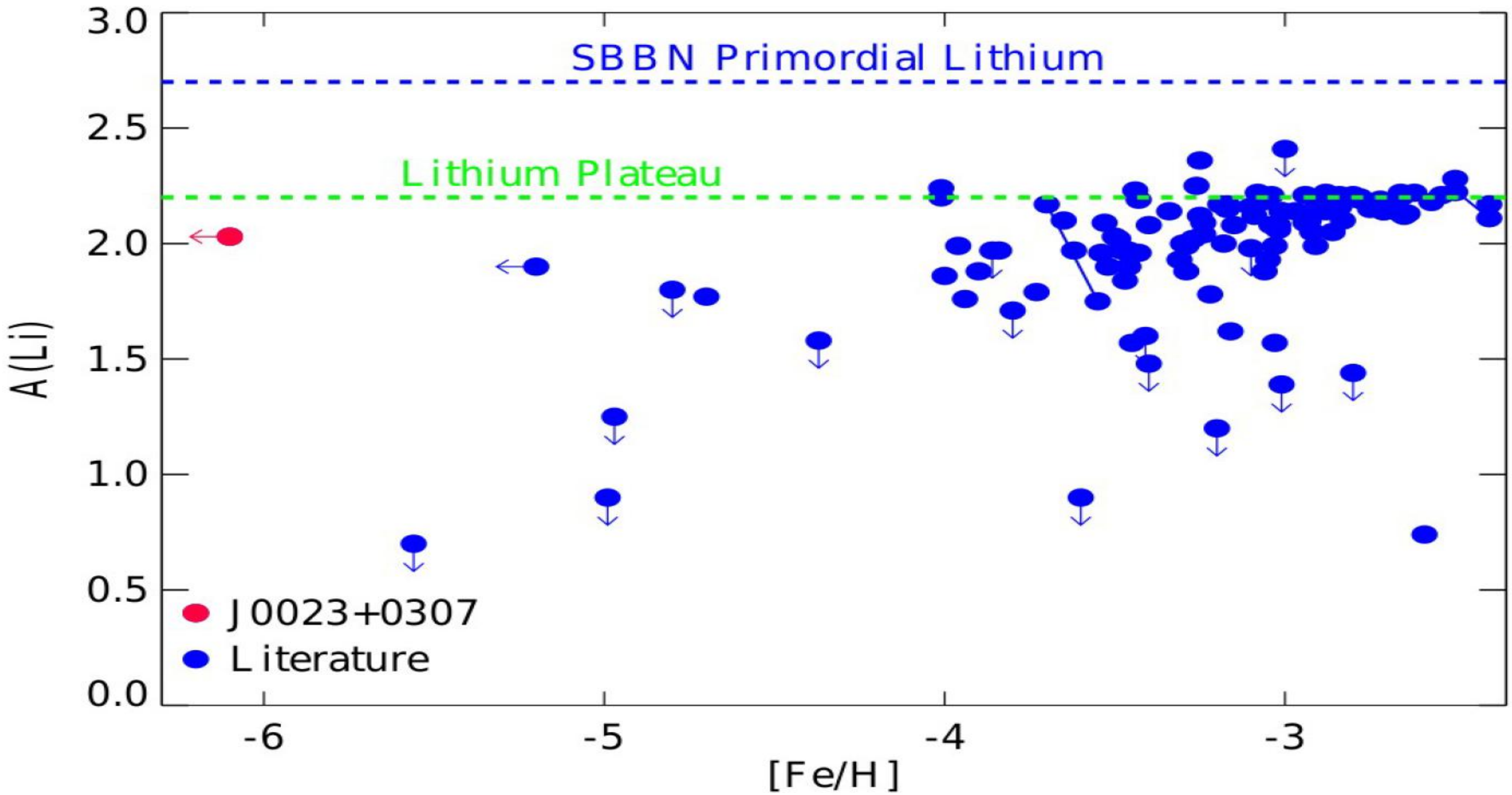
展 望

天体物理解

天文元素丰度观测：

尚未演化到巨星的贫金属星保有原初锂丰度

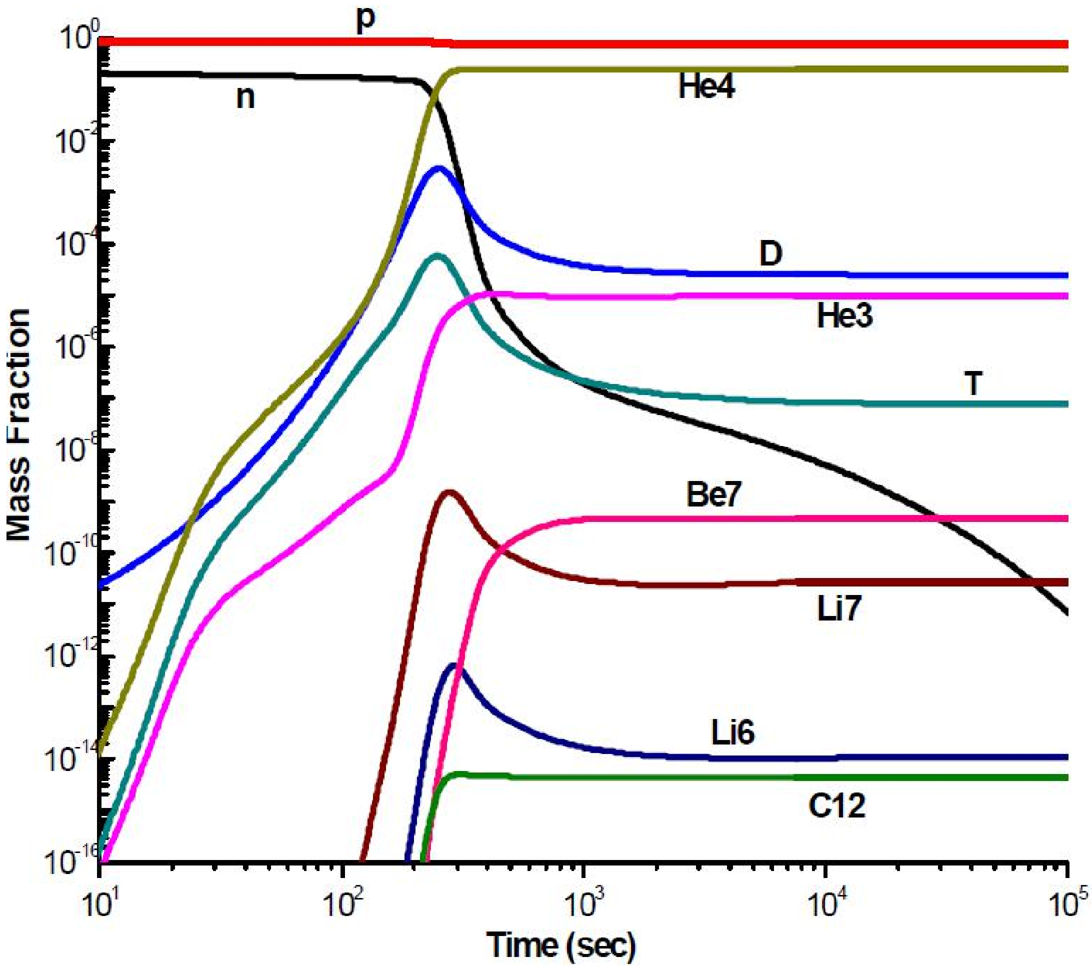
Spite平台



锦屏深地实验室

谢谢大家听讲！

BBN元素丰度随时间演化



BBN开始时只存在质子与中子，二者通过弱反应保持一定的比例

时间约为180秒（也即3分钟）时，核合成开始有效地进行

生成的^{3}H（半衰期为12年）最终衰变为^{3}He

^{7}Be 通过电子俘获（半衰期为53天）最后变为^{7}Li。因此，^{7}Li丰度主要来自于^{7}Be。