中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

Study of cosmological lithium problem from nuclear physics perspective

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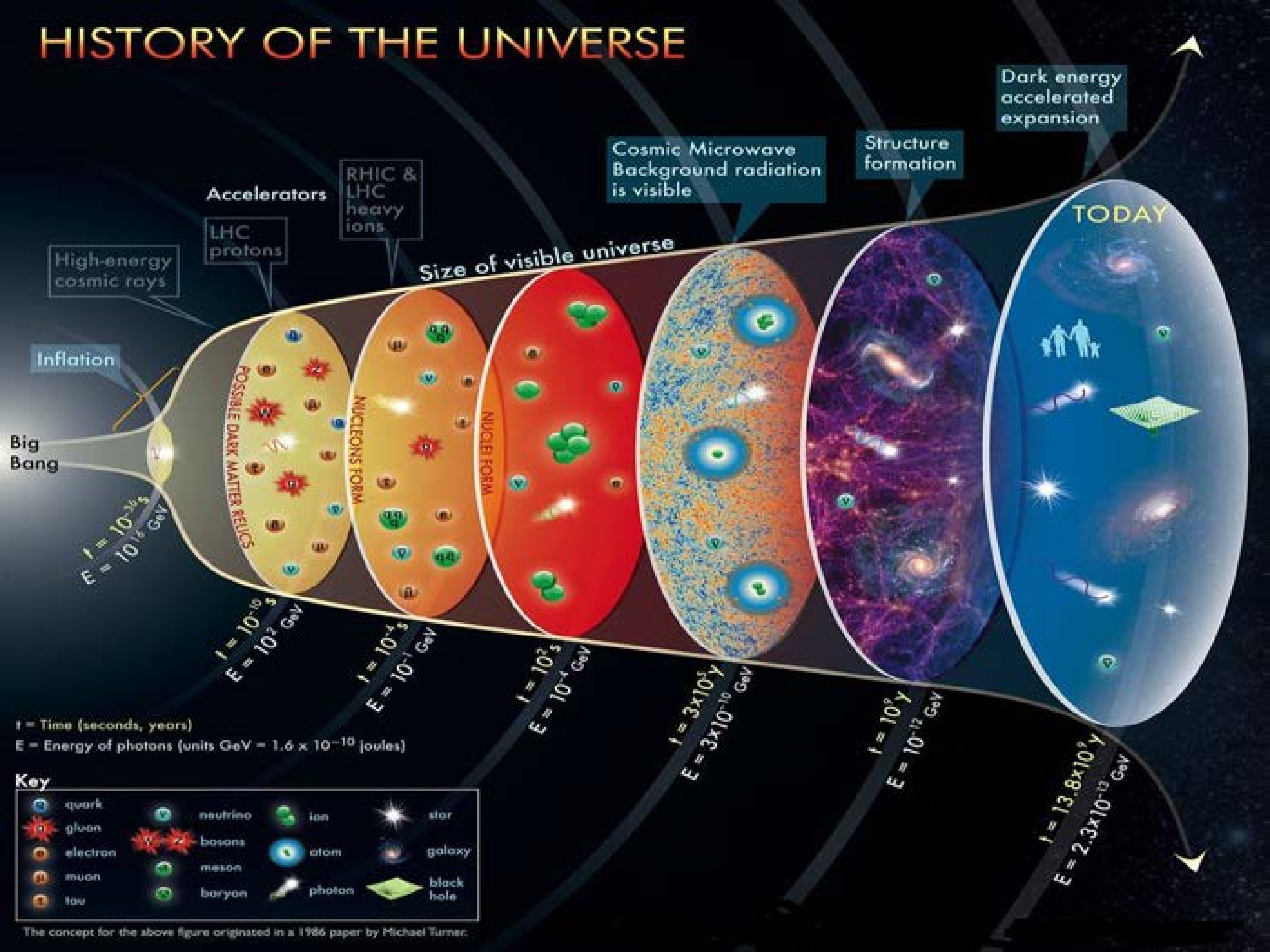
Institute of Modern Physics(IMP), CAS
&
NuGrid Collaboration

Outline

- Introduction to Big Bang model
- Cosmological Lithium Problem
- Study of several relevant reactions
- Summary


HISTORY OF THE UNIVERSE
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 = 10⁻³⁵ s E = 10¹⁶ GeV
t = 10⁻¹⁰ s E = 10² GeV
t = 10⁻⁴ s E = 10⁻¹ GeV
t = 10² s E = 10⁻⁴ GeV
t = 3x10⁵ y E = 3x10⁻¹⁰ GeV
t = 10⁹ y E = 10⁻¹² GeV
t = 13.8x10⁹ y E = 2.3x10⁻¹³ GeV
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.

Standard BBN Model

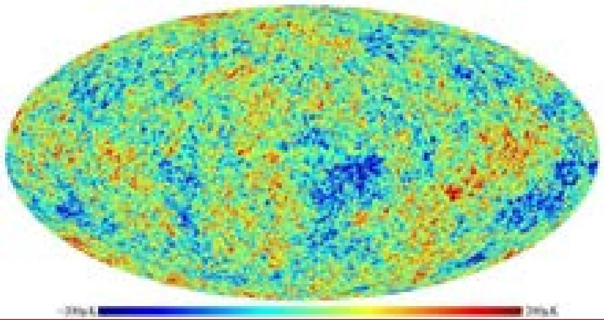
Hypothesis

- Isotropic and homogeneous
- No convection, no diffusion, no unknown physics
- Pure nucleosynthesis in radiation-dominated expansion

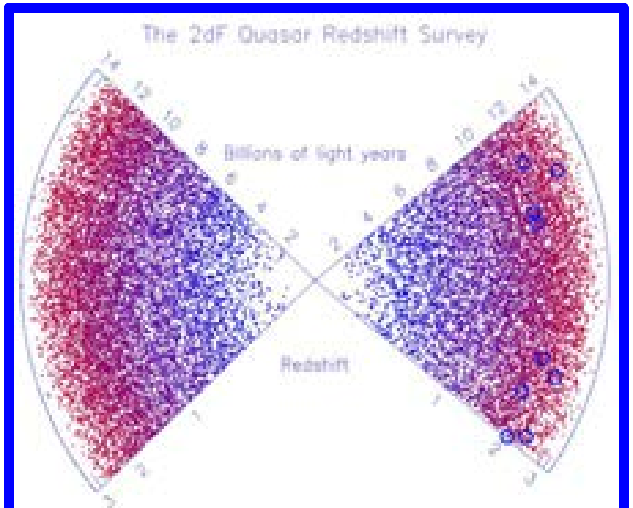
Prediction

- Main products: D, ^{3}He, ^{4}He, ^{7}Li
- Cosmic Microwave background (CMB) can be obseved today

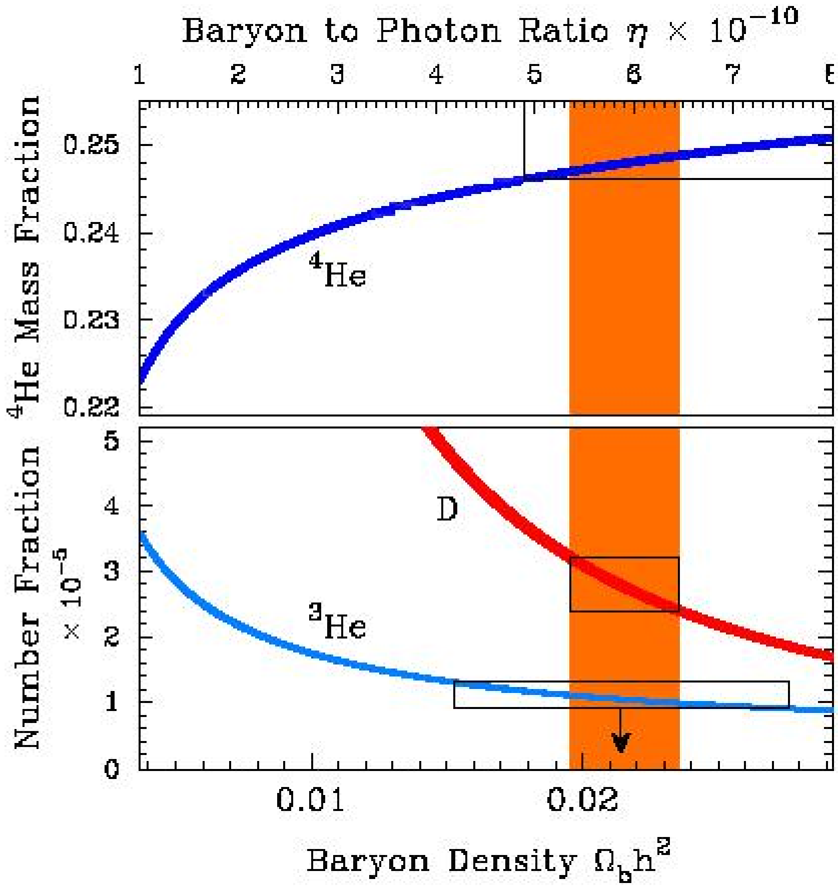
Evidence to support BBN



Isotropic



Homogeneous



Consistency between predicted abundance of D, ^{4}He, ^{3}He and their abundance observed today

Is BBN theory perfect?

^{7}Li problem

- ❑New reaction rates
- ❑New observational data
- ❑^{4}He, D and ^{3}He match well
- ❑^{7}Li ∼3 times discrepancy

Rep. Prog. Phys. 74 (2011) 096901 (48pp) doi:10.1088/003-

Nuclear astrophysics: the unfinished quest for the origin of the elements

Jordi José[1,2] and Christian Iliadis[3,4]

(i) Why do predictions of helioseismology disagree with those of the standard solar model?

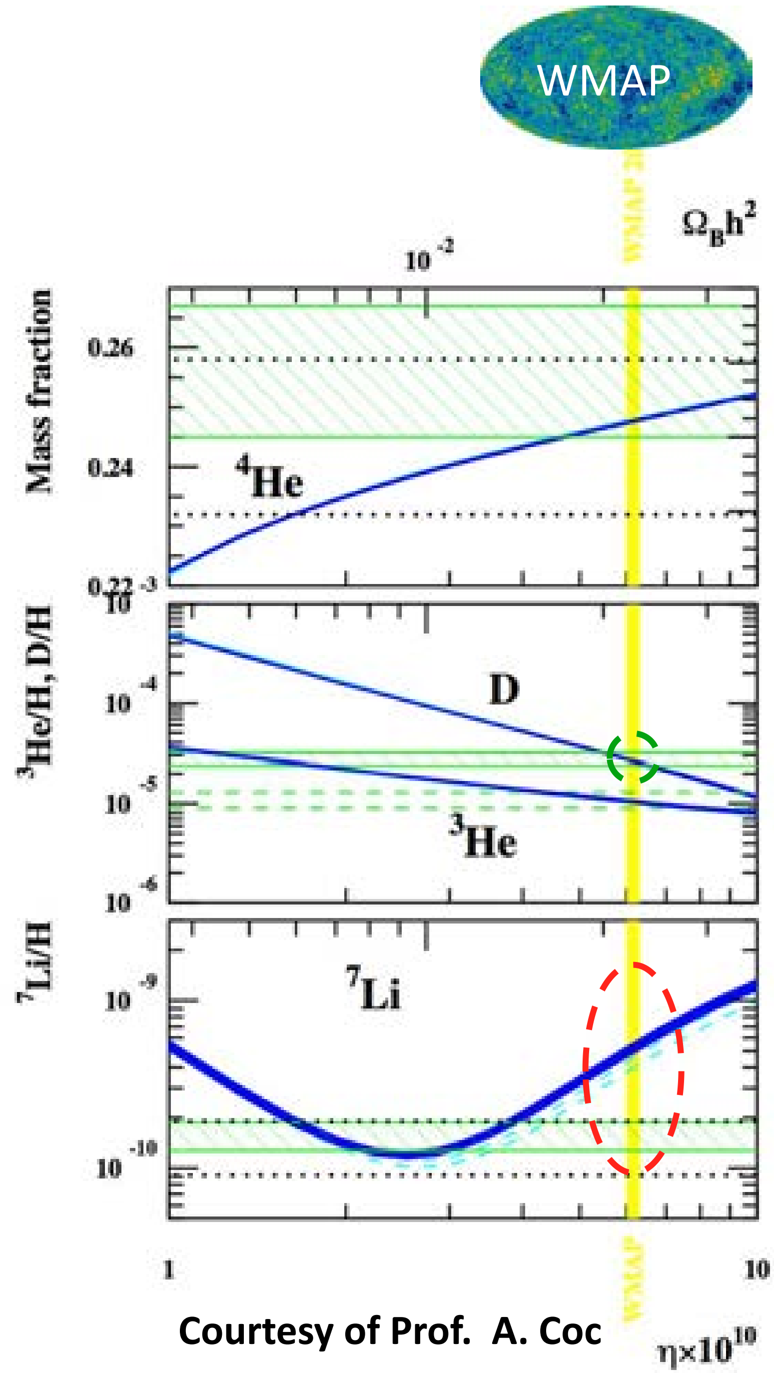
(ii) What is the solution to the lithium problem in Big Bang nucleosynthesis?

(iii) What do the observed light-nuclide and s-process abundances tell us about convection and dredge-up in massive stars and AGB stars?

(iv) What are the production sites of the γ-ray emitting radioisotopes ^{26}Al, ^{44}Ti and ^{60}Fe?

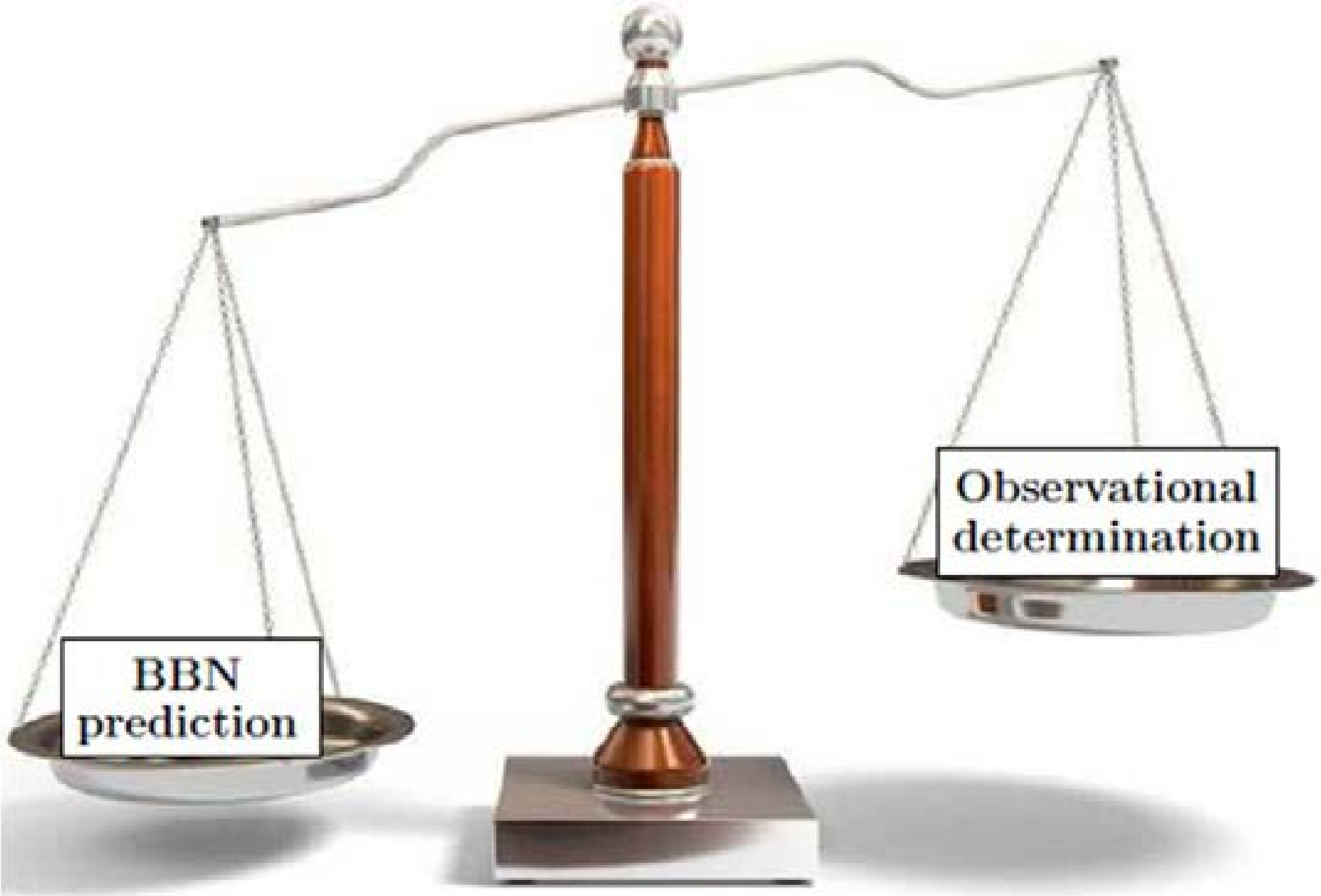
(v) What is the origin of about 30 rare and neutron-deficient nuclides beyond the iron peak (p-nuclides)?

(vi) What causes core-collapse supernovae to explode?



Courtesy of Prof. A. Coc

How to address it



Potential solution

- Astrophysics：

((1))Lithium depletion exists in halo star

((2))Inappropriate target

- Non-standard Model：

(1) Beyond standard model of particle physics

(2) Changing Fundamental Constants

(3) Nonstandard cosmologies

- Nuclear physics:

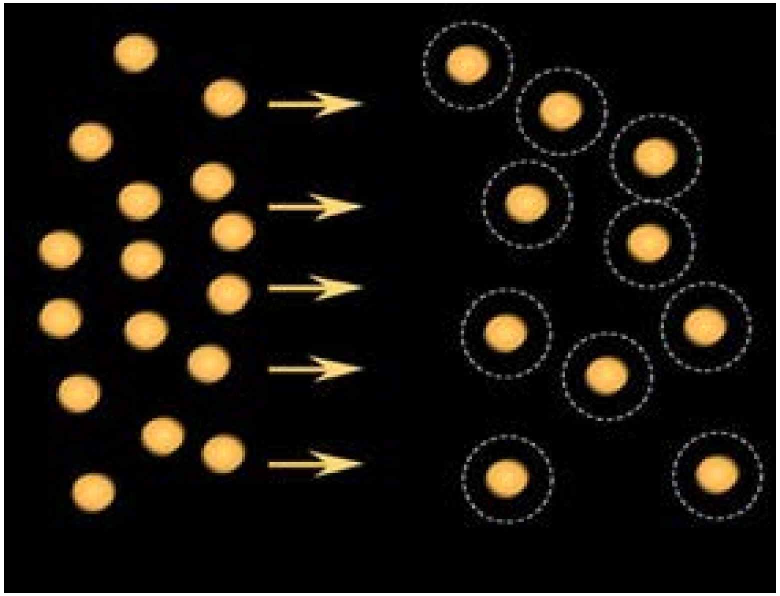
(1) Uncertainties of nuclear reactions rates

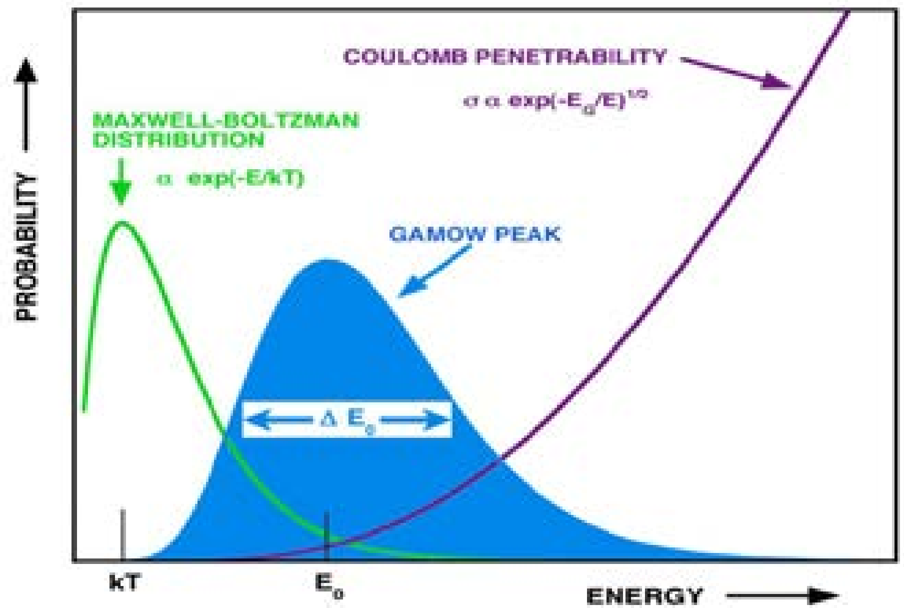
Reaction rate

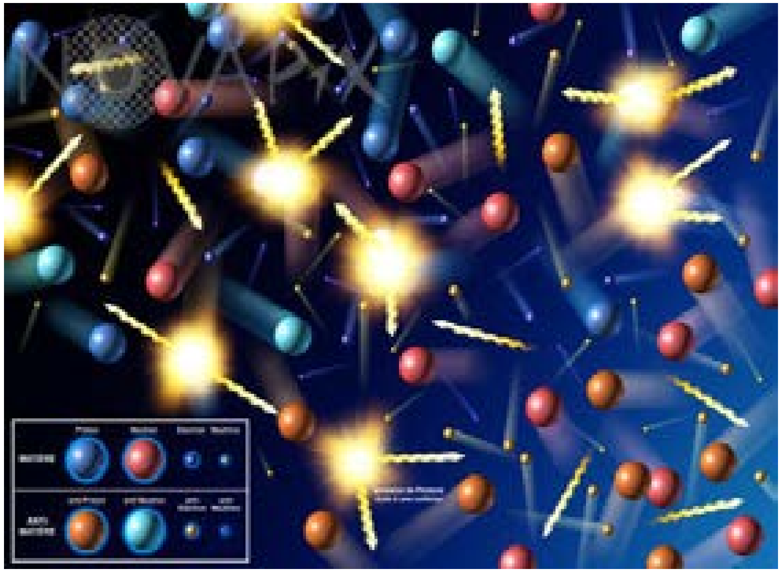
- Astrophysical reaction rate

$$<\sigma v> = \left(\frac{8}{\pi\mu}\right)^{1/2} (kT)^{-3/2} \int \sigma(E) E \exp\left(-\frac{E}{kT}\right) \mathrm{d}E$$

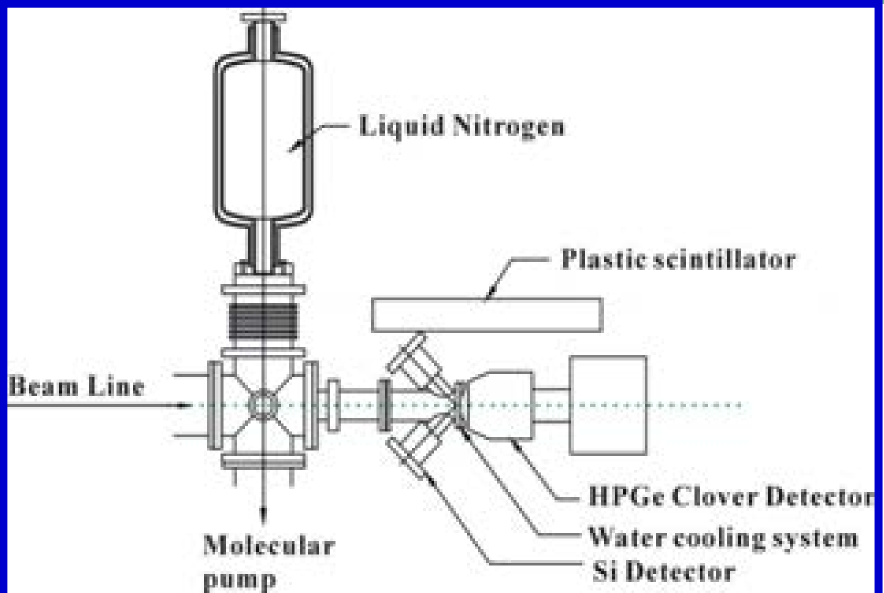
$$S(E) = E\sigma(E)\exp(2\pi\eta)$$







Facility: A 320 kV Highly-charged Heavy Ions Platform



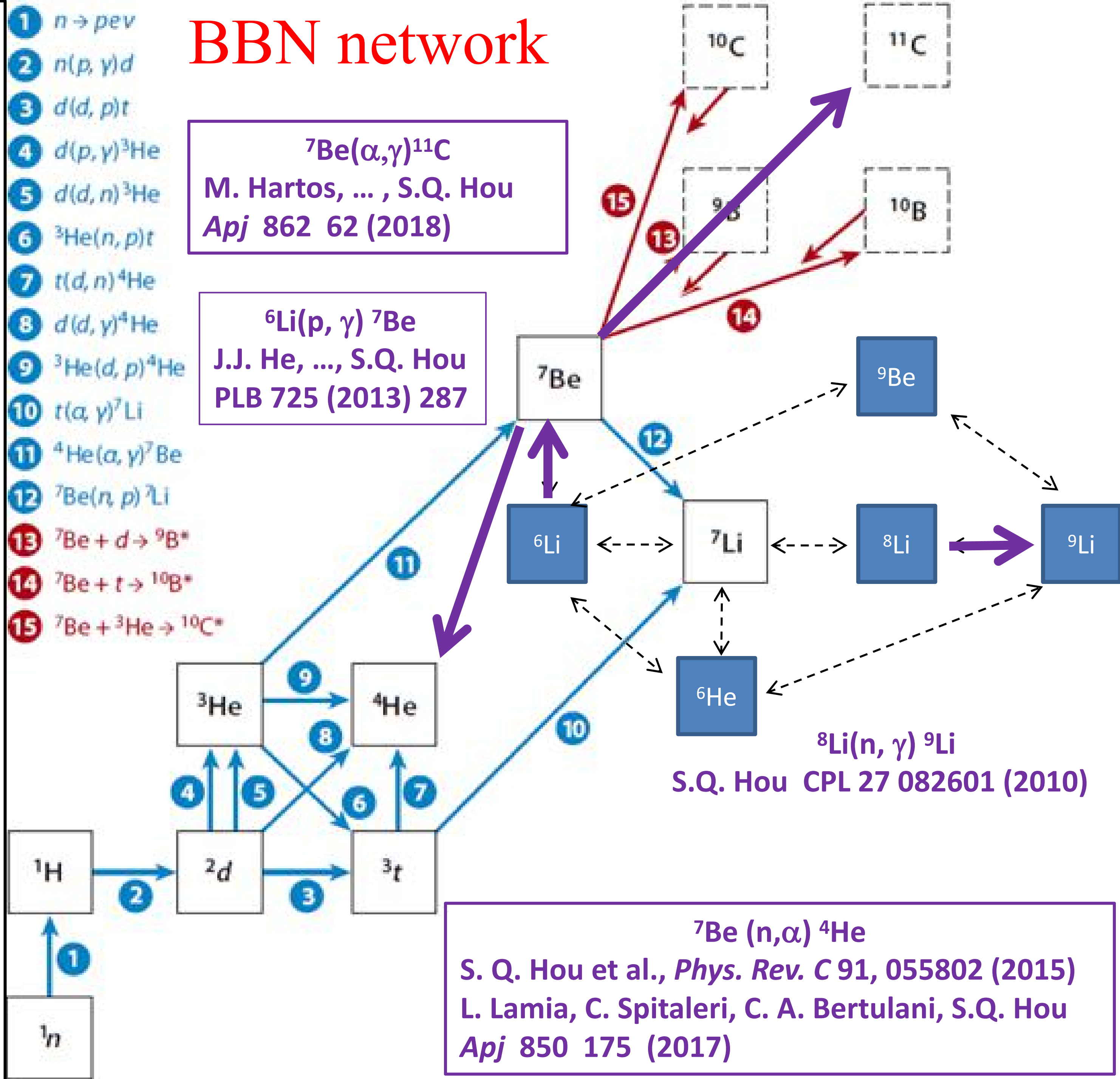
2. Contributions from Chinese Nuclear physics committee

CIAE:
a bunch of reactions associated with Lithium yield done by Prof. **Z.H. Li** (dashed arrow)

^{6}Li(n, γ)^7Li
$^7Li(n, \gamma)^8Li$
$^8Li(n,\gamma)^9$Li
^{6}Li(p, γ)^7Be
$^6He(p, \gamma)^7Li$
$^6He(p, n)^6Li$
$^6He(d, n)^7Li$
^{8}Li(p, γ)^9Be
$^8Li(p, d)^7Li$
$^8Li(p, t)^6Li$
$^8Li(d, p)^9Li$
$^8Li(d,n)^9Be$

Z.H. Li ,…,S.Q. HOU et al ., SCIENCE CHINA 54 s67 (2011)

BBN network



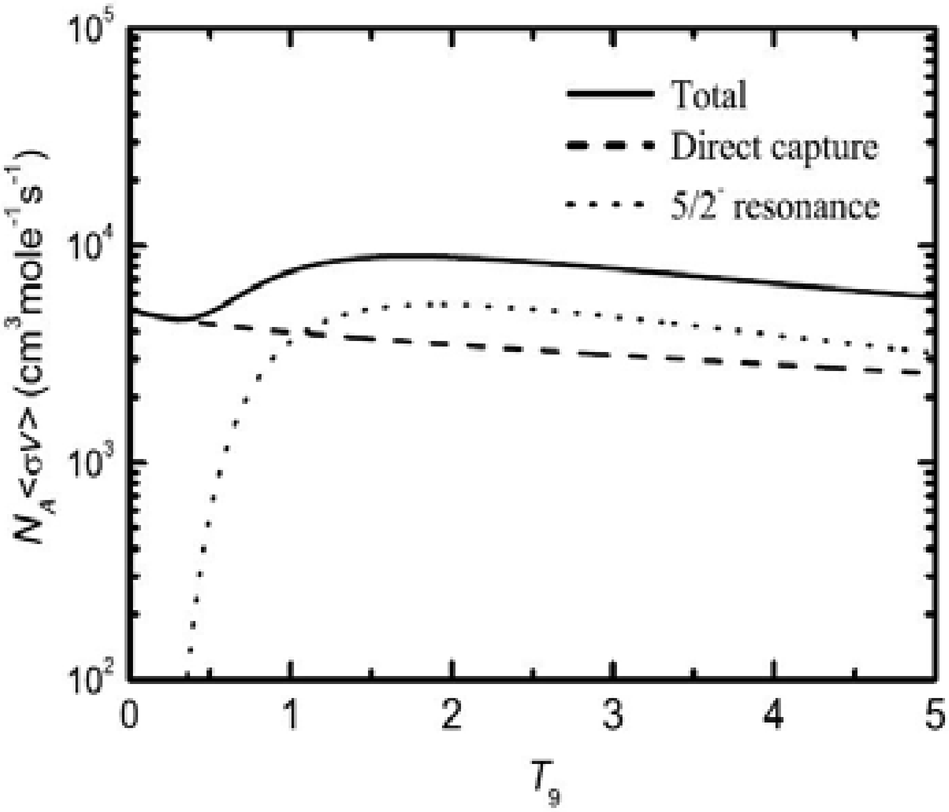
^{7}Be(α,γ)^{11}C
M. Hartos, … , S.Q. Hou
***Apj* 862 62 (2018)**

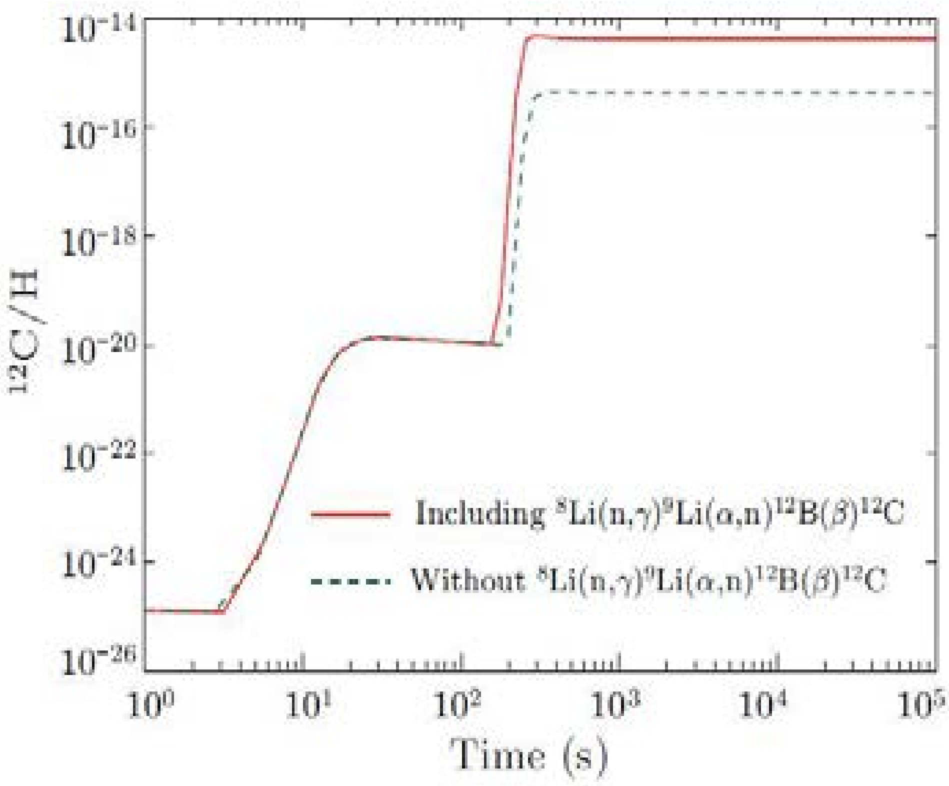
^{6}Li(p, γ) ^{7}Be
J.J. He, …, S.Q. Hou
PLB 725 (2013) 287

^{8}Li(n, γ) ^{9}Li
S.Q. Hou CPL 27 082601 (2010)

^{7}Be (n,α) ^{4}He
S. Q. Hou et al., *Phys. Rev. C* 91, 055802 (2015)
L. Lamia, C. Spitaleri, C. A. Bertulani, S.Q. Hou
***Apj* 850 175 (2017)**

$^{8}Li(n, \gamma)\ ^{9}Li$

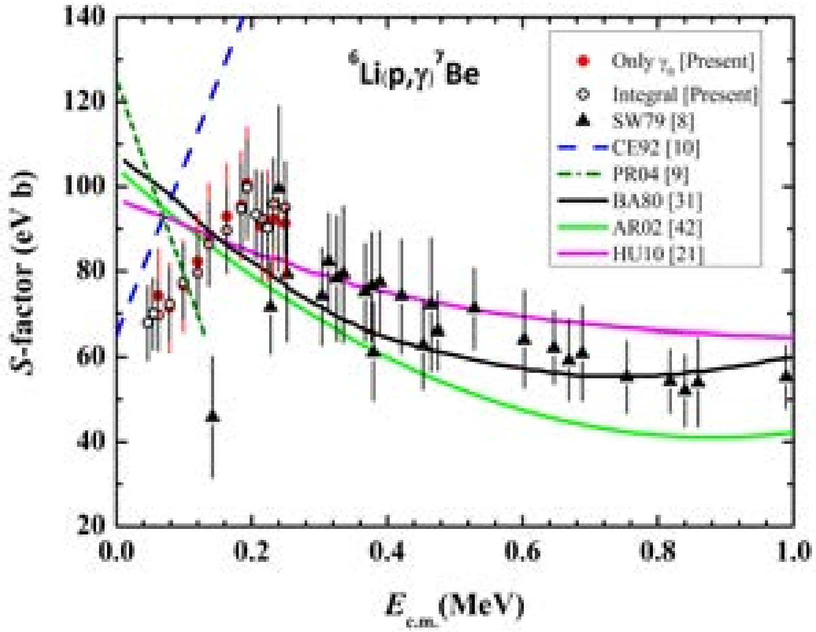


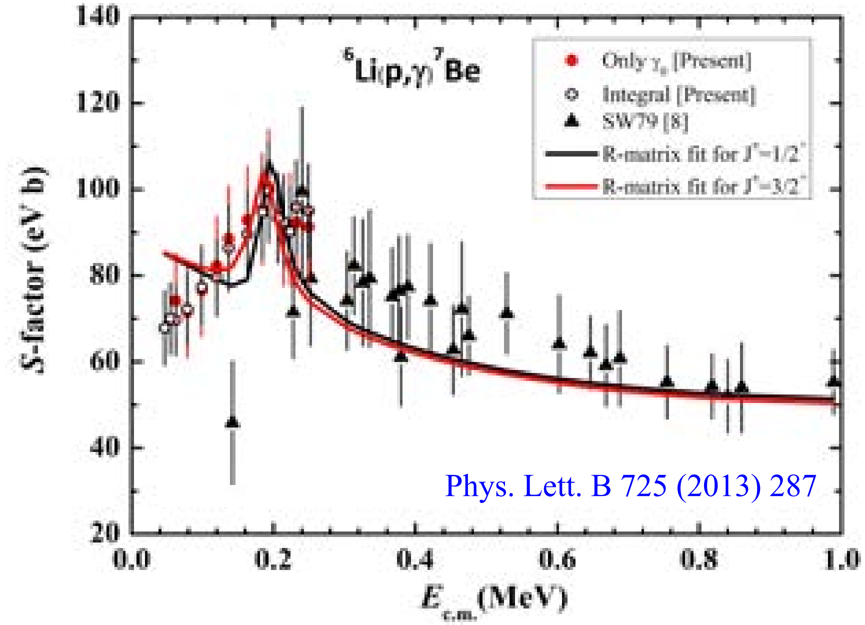


Temperature dependence of the reaction rates for $^{8}Li(n, \gamma)^{9}Li$. Z. H. Li et al. PRC 71 052801(R) (2005)

Impact of $^{8}Li(n, \gamma)^{9}Li$ reaction on Big Bang Nucleosynthesis. S.Q. Hou et al. CPL 27 082601 (2010)

^{6}Li(p,γ)^{7}Be



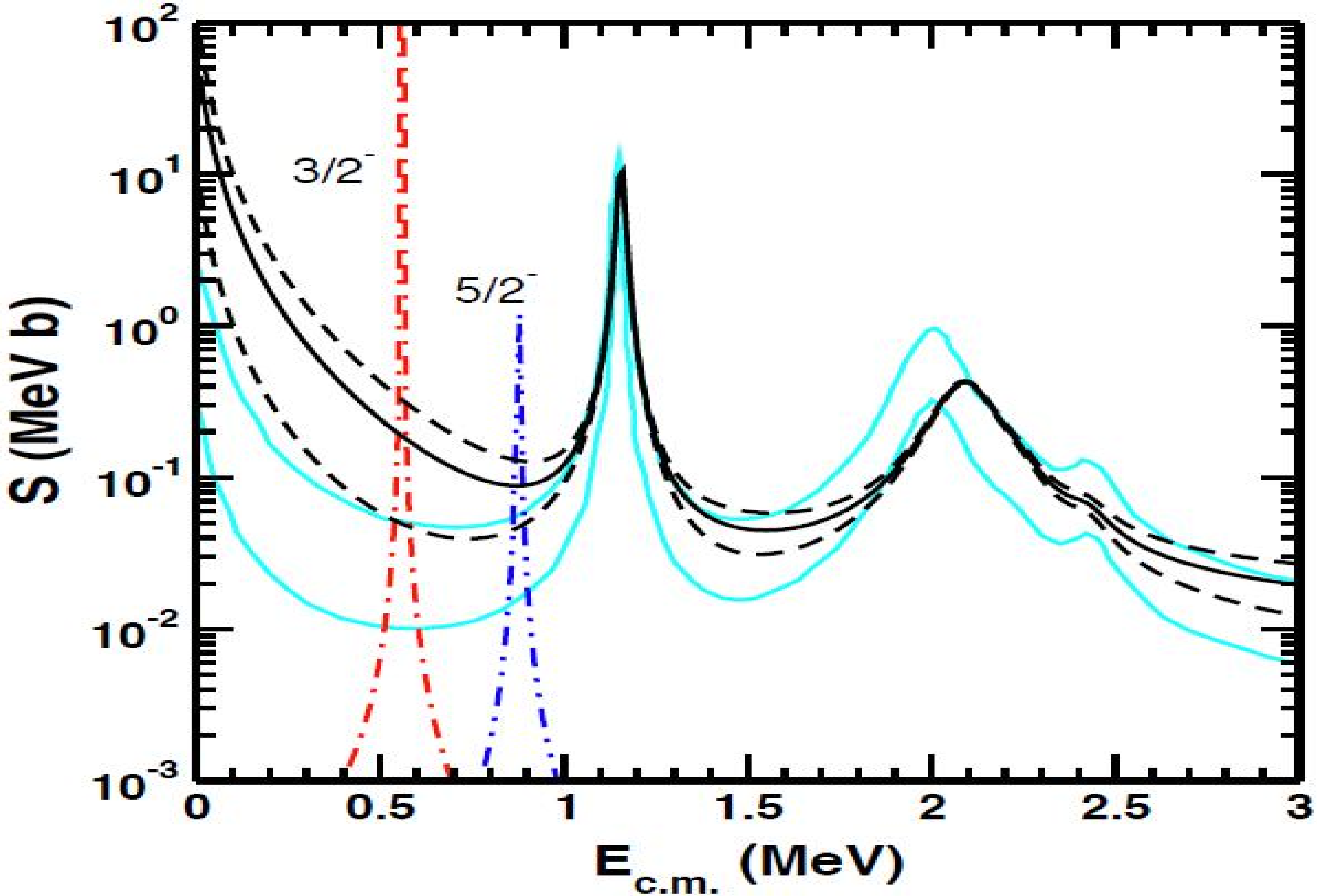


Phys. Lett. B 725 (2013) 287

$$S(E) = E\sigma(E)\exp(2\pi\eta)$$

Conclusion: the measured S factors decreases below 200 keV, which contradicts with all theoretical predictions. A new excited state around 5.8 MeV ($1/2^+$ or $3/2^+$, Γ≈50 keV) in ^{7}Be is predicted. This work demonstrates the simply extrapolation of experiment data to low energy region is unreliable. **No impact on ^{7}Li production**

$^{7}Be(\alpha,\gamma)^{11}C$



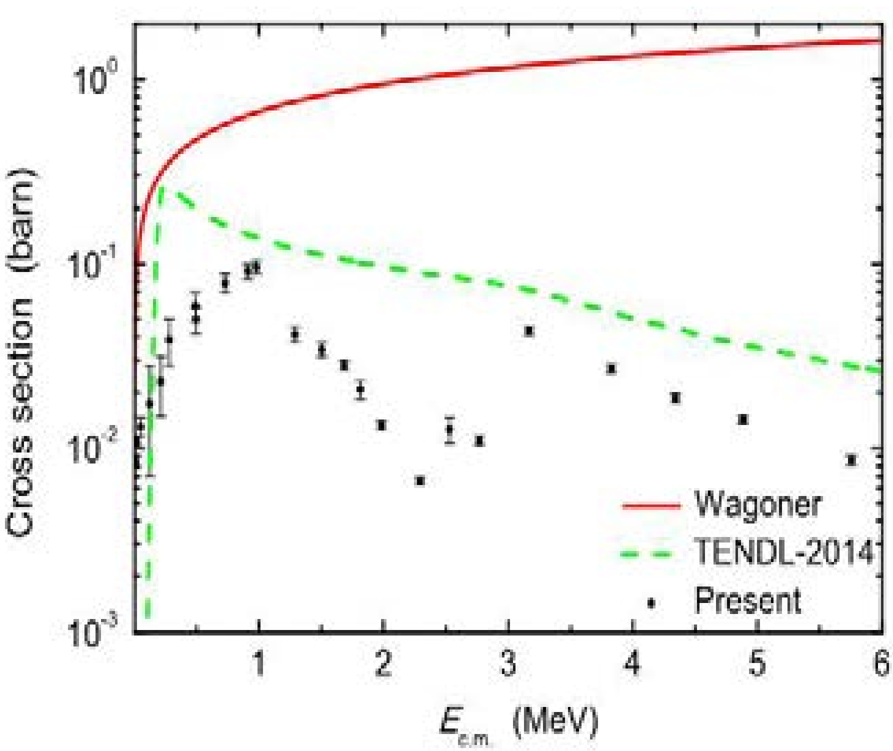
Also no impact on ^{7}Li yeild

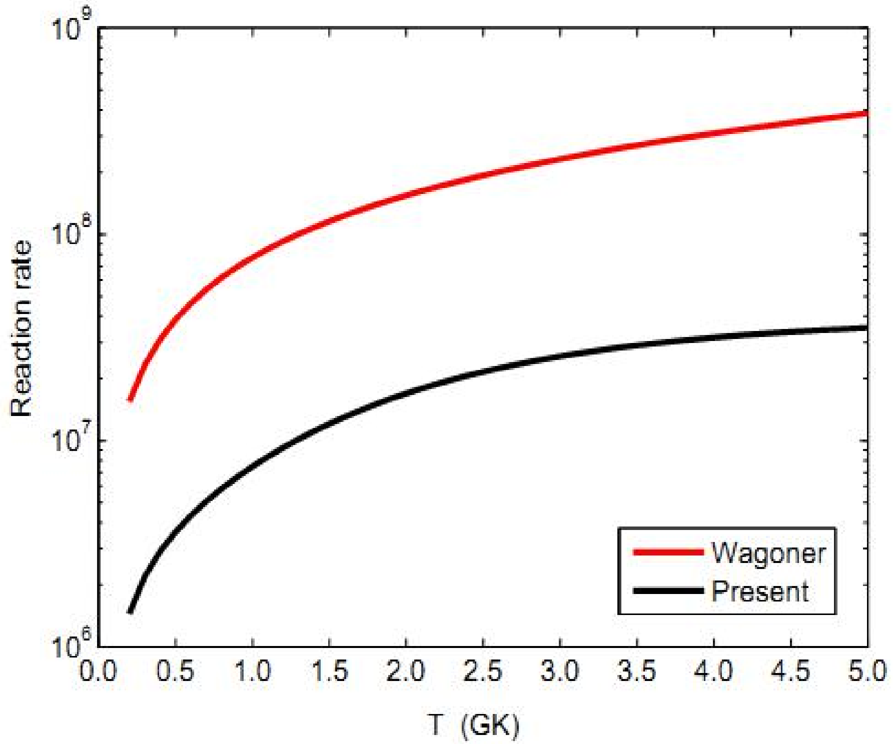
M. Hartos, … , S.Q. Hou *Apj* 862 62 (2018)

$^7Be(n,\alpha)^4He$

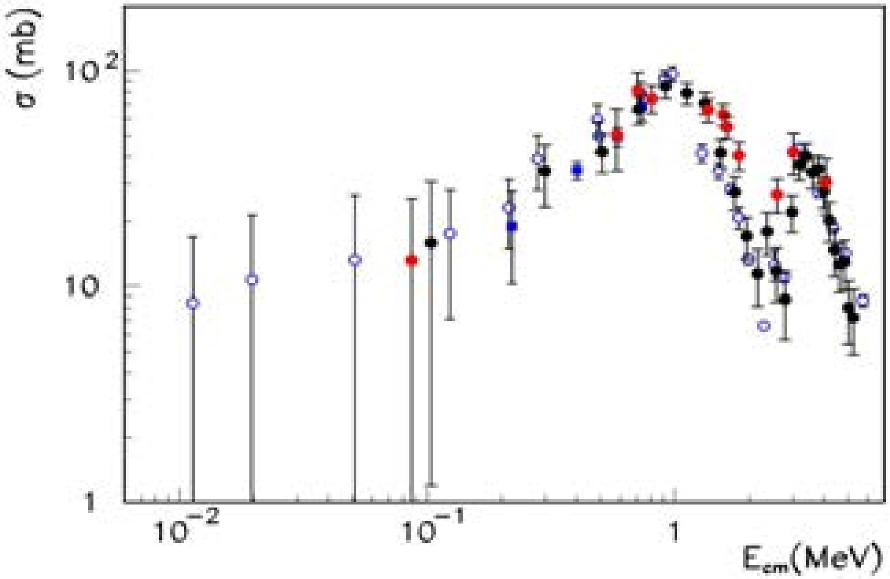
$$\sigma_n = \sigma_{n_0} + \sigma_{n_1} = \frac{P_l^{n_0}}{P_l^{p_0}}\sigma_{p_0} + \frac{P_l^{n_1}}{P_l^{p_1}}\sigma_{p_1} \quad (1)$$

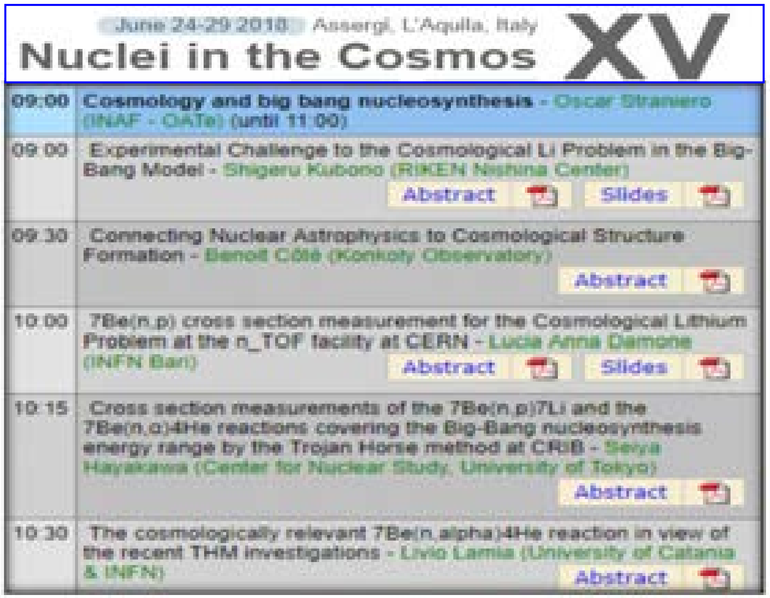
$$\sigma_{^4He(\alpha,p)^7Li} \xrightarrow{\text{Eq. (1)}} \sigma_{^4He(\alpha,n)^7Be} \xrightarrow{\text{Detailed Balance}} \sigma_{^7Be(n,\alpha)^4He}$$





Confirmed by international colleague





June 24-29 2018 Assergi, L'Aquila, Italy

Nuclei in the Cosmos XV

09:00	Cosmology and big bang nucleosynthesis - Oscar Straniero (INAF - OATe) (until 11:00)
09:00	Experimental Challenge to the Cosmological Li Problem in the Big-Bang Model - Shigeru Kubono (RIKEN Nishina Center) Abstract Slides
09:30	Connecting Nuclear Astrophysics to Cosmological Structure Formation - Benoit Côté (Konkoly Observatory) Abstract
10:00	7Be(n,p) cross section measurement for the Cosmological Lithium Problem at the n_TOF facility at CERN - Lucia Anna Damone (INFN Bari) Abstract Slides
10:15	Cross section measurements of the 7Be(n,p)7Li and the 7Be(n,α)4He reactions covering the Big-Bang nucleosynthesis energy range by the Trojan Horse method at CRIB - Seiya Hayakawa (Center for Nuclear Study, University of Tokyo) Abstract
10:30	The cosmologically relevant 7Be(n,alpha)4He reaction in view of the recent THM investigations - Livio Lamia (University of Catania & INFN) Abstract

This conclusion is confirmed by three completely different experimental methods

S.Q. Hou et al. PRC **91** 055802 (2015)

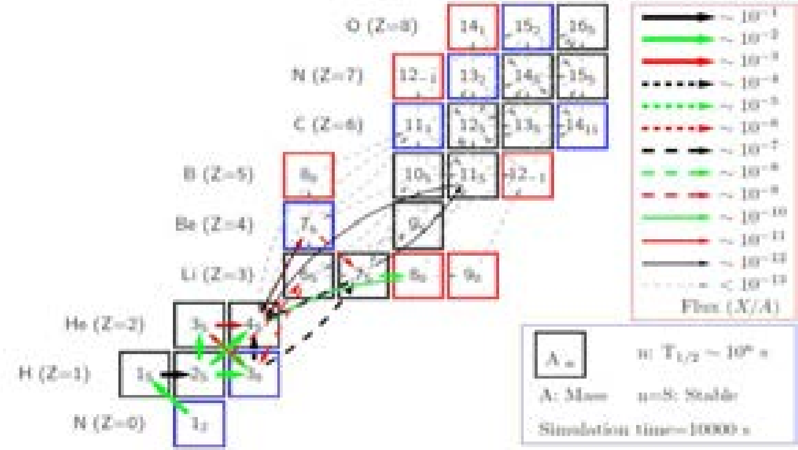
M. Barbagallo et al. PRL **117** 152701 (2016)

T. Kawabata et al. PRL **118** 052701 (2017)

L. Lamia et al. APJ **850** 175 (2017)

C. Pitrou et al. Phys. Rep. 754 1 (2018)

Ultimate impact: leads to a 1.2% increase in the final ^{7}Li production. Hence, present rate even worsens the ^{7}Li problem.



Big bang nucleosynthesis: Present status

Richard H. Cyburt, Brian D. Fields, Keith A. Olive, and Tsung-Han Yeh
Rev. Mod. Phys. **88**, 015004 – Published 23 February 2016

While precise predictions from SBBN are feasible, they rely on well-measured cross sections and a well-measured neutron lifetime. Indeed, even prior to the WMAP era, theoretical predictions for D, ^{3}He, and ^{4}He were reasonably accurate; however, uncertainties in nuclear cross sections leading to ^{7}Be and ^{7}Li were relatively large. Several modern analyses of nuclear rates for BBN were based on the NACRE compilation (Angulo *et al.*, 1999) and recent BBN calculations [some using rate calculations with less ambiguous definitions of rate uncertainties (Cyburt, 2004; Descouvemont *et al.*, 2004; Serpico *et al.*, 2004)] by several groups are in good agreement (Nollett and Burles, 2000; Vangioni-Flam, Coc, and Casse, 2000; Burles, Nollett, and Turner, 2001; Cyburt, Fields, and Olive, 2001, 2003; Coc *et al.*, 2002, 2004, 2012; Cuoco *et al.*, 2004; Descouvemont *et al.*, 2004; Serpico *et al.*, 2004; Cyburt, 2004). Recent remeasurements of the ^{3}He$(\alpha,\gamma)^7$Be cross section (Singh *et al.*, 2004; Brown *et al.*, 2007; Confortola *et al.*, 2007; Gyürky *et al.*, 2007) did improve the theoretical accuracy of the prediction but exacerbated the discrepancy between theory and observation (Cyburt, Fields,

Summary

- BBN is the most successful theory to explain the origin of universe
- Cosmological lithium problem is a longstanding problem in BBN
- It seems hopeless from perspective of nuclear physics
- Hope to be explored further from other perspective

Collaborator

- Jianjun He， Beijing Normal University
- Taka Kajino， Beihang University & University of Tokyo & NAO of Japan
- Shigeru Kubono， University of Tokyo &RIKEN
- Livio Lamia， Università degli Studi di Catania
- Carlos Bertulani， Texas A&M University-Commerce,
- Grant Mathews， University of Notre dame
- Anuj Parikh， Universitat Politècnica de Catalunya
- David Kahl， The University of Edinburgh
- Shubhchintak， Universite Libre de Bruxelles

Thanks for your attentions

已发表的可能解决方案

相关文章发表：

Nature: 2篇，Rev. Mod. Phys.：1篇，PRL: 5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]

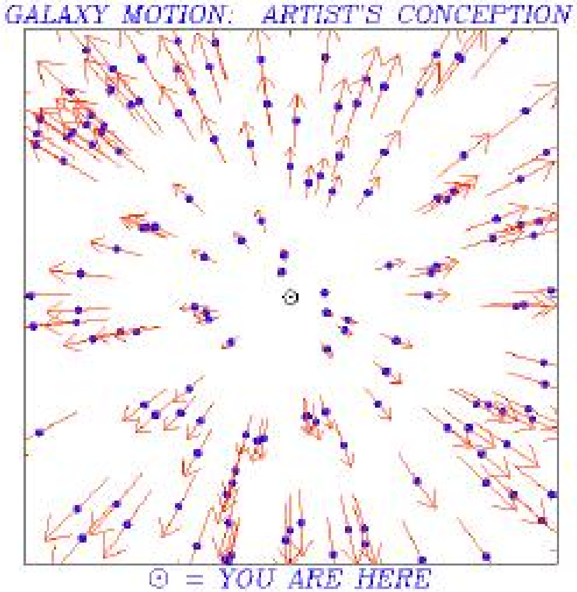
LETTER

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]

Hubble's Law and Its Meaning



Edwin Hubble (1929):

- measured galaxy motions, distances
- galaxies moving away from us
- farther ⇨ faster
- that is, $\vec{v} = H\ \vec{r}$

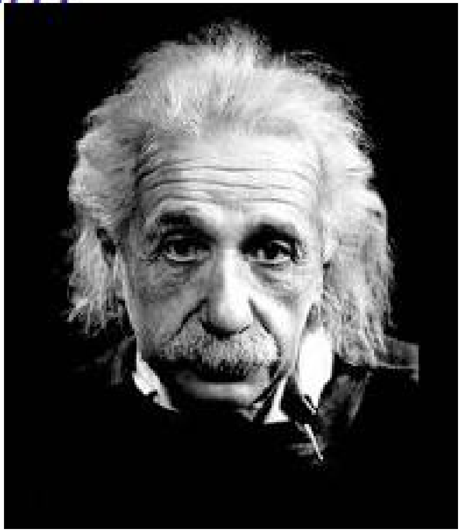
Interpretation: *What does it mean?*

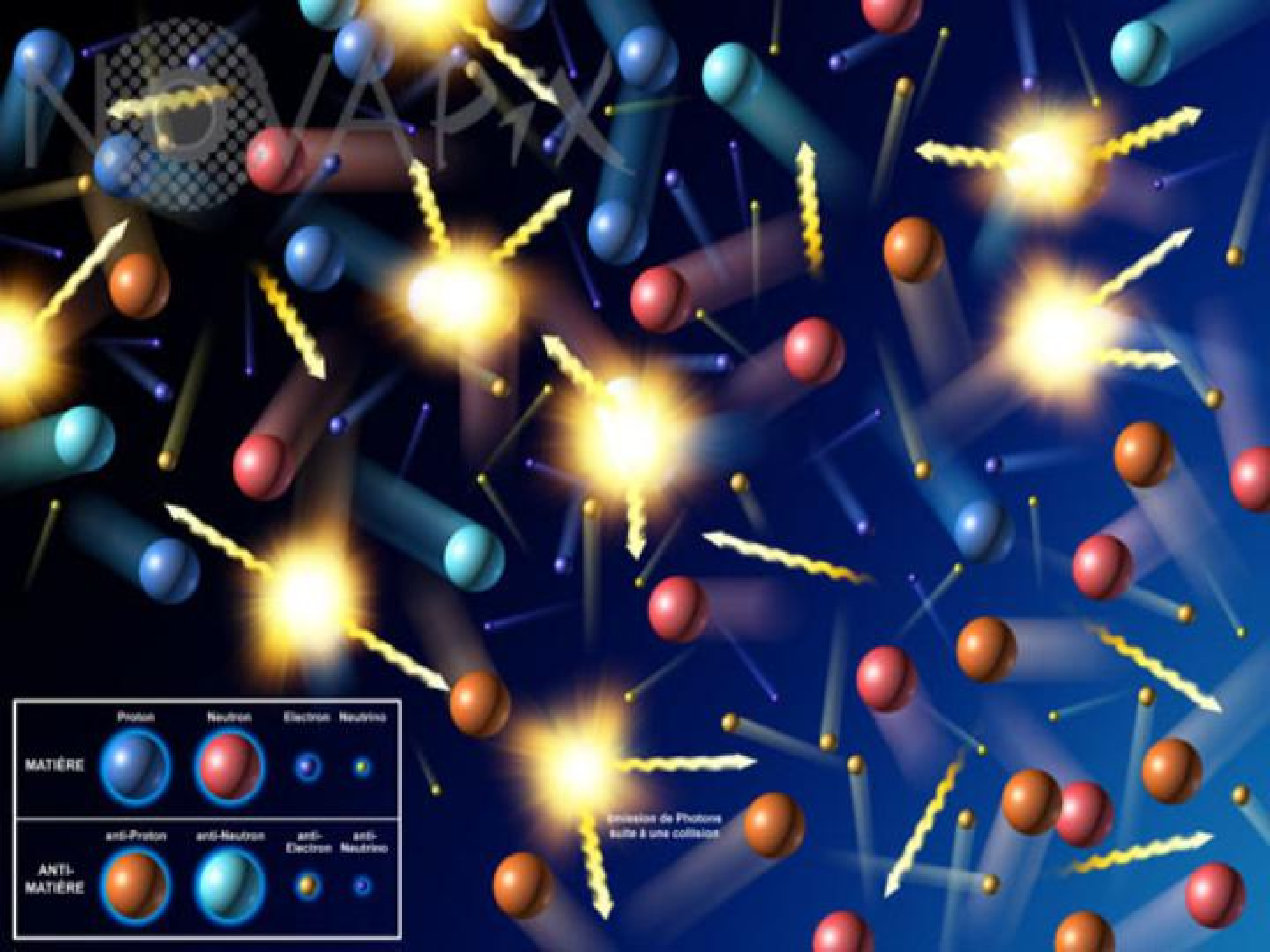
- Egoist view:

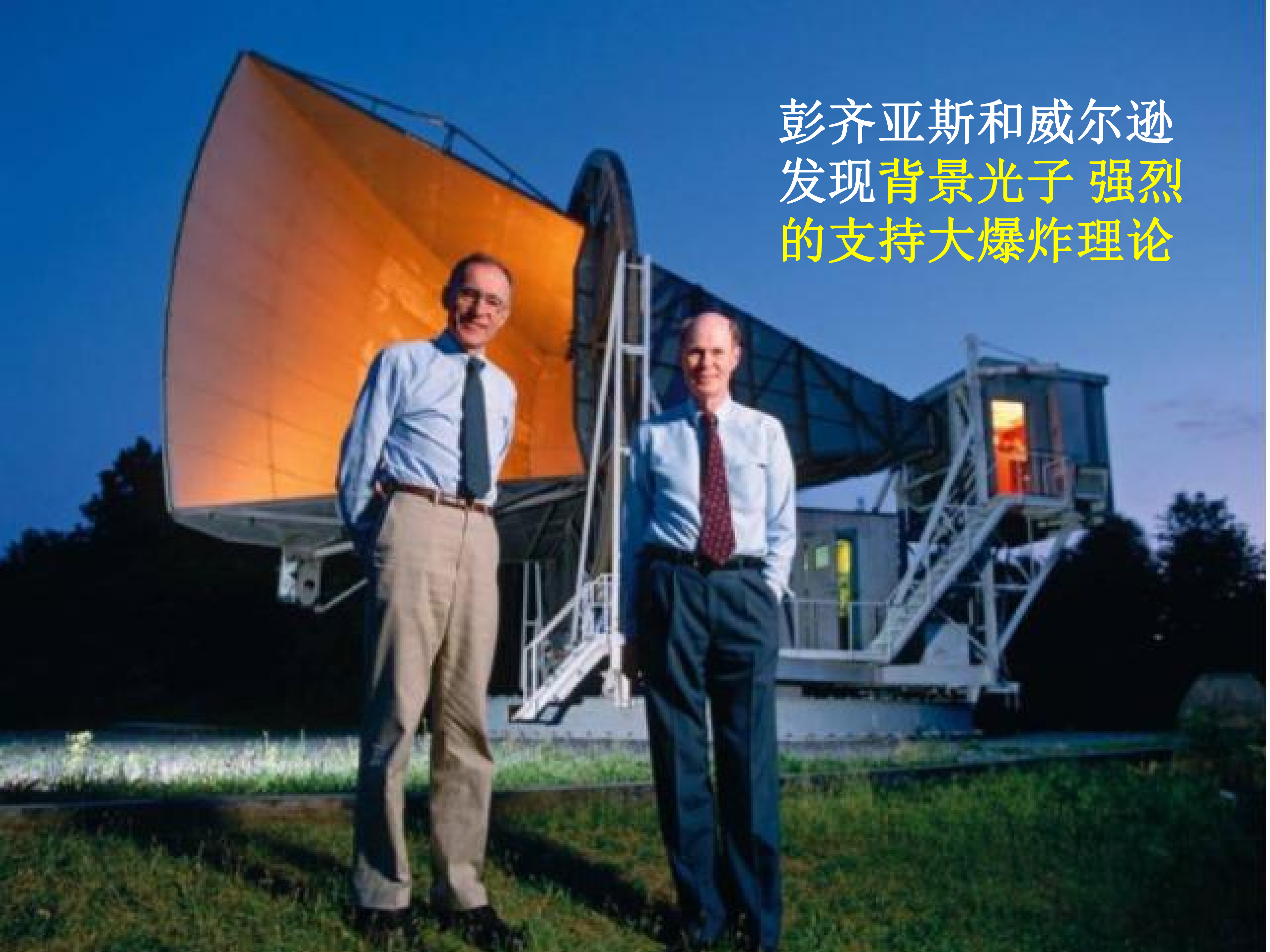
We are at center of Universe

- Einstein view

Universe is expanding! No center!



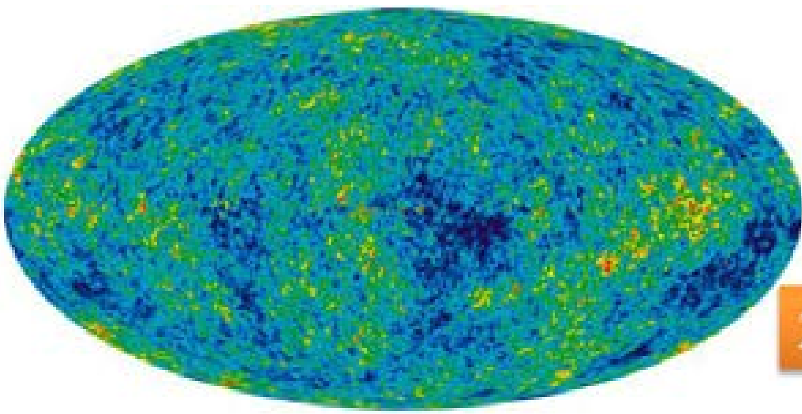

NOVAPIX
Proton
Neutron
Electron
Neutrino
MATIÈRE
anti-Proton
anti-Neutron
anti-Electron
anti-Neutrino
ANTI-MATIÈRE
Emission de Photons suite à une collision


彭齐亚斯和威尔逊
发现背景光子 强烈
的支持大爆炸理论

宇宙微波背景辐射

大作为“大爆炸”的“余烬”，宇宙微波背景辐射大约在“大爆炸”后38万年产生

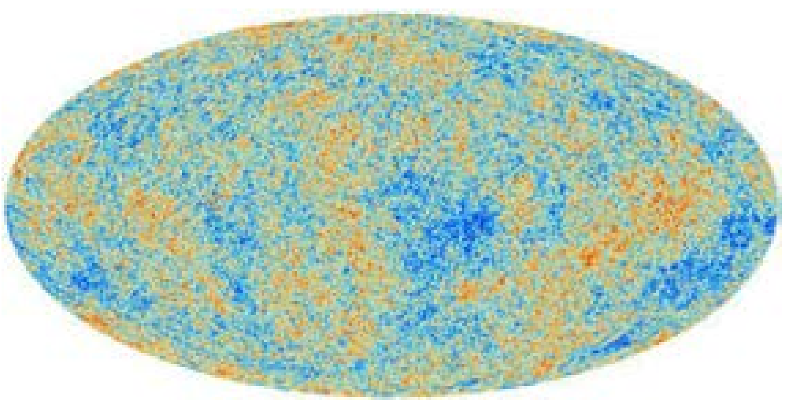
NASA（美国航空航天局）WMAP卫星得到的宇宙诞生初期的图景
(Wilkinson Microwave Anisotropy Probe威尔金森微波各向异性探测器，2001年)



	宇宙年龄
WMAP	137.3±1.2亿年
PLANCK	138.13±0.38亿年(2015)

2.72548±0.00057 K (0.02%，2009年)

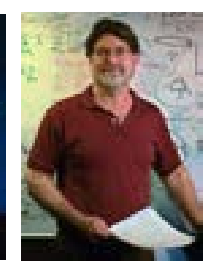
ESA（欧洲航天局）PLANCK卫星得到的宇宙诞生初期的图景（2009年）



诺奖（1978年）

彭齐亚斯&R·威尔逊

诺奖（2006年）



马瑟&斯穆特

Reactions involved in BBN

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

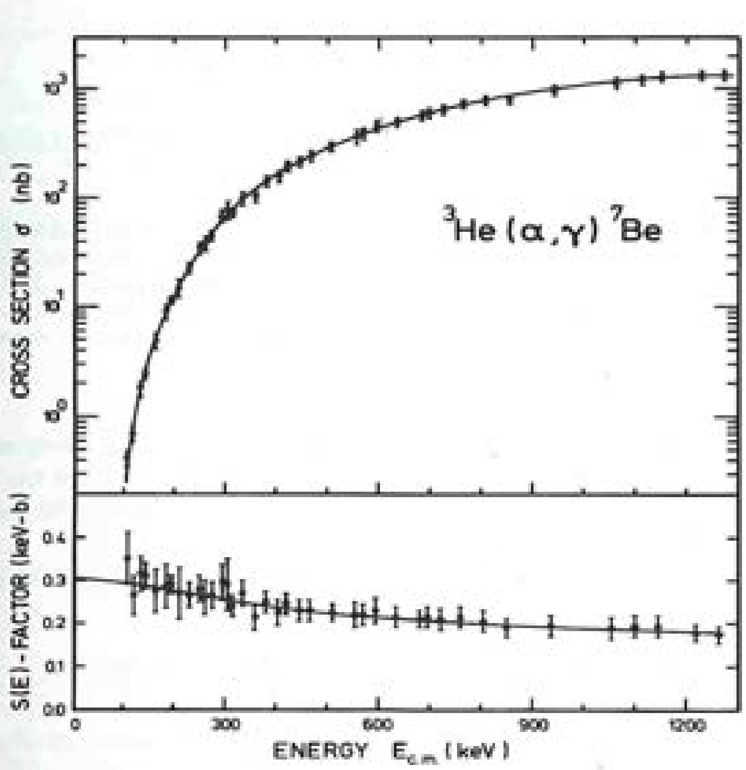
Most important

Secondary

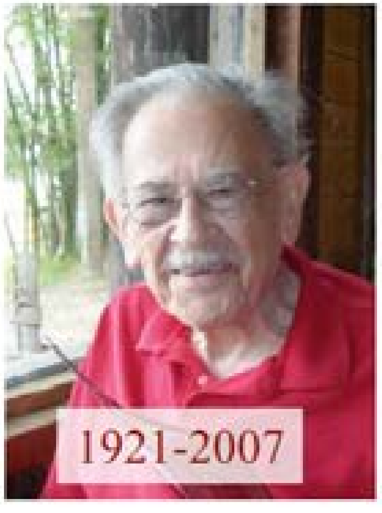
unimportant

- Astrophysical S factor

$$S(E) = E\sigma(E)\exp\left(2\pi\eta\right)$$



- 1946-1950, (Gamow, α β γ): Origin of chemical elements
- 1949, Fermi and Turkevich: nuclei of A > 7 do not form in significant quantity
- 1964, Peebles, Hoyle & Tayler: $Y_p \sim 0.25$
- 1967, Wagoner, Fowler & Hoyle: perform BBN network calculation for the first time

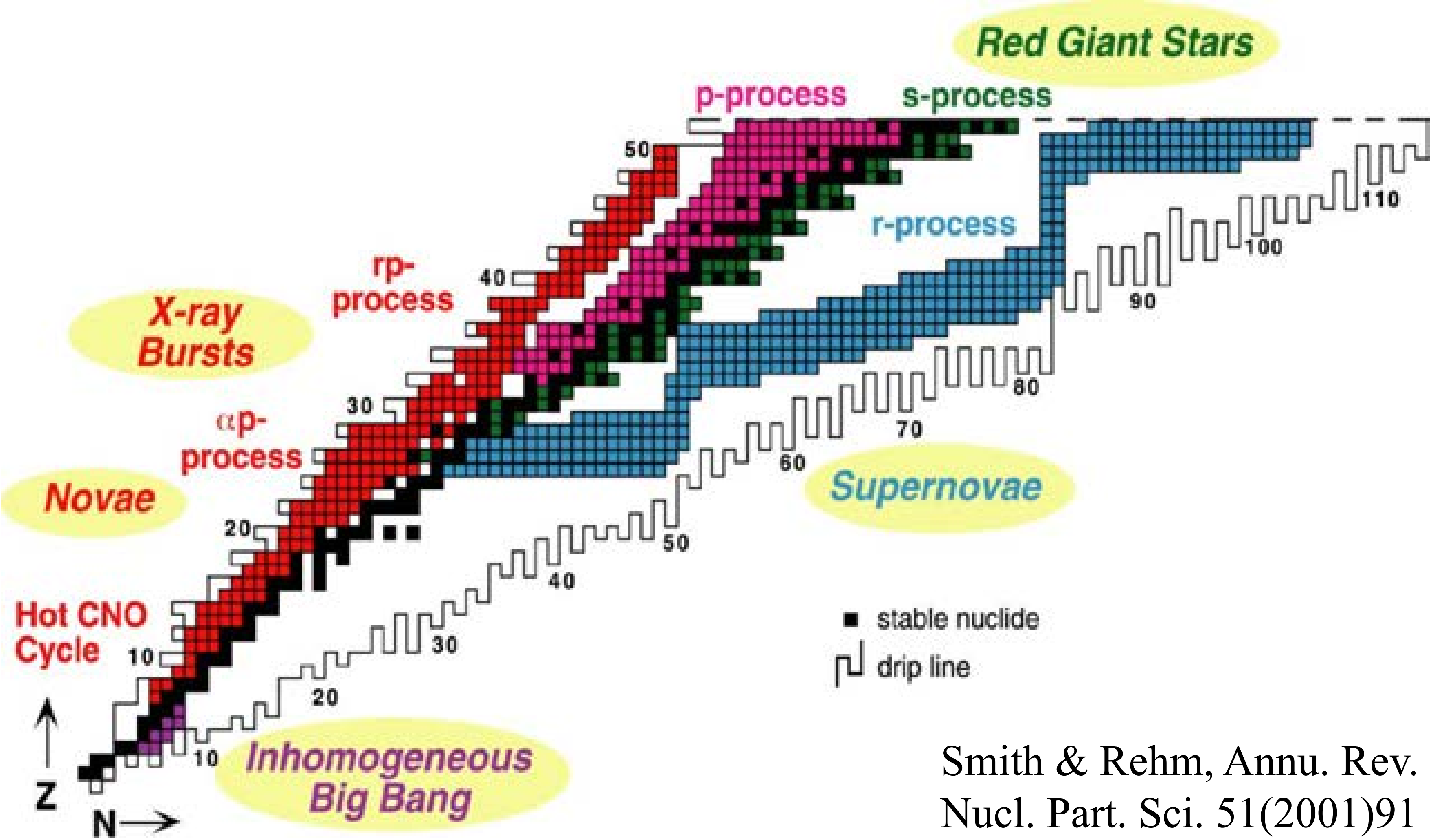


R.A. Alpher, H. Bethe and G. Gamow
"The Origin of Chemical Elements," Physical Review, 73, Issue 7, (1948), 803-804.

Timeline summary

Energy (γ)	time	event
1 MeV	7s	neutrino freeze-out
0.5 MeV	10s	e^+/e^- annihilation, $T_\gamma \sim 1.4\ T_\nu$
70 keV	3 minutes	BBN, light elements formed
0.77 eV	70’000 yr	onset of matter domination
0.31 eV	300’000 yr	recombination
0.26 eV	380’000 yr	photon decoupling, origin of CMB
0.2 meV	14 Gyr	today

Processes and Sites



Smith & Rehm, Annu. Rev. Nucl. Part. Sci. 51(2001)91

Understanding Origins means understanding processes that transmute nuclei and the sites where these processes occur.

Contents lists available at ScienceDirect

Physics Reports

journal homepage: www.elsevier.com/locate/physrep

Precision big bang nucleosynthesis with improved Helium-4 predictions

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At the CMB deduced density, ^{7}Li is produced through the formation of ^{7}Be via the ^{3}He(α,γ)^{7}Be reaction as ^{7}Be will decay much later to ^{7}Li. The destruction of ^{7}Be occurs through the ^{7}Be(n,p)^{7}Li(p,α)^{4}He channel which is limited by the scarcity of late time neutron abundance. The most influential reaction rates on ^{7}Li nucleosynthesis are (e.g. Table 1 in Coc and Vangioni, 2010) ^{1}H(n,γ)^{2}H (indirectly by affecting the neutron abundance) and ^{3}He(α,γ)^{7}Be, but large deviations from their nominal cross sections are strongly constrained by experiments. Even though, there has not been new experimental data, since it is the major source of uncertainty on the ^{7}Li production, the ^{3}He(α,γ)^{7}Be reaction rate has also been recently re-evaluated using Bayesian methods (Gómez Iñesta et al., 2017) to scale the theoretical S-factor of Neff (2011). It was known that the ^{7}Be(n,α)^{4}He reaction could not help solve the lithium problem, but its rate was highly uncertain and affected the ^{7}Li production at the few percent level. Until recently, the only published rate came from an evaluation by Wagoner (1969) based on very scarce data. We used either this rate or the one obtained by TALYS (Goriely et al., 2008) in previous publications (Coc et al., 2012, 2014). A new re-evaluation (Hou et al., 2015) and experiments (Barbagallo et al., 2016; Kawabata et al., 2017) confirmed that the ^{7}Be(n,α)^{4}He rate is approximately, one order of magnitude below the Wagoner one, rendering negligible the effect this reaction. Hence, we now use the rate provided by the n_TOF collaboration (Barbagallo et al., 2016) that now has no impact on ^{7}Be.

Major Facility: HIRFL

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