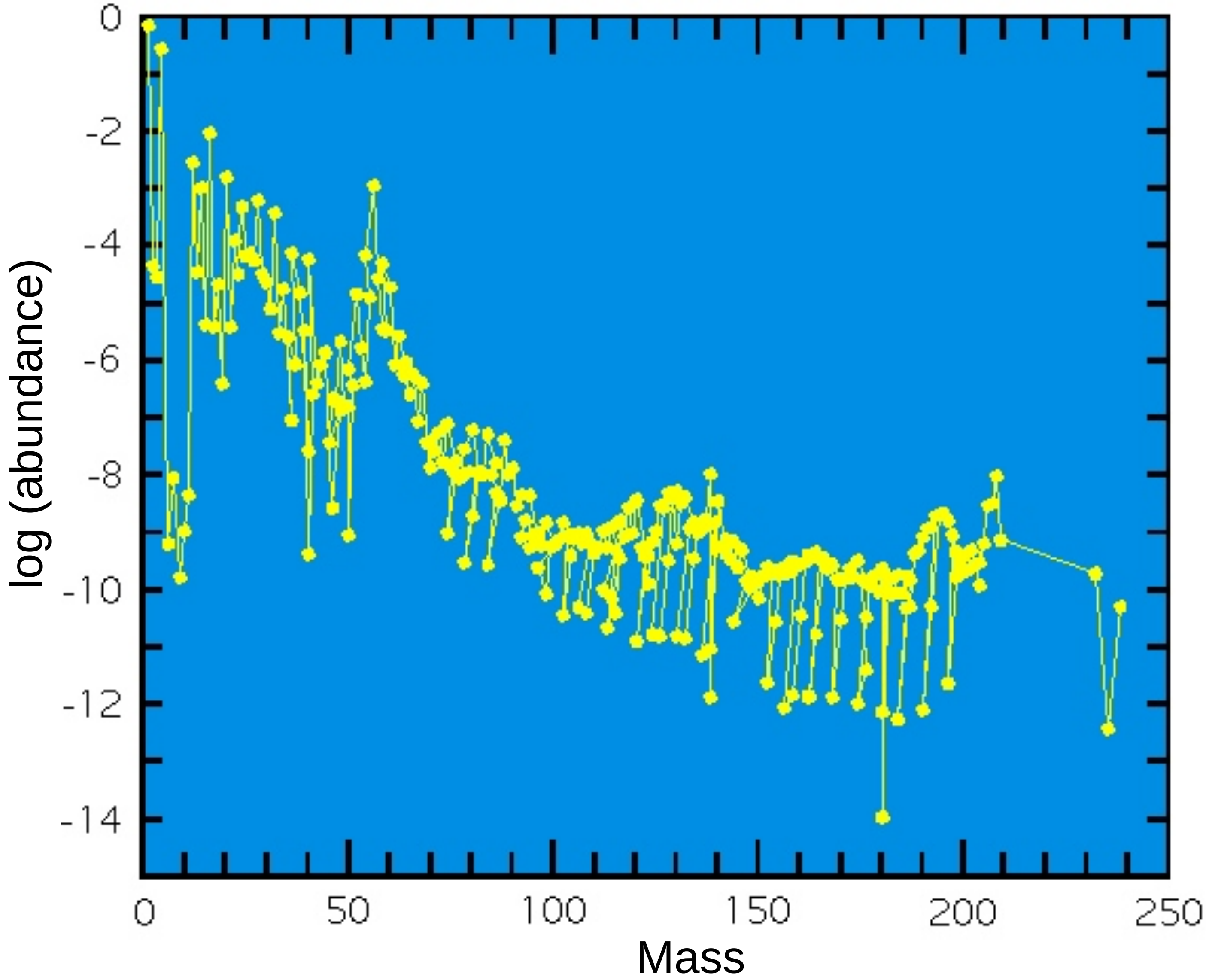
# *Nuclear Physics in Astrophysics*

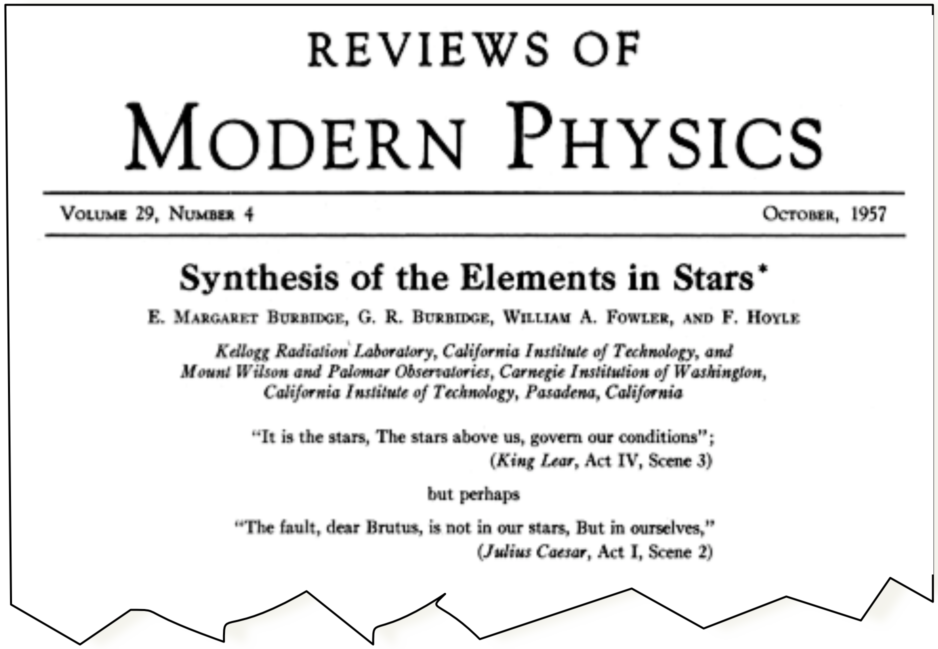
Jeff Blackmon (LSU)

1. *Introduction, BBN & charged-particle reactions*
2. *Stars, stellar evolution, heavy elements & neutrons*
3. *Stellar explosions & neutron stars*

# Solar system abundances



# *Synthesis of the Elements in Stars*



REVIEWS OF

MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

**Synthesis of the Elements in Stars***

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

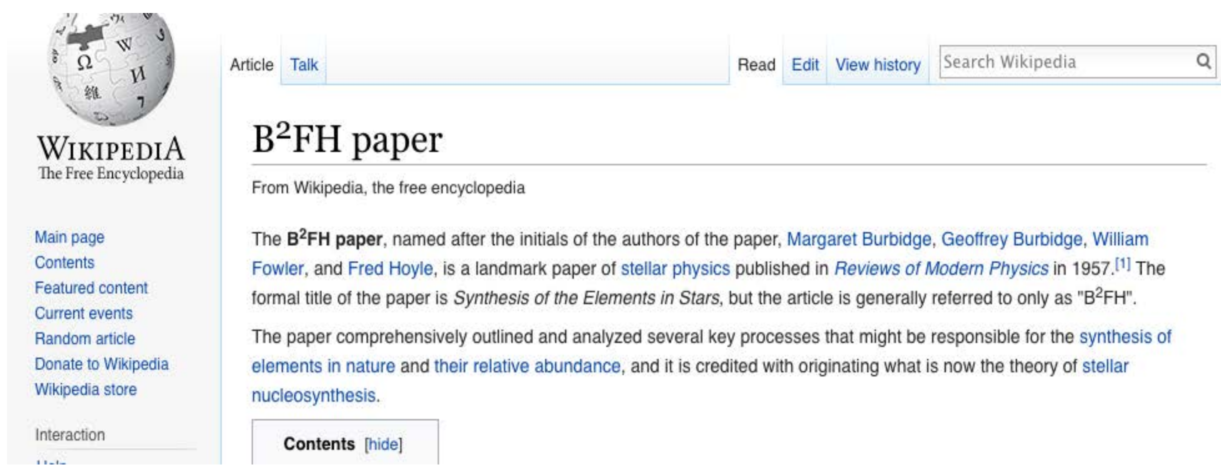
*Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California*

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

but perhaps

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

- 1952 Technitium is observationed in absorption lines in stellar spectra
- $B^2FH$: coherent description of how isotopes arise from stellar processes
- Chemical composition of the cosmos is evolving

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## $B^2FH$ paper

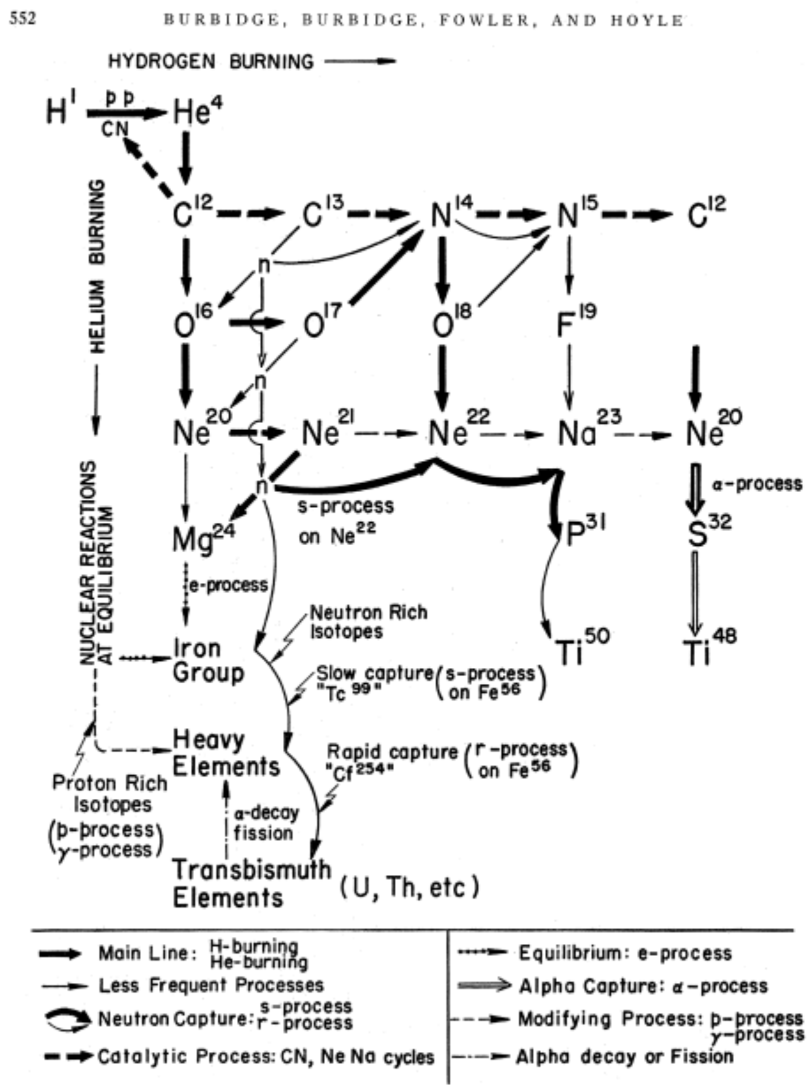
From Wikipedia, the free encyclopedia

The **$B^2FH$ paper**, named after the initials of the authors of the paper, Margaret Burbidge, Geoffrey Burbidge, William Fowler, and Fred Hoyle, is a landmark paper of stellar physics published in *Reviews of Modern Physics* in 1957.[1] The formal title of the paper is *Synthesis of the Elements in Stars*, but the article is generally referred to only as "$B^2FH$".

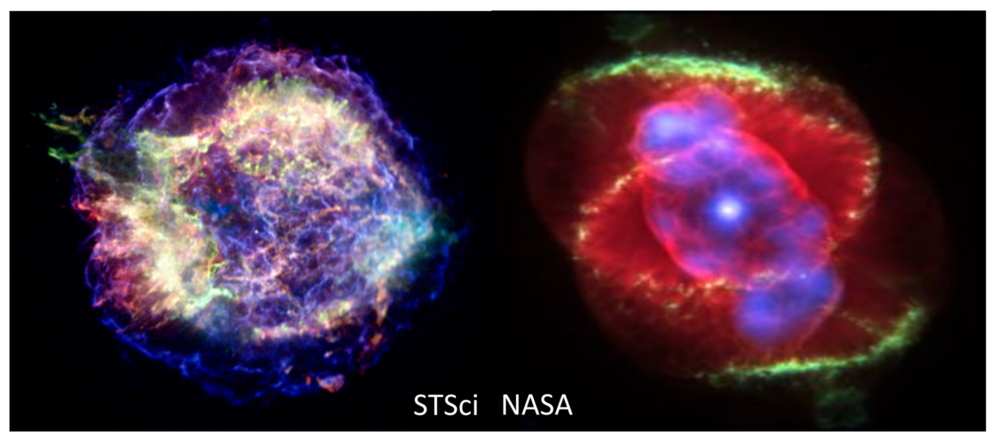
The paper comprehensively outlined and analyzed several key processes that might be responsible for the synthesis of elements in nature and their relative abundance, and it is credited with originating what is now the theory of stellar nucleosynthesis.

**Contents** [hide]

# B$^2$FH Astrophysical processes



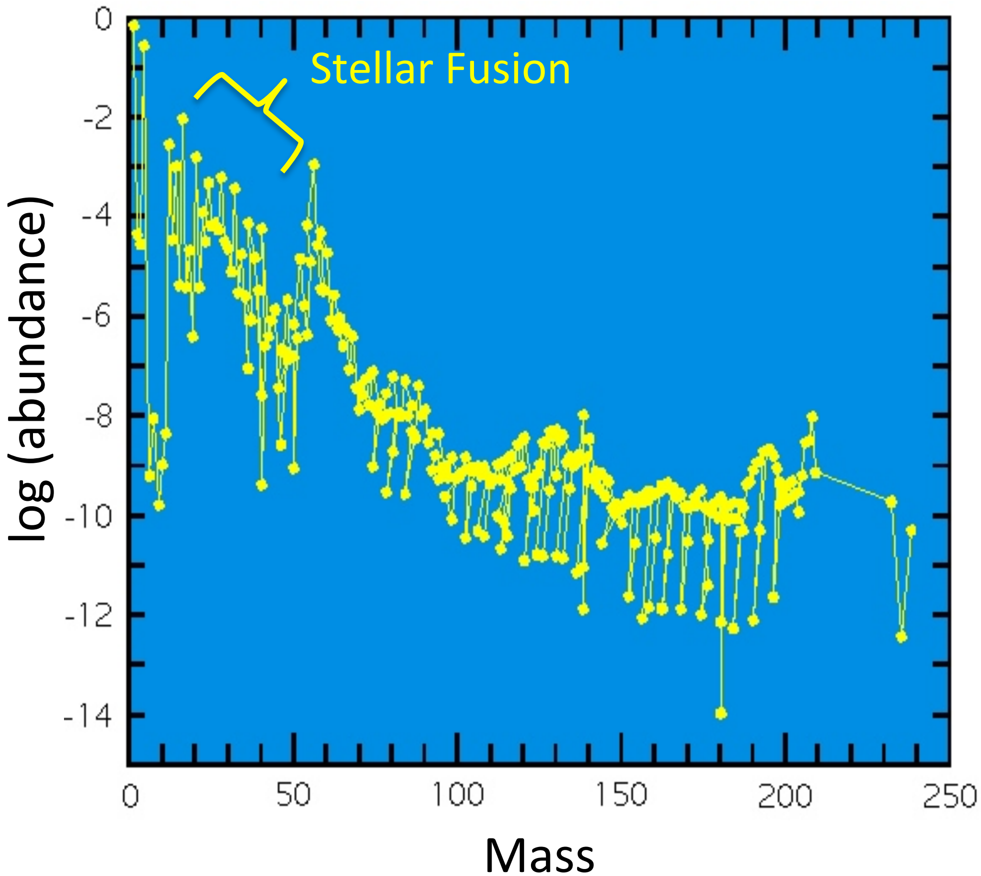

- 7 different astrophysical processes
- 2 main astrophysical sites
  - Supernovae
  - Asymptotic Giant Branch Stars
- Many of the basic ideas validated
- But new developments!




Cas A Supernova Remnant Cat's Eye Nebula

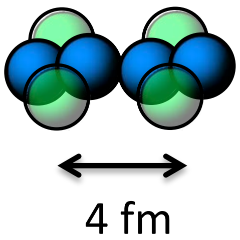
# Fusion in stellar cores

- Fusion can explain the origin of most isotopes up to Ca



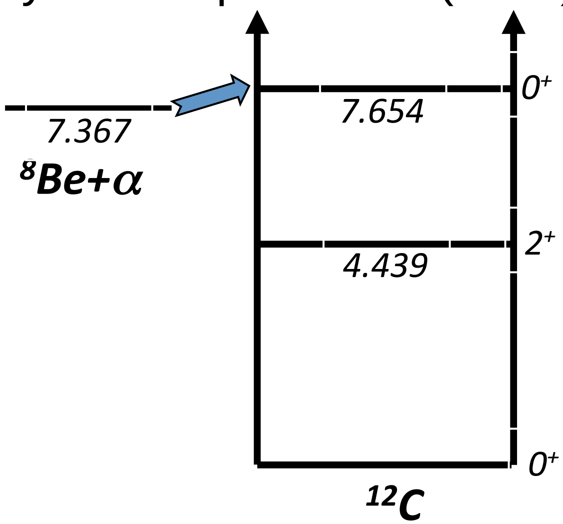

- Fusion inhibited by Coulomb force

$$U = \frac{1}{4\pi\varepsilon_0}\frac{(2e)^2}{4\,fm} = 1.4MeV$$



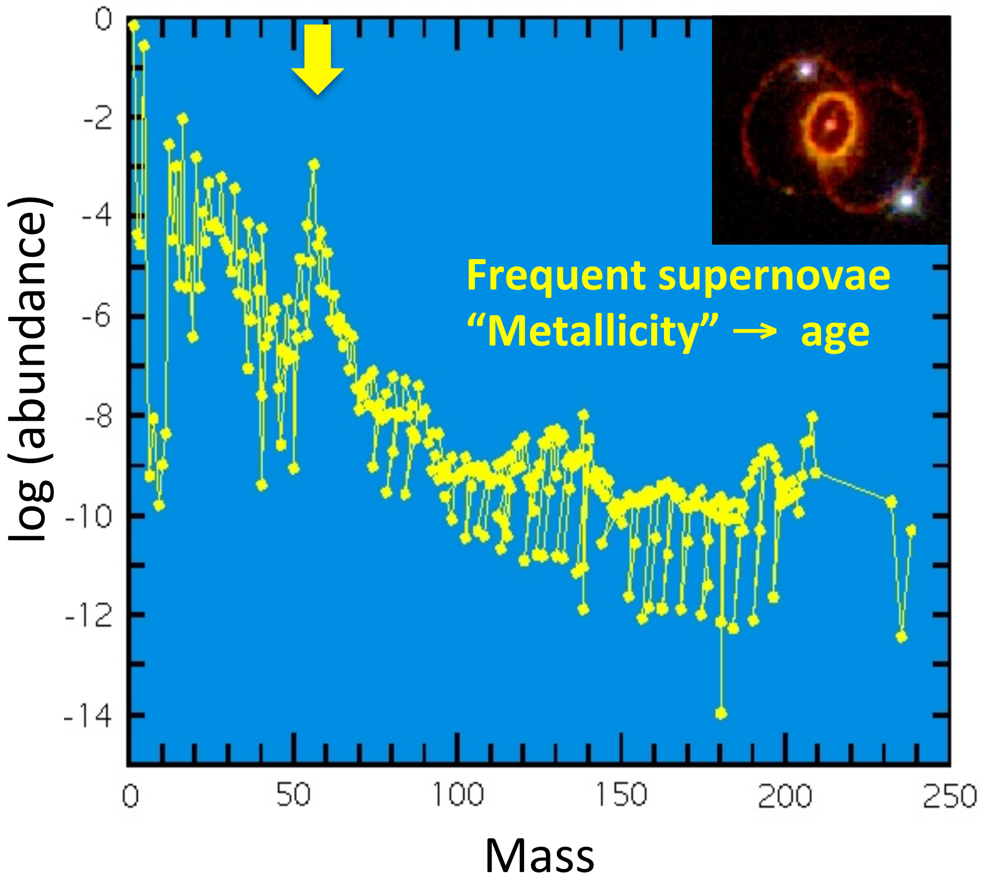

$$kT_{sun} = 1.3keV$$

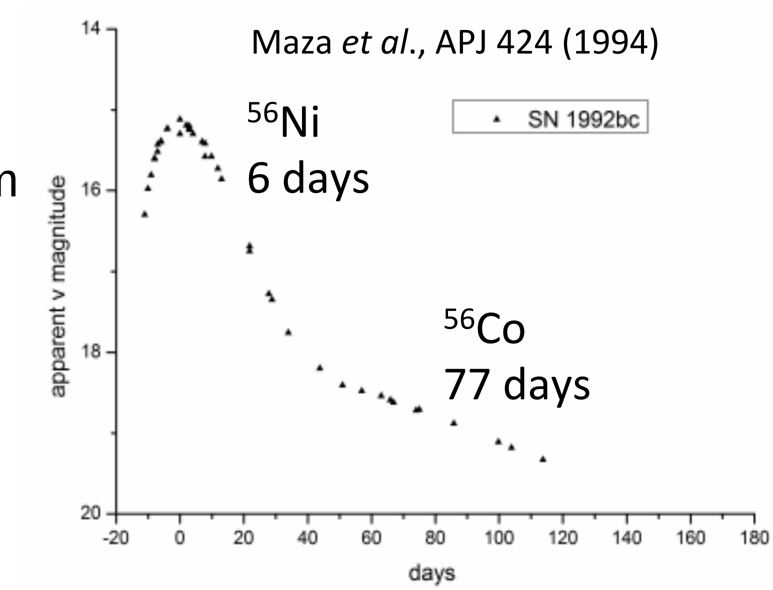
- Helium burning further inhibited by the short lifetime of $^{8}$Be ($10^{-16}$ *s*)
  - Hoyle-state prediction (1954)

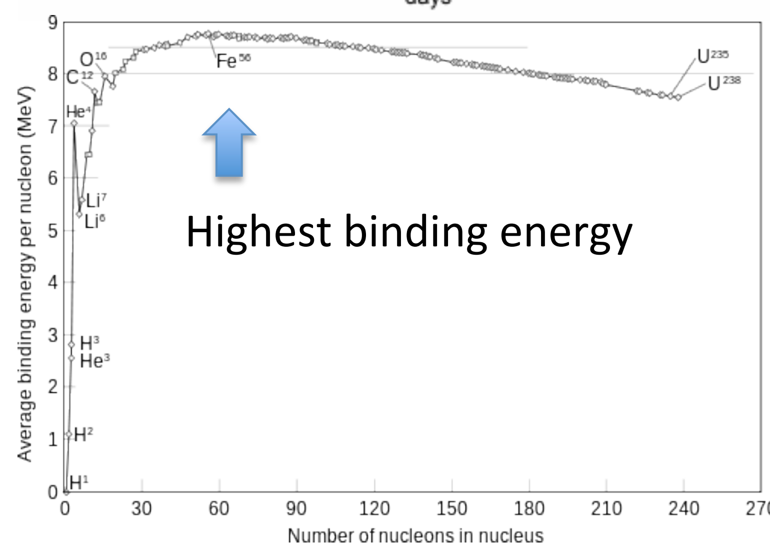


# “e-process” → iron peak

- Fe group produced by supernovae
- Known from light curves
- High temperatures → statistical equilibrium



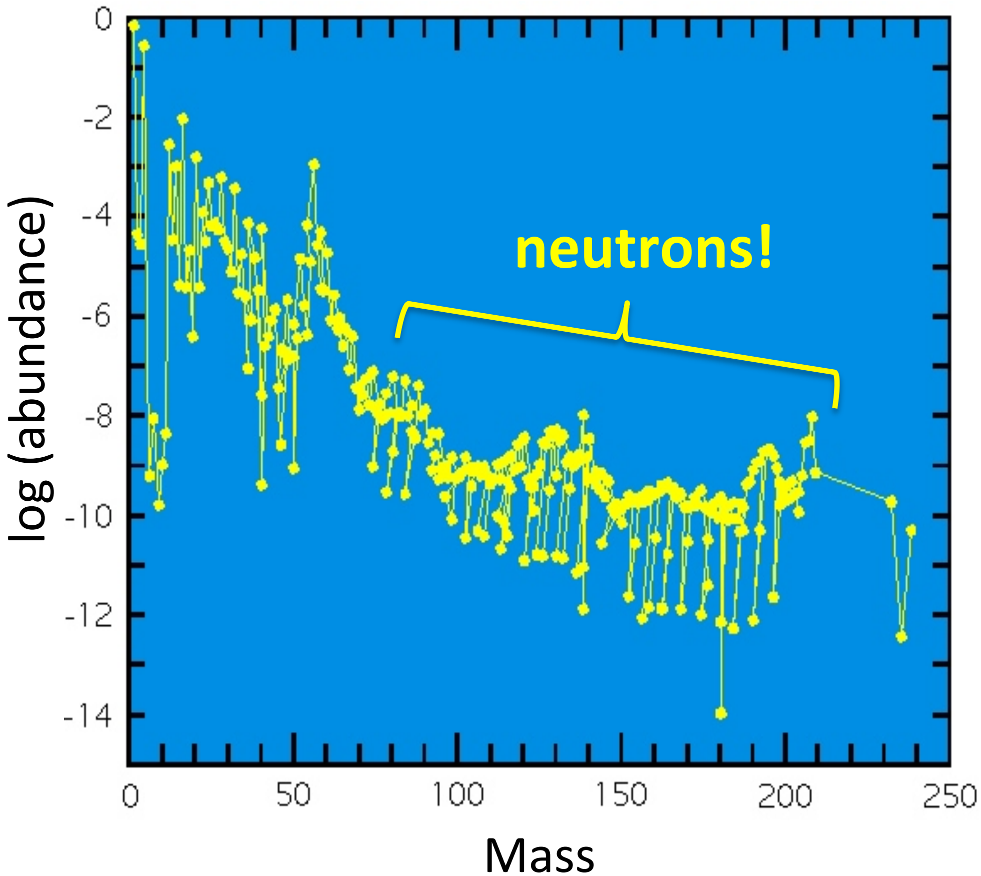



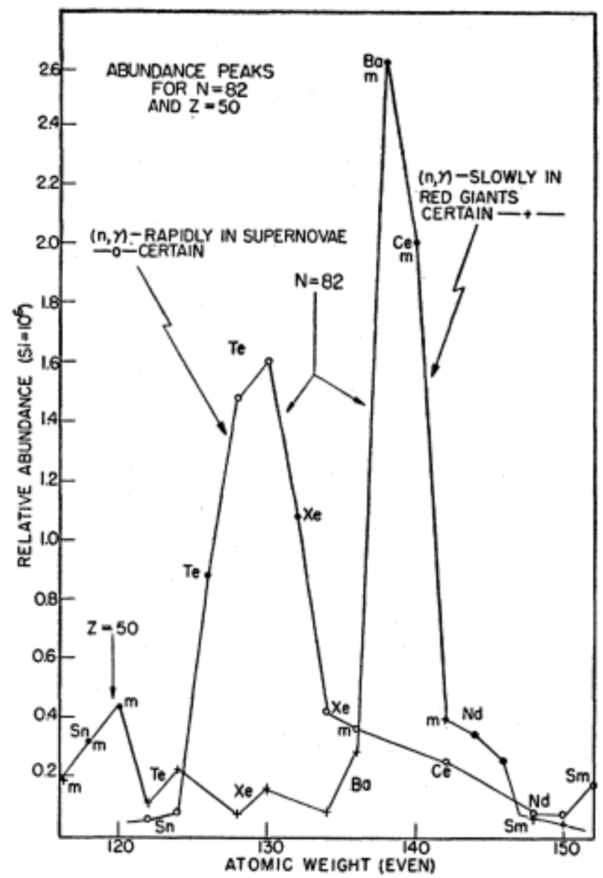



# Heavy isotopes produced with neutrons

- Only slight decrease in abundance with increasing mass
- Sharp peaks in abundance at closed neutron shells
- Broad peaks in abundance at lower mass than closed shells

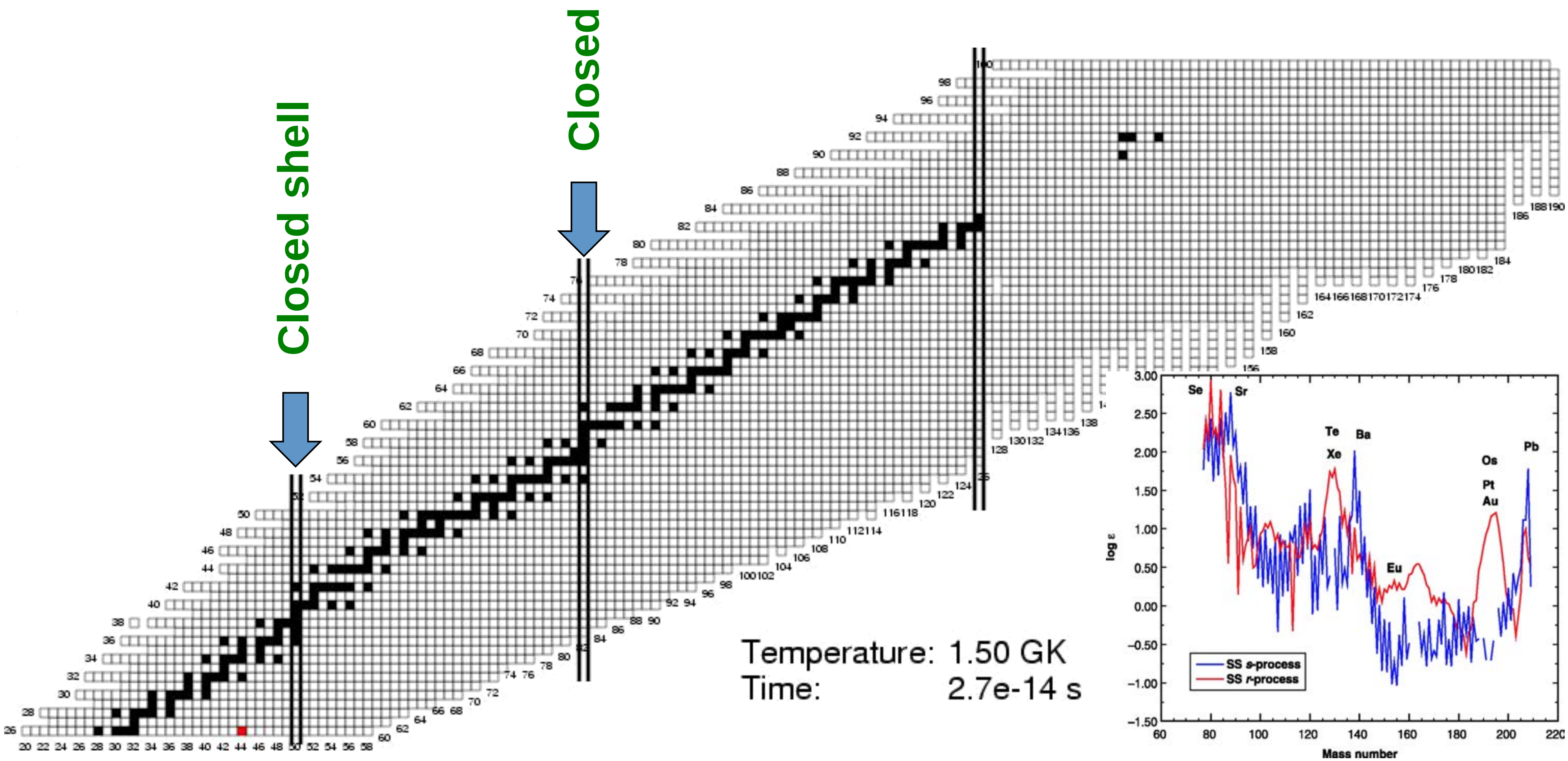
*2 different n exposures*



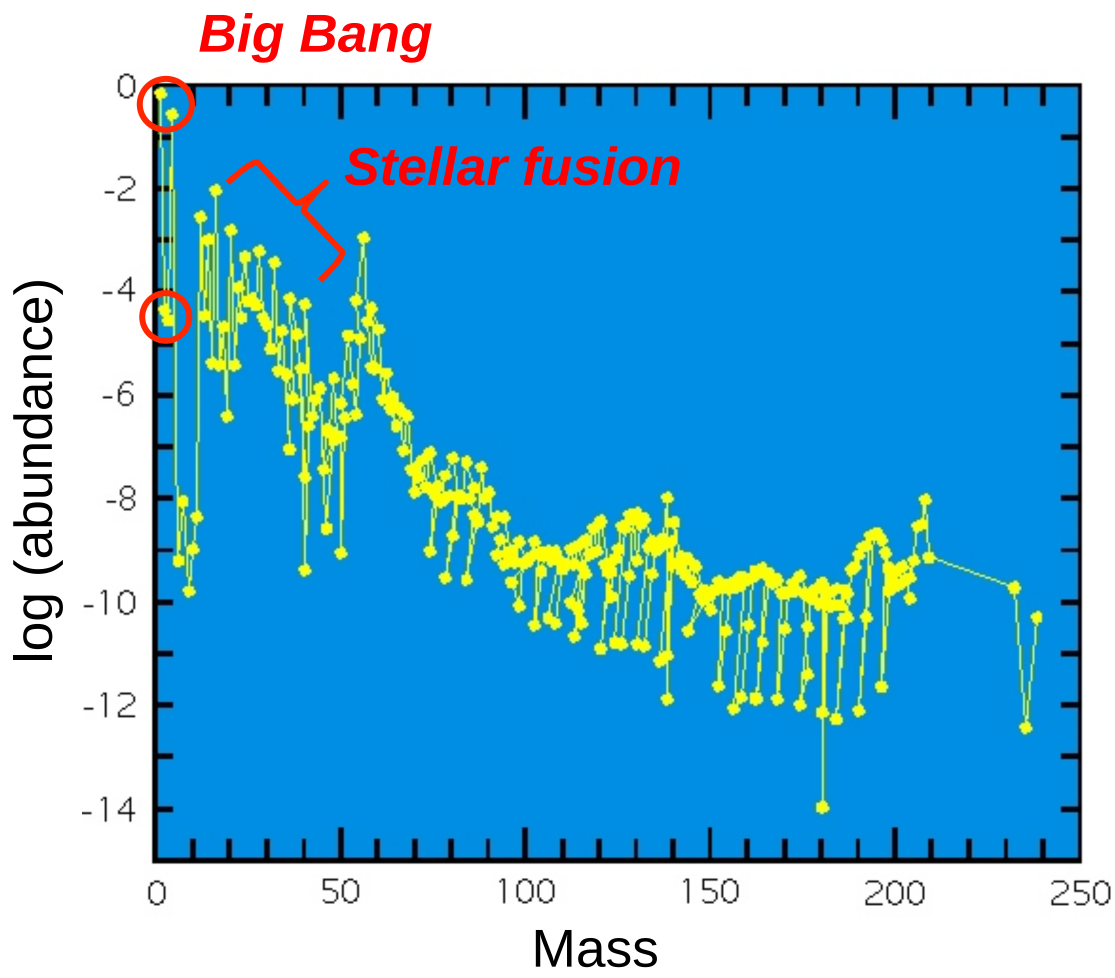



# r vs s process

- r process is hard to understand
  - Isotopes involved are mostly unknown
  - Conditions are difficult to produce

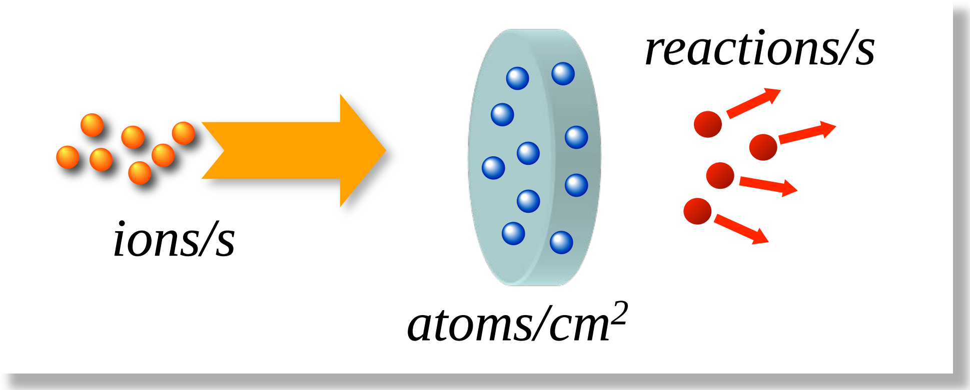


# *Solar system abundances*



# Nuclear reactions in the lab & in space

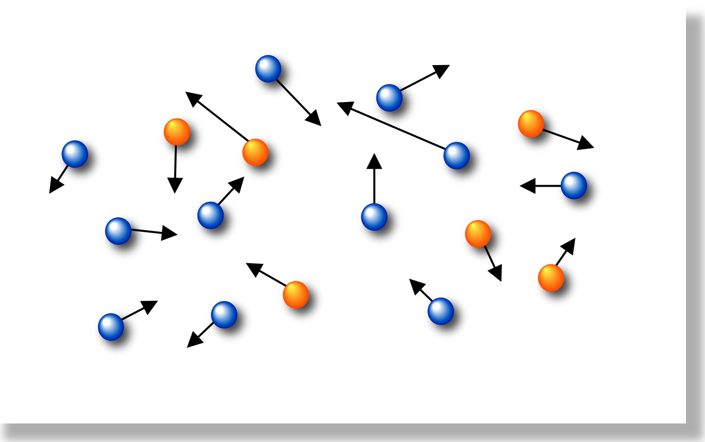
In the lab:




**cross section**

$$\frac{reactions}{s} = \frac{ions}{s}\frac{atoms}{cm^2}\sigma$$

In astrophysical events:



**reaction rate**

$$\frac{reactions}{cm^3 s} = \int \frac{n_x}{cm^3}\frac{n_y}{cm^3} v\sigma(v)\phi(v)dv$$

$$\phi(v) = 4\pi v^2 \left(\frac{\mu}{2\pi kT}\right)^{3/2}\exp\left(-\frac{\mu v^2}{2kT}\right)$$

$$\frac{reactions}{cm^3 s} = \frac{n_x}{cm^3}\frac{n_y}{cm^3}\langle\sigma v\rangle$$

$$\langle\sigma v\rangle = \sqrt{\frac{8}{\pi\mu}}(kT)^{3/2}\int_0^\infty \sigma E e^{-E/(kT)} dE$$

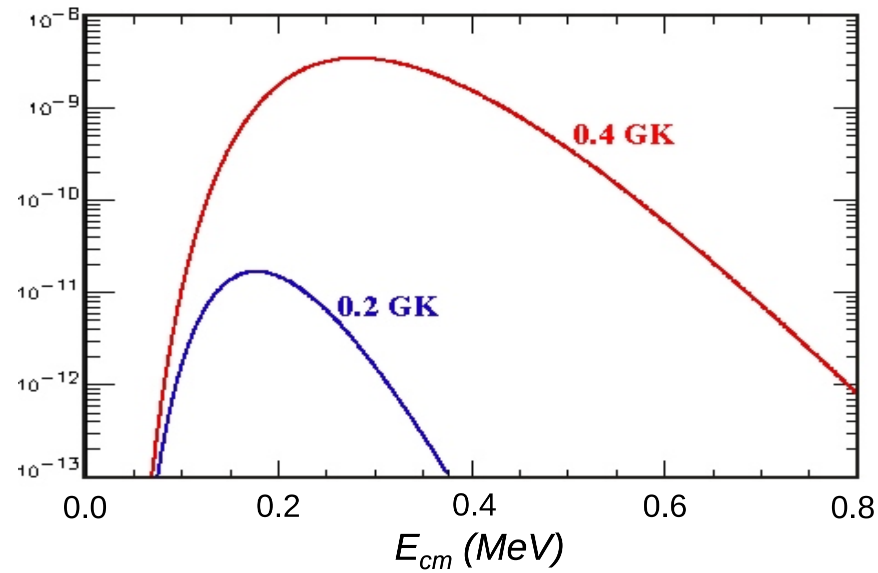
# Charged-particle reactions

$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi\mu}} (kT)^{3/2} \int_0^\infty \sigma E e^{-E/(kT)} dE$$

$$\sigma \equiv \frac{S}{E} e^{-\sqrt{E_G/E}} \qquad E_G \equiv \frac{2\mu}{\hbar^2} \left(\pi Z_1 Z_2 e^2\right)^2$$

$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi\mu}} (kT)^{3/2} \int_0^\infty S e^{-\sqrt{E_G/E}} e^{-E/(kT)} dE$$

Nova Gamow Window



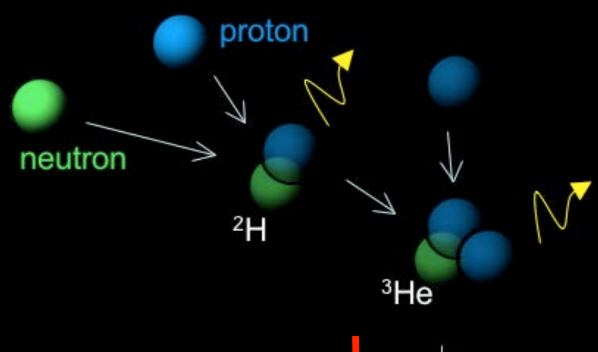

| Reaction | site | $T$ ($10^6$ K) | $kT$ (keV) | $r_{turn}$ (fm) | $r$ (fm) | $E_0$ (keV) |
|---|---|---|---|---|---|---|
| p+p | sun | 15 | 1.3 | 1100 | 2.5 | 6 |
| p+N | CNO | 30 | 2.6 | 3900 | 4.3 | 42 |
| $\alpha$+C | red giant | 190 | 16 | 1060 | 4.8 | 300 |
| p+F | nova | 300 | 26 | 500 | 4.5 | 230 |
| $\alpha$+S | x-ray burst | 1000 | 86 | 500 | 5.9 | 1800 |
| He+He | big bang | 2000 | 170 | 33 | 3.8 | 580 |

# *In the beginning. . . .*

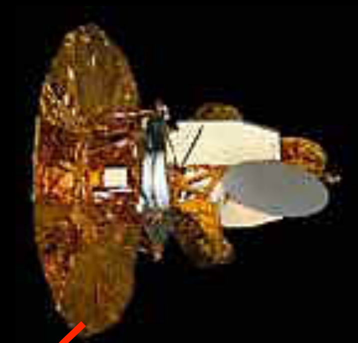
Space, time, matter, & energy began with the Big Bang

"Big Bang" Observations:

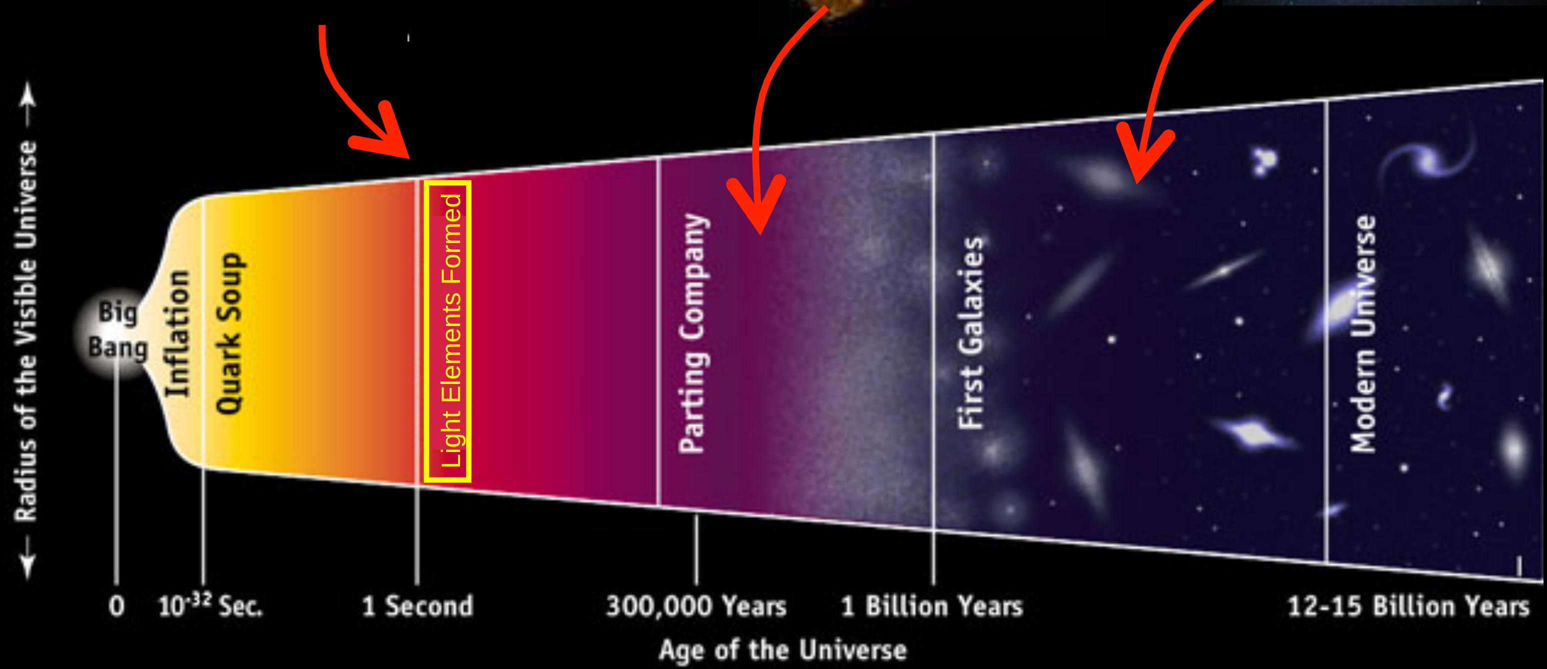
Nucleosynthesis




CMB -The afterglow



Stellar observations



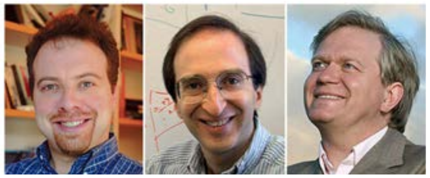
# Optical Observations: Type Ia Supernova

Type Ia: very bright thermonuclear explosions resulting in the total destruction of a star

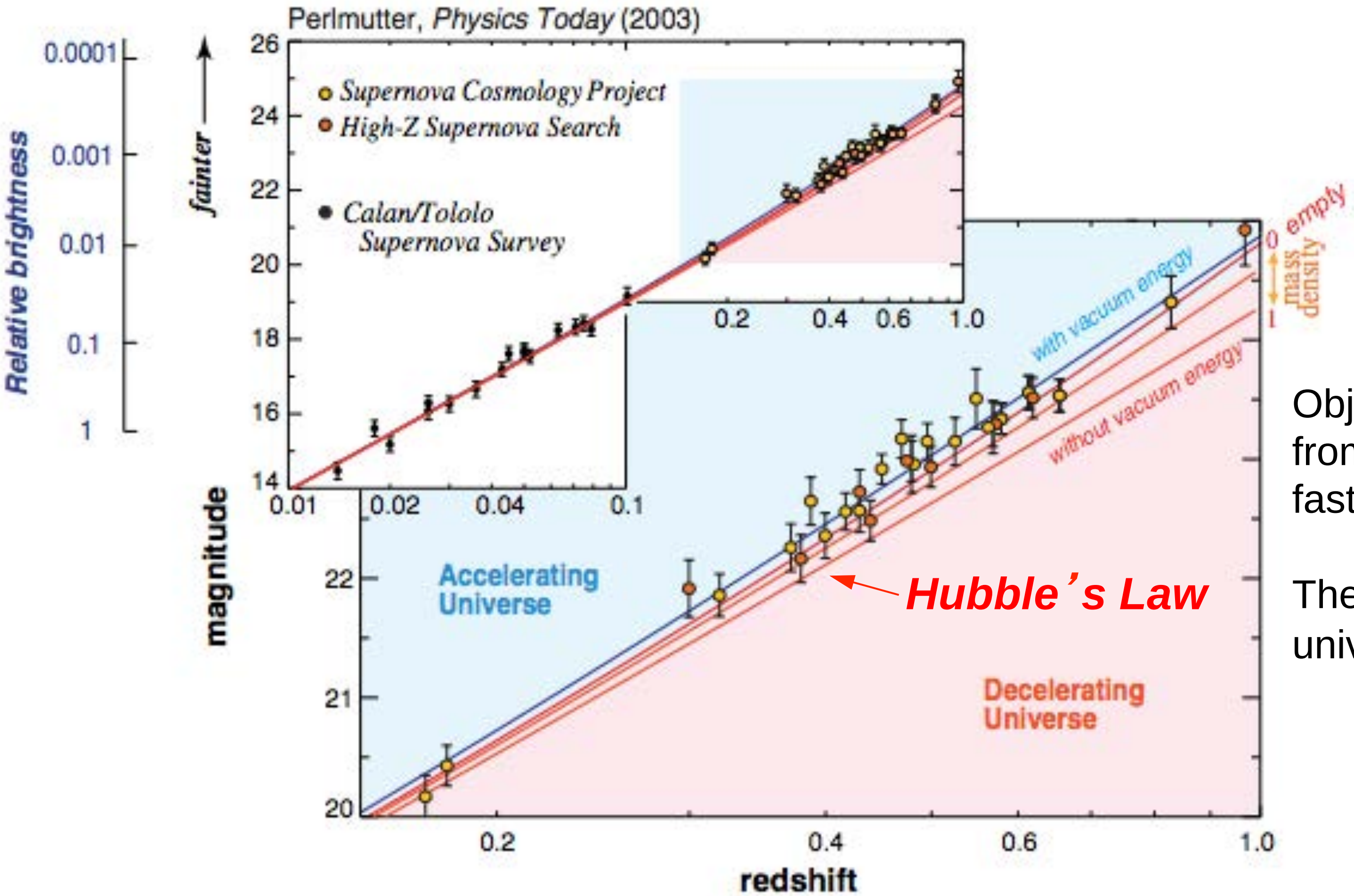
- Shape of light curve → true brightness
- Observed brightness → distance from earth
- Doppler shift → velocity relative to earth

Tycho's supernova

2011 Nobel Prize



Riess Perlmutter Schmidt

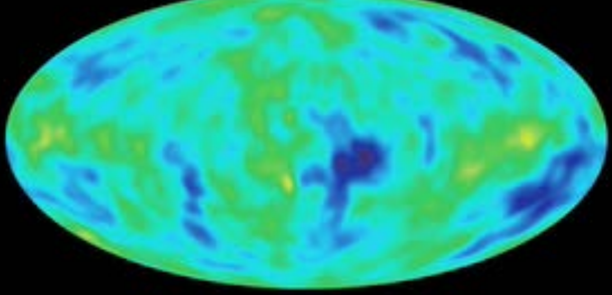


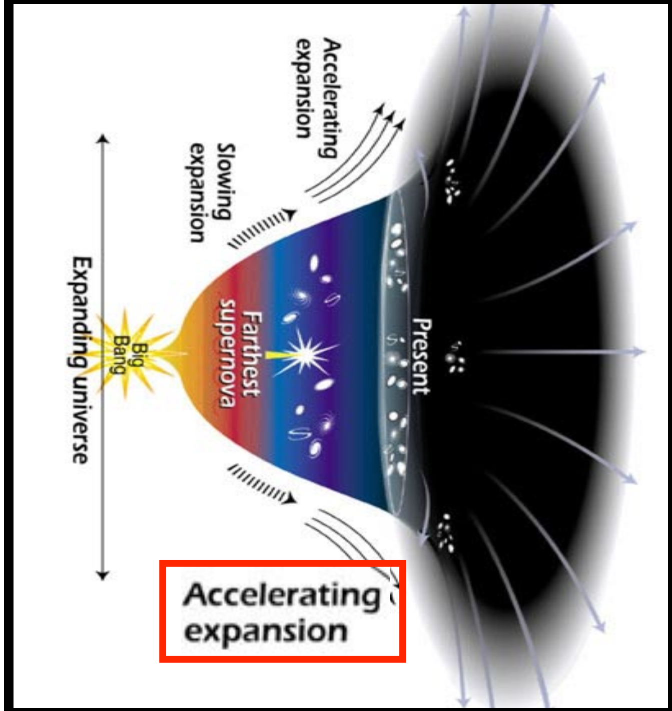

Objects are moving away from earth with velocity faster than Hubble's Law

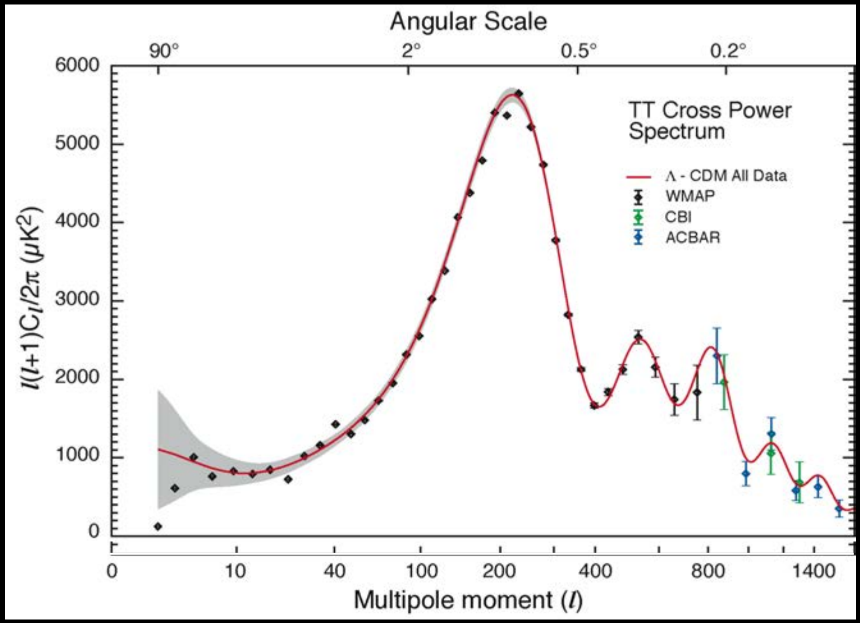
The expansion of the universe is ***accelerating***

# *Cosmic Microwave Background*

WMAP: CMB Observations
Photons left over from Big Bang
From instant when atoms/molecules form
Matter and energy composition is imprinted on variations in temperature with position

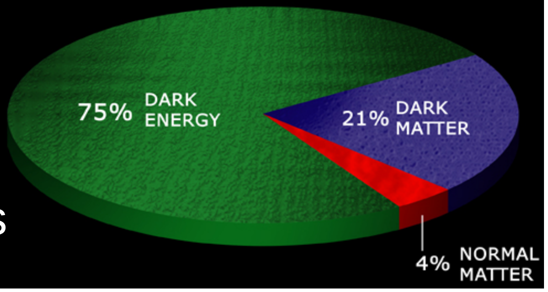




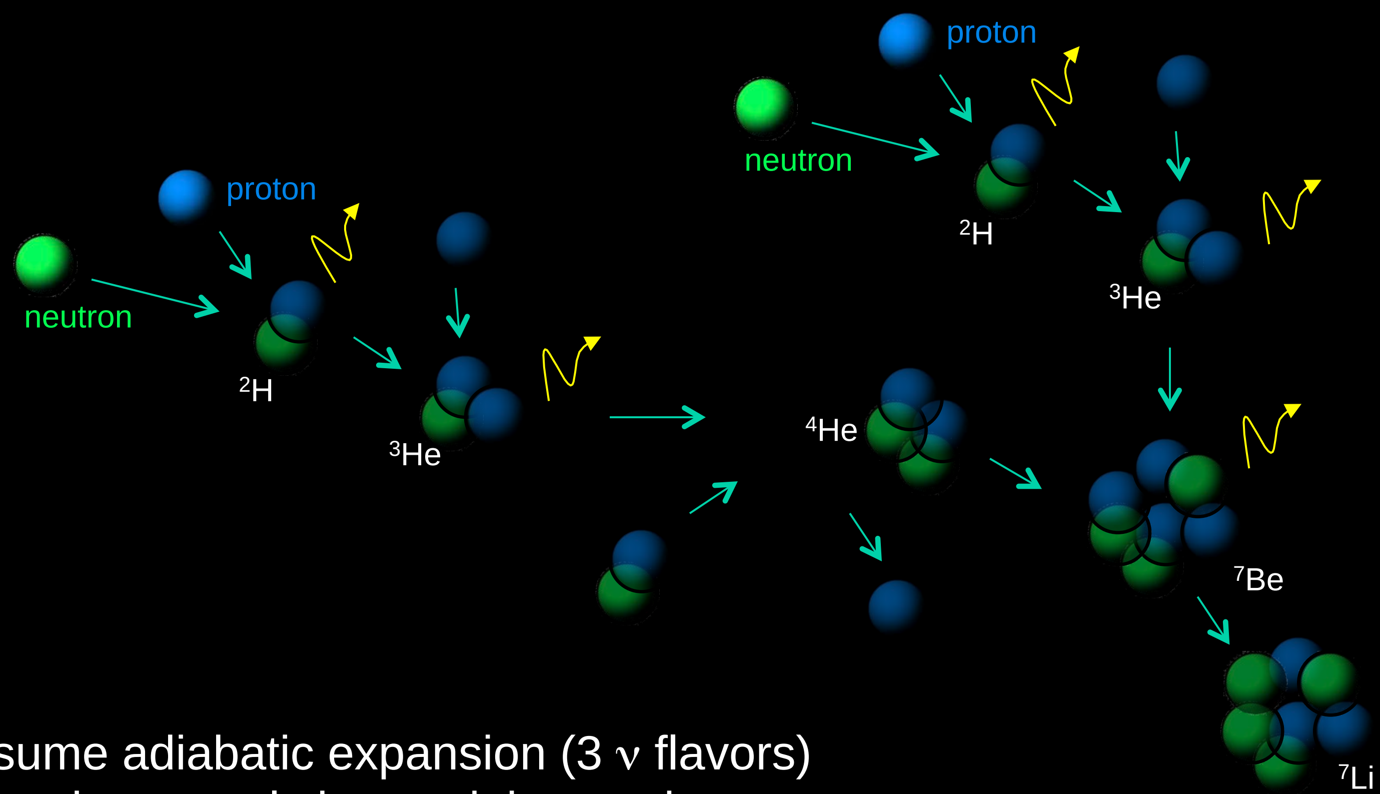




DARK ENERGY (e.g. cosmological constant) exerts a "negative pressure" causing the acceleration

4.5 ± 0.3% of universe is baryonic → test with nucleosynthesis



# *The Homogeneous BBN Model*



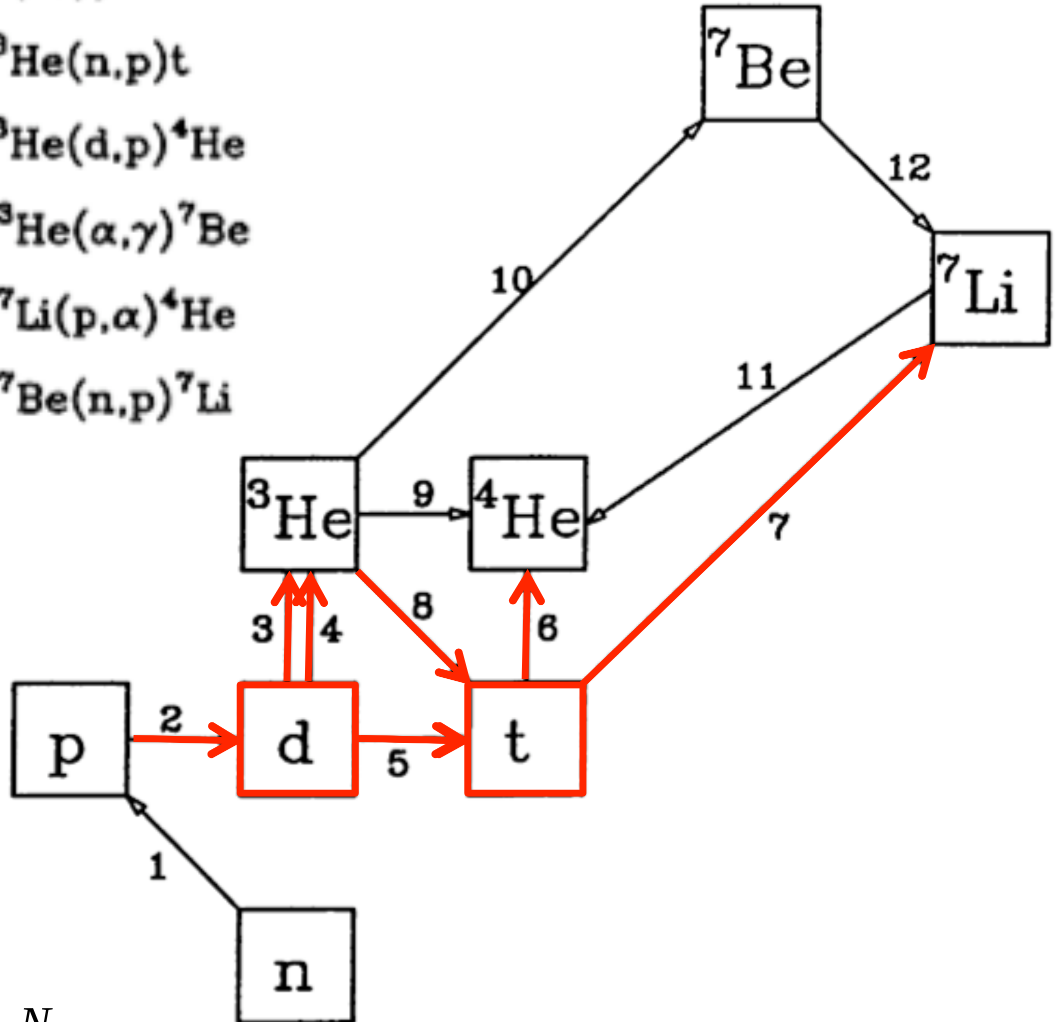

Assume adiabatic expansion (3 $\nu$ flavors)
n/p ratio set early by weak interaction
***No "free" parameters***

~All neutrons → $^4He$
Mass 5 & 8 gaps inhibit formation of heavy elements

p ~75%
$^4He$ ~25%
$^2H$, $^3He$ ~ $10^{-5}$
$^7Li$ ~ $10^{-10}$

# Simple Big Bang Reaction Network

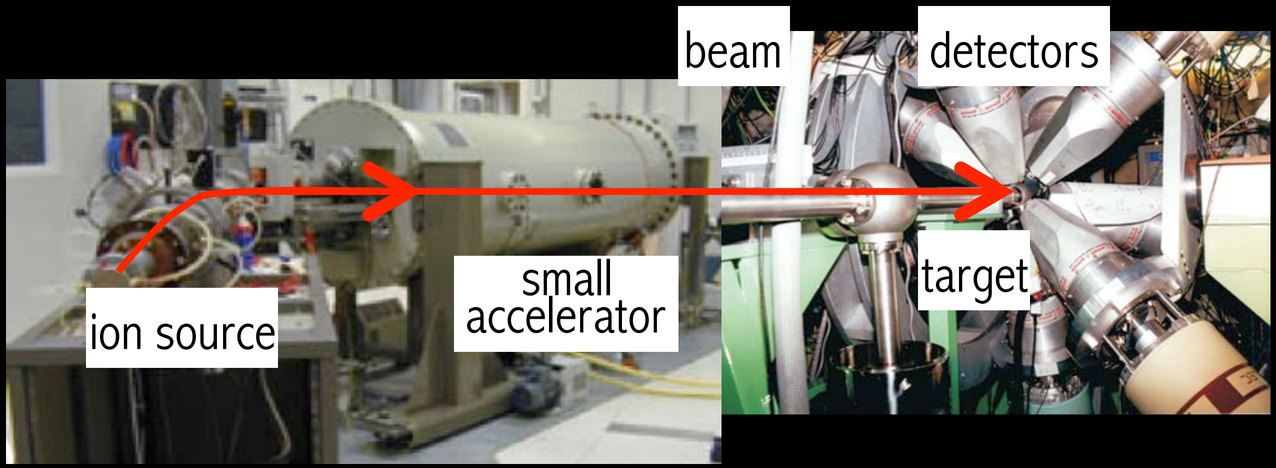
1. n <-> p
2. p(n,γ)d
3. d(p,γ)$^3$He
4. d(d,n)$^3$He
5. d(d,p)t
6. t(d,n)$^4$He
7. t(α,γ)$^7$Li
8. $^3$He(n,p)t
9. $^3$He(d,p)$^4$He
10. $^3$He(α,γ)$^7$Be
11. $^7$Li(p,α)$^4$He
12. $^7$Be(n,p)$^7$Li




$$\frac{dN_d}{dt} = N_p N_n \langle \sigma v \rangle_2 - N_d N_p \langle \sigma v \rangle_3 - N_d N_d \langle \sigma v \rangle_4 - N_d N_d \langle \sigma v \rangle_5$$

$$\frac{dN_t}{dt} = N_d N_d \langle \sigma v \rangle_5 + N_{3He} N_n \langle \sigma v \rangle_8 - N_t N_d \langle \sigma v \rangle_6 - N_t N_\alpha \langle \sigma v \rangle_7 - \lambda_t N_t$$

# Direct Laboratory Measurements




Directly measure cross sections in the lab at the lowest possible energies

Bombarding energy range ~ 10 keV to ~MeV

High currents (~ mA)
Long run times
Efficient detectors to obtain high statistics
Pure, stable targets
Absolute cross section measurements
    Good normalization & careful control of systematic uncertainties
Background suppression crucial

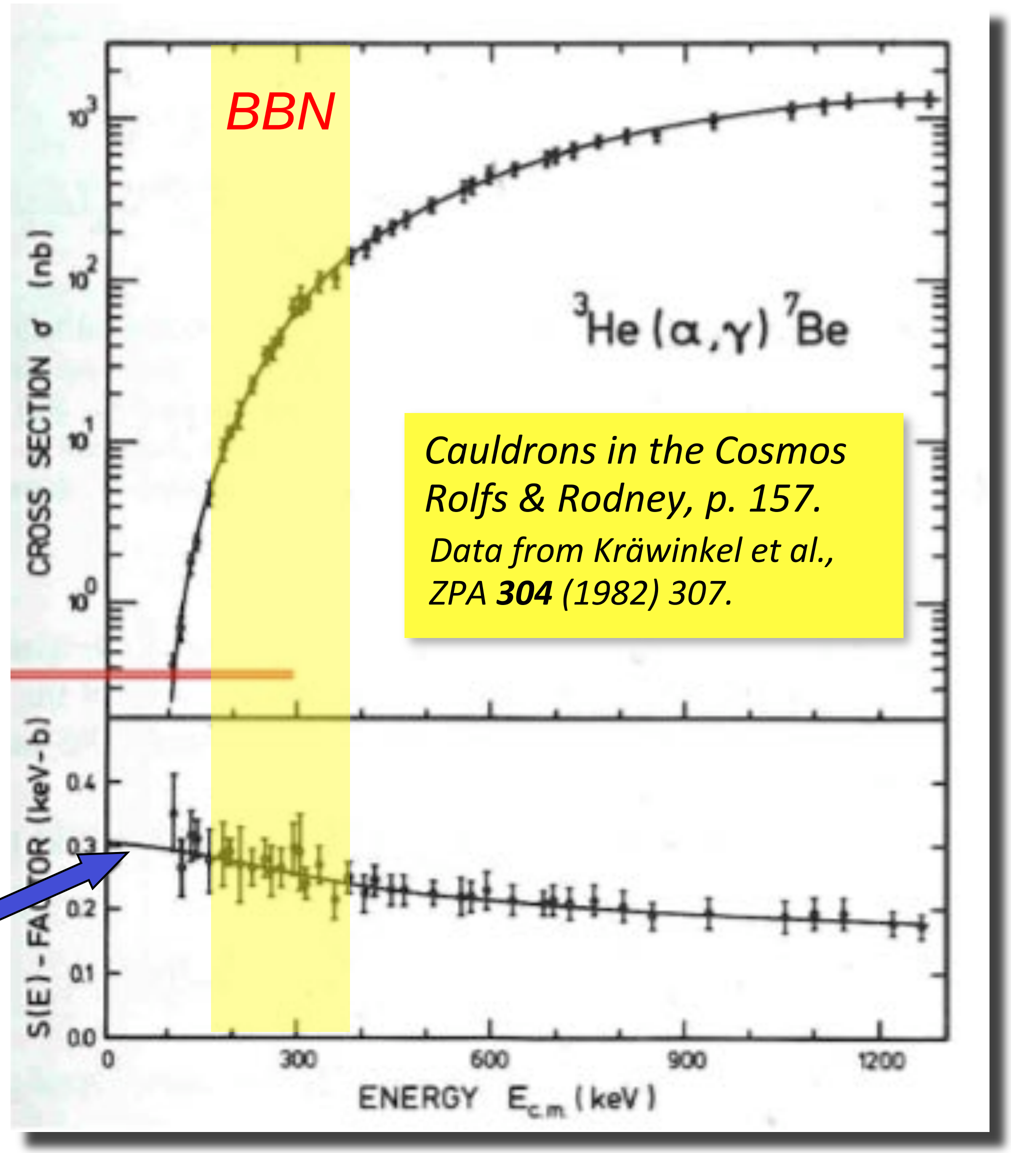
# Textbook example

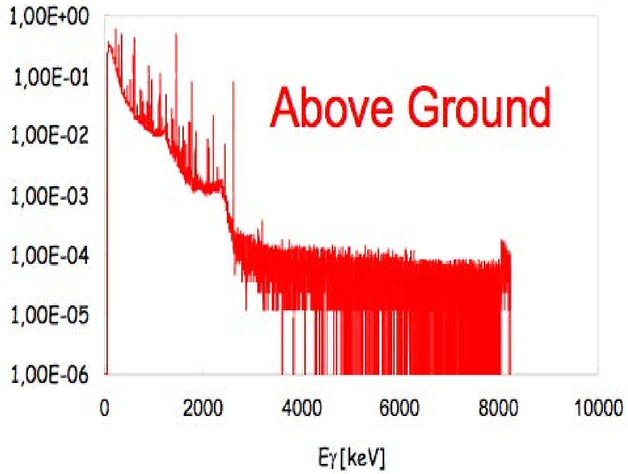
$$S \equiv \sigma E e^{\sqrt{E_G/E}}$$

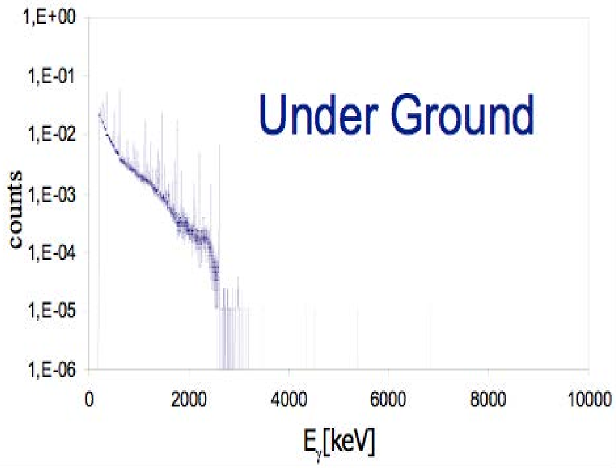
$$E_G \equiv \frac{2\mu}{\hbar^2}\left(\pi Z_1 Z_2 e^2\right)^2$$

Previous experimental limit

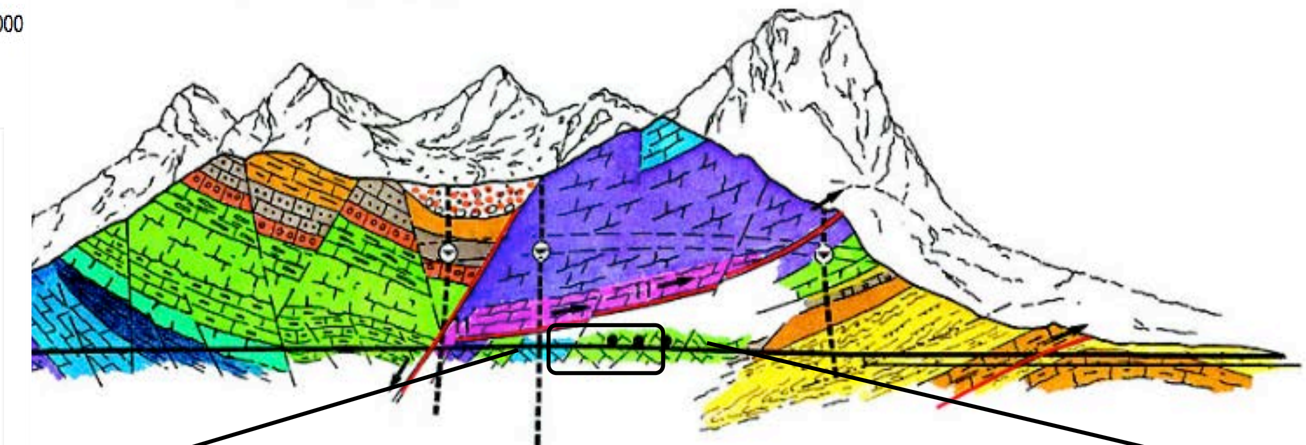
**Need σ here for sun**

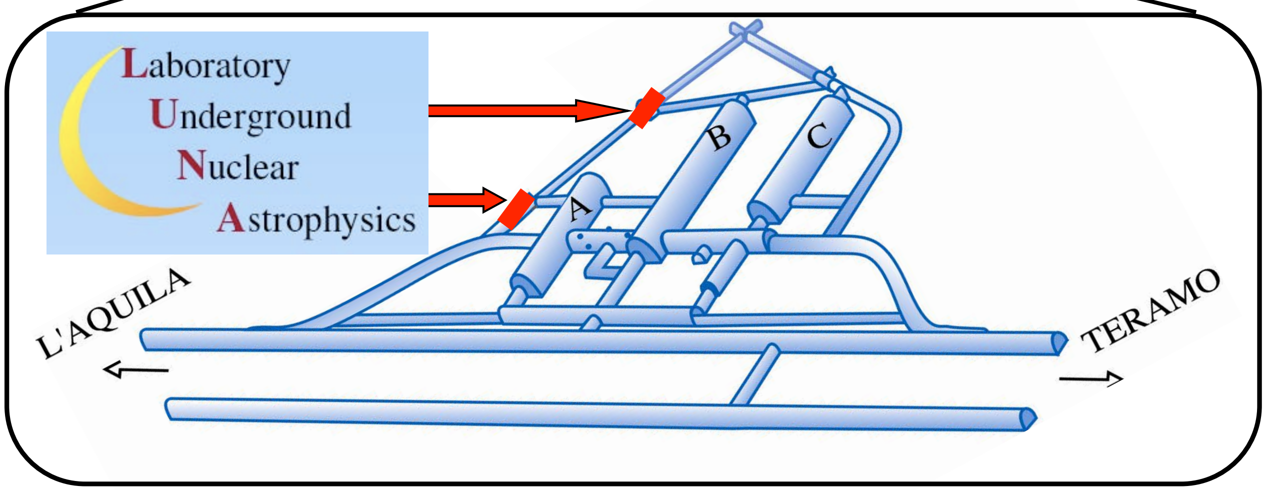





Laboratori Nazionali del Gran Sasso





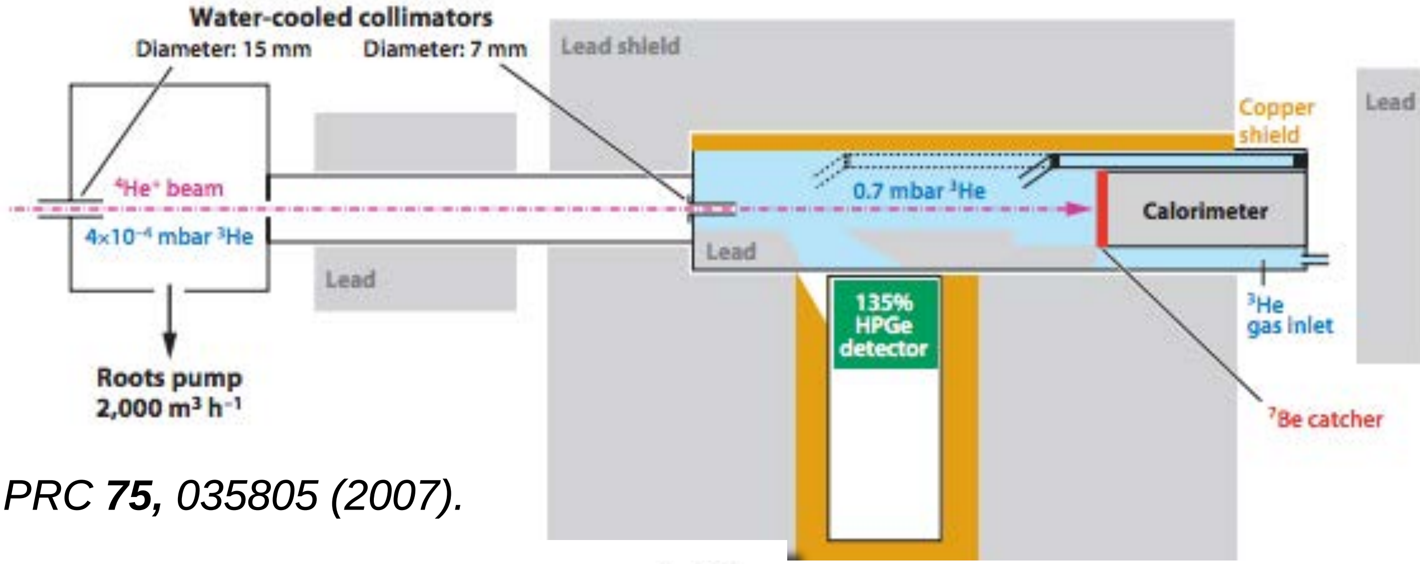

1400 m rock coverage

cosmic μ reduction= $10^{-6}$

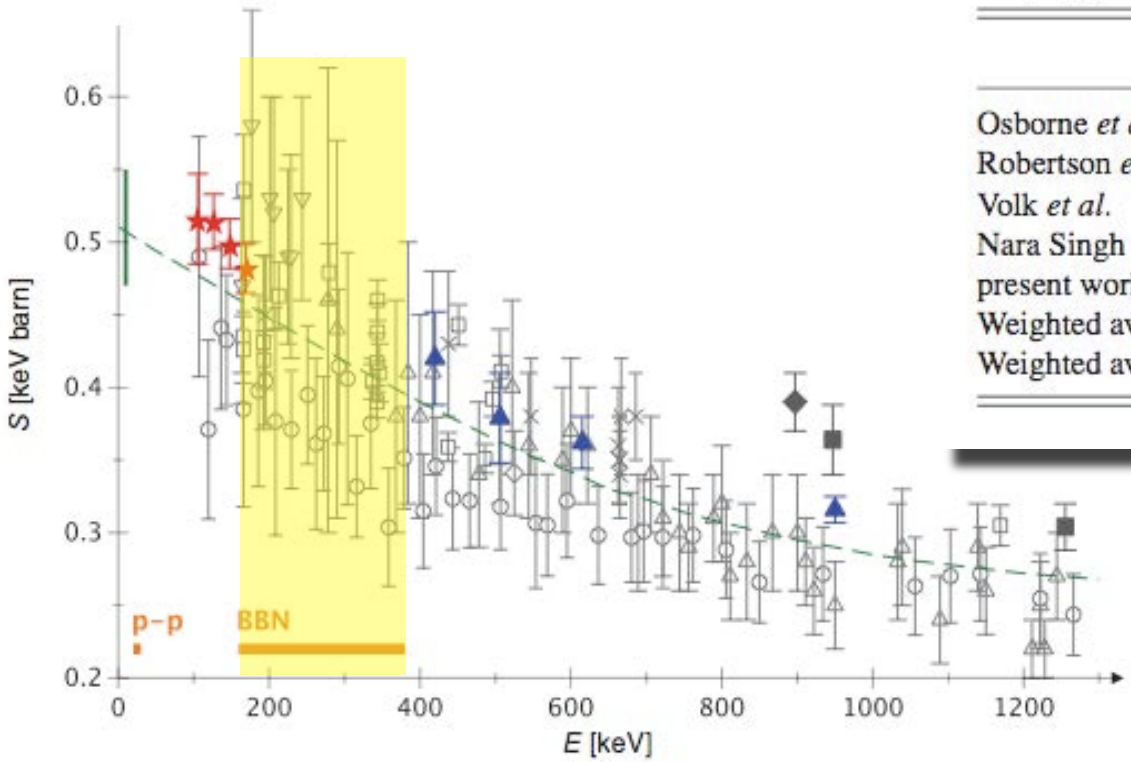
muon rate ~ 1 (/$m^2$ h)

# $^3He(\alpha,\gamma)^7Be$

**L**aboratory **U**nderground **N**uclear **A**strophysics

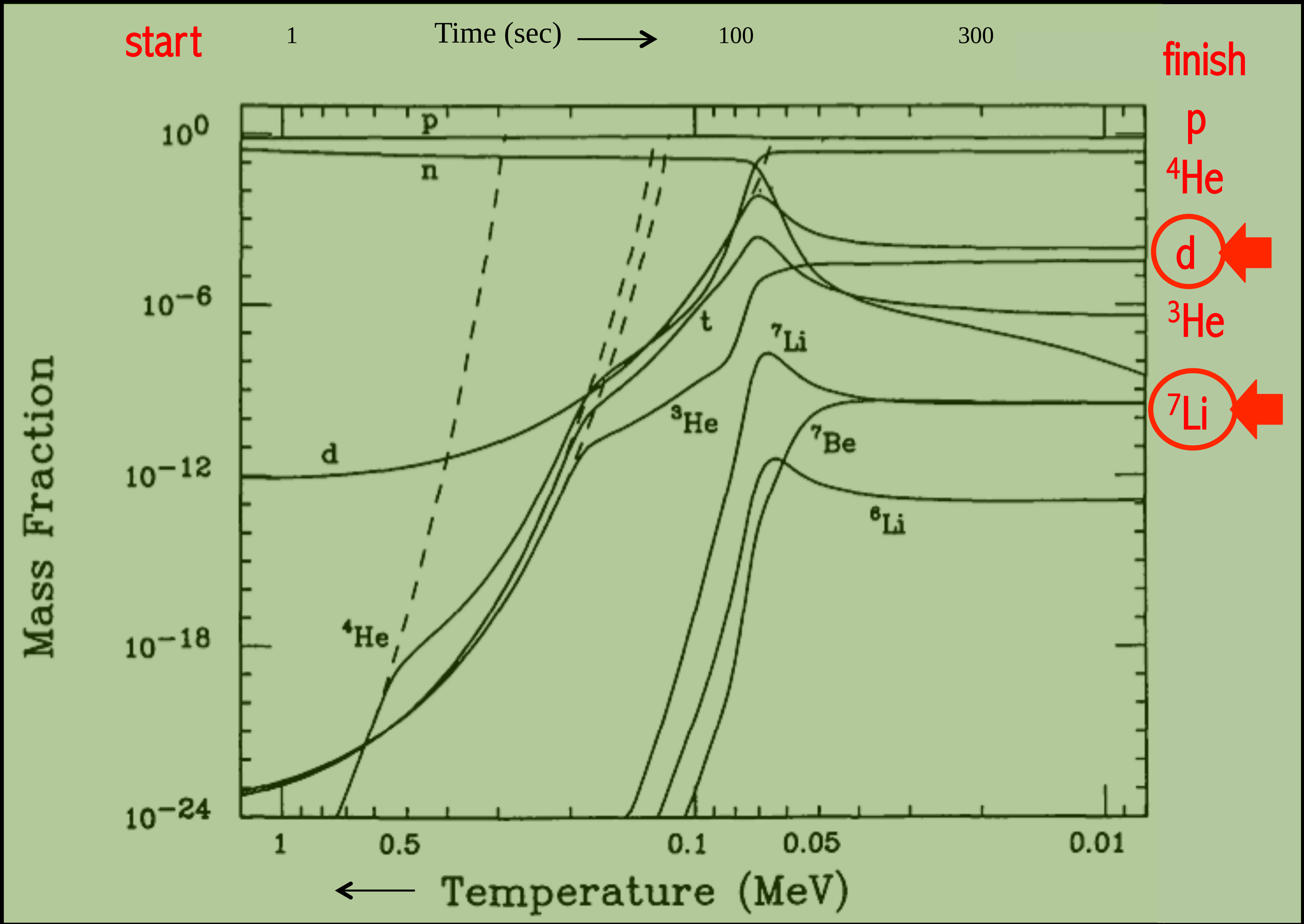



*Gyürky et al., PRC **75,** 035805 (2007).*




| | $S(0)$ (keV b) |
|---|---|
| Osborne *et al.* | $0.535 \pm 0.040$ |
| Robertson *et al.* | $0.63 \pm 0.04$ |
| Volk *et al.* | $0.56 \pm 0.03$ |
| Nara Singh *et al.* | $0.53 \pm 0.02$ |
| present work | $0.547 \pm 0.017$ |
| Weighted average, all activation studies | $0.553 \pm 0.012$ |
| Weighted average, all prompt-$\gamma$ studies | $0.507 \pm 0.016$ |

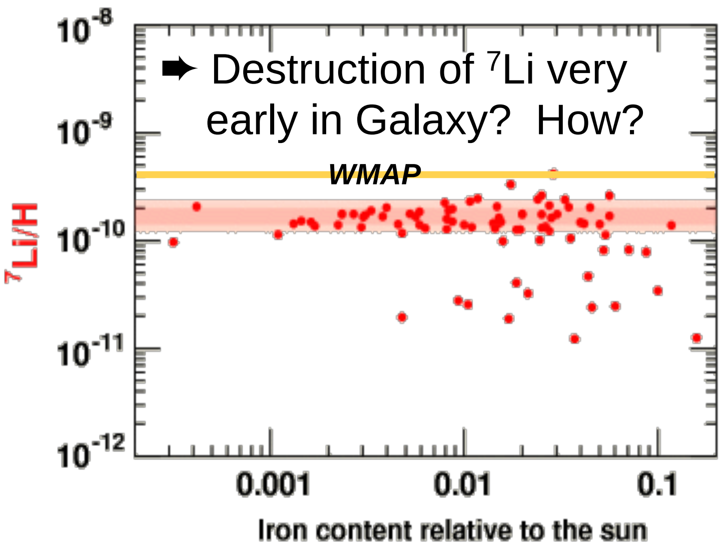
# *Solve the reaction rate network*

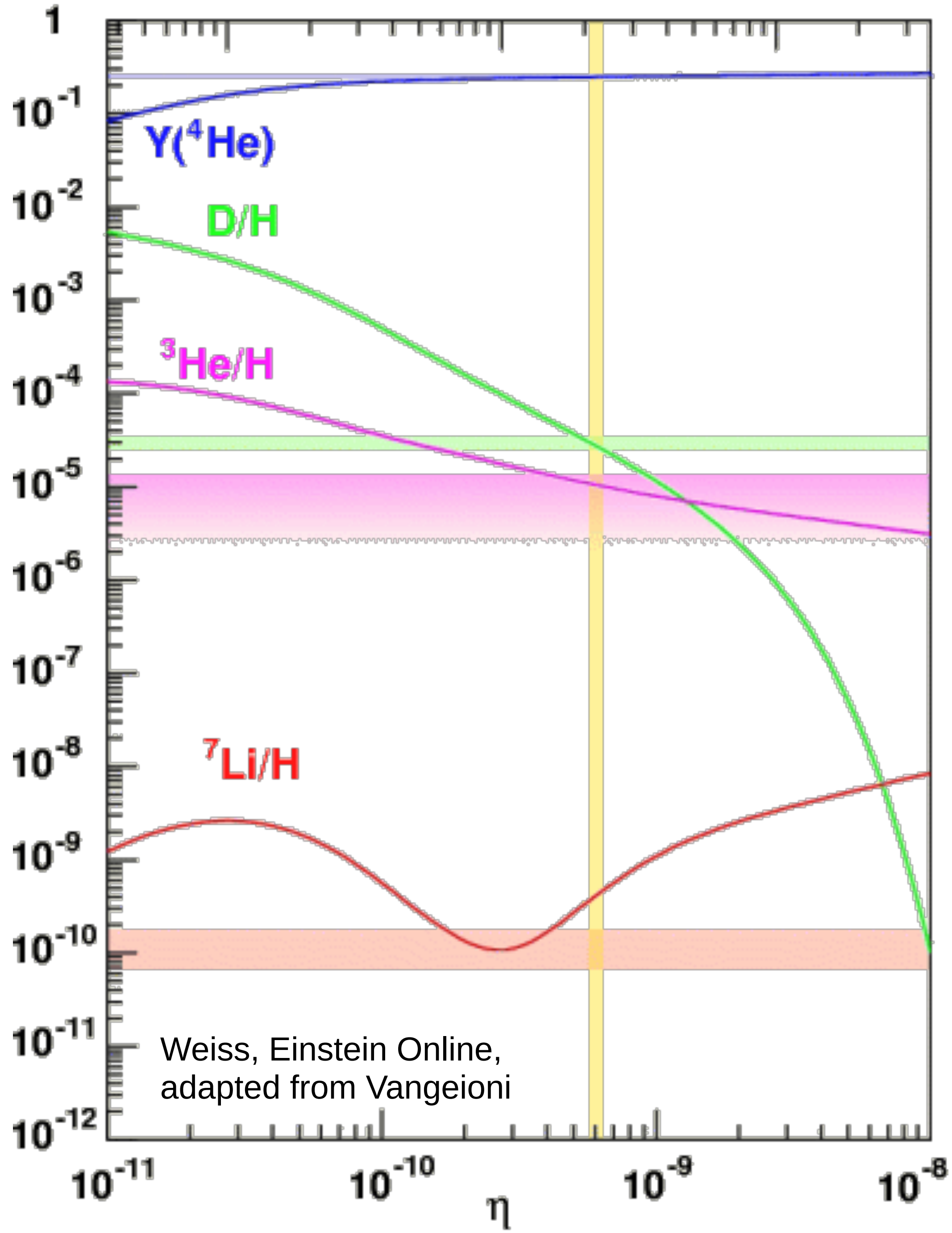


- Most abundances agree with BBN calculations using WMAP $\eta$
- One problem: $^{7}$Li

***Cosmological Li problem***

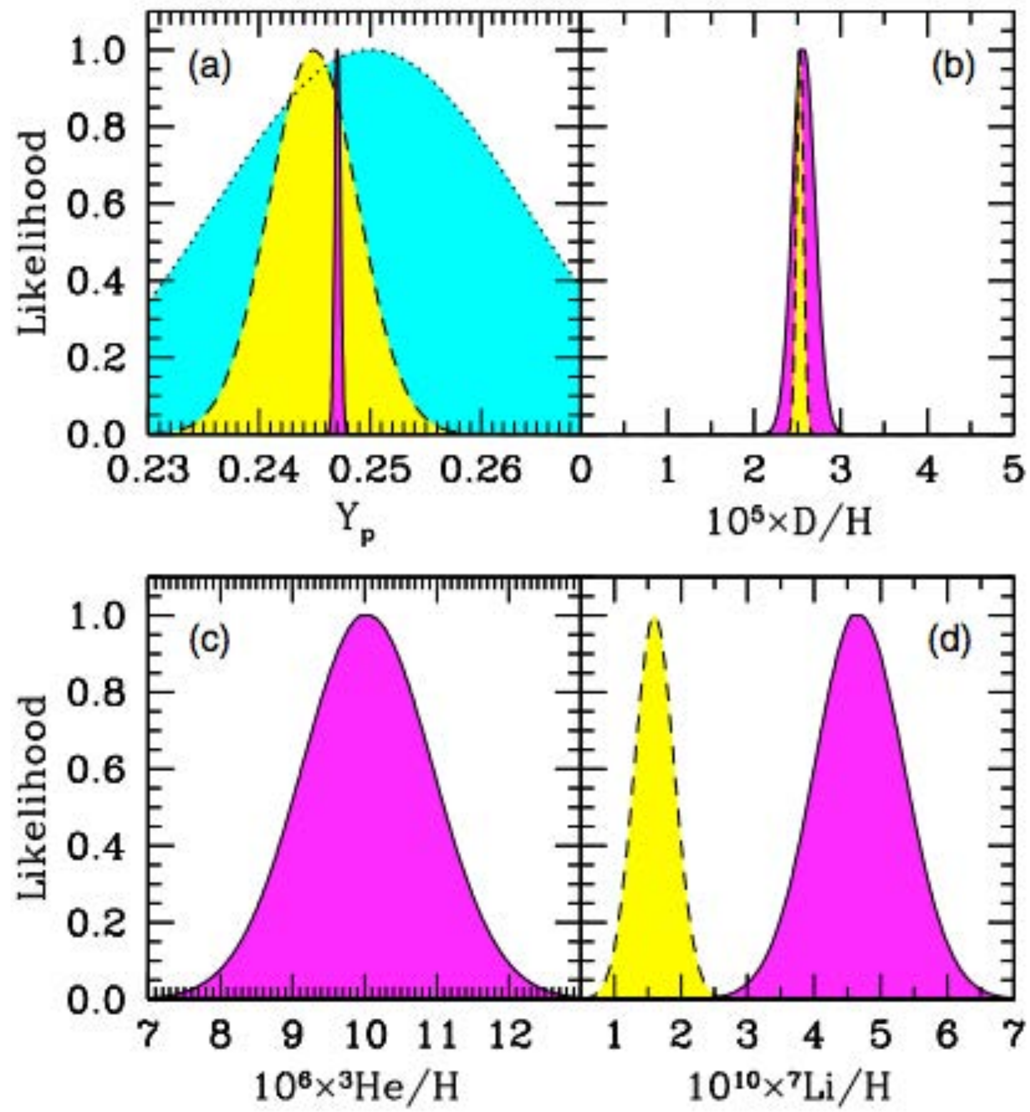
- Direct $\sigma$ measurements have seemingly ruled out any nuclear solution
- Is Spite plateau really reflective of primoridal abundances?



# The Lithium Problem

*Cyburt et al. Rev. Mod. Phys.* ***88*** *(2016)*




- $^1$H, $^2$H, $^4$He in good agreement
- Li disagrees by more than $3\sigma$

"All of the reactions that are ordinarily the most important for BBN have been well measured at the energies of interest. Typically, cross sections are known to ~10% or better, and these errors are already folded in."

*Cyburt et al. (2016)*

# Ways to fix the big bang

New Scientist

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FEATURE 2 July 2008

## Lithium: The hole in the big bang theory

PRL **116,** 211303 (2016) PHYSICAL REVIEW LETTERS week ending 27 MAY 2016

**Light Particle Solution to the Cosmic Lithium Problem**

Andreas Goudelis,[1] Maxim Pospelov,[2,3] and Josef Pradler[1]
*gh Energy Physics, Austrian Academy of Sciences, Nikolsdorfergasse 18, 1050 Vienna, Austria*

PHYSICAL REVIEW D **90,** 023001 (2014)

**Cosmological solutions to the lithium problem: Big-bang nucleosynthesis with photon cooling, *X*-particle decay and a primordial magnetic field**

Dai G. Yamazaki,[1,*] Motohiko Kusakabe,[2,3] Toshitaka Kajino,[1,4] Grant. J. Mathews,[1,5] and Myung-Ki Cheoun[3]
[1]*National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan*

THE ASTROPHYSICAL JOURNAL, 834:165 (5pp), 2017 January 10 doi:10.3847/1538-4357/834/2/165


NON-EXTENSIVE STATISTICS TO THE COSMOLOGICAL LITHIUM PROBLEM

S. Q. Hou[1], J. J. He[1,2,11], A. Parikh[3,4], D. Kahl[5], C. A. Bertulani[6], T. Kajino[7,8,9], G. J. Mathews[8,10], and G. Zhao[2]
[1] Key Laboratory of High Precision Nuclear Spectroscopy, Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[2] Key Laboratory of Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China; hejianjun@nao.cas.cn

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]

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

## Cosmic rays during BBN as origin of Lithium problem

Ming-ming Kang,[a] Yang Hu,[b] Hong-bo Hu[a] and Shou-hua Zhu[b,c]

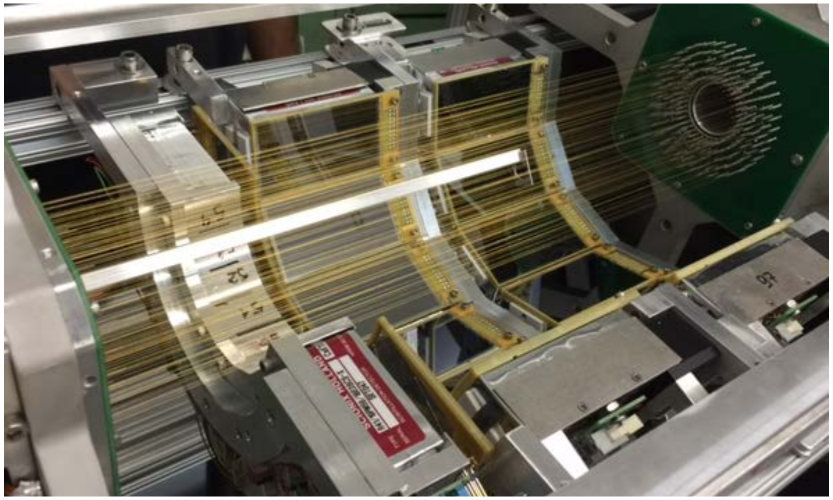
# $^7$Be+d → α+α+p with ANASEN

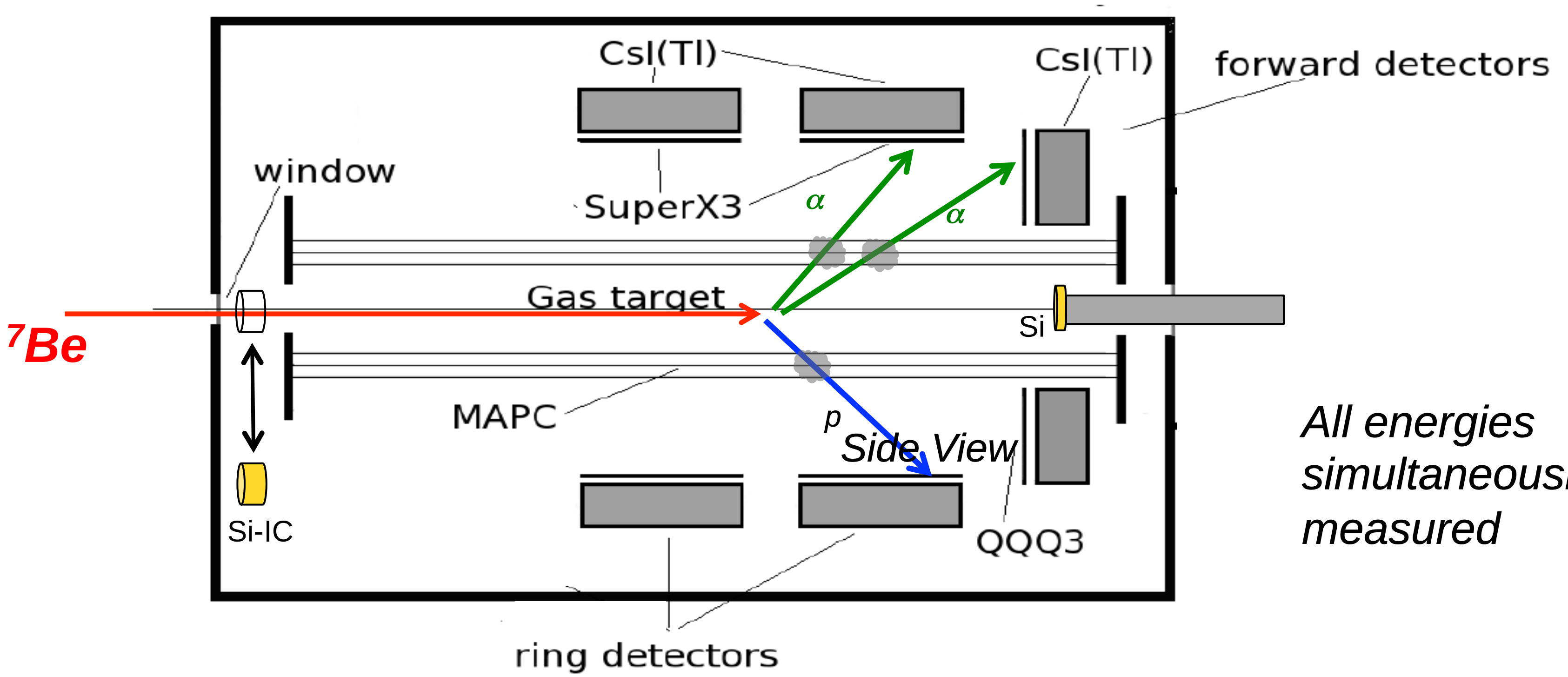
Rijal *et al.* PRL (2019)

*Array for Nuclear Astrophysics and Structure with Exotic Nuclei*

- Extended active gas target/detector
- Cylindrical proportional counter
- Over 1000 cm$^2$ of Si-strip detectors
- Triple coincidence of light ions

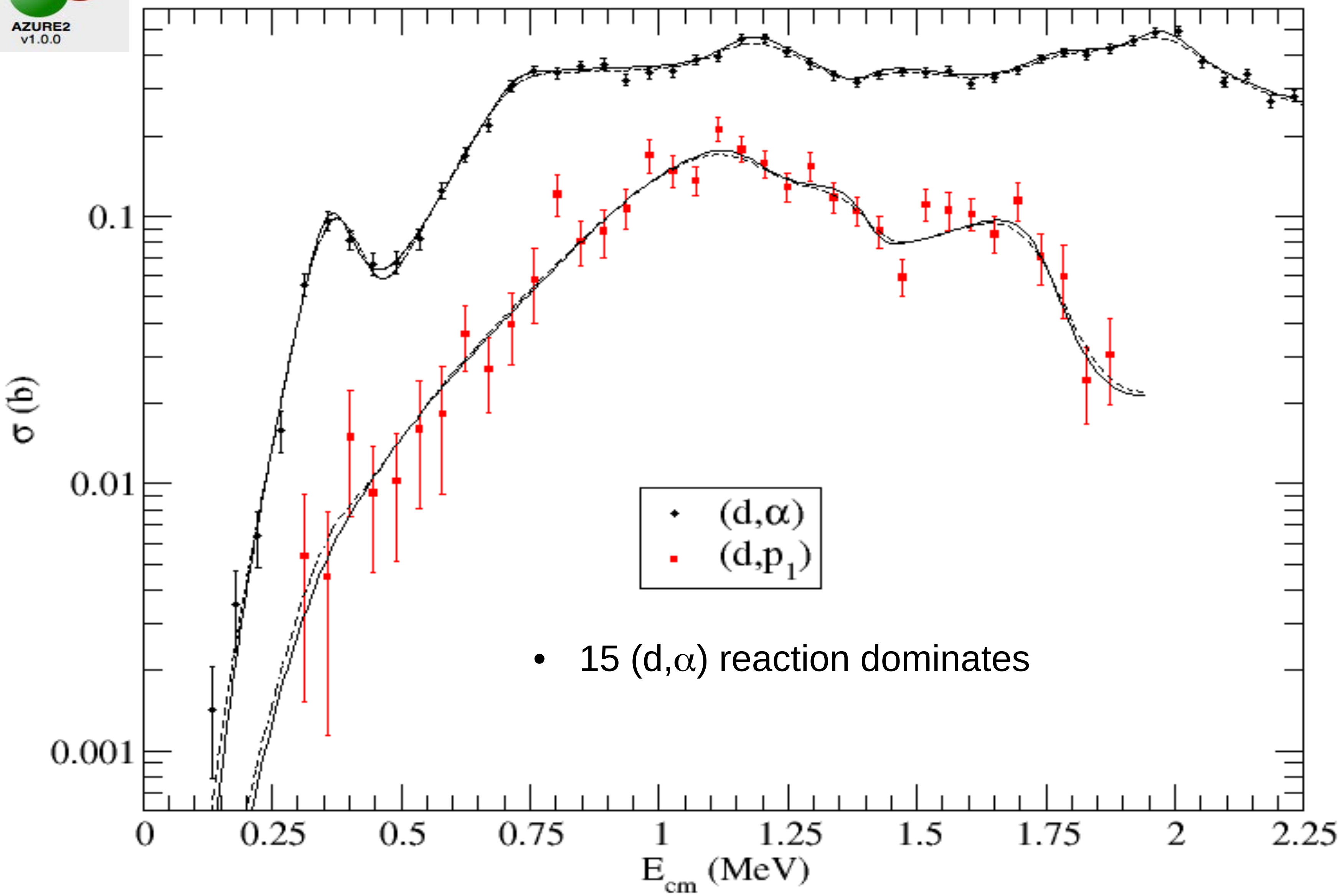
1. ΔE in PC → particle identification
2. Position Si + Position PC → $\theta_{lab}$
3. Energy Si +$\theta_{lab}$ → $E_{cm}$





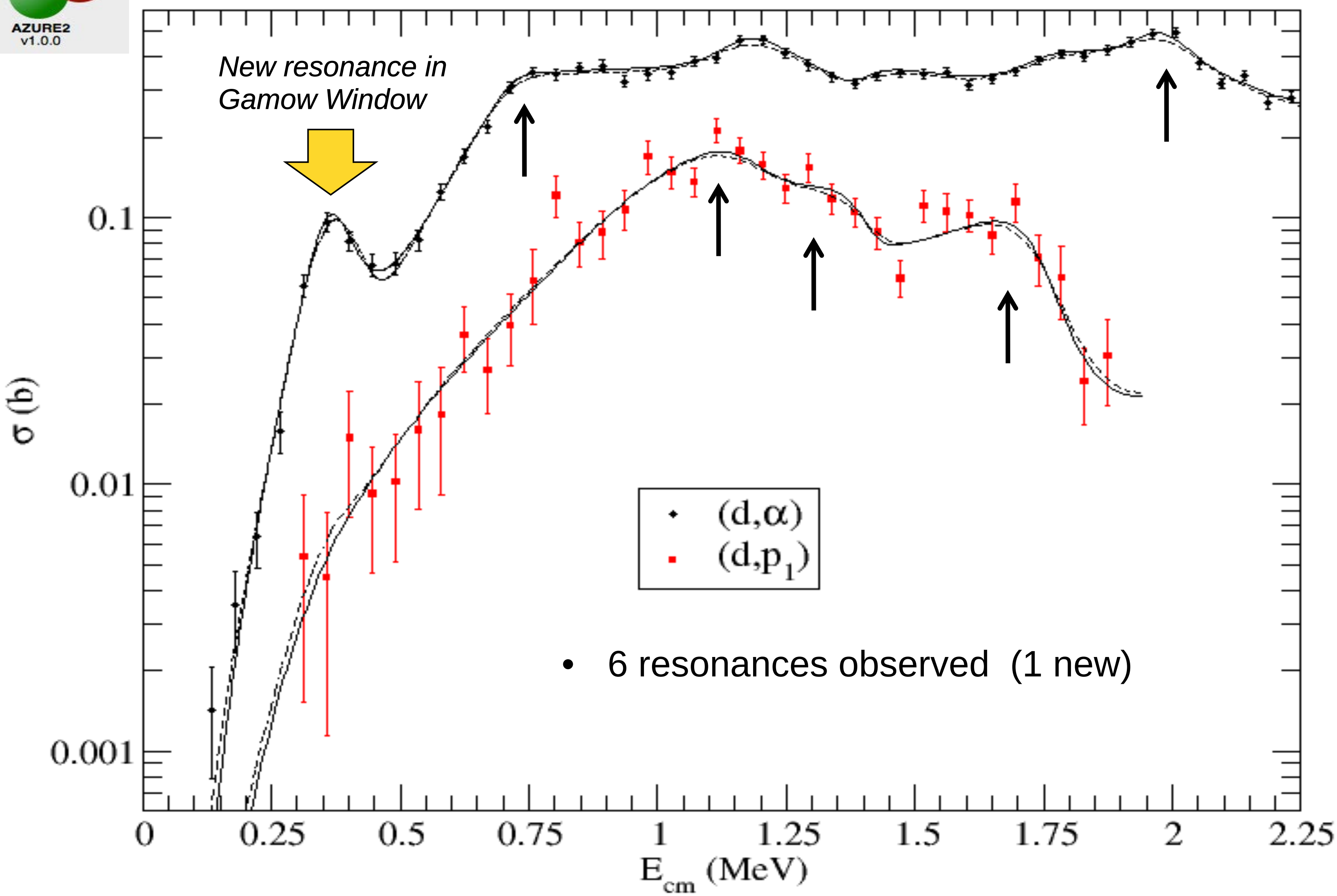

*All energies simultaneously measured*

# *R-matrix Analysis of Total Cross Sections*




- 15 (d,α) reaction dominates

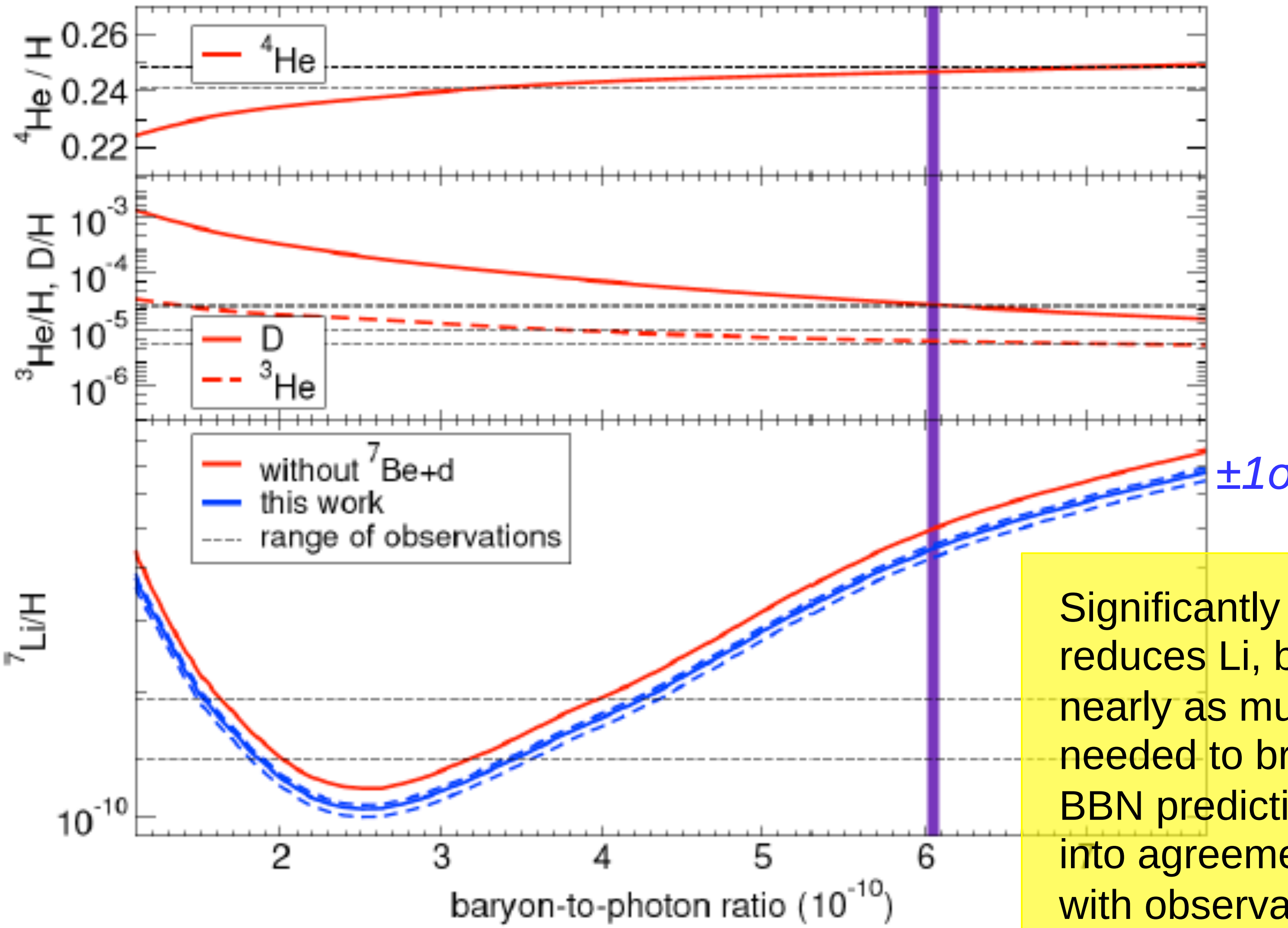
# *R-matrix Analysis of Total Cross Sections*




- 6 resonances observed (1 new)

# *Impact on BBN*

Rijal *et al.* PRL (2019)




Significantly reduces Li, but not nearly as much as needed to bring BBN predictions into agreement with observations