Primordial Nucleosynthesis

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- ☐ Introduction to Standard Big-Bang Nucleosynthesis
- ☐ ^{4}He, D, ^{3}He, ^{7}Li observations
- ☐ Nuclear reactions
- ☐ Concordance observations/SBBN
- ☐ Physics of Standard BB
- ☐ Examples of non-Standard BBN
- ☐ Conclusions

Three observational evidences for the Big-Bang Model

1. The expansion of the Universe

Galaxies move away from each other according to Hubble's law:
$V = H_0 \times D$ with $H_0 \approx 72$ km/s/Mpc, the Hubble parameter (or "constant").
$D \propto a(t)$ (length scale parameter)

2. The Cosmic Microwave Background radiation (CMB)

A black body radiation at 2.7 K corresponding to the redshifted spectrum emitted when the universe became transparent

3. Primordial nucleosynthesis

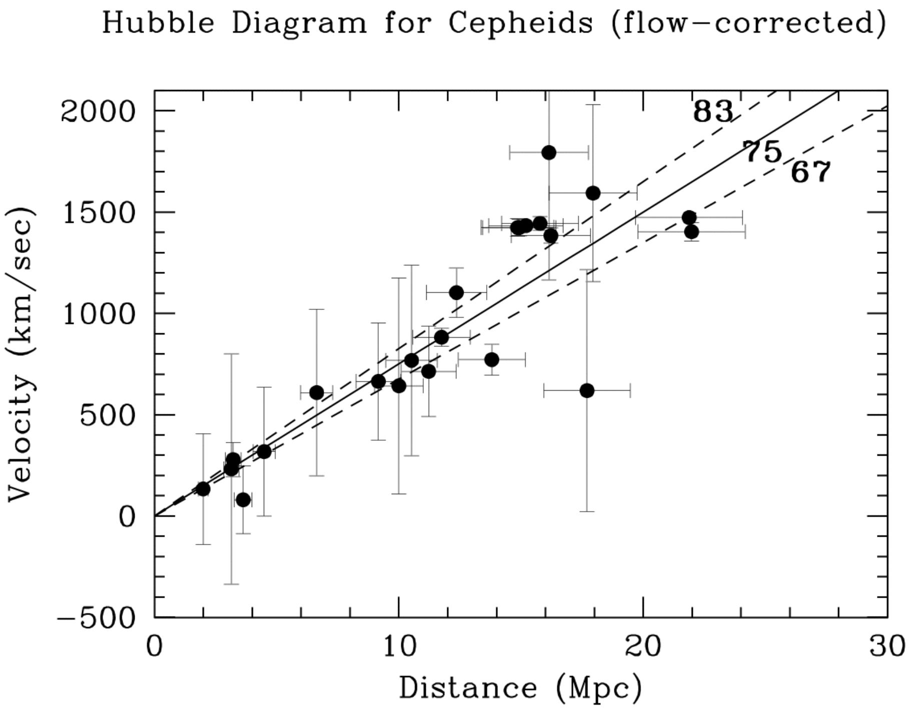
Reproduces the light-elements primordial abundances over a range of nine orders of magnitudes.

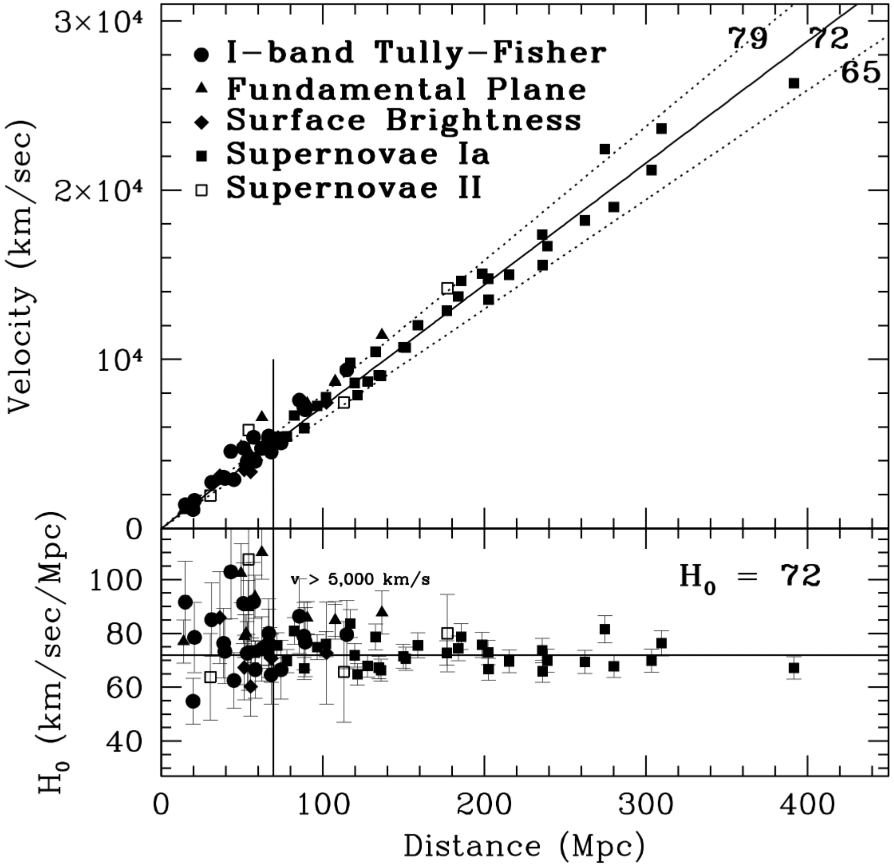
Hubble's law

$V = H_0 \times D$, $H_0 \approx 72$ km/s/Mpc, $h \equiv H_0/(100\ \text{km/s/Mpc})$

Where V is the recession velocity of a galaxy at a distance D

[Freedman et al. (2001)]





Hubble's law: $V = H_0 \times D$

Direct consequence of the expansion of the Universe

Mean distance between galaxies ∝ a(t) [scale factor]:

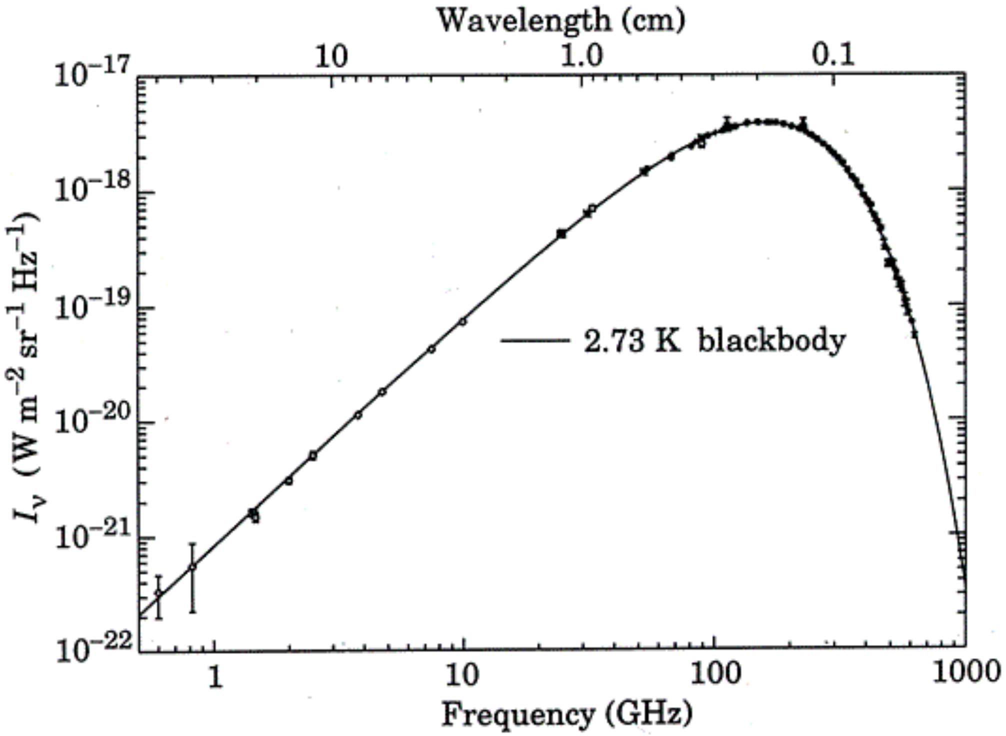
$$D(t) = \chi \times a(t)$$

$$V \equiv \dot{D}(t) = \chi \times \dot{a}(t) = \overset{D}{\boxed{\chi \times a}} \times \dot{a}(t)/a(t)$$

$$\boxed{H(t) \equiv \dot{a}(t)/a(t)}$$

Cosmic Microwave Background radiation (CMB)

Black body radiation spectrum
at T = 2.728±0.004 K



Redshifted spectrum of the photons released when the universe became transparent (electrons and nuclei recombination into neutral atoms)

Opacity caused by Compton scattering of photons on free electrons

As long as photoionization $\mathrm{H}+\gamma\leftrightarrow p+e$- is effective i.e. until ≈300,000 years after the Big-Bang when T dropped to ≈3000 K

$$\boxed{T = 3000\ \mathrm{K} \rightarrow 2.7\ \mathrm{K}}$$

Redshift (z)

T = 3000 K → 2.7 K

λ(present) = λ(recombination) × a(present) / a(recombination)

$$z \equiv \frac{\lambda_{observed} - \lambda_{emitted}}{\lambda_{emitted}}$$

$$z + 1 \equiv \frac{a(t_0)}{a(t = t_{emission})}$$

$\lambda_{emitted} = \lambda$ as measured in laboratory

0≡present value

Temperature of photons-electrons decoupling

$n_e = n_p$ (neutrality)

$n_b = n_p + n_H$

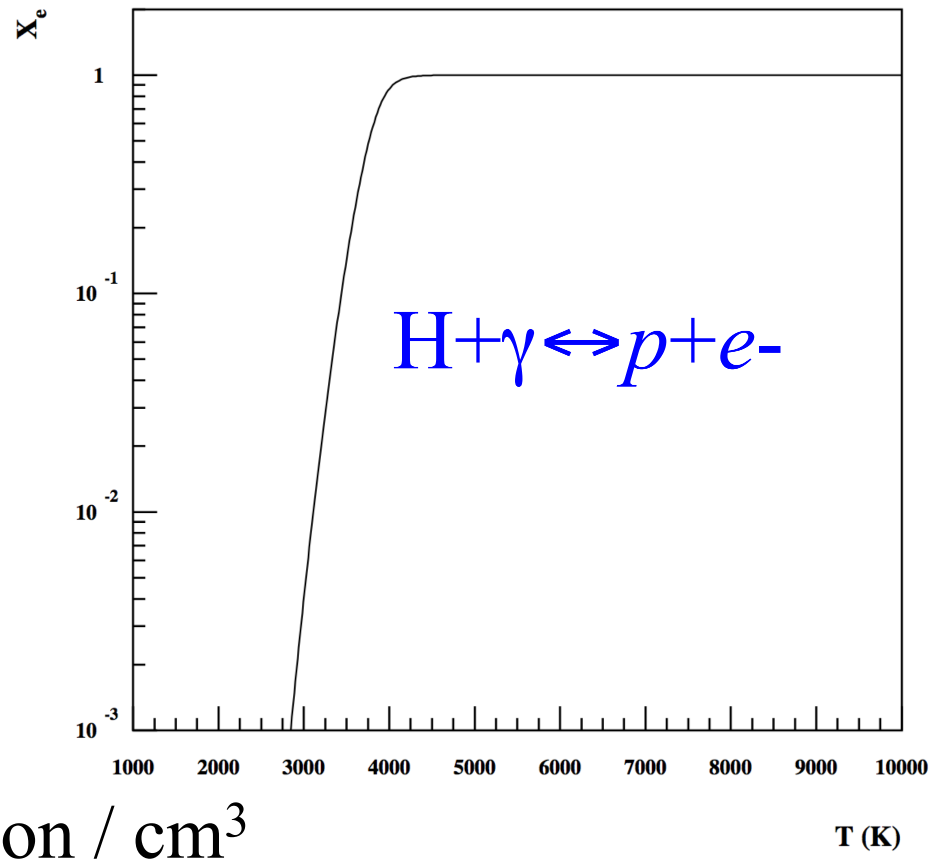
n_e, n_p, n_H, n_b = electron, proton, atomic, baryonic densities

$E_I = 13.6$ eV ($1.6\ 10^5$ K)

$$X_e \equiv \frac{n_e}{n_p + n_H}$$

Saha equation :

$$\frac{X_e^2}{1-X_e} = \left(\frac{m_e c^2 k_B T}{2\pi(\hbar c)^2}\right)^{3/2} \frac{e^{-E_I/k_B T}}{n_b}$$



$T = 2.725 \times (1+z)$ K

$n_b \approx \Omega_b h^2 \times 10^{-5} \times (1+z)^3$ baryon / cm^3

Determination of the baryonic density of the Universe

☐ Standard Big Bang Nucleosynthesis

Calculated and observed ^{4}He, D, ^{3}He, ^{7}Li primordial abundances
⇒ η (or $\Omega_B h^2$)

Need good:

- Observational data
- Nuclear data

☐ HI and HeII Lyman-α forest absorption (on the line of sight of quasars)

☐ Anisotropies in the Cosmic Microwave Background radiation

BOOMERanG, CBI, DASI, MAXIMA, ARCHEOPS, WMAP,…..

Density components of the Universe

A natural reference : the critical density

$$\rho_{0,C} = \frac{3H_0^2}{8\pi G} = 1.88\, h^2 \times 10^{-29}\ \mathrm{g/cm^3} \text{ or } 2.9\, h^2 \times 10^{11}\ M_{\odot}/\mathrm{Mpc}^3$$

$H_0 \equiv$ Hubble "constant" ($h = H_0/100$ km/s/Mpc $h \approx 0.7$)

$$\boxed{\Omega \equiv \rho/\rho_C}$$

Some Ω values *[Komatsu et al. 2009]*		
Radiation (CMB)	Ω_R	$5\ 10^{-5}$
Visible matter	Ω_L	≈0.003
Baryons	Ω_b	0.0456±0.0015
Matter (Dark+Baryonic)	Ω_m	0.274±0.013
Vacuum	Ω_Λ	0.726±0.015
Total	Ω_T	≈1.0

Number of baryons per photon : $\eta \equiv n_b/n_\gamma$ et $\Omega_b h^2 = 3.65 \times 10^7\, \eta$

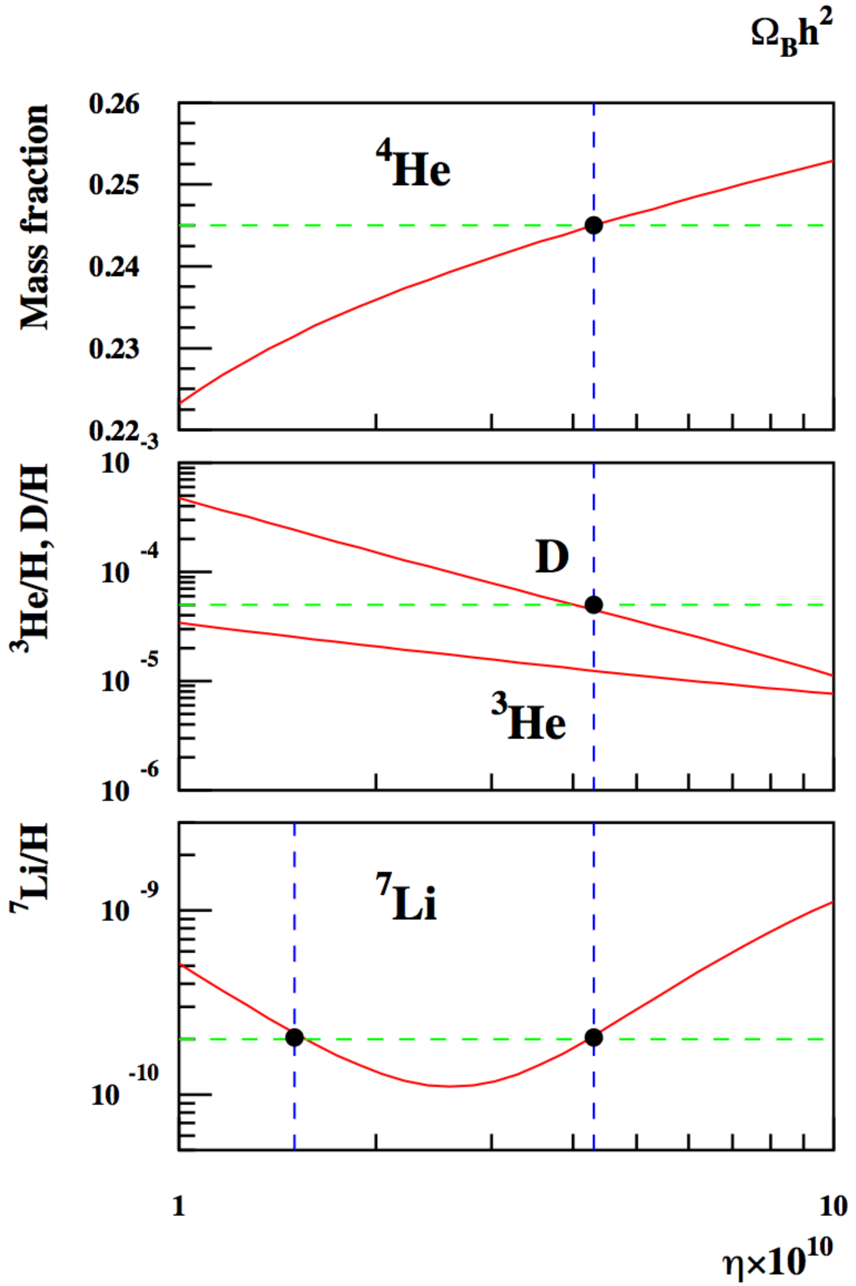
Isotopes to constrain η :

^{4}He : little sensitive to η

^{3}He : complex stellar production / destruction history.

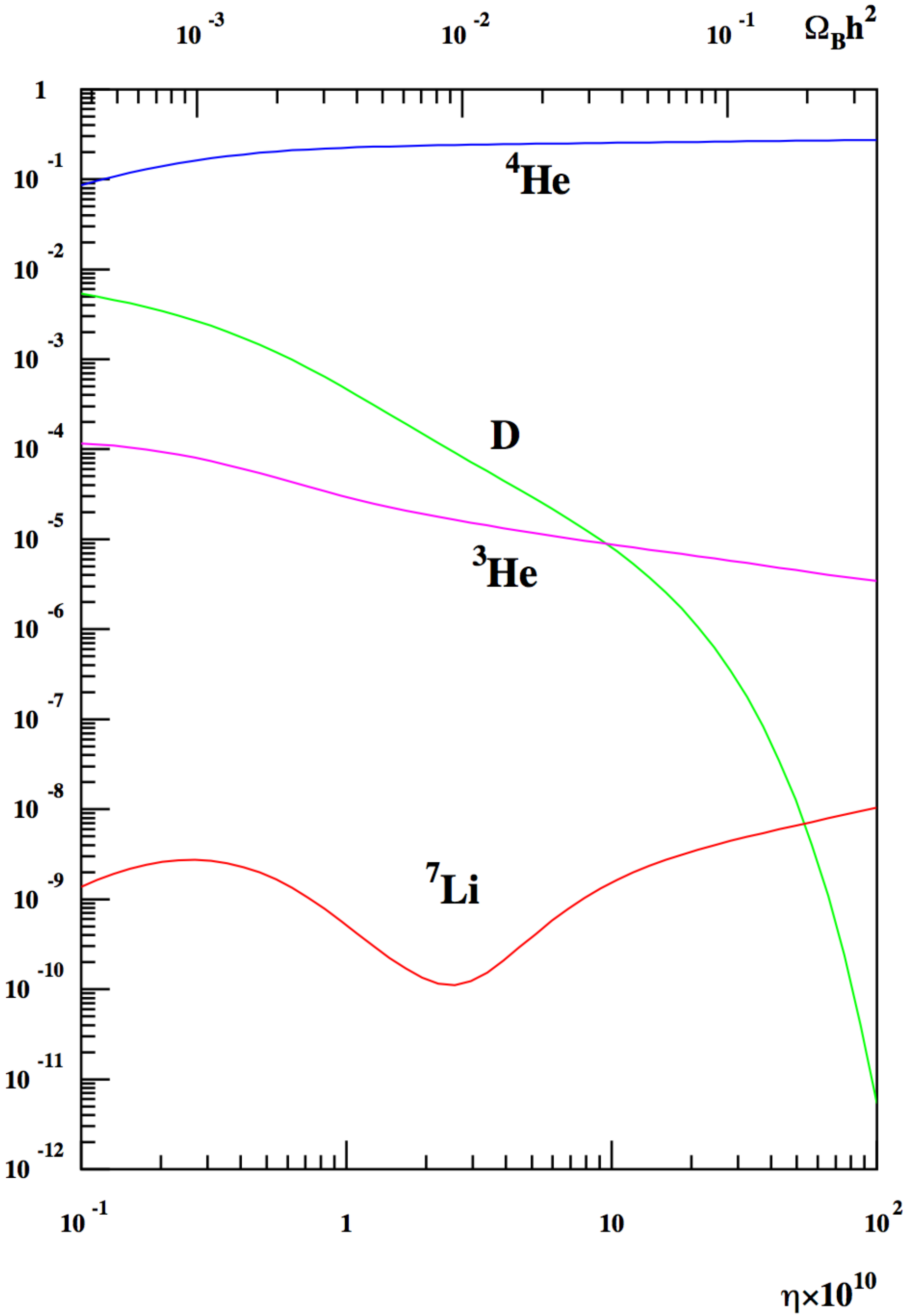
D : seems the best candidate: a strong monotonic evolution with η and no stellar production.

^{7}Li : main drawback: a non monotonic evolution with η; two η values for a given Li/H

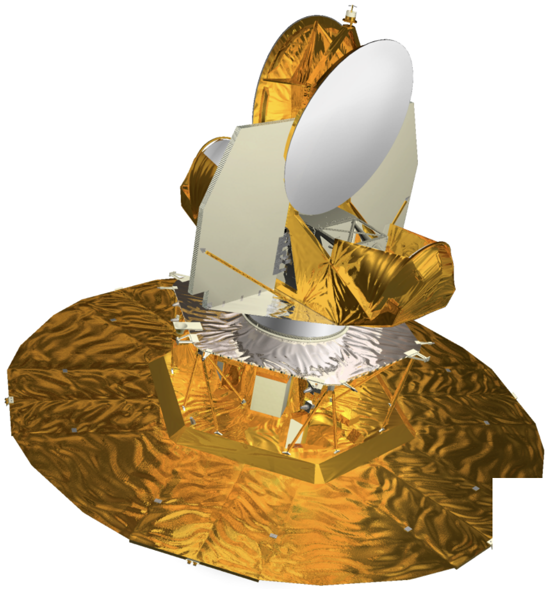


Baryonic density range

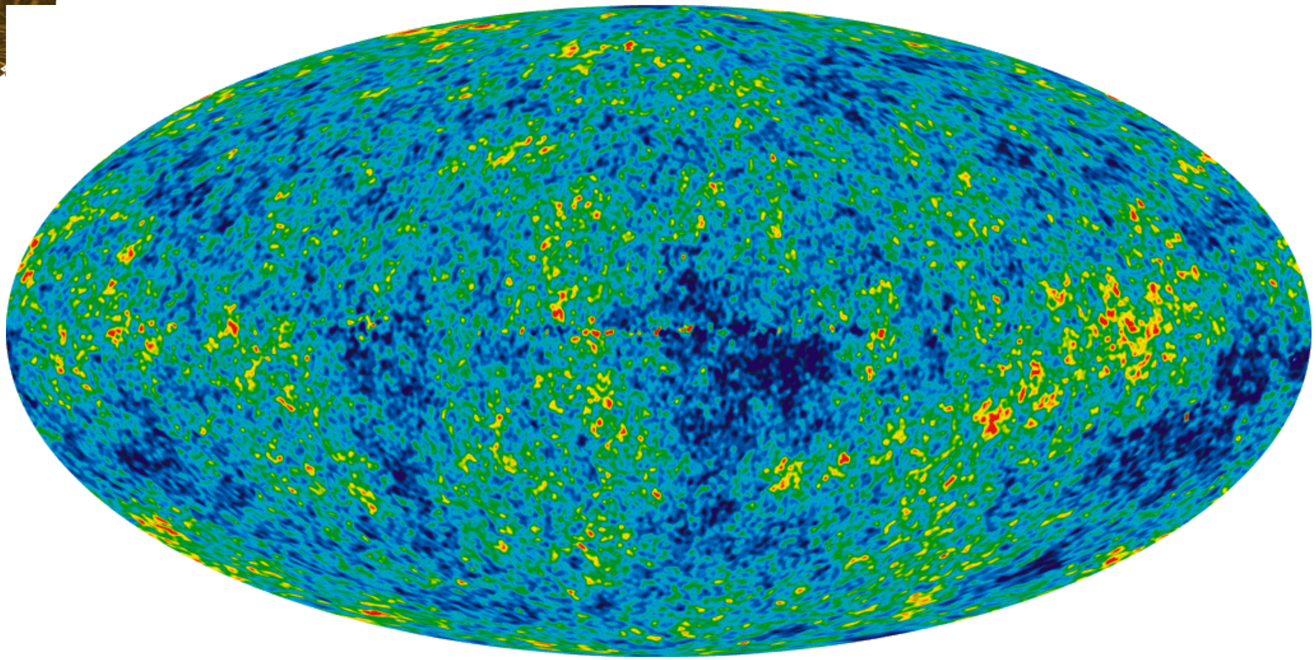
Thanks to deuterium, η can be safely restricted to the 10^{-10} to 10^{-9} range



Anisotropies of the Cosmic Microwave Background (CMB)



At $t \approx 0.3$ My, and $T \approx 3000$ K : recombination, the Universe becomes transparent (presently 2.725 K)



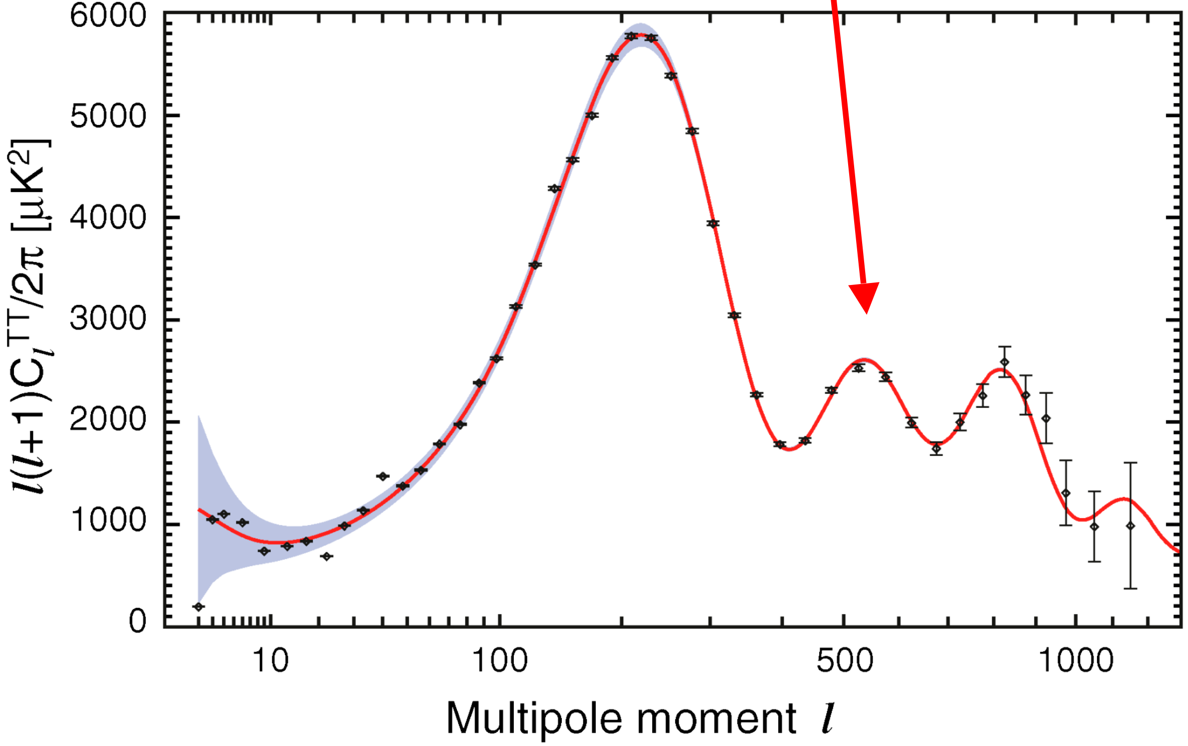
© WMAP web page (http://map.gsfc.nasa.gov/)

Anisotropies of the Cosmic Microwave Background (CMB)

- Geometry ($\Omega_T \approx 1$), 1st peak
- Ω_b (2nd/1st peaks)

Spatial fluctuation spectrum of CMB →
(Inertia from baryons)

$\Omega_b h^2 = 0.02267 \pm 0.00060$
$\eta = (6.21 \pm 0.16) \times 10^{-10}$
[WMAP: Komatsu et al. (2009)]



Nucleosynthesis (I)

Equilibrium $p \leftrightarrow n$: $N_n/N_p = \exp(-Q_{np}/kT)$; $Q_{np} = 1.29$ MeV

$$\nu_e + n \leftrightarrow e^- + p \qquad \bar{\nu}_e + p \leftrightarrow e^+ + n$$

Followed by decoupling and freezeout

Equilibrium as long as the reaction rate is faster than the expansion rate:

$$\Gamma_{\leftrightarrow} >> \frac{\dot{a}(t)}{a(t)} \quad \left(\equiv H(t)\right)$$

Equilibrium breaks out when :

$$\Gamma_{n\leftrightarrow p} \sim G_F^2 T^5 \sim \frac{\dot{a}}{a} = \sqrt{\frac{8\pi G \rho_R}{3}}$$

$$\rho_R = g_{eff}(T) \frac{k^2 \pi^2}{30\hbar^3} T^4$$

$$\left(g_{eff}(T) = 4 \leftrightarrow 11\right)$$

Then $T \approx 10^{10}$ K and $N_n/N_p \approx 0.2$

Nucleosynthesis (II)

Neutrons decay until T is low enough for :

$$n+p \rightarrow D+\gamma$$

becomes faster then deuterium photodisintegration

$$D+\gamma \rightarrow n+p \quad (Q = -2.2\ \text{MeV})$$

Then, $t = 3$ mn, $T \approx 10^9$ K and N_n has decrased to $N_n/N_p \approx 0.1$

Nucleosynthesis starts to produce essentially ^{4}He together with traces of D, ^{3}He, ^{7}Li, ….

$$X(^4He) \approx 2X(n) \approx 0.2$$

First steps in BBN

n↔p decoupling (A)

n free decay (A-B)

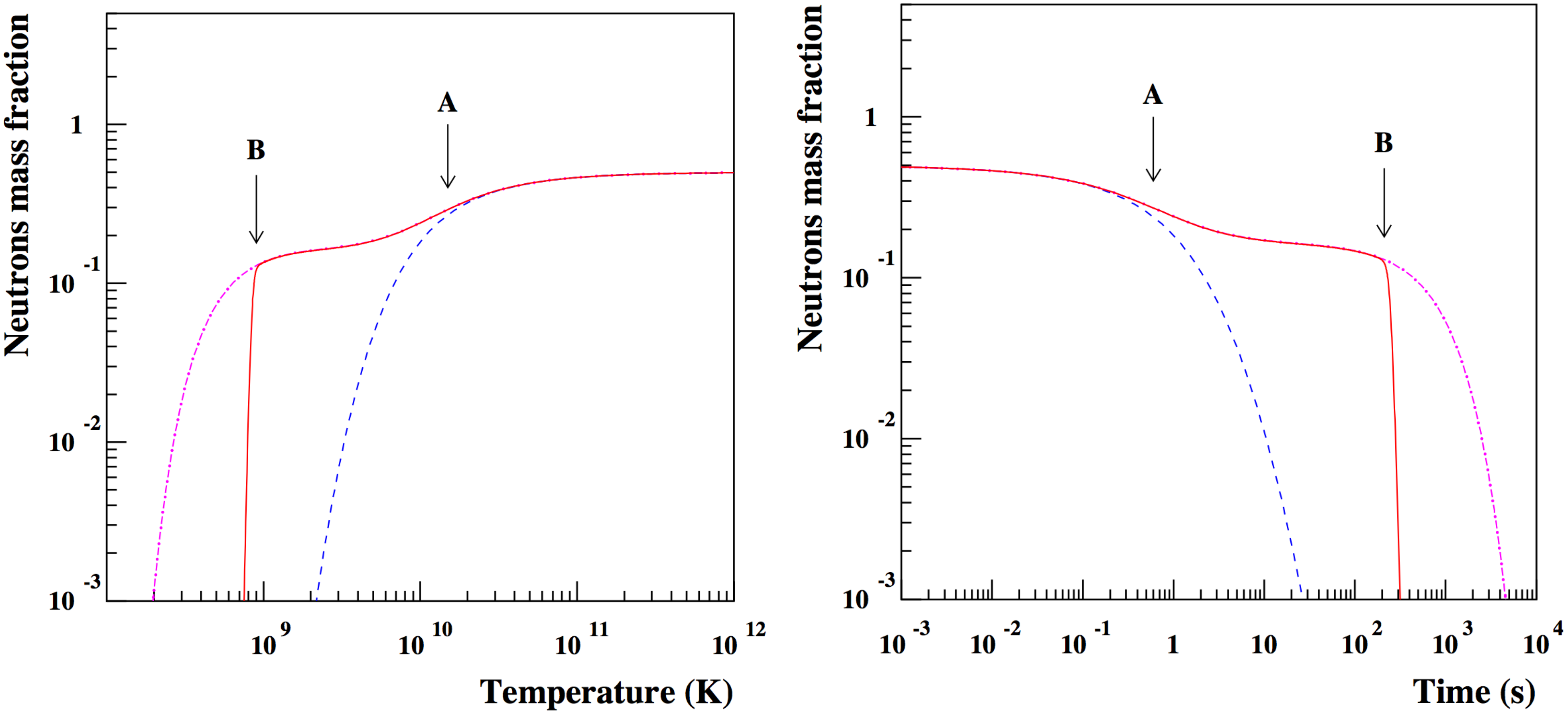
D formation (B)

- - - - - n↔p equilibrium

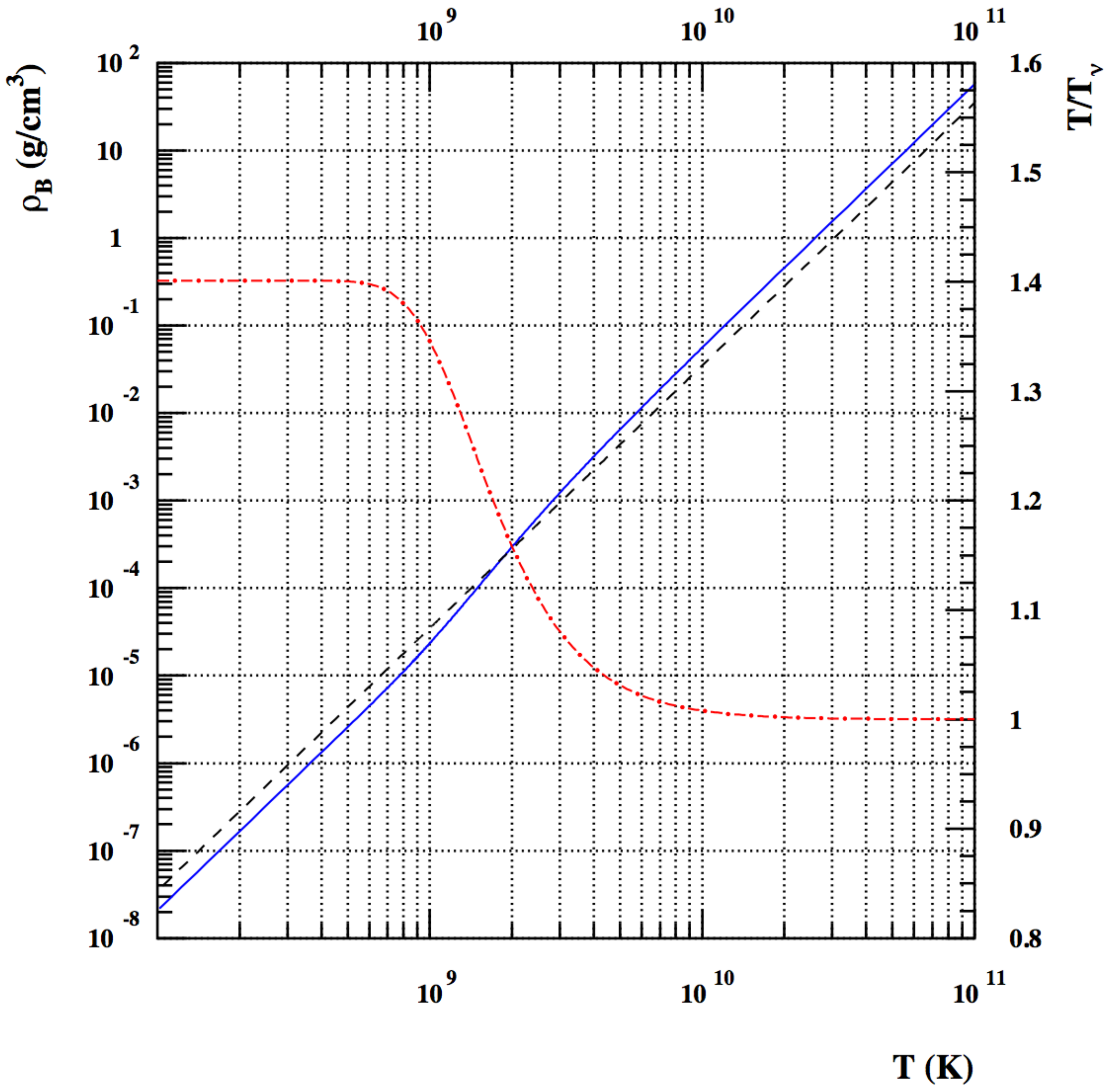
·········· n free decay

—— exact calculation

$\Omega_B h^2$ = WMAP/ΛCMD



Time evolution of baryonic density

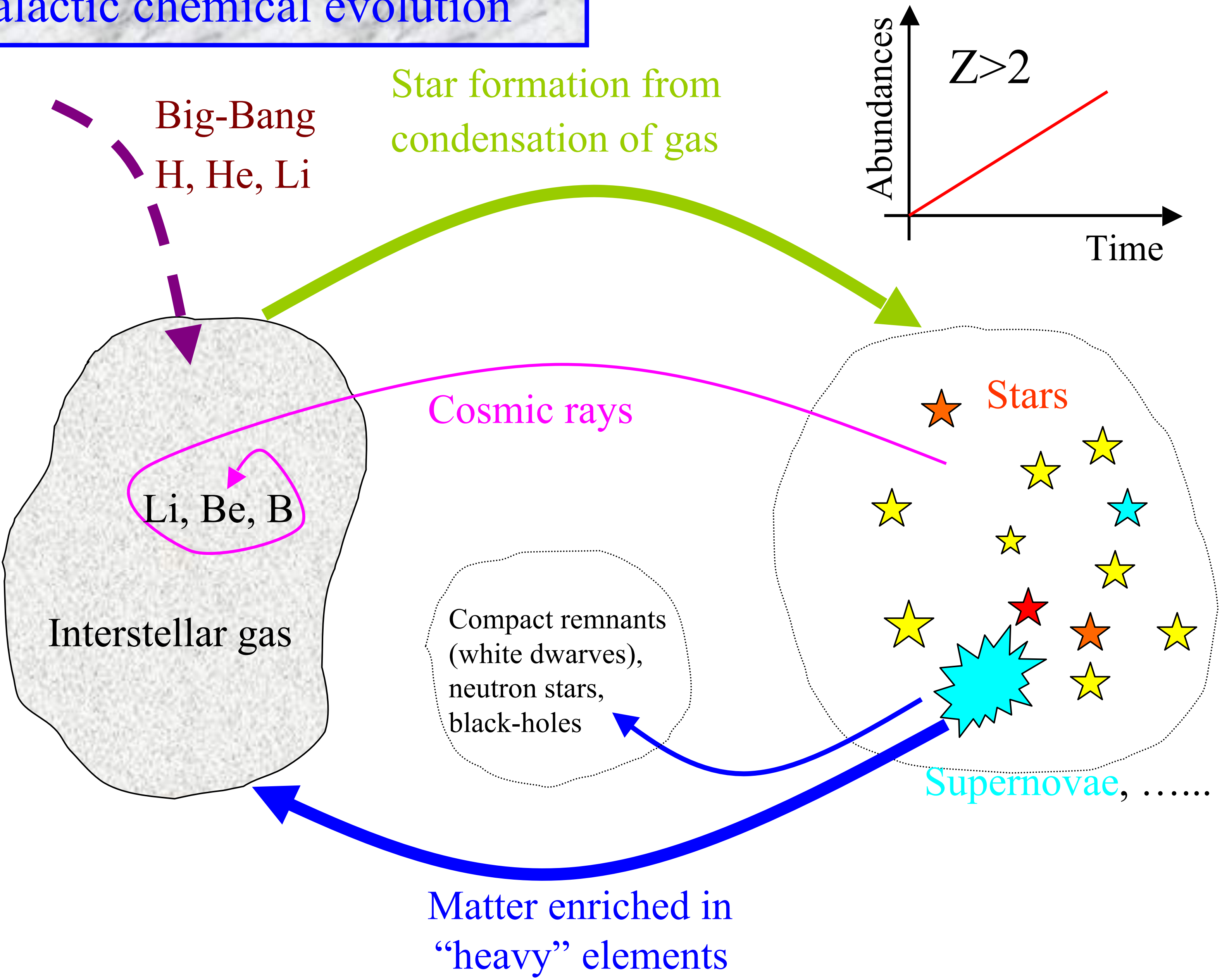


$$\boxed{\rho_b \sim T^3 \ (\sim a^3)}$$

Negligible influence
on expansion rate!

$$\rho_b << \rho_R$$

Galactic chemical evolution



Big-Bang
H, He, Li

Star formation from
condensation of gas

Cosmic rays

Li, Be, B

Interstellar gas

Stars

Compact remnants
(white dwarves),
neutron stars,
black-holes

Supernovae, ……

Matter enriched in
“heavy” elements

“Metallicity”

In astrophysics:

“metals” = everything beyond helium

Metallicity:

- “metal” mass fraction (Z)
- $[\mathrm{Fe/H}] \equiv \log(\mathrm{Fe/H}) - \log(\mathrm{Fe}_\odot/\mathrm{H}_\odot)$

Solar metallicity

$$Z_\odot \approx 0.018$$

$$[\mathrm{Fe/H}] \equiv 0$$

Determination of primordial abundances

Primordial abundances :

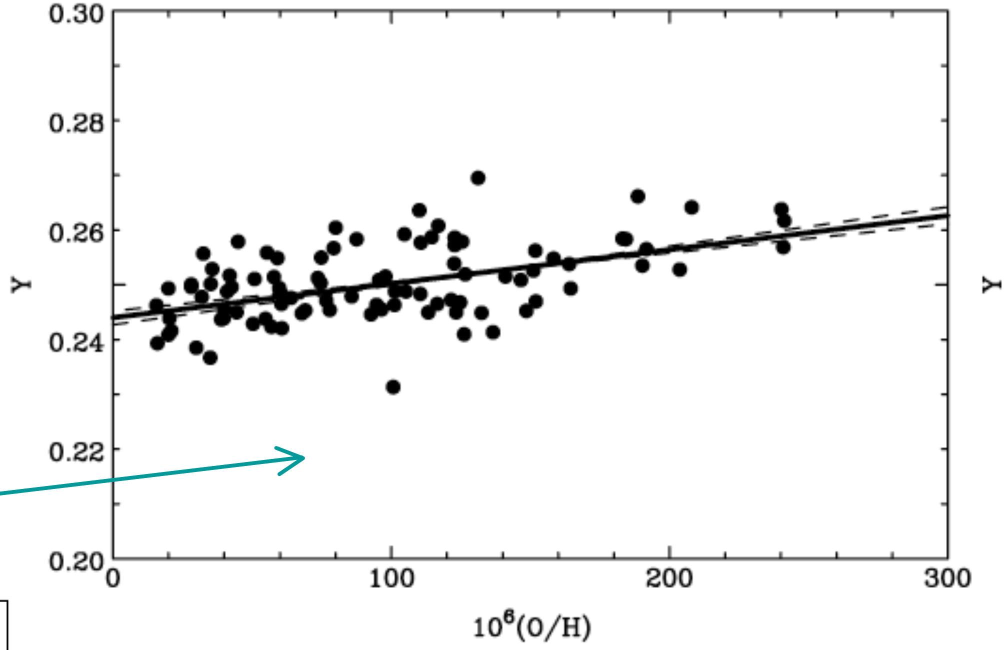
1) Observe a set of primitive objects born when the Universe was young
   - ^{4}**He** in H II (ionized H) regions of blue compact galaxies
   - ^{3}**He** in H II regions of *our* Galaxy
   - **D** in remote cosmological clouds (i.e. at high redshift) on the line of sight of quasars
   - ^{7}Li at the surface of low metallicity stars in the halo of our Galaxy
2) Extrapolate to zero metallicity : Fe/H, O/H, Si/H,…. → 0

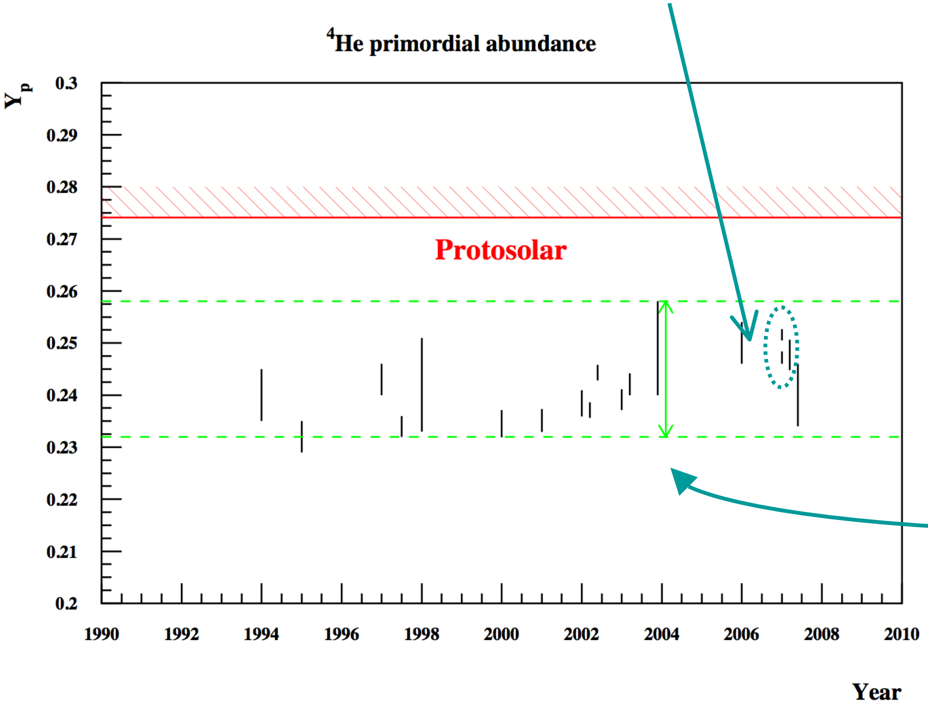
^{4}He observations in blue compact galaxies

^{4}He from a sample of 86 H II regions in 77 blue compact galaxies:

- $Y_p = 0.2472 \pm 0.0012$ or
- $Y_p = 0.2516 \pm 0.0011$

(according to atomic physics data)
[Izotov, Thuan & Stasinska 2007]





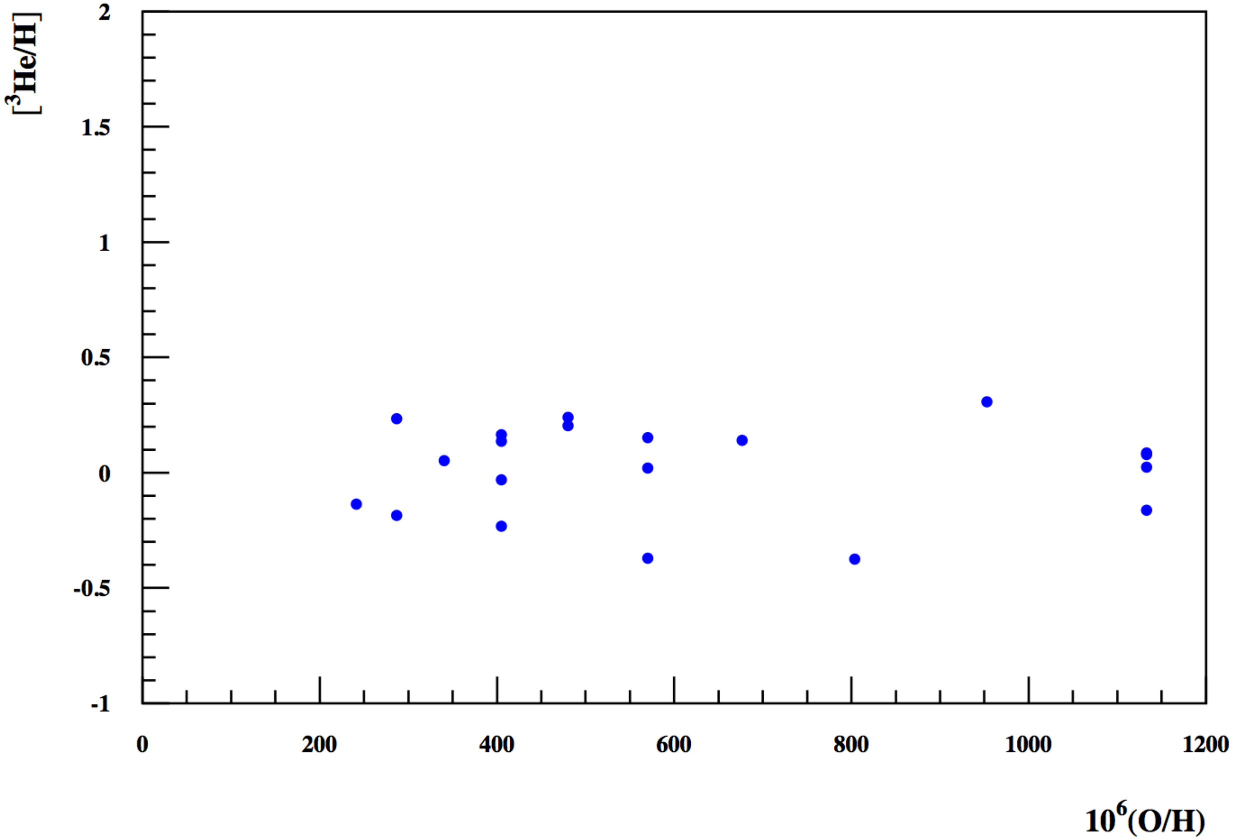
Alternative analysis (≈same data set)

- $0.232 < Y_p < 0.258$

[Olive & Skillman 2004]

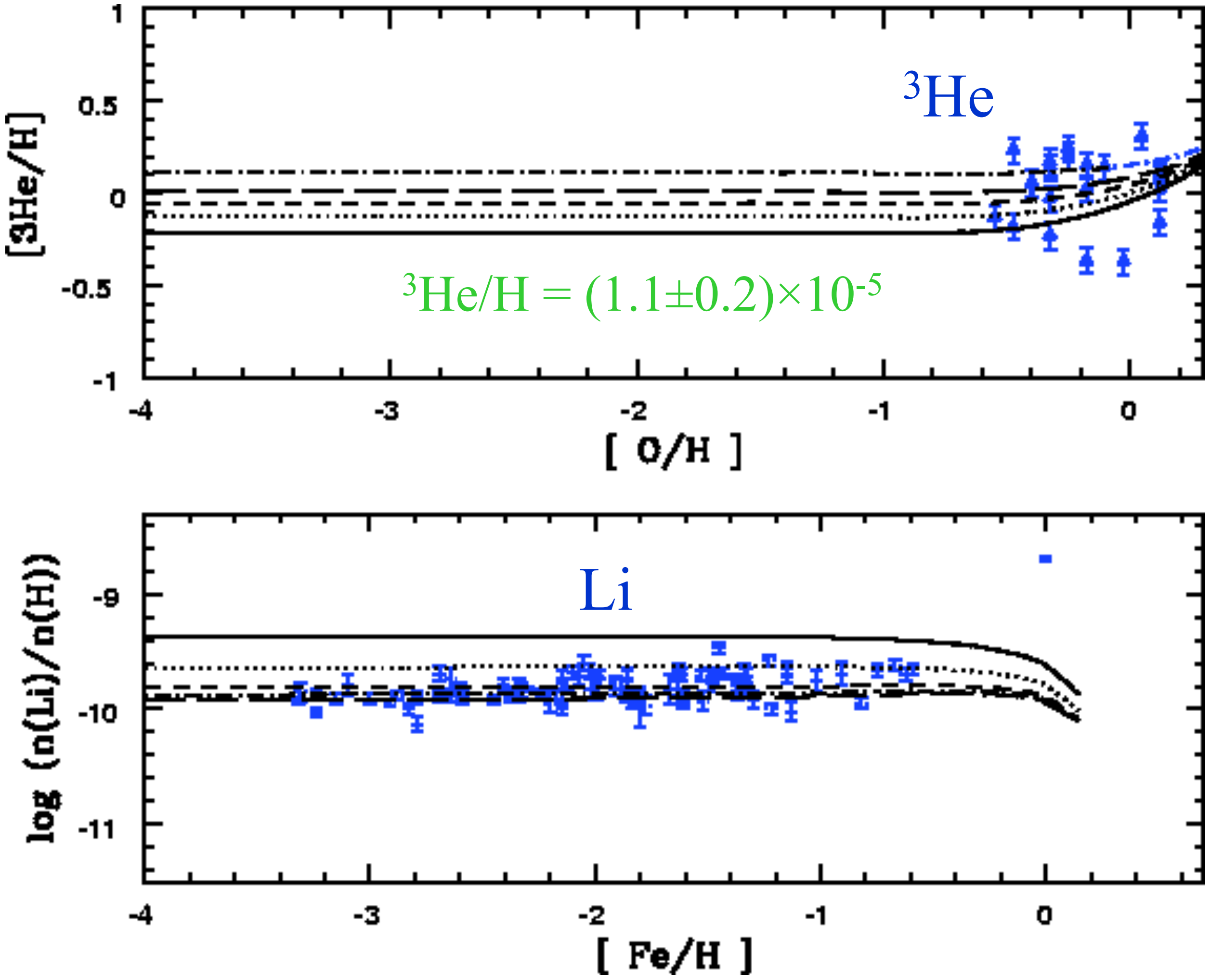
^{3}He primordial abundance

^{3}He from a sample of 21 local galactic H II regions; upper limit from best observation: $^3\mathrm{He/H} \leq (1.1 \pm 0.2) \times 10^{-5}$ *[Bania et al. 2002]*



^{3}He primordial abundance ?

New ^{3}He/H data *[Bania et al. 2002]* but at high metallicity : weak constrains on primordial value *[Vangioni-Flam et al. 2002].*



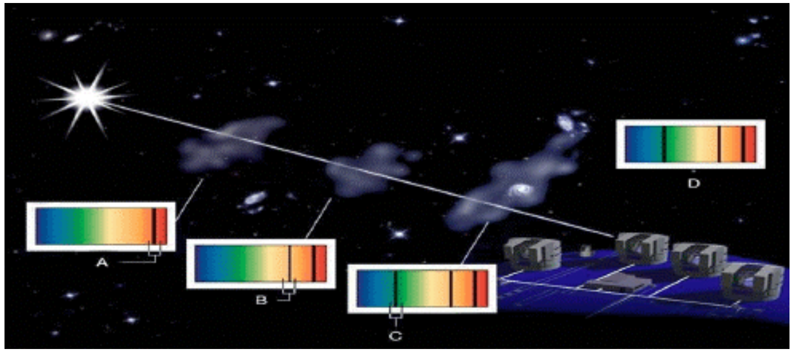
Deuterium primordial abundance

Fragile isotope : only destroyed after BBN

⇒ use highest observed value

1. Local interstellar medium (present) :
   D/H ≈ 10^{-5} *[FUSE: Hébrard & Moos 2003, Wood et al. 2004]*
2. Protosolar cloud (4.6 Gyr ago) :
   D/H = $(2.5 \pm 0.5) \times 10^{-5}$ *[Hersant et al. 2001]*
3. Remote cosmological clouds on the line of sight of quasars

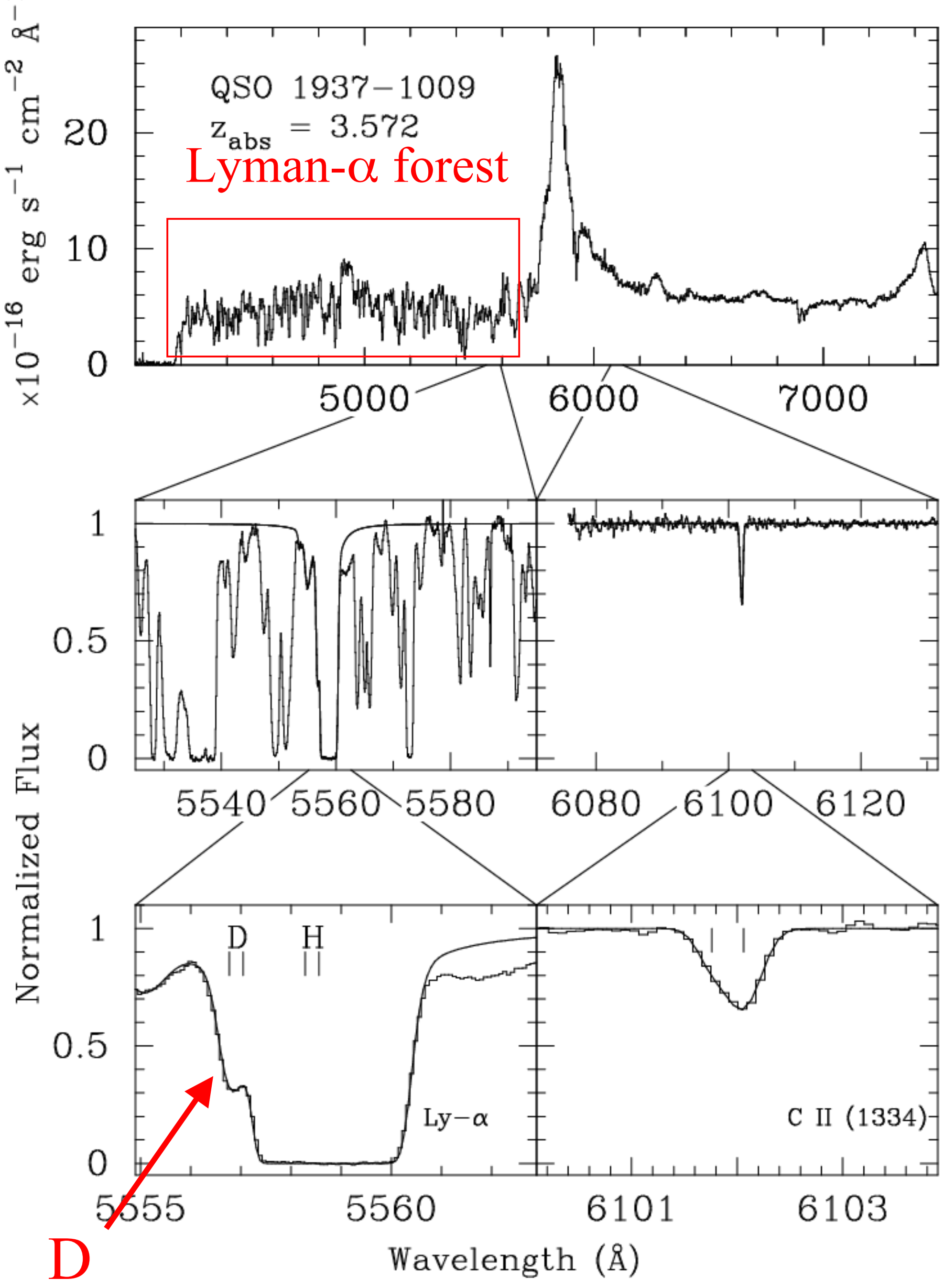
D/H observations in a cosmological cloud



Cloud at redshift of $z = 3.6$ on the line of sight of quasar QSO 1937-1009

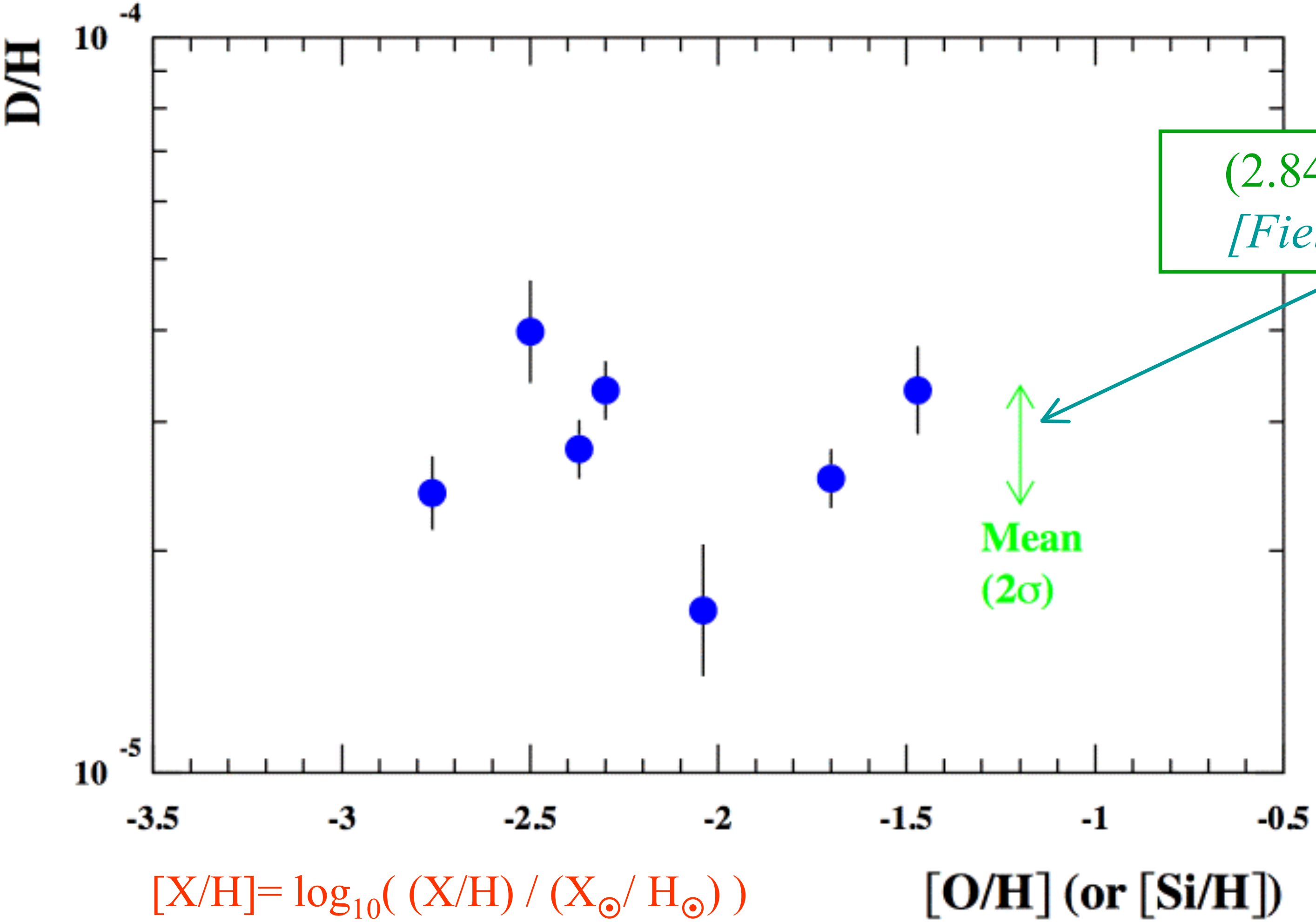
Observations :

- D/H ratio at high redshift from the depth/width of absorption lines
- Baryonic density (Ω_b) from the census of the « Lyman-α Forest » lines



[Burles & Tytler 1998]

D/H observations in cosmological clouds



(2.84±0.26)× 10^{-5} (1-σ)
[Fields &Sarkar 2008]

Mean
(2σ)

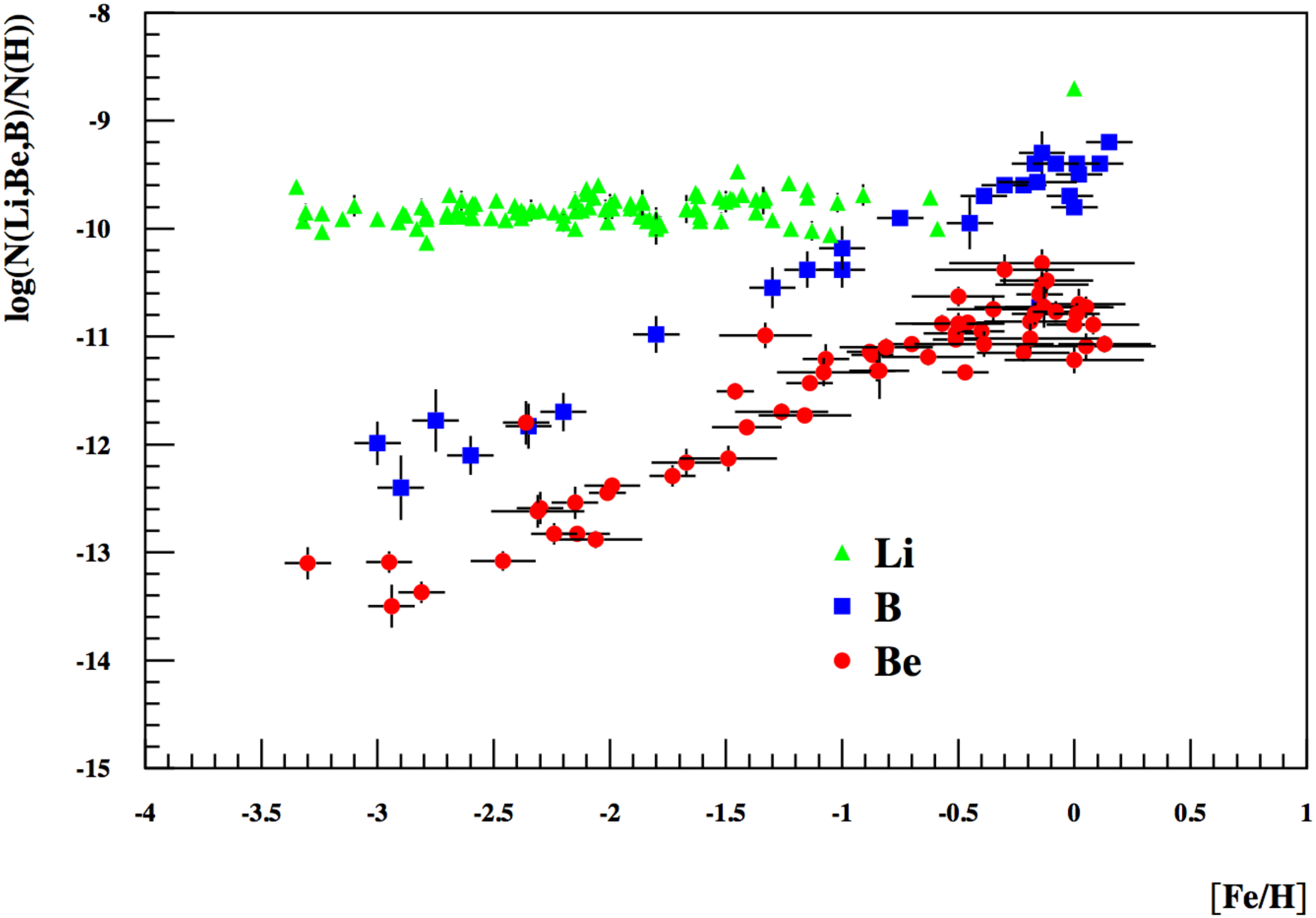
Protosolar

Local ISM
≈ 10^{-5}

$[X/H] = \log_{10}((X/H) / (X_\odot / H_\odot))$

Burles & Tytler 1998a,b; O'Meara et al. 2001; D'Odorico et al. 2001; Pettini & Bowen 2001; Kirkman et al. 2003, Crighton et al. 2004, Pettini et al. 2008

Galactic evolution of Li, Be and B abundances

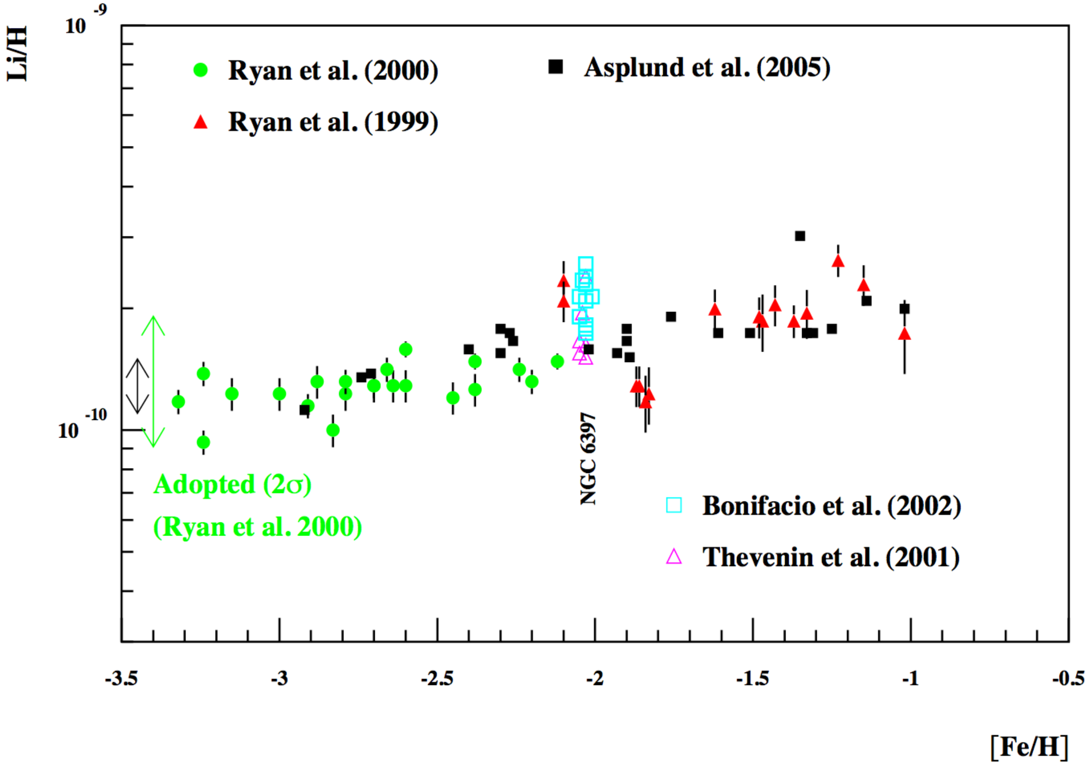


Observation in halo stars, as a function of « metallicity »
≈ [Fe/H] increasing with time ([Fe/H]=0 : 4.5 Gy ago)

Observation of lithium abundances in low metallicity stars

Spite plateau: Li/H versus metallicity (time):

Li/H ≈1.12 10^{-10} *[Spite & Spite, 1982]*



- Low dispersion
- ^{6}Li observations

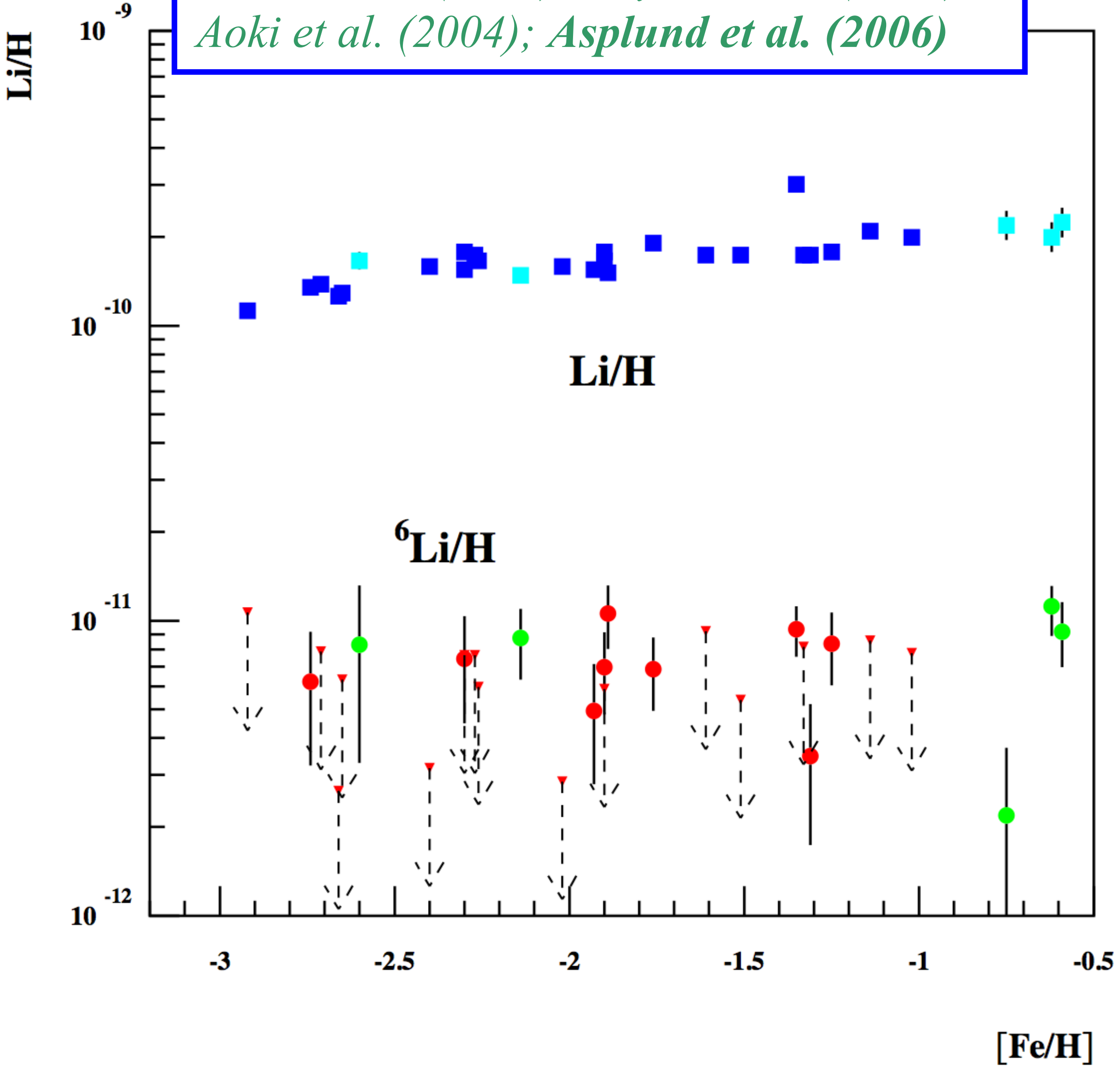
⇒ In principle, low Li destruction ≈ 0.1 dex (?)

⇒Reliable primordial abundance (?)

0.9↔1.9 × 10^{-10} (2σ) *[Ryan et al. (2000)],*
≈2.34 × 10^{-10}*[Meléndez & Ramírez (2004)]*
≈1.3↔2.3 × 10^{-10}*[Charbonnel & Primas (2005)],*
1.1↔1.5 × 10^{-10} *[Asplund et al. (2006)]*

^{6}Li observations in halo stars

Nissen et al. (1999); Cayrel, et al. (1999); Aoki et al. (2004); ***Asplund et al. (2006)***



Observed ratio in halo stars :

$^{6}\mathrm{Li}/^{7}\mathrm{Li} \approx 0.05$

$$\boxed{10^{-12} < {}^{6}\mathrm{Li/H} < 10^{-11}}$$

(conservative range)

The 12 reactions of standard BBN

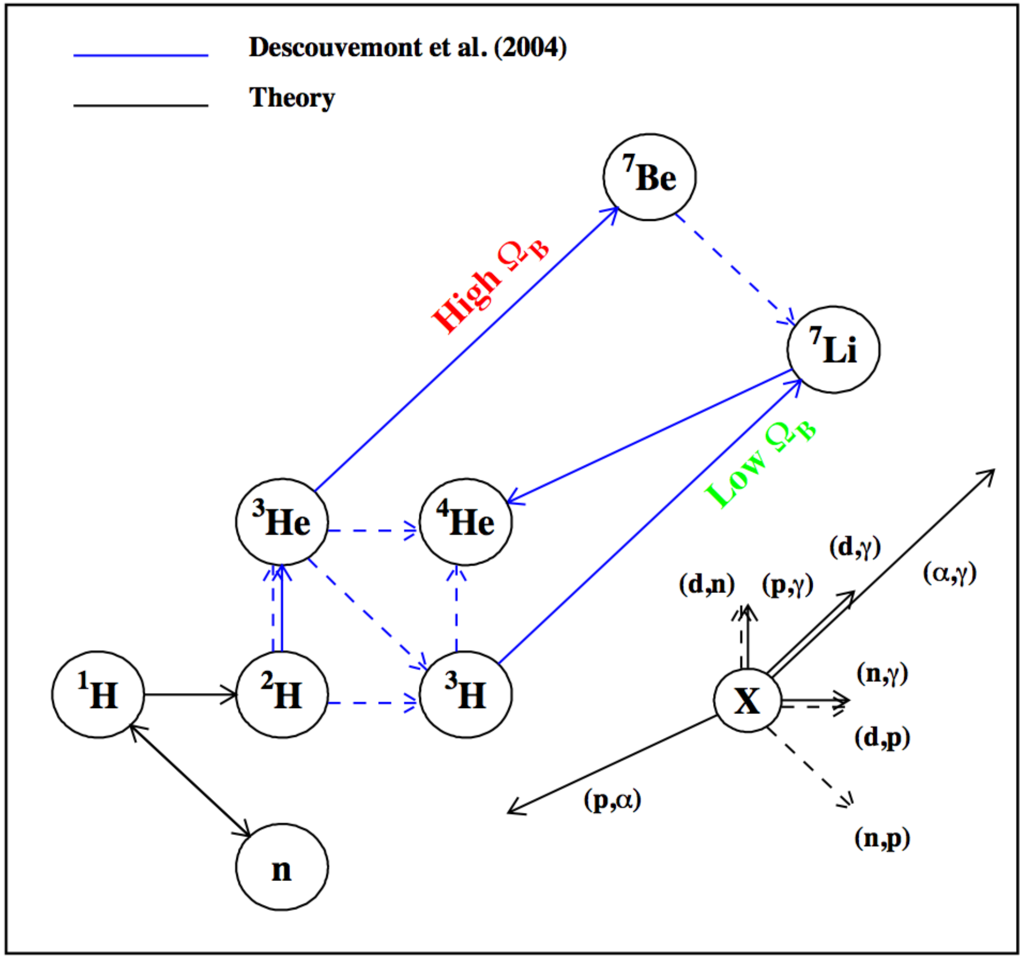
Origin of reaction rates

Theoretical:

- n↔p : with τ_n=885.7±0.8 s *[PDG 2004]* (τ_n=878.5±0.7 ±0.3 *[Serebrov et al. 2005, Mathews, Kajino & Shima 2004]*), otherwise small uncertainty *[Brown & Sawyer (2001)]*
- $^1H(n,\gamma)^2H$: Two nucleons effective field theory *[Chen & Savage (1999)]*

Experimental :

- New compilation *[Descouvemont, Adahchour, Angulo, Coc & Vangioni-Flam (2004)]*



Thermonuclear reaction rates

- Cross section :

$$\text{Cross section } (\sigma) = \frac{\text{Number of reactions / time}}{\text{Beam intensity} \times \text{Number of target nuclei}}$$

σ units : barn (b) $\equiv 10^{-24}$ cm^2

- Thermonuclear reaction rate :

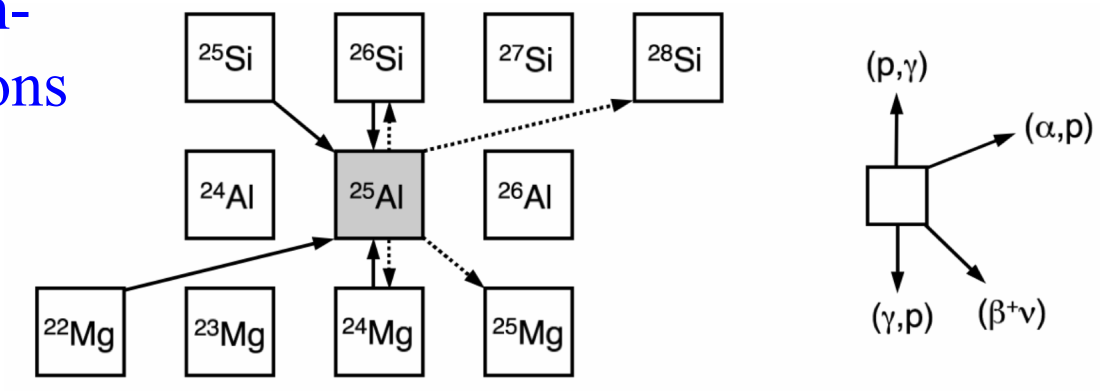
$$N_A\langle\sigma \mathrm{v}\rangle = N_A\int_0^\infty \sigma(\mathrm{v})\mathrm{v}\varphi(\mathrm{v})d\mathrm{v}$$

$\varphi(\mathrm{v})$ = Maxwell-Boltzmann distribution

N_A = Avogadro’s number

Nuclear network equations

Set of coupled , stiff, non-linear differential equations solved numerically



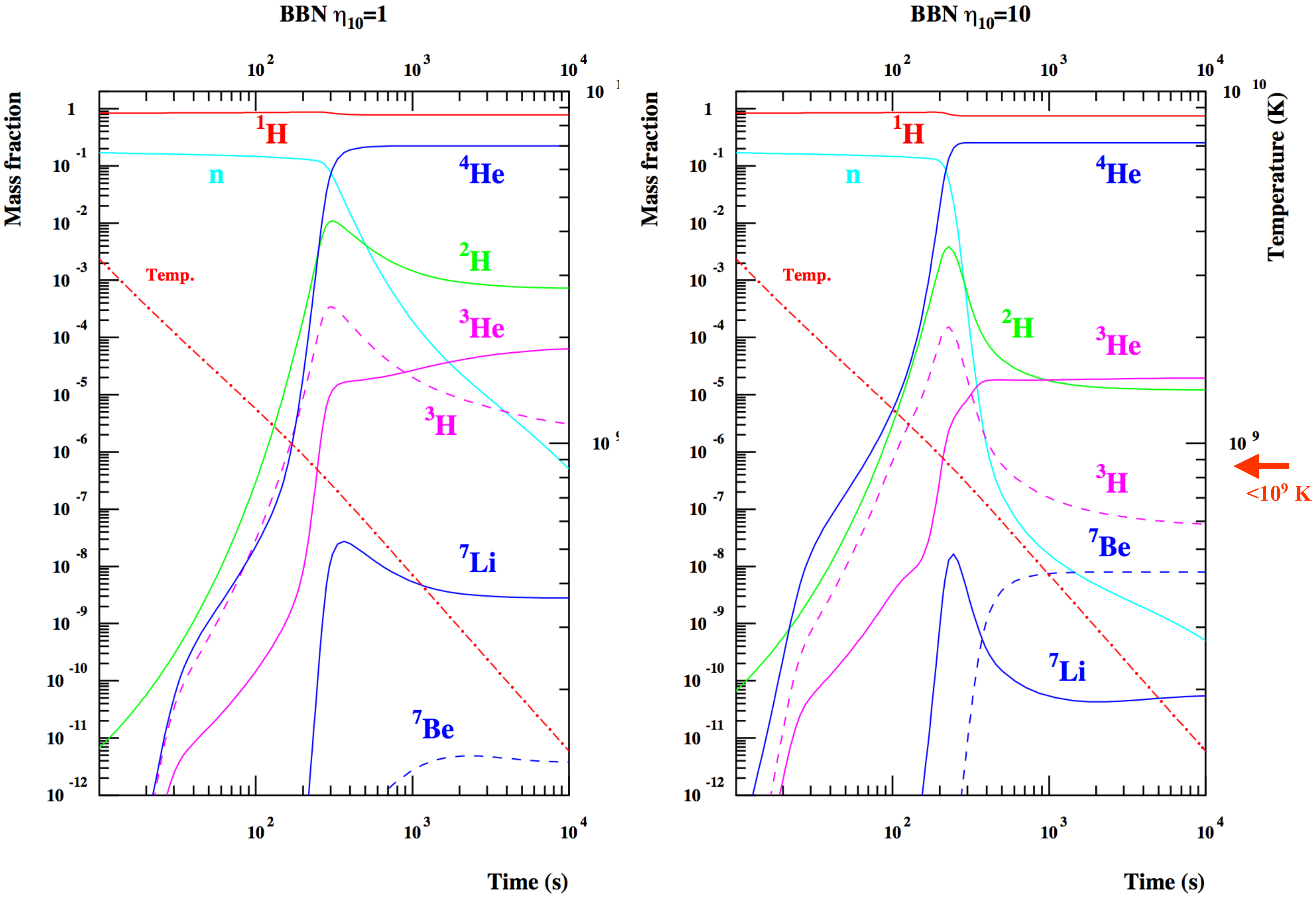
Evolution of abundances :

$$\begin{aligned}\frac{d(N_{^{25}\mathrm{Al}})}{dt} = {} & \left.\begin{array}{l} \mathrm{N_H} N_{^{24}\mathrm{Mg}} \langle \sigma v \rangle_{^{24}\mathrm{Mg(p,}\gamma)} + N_{^4\mathrm{He}} N_{^{22}\mathrm{Mg}} \langle \sigma v \rangle_{^{22}\mathrm{Mg}(\alpha,\mathrm{p})} \\ + N_{^{25}\mathrm{Si}} \lambda_{^{25}\mathrm{Si}(\beta^+\nu)} + N_{^{26}\mathrm{Si}} \lambda_{^{26}\mathrm{Si}(\gamma,\mathrm{p})} + \dots \end{array}\right\} \text{production} \\ & \left.\begin{array}{l} - \mathrm{N_H} N_{^{25}\mathrm{Al}} \langle \sigma v \rangle_{^{25}\mathrm{Al(p,}\gamma)} - N_{^4\mathrm{He}} N_{^{25}\mathrm{Al}} \langle \sigma v \rangle_{^{25}\mathrm{Al}(\alpha,\mathrm{p})} \\ - N_{^{25}\mathrm{Al}} \lambda_{^{25}\mathrm{Al}(\beta^+\nu)} - N_{^{25}\mathrm{Al}} \lambda_{^{25}\mathrm{Al}(\gamma,\mathrm{p})} - \dots \end{array}\right\} \text{destruction}\end{aligned}$$

Rate of energy production :

$$\varepsilon = \sum_{ijk} \frac{N_i N_j}{1+\delta_{ij}} \langle \sigma \mathrm{v} \rangle_{ijk} Q_{ijk}$$

Primordial nucleosynthesis with $\eta_{10} = 1$ et 10



n↔p weak reaction rate

$\lambda_{n\leftrightarrow p} = \tau_n^{-1} \times$

$\sum\int$ (phase space)×(e distribution)×(ν_e distribution) dE

+ small corrections

[Dicus et al. (1982), Brown & Sawyer (2001)]

$$\lambda_{n\to pe\nu} = C\int_1^q \frac{\varepsilon(\varepsilon-q)^2(\varepsilon^2-1)^{1/2}\,\mathrm{d}\varepsilon}{[1+\exp(-\varepsilon z)]\{1+\exp[(\varepsilon-q)z_\nu]\}} \xrightarrow[T\to 0]{} \frac{1}{\tau_n} = C\int_1^q \varepsilon(\varepsilon-q)^2(\varepsilon^2-1)^{1/2}\,\mathrm{d}\varepsilon$$

$(q\equiv Q_{np}/m_e,\ m_e,\ \varepsilon\equiv E_e/m_e,\ z\equiv m_e/T_\gamma,\ z_\nu\equiv m_e/T_\nu)$

$$\lambda_{n+e^+\to p+\bar{\nu}_e},\quad \lambda_{n+\nu_e\to p+e^-},\quad \lambda_{p+e^-\to n+\bar{\nu}_e},\quad \lambda_{p+\bar{\nu}_e\to n+e^+},\quad \lambda_{p+e^-\to n+\nu_e} = \ldots$$

- τ_n=885.7±0.8 s *[PDG 2008]*
- τ_n=878.5±0.7 ±0.3 *[Serebrov et al. 2005]*

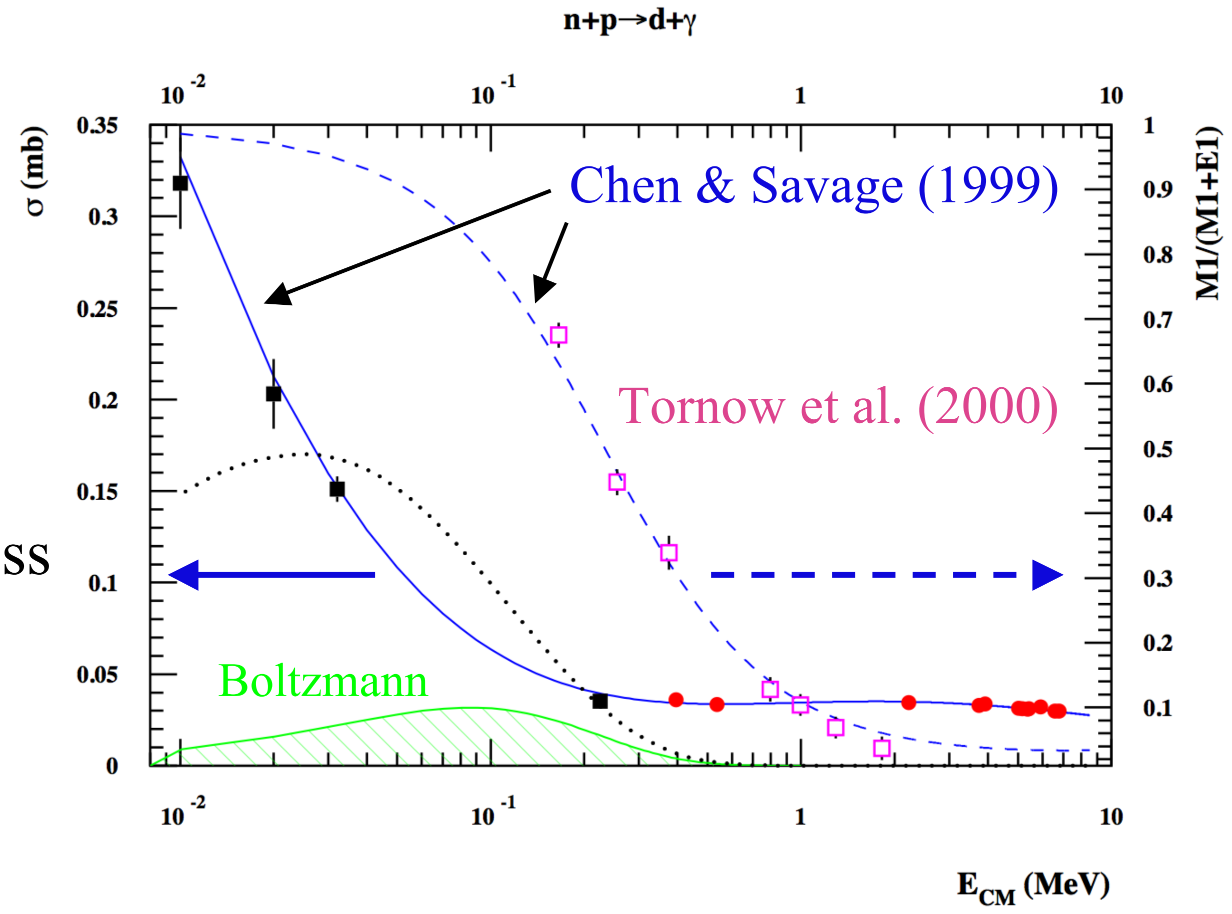
^{1}H(n,γ)D : theory versus experiments

Rate calculated from Effective Field theory with (theoretical) uncertainties of 4% *[Chen & Savage (1999)]* or 1% *[Rupak (2000)]* compared to experiments *[Arenhovel & Sanzone (1991) review]*

BBN energy ~ 25 keV

Additional check with polarized beam *E1* and *M1* measurements *[Tornow et al. (2000)]*

… and new (>1991) cross section measurements *[Suzuki et al. (1995), Tomyo et al. (2003)]*



Reactions with charged particles

➢Below the Coulomb barrier!

➢Very weak cross sections :
$\sigma(E)$ ↘ ↘ ↘ when E ↘

Coulomb and et centrifugal penetrability :

$$P_L = \frac{\rho}{F_L^2(\eta,\rho) + G_L^2(\eta,\rho)}$$

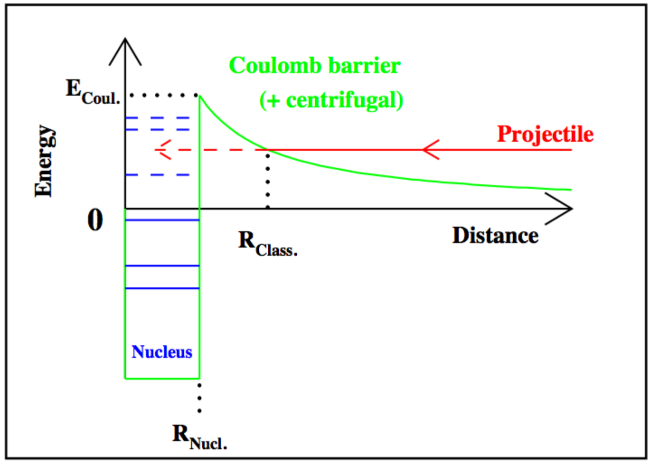
$F,\ G$ = Coulomb functions

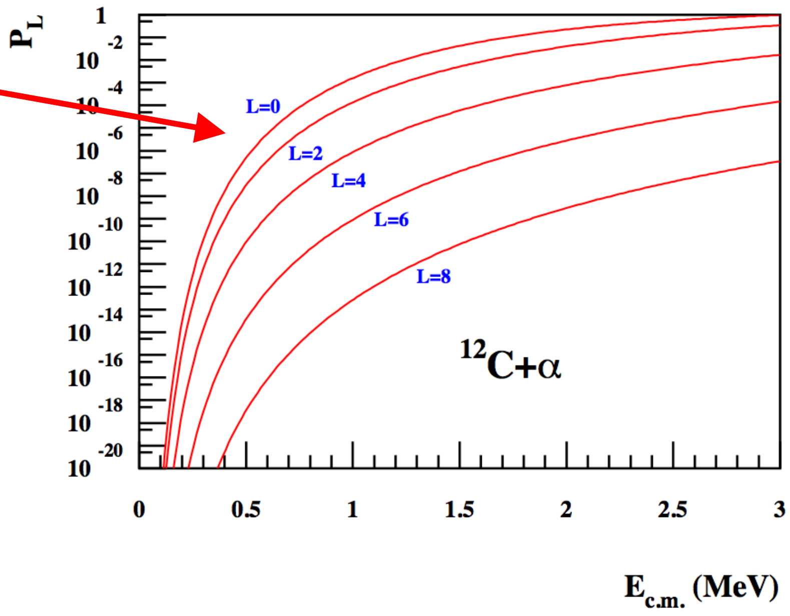
η = Sommerfeld parameter

$$\boxed{\eta = \frac{Z_1 Z_2 e^2}{\hbar v}}$$

$$\boxed{\rho = \frac{R}{\lambda\!\!\!^{-}} = \frac{\sqrt{2\mu E}}{\hbar} R}$$

Penetrability factor





Astrophysical S-factor : *S(E)*

WKB Approximation : $P_{L=0} \propto \exp(-2\pi\eta)$

$$\eta = \frac{Z_1 Z_2 e^2}{\hbar v}$$

Astrophysical *S-factor:*

$$S(E) = \sigma(E)\cdot E\cdot \exp(2\pi\eta) = \sigma(E)\cdot E\cdot \exp\left(-\sqrt{\frac{E_G}{E}}\right)$$

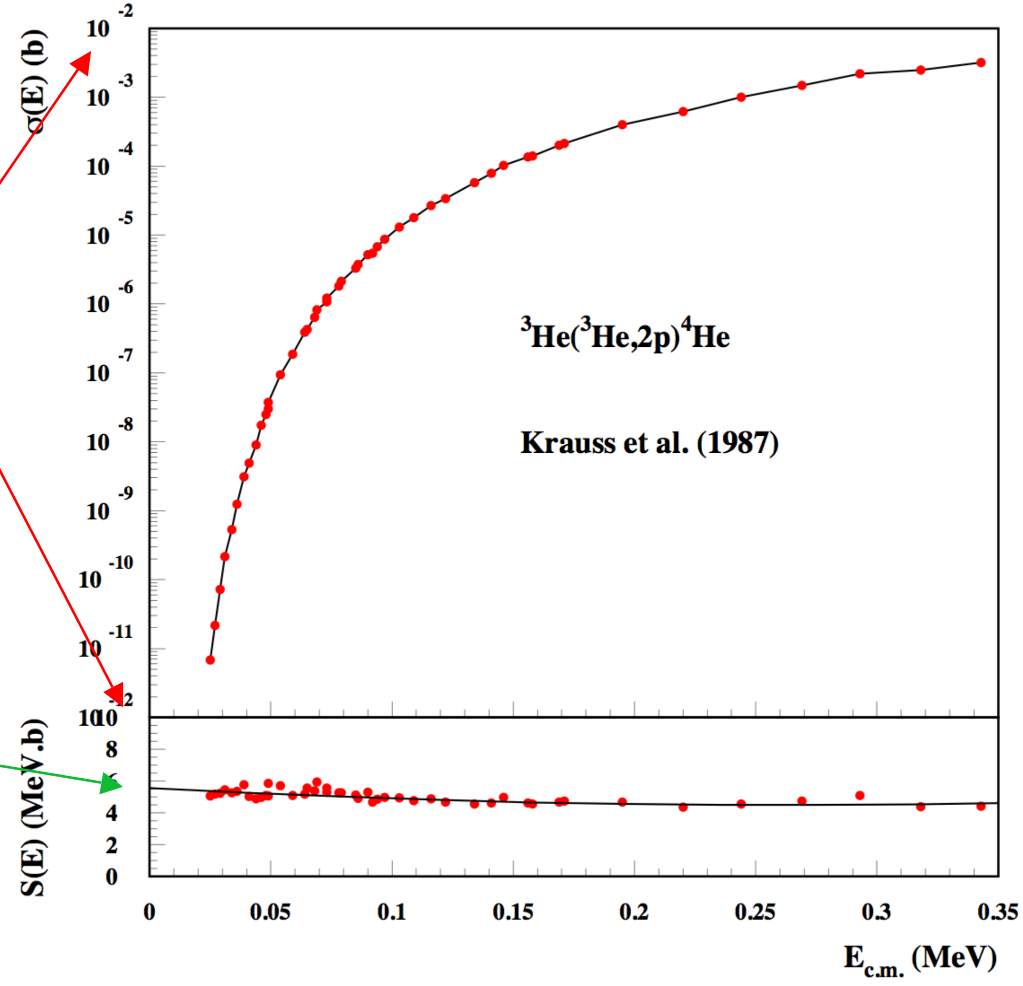
Corrects for the $\sigma(E) \sim \bar{\lambda}^2$ effect where $\bar{\lambda} \propto E^{-1/2}$ is the de Broglie wavelength

Corrects for the effect of penetrability (L=0)

Gamow energy : $E_G = \tfrac{1}{2}(2\pi\alpha Z_1 Z_2)^2\mu c^2 = (0.989\cdot Z_1 Z_2 A^{1/2})^2$ [MeV]

⇒ Much weaker variation of *S(E)* with energy as compared to *σ(E)*

Astrophysical S-factor : *S(E)*



Variation of cross section *σ(E)* :
9 orders of magnitude
between 25 and 340 keV

Variation of the
astrophyscal S-factor
S(E) : 50%

⇒Extrapolation to low energy

10 rates deduced from experimental data

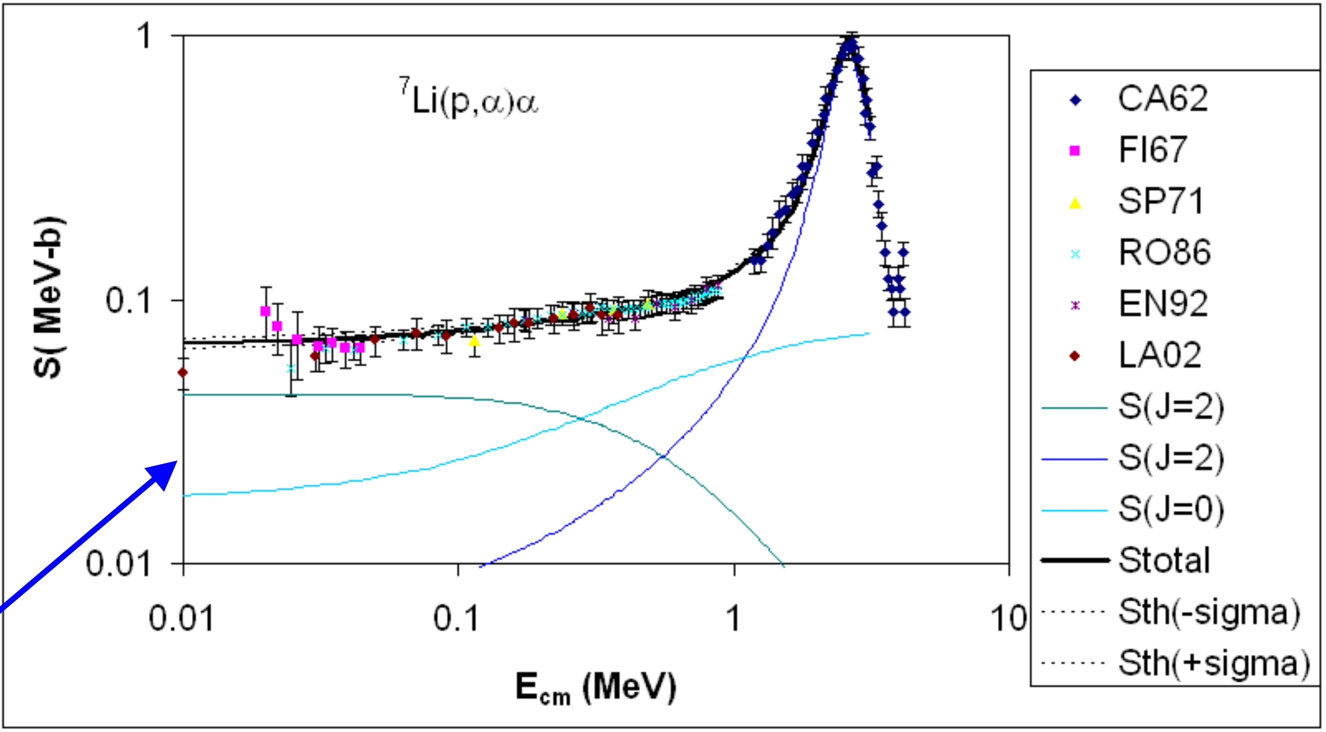
Compilations and evaluations for BBN thermonuclear rates

- *Smith, Kawano & Malaney 1999* (with uncertainties)
- *NACRE, Angulo et al. 1999* (7/10, tabulated rates and uncertainties)
- *Nollett & Burles 2000* (no rates provided)
- *Cyburt, Fields & Olive 2003* (revaluation of NACRE)
- *Serpico et al. 2004* (rates and uncertainties provided)
- *Descouvemont, Adahchour, Angulo, Coc & Vangioni-Flam 2004 [DAACV]*
  - « R-Matrix » formalism: S-factors fits of data constrained by theory
  - Provide also reaction rate uncertainties
- *Cyburt 2004* (rates provided, not the uncertainties)

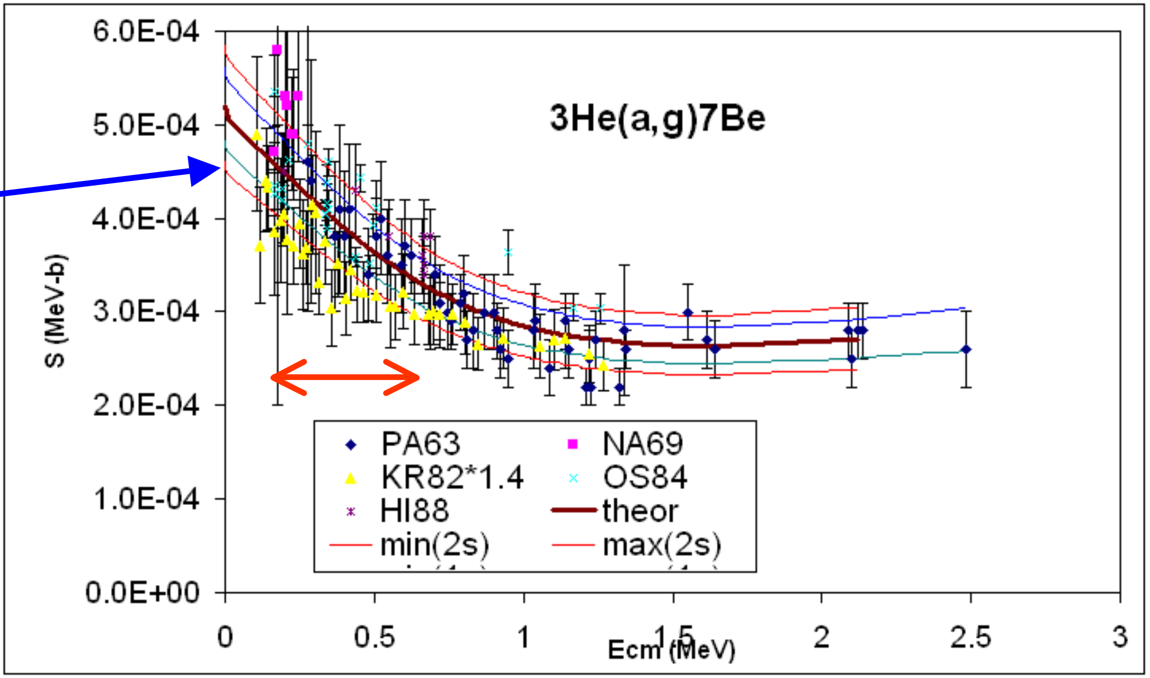
New analysis of BBN rates

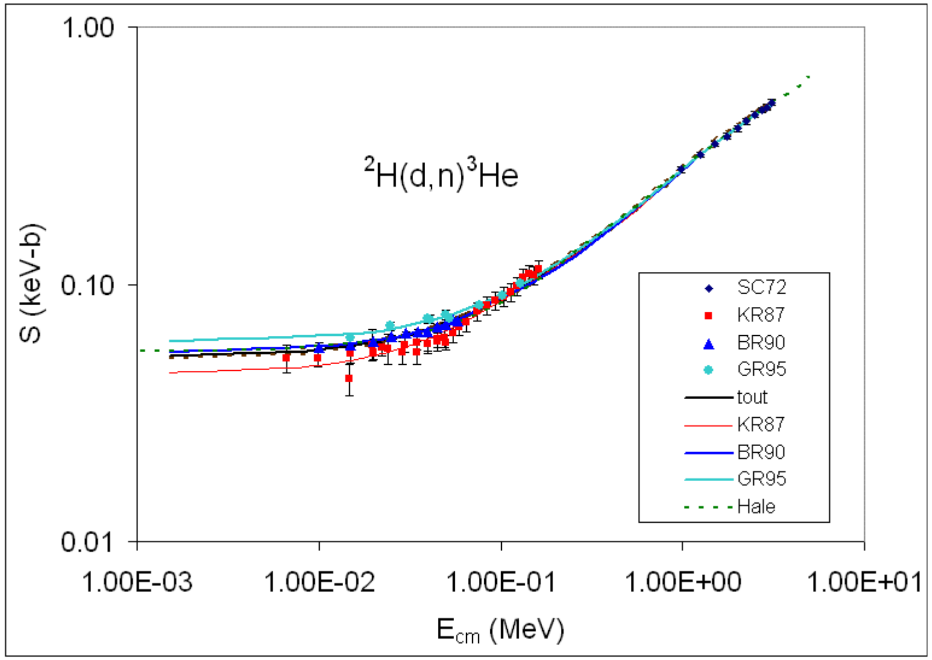
[DAACV] Descouvemont, Adahchour, Angulo, Coc & Vangioni-Flam ADNDT (2004)

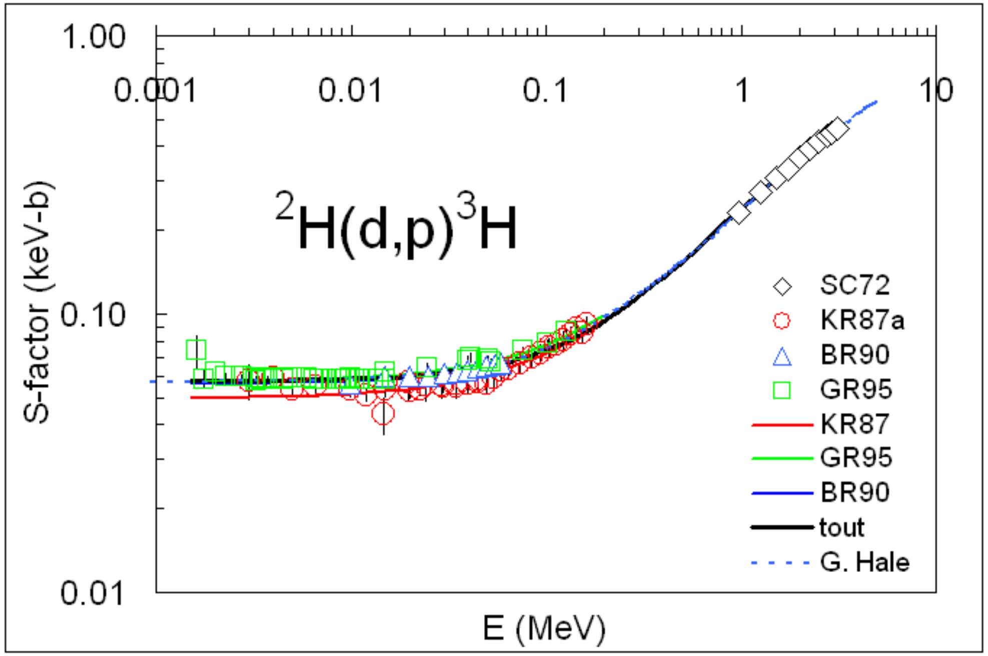
« R-Matrix » formalism: S-factors fits of data constrained by theory



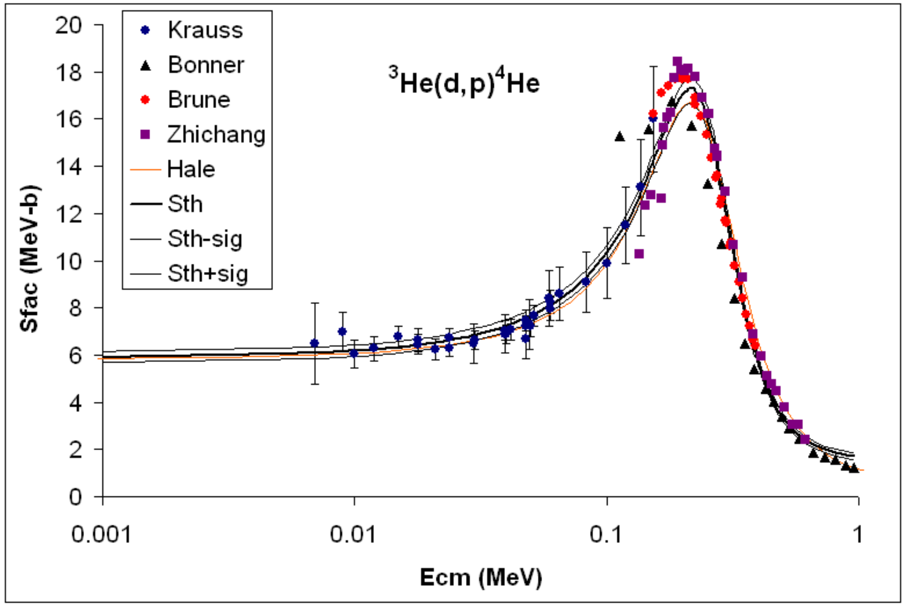
Provide also reaction rate uncertainties

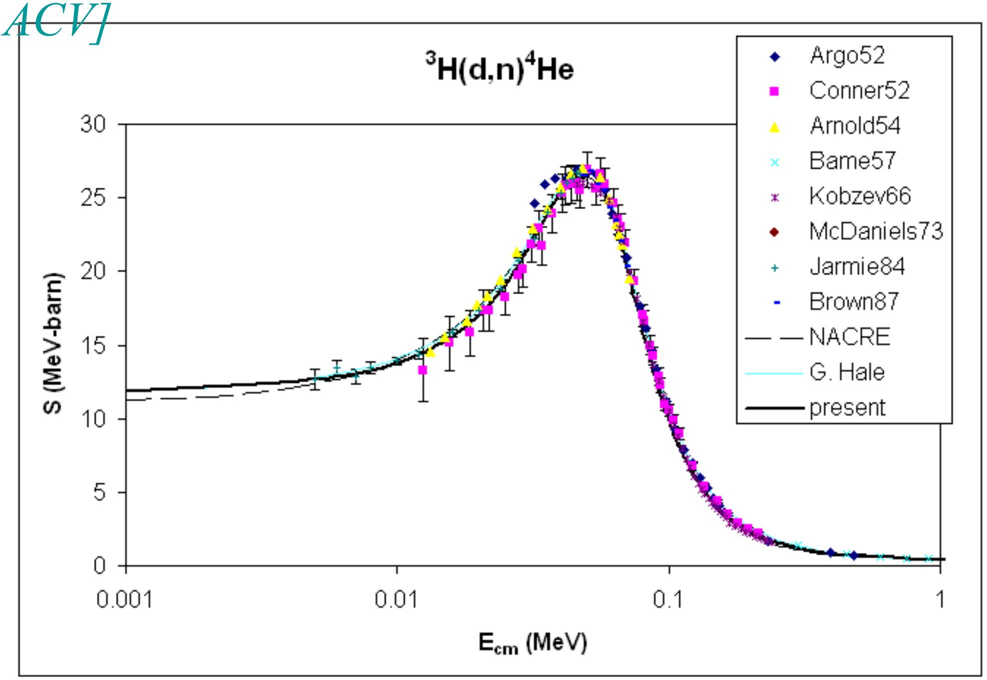


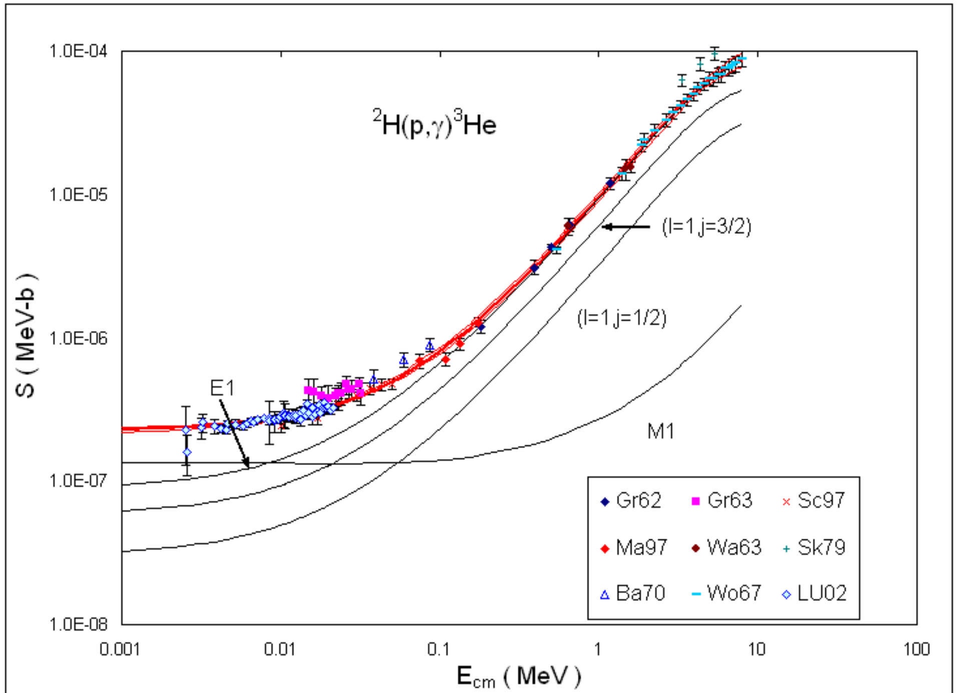

^{2}H(d,n)^{3}He
S (keV-b)
1.00
0.10
0.01
1.00E-03
1.00E-02
1.00E-01
1.00E+00
1.00E+01
E$_{cm}$ (MeV)
SC72
KR87
BR90
GR95
tout
KR87
BR90
GR95
Hale

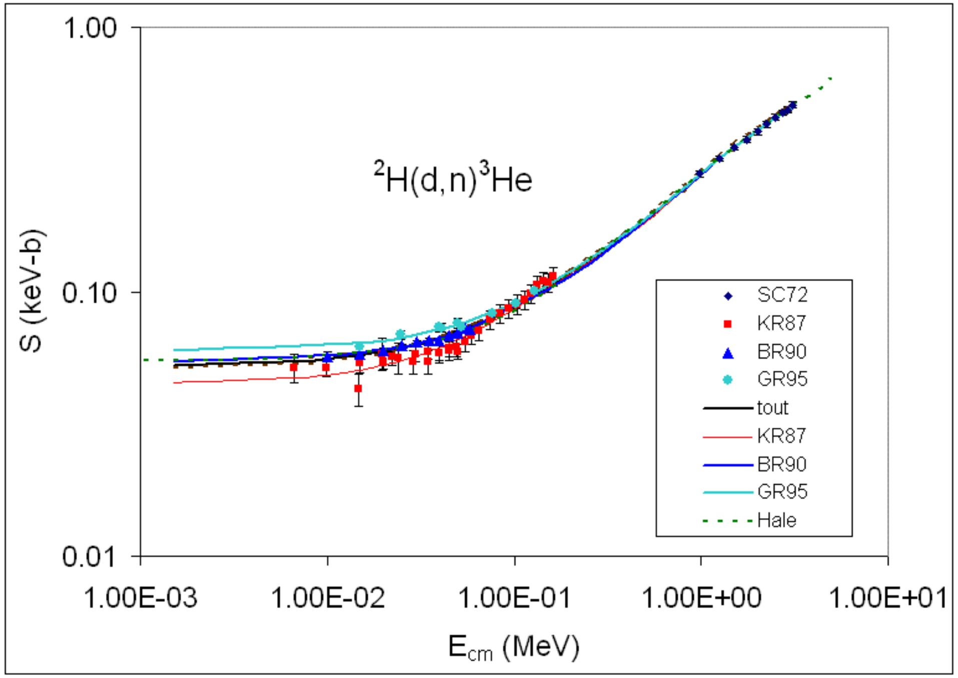

^{2}H(d,p)^{3}H
S-factor (keV-b)
1.00
0.10
0.01
0.001
0.01
0.1
1
10
E (MeV)
SC72
KR87a
BR90
GR95
KR87
GR95
BR90
tout
G. Hale

[DAACV]

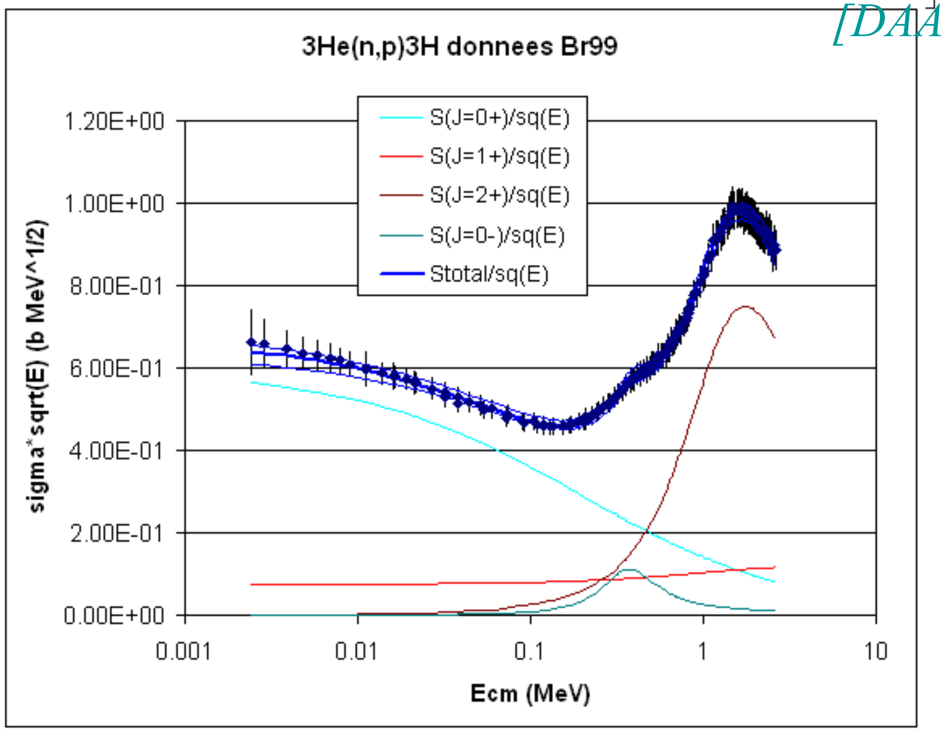

^{3}He(d,p)^{4}He
Sfac (MeV-b)
20
18
16
14
12
10
8
6
4
2
0
0.001
0.01
0.1
1
Ecm (MeV)
Krauss
Bonner
Brune
Zhichang
Hale
Sth
Sth-sig
Sth+sig

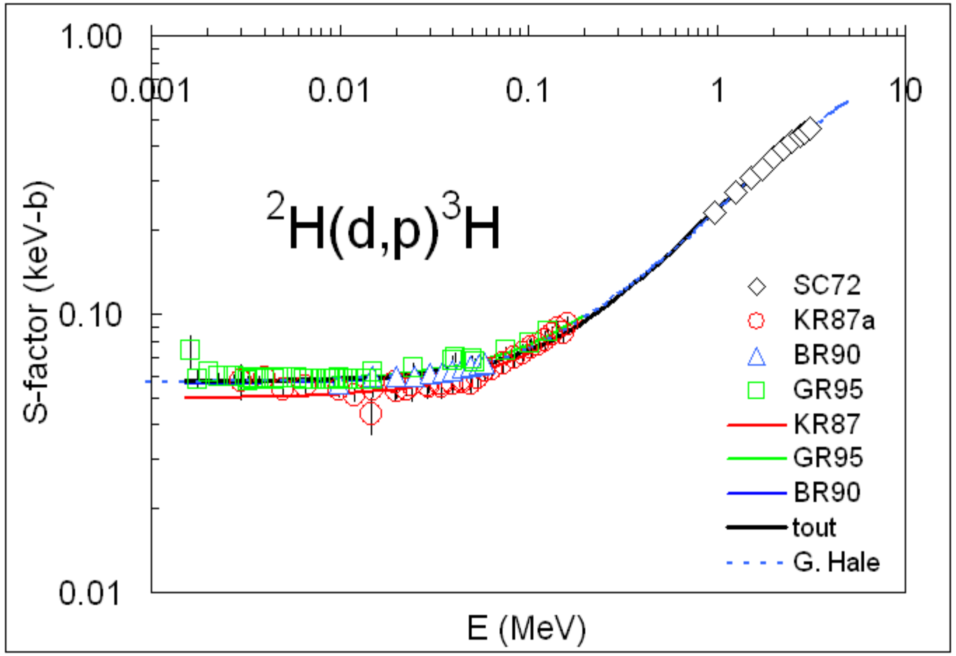

^{3}H(d,n)^{4}He
S (MeV-barn)
30
25
20
15
10
5
0
0.001
0.01
0.1
1
E$_{cm}$ (MeV)
Argo52
Conner52
Arnold54
Bame57
Kobzev66
McDaniels73
Jarmie84
Brown87
NACRE
G. Hale
present


$^2H(p,\gamma)^3He$
S (MeV-b)
1.0E-04
1.0E-05
1.0E-06
1.0E-07
1.0E-08
E1
(l=1,j=3/2)
(l=1,j=1/2)
M1
Gr62
Gr63
Sc97
Ma97
Wa63
Sk79
Ba70
Wo67
LU02
0.001
0.01
0.1
1
10
100
E_{cm} (MeV)


$^2H(d,n)^3He$
S (keV-b)
1.00
0.10
0.01
SC72
KR87
BR90
GR95
tout
KR87
BR90
GR95
Hale
1.00E-03
1.00E-02
1.00E-01
1.00E+00
1.00E+01
E_{cm} (MeV)

[DAACV]


3He(n,p)3H donnees Br99
sigma*sqrt(E) (b MeV^1/2)
1.20E+00
1.00E+00
8.00E-01
6.00E-01
4.00E-01
2.00E-01
0.00E+00
S(J=0+)/sq(E)
S(J=1+)/sq(E)
S(J=2+)/sq(E)
S(J=0-)/sq(E)
Stotal/sq(E)
0.001
0.01
0.1
1
10
Ecm (MeV)

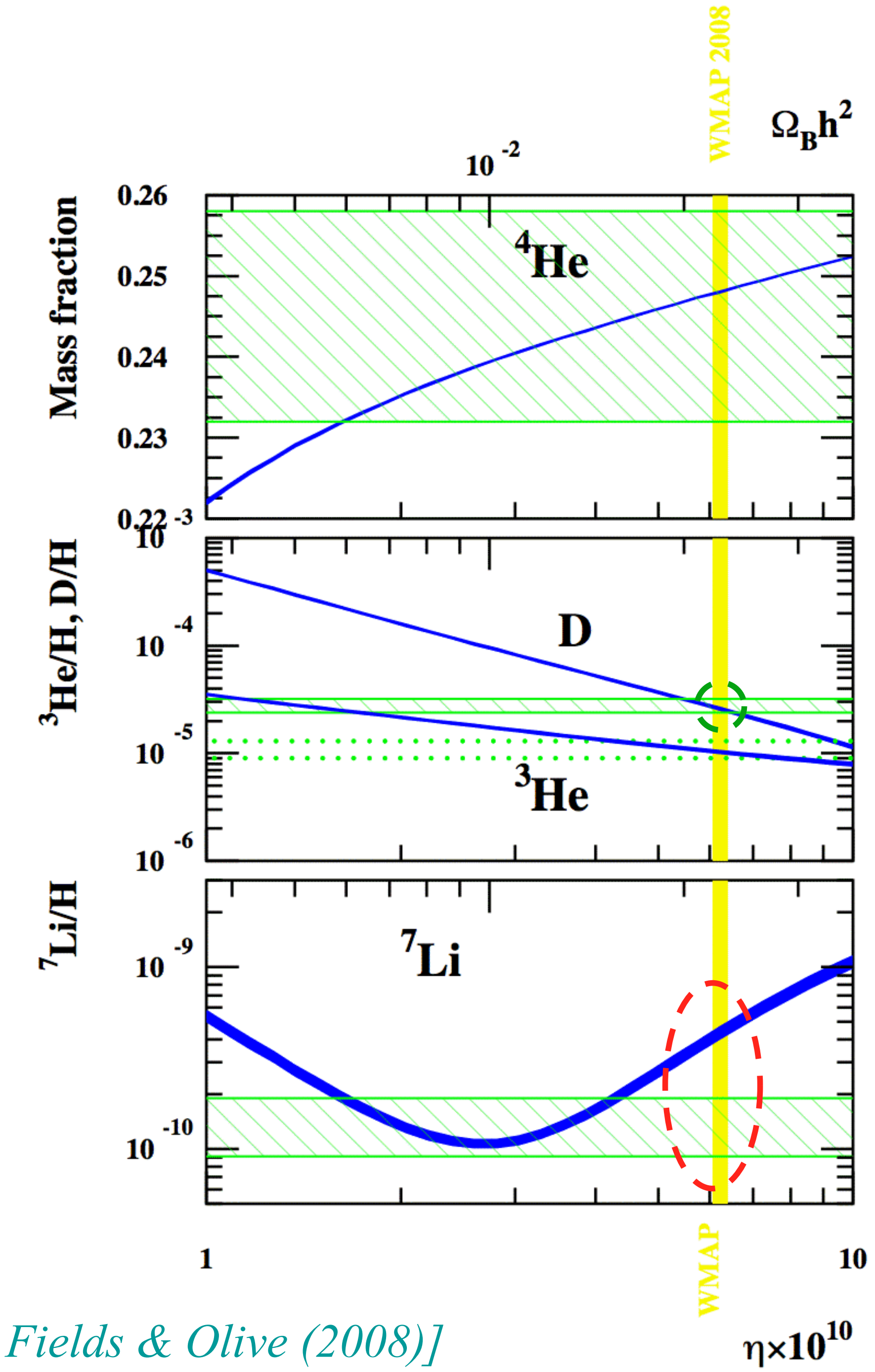

$^2H(d,p)^3H$
S-factor (keV-b)
1.00
0.10
0.01
0.001
0.01
0.1
1
10
SC72
KR87a
BR90
GR95
KR87
GR95
BR90
tout
G. Hale
E (MeV)

Comparison between observed and calculated abundances

Limits (1-σ) obtained by Monte-Carlo from *Descouvemont et al. (2004)* reaction rate uncertainties.

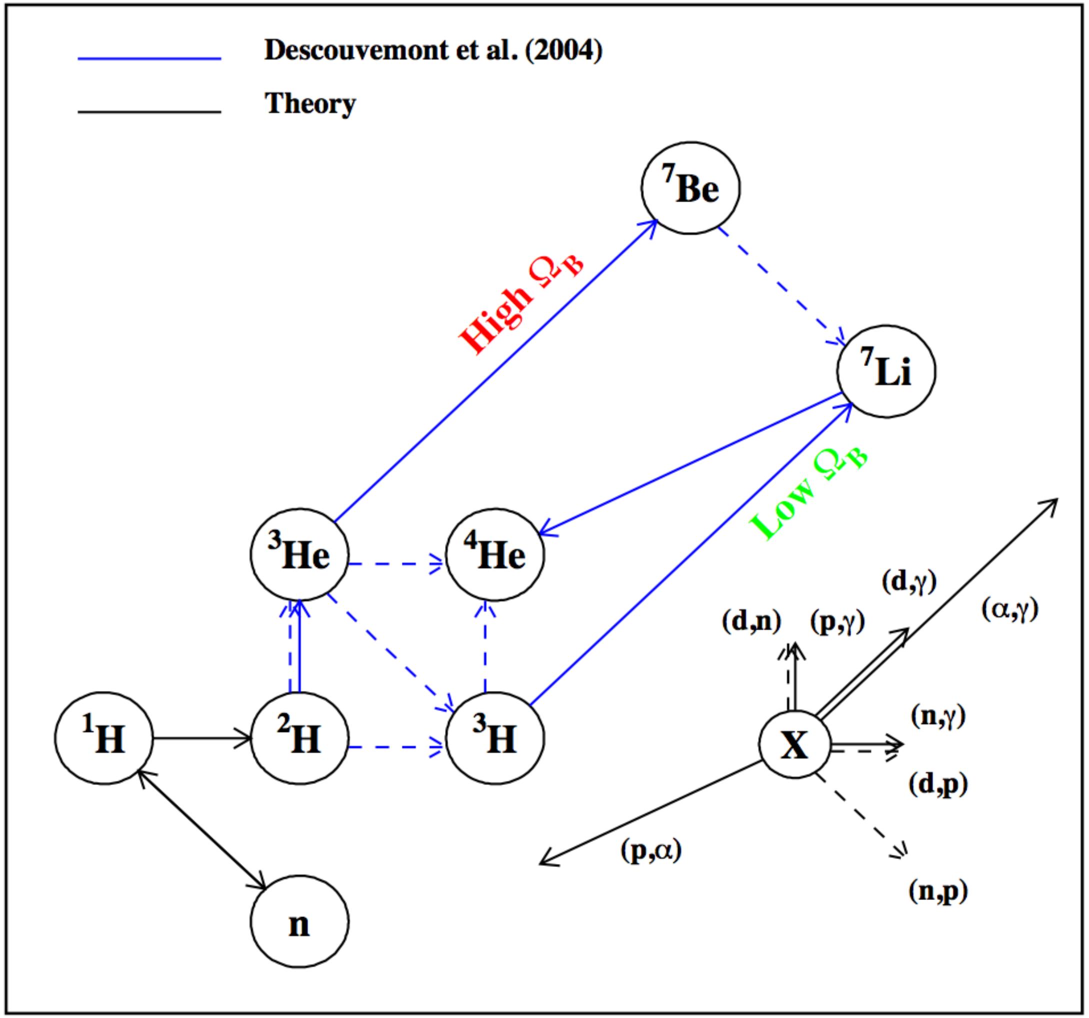
Concordance (?) BBN, spectroscopy and CMB

- $\Omega_B h^2$ *[WMAP: Spergel et al. (2003,2006)]*
- **^{4}He** *[Olive & Skillman (2004)]*
- **D** *[Fields &Sarkar (2008)]*
- **^{3}He** *[Bania et al. (2002)]*
- **^{7}Li** *[Ryan et al. (1999,2000)]* : difference of a factor of 2-3 between calculated (BBN+CMB) and observed (Spite plateau) primordial lithium



[Coc et al. (2006), Cyburt, Fields & Olive (2008)]

The 12 reactions of standard BBN



Sensitivity to thermonuclear reaction rates

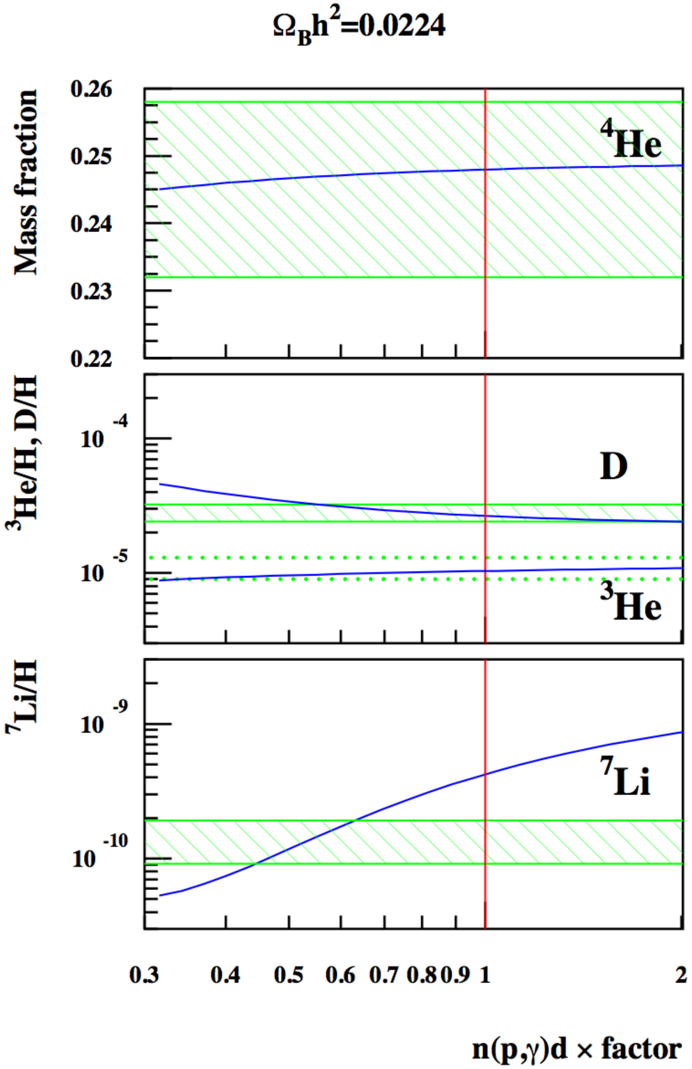
$$\frac{\Delta Y}{Y} = \boxed{\left.\frac{\partial \ln(Y)}{\partial \ln(N_A\langle\sigma v\rangle)}\right|_{\eta=\eta_{WMAP}}} \times \frac{\Delta N_A\langle\sigma v\rangle}{N_A\langle\sigma v\rangle}$$

At WMAP baryonic density

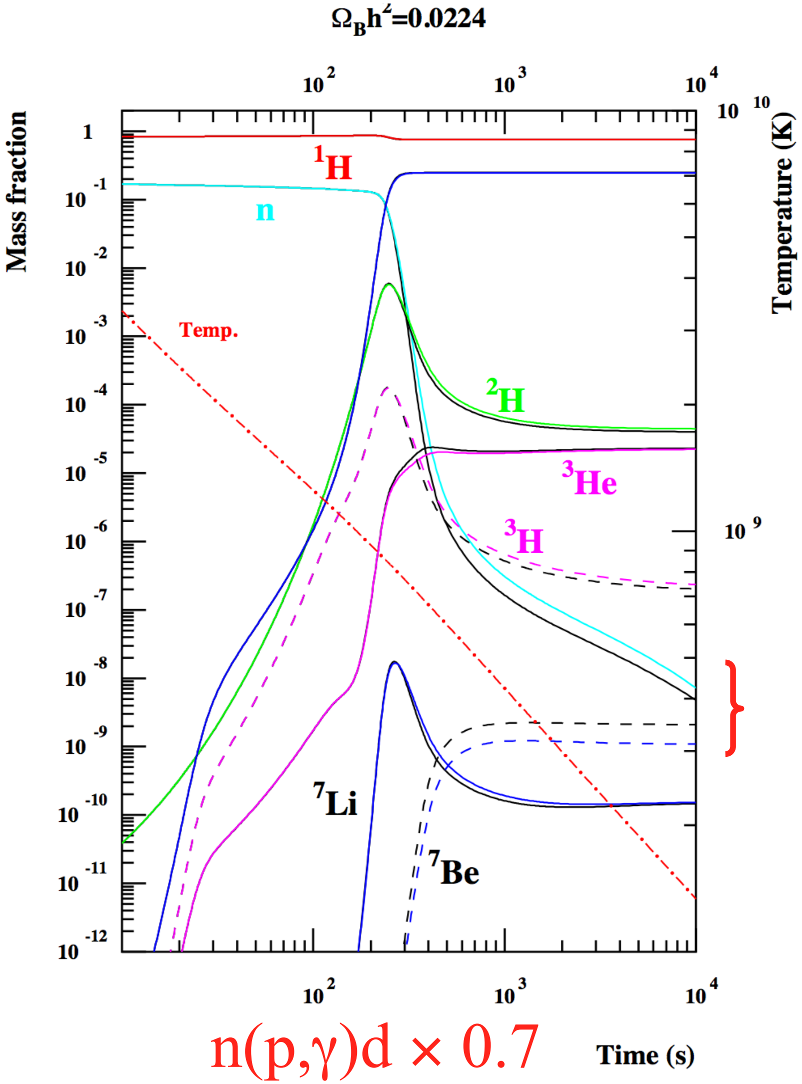
	$\partial \ln(Y) / \partial \ln(N_A\langle\sigma v\rangle)$				$E_0(\Delta E_0/2)$ (MeV @ 1GK)
Reaction	^{4}He	D	^{3}He	^{7}Li	
τ_n (n↔p)	0.73	0.42	0.15	0.40	
^{1}H(n,γ)^{2}H	0	-0.20	0.08	1.33	0.025
^{2}H(p,γ)^{3}He	0	-0.32	0.37	0.57	0.11(0.11)
^{2}H(d,n)^{3}He	0	-0.54	0.21	0.69	0.12(0.12)
^{2}H(d,p)^{3}H	0	-0.46	-0.26	0.05	0.12(0.12)
^{3}H(d,n)^{4}He	0	0	-0.01	-0.02	0.13(0.12)
^{3}H(α,γ)^{7}Li	0	0	0	0.03	0.23(0.17)
^{3}He(n,p)^{3}H	0	0.02	-0.17	-0.27	
^{3}He(d,p)^{4}He	0	0.01	-0.75	-0.75	0.21(0.15)
^{3}He(α,γ)^{7}Be	0	0	0	0.97	0.37(0.21)
^{7}Li(p,α)^{4}He	0	0	0	-0.05	0.24(0.17)
^{7}Be(n,p)^{7}Li	0	0	0	-0.71	

Influence of $^1H(n,\gamma)D$ reaction rate

(at WMAP/ΛCDM baryonic density)



$\Omega_B h^2=0.0224$



$\Omega_B h^2=0.0224$

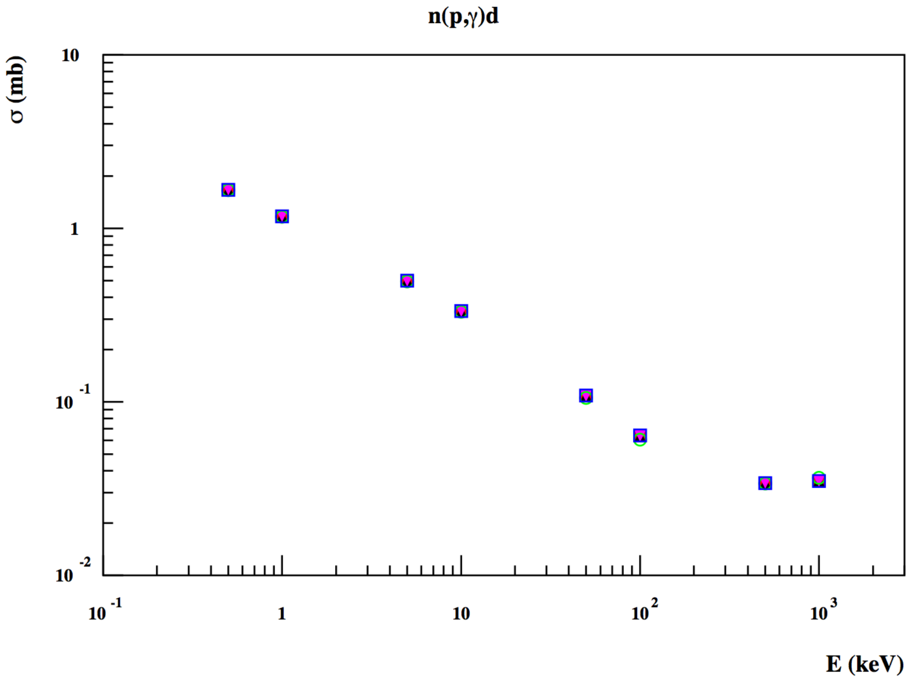
n(p,γ)d × 0.7

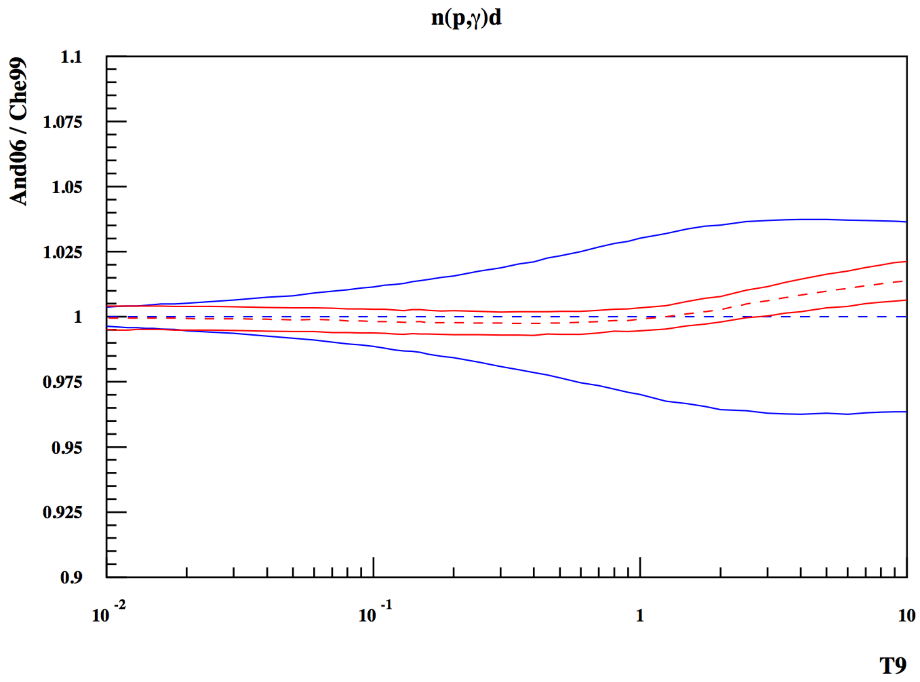
The $^1H(n,\gamma)^2H$ reaction

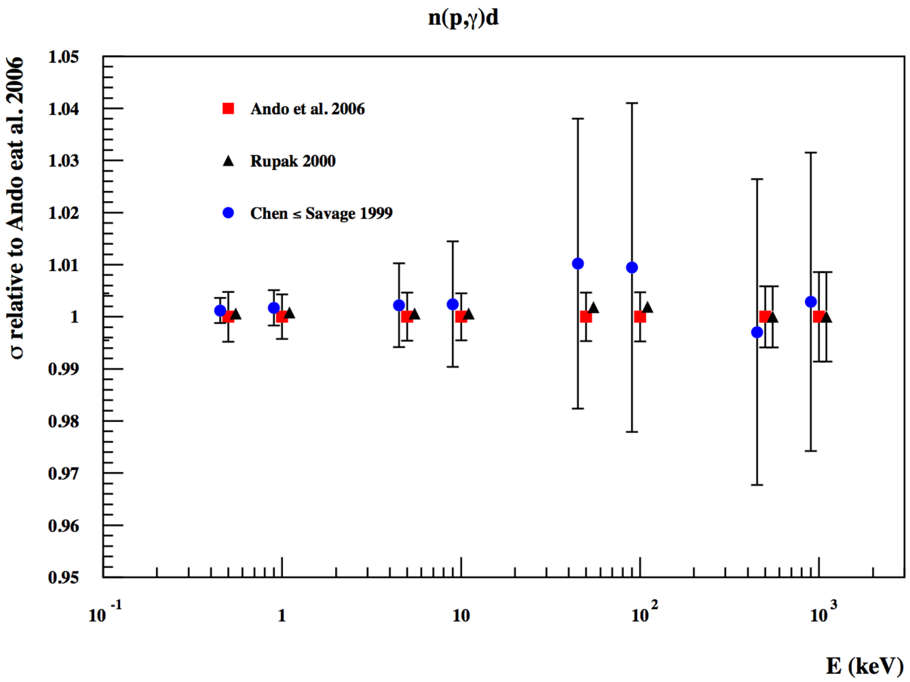
Sensitivity = 1.33

E ~ 25 keV

New precise n(p,γ)d EFT cross section ar
rate calculation *[Ando et al. 2006]*

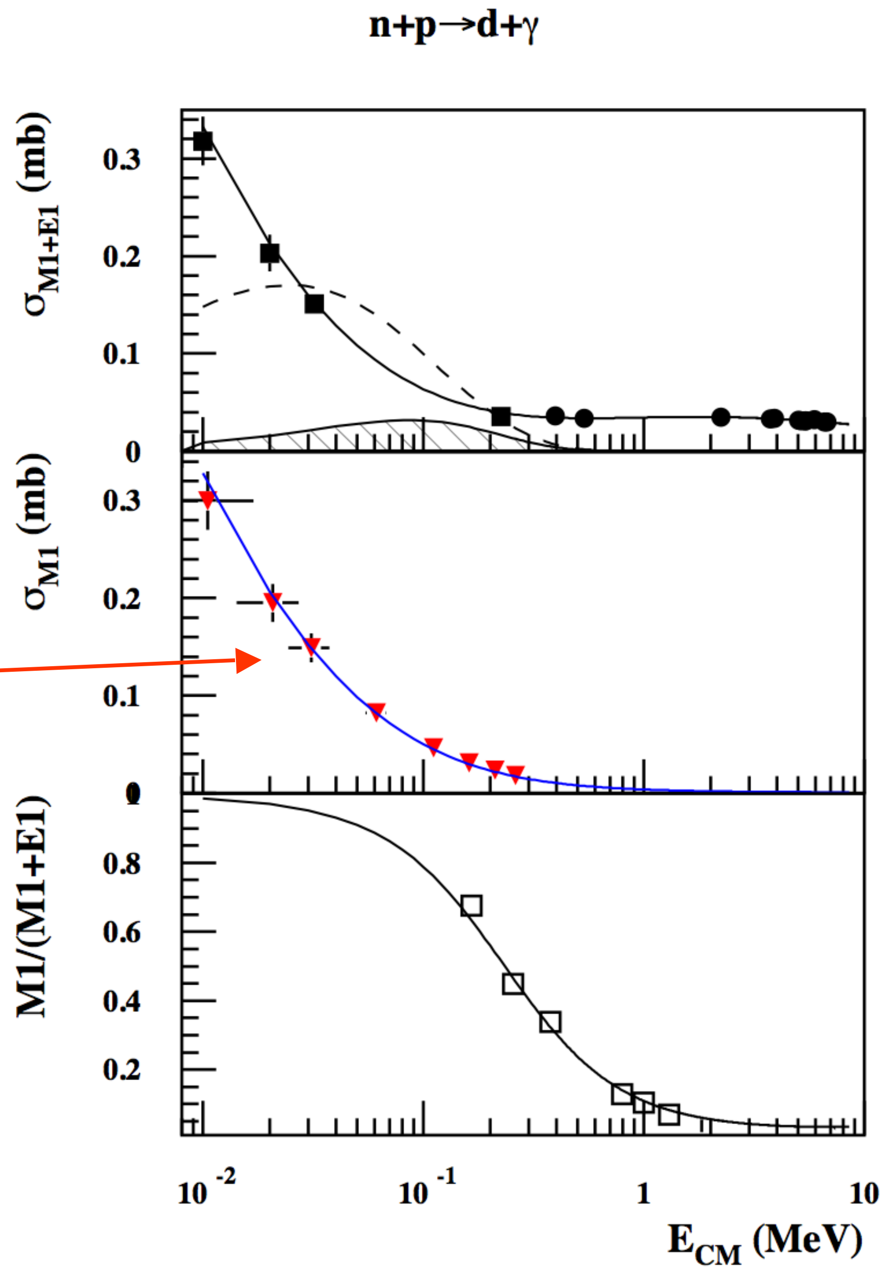






The $^1H(n,\gamma)^2H$ reaction

New measurement of the M1 contribution *[Ryezaveva et al. 2006]* by inelastic electron scattering off *D*



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

Sensitivity = 0.97

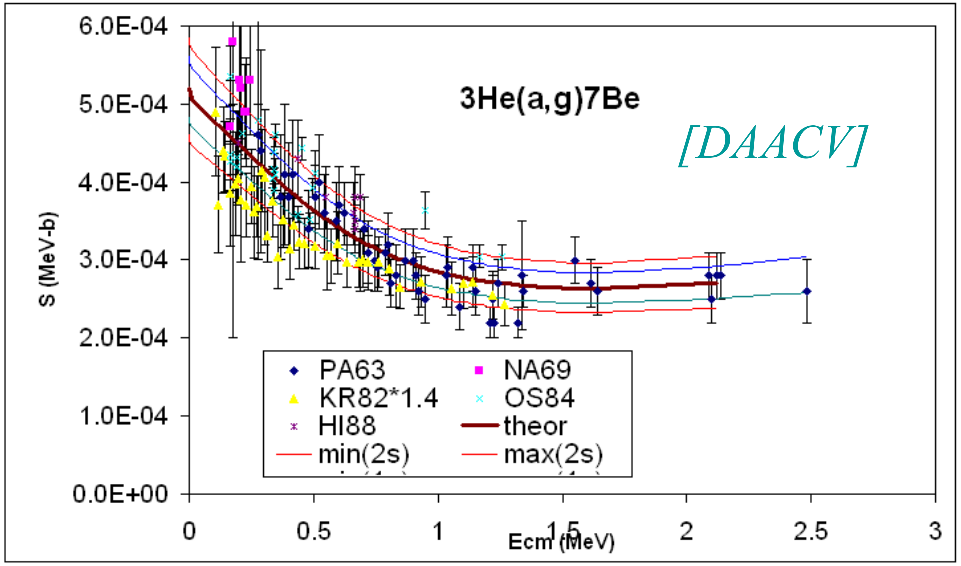
$E_0(\Delta E_0/2) = 0.37(0.21)$ MeV

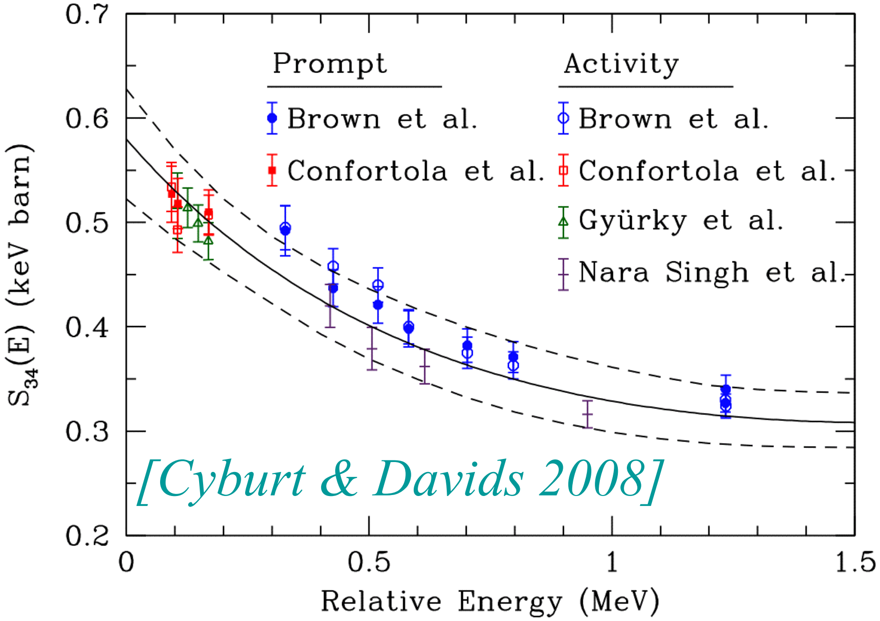
Systematic uncertainties : *prompt* versus *activation* measurements

New precise measurements (in particular at LUNA) :

- Prompt *[Brown et al. 2007, Confortola et al. 2007, Costantini et al. 2008]*
- Activation *[Nara Singh et al. 2005, Brown et al. 2007, Confortola et al. 2007, Gyürky et al. 2007]*
- Recoil *[Di Leva et al. 2009]*

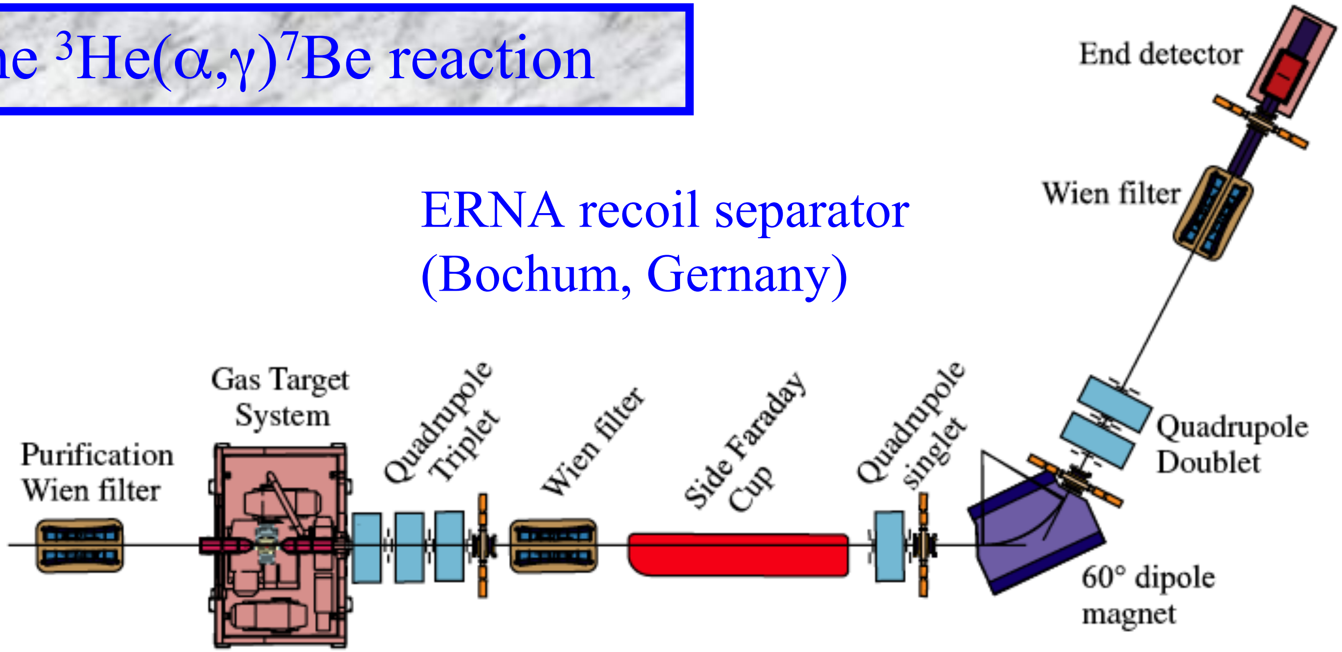
Reanalysis of $^3He(\alpha,\gamma)^7Be$ rate *[Cyburt & Davids 2008]*: *S(0)* = 0.580±0.043 keV.b (13% higher than in DAACV04)





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

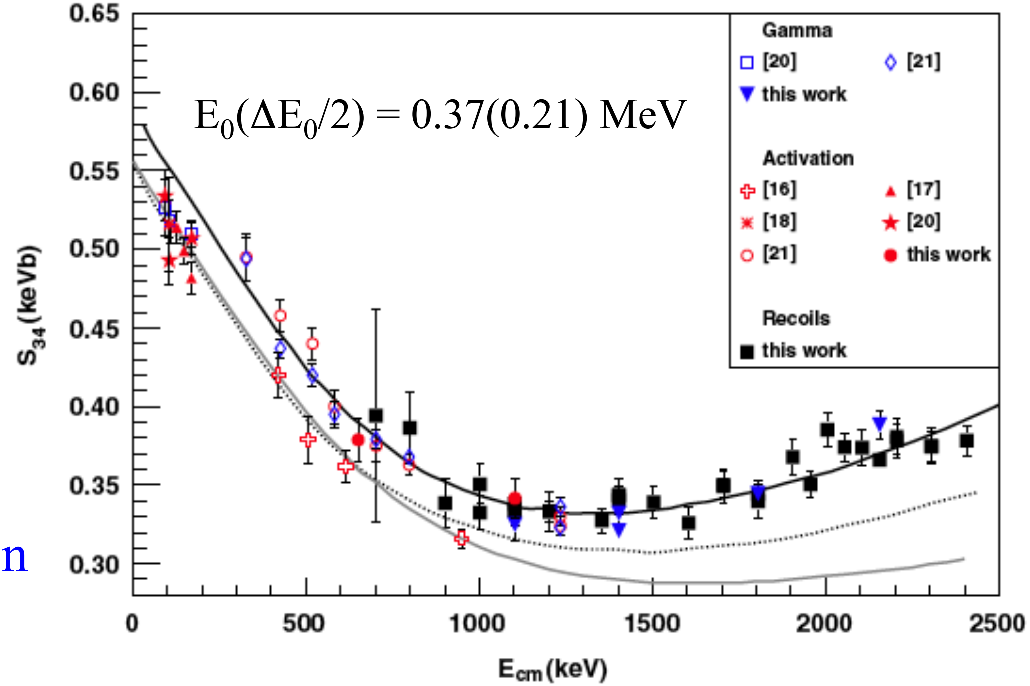
ERNA recoil separator
(Bochum, Gernany)



Recoil (+ prompt) *[Di Leva et al. 2009]* with ERNA

S(0) = 0.57±0.04 keV.b

S(0) = 0.56±0.02±0.02 keV.b
Adelberger et al. 2010 latest evaluation of solar fusion cross sections



The $^2H(d,n)^3He$ reaction

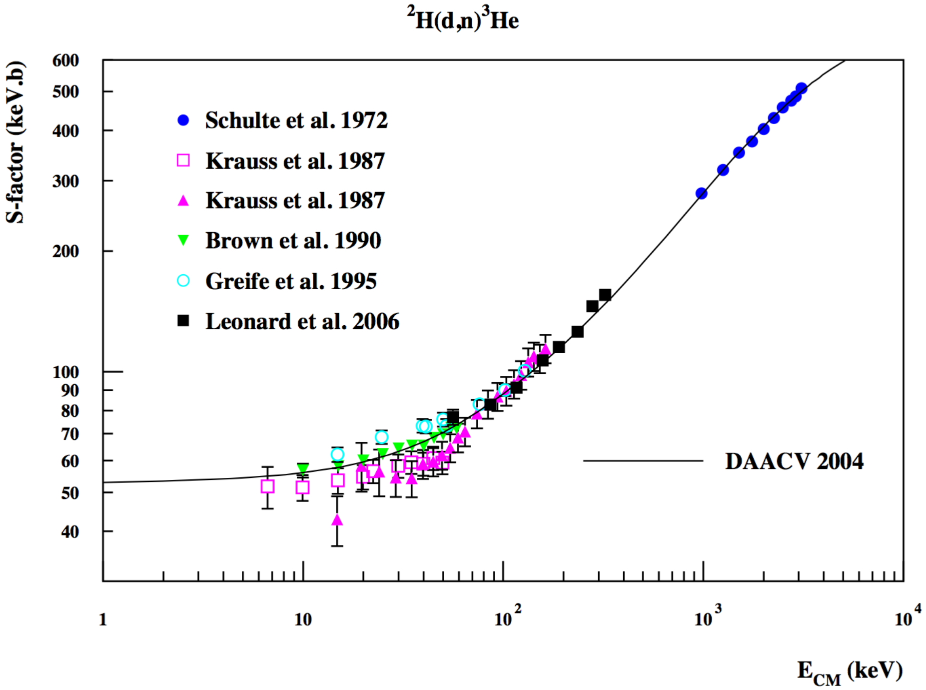
Sensitivity = 0.61

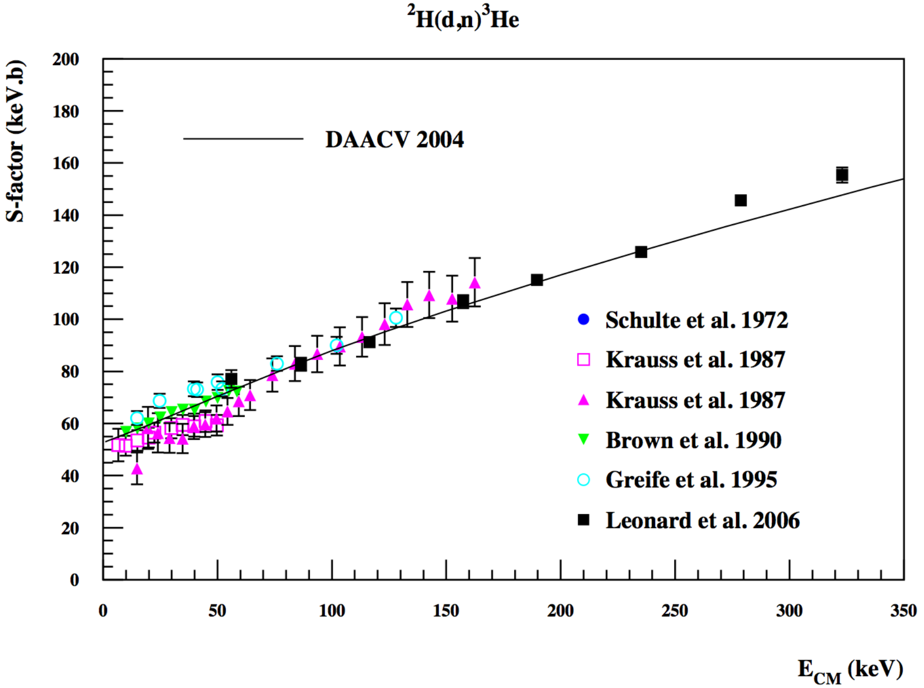
$E_0(\Delta E_0/2) = 0.12(0.12)$ MeV

New precise measurements of $^2H(d,n)^3He$ (and $^2H(d,p)^3H$) reaction at TUNL *[Leonard et al. 2006]*

Excellent agreement with *DAACV 2004* fit within Gamow window

- ➢ No change in central Li/H value
- ➢ Reduced uncertainty
- ➢ R-matrix fit reliability





Astrophysical aspects

Extracting Li/H abundances from observed atomic spectra *(See Ryan et al. 2000)*

- Extrapolation to zero metallicity
- 1D versus 3D atmosphere model
- Surface gravity
- Non Local Thermodynamical Equillibrium
- Stellar depletion *[Richard, Michau & Richer, 2005; Korn et al. 2006]*
  - Diffusion and turbulent mixing depletes Li surface abundance
- Effective temperature scale *[Hosford et al. 2008]*
  - Improved temperature scale (ΔLi/Li $\approx 6\ 10^{-4}\ \Delta T_{eff}$) :
    Li/H = $(1.14 \pm 0.07) \times 10^{-10}$ (reduced uncertainty)

The Li problem update

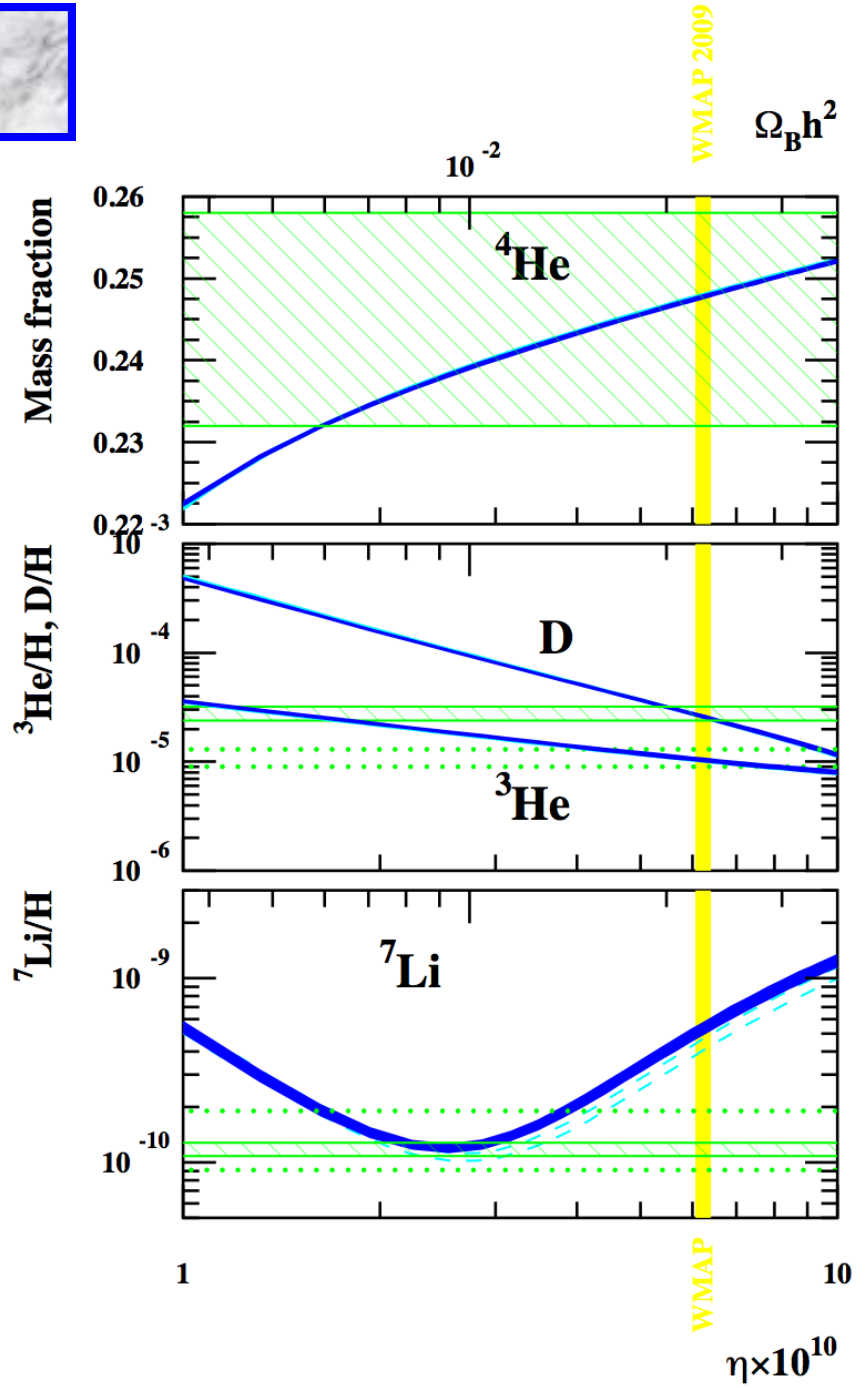
❑New ^{3}He(α,γ)^{7}Be and n(p,g)d rates :

- Li/H = $(5.24\pm0.67)\times10^{-10}$ *[Cyburt, Fields & Olive 2008]*
- Li/H = $(5.14\pm0.50)\times10^{-10}$ *[Coc & Vangioni 2010]*

New abundance determinations :

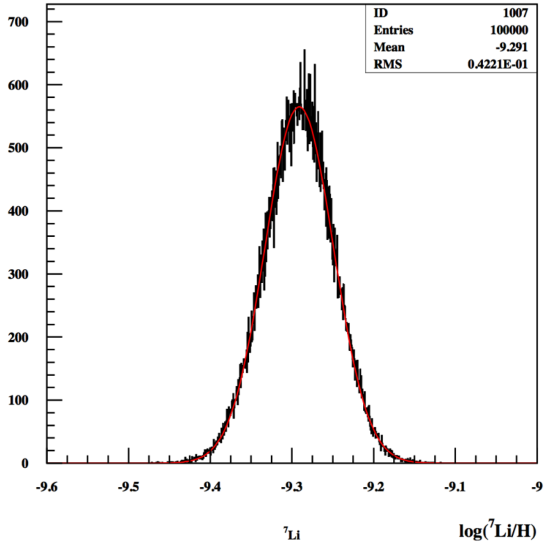
- Li/H = $(1.14\pm0.07)\times10^{-10}$ *[Hosford et al. 2008]*, ...

❑^{7}**Li** difference of a factor of ≈5 rather than ≈3!



Monte-Carlo BBN versus observations

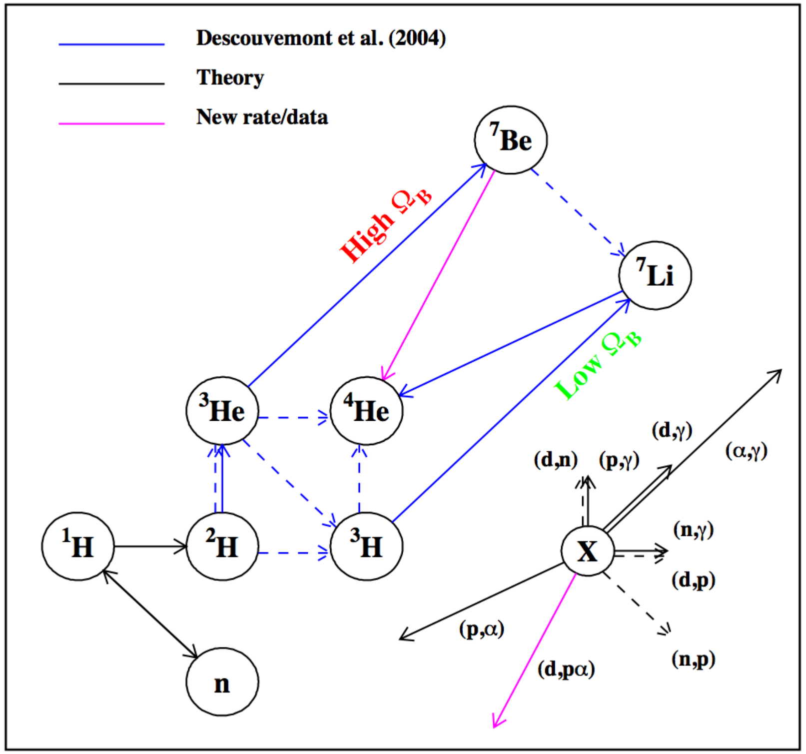
Using log-normal distribution (see Iliadis et al., to be submitted to NPA) for the reaction rates from *DAACV*, *Ando et al. 2006*, *Leonard et al. 2006*, and *Cyburt & Davids 2008*.



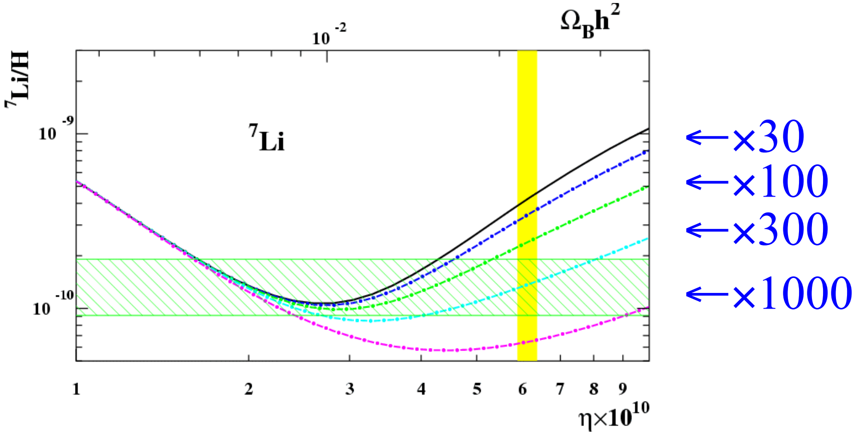
	BBN calculations		Observations	
	Cyburt et al. 2008	*Coc & Vangioni 2010*		
^{4}He	0.2486±0.0002	0.2476±0.0004	0.232-0.258	$\times 10^{0}$
D/H	2.49±0.17	2.68±0.15	2.84±0.26	$\times 10^{-5}$
^{3}He/H	1.00±0.07	1.05±0.04	(0.9-1.3)	$\times 10^{-5}$
^{7}Li/H	$5.24^{+0.71}_{-0.62}$	5.14±0.50	1.14±0.07	$\times 10^{-10}$

Other nuclear reaction rates

- About 100 other reactions involved in SBBN from H to B
- Among them ≈40 remain whose uncertainty on rate is not available
- Systematic check by varying the rates by factors of 10, 100, 1000.



An interesting case :
the ^{7}Be(d,p)2α reaction

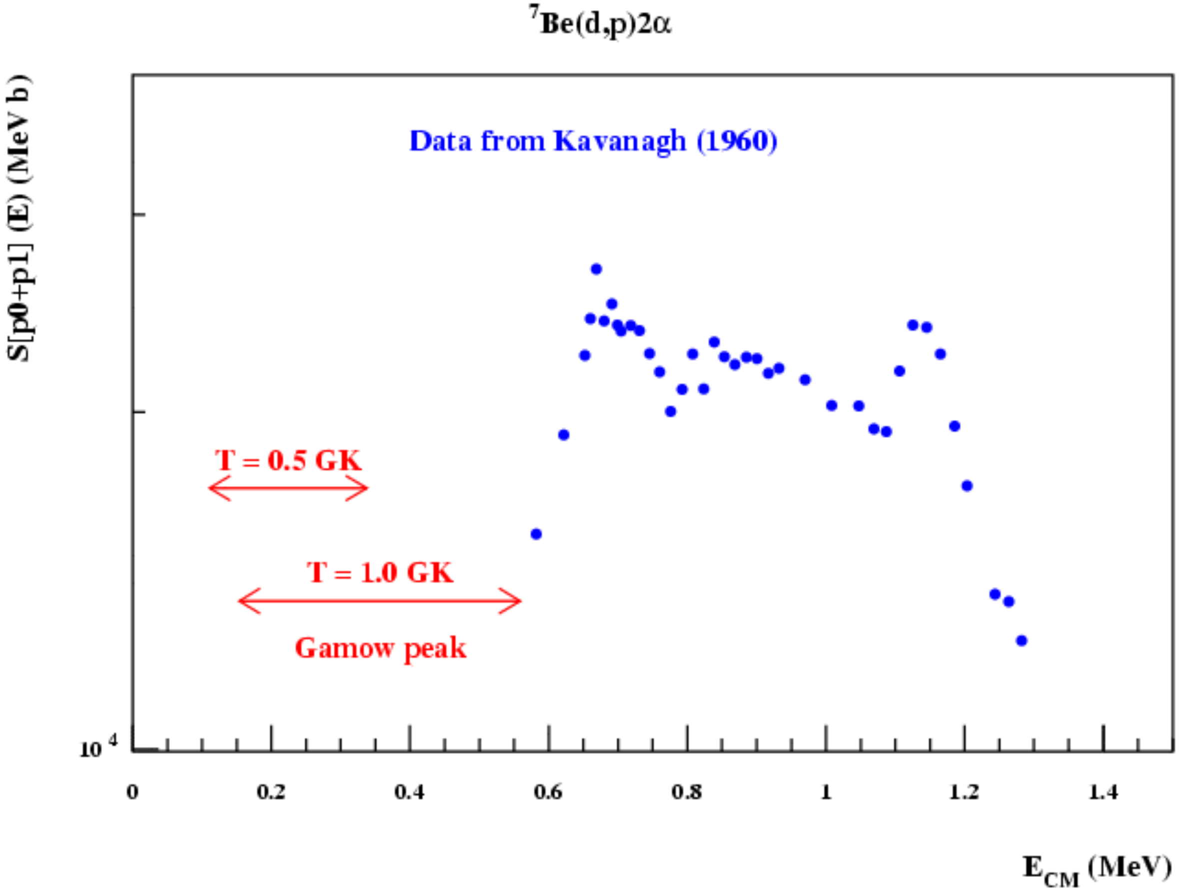


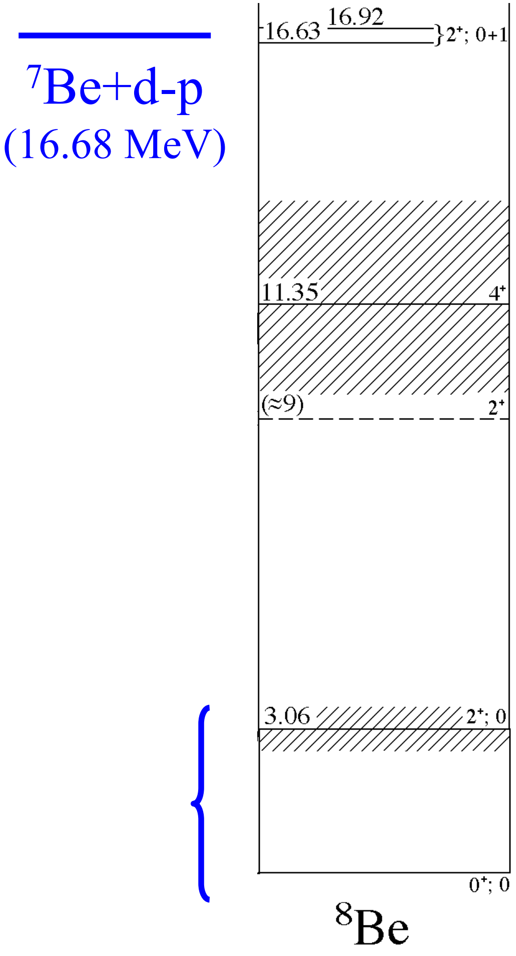
Experimental data on ^{7}Be(d,p)2α reaction

Reaction rate *[CF88]* from an estimate *[Parker, 1972]* based on partial experimental data *[Kavanagh, 1960]*

No data at BBN energies! Only ^{8}Be g.s. and 1st level

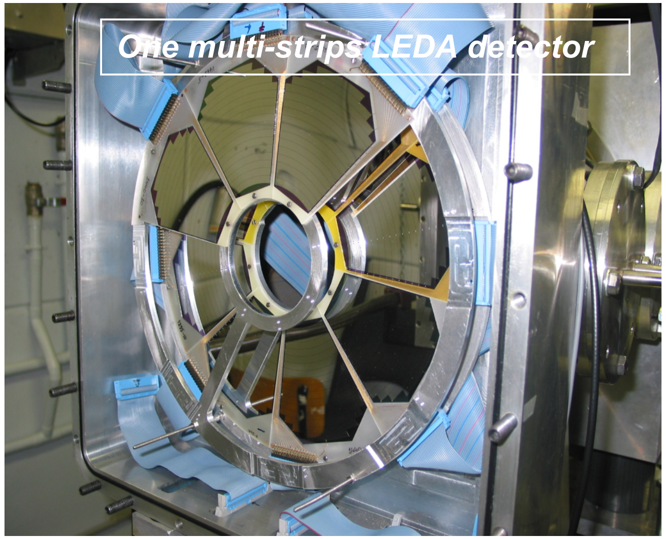
^{7}Be(d,p)^{8}Be*→2α

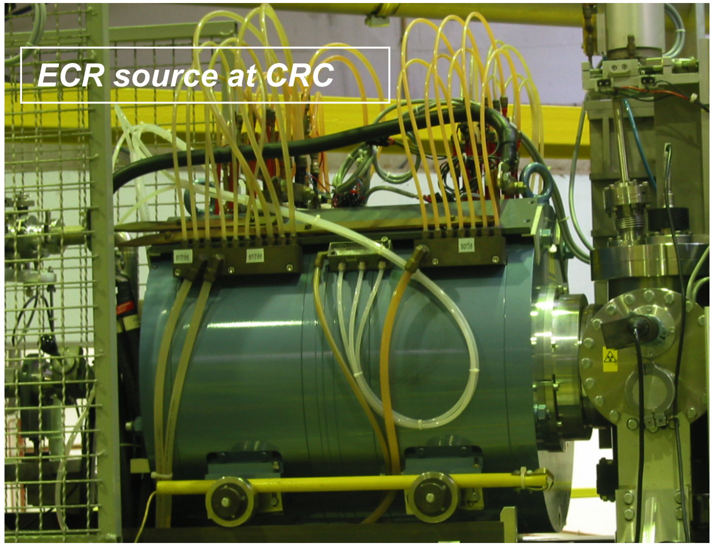


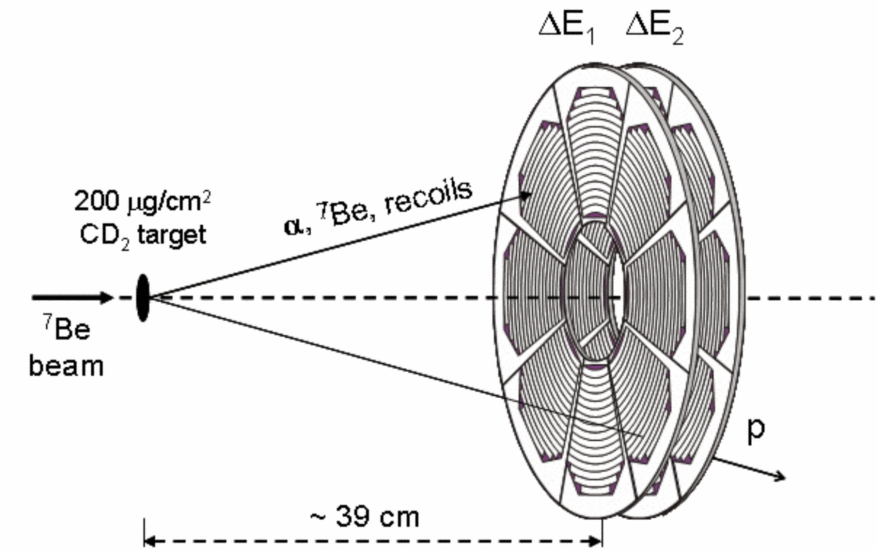


The ^{7}Be(d,p)2α experiment

Centre de Recherche du Cyclotron, Louvain-la-Neuve







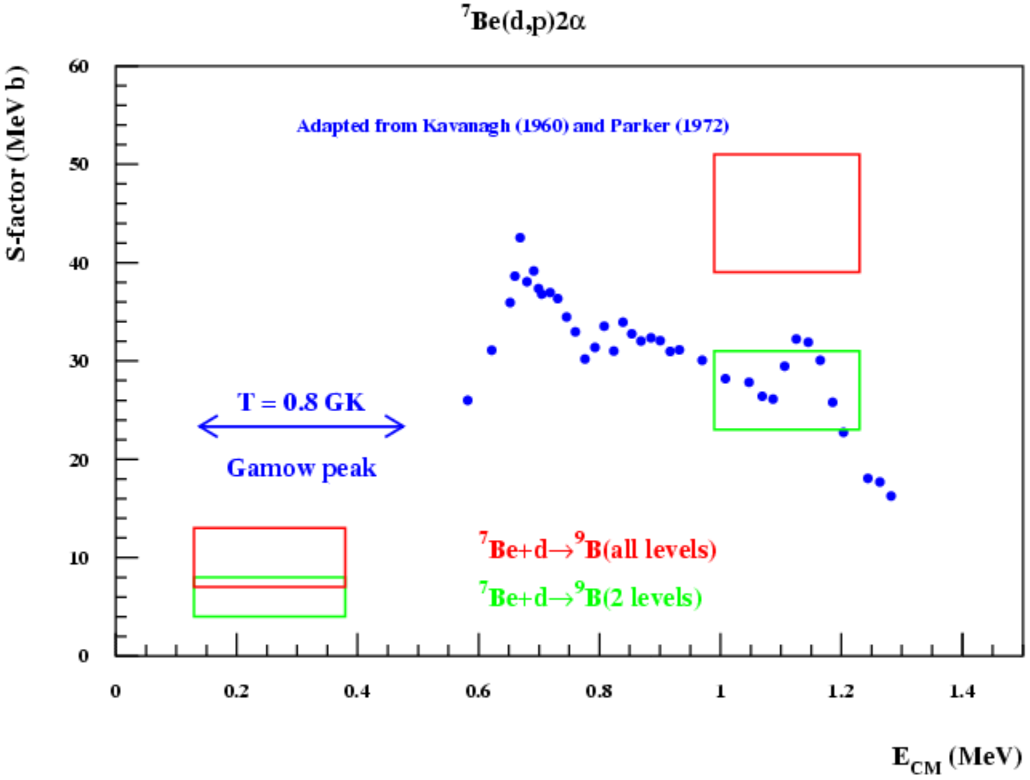
Beam : 0.2-1. 10^7 pps of ^{7}Be at 5.8 MeV, degraded to 1.8 MeV (0.4 MeV c.m.)

Target : 200 µg/cm^2 CD_2 poliethylene

Detectors : two (LEDA) multistrips (8× 16) Si detectors (300 and 500 µm)

^{7}Be(d,p)2α cross-section

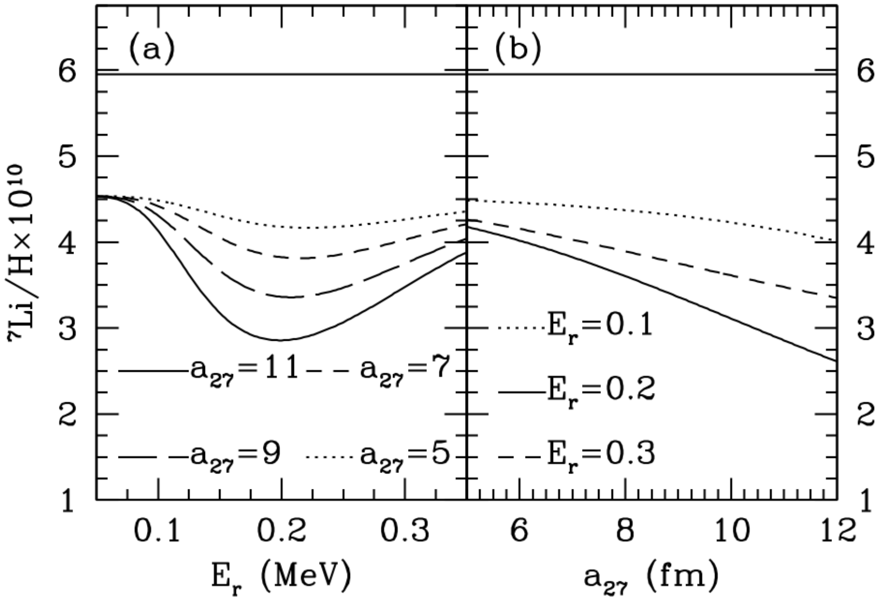
Integrated (ΔE≈0.23 MeV) cross section *[Angulo et al. , ApJL (2005)]*

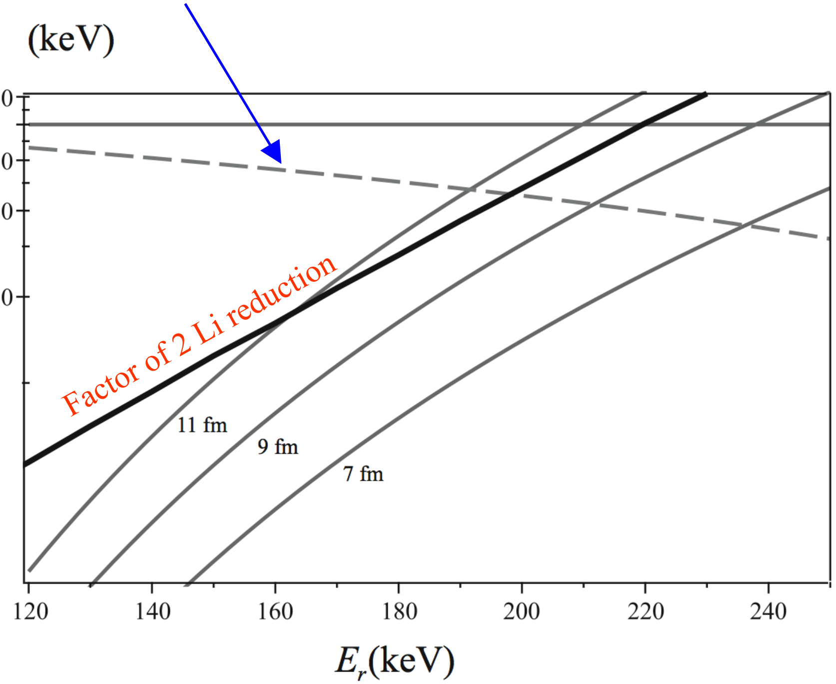


- ➢^{9}B ground state and first excited level contribution (comparison with Kavanagh)
  - ➢All ^{9}B level contribution
  - ➢No cross section enhancement

A new resonance in ^{7}Be(d,p)2α ???

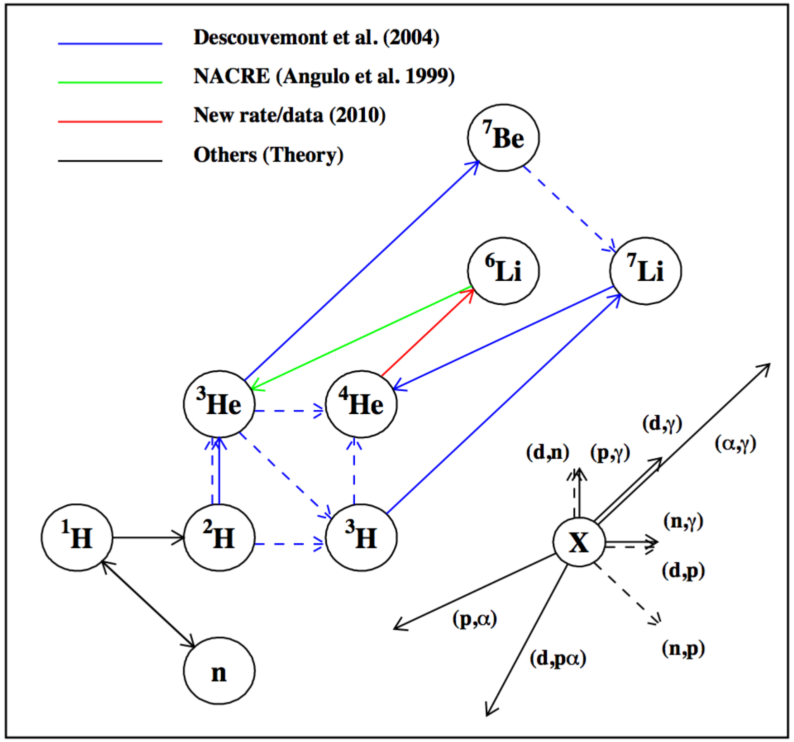
- Hypothetical resonance at $E_R = 200 \pm 100$ keV with $\Gamma \leq 40$ keV *[Cyburt & Pospelov 2009]*
  - corresponding to a ^{9}B level analog of the 16.7 MeV 5/2+ one in ^{9}Be
  - extreme Γ_d value at “Wigner limit” with very large interaction radius
  - within limits given by Louvain-la-Neuve experiment

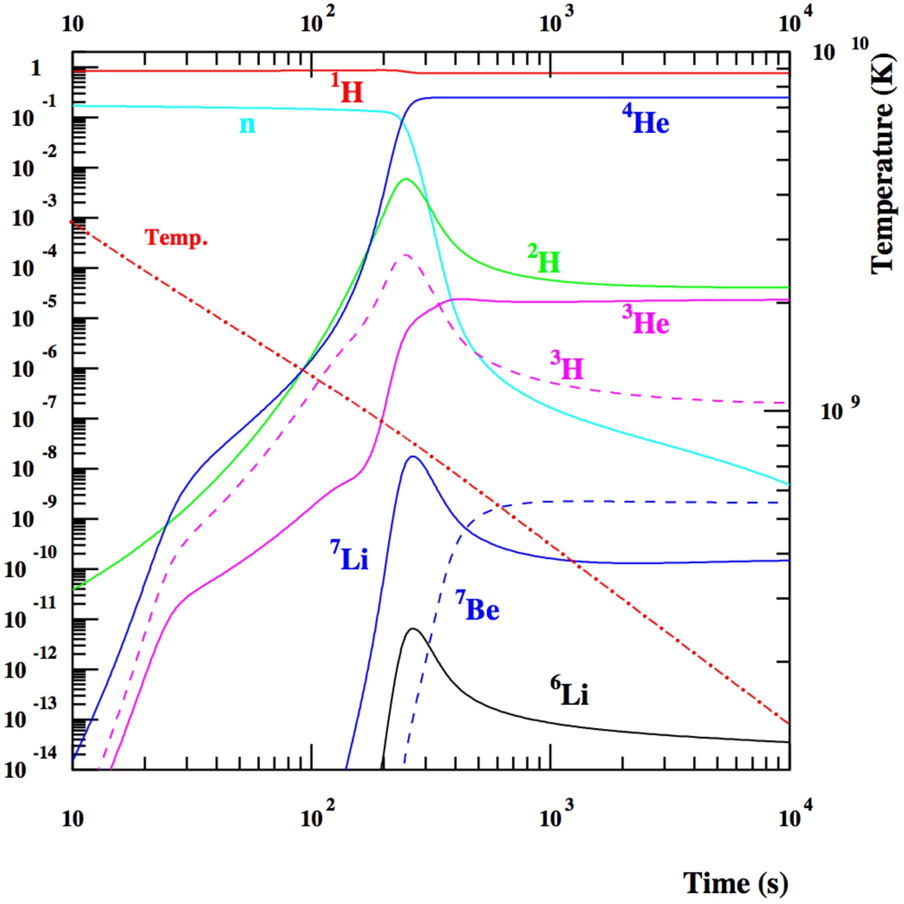




^{6}Li nucleosynthesis

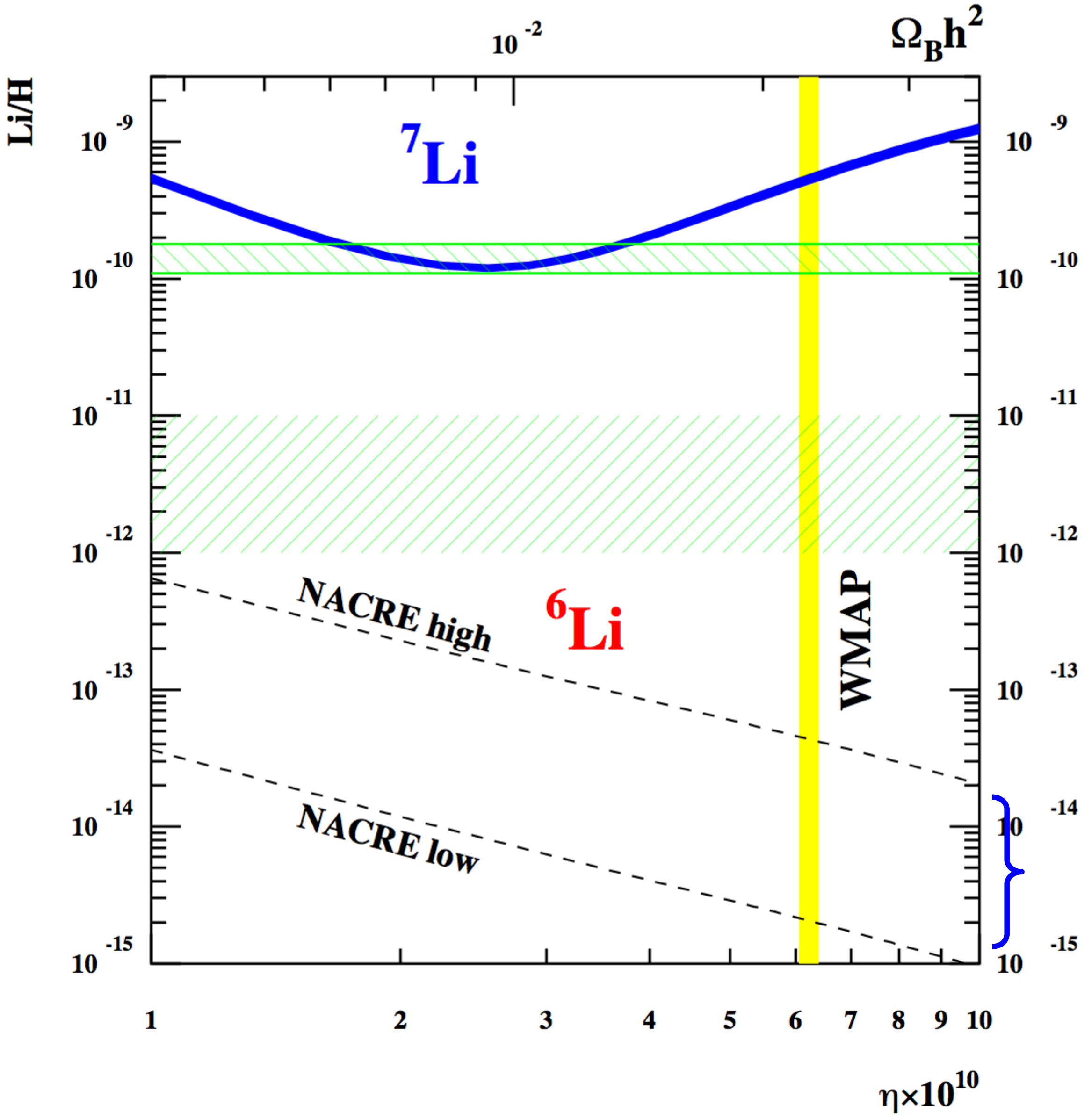
At WMAP baryonic density





12 main reactions for ^{4}He, D, ^{3}He, ^{7}Li (+2 for ^{6}Li) nucleosynthesis:
10 (+2) from experiments and 2 from theory

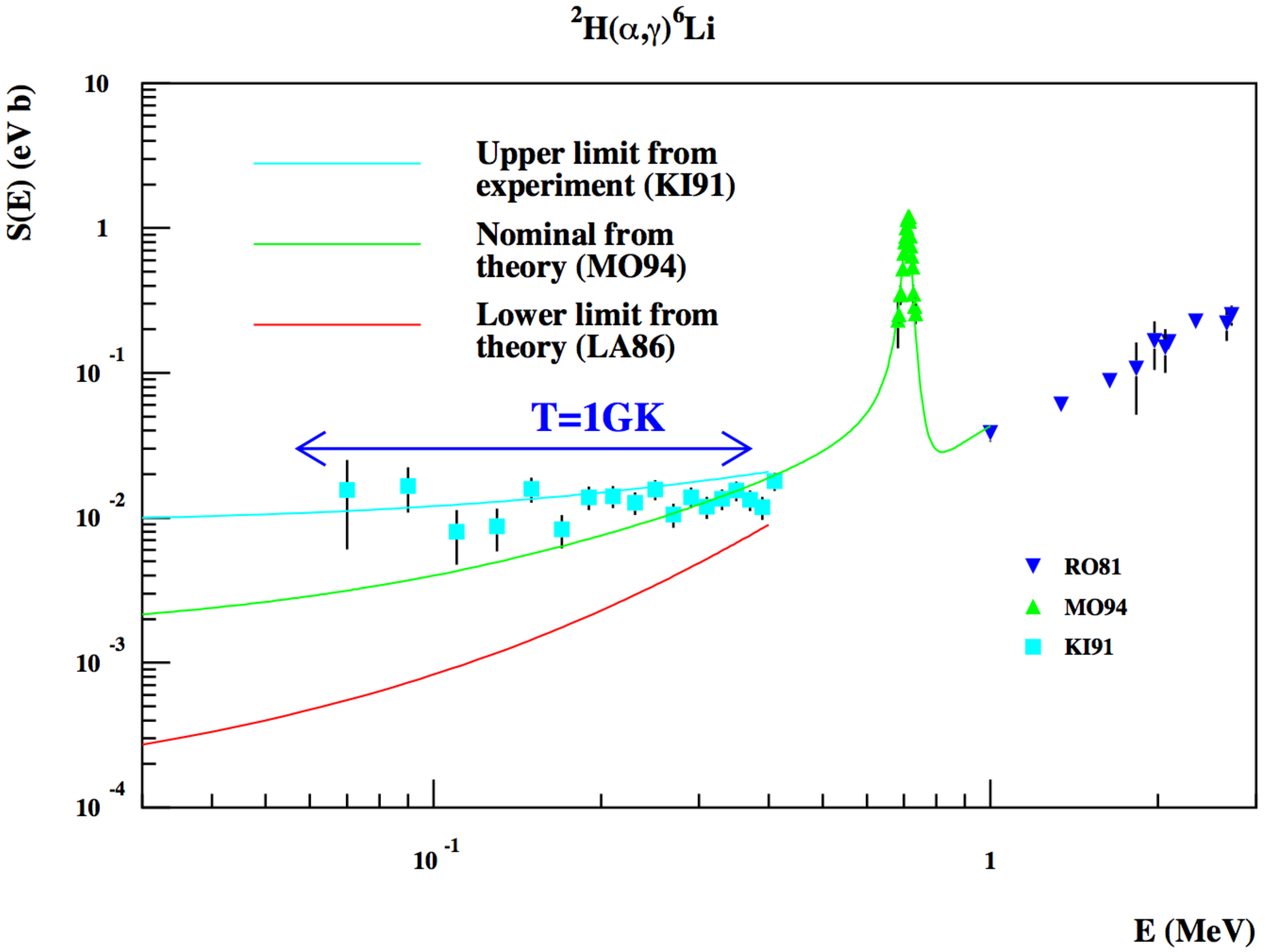
The ^{6}Li problem vs nuclear physics



- ^{4}He(t,n)^{6}Li, ^{7}Li(p,d)^{6}Li : Q ≈ -5MeV
- ^{3}He(t,γ)^{6}Li : too slow

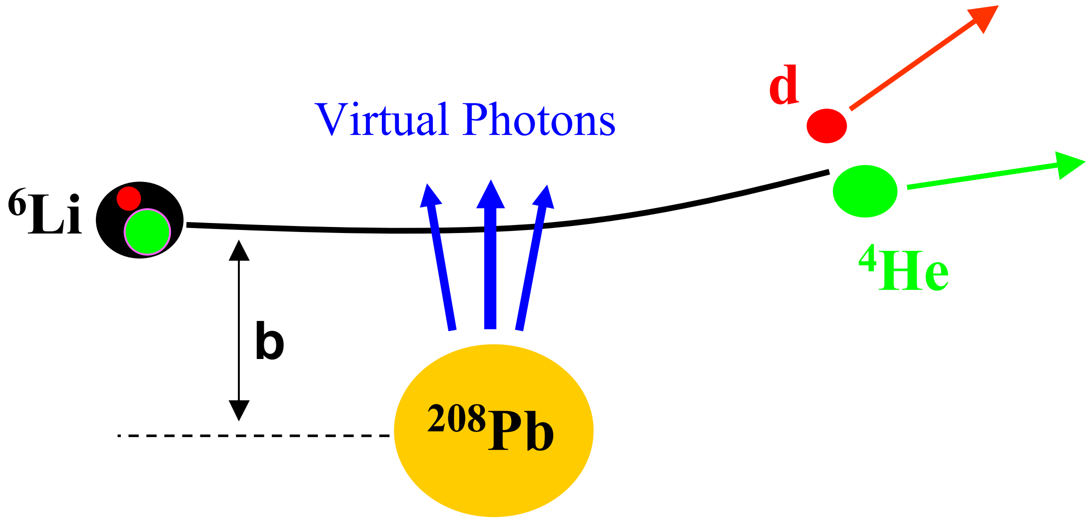
Uncertainty from ^{2}H(α,γ)^{6}Li (NACRE)

The ^{2}H(α,γ)^{6}Li rate in NACRE

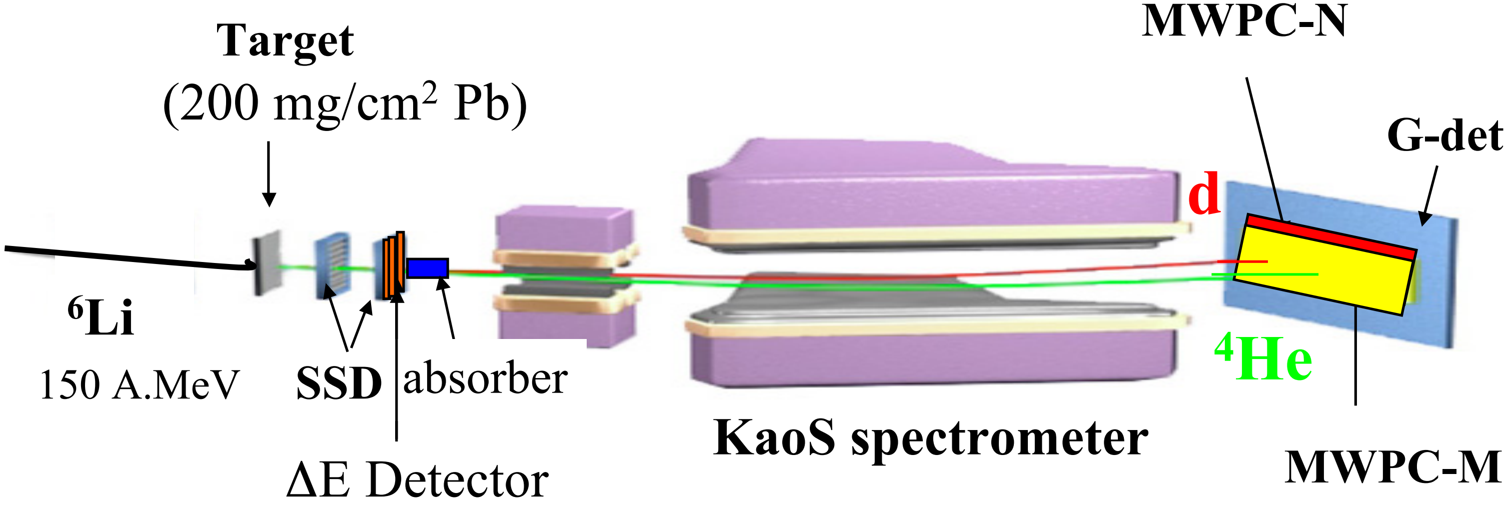


Coulomb dissociation of ^{6}Li

$^{2}H(\alpha,\gamma)^{6}Li$ ⇔ ^{6}Li Coulomb dissociation



Coulomb dissociation of ^{6}Li at GSI

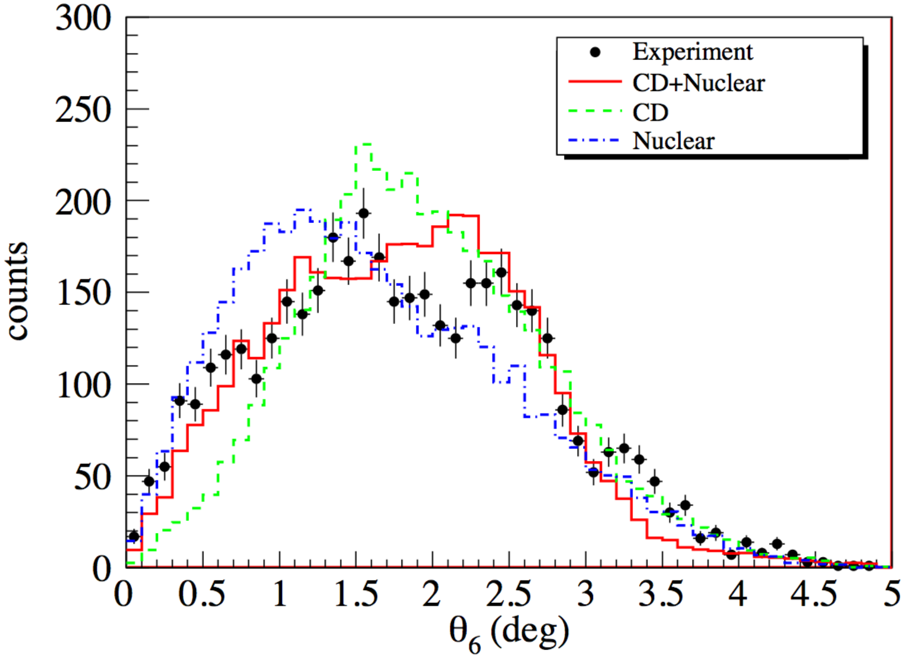


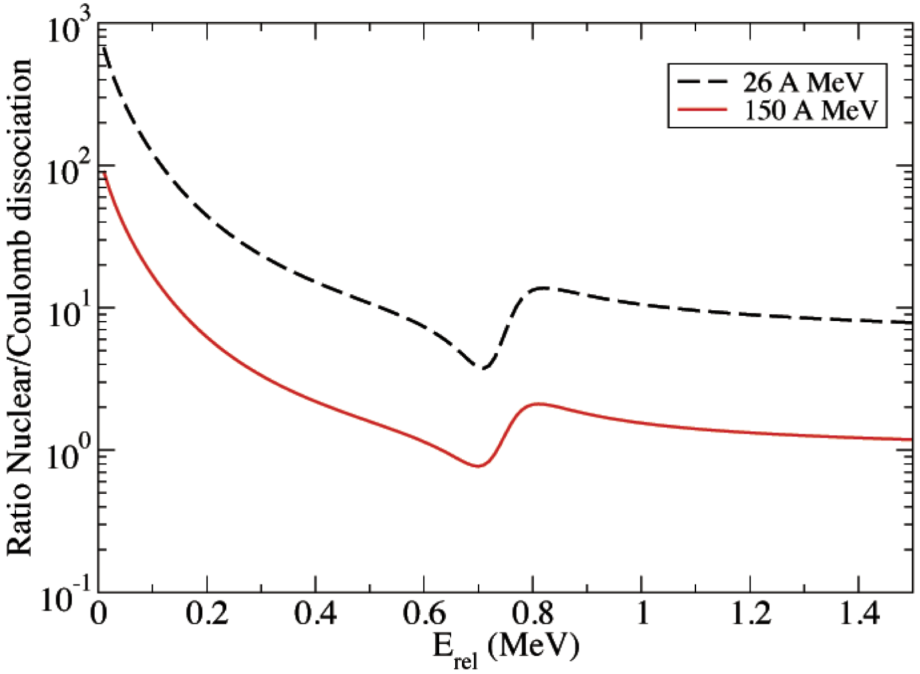
Coulomb dissociation of ^{6}Li at GSI

❑ From *S. Typel*'s calculations :

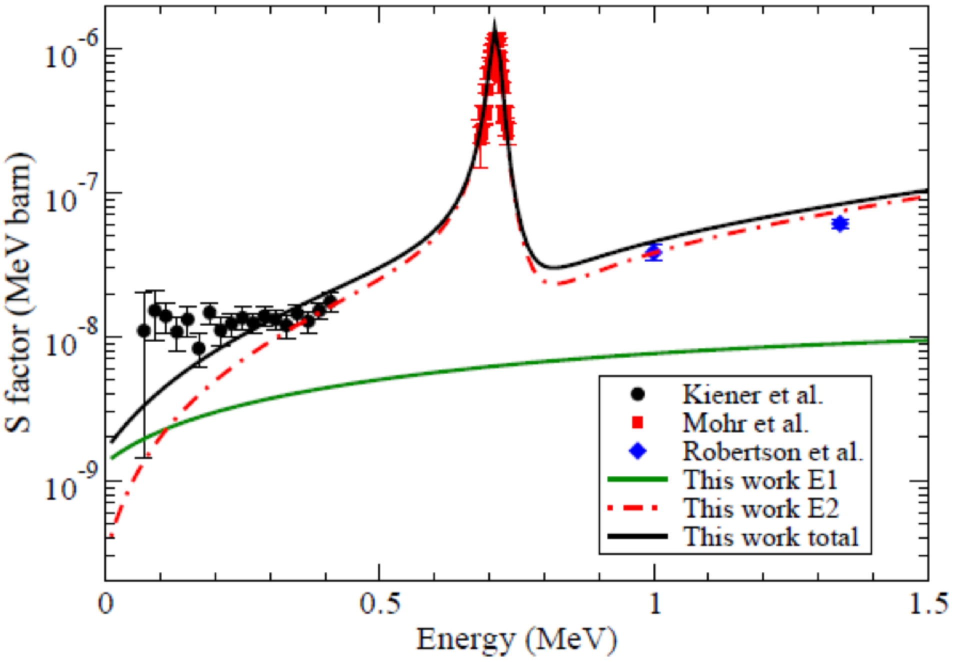
➢ At 150 A MeV (GSI), the nuclear breack-up contribution is important

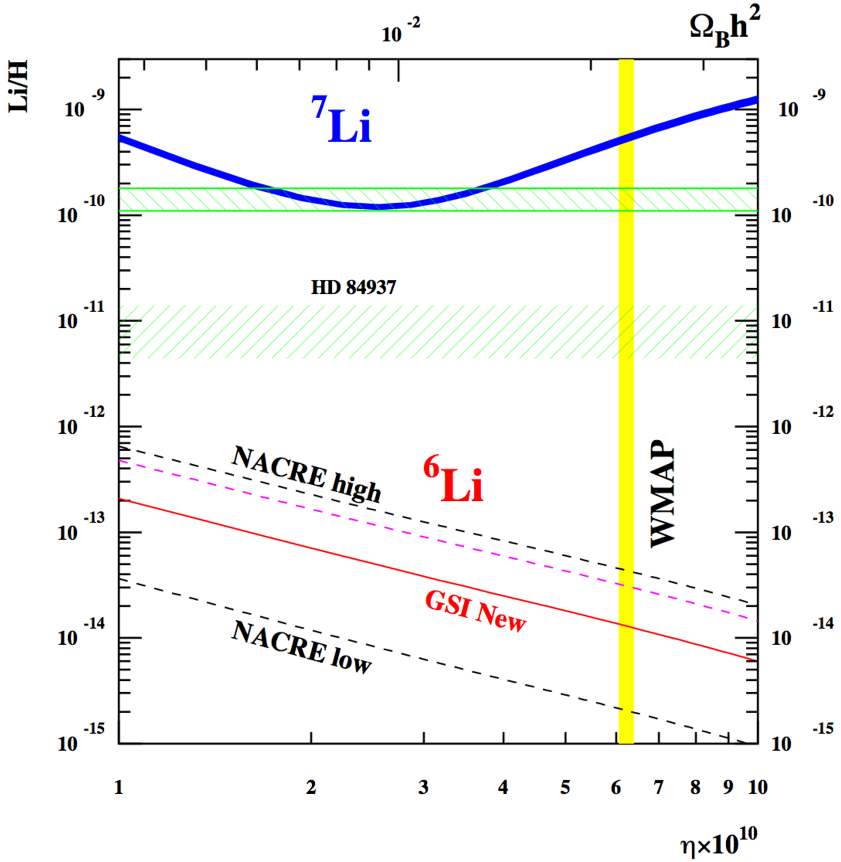
➢ At 26 A MeV *[Kiener al. 1991]*, the nuclear breack-up contribution *is dominant*





[Hammache et al. 2010]

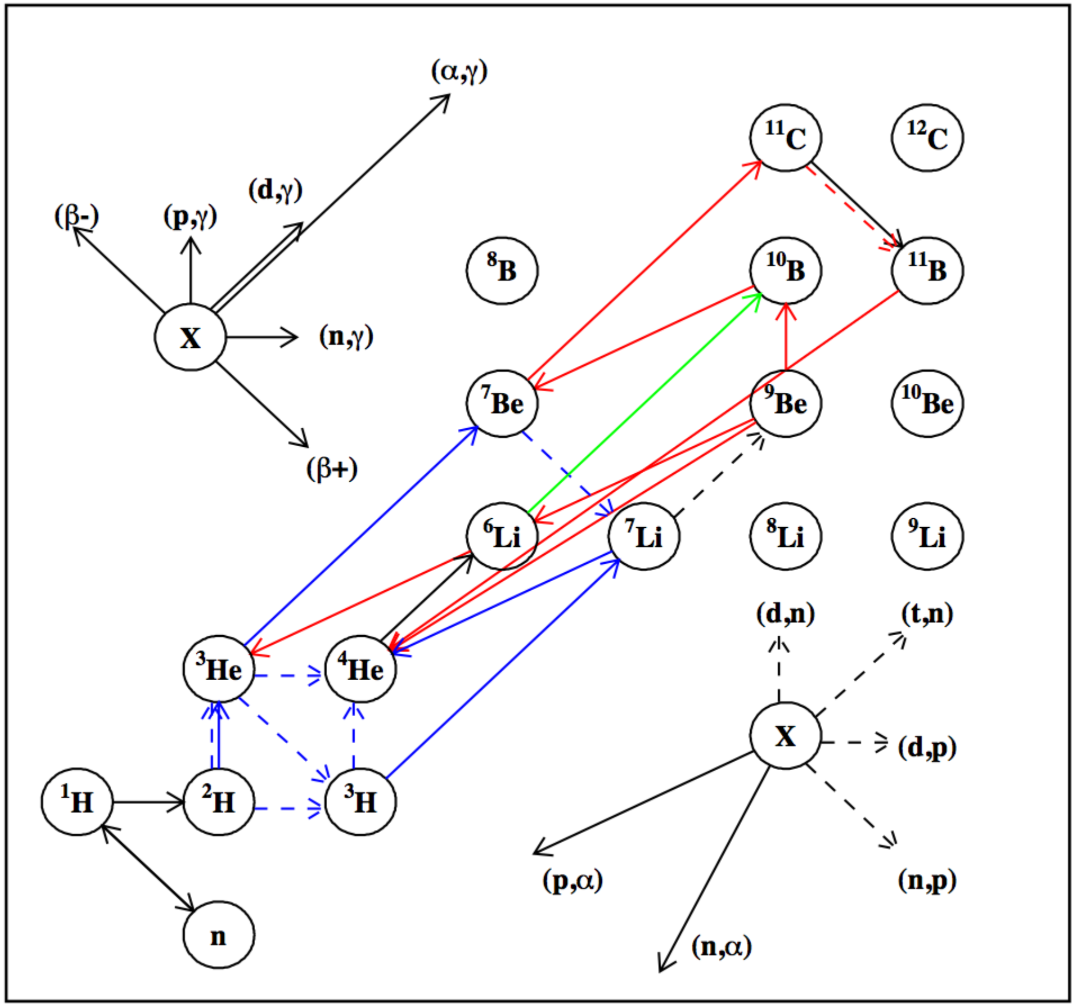




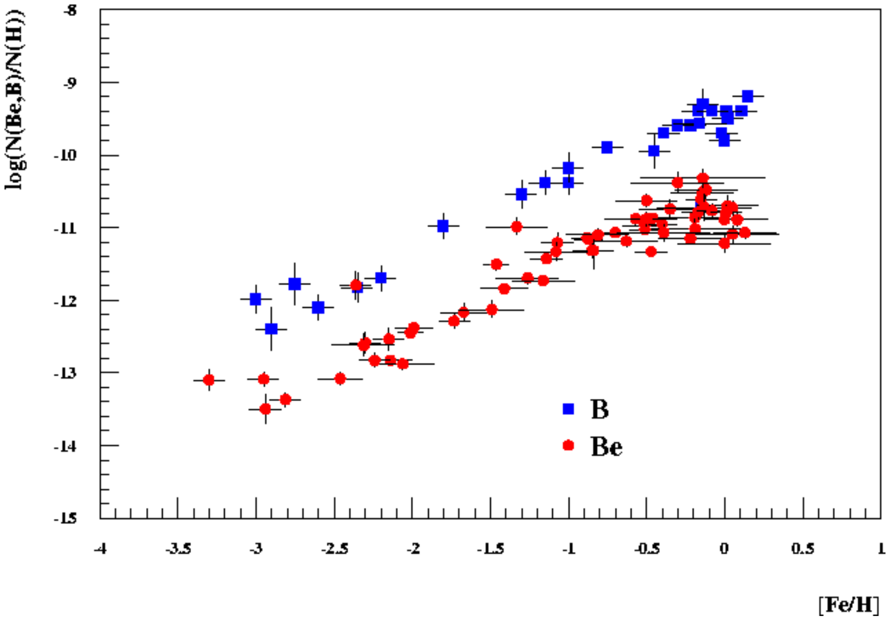
[Hammache et al. 2011]

Isotopes produced during BBN

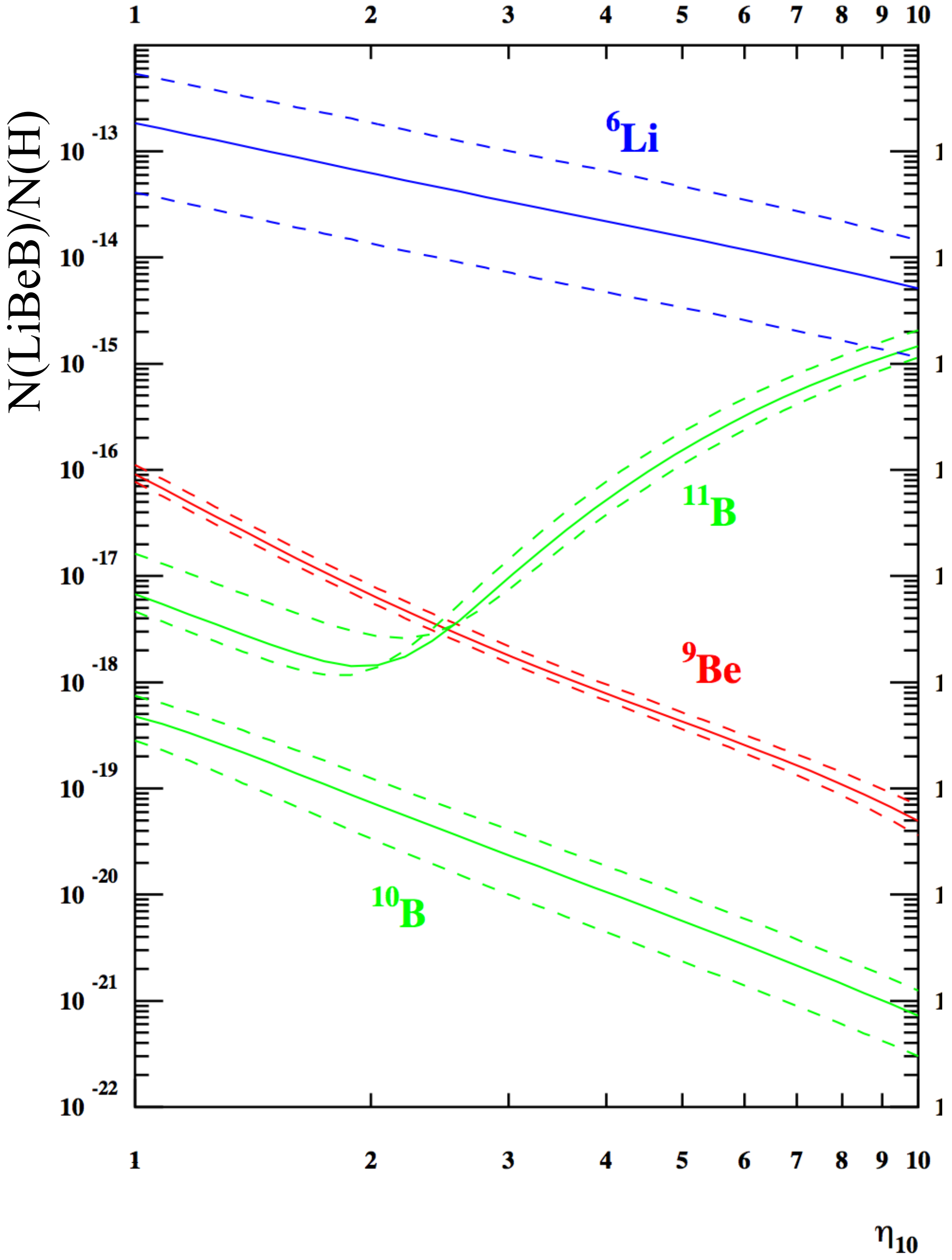
Absence of stable A=5 and 8 nuclei limits nucleosynthesis



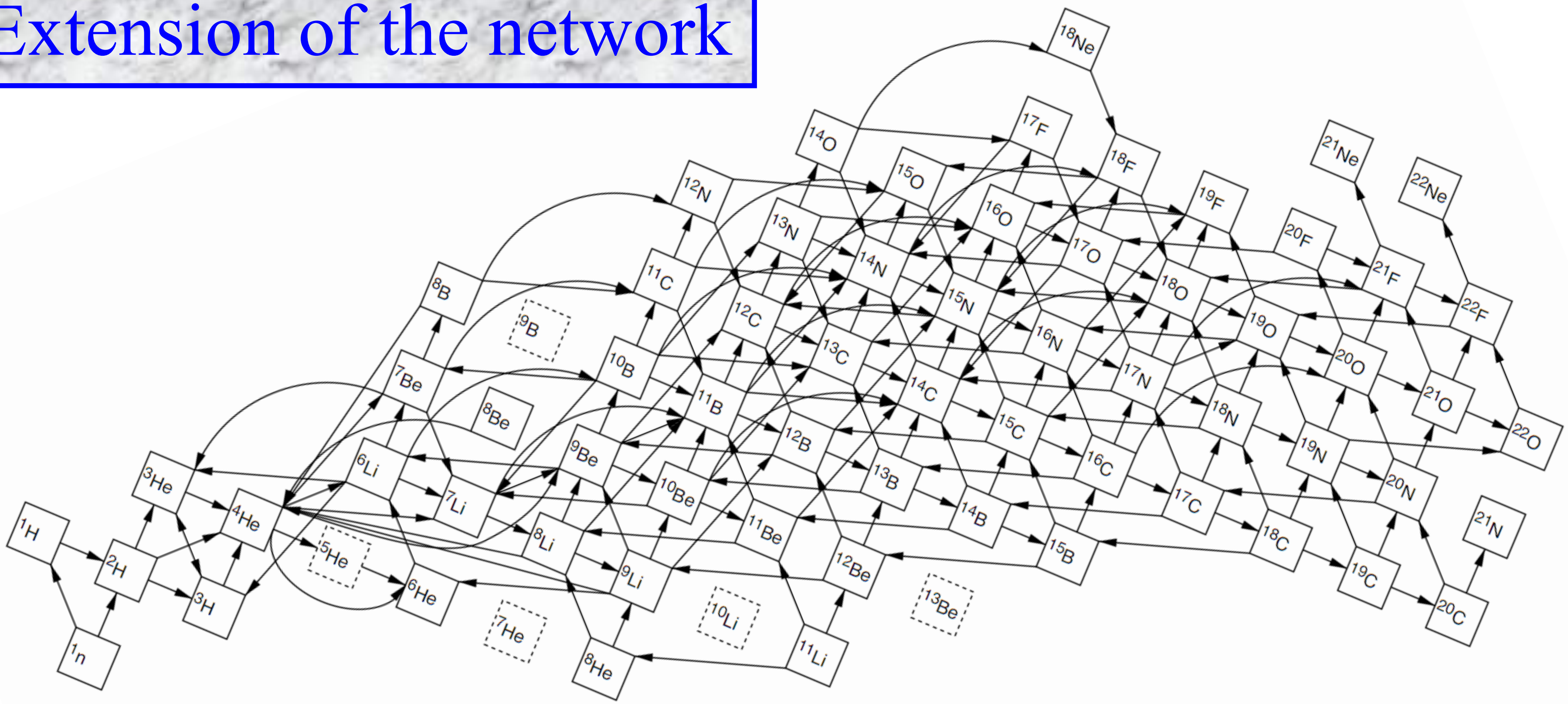
Leftovers from BBN

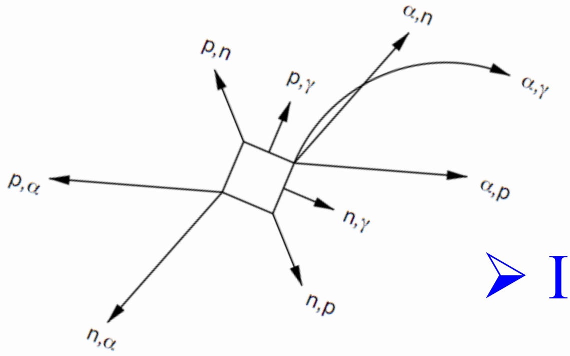


Beryllium and Boron are not produced in observable quantities during (standard) BBN.



Extension of the network





- ➢ Inhomogeneous BBN (????)
- ➢ CNO seeds for first stars (?)

Origin of CMB, SBBN and Li observations discrepancies

- ❑ Nuclear physics : *Most probably no* but important!
  - ➢ To quantify the amount of needed depletion
- ❑ Stellar depletion : Possibly ?
  - ➢ Persistence of a plateau ? ^{6}Li ?
- ❑ Standard BBN inadequate : ?
  - ➢ Modified gravity
  - ➢ Variation of fundamental constants
  - ➢ Catalysis by charged heavy relics
  - ➢ Heavy particle decay
  - ➢ …..
- ❑ When looking back in time, ***Standard*** BBN is the last milestone of know physics