Primordial Nucleosynthesis

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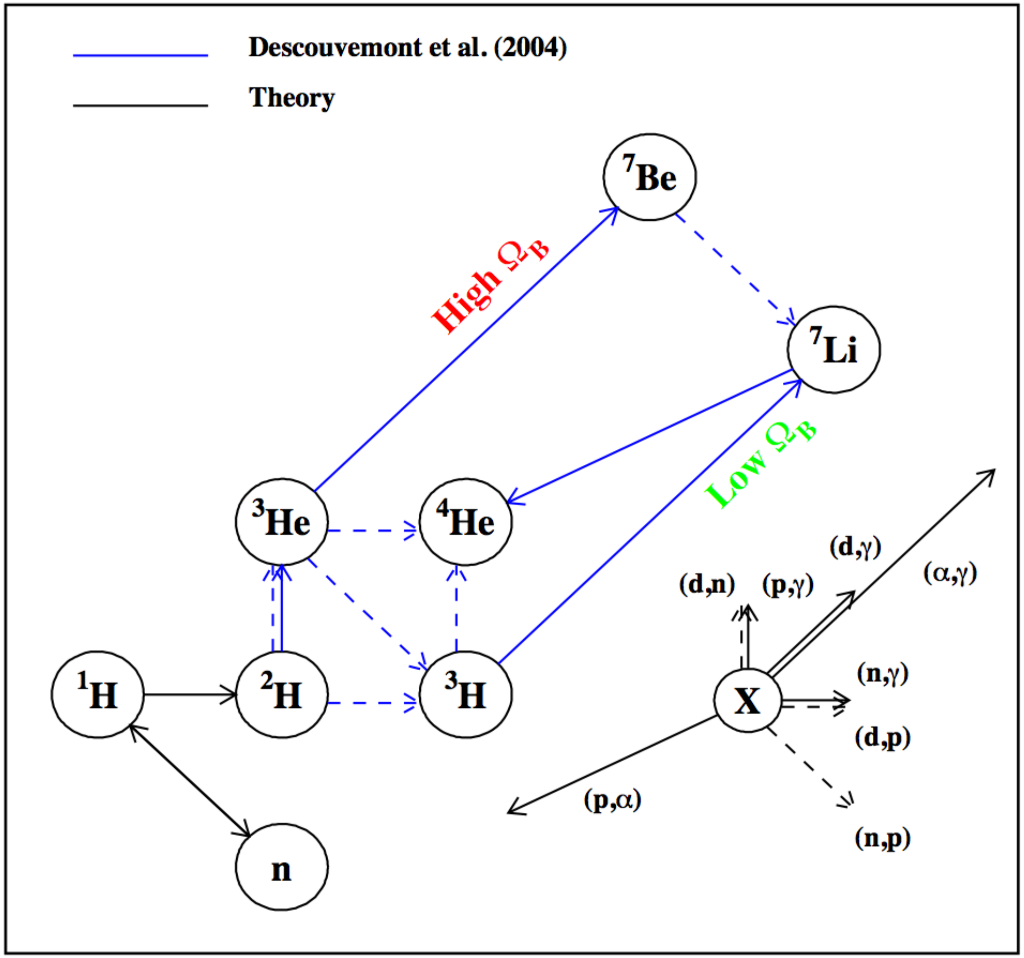
- Standard Big-Bang Nucleosynthesis of ^{4}He, D, ^{3}He, ^{7}Li compared with observations
- The SBBN "lithium problem": nuclear aspects
- (^{6}Li, ^{9}Be , ^{10,11}B) and CNO in extended SBBN network
- Conclusions

The 12 reactions of standard BBN



Standard BBN

- No convection
- No diffusion
- No mixing
- Known physics
- <12 reactions

⇓

Simple nucleosynthesis (?)

n↔p weak reaction rates

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

$$\sum\int \text{(phase space)}\times\text{(e distribution)}\times(\nu_e \text{ distribution})\, dE$$

+ small corrections

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

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

[Dicus et al. (1982), Lopez & Turner (1999)]

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

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

τ_n = 885.7±0.8 s *[PDG 2008]* or τ_n=878.5±0.7 ±0.3 *[Serebrov et al. 2005]*
881.5 ± 1.5 s *[PDG 2011]*

- Weak rate change mostly affects n/p ratio at freeze out and hence ^{4}He abundance
- Change in expansion rate gives similar effect (n/p freezeout when weak rate ≈ expansion rate)

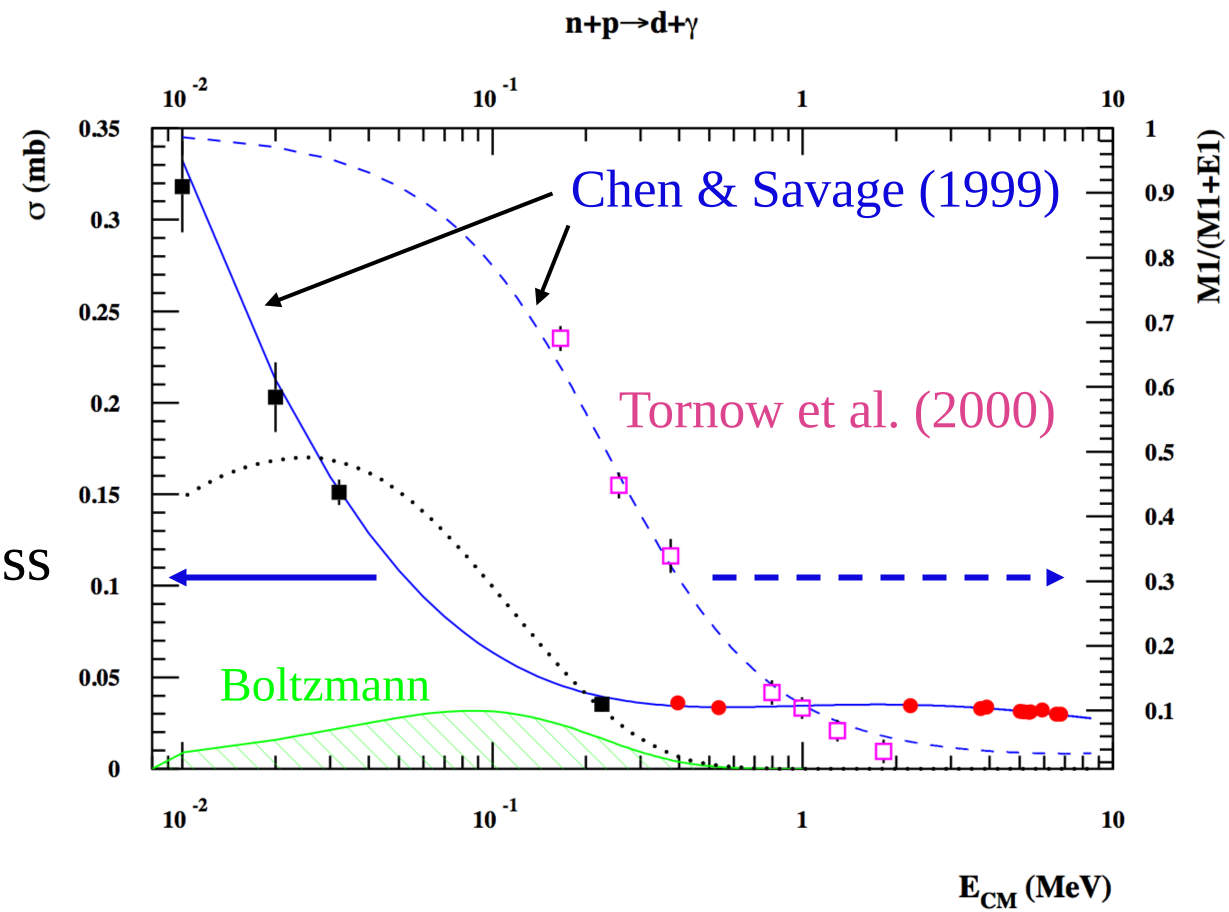
$^1H(n,\gamma)D$: theory versus experiments

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)]*



10 rates deduced from experimental data

Compilations and evaluations for/including 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, uncertainties calculated but not provided)
- Update: TBD

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

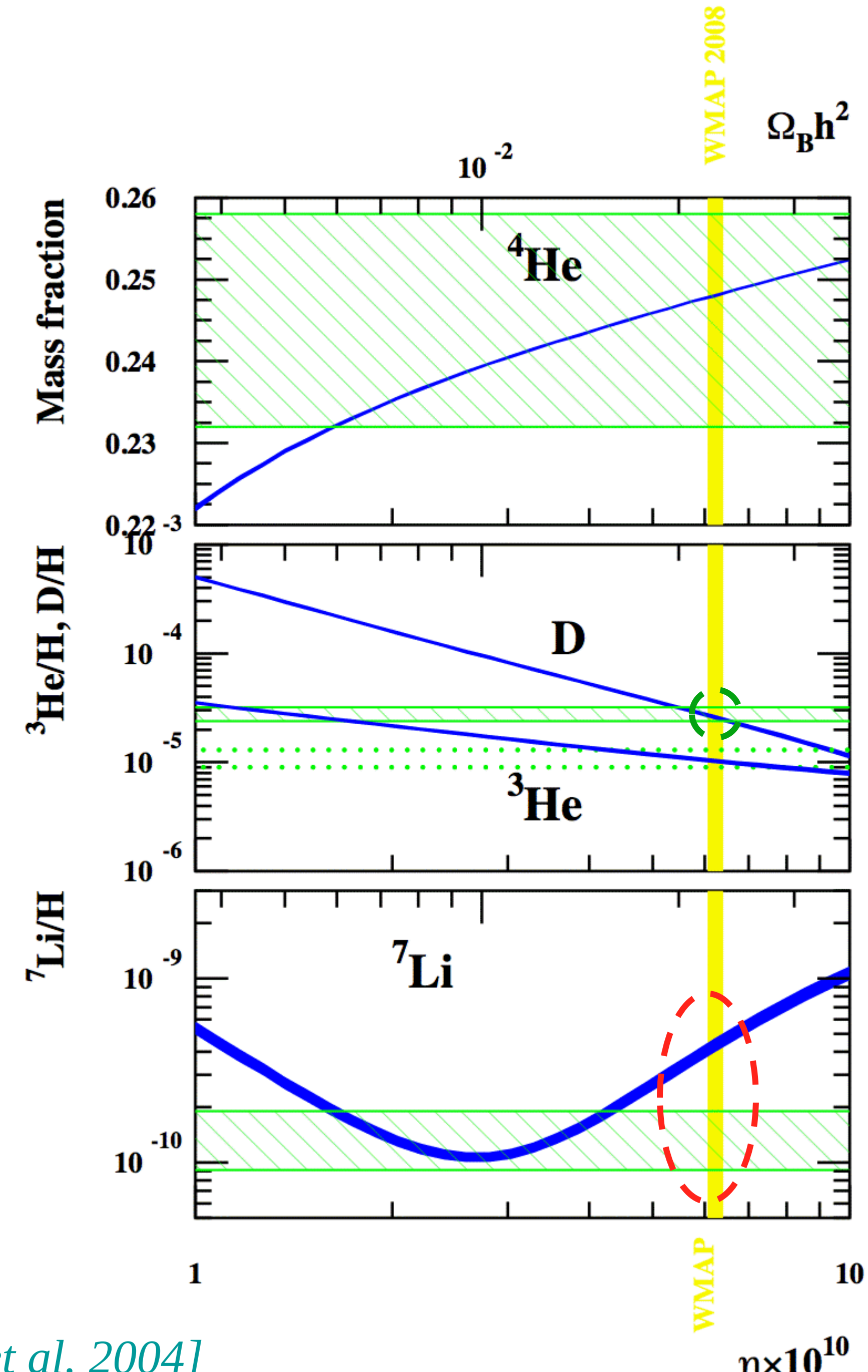
2) Extrapolate to zero metallicity : Fe/H, O/H, Si/H,…. $\rightarrow$ 0

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. 2004]

Sensitivity to thermonuclear reaction rates

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

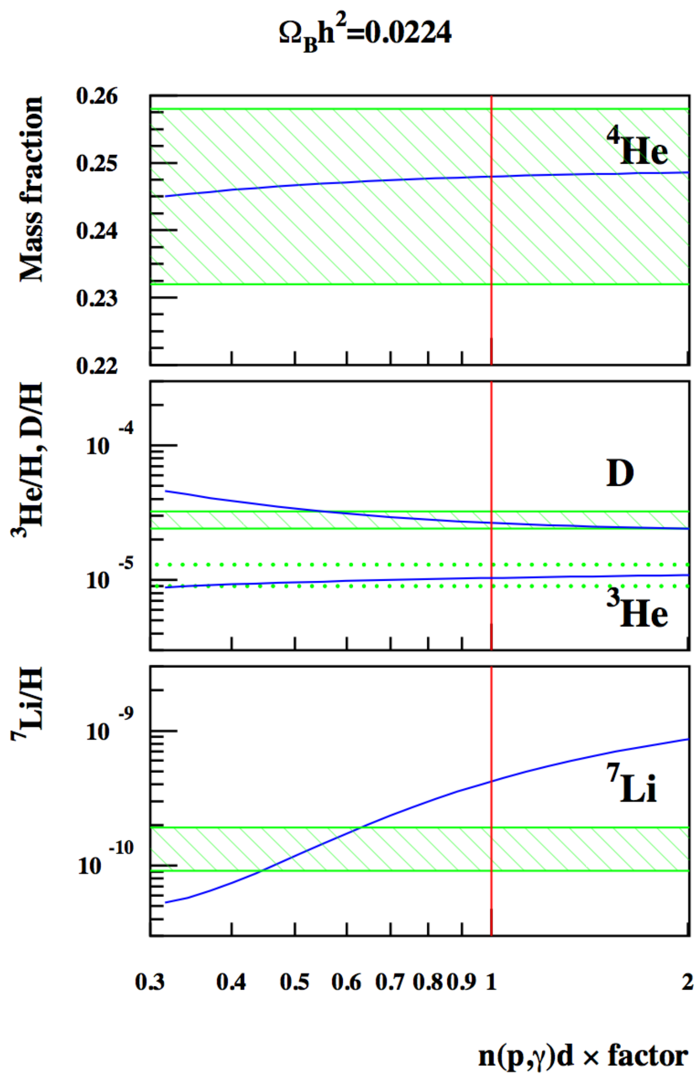
At WMAP baryonic density

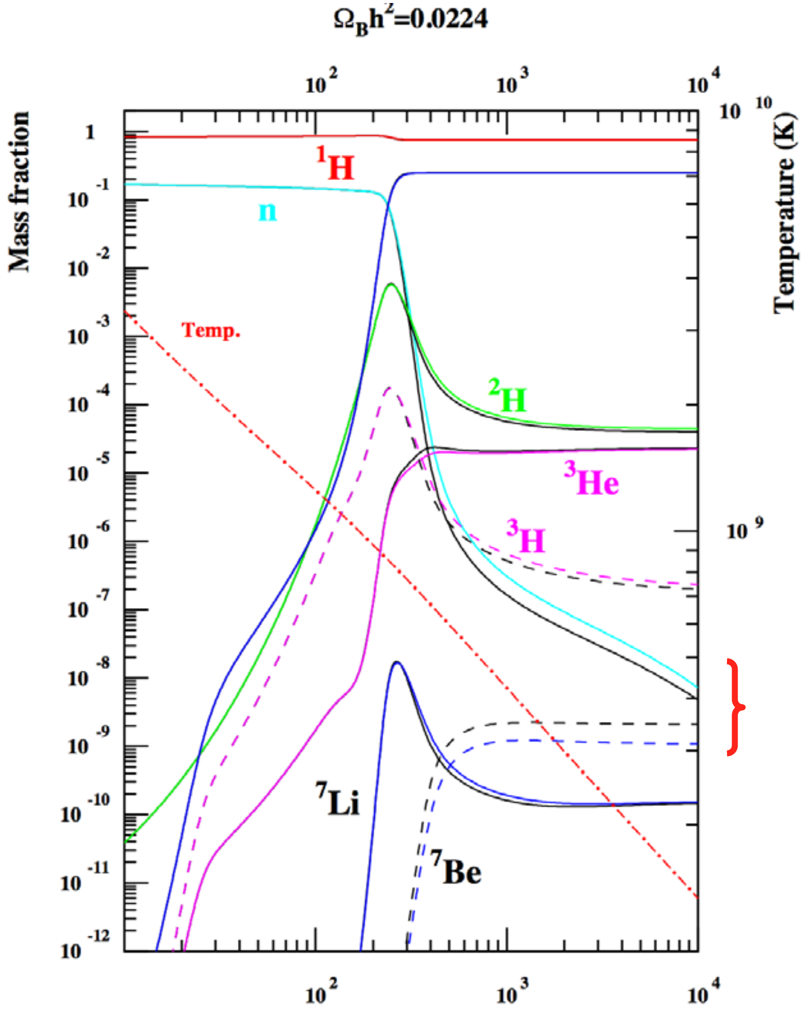
[10] *[Coc & Vangioni 2010]*

	$\partial\ln(Y)/\partial\ln(N_A<\sigma v>)$				$E_0(\Delta E_0/2)$ (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)





n(p,γ)d × 0.7

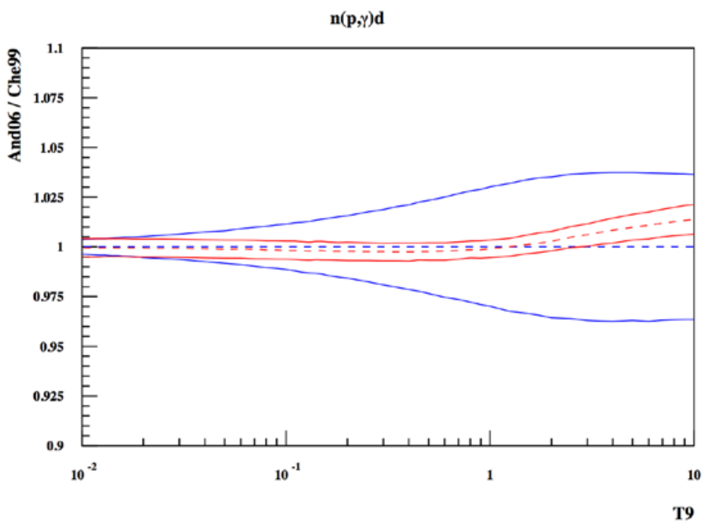
The $^1H(n,\gamma)^2H$ reaction

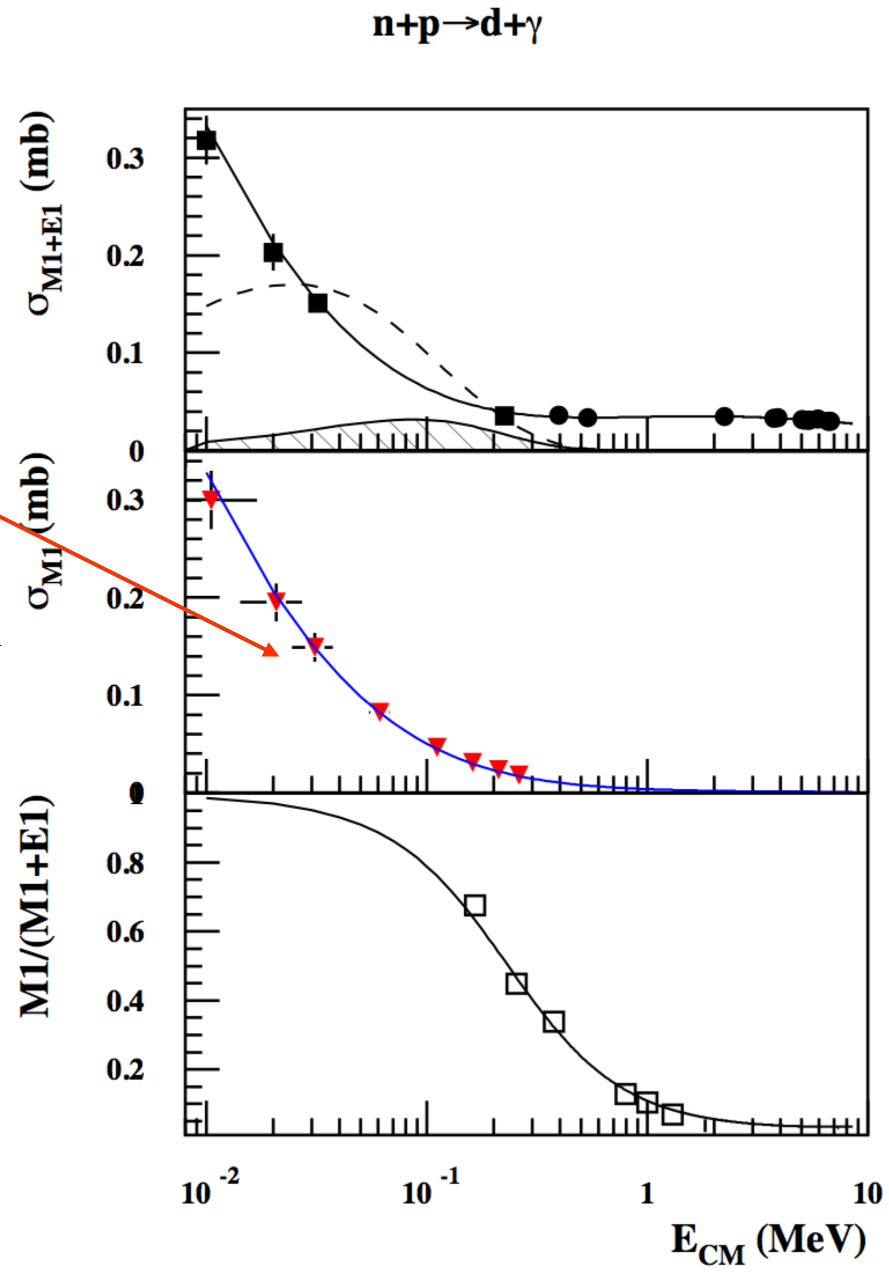
Sensitivity = 1.33

E ~ 25 keV

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

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





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

Sensitivity = 0.97

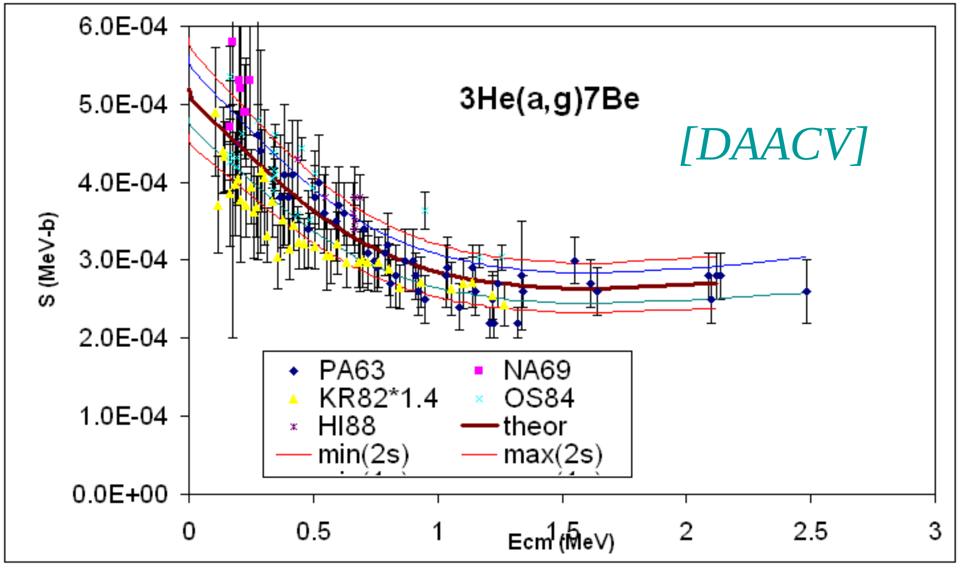
$E_0(\Delta E_0/2) = 0.37(0.21)$ MeV

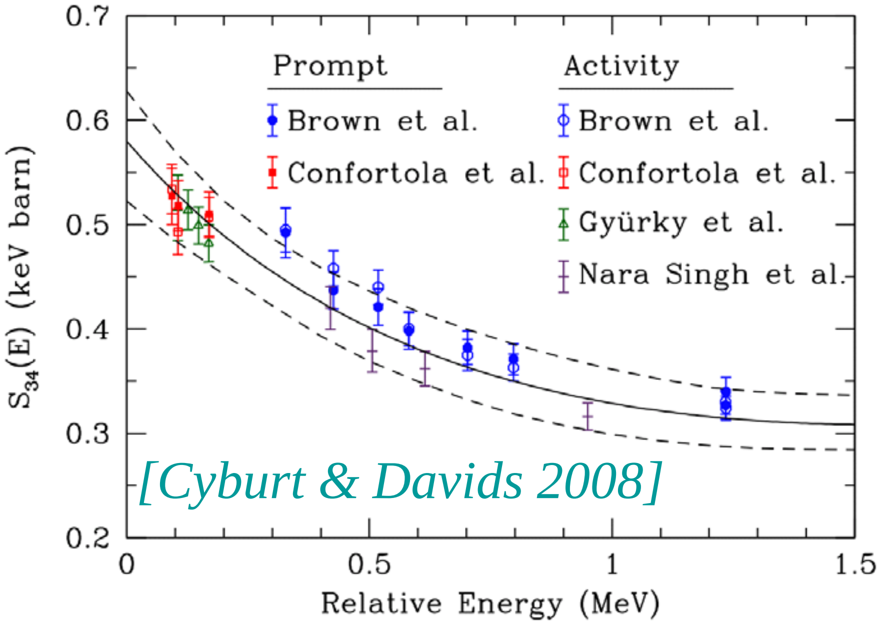
Systematic uncertainties : *prompt* versus *activation* measurements

New precise measurements (in particular at LUNA) :

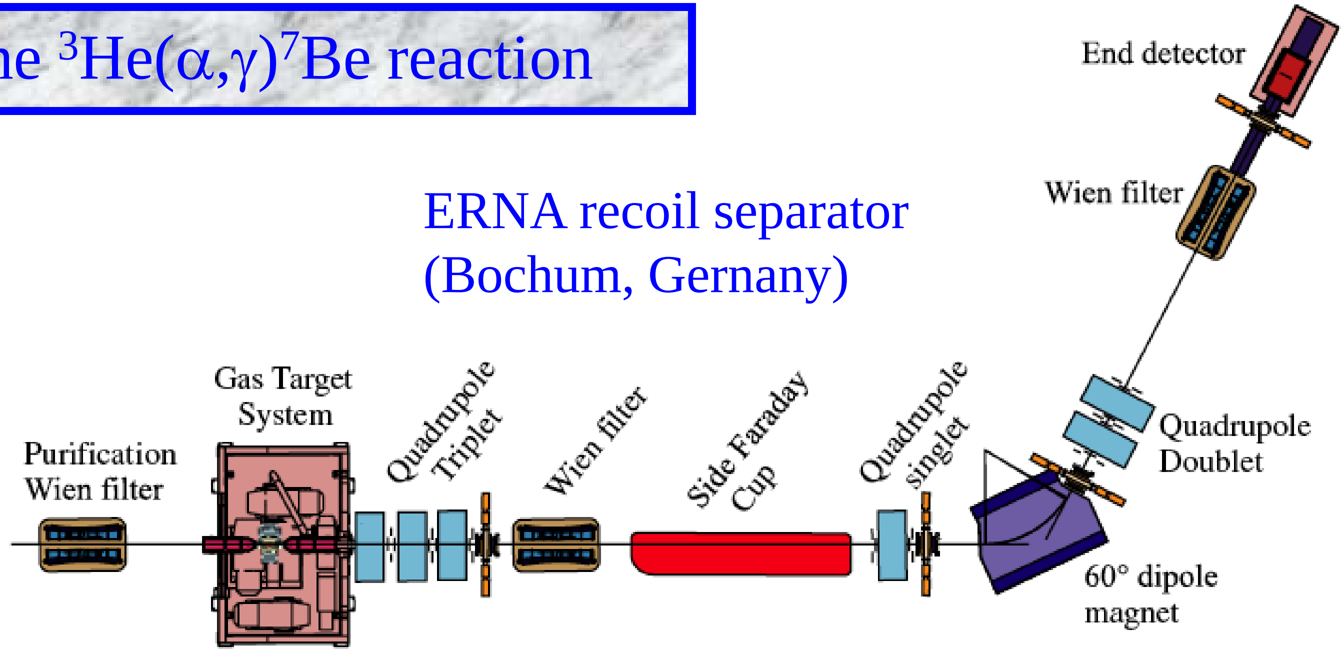
- Prompt *[Brown et al. 2007, Confortola et al. 2007, Costantini et al. 2008]*
- Activation *[Nara Singh et al. 2005, Brown et al. 2007, Confortola et al. 2007, Gyürky et al. 2007]*
- Recoil *[Di Leva et al. 2009]*

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

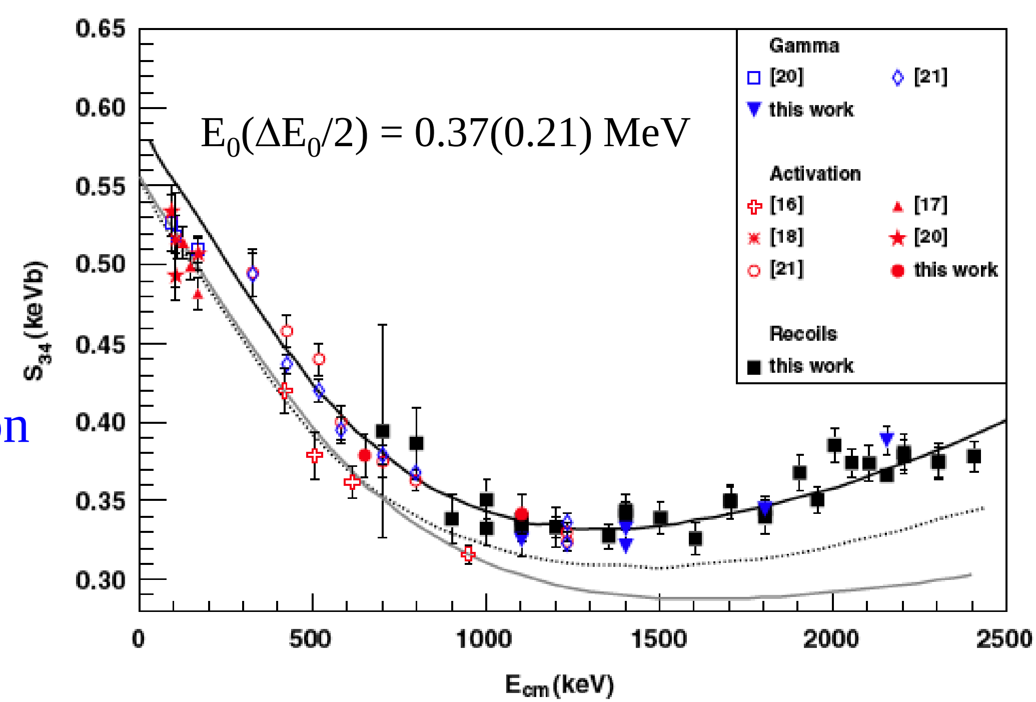


Recoil (+ prompt) *[Di Leva et al. 2009]* with ERNA

S(0) = 0.57±0.04 keV.b

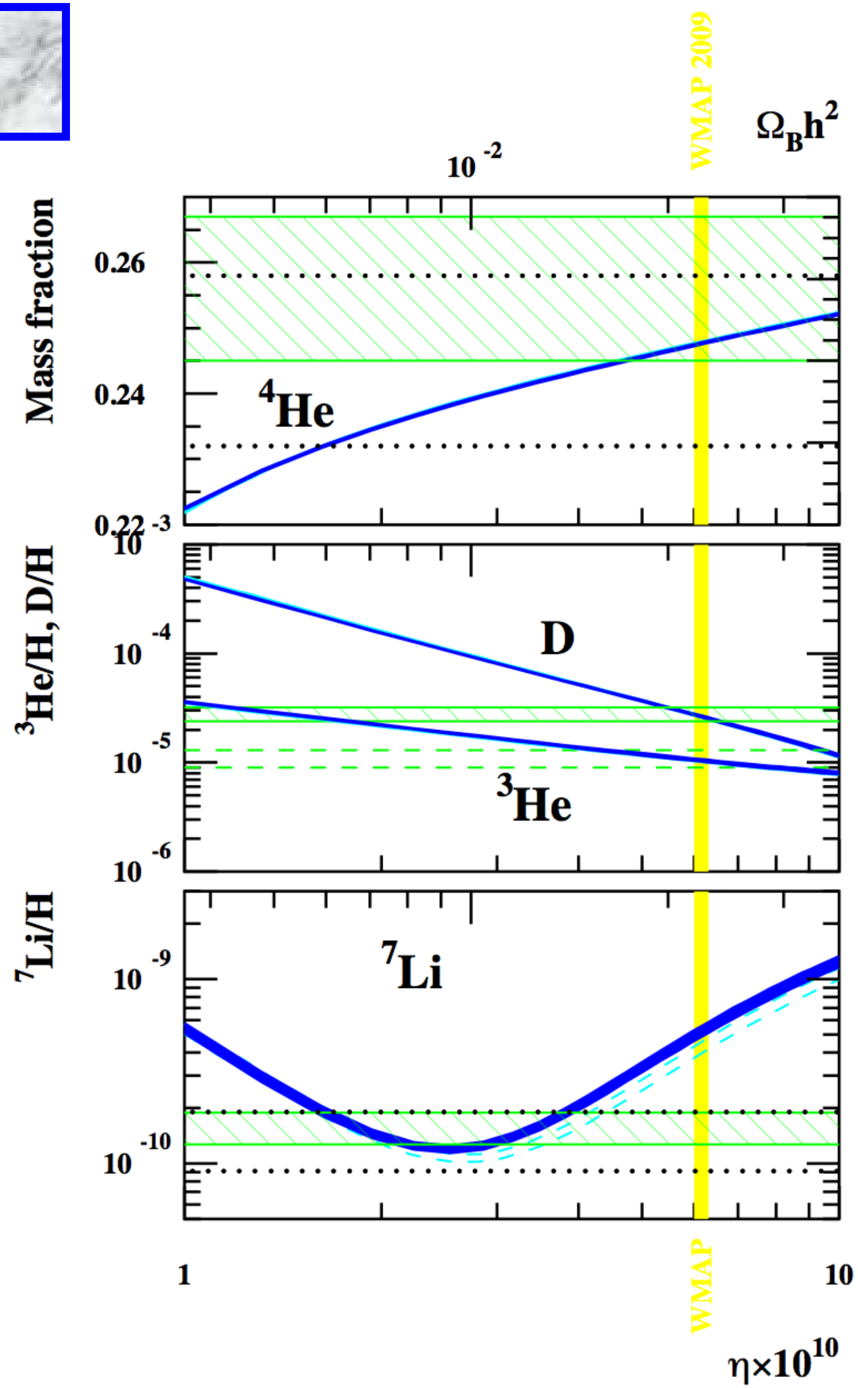
S(0) = 0.56±0.02±0.02 keV.b

Adelberger et al. 2010 latest evaluation of solar fusion cross sections



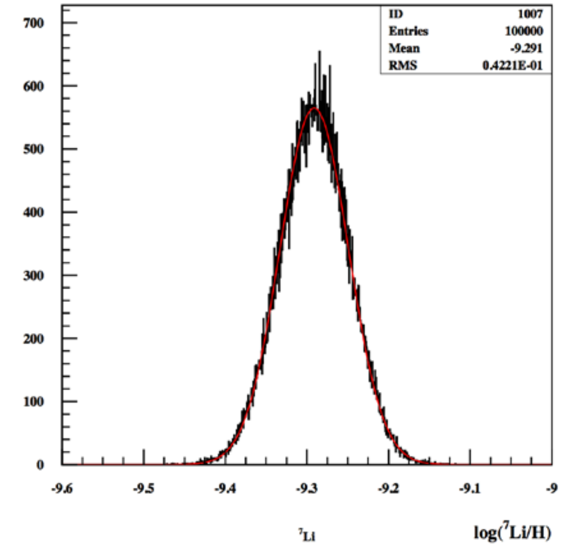
The Li problem update

- ❑New $^{3}He(\alpha,\gamma)^{7}Be$ and $n(p,\gamma)d$ rates :
- ❑ New abundance determinations :
  - Li/H = $(1.58 \pm 0.35) \times 10^{-10}$ *[Sbordone et al. 2010]*
  - $0.245 < Y_p < 0.267$ *[Aver, Olive & Skillman 2010]*
- ❑**^{7}Li** difference of a factor of > 3 !



Monte-Carlo BBN versus observations

Using log-normal distribution *[Iliadis et al., 2010]* 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	0.245-0.267	$\times 10^{0}$
D/H	2.49±0.17	2.68±0.15	2.82±0.20	$\times 10^{-5}$
^{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	1.58±0.35	$\times 10^{-10}$

The lithium BBN problem

February 2012, 27 / 29 - Institut d'Astrophysique de Paris

Local Organizing Committee :
Piercarlo Bonifacio, Fabio Iocco, Elisabeth Vangioni

A nuclear solution ???

New ^{7}Be (i.e. ^{7}Li) destruction channels

- The ^{7}Be(d,p)^{8}Be*$\rightarrow 2\alpha$ reaction *[Coc et al. 2004]*
  - Experiment at Louvain LN *[Angulo et al. 2005]* : no (integrated) cross-section enhancement
  - Hypothetical resonance at E_R = 200$\pm$100 keV with $\Gamma \leq 40$ keV *[Cyburt & Pospelov 2009]*; corresponding to ≈16.7 MeV ^{9}B level ?
  - No resonance observed at Oak Ridge in D(^{7}Be,d)^{7}Be scattering *[O'Malley et al. 2011]*
  - Measured E_x=16.8 MeV and Γ=81 keV *[Scholl et al. 2011]* ⇒primordial effect on ^{7}Li < 4% *[Kirsebom & Davids 2011]*
- Thermal population of excited states and non-thermal neutrons: negligible effects *[Boyd, Brune, Fuller & Smith 2010]*
- Unknown Resonances in ^{7}Be + n, p, d, t, ^{3}He and α ? *[Chakraborty, Fields & Olive 2011]*

Other resonances ?

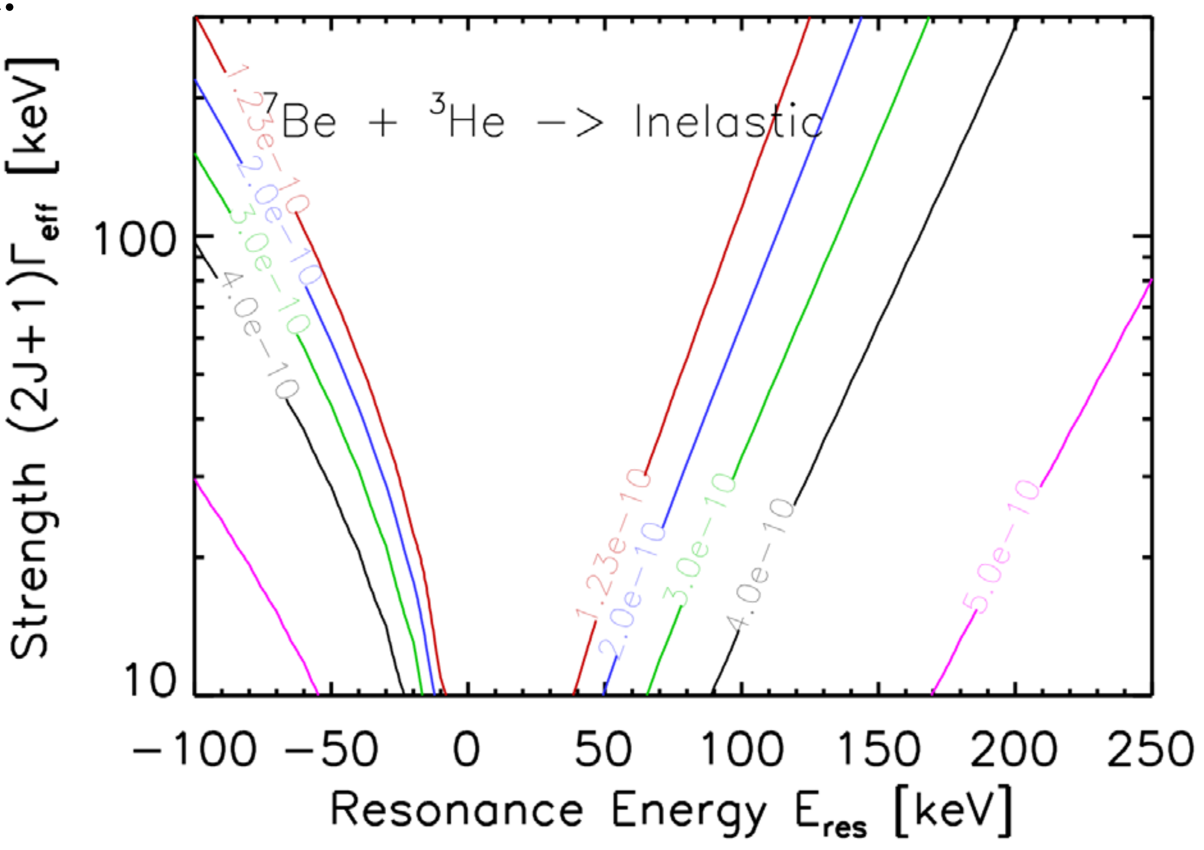
[Chakraborty, Fields & Olive (2011)]

Unknown Resonances in ^{7}Be + n, p, d, t, ^{3}He and α ?

^{8}Be, ^{9,10,11}B, ^{10,11}C c.n.

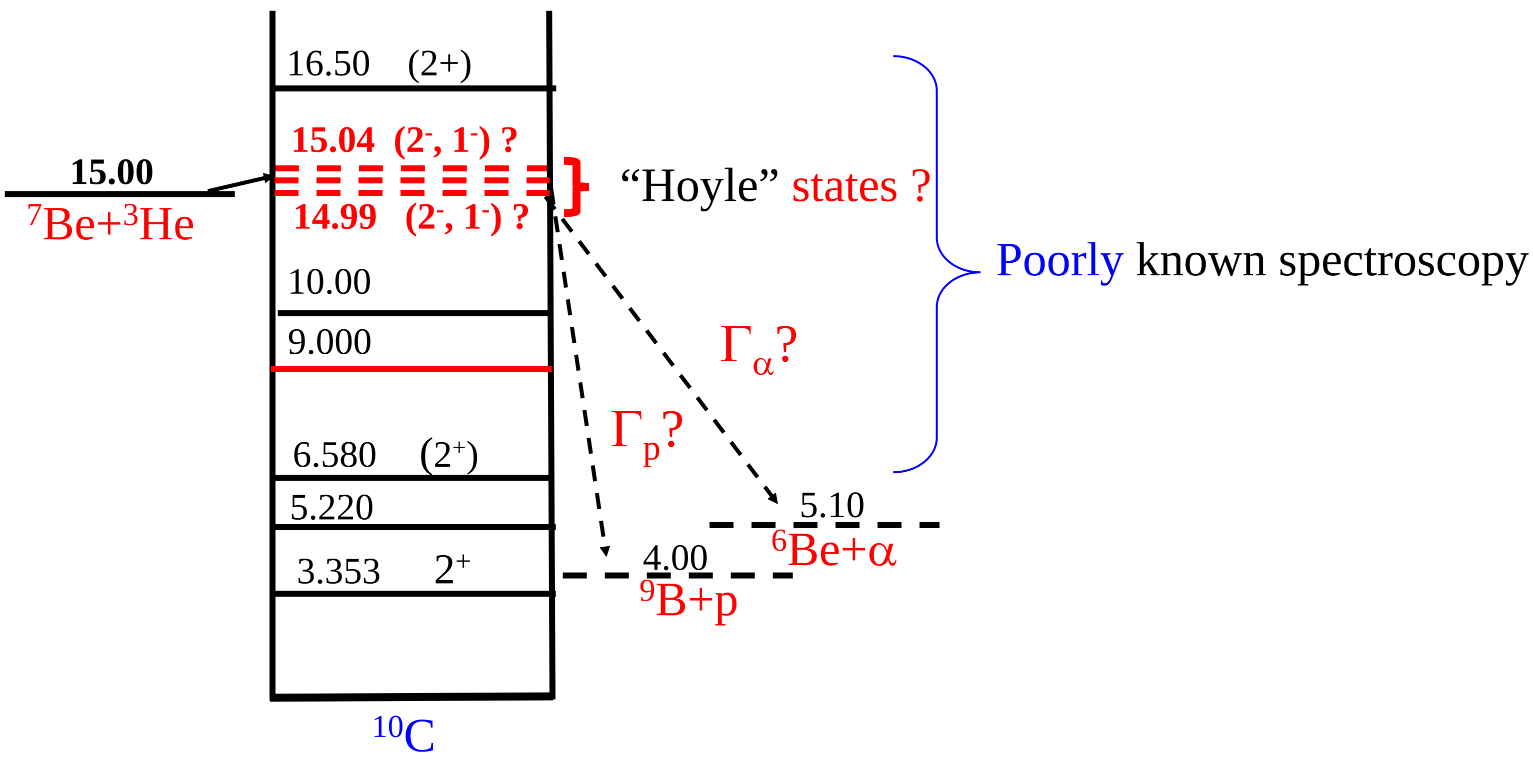
Unknown level properties in ^{9,11}B and unknown levels in ^{10}C

- ^{7}Be(t,p)^{9}Be
- ^{7}Be(t,^{3}He)^{7}Li
- ^{7}Be(t,α)^{6}Li
- ^{7}Be(^{3}He,2p) 2α



Spectroscopy Status of ^{10}C, ^{9}B & ^{10}B

^{10}C case



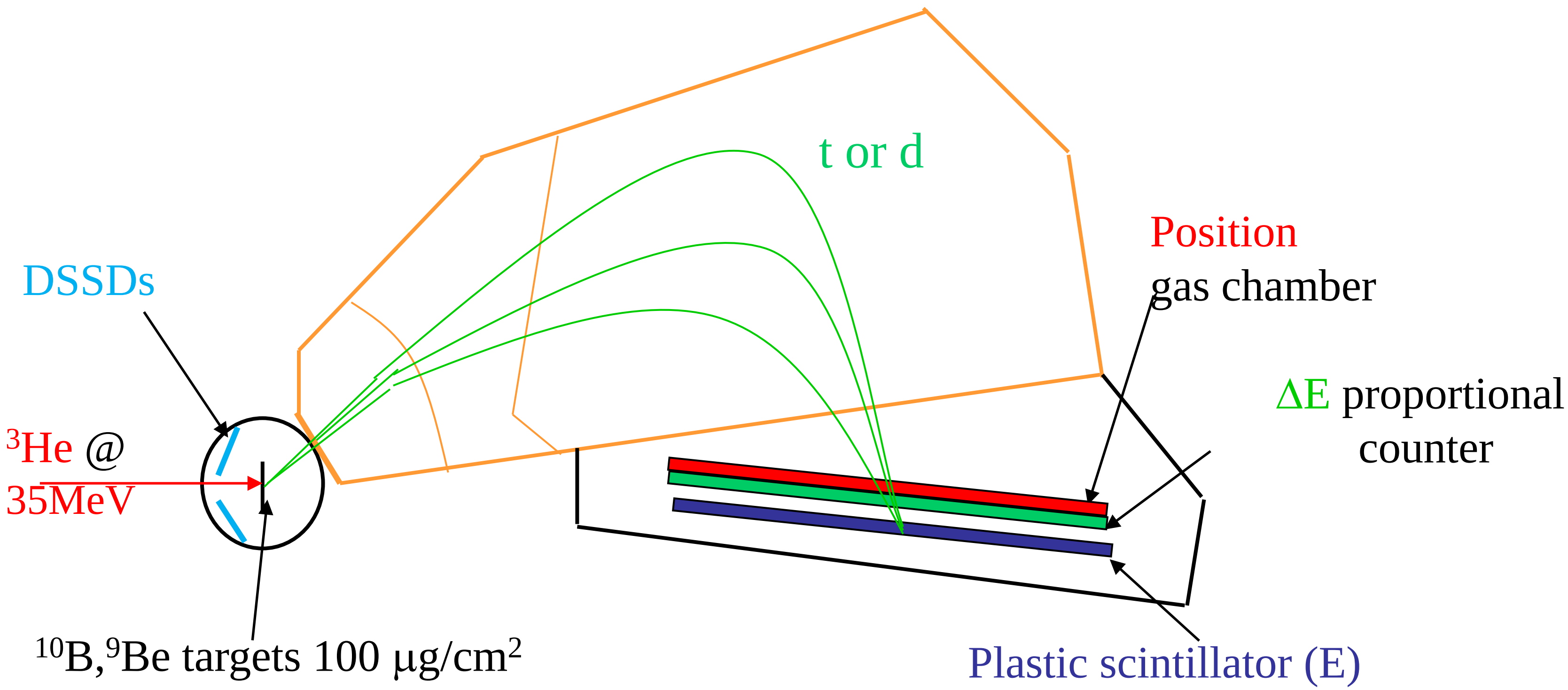
~~Proposed~~ Ongoing Tandem Experiment

Indirect study of ^{10}**C**, ^{9}**B** & ^{10}**B** states via (^{3}He,t), (^{3}He,d) reactions on ^{10}B and ^{9}Be targets

ORSAY SPLIT-POLE spectrometer

- **Bρ(pos)**
- **ΔE**
- **E**

} particle identification



First results from Tandem experiment

Preliminary!

↓

Possible E_x=15.05 MeV (E_r=50 keV) level

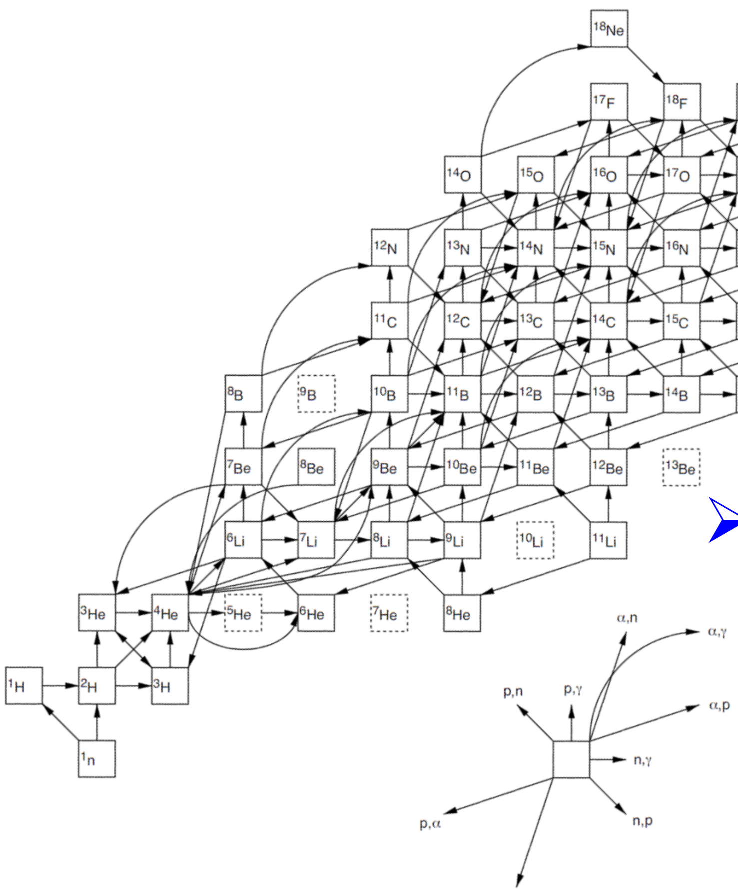
- To be confirmed (next week?)
- Spin-parity ?
- Partial widths ?

CNO nucleosynthesis with an extended BBN network

- Applications of extended network:
  - CNO seeds for first stars : CNO/H > 10^{-11} *[Cassisi & Castellani 1993]* : CNO/H > 10^{-13} *[Ekström et al. 2008]*
  - Standard CNO primordial abundances versus exotic production (e.g. "variation of fundamental constants")
  - Future observations CNO ?
  - Potential neutron sources for ^{7}Be destruction by ^{7}Be(n,p)^{7}Li(p,α)^{4}He in BBN (the lithium problem)? Unexpected effect (e.g. ^{7}Li sensitivity to n(p,γ)d)
- Extended network predictions : CNO/H $\approx 10^{-15}$ *[Iocco et al. 2007]*

CNO nucleosynthesis with an extended BBN network

- Involves many (>400), ^{A}Z + n, p, d, t, ^{3}He and α, reactions
- *Mostly unknown rates* hence possibly high yield uncertainty

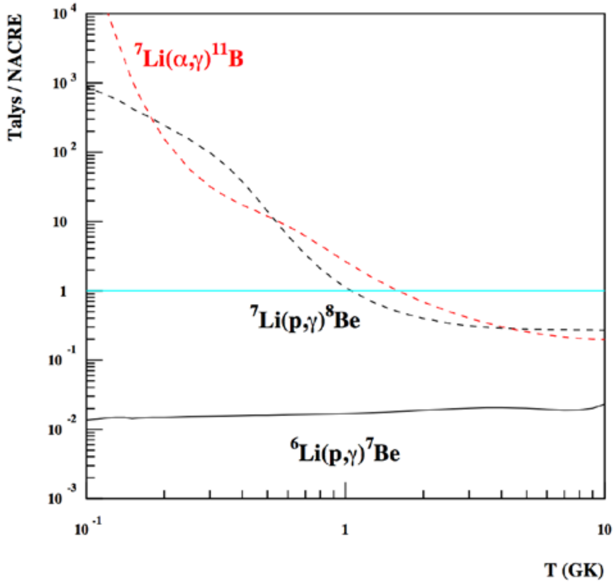


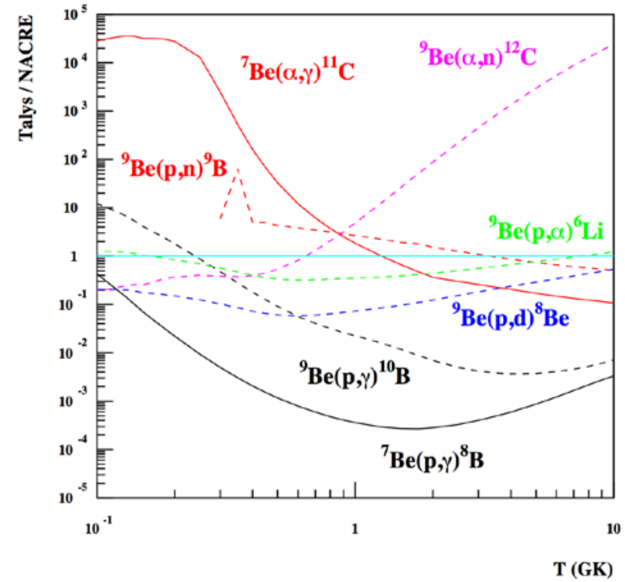
©Fields & Olive 2006

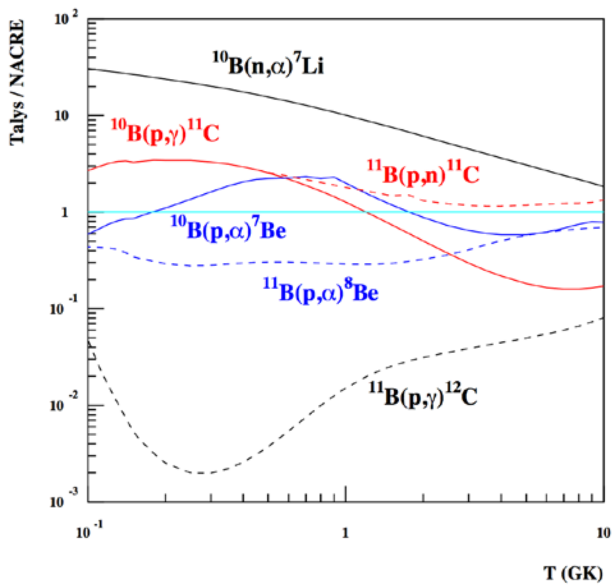
- Origin of the rates ???
  - Data bases of nuclear level properties
  - Estimates following *Fowler & Hoyle 1964; Wagoner 1967* prescriptions

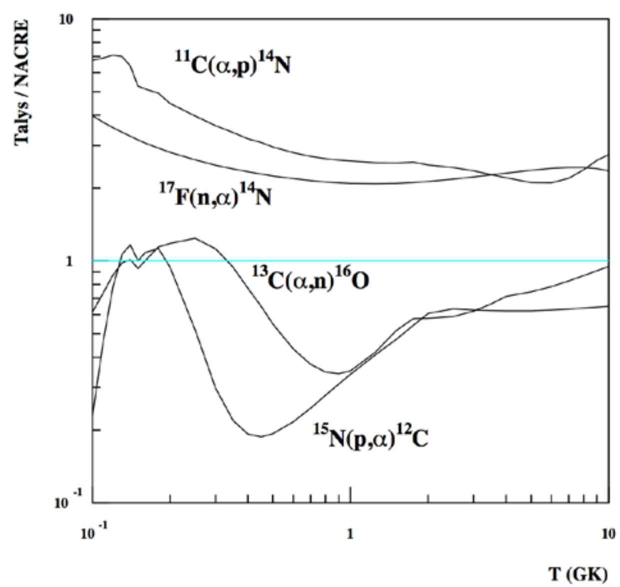
Comparison between Talys and experiments

[NACRE 1999]









CNO nucleosynthesis updated network

- 59 isotopes :

Z	A
n	1
H	1-3
He	3,4,6
Li	6-9
Be	7,9-12
B	8,10-15
C	9-16
N	12-17
O	13-20
F	17-20
Ne	18-23
Na	20-23

- 33 decay rates *[Audi et al. 2003]*
- 391 reaction rates
  - ✓ *Caughlan & Fowler 1988*
  - ✓ *Descouvemont et al. 2004 (DAACV)*
  - ✓ *Angulo et al. 1999 (NACRE I)*
  - ✓ *Xu et al., in preparation (NACRE II)*
  - ✓ *Iliadis et al. 2010*
  - ✓ *Talys (271 rates)** within 3 orders of magnitude, at T=1 GK, compared with experiments!
  - ✓ …...

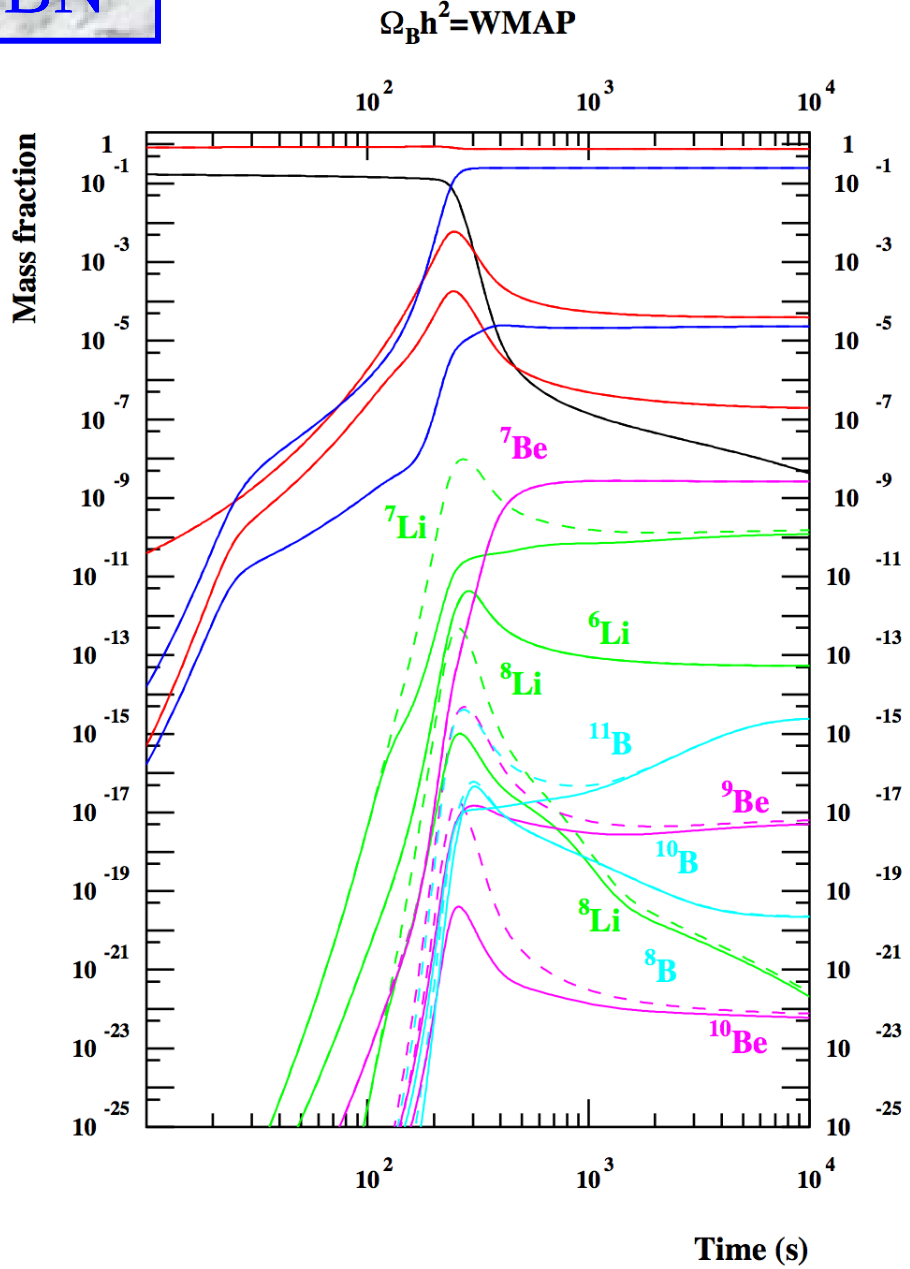
*http://www.astro.ulb.ac.be/pmwiki/Brusslib/BigbangTalys

Most important reactions for CNO nucleosynthesis

Reaction	Fractional change in CNO abundance						Test rate reference
Rate factor	0.001	0.01	0.1	10.	100.	1000.	
^{7}Li(d,γ)^{9}Be	1.00	1.00	1.00	1.01	1.11	2.10	TALYS
^{7}Li(d,n)2α	1.66	1.65	1.55	0.28	0.06	0.02	Boy93
^{7}Li(t,n)^{9}Be	0.99	0.99	0.99	1.10	2.14	11.7	Bru90
^{7}Li(t,2n)2α	1.00	1.00	1.00	0.99	0.91	0.53	MF89
^{8}Li(n,γ)^{9}Li	1.00	1.00	1.00	1.01	1.06	1.62	Rau94
^{8}Li(t,n)^{10}Be	1.00	1.00	1.00	1.00	1.02	1.23	TALYS
^{8}Li(α,γ)^{12}B	1.00	1.00	1.00	1.01	1.11	2.15	TALYS
^{8}Li(α,n)^{11}B	0.89	0.89	0.90	1.97	11.2	78.1	Miz01
^{9}Li(α,n)^{12}B	1.00	1.00	1.00	1.01	1.08	1.73	TALYS
^{10}Be(α,n)^{13}C	1.00	1.00	1.00	1.00	1.03	1.28	TALYS
^{11}B(n,γ)^{12}B	0.91	0.91	0.92	1.81	9.91	87.7	Rau94
^{11}B(d,n)^{12}C	0.70	0.71	0.73	3.67	30.2	280.	TALYS
^{11}B(d,p)^{12}B	0.99	0.99	0.99	1.08	1.83	9.33	TALYS
^{11}B(t,n)^{13}C	1.00	1.00	1.00	1.01	1.12	2.17	TALYS
^{11}C(n,γ)^{12}C	1.00	1.00	1.00	1.01	1.08	1.75	Rau94
^{11}C(d,p)^{12}C	0.99	0.99	0.99	1.05	1.55	5.67	TALYS
^{12}C(t,α)^{11}B	1.00	1.00	1.00	1.00	0.97	0.75	TALYS
^{13}C(d,α)^{11}B	1.00	1.00	1.00	0.96	0.84	0.75	TALYS

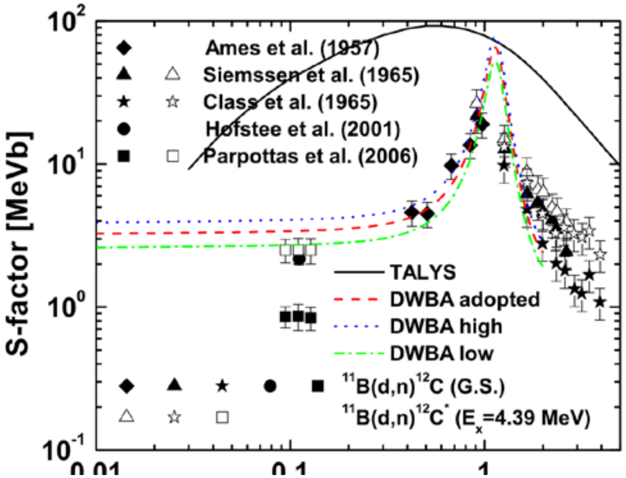
Counter intuitive effects in BBN

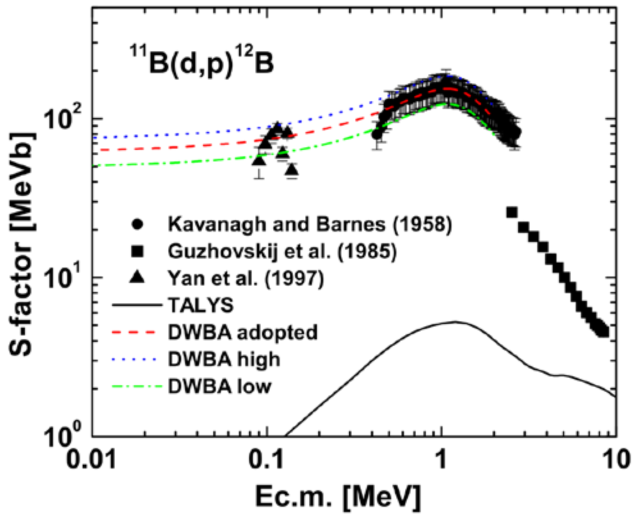
- The $^1H(n,\gamma)D$ reaction affects mostly ^7Li
- The $^7Li(d,n)2^4He$ reaction affects strongly the CNO but leaves ^7Li (and other isotopes) unchanged!
- Systematic sensitivity studies are important



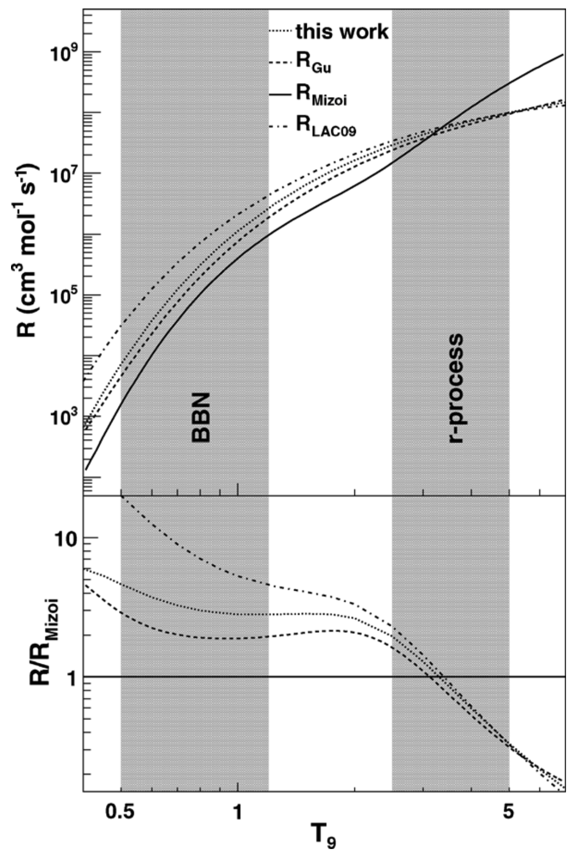
Stability of results with re-evaluated reaction rates

Changes in ^{11}B(d,n) by ^{11}B(d,p) cancel each other





Independent re-evaluation of ^{8}Li(α,n)^{11}B by *La Cognata & Del Zoppo 2011*



Changes CNO by 1.5%

CNO nucleosynthesis

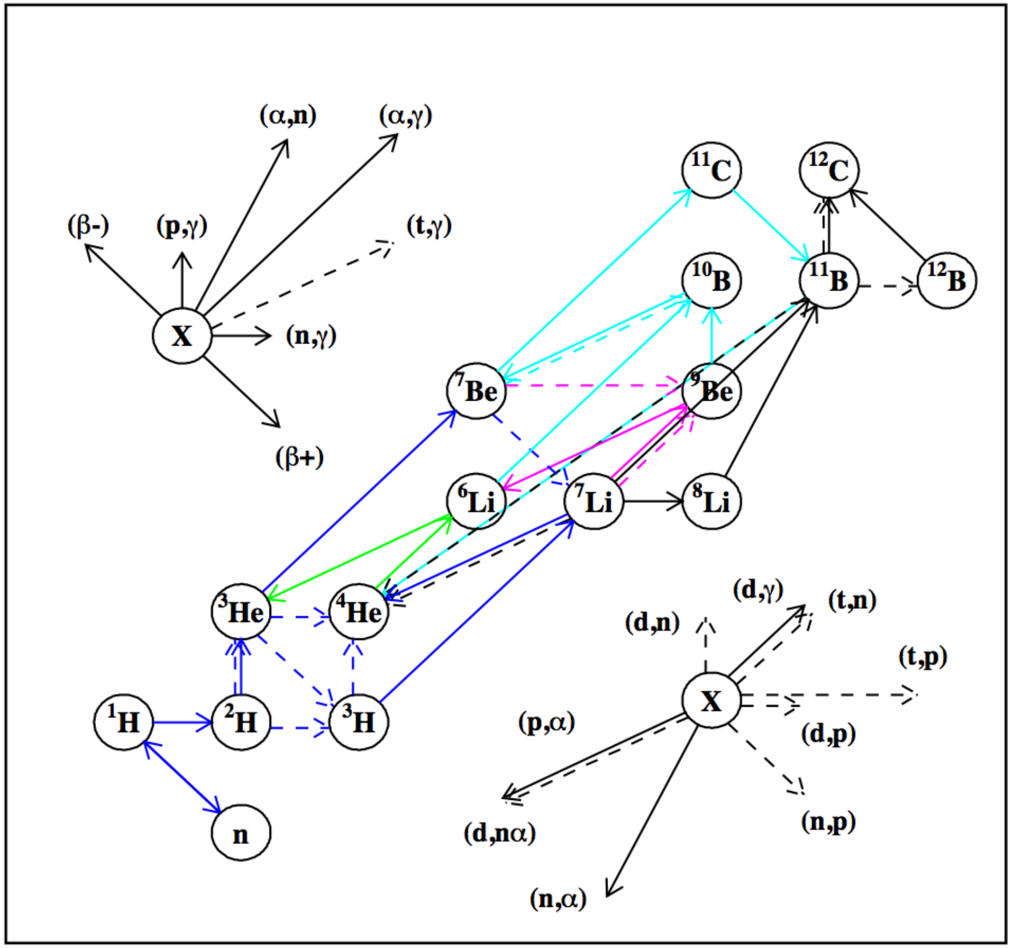
Stability of results:

Number of atoms	*[Iocco et al. 2007]*	Initial Network	Updated Network
$(^{12}C+^{13}C)/H$ ($\times 10^{-16}$)	5.5	4.43	6.75
$(^{14}C+^{14}N)/H$ ($\times 10^{-17}$)	5.0	3.98	6.76
$^{16}O/H$ ($\times 10^{-20}$)	2.7	5.18	9.13
CNO/H ($\times 10^{-16}$)	6.0	4.83	7.43

Nuclear uncertainties?

- Need a Monte-Carlo and statistically defined uncertainties: TBD
- Estimate from i) rate factor uncertainties <10 at T=1 GK, ii) sensitivity study ⇒ CNO factor uncertainty ≈4

Main paths of BB nucleosynthesis



Main path for:

- H, D, ^{3}He, ^{4}He, ^{7}Li
- ^{6}Li
- ^{9}Be
- ^{10,11}B
- CNO (^{12}C)

Conclusions

- SBBN calculations confirms good agreement for Ω_B values deduced from : CMB and SBBN (D and ^{4}He),
- However disagreement between Li observations, SBBN and CMB :
  - Nuclear : most probably no but important to quantify needed depletion
  - Stellar depletion ?
  - Cosmology and particle physics ?
- Using extended network*: minute amounts of ^{6}Li, ^{9}Be, ^{10,11}B and CNO produced
- Systematic sensitivity studies are important
- **SBBN is now a parameter free model !**
  - When looking back in time, ***Standard*** BBN is the last milestone of know physics : probe of the physics of the early Universe

**Coc, Goriely, Xu, Saimpert & Vangioni, 2011, ApJ in press* and
http://www.astro.ulb.ac.be/pmwiki/Brusslib/BigbangTalys

Main collaborators on SBBN

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