Primordial Nucleosynthesis

Alain Coc

CSNSM

(**C**entre de **S**ciences **N**ucléaires et de **S**ciences de la **M**atière, Orsay)

1. Standard Big-Bang Model and Nucleosynthesis
2. Nuclear Physics aspects
3. Beyond the Standard Model(s)

cnrs
dépasser les frontières
IN2P3
Institut national de physique nucléaire
et de physique des particules

CSNSM
CENTRE DE SCIENCES NUCLÉAIRES ET DE SCIENCES DE LA MATIÈRE

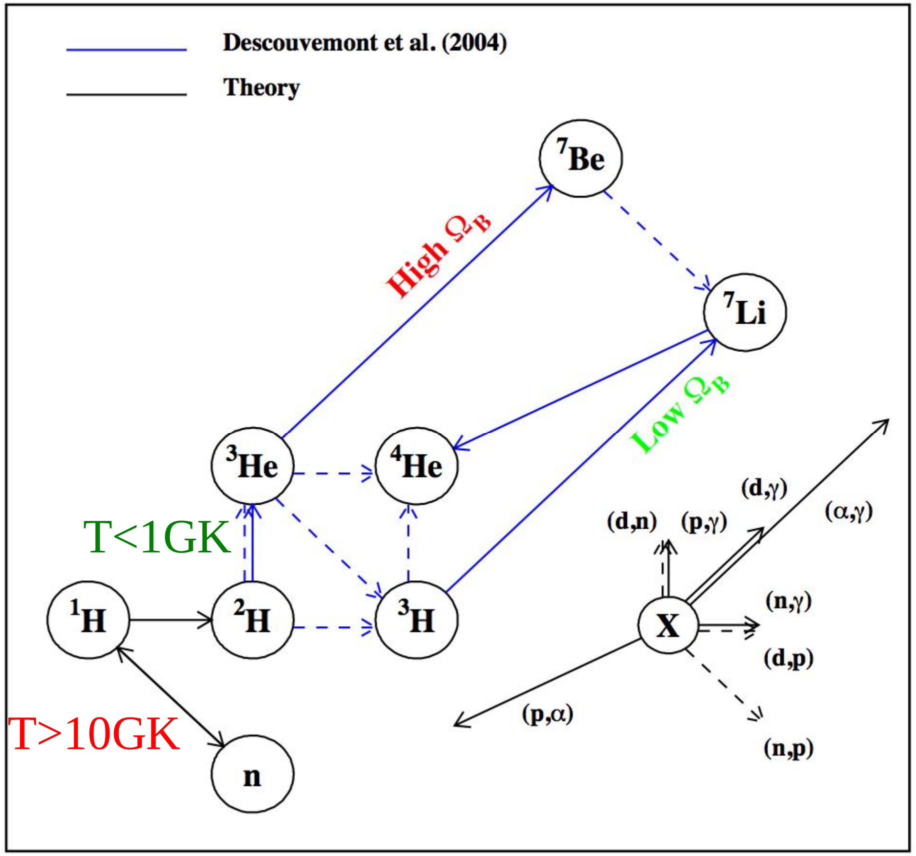
UNIVERSITÉ
PARIS
SUD
FACULTÉ
DES SCIENCES
D'ORSAY

Nuclear Physics aspects

1. The main reactions for H, He and Li BBN production
2. Search for nuclear solutions to the lithium problem
3. Be, B and CNO production in BBN
4. Monte-Carlo evaluation of reaction rates
5. Monte-Carlo investigation of BBN

The 12 reactions of standard BBN

- 10 thermonuclear reaction rates deduced from experimental data: *[Serpico+ 2004, Descouvemont+2004, Cyburt 2004]* evaluations
- First 2 from theory: weak $n \leftrightarrow p$ rate and $p(n,\gamma)d$ (i.e. $p+n \rightarrow d+\gamma$)



Standard BBN

- No convection
- No diffusion
- No mixing
- No screening
- Known physics
- 11/12 reactions measured at BBN energies

⇓

Simple problem (?)

Sensitivity to thermonuclear reaction rates

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

At WMAP baryonic density

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

$n \leftrightarrow p$ weak reaction rates

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

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

+ small corrections

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

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

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

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

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

The neutron lifetime is still a matter of debate (but not essential to BBN)

- 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)

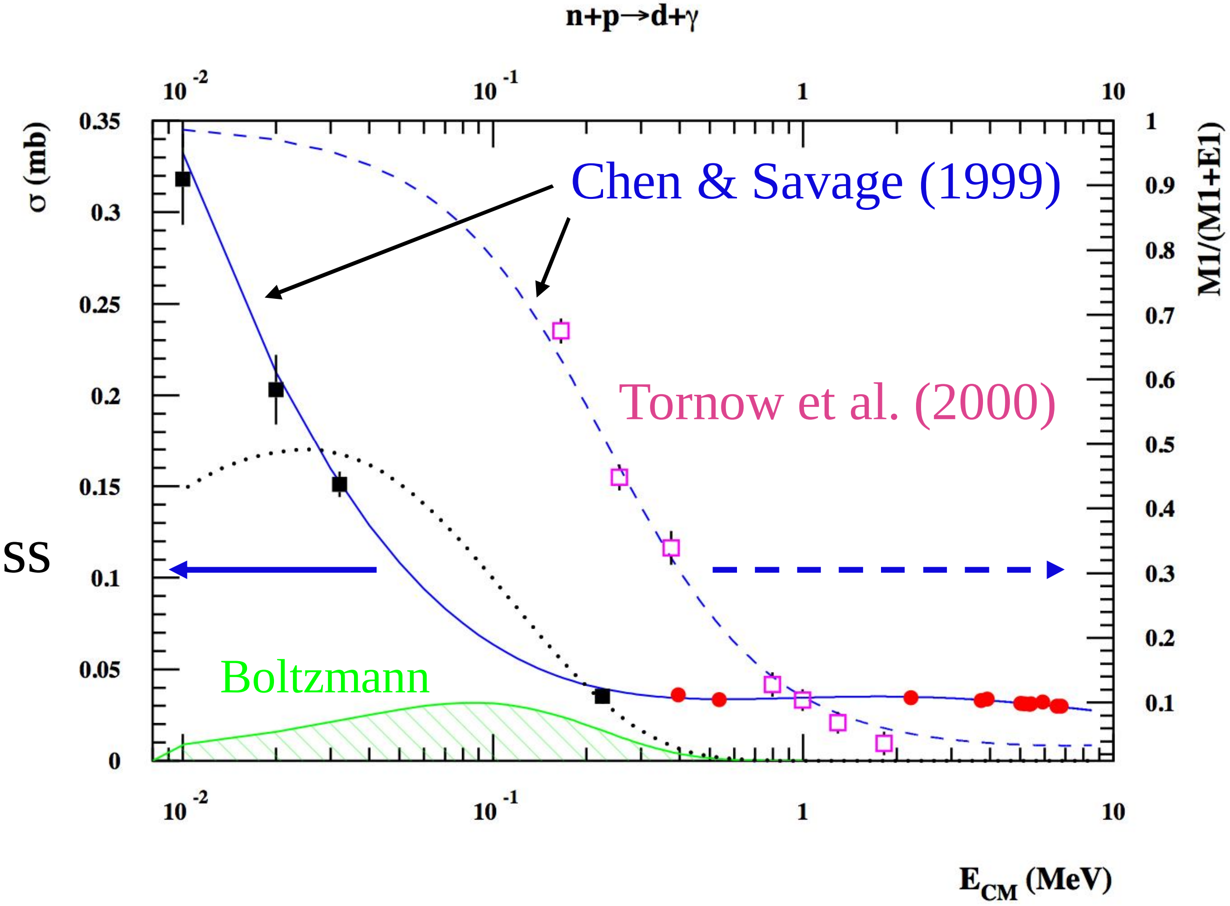
^{1}H(n,γ)D : theory versus experiments

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)]*

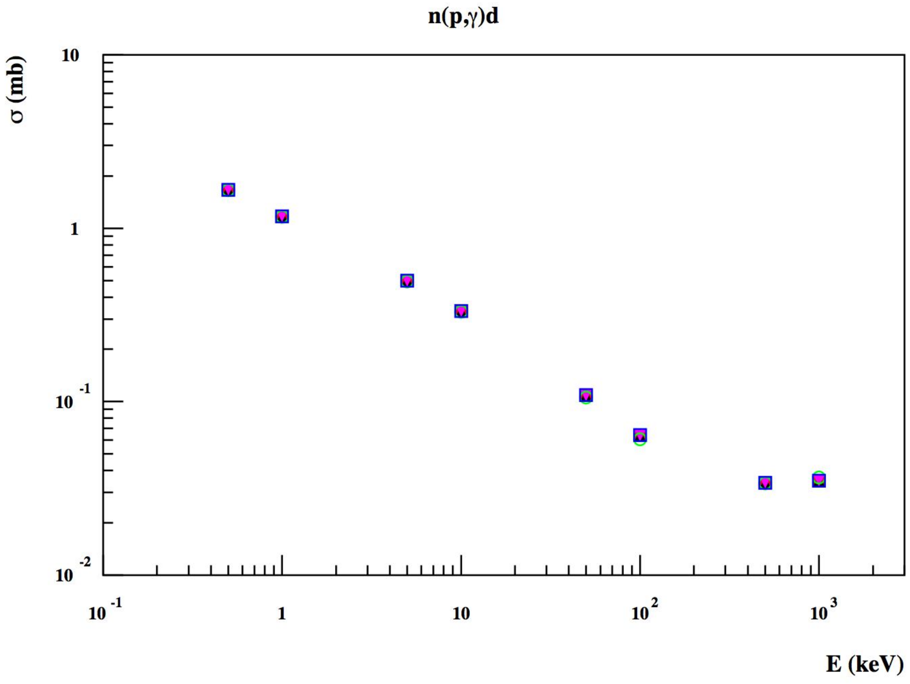


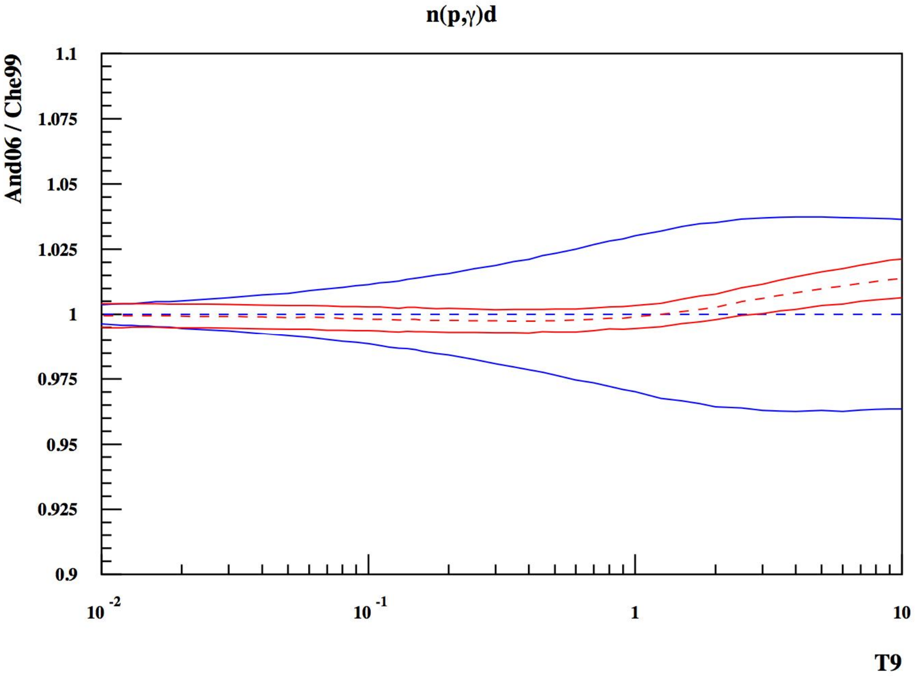
The $^{1}H(n,\gamma)^{2}H$ reaction

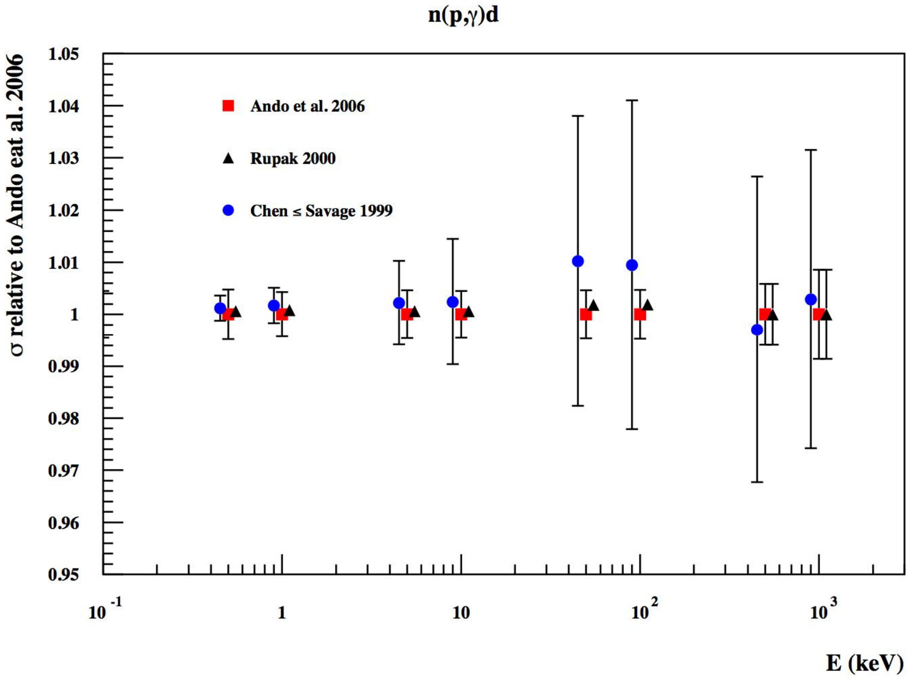
Sensitivity = 1.33

E ~ 25 keV

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







Reactions with charged particles

- Below the Coulomb barrier!
- Very weak cross sections :

σ(E) ↘ ↘ ↘ when E ↘

Coulomb and et centrifugal penetrability :

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

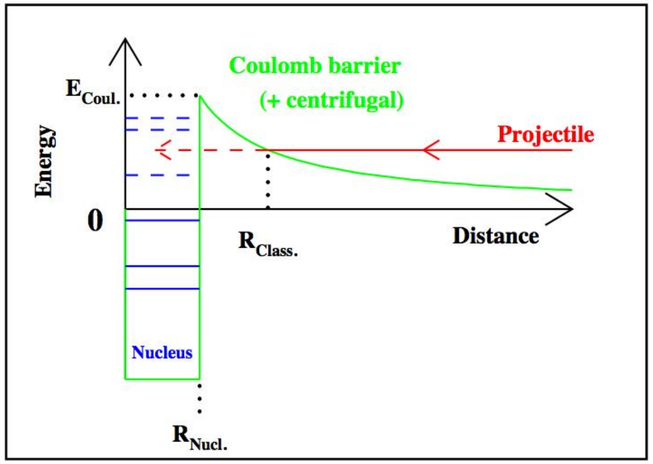
F, *G* = Coulomb functions

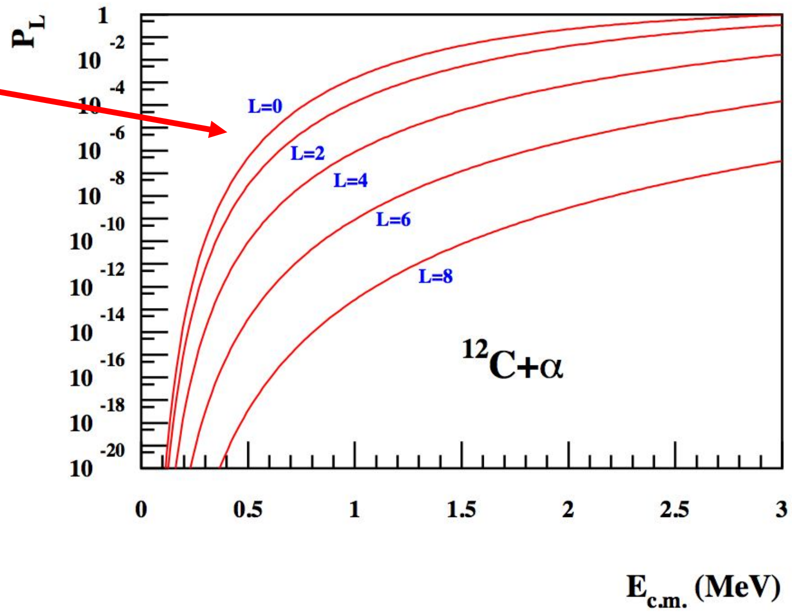
η = Sommerfeld parameter

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

$$\boxed{\rho = \frac{R}{\bar{\lambda}} = \frac{\sqrt{2\mu E}}{\hbar} R}$$

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 : $E_G = \frac{1}{2}(2\pi\alpha Z_1 Z_2)^2 \mu c^2 = (0.989 \cdot Z_1 Z_2 A^{1/2})^2$ [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)* :

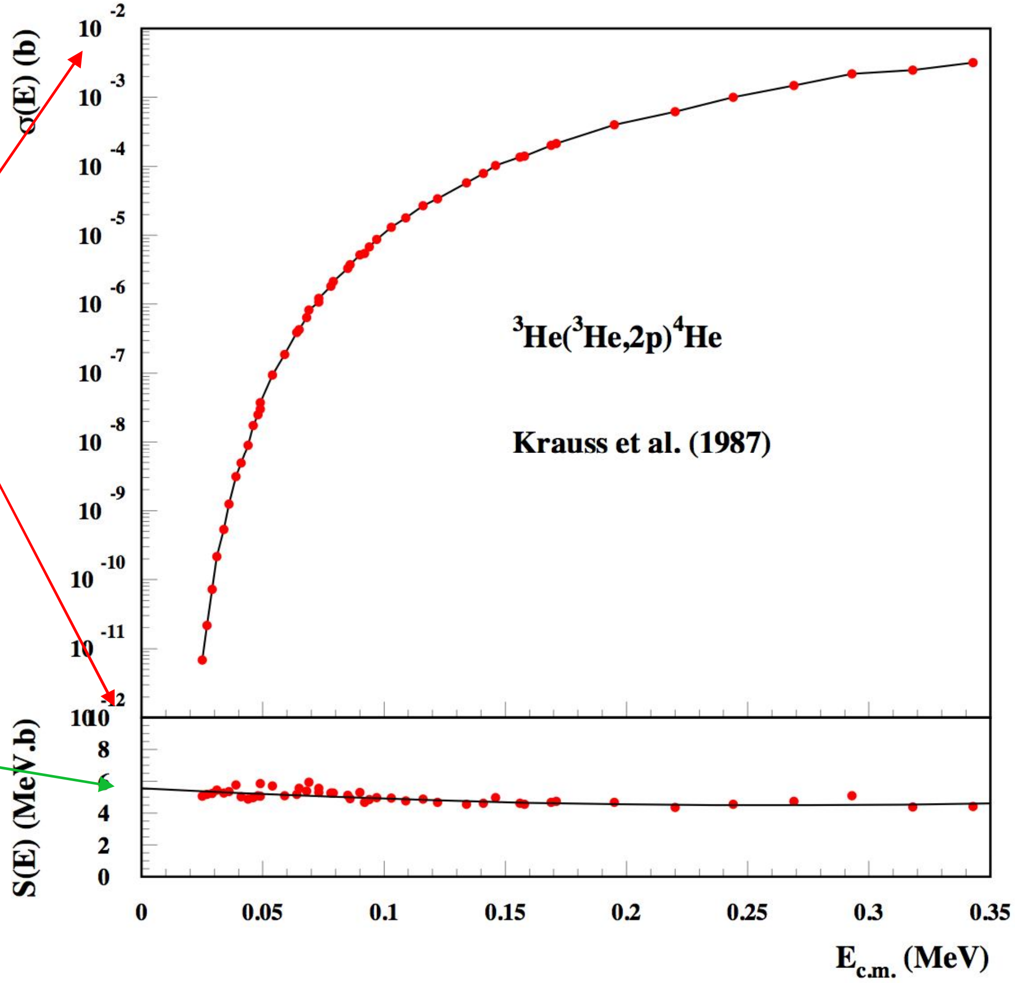
9 orders of magnitude

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)
- *Cyburt, Matthews,... 2014 (?)*

R-Matrix formalism

(P. Descouvemont lectures next week)

Parametrization (interpolation/extrapolation) of nuclear cross sections with a reduced set of parameters $\{p_i\}$ *related* to nuclear quantities

•Two regions of space (*a* ~ nuclear radius)

- ➢External ($r \geq a$) : nuclear force negligible, Coulomb wave functions
- ➢Internal ($r \leq a$) : complicated

•R-matrix

- ➢Connects internal and external wave functions at $r=a$
- ➢Introducing poles *related* to resonant and non resonant contributions

Rate uncertainties

- Solve for $\{p_i\}$: $\chi^2(\{p_i\}) = \chi^2(\{p_i^{min}\}) + \Delta\chi^2$

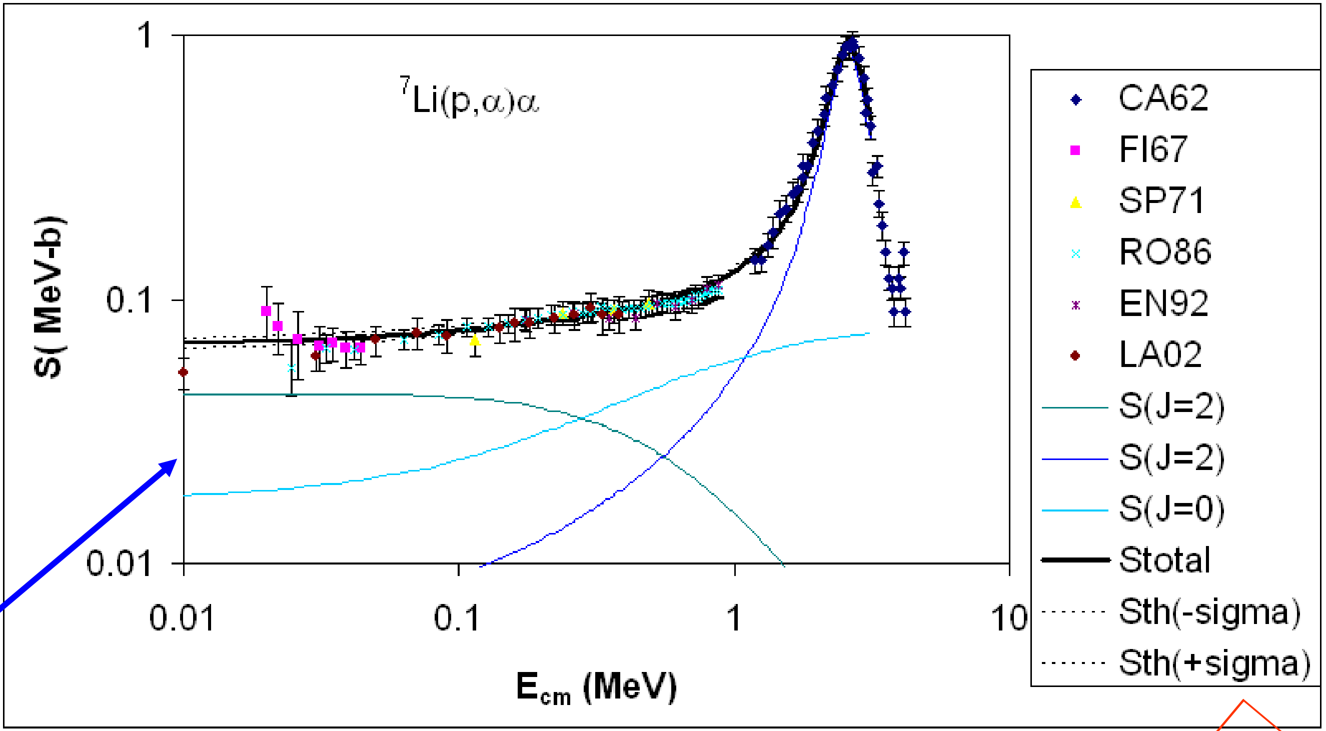
where $\{p_i^{min}\}$ is the set of parameters that minimizes the χ^2 and $\Delta\chi^2$ is a function of the confidence level (68% or 1-σ here)

- Calculate ± 1-σ rate limits by spanning the parameter space limited by the above condition;

- Special treatments
  - $\chi^2>1$: errors are scaled by $(\chi^2)^{½}$
  - Incompatible data sets (normalization) : individual fits of data sets

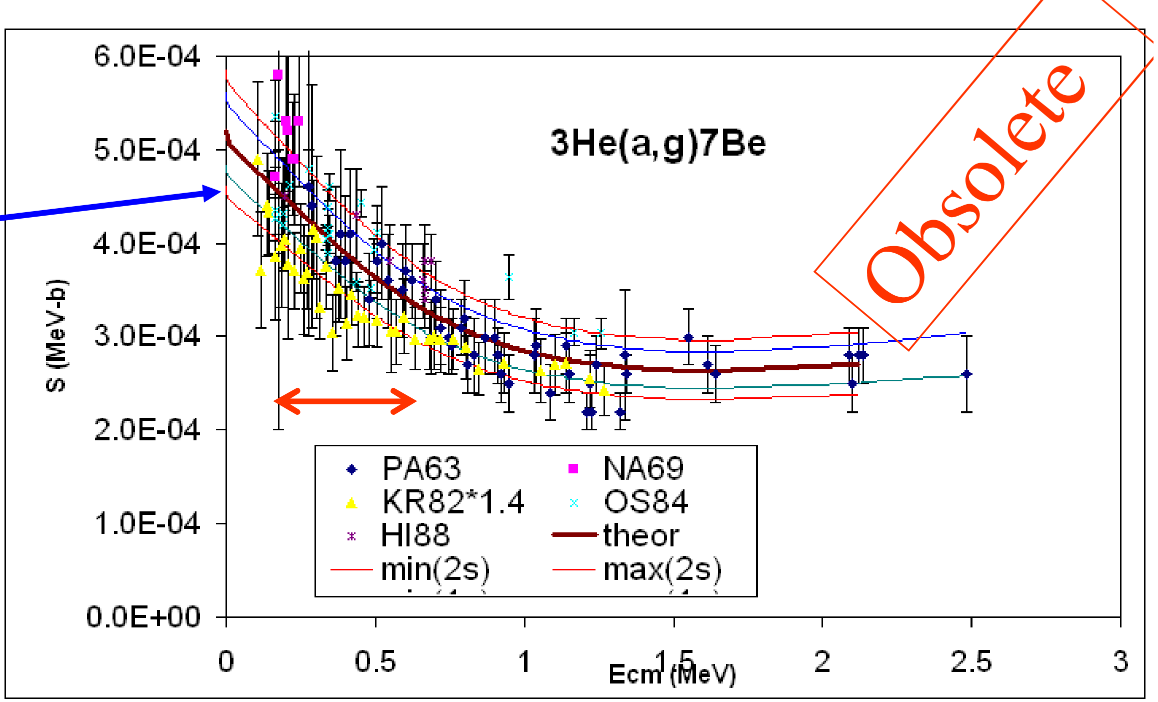
New analysis of BBN rates

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

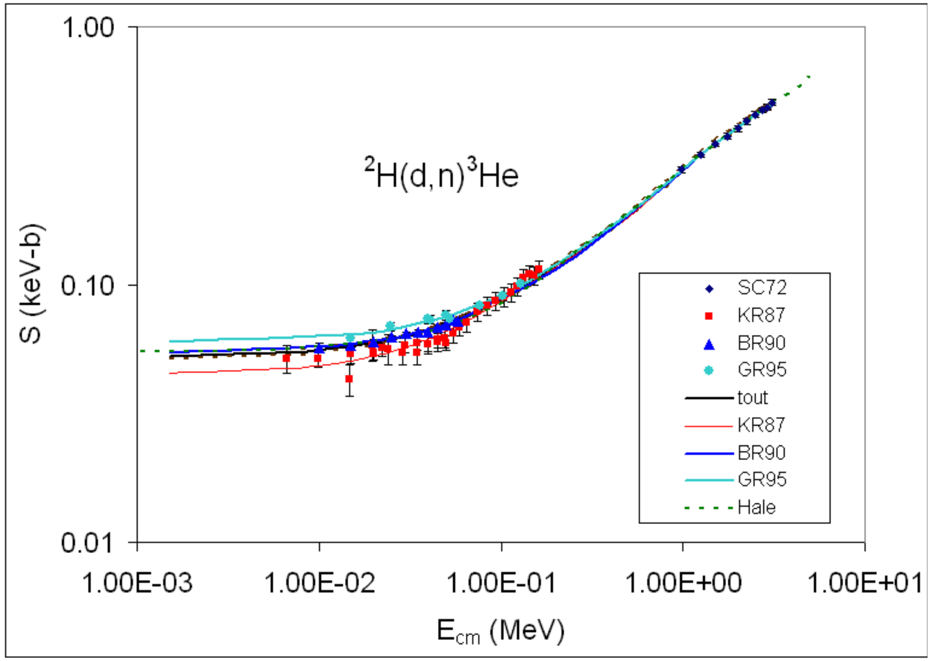


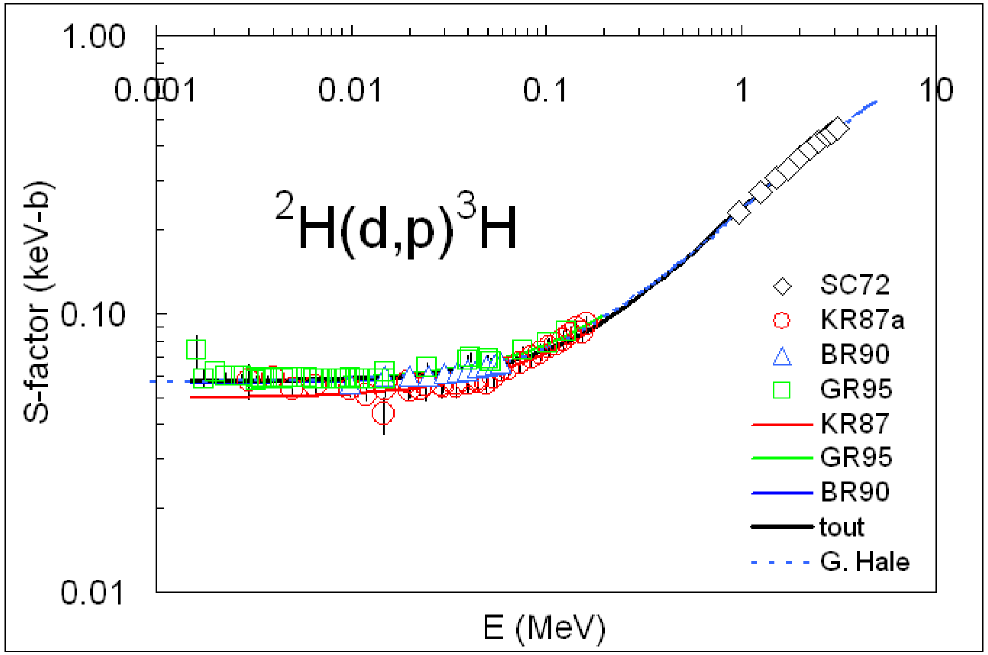
« R-Matrix » formalism: S-factors fits of data constrained by theory

Provide also reaction rate uncertainties

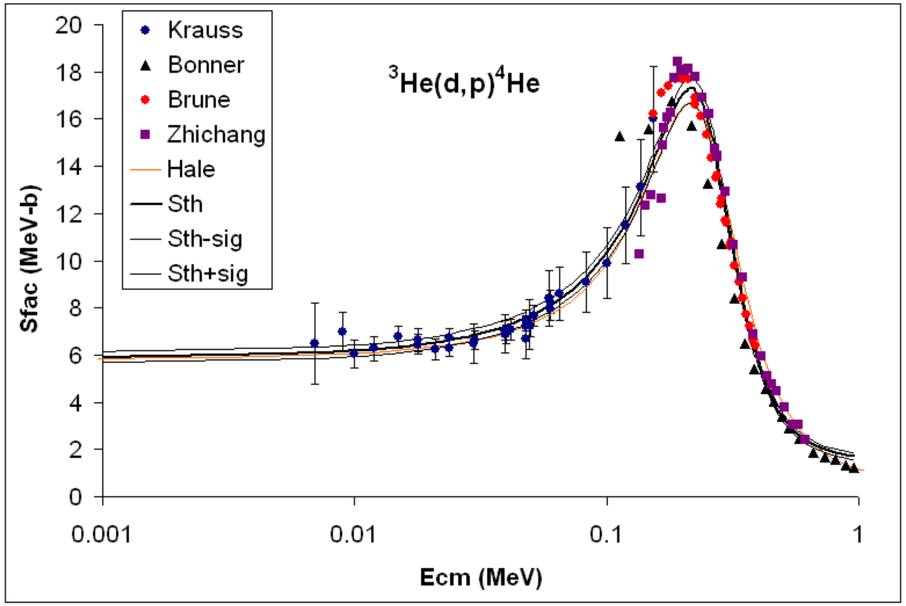


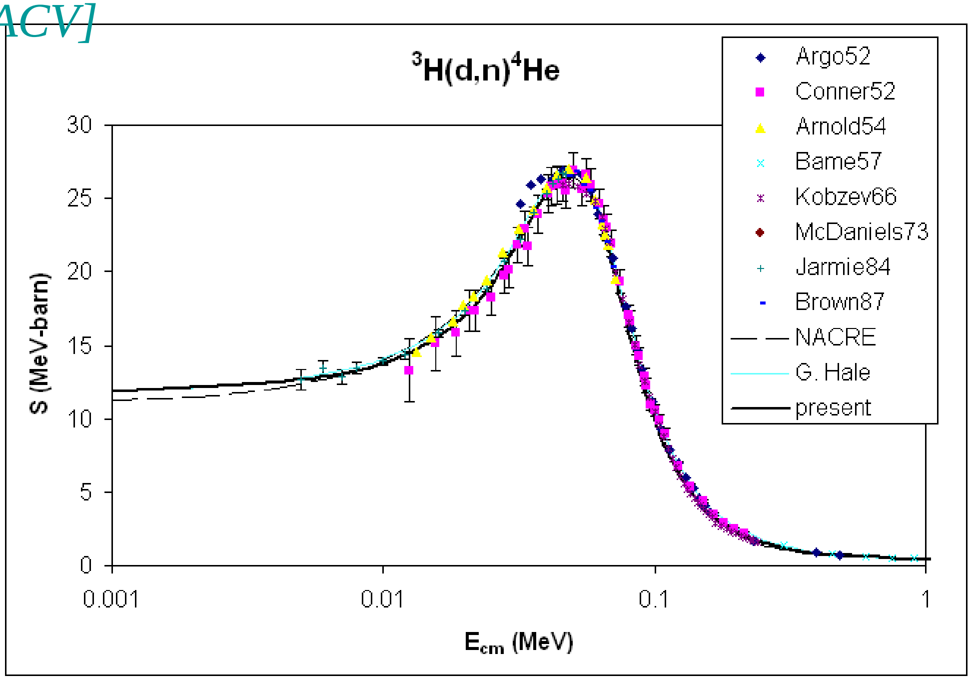
Obsolete

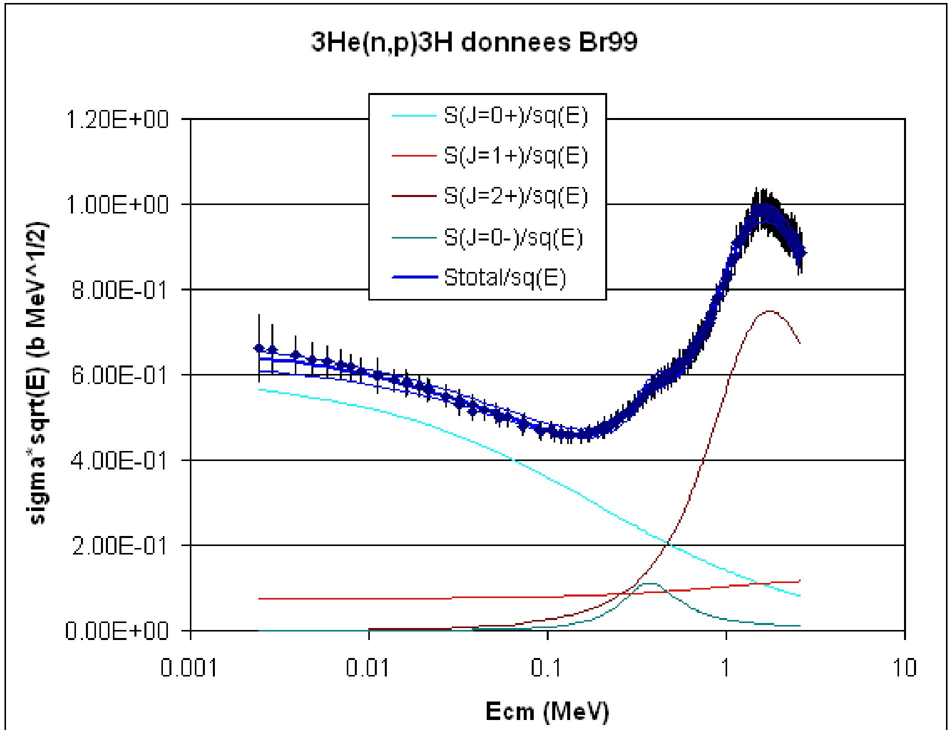

^{2}H(d,n)^{3}He
S (keV-b)
1.00
0.10
0.01
1.00E-03
1.00E-02
1.00E-01
1.00E+00
1.00E+01
E$_{cm}$ (MeV)
SC72
KR87
BR90
GR95
tout
KR87
BR90
GR95
Hale

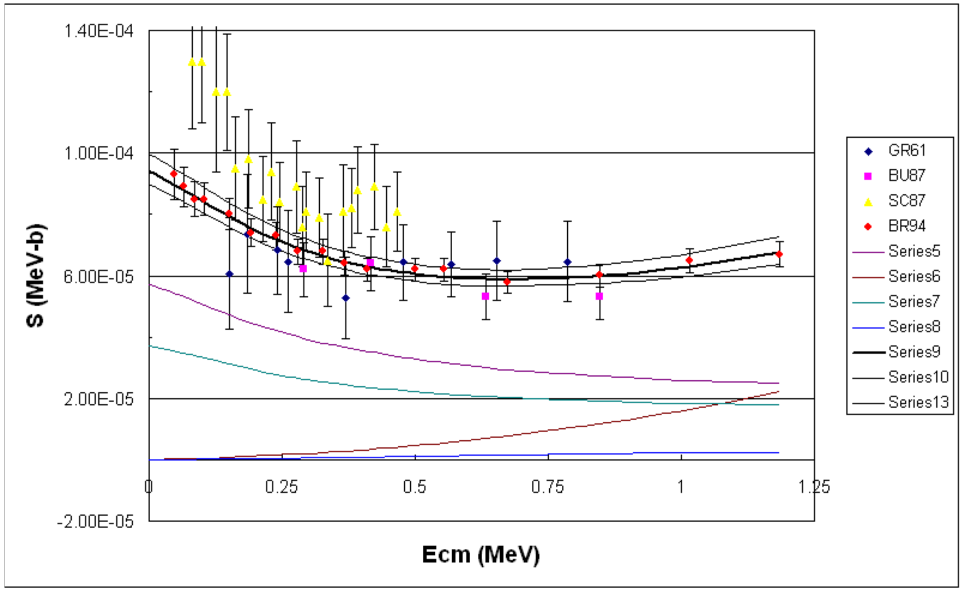

^{2}H(d,p)^{3}H
S-factor (keV-b)
1.00
0.10
0.01
0.001
0.01
0.1
1
10
E (MeV)
SC72
KR87a
BR90
GR95
KR87
GR95
BR90
tout
G. Hale

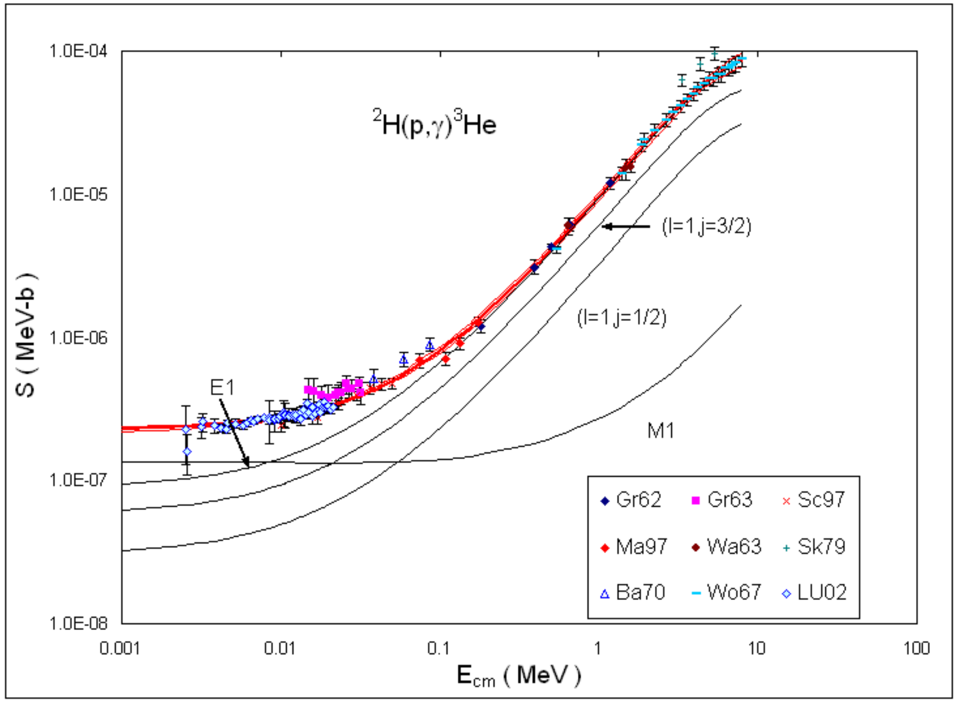
[DAACV]

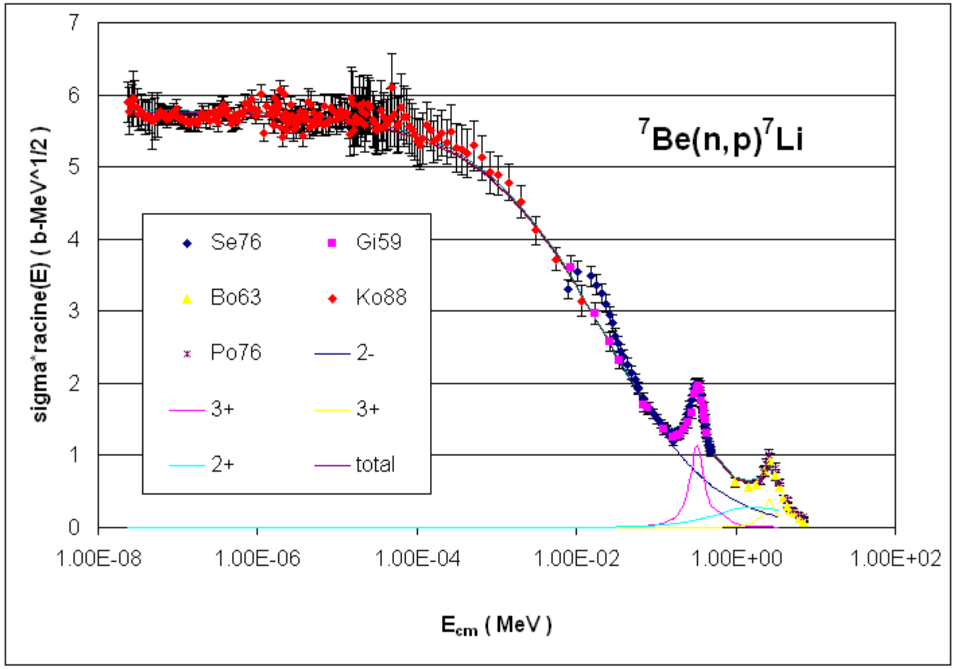

^{3}He(d,p)^{4}He
Sfac (MeV-b)
20
18
16
14
12
10
8
6
4
2
0
0.001
0.01
0.1
1
Ecm (MeV)
Krauss
Bonner
Brune
Zhichang
Hale
Sth
Sth-sig
Sth+sig


^{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

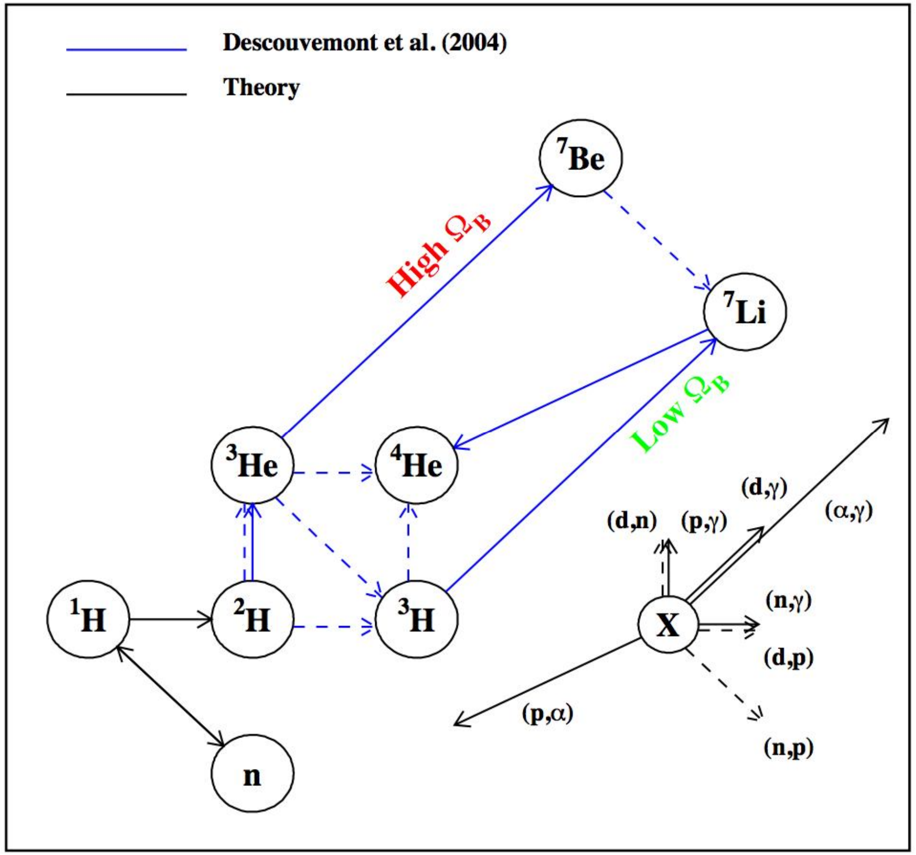

3He(n,p)3H donnees Br99
S(J=0+)/sq(E)
S(J=1+)/sq(E)
S(J=2+)/sq(E)
S(J=0-)/sq(E)
Stotal/sq(E)
sigma*sqrt(E) (b MeV^1/2)
1.20E+00
1.00E+00
8.00E-01
6.00E-01
4.00E-01
2.00E-01
0.00E+00
0.001
0.01
0.1
1
10
Ecm (MeV)


1.40E-04
1.00E-04
6.00E-05
2.00E-05
-2.00E-05
S (MeV-b)
0
0.25
0.5
0.75
1
1.25
Ecm (MeV)
GR61
BU87
SC87
BR94
Series5
Series6
Series7
Series8
Series9
Series10
Series13


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


^{7}Be(n,p)^{7}Li
7
6
5
4
3
2
1
0
sigma*racine(E) (b-MeV^1/2)
Se76
Gi59
Bo63
Ko88
Po76
2-
3+
3+
2+
total
1.00E-08
1.00E-06
1.00E-04
1.00E-02
1.00E+00
1.00E+02
E_{cm} (MeV)

Nuclear physics experiments since 2004

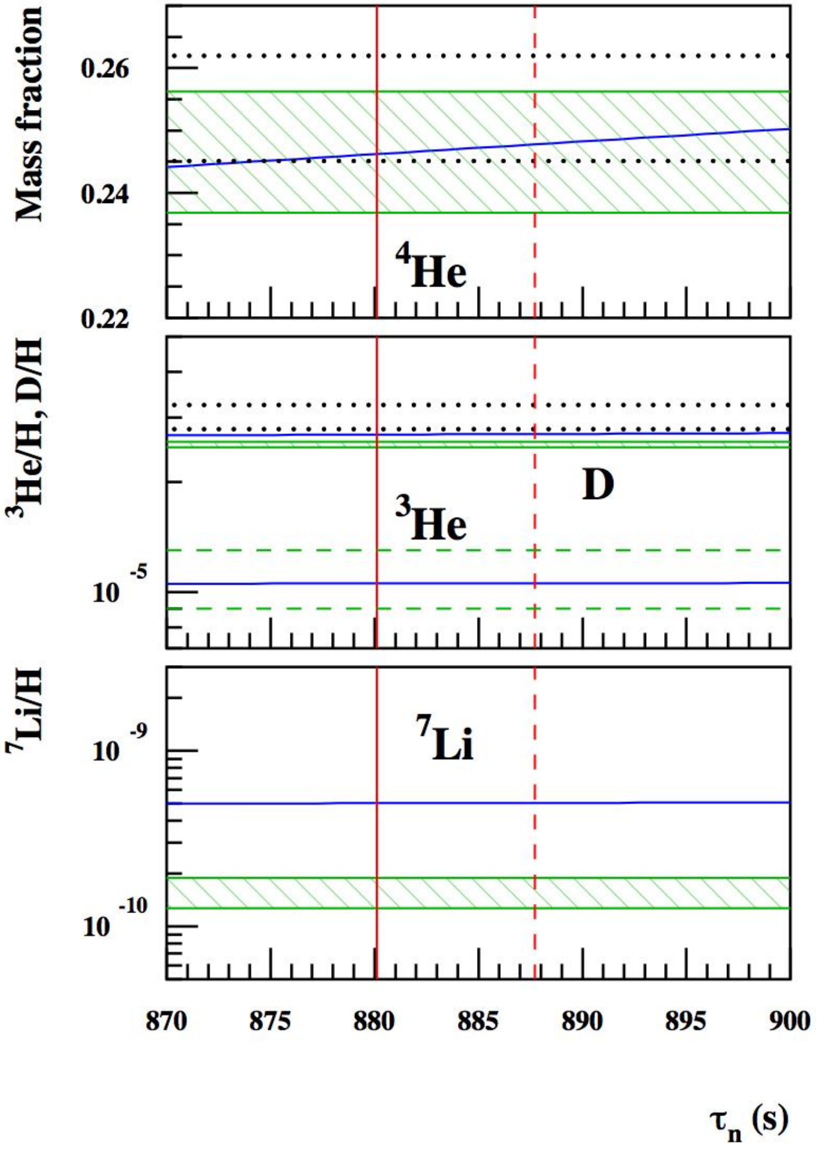


Concerning the main reactions

- Neutron lifetime
- ^{1}H(n,γ)^{2}H reaction
- ^{3}He(α,γ)^{7}Be *[Many….]*
- D(d,p)^{3}H and D(d,n)^{3}He *[Leonard et al. (2006)]*

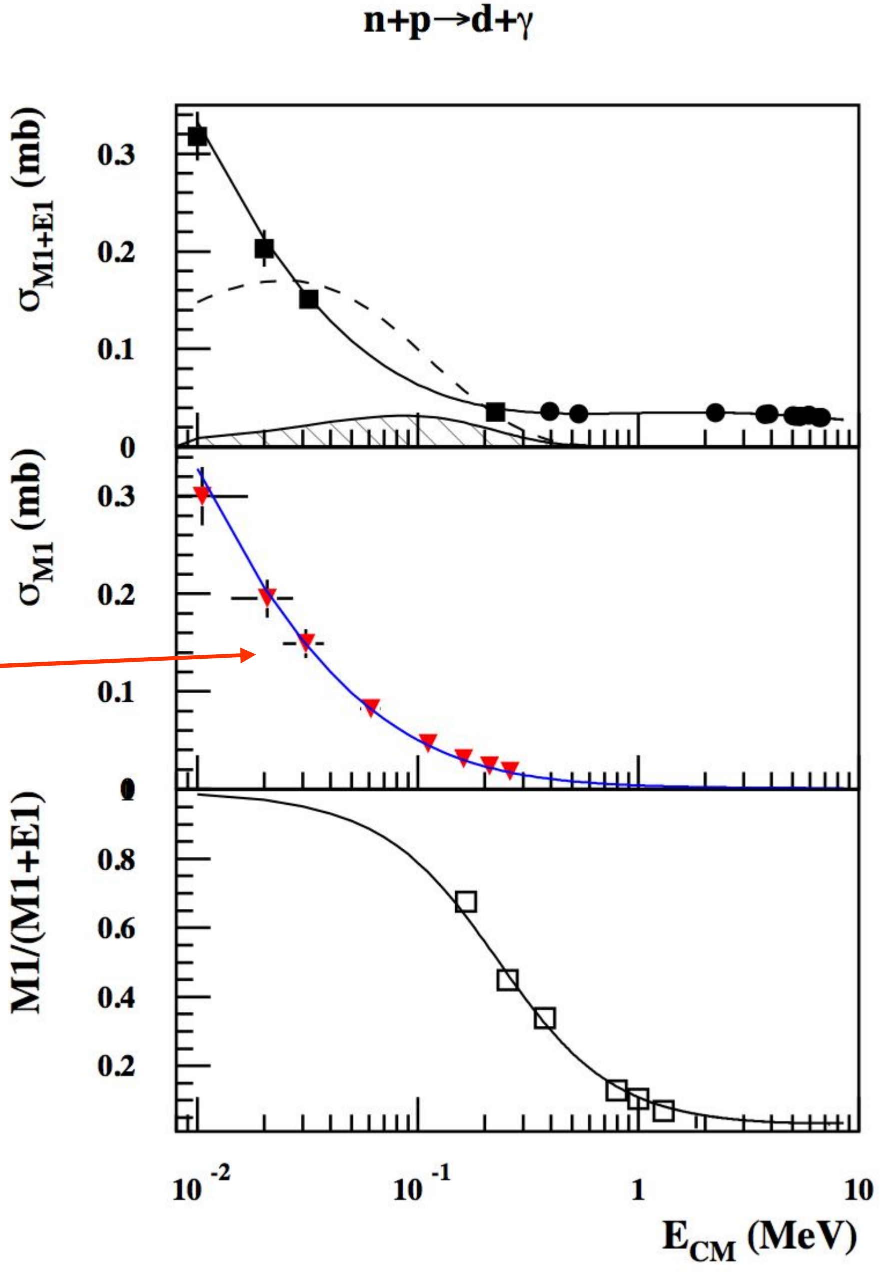
Influence of the neutron lifetime

- τ_n = 885.7±0.8 s *[PDG 2008]*
- τ_n=878.5±0.7 ±0.3 s *[Serebrov+ 2005]*
- τ_n= 880–884 s *[Wietfeldt & Greene 2011]*
- τ_n= 880.1 ± 1.1 s *[PDG 2013]*
- τ_n=887.7 ± 1.2 ± 1.9 s *[Yue+ 2013]*



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

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

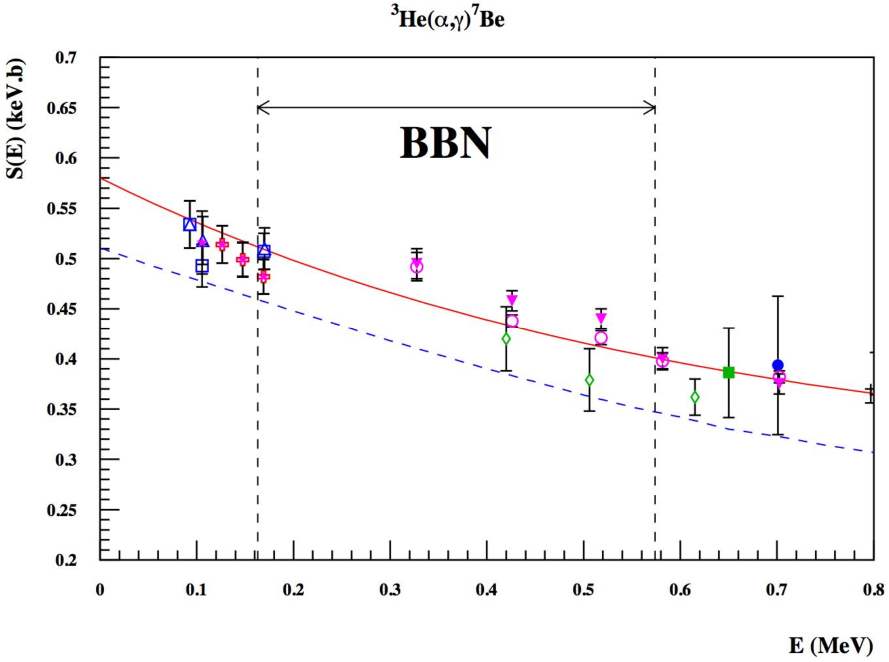


The ^{3}He(α,γ)^{7}Be reaction

- ^{3}He(α,γ)^{7}Be (^{7}Li sensitivity 0.97)

New precise (*prompt, activation, recoil)* measurements to resolve previous systematic uncertainties *[Brown+ 2007; Confortola+ 2007; Costantini+ 2008; Nara Singh+ 2005, 2013; Brown+ 2007; Gyürky+ 2007; Di Leva+ 2009; Carmona-Gallardo+ 2012; Bordeanu+ 2013;....(?),..* ***NPA VI]***

Reanalysis of ^{3}He(α,γ)^{7}Be rate ***[Cyburt & Davids 2008]***: *S(0)* = 0.580 ± 0.043

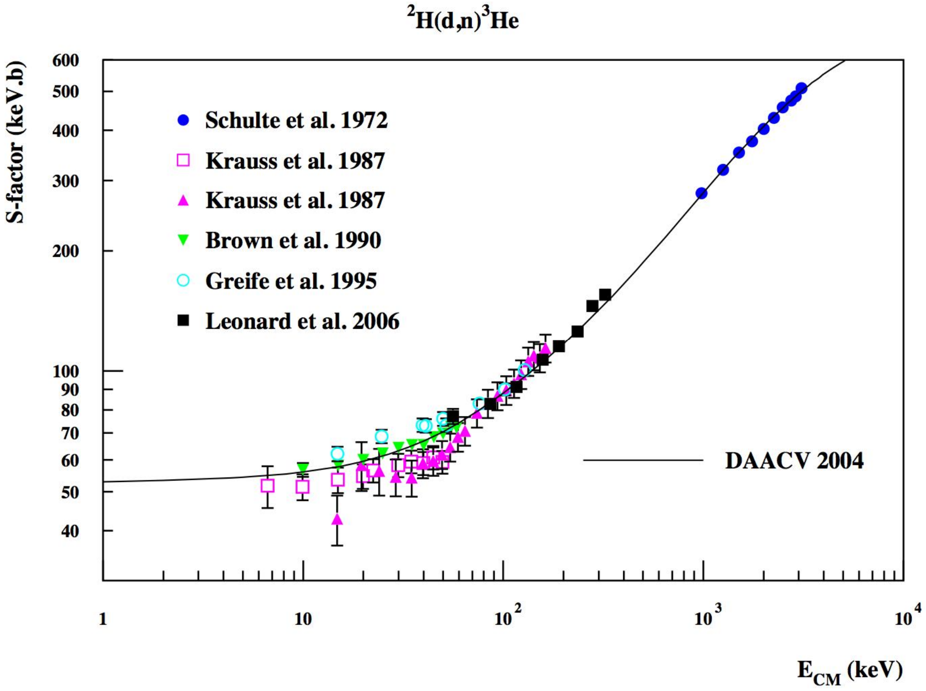


The $^{2}H(d,n)^{3}He$ reaction

Sensitivity = 0.61

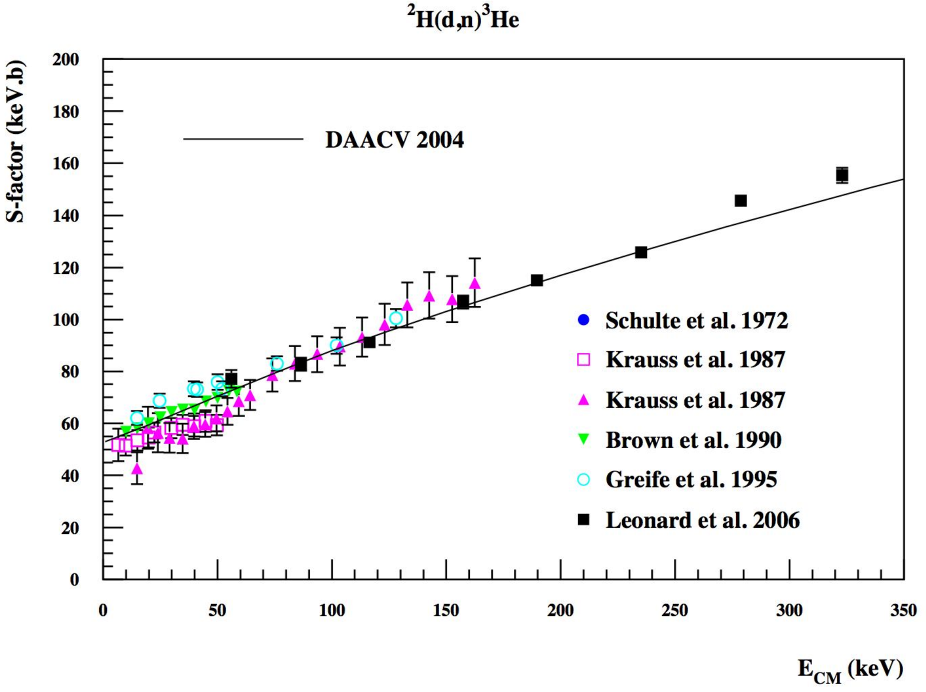
$E_0(\Delta E_0/2) = 0.12(0.12)$ MeV

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



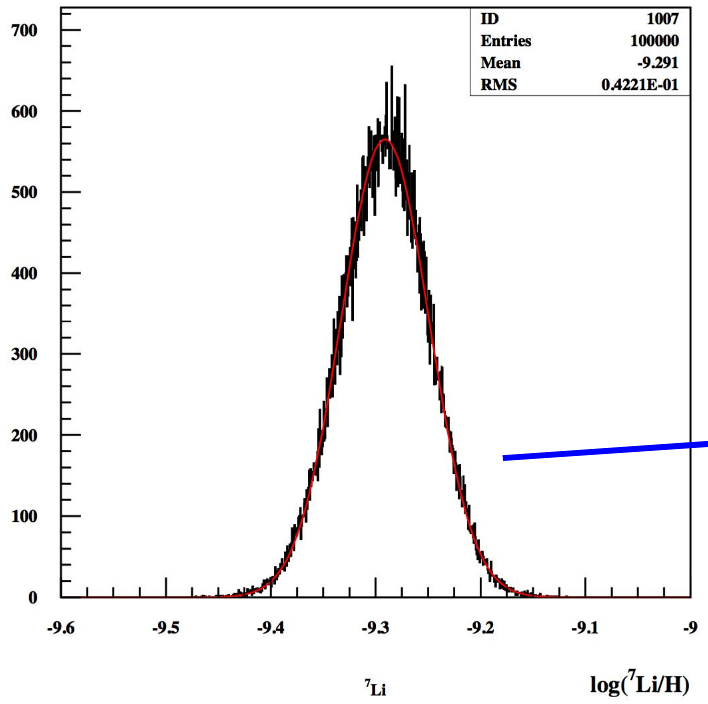
Excellent agreement with *DAACV 2004* fit within Gamow window

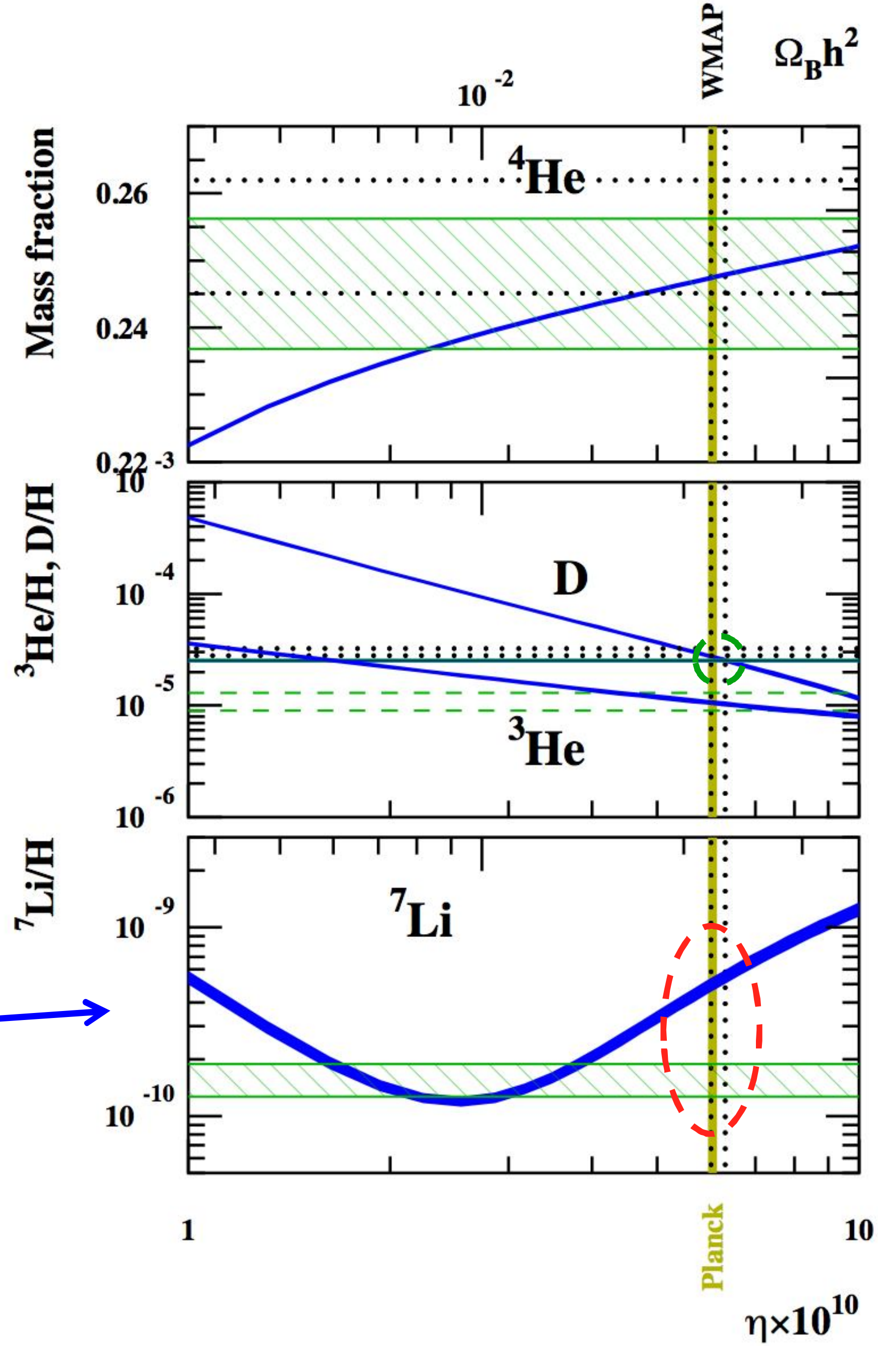
- No change in central Li/H value
- Reduced uncertainty
- R-matrix fit reliability



Monte Carlo BBN calculations

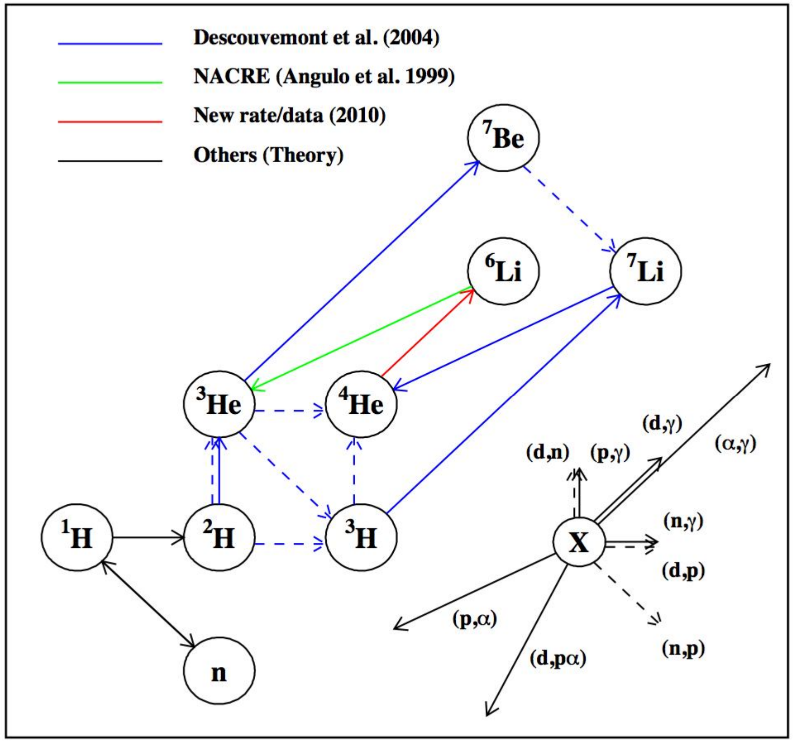
Using log-normal distribution *[Iliadis+ 2010]* for the reaction rates from *DAACV*, *Ando et al. 2006*, *Leonard et al. 2006*, and *Cyburt & Davids 2008*.

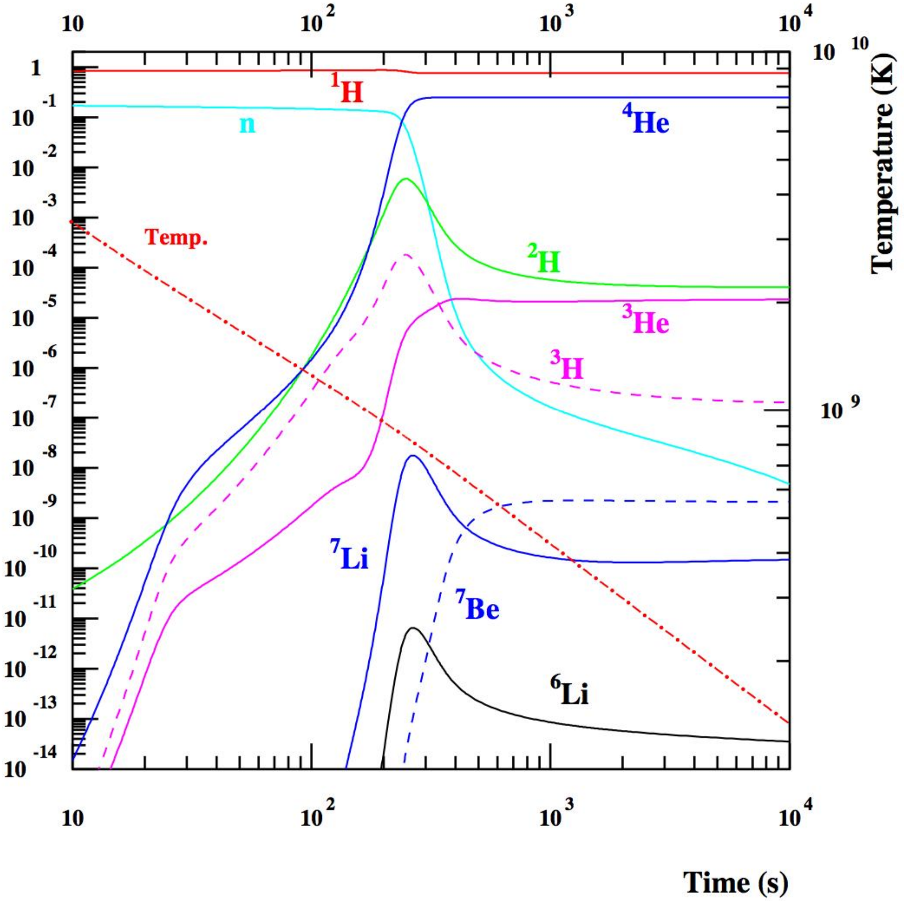




^{6}Li nucleosynthesis

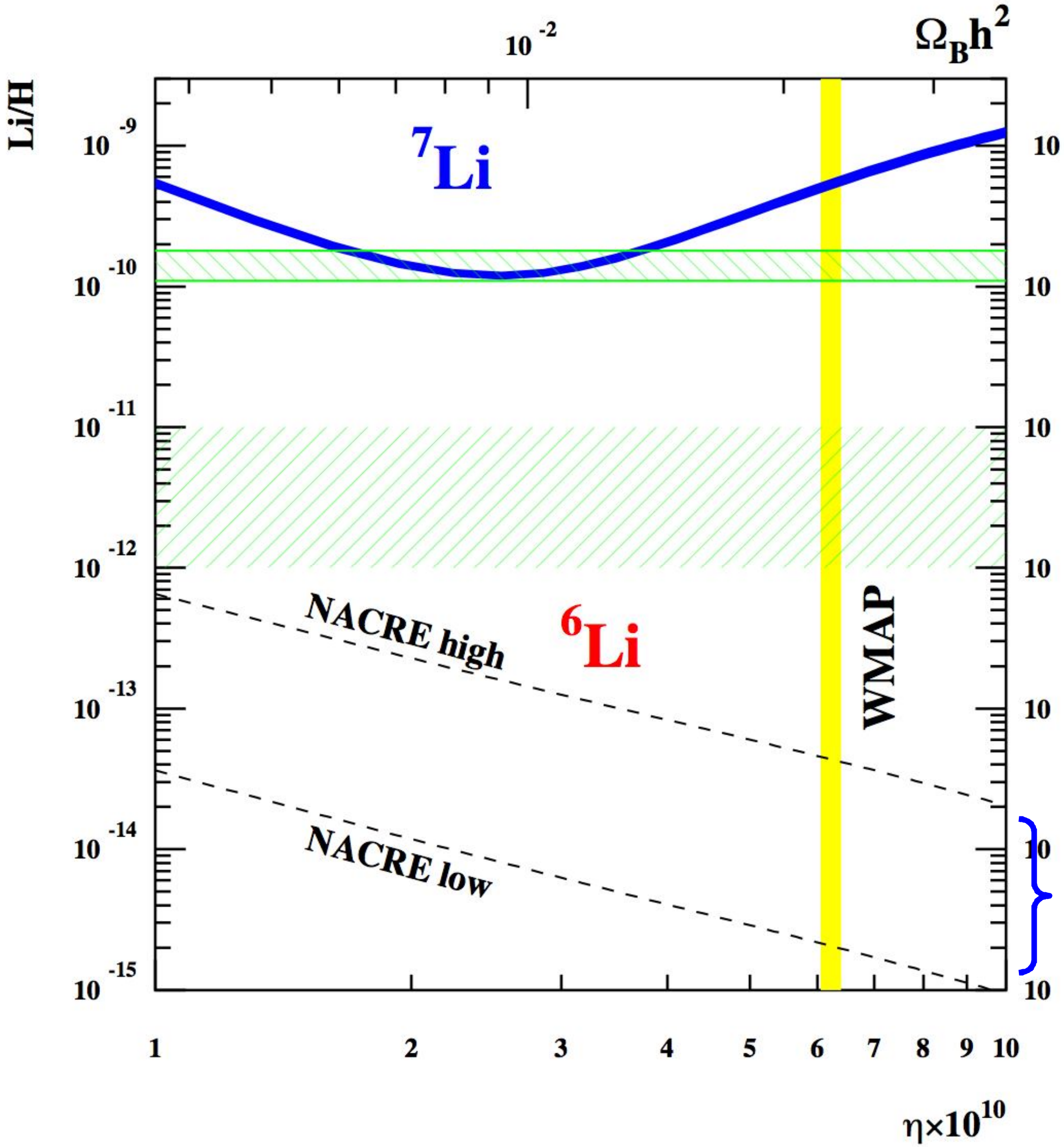
At WMAP baryonic density





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

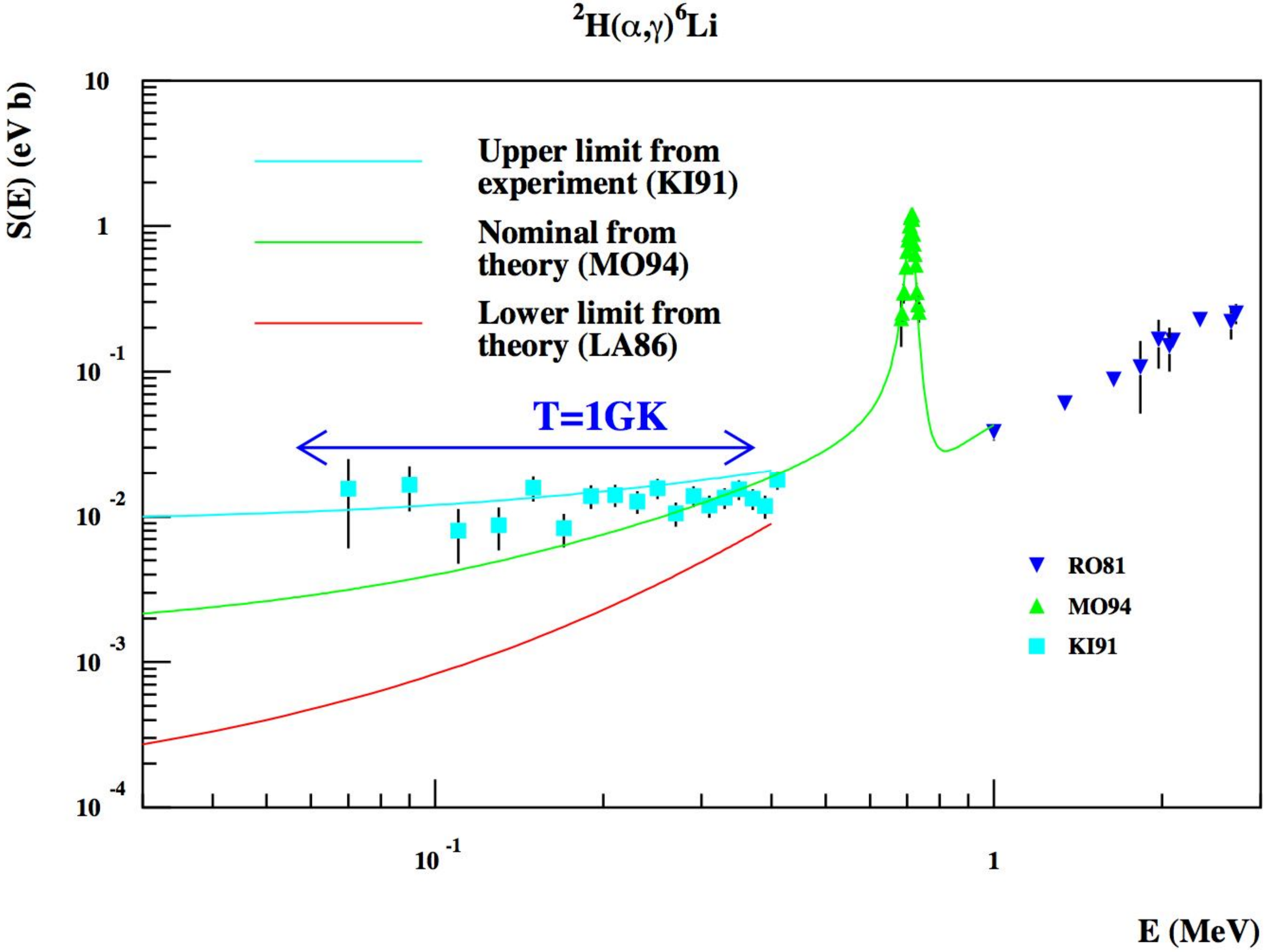
The ^{6}Li problem vs nuclear physics



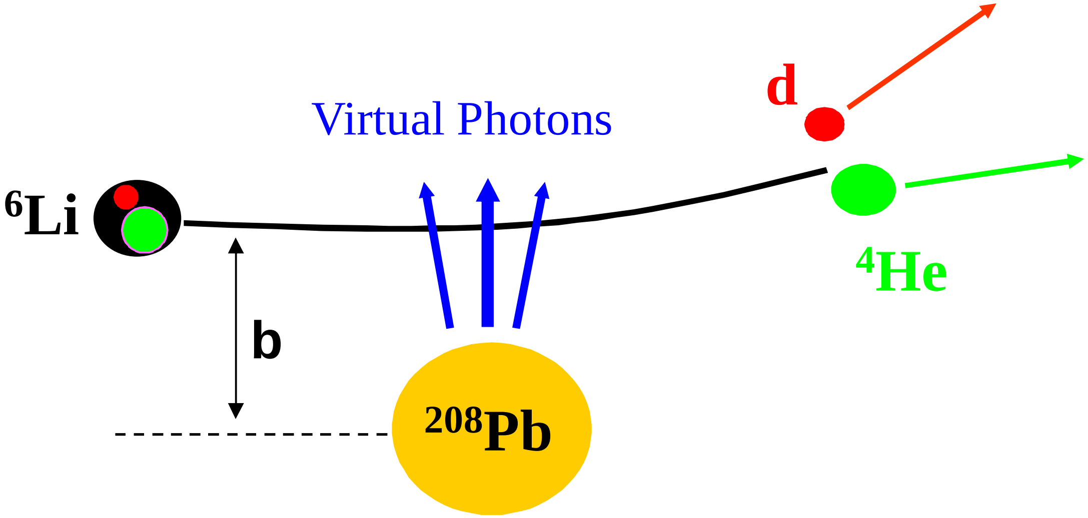
- ^{4}He(t,n)^{6}Li, ^{7}Li(p,d)^{6}Li : Q ≈ -5MeV
- ^{3}He(t,γ)^{6}Li : too slow

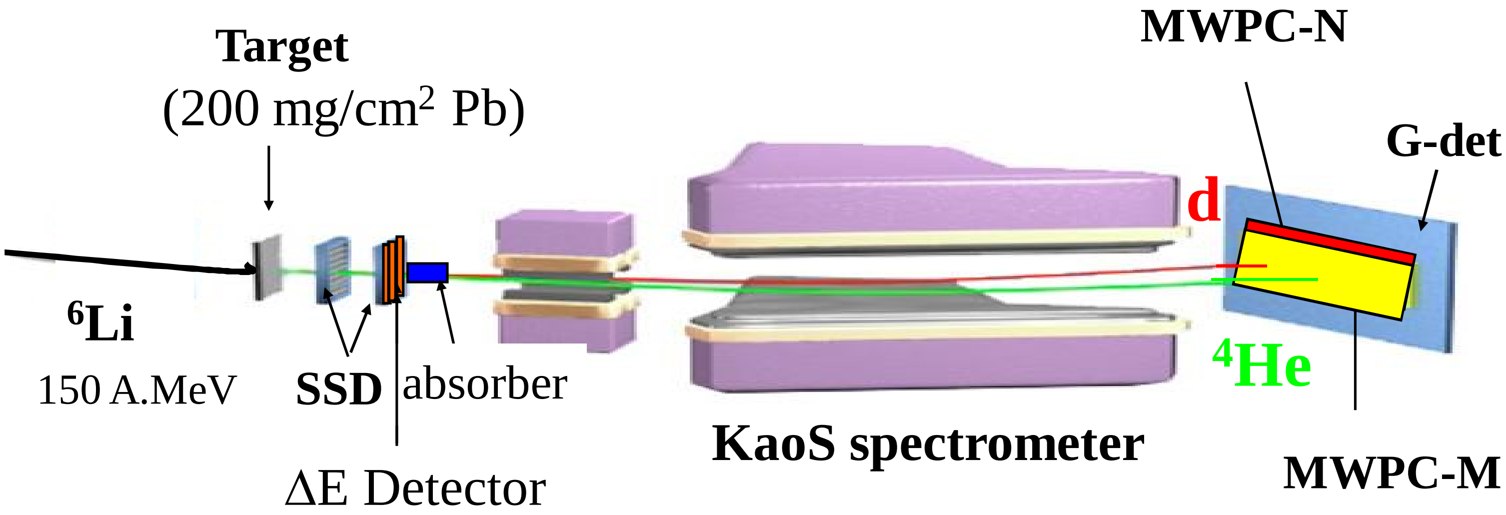
Uncertainty from ^{2}H(α,γ)^{6}Li
(NACRE)

The $^{2}\mathrm{H}(\alpha,\gamma)^{6}\mathrm{Li}$ rate in NACRE



Coulomb dissociation of ^{6}Li at GSI



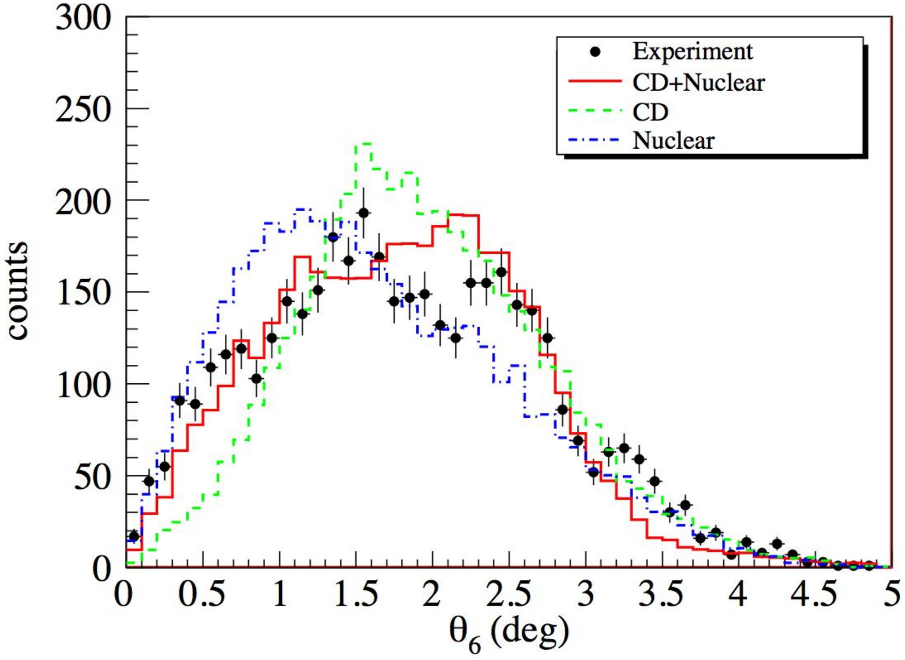


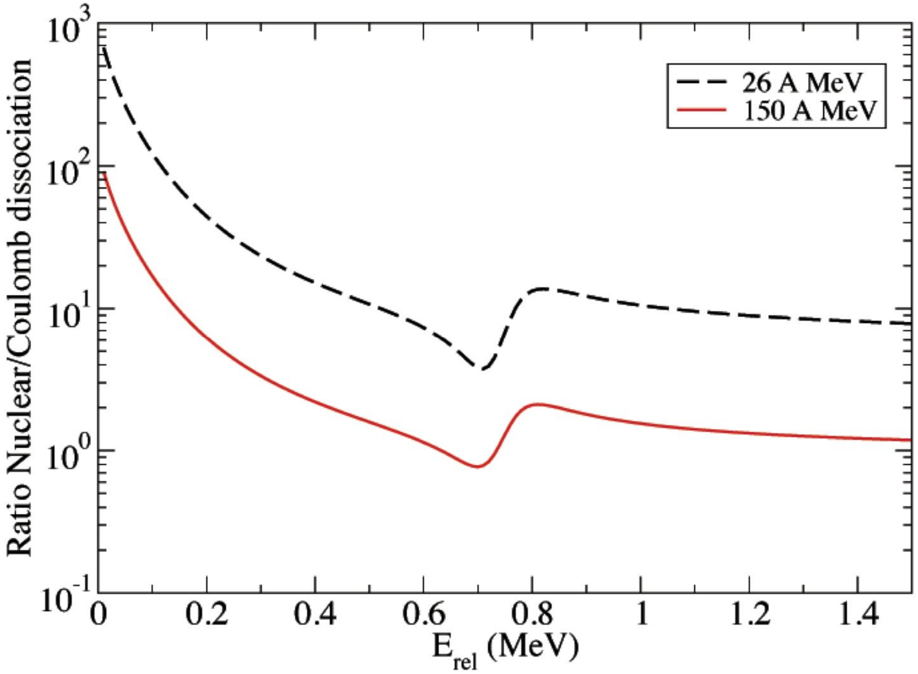
Coulomb dissociation of ^{6}Li at GSI

❑ From *S. Typel*'s calculations :

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

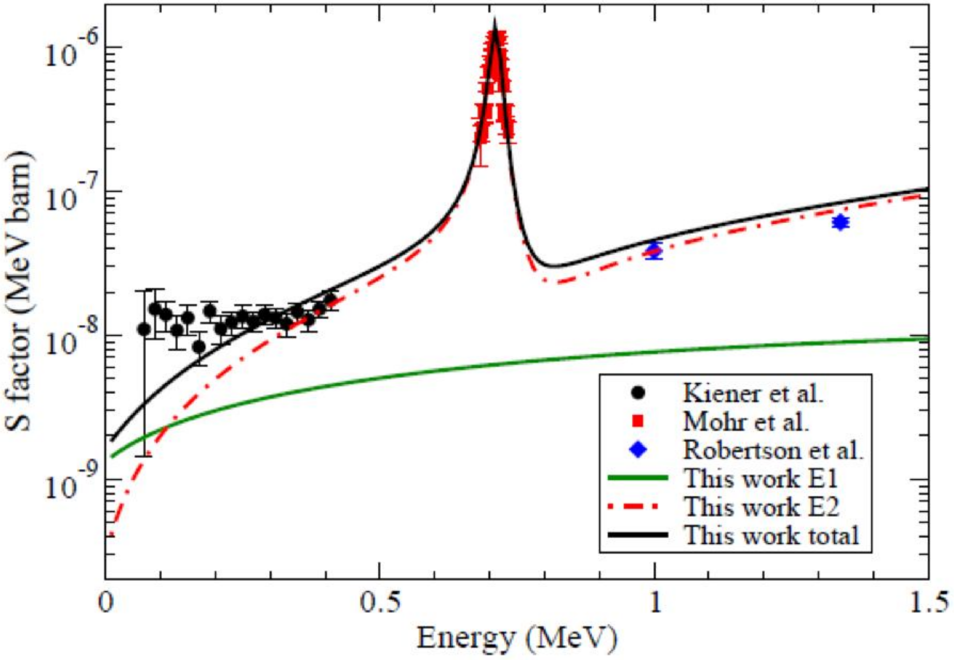
➢ At 26 A MeV *[Kiener al. 1991]*, the nuclear breack-up contribution *is dominant*

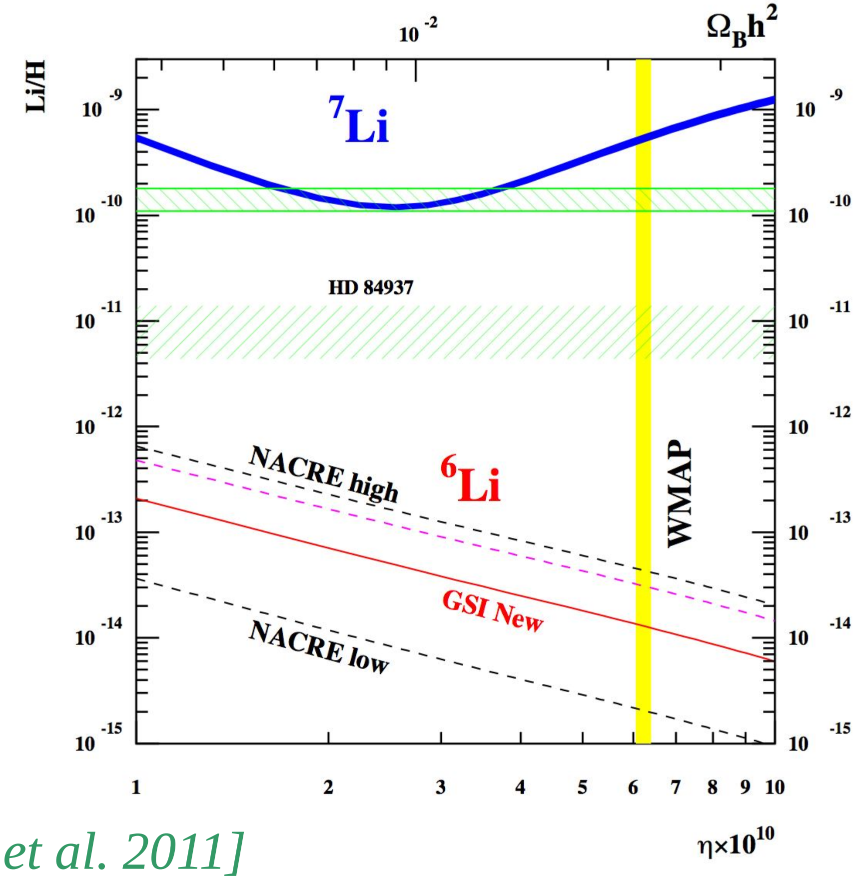




[Hammache et al. 2010]

Reduction of the uncertainty on ^{6}Li yield





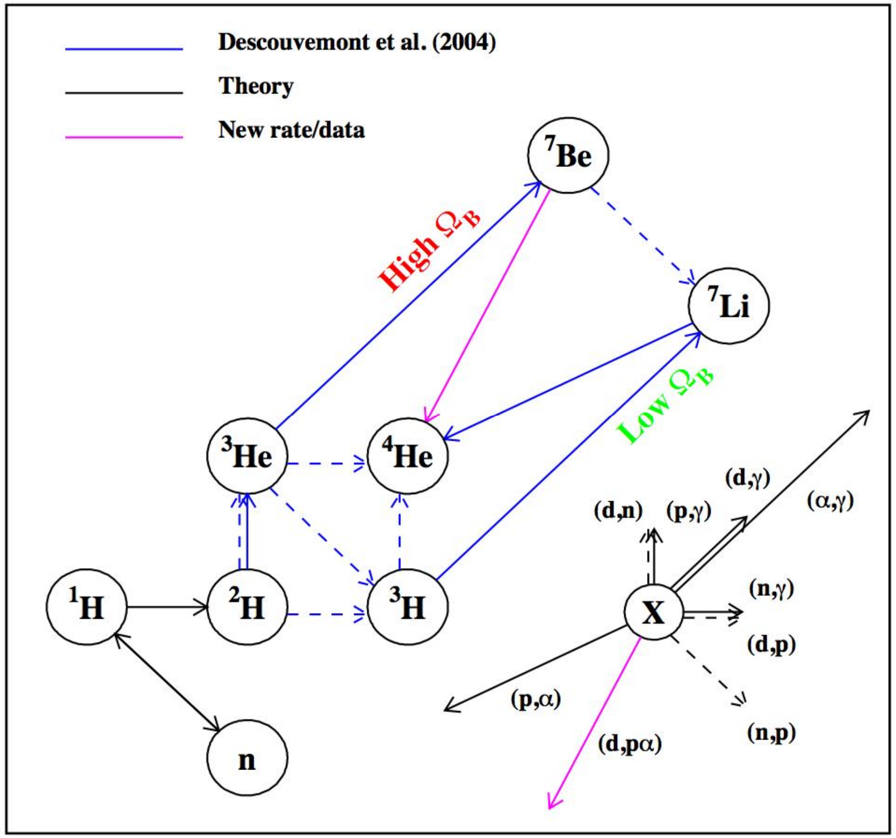
[Hammache et al. 2011]

Coming next : results from LUNA *[Gustavino et al. NIC XII; NPA 6]*

Nuclear Physics aspects

1. The main reactions for H, He and Li BBN production
2. Search for nuclear solutions to the lithium problem
3. Be, B and CNO production in BBN
4. Monte-Carlo evaluation of reaction rates
5. Monte-Carlo investigation of BBN

Nuclear solution to the Li problem ?



At η_{WMAP} ^{7}Li from ^{7}Be post BBN decay

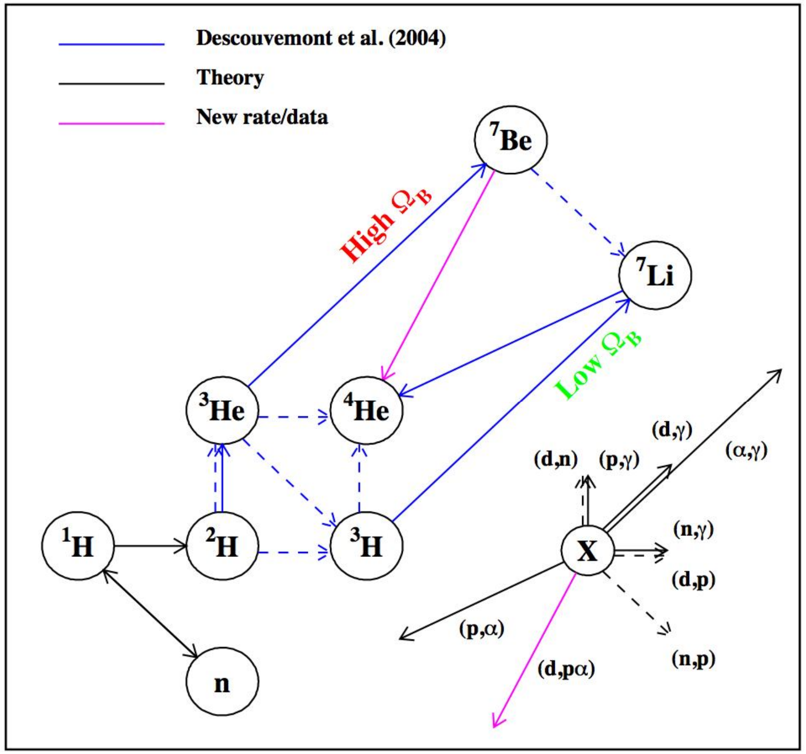
Tentatives nuclear solutions:
^{7}Be destruction by:

1. Supplementary reactions]
   e.g. ^{7}Be(d,p)^{8}Be*$\rightarrow$2α

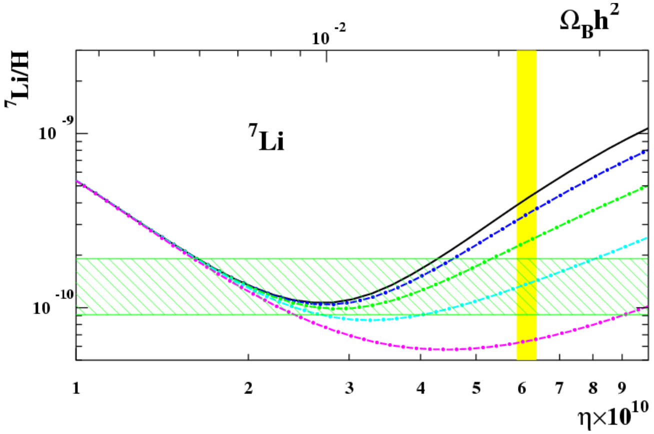
2. Extra neutron sources in
   ^{7}Be(n,p)^{7}Li(p,α)^{4}He
   destruction channel

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.

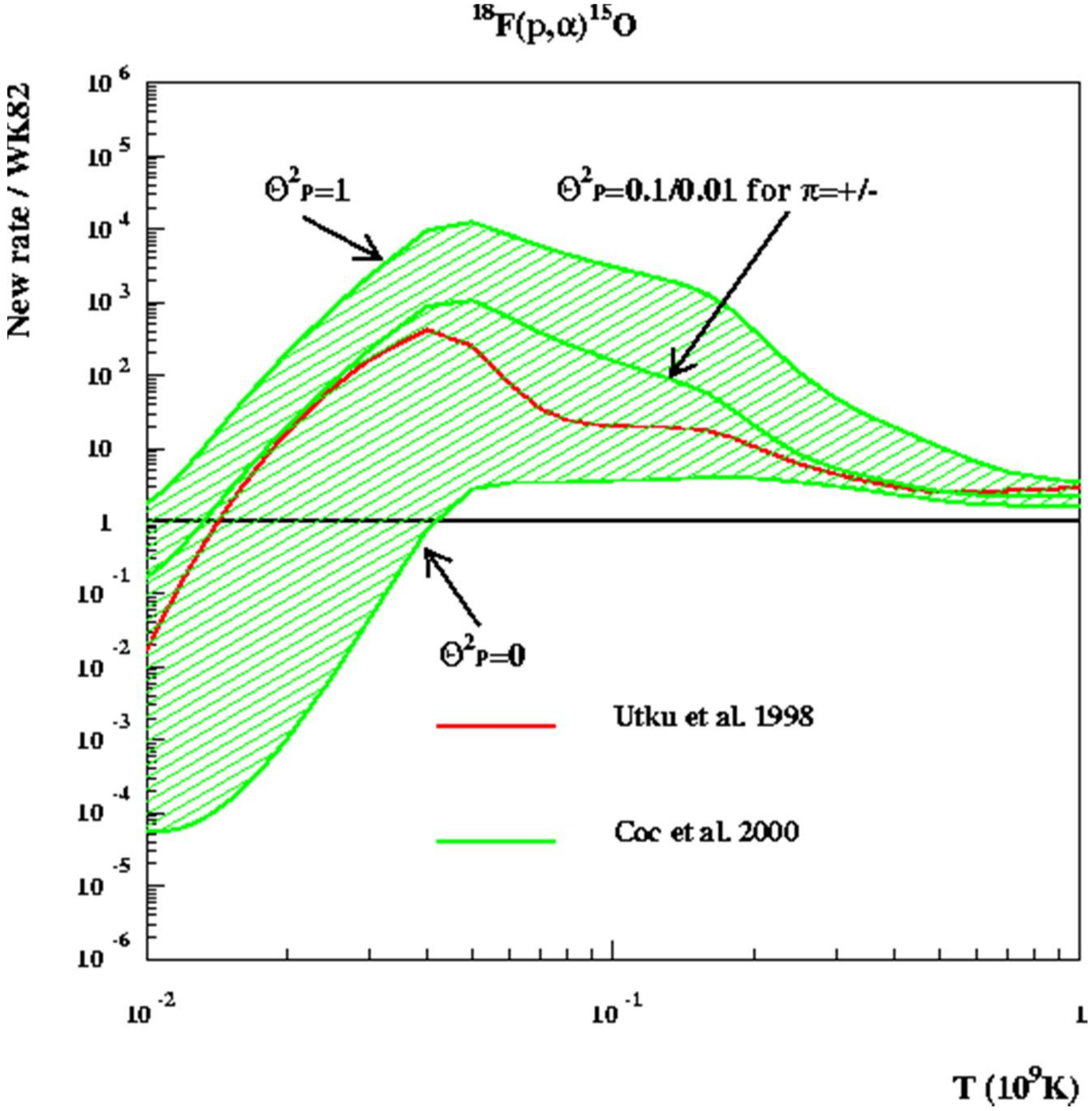


An interesting case :
the ^{7}Be(d,p)2α reaction



←×30
←×100
←×300
←×1000

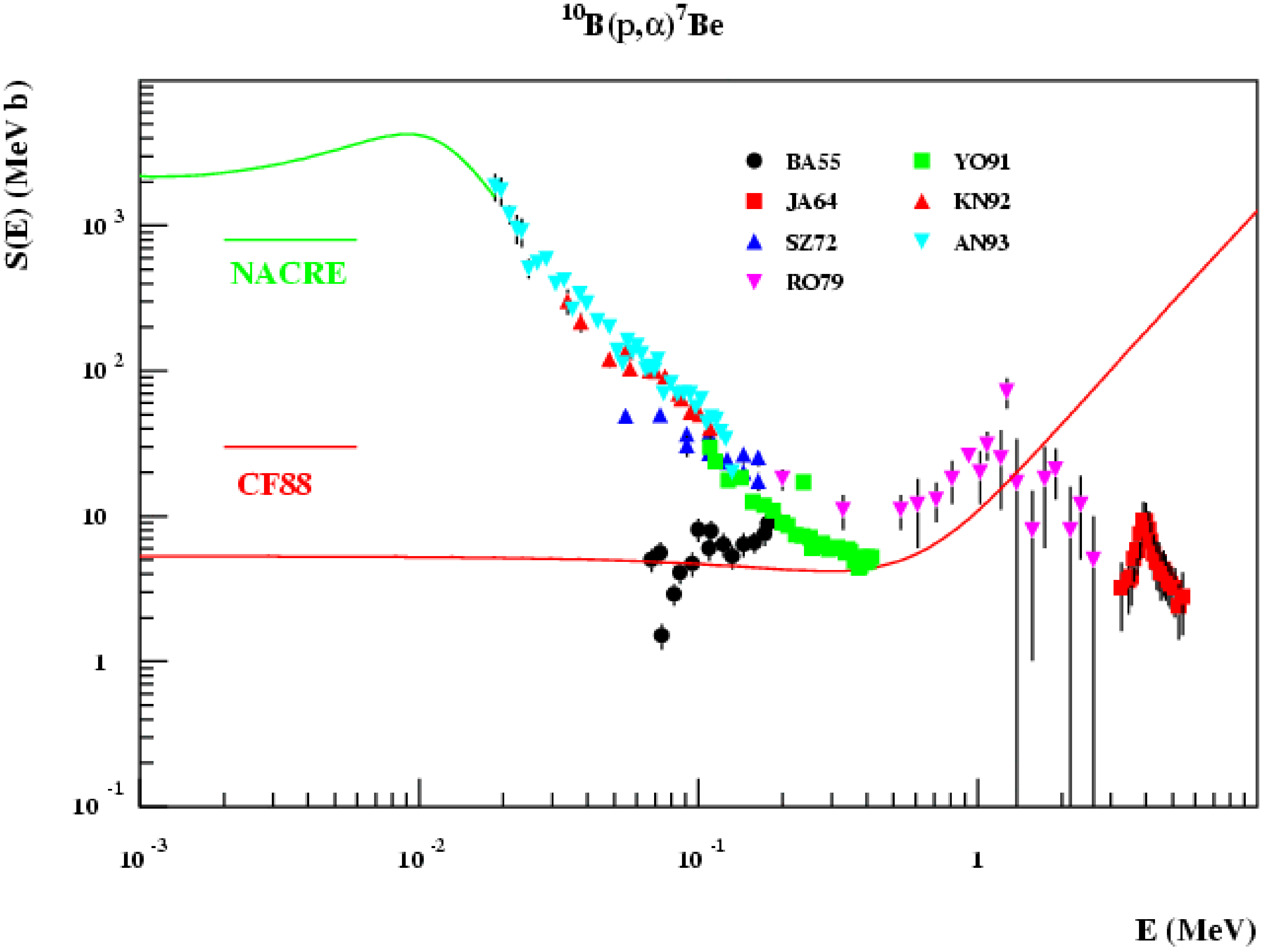
Example: uncertainties on $^{18}F(p,\alpha)^{15}O$ reaction



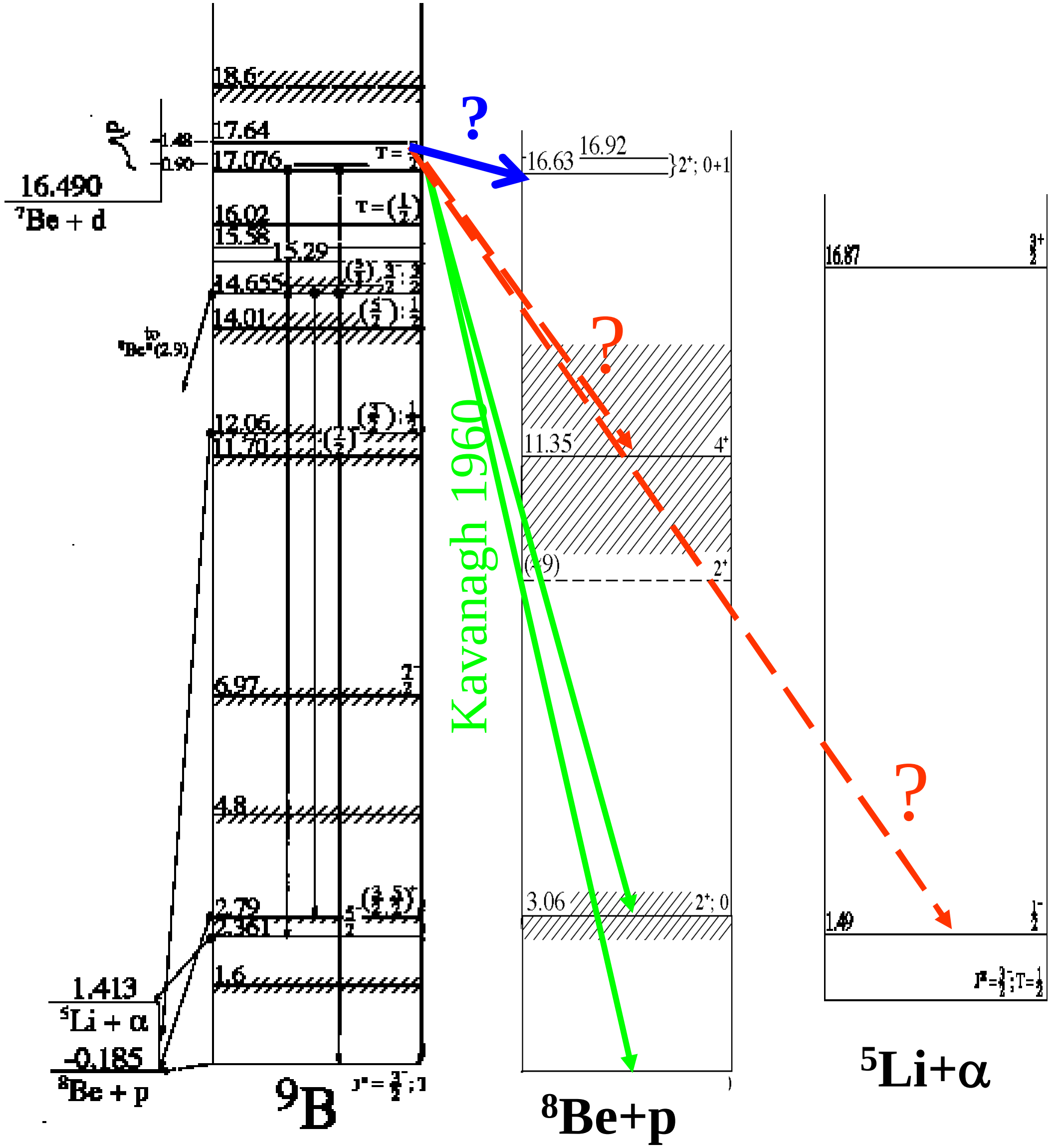
Comparison w.r.t. CF88

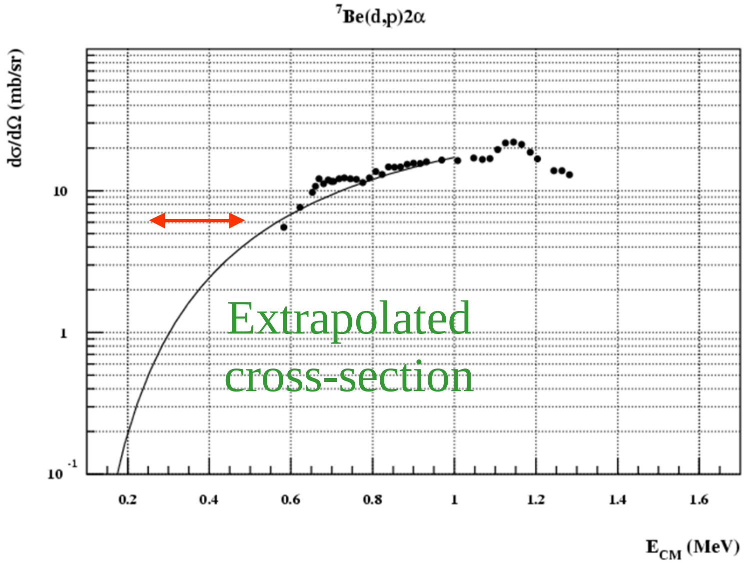
- A factor of 300 uncertainty in 2000
- After many experiments, the situation is stilll confused in 2014

Example: experimental data on $^{10}B(p,\alpha)^{7}Be$ reaction



The ^{7}Be(d,p)2α and ^{7}Be(d,α)^{5}Li reactions



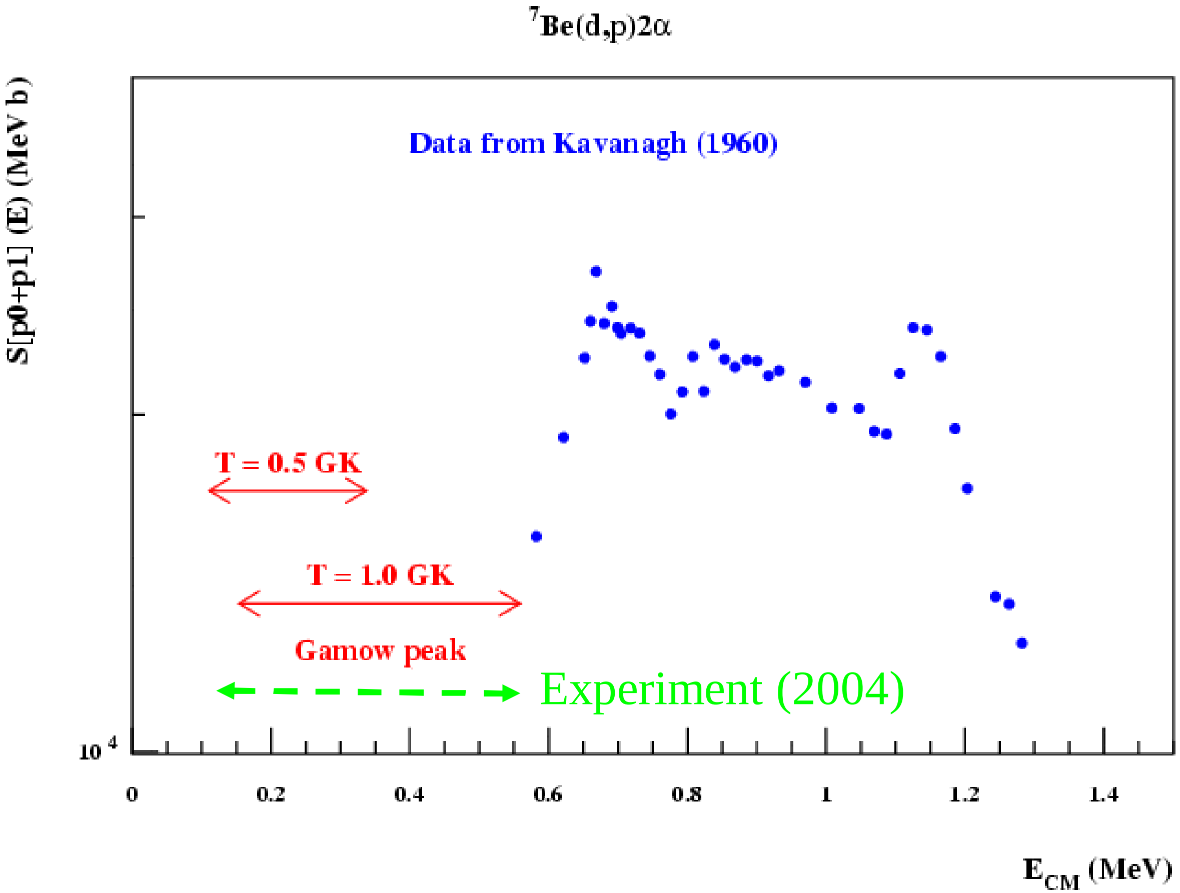


Experimental data on ^{7}Be(d,p)2α reaction

$^{7}\text{Be}(d,p)^{8}\text{Be}^{*} \rightarrow 2\alpha$

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

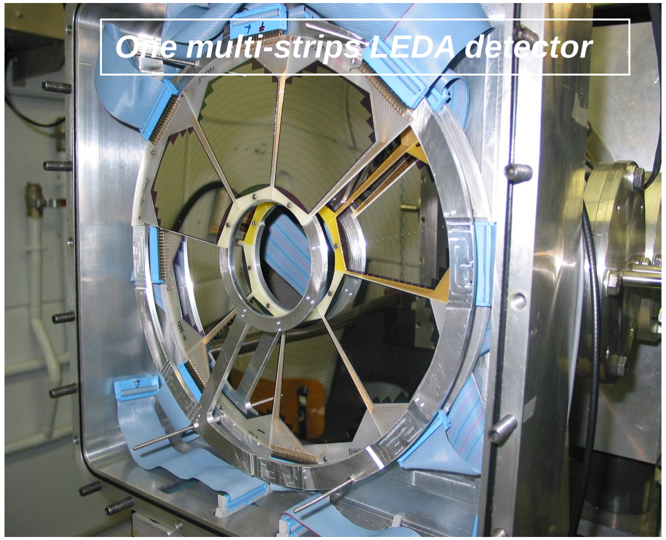
No data at BBN energies!

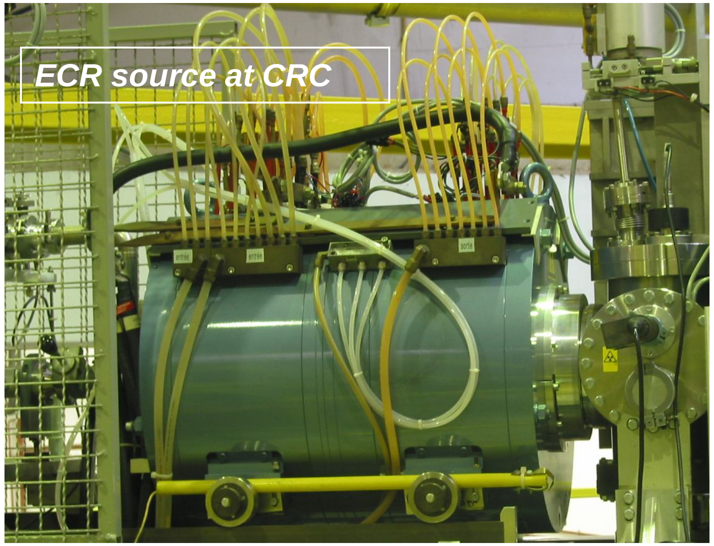


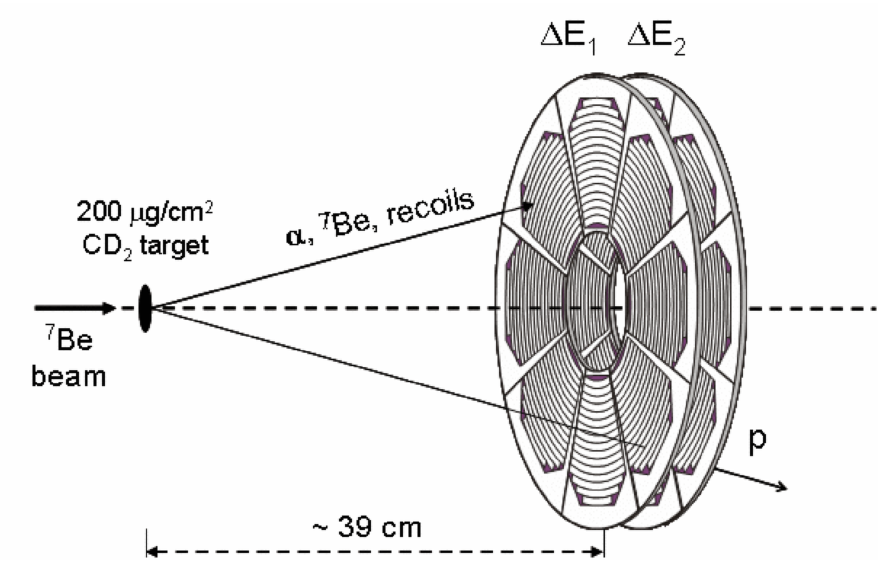
Reverse kinematics : ^{7}Be beam (Louvain la Neuve) and CD_2 target.
(*CRC (Louvain LN), CSNSM, Edinburgh, ULB*)

The ^{7}Be(d,p)2α experiment

Centre de Recherche du Cyclotron, Louvain-la-Neuve


One multi-strips LEDA detector


ECR source at CRC



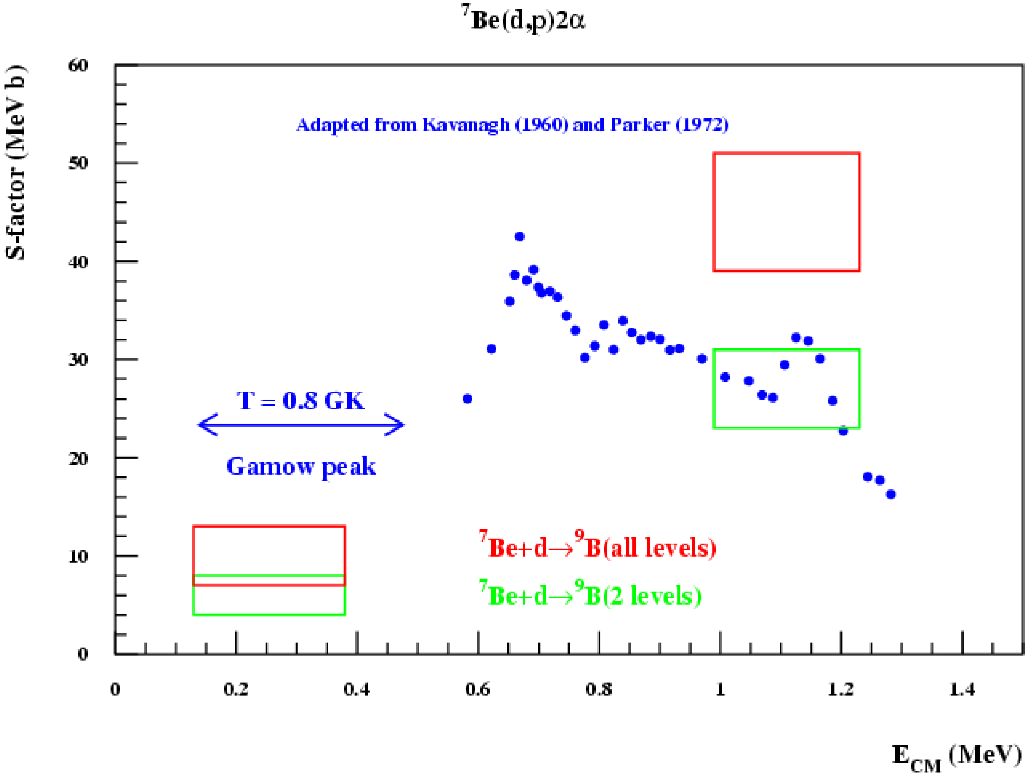
Beam : 0.2-1. 10^7 pps of ^{7}Be at 5.8 MeV, degraded to 1.8 MeV (0.4 MeV c.m.)

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

Section efficace résonnante

Section efficace de Breit-Wigner

Mesures indirecte

Mesure directe

$$\sigma_{BW}(E) = \pi \bar{\lambda}^2 \omega \frac{\Gamma_e(E)\Gamma_s(E+Q)}{(E-E_R)^2 + \Gamma_T^2(E)/4}$$

- ω = le facteur statistique de spin
- Γ_x = la largeur partielle pour la voie x = p, n, α, γ, β,…, (avec un moment angulaire transféré L)

  - ➢$\Gamma(E) \propto P_L(E)$ pour des particules chargées
  - ➢$\Gamma(E) \propto E^{½}$ pour des neutrons (L=0)
  - ➢$\Gamma(E) \propto E^{2L+1}$ pour des photons

Avec $\Gamma_T = \sum_x \Gamma_x$ la largeur totale et $\tau = \hbar \Gamma^{-1}$

Largeur à une particule

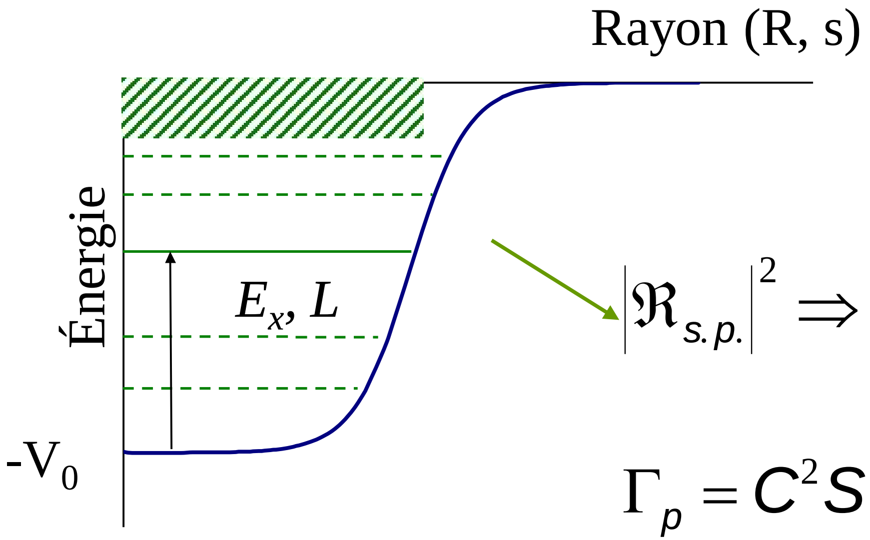
P_L : Facteur de pénétrabilité

$$\Gamma_p(E) = \frac{\hbar^2 s}{\mu} \left|\Re(s)\right|^2 P_L(E,s)$$

s : rayon de la voie

μ : masse réduite

Fonction d’onde radiale



Une particule dans un puis de potentiel de Woods-Saxon

$$\left|\Re_{s.p.}\right|^2 \Rightarrow \Gamma_{s.p.}$$

$$\frac{-V_0}{1+\exp\left(\frac{R-R_0}{a}\right)}$$

$$\Gamma_p = C^2 S\, \Gamma_{s.p.}$$

avec $C^2 S \leq 1$ (facteur spectroscopique)

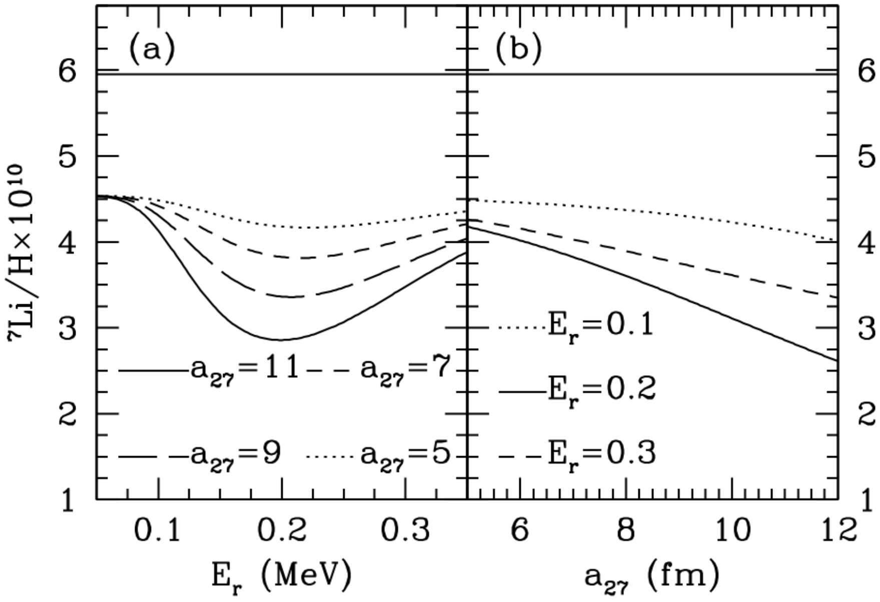
$$S = \left|\langle A+1 | \left(|A\rangle \otimes |p\rangle \right)\right|^2$$

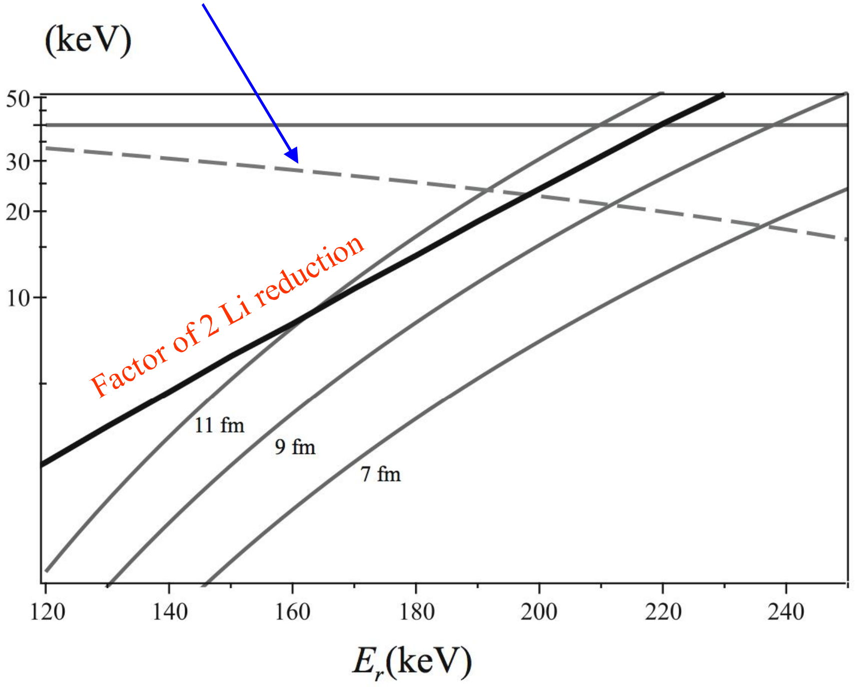
Approximation de la limite de Wigner (Γ_W):

Densité de probabilité uniforme ⇒ $\left|\Re_W\right|^2 = \frac{3}{s^3}$ $\Gamma_p = \theta^2\, \Gamma_W$ $\theta^2 < 1$

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

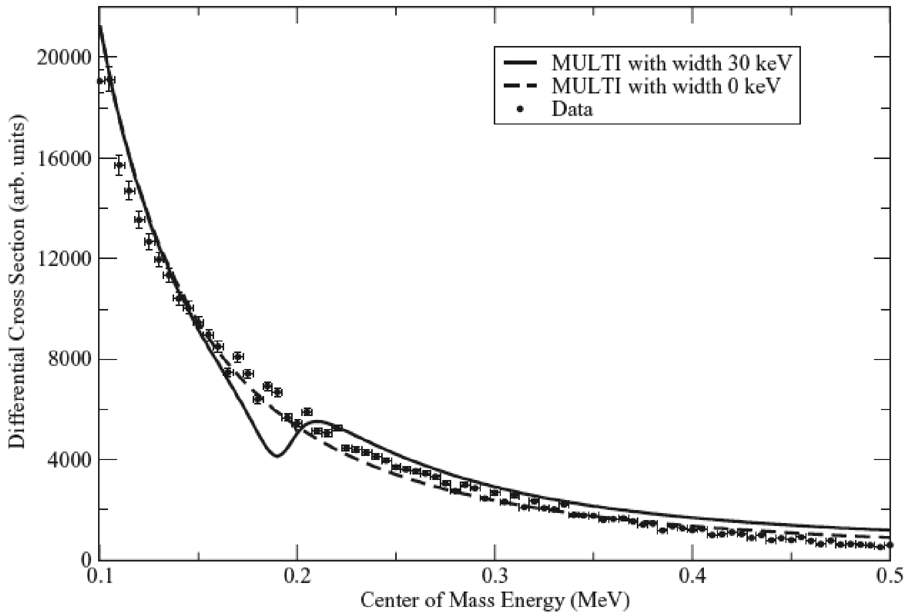


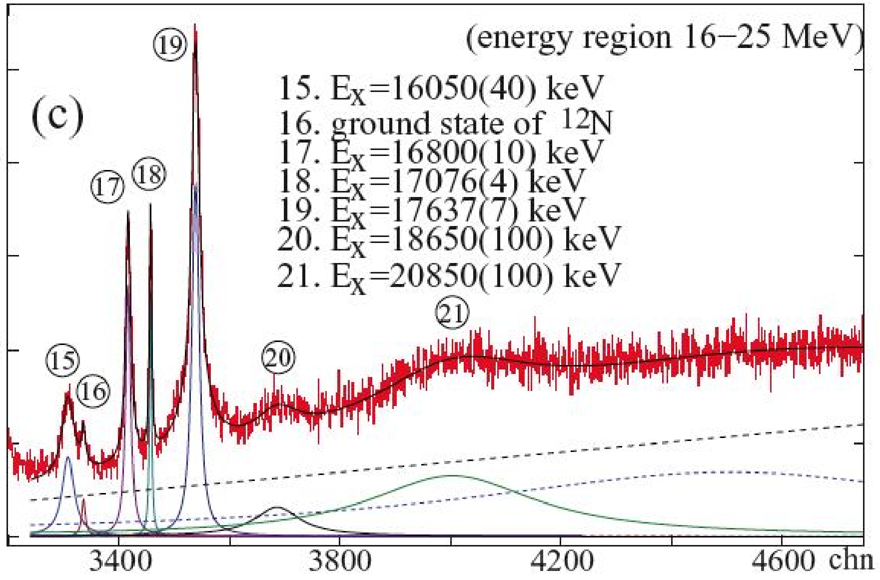


Search for new resonances in ^{7}Be(d,p)2α

Search for resonance in ^{2}H(^{7}Be,d)^{7}Be with a ^{7}Be beam at Oak Ridge *[O'Malley+ 2011]* shows no sign of large Γ_d

High resolution ^{9}Be(^{3}He,t)^{9}B analysis at Osaka *[Scholl+ 2011]* gives E_X=16.800(10) MeV and Γ_T=81(5) keV





Effect on ^{7}Li < 4% in BBN *[Kirsebom & Davids 2011]*

Other resonances ?

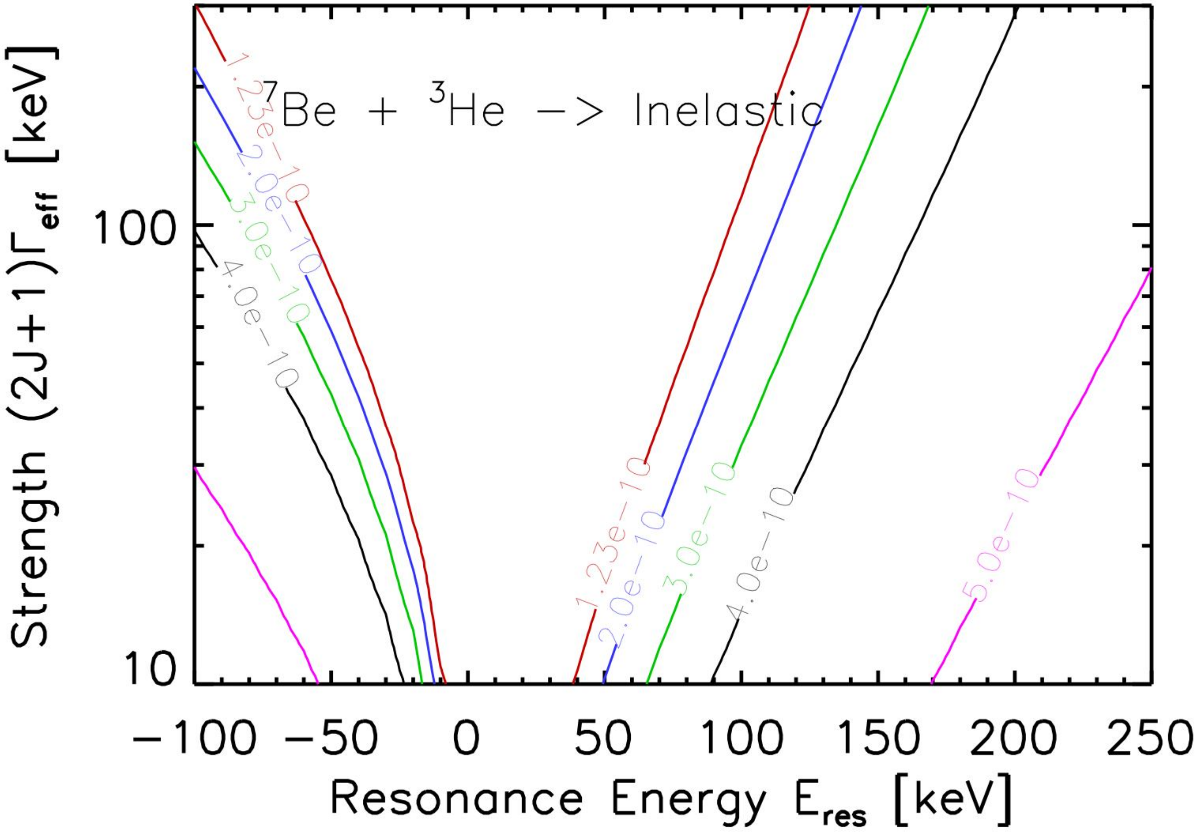
[Chakraborty, Fields & Olive (2011)]

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

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

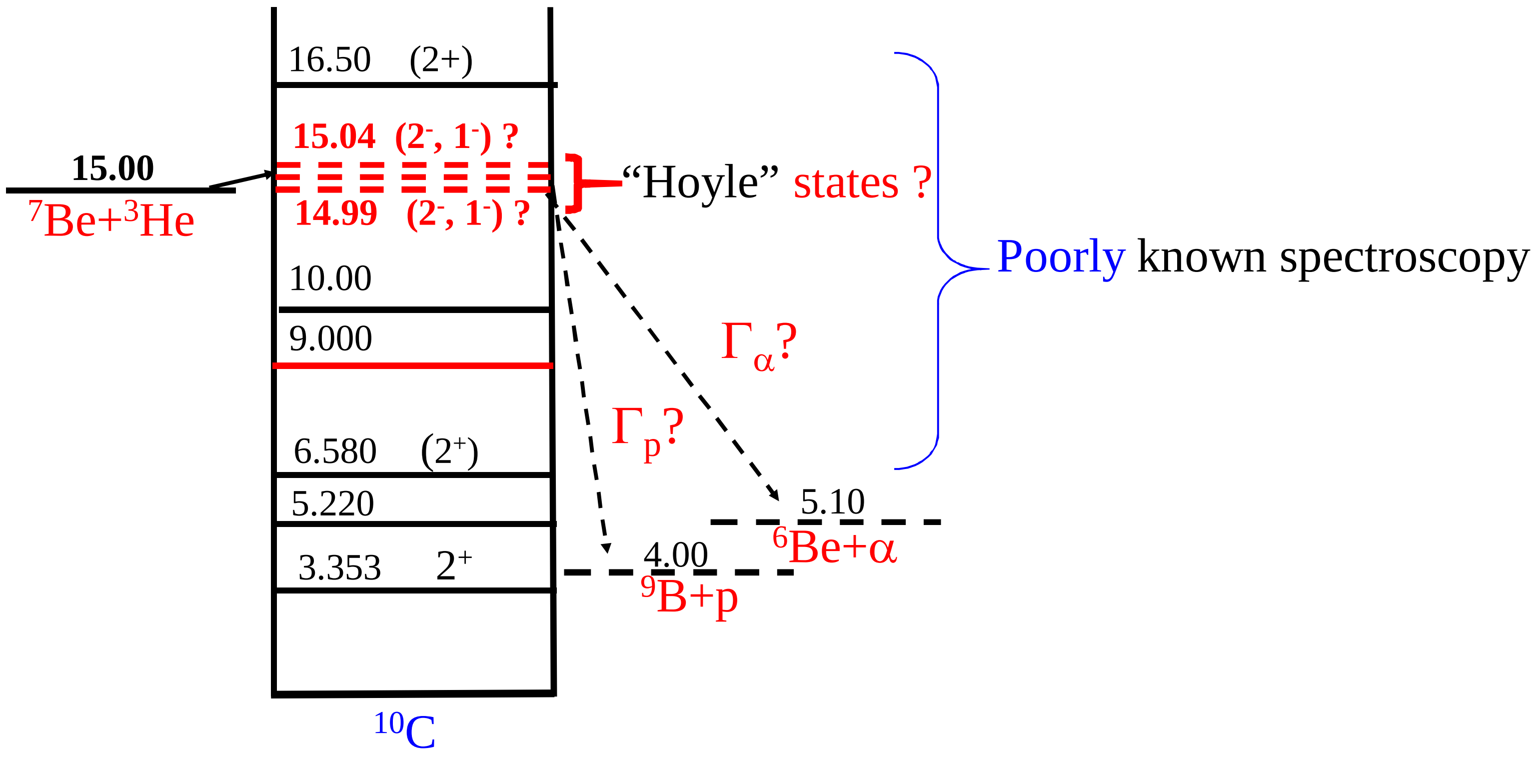
Unknown level properties in ^{9,11}B and unknown levels in ^{10}C

- ^{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



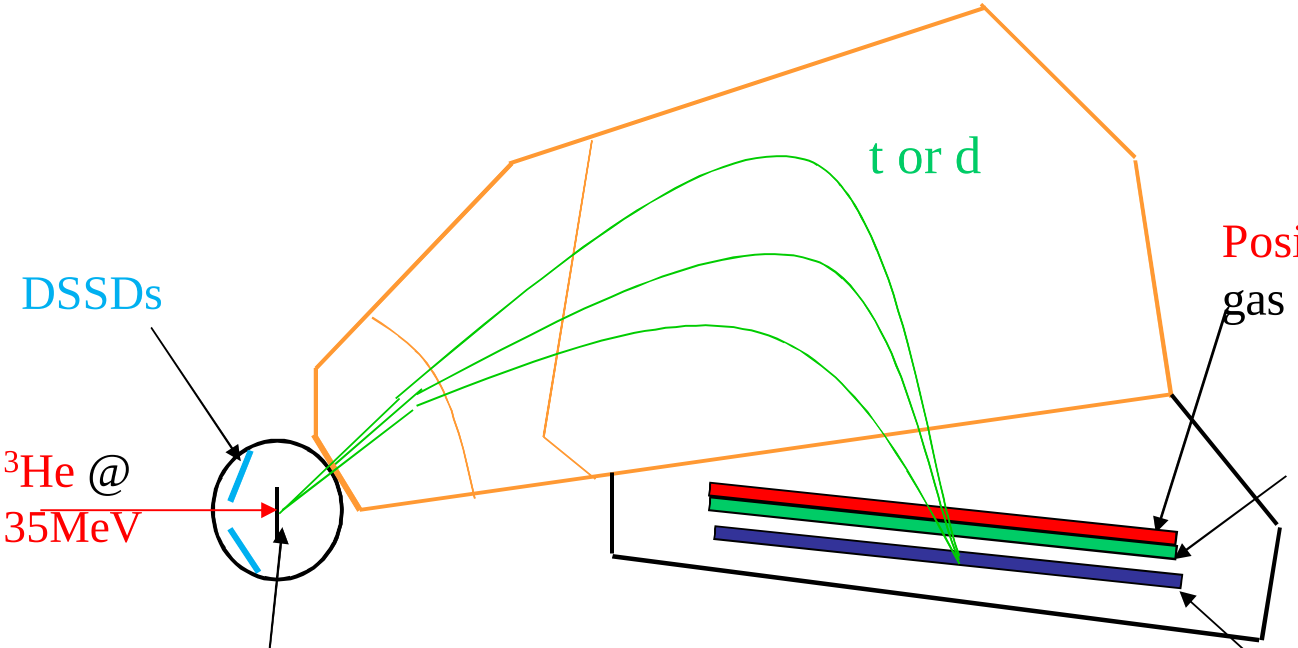
Recent Orsay Tandem Experiment

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



t or d

DSSDs

^{3}He @ 35MeV

Position gas chamber

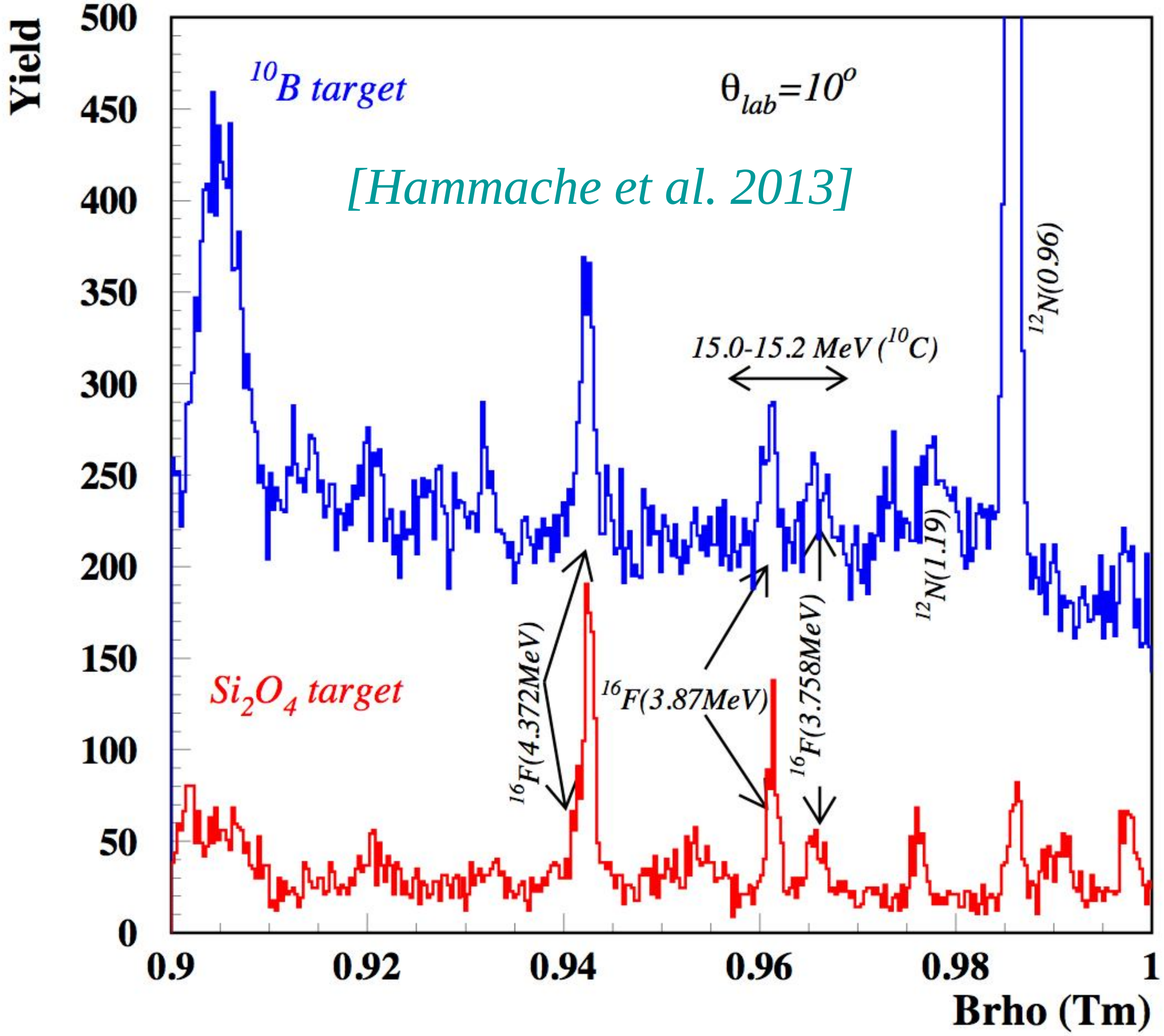
ΔE proportional counter

Plastic scintillator (E)

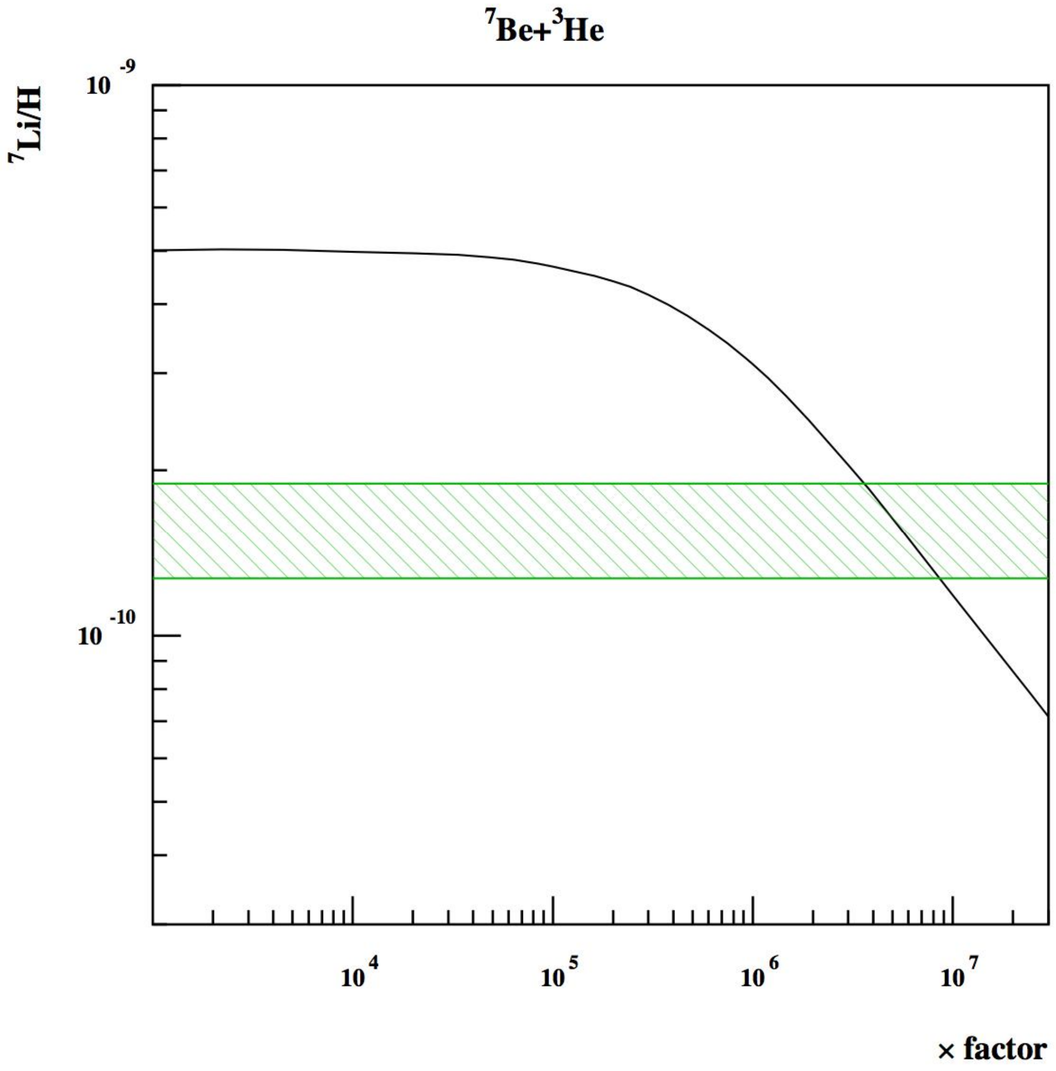
^{10}B,^{9}Be targets 100 μg/cm^{2}

Results from Orsay Tandem experiment

In search of new ^{10}C levels: $^{10}B(^{3}He,t)^{10}C$



- No new ^{10}C level (^{12}C ^{16}O contaminants in spectra) nor in ^{11}C [^{7}Be+α]
- Broad levels?
- No ^{7}Be+^{3}He or ^{7}Be+α rate increase *[Hammache et al. 2013]*



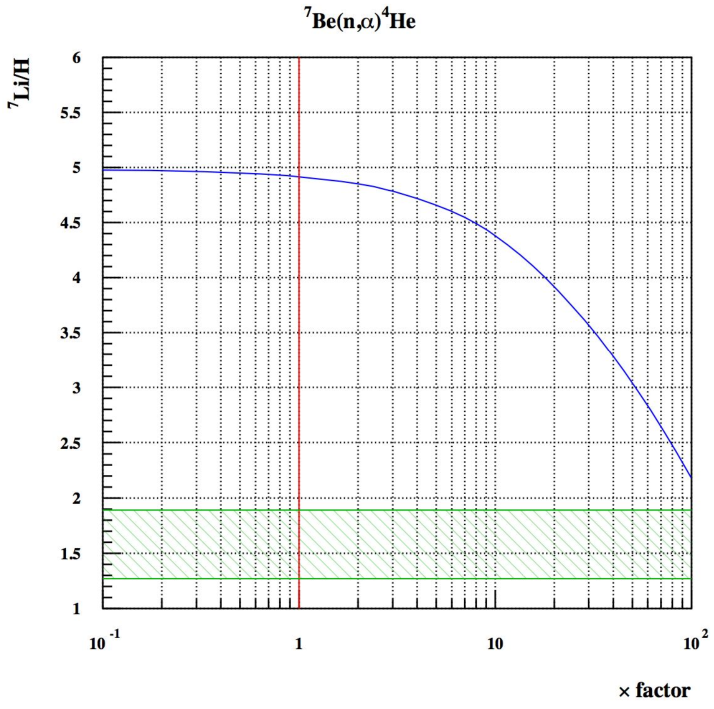
Rate from experimental upper limits too low by ~ 10^6 factor !

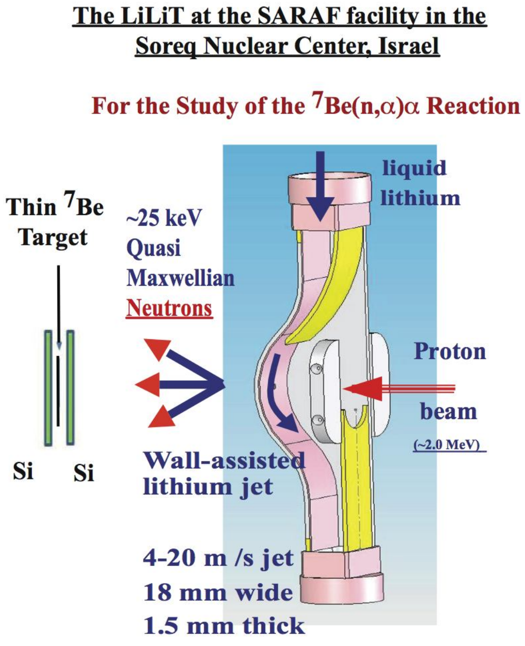
Unlikely to contribute (Coulomb barrier)

[Broggini+ 2012] and F. Villante seminar tomorrow

The ^{7}Be(n,α)^{4}He reaction

- If l=0, ^{7}Be+n→2α (forbiden) rate from *Wagoner 1969*, much slower than ^{7}Be(n,p)^{7}Li (data from *Bassi et al. 1962; 1963*)
- If l=1, could contribute to ^{7}Be destruction *[Serpico+ 2004]*




The LiLiT at the SARAF facility in the Soreq Nuclear Center, Israel

For the Study of the ^{7}Be(n,α)α Reaction

- Experimental project with n beam from Liquid Lithium Target at the Soreq Accelerator Facility *[M. Gai, M. Paul priv. comm.]*

Nuclear Physics aspects

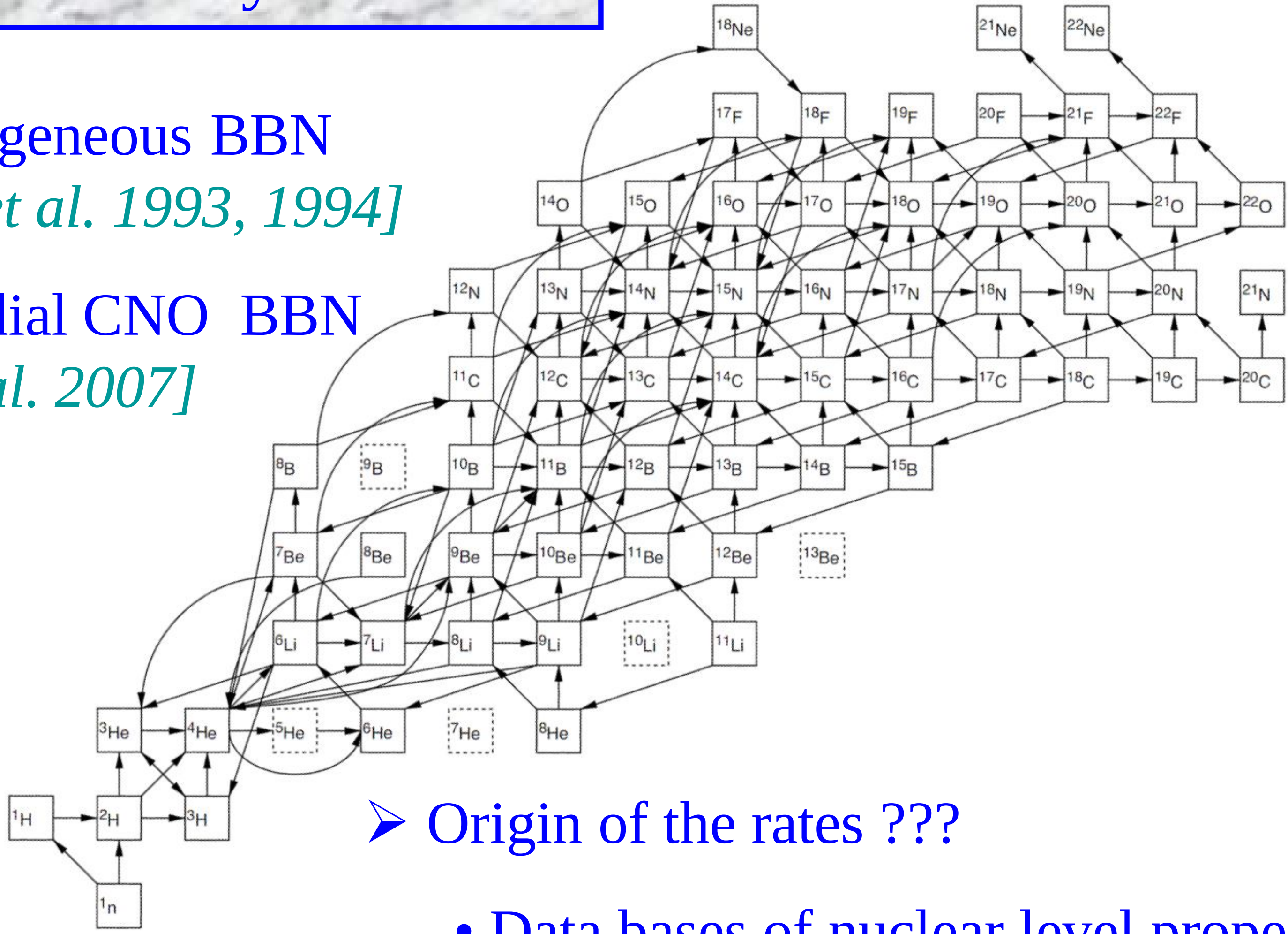
1. The main reactions for H, He and Li BBN production
2. Search for nuclear solutions to the lithium problem
3. Be, B and CNO production in BBN
4. Monte-Carlo evaluation of reaction rates
5. Monte-Carlo investigation of BBN

Extension of the network up to CNO

- Applications:
  - Potential neutron sources for ^{7}Be destruction by ^{7}Be(n,p)^{7}Li(p,α)^{4}He in BBN (the lithium problem)
  - CNO seeds for first stars
  - Standard CNO primordial abundances versus exotic production (e.g. “variation of fundamental constants”)
  - Future observations ?
- Involves many (>400), ^{A}Z + n, p, d, t, ^{3}He and α, reactions
- *Mostly unknown rates* hence possibly high yield uncertainty

CNO nucleosynthesis

- ➢ Inhomogeneous BBN
  [Thomas et al. 1993, 1994]
- ➢ Primordial CNO BBN
  [Iocco et al. 2007]



©Fields & Olive 2006

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

Sensitivity study (I)

1. Start from “best guess” set of reaction rates
2. Systematic, one by one, reaction rate variation within evaluated rate uncertainty or guessed uncertainty factor e.g. 0.001, 0.01, 0.1, 10., 100. & 1000.
3. Identification of important reactions e.g. variation >20% on selected yields
4. Reevaluation of selected rates following re-analyses of available experimental and theoretical data
5. Calculations with set of improved reaction rates (and uncertainties)

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

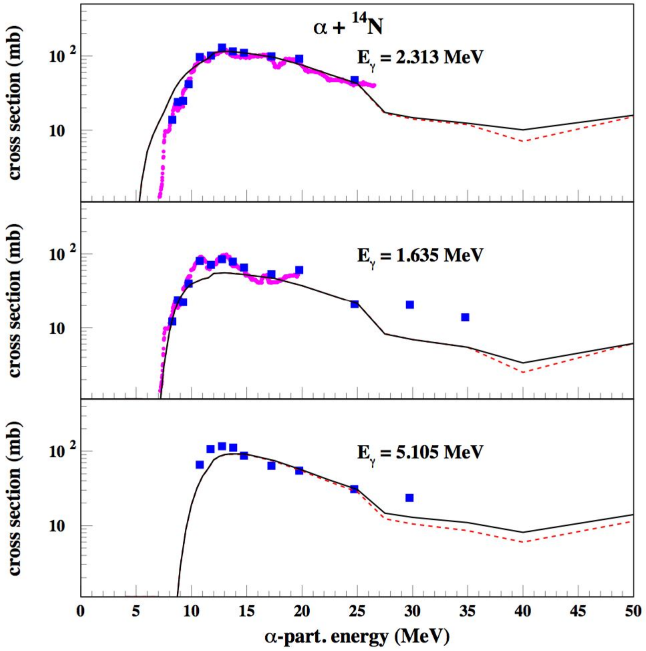
- 33 decay rates
  [Audi et al. 2003]

- 391 reaction rates ^{A}Z + n, p, d, t, ^{3}He and α, *mostly unknown* hence possibly high yield uncertainty
  - ✓ *Descouvemont et al. 2004 (DAACV)*
  - ✓ *Angulo et al. 1999 (NACRE I)*
  - ✓ *Iliadis et al. 2010*
  - ✓ *Talys (271 rates)* within 3 orders of magnitude, at $T\approx 1$ GK, compared with experiments!
  - ✓ …..

Talys code *[Koning et al. 2005; Goriely et al. 2008]*

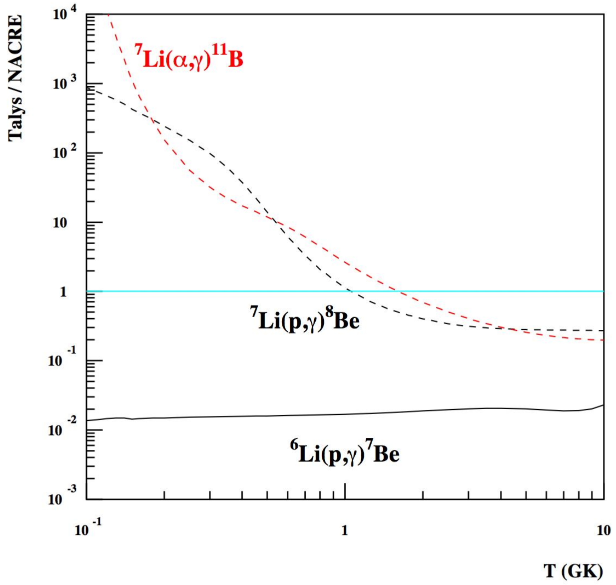
- ❑ Based on Hauser-Feshbach statistical model
  - ➢ Compound nucleus mechanism assuming high level densities
  - ➢ *n*, *p*, *d*, *t*, ^{3}He and α capture and emission on $Z \geq 3$ nuclei
  - ➢ A priori not adapted to low mass nuclei but…

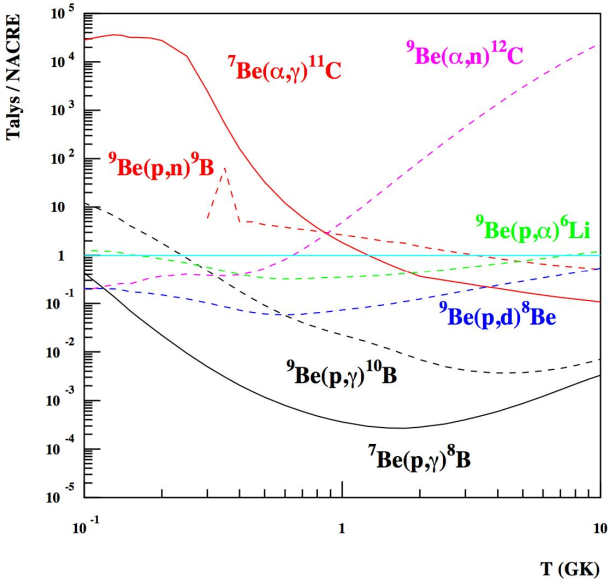
Comparison Orsay experiment with Talys
[Benhabiles-Mezhoud, Kiener et al. 2011]

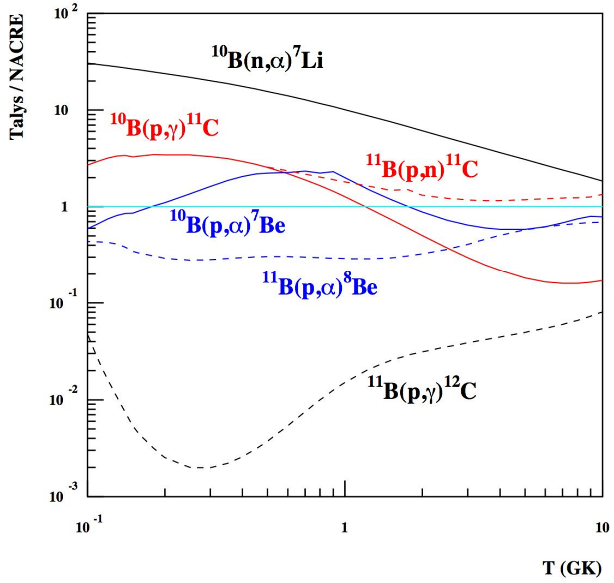


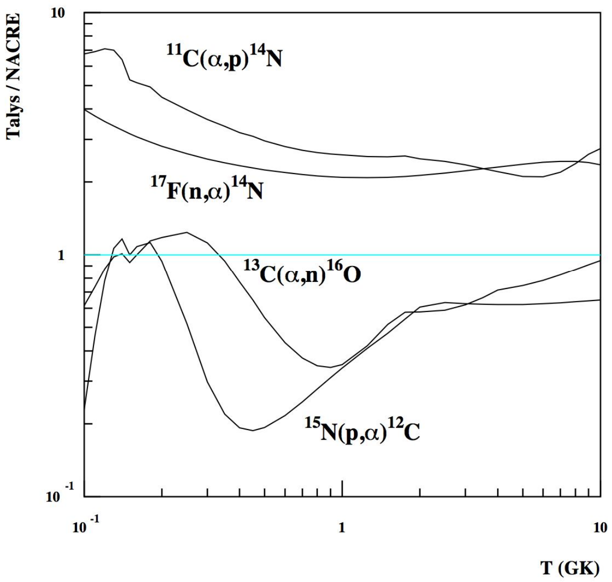
Comparison between Talys and experiments

[NACRE 1999]



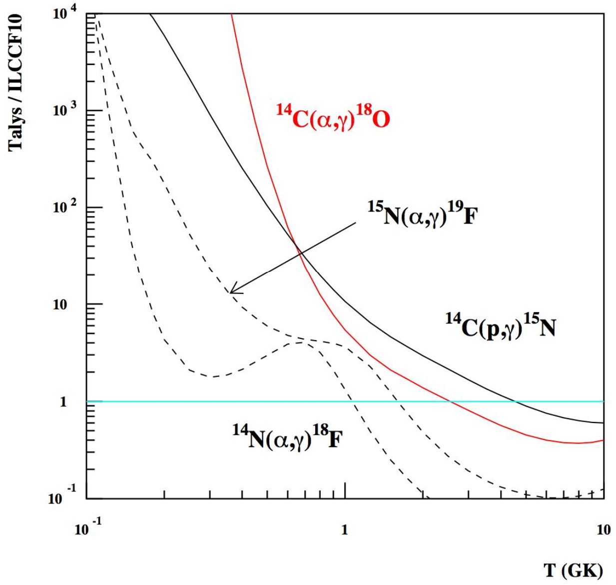


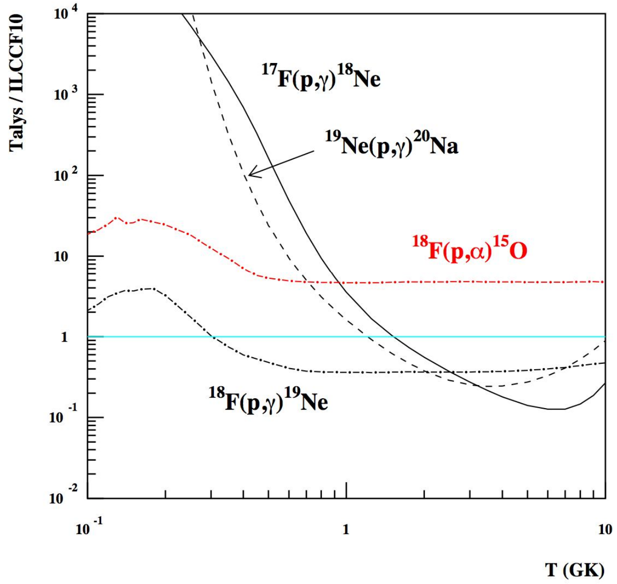


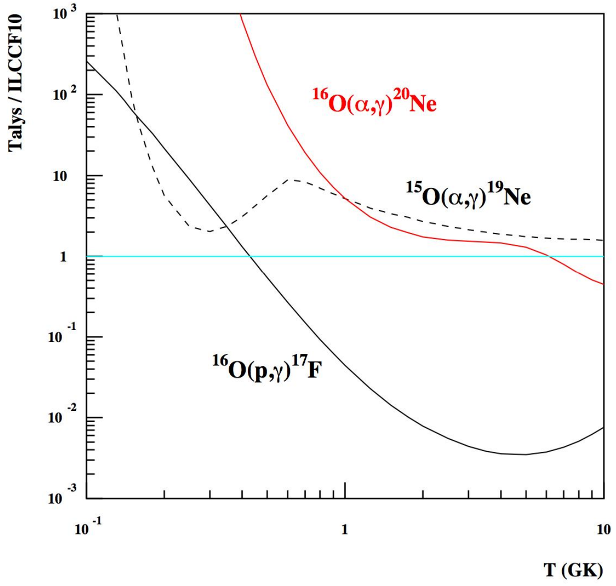


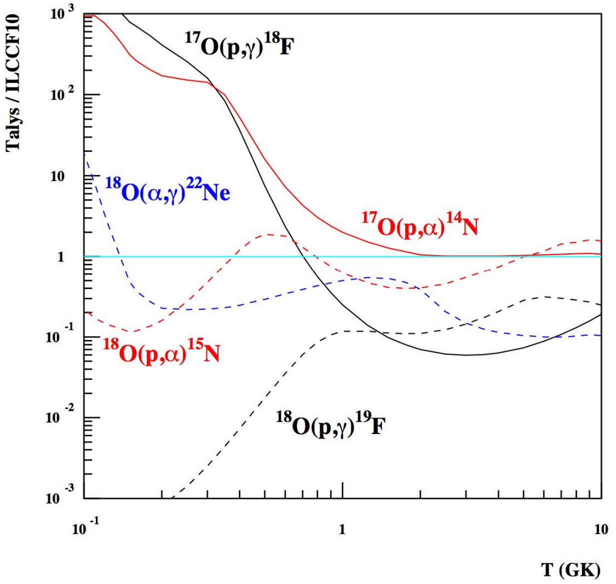
Comparison between Talys and experiments

[Iliadis et al. 2010]









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

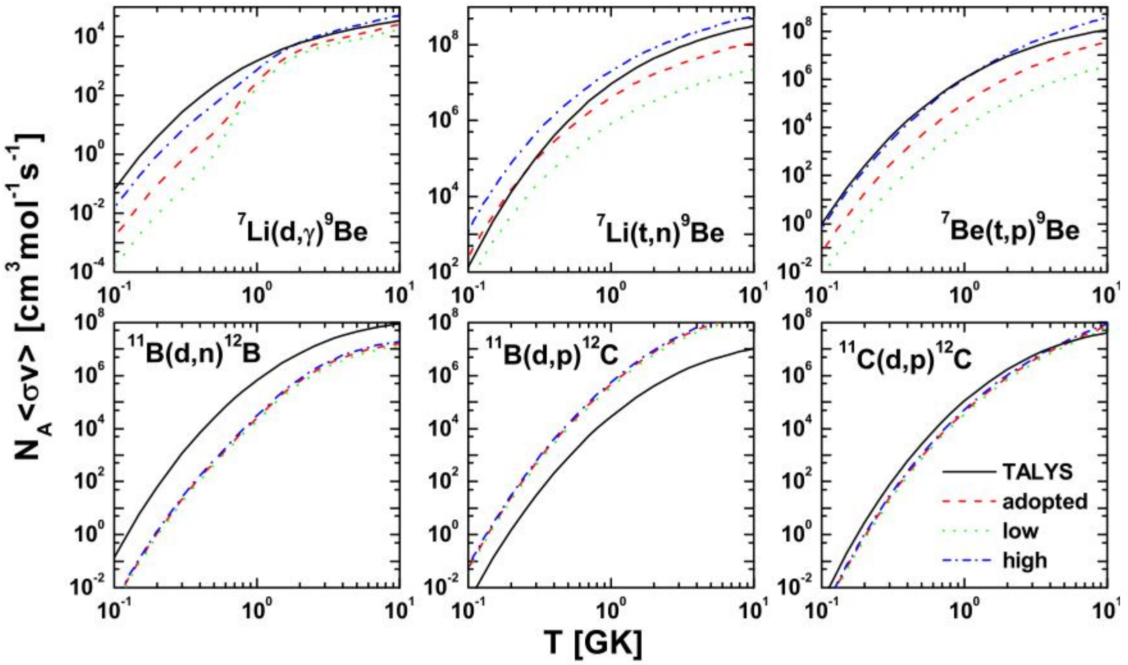
Most important reactions for ^{6}LiBe^{11}B nucleosynthesis

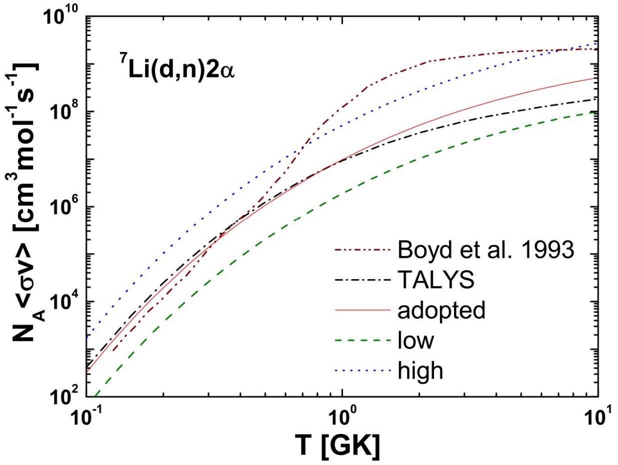
Reaction	Fractional change in ^{6}Li abundance						Test rate reference
Rate factor	0.001	0.01	0.1	10.	100.	1000.	
^{3}He(t,γ)^{6}Li	1.00	1.00	1.00	1.03	1.31	4.11	FK90
^{4}He(d,γ)^{6}Li	0.004	0.013	0.010	9.97	99.7	995.	Ham10

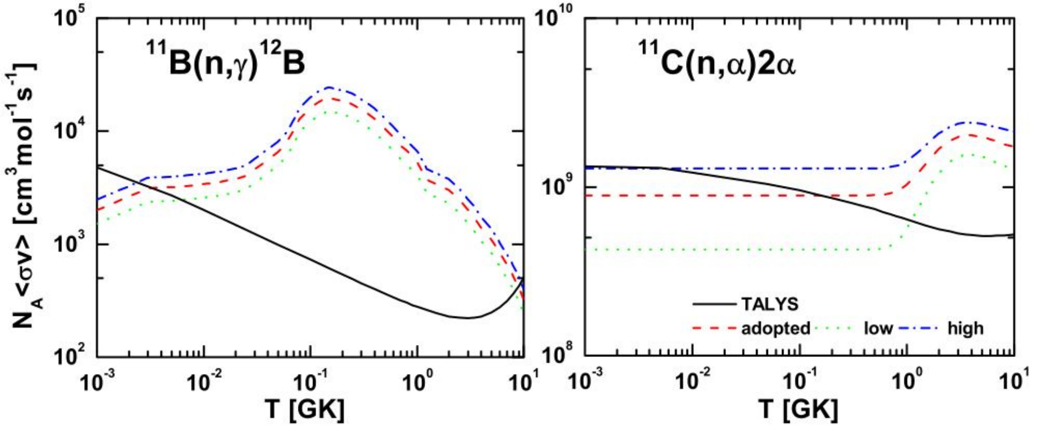
Reaction	Fractional change in ^{9}Be abundance						Test rate reference
Rate factor	0.001	0.01	0.1	10.	100.	1000.	
^{7}Li(d,γ)^{9}Be	0.83	0.83	0.85	2.52	17.7	170.	TALYS
^{7}Li(t,n)^{9}Be	0.52	0.53	0.57	5.29	48.2	477.	Bru90
^{7}Li(^{3}He,p)^{9}Be	1.00	1.00	1.00	1.04	1.45	5.49	TALYS
^{7}Be(d,p)2α	1.01	1.01	1.01	0.95	0.67	0.38	CF88
^{7}Be(t,p)^{9}Be	0.65	0.65	0.69	4.15	35.6	345.	TALYS

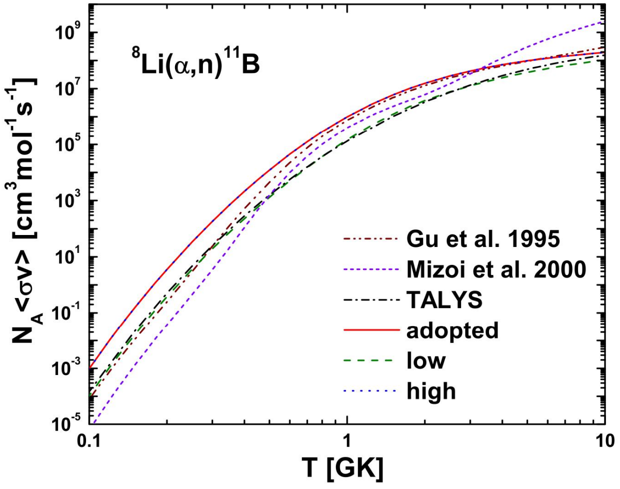
Reaction	Fractional change in ^{11}B abundance						Test rate reference
Rate factor	0.001	0.01	0.1	10.	100.	1000.	
^{3}He(t,np)^{4}He	1.00	1.00	1.00	1.00	0.97	0.79	CF88
^{7}Be(d,p)2α	1.01	1.01	1.01	0.93	0.55	0.11	CF88
^{11}C(n, α)2α	1.16	1.16	1.15	0.40	0.01	0.0001	Rau94

Reevaluated reaction rates



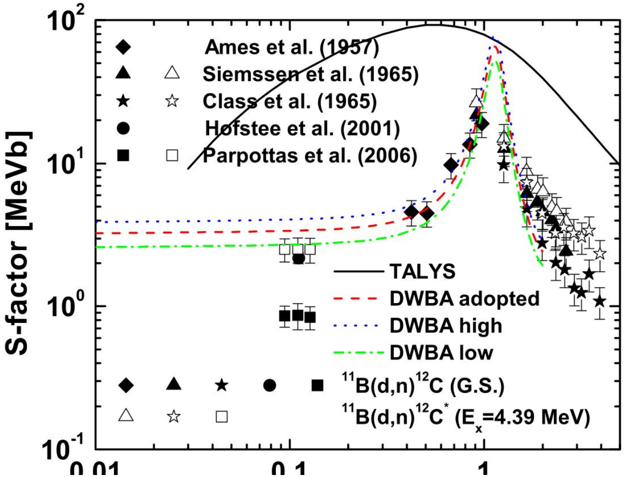


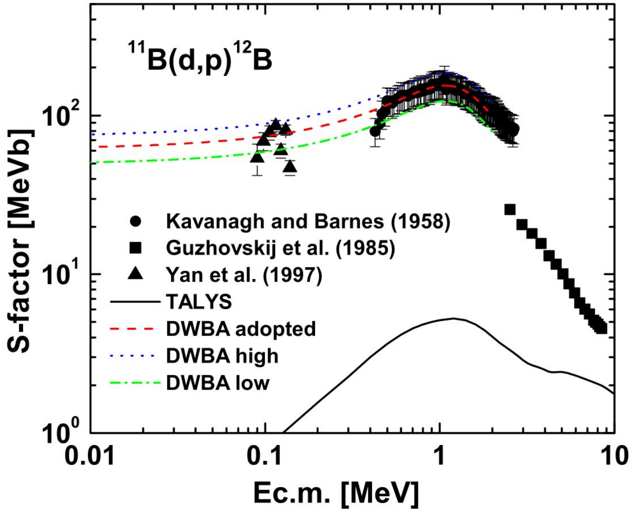




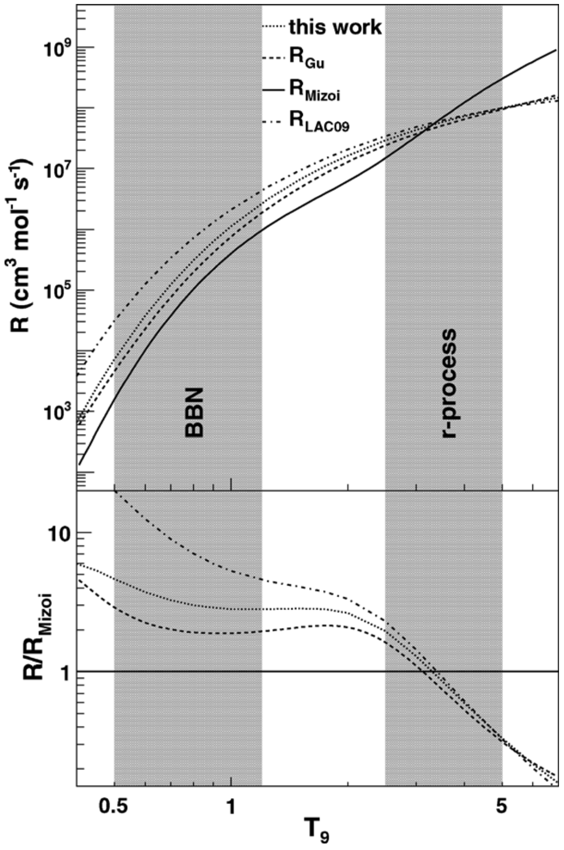
Stability of results with re-evaluated reaction rates

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



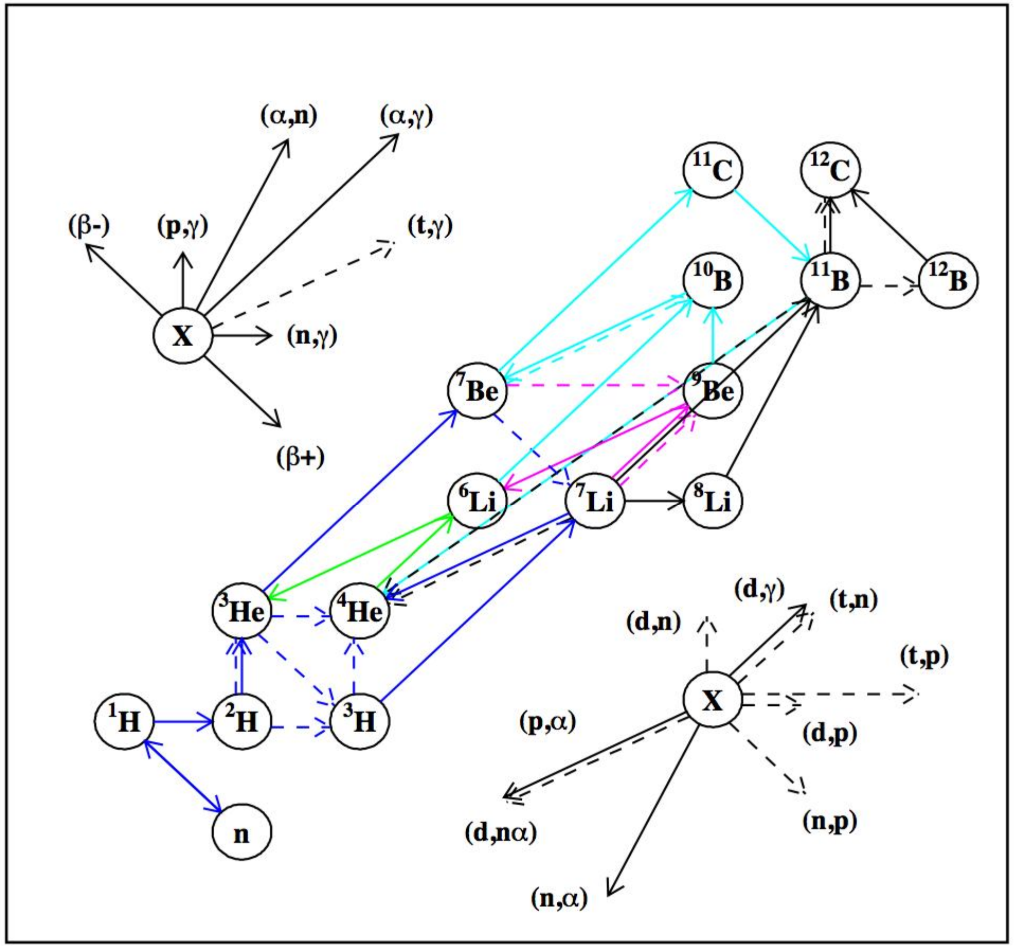


Independent re-evaluation of ^{8}Li(α,n)^{11}B by *La Cognata & Del Zoppo 2011*



Changes CNO by 1.5%

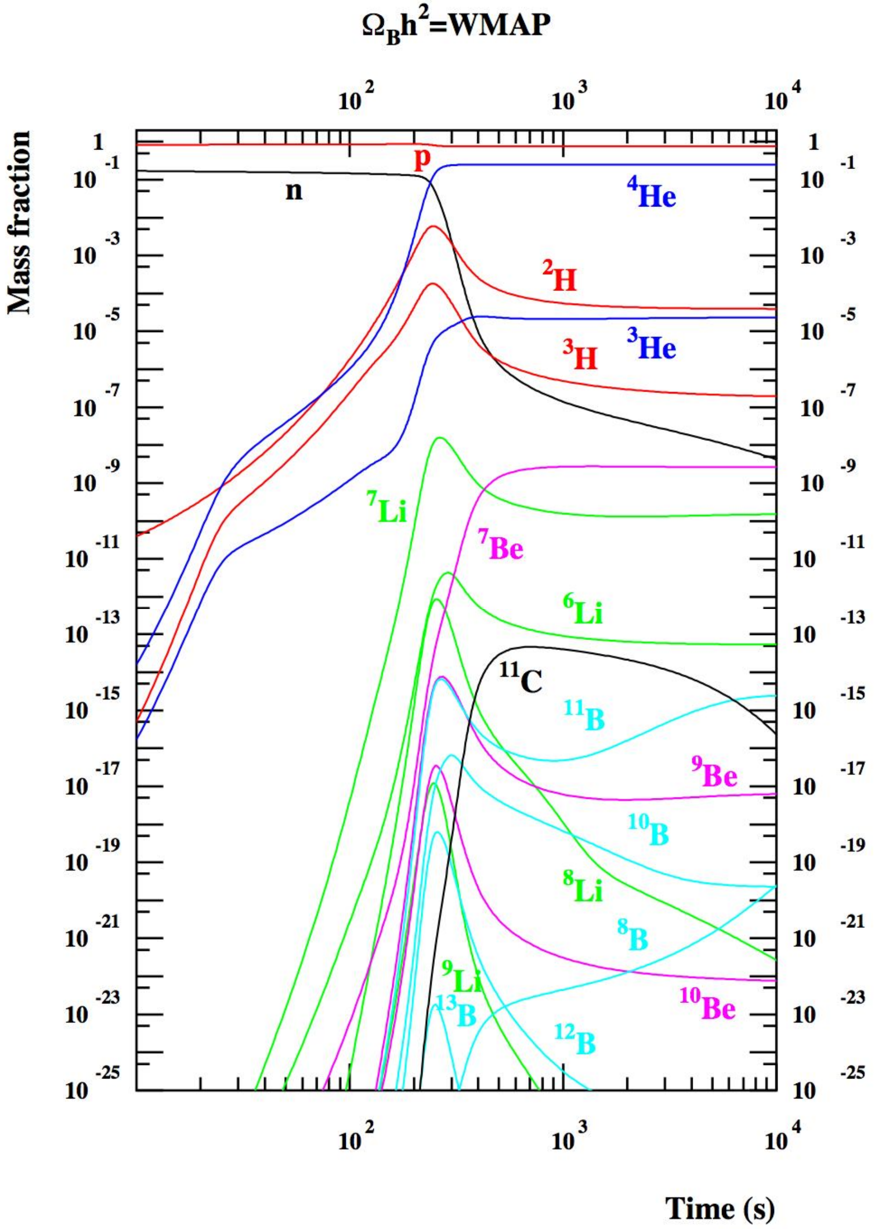
Main paths of BB nucleosynthesis

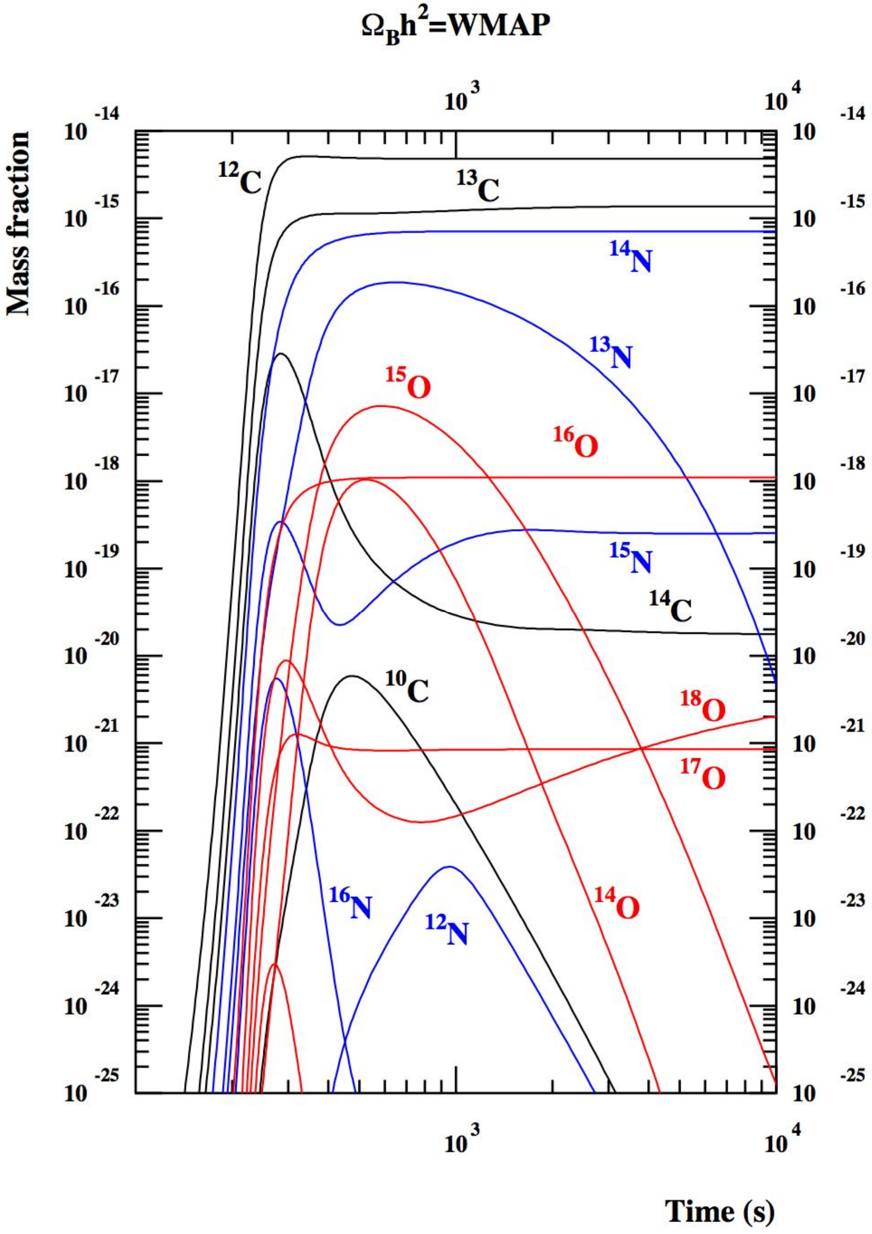


Main path for:

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

CNO nucleosynthesis





CNO nucleosynthesis

Stability of results:

Number of atoms	*[Iocco et al. 2007]*	Initial Network	Updated Network
^{6}Li/H (×10^{-14})		1.23*	1.23*
^{9}Be/H (×10^{-19})	2.5	2.24	9.60
(^{10}B+^{11}B)/H (×10^{-16})	3.9	5.86	3.00
(^{12}C+^{13}C)/H (×10^{-16})	5.5	4.43	6.75
(^{14}C+^{14}N)/H (×10^{-17})	5.0	3.98	6.76
^{16}O/H (×10^{-20})	2.7	5.18	9.13
CNO/H (×10^{-16})	6.0	4.83	7.43

*With the ^{2}H(α,γ)^{6}Li rate from *Hammache et al. 2010*

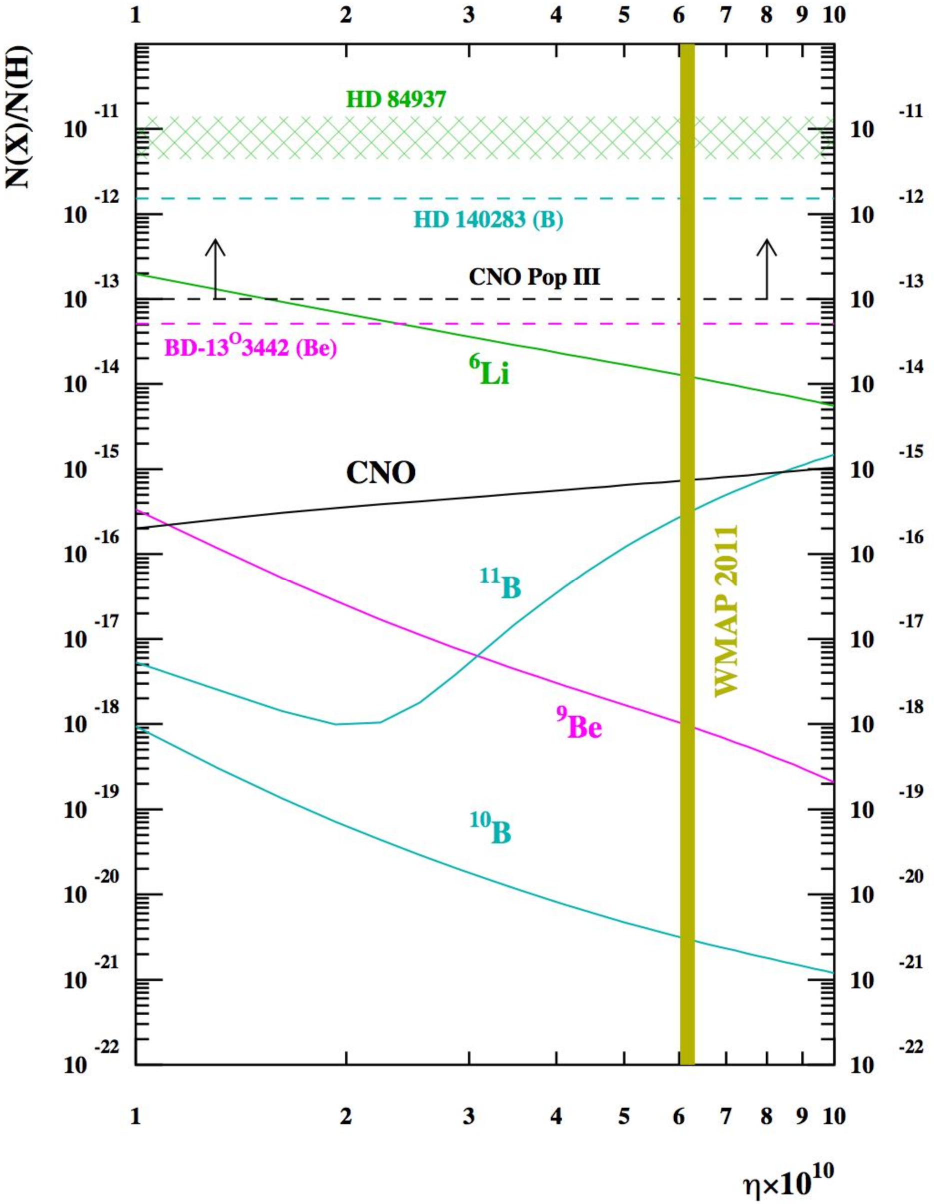
Even though important rates (Updated vs Initial)
or isotopic ratio (vs *Iocco et al.*) differ

Nucleosynthesis with extended network

The lithium problem:

- No important reaction besides already known [e.g. ^{7}Be(d,p)2α]
- No extra neutron source

Number of atoms	*[Iocco et al. 2007]*	*[Coc et al. 2012]*
(^{12}C+^{13}C)/H ($\times10^{-16}$)	5.5	6.75
(^{14}C+^{14}N)/H ($\times10^{-17}$)	5.0	6.76
^{16}O/H ($\times10^{-20}$)	2.7	9.13
CNO/H ($\times10^{-16}$)	6.0	7.43



Importance of “brute force” sensitivity studies

Standard BBN

- No convection
- No diffusion
- No mixing
- No screening
- Known physics
- Reactions measurable at BBN energies

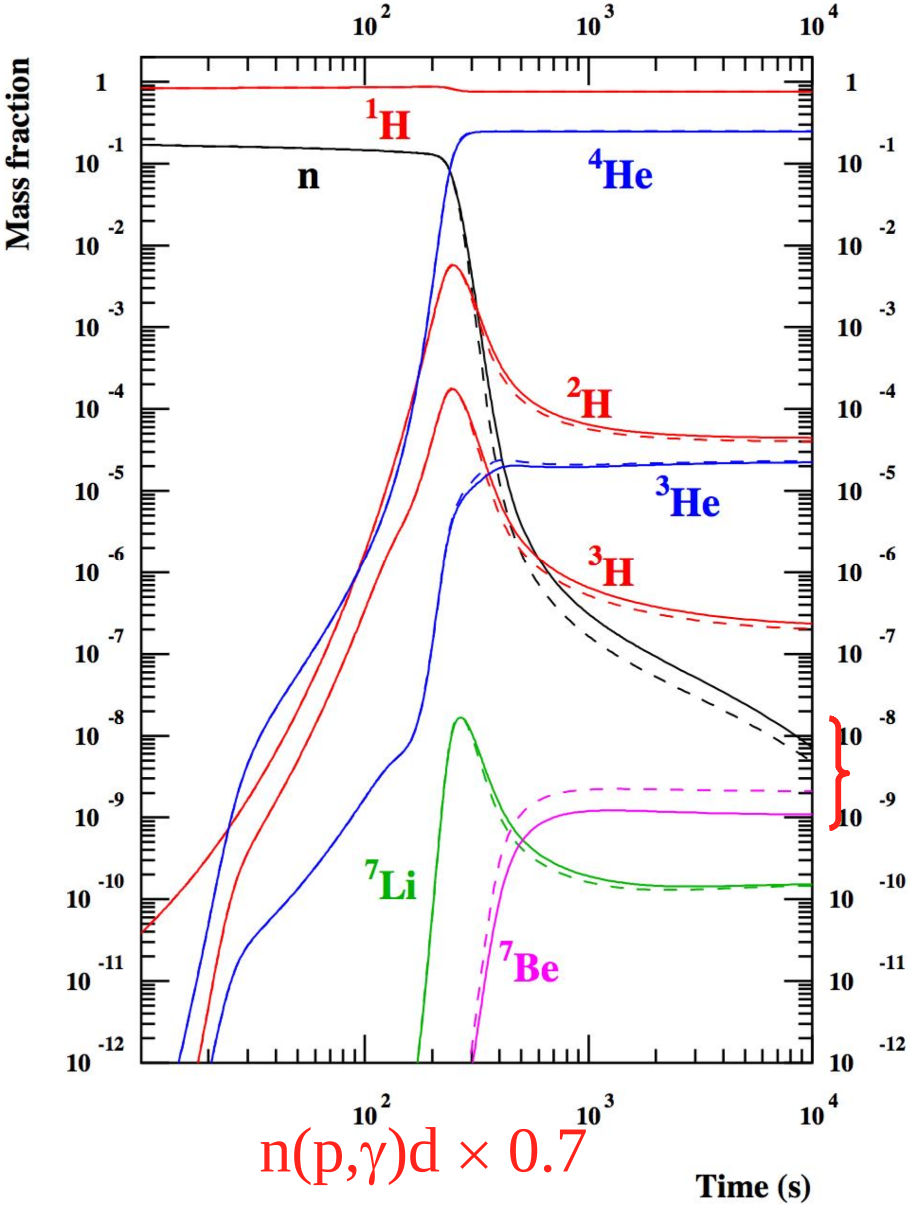
⇓

Simple problem (?)

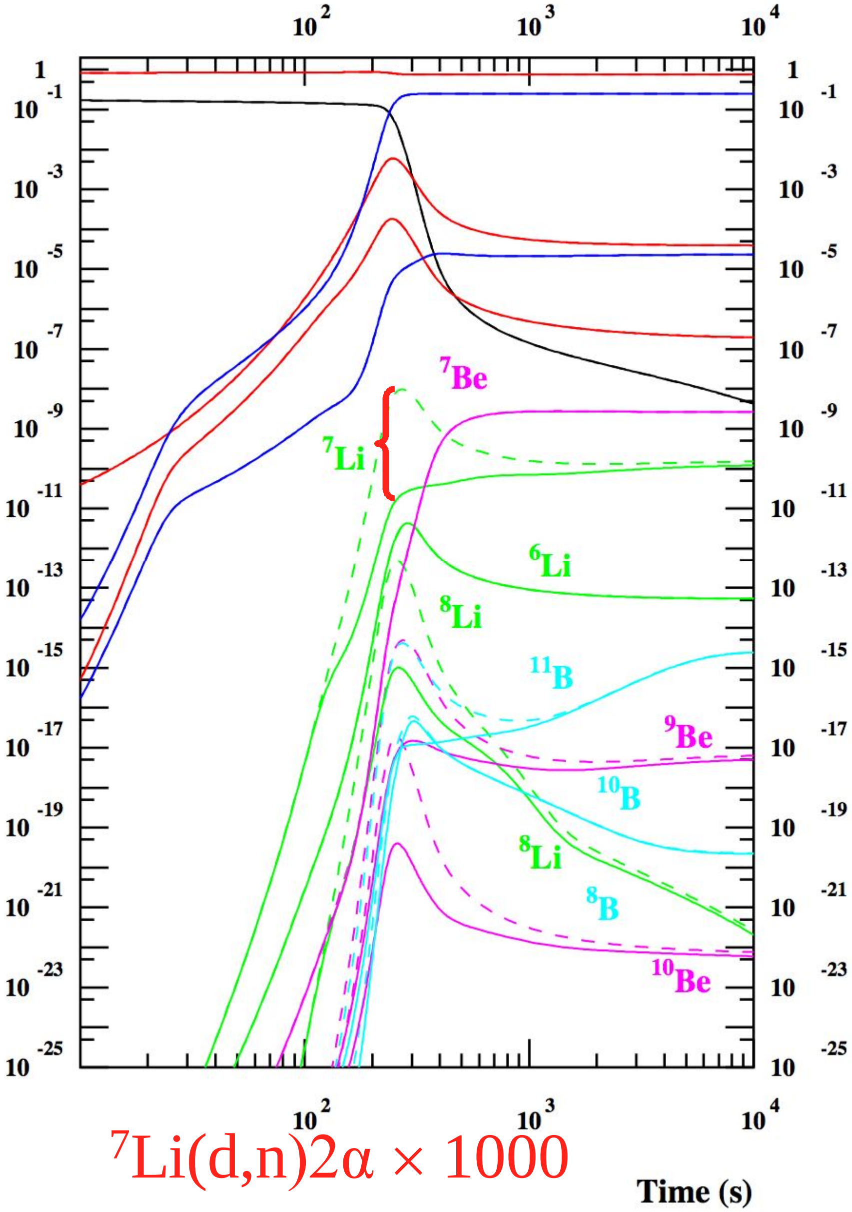
But totally unexpected effects:

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

Influence of $^{1}H(n,\gamma)D$ &$^{7}Li(d,n)2^{4}He$ reactions



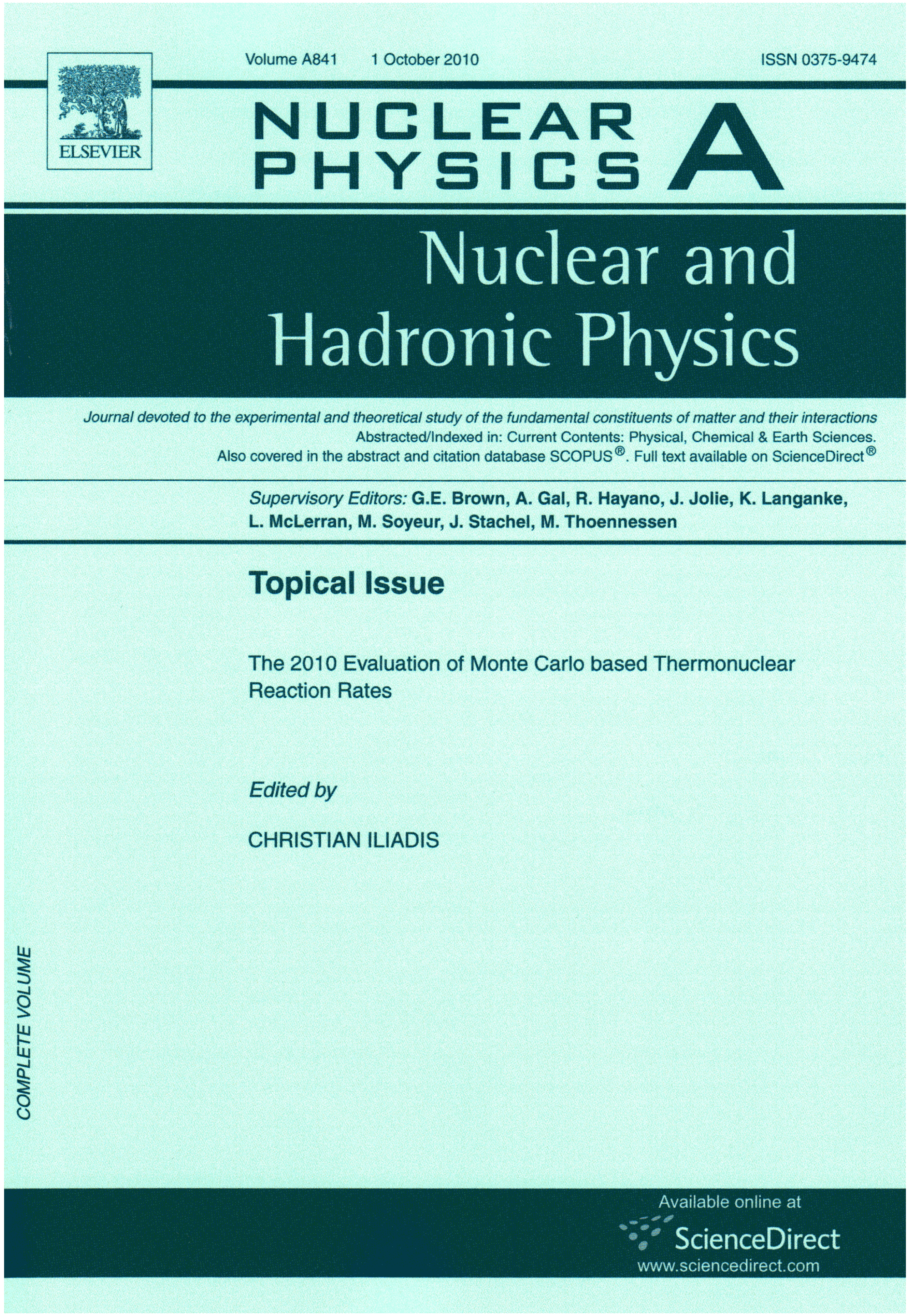
$n(p,\gamma)d \times 0.7$



$^{7}Li(d,n)2\alpha \times 1000$

Nuclear Physics aspects

1. The main reactions for H, He and Li BBN production
2. Search for nuclear solutions to the lithium problem
3. Be, B and CNO production in BBN
4. Monte-Carlo evaluation of reaction rates
5. Monte-Carlo investigation of BBN



ELSEVIER

Volume A841 1 October 2010 ISSN 0375-9474

NUCLEAR PHYSICS A

Nuclear and Hadronic Physics

Journal devoted to the experimental and theoretical study of the fundamental constituents of matter and their interactions

Abstracted/Indexed in: Current Contents: Physical, Chemical & Earth Sciences.

Also covered in the abstract and citation database SCOPUS®. Full text available on ScienceDirect®

Supervisory Editors: **G.E. Brown, A. Gal, R. Hayano, J. Jolie, K. Langanke, L. McLerran, M. Soyeur, J. Stachel, M. Thoennessen**

Topical Issue

The 2010 Evaluation of Monte Carlo based Thermonuclear Reaction Rates

Edited by

CHRISTIAN ILIADIS

COMPLETE VOLUME

Available online at

ScienceDirect

www.sciencedirect.com

THE UNIVERSITY
of NORTH CAROLINA
at CHAPEL HILL

C. Iliadis, A. Champagne,
R. Longland, J. Newton,
C. Ugalde

TUNL

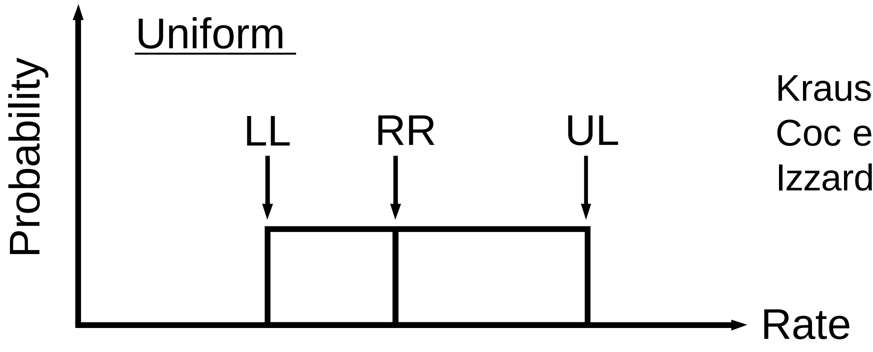
A. Coc
(CSNSM, Orsay)

R. Fitzgerald (National Institute of
Standards and Technology)

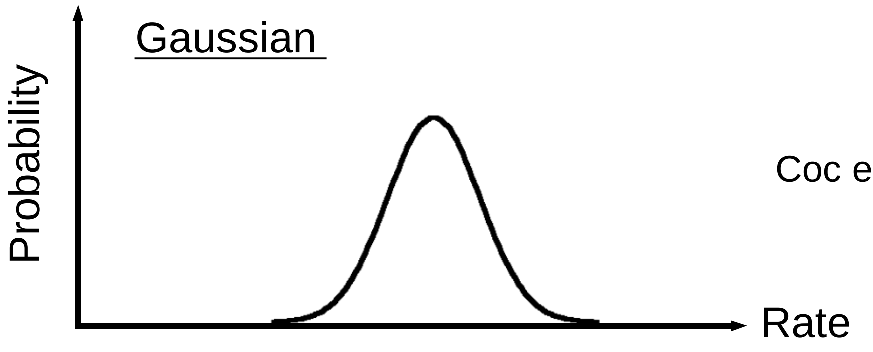
The need for a new evaluation

- ❑ Almost ten years since the last evaluations
  - ➢ The series of papers by Fowler and collaborators ended with *Caughlan and Fowler (1988)*, including 128, mostly proton and α induced reactions on up to Si nuclei
  - ➢ The NACRE evaluation *[Angulo et al. 1999]* followed with 86 charged-particle induced reactions (also up to Si) including uncertainties
  - ➢ Extended from Ne to Ca and to unstable targets (55 reactions) by *Iliadis et al. (2001)* also including uncertainties
  - ➢ More specific evaluations for solar physics *[Adelberger et al. 1998, 2010]* or BBN *[e.g. Descouvemont et al. 2004]*
- ❑ Need of statistically derived uncertainties
  - ➢ Sensitivity study to nuclear uncertainties (BBN, novae, AGB, XRB,…)
  - ➢ Yield uncertainties from Monte-Carlo calculations (BBN, XRB,…)

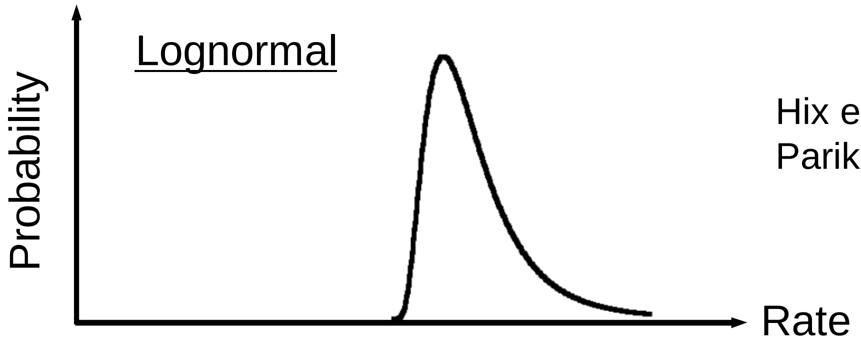
Classical interpretation of rate PDF



Krauss & Chaboyer, Science 299, 65 (2003)
Coc et al., PRD 65, 043510 (2002)
Izzard et al., AA 466, 641 (2007)

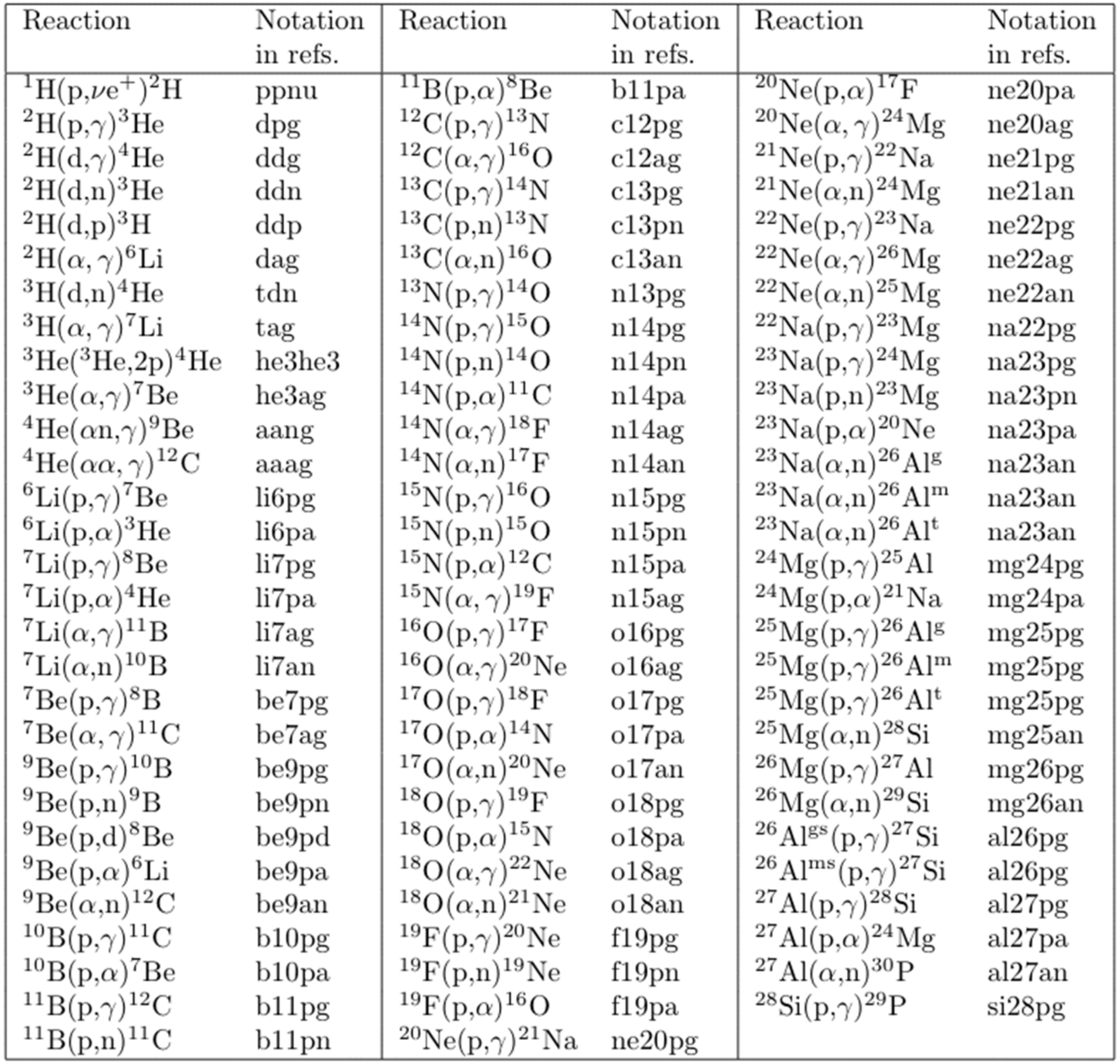


Coc et al., ApJ 600, 544 (2004)



Hix et al., NPA 718, 620 (2003)
Parikh et al., ApJS (2008)

The 1999 NACRE evaluation



Reaction	Notation in refs.	Reaction	Notation in refs.	Reaction	Notation in refs.
^{1}H(p,νe^{+})^{2}H	ppnu	^{11}B(p,α)^{8}Be	b11pa	^{20}Ne(p,α)^{17}F	ne20pa
^{2}H(p,γ)^{3}He	dpg	^{12}C(p,γ)^{13}N	c12pg	^{20}Ne(α,γ)^{24}Mg	ne20ag
^{2}H(d,γ)^{4}He	ddg	^{12}C(α,γ)^{16}O	c12ag	^{21}Ne(p,γ)^{22}Na	ne21pg
^{2}H(d,n)^{3}He	ddn	^{13}C(p,γ)^{14}N	c13pg	^{21}Ne(α,n)^{24}Mg	ne21an
^{2}H(d,p)^{3}H	ddp	^{13}C(p,n)^{13}N	c13pn	^{22}Ne(p,γ)^{23}Na	ne22pg
^{2}H(α,γ)^{6}Li	dag	^{13}C(α,n)^{16}O	c13an	^{22}Ne(α,γ)^{26}Mg	ne22ag
^{3}H(d,n)^{4}He	tdn	^{13}N(p,γ)^{14}O	n13pg	^{22}Ne(α,n)^{25}Mg	ne22an
^{3}H(α,γ)^{7}Li	tag	^{14}N(p,γ)^{15}O	n14pg	^{22}Na(p,γ)^{23}Mg	na22pg
^{3}He(^{3}He,2p)^{4}He	he3he3	^{14}N(p,n)^{14}O	n14pn	^{23}Na(p,γ)^{24}Mg	na23pg
^{3}He(α,γ)^{7}Be	he3ag	^{14}N(p,α)^{11}C	n14pa	^{23}Na(p,n)^{23}Mg	na23pn
^{4}He(αn,γ)^{9}Be	aang	^{14}N(α,γ)^{18}F	n14ag	^{23}Na(p,α)^{20}Ne	na23pa
^{4}He($\alpha\alpha$,γ)^{12}C	aaag	^{14}N(α,n)^{17}F	n14an	^{23}Na(α,n)^{26}Al^{g}	na23an
^{6}Li(p,γ)^{7}Be	li6pg	^{15}N(p,γ)^{16}O	n15pg	^{23}Na(α,n)^{26}Al^{m}	na23an
^{6}Li(p,α)^{3}He	li6pa	^{15}N(p,n)^{15}O	n15pn	^{23}Na(α,n)^{26}Al^{t}	na23an
^{7}Li(p,γ)^{8}Be	li7pg	^{15}N(p,α)^{12}C	n15pa	^{24}Mg(p,γ)^{25}Al	mg24pg
^{7}Li(p,α)^{4}He	li7pa	^{15}N(α,γ)^{19}F	n15ag	^{24}Mg(p,α)^{21}Na	mg24pa
^{7}Li(α,γ)^{11}B	li7ag	^{16}O(p,γ)^{17}F	o16pg	^{25}Mg(p,γ)^{26}Al^{g}	mg25pg
^{7}Li(α,n)^{10}B	li7an	^{16}O(α,γ)^{20}Ne	o16ag	^{25}Mg(p,γ)^{26}Al^{m}	mg25pg
^{7}Be(p,γ)^{8}B	be7pg	^{17}O(p,γ)^{18}F	o17pg	^{25}Mg(p,γ)^{26}Al^{t}	mg25pg
^{7}Be(α,γ)^{11}C	be7ag	^{17}O(p,α)^{14}N	o17pa	^{25}Mg(α,n)^{28}Si	mg25an
^{9}Be(p,γ)^{10}B	be9pg	^{17}O(α,n)^{20}Ne	o17an	^{26}Mg(p,γ)^{27}Al	mg26pg
^{9}Be(p,n)^{9}B	be9pn	^{18}O(p,γ)^{19}F	o18pg	^{26}Mg(α,n)^{29}Si	mg26an
^{9}Be(p,d)^{8}Be	be9pd	^{18}O(p,α)^{15}N	o18pa	^{26}Al^{gs}(p,γ)^{27}Si	al26pg
^{9}Be(p,α)^{6}Li	be9pa	^{18}O(α,γ)^{22}Ne	o18ag	^{26}Al^{ms}(p,γ)^{27}Si	al26pg
^{9}Be(α,n)^{12}C	be9an	^{18}O(α,n)^{21}Ne	o18an	^{27}Al(p,γ)^{28}Si	al27pg
^{10}B(p,γ)^{11}C	b10pg	^{19}F(p,γ)^{20}Ne	f19pg	^{27}Al(p,α)^{24}Mg	al27pa
^{10}B(p,α)^{7}Be	b10pa	^{19}F(p,n)^{19}Ne	f19pn	^{27}Al(α,n)^{30}P	al27an
^{11}B(p,γ)^{12}C	b11pg	^{19}F(p,α)^{16}O	f19pa	^{28}Si(p,γ)^{29}P	si28pg
^{11}B(p,n)^{11}C	b11pn	^{20}Ne(p,γ)^{21}Na	ne20pg		

86 charged-particle induced reactions on stable targets + ^{3}H, ^{7}Be, ^{22}Na and ^{26}Al

10 institutes (Brussels×2, Orsay, Bochum, Stuttgart, Athens, Ferrara, Lisboa, Bucharest and Edinburgh)

Directed by C. Rolfs and M. Arnould and coordonated by C. Angulo and P. Descouvemont

The 1999 NACRE evaluation

- ❑ Improvement w.r.t. CF88
  - ➢ References to the original data provided
  - ➢ Information on the evaluation procedure given for each reaction
  - ➢ Systematic estimation of uncertainties leading to “lower and upper bounds” for the rates
  - ➢ Tabulated recommended and lower and upper bounds for the rates
- ❑ Limitations and shortcomings
  - ➢ Uniformity of evaluations within the (10 institutes) collaboration
  - ➢ No definition of “lower and upper bounds” (and even rec. rate) renders precise statistical interpretation meaningless
  - ➢ Only partial documentation on specific reaction evaluation and input data

The 1999 NACRE evaluation

- ☐ Examples of lower, recommended and upper rates evaluations
  - ➢ Upper limit with $\omega\gamma < X$
    - ▪ “low” with $\omega\gamma = 0$
    - ▪ “rec.” with $\omega\gamma = 0.1 \times X$ as in Fowler’s papers
    - ▪ “high” with $\omega\gamma = X$
  - ➢ Sharp resonance at $E_R \pm \Delta E_R$ and with $\omega\gamma \pm \Delta\omega\gamma$ strength:
    - ▪ “low” with $E_R + \Delta E_R$ and $\omega\gamma - \Delta\omega\gamma$
    - ▪ “rec.” with E_R and $\omega\gamma$
    - ▪ “high” with $E_R - \Delta E_R$ and $\omega\gamma + \Delta\omega\gamma$

Our evaluation

- ❑ Improvements w.r.t. NACRE (and most other) evaluations
  - ➢ Better uniformity by using the *same code* for rate calculations
  - ➢ Precise definitions of *low*, *median* and *high* rates, obtained form Monte-Carlo calculations
  - ➢All input data given and evaluation better documented
  - ➢ Short lived radioactive targets added (^{14}C, $^{17,18}F$, ^{19}Ne, ^{21}Na, $^{22,23}Mg$, $^{23\text{-}25}Al$, $^{26,27}Si$, $^{27,29}P$, $^{30,31}S$,…)
- ❑ However
  - ➢ For technical reasons, important reactions not included as $^{12}C(\alpha,\gamma)^{16}O$, some CNO reactions and A<14 targets

List of reactions

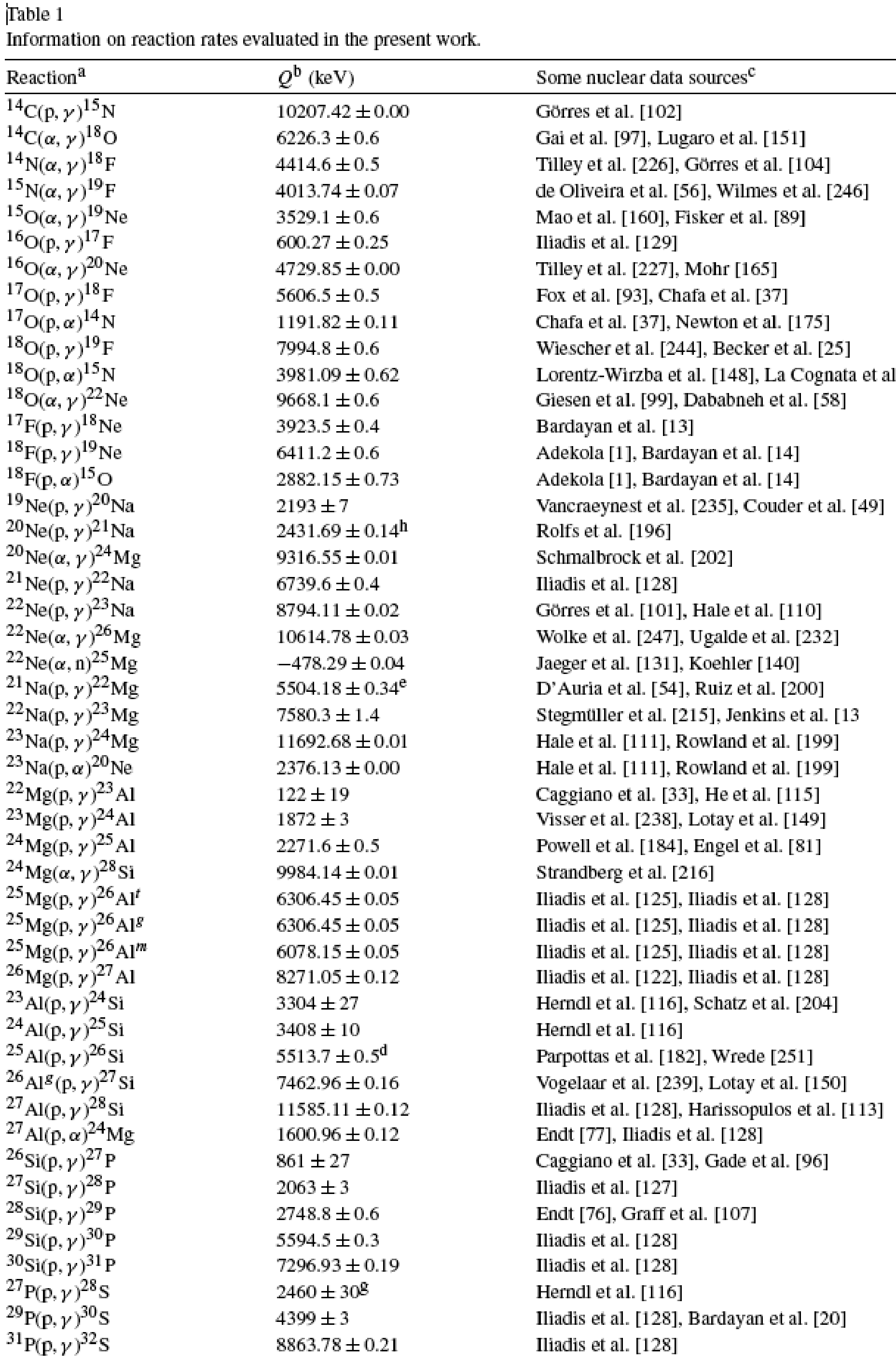


Table 1
Information on reaction rates evaluated in the present work.

Reaction[a]	Q[b] (keV)	Some nuclear data sources[c]
^{14}C(p, γ)^{15}N	10207.42 ± 0.00	Görres et al. [102]
^{14}C(α, γ)^{18}O	6226.3 ± 0.6	Gai et al. [97], Lugaro et al. [151]
^{14}N(α, γ)^{18}F	4414.6 ± 0.5	Tilley et al. [226], Görres et al. [104]
^{15}N(α, γ)^{19}F	4013.74 ± 0.07	de Oliveira et al. [56], Wilmes et al. [246]
^{15}O(α, γ)^{19}Ne	3529.1 ± 0.6	Mao et al. [160], Fisker et al. [89]
^{16}O(p, γ)^{17}F	600.27 ± 0.25	Iliadis et al. [129]
^{16}O(α, γ)^{20}Ne	4729.85 ± 0.00	Tilley et al. [227], Mohr [165]
^{17}O(p, γ)^{18}F	5606.5 ± 0.5	Fox et al. [93], Chafa et al. [37]
^{17}O(p, α)^{14}N	1191.82 ± 0.11	Chafa et al. [37], Newton et al. [175]
^{18}O(p, γ)^{19}F	7994.8 ± 0.6	Wiescher et al. [244], Becker et al. [25]
^{18}O(p, α)^{15}N	3981.09 ± 0.62	Lorentz-Wirzba et al. [148], La Cognata et al. [144]
^{18}O(α, γ)^{22}Ne	9668.1 ± 0.6	Giesen et al. [99], Dababneh et al. [58]
^{17}F(p, γ)^{18}Ne	3923.5 ± 0.4	Bardayan et al. [13]
^{18}F(p, γ)^{19}Ne	6411.2 ± 0.6	Adekola [1], Bardayan et al. [14]
^{18}F(p, α)^{15}O	2882.15 ± 0.73	Adekola [1], Bardayan et al. [14]
^{19}Ne(p, γ)^{20}Na	2193 ± 7	Vancraeynest et al. [235], Couder et al. [49]
^{20}Ne(p, γ)^{21}Na	2431.69 ± 0.14[h]	Rolfs et al. [196]
^{20}Ne(α, γ)^{24}Mg	9316.55 ± 0.01	Schmalbrock et al. [202]
^{21}Ne(p, γ)^{22}Na	6739.6 ± 0.4	Iliadis et al. [128]
^{22}Ne(p, γ)^{23}Na	8794.11 ± 0.02	Görres et al. [101], Hale et al. [110]
^{22}Ne(α, γ)^{26}Mg	10614.78 ± 0.03	Wolke et al. [247], Ugalde et al. [232]
^{22}Ne(α, n)^{25}Mg	−478.29 ± 0.04	Jaeger et al. [131], Koehler [140]
^{21}Na(p, γ)^{22}Mg	5504.18 ± 0.34[e]	D'Auria et al. [54], Ruiz et al. [200]
^{22}Na(p, γ)^{23}Mg	7580.3 ± 1.4	Stegmüller et al. [215], Jenkins et al. [13
^{23}Na(p, γ)^{24}Mg	11692.68 ± 0.01	Hale et al. [111], Rowland et al. [199]
^{23}Na(p, α)^{20}Ne	2376.13 ± 0.00	Hale et al. [111], Rowland et al. [199]
^{22}Mg(p, γ)^{23}Al	122 ± 19	Caggiano et al. [33], He et al. [115]
^{23}Mg(p, γ)^{24}Al	1872 ± 3	Visser et al. [238], Lotay et al. [149]
^{24}Mg(p, γ)^{25}Al	2271.6 ± 0.5	Powell et al. [184], Engel et al. [81]
^{24}Mg(α, γ)^{28}Si	9984.14 ± 0.01	Strandberg et al. [216]
^{25}Mg(p, γ)^{26}Al^t	6306.45 ± 0.05	Iliadis et al. [125], Iliadis et al. [128]
^{25}Mg(p, γ)^{26}Al^g	6306.45 ± 0.05	Iliadis et al. [125], Iliadis et al. [128]
^{25}Mg(p, γ)^{26}Al^m	6078.15 ± 0.05	Iliadis et al. [125], Iliadis et al. [128]
^{26}Mg(p, γ)^{27}Al	8271.05 ± 0.12	Iliadis et al. [122], Iliadis et al. [128]
^{23}Al(p, γ)^{24}Si	3304 ± 27	Herndl et al. [116], Schatz et al. [204]
^{24}Al(p, γ)^{25}Si	3408 ± 10	Herndl et al. [116]
^{25}Al(p, γ)^{26}Si	5513.7 ± 0.5[d]	Parpottas et al. [182], Wrede [251]
^{26}Al^g(p, γ)^{27}Si	7462.96 ± 0.16	Vogelaar et al. [239], Lotay et al. [150]
^{27}Al(p, γ)^{28}Si	11585.11 ± 0.12	Iliadis et al. [128], Harissopulos et al. [113]
^{27}Al(p, α)^{24}Mg	1600.96 ± 0.12	Endt [77], Iliadis et al. [128]
^{26}Si(p, γ)^{27}P	861 ± 27	Caggiano et al. [33], Gade et al. [96]
^{27}Si(p, γ)^{28}P	2063 ± 3	Iliadis et al. [127]
^{28}Si(p, γ)^{29}P	2748.8 ± 0.6	Endt [76], Graff et al. [107]
^{29}Si(p, γ)^{30}P	5594.5 ± 0.3	Iliadis et al. [128]
^{30}Si(p, γ)^{31}P	7296.93 ± 0.19	Iliadis et al. [128]
^{27}P(p, γ)^{28}S	2460 ± 30[g]	Herndl et al. [116]
^{29}P(p, γ)^{30}S	4399 ± 3	Iliadis et al. [128], Bardayan et al. [20]
^{31}P(p, γ)^{32}S	8863.78 ± 0.21	Iliadis et al. [128]

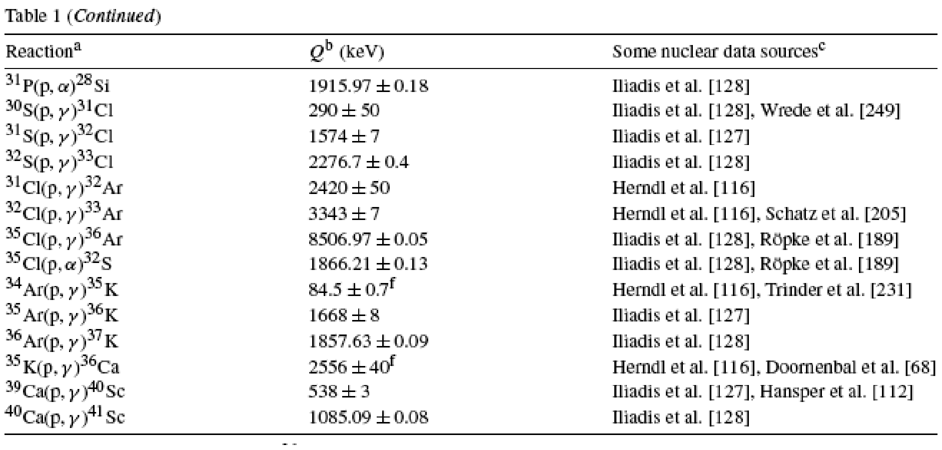


Table 1 (*Continued*)

Reaction[a]	Q[b] (keV)	Some nuclear data sources[c]
^{31}P(p, α)^{28}Si	1915.97 ± 0.18	Iliadis et al. [128]
^{30}S(p, γ)^{31}Cl	290 ± 50	Iliadis et al. [128], Wrede et al. [249]
^{31}S(p, γ)^{32}Cl	1574 ± 7	Iliadis et al. [127]
^{32}S(p, γ)^{33}Cl	2276.7 ± 0.4	Iliadis et al. [128]
^{31}Cl(p, γ)^{32}Ar	2420 ± 50	Herndl et al. [116]
^{32}Cl(p, γ)^{33}Ar	3343 ± 7	Herndl et al. [116], Schatz et al. [205]
^{35}Cl(p, γ)^{36}Ar	8506.97 ± 0.05	Iliadis et al. [128], Röpke et al. [189]
^{35}Cl(p, α)^{32}S	1866.21 ± 0.13	Iliadis et al. [128], Röpke et al. [189]
^{34}Ar(p, γ)^{35}K	84.5 ± 0.7[f]	Herndl et al. [116], Trinder et al. [231]
^{35}Ar(p, γ)^{36}K	1668 ± 8	Iliadis et al. [127]
^{36}Ar(p, γ)^{37}K	1857.63 ± 0.09	Iliadis et al. [128]
^{35}K(p, γ)^{36}Ca	2556 ± 40[f]	Herndl et al. [116], Doornenbal et al. [68]
^{39}Ca(p, γ)^{40}Sc	538 ± 3	Iliadis et al. [127], Hansper et al. [112]
^{40}Ca(p, γ)^{41}Sc	1085.09 ± 0.08	Iliadis et al. [128]

Principle of the new evaluation

1. Compilation and evaluation of available original data *[paper II]* with all evaluated data published *[paper III]*
2. Monte-Carlo sampling of input data according to relevant statistical distributions *[paper I]*, allowing for 2 level interferences, better treatment of upper limits,… to obtain the distribution of rates on a temperature grid *[R. Longland's RatesMC code]*.
3. In general, matching of the "experimental" rate to Hauser-Feschbach theoretical rate above a calculated *[Newton, Longland & Iliadis 2008]* temperature
4. Production of tables for the statistically calculated low, median and high rates and of the log-normal parameters μ and σ of the rate distribution *[paper II]*
5. Comparison with previous rates *[paper IV]*

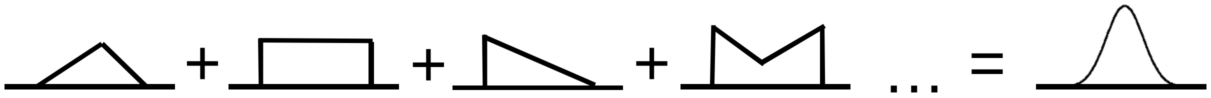
PDF of a resonance energy

$$E_r,\ \Delta E_r \quad \rightarrow 50\% \text{ of thick - target yield curves}$$

$$E_r = E_x - Q \quad \rightarrow \ \gamma \text{ - ray spectroscopy}$$

Central limit theorem of statistics:

sum of n independent random variables x_i becomes a Gaussian random variable in the limit of large n, independent of the form of the individual PDFs of the x_i



E_r is Gaussian distributed :

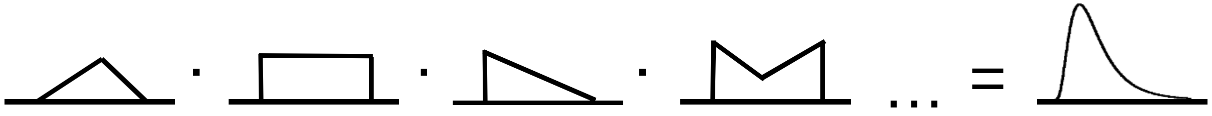
$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/(2\sigma^2)}$$

$$E[x] = \mu, \quad V[x] = \sigma^2$$

PDF of a resonance strength or partial width

Central limit theorem of statistics:

product of n independent random variables x_i becomes a lognormal random variable in the limit of large n, independent of the form of the individual PDFs of the x_i



$\omega\gamma$, Γ_i are lognormally distributed:

$$f(x)=\frac{1}{\sigma\sqrt{2\pi}}\,\frac{1}{x}\,e^{-(\ln x-\mu)^2/(2\sigma^2)}$$

$x > 0!$

$$E(x)=\exp(\mu+\sigma^2/2) \qquad V(x)=E^2(x)(\exp(\sigma^2)-1)$$

If y is Gaussian distributed, then $x=e^y$ will be lognormally distributed

The lognormal probability density function

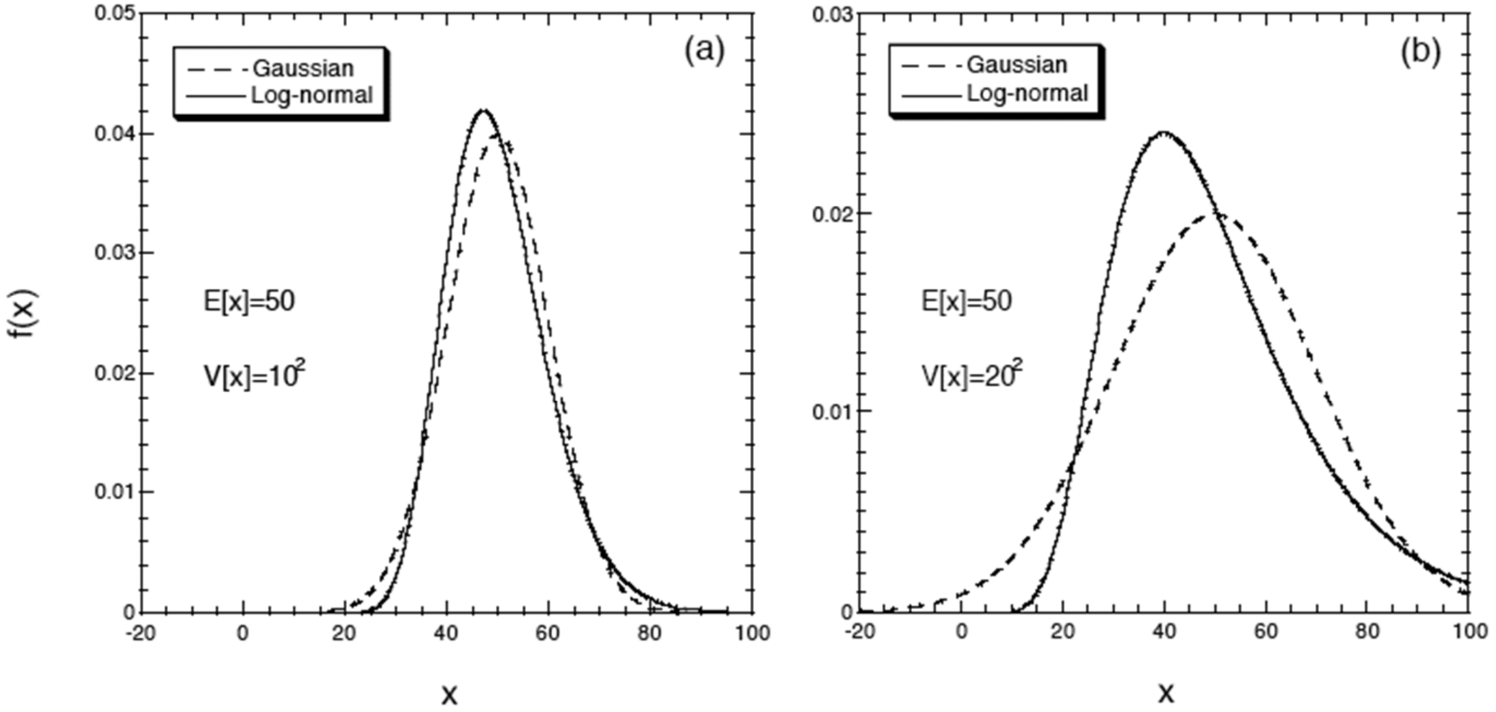


Fig. 1. Comparison of Gaussian (dashed lines) and lognormal (solid lines) probability density functions; (a) $E[x] = 50$ and $V[x] = 10^2$, and (b) $E[x] = 50$ and $V[x] = 20^2$. See text.

- For small variance, Gaussian PDF ≈ Lognormal PDF
- Lognormal MC sampling ensures that variable remains positive

Upper limits resonance strength or partial width

θ_a^2 is Porter - Thomas distributed:

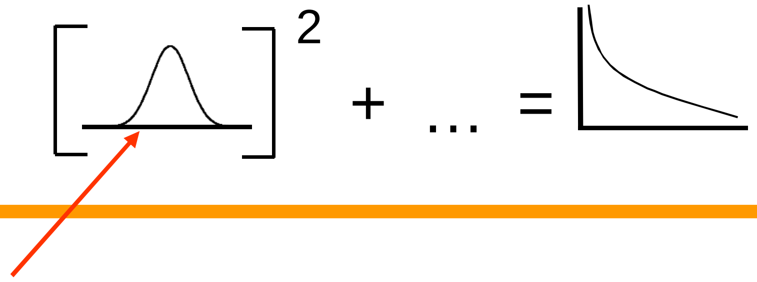
$$f(\theta^2) = \frac{c}{\sqrt{\theta^2}} e^{-\theta^2/(2\langle\theta^2\rangle)}$$

$$\theta^2 > 0!$$

Porter and Thomas, PR 104, 483 (1956)

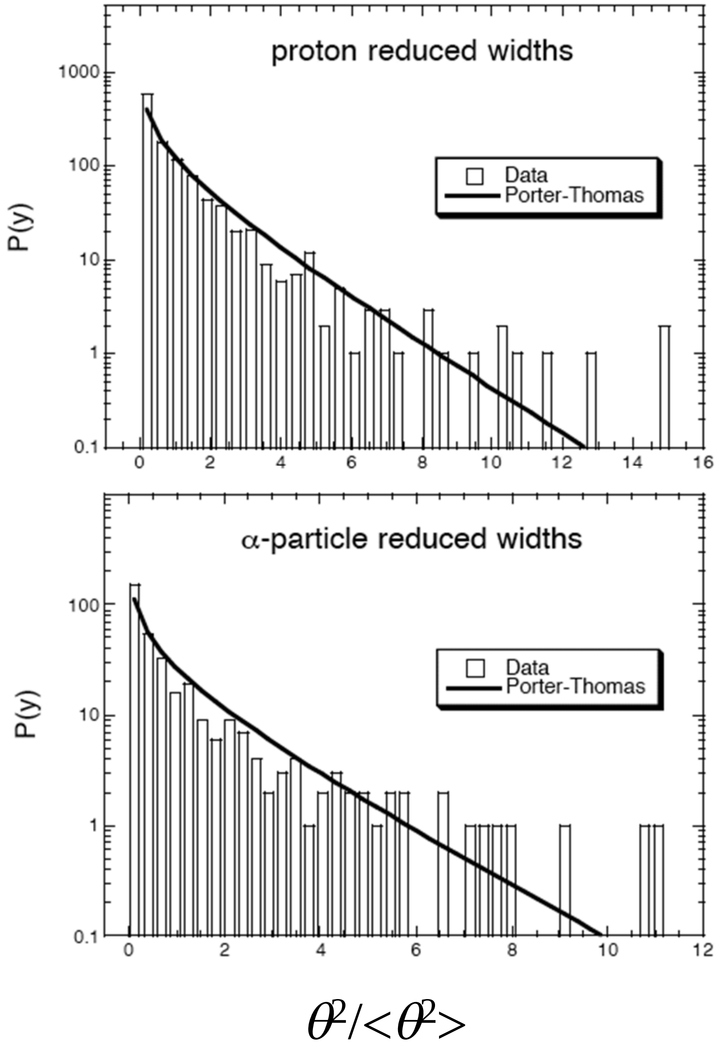
Porter - Thomas distribution = chi - squared distribution with one degree of freedom

If x is Gaussian distributed, then x^2 is chi-squared distributed



Sum of amplitudes expected to follow a normal PDF centered at zero

Upper limits of partial widths



Charged particles

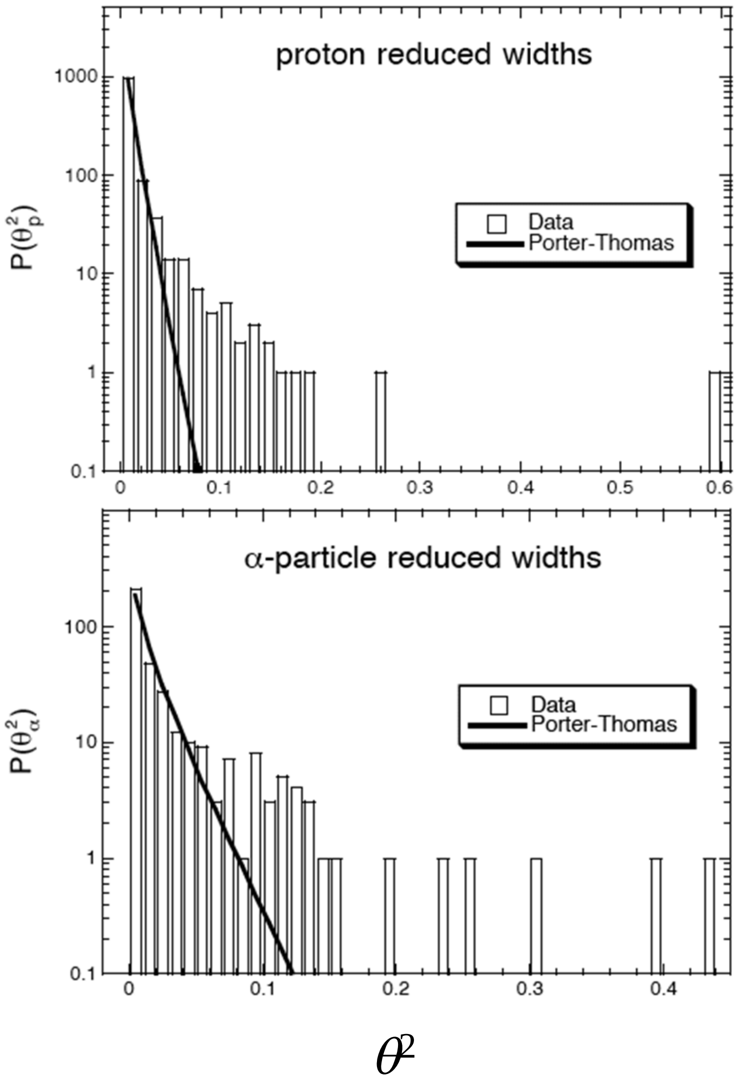
Theory: Reduced width, θ^2 or spectroscopic factors, are expected to follow a Porter-Thomas PDF.

Experiment: While experimental bias favors high θ^2 measured values, statistics shows that $\theta^2/<\theta^2>$locally follows a Porter-Thomas PDF.

Experimental distribution of $\theta^2/<\theta^2>$ for 1127 *p* and 360 α, (after nucleus and *l* grouping) and for ^{24}Mg, ^{28}Si, ^{30}P, ^{32}S, ^{36}Ar, ^{40}Ca levels

Data from TUNL *[Mitchell et al. 1975-1995]*

Upper limits of partial widths



$$f_{PT}\left(\theta^2\right) \propto \frac{1}{\sqrt{\theta^2}} \exp\left(\frac{\theta^2}{2\left\langle\theta^2\right\rangle}\right)$$ (P.-T. PDF)

However, in general, *local value* of $<\theta^2>$ is not known!

The best fits of experimental data give
$<\theta^2_p> = 0.0045$ for protons and
$<\theta^2_\alpha> = 0.01$ for α-particles

➢ Different from the often assumed $\theta^2_\mathrm{p} = 0.1$ value

➢ $<\theta^2_\alpha>$ larger than $<\theta^2_p>$

Upper limits: $\theta^2 < \theta^2_\mathrm{upper} \rightarrow f(\theta^2) = f_{PT}(\theta^2)$ below θ^2_upper and *0* above.

The Porter-Thomas probability density function

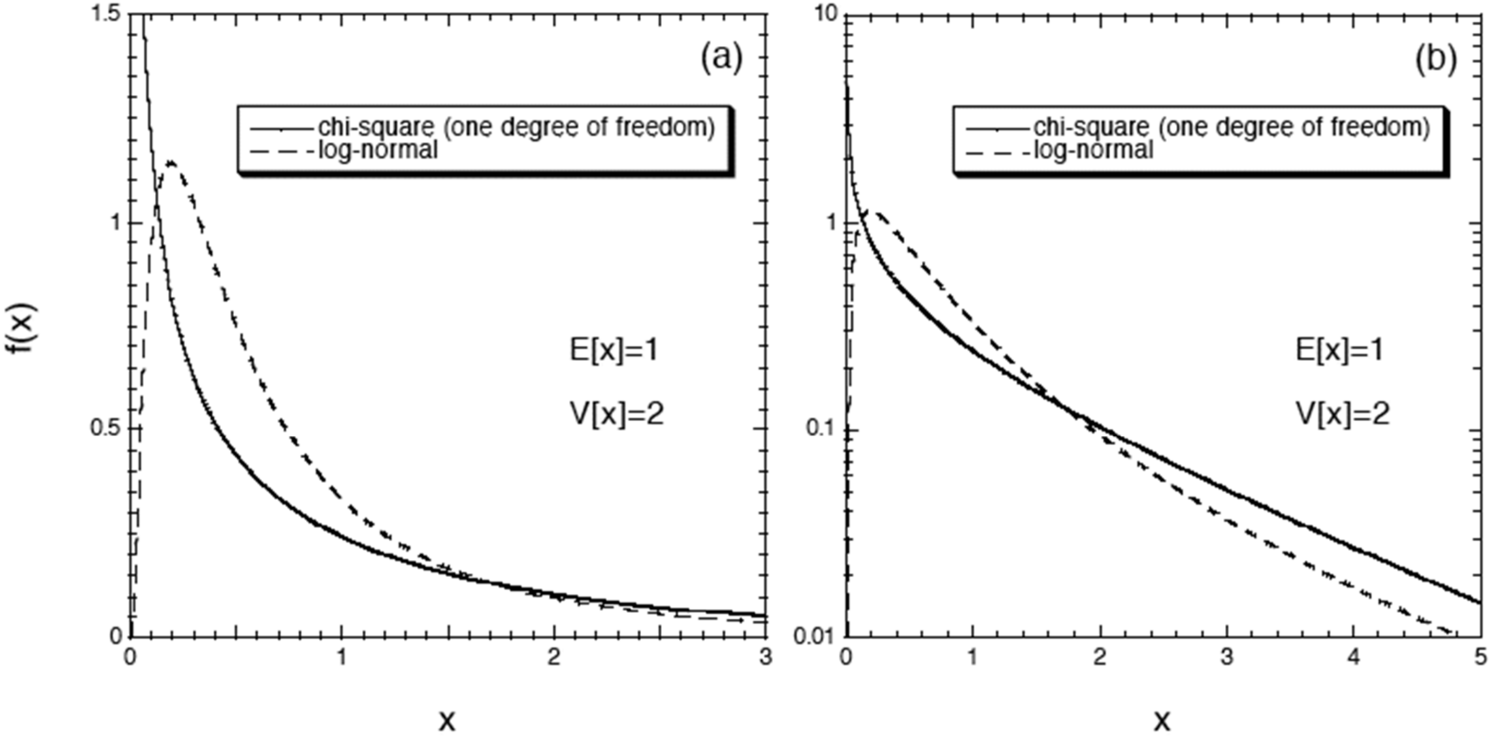


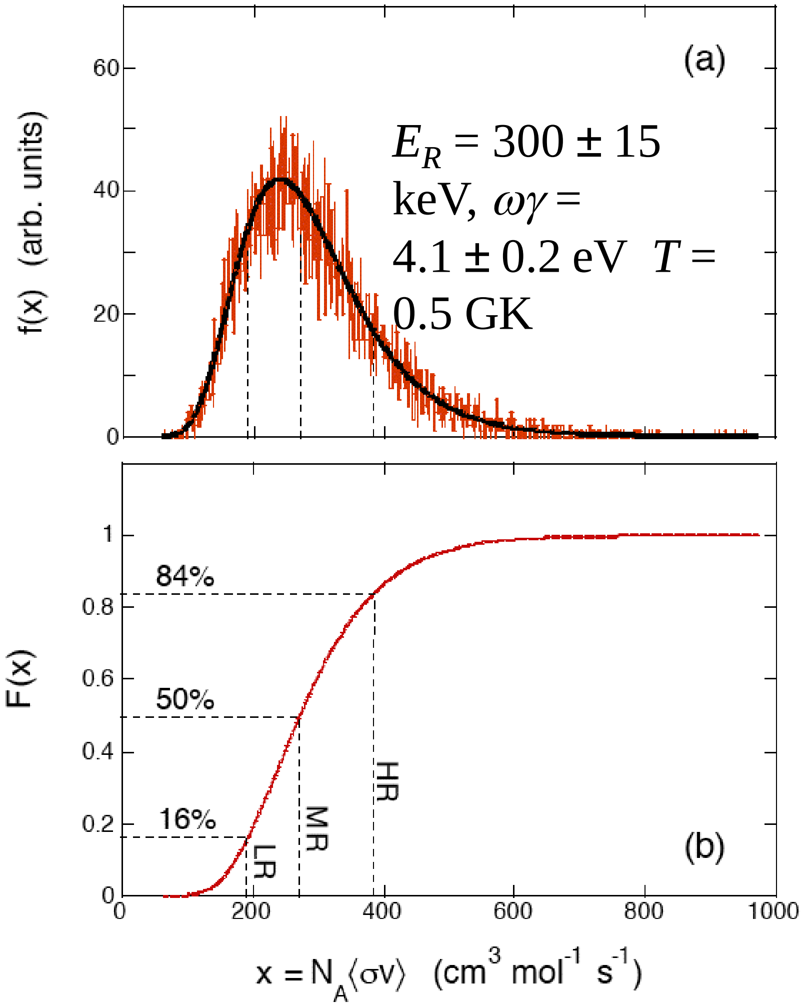
Fig. 2. Chi-square distribution of one degree of freedom (solid line) on (a) a linear vertical axis scale, and (b) a logarithmic vertical axis scale. For comparison, a lognormal distribution (dashed line) of same expectation value and variance as the chi-squared distribution is shown. The lognormal parameters amount to $\mu = -0.54931$ and $\sigma = 1.0482$, according to Eq. (27).

Summary of MC sampling

Monte-Carlo rate calculations assume

- Normal PDF for resonance energies
- Lognormal PDFs for resonance strengths and partial widths
- Truncated Porter-Thomas PDF for p and α upper limits of partial widths
- Lognormal PDF for spectroscopic factors with a 40% uncertainty
- “ “ for radiative widths with a 50% uncertainty
- “ “ direct capture with a 40% uncertainty
- Numerical integration: in general, no other non-resonant contribution
- Two level interference : “+”, “-”, or unknown “+/-” sampling
- Correlations, e.g. energy in penetrability and Boltzmann factor

Output of MC sampling



E_R = 300 ± 15 keV, $\omega\gamma$ = 4.1 ± 0.2 eV T = 0.5 GK

Distribution of rates (10^4 trials) at a selected temperature (schematic, not real example)

The low, median and high rates are then obtained as:

- Low Rate ($e^{\mu-\sigma}$) = 0.16 quantile
- Median Rate (e^{μ}) = 0.5 quantile
- High Rate ($e^{\mu+\sigma}$) = 0.84 quantile

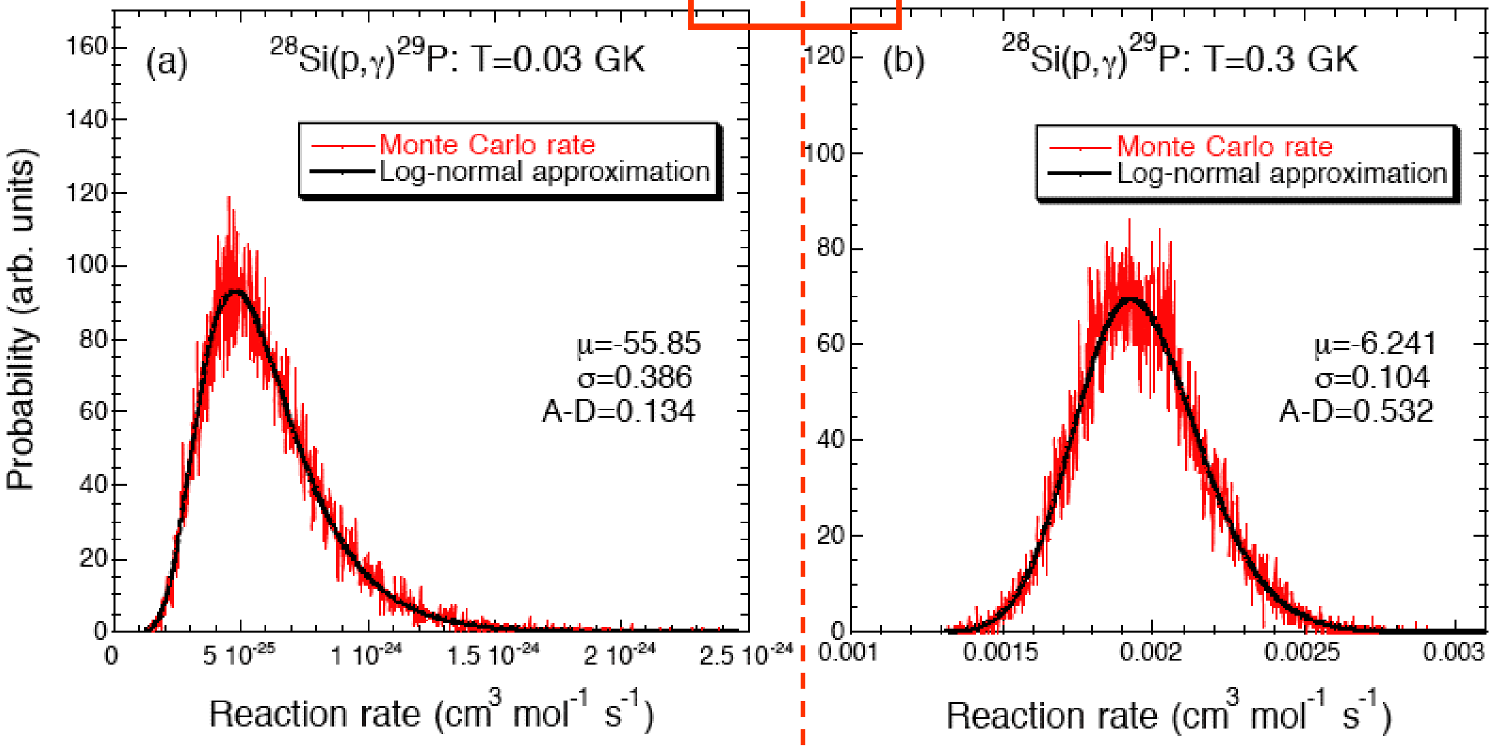
from the cumulative distribution.

Lognormal distribution with μ and σ calculated from the distribution

- Tabulated : T, LR, MR, HR, μ, σ, (and AD)

A real output of MC sampling

$\sigma \approx 0.1$



Lognormal DC dominates
→ lognormal PDF

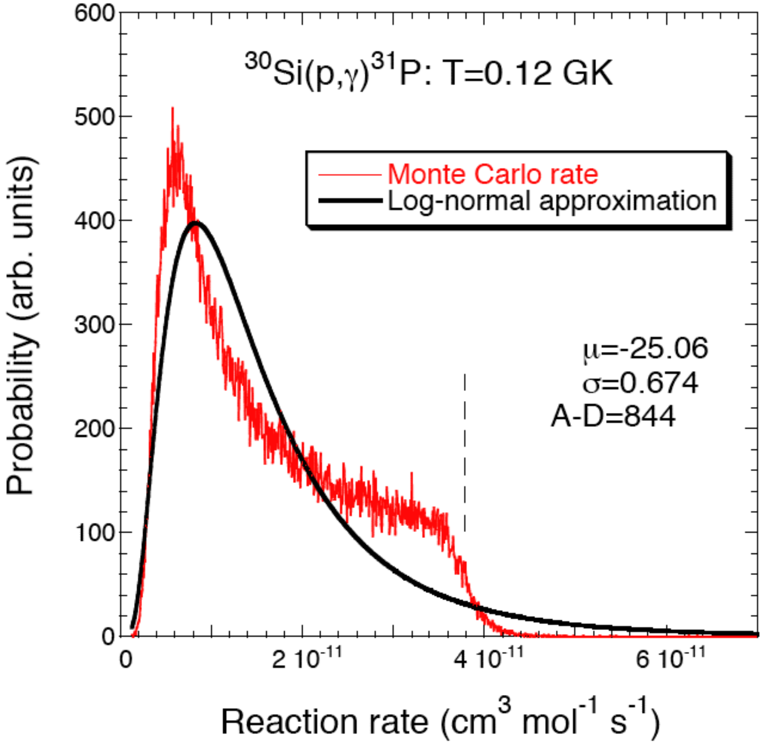
Small (σ ≤0.1) $\omega\gamma$ uncertainty
dominates → ≈ normal PDF

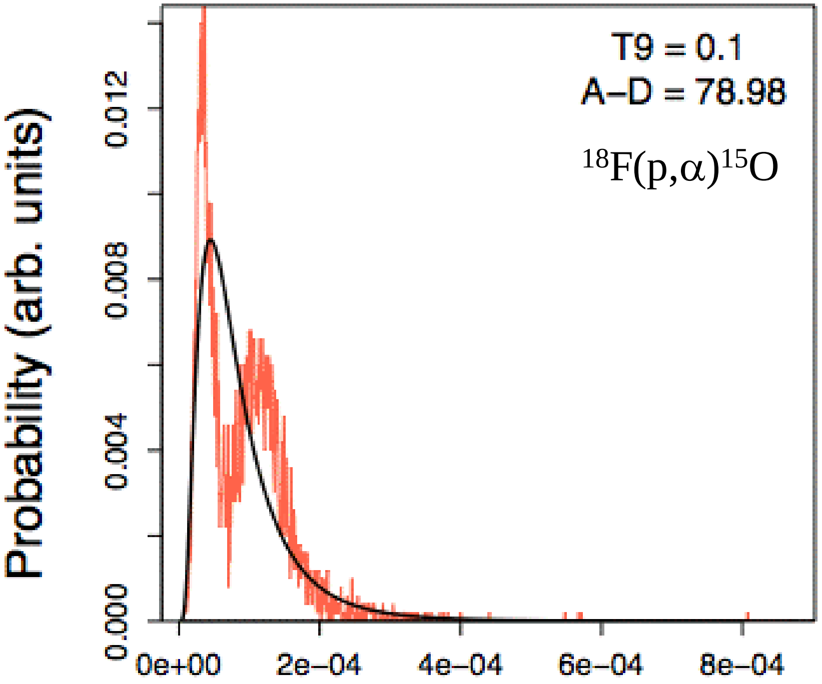
"A-D" = Anderson–Darling statistical test that a sample follows a PDF

99% c.l. rejection if A-D > 1.092 but still acceptable up to A-D ≈ 30

Most (but not all) rates lognormally distributed

Rate dominated by:

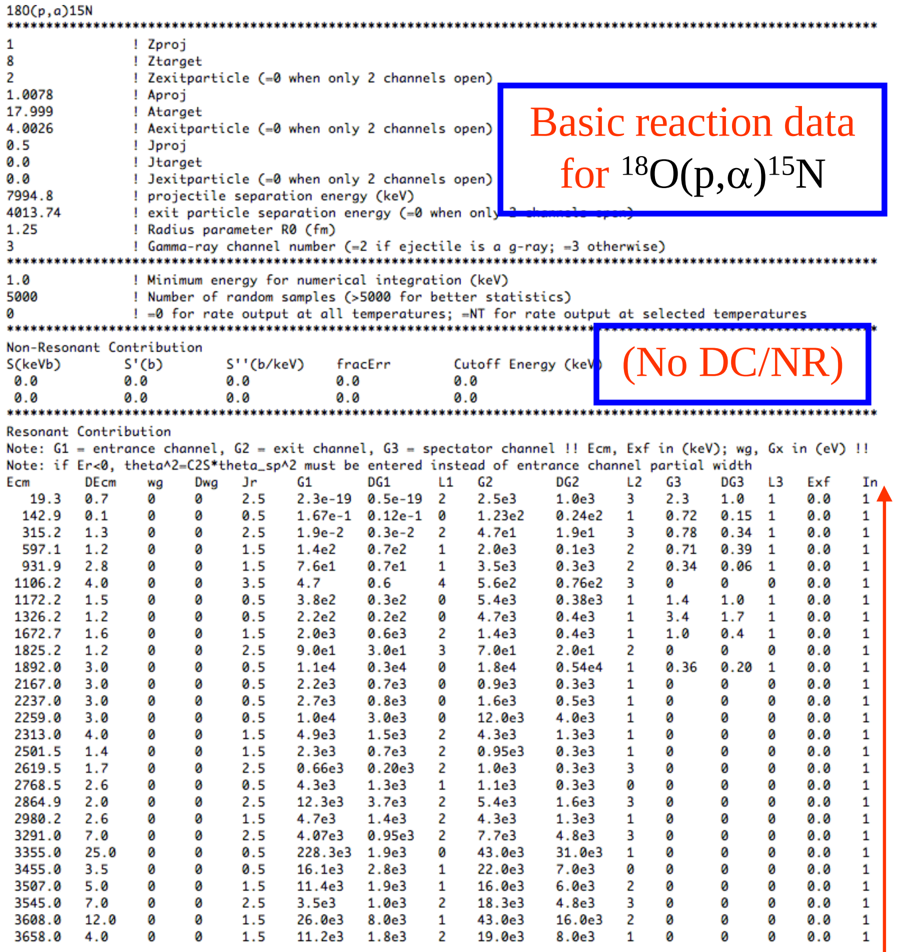




- Upper limit on θ^2_p

- Two level interferences with unknown sign

A real example of MC input *[Paper III]*



```
18O(p,a)15N
**************************************************************************************
1                ! Zproj
8                ! Ztarget
2                ! Zexitparticle (=0 when only 2 channels open)
1.0078           ! Aproj
17.999           ! Atarget
4.0026           ! Aexitparticle (=0 when only 2 channels open)
0.5              ! Jproj
0.0              ! Jtarget
0.0              ! Jexitparticle (=0 when only 2 channels open)
7994.8           ! projectile separation energy (keV)
4013.74          ! exit particle separation energy (=0 when only 2 channels open)
1.25             ! Radius parameter R0 (fm)
3                ! Gamma-ray channel number (=2 if ejectile is a g-ray; =3 otherwise)
**************************************************************************************
1.0              ! Minimum energy for numerical integration (keV)
5000             ! Number of random samples (>5000 for better statistics)
0                ! =0 for rate output at all temperatures; =NT for rate output at selected temperatures
**************************************************************************************
Non-Resonant Contribution
S(keVb)      S'(b)       S''(b/keV)    fracErr      Cutoff Energy (keV)
 0.0         0.0         0.0           0.0          0.0
 0.0         0.0         0.0           0.0          0.0
**************************************************************************************
Resonant Contribution
Note: G1 = entrance channel, G2 = exit channel, G3 = spectator channel !! Ecm, Exf in (keV); wg, Gx in (eV) !!
Note: if Er<0, theta^2=C2S*theta_sp^2 must be entered instead of entrance channel partial width
Ecm      DEcm   wg    Dwg   Jr    G1        DG1       L1   G2       DG2      L2   G3     DG3    L3   Exf    In
   19.3  0.7    0     0     2.5   2.3e-19   0.5e-19   2    2.5e3    1.0e3    3    2.3    1.0    1    0.0    1
  142.9  0.1    0     0     0.5   1.67e-1   0.12e-1   0    1.23e2   0.24e2   1    0.72   0.15   1    0.0    1
  315.2  1.3    0     0     2.5   1.9e-2    0.3e-2    2    4.7e1    1.9e1    3    0.78   0.34   1    0.0    1
  597.1  1.2    0     0     1.5   1.4e2     0.7e2     1    2.0e3    0.1e3    2    0.71   0.39   1    0.0    1
  931.9  2.8    0     0     1.5   7.6e1     0.7e1     1    3.5e3    0.3e3    2    0.34   0.06   1    0.0    1
 1106.2  4.0    0     0     3.5   4.7       0.6       4    5.6e2    0.76e2   3    0      0      0    0.0    1
 1172.2  1.5    0     0     0.5   3.8e2     0.3e2     0    5.4e3    0.38e3   1    1.4    1.0    1    0.0    1
 1326.2  1.2    0     0     0.5   2.2e2     0.2e2     0    4.7e3    0.4e3    1    3.4    1.7    1    0.0    1
 1672.7  1.6    0     0     1.5   2.0e3     0.6e3     2    1.4e3    0.4e3    1    1.0    0.4    1    0.0    1
 1825.2  1.2    0     0     2.5   9.0e1     3.0e1     3    7.0e1    2.0e1    2    0      0      0    0.0    1
 1892.0  3.0    0     0     0.5   1.1e4     0.3e4     0    1.8e4    0.54e4   1    0.36   0.20   1    0.0    1
 2167.0  3.0    0     0     0.5   2.2e3     0.7e3     0    0.9e3    0.3e3    1    0      0      0    0.0    1
 2237.0  3.0    0     0     0.5   2.7e3     0.8e3     0    1.6e3    0.5e3    1    0      0      0    0.0    1
 2259.0  3.0    0     0     0.5   1.0e4     3.0e3     0    12.0e3   4.0e3    1    0      0      0    0.0    1
 2313.0  4.0    0     0     1.5   4.9e3     1.5e3     2    4.3e3    1.3e3    1    0      0      0    0.0    1
 2501.5  1.4    0     0     1.5   2.3e3     0.7e3     2    0.95e3   0.3e3    1    0      0      0    0.0    1
 2619.5  1.7    0     0     2.5   0.66e3    0.20e3    2    1.0e3    0.3e3    3    0      0      0    0.0    1
 2768.5  2.6    0     0     0.5   4.3e3     1.3e3     1    1.1e3    0.3e3    0    0      0      0    0.0    1
 2864.9  2.0    0     0     2.5   12.3e3    3.7e3     2    5.4e3    1.6e3    3    0      0      0    0.0    1
 2980.2  2.6    0     0     1.5   4.7e3     1.4e3     2    4.3e3    1.3e3    1    0      0      0    0.0    1
 3291.0  7.0    0     0     2.5   4.07e3    0.95e3    2    7.7e3    4.8e3    3    0      0      0    0.0    1
 3355.0  25.0   0     0     0.5   228.3e3   1.9e3     0    43.0e3   31.0e3   1    0      0      0    0.0    1
 3455.0  3.5    0     0     0.5   16.1e3    2.8e3     1    22.0e3   7.0e3    0    0      0      0    0.0    1
 3507.0  5.0    0     0     1.5   11.4e3    1.9e3     1    16.0e3   6.0e3    2    0      0      0    0.0    1
 3545.0  7.0    0     0     2.5   3.5e3     1.0e3     2    18.3e3   4.8e3    3    0      0      0    0.0    1
 3608.0  12.0   0     0     1.5   26.0e3    8.0e3     1    43.0e3   16.0e3   2    0      0      0    0.0    1
 3658.0  4.0    0     0     1.5   11.2e3    1.8e3     2    19.0e3   8.0e3    1    0      0      0    0.0    1
```

Basic reaction data for ^{18}O(p,α)^{15}N

(No DC/NR)

$E_R \pm \Delta E_R$

$\omega\gamma \pm \Delta\omega\gamma$

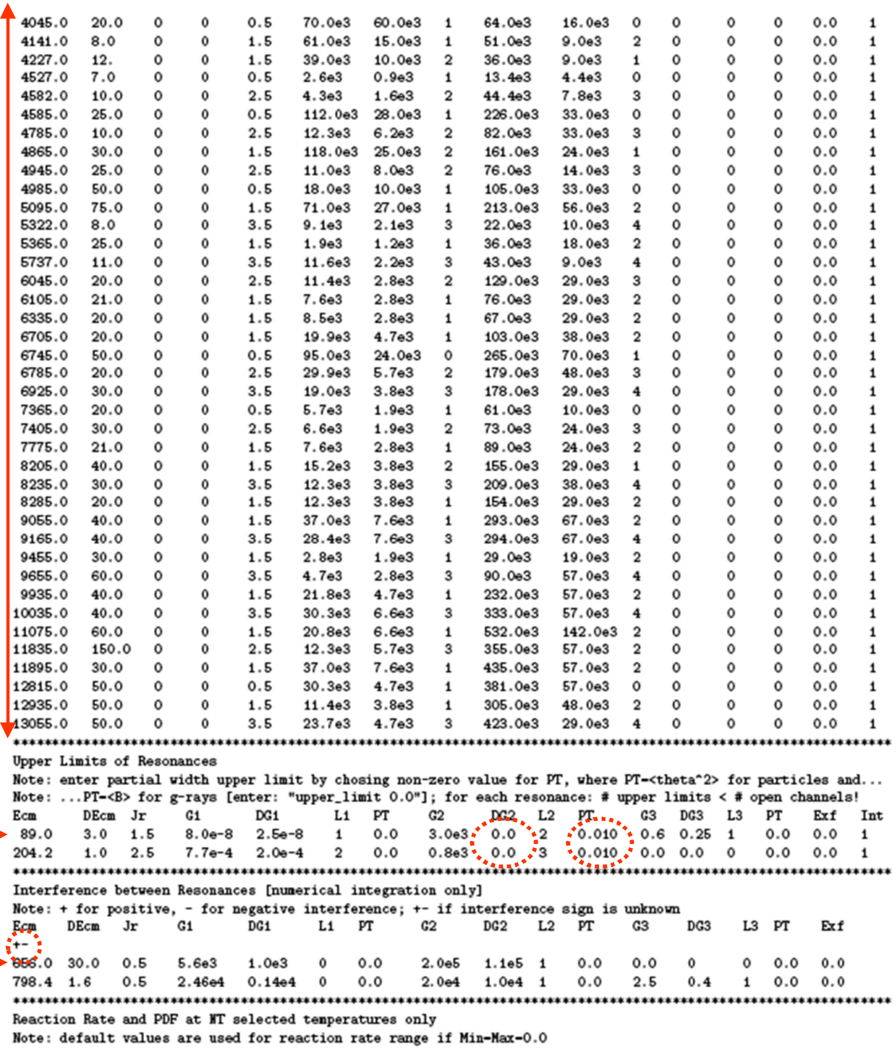
J

$\Gamma_p \pm \Delta\Gamma_p$

$\Gamma_\alpha \pm \Delta\Gamma_\alpha$

$\Gamma_\gamma \pm \Delta\Gamma_\gamma$

66 numerically integrated resonances



```
 4045.0  20.0   0   0   0.5   70.0e3   60.0e3   1   64.0e3    16.0e3   0   0    0   0   0.0   1
 4141.0  8.0    0   0   1.5   61.0e3   15.0e3   1   51.0e3    9.0e3    2   0    0   0   0.0   1
 4227.0  12.    0   0   1.5   39.0e3   10.0e3   2   36.0e3    9.0e3    1   0    0   0   0.0   1
 4527.0  7.0    0   0   0.5   2.6e3    0.9e3    1   13.4e3    4.4e3    0   0    0   0   0.0   1
 4582.0  10.0   0   0   2.5   4.3e3    1.6e3    2   44.4e3    7.8e3    3   0    0   0   0.0   1
 4585.0  25.0   0   0   0.5   112.0e3  28.0e3   1   226.0e3   33.0e3   0   0    0   0   0.0   1
 4785.0  10.0   0   0   2.5   12.3e3   6.2e3    2   82.0e3    33.0e3   3   0    0   0   0.0   1
 4865.0  30.0   0   0   1.5   118.0e3  25.0e3   2   161.0e3   24.0e3   1   0    0   0   0.0   1
 4945.0  25.0   0   0   2.5   11.0e3   8.0e3    2   76.0e3    14.0e3   3   0    0   0   0.0   1
 4985.0  50.0   0   0   0.5   18.0e3   10.0e3   1   105.0e3   33.0e3   0   0    0   0   0.0   1
 5095.0  75.0   0   0   1.5   71.0e3   27.0e3   1   213.0e3   56.0e3   2   0    0   0   0.0   1
 5322.0  8.0    0   0   3.5   9.1e3    2.1e3    3   22.0e3    10.0e3   4   0    0   0   0.0   1
 5365.0  25.0   0   0   1.5   1.9e3    1.2e3    1   36.0e3    18.0e3   2   0    0   0   0.0   1
 5737.0  11.0   0   0   3.5   11.6e3   2.2e3    3   43.0e3    9.0e3    4   0    0   0   0.0   1
 6045.0  20.0   0   0   2.5   11.4e3   2.8e3    2   129.0e3   29.0e3   3   0    0   0   0.0   1
 6105.0  21.0   0   0   1.5   7.6e3    2.8e3    1   76.0e3    29.0e3   2   0    0   0   0.0   1
 6335.0  20.0   0   0   1.5   8.5e3    2.8e3    1   67.0e3    29.0e3   2   0    0   0   0.0   1
 6705.0  20.0   0   0   1.5   19.9e3   4.7e3    1   103.0e3   38.0e3   2   0    0   0   0.0   1
 6745.0  50.0   0   0   0.5   95.0e3   24.0e3   0   265.0e3   70.0e3   1   0    0   0   0.0   1
 6785.0  20.0   0   0   2.5   29.9e3   5.7e3    2   179.0e3   48.0e3   3   0    0   0   0.0   1
 6925.0  30.0   0   0   3.5   19.0e3   3.8e3    3   178.0e3   29.0e3   4   0    0   0   0.0   1
 7365.0  20.0   0   0   0.5   5.7e3    1.9e3    1   61.0e3    10.0e3   0   0    0   0   0.0   1
 7405.0  30.0   0   0   2.5   6.6e3    1.9e3    2   73.0e3    24.0e3   3   0    0   0   0.0   1
 7775.0  21.0   0   0   1.5   7.6e3    2.8e3    1   89.0e3    24.0e3   2   0    0   0   0.0   1
 8205.0  40.0   0   0   1.5   15.2e3   3.8e3    2   155.0e3   29.0e3   1   0    0   0   0.0   1
 8235.0  30.0   0   0   3.5   12.3e3   3.8e3    3   209.0e3   38.0e3   4   0    0   0   0.0   1
 8285.0  20.0   0   0   1.5   12.3e3   3.8e3    1   154.0e3   29.0e3   2   0    0   0   0.0   1
 9055.0  40.0   0   0   1.5   37.0e3   7.6e3    1   293.0e3   67.0e3   2   0    0   0   0.0   1
 9165.0  40.0   0   0   3.5   28.4e3   7.6e3    3   294.0e3   67.0e3   4   0    0   0   0.0   1
 9455.0  30.0   0   0   1.5   2.8e3    1.9e3    1   29.0e3    19.0e3   2   0    0   0   0.0   1
 9655.0  60.0   0   0   3.5   4.7e3    2.8e3    3   90.0e3    57.0e3   4   0    0   0   0.0   1
 9935.0  40.0   0   0   1.5   21.8e3   4.7e3    1   232.0e3   57.0e3   2   0    0   0   0.0   1
10035.0  40.0   0   0   3.5   30.3e3   6.6e3    3   333.0e3   57.0e3   4   0    0   0   0.0   1
11075.0  60.0   0   0   1.5   20.8e3   6.6e3    1   532.0e3   142.0e3  2   0    0   0   0.0   1
11835.0  150.0  0   0   2.5   12.3e3   5.7e3    3   355.0e3   57.0e3   2   0    0   0   0.0   1
11895.0  30.0   0   0   1.5   37.0e3   7.6e3    1   435.0e3   57.0e3   2   0    0   0   0.0   1
12815.0  50.0   0   0   0.5   30.3e3   4.7e3    1   381.0e3   57.0e3   0   0    0   0   0.0   1
12935.0  50.0   0   0   1.5   11.4e3   3.8e3    1   305.0e3   48.0e3   2   0    0   0   0.0   1
13055.0  50.0   0   0   3.5   23.7e3   4.7e3    3   423.0e3   29.0e3   4   0    0   0   0.0   1
**************************************************************************************
Upper Limits of Resonances
Note: enter partial width upper limit by chosing non-zero value for PT, where PT=<theta^2> for particles and...
Note: ...PT=<B> for g-rays [enter: "upper_limit 0.0"]; for each resonance: # upper limits < # open channels!
Ecm     DEcm  Jr    G1       DG1      L1   PT    G2      DG2   L2   PT      G3    DG3    L3   PT    Exf   Int
 89.0   3.0   1.5   8.0e-8   2.5e-8   1    0.0   3.0e3   0.0   2    0.010   0.6   0.25   1    0.0   0.0   1
204.2   1.0   2.5   7.7e-4   2.0e-4   2    0.0   0.8e3   0.0   3    0.010   0.0   0.0    0    0.0   0.0   1
**************************************************************************************
Interference between Resonances [numerical integration only]
Note: + for positive, - for negative interference; +- if interference sign is unknown
Ecm     DEcm   Jr    G1       DG1      L1   PT    G2      DG2     L2   PT    G3    DG3   L3   PT    Exf
+-
655.0   30.0   0.5   5.6e3    1.0e3    0    0.0   2.0e5   1.1e5   1    0.0   0.0   0     0    0.0   0.0
798.4   1.6    0.5   2.46e4   0.14e4   0    0.0   2.0e4   1.0e4   1    0.0   2.5   0.4   1    0.0   0.0
**************************************************************************************
Reaction Rate and PDF at NT selected temperatures only
Note: default values are used for reaction rate range if Min-Max=0.0
```

2-level interferences with unknown signs

Two upper limits on Γ_α

A real example of MC ouput *[Paper II]*

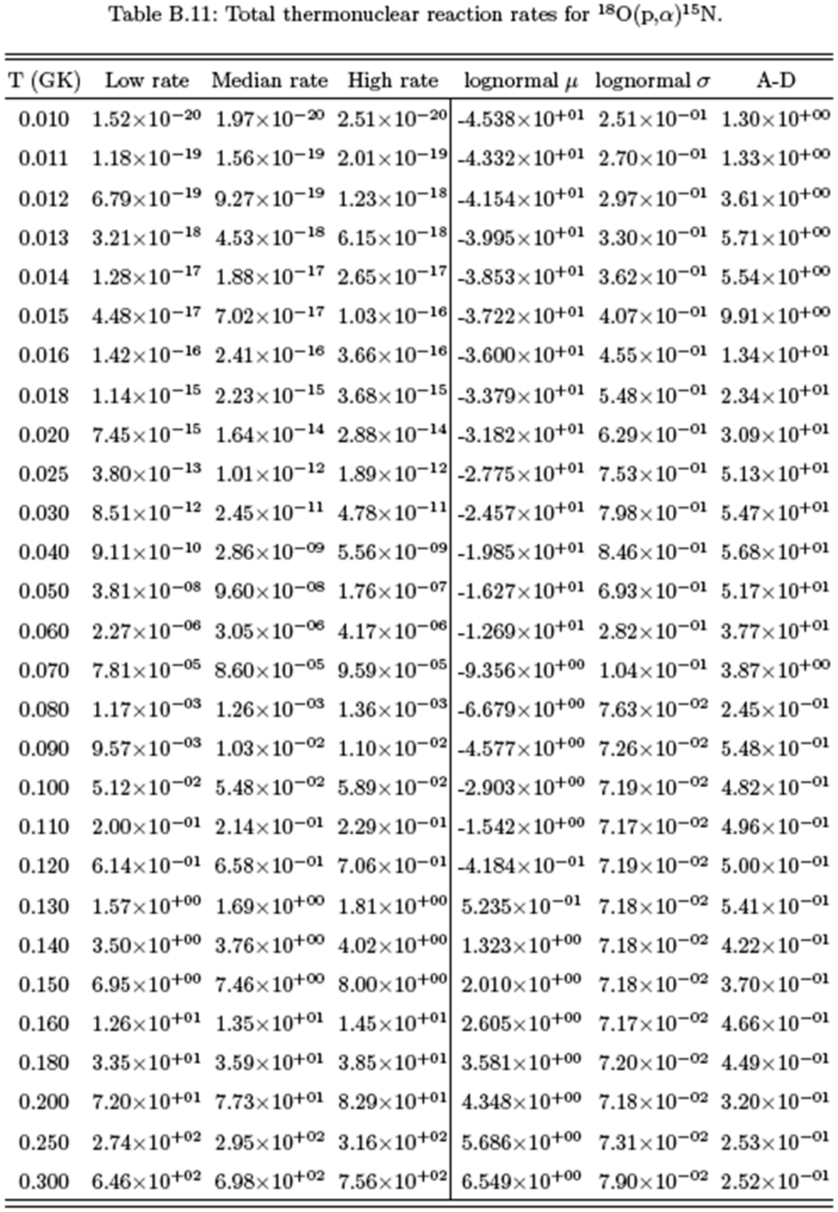
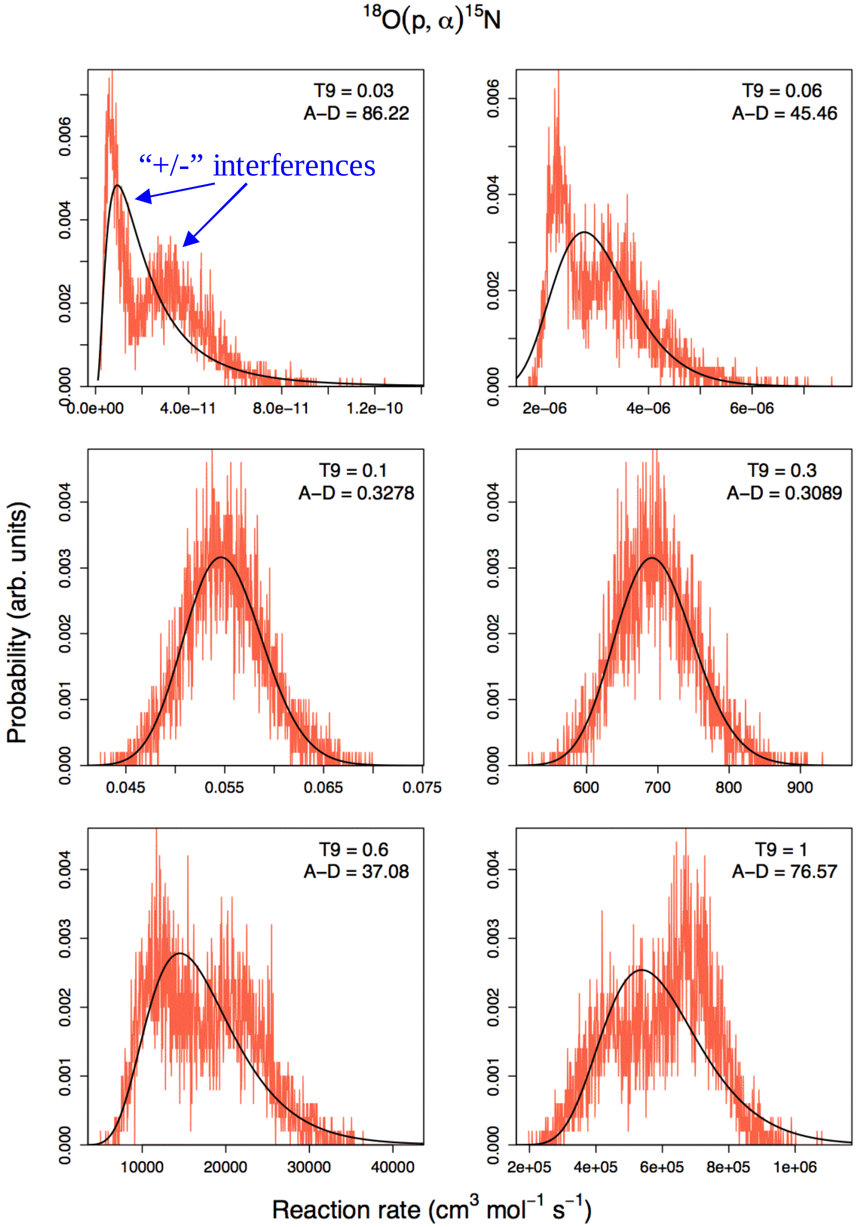


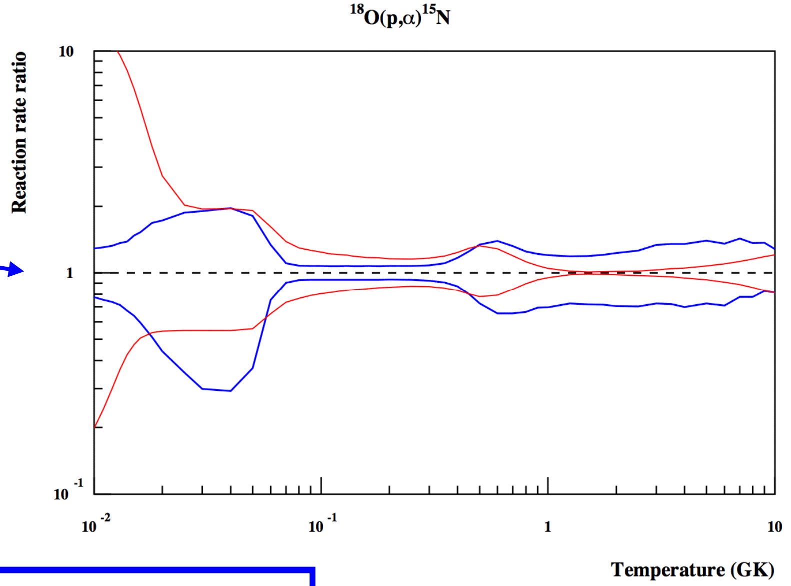
Table B.11: Total thermonuclear reaction rates for ^{18}O(p,α)^{15}N.

T (GK)	Low rate	Median rate	High rate	lognormal μ	lognormal σ	A-D
0.010	1.52×10^{-20}	1.97×10^{-20}	2.51×10^{-20}	$-4.538\times10^{+01}$	2.51×10^{-01}	$1.30\times10^{+00}$
0.011	1.18×10^{-19}	1.56×10^{-19}	2.01×10^{-19}	$-4.332\times10^{+01}$	2.70×10^{-01}	$1.33\times10^{+00}$
0.012	6.79×10^{-19}	9.27×10^{-19}	1.23×10^{-18}	$-4.154\times10^{+01}$	2.97×10^{-01}	$3.61\times10^{+00}$
0.013	3.21×10^{-18}	4.53×10^{-18}	6.15×10^{-18}	$-3.995\times10^{+01}$	3.30×10^{-01}	$5.71\times10^{+00}$
0.014	1.28×10^{-17}	1.88×10^{-17}	2.65×10^{-17}	$-3.853\times10^{+01}$	3.62×10^{-01}	$5.54\times10^{+00}$
0.015	4.48×10^{-17}	7.02×10^{-17}	1.03×10^{-16}	$-3.722\times10^{+01}$	4.07×10^{-01}	$9.91\times10^{+00}$
0.016	1.42×10^{-16}	2.41×10^{-16}	3.66×10^{-16}	$-3.600\times10^{+01}$	4.55×10^{-01}	$1.34\times10^{+01}$
0.018	1.14×10^{-15}	2.23×10^{-15}	3.68×10^{-15}	$-3.379\times10^{+01}$	5.48×10^{-01}	$2.34\times10^{+01}$
0.020	7.45×10^{-15}	1.64×10^{-14}	2.88×10^{-14}	$-3.182\times10^{+01}$	6.29×10^{-01}	$3.09\times10^{+01}$
0.025	3.80×10^{-13}	1.01×10^{-12}	1.89×10^{-12}	$-2.775\times10^{+01}$	7.53×10^{-01}	$5.13\times10^{+01}$
0.030	8.51×10^{-12}	2.45×10^{-11}	4.78×10^{-11}	$-2.457\times10^{+01}$	7.98×10^{-01}	$5.47\times10^{+01}$
0.040	9.11×10^{-10}	2.86×10^{-09}	5.56×10^{-09}	$-1.985\times10^{+01}$	8.46×10^{-01}	$5.68\times10^{+01}$
0.050	3.81×10^{-08}	9.60×10^{-08}	1.76×10^{-07}	$-1.627\times10^{+01}$	6.93×10^{-01}	$5.17\times10^{+01}$
0.060	2.27×10^{-06}	3.05×10^{-06}	4.17×10^{-06}	$-1.269\times10^{+01}$	2.82×10^{-01}	$3.77\times10^{+01}$
0.070	7.81×10^{-05}	8.60×10^{-05}	9.59×10^{-05}	$-9.356\times10^{+00}$	1.04×10^{-01}	$3.87\times10^{+00}$
0.080	1.17×10^{-03}	1.26×10^{-03}	1.36×10^{-03}	$-6.679\times10^{+00}$	7.63×10^{-02}	2.45×10^{-01}
0.090	9.57×10^{-03}	1.03×10^{-02}	1.10×10^{-02}	$-4.577\times10^{+00}$	7.26×10^{-02}	5.48×10^{-01}
0.100	5.12×10^{-02}	5.48×10^{-02}	5.89×10^{-02}	$-2.903\times10^{+00}$	7.19×10^{-02}	4.82×10^{-01}
0.110	2.00×10^{-01}	2.14×10^{-01}	2.29×10^{-01}	$-1.542\times10^{+00}$	7.17×10^{-02}	4.96×10^{-01}
0.120	6.14×10^{-01}	6.58×10^{-01}	7.06×10^{-01}	-4.184×10^{-01}	7.19×10^{-02}	5.00×10^{-01}
0.130	$1.57\times10^{+00}$	$1.69\times10^{+00}$	$1.81\times10^{+00}$	5.235×10^{-01}	7.18×10^{-02}	5.41×10^{-01}
0.140	$3.50\times10^{+00}$	$3.76\times10^{+00}$	$4.02\times10^{+00}$	$1.323\times10^{+00}$	7.18×10^{-02}	4.22×10^{-01}
0.150	$6.95\times10^{+00}$	$7.46\times10^{+00}$	$8.00\times10^{+00}$	$2.010\times10^{+00}$	7.18×10^{-02}	3.70×10^{-01}
0.160	$1.26\times10^{+01}$	$1.35\times10^{+01}$	$1.45\times10^{+01}$	$2.605\times10^{+00}$	7.17×10^{-02}	4.66×10^{-01}
0.180	$3.35\times10^{+01}$	$3.59\times10^{+01}$	$3.85\times10^{+01}$	$3.581\times10^{+00}$	7.20×10^{-02}	4.49×10^{-01}
0.200	$7.20\times10^{+01}$	$7.73\times10^{+01}$	$8.29\times10^{+01}$	$4.348\times10^{+00}$	7.18×10^{-02}	3.20×10^{-01}
0.250	$2.74\times10^{+02}$	$2.95\times10^{+02}$	$3.16\times10^{+02}$	$5.686\times10^{+00}$	7.31×10^{-02}	2.53×10^{-01}
0.300	$6.46\times10^{+02}$	$6.98\times10^{+02}$	$7.56\times10^{+02}$	$6.549\times10^{+00}$	7.90×10^{-02}	2.52×10^{-01}



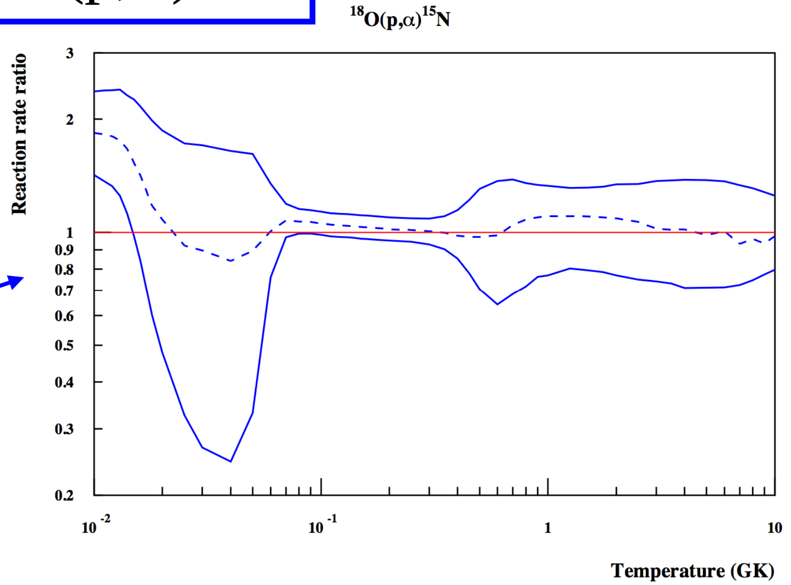
Comparison with previous work *[Paper IV]*

- ☐ Comparison between ranges of uncertainties i.e. LR/MR and HR/MR for previous (often NACRE) and new rates



- ☐ Origin of the differences w.r.t. NACRE:
  - ➢ E_R = 19 keV resonance
  - ➢ $\Delta\Gamma_\alpha$ for E_R = 656 keV resonance
  - ➢ Interferences

$^{18}O(p,\alpha)^{15}N$



- ☐ Comparison between new LR, MR and HR and previous mean or recommended rate

Conclusions (I)

- 62 reactions from $^{14}C(p,\gamma)^{15}O$ to $^{40}Ca(p,\gamma)^{41}Sc$
- Better uniformity by using the *same code* for rate calculations
- Numerical integration whenever possible
- Precise definitions of *low*, *median* and *high* rates, obtained form Monte-Carlo calculations
- All input data given and evaluation better documented
- Short lived radioactive targets added (^{14}C, $^{17,18}F$, ^{19}Ne, ^{21}Na, $^{22,23}Mg$, $^{23\text{-}25}Al$, $^{26,27}Si$, $^{27,29}P$, $^{30,31}S$,…)
- Tables of parameters to be used in Monte Carlo for astrophysical applications

http://starlib.physics.unc.edu/

Nuclear Physics aspects

1. The main reactions for H, He and Li BBN production
2. Search for nuclear solutions to the lithium problem
3. Be, B and CNO production in BBN
4. Monte-Carlo evaluation of reaction rates
5. Monte-Carlo investigation of BBN

Sensitivity study (II)

1. Start from “best guess” set of reaction rates and evaluated or guessed uncertainties
2. Perform Monte-Carlo calculations storing for each event sampled reaction rates and yields
3. Calculate correlations between reaction rates and yields
4. Identification of important reactions e.g. >10% correlation with selected yields
5. Reevaluation of selected rates following re-analyses of available experimental and theoretical data
6. Calculations with set of improved reaction rates

Monte-Carlo sampling

Let x be the short notation for a reaction rate: $x \equiv N_A \langle \sigma v \rangle$

Assumed to follow a Log-Normal distribution: $f(x) = \frac{1}{\sigma\sqrt{2\pi}} \frac{1}{x} e^{-(\ln x - \mu)^2/(2\sigma^2)}$

i.e $\ln(x)$ follows a Normal distribution with mean μ and variance σ^2

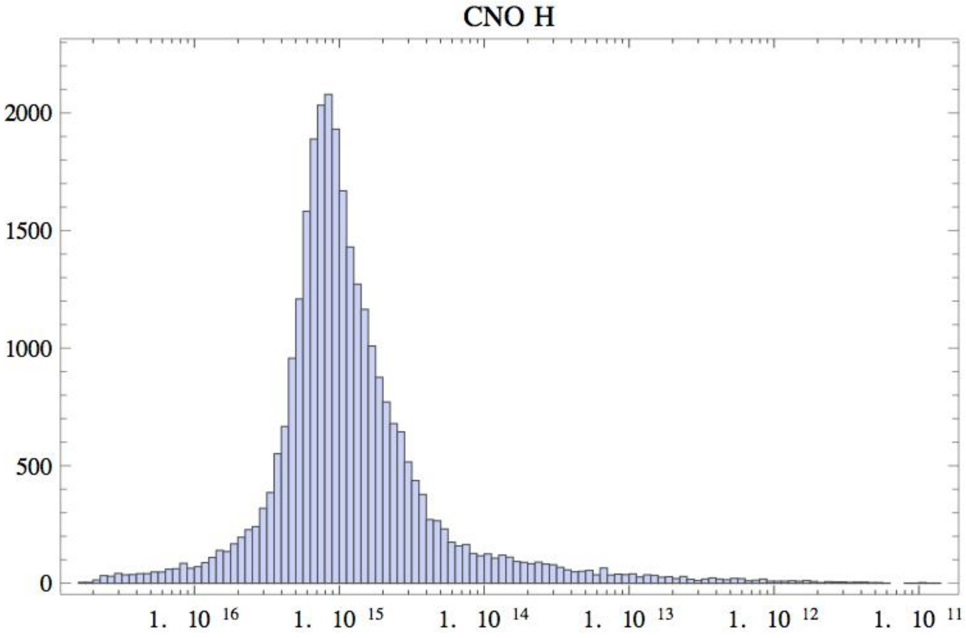
Monte-Carlo sampling : p follows a Normal distribution with mean 0 and variance 1 (i = trial number)

$$x_{\text{med}} \equiv \exp(\mu)$$

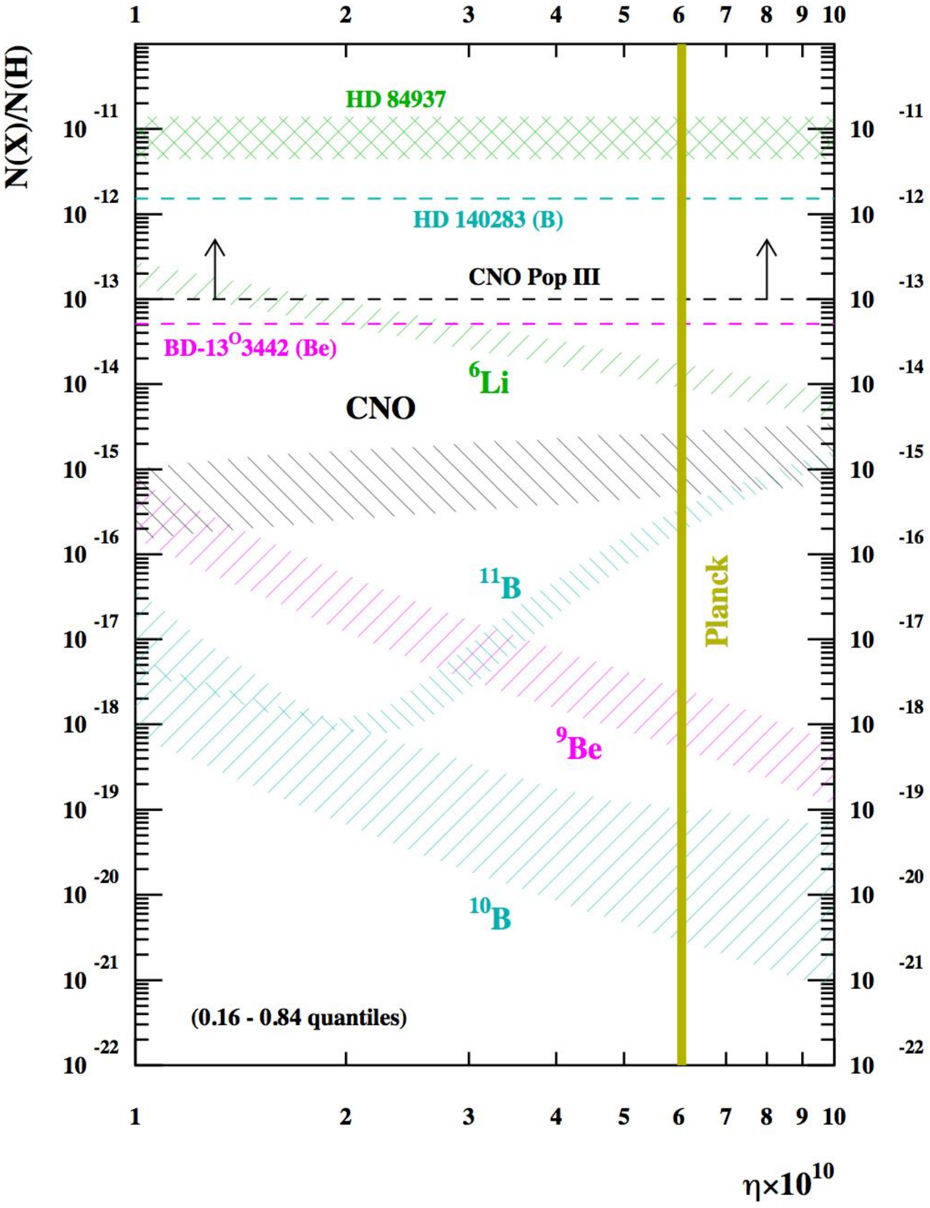
$$f.u. \equiv \exp(\sigma)$$

$$x_i = \exp(\mu + p_i \sigma) \equiv x_{\text{med}} (f.u.)^{p_i} \rightarrow y_{j;i}$$ (yield of isotope j)

Monte-Carlo results: improved uncertainties



Number of atoms	*[Coc et al. 2012]*	*[Coc et al. 2014]*
^{6}Li/H (×10^{-14})	1.23	0.90-1.77
^{9}Be/H (×10^{-19})	9.60	5.10-26.3
^{11}B/H (×10^{-16})	3.05	1.85-3.56
CNO/H (×10^{-16})	7.43	4.94-28.5



Monte-Carlo results: correlations

Correlation coefficient between yield of isotope j (y_j) and rate of reaction k (x_k) rate:

$$C_{j,k} = \frac{\frac{1}{N}\sum_{i=1}^{N} y_{j;i}\, p_{k;i} - \bar{y}_j\, \bar{p}_k}{\sigma_j \sigma'_k}$$

$$\bar{y}_j = \frac{1}{N}\sum_{i=1}^{N} y_{j;i}$$

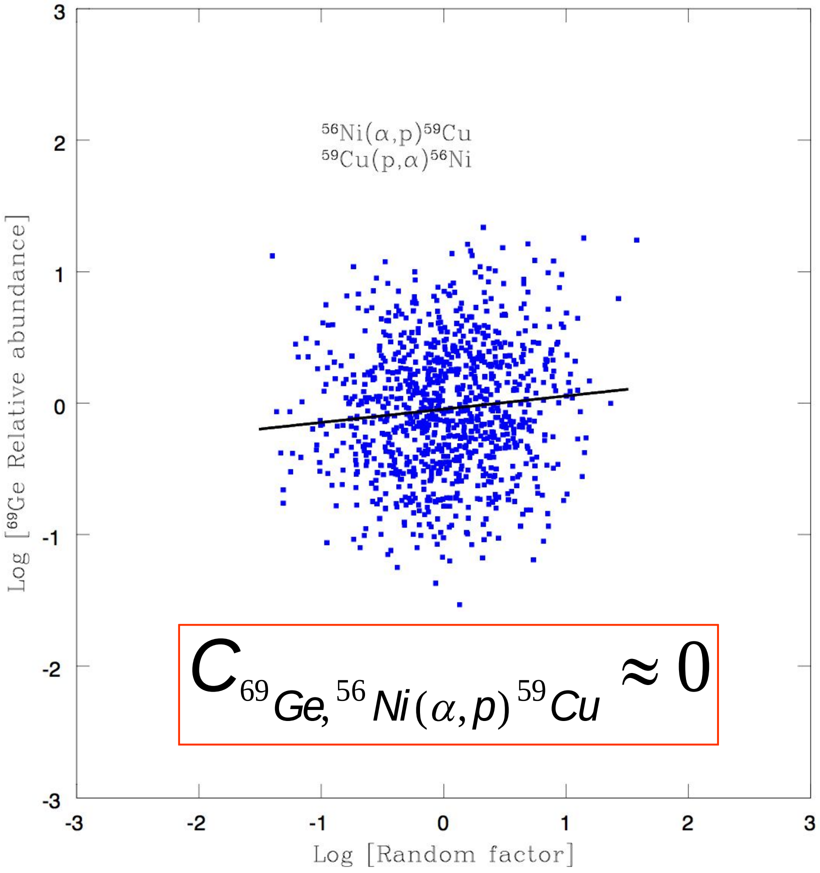
Mean and variance of y_j ($\bar{p}_k=0$ and $\sigma'_k=1$)

$$\sigma_j^2 = \frac{1}{N}\sum_{i=1}^{N}\left(y_{j;i} - \bar{y}_j\right)^2$$

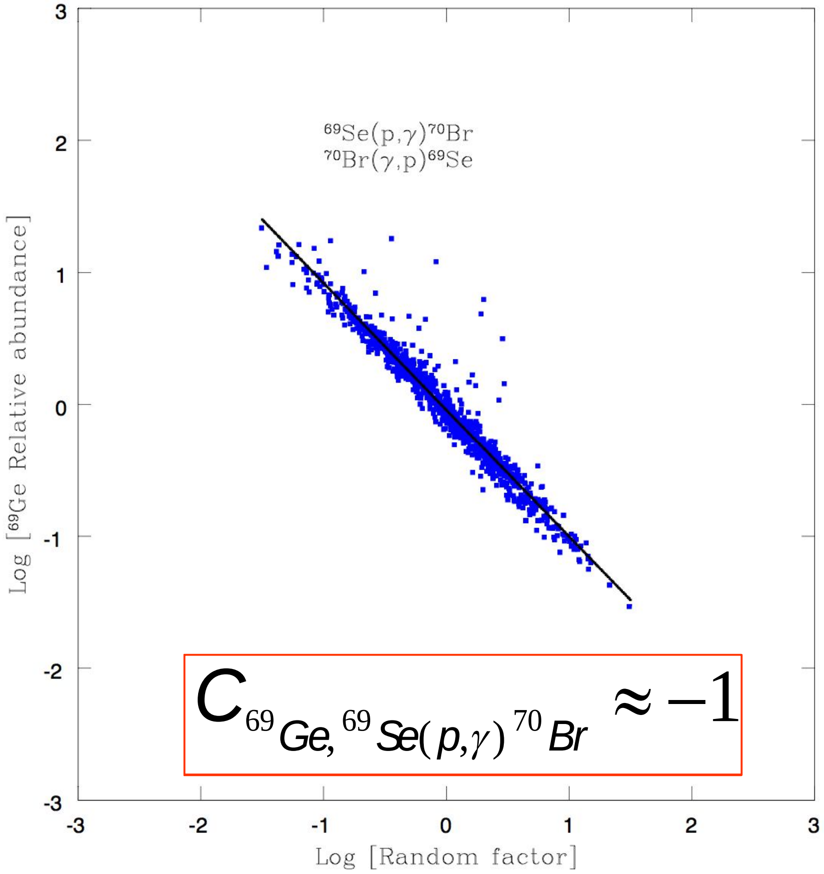
Monte-Carlo: example of correlations

« The Effects of Variations in Nuclear Processes
on Type I X-Ray Burst Nucleosynthesis »

[Parikh, Jose, Moreno & Iliadis 2008]



$$C_{^{69}Ge,\,^{56}Ni(\alpha,p)^{59}Cu} \approx 0$$



$$C_{^{69}Ge,\,^{69}Se(p,\gamma)^{70}Br} \approx -1$$

Correlations > 10%

^{4}He	
Reaction	C_{jk}
$1/\tau_n$	-0.9677
^{3}He(t,np)^{4}He	0.1151
D(d,n)^{3}He	0.1282
D(d,p)^{3}H	0.1296

^{3}He+T	
Reaction	C_{jk}
D(p,γ)^{3}He	0.6699
D(d,n)^{3}He	0.1640
D(d,p)^{3}H	-0.1897
^{3}He(d,p)^{4}He	-0.6841

D	
Reaction	C_{jk}
D(p,γ)^{3}He	-0.7790
D(d,n)^{3}He	-0.4656
D(d,p)^{3}H	-0.4082

^{7}Be+^{7}Li	
Reaction	C_{jk}
D(p,γ)^{3}He	0.4043
D(d,n)^{3}He	0.1547
^{3}He(d,p)^{4}He	-0.2232
^{3}He(α,γ)^{7}Li	0.7107
^{7}Be(n,α)^{4}He	-0.3057
^{7}Be(d,p)2^{4}He	-0.2079

Correlations > 10%

^{6}Li	
Reaction	C_{jk}
D(α,γ)^{6}Li	0.9835
^{6}Li(p,α)^{3}He	-0.1333

^{9}Be	
Reaction	C_{jk}
^{7}Li(^{3}He,p)^{9}Be	0.2820
^{7}Li(t,n)^{9}Be	0.8910

^{11}B+^{11}C	
Reaction	C_{jk}
D(p,γ)^{3}He	0.1081
^{3}He(α,γ)^{7}Li	0.1621
^{7}Be(α,γ)^{11}C	0.2188
^{11}C(n,α)2^{4}He	-0.9069

CNO	
Reaction	C_{jk}
^{12}B(p,α)^{9}Be	-0.1030
^{10}Be(p,α)^{7}Li	-0.2479
^{10}Be(α,n)^{13}C	0.2175
^{7}Li(t,γ)^{10}Be	0.1363
^{8}Li(α,n)^{11}B	0.1449
^{8}Li(t,n)^{10}Be	0.1958
^{10}Be(t,n)^{12}B	0.1139
^{13}C(d,α)^{11}B	-0.2378
^{10}Be(p,t)2^{4}He	-0.1297
^{7}Li(d,n)2^{4}He	-0.1806

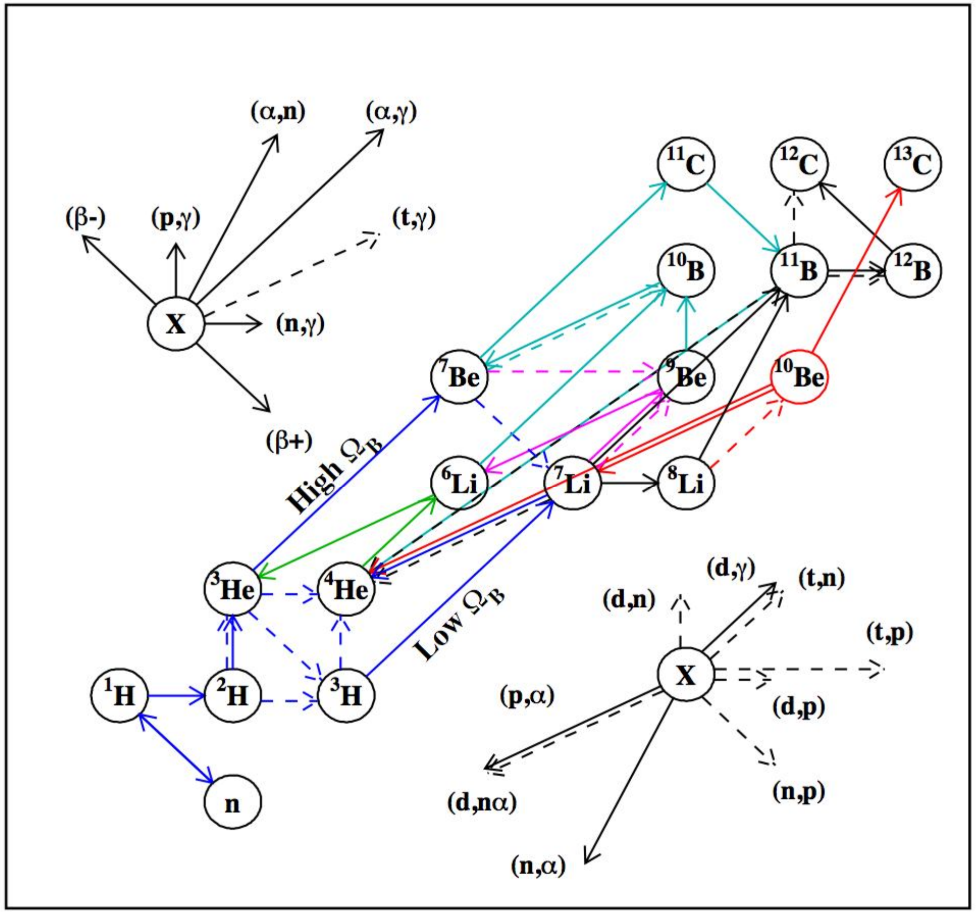
Known from the previous analysis

Combinatorial analysis

For the 6 reactions change the rate by factor 10^{-n}, 10^{0} and 10^{+n} (e.g. n=2), i.e. $3^{6}=729$ combinations

Reaction	CNO/H > 10^{-13} combinations								
$^{10}\mathrm{Be}(p,\alpha)^{7}\mathrm{Li}$	-	-	-	-	-	-	-	-	-
$^{10}\mathrm{Be}(\alpha,n)^{13}\mathrm{C}$	+	+	+	+	+	+	+	+	+
$^{7}\mathrm{Li}(t,\gamma)^{10}\mathrm{Be}$	-	-	-	0	0	0	+	+	+
$^{8}\mathrm{Li}(t,n)^{10}\mathrm{Be}$	+	+	+	+	+	+	+	+	+
$^{10}\mathrm{Be}(t,n)^{12}\mathrm{B}$	-	0	+	-	0	+	-	0	+
$^{10}\mathrm{Be}(p,t)2^{4}\mathrm{He}$	-	-	-	-	-	-	-	-	-

New path of BB nucleosynthesis to CNO?



Shopping list for nuclear physicists

Precision cosmology ?

- ^{4}He : Neutron lifetime controversy
- D : D/H at ± 1.6% (!?!?) *[Cooke+ 2014]* what about ^{2}H(p,γ)^{3}He, ^{2}H(d,n)^{3}He, ^{2}H(d,p)^{3}H rates (sensitivity: -0.32 to -0.54) ?
- ^{7}Li : The unsolved lithium problem
  - New conventional ^{7}Be destruction channel or neutron source ???
  - Reduce uncertainties on ^{7}Be(n,α) ^{4}He, ^{3}He(α,γ)^{7}Be rates
  - Spallation reactions for relic decay (Friday)
- CNO: Explore new paths
  - ^{10}Be(p,α)^{7}Li, ^{10}Be(α,n)^{13}C, ^{8}Li(t,n)^{10}Be, ^{10}Be(p,t)2^{4}He