HIRSCHEGG 2013: ASTROPHYSICS AND NUCLEAR STRUCTURE

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2H(d,p)3H and 2H(d,n)3He reaction rates at astrophysical energies

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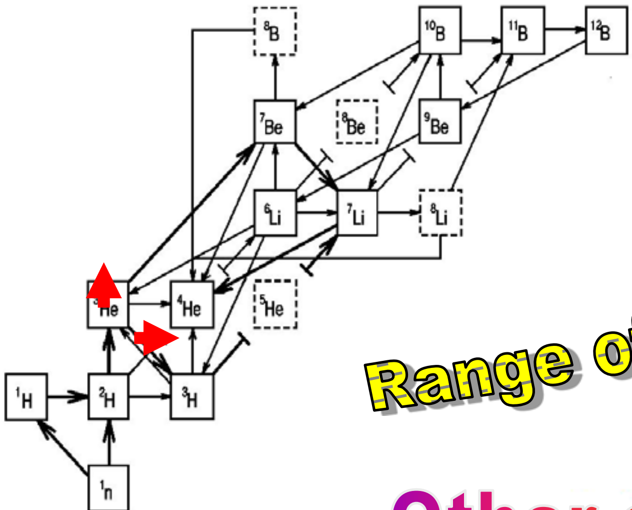
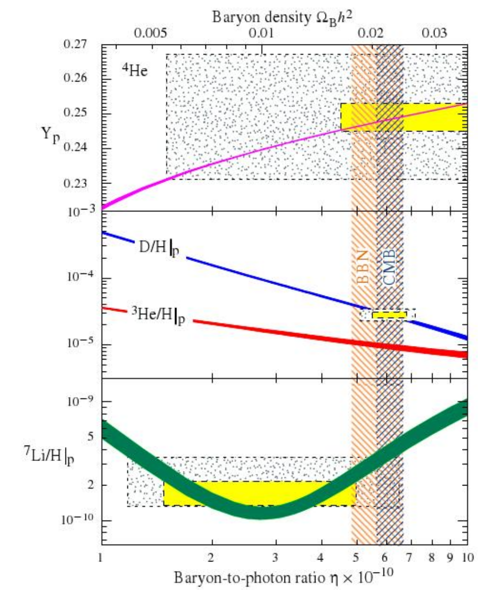
2H+2H reactions in the primordial nucleosynthesis

$^2H(d,p)^3H$ and $^2H(d,n)^3He$

$T \approx 10^9 \div 10^{11}$ K – 0.1÷10 MeV t ≈ $10^2 \div 10^3$ s



Range of interest: 50-350 keV



Other contexts of interest

- In the *Pre Main Sequence* phase (PMS) of the stellar

- In the future fusion power plants: nuclear energy production with inertial confinement

Range of interest : 0-30 keV

Status of art of the 2H+2H reactions

Prominent data sets for both $^2H(d,p)^3H$ and $^2H(d,n)^3He$

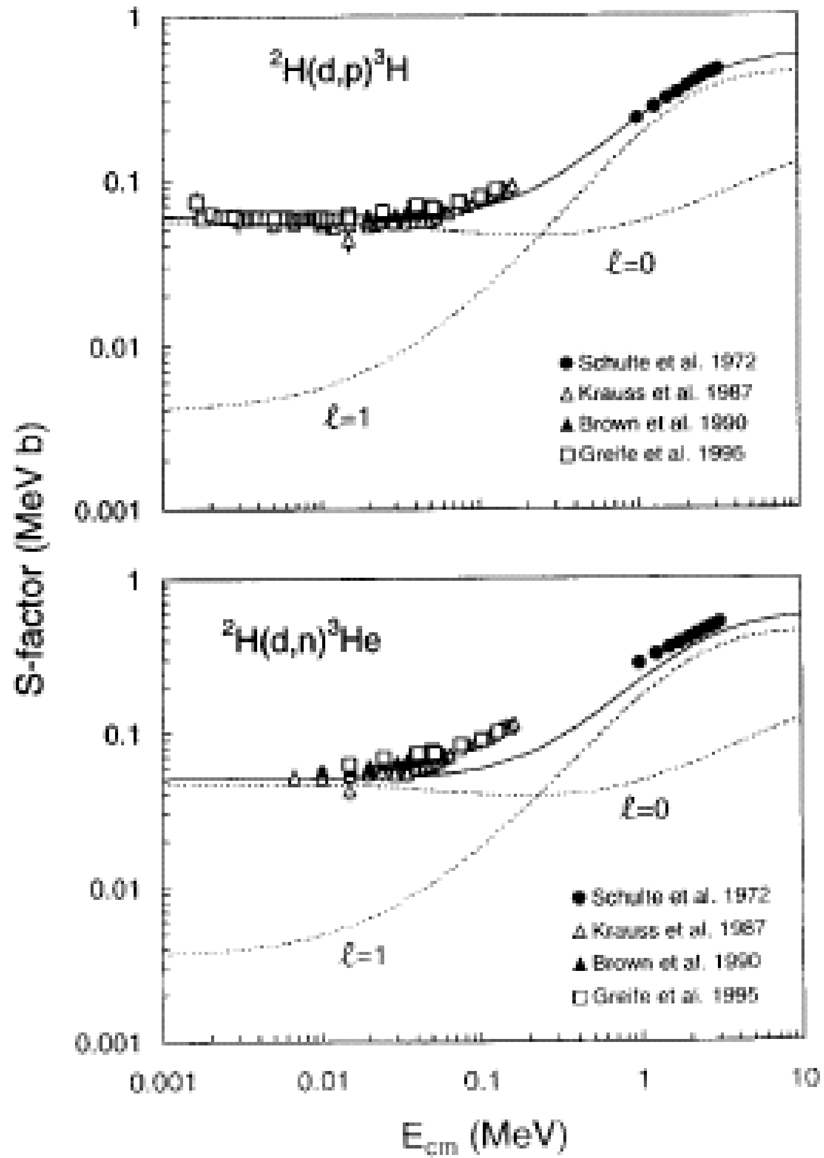
Open problems:

Missing data in the higher energy relevant BBN region: E_{cm} = 50 – 350 keV

Electron screening in the ultra-low energy region below 10 keV: almost twice the adiabatic limit (14 eV)

Laboratory electron screening different from that of stellar plasma
→Screening should be removed to assess the reaction rate correctly

→Need to get the bare nucleus S(E) factor



C. Angulo and P. Descouvemont (NPA 639 (1998) 733)

Trojan Horse Method

Basic principle: astrophysically relevant two-body σ from quasi- free contribution of an appropriate three-body reaction

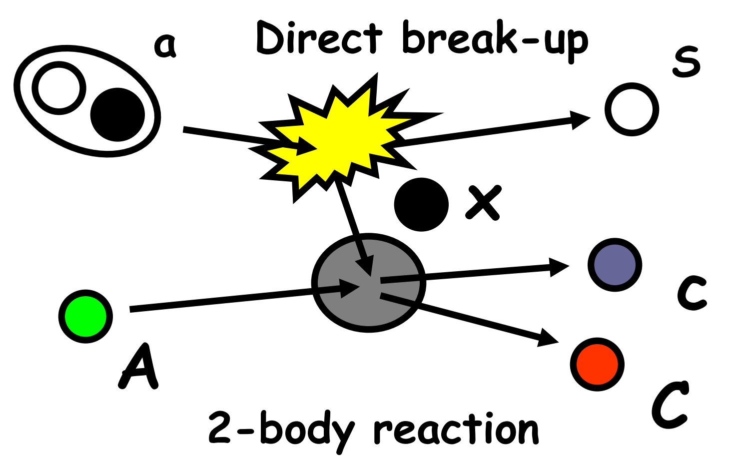
$$A + a \rightarrow c + C + s \quad \rightarrow\rightarrow\rightarrow \quad A + x \rightarrow c + C$$

a: x ⊕ s clusters

Quasi-free mechanism

✓ only *x* - A interaction

✓ *s* = spectator (E_s~0)



$E_A > E_{Coul} \Rightarrow$ <u>NO Coulomb suppression</u>

<u>NO electron screening</u>

$E_{q.f.} = E_{Ax} - B_{x\text{-}s}$ → $E_{q.f.} \approx 0$!!!

plays a key role in compensating for the beam energy

In PWIA

$$\sigma_3 \propto KF|\Phi(p_s)|^2 \sigma_2$$

C. Spitaleri *et al., Phys. Rev. C 63, 005801 (2001)*
A.Tumino *et al., Phys. Rev. Lett. 98, 252502 (2007)*

THM experiment

$^{2}H(d,p)^{3}H$ $^{2}H(d,n)^{3}He$ using ^{3}He as TH nucleus

d-d relative energy range: from 2 keV up to 1.5 MeV

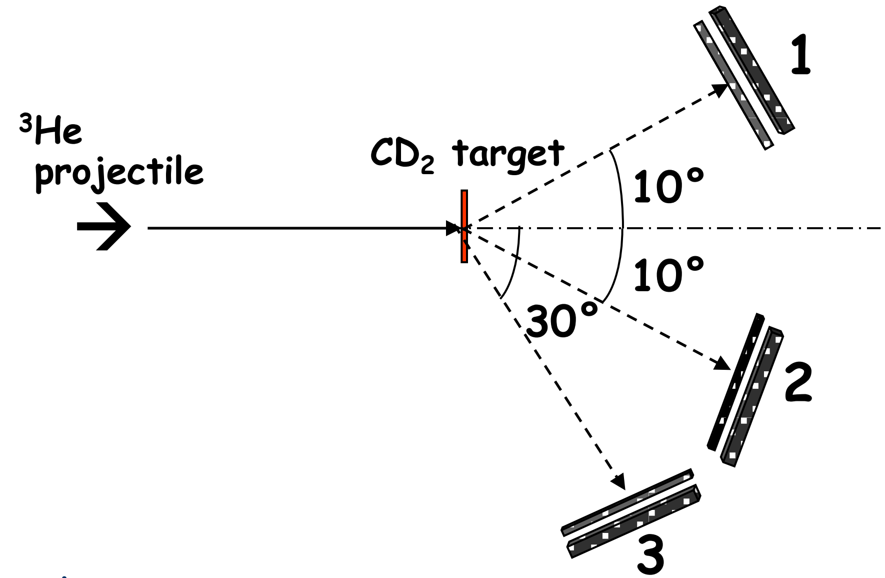
Aim:

* Astrophysical factor throughout the relevant region and up, in order to have a wide energy range to be joint with available higher energy data (for the integral to converge at the relevant BBN temperature). This ensures an accurate calculation of the reaction rate

*Available unscreened data below 10 keV, needed for studying fusion dynamics in plasmas

Experimental set up

Nuclear Physics Institute of Academy of Science in Rez near Prague, Czech Republic



^{3}H/^{3}He – p concidences (1-2 and 1-3)

For the first time detection of the proton spectator!

Advantages: no contribution from target break-up; dector granularity ensured → angular resolution of the order of 0.1°; 100% detection efficiency

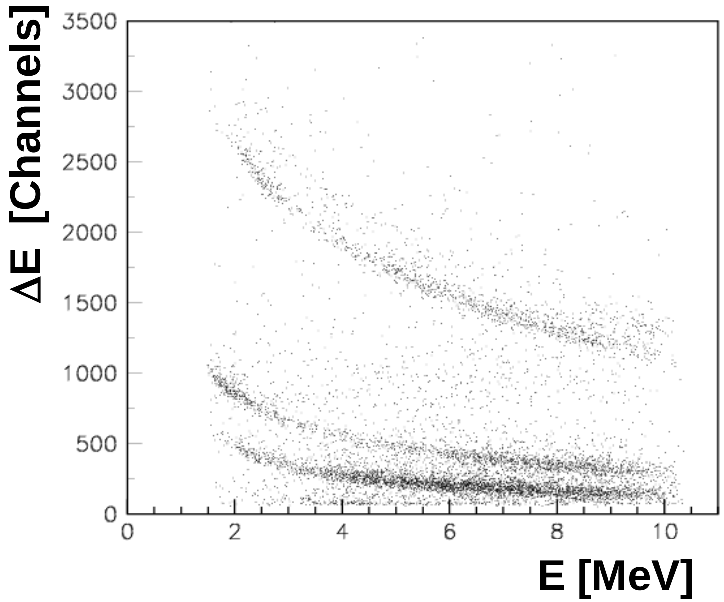
Not possible with neutron detectors

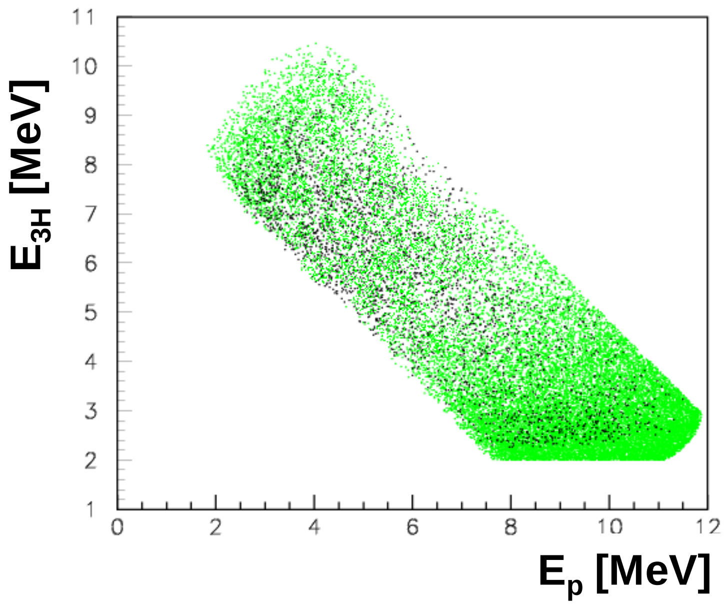
^{2}H(^{3}He,n ^{3}He)p ⟶ ^{2}H(d,n)^{3}He

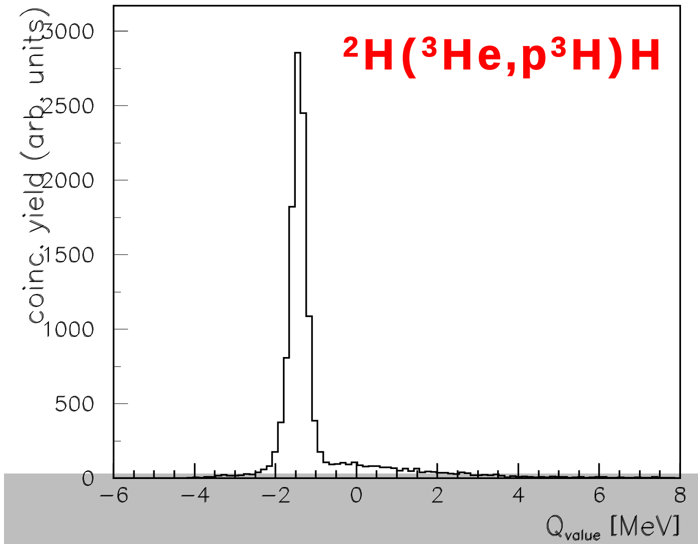
^{2}H(^{3}He,p ^{3}H)p ⟶ ^{2}H(d,p)^{3}H

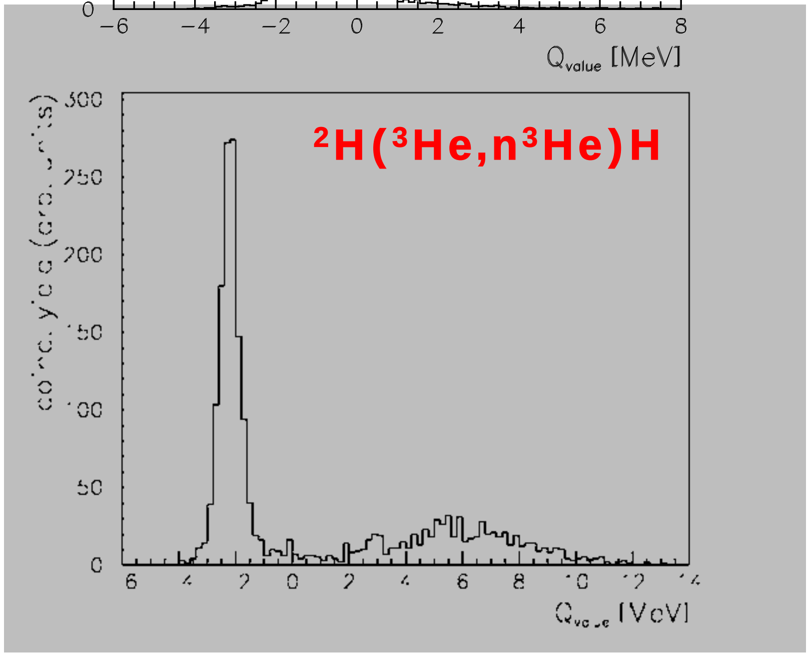
Data analysis follows standard procedure

Selection of the 3-body channels





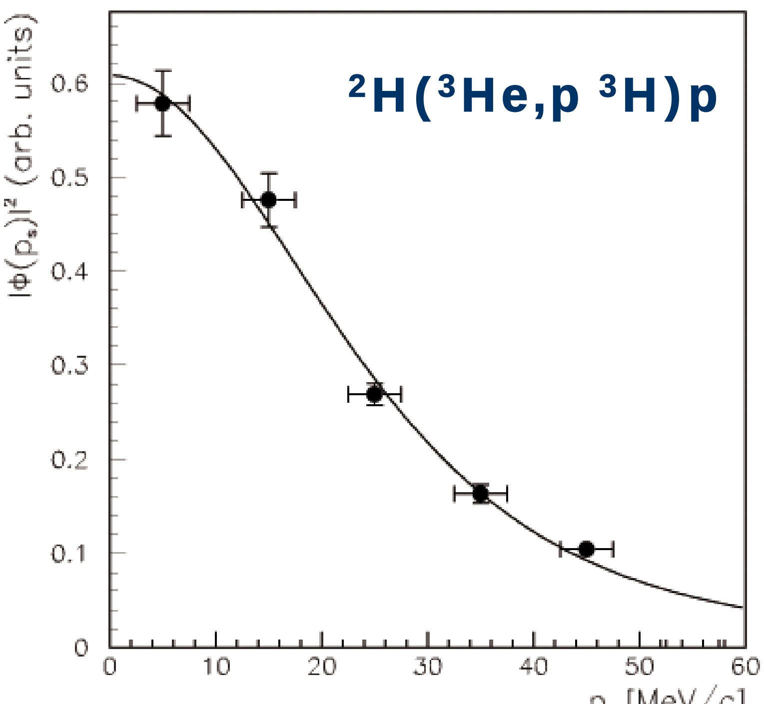


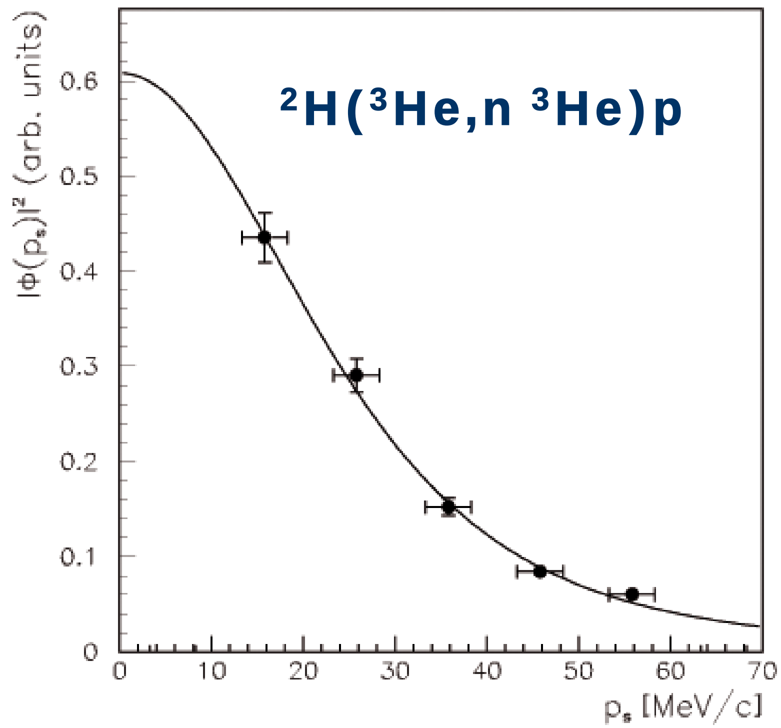


Selection of the quasi-free mechanism

Comparison between the experimental momentum distribution and the theoretical one (for ^{3}He given by the Eckart function) → QF mechanism

$$|\Phi(\overrightarrow{p_s})|^2 \propto \frac{\dfrac{d^3\sigma}{d\Omega_t d\Omega_p dE_p}}{(KF)\left(\dfrac{d\sigma_{dd}}{d\Omega}\right)^N}$$





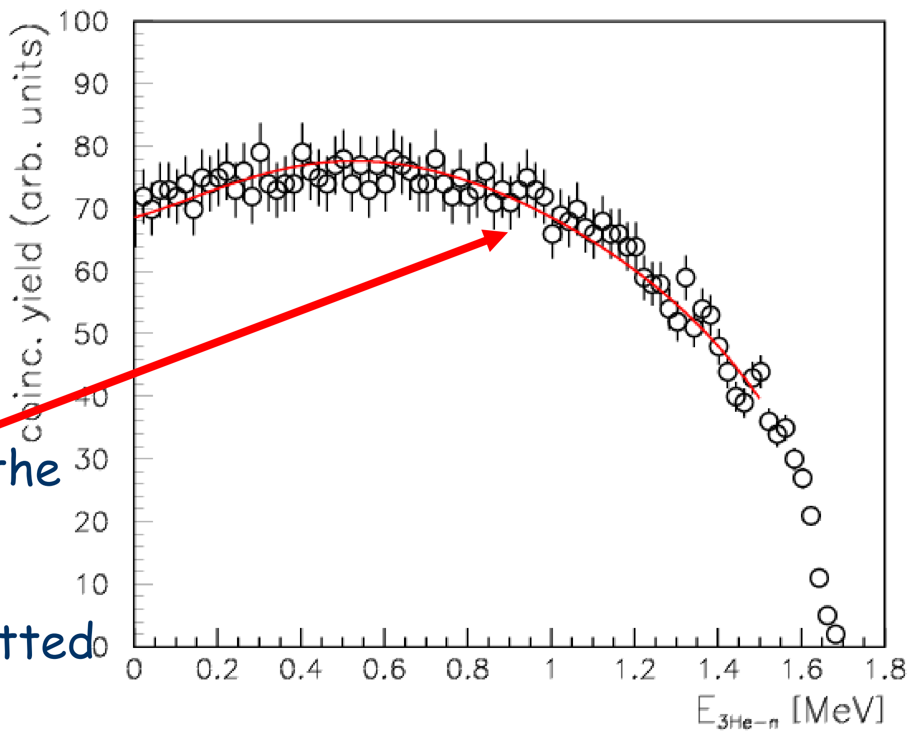
Extraction of the two-body cross section (1)

R-matrix by C. Angulo and P. Descouvemont (NPA 639 (1998) 733)
Inclusion of both l=0 and l=1 components in the cross section, whose energy dependence is very well represented by their penetrabilities

$$\frac{d\sigma}{dEd\Omega}(d+d\rightarrow C+c)=\frac{1}{E_{cm}}\sum_{l=0,1}C_lP_l^2T_l(k_{dd}R)$$

$$\frac{d\sigma_3}{dE}=KF|\varphi(p_s)|^2\frac{d\sigma}{dE}$$

Free parameters are scaling factors C_l and channel radius R: determined from the fit of the theoretical distributions to the measured coincidence yields



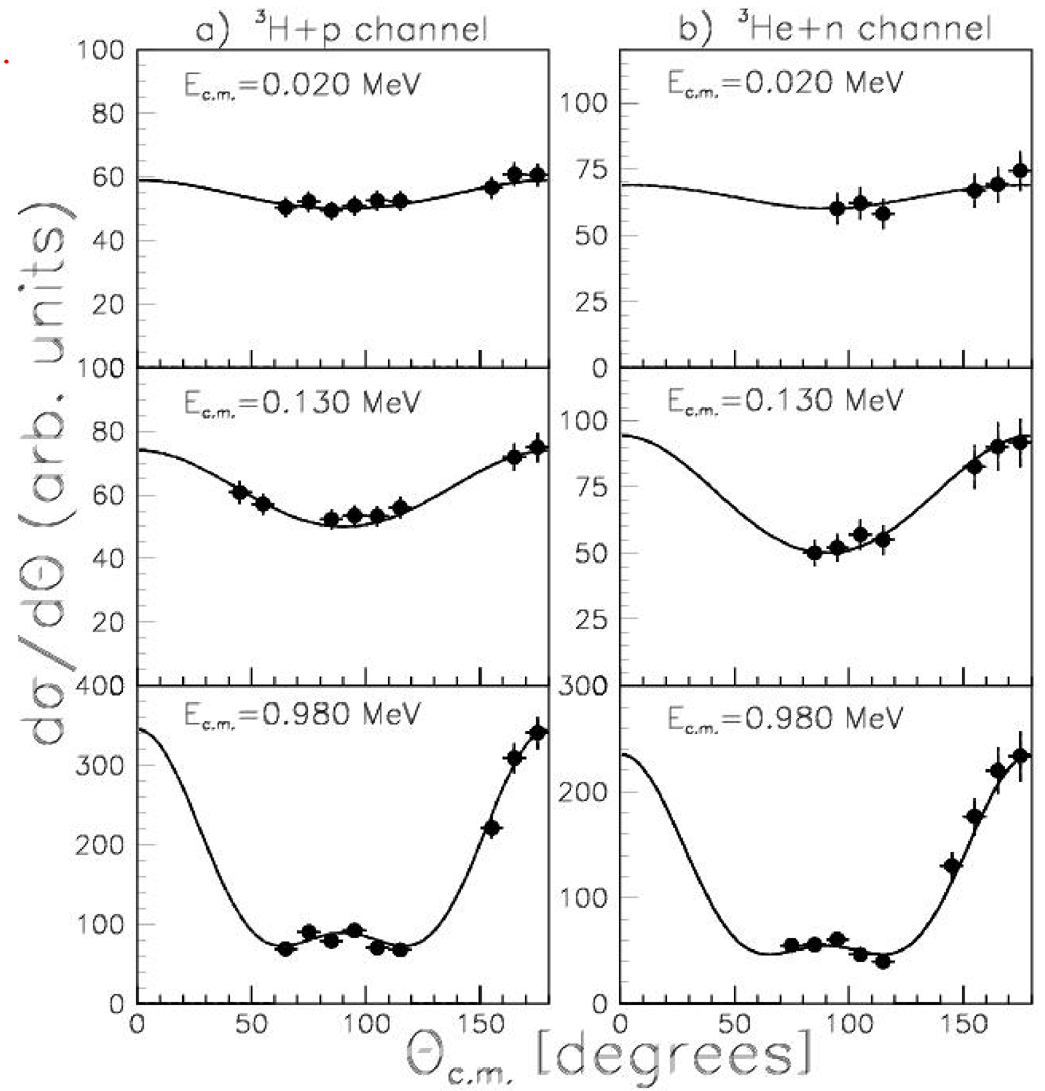
Two coincidence yields per channel to be fitted at the same time

Extraction of the two-body cross section (2)

$$d\sigma/d\theta_{c.m.} = \frac{\text{Coinc. yield at fixed } \Delta E_{c.m.}}{KF\ |\phi(p_s)|^2}$$

Solid lines: fit of direct data by

A. Krauss *et al.*, Nucl. Phys. A465, 150 (1987)
R.L. Schulte *et al.*, Nucl. Phys. A192, 609 (1972)

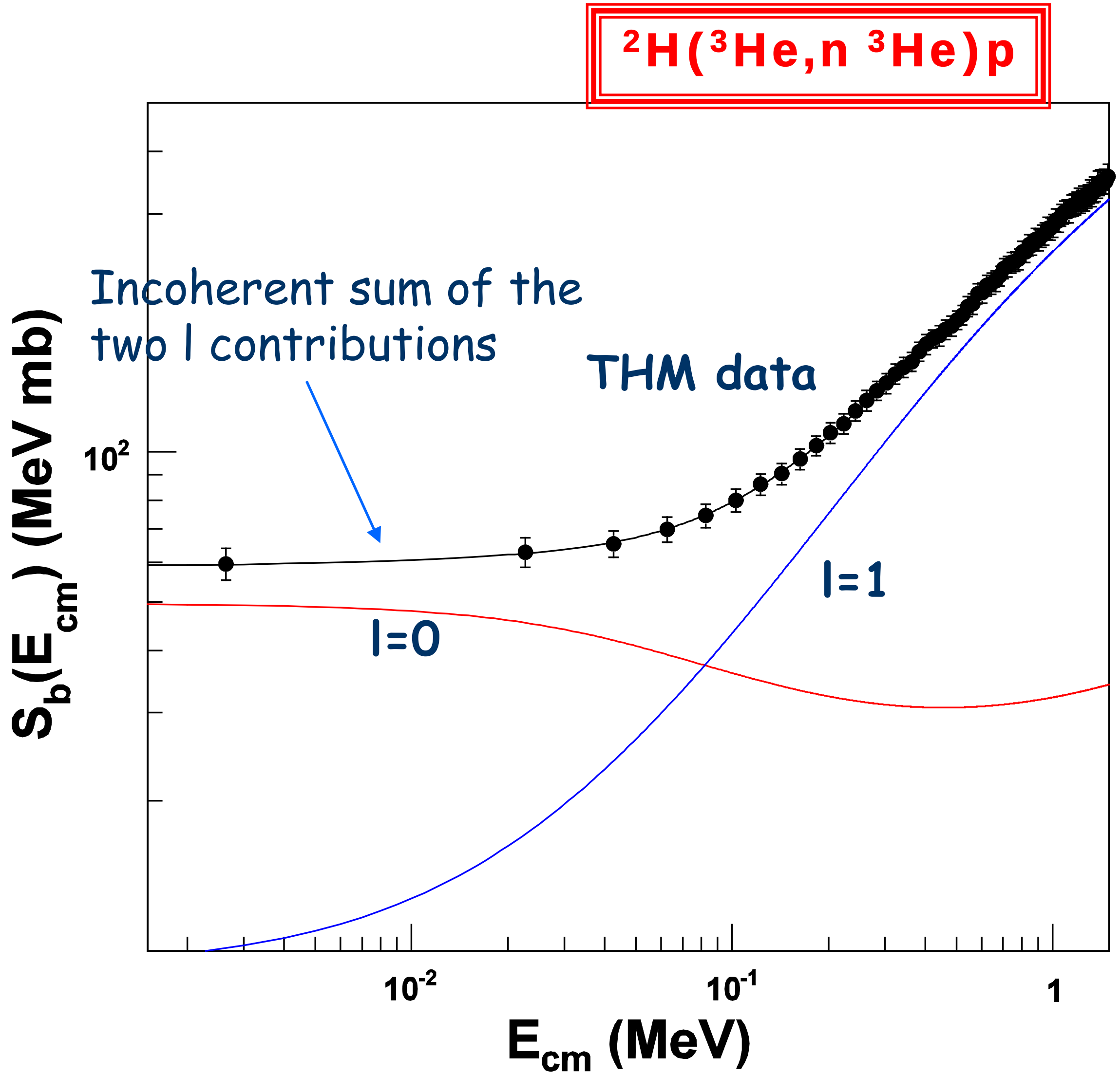


Extraction of the two-body cross section (3)

$$S(E) = \sigma(E) E e^{2\pi\eta}$$

With the deduced scaling ratio of the s and p waves, →S(E) factor after normalization to direct data

Direct data have different accuracies → weighted normalization to available direct data from 15 keV to 1.5 MeV



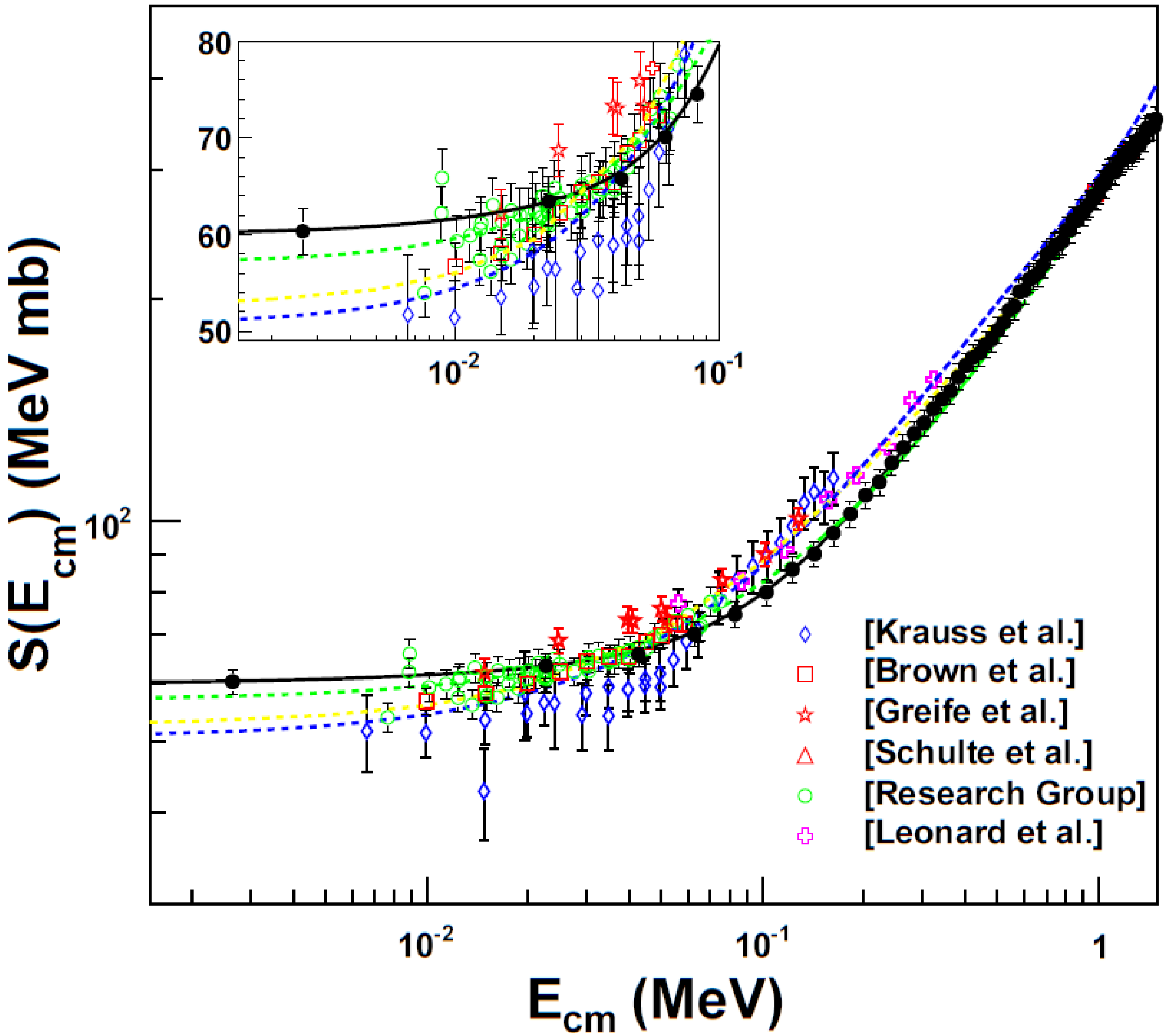
Extraction of the two-body cross section (4)

Comparison between the incoherent sum (black line) and direct data (colored symbols)

Yellow line: polynomial expansion reported in the NACRE compilation
C. Angulo et al., NPA 656, 3 (1999)

Blue line: from
R.H. Cyburt, PRD 70, 023505 (2004)

Green line: from
P. Descouvement et al., At. Data Nucl. Data Tables 88, 203 (2004)

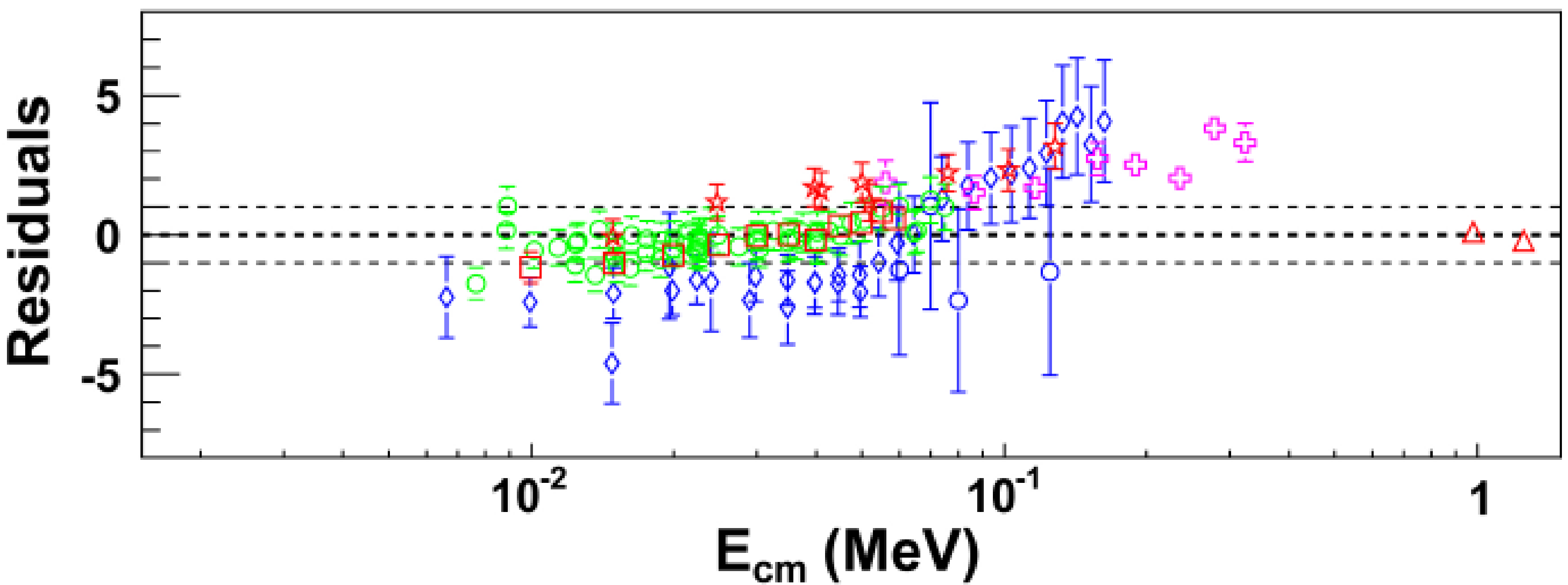


A. Tumino et al., Few Body Syst. 50 (2011) 323
A.Tumino et al., Phys. Lett. B 700 (2011) 111

Residual scattering in the direct data about the THM theoretical curve divided by the weighted dispersion σ (4.24 keVb for the 3He+n channel)

Dashed horizontal lines: 1-sigma error bars. These plots help to visualize the trends of the deviation from the normalized theoretical *S(E) factor for each of the direct data* sets.

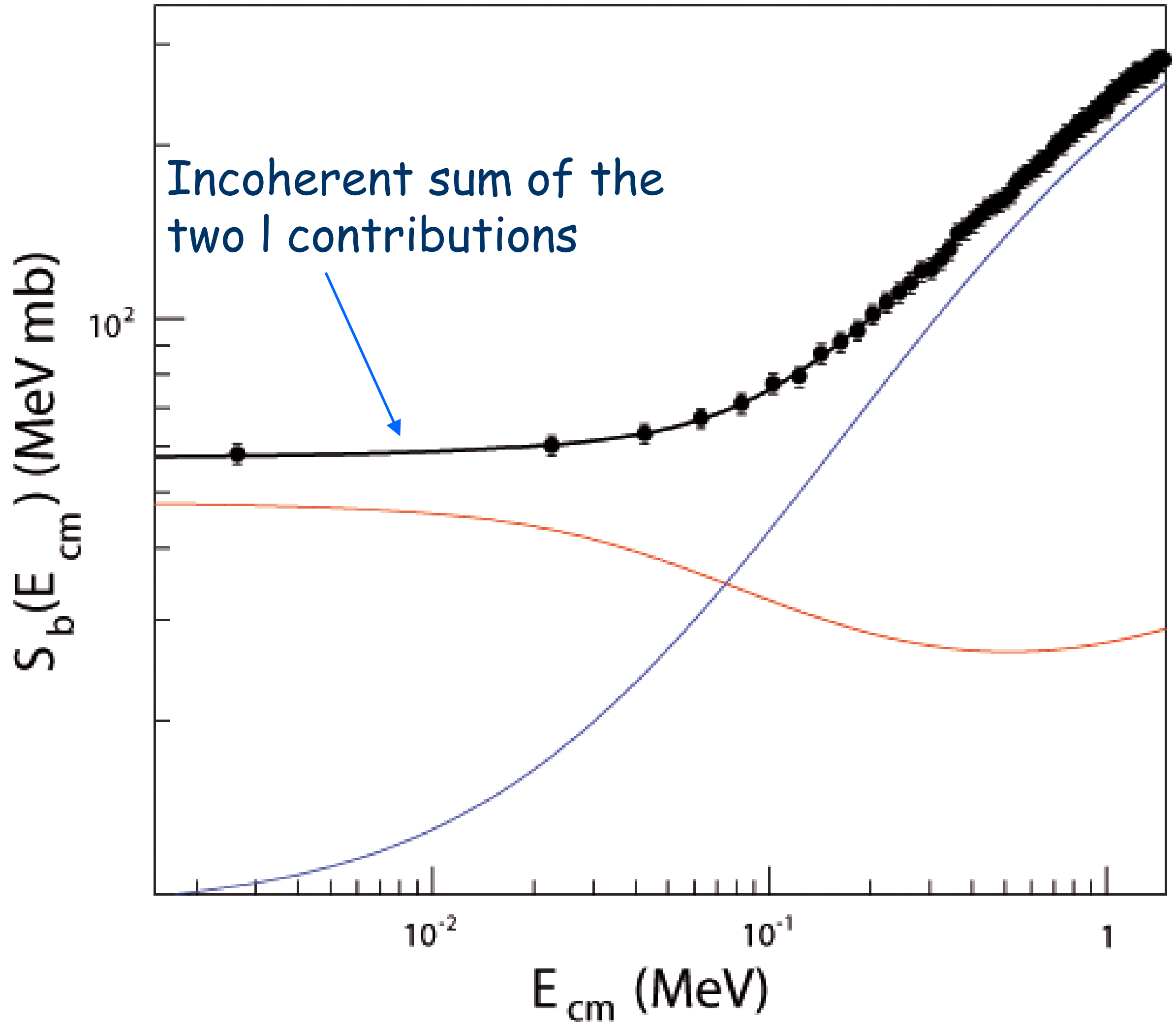
σ=4.24 keVb



Extraction of the two-body cross section (3)

$^{2}H(^{3}He,p\ ^{3}H)p$

$$S(E) = \sigma(E) E e^{2\pi\eta}$$



Extraction of the two-body cross section (4)

Direct data at 15 keV normalized to the THM bare S(E) and fitted with

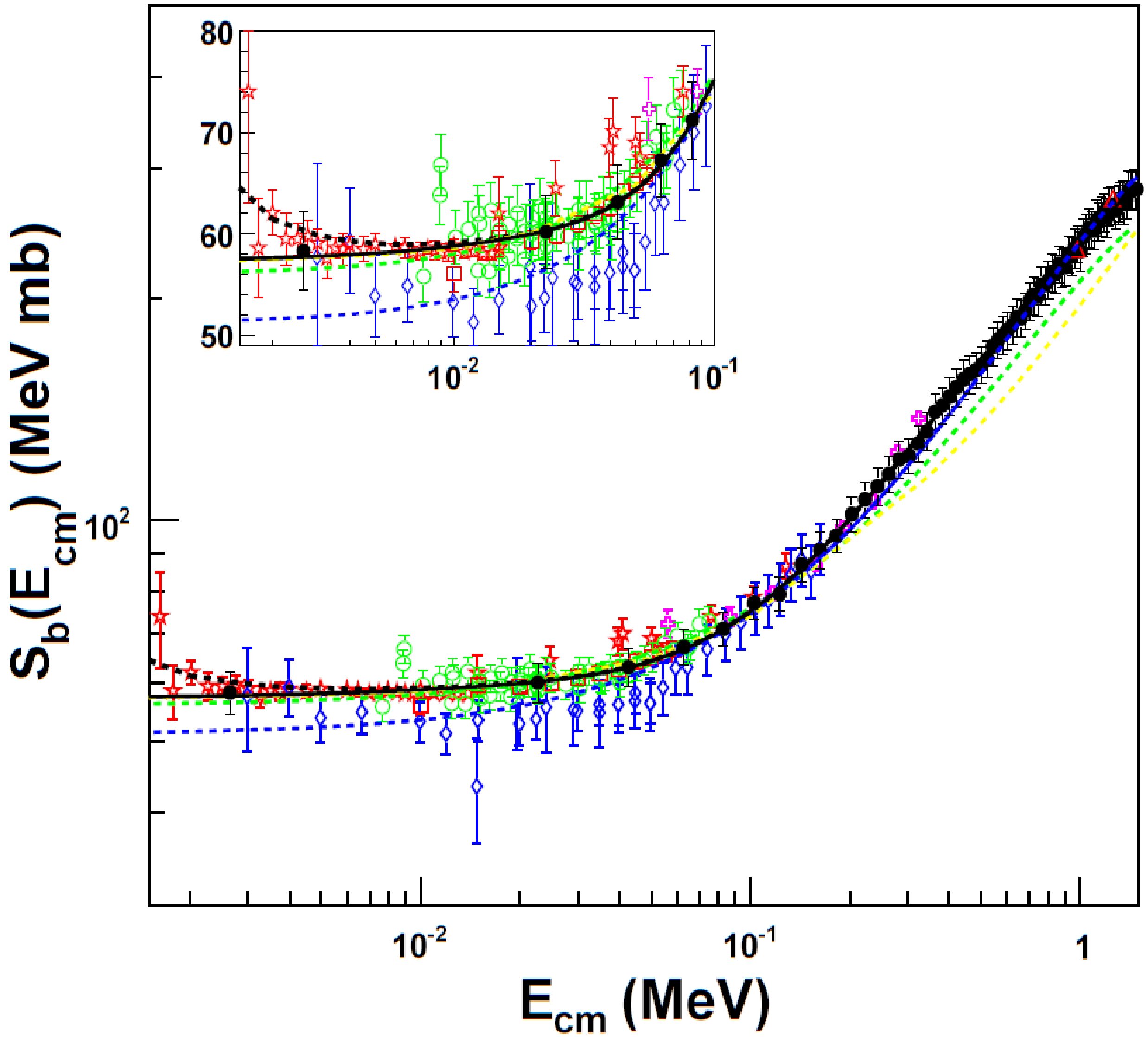
$f_{lab}(E)=\exp(U_e/E)$
(Assenbaum, H.J. et al., 1987, Z. Phys. A, 327, 461)

with the screening potential U_e as free parameter:

$\rightarrow U_e = 13.2 \pm 1.8$ eV

In agreement with the adibatic limit

$^2H(^3He,p\,^3H)p$

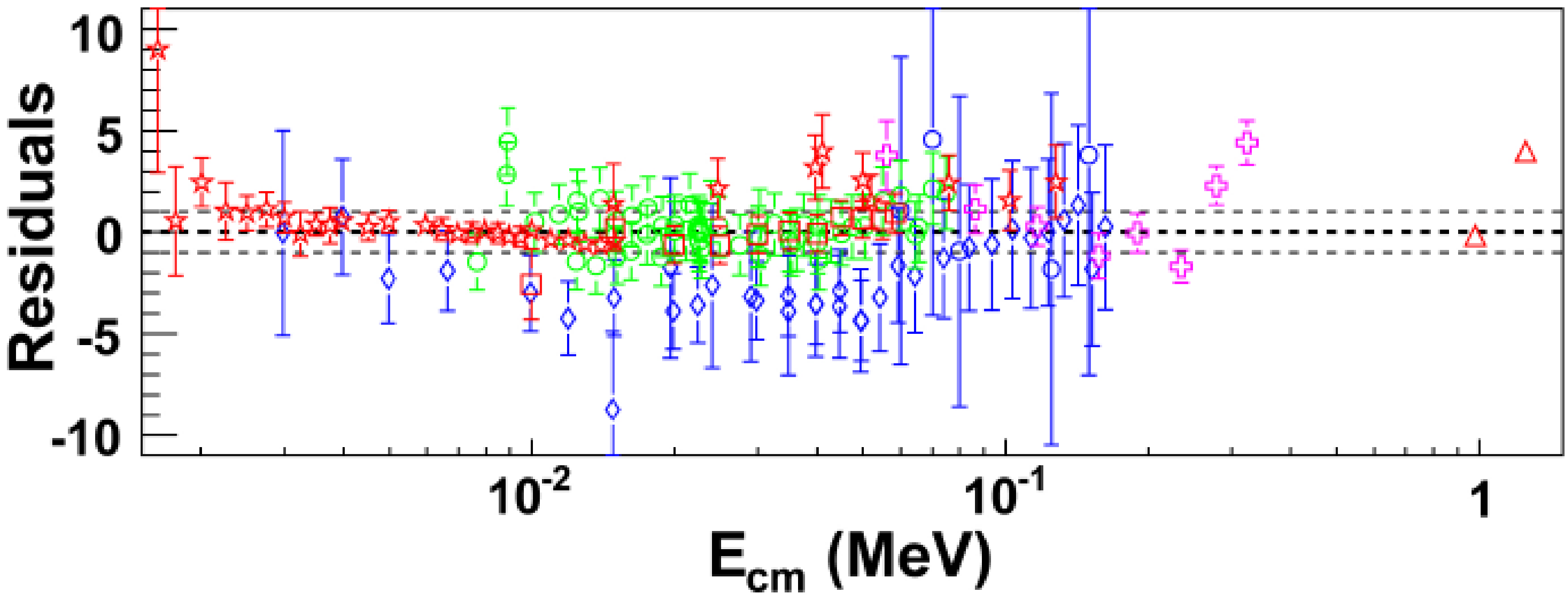


A. Tumino et al., Few Body Syst. 50 (2011) 323
A.Tumino et al., Phys. Lett. B 700 (2011) 111

Residual scattering in the direct data about the THM theoretical curve divided by the weighted dispersion σ (1.82 keVb for the ^3H+p channel)

Dashed horizontal lines: 1-sigma error bars

σ=1.82 keVb



Tentative estimate of the screening potential from d+d->n+ ^{3}He

Ingredients:

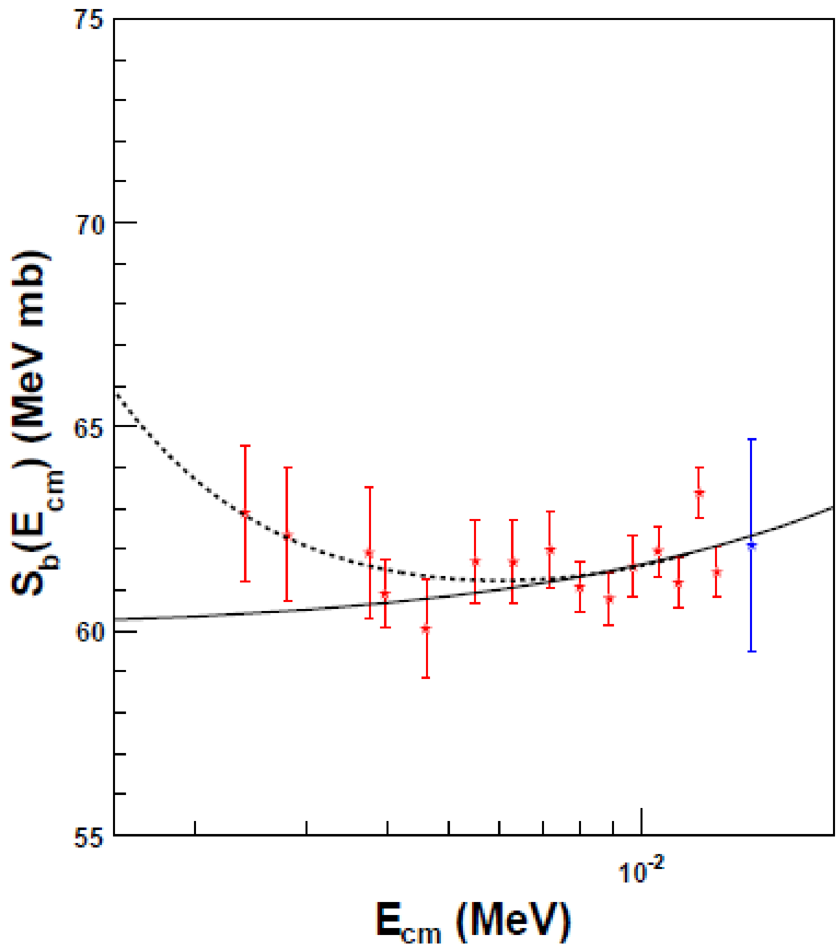
-σ_{pt} /σ_{n3He} from Greife et al. 1995, with σ_{n3He} further corrected by a factor 1.02 to be consistent with their data in far geometry

-THM bare S(E) factor

- screening function with U_e as free parameter

→U_e = 11.7 ± 1.6 eV

in agreement within experimental errors with the previous estimate from d+d→t+p



Some numbers

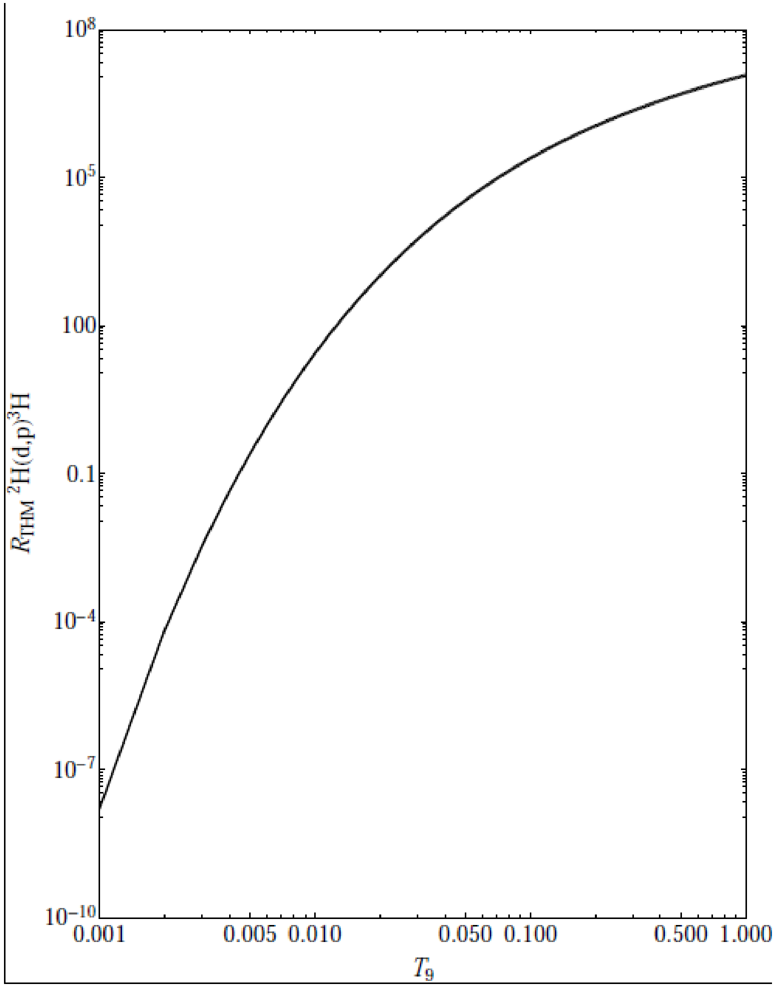
S(0) for ^{3}He+n [keV b]	ΔS(0) [keV b]	Ref.
60.1	1.9	Present results from THM
53 keV		C. Angulo et al. (NACRE)
50.67 keV		R.H. Cyburt
57.2 keV	3.5	P. Descouvemont et al.

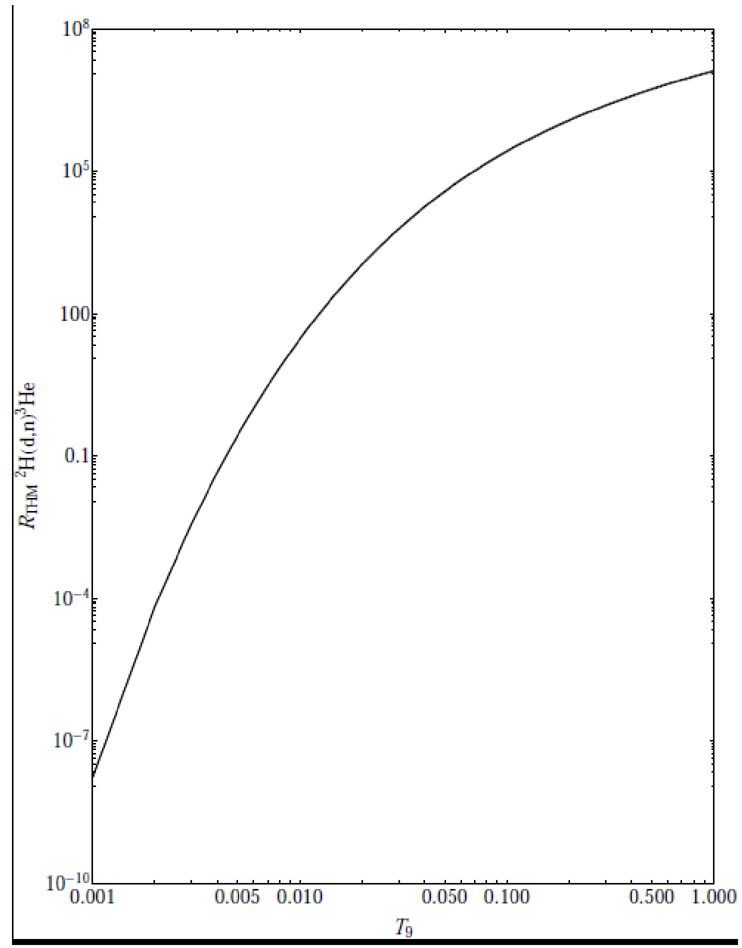
S(0) for ^{3}H+p [keV b]	ΔS(0) [keV b]	Ref.
57.4	1.8	Present results from THM
56 keV		C. Angulo et al. (NACRE)
51.15 keV		R.H. Cyburt
57.1 keV	1.8	P. Descouvemont et al.

However, none of the lines provide the correct slope of the THM data throughout the investigated region, with deviations by more than 15%.

$S(0)_{3H+p}S(0)_{3He+n}$ = 0.96±0.04 in agreement with prediction by A. Bonasera and S. Kimura: this little difference in the *S(0) values* is attributed to the different *Q -values of the two mirror d + d fusion* channels.

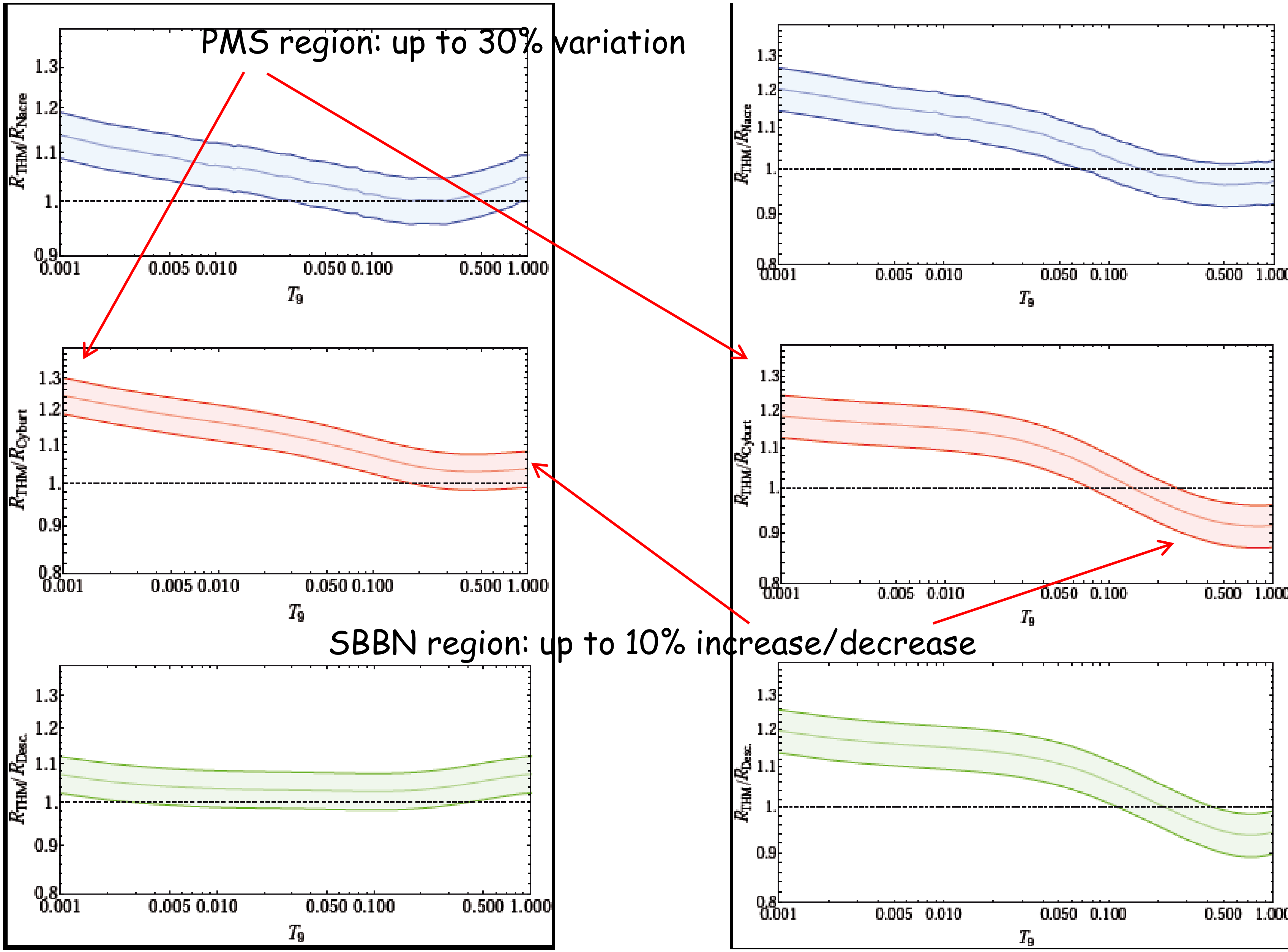
Reaction rates





A.Tumino et al., submitted to APJ

THM results compared with the calculated reaction rates available in the literature



Conclusions

$^{2}H(d,n)^{3}He$ and $^{2}H(d,p)^{3}H$ via $^{2}H(^{3}He,n\ ^{3}He)^{1}H$ and $^{2}H(^{3}He,p\ ^{3}H)^{1}H$: first experiments where the spectator is detected

S(E) factor and reaction rates determined from 2 keV up to 1.5 MeV, throughout the energy region of interest for pure and applied physics and up

Estimate of screening potential from $^{3}H+p$: $U_e = 13.2 \pm 1.8$ eV
Tentative estimate from $^{3}He+n$: $U_e = 11.7 \pm 1.6$ eV
…both in agreement with the adiabatic limit

… next step → astrophysical implications: applying recent abundance sensitivity studies (Coc & Vangioni 2010), the new rates imply a 8% decrease in the ^{7}Li abundance … solving the Li depletion problem ?!

PMS: up to 30% variations in the rates and new investigation of fusion dynamics in plasmas

Thank you!

The collaboration

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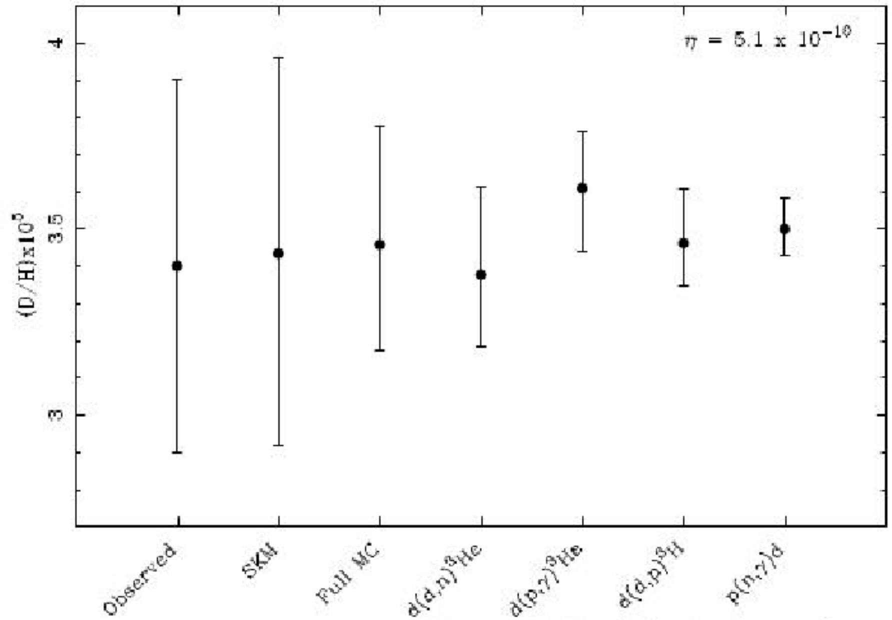
Deuterium and uncertainty of η



Uncertainty on η from deuterium:
50 % observative
50 % cross section uncertainty of reactions involving deuterium.

[Smith et al., 1993]