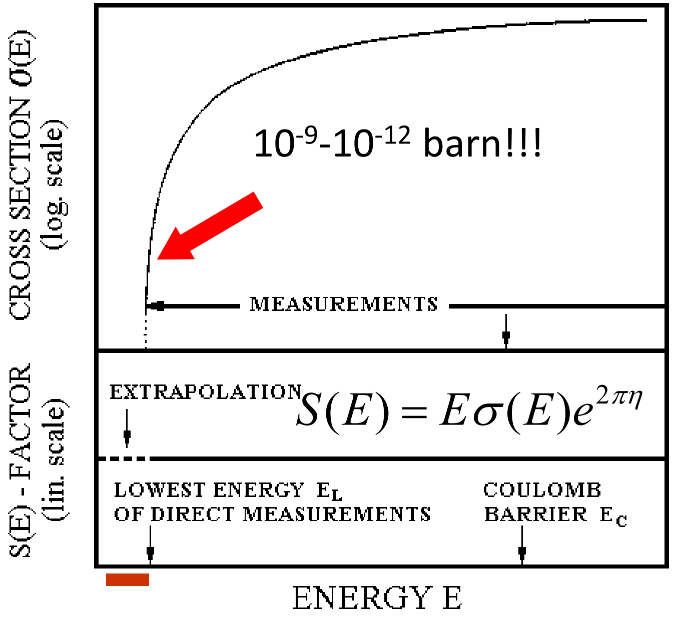
Roberta Spartà

Trojan Horse Method for nuclear astrophysics

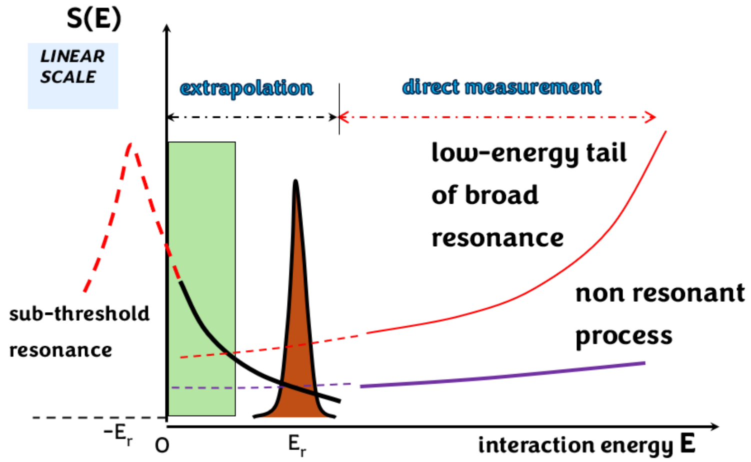
Why we need the indirect methods?

Problems of cross sections measurements at energies of interest for astro → LOW (keV)! While CB~MeV

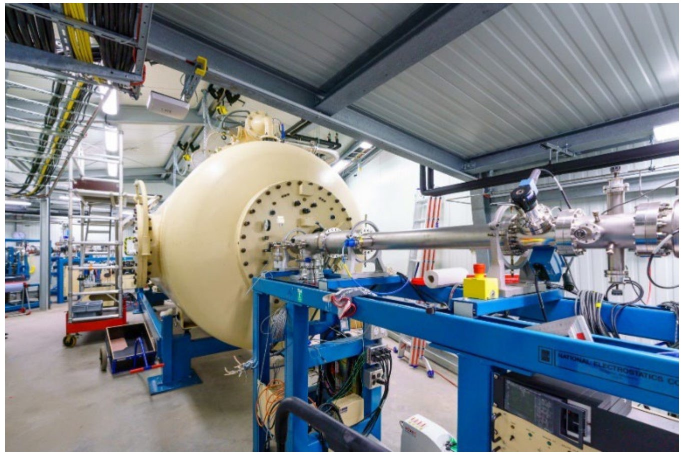


reactions occur through <u>TUNNEL EFFECT</u>

tunneling probability P ∝ exp(-2πη)



Direct measurements with high S/N



Increase the number of detected particles

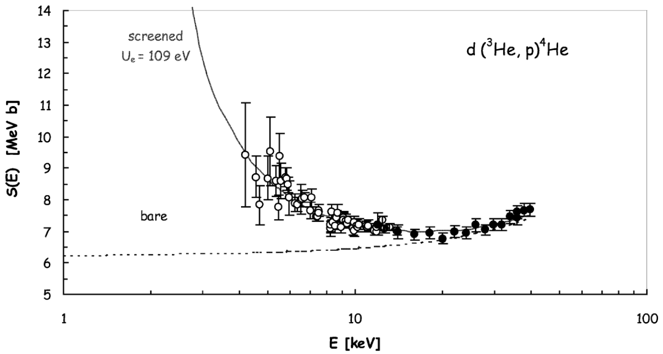
(4π detectors or new accelerators with high intensity beam)

Reduce the background

(underground physics or Recoil Mass Separator)

Few events… + **electron screening** cannot be avoided!

[Aliotta et al 2001] *#oldbutgold*



Plasma screening ≠ Lab screening

Then… indirect methods!

NEW METHODS ARE NECESSARY

- to measure cross sections at never reached energies

- to retrieve information on electron screening effect when ultra-low energy measurements are available

INDIRECT METHODS ARE NEEDED

complementary to the direct ones

THM description: overcoming the CB

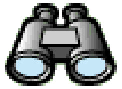
Main idea: to get the 2-body reaction σ selecting the quasi-free mechanism from the σ of a properly chosen 3-body reaction

x+B→C+D
The binary reaction of interest

A+B→C+D+S
The 3-body reaction you perform in the lab

A is the Trojan Horse nucleus

x+S

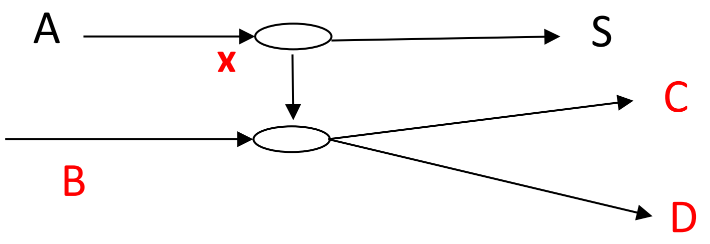


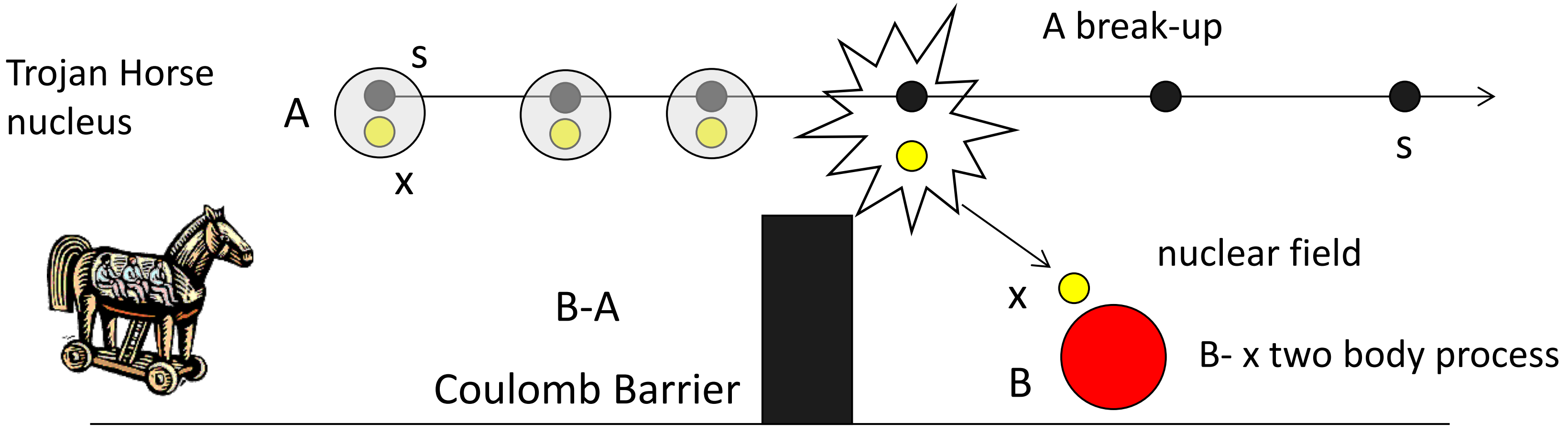
THM description: overcoming the CB

$E_A > (E_{AB})_{\text{Coulomb Barrier}}$

The nucleus A can be brought into nuclear field of nucleus B and the cluster x induces the reaction

$x + B \rightarrow C + D$





Nuclear “city walls”

Coulomb effects and electron screening are negligible

THM description: going to low energies

Beyond the walls!
But now… at which energy the 2-body reaction takes place?
(remember: very low energies for astrophysical interest)

$$E_{qf} = E_{xB} - B_{x\text{-}S} = E_{cD} - Q_{2b}$$

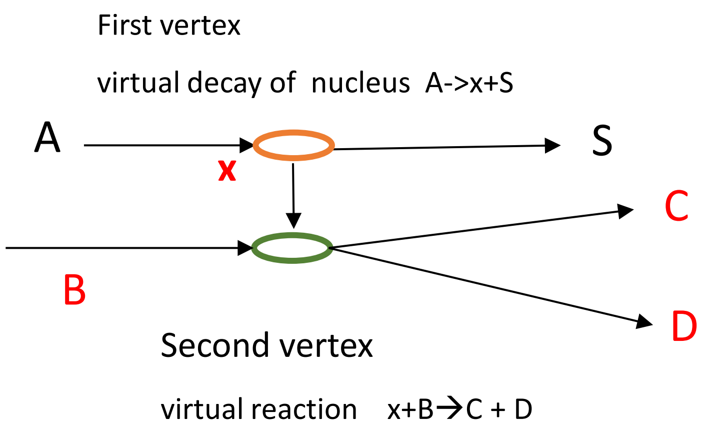
E_{xB} is the beam energy in the center of mass of the two body reaction

$B_{x\text{-}S}$ binding energy of the two clusters inside the Trojan Horse

plays a key role in compensating for the beam energy

➡ *under proper kinematical conditions*

THM description: QF mechanism



QF mechanism: the spectator in the exit channel keeps the same momentum inside the TH nucleus.

In PWIA the cross section of the 3-body reaction can be factorized in two terms corresponding to the two vertices

kinematical factor

$$\frac{d^3\sigma}{dE_C d\Omega_C d\Omega_D} \propto KF\left|F(q)_{xS}\right|^2 \left[\frac{d\sigma}{d\Omega}\right]^{TH}_{x+B\rightarrow C+D}$$

$|F(q_{xS})|^2$ describes the intercluster (x-S) momentum distribution

THM description: PWIA

$$\left[\frac{d\sigma}{d\Omega}\right]^{TH}_{x+B\rightarrow C+D} \propto \frac{\dfrac{d^3\sigma}{dE_C d\Omega_C d\Omega_D}}{KF\left|F(q)_{xs}\right|^2}$$

Measured
(well above the CB)

Measured

Calculated

Coulomb effects and electron screening are negligible

Experiments+theory

$E_{qf} \sim 0$

THM description: direct-indirect σ

THM no absolute cross section → Normalization to direct measurements at higher energies

(main validity test)

Excitation function

ABOVE COULOMB BARRIER

$$\left[\frac{d\sigma}{dE_c d\Omega}\right]^{TH\ (HOES)}_{x+B\to C+D} \propto \left[\frac{d\sigma}{dE_c d\Omega}\right]^{Direct\ (OES)}_{x+B\to C+D}$$

BELOW COULOMB BARRIER

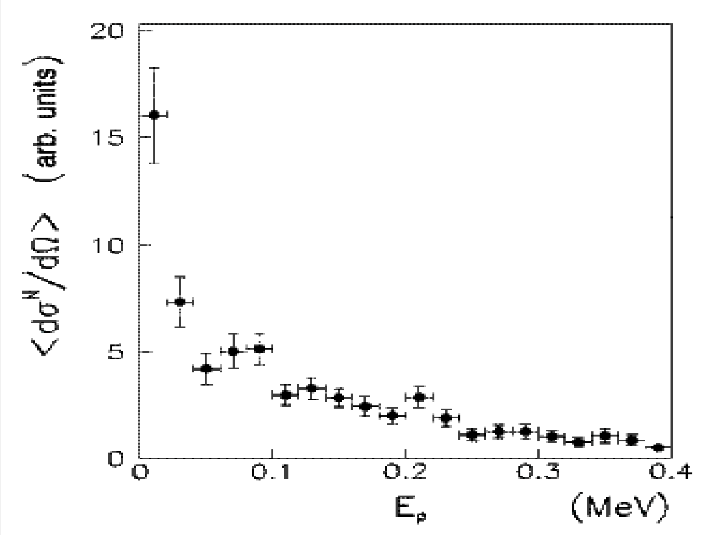
$$\left[\frac{d\sigma}{dE_c d\Omega}\right]^{TH\ (HOES)}_{x+B\to C+D} * \sum P_l \propto \left[\frac{d\sigma}{dE_c d\Omega}\right]^{Direct\ (OES)}_{x+B\to C+D}$$

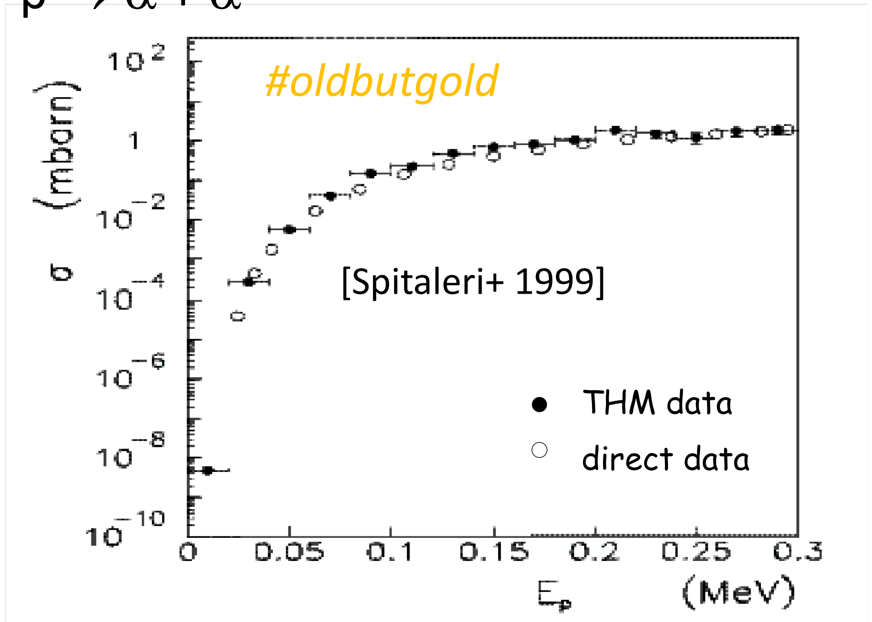
$$P_l(q_{ax}) = \frac{1}{G_l^2(k_{ax}R) + F_l^2(k_{ax}R)}$$

THM description: direct-indirect σ

$$\left[\frac{d\sigma}{dE_c d\Omega}\right]^{TH\ (HOES)}_{x+B\to C+D} * \sum P_l \propto \left[\frac{d\sigma}{dE_c d\Omega}\right]^{Direct\ (OES)}_{x+B\to C+D}$$

$^7Li + p \rightarrow \alpha + \alpha$





THM description: measurements

	Indirect reaction	Direct reaction	References
[1]	$^{2}H(^{7}Li,\alpha\alpha)n$	$^{1}H(^{7}Li,\alpha)^{4}He$	Spitaleri et al 1999, Lattuada et al 2001 [193]
[2]	$^{3}He(^{7}Li,\alpha\alpha)d$	$^{2}H(^{7}Li,\alpha)^{4}He$	Tumino et al 2006 [194]
[3]	$^{2}H(^{6}Li,\alpha^{3}He)n$	$^{1}H(^{6}Li,\alpha)^{3}He$	Tumino 2003 [84]
[4]	$^{6}Li(^{6}Li,\alpha\alpha)^{4}He$	$^{2}H(^{6}Li,\alpha)^{4}He$	Spitaleri et al 2001 [18]
[5]	$^{2}H(^{9}Be,\alpha^{6}Li)n$	$^{1}H(^{9}Be,\alpha)^{6}Li$	Wen et al 2008 [195]
[6]	$^{2}H(^{10}B,\alpha^{7}Be)n$	$^{1}H(^{10}B,\alpha)^{7}Be$	Lamia et al 2008, Rapisarda et al 2018, Cvetinovic et al 2018 [196, 197, 198]
[7]	$^{2}H(^{11}B,\alpha_0{}^{8}Be)n$	$^{1}H(^{11}B,\alpha)^{8}Be$	Spitaleri et al 2004,Lamia et al 2011 [199, 200]
[8]	$^{2}H(^{15}N,\alpha^{12}C)n$	$^{1}H(^{15}N,\alpha)^{12}C$	La Cognata et al 2007 [201]
[9]	$^{2}H(^{18}O,\alpha^{15}N)n$	$^{1}H(^{18}O,\alpha)^{15}N$	La Cognata et al 2009 [202]
[10]	$^{2}H(^{17}O,\alpha^{14}N)n$	$^{1}H(^{17}O,\alpha)^{14}N$	Sergi et al 2010, Sergi et al. 2015 [85, 86]
[11]	$^{6}Li(^{3}He,p^{4}He)^{4}He$	$^{2}H(^{3}He,p)^{4}He$	La Cognata et al 2005 [203]
[12]	$^{2}H(^{6}Li,p^{3}H)^{4}He$	$^{2}H(d,p)^{3}H$	Rinollo et al 2005 [204]
[13]	$^{6}Li(^{12}C,\alpha^{12}C)^{2}H$	$^{4}He(^{12}C,^{12}C)^{4}He$	Spitaleri et al 2000 [205]
[14]	$^{2}H(^{6}Li,t^{4}He)^{1}H$	$n(^{6}Li,t)^{4}He$	Tumino et al 2005, Gulino et al 2010 [206, 207]
[15]	$^{2}H(p,pp)n$	$^{1}H(p,p)^{1}H$	Tumino et al 2007, Tumino et al 2008 [208, 209]
[16]	$^{2}H(^{3}He,p^{3}H)^{1}H$	$^{2}H(^{2}H,p)^{3}H$	Tumino et al 2011, Tumino et al 2014 [94, 89]
[17]	$^{2}H(^{3}He,n^{3}He)^{1}H$	$^{2}H(^{2}H,n)^{3}He$	Tumino et al 2011, Tumino et al 2014 [94, 89]
[18]	$^{2}H(^{19}F,\alpha^{16}O)n$	$^{1}H(^{19}F,\alpha)^{16}O$	La Cognata et al 2011, Indelicato et al 2017 [28, 139]
[19]	$^{13}C(^{6}Li,n^{16}O)^{2}H$	$^{13}C(\alpha,n)^{16}O$	La Cognata et al 2014 [210]
[20]	$^{2}H(^{18}F,\alpha^{15}O)n$	$^{1}H(^{18}F,\alpha)^{15}O$	Cherubini et al 2015, Pizzone et al. 2016, La Cognata et al., 2017 [211, 212, 213]
[21]	$^{2}H(^{10}B,\alpha^{7}Li)^{1}H$	$n(^{10}B,\alpha)^{7}Li$	Guardo et al 2019, Sparta et al 2021 [214, 215]
[22]	$^{2}H(^{7}Be,\alpha\alpha)^{1}H$	$n(^{7}Be,\alpha)^{4}He$	Lamia et al 2017, Lamia et al 2019, Hayakawa et al 2021 [106, 108, 110]
[23]	$^{12}C(^{14}N,\alpha^{20}Ne)^{2}H$	$^{12}C(^{12}C,\alpha)^{20}Ne$	Tumino et al 2018 [26]
[24]	$^{12}C(^{14}N,p^{23}Na)^{2}H$	$^{12}C(^{12}C,p)^{23}Na$	Tumino et al 2018 [26]
[25]	$^{6}Li(^{19}F,p^{22}Ne)^{2}H$	$^{4}He(^{19}F,p)^{22}Ne$	Pizzone et al 2017, Dagata et al 2018 [212, 216]
[26]	$^{2}H(^{17}O,\alpha^{14}C)^{1}H$	$^{17}O(n,\alpha)^{14}C$	Oliva et al 2020 [217]
[27]	$^{2}H(^{3}He,pt)^{1}H$	$^{3}He(n,p)^{3}H$	Pizzone et al 2021 [218]
[28]	$^{2}H(^{7}Be,p^{7}Li)^{1}H$	$n(^{7}Be,p)^{7}Li$	Hayakawa et al 2021 [110]
[29]	$^{2}H(^{27}Al,\alpha^{24}Mg)n$	$^{27}Al(p,\alpha)^{24}Mg$	Palmerini et al 2021, La Cognata et al. 2022 [137, 135, 136]

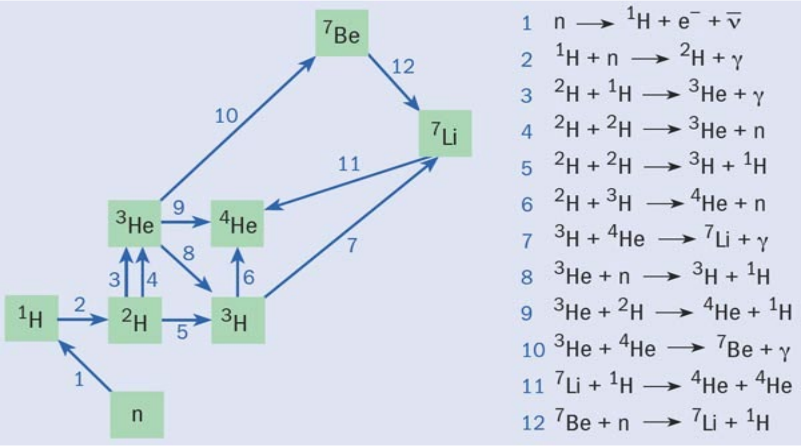
Indirect Methods with Transfer Reactions: the Trojan Horse Method and the Asymptotic Normalization Coefficient
– coming soon on *Progress on Particle and Nuclear Physics*

A TH measurement: $d(d,p)t$ & $d(d,n)^3He$

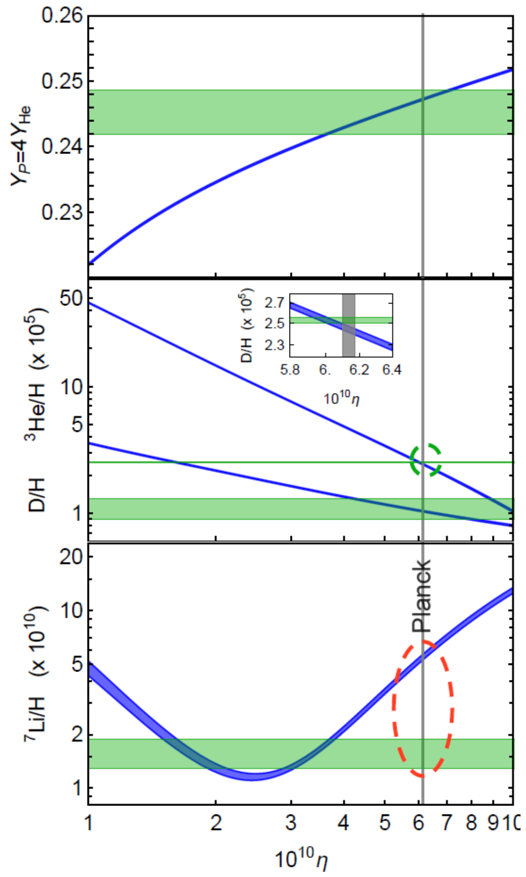
0) Which reaction? Where is the problem?

Big Bang Nucleosynthesis (BBN) or Primordial Nucleosynthesis

great success of NA: good agreement + small problems (CLiP + D-tension)

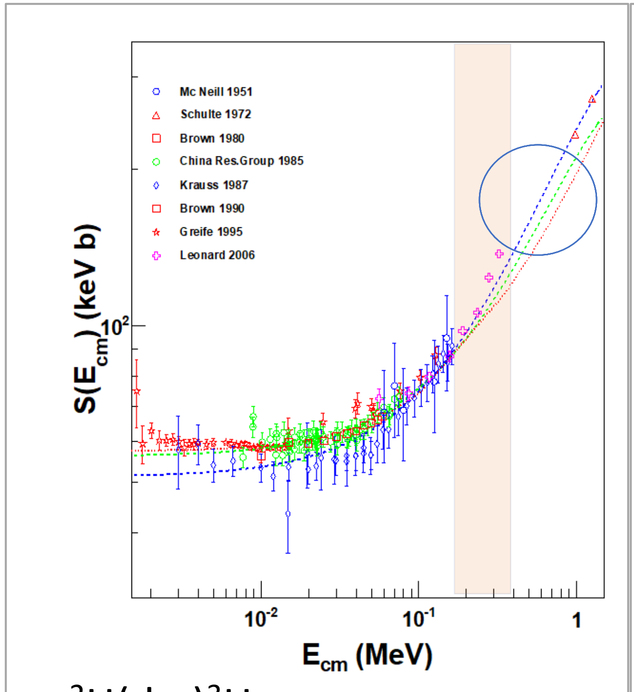


$$
\begin{aligned}
\frac{^7\mathrm{Li}}{\mathrm{H}} &= 4.702\times10^{-10}\left(\frac{\eta_{10}}{6.129}\right)^{2.094}\left(\frac{N_\nu}{3.0}\right)^{-0.280}\left(\frac{G_N}{G_{N,0}}\right)^{-0.719}\left(\frac{\tau_n}{879.4s}\right)^{0.434}\\
&\times [p(n,\gamma)d]^{1.323}\,[d(d,n)^3\mathrm{He}]^{0.696}\,[d(d,p)t]^{0.064}\\
&\times [d(p,\gamma)^3\mathrm{He}]^{0.589}\,[^3\mathrm{He}(n,p)t]^{-0.267}\,[^3\mathrm{He}(d,p)^4\mathrm{He}]^{-0.754}\,[t(d,n)^4\mathrm{He}]^{-0.023}\\
&\times [^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}]^{0.964}\,[^7\mathrm{Be}(n,p)^7\mathrm{Li}]^{-0.707}\,[^7\mathrm{Li}(p,\alpha)^4\mathrm{He}]^{-0.055}\,[t(\alpha,\gamma)^7\mathrm{Li}]^{0.029}\\
&\times [^7\mathrm{Be}(n,\alpha)^4\mathrm{He}]^{-0.001}\,[^7\mathrm{Be}(d,p)^4\mathrm{He}^4\mathrm{He}]^{-0.008}
\end{aligned}
$$

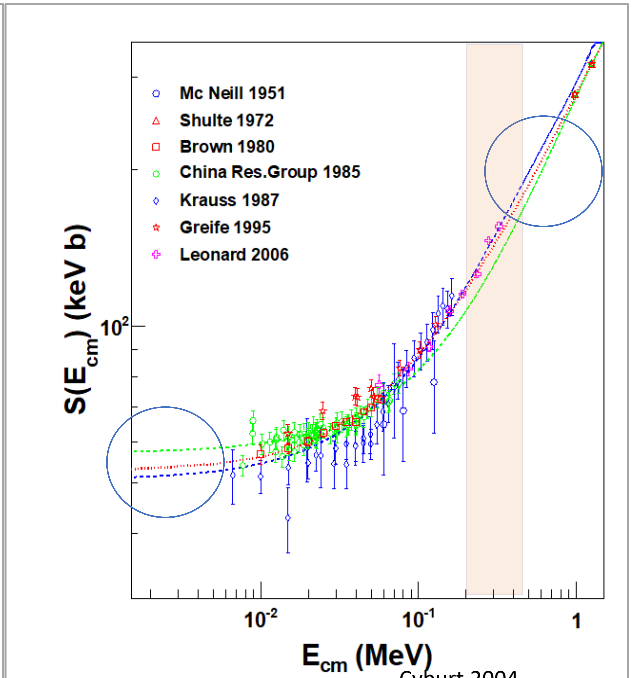


A TH measurement:d(d,p)t & d(d,n)^{3}He

State of the art for d+d before our measurement



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



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

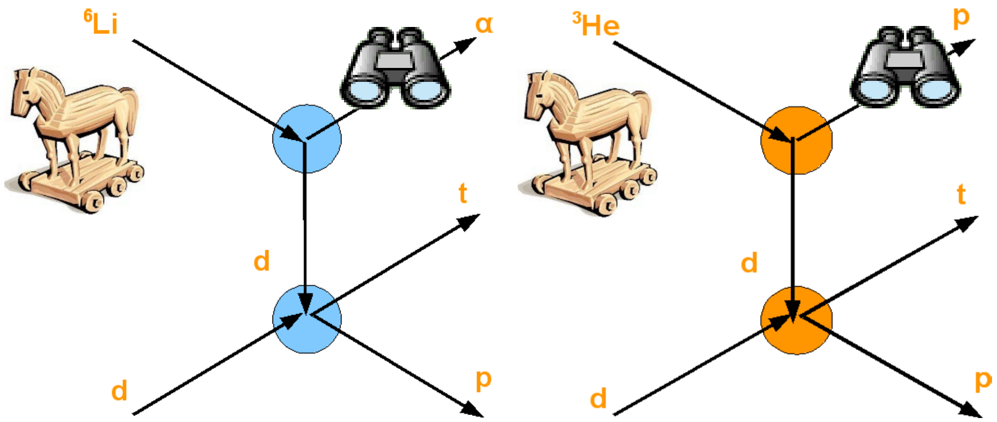
Energies relevant for the BBN scenario (50-350 keV)
→ 0-1 MeV
But CB ~200-400 keV

Thus we need:

- Bare nucleus cross section
- Errors reduction

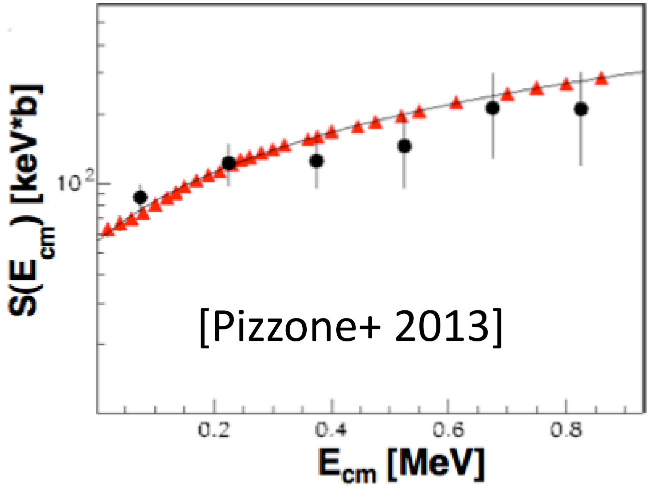
A TH measurement: d(d,p)t & d(d,n)^{3}He

1) Choose the proper 3-body reaction to measure in the lab,
2) find a suitable TH nucleus (clusters!),
3) find set-up that maximize the QF contribution (easy set-up)



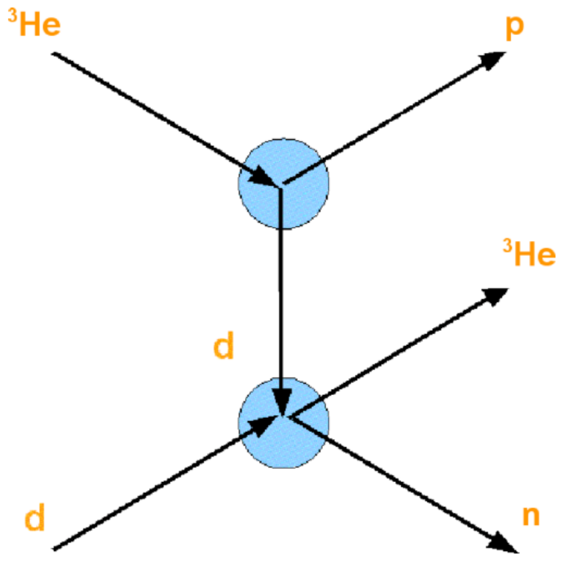
Pole invariance

This resembles previous results obtained for ^{7}Li(p,α)α [Pizzone+ 2011] and ^{6}Li(d,α)α [Tumino+ 2006]



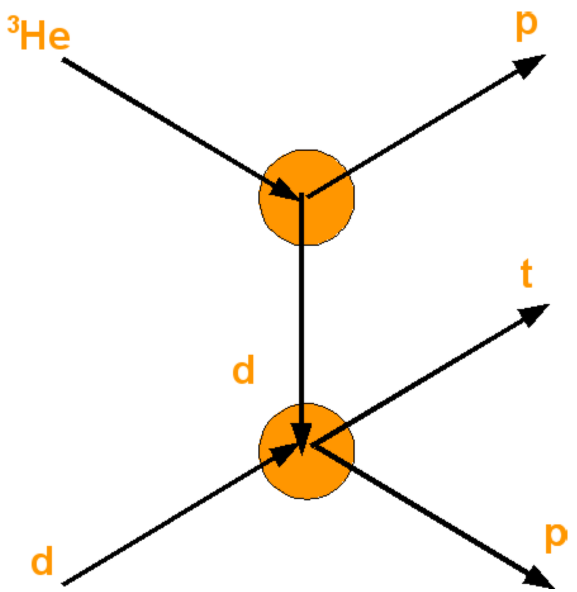
[Tumino+ 2014]: red triangles
[Rinollo+ 2005]: black dots

A TH measurement:d(d,p)t & d(d,n)^{3}He



$^2H(^3He,n^3He)H \rightarrow ^2H(d,n)^3He$

$^2H(^3He,pt)H \rightarrow ^2H(d,p)^3H$



^{3}He is the new TH nucleus

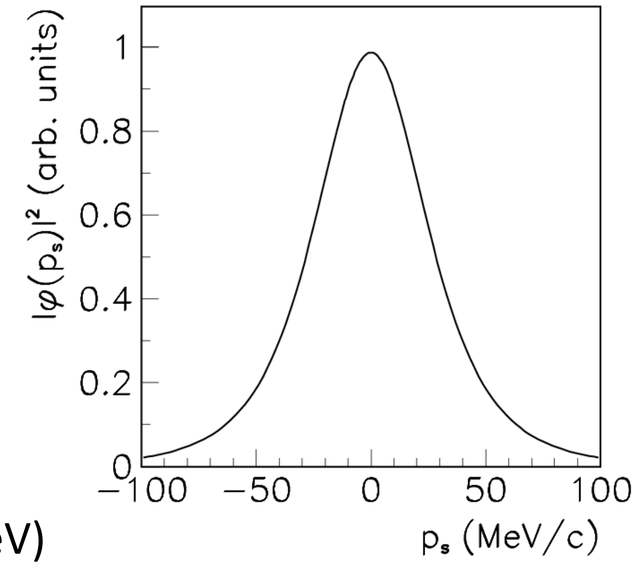
$^3He=d+p$

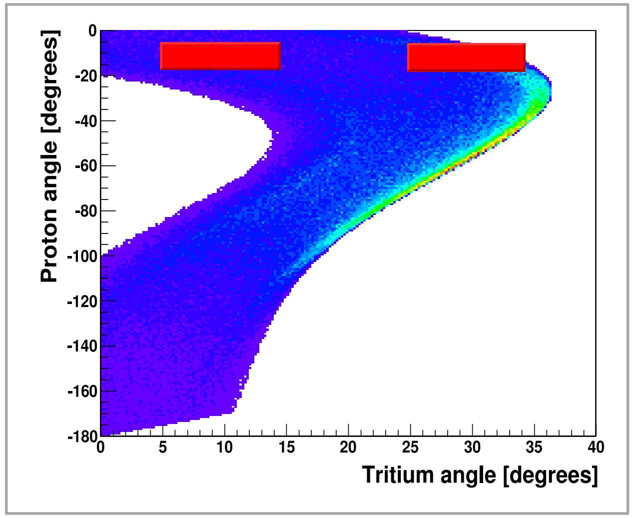
A TH measurement:d(d,p)t & d(d,n)^{3}He

<u>Experimental angles are chosen to **maximize** QF contribution</u>

Maximum contribution p_{spec} =0 MeV/c

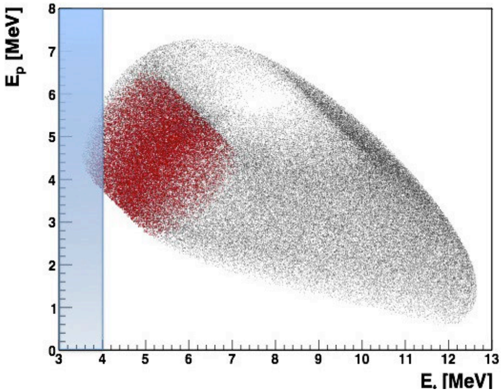
(Eckart function for ^{3}He)





(E_{beam}=18 MeV)

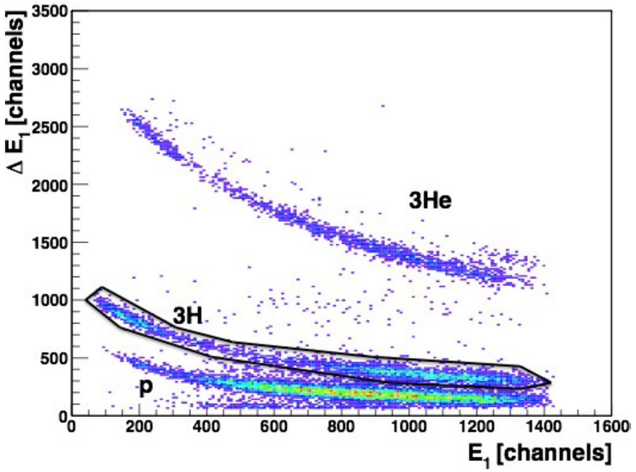
Avoid n-detection



A TH measurement:d(d,p)t & d(d,n)^{3}He

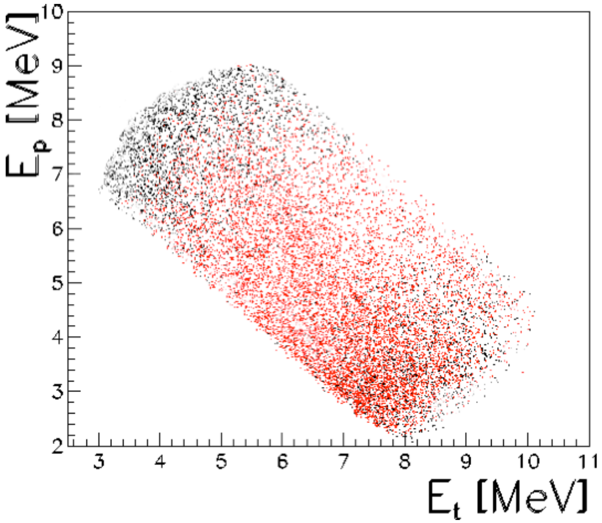
@Nuclear Physics Institute of ASCR (Prague)

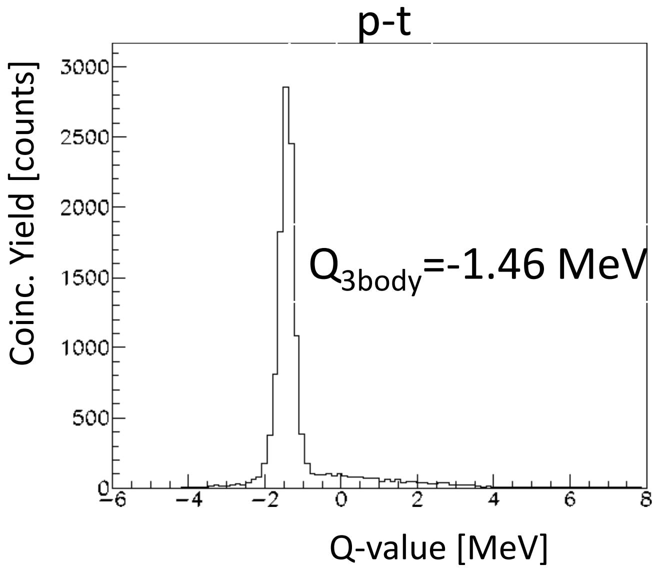
Cyclotron→ ^{3}He beam (18 MeV, *i*=1.5 pnA) impinging on a CD_2 target (150 μg/cm^2)

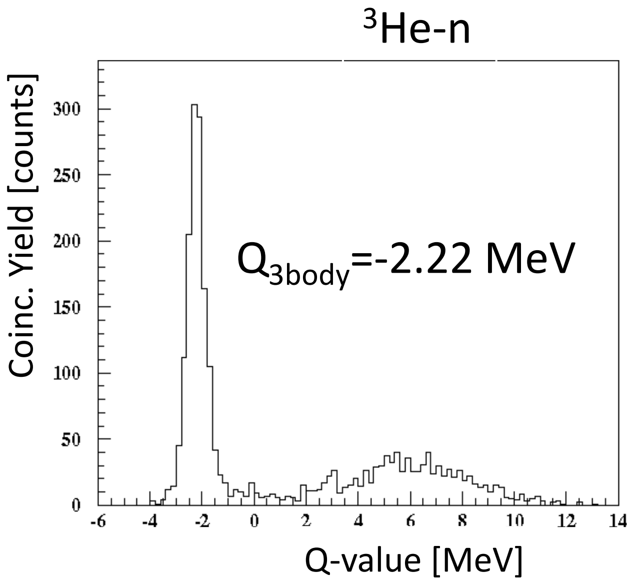


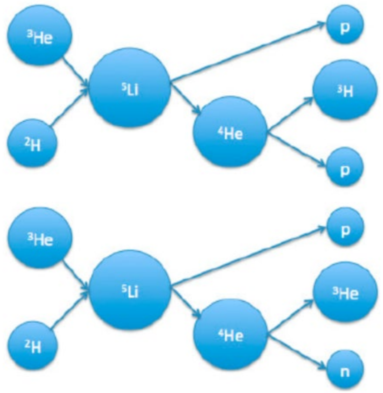
Offline data analysis:
Select the 3-body reaction of interest among the ones occurring in the target

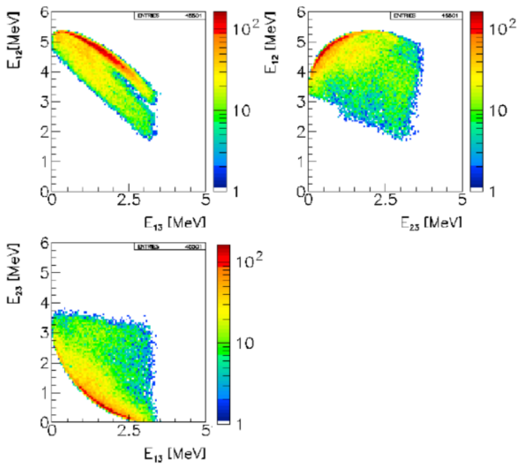
A TH measurement:d(d,p)t & d(d,n)^{3}He







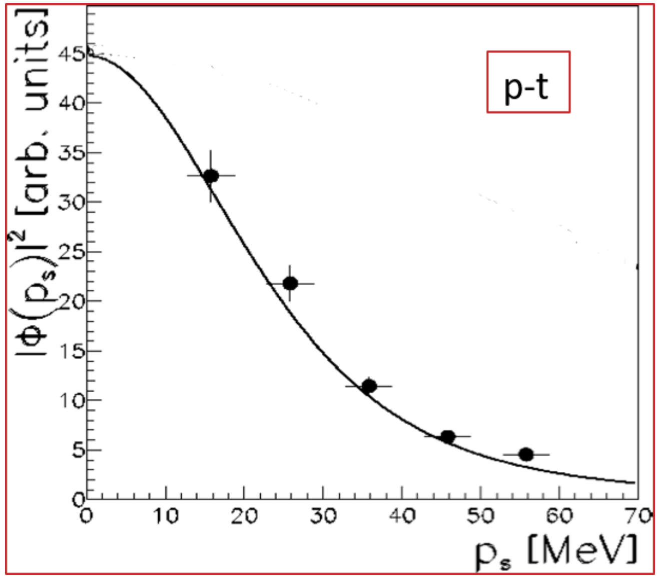


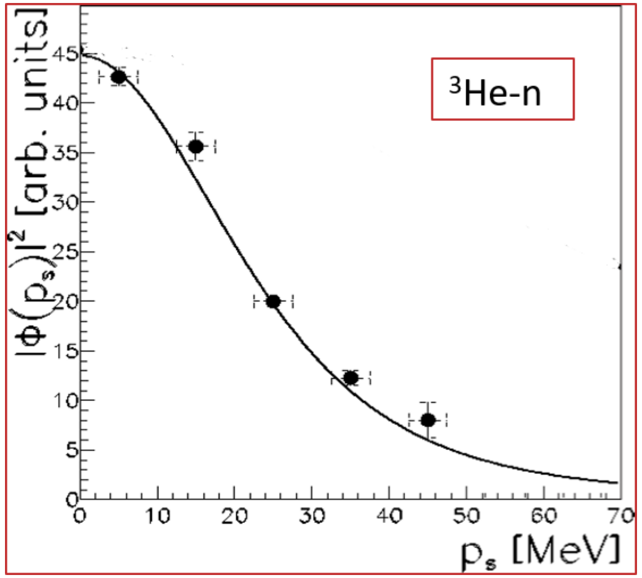


Relative energies
(+Angular correlations…)

A TH measurement:d(d,p)t & d(d,n)^{3}He

QF mechanism selection





Eckart function!

The applicability of the pole approximation
is limited to small momentum p_{x-s}.

[Shapiro+ 1965]

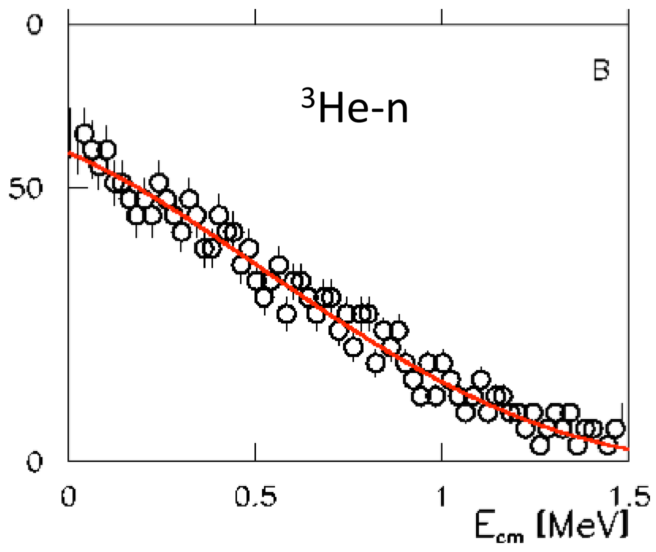
$$0 \leq \left| p_{d-p} \right| \leq k_{d-p}$$

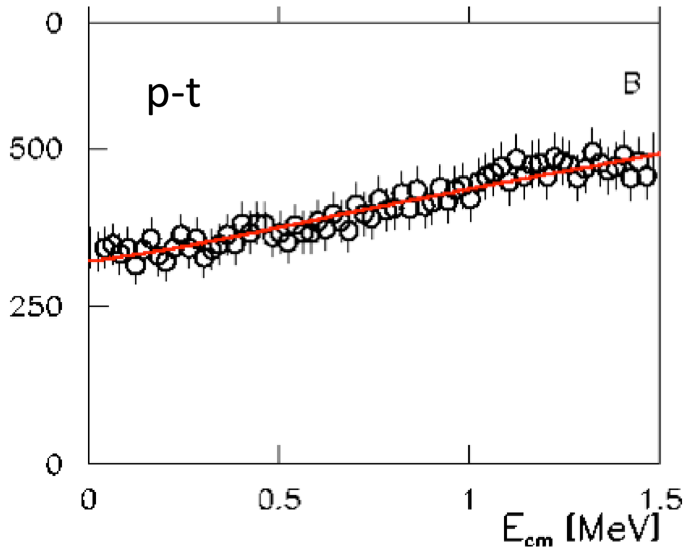
$$k_{d-p} = \sqrt{2\ \mu_{dp}\ B_{dp}} \approx 53\ MeV/c$$

A TH measurement:d(d,p)t & d(d,n)^{3}He

Cross sections

[Tumino+ 2014 (APJ)]

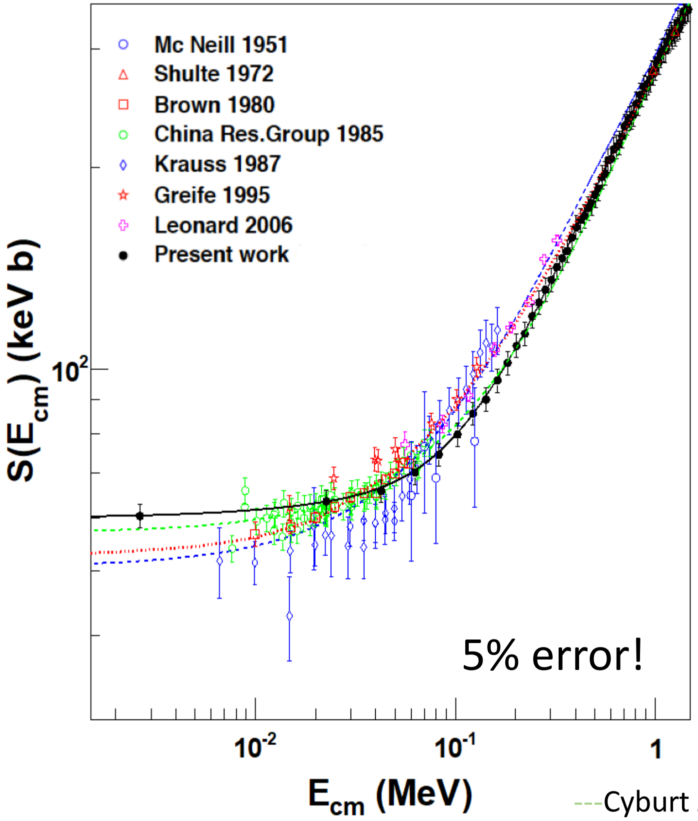


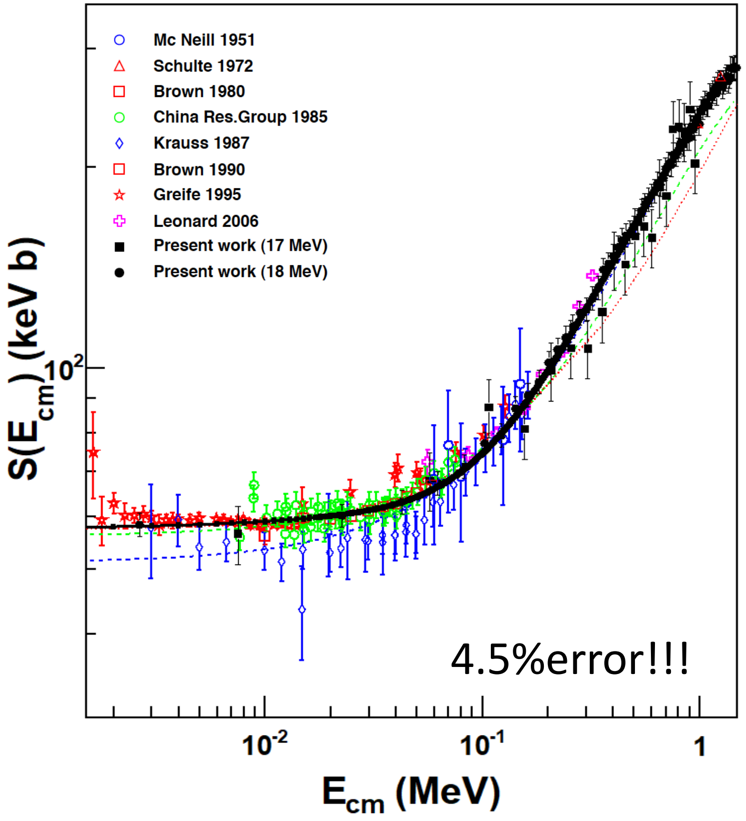


$$\left[\frac{d\sigma}{d\Omega}\right]^{TH}_{x+B\to C+D} \propto \frac{\frac{d^3\sigma}{dE_C d\Omega_C d\Omega_D}}{KF\lfloor F(q)_{xS}\rfloor^2}$$

A TH measurement:d(d,p)t & d(d,n)^{3}He

Normalization and comparison with literature





---Cyburt 2004
---Angulo 1999
---Descouvemont 2004

[Tumino+ 2014 (APJ)]

(MPWBA)

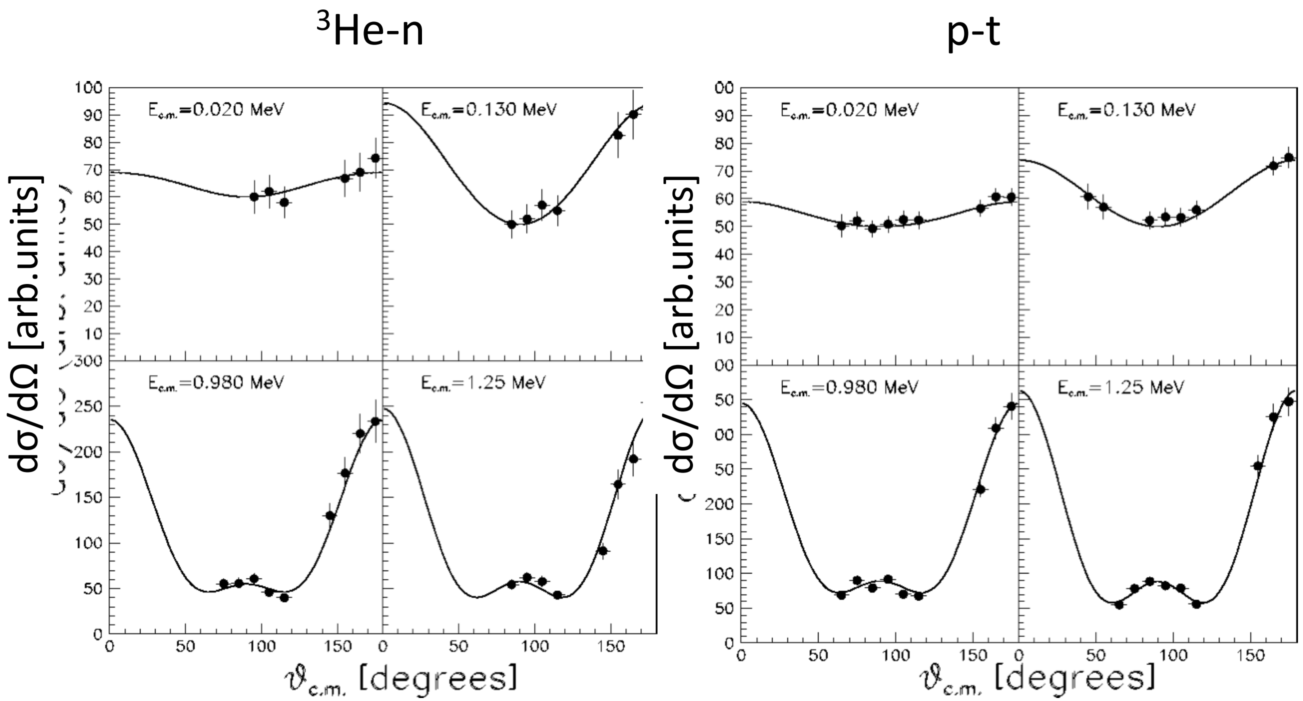
A TH measurement:d(d,p)t & d(d,n)^{3}He

Normalization and comparison with literature

Angular Distributions

Krauss1987 + Schulte1990
Same partial waves contribute for direct and indirect measurements

$$\left[\frac{d\sigma(\theta)}{d\Omega}\right]^{HOES} \propto \left[\frac{d\sigma(\theta)}{d\Omega}\right]^{OES}$$



[Tumino+ 2014 APJ]

A TH measurement:d(d,p)t & d(d,n)^{3}He

Once we have the S(E)-factor it is possible to calculate the «**results**»

Electron screening

Comparison with Greife data sets

- *p-t channel*:

U_e= 13.2±1.8 eV (not exceeding 14 eV= adiabatic limit)

- *^{3}He-n channel*:

U_e= 11.7±1.6 eV (not exceeding 14 eV= adiabatic limit)

$$f_{lab} = \frac{S_s}{S_b} = \frac{E}{E+U_e} e^{\frac{\pi\eta U_e}{E}}$$

A TH measurement: d(d,p)t & d(d,n)^{3}He

Reaction rates

[Tumino+ 2014 (APJ)]

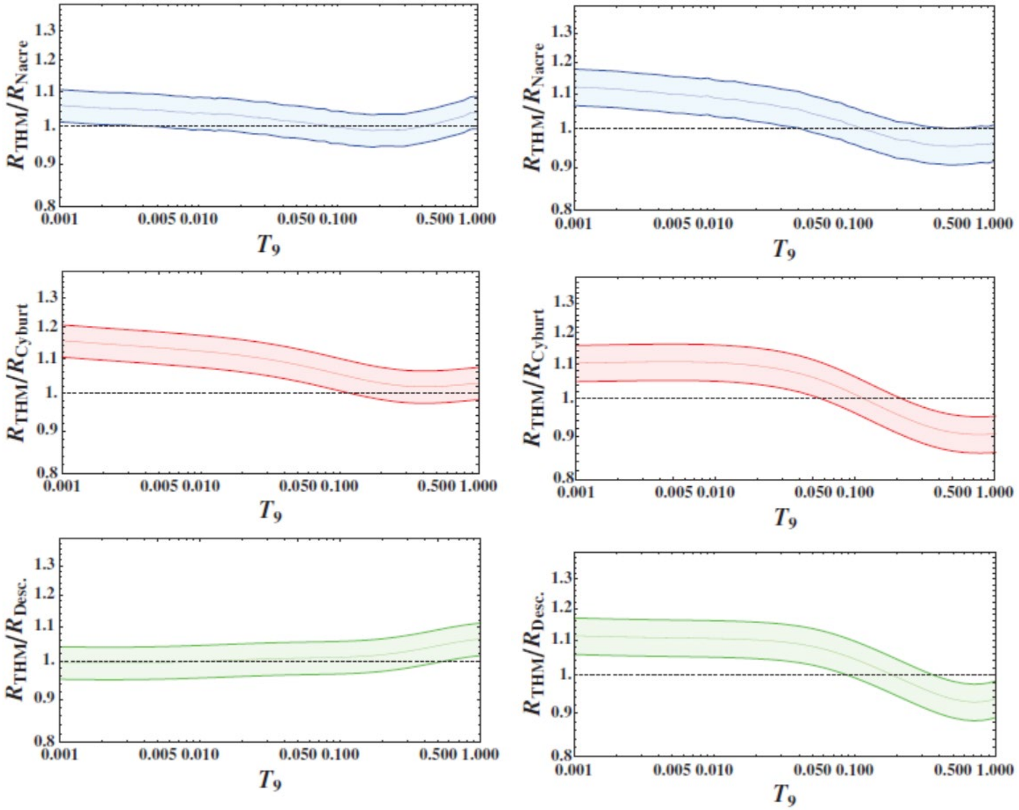
p-t

^{3}He-n

[Angulo+ 1999]

[Cyburt 2004]

[Descouvemont+ 2004]



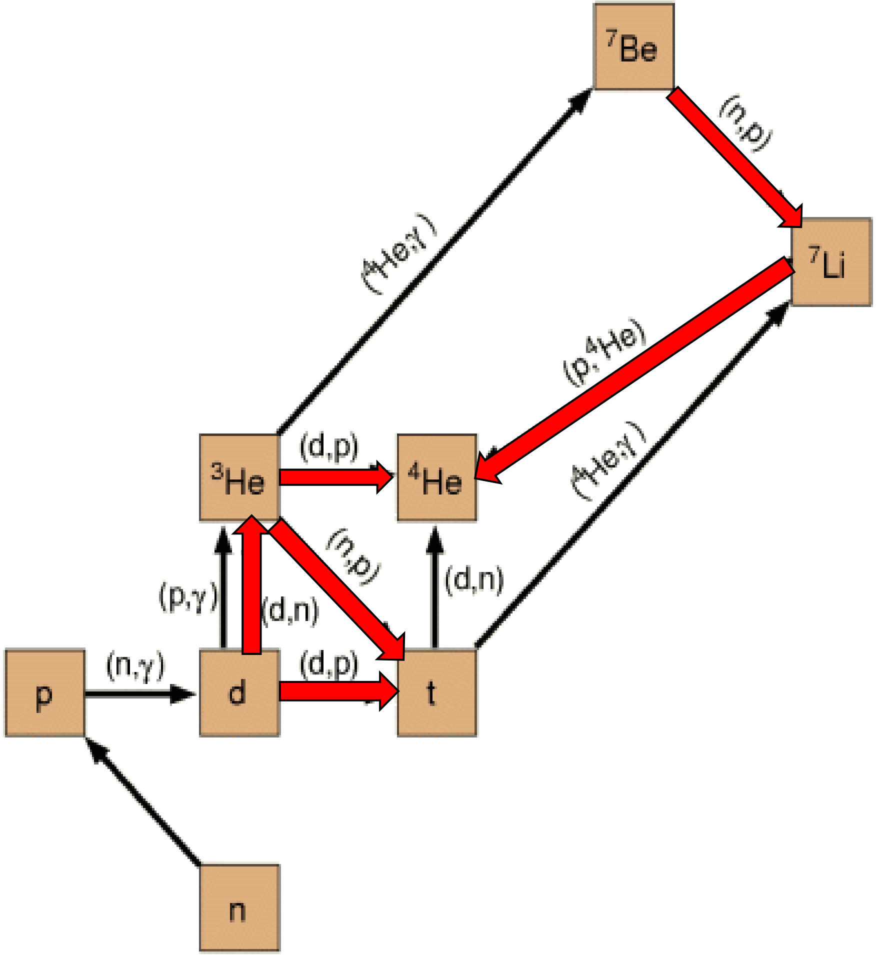
Advantages vs. Limitations

- Bare nucleus σ_b or $S_b(E)$
- Wide E range for excitation function only one beam energy
- RIB's and n-induced reaction
- So many validity tests!
- Easy set-up
- No need of extrapolation

- Necessity of preliminary study of QF and validity test
- Possible presence of different 3-body reaction mechanisms
- σ is in arbitrary units (need of direct data to normalize)
- High angular and energy resolutions are needed
- Theoretical analysis is needed: PWIA, MPWBA, Modified R-matrix…
- Long data analysis

It is *complementary* to direct measurements

TH campaign on BBN



- $d(d,p)t + d(d,n)^3He$

[Tumino+2014, ApJ]

- $^3He(d,p)^4He$

[La Cognata+2005, Phys.Rev.C]

- $^7Li(p,a)^4He$

[Lattuada+2001, ApJ] [Lamia+2012, A&A]

- $^3He(n,p)t$

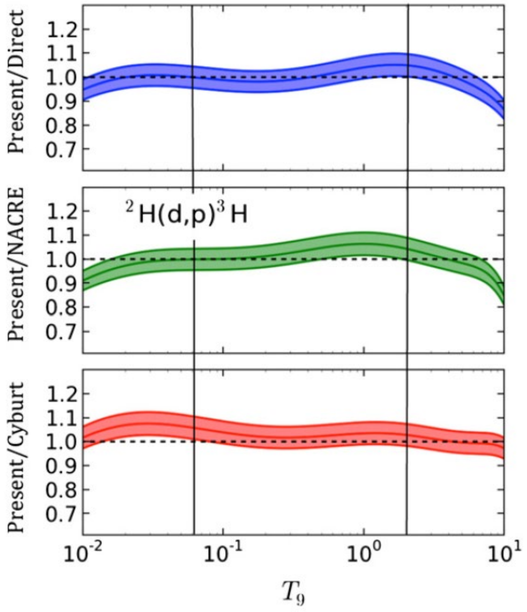
[Pizzone+2020,EpJ]

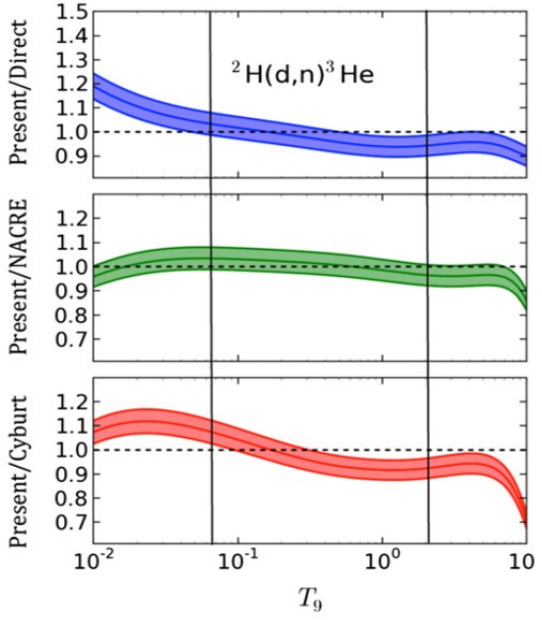
And using RIBs

- $^7Be(n,p)^7Li$ & $^7Be(n,\alpha)^4He$

[Lamia+2019, ApJ][Lamia+2017, ApJ]
[Hayakawa+2021,ApJLett.]

TH campaign on BBN



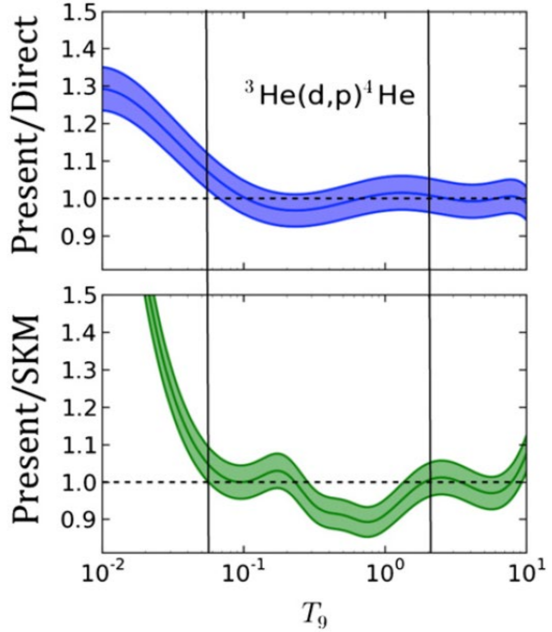


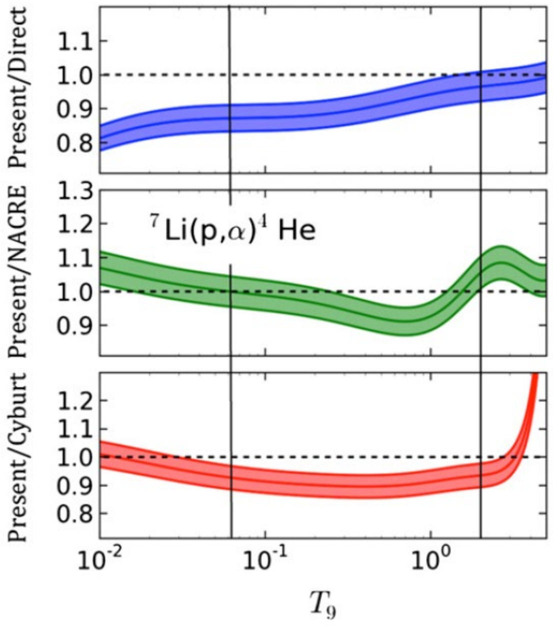
In *[Spartà+2021,FSPAS]* rates comparison with

- Nacre*[Angulo+1999, N.Phys.A]*
- Cyburt*[Cyburt 2004, Phys.Rev.D]*

or TH/SKM [*Smith+ 1993, ApJ]*)

- «Direct»=2012 direct data compilation





TH campaign on BBN

TH rates in **BBN-BEW** code (C.A. Bertulani)

Yields	Direct	^{2}H(d,p)^{3}H	^{2}H(d,n)^{3}He	^{3}He(d,p)^{4}He	^{7}Li(p,α)^{4}He	All	Observed
Y_p	0.249	$0.248^{+0.001}_{-0.001}$	$0.25^{+0.00}_{-0.00}$	$0.249^{+0.000}_{-0.000}$	$0.249^{+0.000}_{-0.000}$	$0.248^{+0.001}_{-0.002}$	0.256 ± 0.006
$\frac{D}{H}/10^{-5}$	2.645	$2.621^{+0.079}_{-0.046}$	$2.718^{+0.077}_{-0.036}$	$2.645^{+0.002}_{-0.007}$	$2.645^{+0.000}_{-0.000}$	$2.692^{+0.177}_{-0.070}$	2.82 ± 0.26
$\frac{^3He}{H}/10^{-6}$	9.748	$9.778^{+0.216}_{-0.076}$	$9.722^{+0.052}_{-0.092}$	$9.599^{+0.050}_{-0.003}$	$9.748^{+0.000}_{-0.000}$	$9.441^{+0.511}_{-0.466}$	$\geq 11. \pm 2.$
$\frac{^7Li}{H}/10^{-10}$	4.460	$4.460^{+0.001}_{-0.001}$	$4.470^{+0.010}_{-0.006}$	$4.441^{+0.190}_{-0.088}$	$4.701^{+0.119}_{-0.062}$	$4.683^{+0.335}_{-0.292}$	1.58 ± 0.31

[Spartà+ 2021]

Reaction rate	^{7}Li/H	^{7}Be/H	^{7}Li/H+^{7}Be/H
TH2014 + Hou15	2.840×10^{-11}	4.149×10^{-10}	4.433×10^{-10}
TH2014 + Lamia17	2.845×10^{-11}	4.156×10^{-10}	4.441×10^{-10}
TH2014 + Lamia19	2.670×10^{-11}	3.990×10^{-10}	4.260×10^{-10}

THM@BBN*: our bare nucleus measurements confirm the Standard BBN model, including the CLiP.*

Thus, variations up to 20% in the rates do not affect what expected by observations, at least considering these reactions!

TH campaign on BBN

A new tension in the cosmological model from primordial deuterium?

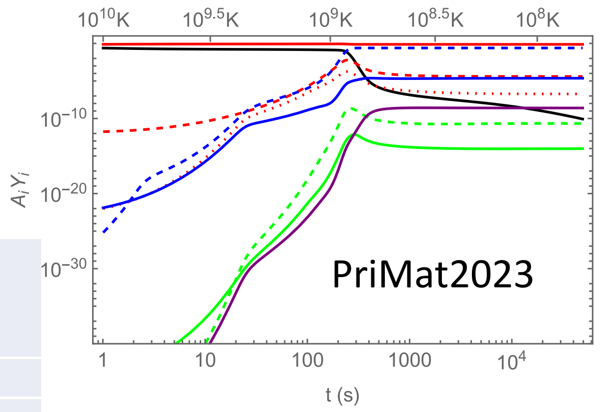
Cyril Pitrou,[1⋆] Alain Coc,[2] Jean-Philippe Uzan,[1] Elisabeth Vangioni[1]

- 2020 LUNA measurement of the D(p,γ) 3He cross-section
- New neutron lifetime
- Re-evaluation of the cosmological baryon abundance from CMB+BAO

→ new 1.8σ-tension on the baryonic density (equivalently on the D/H)

…TH on PriMat2023!

TH campaign on BBN



	Observations		PriMat2023	PriMat2023 + TH[d(d,p)t & d(d,n)3He]	%	PriMat2023 + TH[d(d,p)t]	%	PriMat2023 + TH[d(d,n)3He]	%
		H	0,75272872	0,75294499	0,028731	0,75277354	0,005954	0,75289733	0,0224
[Aver+,2020]	0,25453	Y_p	0,24721111	0,24699225	-0,08853	0,24716551	-0,01845	0,24704076	-0,06891
[Cooke+,2018]	2,527	(D/H)E+05	2,4376907	2,6178349	**7,389953**	2,4748711	1,52523	2,5762967	5,685955
[Bania+,2002]	1,1	(^{3}He/H)E+05	1,0315673	1,0246836	-0,6673	1,0409139	0,906058	1,0149493	-1,61095
		(T/H)E+08	7,7610446	8,2719106	6,582439	7,8812512	1,548846	8,1334452	4,798331
		(^{3}He+T)E+05	1,0393284	1,0329555	-0,61317	1,0487951	0,910848	1,0230828	-1,56309
[Sbordone+,2010]	1,58	(^{7}Li/H)E+11	2,845351	2,9445271	3,485549	2,876617	1,098845	2,9104938	2,289447
		(^{7}Be/H)E+11	5,2245145	4,793241	-8,25481	5,2092733	-0,29172	4,8118025	-7,89953
		(^{7}Li+^{7}Be)E+11	5,5090496	5,0876938	-7,64843	5,496935	-0,2199	5,1028519	-7,37328
		(^{6}Li/H)E+14	1,1826905	1,2689438	7,292973	1,2005552	1,510514	1,2489952	5,60626
		(^{9}Be/H)E+19	8,782494	9,57247	8,994894	8,9459697	1,861381	9,3798448	6,801608
		(^{10}B/H)E+21	2,8722717	2,9769721	3,645212	2,8959387	0,823982	2,9495365	2,690024
		(^{11}B/H)E+16	3,2546901	2,8659418	-11,9442	3,2242954	-0,93387	2,8976108	-10,9712
		(CNO/H)E+16	7,8286994	7,542013	-3,66199	7,764397	-0,82137	7,6080047	-2,81905
		N_{eff}	3,0439773	3,0439773	0	3,0439773	0	3,0439773	0

Preliminary

- Other TH reactions in PriMat2023
- Comparison with BBN_BEW and other codes

Future work ahead

BBN: New data (*t(d,n)*α), new codes calculations, Bayesian reanalysis of the d+d reactions

THM:

- upcoming results from:

$^{26}Al(n,p)^{26}Si$ & $^{26}Al(n,\alpha)^{23}Na$
$^{19}F(p,\alpha_{\pi,\gamma})^{23}Na$
$^{14}N(n,p)^{14}C$
$^{12}C(^{16}O,\alpha_{0,1})^{12}C$

- search for new Trojan Horse nuclei
- new measurements, *e.g.* $^{22}Ne(\alpha,n)^{25}Mg$, $^{17}O(\alpha,n)^{20}Ne$ …

s-process
n-sources & n-poisons

Thanks for your attention!