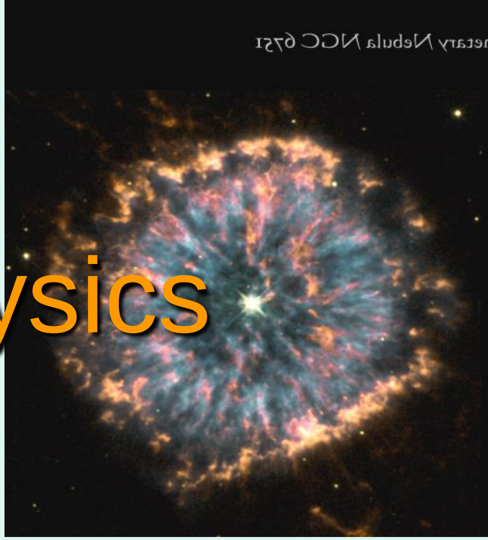
Some key problems and key reactions in Nuclear Astrophysics



Main issues:

- BBN: was the universe always the same?
- What's in the core of Sun and other MS stars?
- Carbon and Oxygen in the universe

Gianni Fiorentini Torino 1st June 2004
Based on work with ***C. Bambi B. Ricci and F. Villante***

Key reactions

- $^{14}N(p,\gamma)^{15}O$: the key reaction for CN(O) burning
- $^{3}He(^{4}He,\gamma)^{7}Be$: the main uncertainty for Sun and BBN
- $^{12}C(\alpha,\gamma)^{16}O$: the regulator of C/O abundance in the universe
- [Neutron capture on light nuclei and BBN]

Destroy a prejudice

- Astrophysical prejudice: “astrophysics does not matter nuclear cross sections. Change them and the palsma readjusts its temperature so as to keep reaction rate fixed and outcome unchanged”

- It does not hold if you can measure temperature and/or the outcome of competing reactions occurring at the same temperature.

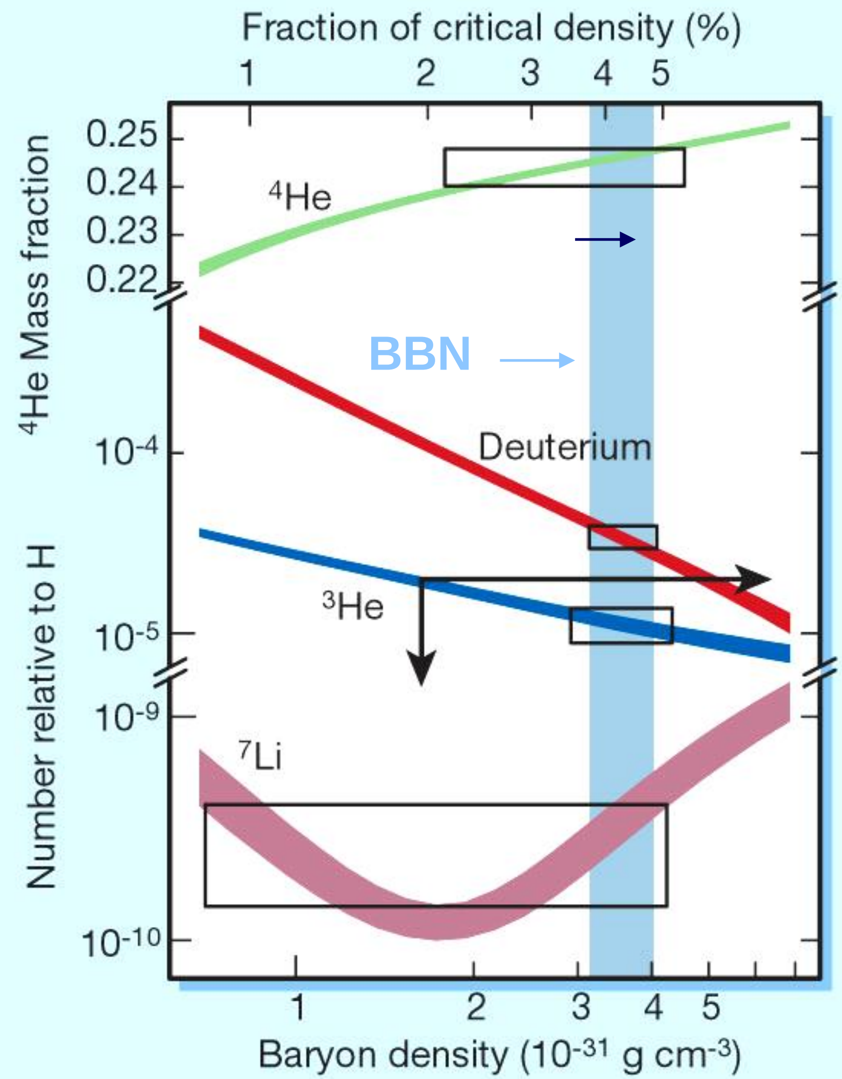
Apologies

- I'll not speak of the interesting physics which can be done with radioactive ion beams.
- Strong effort worldwide and interesting prospects in Italy
- It's just due to my ignorance

BBN: the first nuclear kitchen

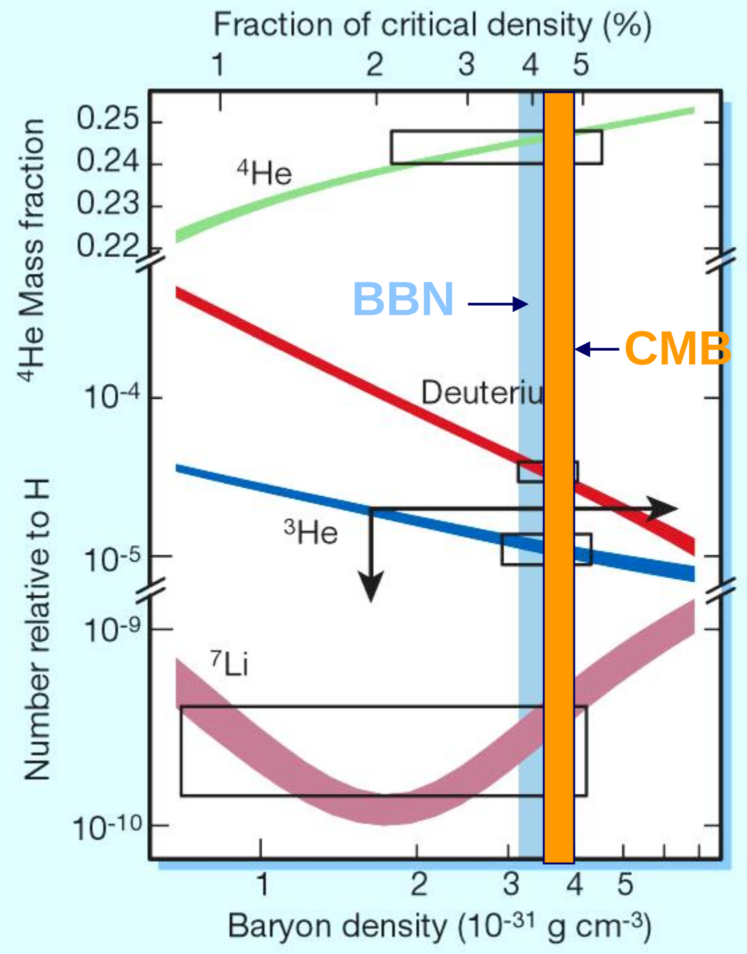
- Significant observational progress in the last decade
- D abundance reduced by an order of magnitude
- Some hint on ^3He abundance
- Still some inconsistencies for ^4He
- Large errors on ^7Li
- The picture is essentially concordant with the value of just one parameter,

$$\eta = n_B / n_\gamma$$



BBN: was the universe all the same?

- The abundances picture is consistent with the Baryon density inferred from **CMB**
- **CMB** probes universe at
- t≈4 10^5 yrs; z≈10^3 T≈0.3 eV,
- ^{4}He production probes t≈1s; z≈10^9 T≈1 MeV
- D production probes t≈100 s z≈10^8 T≈0.1 MeV



Were the “fundamental constants” the same in the early universe ?

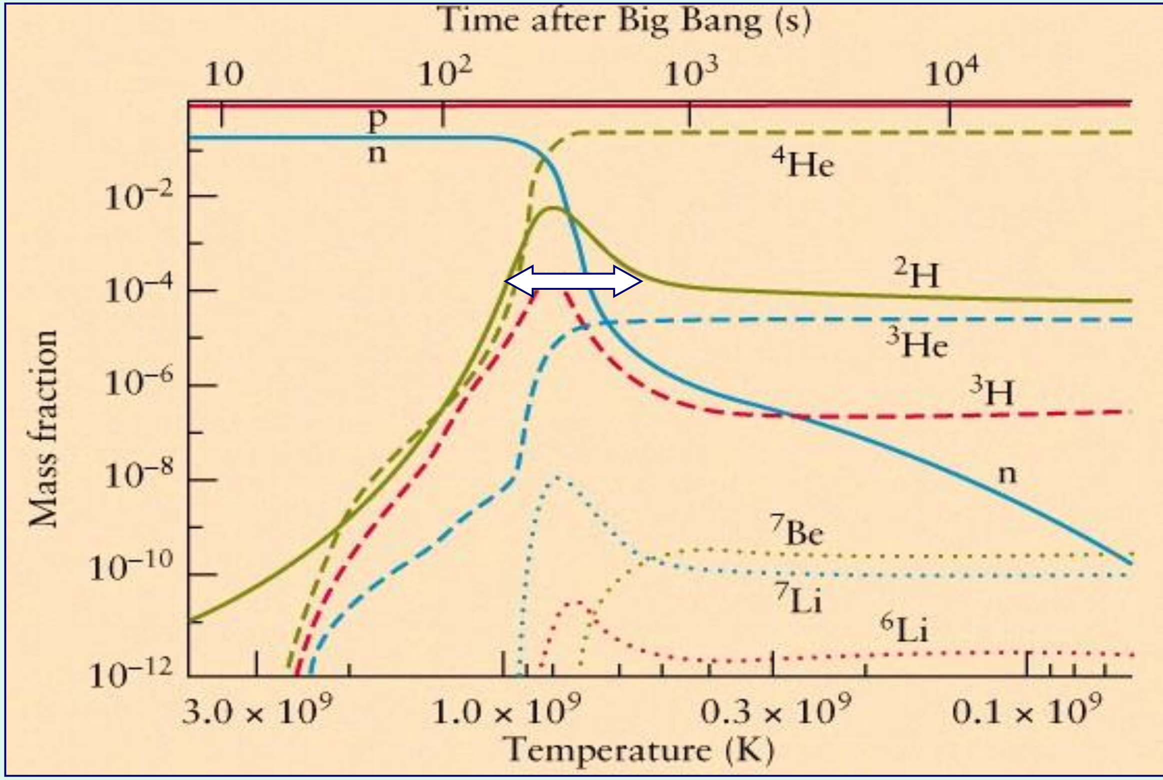
Deuterium

- D is produced by

  $p+n \rightarrow d+\gamma$

  and destroyed (mainly) by

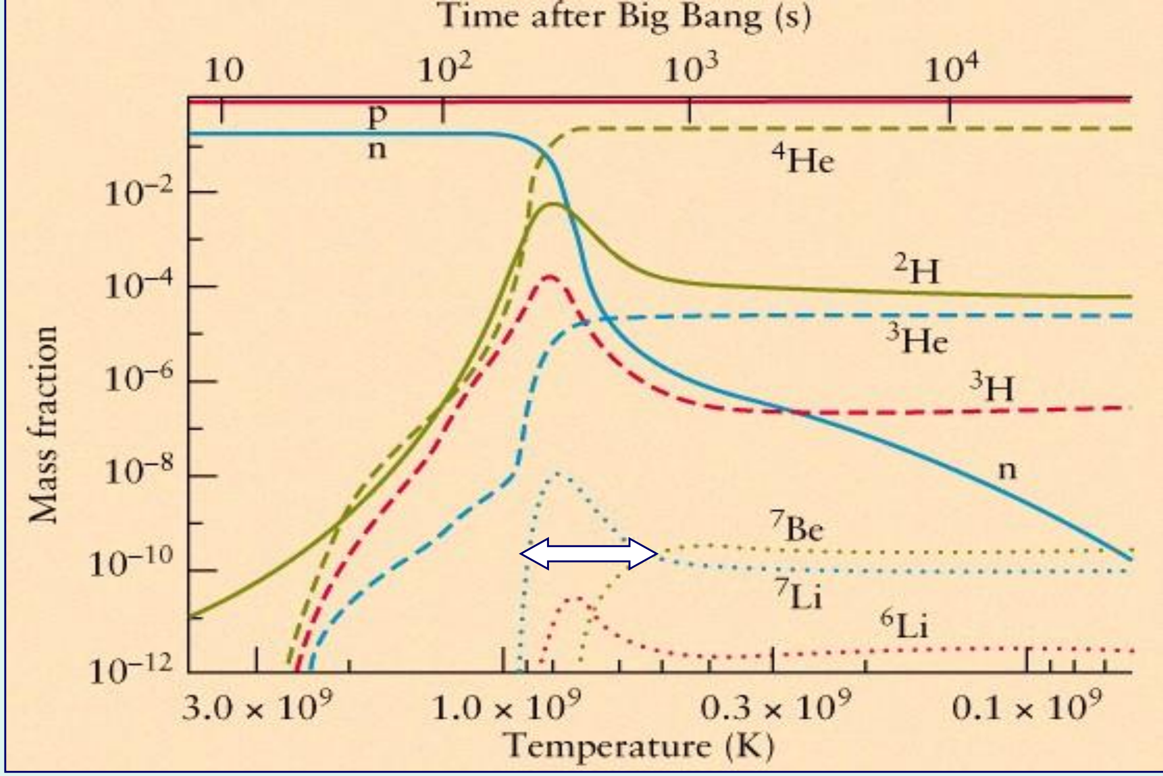
  $p+d \rightarrow {}^3He + \gamma$
- Relevant temperature near 70 keV



- LUNA has significantly reduced the error on the production reaction
- Significant uncertainty arising from neutron capture reactions (also important for Li abundance…

^{7}Li

- ^{7}Li is the decay product of ^{7}Be
- At high η ^{7}Be is mainly produced by:



^{3}He+4He → 7Be+γ

- It is destroyed by:

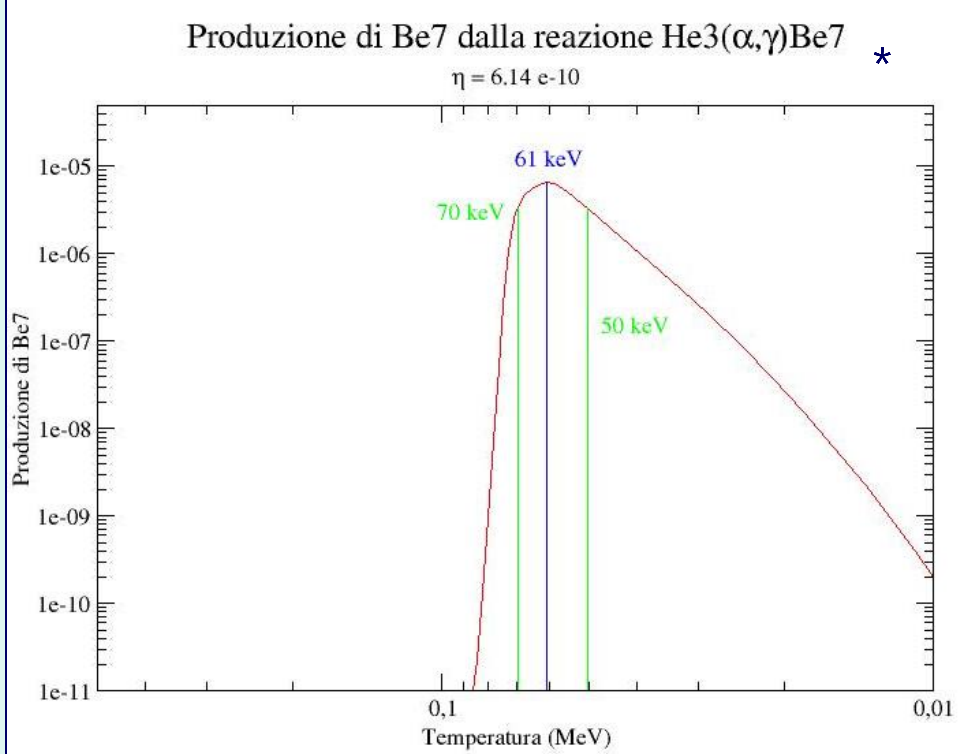
  n+^{7}Be →^{7}Li +p

  and at later times by ^{7}Be electronic capture.

- Relevant temperature near 60 keV due to deuterium bottleneck

$^{3}He + ^{4}He \rightarrow {}^{7}Be + \gamma$ and BBN

- During BBN ^{7}Be production peaked near 60 keV



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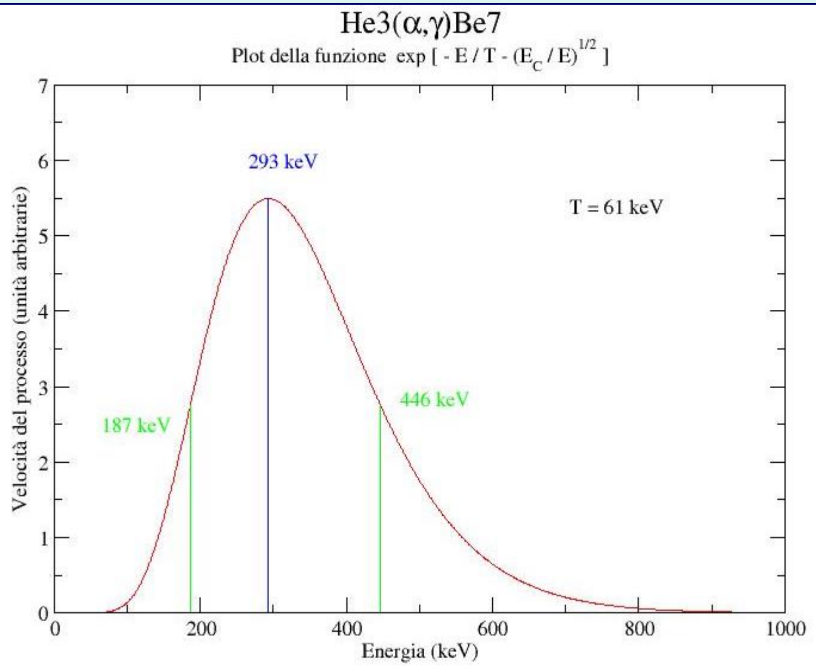


*

- Need (reliable) data in the window around:

  150- 500 keV

* C. Bambi, Ferrara

Nuclear cross sections and BBN abundances

- Relative errors on σ and their relative contribution to the theoretical uncertainty on BBN abundances

- Inputs can be taken from different analysis of nuclear data

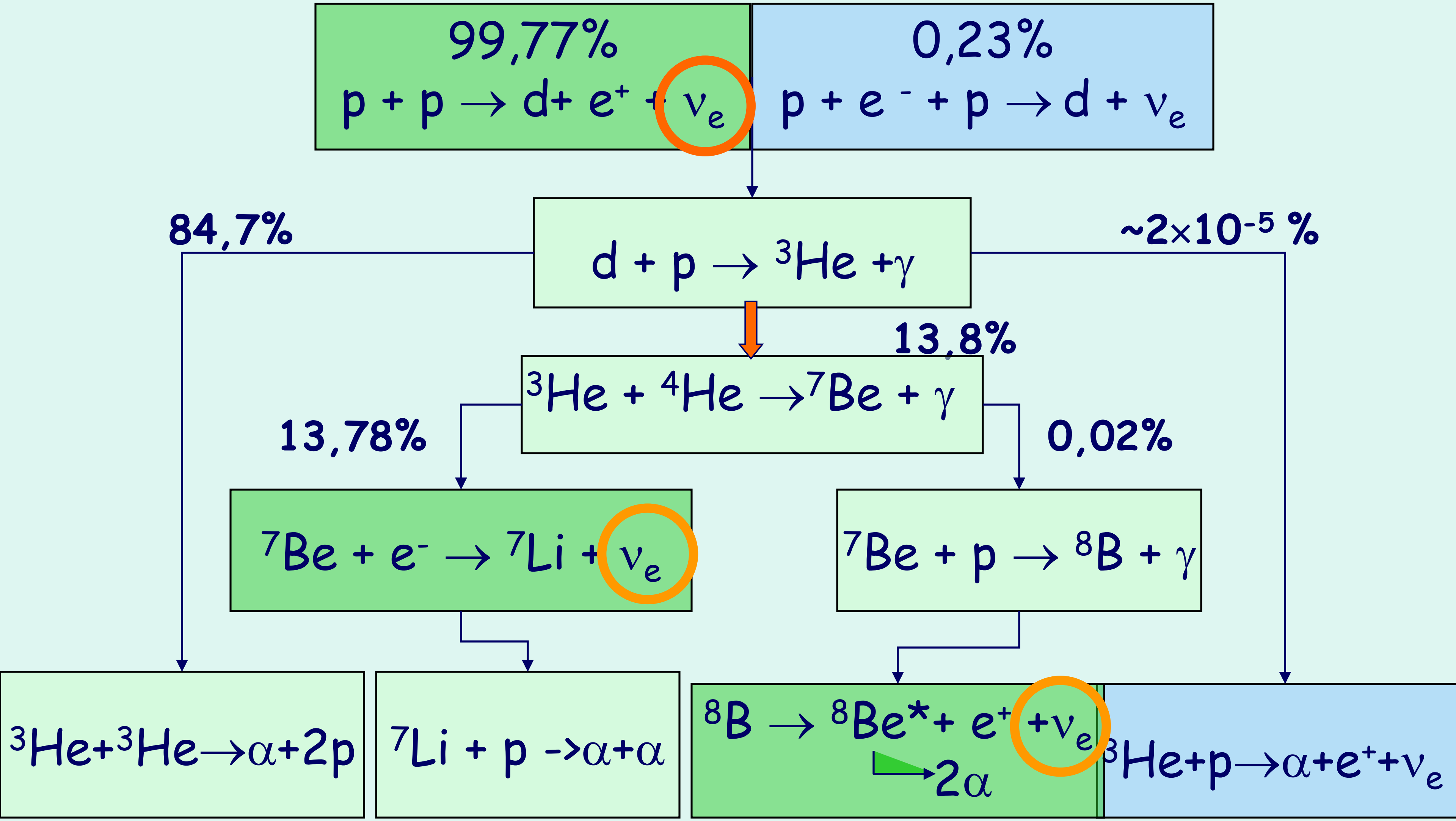
k	Reaction	Des03 dR/R
1	n lifetime	0,0009
2	p(n,g)d	0,040
3	d(p,g)3He	0,050
4	d(d,n)3He	0,030
5	d(d,p)t	0,020
6	t(d,n)4He	0,020
7	t(a,g)7Li	0,040
8	3He(n,p)t	0,015
9	3He(d,p)4He	0,040
10	3He(a,g)7Be	0,080
11	7Li(p,a)4He	0,060
12	7Be(n,p)7Li	0,007

Contributo all'errore totale ($\Delta Y_k / \Delta Y$)			
He4	D	Li	He3
0,92	0,01	0,00	0,00
0,27	0,29	0,51	0,10
0,00	0,64	0,28	0,54
0,25	0,61	0,19	0,15
0,14	0,35	0,01	0,14
0,00	0,00	0,00	0,00
0,00	0,00	0,01	0,00
0,00	0,01	0,04	0,07
0,00	0,02	0,28	0,81
0,00	0,00	0,73	0,00
0,00	0,00	0,02	0,00
0,00	0,00	0,05	0,00

Errore Teorico Percentuale ΔY (%)			
He4	D	Li	He3
0,07	2,6	10,7	3,7

k	Reaction	SKM93	Cyburt01	Des03	Cyburt04
1	n lifetime				
2	p(n,g)d	0,07	0,0445	0,0400	0,0250
3	d(p,g)3He	0,10	0,1320	0,0500	0,0698
4	d(d,n)3He	0,10	0,0310	0,0300	0,0545
5	d(d,p)t	0,10	0,0159	0,0200	0,0693
6	t(d,n)4He	0,08	0,0401	0,0200	0,0516
7	t(a,g)7Li	0,26	0,0421	0,0400	0,2313
8	3He(n,p)t	0,10	0,0352	0,0150	0,0440
9	3He(d,p)4He	0,08	0,0915	0,0400	0,0730
10	3He(a,g)7Be	0,16	0,1060	0,0800	0,1692
11	7Li(p,a)4He	0,08	0,1140	0,0600	0,0802
12	7Be(n,p)7Li	0,09	0,0387	0,0070	0,0625

$^3He + ^4He \rightarrow 7Be + \gamma$ and solar neutrinos



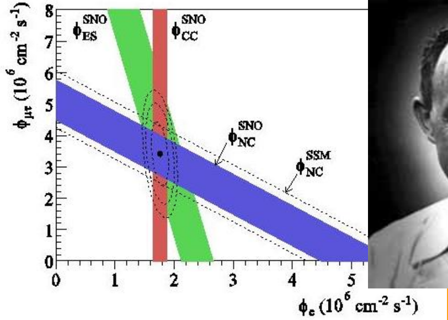
It determines the branch between ppII+ppIII with respect to ppI

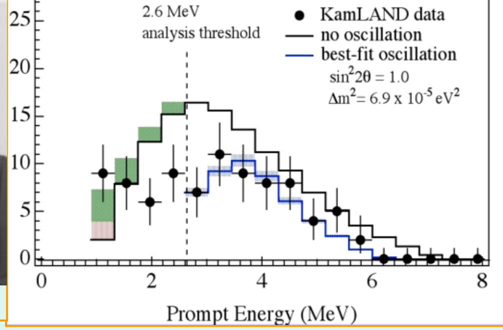
$^3He + ^4He \rightarrow$ 7Be+γ and solar neutrinos

- It is the key reaction for predicting the produced neutrino flux from ^7Be in the Sun, which will be measured by KamLAND and/or Borexino

$$\Phi(Be)/\Phi(pp) \propto S_{34}/S_{33}^{1/2}$$

- S_{33} at solar energy has been measured by LUNA with 6% accuracy.
- S_{34} is now the main source of uncertainty

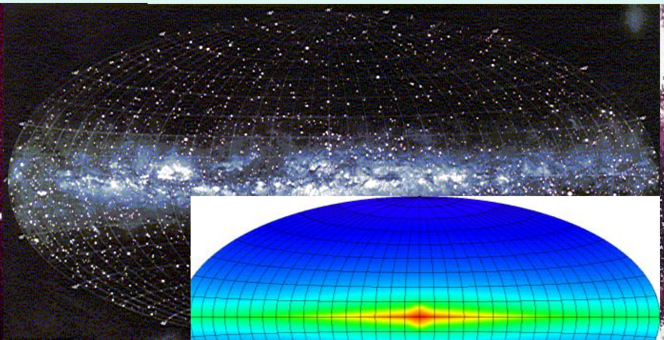


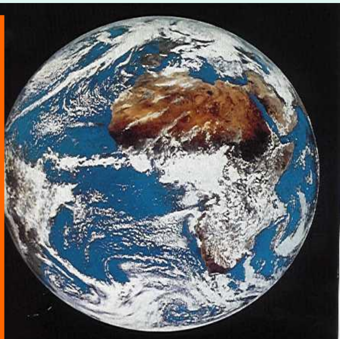


A new era of neutrino physics

- **We have still a lot to learn for a precise description of the mass matrix (and other neutrino properties…), however…**

- **Now we know the fate of neutrinos and we can learn a lot <u>from</u> neutrinos, in particularly on the Sun**



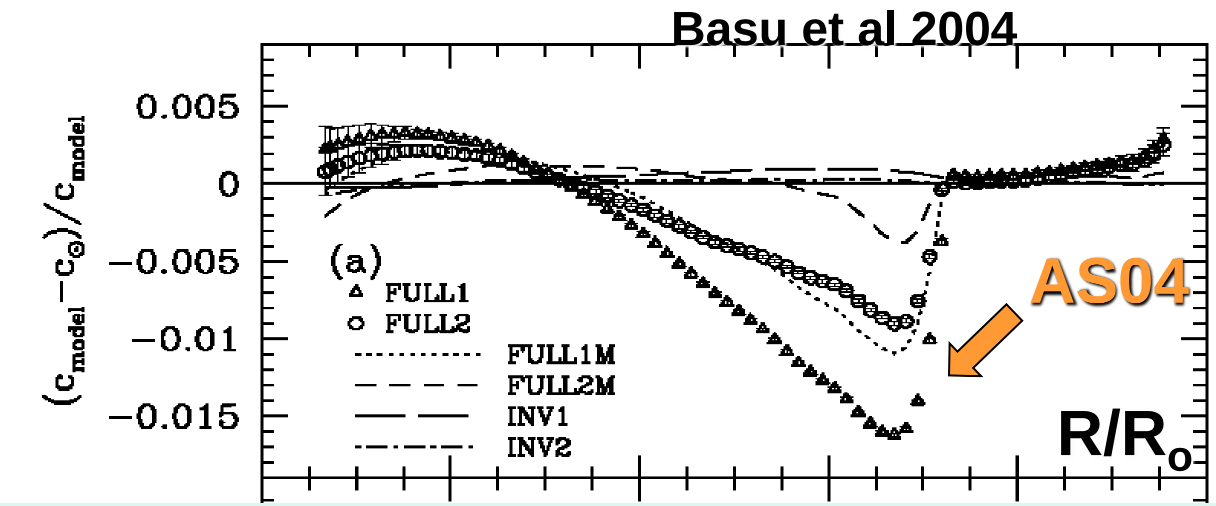


The metal content of the Sun

	A&Gr 89	G&N 93	G&S 98	As 04
C/X	0.0044	0.0043	0.0040	0.0031
N/X	0.0016	0.0013	0.0012	0.0009
O/X	**0.0136**	**0.0119**	**0.0108**	**0.0073**
Z/X	0.0267	0.0245	0.0230	0.0176

- Estimated oxygen abundance halved and total metal content decreased by 1/3 in the last fifteen years.
- With the progress of photospheric observations, our uncertainty on the metal content of the solar photosphere has grown.

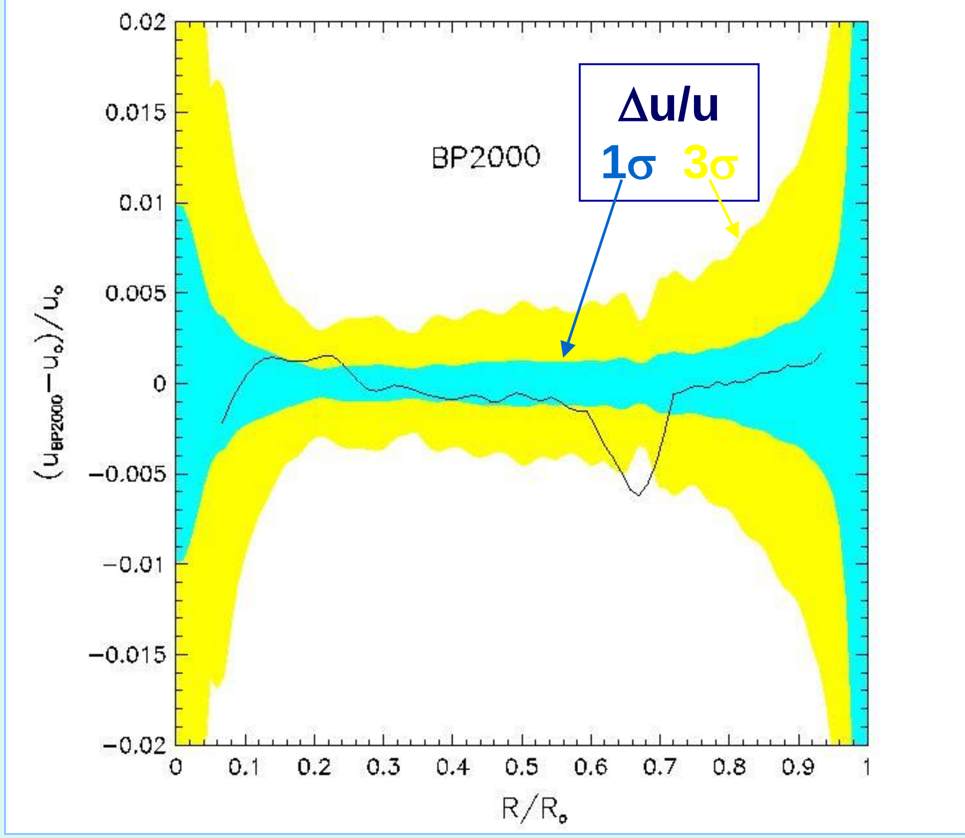
Warning: recent "crisis" of solar models



- When new (AS04) photospheric metal abundances are included in solar models agreement with helioseismology is "destroyed".
- Less metals means smaller opacity and the bottom of the convective zone rises.
- Possibly the knowledge of opacity (at bottom of C.E.) is not so good and the previous excellent agreement was somehow accidental.

The two probes of the solar interior

- Helioseismology measures sound speed.
- Its accuracy (10^{-3} on the sun average) degrades near the center (to 10^{-2})



- Boron (and Be) neutrinos test the central part of the Sun.
- They are essentially sensitive to temperature and can provide measurement to few 10^{-3}

•Temperature in the solar core depends on opacity, i.e. essentially on the metal content

•May be neutrinos can tell us the metal content of the solar interior?

The significance of ^8B neutrinos

- SNO+SK have meaured produced Φ(B) with 7 % uncertainty
- Nuclear physics uncertainties now dominated by **S_{34}**
- Dominant uncertainty now from metal abundance (**Com**)
- For the first time we can learn from neutrinos on the Sun

Source	ΔX/X	$\Delta\Phi_B/\Phi_B$
S_{33}	0.06	0.03
S_{34}	0.09	0.08
S_{17}**	0.05	0.05
S_{e7}	0.02	0.02
S_{pp}	0.02	0.05
Com	0.15 ?	0.20*?
Opa	0.025	0.05
Dif	0.10	0.03
Lum	0.004	0.03

- **New measurement of S_{34} in the energy region pertinent to the Sun are thus important**

What do we (not) know theoretically about solar neutrino fluxes?

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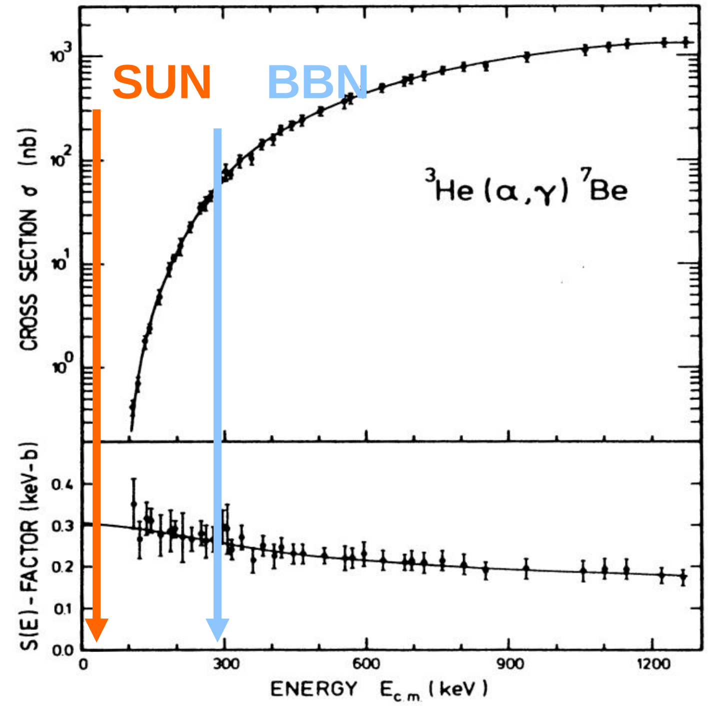
M. H. Pinsonneault
Department of Astronomy, Ohio State University, Columbus, OH 43210

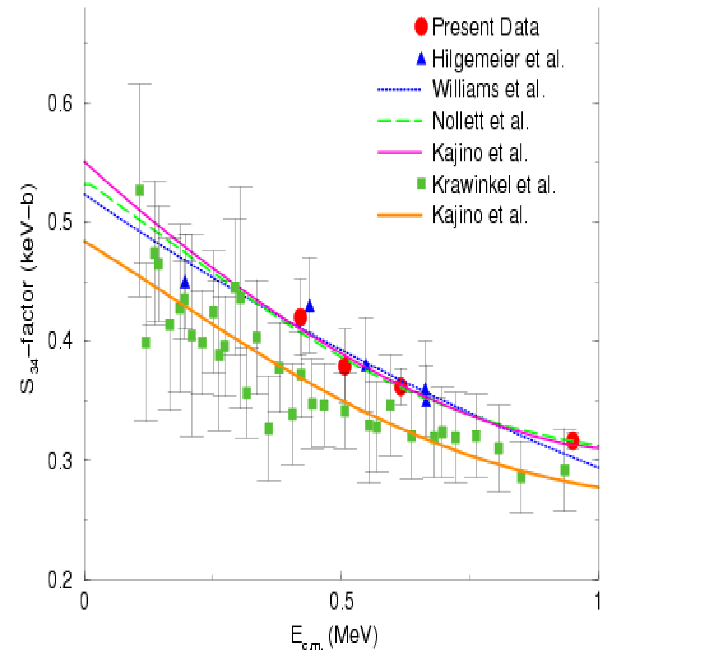
Solar model predictions of ^{8}B and p-p neutrinos agree with the experimentally-determined fluxes (including oscillations): $\phi(\mathrm{pp})_{\mathrm{measured}} = (1.02 \pm 0.02 \pm 0.01)\phi(\mathrm{pp})_{\mathrm{theory}}$, and $\phi(^8\mathrm{B})_{\mathrm{measured}} = (0.88 \pm 0.04 \pm 0.23)\phi(^8\mathrm{B})_{\mathrm{theory}}$, 1σ experimental and theoretical uncertainties, respectively. We use improved input data for nuclear fusion reactions, the equation of state, and the chemical composition of the Sun. The solar composition is the dominant uncertainty in calculating the ^{8}B and CNO neutrino fluxes; the cross section for the $^3\mathrm{He}(^4\mathrm{He},\gamma)^7\mathrm{Be}$ reaction is the most important uncertainty for the calculated ^{7}Be neutrino flux.

"…..The rate of the reaction 3He(4He,γ)7Be is the largest nuclear physics contributor to the uncertainties in the solar model predictions of the neutrino fluxes in the p-p chain. In the past 15 years, no one has remeasured this rate; it should be the highest priority for nuclear astrophysicists. "

The experimental situation

- Existing data look internally inconsistent, to the 10-20% level
- No measurement since 15 years
- There are important motivations (BBN and SUN) for new measurements
- A program to be pursued with extreme decision.





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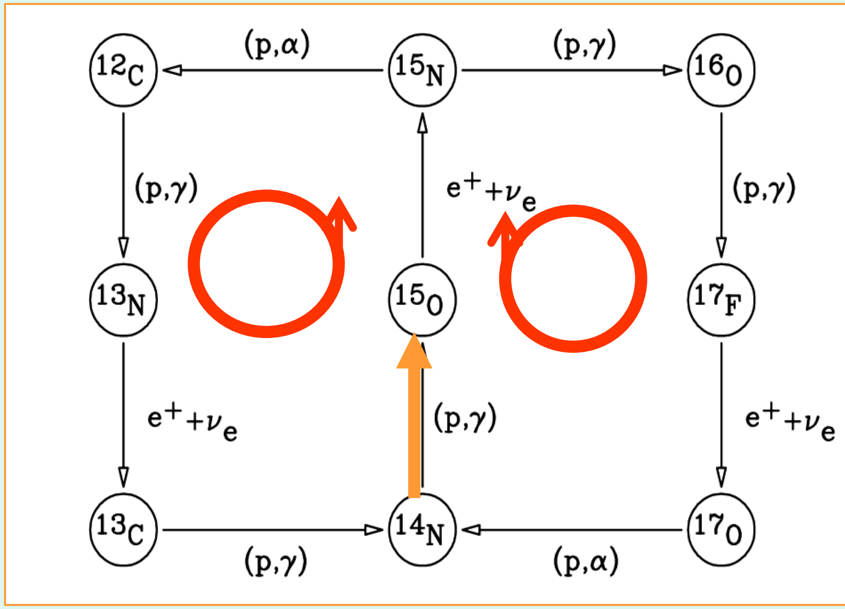
…The cross section for the reaction $^{14}N(p,\gamma)^{15}O$ is the largest nuclear physics contributor to the uncertainties in the calculated CNO neutrino fluxes. It is important to measure this cross section more accurately in order to understand well energy production in stars heavier than the Sun…

CNO neutrinos, LUNA and the solar interior



- Solar model predictions for CNO neutrino fluxes are not precise because the CNO fusion reactions are not as well studied as the pp reactions.

- For the key reaction $^{14}N(p,\gamma)^{15}O$ the NACRE recommended value:

$$S_{1,14}=(3.2\pm0.8)\text{keV b}$$

mainly based on Schroeder et al. data.

- Angulo et al. reanalysed data by Schroeder et al. within an R-matrix model, finding:

$$S_{1,14} \rightarrow ½\ S_{1,14}$$

- **The new measurement by LUNA is obviously important**

$S_{1,14}=(1.7\pm0.2)$keV b

What if $S_{1,14}$->1/2 $S_{1,14}$?

The $^{14}N(p,\gamma)^{15}O$ reaction, solar neutrinos and the age of the globular clusters

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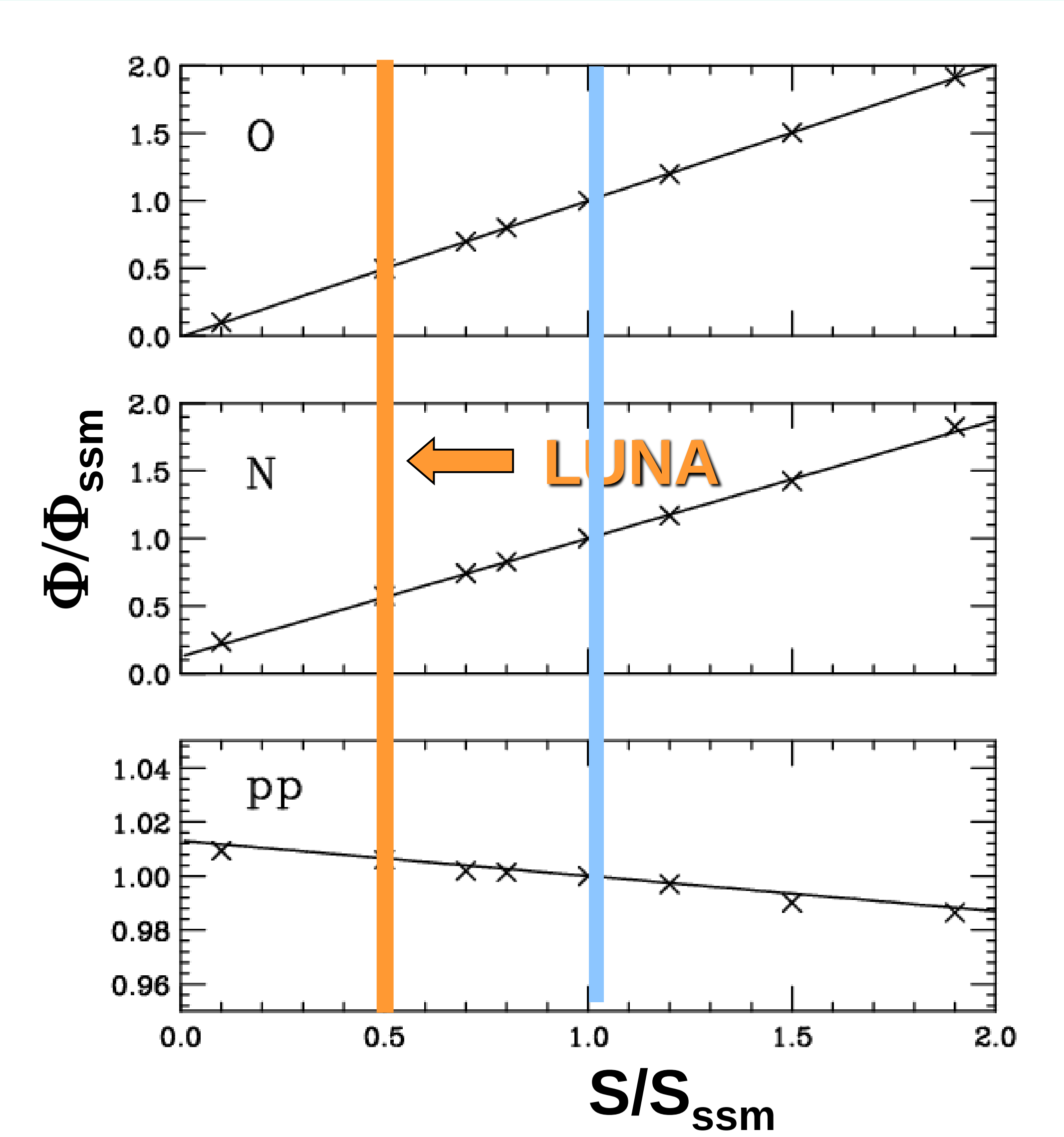
20 Dec 2003

Abstract

We discuss implications of a new measurement of $^{14}N(p,\gamma)^{15}O$ concerning solar neutrinos, solar models and globular cluster dating. Predictions for the gallium and chlorine experiments are reduced by 2 and 0.1 SNU respectively. Predictions for helioseismic observables are unchanged within uncertainties. The age of globular clusters as deduced from the Turn-Off luminosity is increased by about 0.7 Gyr.

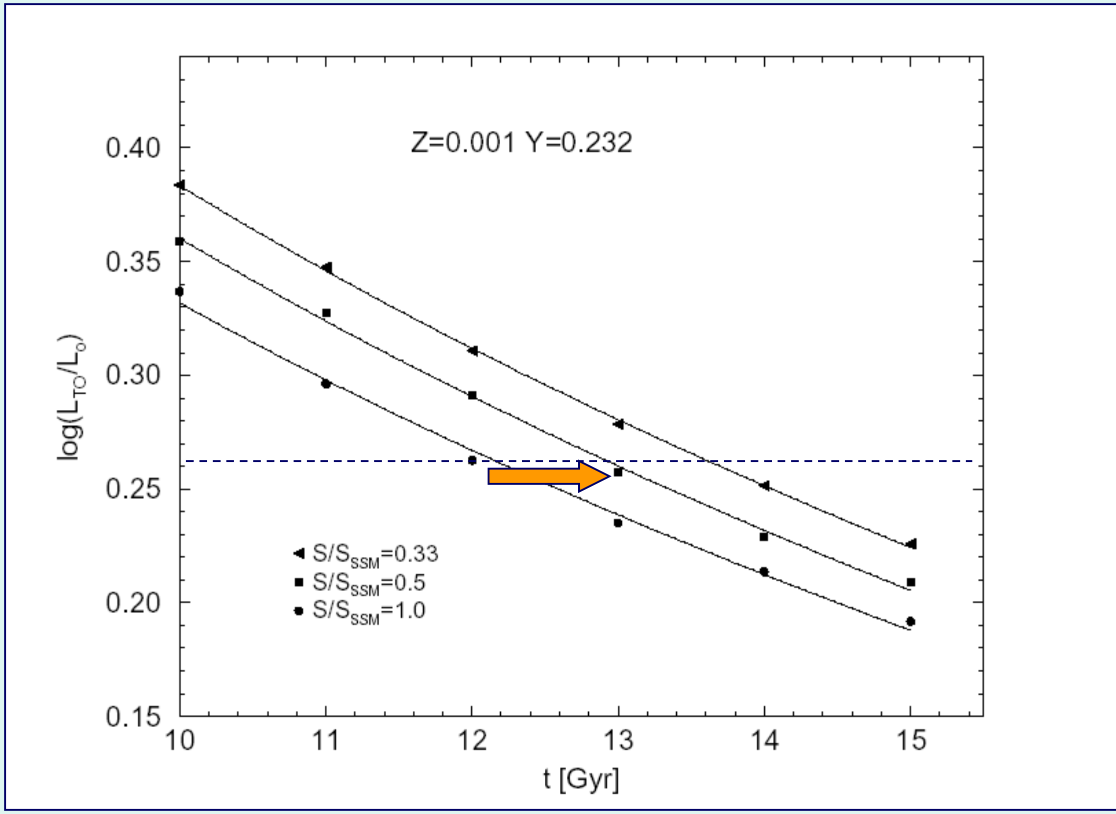
What if $S_{1,14}$->1/2 $S_{1,14}$ in the Sun?

- Neutrino fluxes from N and O are halved
- pp-neutrinos increase, so as to keep total fusion rate constant
- The SSM+LMA signal for Ga and Cl expts decrease by 2.1 and 0.12 SNU.
- It alleviates the (slight) tension between th. and expt. for Chlorine.



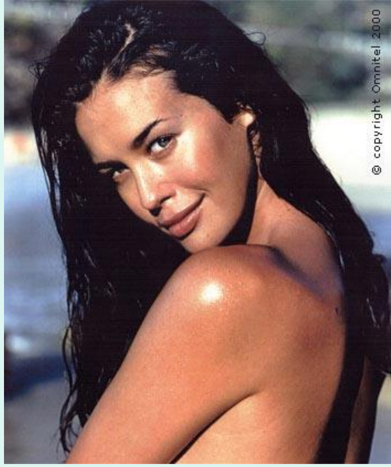
What if $S_{1,14}$->1/2 $S_{1,14}$ in the Galaxy?

- Smaller $S_{1,14}$ means smaller CNO efficiency
- It affects globular clusters evolution near turn off (Brocato et al 96) changing the relationship between Turnoff Luminosity and Age.
- Turn Off is reached later and with higher luminosity
- Galaxy age is increased by about 0.7 Gyr



Determination of globular clusters ages is presently affected by several uncertainties (chemical composition, the adopted physical inputs the efficiency of diffusion, comparison between theor. and observed luminosity…) the total uncertainty being 1-2 GYr

Carbon and Oxygen in the Universe



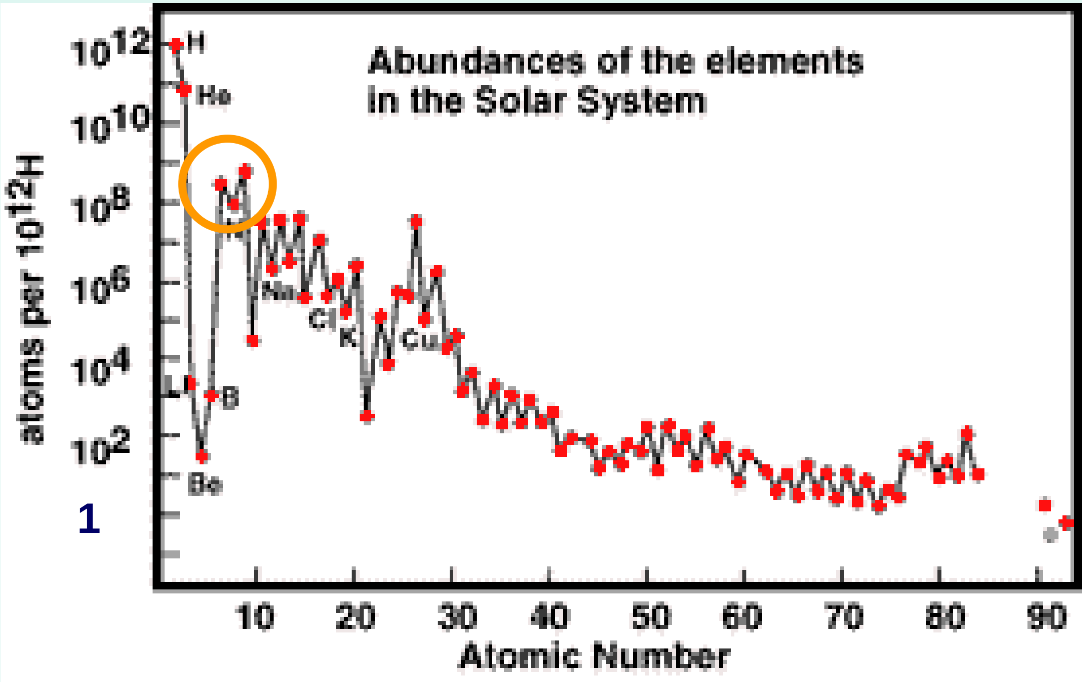
•After H and He, Carbon and Oxygen are the two most abundant/important elements in the universe

•Carbon is produced by 3 α process.

•In the same environment it is destroyed by

$$^{12}C+\alpha\rightarrow {}^{16}O+\gamma$$

The C/O ratio we live in is from a delicate balance of competing reactions

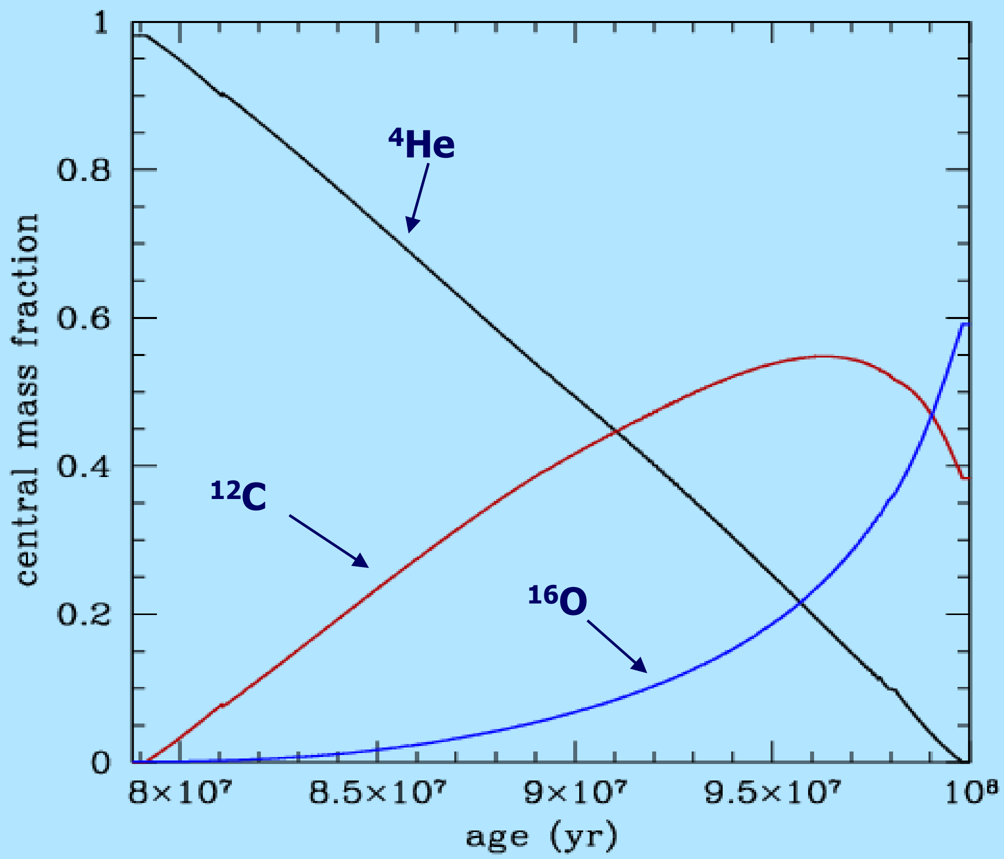


He-burning: the competition between

$3\alpha \to {}^{12}C$ and ${}^{12}C+\alpha \to {}^{16}O+\gamma$

5 $M_\odot$

Z=0.02
Y=0.28



O. Straniero

Informal Meeting on 12C(a,g)16O

- Ferrara 26-30 April 2004 -

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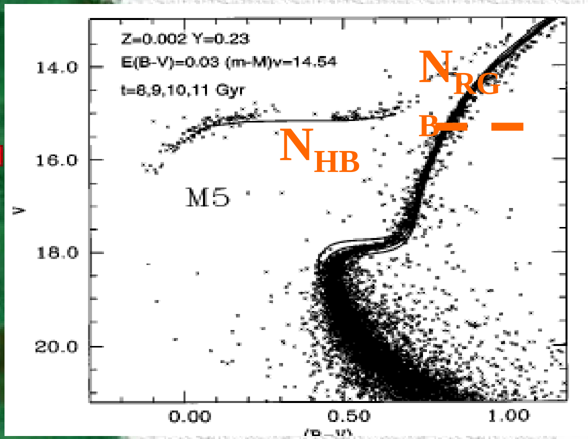
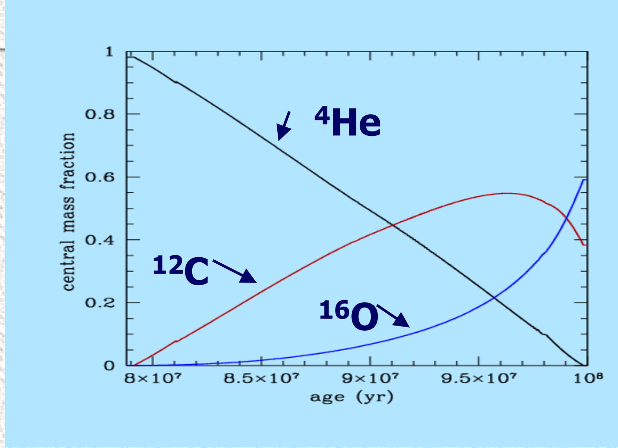
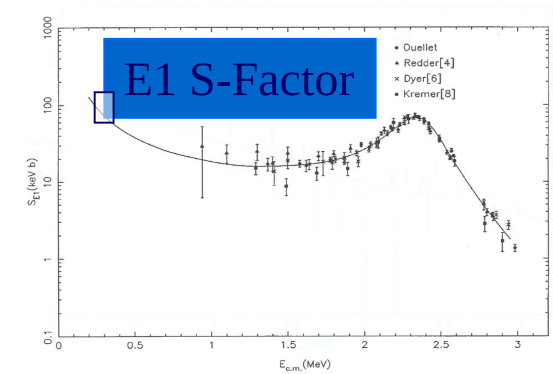
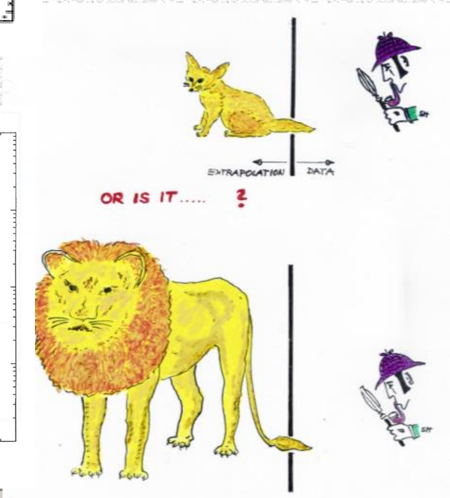
Informal Meeting on 12C(a,g)16O

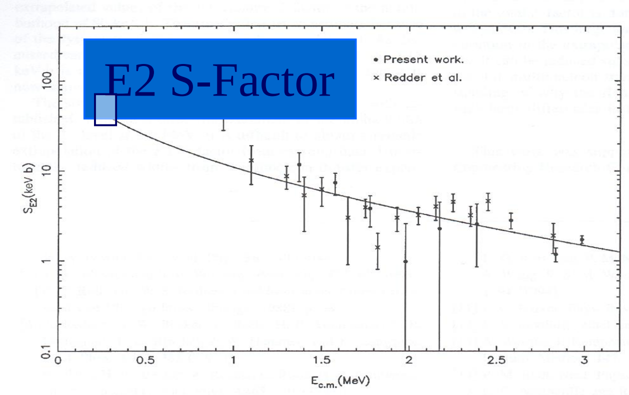


- Program
- List of Participants
- Transparencies





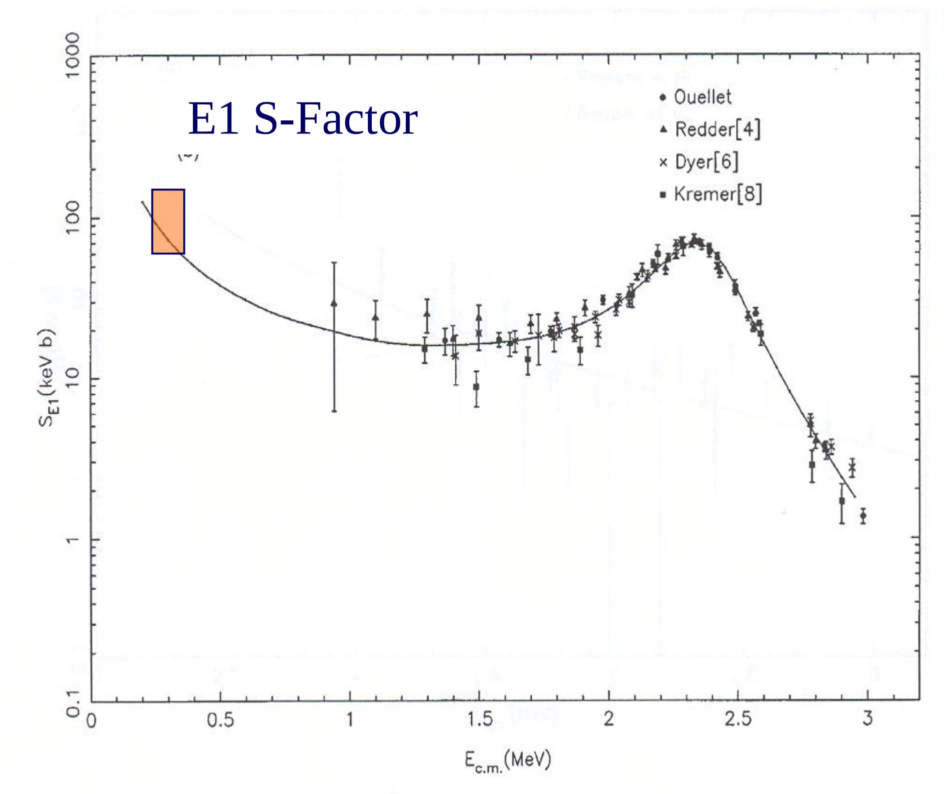


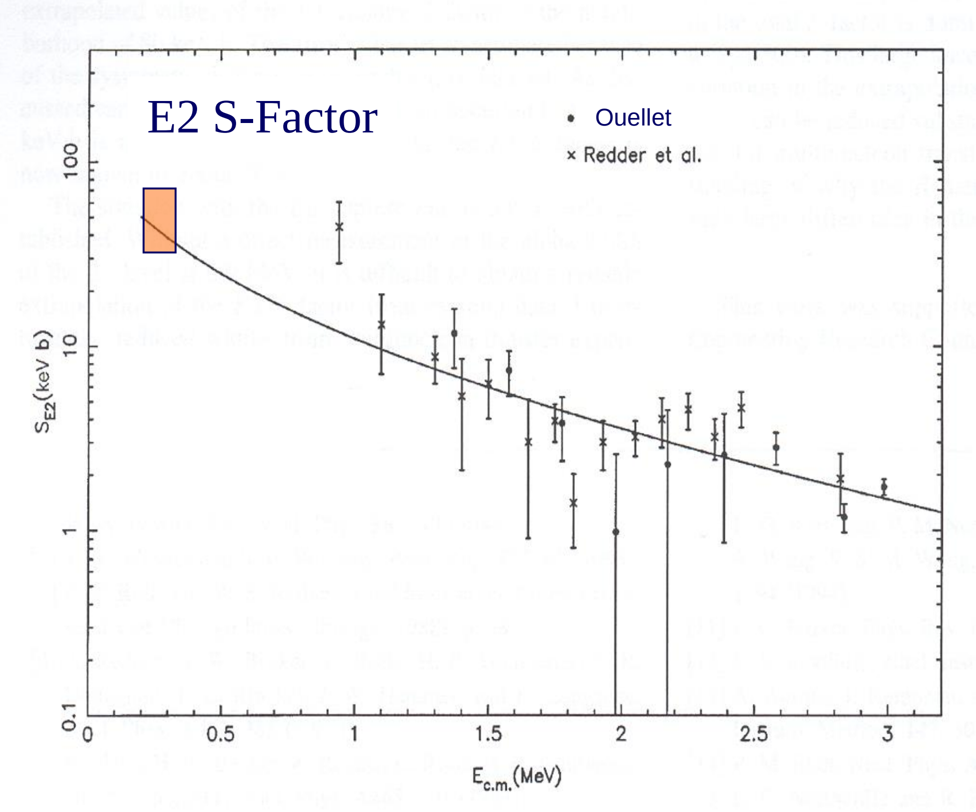


The relevance of $^{12}C(\alpha,\gamma)$

- Castellani: want to know if the Sun ends up in a diamond
- Internal C/O content of dwarfs “almost measurable” with asteroseismology
- The time spent by stars in horizontal branch depends on $^{12}C(\alpha,\gamma)$ (more energy available and thus more time if $C\rightarrow 0$)
- All subsequent nucleosynthesis and explosion mechanism influence by $^{12}C(\alpha,\gamma)$
- Presently uncertainties on diffusion treatment are mixed with those from $^{12}C(\alpha,\gamma)$ and should be disentangled

Summary of experimental results





- The relevant energy is near 300 keV, data are above 1MeV
- Available data have to be extrapolated by an order of magnitude
- S(300 KeV) is known, perhaps, with an uncertainty of ±100%

The experimental problems of $^{12}C(\alpha,\gamma)$

- Barnes: " $^{12}C(\alpha,\gamma)$ is not for amateurs"

- If ^{12}C is used as a target, ^{13}C produces background from the strong interaction:

$$\alpha + {}^{13}C \rightarrow {}^{16}O + n$$

- If ^{12}C is used as a beam, then intensity is much smaller

- Interesting approach opened by ERNA

$^{12}C(\alpha,\gamma)$ underground?

- Surely one can benefit from low background environment (e.g. go underground) if other backgrounds are reduced.
- So far ingenious experiments, may be with relatively poor-man detectors.

What else might be studied underground?

$^{12}C(\alpha,\gamma)$, $^{16}O(\alpha,\gamma)$ *Supernovae ~ He burning*

$^{14}N(\alpha,\gamma)$
$^{18}O(\alpha,\gamma)$
$^{22}Ne(\alpha,\gamma)$
} *AGB stars ~ s process*

$^{14}N(p,\gamma)$
$^{17}O(p,\gamma)$
$^{17}O(p,\alpha)$
} *Red giants ~ CNO cycle*

$^{22}Ne(p,\gamma)$
$^{23}Na(p,\alpha)$
$^{24}Mg(p,\gamma)$
} *Globular clusters ~ Ne/Mg/Na cycles*

^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}Ar, $^{40}Ca(\alpha,\gamma)$ *Supernova nucleosynthesis*

[J.C. Blackmon, Physics Division, ORNL]

Summary

- INFN experimental groups in N.A, all born in the last 12 years, are and look strong.
- Have devised new methods:
  - troian horses,
  - Nuclear Recoil spectrometry approach to $^{12}C(\alpha,\gamma)$
  - Everybody in the world envies the Italian underground lab. for N.A.

- $^{3}He+^{4}He$ has to be studied both near solar and BBN energies
- A new effort for $^{12}C(\alpha,\gamma)$ (underground?) has to be planned

Thanks to C. Bambi B. Ricci and F. Villante

Uncertainty budget BP04

Source	3-3	3-4	1-7	1-14	Opac	Diff	$L_\odot$	Z/X
pp	0.002	0.005	0.000	0.002	0.003	0.003	0.003	0.010
pep	0.003	0.007	0.000	0.002	0.005	0.004	0.003	0.020
hep	0.024	0.007	0.000	0.001	0.011	0.007	0.000	0.026
^{7}Be	0.023	0.080	0.000	0.000	0.028	0.018	0.014	0.080
^{8}B	0.021	0.075	0.038	0.001	0.052	0.040	0.028	0.200
^{13}N	0.001	0.004	0.000	0.118	0.033	0.051	0.021	0.332
^{15}O	0.001	0.004	0.000	0.143	0.041	0.055	0.024	0.375
^{17}F	0.001	0.004	0.000	0.001	0.043	0.057	0.026	0.391