L’esperimento LUNA fa luce sulla densità della materia barionica

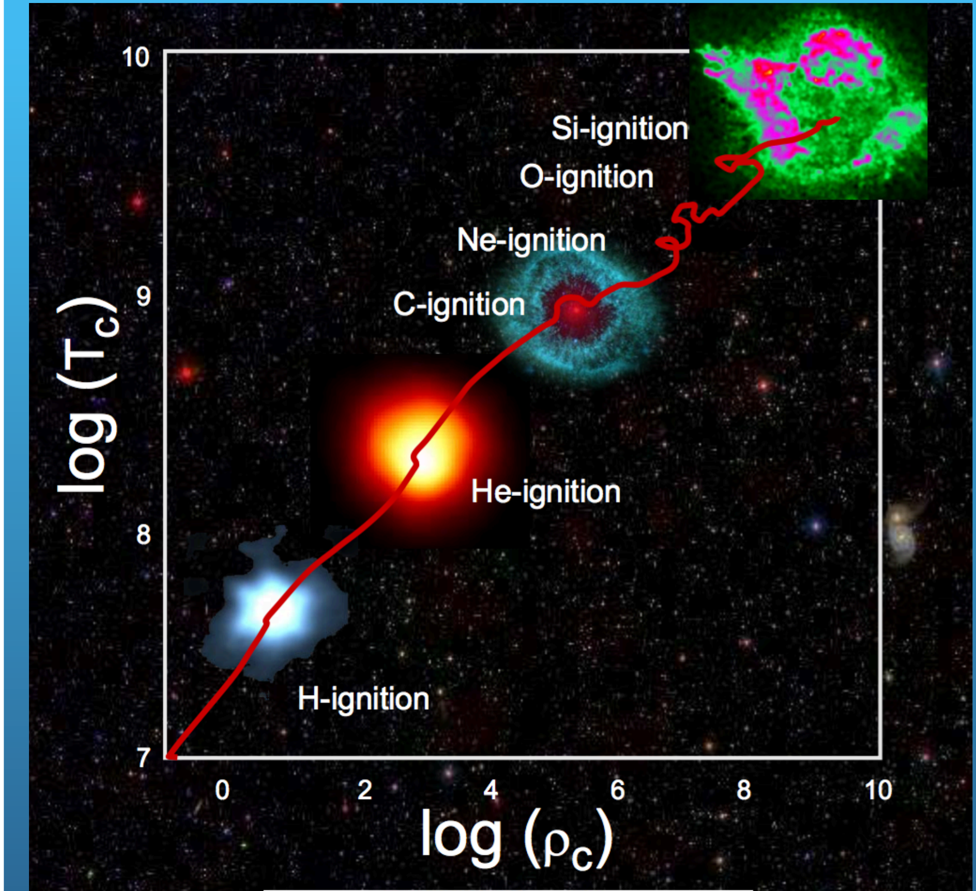
S. Zavatarelli

a nome del Gruppo LUNA di Genova

Talk outline

- Perche' si fanno esperimenti di astrofisica nucleare in laboratori sotterranei?
- L'esperimento LUNA (combustione H congli acceleratori da 50 & 400 kV)
    - Il primo risultato (3He+3He-> problema dei neutrini solari)
    - Il piu' recente (p+d -> BBN)
- Il futuro : il progetto LUNA-MV (combustione He, C, fasi post-sequenza principale)

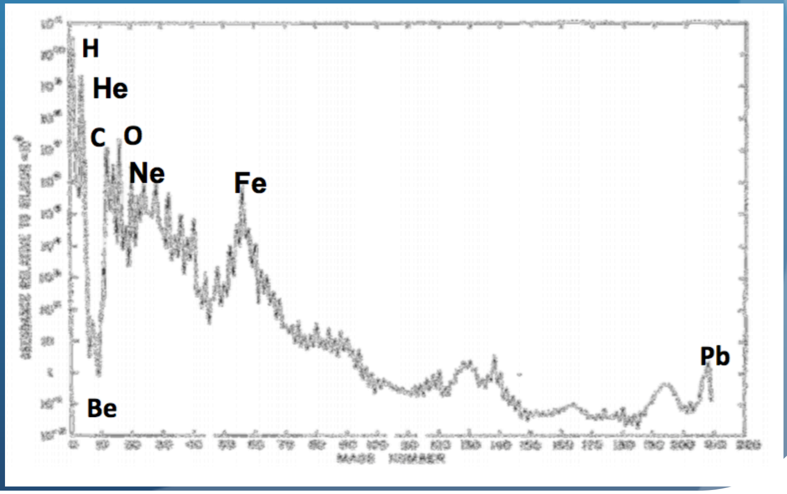
Why nuclear astrophysics?



For a 15 M_{sun} star:

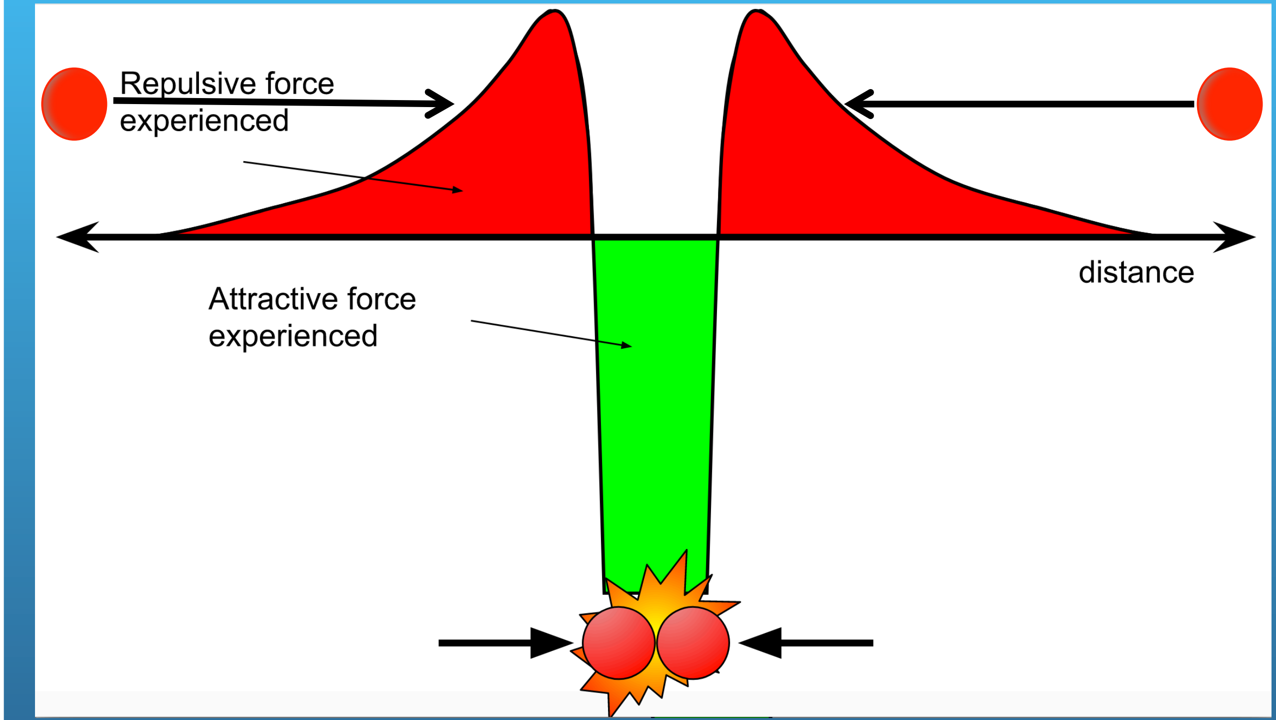
Reaction	Timescale
Hydrogen burning	10 million years
Helium burning	1 million years
Carbon burning	300 years
Oxygen burning	200 days
Silicon burning	2 days

- ✓Nuclear reactions determine the abundances of the elements in the cosmos, stellar evolution and dynamic
- ✓ Many reactions ask for high precision data



Precise direct measurement at stellar energies… Not an easy task!

Low cross sections!!!! Why???



Coulomb barrier

$$V_C = \frac{e^2}{4\pi\varepsilon_0}\frac{Z_a Z_b}{R_a + R_b}$$

$V_c \sim$ MeV

Typical termal energies : 10-100 keV

The reaction can proceed only through the **TUNNEL EFFECT**

Precise direct measurement at stellar energies… Not an easy task!

low cross sections → low yields → poor signal-to-noise ratio

Yield = N_p x N_t x cross section x detection efficiency

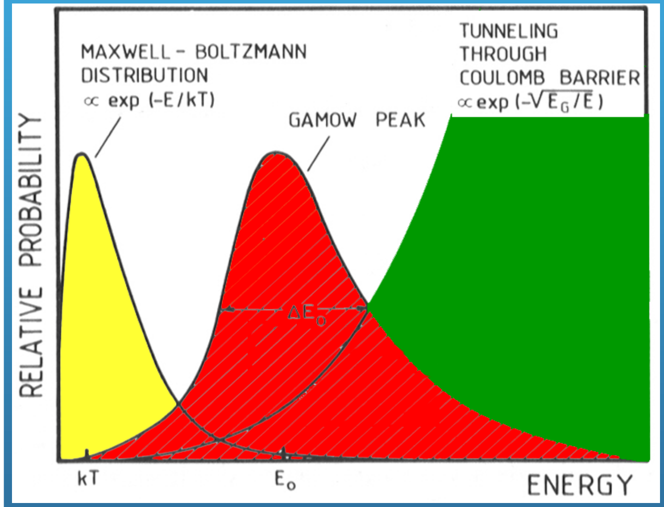
10^{14} pps (~100 μA q=1^+) typical stable beam intensities

10^{19} atoms/cm^2 typical solid state targets

10^{-15} barn (often even smaller)

100% for charged particles

~1-10% for gamma rays (HPGe)



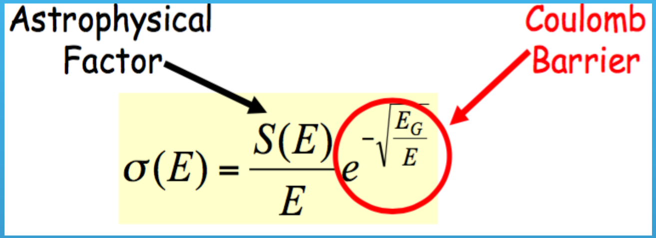
Gamow peak

Y = 0.3-30 counts/year

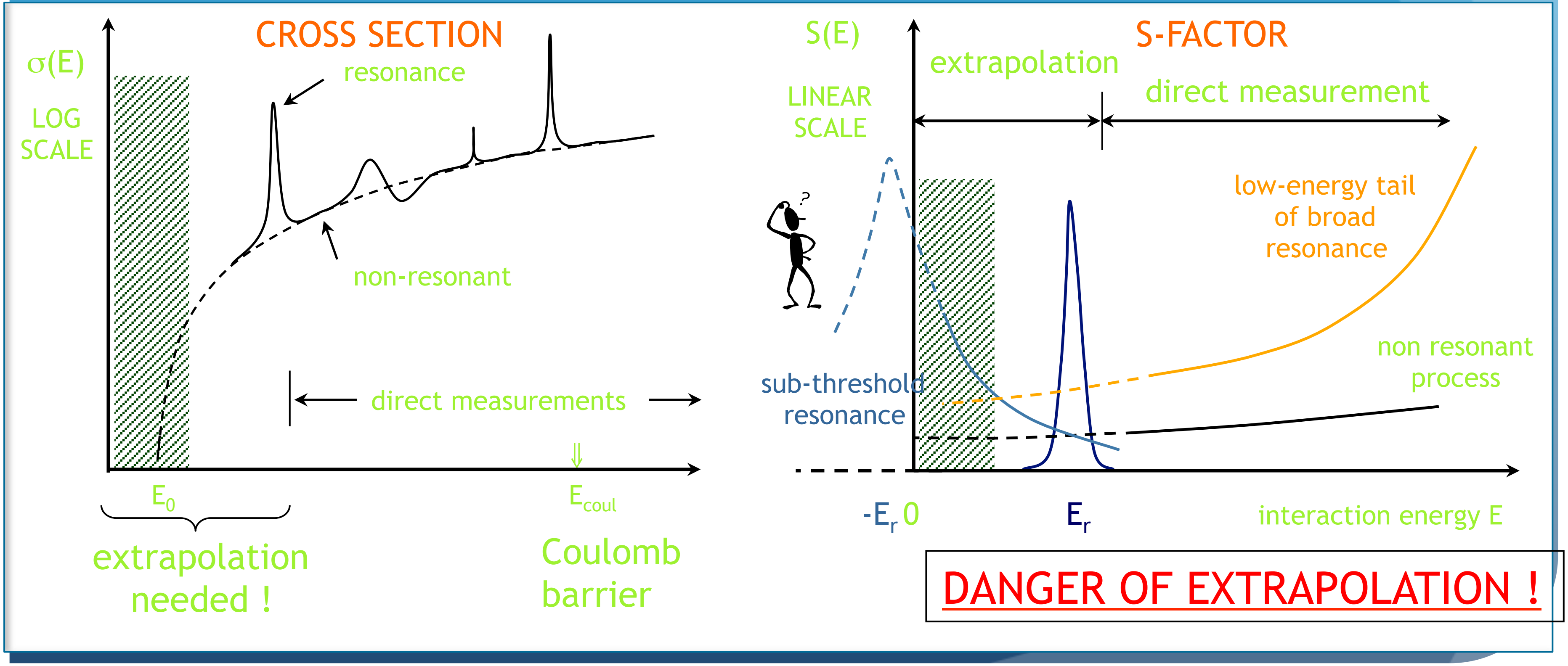
~ 1.2-220 counts/day (background)

Precise direct measurement at stellar energies… Not an easy task!

low cross sections → low yields → poor signal-to-noise ratio



$$\sigma(E) = \frac{S(E)}{E} e^{-\sqrt{\frac{E_G}{E}}}$$



DANGER OF EXTRAPOLATION !

A pivotal encounter..

Nuclei in the Cosmos I, 1990 – Baden/Vienna, Austria

Gianni Fiorentini & Claus Rolfs

Credit : M. Aliotta

Energy production in the Sun

Our Sun has been shining at a constant rate for 5 billion years converting 700 million tonnes of H into He each second

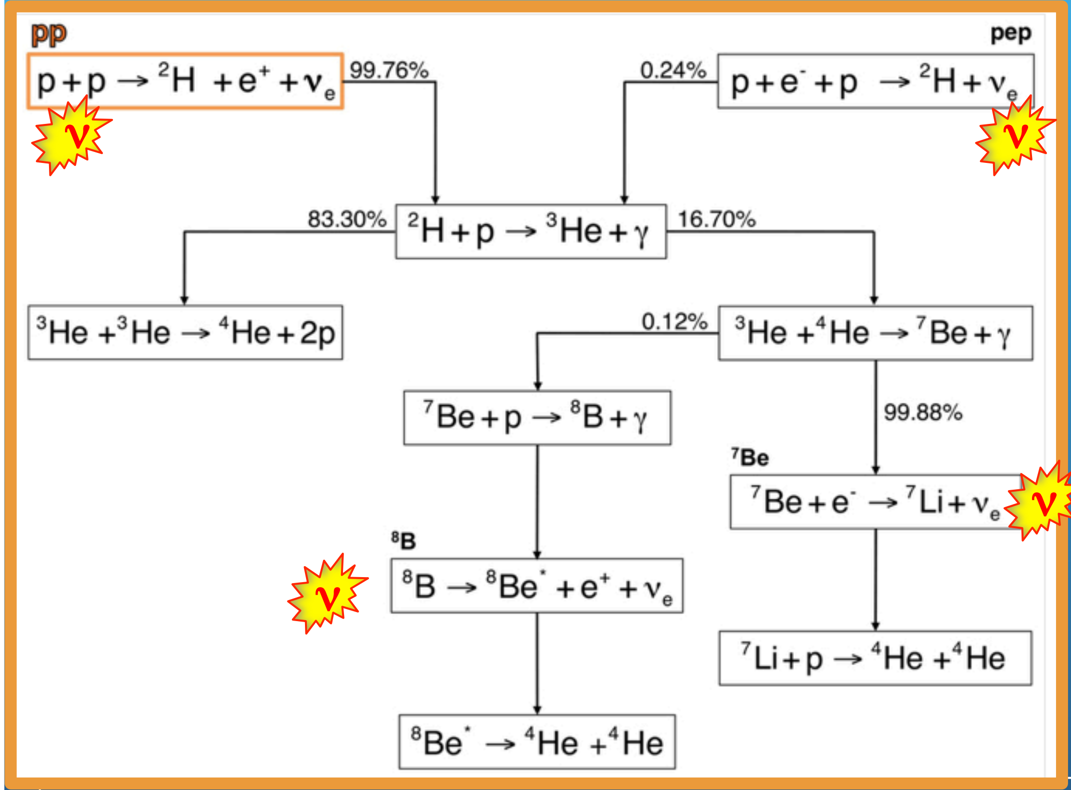
Credit : M. Aliotta

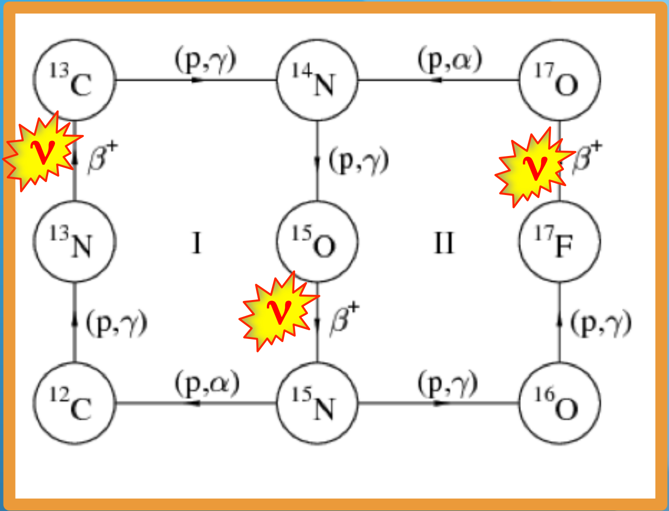
Converting H into He: The Proton-Proton Chain

According to the Standard Solar Model…

pp chain: 99 % of Sun Energy

CNO cycle: <1 % of Sun Energy



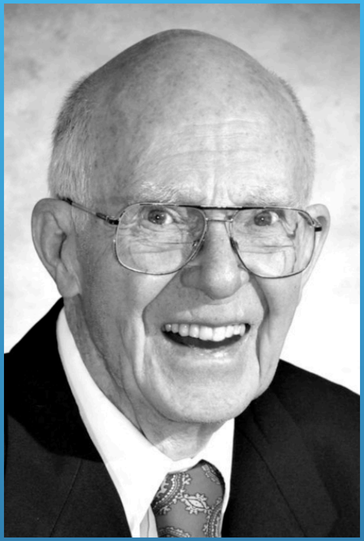


No way of “seeing” what happens in the core of the Sun except if we…

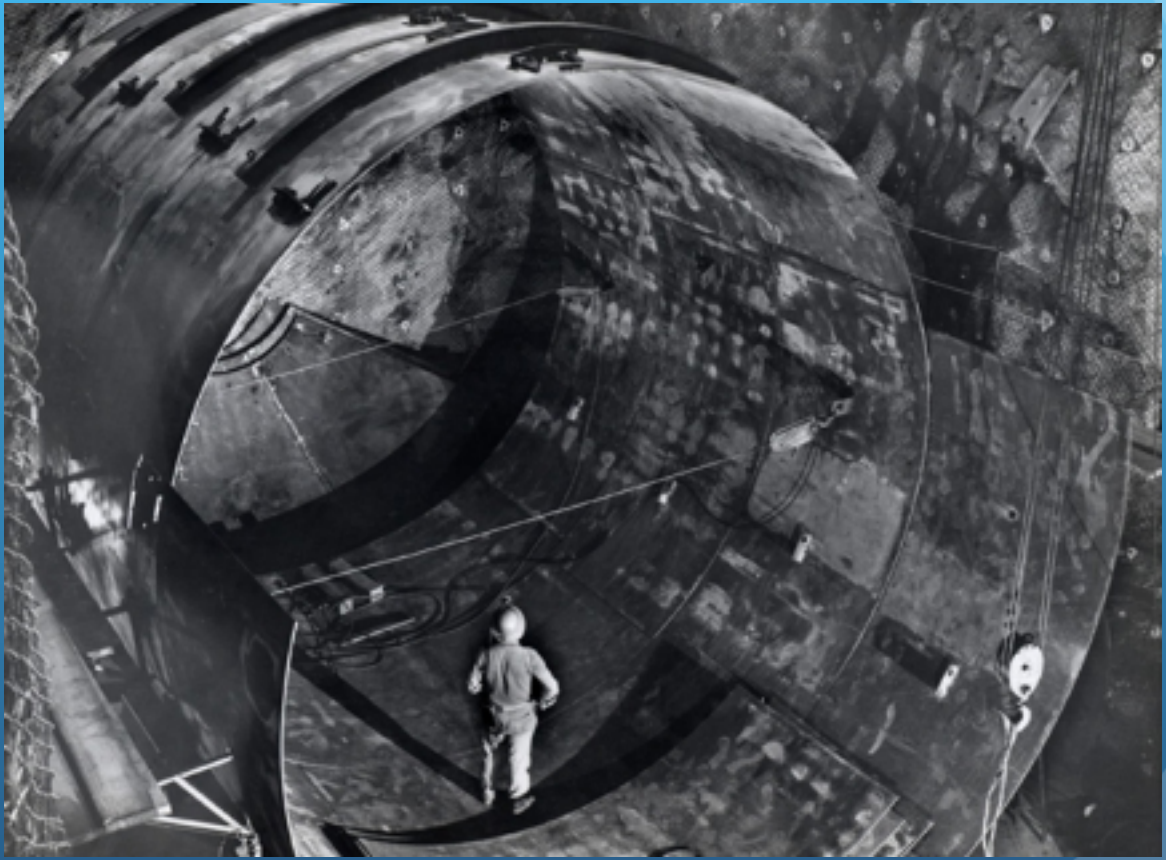
detect neutrinos

Direct evidence of nucleosynthesis in stars

FIRST DIRECT EVIDENCE FOR NUCLEAR REACTIONS IN OUR SUN



Ray Davis Jr.
2002 Nobel Prize

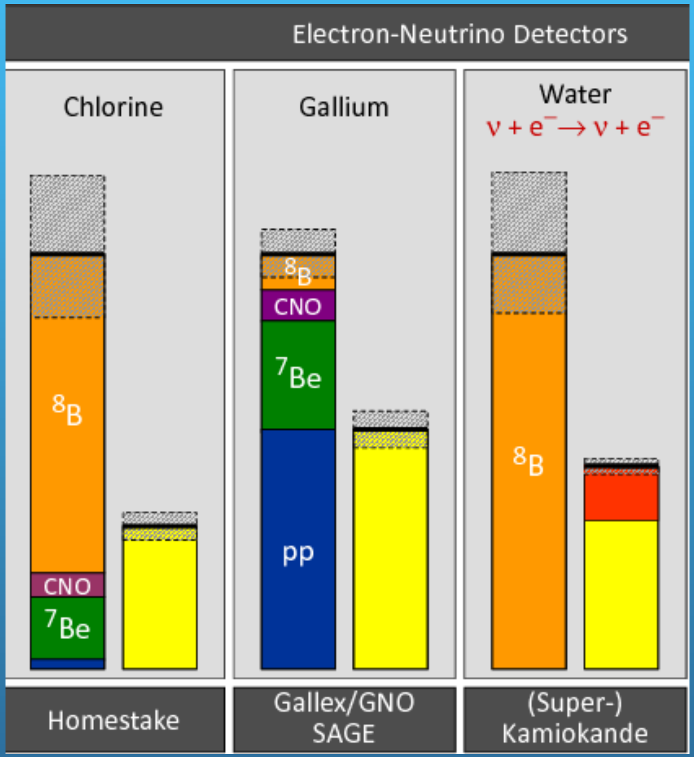


1965: Ray Davis inside chlorine tank used for solar neutrino detection

Credit: Anna Davis

http://sanfordlab.org/article/270

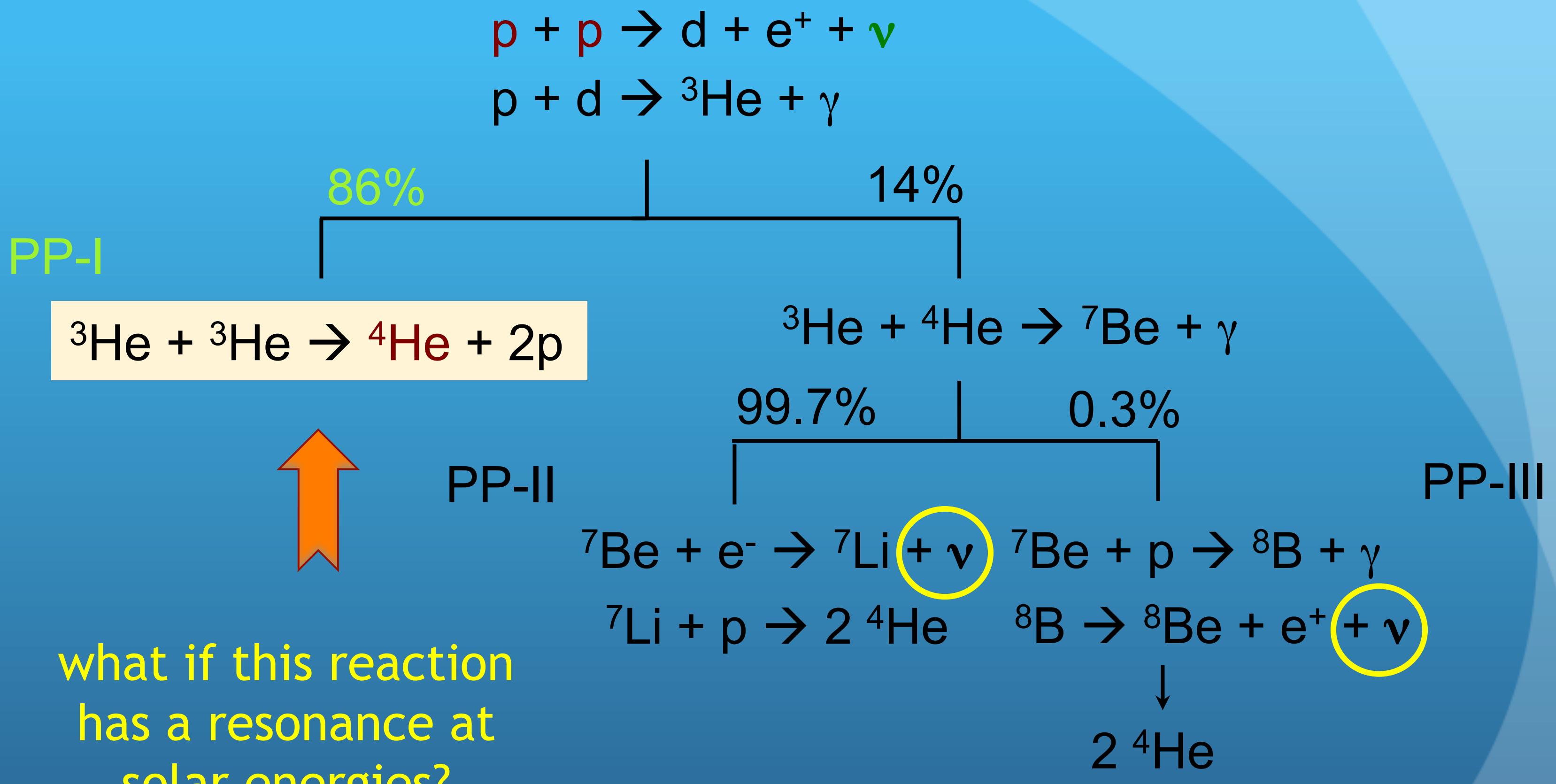
Solar Neutrino Problem



for 30 years all neutrino detection efforts consistently measured **1/3 of expected neutrinos flux** based on **Standard Solar Model**

- wrong assumptions of SSM?
- poor understanding of neutrinos properties?
- unclear nuclear inputs?

A Resonance in $^3He+^3He$ to Solve the Solar Neutrino Problem?



$p + p \rightarrow d + e^+ + \nu$

$p + d \rightarrow {}^3He + \gamma$

86%

14%

PP-I

$^3He + {}^3He \rightarrow {}^4He + 2p$

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

99.7%

0.3%

PP-II

PP-III

$^7Be + e^- \rightarrow {}^7Li + \nu$

$^7Li + p \rightarrow 2\ {}^4He$

$^7Be + p \rightarrow {}^8B + \gamma$

$^8B \rightarrow {}^8Be + e^+ + \nu$

$\downarrow$

$2\ {}^4He$

what if this reaction has a resonance at solar energies?

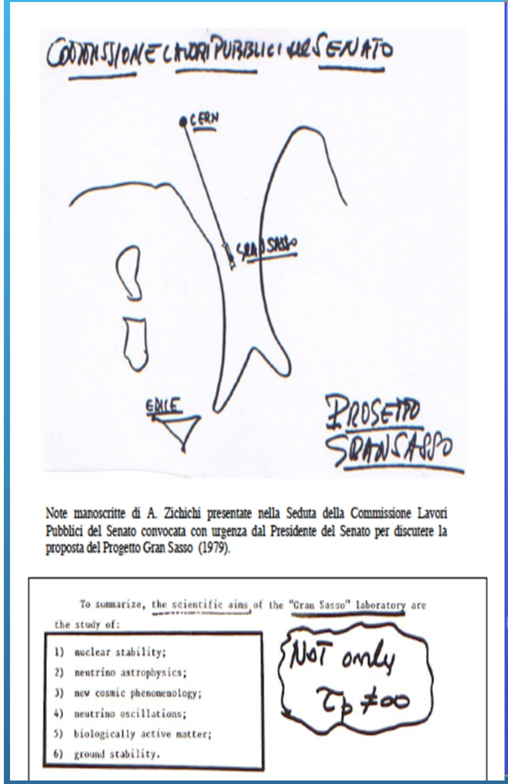
a direct measurement of its cross section was necessary

How to improve the signal-to-noise ratio?

…then they spoke with Piero Corvisiero and LUNA was started

Credit : M. Aliotta

Laboratori Nazionali del Gran Sasso: An Ideal Location



COMMISSIONE LAVORI PUBBLICI DEL SENATO

CERN

GRAN SASSO

ERICE

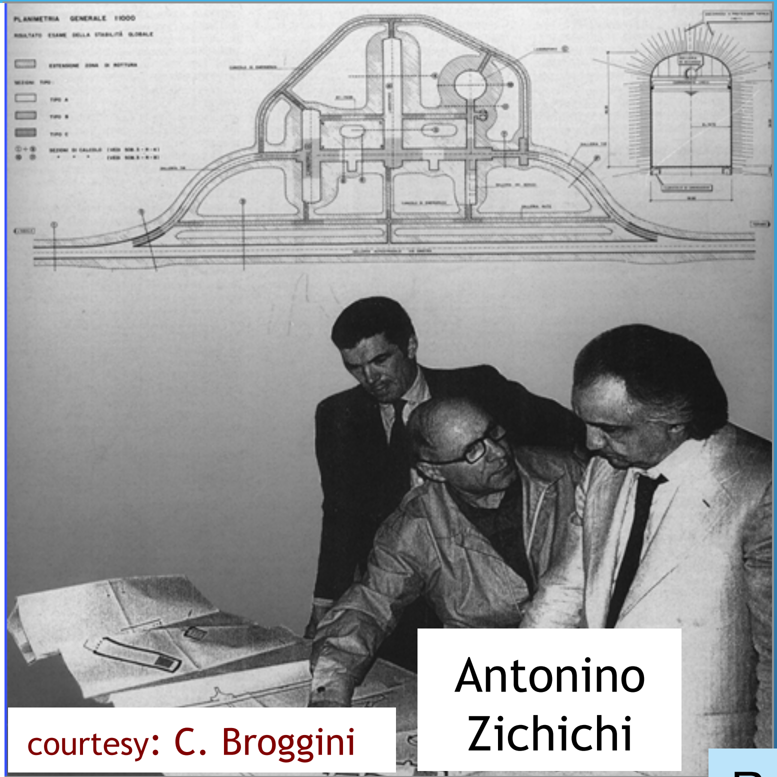
PROGETTO GRAN SASSO

Note manoscritte di A. Zichichi presentate nella Seduta della Commissione Lavori Pubblici del Senato convocata con urgenza dal Presidente del Senato per discutere la proposta del Progetto Gran Sasso (1979).

To summarize, the scientific aims of the "Gran Sasso" laboratory are the study of:

1) nuclear stability;
2) neutrino astrophysics;
3) new cosmic phenomenology;
4) neutrino oscillations;
5) biologically active matter;
6) ground stability.

NOT only $\tau_p \neq \infty$



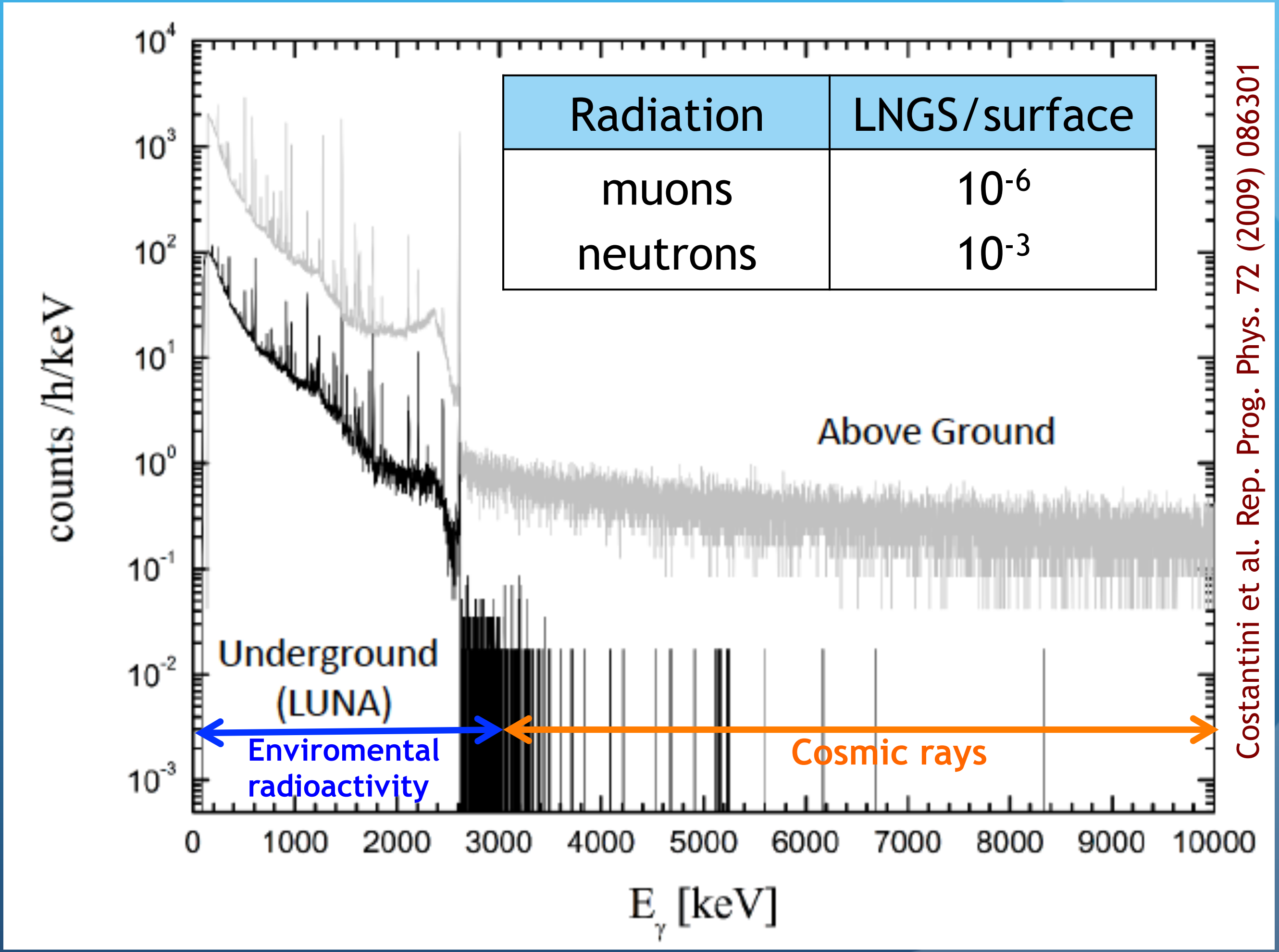
courtesy: C. Broggini

Antonino Zichichi

Radiation	LNGS/surface
Muons	10^{-6}
Neutrons	10^{-3}
Gammas	10^{-2}-10^{-5}

Gamma-ray background: underground vs overground comparison

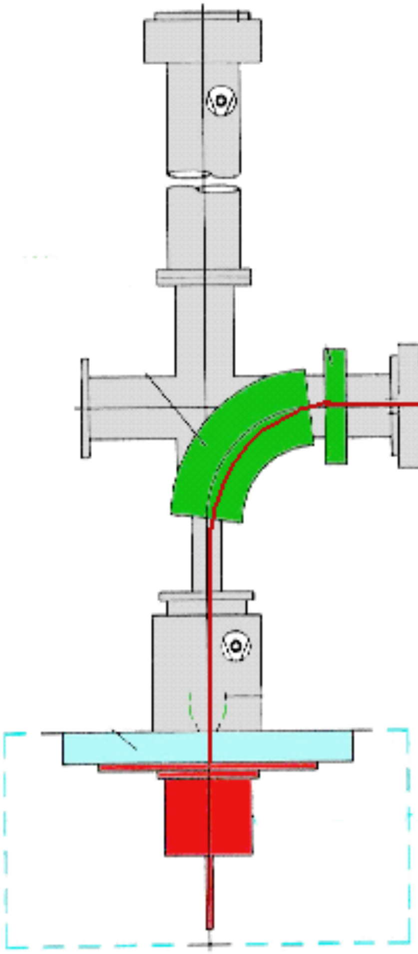
1.4 km rock overburden: million-fold reduction in cosmic background



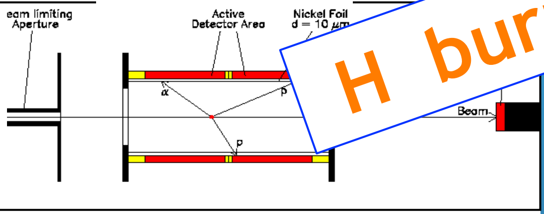
Radiation	LNGS/surface
muons	10^{-6}
neutrons	10^{-3}

Costantini et al. Rep. Prog. Phys. 72 (2009) 086301

LUNA 50 kV accelerator



Energy Range for Protons:
50keV - 3 keV



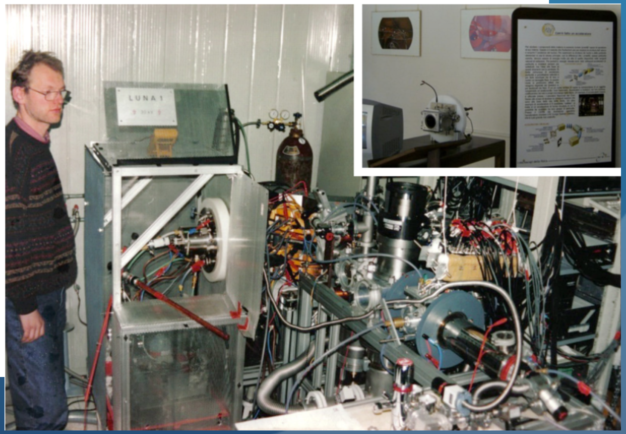
Energy Stability
$\leq 10^{-4}$

H burning

Ions:
p, ^{3}He, ^{4}He

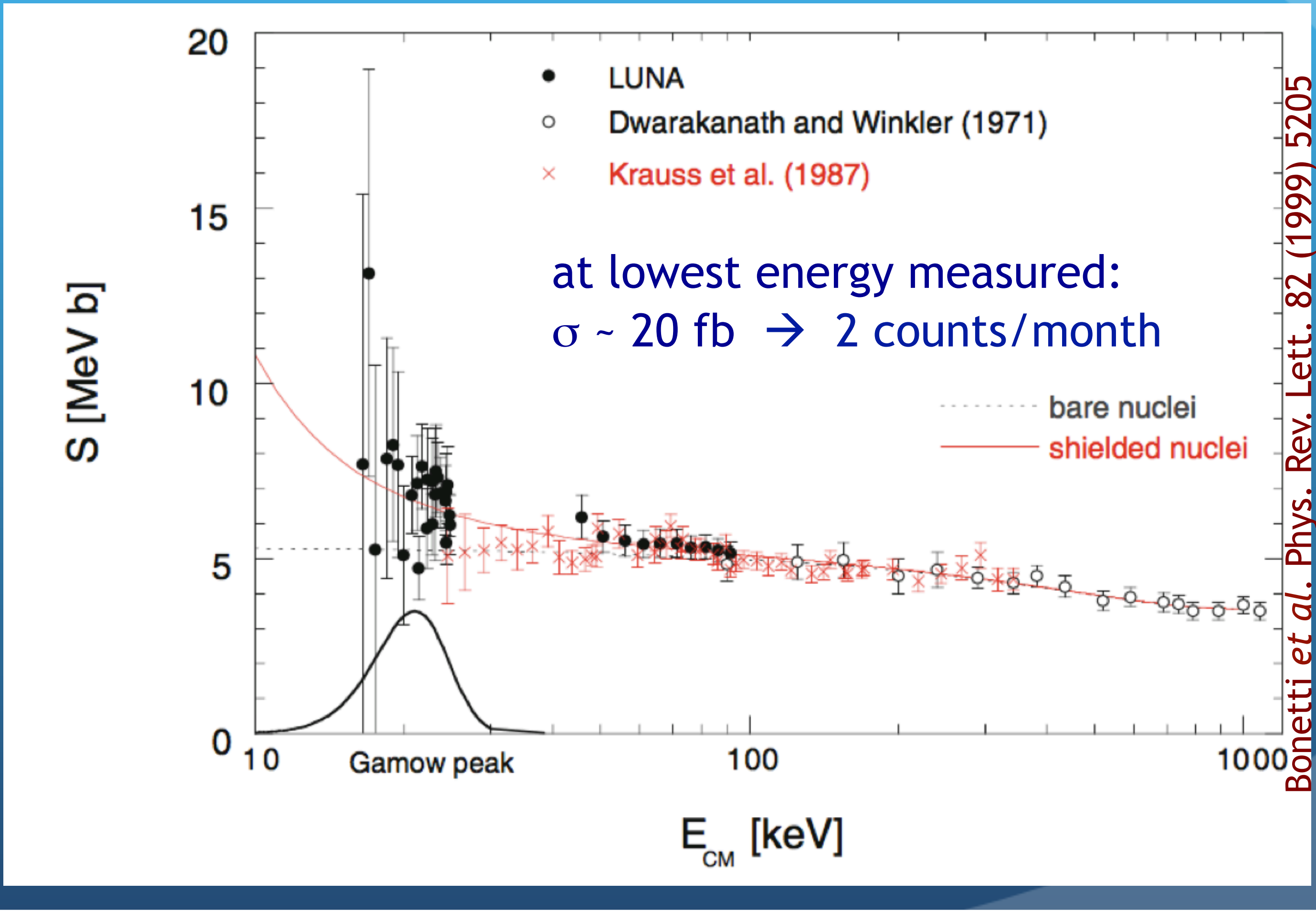
Current:
50- 500 µA

detectors



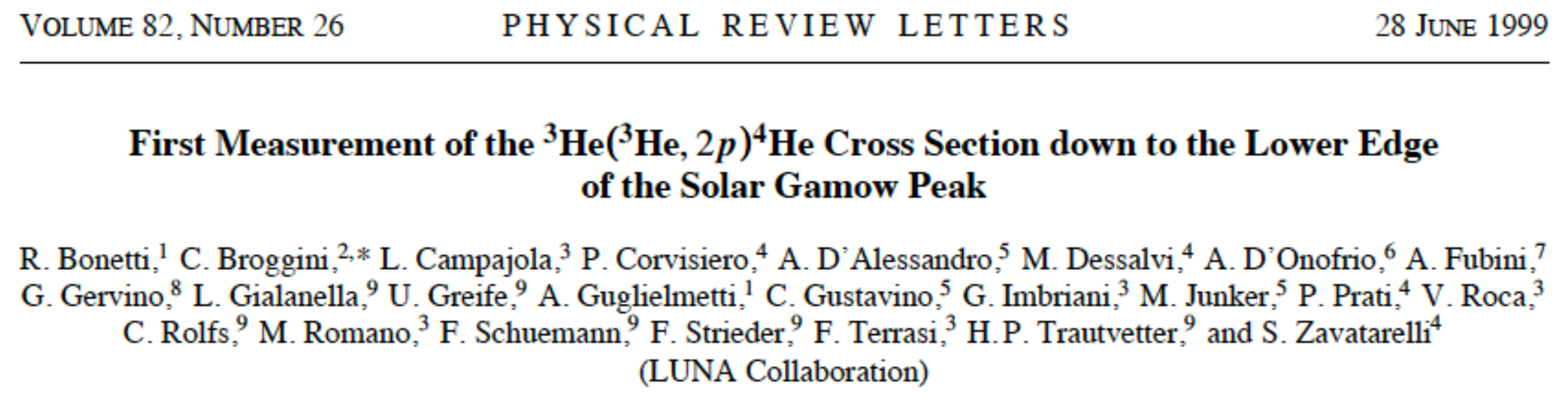
The ^{3}He+^{3}He Reaction at LUNA and the Solar Neutrino Problem

First measurement at Gamow peak energies – No resonance found!



at lowest energy measured:
σ ~ 20 fb → 2 counts/month

Bonetti *et al.* Phys. Rev. Lett. 82 (1999) 5205



VOLUME 82, NUMBER 26 PHYSICAL REVIEW LETTERS 28 JUNE 1999

First Measurement of the ^{3}He(^{3}He, 2p)^{4}He Cross Section down to the Lower Edge of the Solar Gamow Peak

R. Bonetti,[1] C. Broggini,[2,*] L. Campajola,[3] P. Corvisiero,[4] A. D'Alessandro,[5] M. Dessalvi,[4] A. D'Onofrio,[6] A. Fubini,[7]
G. Gervino,[8] L. Gialanella,[9] U. Greife,[9] A. Guglielmetti,[1] C. Gustavino,[5] G. Imbriani,[3] M. Junker,[5] P. Prati,[4] V. Roca,[3]
C. Rolfs,[9] M. Romano,[3] F. Schuemann,[9] F. Strieder,[9] F. Terrasi,[3] H. P. Trautvetter,[9] and S. Zavatarelli[4]
(LUNA Collaboration)

excluded a "nuclear solution" to the missing neutrino problem

photo: A. Mahmoud

T. Kajita

A. McDonald

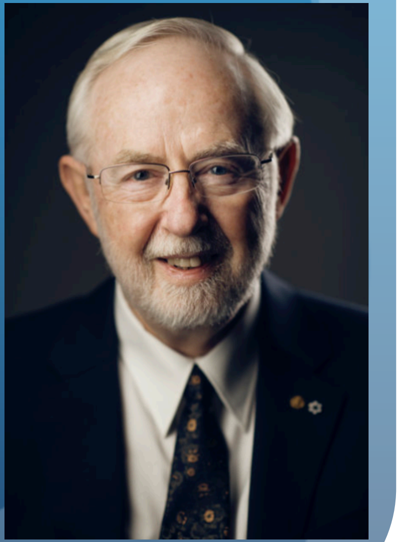
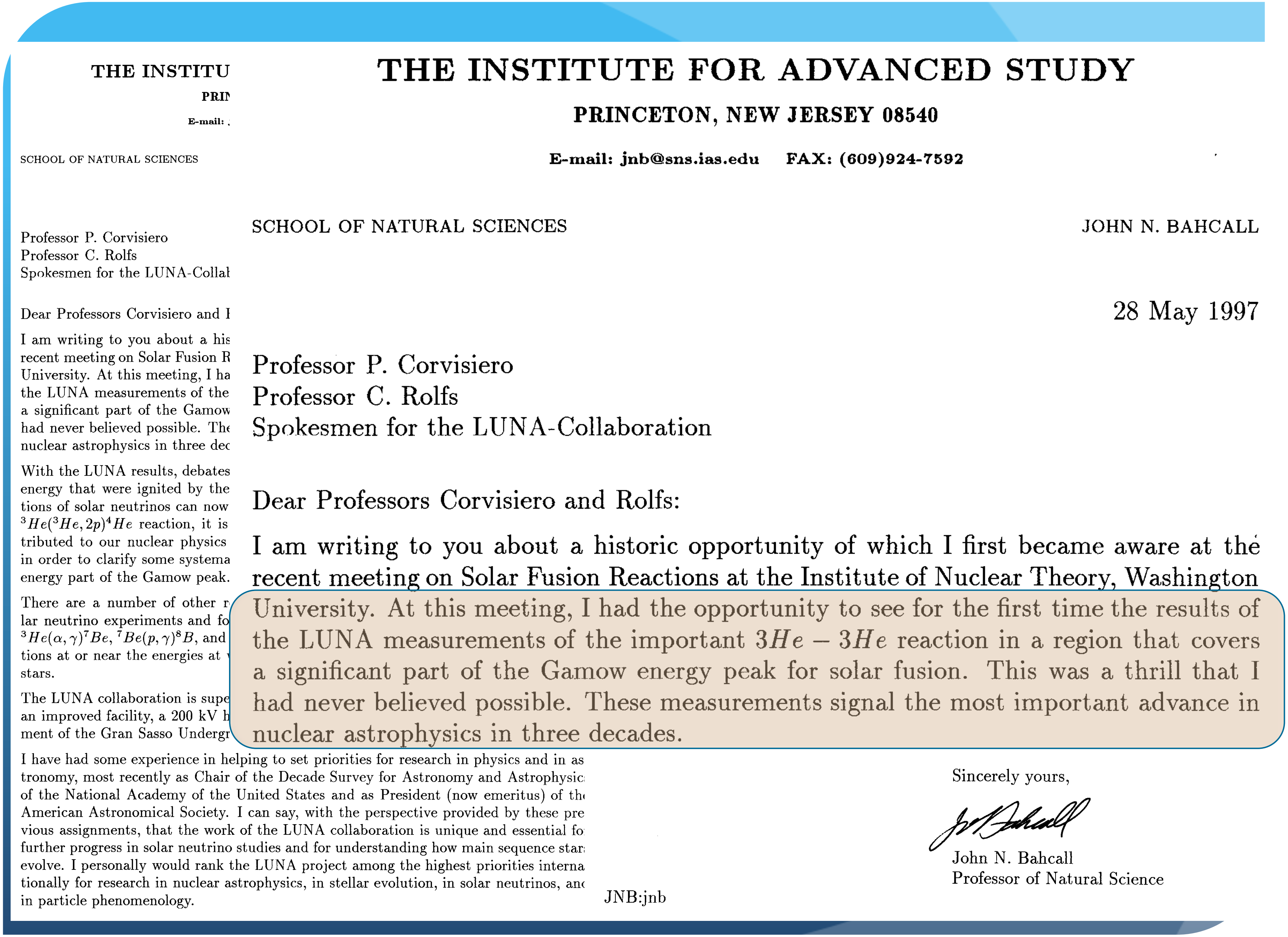


photo: A. Mahmoud

2015 Nobel Prize in Physics
Discovery of Neutrinos Oscillations

Credit : M. Aliotta



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SCHOOL OF NATURAL SCIENCES JOHN N. BAHCALL

28 May 1997

Professor P. Corvisiero
Professor C. Rolfs
Spokesmen for the LUNA-Collaboration

Dear Professors Corvisiero and Rolfs:

I am writing to you about a historic opportunity of which I first became aware at the recent meeting on Solar Fusion Reactions at the Institute of Nuclear Theory, Washington University. At this meeting, I had the opportunity to see for the first time the results of the LUNA measurements of the important $3He - 3He$ reaction in a region that covers a significant part of the Gamow energy peak for solar fusion. This was a thrill that I had never believed possible. These measurements signal the most important advance in nuclear astrophysics in three decades.

THE INSTITU
PRIN
E-mail:

SCHOOL OF NATURAL SCIENCES

Professor P. Corvisiero
Professor C. Rolfs
Spokesmen for the LUNA-Collal

Dear Professors Corvisiero and I

I am writing to you about a his
recent meeting on Solar Fusion R
University. At this meeting, I ha
the LUNA measurements of the
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nuclear astrophysics in three dec

With the LUNA results, debates
energy that were ignited by the
tions of solar neutrinos can now
$^3He(^3He,2p)^4He$ reaction, it is
tributed to our nuclear physics
in order to clarify some systema
energy part of the Gamow peak.

There are a number of other r
lar neutrino experiments and fo
$^3He(\alpha,\gamma)^7Be$, $^7Be(p,\gamma)^8B$, and
tions at or near the energies at
stars.

The LUNA collaboration is supe
an improved facility, a 200 kV h
ment of the Gran Sasso Undergr

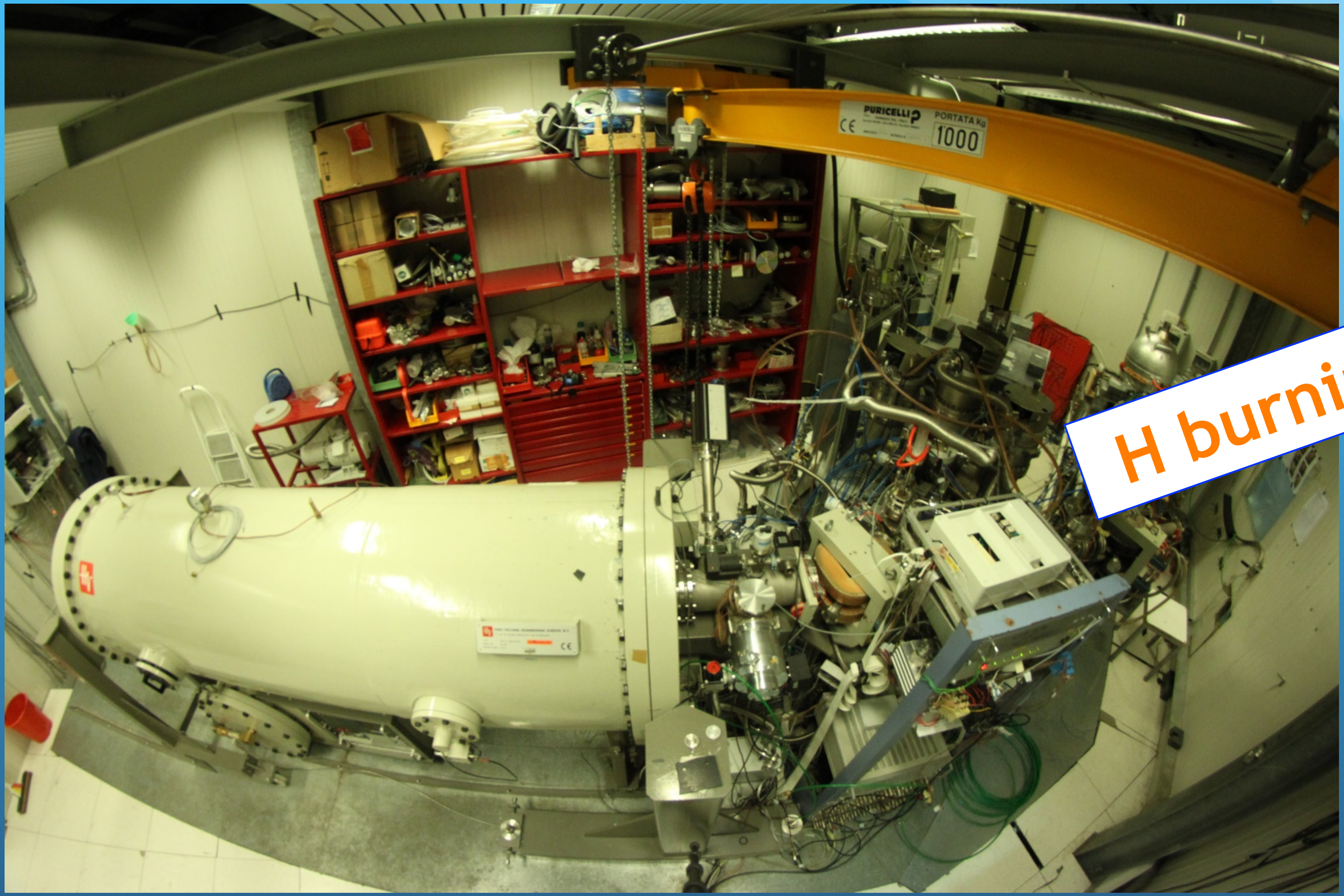
I have had some experience in helping to set priorities for research in physics and in as
tronomy, most recently as Chair of the Decade Survey for Astronomy and Astrophysic
of the National Academy of the United States and as President (now emeritus) of th
American Astronomical Society. I can say, with the perspective provided by these pre
vious assignments, that the work of the LUNA collaboration is unique and essential fo
further progress in solar neutrino studies and for understanding how main sequence star
evolve. I personally would rank the LUNA project among the highest priorities interna
tionally for research in nuclear astrophysics, in stellar evolution, in solar neutrinos, anc
in particle phenomenology.

Sincerely yours,

John N. Bahcall
Professor of Natural Science

JNB:jnb

LUNA 400kV accelerator



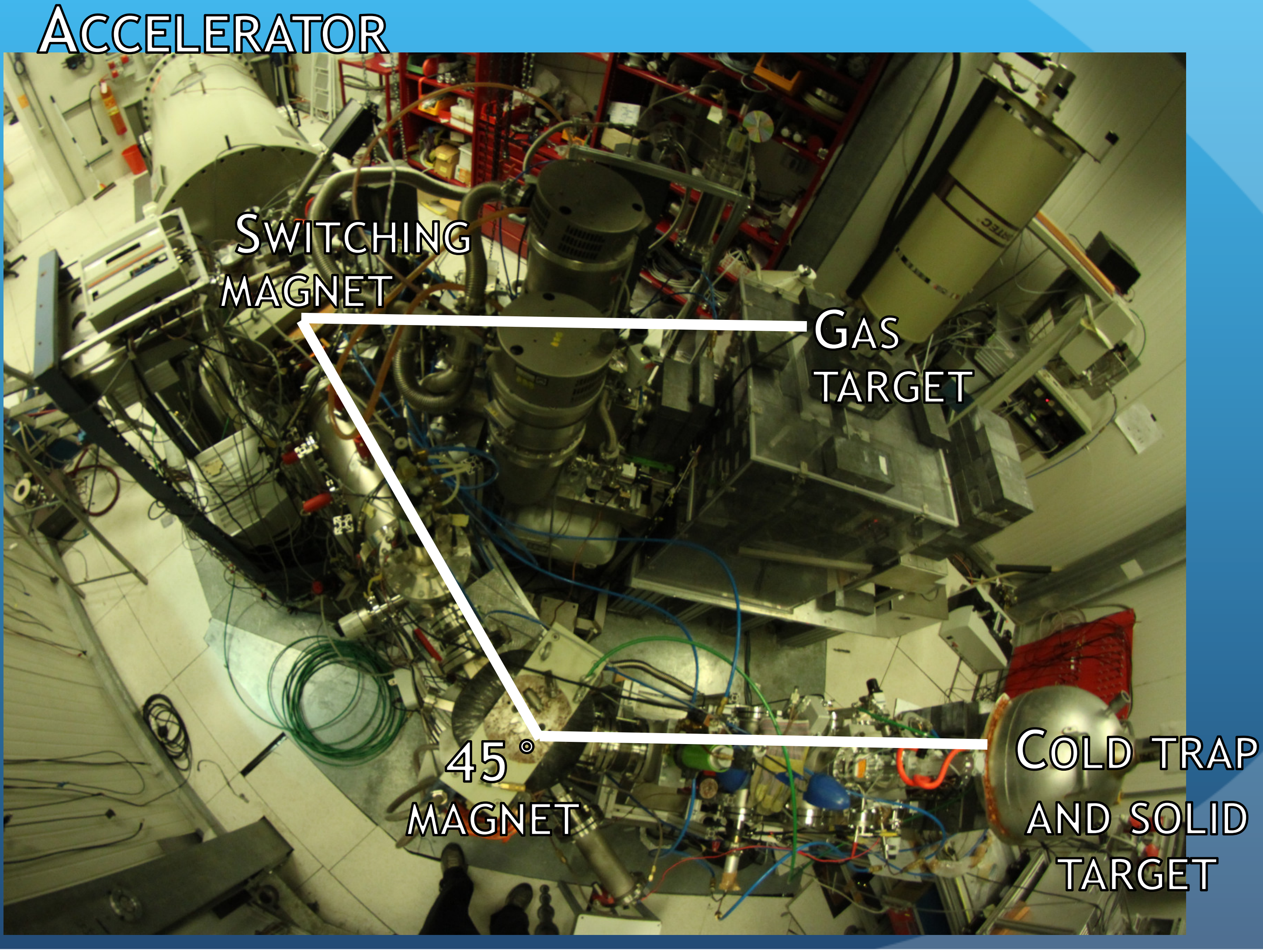
H burning

$E_{beam} \approx 50 - 400$ keV

$I_{max} \approx 500\ \mu A$ protons $I_{max} \approx 250\ \mu A$ alphas

Energy spread ≈ 70 eV Long term stability ≈ 5eV/h

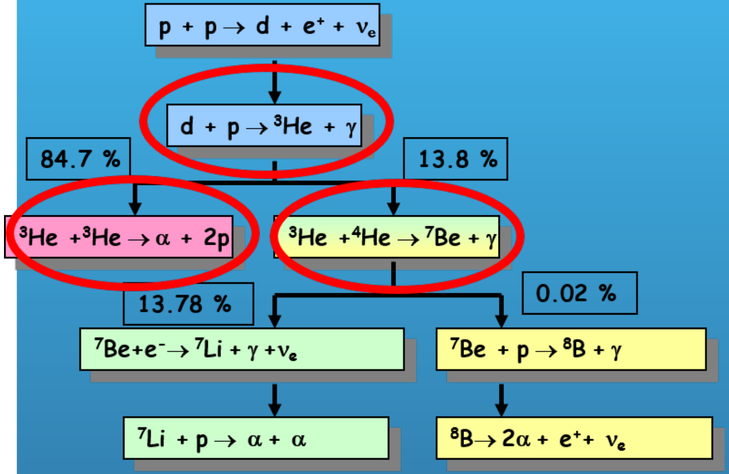
The LUNA 400 KV accelerator and beam lines



25 years @ LUNA : H burning

$4p \rightarrow {}^{4}He + 2e^{+} + 2\nu_{e} + 26.73$ MeV

pp chain



$p + p \rightarrow d + e^{+} + \nu_{e}$

$d + p \rightarrow {}^{3}He + \gamma$

84.7 %

13.8 %

${}^{3}He + {}^{3}He \rightarrow \alpha + 2p$

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

13.78 %

0.02 %

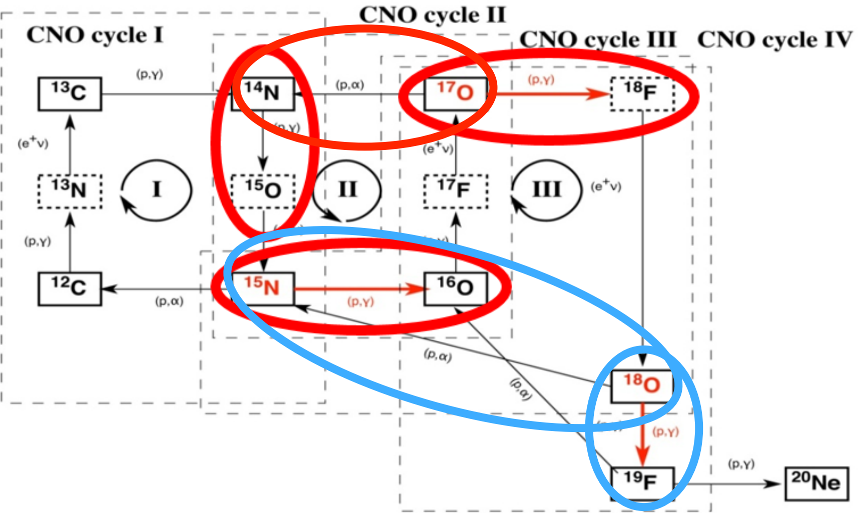
${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \gamma + \nu_{e}$

${}^{7}Be + p \rightarrow {}^{8}B + \gamma$

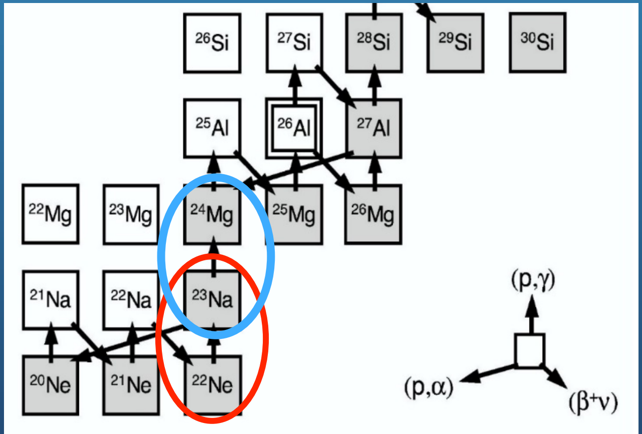
${}^{7}Li + p \rightarrow \alpha + \alpha$

${}^{8}B \rightarrow 2\alpha + e^{+} + \nu_{e}$

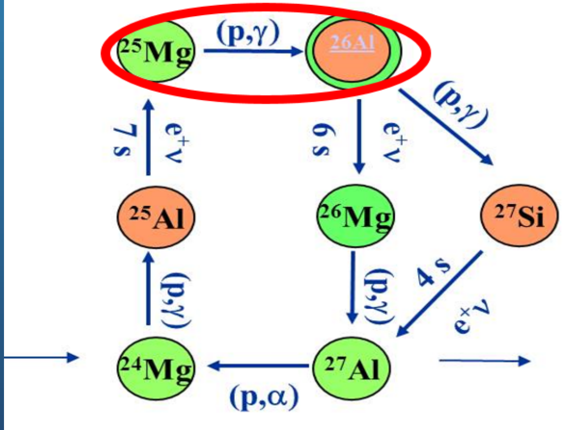
CNO cycle



Ne-Na cycle



Mg-Al cycle



25 years @ LUNA : H burning

pp chain

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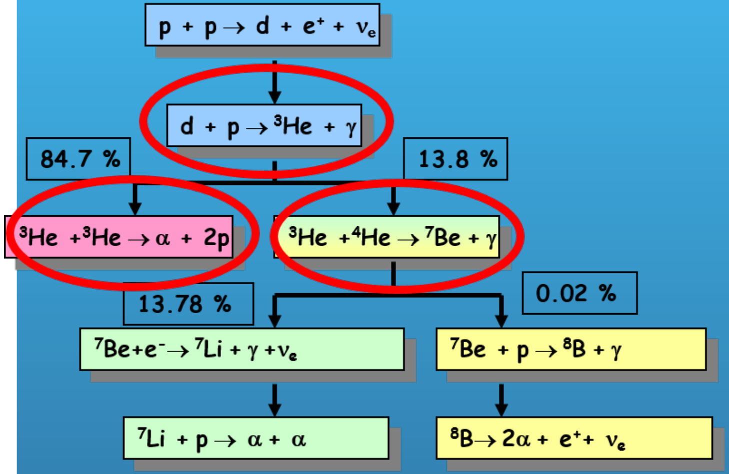
CNO cycle



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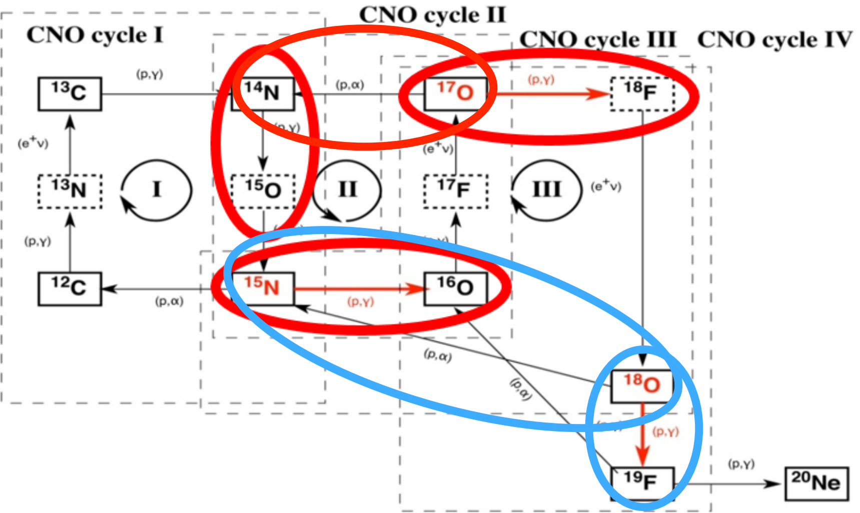
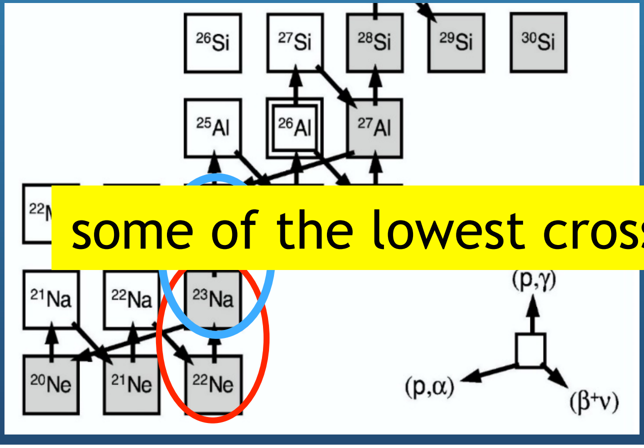
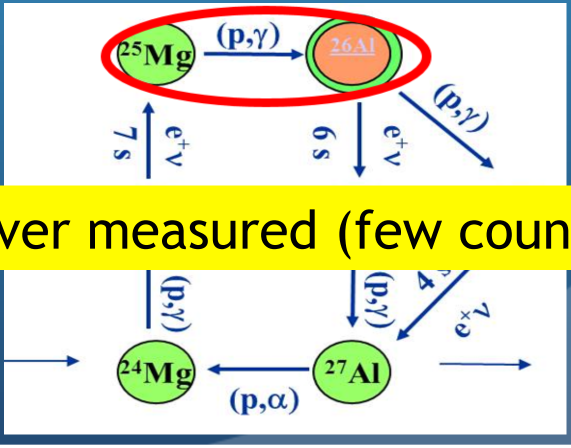


Ne-Na cycle

Mg-Al cycle





some of the lowest cross sections ever measured (few counts/month)

Last results!

Big Bang Nucleosynthesis

BBN is a fundamental handle to probe state of early universe

Early universe

- The early universe was a **hot and dense** state. At high energies, all particles species are in **thermodynamic equilibrium.**
- As the universe expands, it also cools down. Some species drop out of equilibrium, **decoupling** from the thermal bath.

- At T ~ 100 MeV (t ~ $10^{-4}s$), the particle species left in thermal equilibrium in the universe are: n, p, ν, $\overline{\nu}$, $e\pm$, γ

At T ~ 1 MeV (t ~ $1s$): **neutrino decoupling** and **neutron "freeze-out"**

$$\begin{cases} e^+ + e^- \leftrightarrow \nu + \bar{\nu} \\ e^- + \nu \leftrightarrow e^- + \nu \end{cases}$$

$$t \approx 1 \text{ sec } \left(\frac{1 \text{ MeV}}{T}\right)^2$$

For radiation dominated epoch

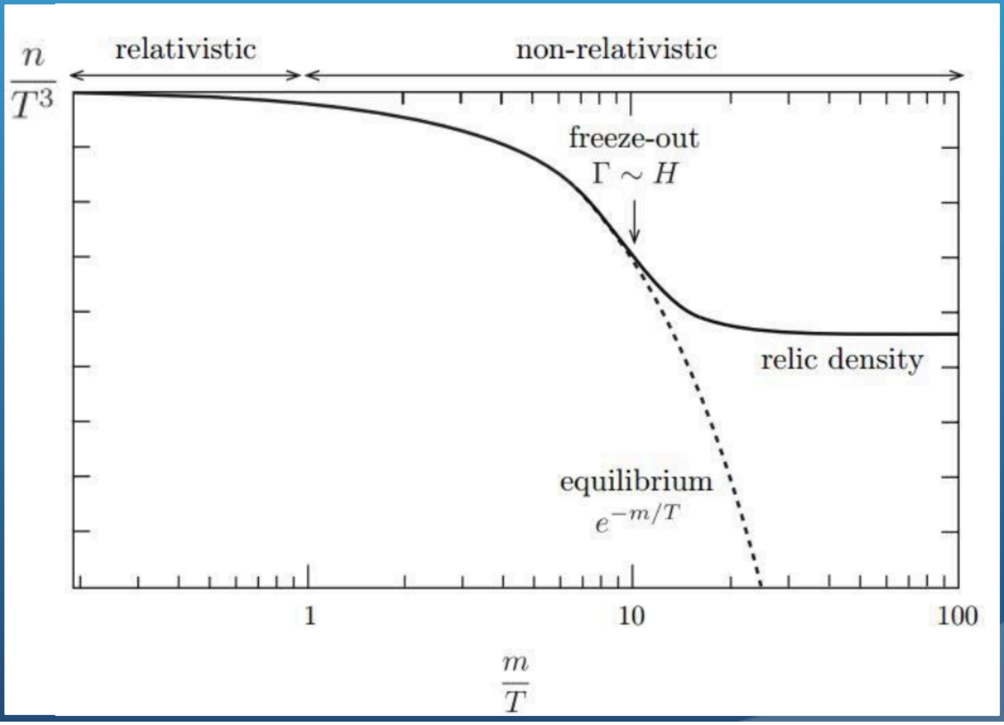
Neutron freeze-out

At equilibrium, before neutrino decoupling:

$$\frac{n}{p} = \left(\frac{m_n}{m_p}\right)^{2/3} e^{-(m_n-m_p)/T} \approx e^{-(m_n-m_p)/T}$$

$$\nu_e + n \leftrightarrow p + e^-$$
$$e^+ + n \leftrightarrow p + \bar{\nu}_e$$

As neutrinos decouple, the ratio freezes at the equilibrium value corresponding to T ~ 1 MeV : **n/p ~1/6**

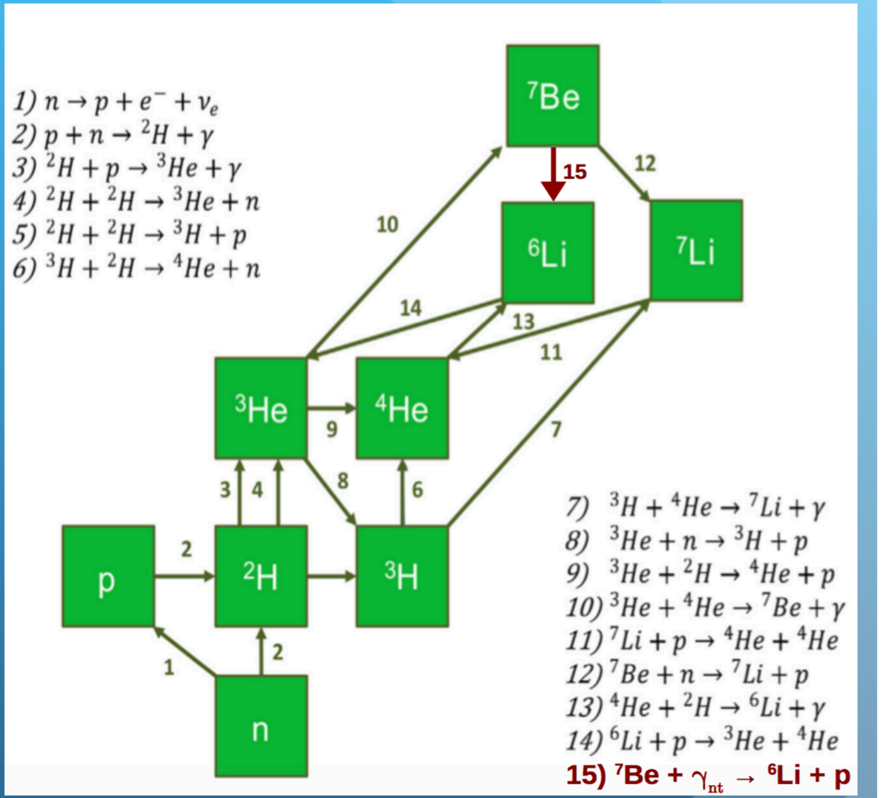


Big Bang Nucleosynthesis

- At the beginning photons dissociate just formed deuterium

$p+n \leftrightarrow D+\gamma$

- The deuterium binding energy is low (2.23 MeV)
- When temperature decreases, some D is left and BBN can start!
- In the mean time neutrons are left to β-decay. Their density drops to n(t)= $n_0 e^{-t/\tau_n}$
- The initial condition for nucleosynthesis is : n/p ~ 1/7



1) $n \rightarrow p + e^- + \nu_e$
2) $p + n \rightarrow {}^2H + \gamma$
3) ${}^2H + p \rightarrow {}^3He + \gamma$
4) ${}^2H + {}^2H \rightarrow {}^3He + n$
5) ${}^2H + {}^2H \rightarrow {}^3H + p$
6) ${}^3H + {}^2H \rightarrow {}^4He + n$

7) ${}^3H + {}^4He \rightarrow {}^7Li + \gamma$
8) ${}^3He + n \rightarrow {}^3H + p$
9) ${}^3He + {}^2H \rightarrow {}^4He + p$
10) ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$
11) ${}^7Li + p \rightarrow {}^4He + {}^4He$
12) ${}^7Be + n \rightarrow {}^7Li + p$
13) ${}^4He + {}^2H \rightarrow {}^6Li + \gamma$
14) ${}^6Li + p \rightarrow {}^3He + {}^4He$
15) ^{7}Be + γ_{nt} → ^{6}Li + p

At T~ 0.07 MeV, primordial nucleosynthesis starts..

Big Bang Nucleosynthesis

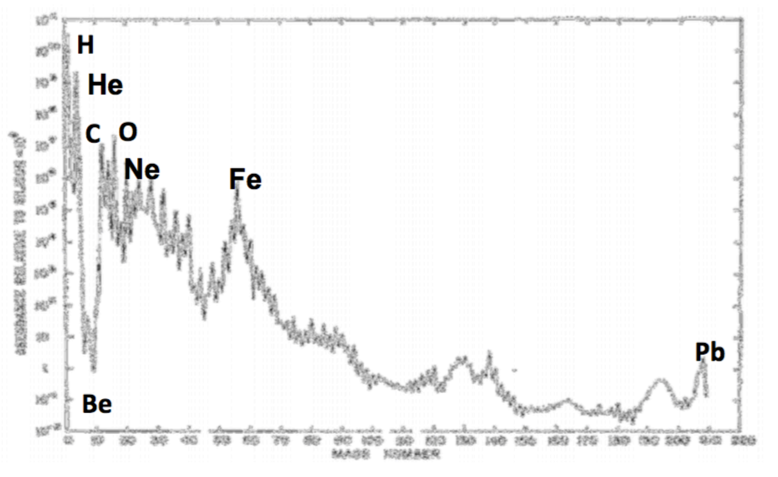
Almost all neutrons end up in ^{4}He, which is stable and a local maximum in terms of binding energy ($\Delta^4 He$=28.3MeV)

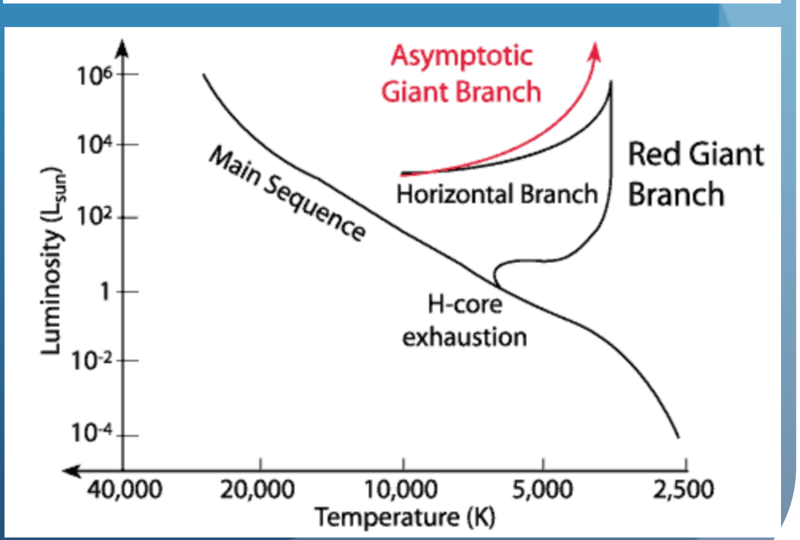
Helium mass fraction Y_P

$$Y = \frac{(2m_p + 2m_n)n_{He}}{nm_n + p\,m_p} \approx \frac{2n}{n+p} = \frac{2\left({}^{n}/{}_{p}\right)}{1 + {}^{n}/{}_{p}} = 0.25$$

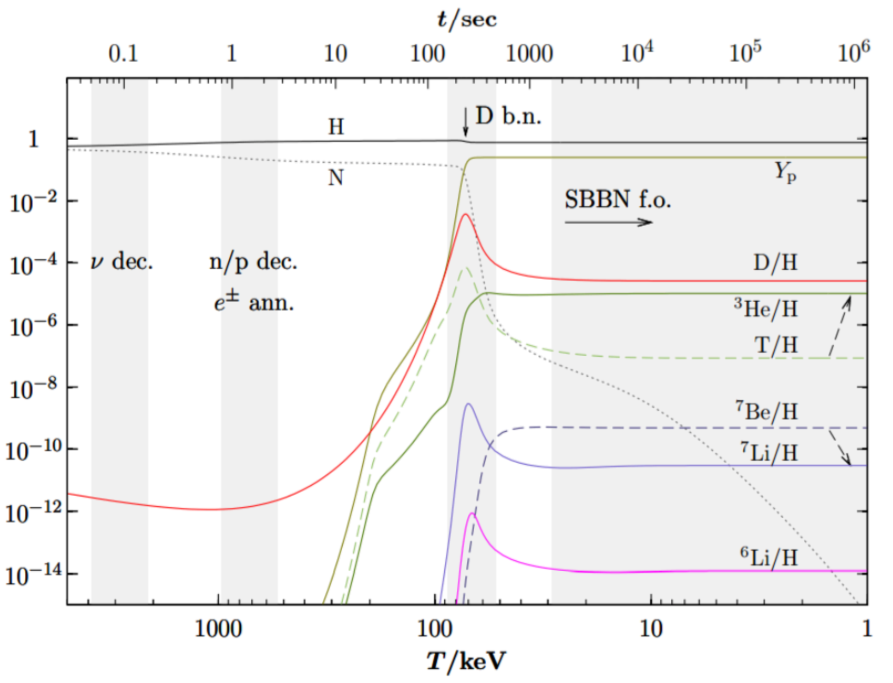
The drop of the binding energies disfavours the formation of elements with A = 5 and 8
No production of heavier nuclides=>

giant stars needed to form ^{12}C!!!



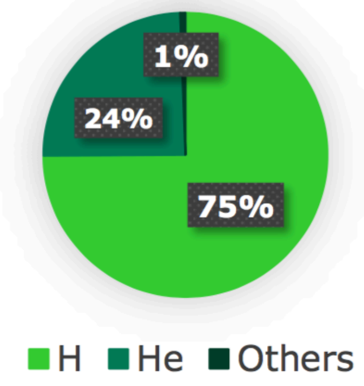


BBN: light elements abundances



The elemental abundances after BBN are the following

- $n \approx 0$
- $\mathrm{H} \approx 0.75$
- $^2\mathrm{H} \approx 2.5 \cdot 10^{-5}$
- $^4\mathrm{He} \approx 0.25$
- $^3\mathrm{He} \approx 1 \cdot 10^{-5}$
- $^7\mathrm{Li} \approx 5 \cdot 10^{-10}$
- $^6\mathrm{Li} \approx 7 \cdot 10^{-15}$



Big Bang Nucleosynthesis codes

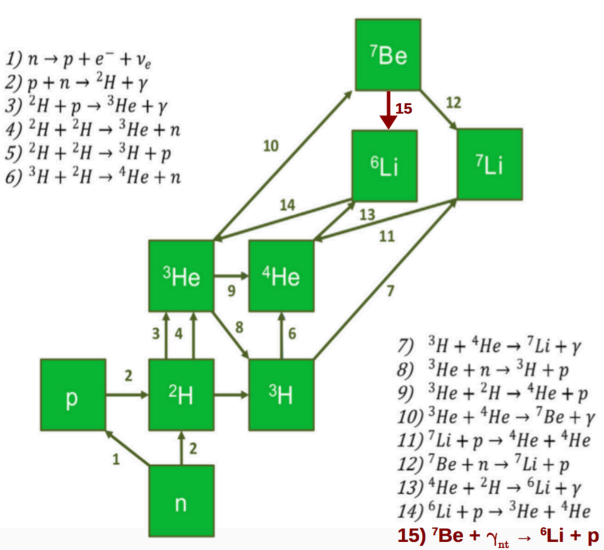
Free parameters

Baryon density parameter

$\Omega_B h^2$ or $\eta = n_B / n\gamma$

Effective number of relativistic species

N_{eff}



1) $n \rightarrow p + e^- + \nu_e$
2) $p + n \rightarrow {}^2H + \gamma$
3) ${}^2H + p \rightarrow {}^3He + \gamma$
4) ${}^2H + {}^2H \rightarrow {}^3He + n$
5) ${}^2H + {}^2H \rightarrow {}^3H + p$
6) ${}^3H + {}^2H \rightarrow {}^4He + n$
7) ${}^3H + {}^4He \rightarrow {}^7Li + \gamma$
8) ${}^3He + n \rightarrow {}^3H + p$
9) ${}^3He + {}^2H \rightarrow {}^4He + p$
10) ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$
11) ${}^7Li + p \rightarrow {}^4He + {}^4He$
12) ${}^7Be + n \rightarrow {}^7Li + p$
13) ${}^4He + {}^2H \rightarrow {}^6Li + \gamma$
14) ${}^6Li + p \rightarrow {}^3He + {}^4He$
15) ${}^7Be + \gamma_{nt} \rightarrow {}^6Li + p$

Abundances

- Y_P Helium mass fraction
- D/H
- 3He/H
- 7Li/H

The abundances are calculated by solving coupled Boltzmann equation

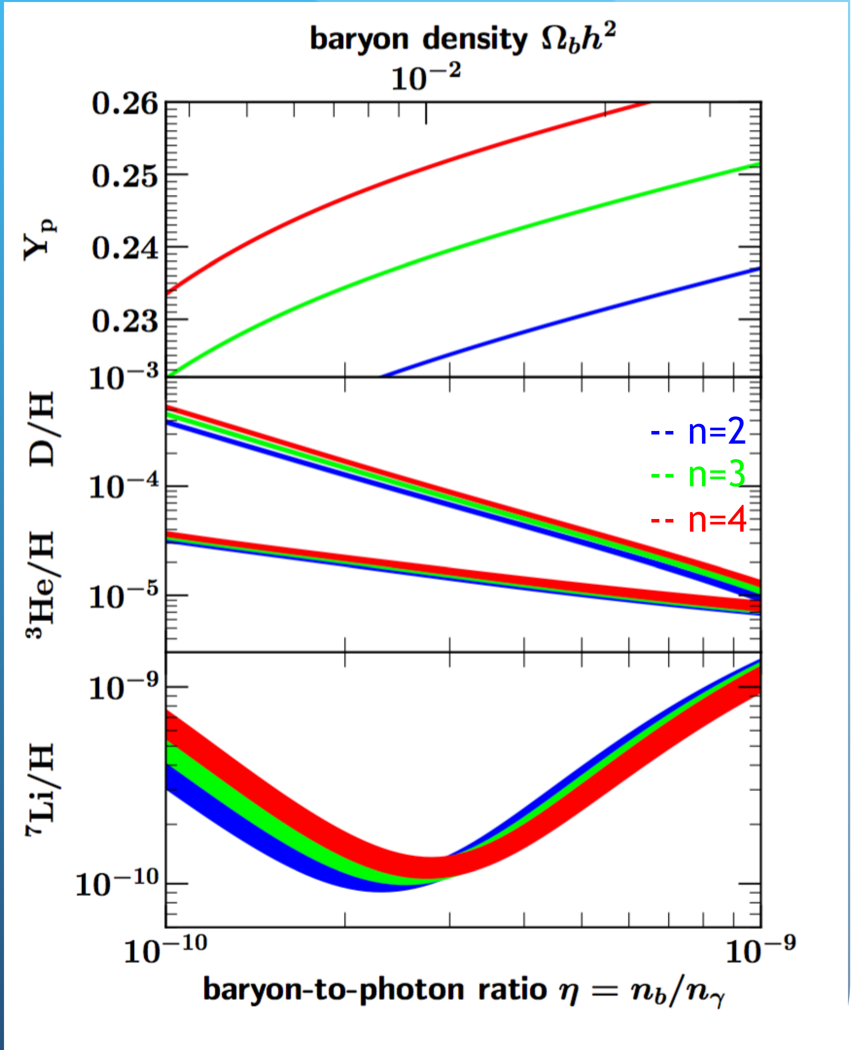
Ingredients : nuclear cross section

Primordial abundances and N_{eff}

The number of neutrino (in general of relativistic species) contributes to determine the expansion rate of the universe and therefore T_{dec}

$$n/p \approx e^{-(m_n - m_p)/T}$$

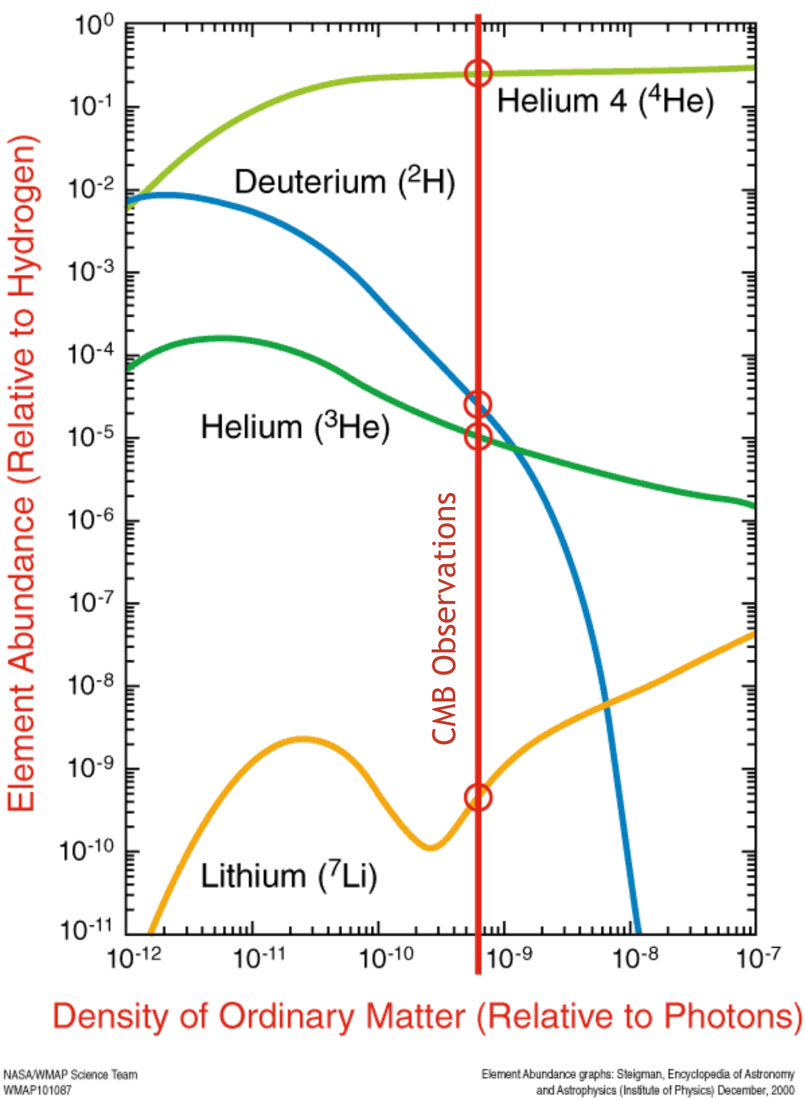
Increasing N_{eff} increases T_{dec}, the n/p ratio at freeze-out and hence the final light elements abundances.



Primordial Nucleosynthesis (BBN): 3 minutes after Big Bang

observations of D, ^{3}He, ^{4}He, and ^{7}Li in very old (**metal poor**) stars provide stringent tests of BBN

- ^4He: emission lines in low-metallicity extragalactic regions HII. Probe for n/p ratio and N_{eff}
- D: light spectra of quasars crossing H gas clouds at high redshift. Consumed during stellar evolution: if observed, it's primordial.
- ^3He: both produced and destroyed by stars, difficult to extract primordial sample.
- ^7Li: absorption line in low metallicity stars in the galactic halo. ^6Li: thermal broadening in the stellar atmospheres exceeds the isotope separation. Disputed measurements: if true, "**second Lithium problem**".



NASA/WMAP Science Team
WMAP101087

Element Abundance graphs: Steigman, Encyclopedia of Astronomy and Astrophysics (Institute of Physics) December, 2000

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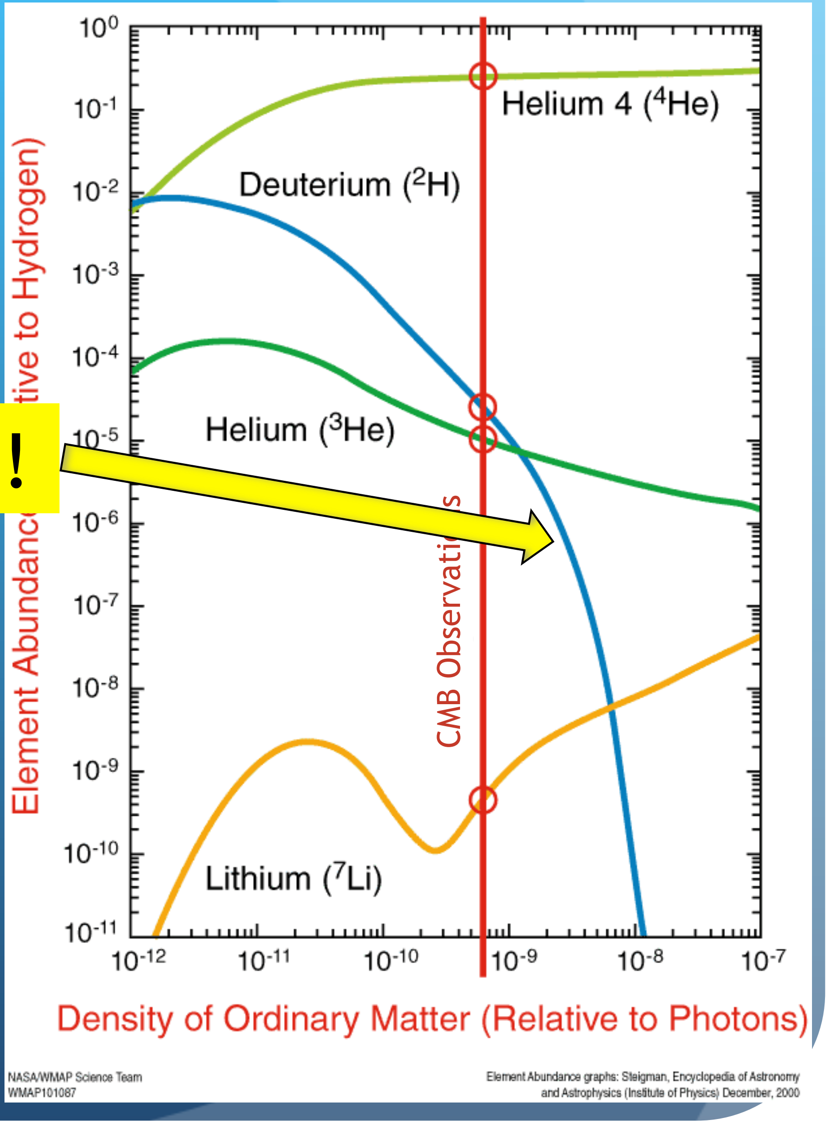
Deuterium is a bariometer !!!!



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WMAP101087

Element Abundance graphs: Steigman, Encyclopedia of Astronomy and Astrophysics (Institute of Physics) December, 2000

Primordial Deuterium Abundance:

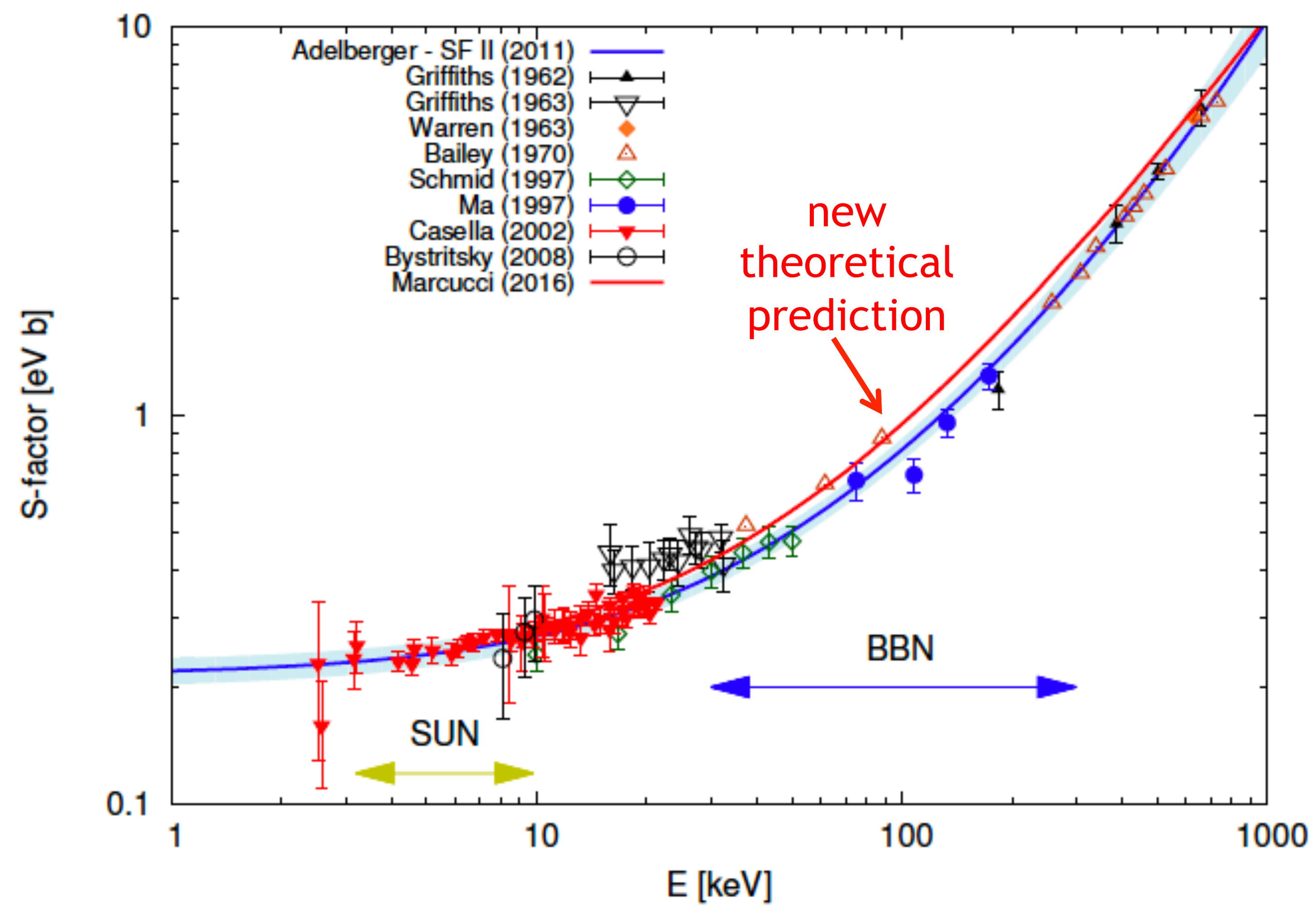
main uncertainty in BBN prediction due

to d(p,γ)^{3}He cross section

⬇

high precision data at BBN energies required

The d(p,γ)^{3}He reaction : theory vs experiments



new theoretical prediction

Broggini et al. Progr. Part. Nucl. Phys. 98 (2018) 55

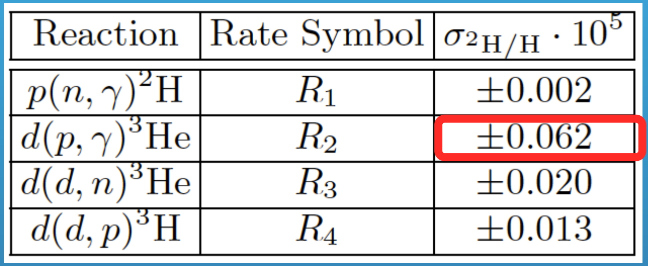
New theoretical models based on an ab-initio approach (Marcucci et al PRL 116, 102501 - 2016), predict higher values for the cross section, at the level of 20%.

D/H ratio and cosmology

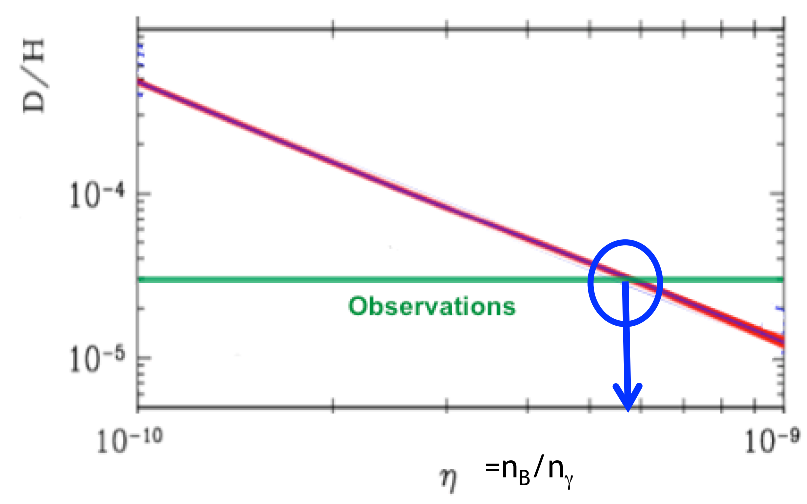
$10^5(D/H)_{obs}$ =(2.527±0.030)

R. Cooke et al.,
Ap. J. 855 (2018) 102

-BBN provides a precise estimate of Baryon density Ω_b, through the comparison of $(D/H)_{BBN}$ and $(D/H)_{obs}$:



Reaction	Rate Symbol	$\sigma_{^2H/H} \cdot 10^5$
$p(n,\gamma)^2$H	R_1	±0.002
$d(p,\gamma)^3$He	R_2	±0.062
$d(d,n)^3$He	R_3	±0.020
$d(d,p)^3$H	R_4	±0.013



From CMB data:
$100\Omega_{b,0}h^2$(CMB)=2.23±0.02 (PLANCK2015)

Need for a new measurement with precision below 3 % to make negligible the contribution of $d(p,\gamma)^3$He to the error budget

D/H ratio and cosmology

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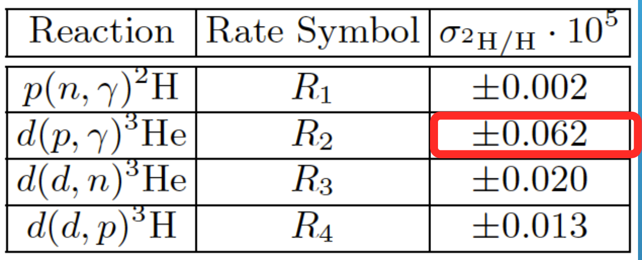

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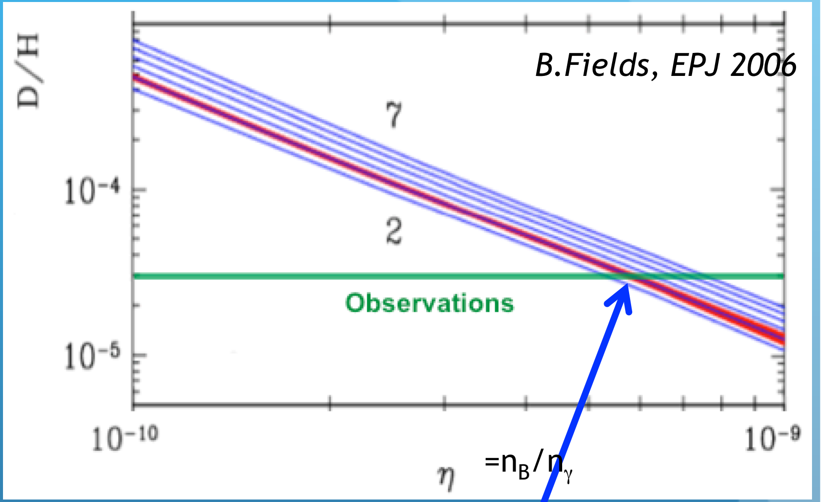


B.Fields, EPJ 2006

From CMB data:
$100\Omega_{b,0}h^2$(CMB)=2.237±0.015 (PLANCK2018)

Need for a new measurement with precision below 3 % make negligible the contribution of $d(p,\gamma)^3He$ to the error budget

-Deuterium abundance also depends on the density of relativistic particles (photons and 3 neutrinos in SM). Therefore it is a tool to constrain possible new physics

$$\Omega_B = \rho_B/\rho_{\rm crit} = 8\pi G\rho_B/3H_0^2$$

$$H_0 = 100h \ {\rm km/s/Mpc}$$

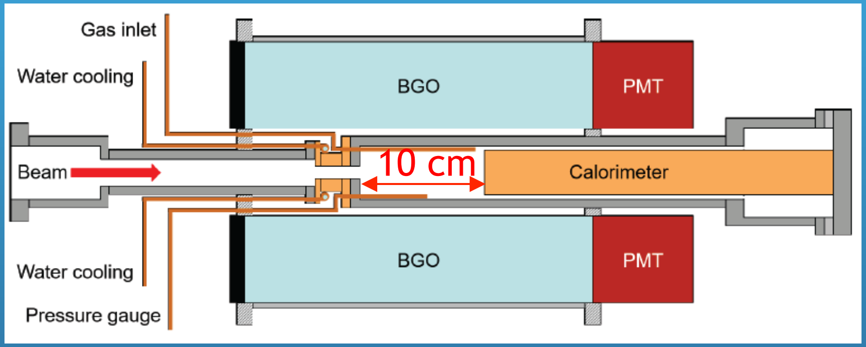
$$\eta=n_B/n_\gamma$$

The D(p,γ)^{3}He study at LUNA : goal = high precision!!

D(p,γ)^{3}He: Q-value = 5.493 MeV

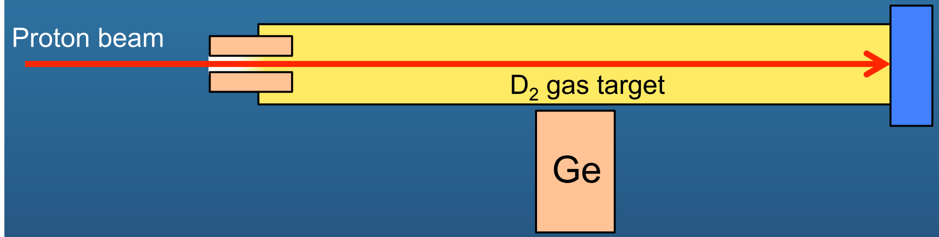
The emitted gamma is not isotropic

High precision => 2 different setups



BGO setup

High detection efficiency for 5.5 MeV- γ (~62%)
Energy resolution ~ 8% in the total abs. peak
~4π geometry



Hp-Ge setup

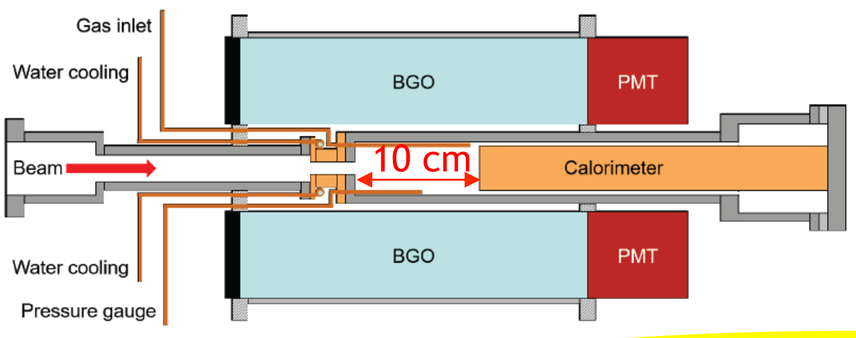
High energy resolution (~10 keV @ 6 MeV)
$\Rightarrow$ Better rejection of backgrounds
$\Rightarrow$ Efficiency for 5.5 MeV γ ~2%
Possibility of angular distribution measurements with extended gas target (33 cm)

The D(p,γ)^{3}He study at LUNA : goal = high precision!!

D(p,γ)^{3}He: Q-value = 5.493 MeV

The emitted gamma is not isotropic but it has a large electric dipole component

High precision => 2 different setups



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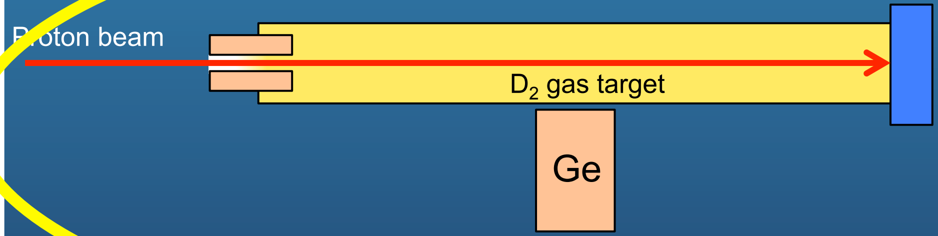

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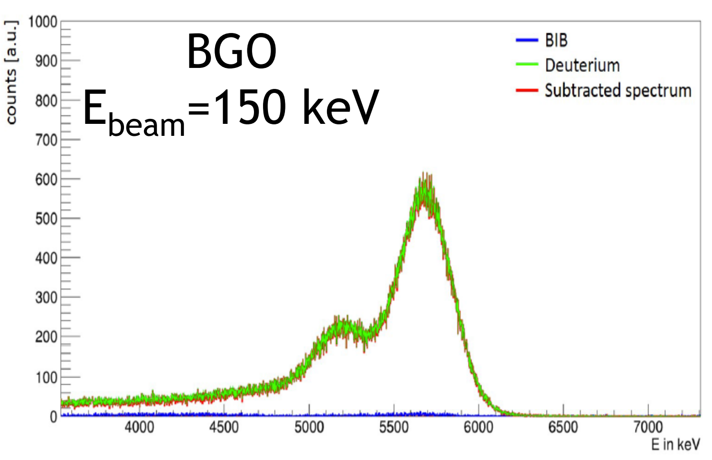
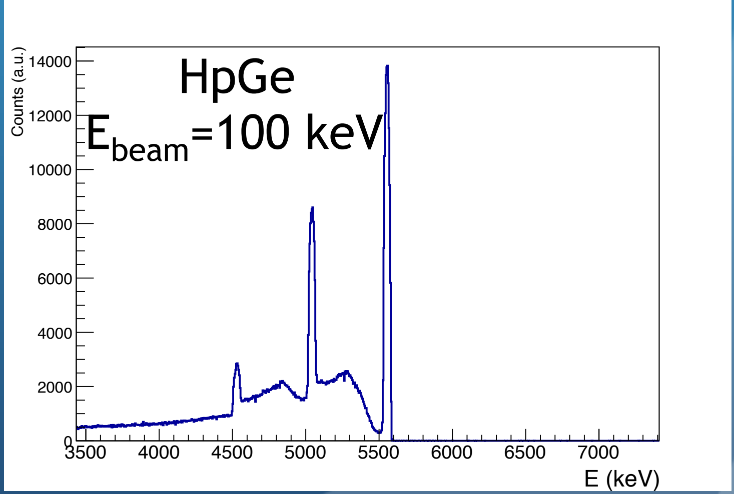
The D(p,γ)^{3}He study at LUNA

$$\overline{\sigma} = \frac{N_\gamma}{\frac{t \cdot I_{beam}}{e} \int_0^L \rho(z) \cdot \eta(z) \cdot W(z) \cdot dz}$$

Where:

- e=electron charge
- E=beam energy
- L=target lenght
- N_γ=total counts
- T=measuring time
- I_{beam}=beam current
- ρ(z)=target density
- ε(z)=detection efficiency
- W(z)=correction for photon angular distribution



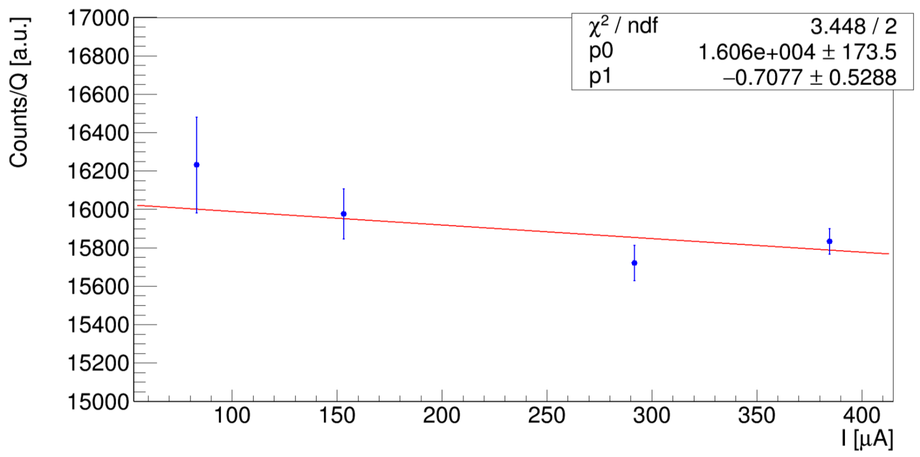


- Precise measurement of each quantity contributing to the total cross section
- Runs with inert gas (^{4}He) to measure the beam induced background (BIB)

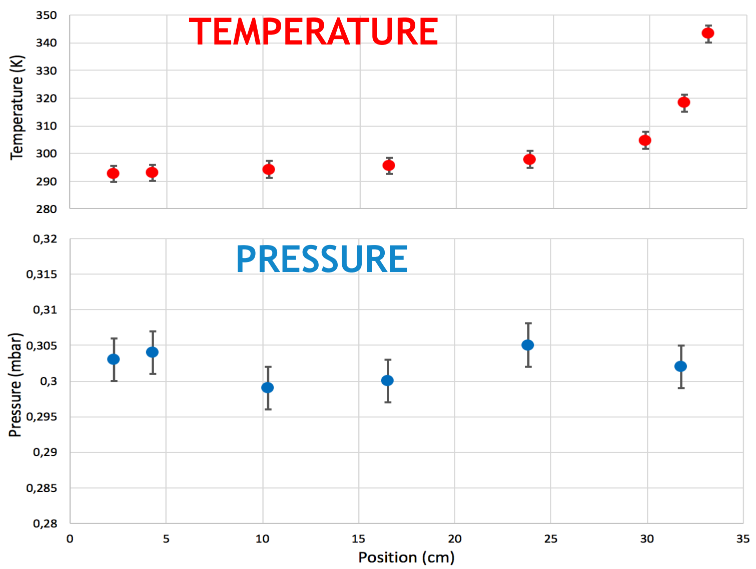
Density profile : direct measurement

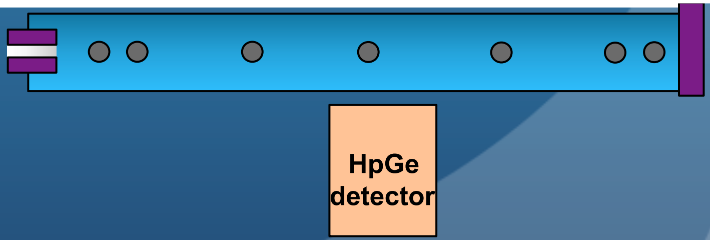
$$\overline{\sigma} = \frac{N_\gamma}{\frac{t \cdot I_{beam}}{e} \int_0^L \rho(z) \cdot \eta(z) \cdot W(z) \cdot dz}$$

P+D rate VS BEAM CURRENT



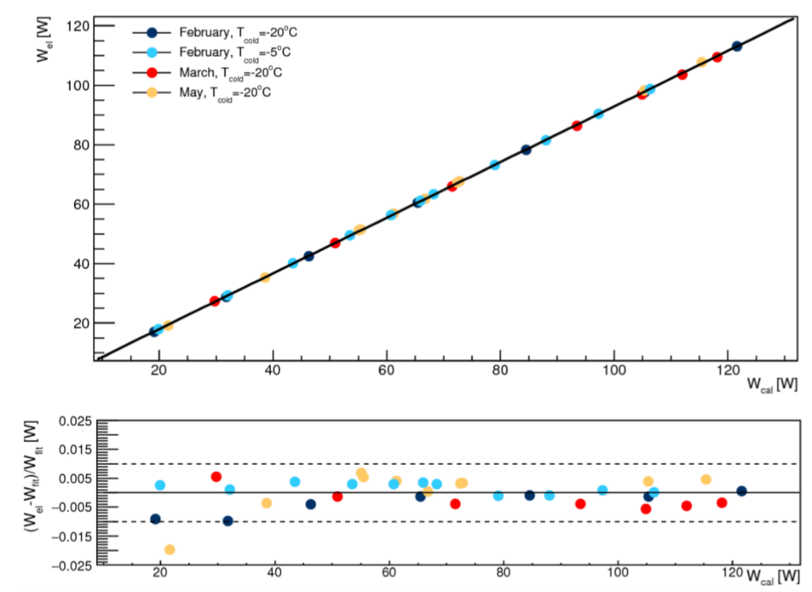
Beam heating effect <1%





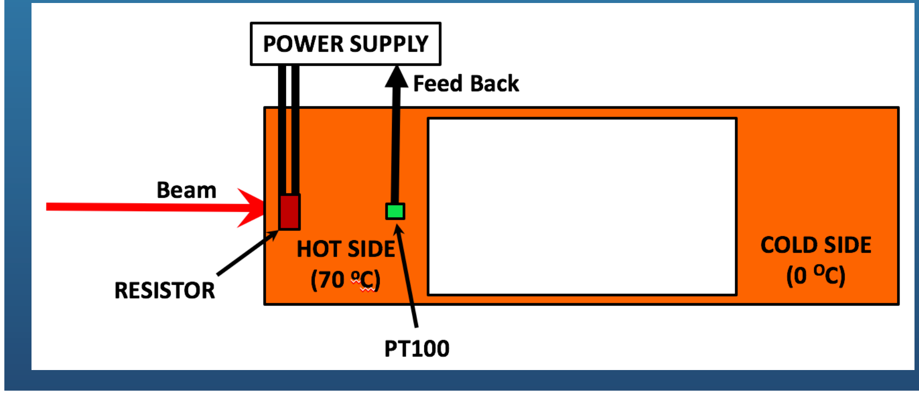
Beam intensity: calorimeter calibrated by comparison with a Faraday Cup

$$\overline{\sigma} = \frac{N_\gamma}{\frac{t\cdot \boxed{I_{beam}}}{e}\int_0^L \rho(z)\cdot\eta(z)\cdot W(z)\cdot dz}$$



Constant temperature gradient calorimeter

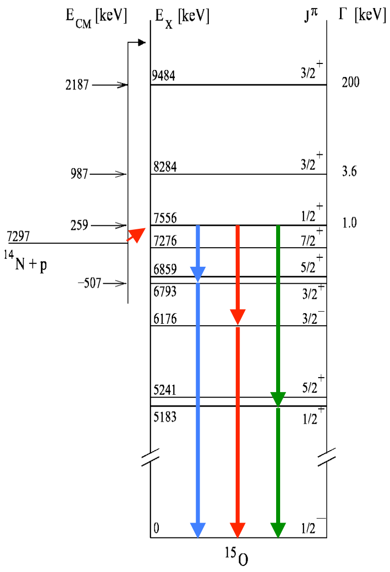
$$I_{beam} = \frac{W_0 - W_{beam}}{E_p}\cdot e$$



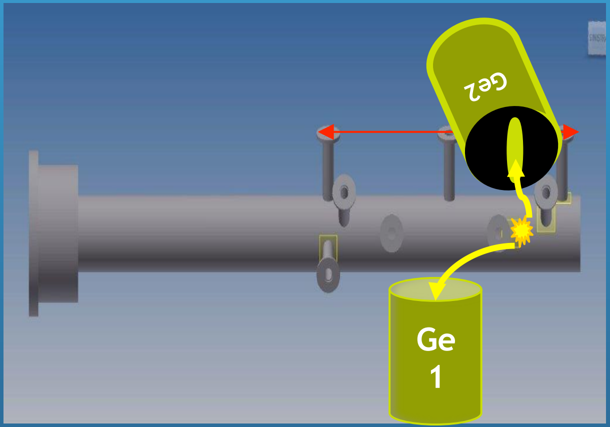
Efficiency: calibration with p+^{14}N and radioactive sources

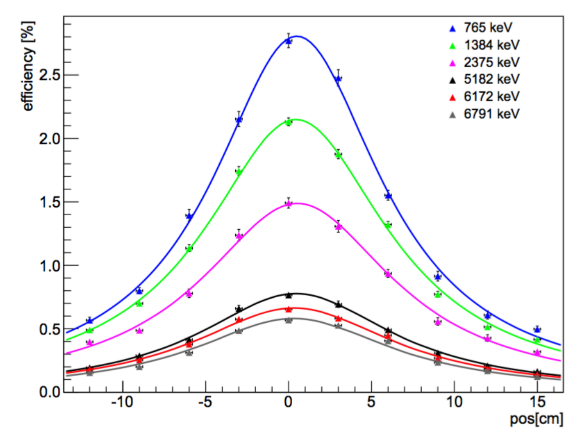
Method :

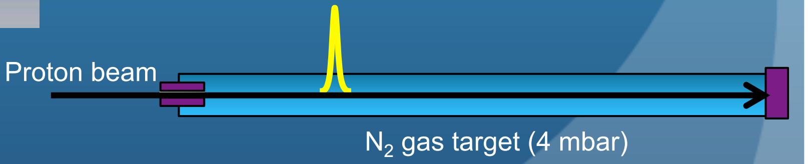
- At low energies: radioactive sources (^{137}Cs,^{60}Co, ^{88}Y of very precisely known activity (<1%)
- At medium-high energies : ^{14}N(p,γ)^{15}O (resonance at E_{cm}=259 keV)
- In case of a 2 gammas cascade => coincidence with two detectors



Eγ (keV)	BR (%)
765+6791	22.9
1384+6172	57.8
2375+5181	17.1





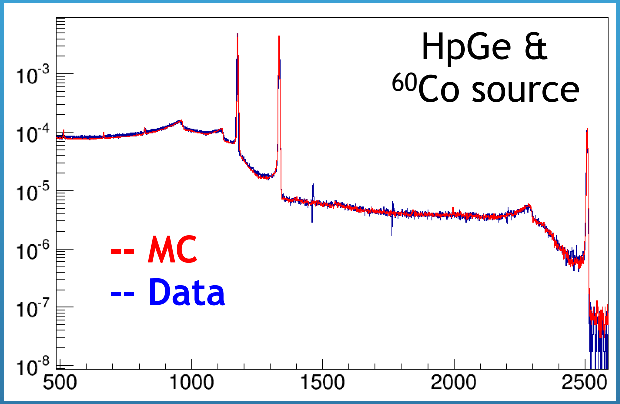


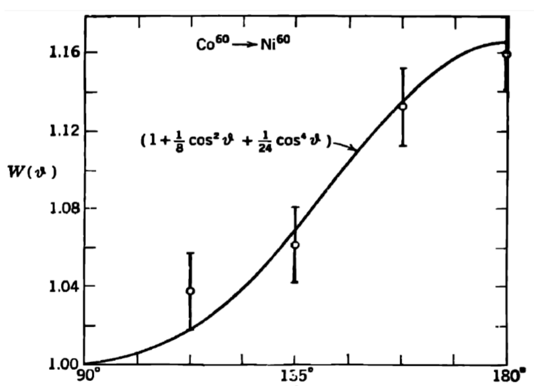
$$\eta = \frac{N_{Ge1}}{N_{Ge2}} \times corr$$

γ angular correlation => devoted MC code

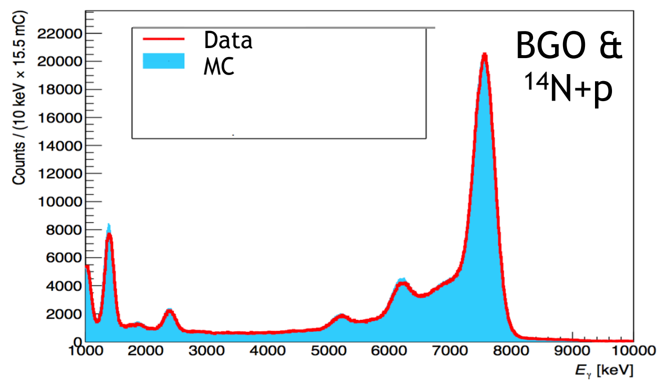
A dedicated simulation code…

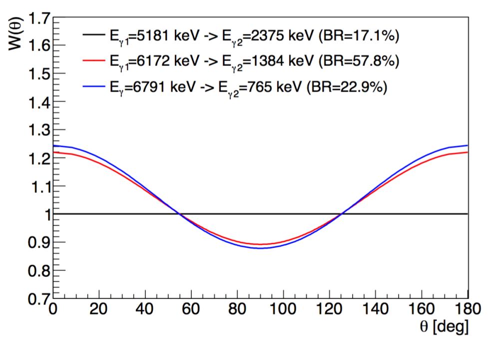
Geant based MC code able to simulate the proton beam interactions with target atoms (energy and angular straggling, fusion reaction) and to follow the ejectiles in the active and passive materials, and to register the deposited energy





^{60}Co γs angular correlation





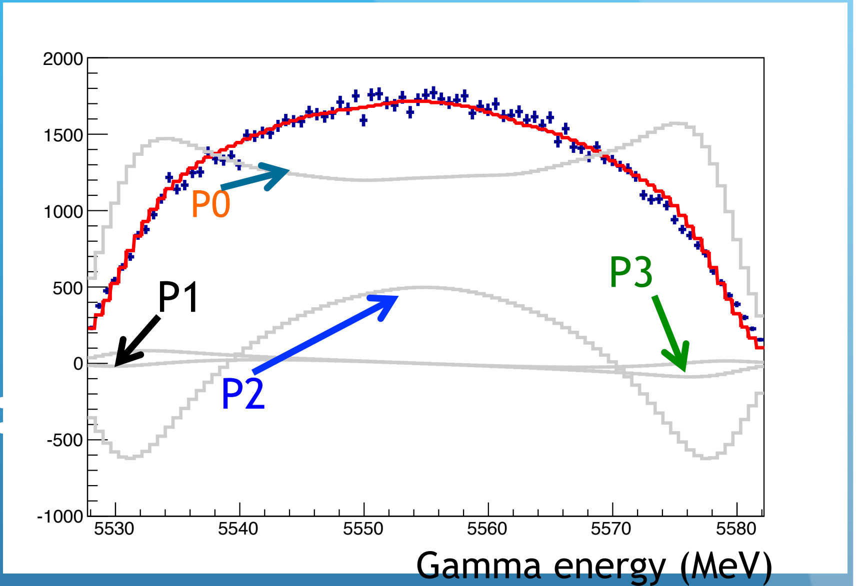
^{14}N+p γs angular correlation

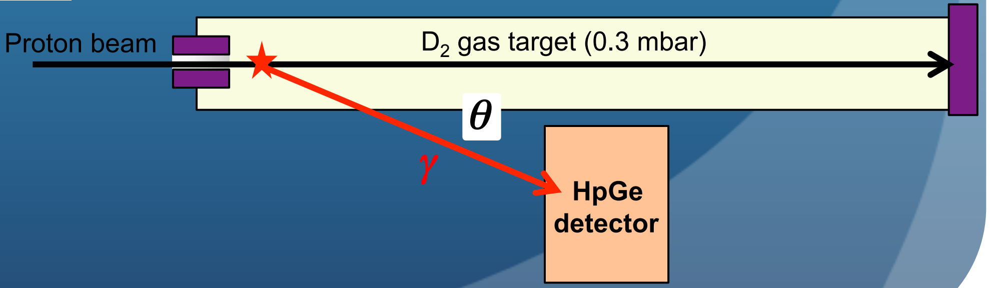
Angular distribution: peak shape analysis

$$\overline{\sigma} = \frac{N_{\gamma}}{\dfrac{t \cdot I_{beam}}{e} \displaystyle\int_{0}^{L} \rho(z) \cdot \eta(z) \cdot \boxed{W(z)} \cdot dz}$$

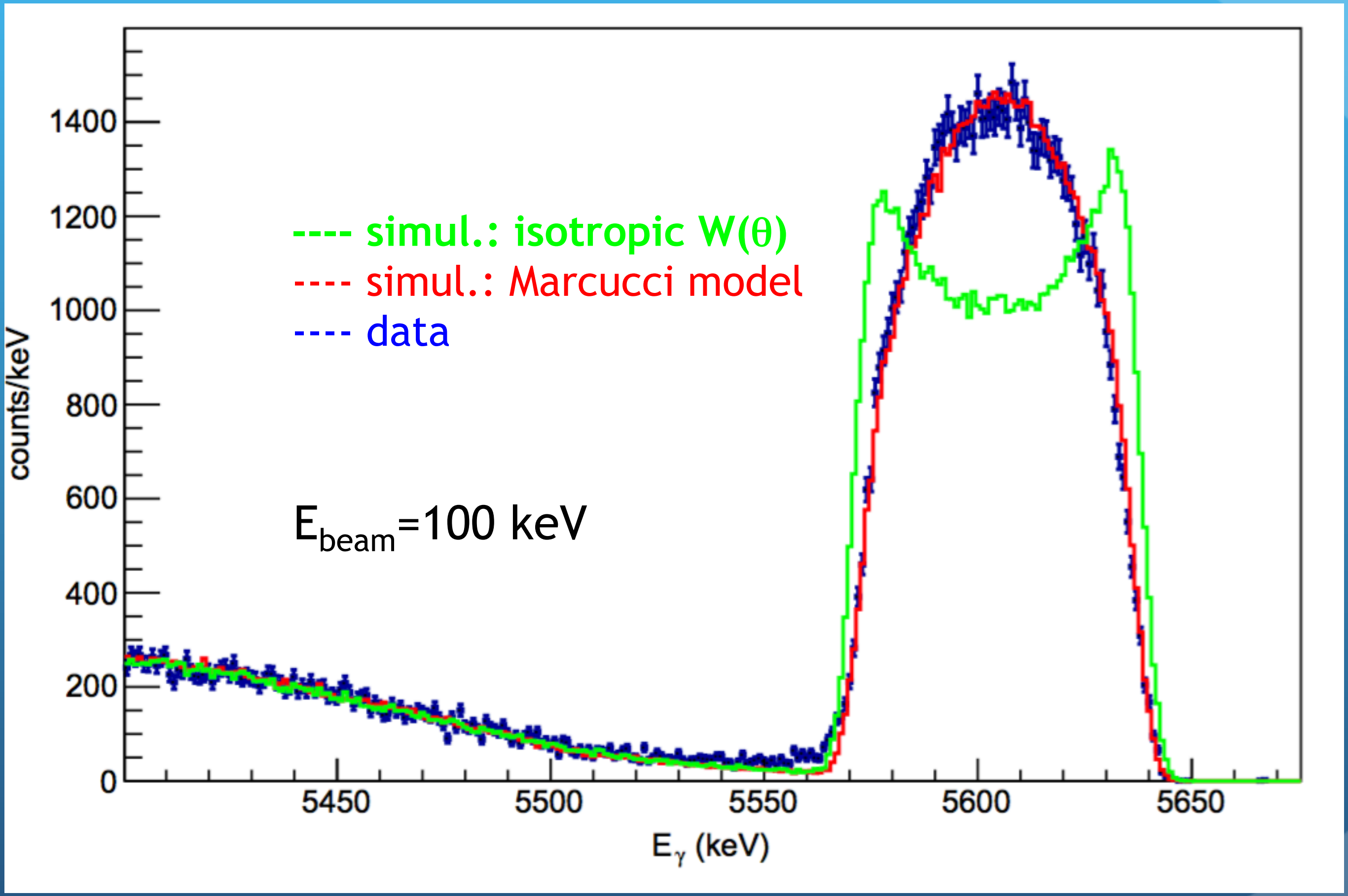
Doppler effect for the emitted γ_s:

$$\boxed{E_{\gamma}} = \frac{m_p^2 + m_d^2 - m_{He}^2 - 2\boxed{E_p}m_d}{2\left(E_p + m_d - p_p\boxed{\cos(\theta_{lab})}\right)}$$

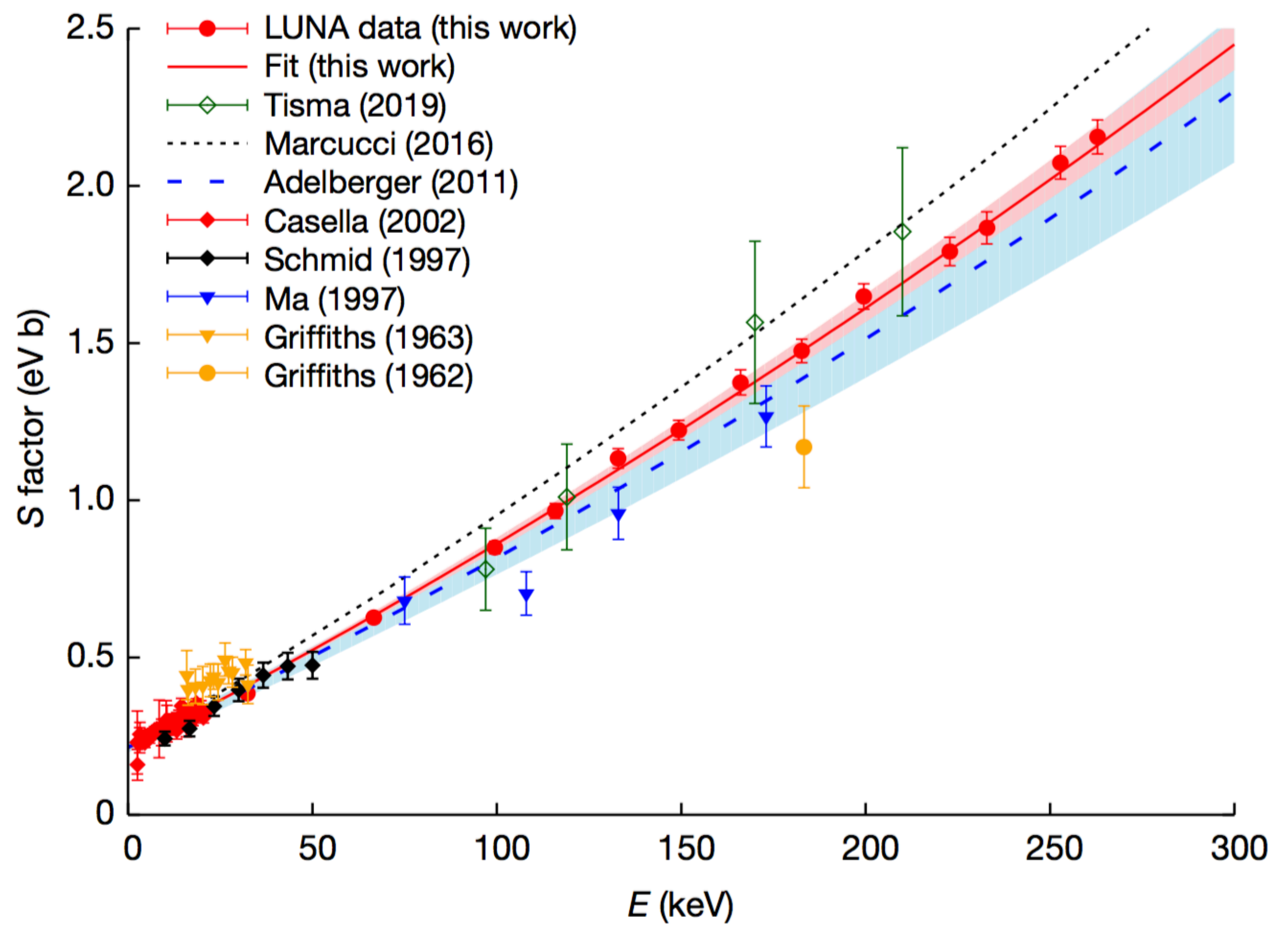




D(p,γ)^{3}He energy spectrum: full absorption peak shape



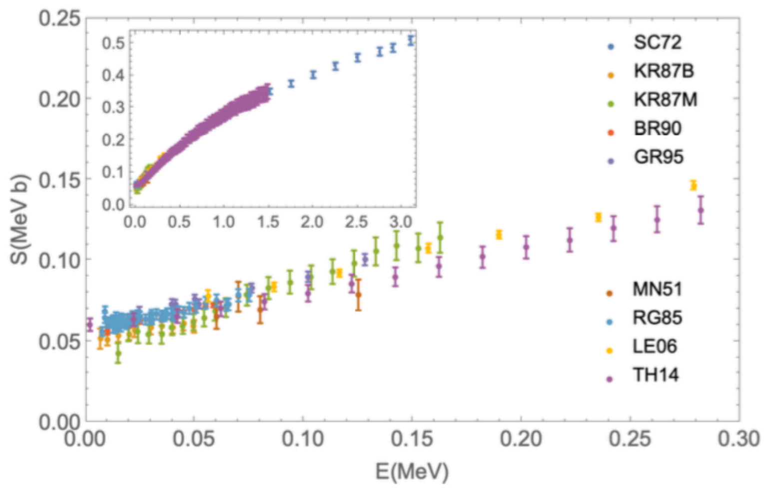
Astrophysical S(E) factor



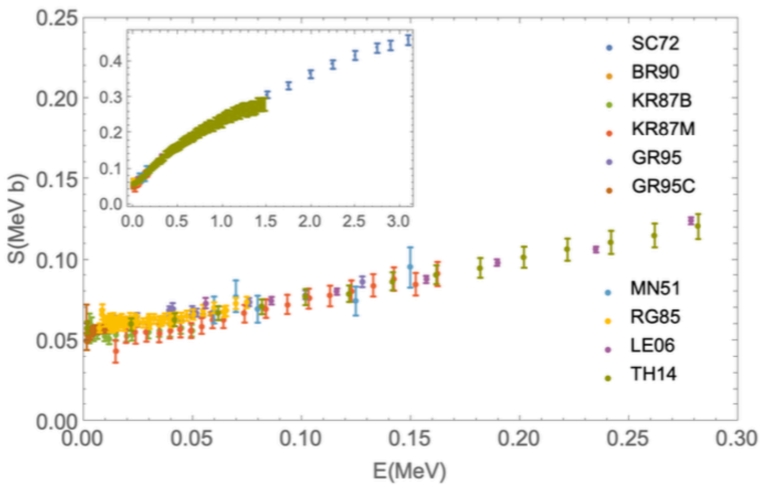
Other reactions relevant to deuterium abundance

- $^{1}H(n,\gamma)^{2}H$:cross-section from an effective field theory computation (Ando et al. 2006), reliable at the 1%-level

- $D(d,n)^{3}He$

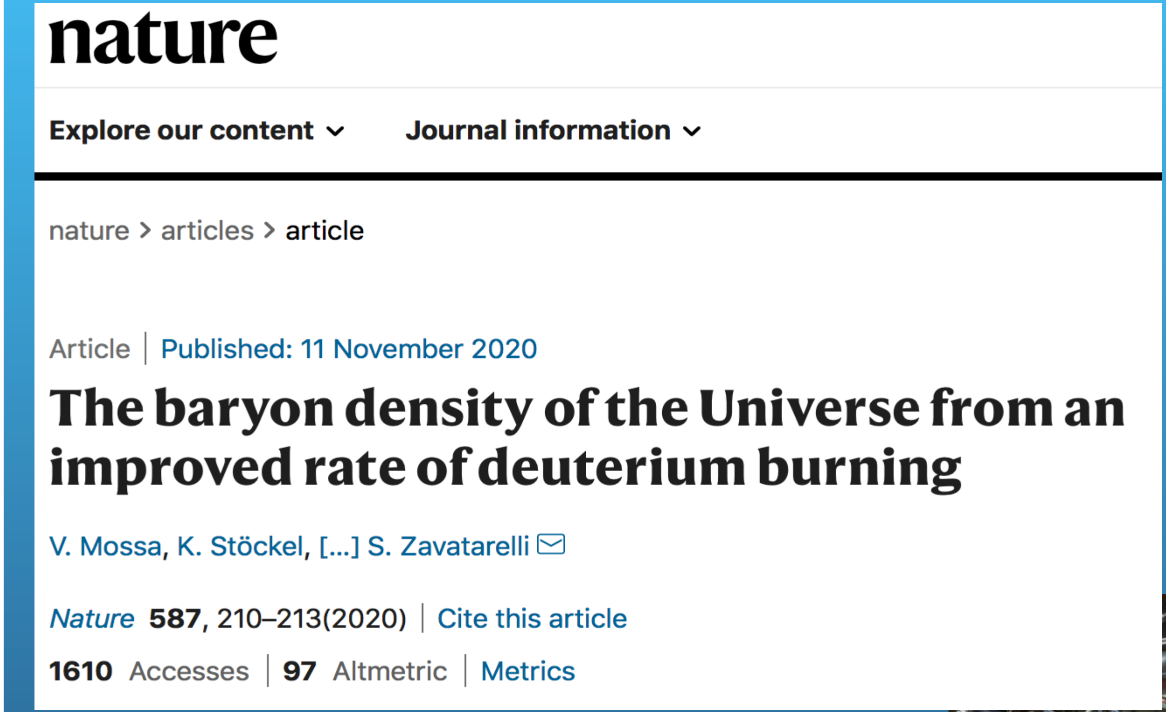


- $D(d,p)^{3}H$



few% precision : Leonard et al. 2006 provides an error matrix and quote a scale error as low as 2%±1%.

Important consequences for the baryon density



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Article | Published: 11 November 2020

The baryon density of the Universe from an improved rate of deuterium burning

V. Mossa, K. Stöckel, [...] S. Zavatarelli ✉

Nature **587**, 210–213(2020) | Cite this article

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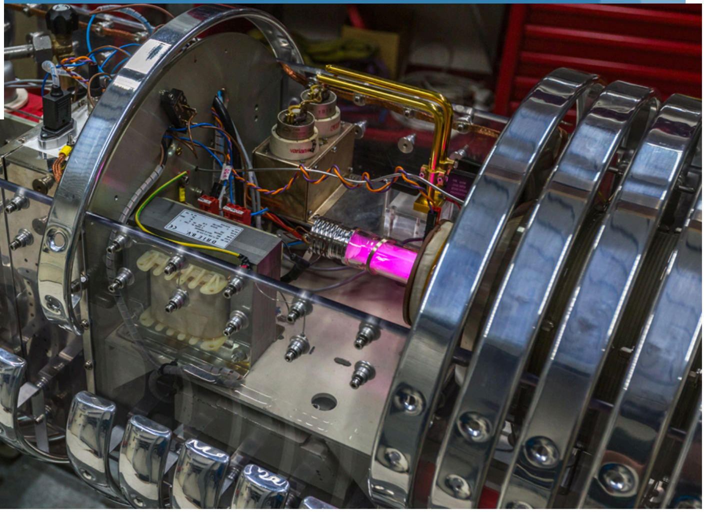
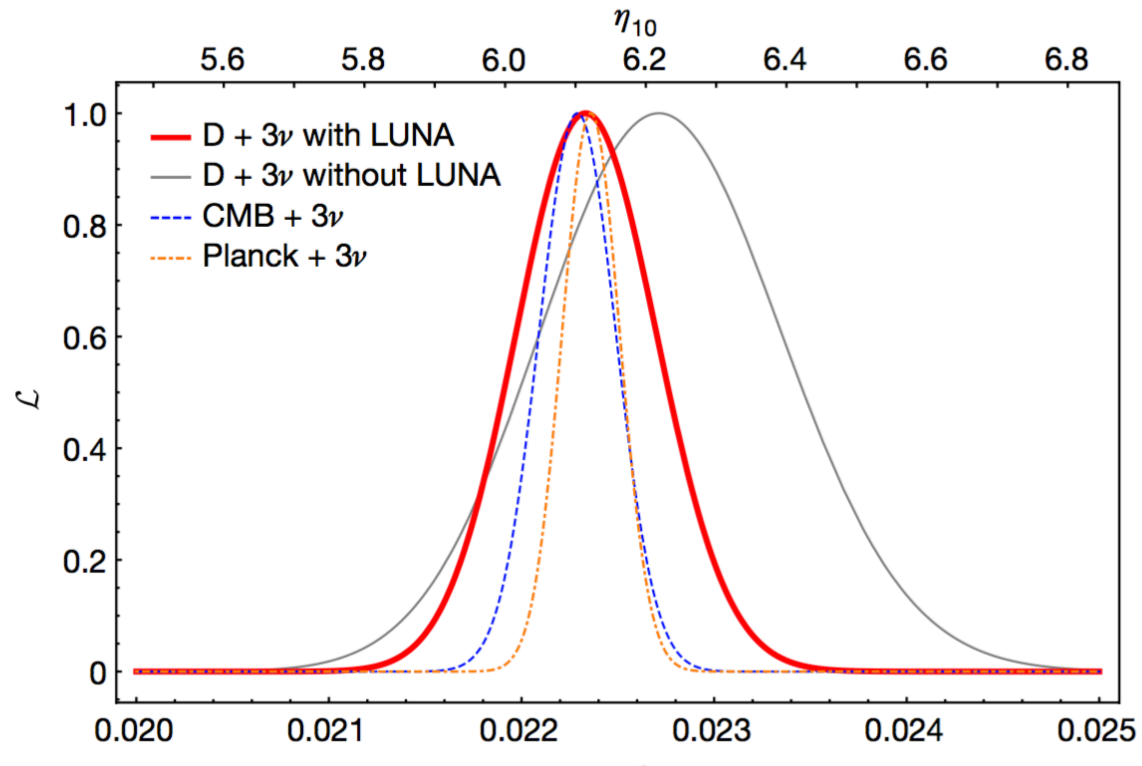
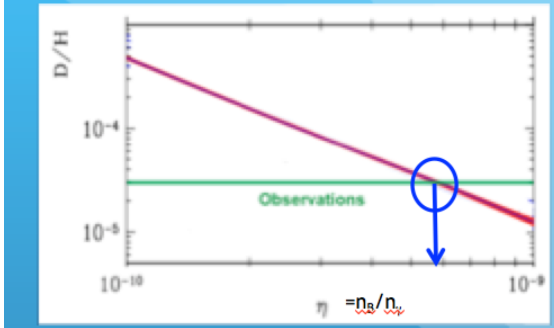


Baryon density (standard Neff)

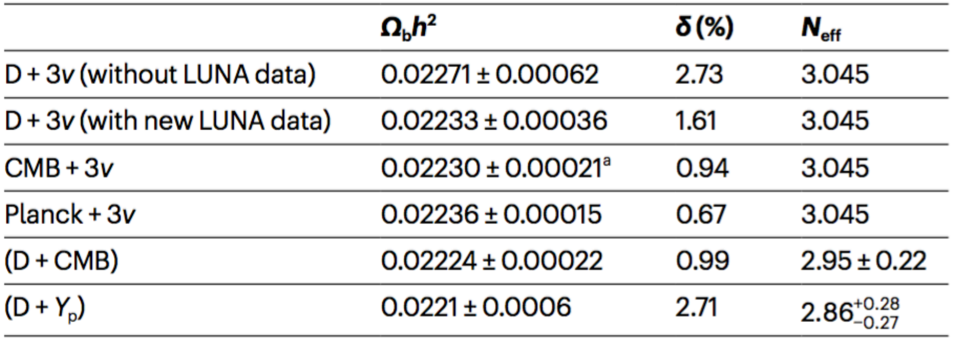


Idea



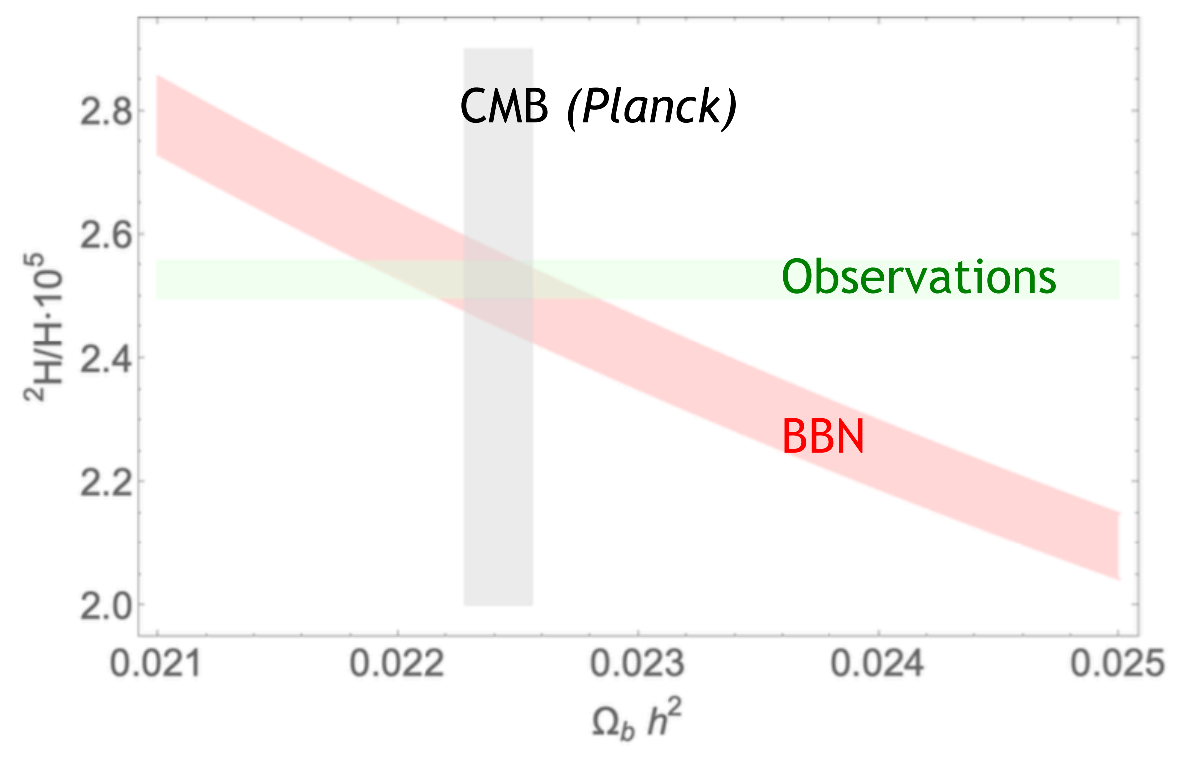
Likelihood analysis to derived $\Omega_b h^2$ by using the observed deuterium abundance, $(D/H)_{obs}$, and the theoretical behaviour of $(D/H)_{BBN}$

BBN & CMB do agree on $\Omega_b h^2$!!!



	$\Omega_b h^2$	δ (%)	N_{eff}
D + 3ν (without LUNA data)	0.02271 ± 0.00062	2.73	3.045
D + 3ν (with new LUNA data)	0.02233 ± 0.00036	1.61	3.045
CMB + 3ν	0.02230 ± 0.00021[a]	0.94	3.045
Planck + 3ν	0.02236 ± 0.00015	0.67	3.045
(D + CMB)	0.02224 ± 0.00022	0.99	2.95 ± 0.22
(D + Y_p)	0.0221 ± 0.0006	2.71	$2.86^{+0.28}_{-0.27}$

Deuterium abundance



$\Omega_B h^2$ constrained in the analysis to the Planck value (with error): 0.02236 ± 0.00015

$(D/H)_{obs} = (2.527 \pm 0.030) \times 10^{-5}$ $(D/H)_{BBN} = (2.52 \pm 0.03 \pm 0.06) \times 10^{-5}$

Cooke 2018)

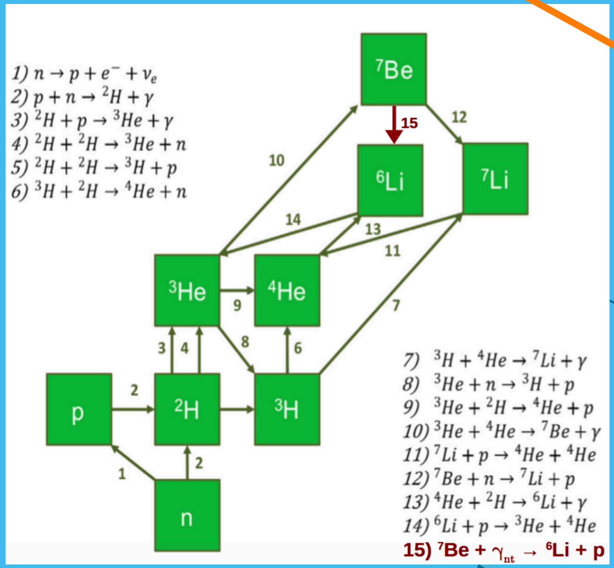
N_{eff} vs $\Omega_b h^2$: first case (D+CMB)

Constrains

Free parameters

$\Omega_B h^2$ or $\eta = n_B / n\gamma$

N_{eff}



1) $n \rightarrow p + e^- + \nu_e$
2) $p + n \rightarrow {}^2H + \gamma$
3) ${}^2H + p \rightarrow {}^3He + \gamma$
4) ${}^2H + {}^2H \rightarrow {}^3He + n$
5) ${}^2H + {}^2H \rightarrow {}^3H + p$
6) ${}^3H + {}^2H \rightarrow {}^4He + n$
7) ${}^3H + {}^4He \rightarrow {}^7Li + \gamma$
8) ${}^3He + n \rightarrow {}^3H + p$
9) ${}^3He + {}^2H \rightarrow {}^4He + p$
10) ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$
11) ${}^7Li + p \rightarrow {}^4He + {}^4He$
12) ${}^7Be + n \rightarrow {}^7Li + p$
13) ${}^4He + {}^2H \rightarrow {}^6Li + \gamma$
14) ${}^6Li + p \rightarrow {}^3He + {}^4He$
15) ^{7}Be + γ_{nt} → ^{6}Li + p

Abundances

Y_P

D/H

3He/H

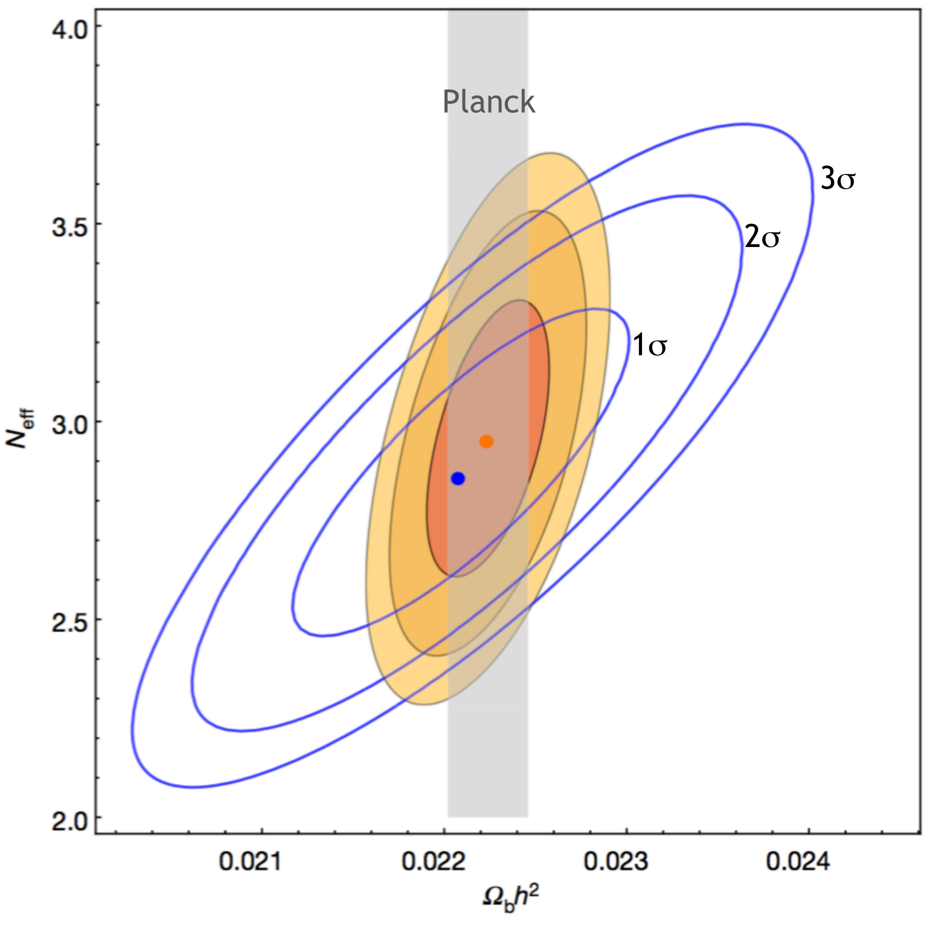
7Li/H

$\Omega_{b0}h^2$(CMB)=0.0.22237±0.00015
(PLANCK2018)
h= reduced Hubble constant

D/H = $(2.527 \pm 0.030) \times 10^{-5}$
(Cooke 2015)

(D + CMB) case : used as constrains $(D/H)_{obs}$ + $\Omega_b h^2$ by Planck

N_{eff} vs $\Omega_b h^2$: first case (D+CMB)



Prior on $\Omega_b h^2$;

0.02236 ± 0.00015

$N_{eff} = 2.95^{+0.61}_{-0.57}$

99% C.L.

Orange (D + CMB) case : used as constrains $(D/H)_{obs}$ + $\Omega_b h^2$ by Planck

N_{eff} vs $\Omega_b h^2$: second case (D+Y_P)

Constrains

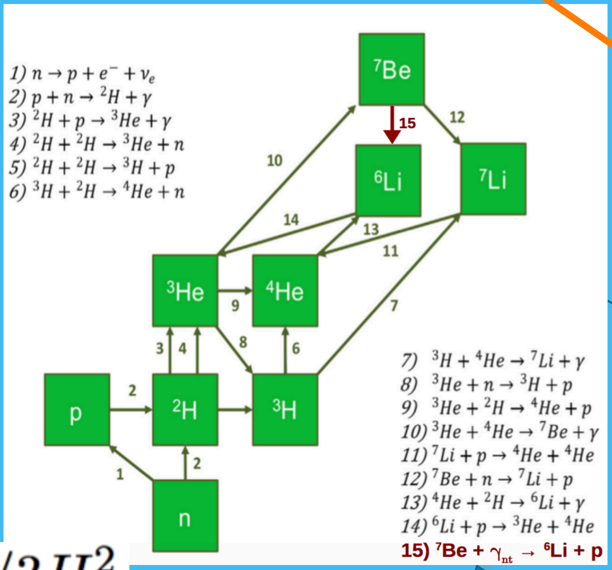
Free parameters

$\Omega_B h^2$ or $\eta = n_B/n\gamma$

N_{eff}

$$\Omega_B = \rho_B/\rho_{\rm crit} = 8\pi G\rho_B/3H_0^2$$

$$H_0 = 100h \ {\rm km/s/Mpc}$$



1) $n \rightarrow p + e^- + \nu_e$
2) $p + n \rightarrow {}^2H + \gamma$
3) ${}^2H + p \rightarrow {}^3He + \gamma$
4) ${}^2H + {}^2H \rightarrow {}^3He + n$
5) ${}^2H + {}^2H \rightarrow {}^3H + p$
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7) ${}^3H + {}^4He \rightarrow {}^7Li + \gamma$
8) ${}^3He + n \rightarrow {}^3H + p$
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12) ${}^7Be + n \rightarrow {}^7Li + p$
13) ${}^4He + {}^2H \rightarrow {}^6Li + \gamma$
14) ${}^6Li + p \rightarrow {}^3He + {}^4He$
15) ${}^7Be + \gamma_{nt} \rightarrow {}^6Li + p$

Abundances

Y_P

D/H

3He/H

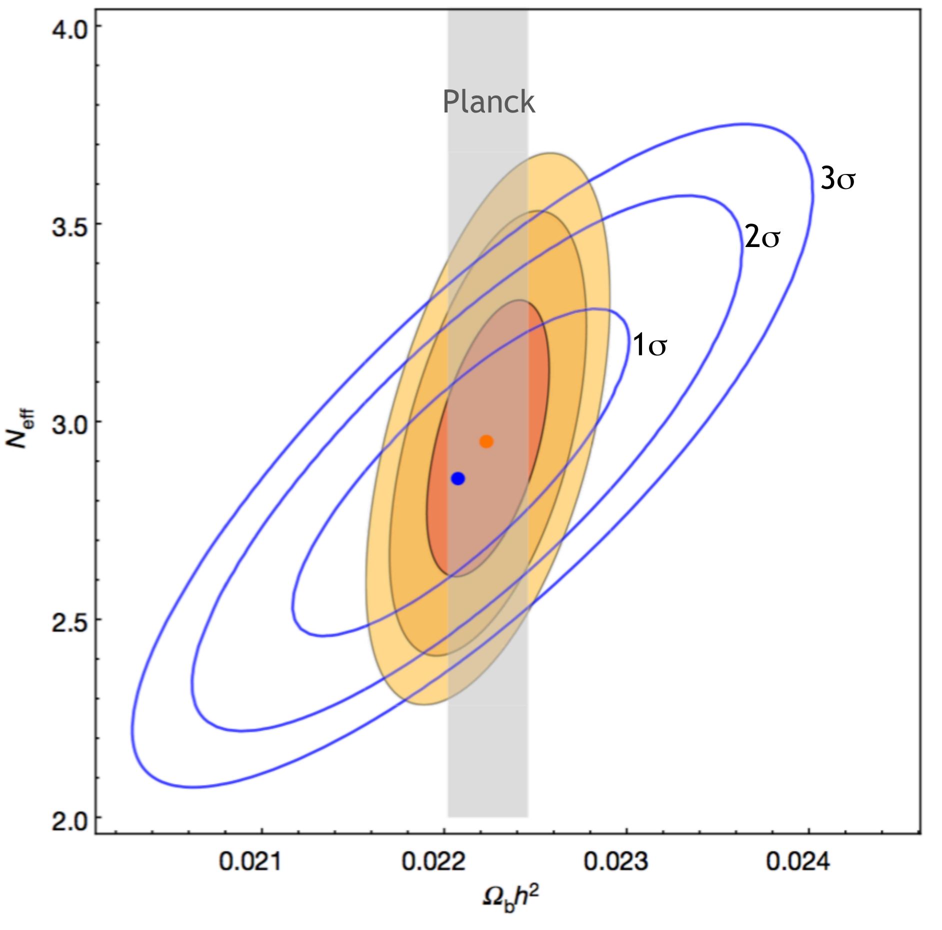
7Li/H

Y_P = 0.2449 ± 0.0040 *(Aver 2015)*

D/H = (2.527 ± 0.030) × 10^{-5} (*Cooke 2015*)

(D + *Yp*) case : used as constrains $(D/H)_{obs}$ + the ^{4}He mass fraction *Yp*

N_{eff} vs $\Omega_b h^2$: second case (D+Y_P)



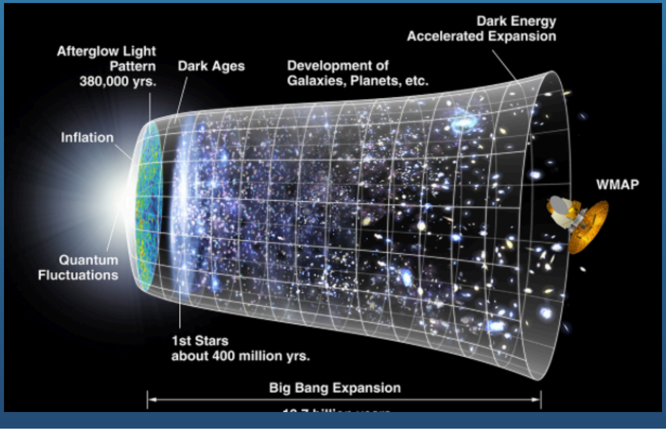
$$N_{eff} = 2.86^{+0.75}_{-0.67}$$

99% C.L.

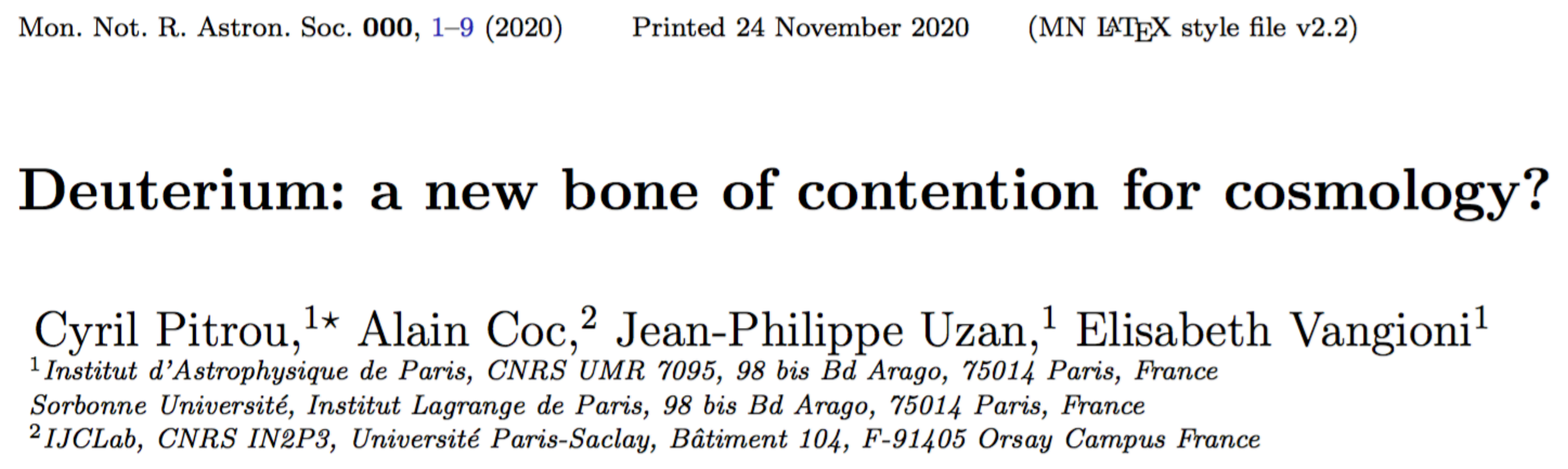
Blue (D + *Yp*) case : used as constrains $(D/H)_{obs}$ + the ^{4}He mass fraction *Yp*

Summary:

- BBN + $(D/H)_{obs}$ very good agreement on the baryon density with cosmic microwave background (Planck) -> no tension between few minutes and 380000 years after Big Bang, no need for new physics
- We confirm $N_{eff} = 3$ (by excluding at more that 3 σ the values $N_{eff} = 2,4$)
- Direct observation, BBN and CMB do agrees on D abundance!
- We support the standard cosmological model



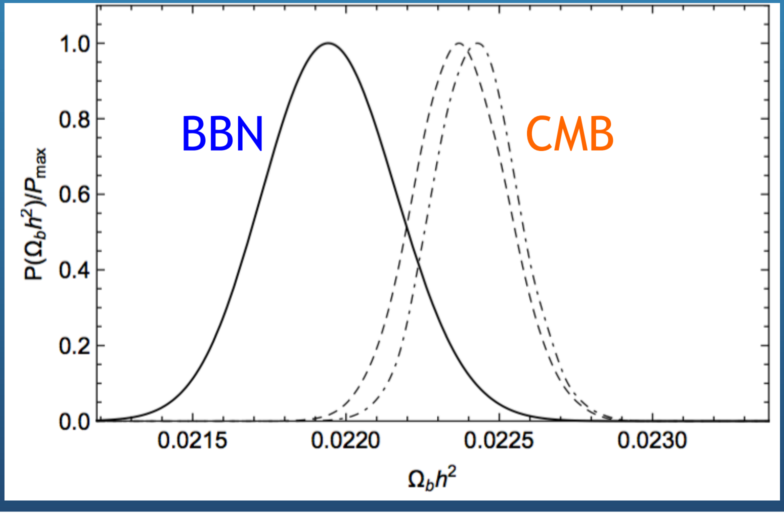
But… one week ago…



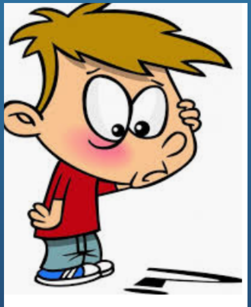
Mon. Not. R. Astron. Soc. **000**, 1–9 (2020) Printed 24 November 2020 (MN LaTeX style file v2.2)

Deuterium: a new bone of contention for cosmology?

Cyril Pitrou,[1⋆] Alain Coc,[2] Jean-Philippe Uzan,[1] Elisabeth Vangioni[1]
[1] *Institut d'Astrophysique de Paris, CNRS UMR 7095, 98 bis Bd Arago, 75014 Paris, France*
Sorbonne Université, Institut Lagrange de Paris, 98 bis Bd Arago, 75014 Paris, France
[2] *IJCLab, CNRS IN2P3, Université Paris-Saclay, Bâtiment 104, F-91405 Orsay Campus France*

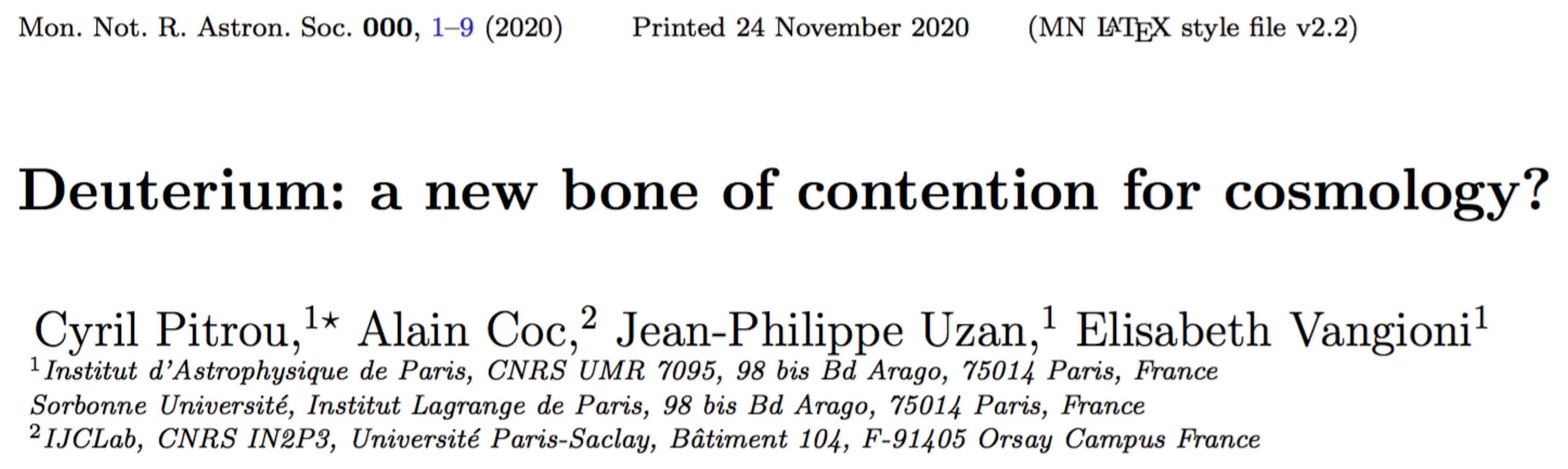


Different fit of d(d,n) and d(d,p) reactions !!!



New work for us???

But… one week ago…



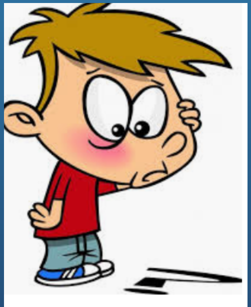
Mon. Not. R. Astron. Soc. **000**, 1–9 (2020) Printed 24 November 2020 (MN LATEX style file v2.2)

Deuterium: a new bone of contention for cosmology?

Cyril Pitrou,[1⋆] Alain Coc,[2] Jean-Philippe Uzan,[1] Elisabeth Vangioni[1]
[1] *Institut d'Astrophysique de Paris, CNRS UMR 7095, 98 bis Bd Arago, 75014 Paris, France*
Sorbonne Université, Institut Lagrange de Paris, 98 bis Bd Arago, 75014 Paris, France
[2] *IJCLab, CNRS IN2P3, Université Paris-Saclay, Bâtiment 104, F-91405 Orsay Campus France*

Different fit of d(d,n) and d(d,p) reactions !!!

Yesterday : Fields &C
https://arxiv.org/pdf/2011.13874.pdf
confirmed our analysis results!!!



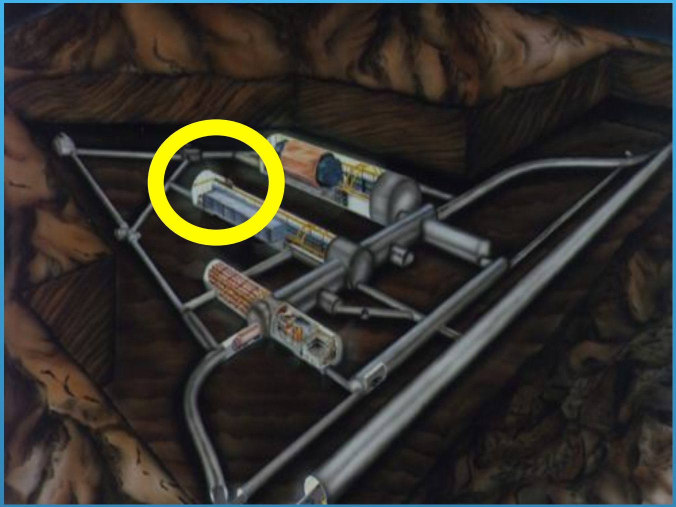
New work
for us???

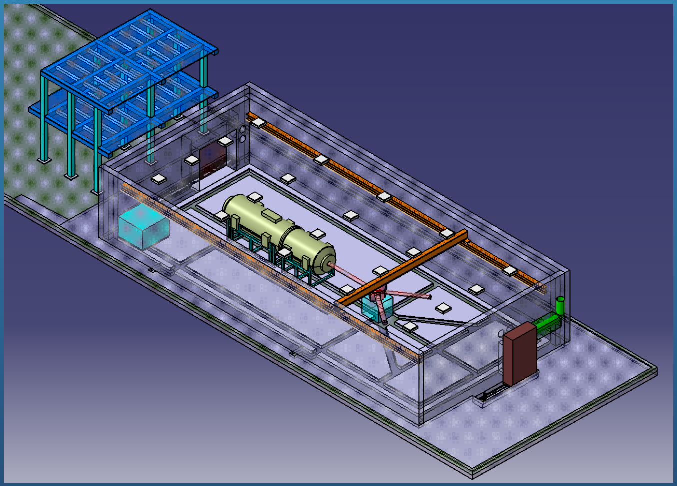
Whats’ next?

- Post main sequence phases, He and C burning
- The creation of the heavy element

LUNA MV accelerator (3.5 MV)

A new 3.5 MV accelerator will be installed in the Hall B at Gran Sasso

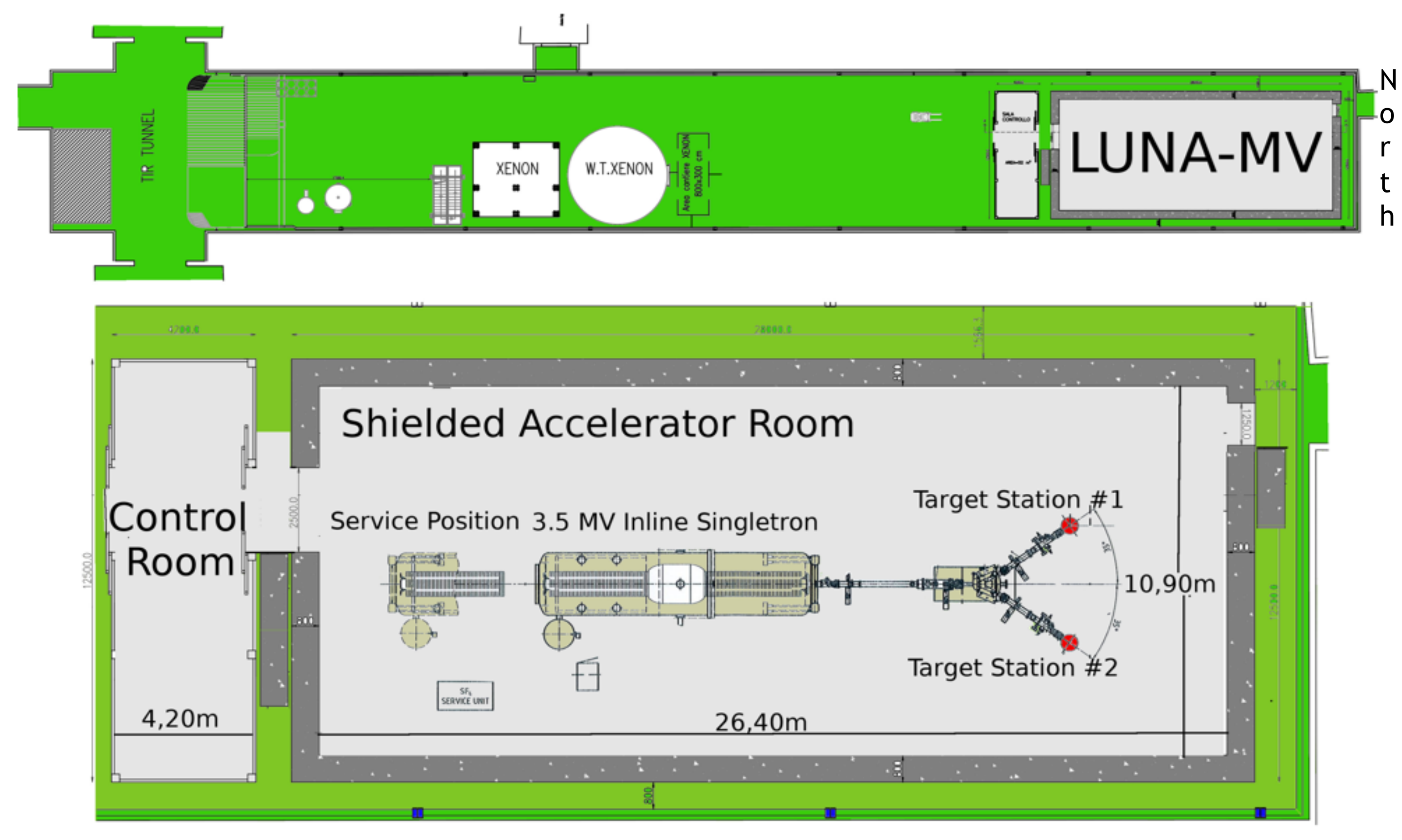




Concrete bunker during construction

LUNA MV accelerator (3.5 MV)

Supported by a 3.5 MEuro grant from the Italian ministery of Research



Accelerator performances and neutron shielding

H

$^{1}H^{+}$ (TV: 0.3 – 0.5 MV): 500 μA
$^{1}H^{+}$ (TV: 0.5 – 3.5 MV): 1000 μA

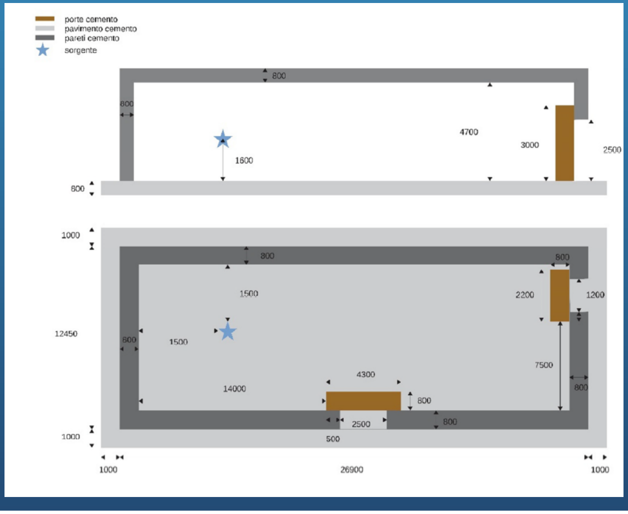
He

$^{4}He^{+}$ (TV: 0.3 – 0.5 MV): 300 μA
$^{4}He^{+}$ (TV: 0.5 – 3.5 MV): 500 μA

C

$^{12}C^{+}$ (TV: 0.3 – 0.5 MV): 100 μA
$^{12}C^{+}$ (TV: 0.5 – 3.5 MV): 150 μA
$^{12}C^{++}$ (TV: 0.5 – 3.5 MV): 100 μA

- inline Cockcroft Walton accelerator
- ECR ion source
- **TERMINAL VOLTAGE: 0.2 – 3.5 MV**
- Precision of terminal voltage reading: 350 V
- Beam energy reproducibility: 0.01% TV
- Beam energy stability: 0.001% TV / h
- Beam current stability: < 5% / h



- 80 cm thick concrete shielding calculated by GEANT4 & MCNP
- E_n = 5.6 MeV, 2 10^3 n/s, isotropic

MCNP: $\Phi_n = 1.38\ 10^{-7}$ n/(cm^2 s)
GEANT4: $\Phi_n = 3.40\ 10^{-7}$ n/(cm^2 s)

Φ_n(LNGS) = 3 10^{-6} n/(cm^2 s)

THE LUNA Collaboration

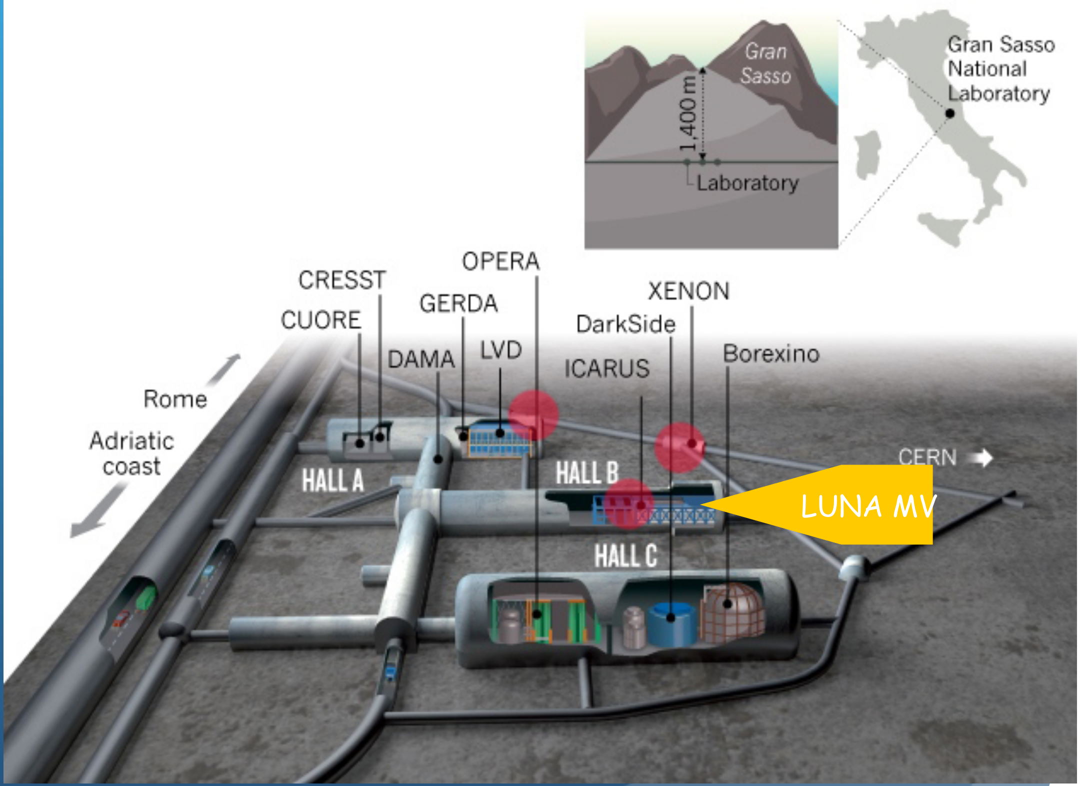
LUNA-MV (from 2020)

First 5 years proposal:

- ^{14}N(p,g)^{15}O test & calib
- ^{13}C(α,n)^{16}O
- ^{22}Ne(α,n)^{25}Mg
- ^{12}C(^{12}C,p)^{23}Na
- ^{12}C(^{12}C,α)^{20}Ne

n for s-process in AGB stars

C burning



https://luna.lngs.infn.it

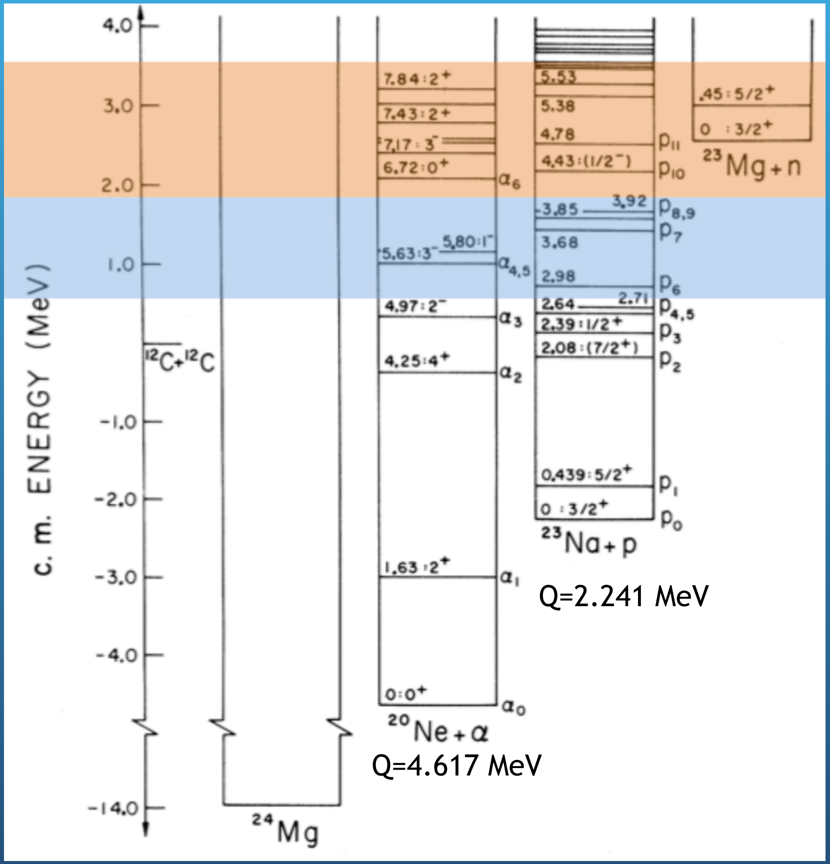
Carbon burning

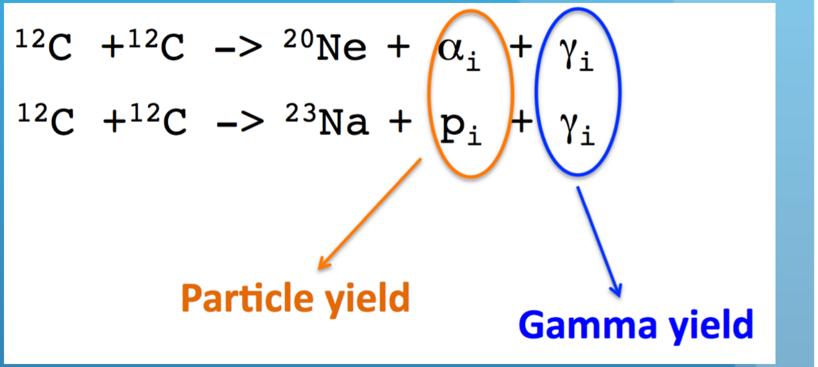
^{12}C + ^{12}C

- ✓ ^{12}C+^{12}C rate determines which stars explode as Supernovae and which die as White Dwarfs
- ✓ Energy region of interest ≈ 0.7 - 2.5 MeV

Quiescent C burning 0.5-1 GK

SN Ia 0.15 GK





^{12}C + ^{12}C -> ^{20}Ne + α_i + γ_i

^{12}C + ^{12}C -> ^{23}Na + p_i + γ_i

Particle yield

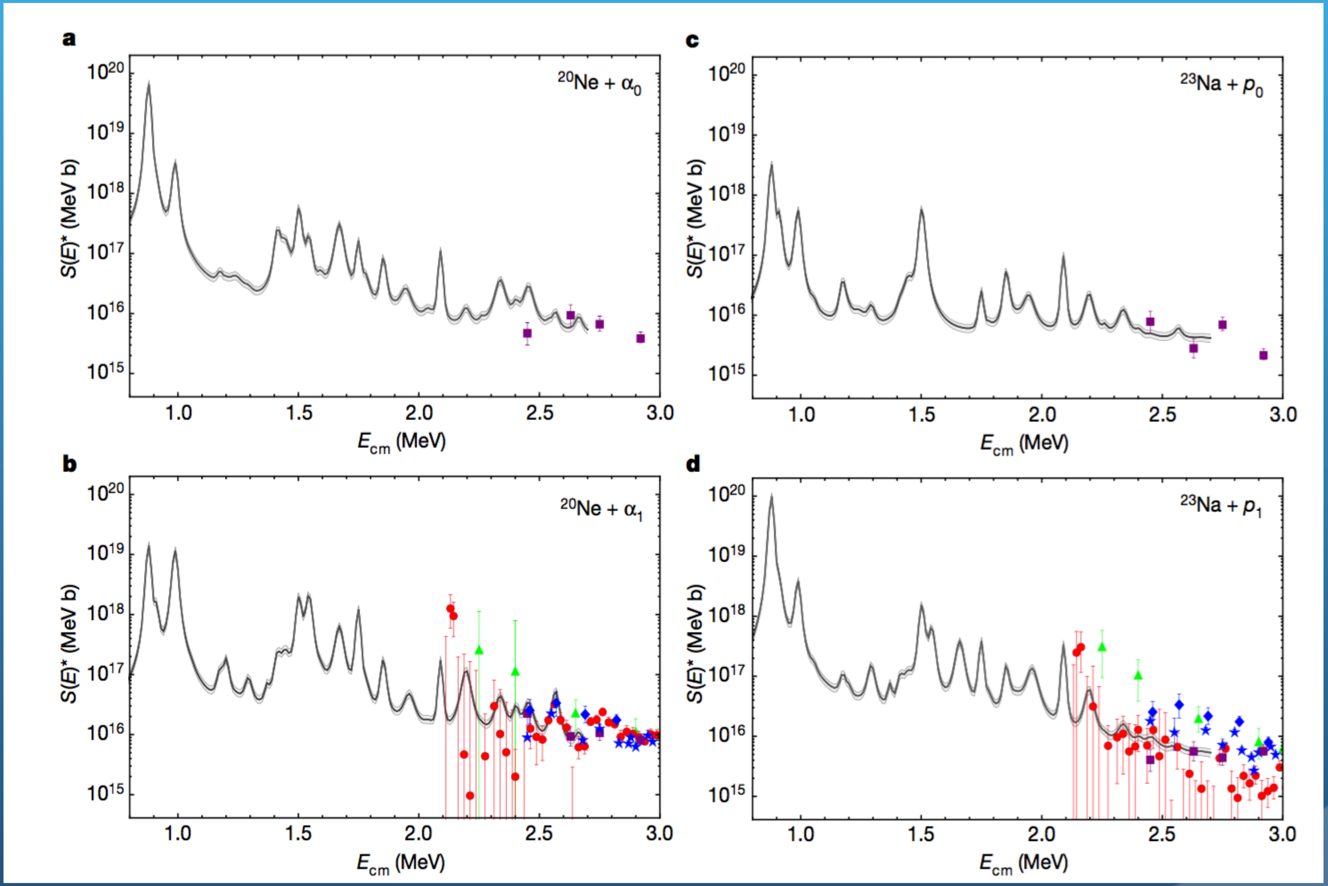
Gamma yield

- Both particle and gamma detectors are needed
- Background : $^{1}H(^{12}C,\gamma)^{13}N$ and $^{2}H(^{12}C,p\gamma)^{13}C$ -> reduced by heating at 700° C the target

$^{12}C + ^{12}C$

✓ $^{12}C+^{12}C$ rate determines which stars explode as Supernovae and which die as White Dwarfs

✓ Energy region of interest ≈ 0.7 - 2.5 MeV

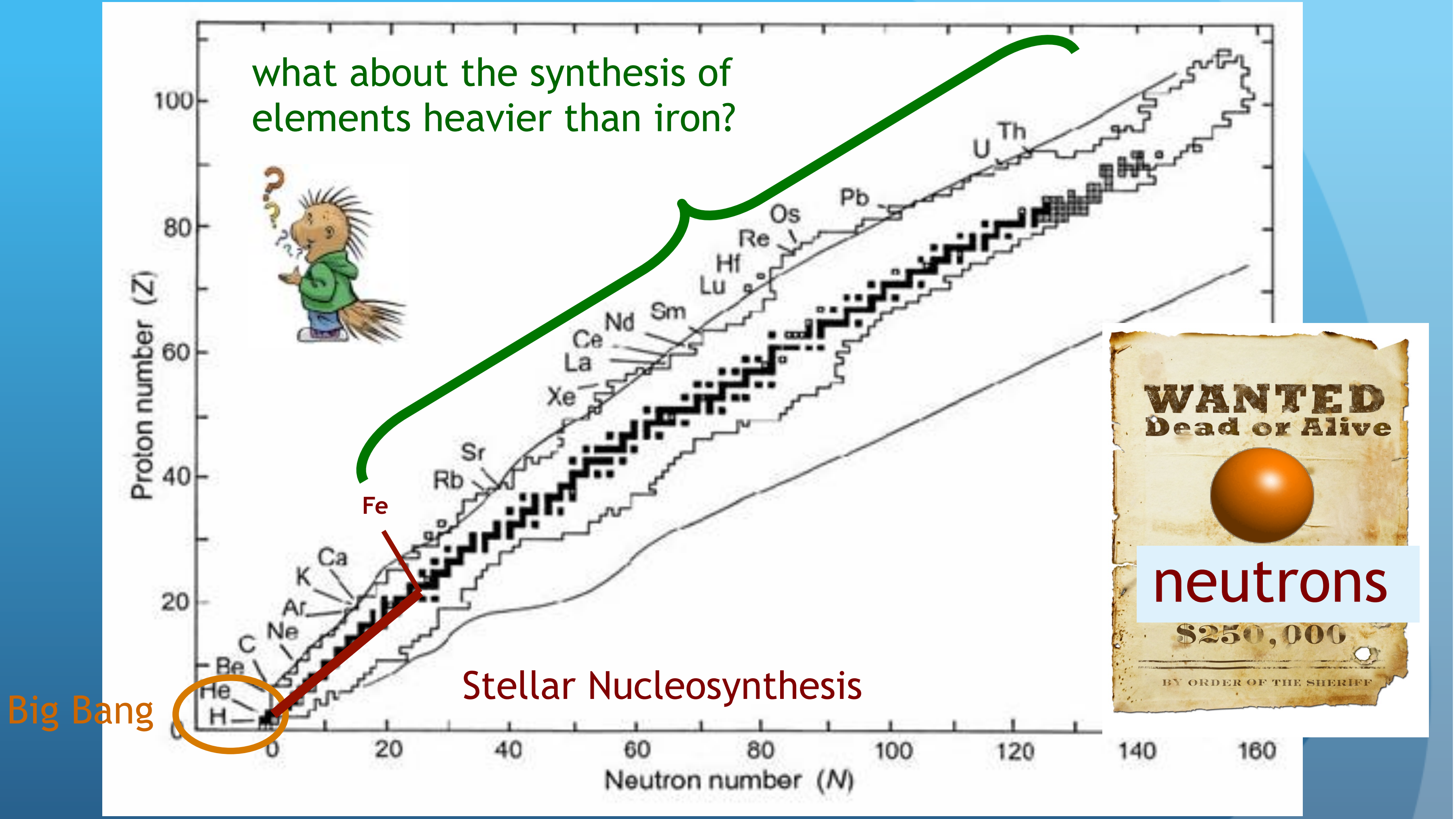


Tumino et al., Nature 557 (2018) 687

Al low energies only data with Trojan horse method: $^{12}C(^{14}N, \alpha\ ^{20}Ne)^2H$ and $^{12}C(^{14}N, p\ ^{23}Na)^2H$

The Creation of Heavy Elements

Nucleosynthesis beyond iron


what about the synthesis of elements heavier than iron?

Stellar Nucleosynthesis

Big Bang

Neutron capture reactions: the s(low) and the r(apid) processes

Courtesy : M. Aliotta

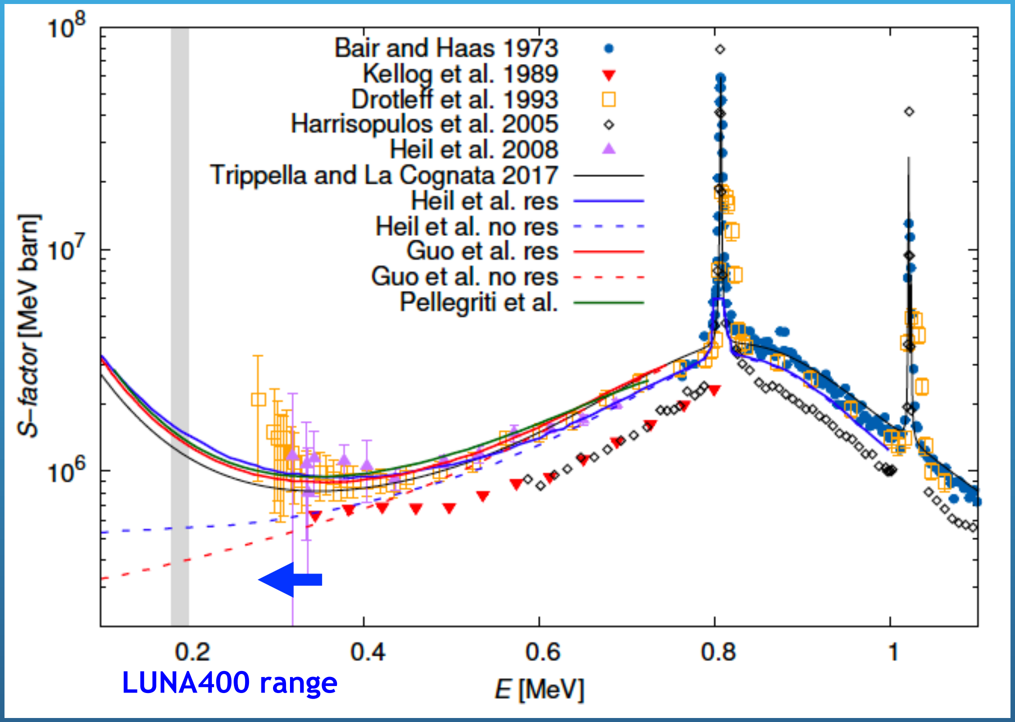
$^{13}C(\alpha,n)^{16}O$

Q=2.216 MeV

importance: main s-process in TP-AGB stars ~90<A<210

Gamow region: 130 - 250 keV

min. meas. E_{cm}: 280 keV

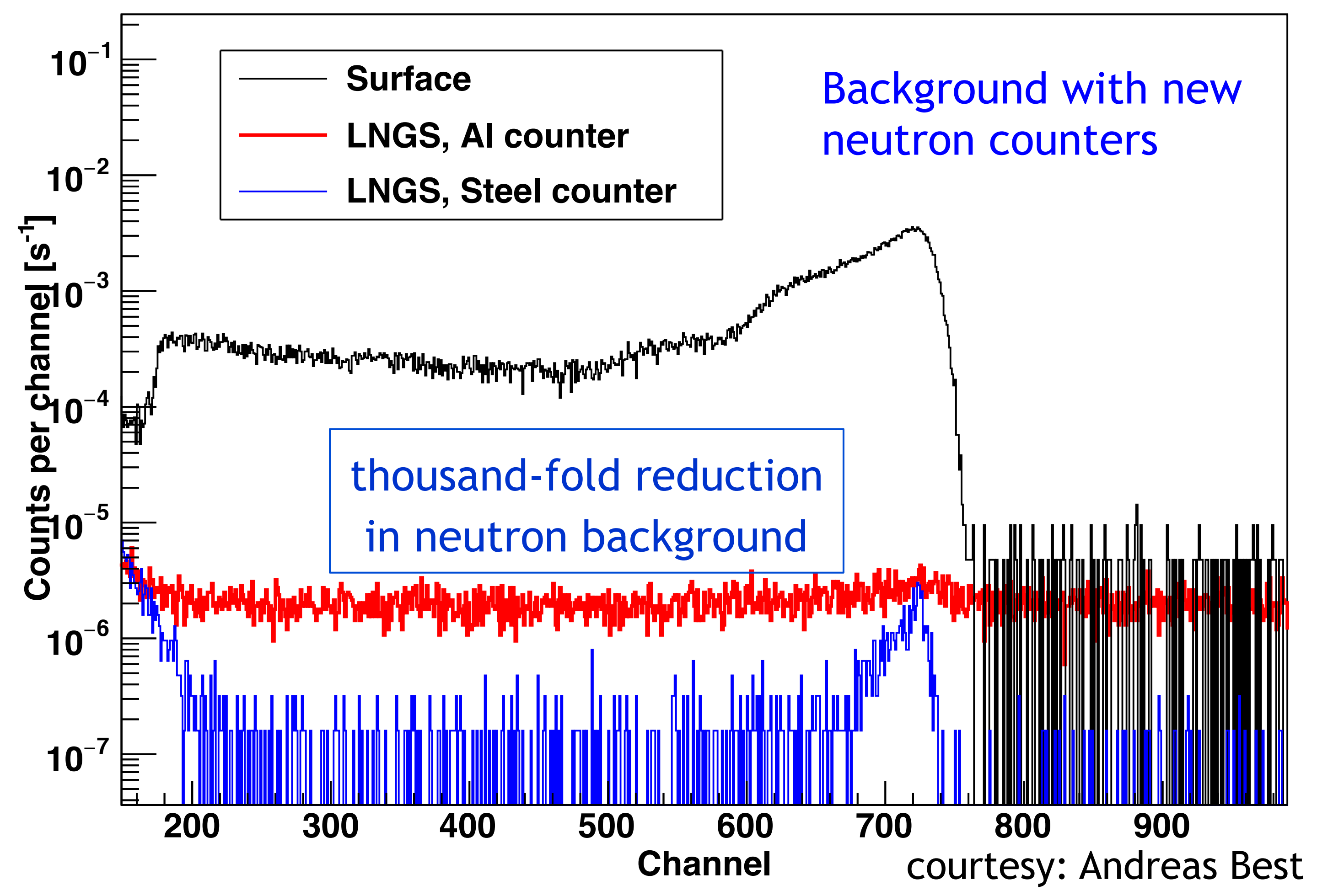


Broggini et al. Progr. Part. Nucl. Phys. 98 (2018) 55

- large statistical uncertainties at low energies
- large scatter in absolute values (normalization problem)
- unknown systematic uncertainties
- uncertainties in detection efficiencies
- contribution from sub-threshold state (E=6.356 MeV in ^{17}O)

mainly hampered by cosmic background → excellent case for underground study

LUNA: an ideal environment for neutron detection

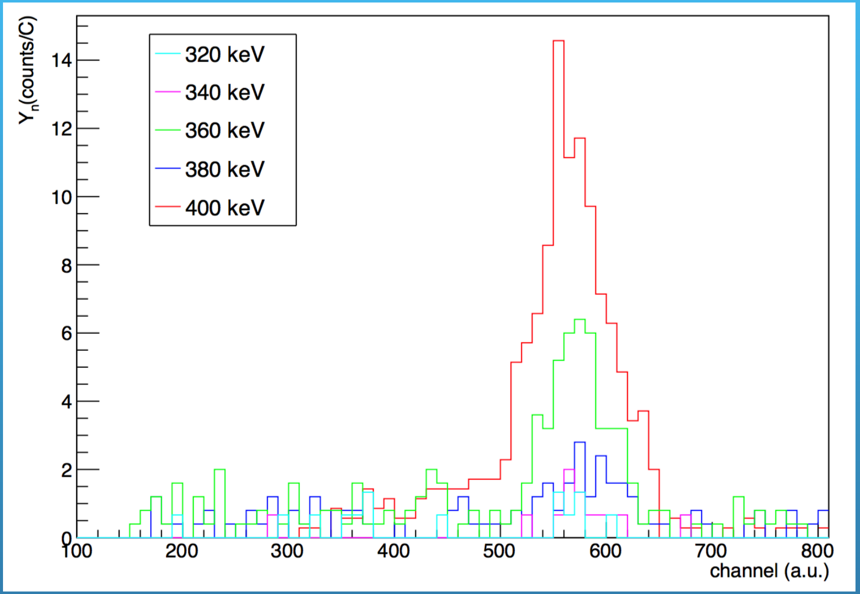


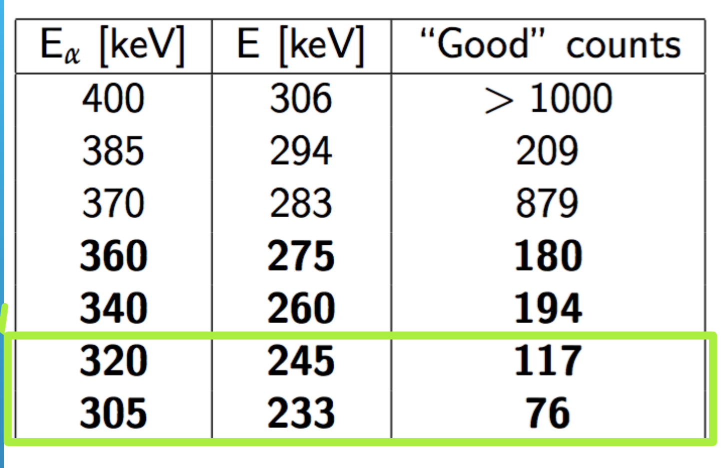
courtesy: Andreas Best

Proper material selection + pulse shape analysis : background < 1 count/hour

$^{13}C(\alpha,n)^{16}O$ at LUNA-400 completed!

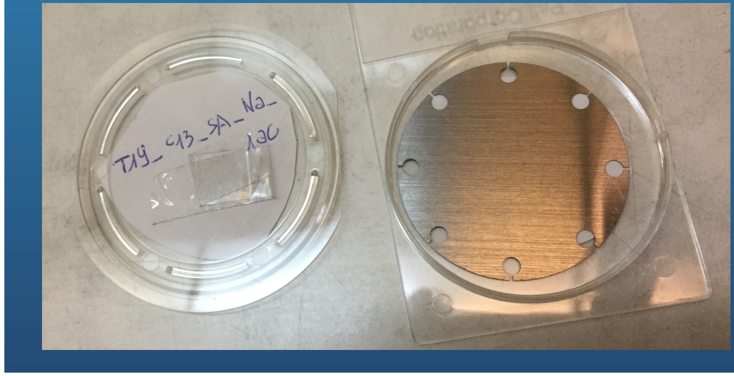
- 3 beam times, about 6 months, > 100 target
- Range into Gamow window, below Drotleff et al.





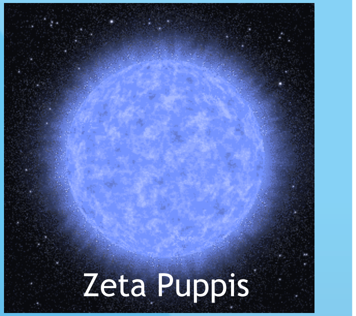
E_α [keV]	E [keV]	"Good" counts
400	306	> 1000
385	294	209
370	283	879
360	**275**	**180**
340	**260**	**194**
320	**245**	**117**
305	**233**	**76**

99% enriched ^{13}C targets on Ta backing



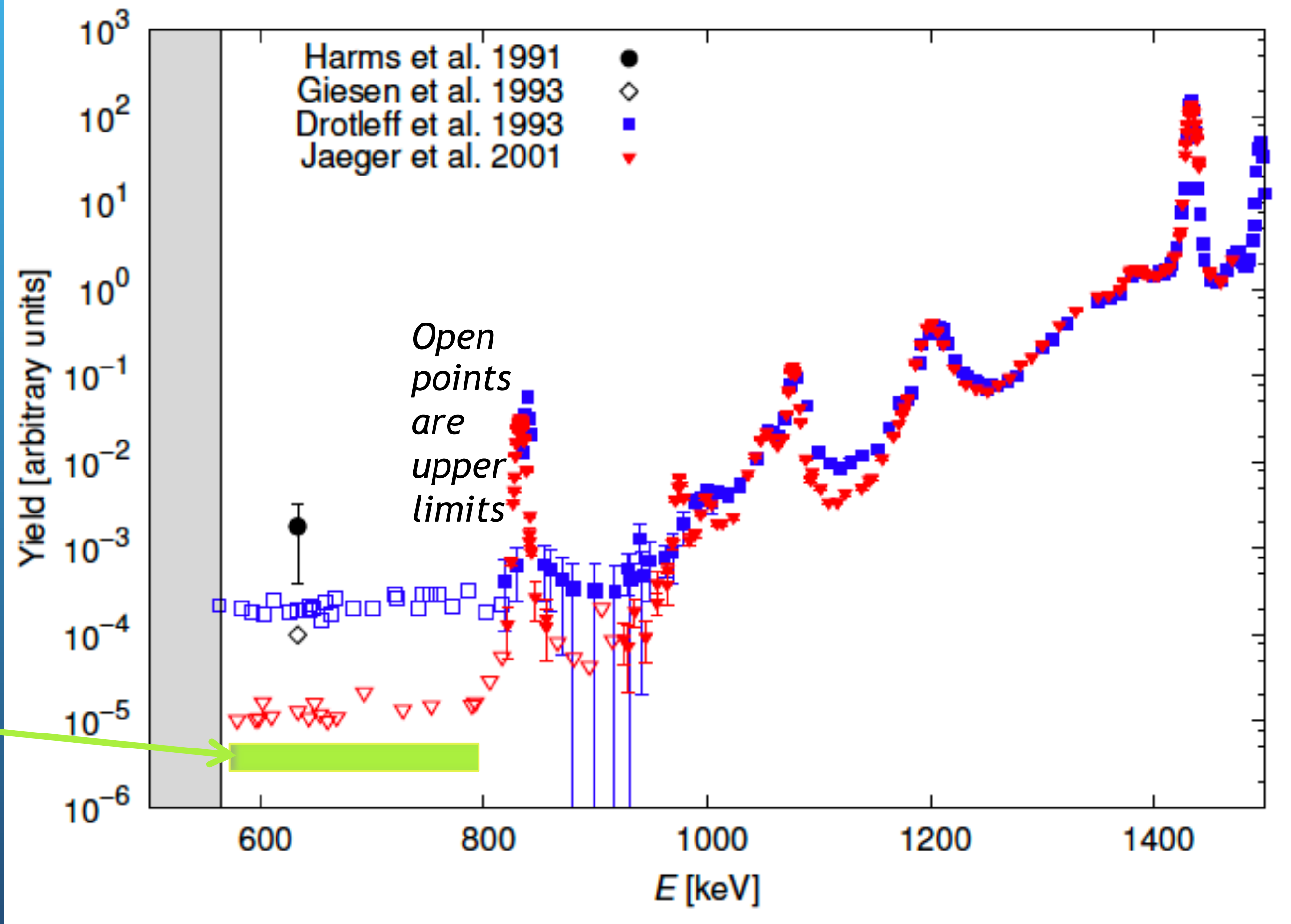
courtesy: A Best

$^{22}Ne(\alpha,n)^{25}Mg$



Q=-478 keV importance: weak s-process component

min. measured E_α: 800 keV



Open points are upper limits

Region of interest for s-process in He shell

Broggini et al. Progr. Part. Nucl. Phys. 98 (2018) 55

$^{22}Ne(\alpha,n)^{25}Mg$


Zeta Puppis

Q=-478 keV

- Windowless gas target enriched in ^{22}Ne + neutron detector.
- Most severe beam induced background from the 11B(a,n)14N
- accurate cross section measurement down to $E_{c.m.}$~ 600 keV
-

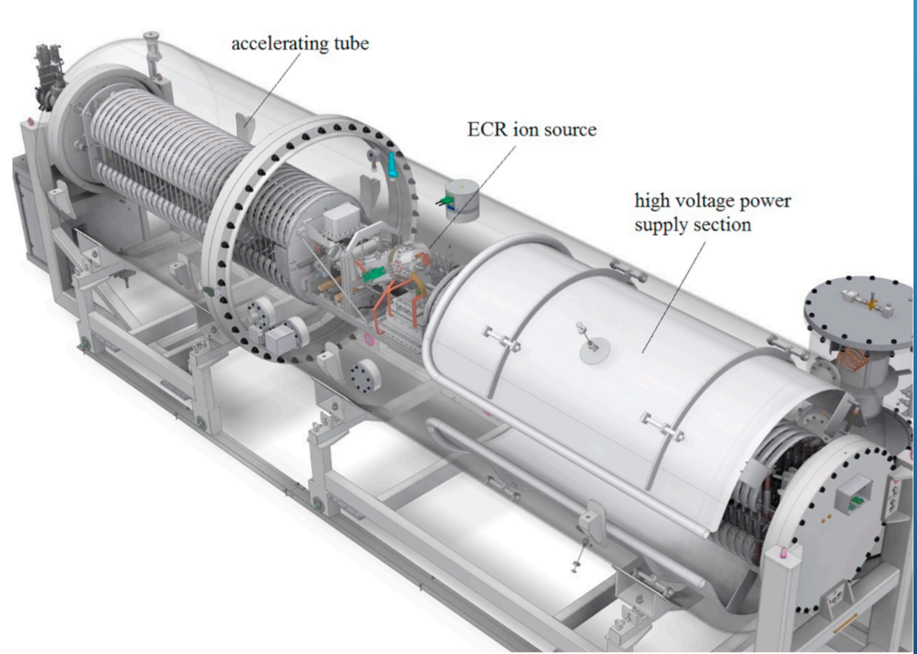
European Research Council
Established by the European Commission

SHADES (Scintillator-He3 Array for Deep underground Experiments on the S-process)

ERC starting grant (A. Best-Grant agreement ID: 852016)

- Recently awarded to realize a new setup for the measurement of the reaction at energies of astrophysical interest.
- Idea: 3He counters (high eff.) + scintillators (moderators + neutron energy)

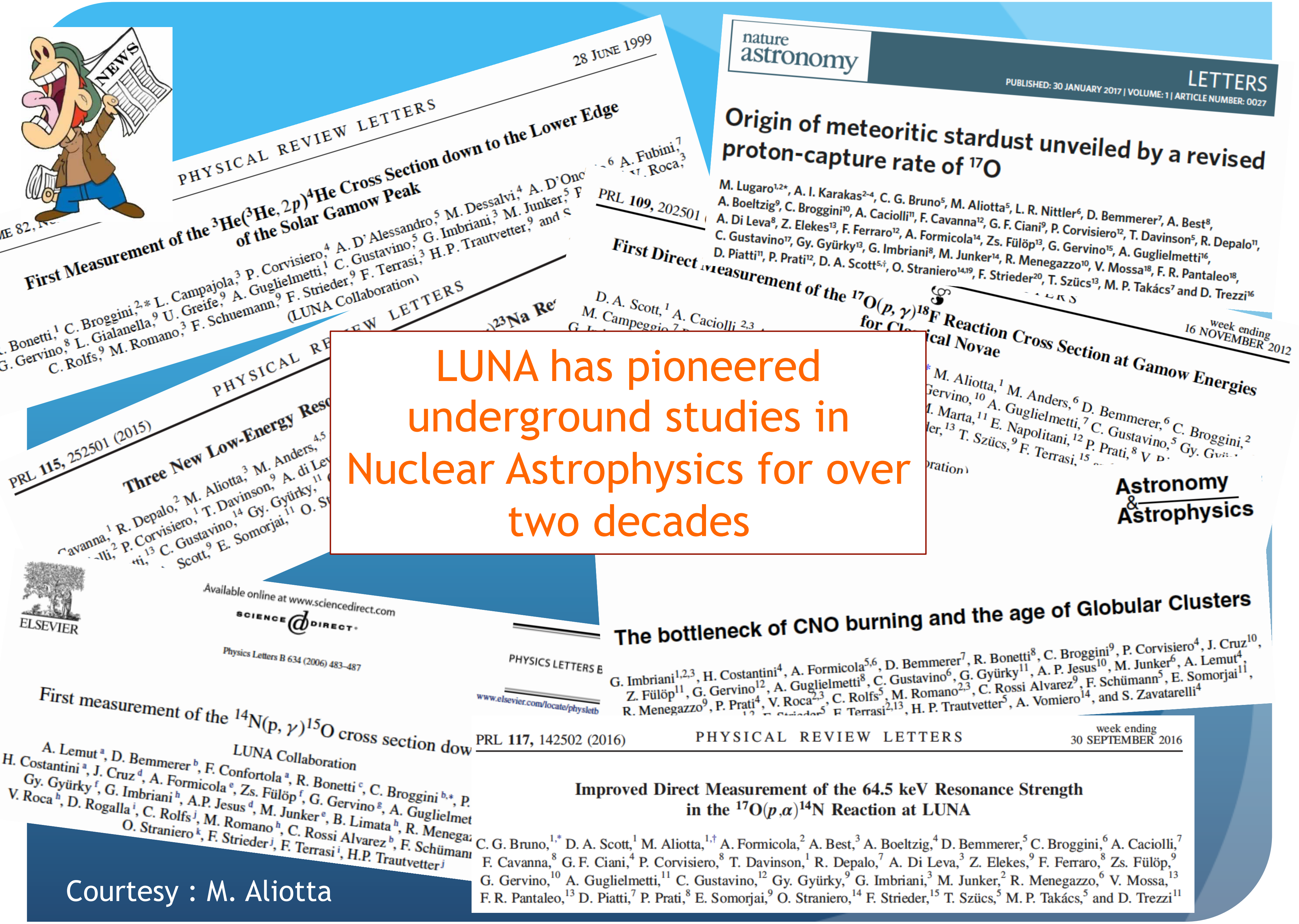
- Accelerator ready at High Voltage Engineering and already tested
- Installation at Gran Sasso: 2021



- Two beam lines equipped with solid and gas target setups;
- Possibility to run contemporary more experiments
- Likely also the 400 KV accelerator will be moved closeby.

To Conclude…

LUNA has pioneered underground studies in Nuclear Astrophysics for over two decades



PHYSICAL REVIEW LETTERS 28 JUNE 1999

First Measurement of the ^{3}He(^{3}He, $2p$)^{4}He Cross Section down to the Lower Edge of the Solar Gamow Peak

. Bonetti,[1] C. Broggini,[2,*] L. Campajola,[3] P. Corvisiero,[4] A. D'Alessandro,[5] M. Dessalvi,[4] A. D'Ono
G. Gervino,[8] L. Gialanella,[9] U. Greife,[9] A. Guglielmetti,[1] C. Gustavino,[5] G. Imbriani,[3] M. Junker,[5] P
C. Rolfs,[9] M. Romano,[3] F. Schuemann,[9] F. Strieder,[9] F. Terrasi,[3] H.P. Trautvetter,[9] and S
(LUNA Collaboration)

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nature astronomy

LETTERS

PUBLISHED: 30 JANUARY 2017 | VOLUME: 1 | ARTICLE NUMBER: 0027

Origin of meteoritic stardust unveiled by a revised proton-capture rate of ^{17}O

M. Lugaro[1,2*], A. I. Karakas[2-4], C. G. Bruno[5], M. Aliotta[5], L. R. Nittler[6], D. Bemmerer[7], A. Best[8], A. Boeltzig[9], C. Broggini[10], A. Caciolli[11], F. Cavanna[12], G. F. Ciani[9], P. Corvisiero[12], T. Davinson[5], R. Depalo[11], A. Di Leva[8], Z. Elekes[13], F. Ferraro[12], A. Formicola[14], Zs. Fülöp[13], G. Gervino[15], A. Guglielmetti[16], C. Gustavino[17], Gy. Gyürky[13], G. Imbriani[8], M. Junker[14], R. Menegazzo[10], V. Mossa[18], F. R. Pantaleo[18], D. Piatti[11], P. Prati[12], D. A. Scott[5,†], O. Straniero[14,19], F. Strieder[20], T. Szücs[13], M. P. Takács[7] and D. Trezzi[16]

PRL 109, 202501

week ending 16 NOVEMBER 2012

First Direct Measurement of the ^{17}O(p, γ)^{18}F Reaction Cross Section at Gamow Energies for Classical Novae

D. A. Scott,[1] A. Caciolli,[2,3]
M. Campeggio,[7]

M. Aliotta,[1] M. Anders,[6] D. Bemmerer,[6] C. Broggini,[2]
Gervino,[10] A. Guglielmetti,[7] C. Gustavino,[5] Gy. Gyü
. Marta,[11] E. Napolitani,[12] P. Prati,[8]
ler,[13] T. Szücs,[9] F. Terrasi,[15]
oration)

PRL 115, 252501 (2015) PHYSICAL REVIEW LETTERS

Three New Low-Energy Reso

Cavanna,[1] R. Depalo,[2] M. Aliotta,[3] M. Anders,[4,5]
lli,[2] P. Corvisiero,[1] T. Davinson,[9] A. di Le
C. Gustavino,[14] Gy. Gyürky,[11]
Scott,[9] E. Somorjai,[11] O. S

Astronomy & Astrophysics

The bottleneck of CNO burning and the age of Globular Clusters

G. Imbriani[1,2,3], H. Costantini[4], A. Formicola[5,6], D. Bemmerer[7], R. Bonetti[8], C. Broggini[9], P. Corvisiero[4], J. Cruz[10], Z. Fülöp[11], G. Gervino[12], A. Guglielmetti[8], C. Gustavino[6], G. Gyürky[11], A. P. Jesus[10], M. Junker[6], A. Lemut[4], R. Menegazzo[9], P. Prati[4], V. Roca[2,3], C. Rolfs[5], M. Romano[2,3], C. Rossi Alvarez[9], F. Schümann[5], E. Somorjai[11], F. Terrasi[2,13], H. P. Trautvetter[5], A. Vomiero[14], and S. Zavatarelli[4]

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Physics Letters B 634 (2006) 483–487

PHYSICS LETTERS B

www.elsevier.com/locate/physletb

First measurement of the ^{14}N(p, γ)^{15}O cross section dow

LUNA Collaboration

A. Lemut[a], D. Bemmerer[b], F. Confortola[a], R. Bonetti[c], C. Broggini[b,*], P.
H. Costantini[a], J. Cruz[d], A. Formicola[e], Zs. Fülöp[f], G. Gervino[g], A. Guglielmet
Gy. Gyürky[f], G. Imbriani[h], A.P. Jesus[d], M. Junker[e], B. Limata[h], R. Menegaz
V. Roca[h], D. Rogalla[i], C. Rolfs[j], M. Romano[h], C. Rossi Alvarez[b], F. Schümann
O. Straniero[k], F. Strieder[j], F. Terrasi[i], H.P. Trautvetter[j]

PRL 117, 142502 (2016) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2016

Improved Direct Measurement of the 64.5 keV Resonance Strength in the ^{17}O(p,α)^{14}N Reaction at LUNA

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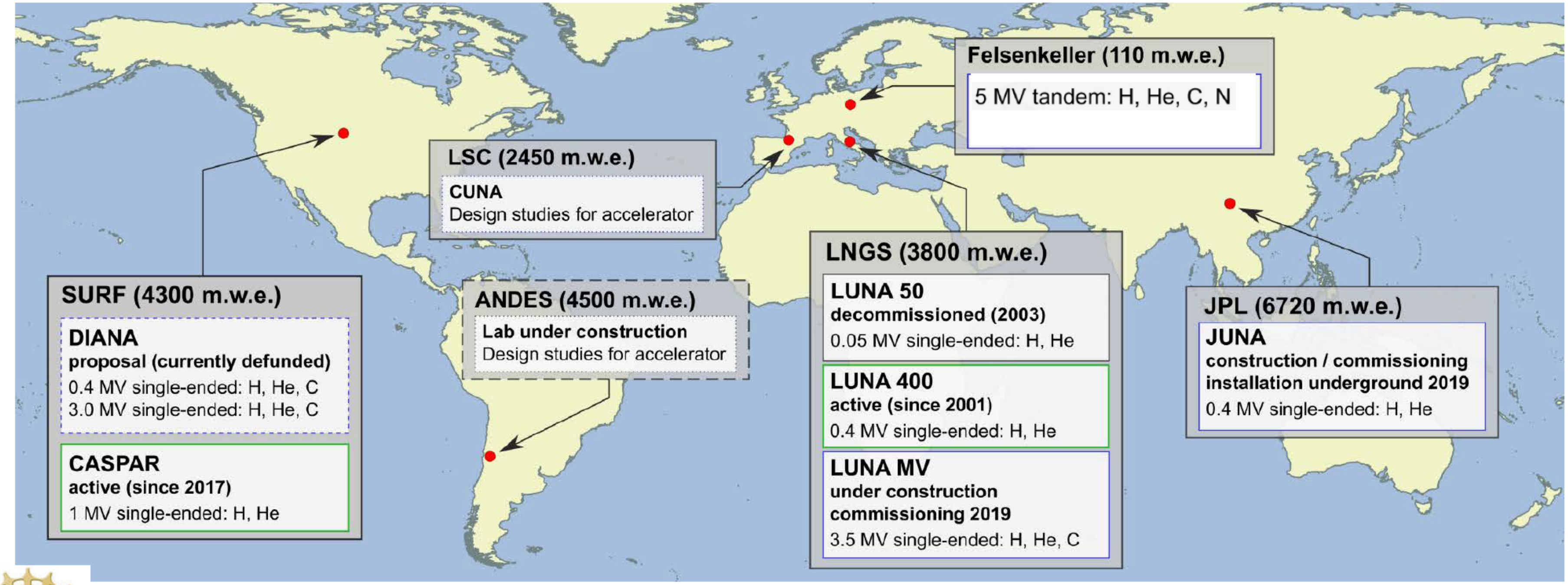
Courtesy : M. Aliotta

Nuclear astrophysics undeground laboratories

Nuclear Astrophysics Underground Laboratories



Felsenkeller (110 m.w.e.)

5 MV tandem: H, He, C, N

LSC (2450 m.w.e.)

CUNA
Design studies for accelerator

SURF (4300 m.w.e.)

DIANA
proposal (currently defunded)
0.4 MV single-ended: H, He, C
3.0 MV single-ended: H, He, C

CASPAR
active (since 2017)
1 MV single-ended: H, He

ANDES (4500 m.w.e.)

Lab under construction
Design studies for accelerator

LNGS (3800 m.w.e.)

LUNA 50
decommissioned (2003)
0.05 MV single-ended: H, He

LUNA 400
active (since 2001)
0.4 MV single-ended: H, He

LUNA MV
under construction
commissioning 2019
3.5 MV single-ended: H, He, C

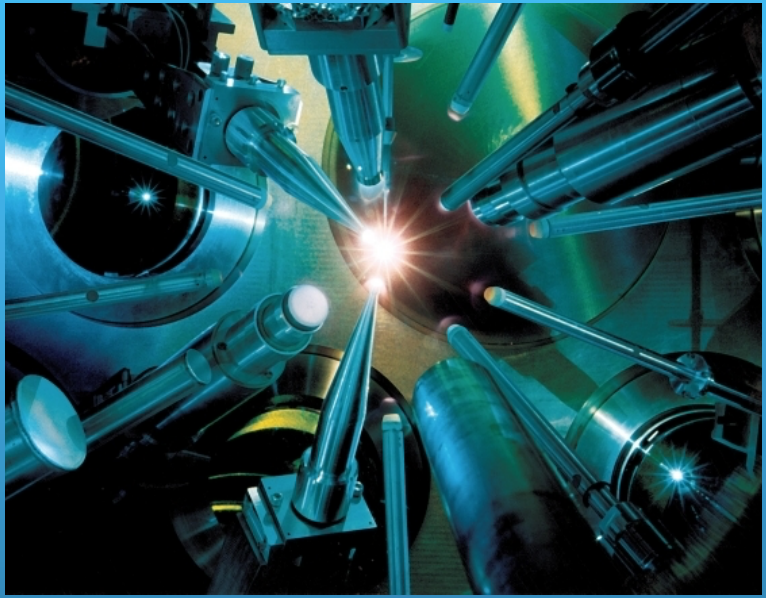
JPL (6720 m.w.e.)

JUNA
construction / commissioning
installation underground 2019
0.4 MV single-ended: H, He

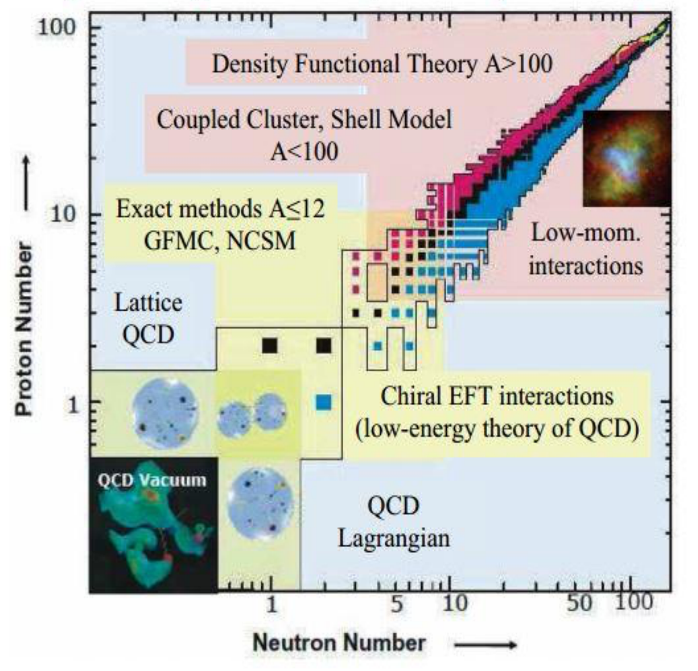
courtesy: A. Boeltzig

Ingredients from Future Breakthroughs

experiments



theory



observations

the human factor

training and retention of

young researchers

Courtesy : M. Aliotta

Grazie!!!!

Courtesy : M. Aliotta

THE LUNA COLLABORATION

http://luna.lngs.infn.it

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- D. Bemmerer, K. Stoeckel, M. Takacs | HZDR, Germany
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- R. Perrino | INFN Lecce, Italy
- M. Aliotta, C.G. Bruno, T. Chillery, T. Davinson | University of Edinburgh
- F. Cavanna, P. Corvisiero, F. Ferraro, **P. Prati**, S. Zavatarelli | Università di Genova and INFN Genova, Italy
- A. Guglielmetti | Università di Milano and INFN Milano, Italy
- J. Balibrea, A. Best, A. Di Leva, G. Imbriani | Università di Napoli "Federico II" and INFN Napoli, Italy
- G. Gervino | Università di Torino and INFN Torino, Italy
- C. Broggini, A. Caciolli, R. Depalo, P. Marigo, R. Menegazzo, D. Piatti | Università di Padova and INFN Padova, Italy
- C. Gustavino | INFN Roma1, Italy

CASPAR: Compact Accelerator Systems for Performing Astrophysical Research

SURF: Sanford Underground Laboratory at Homestake (4300 mwe)

Collaboration between:

- University of Notre Dame
- Colorado School of Mines
- South Dakota School of Mines and Technology

Thermal equilibrium

- At T < 100 MeV (t ~ $10^{-4}s$), the particle species left in thermal equilibrium in the universe are: n, p, ν, ν, $e\pm$, γ

$$\begin{cases} e^+ + e^- \leftrightarrow \gamma + \gamma \\ e^\pm + \gamma \leftrightarrow e^\pm + \gamma \end{cases} \quad \begin{cases} e^+ + e^- \leftrightarrow \nu + \bar{\nu} \\ e^- + \nu \leftrightarrow e^- + \nu \end{cases} \quad \begin{cases} \nu_e + n \leftrightarrow p + e^- \\ e^+ + n \leftrightarrow p + \bar{\nu}_e \\ n \leftrightarrow p + e^- + \bar{\nu}_e \end{cases}$$

Rate of interactions (Γ) and rate of expansion of the universe (H): thermal equilibrium breaks if $\Gamma \ll H$

Weak interactions (σ ~ G^2T^2, n ~ T^3, v ~ 1):

Γ = $n\sigma v$ ~ G^2T^5

$$\Gamma = n\sigma v \sim G_F^2 T^5$$

Expansion rate of the universe

$$H \sim \sqrt{g^* G_N}\, T^2$$

$$\frac{\Gamma}{H} = \frac{G_F^2 T^3}{\sqrt{g^* G_N}} \sim \left(\frac{T}{1\,MeV}\right)^3$$

At T_{dec} ~ 1 MeV (t ~ $1s$): **neutrino decoupling** and **neutron "freeze-out"**

Reaction chain

Almost all neutrons end up in 4He, which is stable and a local maximum in terms of binding energy($\Delta 4He$ =28.3MeV)

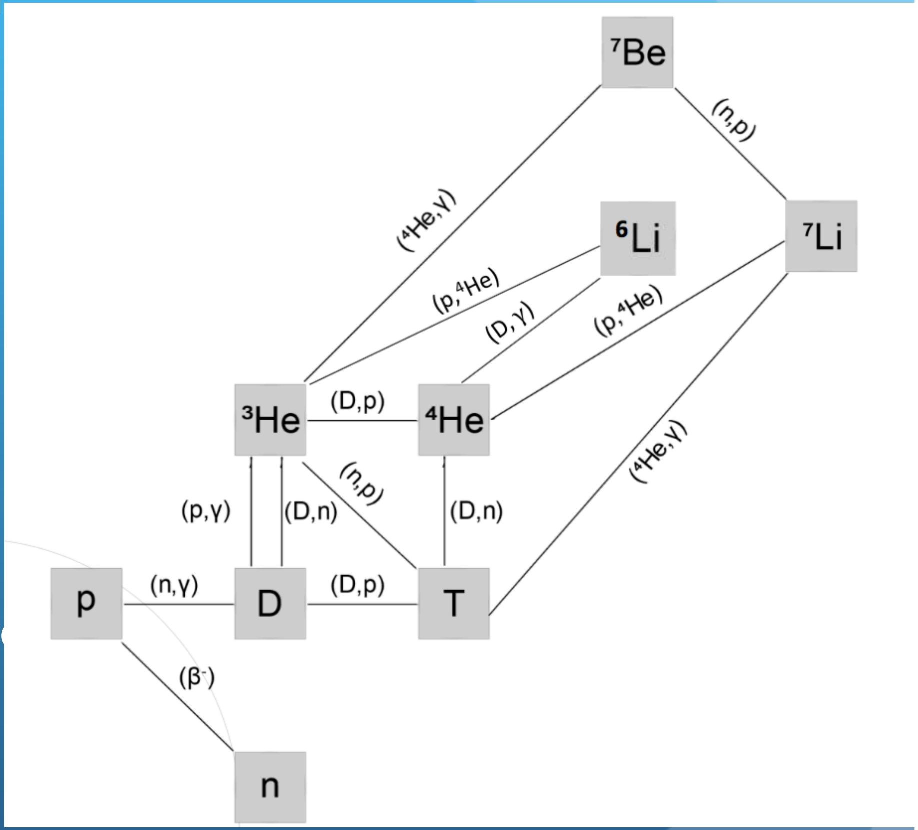
Production of heavier nuclei remains low.

➢The lack of nuclei with A = 5 and 8 prohibits reactions such as p+ 4He, n+ 4He, 4He+ 4He

➢Coulomb barriers suppress the production of heavier nuclei (even if the have higher binding energies, like 12C, 16O)

The only free parameter of the model is the **baryon density**, which determines th reaction rates. It usually expressed normalized to the relic photon density:

$$\eta \equiv \frac{n_b}{n_\gamma}$$



or equivalently the present baryon density

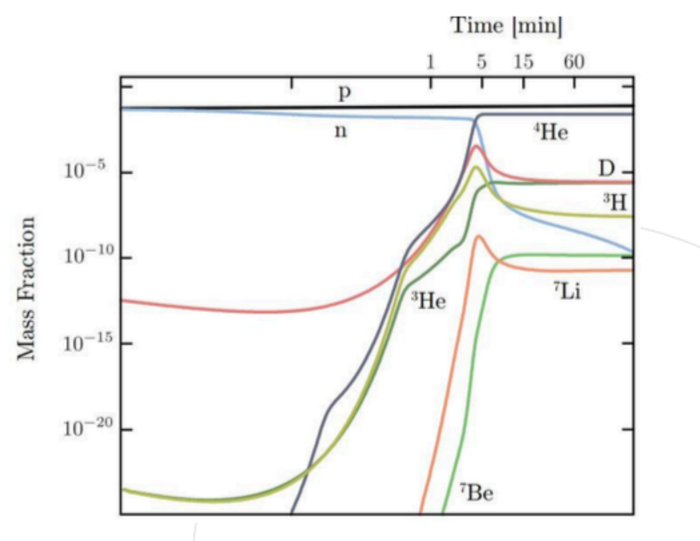
$$\Omega_b h^2 \equiv \omega_b$$

BBN calculatios

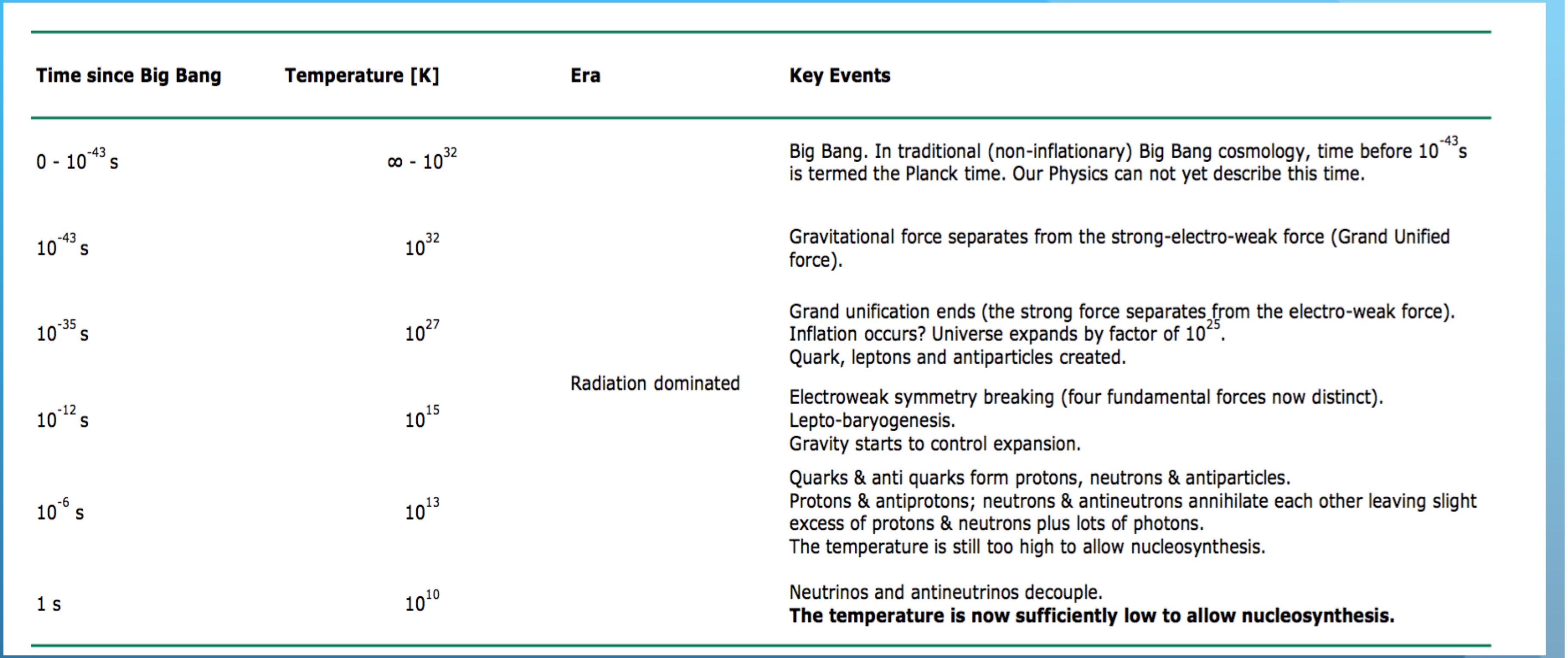
- Since all neutrons end up in $4He$: $n_{He} = n/2$

$$Y = \frac{(2m_p + 2m_n)n_{He}}{nm_n + p\,m_p} \approx \frac{2n}{n+p} = \frac{2(^n/_p)}{1 + {^n/_p}} = 0.25$$

All the other abundances are calculated by solving coupled Boltzmann equations, as a function of η, using **nuclear cross sections** as parameters.



Early universe



Time since Big Bang	Temperature [K]	Era	Key Events
0 - 10^{-43} s	∞ - 10^{32}	Radiation dominated	Big Bang. In traditional (non-inflationary) Big Bang cosmology, time before 10^{-43}s is termed the Planck time. Our Physics can not yet describe this time.
10^{-43} s	10^{32}		Gravitational force separates from the strong-electro-weak force (Grand Unified force).
10^{-35} s	10^{27}		Grand unification ends (the strong force separates from the electro-weak force). Inflation occurs? Universe expands by factor of 10^{25}. Quark, leptons and antiparticles created.
10^{-12} s	10^{15}		Electroweak symmetry breaking (four fundamental forces now distinct). Lepto-baryogenesis. Gravity starts to control expansion.
10^{-6} s	10^{13}		Quarks & anti quarks form protons, neutrons & antiparticles. Protons & antiprotons; neutrons & antineutrons annihilate each other leaving slight excess of protons & neutrons plus lots of photons. The temperature is still too high to allow nucleosynthesis.
1 s	10^{10}		Neutrinos and antineutrinos decouple. **The temperature is now sufficiently low to allow nucleosynthesis.**

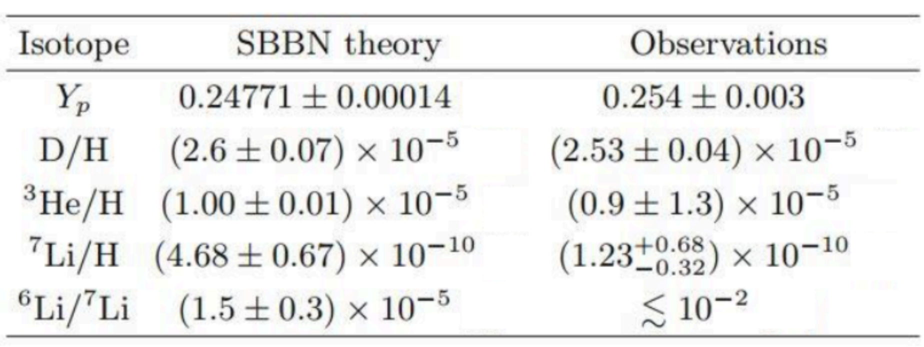
The timeline above is just a brief reminder of some of the most important events.

To have more details:

- "Gravitation" by Misner, Thorne and Wheeler (also known as “the Bible" or “the telephone book” of Cosmology).
- "The Early Universe" by Kolb and Turner.
- "Gravitation and Cosmology" by Steven Weinberg.

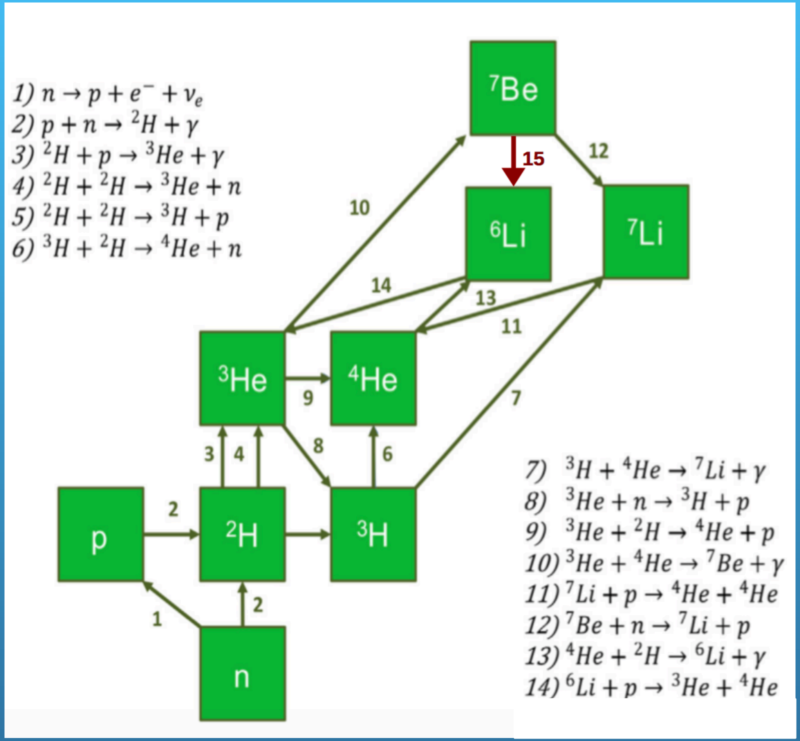
Observed abundances

- $4He$: emission lines in low-metallicity extragalactic regions. Probe for n/p ratio and number of effective species.
- D: light spectra of quasars crossing gas clouds at high redshift. No known astrophysical sources, and completely consumed during stellar evolution: if observed, it's primordial.
- $3He$: both produced and destroyed by stars, difficult to extract primordial sample.
- $7Li$: absorption line in low metallicity stars in the galactic halo. “**Lithium problem**”.
- $6Li$: thermal broadening in the stellar atmospheres exceeds the isotope separation. Disputed measurements: if true, “**second Lithium problem**”.



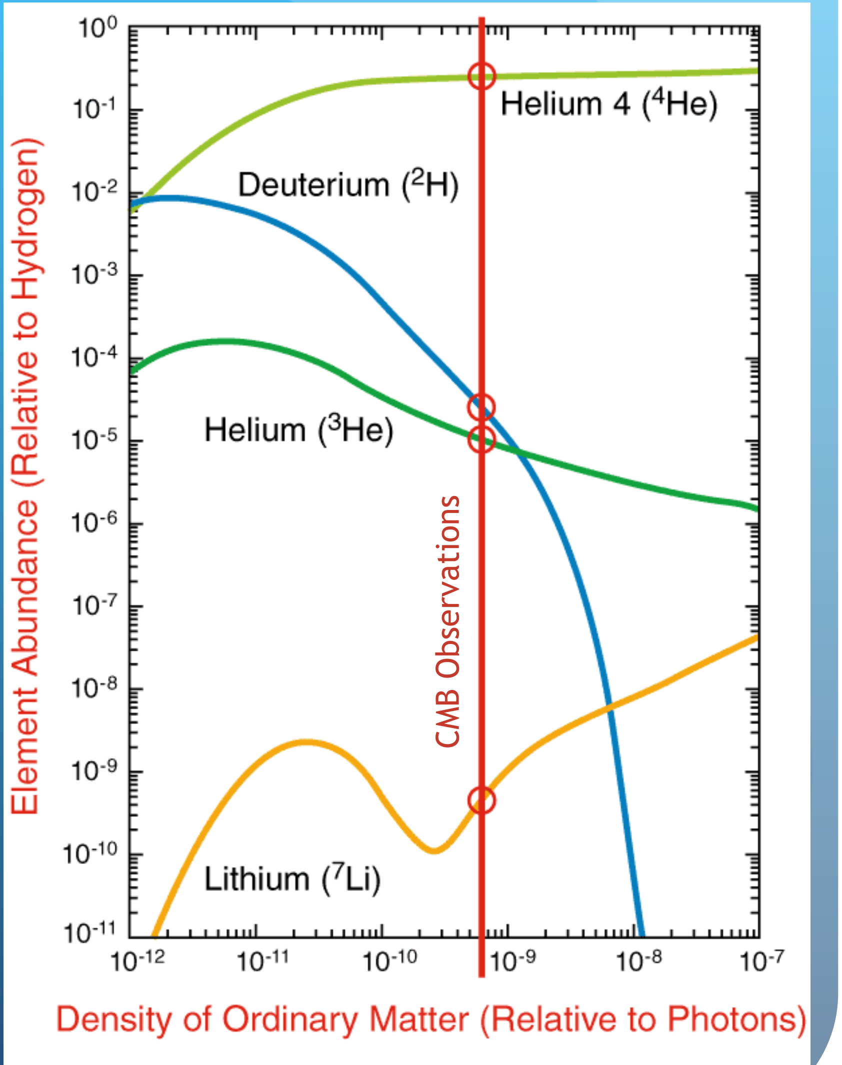
Isotope	SBBN theory	Observations
Y_p	0.24771 ± 0.00014	0.254 ± 0.003
D/H	$(2.6 \pm 0.07) \times 10^{-5}$	$(2.53 \pm 0.04) \times 10^{-5}$
^{3}He/H	$(1.00 \pm 0.01) \times 10^{-5}$	$(0.9 \pm 1.3) \times 10^{-5}$
^{7}Li/H	$(4.68 \pm 0.67) \times 10^{-10}$	$(1.23^{+0.68}_{-0.32}) \times 10^{-10}$
^{6}Li/^{7}Li	$(1.5 \pm 0.3) \times 10^{-5}$	$\lesssim 10^{-2}$

Primordial Nucleosynthesis (BBN): 3 minutes after Big Bang



1) $n \rightarrow p + e^- + \nu_e$
2) $p + n \rightarrow {}^2H + \gamma$
3) ${}^2H + p \rightarrow {}^3He + \gamma$
4) ${}^2H + {}^2H \rightarrow {}^3He + n$
5) ${}^2H + {}^2H \rightarrow {}^3H + p$
6) ${}^3H + {}^2H \rightarrow {}^4He + n$

7) ${}^3H + {}^4He \rightarrow {}^7Li + \gamma$
8) ${}^3He + n \rightarrow {}^3H + p$
9) ${}^3He + {}^2H \rightarrow {}^4He + p$
10) ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$
11) ${}^7Li + p \rightarrow {}^4He + {}^4He$
12) ${}^7Be + n \rightarrow {}^7Li + p$
13) ${}^4He + {}^2H \rightarrow {}^6Li + \gamma$
14) ${}^6Li + p \rightarrow {}^3He + {}^4He$



NASA/WMAP Science Team
WMAP101087

Element Abundance graphs: Steigman, Encyclopedia of Astronomy and Astrophysics (Institute of Physics) December, 2000

observations of D, ^{3}He, ^{4}He, and ^{7}Li in very old (**metal poor**) stars provide stringent tests of BBN

Big Bang Nucleosynthesis codes

The abundances are calculated by solving coupled Boltzmann equations, using **nuclear cross sections as ingredients**.

Free parameters of the model:

- **Baryon density**, which determines the reaction rates

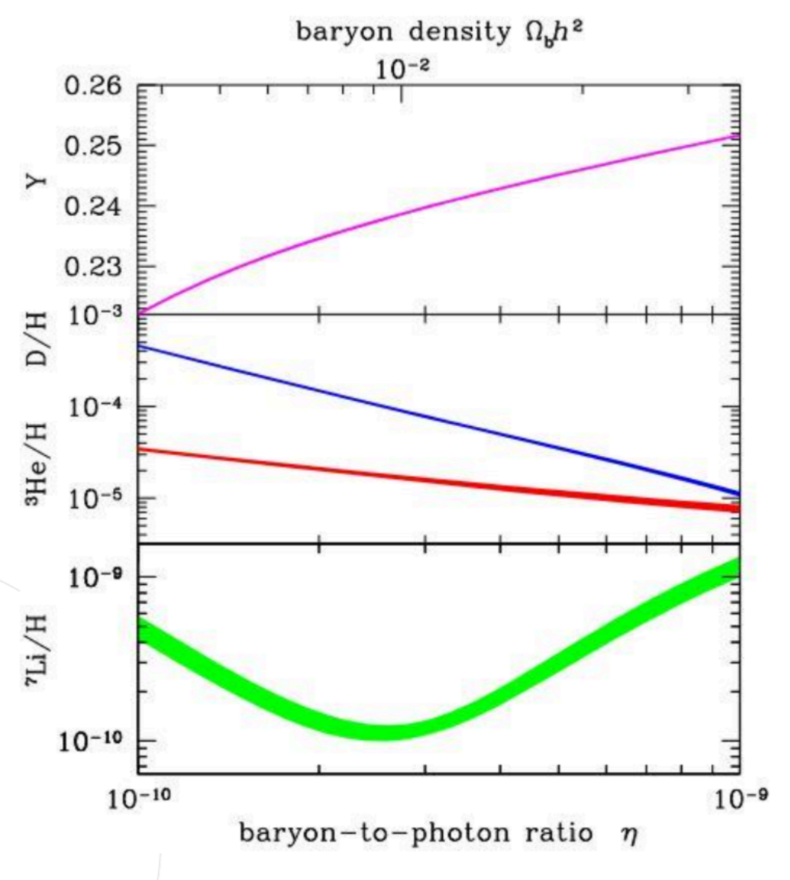
$$\eta \equiv \frac{n_b}{n_\gamma}$$

or

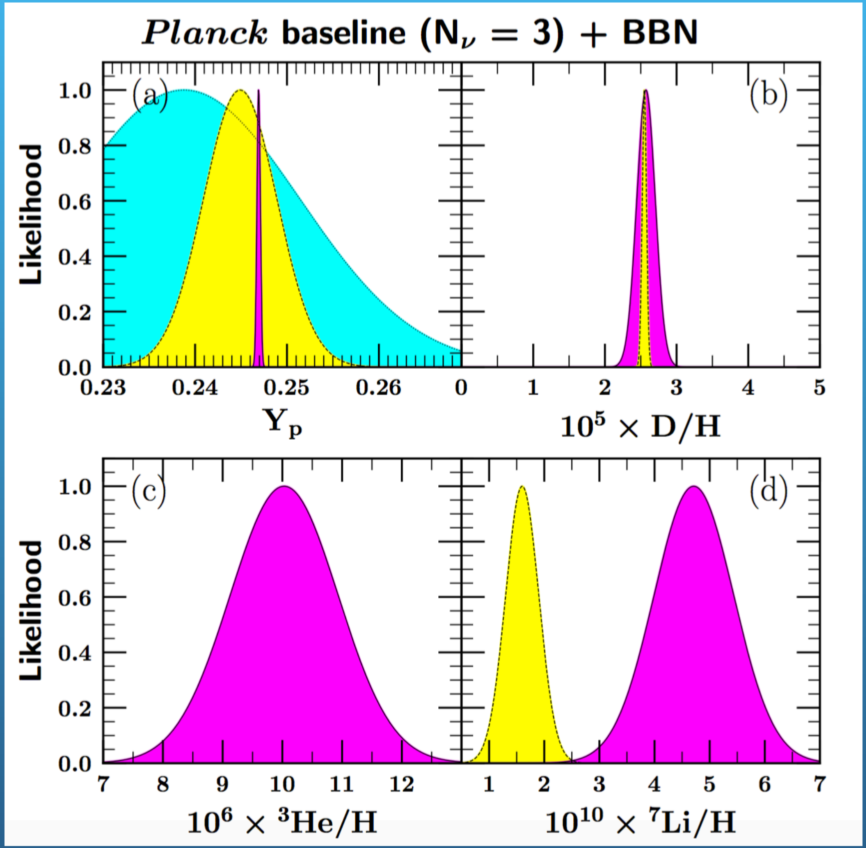
$$\Omega_b h^2 \equiv \omega_b$$

- Effective number of relativistic species

$$N_{eff}$$



Primordial Nucleosynthesis (BBN): light element abundances



Isotope	BBN Theory	Observations
Yp	0.24691±0.00018	0.254±0.003
D/H	$(2.57\pm0.13)\times10^{-5}$	$(2.53\pm0.03)\times10^{-5}$
^{3}He/H	$(1.00\pm0.09)\times10^{-5}$	$(0.9\pm1.3)\times10^{-5}$
^{7}Li/H	$(4.72\pm0.72)\times10^{-10}$	$(1.23\,^{+0.68}_{-0.32})\times10^{-10}$
^{6}Li/^{7}Li	$(1.5\pm0.3)\times10^{-5}$	~10^{-2}

^{4}He, D, ^{3}He abundances measurements are (broadly) consistent with expectations.

^{7}Li: Long standing “Lithium problem”

^{6}Li: “Second Lithium problem”?

Fields 2019

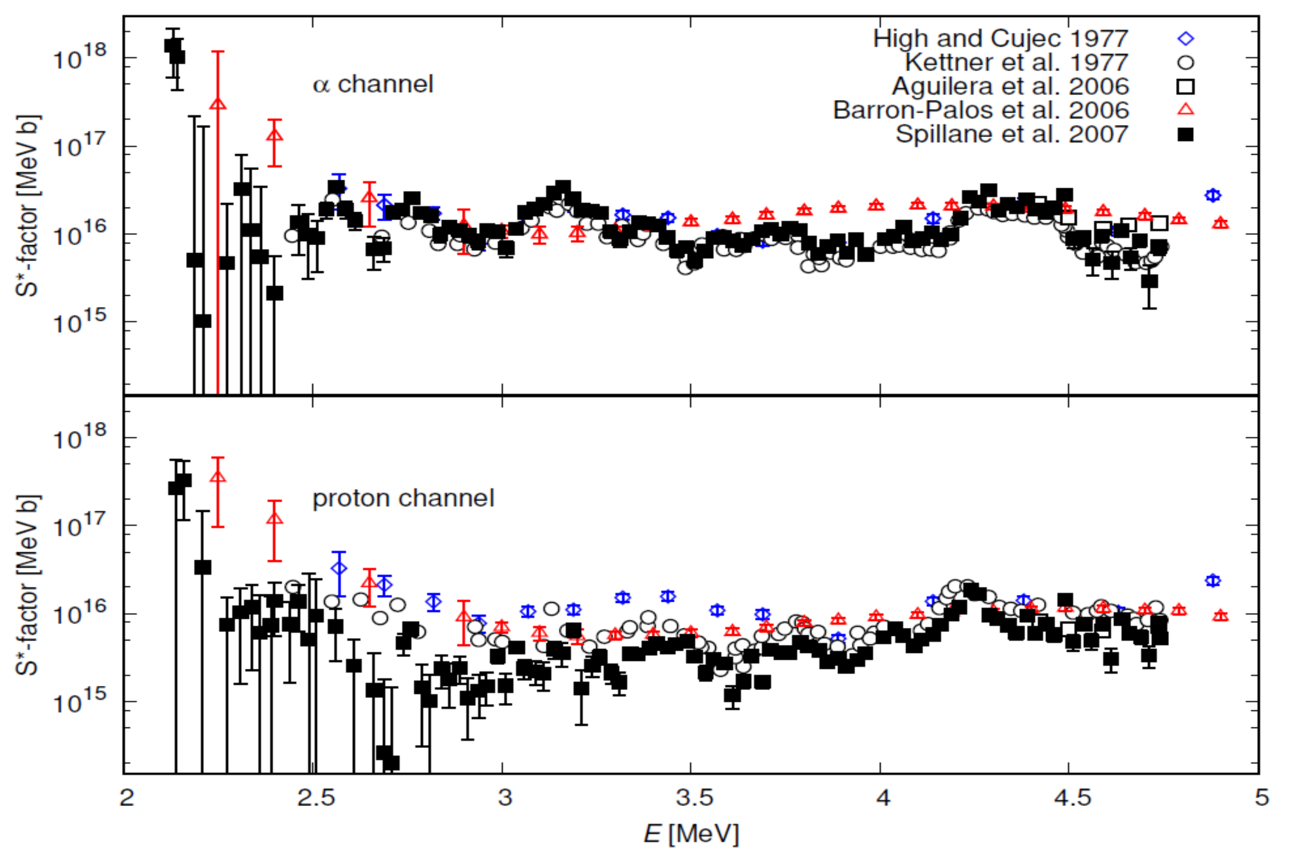
🟨 Astron. measurements

🟪 BBN + CMB (Planck)

🟦 CMB (Planck)

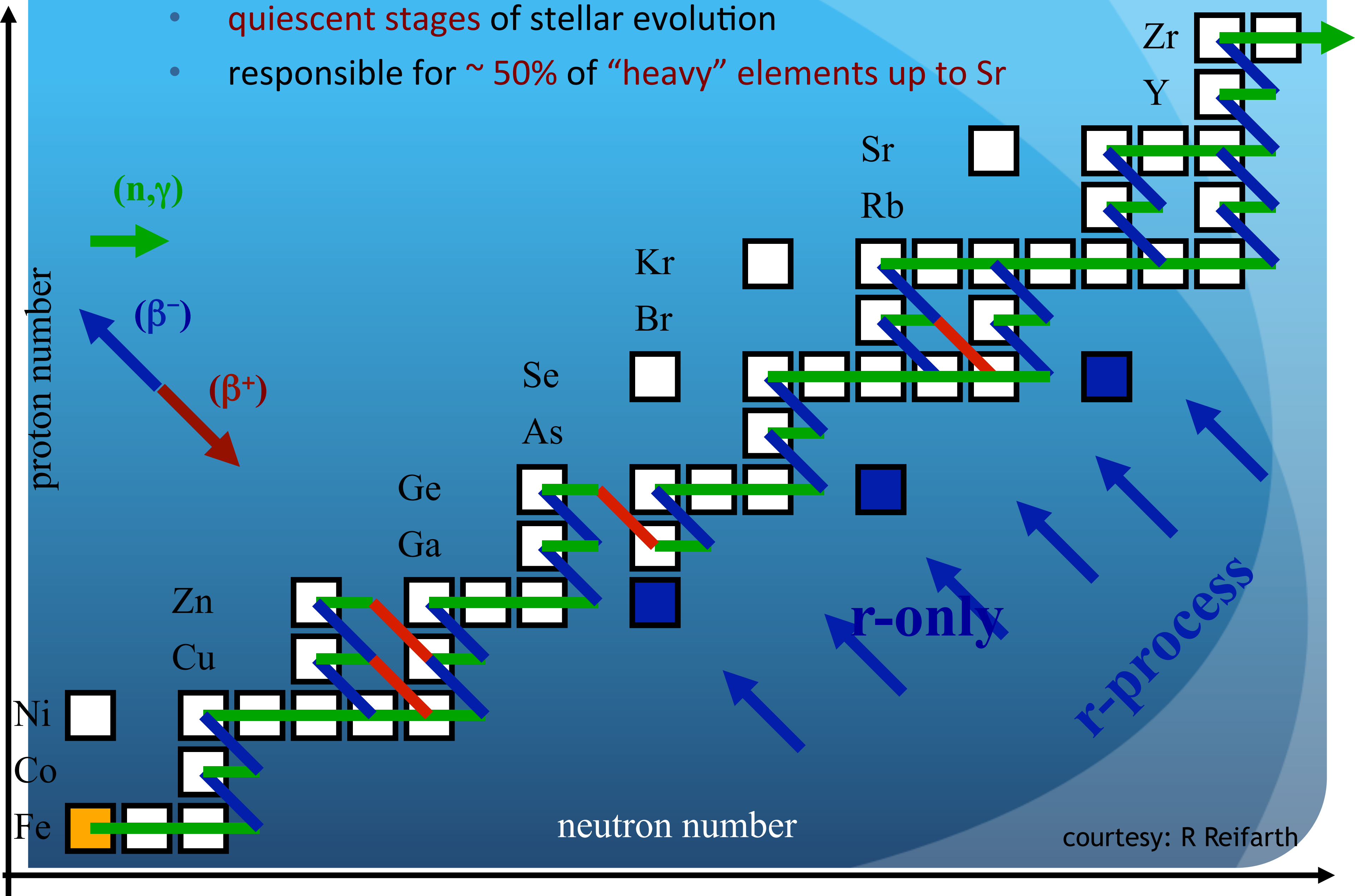
$^{12}C + ^{12}C$

- ✓ $^{12}C+^{12}C$ rate determines which stars explode as Supernovae and which die as White Dwarfs
- ✓ Energy region of interest ≈ 0.7 - 2.5 MeV



Broggini et al. Progr. Part. Nucl. Phys. 98 (2018) 55

- s (slow) process
- quiescent stages of stellar evolution
- responsible for ~ 50% of “heavy” elements up to Sr



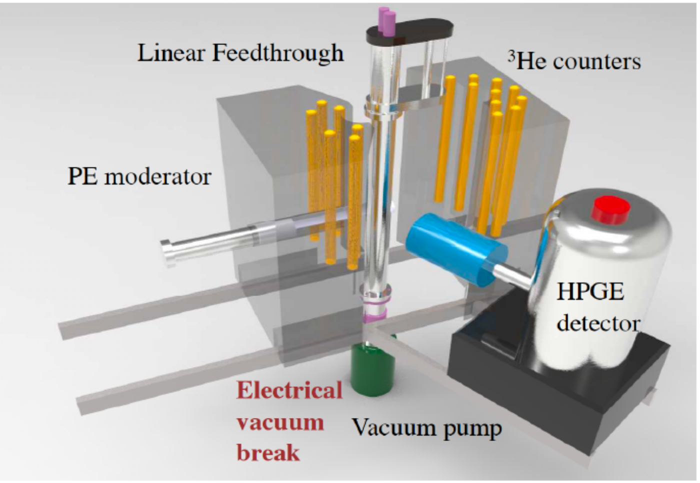
courtesy: R Reifarth

$^{13}C(\alpha,n)^{16}O$

Important to:

1) cover a wide energy range, up to E = 1 MeV for improved low-energy extrapolations and global data analysis, to address the issue of normalization discrepancies;
2) access the energy of astrophysical interest;
3) minimize overall statistical and systematic uncertainties.

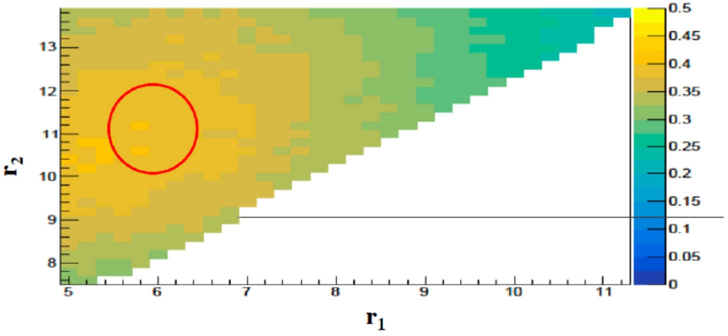
A study has been already completed at LUNA-400



Efficiency ~ 37%

Counters arranged in two rings
INNER: 6 tubes (25 cm active lenght) at r1 from the target
OUTER: 12 tubes (40 cm active lenght) at r2

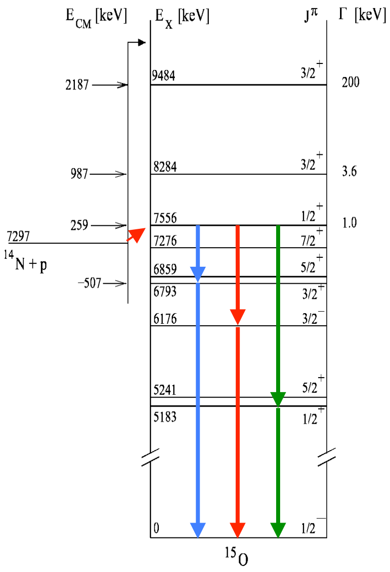
Geant4 simulations in order to maximise the efficiency (40%)



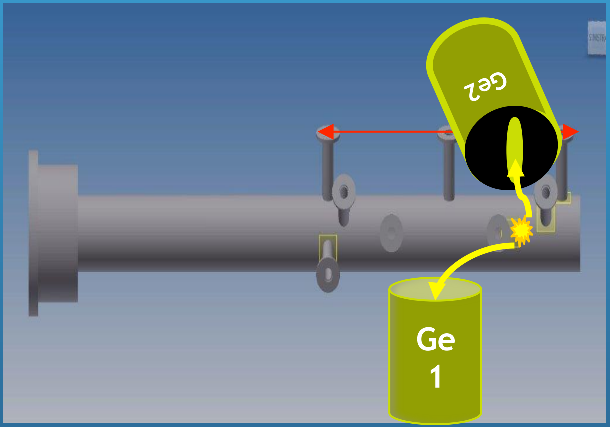
Efficiency: calibration with p+^{14}N and radioactive sources

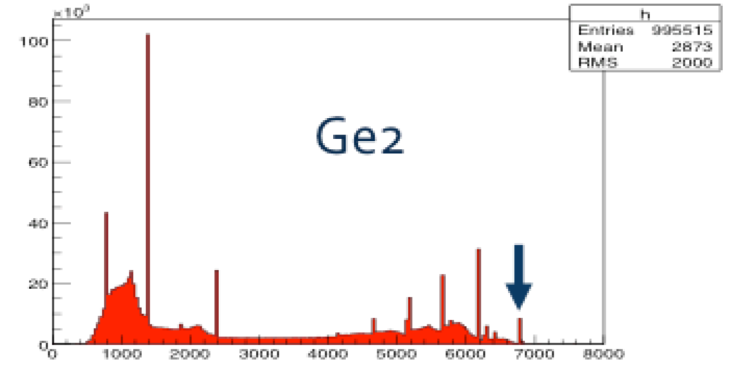
Method :

- At low energies: radioactive sources (^{137}Cs,^{60}Co, ^{88}Y of very precisely known activity (<1%)
- At medium-high energies : $^{14}N(p,\gamma)^{15}O$ (resonance at E_{cm}=259 keV)
- In case of a 2 gammas cascade => coincidence with two detectors



Eγ (keV)	BR (%)
765+6791	22.9
1384+6172	57.8
2375+5181	17.1





$$\eta = \frac{N_{Ge1}}{N_{Ge2}} \times corr$$

Efficiency: calibration with p+^{14}N and radioactive sources

Method :

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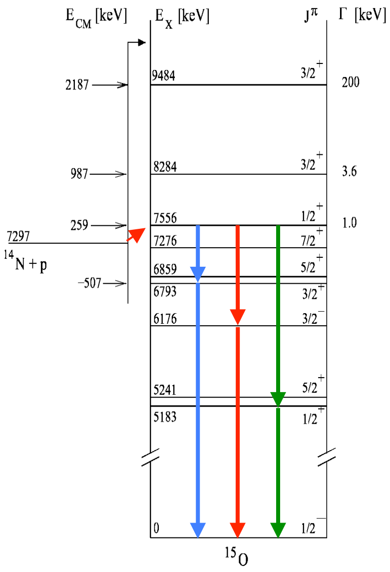

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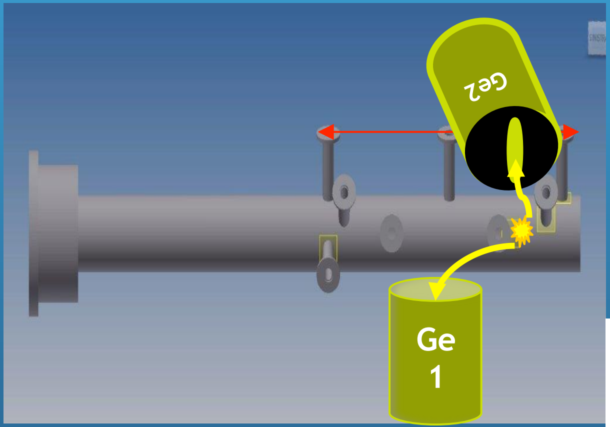
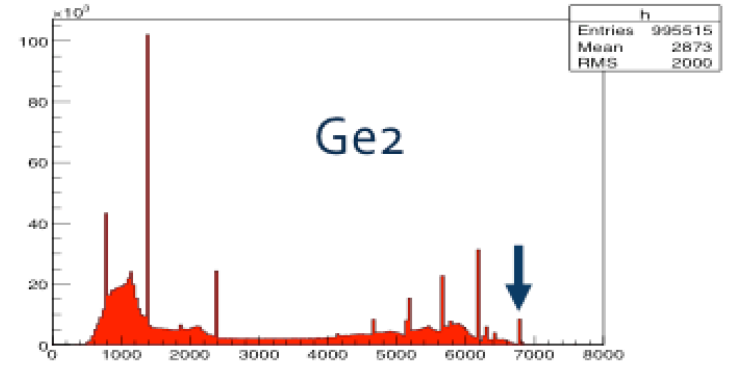
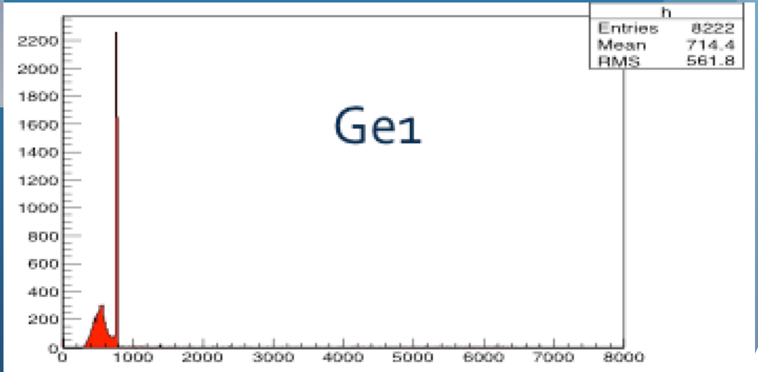


$$\eta = \frac{N_{Ge1}}{N_{Ge2}} \times corr$$





Neutron sources for the s-process: $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$

Main s-process ~90<A<210
(from zirconium to bismuth)

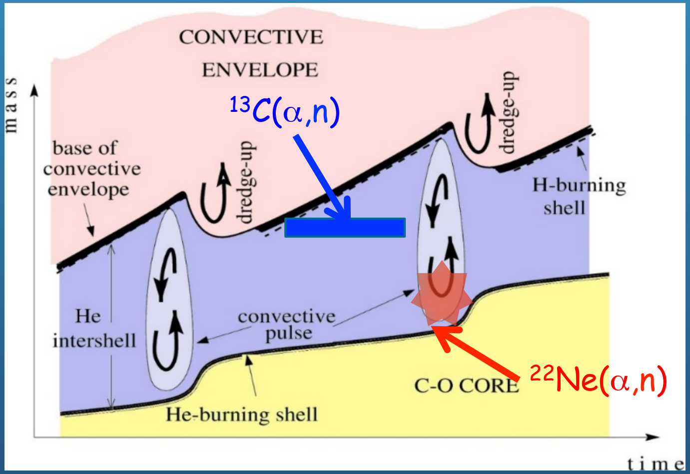
TP-AGB stars

shell H-burning
$T_9 \sim 0.1$ K
10^7-10^8 cm^{-3}

$^{13}C(\alpha,n)^{16}O$

He-flash
$0.25 \leq T_9 \sim 0.4$ K
10^{10}-10^{11} cm^{-3}

$^{22}Ne(\alpha,n)^{25}Mg$

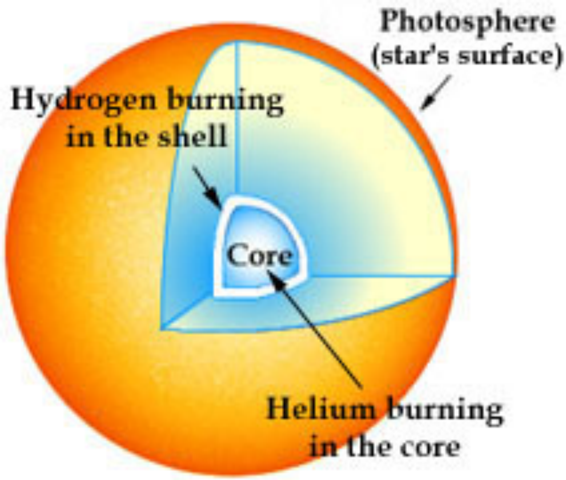


Weak s-process 56<A<~90
(form iron to zirconium)

massive stars > 8 M_{Sun}

core He-burning
3-$3.5 \cdot 10^8$ K
10^6 cm^{-3}

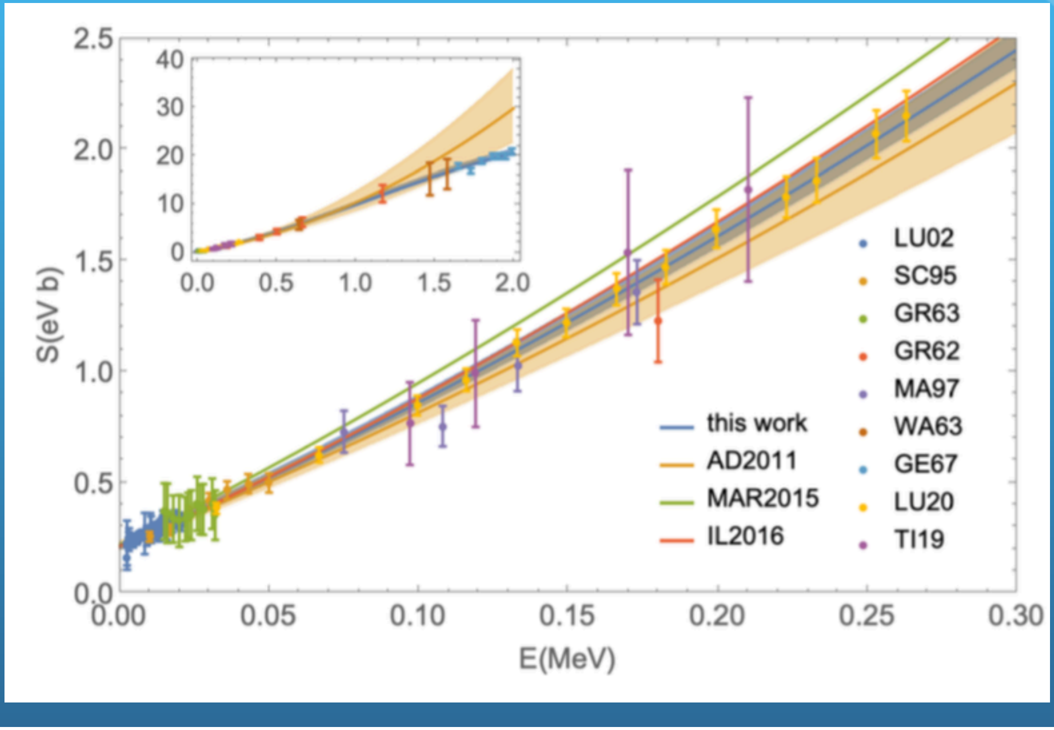
$^{22}Ne(\alpha,n)^{25}Mg$



The number of free neutrons in AGB stars determines the abundances of elements heavier than iron and their elemental and isotopic ratios

Data fit procedure

Polinomial fit (n=3) with different normalization constant for the different data set



LUNA rules
the fit

$$\chi^2(a_l,\omega_k)=\sum_{i_k}\frac{(S_{th}(E_{i_k},a_l)-\omega_k\,S_{i_k})^2}{\omega_k^2\,\sigma_{i_k}^2}+\sum_k\frac{(\omega_k-1)^2}{\epsilon_k^2}\equiv\chi^2_{stat}+\chi^2_{norm}$$