UNIVERSITÀ DEGLI STUDI DI MILANO

INFN Istituto Nazionale di Fisica Nucleare

Introduction to Nuclear Astrophysics

Rosanna Depalo

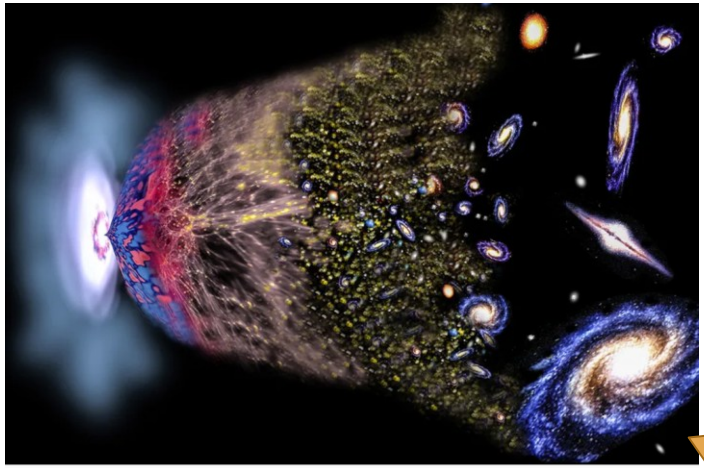
Università degli Studi di Milano and INFN Milano

GRAN SASSO hands-on 2025

PhD school on experimental astroparticle physics
September 8th - 18th, 2025

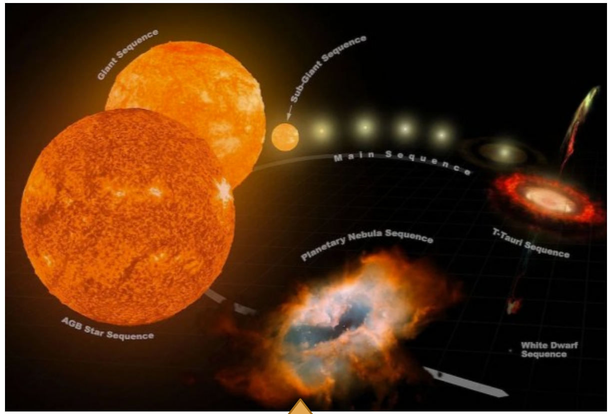
Nuclear reactions in Astrophysics

Evolution of early Universe

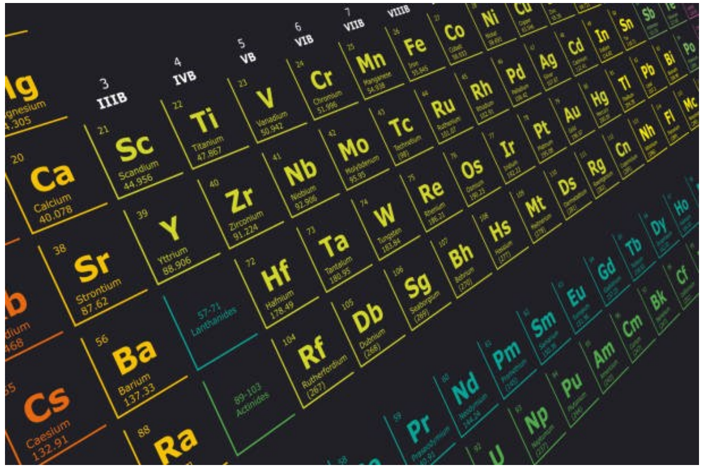


An artist's rendition of the Big Bang. Photo by David A. Aguilar

Stellar evolution

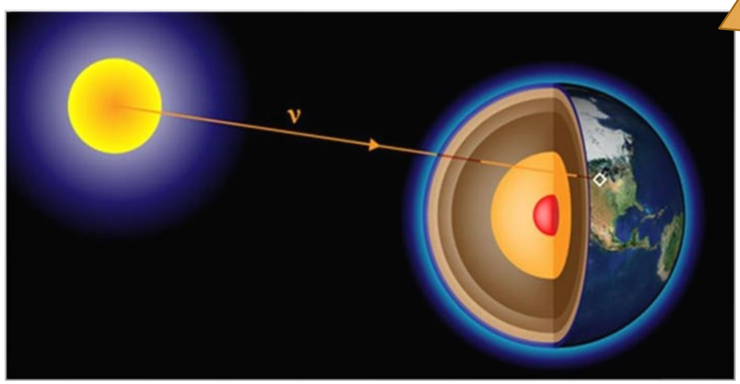


Nucleosynthesis

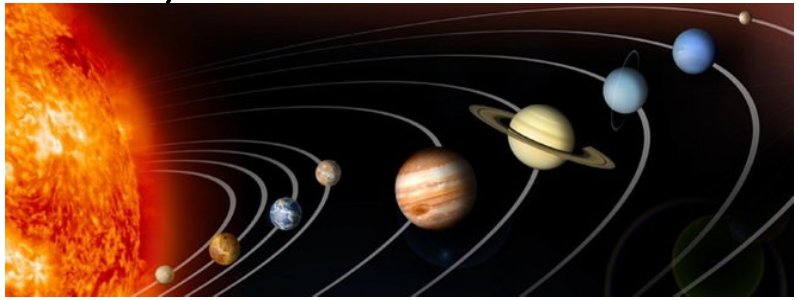


Nuclear reactions cross sections

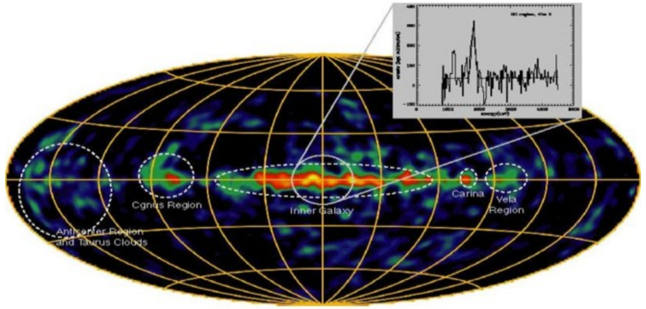
Solar neutrinos



Solar system formation and evolution

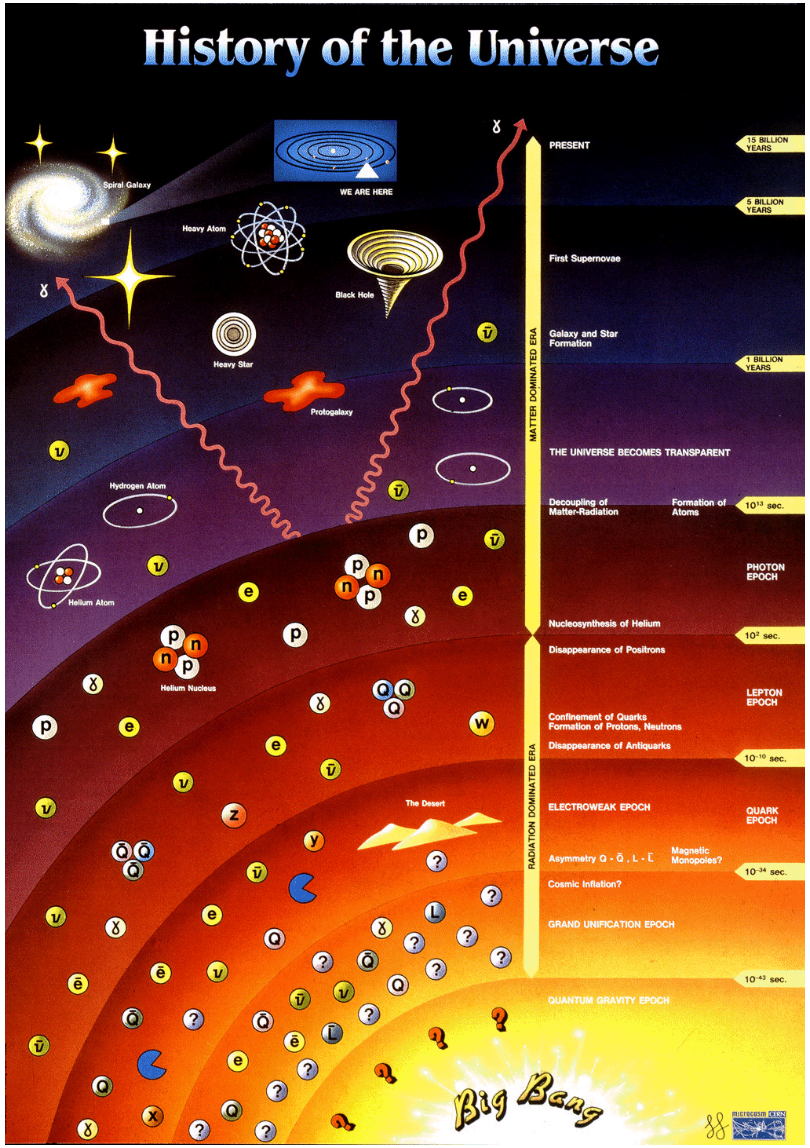


Astronomy with radioactivity



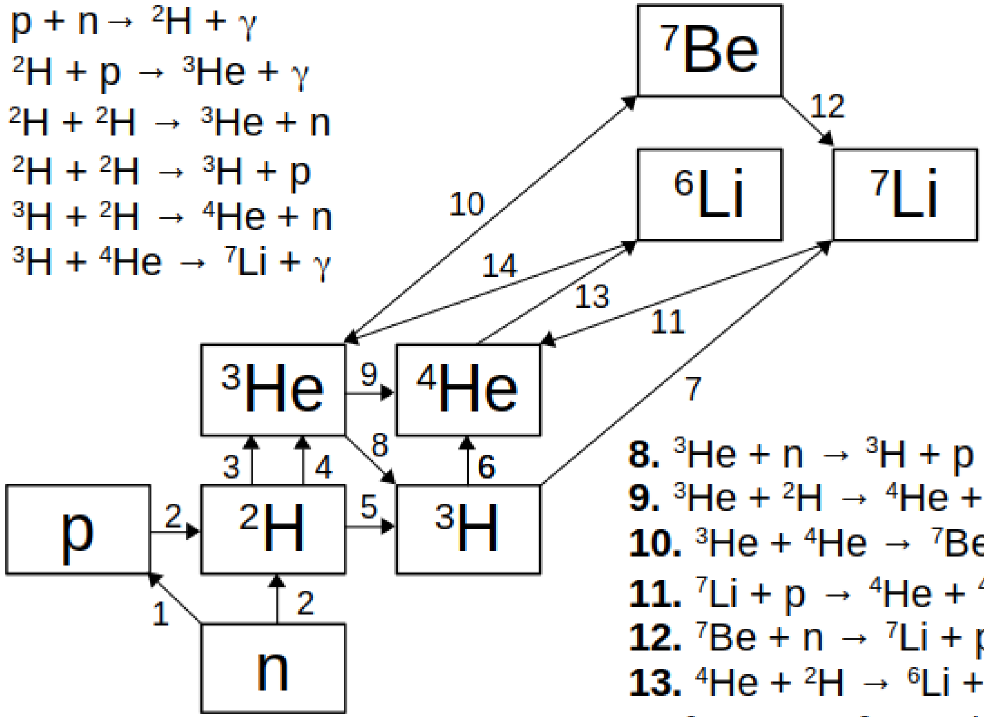
(Oberlack et al., 1996; Pluschke et al., 2001)

Big Bang Nucleosynthesis



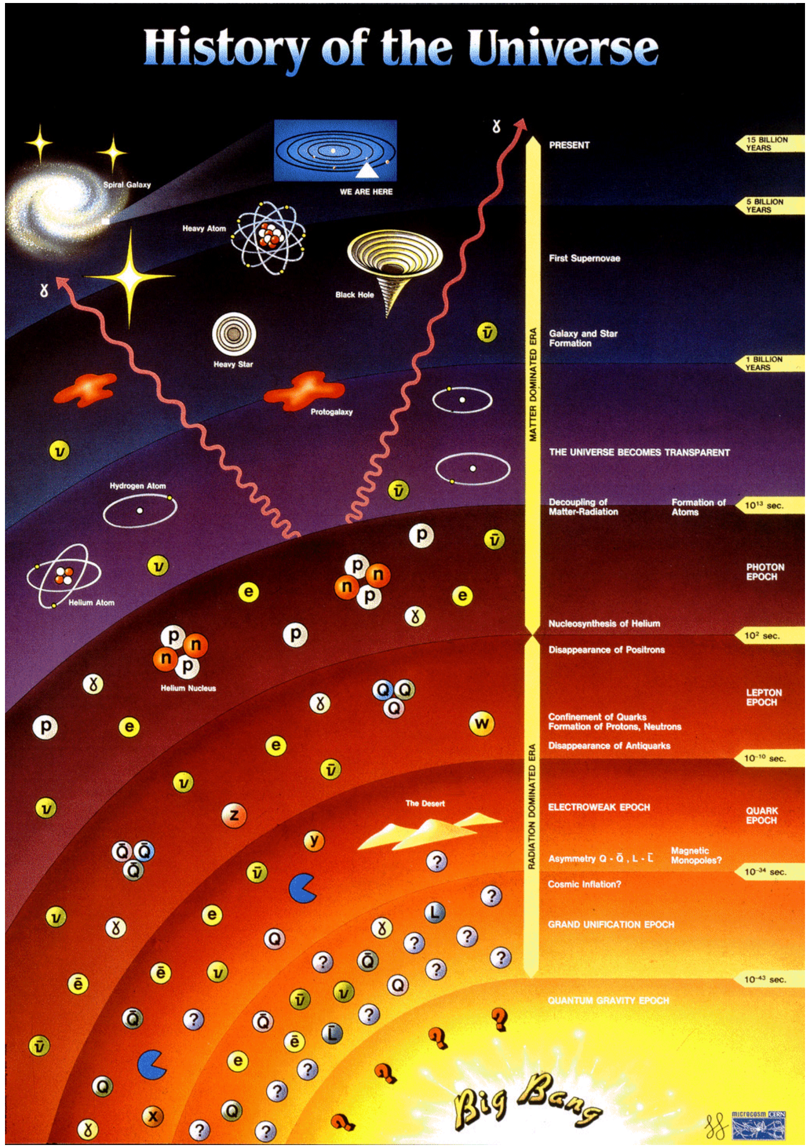
3 – 20 min after the Big Bang: Production of the lightest elements (D, ^{3}He, ^{4}He, ^{7}Li, ^{6}Li) through a network of few nuclear reactions

1. $n \rightarrow p + e^{-} + \nu^{*}_{e}$
2. $p + n \rightarrow {}^{2}H + \gamma$
3. ${}^{2}H + p \rightarrow {}^{3}He + \gamma$
4. ${}^{2}H + {}^{2}H \rightarrow {}^{3}He + n$
5. ${}^{2}H + {}^{2}H \rightarrow {}^{3}H + p$
6. ${}^{3}H + {}^{2}H \rightarrow {}^{4}He + n$
7. ${}^{3}H + {}^{4}He \rightarrow {}^{7}Li + \gamma$



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

Big Bang Nucleosynthesis



The **final abundance** of the elements depends on the **baryon density** of the Universe

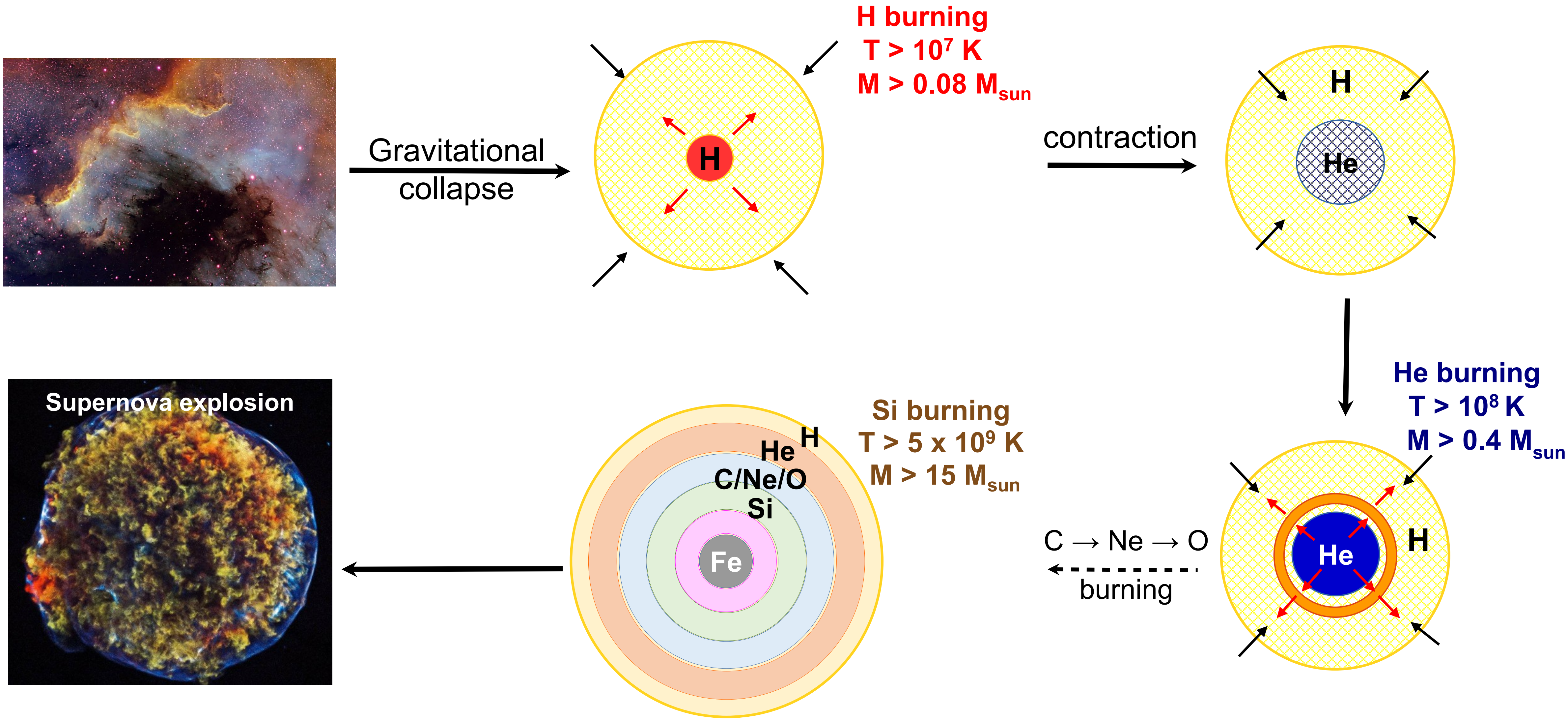
The comparison between **predicted** (BBN theory) and **observed** (stellar spectra) abundances gives a direct probe of the baryon density

CMB anisotropy measurement (e.g. Planck satellite) gives an independent measurement of the baryon density

The agreement of the two results must be understood in terms of uncertainties in the BBN predictions.

Besides ^{4}He, **uncertainties are dominated by systematic errors in the nuclear cross sections**

Life of a star



Evolutionary stages of a 25 M_{sun} star

Burning stage	Main products	Time scale	Temperature [GK]	Density [g/cm^3]
Hydrogen	^{4}He	$7 \cdot 10^6$ y	0.06	5
Helium	^{12}C, ^{16}O	$5 \cdot 10^5$ y	0.23	$7 \cdot 10^2$
Carbon	^{20}Ne, ^{23}Na	600 y	0.93	$2 \cdot 10^5$
Neon	^{16}O, ^{28}Si, ^{29}Si,	1 y	1.7	$4 \cdot 10^6$
Oxygen	^{28}Si, ^{31}P, ^{31}S, ^{32}S	6 months	2.3	$1 \cdot 10^7$
Silicon	^{52}Fe, ^{56}Ni, ^{60}Zn	1 d	4.1	$3 \cdot 10^7$
Core collapse		Seconds	8.1	$3 \cdot 10^9$
Core bounce		Milliseconds	34.8	$\approx 3 \cdot 10^{14}$
Explosive burning		0.1 – 10 s	1.2 – 7.0	Varies

Weaver et al. 1980

Synthesis of heavy elements

Beyond A>60, nuclear fusion becomes **endothermic**.

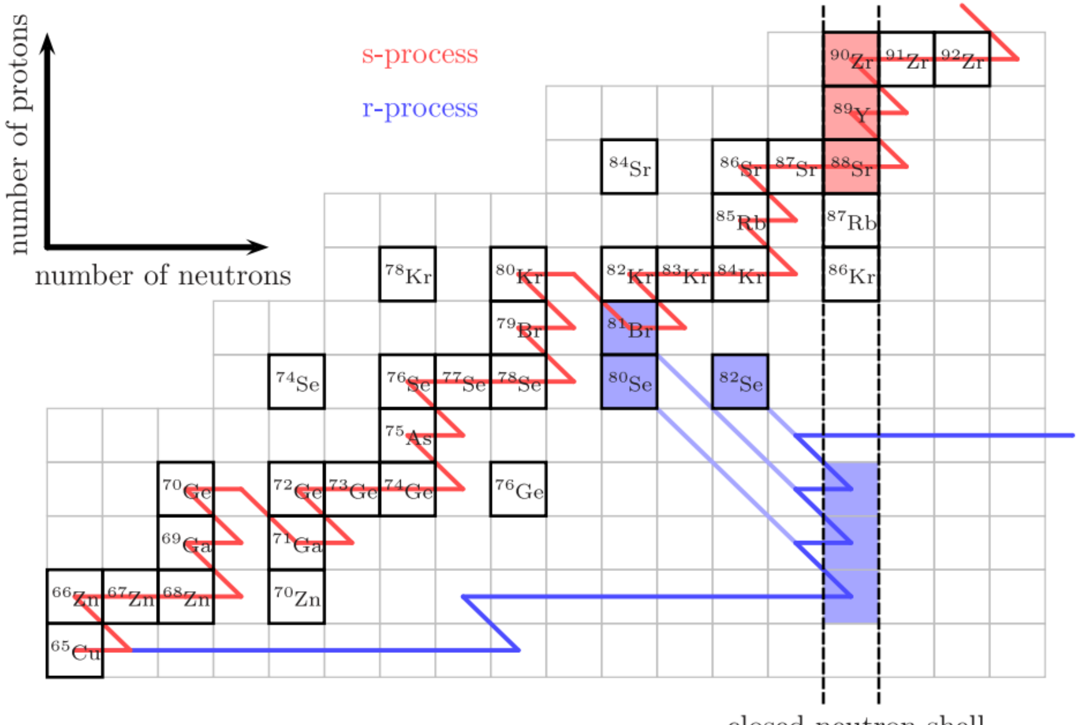
The synthesis of heavy elements occurs through consecutive **neutron captures**, followed by β decay:

$$^{A}X+n\rightarrow {}^{A+1}X+\gamma$$

$$^{A+1}X+n\rightarrow {}^{A+1}Y+e^{-}+\underline{n}$$

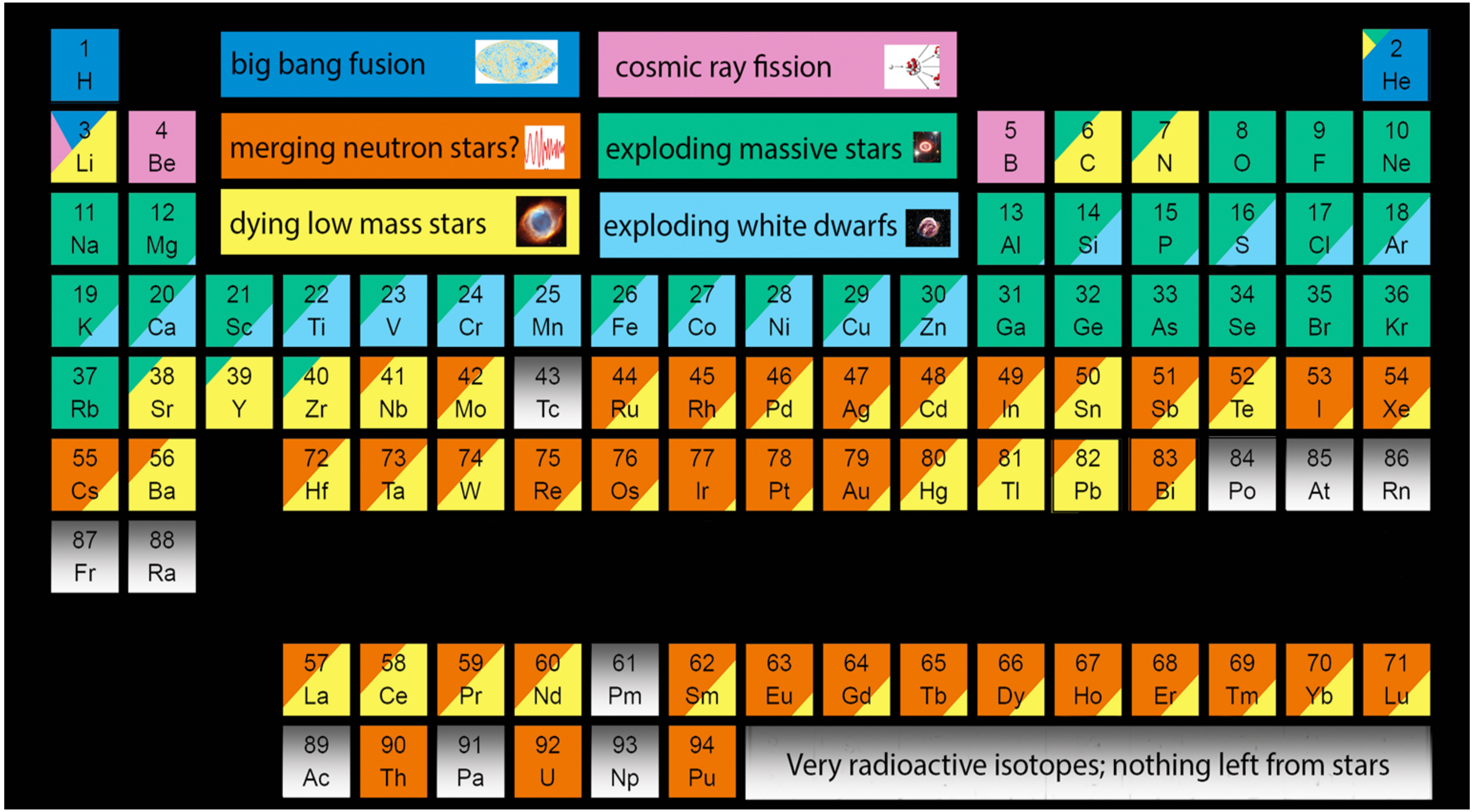
The abundances of heavy ions depend on the balance between nutron capture rate λ_n , and the β decay constant λ_b:

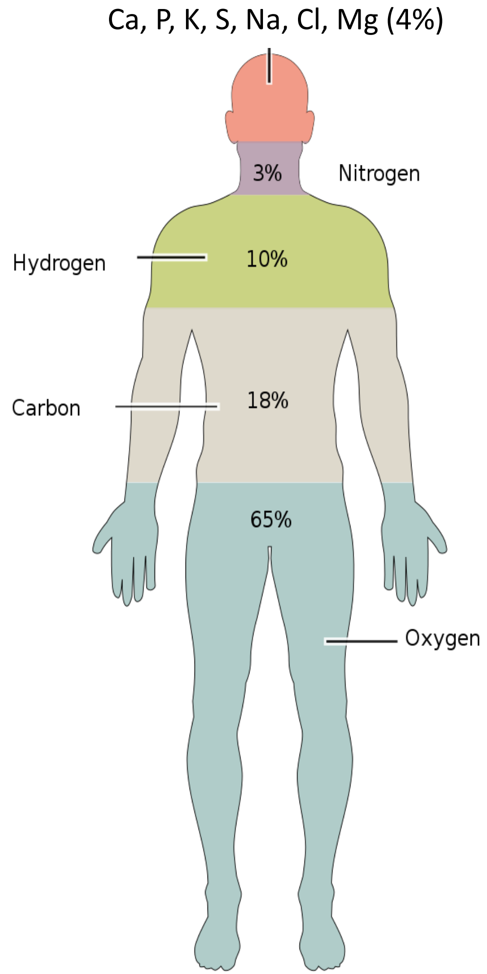
- $\lambda_n \ll \lambda_\beta$ the nucleus formed by neutron capture ^{A+1}X undergoes β decay before it can capture another neutron: **s-process (slow)**
- $\lambda_n \gg \lambda_\beta$ The nucleus ^{A+1}X does not have enough time to β decay and instead undergoes multiple consecutive neutron captures, producing elements far away from the valley of stability ($^{A}X\rightarrow{}^{A+1}X\rightarrow{}^{A+2}X\rightarrow$……): **r-process (rapid)**



Horowitz et al 2019 J. Phys. G **46**, 083001

Origin of the elements





Nuclear cross sections are needed to explain the **origin** and **relative abundances** of the elements

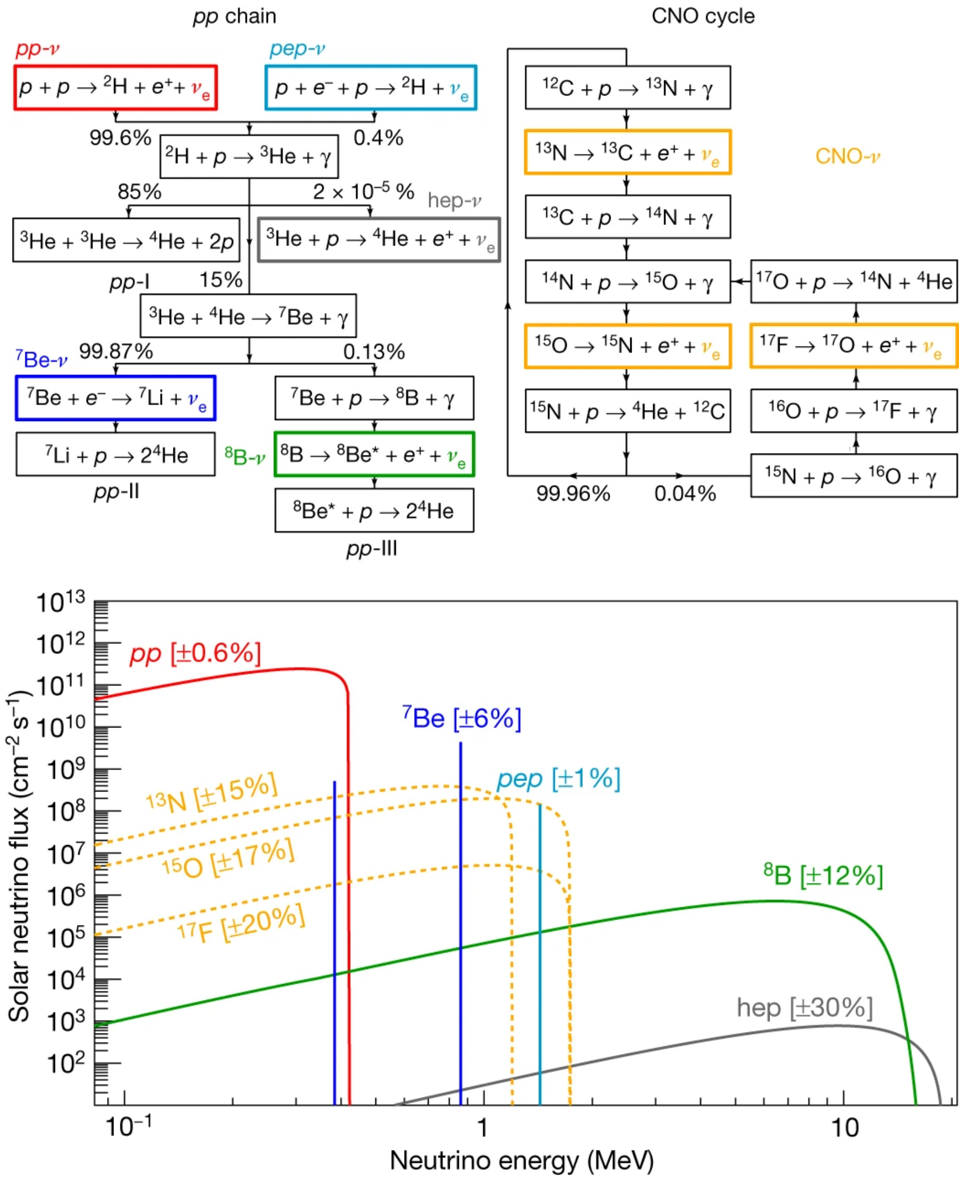
Solar neutrinos

Solar neutrinos are produced by nuclear reactions occurring in the solar core.

The **flux** and **energy spectrum** of neutrinos from the Sun can be used to study:

- **Solar interior composition**
- **Neutrino properties**

only if the cross sections of the involved reactions are known with high-enough accuracy



Borexino collab. Nature 562, 505-510 (2018)

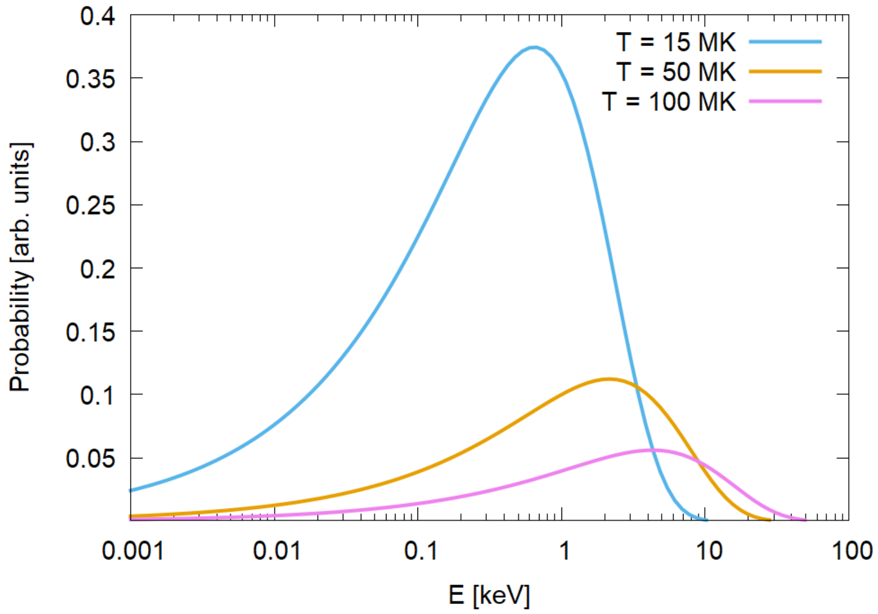
Nuclear reactions at astrophysical energies

$$\text{REACTION RATE} = \frac{\text{N° Reactions}}{\text{time} \cdot \text{volume}} = N_0 \cdot N_1 \cdot \mathbf{v} \cdot \boldsymbol{\sigma}(\mathbf{v})$$

← CROSS SECTION (σ(v))

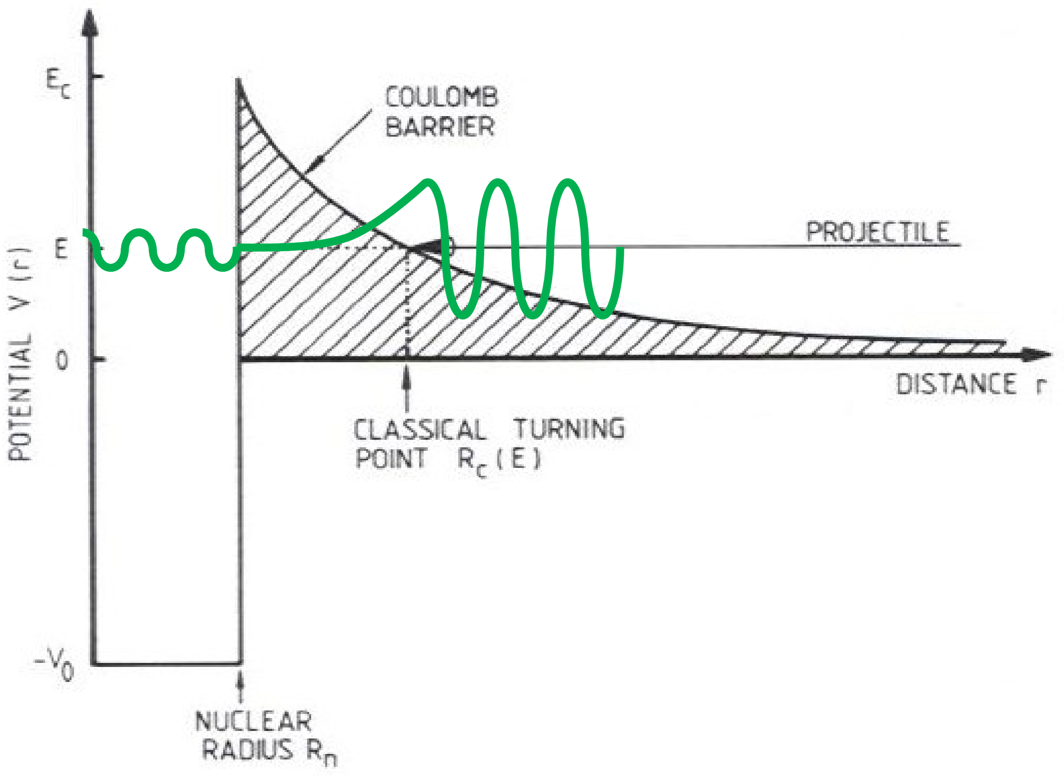
↑ RELATIVE VELOCITY (v)

MAXWELL BOLTZMANN DISTRIBUTION vs COULOMB REPULSION



$$E_C = \frac{Z_a Z_b e^2}{R} \sim MeV$$

Nuclear reactions at astrophysical energies



In many astrophysical scenarios, nuclear reactions occur at energies **far below** the Coulomb barrier, through **quantum-mechanical tunnel**.

Fusion cross section depends on the **transmission probability**:

$$\hat{T} \approx \exp\left(-\frac{2\pi}{\hbar}\sqrt{\frac{m}{2E}}Z_0 Z_1 e^2\right) \equiv e^{-2\pi\eta}$$

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CROSS SECTION (σ(v))

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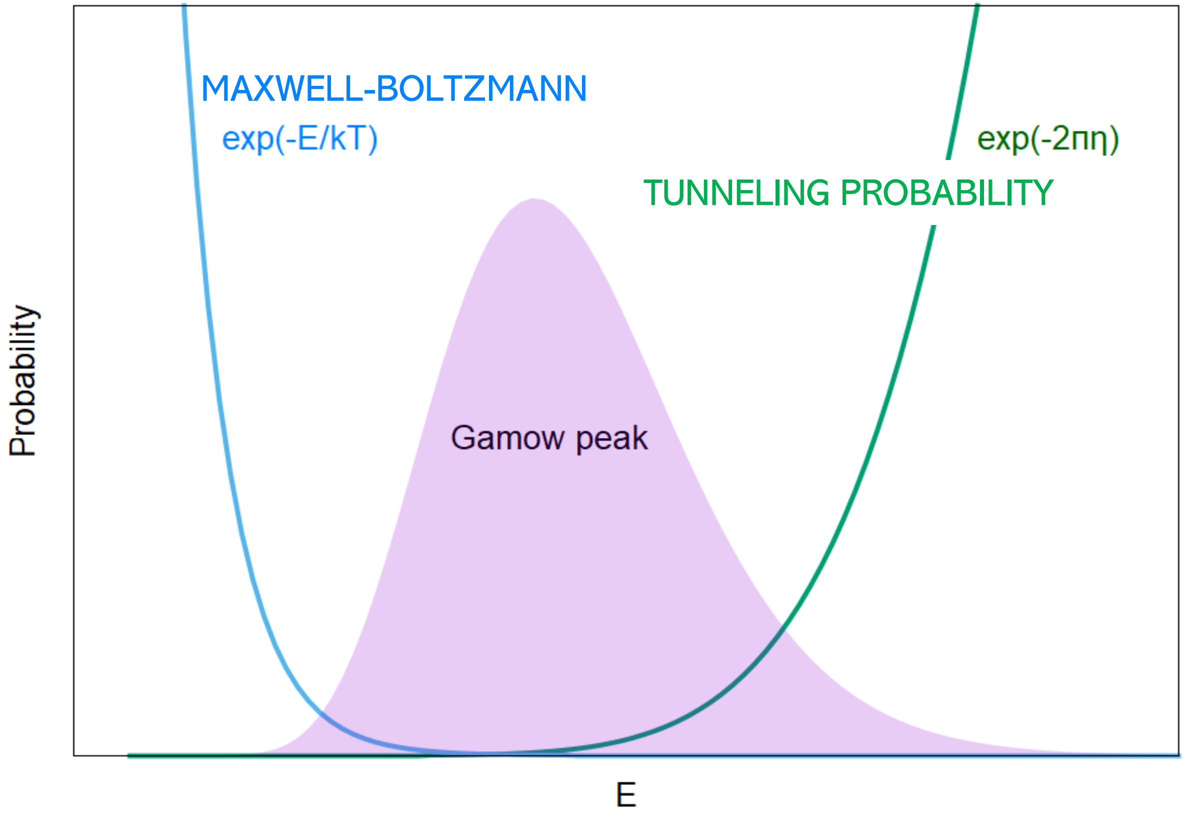
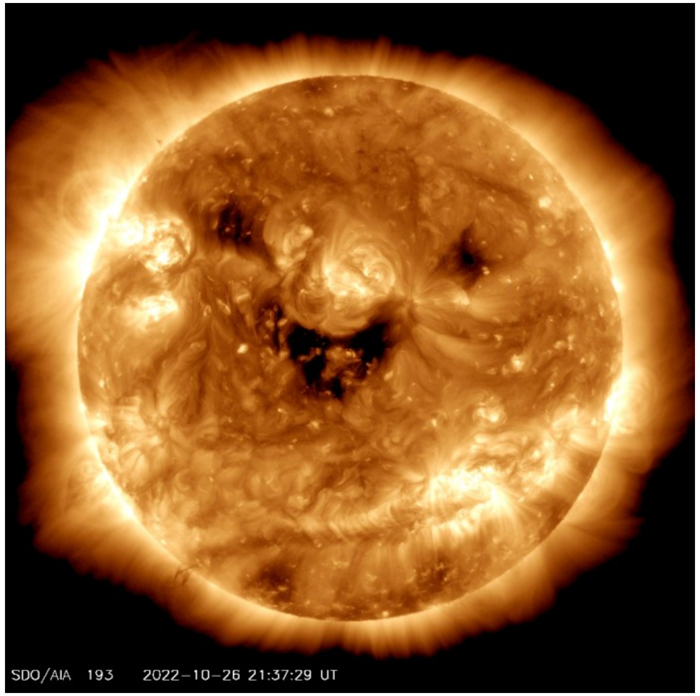


Nuclear reactions at astrophysical energies

$T_{center} = 1.5 \times 10^7$ K $\rightarrow E_{MB} = k_B T_{center} = 1.3$ keV

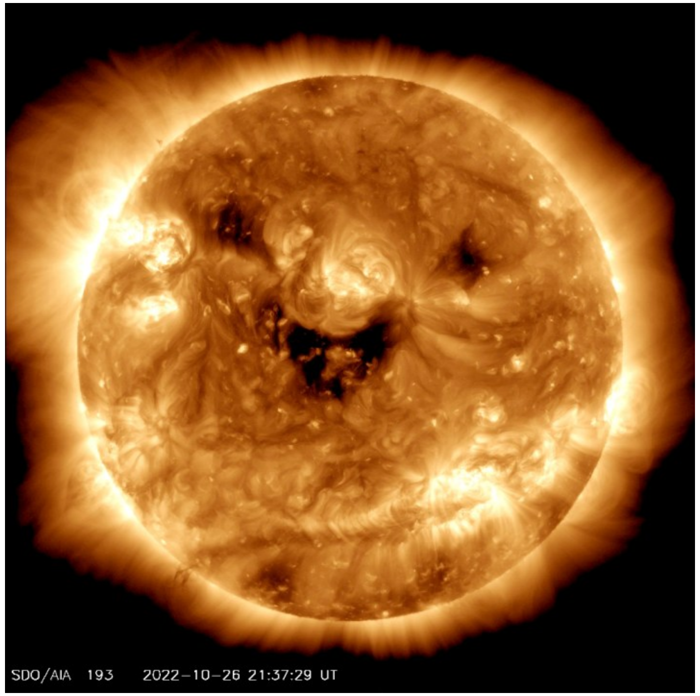
reaction	exp($-2\pi\eta$) @ E_{MB}	E_{Gamow}	exp($-2\pi\eta$) @ E_{Gamow}
p+p	3.5×10^{-9}	6 keV	1×10^{-4} *
p+^{12}C	1.2×10^{-69}	24 keV	9×10^{-17}

*The probability for the p + p $\rightarrow$ d + e^+ + ν_e reaction to happen is much smaller (~2×10^{-31}), being it mediated by weak force



Inside the Gamow peak, nuclear fusion cross sections can be very low (fb – nb, 1b = 10^{-24} cm^2)

Hydrogen burning in the Sun



How much energy is released in the conversion of 4 protons into 1 He nucleus?

Input data:

M_{sun} = 2 x 10^{30} kg

L_{sun} = 3.9 × 10^{26} W = 2.4 × 10^{39} MeV/s

m_H = 1.007825 amu

m_{He} = 4.002603 amu

1 amu = 931.4941 MeV

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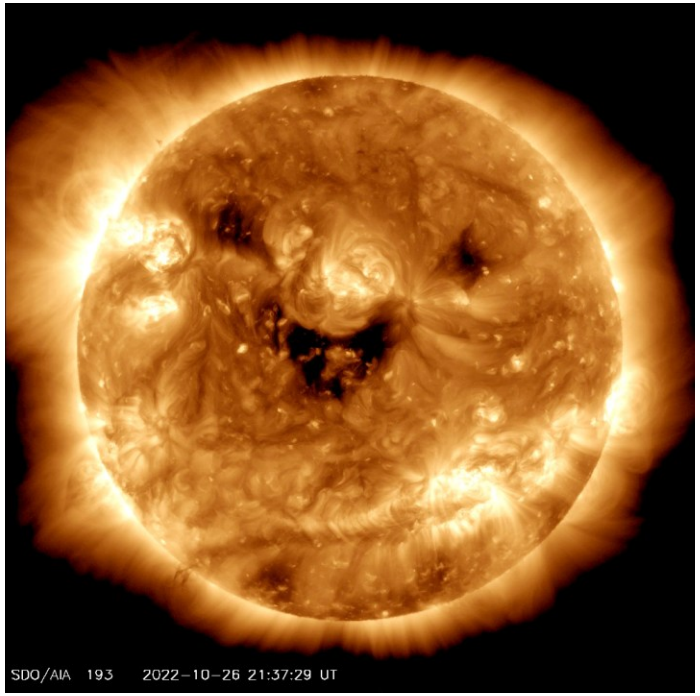

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$$4\ H \rightarrow He + 2\beta^{+} + 2\nu_e + \underline{26.7\ MeV}$$

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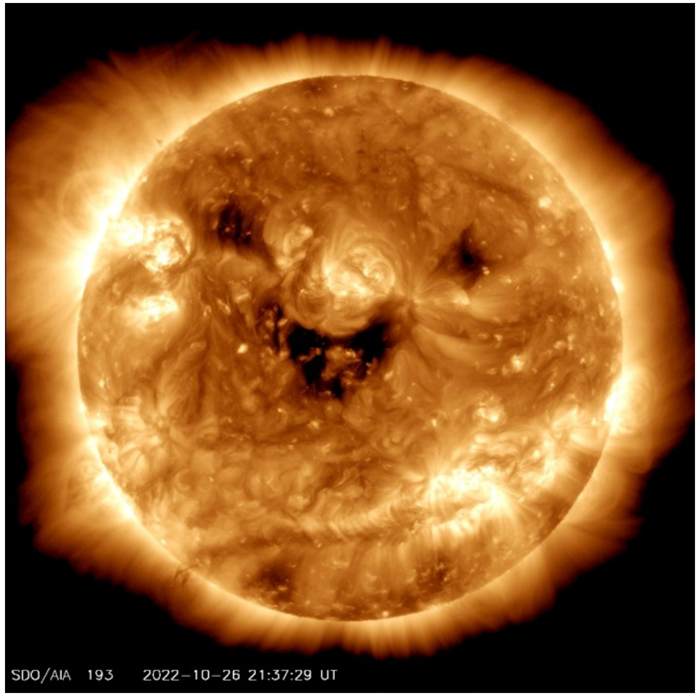

How much hydrogen is the Sun burning every second?

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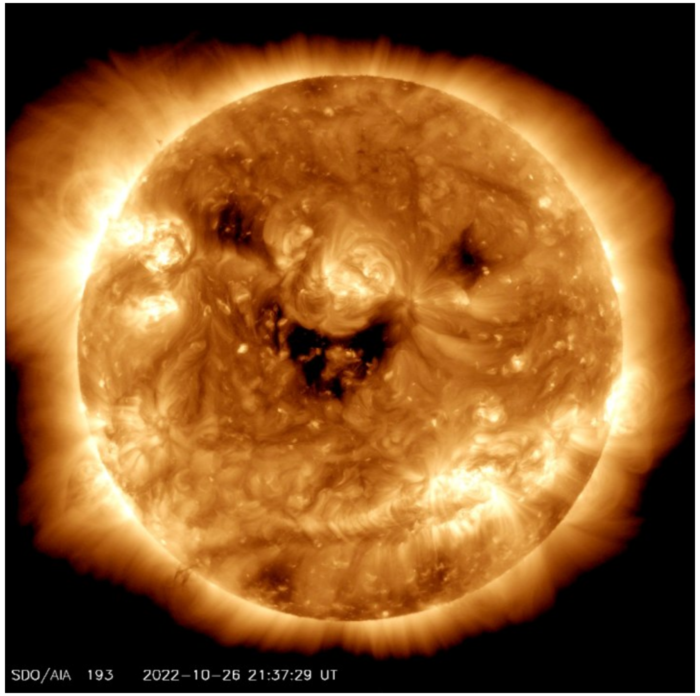

How much hydrogen is the Sun burning every second?

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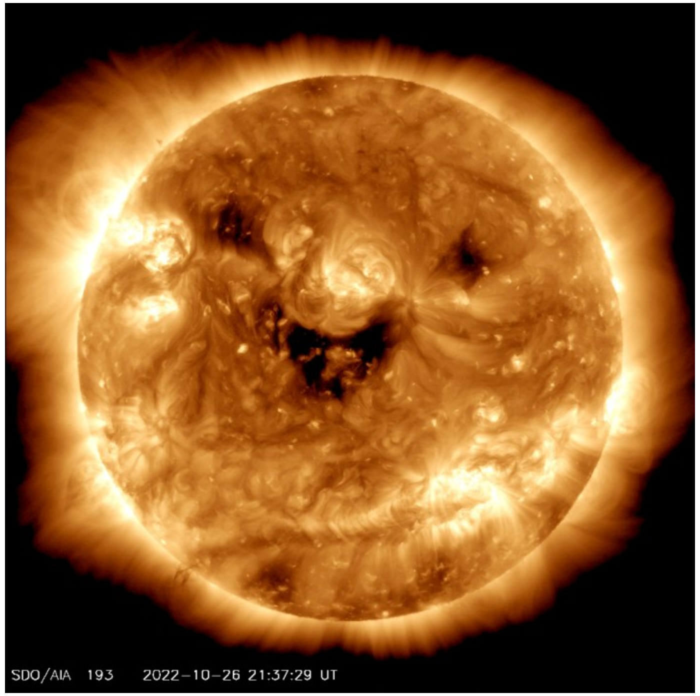
Fusion rate: $N = \frac{L_\odot}{26.7MeV} = \frac{2.4 \cdot 10^{39}\, MeV/s}{26.7\, MeV} \sim 10^{38} \frac{fusions}{s}$

H mass burned per unit time: $M = 4M_H \cdot N \sim 6.4 \cdot 10^{14} \frac{g}{s} = 640\ Million\ tons\ per\ second!$

Hydrogen burning in the Sun



How much of the solar mass needs to burn to keep the Sun alive for 10 Gy?

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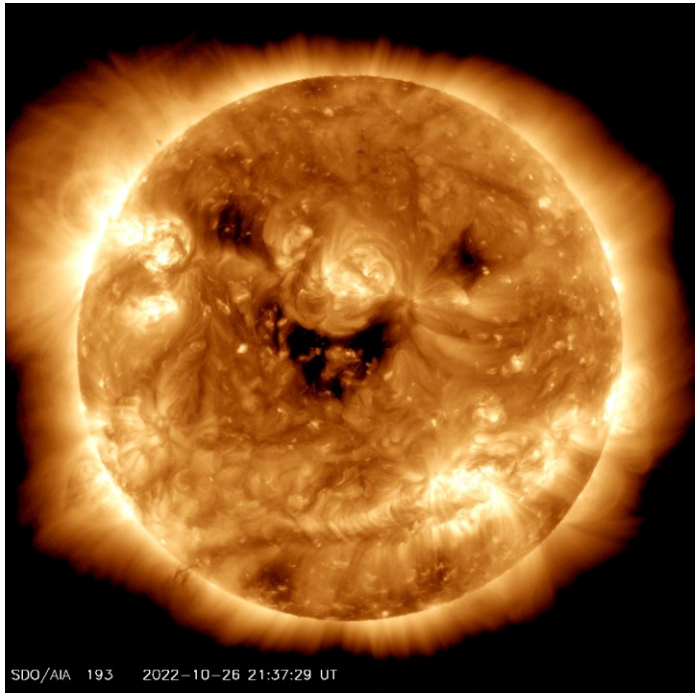

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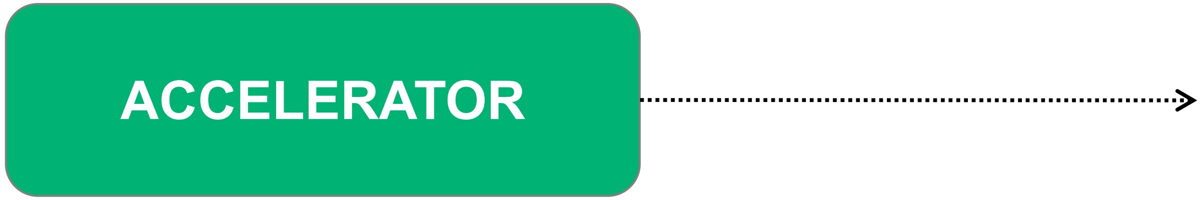
Hydrogen burning timescale: $t = \frac{10\% M_{\odot}}{M} \sim 10^{10} years$

Although fusion probability is very low, the reaction rate in stars is high because there is a huge number of interacting particles

Typical counting rate in the laboratory



- High intensity
- High stability
- Small energy spread

Typical counting rate in the laboratory

- High purity
- Stable against irradiation

Typical counting rate in the laboratory

- Best compromise between detection efficiency and energy resolution

Typical counting rate in the laboratory

Counting rate = $N_{PROJECTILES}$ x $N_{TARGETS}$ x **cross section** x **detection efficiency**

- $N_{PROJECTILES}$: 10^{14} pps ($I \sim 100\ \mu A$)
- $N_{TARGETS}$: 10^{18} atoms/cm^2 (typical solid-state target)
- cross section: 10^{-36} cm^2 (1 pb)
- detection efficiency: 1% - 100%

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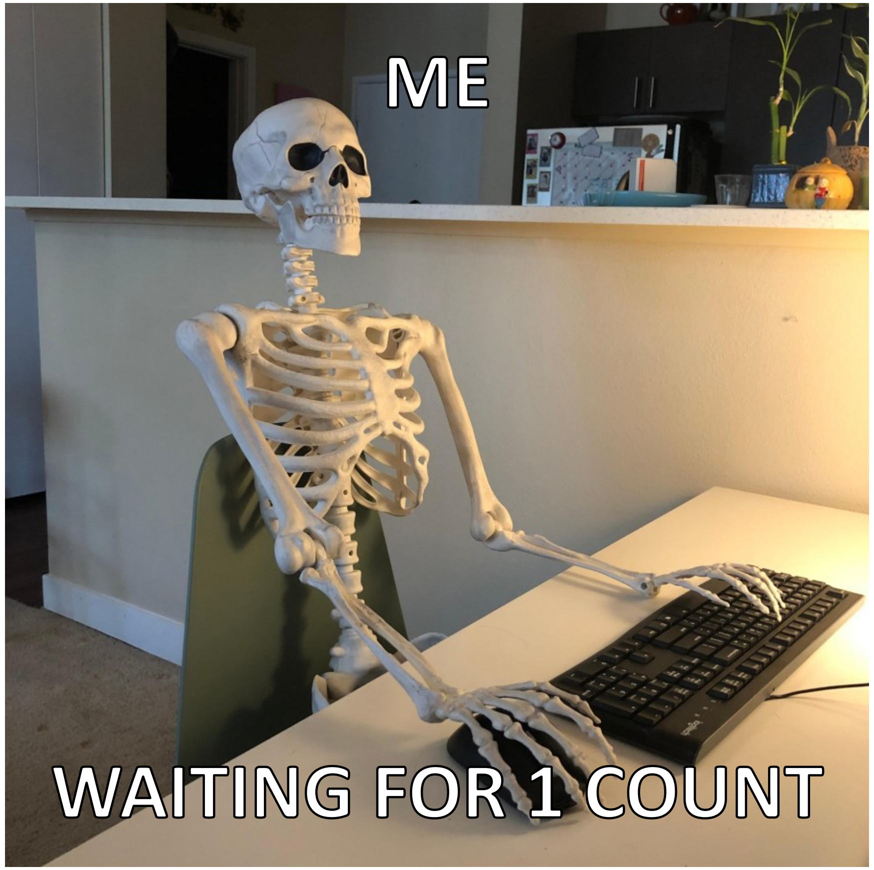
C = 0.004 – 0.4 counts/hour



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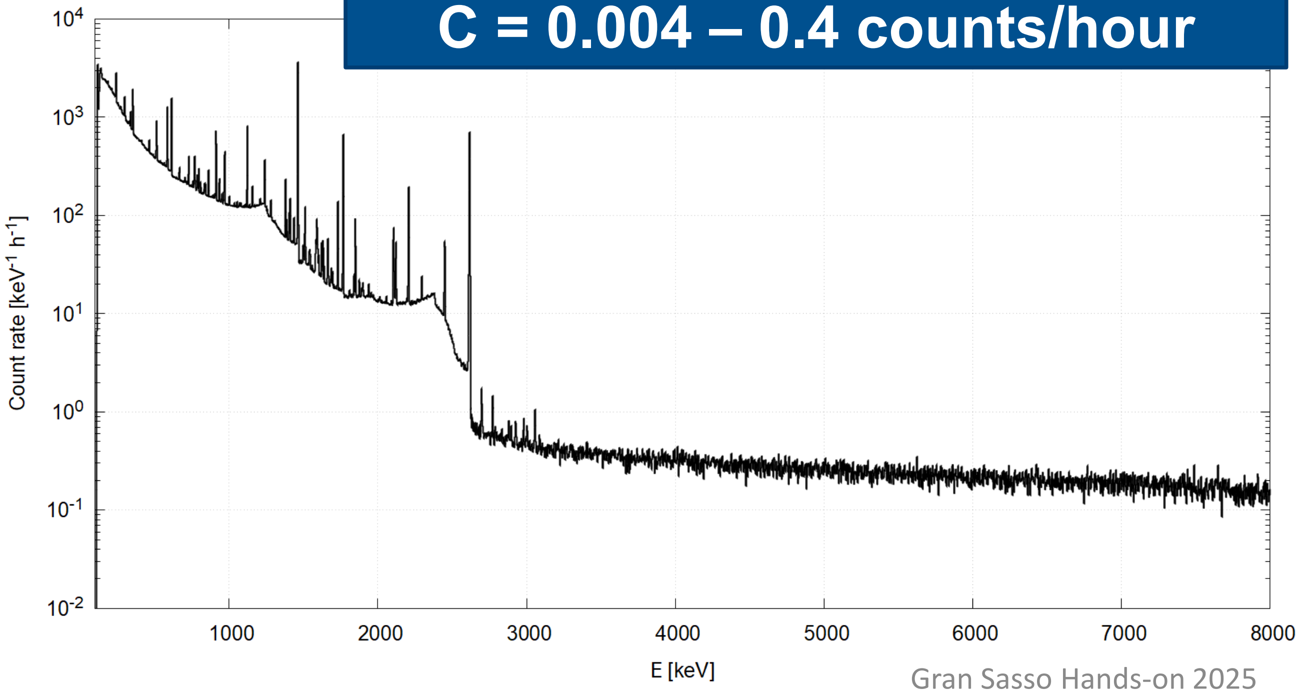
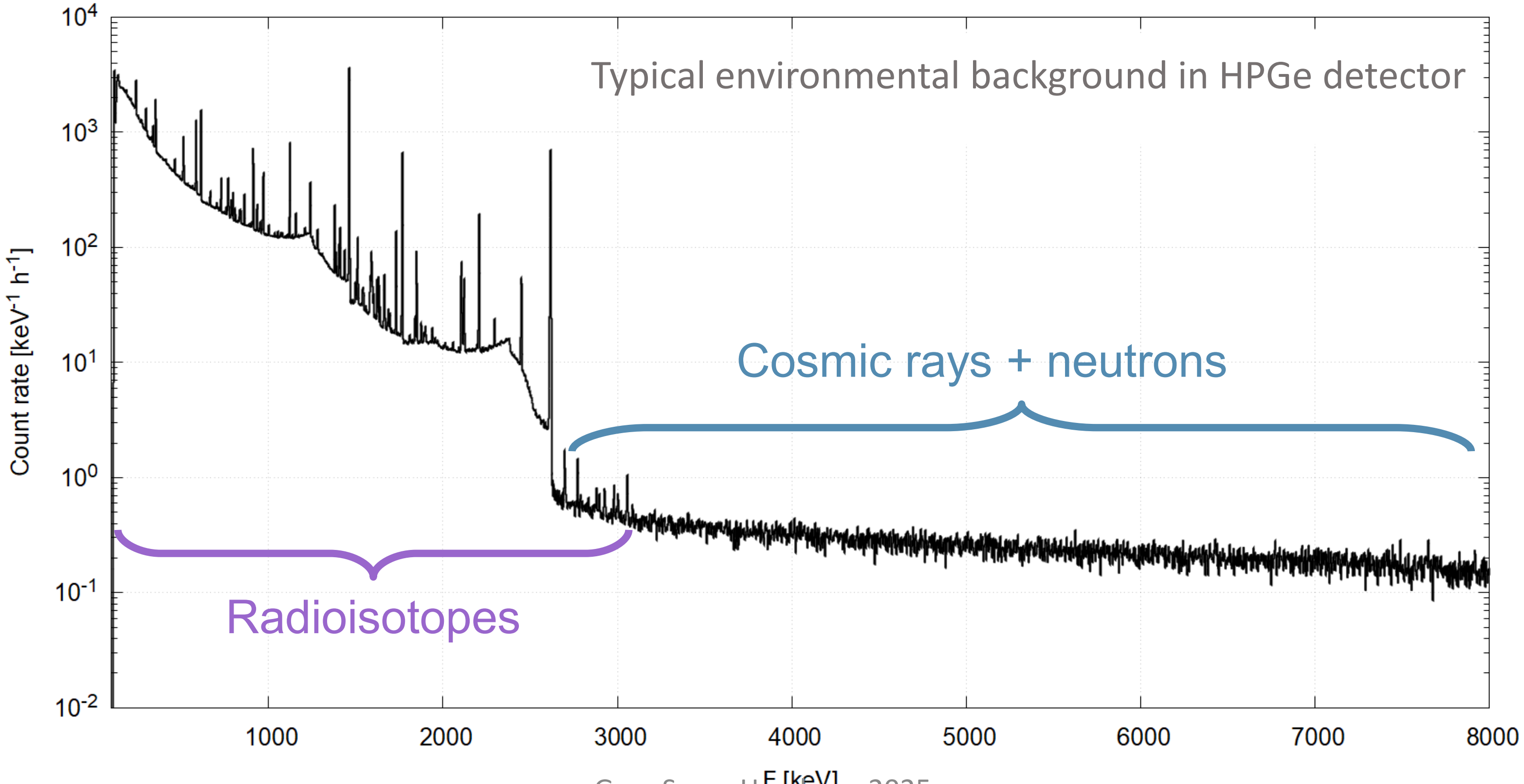


Environmental background sources

- **Environmental radioactivity**: $^{235,238}U$, ^{232}Th chains and ^{40}K
- **Cosmic rays:** mainly muons at sea level
- **Neutrons from (α,n) and spallation reactions**



How can we improve signal-to-background ratio?

1. **Increase signal**

    a. Increase beam current ⚠ Target degradation

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   b. Increase target density — ⚠ Beam energy loss and straggling

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⚠ Target degradation

⚠ Beam energy loss and straggling

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2. **Reduce background**
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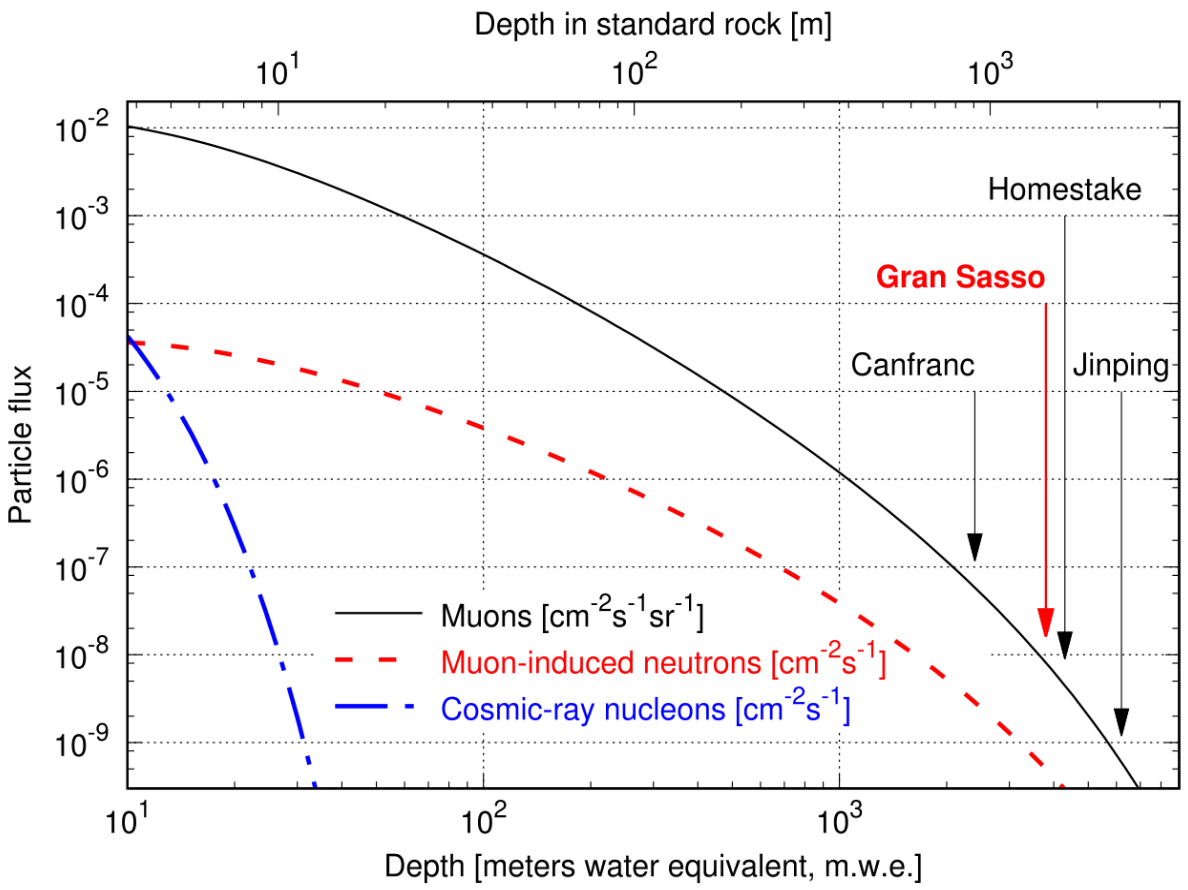
a. Active/passive shielding

b. Background rejection techniques (PSA, coincidences,…)

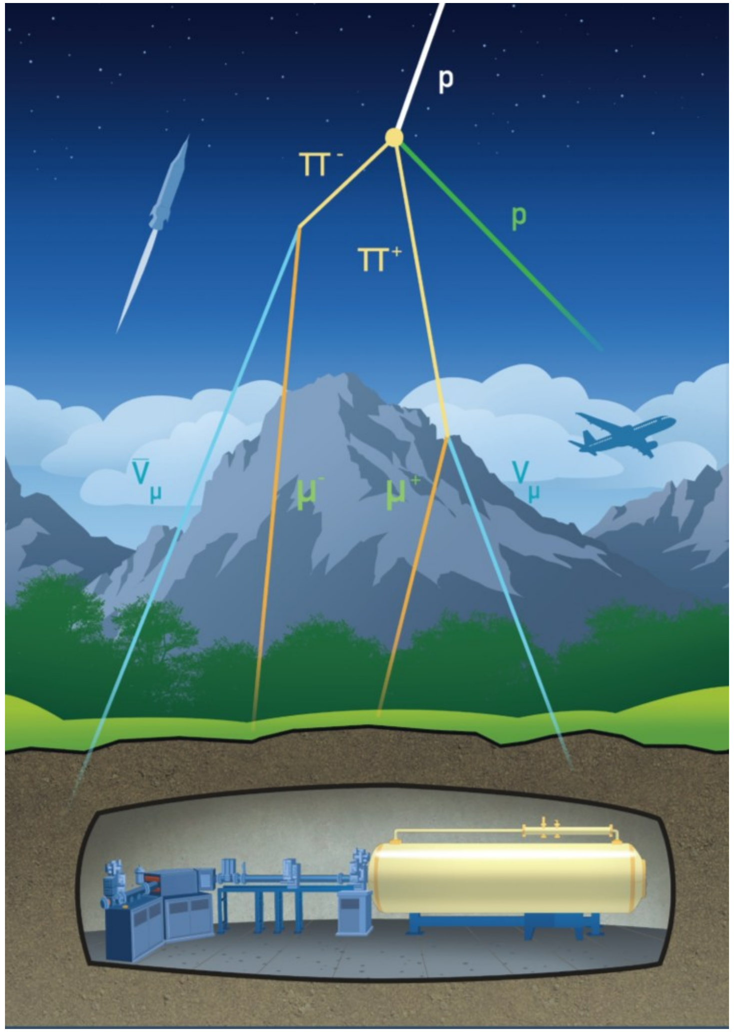
c. Move underground…

Why underground?

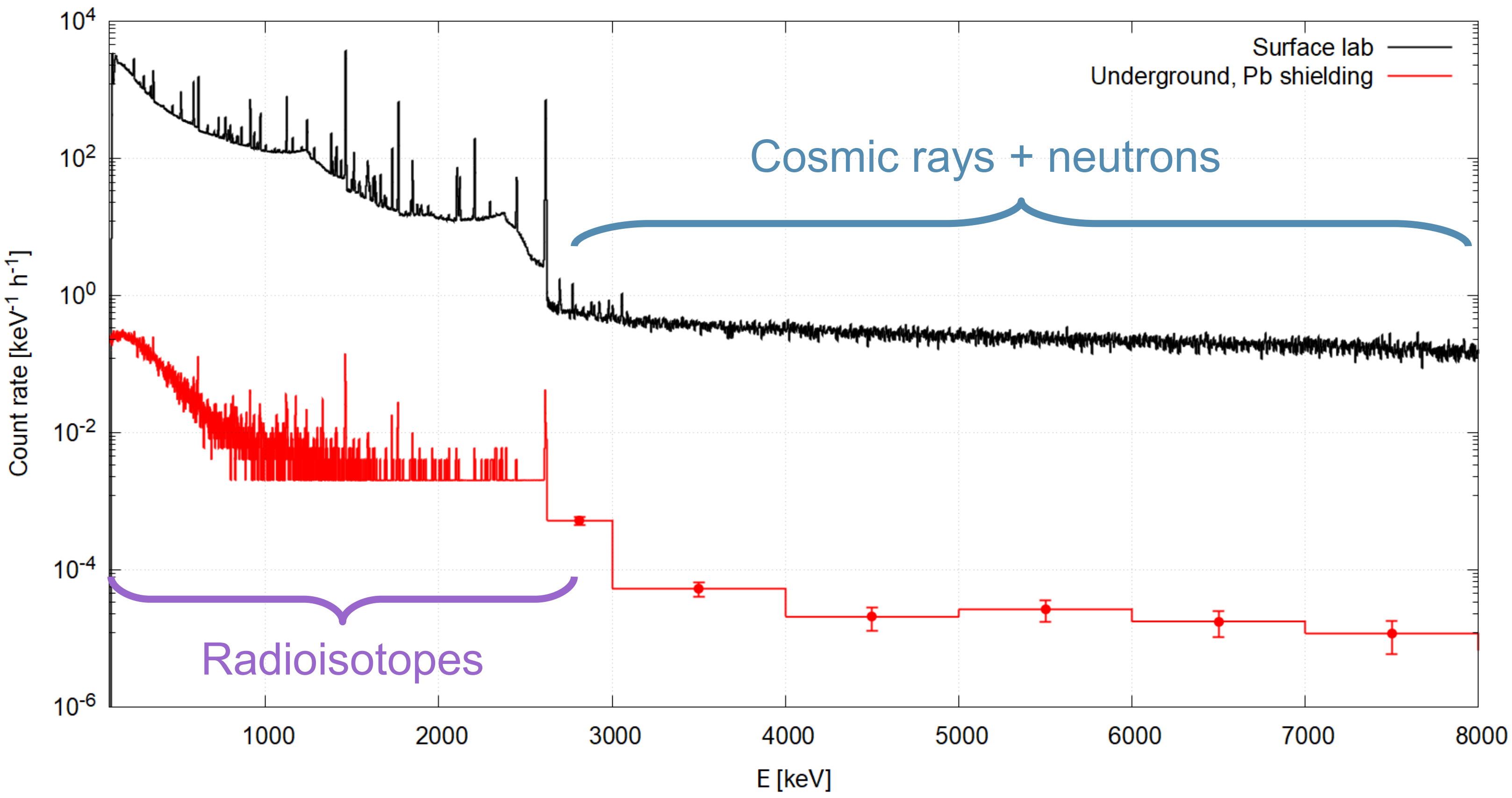
Rocks can efficiently suppress cosmic ray flux

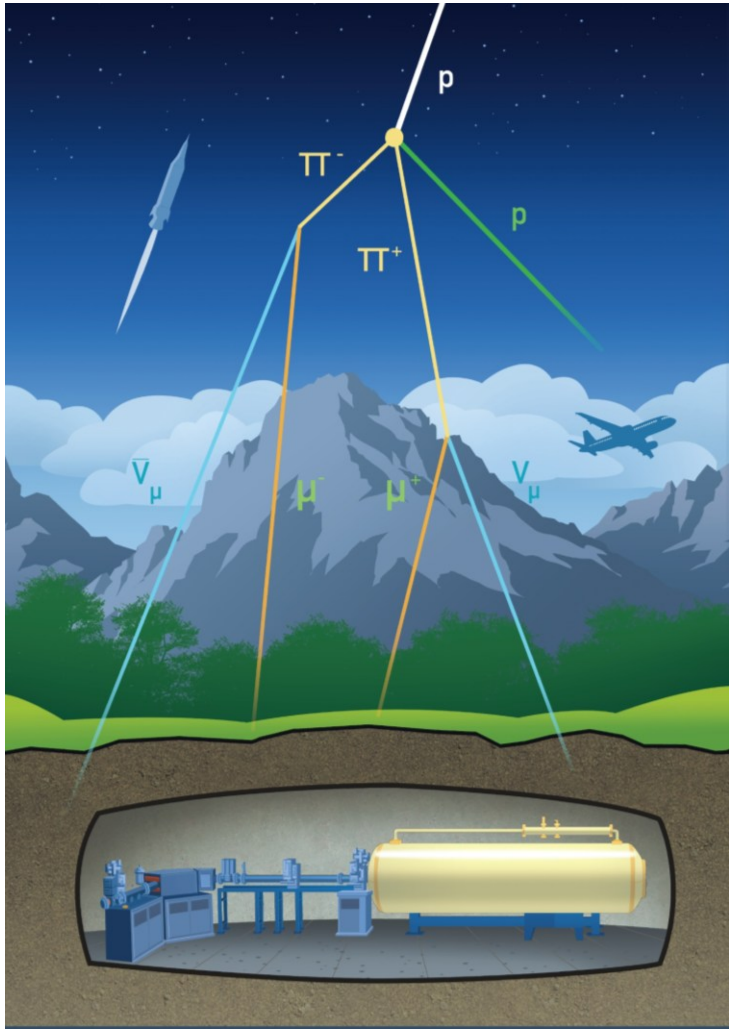


C. Broggini+, Prog. Part. Nuc. Phys. 98 (2018) 55–84



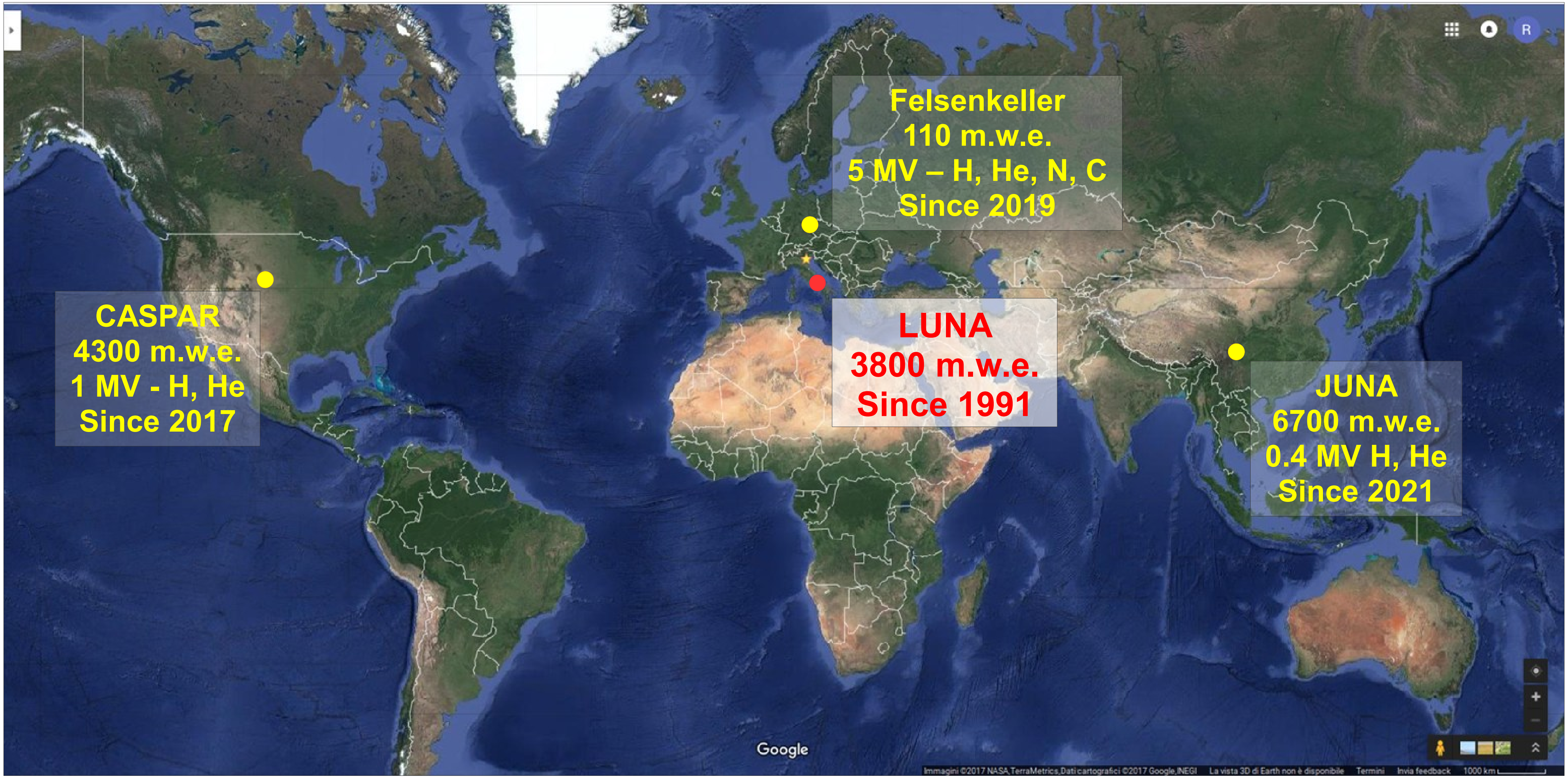
Why underground?





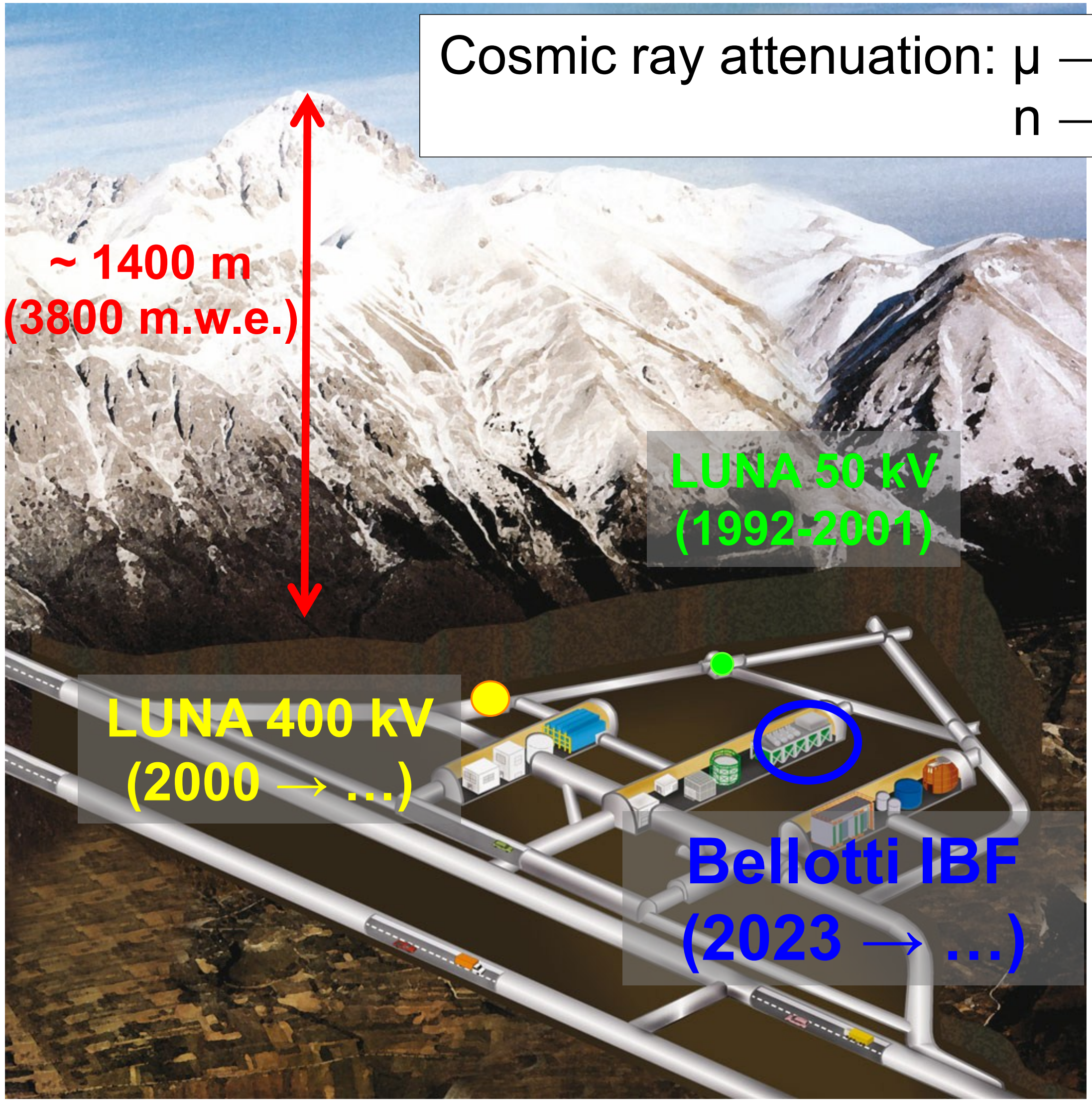
+ More effective passive shielding

Underground nuclear astro worldwide



The LUNA experiment at LNGS

Cosmic ray attenuation: $\mu \rightarrow 10^{-6}$
$n \rightarrow 10^{-3}$



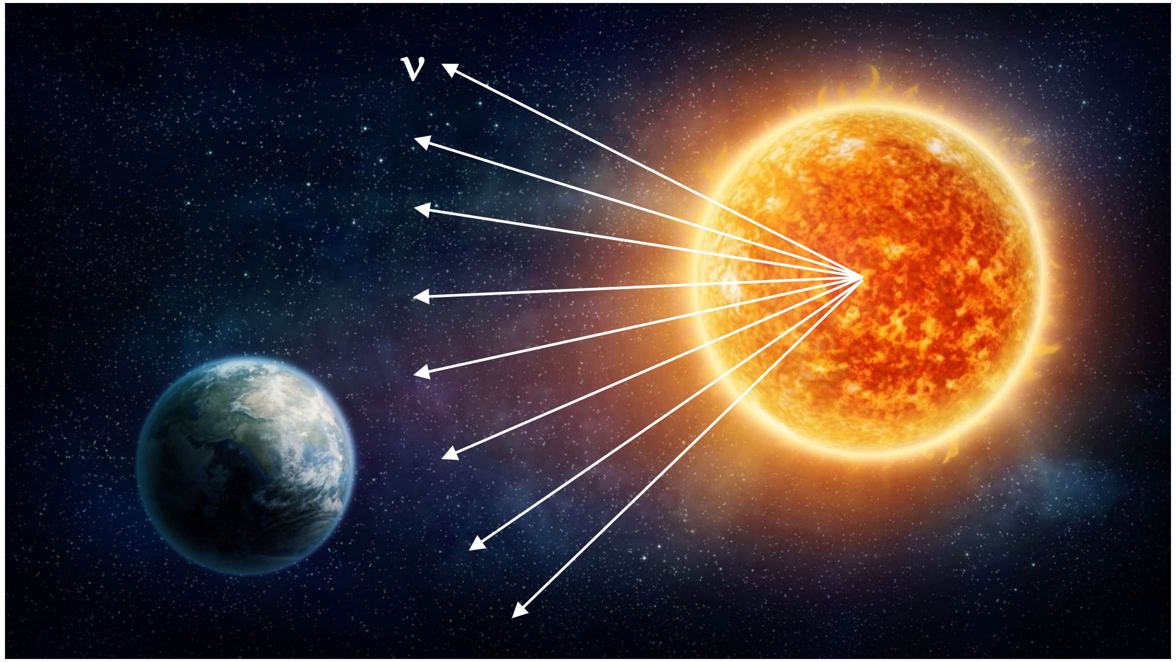
The past: LUNA-50 kV accelerator

Homemade accelerator devoted to the study of **$^{3}He(^{3}He, 2p)^{4}He$** and **$^{2}H(p,\gamma)^{3}He$**

Solar neutrino problem

$$4\,p \rightarrow {}^{4}He + 2e^{+} + 2\nu_e + 26.7\ \text{MeV}$$

Fusion rate = 10^{38} fusions/s → **Emitted neutrinos = 2×10^{38} neutrinos/s**



Solar neutrino problem

VOLUME 12, NUMBER 11 PHYSICAL REVIEW LETTERS 16 MARCH 1964

SOLAR NEUTRINOS. I. THEORETICAL*

John N. Bahcall
California Institute of Technology, Pasadena, California
(Received 6 January 1964)

The principal energy source for main-sequence stars like the sun is believed to be the fusion, in the deep interior of the star, of four protons to form an alpha particle.[1] The fusion reactions are thought to be initiated by the sequence $^1H(p, e^+\nu)^2H(p,\gamma)^3He$ and terminated by the following sequences: (i) $^3He(^3He, 2p)^4He$; (ii) $^3He(\alpha,\gamma)^7Be(e^-\nu)^7Li(p,\alpha)^4He$; and (iii) $^3He(\alpha,\gamma)^7Be(p,\gamma)^8B(e^+\nu)^8Be^*(\alpha)^4He$. No direct evidence for the existence of nuclear reactions in the interiors of star is typically less than 10^{-10} of the radius of the star. Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars.

The most promising method[2] for detecting solar neutrinos is based upon the endothermic reaction ($Q = -0.81$ MeV) $^{37}Cl(\nu_{solar}, e^-)^{37}Ar$, which was first discussed as a possible means of detecting

expected flux ~ 3x measured flux

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SOLAR NEUTRINOS. II. EXPERIMENTAL*

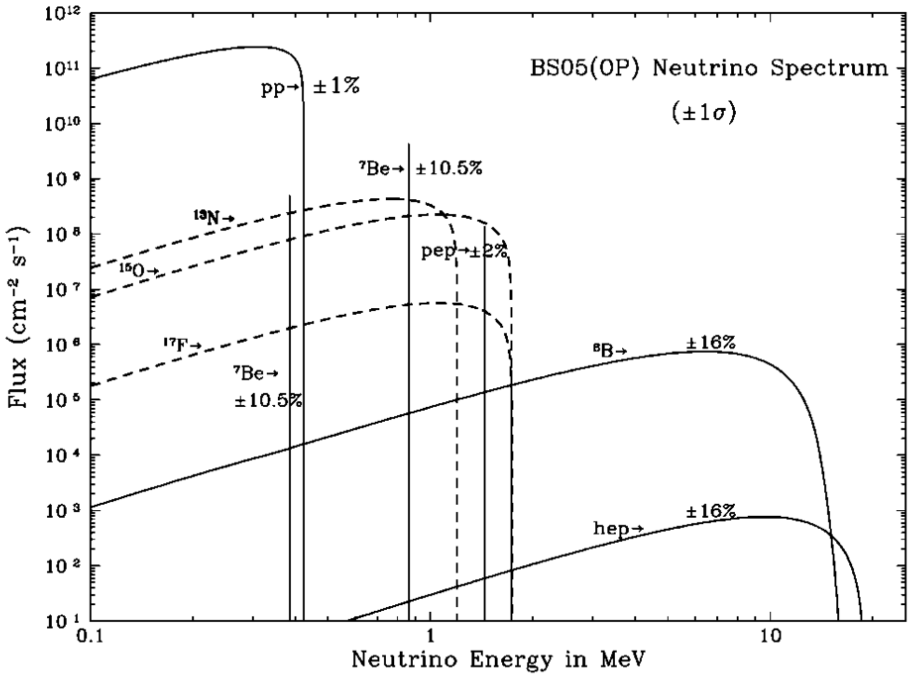
Raymond Davis, Jr.
Chemistry Department, Brookhaven National Laboratory, Upton, New York
(Received 6 January 1964)

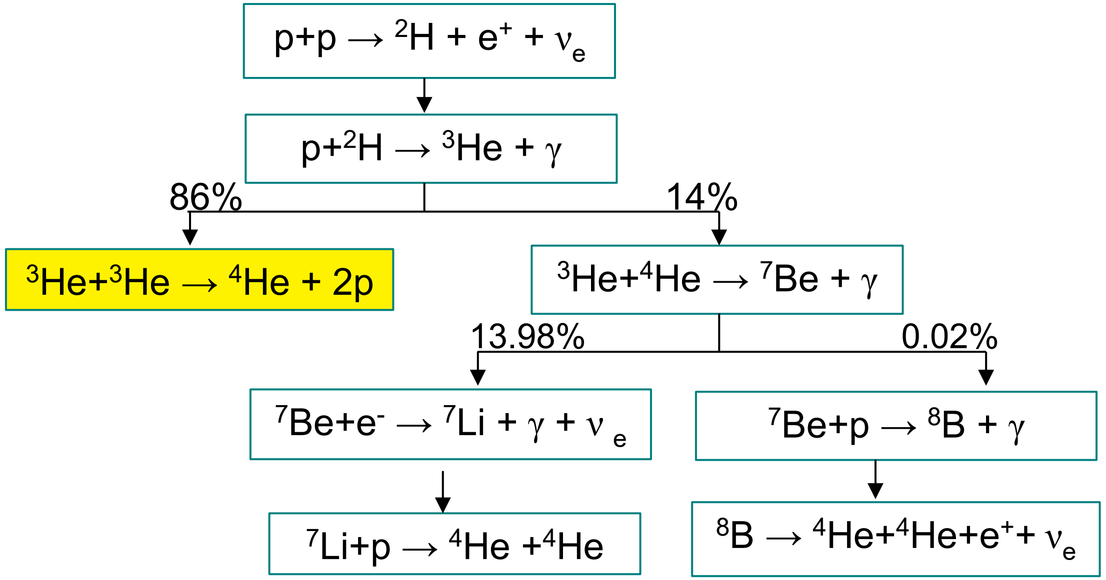
The prospect of observing solar neutrinos by means of the inverse beta process $^{37}Cl(\nu, e^-)^{37}Ar$ induced us to place the apparatus previously described[1] in a mine and make a preliminary search. This experiment served to place an upper limit on the flux of extraterrestrial neutrinos. These results will be reported, and a discussion will be given of the possibility of extending the sensitivity of the method to a degree capable of measuring the solar neutrino flux calculated by Bahcall in the preceding paper.[2]

3 counts in 18 days is probably entirely due to the background activity. However, if one assumes that this rate corresponds to real events and uses the efficiencies mentioned, the upper limit of the neutrino capture rate in 1000 gallons of C_2Cl_4 is ≤ 0.5 per day or $\varphi\bar{\sigma} \leq 3\times10^{-34}$ sec^{-1} (^{37}Cl atom)$^{-1}$. From this value, Bahcall[2] has set an upper limit on the central temperature of the sun and other relevant information.

On the other hand, if one wants to measure the solar neutrino flux by this method one must use

$^{3}He(^{3}He, 2p)^{4}He$: A solution to the solar neutrino problem?

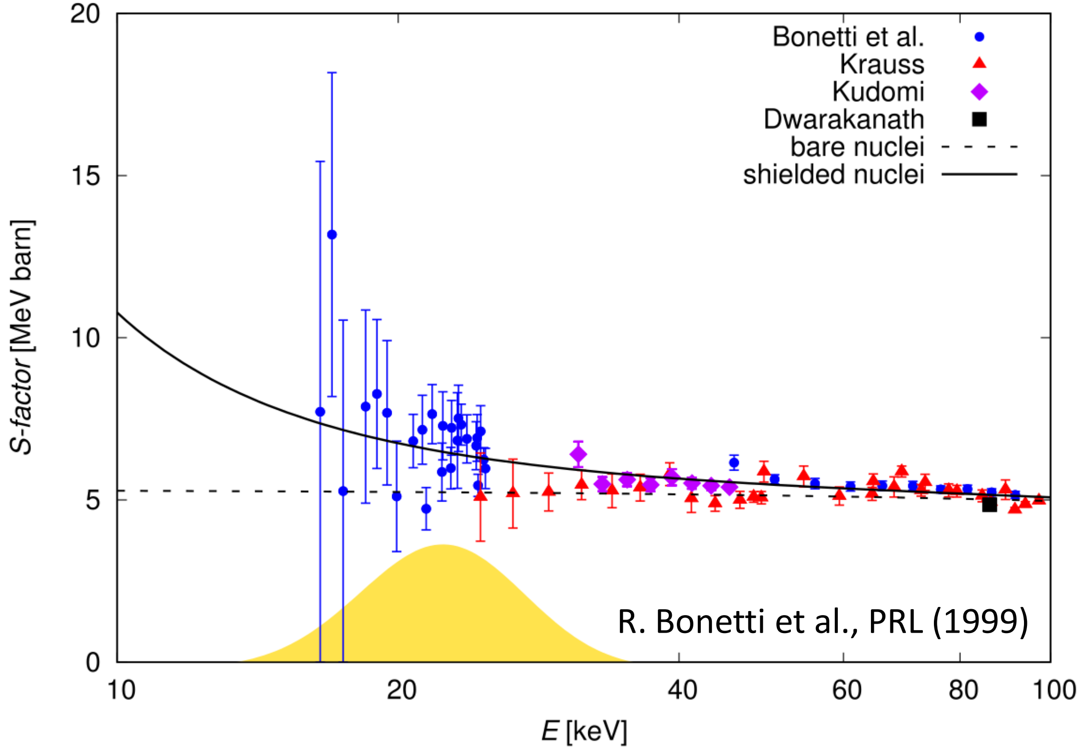


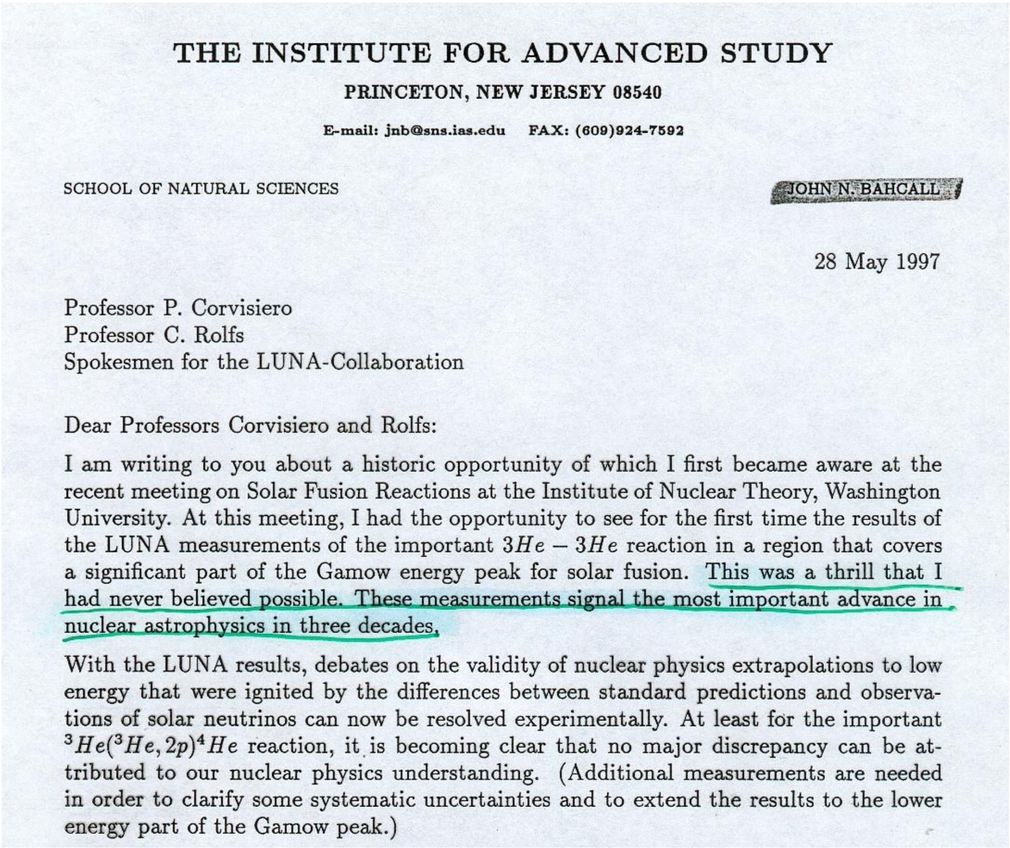


SOLAR NEUTRINO PROBLEM:
predicted ν flux ~ 3 x measured flux

→ POSSIBLE SOLUTION:
Resonance in $^{3}He(^{3}He, 2p)^{4}He$ reaction

$^3He(^3He, 2p)^4He$: A solution to the solar neutrino problem?





THE INSTITUTE FOR ADVANCED STUDY

PRINCETON, NEW JERSEY 08540

E-mail: jnb@sns.ias.edu FAX: (609)924-7592

SCHOOL OF NATURAL SCIENCES

JOHN N. BAHCALL

28 May 1997

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

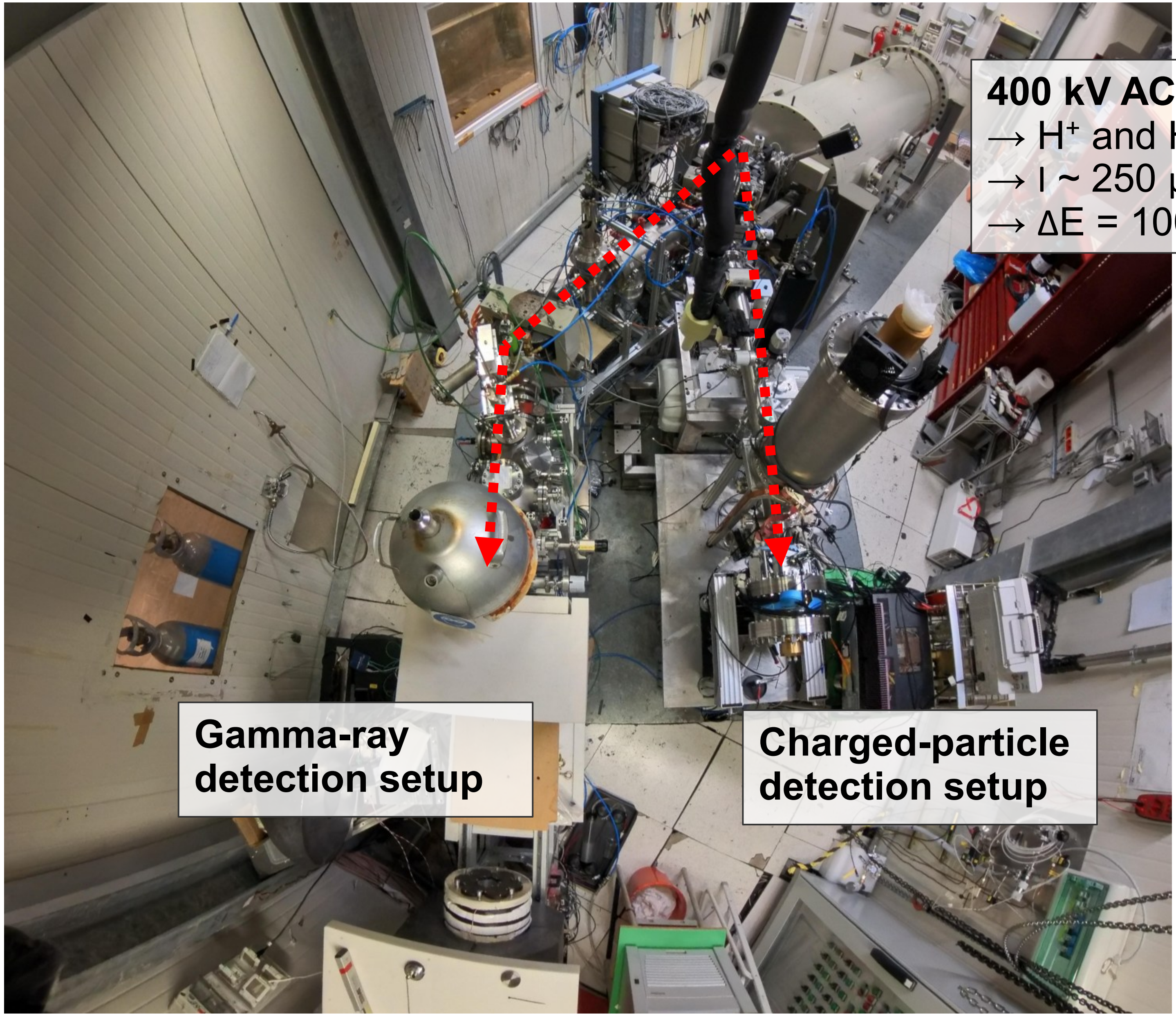
Dear Professors Corvisiero and Rolfs:

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.

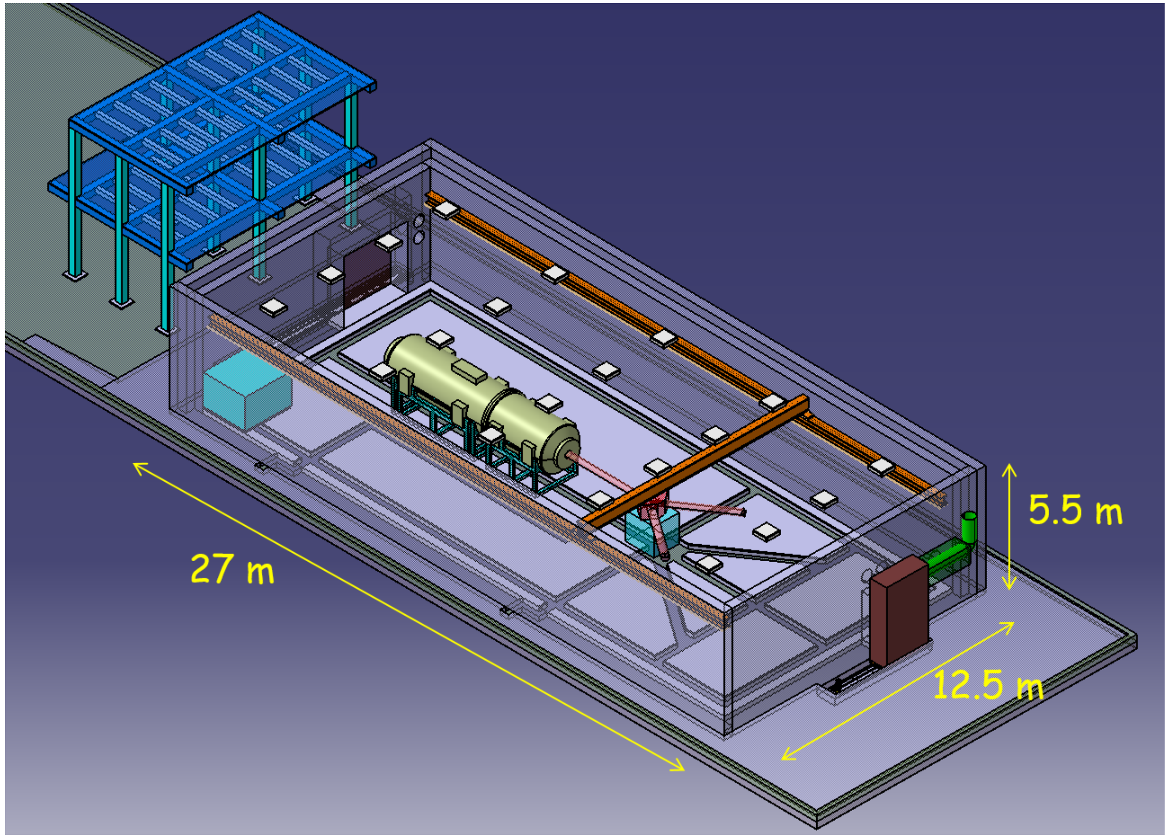
With the LUNA results, debates on the validity of nuclear physics extrapolations to low energy that were ignited by the differences between standard predictions and observations of solar neutrinos can now be resolved experimentally. At least for the important $^3He(^3He, 2p)^4He$ reaction, it is becoming clear that no major discrepancy can be attributed to our nuclear physics understanding. (Additional measurements are needed in order to clarify some systematic uncertainties and to extend the results to the lower energy part of the Gamow peak.)

→ Direct measurement within the Gamow peak
→ No resonance found
→ cross section at the lowest energy ~ 20 fb (2 events per month)

The present: LUNA-400 kV accelerator



The present: Bellotti Ion Beam Facility



- **Inline Cockcroft Walton accelerator**
- **TERMINAL VOLTAGE: 0.2 – 3.5 MV**
- **Beam energy reproducibility:** 0.01% TV or 50V
- **Beam energy stability:** 0.001% TV / h
- **Beam current stability:** < 5% / h

H^+ beam: 500 - 1000 eμA

He^+ beam: 300 - 500 eμA

C^+ beam: 100 - 150 eμA

C^{++} beam: 100 eμA

80 cm thick concrete shielding around accelerator room. This will reduce the neutron flux just outside the shielding to a value about one order of magnitude lower than the neutron flux at LNGS, $\Phi = 3 \cdot 10^{-6}$ n/(cm^2 s)

The present: Bellotti Ion Beam Facility

Accelerator operative since June 2023

LUNA-MV: 5 yr scientific program

$^{14}N(p,\gamma)^{15}O$: the bottleneck reaction of the CNO cycle in connection with the solar abundance problem. Also commissioning measurement for the LUNA MV facility

$^{12}C+^{12}C$: energy production and nucleosynthesis in Carbon burning. Global chemical evolution of the Universe

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

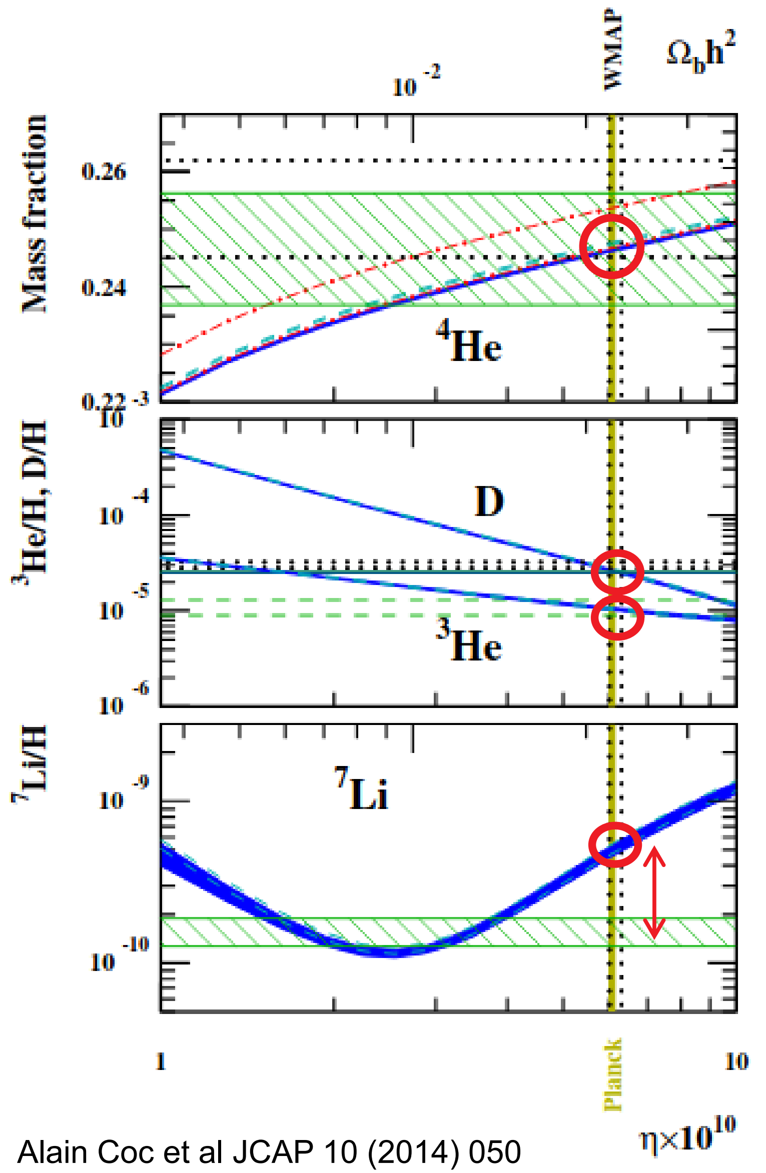
Later on…

$^{12}C(a,\gamma)^{16}O$: key reaction of Helium burning: determines C/O ratio and stellar evolution

Recent results by the LUNA Collaboration

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

The comparison of observed primordial elemental abundances with the abundances predicted by BBN (intersection of blue curves with vertical line)provides stringent constraints to cosmological parameters and the Big Bang model



Alain Coc et al JCAP 10 (2014) 050

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

PRIMORDIAL ABUNDANCE OF ^{2}H:

- Direct measurements: observation of absorption lines in DLA system

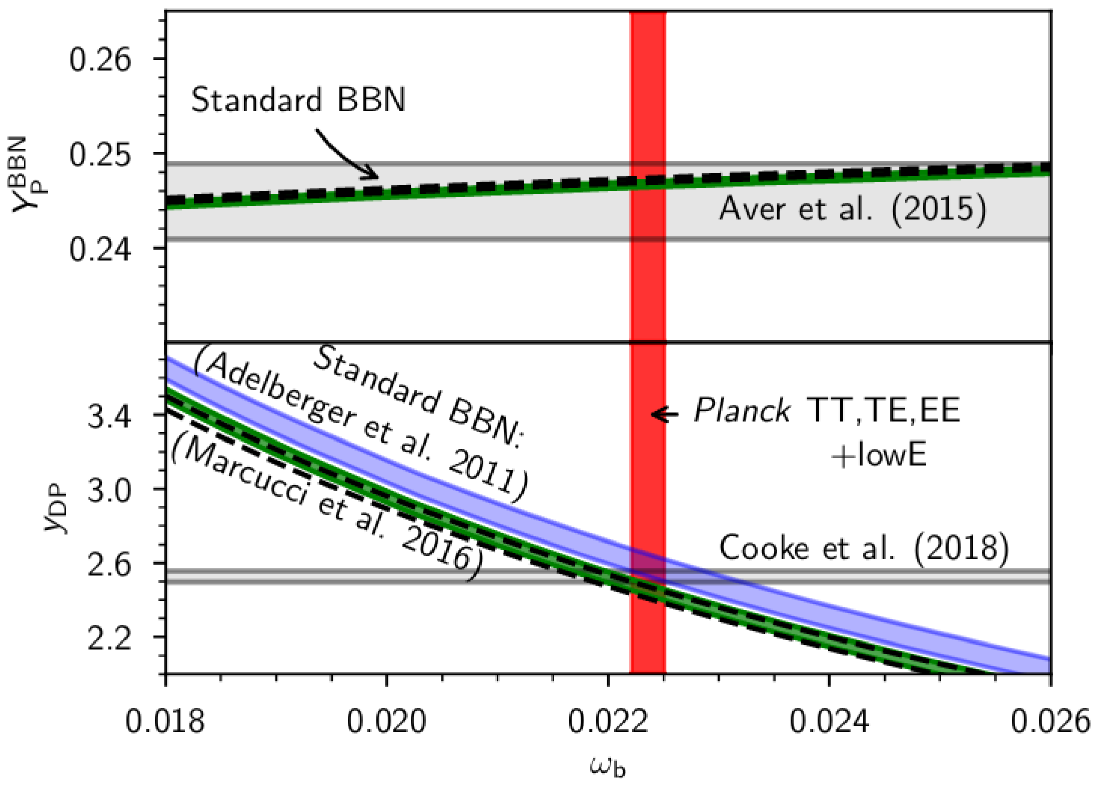
$$\left[\frac{D}{H}\right]_{OBS} = (2.527 \pm 0.030) \cdot 10^{-5}$$

R. Cooke at al., ApJ. 855, 102 (2018)

- BBN theory: from the cosmological parameters and the cross sections of the processes involved in ^{2}H creation and destruction

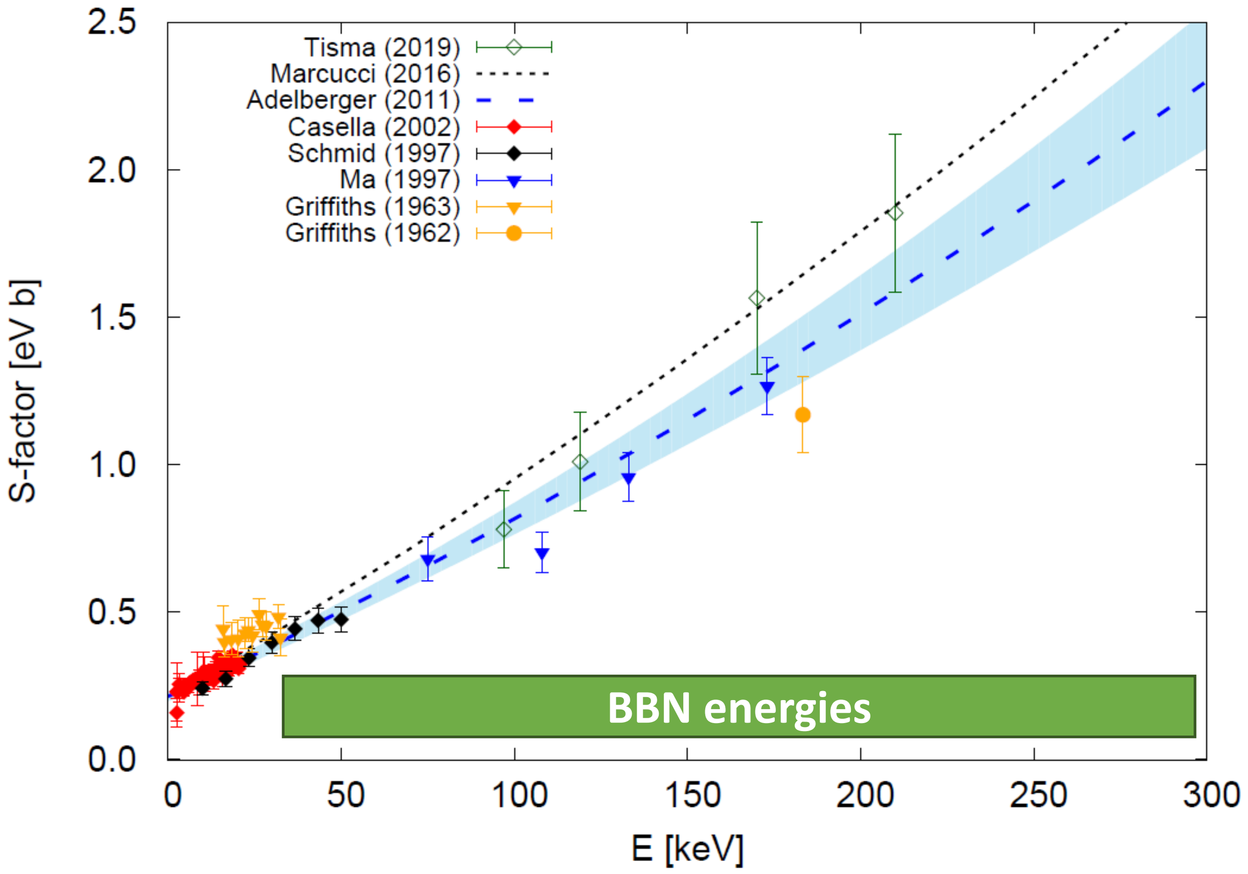
$$\left[\frac{D}{H}\right]_{BBN} = \begin{matrix}(2.587 \pm 0.055) \cdot 10^{-5} \\ (2.439 \pm 0.052) \cdot 10^{-5}\end{matrix}$$

Plank 2018 results arXiv:1807.06209v1



The D/H predicted by BBN changes by 6% depending on the $^{2}H(p,\gamma)^{3}He$ cross section adopted

$^2H(p,\gamma)^3He$ reaction: State of the art

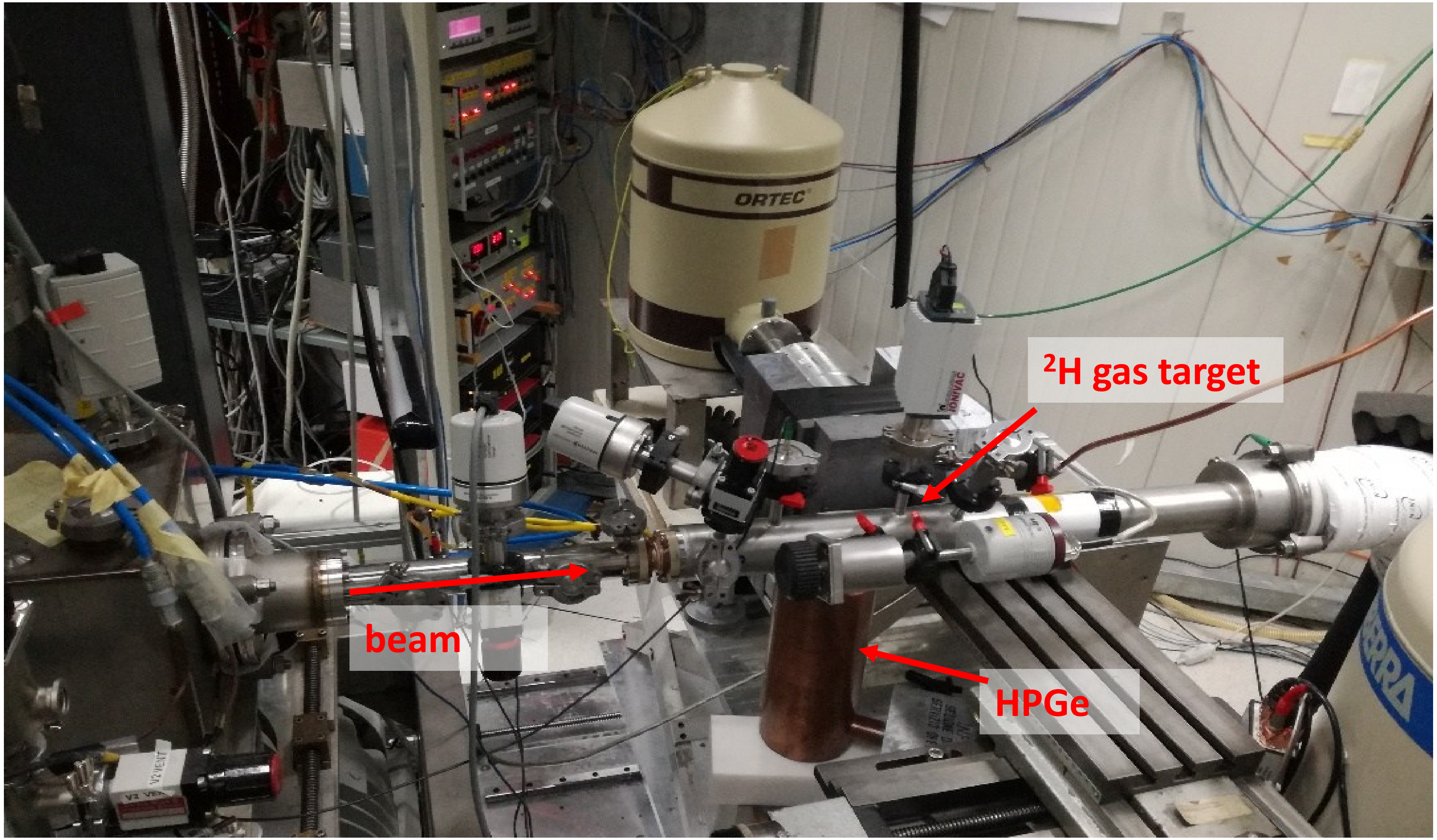


cross section of the $^2H(p,\gamma)^3He$ reaction is the main rce of uncertainty on the primordial ^2H abundance

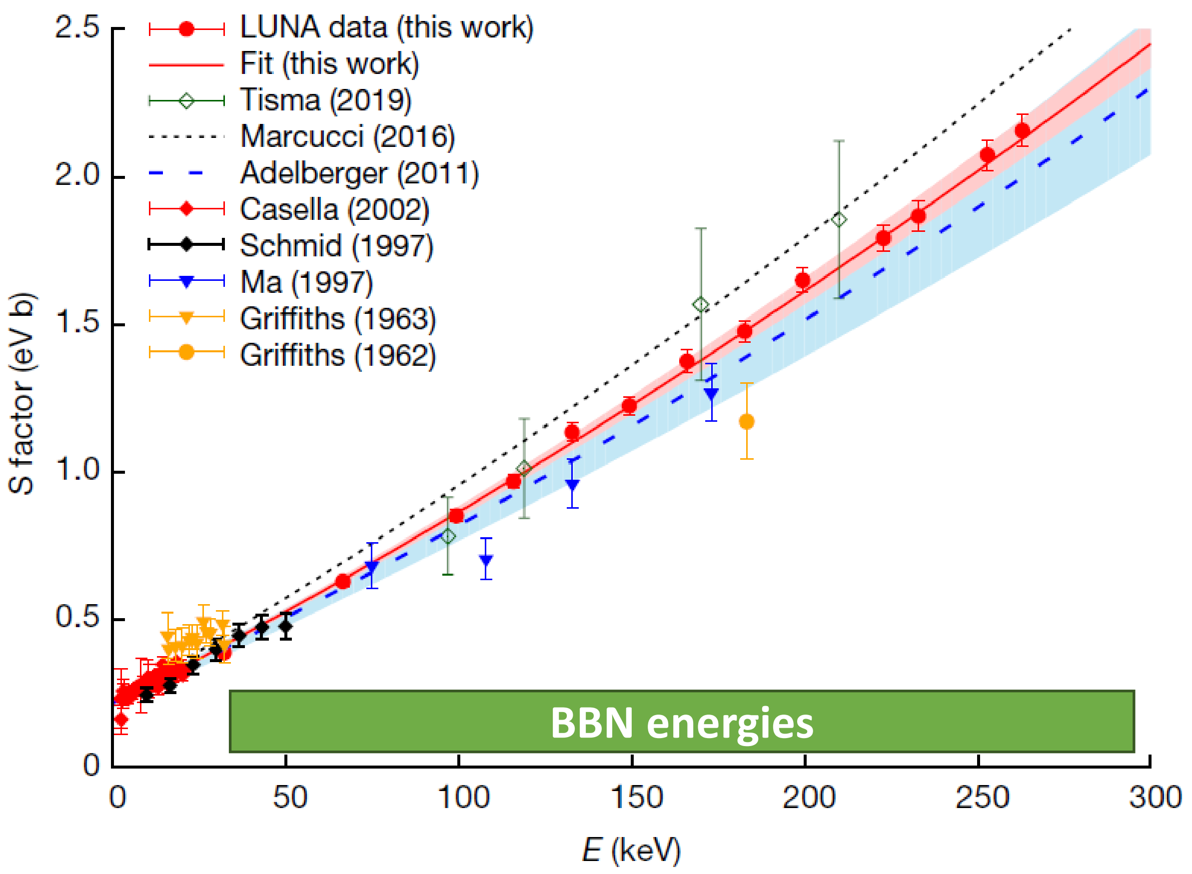
Measurement at solar energies performed at the LUNA – 50 kV accelerator

Only few data points available at BBN energies

$^{2}H(p,\gamma)^{3}He$ reaction: Setup at LUNA



$^2H(p,\gamma)^3He$ reaction: Results



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Article | Published: 11 November 2020

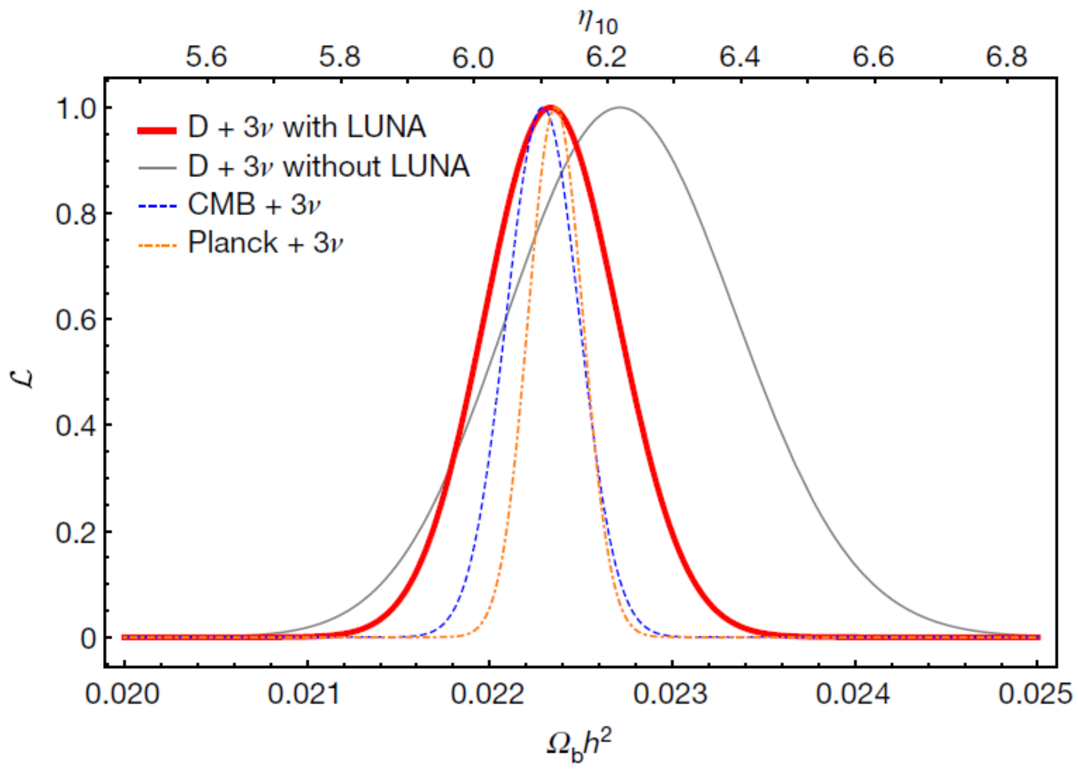
The baryon density of the Universe from an improved rate of deuterium burning

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

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

Systematic uncertainty reduced to **< 3%**

$^2H(p,\gamma)^3He$ reaction: Results



Using the baryon density provided by Planck, we derive

$$\left[\frac{D}{H}\right]_{BBN} = (2.52 \pm 0.07) \cdot 10^{-5}$$

In excellent agreement with astronomical observations

$$\left[\frac{D}{H}\right]_{OBS} = (2.527 \pm 0.030) \cdot 10^{-5}$$

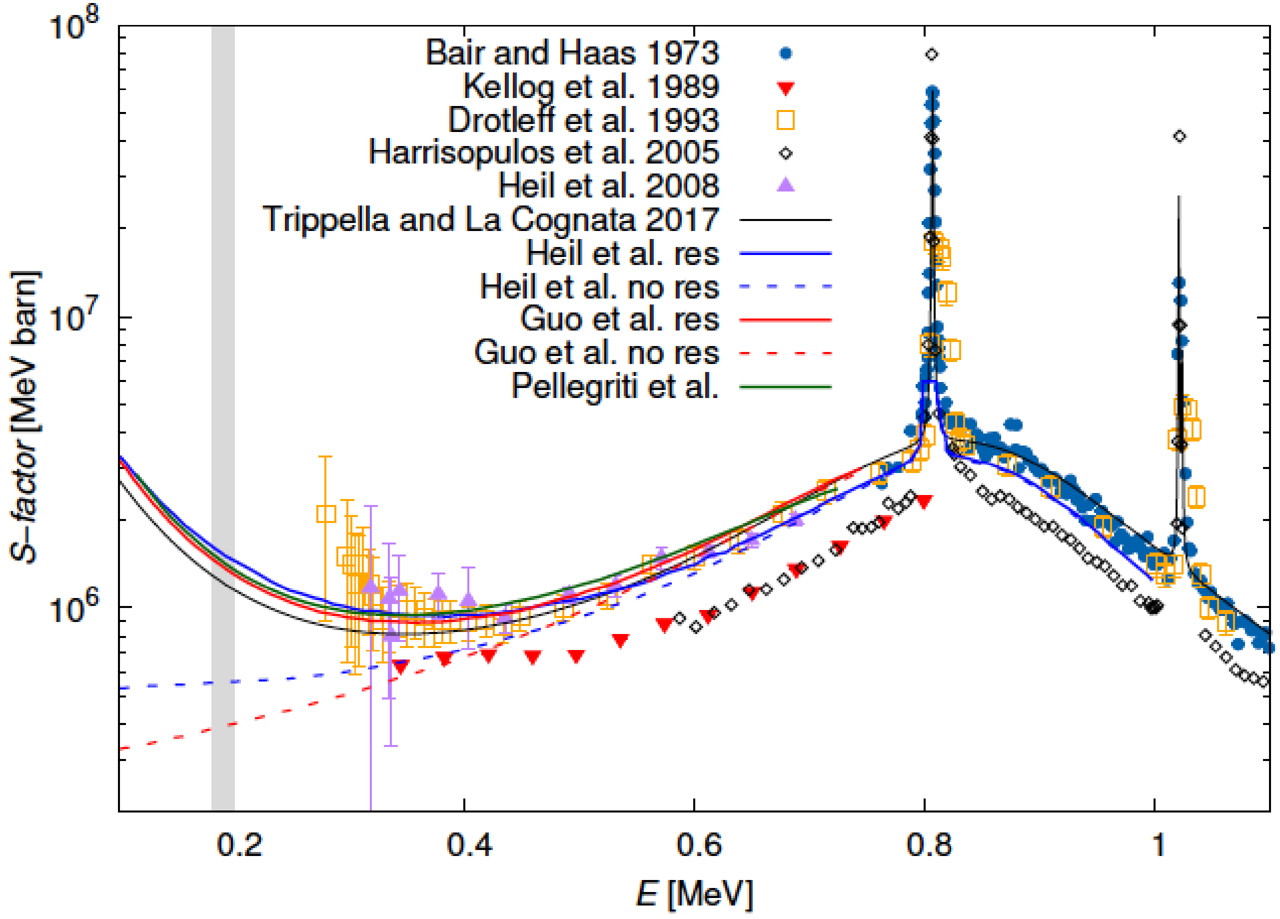
V. Mossa et al. Nature (2020)

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

Major neutron source for the main component of the s-process in low (1-3 $M_\odot$) mass AGB stars
Average temperature 10^8 K → Gamow window 0.13 – 0.25 MeV

minimum measured energy

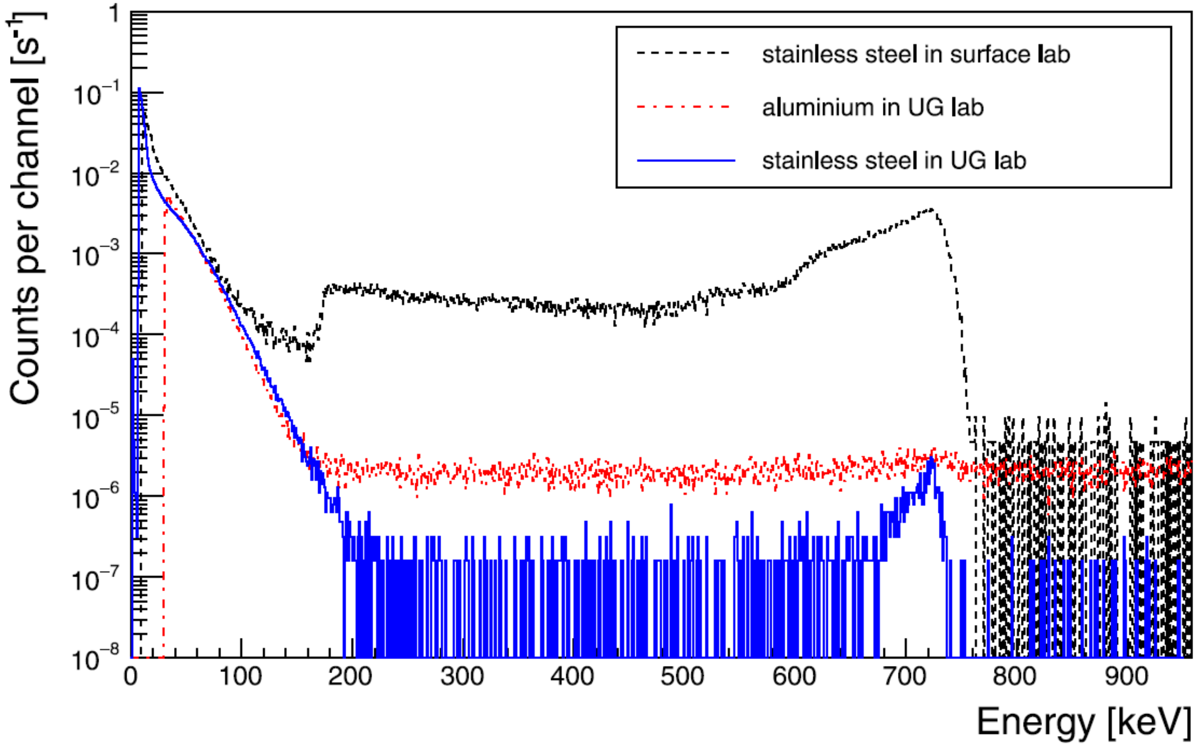
E_{cm}: 0.28 MeV



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

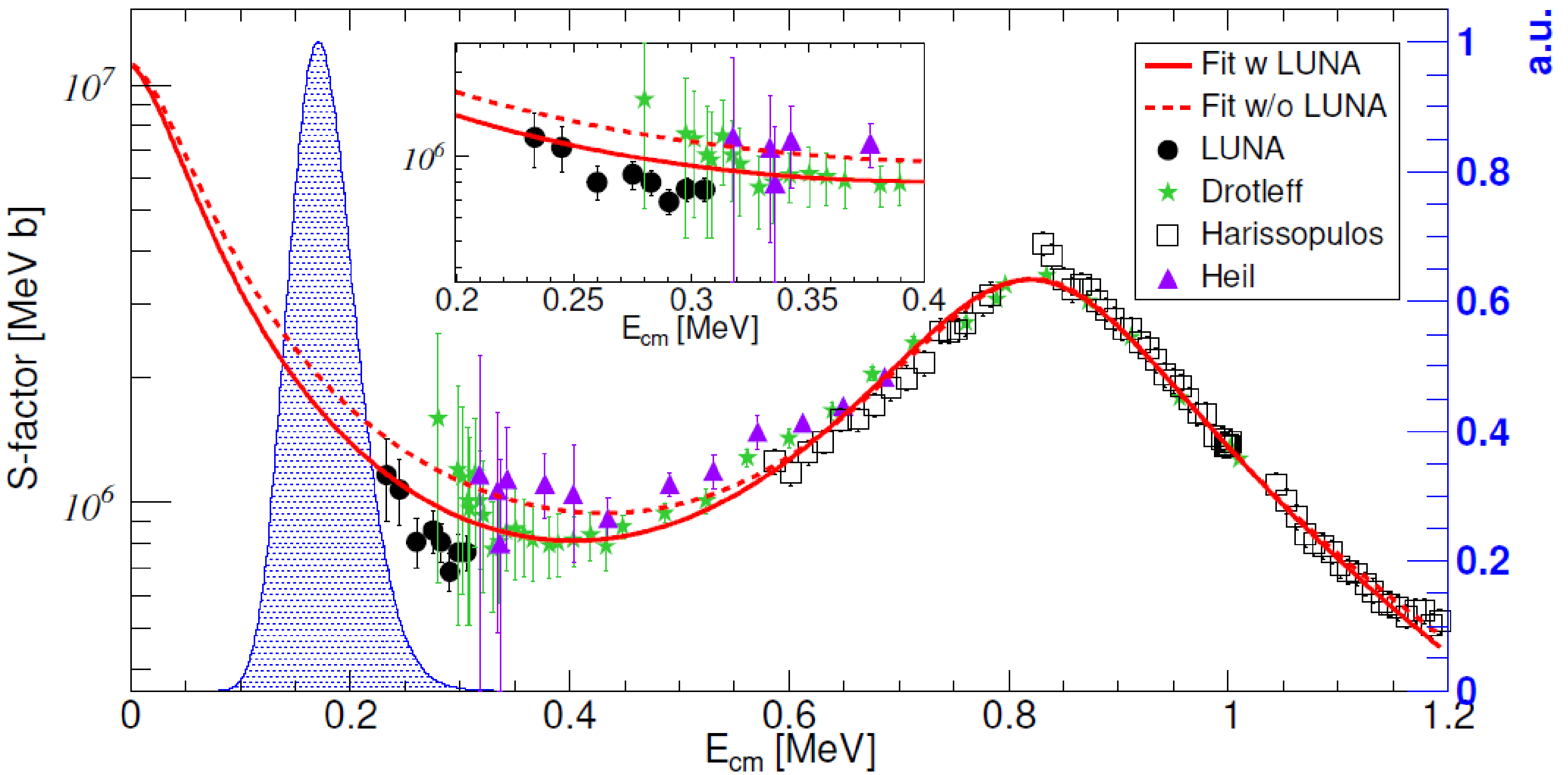
$^{13}C(\alpha,n)^{16}O$ reaction

18 ^{3}He counters arranged in two rings
INNER: 6 tubes (25 cm active length)
OUTER: 12 tubes (40 cm active length)



J. Balibrea Correa et al, NIM A 906 (2018) 103–109
G.F. Ciani et al, Eur. Phys. J. A (2020) 56:75
L. Csedreki et al, NIM A 994 (2021) 165081

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



G.F. Ciani et al PRL 127, 152701 (2021)

- Data taking in 4 campaigns of 3 months each in about 2 years
- Statistical uncertainty lower than 10% for our data
- Lowest energy data ever achieved and at the Gamow window edge of low mass AGB.
- Reaction rate uncertainty reduced from 20% to about 10%

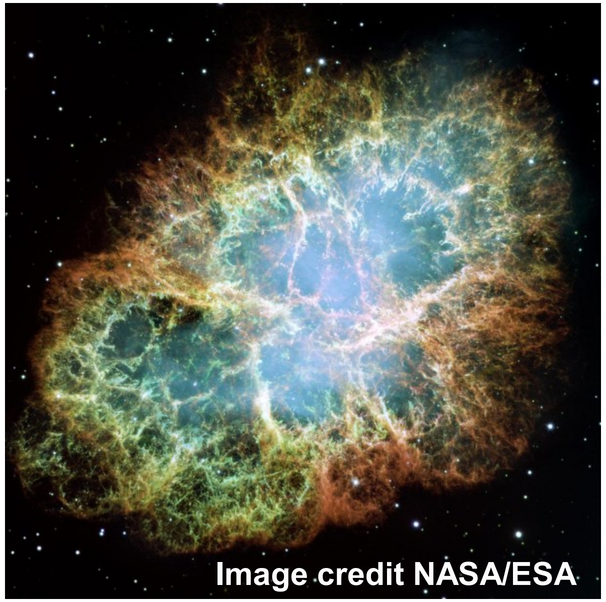
Stellar carbon burning

In stars, carbon burning is the first evolutionary stage involving the fusion of heavy ions.

Only stars with mass higher than a threshold M_{UP} (~ 8 M_{SUN}) can ignite carbon burning:

$M < M_{up}$
White dwarfs/classical novae

$M > M_{up}$
Supernovae→ neutron stars and black holes



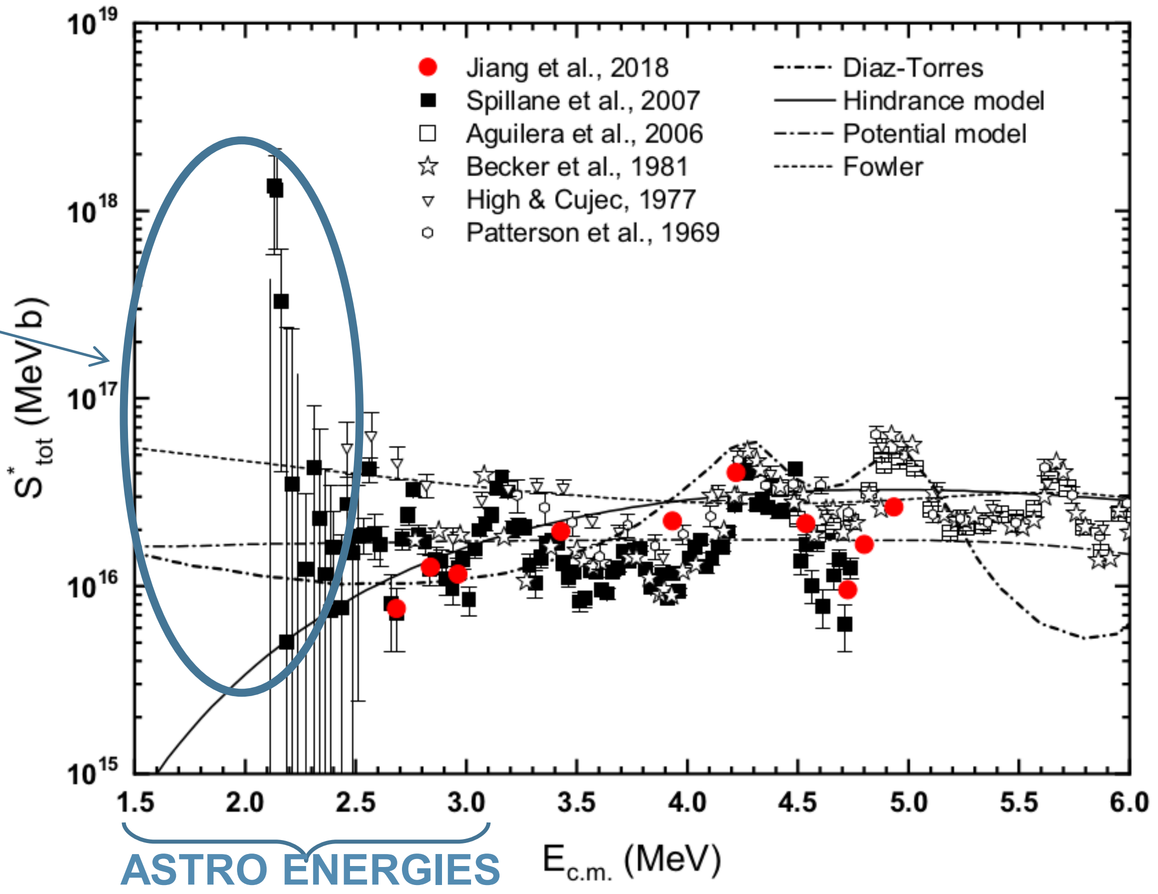
M_{UP} (and hence the whole life and fate of a star) depends on the $^{12}C+^{12}C$ cross section

Stellar carbon burning

$^{12}C+^{12}C \rightarrow ^{20}Ne + \alpha\ (+\gamma)$ (Q = 4.62 MeV)
$\rightarrow ^{23}Na + p\ (+\gamma)$ (Q = 2.24 MeV)

Main exit channels
Experiments are performed detecting charged particles and/or gamma rays

IS THERE A LOW-ENERGY RESONANCE?
If so, M_{UP} may decrease by 2 solar masses!



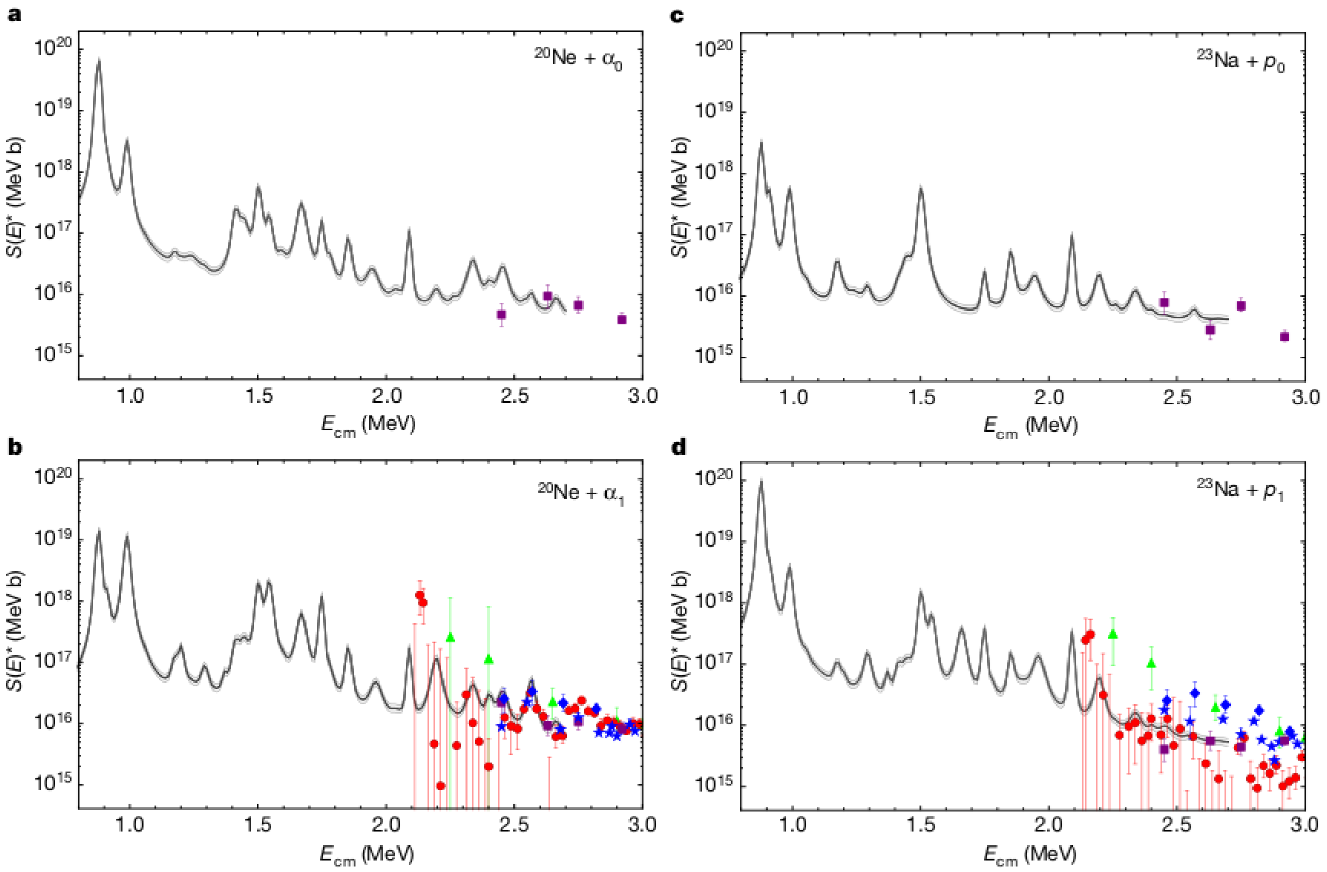
J. Zickefoose et al. PRC97, 065806 (2018)

Stellar carbon burning

$^{12}C + ^{12}C \rightarrow ^{20}Ne + \alpha\ (+\gamma)\ (Q = 4.62\ MeV)$
$\rightarrow ^{23}Na + p\ (+\gamma)\ (Q = 2.24\ MeV)$

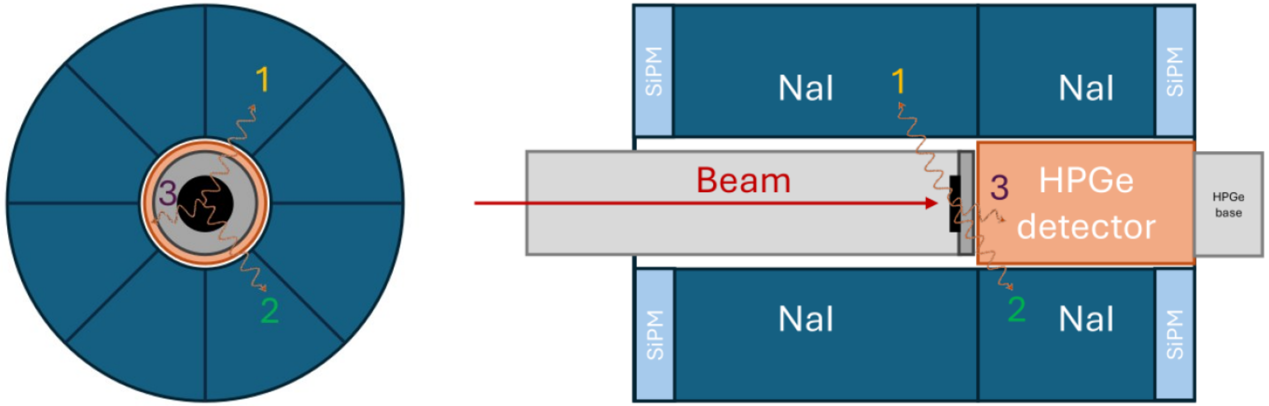
Main exit channels
Experiments are performed detecting charged particles and/or gamma rays

A. Tumino et al. Nature 557, 687 (2018)



Carbon burning at the Bellotti IBF

- ^{12}C beam on thick graphite target
- gamma-rays detected by one large-volume HPGe
- detector surrounded by 7cm Cu + 25cm Pb shielding to suppress background
- NaI detectors to suppress Compton continuum
- Data taking just started!



Front view

Lateral view

«If you wish to make an apple pie from scratch, you must first invent the Universe.»

Carl Sagan

LUNA Collaboration

~50 researchers from:

Laboratori Nazionali del Gran Sasso, INFN, ASSERGI, Italy/GSSI, L'AQUILA
Università degli Studi di Milano and INFN, MILANO
Università degli Studi di Padova and INFN, PADOVA
Università degli Studi di Genova and INFN, GENOVA
Università di Torino and INFN, TORINO
Università degli Studi di Bari and INFN, BARI
Università degli Studi di Napoli "Federico II" and INFN, NAPOLI
INFN Lecce, LECCE
INFN Roma, ROMA
Laboratori Nazionali di Legnaro
Osservatorio Astronomico di Collurania, TERAMO

Konkoly Observatory, Hungarian Academy of Sciences, BUDAPEST, Hungary
Institute of Nuclear Research (ATOMKI), DEBRECEN, Hungary

Helmholtz-Zentrum Dresden-Rossendorf, DRESDEN, Germany

University of Edinburgh, EDINBURGH, United Kingdom