Looking the Universe from Deep Underground

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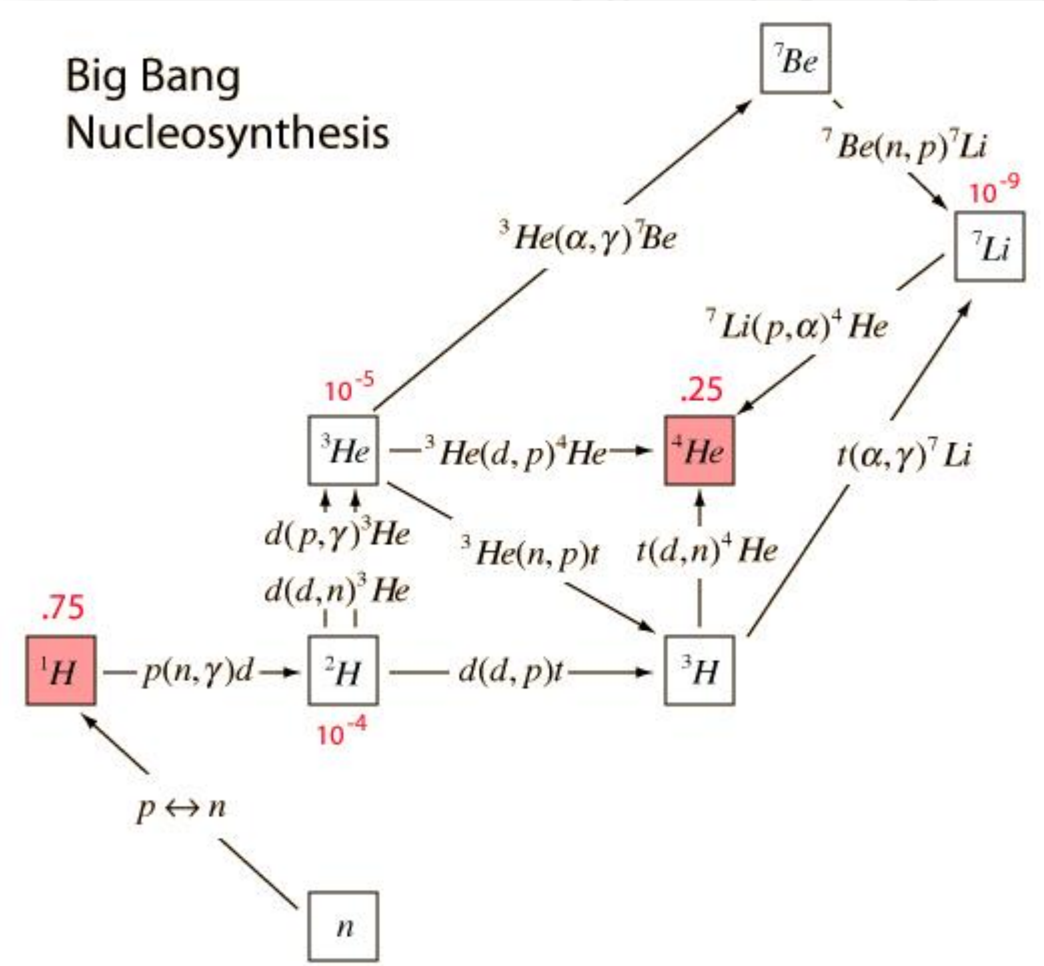
What we know about the Universe and its history?

The most important evidences for the Big Bang Model are:

- the cosmic expansion,
- the Cosmic Microwave Background (CMB) radiation,
- **the Big Bang or primordial Nucleosynthesis (BBN)**



What is the Big Bang Nucleosynthesis?

BBN predicts the primordial abundances of the “light cosmological nuclei”: H, He, Li and Be that are produced during the first 20 minutes after the Big Bang.

INGREDIENTS: temperature of the Universe T, baryon density Ω_b, neutron to proton ratio n/p and all the cross section σ_i of the processes involved.

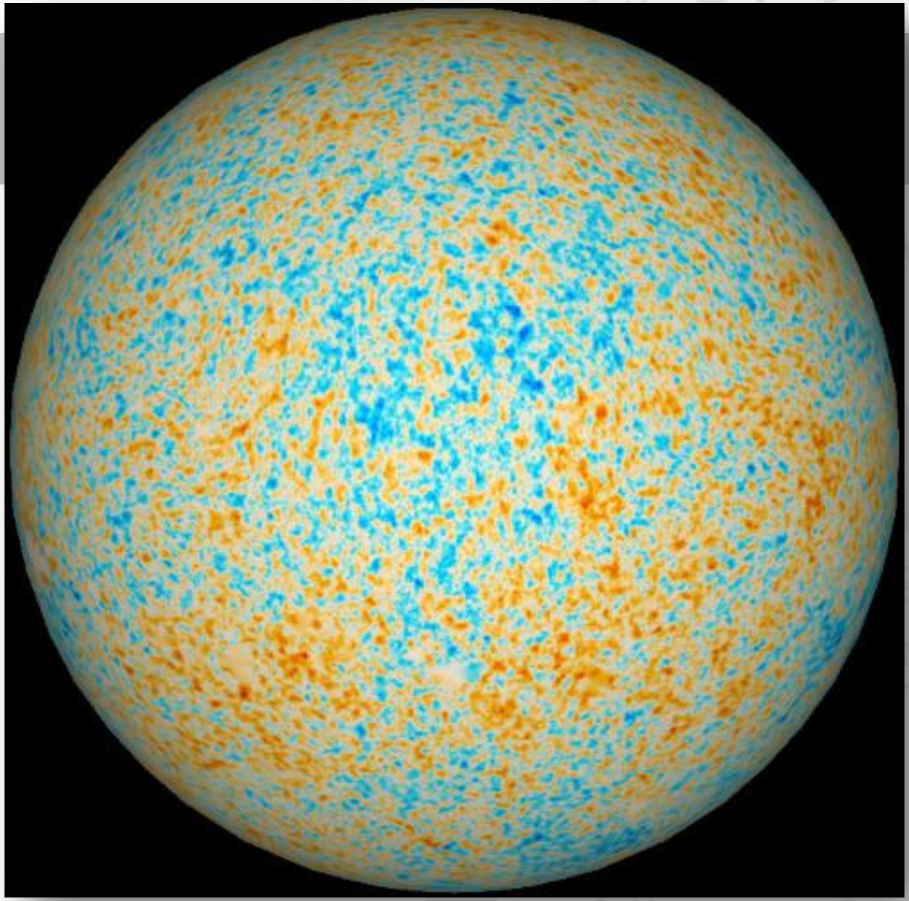
THE TEMPERATURE OF THE UNIVERSE

In order to obtain the temperature of the Universe at a given time after the Big Bang we must solve the **Friedmann-Lemaitre equation**

ASSUMPTIONS:

- Curvature term neglected (flat Universe)
- Radiation dominated the Universe $\rho = \rho_r$

$$T(0.002s) = 10^{12}K$$
$$T(2s) = 10^{10}K$$
$$T(200s) = 10^{9}K$$
$$T(\simeq 5.5h) = 10^{8}K$$



$$\eta_{PLANCK} = 0.02218 \pm 0.00026$$

BARYON DENSITY

The time evolution of the baryon density Ω_b can be inferred using again the **Friedmann-Lemaitre equation**

$$\Omega_b(t) = \Omega_b(now)\left[\frac{T(t)}{T(now)}\right]^3$$

$\Omega_b(now) = 0.044$

$T(now) = 2.73K$

The baryon density is related to the baryon to photon ratio $\eta = 2.738 \times 10^{-8}\,\Omega_b h^2$ measured from the angular power spectrum of the CMB temperature anisotropies.

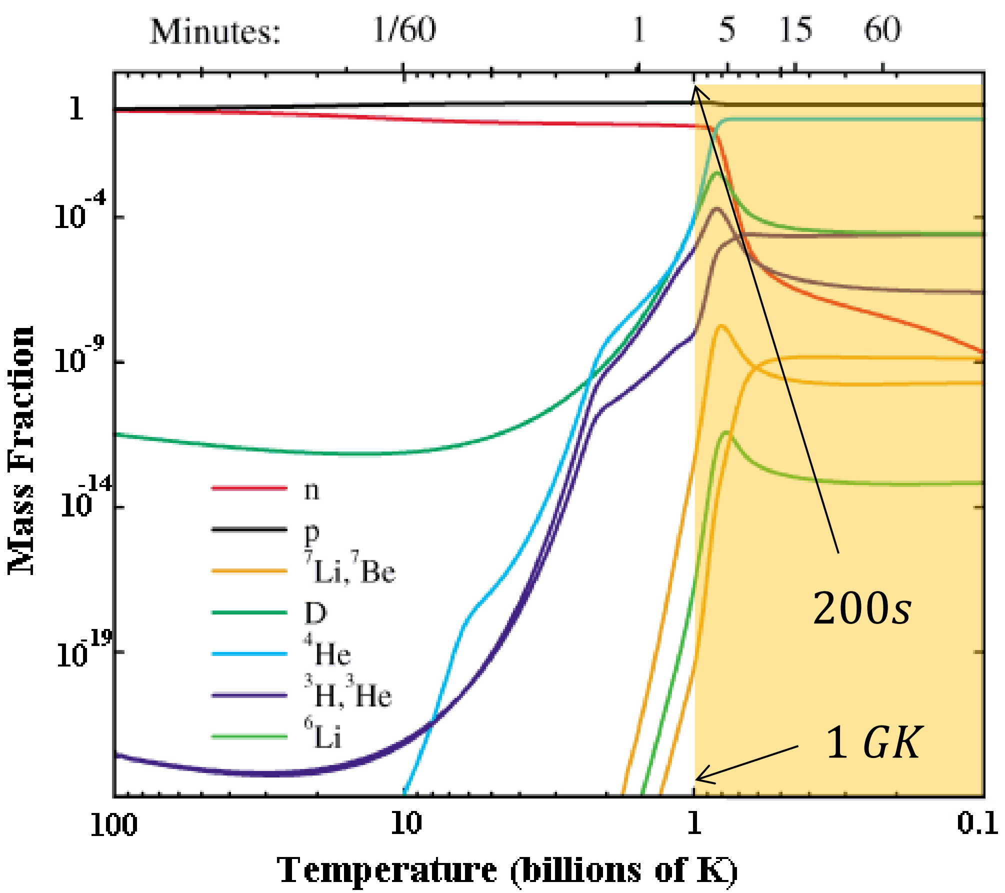
NEUTRON TO PROTON RATIO

- At $T > 1\ MeV$ weak and electromagnetic interactions give neutron-proton equilibrium

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

- At $T = 1\ MeV$ freezeout

$$\left(\frac{n}{p}\right)_{freezeout} \cong \frac{1}{6}$$



The Big Bang Nucleosynthesis Epoch

CROSS SECTION OF THE REACTIONS INVOLVED/BBN

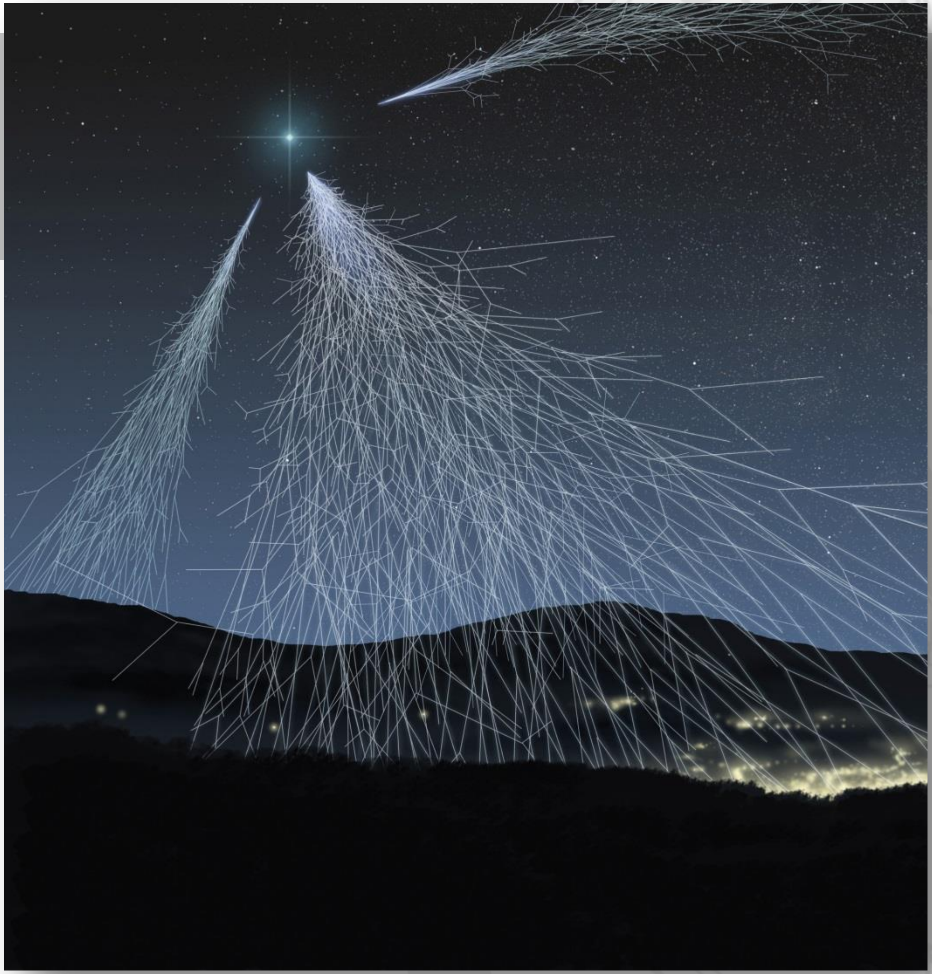
Starting from the knowledge of:

- Temperature of the Universe
- Baryon density Ω_b
- Neutron to proton ratio

$$\left(\frac{\mathrm{n}}{\mathrm{p}}\right) = \left(\frac{n}{p}\right)_{freezeout} e^{-t/\tau}$$

- The nuclear cross sections of the reactions involved

IT IS POSSIBLE TO ESTIMATE THE PRIMORDIAL ABUNDANCES OF LIGHT ELEMENTS



NUCLEAR CROSS SECTION MEASUREMENTS

BBN fusion reactions take place at low energies ($E \cong 50\ keV - 500\ keV$)

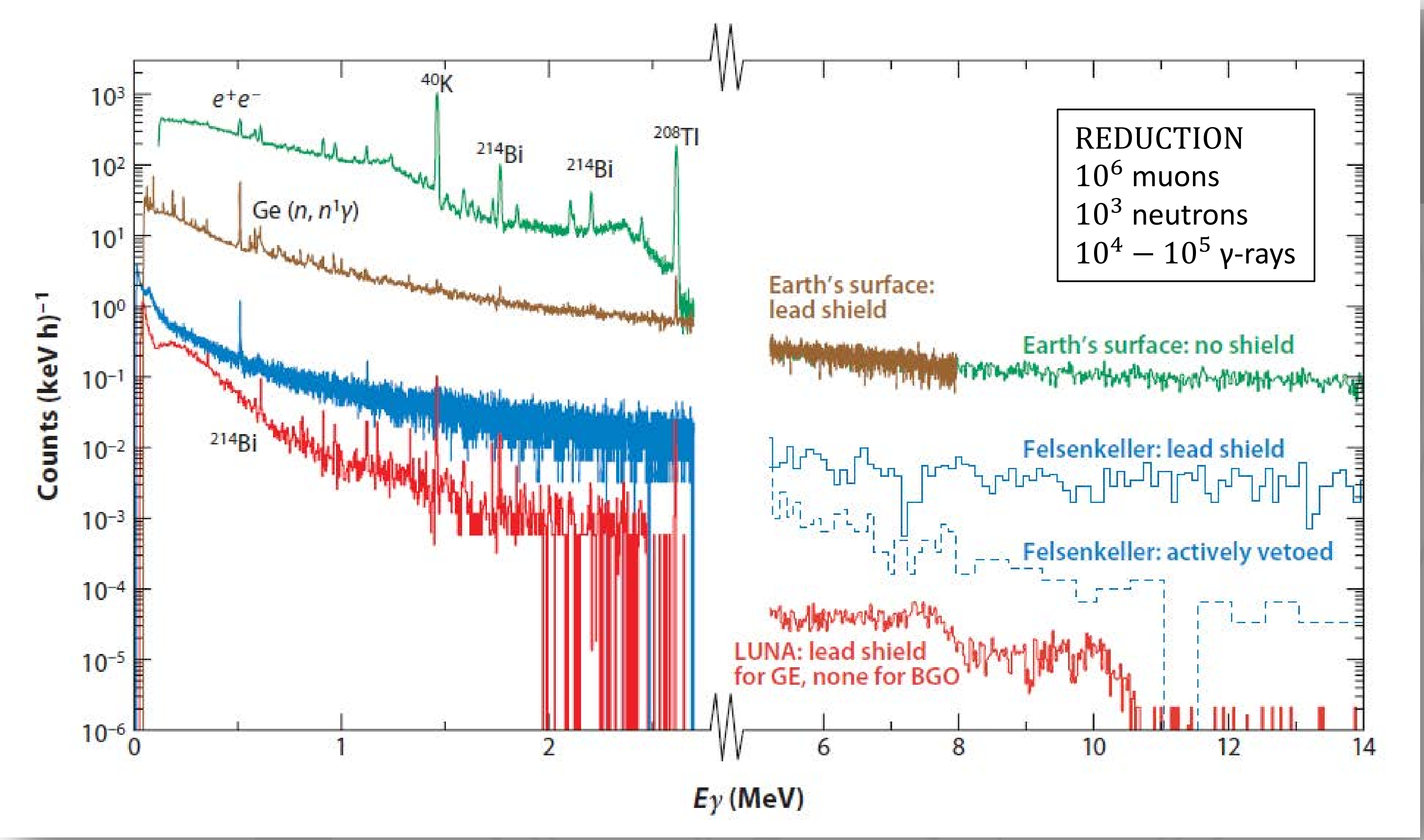
Nuclear cross sections drop to **very low values** and the reaction signal is usually completely covered by natural background

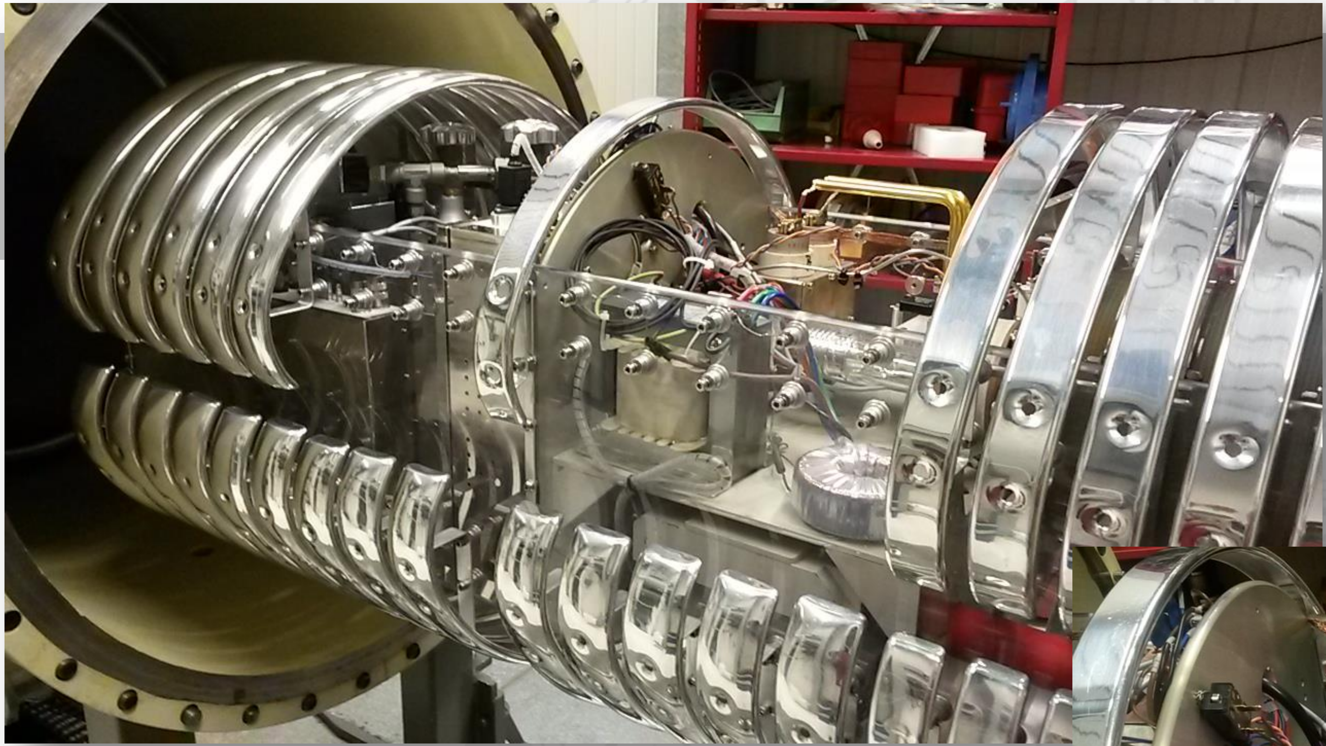
- Extrapolation,
- Indirect measurements
- **Natural background reduction → LNGS**

EXTRAPOLATION AND INDIRECT MEASUREMENTS

Extrapolation could be dangerous because it's possible to neglect some unknown low energy channels (narrow, broad or under threshold resonances…)

Indirect measurements require assumptions.


REDUCTION
10^6 muons
10^3 neutrons
10^4 – 10^5 γ-rays
Counts (keV h)^-1
Eγ (MeV)
e+e−
40K
214Bi
214Bi
208Tl
Ge (n, n'γ)
214Bi
Earth's surface: lead shield
Earth's surface: no shield
Felsenkeller: lead shield
Felsenkeller: actively vetoed
LUNA: lead shield for GE, none for BGO



LUNA 400 kV accelerator
(since 2000)

Laboratory for
Underground
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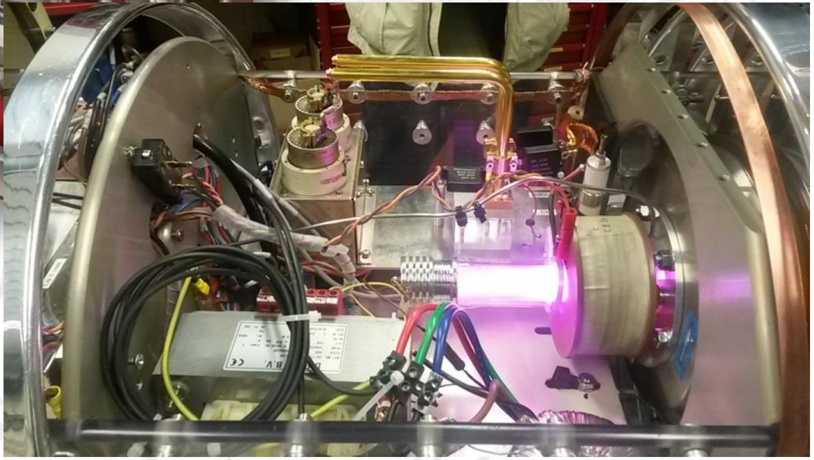
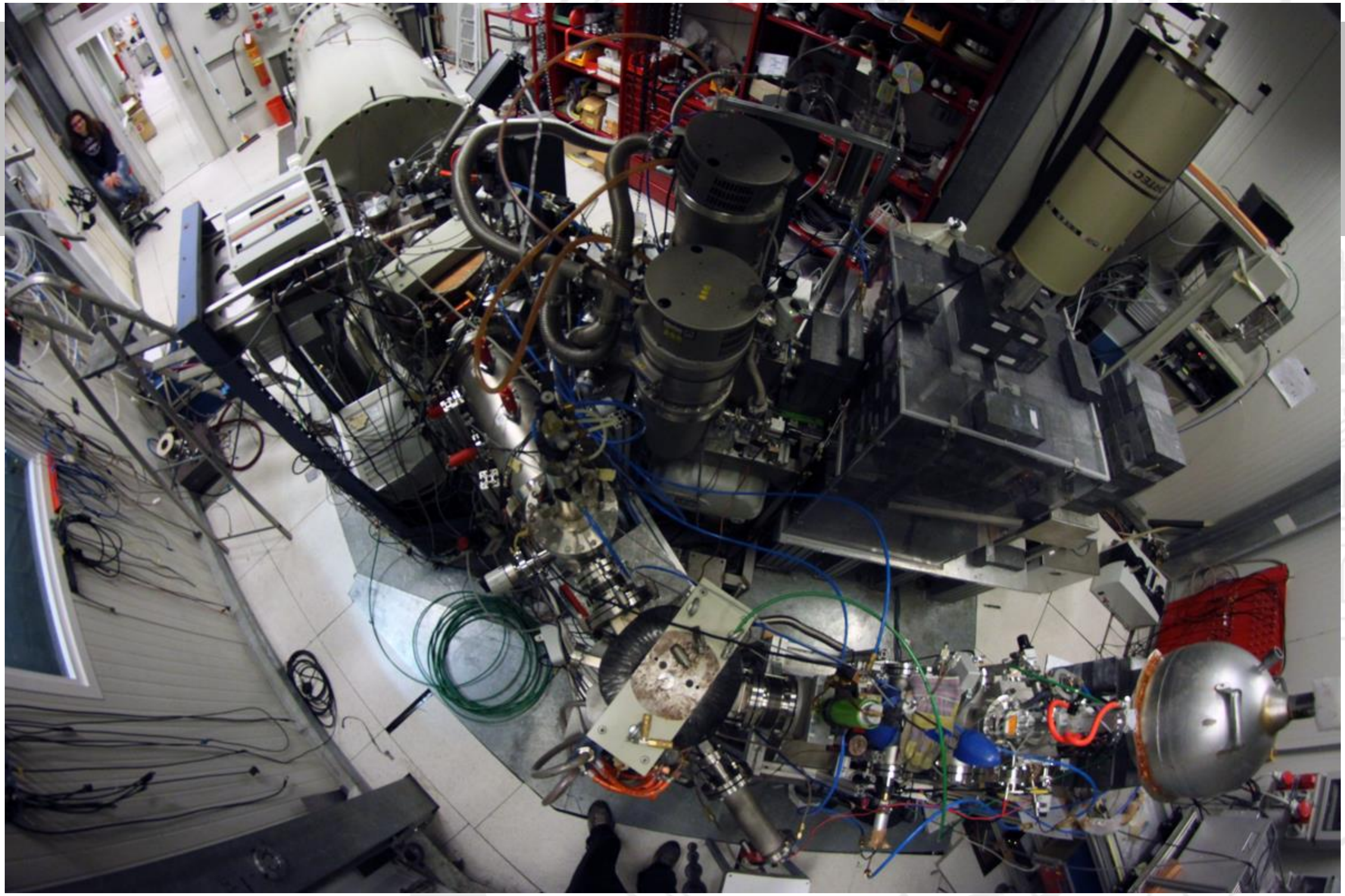
Astrophysics



Beam Energy: 40-400 kV (absolute value $\pm 0.3\ keV$, spread $<\ 0.1\ keV$)
Current: p (1000 μA), ^{4}He – ^{3}He (500 μA)
Long-term stability: $5\ eV/h$



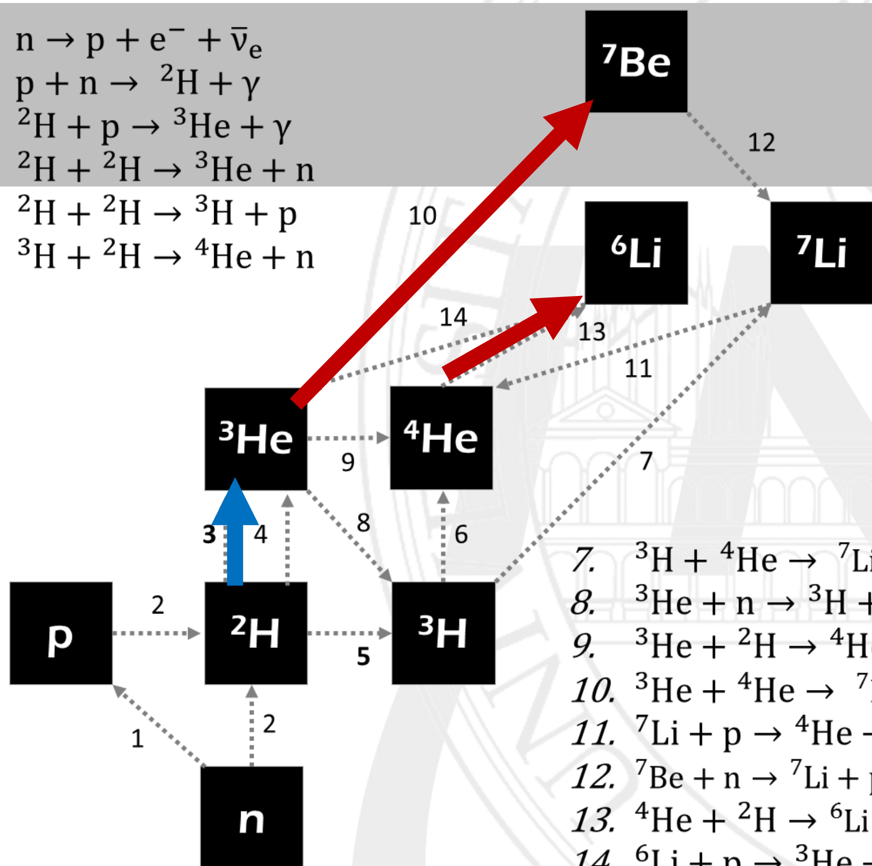
LUNA GAS & SOLID TARGETS

- **BEAM LINE #1**
  windowless gas target (constant-gradient calorimeter)
- **BEAM LINE #2**
  solid target (Faraday cup)

SILICON, HPGe, BGO and NaI DETECTORS

BIG BANG NUCLEOSYNTHESIS
Comparison with observations

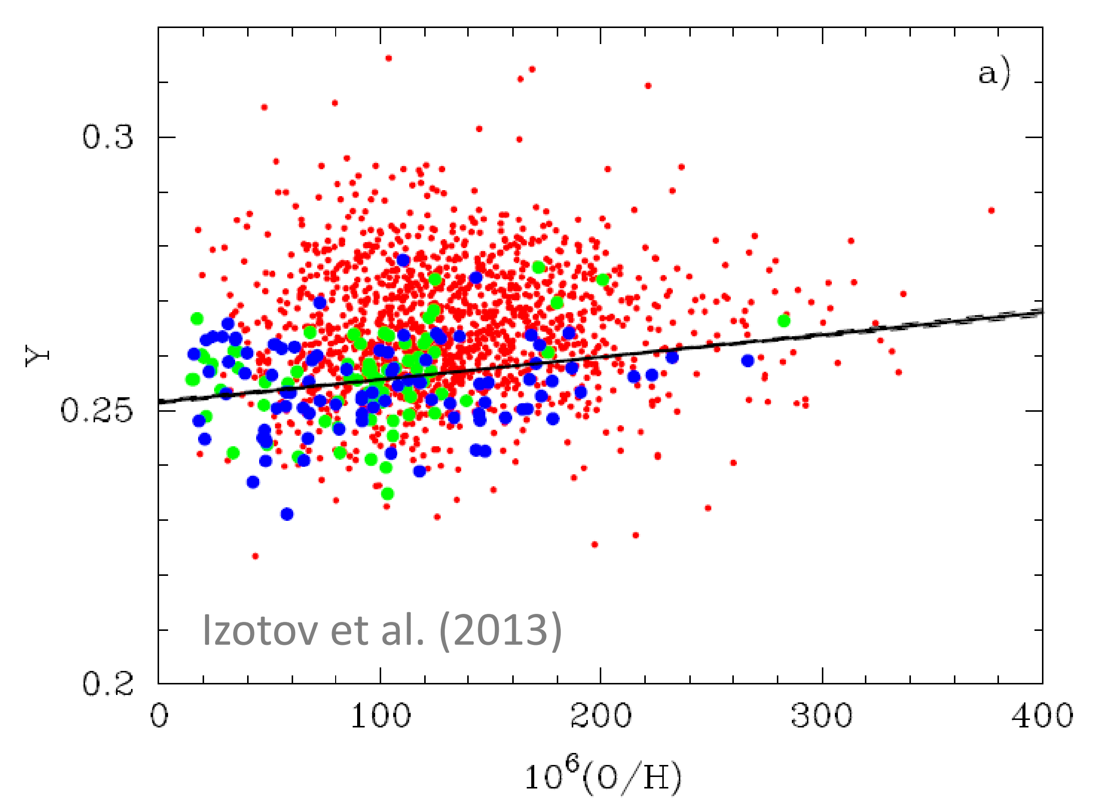
1. $n \rightarrow p + e^- + \bar{\nu}_e$
2. $p + n \rightarrow {}^2H + \gamma$
3. ${}^2H + p \rightarrow {}^3He + \gamma$
4. ${}^2H + {}^2H \rightarrow {}^3He + n$
5. ${}^2H + {}^2H \rightarrow {}^3H + p$
6. ${}^3H + {}^2H \rightarrow {}^4He + n$



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. ${}^6Li + p \rightarrow {}^3He + {}^4He$

Big Bang Nucleosynthesis calculations must be compared with astronomical data. This can be done for ${}^4He$, ${}^2H$, ${}^3He$, ${}^7Li$ and ${}^6Li$.

Reactions investigated at LUNA:
- ${}^3He(\alpha,\gamma){}^7Be$ [2006]
- ${}^2H(\alpha,\gamma){}^6Li$ [2014] → Bormio 2014
- **${}^2H(p,\gamma)3\,{}^3He$ [2015-2016]**



Helium primordial abundance (^{4}He)

$$^4He/H = 0.254 \pm 0.003$$

Izotov et al. (2013)

$$^4He/H = 0.2464 \pm 0.0097$$

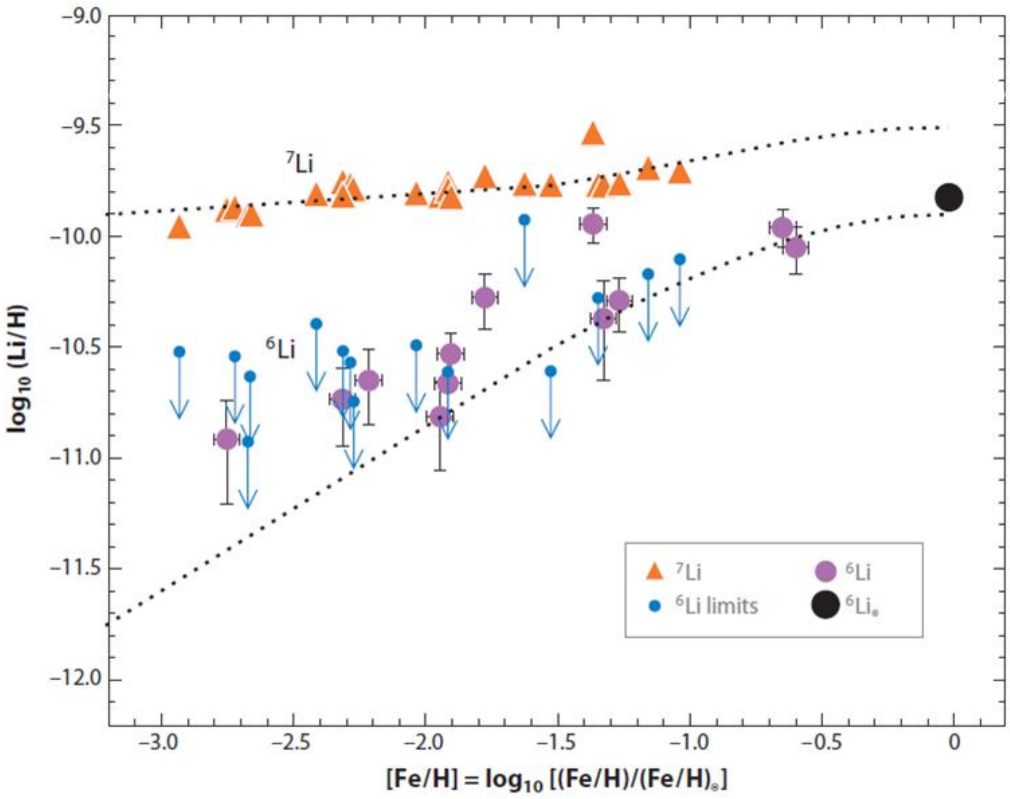
Aver et al. (2013)

$$^4He/H = 0.2477 \pm 0.0001$$

Planck collaboration (2013)

Measured starting from the emission lines detected in low metallicity extragalactic HII regions.

Lithium primordial abundances ($^7Li/^6Li$)



$^7Li/^6Li$ are measured in the atmospheres of metal-poor stars in the galactic halo

$$^7Li/H = \left(1.58^{+0.35}_{-0.28}\right) \times 10^{-10}$$

Sbordone et al. (2010)

$$^6Li/^7Li \cong 5 \cdot 10^{-2} \qquad ^6Li/H \lesssim 10^{-11}$$

Coc et al. (2014)

$$^7Li/H = (4.88^{+0.71}_{-0.62}) \times 10^{-10}$$

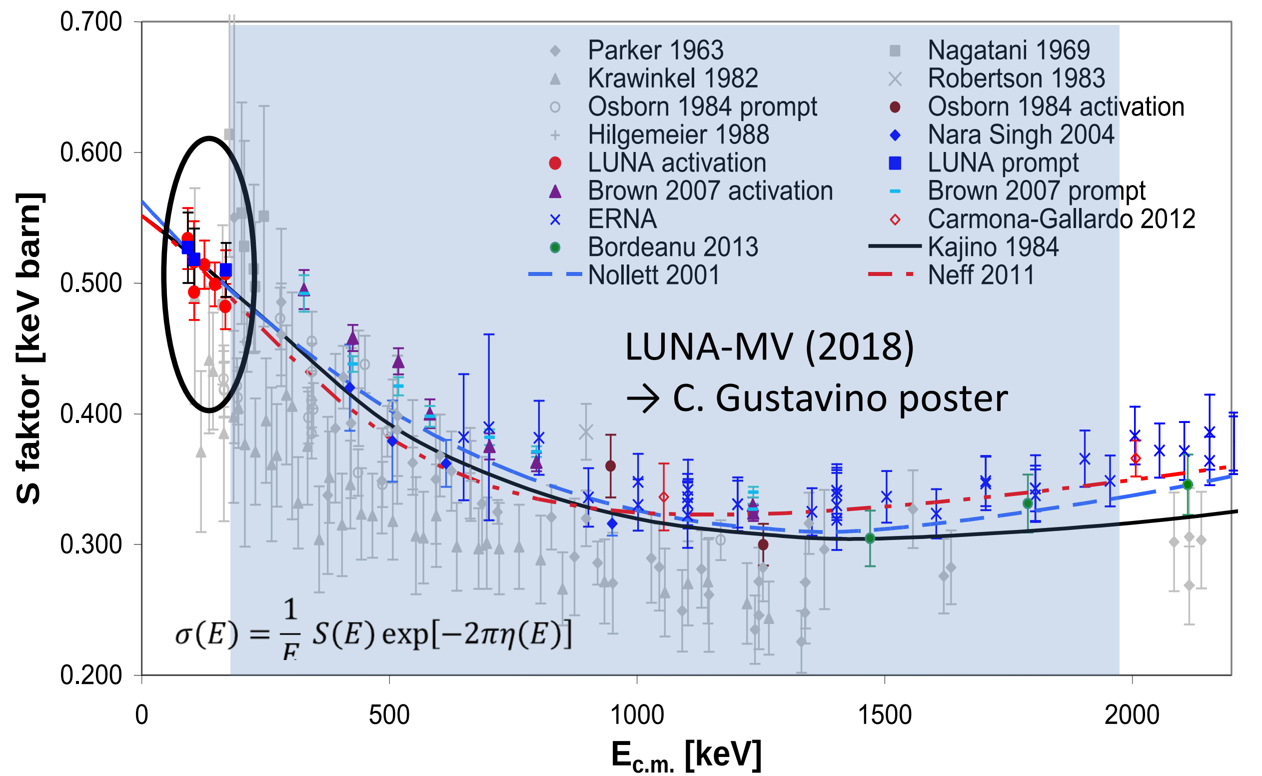
Olive (2013)

$$^6Li/^7Li = (1.5 \pm 0.3) \times 10^{-5}$$

Anders (2014)

The First Primordial Lithium Problem (^7Li)

The Second Primordial Lithium Problem (^6Li)



The First Lithium Problem at LUNA

^{7}Li is mainly produced from 7Be via electron capture process:

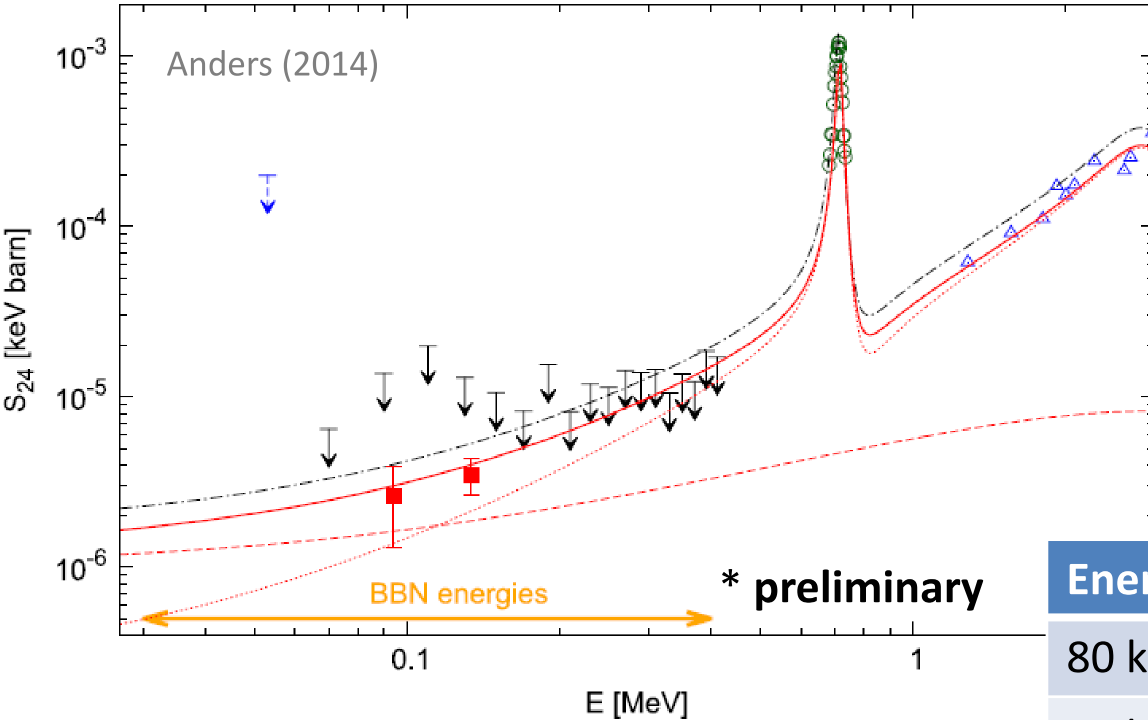
$$^7\boldsymbol{Be} + e^- \rightarrow {}^7Li + \nu_e$$

Thus nuclear reactions producing and destroying ^{7}Be must be considered.

The $^3He(\alpha,\gamma)^7Be$ cross section has been measured at LUNA in 2007 outside the BBN energy range.

«^{7}Li uncertainty is still dominated by nuclear uncertainty on the $^3He(\alpha,\gamma)^7Be$ rate.”
Coc (2014)

The Second Lithium Problem at LUNA

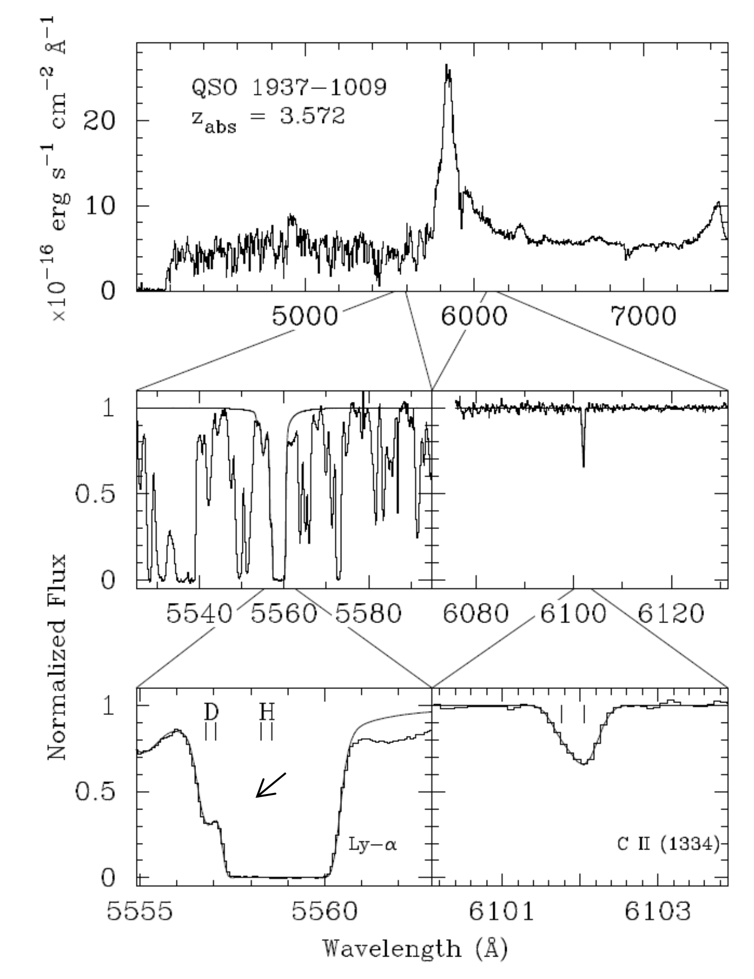


* **preliminary**

The $^{2}H(\alpha,\gamma)^{6}Li$ cross section has been measured in the BBN energy range at LUNA in 2014 and presented here in Bormio (preliminary S-factor values)

The ^{6}Li abundance measured by LUNA is $(0.74 \pm 0.16) \times 10^{-14}$, **20% lower** than the previously adopted one.

Energy	S-factor [keV µb]
80 keV*	$3.98 \pm 5.29^{(stat)}$
94 keV	$2.7^{+1.5\,(stat)}_{-1.6} \pm 0.3^{(syst)}$
120 keV*	$3.42 \pm 1.55^{(stat)}$
134 keV	$4.0^{+0.8\,(stat)}_{-0.9} \pm 0.5^{(syst)}$



Deuterium primordial abundance

Deuterium is a fragile isotope. It can only be destroyed after BBN.
Its primordial abundance is estimated from the observation of absorption lines in clouds at high redshift, on the line of sight of very distant quasars.

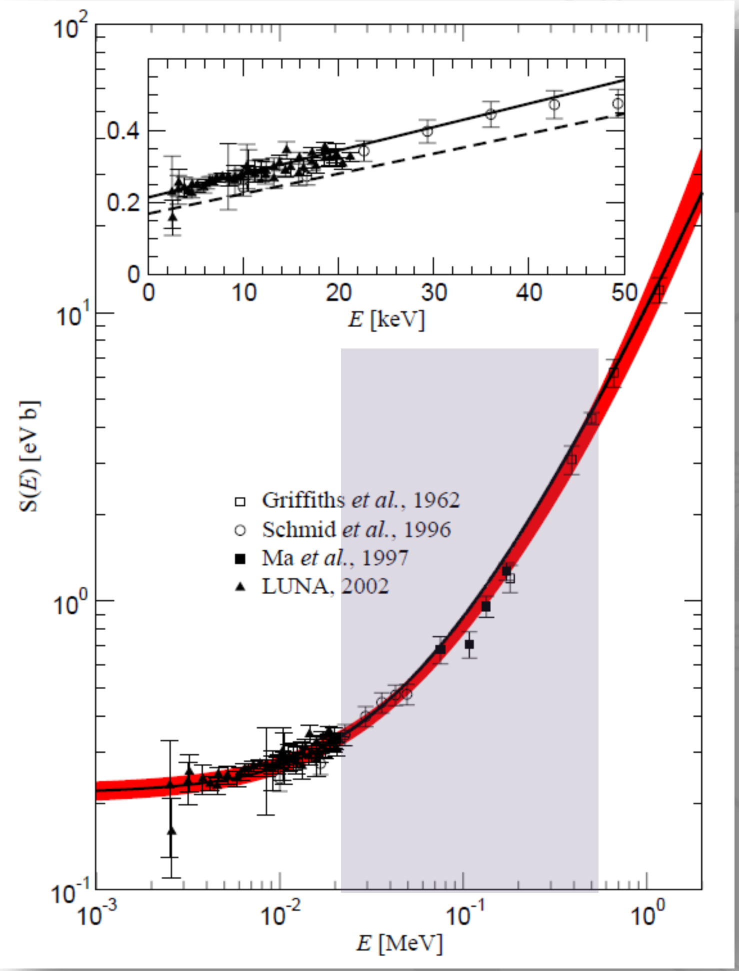
$$D/H = (2.53 \pm 0.04) \times 10^{-5}$$

Pettini et al. (2012)

$$D/H = (2.65 \pm 0.07) \times 10^{-5}$$

Di Valentino (2014)

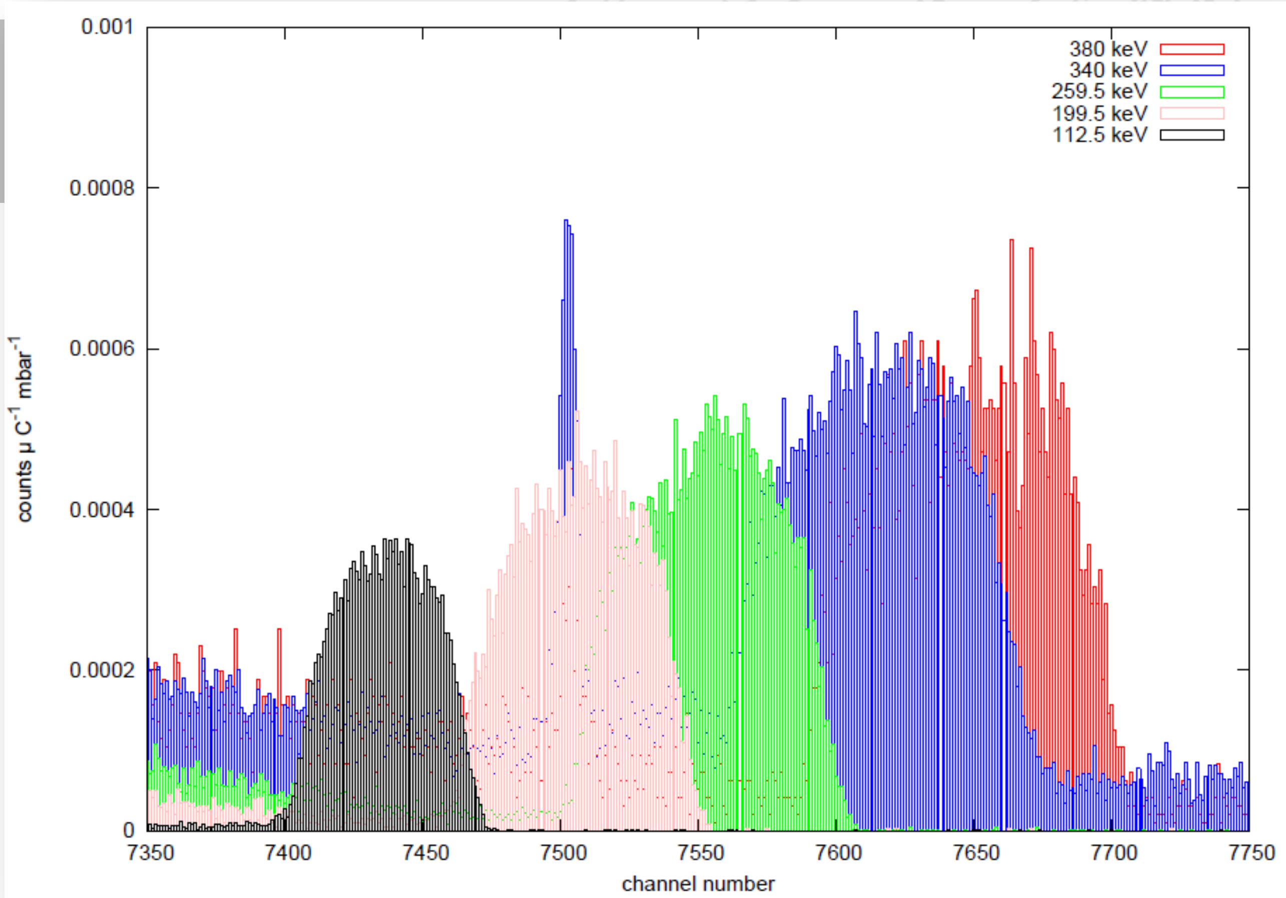
Deuterium primordial abundance at LUNA (2014-2016)



In order to reduce the BBN calculation uncertainty, a mesurament of the $^2H(p,\gamma)^3He$ cross section in the BBN energy range with a 3% accuracy is thus desirable → **LUNA** measurement campaign (2015-2016) | C. Gustavino talk Bormio 2014

Reaction	$\sigma_{^2\mathrm{H/H}} \times 10^5$
$p(n,\gamma)^2\mathrm{H}$	± 0.002
$d(p,\gamma)^3\mathrm{He}$	± 0.062
$d(d,n)^3\mathrm{He}$	± 0.020
$d(d,p)^3\mathrm{H}$	± 0.013

Feasibility test (October 2015) results | NEW!

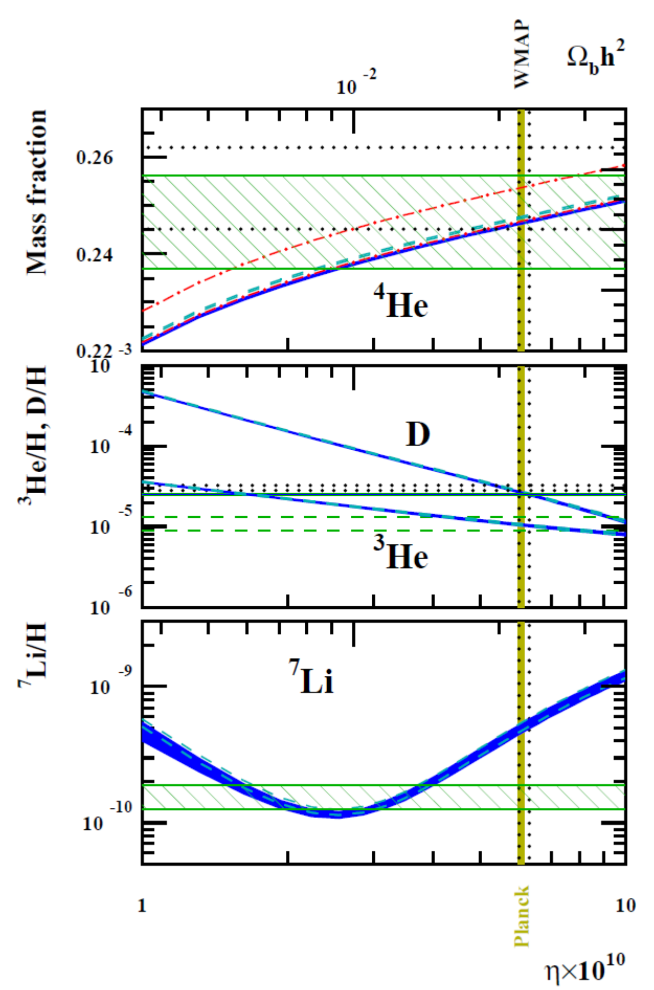


$^2H(p,\gamma)^3He$ at LUNA – Oct2014

- Innovative procedure in order to measure the $d\sigma/d\Omega$ at very low energies.
- The $^2H(p,\gamma)^3He$ cross section seems to be higher than literature values

PRELIMINARY!

Stay tuned!



Big Bang Nucleosynthesis
Status of the art 2015

BBN Calculation vs Astronomical Observation:

- **^{4}He**: possible agreement.
- **^{3}He**: agreement. “Poor” astronomical observations.
- **^{2}H**: tension. Investigation of the ^{2}H(p,γ)^{3}He is needed (confirmation or new scenarios). → LUNA (2015-2016)
- **^{7}Li**: disagreement. The First Primordial Lithium Problem. A new measurement of the ^{3}He(α,γ)^{7}Be is desirable. → LUNA-MV (> 2018)
- **^{6}Li**: disagreement. Poor astronomical observations.

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The LUNA collaboration

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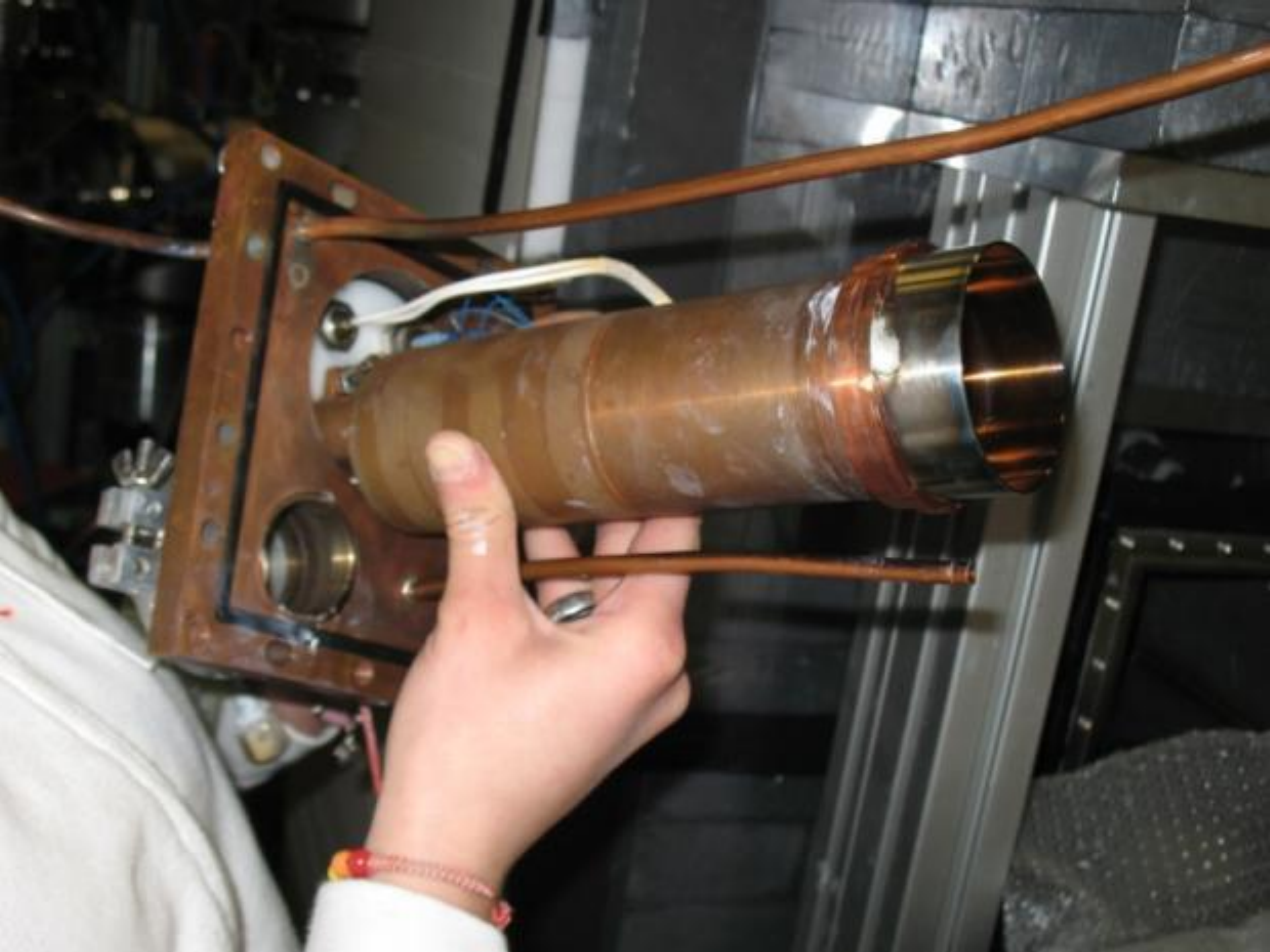
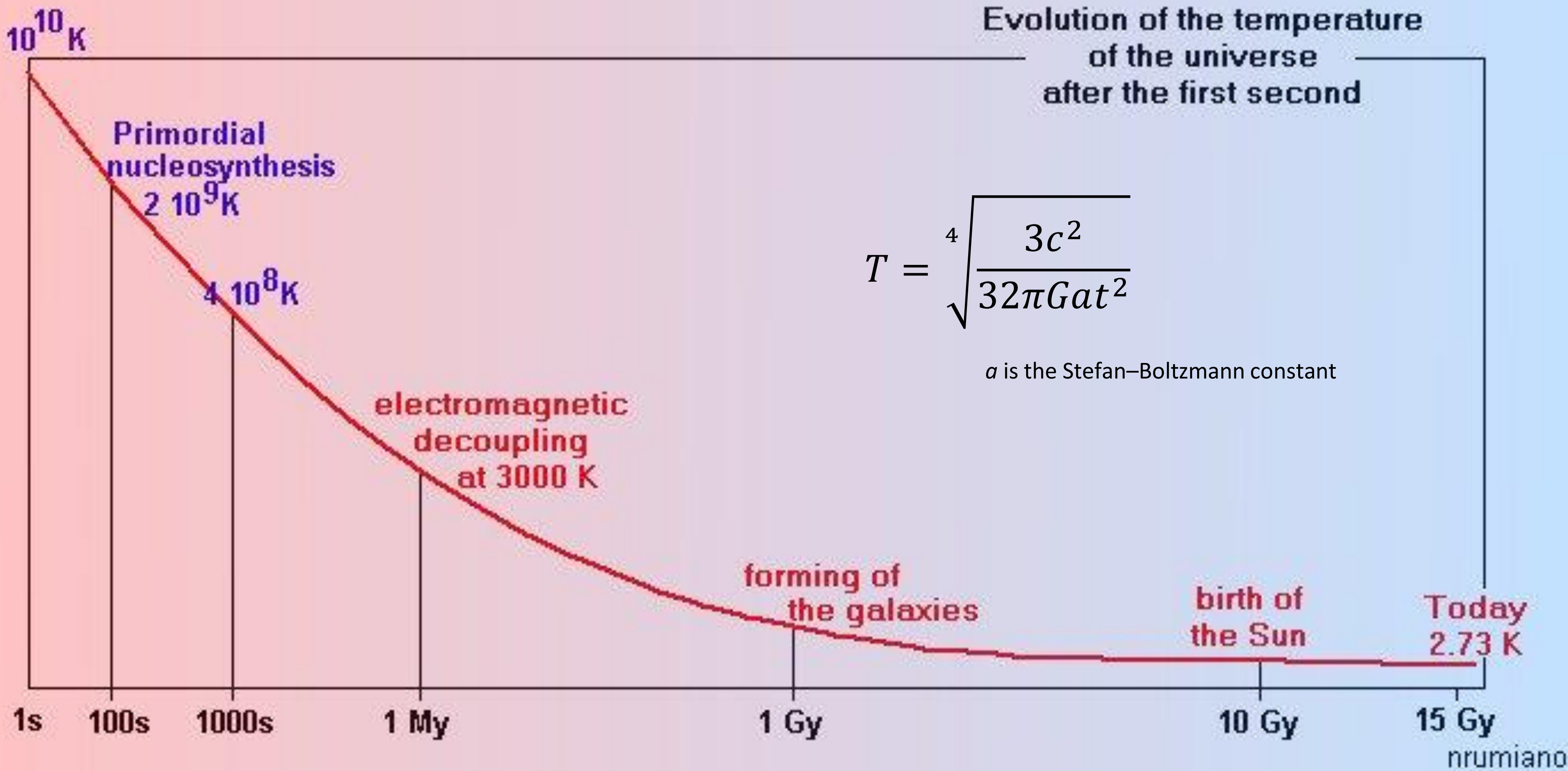
Questions?




CANBERRA



$$T = \sqrt[4]{\frac{3c^2}{32\pi G a t^2}}$$

a is the Stefan–Boltzmann constant