How the Sun shines: an underground point of view

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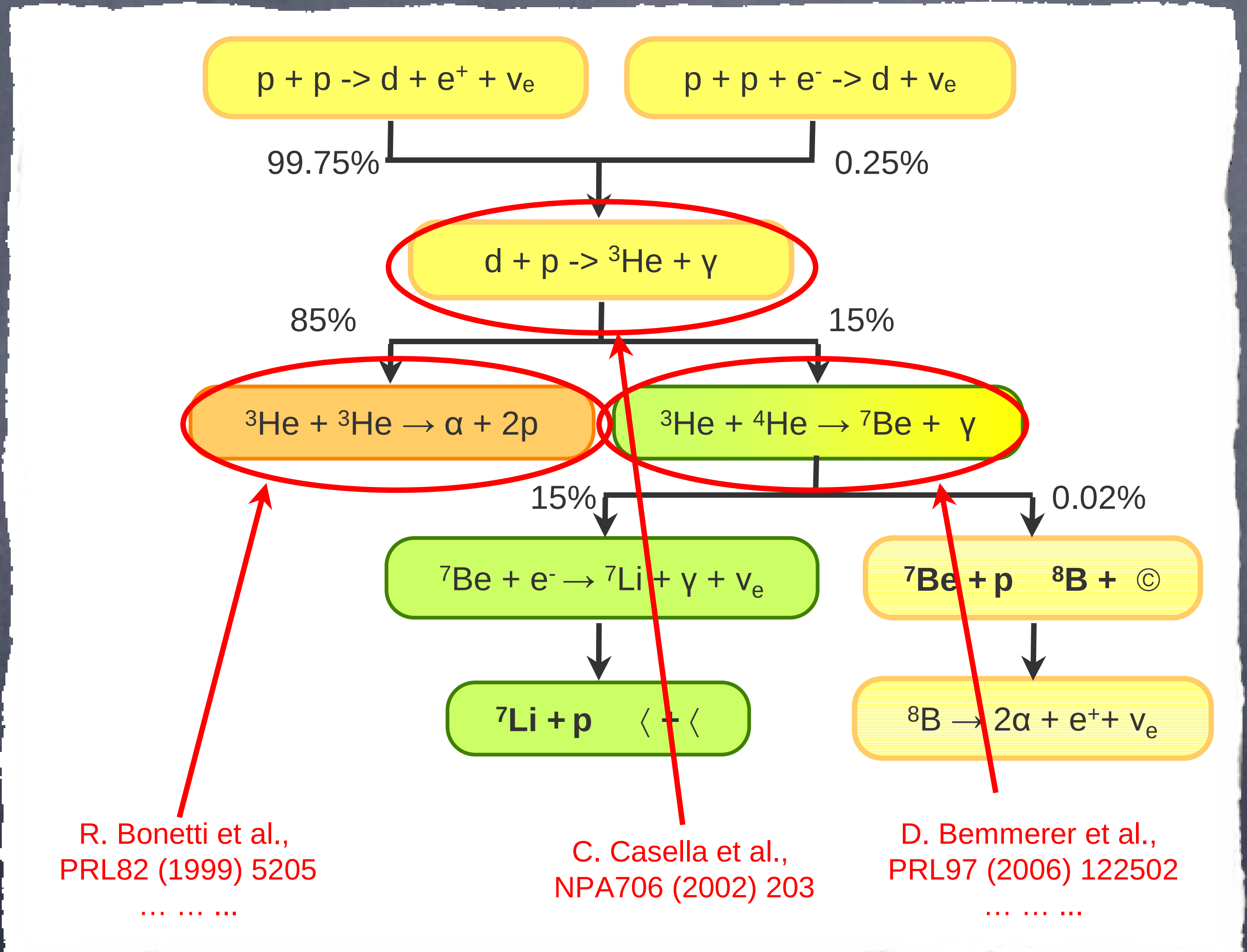
Overview

- the astrophysical scenario:
  - H-burning (pp-chain, CNO cycle, MgAl cycle)
  - BBN
- why underground?
- the luna experiment
- recent results
- outlook

Astrophysical scenario
hydrogen burning: pp chain



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

$p + p + e^- \rightarrow d + \nu_e$

99.75%

0.25%

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

85%

15%

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

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

15%

0.02%

${}^7Be + e^- \longrightarrow {}^7Li + \gamma + \nu_e$

^{7}Be + p ^{8}B + ©

^{7}Li + p 〈 + 〈

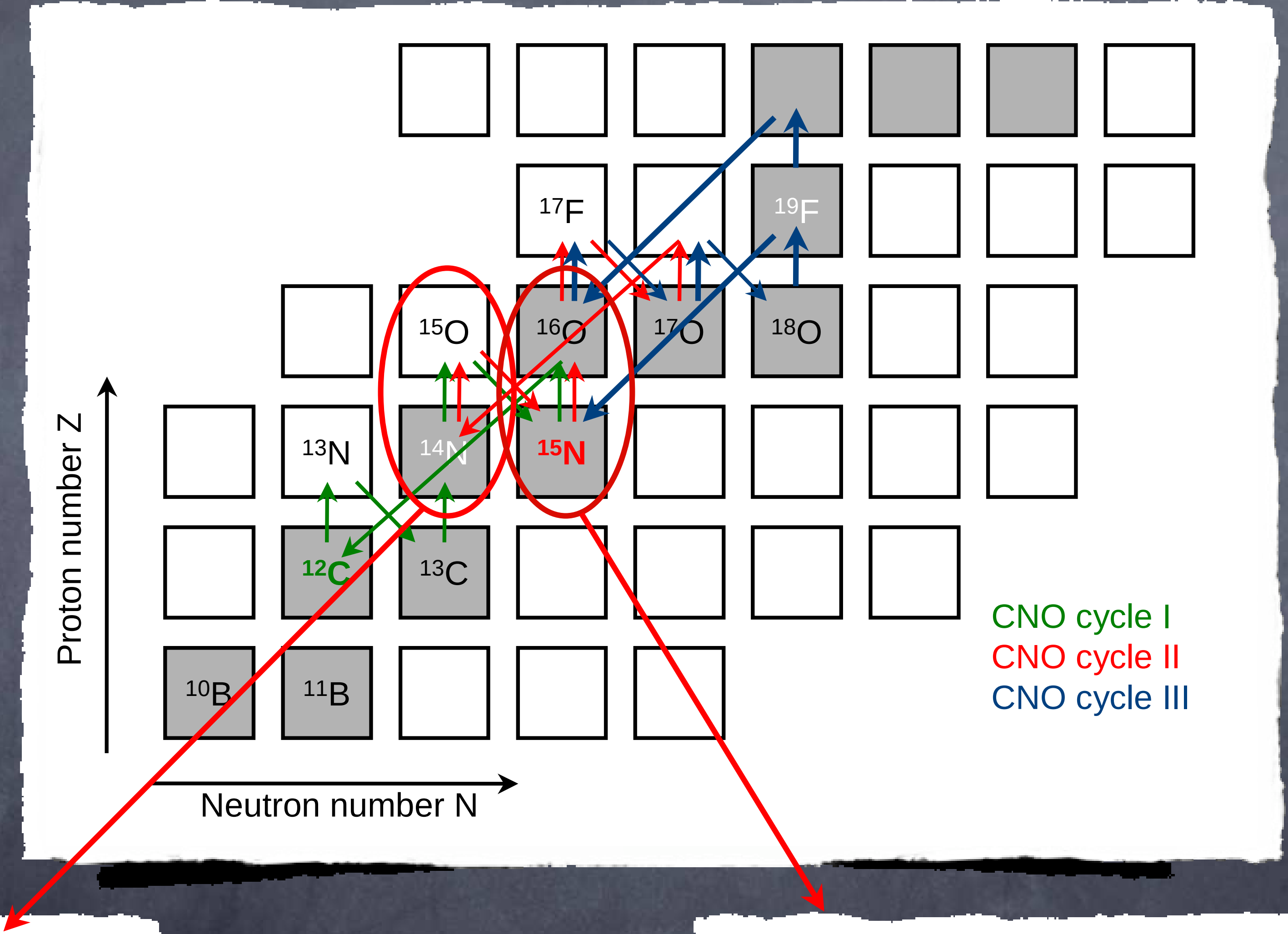
${}^8B \longrightarrow 2\alpha + e^+ + \nu_e$

R. Bonetti et al.,
PRL82 (1999) 5205
… … ...

C. Casella et al.,
NPA706 (2002) 203

D. Bemmerer et al.,
PRL97 (2006) 122502
… … ...

Astrophysical scenario
hydrogen burning: CNO cycle



A. Formicola et al.,
Phys. Lett B591 (2004) 61
… … …

^{15}N(p,γ)^{16}O: Bridge reaction between
CN and NO sub-cycles + all further cycles
-> relevant for Oxygen production
& for all further CNO cycles

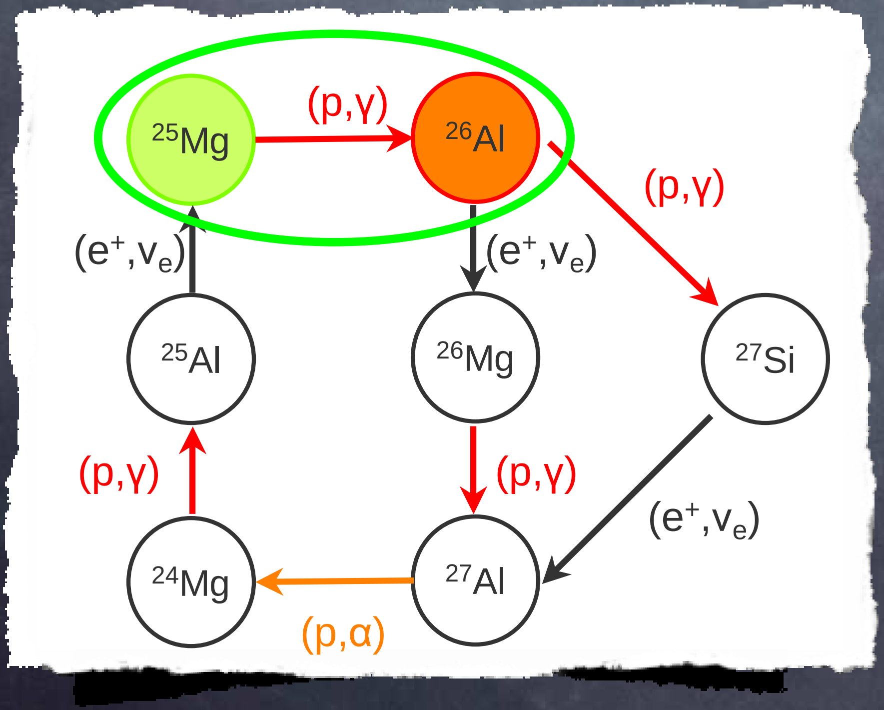
Astrophysical scenario
hydrogen burning: MgAl cycle

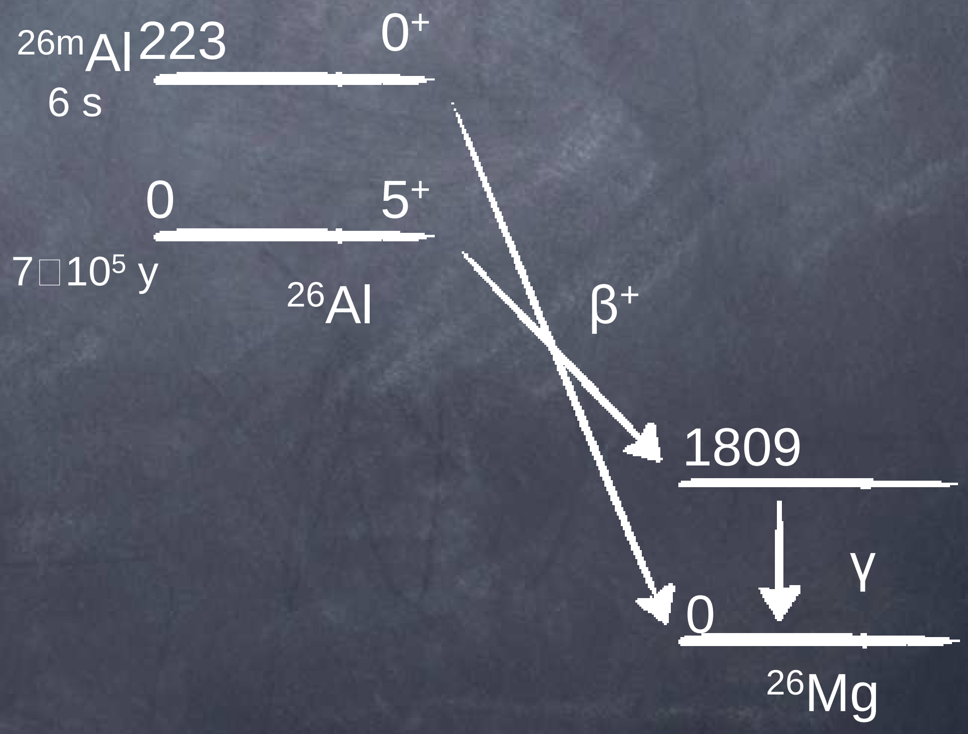
$^{25}\mathrm{Mg}(p,\gamma)^{26}\mathrm{Al}$: astrophysical relevance

- slowest reaction of the MgAl cycle

- $^{26\mathrm{g.s.}}\mathrm{Al} \rightarrow {}^{26}\mathrm{Mg}(\beta^{+})$ => $E_{\gamma} = 1.8$ MeV:

one of the most important γ-transitions in astronomy!

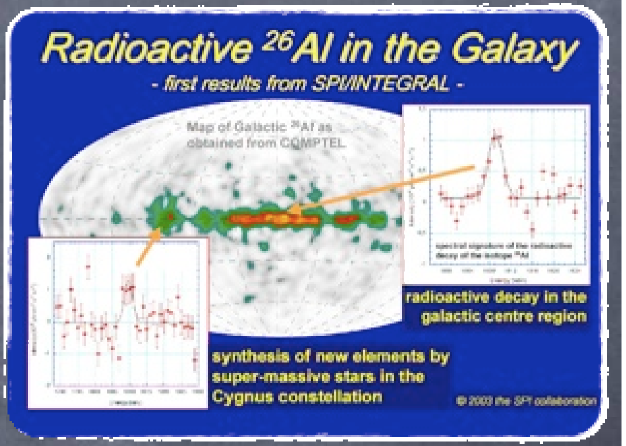




Astrophysical scenario
hydrogen burning: MgAl cycle

Open questions:

- measured ^{26}Al quantity:
☐ observations of satellites (COMPTEL/INTEGRAL):
1.8 MeV γ
=> nucleosynthesis of ^{26}Al is still active
on large scale



☐ isotopic variation in CaAl inclusions in meteorites:
^{26}Mg isotopic enrichment
=> ^{26}Al was produced no later
than $4.6 \cdot 10^9$ years ago

=> an astrophysical scenario for ^{26}Al nucleosynthesis MUST be in agreement with both observations

Astrophysical scenario
hydrogen burning: MgAl cycle

MgAl cycles: astrophysical sites

- hottest region of an H-burning star, close to the point of max. energy release
- can be active also in the region of carbon-burning of very massive stars

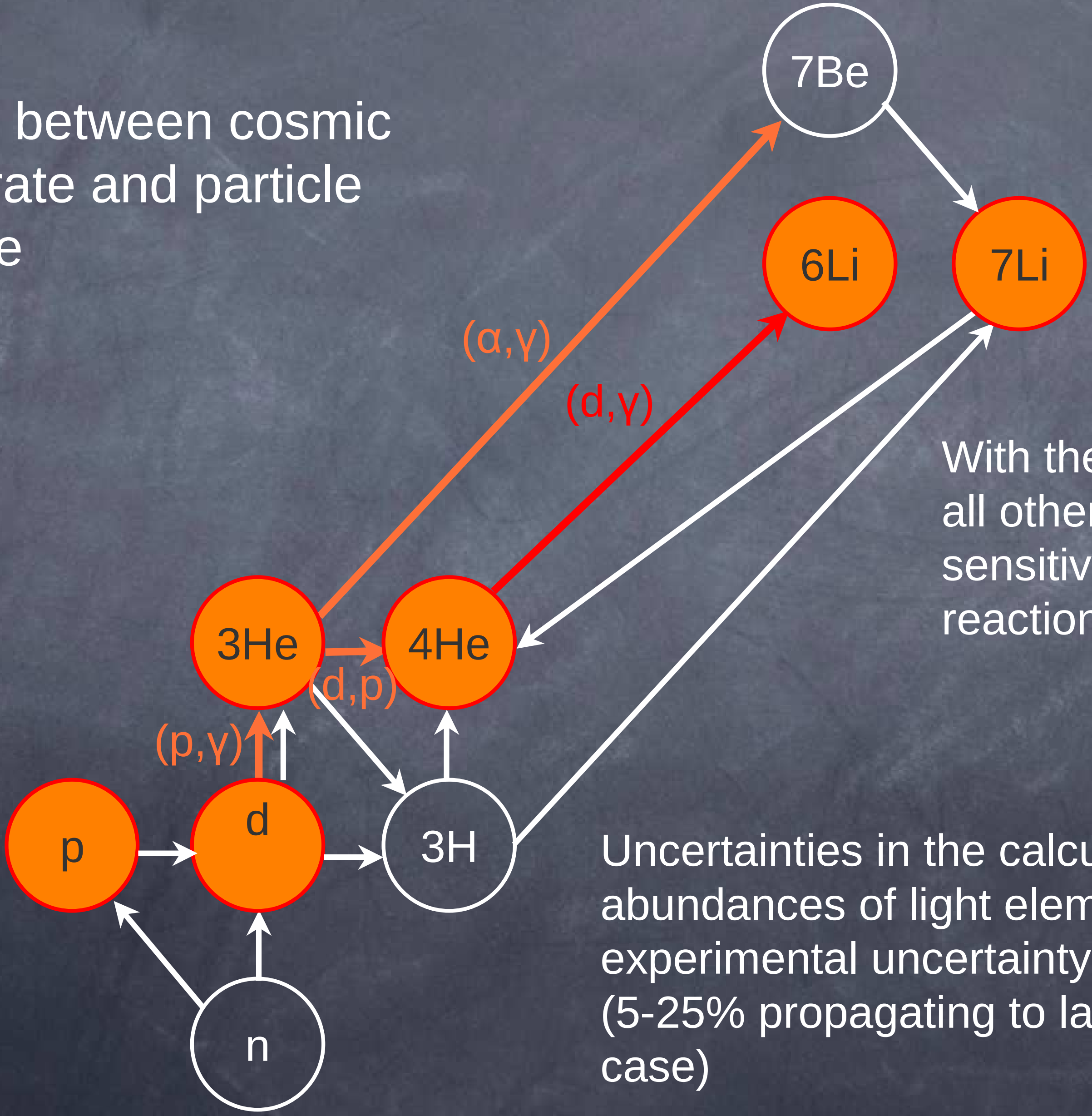
-> quantitative evaluation of ^{26}Al in the ashes of stars with active hydrogen burning is complicated because of the many variables

=> precise knowledge of reaction rates relevant to reduce the free parameters in models is necessary

==>> measurement of the cross-section/strength
for the ^{25}Mg(p,γ)^{26}Al reaction

Astrophysical scenario
The big-bang nucleosynthesis reactions

BBN:
competition between cosmic expansion rate and particle reaction rate

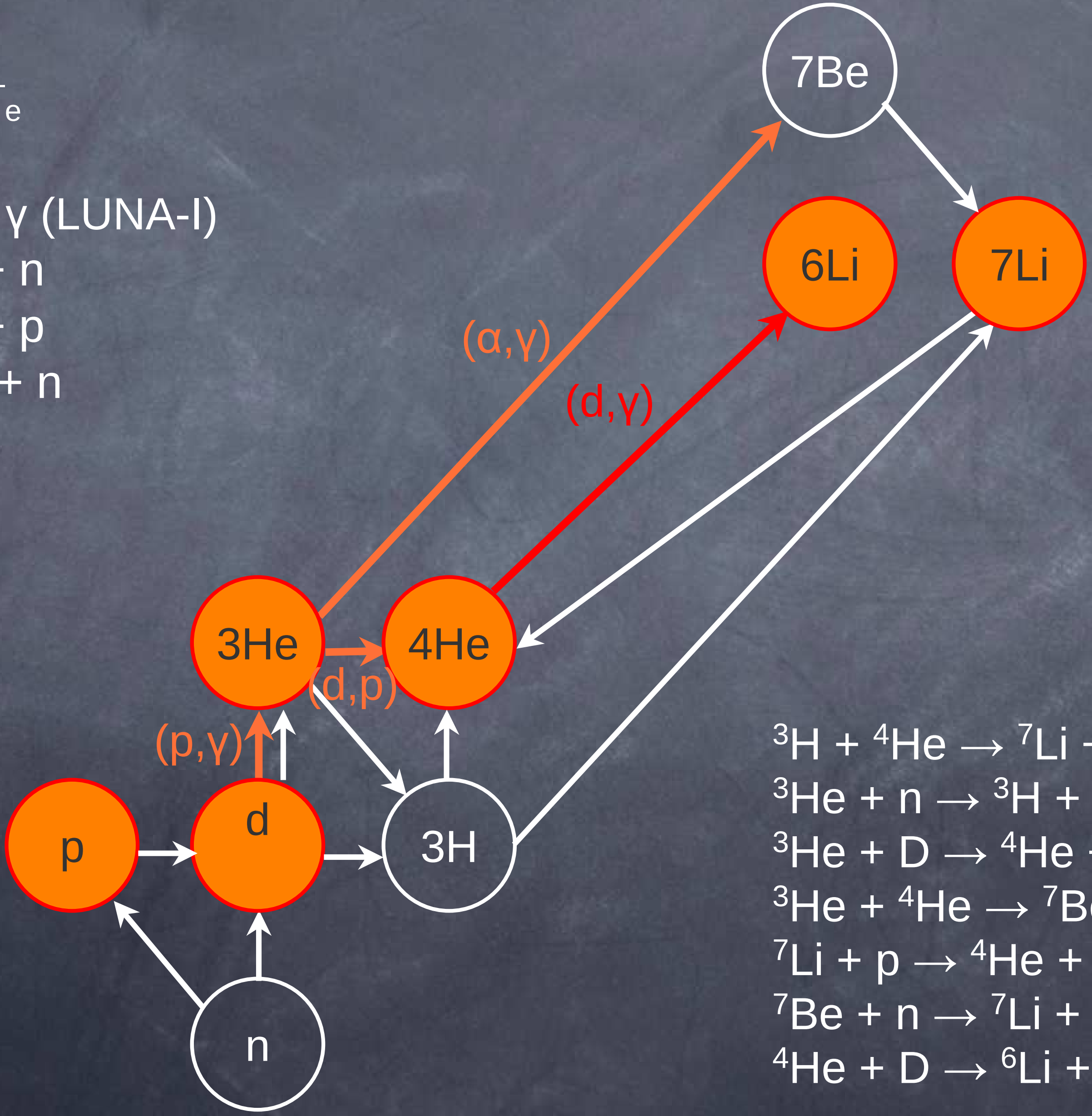


With the exception of He, all other nuclides are sensitive to the nuclear reaction network

Uncertainties in the calculations of abundances of light elements arise from experimental uncertainty in the cross section (5-25% propagating to large factors in the ^{7}Li case)

Astrophysical scenario
The big-bang nucleosynthesis reactions

$n \rightarrow p + e^- + \bar{\nu}_e$
$p + n \rightarrow D + \gamma$
$D + p \rightarrow {}^3He + \gamma$ (LUNA-I)
$D + D \rightarrow {}^3He + n$
$D + D \rightarrow {}^3He + p$
${}^3H + D \rightarrow {}^4He + n$



${}^3H + {}^4He \rightarrow {}^7Li + \gamma$
${}^3He + n \rightarrow {}^3H + p$
${}^3He + D \rightarrow {}^4He + p$ (LUNA-I)
${}^3He + {}^4He \rightarrow {}^7Be + \gamma$ (LUNA-II)
${}^7Li + p \rightarrow {}^4He + {}^4He$
${}^7Be + n \rightarrow {}^7Li + p$
${}^4He + D \rightarrow {}^6Li + \gamma$ (in progress)

Astrophysical scenario
The big-bang nucleosynthesis reactions

d(α,γ)^{6}Li reaction: the ^{6}Li puzzle

Primordial nucleosynthesis models predict

- amount of ^{6}Li 2-3 orders of magnitude smaller than detected in metal-poor stars
- amount of ^{7}Li ~ factor of 3 larger than measured

⇒ puzzle which solution depends also on the d(α,γ)^{6}Li production cross-section:

^{6}Li in excess could be justified by σ much larger than expected or by ^{6}Li sources older than the birth of the galaxy, sources that have not been identified yet

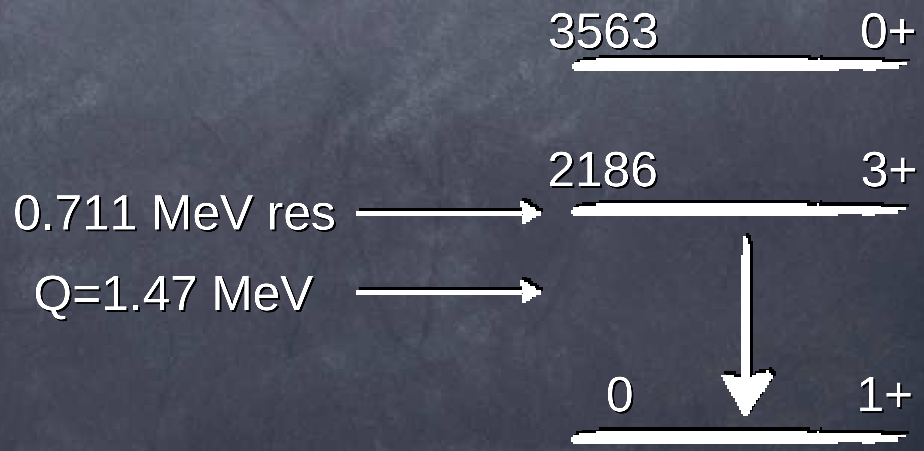
Astrophysical scenario
The big-bang nucleosynthesis reactions

$d(\alpha,\gamma)^6Li$ reaction: the ^6Li puzzle

- Important to explain ^6Li abundance
- Dominated by d-wave capture to the 1st excited state:

⇒ single γ transition at $E_\gamma = 1.47 + E_{cm}$ MeV

- region of interest 50-500 keV (c.m.)



Astrophysical scenario
The big-bang nucleosynthesis reactions

d(α,γ)^{6}Li reaction: state of the art

- Available data:

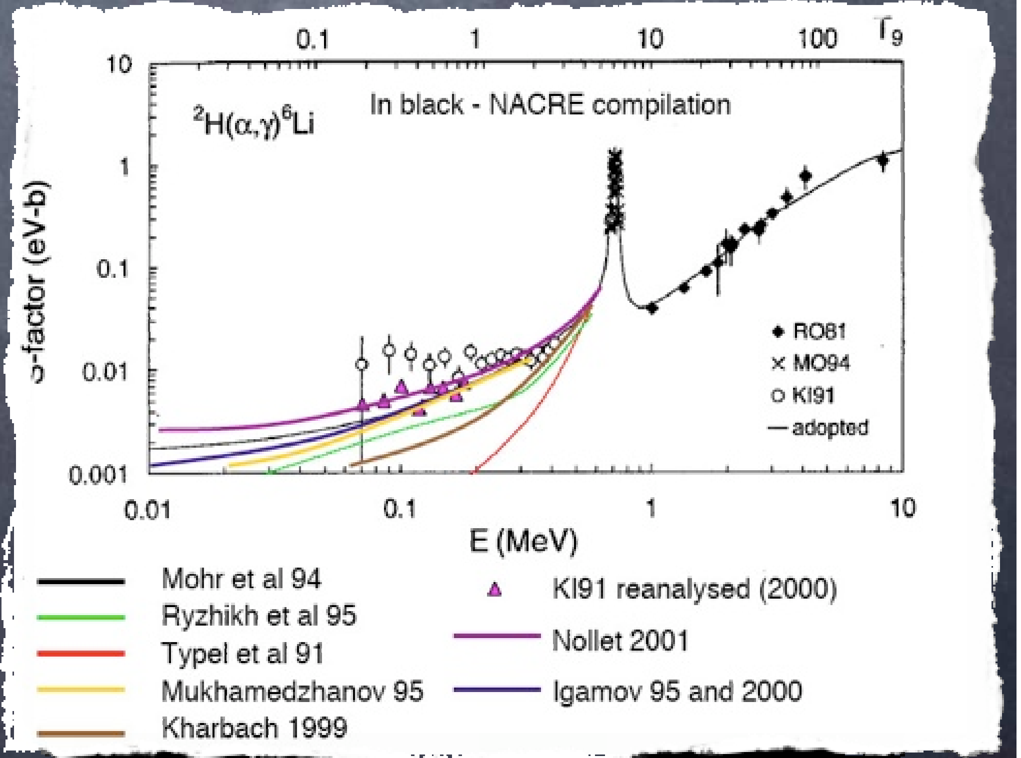
-cover an energetic range that is far from that of interest

-in the lower-energy range data are derived from indirect measurements (coulomb break-up): data-sets are in strong disagreement with each other

-no direct measurements at low energy

- Theoretical calculations predict much lower cross sections than measured
- S(0) given in NACRE has very large uncertainty

=> a direct measurement at Big-Bang energies is strongly needed



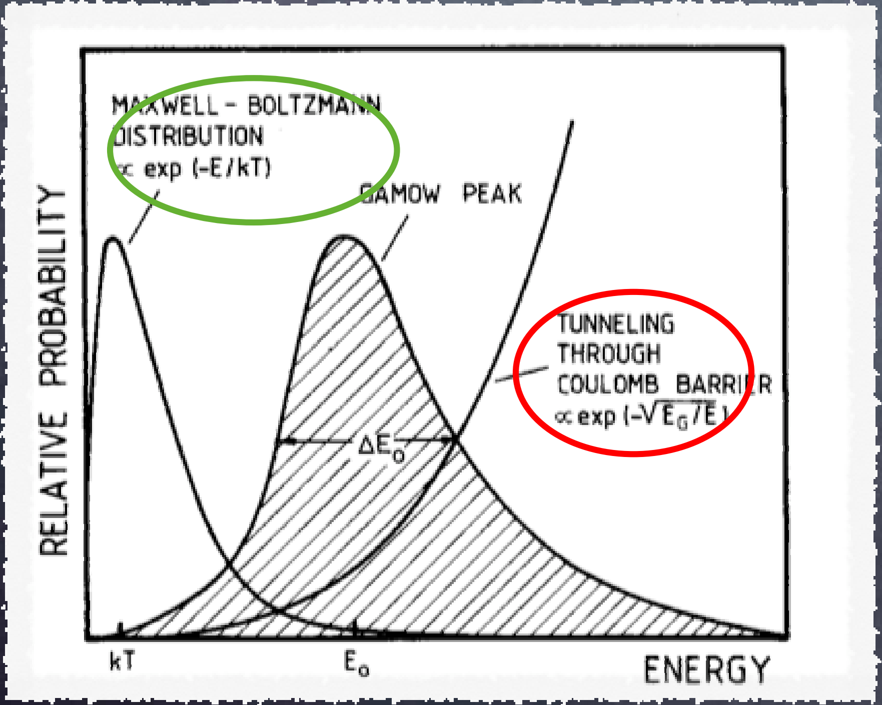
Why going underground? Nuclear reactions in stars: cross section and astrophysical S-factor

in the Sun: T = 1.5 10^7K
KT = 1 keV << E_{Coul}(0.5-2MeV)

$$\sigma(E) = \frac{S(E)}{E}\exp\left(-31.29\cdot Z_1\cdot Z_2\cdot\sqrt{\frac{\mu}{E}}\right)$$

Astrophysical factor

Gamow factor



Nuclear reactions that generate energy and synthesize elements take place inside the stars in a relatively narrow energy window: the Gamow peak

Gamow Energy for H-burning reactions:
few to several tens keV

Why going underground? Reaction rate in the laboratory

-> Very low cross sections at astrophysically-relevant energies because of the Coulomb barrier (pbarn-nbarn!!)

$$R_{lab} = \sigma\ \varepsilon\ I_p\ \rho\ N_{av}/A$$

pbarn < σ < nbarn
$\varepsilon \sim 10\%$
$I_p \sim$ mA
$\rho \sim \mu g/cm^2$

=> event/month < R_{lab} < event/day

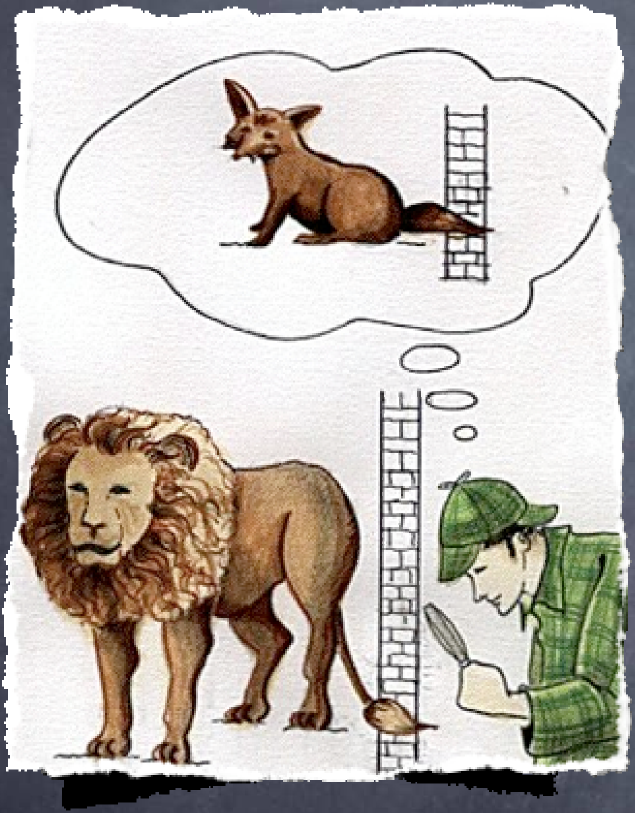
$$\boxed{\sigma(E) = \frac{S(E)}{E} e^{-\sqrt{E_G/E}}}$$

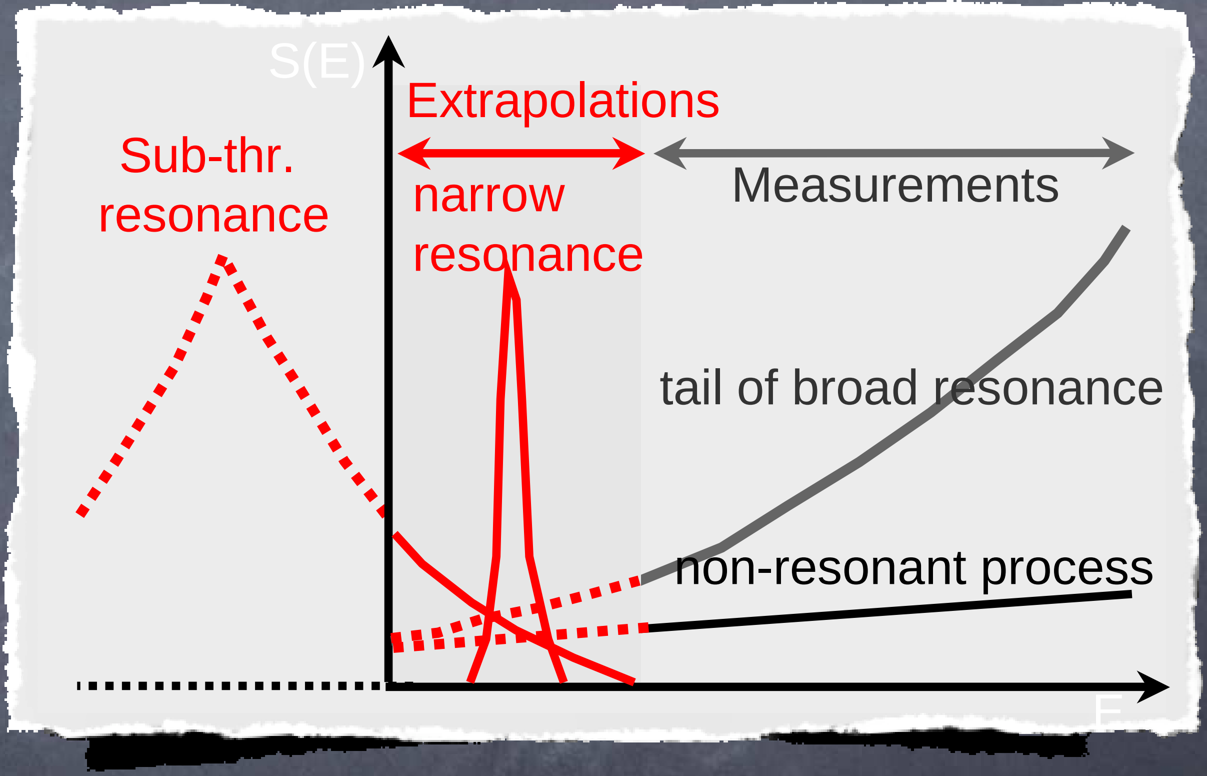
-> cross section decreases exponentially with the energy

=> extrapolation is needed...

Why going underground?

but ...

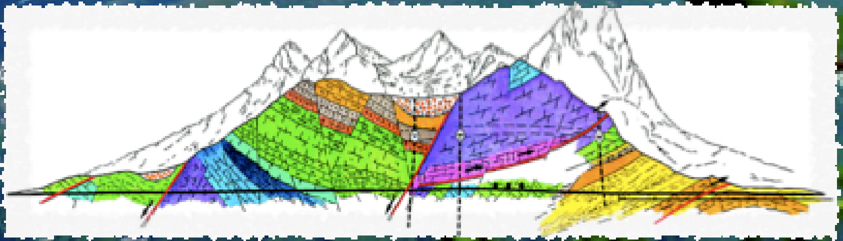


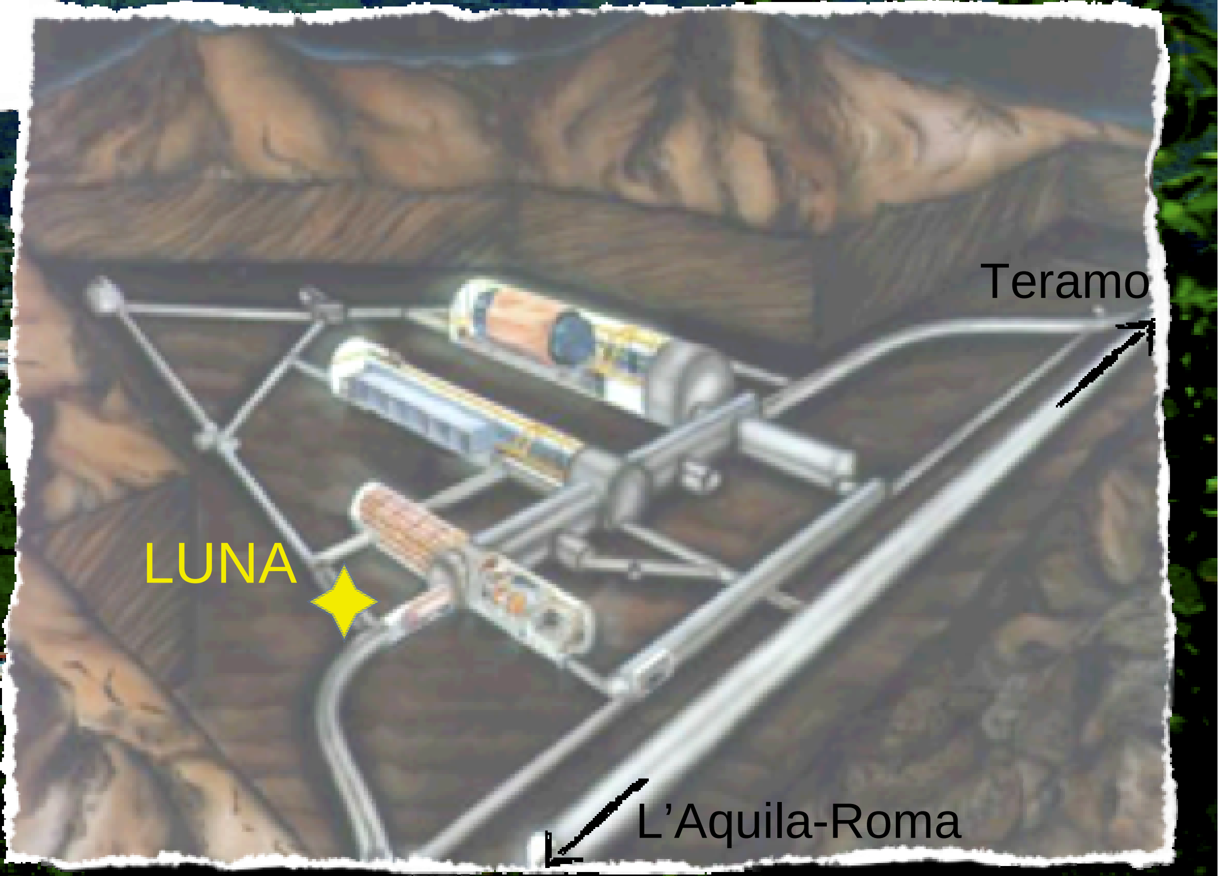


extrapolation does not always work!

-> Underground experiments to measure directly the reactions with reduced cosmic-ray induced background

Gran Sasso National Laboratories
Laboratory for Underground Nuclear Astrophysics





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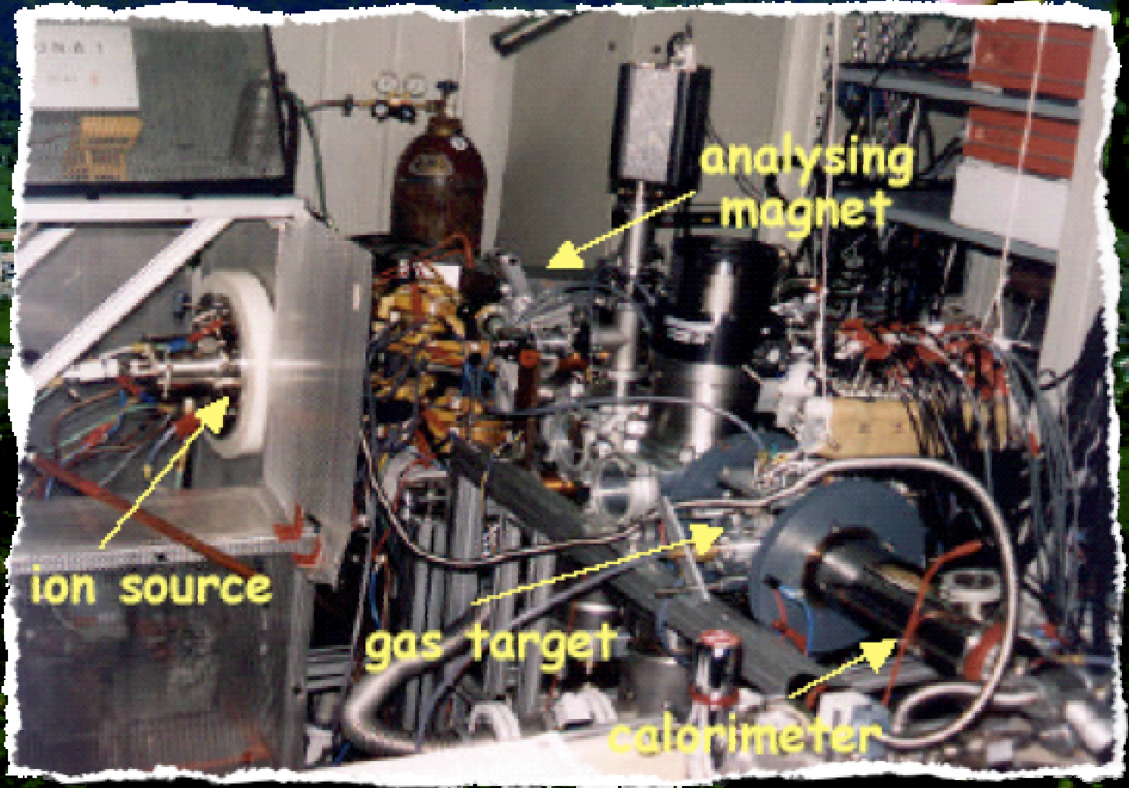

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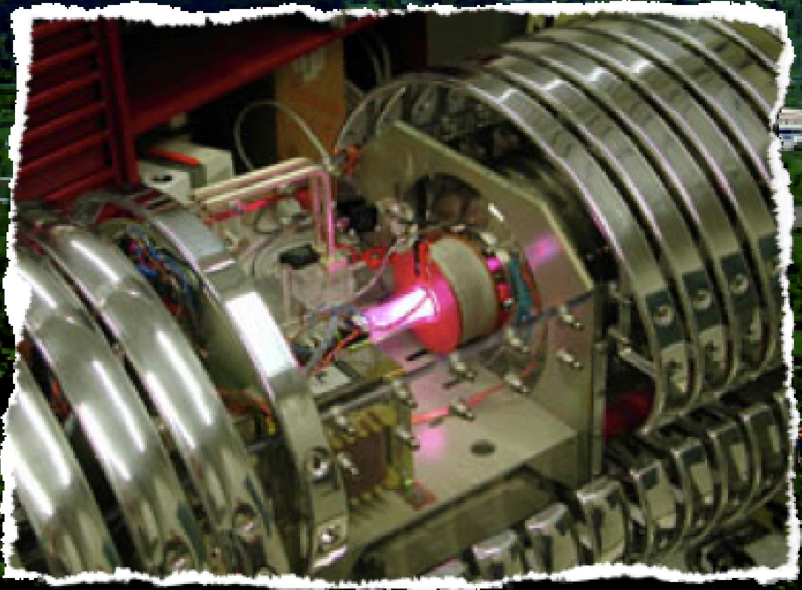
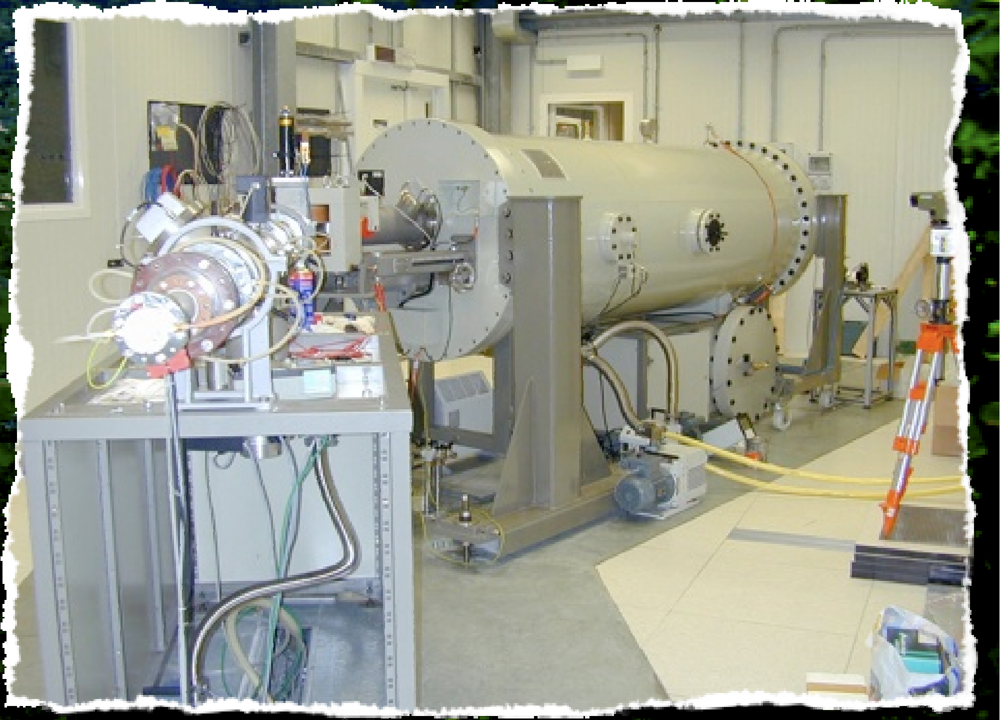




The CNO cycle:
$^{15}N(p,\gamma)^{16}O$: why measuring it again?

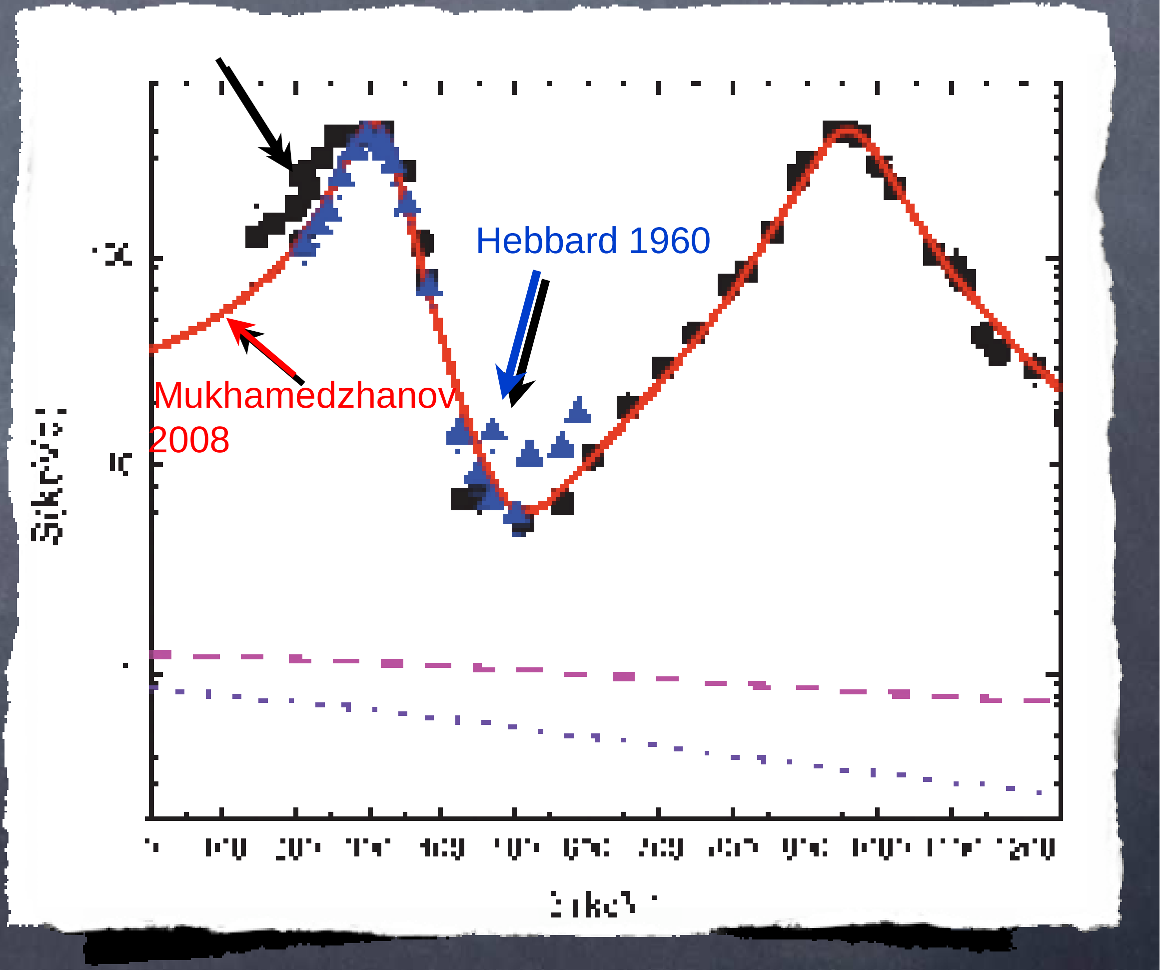
At astrophysically-relevant energies (E<1MeV):

- 2 resonances influence the excitation function (E_p=335, 1028 keV)

- data exist in literature for direct measurements of resonant and non-reasonant x-section

$E_p \geq 155$ keV [Rolfs&Rodney, 1974]
$E_p \geq 220$ keV [Hebbard 1960]

but...



Hebbard 1960

Mukhamedzhanov 2008

The CNO cycle:
$^{15}N(p,\gamma)^{16}O$: why measuring it again?

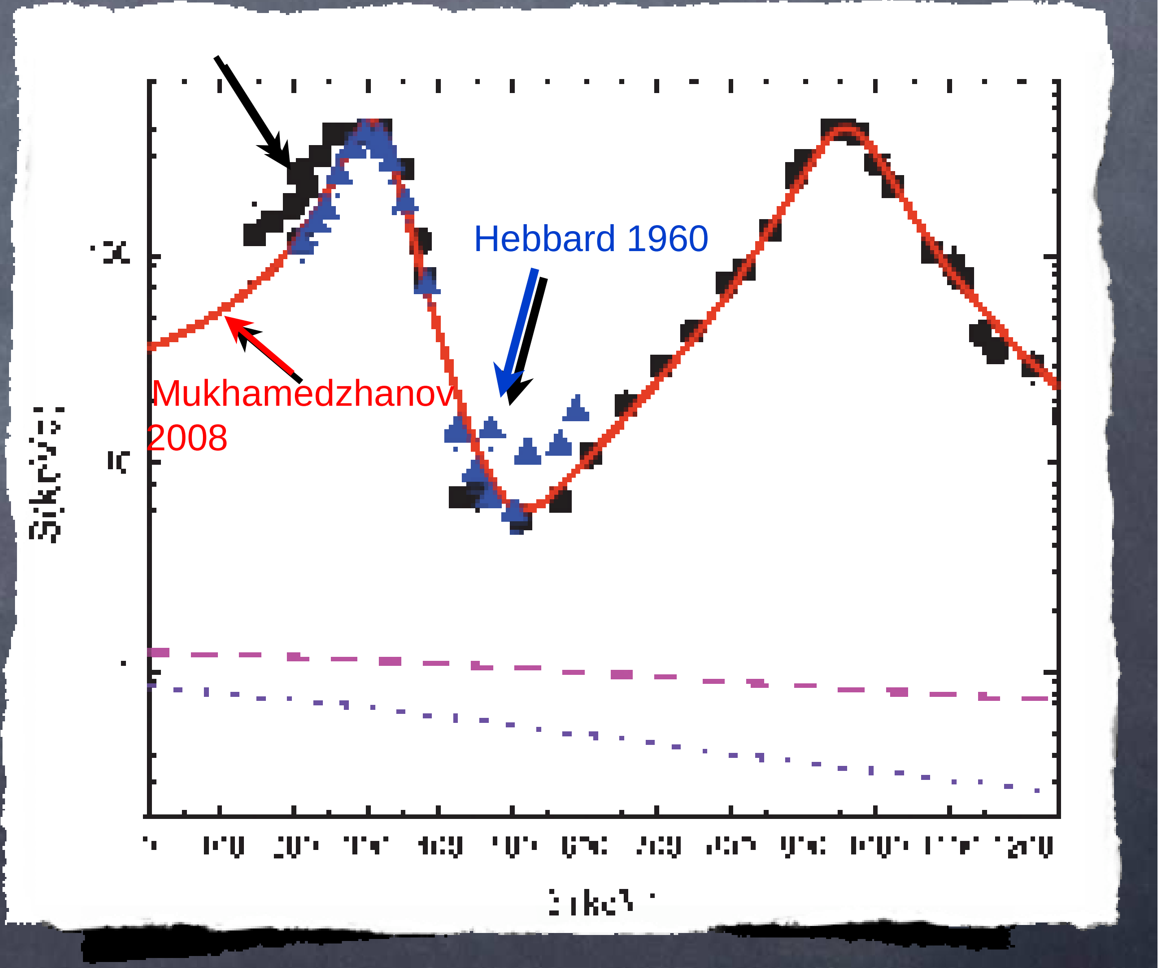
… a discrepancy exists between the two direct measurements at low energy existing in literature:

$S(O)_{Heb} = 29.8 \pm 5.4$ keV·barn
$S(0)_{R\&R} = 64.0 \pm 6.0$ keV·barn

Moreover, ANC method (Mukhamedzhanov 2008) suggests an S-factor factor of 2 lower than in R&R1974 data:

$S(0)_{Mukh} = 36.0 \pm 6.0$ keV·barn

i.e. ...



Hebbard 1960

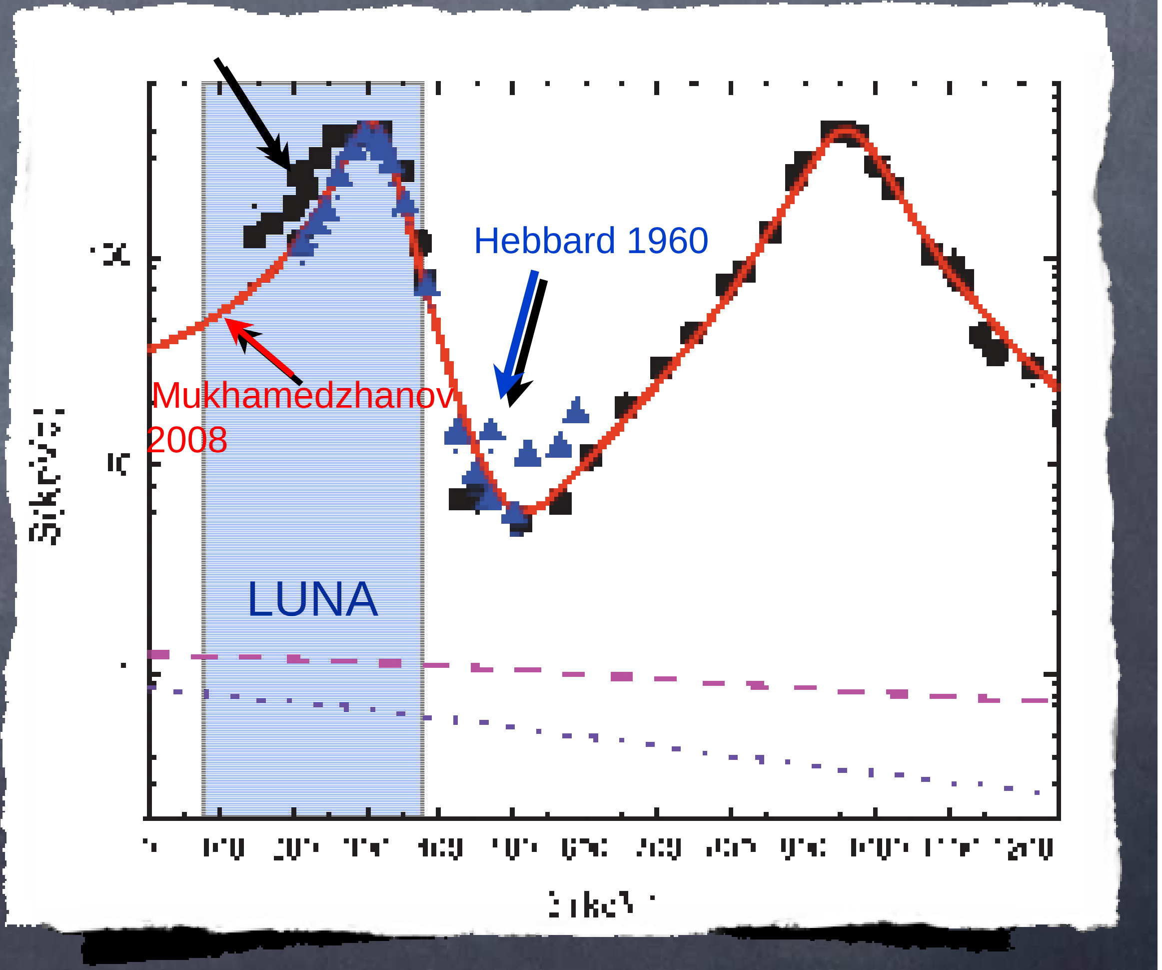
Mukhamedzhanov 2008

The CNO cycle:
$^{15}N(p,\gamma)^{16}O$: why measuring it again?

… leak rates (at Ep = 25 keV):

one CN catalyst lost because of $^{15}N(p,\gamma)^{16}O$ reaction for every

2600 ± 400 cycles of main CN cycle [Hebb. ‘60]
1200 ± 100 cycles of main CN cycle [Rolfs ‘74]
2200 ± 300 cycles of main CN cycle [Mukh. ‘08]



=> Need for NEW direct measurement(s) at energies corresponding to H-burning in novae

(T_6=200-400, i.e. E_{Gamow}=150-240 keV)

The CNO cycle:
$^{15}N(p,\gamma)^{16}O$: experiment(s)

Gas Target

Natural N_2 gas:
^{15}N -> 0.4%

Solid Target

Enriched $Ti^{15}N$ on Ta backing:
^{15}N -> 98%

Low-resolution/High efficiency measurements
BGO tot. absorption (ε=70% @12 MeV)

High-res./Low eff. meas.
HPGe

LUNA Gas Target phase
90-230 keV

LUNA-bgo phase
70-350 keV

LUNA-Notre Dame phase
130-2000 keV

all systematic uncertainties (most important being bkg subtraction) are well understood

targets analyzed to evaluate their deterioration due to the high charge (up to 40C!) deposited on them:
$^{15}N(p,\alpha\gamma)^{12}C$ at 430 keV -> FZD
ERDA -> Munich

possible perform R-matrix fits with a unique set of data

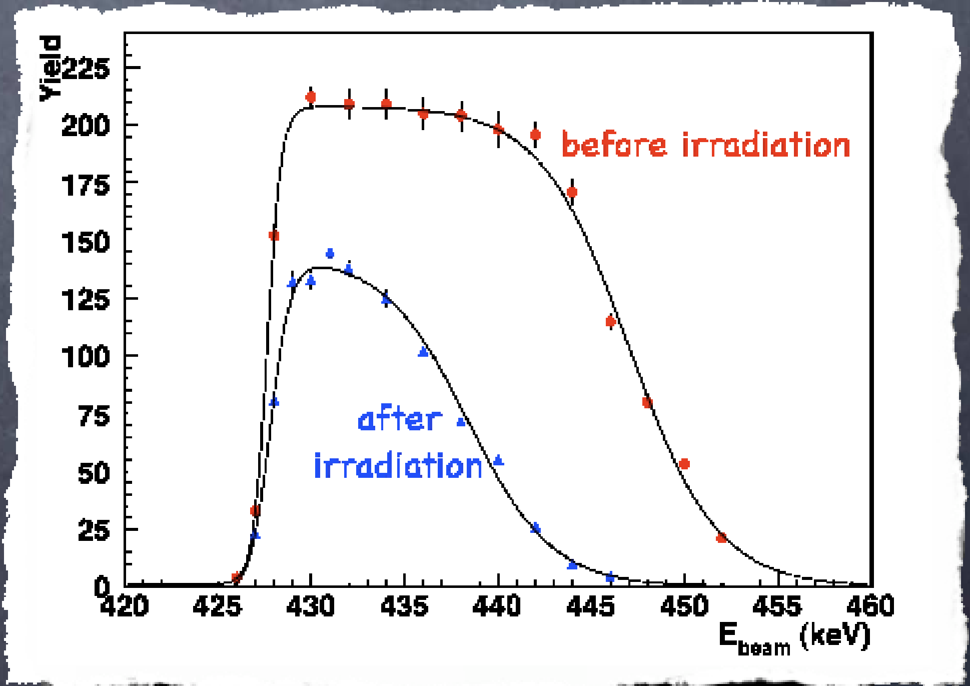
The CNO cycle:
$^{15}N(p,\gamma)^{16}O$: experiment(s)

The solid target BGO experiment

- The targets were subdued to rather large amounts of charge deposited
-> complimentary measurements had to be carried out at over-ground laboratories in order to understand the target deterioration:

- Target scan with the 429 keV resonance in $^{15}N(p,\alpha\gamma)^{16}O$ (FZD, Germany)
- Elastic Recoil Detection Analysis (TU Munich, Germany)
    -> absolute stoichiometry (unfortunately destructive technique)

Target scan with the 429 keV resonance in $^{15}N(p,\alpha\gamma)^{16}O$ (FZD)



The CNO cycle: $^{15}N(p,\gamma)^{16}O$: experiment(s)

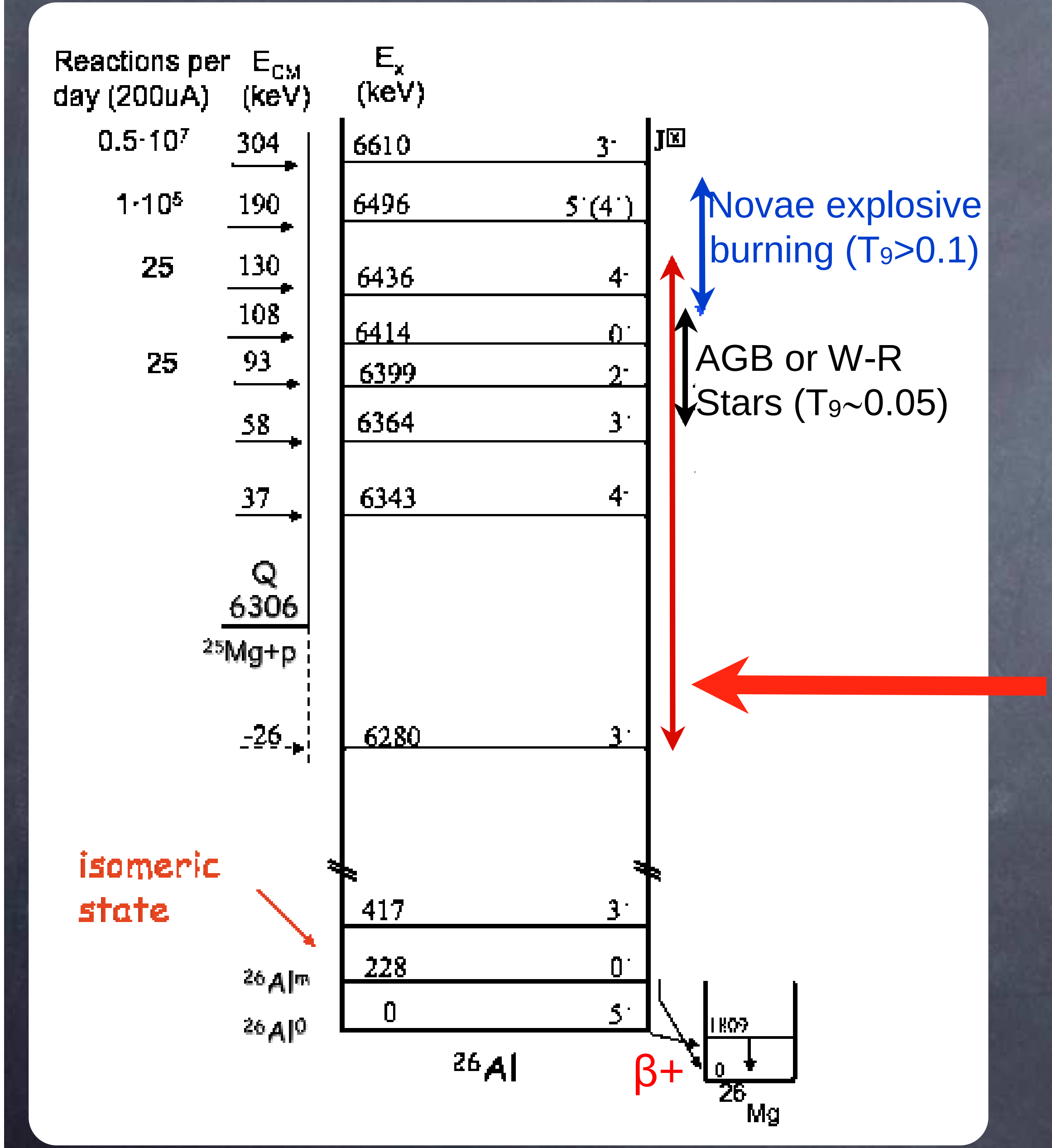
- $^{15}N(p,\gamma)^{16}O$ has been studied using two different approaches: gas and solid target

- cross section measured in the 70 - 375 keV energy range

- good agreement among 3 data sets characterized by totally different systematics

- S(0)-factor has been reduced by a factor of 2 with respect the previous direct data from Rolfs and Rodney and the NACRE extrapolation which are traditionally used in CNO nucleosynthesis simulations -> the change in rate will modify the equilibrium abundance of ^{16}O (correlated to the leakage rate from the CN cycle and the rate of $^{16}O(p,\gamma)^{17}F$ in the NO cycle

The MgAl cycle: ^{25}Mg(p,γ)^{26}Al experiment

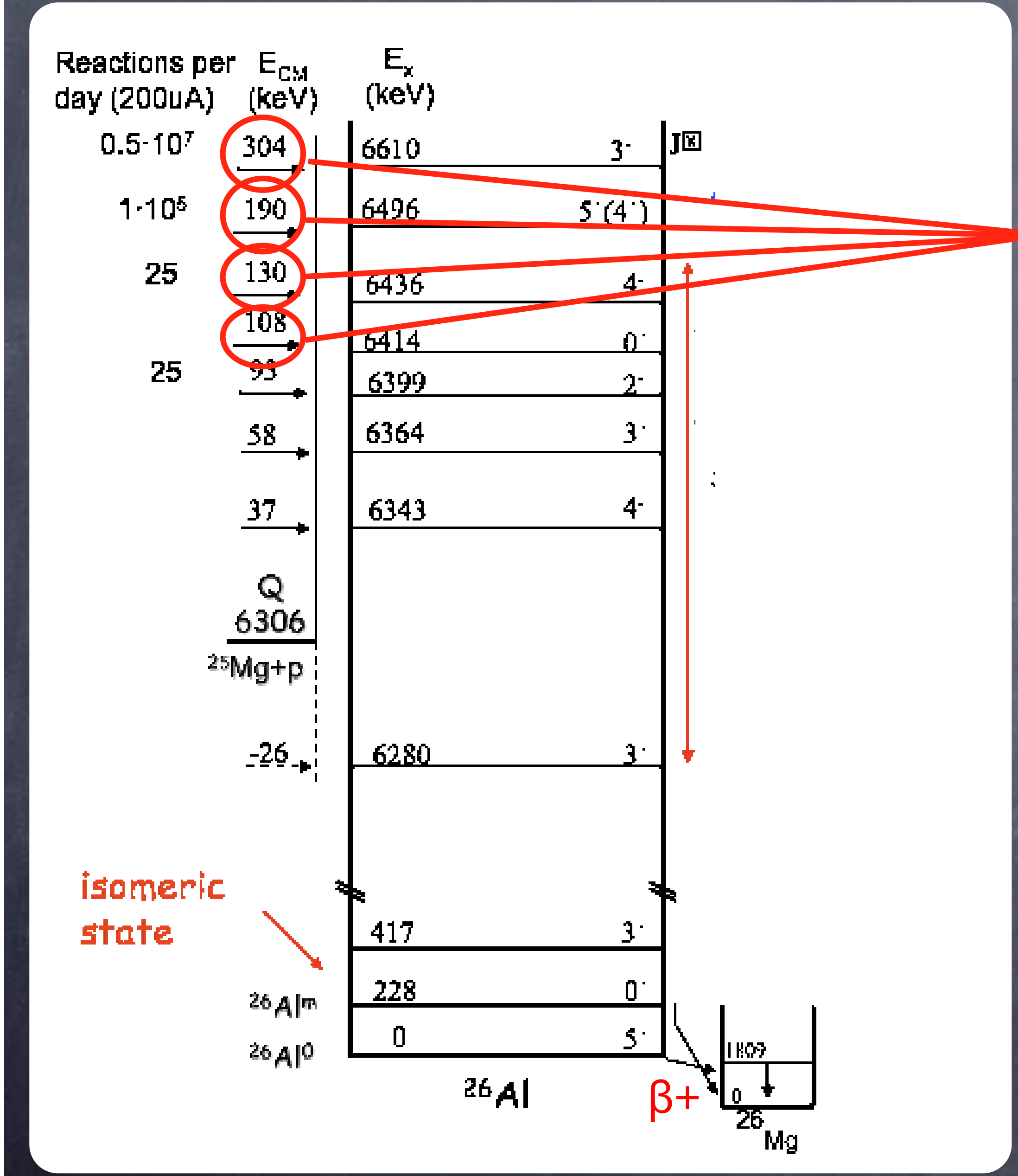


No direct strength resonance data (level structure derived from the single particle transfer reaction ^{25}Mg(^{3}He,d)^{26}Al)

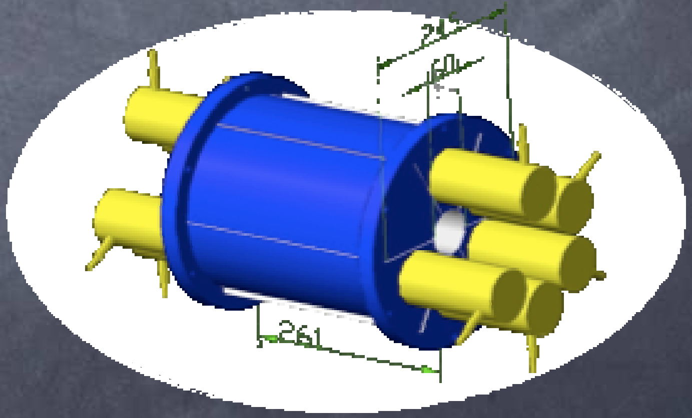
\+

Reported disagreement between resonance strength measured by γ-ray spectroscopy and delayed AMS detection of ^{25}Al nuclei after irradiation of ^{25}Mg with protons (Arazi, 2006)

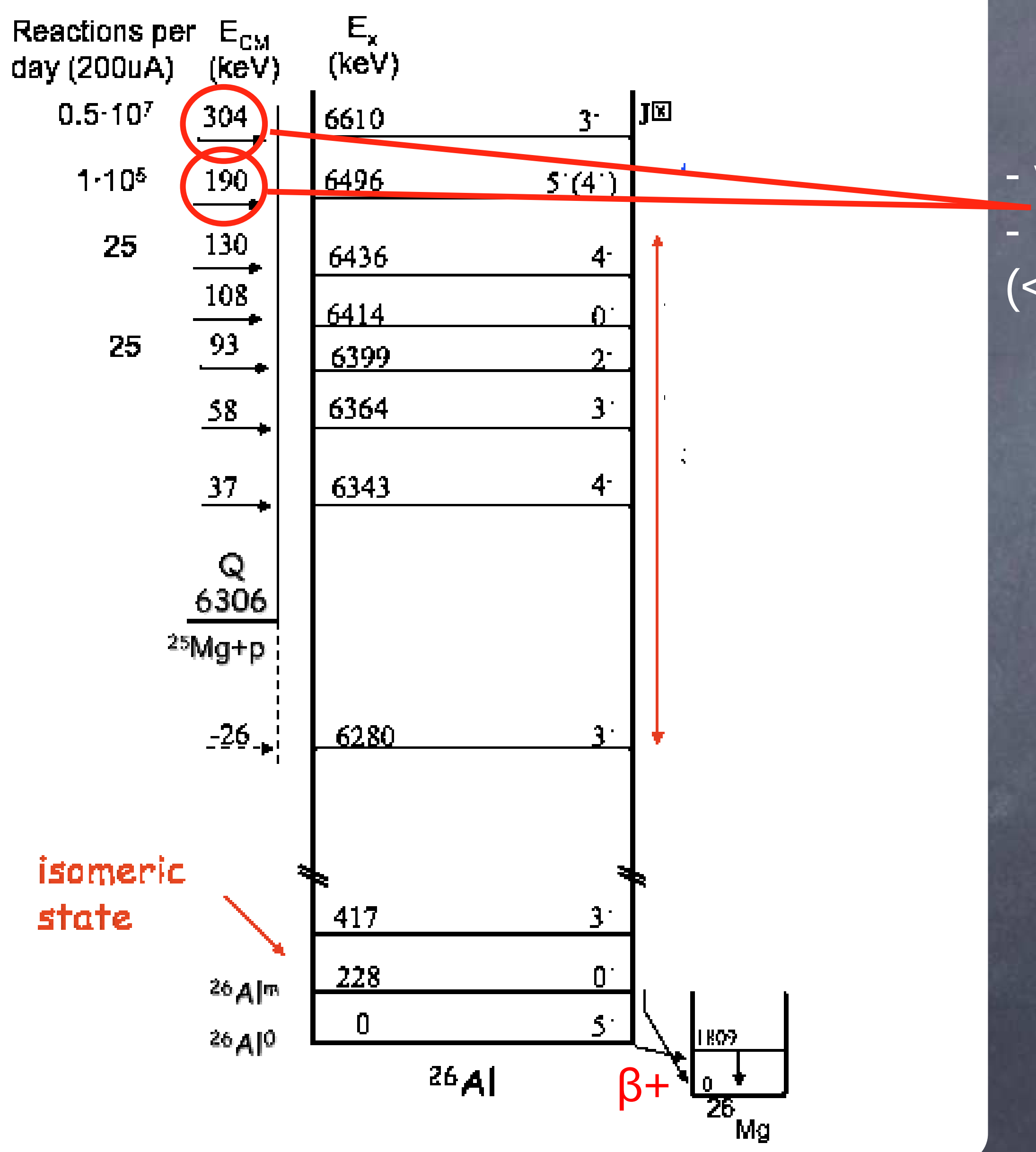
The MgAl cycle:
^{25}Mg(p,γ)^{26}Al experiment



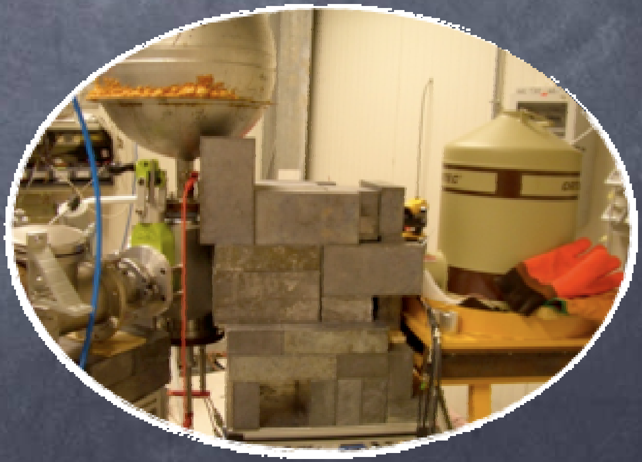
- High efficiency (about 50%)
  - -> Low resolution set-up
- γ-ray spectroscopy with 4πBGO
  - + solid target



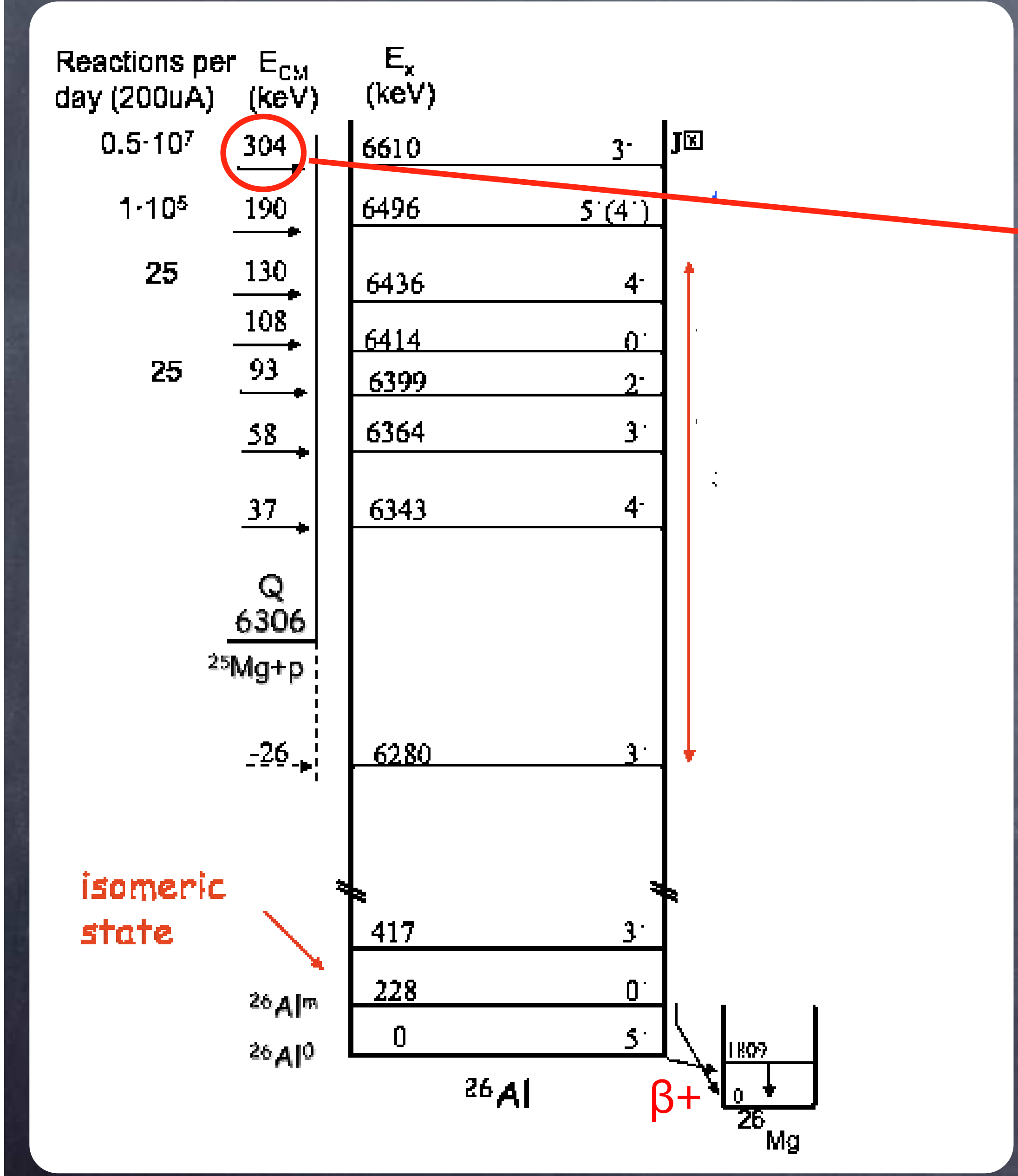
The MgAl cycle:
^{25}Mg(p,γ)^{26}Al experiment



- γ-ray spectroscopy with HPGe
- high resolution - low efficiency (<1% at high energy) + solid target @55°



The MgAl cycle:
$^{25}Mg(p,\gamma)^{26}Al$ experiment

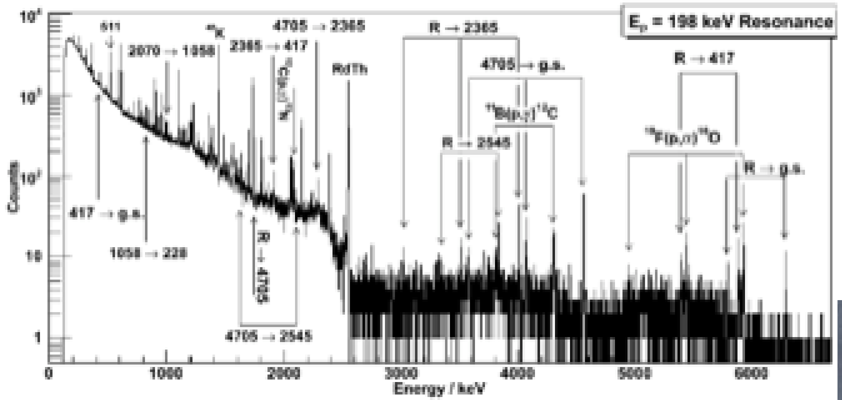


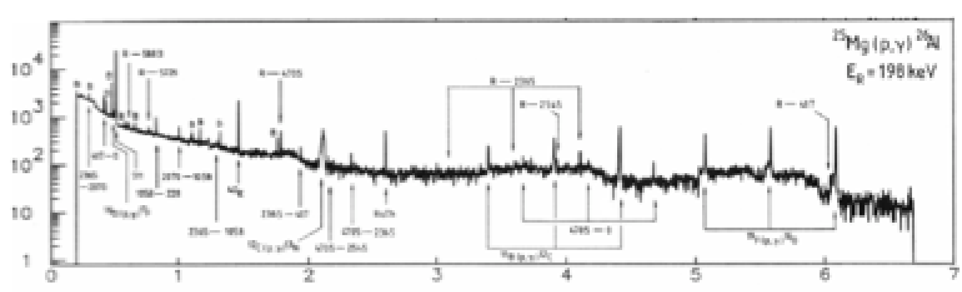
AMS Irradiation & Measurement
-> resonance strength

CIRCE laboratory, Caserta

The MgAl cycle:
$^{25}Mg(p,\gamma)^{26}Al$ experiment

HPGe spectra E_R = 190 keV





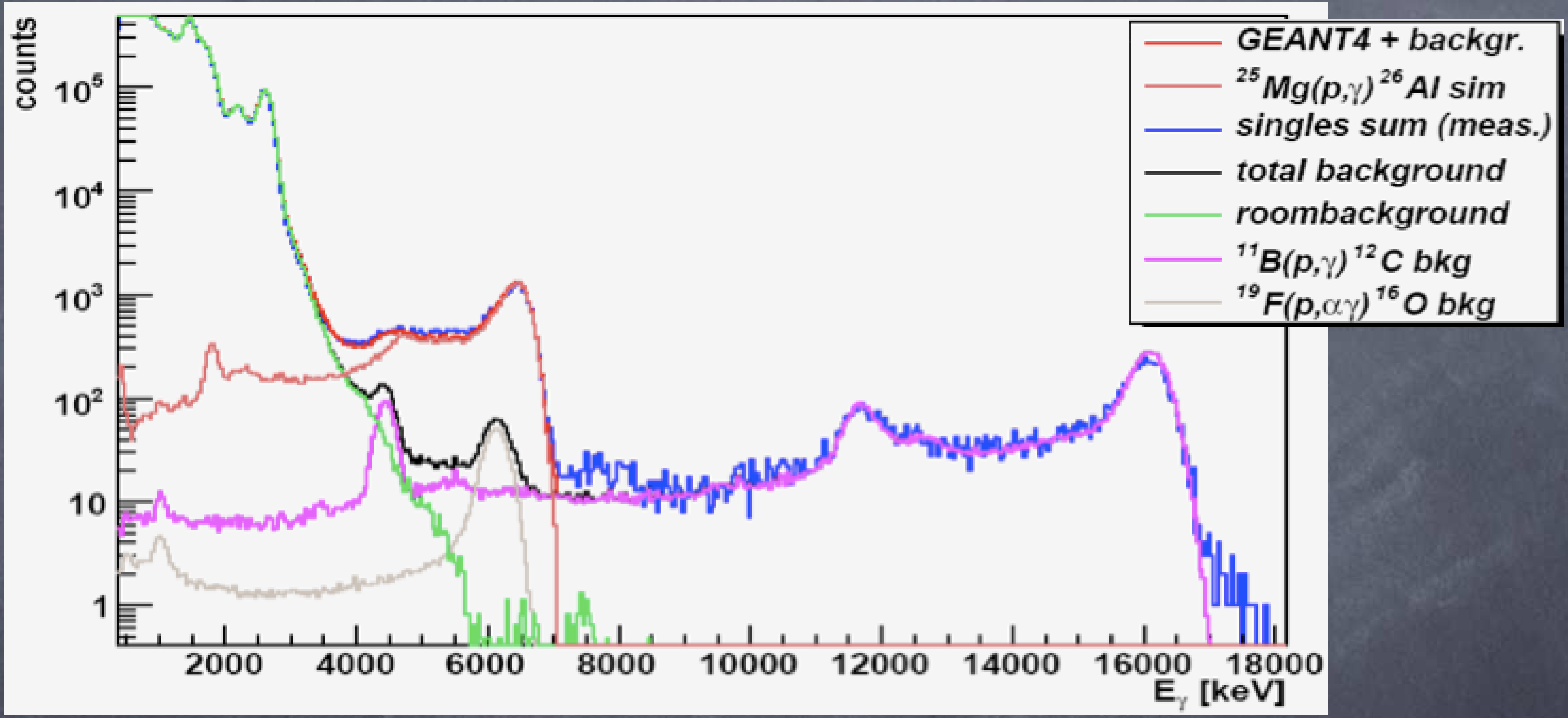
Iliadis et al, 1990

E_γ	1791	3092	3951	4131	6079	6496
E_X	4705	3404	2545	2365	417	0
LUNA [%]	50.7	1.6	8.2	22.9	10.8	5.8
err	1.9	0.5	1.0	1.5	1.3	1.1
Endt [%]	50	4.5	5.8	19	21	0

B.N. Limata et al., PRC82 (2010) 015801

The MgAl cycle: ^{25}Mg(p,γ)^{26}Al experiment

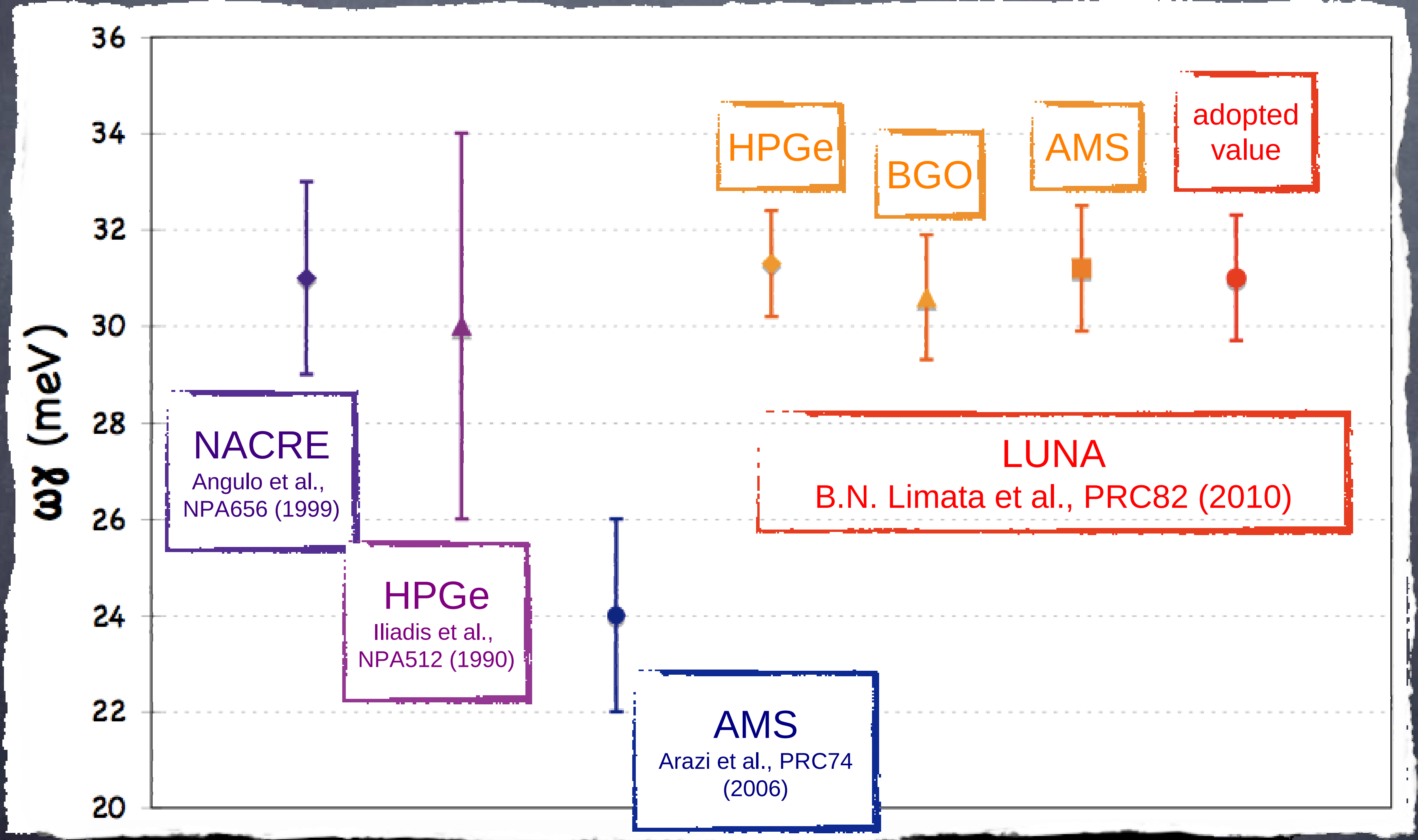
BGO spectra E_R = 190 keV



B.N. Limata et al., PRC82 (2010) 015801

The MgAl cycle:
^{25}Mg(p,γ)^{26}Al experiment

E_R = 304 keV: all techniques



BR->0 = 87.8 %

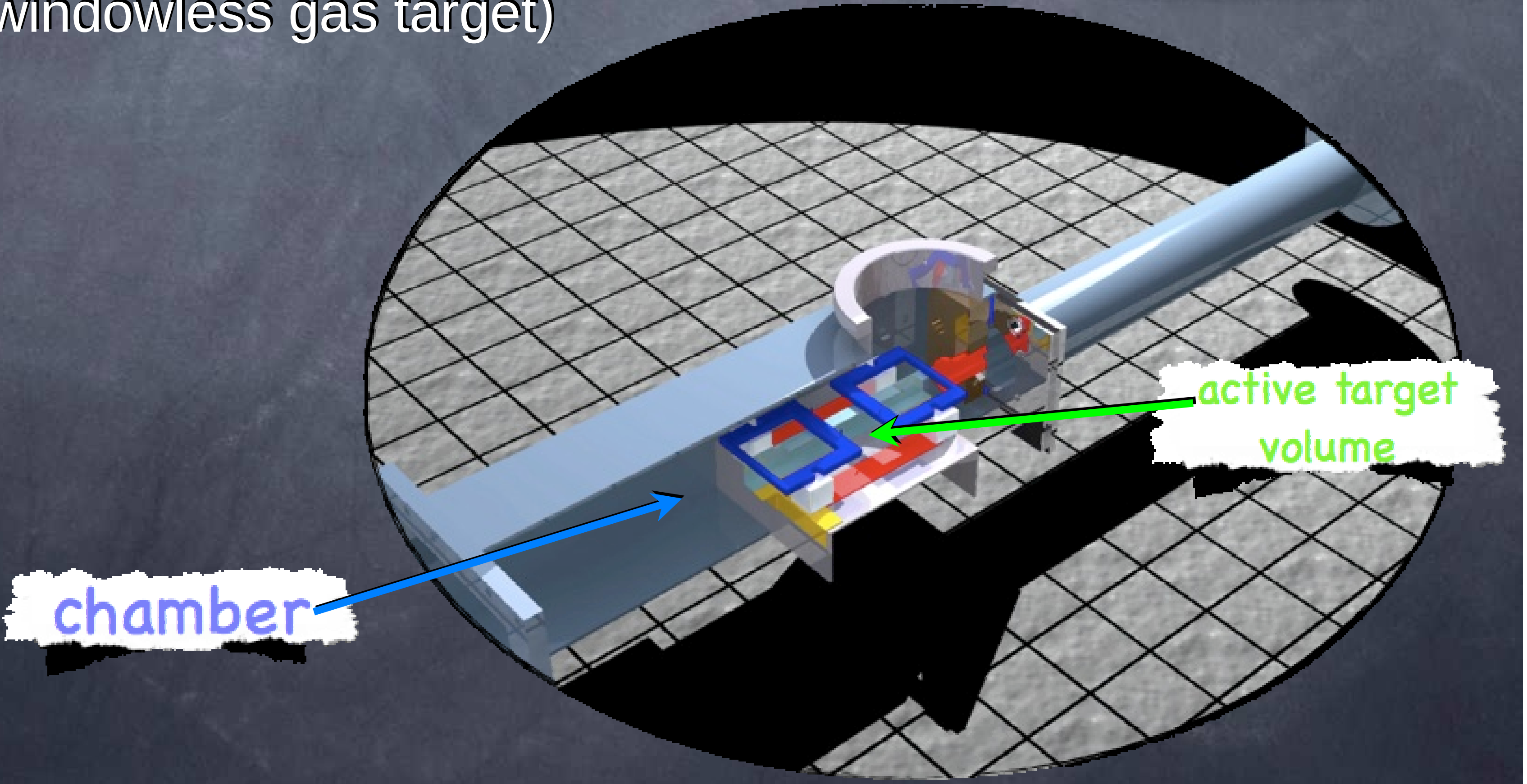
The BBN reactions:
$d(\alpha,\gamma)^6Li$ experiment

- Alpha beam from LUNA-400 kV accelerator

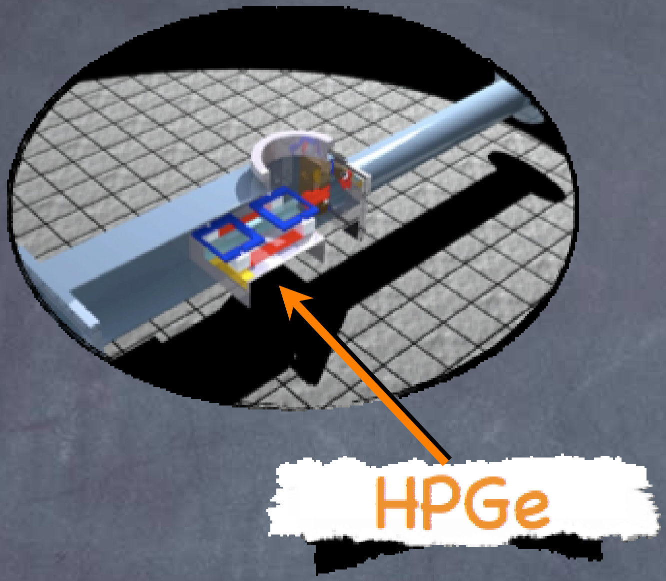
- $E_\alpha \leq 400$ keV

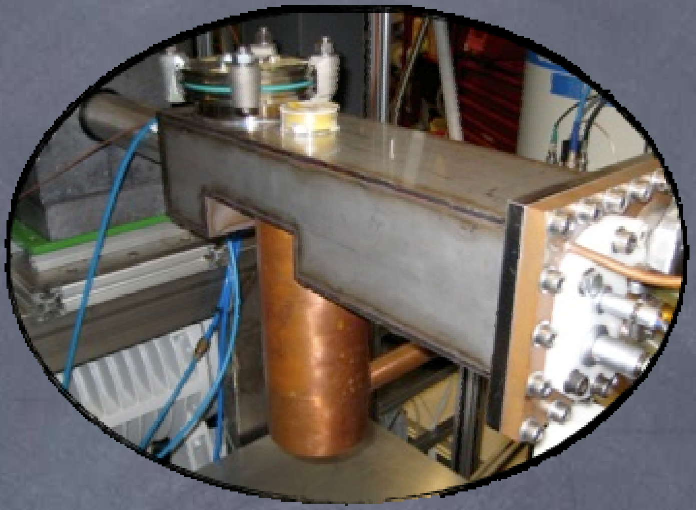
- $I_\alpha \sim 200$ μA

- D_2 target (windowless gas target)



The BBN reactions:
$d(\alpha,\gamma)^6$Li experiment





- HpGe single-crystal large-volume (135%) detector in close geometry
- Pb shielding and Rn box to reduce natural background contribution + shielding granted by the mountain to suppress cosmic ray contribution to γ-ray spectra
- Beam-induced background: dedicated test measurements to study it

-> measurement is running in these weeks

Summary

- several reactions belonging to H-burning or BBN astrophyscial scenarios have been investigated at LUNA taking advantage of the unique shield offered by the Gran Sasso mountain

- among them those studied most recently are

  - $^{25}Mg(p,\gamma)^{26}Al$

  - $^{15}N(p,\gamma)^{16}O$

  - $d(\alpha,\gamma)^{6}Li$ (in progress)

Outlook: what next at LUNA-II (400kV)?

reaction	Q-value (MeV)	Gamow energy (keV)	Lowest meas. energy (keV)	LUNA limit
$^{17}O(p,\gamma)^{18}F$	5.6	35-260	300	65
$^{18}O(p,\gamma)^{19}F$	8.0	50-200	143	89
$^{23}Na(p,\gamma)^{24}Mg$	11.7	100-200	240	138
$^{22}Ne(p,\gamma)^{23}Na$	8.8	50-300	250	68
$d(\alpha,\gamma)^{6}Li$	1.47	50-300	700 (direct) 50 (indirect)	50

In progress

proposal approved by INFN (2008-2012)