LUNA and LUNA-MV, achievements and outlook

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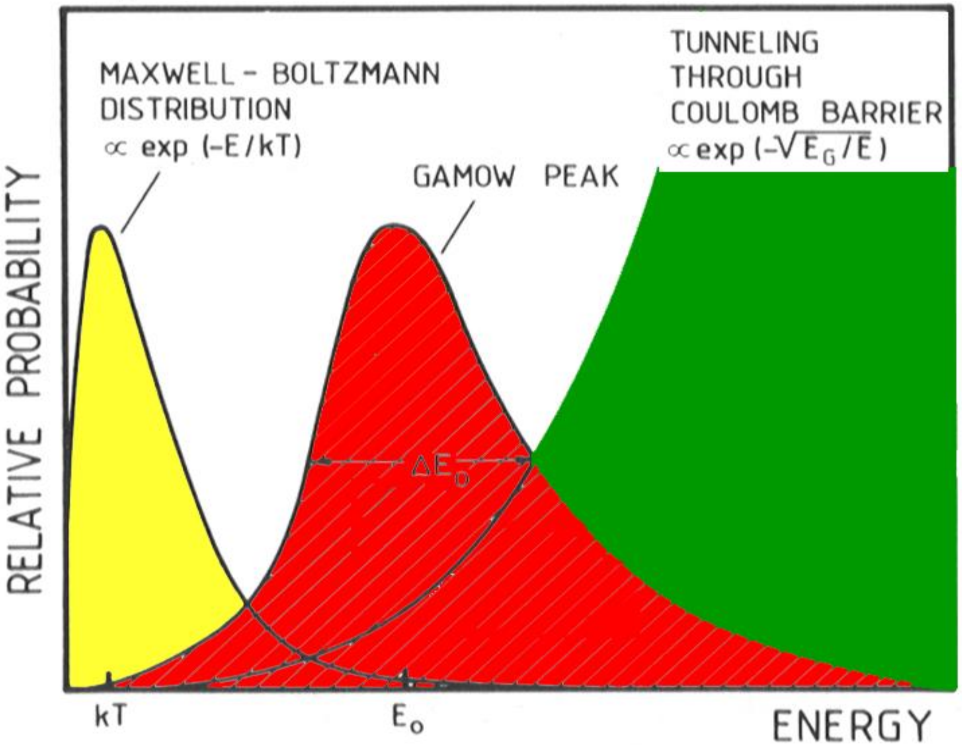
Workshop on Nuclear Astrophysics at the Dresden Felsenkeller, June 26-28 2017

$T_{sun} \approx$ 16 10^6 K

$E_{MB} \approx$ 1.3keV

Exponential drop of cross section in the energy range of the sun

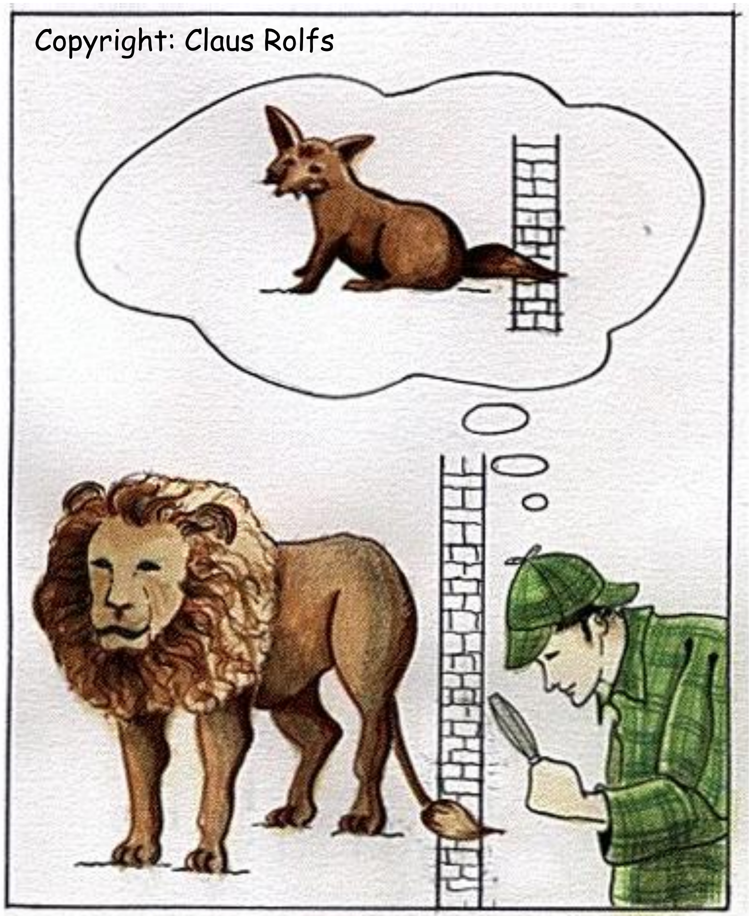


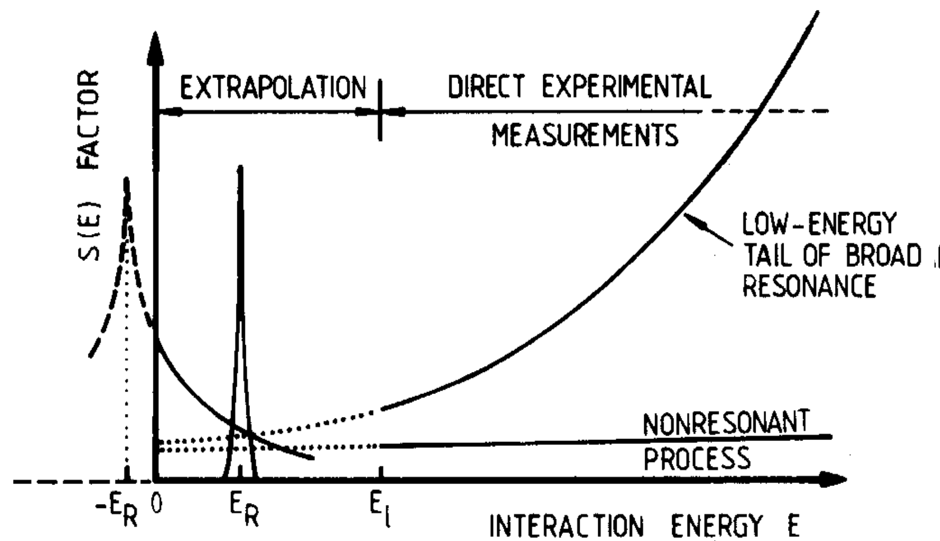
The Gamow Peak

Energy window in which non resonant reactions take place in stellar environment.

Examples:	E_c/keV	E_0/keV	σ (E_0)/barn	E_{min}/keV
^{3}He(^{3}He,2p) ^{4}He	1540	21	7 10^{-13}	16.5
^{3}He(α,γ) ^{7}Be	1540	22	9 10^{-18}	102
^{14}N(p,γ) ^{15}O	2270	26	4 10^{-21}	70

But extrapolation is always dangerous !





Note: Indirect methods (THM, CB, etc) are succesfully adopted to overcome the problem but they are, at some level, model-dependent

"Some people are so crazy that they actually venture into deep mines to observe the stars in the sky"

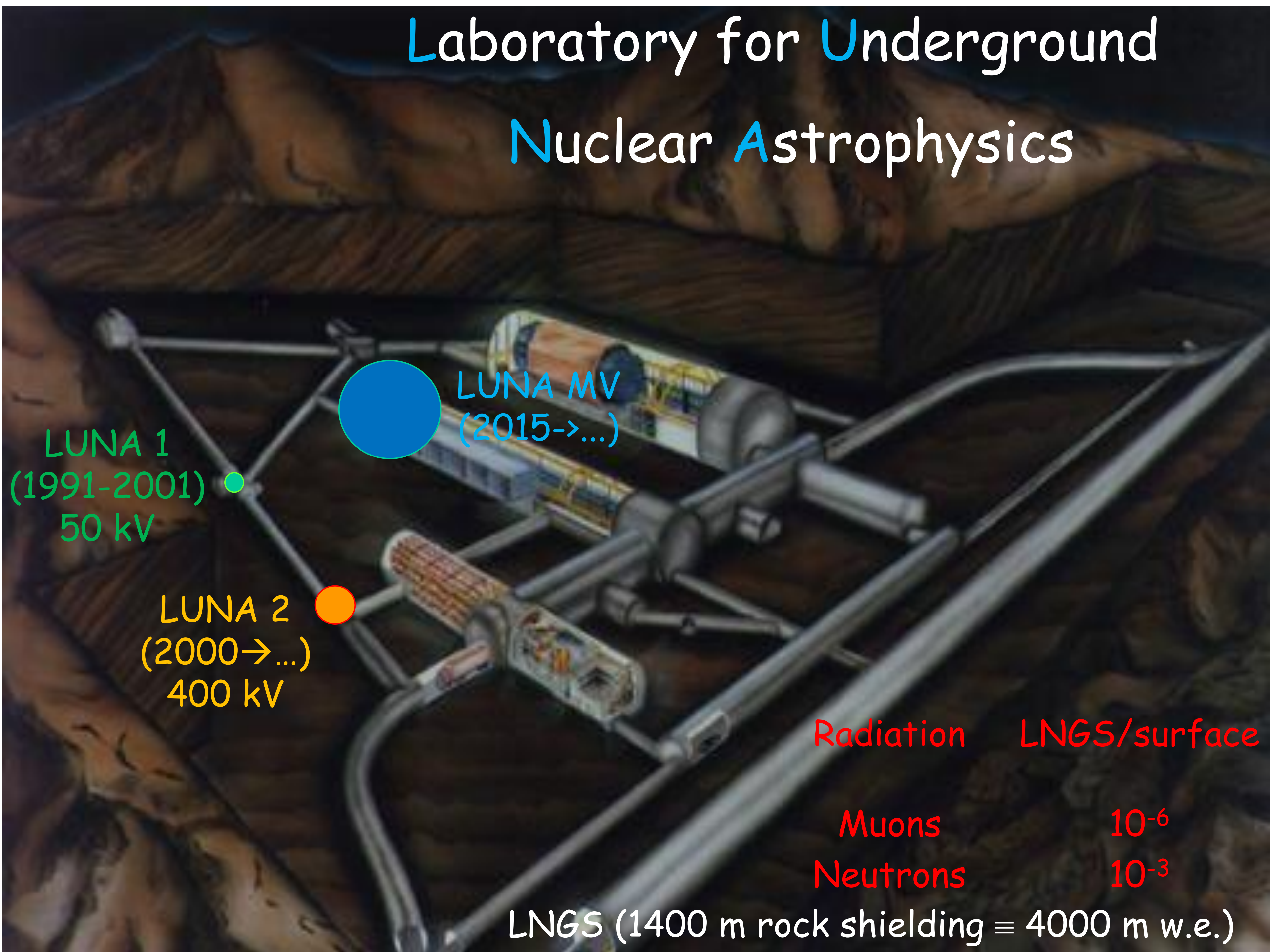
De origine animalium – Aristotele

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

Why are we not going into the Gran Sasso?

LUNA
Laboratory for Underground Nuclear Astrophysics

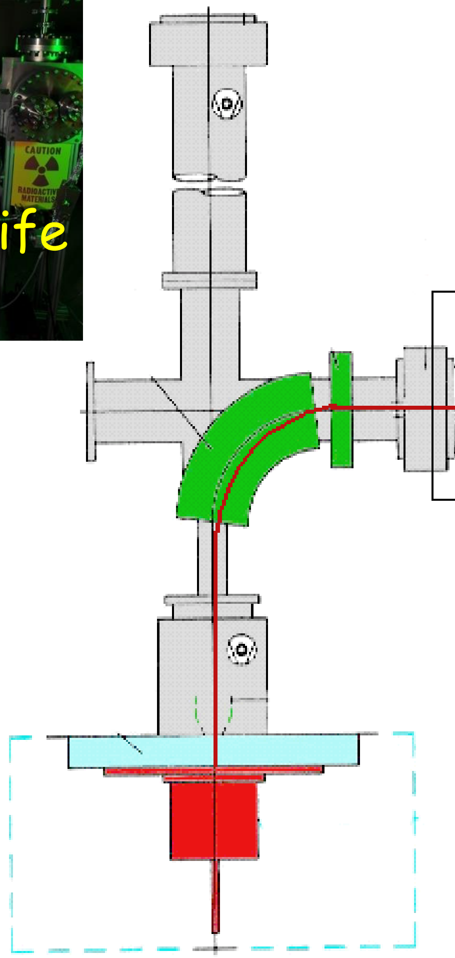
Laboratory for Underground Nuclear Astrophysics



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

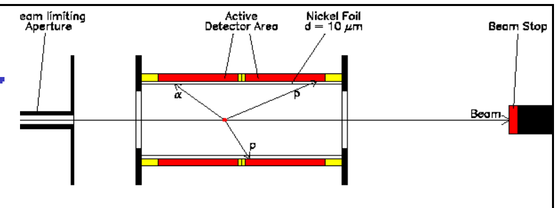
LNGS (1400 m rock shielding ≡ 4000 m w.e.)

LUNA -50 kV accelerator



Energy Range
for Protons:
50keV - 3 keV

Energy Stability
≤ 10^{-4}

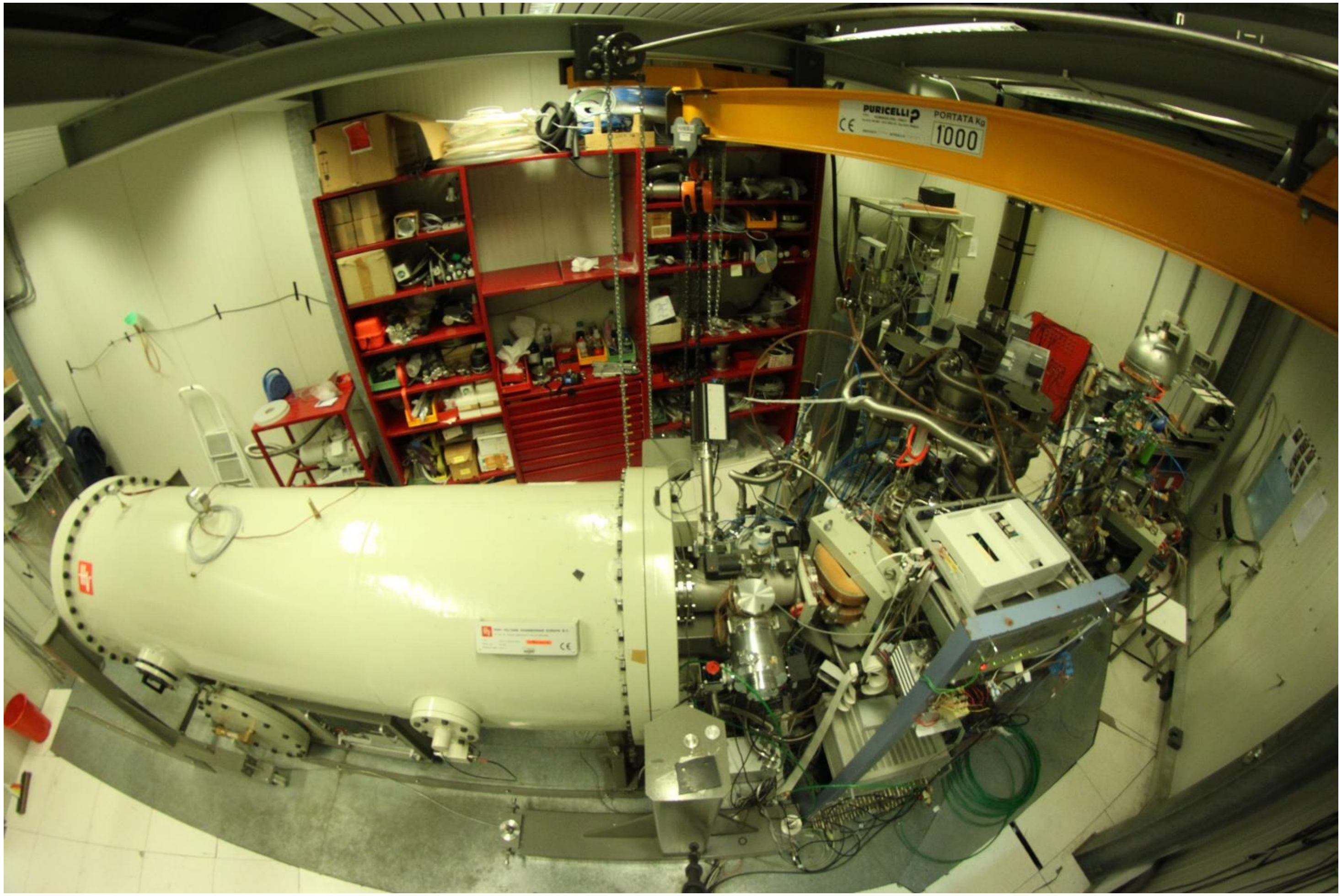


detectors

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

Current:
50- 500 µA

LUNA 400kV accelerator



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

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

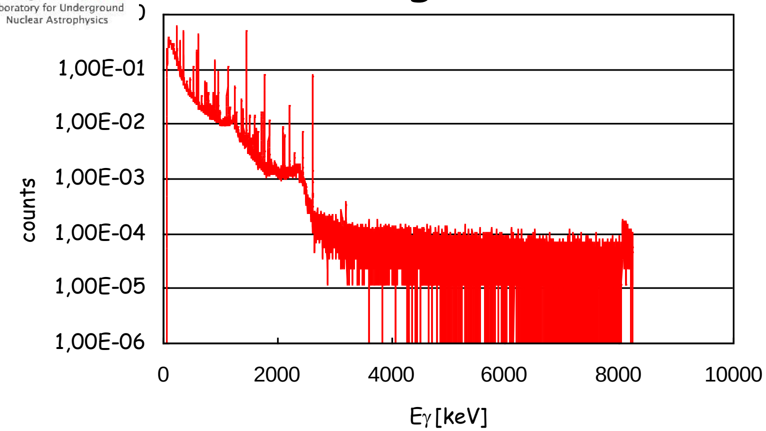
$I_{max} \approx 250\ \mu A$ alphas

Energy spread ≈ 70 eV

Long term stability ≈ 5eV/h

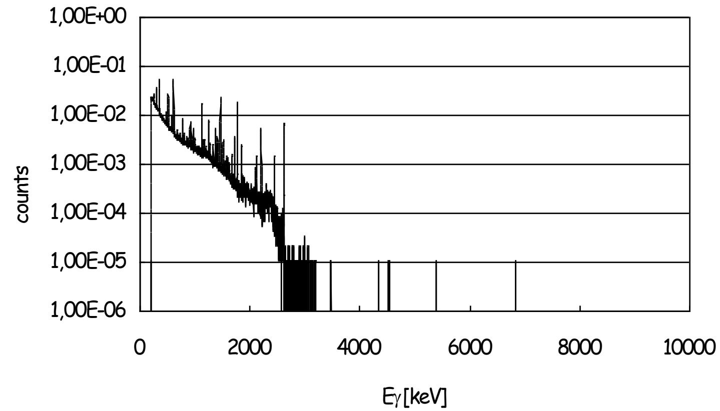
Background reduction - HPGe detector

Overground



3MeV < Eγ < 8MeV
0.5 Counts/s

Underground



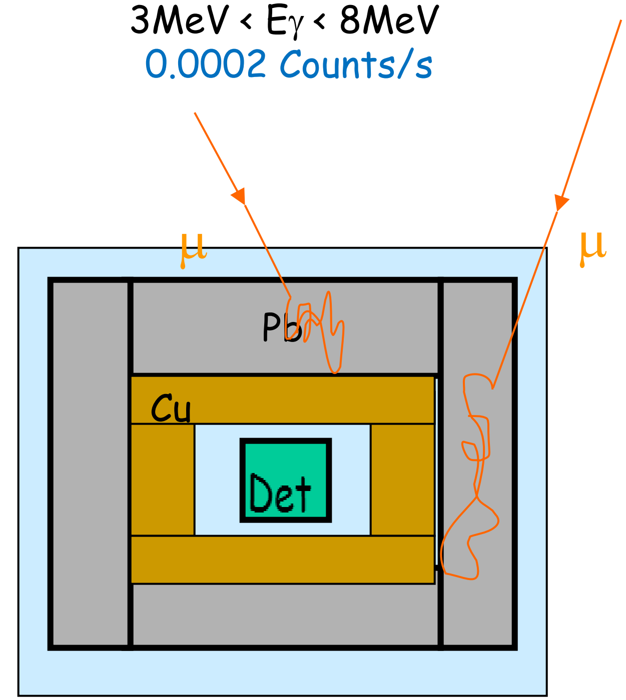
3MeV < Eγ < 8MeV
0.0002 Counts/s

E_γ<3MeV→passive shielding for environmental bck.

Secondary gammas created by μ interactions are reduced

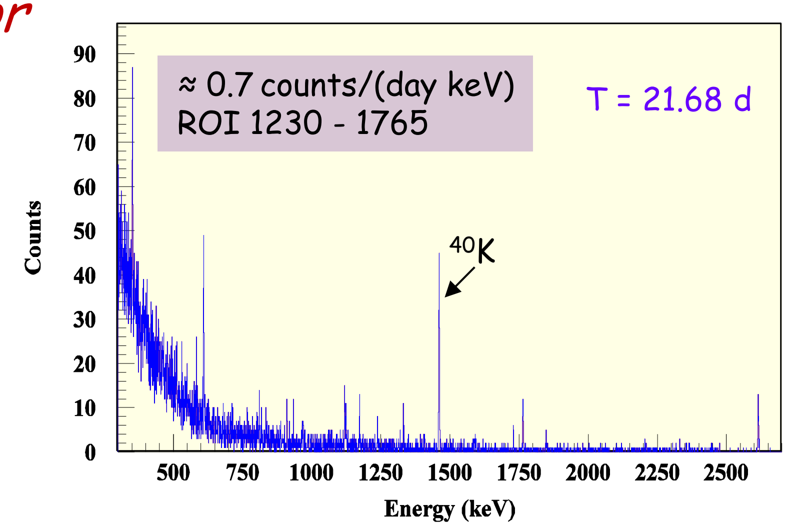
↓

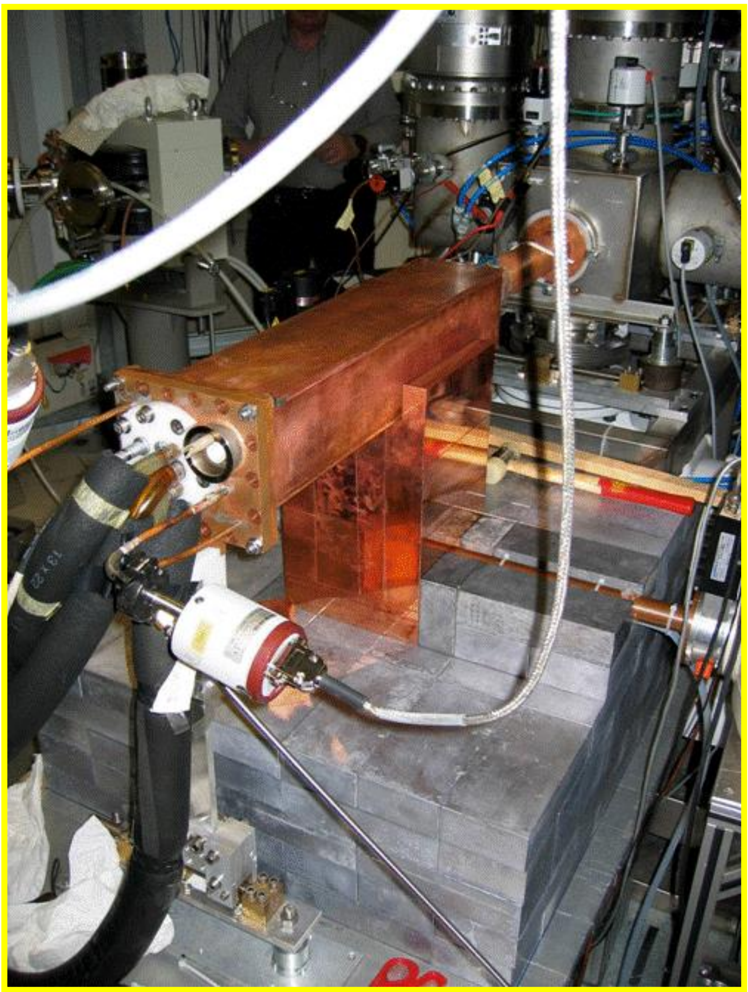
underground passive shielding is more effective!



Ultra low-background gas target set-up based on a 130% HPGe detector

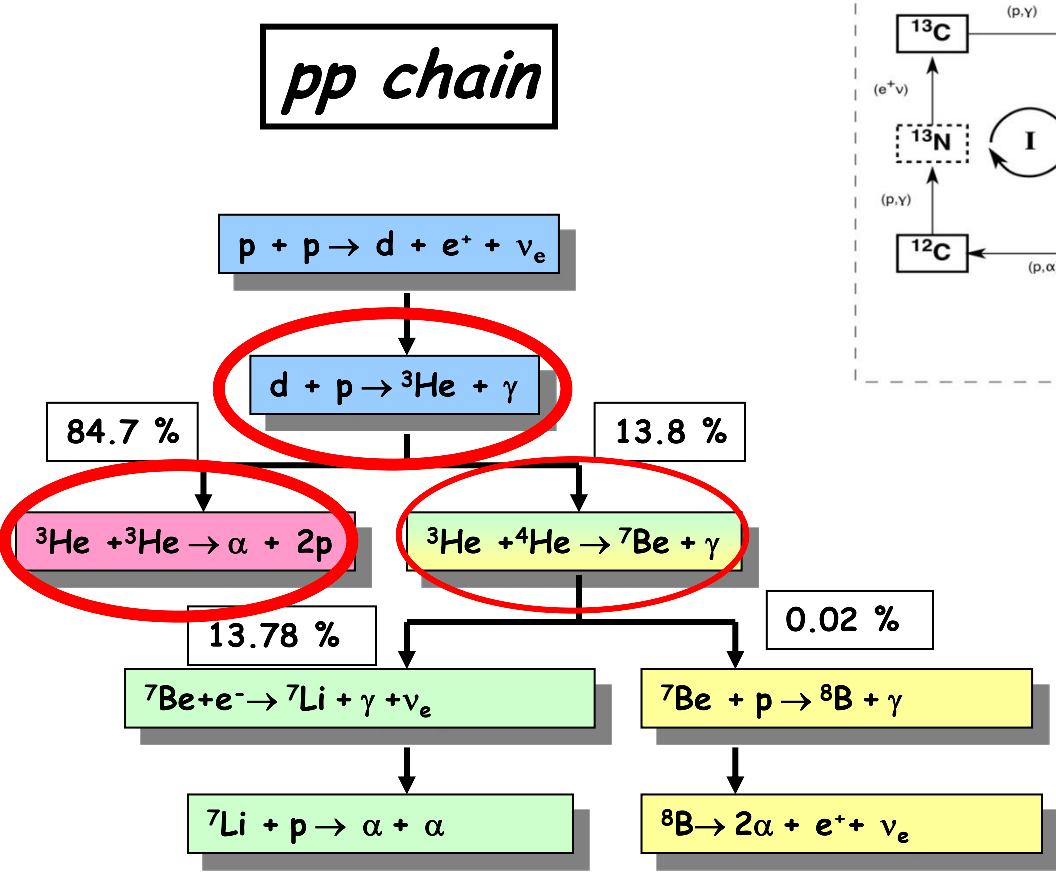
0.4 m^3 Pb and Cu shield in a Radon box
→ bck reduction: 10^5

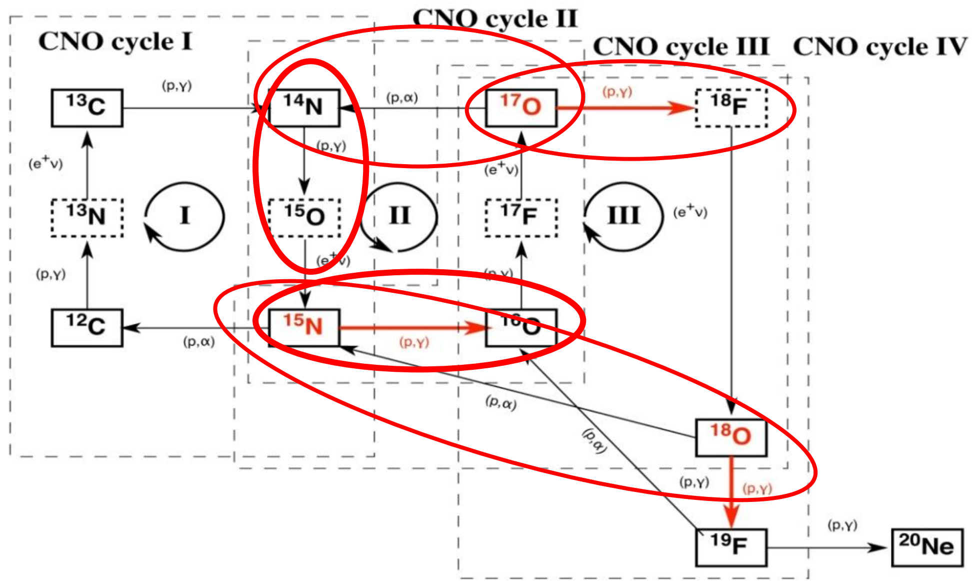


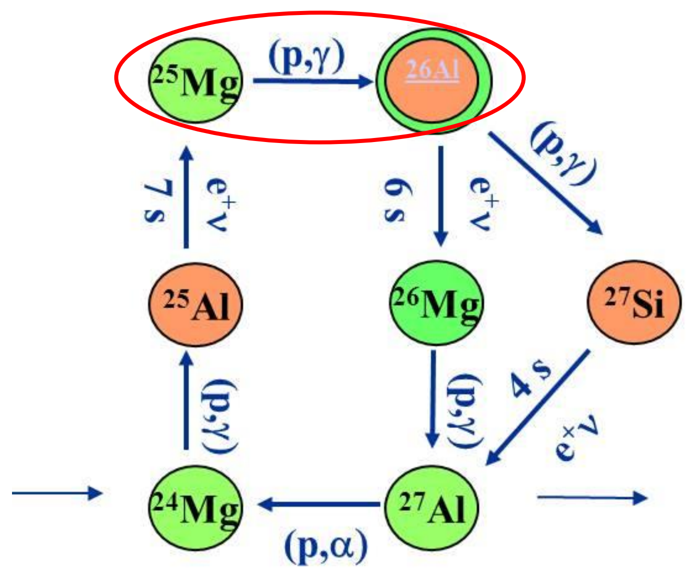


Hydrogen burning at LUNA

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

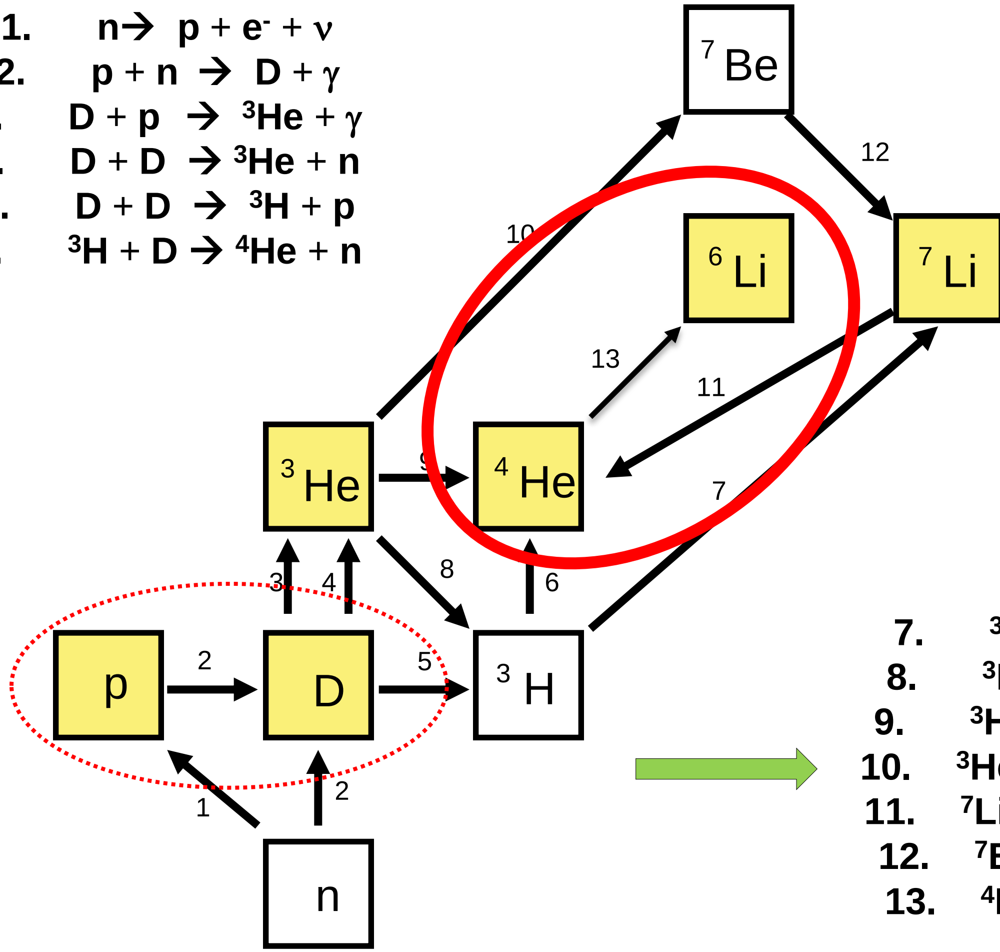






BBN reaction network at LUNA

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



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

LUNA 400 kV new program 2016-2019: a bridge toward LUNA MV

$^{2}H(p,\gamma)^{3}He$ – ^{2}H production in BBN

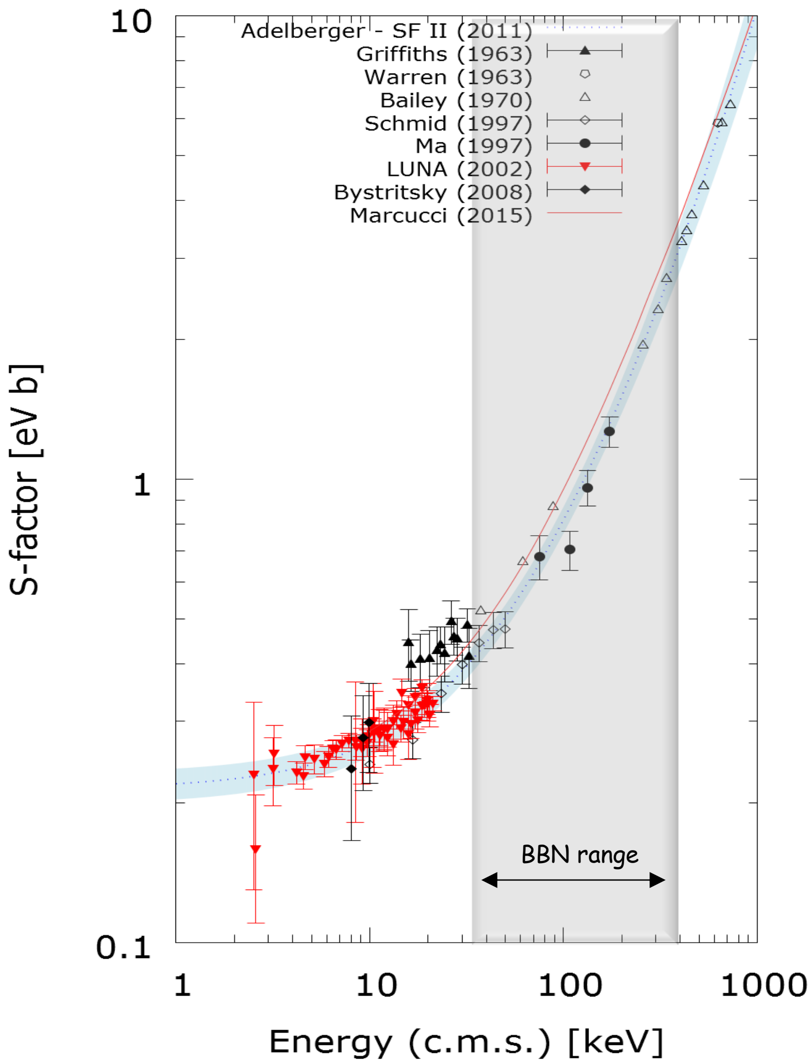
$^{22}Ne(\alpha,\gamma)^{26}Mg$ – competes with $^{22}Ne(\alpha,n)^{25}Mg$ neutron source (*LUNA MV*)

$^{13}C(\alpha,n)^{16}O$ – neutron source (*LUNA MV*)

$^{6}Li(p,\gamma)^{7}Be$ – BBN & Li depletion in early stages of star evolution

$^{12}C(p,\gamma)^{13}N$ and $^{13}C(p,\gamma)^{14}N$ – relative abundance of ^{12}C-^{13}C in the deepest layers of H-rich envelopes of any star

Interest in a new $^{2}H(p,\gamma)^{3}He$ experiment



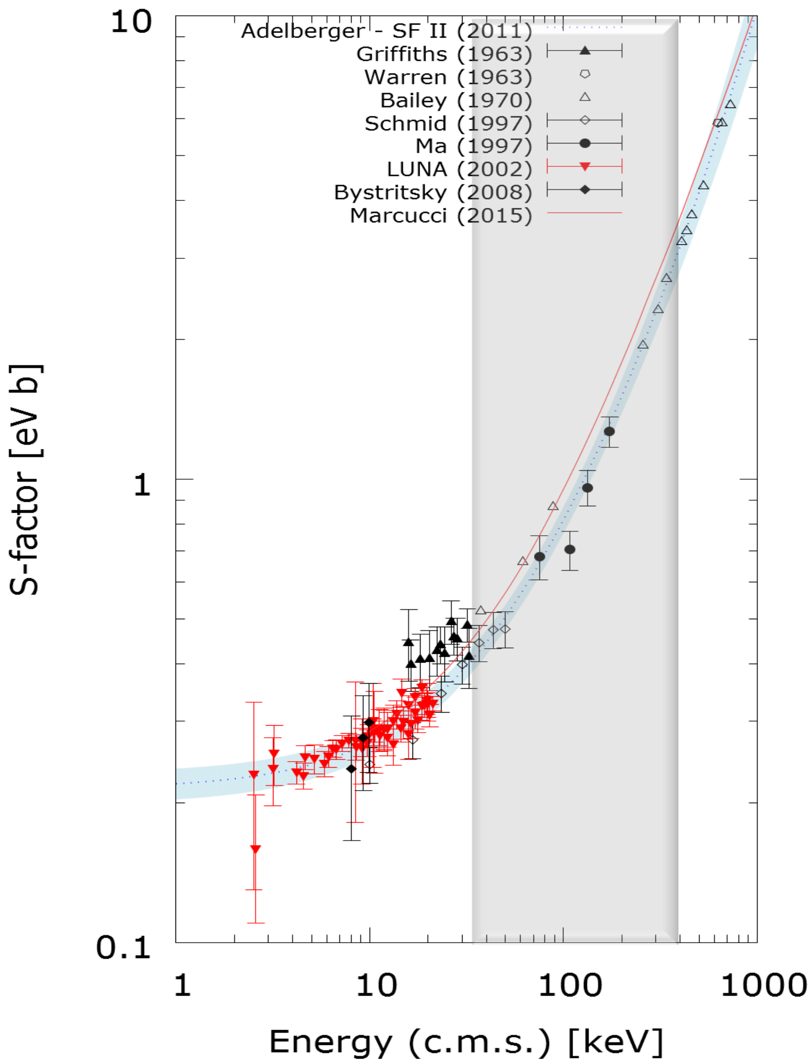
The error budget of computed abundance of deuterium is mainly due to the $d(p,\gamma)^{3}He$ reaction

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

*E. Di Valentino et al., Phys. Rev. D 90 (2014) 023543

- Precise low energy data coming from LUNA 50 kV
- Only a single dataset is currently available at the BBN energy range with a systematic error of 9%
- No perfect agreement with recent «Ab-initio» calculations

Interest in a new $^2H(p,\gamma)^3He$ experiment



The $^2H(p,\gamma)^3He$ reaction is of high interest also in <u>theoretical nuclear physics</u>, in particular for what concern "ab-initio" modelling, as light nuclei are involved in this process

There is a maximum discrepancy of 15% between theoretical predictions (red line) and the best fit of experimental data (blue band)

The difference between theory and the data let some author to adopt the theoretical curve or the S-factor value obtained from measurement.

**Marcucci 2016 Phys. Rev. Lett.*

**Adelberger 2011 Rev. Mod. Phys.*

Interest in a new $^2H(p,\gamma)^3He$ measurement

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

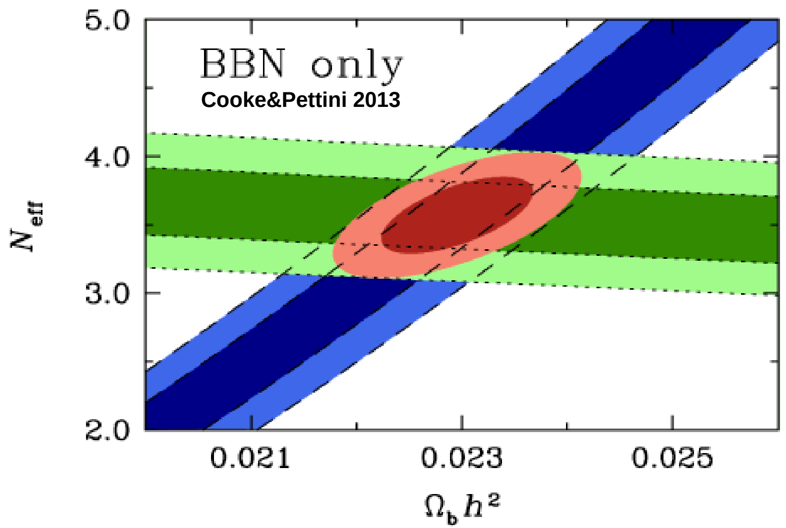
Assuming the Standard Model

- $100\Omega_{b,0}h^2$(CMB)= 2.22 ± 0.02 (PLANCK 201

d(p,γ)^{3}He data fit

- $100\Omega_{b,0}h^2$(BBN)= 2.20 ± 0.04 ± 0.02 (Cooke

D/H observations



Measurement goal:

Cross section at

30 keV < E_{cm}< 300 keV

with ~ (<) 5% accuracy

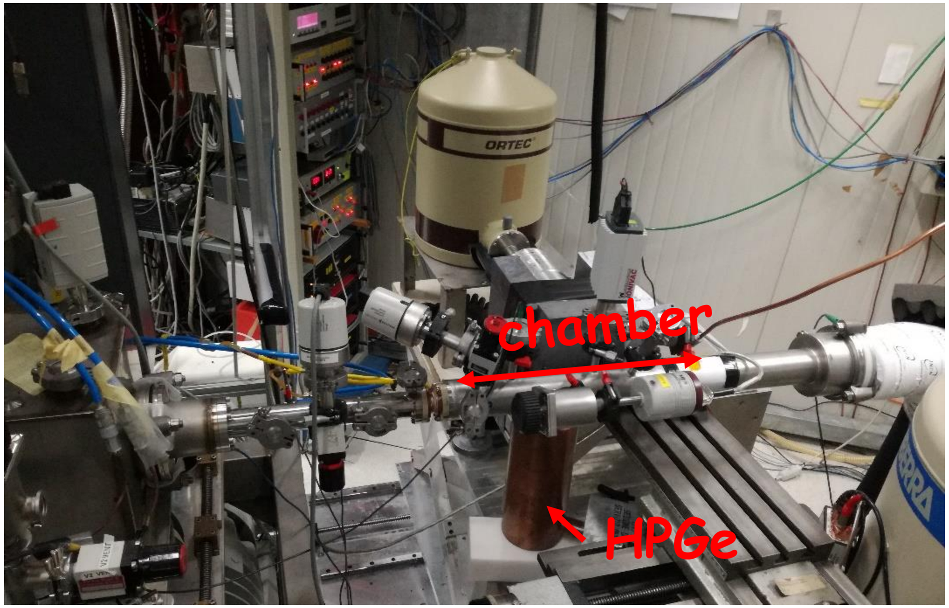
Physics:

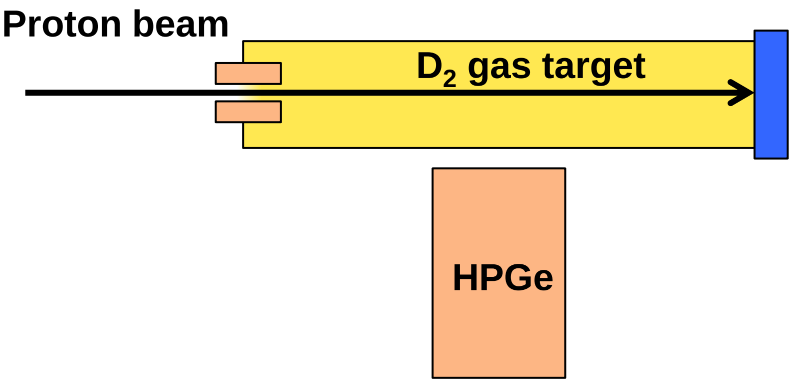
1. Cosmology: measurement of Ω_b
2. Cosmology : measurement of N_{eff}
3. Nuclear physics: comparison of data with "ab initio" predictions

The $^2H(p,\gamma)^3He$ *reaction at BBN energies at LUNA*

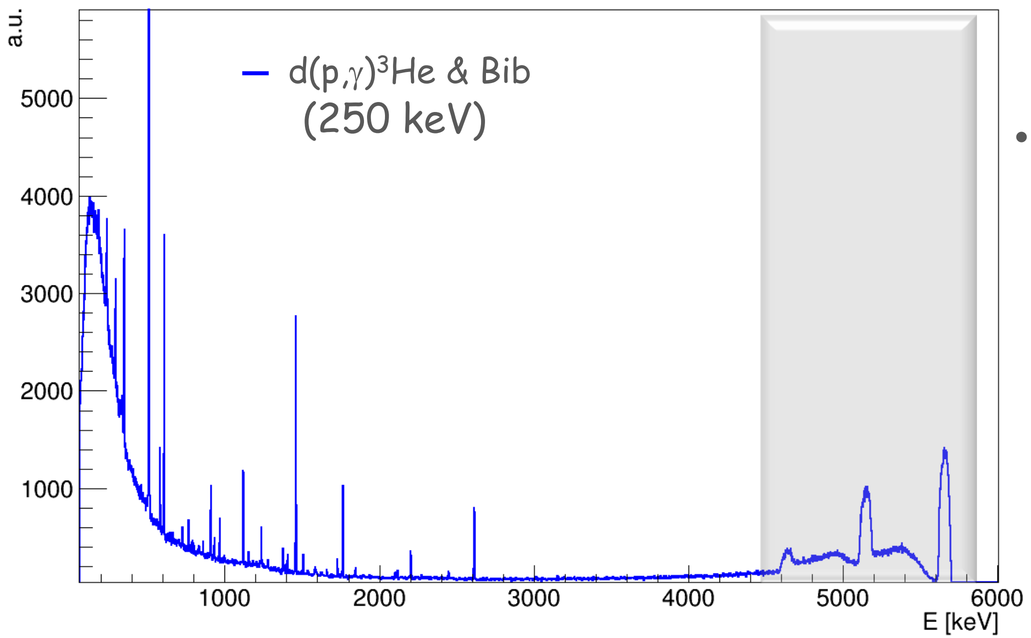
Gas target & HPGe setup

- High energy resolution in the total absorption peak < 0.10%
- Possibility of performing angular distribution measurements with extended gas target (33 cm)

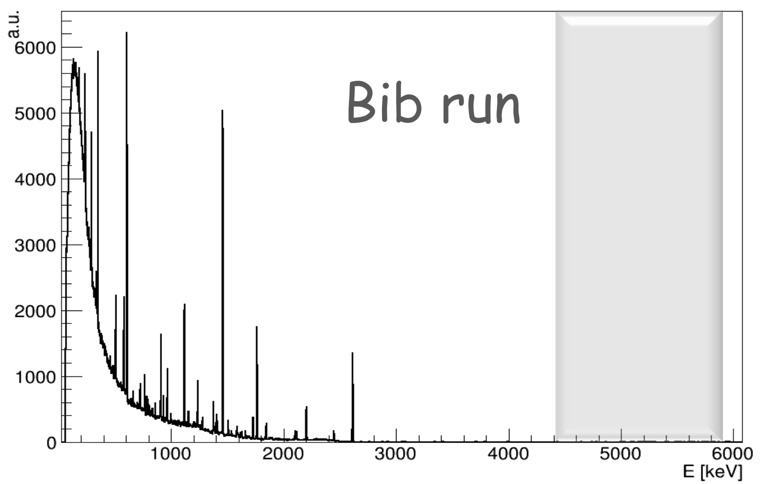




The $^2H(p,\gamma)^3He$ reaction at BBN energies at LUNA

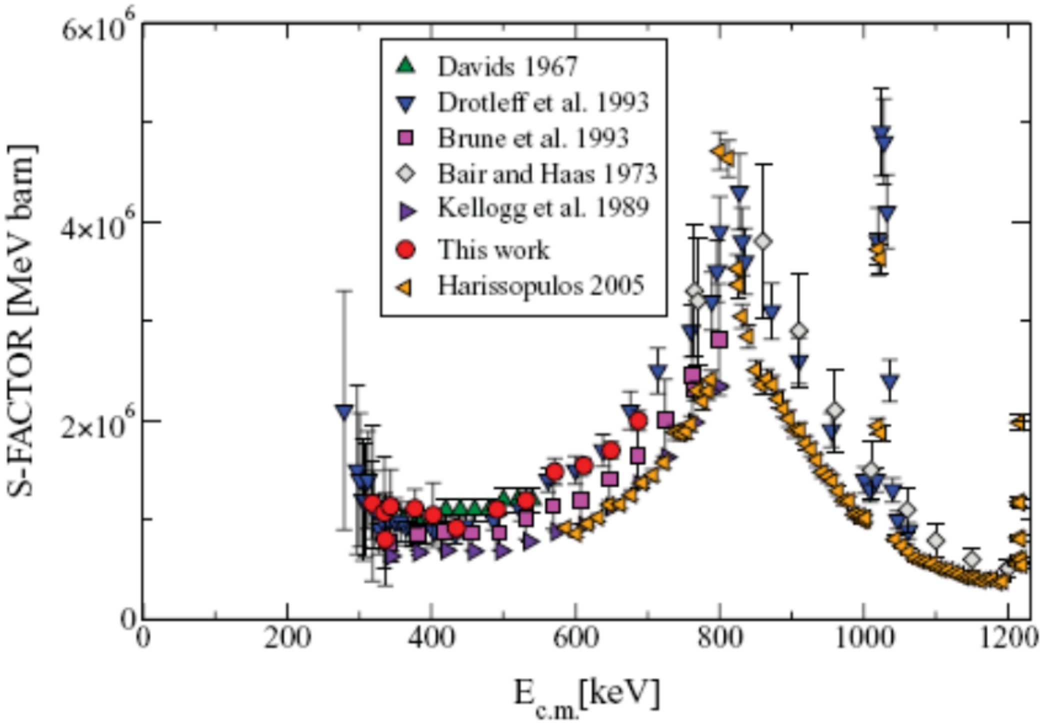


- $d(p,\gamma)^3He$ run at 0.3 mbar of pressure inside the chamber
- Beam induced background run in ^4He



Data taking on going!

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



M. HEIL *et al.*

PHYSICAL REVIEW C **78**, 025803 (2008)

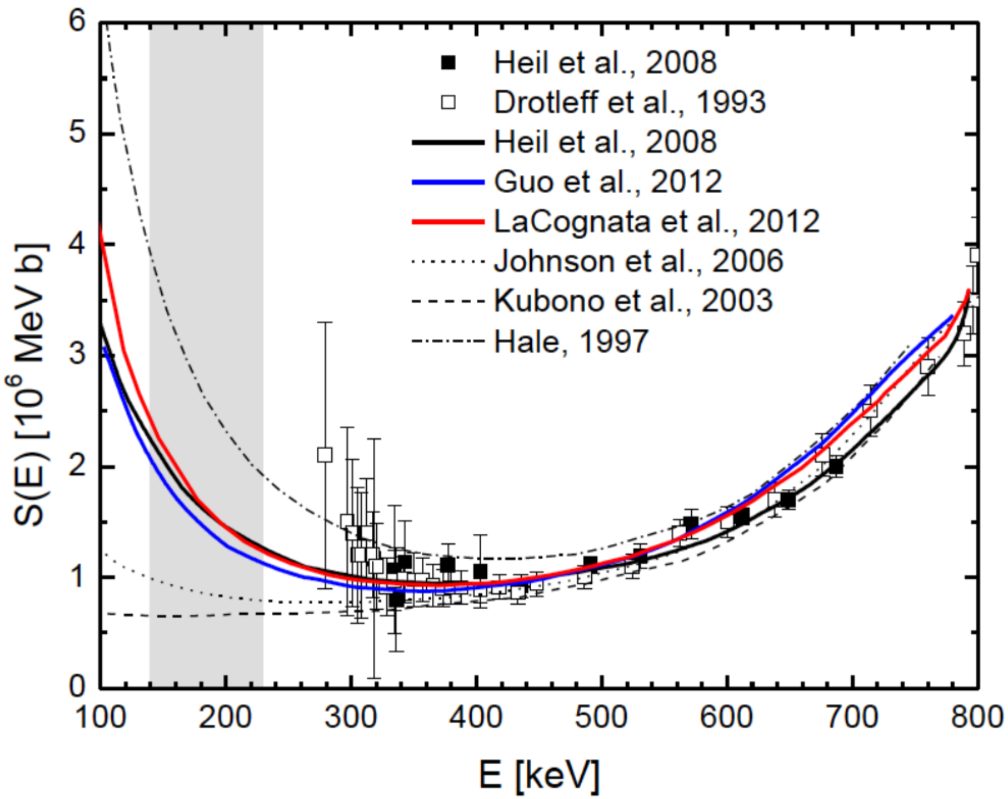
Q=2.216 MeV

<u>open issues for raw data:</u>

- large statistical uncertainties at low energies
- scattering in absolute normalization
- systematic (normalization) uncertainty
  - → Heil et al. do not quote common systematic uncertainty of the data set (only non-statistical)
  - → treatment in global analysis of Heil et al, questionable (not trivial anyway)

- final „global" data set by scaling of previous data to Heil et al. – systematic uncertainty not considered consistently
- electron screening: at lowest energy of Drotleff < 7% (in adiabatic limit) note: overestimated in Drotleff et al.

$^{13}C(\alpha,n)^{16}O$: extrapolation to the Gamow window



some conclusion:

- low energy data points do not constrain the fit with respect to the subthreshold resonance
- quoted uncertainties are large

→ probably also a mixture of systematic and statistical uncertainties, e.g. in Drotleff scattering of data is unexpectely small with respect to error bars

- most data point below E = 350 keV are higher than the fit curves, i.e. Heil R-matrix curve

→ indication for beam induced background?

Astrophysical requirements : uncertainty on S(E) < 10%

$^{13}C(\alpha,n)^{16}O$: expected reaction rate @ LUNA400

Target enrichment in ^{13}C: 99%, I_α = 200 μA

N_t = 10^{18} $2\ 10^{17}$ at/cm^2

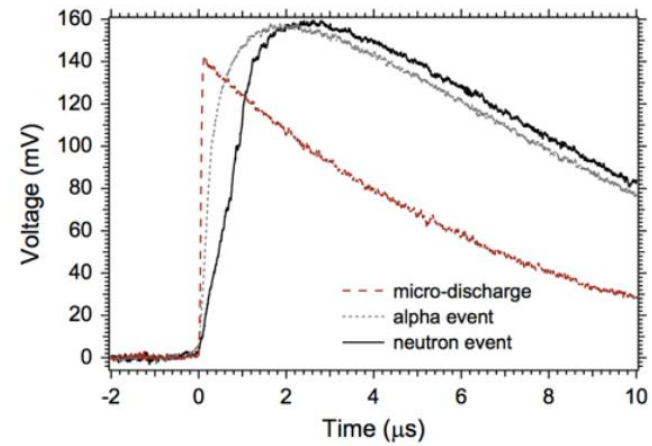
Elab [keV]	Ecm [keV]	Rate [neutr/h]	Rate [neutr/h]
400	306	339	121
375	287	103	38.5
350	268	28	10.9
300	229	1.3	0.6
275	210	**0.2**	**0.1**
250	191	**0.02**	**0.01**

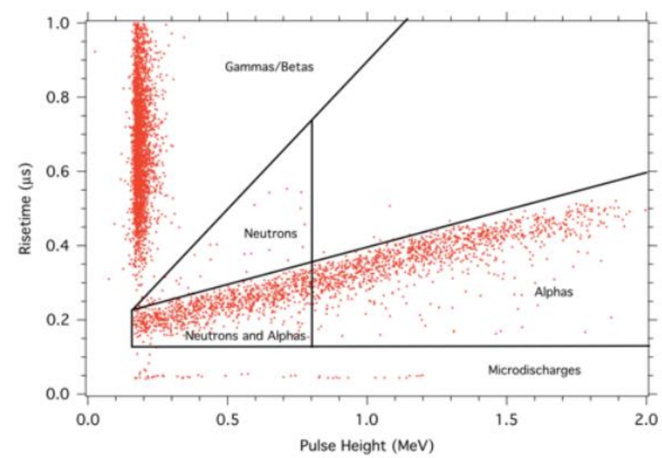
≈ 1-2 month beam time IF bck =0

$^{13}C(\alpha,n)^{16}O$: a new n-detector @ LUNA

Bck rate with standard ^{3}He tubes ~ 1cnt/counter/hour

- Alpha decays from counter compete with n signal
- New counter < 0.3 counts/counter/hour
- PSD can reject by factor of 50 /100





Nuclear Instruments and Methods in Physics Research A 717 (2013) 51–57

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Event identification in ^{3}He proportional counters using risetime discrimination

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$^{13}C(\alpha,n)^{16}O$ @ LUNA400: R&D on solid targets

ISTITUTO NAZIONALE di FISICA NUCLEARE sezione di BARI

Synthetic Diamond
- Ta + Au backings

Istituto Nazionale di Fisica Nucleare Sezione di Napoli

Polymerisation
- Ta and Cu

ISTITUTO ITALIANO DI TECNOLOGIA

Graphene
- top-down process graphite to graphene
- Cu + Au backing

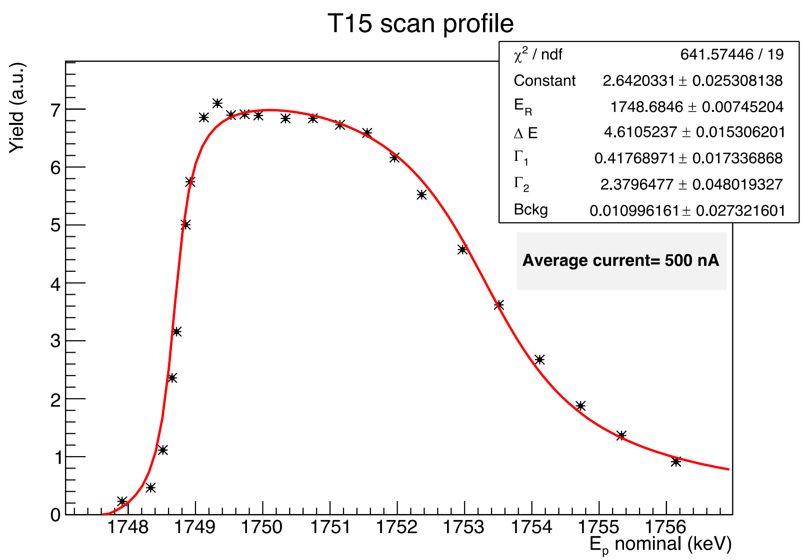
MTA atomki DEBRECEN

Electron Gun Evaporation
- under study

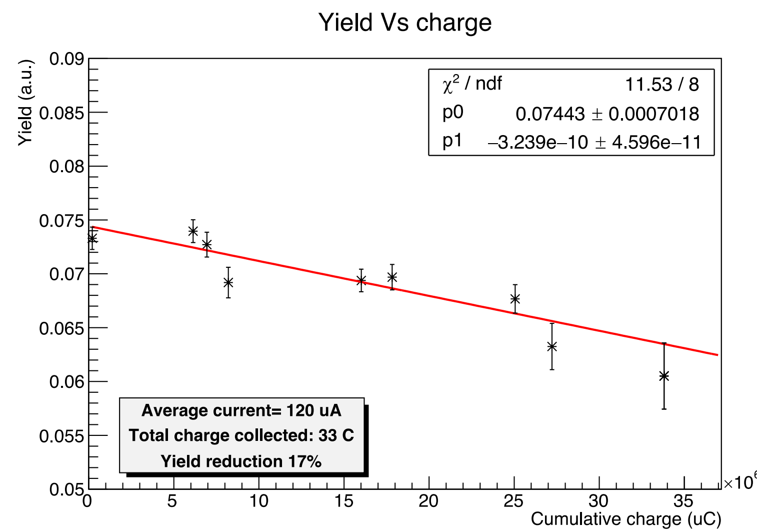
$^{13}C(\alpha,n)^{16}O$ @ LUNA400: R&D on solid targets

TARGETS

99% enriched ^{13}C evaporated on Tantalum with electron gun @ MTA ATOMKI (Debrecen, HU)



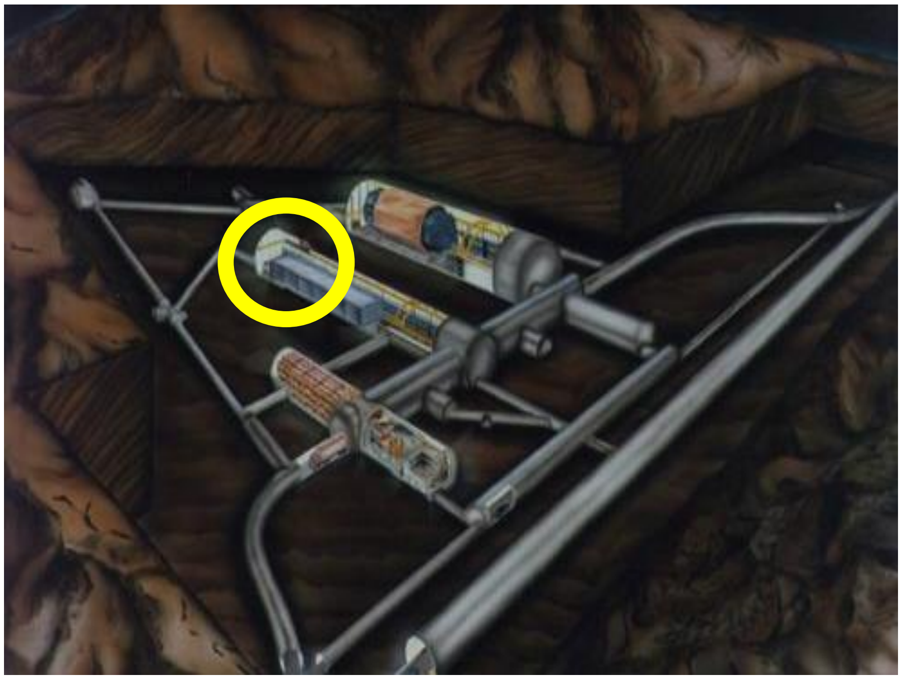
E_r = 1748 keV resonance scan @ ATOMKI



Good target stability with high current intensity proton beam @ LUNA (120 uA)
Ep = 310 KeV

LUNA-MV

LUNA MV will be installed in the North part of Hall B of LNGS

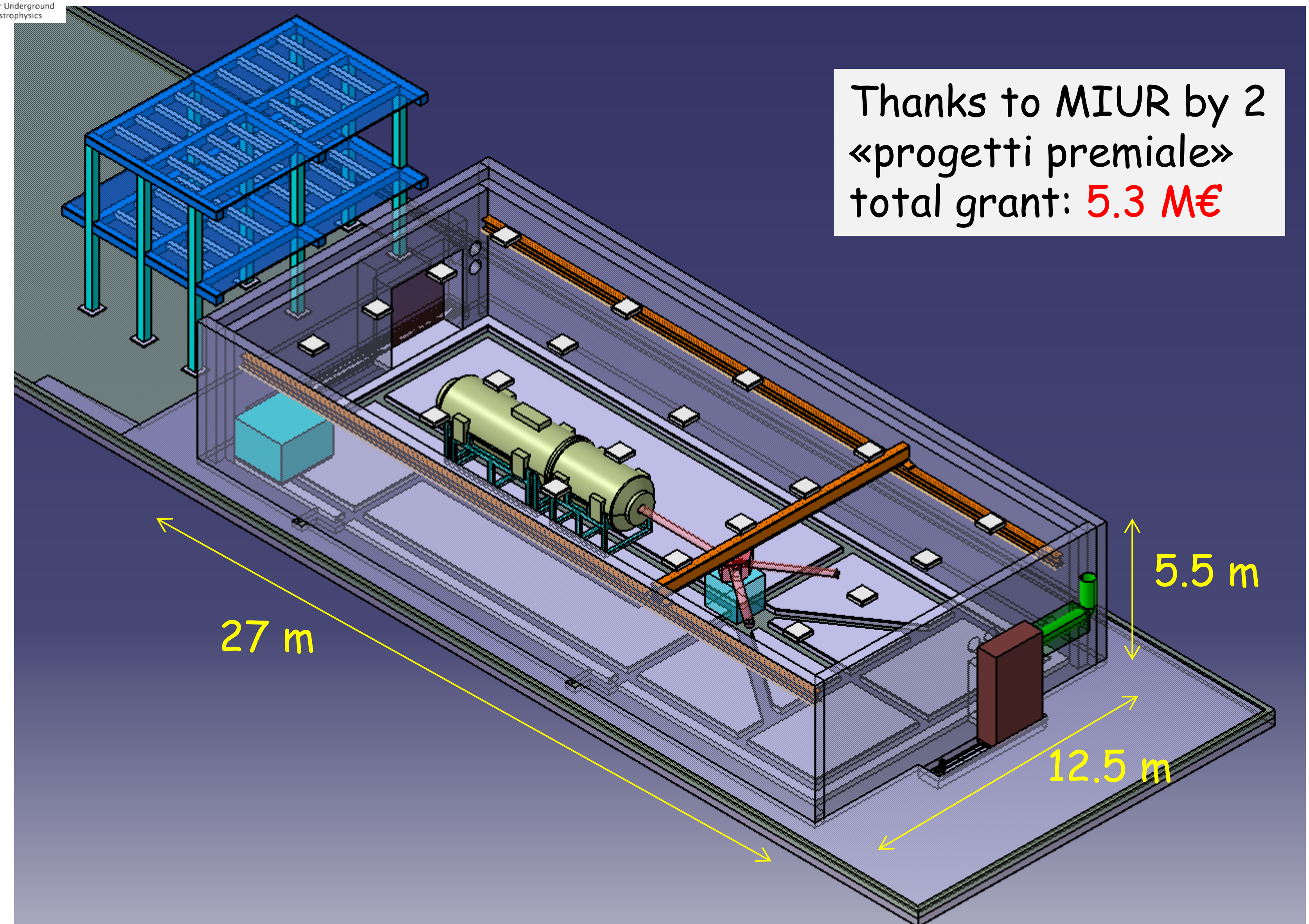


Hall B

(ICARUS decommissioning almost complete – some areas used for OPERA decommissioning storage)

The area so far allocated to ICARUS will be cleared within summer 2017

Layout of the new LUNA-MV facility (from 2018/2019)



Thanks to MIUR by 2 «progetti premiale» total grant: 5.3 M€

Accelerated species

12.1 ECR ion source Model SO-201

1. **Gas type:** **HELIUM**
   - Purity level: 99.999% (grade 5)
   - Bottle: Lecture bottle type LB including outlet valve CGA 180, capacity 0.4 liters, dimensions 51 mm OD x 375 mm OAL
   - Charging pressure: 150 bar

2. **Gas type:** **HYDROGEN**
   - Purity level: 99.999% (grade 5)
   - Bottle: Lecture bottle type LB including outlet valve CGA 180, capacity 0.4 liters, dimensions 51 mm OD x 375 mm OAL
   - Charging pressure: 150 bar

3. **Gas type:** **CARBON DIOXIDE**
   - Purity level: 99.995% (grade 4.5)
   - Bottle: Lecture bottle type LB including outlet valve CGA 180, capacity 0.4 liters, dimensions 51 mm OD x 375 mm OAL
   - Charging pressure: 120 bar

Thanks to the C beam ,
experiments in inverse cinematic will be possible

LUNA-MV basic performance

- Servicing interval : > 700 hrs (at max beam intensity (1000 uA))

- Annual operation capability : > 7400 hrs (at max beam intensity)

- Beam currents****

$^{1}H^{+}$ (TV: 0,3 – 0,5 MV)	: 500 eμA	(700 uA)
$^{1}H^{+}$ (TV: 0,5 – 3,5 MV)	: 1000 eμA	(1200 uA)
$^{4}He^{+}$ (TV: 0,3 – 0,5 MV)	: 300 eμA	(400 uA)
$^{4}He^{+}$ (TV: 0,5 – 3,5 MV)	: 500 eμA	(700 uA)
$^{12}C^{+}$ (TV: 0,3 – 0,5 MV)	: 100 eμA	(120 uA)
$^{12}C^{+}$ (TV: 0,5 – 3,5 MV)	: 150 eμA	(200 uA)
$^{12}C^{2+}$ (TV: 0,5 – 3,5 MV)	: 100 eμA	(100 uA)

- Terminal voltage Ripple (Rms) : 20 -80 V

- Precision of terminal voltage reading : 350 V

- Beam energy reproducibility : 1e-4 * TV or 50V, whichever is higher

- Beam energy stability (1 hrs)** : 1e-5 * TV or 20V, whichever is higher

- Beam current stability (1 hrs)*** : 5% guaranteed
: 2% estimated
: 1% (using feedback of target current)

- Beam current stability (1 min)*** : 2%

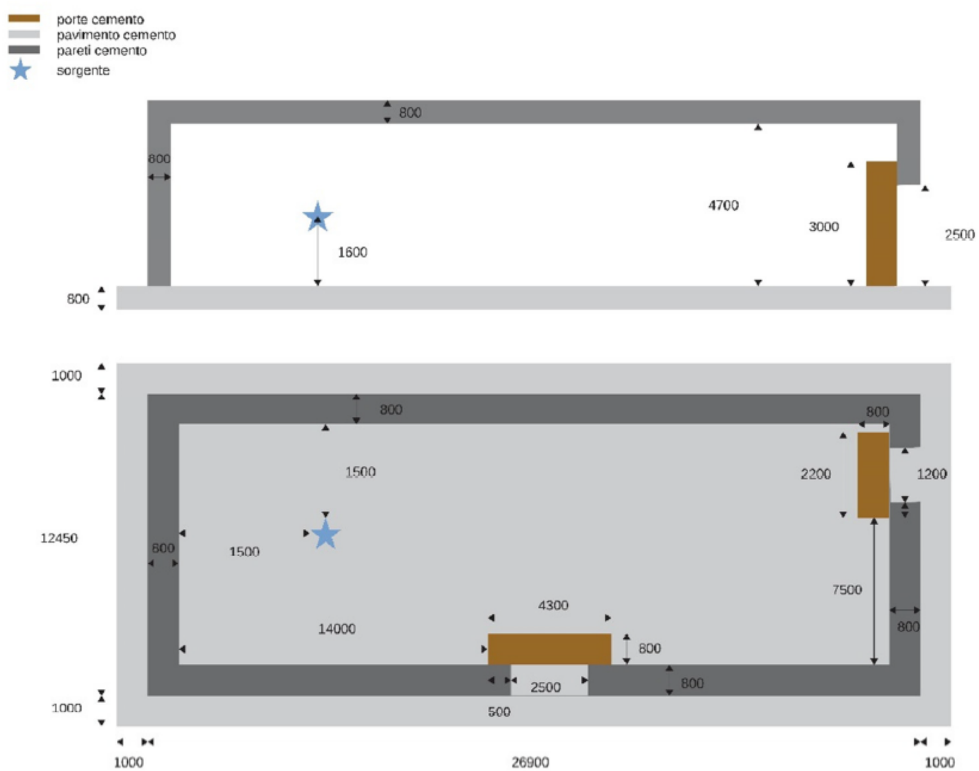
The accelerator and the neutron shielding

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

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

$^{12}C^{+}$ (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
- **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

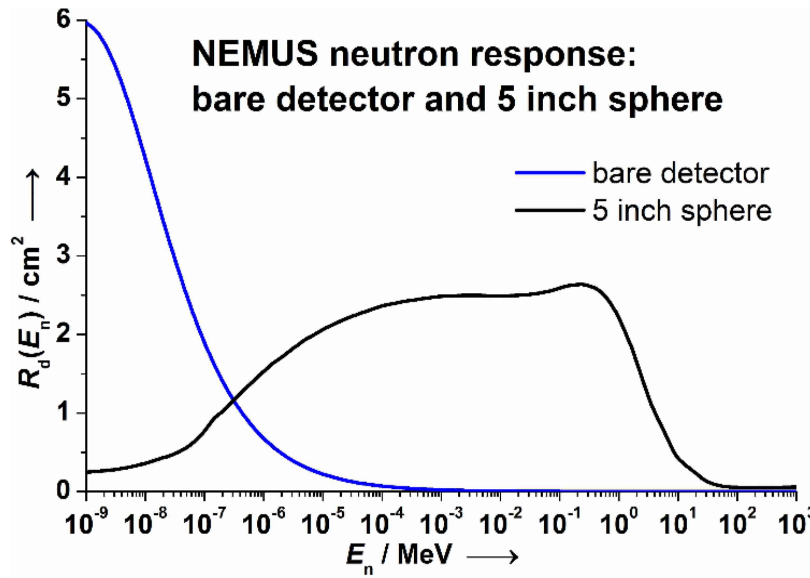
MCNP: $\Phi_n = 1.38\ 10^{-7}$ n/(cm^2 s)
GEANT4: $\Phi_n = 3.40\ 10^{-7}$ n/(cm^2 s)

Φ_n(LNGS) = 3 10^{-6} n/(cm^2 s)

Preliminary neutron flux monitoring in Hall B

BONNER SPHERE SPECTROMETER

PTB (Physikalisch-Technische Bundesanstalt) property and certification



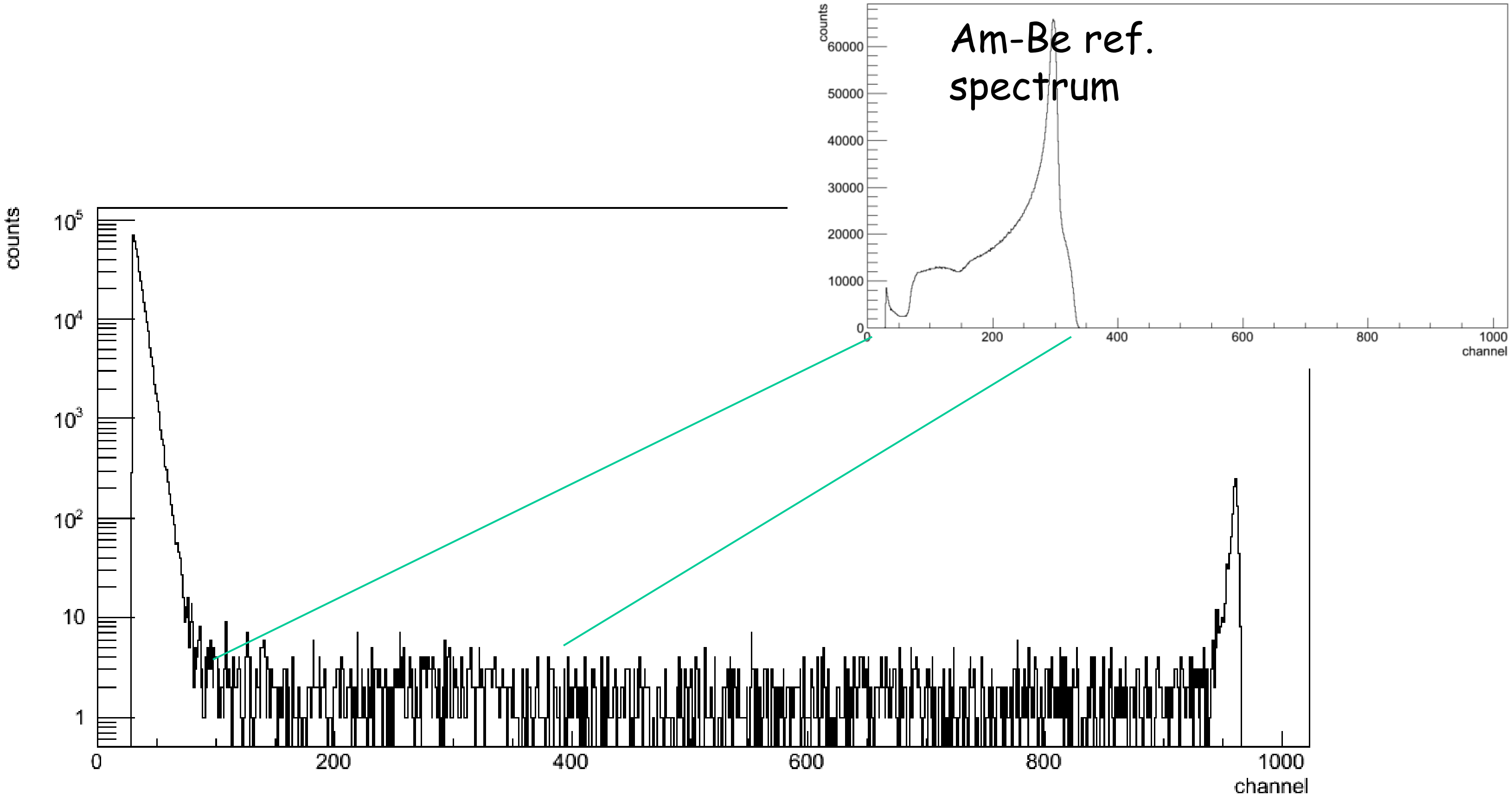
^3He detector for thermal neutrons

Data taking started Oct 20th 2016…still ongoing !

Neutron flux monitoring in Hall B
(first 142 days)

Net counts in RoI = 157 ± 26

Mean neutron flux ≈ (6.4 ± 2.0) 10^{-6} n/(cm^2 s)



LUNA-MV : basic schedule

Action	Date
Approval of the first HVEE technical design	October 2016
Opening of the tendering procedure for LUNA-MV plants	November 2016
Submission of the Authorization request to «Prefettura dell'Aquila»	December 2016
Beginning of the clearing works in Hall B	February 2017
End of the tendering procedure for the new LUNA-MV building	June 2017
Beginning of the construction works in Hall B	September 2017
End of the tendering procedure for LUNA-MV plants	October 2017
Beginning of the construction of the plants in the LUNA-MV building	December 2017
Completion of the new LUNA-MV building and plants	April 2018
In-house acceptance test for the new LUNA-MV accelerator	May 2018
LUNA-MV accelerator delivering at LNGS	July 2018
Conclusion of the commissioning phase	December 2018
Beginning First Experiment	January 2019

LUNA MV- scientific program (2018 → 2022)

Commissioning measurement: $^{14}N(p,\gamma)^{15}O$. High scientific interest for revised data covering a wide energy range (400 keV- 3.5 MeV). Scientific results of high impact but reduced risk immediately after commissioning phase

$^{12}C+^{12}C$: solid state target. Gamma and particle detectors

$^{13}C(\alpha,n)^{16}O$: enriched ^{13}C solid or gas target. Neutron detector

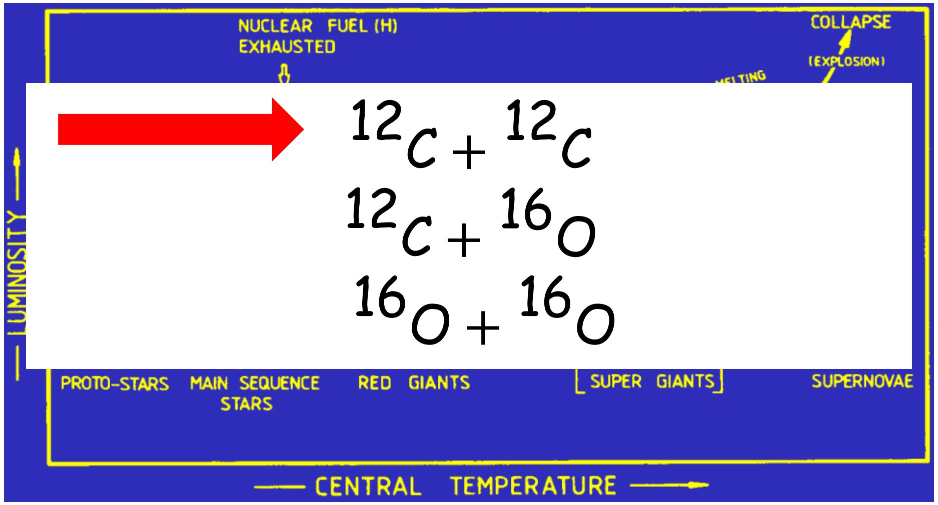
Data taking at LUNA 400 kV in 2017-2018.

$^{22}Ne(\alpha,n)^{25}Mg$: enriched ^{22}Ne gas target. Neutron detector.

Next steps (not before 2023…):

$^{12}C(\alpha,\gamma)^{16}O$: ^{12}C solid target depleted in ^{13}C and alpha beam or α jet gas target and ^{12}C beam.

Carbon burning: toward the final fate of the stars



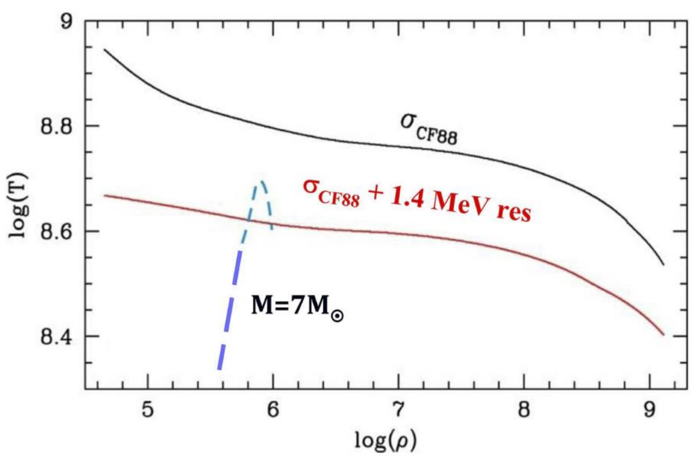
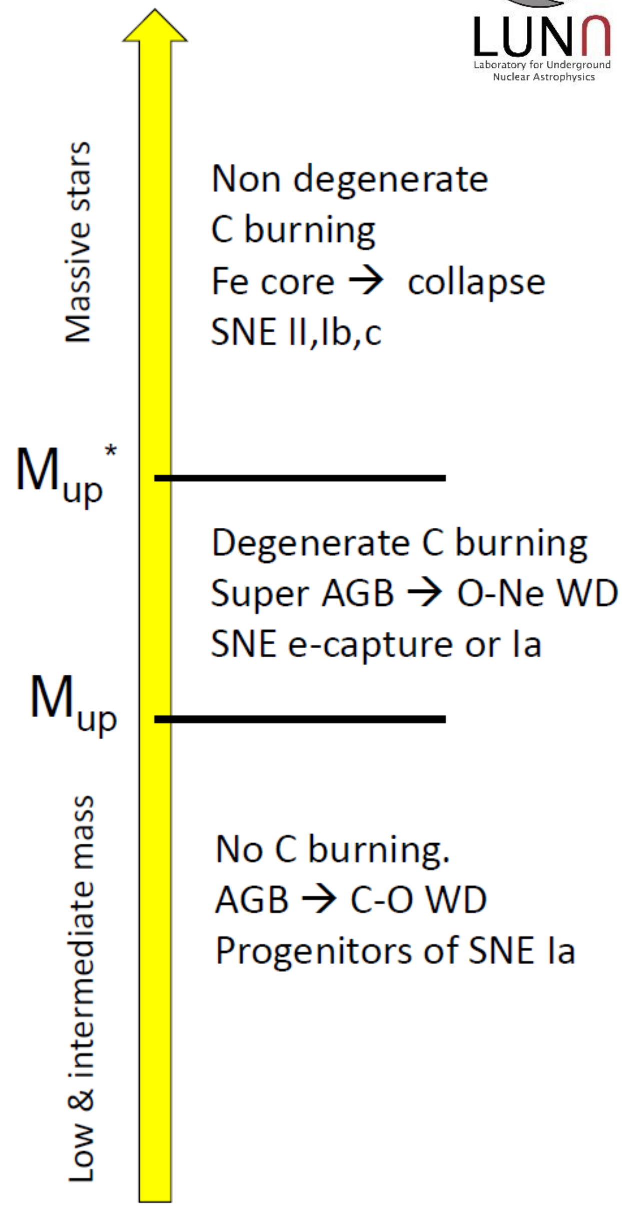


Figure 5: C ignition curves with different $^{12}C+^{12}C$ as defined as the loci where the rate of nuclear energy production ($^{12}C+^{12}C$) is equal to the rate of plasma-neutrino energy loss (solid line). C burning occurs when the (T,ρ) in the stellar core cross this line. Different $^{12}C+^{12}C$ rate have been used: Caughlan and Fowler 1988 (CF88, black line) and CF88 plus the artificial contribution from a low energy (1.4 MeV) resonance. The dashed line show the evolutionary track of the maximum temperature layer in the core of a star with initial mass 7 $M_\odot$. For this particular model, the conditions for the C ignition are attained only if the artificial contribution to the $^{12}C+^{12}C$ rate is included.

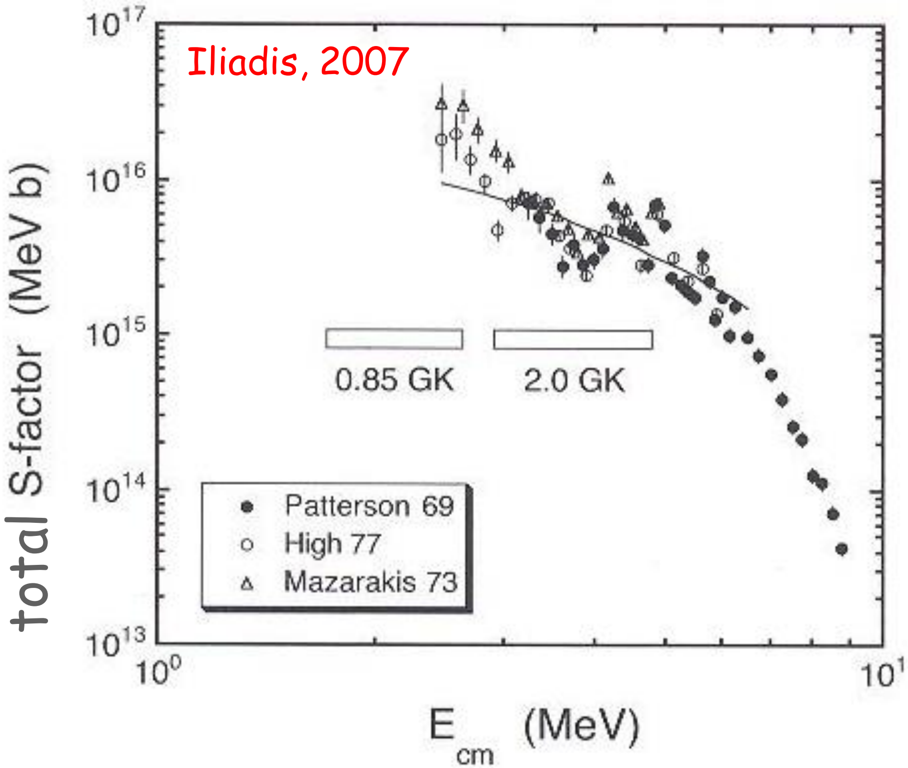


The challenging measurement of $\sigma(^{12}C+^{12}C)$

$^{12}C(^{12}C,p)^{23}Na$ Q= 2.241 MeV

$^{12}C(^{12}C,\alpha)^{20}Ne$ Q= 4.617 MeV

$^{12}C(^{12}C,n)^{23}Mg$ Q= -2.599 MeV



LUNA-MV proposal, 2016

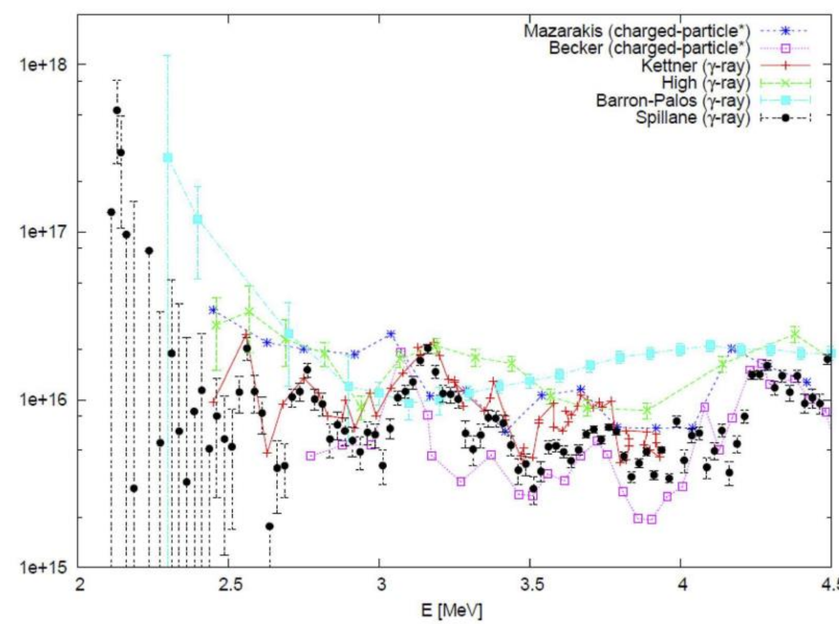


Figure 6: Modified astrophysical S factor relative to the 1634 keV transition (i.e., the de-excitation of the first excited state of ^{20}Ne populated by the $^{12}C(^{12}C,\alpha)^{20}Ne$ reaction).

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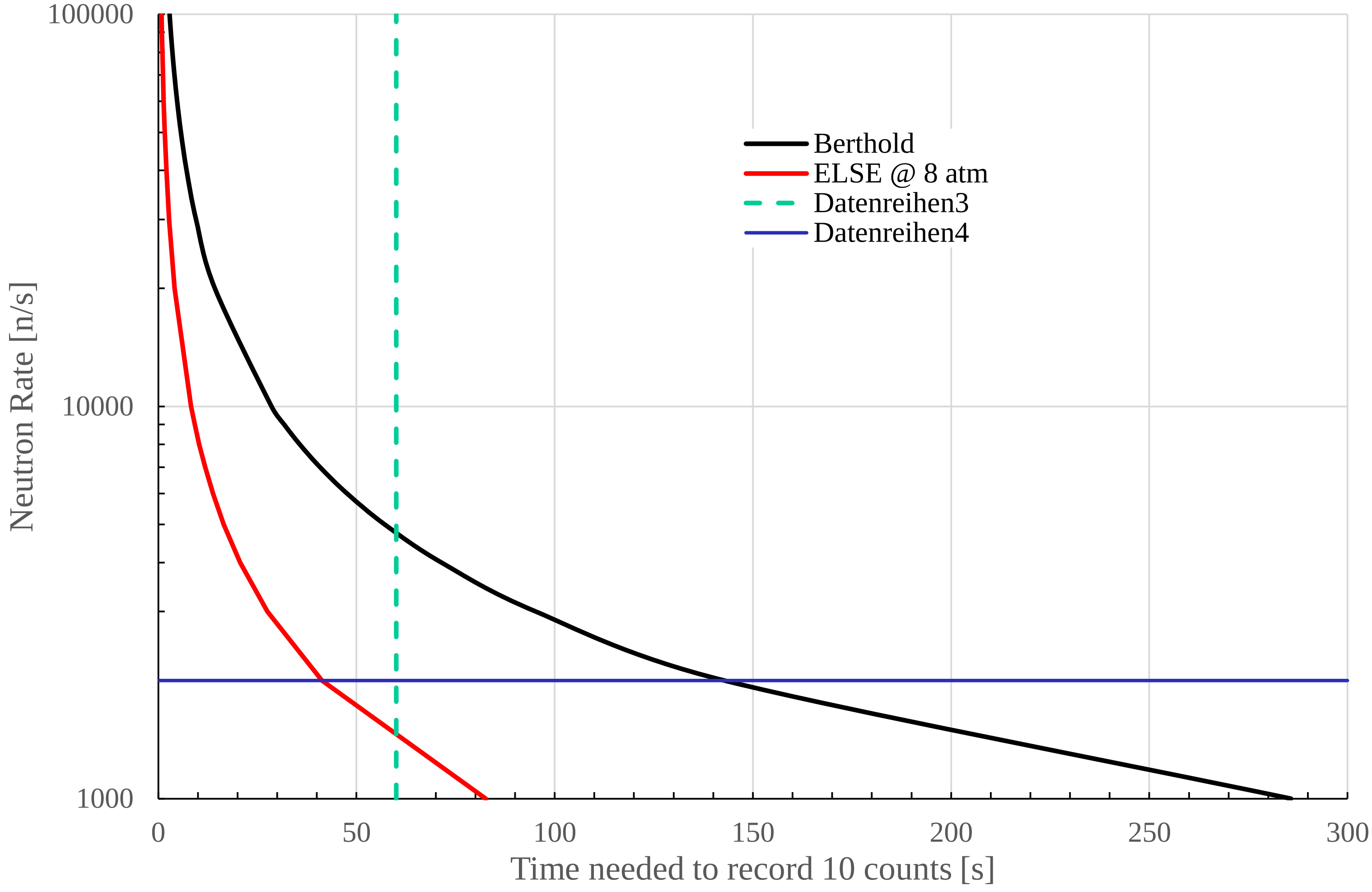
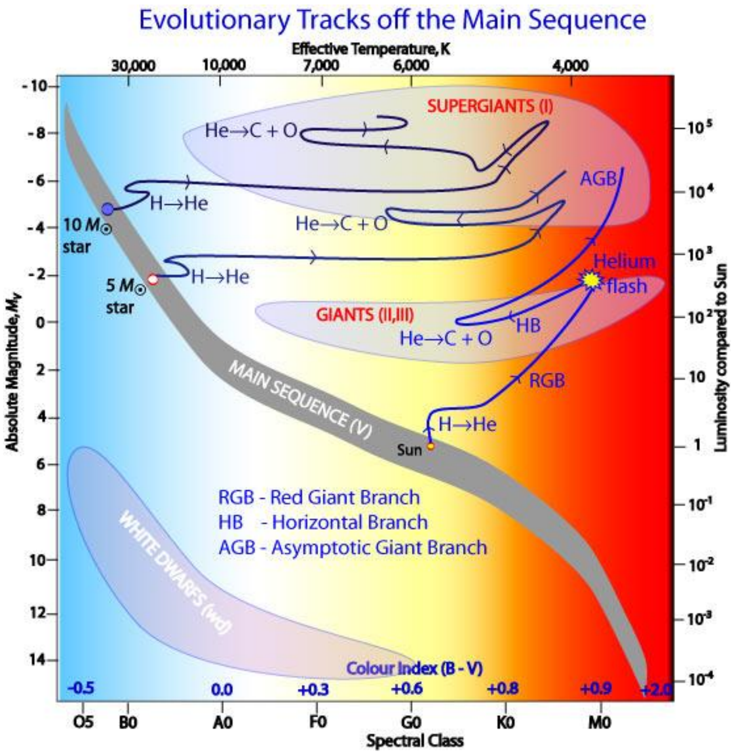
LUNA-MV: neutron flux momitoring

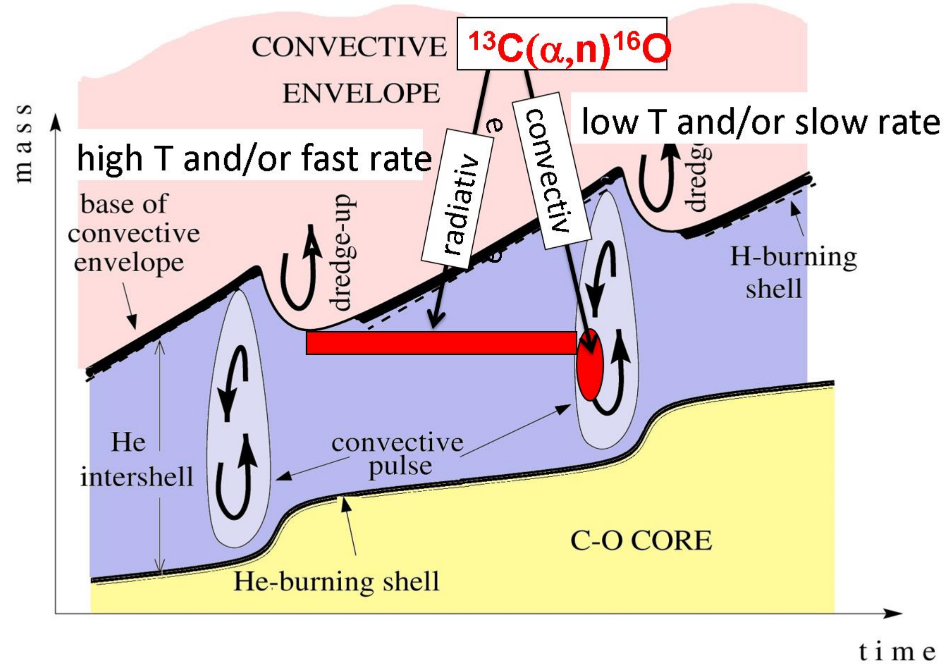


$^{13}C(\alpha,n)^{16}O$: astrophysical impact

The reaction takes place in thermally pulsating, low-mass, Asymptotic Giant Branch stars at Gamow energies **E = 140 -230 keV** (T = 90 10^6 K).
The cosmic creation of roughly half of all elements heavier than iron, occurs in AGB stars, where the neutrons necessary to drive the slow neutron-capture (s) process are released by the $^{13}C(\alpha,n)$.

Radiativ: i.e inter-pulse→ lower n density
Convective: i.e partially in-pulse→ higher n density

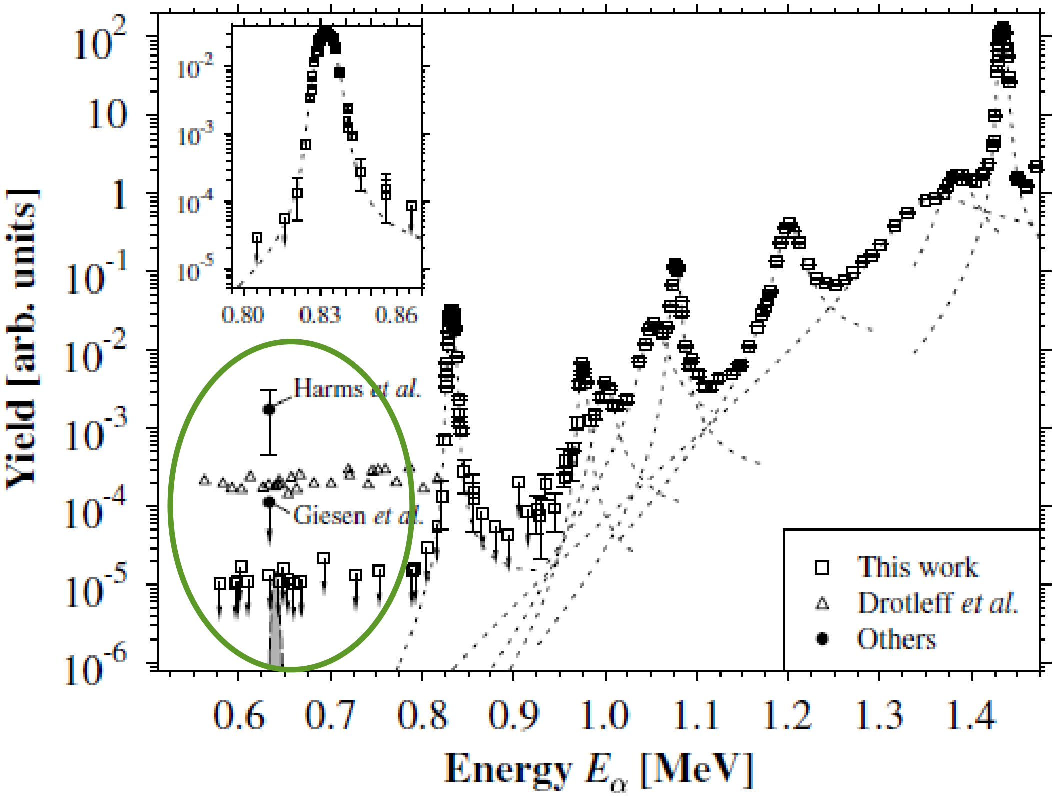


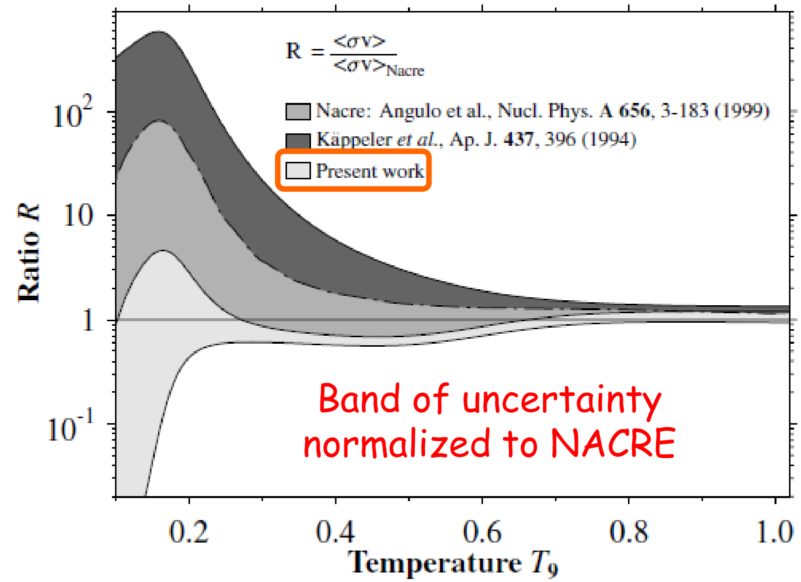


The neutron source in massive stars: $^{22}Ne(\alpha,n)^{25}Mg$

Jaeger et al. (2001)

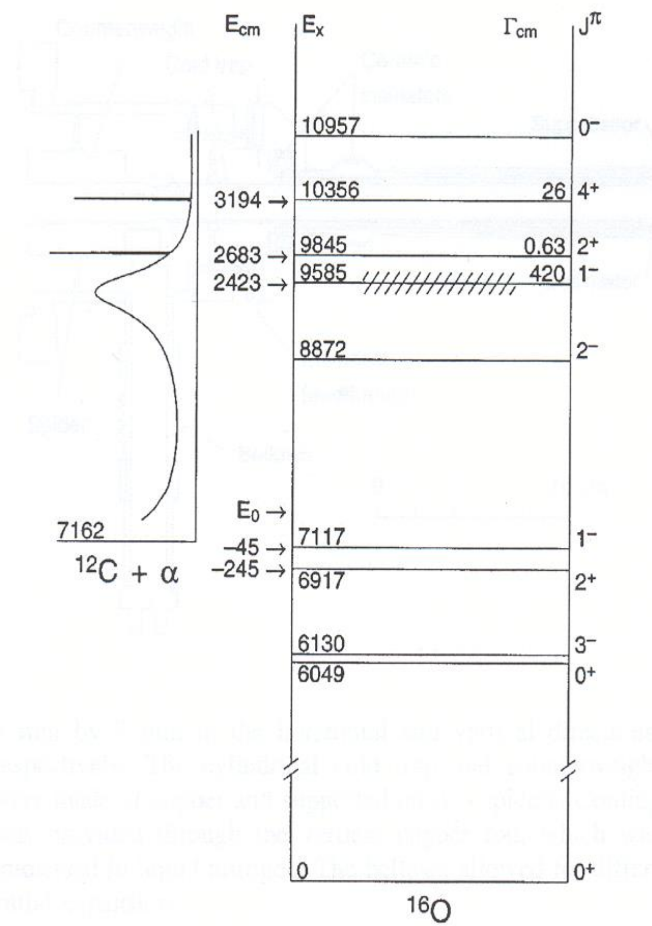
E_{th} = 560 keV



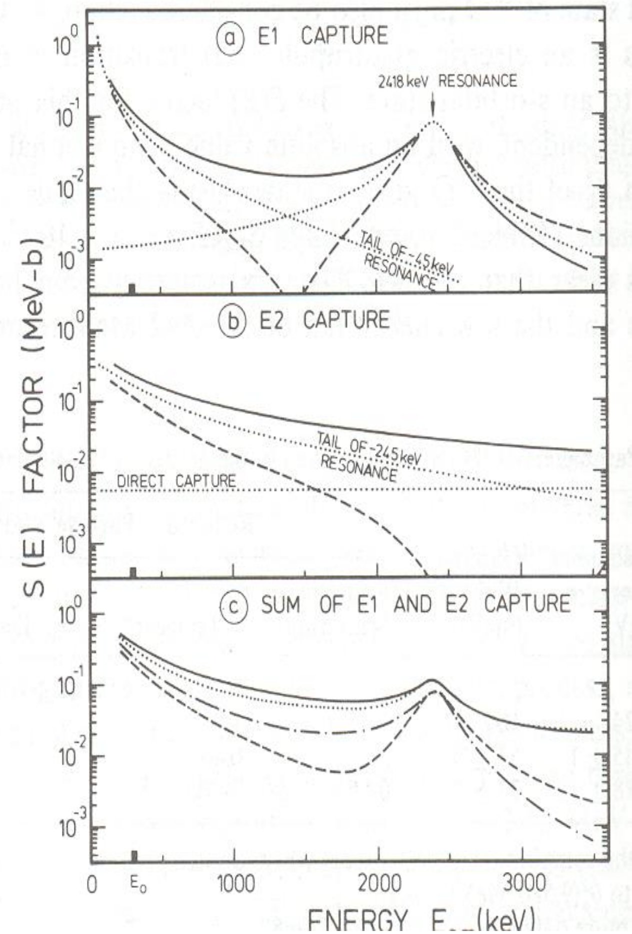


- Large uncertainties in the reaction rate
- Resonance at $E_{r,lab}$ = 635 keV corr. to E_{level} = 11152 keV?

$^{12}C(\alpha,\gamma)^{16}O$:Reaction Mechanism



$\sigma(E_0)$ is expected to be dominated by E1 transition due to a broad 1^- state (E_x=9585 keV, E_{cm}=2423 keV) and to the high energy tail of the sub-threshold 1^- state (E_x=7117 keV, E_{cm}=-45 keV). An E2 transition comes from a 2^+ state (E_x=6917 keV, E_{cm}=-245 keV). Direct capture also plays a role. E1 and E2 are expected to be comparable at E_0.

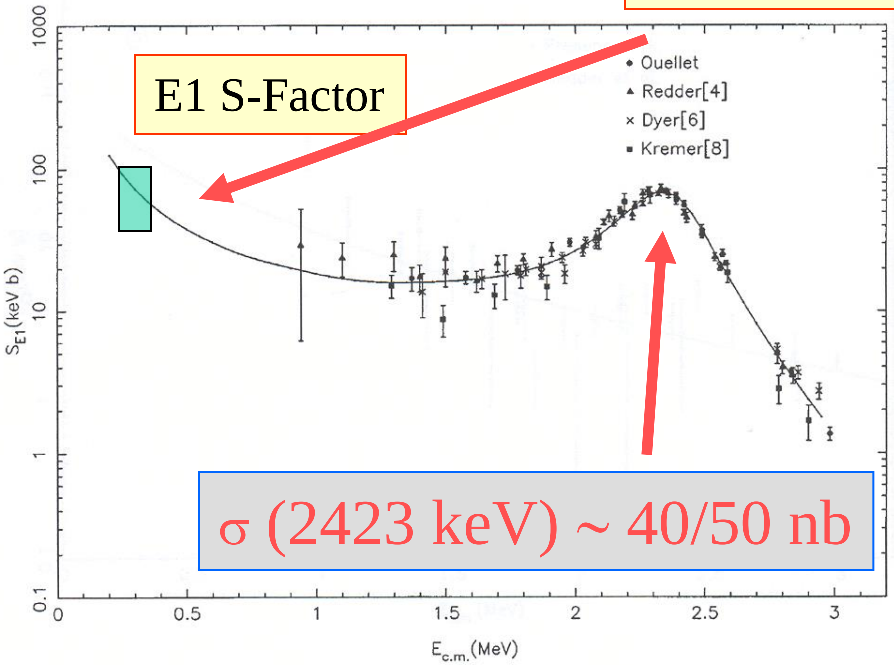


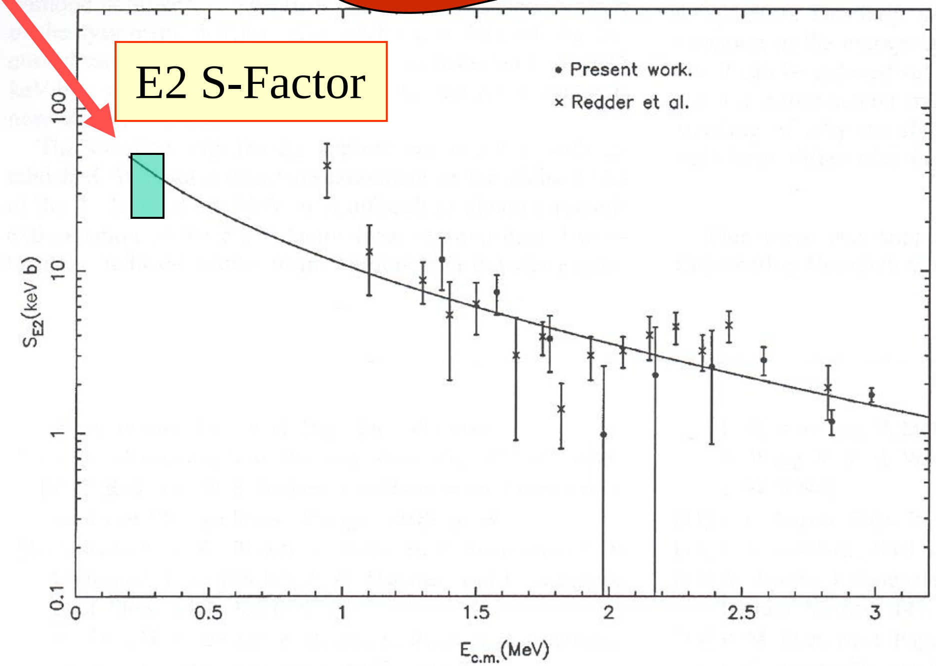
Rolfs & Rodney: Cauldrons in the cosmos

$^{12}C(\alpha,\gamma)^{16}O$: literature data for the S-factor

4 reaction/month with I ~ 1 mA !!!!

σ(300 keV) ~ 10^{-8} nb





Ouellet et al. Phy. Rev. C 54 4 (1996) 1982-1998

Lowest energy directly investigated: 940 keV c.m.

LUNA and the others

	Bck.	Acceler.	Beam intensity	Program	Expected start	Notes
LUNA	LNGS	LUNA 400	~300 μA	$^{13}C(\alpha,n)$ et al.,	2017	Solid target
JUNA	~ 2 OoM better	400 kV – ECR	10 mA !	$^{25}Mg(p,\gamma)$ $^{13}C(\alpha,n)$ $^{12}C(\alpha,\gamma)$	Mid 2016 2019	Gas target + ^{3}He tubes in liq. Scint.
CASPAR	~ LUNA	Old 1 MV	150 μA	$^{14}N(p,\gamma)$? $^{13}C(\alpha,n)$ $^{22}Ne(\alpha,n)$	Mid 2016 ? ?	Gas target + ^{3}He tubes
LUNA MV	LNGS	3.5 MV + ECR	1 mA	$^{14}N(p,\gamma)$? $^{13}C(\alpha,n)$ $^{22}Ne(\alpha,n)$ $^{12}C(\alpha,\gamma)$ $^{12}C + ^{12}C$	2019 ? ? ? ?	

Starting from 2016 LUNA will be no more alone !