Underground laboratories

496. Wilhelm und Else Heraeus - Seminar
„Astrophysics with
modern small-scale accelerators“
Bad Honnef, 07.02.2012

Daniel Bemmerer
for the LUNA collaboration

Underground laboratories

The quest for precision data on the Sun

Cross section measurements underground: LUNA at Gran Sasso

- The ^{3}He(α,γ)^{7}Be reaction
- The ^{14}N(p,γ)^{15}O reaction
- The ^{25}Mg(p,γ)^{26}Al reaction

But why is the background actually so low when you go underground?

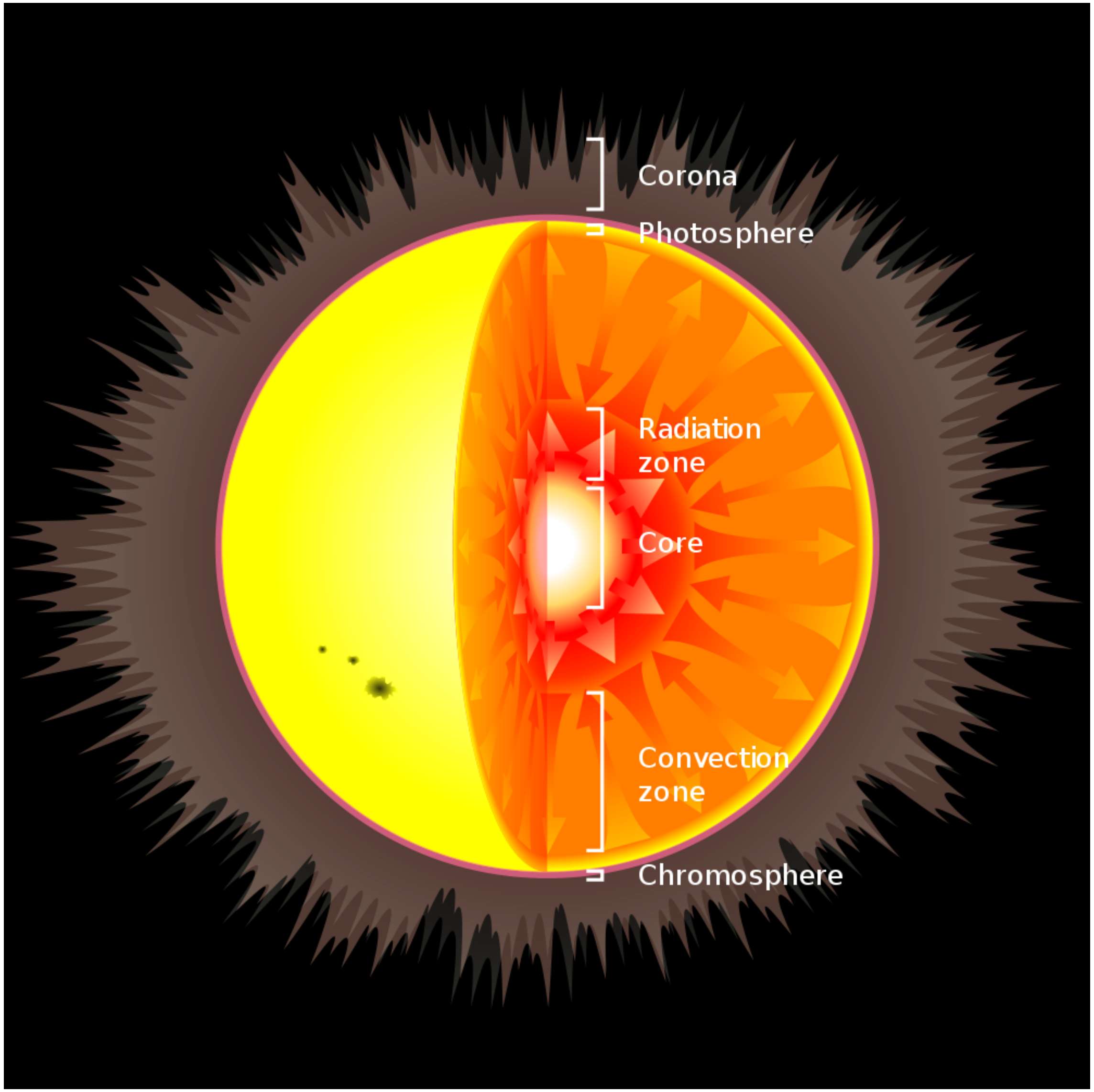
The future of underground accelerator laboratories

- Science case for future underground accelerator work
- Possible future underground accelerators in Europe

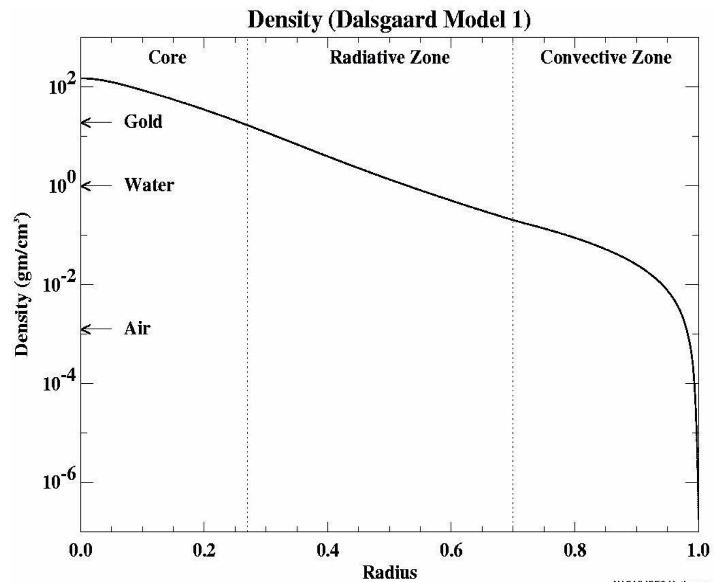
Synergies between underground and overground laboratories

- The ^{14}N(p,γ)^{15}O reaction at higher energies
- The ^{144}Sm(γ,α)^{140}Pr reaction and the astrophysical p-process

Structure of the Sun red: Observable



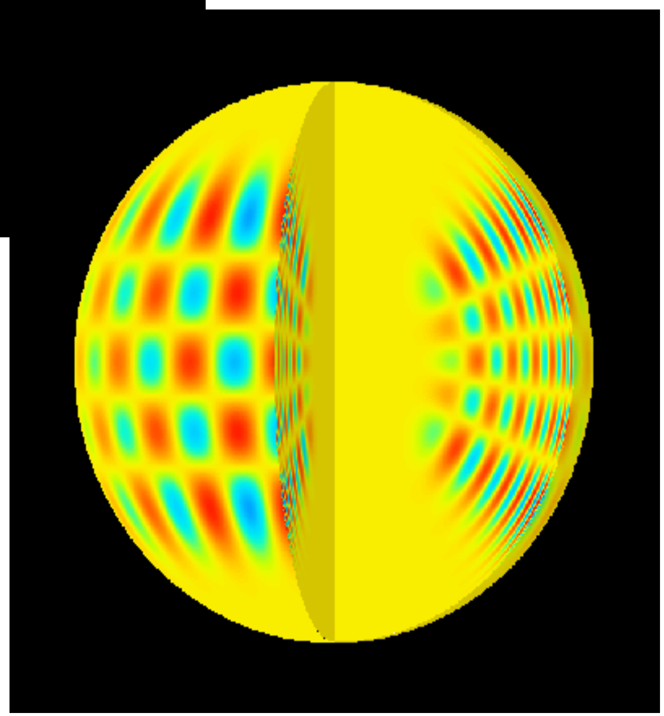
- Corona
- Chromosphere
- Photosphere
  Fraunhofer lines
- Convection zone
  p-modes (helioseismology)
- Radiation zone
- Core
  Neutrinos

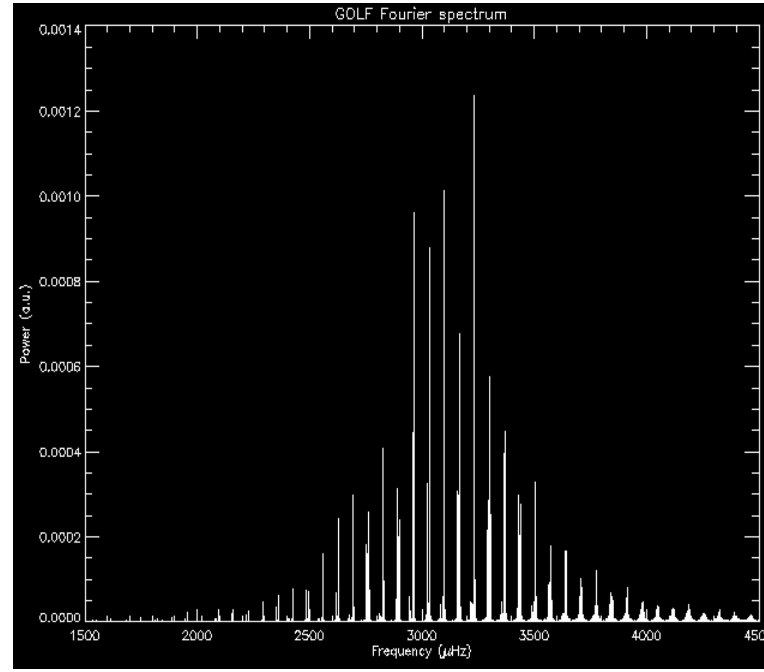


Data on the Sun (1): Helioseismology

Satellite “SoHo”

(Solar and Heliospheric Observatory)



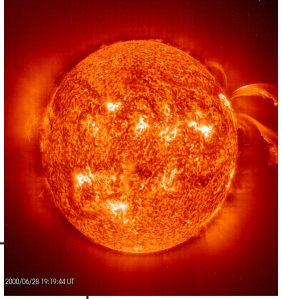


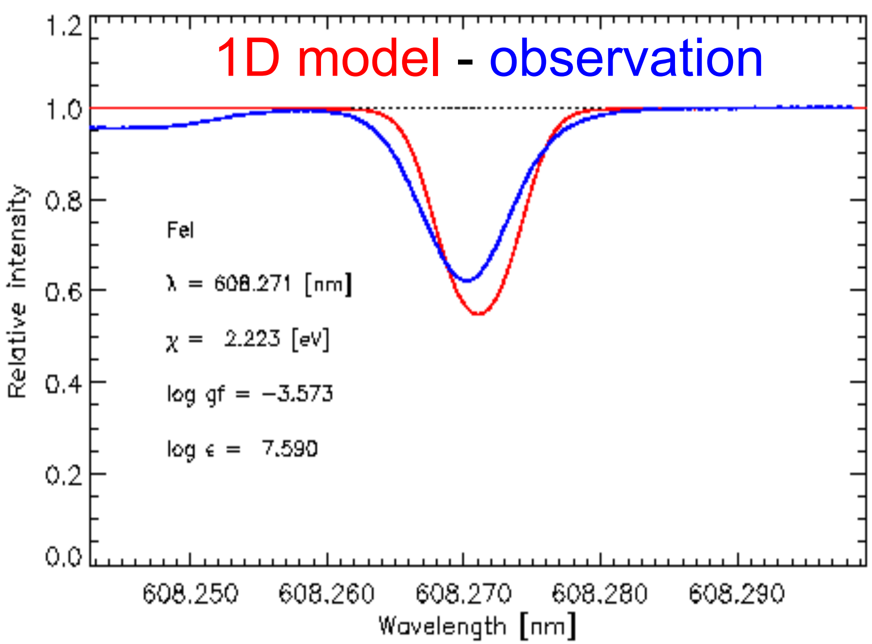
Fourier transformed spectrum from GOLF instrument on SoHo

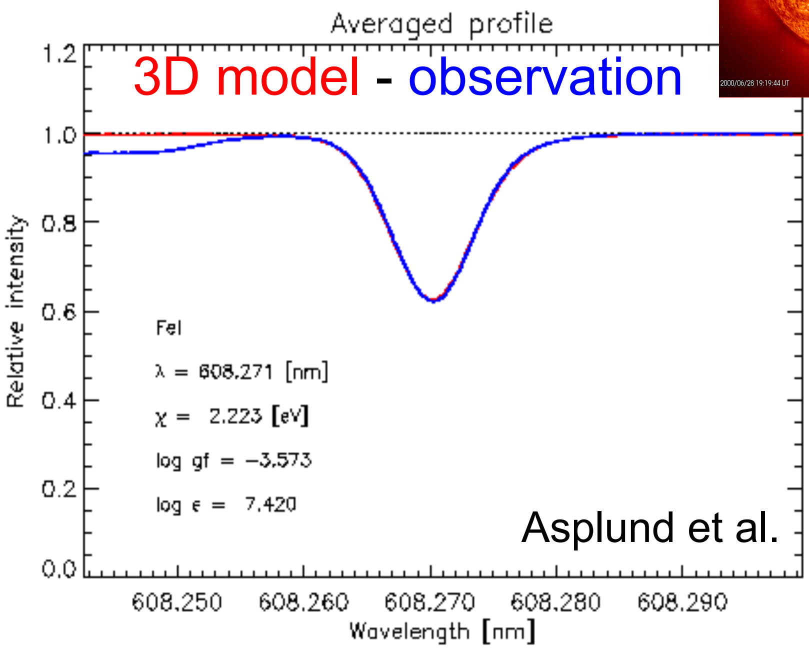
Simulated standing waves, p-mode ~3 mHz

Data on the Sun (2): Elemental abundances

from the model-based interpretation of the Fraunhofer lines







3-dimensional models of the photosphere lead to lower derived abundances:

1D: 2.29% (by mass) of the Sun are "metals" (Li...U)

3D: 1.78% (by mass) of the Sun are "metals" (Li...U)

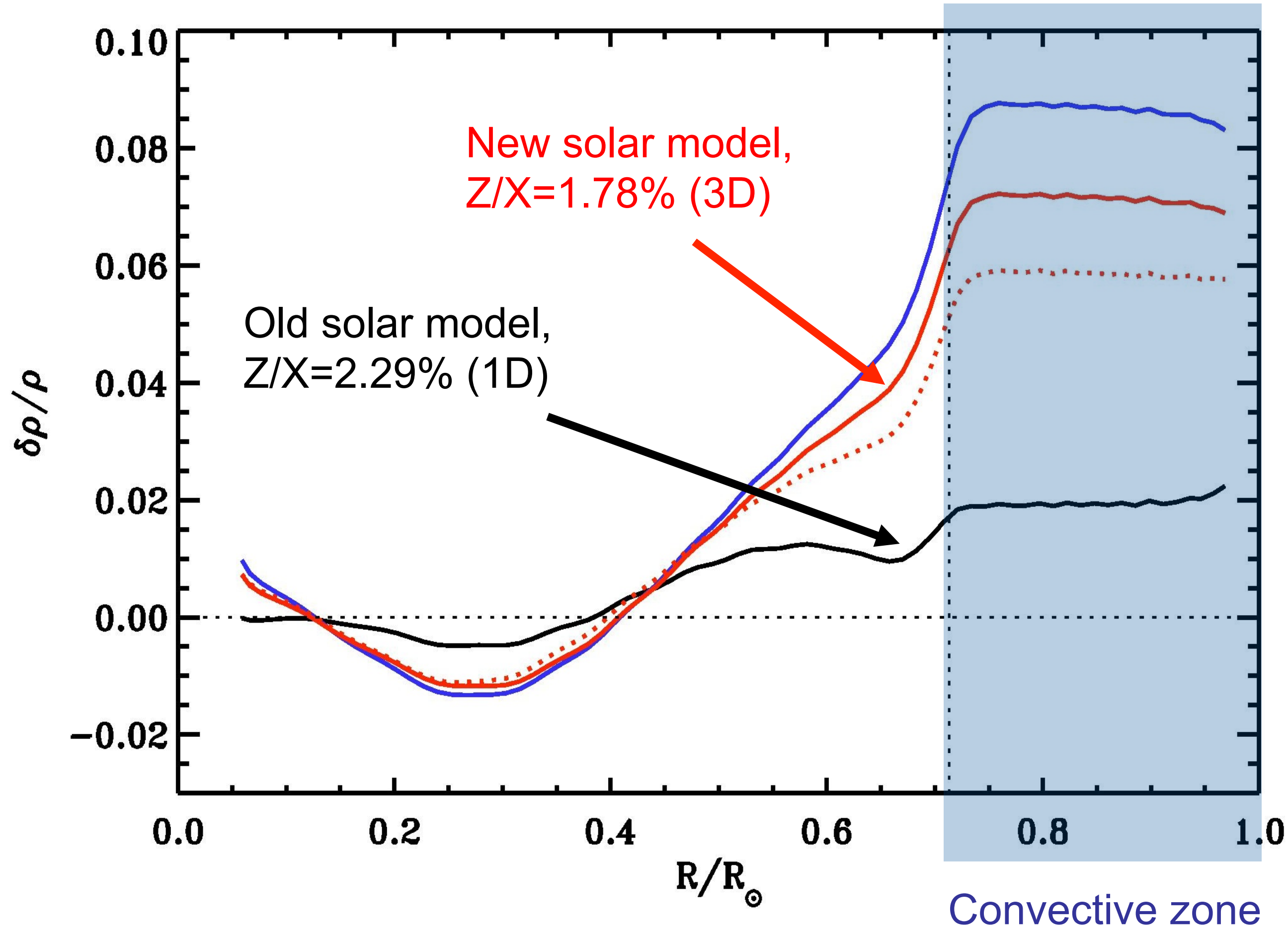
A new problem:
Contradiction between helioseismology and solar model predictions

Difference between model and data:
Density ρ of the Sun

(δρ/ρ Deviation of model from data)

Further contradictions:

- Depth of the convective zone
- Helium-Abundance



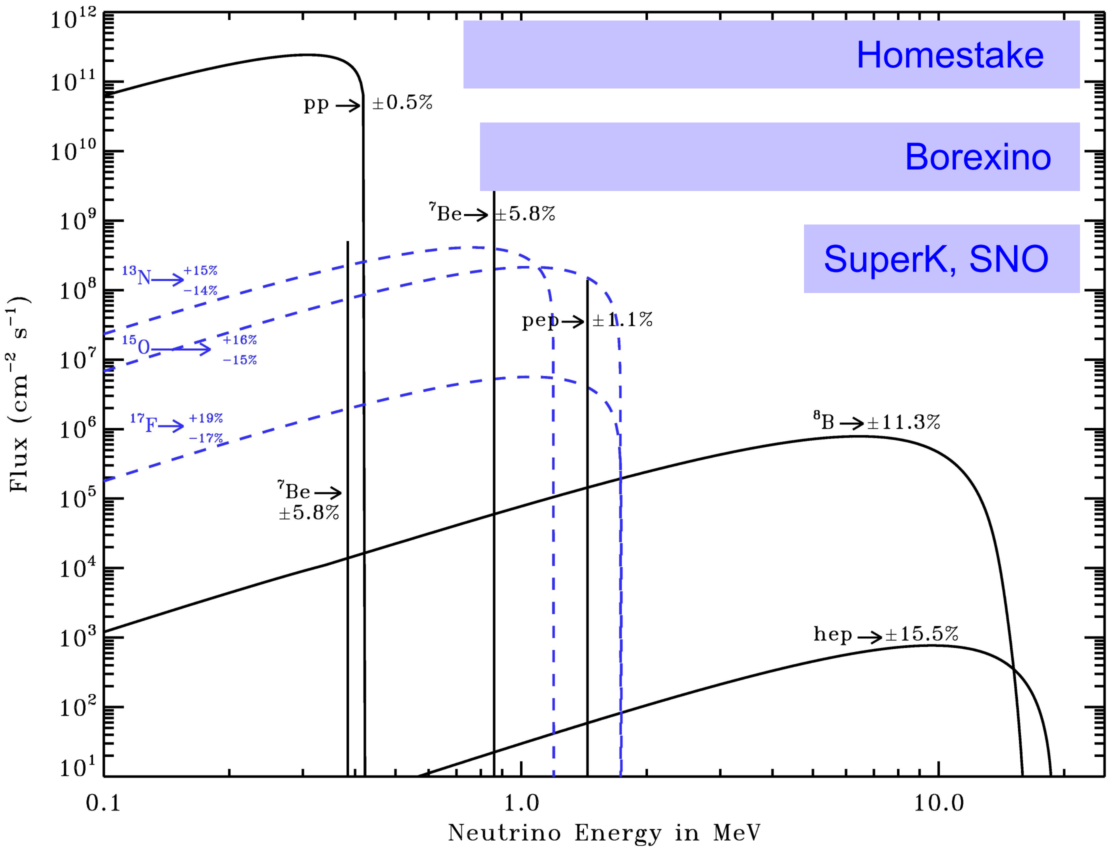
This may be called the "solar abundance problem"!

Haxton and Serenelli (2008)

Serenelli et al. (2009)

Neutrino fluxes predicted by the standard solar model

A. Serenelli et al. (2009): Two versions of standard solar model: GS98 and AGSS09



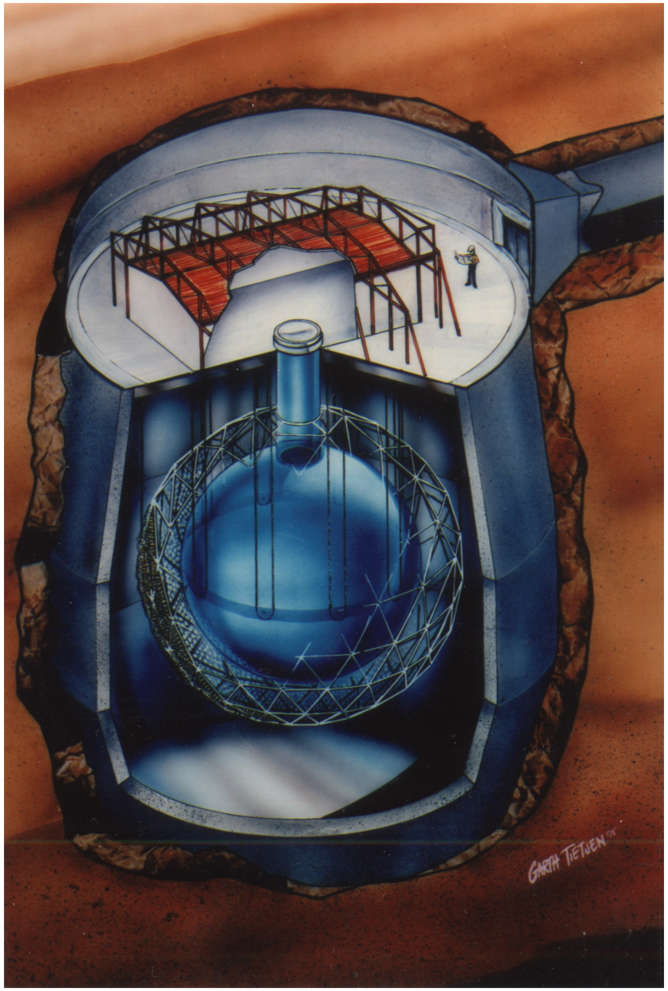
- GS98
  Old (<2005) elemental abundances
  Consistent with helioseismology
  $\Phi(^8B) = 5.88$ $\Phi(^{15}O) = 2.09$
- AGSS09
  New (>2005) elemental abundances
  Not consistent with helioseismology
  $\Phi(^8B) = 4.85$ $\Phi(^{15}O) = 1.47$
- Experiment (SNO, Super-Kamiokande)
  $\Phi(^8B) = 5.09 \pm 0.16$
  $\Phi(^{15}O)$ ... Borexino/SNO+ detectors

^{8}B neutrino flux in 10^6/(cm^2 s)
^{15}O neutrino flux in 10^8/(cm^2 s)

Neutrino fluxes can be used to measure the elemental abundances in the center of the Sun, if the nuclear physics input is precise enough.

(Haxton and Serenelli 2008)

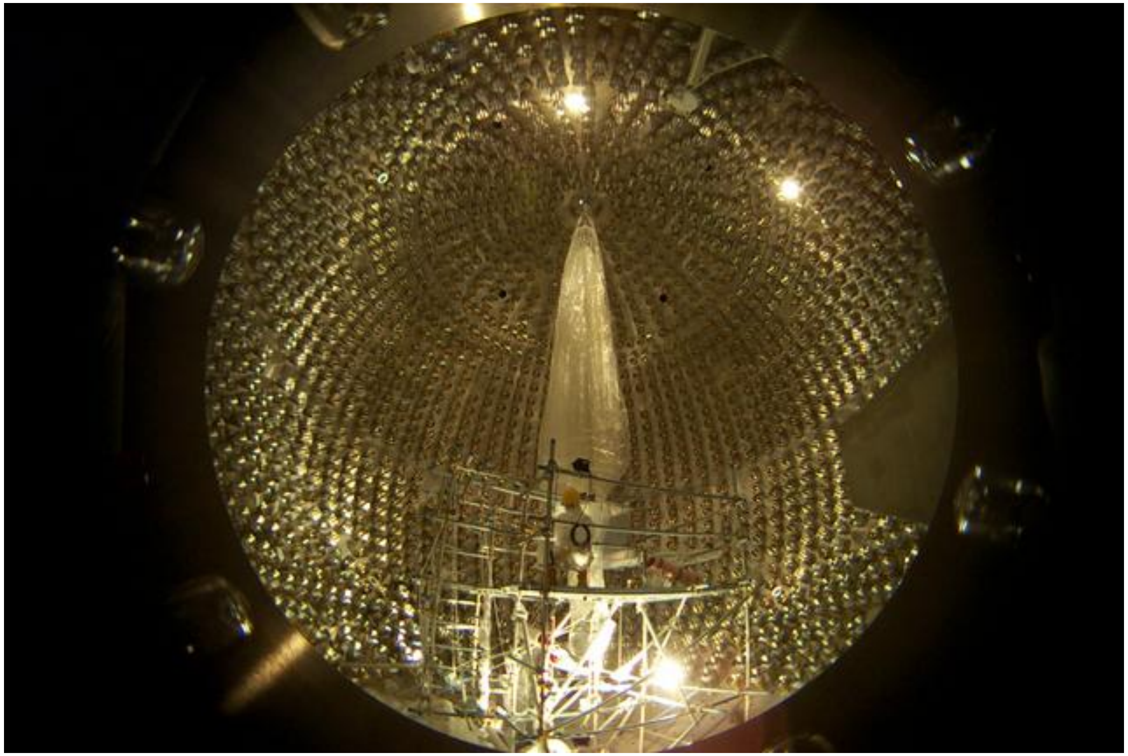
How precise does the nuclear physics input have to be?



The precision benchmark is given by the solar neutrino detectors:

SNO (Sudbury/Canada)

Borexino (Gran Sasso/Italy)



^{8}B neutrino flux measured to 3% precision!

^{7}Be neutrino flux measured to 5% precision!

The proton-proton chain of hydrogen burning and solar ^7Be, ^8B neutrinos

$^1H(p,e^+\nu)^2H$ — 99.75 %

$^1H(p\ e^-,\nu)^2H$ — 0.25 %

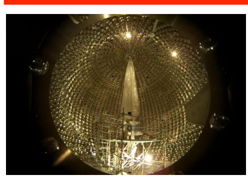
$^2H(p,\gamma)^3He$

86 % — $^3He(^3He,2p)^4He$

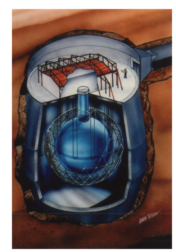
14 % — $^3He(^4He,\gamma)^7Be$

0.00003 % — $^3He(p,e^+\nu)^4He$

14 % — Borexino, SNO+ $^7Be(e^-,\nu)^7Li$ → $^7Li(p,^4He)^4He$



0.02 % — $^7Be(p,\gamma)^8B$ → $^8B(e^+\nu)^8Be^*$ SuperK, SNO → $^8Be^*(^4He)^4He$



Flux known ±5%

Flux known ±3%

Impact of cross section σ on neutrino flux Φ_B from model:

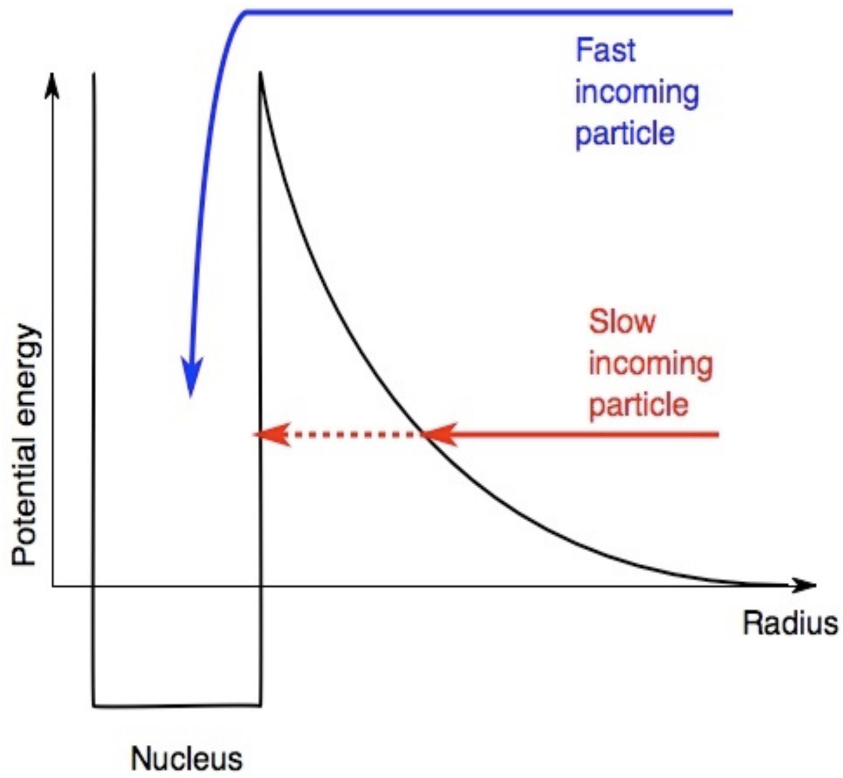
Reaction	$\frac{\partial \Phi_B}{\partial \sigma}$	$\Delta\Phi_B/\Phi_B$
$^3He(^3He,2p)^4He$	-0.43	1.8%
$^3He(\alpha,\gamma)^7Be$	0.85	7.5%
$^7Be(p,\gamma)^8B$	1.00	7.5%

Limiting the precision of the prediction for the ^8B neutrino flux

DRESDEN concept

HZDR

Nuclear reaction cross section σ for low-energy charged particles



- Typical Coulomb barrier height : ~ MeV
- Typical temperature k_B * T ~ keV

→ The energy dependence of the cross section is dominated by the tunneling probability.

↓

Definition of the astrophysical S-factor *S(E)*:

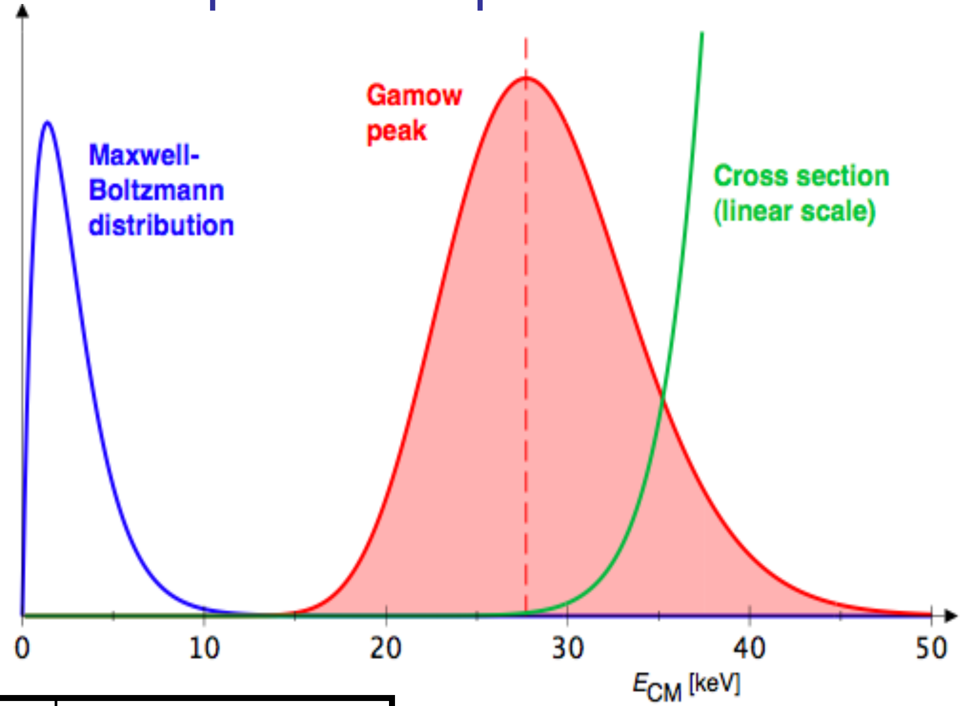
$$\sigma(E) = \frac{S(E)}{E} \exp\left[-2\pi Z_1 Z_2 \alpha \left(\frac{\mu c^2}{2E} \right)^{0.5} \right]$$

↓

Thermal neutron capture: ~1 barn ⟷ Charged-particle capture at astrophysical energies: σ < 1 nanobarn

At which energies do the reactions take place in a plasma?

Answer:
Inside the Gamow peak



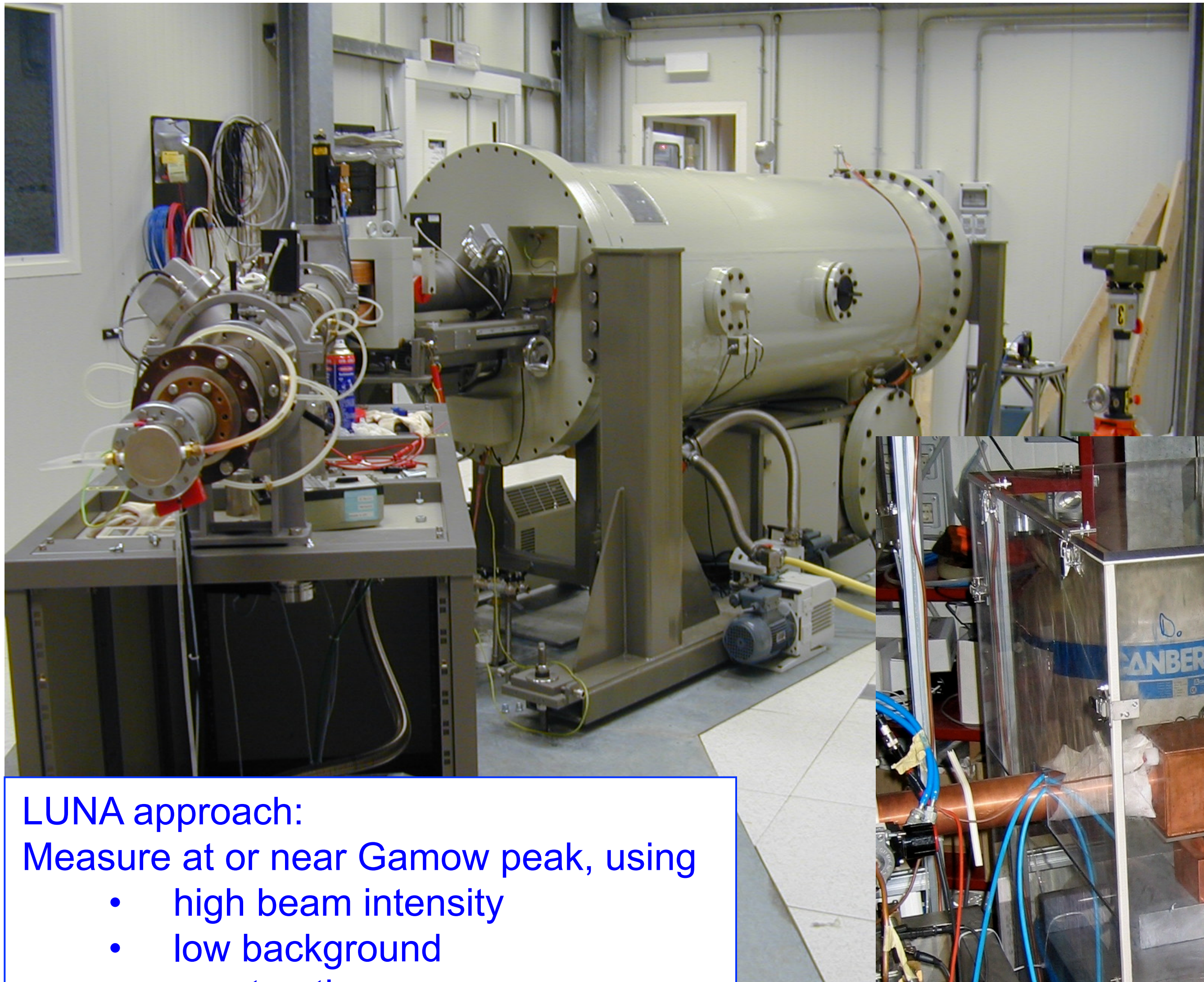
Scenario	Reaction	E_G[keV]	σ [barn]	Detected events/ hour
Sun (16 MK)	$^3He(\alpha,\gamma)^7Be$	23	10^{-17}	10^{-9}
	$^{14}N(p,\gamma)^{15}O$	28	10^{-19}	10^{-11}
AGB stars (80 MK)	$^{14}N(p,\gamma)^{15}O$	81	10^{-12}	10^{-4} done
Big bang (300 MK)	$^3He(\alpha,\gamma)^7Be$	160	10^{-9}	10^{-1} done
	$^2H(\alpha,\gamma)^6Li$	96	10^{-11}	10^{-3} in progress

Assume 10^{16} s^{-1} beam
10^{18} at/cm^2 target
10^{-2} detection efficiency

DRESDEN concept

HZDR

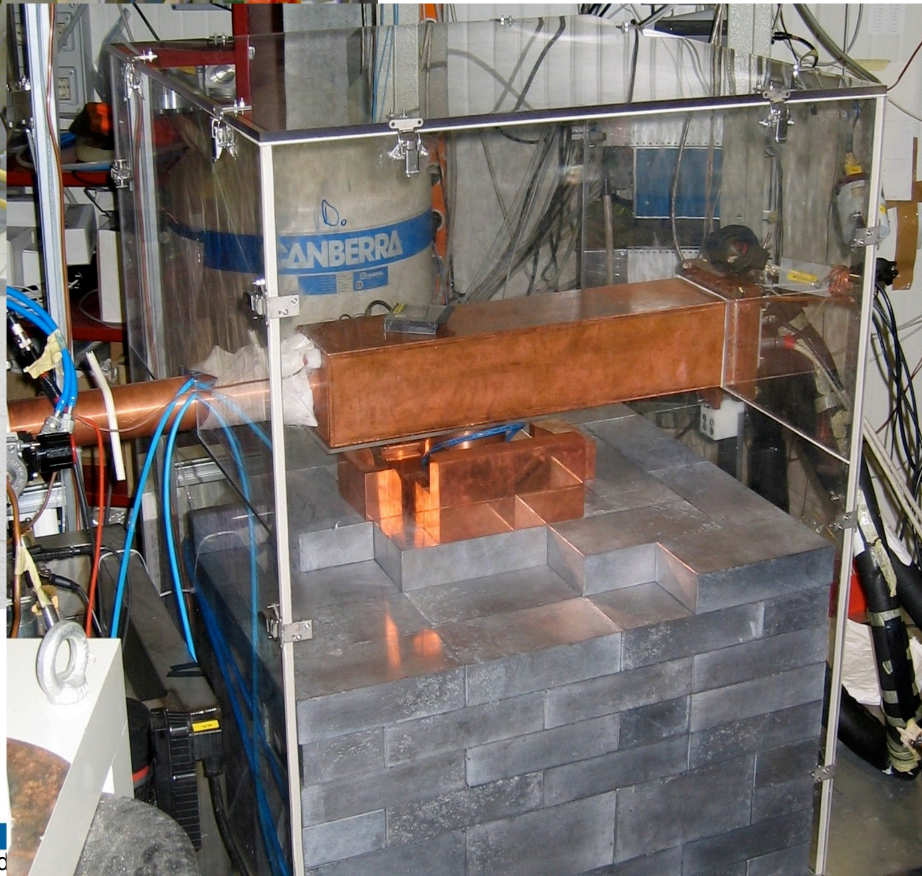
The $^3He(\alpha,\gamma)^7Be$ reaction at the LUNA 0.4 MV accelerator



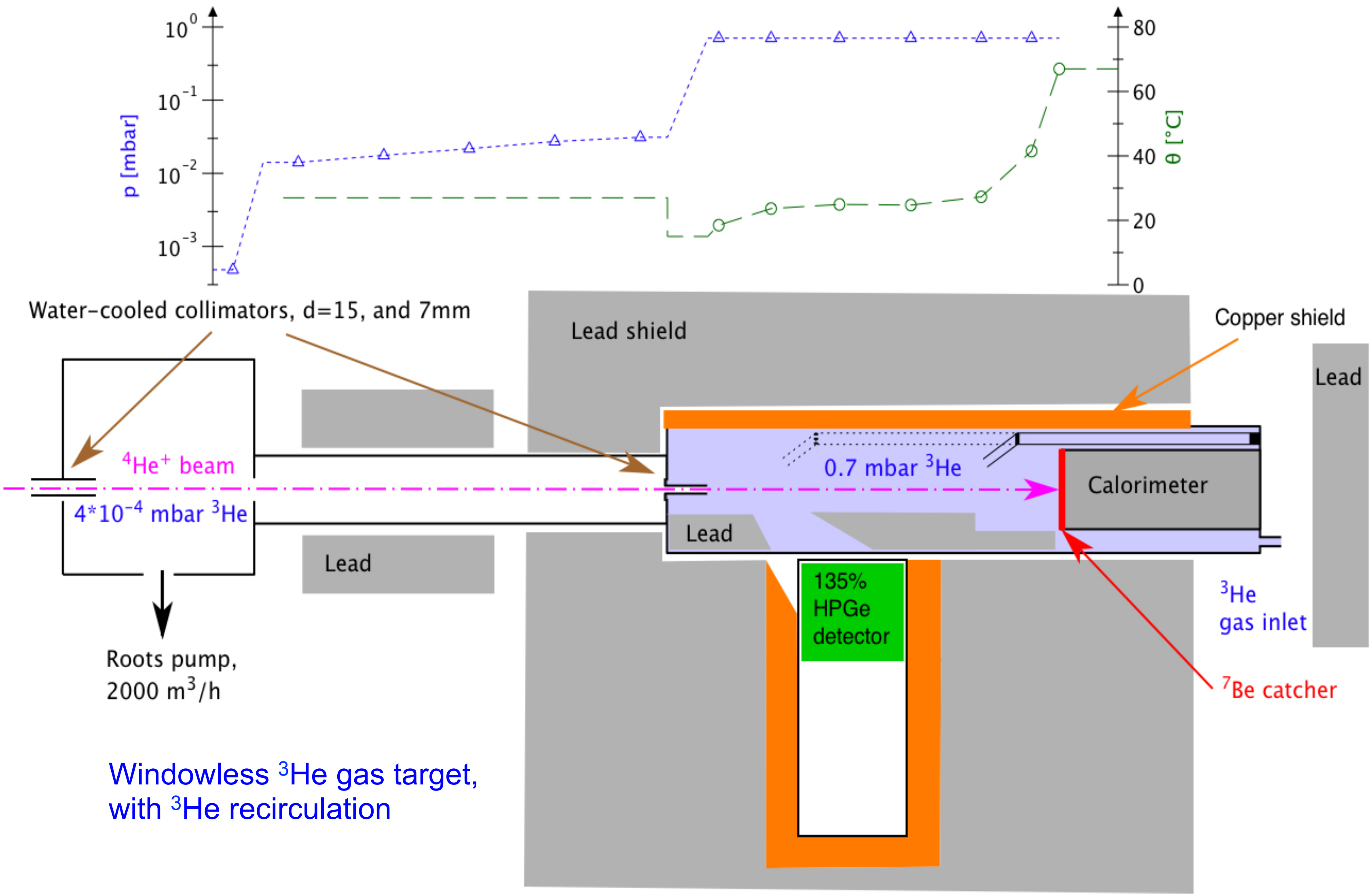
LUNA = Laboratory Underground for Nuclear Astrophysics

Gran Sasso national underground lab / Italy

LUNA approach:
Measure at or near Gamow peak, using
- high beam intensity
- low background
- great patience

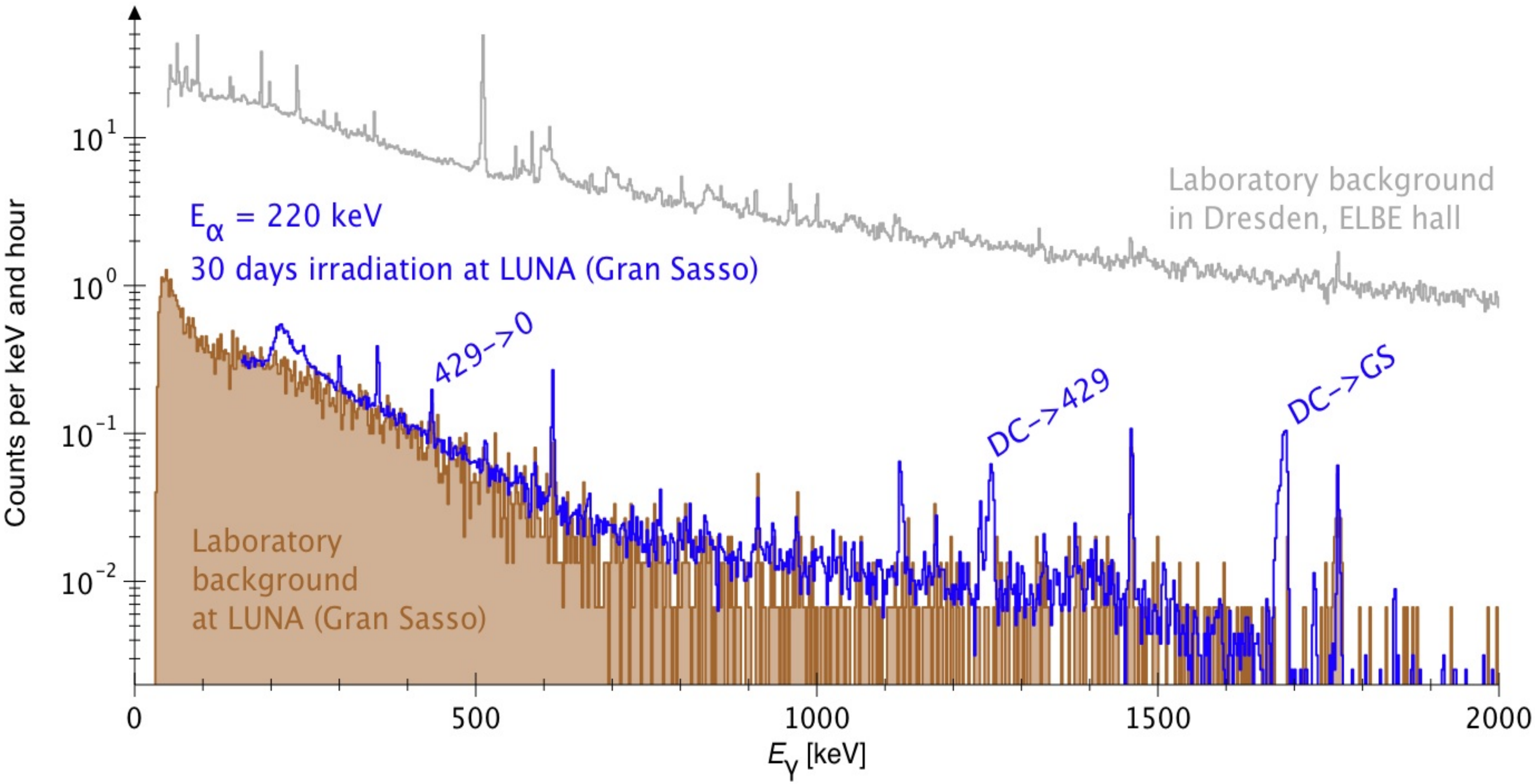


^{3}He(α,γ)^{7}Be at LUNA (activation and prompt-γ technique)

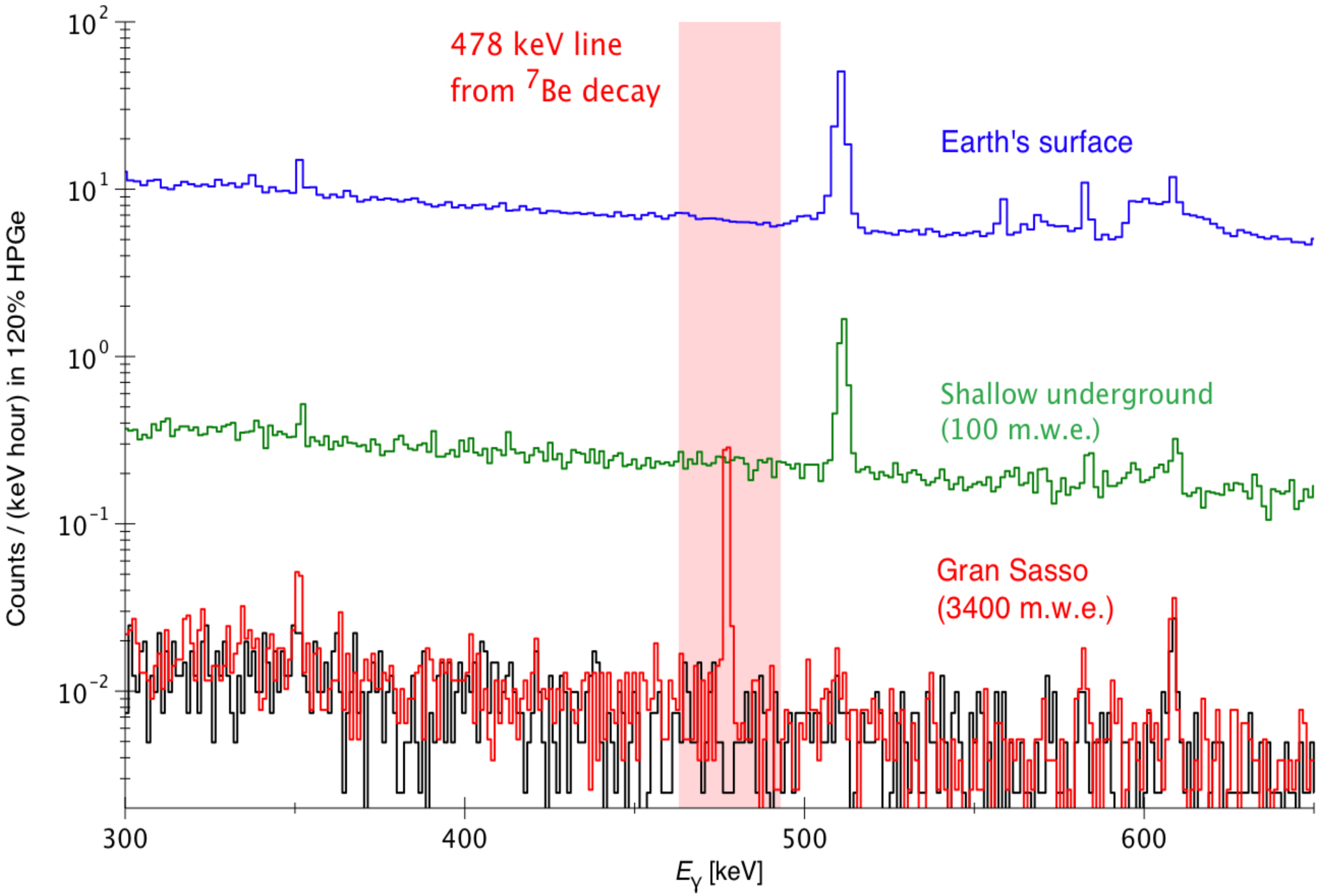


Windowless ^{3}He gas target, with ^{3}He recirculation

$^3He(\alpha,\gamma)^7Be$ experiment at LUNA-0.4 MV, prompt-γ spectrum



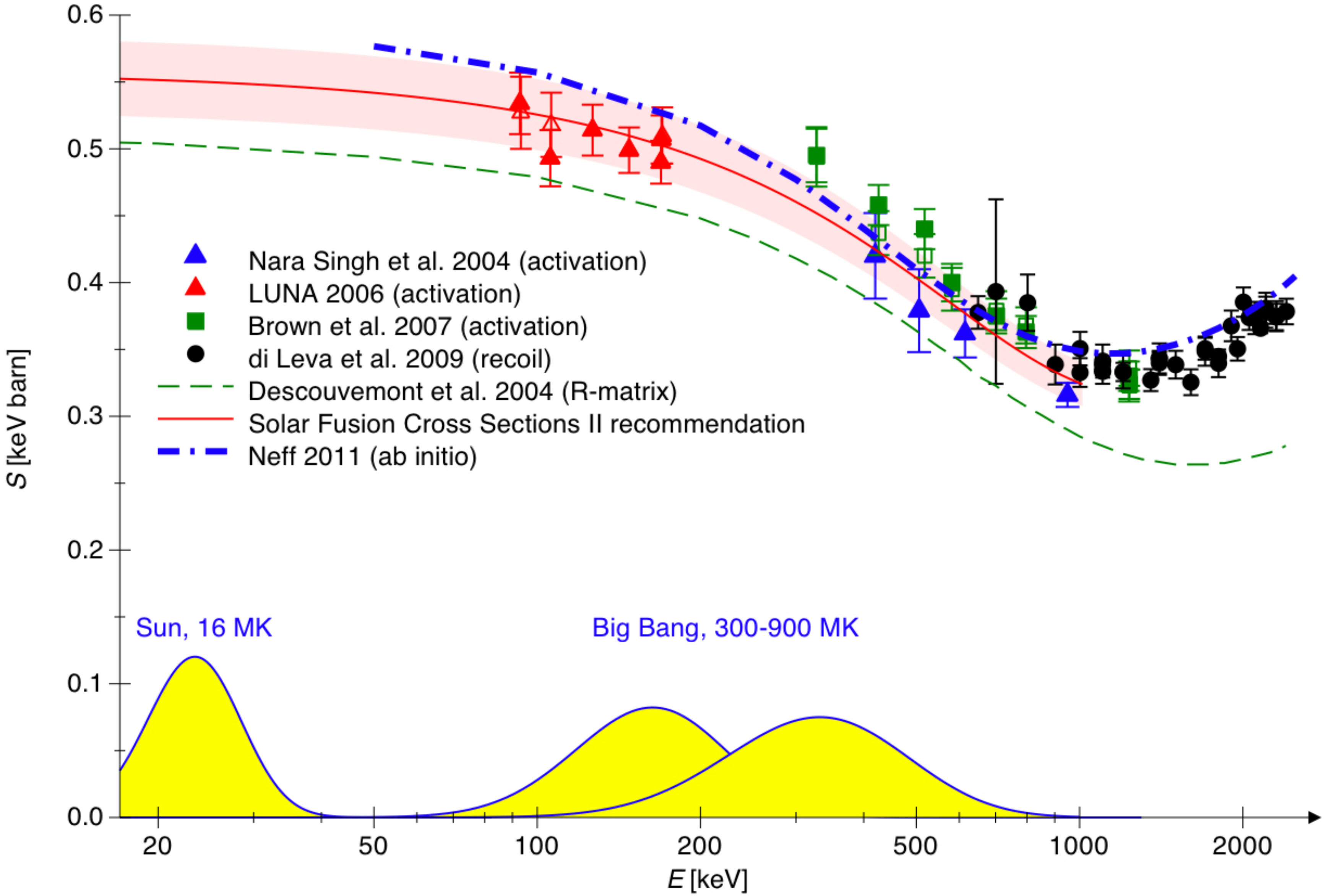
$^{3}He(\alpha,\gamma)^{7}Be$ at LUNA, ^{7}Be activation spectra



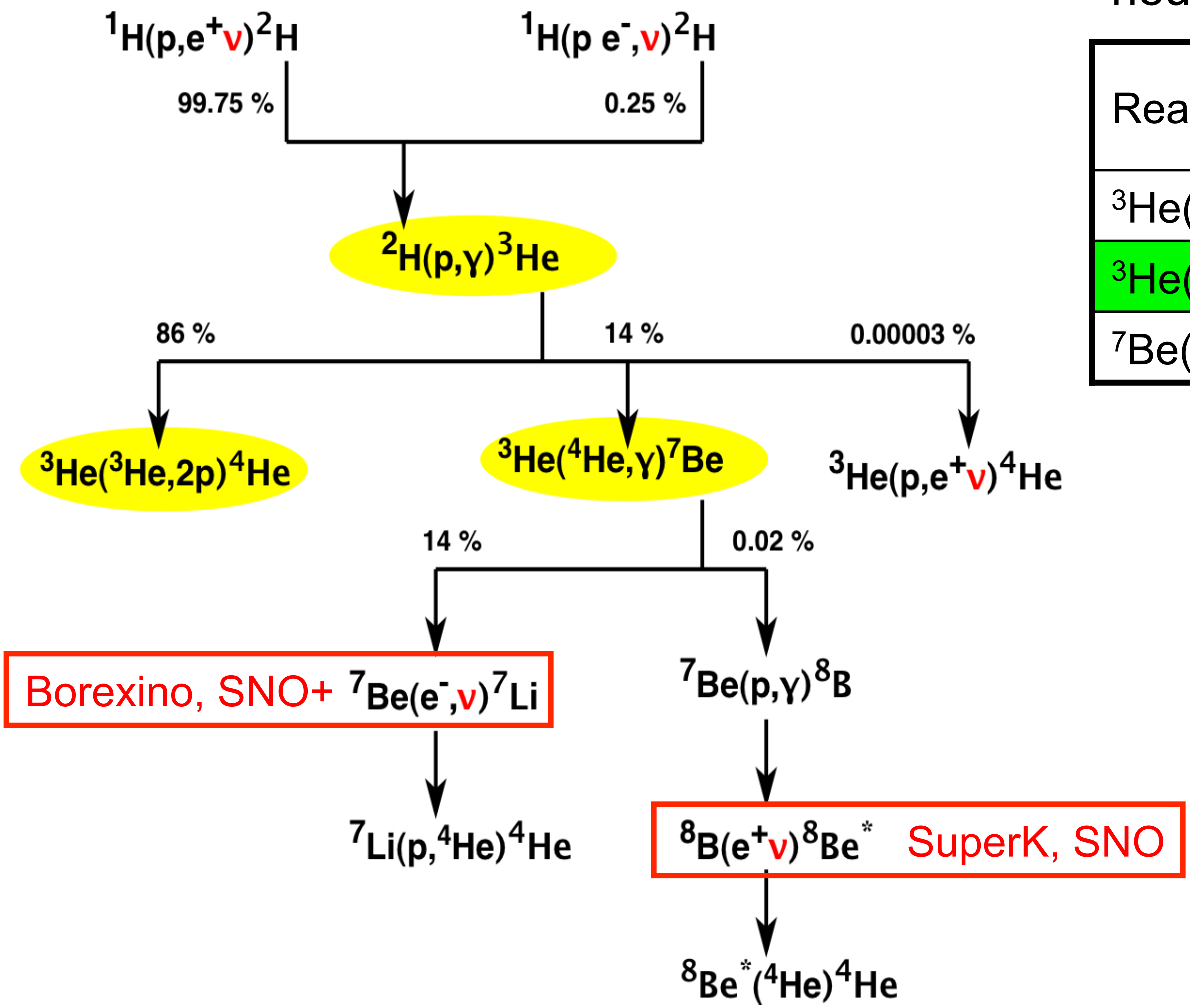
Detected ^{7}Be activities: 0.8 - 600 mBq

Home-made ^{7}Be calibration sources: 100 Bq

$^3He(\alpha,\gamma)^7Be$ reaction, S-factor results from LUNA and others



Impact of the $^3He(\alpha,\gamma)^7Be$ data: More precise inputs for solar ^7Be, ^8B neutrinos



Impact of cross section σ on neutrino flux Φ_B from model:

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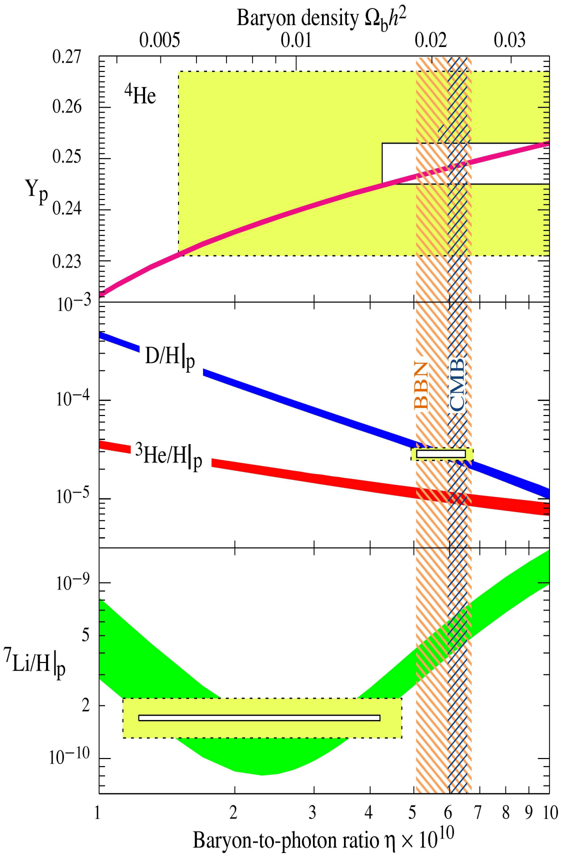
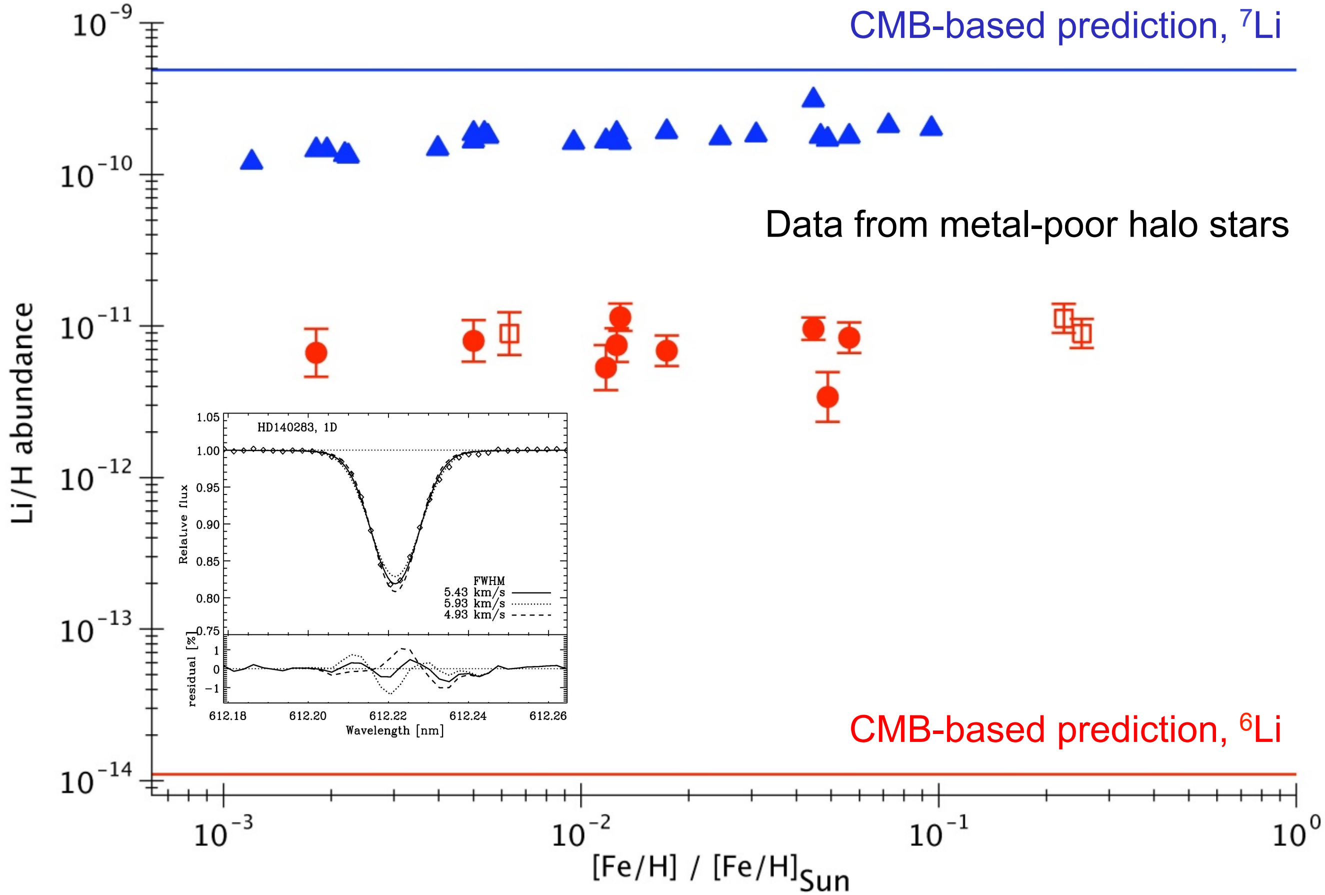
$^3He(^3He,2p)^4He$	-0.43	1.8%
$^3He(\alpha,\gamma)^7Be$	0.85	~~7.5%~~ 4.2%
$^7Be(p,\gamma)^8B$	1.00	7.5%

The Spite abundance plateau and the two lithium problems



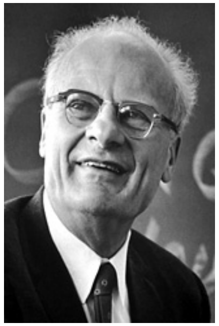


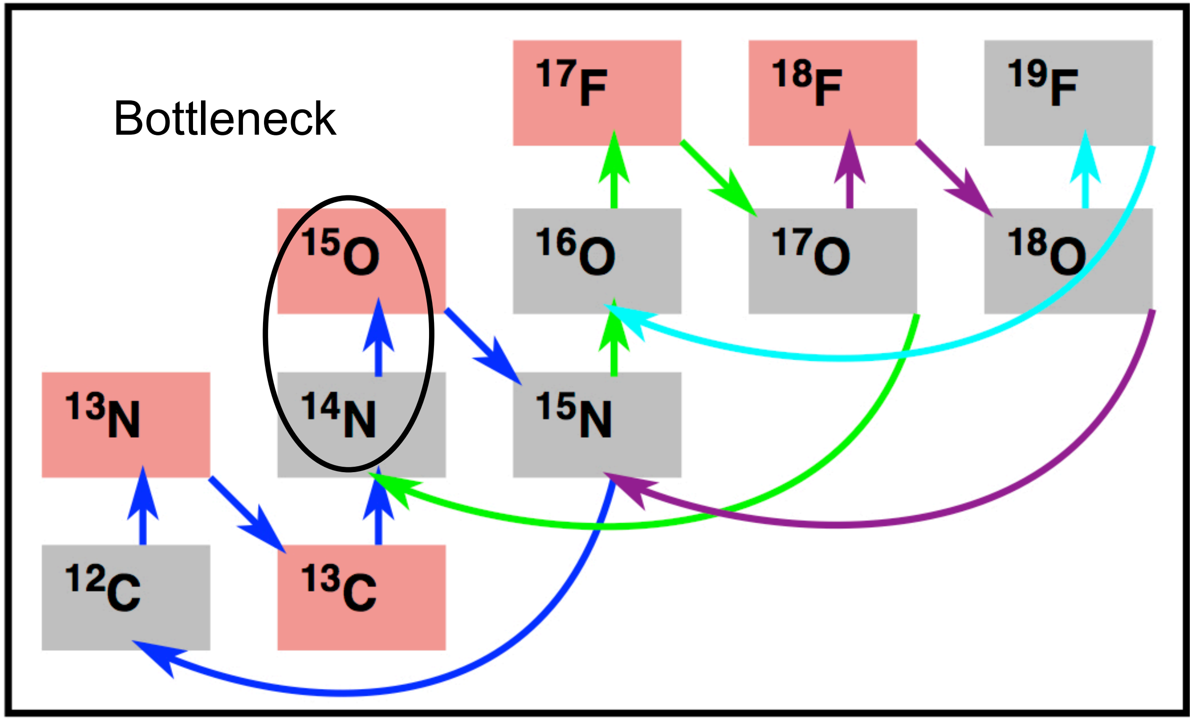
- No easy solution, especially not for both the ^{7}Li and the ^{6}Li problem at the same time!
- See talk by Michael Anders on Big Bang ^{6}Li (Thursday)!

DRESDEN concept

HZDR

Carbon-nitrogen-oxygen (Bethe-Weizsäcker) cycle: $^{14}N(p,\gamma)^{15}O$



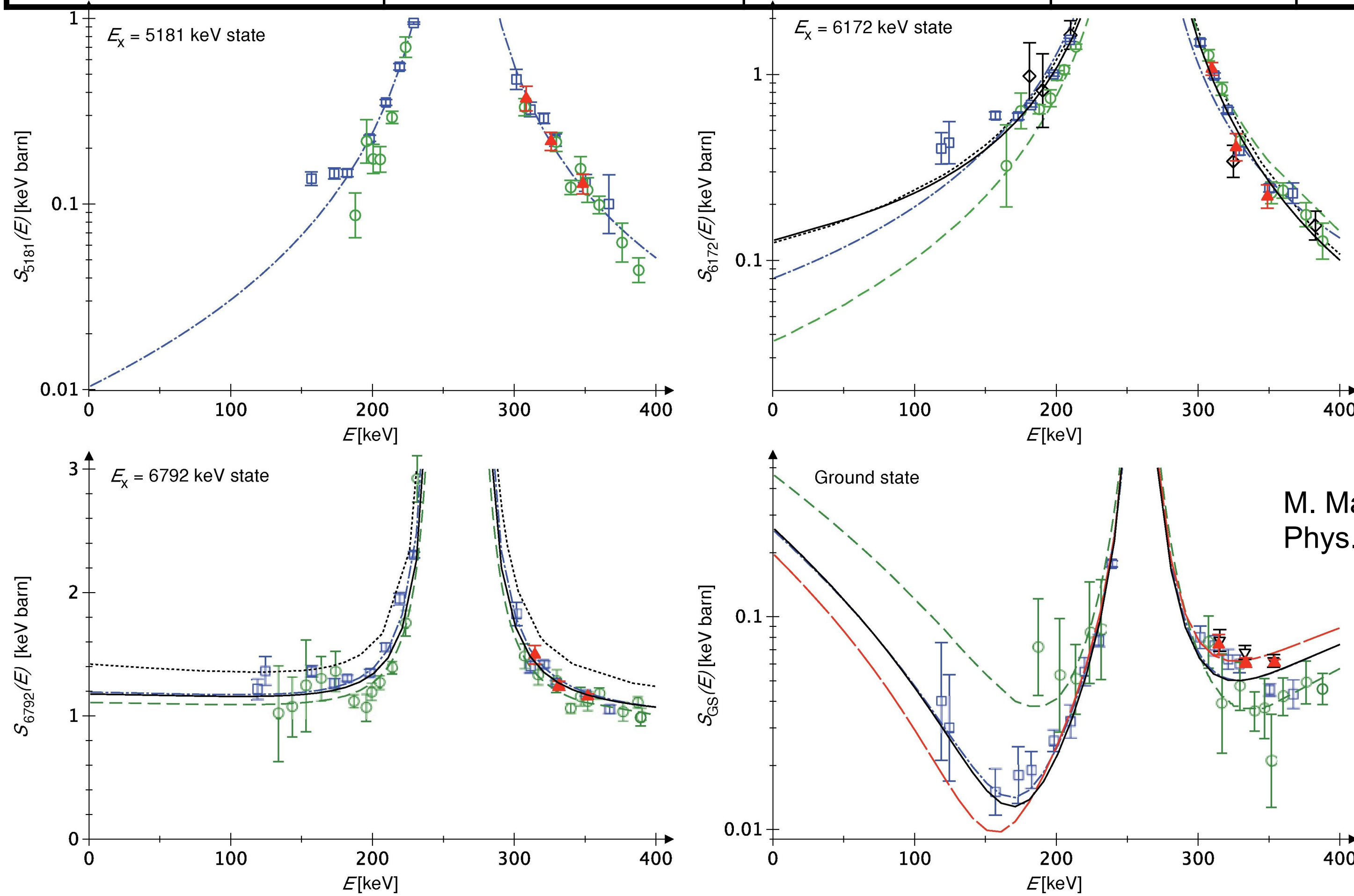


Postulated in 1938

- Slowest reaction: $^{14}N(p,\gamma)^{15}O$
- Some of the oldest observed stars burn mainly by CNO
- ~0.8% contribution in our Sun
  →CNO neutrinos as a probe of the concentration of carbon and nitrogen in the solar core

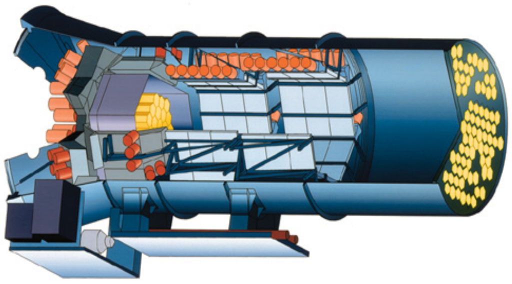
LUNA divided the $^{14}N(p,\gamma)^{15}O$ cross section by 2!

Capture to...	NACRE compilation 1999	LUNA, phase 1 2004	TUNL 2005	LUNA, phase 3 2008+2011
...ground state in ^{15}O	1.55 ± 0.34	0.25 ± 0.06	0.49 ± 0.08	0.27 ± 0.05
...excited states in ^{15}O	1.65 ± 0.05	1.36 ± 0.05	1.27 ± 0.05	(1.39 ± 0.05)
S(0) in keV barn	3.2 ± 0.5 (tot)	1.6 ± 0.2 (tot)	1.8 ± 0.2 (tot)	1.66 ± 0.12 (tot)



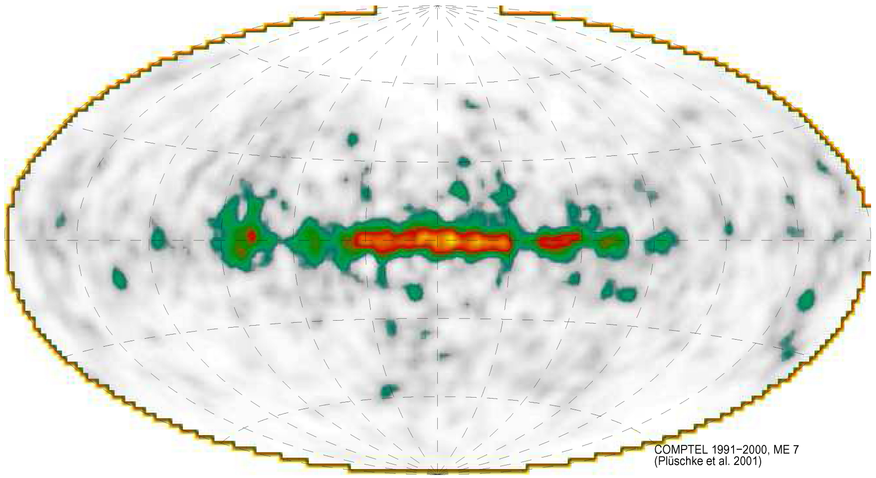
M. Marta et al.,
Phys. Rev. C 83, 045804 (2011)

^{26}Al, a tracer of live nucleosynthesis

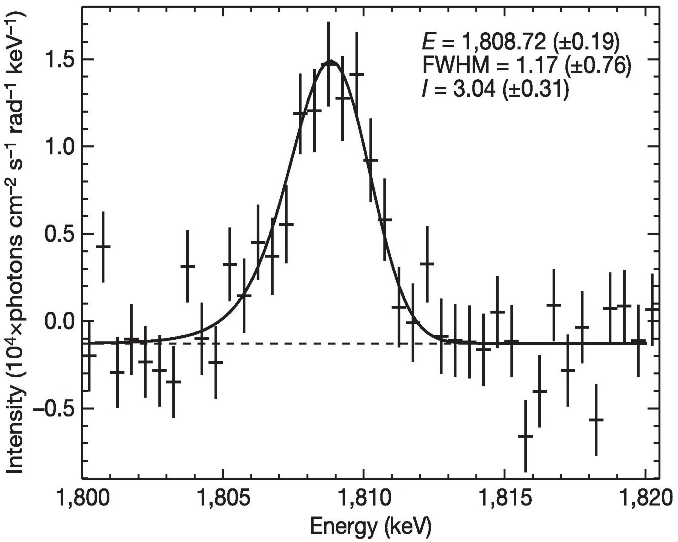


$t_{1/2}$ = 717 000 y

E_γ = 1809 keV

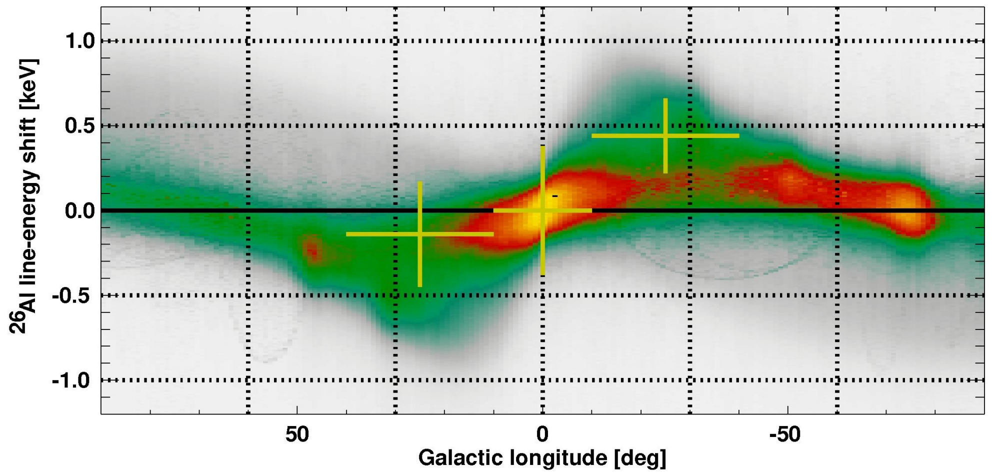


R. Diehl et al. 2006



^{26}Al amount in the galaxy 2.8±0.8 $M_\odot$

➔Rate of core-collapse supernovae 1.9±1.1 per century



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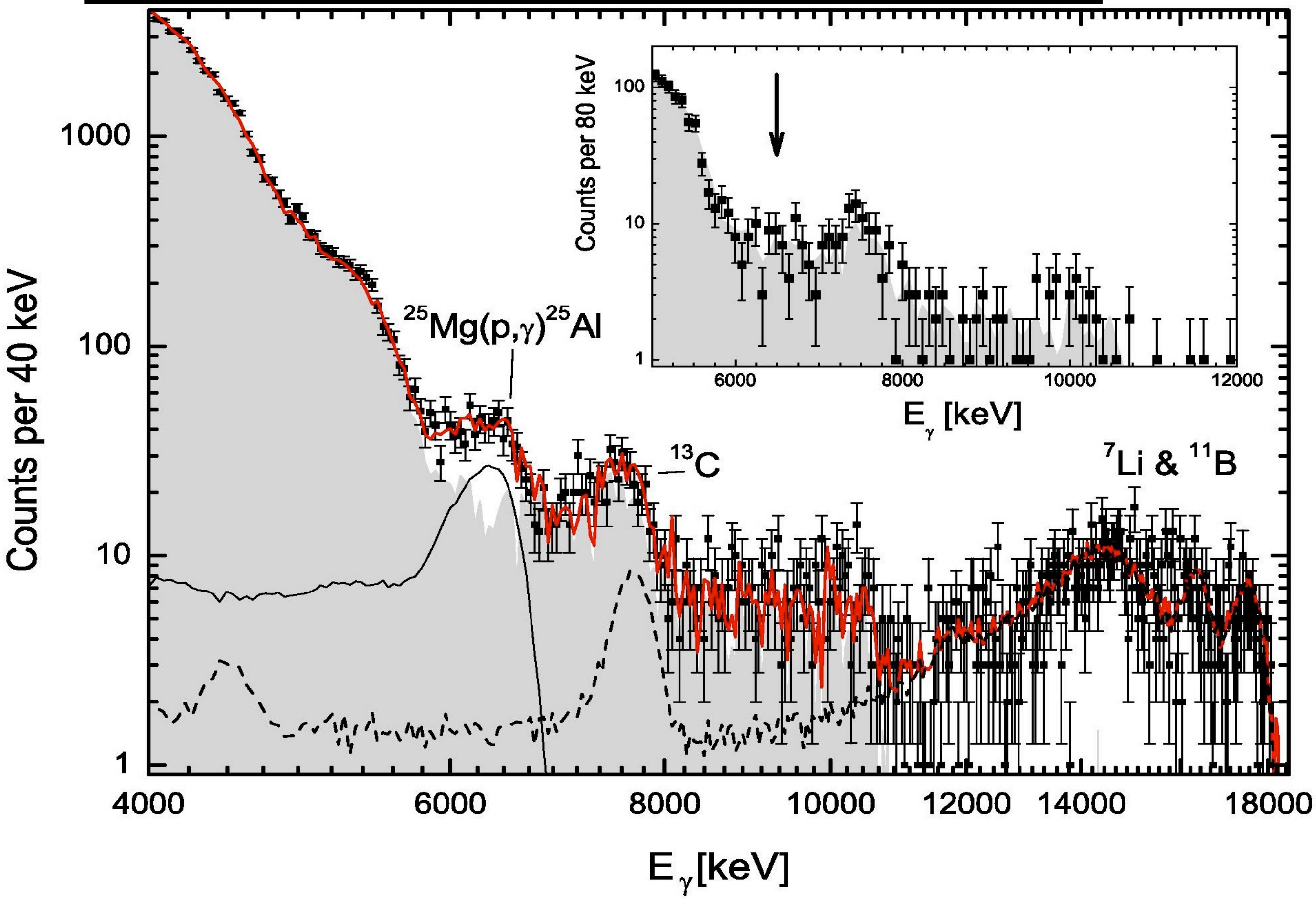
^{26}Al production by the ^{25}Mg(p,γ)^{26}Al reaction studied at LUNA

^{25}Mg(p,γ)^{26}Al resonance strengths ωγ in eV

E_R [keV]	in-beam γ Iliadis et al. 1990	AMS Arazi et al. 2006	in-beam γ and AMS LUNA
93		< 2 * 10^{-8}	(2.9±0.6) * 10^{-10}
190	(7.4±1.0) * 10^{-7}	(1.5±0.3) * 10^{-7}	(9.0±0.6) * 10^{-7}
304	(3.0±0.4) * 10^{-2}	(2.4±0.2) * 10^{-2}	(3.08±0.13) * 10^{-2}

Lowest resonance strength ever measured directly!

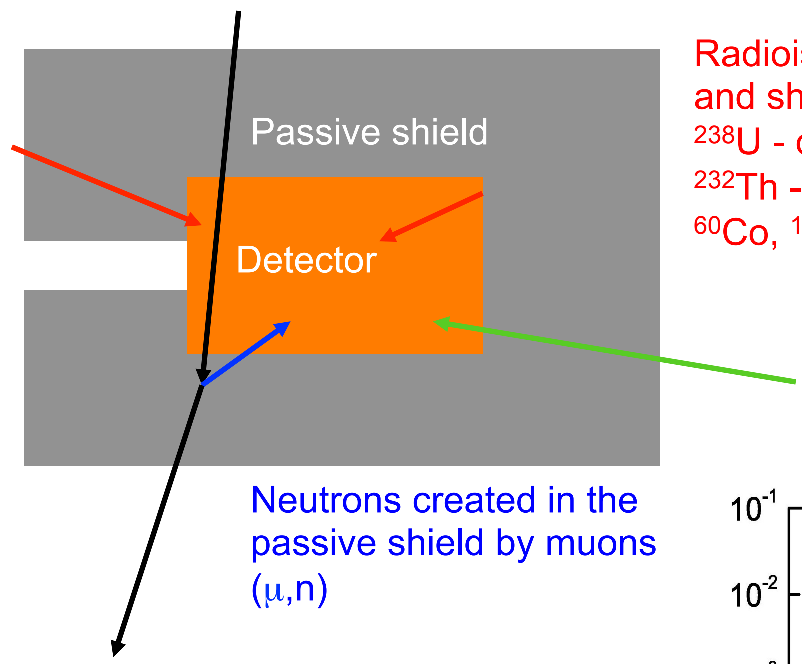


F. Strieder et al.
Phys. Lett. B 707, 60 (2012)

But why is the laboratory background in γ-ray detectors so low?

Energetic muons

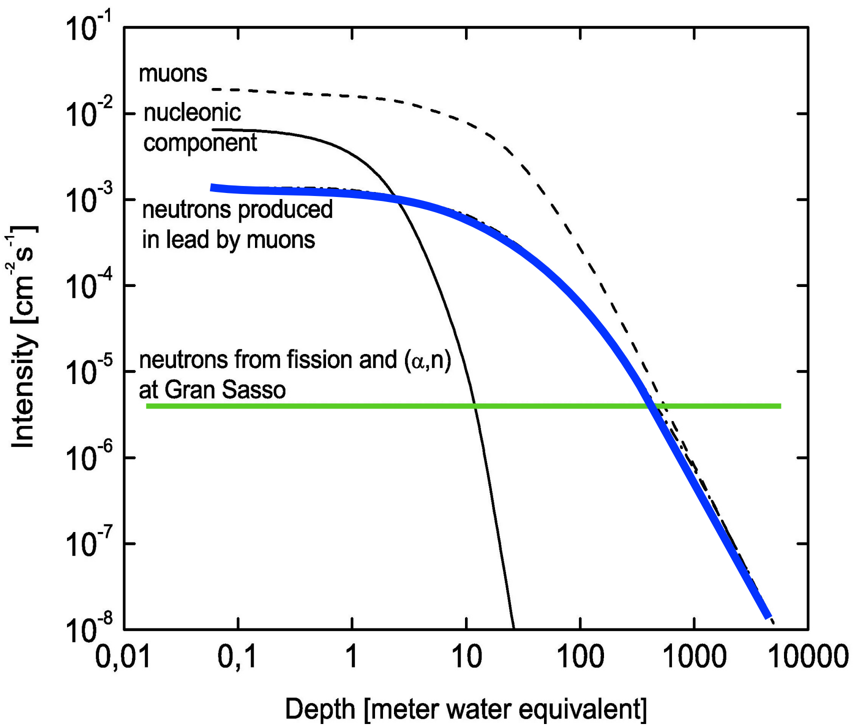
Radioisotopes in the laboratory:
^{238}U - daughters
^{232}Th - daughters
^{40}K



Radioisotopes in detector and shield:
^{238}U - daughters
^{232}Th - daughters
^{60}Co, ^{138}La

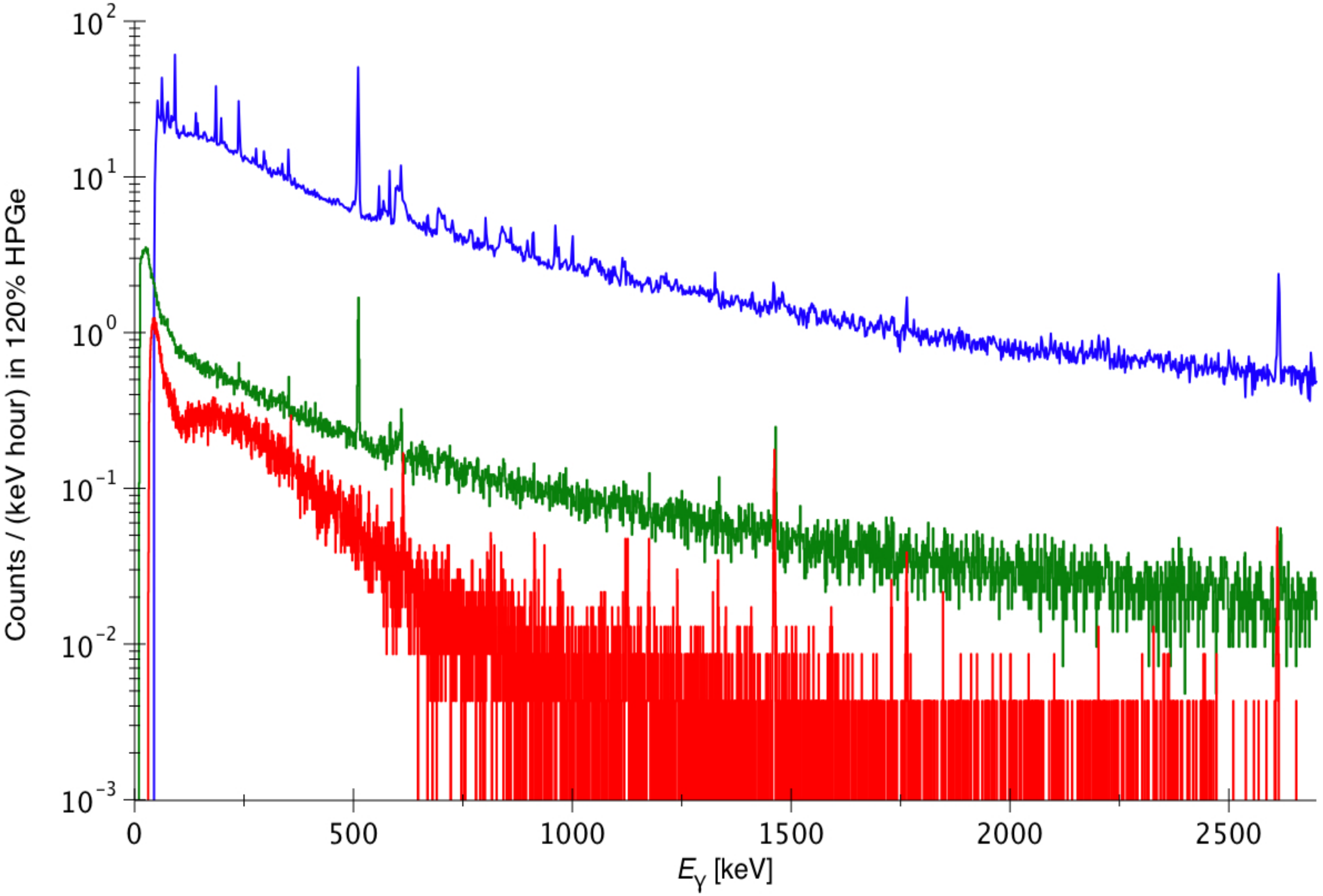
Neutrons from outside:
- cosmic ray
- (α,n) in rock

Neutrons created in the passive shield by muons (μ,n)



Red: $E_\gamma < 3$ MeV, can be addressed by shielding or purification

Laboratory γ-ray background in a HPGe detector at E_γ< 3 MeV, shielded



E_γ = 1.5 MeV

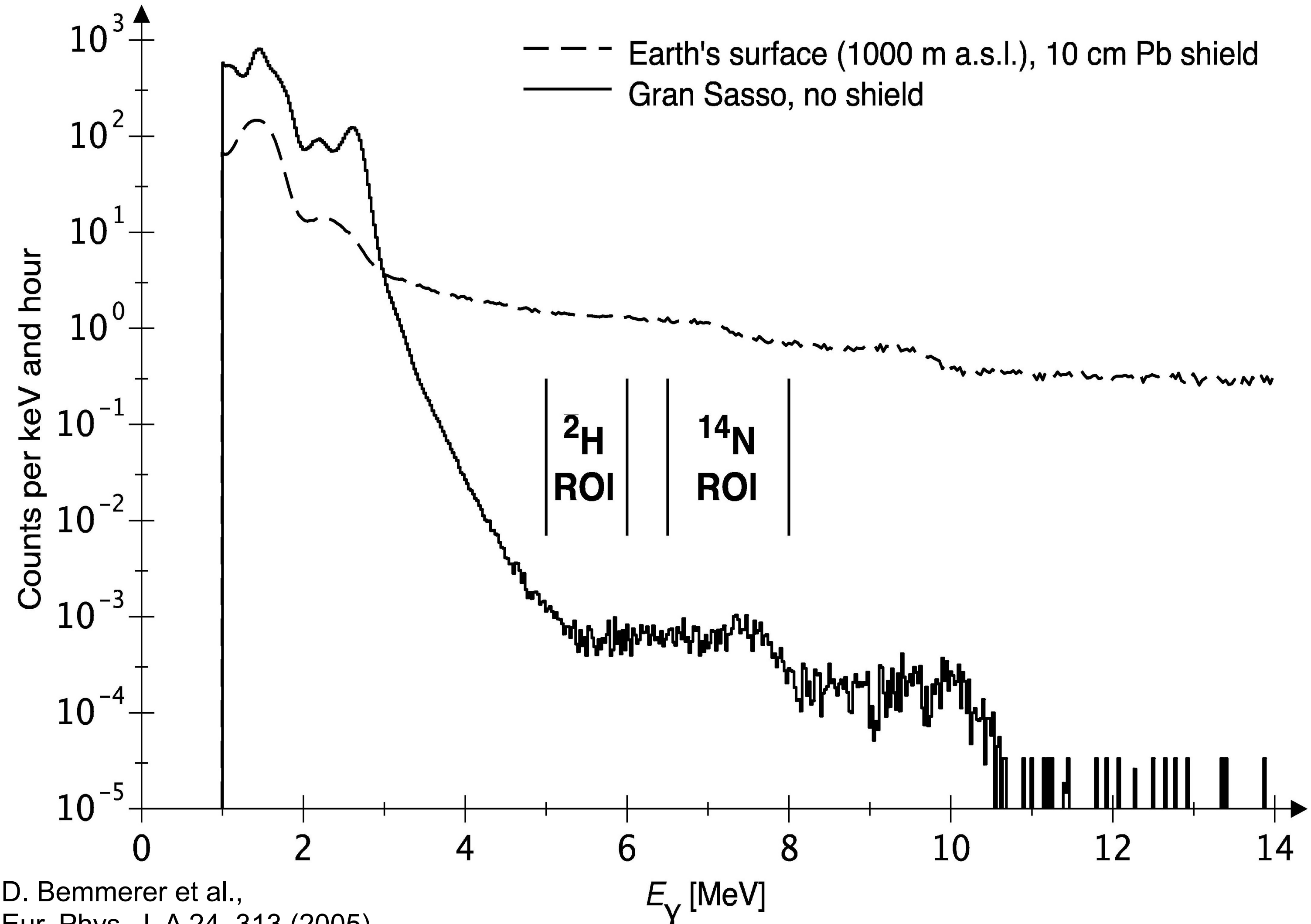
Earth's surface:
4 counts/hour

Shallow, ~110 mwe:
0.13 counts/hour

Gran Sasso, ~3800 mwe:
0.007 counts/hour

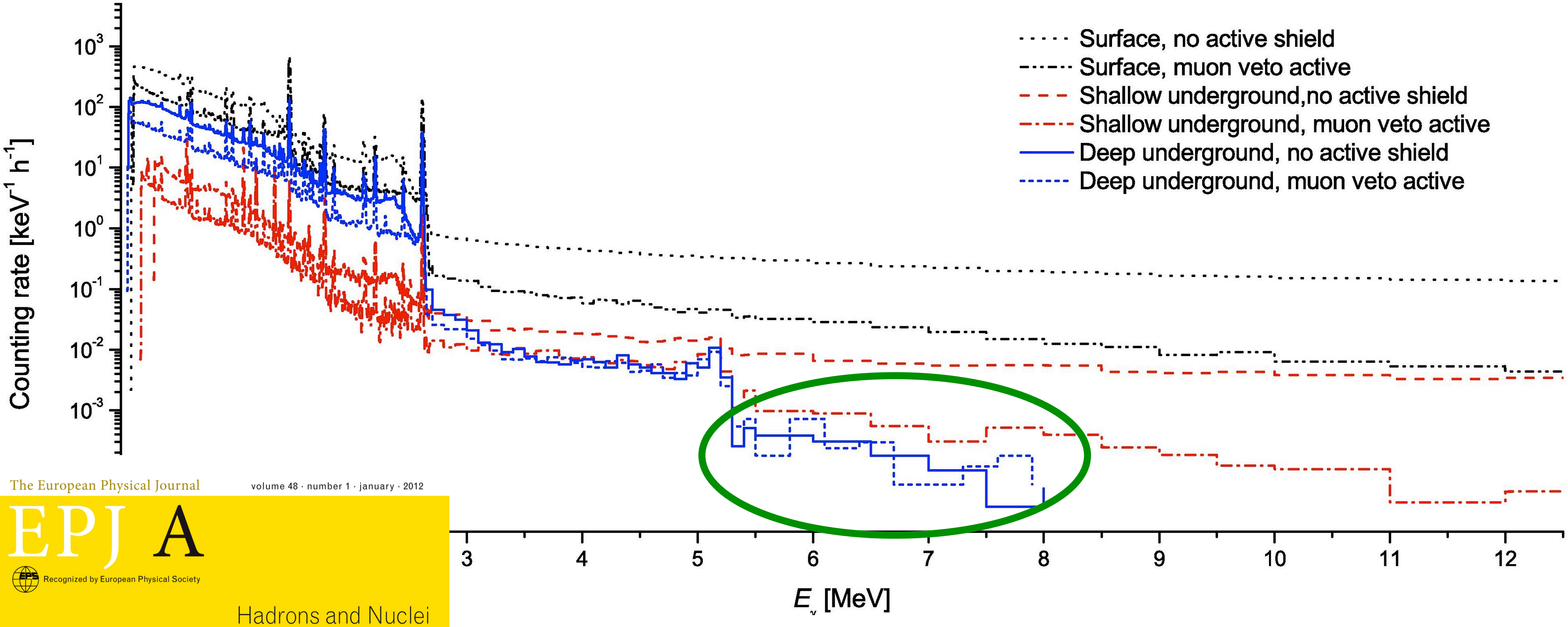
A. Caciolli et al., Eur. Phys. J. A 39, 179 (2009)

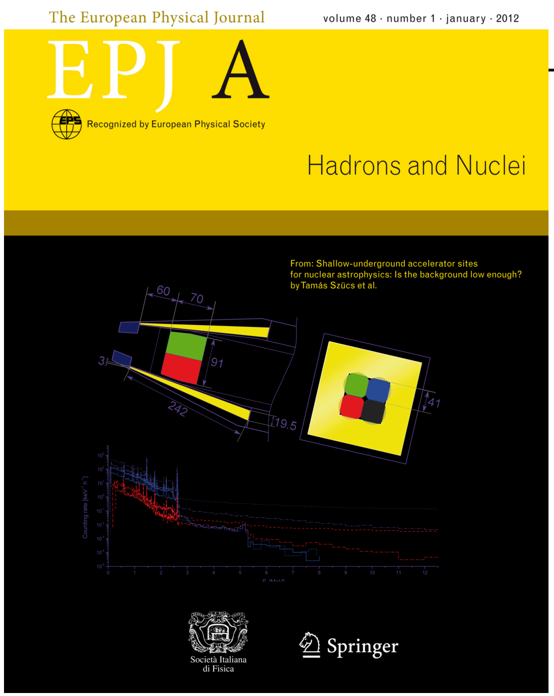
Laboratory background in a BGO detector at E_γ> 3 MeV, unshielded



D. Bemmerer et al.,
Eur. Phys. J. A 24, 313 (2005)

Laboratory background in a HPGe detector with active shielding





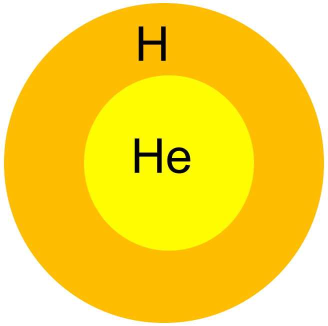
→ Active muon veto reduces the background due to passing muons.

→ Combination of active veto and ~50m rock gives a background close to the current deep-underground background in 6-8 MeV region.

→ Further neutron shield agains wall (α,n) neutrons would greatly reduce the background deep-underground.

T. Szücs et al.,
Eur. Phys. J. A 48, 8 (2012)

Stellar helium burning



- After exhaustion of hydrogen fuel in the core, core helium burning (and shell hydrogen burning) start

- ^{12}C produced by $^{8}Be(\alpha,\gamma)^{12}C$ (triple-α reaction)
- ^{12}C destroyed by $^{12}C(\alpha,\gamma)^{16}O$ (triple-α reaction)

- Main end products ^{12}C, ^{16}O

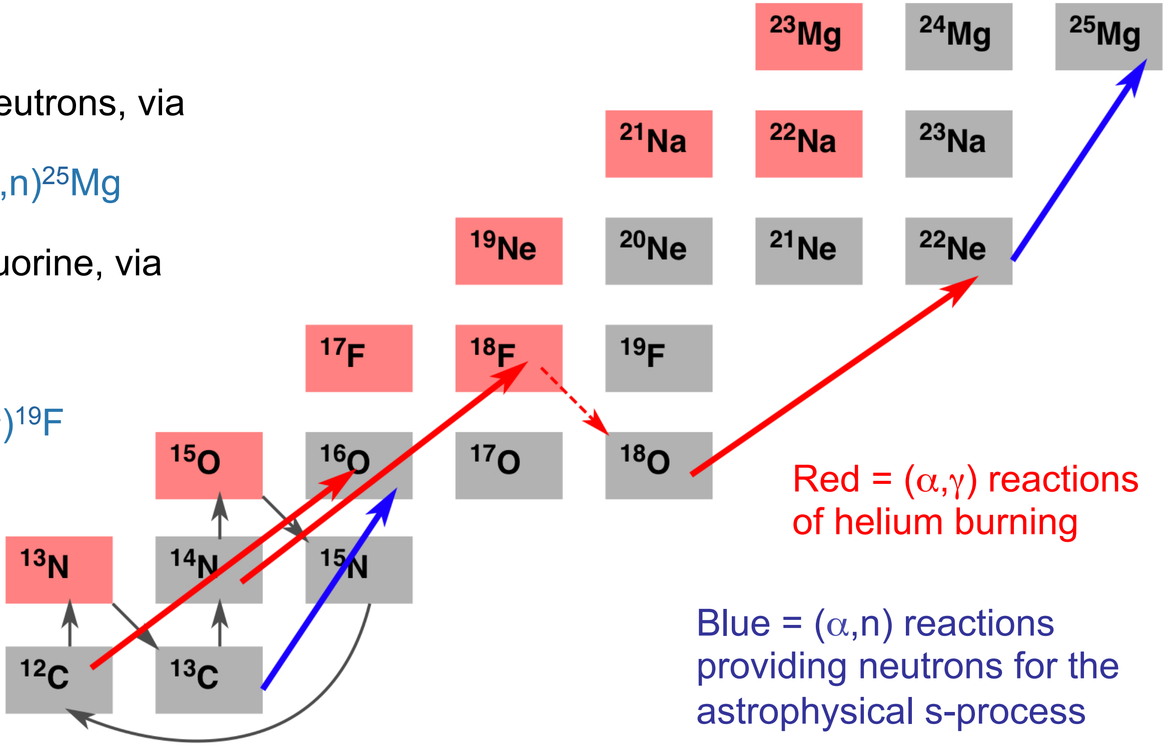
- Paves the way for the production of neutrons, via

  $^{14}N(\alpha,\gamma)^{18}F \rightarrow {}^{18}O(\alpha,\gamma)^{22}Ne \rightarrow {}^{22}Ne(\alpha,n)^{25}Mg$

- Paves the way for the production of fluorine, via

  $^{15}N(\alpha,\gamma)^{19}F$

  $^{14}N(\alpha,\gamma)^{18}F \rightarrow {}^{18}O(p,\alpha)^{15}N \rightarrow {}^{15}N(\alpha,\gamma)^{19}F$



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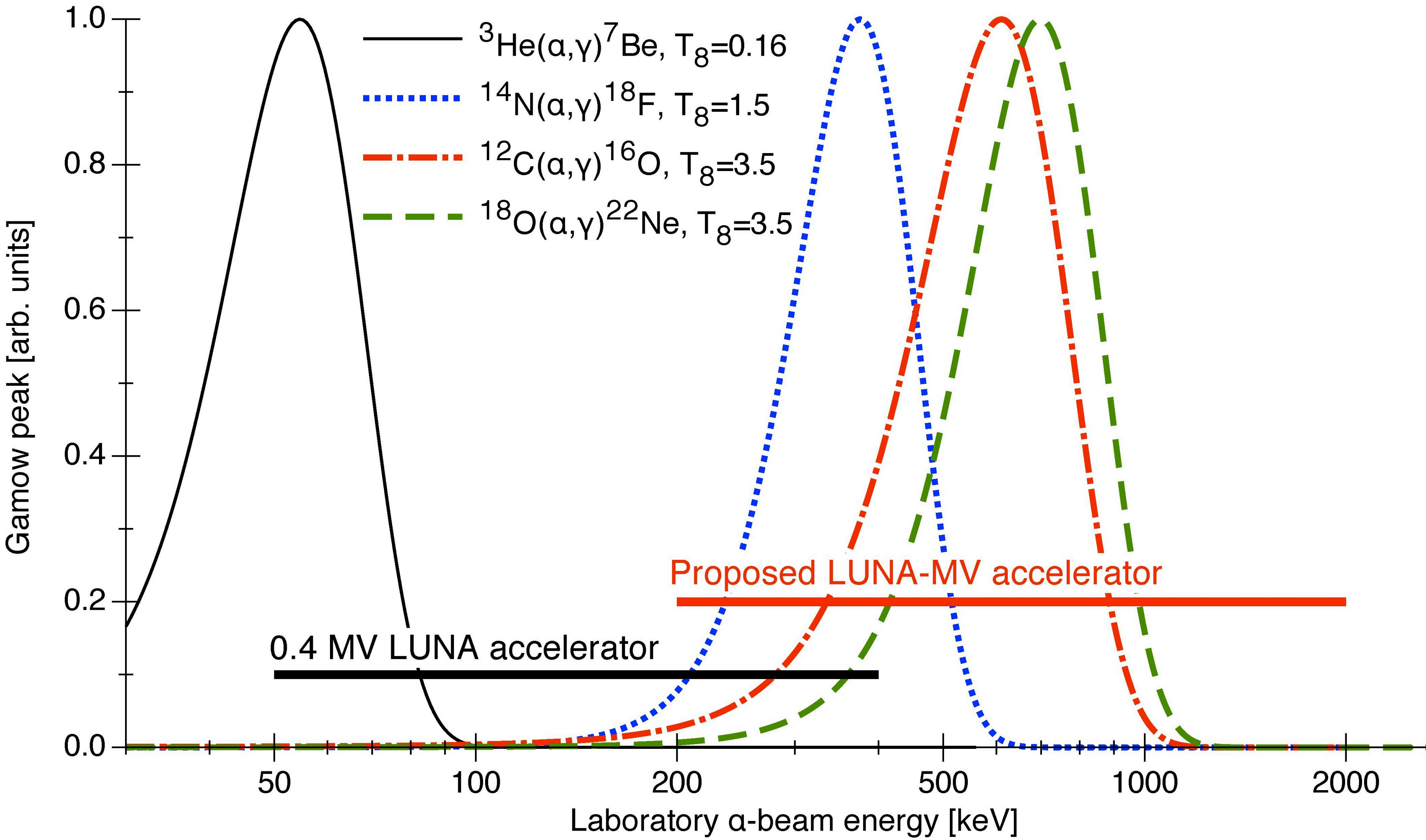
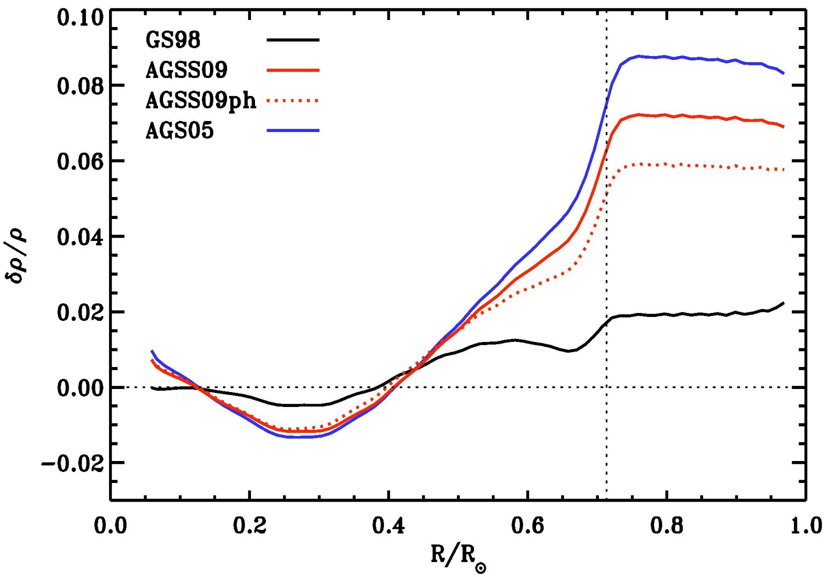
Gamow peaks for helium burning reactions

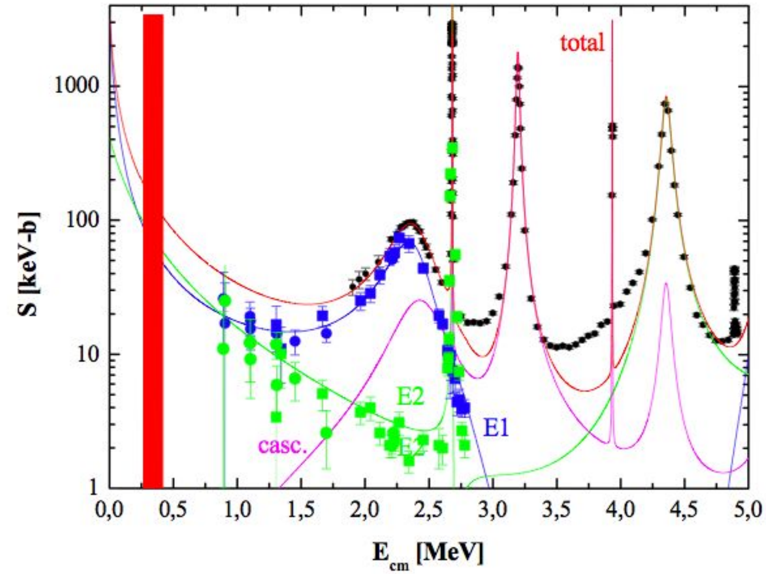


Higher-energy accelerator underground: Science case (1)



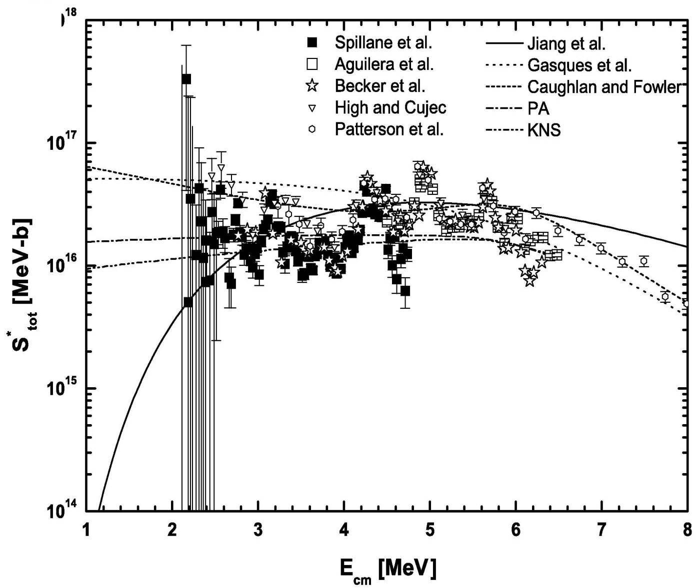
Helium burning

- $^{12}C(\alpha,\gamma)^{16}O$
- $^{14}N(\alpha,\gamma)^{18}F$
- $^{15}N(\alpha,\gamma)^{19}F$
- $^{18}O(\alpha,\gamma)^{22}Ne$



Solar composition problem

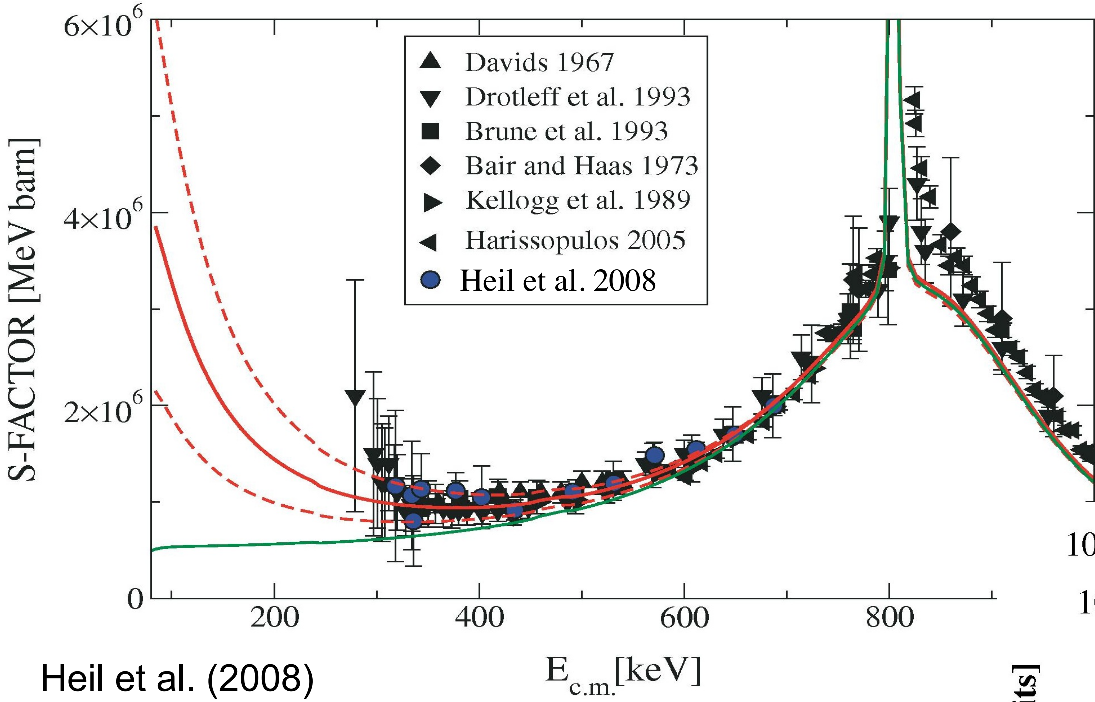
- $^{3}He(\alpha,\gamma)^{7}Be$, E>0.4 MeV
- $^{14}N(p,\gamma)^{15}O$, E>0.4 MeV



Carbon burning

- $^{12}C(^{12}C,\alpha)^{20}Ne$

Higher-energy accelerator underground: Science case (2)

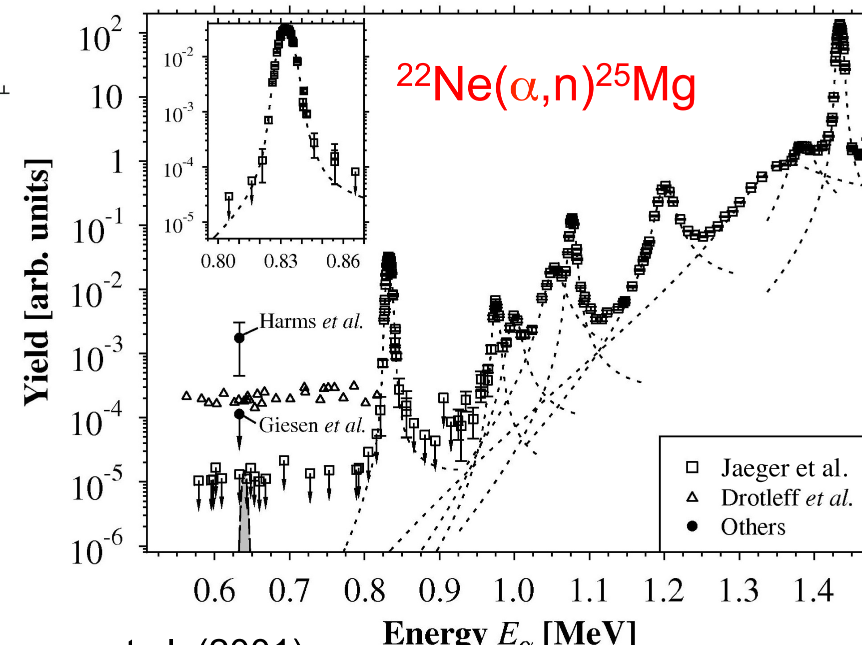


Heil et al. (2008)

The two astrophysical neutron source reactions:

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

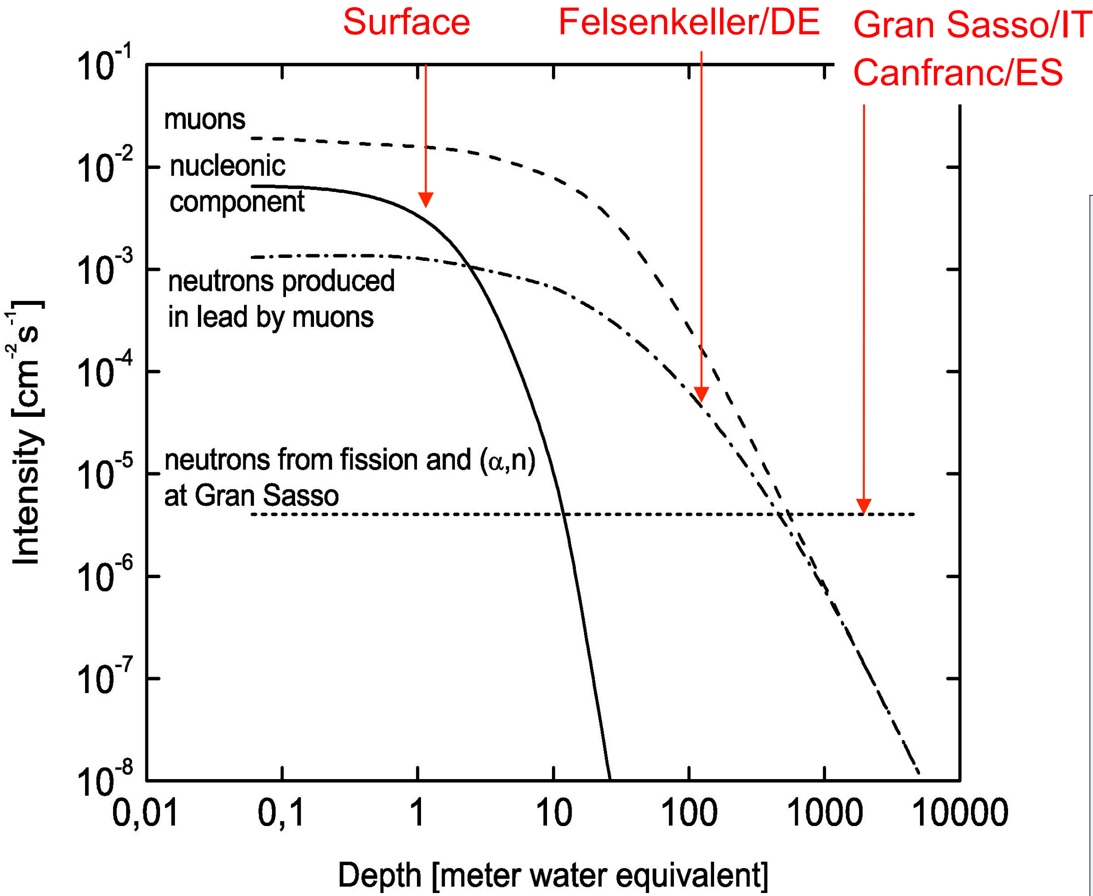
$^{22}Ne(\alpha,n)^{25}Mg$



Jaeger et al. (2001)

In both cases, high uncertainty for the cross section at low energies, just where it matters for astrophysics!

Projects for new underground accelerators in Europe

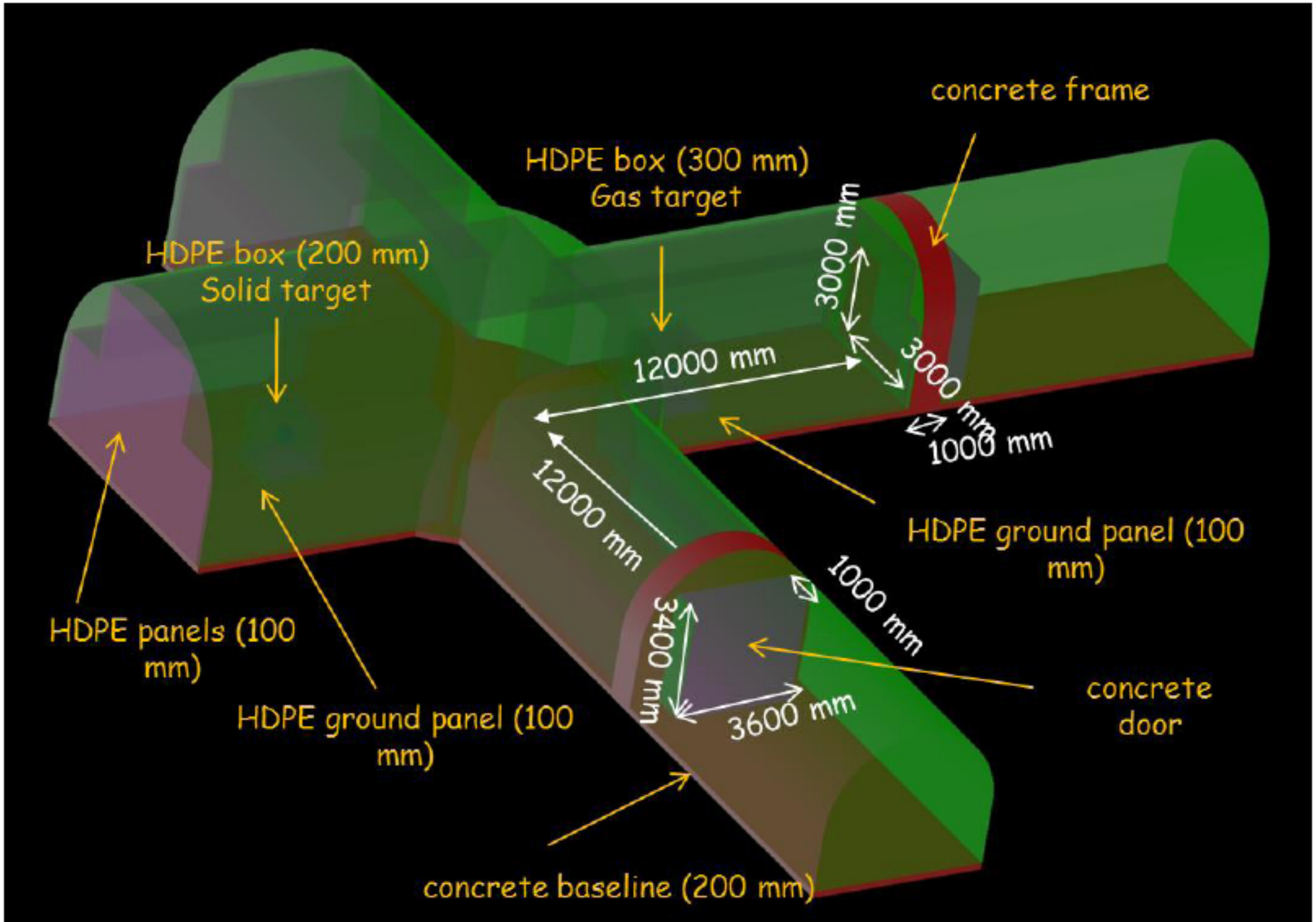


Other option: Boulby / UK

Outside Europe:
United States: DIANA (talk by Michael Wiescher)
China, South America

The LUNA-MV project at Gran Sasso / Italy

3.5 MV single-ended accelerator, with terminal ion source



courtesy A. Guglielmetti

- In a very low background environment such as LNGS, it is mandatory not to increase the neutron flux above its average value

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

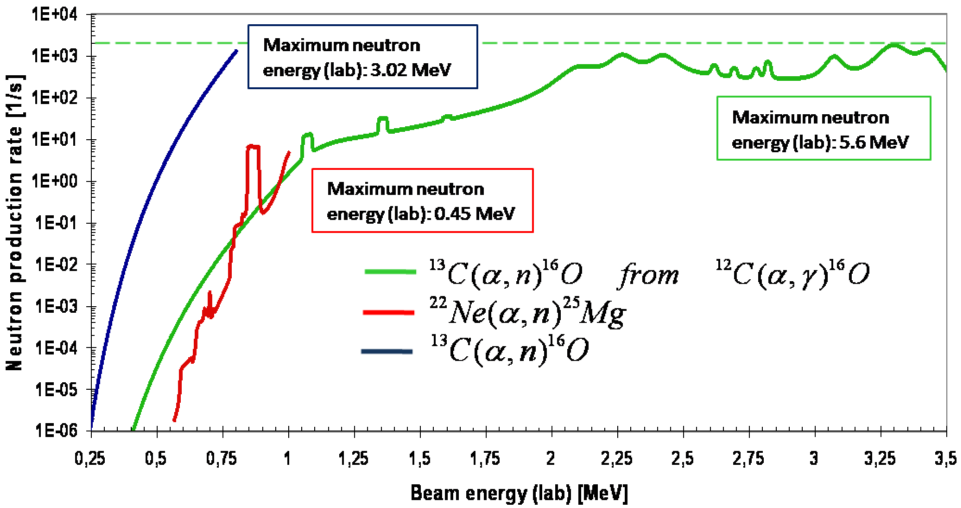
α beam intensity: 200 μA
Target: ^{13}C, 2 10^{17}at/cm^2 (99% ^{13}C enriched)
Beam energy(lab) ≤ 0.8 MeV

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

α beam intensity: 200 μA
Target: ^{22}Ne, 1 10^{18}at/cm^2
Beam energy(lab) ≤ 1.0 MeV

$^{13}C(\alpha,n)^{16}O$ from $^{12}C(\alpha,\gamma)^{16}O$

α beam intensity: 200 μA
Target: ^{13}C, 1 10^{18}at/cm^2 (^{13}C/^{12}C = 10^{-5})
Beam energy(lab) ≤ 3.5 MeV



- Maximum neutron production rate : 2000 n/s
- Maximum neutron energy (lab) : 5.6 MeV

DRESDEN concept HZDR

Laboratory for Underground Nuclear Astrophysics

LUNA MV

Round Table: "LUNA - MV at LNGS"

February 10-11, 2011

- **STATUS OF SIMILAR UNDERGROUND PROJECTS**
  - Status of the Canfranc project, Luis FRAILE
  - The Bulby mine: an opportunity for underground nuclear astrophysics, Maria Luisa ALIOTTA
  - The Dresden Felsenkeller: A shallow underground option for accelerator – based nuclear astrophysics, Daniel BEMMERER
  - Status of the DIANA project, Alberto LEMUT
- **GENERAL DESCRIPTION OF THE LUNA-MV PROJECT**
  - The LUNA-MV project: from 2007 to now, Alessandra GUGLIELMETTI
  - A Megavolt Accelerator for Underground Nuclear Astrophysics, Matthias JUNKER
  - The Site for LUNA-MV at LNGS, Paolo MARTELLA
  - The Shielding of the LUNA-MV site, Davide TREZZI
- **PHYSICS CASES FOR LUNA-MV**
  - The $^{12}C(\alpha,\gamma)^{16}O$ reaction from the astrophysical point of view, Oscar STRANIERO
  - The rates of neutron – realeasing reactions in He-burning phases and their astrophysical consequences, Maurizio BUSSO
  - The seeds of the S-process: experimental issues in the study of $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$, Paolo PRATI
  - Towards the Gamow peak of the $^{12}C(\alpha,\gamma)^{16}O$ reaction, Roberto MENEGAZZO
  - Stellar helium burning studied at LUNA-MV. The $^{14}N(\alpha,\gamma)^{18}F$, $^{15}N(\alpha,\gamma)^{19}F$, $^{16}O(\alpha,\gamma)^{20}Ne$, and $^{18}O(\alpha,\gamma)^{22}Ne$, Daniel BEMMERER
- **DISCUSSION AND LAYOUT OF A POSSIBLE LOI EXTENDED TO OTHER GROUPS**
  - Workpackages towards European Underground Accelerator

Next-generation underground laboratory for Nuclear Astrophysics

Executive summary

This document originates from discussions held at the LUNA MV Roundtable Meeting that took place at Gran Sasso on 10-11 February 2011. It serves as a call to the European Nuclear Astrophysics community for a wider collaboration in support of the next-generation underground laboratory. To state your interest to contribute to any of the Work Packages, please add your name, contact details, and WP number under *International Collaboration*.

WP1: Accelerator + ion source

WP2: Gamma detectors

WP3: Neutron detectors

WP5: Solid targets

WP6: Gas target

WP7: Simulations

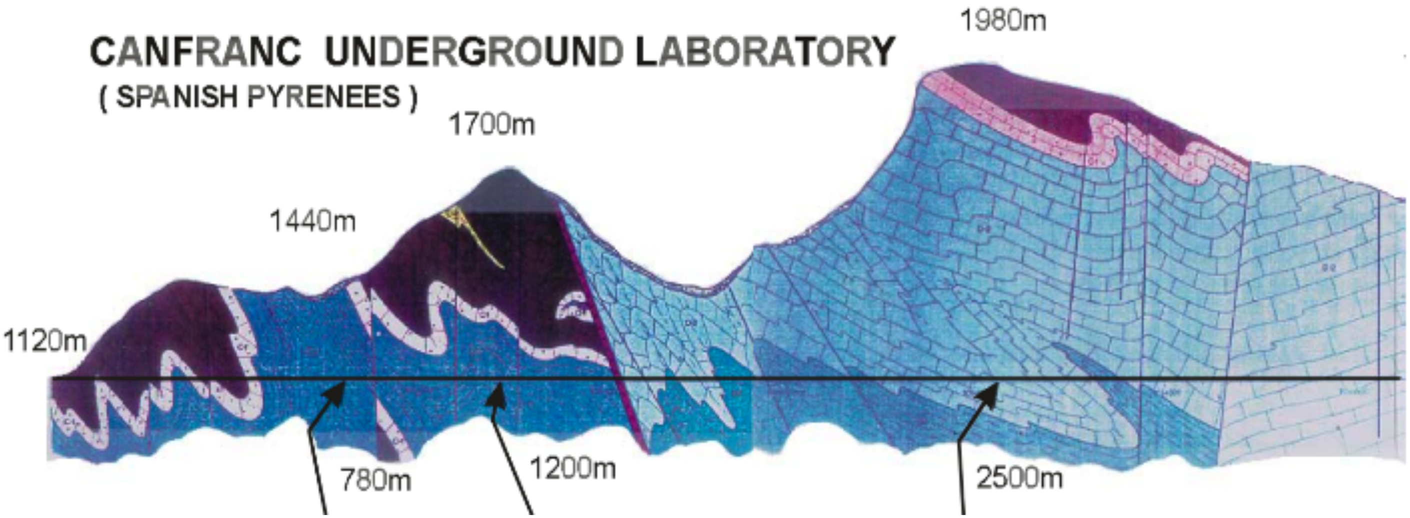
WP8: Stellar model calculations

DRESDEN concept

HZDR

Mitglied der Helmholtz-Gemeinschaft

Laboratorio Subterráneo de Canfranc / Spain



LSC

➔Poster presentation by Luis M. Fraile (today)

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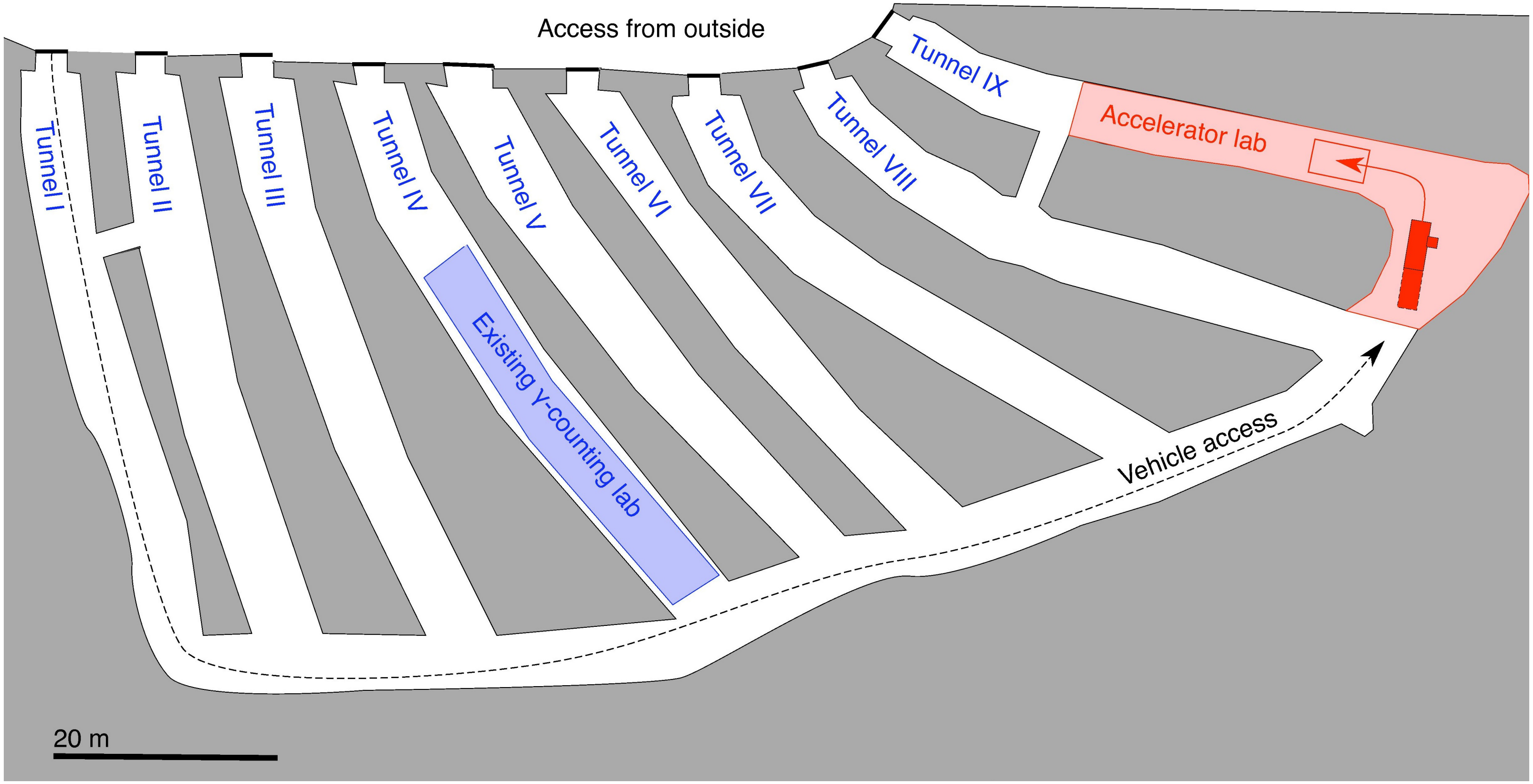
Dresden underground laboratory: Felsenkeller, below 47 m of rock

- γ-counting facility for analytics, established 1982
  founding member of CELLAR collaboration
- 10 HPGe detectors
- Since 2009, contract enabling scientific use of Felsenkeller by HZDR and TU Dresden
- Several active Masters+PhD theses using Felsenkeller

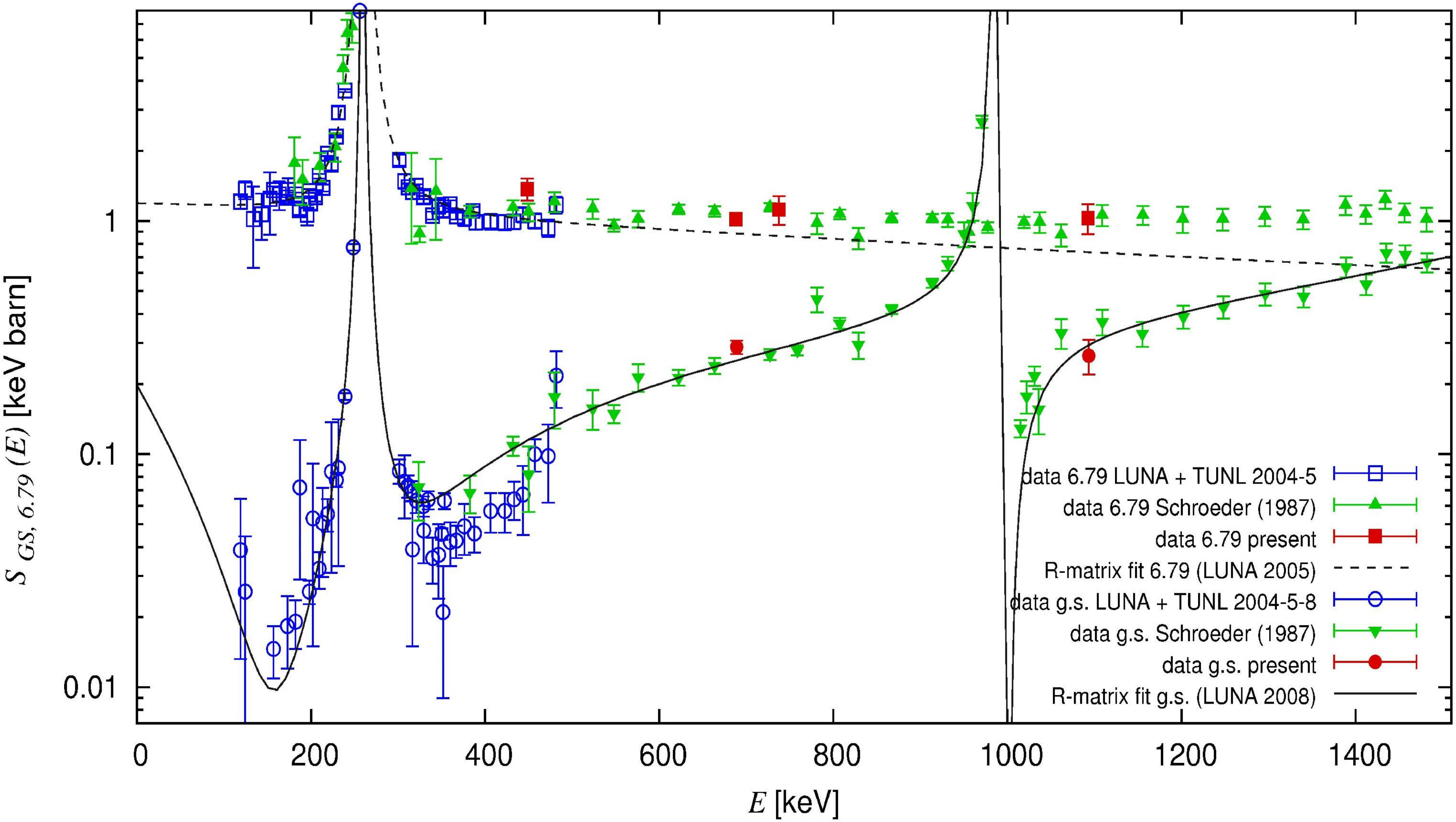
Felsenkeller, site for planned accelerator



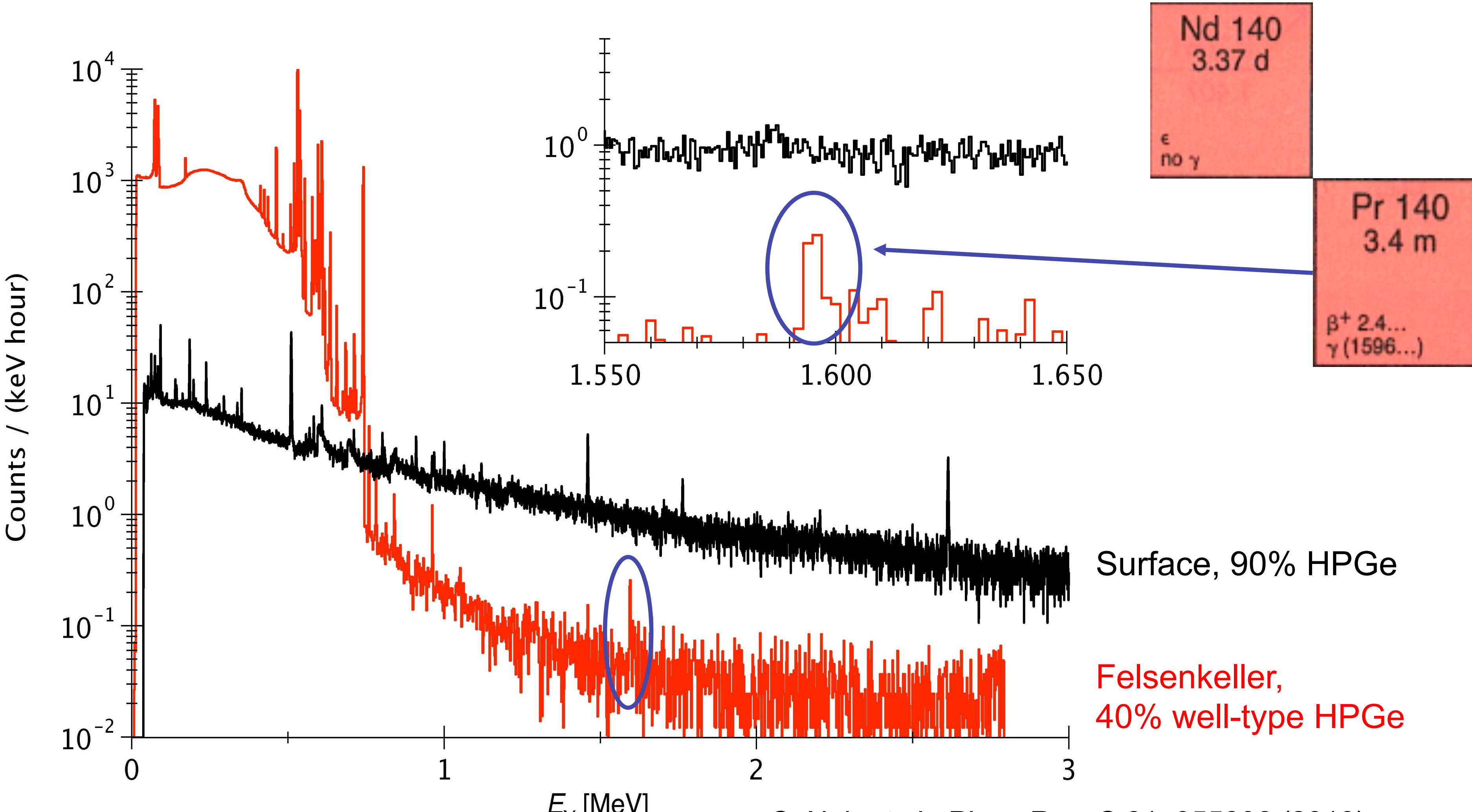
- Tunnels exist since the 1850's, currently used for storing sausage skins, truck parking, etc.
- Background level only ~3 times worse than at LUNA
- 5 km from TU Dresden, 25 km from HZDR campus (technicians available)
- Startup possible with a used accelerator (negotiating to buy one)
- May be part of a staged approach facilitating other underground accelerators

Synergies overground-underground: The $^{14}N(p,\gamma)^{15}O$ reaction

- Also high-energy data influence the R-matrix extrapolation to low energy
- Plot includes preliminary data from the Dresden 3.3 MV Tandetron
- More higher-energy and also indirect (e.g. level lifetime) data are necessary
- Talk by Rosanna Depalo on the lifetime measurement of the 6.79 MeV state in ^{15}O (Thursday)



Photoactivation study at Felsenkeller: $^{144}Sm(\gamma,\alpha)^{140}Nd(EC)^{140}Pr$



C. Nair et al., Phys. Rev. C 81, 055806 (2010)

Similar approach, with α-beam: talk by Konrad Schmidt (Monday)

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Summary, underground laboratories

- Solar abundance problem calls for precise data on nuclear reactions in the Sun

- Rich science case for future, higher-energy underground accelerators
  - → recommendation from NuPECC for "one or more projects" to be started "as soon as possible"
  - → Successful workshops in Dresden in April 2010 and at Gran Sasso in February 2011
  - → Next follow-up: 22.-23.03.2012 at Canfranc/Spain (L. Fraile)

- Synergies with overground small accelerators, and with radioactive ion beam facilities
  - → Activation measurements
  - → Target characterization
  - → Complex experiments (recoil mass spectrometer, Doppler shift attenuation, ….)

- LUNA presentations at this conference
  - → Antonio Caciolli, talk on $^{17}O(p,\gamma)^{18}F$ (now)
  - → Michael Anders, talk on $^{2}H(\alpha,\gamma)^{6}Li$ (Thursday)
  - → Marie-Luise Menzel, poster on $^{22}Ne(p,\gamma)^{23}Na$ (today)