Nuclear reactions for astrophysics studied at LUNA and in the Dresden Felsenkeller

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Laboratory
Underground
Nuclear
Astrophysics

EuroGENESIS
FirstStars CoDustMas EXNUC MASCHE
Origin of the Elements and Nuclear History of the Universe

DFG

NAVI
Nuclear Astrophysics Virtual Institute

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Nuclear reactions for astrophysics, studied at LUNA and in the Dresden Felsenkeller

1. Motivation: The solar abundance problem and solar neutrinos
2. Technique: Experiments in underground laboratories
3. Hydrogen burning in our Sun, in asymptotic giant branch stars, and in classical novae
4. Stable-ion beam nuclear physics for supernovae
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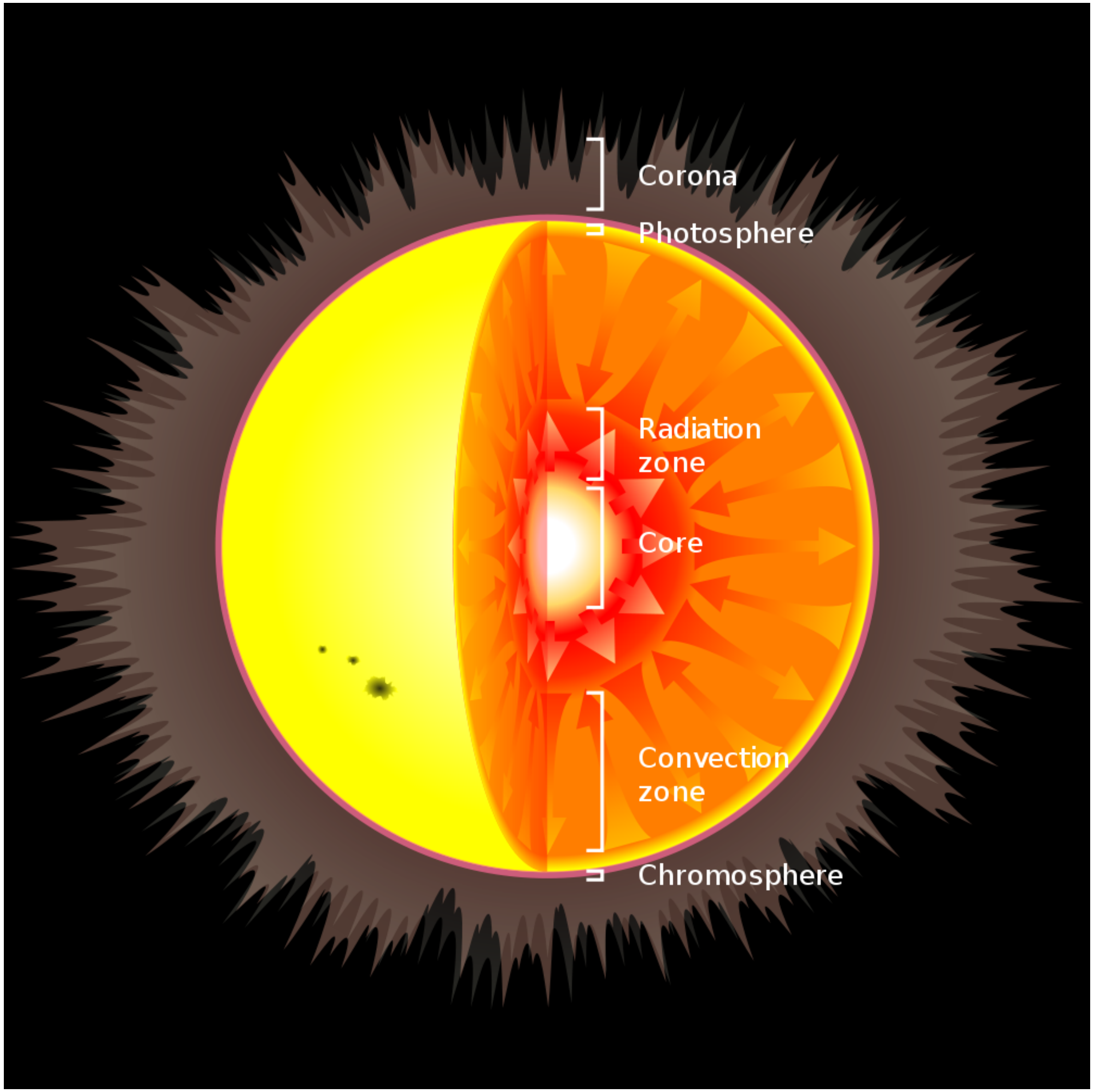
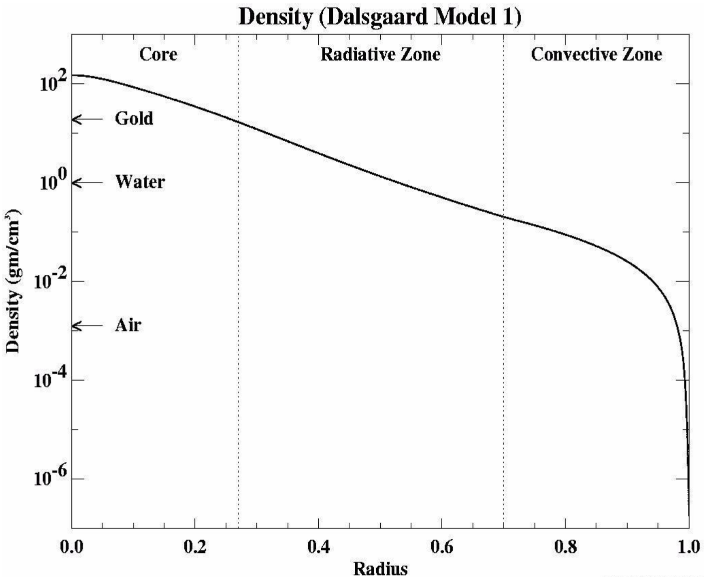
Structure of the Sun red: Observable



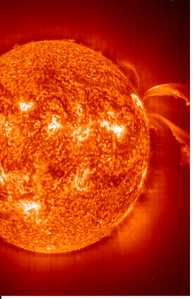
- Corona
- Chromosphere
- Photosphere
  Fraunhofer lines
- Convection zone
  p-modes (helioseismology)
- Radiation zone
- Core
  Neutrinos

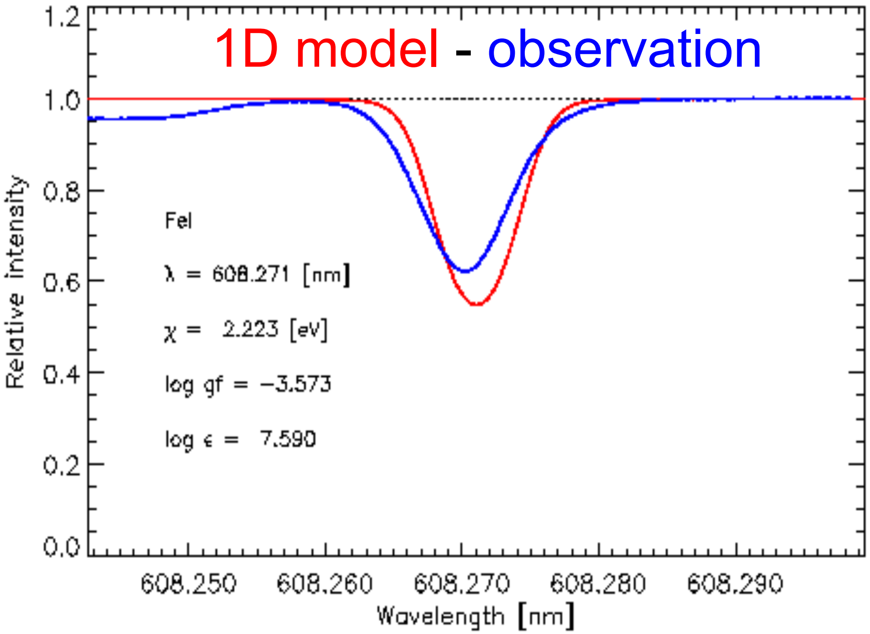


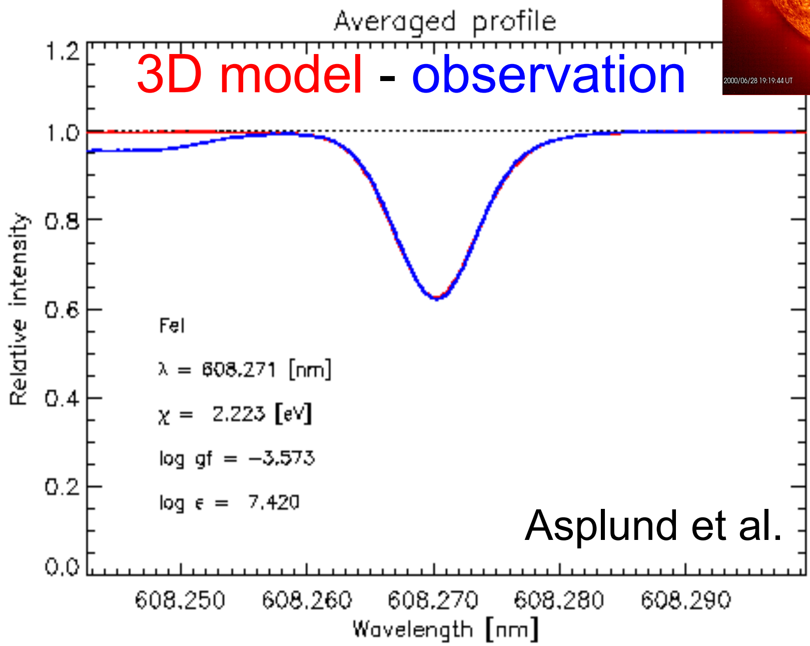
NASA/MSFC Hathaway

Data on the Sun (1): Elemental abundances

from the model-based interpretation of the Fraunhofer lines







Asplund et al.

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

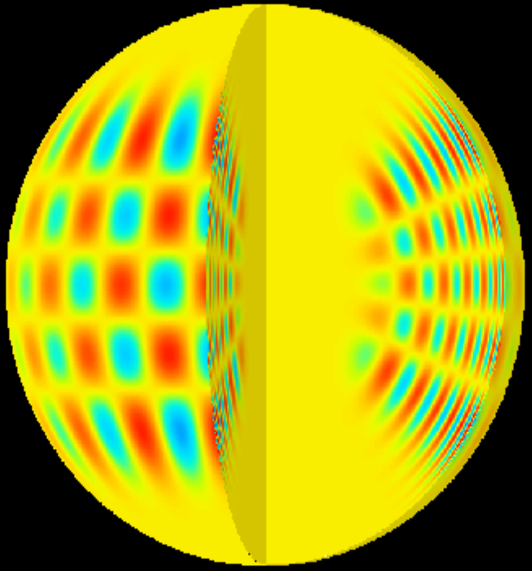
1D: 2.29% (by mass) of the Sun are “metals” (Li...U)

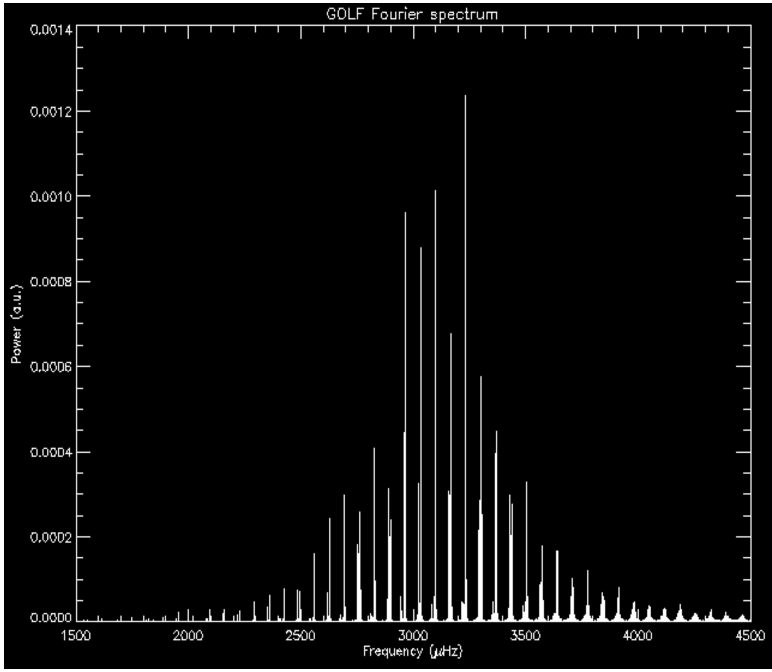
3D: 1.78% (by mass) of the Sun are “metals” (Li...U)

Data on the Sun (2): Helioseismology

Satellite “SoHo”

(Solar and Heliospheric Observatory)





Fourier transformed spectrum from GOLF instrument on SoHo

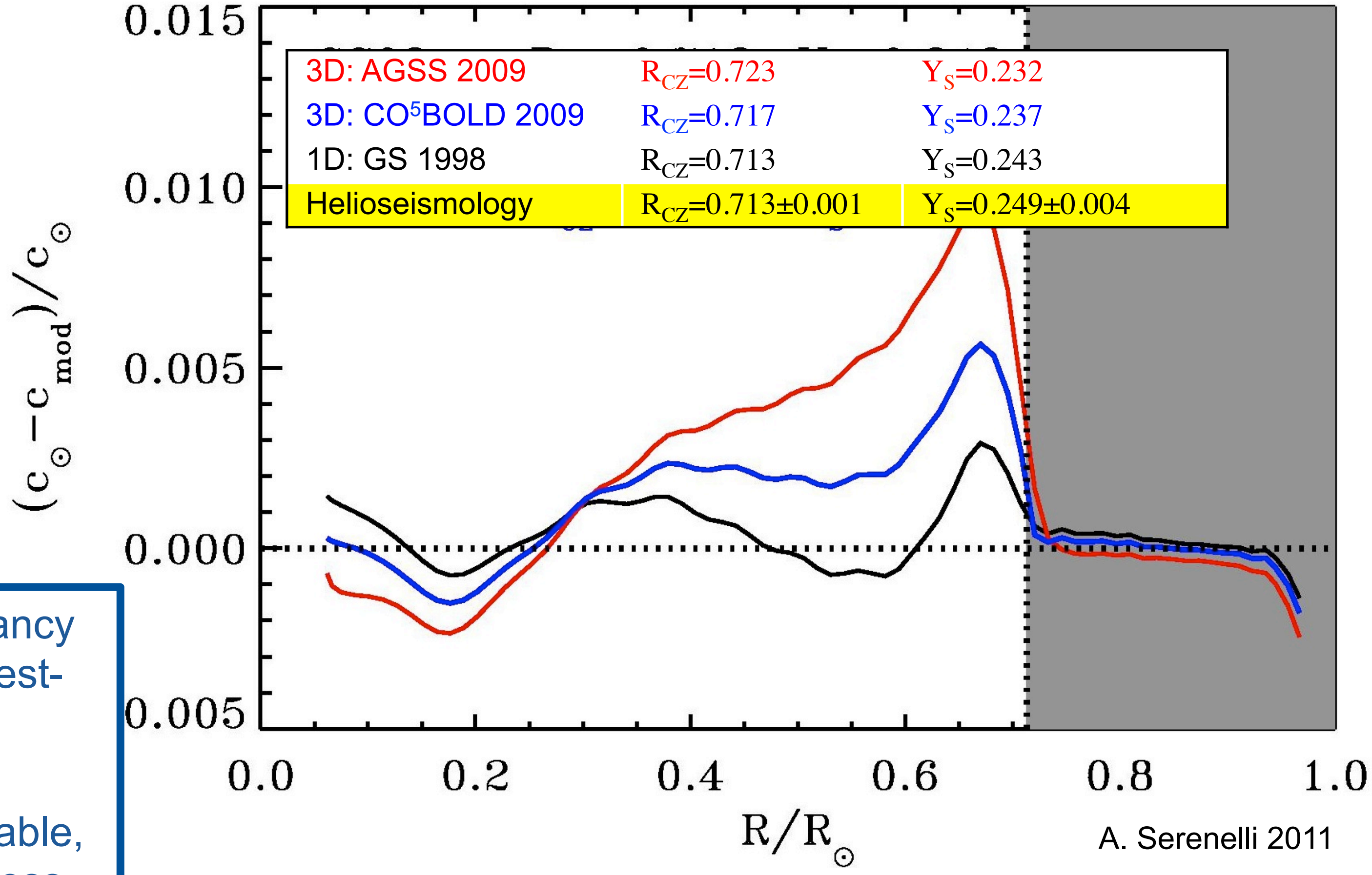
Simulated standing waves, p-mode ~3 mHz

The solar abundance problem:
Contradiction between elemental abundances and helioseismology

Solar models computed with different sets of elemental 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)

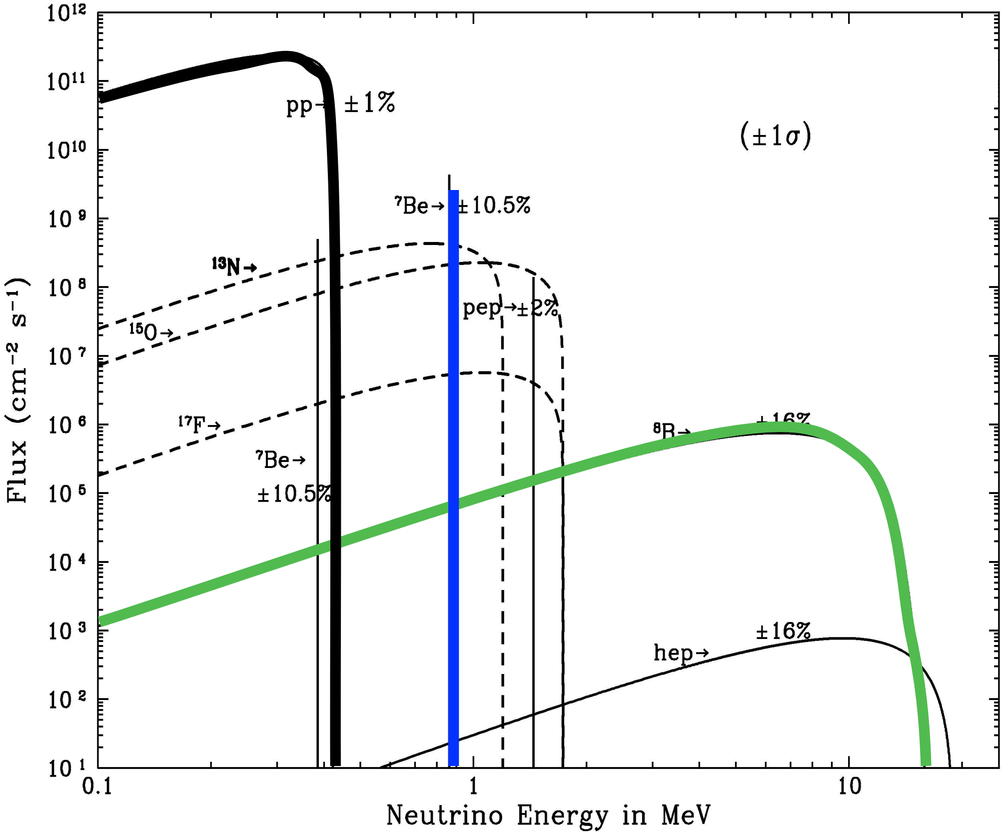


3D: AGSS 2009	$R_{CZ}=0.723$	$Y_S=0.232$
3D: CO^{5}BOLD 2009	$R_{CZ}=0.717$	$Y_S=0.237$
1D: GS 1998	$R_{CZ}=0.713$	$Y_S=0.243$
Helioseismology	$R_{CZ}=0.713\pm0.001$	$Y_S=0.249\pm0.004$

A. Serenelli 2011

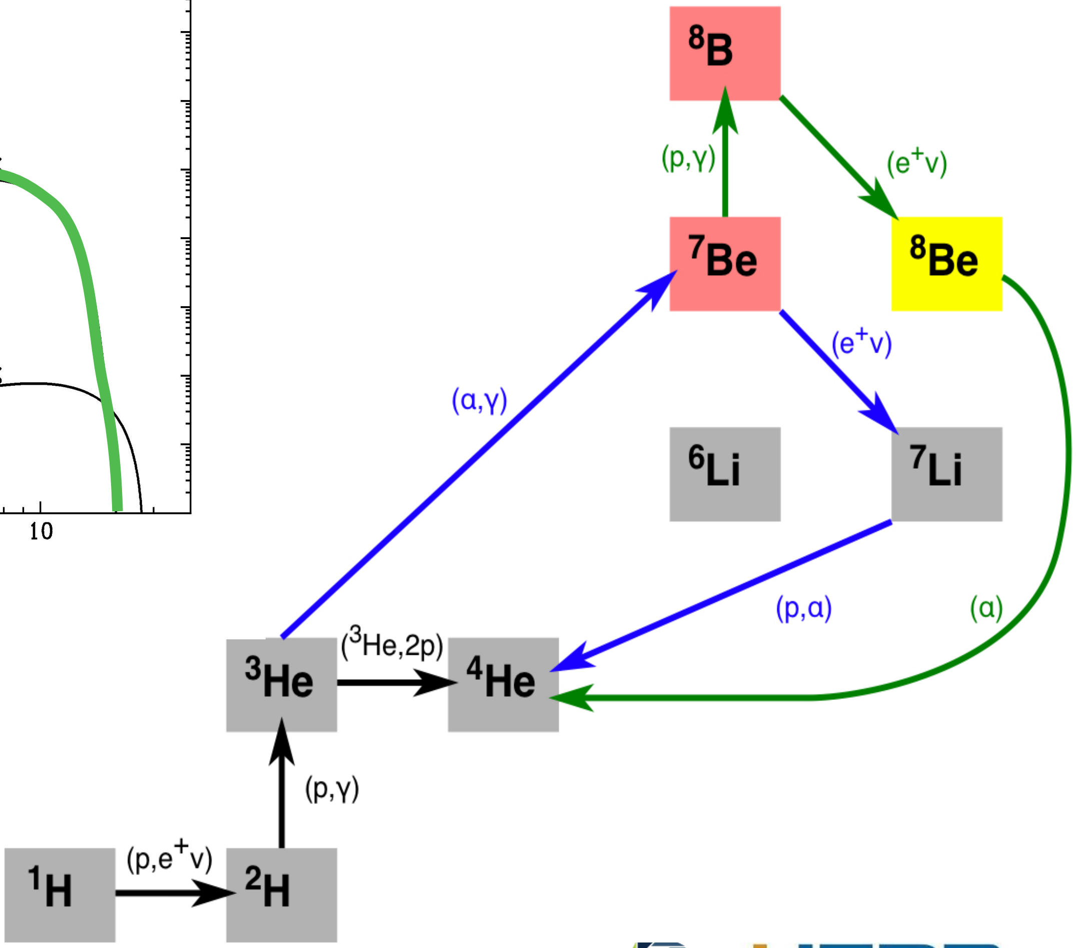
- A significant discrepancy for the closest and best-observed star in the universe!
- Can the third observable, solar neutrinos, address this problem?

The proton-proton chain (pp chain) of hydrogen burning

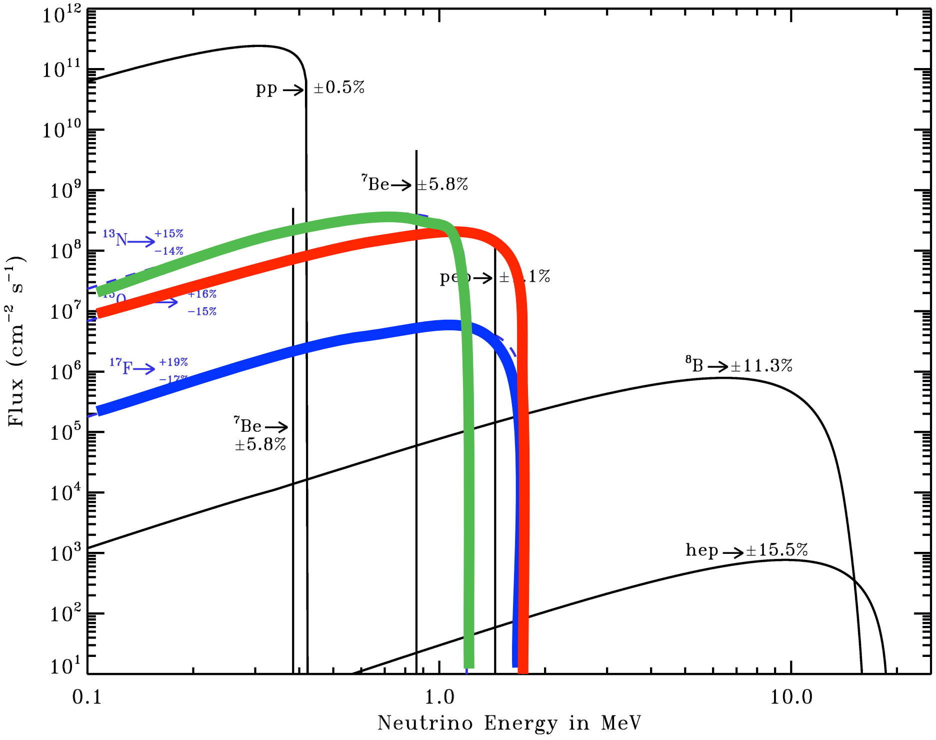


99% of energy production in the Sun

pp-1	**pp-2**	**pp-3**
85%	**15%**	**0.02%**



The carbon-nitrogen-oxygen (CNO) cycle of hydrogen burning

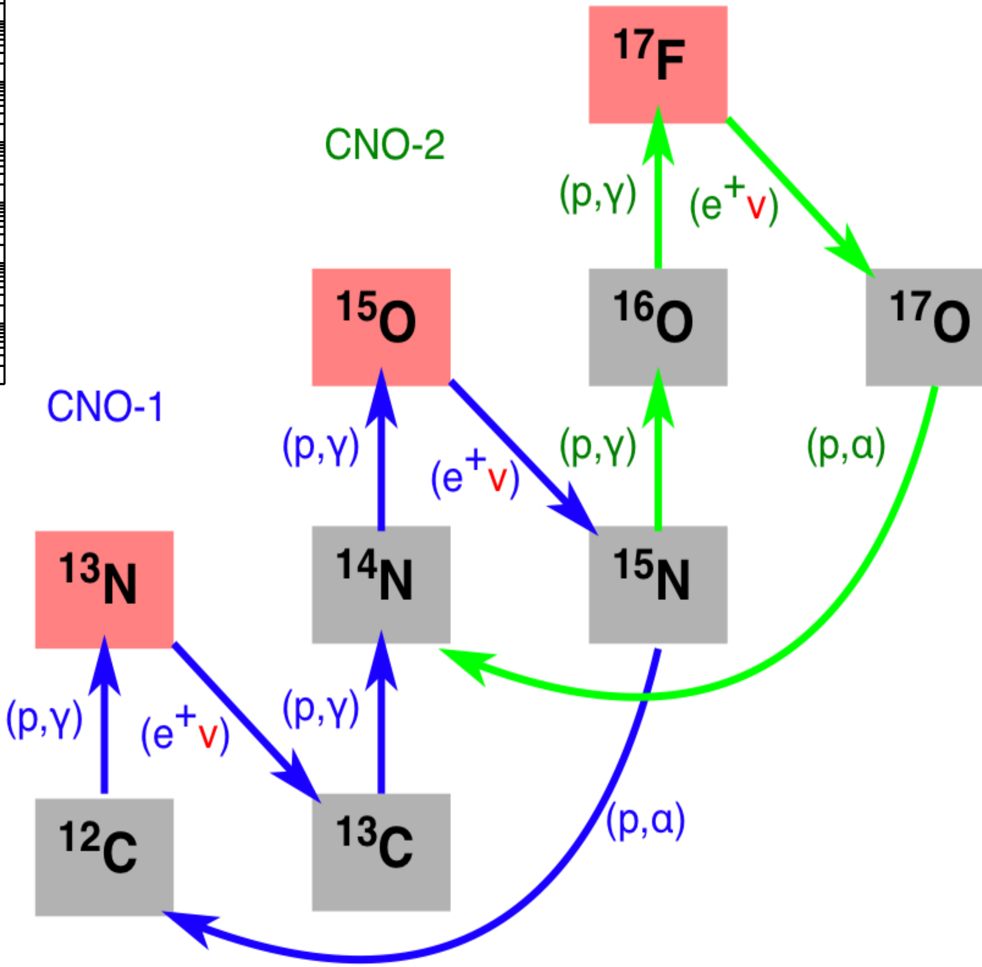


1% of energy production in the Sun

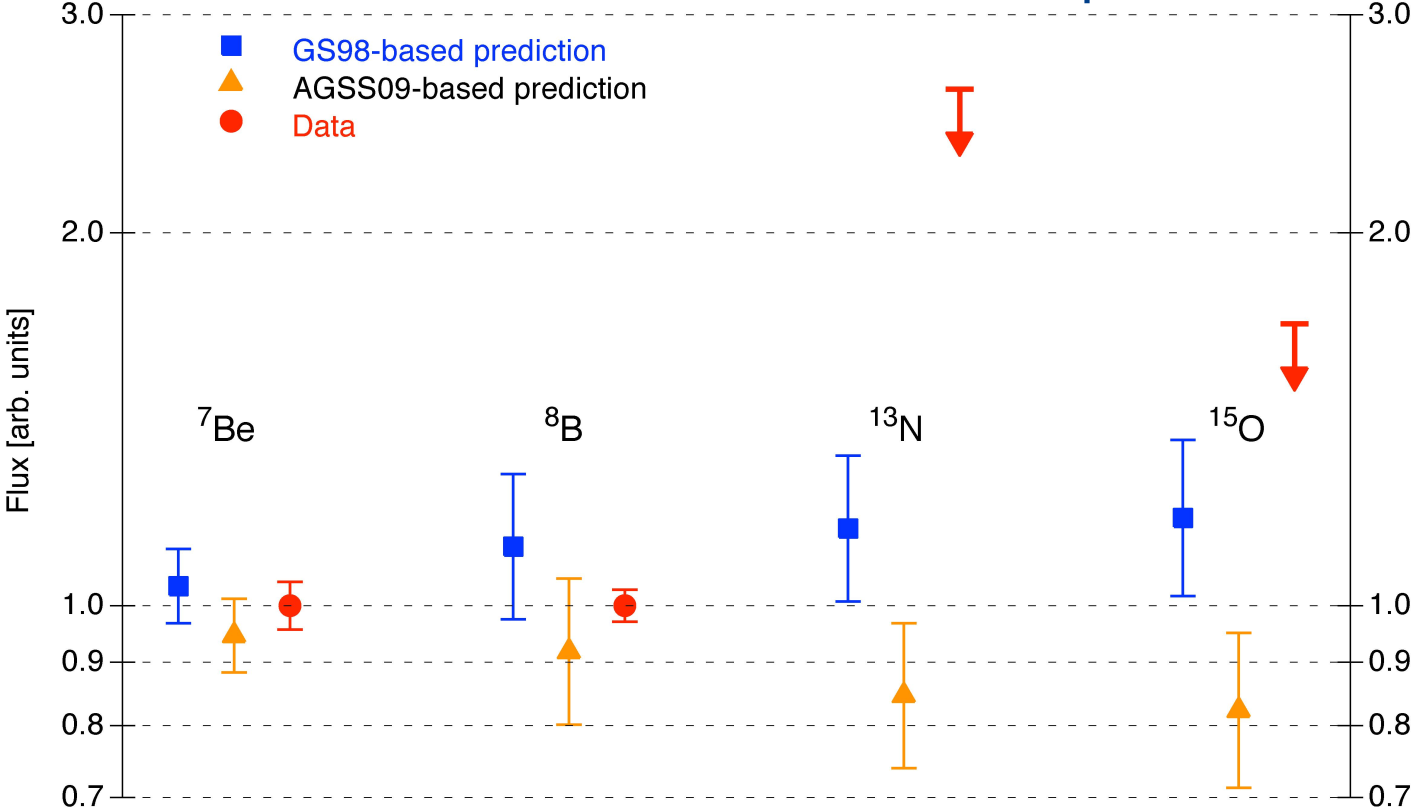
^{13}N, Q(β^+) = 2.220 MeV

^{15}O, Q(β^+) = 2.754 MeV

^{17}F, Q(β^+) = 2.761 MeV



Solar neutrino fluxes: Data and model predictions

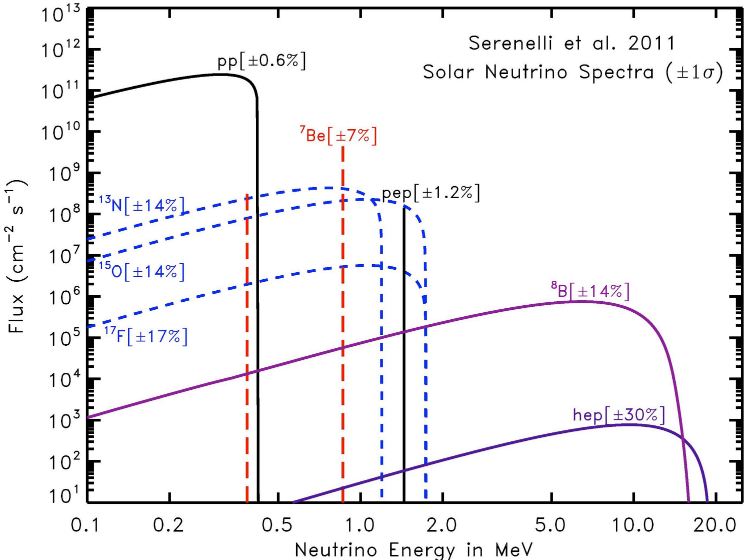


Neutrino fluxes:
Standard Solar Model;
Antonelli et al., 1208.1356

GS98 = Old, high CNO elemental abundances

AGSS09 = New, low CNO elemental abundances

- ^{7}Be, ^{8}B: Data more precise than the models
- ^{13}N, ^{15}O: No data yet, but models are not very precise
- **Need smaller error bars for the models!**



What drives the uncertainties in the predicted solar neutrino fluxes?

Nuclear reaction rates

	S_{11}	S_{33}	S_{34}	S_{17}	$S_{1,14}$	Opac	Diff
pp	0.1	0.1	0.3	0.0	0.0	0.2	0.2
pep	0.2	0.2	0.5	0.0	0.0	0.7	0.2
hep	0.1	2.3	0.4	0.0	0.0	1.0	0.5
^{7}Be	1.1	2.2	4.7	0.0	0.0	3.2	1.9
^{8}B	2.7	2.1	4.5	7.7	0.0	6.9	4.0
^{13}N	2.1	0.1	0.3	0.0	5.1	3.6	4.9
^{15}O	2.9	0.1	0.2	0.0	7.2	5.2	5.7
^{17}F	3.1	0.1	0.2	0.0	0.0	5.8	6.0

Uncertainty contributed to neutrino flux, in percent

Antonelli et al., 1208.1356

^{3}He(α,γ)^{7}Be

^{7}Be(p,γ)^{8}B

^{14}N(p,γ)^{15}O

- **Nuclear reaction rates are the largest contributor to the uncertainty!**

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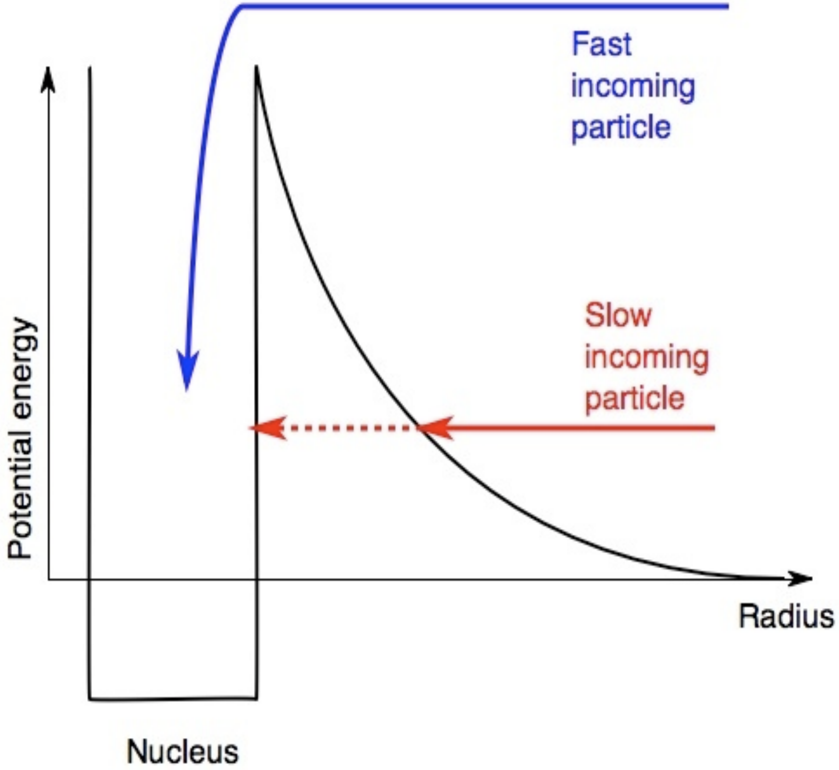
Nuclear reaction cross section σ for low-energy charged particles



- Typical Coulomb barrier height : ~ MeV
- Typical stellar 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)*:

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

↓

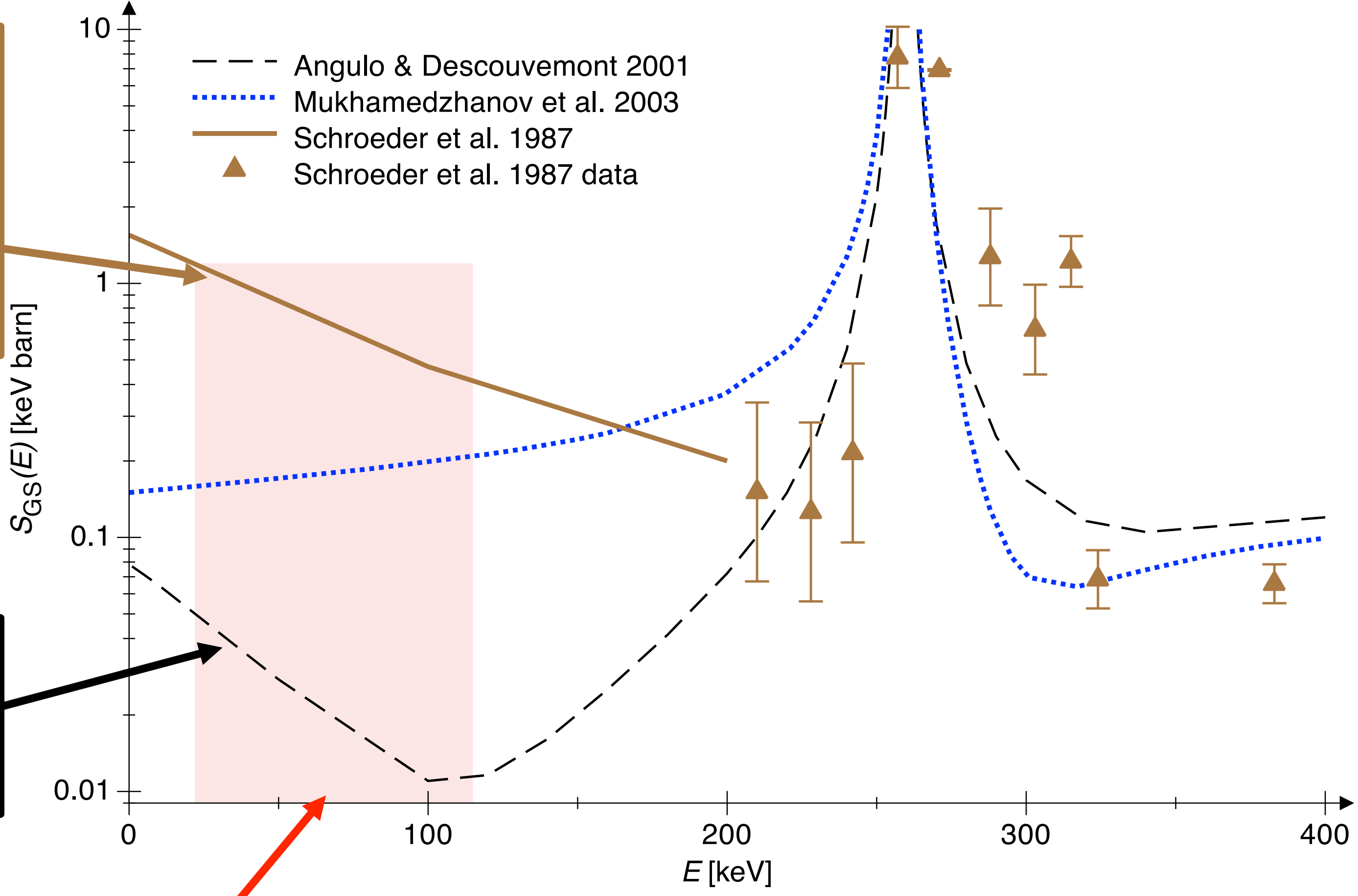
1. Measure cross section at high energy.
2. Convert to the astrophysical S factor.
3. Extrapolate to low, astrophysically relevant energy

Extrapolations can be dangerous: Example CNO cycle

State of the art, 2004

$^{14}N(p,\gamma)^{15}O$, capture to the ^{15}O ground state

Schröder et al. 1987:
Ground state capture contributes 50% of total S factor.
Adopted in astrophysical reaction rate compilations!



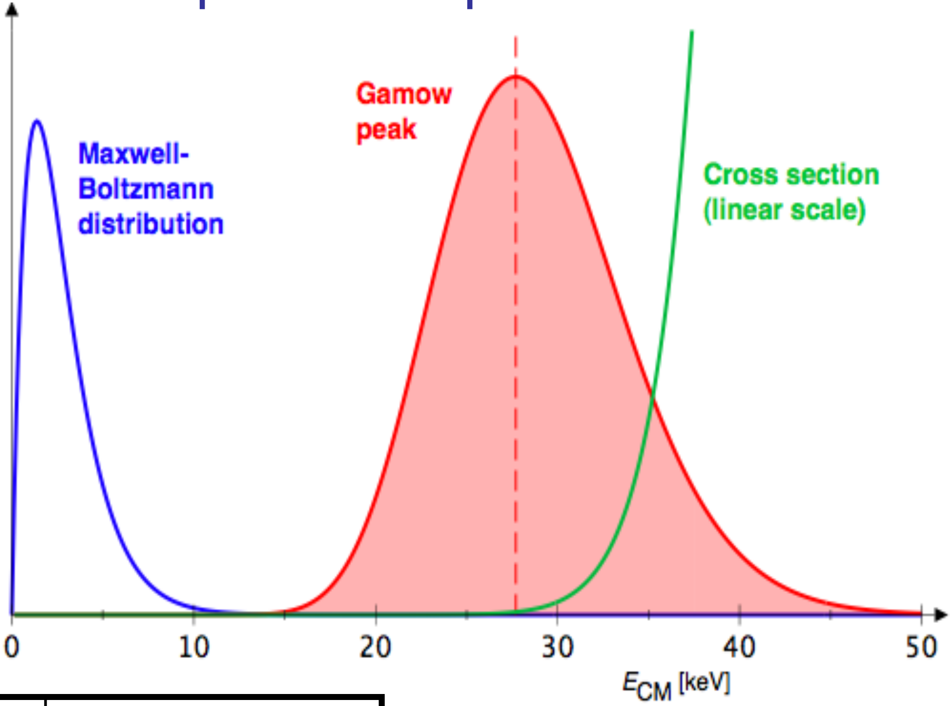
Angulo et al. 2001:
Ground state capture contributes 5% of total S factor.

Astrophysically relevant energy range

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

Astrophysical reaction rate:
Integral under the red curve

$$N_A\langle\sigma v\rangle = N_A \underline{\sqrt{\frac{8}{\pi A}}(kT)^{-3/2}} \int \underline{\sigma(E)} \underline{E\exp(-E/kT)}\,\mathrm{d}E$$



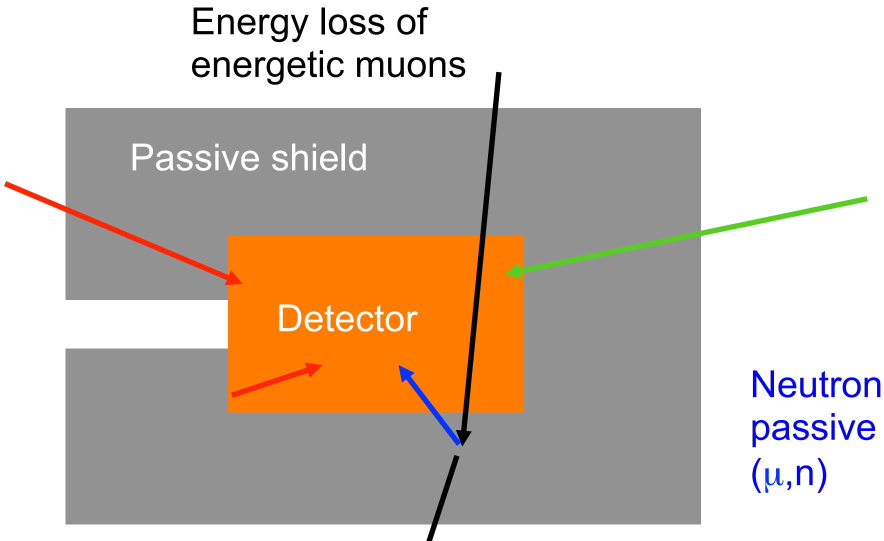
Scenario	Reaction	E_G[keV]	σ [barn]	Detected events/ hour
Sun (16 MK)	^{3}He(α,γ)^{7}Be	23	10^{-17}	10^{-9}
	^{14}N(p,γ)^{15}O	28	10^{-19}	10^{-11}
AGB stars (80 MK)	^{14}N(p,γ)^{15}O	81	10^{-12}	10^{-4}
Big bang (300 MK)	^{3}He(α,γ)^{7}Be	160	10^{-9}	10^{-1}
	^{2}H(α,γ)^{6}Li	96	10^{-11}	10^{-3}

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

Low signal counting rate…

…requires very low background counting rate!

What drives the laboratory background in γ-ray detectors?



Energy loss of energetic muons

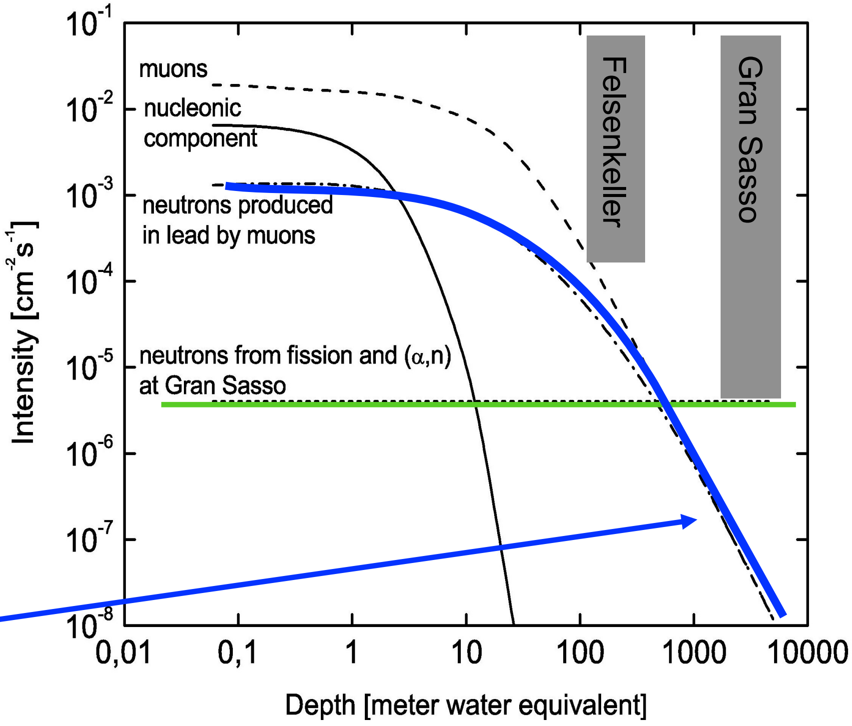
Radionuclides in the laboratory:
^{238}U - daughters
^{232}Th - daughters
^{40}K

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

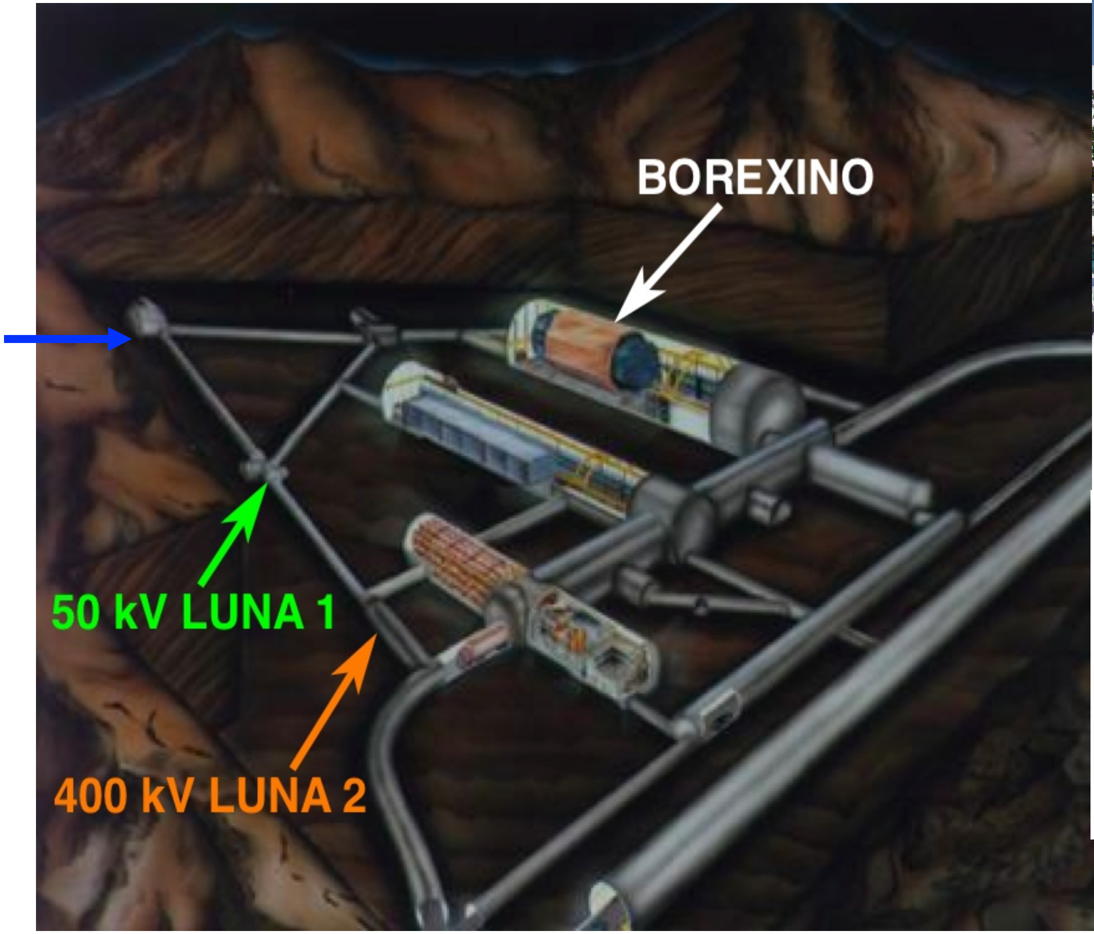
Radionuclides in detector and shield:
^{238}U - daughters
^{232}Th - daughters
^{60}Co, ^{138}La

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

	Affects…	Address by..
Radionuclides	$E_\gamma < 2.7$ MeV	shielding or purification
Neutrons	$E_\gamma < 12$ MeV	shielding
Muons	$E_\gamma < 70$ MeV	active veto
μ-ind. neutrons	$E_\gamma < 12$ MeV	**1000 m rock**



LUNA laboratory at Gran Sasso / Italy



LUNA-MV, planned

1992-2001

2000-2014

150 km from Rome

Access by motorway

LUNA = Laboratory Underground for Nuclear Astrophysics

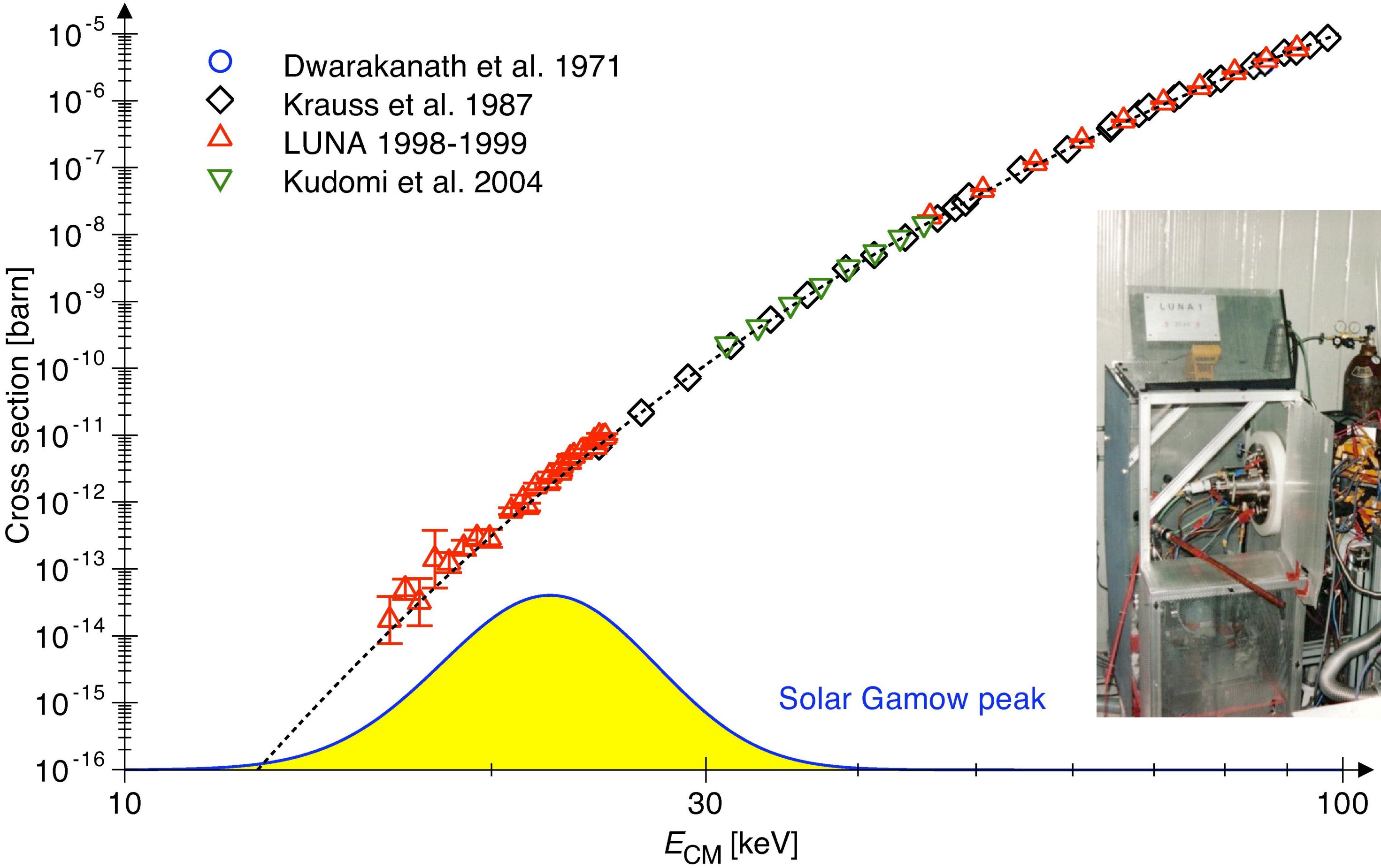
- Italy
- Germany (Bochum, Dresden)
- Hungary
- UK

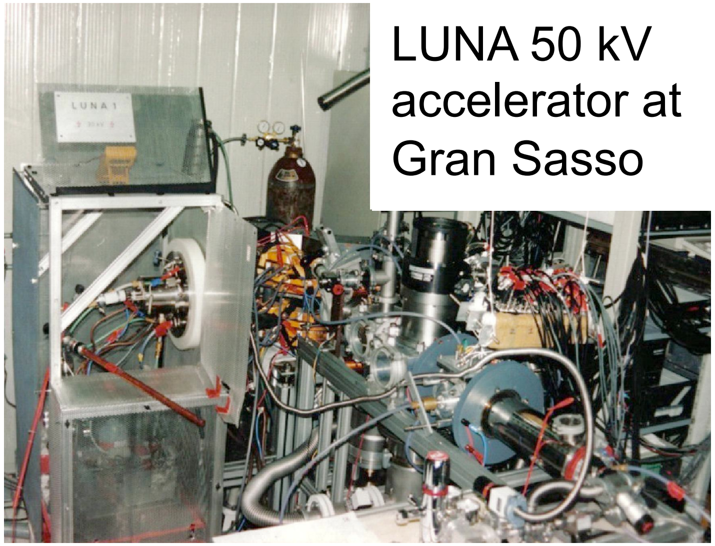
~1400 m rock 10^6 μ-reduction 10^3 n-reduction

First direct measurements in the solar Gamow peak: LUNA 0.05 MV accelerator, 1992-2001

- 50 kV accelerator deep underground
- Direct experimental data ruled out a possible nuclear solution for the solar neutrino problem
- Solar Gamow peak covered with data

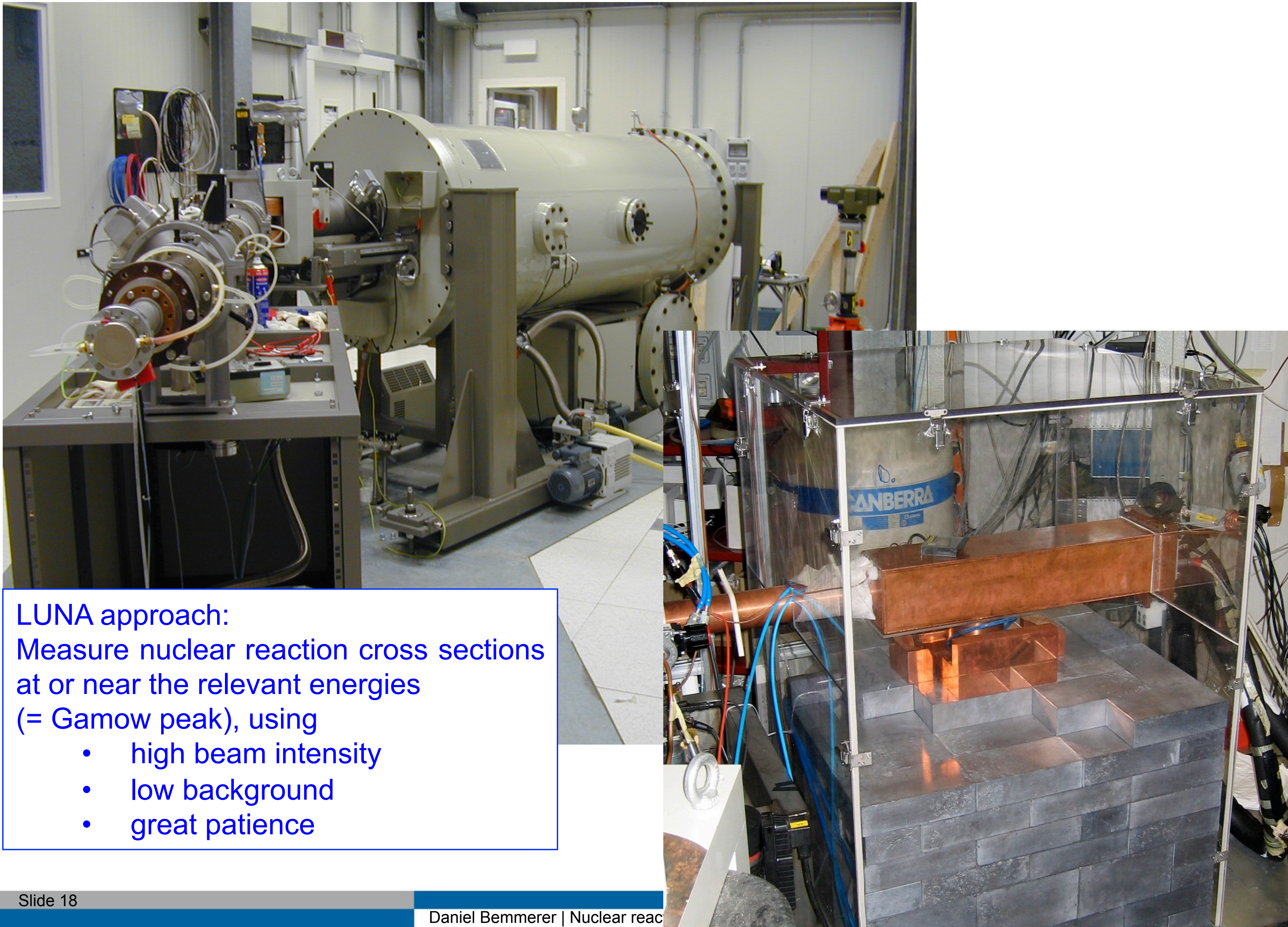
^{3}He(^{3}He,2p)^{4}He cross section, at the branch between pp-chains I and II





LUNA 50 kV accelerator at Gran Sasso

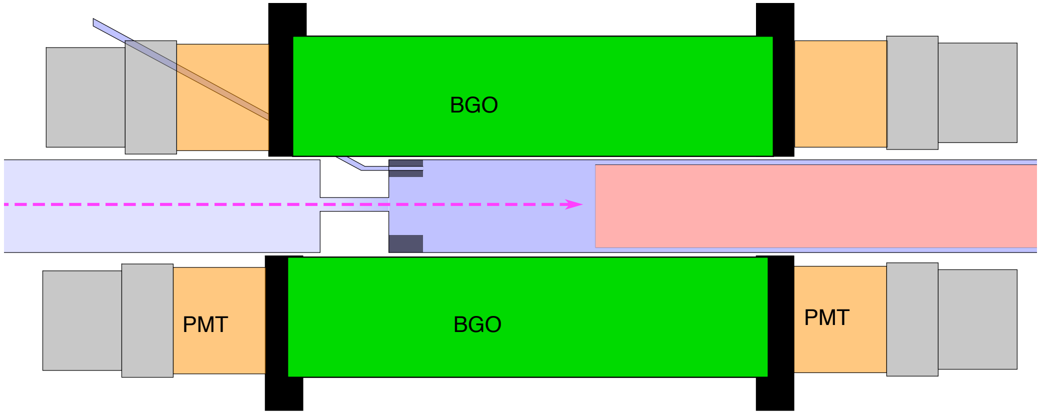
The LUNA 0.4 MV accelerator in Gran Sasso

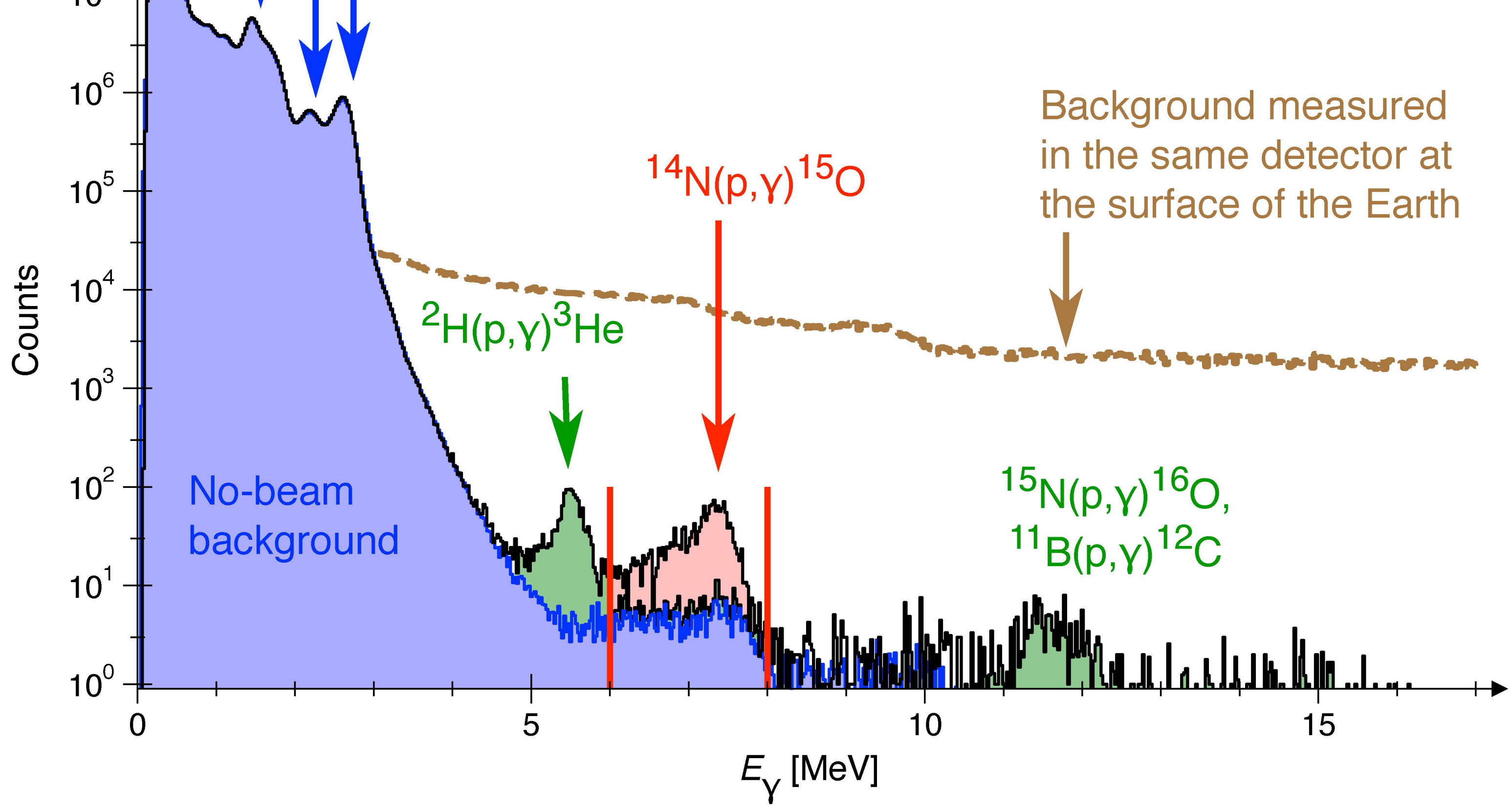


LUNA approach:
Measure nuclear reaction cross sections at or near the relevant energies
(= Gamow peak), using

- high beam intensity
- low background
- great patience

LUNA experiment on $^{14}N(p,\gamma)^{15}O$ in a 4π BGO summing crystal





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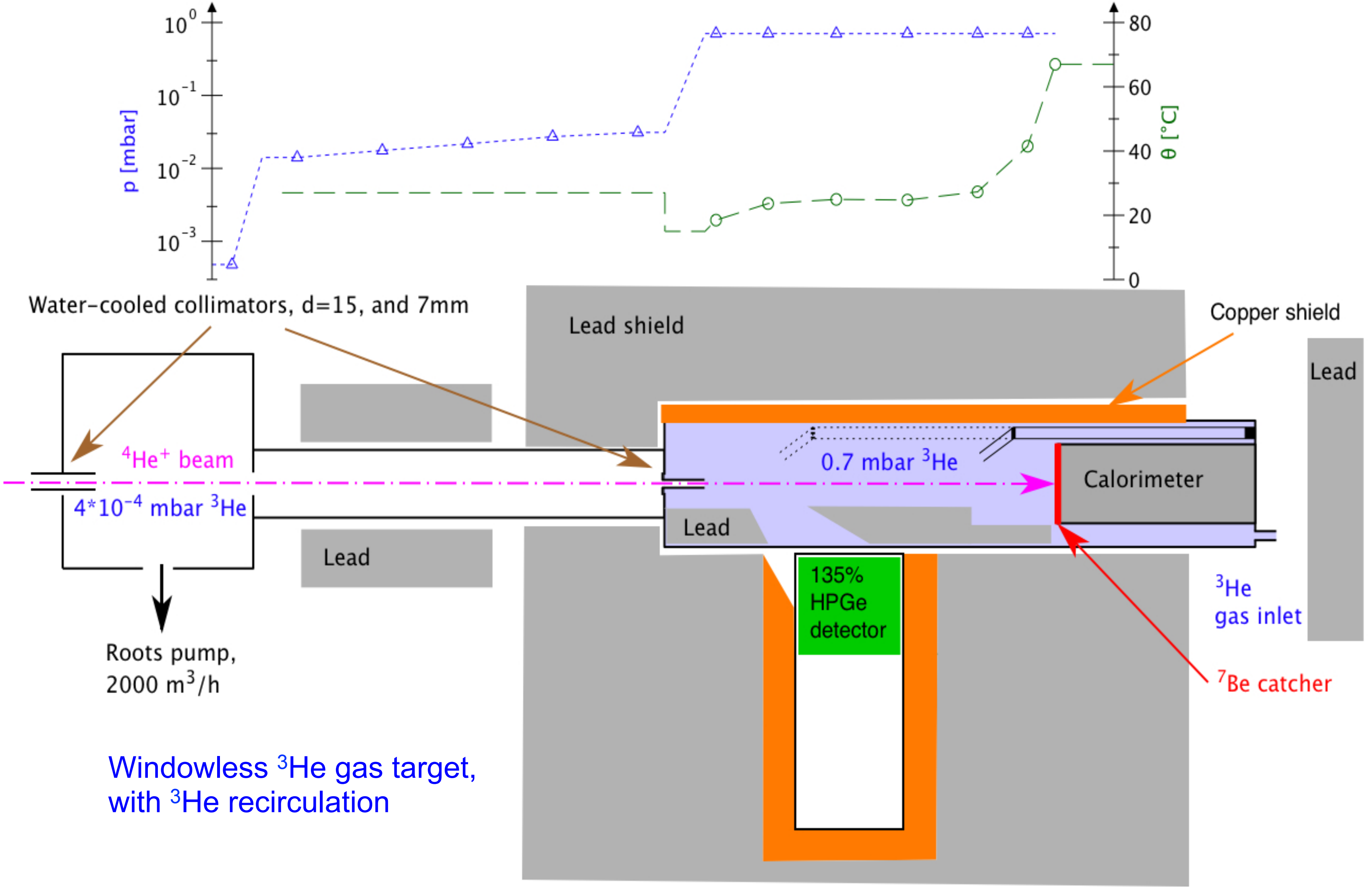
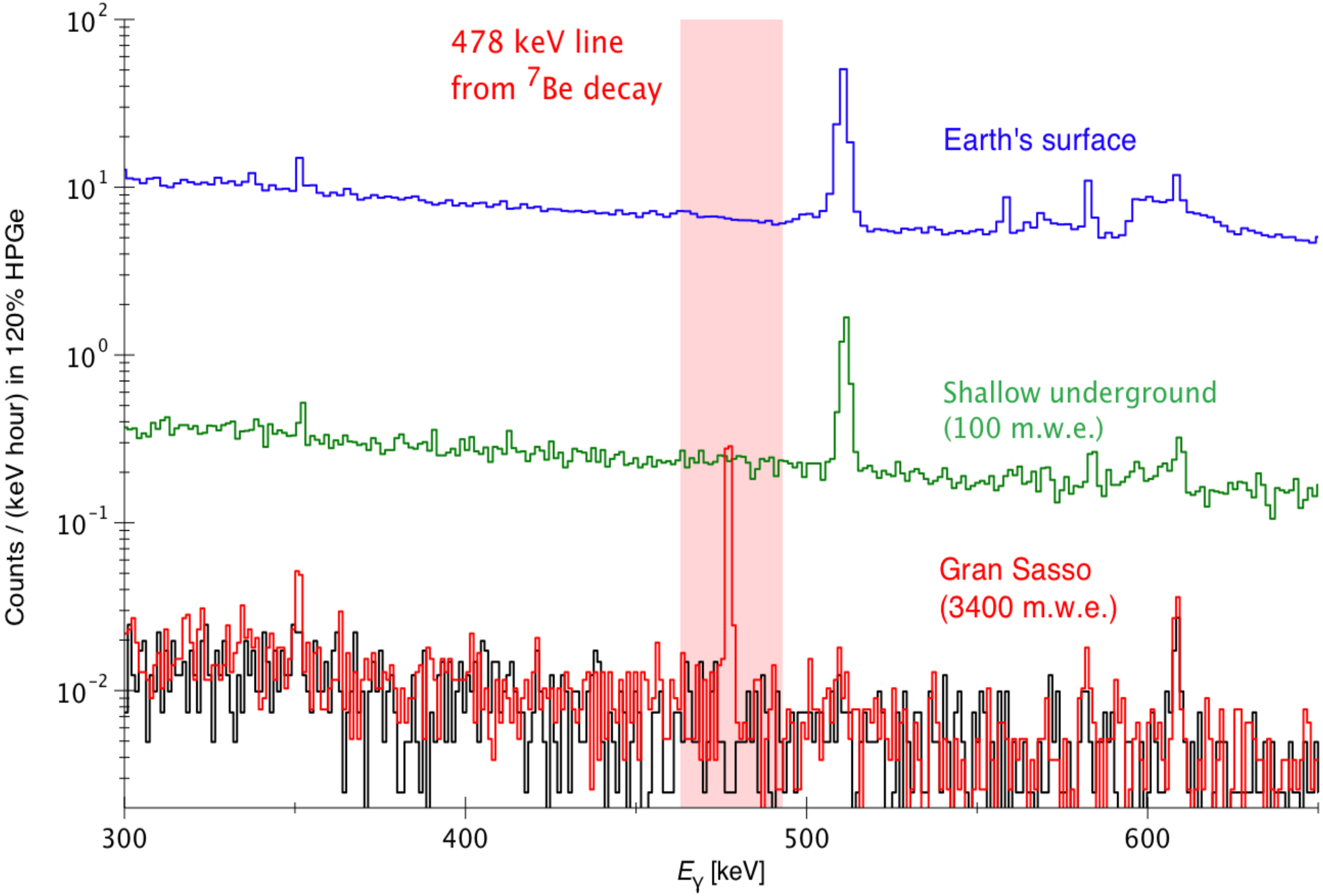
^{3}He(α,γ)^{7}Be experiment at LUNA (activation and prompt-γ technique)



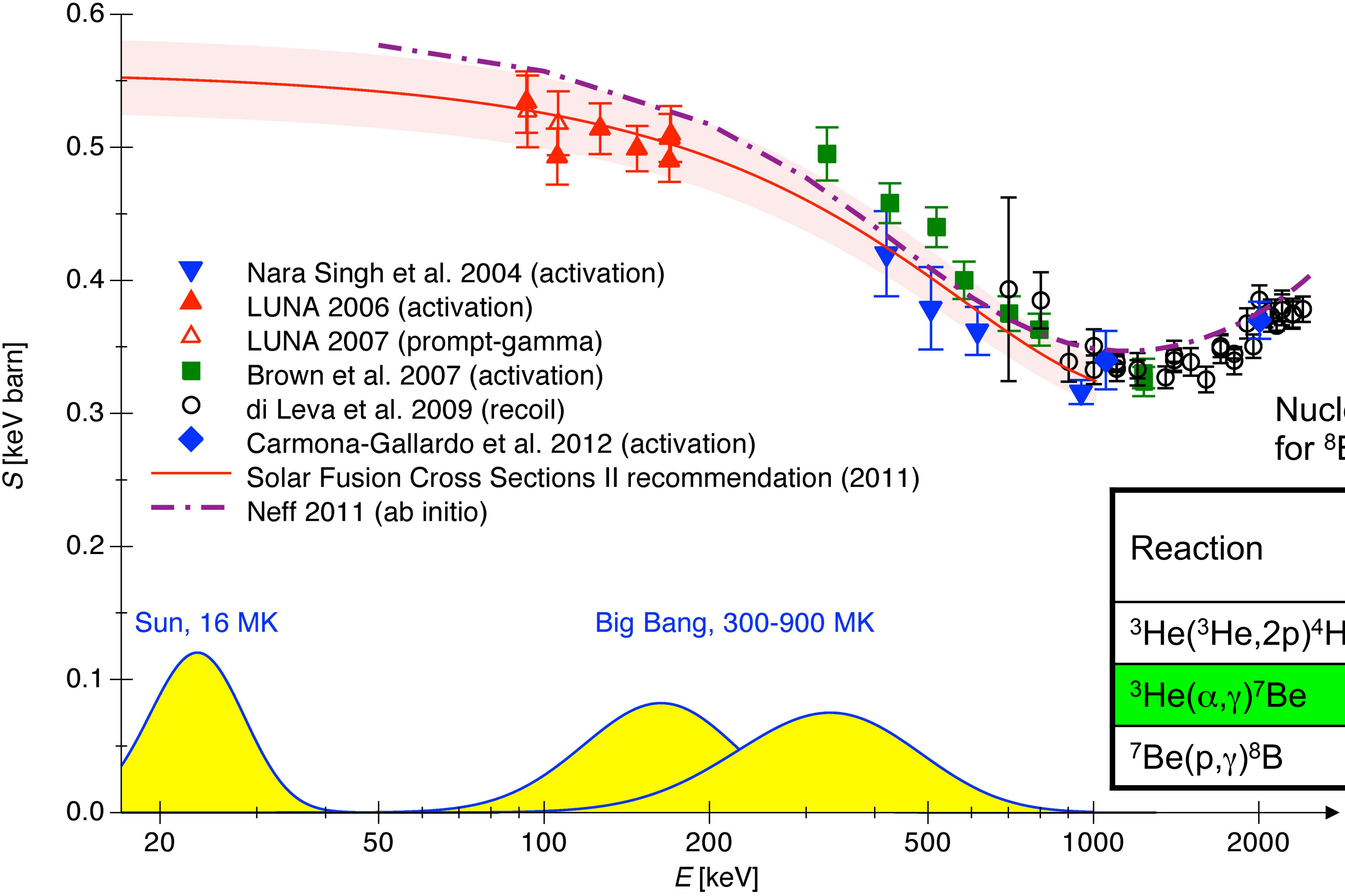
Windowless ^{3}He gas target, with ^{3}He recirculation

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



Detected ^7Be activities: 0.8 - 600 mBq

^{3}He(α,γ)^{7}Be reaction, S-factor results from LUNA and others

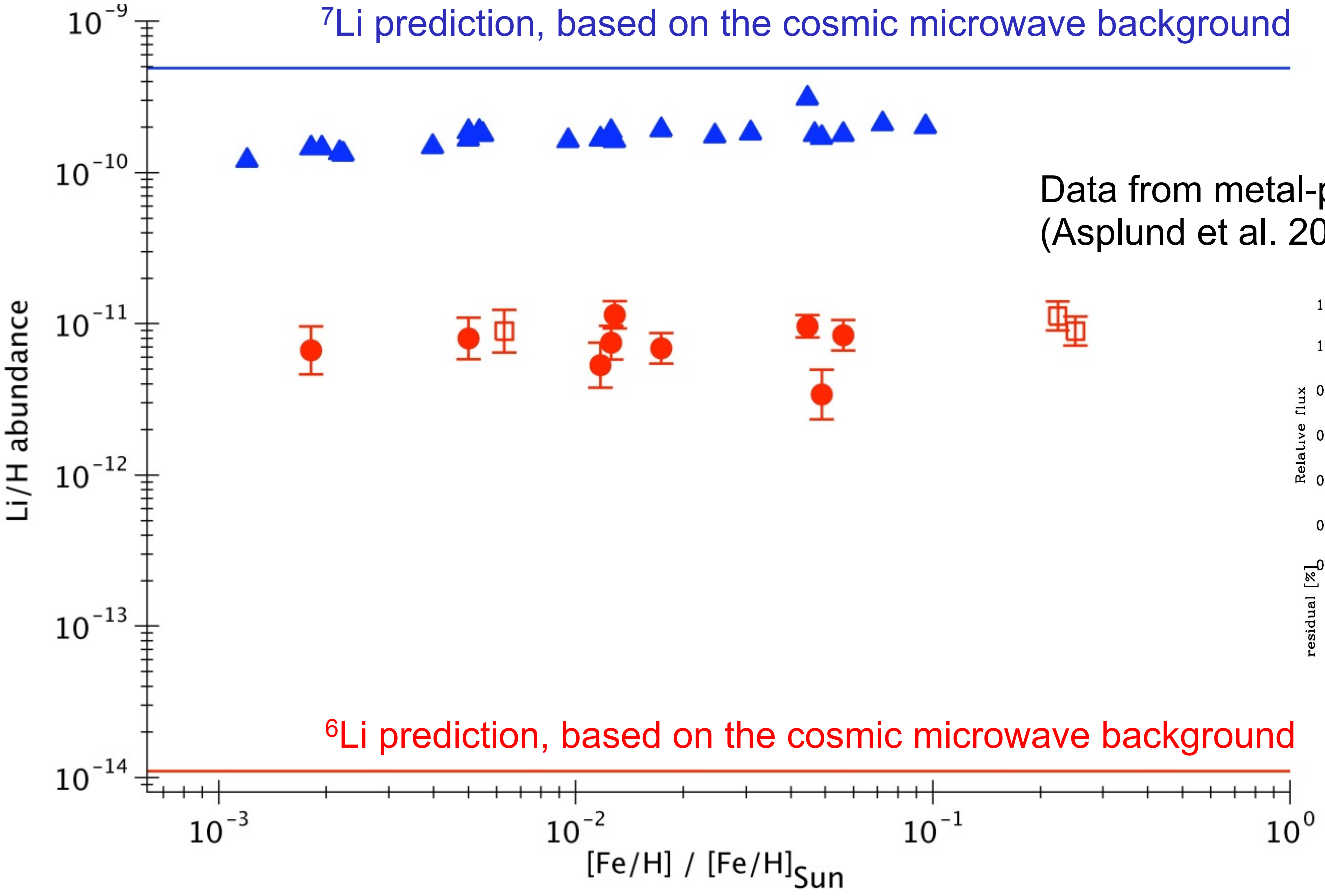


Nuclear physics input
for ^{8}B neutrino flux Φ_B:

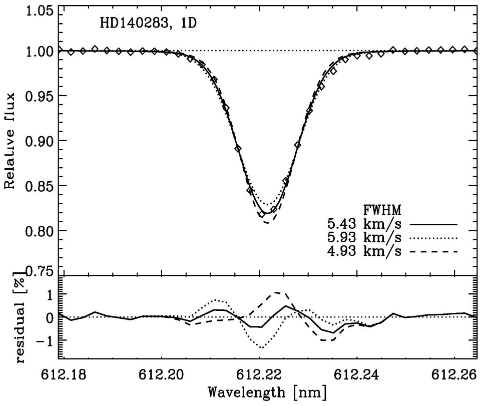
Reaction	$\frac{\partial \ln \Phi_B}{\partial \ln \sigma}$	$\Delta\Phi_B/\Phi_B$	
^{3}He(^{3}He,2p)^{4}He	-0.43	1.8%	
^{3}He(α,γ)^{7}Be	0.85	~~7.5%~~	4.5%
^{7}Be(p,γ)^{8}B	1.00	7.7%	

Further improvements require a comprehensive data set covering both low and high energies.

Byproduct: The Spite abundance plateau and the lithium problem(s)



Data from metal-poor halo stars
(Asplund et al. 2006)



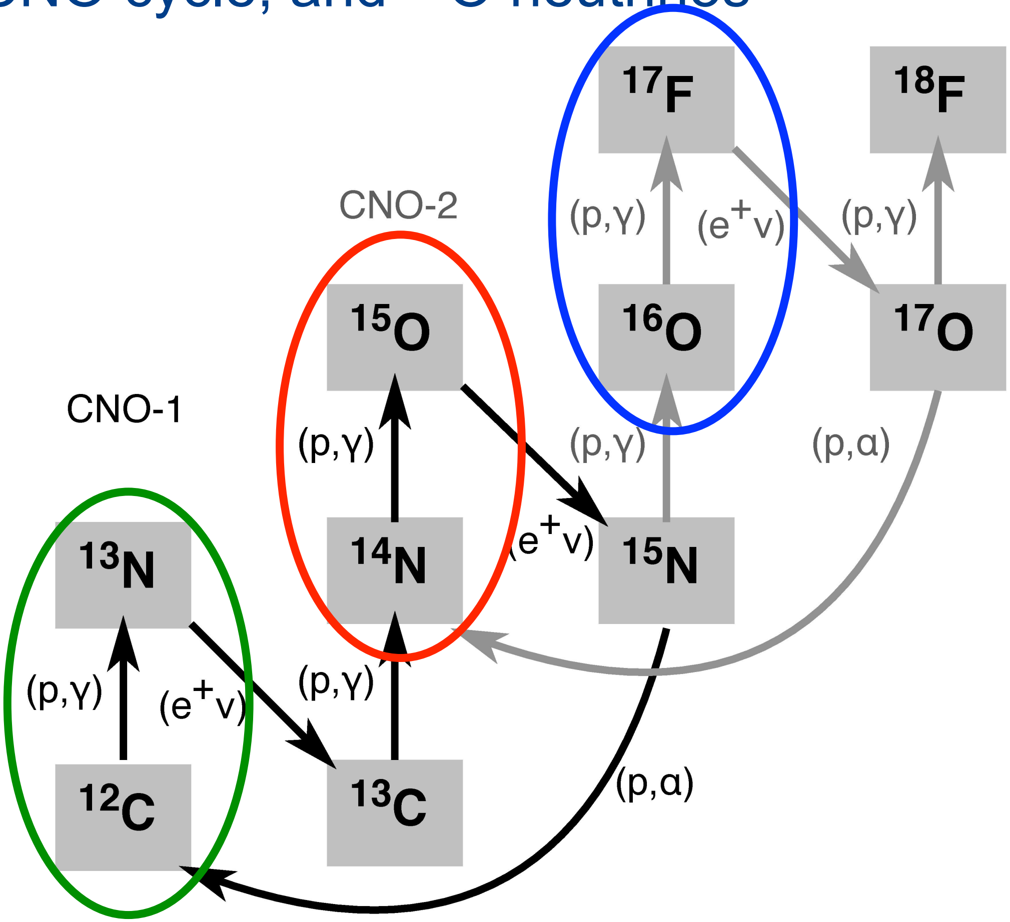
- Cosmic ^{7}Li problem: Less ^{7}Li in old stars than predicted.
  ^{7}Li production mainly by ^{3}He(α,γ)^{7}Be ➔ ^{7}Li
  LUNA data rules out a nuclear solution for the cosmic ^{7}Li problem.

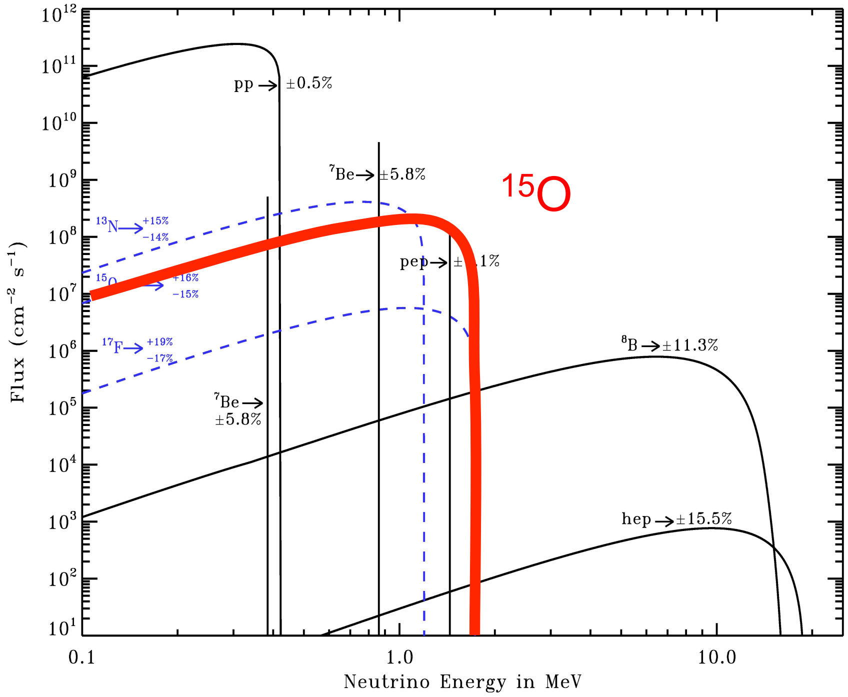
- Possible cosmic ^{6}Li problem: Much more ^{6}Li in some old stars than predicted.
  ^{6}Li production mainly by the ^{2}H(α,γ)^{6}Li reaction.

Michael Anders, HK 33.7

^{14}N(p,γ)^{15}O, bottleneck of the CNO cycle, and ^{15}O neutrinos

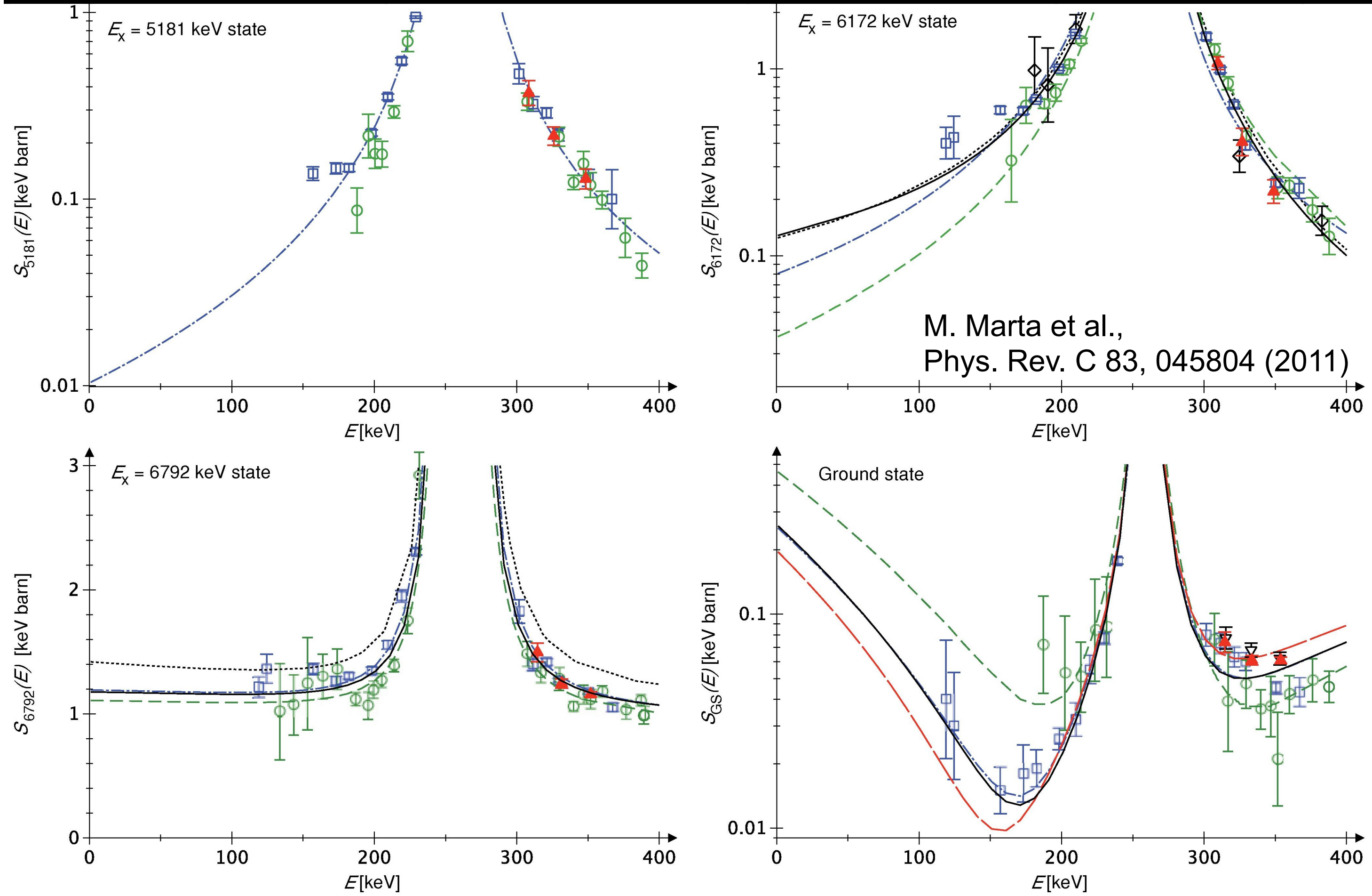
- Q(β^+, ^{15}O) = 2.754 MeV
- Lifetime of ^{14}N in the solar center 10^8 a
- Bottleneck of the whole cycle: ^{14}N(p,γ)^{15}O
- $$\frac{\partial \ln \Phi_{\nu(\text{O-15})}}{\partial \ln S[^{14}\text{N}(p,\gamma)^{15}\text{O}]} = 1$$





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)

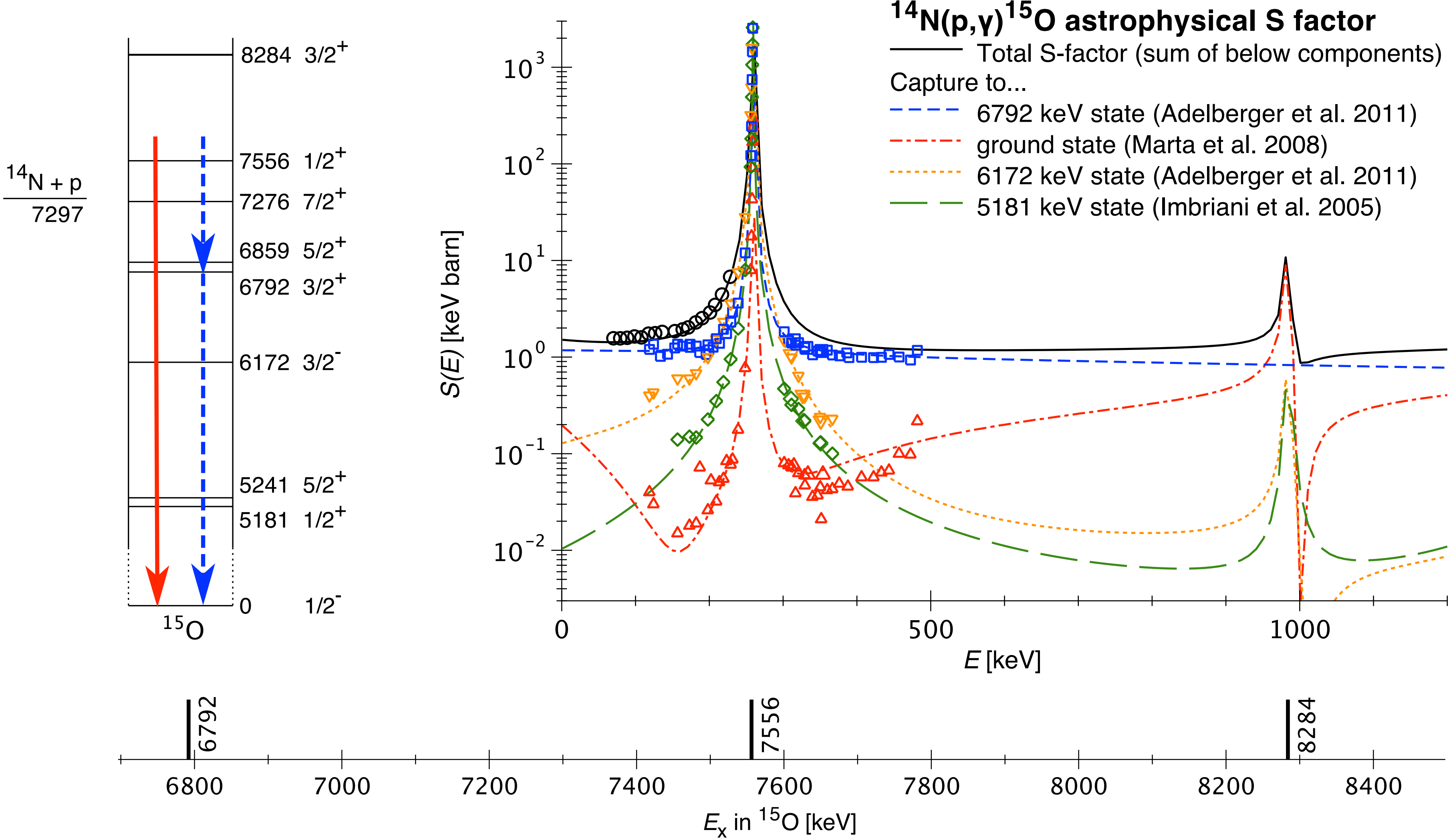


M. Marta et al.,
Phys. Rev. C 83, 045804 (2011)

Adelberger *et al.* 2011 recommended precision 7%...

...but it should be further improved!

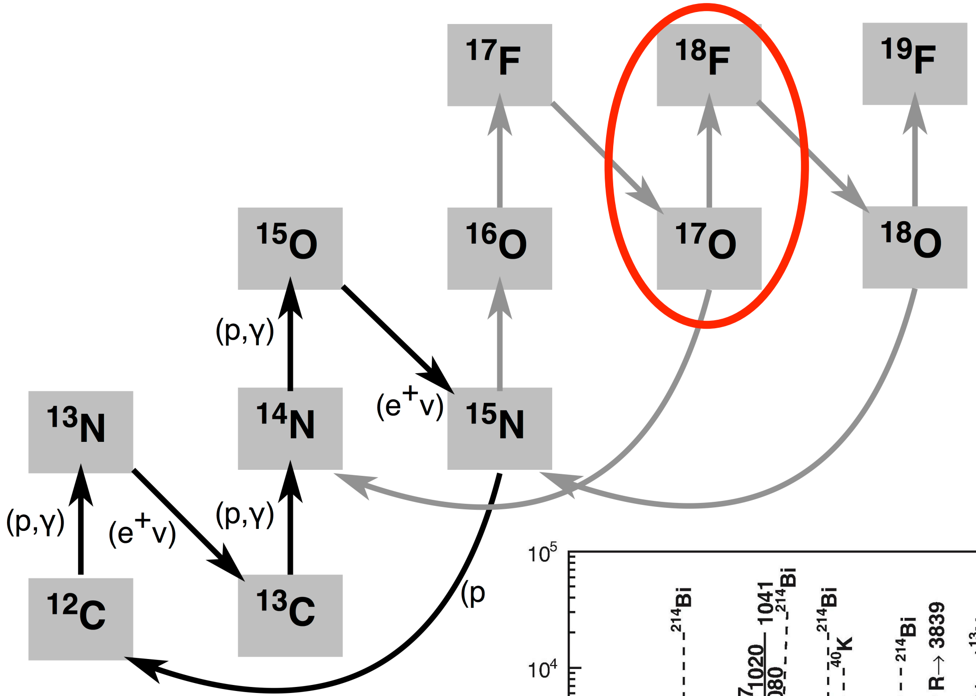
Needed: new experimental data on $^{14}N(p,\gamma)^{15}O$



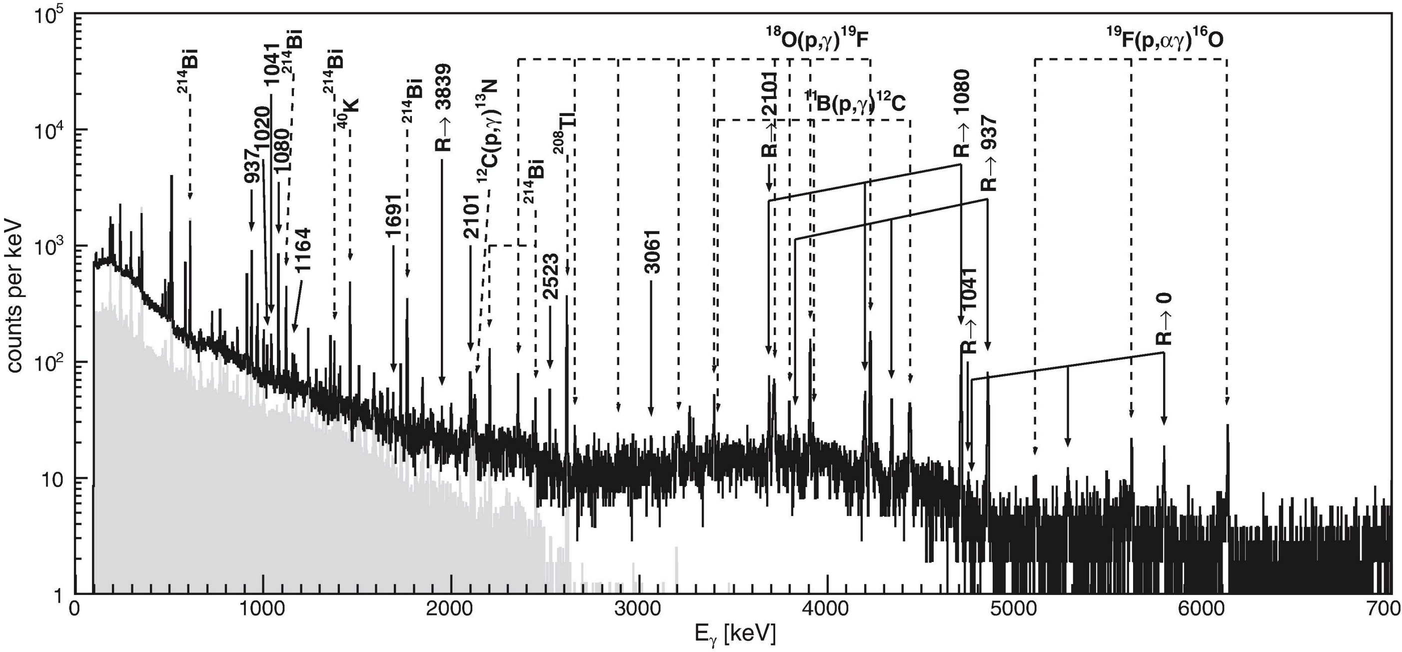
- The *S* factor is the sum of several components with very different energy dependence.
- New cross section data between 0.4 and 2.0 MeV are needed!
- This requires a high-intensity, low background accelerator with a few MeV energy range.

Louis Wagner, HK 33.8

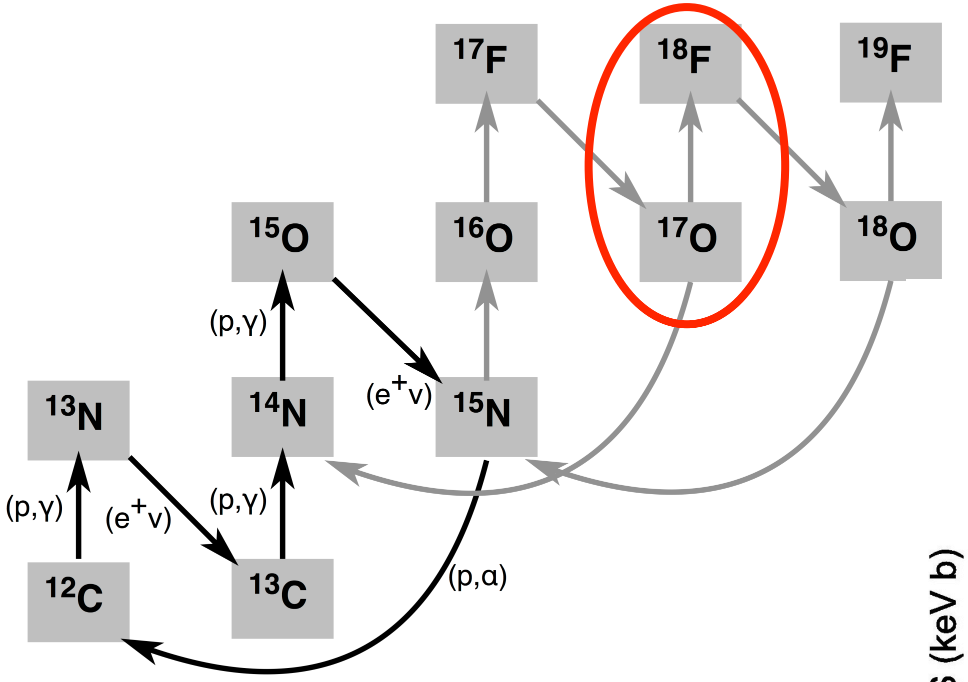
Hydrogen burning: LUNA experiment on the $^{17}O(p,\gamma)^{18}F$ reaction (1)



- The $^{17}O(p,\gamma)^{18}F$ reaction controls ^{18}F production in classical novae
- Observation of the 511 keV annihilation quantae from ^{18}F β+ decay would be a “smoking gun” for nucleosynthesis in a nova explosion.



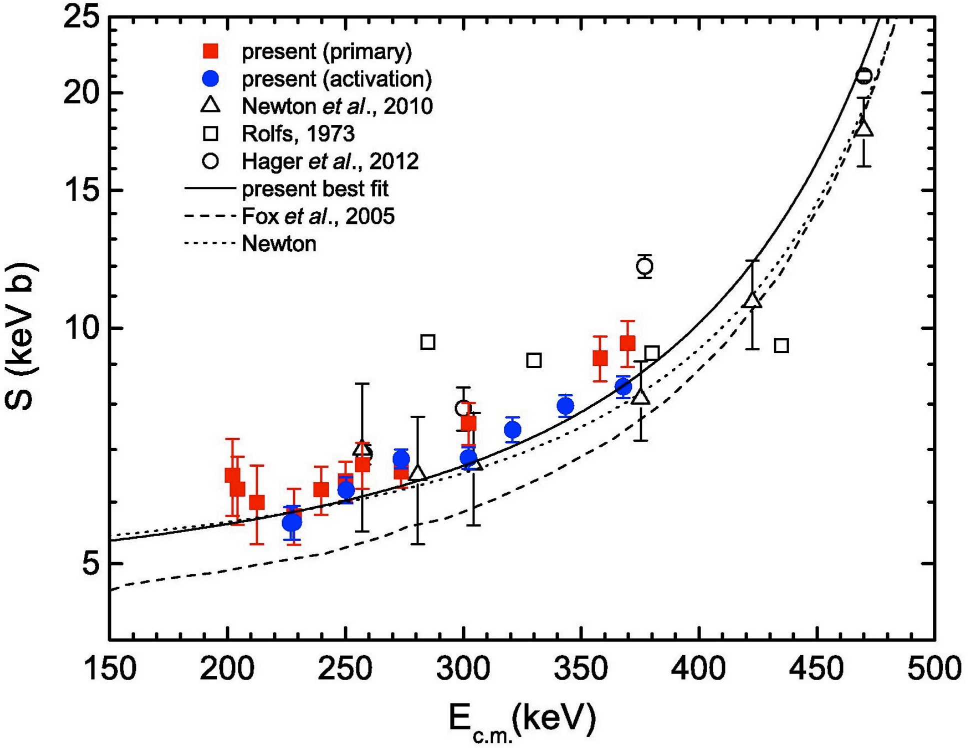
Hydrogen burning: LUNA experiment on the ^{17}O(p,γ)^{18}F reaction (2)



- Strength of 183 keV resonance:

1.67 ± 0.12 μeV	**LUNA 2012**
1.2 ± 0.4 μeV	Fox et al. 2004
2.2 ± 0.4 μeV	Chafa et al. 2006

- Reaction rate uncertainty reduced by a factor 4 in the novae energy range



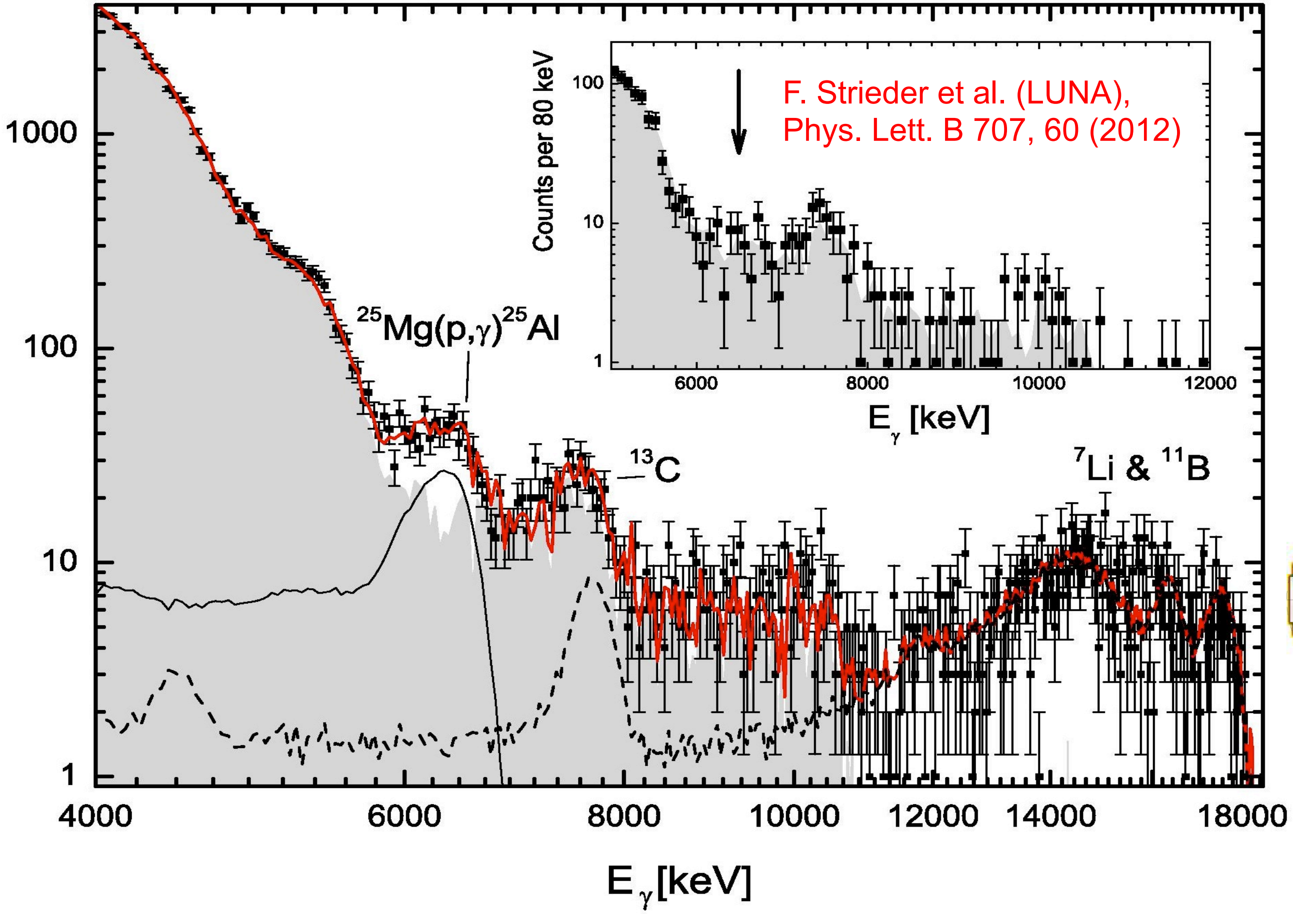
D. Scott et al. (LUNA),
Phys. Rev. Lett. 109, 202501 (2012)

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

^{25}Mg(p,γ)^{26}Al resonance strengths $\omega\gamma$ in eV

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

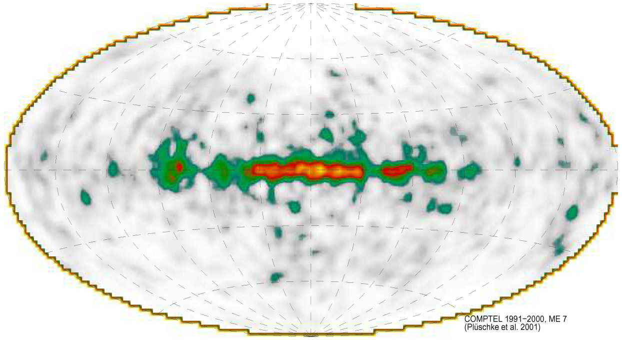
Lowest resonance strength ever measured directly!



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

^{26}Al, a tracer of live nucleosynthesis:

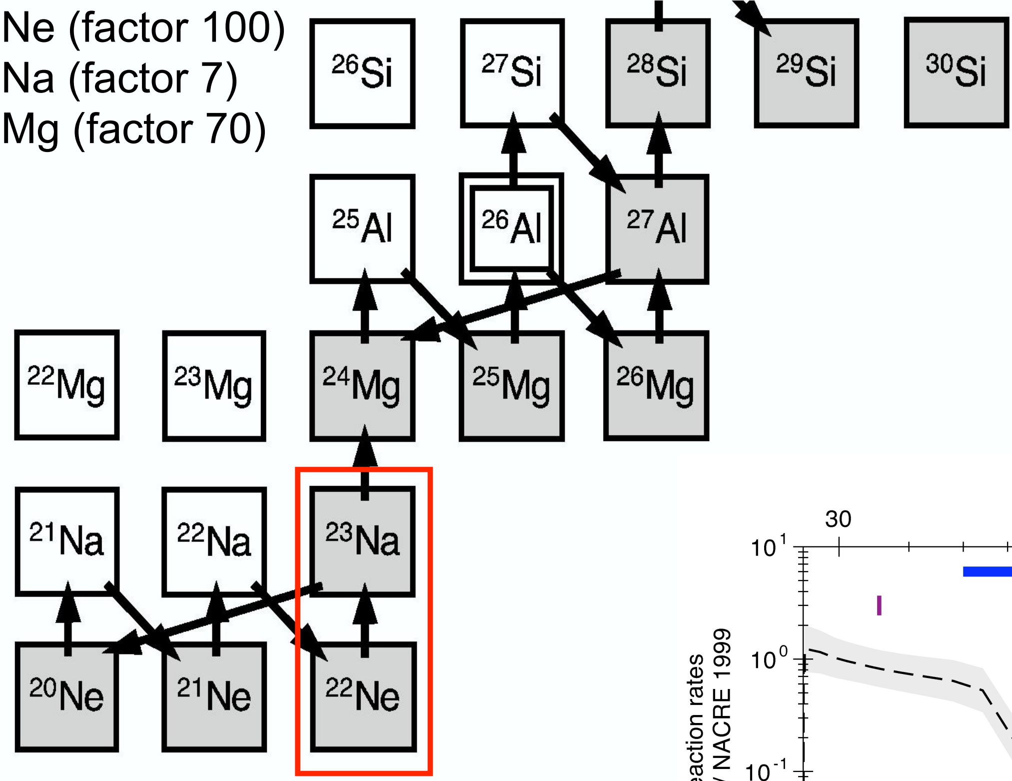
$t_{1/2}$ = 717 000 y
E_γ = 1809 keV

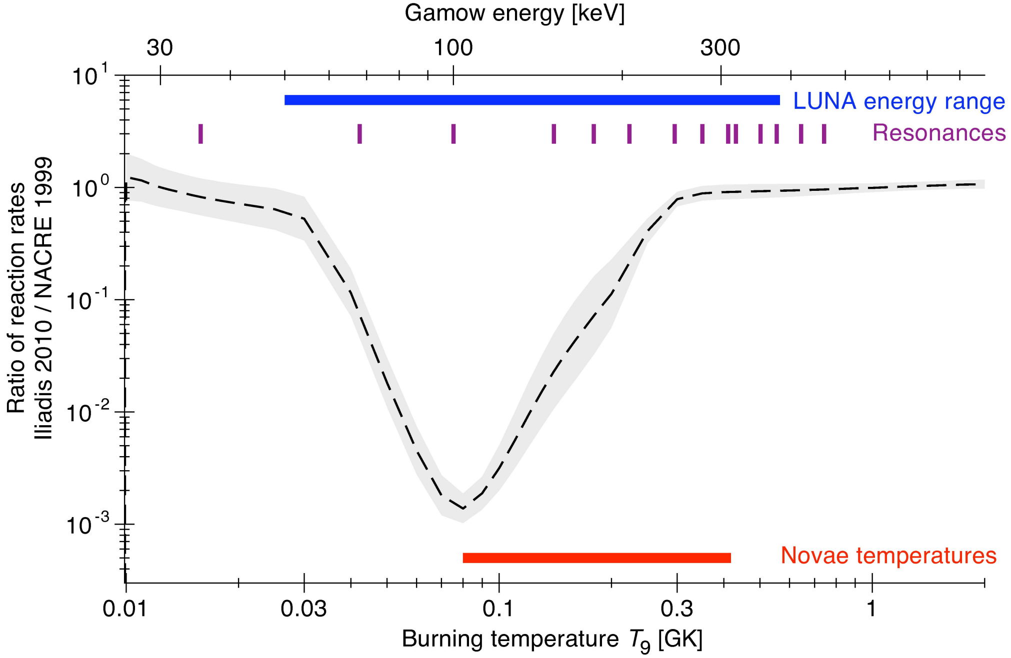


COMPTEL 1991–2000, ME 7 (Plüschke et al. 2001)

Next experiment at LUNA: Hydrogen burning and ^{22}Ne(p,γ)^{23}Na

- NeNa cycle of hydrogen burning in astrophysical novae
- Sensitivity study by C. Iliadis, J. José et al. 2002 shows impact on the abundances of
  ^{22}Ne (factor 100)
  ^{23}Na (factor 7)
  ^{24}Mg (factor 70)





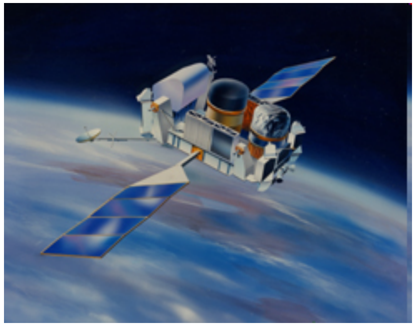
Is there also an effect on the ^{22}Ne abundance in SN Ia precursors?

Nuclear reactions for astrophysics, studied at LUNA and in the Dresden Felsenkeller

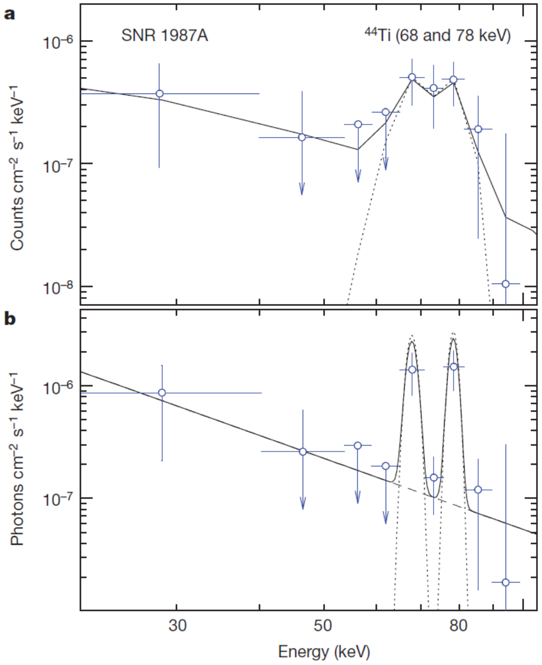
1. Motivation: The solar abundance problem and solar neutrinos
2. Technique: Experiments in underground laboratories
3. Hydrogen burning in our Sun, in asymptotic giant branch stars, and in classical novae
4. Stable-ion beam nuclear physics for supernovae
5. The science case for new underground accelerators

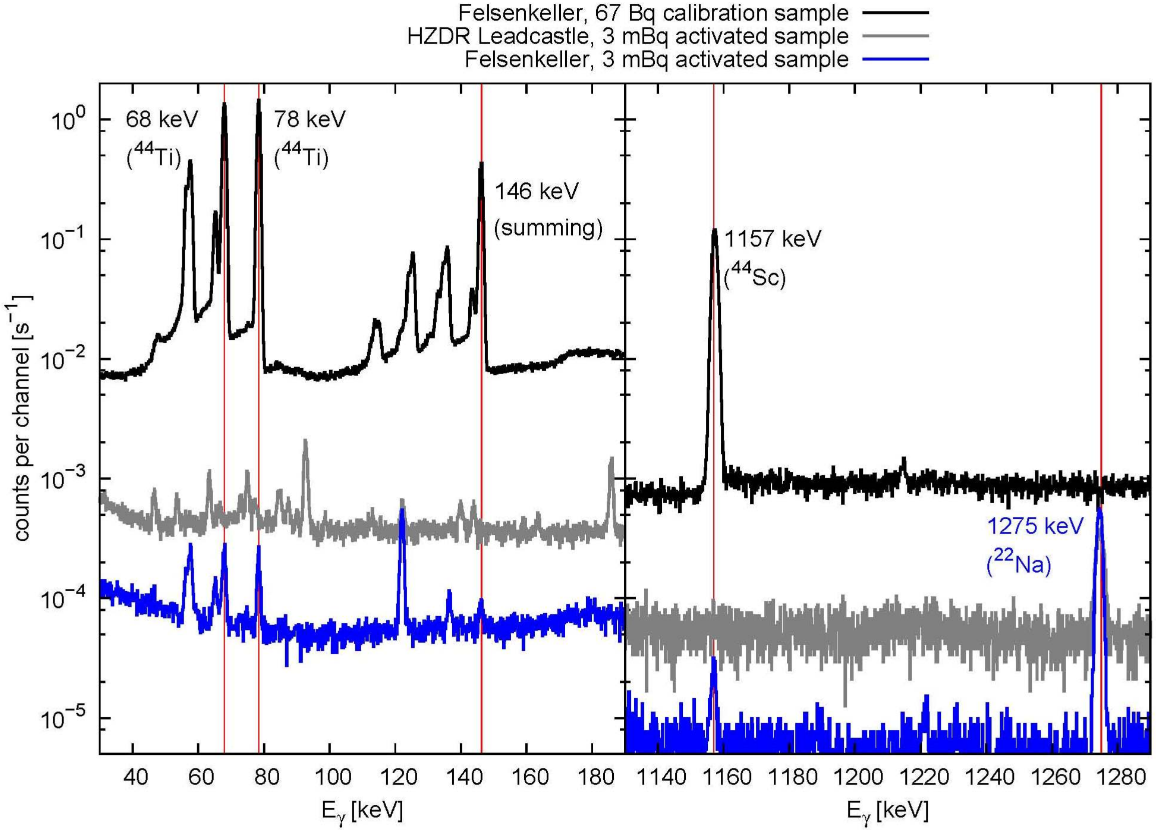
^{44}Ti from SN 1987A and ^{40}Ca(α,γ)^{44}Ti, studied by activation

- ^{44}Ti half-life is 60 years
- Energy source for late light curve of SN1987A



INTEGRAL data:
Grebenev et al.,
Nature (2012)





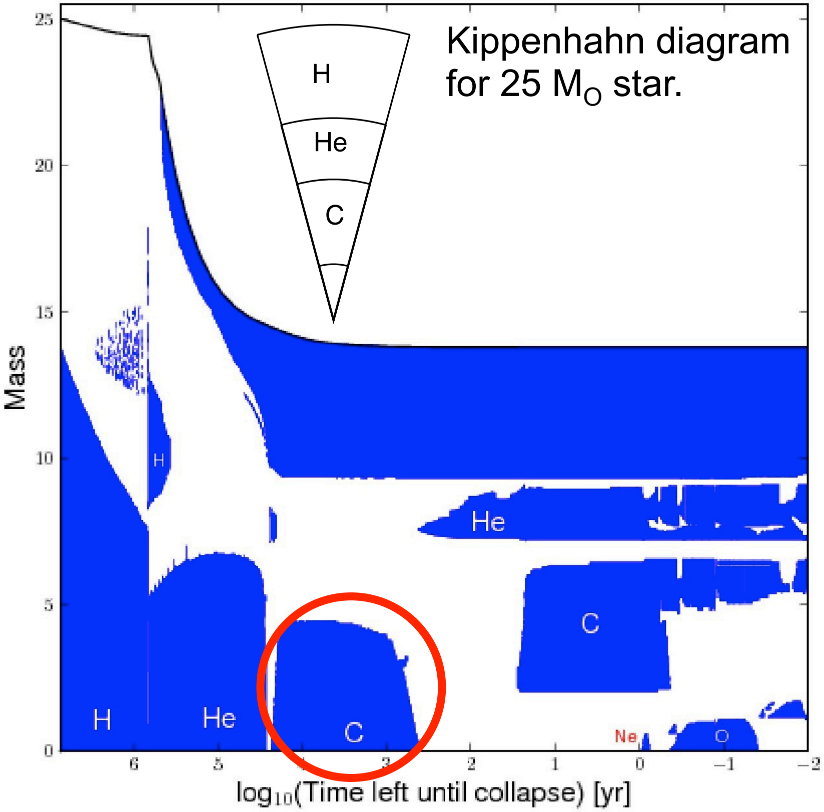
Felsenkeller laboratory, Dresden

- 47 m rock cover
- 10 HPGe detectors
- VKTA operated, science use by TU Dresden + HZDR
- Lowest background γ-counting facility in Germany
- Just 4 km from here

Konrad Schmidt, HK 67.6 Thu 15:30

DRESDEN concept

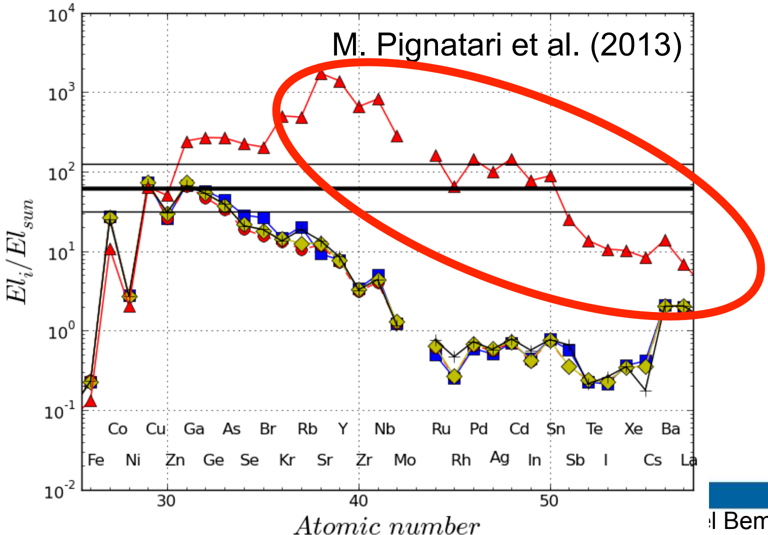
Carbon burning in massive stars: The $^{12}C+^{12}C$ fusion reactions



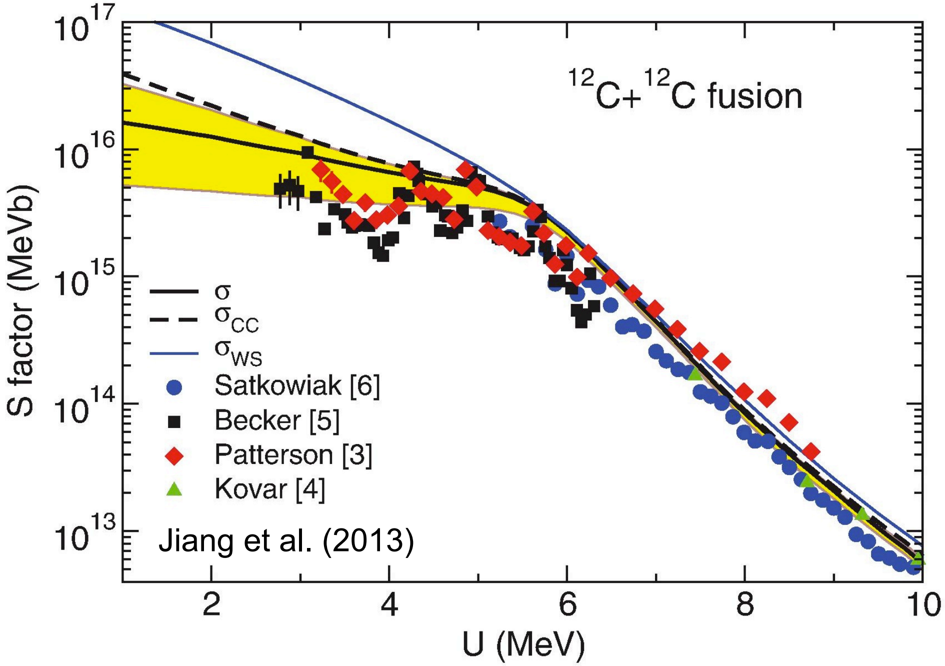
Kippenhahn diagram for 25 M_O star.

- Higher ^{12}C +^{12}C nuclear reaction rate leads to earlier+longer ^{12}C core burning phase
- In turn, $^{13}C(\alpha,n)^{16}O$ neutron source regains importance in 25 M_O scenario.
- Higher production of s-process elements.

- ^{12}C +^{12}C cross section is highly uncertain!



M. Pignatari et al. (2013)



Jiang et al. (2013)

Nuclear reactions for astrophysics, studied at LUNA and in the Dresden Felsenkeller

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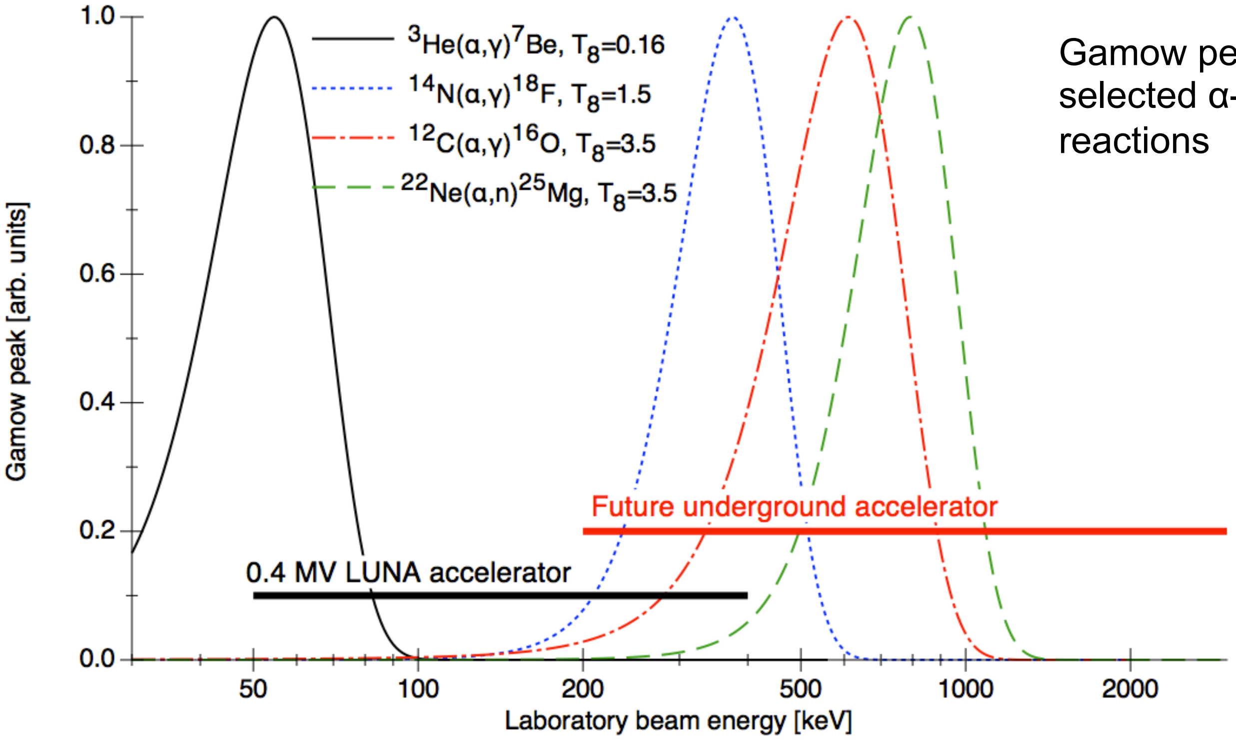
Limitations of the existing LUNA 0.4 MV accelerator



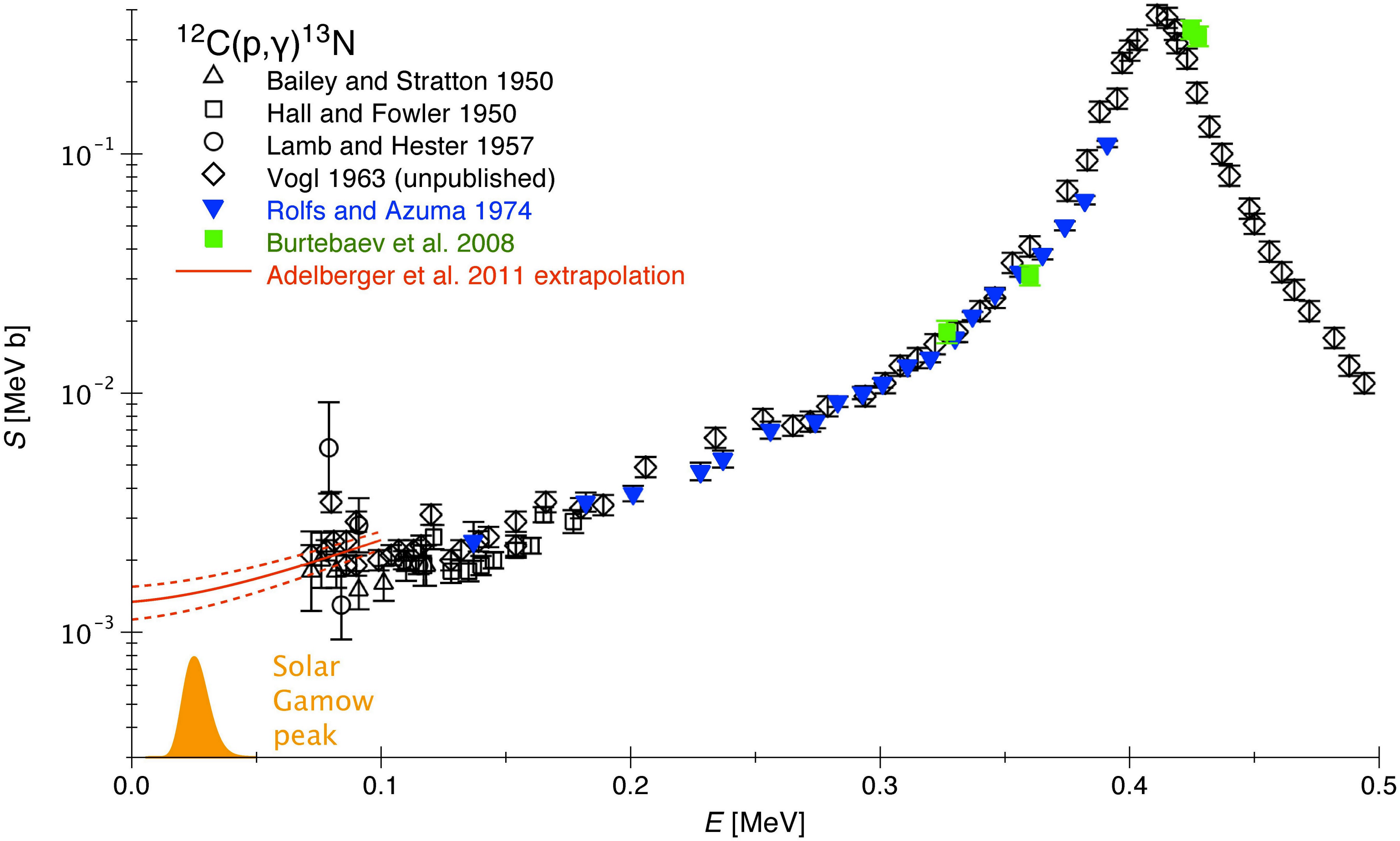
Gamow peak for selected α-induced reactions

NuPECC
Long Range Plan 2010:

"An immediate, pressing issue is to select and construct the next generation of underground accelerator facilities. Europe was a pioneer in this field, but risks a loss of leadership to new initiatives in the USA. (…) There are a number of proposals being developed in Europe and it is vital that construction of one or more facilities starts as soon as possible."

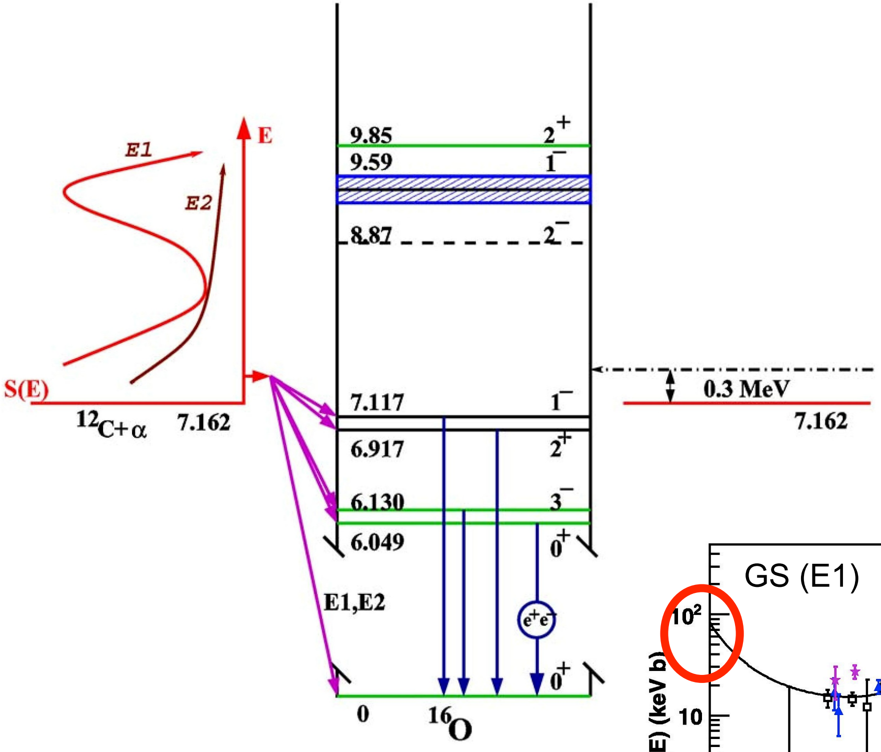
- Many reactions cannot be studied with a 0.4 MV accelerator alone.
  - Solar fusion reactions
  - Stellar helium and carbon burning
  - Neutron sources for the astrophysical s-process
- A new, higher-energy underground accelerator is needed!

Solar ^{13}N neutrinos and the ^{12}C(p,γ)^{13}N reaction



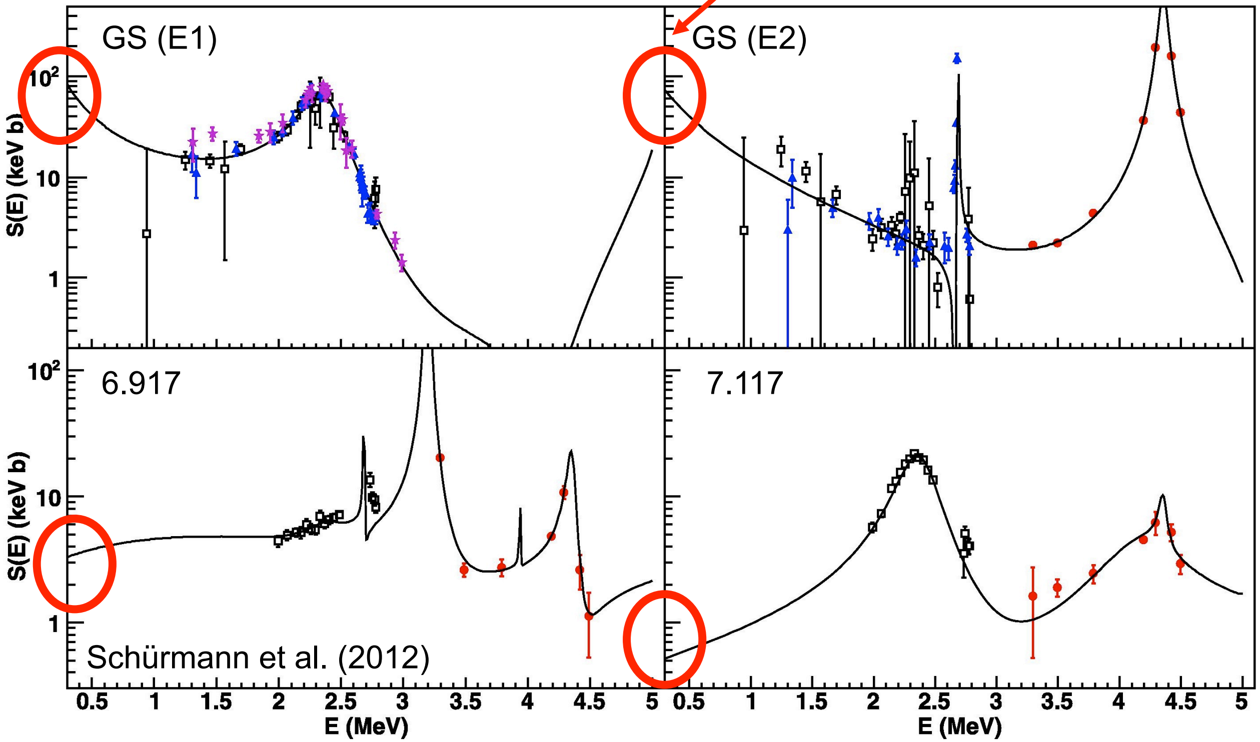
- No experimental data at or near the solar Gamow peak
- Existing data near E = 0.1 MeV are from the 1950's
- Adelberger *et al.* 2011 cites 17% uncertainty
- New data at low and high energy are needed!

The $^{12}C(\alpha,\gamma)^{16}O$ reaction, determining the $^{12}C/^{16}O$ abundance ratio



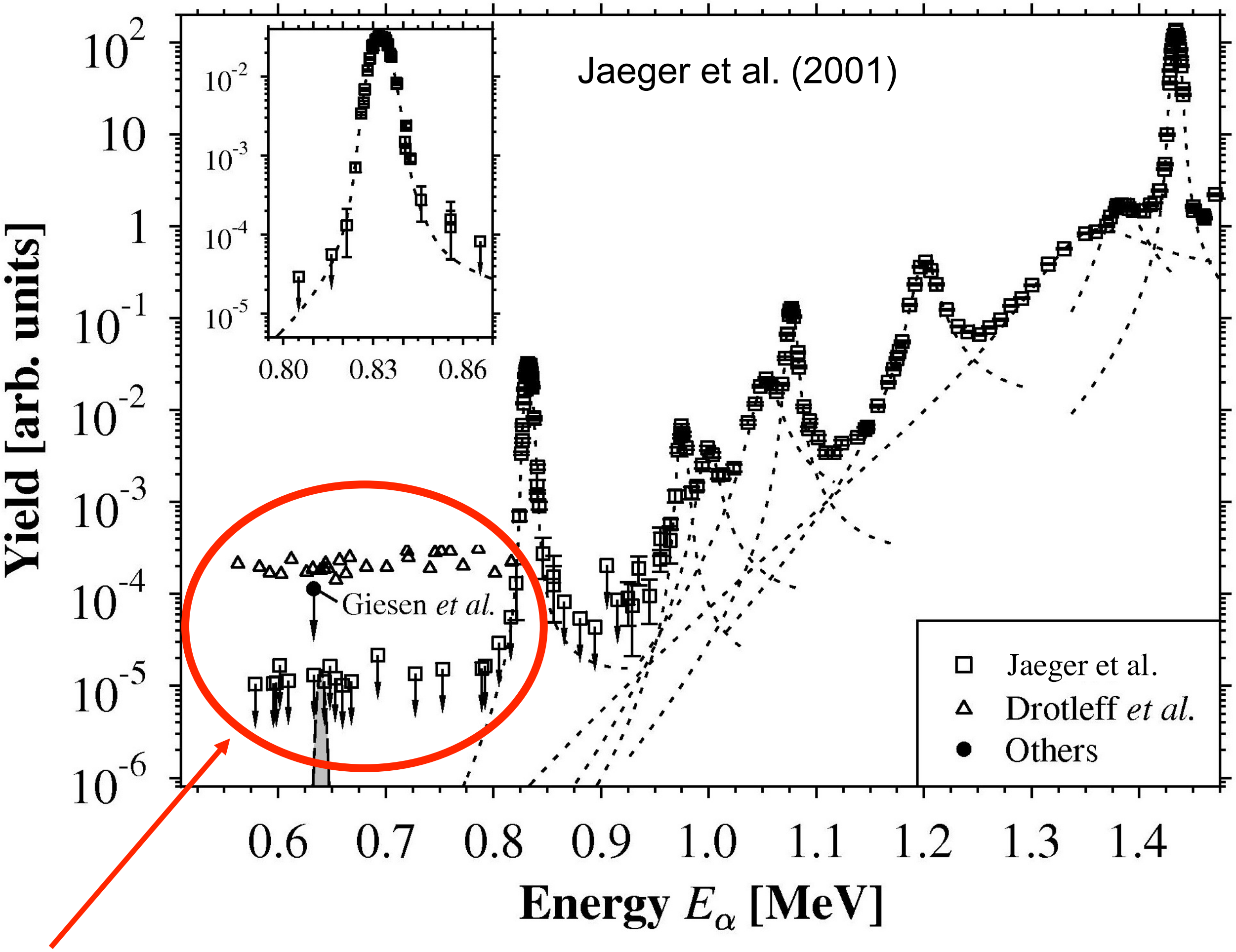
- The „Holy Grail of Nuclear Astrophysics“ (Willy Fowler, 1983 Nobel Laureate in Physics)
- Extrapolations to the Gamow energy still are only poorly constrained 30 years later
- New, low-energy cross section data may provide the needed breakthrough in precision!

Gamow energy for core helium burning



Schürmann et al. (2012)

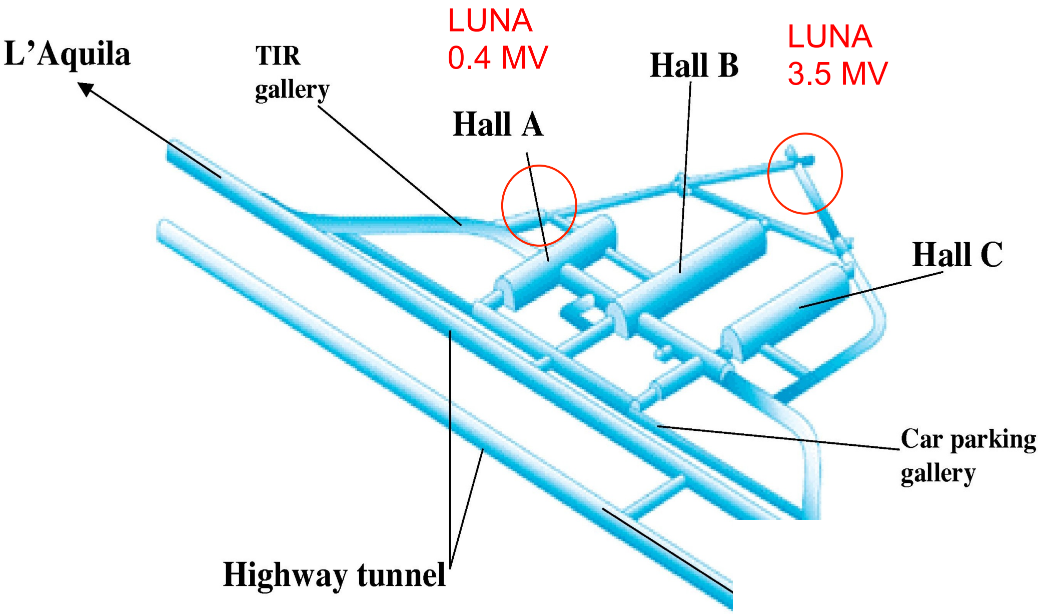
^{22}Ne(α,n)^{25}Mg, neutron source for the astrophysical s-process



Relevant energy range;
only upper limits exist

- Neutron source in a massive, $M > 8\ M_{\mathrm{Sun}}$ star
- Resulting „weak" s-process provides the basis for nucleosynthesis in the subsequent supernova explosion
- Previous experiments were limited by cosmic-ray induced neutron background
- Factor 1000 lower neutron background in a deep underground lab

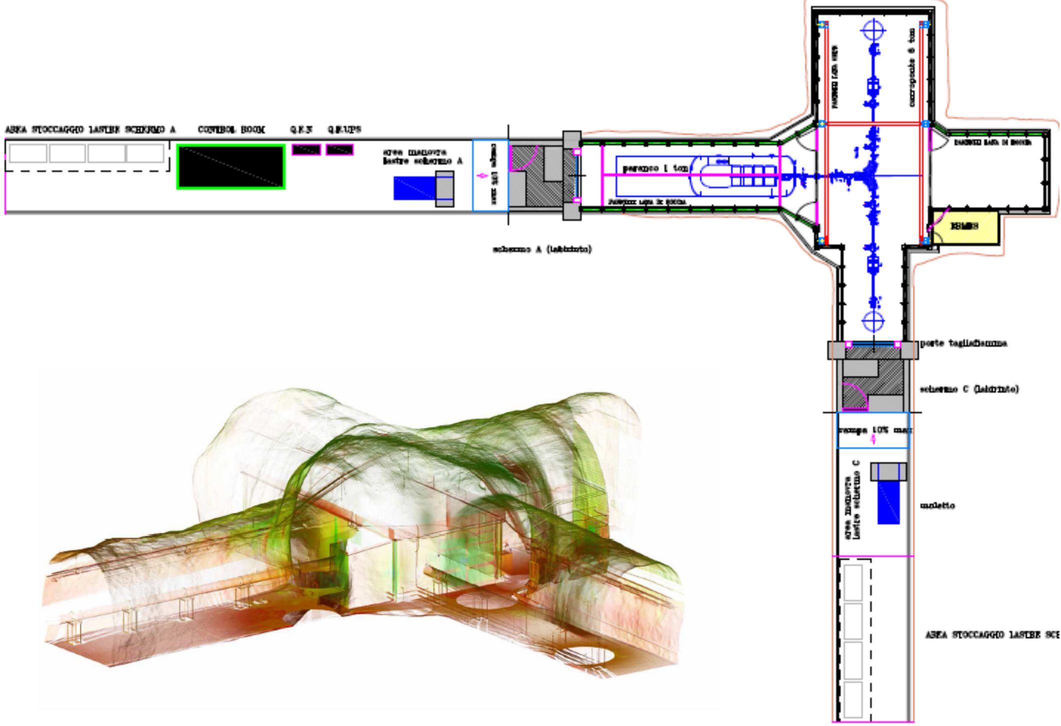
Gran Sasso / Italy: LUNA-MV 3.5 MV accelerator



Italian research ministry approved 2.8 M€ for purchasing a 3.5 MV single-ended accelerator, with radio-frequency ion source (2012).

Still need beam lines, magnets, instrumentation.

LUNA-MV collaboration is starting up: `http://luna-mv.lngs.infn.it`



Scientific program:

- Stellar helium burning, including the „Holy Grail of Nuclear Astrophysics“ $^{12}C(\alpha,\gamma)^{16}O$
- $^{3}He(\alpha,\gamma)^{7}Be$ for solar fusion
- Neutron source reactions for the astrophysical s-process: $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$

Planned Felsenkeller accelerator, HZDR and TU Dresden

- 12-year old, working 5 MV accelerator
- Bought and transported to HZDR (July 2012)
- 250 µA upcharge current (double pellet chains)
- Two Cs sputter ion sources: 100 µA H^- and C^-
- Well-suited for low-energy nuclear astrophysics

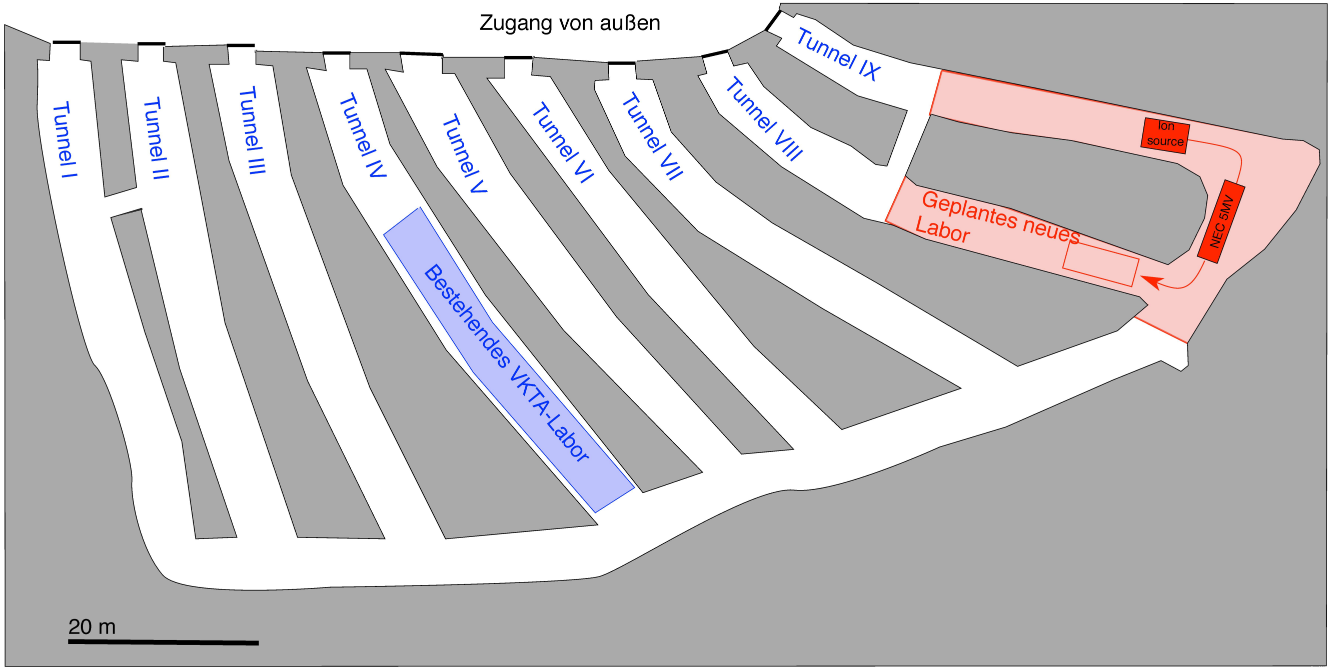
- Develop new terminal ion source

  Stefan Reinicke, HK 36.5 Tue 15:00

- Work on CAMAC control and gas target systems

Site: Dresden, former Felsenkeller brewery

- Additional space available underground
- Background 3 times worse than LUNA
  T. Szücs et al., Eur. Phys. J. A 48, 8 (2012)
- Great interest by students and the public



HZDR (Daniel Bemmerer et al.),
TU Dresden (Kai Zuber et al.)

- Solar fusion reactions: CNO cycle
- Carbon burning in type Ia supernova precursors
- User-driven, applied physics also welcome
- Educational tool to teach low-background methods and maintain nuclear competence
- We hope to be running early 2014!

LUNA collaboration

Italy	Genova	F. Cavanna, P. Corvisiero, P. Prati
	Gran Sasso	A. Formicola, M. Junker
	Milano	C. Bruno, A. Guglielmetti (LUNA spokeswoman), D. Trezzi
	Napoli	A. di Leva, G. Imbriani, V. Roca, F. Terrasi
	Padova	C. Broggini, A. Caciolli, R. Depalo, R. Menegazzo
	Roma	C. Gustavino
	Teramo	O. Straniero
	Torino	G. Gervino
Germany	Bochum	C. Rolfs, F. Strieder, H.-P. Trautvetter
	Dresden	M. Anders, D. Bemmerer, Z. Elekes, M.-L. Menzel
Hungary	Debrecen	Zs. Fülöp, Gy. Gyürky, E. Somorjai, T. Szücs
UK	Edinburgh	M. Aliotta, T. Davinson, D. Scott

Nuclear reactions for astrophysics, studied at LUNA and in the Dresden Felsenkeller

- Nuclear reaction data should be as precise as astronomical observations, in order not to limit their interpretation.

- Many nuclear reactions important for hydrogen burning have been studied at the world's only underground accelerator laboratory, LUNA.

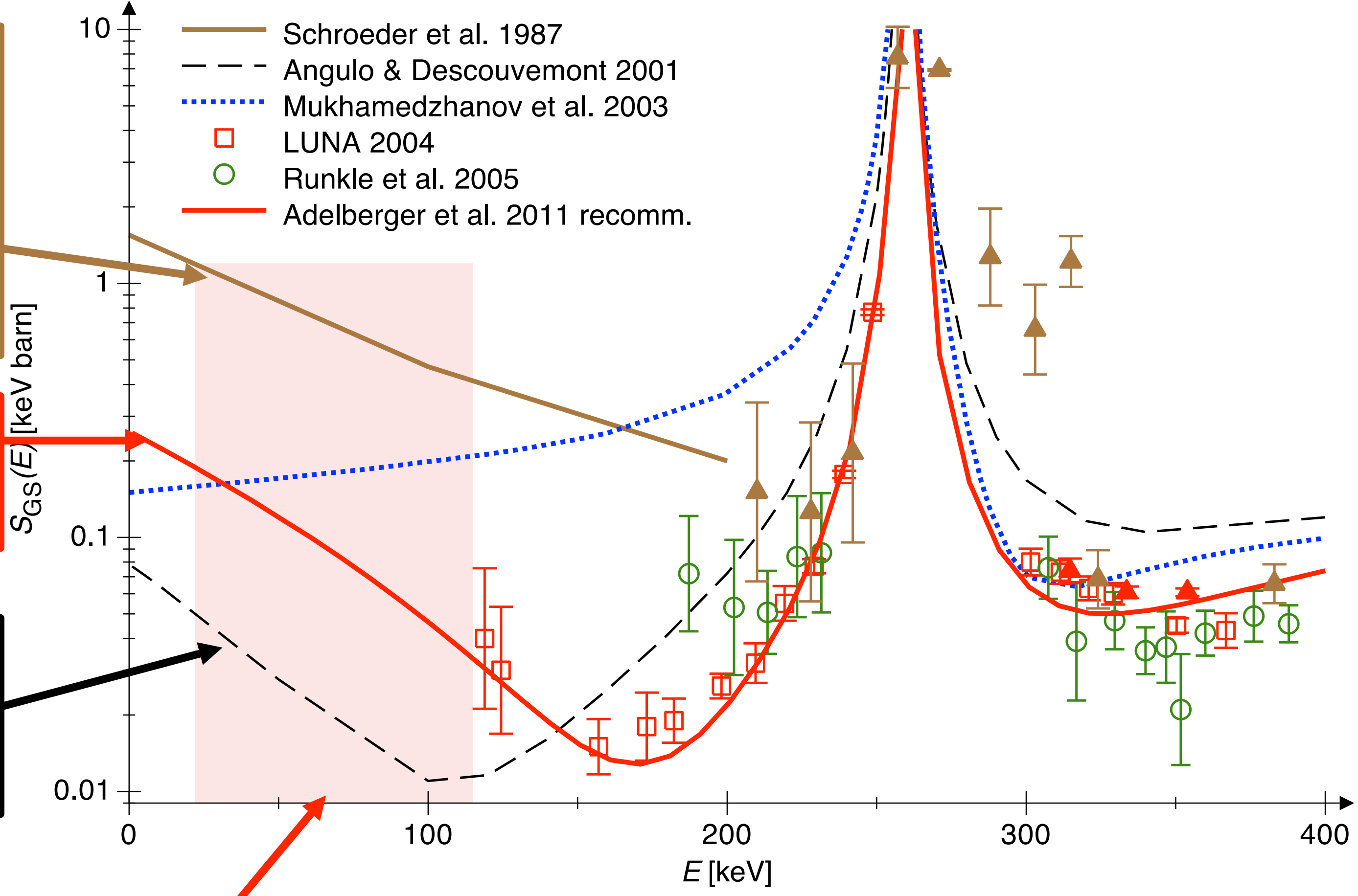
- In order to complete the picture on hydrogen burning and also address helium and carbon burning, higher-energy underground accelerators are planned:
  - LUNA-MV at Gran Sasso, Italy
  - Felsenkeller Dresden, Germany
  - Projects in Spain and the US

Bonus material

Low-energy data improve the situation!

State of the art, 2013

$^{14}N(p,\gamma)^{15}O$, capture to the ^{15}O ground state



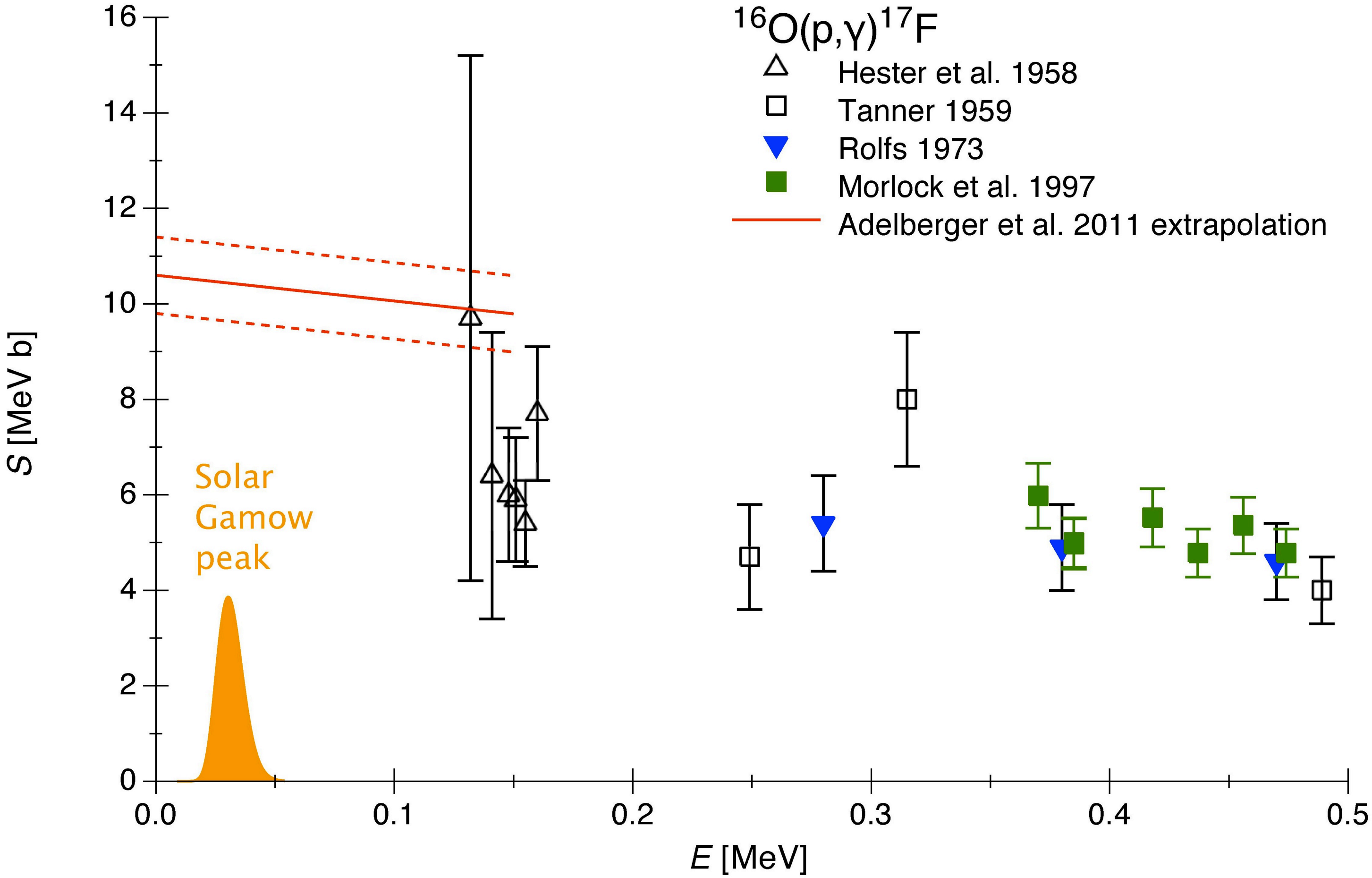
Schröder et al. 1987: Ground state capture contributes 50% of total S factor.
Adopted in astrophysical reaction rate compilations!

Adelberger et al. 2011 recommendation, using new low-energy data

Angulo et al. 2001: Ground state capture contributes 5% of total S factor.

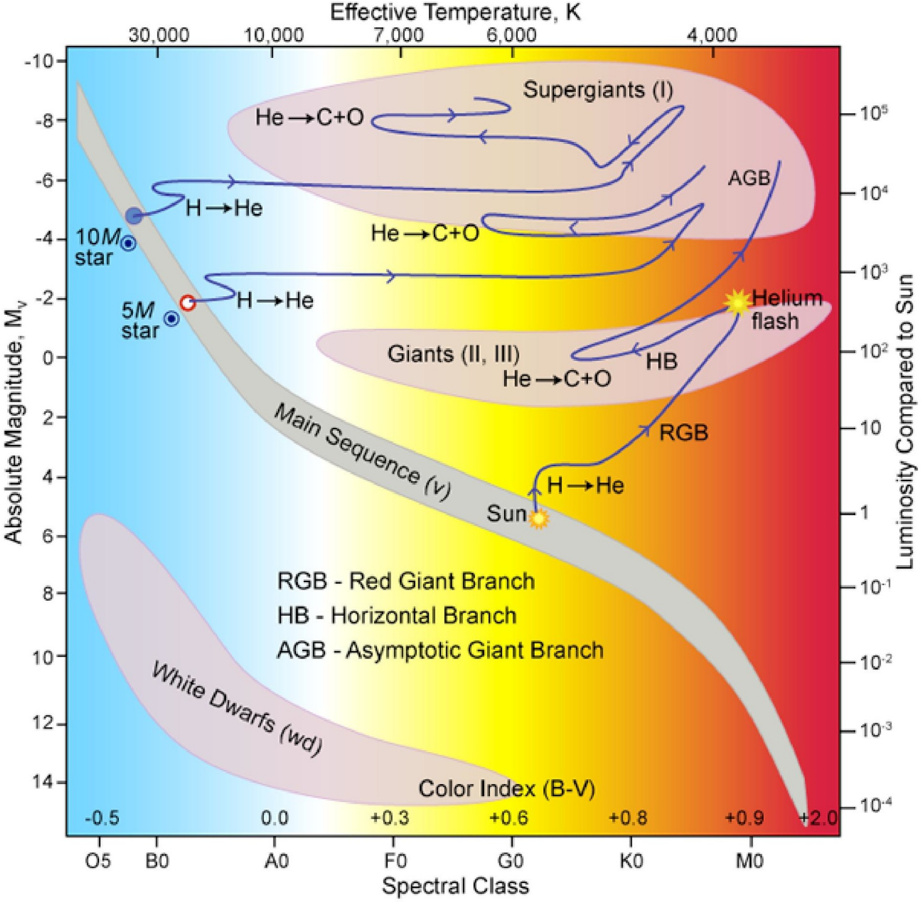
Astrophysically relevant energy range

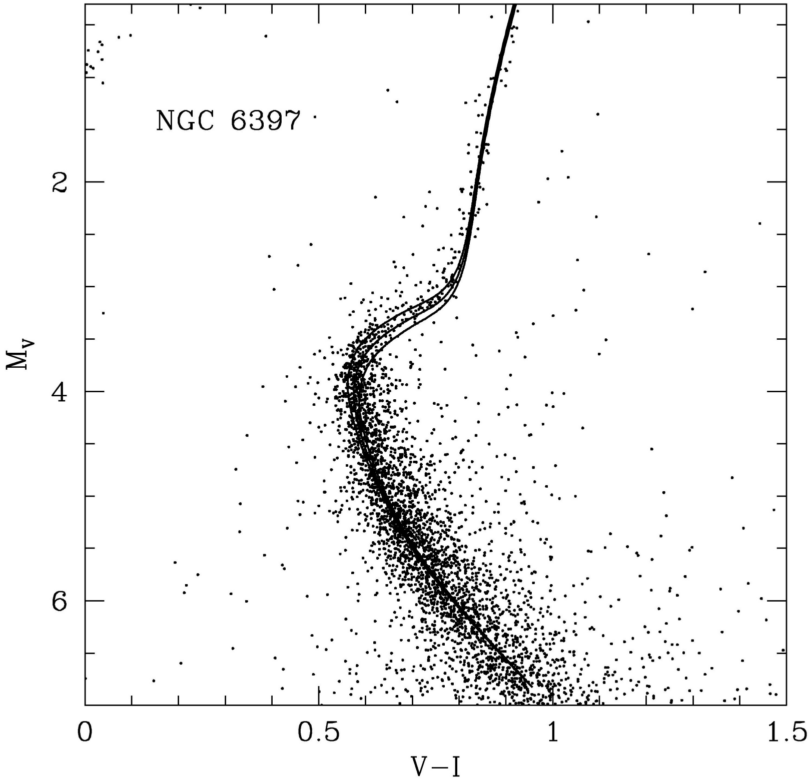
^{17}F neutrinos and the ^{16}O(p,γ)^{17}F reaction



- No experimental data at the solar Gamow peak
- High-energy data are extrapolated using direct-capture model
- Adelberger et al. 2011 cites 8% uncertainty
- Measurable impact only if ^{17}F and ^{15}O neutrinos can be separated
- New data at low and medium energy needed!

Age determination of very old stars (in globular clusters)





- → Hertzsprung-Russel diagram, turnoff of globular cluster stars from the main sequence
- → Lower CNO rate leads to higher derived age for a given globular cluster
- → Independent lower limit for the age of the universe of 14±2 Ga

Gran Sasso / Italy: LUNA-MV 3.5 MV accelerator

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

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

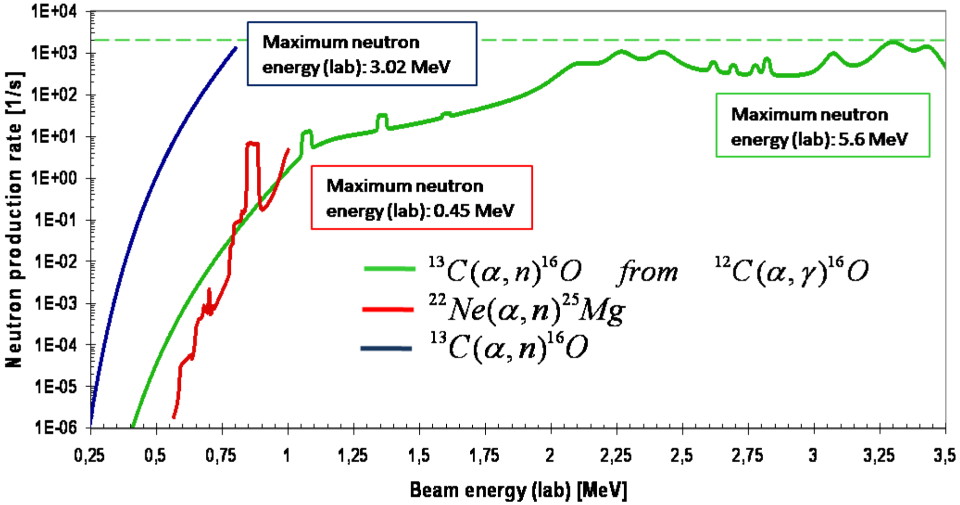
α beam intensity: 200 μA
Target: ^{13}C, 2 10^{17}at/cm^2 (99% ^{13}C enriched)
Beam energy(lab) ≲ 0.8 MeV

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

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

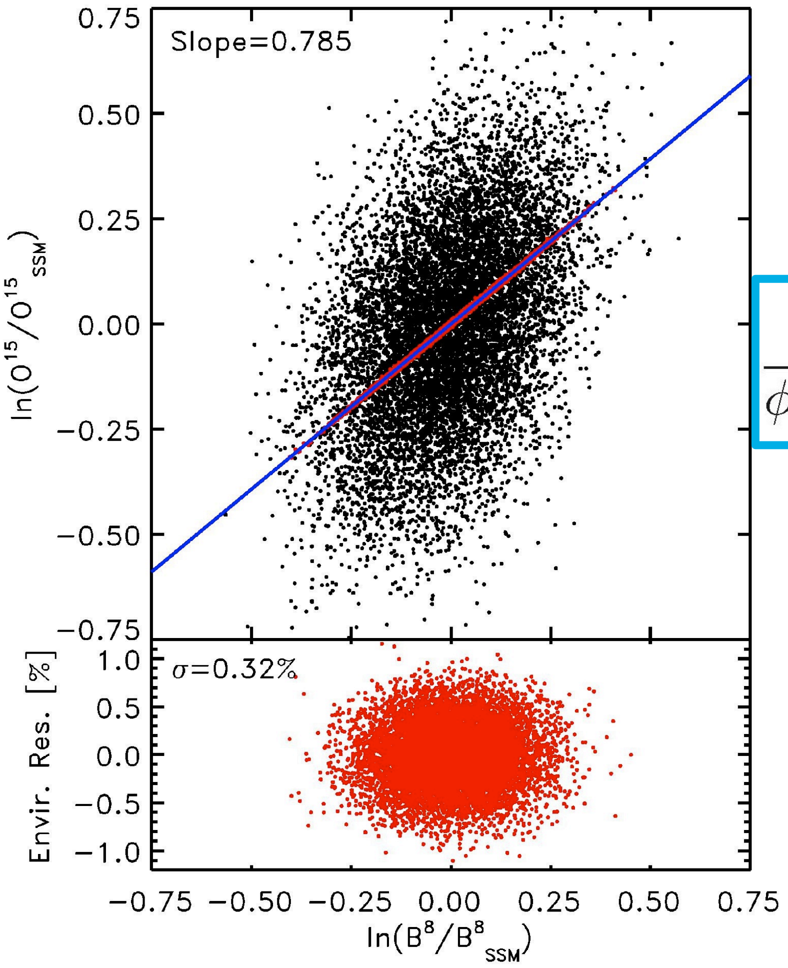
$^{13}C(\alpha,n)^{16}O$ from $^{12}C(\alpha,\gamma)^{16}O$

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



- Neutron production rate ≲ 2000 n/s
- Neutron energy ≲ 5.6 MeV
- 1m thick borated polyethylene shielding will be added on all sides (also against the rock)
- Additional neutron flux outside LUNA-MV < 1% of ambient neutron flux

Using CNO neutrinos to measure the C+N abundance



Serenelli et al. 2011:
Ratio of ^{15}O and ^{8}B neutrino fluxes, ^{8}B flux as „thermometer“:

Elemental abundances of C and N

$$\boxed{\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} \Big/ \left[\frac{\phi(^{8}\mathrm{B})}{\phi^{\mathrm{SSM}}(^{8}\mathrm{B})}\right]^{0.785}} = \boxed{x_C^{0.794}\, x_N^{0.212}}\, D^{0.172}$$

$$\times \left[L_\odot^{0.515}\, O^{-0.016}\, A^{0.308}\right]$$

$$\times \boxed{\left[\mathrm{S}_{11}^{-0.831}\ \mathrm{S}_{33}^{0.342}\ \mathrm{S}_{34}^{-0.685}\ \mathrm{S}_{17}^{-0.785}\ \mathrm{S}_{e7}^{0.785}\ \mathrm{S}_{114}^{0.995}\right]}$$

$$\times \left[x_{\mathrm{O}}^{0.003}\, x_{\mathrm{Ne}}^{-0.005}\, x_{\mathrm{Mg}}^{-0.003}\, x_{\mathrm{Si}}^{-0.001}\, x_{\mathrm{S}}^{-0.001}\, x_{\mathrm{Ar}}^{0.001}\, x_{\mathrm{Fe}}^{0.003}\right]$$

Nuclear physics:
S_{34} : ^{3}He(α,γ)^{7}Be
S_{17} : ^{7}Be(p,γ)^{8}B
S_{114}: ^{14}N(p,γ)^{15}O

Flux ratio is mainly sensitive to

1. Elemental abundances of C and N
2. Nuclear physics S factors

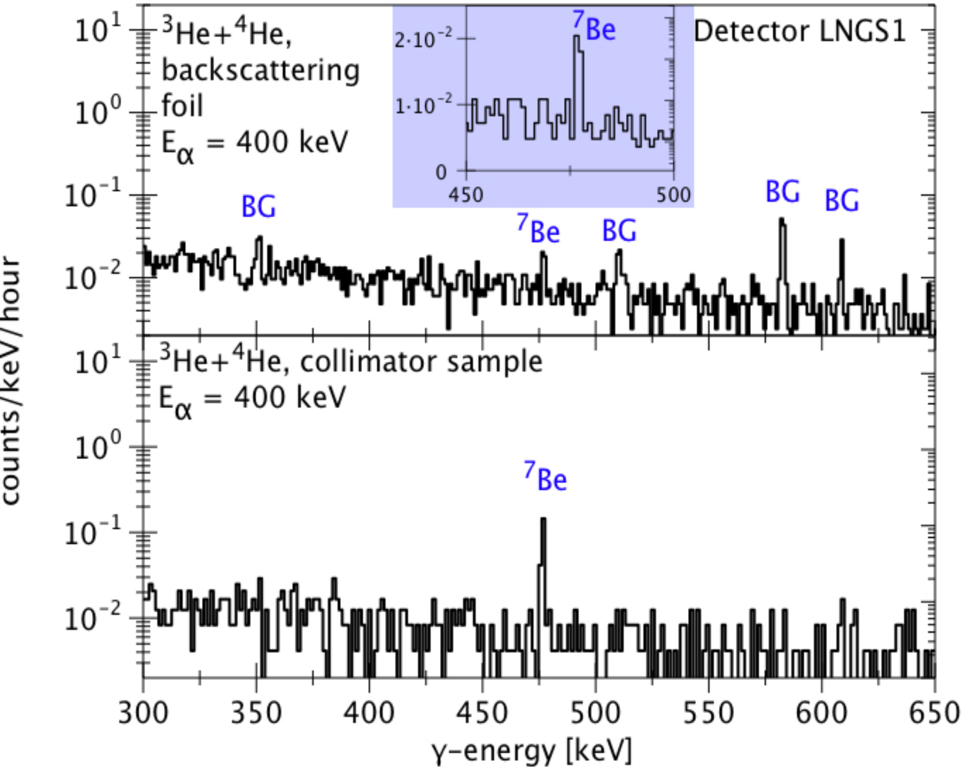
and insensitive to other elemental abundances, luminosity, opacity, ...

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

Collimator (Cu, d=7 mm) and catcher (Cu) for ^{7}Be produced in connection pipe

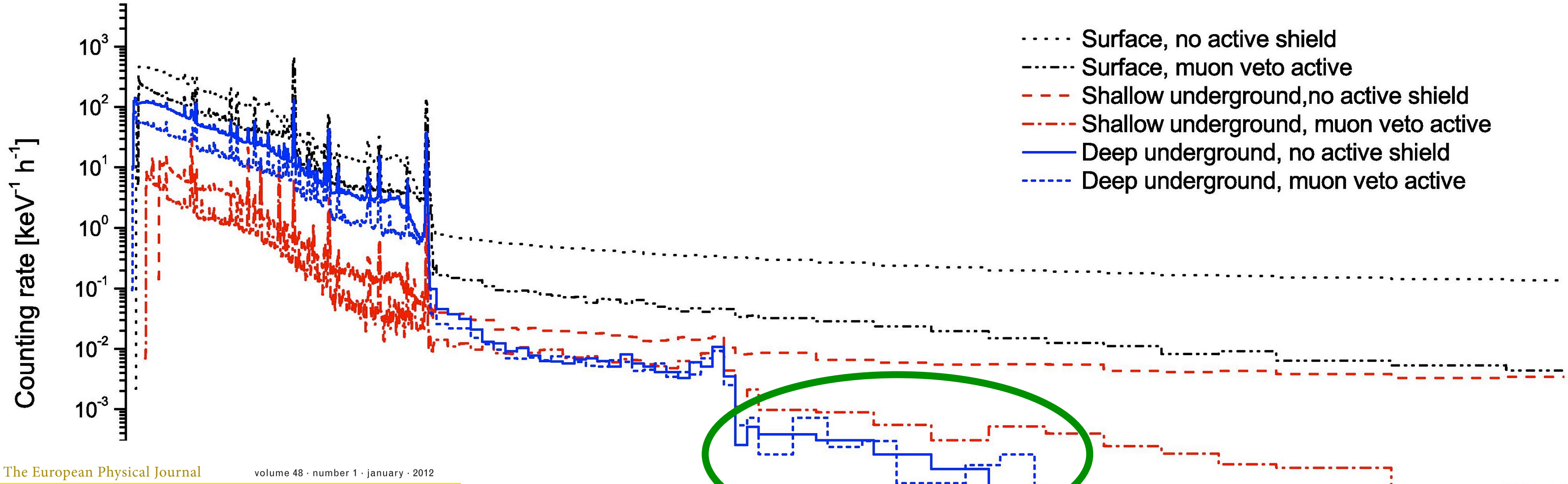
Catcher (Al) for backscattered ^{7}Be

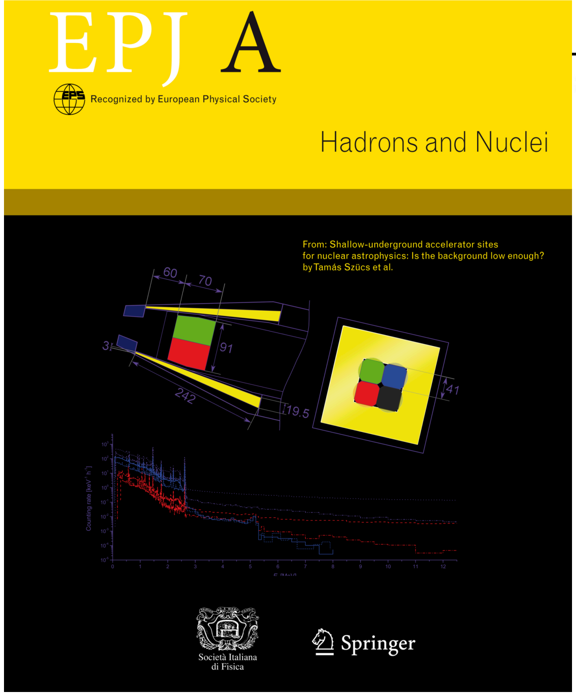
Primary ^{7}Be catcher (Cu)



γ-efficiency	1.8%
Beam intensity	1.5%
Target density	1.5%
^{7}Be losses	0.7%
Systematic uncertainty, activation	**3.0%**
Systematic uncertainty, prompt-γ	**3.6%**

Background, in a typical HPGe detector for nuclear astrophysics





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Hadrons and Nuclei

From: Shallow-underground accelerator sites for nuclear astrophysics: Is the background low enough? by Tamás Szücs et al.

Società Italiana di Fisica

Springer

- → Felsenkeller: Combination of active veto and 47m rock gives a background close to the deep-underground background at 6-8 MeV.
- → Explanation: Environmental (α,n) neutrons dominate the deep-underground background.

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