Nuclear reactions, solar neutrinos, and the importance of the CNO cycle

522. Wilhelm und Else Heraeus Seminar:

Exploring the neutrino sky and fundamental particle physics on the Megaton scale

Bad Honnef, 23.01.2013

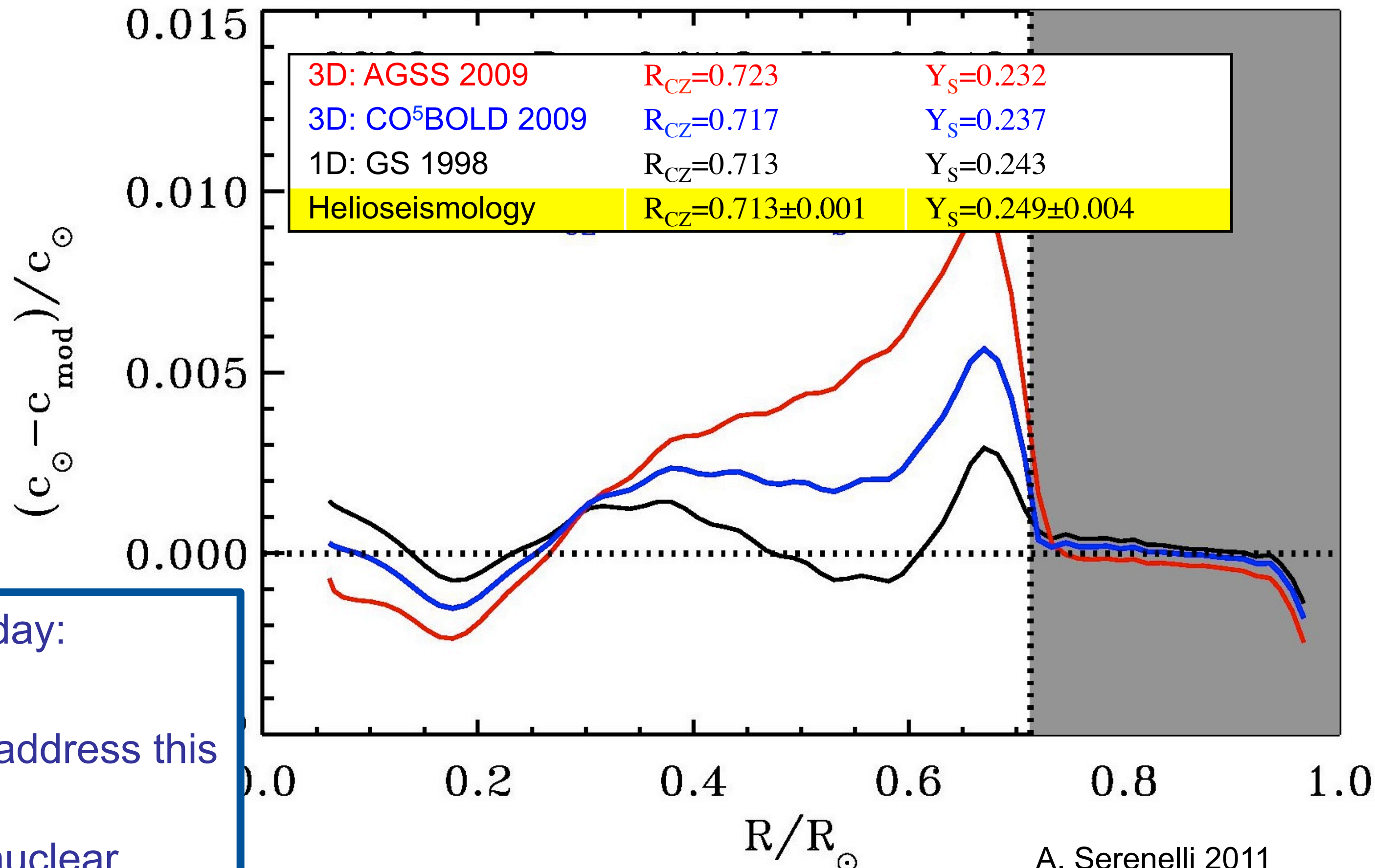
Daniel Bemmerer

The solar abundance problem:
Contradiction between solar abundances and helioseismology

New, 3-dimensional models of the photosphere lead to lower derived 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)



A. Serenelli 2011

My guiding questions today:

1. Can solar neutrinos address this discrepancy?
2. Is the quality of the nuclear physics input data good enough for this task?

Nuclear reactions, solar neutrinos, and the importance of the CNO cycle

1. Which nuclear reactions take place in the Sun?
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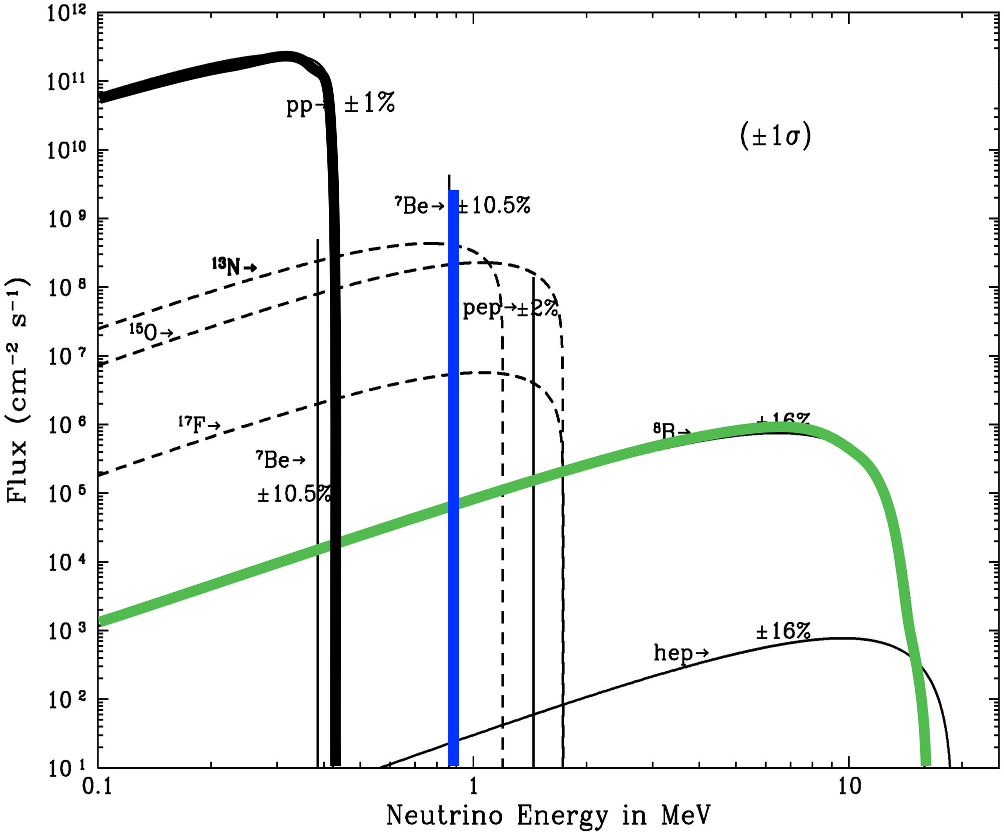
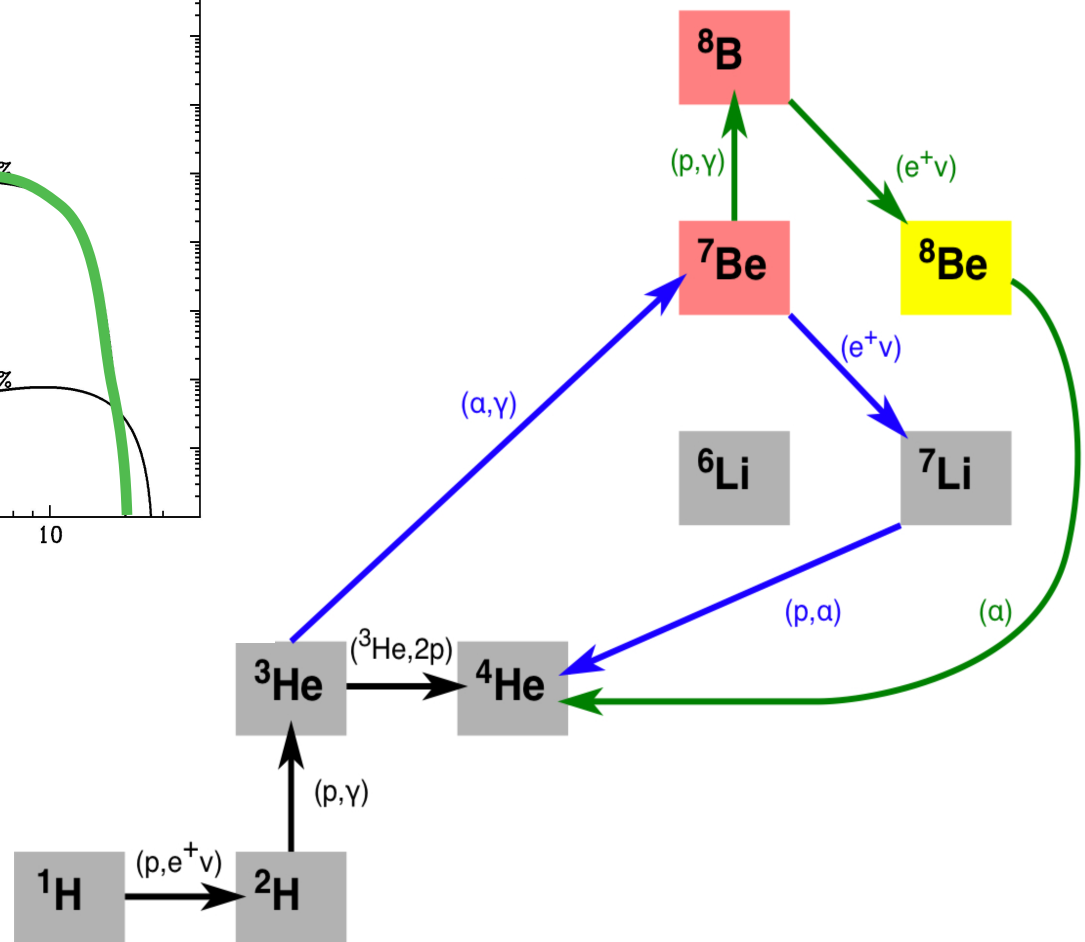
3. The nuclear physics of the proton-proton chain (pp chain)
4. The nuclear physics of the carbon-nitrogen-oxygen cycle (CNO cycle)
5. The science case for new underground accelerators

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

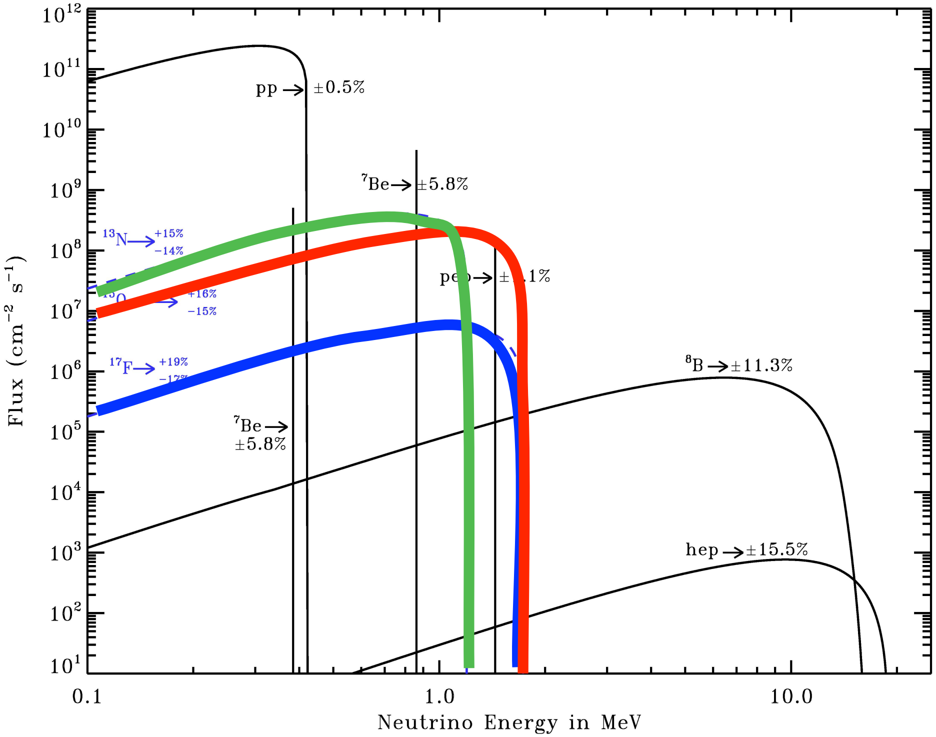


99% of energy production

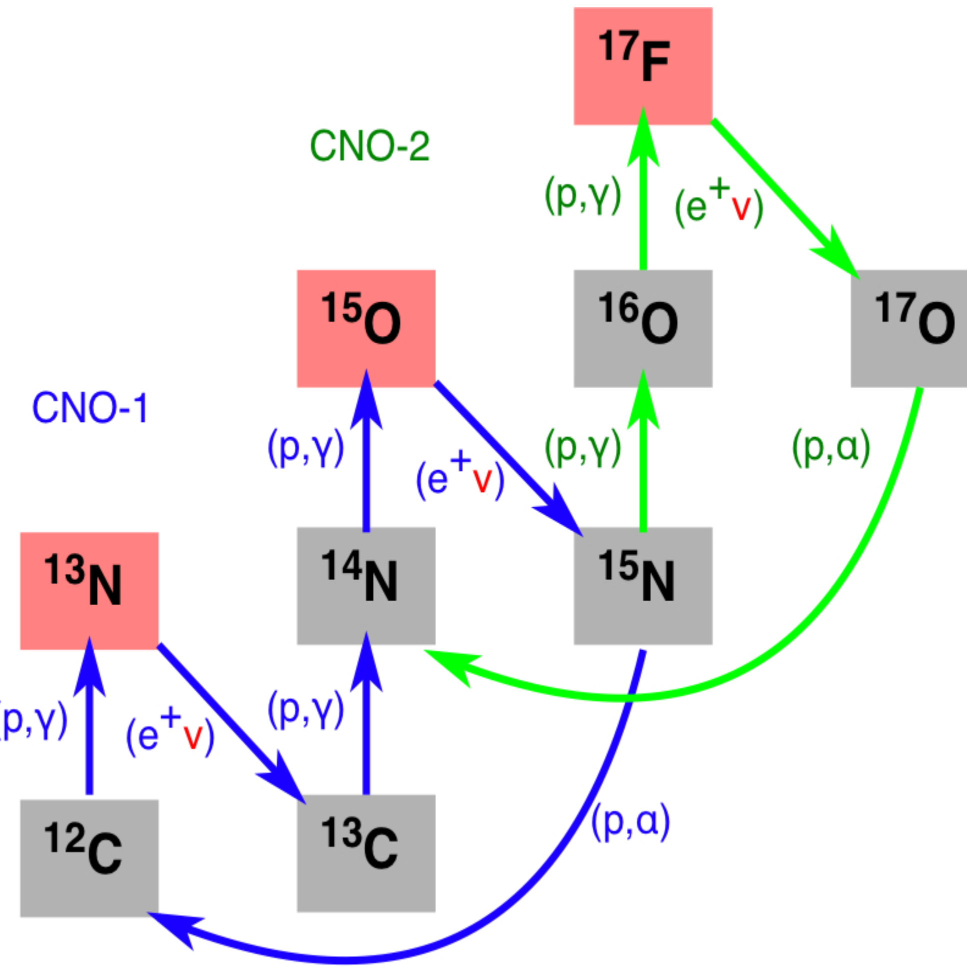


pp-1	pp-2	pp-3
85%	15%	0.02%

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



1% of energy production



^{13}N, $Q(\beta^+)$ = 2.220 MeV

^{15}O, $Q(\beta^+)$ = 2.754 MeV

^{17}F, $Q(\beta^+)$ = 2.761 MeV

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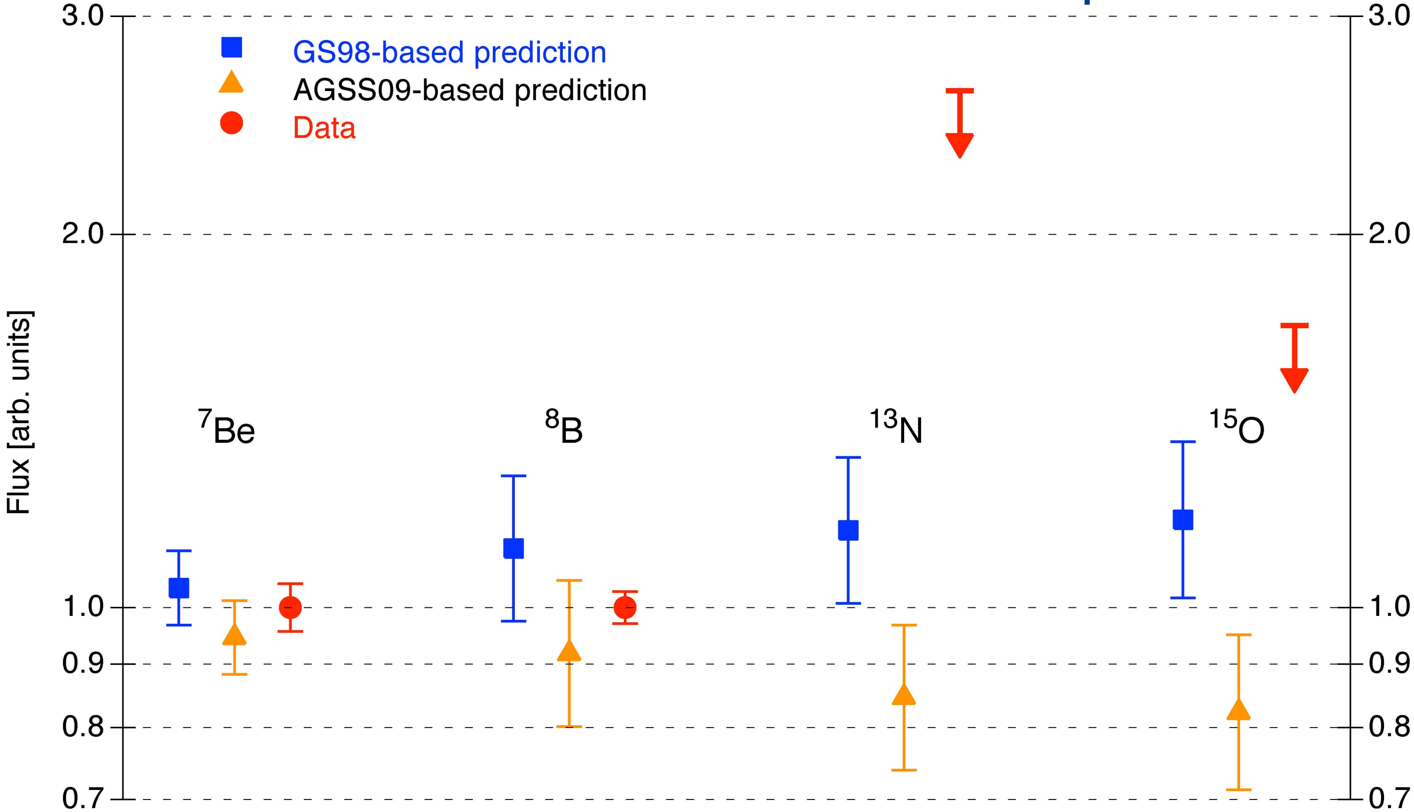
Solar neutrino fluxes: Data and model predictions

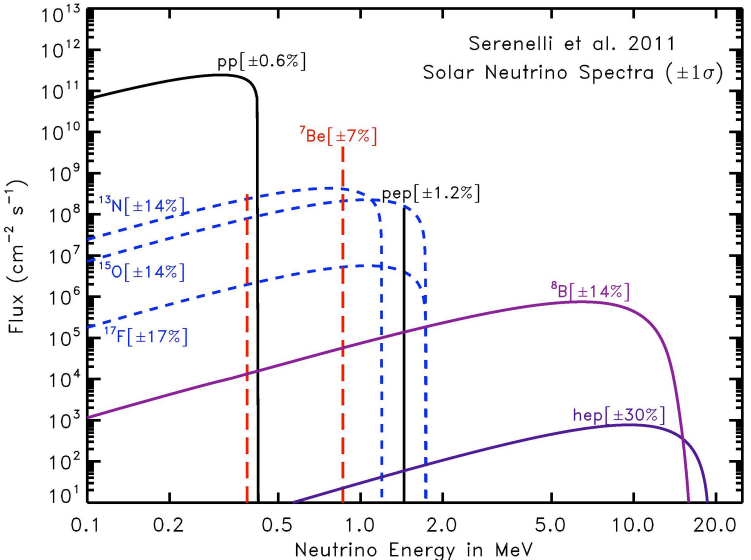


Neutrino fluxes:
Standard Solar Model;
Antonelli et al., 1208.1356

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 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

^{3}He(α,γ)^{7}Be

^{7}Be(p,γ)^{8}B

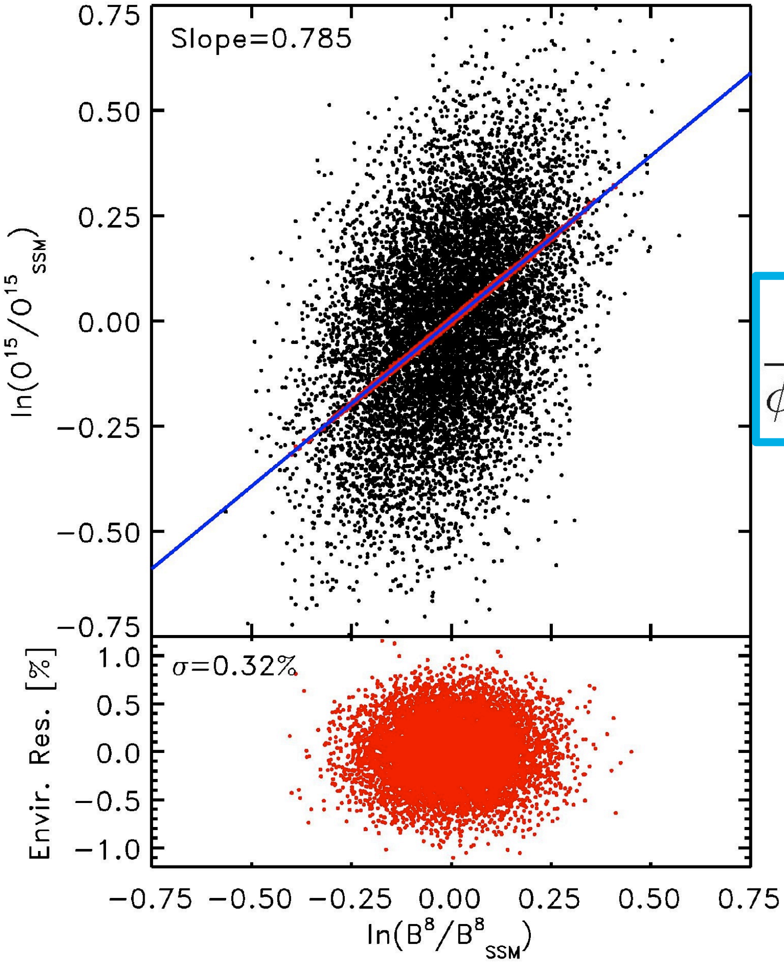
^{14}N(p,γ)^{15}O

Uncertainty contributed to neutrino flux, in percent

Antonelli et al., 1208.1356

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

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

$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} \Big/ \left[\frac{\phi(^{8}\mathrm{B})}{\phi^{\mathrm{SSM}}(^{8}\mathrm{B})}\right]^{0.785} = x_C^{0.794} x_N^{0.212} D^{0.172}$$
$$\times \left[L_\odot^{0.515} O^{-0.016} A^{0.308}\right]$$
$$\times \left[\mathrm{S}_{11}^{-0.831}\ \mathrm{S}_{33}^{0.342}\ \mathrm{S}_{34}^{-0.685}\ \mathrm{S}_{17}^{-0.785}\ \mathrm{S}_{e7}^{0.785}\ \mathrm{S}_{114}^{0.995}\right]$$
$$\times \left[x_{\mathrm{O}}^{0.003} x_{\mathrm{Ne}}^{-0.005} x_{\mathrm{Mg}}^{-0.003} x_{\mathrm{Si}}^{-0.001} x_{\mathrm{S}}^{-0.001} x_{\mathrm{Ar}}^{0.001} x_{\mathrm{Fe}}^{0.003}\right]$$

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, ...

"Mainstream" recommended cross sections: Adelberger *et al.*, Rev. Mod. Phys. 83, 195 (2011) "Solar Fusion II"

REVIEW OF MODERN PHYSICS, VOLUME 83, JANUARY–MARCH 2011

Solar fusion cross sections. II. The *pp* chain and CNO cycles

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- Workshop at INT Seattle (2009)
- Large community involvement
- Recommended cross section factors and uncertainties

TABLE I. The Solar Fusion II recommended values for $S(0)$, its derivatives, and related quantities, and for the resulting uncertainties on $S(E)$ in the region of the solar Gamow peak—the most probable reaction energy—defined for a temperature of 1.55×10^7 K characteristic of the Sun's center. See the text for detailed discussions of the range of validity for each $S(E)$. Also see Sec. VIII for recommended values of CNO electron-capture rates, Sec. XI.B for other CNO S factors, and Sec. X for the ^{8}B neutrino spectral shape. Quoted uncertainties are 1σ.

Reaction	Section	$S(0)$ (keV b)	$S'(0)$ (b)	$S''(0)$ (b/keV)	Gamow peak uncertainty (%)
$p(p, e^+\nu_e)d$	III	$(4.01 \pm 0.04) \times 10^{-22}$	$(4.49 \pm 0.05) \times 10^{-24}$	...	± 0.9
$d(p, \gamma)^3$He	IV	$(2.14^{+0.17}_{-0.16}) \times 10^{-4}$	$(5.56^{+0.18}_{-0.20}) \times 10^{-6}$	$(9.3^{+3.9}_{-3.4}) \times 10^{-9}$	± 7.1 [a]
^{3}He$(^3$He$, 2p)^4$He	V	$(5.21 \pm 0.27) \times 10^3$	-4.9 ± 3.2	$(2.2 \pm 1.7) \times 10^{-2}$	± 4.3 [a]
^{3}He$(^4$He$, \gamma)^7$Be	VI	0.56 ± 0.03	$(-3.6 \pm 0.2) \times 10^{-4}$ [b]	$(0.151 \pm 0.008) \times 10^{-6}$ [c]	± 5.1
^{3}He$(p, e^+\nu_e)^4$He	VII	$(8.6 \pm 2.6) \times 10^{-20}$	...	...	± 30
^{7}Be$(e^-, \nu_e)^7$Li	VIII	See Eq. (40)	...	...	± 2.0
$p(pe^-, \nu_e)d$	VIII	See Eq. (46)	...	...	± 1.0 [d]
^{7}Be$(p, \gamma)^8$B	IX	$(2.08 \pm 0.16) \times 10^{-2}$ [e]	$(-3.1 \pm 0.3) \times 10^{-5}$	$(2.3 \pm 0.8) \times 10^{-7}$	± 7.5
^{14}N$(p, \gamma)^{15}$O	XI.A	1.66 ± 0.12	$(-3.3 \pm 0.2) \times 10^{-3}$ [b]	$(4.4 \pm 0.3) \times 10^{-5}$ [c]	± 7.2

+ ^{12}C(p,γ)^{13}N, ^{16}O(p,γ)^{17}F

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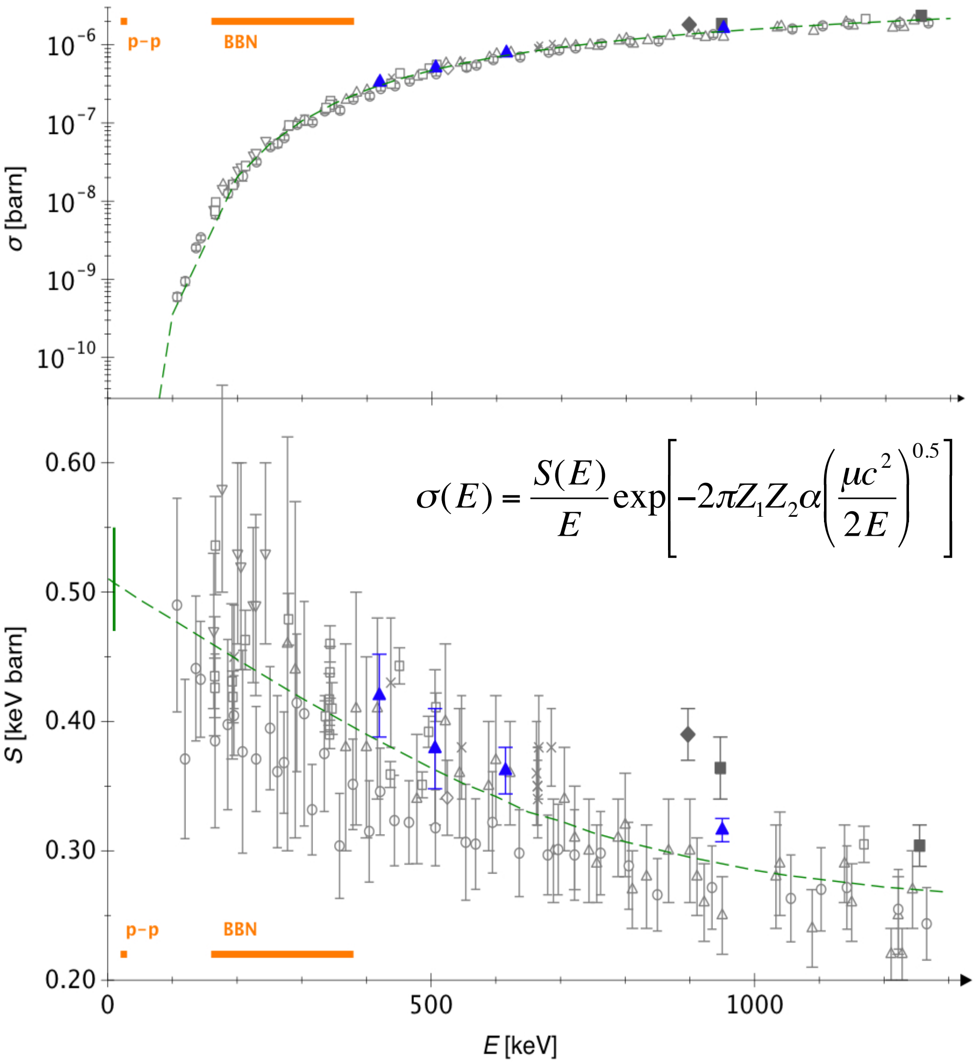
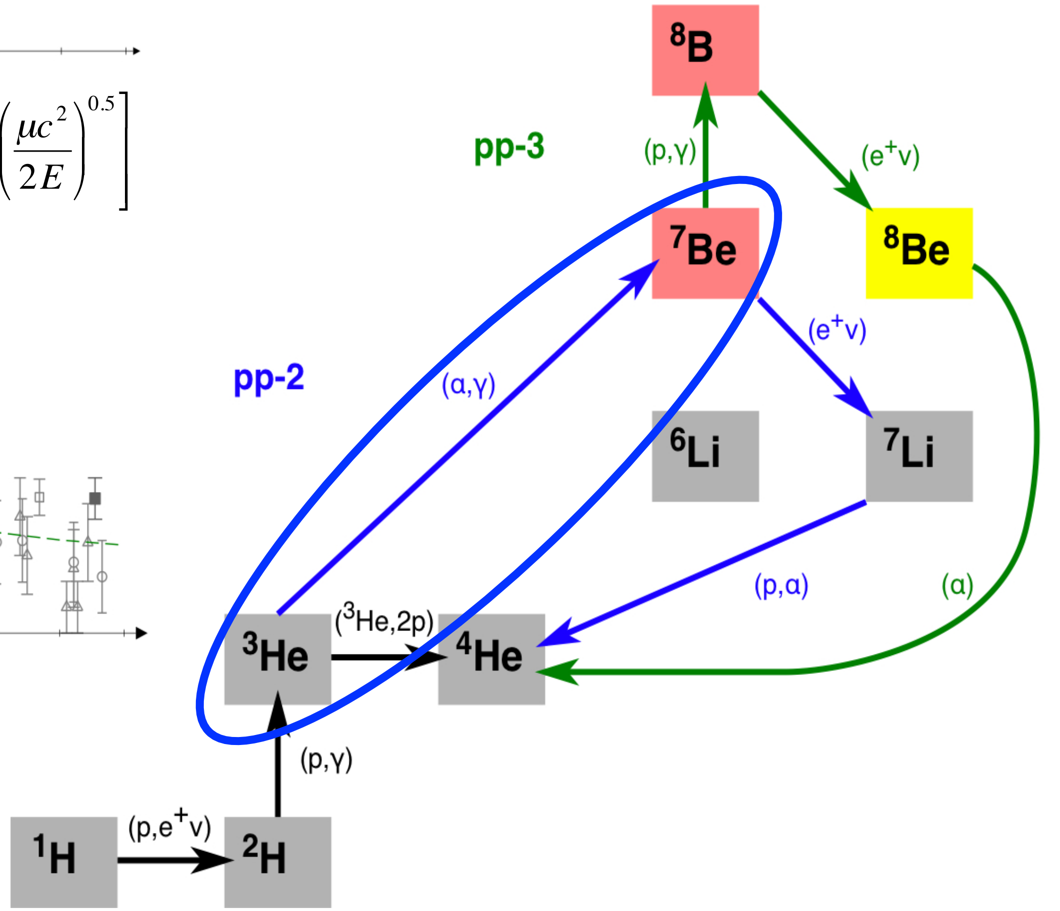
^{7}Be and ^{8}B neutrinos and the proton-proton chain: S_{34} = ^{3}He(α,γ)^{7}Be



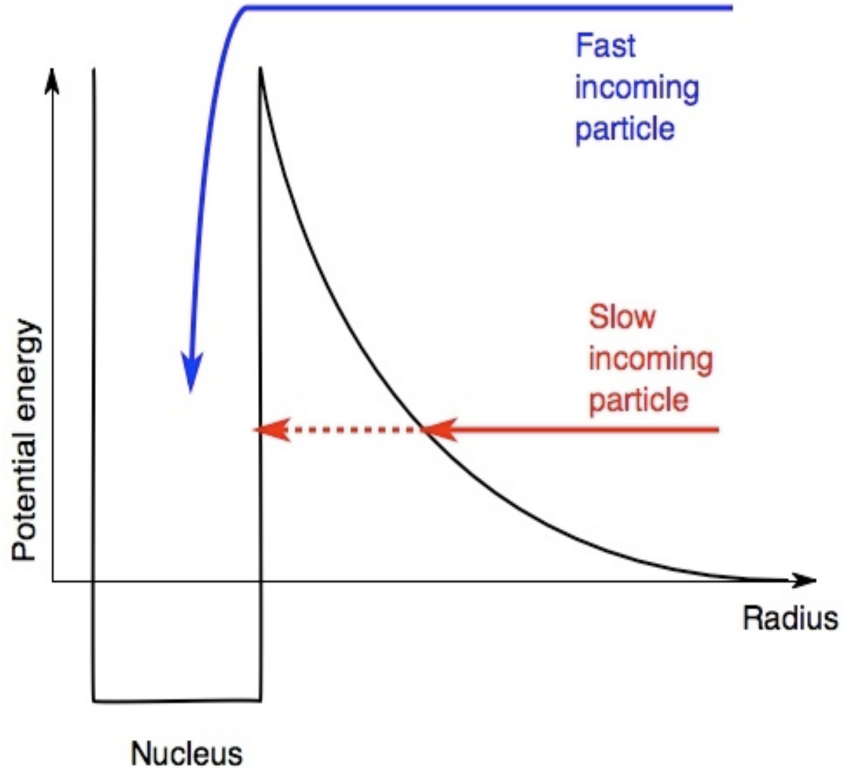
$$\sigma(E) = \frac{S(E)}{E} \exp\left[-2\pi Z_1 Z_2 \alpha \left(\frac{\mu c^2}{2E}\right)^{0.5}\right]$$

State of the art in 2006

$$\frac{\partial \ln \Phi_{\text{Be-7, B-8}}}{\partial \ln \sigma[{}^3\text{He}(\alpha,\gamma){}^7\text{Be}]} = 0.85$$



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)*:

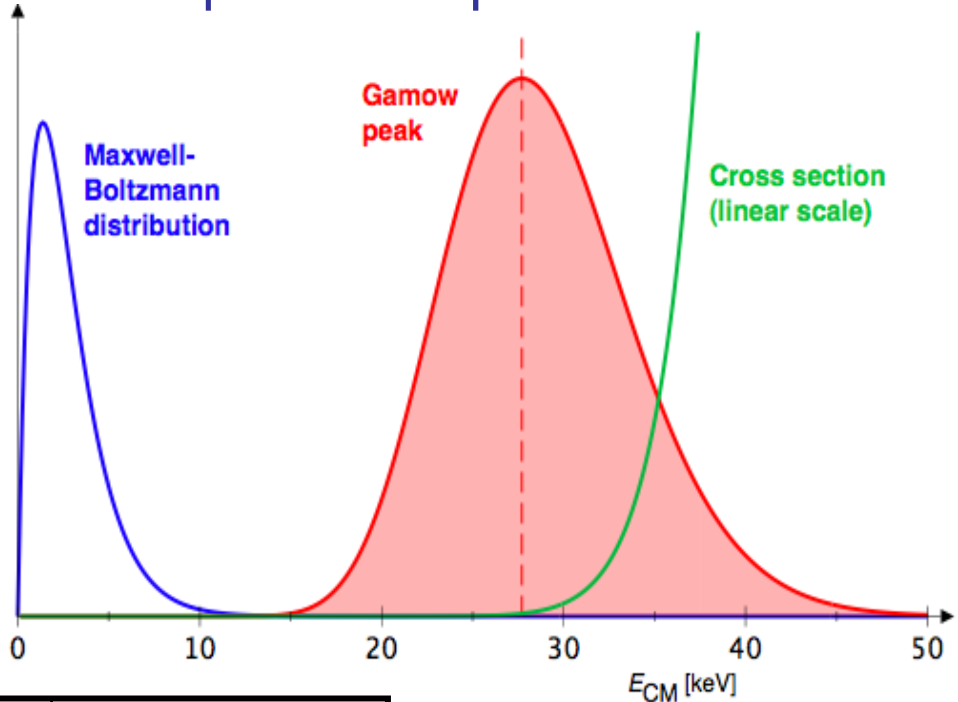
$$\sigma(E) = \frac{S(E)}{E} \exp\left[-2\pi Z_1 Z_2 \alpha \left(\frac{\mu c^2}{2E} \right)^{0.5} \right]$$

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?

Astrophysical reaction rate:
Integral under the red curve

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



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}
Big bang (300 MK)	$^3He(\alpha,\gamma)^7Be$	160	10^{-9}	10^{-1}
	$^2H(\alpha,\gamma)^6Li$	96	10^{-11}	10^{-3}

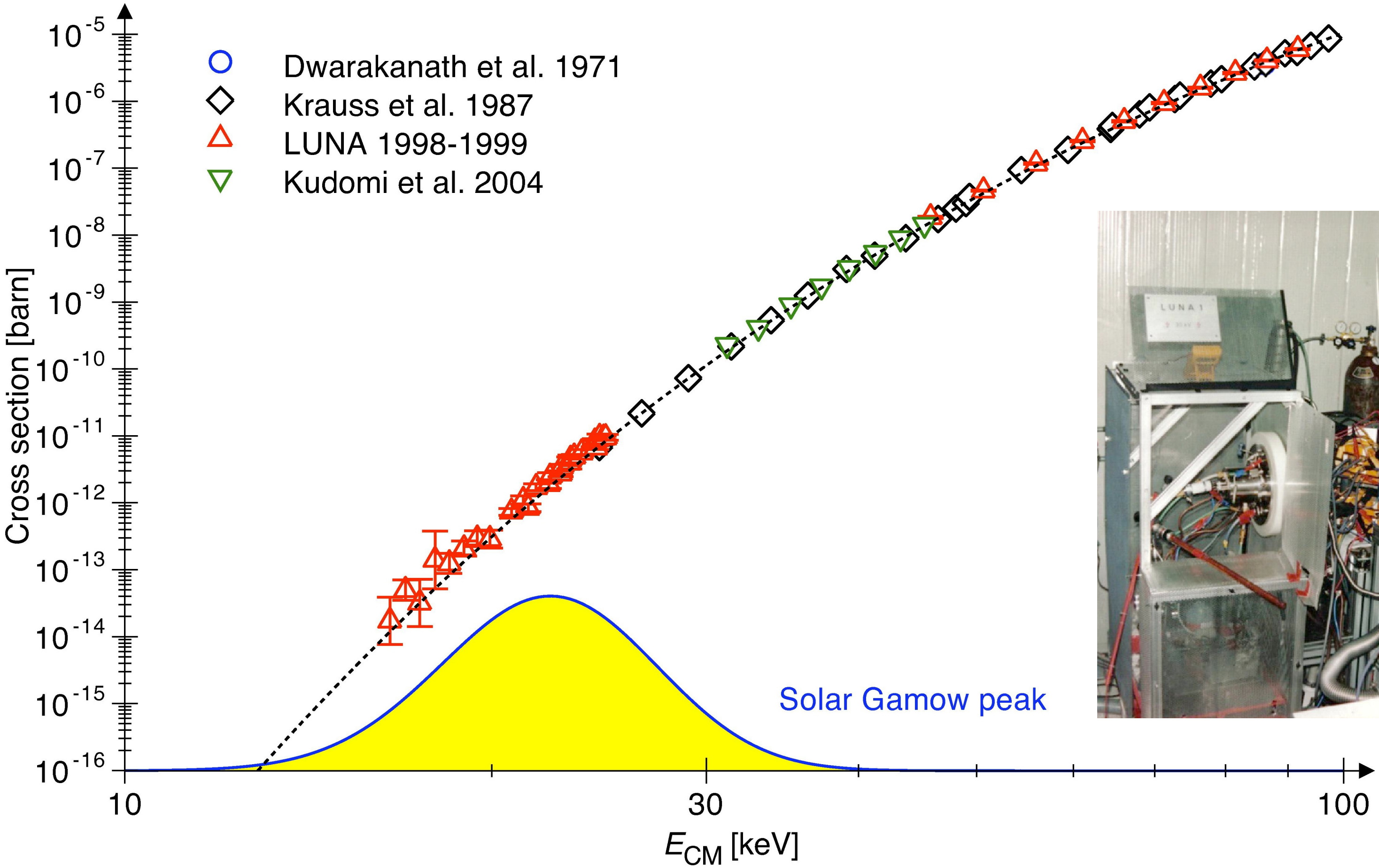
Assume 10^{16} s^{-1} beam
10^{18} at/cm^2 target
10^{-2} detection efficiency

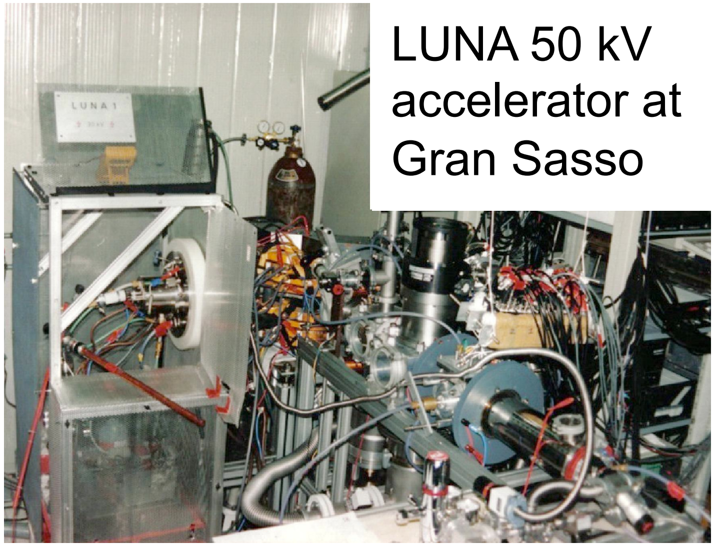
??? Is it even possible to gain data at Gamow peak energies ???

YES, direct measurements are possible! 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

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





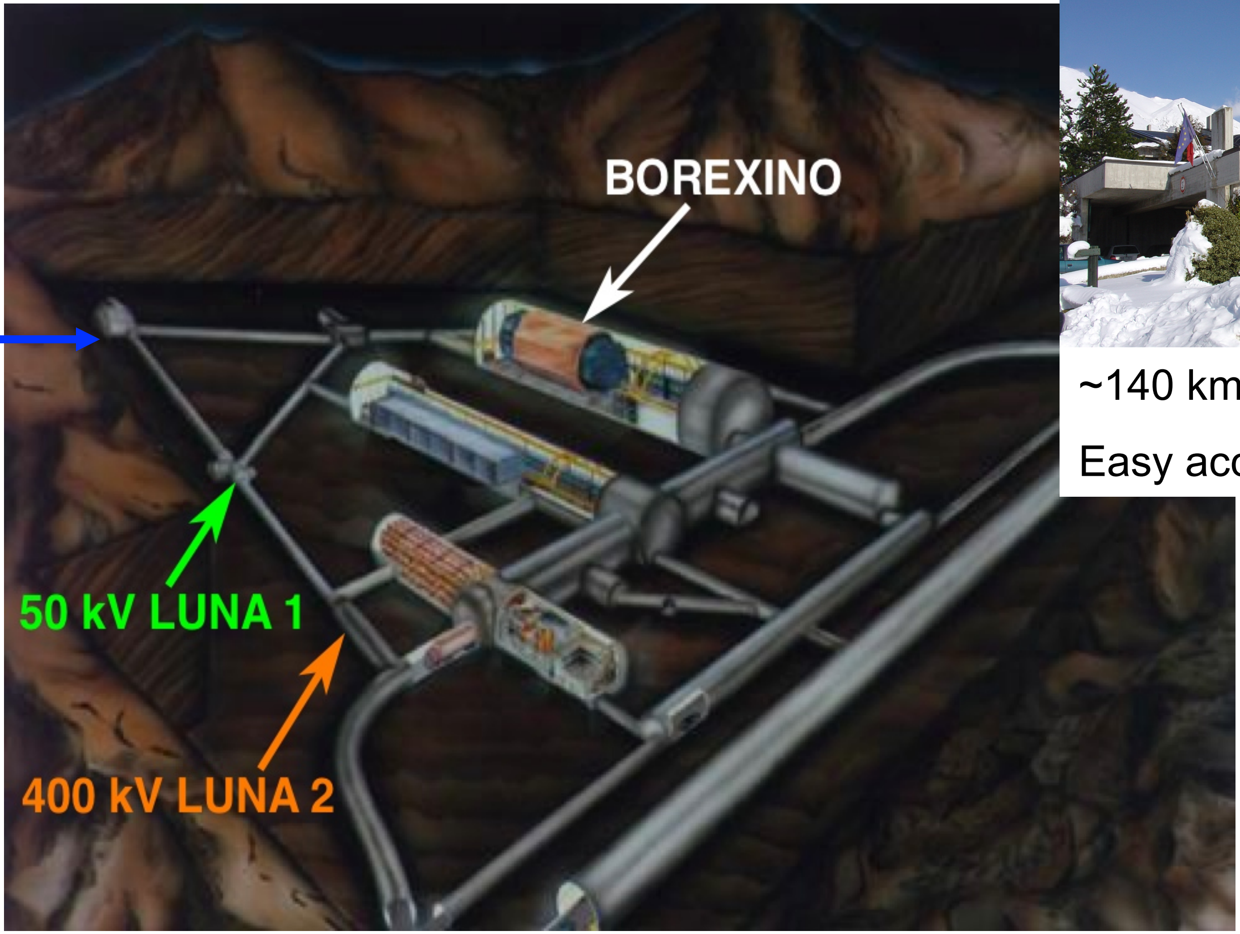
LUNA 50 kV accelerator at Gran Sasso

LUNA laboratory at Gran Sasso / Italy today

LUNA-MV, planned

1992-2001

2000-2014

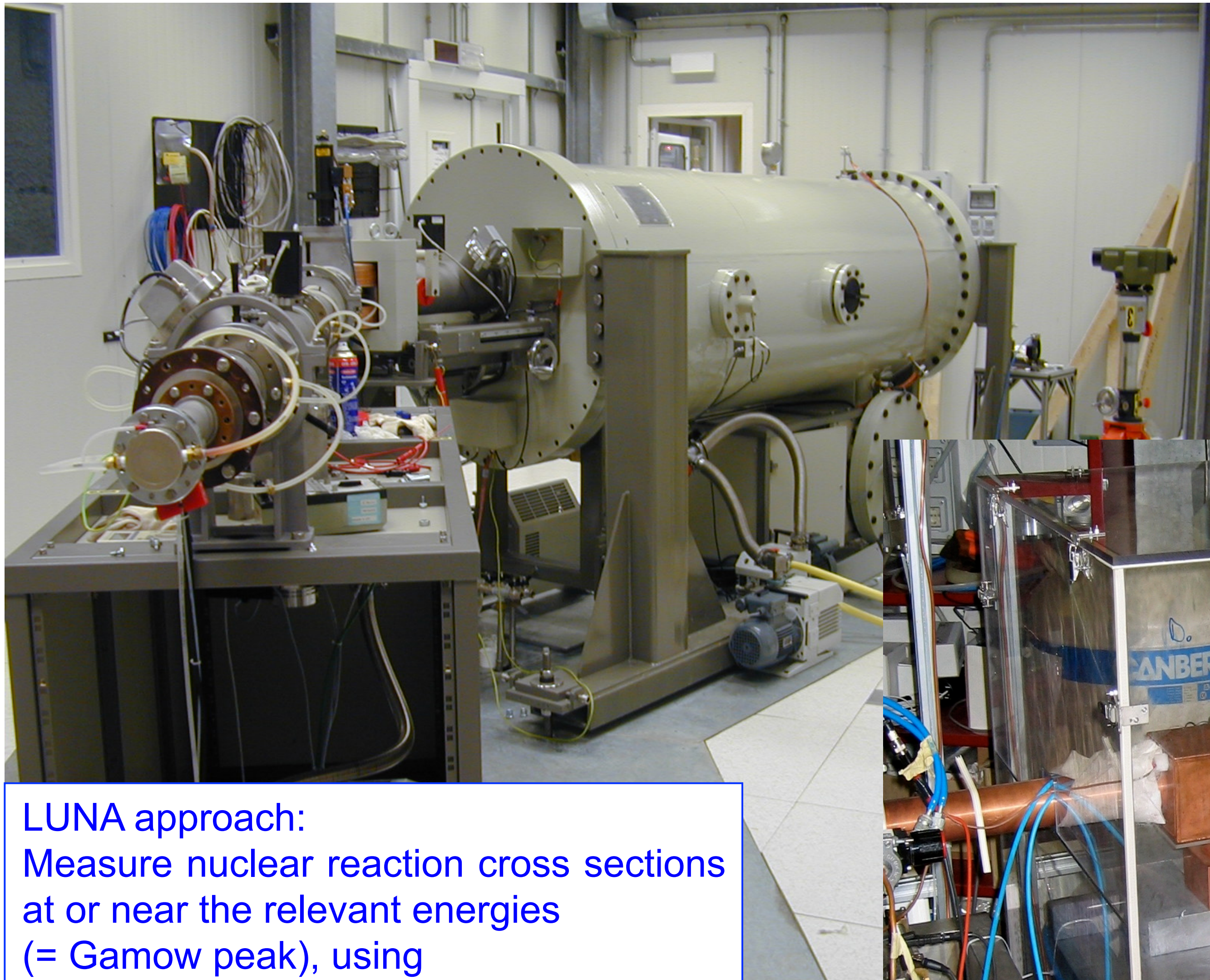


~140 km from Rome

Easy access (motorway)

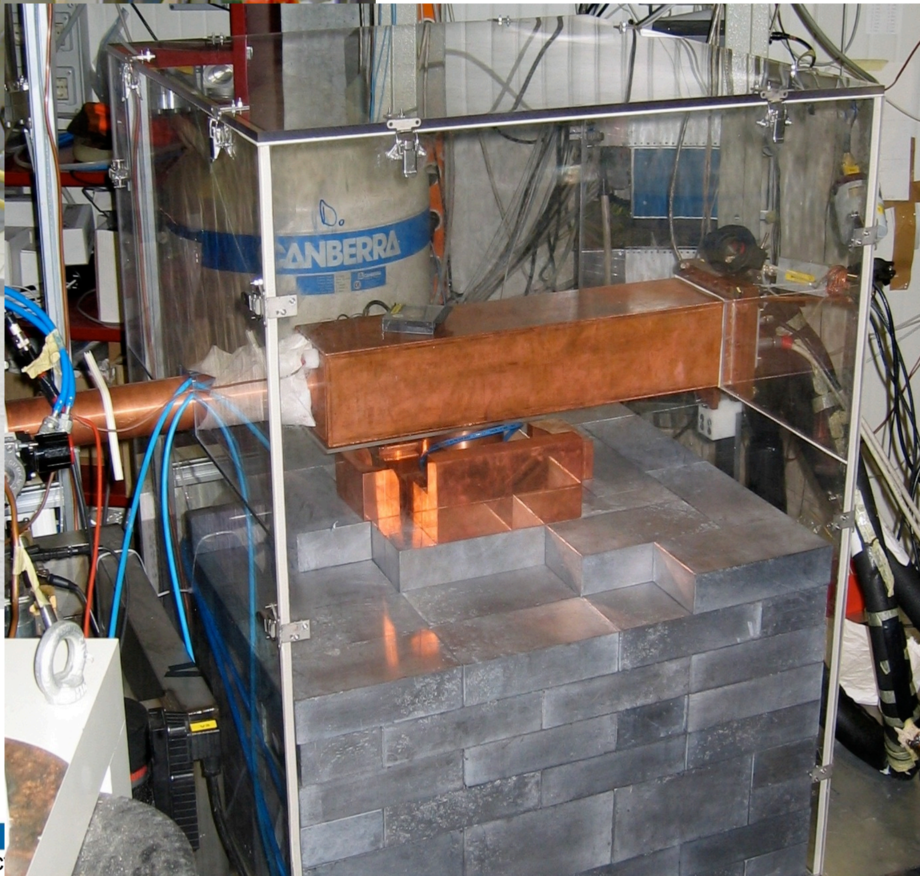
~1400 m rock 10^6 μ-reduction 10^3 n-reduction

The LUNA 0.4 MV accelerator deep underground



LUNA = Laboratory Underground for Nuclear Astrophysics

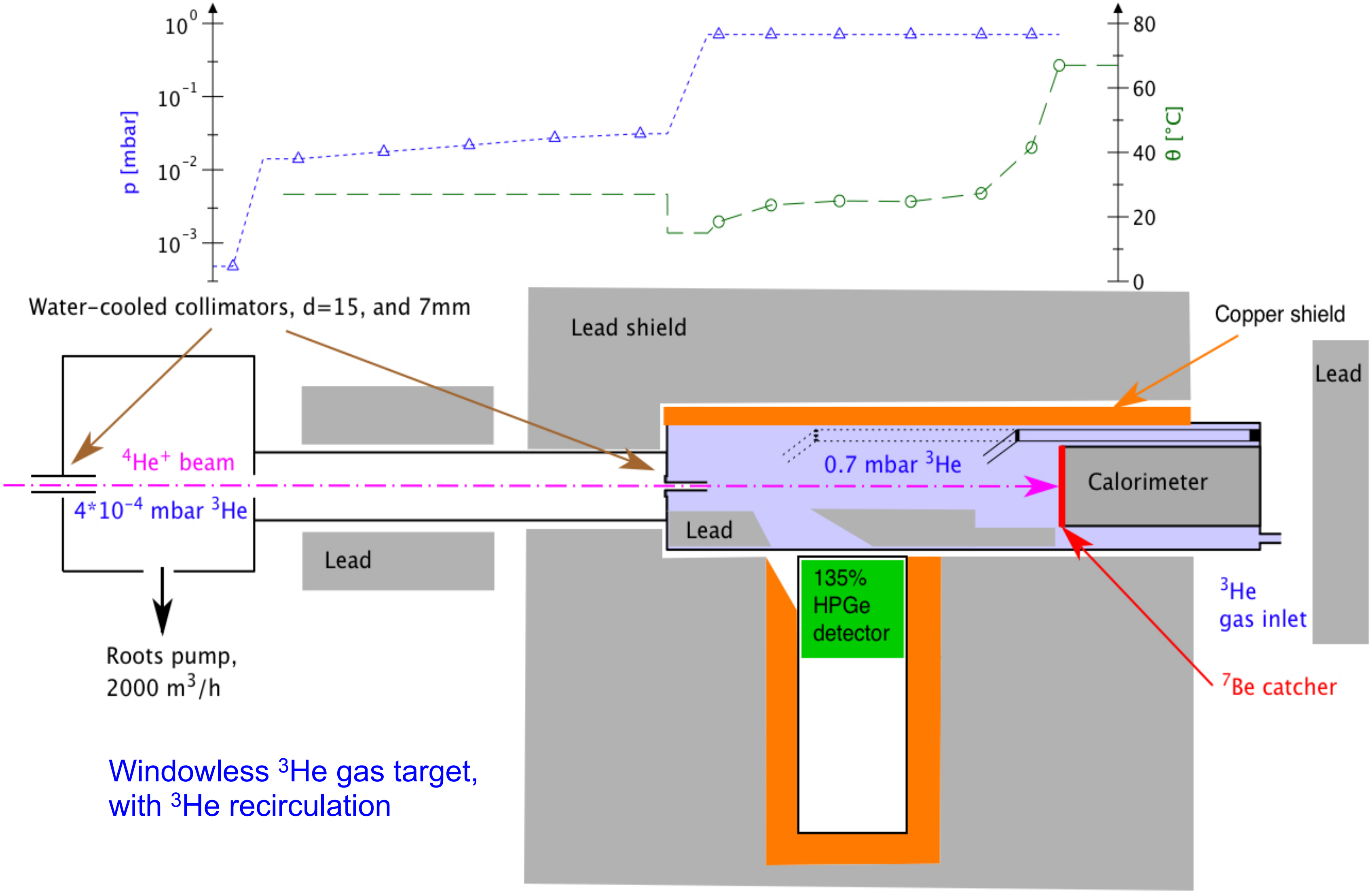
- Italy
- Germany (Bochum, Dresden)
- Hungary
- UK



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

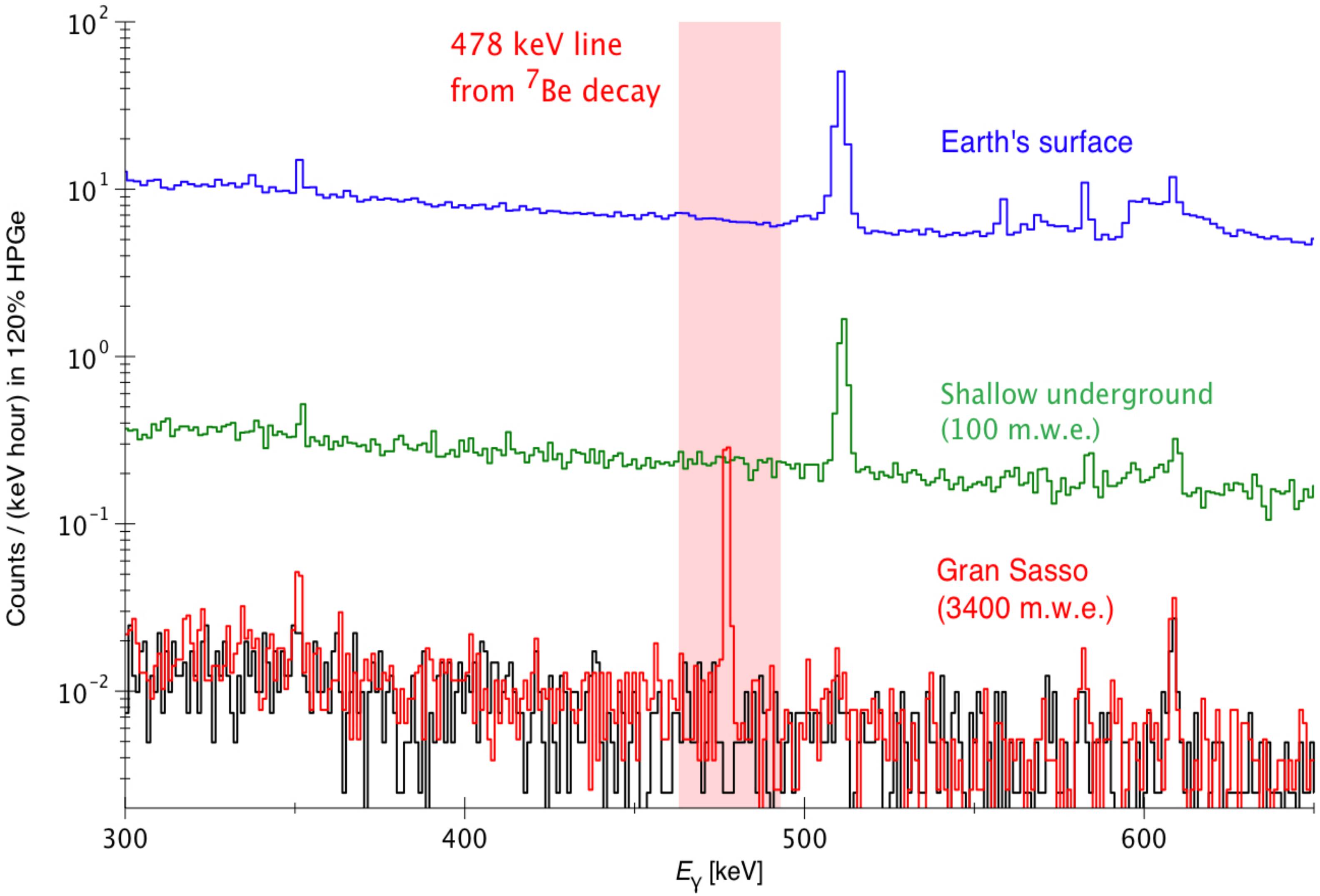
- high beam intensity
- low background
- great patience

$^3He(\alpha,\gamma)^7Be$ experiment at LUNA (activation and prompt-γ technique)



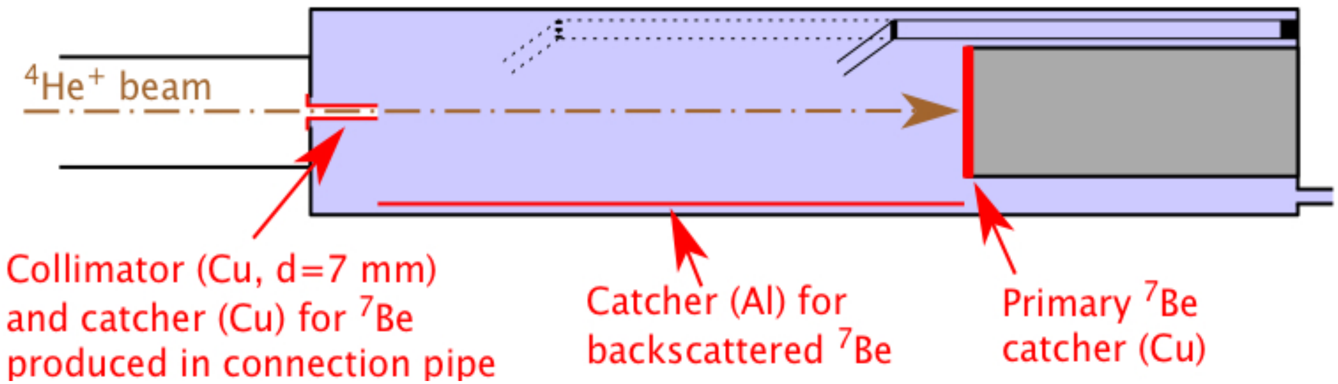
Windowless ^3He gas target, with ^3He recirculation

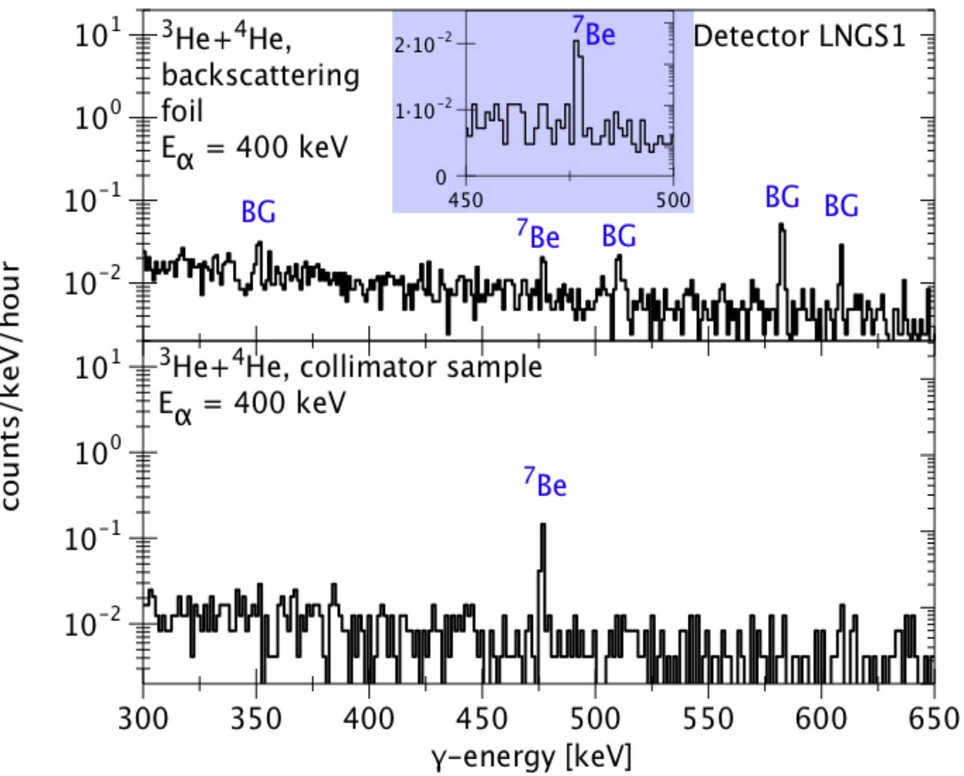
$^3He(\alpha,\gamma)^7Be$ at LUNA, ^7Be activation spectra



Detected ^7Be activities: 0.8 - 600 mBq

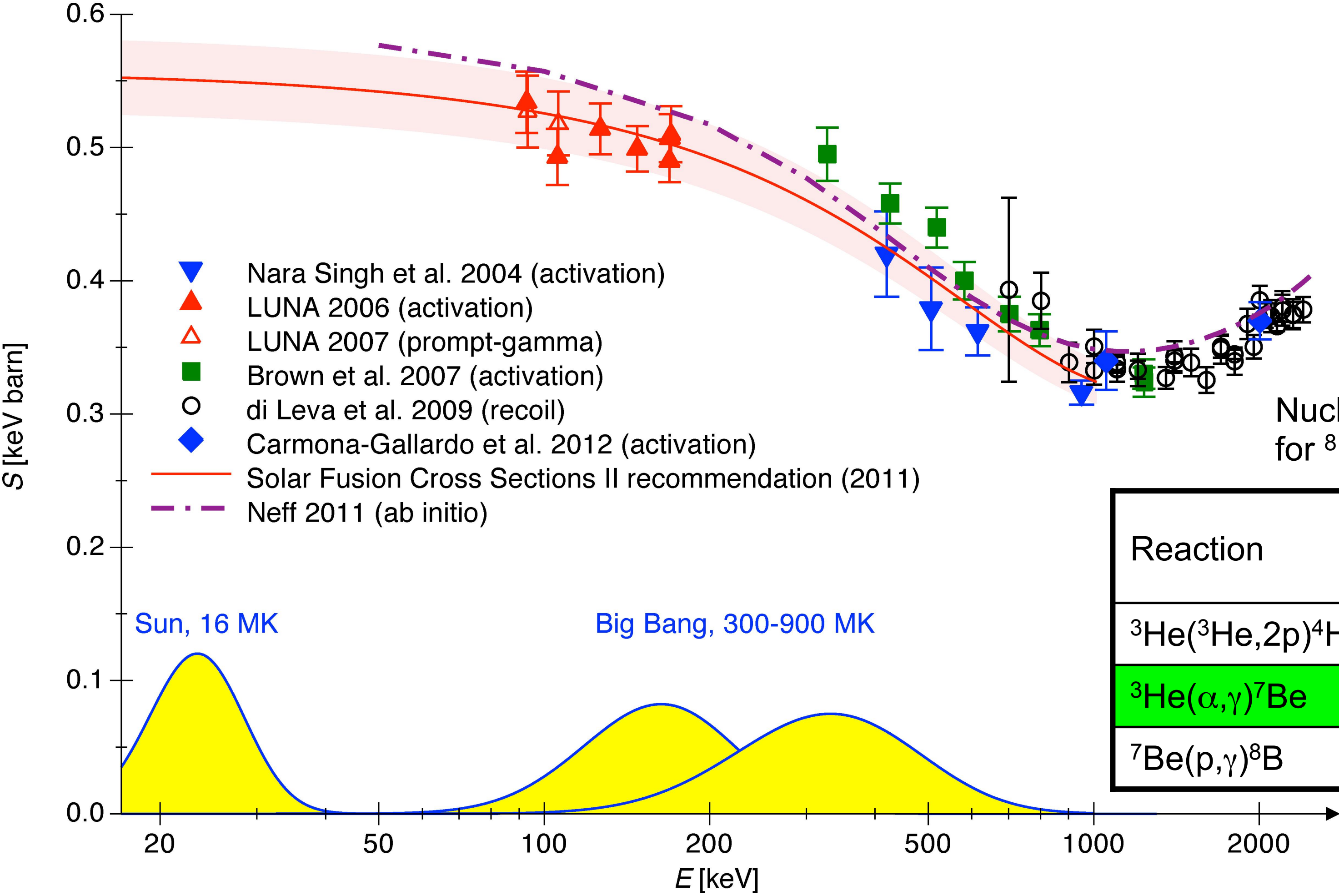
$^3He(\alpha,\gamma)^7Be$ at LUNA, systematic uncertainty





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

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



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

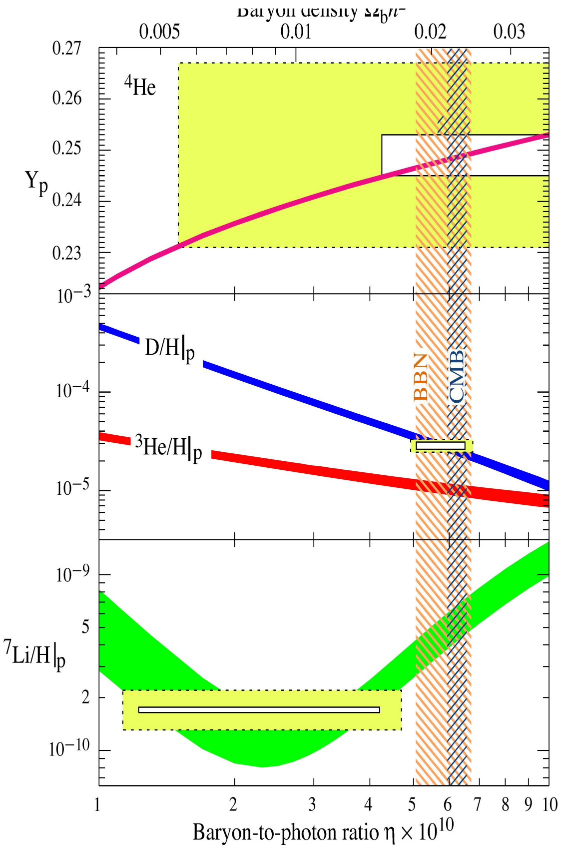
Reaction	$\frac{\partial \ln \Phi_B}{\partial \ln \sigma}$	$\Delta\Phi_B/\Phi_B$
^{3}He(^{3}He,2p)^{4}He	-0.43	1.8%
^{3}He(α,γ)^{7}Be	0.85	~~7.5%~~ 4.5%
^{7}Be(p,γ)^{8}B	1.00	7.7%

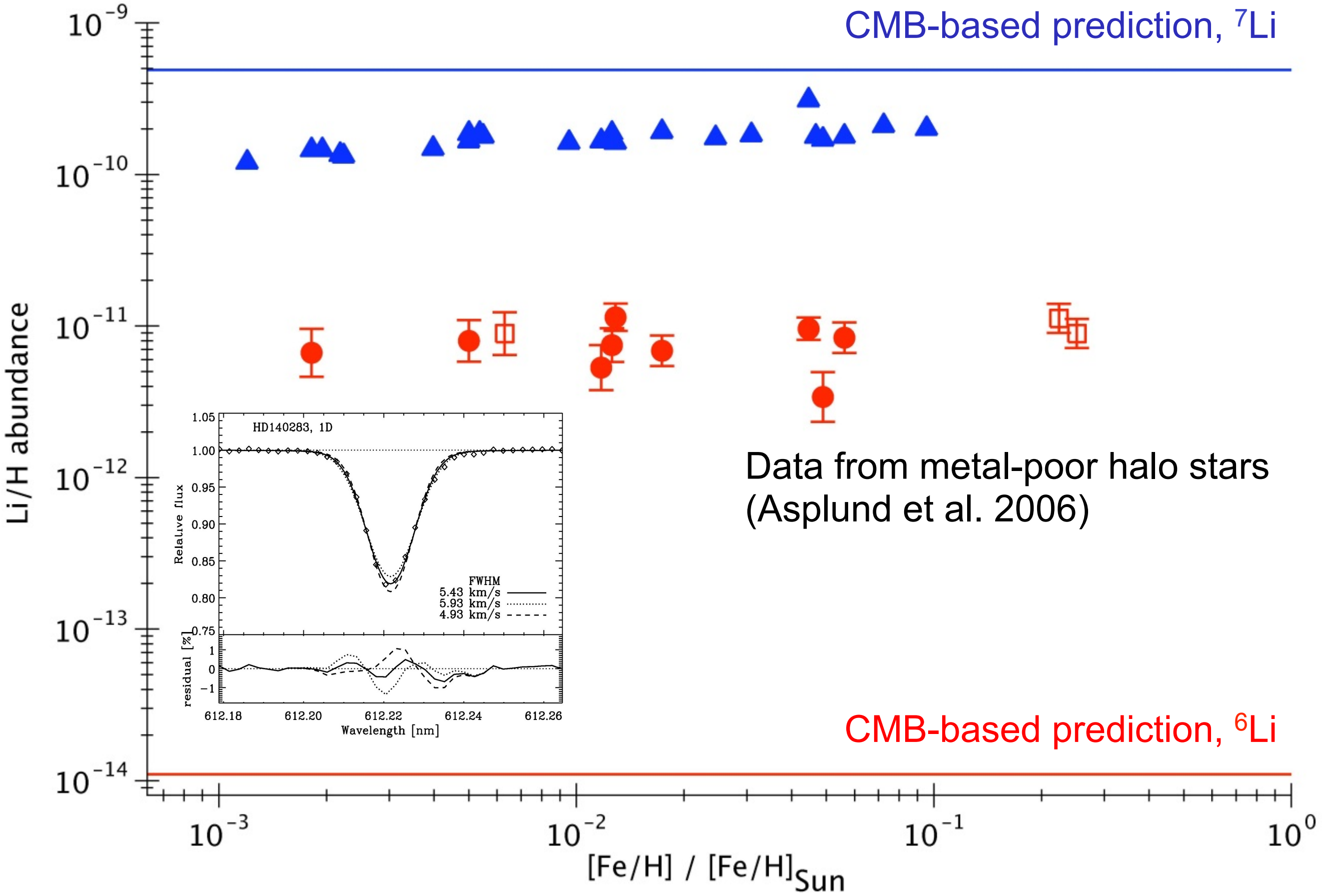
Further improvements require a comprehensive data set covering both low and high energies with one technique.

DRESDEN concept

HZDR

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





- ^{7}Li production mainly by ^{3}He(α,γ)^{7}Be ➔ ^{7}Li
  LUNA data rules out a nuclear solution for the ^{7}Li problem.

- ^{6}Li production mainly by the ^{2}H(α,γ)^{6}Li reaction
  …under study at LUNA.

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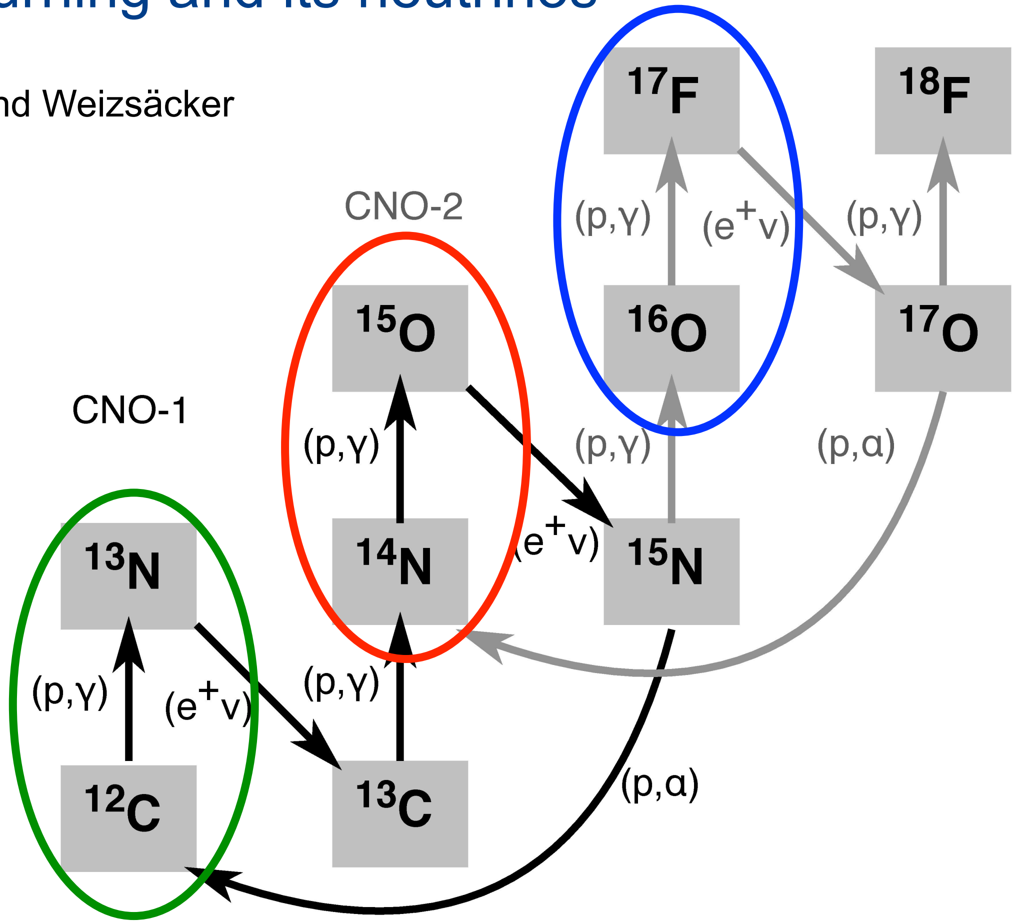
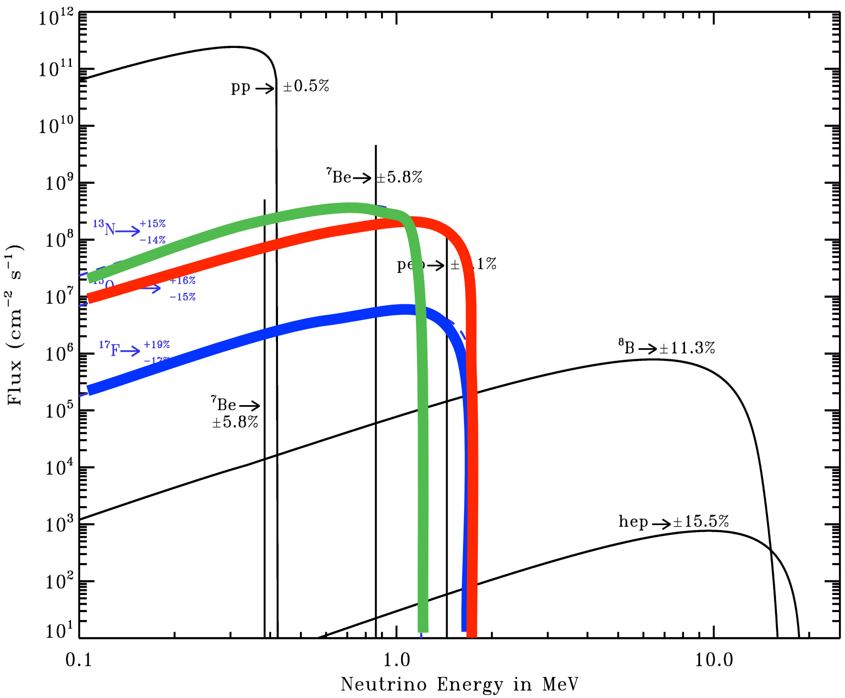
The CNO cycle of hydrogen burning and its neutrinos

CNO cycle was postulated in 1938 by Bethe and Weizsäcker

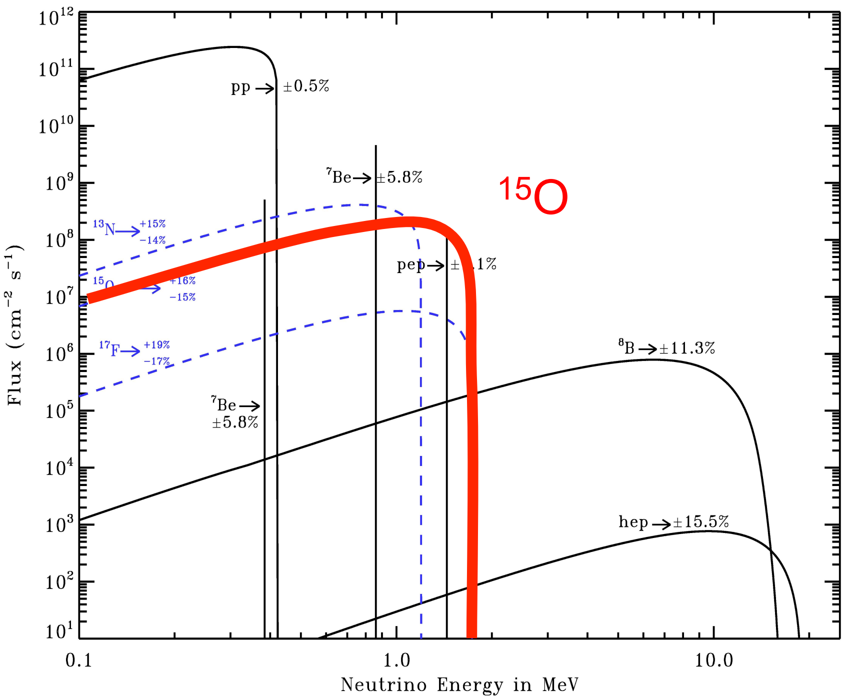
- Some of the oldest observed stars burn mainly by CNO
- ~0.8% contribution to energy production in our Sun
- In equilibrium, bottleneck reaction: $^{14}N(p,\gamma)^{15}O$

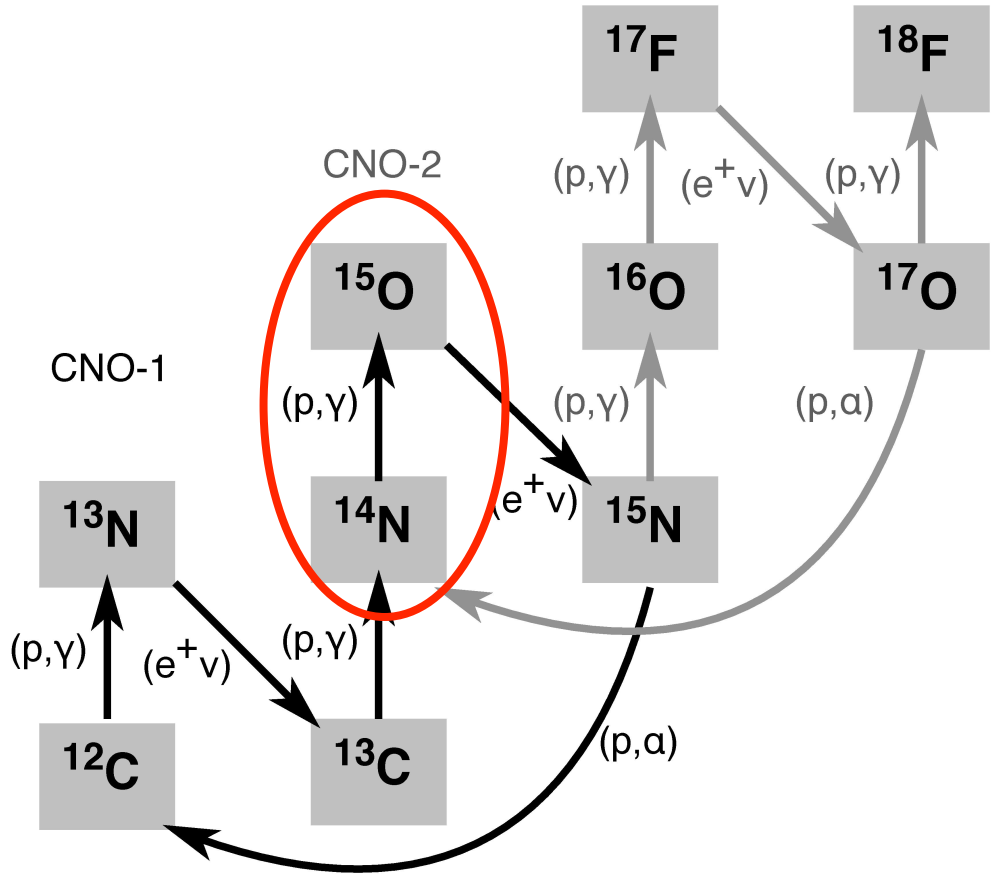




$^{14}N(p,\gamma)^{15}O$, bottleneck of the CNO cycle, and ^{15}O neutrinos

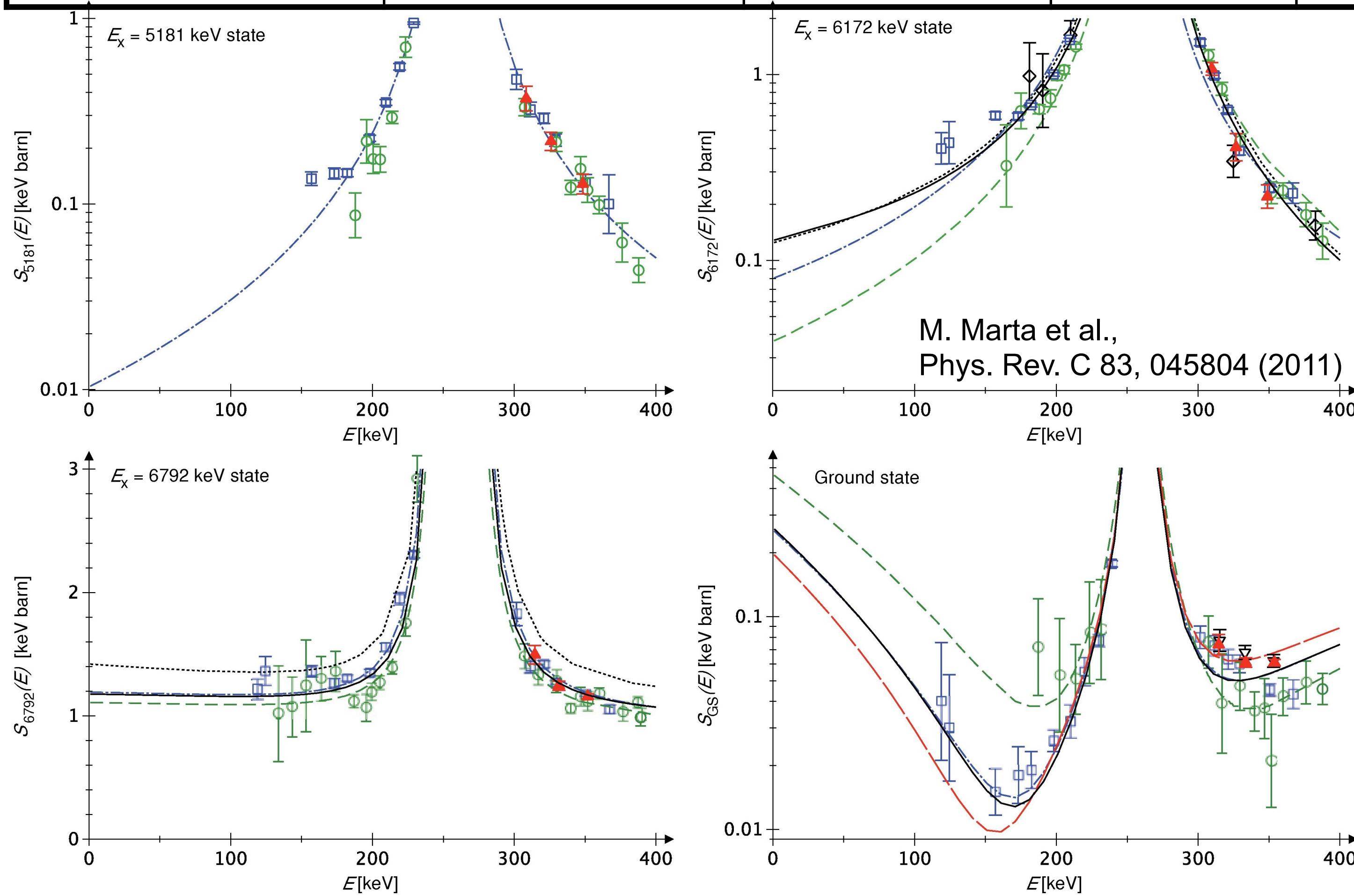
- $Q(\beta^+, {}^{15}O) = 2.754$ MeV
- Lifetime of ^{14}N in the solar center 10^8 a
- Bottleneck of the whole cycle: $^{14}N(p,\gamma)^{15}O$
- $$\frac{\partial \ln \Phi_{\nu(\text{O-15})}}{\partial \ln S[{}^{14}\text{N}(p,\gamma){}^{15}\text{O}]} = 1$$





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

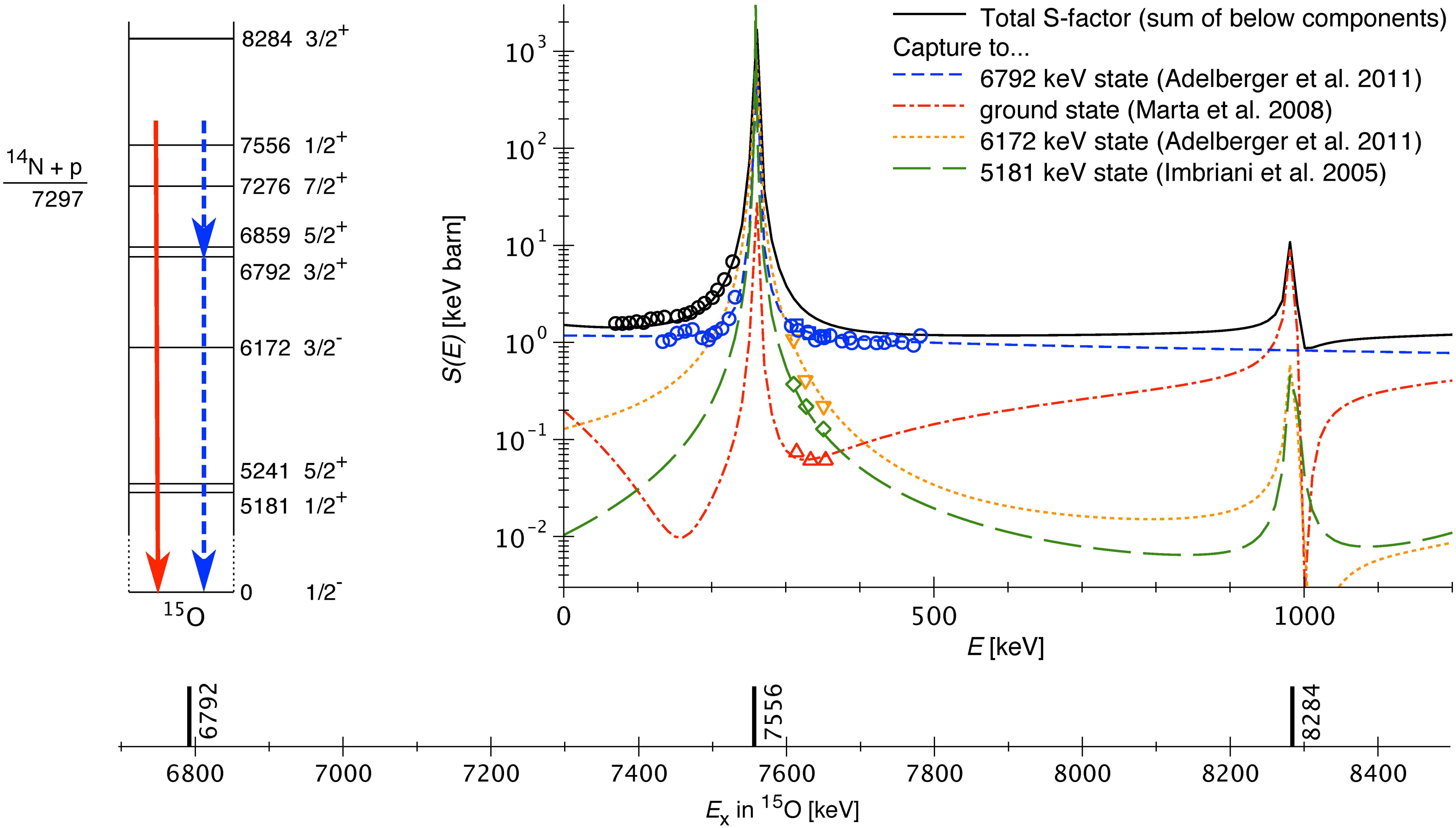
Capture to...	NACRE compilation 1999	LUNA, phase 1 2004	TUNL 2005	LUNA, phase 3 2008+2011
...ground state in ^{15}O	1.55 ± 0.34	0.25 ± 0.06	0.49 ± 0.08	0.27 ± 0.05
...excited states in ^{15}O	1.65 ± 0.05	1.36 ± 0.05	1.27 ± 0.05	(1.39 ± 0.05)
S(0) in keV barn	3.2 ± 0.5 (tot)	1.6 ± 0.2 (tot)	1.8 ± 0.2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



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

...but it should be further improved!

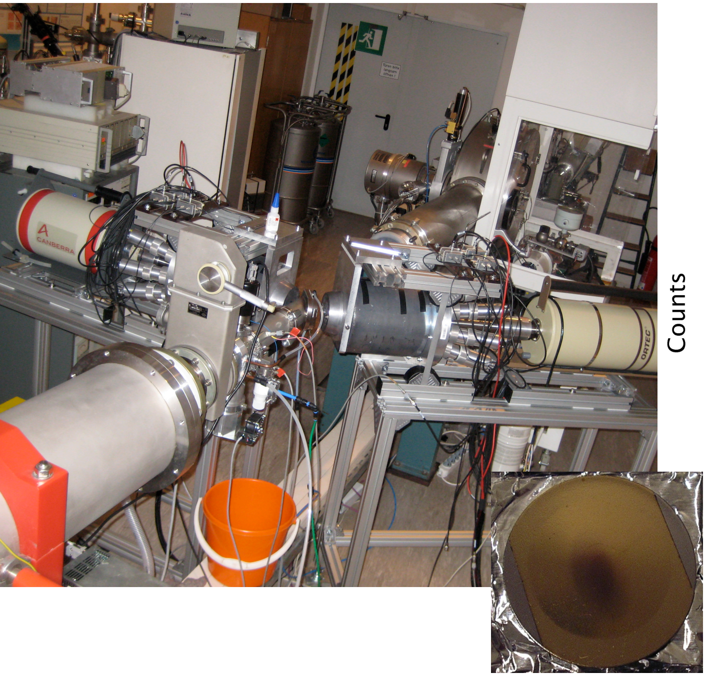
Outlook on new experimental data on $^{14}N(p,\gamma)^{15}O$

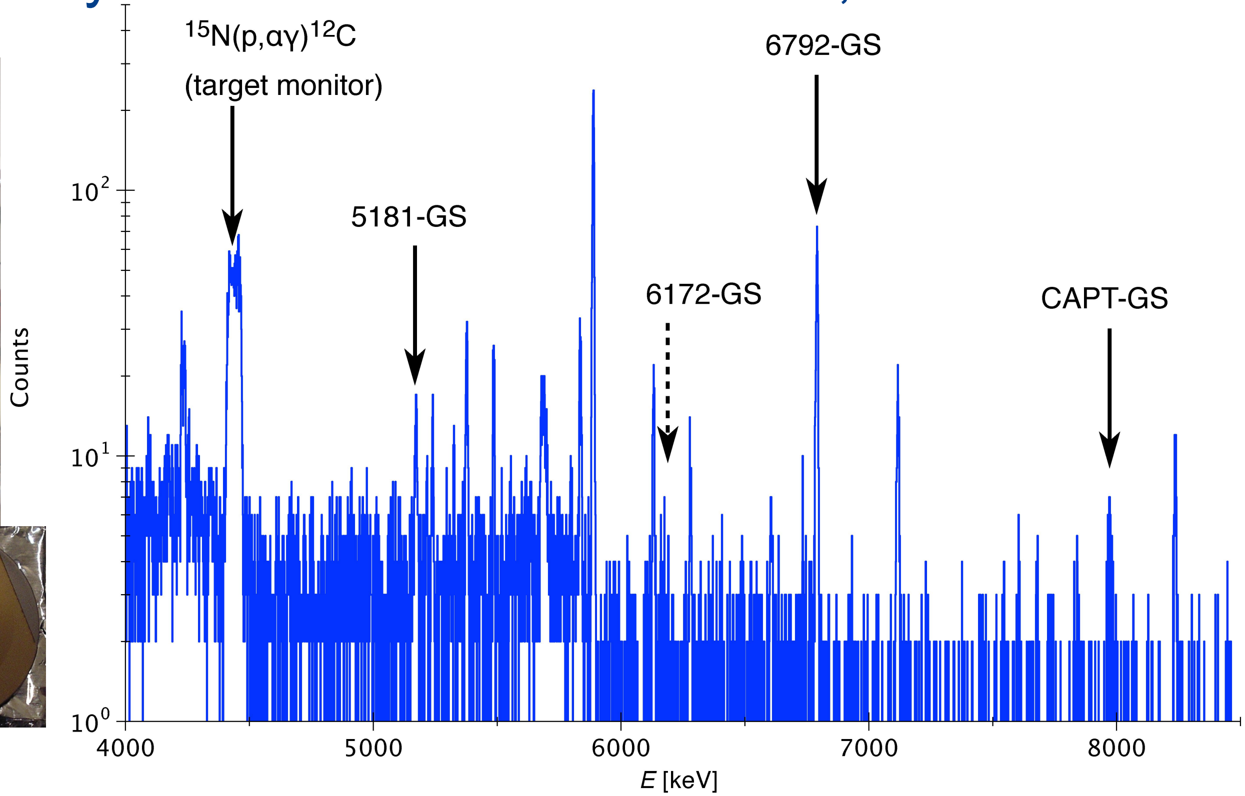


- The S-factor is the sum of several components with very different energy dependence.
- New cross section data between 0.4 and 2.0 MeV are needed!
- This requires a high-intensity, low background accelerator with a few MeV energy range.

DRESDEN concept HZDR

Experiment on the CNO cycle at the 3.3 MV Tandetron, HZDR





Phys. Rev. C 81, 055807 (2010):
Resonance strengths

Louis Wagner et al.,
new experiment (January 2013):
Off-resonance cross section

	Literature [23, 49]		Present		Literature
Reaction	E_p [keV]	Γ_{lab} [keV]	$\omega\gamma_i/\omega\gamma_{278}$	$\omega\gamma$ [eV]	$\omega\gamma$ [eV]
$^{14}N(p,\gamma)^{15}O$	278	1.0	$\stackrel{!}{=}1$	Reference	0.0131±0.0006 [21][a]
$^{14}N(p,\gamma)^{15}O$	1058	3.9[b]	27.5±0.9	0.360±0.020	0.31±0.04 [22]
$^{15}N(p,\alpha\gamma)^{12}C$	897	1.57	$(2.77\pm0.11)\cdot10^4$	362±22	293±38 [59]
$^{15}N(p,\alpha\gamma)^{12}C$	430	0.1	$(1.73\pm0.08)\cdot10^3$	22.7±1.5	21.1±1.4 [44]

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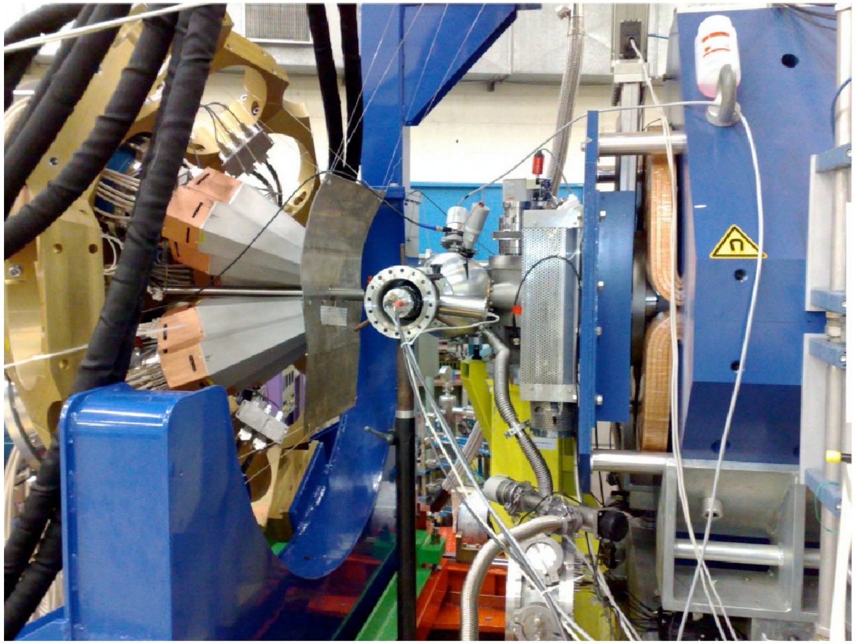
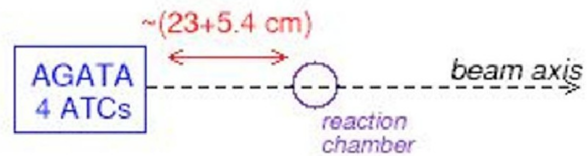
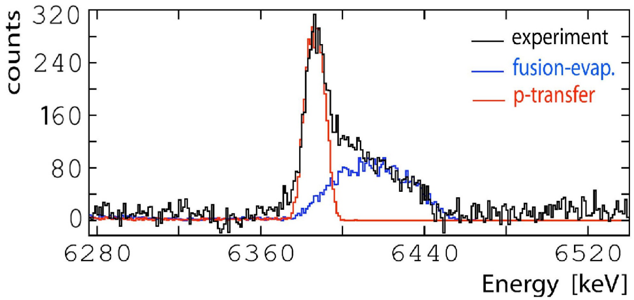
Lifetime of the 6.792 MeV level in ^{15}O studied at AGATA demonstrator

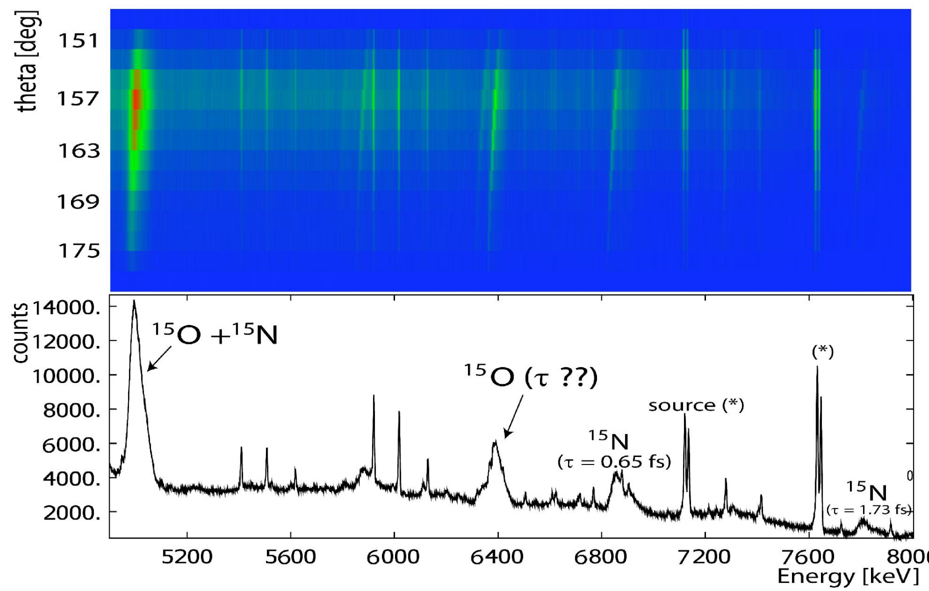


$$\Delta E_\gamma(6792) = \frac{\hbar}{\tau(6792)}$$

$$0.9\,\mathrm{eV} = \frac{\hbar}{0.7\,\mathrm{fs}}$$

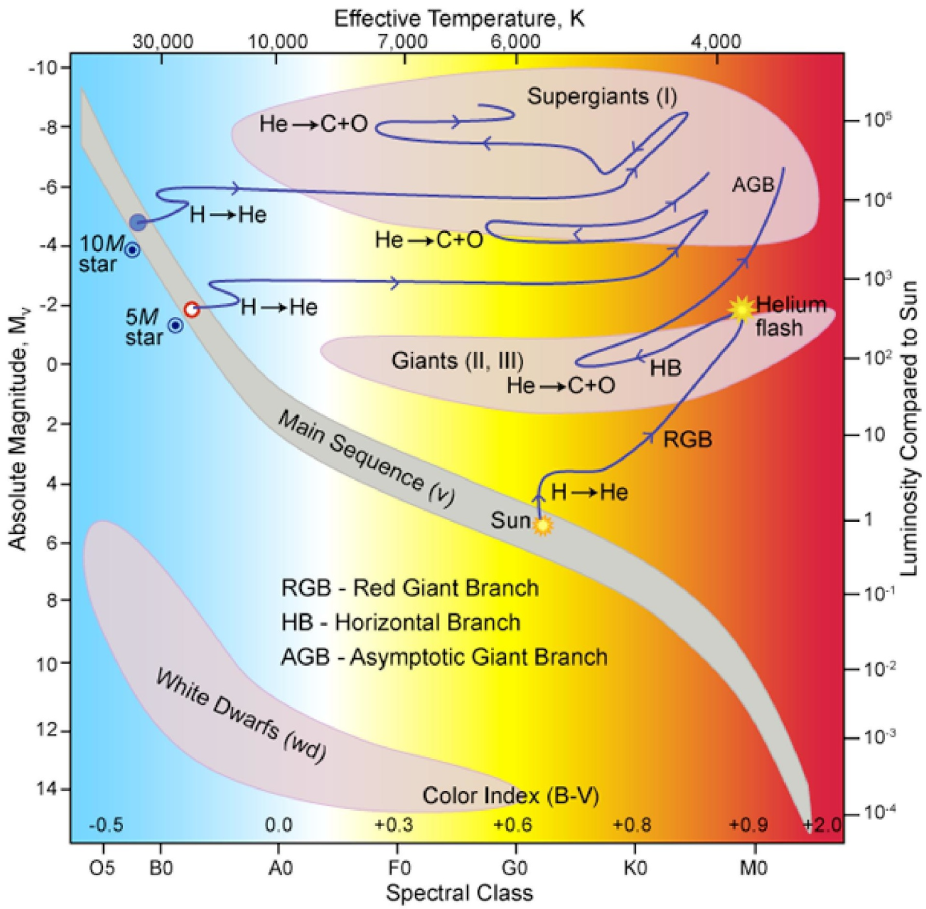


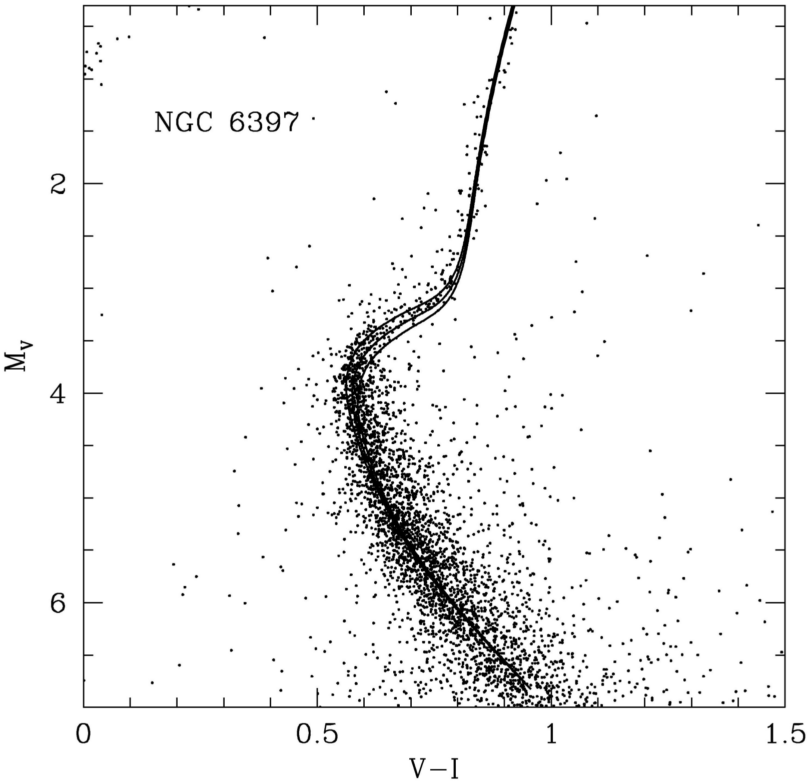




- Subthreshold level populated in ^{14}N(d,n)^{15}O reaction
- Upper limit for lifetime in the fs range
- C. Michelagnoli, R. Depalo et al. (INFN Padua)

Byproduct: Age determination of very old stars (in globular clusters)





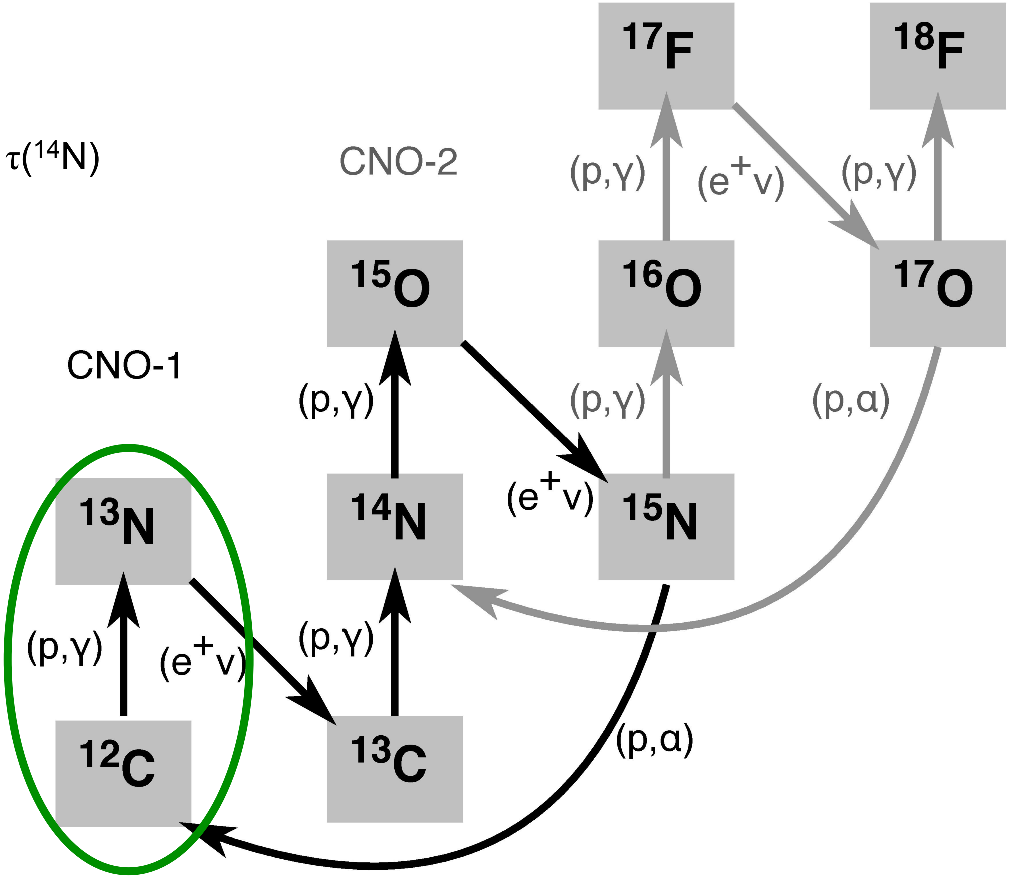
→ Hertzsprung-Russel diagram, turnoff of globular cluster stars from the main sequence

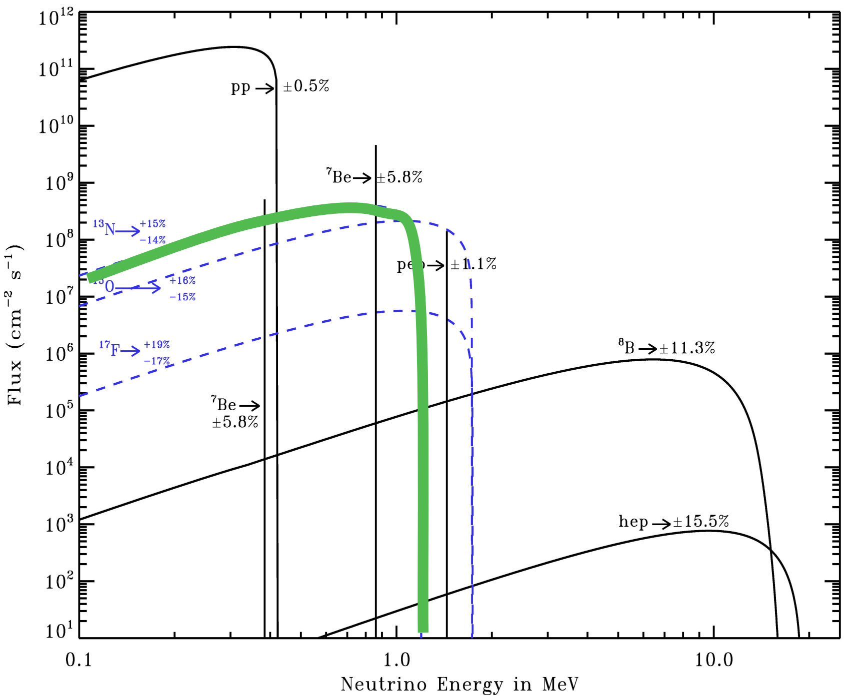
→ Lower CNO rate leads to higher derived age for a given globular cluster

→ Independent lower limit for the age of the universe of 14±2 Ga

^{13}N neutrinos and the ^{12}C(p,γ)^{13}N and ^{14}N(p,γ)^{15}O reactions

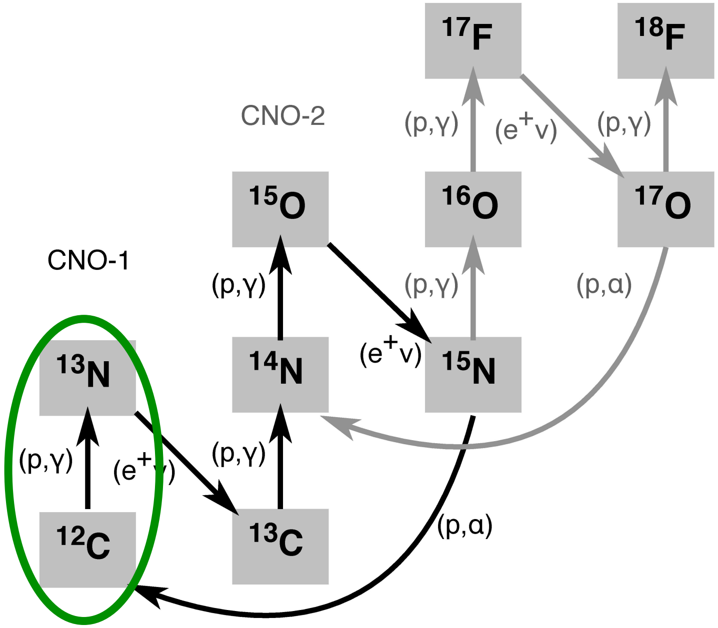
- Q(β⁺, ^{13}N) = 2.220 MeV
- Lifetime $\tau(^{12}C)$ in the solar center 10^6 a << $\tau(^{14}N)$
- ^{13}N emission in the solar center determined by ^{14}N(p,γ)^{15}O rate
- $$\frac{\partial \ln \Phi_{\nu(\text{N-13})}}{\partial \ln S[^{14}\text{N}(p,\gamma)^{15}\text{O}]} = 0.75$$

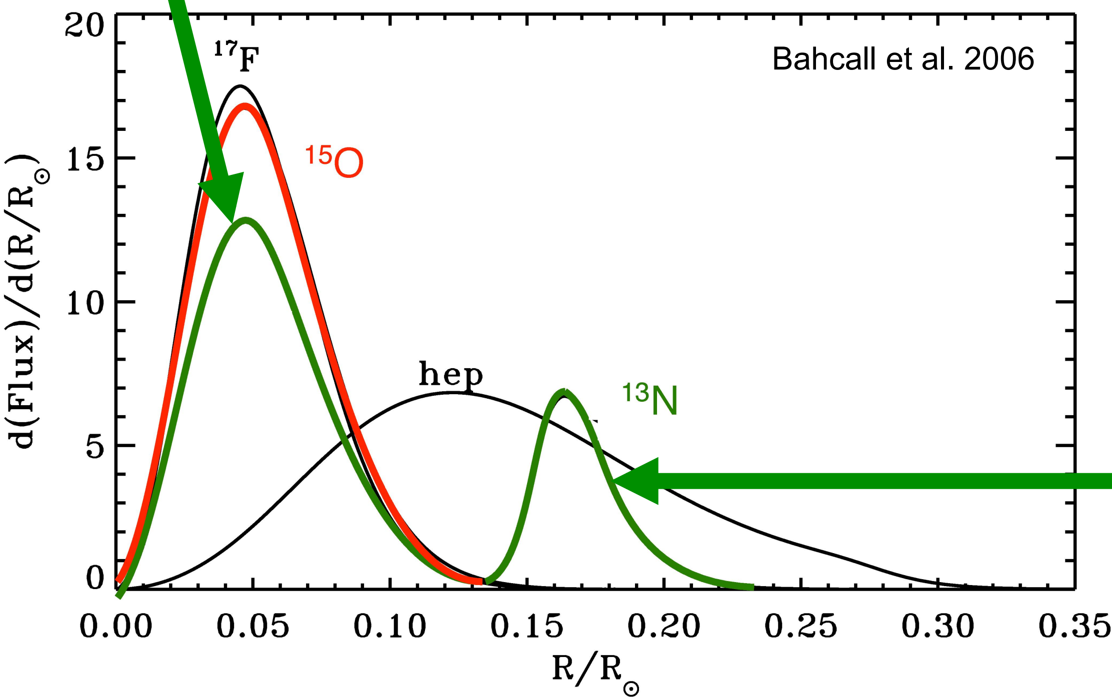




Double-peaked source distribution for ^{13}N neutrinos

- Center of the Sun, T = 16 MK
- Lifetime $\tau(^{12}C) = 7 * 10^5$ a << $2 * 10^8$ a = $\tau(^{14}N)$
- ^{12}C in the solar center is quickly converted to ^{14}N, and CNO cycle reaches equilibrium
- ^{13}N neutrino emission at the center of the Sun is determined by the $^{14}N(p,\gamma)^{15}O$ rate





- R/R_O~0.16, T = 12 MK
- $\tau(^{12}C) = 2 * 10^8$ a
- $\tau(^{14}N) = 10^{11}$ a >> age of the Sun
- CNO cycle never reaches equilibrium
- ^{13}N neutrino emission at R/R_O~0.16 depends on $^{12}C(p,\gamma)^{13}N$ rate

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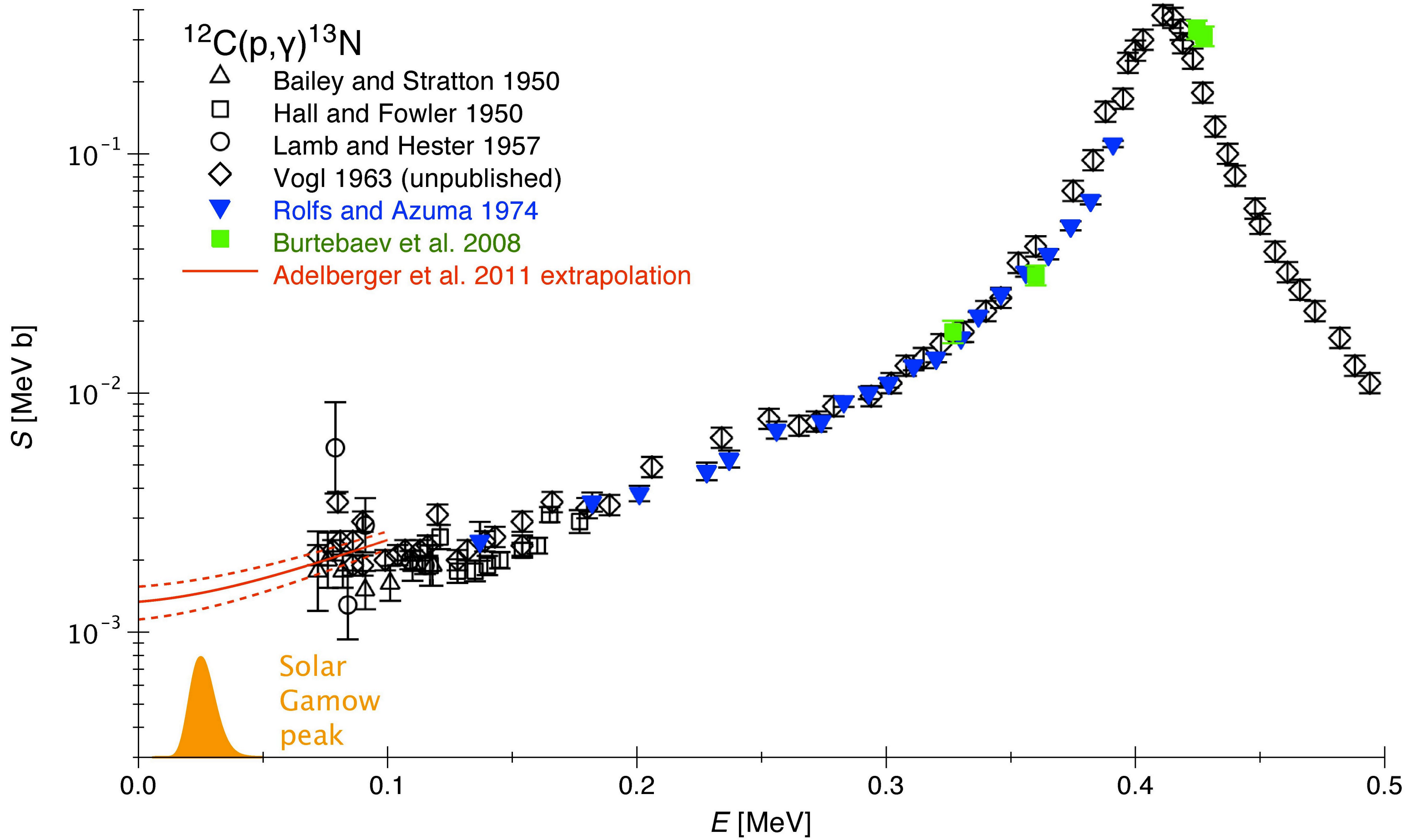
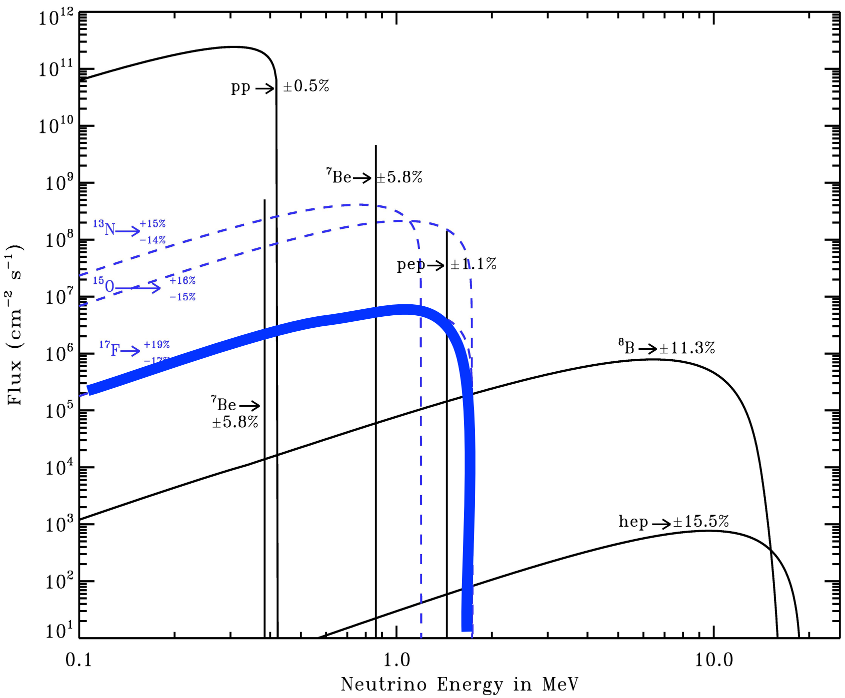
The $^{12}C(p,\gamma)^{13}N$ reaction, starting point of the CNO cycle

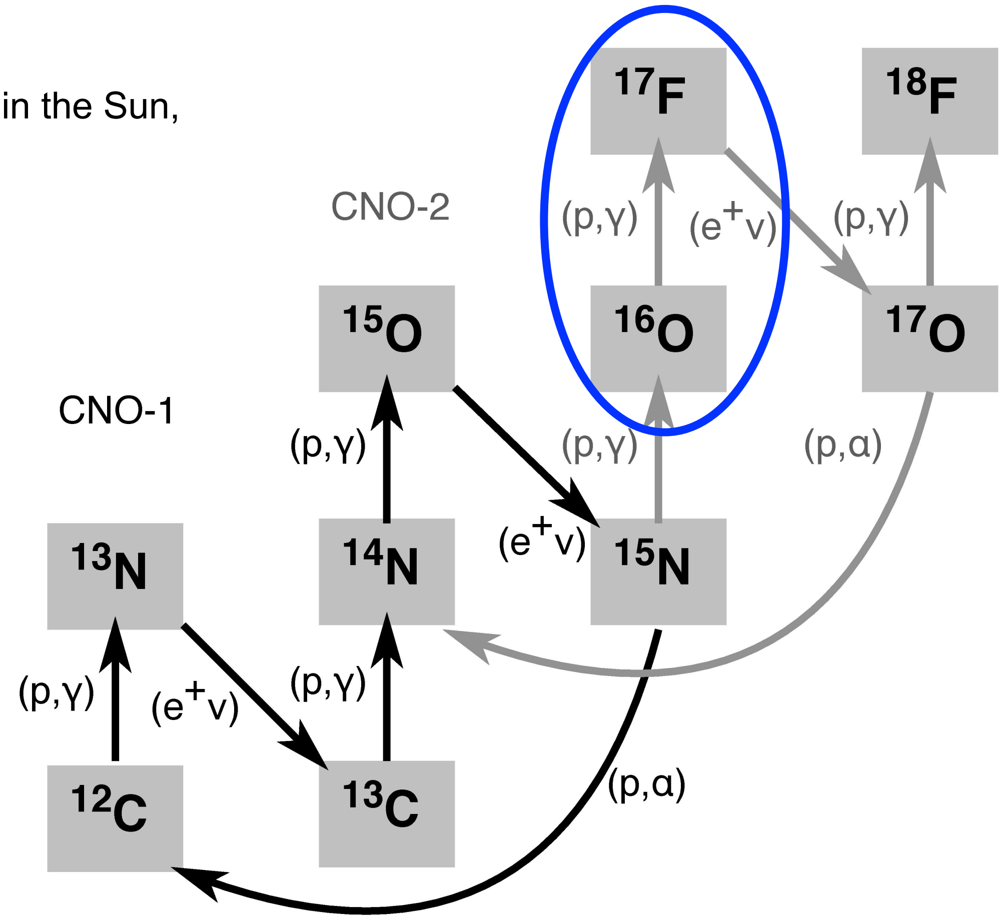


- No experimental data at or near the solar Gamow peak
- Existing data near E = 0.1 MeV are from the 1950's
- Adelberger *et al.* 2011 cites 17% uncertainty
- New data at low and high energy are needed!

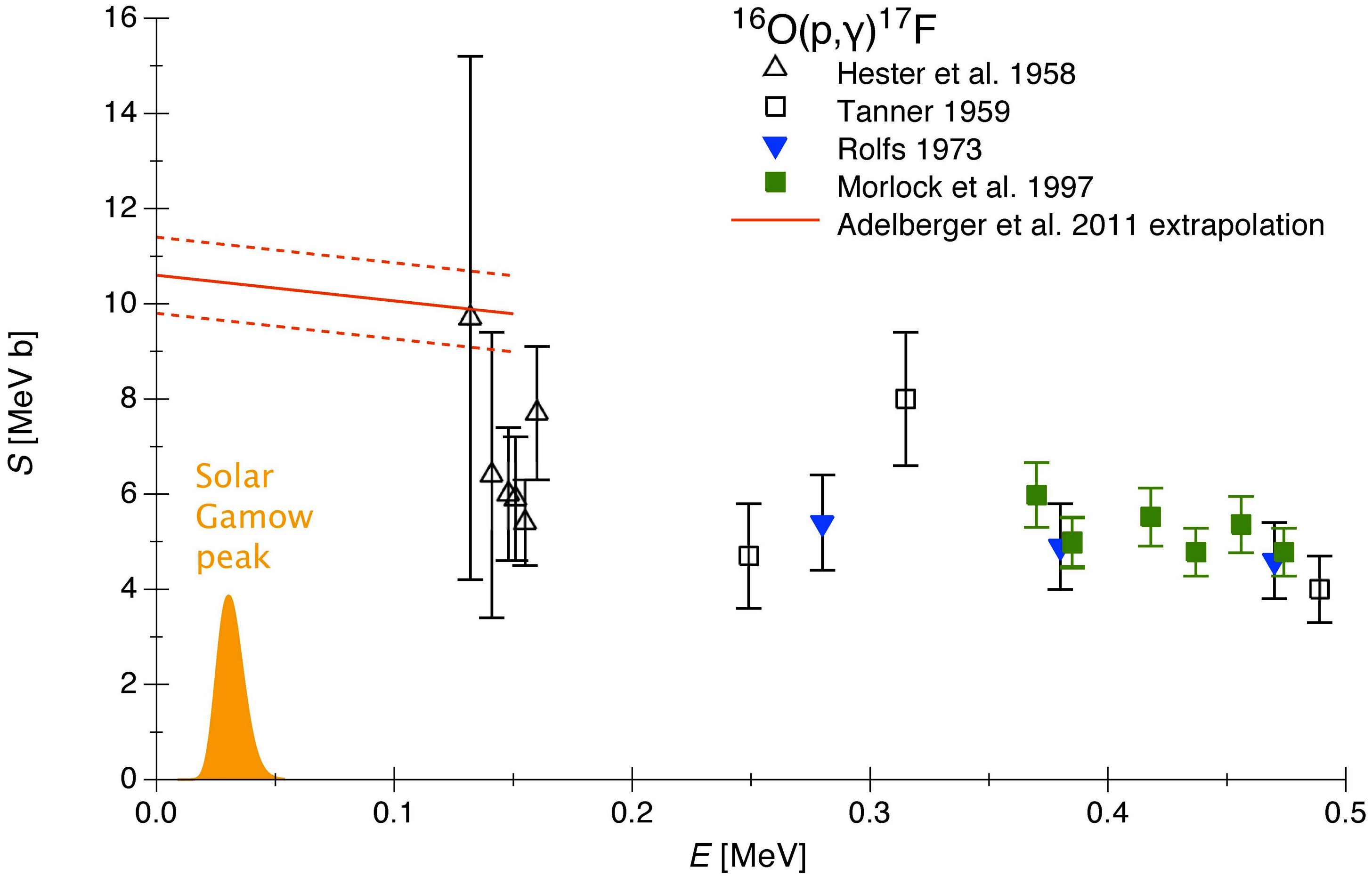
^{17}F neutrinos and the $^{16}O(p,\gamma)^{17}F$ reaction (1)

- $Q(\beta^+, {}^{17}F) = 2.761$ MeV – very close to ^{15}O Q-value
- Lifetime $\tau(^{16}O) = 2 \cdot 10^{10}$ a > age of the Sun
- ^{16}O supply is dominated by ^{16}O pre-existing in the Sun, independent of CNO-1 cycle
- ^{17}F emission in the solar center determined by $^{16}O(p,\gamma)^{17}F$ reaction rate





^{17}F neutrinos and the $^{16}O(p,\gamma)^{17}F$ reaction (2)

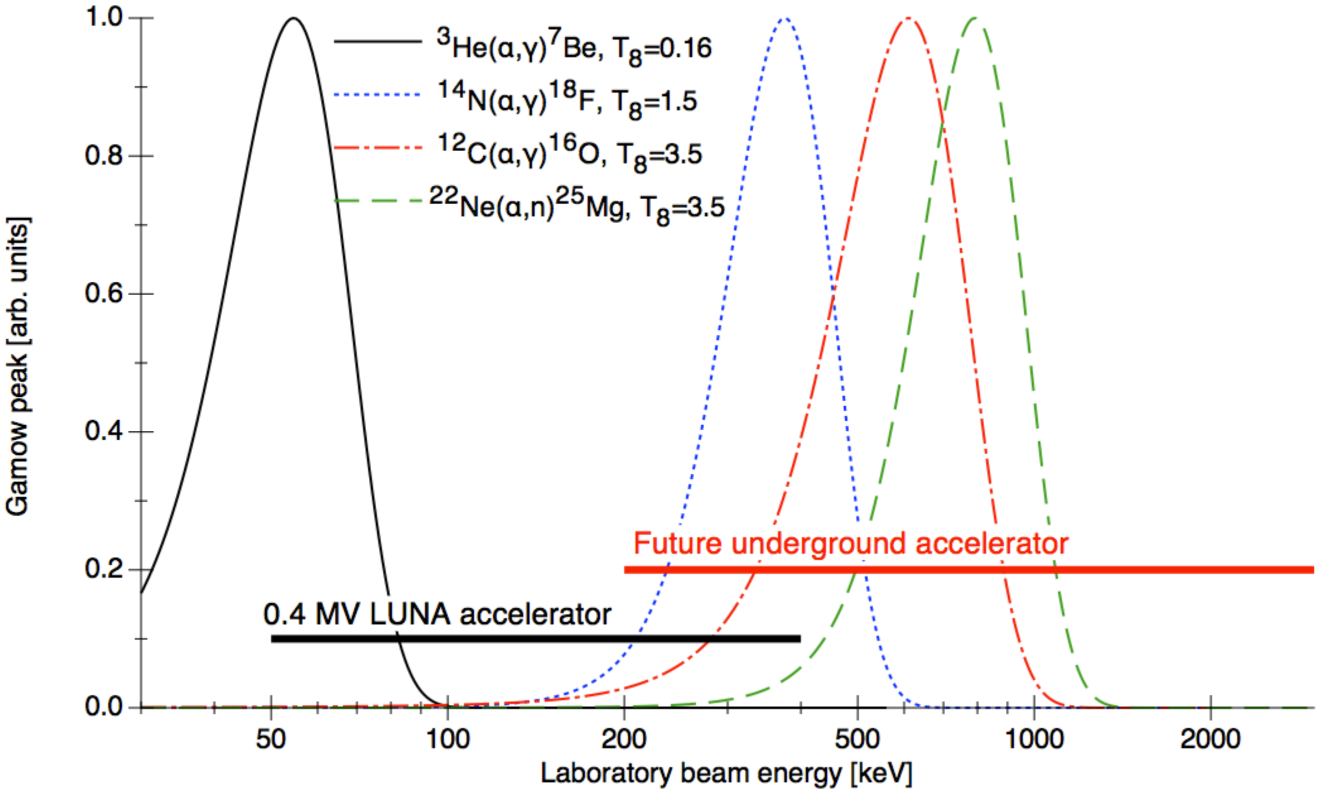


- No experimental data at the solar Gamow peak
- High-energy data are extrapolated using direct-capture model
- Adelberger et al. 2011 cites 8% uncertainty
- Measurable impact only if ^{17}F and ^{15}O neutrinos can be separated
- New data at low and medium energy needed!

Nuclear reactions, solar neutrinos, and the importance of the CNO cycle

1. Which nuclear reactions take place in the Sun?
2. Can solar neutrinos address the solar abundance problem?
3. The nuclear physics of the proton-proton chain (pp chain)
4. The nuclear physics of the carbon-nitrogen-oxygen cycle (CNO cycle)
5. The science case for new underground accelerators

Motivation for a higher-energy underground accelerator



Stellar energy range (Gamow peak) for selected α-induced reactions

- 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!

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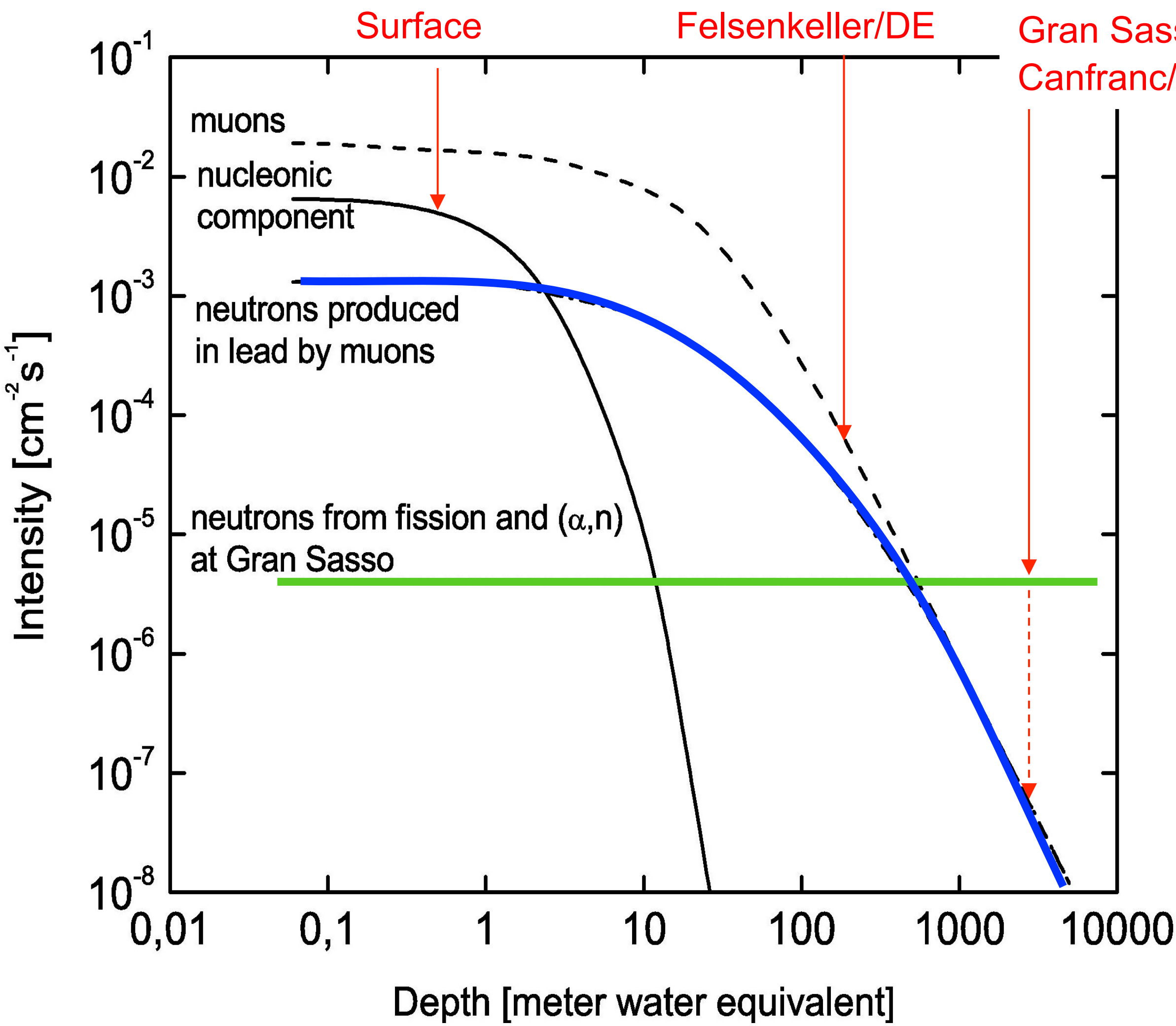
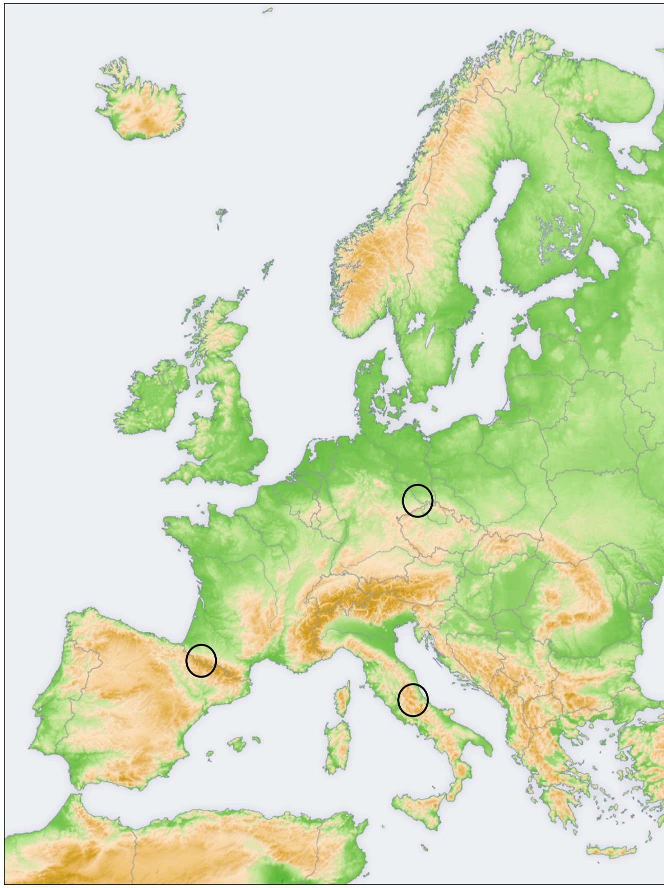
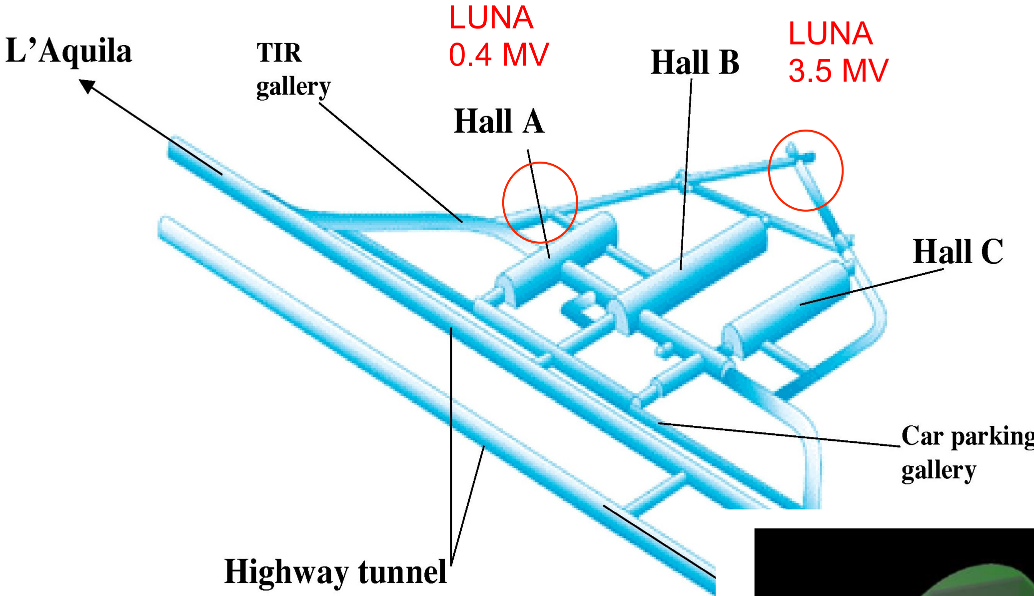
Rock overburdens for new underground accelerators





United States: DIANA (formerly part of DUSEL)
China
South America

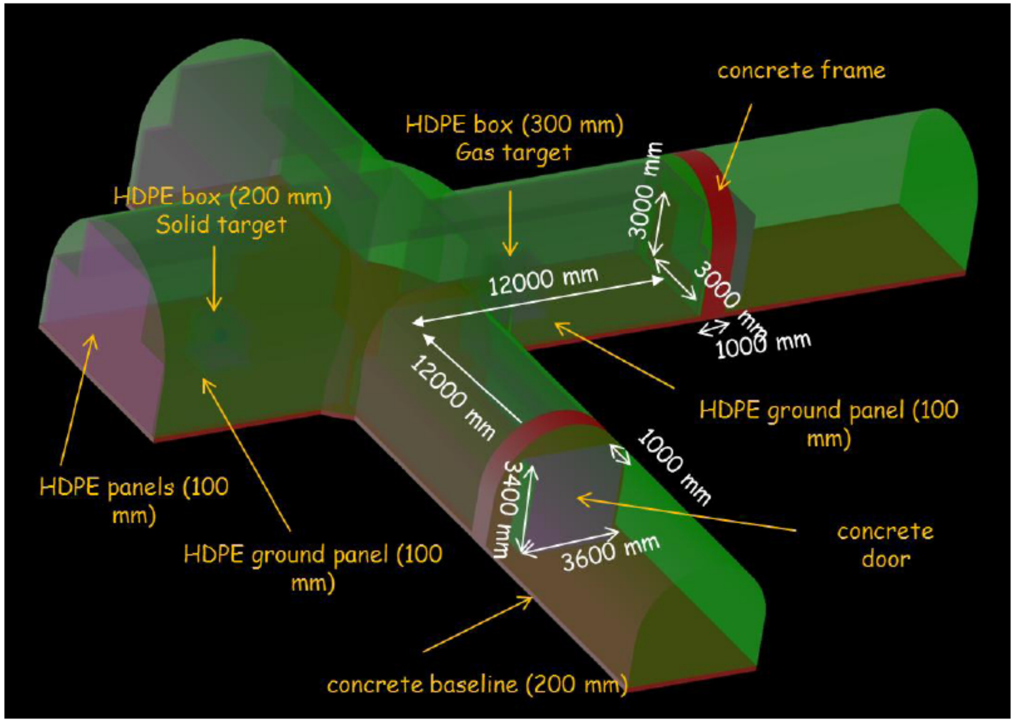
Gran Sasso / Italy: LUNA-upgrade 3.5 MV accelerator



Italian government approved 2.8 M€ for purchasing a 3.5 MV single-ended accelerator, with RF ion source (2012).

Collaboration-building workshop at Gran Sasso, 6-8 February 2013:

http://luna-mv.lngs.infn.it

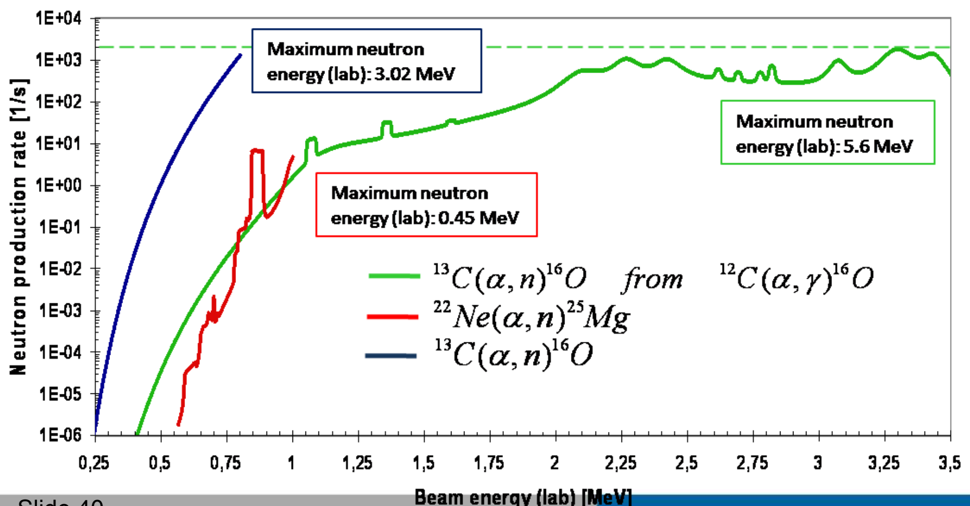


Scientific program:

- 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 sources for the astrophysical s-process

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

$^{13}C(\alpha,n)^{16}O$	$^{22}Ne(\alpha,n)^{25}Mg$	$^{13}C(\alpha,n)^{16}O$ from $^{12}C(\alpha,\gamma)^{16}O$
α beam intensity: 200 μA Target: ^{13}C, 2 10^{17}at/cm^2 (99% ^{13}C enriched) Beam energy(lab) ≤ 0.8 MeV	α beam intensity: 200 μA Target: ^{22}Ne, 1 10^{18}at/cm^2 Beam energy(lab) ≤ 1.0 MeV	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
- 1m thick borated polyethylene shielding will be added on all sides (also against the rock)
- Additional neutron flux outside LUNA-MV will be <1% of ambient neutron flux

Dresden, former Felsenkeller brewery

- Existing γ-counting facility
- Additional space available underground
- Background 3 times worse than LUNA
- Great interest by students and the public

- 12-year old, working 5 MV accelerator
- Bought off an insolvent spin-off of York Univ.
- 250 µA upcharge current (double pellet chains)
- Two Cs sputter ion sources: 100 µA H^- and C^-
- Well-suited for low-energy nuclear astrophysics

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 OK
- Educational tool to teach low-background methods and maintain nuclear competence
- We hope to have it available end of 2013!

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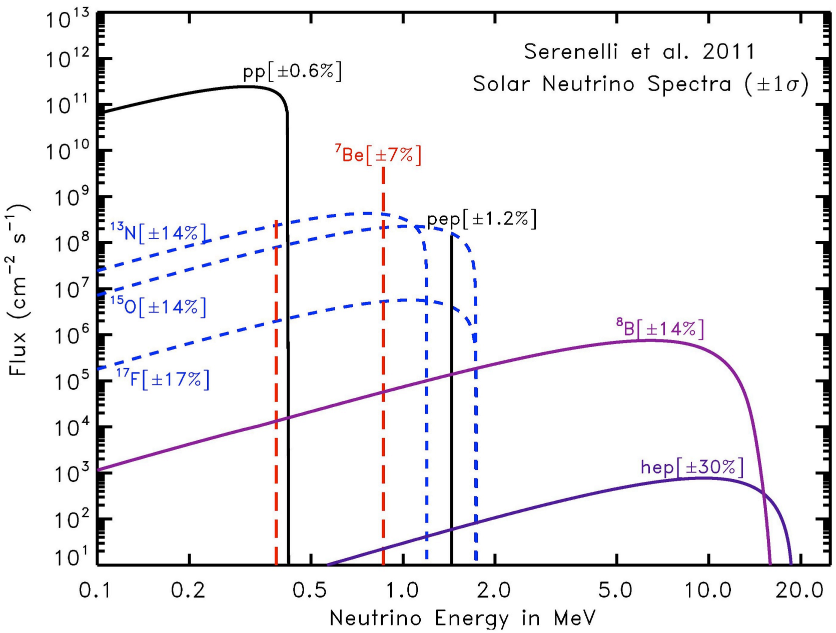
Nuclear reactions, solar neutrinos, and the importance of the CNO cycle

- New nuclear reaction data are necessary for pp-chain and CNO-cycle, as a precondition to solve the solar abundance problem
- Precision studies of light, stable-ion nuclear reactions require intensive ion beams in a low-background environment
- Underground Mega-ton neutrino detectors need underground Mega-volt accelerators



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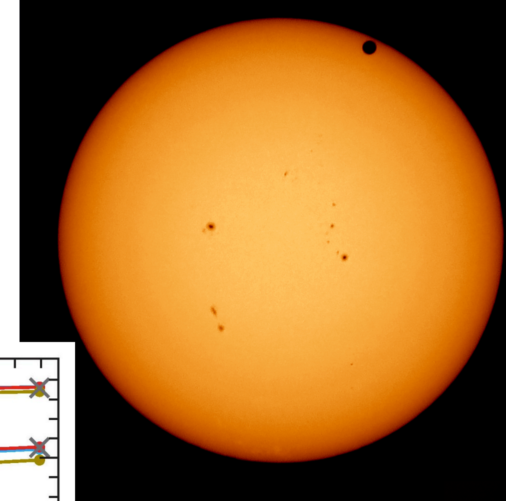
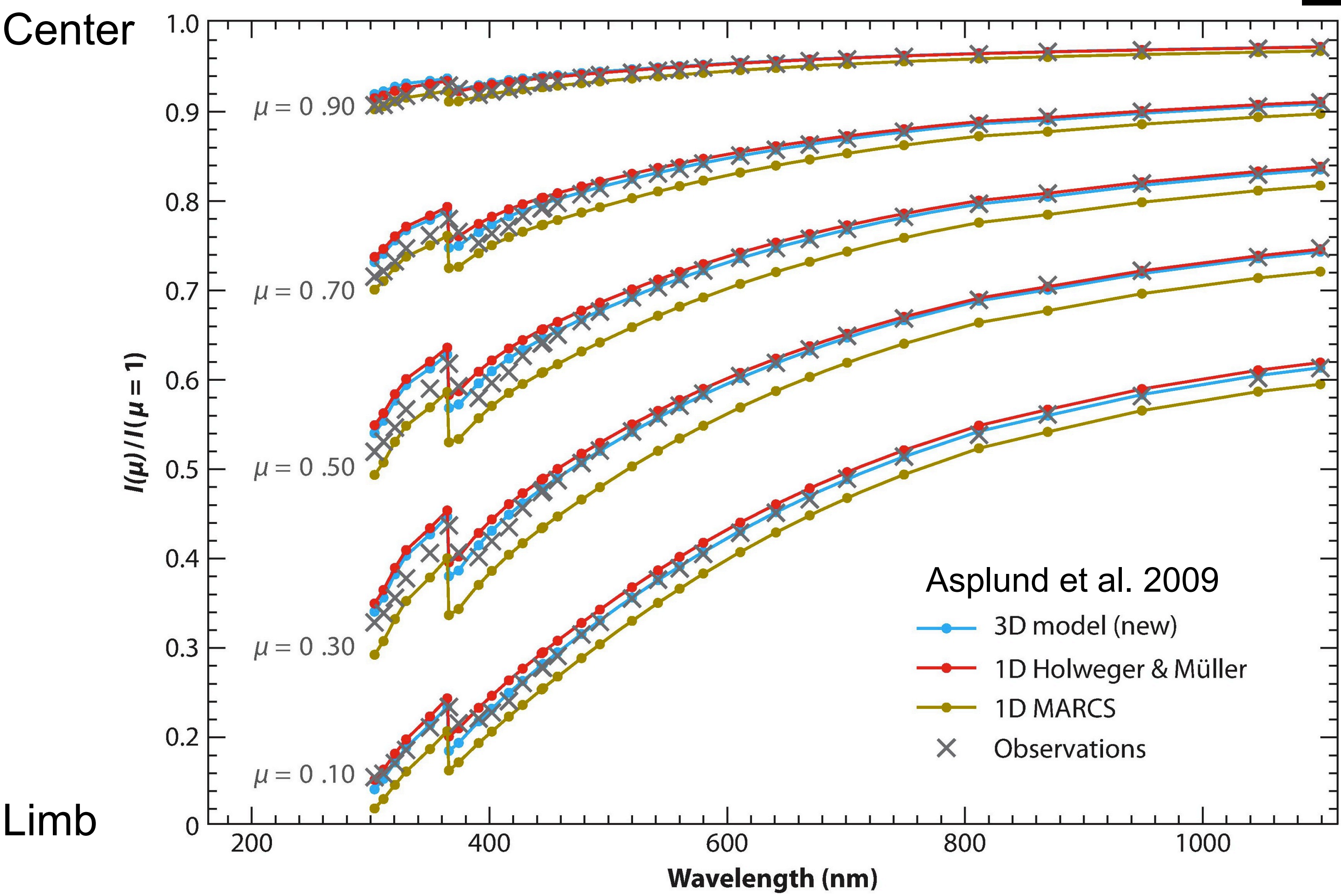
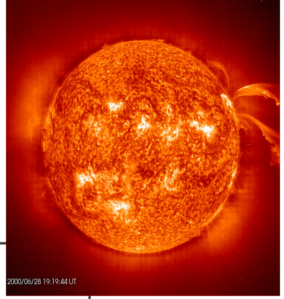
Backup slides

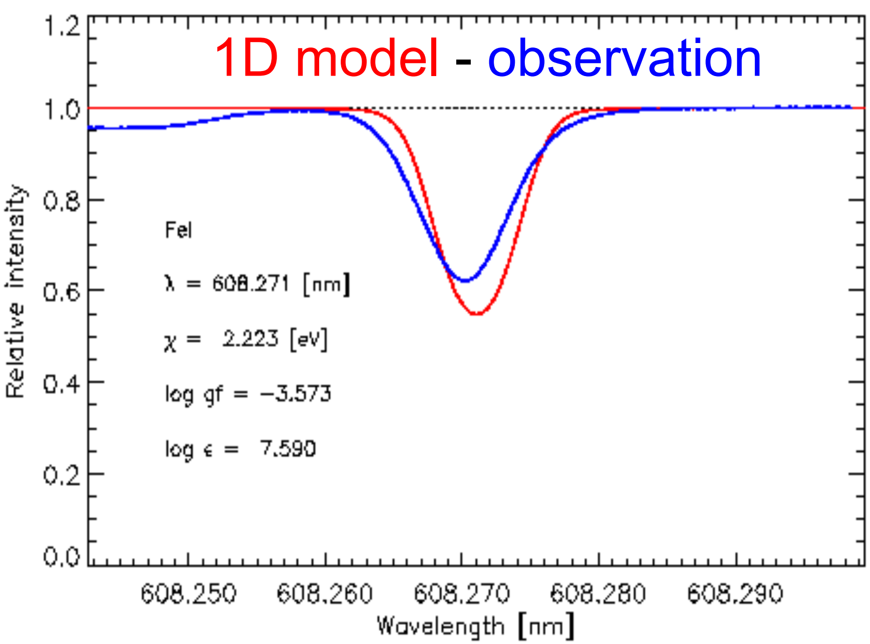
3D versus 1D model atmospheres: Center to limb variation in intensity

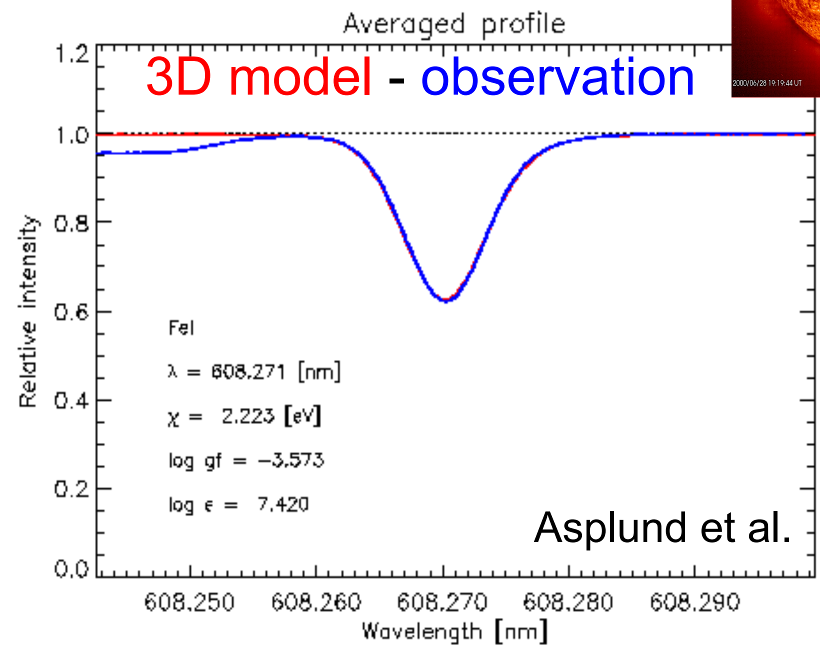




Data on the Sun (2): Elemental abundances
from the model-based interpretation of the Fraunhofer lines







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)

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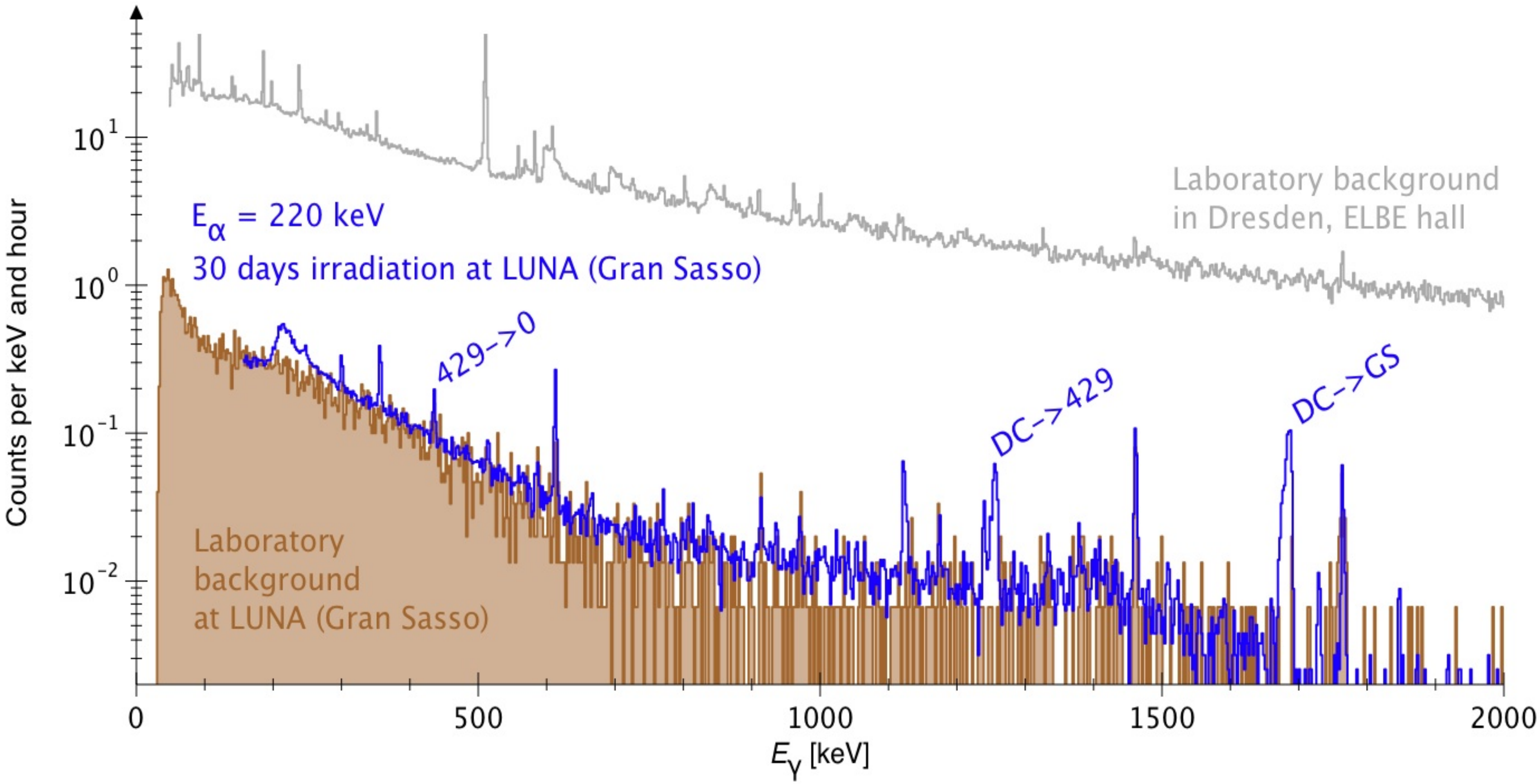
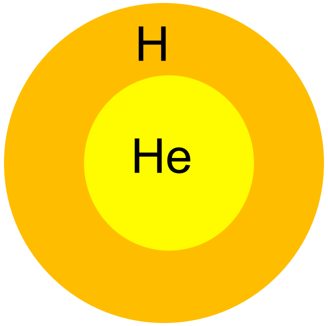
$^3He(\alpha,\gamma)^7Be$ at LUNA, in-beam γ-spectra



Stellar helium burning

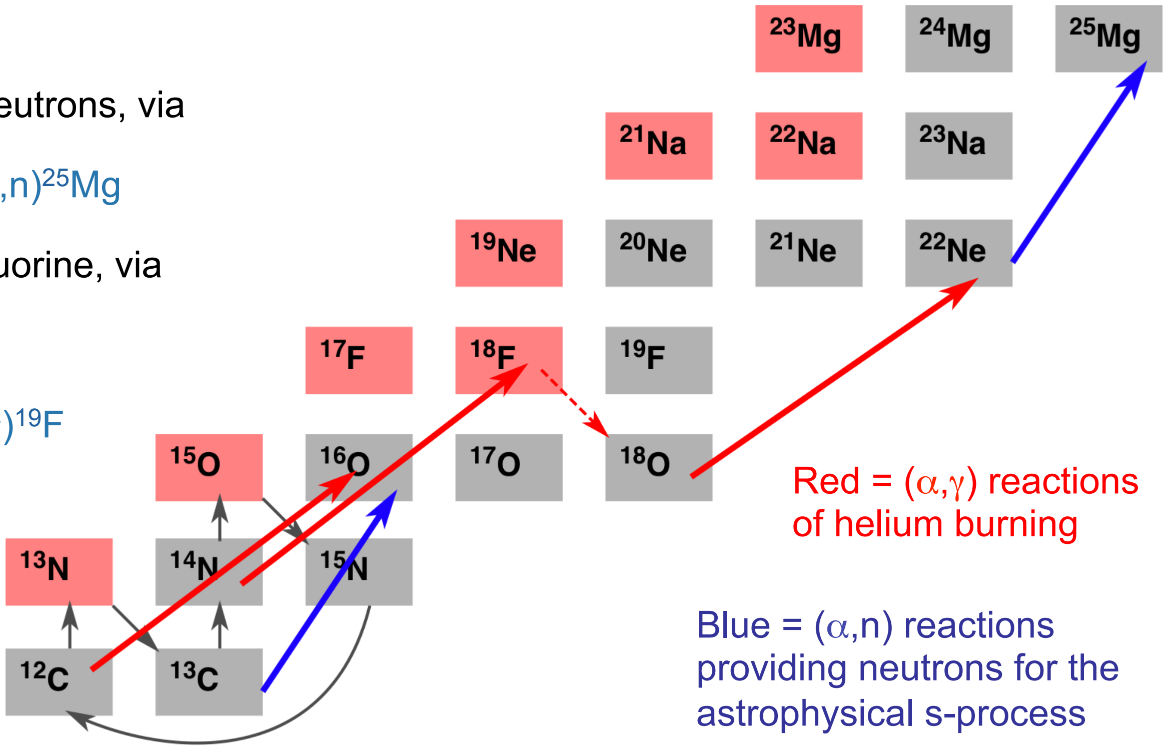


- After exhaustion of hydrogen fuel in the core, core helium burning (and shell hydrogen burning) start
- ^{12}C produced by ^{8}Be(α,γ)^{12}C (triple-α reaction)
- ^{12}C destroyed by ^{12}C(α,γ)^{16}O (triple-α reaction)
- Main end products ^{12}C, ^{16}O
- Paves the way for the production of neutrons, via

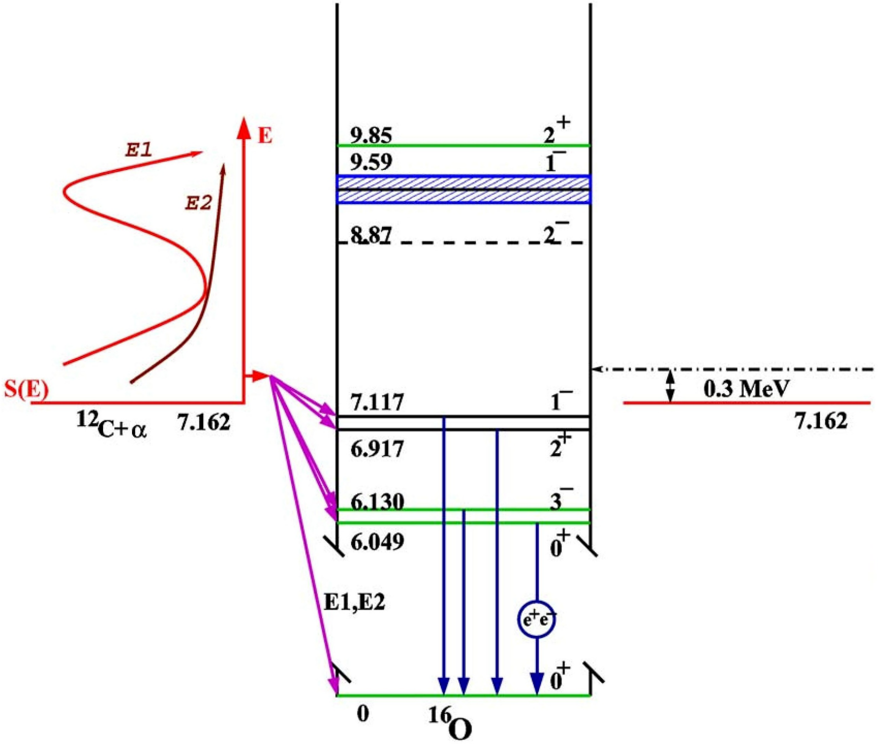
  ^{14}N(α,γ)^{18}F $\rightarrow$ ^{18}O(α,γ)^{22}Ne $\rightarrow$ ^{22}Ne(α,n)^{25}Mg
- Paves the way for the production of fluorine, via

  ^{15}N(α,γ)^{19}F

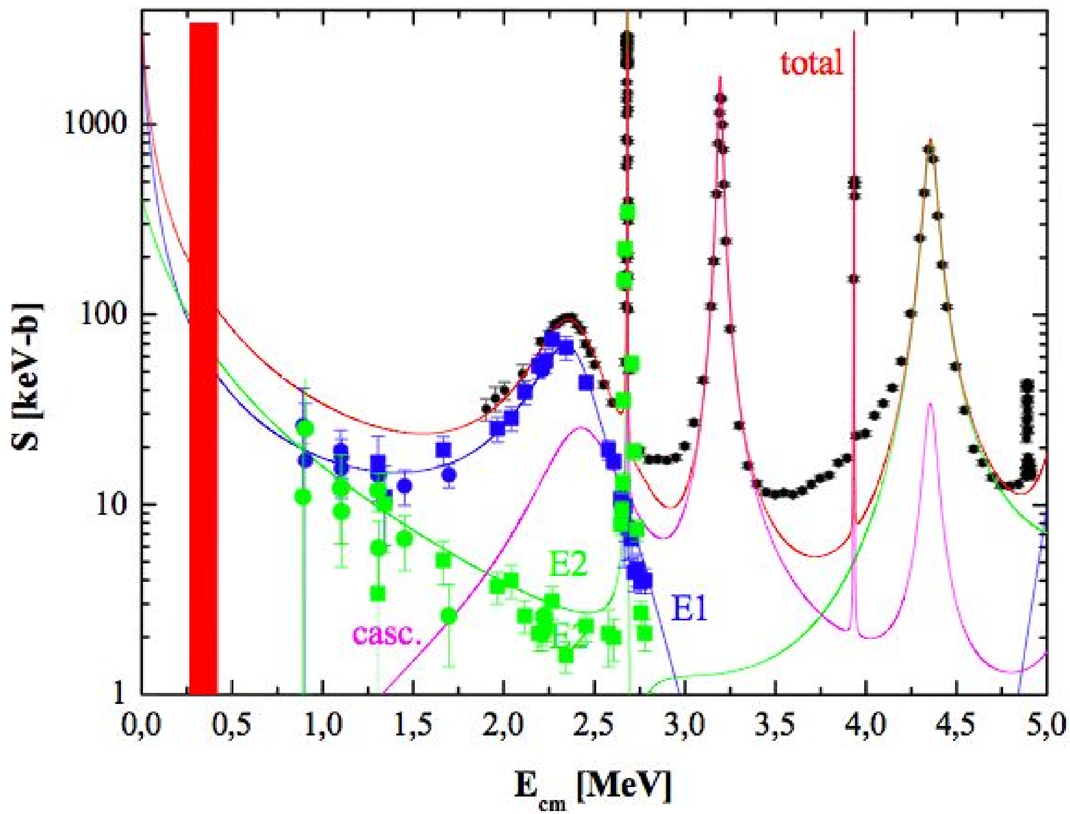
  ^{14}N(α,γ)^{18}F $\rightarrow$ ^{18}O(p,α)^{15}N $\rightarrow$ ^{15}N(α,γ)^{19}F



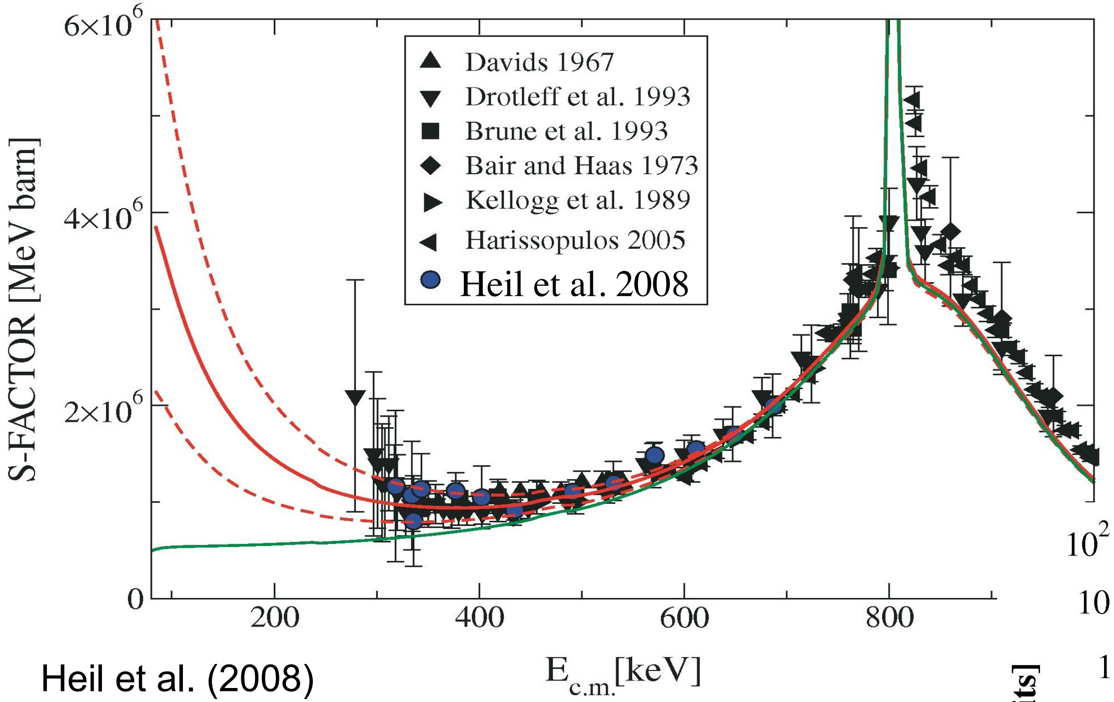
The $^{12}C(\alpha,\gamma)^{16}O$ reaction, determining the $^{12}C/^{16}O$ ratio



Gamow peak for core helium burning



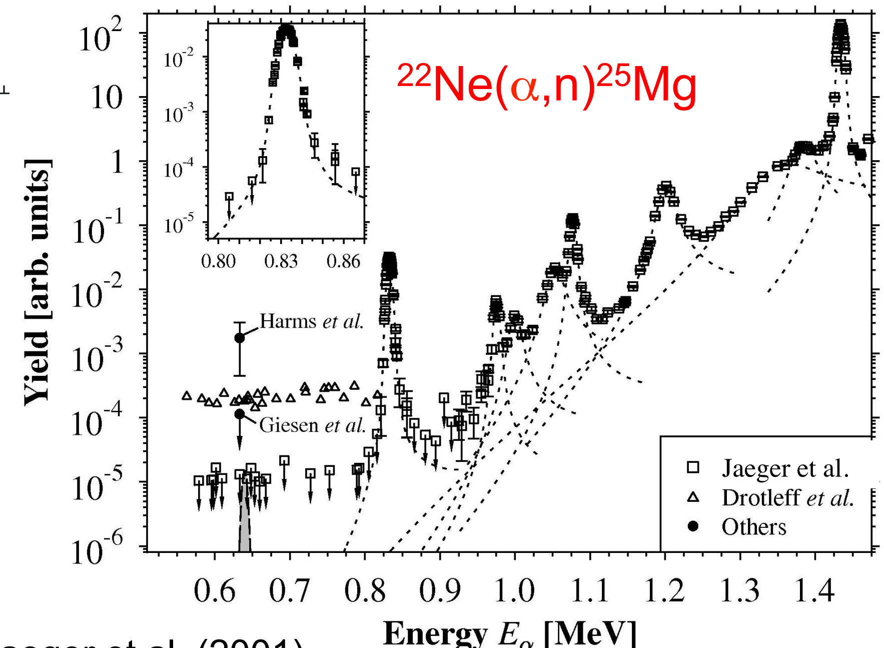
The two astrophysical neutron source reactions



Heil et al. (2008)

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

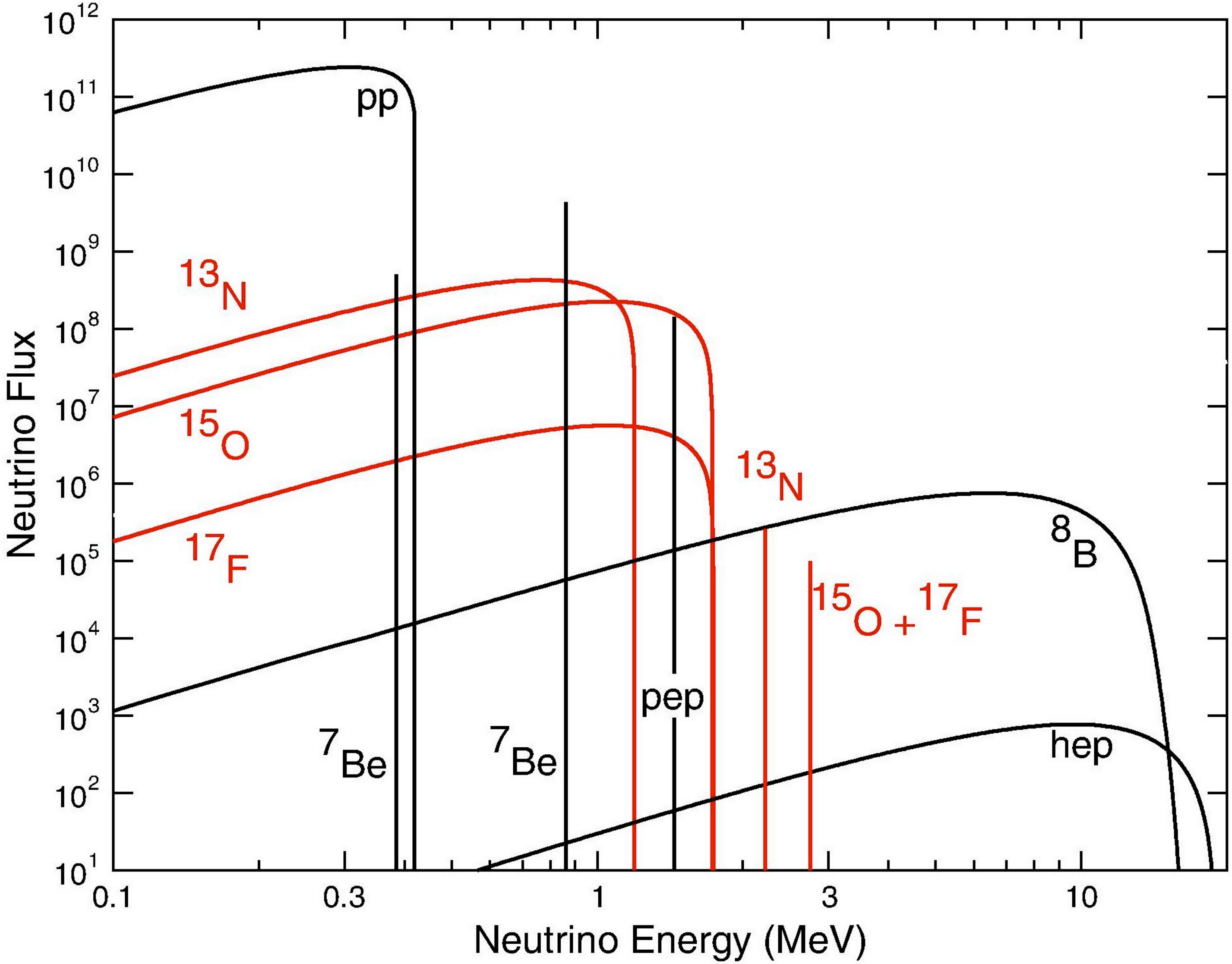
$^{22}Ne(\alpha,n)^{25}Mg$



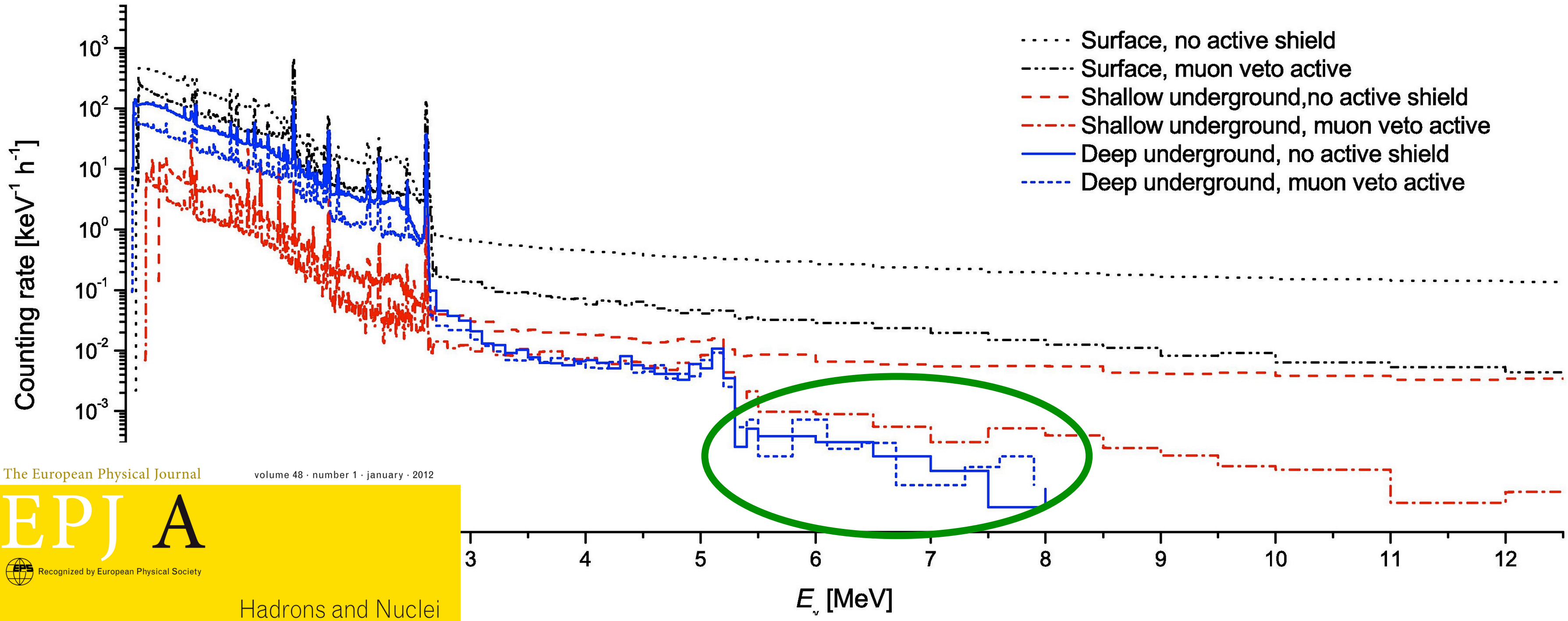
Jaeger et al. (2001)

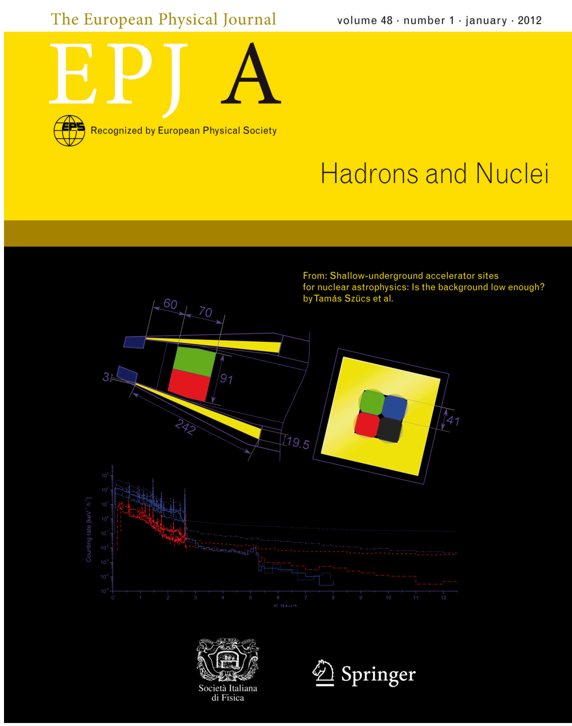
In both cases, high uncertainty for the cross section at low energies, just where it matters for astrophysics!

Electron capture on CNO nuclides (Stonehill et al. 2004)



Background, in a typical HPGe detector for nuclear astrophysics





→ 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)

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$^{40}Ca(\alpha,\gamma)^{44}Ti$ activation experiment, offline spectra from Felsenkeller