Solar neutrinos and LUNA

(Laboratory Underground for
Nuclear Astrophysics)

Seminar DESY, 10.06.2008

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Outline of the talk

- The standard solar model
- LUNA - approaching the Gamow peak
- Hydrogen burning in the Sun
    - Proton-proton-chain: $^{3}\text{He}(\alpha,\gamma)^{7}\text{Be}$ ^{7}Be, ^{8}B neutrinos
    - CNO-cycle: $^{14}\text{N}(p,\gamma)^{15}\text{O}$ ^{13}N, ^{15}O neutrinos
- Hydrogen burning in stars with mass greater than the sun
    - $^{25}\text{Mg}(p,\gamma)^{26}\text{Al}$, $^{15}\text{N}(p,\gamma)^{16}\text{O}$
- Future perspectives

Short review of the standard solar model

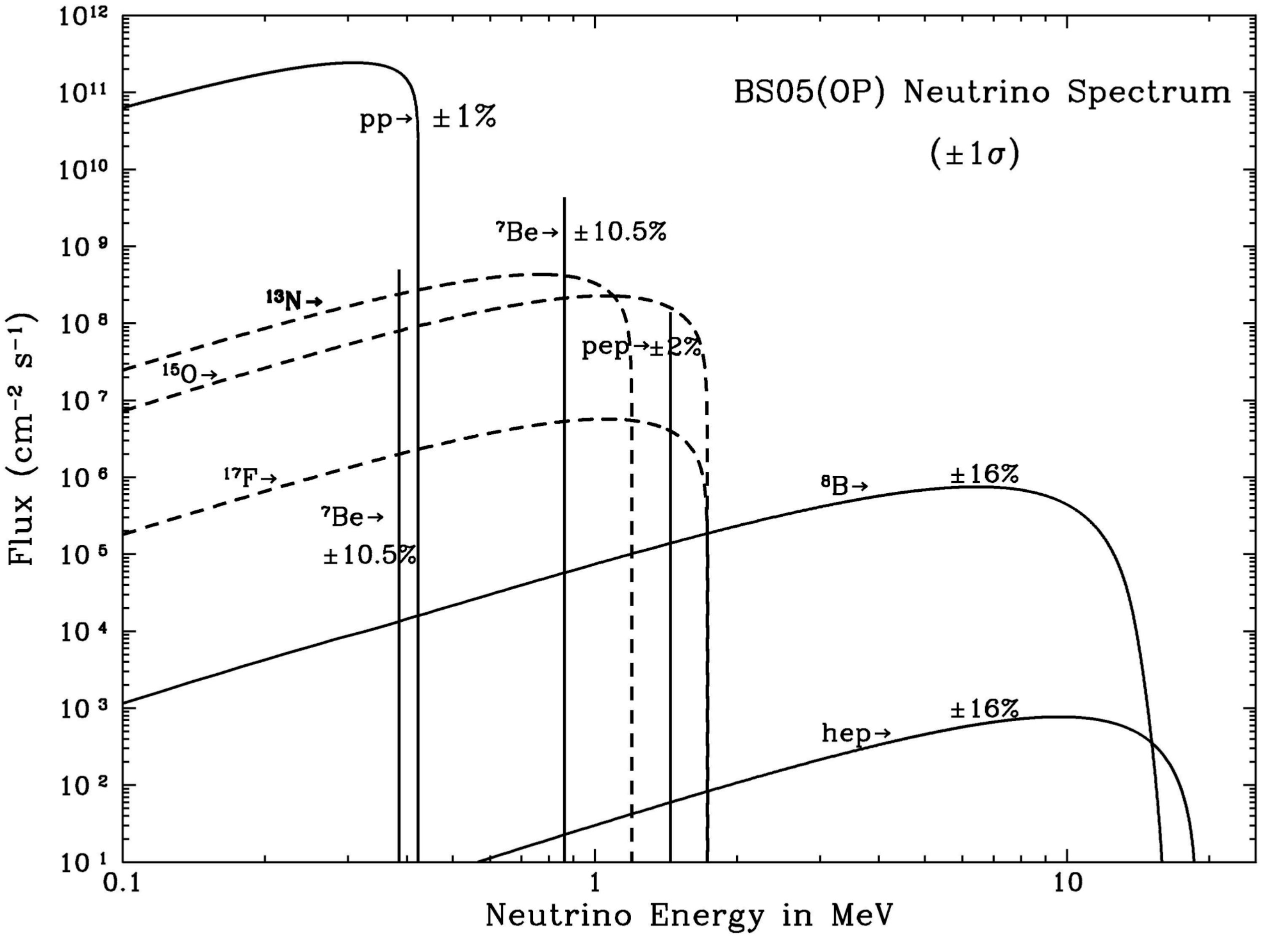
Main parameters:

- Nuclear reaction rates
  (from the laboratory)
- Elemental abundances
  (from the solar atmosphere)
- Luminosity

Main observables:

- Helioseismological data
- Neutrino fluxes

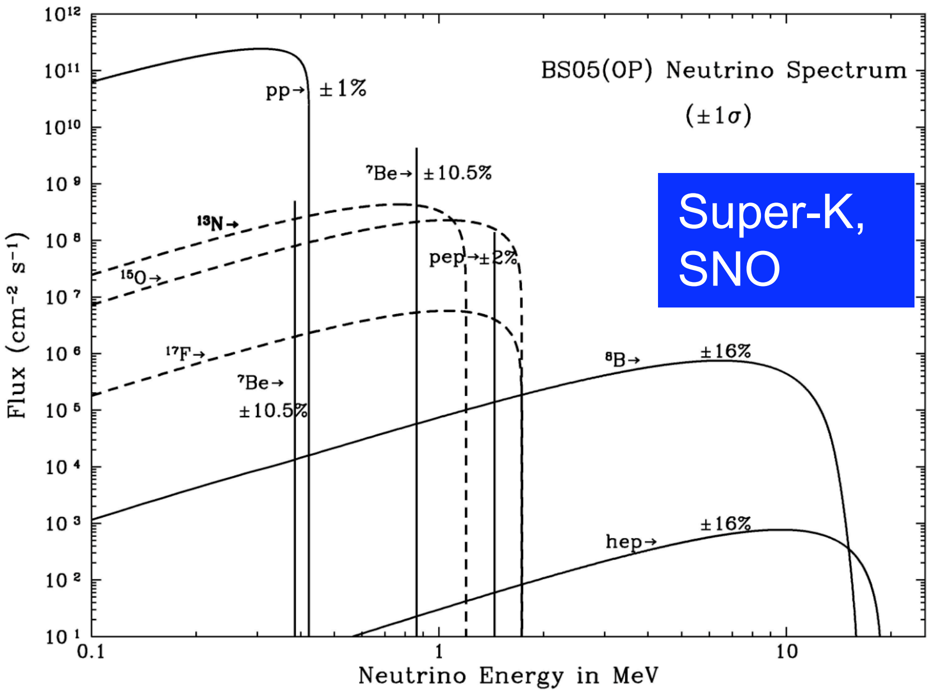
(Bahcall & Serenelli 2005)



Precision test of the solar model: Flux of ^{8}B neutrinos

Super-Kamiokande, based on known oscillation parameters (SNO, KamLAND, ...)

$\Phi(^{8}\mathrm{B}) = 4.91 * 10^{6}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \pm 3.6\%$



Super-K, SNO

Standard solar model:

$\Phi(^{8}\mathrm{B}) = 5.69 * 10^{6}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

± 16% total, resulting from:

± 12% abundances (Asplund 2005)

± 9% nuclear physics (this talk)

± 5% opacity

± 4% diffusion

± 3% luminosity

(Bahcall & Serenelli 2005)

Primary goal of nuclear astrophysics:

- Measure a cross section σ directly at the astrophysically relevant energy!

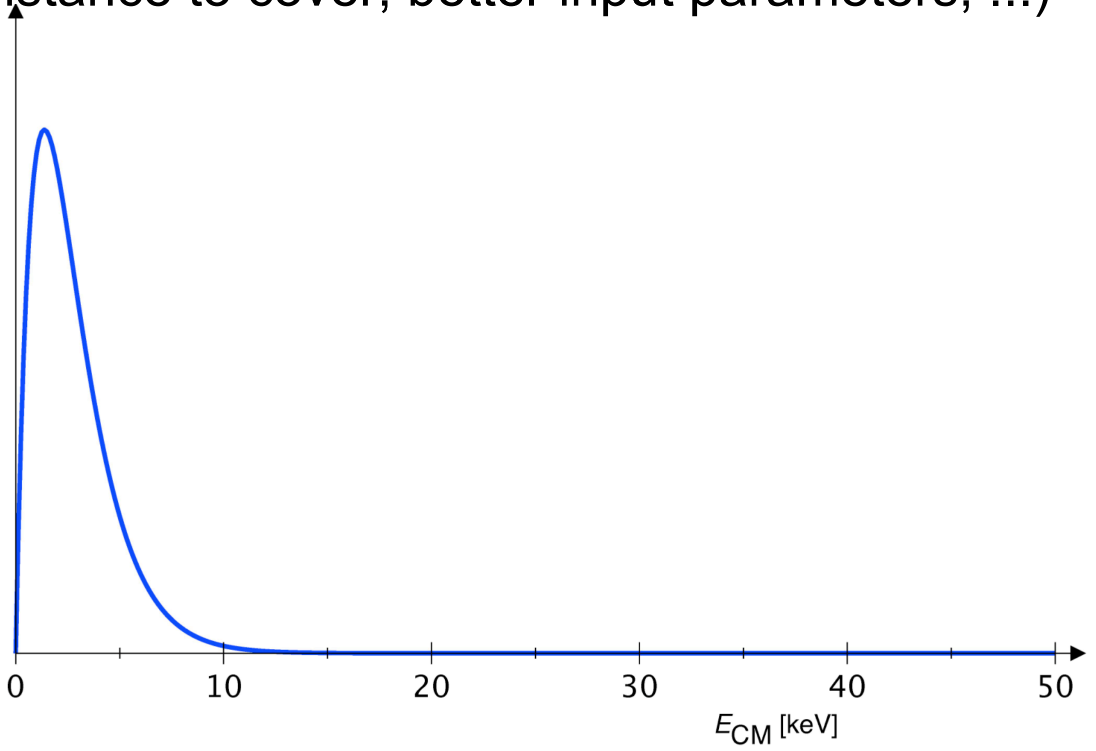
Secondary goal (if primary goal cannot be reached)

- Improve extrapolations (smaller distance to cover, better input parameters, ...)

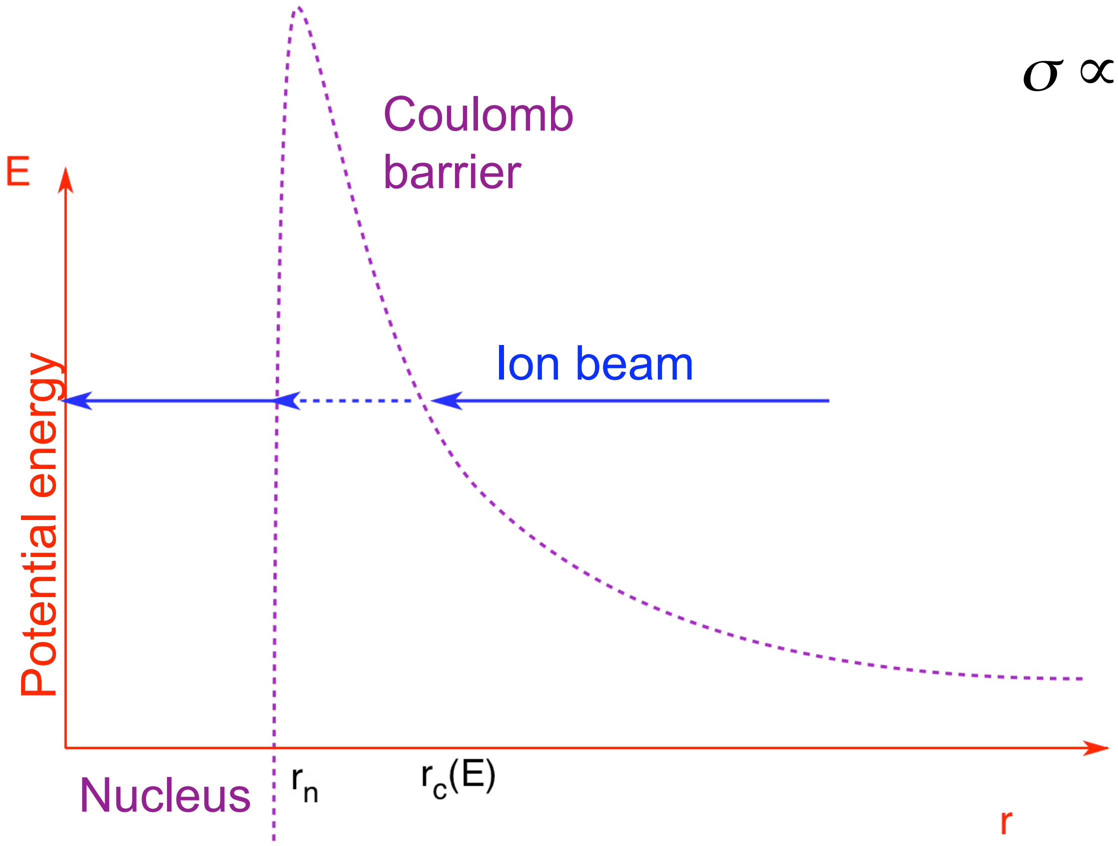
Example: the Sun

$T = 16 * 10^6$ K

Maxwell-Boltzmann distribution



Nuclear reaction cross section σ below the Coulomb barrier



$$\sigma \propto \frac{1}{\sqrt{E}} \boxed{2\pi\eta(E)\, e^{2\pi\eta(E)}} \boxed{S(E)}$$

Coulomb barrier

Nuclear physics

Penetrability (s-waves)

$$2\pi\eta(E) = 2\pi Z_1 Z_2 \alpha \sqrt{\frac{mc^2}{2E}}$$

Typical height of Coulomb barrier: ~ MeV

Typical temperature k_B * T ~ keV

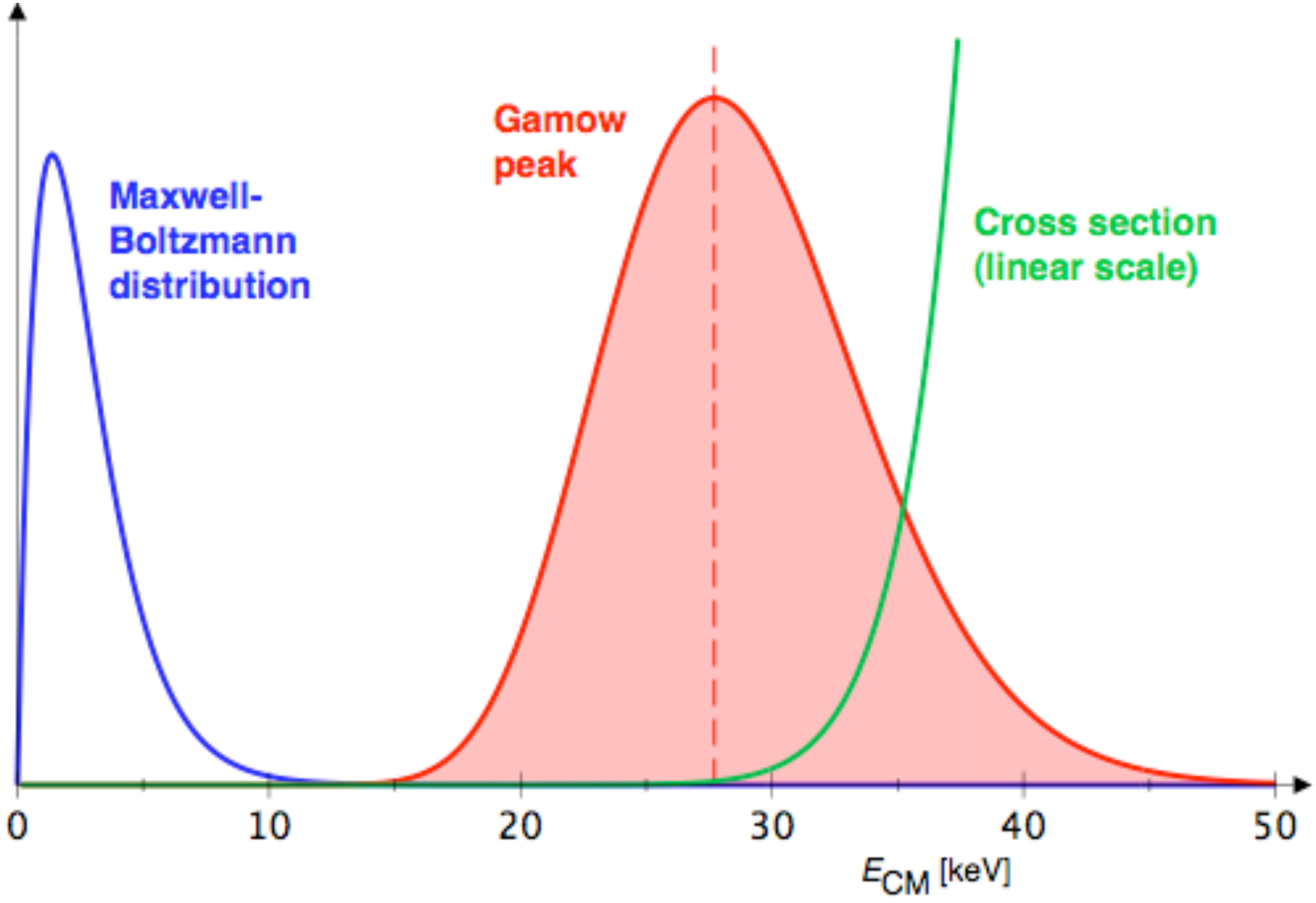
What does this all mean?

→ σ is small

→ σ varies quickly with energy

At which energy do we have to know the cross section σ?

...in the
Gamow peak!



Example: Sun, $T = 16 * 10^6$ K, $^{14}N(p,\gamma)^{15}O$

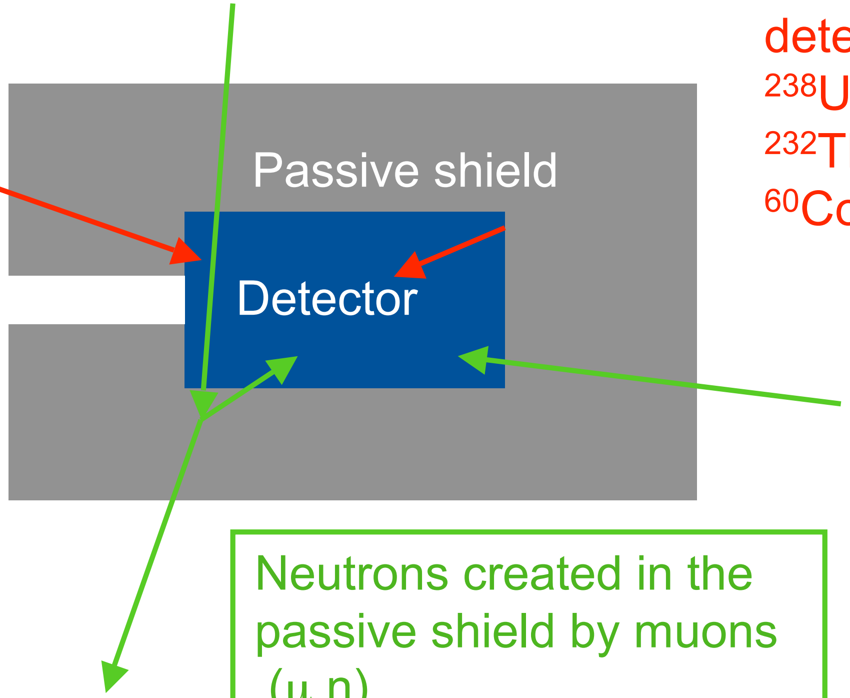
Gamow energy E_G, some examples

Scenario	**Reaction**	**E_G[keV]**	**σ [barn]**	**Detected events/hour**	
Sun (16 MK)	$^3He(\alpha,\gamma)^7Be$	23	10^{-17}	10^{-9}	impossible
	$^{14}N(p,\gamma)^{15}O$	28	10^{-19}	10^{-11}	impossible
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}	planned

1 barn= 10^{-24} cm^2; assume 10^{16} s^{-1} beam, 10^{18} at/cm^2 target, 10^{-2} detection efficiency

Need to measure small cross sections with precision (compare with 3.6% precision in solar neutrino flux Φ_B)!

Low cross section: low laboratory background is needed → What are the sources of laboratory background?



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

Neutrons from outside:
- (α,n) in rock/salt

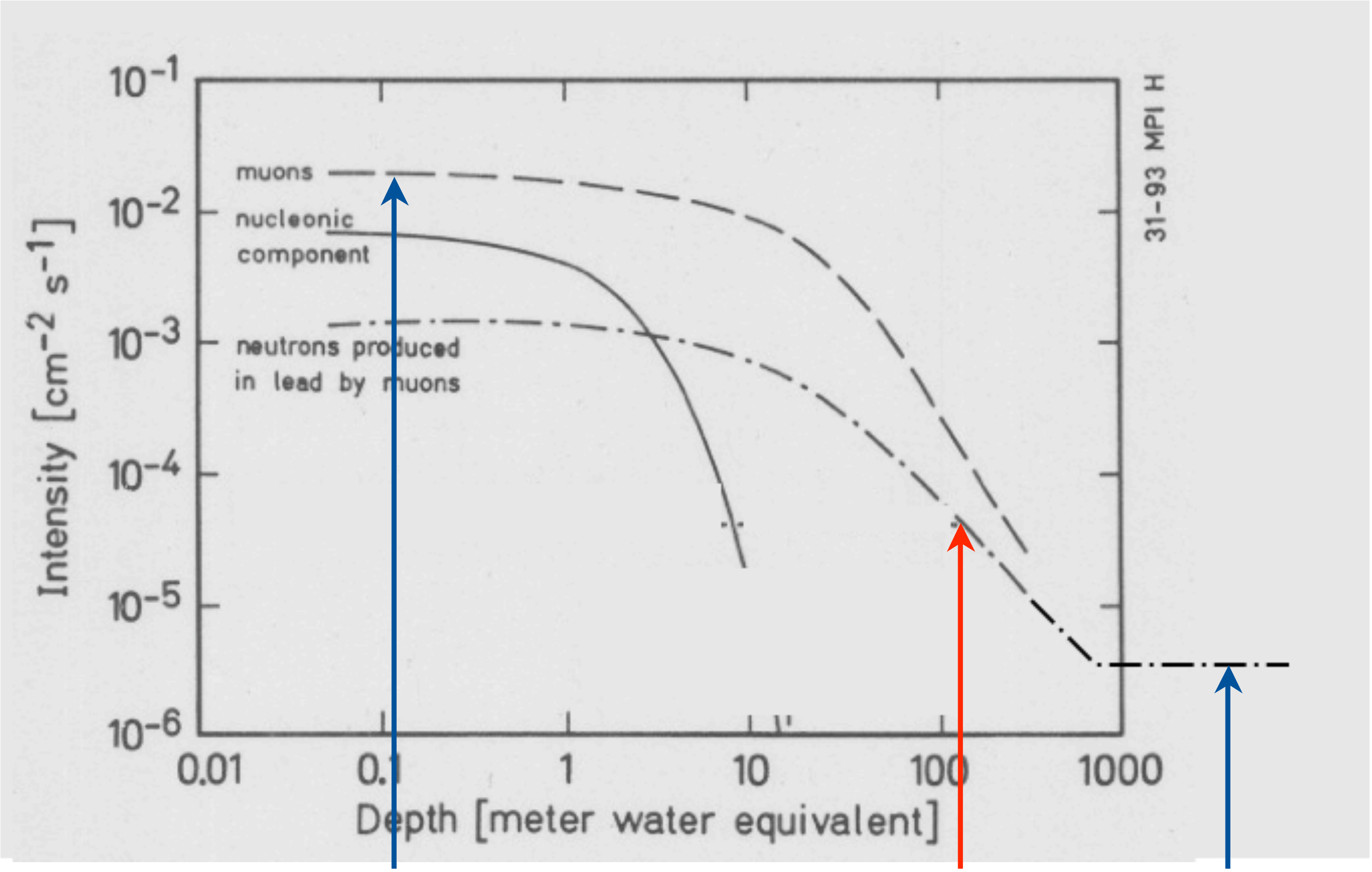
Neutrons created in the passive shield by muons (μ,n)

Red: $E_\gamma < 3$ MeV

Green: $E_\gamma < 3$ MeV and $E_\gamma > 3$ MeV

How to attenuate cosmic rays?

Underground depth measured in mwe = meters water equivalent; 1 m rock = 2.7 mwe



Earth’s surface

Felsenkeller Dresden

Gran Sasso

LUNA = Laboratory underground for nuclear astrophysics at Gran Sasso / Italy

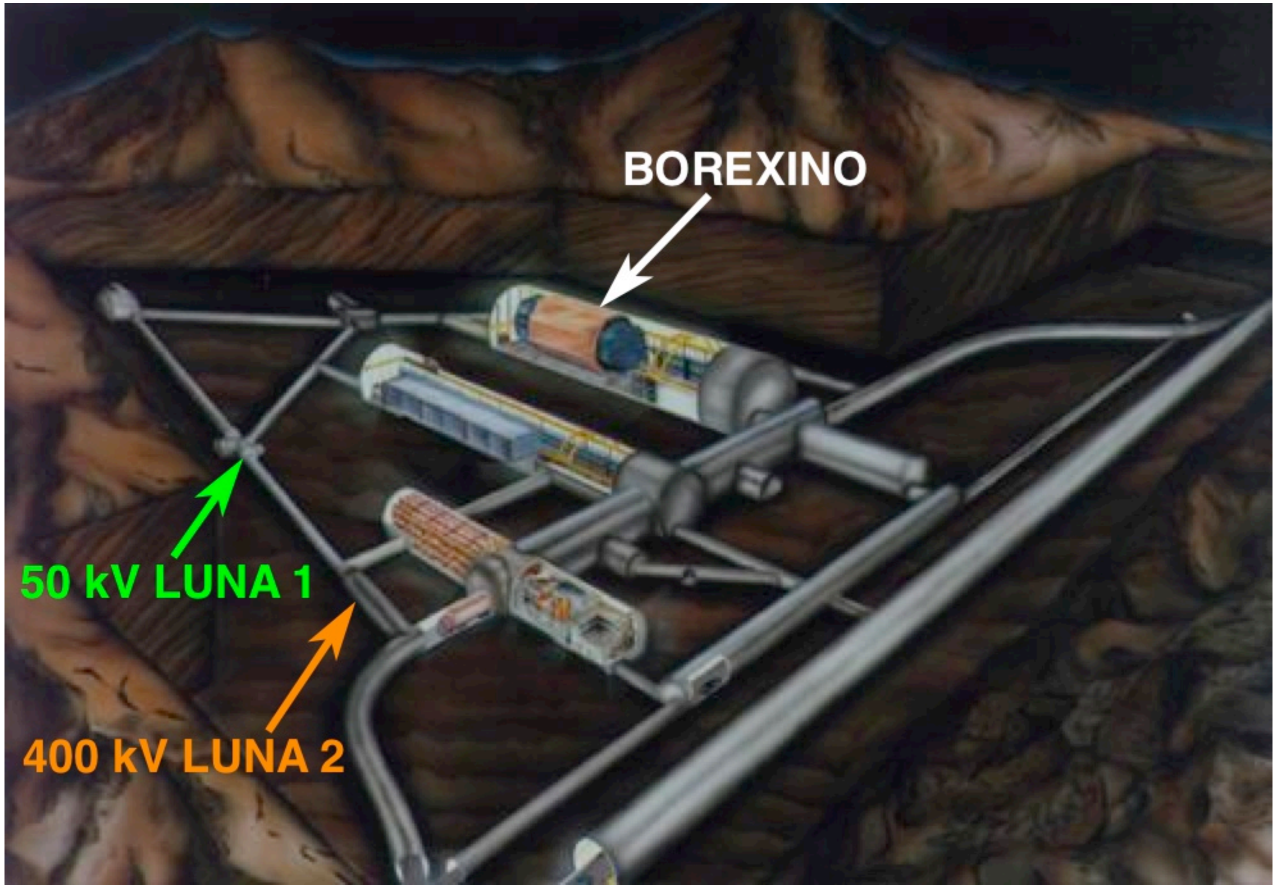
~3400 mwe rock
10^6 μ reduction
10^4 n reduction

150 km from Rome,
motorway access

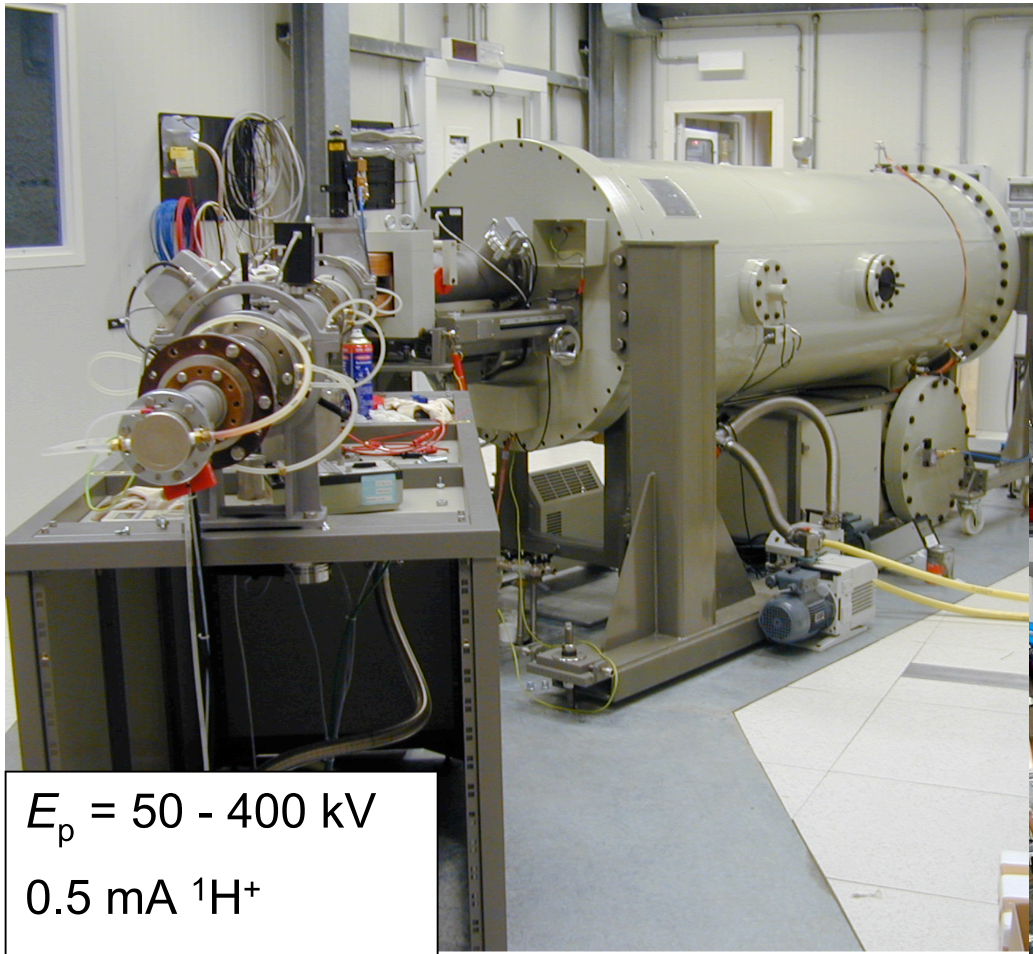
LUNA1, 1992-2001

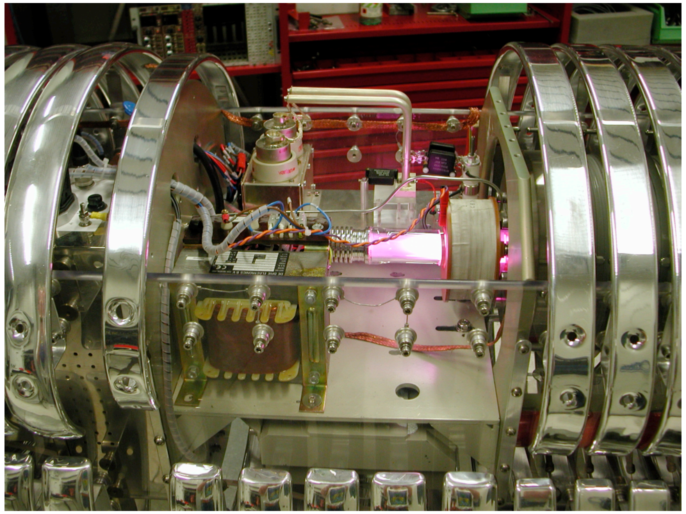
LUNA2, 2000-2012+

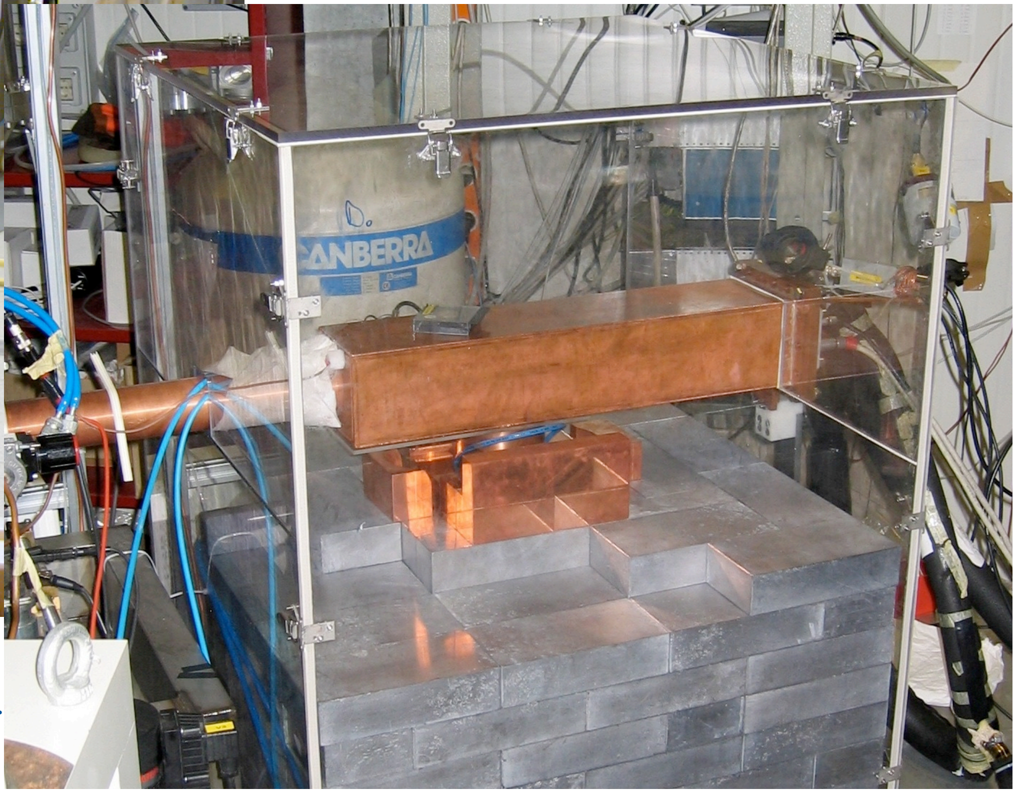
LUNA-MV, under study



Inside the LUNA2 hall







$E_p = 50 - 400$ kV

0.5 mA $^1H^+$

0.3 mA $^4He^+$

Nuclear reactions studied at LUNA

LUNA1, 50 kV, 1992-2001

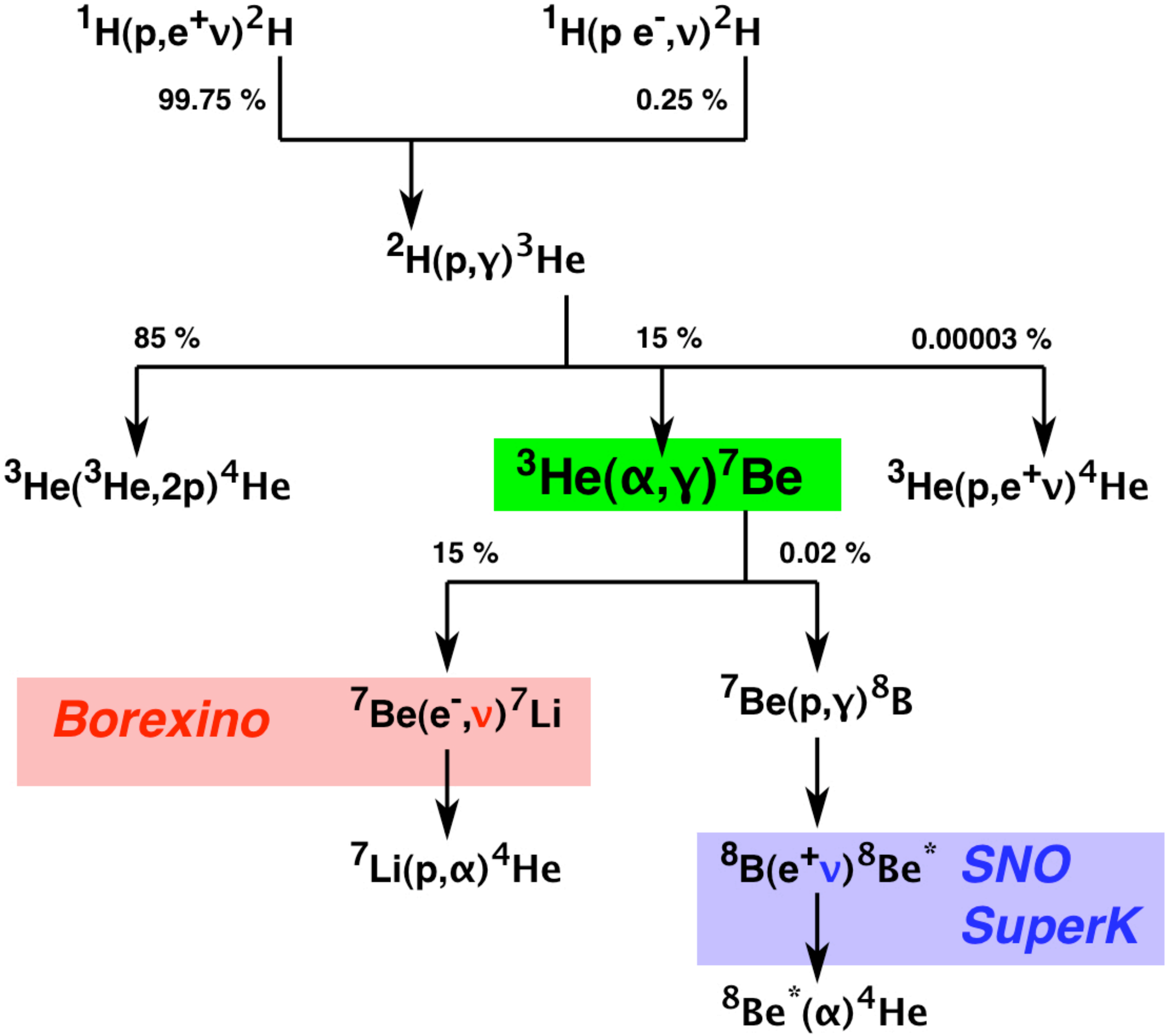
$^{3}He(^{3}He,2p)^{4}He$	Phys. Rev. Lett. 82, 5205 (1999)	
$^{2}H(p,\gamma)^{3}He$	Nucl. Phys. A 706, 203 (2002)	

LUNA2, 400 kV, 2000-2012+

$^{3}He(\alpha,\gamma)^{7}Be$	Phys. Rev. Lett. 97, 122502 (2006) Phys. Rev. C 75, 065803 (2007)	Phase 1 Phase 2
$^{14}N(p,\gamma)^{15}O$	Phys. Lett. B 591, 61 (2004) Phys. Lett. B 634, 483 (2006) (in progress)	Phase 1 Phase 2 Phase 3

- $^{25}Mg(p,\gamma)^{26}Al$, $^{15}N(p,\gamma)^{16}O$, $^{2}H(\alpha,\gamma)^{6}Li$, $^{22}Ne(p,\gamma)^{23}Na$, ...

The proton-proton chain of hydrogen burning



$^{1}H(p,e^{+}\nu)^{2}H$

$^{1}H(p\ e^{-},\nu)^{2}H$

99.75 %

0.25 %

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

85 %

15 %

0.00003 %

$^{3}He(^{3}He,2p)^{4}He$

$^{3}He(\alpha,\gamma)^{7}Be$

$^{3}He(p,e^{+}\nu)^{4}He$

15 %

0.02 %

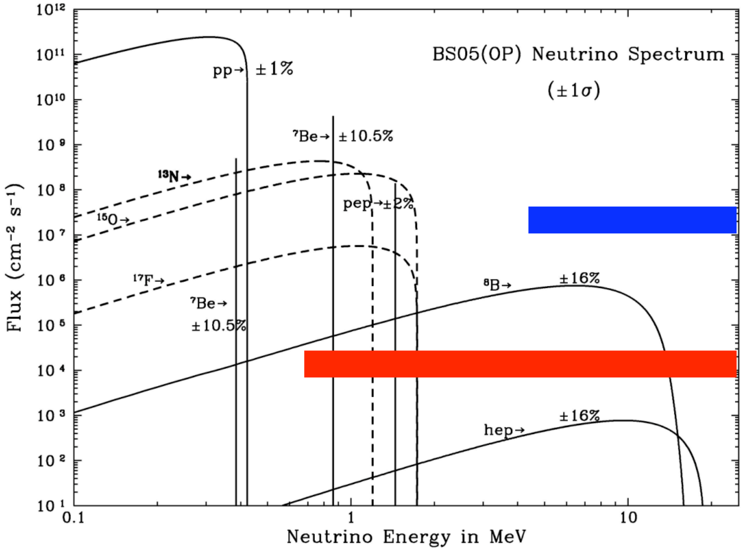
Borexino $^{7}Be(e^{-},\nu)^{7}Li$

$^{7}Be(p,\gamma)^{8}B$

$^{7}Li(p,\alpha)^{4}He$

$^{8}B(e^{+}\nu)^{8}Be^{*}$ ***SNO*** ***SuperK***

$^{8}Be^{*}(\alpha)^{4}He$

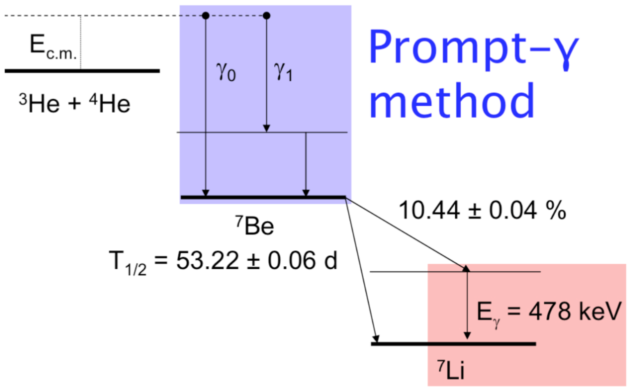


99% of solar luminosity

Remainder: CNO-cycle

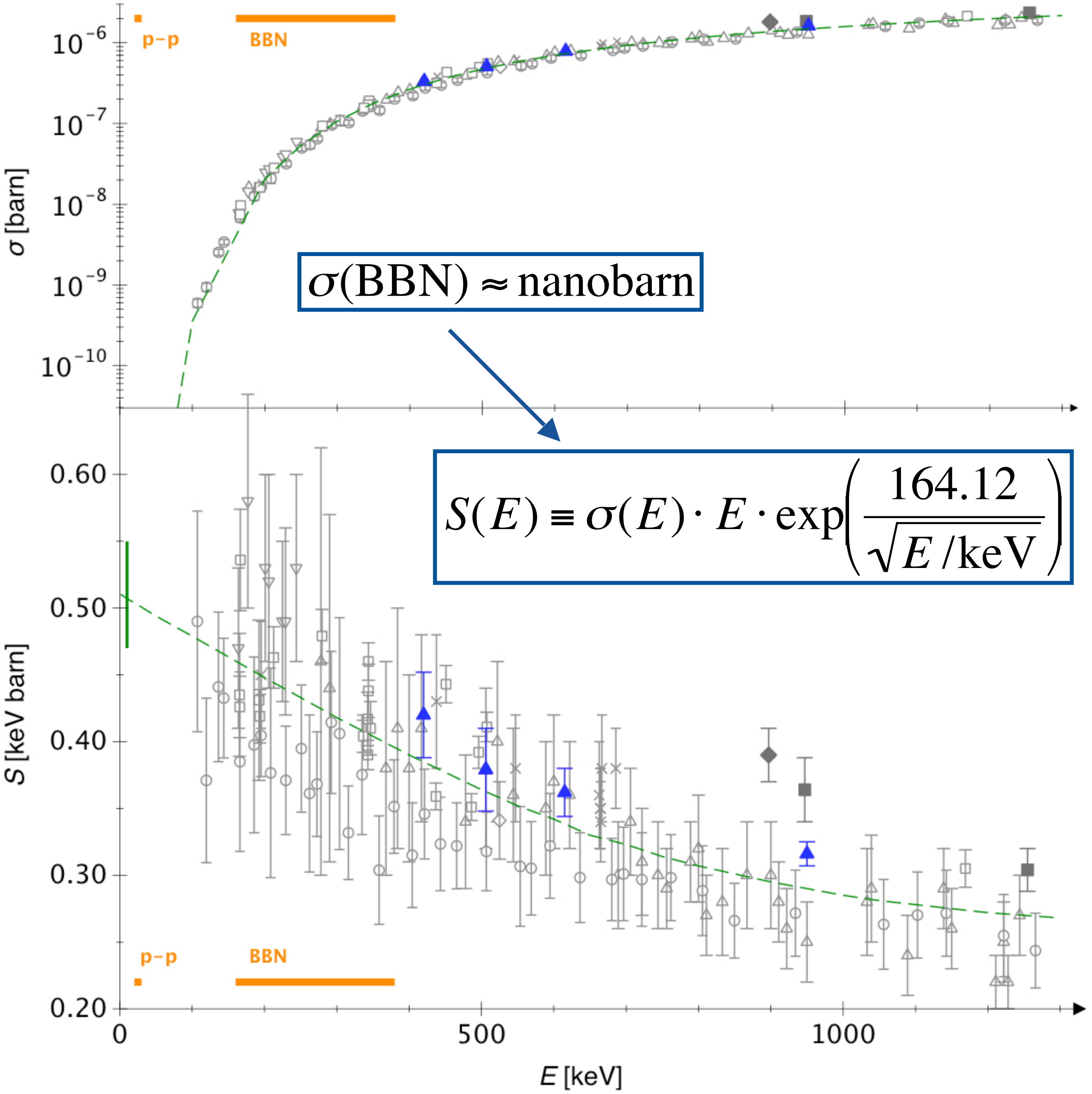
$$\frac{\partial \ln \Phi_{B}}{\partial \ln \sigma[^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}]} \approx 0.84$$

^{3}He(α,γ)^{7}Be: State of the art, 2005



Prompt–γ method

Activation method

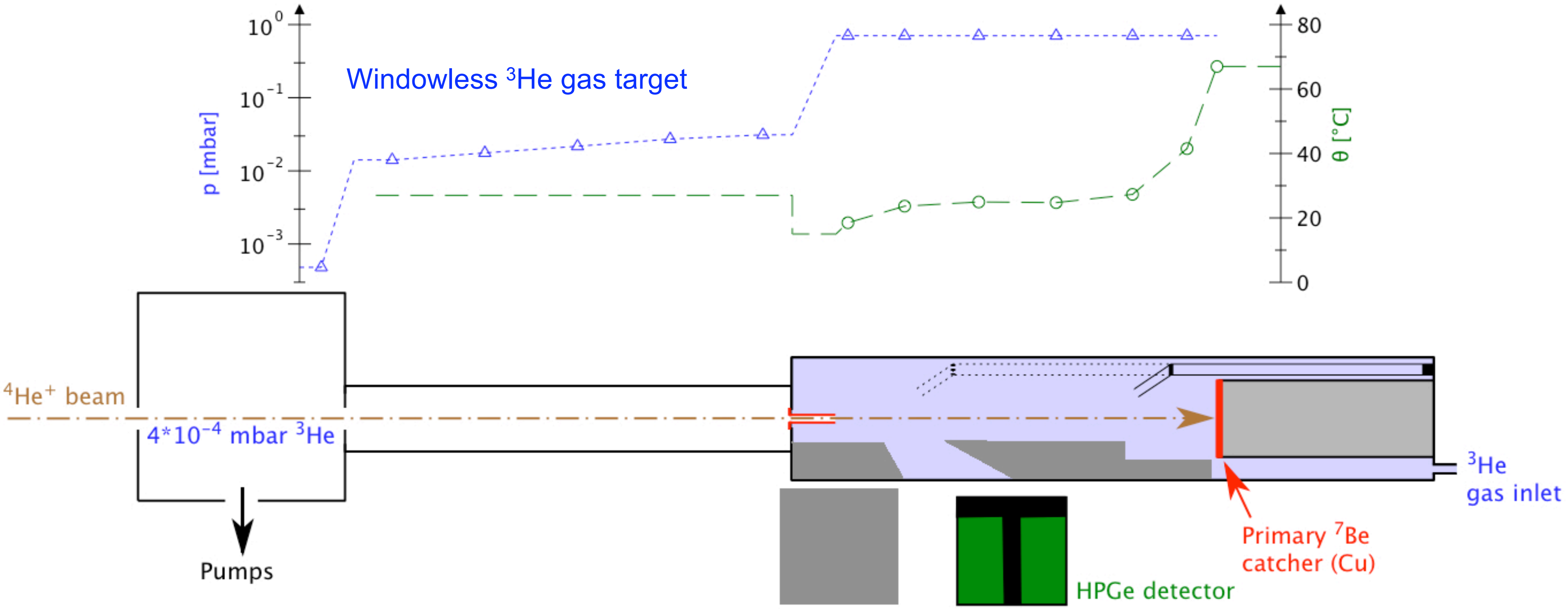


$\sigma(\text{BBN}) \approx \text{nanobarn}$

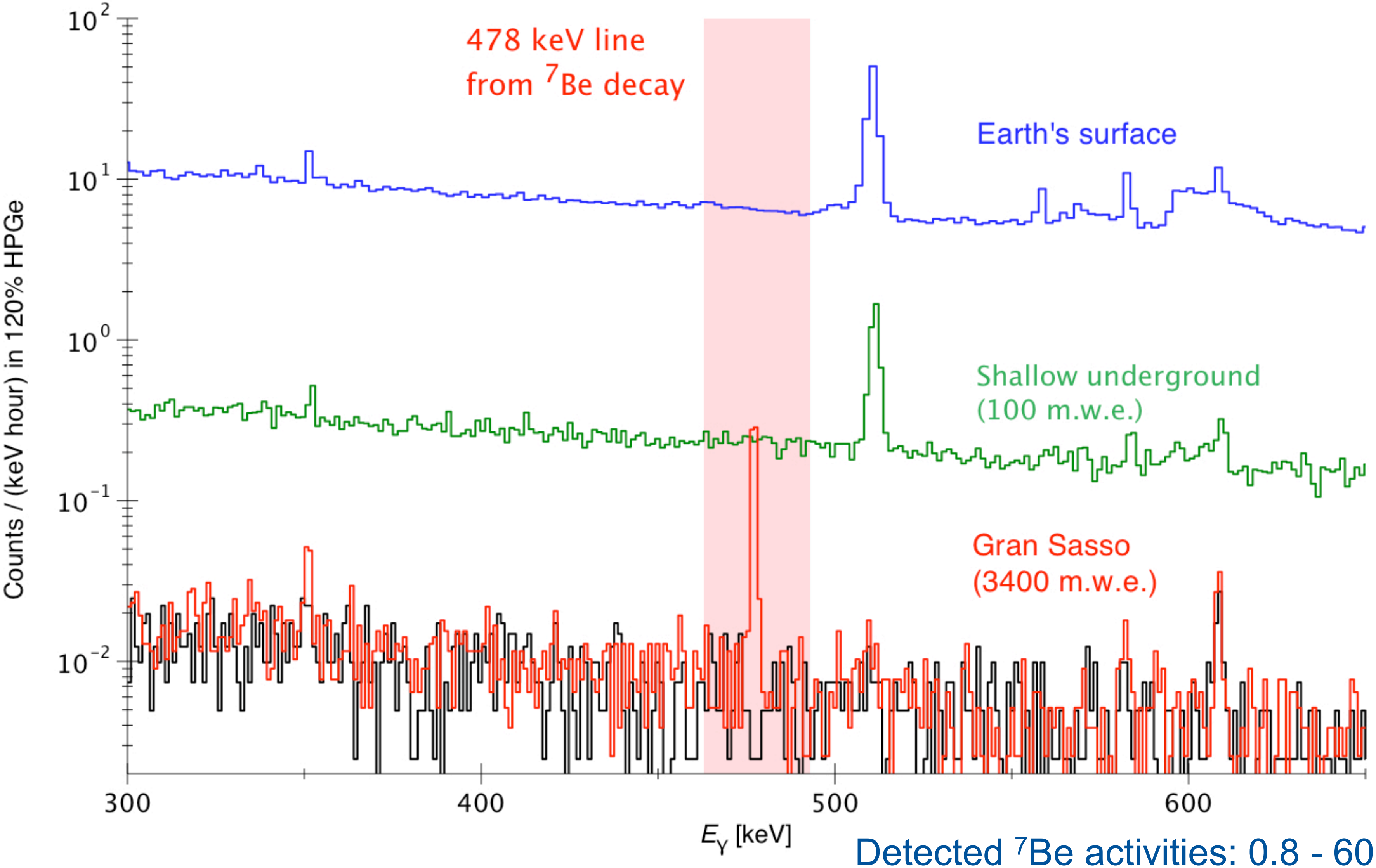
$$S(E) \equiv \sigma(E)\cdot E \cdot \exp\left(\frac{164.12}{\sqrt{E/\text{keV}}}\right)$$

^{3}He(α,γ)^{7}Be: LUNA experiment (Phase 1, activation)

$t_{1/2}$ = 53 d E_γ = 478 keV

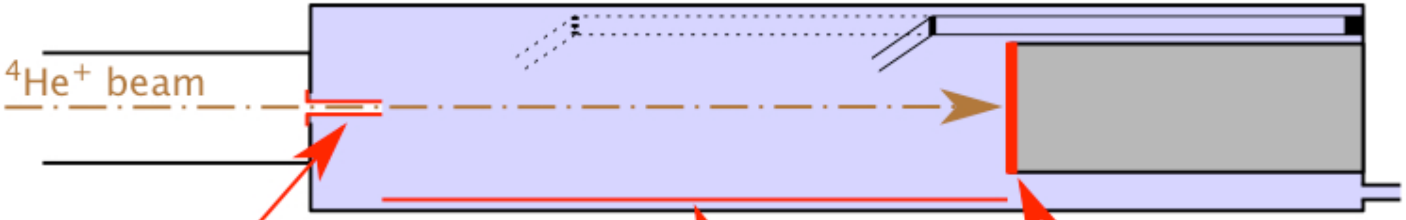


^{3}He(α,γ)^{7}Be: LUNA experiment (Phase 1, activation): ^{7}Be spectra



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

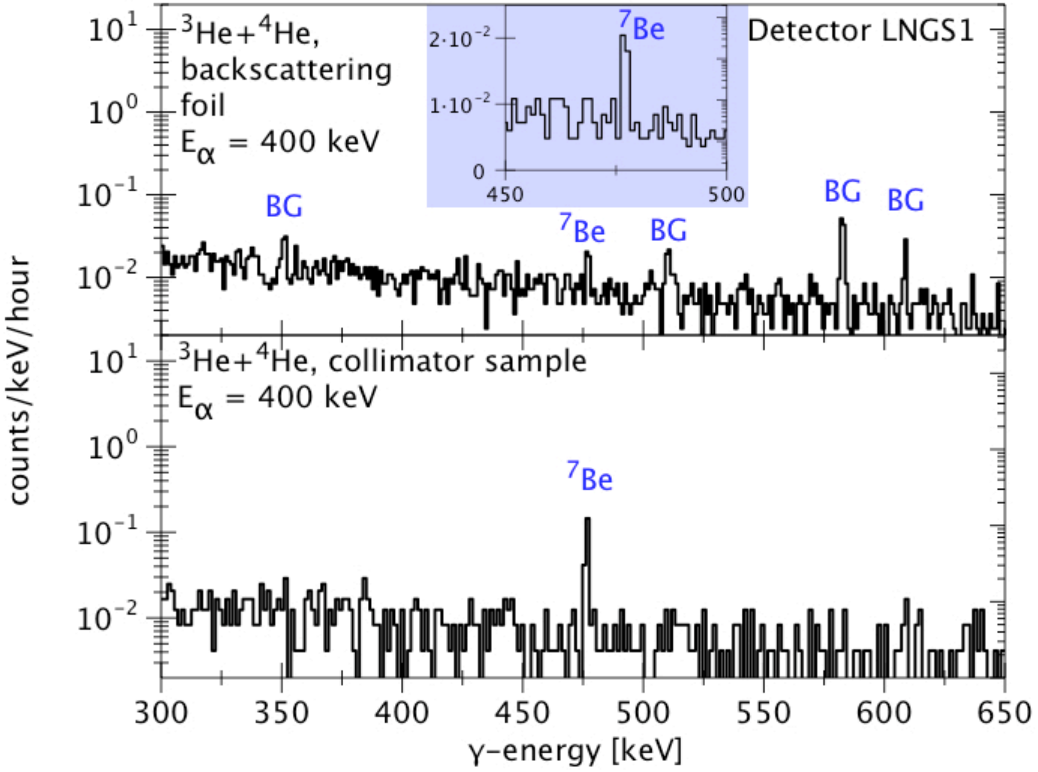
^{3}He(α,γ)^{7}Be: LUNA experiment (Phase 1, activation): Systematic uncertainty



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

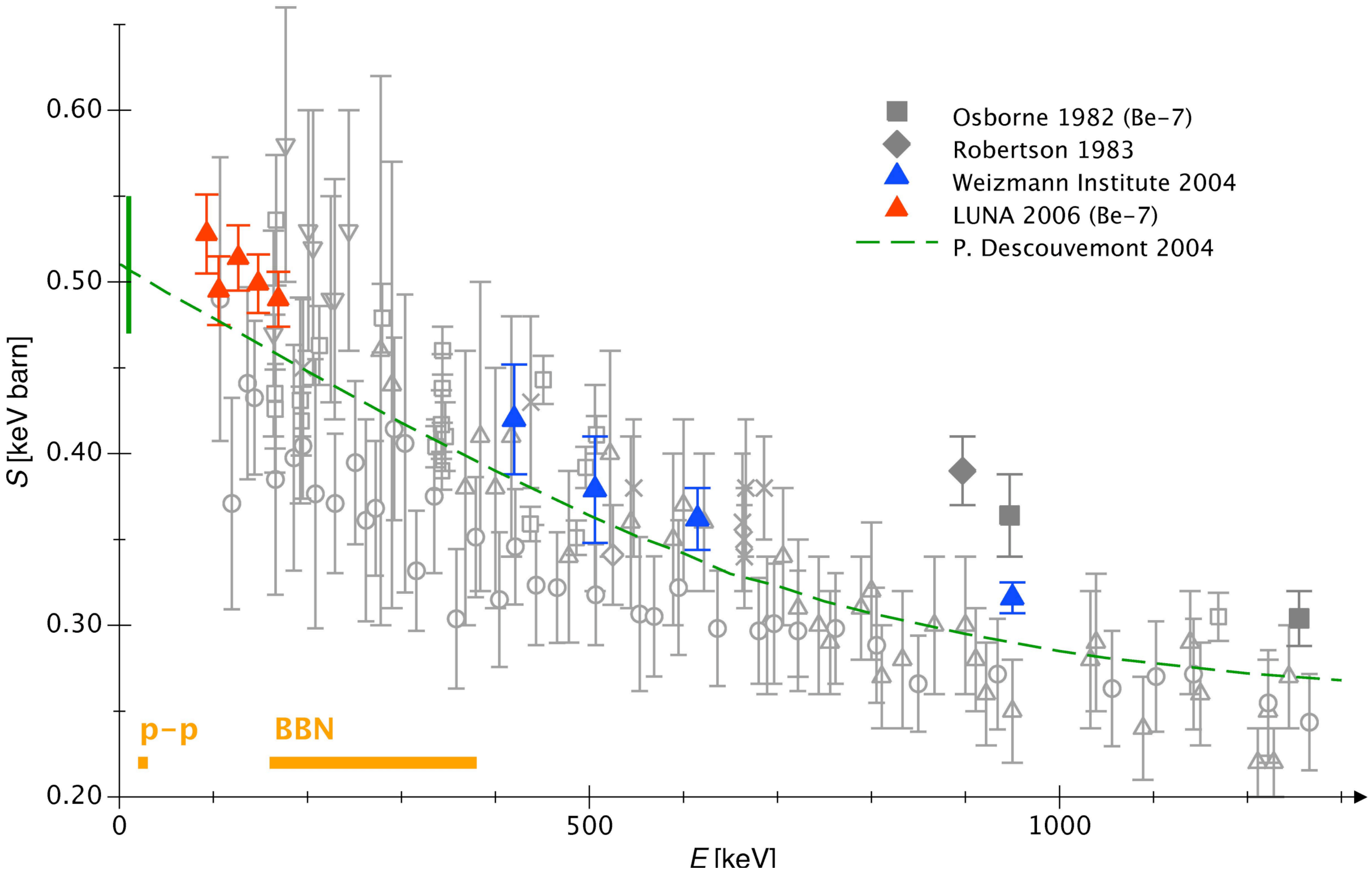
Catcher (Al) for backscattered ^{7}Be

Primary ^{7}Be catcher (Cu)



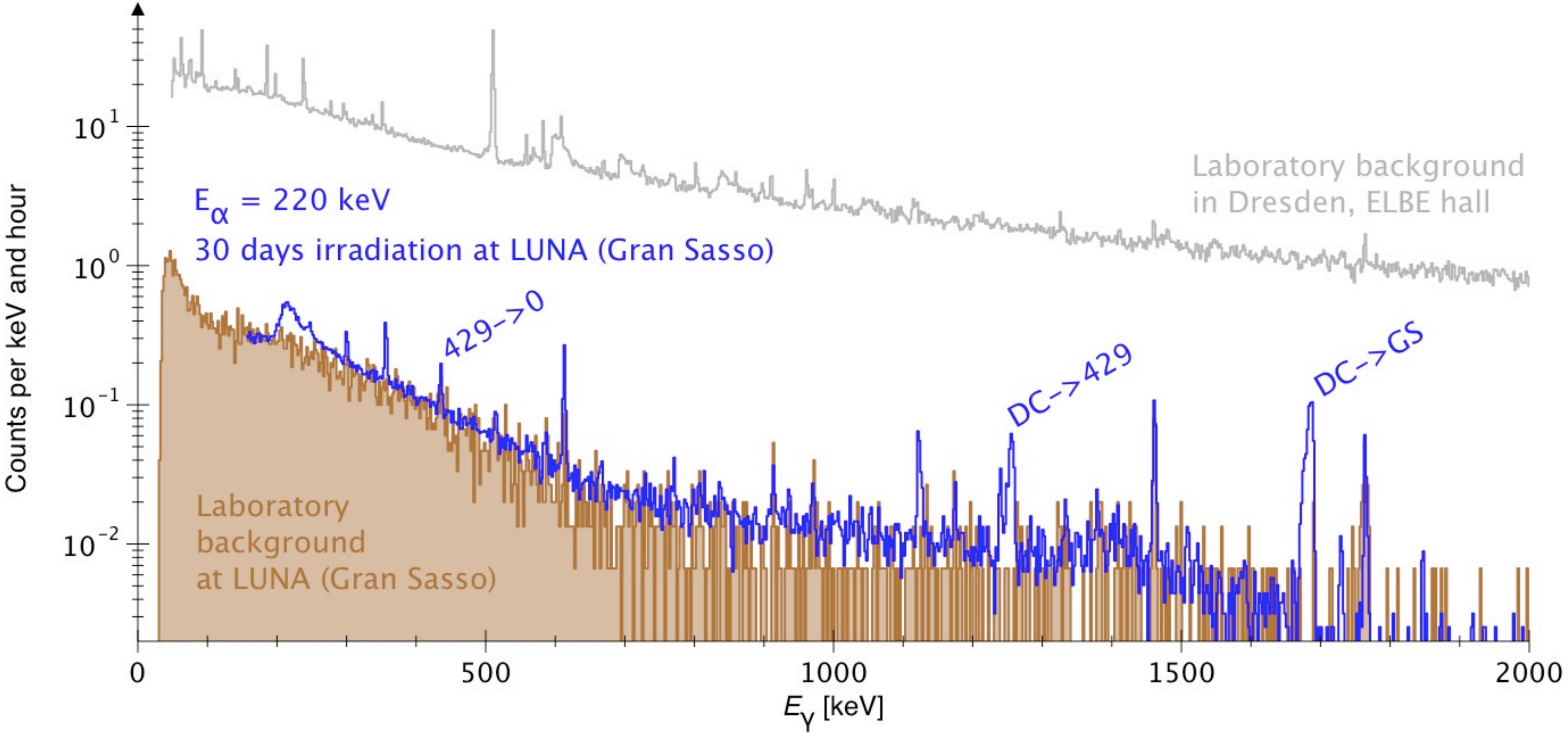
γ-efficiency	1.8%
Beam intensity	1.5%
Target density	1.5%
^{7}Be losses	0.7%
Total systematic uncertainty	**3.0%**

$^3He(\alpha,\gamma)^7Be$: LUNA experiment (Phase 1, activation): Results

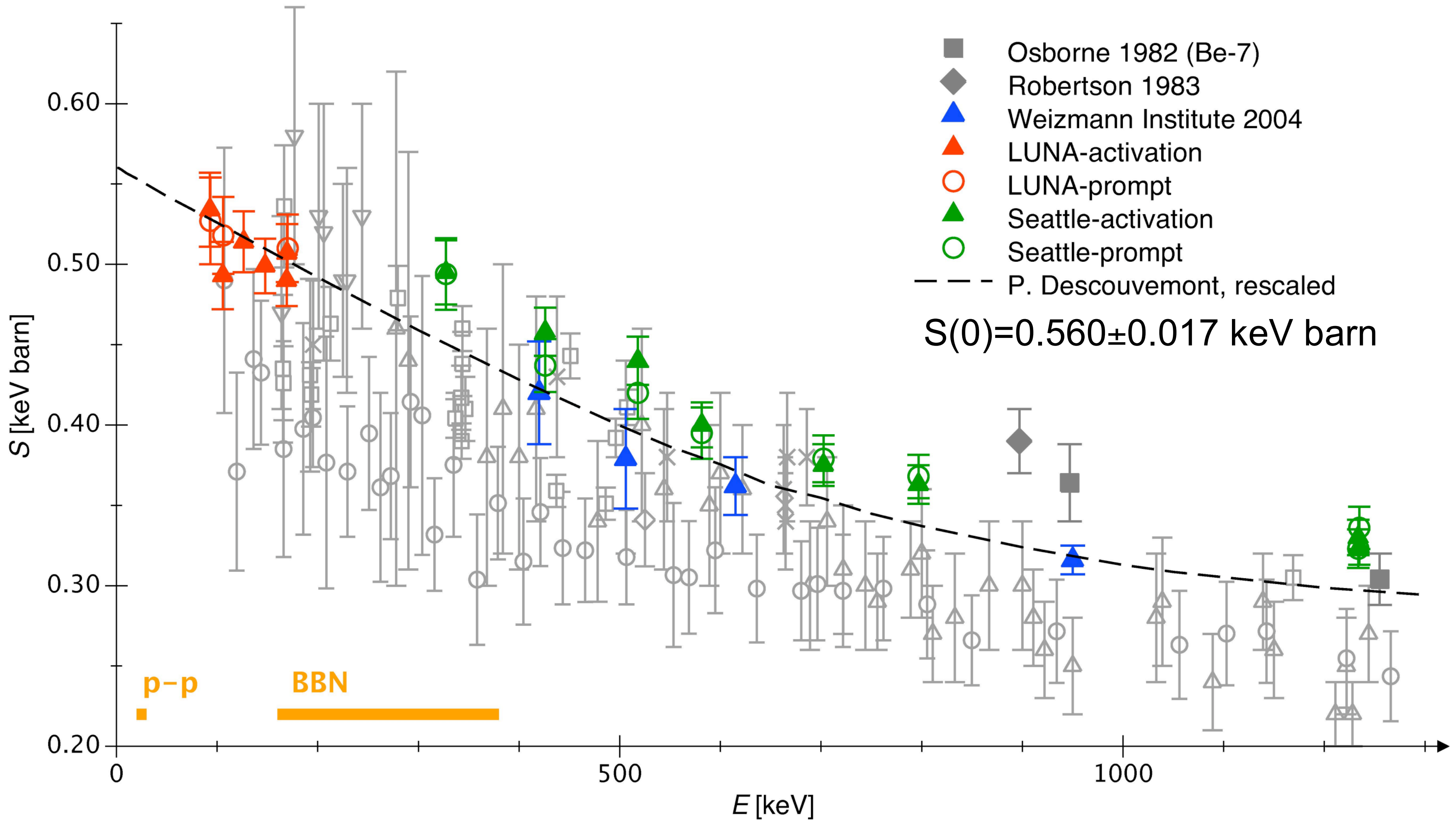


D. Bemmerer *et al.*, Phys. Rev. Lett. 97, 122502 (2006)

^{3}He(α,γ)^{7}Be: LUNA experiment (Phase 2, in-beam γ-spectrometry)

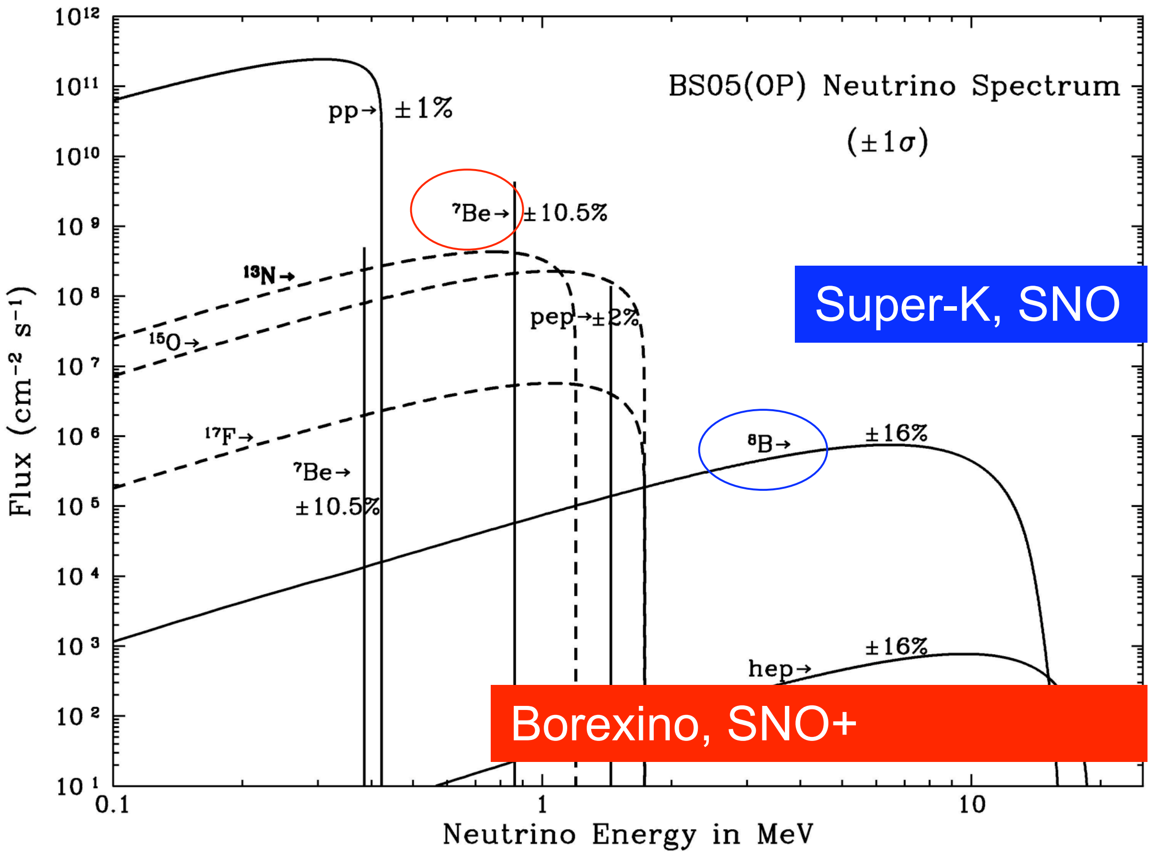


$^{3}He(\alpha,\gamma)^{7}Be$: LUNA experiment (Phases 1 and 2): Results



D. Bemmerer *et al.*, Phys. Rev. Lett. 97, 122502 (2006)   F. Confortola *et al.*, Phys. Rev. C 75, 065803 (2007)

Astrophysical impact: More precise inputs for solar ^{7}Be, ^{8}B neutrinos



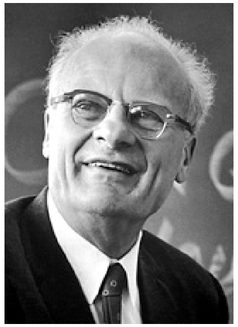
Nuclear physics input for ^{8}B neutrino flux Φ_B:

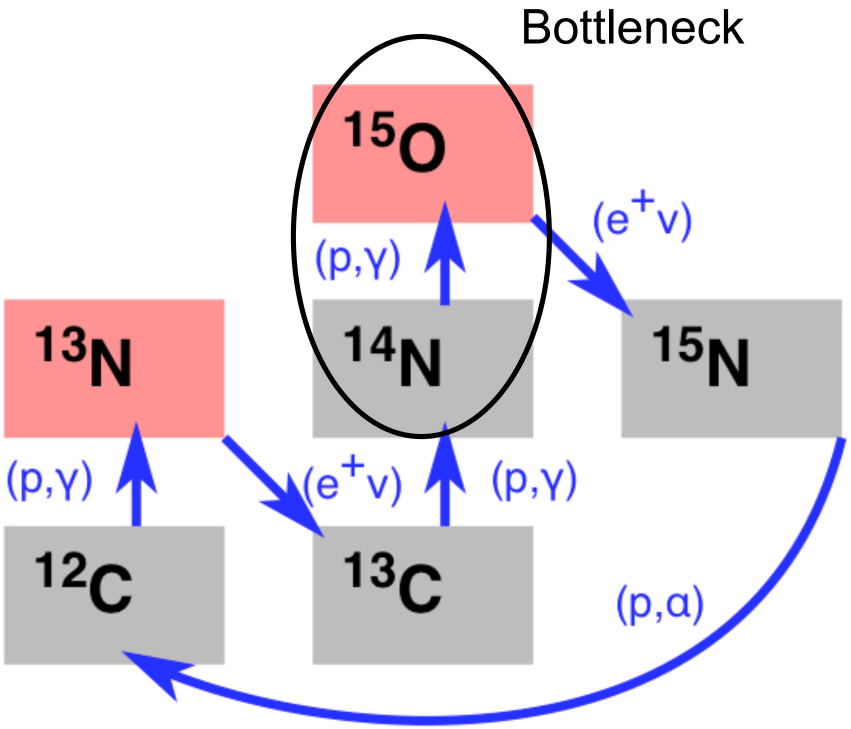
	$\frac{\partial \ln \Phi_B}{\partial \ln \sigma}$	$\Delta\Phi_B/\Phi_B$
^{3}He(^{3}He,2p)^{4}He	-0.43	2.1%
^{3}He(α,γ)^{7}Be	0.84	~~7.5%~~ 2.5%
^{7}Be(p,γ)^{8}B	1.00	3.8%

Super-Kamiokande: 3.6% (syst.+stat.) precision for Φ_B

Borexino, SNO+: expect 10% statistics for Φ_{Be}

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



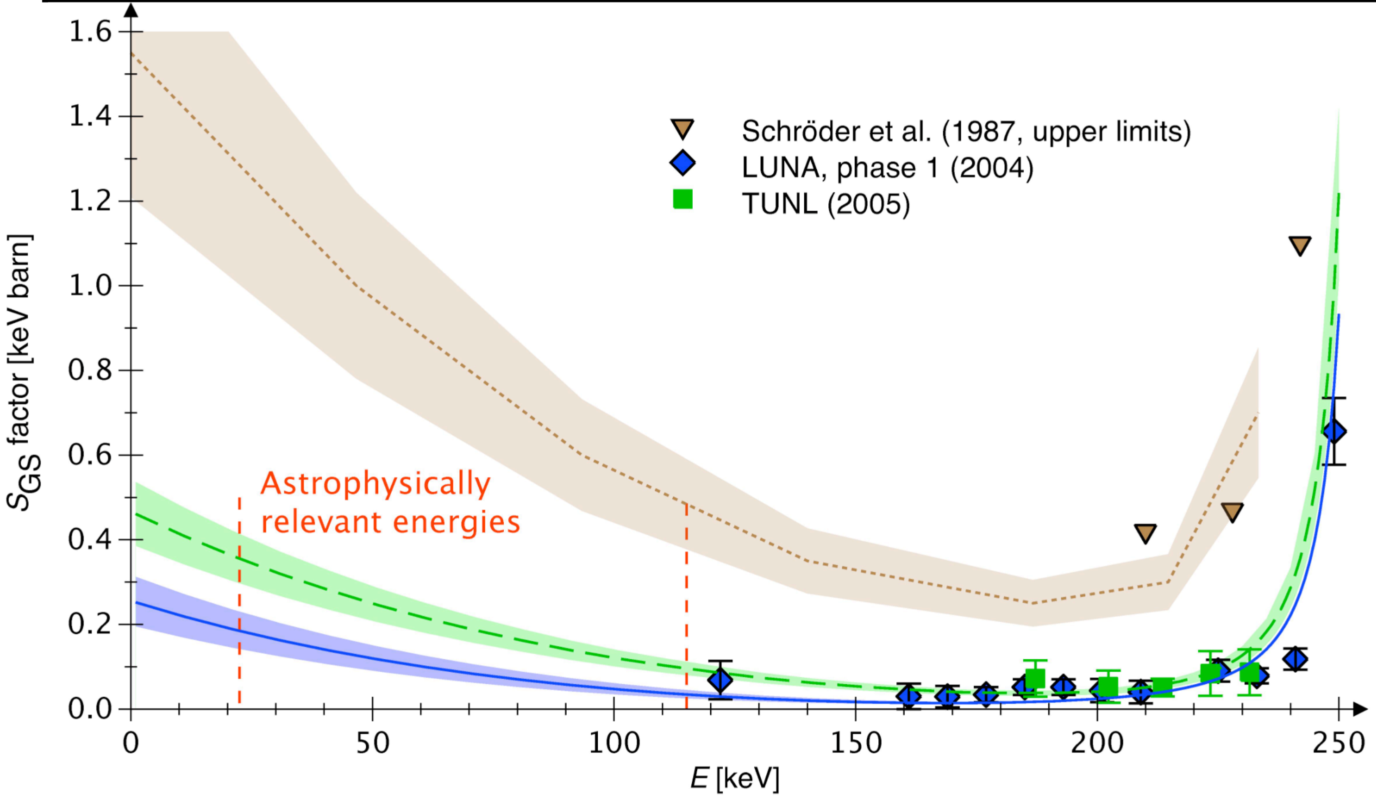


Postulated in 1938

- Slowest reaction: $^{14}N(p,\gamma)^{15}O$
- Some of the oldest observed stars burn mainly by CNO
- 1% contribution in our Sun →CNO neutrinos probe solar metalicity

$^{14}N(p,\gamma)^{15}O$ study, phase 1: S-factor only half as large as believed in 1999

Capture to...	NACRE compilation 1999	LUNA, phase 1 (2004)
...ground state in ^{15}O	1.55 ± 0.34 →	0.25 ± 0.06
...excited states in ^{15}O	1.65 ± 0.05	1.36 ± 0.05
S(0) in keV barn	3.2 ± 0.5 (tot)	1.6 ± 0.2 (tot)



NACRE compilation based on:

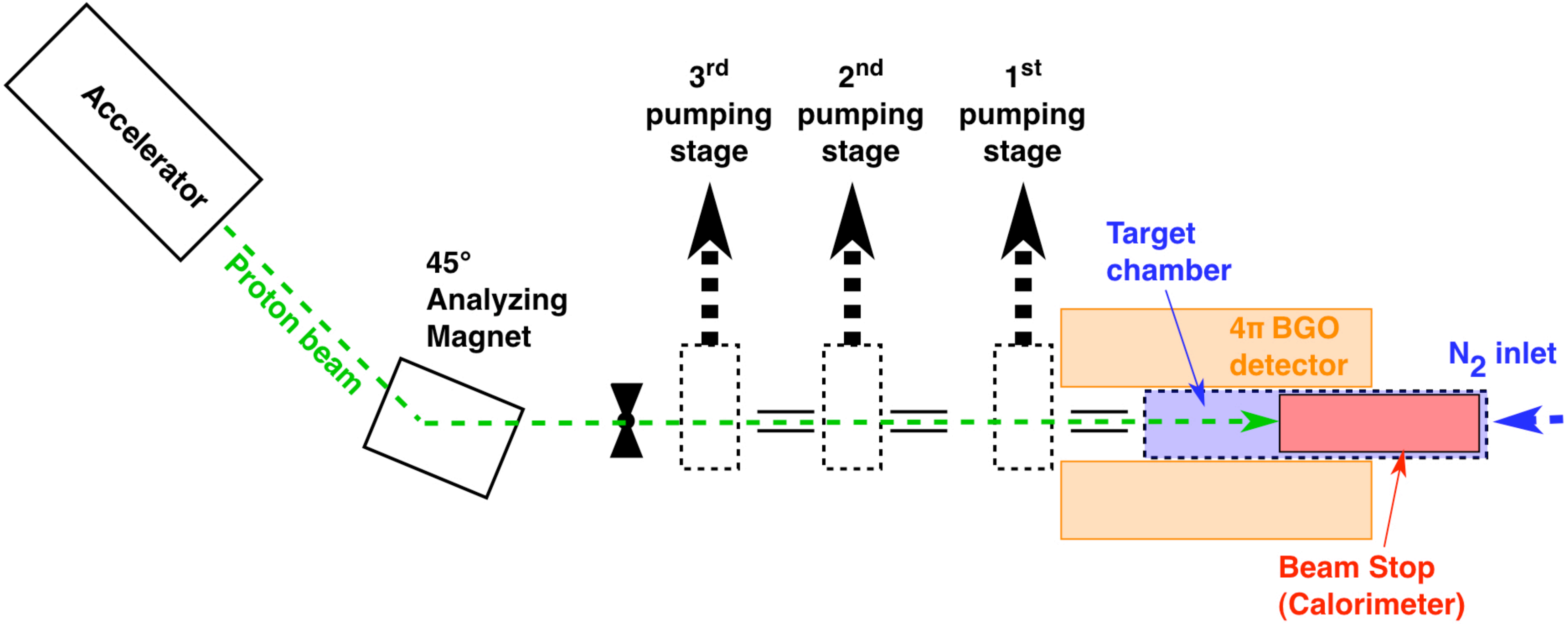
Schröder et al.,
Nucl. Phys. A 467, 240 (1987)

LUNA:
Formicola et al.,
Phys. Lett. B 591, 61 (2004)

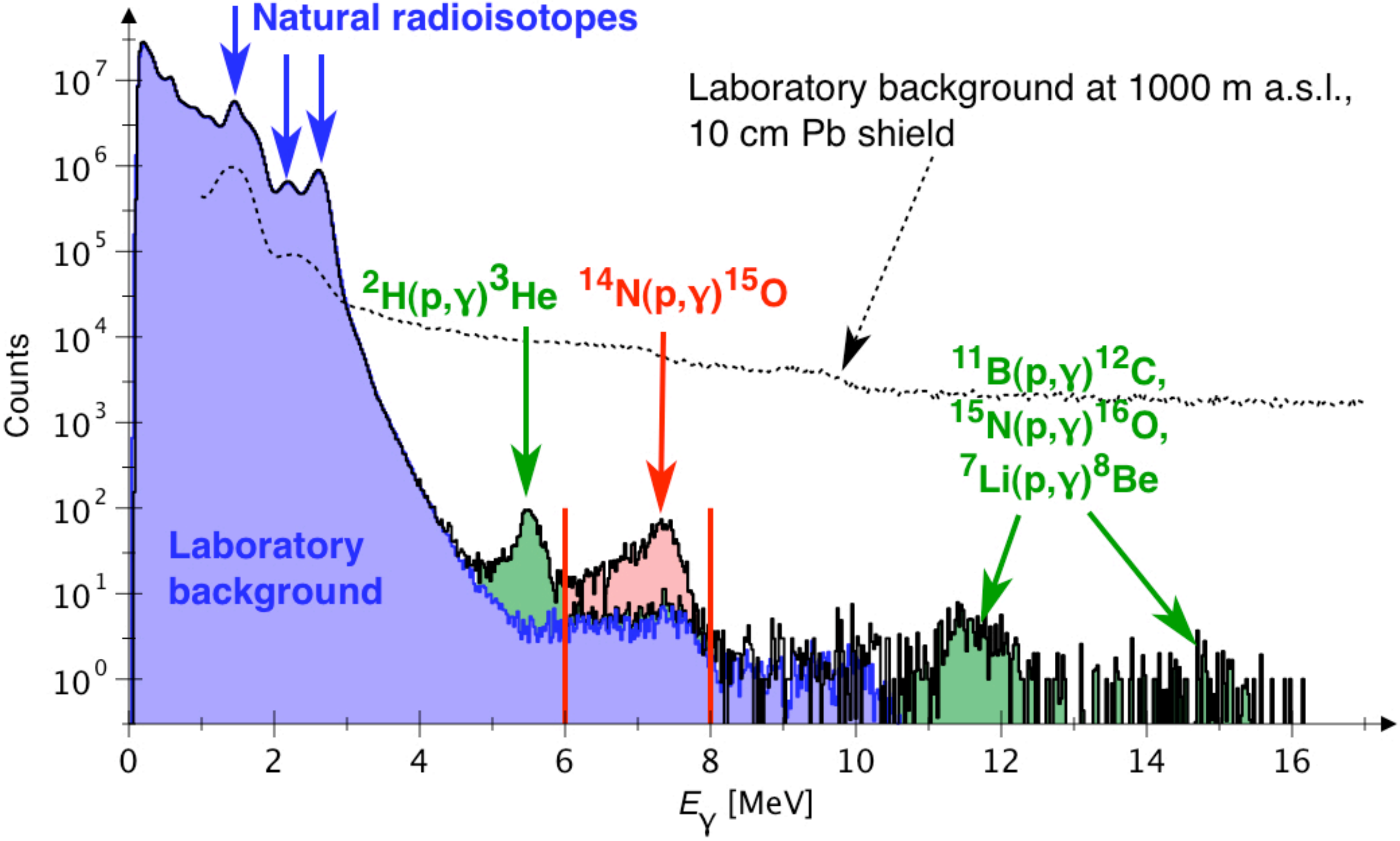
TUNL:

Runkle et al.,
PRL 94, 082503 (2005)

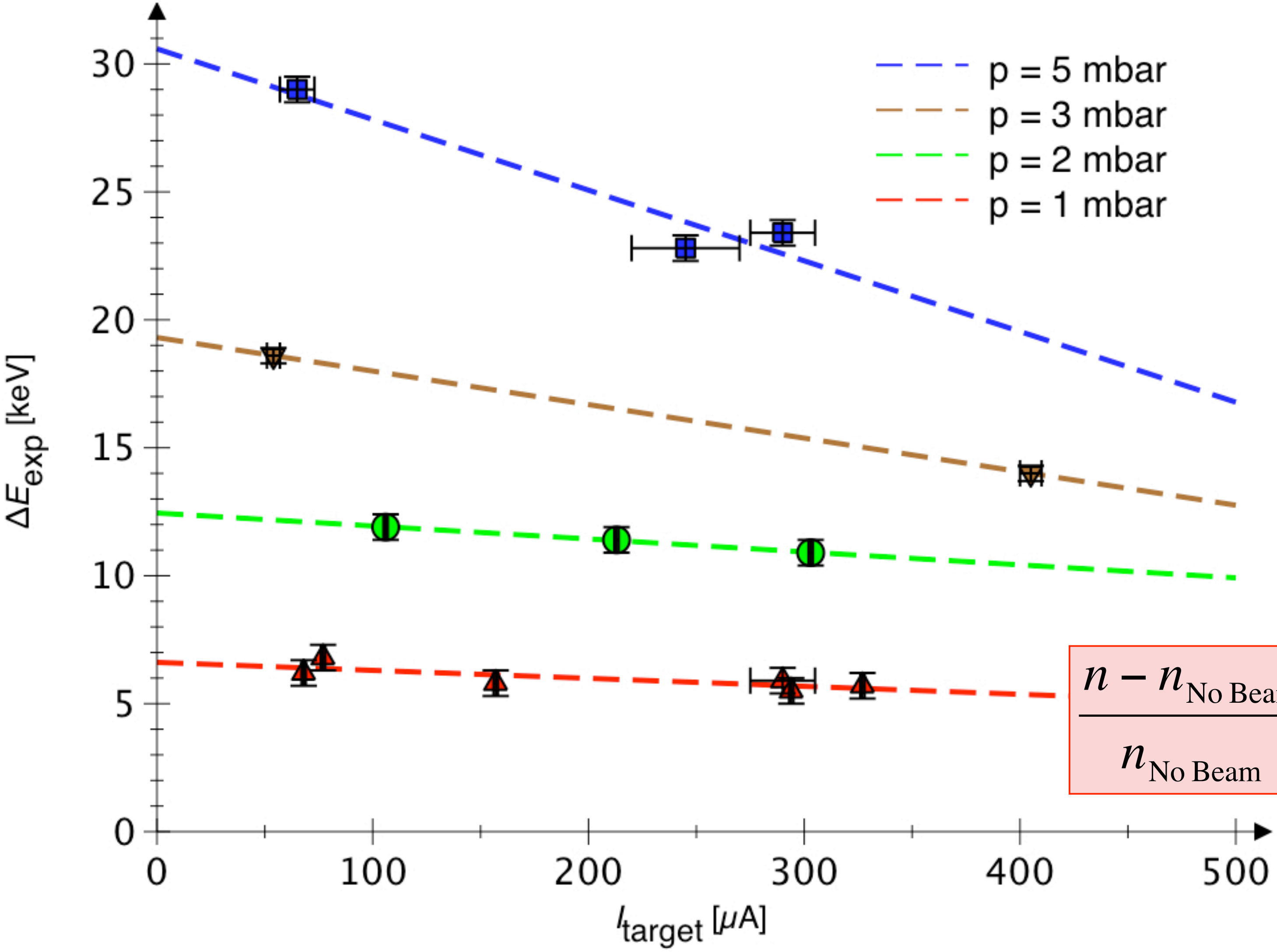
$^{14}N(p,\gamma)^{15}O$ study, phase 2:
Setup with differentially pumped gas target and 4π BGO detector



$^{14}N(p,\gamma)^{15}O$ study, phase 2: γ-ray spectrum at E = 90 keV, 4π BGO detector

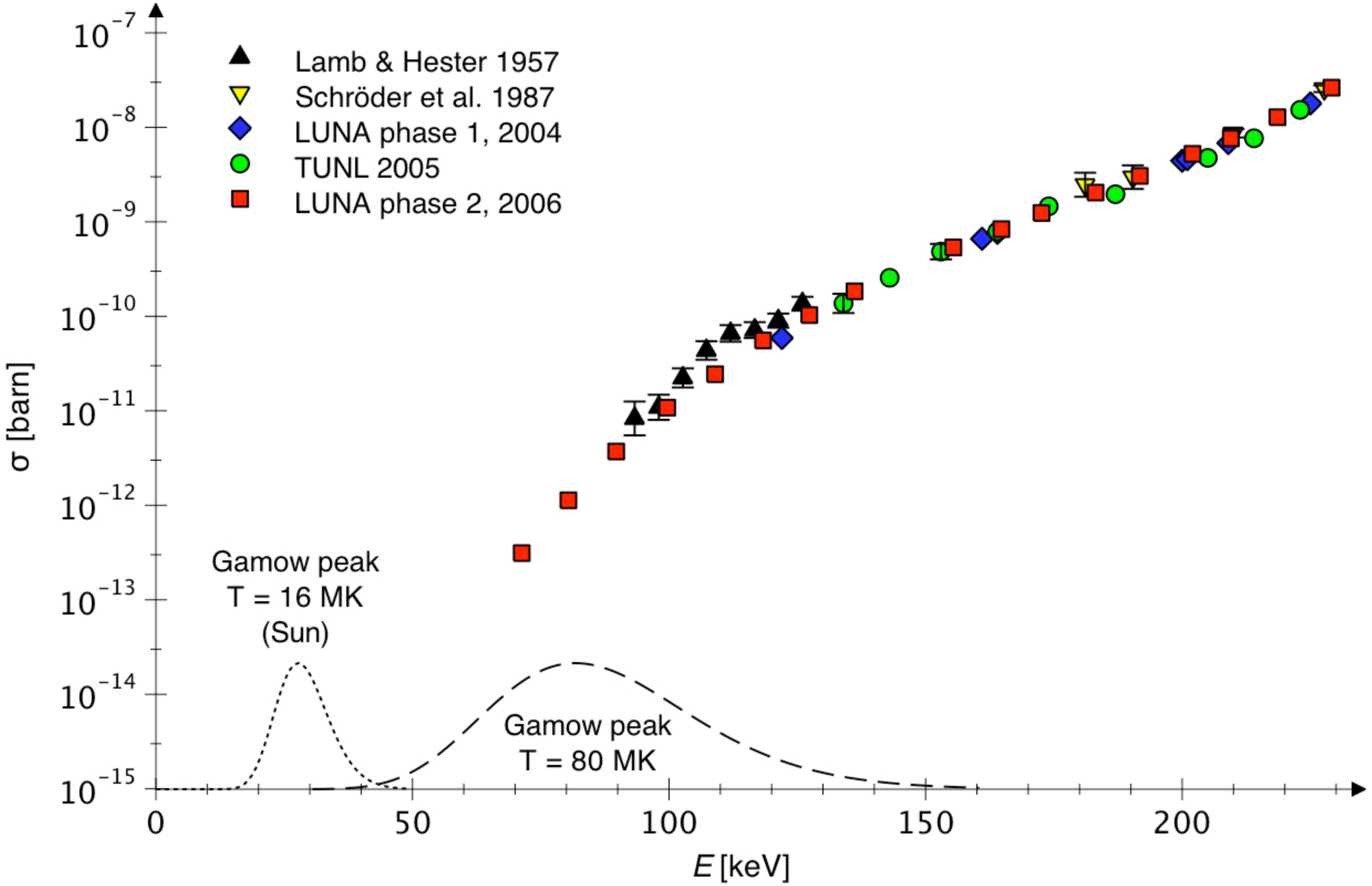


^{14}N(p,γ)^{15}O study, phase 2: Influence of the ion beam on the gas target density

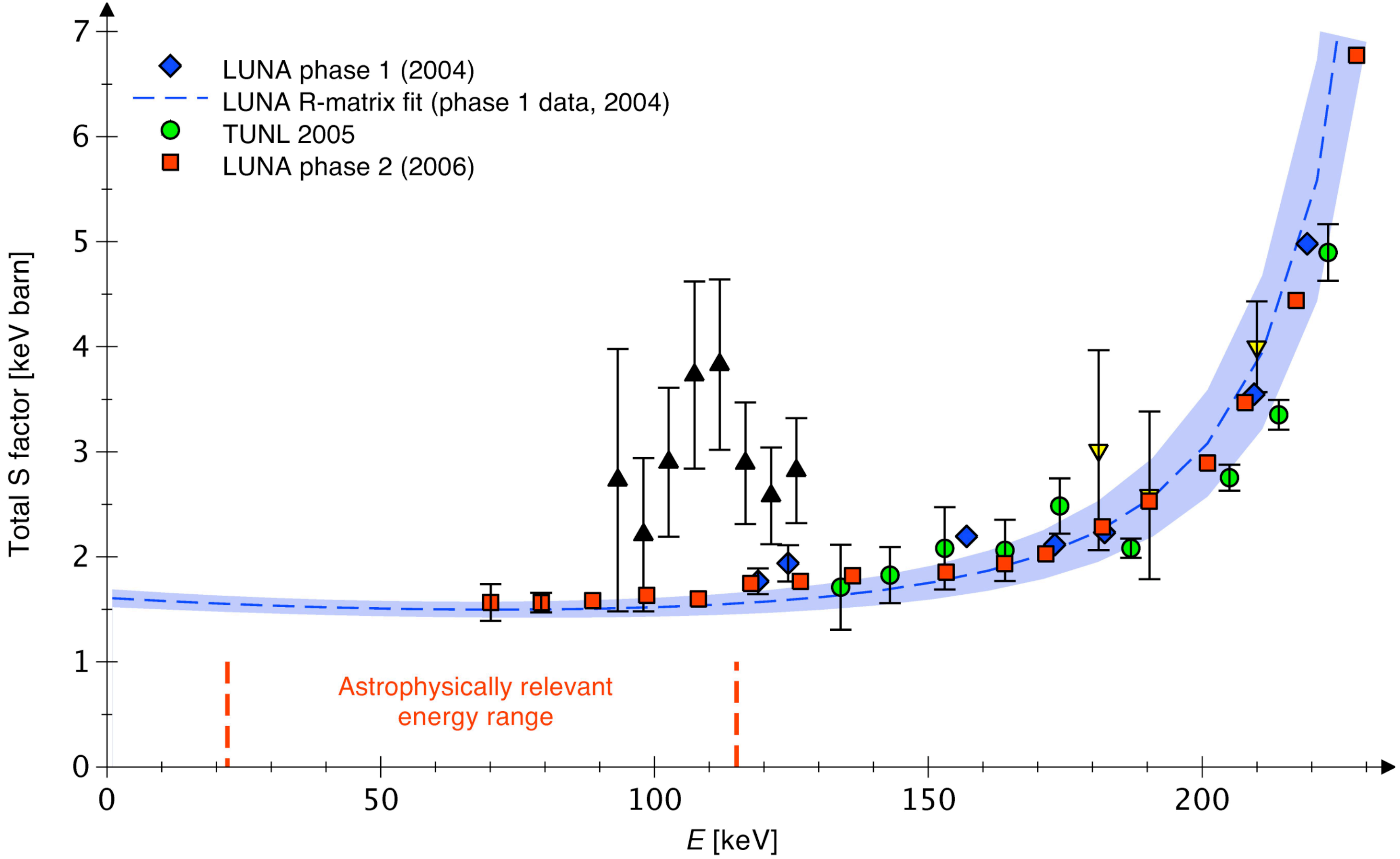


$$\frac{n - n_{\text{No Beam}}}{n_{\text{No Beam}}} \propto \frac{\Delta W}{\Delta x} \propto p\, I_{\text{target}}$$

$^{14}N(p,\gamma)^{15}O$ study, phase 2: Results (total cross section)

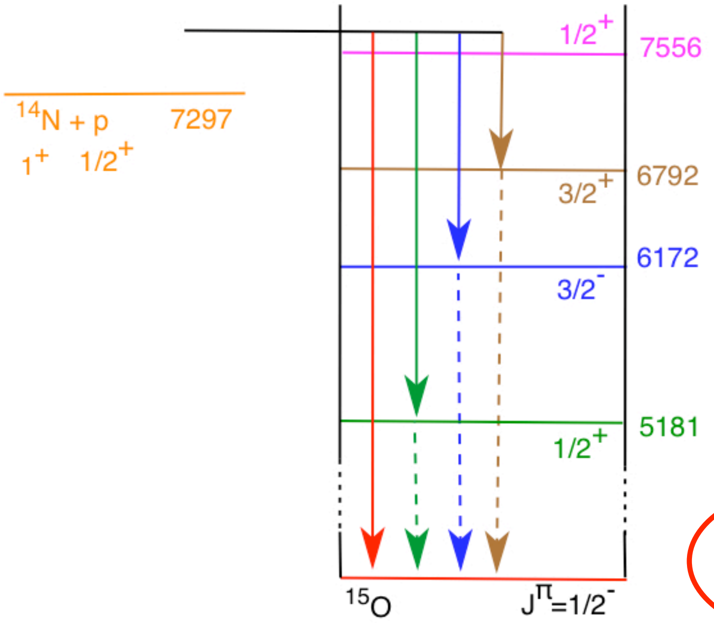


^{14}N(p,γ)^{15}O study, phase 2: Results (total S-factor)



A. Lemut et al., Phys. Lett. B 634, 483 (2006)

$^{14}N(p,\gamma)^{15}O$ study, phase 3: Again capture to the ground state in ^{15}O



(75±5)%

(5±1)%

(5±1)%

(15±15)%

The problem (phase 1, TUNL):

Cascade transitions can mimic the signal from the ground state contribution.

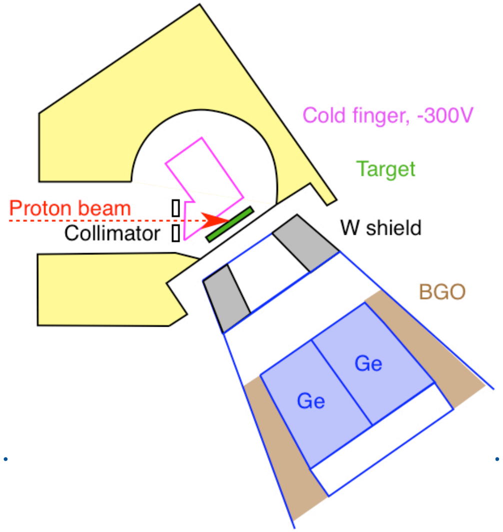
$\gamma(800) + \gamma(6800) \longleftrightarrow \gamma(7600)$

The solution (phase 3):

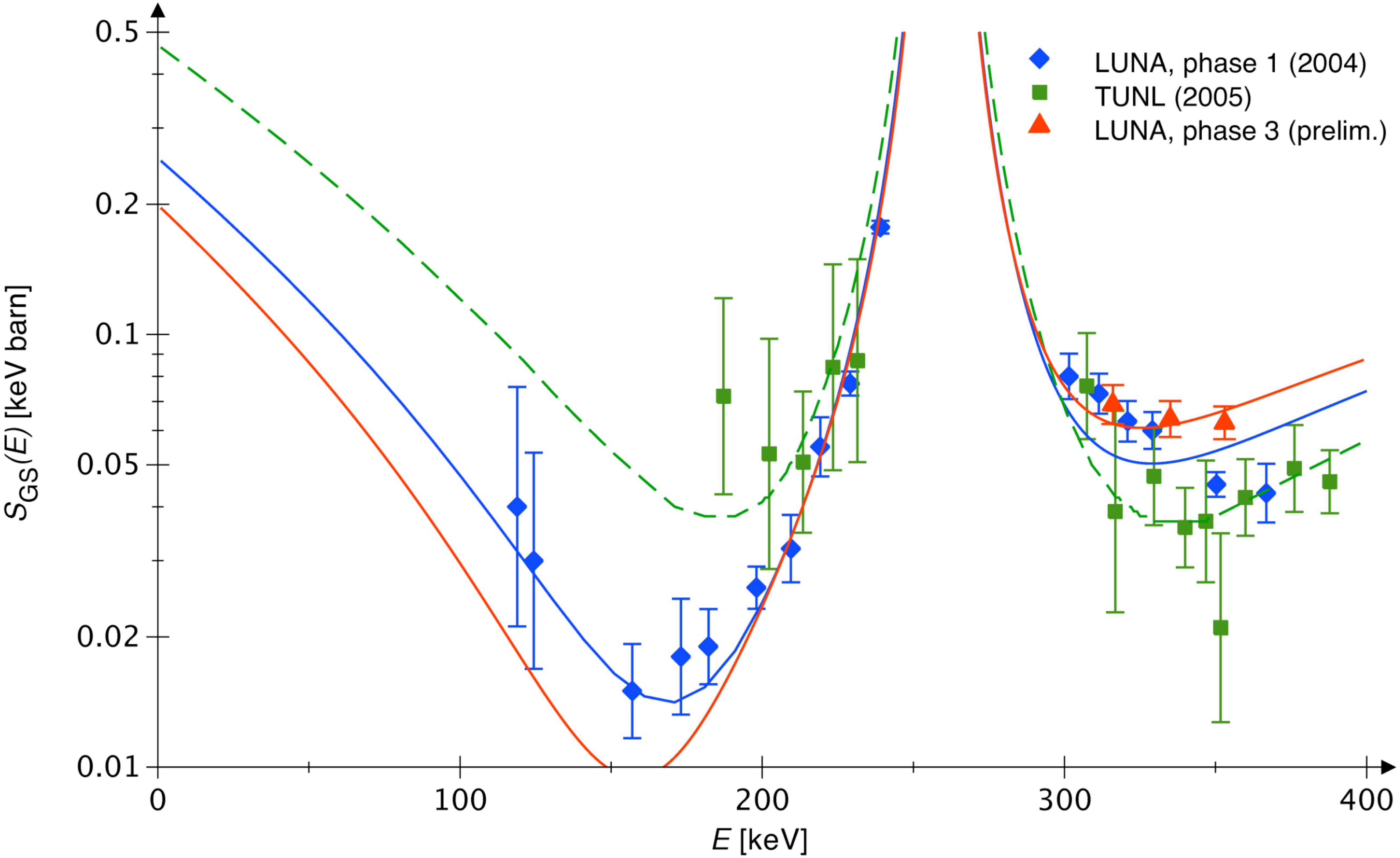
➔ Reduce efficiency

➔ Segmented detector

LUNA-phase 1 (2004):	0.25±0.06 keV barn, 250% summing-in
TUNL (2005):	0.49±0.08 keV barn, 240% summing-in



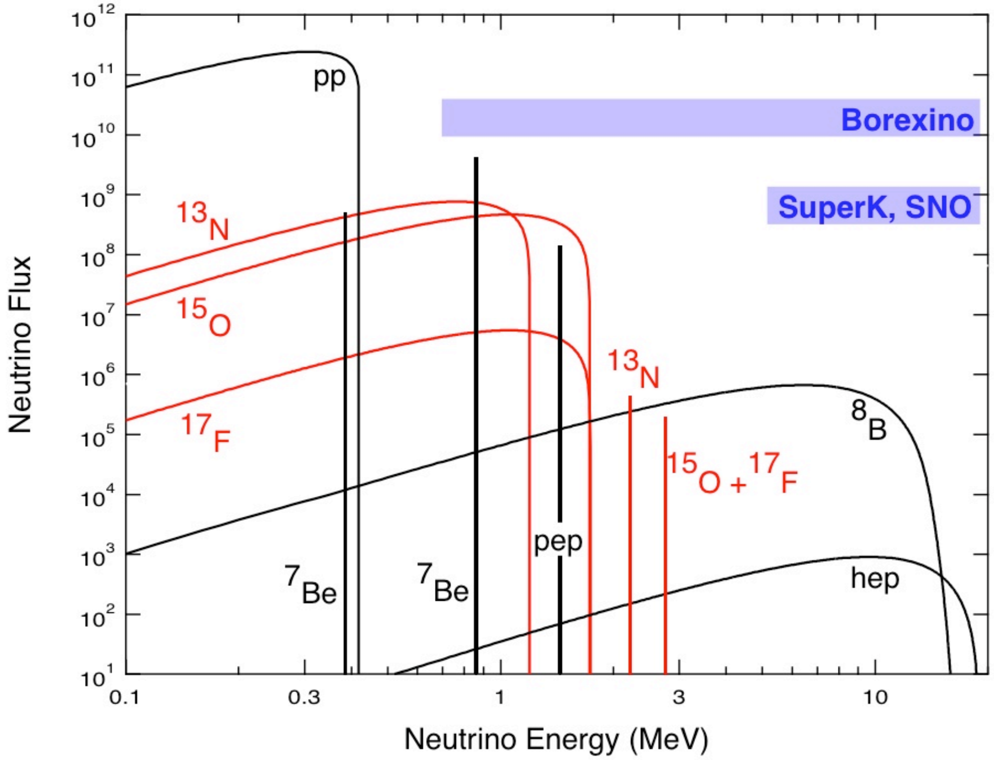
$^{14}N(p,\gamma)^{15}O$ study, phase 3: Preliminary new data and R-matrix fit



LUNA, phase 1 (2004):	0.25±0.06 keV barn	250% summing-in correction
TUNL (2005):	0.49±0.08 keV barn	240% summing-in correction
LUNA, phase 3 (prelim.):	0.20±0.05 keV barn	8% summing-in correction

$^{14}N(p,\gamma)^{15}O$ study, impact on solar neutrinos

Capture to...	NACRE compilation 1999	LUNA, phase 1 2004	TUNL 2005	LUNA, phase 3, preliminary!
...ground state in ^{15}O	1.55 ± 0.34	0.25 ± 0.06	0.49 ± 0.08	0.24 ± 0.05
...excited states in ^{15}O	1.65 ± 0.05	1.36 ± 0.05	1.27 ± 0.05	(1.33 ± 0.05)
S(0) in keV barn	3.2 ± 0.5 (tot)	1.6 ± 0.2 (tot)	1.8 ± 0.2 (tot)	1.57 ± 0.13 (tot)



Compare upcoming ^{13}N, ^{15}O neutrino flux data (Borexino, SNO+) with solar model, using updated cross section input and ^{8}B neutrino "thermometer":

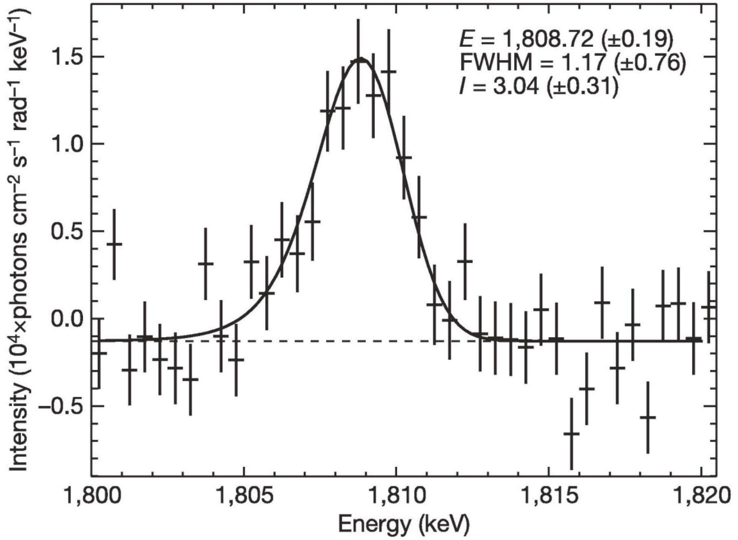
Direct measurement of the carbon and nitrogen abundance in the solar center!

(W. Haxton & A. Serenelli, arXiV:0805.2013)

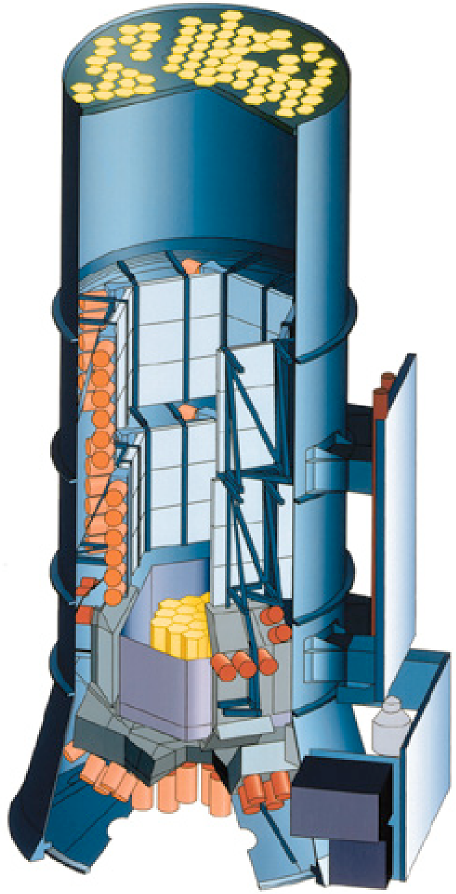
^{26}Al, a tracer of live nucleosynthesis

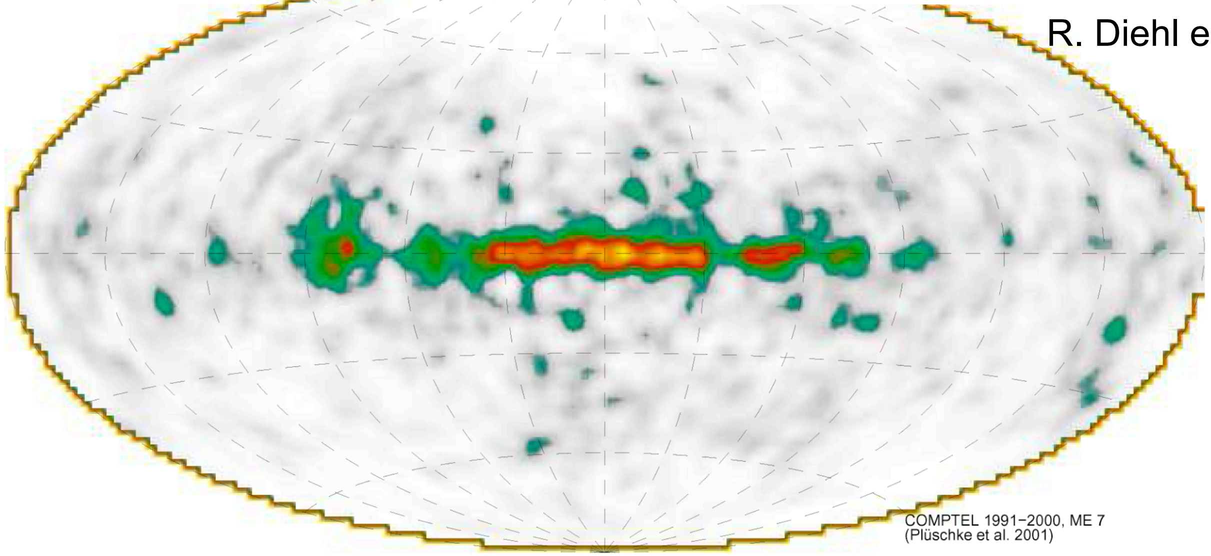
$t_{1/2}$ = 717 000 y

E_γ = 1809 keV



R. Diehl et al. 2006



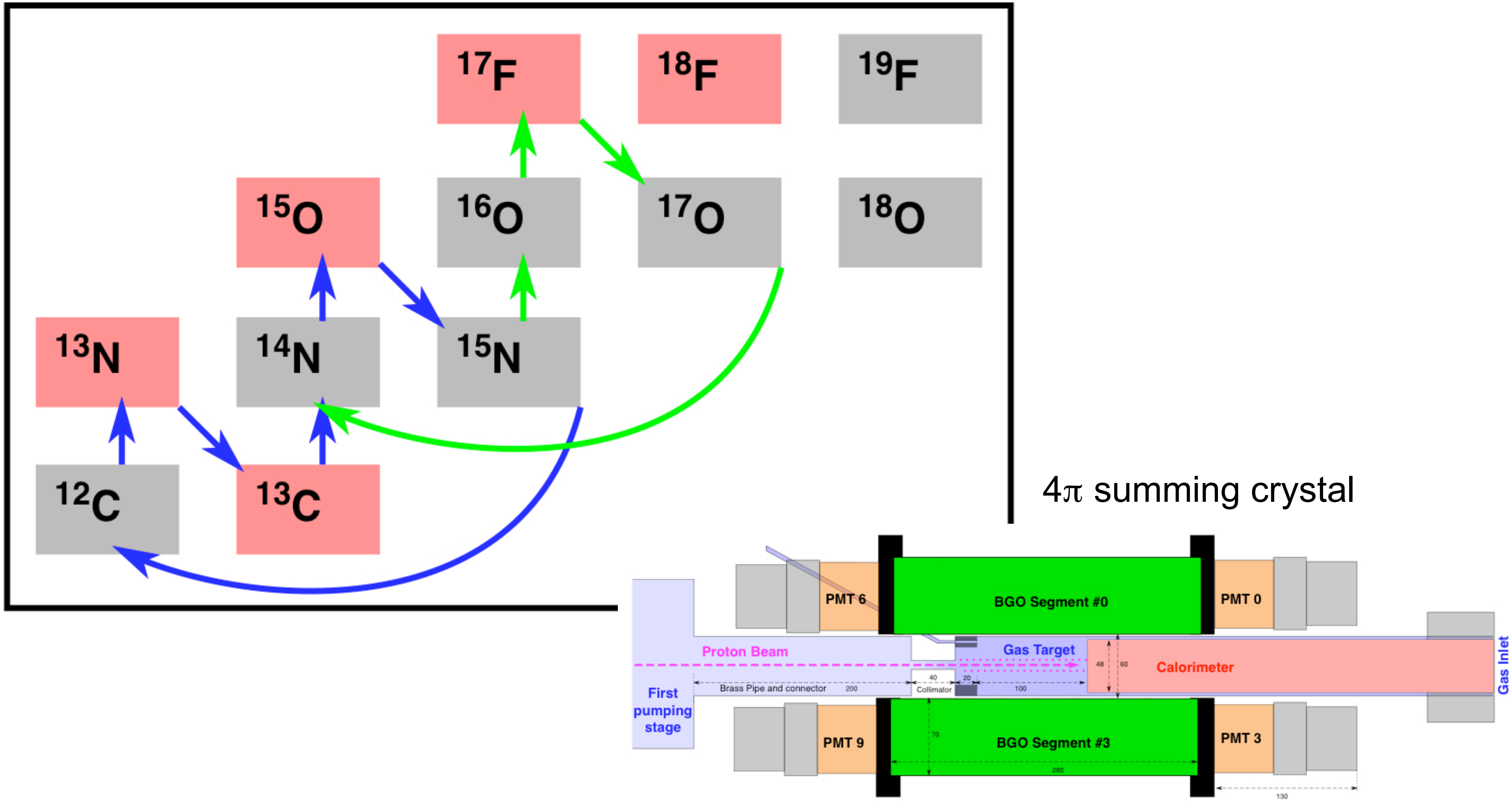


COMPTEL 1991–2000, ME 7
(Plüschke et al. 2001)

SPI spectrometer
(Integral satellite)

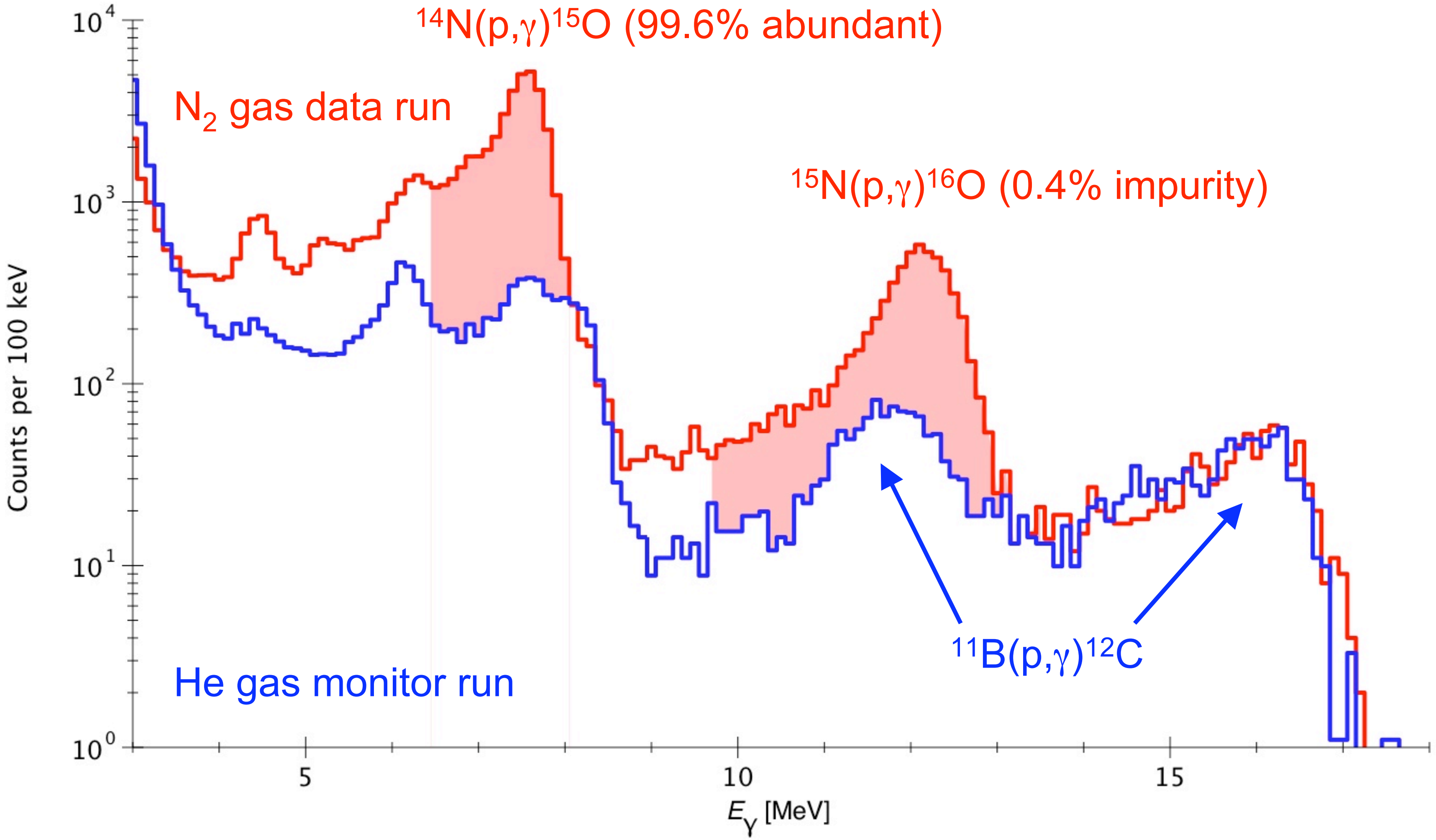
→^{25}Mg(p,γ)^{26}Al, study of resonance strengths

$^{15}N(p,\gamma)^{16}O$, at the crossroads of first and second CNO cycle



4π summing crystal

In-beam experiment, ~70% efficiency ${}^{nat}N(p,\gamma)$



${}^{14}N(p,\gamma){}^{15}O$ (99.6% abundant)

N_2 gas data run

${}^{15}N(p,\gamma){}^{16}O$ (0.4% impurity)

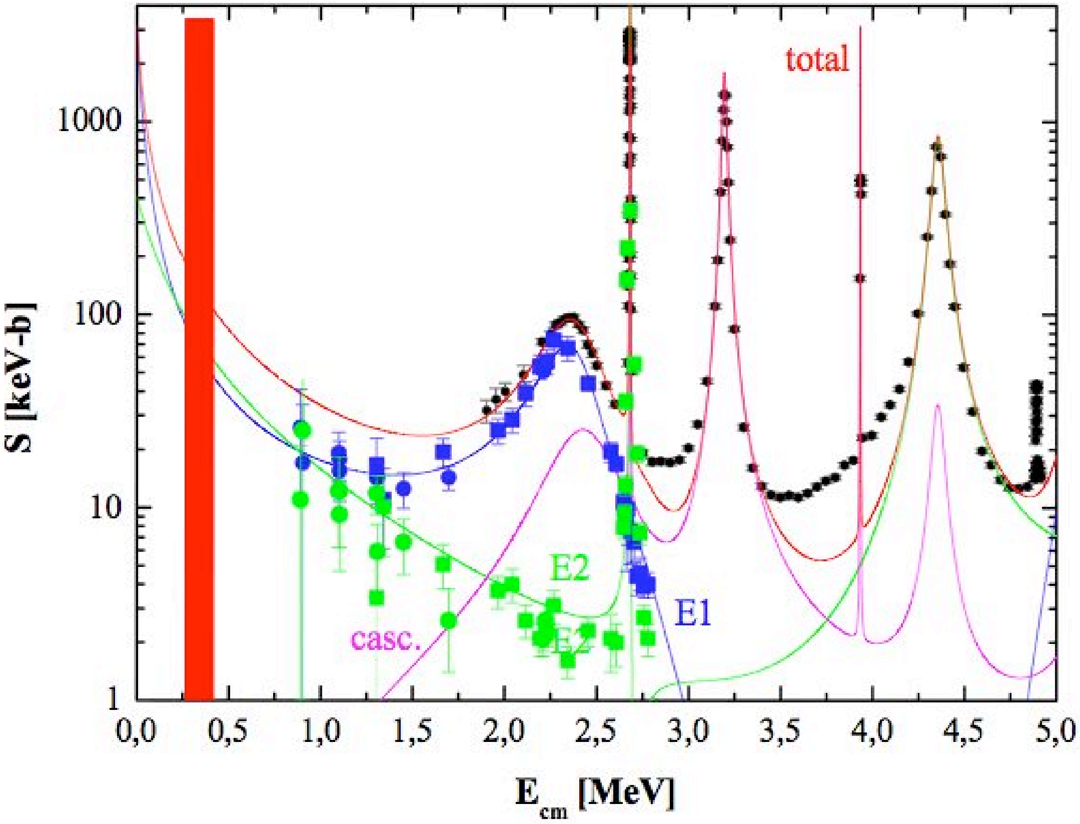
${}^{11}B(p,\gamma){}^{12}C$

He gas monitor run

Proposed LUNA-upgrade

3 MV single-ended accelerator
ECR ion source (~0.3 mA current), H, He, C, O, ...

Ongoing search for underground space: Gran Sasso (Italy), Spain, UK, Romania, US



Reactions on the shopping list:

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

$^{14}N(\alpha,\gamma)^{18}F$	He burning
$^{18}O(\alpha,\gamma)^{22}Ne$	He burning
$^{15}N(\alpha,\gamma)^{19}F$	He burning
$^{13}C(\alpha,n)^{16}O$	s-process
$^{22}Ne(\alpha,n)^{25}Mg$	s-process

etc.

Summary

- Nuclear measurements contribute to the development of the standard solar model
  - Proton-proton-chain: $^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}$ $^{7}\mathrm{Be}$, $^{8}\mathrm{B}$ neutrinos
  - CNO-cycle: $^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$ $^{13}\mathrm{N}$, $^{15}\mathrm{O}$ neutrinos
- More precise neutrino flux data
  call for more precise nuclear cross section data
- Exciting questions have to be answered also beyond solar neutrinos
  - $^{25}\mathrm{Mg}(p,\gamma)^{26}\mathrm{Al}$, $^{15}\mathrm{N}(p,\gamma)^{16}\mathrm{O}$, $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$, ...
- Stay tuned!

LUNA - Collaboration

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