MATTER

Precision cross section measurements - requirements, procedures, validation

Daniel Bemmerer

08.12.2020, Mainz, MITP workshop on “Uncertainties in Calculations of Nuclear Reactions of Astrophysical Interest”

MML ■ FROM MATTER TO MATERIALS AND LIFE

HZDR

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

DRESDEN concept

Precision cross section measurements for nuclear astrophysics

- Astrophysical S-factor and thermonuclear reaction rate
- Precision cross section measurements, example $^{14}N(p,\gamma)^{15}O$
- Interplay between experiment and theory, example $^{3}He(\alpha,\gamma)^{7}Be$
- Experimental facilities
- Other examples and outlook

Astrophysical S-factor, thermonuclear reaction rate, Gamow peak

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

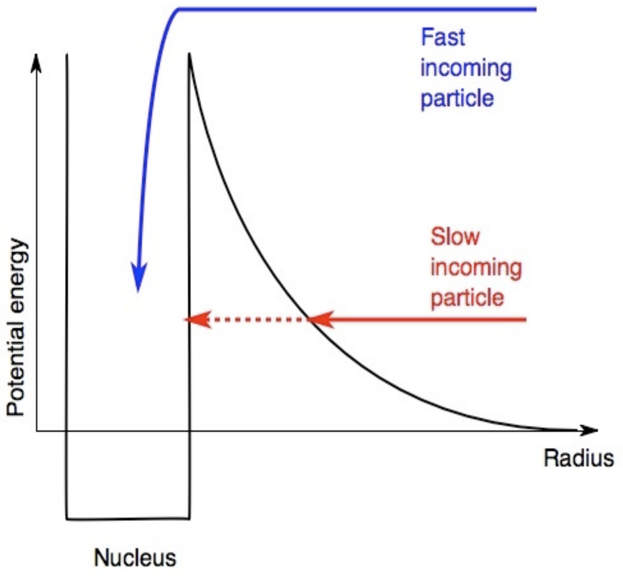
Definition of the astrophysical S-factor *S(E)*:

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

E = center of mass energy

Z_1, Z_2 = charge numbers of projectile and target

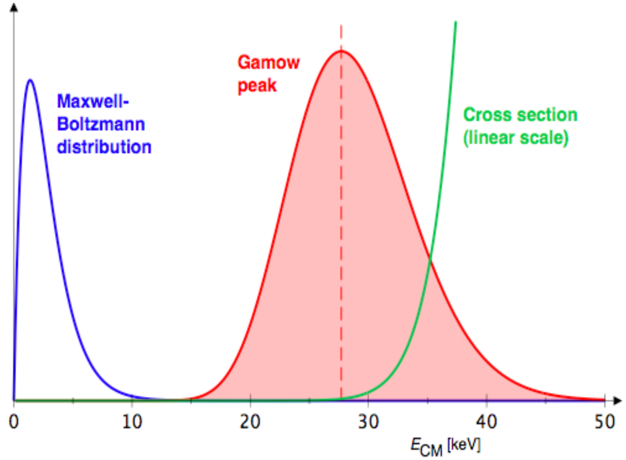
$\mu = \frac{m_1 m_2}{m_1 + m_2}$ = reduced mass



Thermonuclear reaction rate formed by

- Maxwell-Boltzmann velocity distribution
- Coulomb barrier suppression of cross section

$$N_A\langle\sigma v\rangle = N_A \sqrt{\frac{8}{\mu\pi}} (k_B T)^{-\frac{3}{2}} S(E) \times \int_0^\infty \exp\left[-\frac{E}{k_B T} - \frac{b}{\sqrt{E}}\right] dE$$



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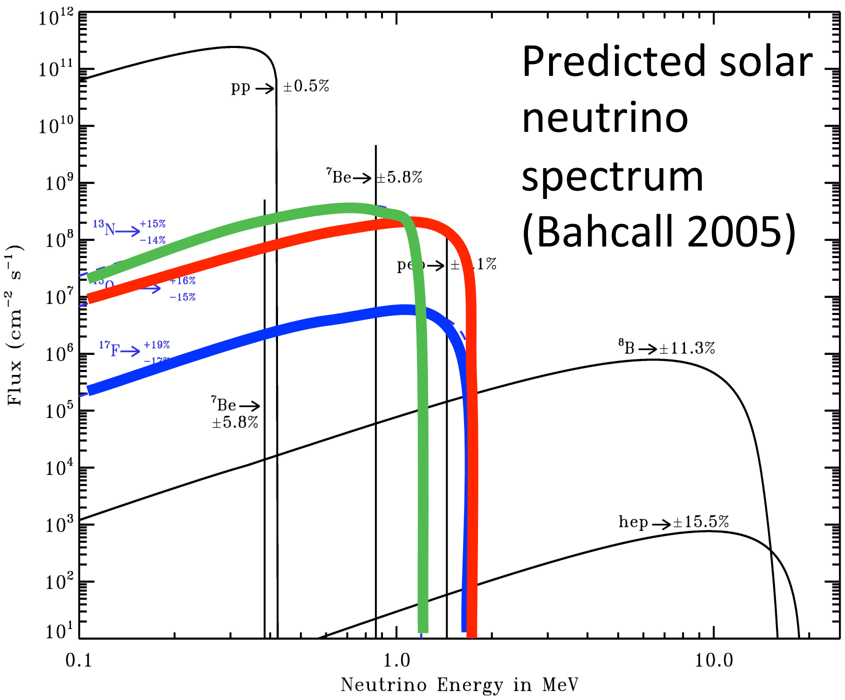
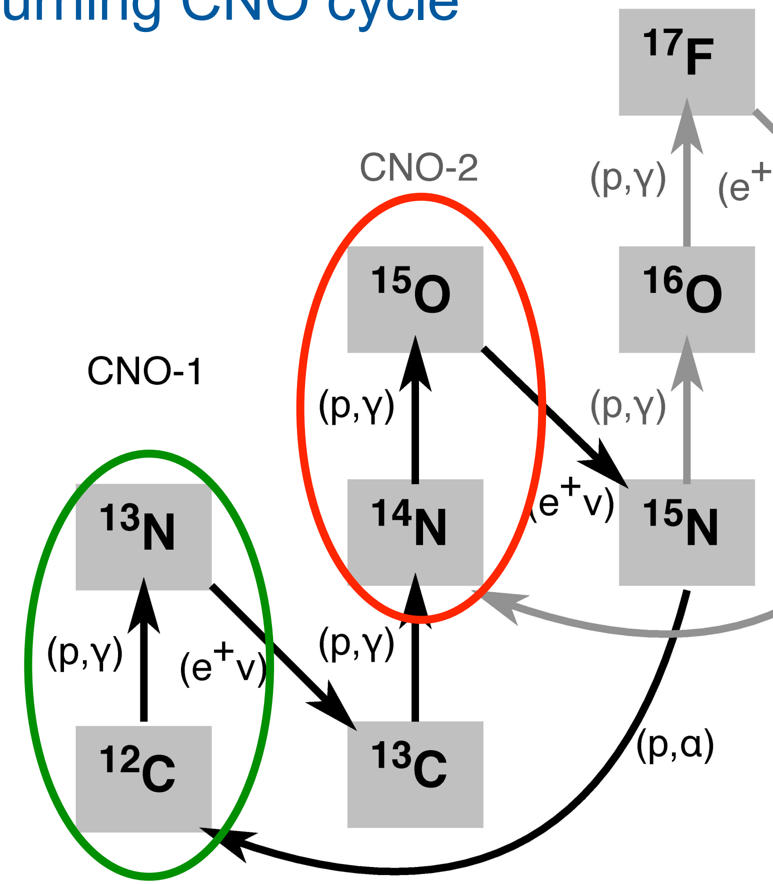
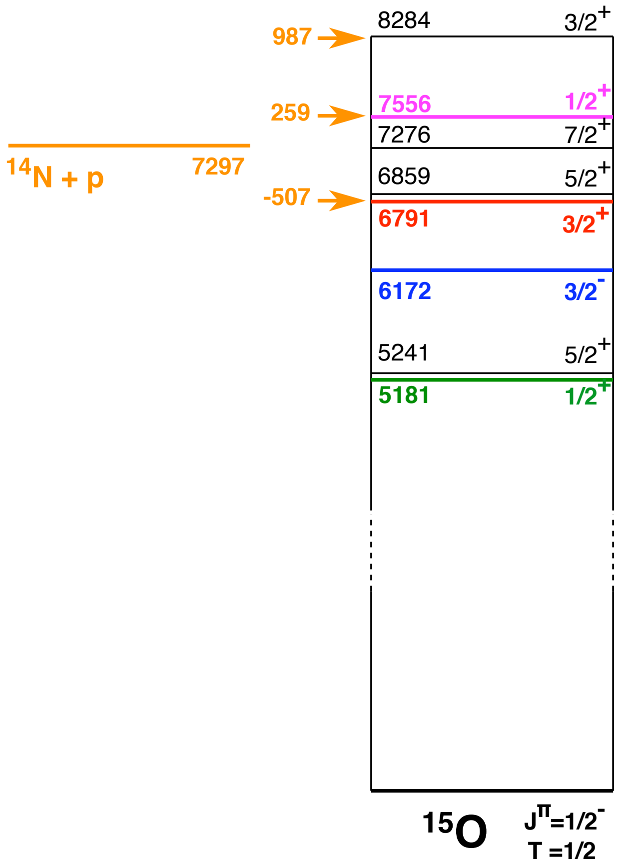
$^{14}N(p,\gamma)^{15}O$, bottleneck of the hydrogen burning CNO cycle

- Slowest reaction of the six-step CNO-1 cycle determines its solar rate
- Coulomb barrier leads to ultra-low cross section in the 10^{-17} barn range
- Potential to directly measure C+N content in the solar core

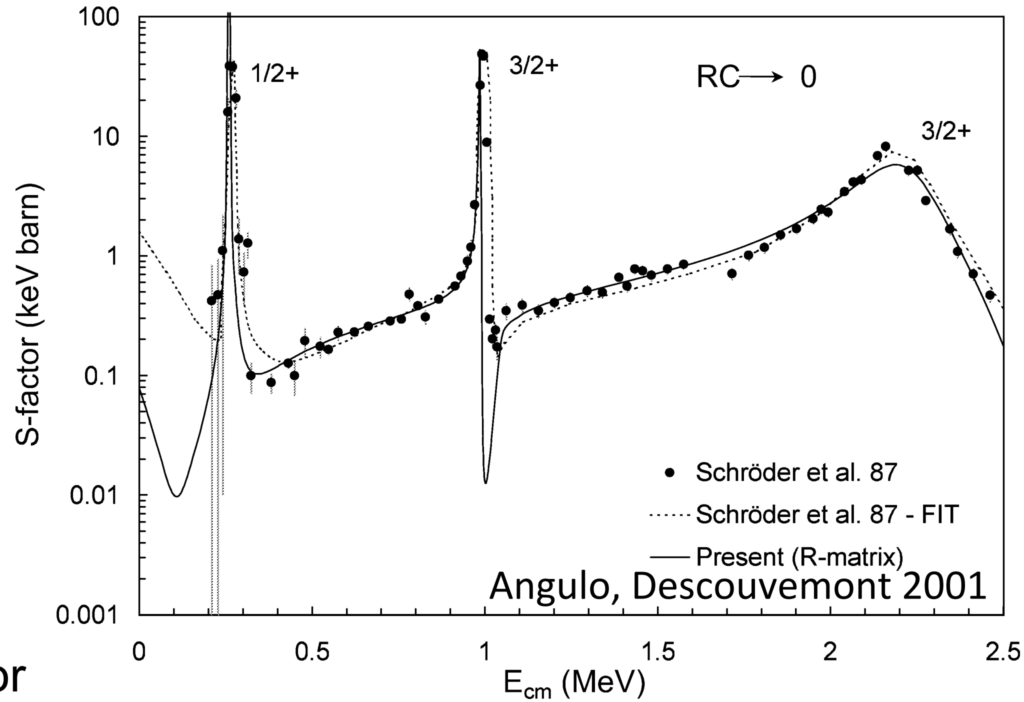




$^{14}N(p,\gamma)^{15}O$, bottleneck of the hydrogen burning CNO cycle



- Many excited ^{15}O levels accessible for ^{14}N+p
- Astrophysics is affected by the sum of capture to several excited levels in ^{15}O.
- A special role is played by the 6791 keV level.

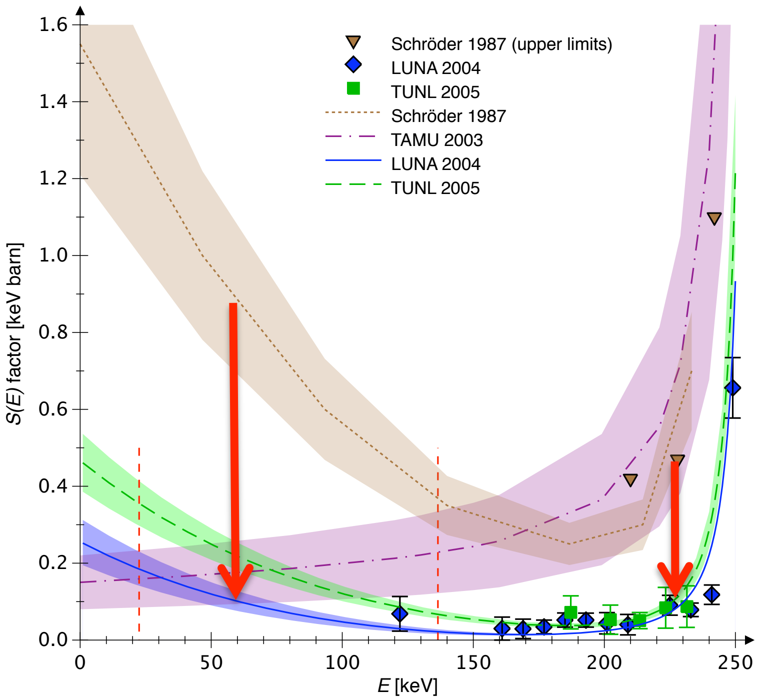


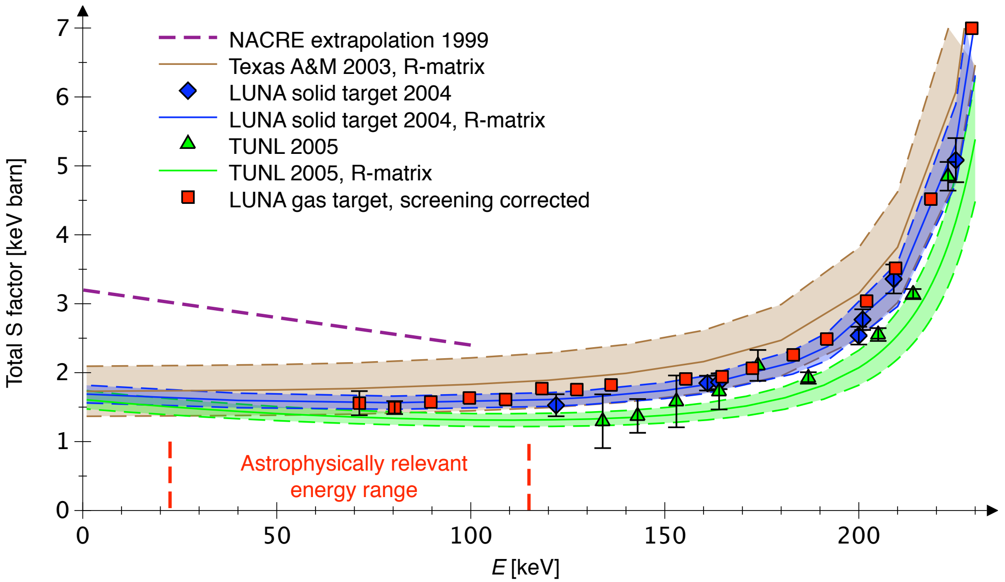
- New nuclear-structure data revised width of 6791 keV level downwards.
- R-matrix re-fit also suggested lower width… and lower S-factor

Experimental data on the $^{14}N(p,\gamma)^{15}O$ S-factor

Ground state capture revised downwards

- Ion accelerators and detectors better in 2004/2005 than in 1987
- Long experimental campaigns
- Careful correction of summing artefacts
- Underground experiment (LUNA 2004)

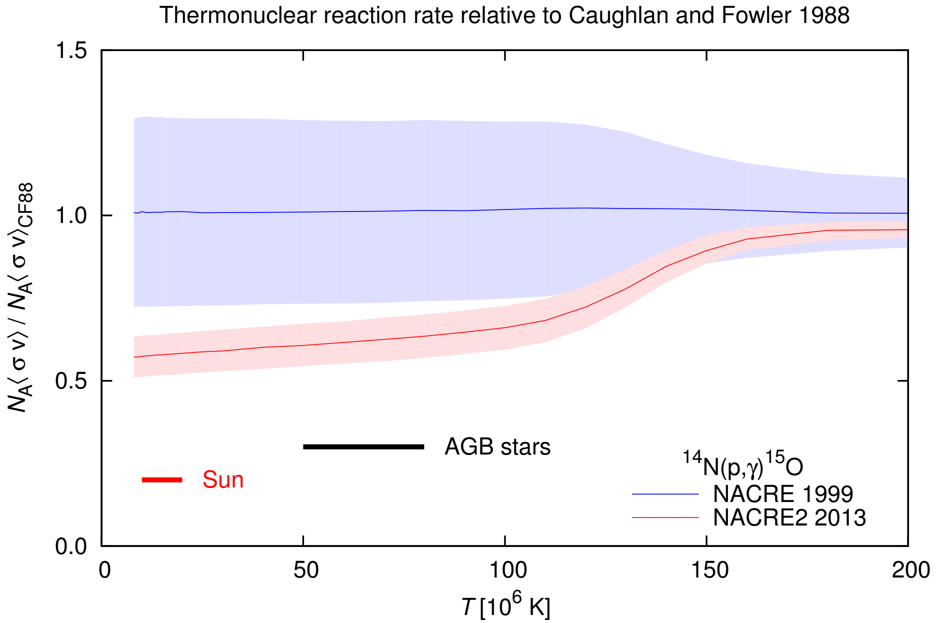


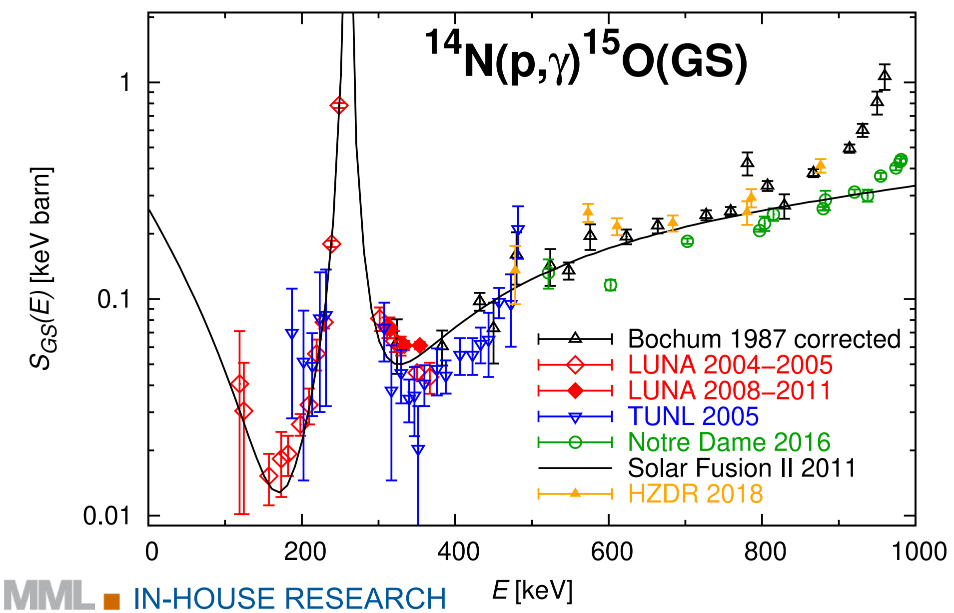


Total S-factor

- γ-calorimeter sums over all transitions and emitted γ-rays
- Detection probability close to 1
- Low background underground
- Some dependence on theoretical input

The $^{14}N(p,\gamma)^{15}O$ S-factor, status, lessons, outlook





Status

- Reduction of S-factor, and of its uncertainty (now 7%), from 1999 to 2013

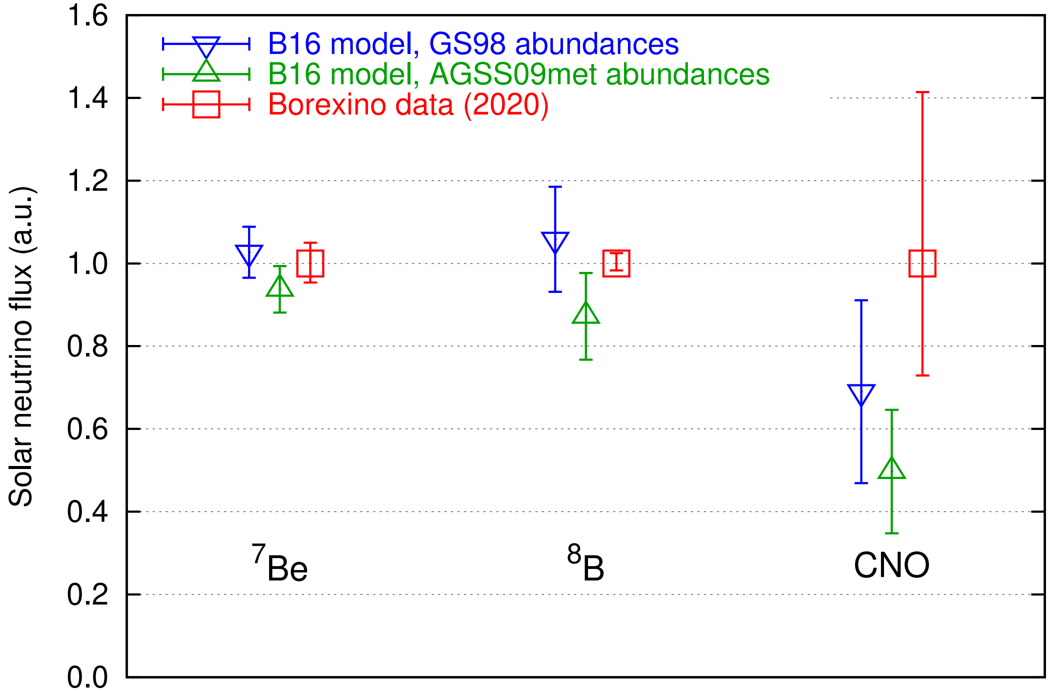
Lesson

- Experiment – theory – experiment – theory interplay is needed for complicated cases such as this one!

Outlook

- Yet more work is needed, in experiment and theory, in order to reach 3-5% uncertainty.

$^{14}N(p,\gamma)^{15}O$ S-factor, solar neutrino fluxes, and solar abundances



Neutrino fluxes from B16 Standard Solar Model, Vinyoles *et al.* 2017:

- **GS98** = Old, high CNO elemental abundances
- **AGSS09met** = New, low CNO elemental abundances

Data more precise than the models

2020 Borexino neutrino data slightly favor the old, high CNO elemental abundances…
… but a higher precision $^{14}N(p,\gamma)^{15}O$ S-factor is needed!

Precision cross section measurements for nuclear astrophysics

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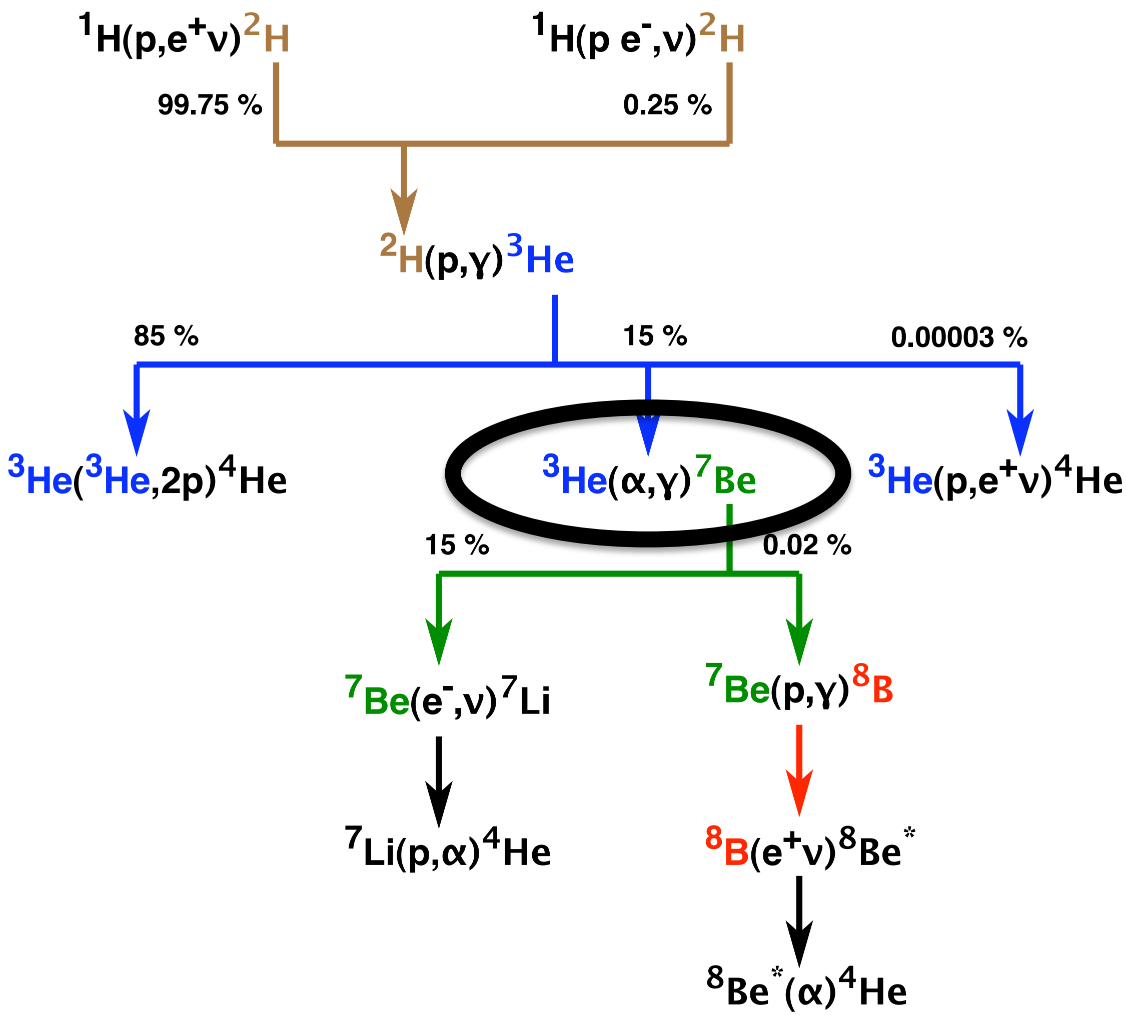
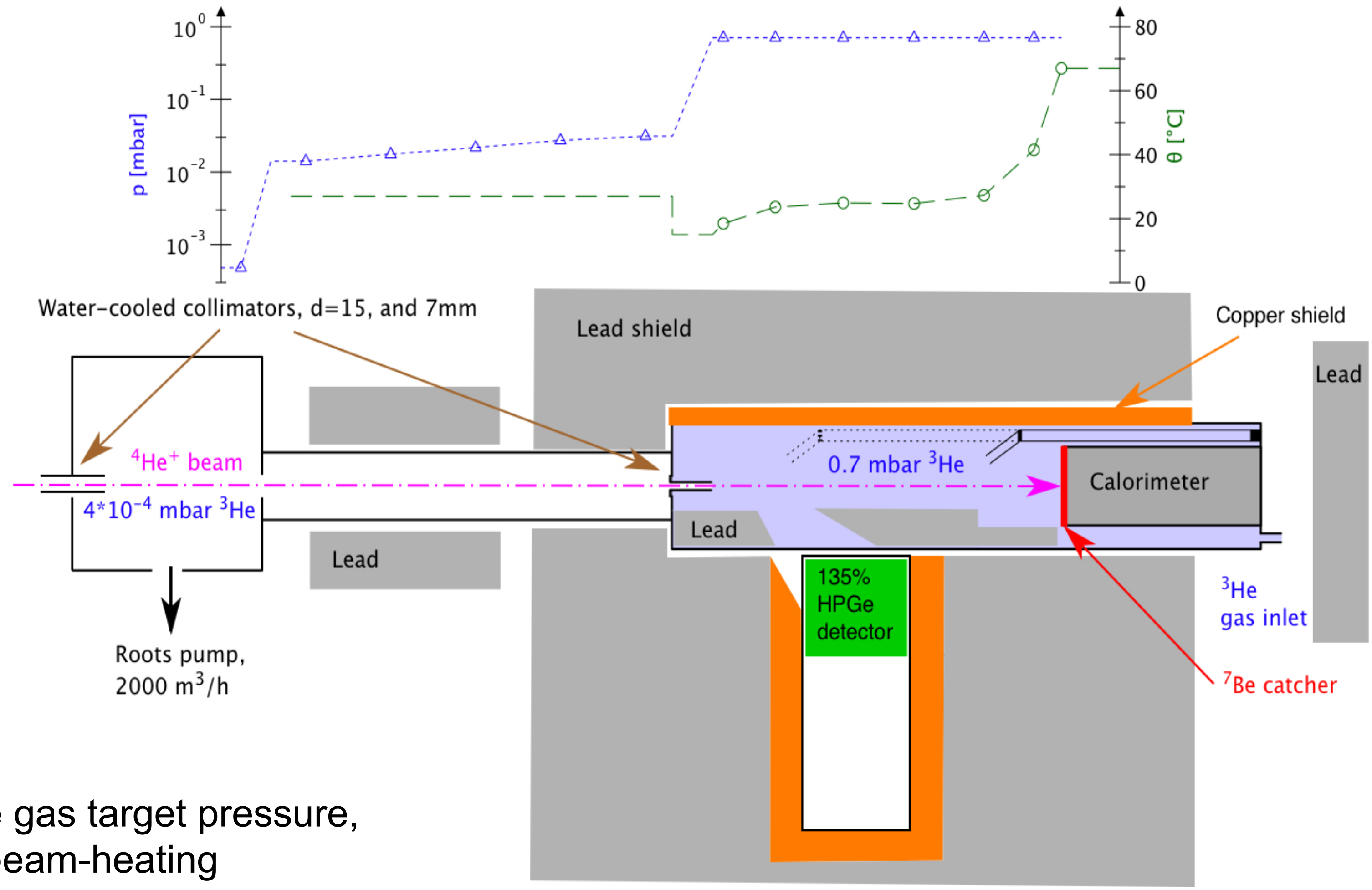
$^3He(\alpha,\gamma)^7Be$, at a crossroads of pp-chain hydrogen burning



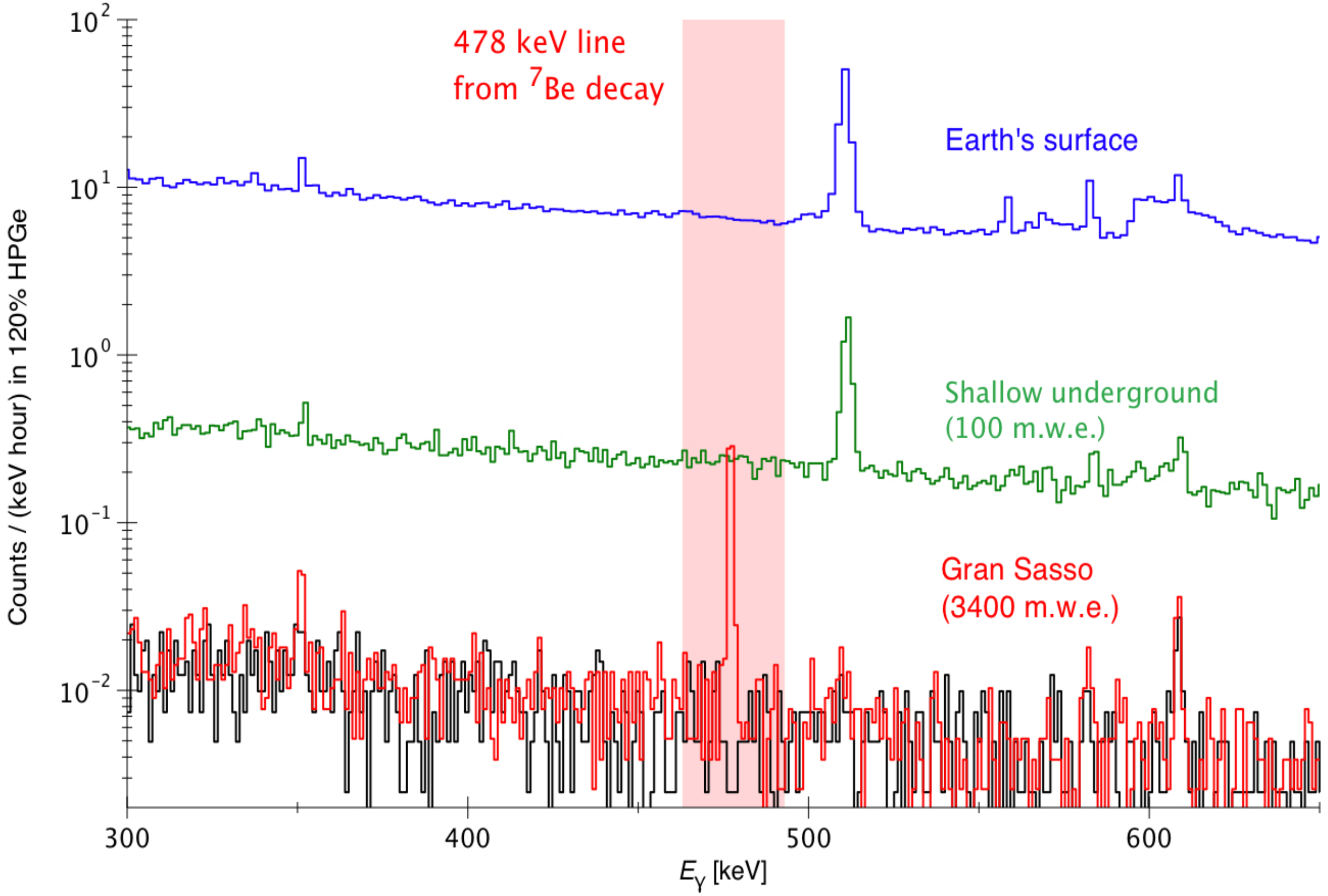
- The solar neutrino producing pp-II and pp-III chains start with $^3He(\alpha,\gamma)^7Be$
- At higher temperatures and energies, the same reaction impacts Big Bang ^7Li production

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



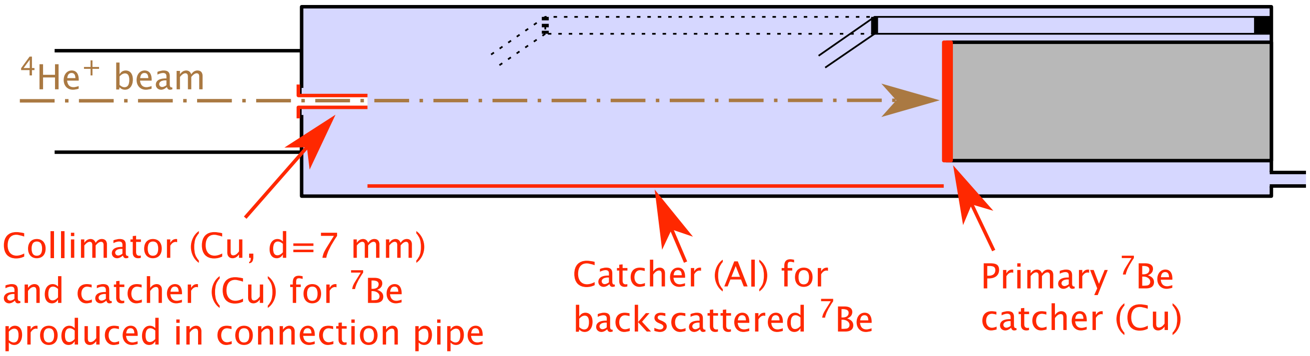
- Calibrated ^{3}He gas target pressure, temperature, beam-heating
- Beam energy and intensity precisely known
- Precise knowledge of detection probabilities for reaction products γ and ^{7}Be

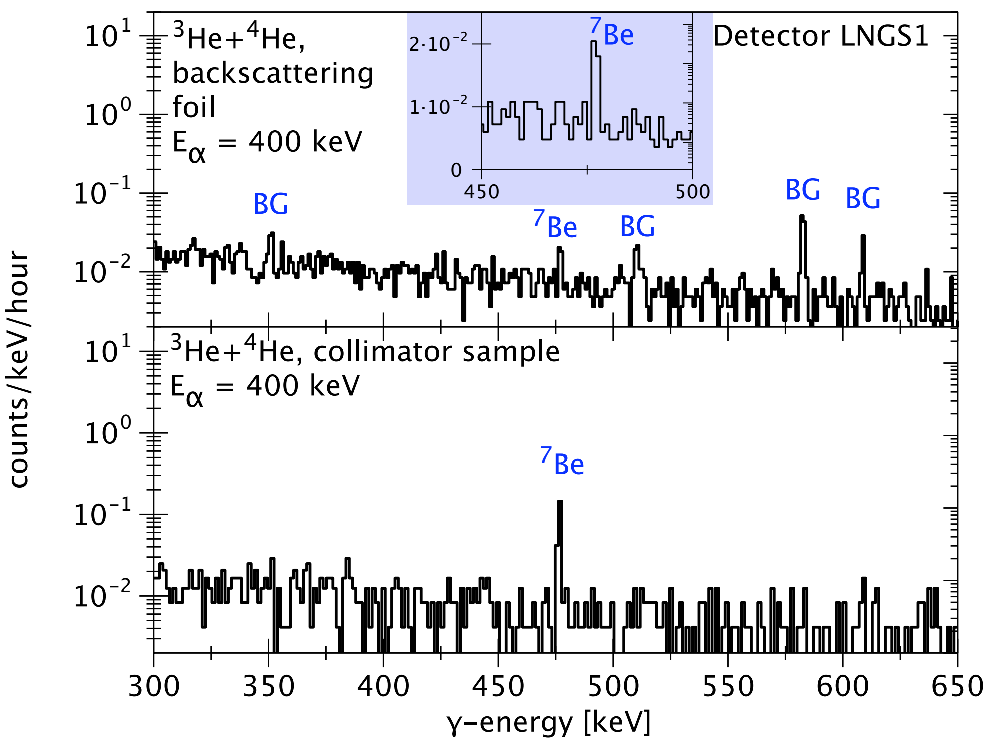
^{3}He(α,γ)^{7}Be at LUNA, ^{7}Be decay line at 478 keV



- Underground (Gran Sasso) suppression of cosmic-ray background.
- Orders of magnitude improvement of signal/noise ratio enables qualitative change.

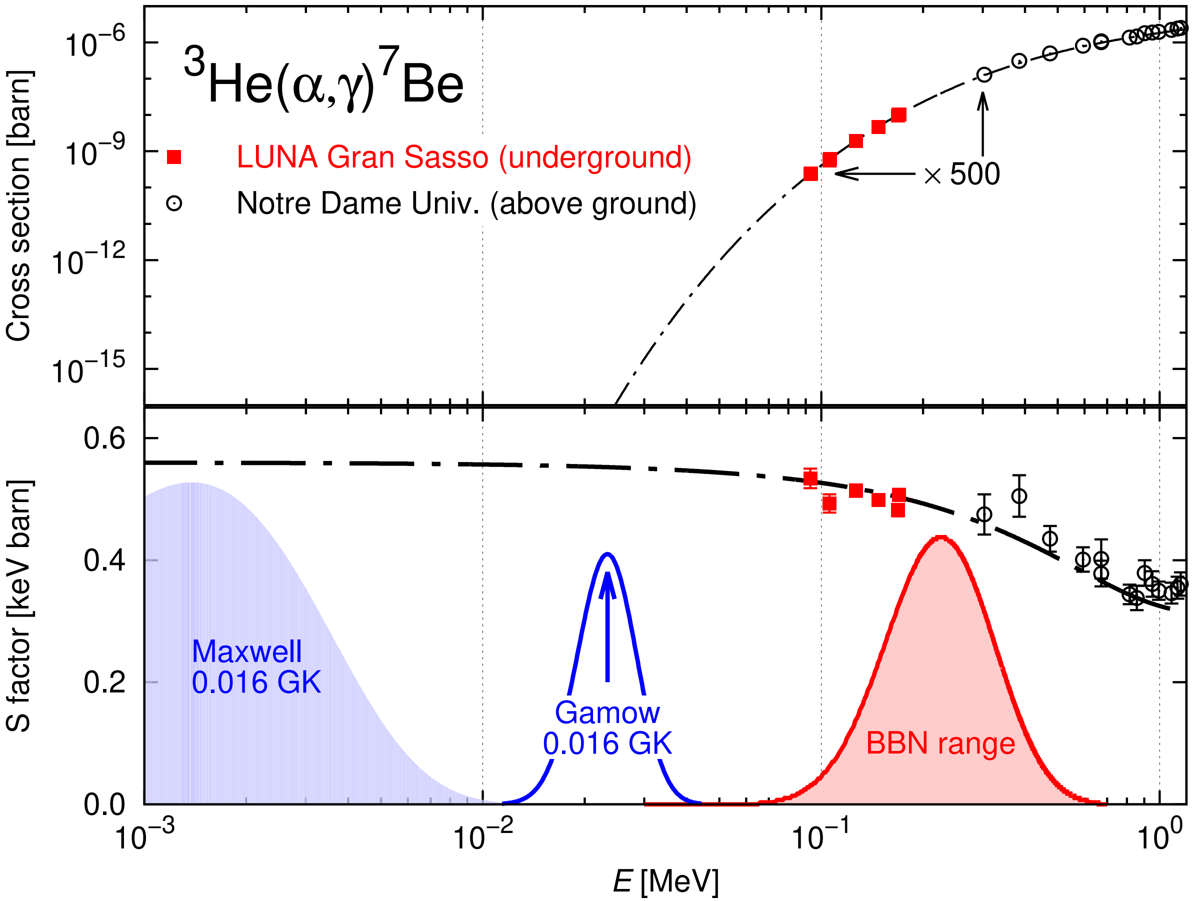
$^3He(\alpha,\gamma)^7Be$ at LUNA, ^7Be corrections and error budget





Systematic error budget	
^3He target gas density	1.5%
^4He ion beam intensity	1.5%
^7Be detection efficiency	1.8%
^7Be losses	0.7%
Total systematic uncertainty	**3.0%**

$^3He(\alpha,\gamma)^7Be$: strength and limitation of underground data



$$N_A\langle\sigma v\rangle = N_A\sqrt{\frac{8}{\mu\pi}}(k_\mathrm{B}T)^{-\frac{3}{2}}\,S(E)\times$$
$$\int_0^\infty \exp\left[-\frac{E}{k_\mathrm{B}T} - \frac{b}{\sqrt{E}}\right] dE$$

- Big Bang 0.3-0.9 GK
- Sun 0.016 GK

Strength:

- 500 times increased sensitivity underground, compared to the most advanced overground experiment

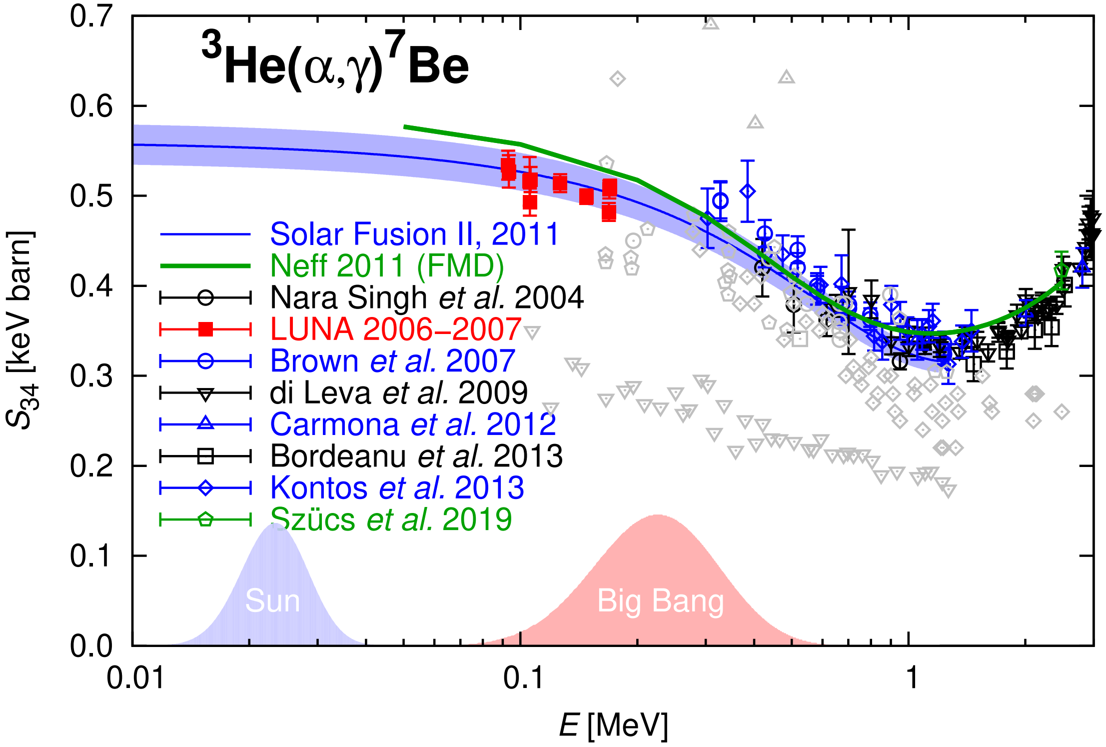
Limitation:

- Theory (very much) needed to extrapolate.

But:

- Theory can now be compared with data at high and low energies.

$^3He(\alpha,\gamma)^7Be$ reaction, S-factor data synopsis



Data, state of the art

- At 1 MeV many data sets
- At 0.1 MeV, one data set
- At 0.03 MeV, no data

Data extrapolation

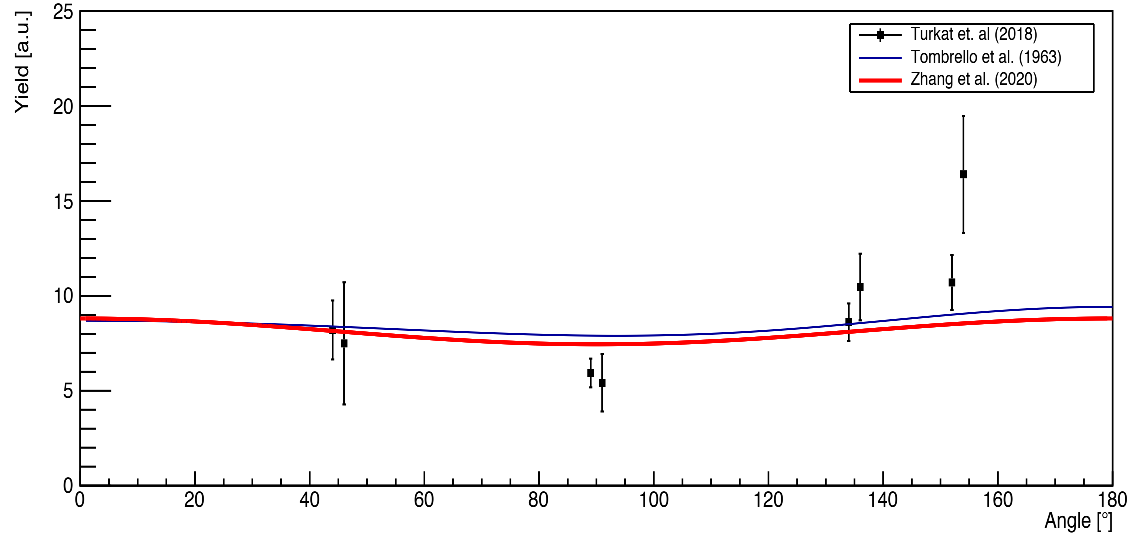
- How to transfer information from the well-studied 1 MeV region to low energy?
- Extrapolation from the "Solar Fusion II" decadal review from an average of several theories (new edition planned for 2022)
- New theory curves upcoming (example shown: Neff)

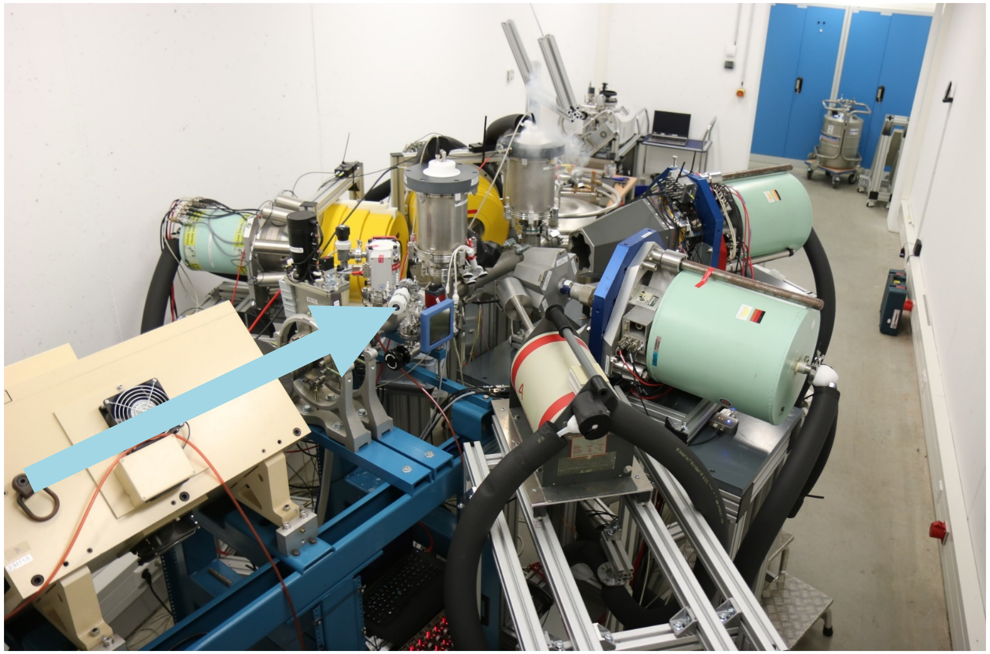
Footnote: High-energy – low-energy connection may be used to connect Big Bang and the Sun

- Takács et al. Phys. Rev. D (2015), Nucl. Phys. A (2018)

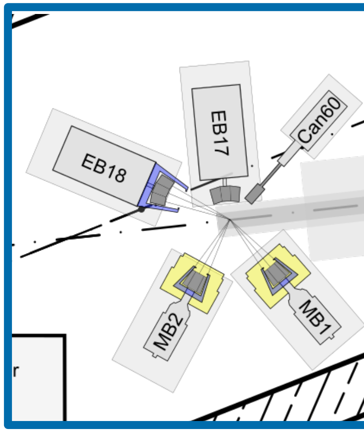
$^{3}He(\alpha,\gamma)^{7}Be$, running measurement of the γ-ray angular distribution

- Test experiment with 5 HPGe detectors at HZDR 3 MV Tandetron overground (preliminary data shown)
- Full experiment with 21 HPGe detectors at Felsenkeller 5 MV accelerator underground (running)





HPGe detectors
→ **EB17**, 7x60%
→ **EB18**, 7x60% + BGO
→ **MB1**, 3x60% + BGO
→ **MB2**, 3x60% + BGO
→ **Can60**, 1x60%



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HZDR

$^3He(\alpha,\gamma)^7Be$ reaction, general lessons and way forward

Low uncertainty for each data set

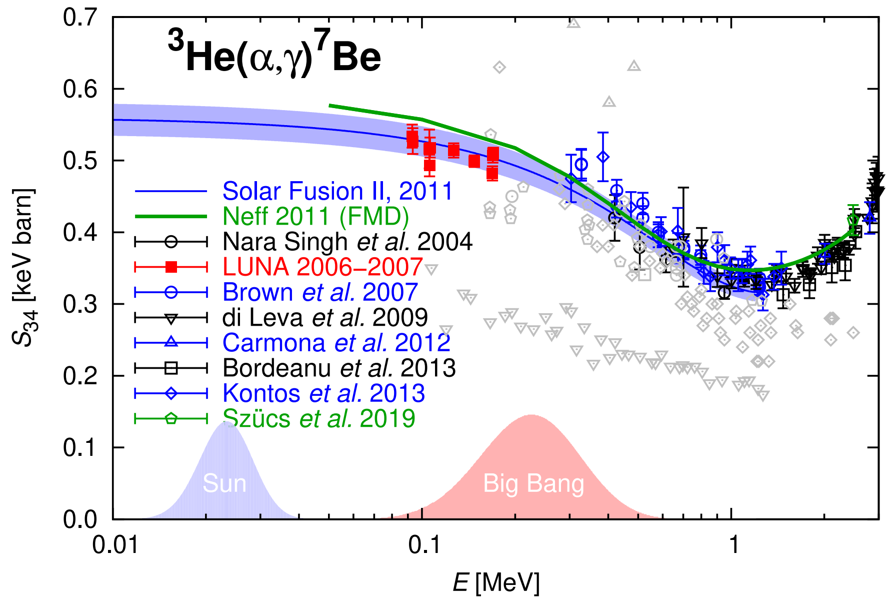
- Absolute target thickness (usually gas) or
- Target thickness relative to a standard
- Beam intensity, energy
- Probability of detecting reaction products

Reproducibility

- Need several independent data sets with independent techniques
- ^7Be activation, in beam γ-detection, accelerator mass spectrometry
- Community-accepted consensus value (Solar Fusion I, II, III workshops)

Transfer of experimental data from high to low energies

- Theory-based excitation function
- γ-ray angular distribution as additional information



For discussion

- Theory re-normalization possible?
- What about the mirror reaction $^3H(\alpha,\gamma)^7Li$?

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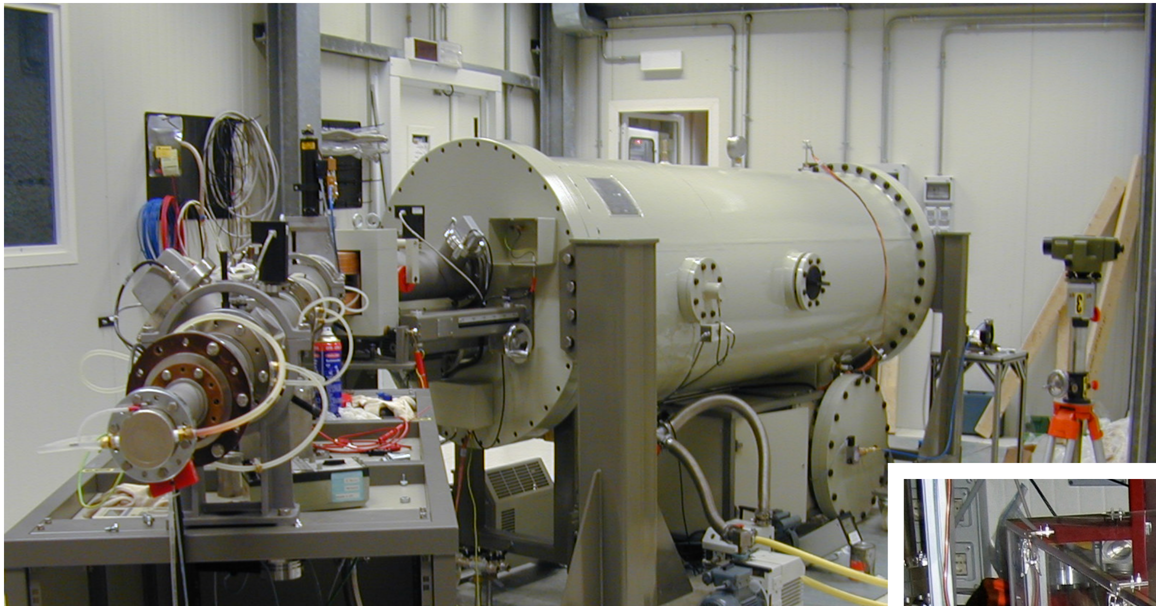
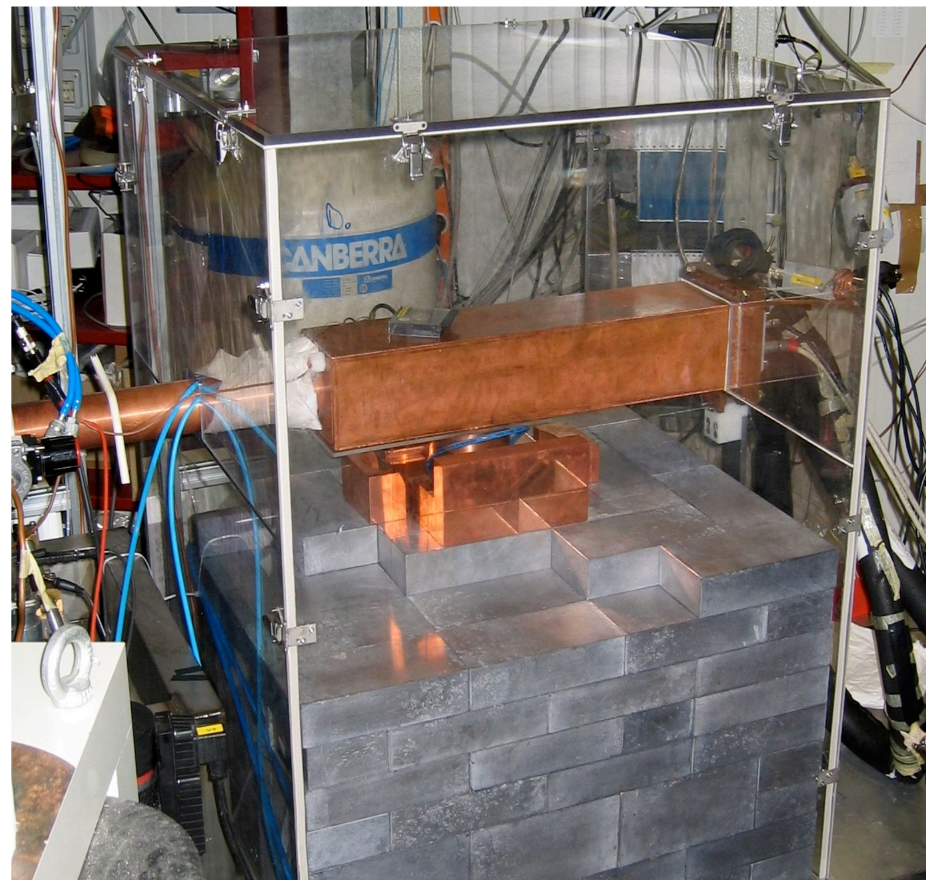
LUNA 0.4 MV accelerator deep underground

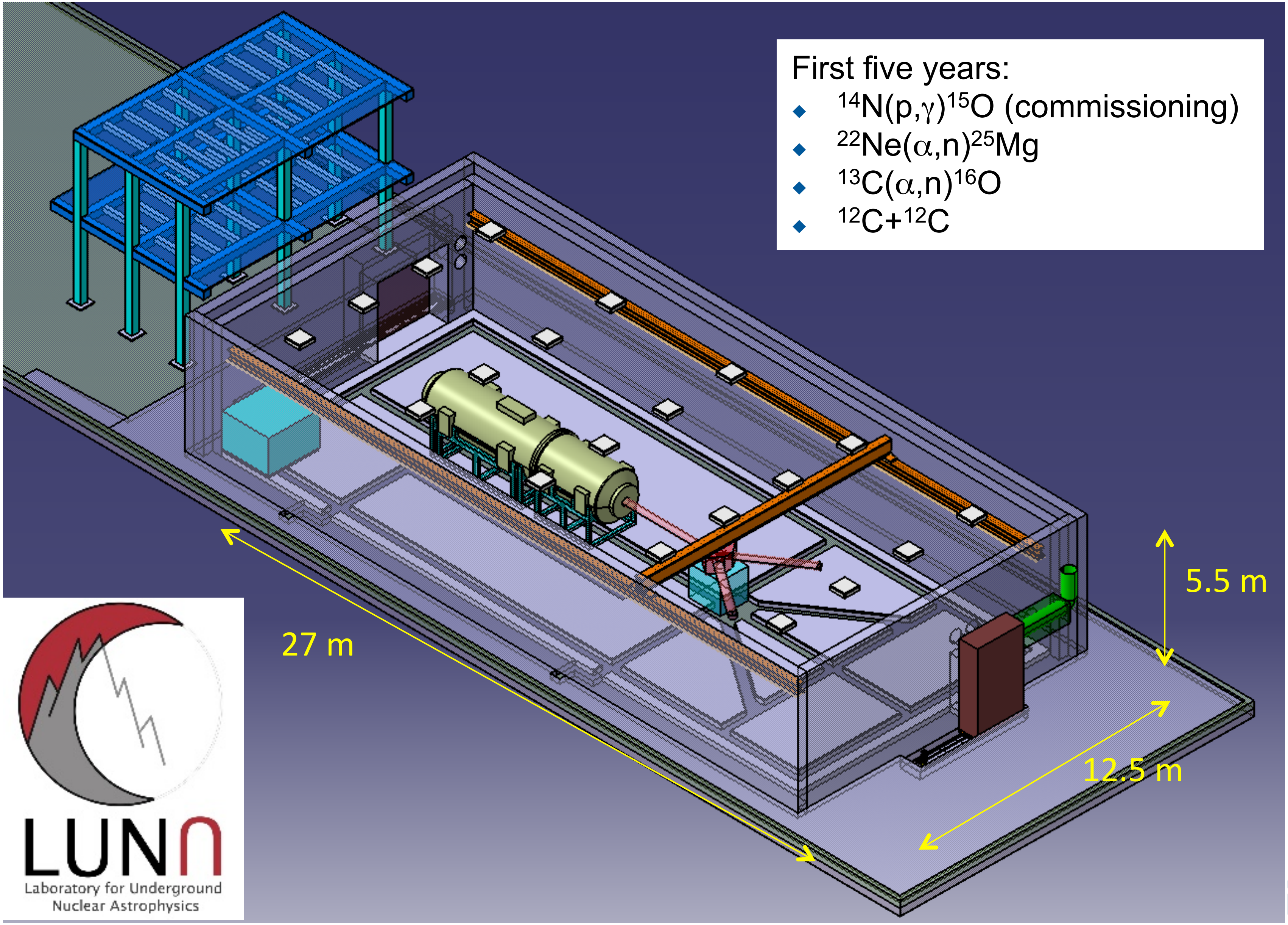


LUNA = Laboratory Underground for Nuclear Astrophysics

- IT, DE, HU, UK
- Cosmic rays strongly suppressed



New LUNA-MV 3.5 MV accelerator for ^{1}H, ^{4}He, ^{12}C beams: Installation in Gran Sasso hall B very soon



First five years:

- $^{14}N(p,\gamma)^{15}O$ (commissioning)
- $^{22}Ne(\alpha,n)^{25}Mg$
- $^{13}C(\alpha,n)^{16}O$
- $^{12}C+^{12}C$

LUNA
Laboratory for Underground
Nuclear Astrophysics

Dresden, Germany: Felsenkeller 5 MV underground accelerator

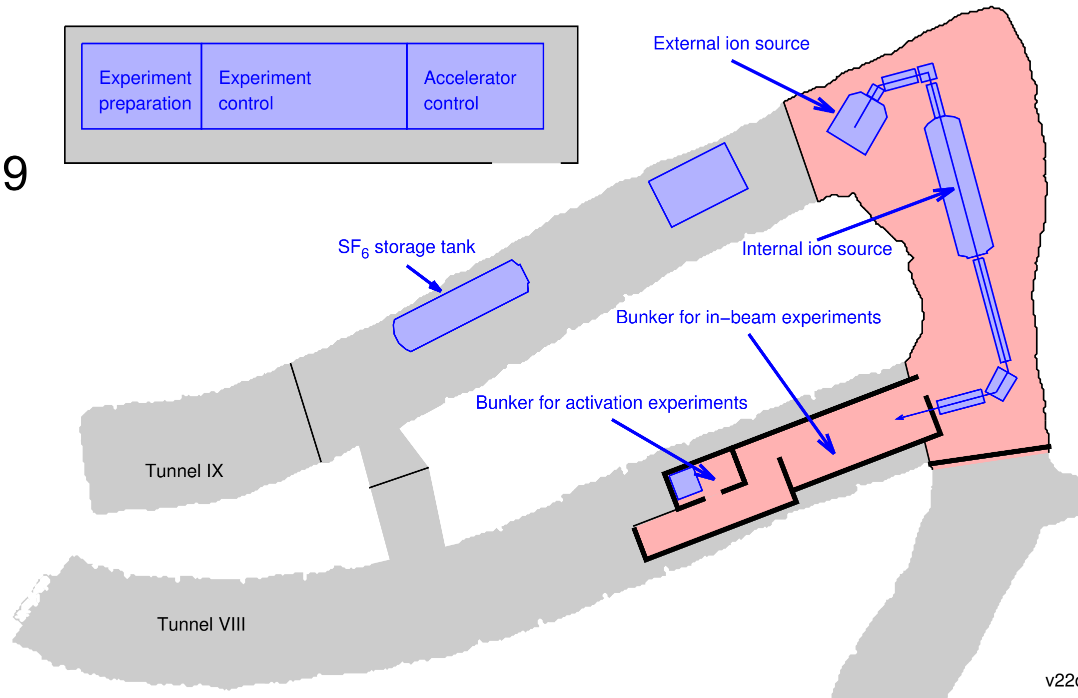
T. Kajita

Joint effort HZDR – TU Dresden

- **HZDR:** 5 MV Pelletron, 30 μA beams of $^{1}H^{+}$, $^{4}He^{+}$ (single-ended), $^{12}C^{+}$ (tandem)
- **TU Dresden:** 150% ultra-low-background HPGe detector for offline γ-counting

Start of beam operations July 2019

- $^{3}He(\alpha,\gamma)^{7}Be$ with ^{4}He beam
- $^{12}C(\alpha,\gamma)^{16}O$ with ^{12}C beam
- Plan to open for external users in 2021



v22d

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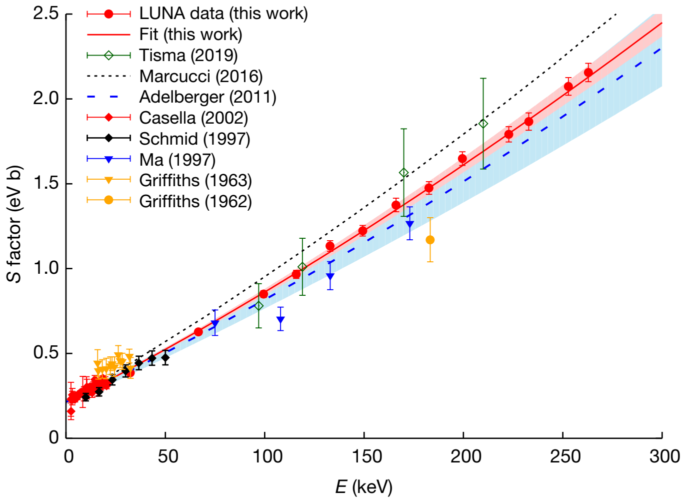
Big Bang ^{2}H studied at LUNA : Nature 587, 210-213 (2020)



Article

The baryon density of the Universe from an improved rate of deuterium burning

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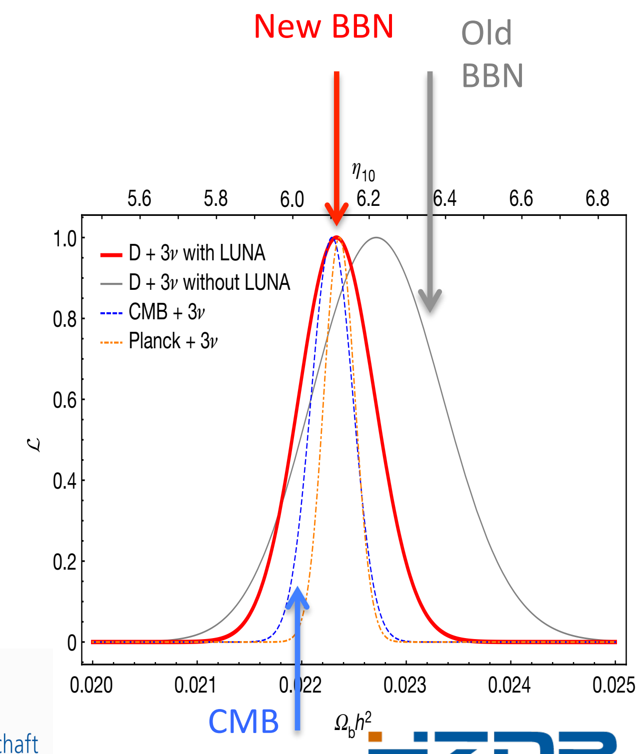
V. Mossa[1], K. Stöckel[2,3], F. Cavanna[4,26], F. Ferraro[4,5], M. Aliotta[6], F. Barile[1], D. Bemmerer[2], A. Best[7,8], A. Boeltzig[9,10], C. Broggini[11], C. G. Bruno[6], A. Caciolli[11,12], T. Chillery[6], G. F. Ciani[9,10], P. Corvisiero[4,5], L. Csedreki[9,10], T. Davinson[6], R. Depalo[11], A. Di Leva[7,8], Z. Elekes[13], E. M. Fiore[1,14], A. Formicola[10], Zs. Fülöp[13], G. Gervino[15,16], A. Guglielmetti[17,18], C. Gustavino[19] ✉, G. Gyürky[13], G. Imbriani[7,8], M. Junker[10], A. Kievsky[20], I. Kochanek[10], M. Lugaro[21,22], L. E. Marcucci[20,23], G. Mangano[7,8], P. Marigo[11,12], E. Masha[17,18], R. Menegazzo[11], F. R. Pantaleo[1,24], V. Paticchio[1], R. Perrino[1,27], D. Piatti[11], O. Pisanti[7,8], P. Prati[4,5], L. Schiavulli[1,14], O. Straniero[10,25], T. Szücs[2], M. P. Takács[2,3], D. Trezzi[17,18], M. Viviani[20] & S. Zavatarelli[4] ✉

Ingredients for 3% precision include

- Absolute target density (^{2}H gas target)
- Precise beam calibration (energy, calorimetric intensity)
- Detection probability for detected γ-rays using several different methods
- Theory support for γ-ray angular distribution
- Theory support for cosmological impact



Gefördert durch DFG Deutsche Forschungsgemeinschaft

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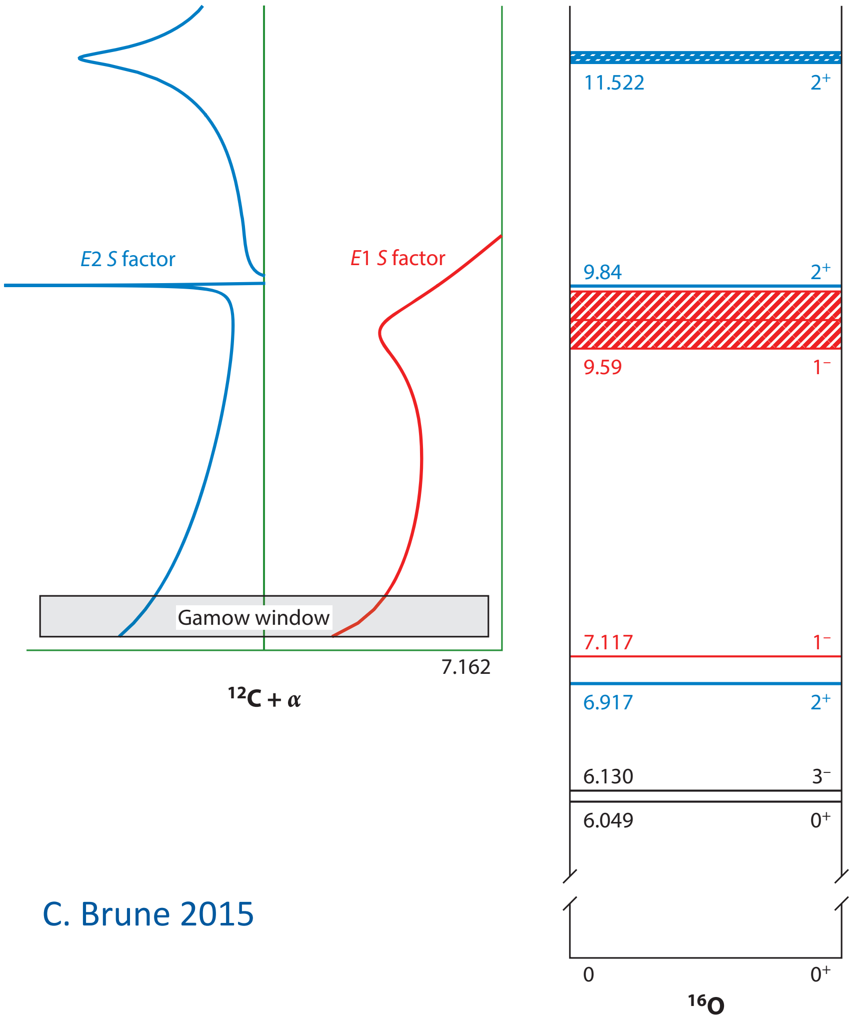
The $^{12}C(\alpha,\gamma)^{16}O$ reaction, the “Holy Grail” of Nuclear Astrophysics



C. Brune 2015

Forward reaction →

Underground accelerators with γ-ray detection

- Felsenkeller 5 MV (gas target)
- LUNA-MV 3.5 MV

$$^{12}\mathrm{C} + {}^{4}\mathrm{He} \rightarrow {}^{16}\mathrm{O}(0, 6.049, 6.130, \ldots)$$

$$^{12}\mathrm{C} + {}^{4}\mathrm{He} \leftarrow {}^{16}\mathrm{O}(0)$$

Time-inverted reaction ←

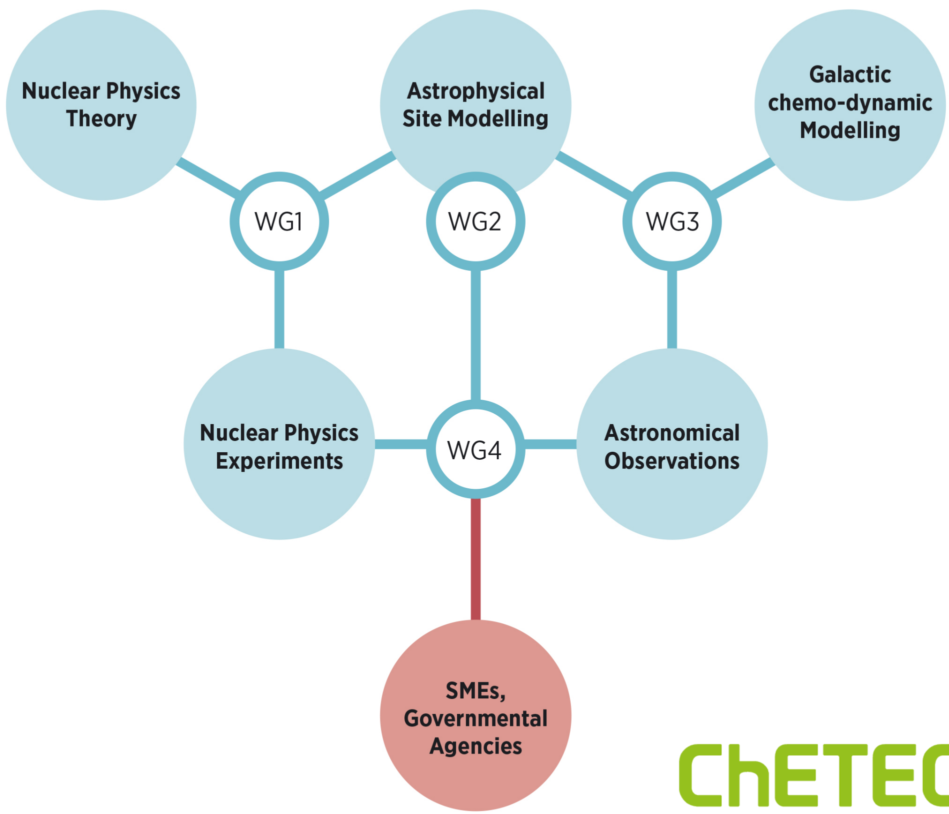
- Real, monochromatic 7 MeV photons: HIγS, ELI-NP
- Virtual 7 MeV photons: R^3B@GSI, by Coulomb dissociation

COST action ChETEC [ketek] 2017-2021

Chemical Elements as Tracers of the Evolution of the Cosmos

A network to bring European research, science and business together to further our understanding of the early universe

cost
EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY



ChETEC Action

http://www.chetec.eu

- ~150 k€/year 2017-2021
- 30 European countries

Support for meetings and schools

- 12 meetings in 2019

Short-term scientific missions (STSMs)

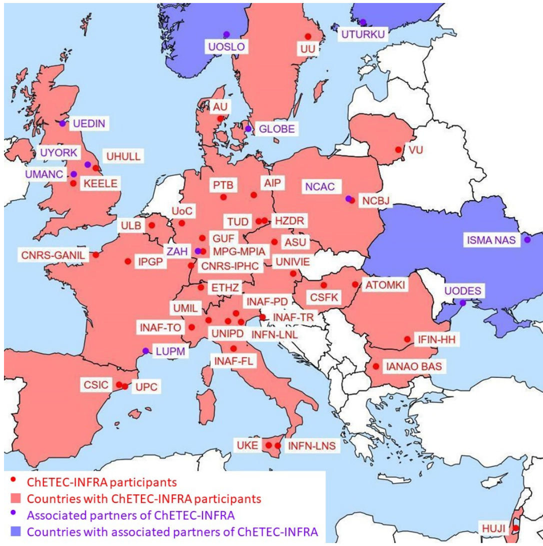
- Up to 90 days visits

Chair:

- Raphael Hirschi, Keele University/UK

ChETEC-INFRA, an EU-supported Starting Community of Research Infrastructures for Nuclear Astrophysics (2021 – 2025)

5.0 M€ HORIZON2020 support (2021-2025)		
TA	JRA	NA
Infrastructure access ◆ 8 nuclear ◆ 4 telescopes ◆ 1 computer	Infrastructure usability ◆ Targets ◆ Abundance corrections ◆ Analysis pipelines	Infrastructure networking ◆ Complementary data ◆ Solar fusion+model ◆ Geochemistry ◆ Outreach
32 partners, 17 countries, open for associate partners		



EuroGENESIS ESF
2010-2013
C: UPC Barcelona

→

ChETEC COST
Action 2017-2021
C: Uni Keele/UK

→

ChETEC-INFRA
2021-2025
C: HZDR/DE

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Potential for collaboration theory – experiment

- The field is rich and growing: new ideas, new labs, new projects
- Feedback loop theory – experiment – theory regarding cross sections
- γ-ray angular distribution helps both experiment and theory
- Study of similar and mirror reactions, etc., etc.

- Helmholtz NAVI, DTS, MML, ERC-RA; DFG
- TU Dresden Excellence Initiative funds (K. Zuber), DFG Großgerät (K. Zuber)
- European Union (H2020 INFRAIA-02)

Felsenkeller underground background characterisation

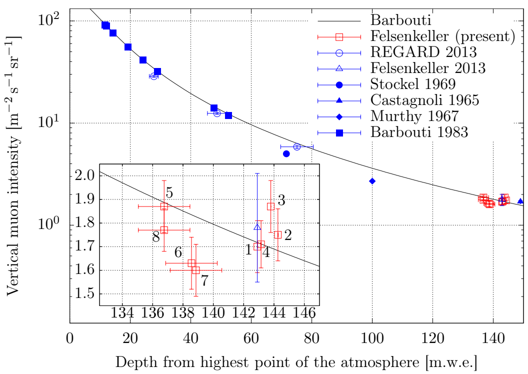
Myon flux and angular distribution

Measured and simulated

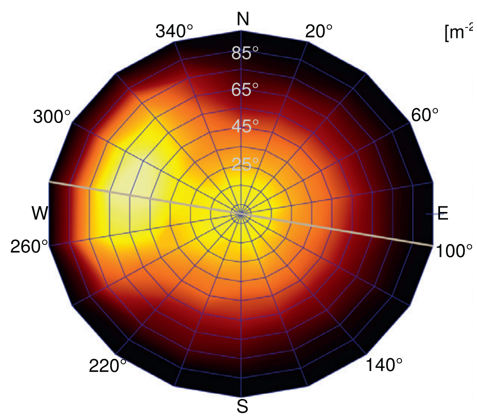
5.4(4) $m^{-2}s^{-1}$

F. Ludwig *et al.*

Astropart. Phys. 112, 24 (2019)



Measured



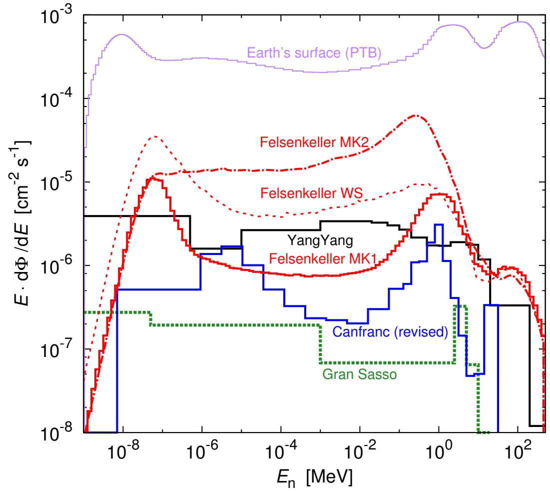
Neutron flux and energy spectrum

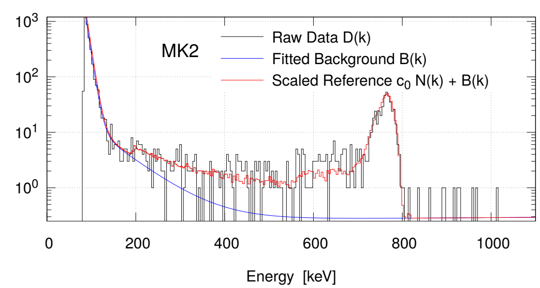
Measured and simulated

4.6(3) $m^{-2}s^{-1}$

M. Grieger *et al.*

Phys. Rev. D 101, 123027 (2020)





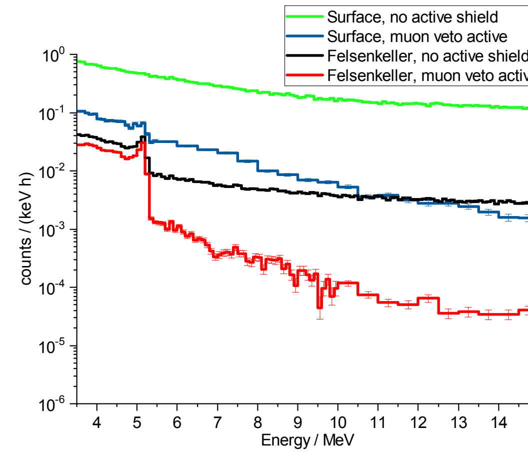
Background in γ-ray detectors with μ veto

Measured

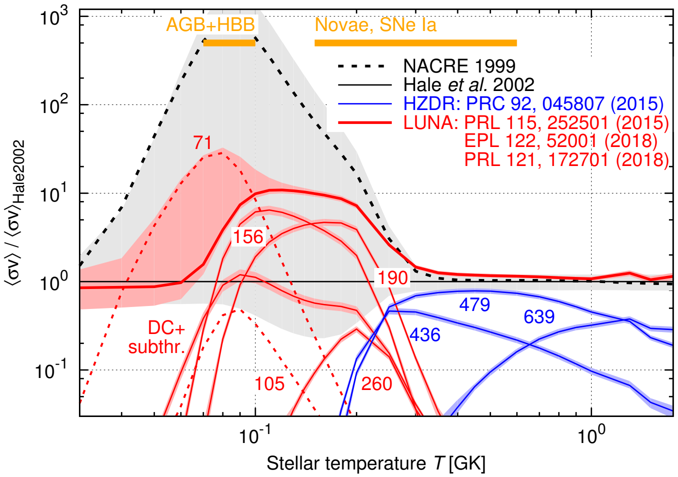
$5.2(9) \times 10^{-5}$ $keV^{-1}h^{-1}$

T. Szücs *et al.*

Eur. Phys. J. A 55, 174 (2019)

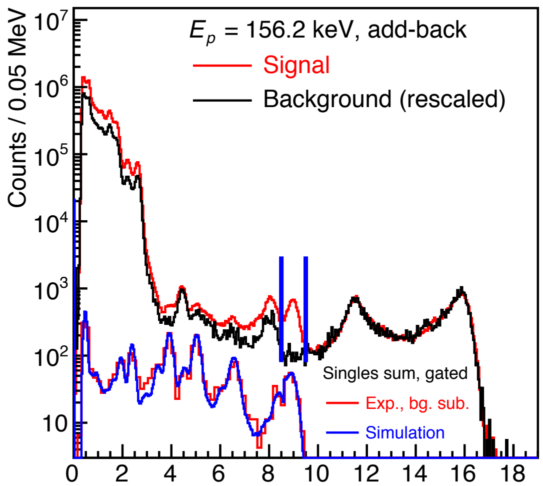


^{23}Na production by hydrogen burning: ^{22}Ne(p,γ)^{23}Na



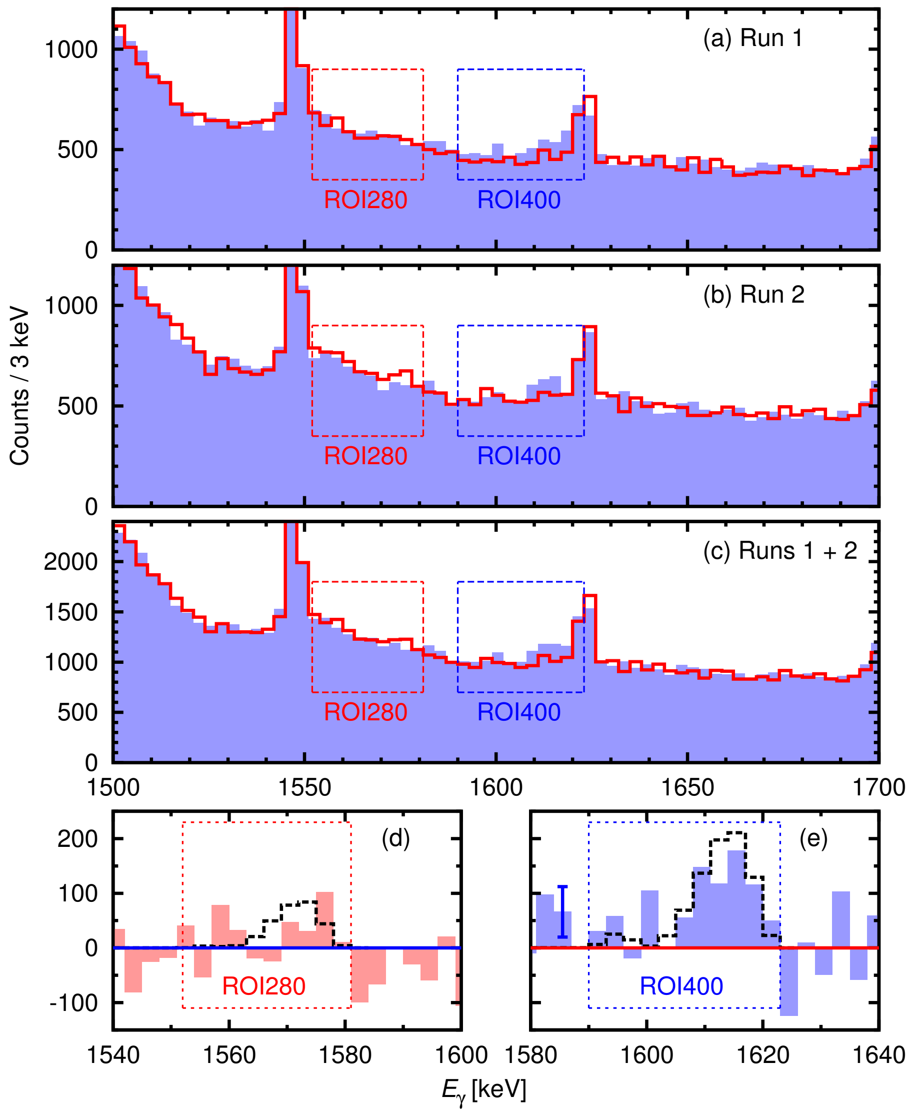
Left: Thermonuclear reaction rate <σv> (relative to standard)

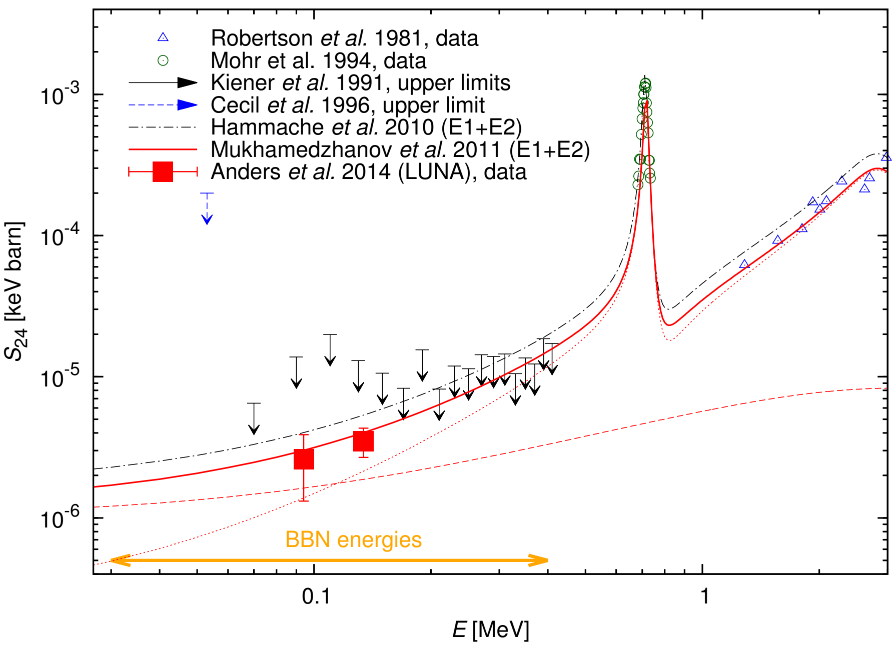
Right: Signal in LUNA γ-calorimeter



Resonance strength ωγ [μeV]	**E_p = 156 keV**	**E_p = 190 keV**	**E_p = 260 keV**	**E_p =479 keV**
Indirect, from nuclear structure data	0.009±0.003	≤ 2.6	≤ 0.13	
Underground, p beam, HPGe det. (LUNA 2015, 2018)	0.18±0.02	2.2±0.2	8.2±0.7	
Underground, p beam, γ-calorimeter (LUNA 2018)	0.22±0.02	2.7±0.2	9.7±0.7	
Overground, ^{22}Ne beam, recoil det. (TRIUMF 2020)	0.17±0.05	2.2±0.4	8.5±1.4	0.44±0.05

^{6}Li production in the Big Bang and ^{2}H(α,γ)^{6}Li, studied at LUNA





- Determine primordial ^{6}Li/^{7}Li ratio = (1.5±0.3) * 10^{-5} entirely from experimental data
- Previous astronomical reports of ^{6}Li/^{7}Li ~ 10^{-2} are probably in error

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