MATTER

Nucleosynthesis in stars and in the big bang – the seeds for the r process

Daniel Bemmerer

MML ■ FROM MATTER TO MATERIALS AND LIFE

HZDR

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

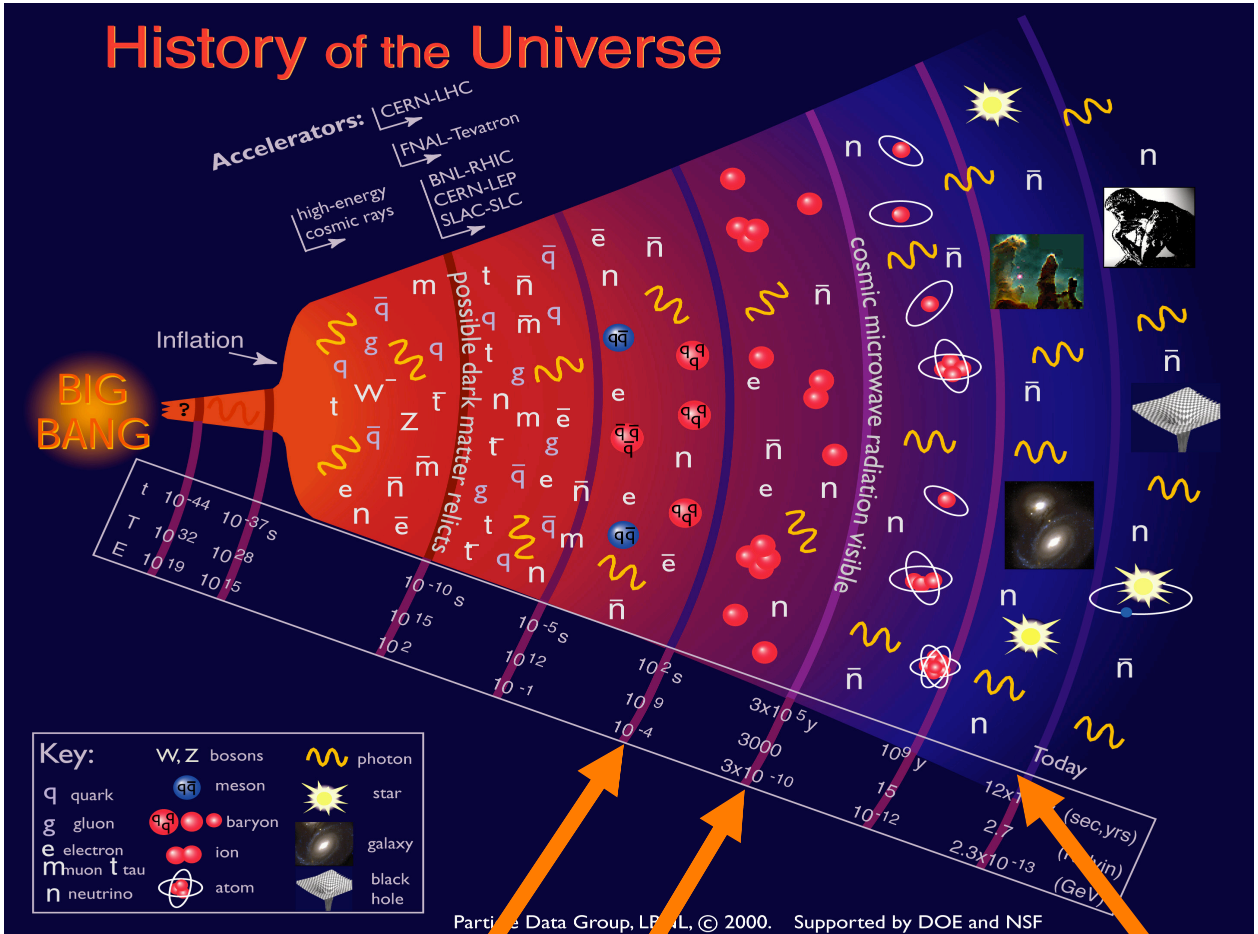
DRESDEN concept

Nucleosynthesis in stars and in the big bang – the seeds for the r process

- **Big Bang nucleosynthesis**
  Astrophysical S-Factor
  Thermonuclear Reaction Rate
  Resonance Strength
  LUNA 0.4 MV underground lab in Italy
- **Experimental facilities underground**
  LUNA-MV underground lab in Italy
  Felsenkeller underground lab in Germany
- **Asymptotic giant branch stars**
  Stellar hydrogen burning
  Neutron sources for the s-process
  Stellar helium burning


Photo: HZDR/O. Killig

Three tools of observational cosmology

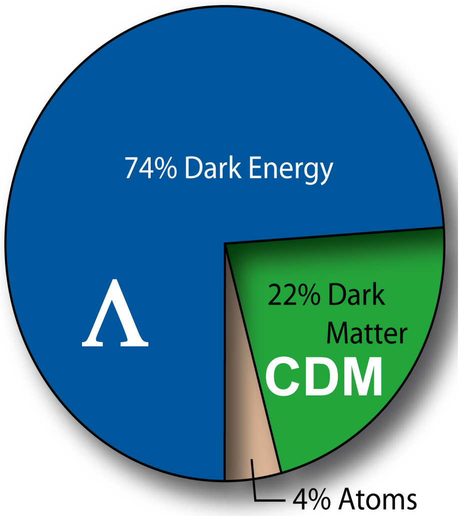


BBN, Big Bang Nucleosynthesis, 10^2 s, 1 GK

CMB, Cosmic micro-wave background, 4 10^5 yr, 3000 K

SN Ia, type Ia supernovae, 14 10^9 yr

State of the art of cosmology, ΛCDM model



State of the art (Planck 2015 data release, arXiv:1502.01589)

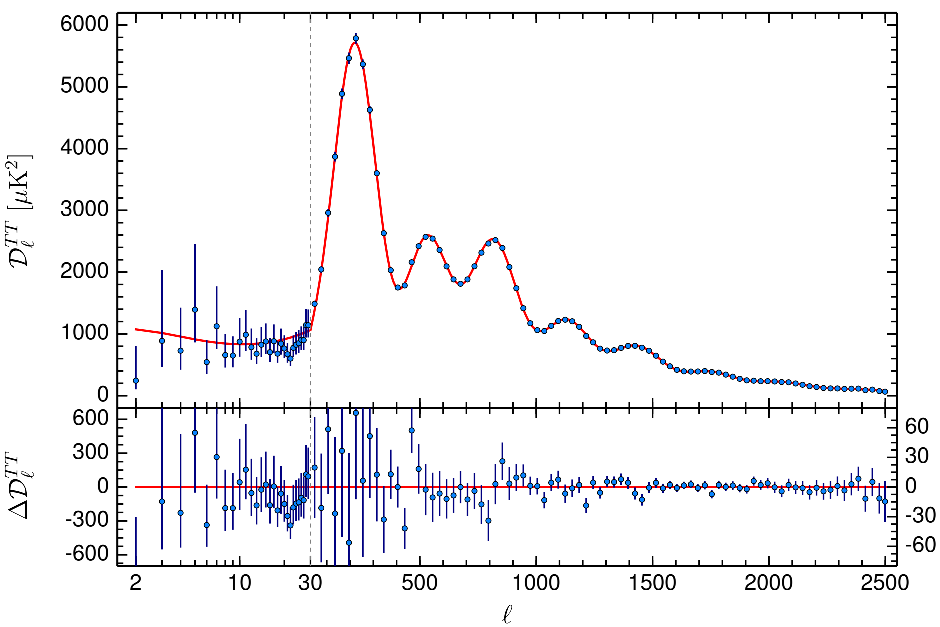
- The universe is flat, i.e. we have ~100% of the critical energy density.
- There is a cosmological constant ("dark energy"), called Λ
- There is significant dark matter, and it has low energy ("cold").
- The universe shows a recently accelerated expansion.

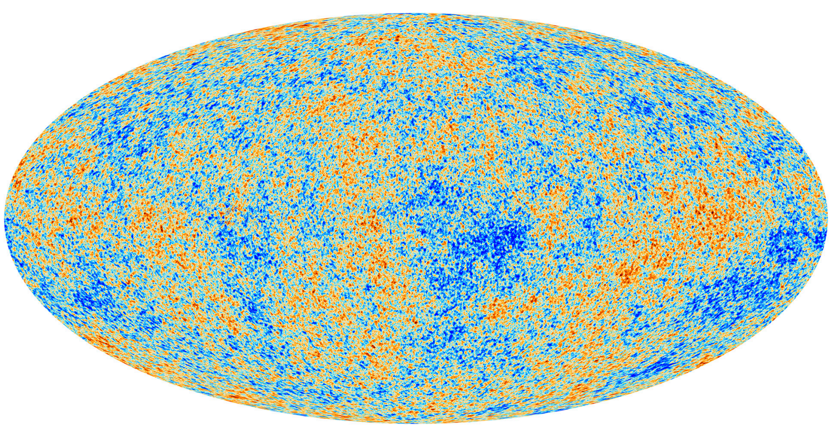
$$\Omega_b h^2 = 0.02230 \pm 0.00014$$

$$H_0 = 67.74 \pm 0.46 \frac{\mathrm{km}}{\mathrm{s\,Mpc}}$$

$$\Omega_\Lambda = 0.6911 \pm 0.0062$$

$$t_{\mathrm{Universe}} = 13.799 \pm 0.021\,\mathrm{Gyr}$$

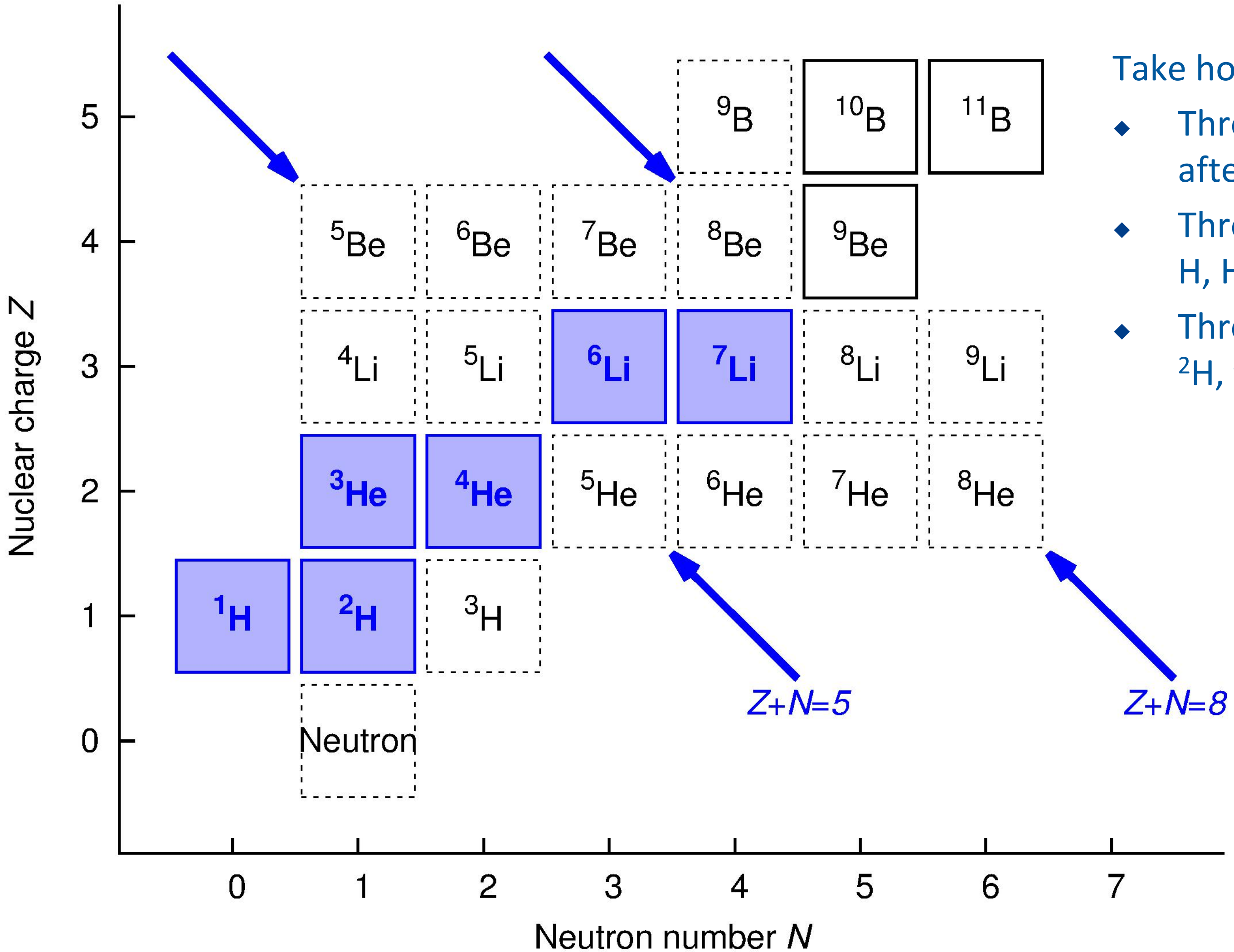




Planck, arXiv:1502.01589

HZDR

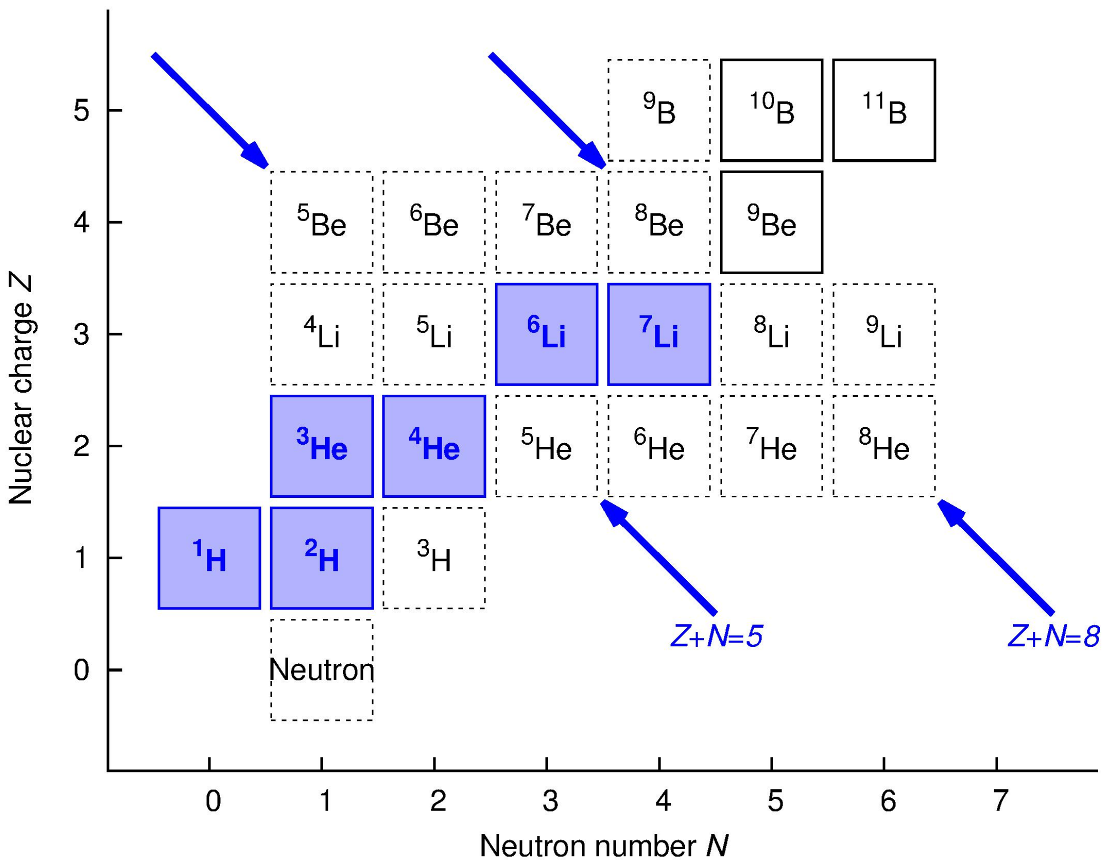
Time t~3 min, temperature T~1 GK: Big Bang Nucleosynthesis (BBN)



Take home textbook knowledge

- Three minutes after the Big Bang
- Three chemical elements: H, He, Li
- Three observed abundances: ^{2}H, ^{4}He, ^{7}Li

Microphysics and Macrophysics: Nuclear Structure and Cosmology



Deuterium bottleneck

- Deuterium only stable at sufficiently low temperature

Mass 5 and 8 barriers

- No stable nucleus with mass $Z+N = 5$
- No stable nucleus with mass $Z+N = 8$

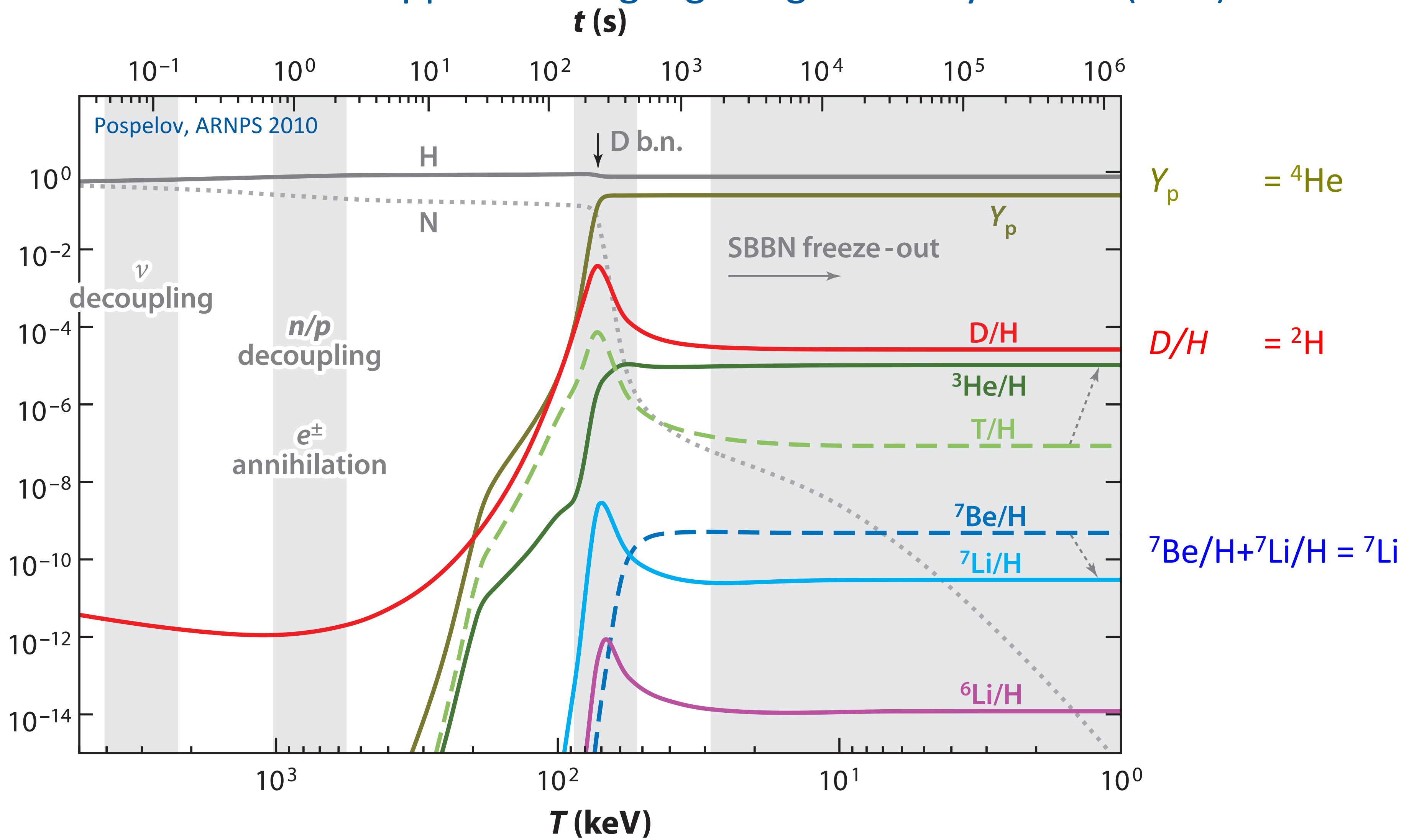
Nuclear binding energy

- ^{4}He has the highest binding energy of all stable light nuclei

Electrostatic repulsion

- Probability for capture of a nuclide drops exponentially for increasing Z and sqrt($Z+N$) of the captured nuclide

What happens during Big Bang Nucleosynthesis (BBN)?

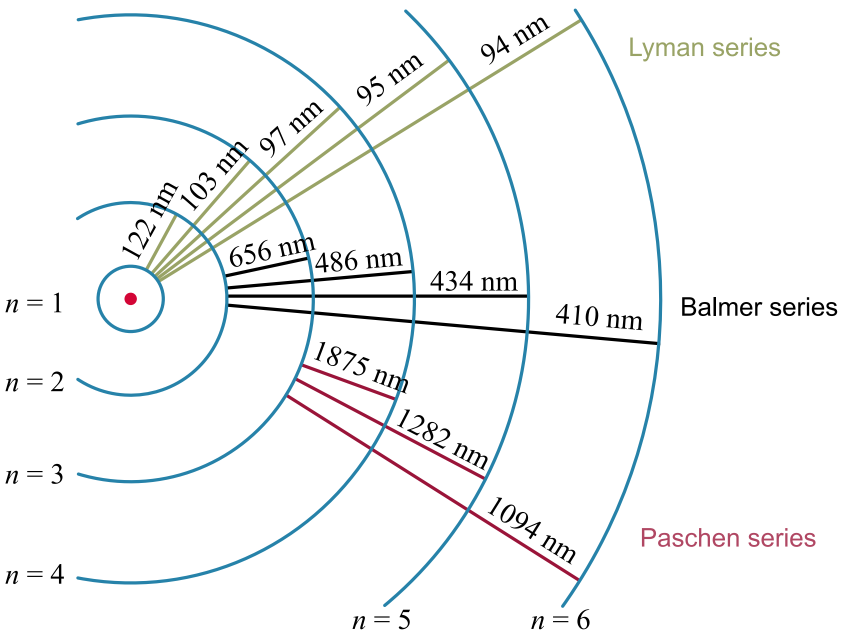


Radioactive ^{3}H (12.3 a) and ^{7}Be (53 d)
end up as stable ^{3}He, ^{7}Li

Isotopic shift for hydrogen absorption lines (Lyman series)

$$\frac{1}{\lambda_\mathrm{H}} = \frac{R_\infty}{1+m_e/m_\mathrm{H}}\left(\frac{1}{n_1^2}-\frac{1}{n_2^2}\right) \qquad \frac{1}{\lambda_\mathrm{D}} = \frac{R_\infty}{1+m_e/m_\mathrm{D}}\left(\frac{1}{n_1^2}-\frac{1}{n_2^2}\right)$$

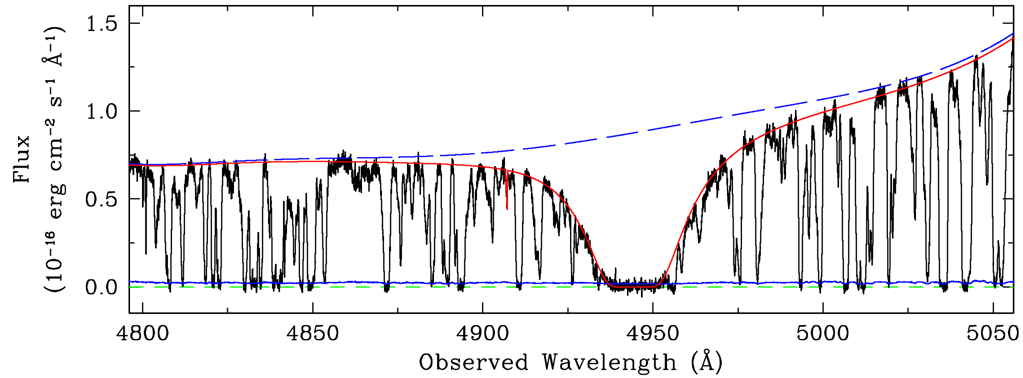
$$\begin{aligned}\frac{\lambda_\mathrm{D}-\lambda_\mathrm{H}}{\lambda_\mathrm{D}} &= \frac{1+\frac{m_e}{m_\mathrm{D}}-(1+\frac{m_e}{m_\mathrm{H}})}{1+\frac{m_e}{m_\mathrm{H}}} \\ &= \frac{1+\frac{1}{1836}-(1+\frac{1}{3669})}{1+\frac{1}{1836}} \\ &\approx 3\times 10^{-4} \equiv 0.03\,\mathrm{nm}\end{aligned}$$

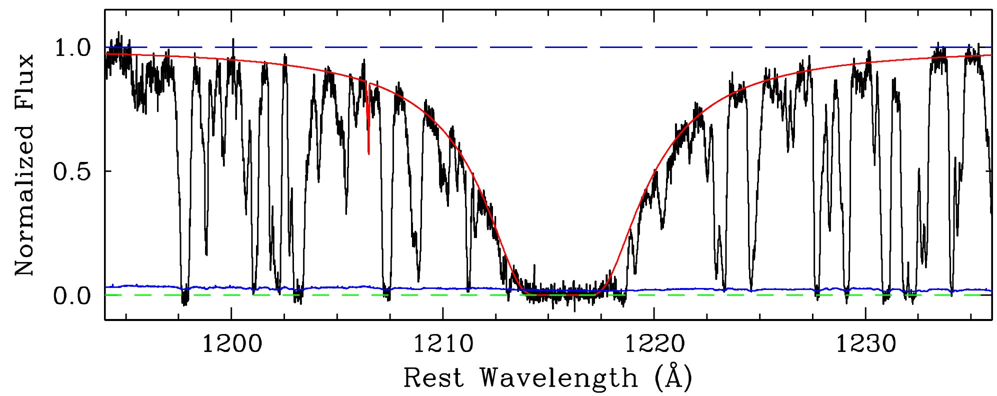


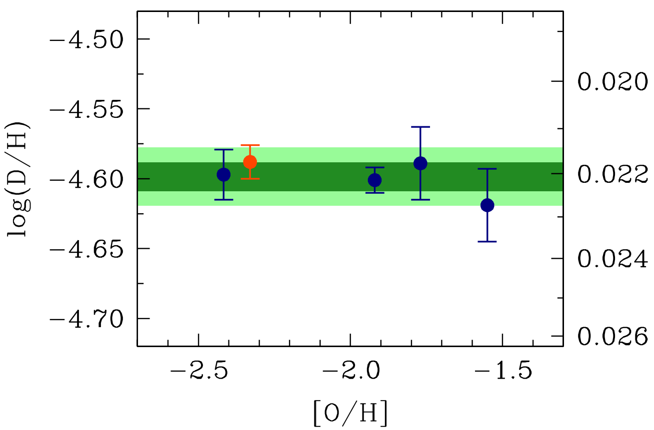
Wikipedia

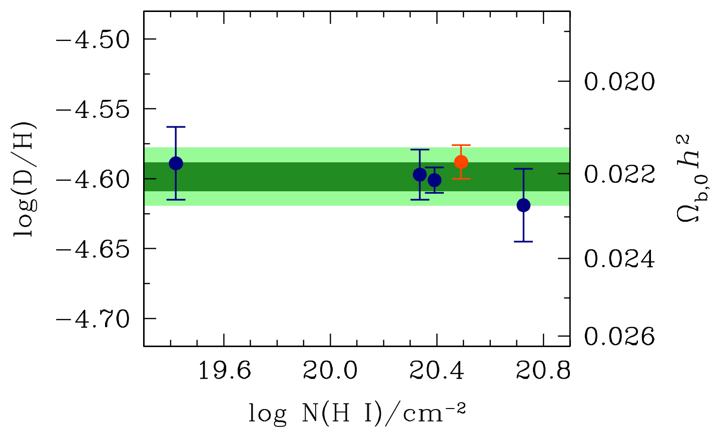
Observed nuclide abundance: ^{2}H

- Observe ^{2}H absorption lines from the Lyman series in gas clouds
- Plot observed ^{2}H abundance as function of the age of the gas cloud, traced by the oxygen abundance O/H
- Fit and extrapolate to zero O/H (=primordial gas cloud)





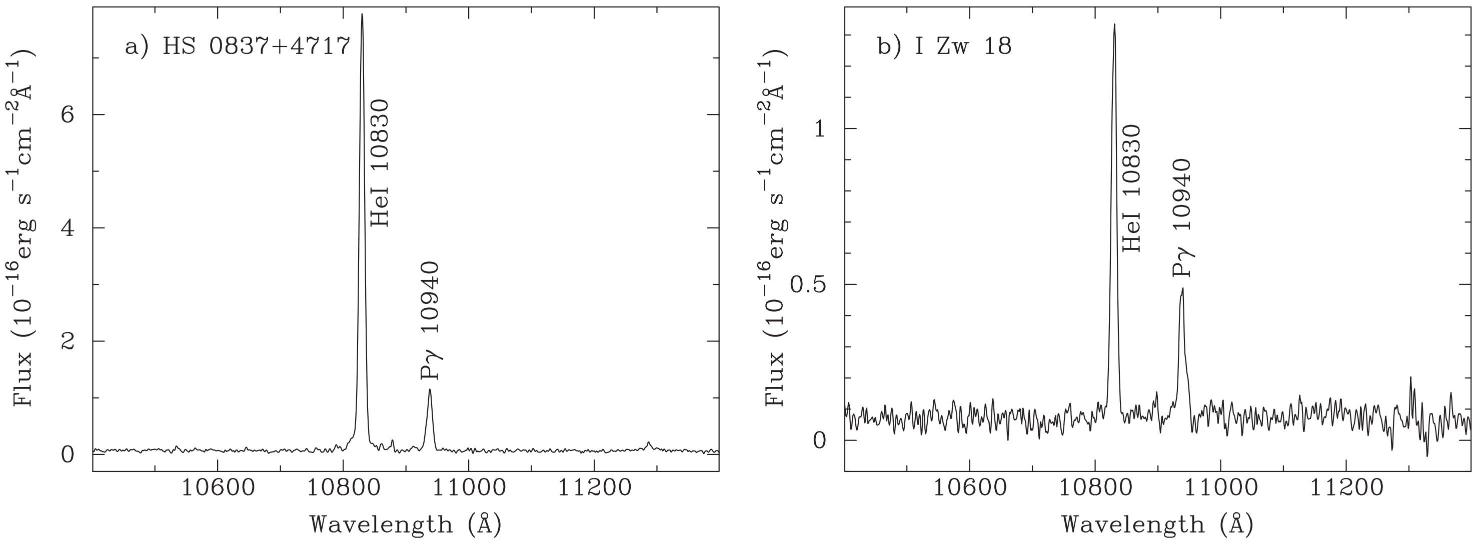




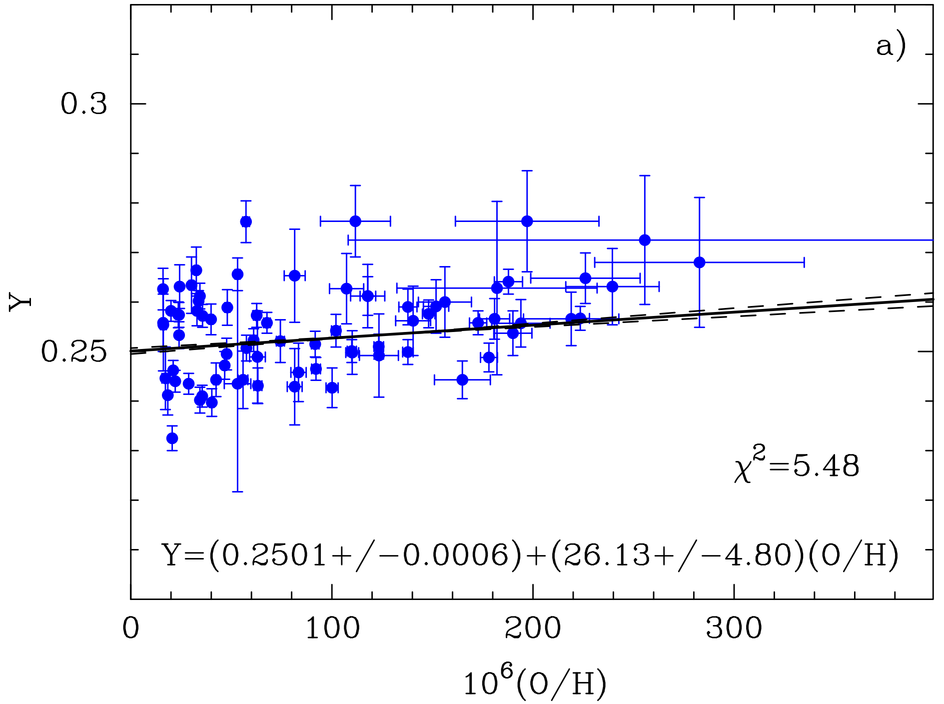
Cooke *et al.*, ApJ 2014

Observed nuclide abundance: ^{4}He

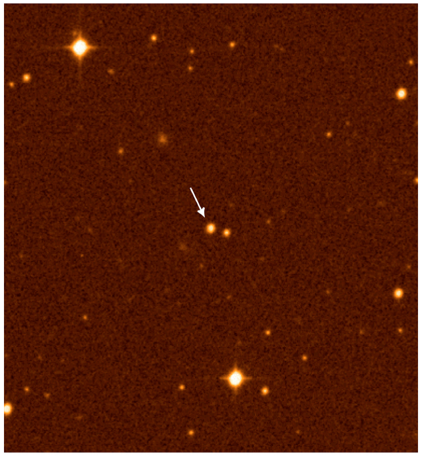
Izotov *et al.*, MNRAS 2014

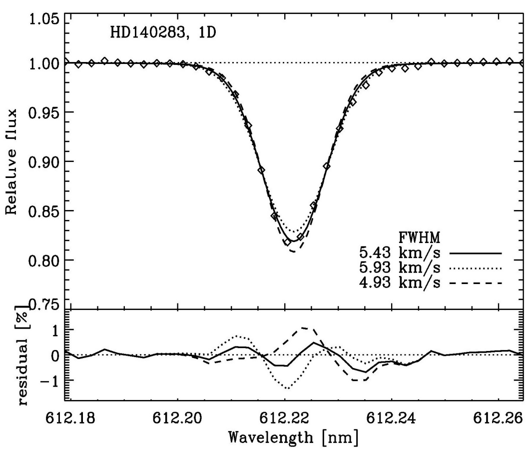


- Observe ^{4}He emission lines in gas clouds
- Plot observed ^{4}He abundance as function of the age of the gas cloud, traced by the oxygen abundance O/H
- Fit and extrapolate to zero O/H (=primordial gas cloud)

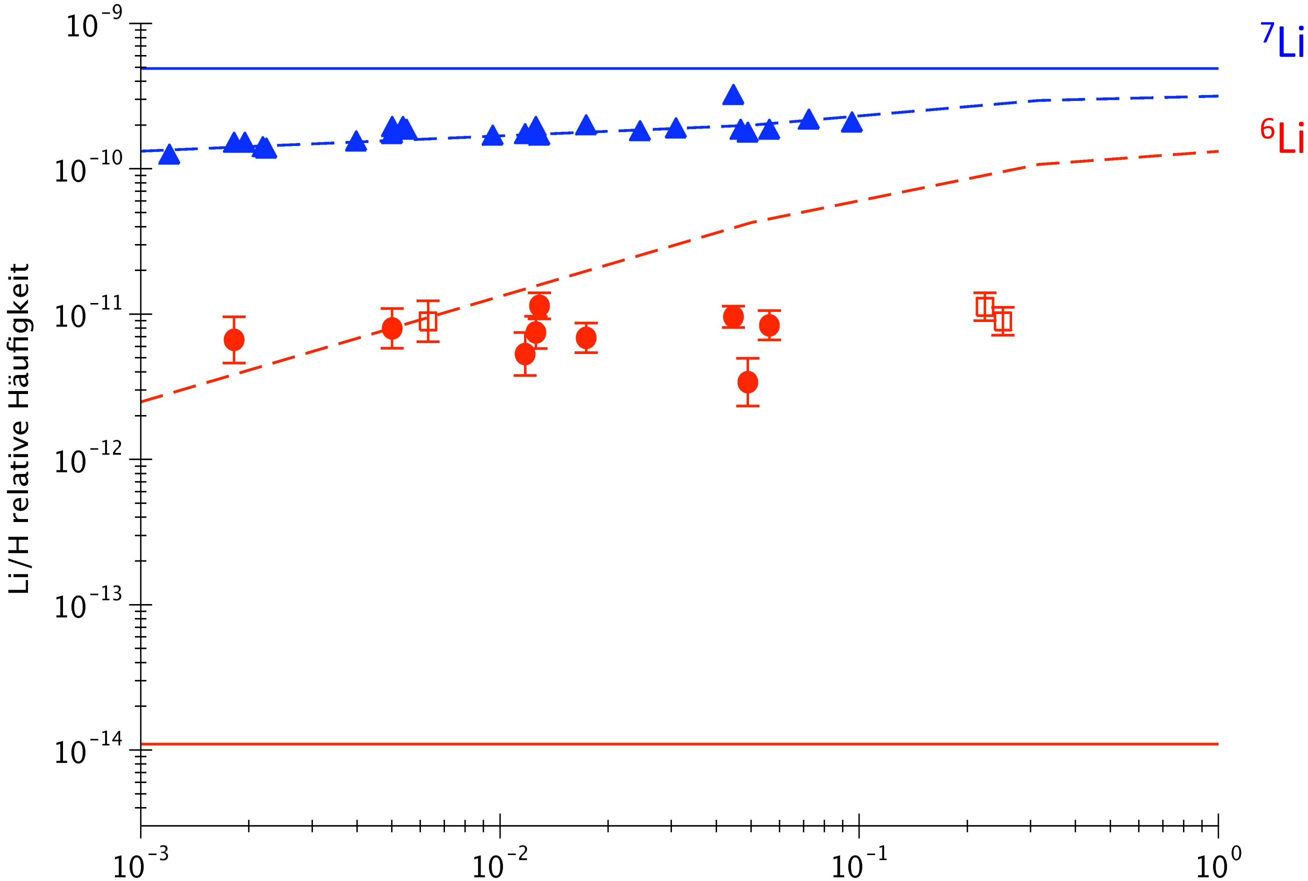


Observed nuclide abundance: ^{7}Li and the “Spite plateau”





- Lithium absorption lines in spectra of metal-poor stars in the halo of our galaxy
- Observe lithium elemental abundance, interpret as ^{7}Li
- Some authors have attempted to measure ^{6}Li, as well



(relativ zur Sonne)

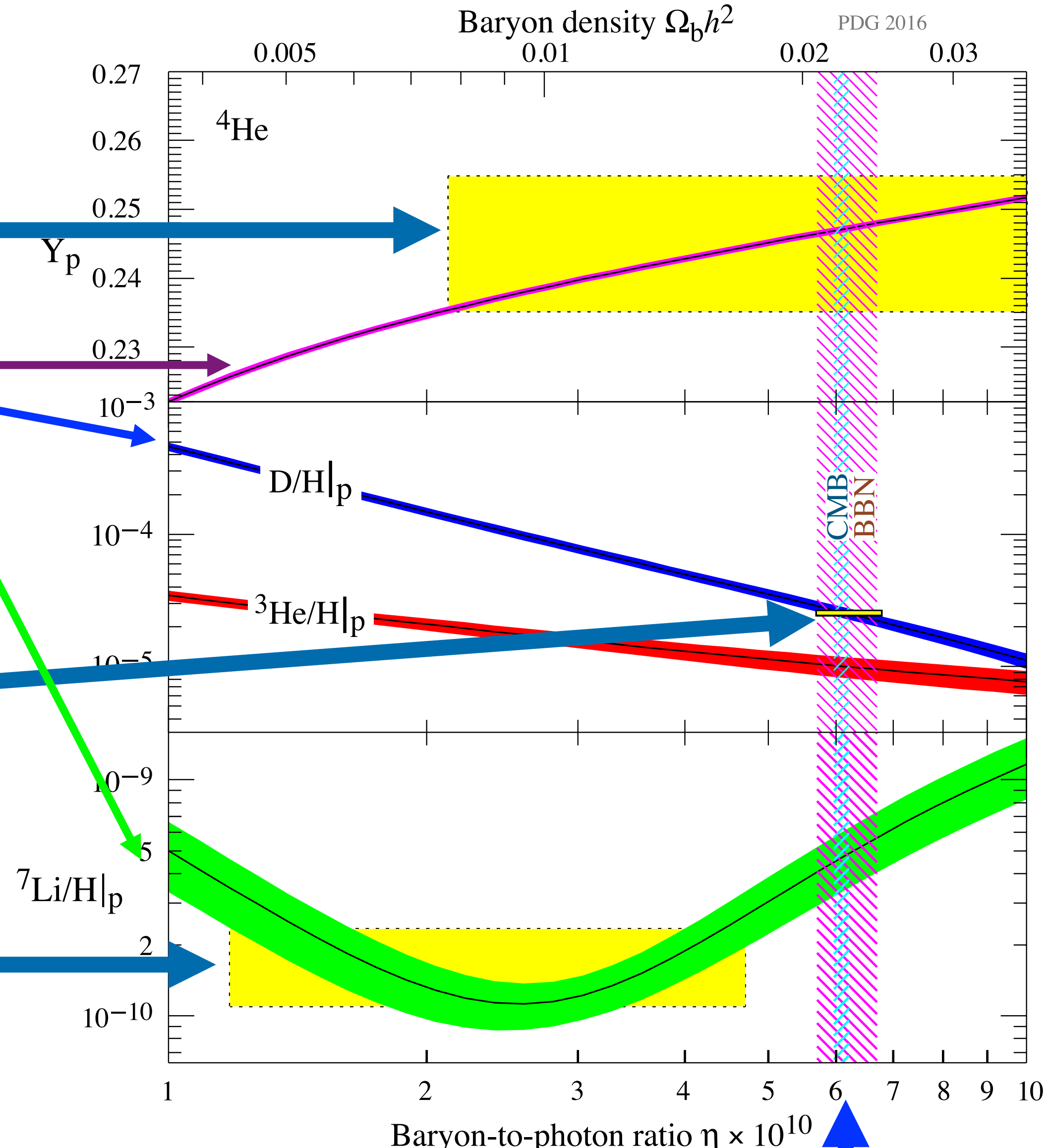
Cosmic concordance

1. Yellow box: ^{4}He observation

3. Purple/blue/green bands: BBN calculated predictions

1. Small yellow box: ^{2}H observation

1. Yellow box: ^{7}Li observation

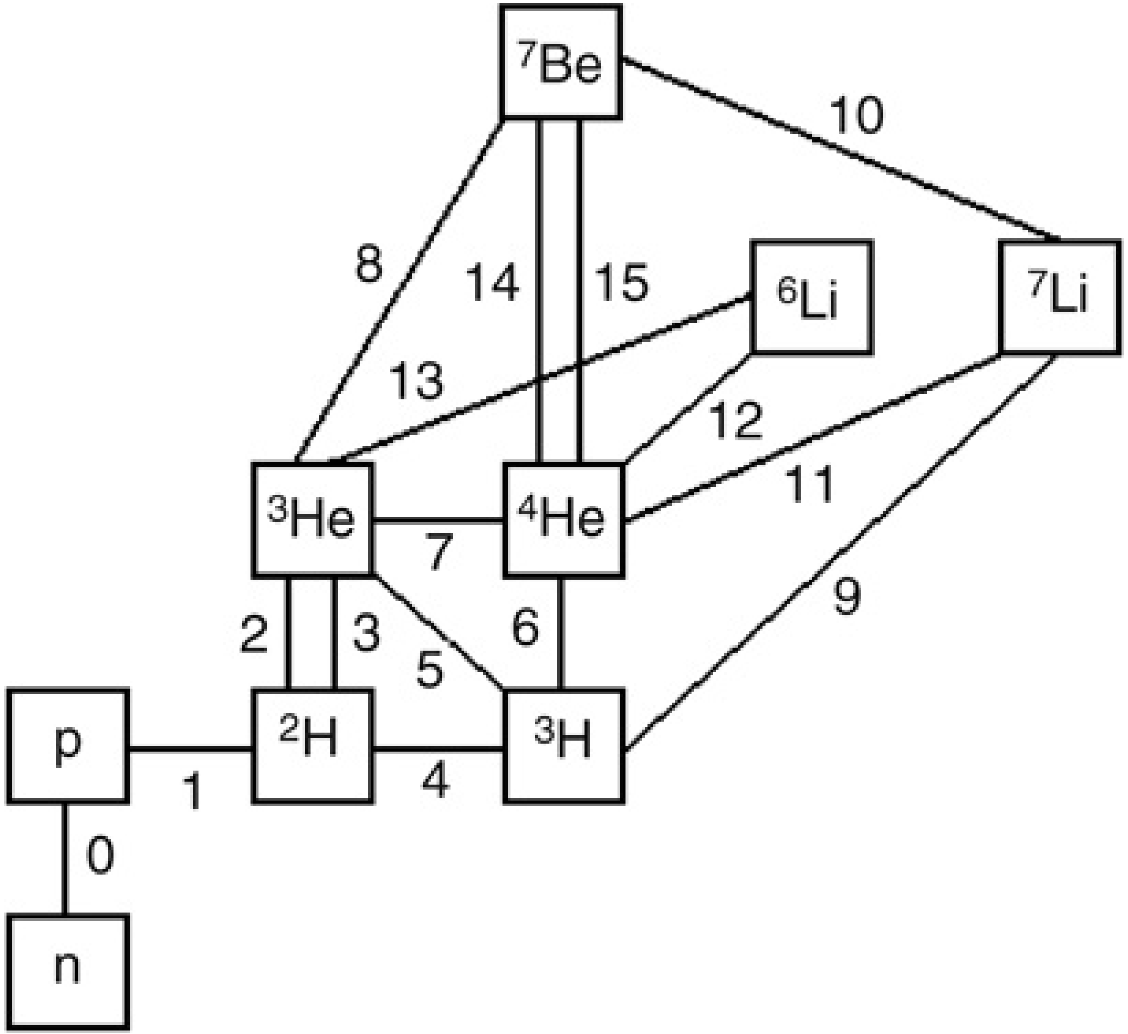


Three aspects agree:

1. Observed nuclide abundances
2. CMB value for η
3. BBN calculated nuclide abundances

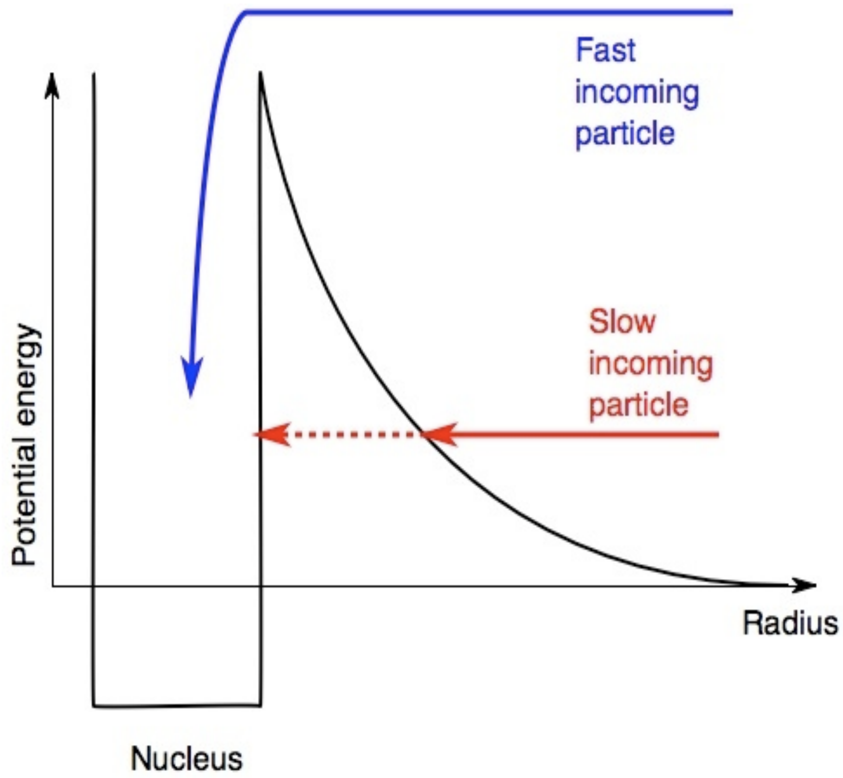
2. Blue hatched area: CMB (Planck 2015)

The Big Bang nuclear reaction network



Iocco *et al.* 2009

Nuclear reaction cross section σ for low-energy charged particles



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

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

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

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

$$= \frac{S(E)}{E} \exp\left(-31.29 Z_1 Z_2 \sqrt{\frac{\mu/\mathrm{amu}}{E/\mathrm{keV}}}\right)$$

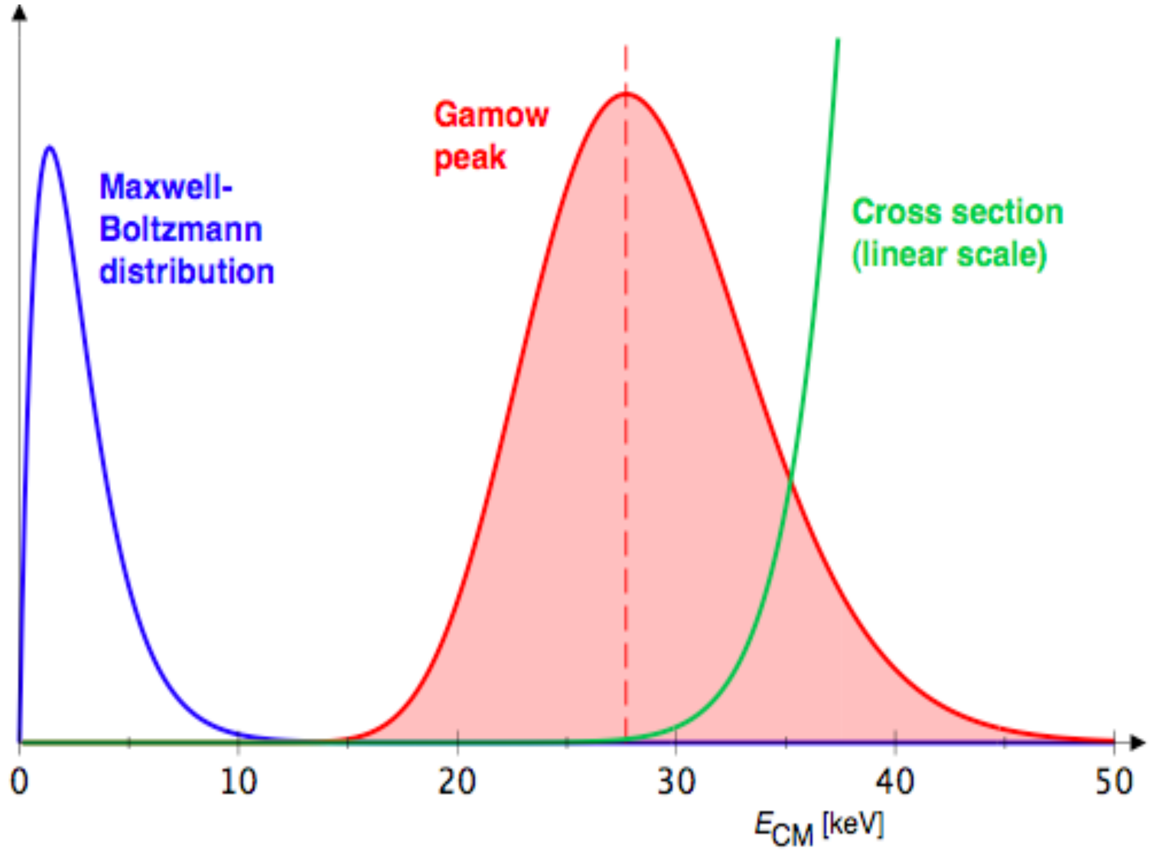
E = center of mass energy

Z_1, Z_2 = charge numbers of projectile and target

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

Neglect angular momentum,
which would lead to an additional barrier.

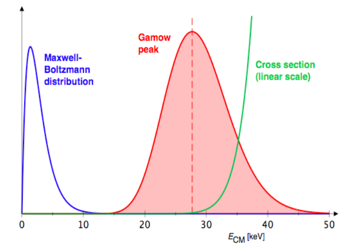
The Gamow peak



Thermonuclear reaction rate $N_A\langle\sigma v\rangle$

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

Thermonuclear reaction rate, nonresonant case



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

$$= N_A\sqrt{\frac{8}{\mu\pi}}(k_\mathrm{B}T)^{-\frac{3}{2}}\, S \int_0^\infty \exp\left[-31.29 Z_1 Z_2\sqrt{\frac{\mu/\mathrm{amu}}{E/\mathrm{keV}}} - \frac{E}{k_\mathrm{B}T}\right] dE$$

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

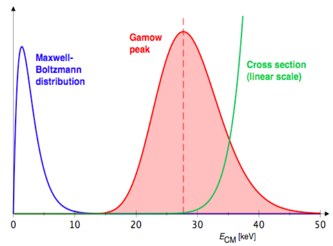
Assumption here:
S(E) = const.(*E*) = *S*

Abbreviations for barrier penetrability b
and Gamow peak energy E_0

$$b/\mathrm{keV} = -31.29 Z_1 Z_2\sqrt{\frac{\mu}{\mathrm{amu}}}$$

$$E_0/\mathrm{keV} = 122\left(Z_1^2 Z_2^2 \frac{\mu}{\mathrm{amu}} T_9^2\right)^{\frac{1}{3}}$$

Thermonuclear reaction rate, nonresonant case



Abbreviation for Gamow peak energy E_0

$$E_0/\mathrm{keV} = 122 \left(Z_1^2 Z_2^2 \frac{\mu}{\mathrm{amu}} T_9^2 \right)^{\frac{1}{3}}$$

Abbreviation τ

$$\tau = \frac{3E_0}{k_\mathrm{B}T} = 4.246 \left(Z_1^2 Z_2^2 \frac{\mu/\mathrm{amu}}{T_9} \right)^{\frac{1}{3}}$$

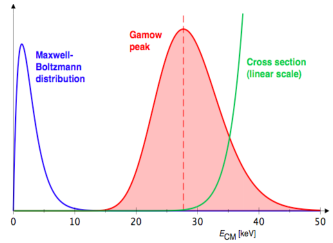
Thermonuclear reaction rate can then be expressed as:

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

$$= 4.33 \times 10^5 \frac{\tau^2}{\frac{\mu}{\mathrm{amu}} Z_1 Z_2} \exp(-\tau) \frac{S(E_0)}{\mathrm{keV\ b}} \frac{\mathrm{cm}^3}{\mathrm{s\ mol}}$$

Assumption: $S(E)$ = const.(E) = $S(E_0)$ near E_0

Thermonuclear reaction rate, sharp Breit-Wigner resonance



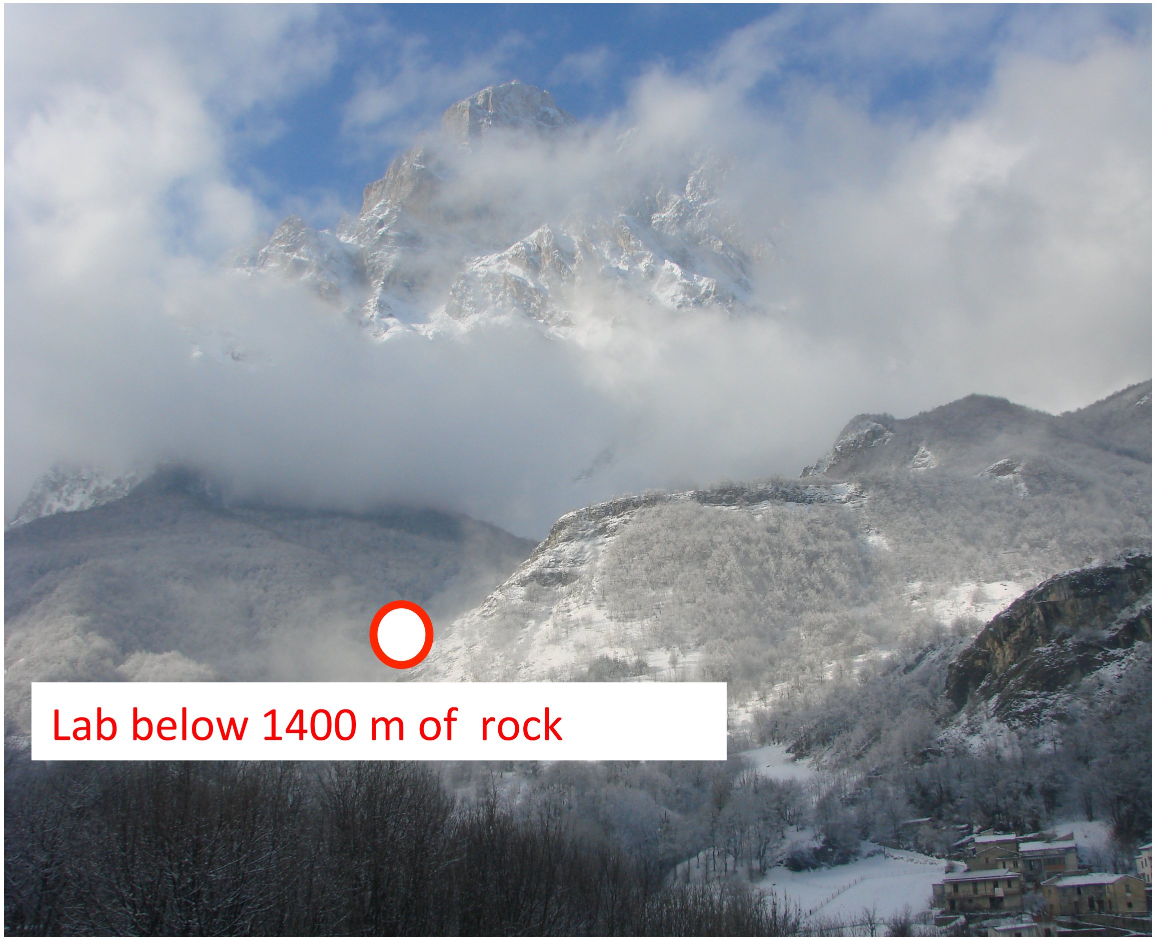
$$N_A\langle\sigma v\rangle = N_A\sqrt{\frac{8}{\mu\pi}}(k_\mathrm{B}T)^{-\frac{3}{2}}\int_0^\infty \sigma(E)E\exp\left[-\frac{E}{k_\mathrm{B}T}\right]dE$$

$$= N_A\left(\frac{2\pi}{\mu k_\mathrm{B}T}\right)^{\frac{3}{2}}\hbar^2\,\omega\gamma\,\exp\left[-\frac{E_\mathrm{reso}}{k_\mathrm{B}T}\right]$$

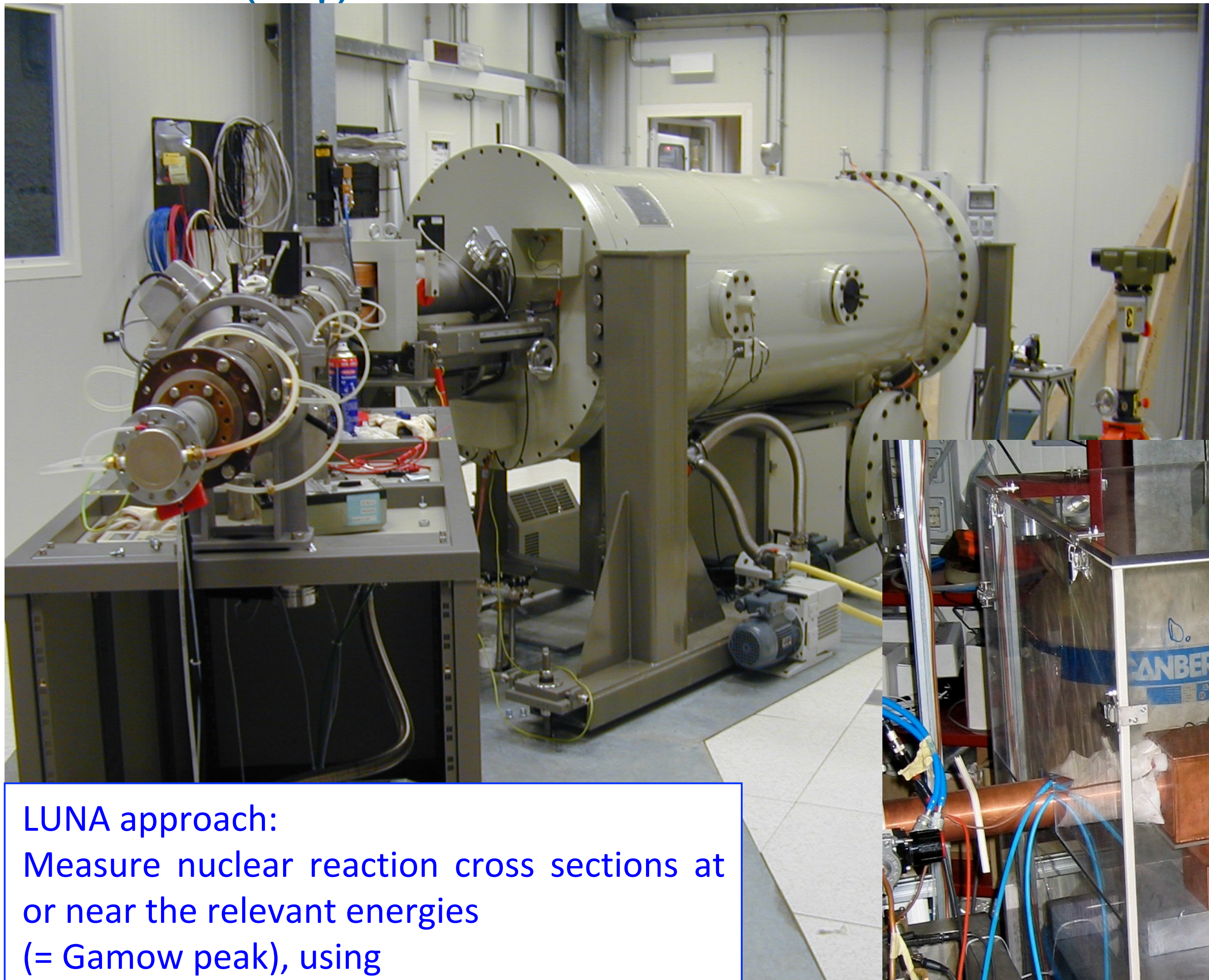
$$= 1.5394\times 10^5\left(\frac{\mu}{\mathrm{amu}}T_9\right)^{-\frac{3}{2}}\frac{\omega\gamma}{\mathrm{eV}}\exp\left[-\frac{0.011605}{T_9}\frac{E_\mathrm{reso}}{\mathrm{keV}}\right]$$

Abbreviations for barrier penetrability b
and Gamow peak energy E_0

Experiment on $^7Be \rightarrow ^7Li$ at LUNA, Gran Sasso (Italy)



$^{3}He(\alpha,\gamma)^{7}Be$, LUNA 0.4 MV accelerator deep underground



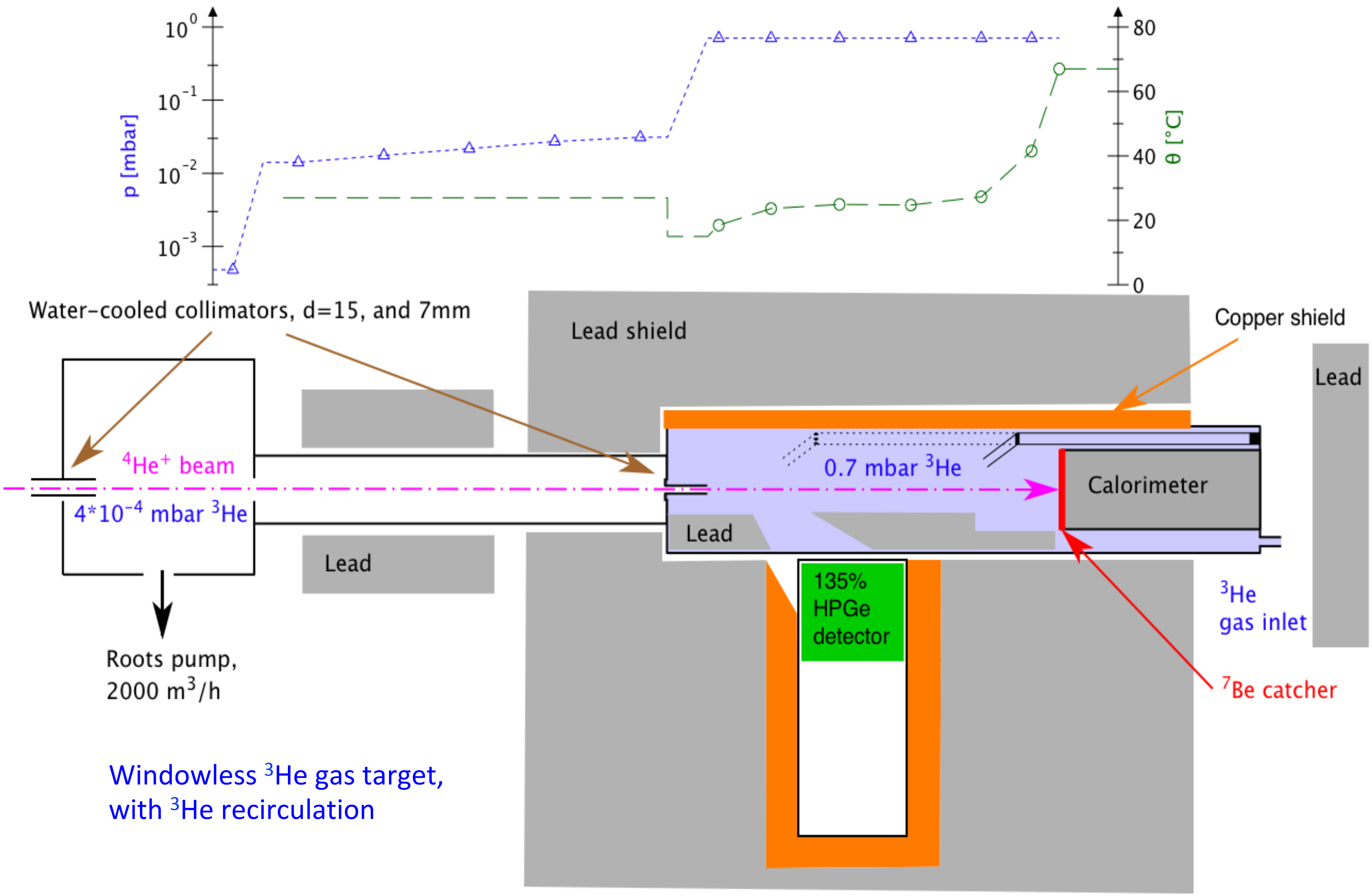
LUNA = Laboratory Underground for Nuclear Astrophysics

- Italy
- Germany
- Hungary
- UK

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

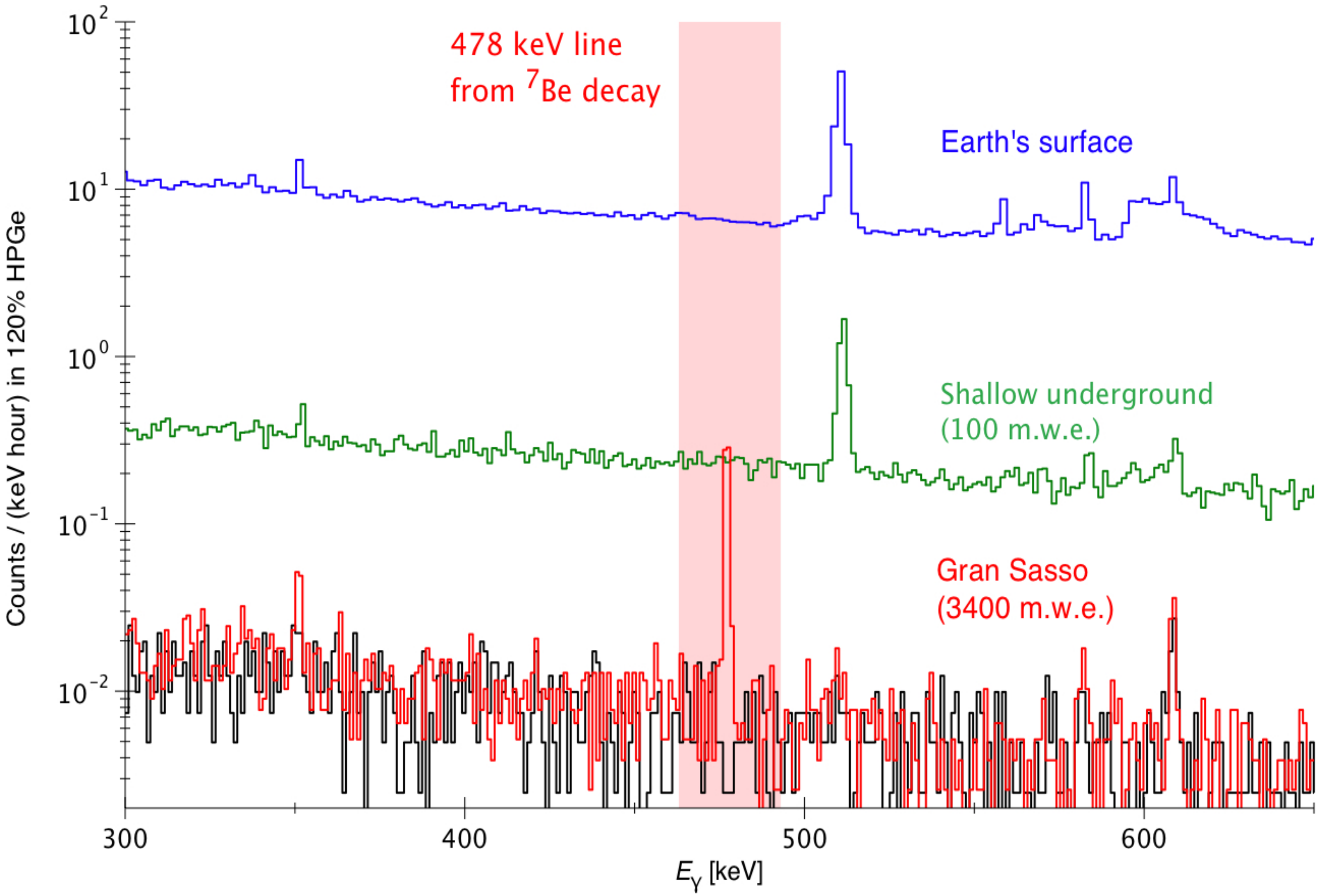
- high beam intensity
- low background
- great patience

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



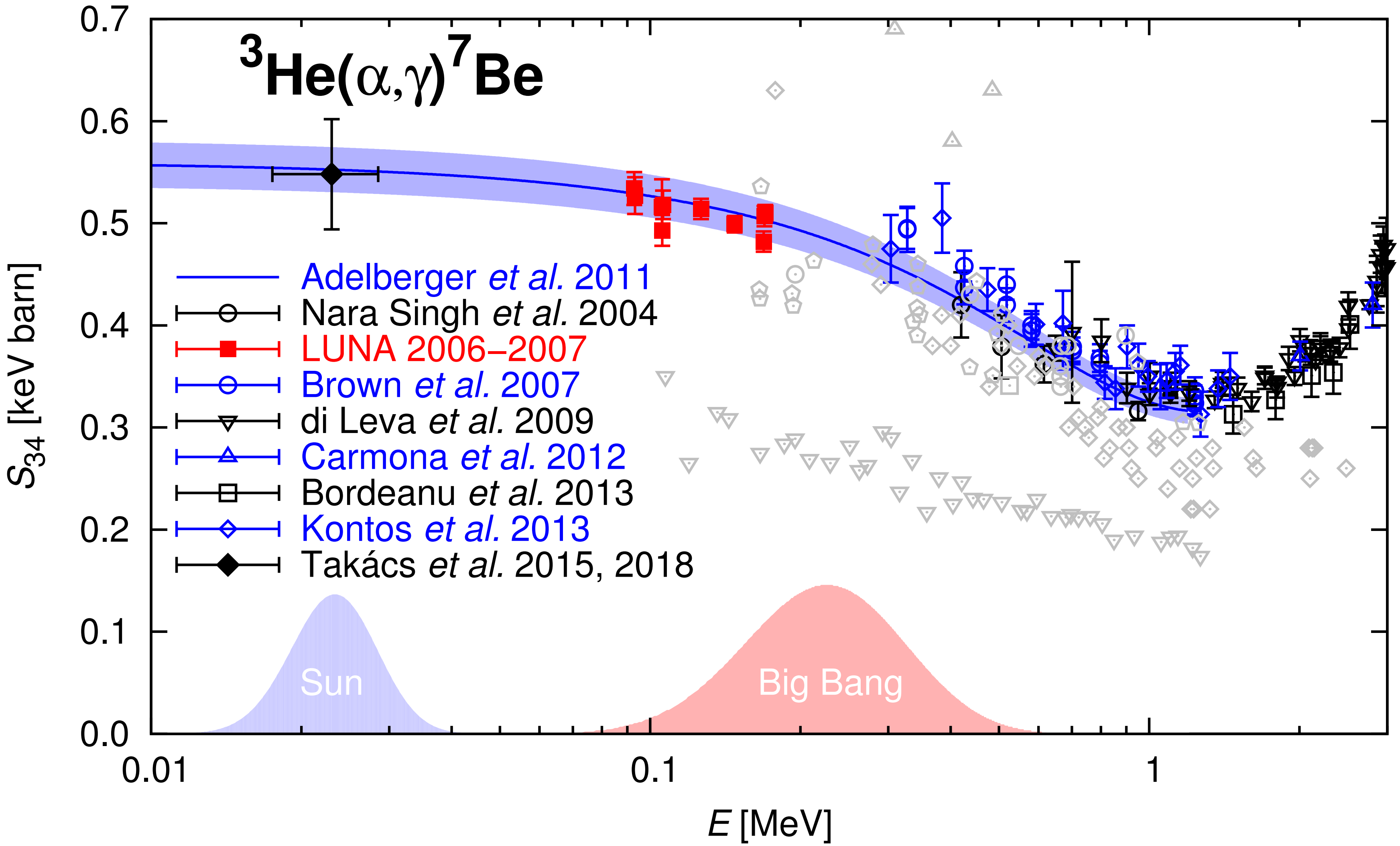
Windowless ^{3}He gas target, with ^{3}He recirculation

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

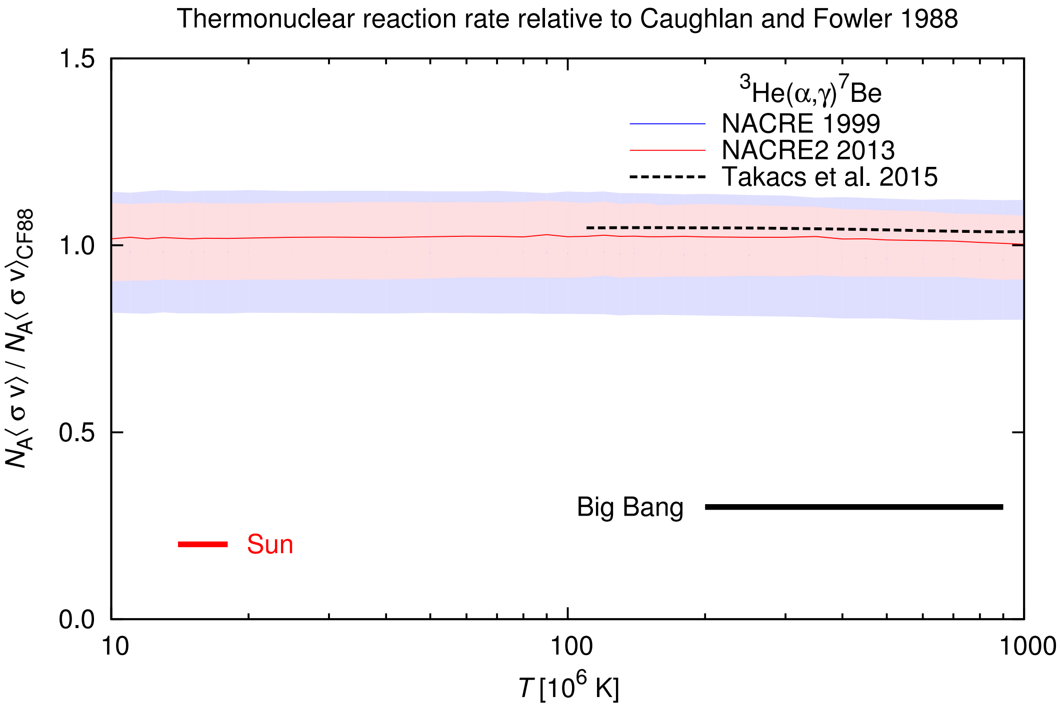


Detected ^7Be activities: 0.8 - 600 mBq

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



^{3}He(α,γ)^{7}Be thermonuclear reaction rate $N_A\langle\sigma v\rangle$



- Present-day reaction rate very close to textbook value.
- Precision improves over the years.

State of the art:

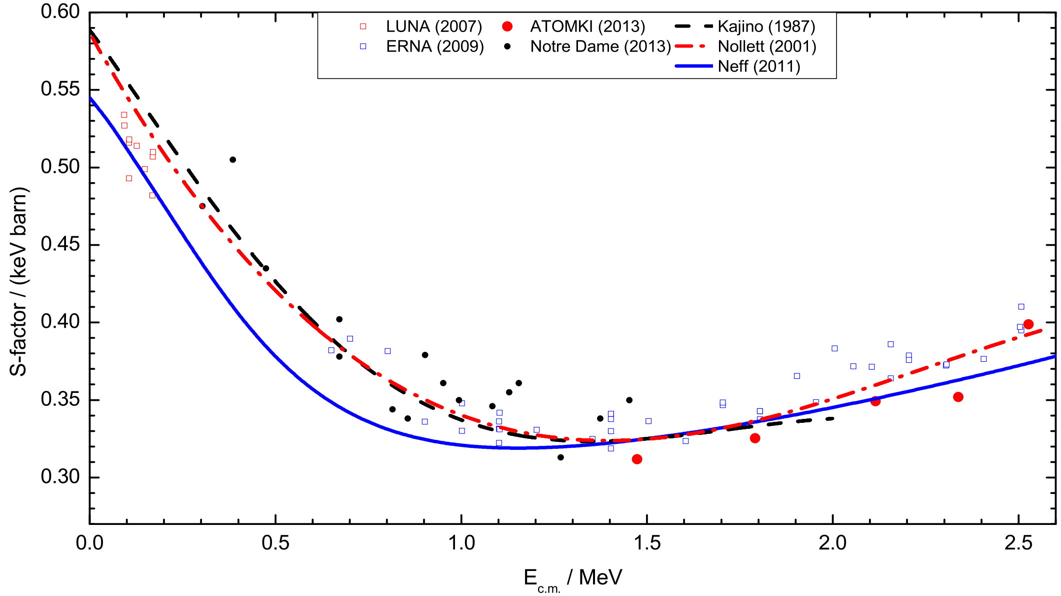
- 5.1% precision at solar temperature
  Adelberger *et al.*, Rev. Mod Phys. 83, 195 (2011)

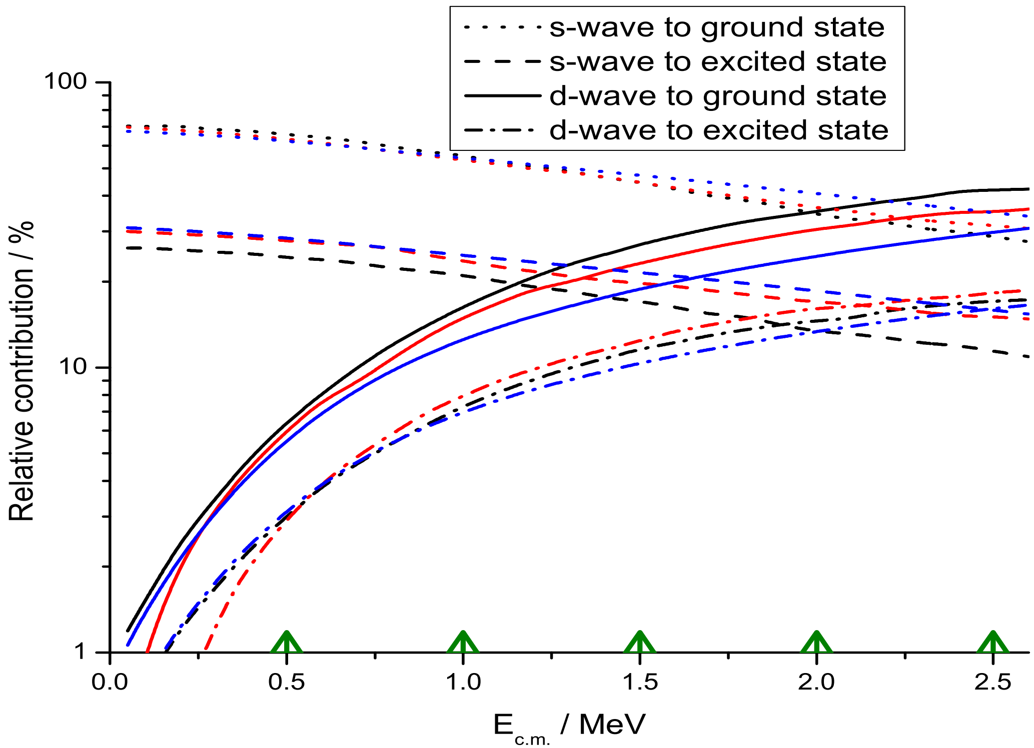
$$N_A\langle\sigma v\rangle = N_A\left(\frac{8}{\pi\mu}\right)^{\frac{1}{2}}(k_B T)^{\frac{3}{2}}\int_0^\infty \sigma(E)E\exp\left(-\frac{E}{k_B T}\right)dE$$

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%~~ 4.3%
^{7}Be(p,γ)^{8}B	1.00	7.7%

$^3He(\alpha,\gamma)^7Be$ reaction, what is needed for even better precision





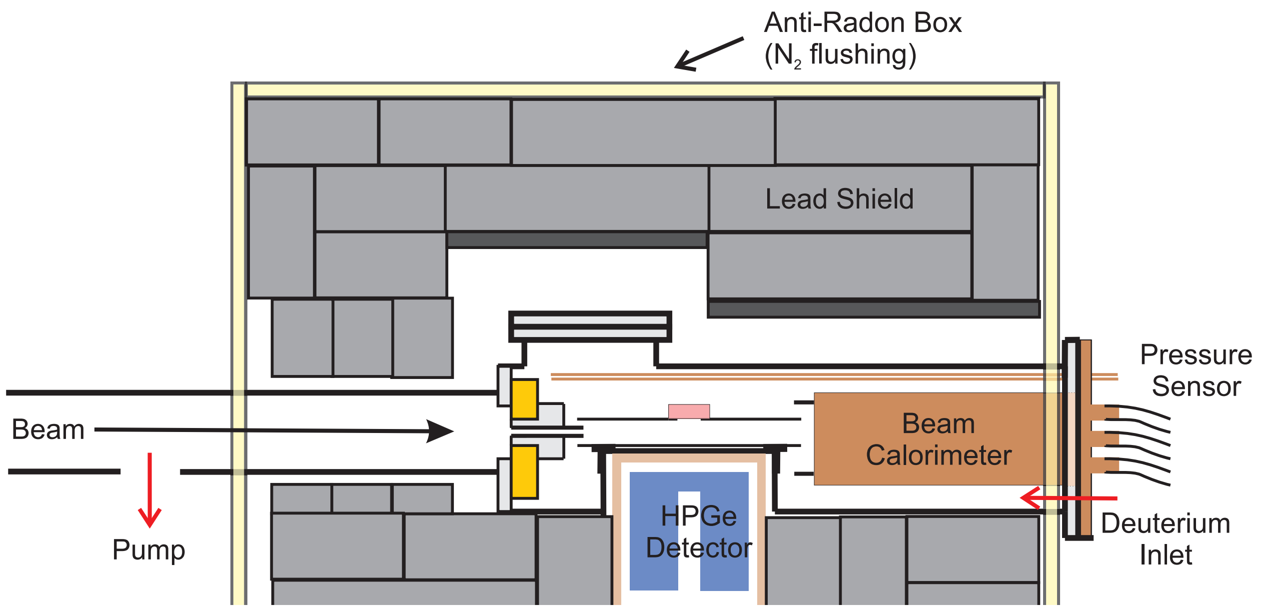
1. One comprehensive data set spanning a wide energy range.

2. Separation of s-wave from d-wave component at 1 – 2 MeV.

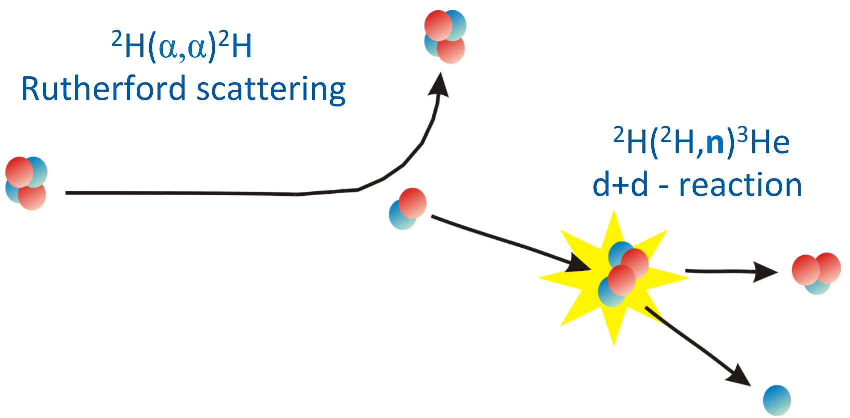
When this is given, the uncertainty of the reaction rate will decrease below 3% also for solar temperature.

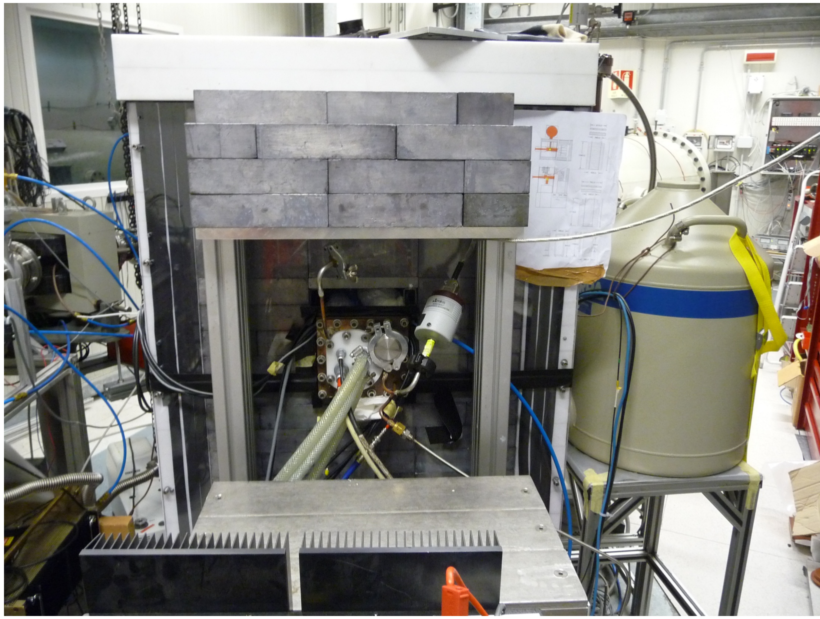
See the poster by Steffen Turkat!

Experiment on $^2H(\alpha,\gamma)^6Li$ at LUNA: Experimental setup



Background by a second order process:





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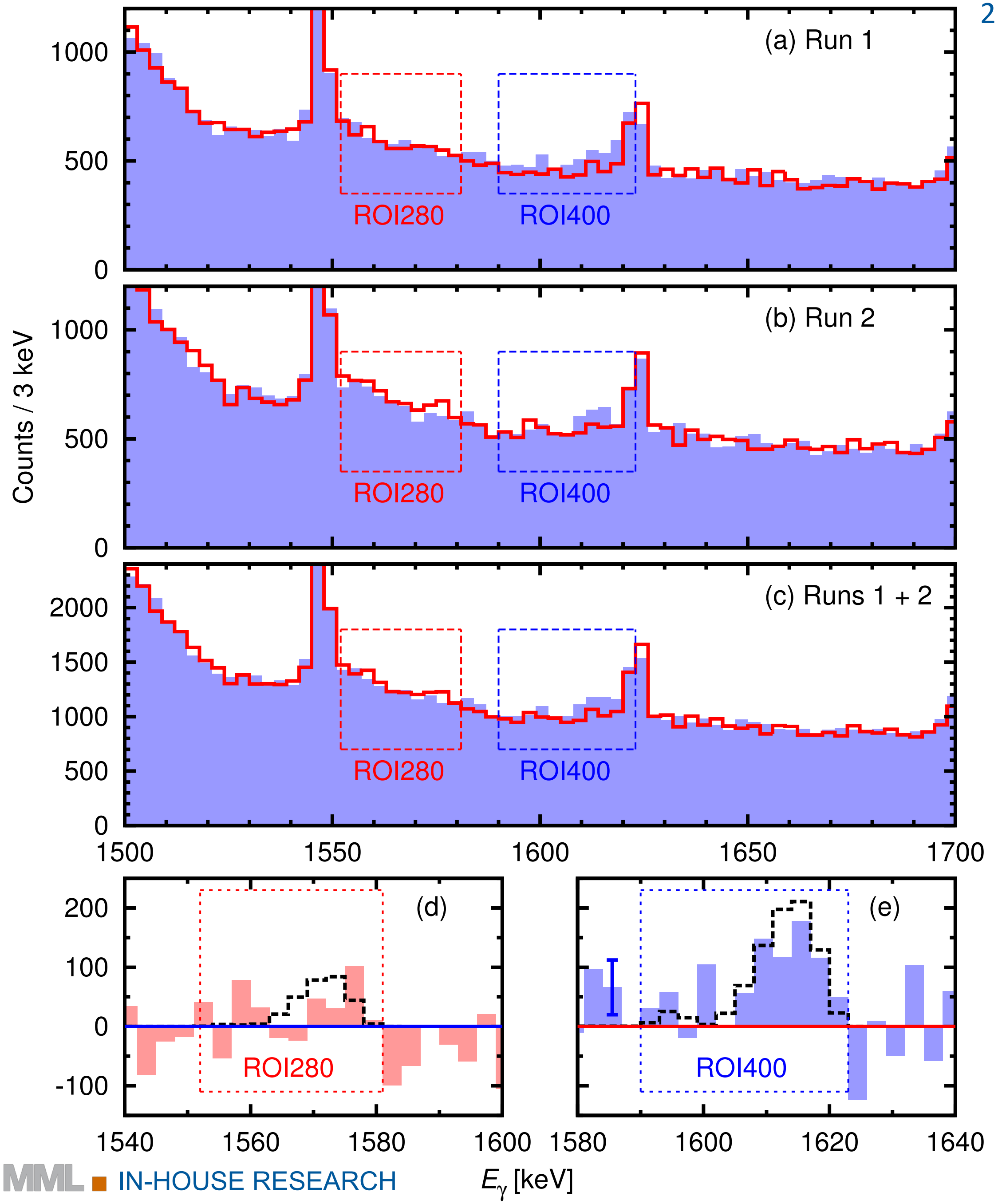
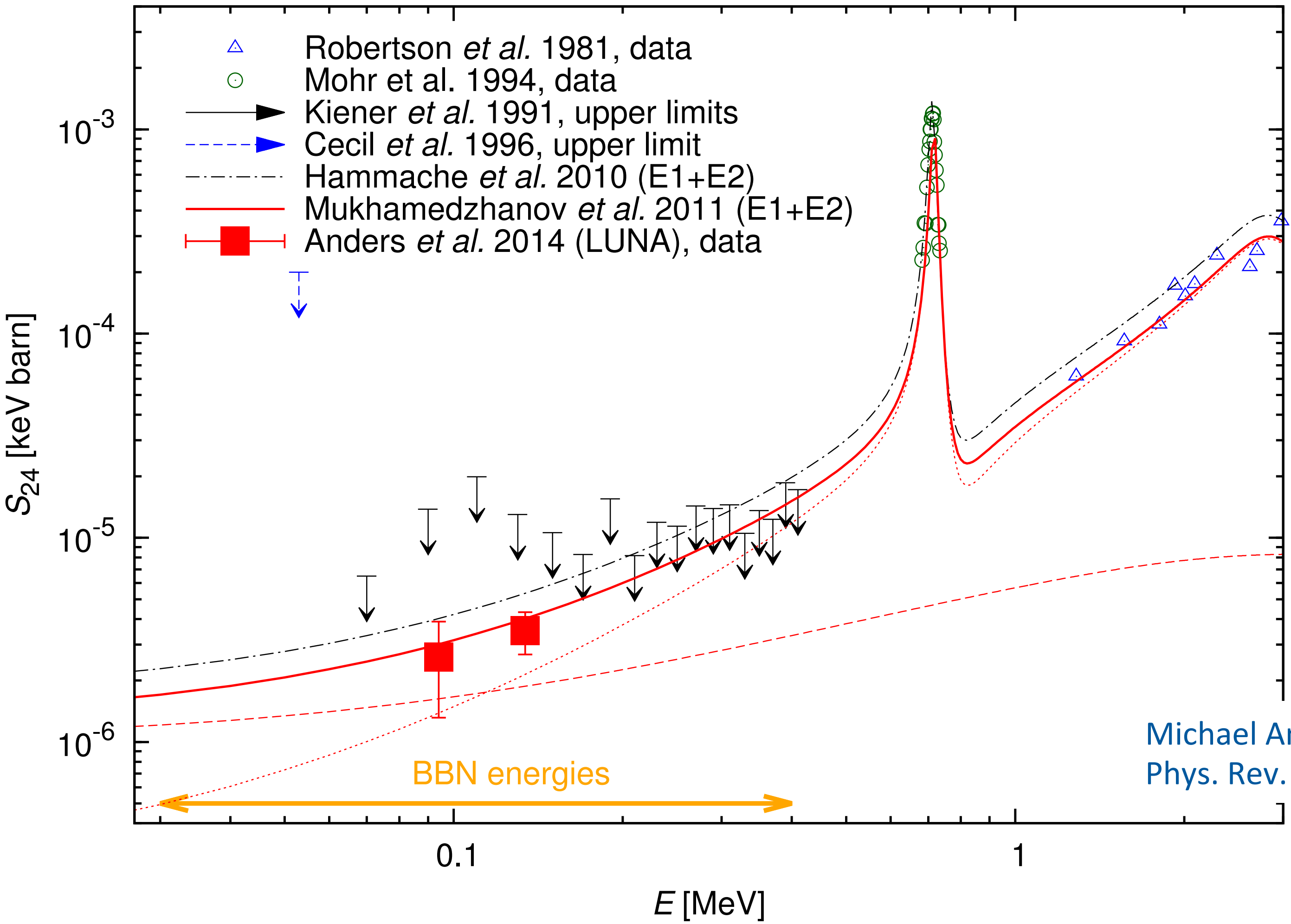
$^{2}H(\alpha,\gamma)^{6}Li$, in-beam spectra



Blue: E_α = 400 keV

Red: E_α = 280 keV

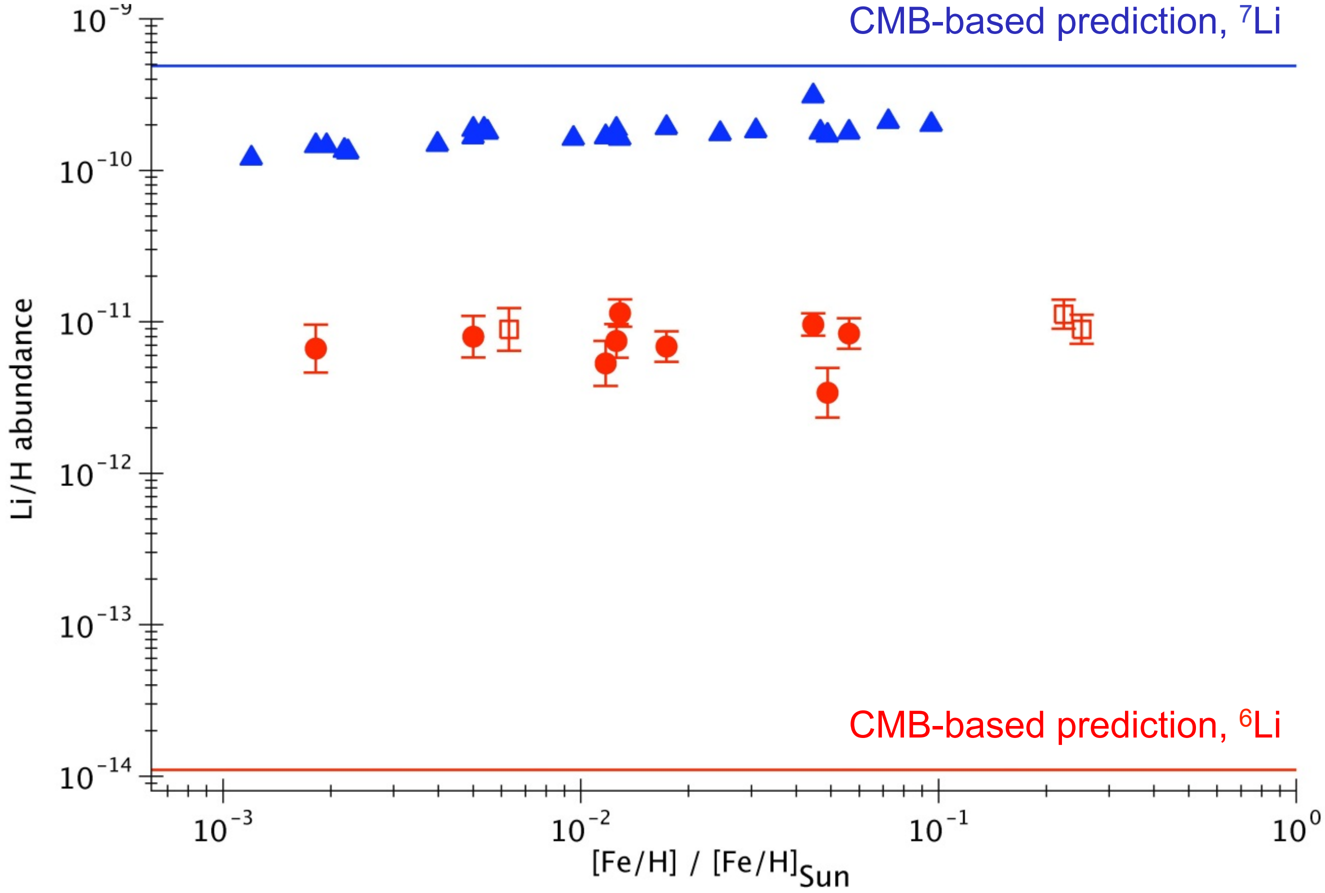
$^{2}H(\alpha,\gamma)^{6}Li$, LUNA results for the S factor and the ^{6}Li abundance



Michael Anders *et al.*,
Phys. Rev. Lett. 113, 042501 (2014)

- First direct data point in the Big Bang energy window
- Determine primordial $^{6}Li/^{7}Li$ ratio = (1.5±0.3) * 10^{-5} entirely from experimental data
- Astronomical reports of $^{6}Li/^{7}Li$ ~ 10^{-2} are probably in error

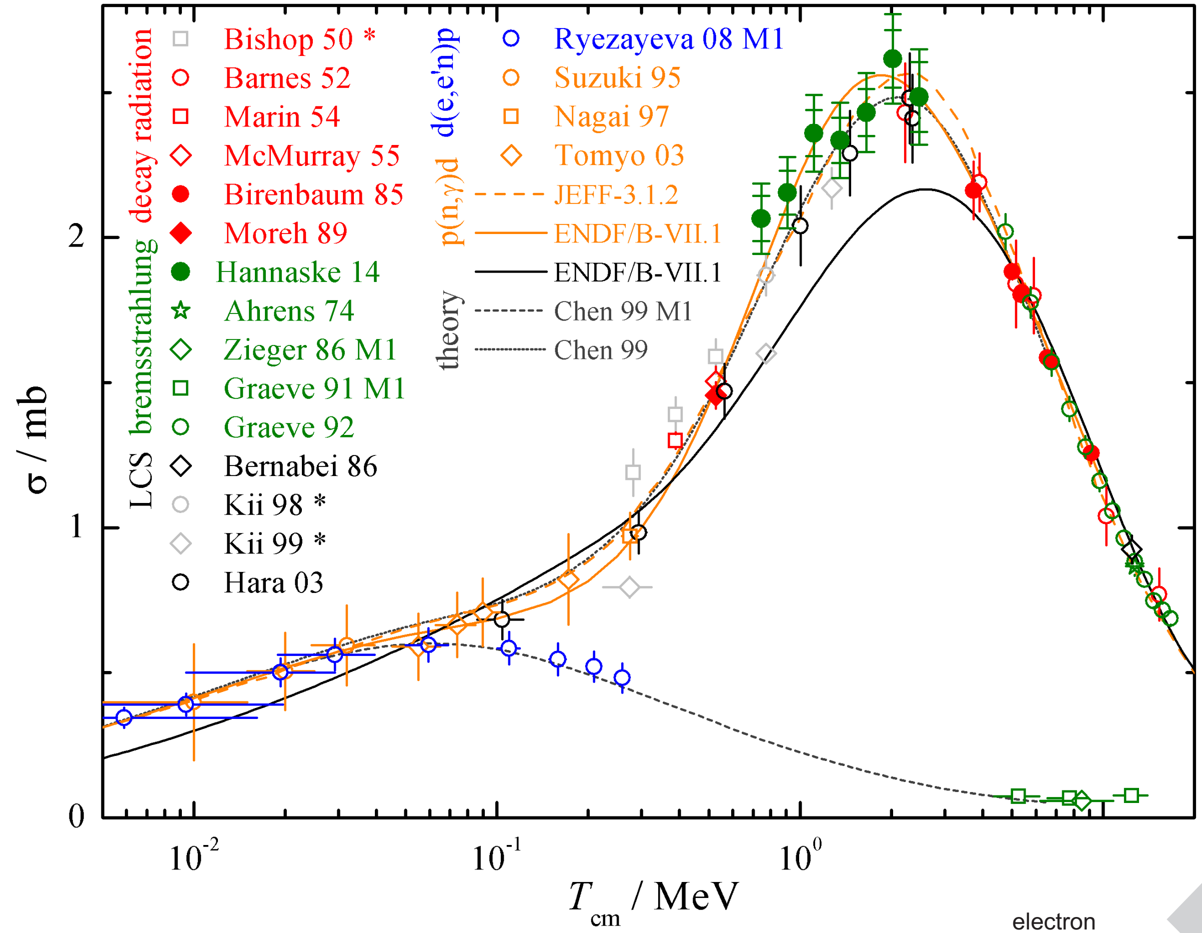
Cosmology: The Spite abundance plateau and the lithium problem(s)



- 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.

- Reported cosmic ^{6}Li problem: Much more ^{6}Li in some old stars than predicted.
  LUNA data show that standard BBN produces much less ^{6}Li than reported by some observers.

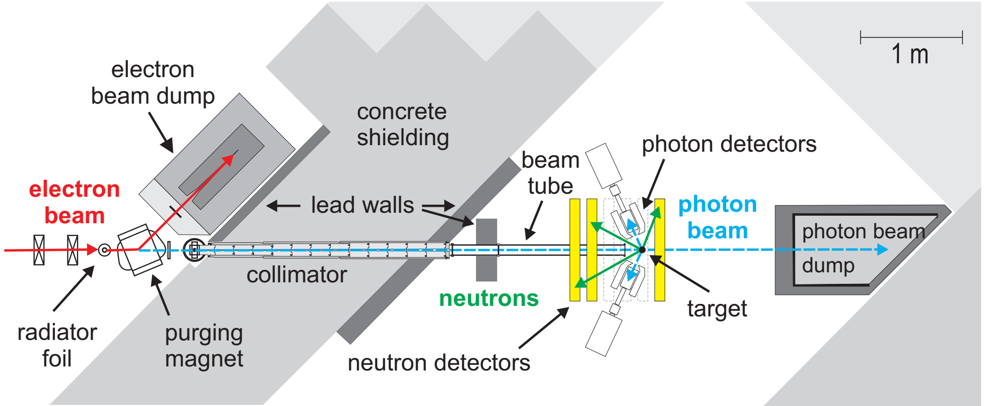
Experiment at HZDR, γELBE bremsstrahlung facility



Photodissociation of the deuteron, controlling the deuterium bottleneck:

$^{1}H(n,\gamma)^{2}H$

$^{2}H(\gamma,n)^{1}H$



A. R. Junghans, R. Hannaske *et al.*

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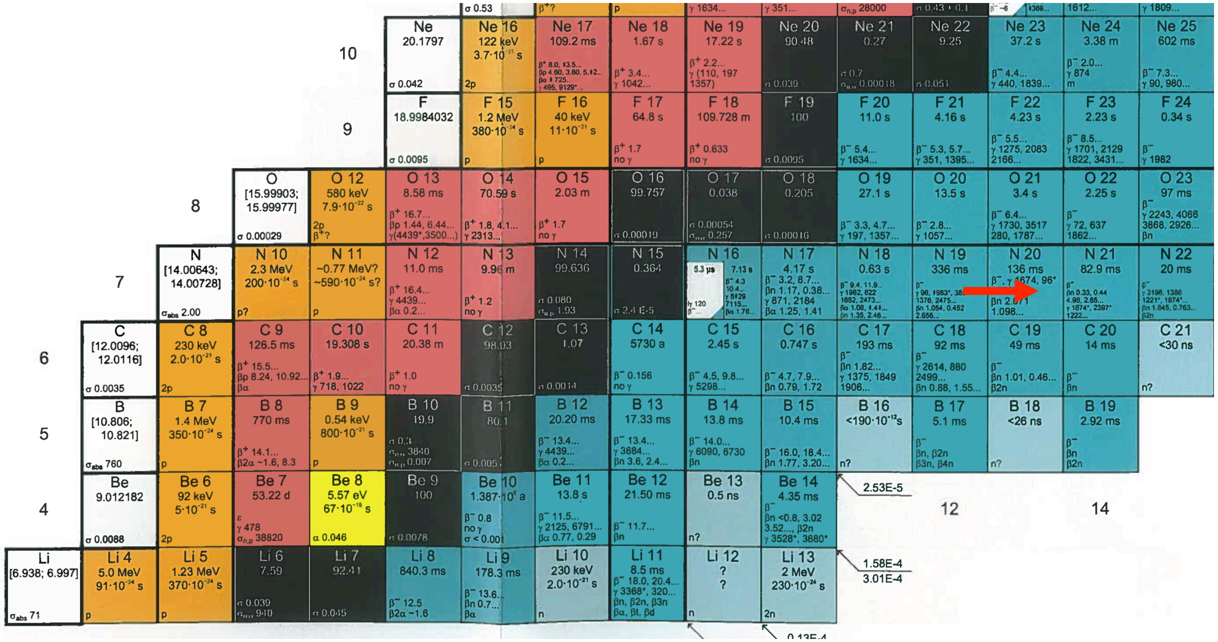
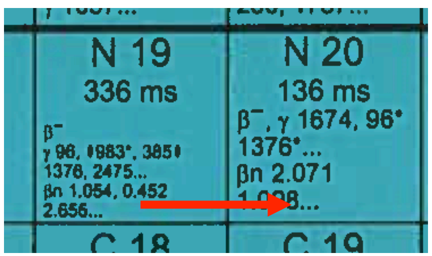
Neutron capture on exotic nuclei and neutron-rich BBN scenarios



Neutron-rich BBN scenarios postulate a nucleosynthesis path on the neutron-rich side of the valley of stability, where data are scarce (Terasawa *et al.*, Sasaqui *et al.*)



Reaction of astrophysical interest:

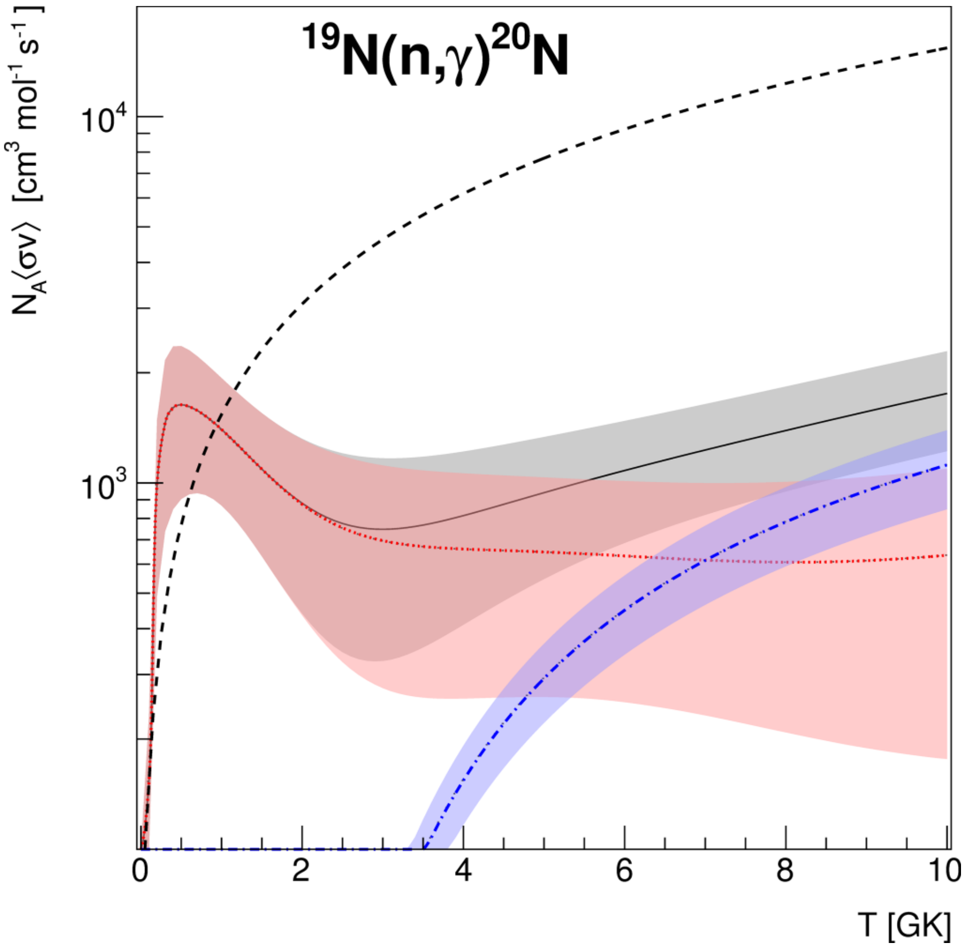
$$^{19}\mathrm{N} + n \rightarrow {}^{20}\mathrm{N} + \gamma$$

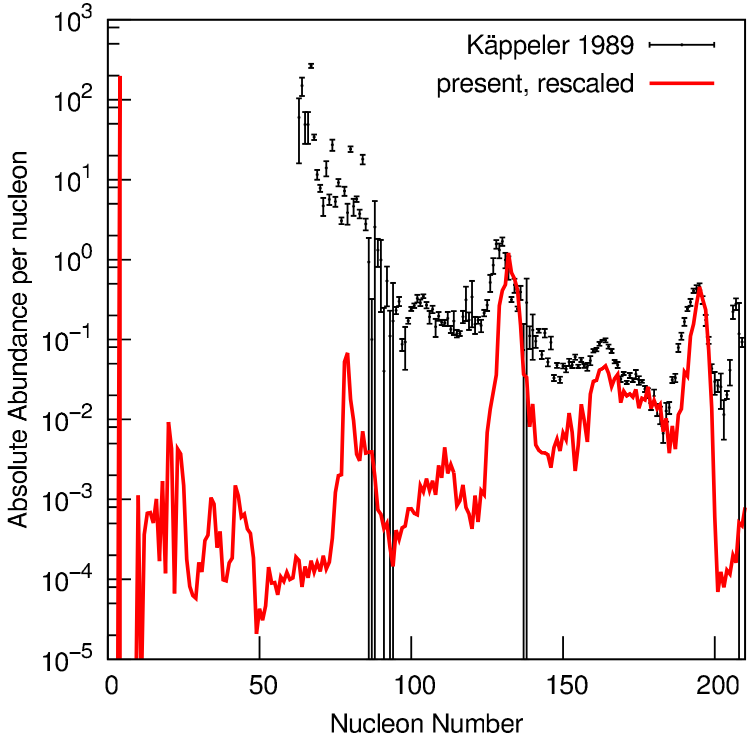
Reaction that can be studied in the laboratory:

$$^{19}\mathrm{N} + n \leftarrow {}^{20}\mathrm{N} + \gamma$$

using… an ion beam of radioactive ^{20}N and virtual photons from a heavy atomic nucleus

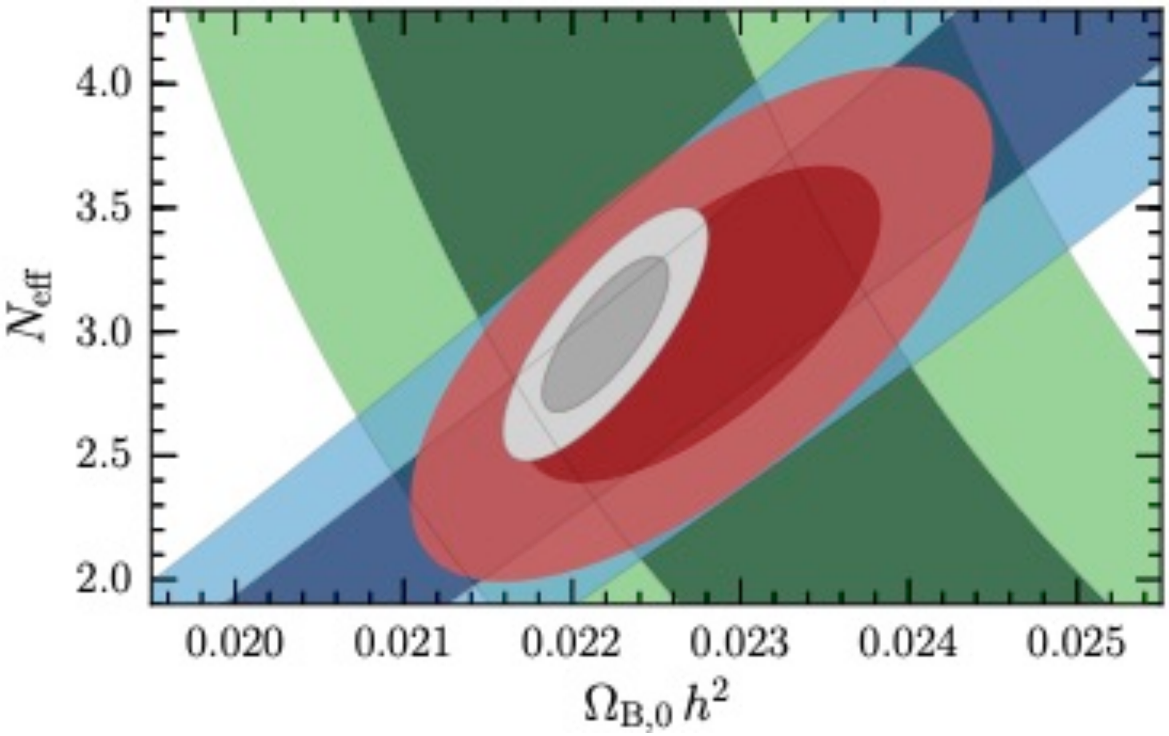
Data show no significant effect on heavy nuclei abundances… contrary to theoretical predictions





Marko Röder *et al.*,
Phys. Rev. C 93, 065807 (2016)

The $^2H(p,\gamma)^3He$ reaction cross section, destroying ^2H

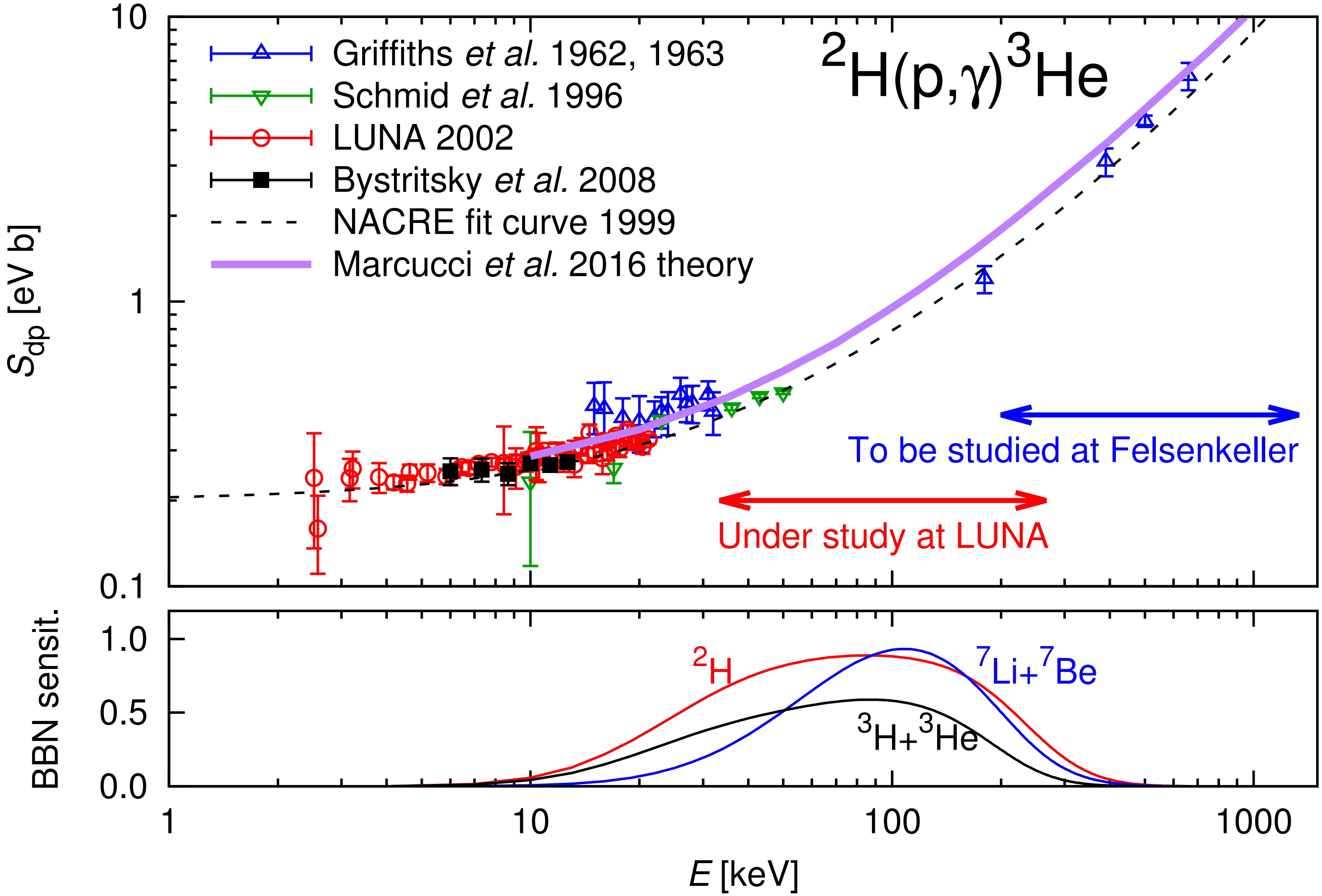


Grey circle: CMB (Planck 2015)
Blue band: ^2H
Green band: $^3He/^4He$
Red circle: ^2H and $^3He/^4He$ combined

R. Cooke *et al.* 2015

1. Currently, CMB (grey) and BBN (red) are in perfect agreement.
2. Currently, BBN is much less precise than CMB.
3. The BBN precision is mainly limited by the nuclear physics of ^2H destruction, more precisely the $^2H(p,\gamma)^3He$ reaction rate.

The $^{2}H(p,\gamma)^{3}He$ reaction cross section, destroying ^{2}H



See the poster by Klaus Stöckel!

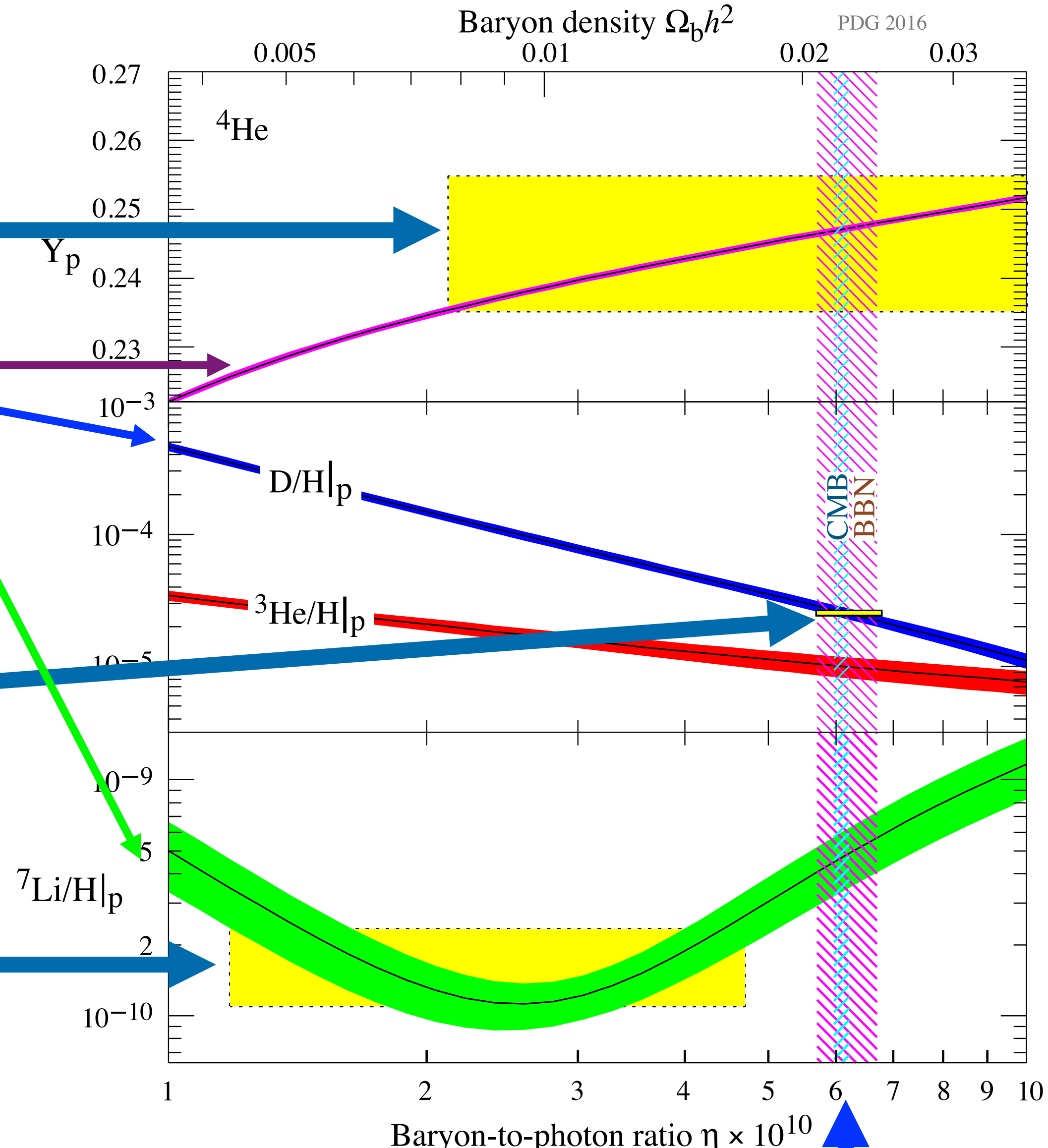
Cosmic concordance

1. Yellow box: ^{4}He observation

3. Purple/blue/green bands: BBN calculated predictions

1. Small yellow box: ^{2}H observation

1. Yellow box: ^{7}Li observation

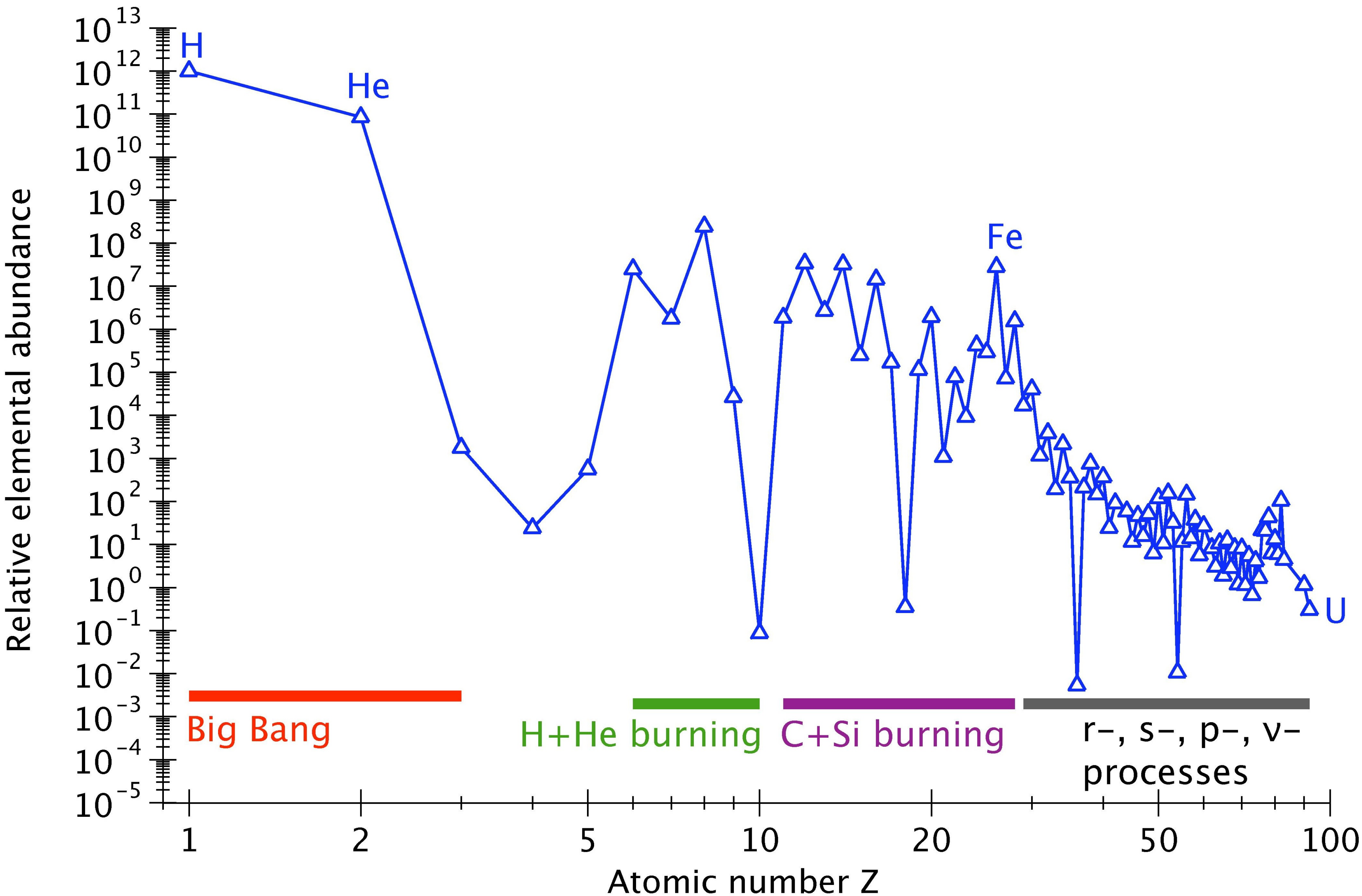


Three aspects agree:

1. Observed nuclide abundances
2. CMB value for η
3. BBN calculated nuclide abundances

2. Blue hatched area: CMB (Planck 2015)

What does BBN mean for the chemical elements around us?



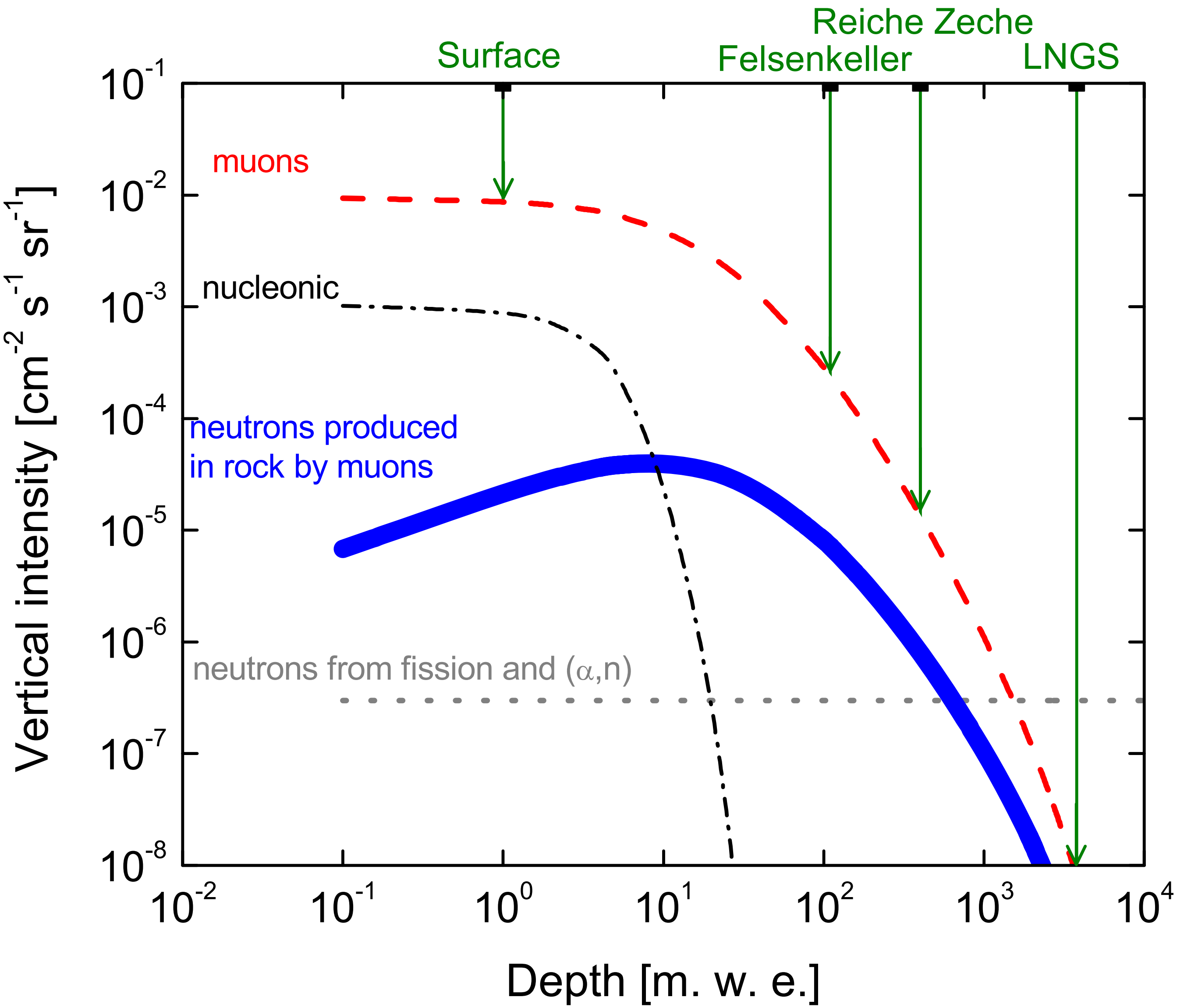
MML ■ IN-HOUSE RESEARCH

HZDR

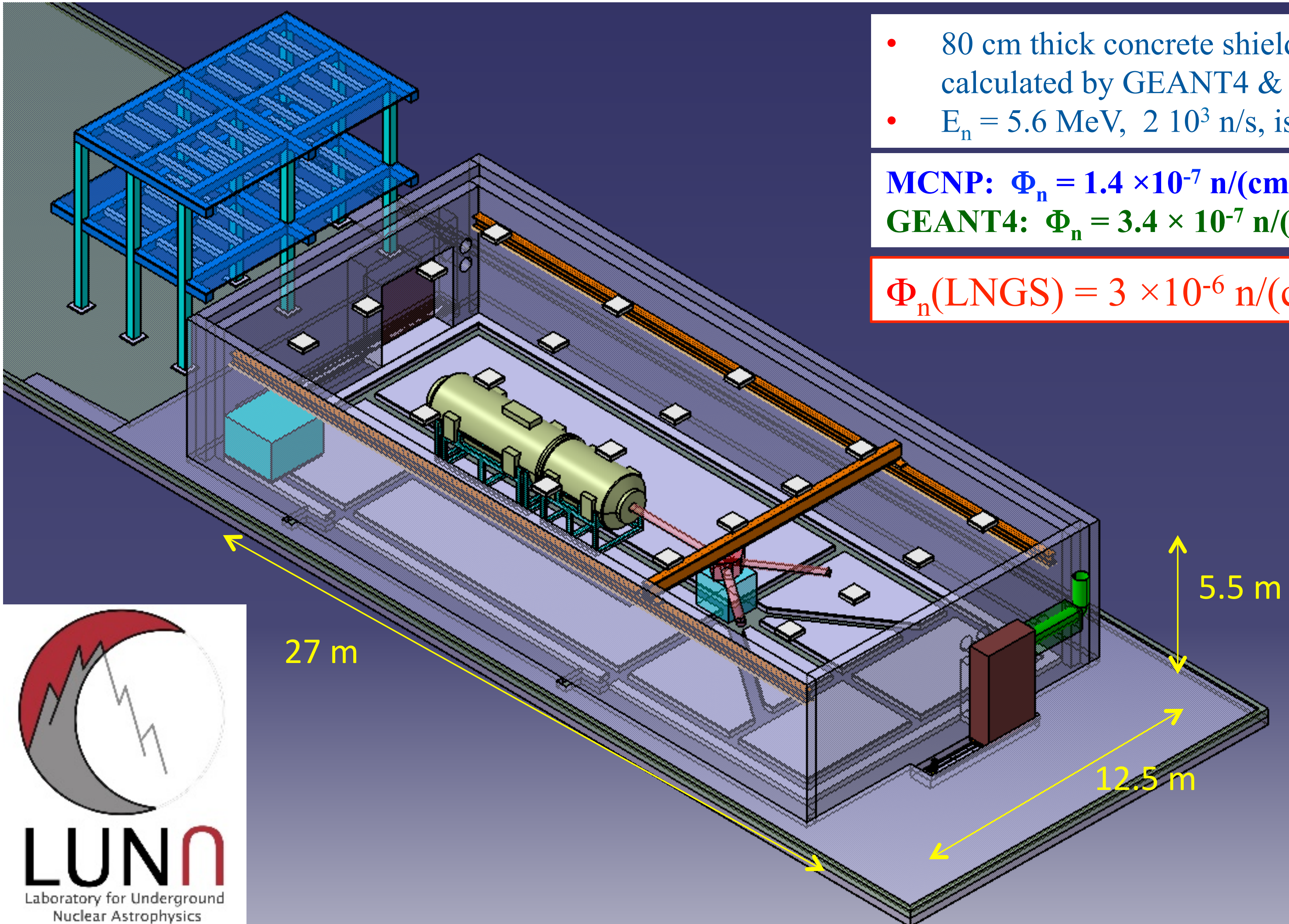
Nucleosynthesis in stars and in the big bang – the seeds for the r process

- **Big Bang nucleosynthesis**
  Astrophysical S-Factor
  Thermonuclear Reaction Rate
  Resonance Strength
  LUNA 0.4 MV underground lab in Italy
- **Experimental facilities underground**
  LUNA-MV underground lab in Italy
  Felsenkeller underground lab in Germany
- **Asymptotic giant branch stars**
  Stellar hydrogen burning
  Neutron sources for the s-process
  Stellar helium burning

Background components in underground laboratories



New LUNA-MV 3.5 MV accelerator for ^{1}H, ^{4}He, ^{12}C beams: Installation in Gran Sasso hall B from July 2019



- 80 cm thick concrete shielding calculated by GEANT4 & MCNP
- $E_n = 5.6$ MeV, $2\ 10^3$ n/s, isotropic

MCNP: $\Phi_n = 1.4 \times 10^{-7}$ n/(cm^2 s)
GEANT4: $\Phi_n = 3.4 \times 10^{-7}$ n/(cm^2 s)

Φ_n(LNGS) = 3×10^{-6} n/(cm^2 s)

LUNA
Laboratory for Underground Nuclear Astrophysics

LUNA MV- scientific program (2019 → 2024)

Commissioning measurement: $^{14}N(p,\gamma)^{15}O$. High scientific interest for revised data covering a wide energy range (400 keV- 3.5 MeV).

$^{12}C+^{12}C$: solid state target. Gamma and particle detection.

$^{13}C(\alpha,n)^{16}O$: enriched ^{13}C solid or gas target.
Data taking at LUNA 400 kV in 2017-2019.

$^{22}Ne(\alpha,n)^{25}Mg$: enriched ^{22}Ne gas target.

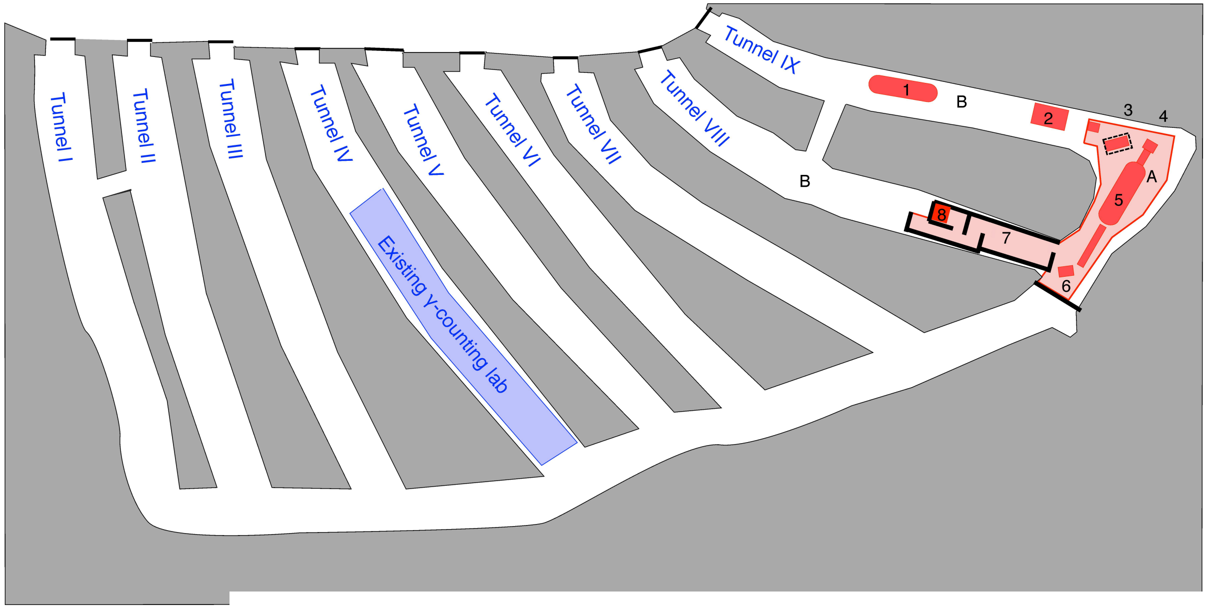
Next steps (not before 2024…):

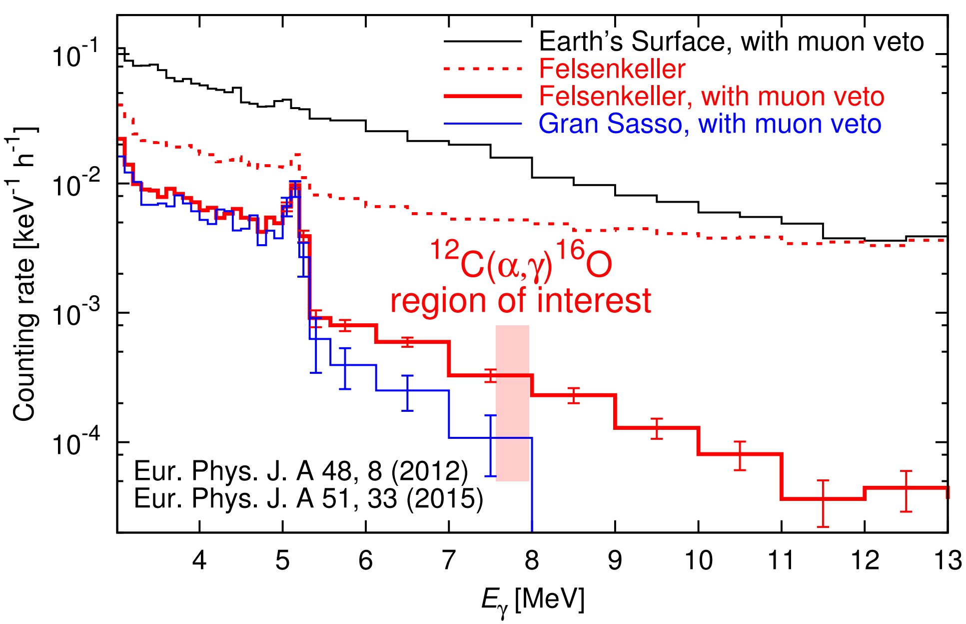
$^{12}C(\alpha,\gamma)^{16}O$: ^{12}C solid target depleted in ^{13}C and alpha beam or α jet gas target and ^{12}C beam.

LUNA
Laboratory for Underground Nuclear Astrophysics

New underground ion beam at Felsenkeller, Dresden

- System of nine tunnels built for Felsenkeller brewery in 1856-59
- Cosmic rays attenuated by 45 m rock and by active μ veto





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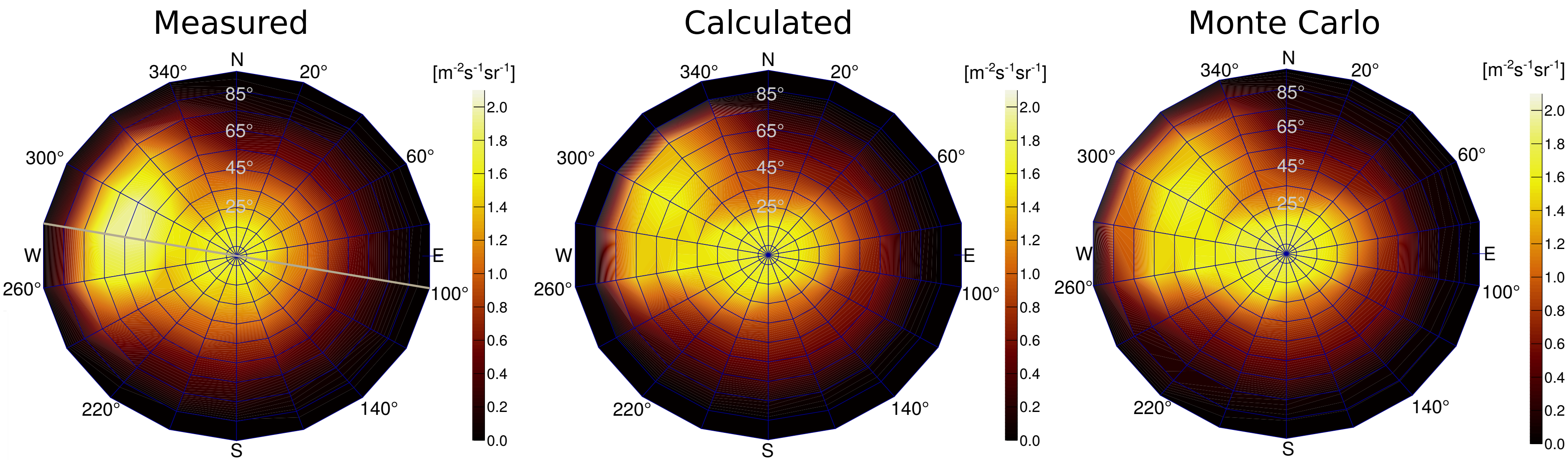
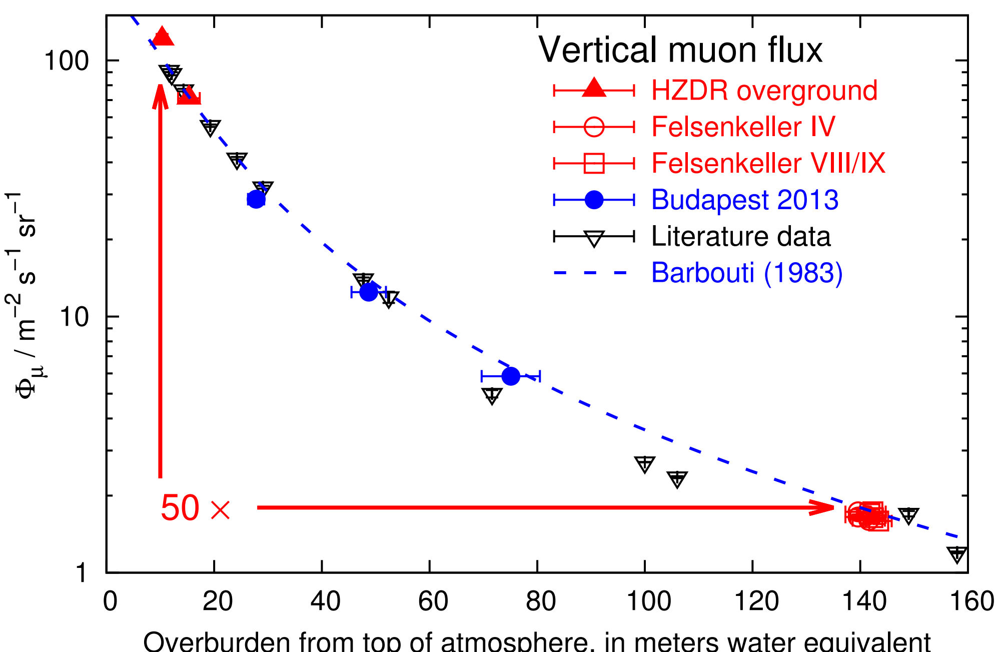
Muon flux and angular distribution with muon tomograph





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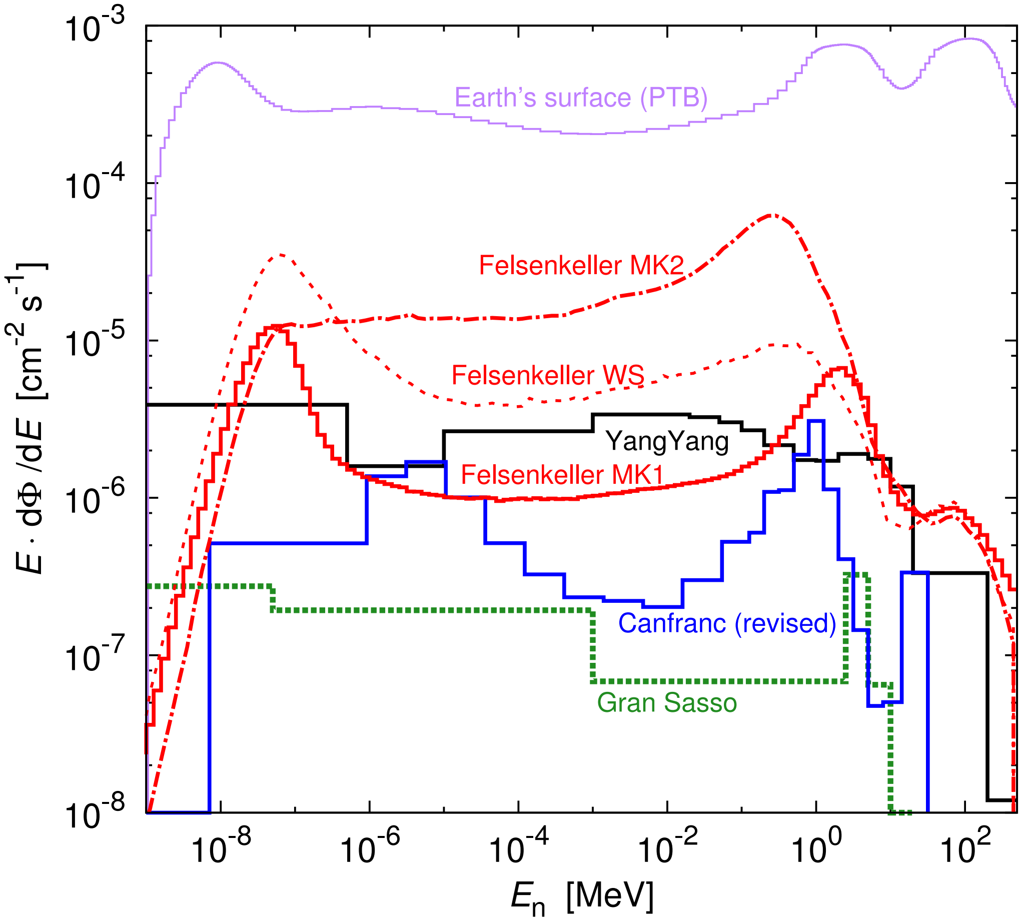
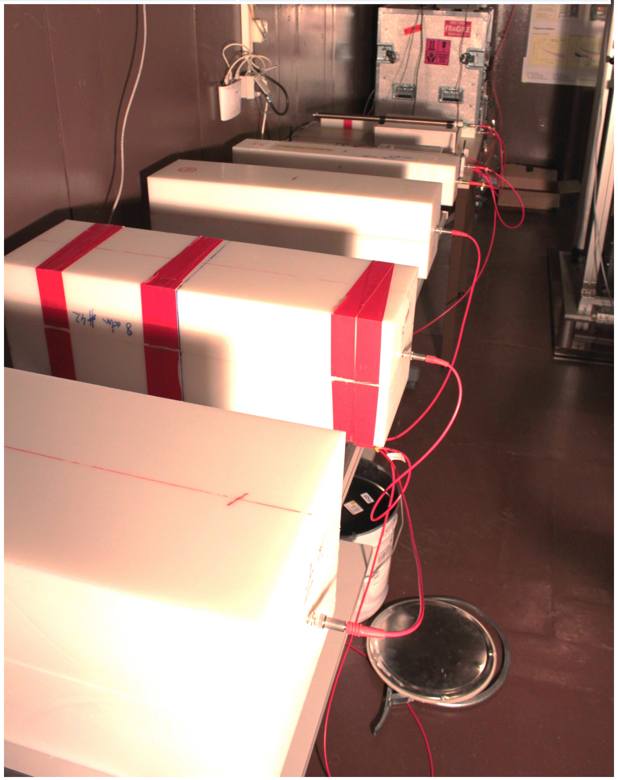
Neutron flux and spectrum with moderated ^{3}He counters

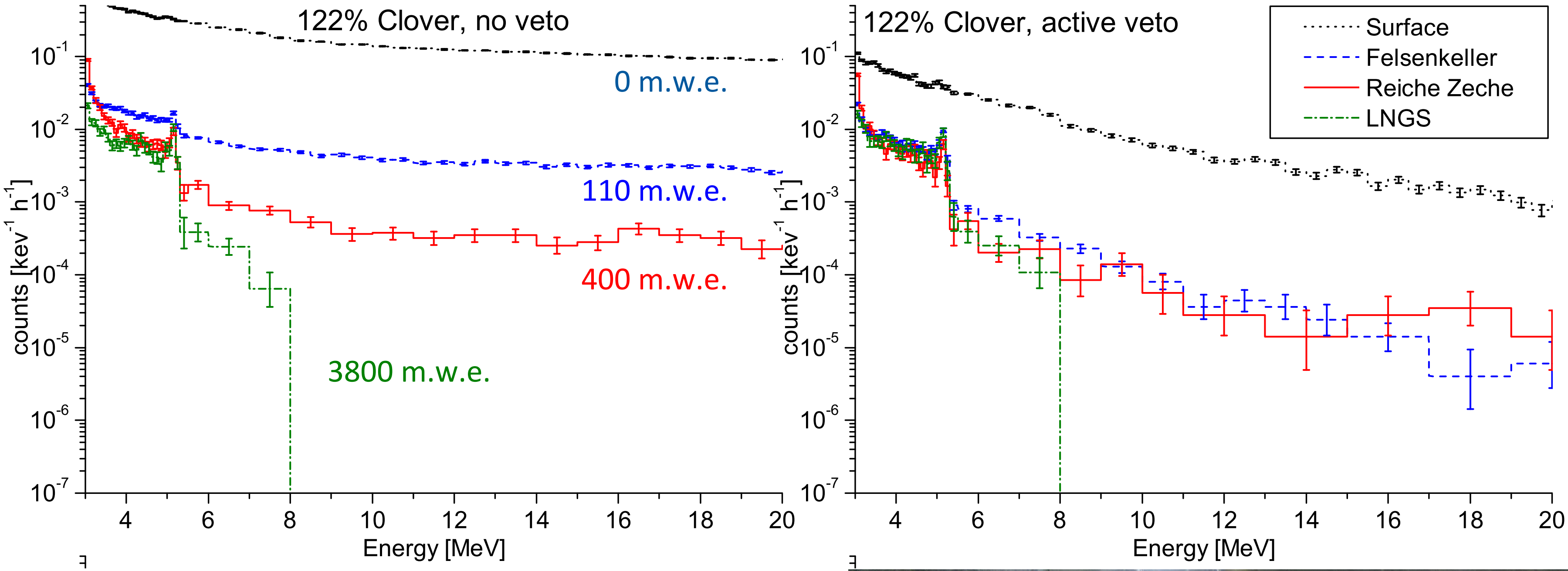


	Integrated n flux [10^{-4} cm^{-2} s^{-1}]
Tunnel	2.07 ± 0.07
Pb+Fe bunker	4.56 ± 0.16
Rock bunker	0.66 ± 0.04
Above ground	(121)



- Flux depends on local shielding
- Neutron data informed the construction project

Felsenkeller, γ-background measurement, with active veto



- One and the same HPGe detector used subsequently at different laboratories
- Background rate at 6-8 MeV γ-ray energy only a factor of 3 higher at Felsenkeller than at Gran Sasso

Tamás Szücs *et al.*
Eur. Phys. J. A 48, 8 (2012)
Eur. Phys. J. A 51, 33 (2015)

MML ■ IN-HOUSE RESEARCH

HZDR

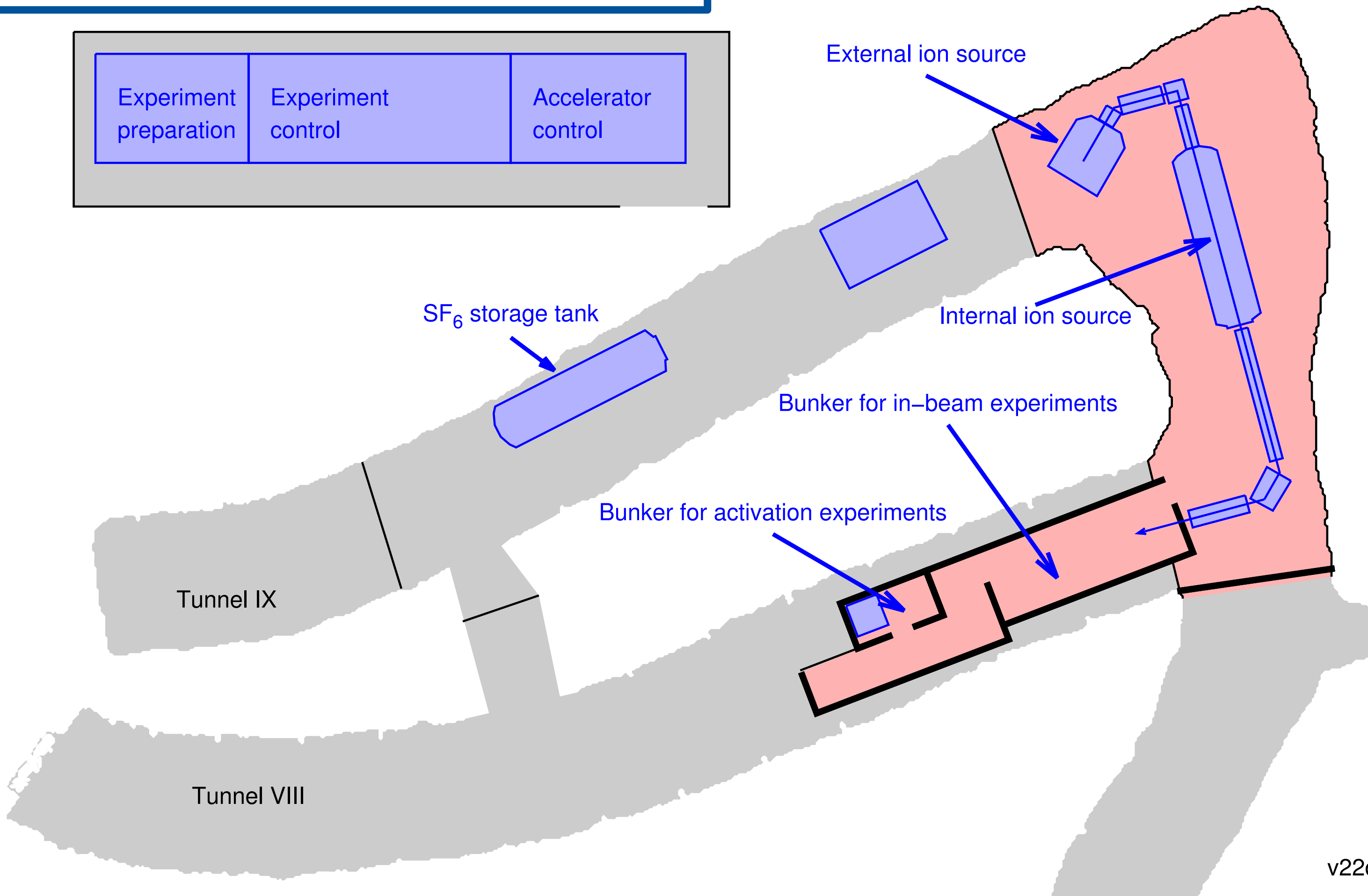
Installations in Felsenkeller

Joint effort HZDR – TU Dresden

- Investment by TU Dresden (Kai Zuber *et al.*) and HZDR (Daniel Bemmerer *et al.*)
- Running cost covered by HZDR
- Engineering and technical staff by HZDR

Two main instruments

- **HZDR:** 5 MV Pelletron, 50 μA beams of $^{1}H^{+}$, $^{4}He^{+}$ (single-ended), $^{12}C^{+}$ (tandem)
- **TU Dresden:** 150% ultra-low-background HPGe detector for offline γ-counting



5 MV Pelletron tank inside the tunnel

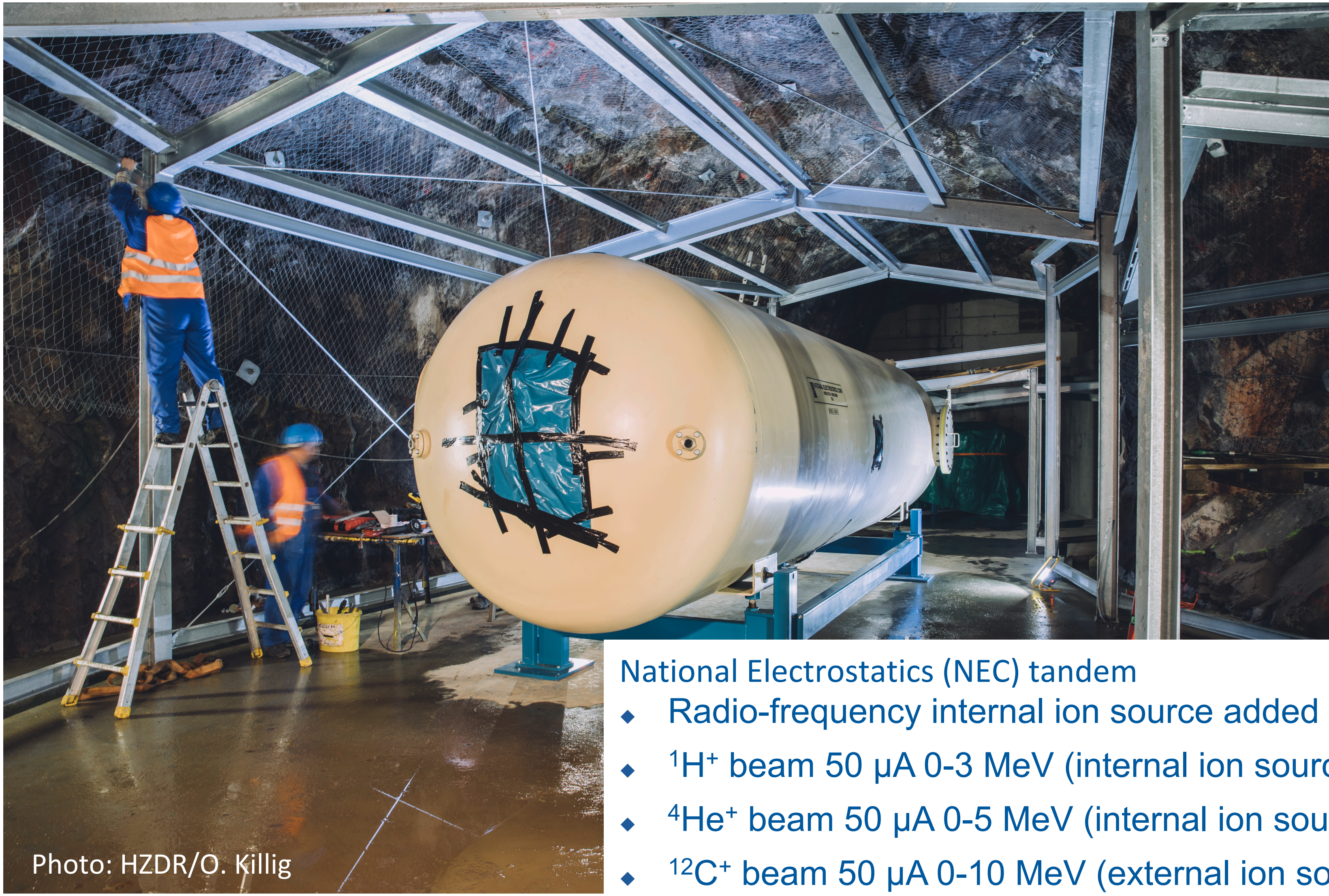


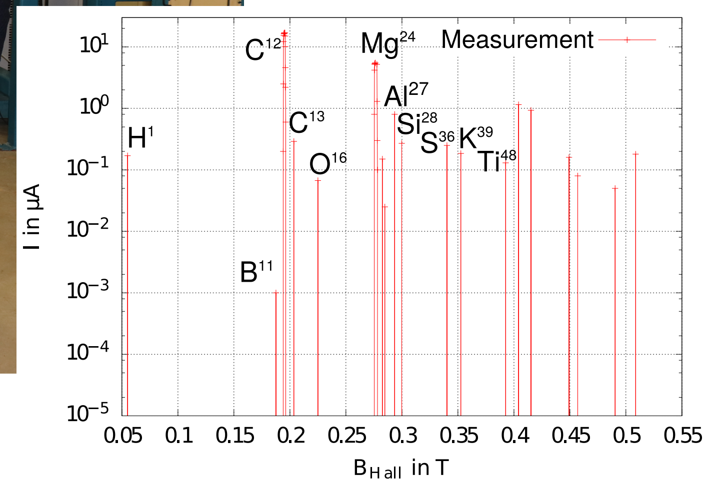
Photo: HZDR/O. Killig

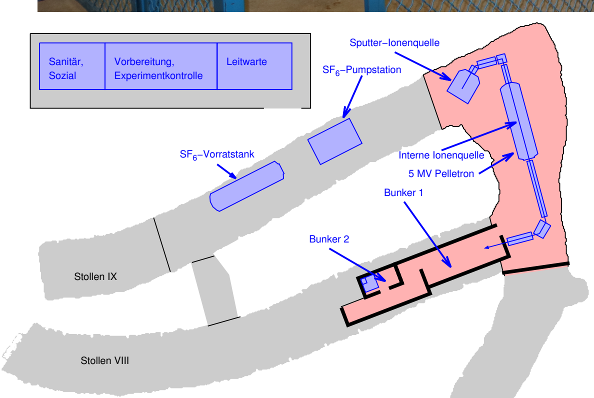
National Electrostatics (NEC) tandem

- Radio-frequency internal ion source added
- $^{1}H^{+}$ beam 50 µA 0-3 MeV (internal ion source)
- $^{4}He^{+}$ beam 50 µA 0-5 MeV (internal ion source)
- $^{12}C^{+}$ beam 50 µA 0-10 MeV (external ion source)

External (=sputter) ion source for ^{12}C beam

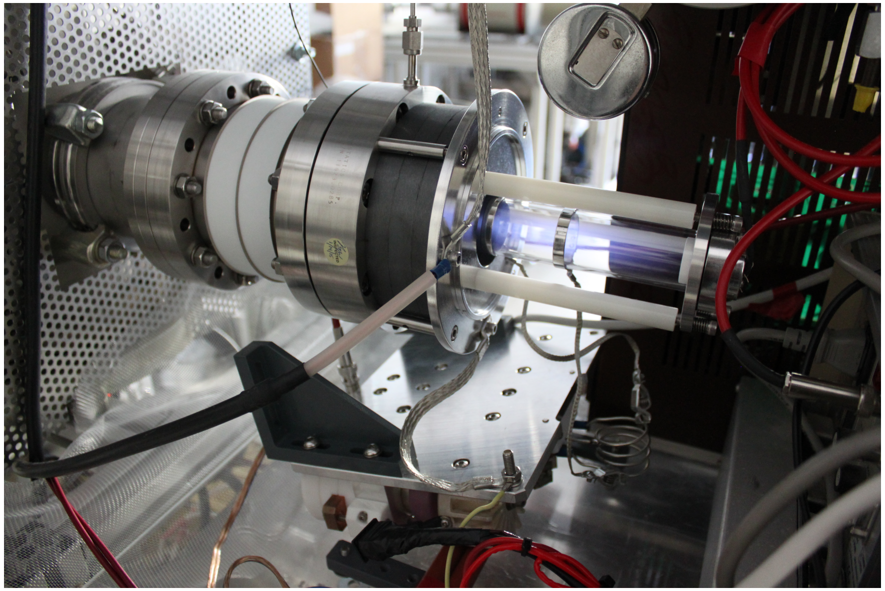
Cesium sputter ion source produces intensive $^{12}C^-$ beam:
140 µA after the source

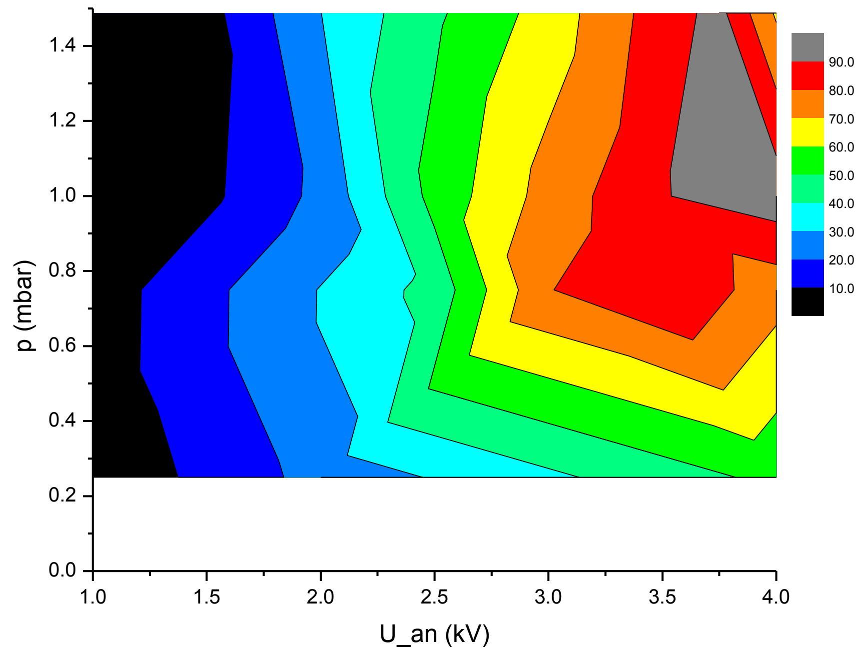


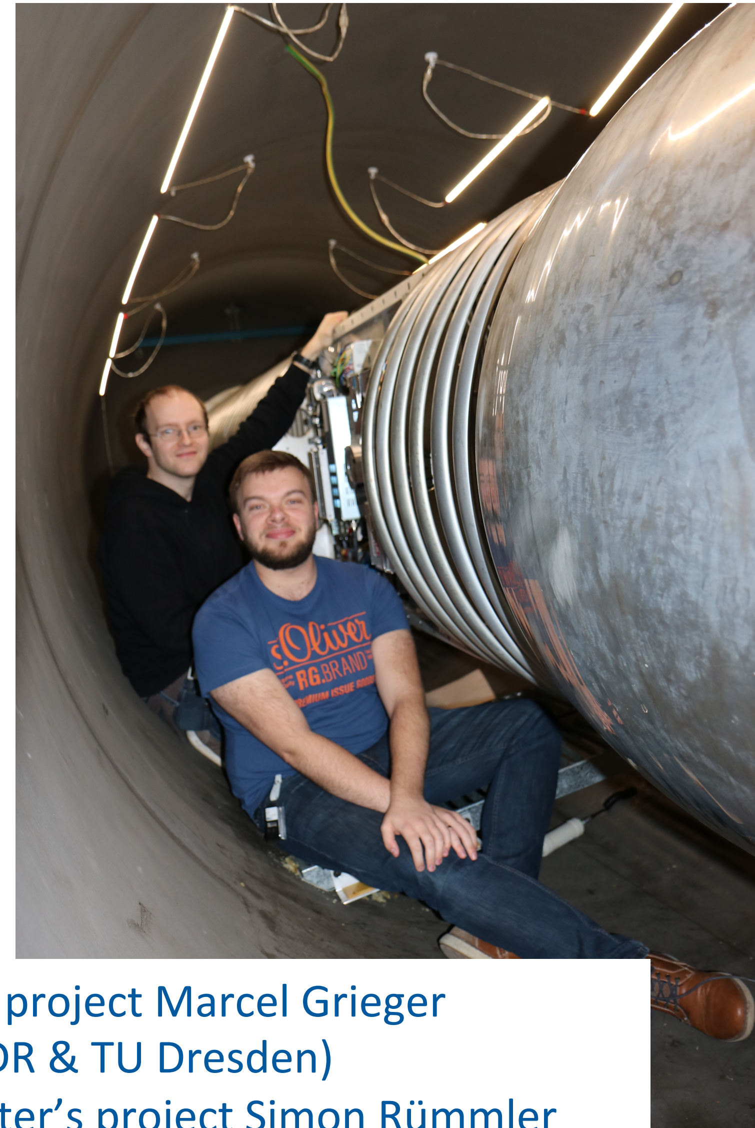


PhD project Felix Ludwig (HZDR & TU Dresden)
Bachelor's project Julia Steckling

Internal (=radio frequency) ion source for ^{1}H, ^{4}He beams





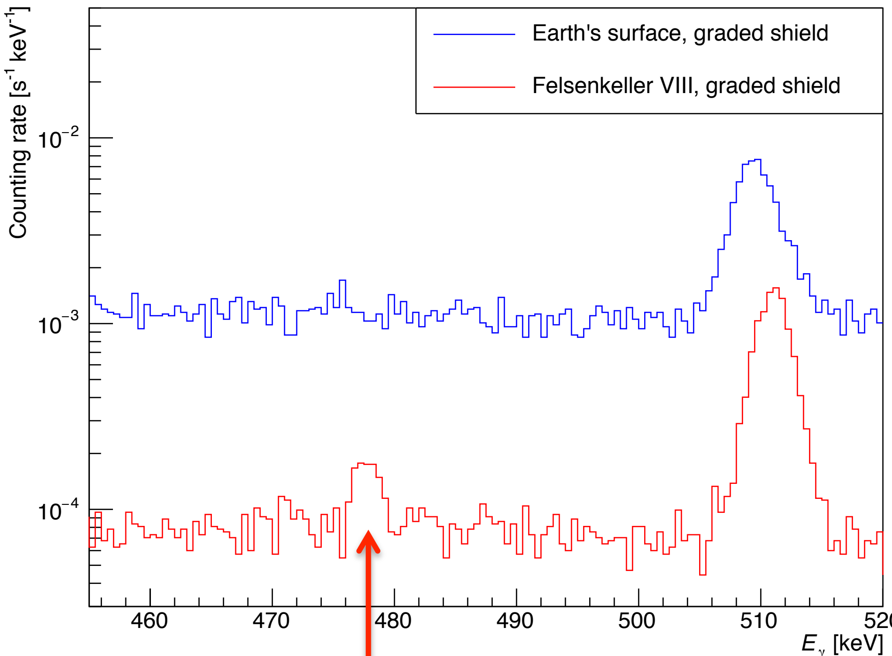


PhD project Marcel Grieger
(HZDR & TU Dresden)
Master's project Simon Rümmler

National Electrostatics 5 MV Tandem, 300 µA upcharge current

TU Dresden activity measurement bunker in Felsenkeller

- 150% ultra low background HPGe detector
- Lowest background radioactivity measurement lab in Germany
- Under commissioning, preliminary data very promising



478 keV γ-ray from ^{3}He(α,γ)^{7}Be activation study for solar fusion

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Nucleosynthesis in stars and in the big bang – the seeds for the r process

- **Big Bang nucleosynthesis**
  Astrophysical S-Factor
  Thermonuclear Reaction Rate
  Resonance Strength
  LUNA 0.4 MV underground lab in Italy
- **Experimental facilities underground**
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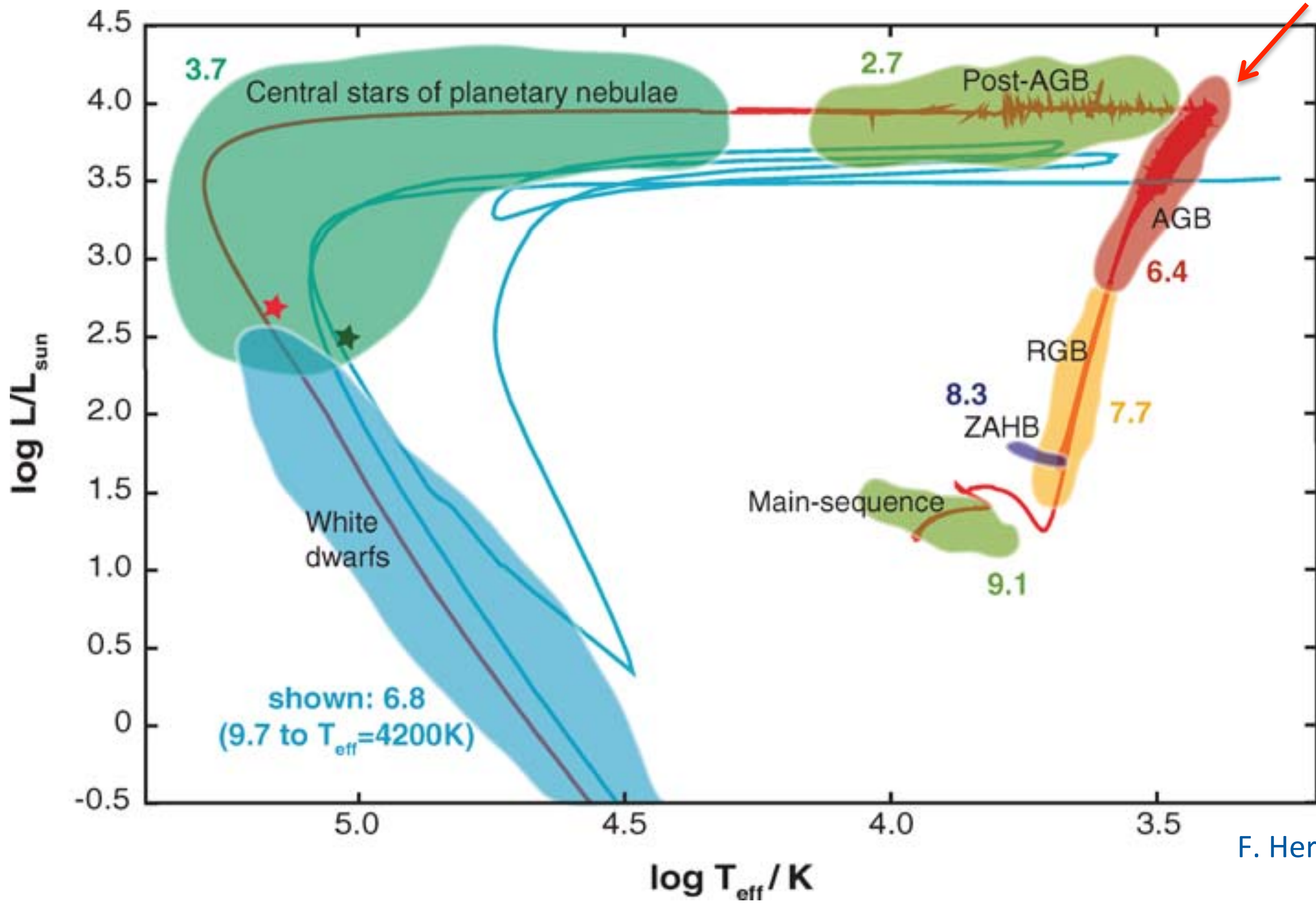
- **Asymptotic giant branch stars**
  Stellar hydrogen burning
  Neutron sources for the s-process
  Stellar helium burning

Photo: HZDR/O. Killig

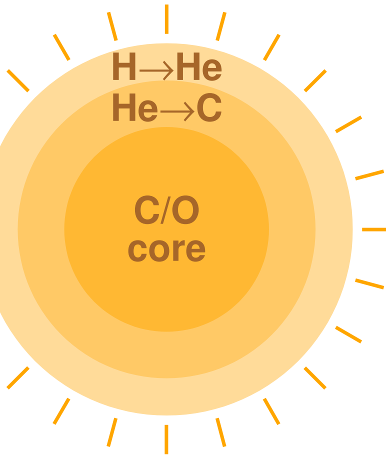
Asymptotic Giant Branch (AGB) stars as a physics laboratory (1)

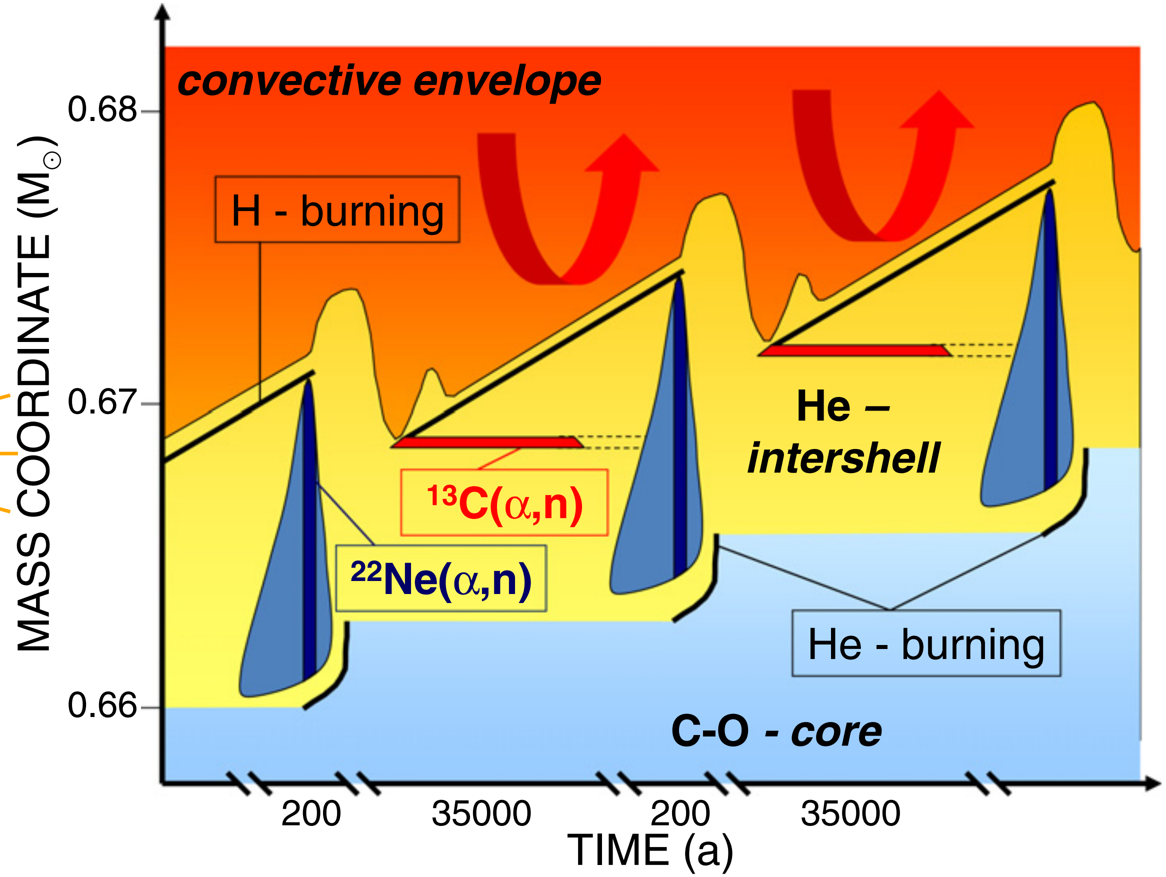
AGB stars on the Hertzsprung-Russell diagram



F. Herwig, ARA&A 2005

Asymptotic Giant Branch (AGB) stars as a physics laboratory (2)





R. Reifarth *et al.* (2014)

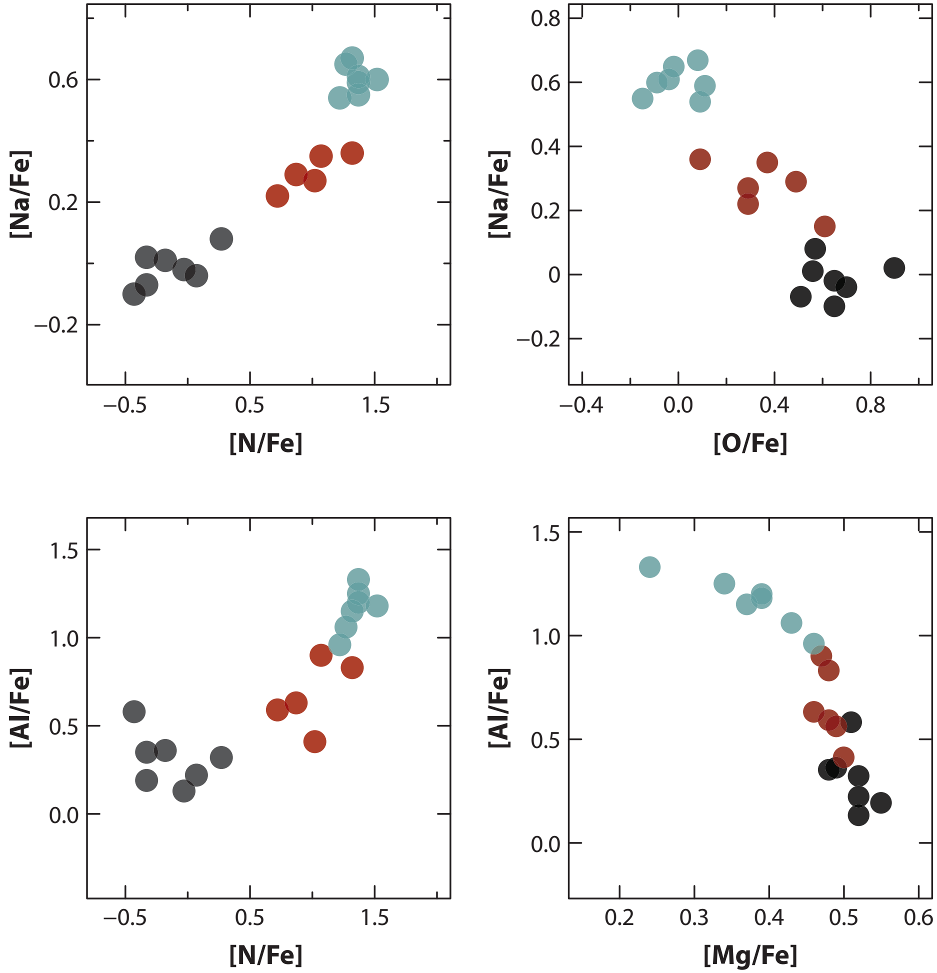
- Convective mixing: H burning zone – He intershell
- Nuclear reactions: Neutron sources / Neutron capture
  - H burning / He burning
- Plasma effects
- Radiative energy transport (opacity)

Sensitive probe of AGB star models, by observed abundances.

Elemental abundances in globular cluster stars, example: NGC 6752

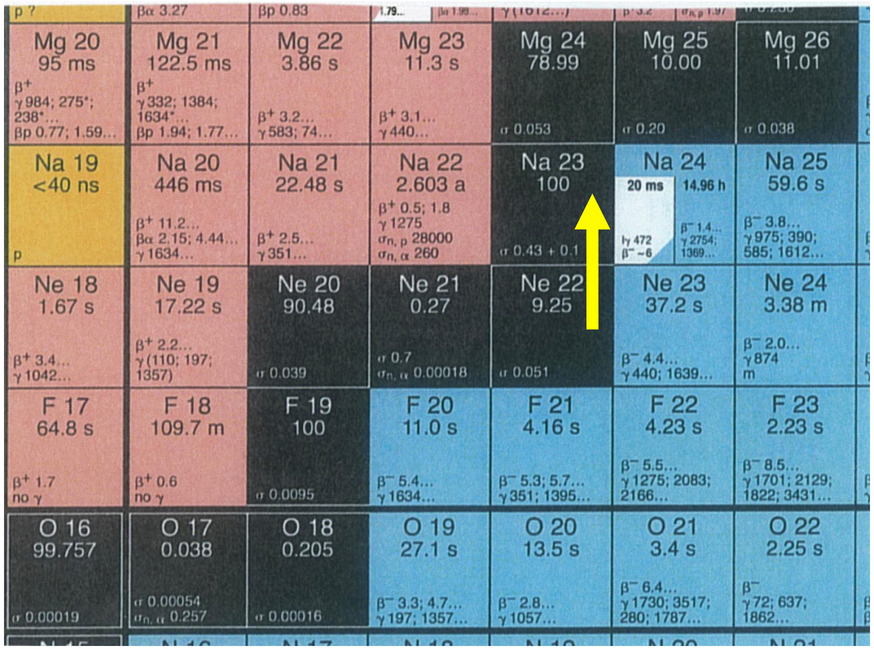
3.5'' view by the Hubble Space Telescope
Image credit: NASA/STScI/WikiSky

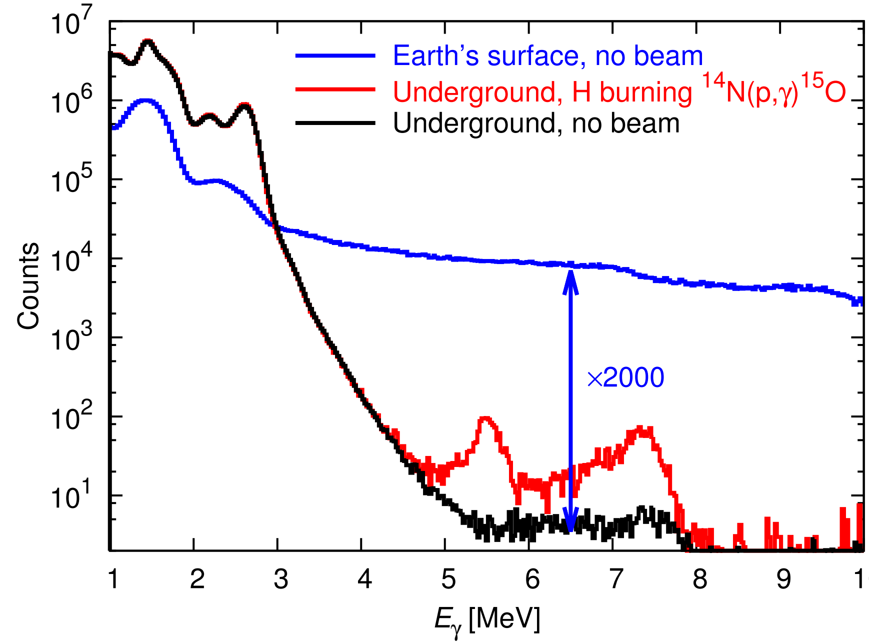
Abundances [Na/Fe]= $\log_{10}(N(Na)/N(Fe))$
Bastian & Lardo (2018)



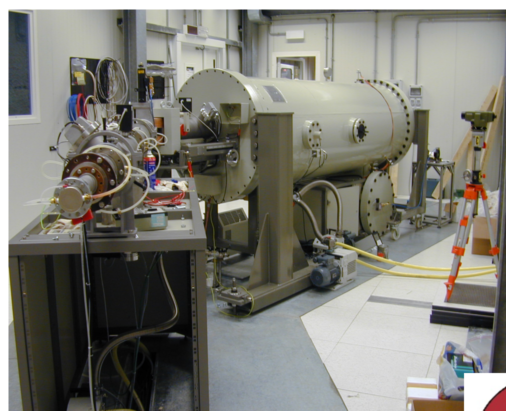
1. We see Na, Mg, Al - imprints of higher hydrogen burning.
2. Some abundances are anticorrelated – why so?

^{23}Na production by hydrogen burning: ^{22}Ne(p,γ)^{23}Na (1)



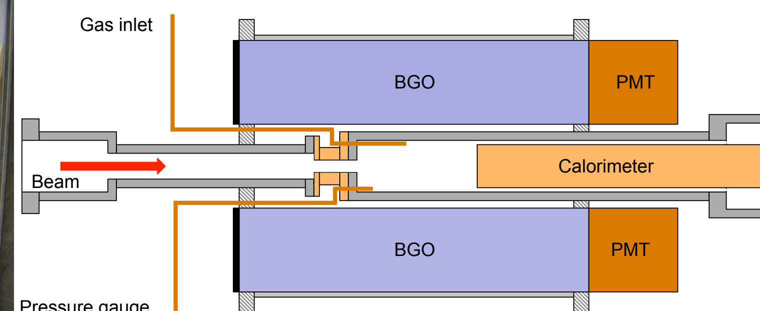


Gran Sasso d'Italia, 2906 m



LUNA 0.4 MV

^{1}H, ^{4}He ion accelerator



Gas target,

surrounded by γ detector

LUNA Laboratory for Underground Nuclear Astrophysics

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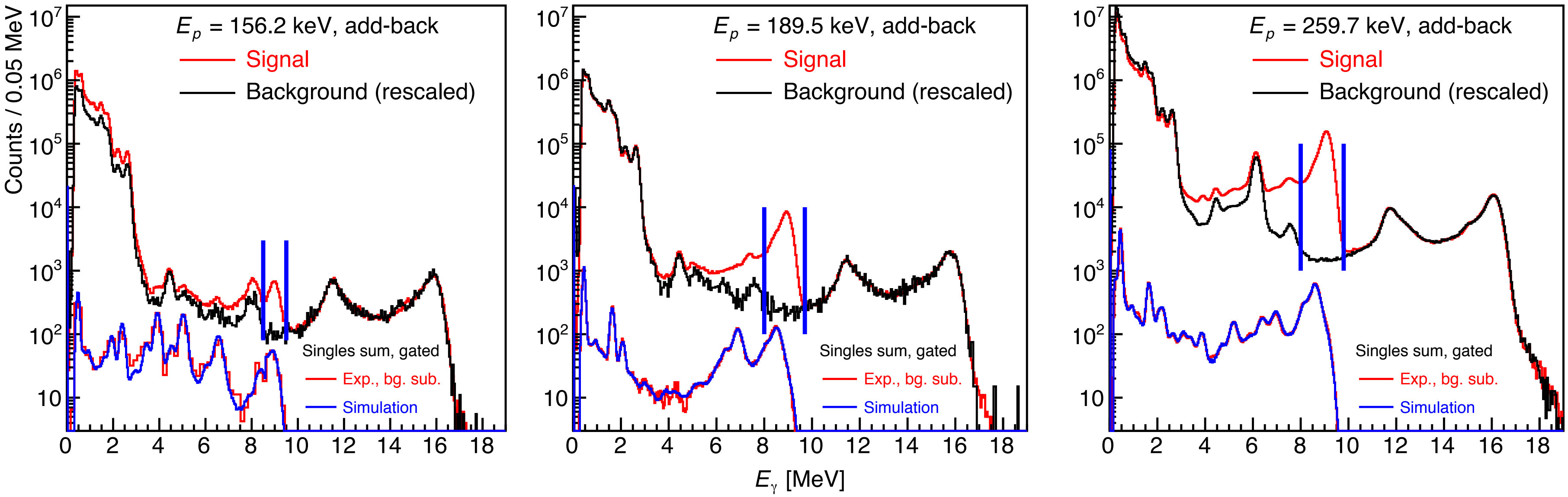
HZDR

^{23}Na production by hydrogen burning: ^{22}Ne(p,γ)^{23}Na (2)



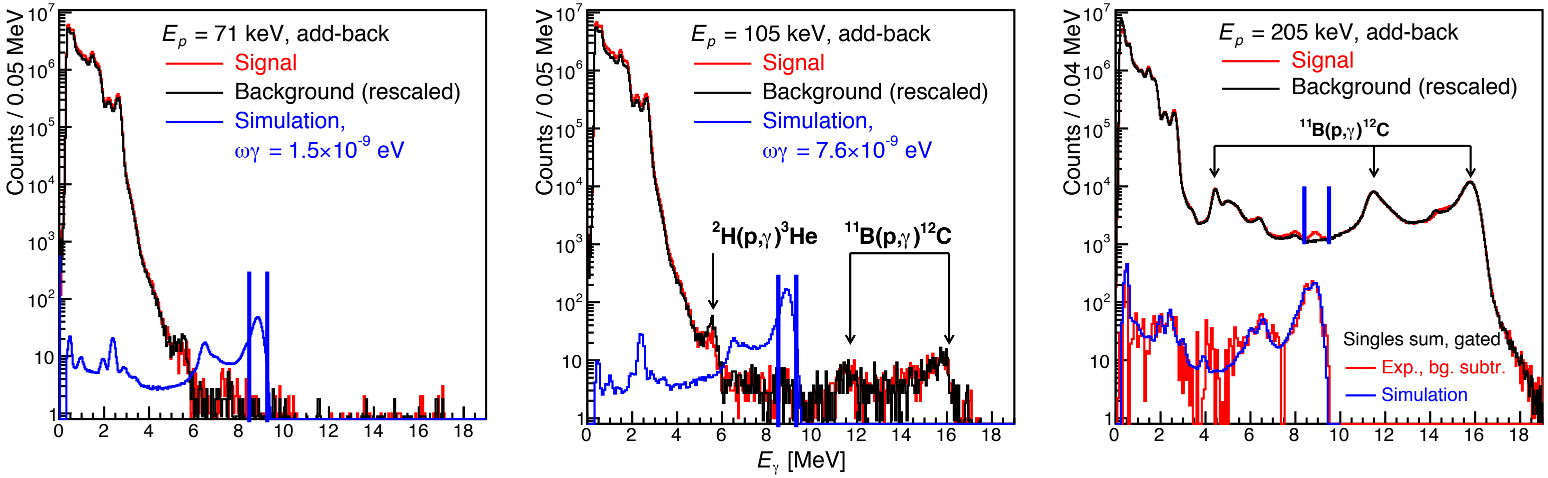
Three new resonances, hitherto unobserved.

Resonance strength ωγ [μeV]	**E_p = 156.2 keV**	**E_p = 189.5 keV**	**E_p = 259.7 keV**
Indirect studies	0.009±0.003	≤ 2.6	≤ 0.13
Direct experiment	0.18±0.02	2.2±0.2	8.2±0.7

F. Cavanna *et al.* (LUNA) Phys. Rev. Lett. 115, 252501 (2015)

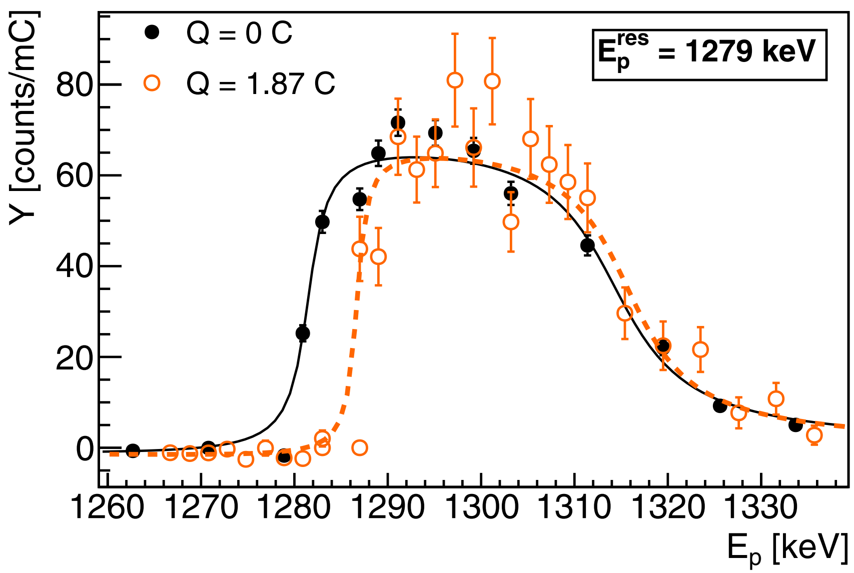
D. Bemmerer *et al.* (LUNA) Europhys. Lett. 122, 52001 (2018)

^{23}Na production by hydrogen burning: ^{22}Ne(p,γ)^{23}Na (3)



Two suspected resonances ruled out.
Direct capture componenz studied.

F. Ferraro *et al.* (LUNA)
Phys. Rev. Lett. 121, 172701 (2018)

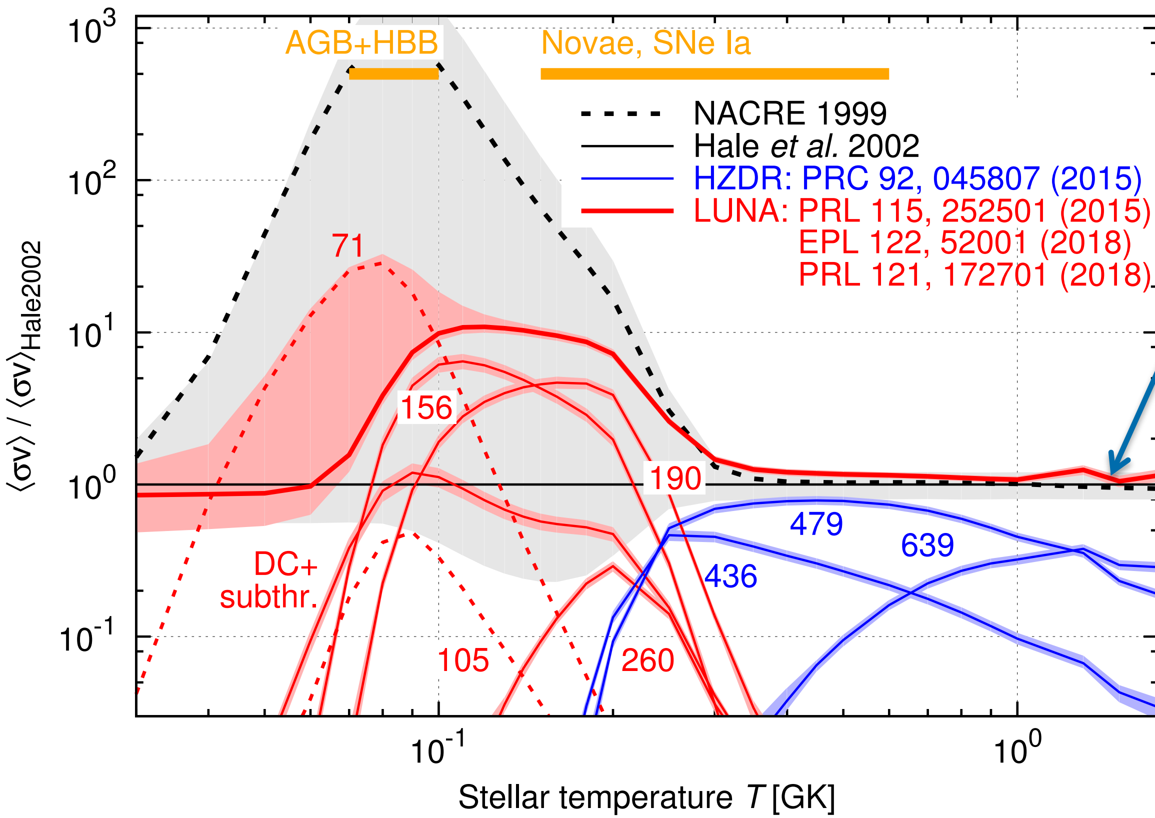


Surface-based experiment at
Rossendorf 3 MV Tandetron (IBC)
R. Depalo *et al.*,
Phys. Rev. C 92, 045807 (2015)

^{23}Na production by hydrogen burning: ^{22}Ne(p,γ)^{23}Na (4)

Thermonuclear reaction rate <σv> from resonance strength ωγ and energy E_{reso}

$$\langle\sigma v\rangle = \left(\frac{2\pi}{\mu k_B T}\right)^{\frac{3}{2}} \hbar^2 \,\omega\gamma\, \exp\left(-\frac{E_{reso}}{k_B T}\right)$$

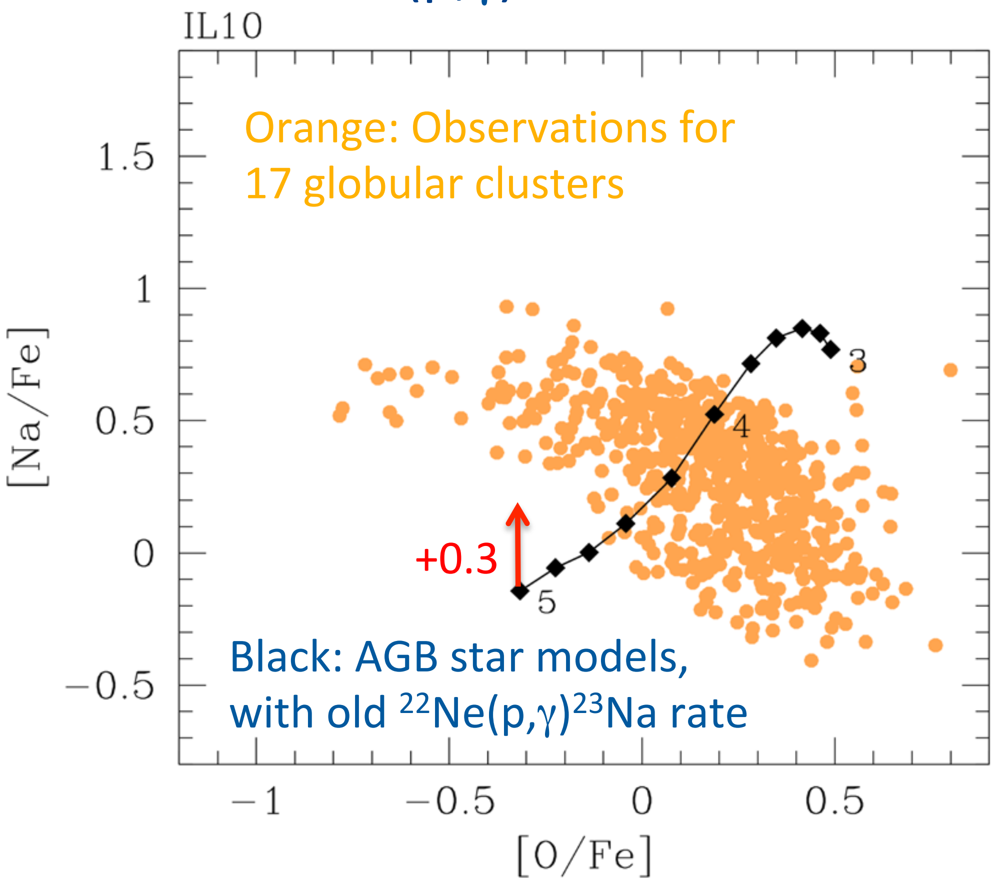


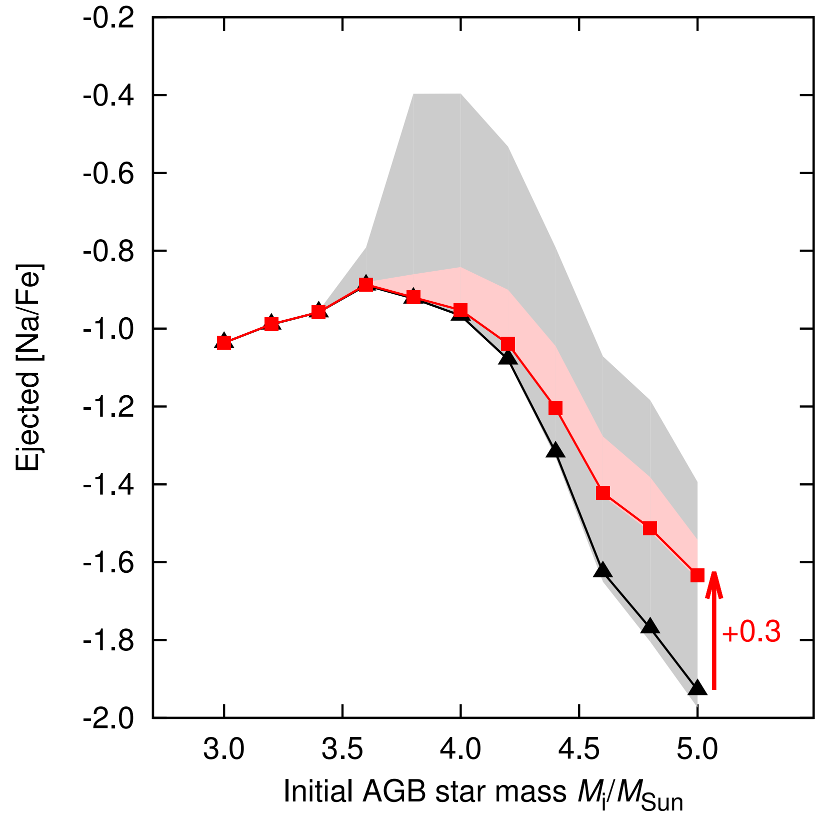
<σv> from low-energy, underground nuclear astrophysics experiment.

Still needed:

- Electron shielding by astrophysical plasma
- Radiative energy transport / opacity
- Convective transport to make the produced ^{23}Na visible

The new $^{22}Ne(p,\gamma)^{23}Na$ data and the Na – O anticorrelation

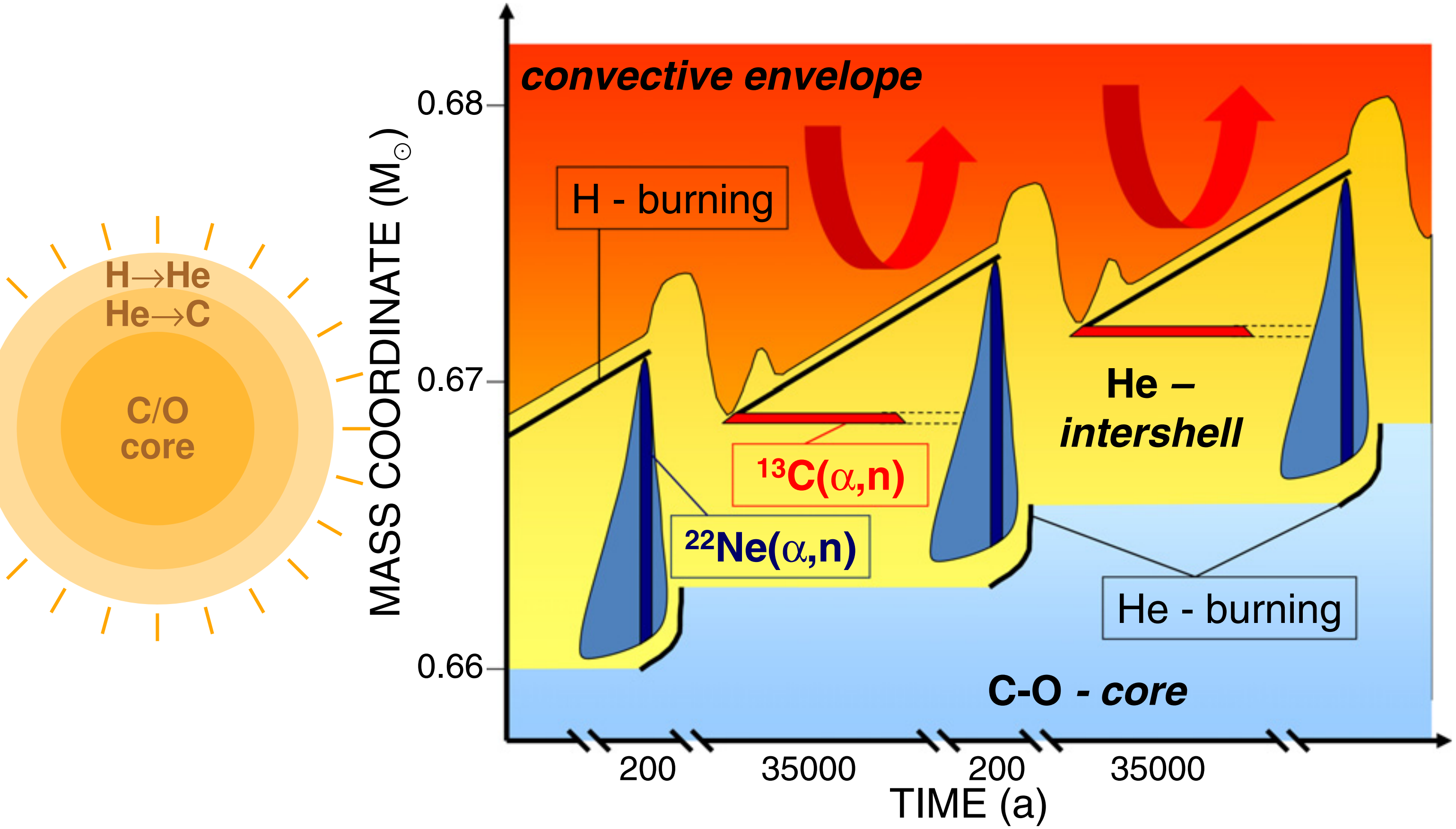




A. Slemer *et al.* (LUNA),
Mon. Not. Royal Astron. Soc.
465, 4817 (2017)

The new nuclear data improve the (previously very bad) description of the Na-O anticorrelation.

Asymptotic Giant Branch (AGB) stars as a physics laboratory

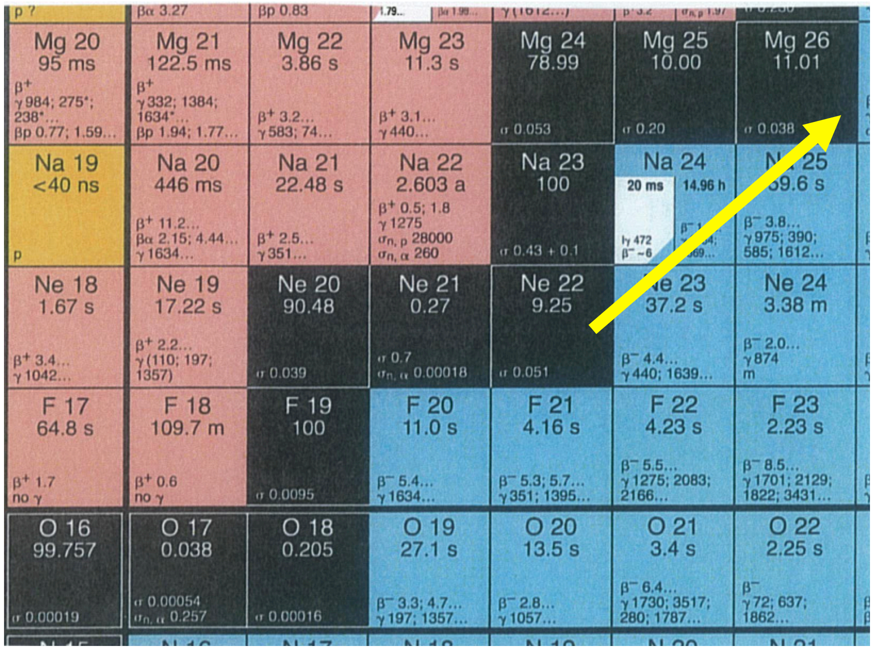


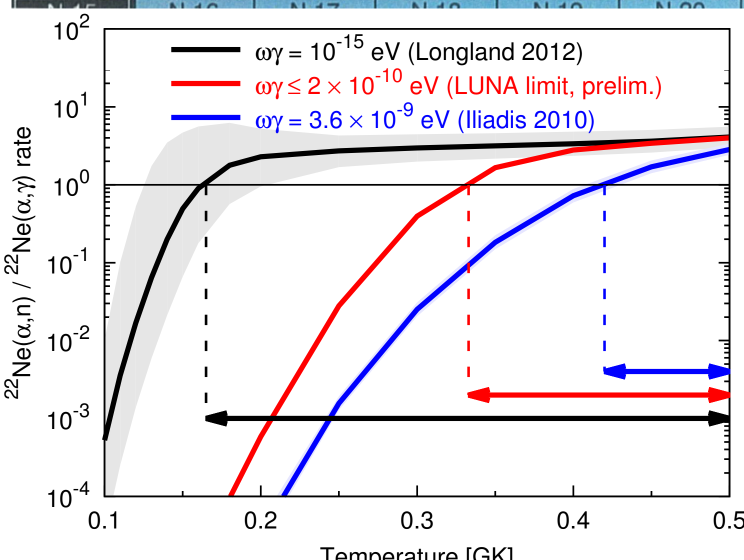
R. Reifarth *et al.* (2014)

- Convective mixing: H burning zone – He intershell
- Nuclear reactions: Neutron sources | Neutron capture
  H burning | He burning
- Plasma effects
- Radiative energy transport (opacity)

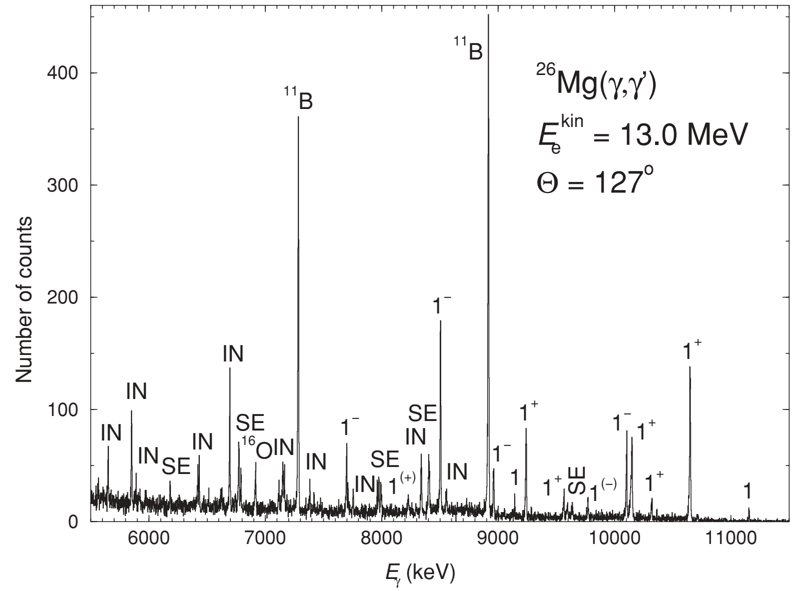
Affect the s-nuclides, roughly half the elements in the periodic table!

$^{22}Ne(\alpha,\gamma)^{26}Mg$, competitor to neutron source $^{22}Ne(\alpha,n)^{25}Mg$





- Bremsstrahlung-based data from γELBE
  R. Schwengner *et al.*,
  Phys. Rev. C 79, 037303 (2009)



- Ongoing experiment at LUNA 0.4 MV on strength of E_x = 10949 keV level
- Experiment planned at Felsenkeller 5 MV on higher-lying levels

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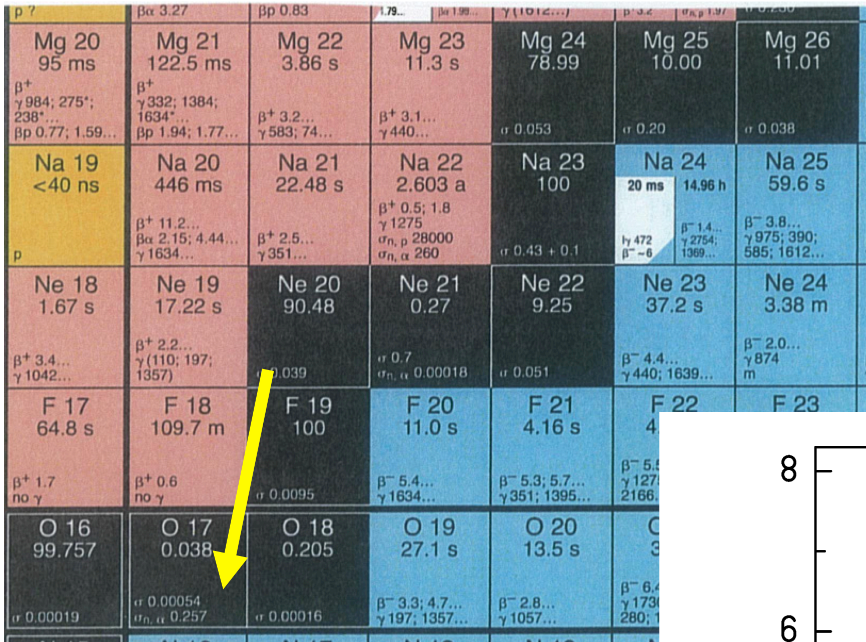
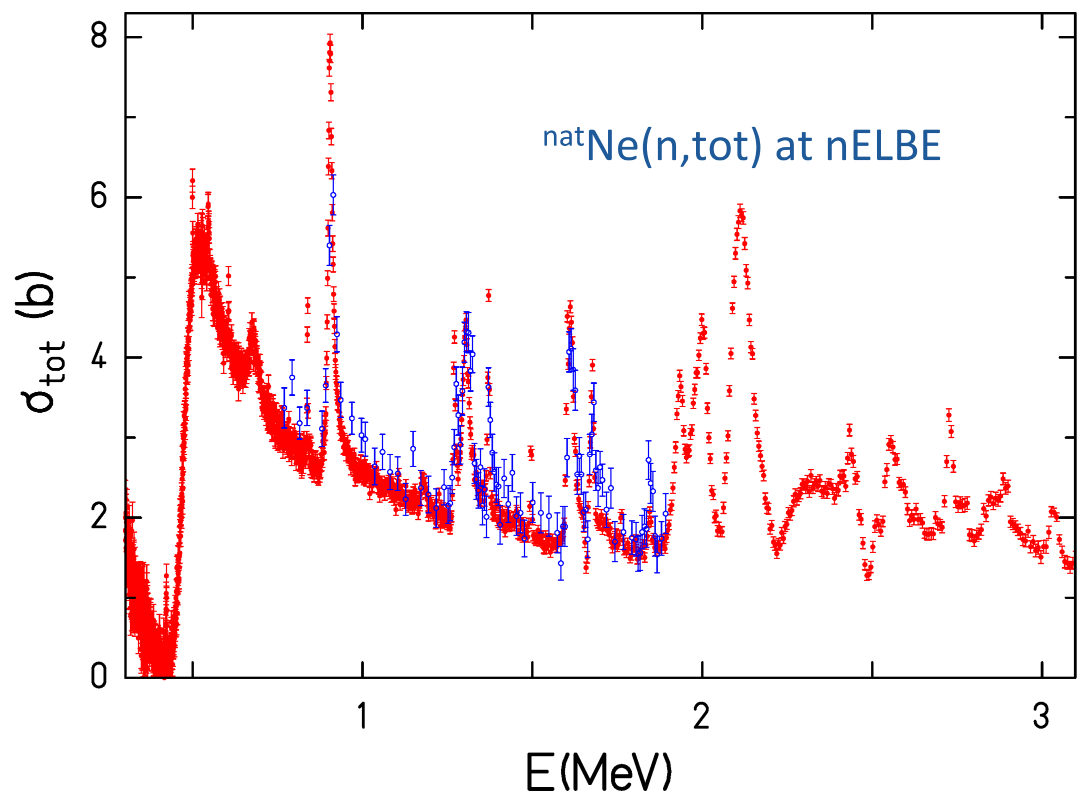
HZDR

$^{17}O(\alpha,n)^{20}Ne$, antidote to neutron poison $^{16}O(n,\gamma)^{17}O$



- Neutron time of flight data from nELBE using the time-reversed reaction J. Görres (Notre Dame), A. Junghans *et al.*



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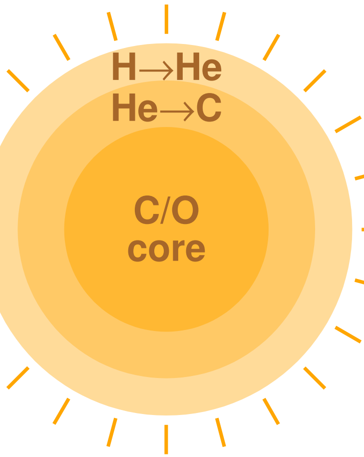
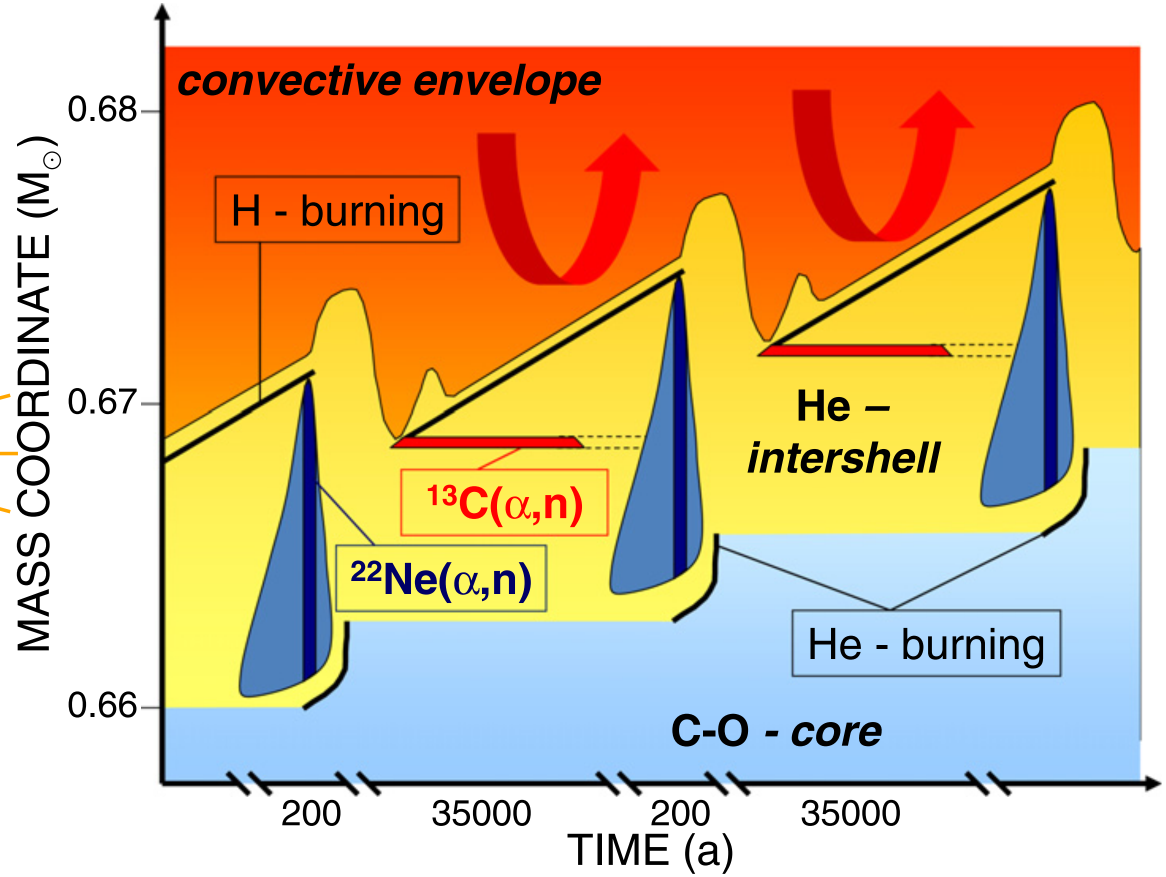
Asymptotic Giant Branch (AGB) stars as a physics laboratory



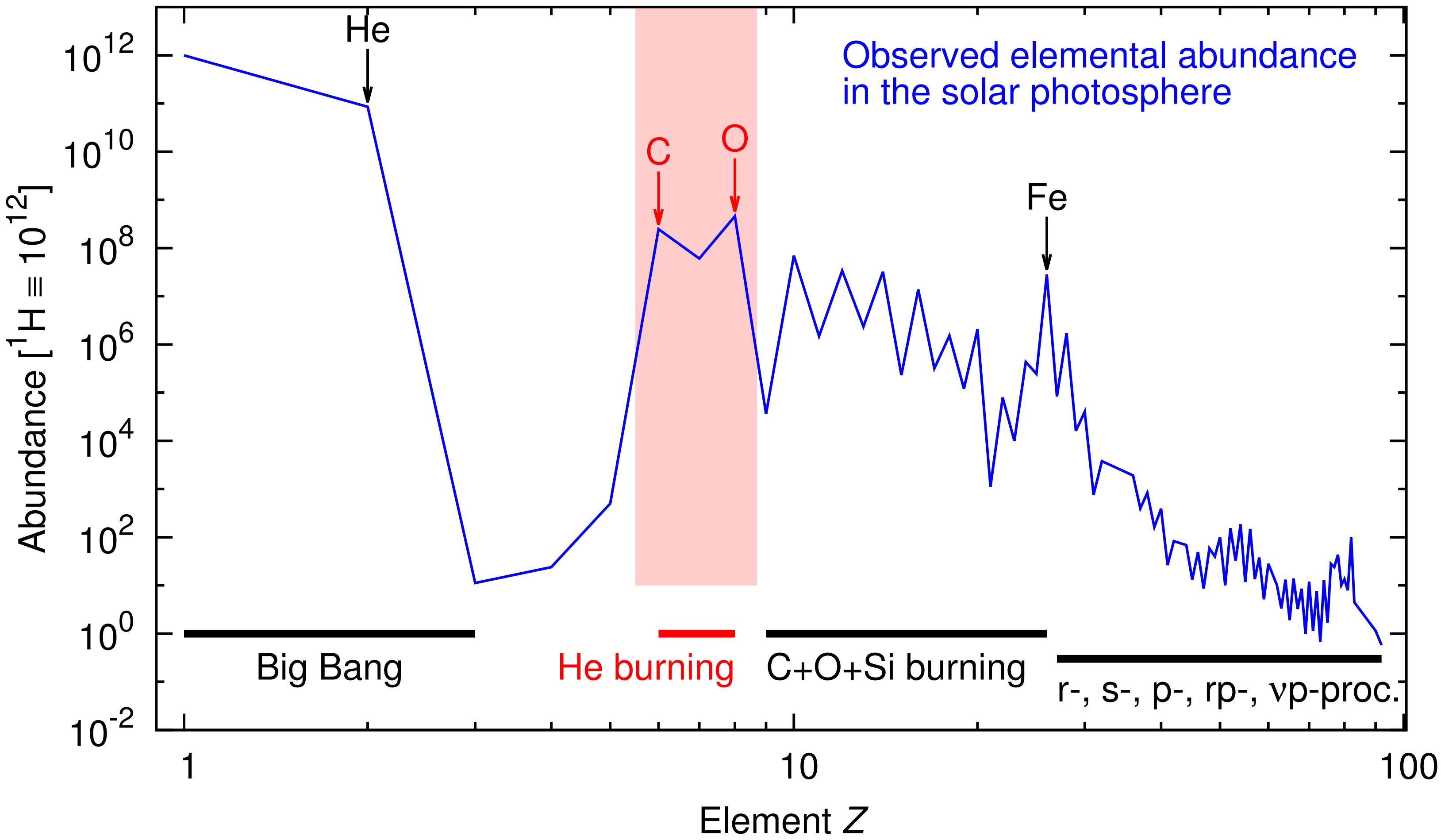


R. Reifarth *et al.* (2014)

- Convective mixing: H burning zone – He intershell
- Nuclear reactions: Neutron sources Neutron capture
  H burning **He burning**
- Plasma effects
- Radiative energy transport (opacity)

Affects the C/O ratio, and hence all chemical elements heavier than oxygen.

The production of the chemical elements

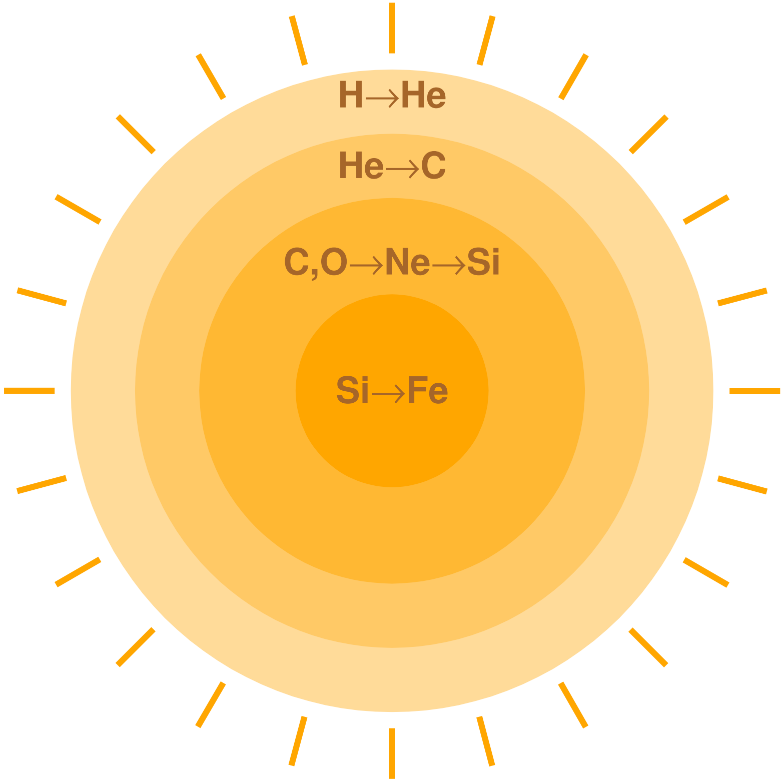


Stellar helium burning and the Holy Grail $^{12}C(\alpha,\gamma)^{16}O$

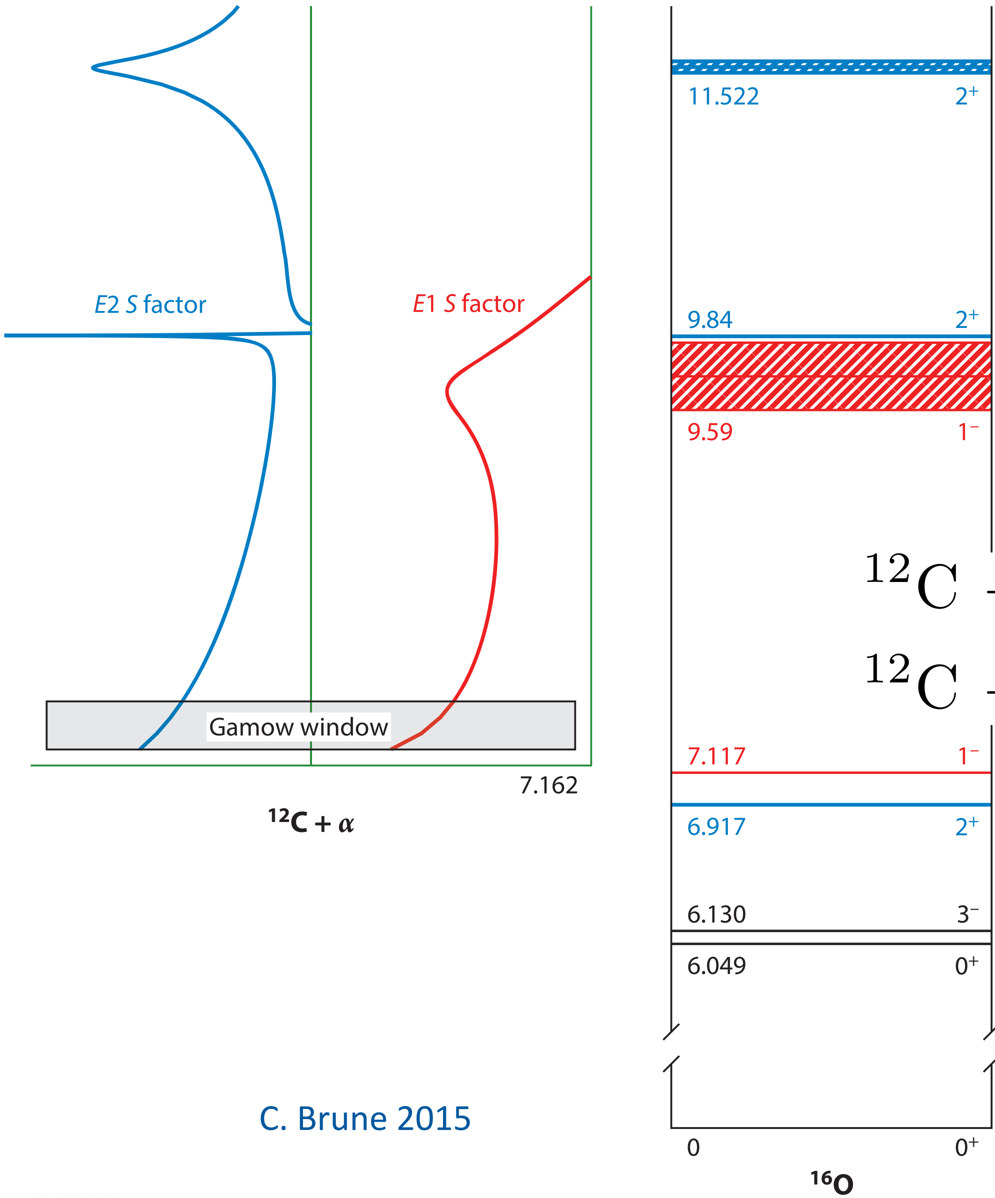
Produce ^{12}C: $$^4\mathrm{He} + {}^4\mathrm{He} \quad \rightarrow \quad {}^8\mathrm{Be} + {}^4\mathrm{He} \quad \rightarrow \quad {}^{12}\mathrm{C} + \gamma$$

Destroy ^{12}C and produce ^{16}O: $$^{12}\mathrm{C} + {}^4\mathrm{He} \quad \rightarrow \quad {}^{16}\mathrm{O} + \gamma$$

- ^{12}C production and destruction controls the ^{12}C / ^{16}O ratio.
- The $^{12}C(\alpha,\gamma)^{16}O$ reaction was called the "holy grail of nuclear astrophysics" by 1983 Physics Nobel Laureate William A. Fowler.



The $^{12}C(\alpha,\gamma)^{16}O$ reaction and the level structure of ^{16}O



C. Brune 2015

Forward reaction →

- Felsenkeller, LUNA-MV etc.

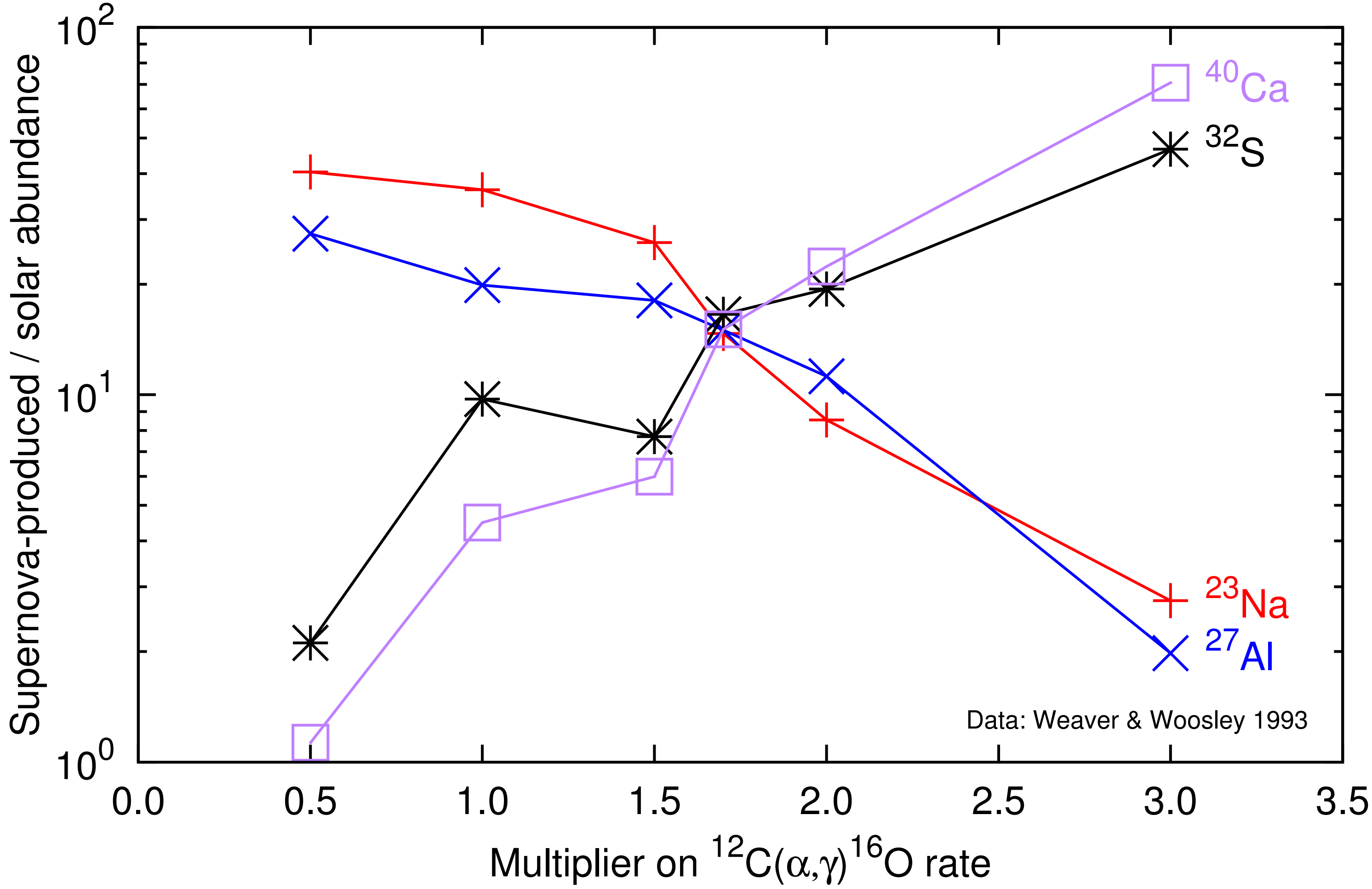
Time-inverted reaction ←

- Real 7 MeV photons: HIγS, ELI-NP sources of monochromatic photons
- Virtual 7 MeV photons: GSI

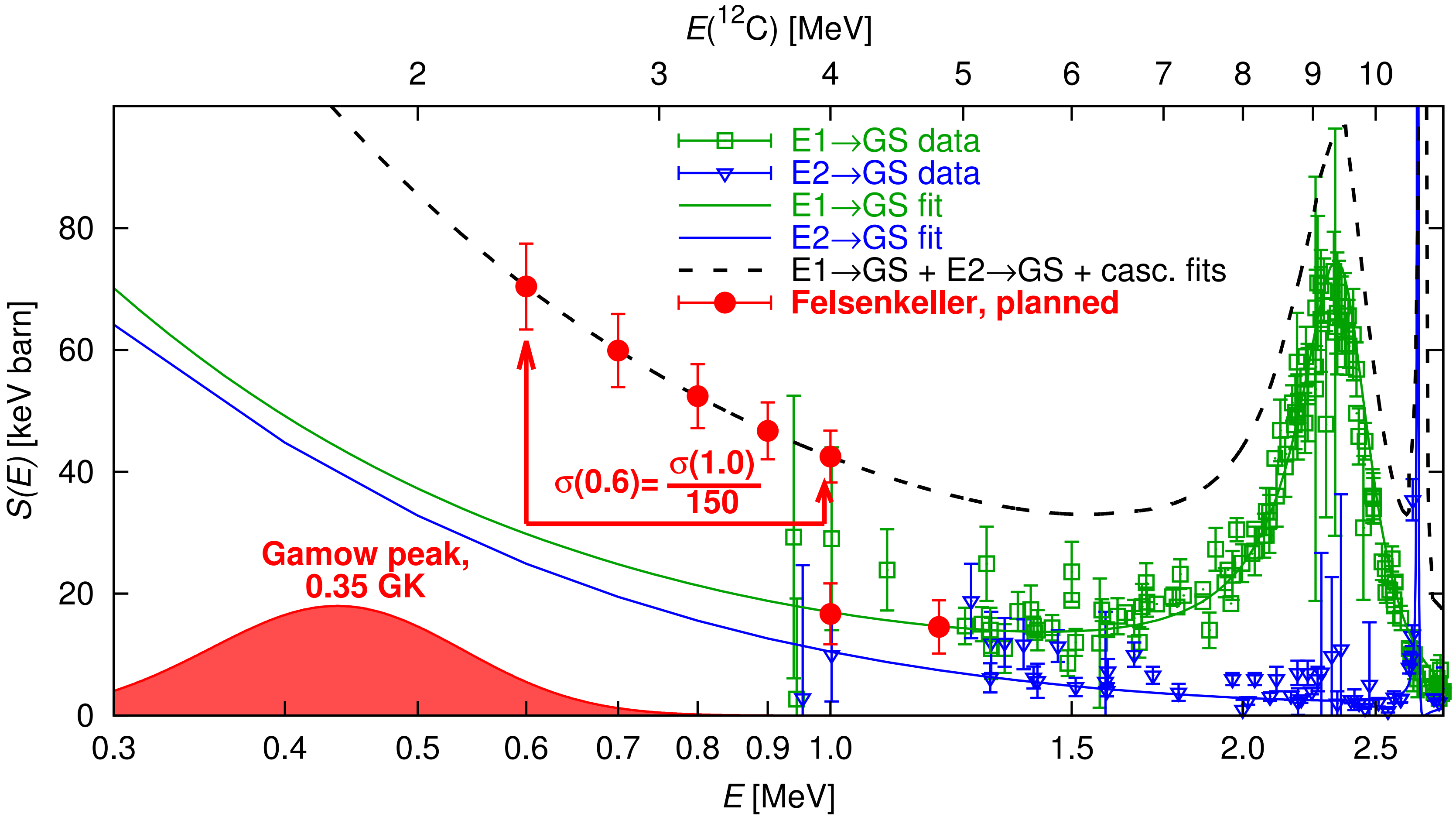
$$^{12}\mathrm{C} + {}^{4}\mathrm{He} \rightarrow {}^{16}\mathrm{O}(0, 6.049, 6.130, \ldots)$$

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

The $^{12}C(\alpha,\gamma)^{16}O$ rate affects the production of many elements!



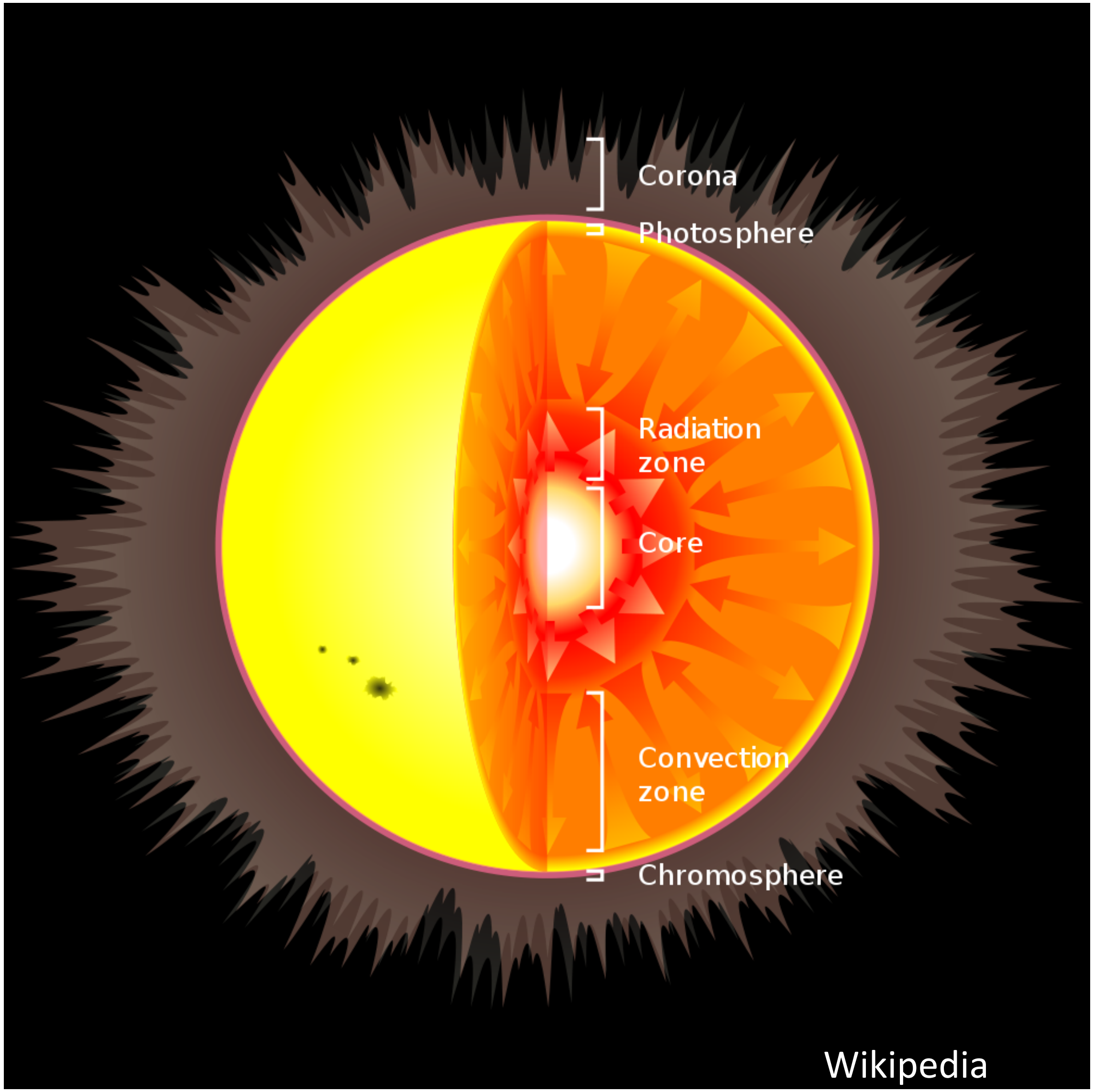
State of the art on $^{12}C(\alpha,\gamma)^{16}O$ and potential for Felsenkeller…
…using $^{12}C^+$ beam, windowless gas target, γ-calorimeter



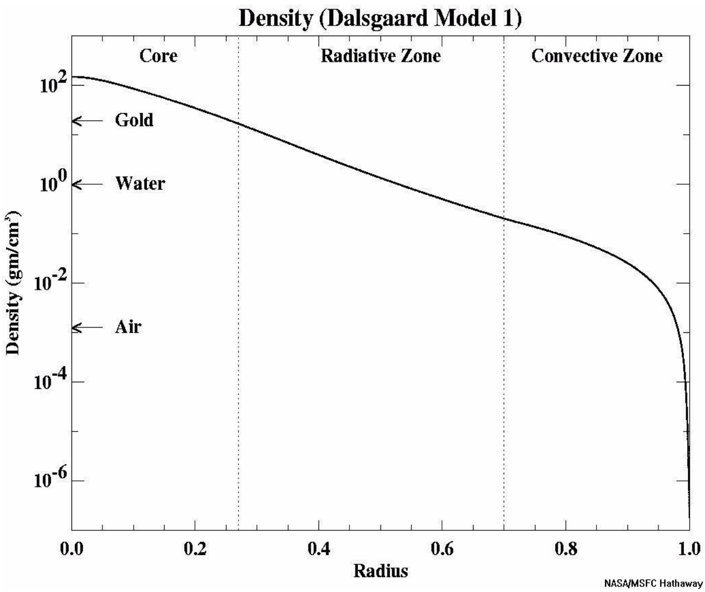
$$S(E) = \sigma(E) E \exp\left(\frac{13.7}{\sqrt{E/\mathrm{MeV}}}\right)$$

MML ■ IN-HOUSE RESEARCH

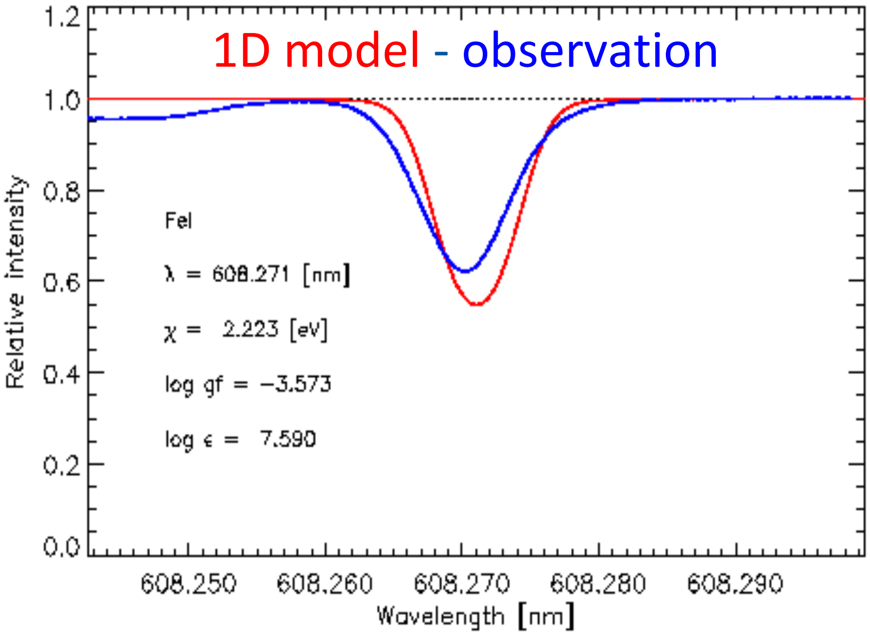
Structure of the Sun red: Observable

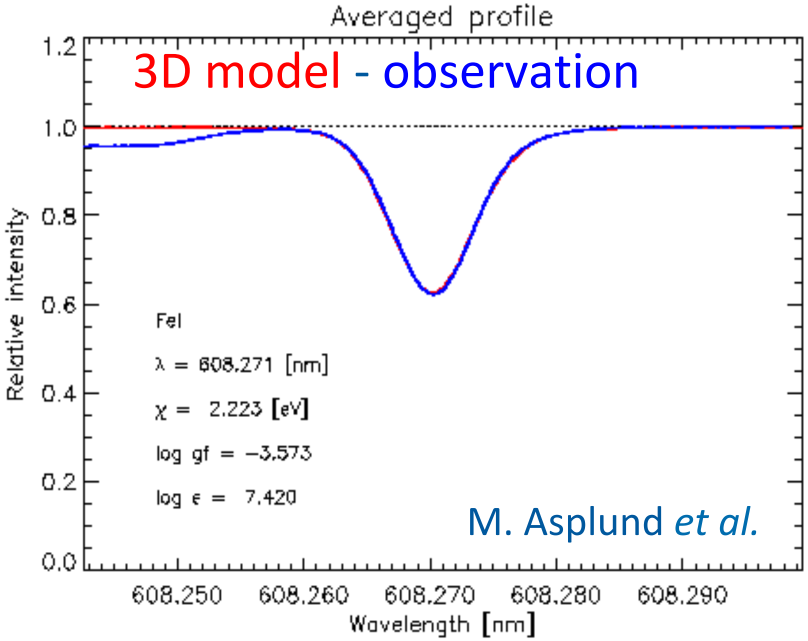


- Corona
- Chromosphere
- Photosphere
  Fraunhofer lines
- Convection zone
  Helioseismology
- Radiation zone
- Core Neutrinos



Data on the Sun: 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)

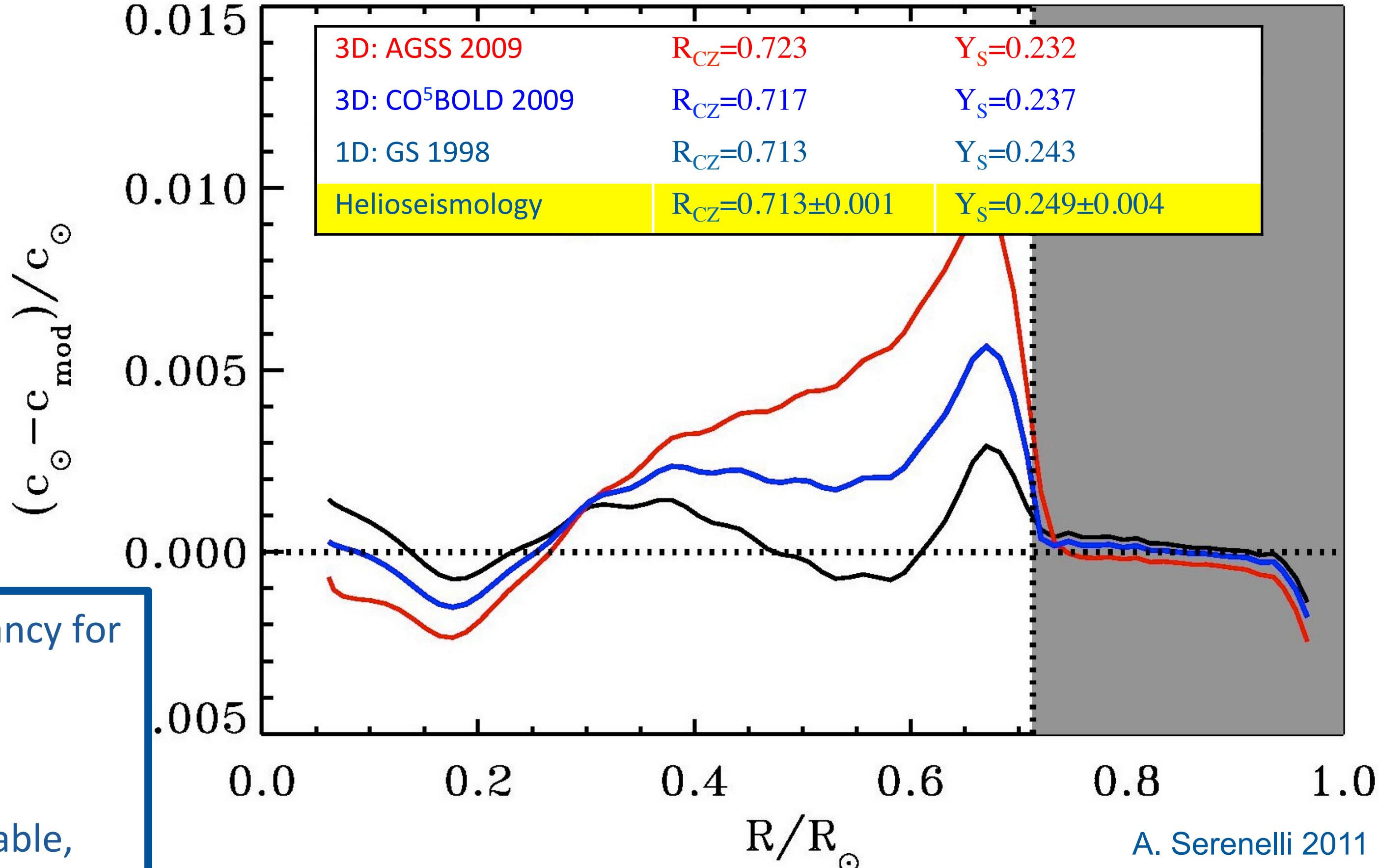
3D: 1.78% (by mass) of the Sun are “metals” (Li...U)

The solar abundance problem:
Contradiction between elemental abundances and helioseismology

Solar models computed with different sets of elemental abundances:

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

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

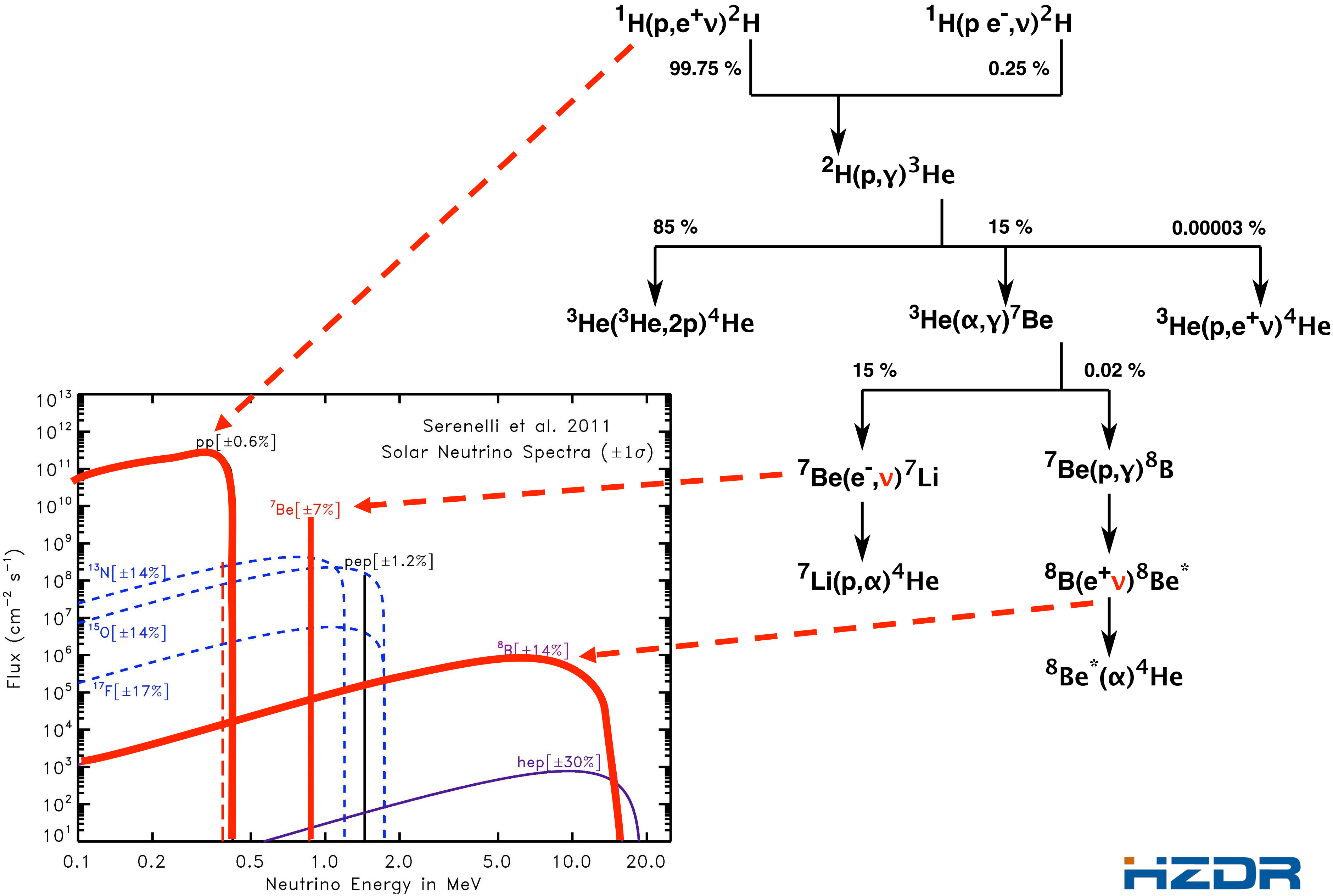


A. Serenelli 2011

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

HZDR

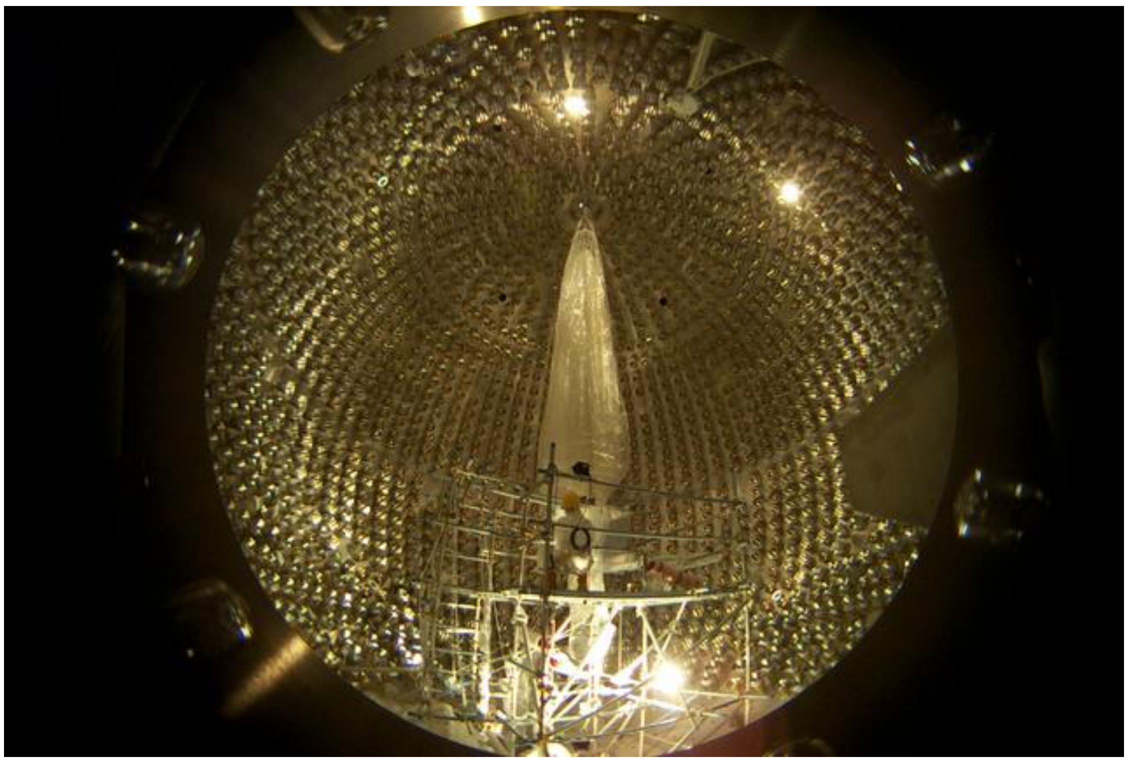
The proton-proton chain and solar neutrinos



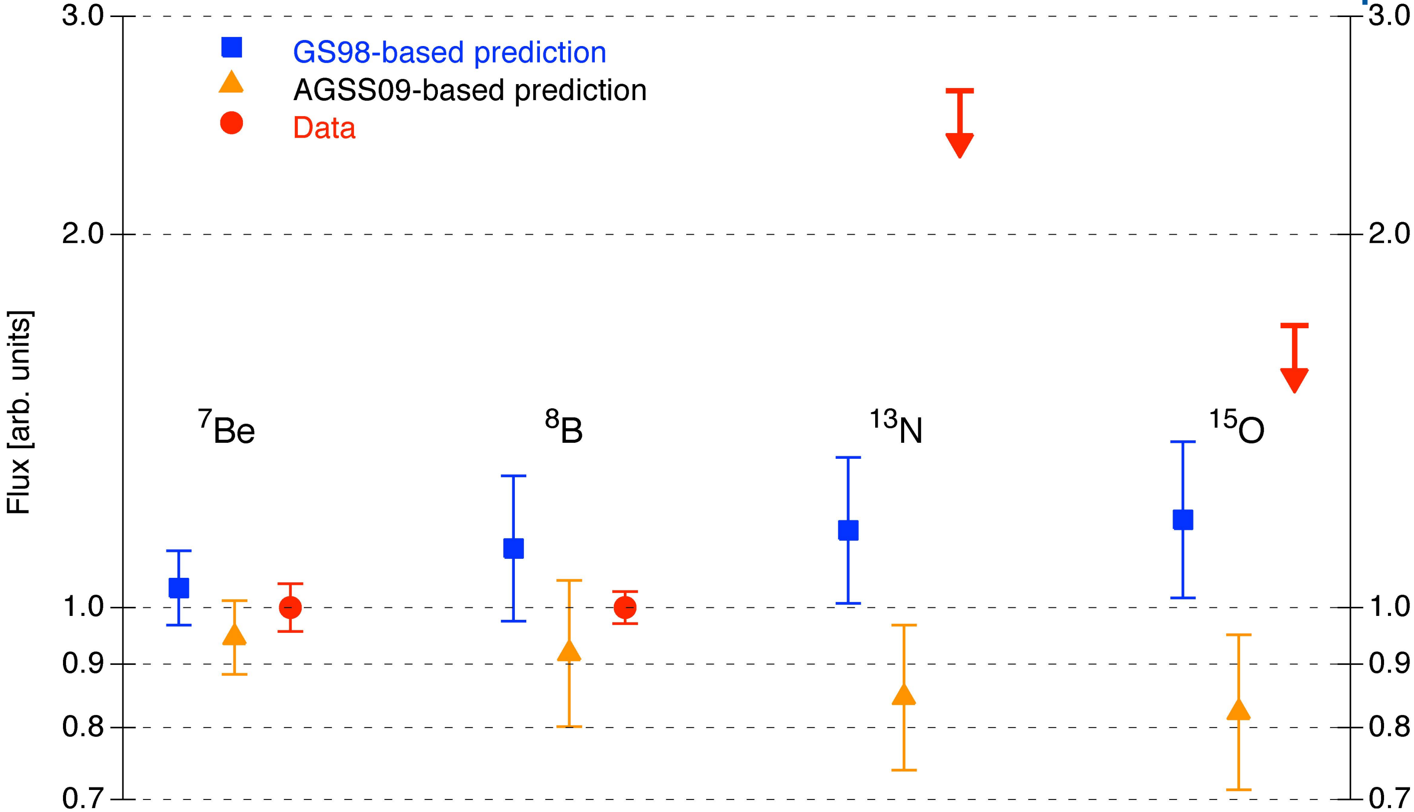
How precise are the neutrino data?

SNO (Sudbury/Canada):
^{8}B neutrino flux measured to 3% precision!

Borexino (Gran Sasso/Italy):
pp neutrino flux measured to 10% precision!
^{7}Be neutrino flux measured to 5% precision!



Solar neutrino fluxes: Data and model predictions

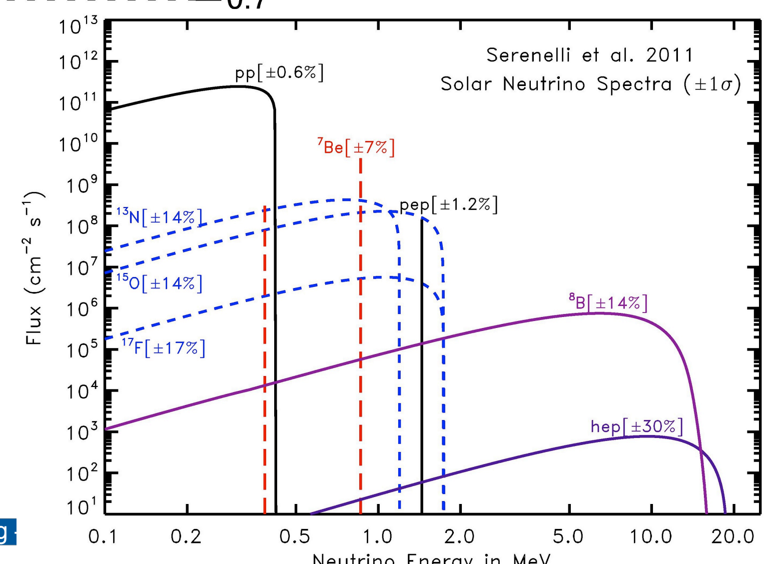


Neutrino fluxes: Standard Solar Model; Antonelli *et al.*, arXiv:1208.1356

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!**



Nuclear physics drives the uncertainties in the predicted solar neutrino fluxes

Dominant Theoretical Error Sources for Neutrino Fluxes and the Main Characteristics of the SSM

Quant.	Dominant Theoretical Error Sources in %							
Φ(pp)	$L_\odot$:	0.3	S_{34}:	0.3	κ:	0.2	Diff:	0.2
Φ(pep)	κ:	0.5	$L_\odot$:	0.4	S_{34}:	0.4	S_{11}:	0.2
Φ(hep)	S_{hep}:	30.2	S_{33}:	2.4	κ:	1.1	Diff:	0.5
$\Phi(^7Be)$	S_{34}:	4.1	κ:	3.8	S_{33}:	2.3	Diff:	1.9
$\Phi(^8B)$	κ:	7.3	S_{17}:	4.8	Diff:	4.0	S_{34}:	3.9
$\Phi(^{13}N)$	C:	10.0	S_{114}:	5.4	Diff:	4.8	κ:	3.9
$\Phi(^{15}O)$	C:	9.4	S_{114}:	7.9	Diff:	5.6	κ:	5.5
$\Phi(^{17}F)$	O:	12.6	S_{116}:	8.8	κ:	6.0	Diff:	6.0

S_{34}: $^3He(\alpha,\gamma)^7Be$

S_{114}: $^{14}N(p,\gamma)^{15}O$

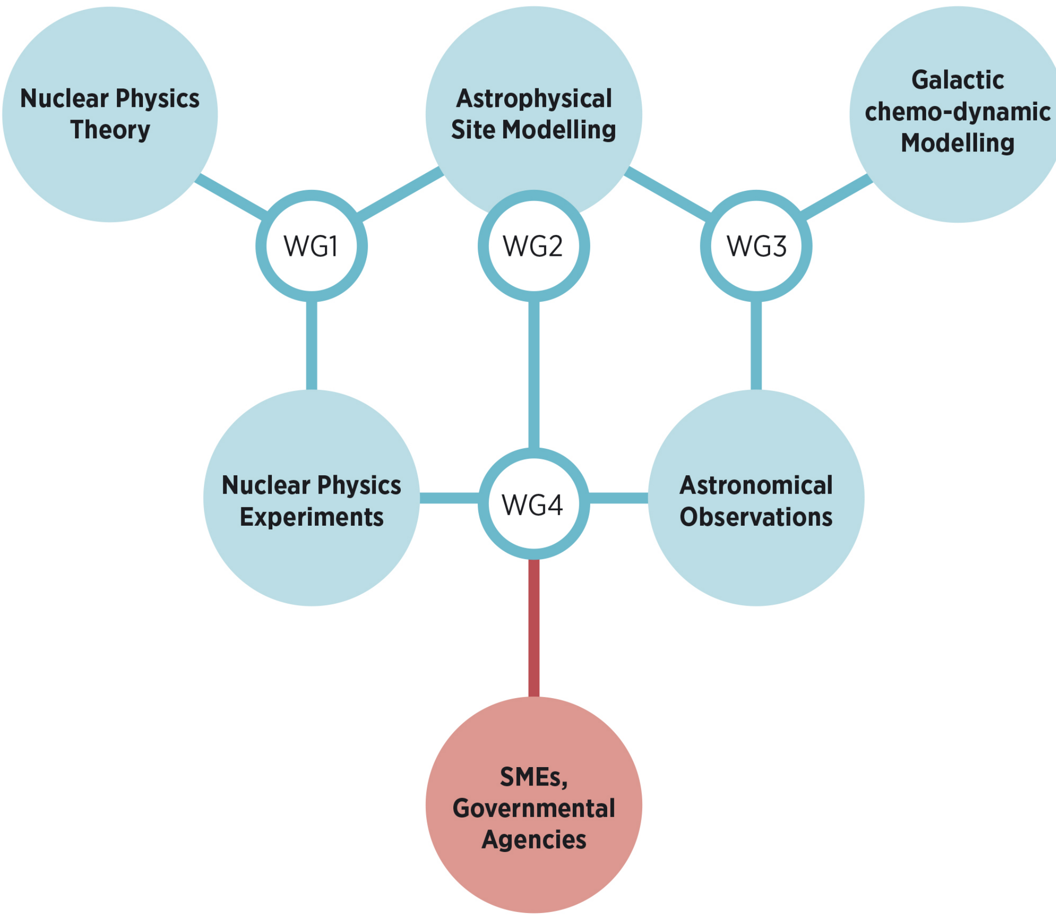
S_{17}: $^7Be(p,\gamma)^8B$

Vinyoles *et al.*,
Astrophys. J. 835, 202 (2017)

COST action ChETEK [ketek] on Nuclear Astrophysics

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



http://www.chetec.eu

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

Meetings:

- Conference on „Nuclear Physics of Stellar Explosions", Debrecen/ HU 12-14 September
- This School!

Short-term scientific missions (STSMs)

Chair:

- Raphael Hirschi, Keele University/UK

Nucleosynthesis in stars and in the big bang – the seeds for the r process

- **Big Bang nucleosynthesis**
  Astrophysical S-Factor
  Thermonuclear Reaction Rate
  Resonance Strength
  LUNA 0.4 MV underground lab in Italy

- **Experimental facilities underground**
  LUNA-MV underground lab in Italy
  Felsenkeller underground lab in Germany

- **Asymptotic giant branch stars**
  Stellar hydrogen burning
  Neutron sources for the s-process
  Stellar helium burning

Photo: HZDR/O. Killig

Three points to take home

- Low-energy charged particle reactions set the stage for all future nucleosynthesis
- New laboratory data have a direct effect on predictions matched to astronomical observations
- Interdisciplinary links are essential to advance understanding