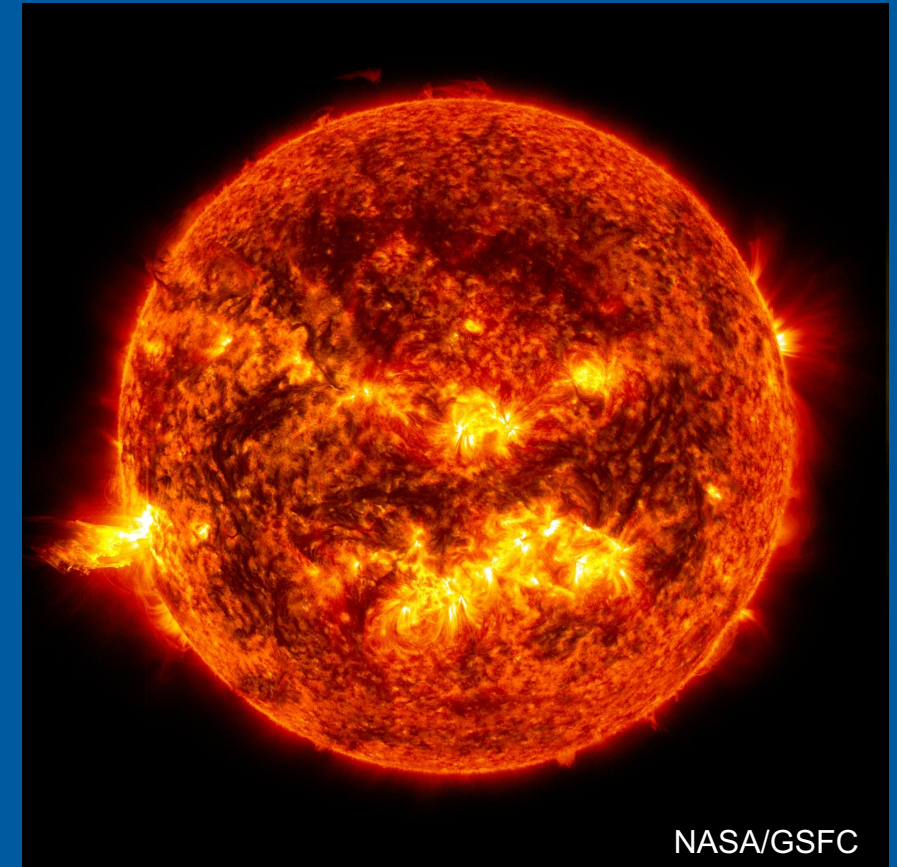




Overview of the solar model and LUNANOVA

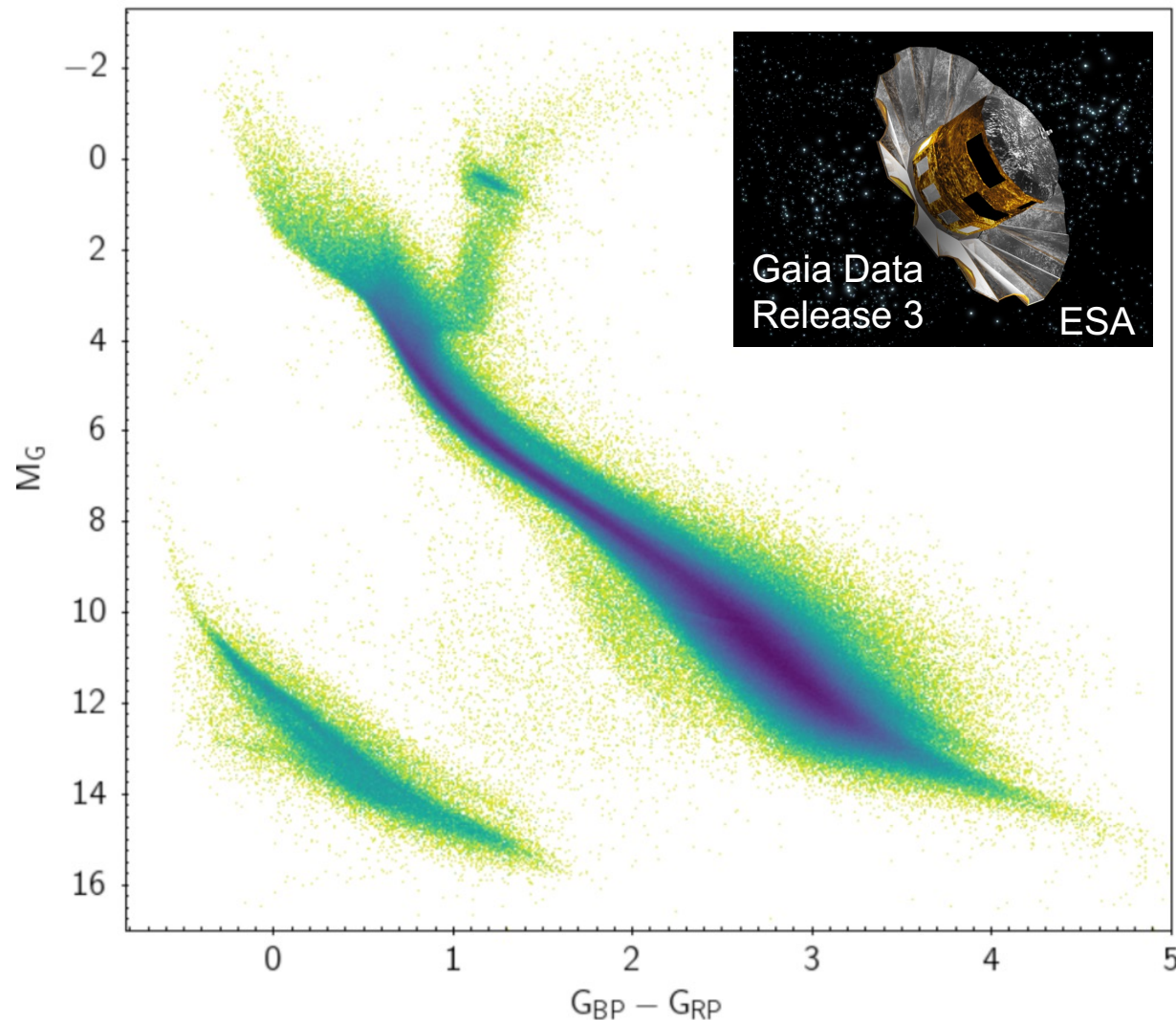
Nuclear Physics in Astrophysics XII
Cluj-Napoca, Romania, 09.09.2026

Daniel Bemmerer
Helmholtz-Zentrum Dresden-Rossendorf



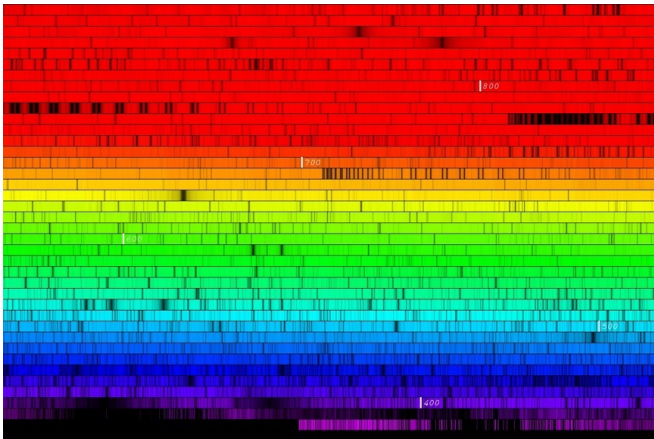
NASA/GSFC

The Sun as foundation science



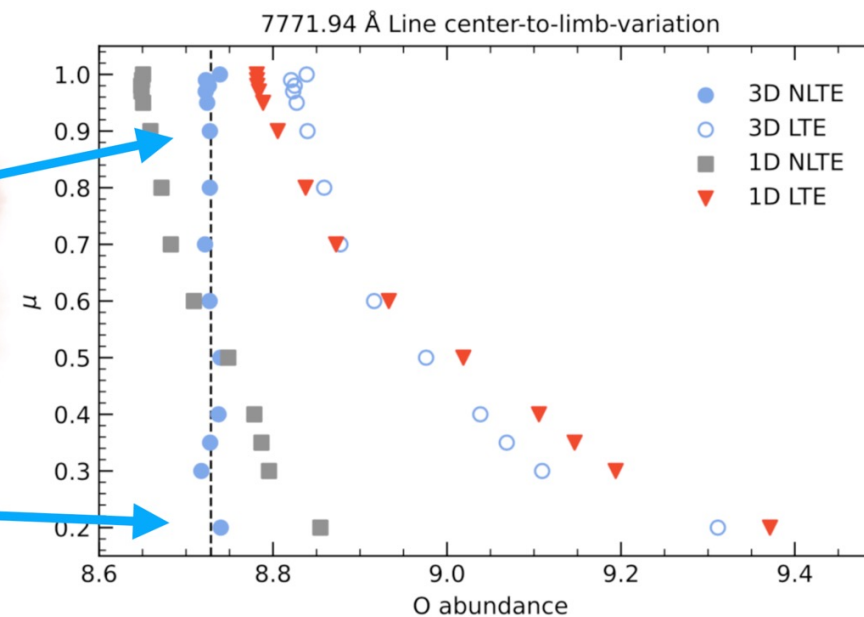
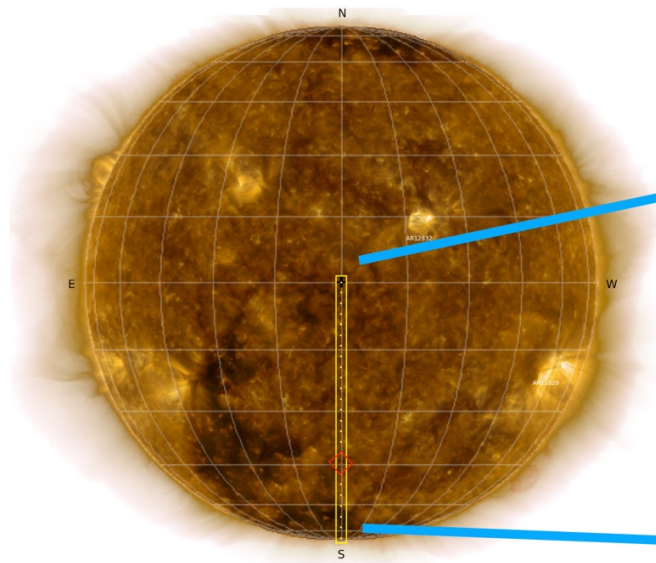
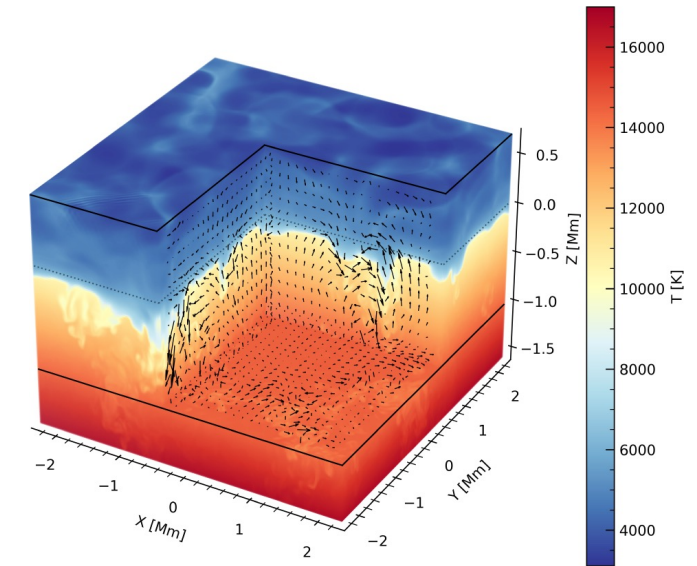
- ~ 10^9 individual stars with measurements of color, temperature, luminosity, (composition)
- ~ 10^3 stars with accurate, precise, (model) independent mass determinations
...selective club: eclipsing binaries
- 1 star with accurate, precise, (model) independent age determination, meteoritic dating, highly accurate radius and mass
- Solar elemental composition is the yardstick for all astronomical abundance determinations

Foundation science: Solar spectrum, solar elemental abundances



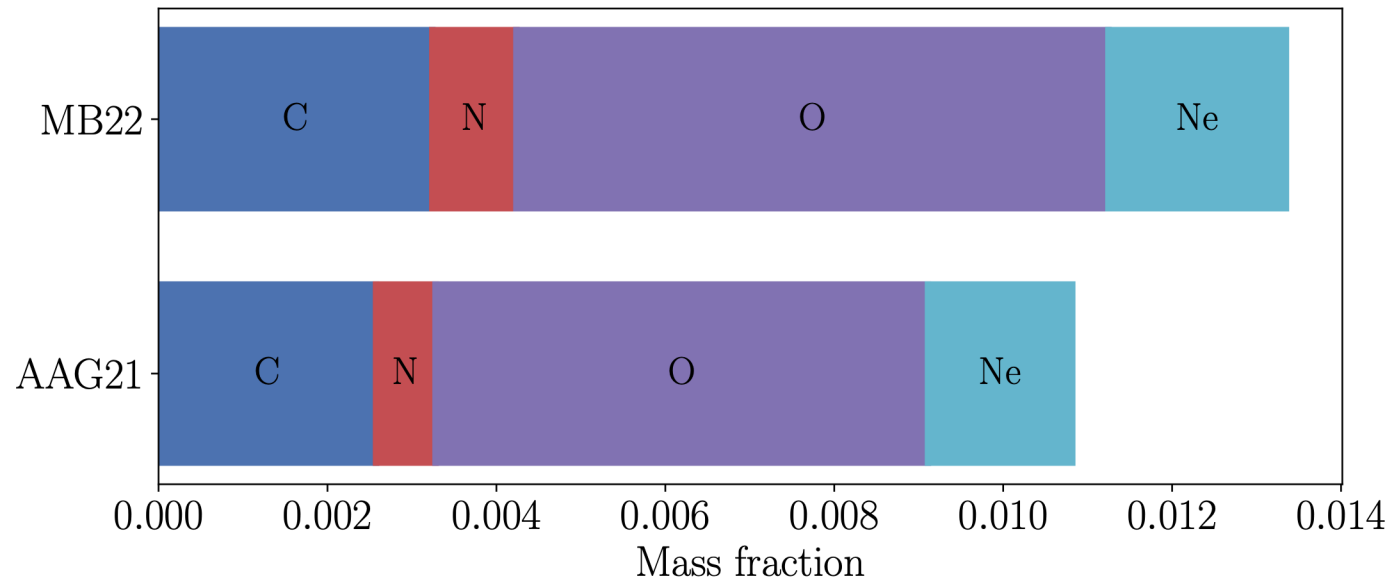
Solar envelope is convective
→ hydrodynamic models
→ 3D atmosphere model

Model atmosphere
→ detailed radiative transfer - NLTE
→ determination of abundances
→ spatially resolved spectroscopy



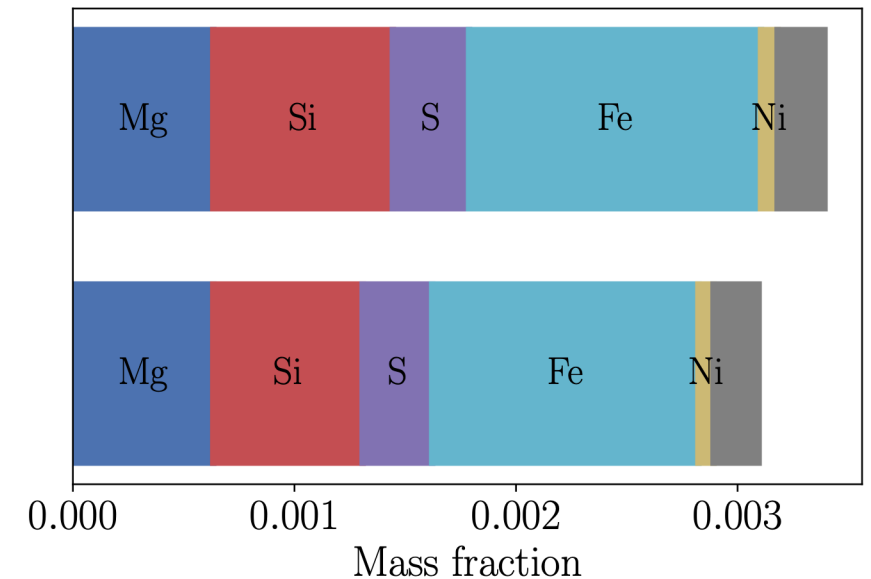
Pietrow, Hoppe, Bergemann et al. 2023
Bergemann, Hoppe, et al. 2021

Which solar elemental abundances?



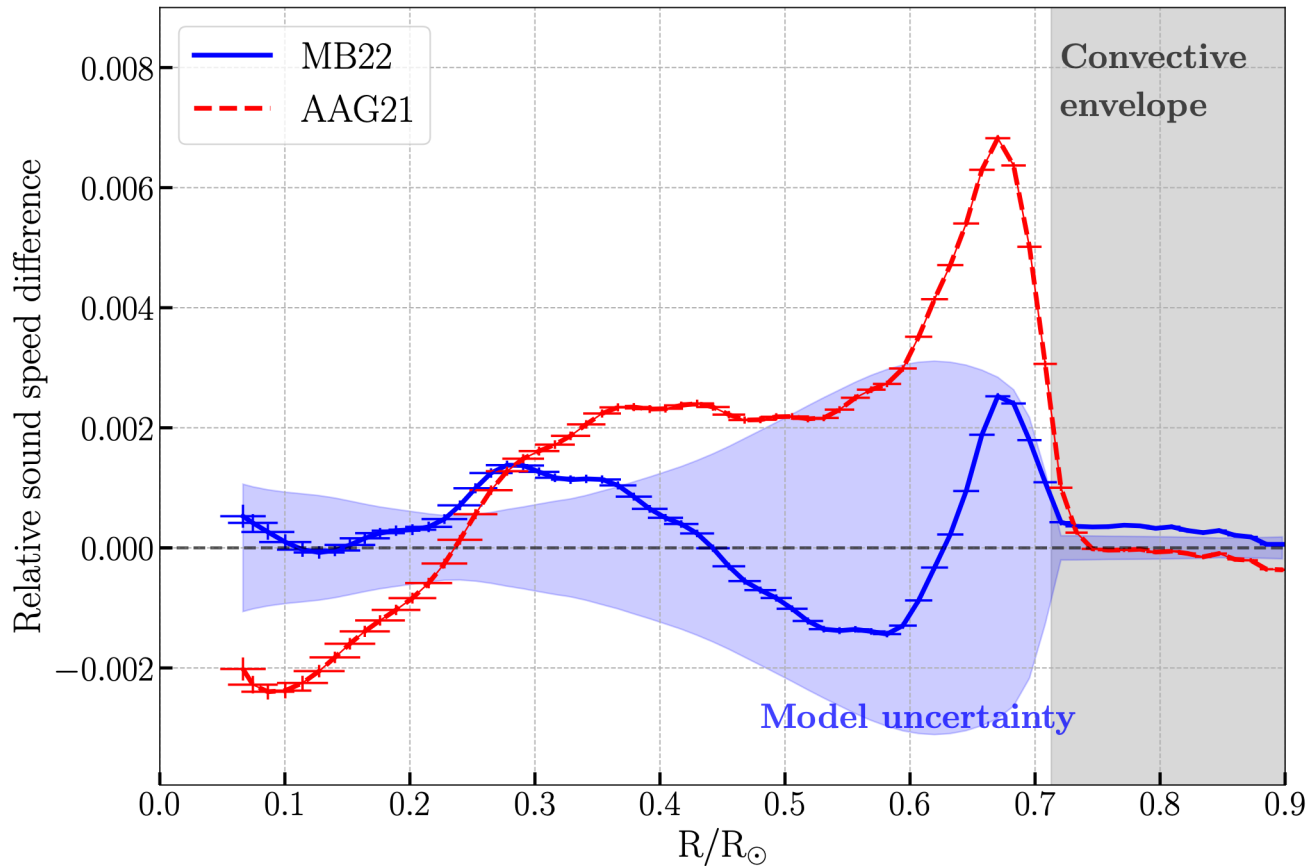
MB22: Magg et al. 2022

AAG21: Asplund et al. 2021



Chemical abundances are a boundary condition imposed to, not a prediction of, solar models.

Helioseismology, the study of acoustic oscillations in the Sun



Model	$R_{CZ}/R_{\odot}$	Y_S	$\langle \delta c/c \rangle$	Y_{ini}	Z_{ini}
MB22-phot	0.7123	0.2439	0.0010	0.2734	0.0176
AAG21	0.7197	0.2343	0.0027	0.2638	0.0155
GS98	0.7122	0.2425	0.0010	0.2718	0.0187
Solar	0.713 ± 0.001	0.2485 ± 0.0035			

$$\nabla T^4 \propto \kappa$$

Temperature T

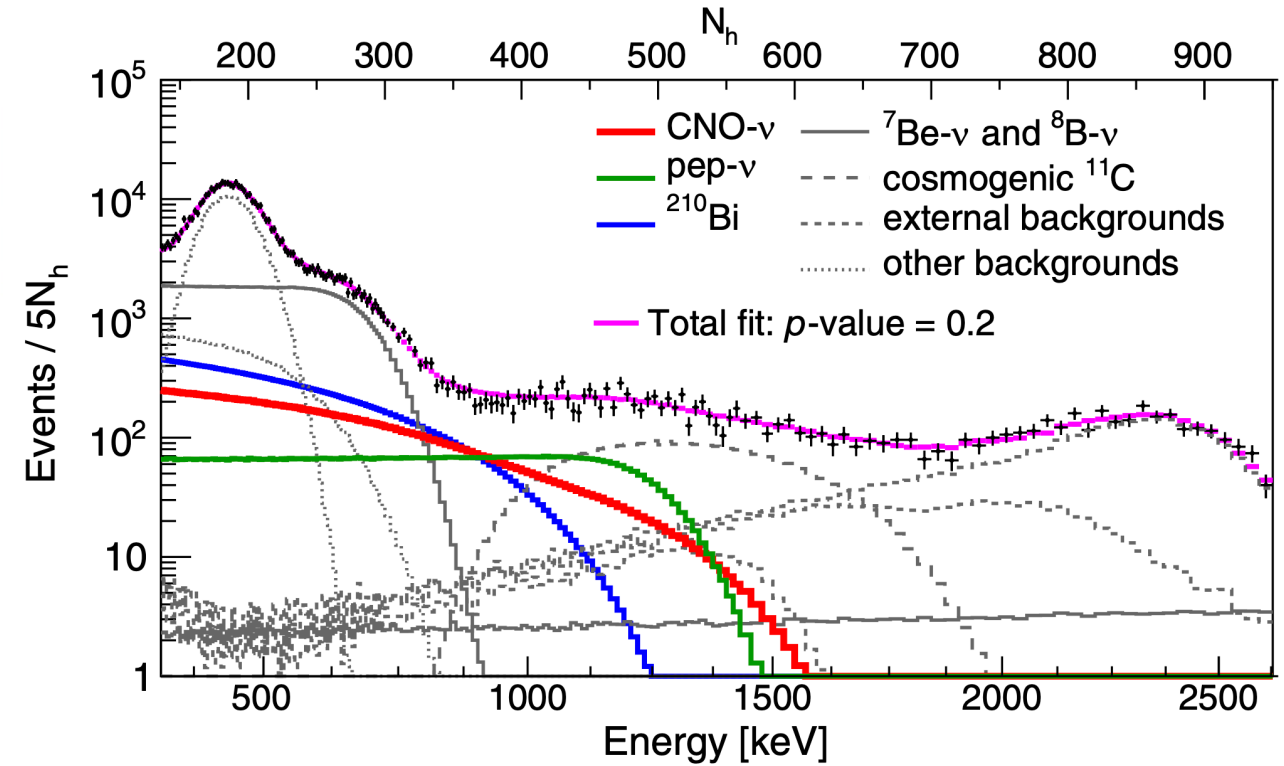
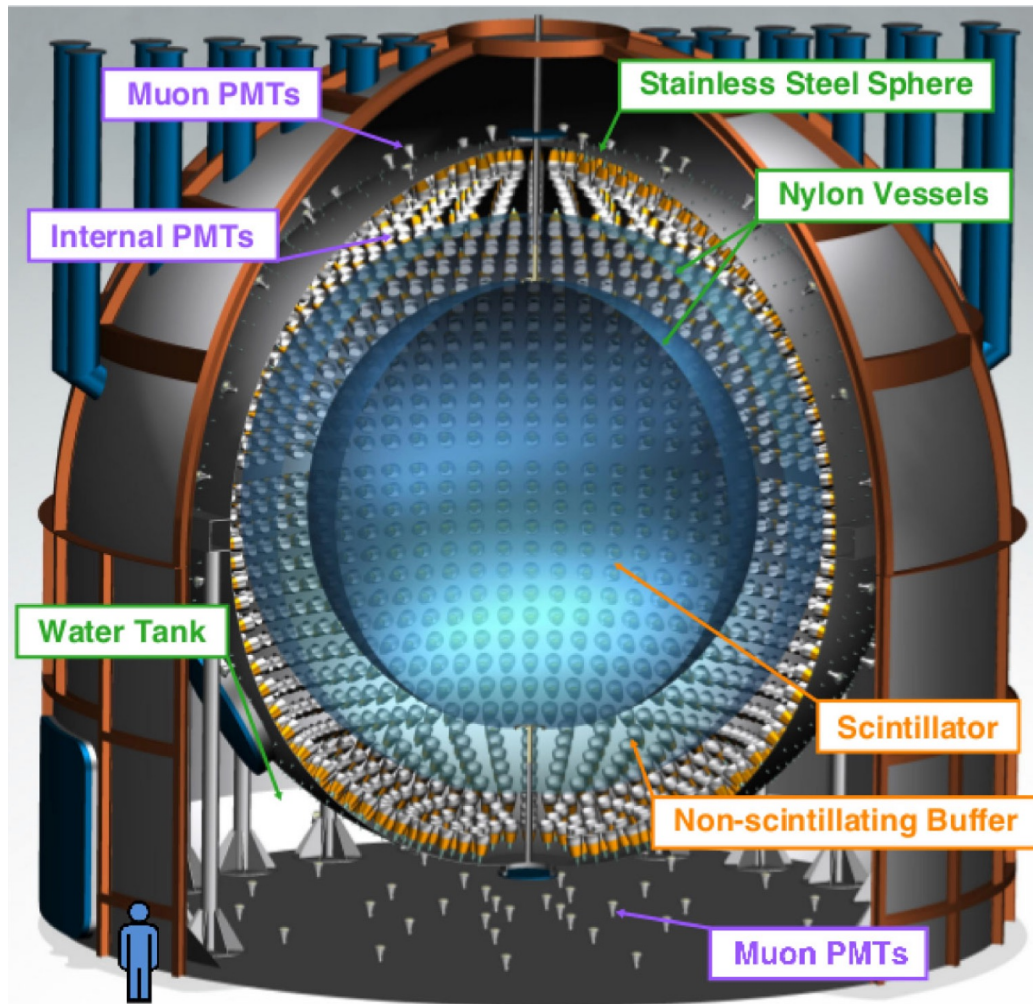
Radiative opacity κ

$$c^2 \propto T/\mu$$

Sound speed c

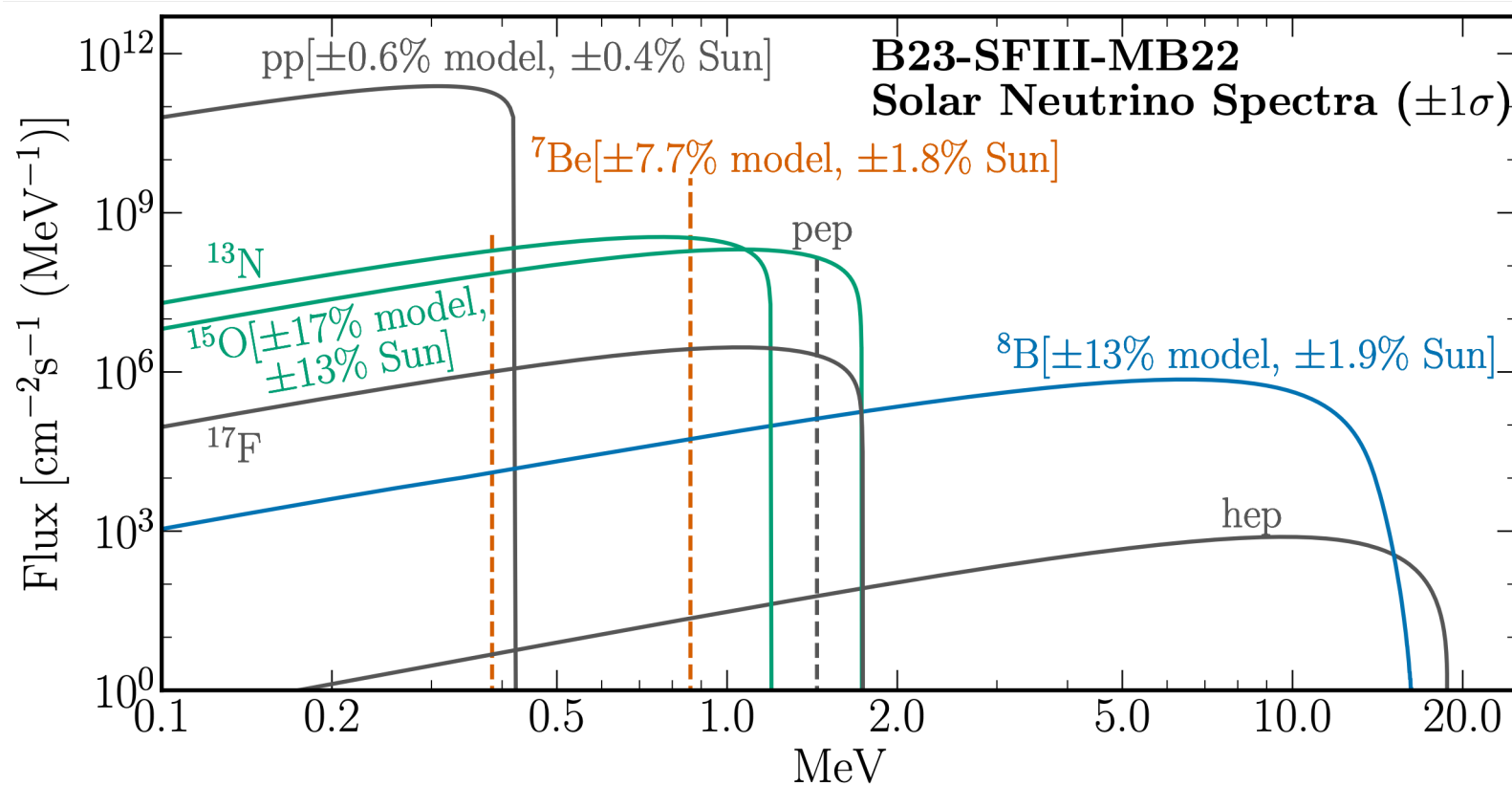
Molar mass μ
(elemental composition)

Detecting neutrinos from the core of the Sun – Borexino (and others)



Phys. Rev. D 108, 102005 (2023)

Solar neutrino energy spectrum from the standard solar model



SSM model ν fluxes...

$\nu(\text{pp})$	$\pm 0.6\%$
$\nu(^{7}\text{Be})$	$\pm 7.7\%$
$\nu(^{8}\text{B})$	$\pm 13\%$
$\nu(^{13}\text{N}+^{15}\text{O})$	$\pm 17\%$

Model not precise

and data

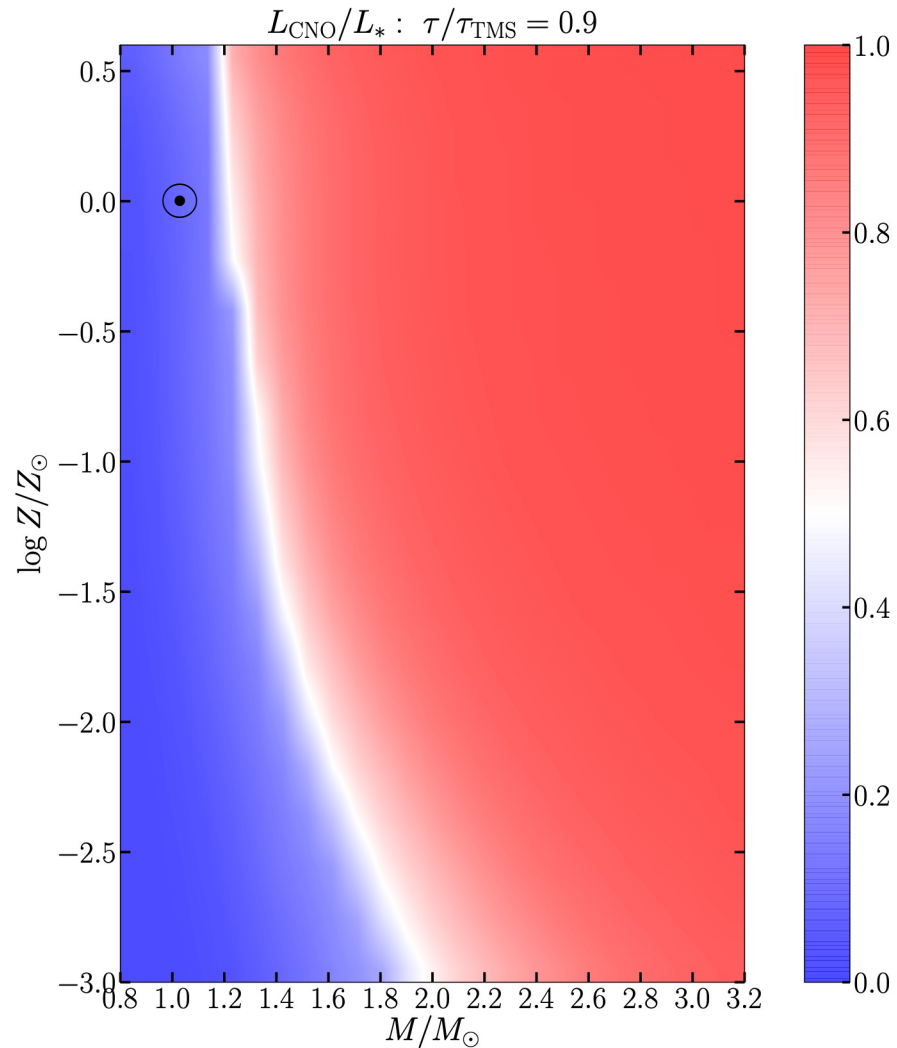
$\nu(\text{pp})$	$\pm 0.4\%$
$\nu(^{7}\text{Be})$	$\pm 1.8\%$
$\nu(^{8}\text{B})$	$\pm 1.9\%$
$\nu(^{13}\text{N}+^{15}\text{O})$	$\pm 13\%$

Data precise

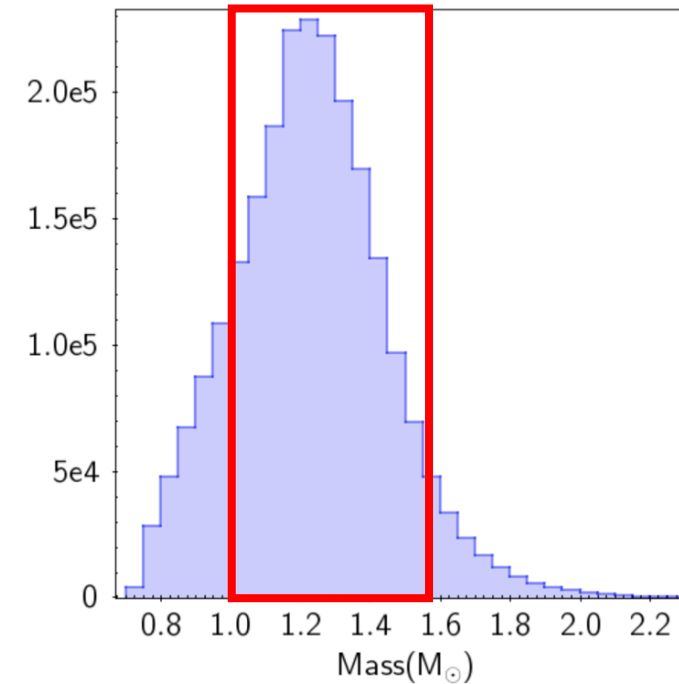
Model uncertainties >> experimental uncertainties!

Impact for solar-like stars, $M \approx 1M_{\odot}$

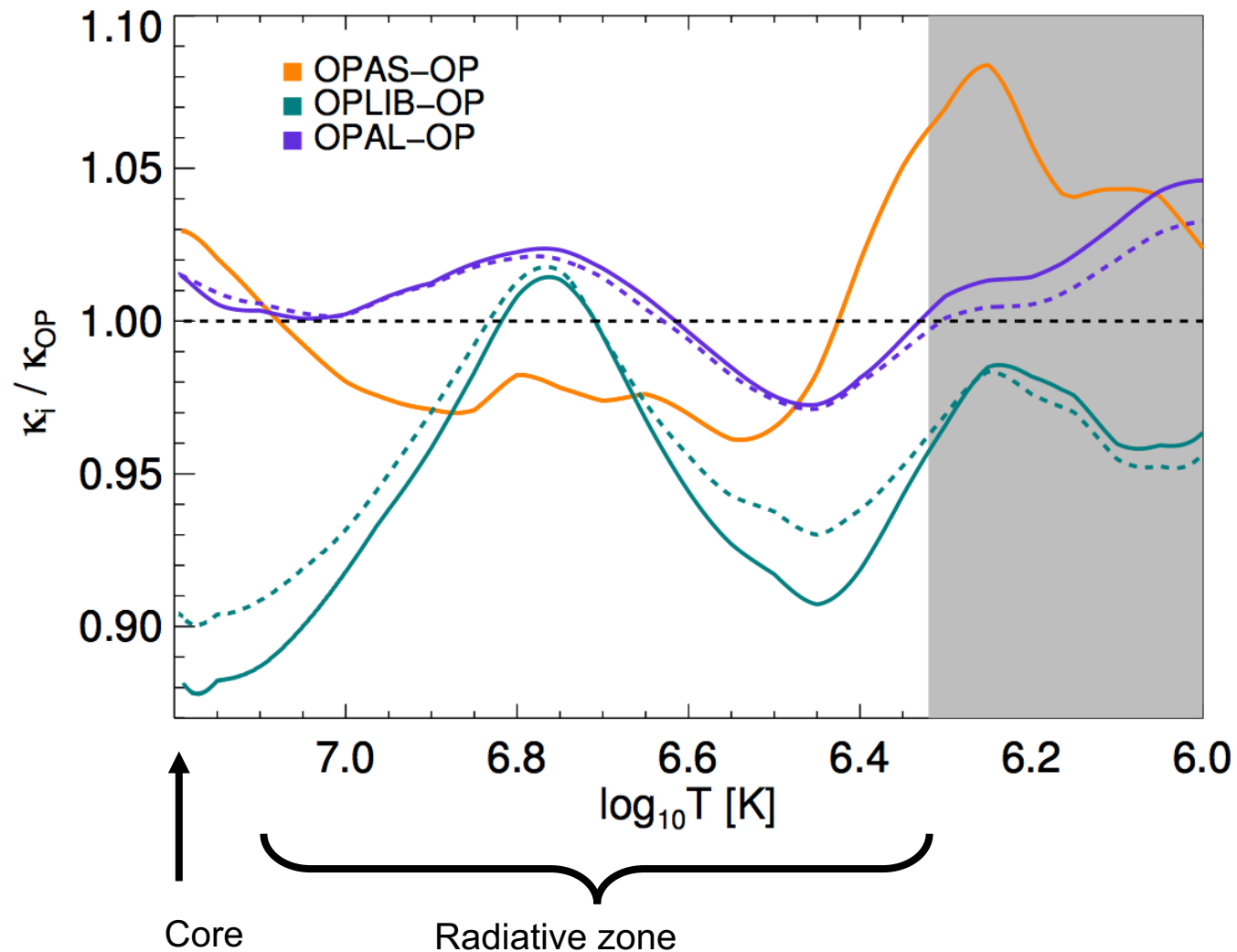
Stellar
luminosity:
CNO vs pp



Mass distribution in the input
catalogue of Plato mission



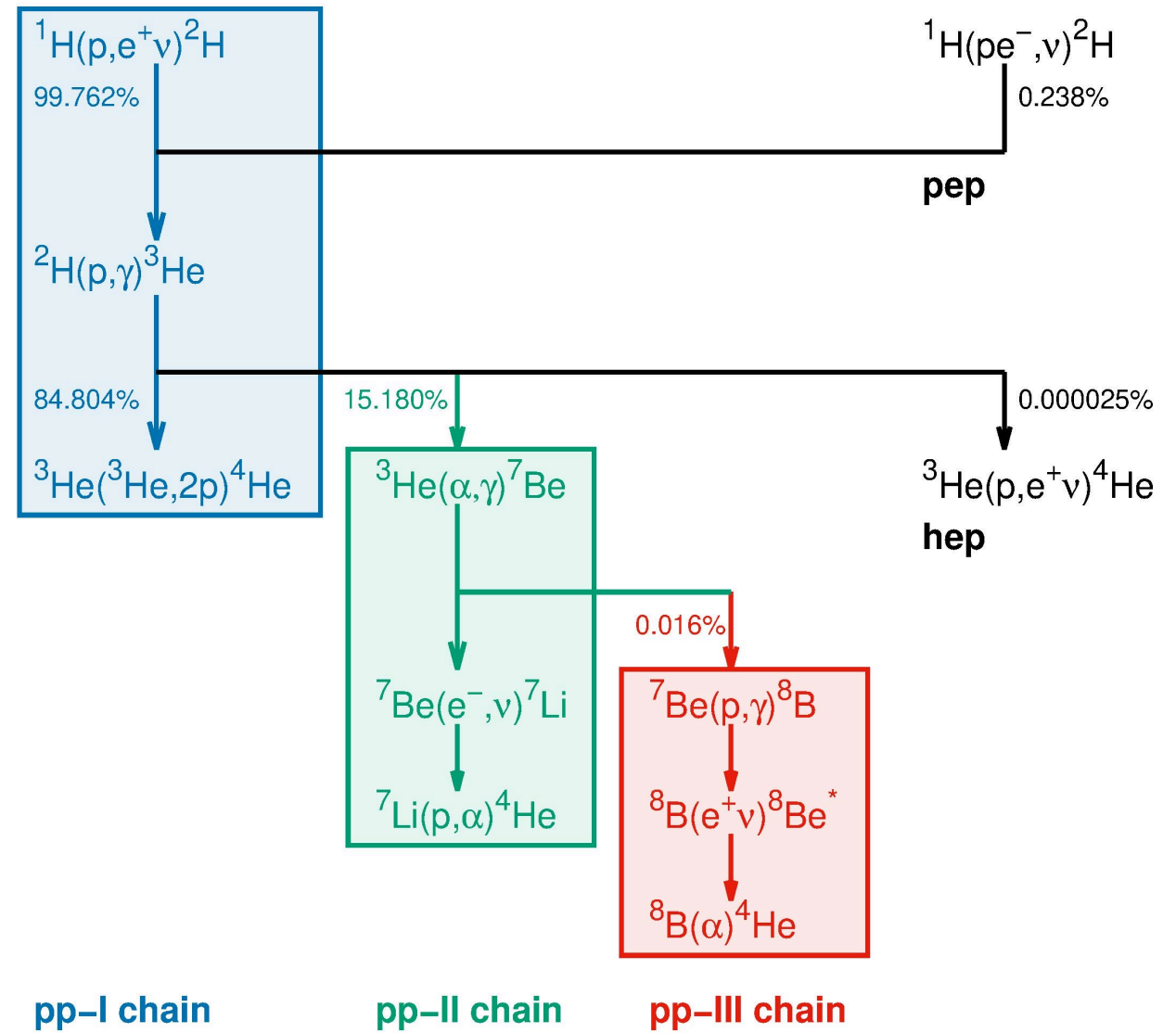
Different versions of the radiative opacity κ , from opacity tables



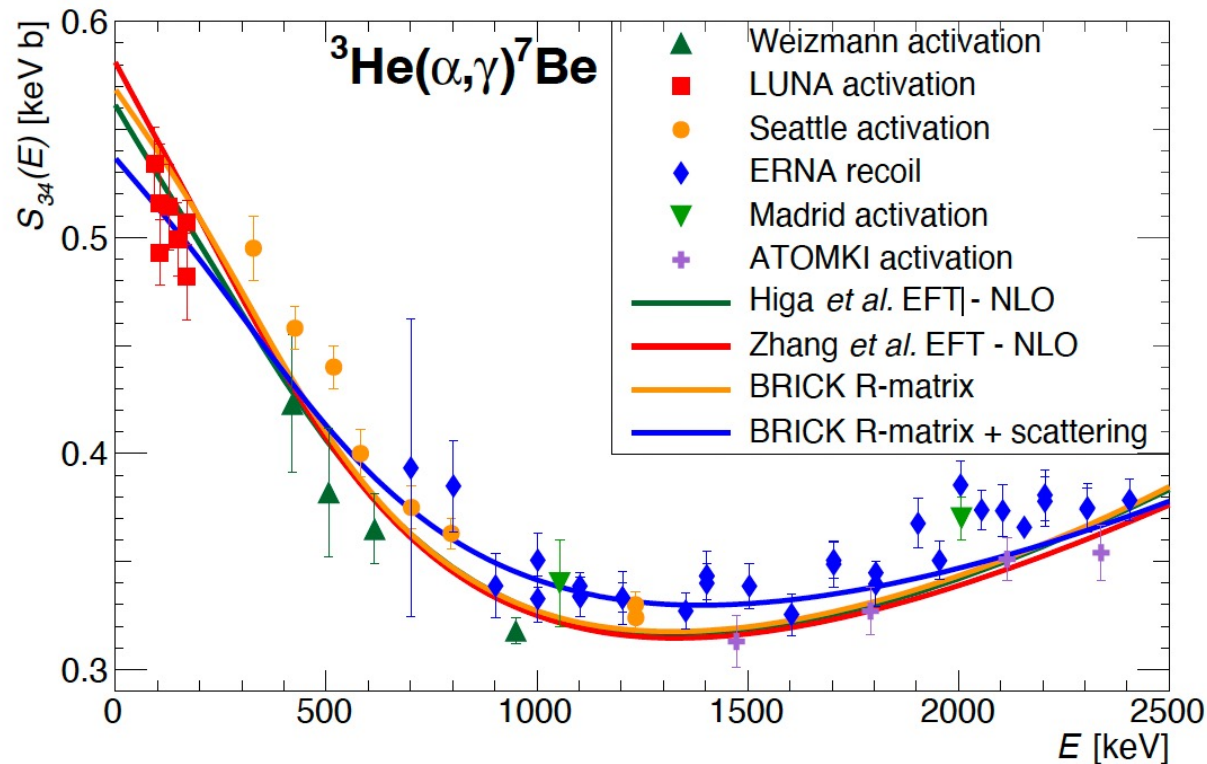
Status of solar (stellar) opacities

- OPAS (2012, 2015; Blancard+, Mundet+)
- OPLIB/Los Alamos (2016; Colgan+)
- OPAL (1996)
- Opacity Project (OP; 2005)

The proton-proton chains



$^3\text{He}(\alpha,\gamma)^7\text{Be}$ – pp-II chain



Evaluated S-factor normalization, 5.1% precision:

$$S_{34}(0) = (0.561 \pm 0.018_{\text{expt}} \pm 0.022_{\text{theor}}) \text{ keV b}$$

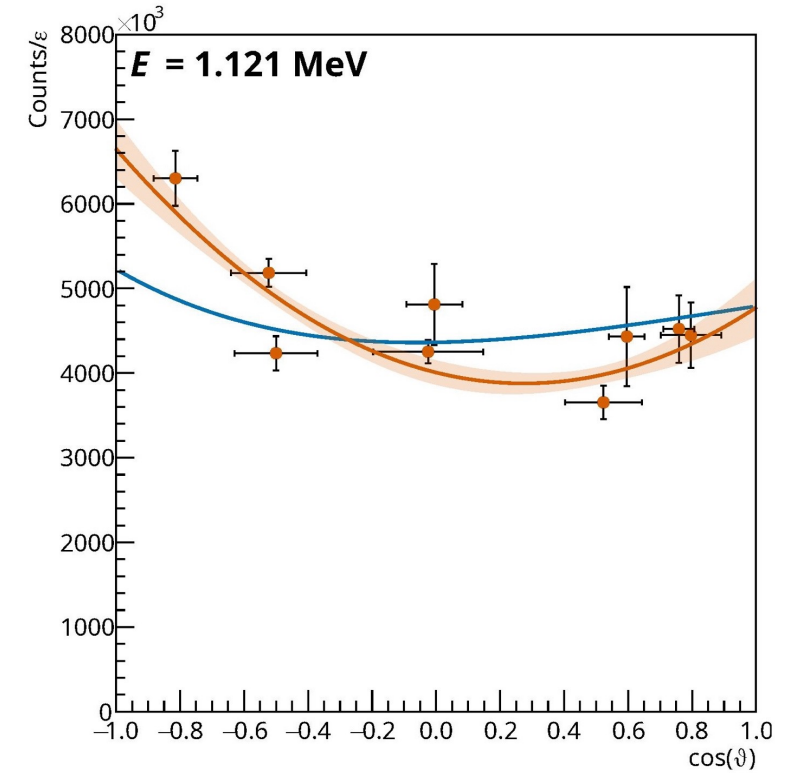
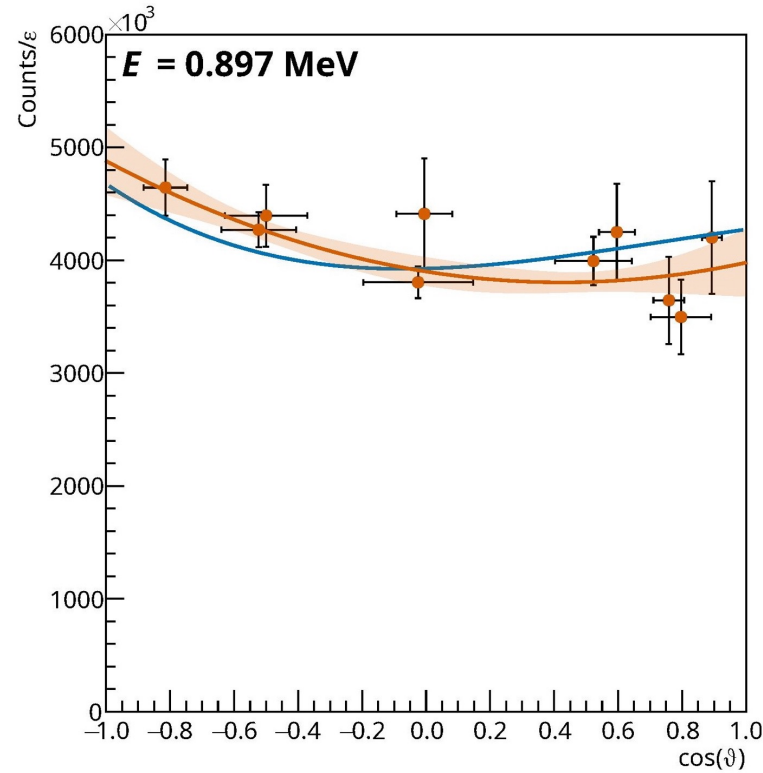
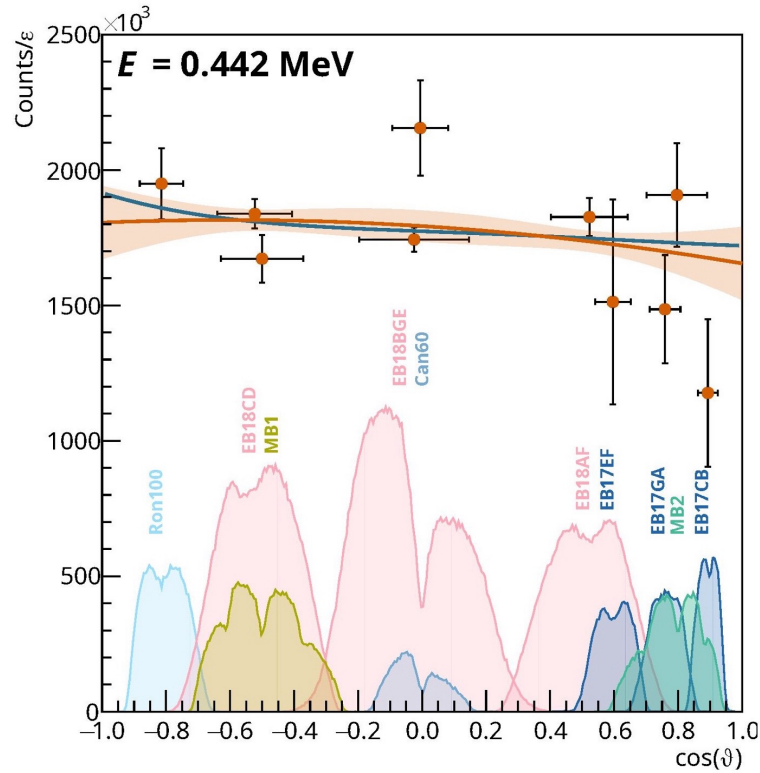
Rev. Mod. Phys. 97, 035002 (2025)

Community-based recommendations for future work:

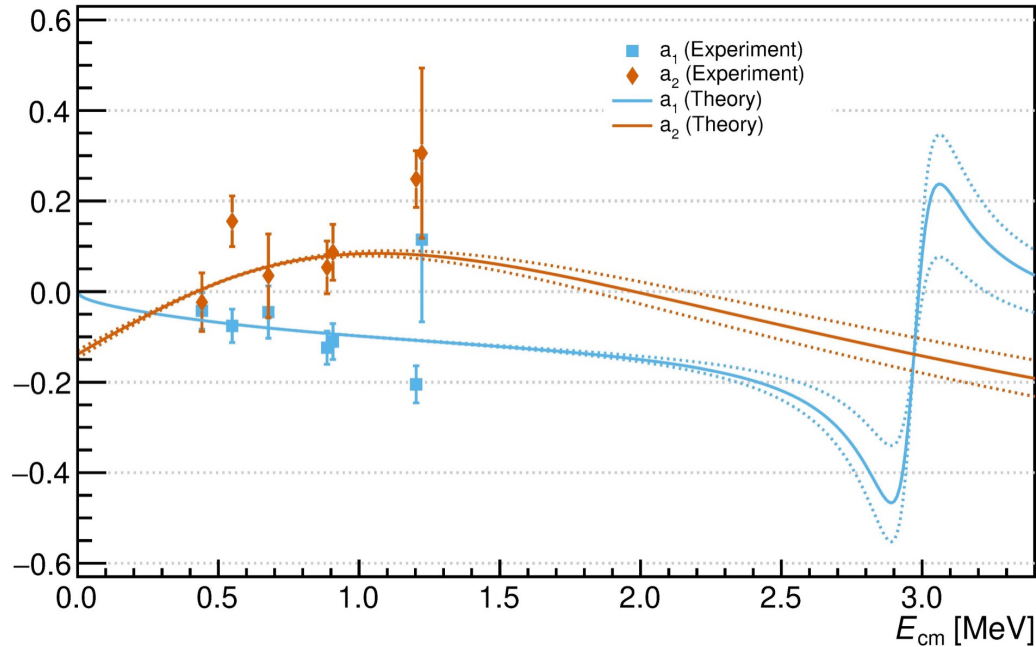
- ◆ Elastic scattering data below 2 MeV
- ◆ γ -ray angular distribution data
- ◆ Study of the S-factor over a wide energy range, 50-1500 keV.
- ◆ Further development of *ab initio* techniques.



Study of the ${}^3\text{He}(\alpha,\gamma){}^7\text{Be}$ γ -ray angular distribution at Felsenkeller (1)

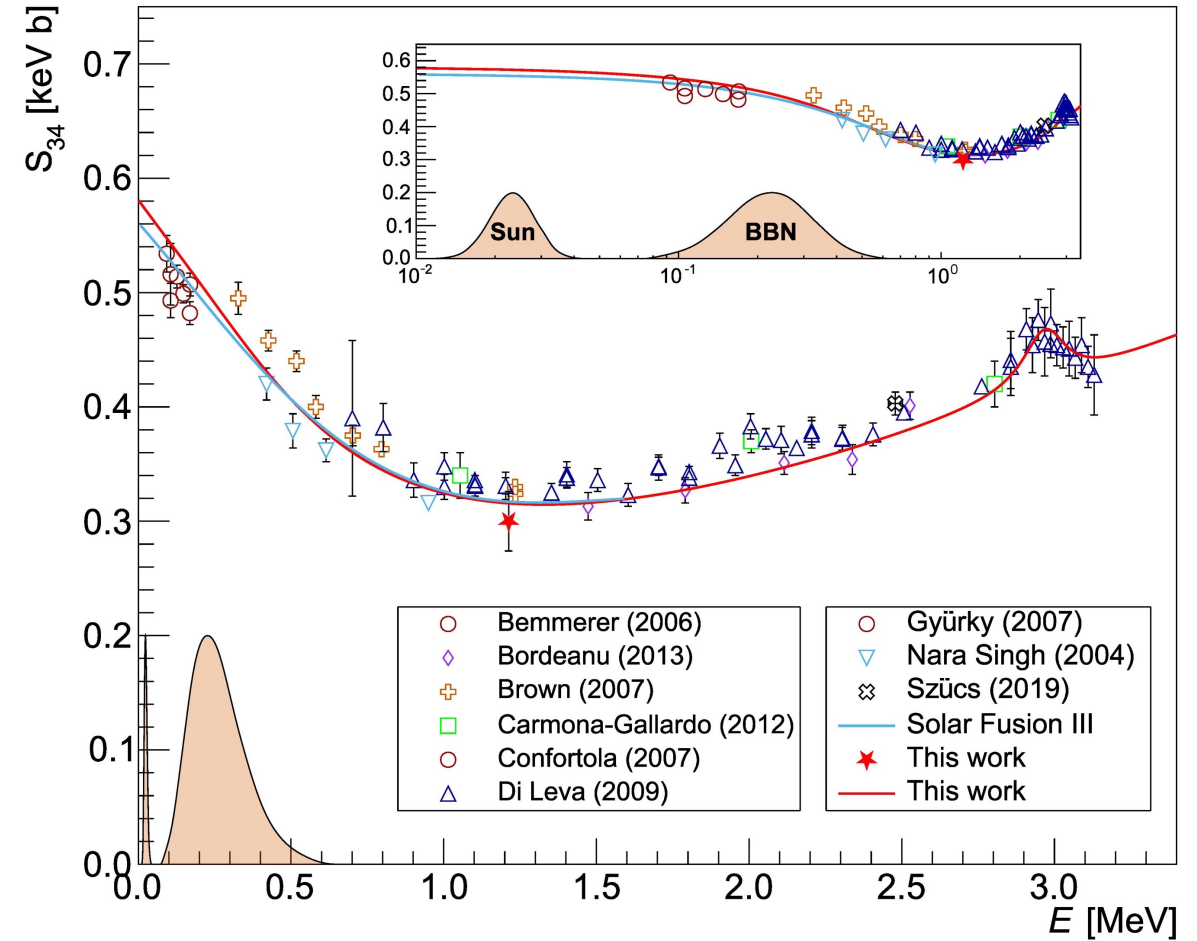


Study of the $^3\text{He}(\alpha,\gamma)^7\text{Be}$ γ -ray angular distribution at Felsenkeller (2)

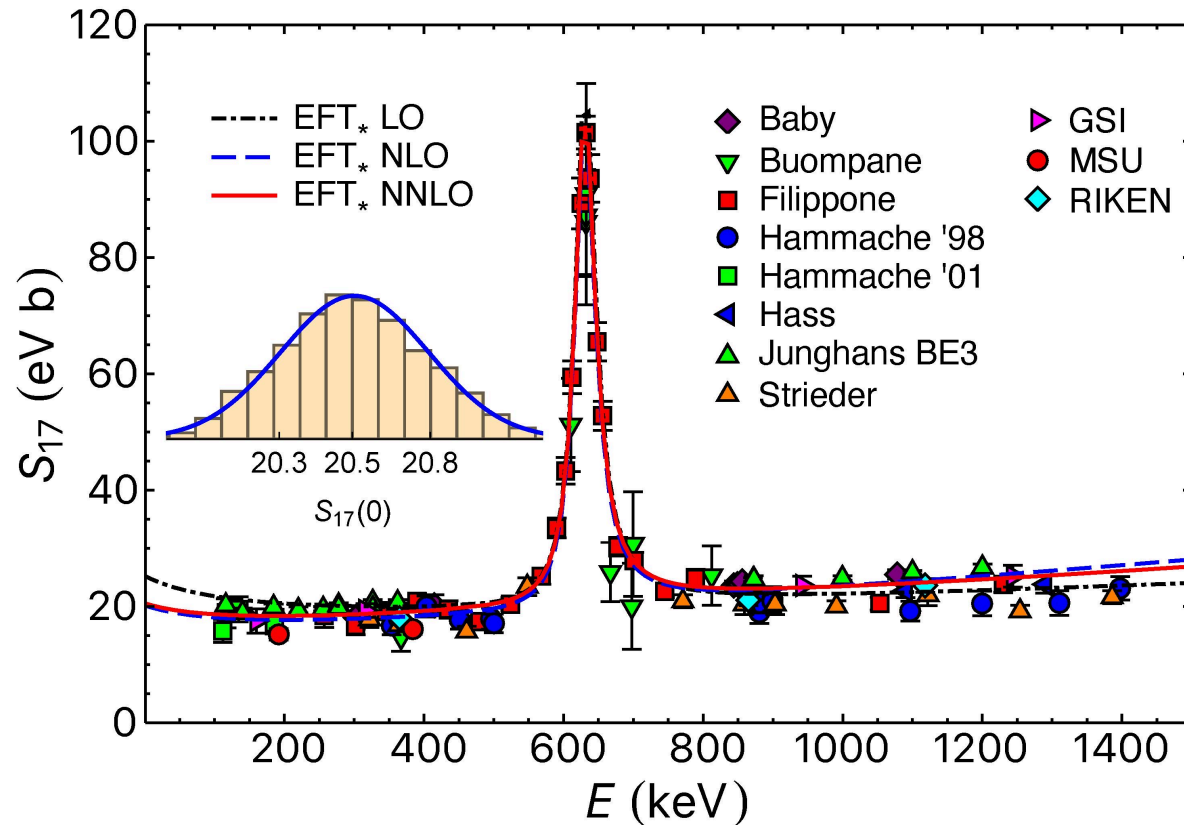


$$\frac{d\sigma}{d\Omega_{\text{c.m.}}} = A_0 \left(1 + \sum_{l=1}^3 a_l P_l(\cos \theta_{\text{c.m.}}) \right)$$

$$= A_0 \left(1 + \sum_{l=1}^3 a_l P_l(E_\gamma) \right).$$



${}^7\text{Be}(p,\gamma){}^8\text{B}$ – pp-III chain



Evaluated S-factor normalization,
3.5% precision:

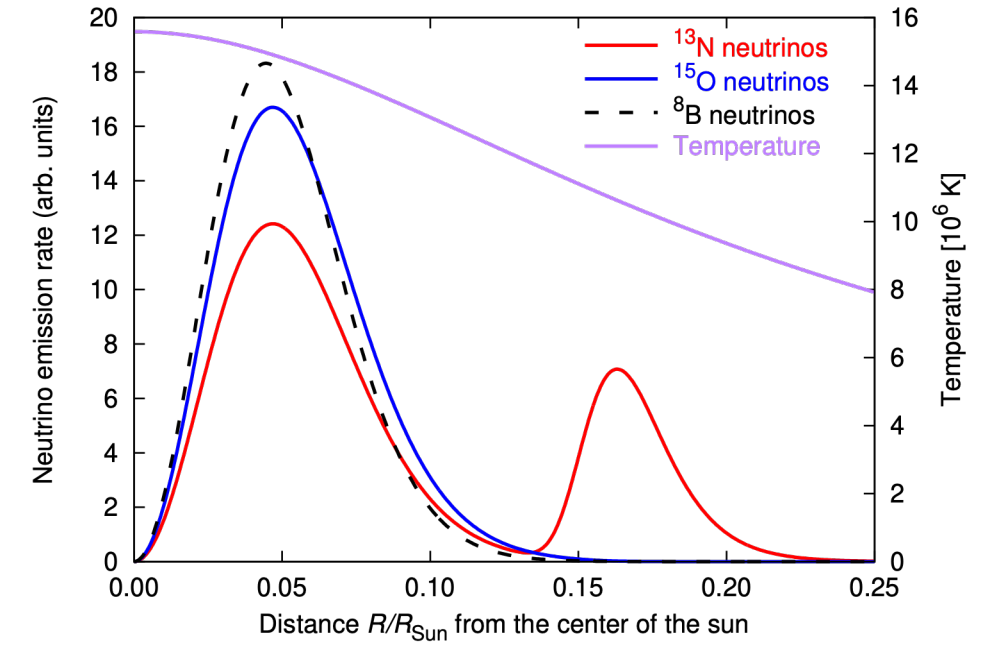
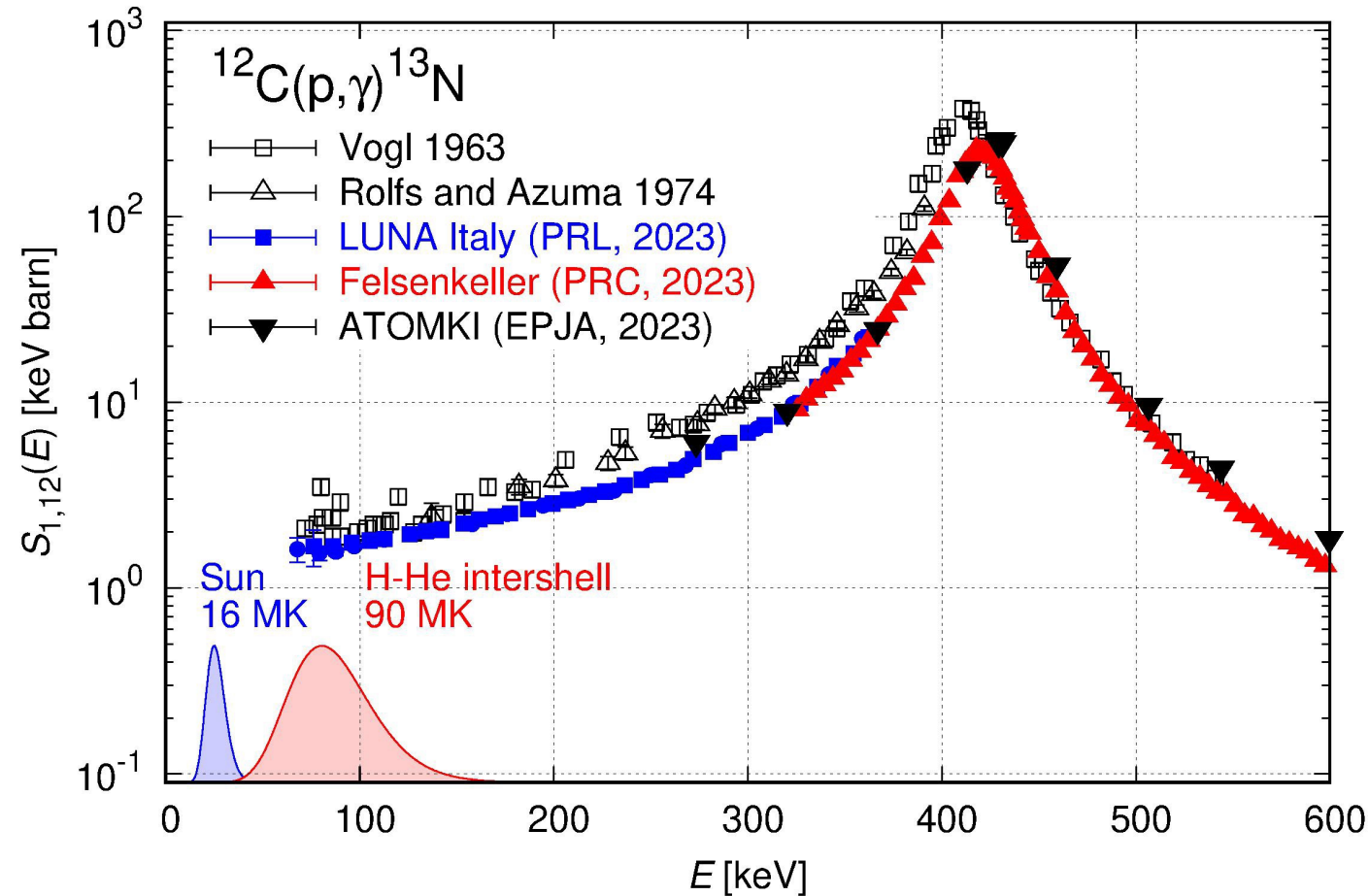
$$S_{17}(0) = 20.5 \pm 0.7 \text{ eV b}$$

Recommendation for future work:

- Precise new measurements with ${}^7\text{Be}$ beams



Study of the $^{12}\text{C}(p,\gamma)^{13}\text{N}$ reaction in Italy, Hungary, Germany



$^{14}\text{N}(p,\gamma)^{15}\text{O}$ – CNO cycle rate

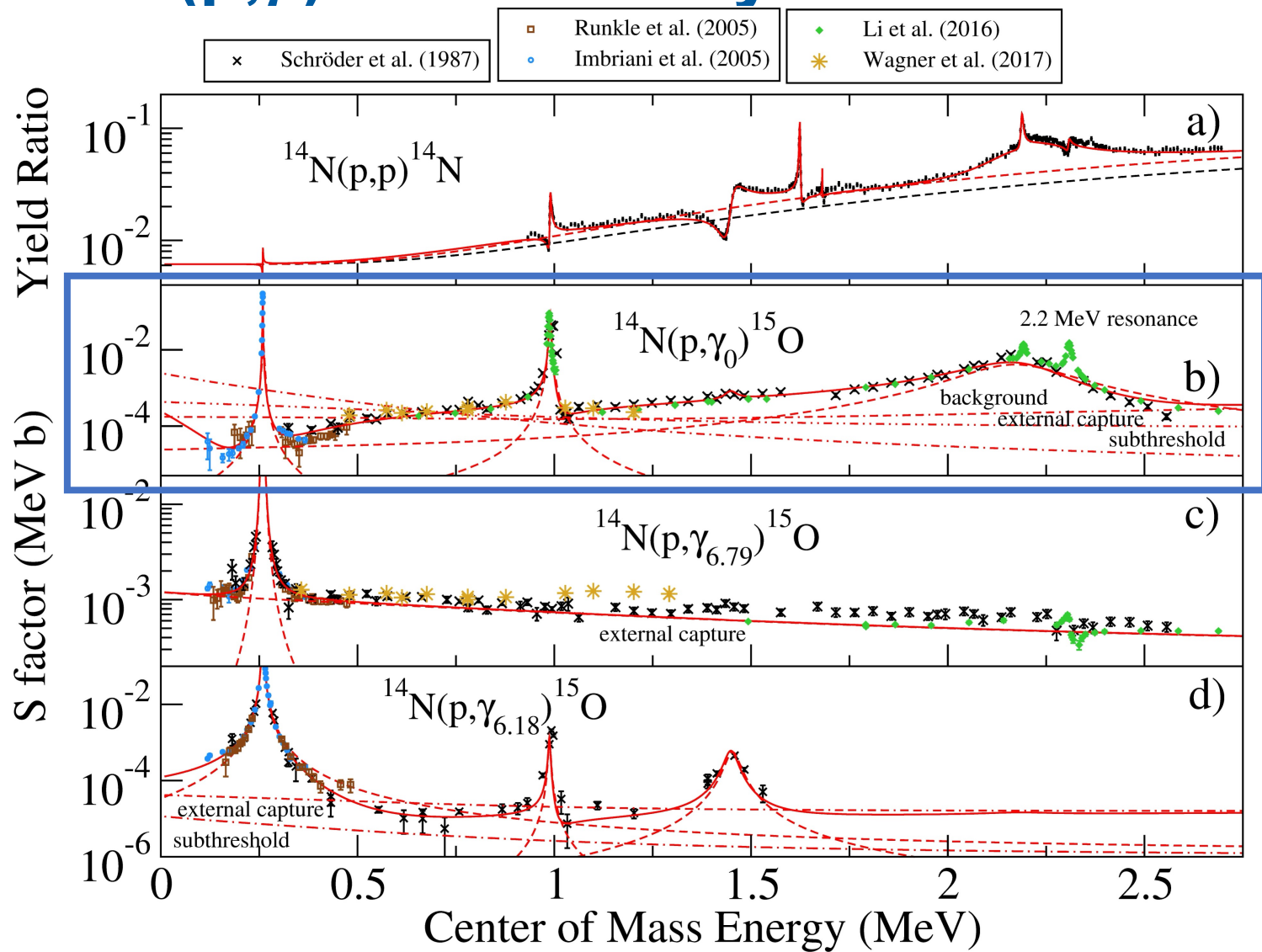


TABLE X. Total $S_{114}(0)$ values as the sum of the partial transitions.

Transition	$S_{114}(0)$ (keV b)	$\Delta S_{114}(0)$	Reference
tr $\rightarrow$ 0	0.30 ± 0.11	37%	This review
tr $\rightarrow$ 6.79	1.17 ± 0.03	2.9%	This review
tr $\rightarrow$ 6.17	0.13 ± 0.05	38%	Adelberger <i>et al.</i> (2011)
tr $\rightarrow$ 5.18	0.010 ± 0.003	30%	Adelberger <i>et al.</i> (2011)
tr(5.24) $\rightarrow$ 0	0.068 ± 0.020	30%	Adelberger <i>et al.</i> (2011)
R-matrix sum	1.68 ± 0.13^a	7.6%	
Additional system uncertainty ^b		3.5%	
Total	1.68 ± 0.14	8.4%	

Recommended error bar from 2025 community-based review:

8.4% uncertainty – higher than in 2011!



European Research Council
Established by the European Commission

LUNANOVA

Laboratory **U**nderground for **N**uclear **A**strophysics
New **O**bservatory for Solar Neutrino Reactions



Daniel Bemmerer (cPI)
Helmholtz-Zentrum Dresden-
Rossendorf (HZDR), Germany

Alba Formicola (PI)
Istituto Nazionale di Fisica
Nucleare (INFN), Italy



Aldo Serenelli (PI)
Instituto de Ciencias del
Espacio (ICE-CSIC), Spain

Gianluca Imbriani (PI)
Università degli studi di
Napoli Federico II, Italy

...ERC Synergy Grant, 01.09.2026 – 31.08.2032, 14 M€



LUNANOVA objective....

SSM model ν fluxes...

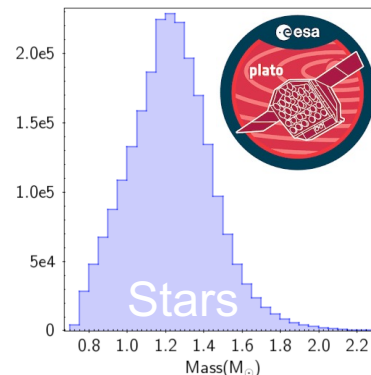
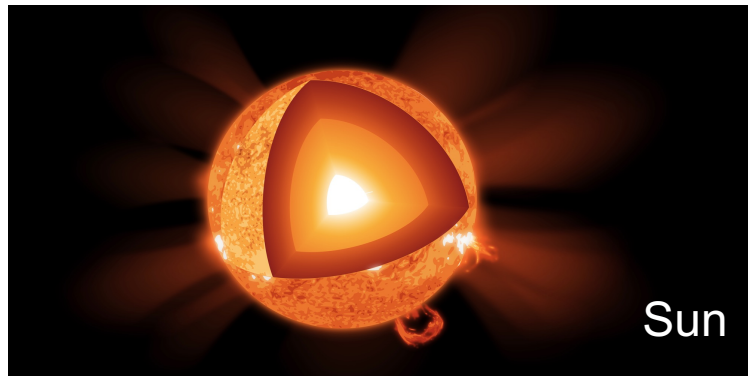
$\nu(\text{pp})$	$\pm 0.6\%$	$\pm 0.4\%$
$\nu(^7\text{Be})$	$\pm 7.7\%$	$\pm 1.8\%$
$\nu(^8\text{B})$	$\pm 13\%$	$\pm 1.9\%$
$\nu(^{13}\text{N}+^{15}\text{O})$	$\pm 17\%$	$\pm 13\%$

LUNANOVA

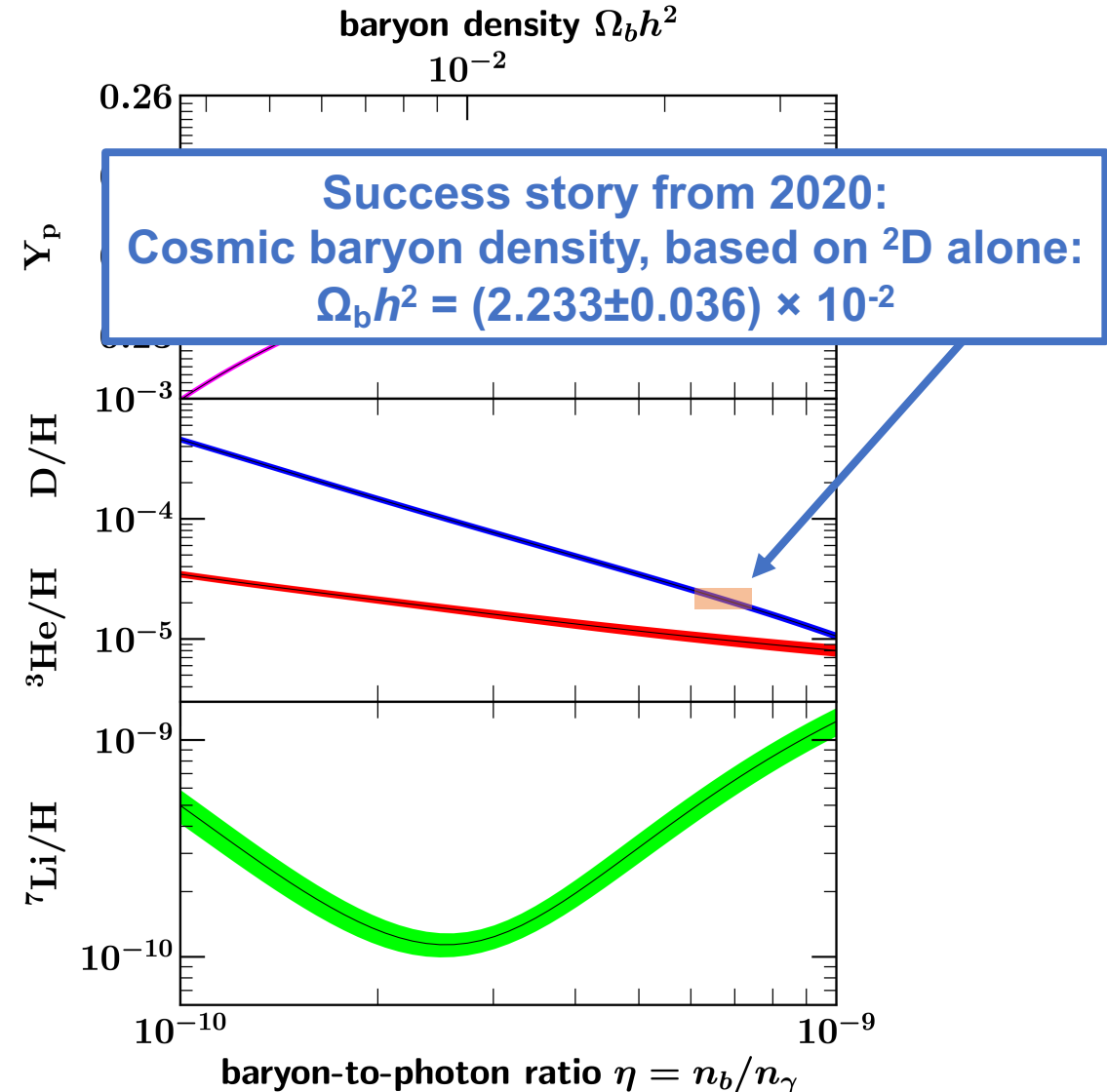
Model not precise

Data precise

Remove nuclear physics uncertainties, and thus break the degeneracy between nuclear and solar/stellar physics.



....and why it might work



LUNANOVA accelerator, to be installed at LNGS Gran Sasso in 2028



Also there at LNGS:

Bellotti Ion Beam Facility (3.5 MV)
open since 2023

LUNA 400 kV accelerator
2001 – ?

THE LOW SEISMIC LAB

/ 20

Innovation platform of ca. $(40 \times 30 \times 30) \text{ m}^3$ size in a depth of 200m in the Lusatia Granite

With a Square-Kilometer 3D seismic sensor array

→ Large scale measurement validation of future seismic isolation concepts

THE PLACE FOR FUTURE «DEEP TECH»:

- Technology development for gravitational wave astronomy
- Adaptive seismic noise suppression
- Subnanometer photolithographie
- Experiments for Quantum computing
- Accelerator Astrophysics (e.g. Felsenkeller)



ChETEC-INFRA EU project for nuclear astrophysics [ketek-infra]

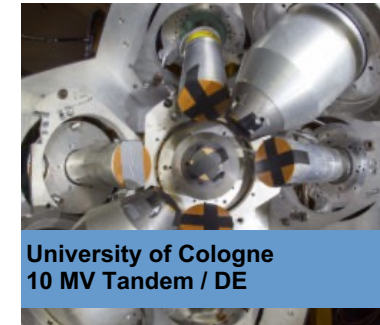
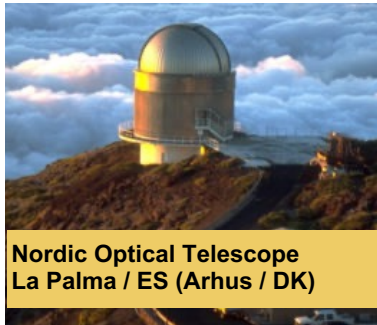


- ◆ **Starting Community** of research infrastructures
- ◆ **31 partners** in 17 EU+ countries
- ◆ May 2021 – October 2025
- ◆ 5 M€ support by EU

<https://www.chetec-infra.eu>



14 research infrastructures made accessible by ChETEC-INFRA



laboratories

supercomputers

telescopes



Transnational access to research infrastructures

Funding tool by the European Union, as part of time-limited "Communities of Research Infrastructures"

- ♦ Member infrastructures must be of **regional or global interest**
- ♦ Member infrastructures must be based in the EU or EU-associated countries, but exceptions apply for unique infrastructures in third countries of strong EU interest

Transnational access, the idea

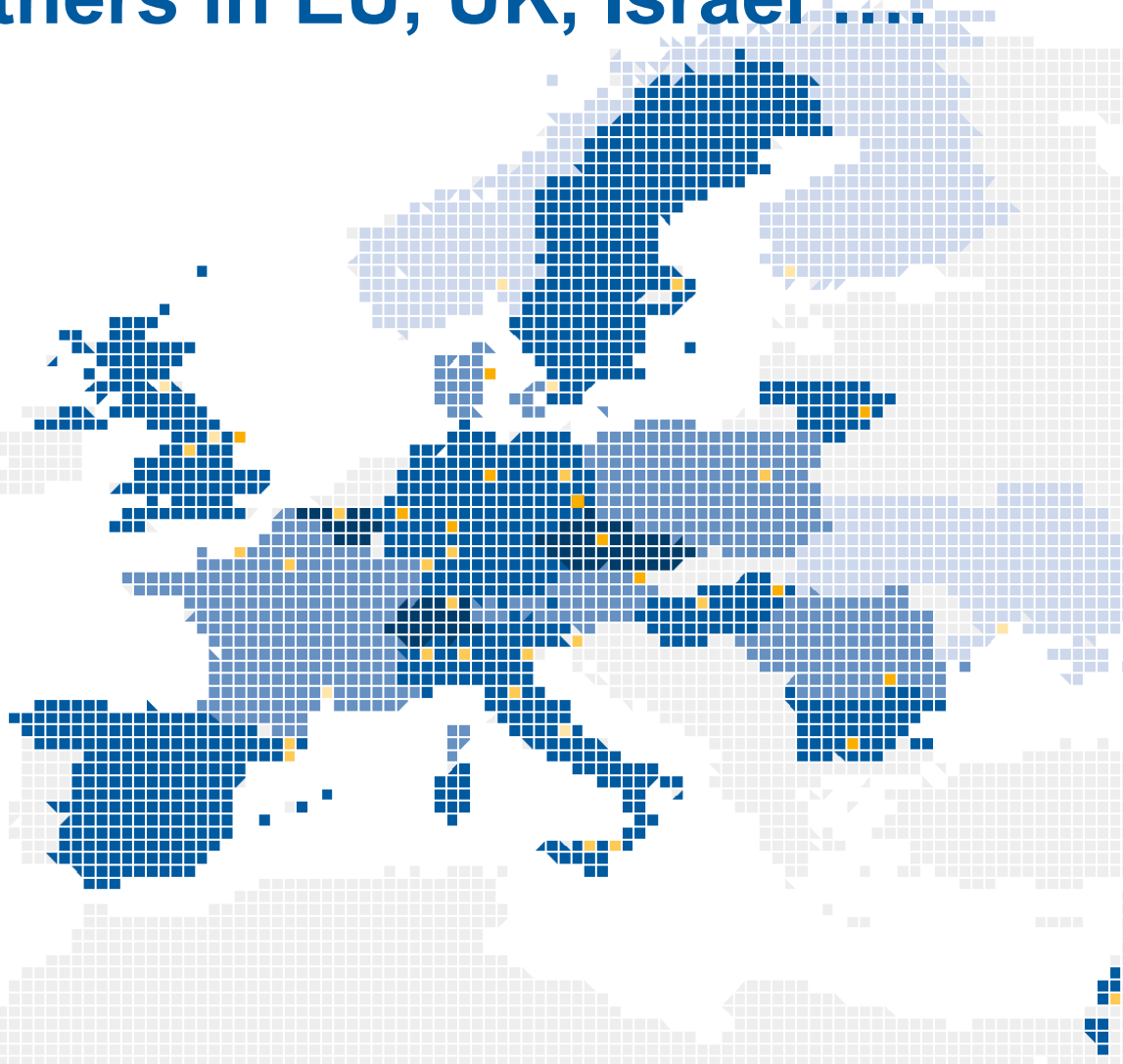
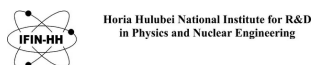
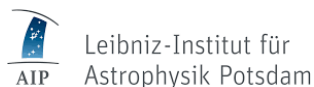
- ♦ Researchers based in countries lacking an infrastructure they need can access it in a different country
- ♦ Selection of proposals based on **scientific excellence** (sole criterion)
- ♦ For the access, researchers must **cross a national border**
- ♦ EU support, part 1 = **Support to the infrastructures** to help defray access costs (e.g. hourly rate)
- ♦ EU support, part 2 = **Travel support** to the infrastructure users
- ♦ Users may also come from any country in the world (20% limit applies)

EURO-LABS Advanced Community of Research Infrastructures (GSI, GANIL, ELI-NP – 2022 - 2026)

ChETEC-INFRA Starting Community of Research Infrastructures, 2021 – 2025

- ♦ **7875 beam hours** of accelerator time, **160 clear nights** of telescope time, **0.4 M cpu-hours**

31 funded partners in EU, UK, Israel



Scientific achievements by ChETEC-INFRA

300 peer-reviewed publications, cited 3000 times, with explicit ChETEC-INFRA acknowledgment

- ◆ Many science papers benefiting from project-funded work
- ◆ Transnational access - based papers are still arriving

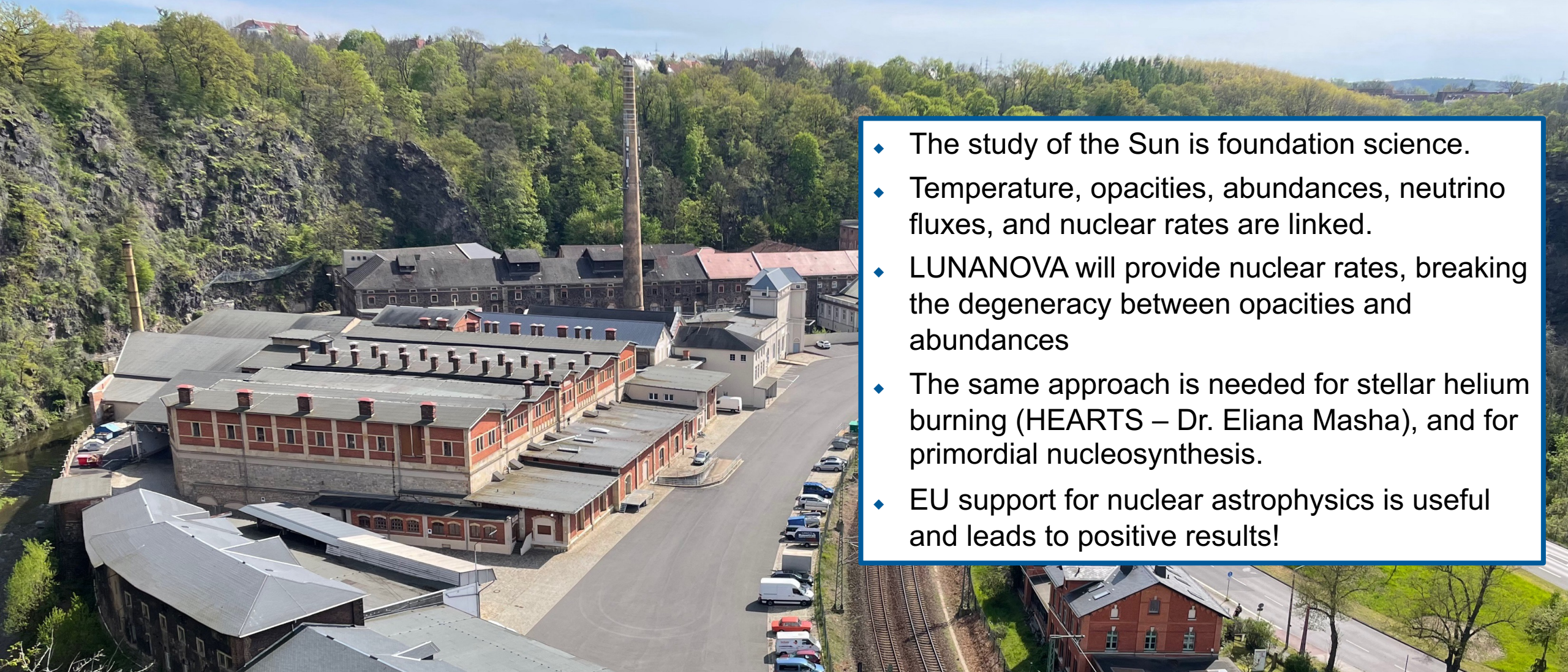
Scientific legacy

- ◆ Previously non-existing interdisciplinary network between astronomers, astrophysicists, nuclear physicists
- ◆ Previously national-only facilities successfully opened up for TNA
- ◆ Several scientific workshops on Solar Fusion, helium, and carbon burning reactions.
- ◆ Strong bridge to meteoritic and planetary science communities

General aspects of ChETEC-INFRA

- ◆ Scientific schools strongly supported for several years
- ◆ Outreach to high school students via Masterclasses, to policymakers, to large national labs, ...
- ◆ Many scientific databases from nuclear physics, astronomy, etc.
- ◆ Inclusiveness across many dimensions (countries, gender, ages, ...), extraordinary for a MINT-based network
- ◆ Active and thriving industry contacts

Overview of the solar model and LUNANOVA – take-home points

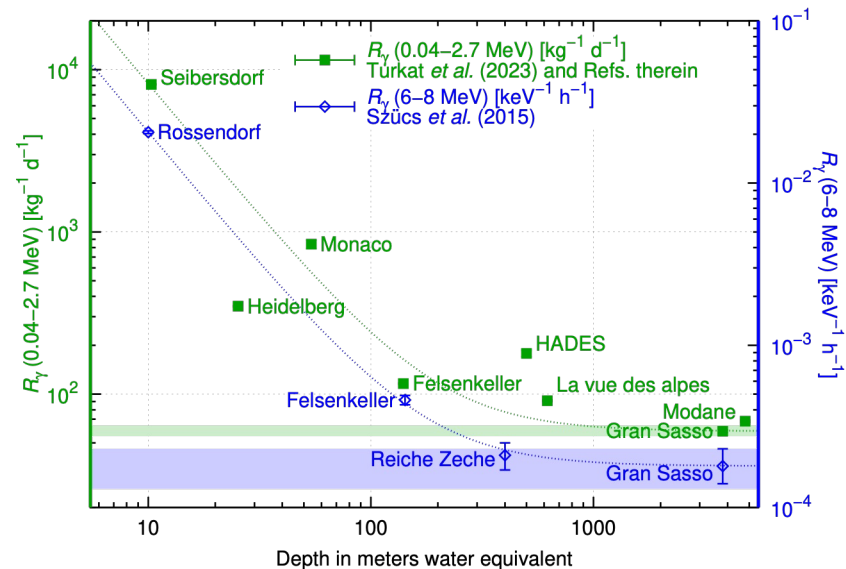
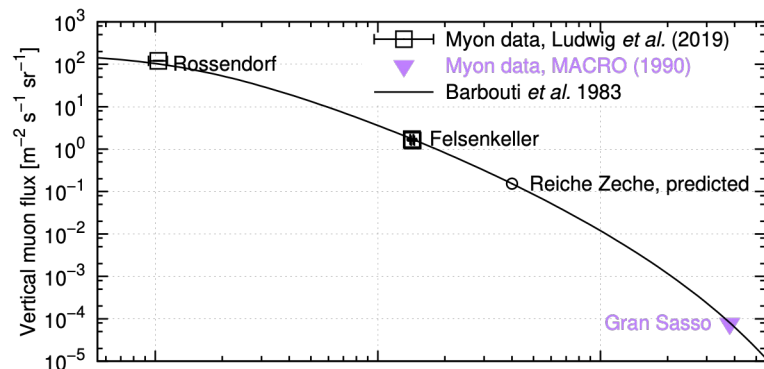


- ◆ The study of the Sun is foundation science.
- ◆ Temperature, opacities, abundances, neutrino fluxes, and nuclear rates are linked.
- ◆ LUNANOVA will provide nuclear rates, breaking the degeneracy between opacities and abundances
- ◆ The same approach is needed for stellar helium burning (HEARTS – Dr. Eliana Masha), and for primordial nucleosynthesis.
- ◆ EU support for nuclear astrophysics is useful and leads to positive results!

Felsenkeller: Studying low cross sections with low background

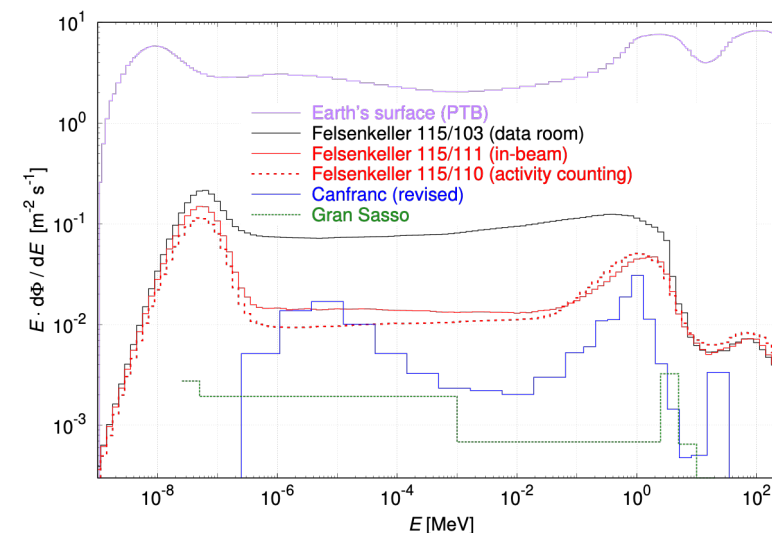
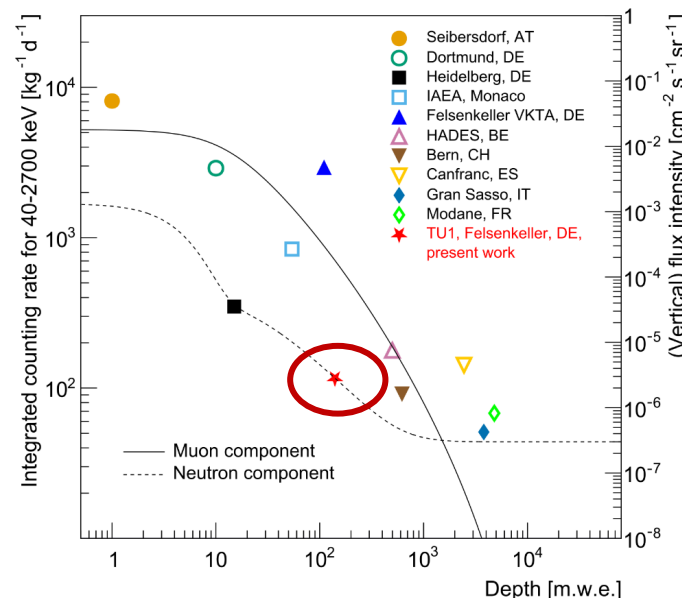
40× lower muon background

Astropart. Phys. 112, 24 (2019)



200× lower neutron background

Phys. Rev. D 101, 123027 (2020)



100× lower γ -background

Eur. Phys. J. A 51, 33 (2015)

Astropart. Phys. 148, 102816 (2023)

Eur. Phys. J. A 61, 19 (2025)

DZA Low Seismic Lab, at the „sweet spot“ for nuclear astrophysics

