

# New ideas for Solar fusion studies - LUNANOVA

## ERC Synergy grant

NUSTAR Meeting

GSI, Germany – February 23<sup>th</sup>-27<sup>th</sup> - 2026

### A. Serenelli on behalf of LUNANOVA



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101008324 (CHETEC-INFRA).

# Outline

➤ Fundamental science with the Sun

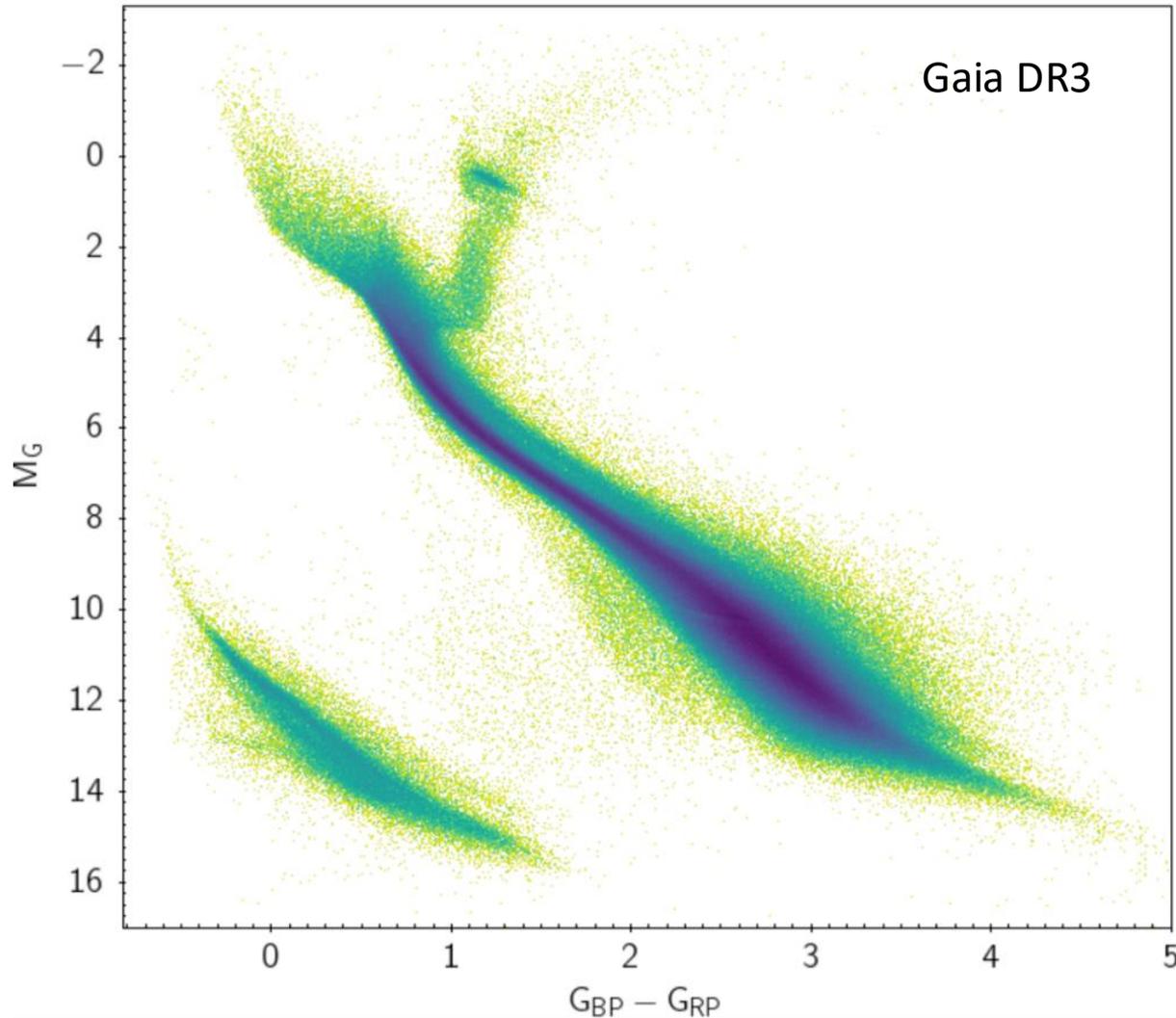
➤ Solar-like stars

convective cores in  $1.1 - 1.5 M_{\odot}$  stars in the context of asteroseismic missions (PLATO)

➤ The need for accurate & precise cross section

➤ LUNANOVA Project

# Why the Sun? It is “foundation” science

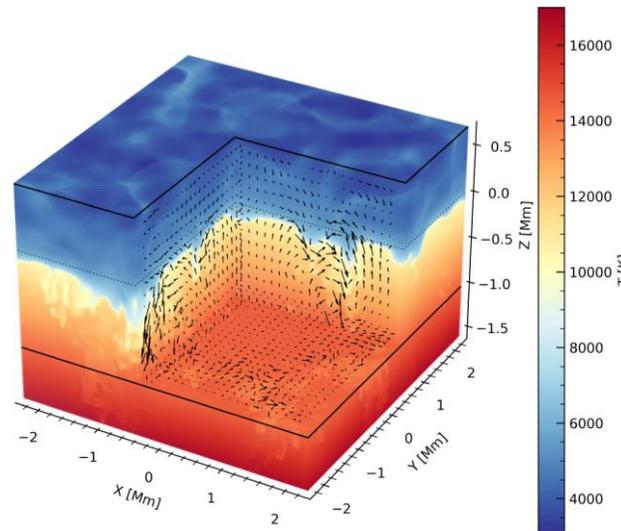
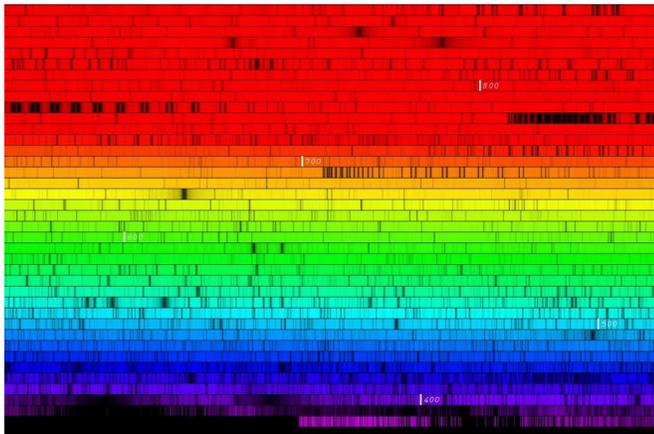


~ $10^9$  individual stars with measurements  
colors, temperature, luminosity, (composition)

~  $10^3$  with accurate, precise, (model) independent  
mass determinations  
selective club: eclipsing binaries

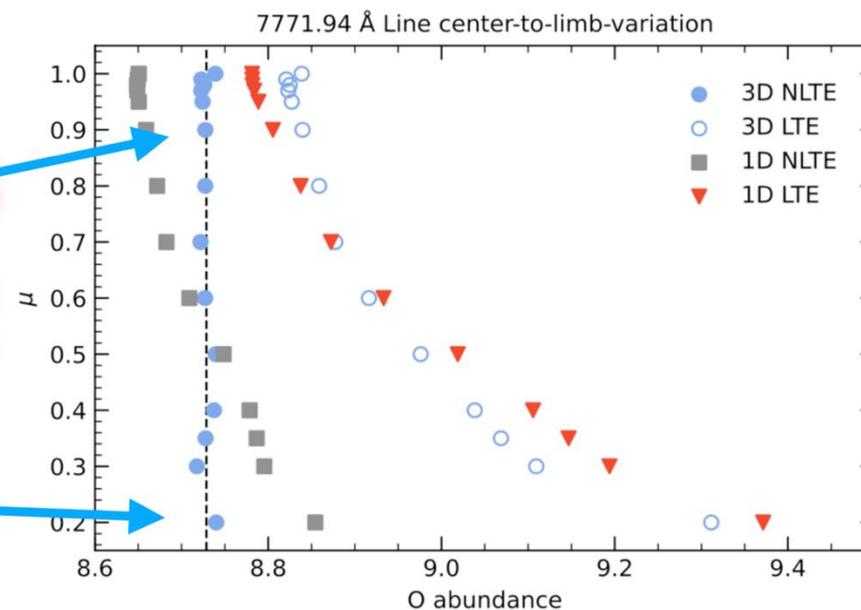
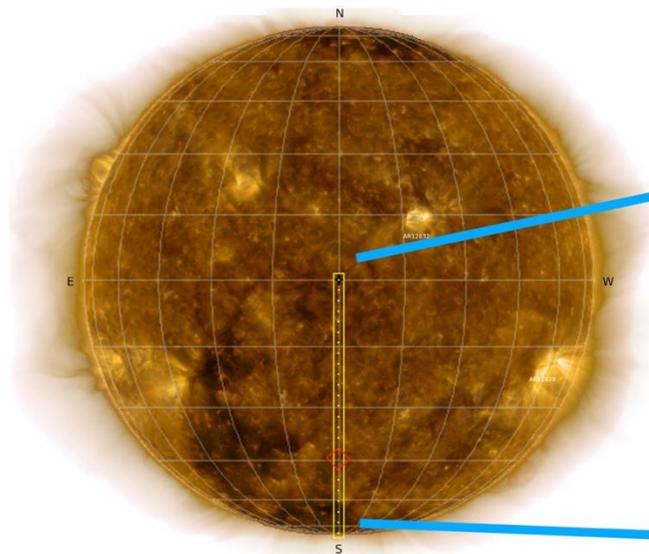
- **1 star with accurate, precise, (model) independent age determination**  
meteoritic dating  
+ highly accurate radius & mass
- **Solar composition is the yardstick for all astronomical abundance determinations**

# Foundation science: Solar spectrum & abundances



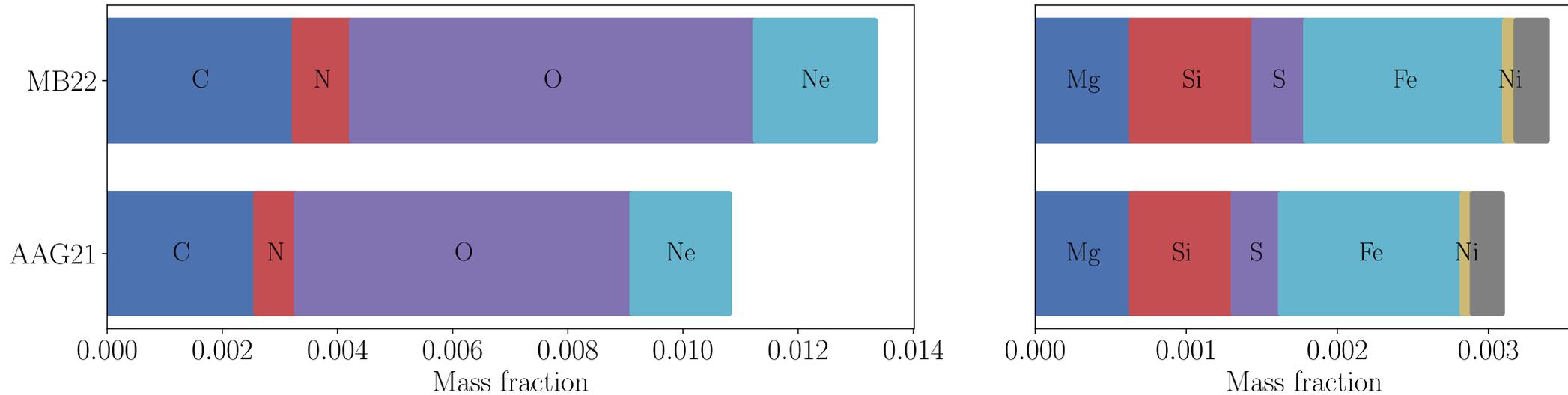
Solar envelope is convective  
 → hydrodynamic models  
 → 3D atmosphere model

Model atmosphere  
 → detailed radiative transfer - NLTE  
 → synthetic spectrum to compare with observed one  
 → determination of abundances  
 → spatially resolved spectroscopy



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

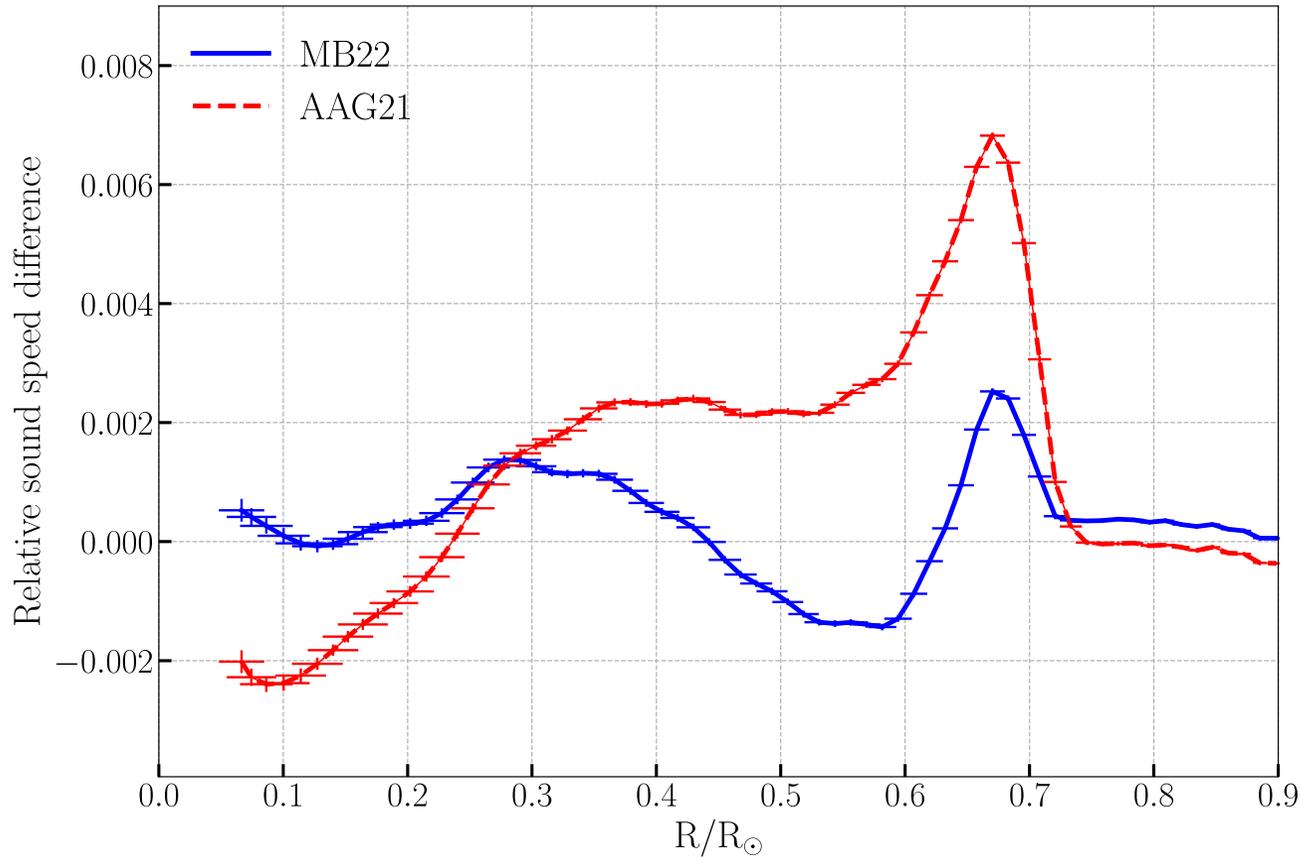
# Which solar composition?



AAG21: Asplund et al. 2021  
MB22: Magg et al. 2022

**Chemical abundances are a boundary condition imposed to, not a prediction of, (non-) standard solar models**

# What helioseismology tells us



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
<b>Solar</b>	<b>0.713</b> <b>±0.001</b>	<b>0.2485</b> <b>±0.0035</b>			

Results sensitive to thermal structure because sound speed scales with  $T^{1/2}$

$$\nabla T^4 \propto \kappa \qquad c^2 \propto \frac{T}{\mu}$$

**thermal gradient →**  
**“composition + radiative opacities”**

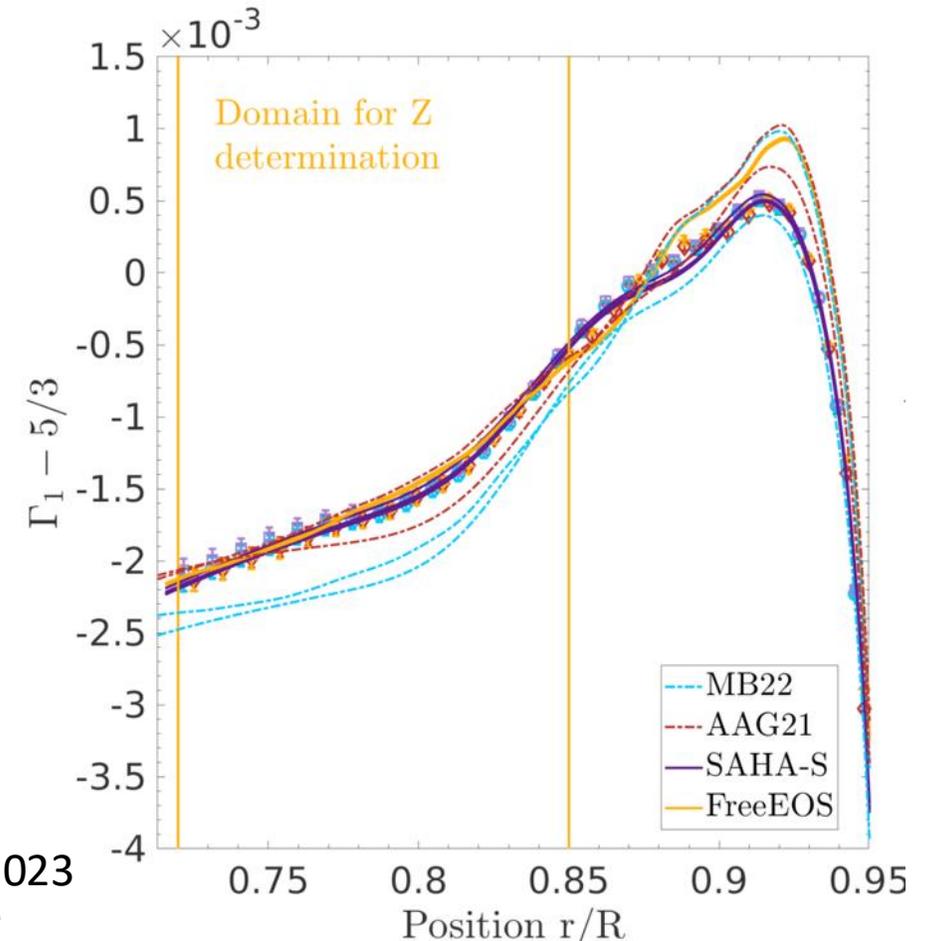
# Another look from helioseismology

Propagation of sound waves carry information about composition through adiabatic index:

$$\Gamma_1 = \left( \frac{\partial \ln P}{\partial \ln \rho} \right)_{\text{ad}} = 5/3 \text{ (for fully ionized gas)} < 5/3 \text{ in partial ionization regions}$$

- It can be determined through inversion of solar oscillations and compared to solar models.
- Sensitive to total Z (very difficult to extract individual elements)

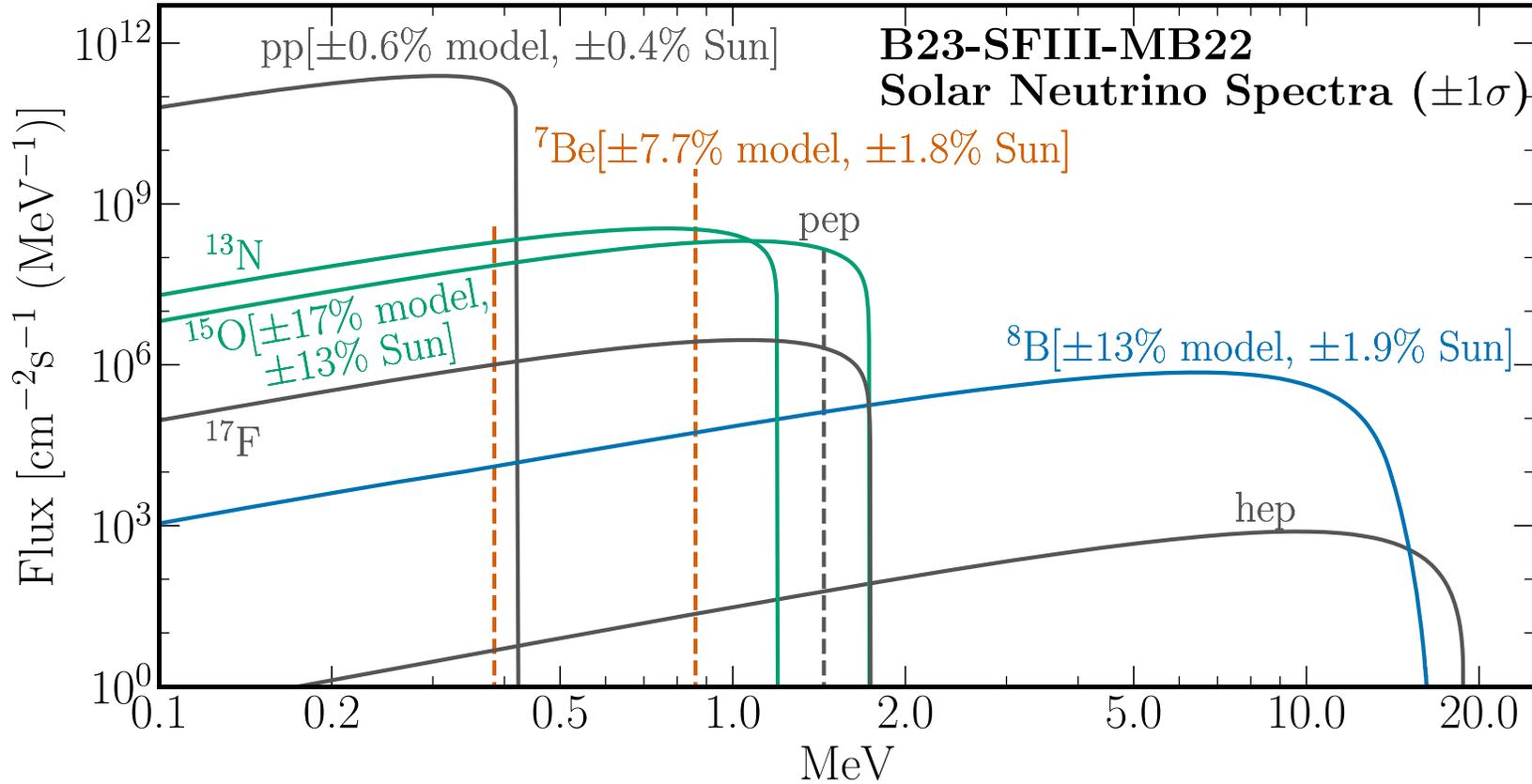
## Composition + Equation of State



Buldgen et al. 2023

# A unique view into the Sun: solar neutrinos

Solar neutrinos → information on solar core, nuclear physics



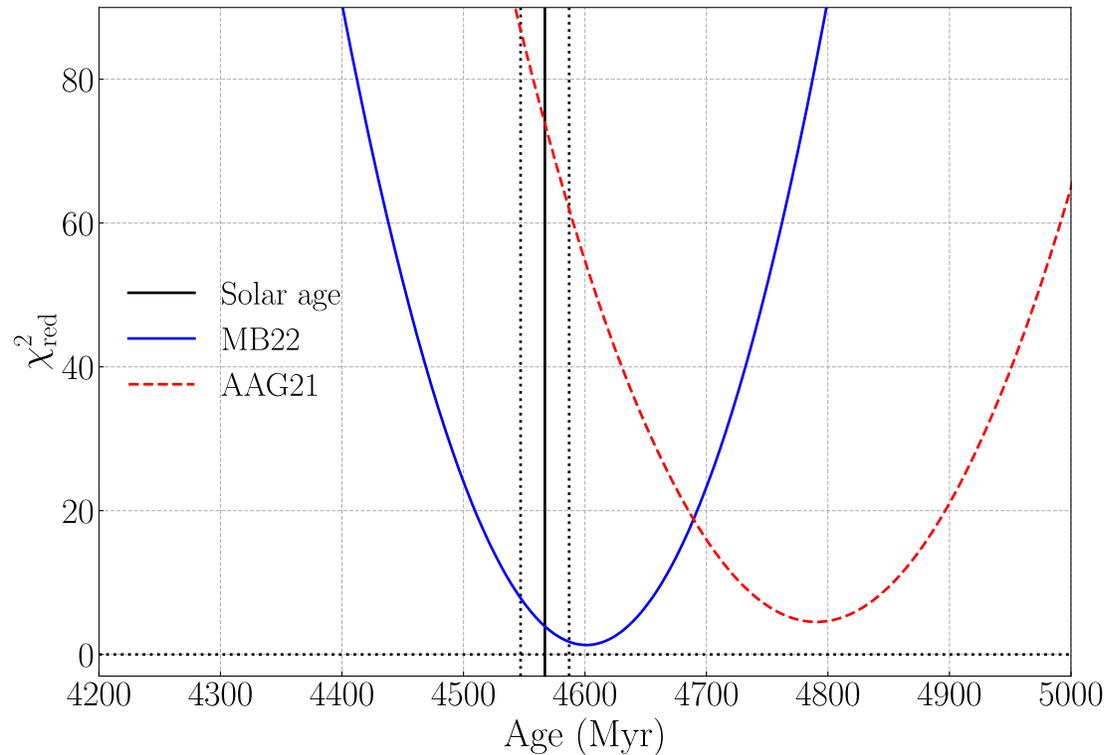
SSM model $\nu$ fluxes...		and data
$\nu(\text{pp})$	$\pm 0.6\%$	$\pm 0.4\%$
$\nu({}^7\text{Be})$	$\pm 7.7\%$	$\pm 1.8\%$
$\nu({}^8\text{B})$	$\pm 13\%$	$\pm 1.9\%$
$\nu({}^{13}\text{N}+{}^{15}\text{O})$	$\pm 17\%$	$\pm 13\%$
<b>Model not precise</b>		<b>Data precise</b>

**Model uncertainties >> experimental uncertainties!**

# The Sun as a star – only independent age calibrator

No independent age for other stars

$$\nu_{n,l} - \nu_{n-1,l+2} \propto \frac{1}{4\pi\nu_{n,l}} \int_0^R \frac{dc}{dr} \frac{dr}{r}$$

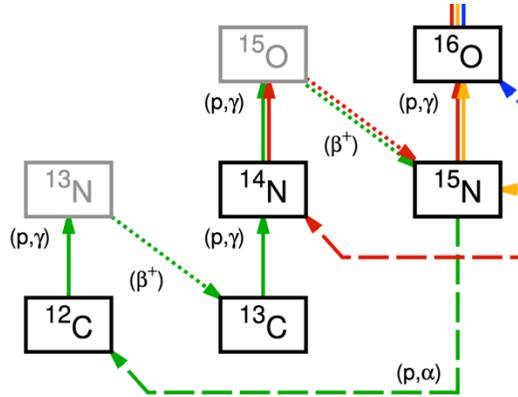


	Solar age (Gyr)
Sun	<b>4.568 ± 0.020</b>
AAG21	4.790 ± 0.034
MB22	4.611 ± 0.032

**Composition+opacities introduces a systematic effect on age determination of about to 250Myr (5%)**

# CN-cycle is a trace contribution to solar structure

CN operates against a “fixed” structure determined by pp-chains



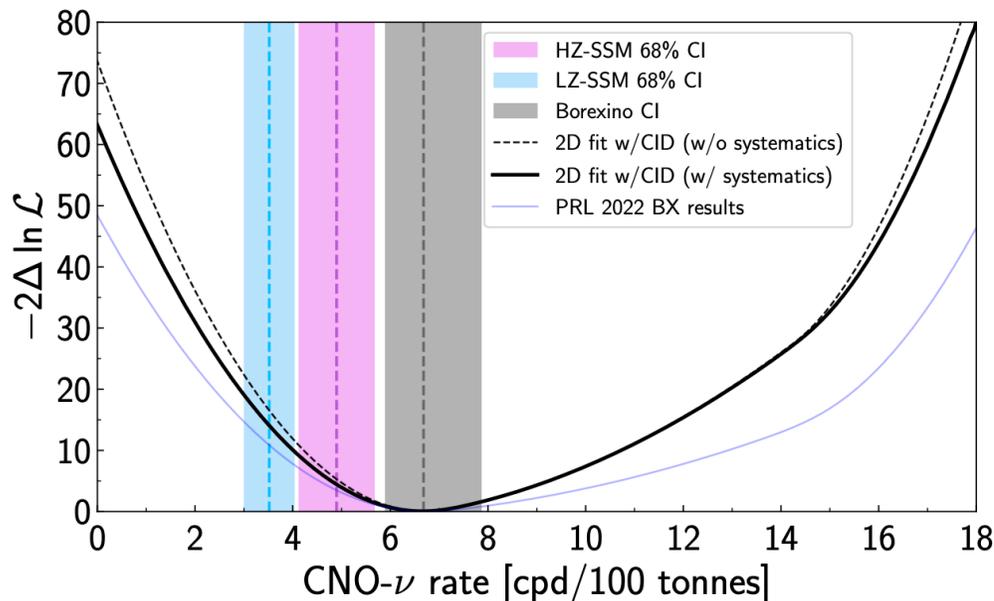
Changes in physics affecting CN do not change structure, **i.e. core temperature**,

→ retain explicit dependences:

➤ e.g. linear response to bottleneck nuclear reaction  
 $^{14}\text{N}(p,\gamma)^{15}\text{O}$

➤ **linear dependence on abundance of catalyzers in solar core: C+N**

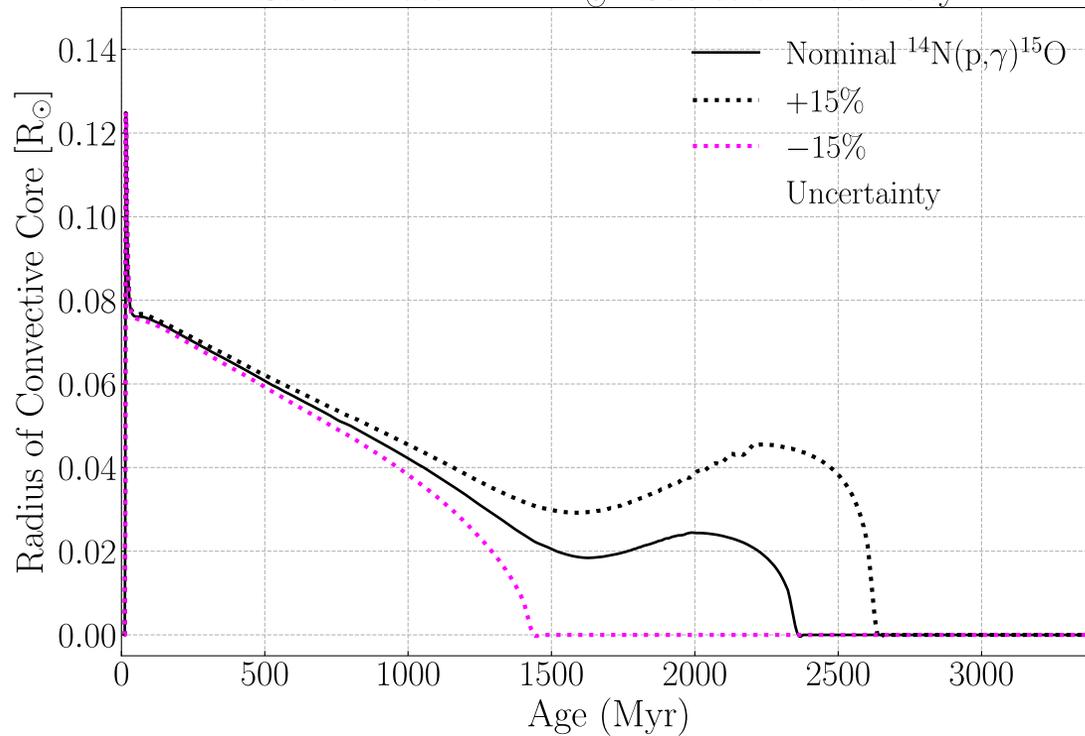
➤ **one-to-one relation between neutrino fluxes and CN abundance → Borexino measurement of CN abundance**



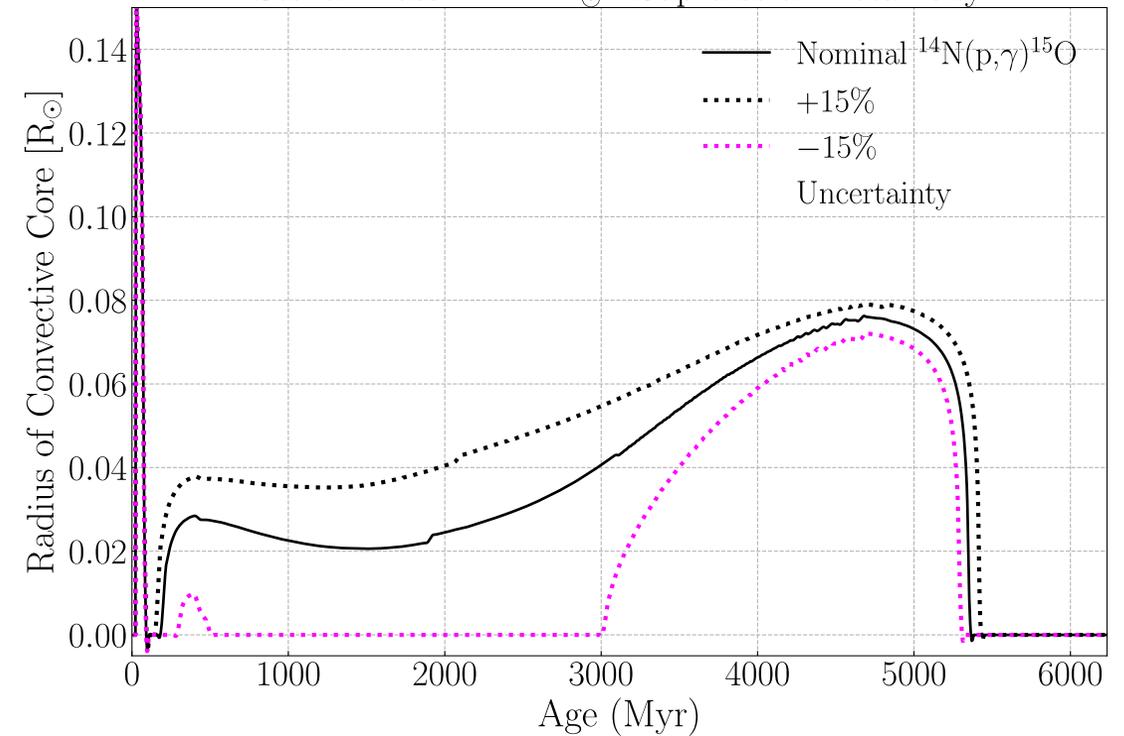
$$\frac{\phi(^{15}\text{O})}{\phi(^{15}\text{O})_{\text{SSM}}} \simeq \left( \frac{\phi(^8\text{B})}{\phi(^8\text{B})_{\text{SSM}}} \right)^{0.785} (x_{\text{C+N}}) [1 \pm 0.10(\text{nuc}) + 0.03(\text{D})]$$

# Impact for Solar-like stars ( $1.1 - 1.5 M_{\odot}$ ): convective cores – to be or not to be

Stellar mass =  $1.2 M_{\odot}$  - Sub-solar metallicity

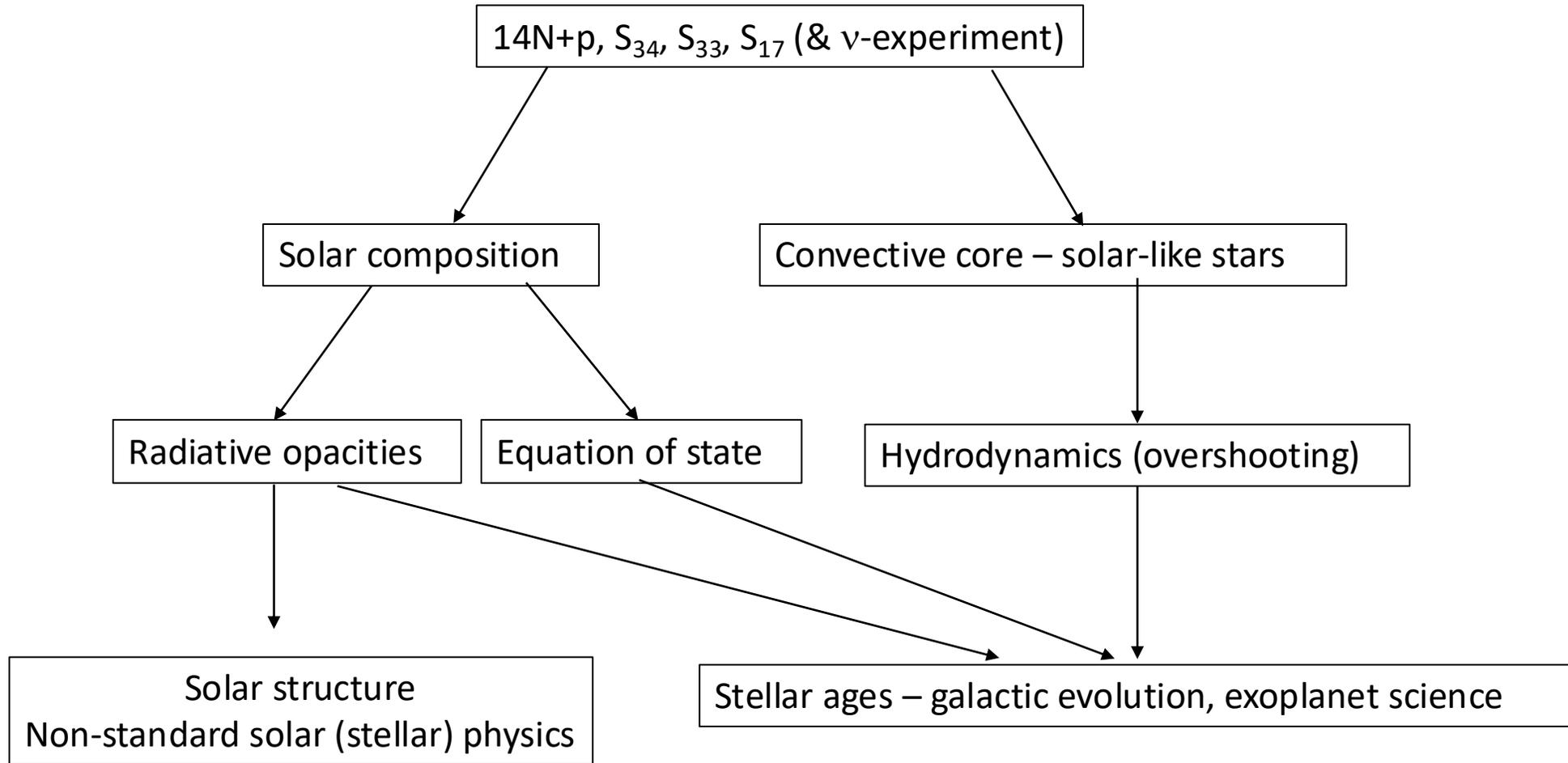


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**Nuclear cross section vs hydrodynamics (convection & overshooting)**

# Why 1% level precision x-sections





European Research Council  
Established by the European Commission

# LUNANOVA

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



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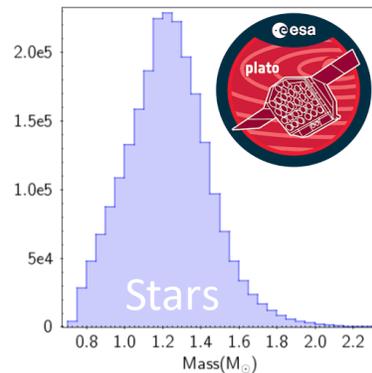
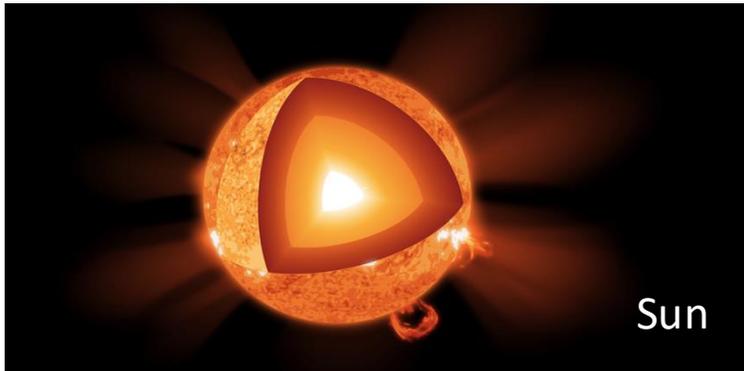


# LUNANOVA objective....

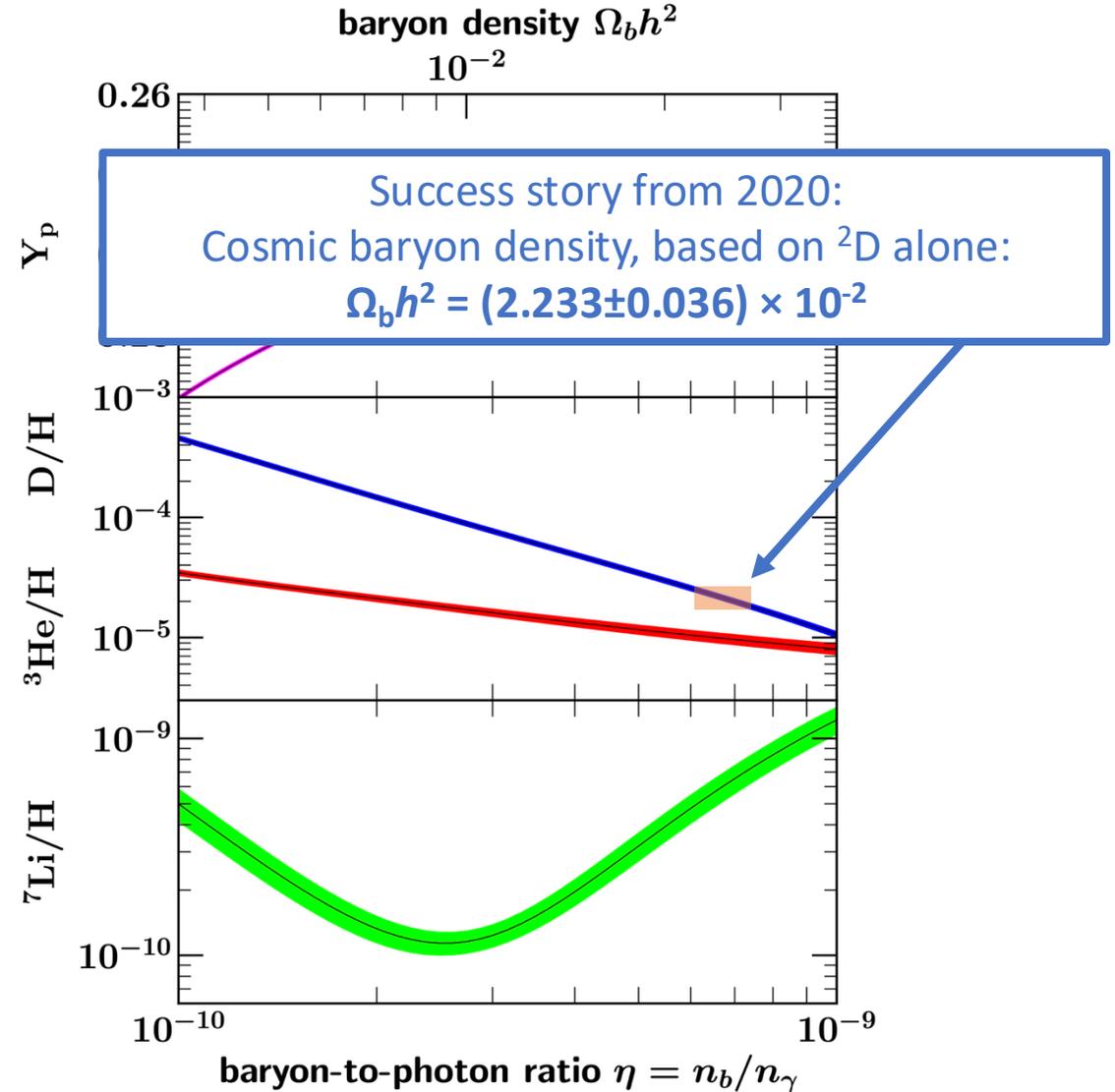
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**Model not precise                      Data precise**

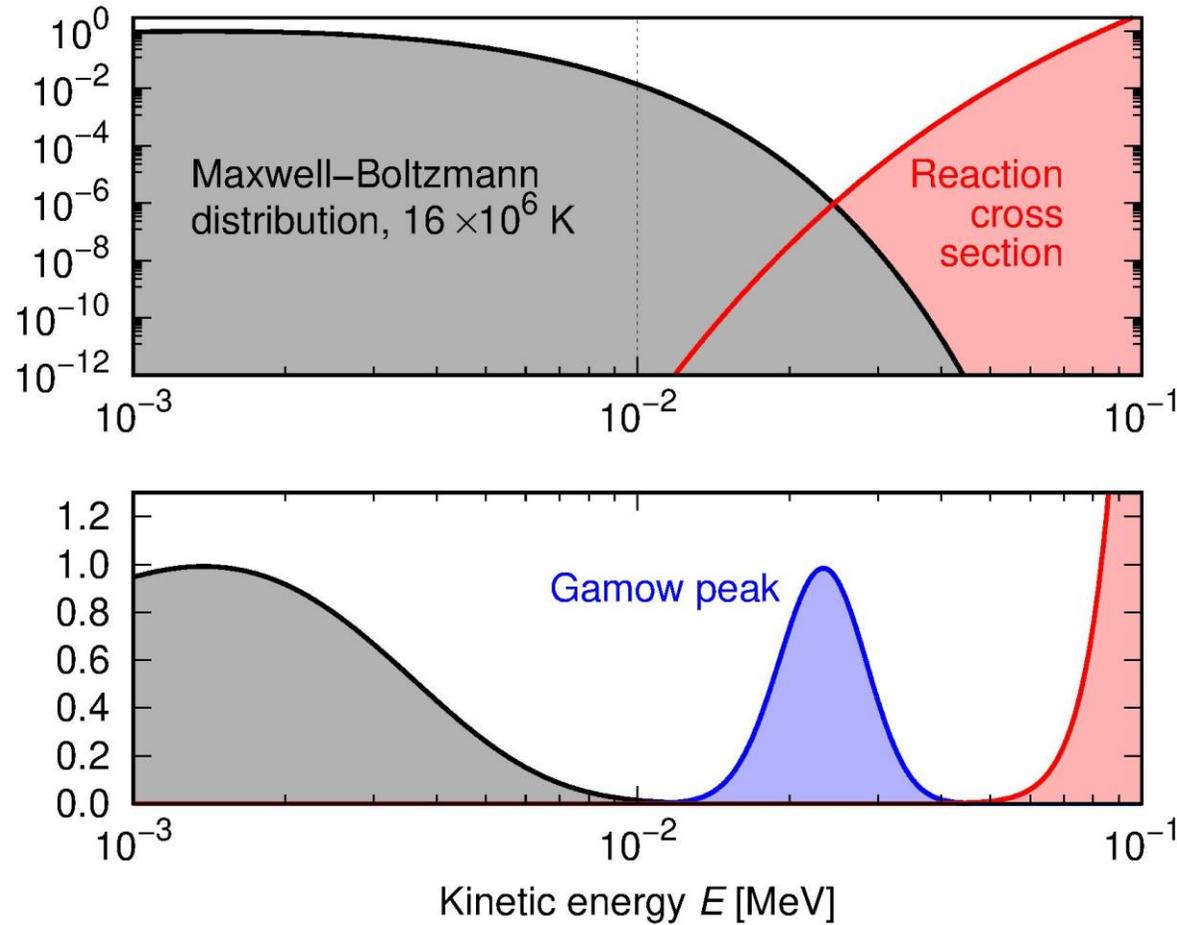
**We will remove nuclear physics uncertainties, and thus break the degeneracy between nuclear and solar/stellar physics**



# ....and why it will work



# LUNANOVA methodology

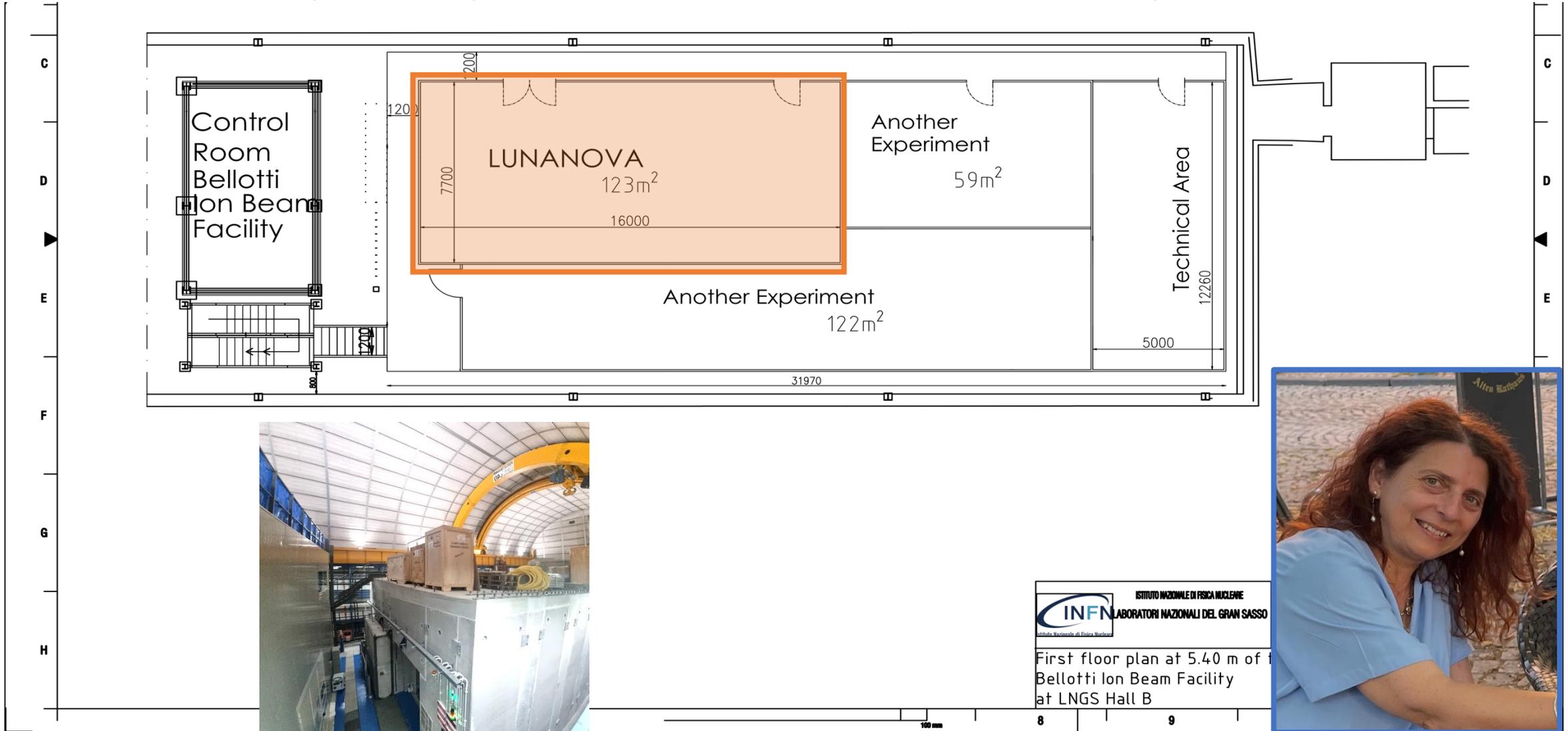


Stellar cores are cold  
 Sensitive, underground experiments needed –  
**LUNANOVA**

Thermonuclear reaction rate

$$\propto \int_0^{\infty} \exp\left[-\frac{E}{k_B T}\right] S(E) \exp\left[-\frac{b}{\sqrt{E}}\right] dE$$

# LUNANOVA accelerator, to be installed at LNGS Gran Sasso: WP2 LUNANOVA-procure (years 1-2) and WP3 LUNANOVA-under (years 3-6)



# WP4 LUNANOVA-over: Experiments at laboratories other than LUNANOVA



Felsenkeller, HZDR DE



ELBE, HZDR DE



Bellotti IBF, INFN IT



CRYRING, GSI/FAIR DE



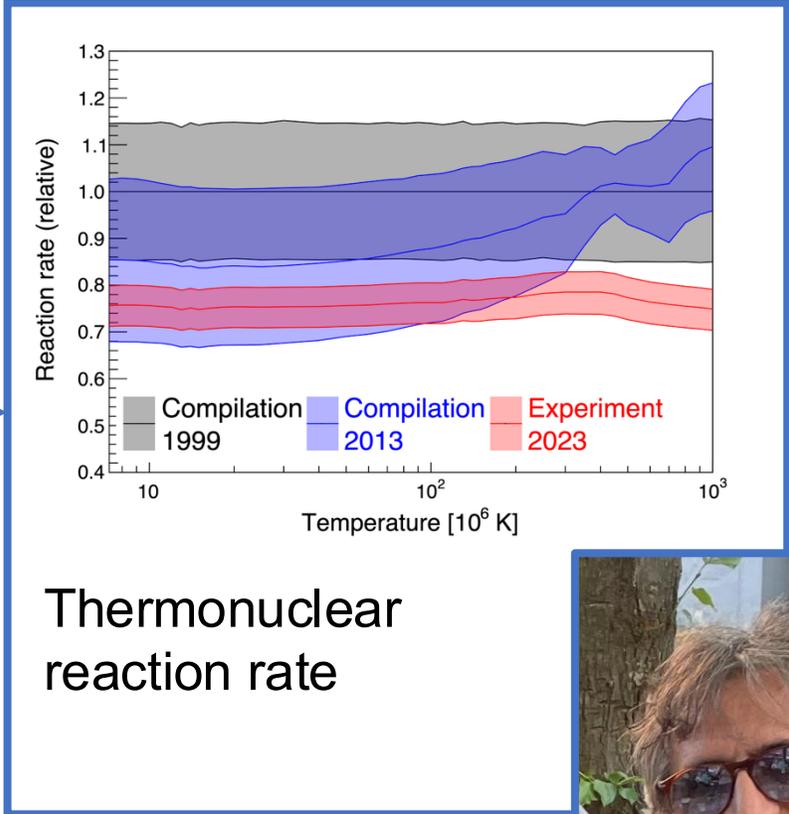
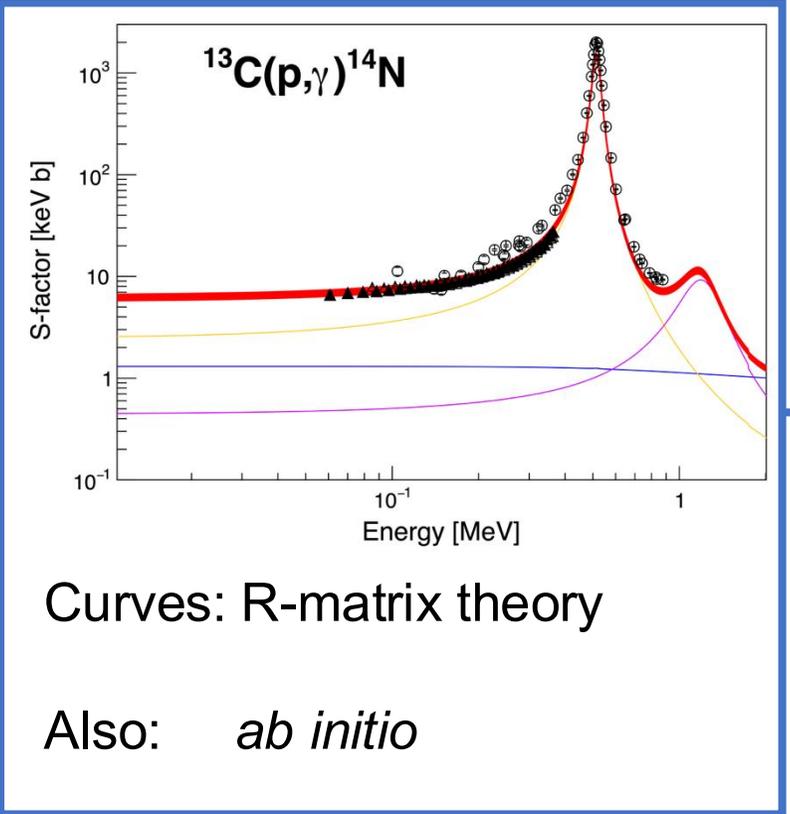
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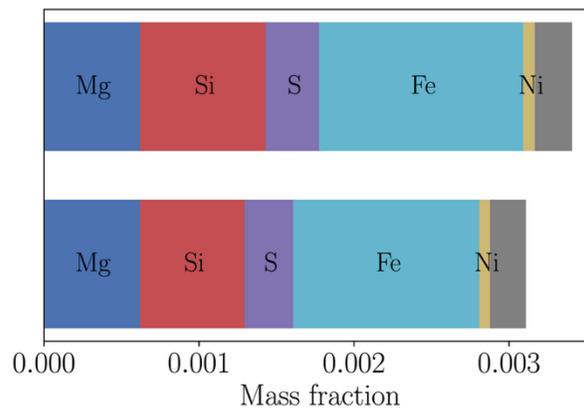
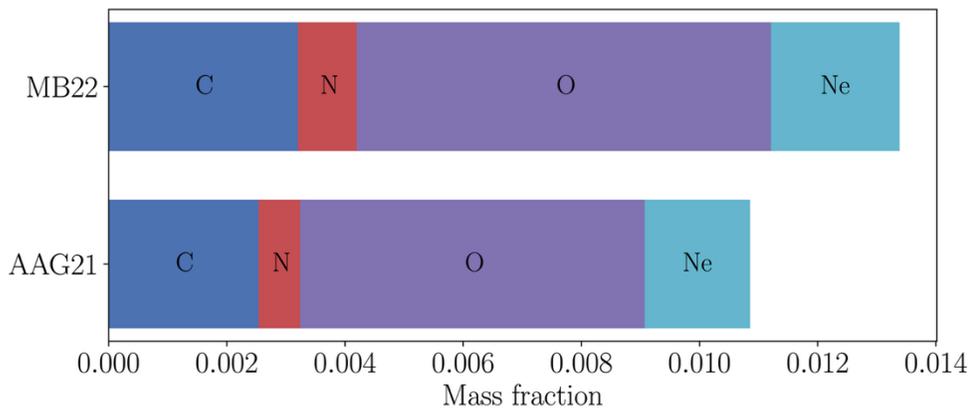
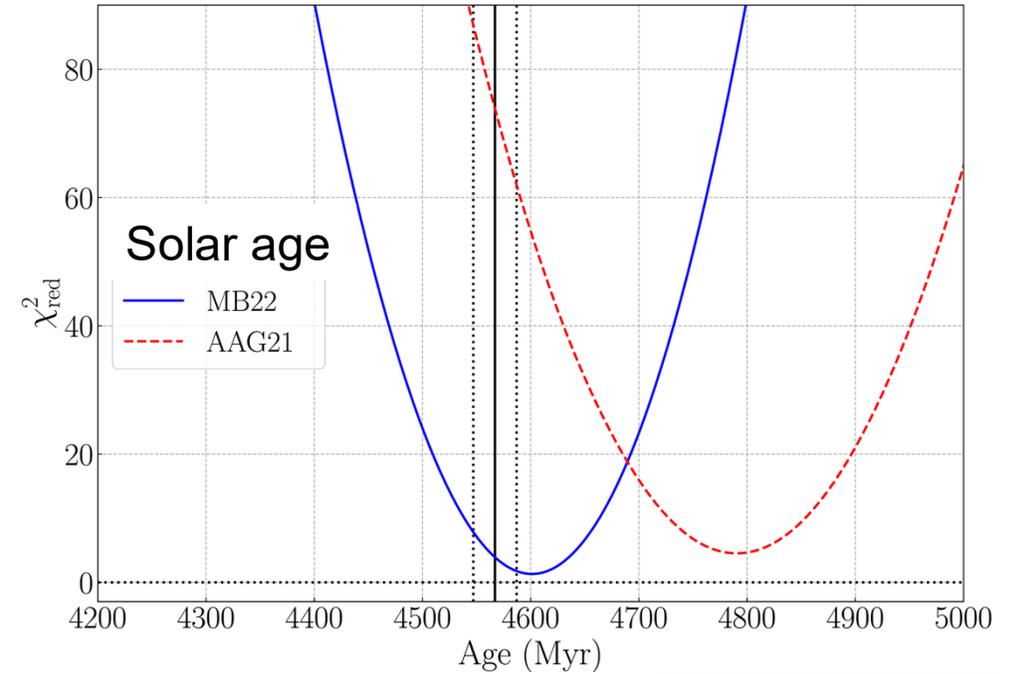
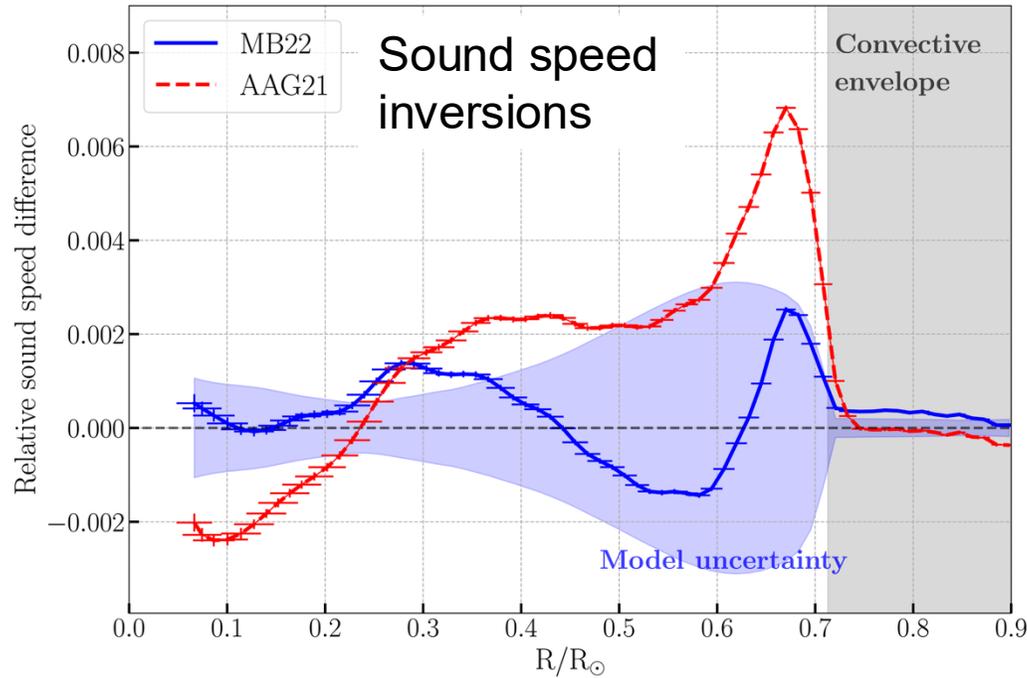
Daniel / HZDR

# WP5 LUNANOVA-rates: R-matrix and thermonuclear reaction rate

Experimental data from underground & overground, WP3 & WP4



# WP6 LUNANOVA-model: New solar model

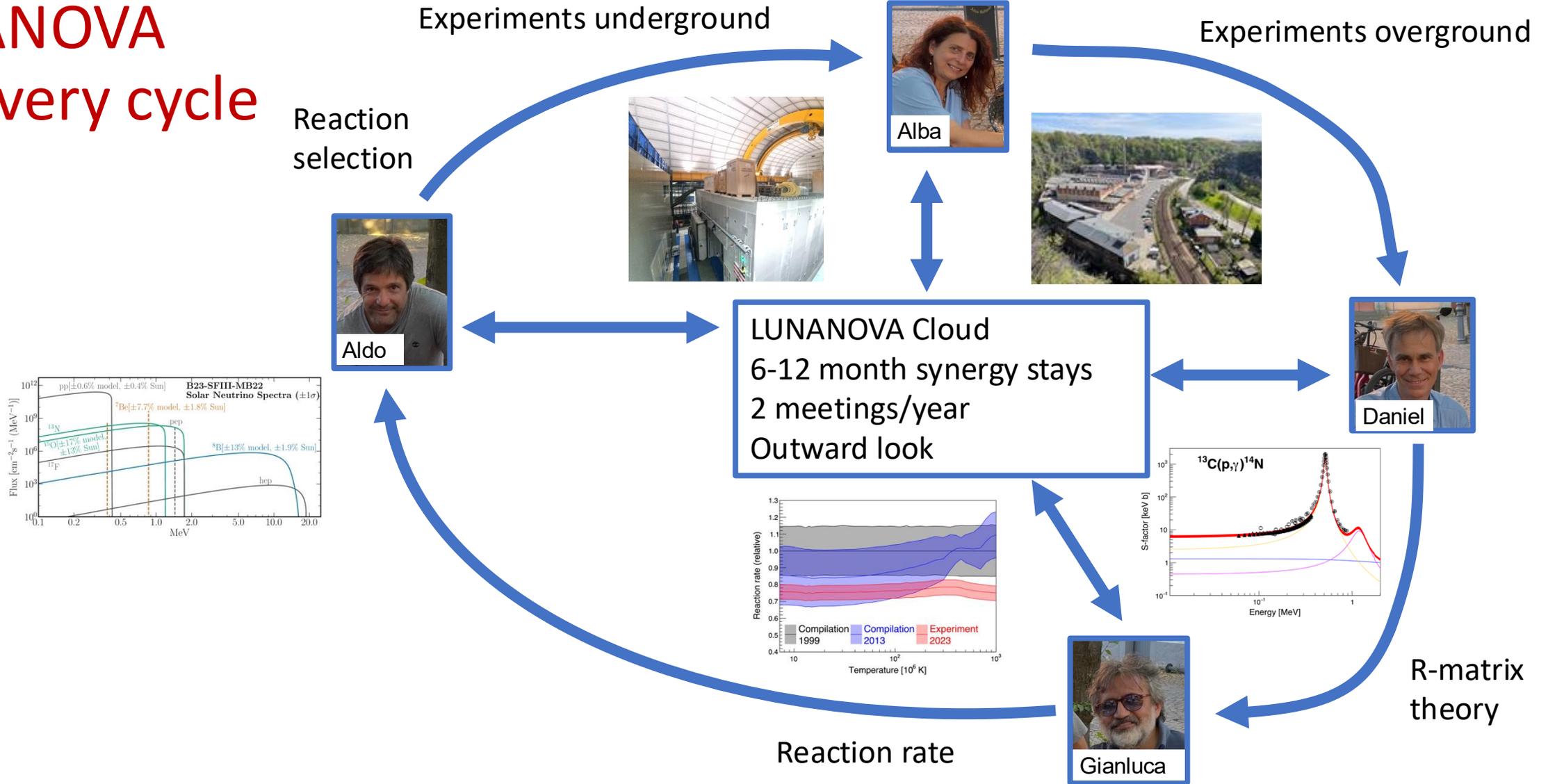


Solar elemental abundances



Aldo / CSIC

# LUNANOVA discovery cycle



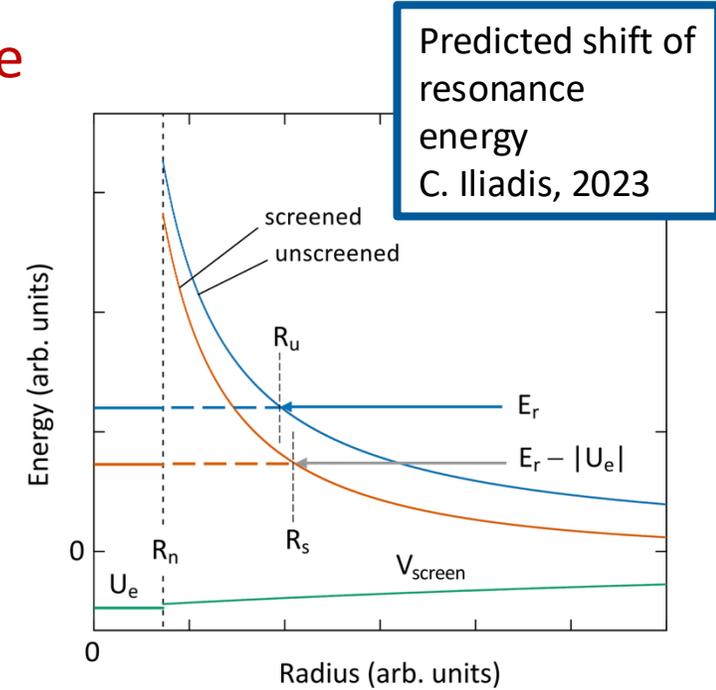
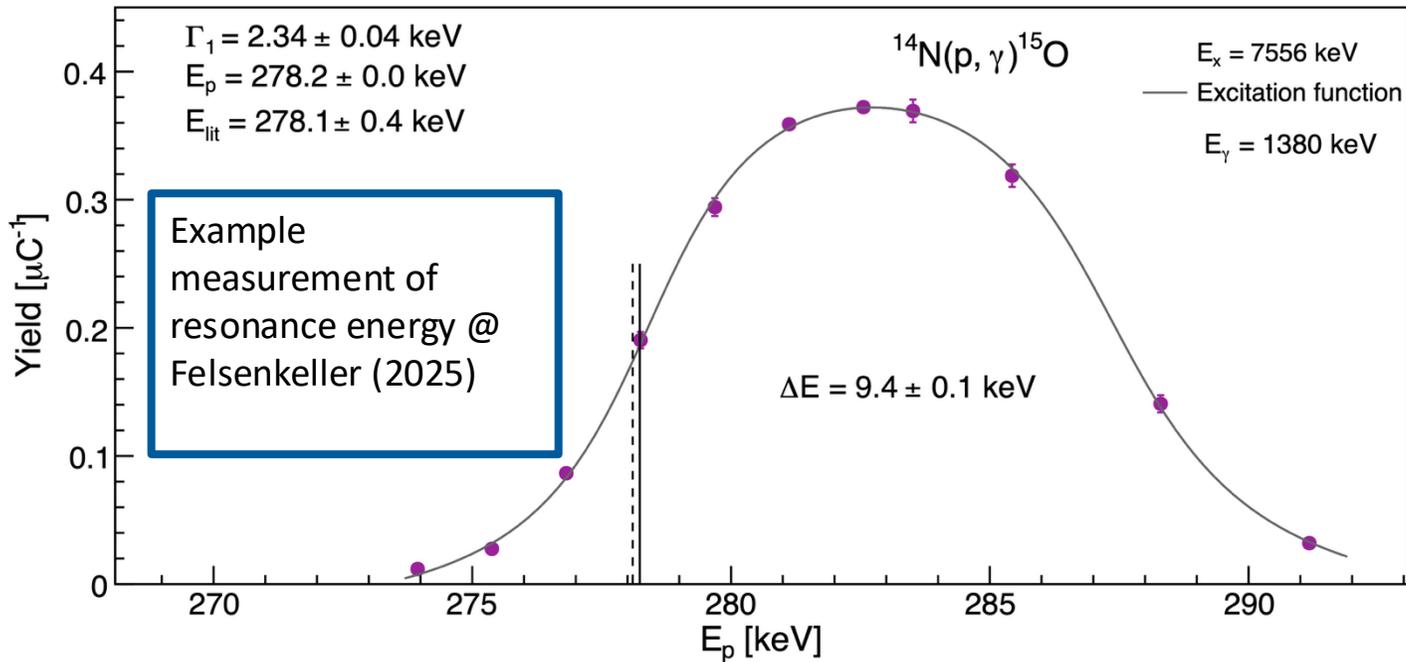
# LUNANOVA, possible experiments at CRYRING, with internal source

Experiments using highly charged stored beams, example:

$^{14,15}\text{N}+\text{p}$  reactions with a stripped N beam on the  $\text{H}_2$  target

Science question: Electron screening of the nuclear charge

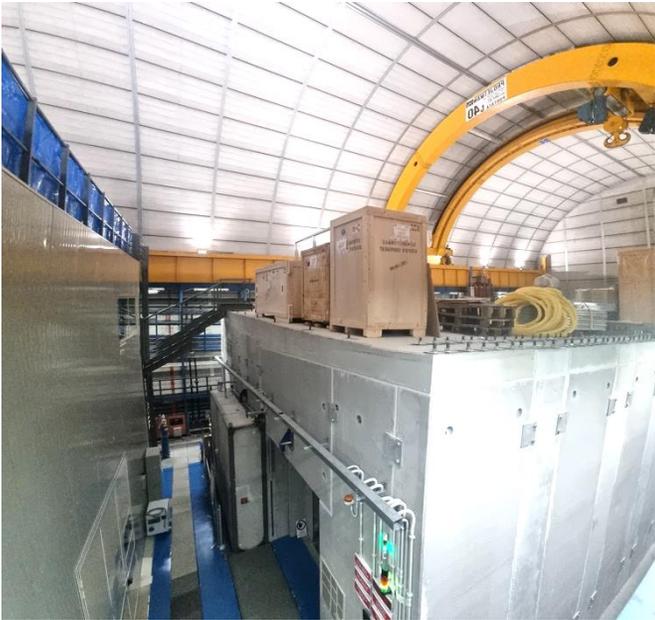
This program is unaffected by the recent fire in the UNILAC hall.



# LUNANOVA Outcome - and Impacts

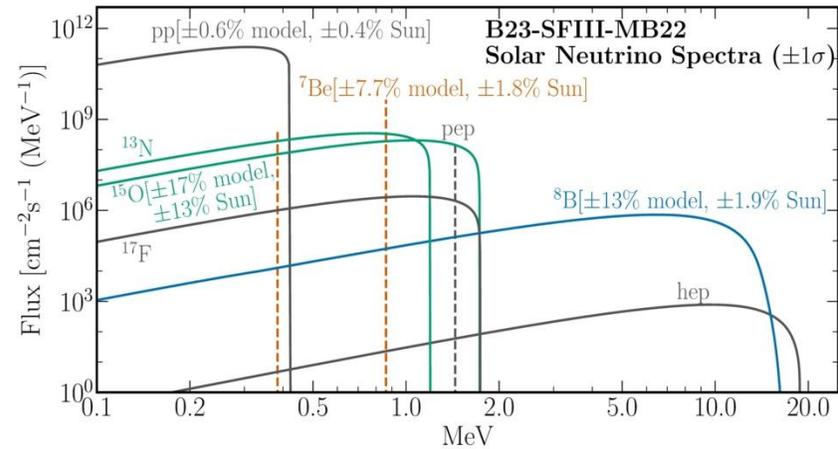
## Outcome

- ◆ LUNANOVA will remove the nuclear physics uncertainties from the solar model, and from all stellar models.



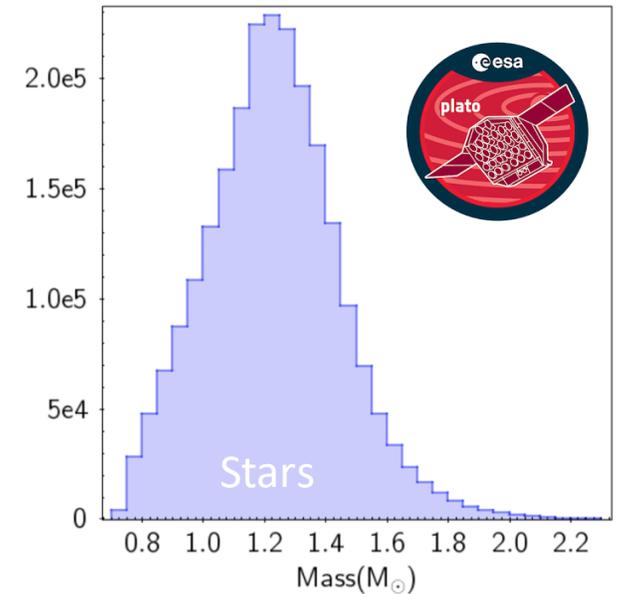
## Impact on the Sun

- ◆ The sun becomes a reference star.



## Impact on $10^5$ stars

- ◆ For the first time, viable models of solar-like stars.



# The End is Where We Start From