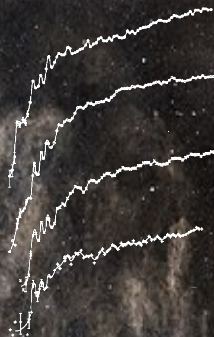
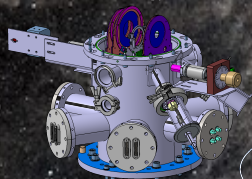
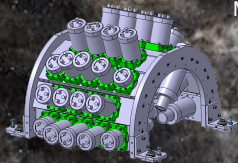


# Carbon fusion cross sections with the STELLar Laboratory

Marcel Heine for the  STELLA Collaboration

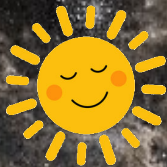
IPHC/CNRS Strasbourg

December 9, 2025



## What is a star?

# What is a star?

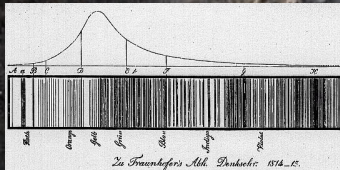


sun: something big and bright

# What is a star?



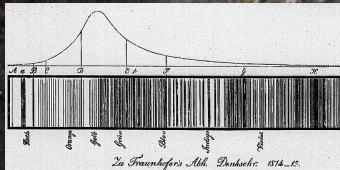




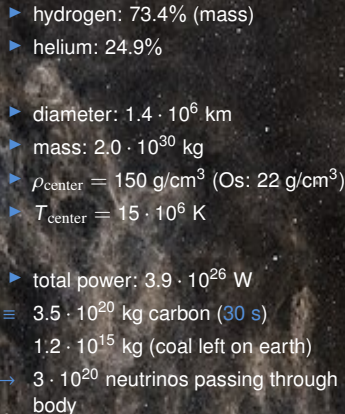
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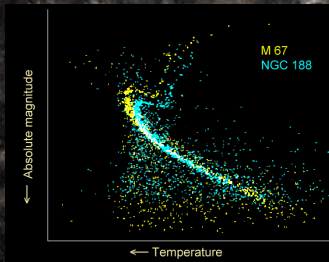


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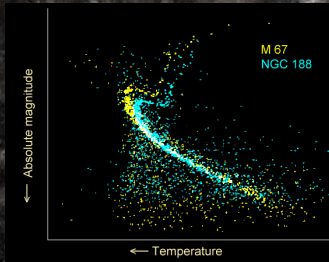


" " "

- 
- ▶ hydrogen: 73.4% (mass)
  - ▶ helium: 24.9%
  - ▶ diameter:  $1.4 \cdot 10^6$  km
  - ▶ mass:  $2.0 \cdot 10^{30}$  kg
  - ▶  $\rho_{\text{center}} = 150 \text{ g/cm}^3$  (Os:  $22 \text{ g/cm}^3$ )
  - ▶  $T_{\text{center}} = 15 \cdot 10^6 \text{ K}$
  - ▶ total power:  $3.9 \cdot 10^{26} \text{ W}$
  - ≡  $3.5 \cdot 10^{20} \text{ kg carbon (30 s)}$
  - $1.2 \cdot 10^{15} \text{ kg (coal left on earth)}$
  - $3 \cdot 10^{20} \text{ neutrinos passing through body}$



- ▶ counter gravitational pressure
- ▶ need to generate energy

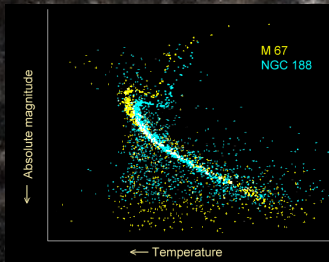


- ▶ Hertzprung-Russel diagram:
  - Temperature: color
  - Absolute magnitude: brightness
- ▶ open clusters

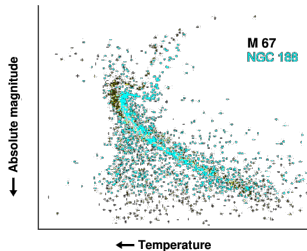


## What is happening in a star?

- ▶ counter gravitational pressure
- ▶ need to generate energy

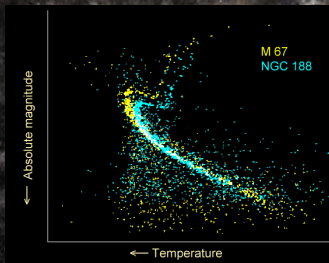


- = Hertzsprung-Russel diagram:
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  - Absolute magnitude: brightness
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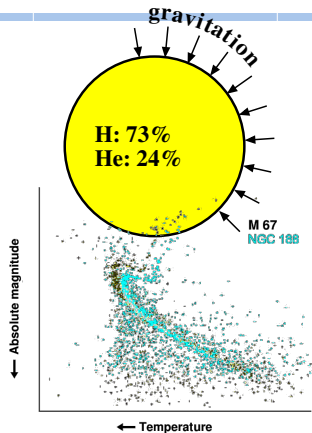


## What is happening in a star?

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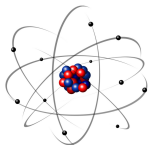
- = Hertzsprung-Russell diagram:
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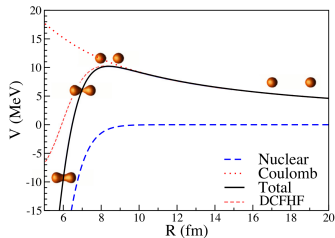


Stars are gigantic, yet utterly inefficient fusion machines

## What is nuclear fusion?



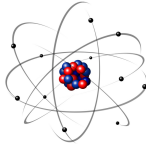
- protons repell each other: barrier



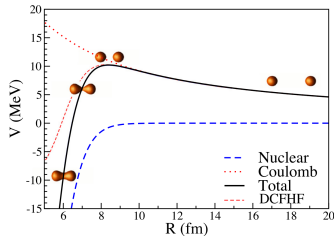
C. Simenel & A.S. Umar, *Prog Part Nuc Phys* **103** (2018), 19–66

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## What is nuclear fusion?

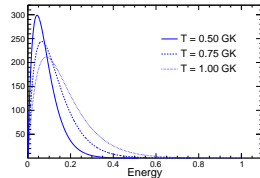


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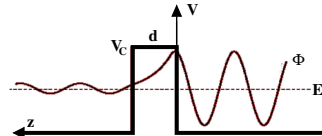
C. Simenel & A.S. Umar, Prog Part Nuc Phys **103** (2018), 19–66

- ▶ temperature distribution in stars:



= Maxwell-Boltzmann distribution

- ▶ barrier in quantum mechanics:



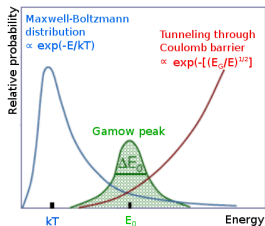
- ▶ tunneling: exponential drop with width



Stars are gigantic, yet utterly inefficient fusion machines

## Gamow peak:

- ▶ temperature distribution
- ▶ tunneling probability

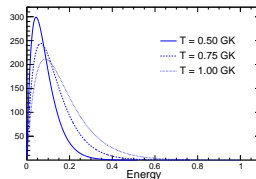


= energy, where reactions take place

→ extremely low cross section

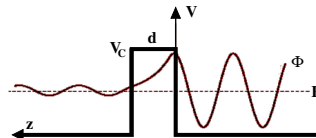
- ▶ background reduction
- ▶ robust setup, data acquisition

- ▶ temperature distribution in stars:



= Maxwell-Boltzmann distribution

- ▶ barrier in quantum mechanics:

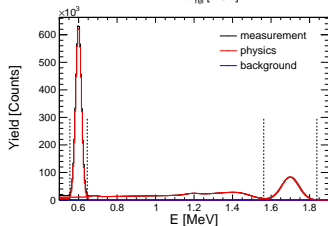
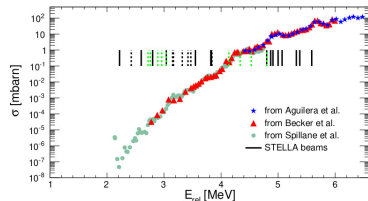


- ▶ tunneling: exponential drop with width

Stars are gigantic, yet utterly inefficient fusion machines

## Typical fusion excitation function into low-count acquisition runs

sub barrier  $^{12}\text{C}+^{12}\text{C}$ :

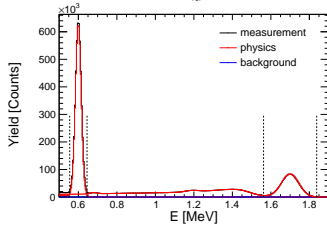
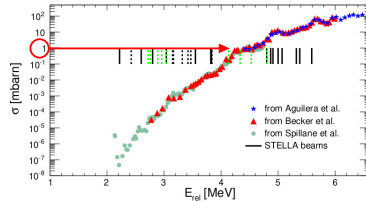


Stars are gigantic, yet utterly inefficient fusion machines

## Typical fusion excitation function into low-count acquisition runs

sub barrier  $^{12}\text{C}+^{12}\text{C}$ :

► **physics**: 0.6 MeV, 1.7 MeV  
well defined peaks,  $\pm 3\sigma$  gates

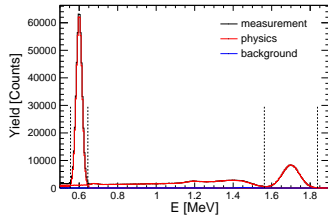
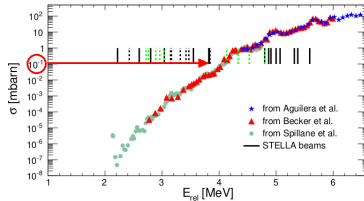


Stars are gigantic, yet utterly inefficient fusion machines

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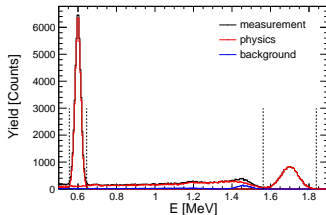
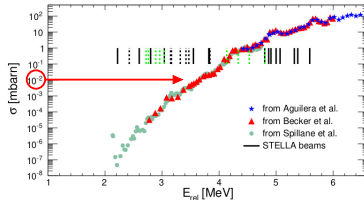
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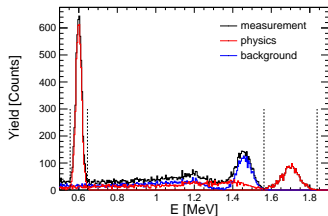
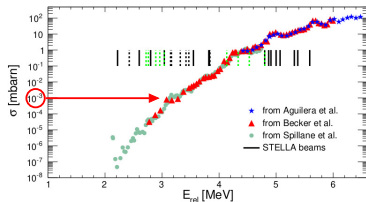
- ▶ **physics**: 0.6 MeV, 1.7 MeV  
well defined peaks,  $\pm 3\sigma$  gates
- ▶ **background**: 1.46 MeV  
background model: linear, exponential



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## Typical fusion excitation function into low-count acquisition runs

sub barrier  $^{12}\text{C}+^{12}\text{C}$ :

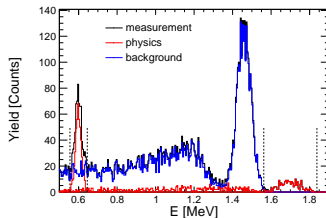
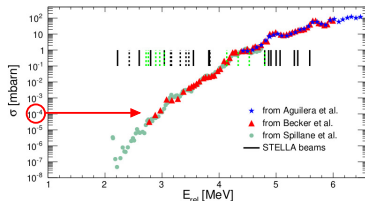


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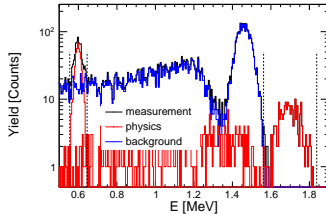
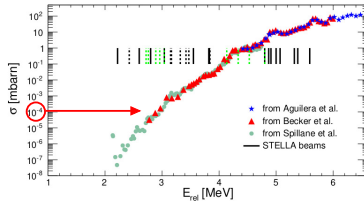


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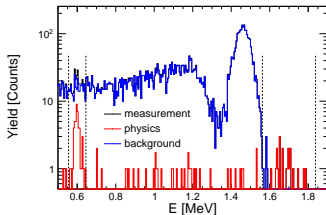
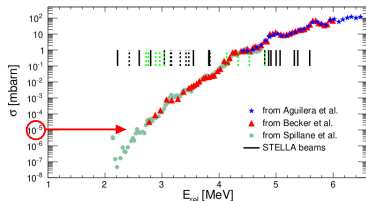


- ▶ **physics**: 0.6 MeV, 1.7 MeV  
well defined peaks,  $\pm 3\sigma$  gates
- ▶ **background**: 1.46 MeV  
background model: linear, exponential
- ▶ statistical uncertainty
- ▶ tails of background contributions

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sub barrier  $^{12}\text{C}+^{12}\text{C}$ :

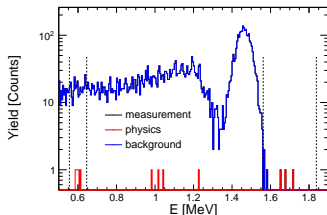
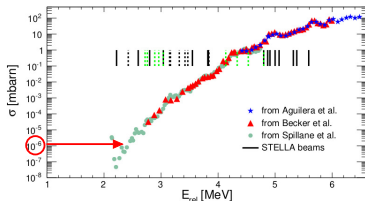


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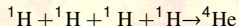
**sub nano barn cross sections:**

- ▶ few counts statistic
- ▶ background fluctuations

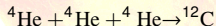


Measurement of particles and gammas

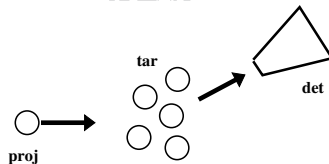
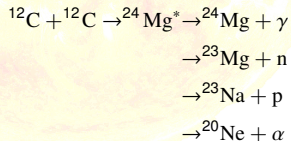
hydrogen burning:



helium burning:

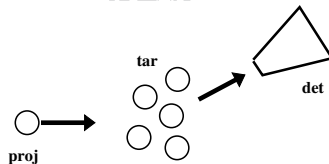
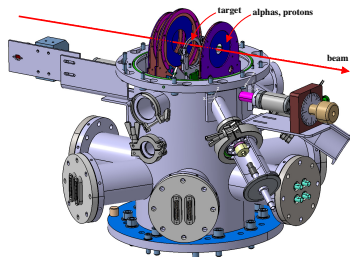
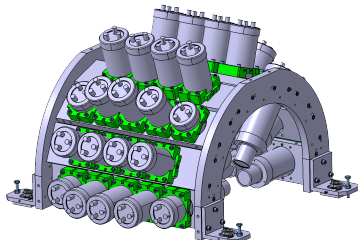


carbon burning:



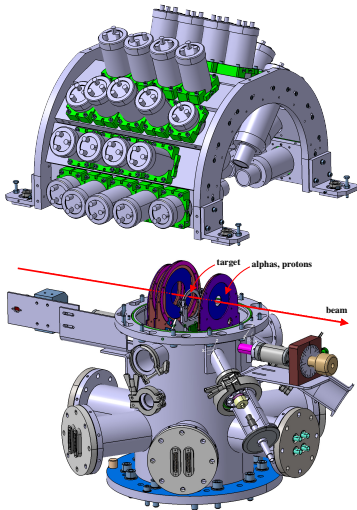
1. beam intensities of a few  $\mu\text{A}$
2. data taking for weeks
3.  $\gamma$ -particle coincidences, granularity
4. low counting statistics analysis

## Measurement of particles and gammas

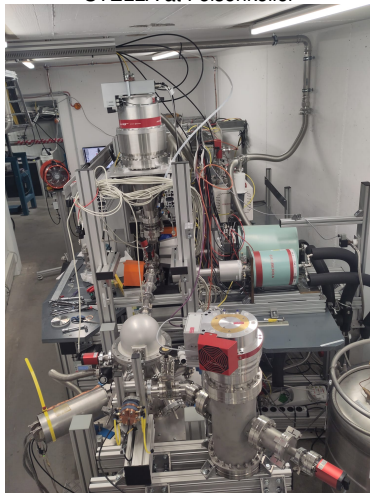


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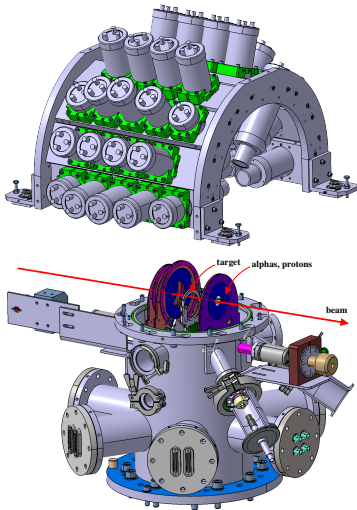
## Measurement of particles and gammas



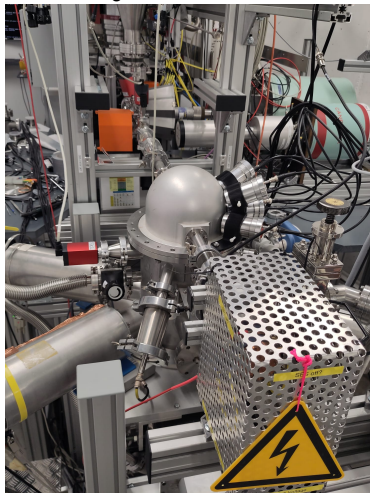
STELLA at Felsenkeller



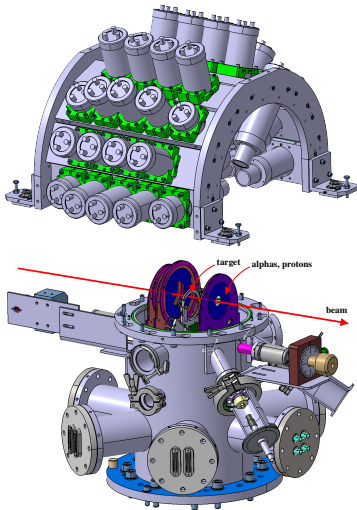
## Measurement of particles and gammas



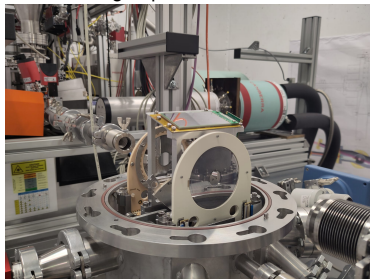
gamma detectors



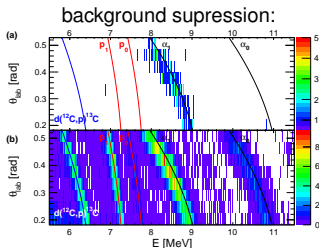
## Measurement of particles and gammas



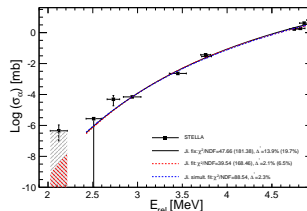
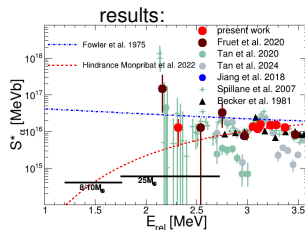
charged particle detectors



## Measurement of particles and gammas

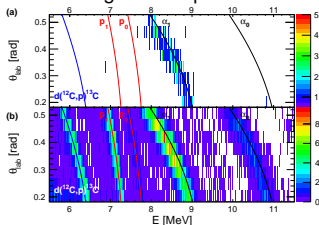


- ▶ improvement of experimental error
- ▶ separation between trends
- ▶ core size varies by  $\sim 30\%$
- ▶ carbon burning phase varies  $\sim 10\%$
- ▶ element abundances vary by  $\sim 30\%$



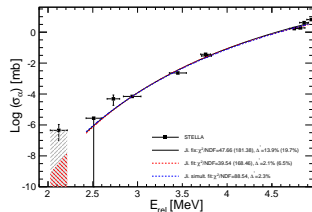
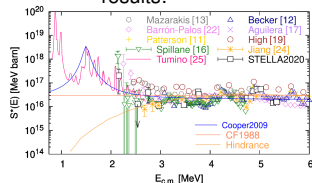
## Measurement of particles and gammas

## background suppression:

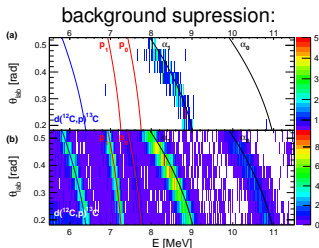


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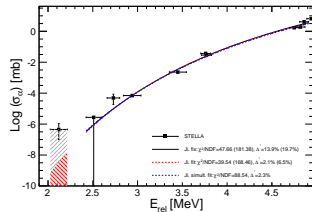
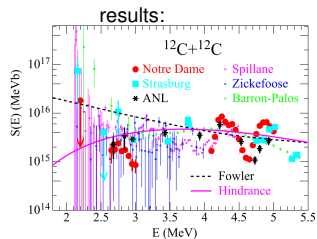
## results:



## Measurement of particles and gammas

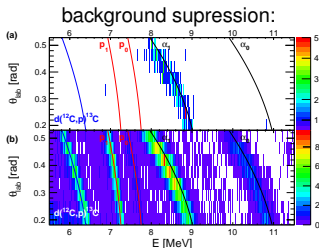


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### Measurement of particles and gammas



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