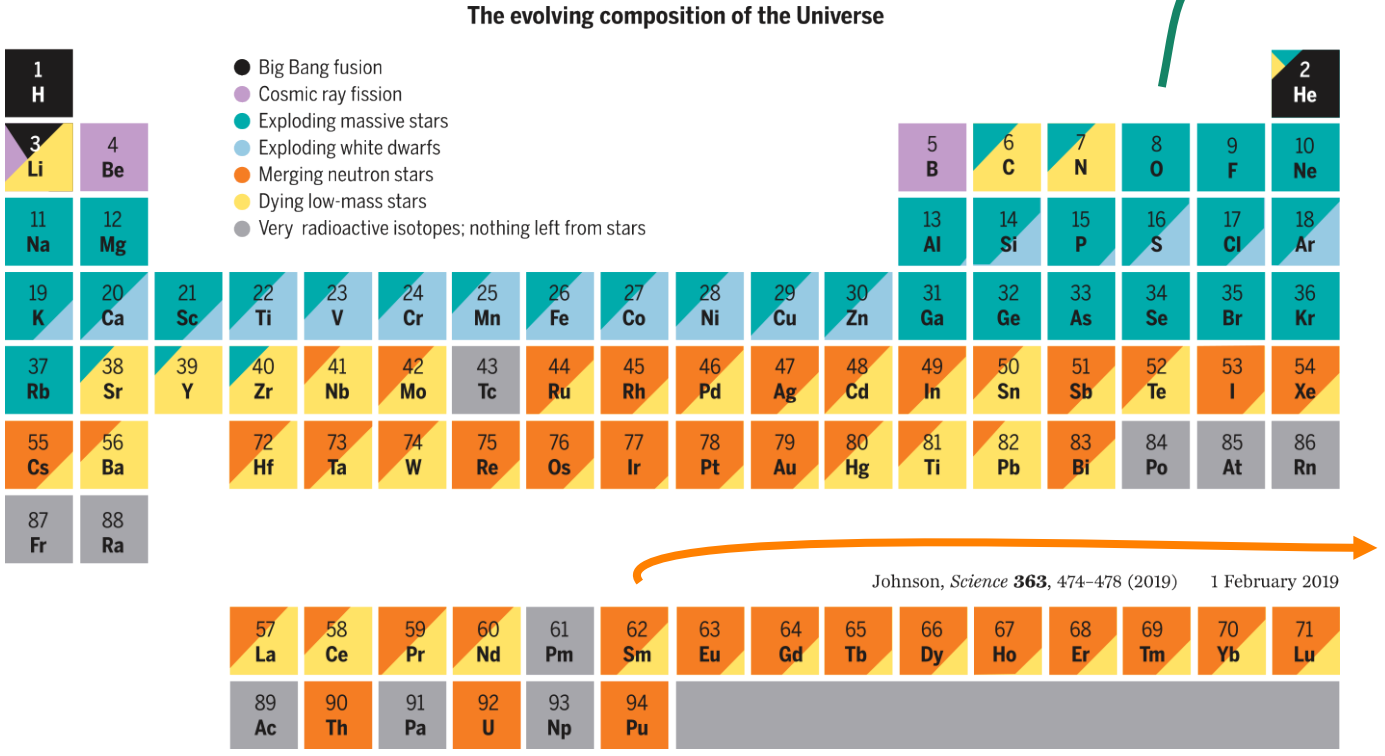
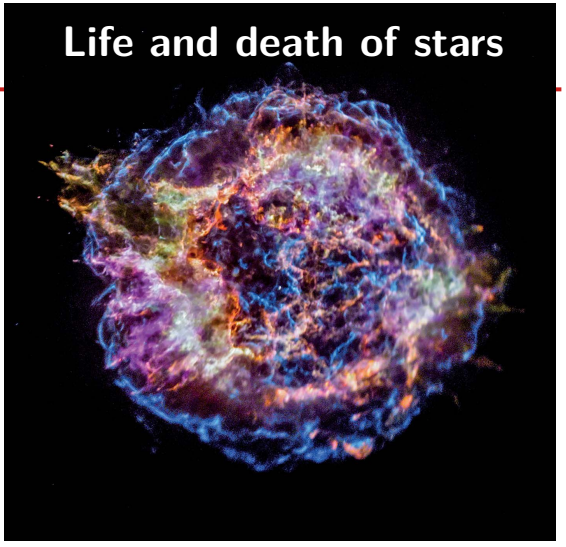
# Coincidence measurements of fusion reactions involving carbon and oxygen with the high-precision STELlar LAboratory

Aurélie Bonhomme
STELLA collaboration
IPHC Strasbourg, France

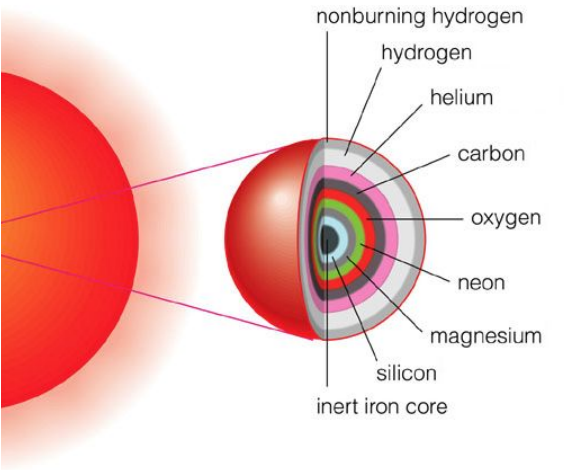
# Nuclear astrophysics

Where and how are the chemical elements produced?

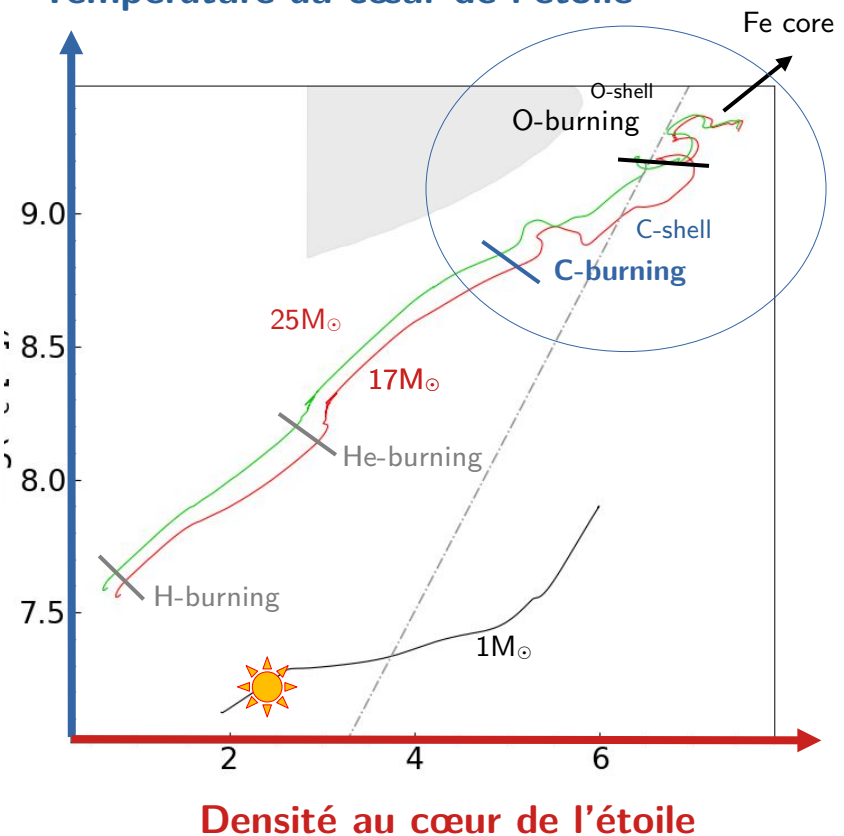



# Life and death of stars



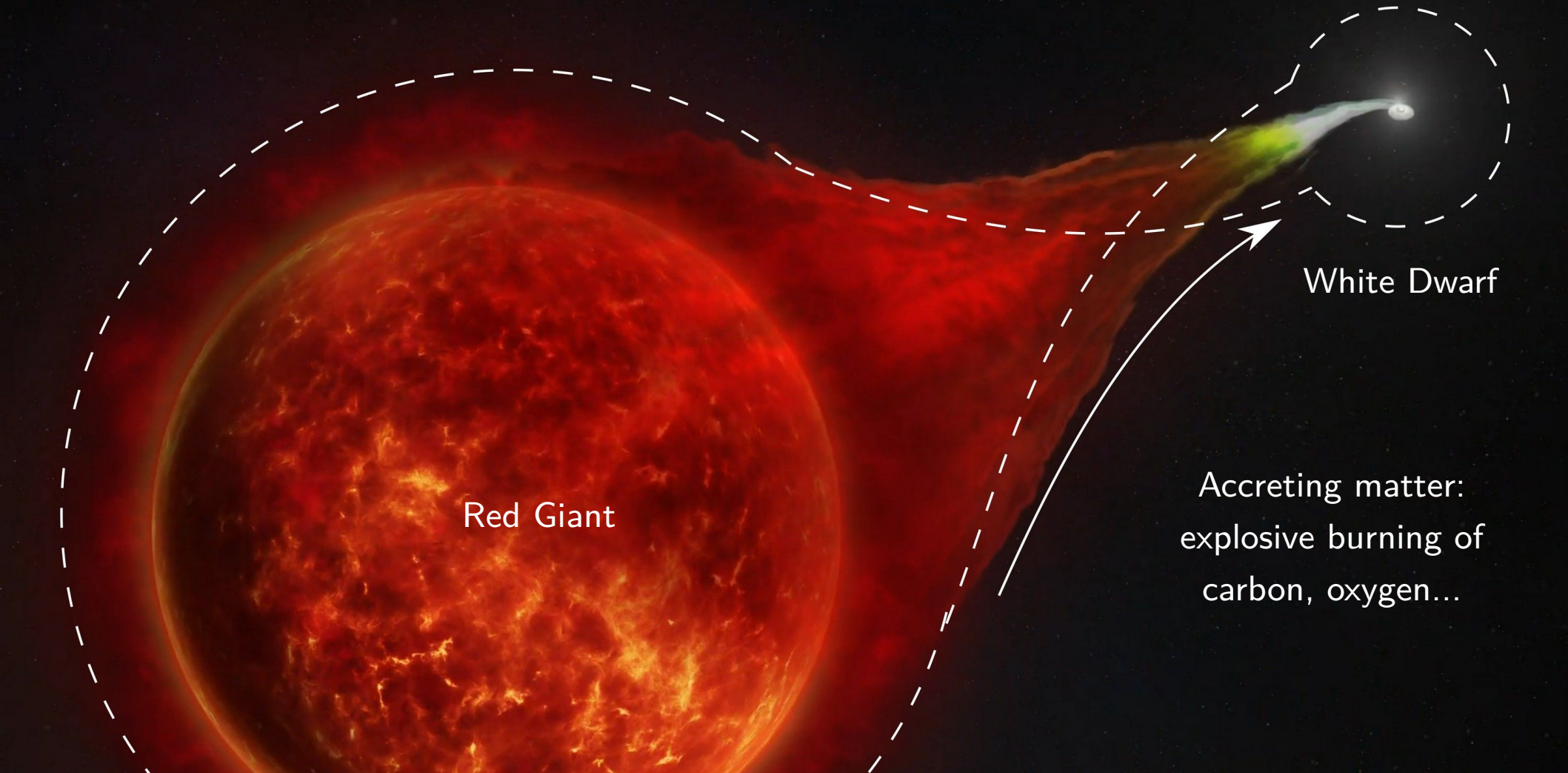

- Nuclear reactions vs. gravitational collapse
- "Onion-like" structure
- Only massive stars will explode as supernova

Nuclear rates impacts
structure, nucleosynthesis

$\rightarrow$ affects the chemical released
in the intergalactic medium during
the core-collapse supernova

# But also: explosive burning (classical Novae/SNIa)



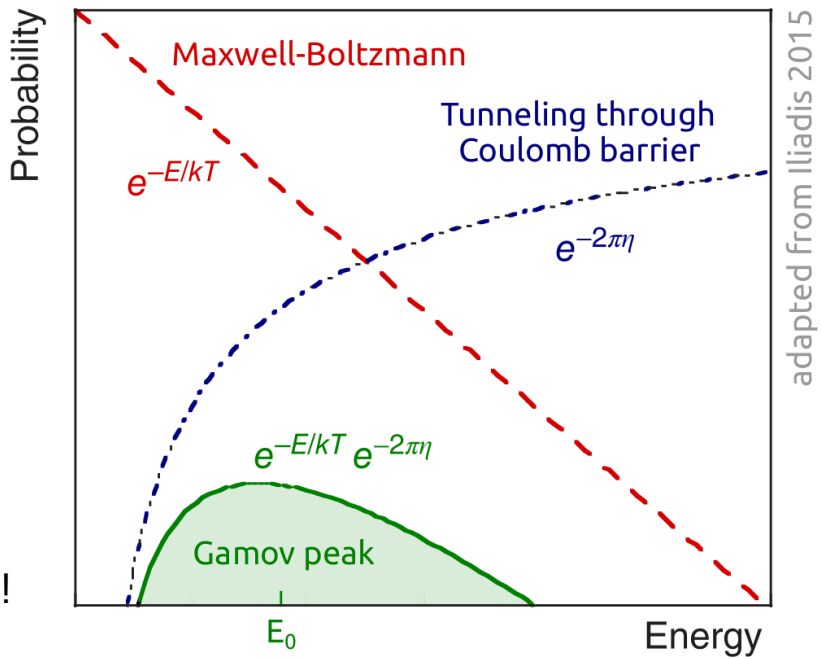
# Measurement in the lab? At which energies?

Nuclear reaction rates governs energy production, creation of elements $r = N_x N_y \langle \sigma\nu \rangle (1+\delta_{xy})$

**nuclear physics!**

Available energy = thermal energy (kT)
→ depends on astrophysical scenario!

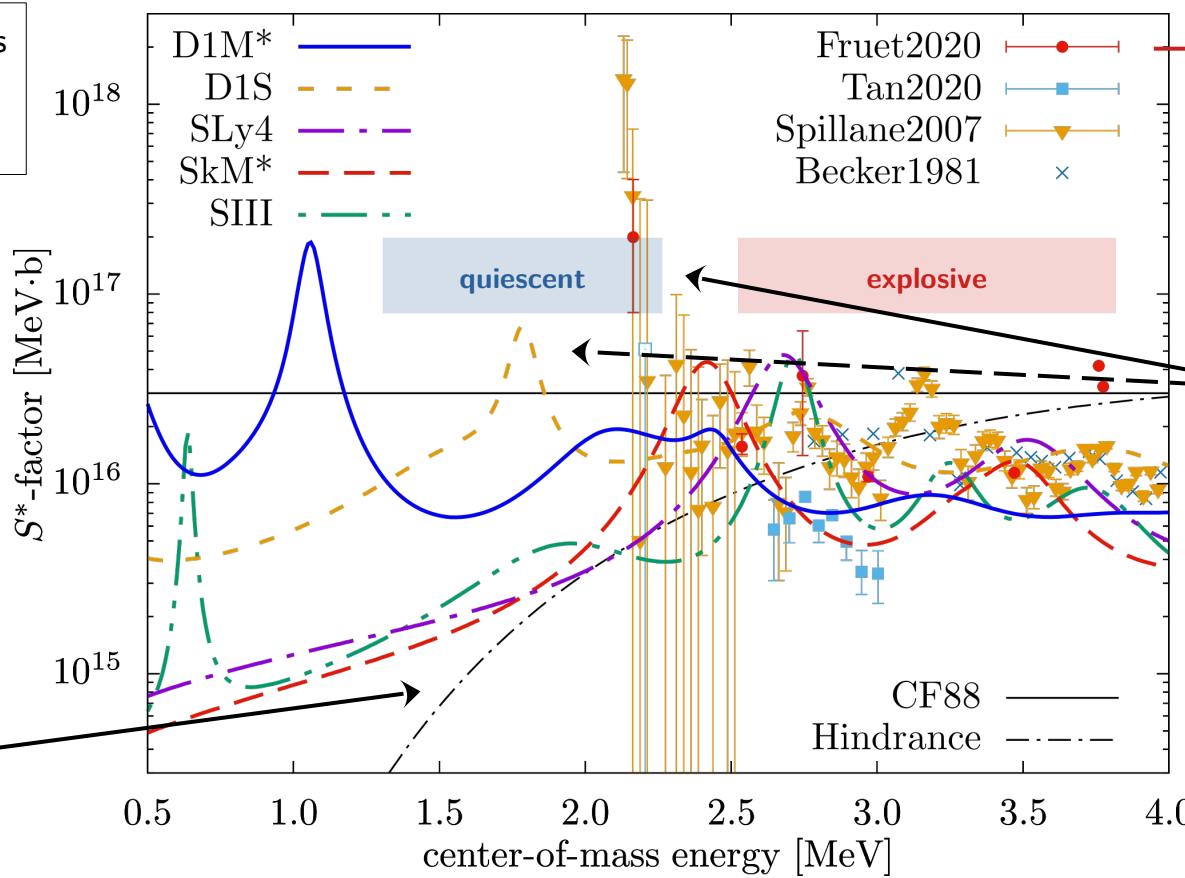
- Neutron captures: E ~ thermal energy (kT)
- **Nuclear reactions between charged particles:**
  thermal energy (kT) vs. Coulomb barrier: TUNNELLING
  → Relevant energy = Gamow windows
  Ex: $T_{sun} \sim 15.10^6$K, kT~1keV $E_C$=500keV → $E_G$=5.9keV




1. Quiescent burning (fusion in stars) → σ ~ (pbarn-nbarn)
2. Explosive burning → higher σ but sometimes unstable species!

# The challenging $^{12}C+^{12}C$ case

S-factor: 'removes' effects of Coulomb barrier:
$\mathbf{S} = E.\sigma(E).\exp(2\pi\eta)$




**STELLA 2020!**

**Presence of resonances?**

**Presence of fusion hindrance?**

Taniguchi+Kimura
Phys. Lett. B **849** (2024)

# Direct measurement principle

$^{12}C + ^{12}C \rightarrow ^{23}Na^* + p$, $^{23}Na^* \rightarrow ^{23}Na + \gamma$

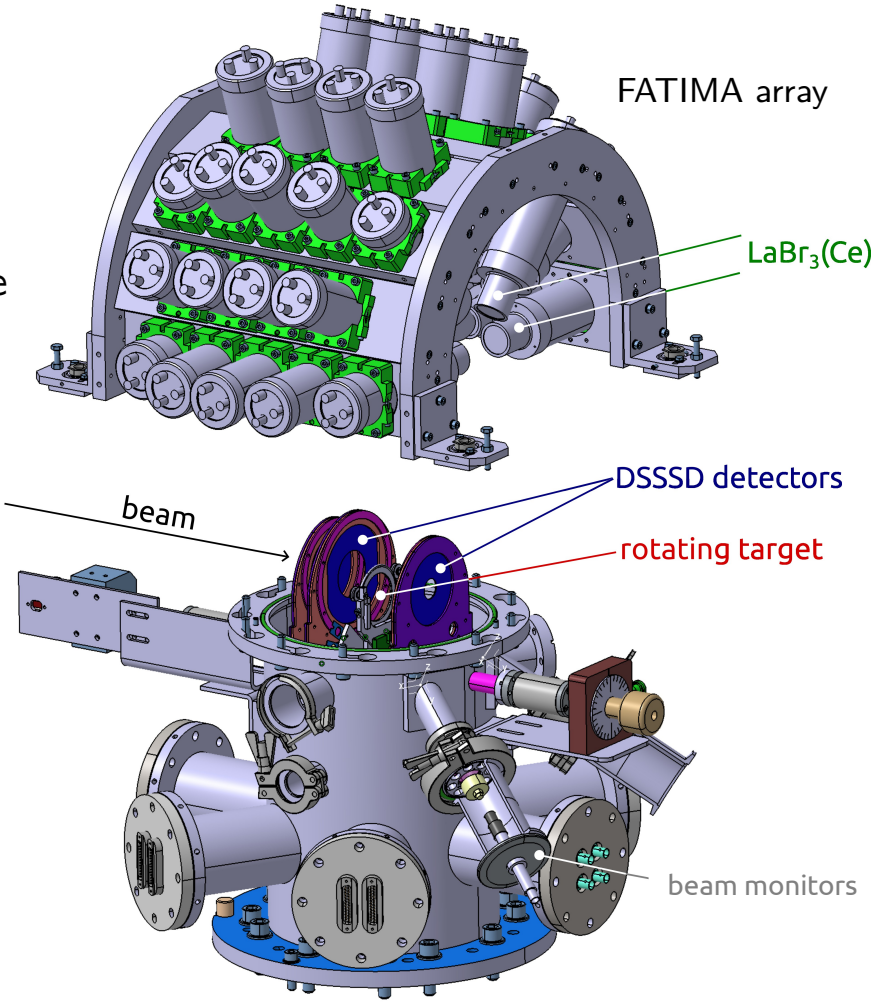
$^{12}C + ^{12}C \rightarrow ^{20}Ne^* + \alpha$, $^{20}Ne^* \rightarrow ^{20}Ne + \gamma$

**Direct measurements:**

- Charged particles (p/α)
- De-excitation gamma-rays
- Coincidence measurement

→ **STELLA setup**

Heine *et al.* NIM A **903** (2018)



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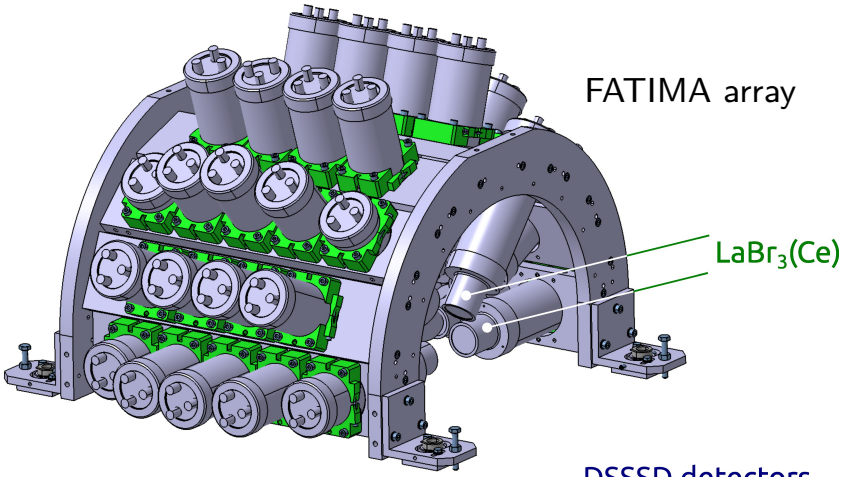
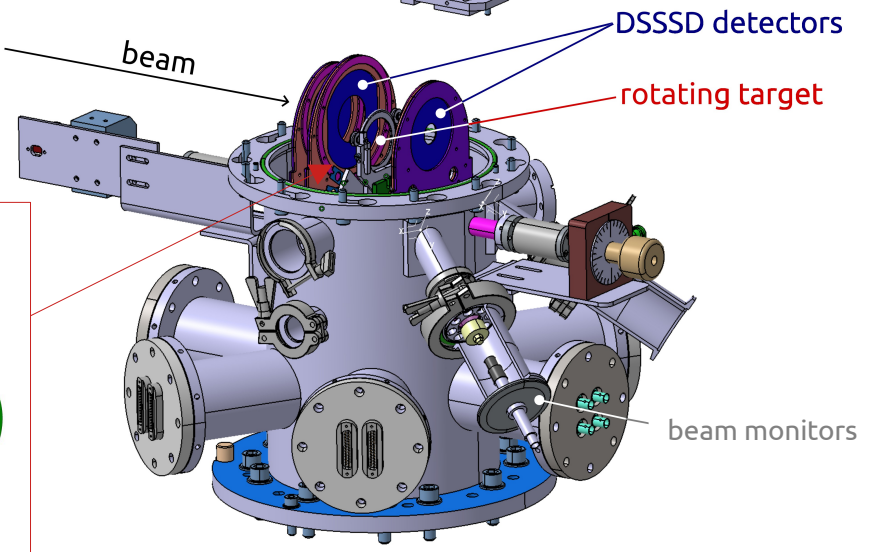



very low cross sections (sub-nb!)

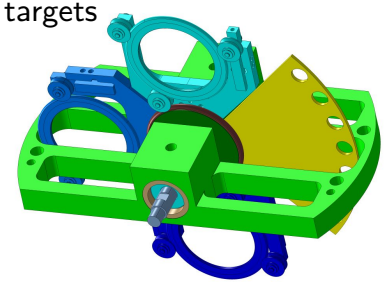
→ 4MV @**Andromède** (ECR source)

→ intensities **up to 3puA**

ANDROMEDE

→ **weeks of measurements!**

Self supporting rotating targets



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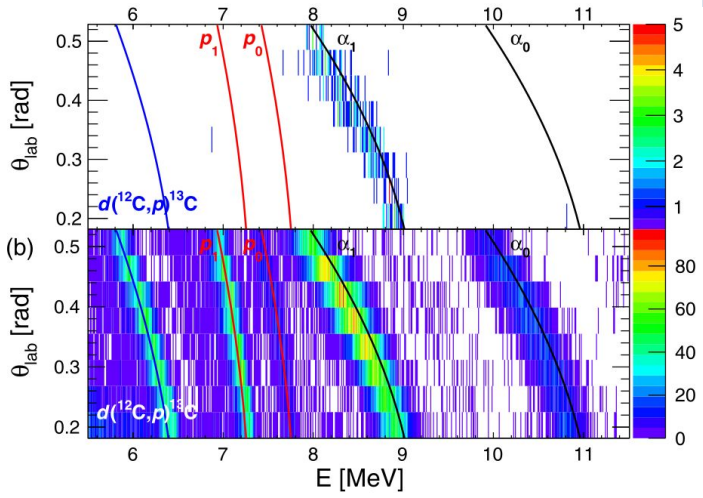



→ **STELLA setup**

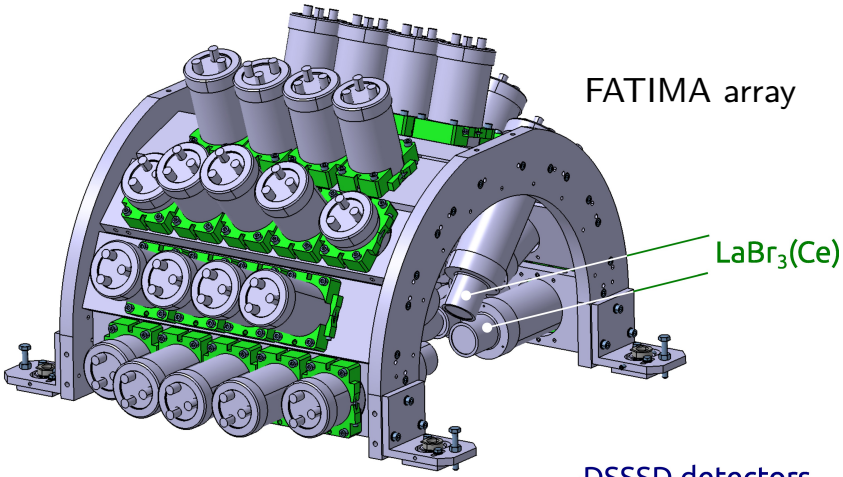
Heine *et al.* NIM A **903** (2018)

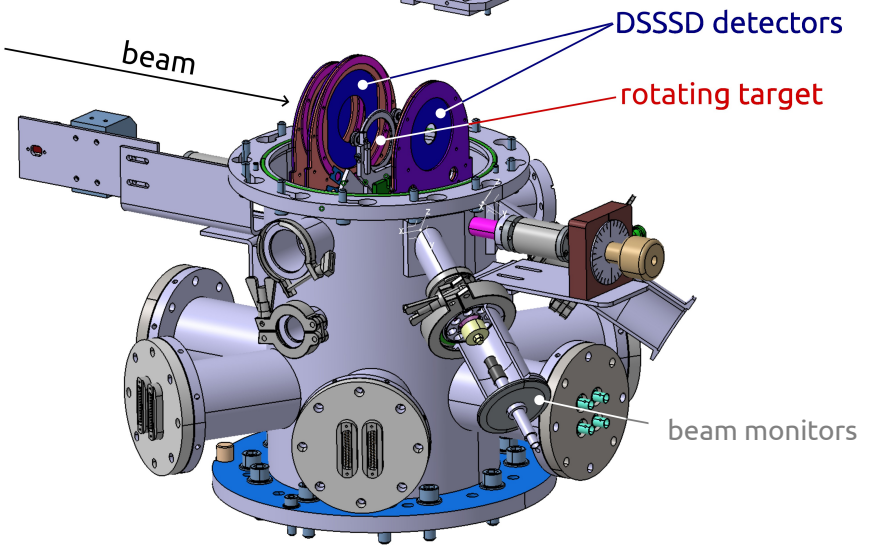
✓ns-precision timing

✓excellent background suppression

✓p/α discrimination

Fruet *et al.* PRL **124** (2020)



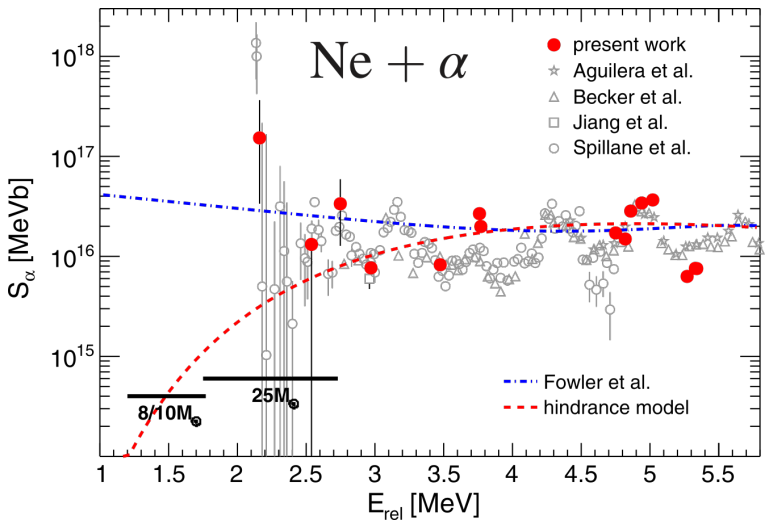



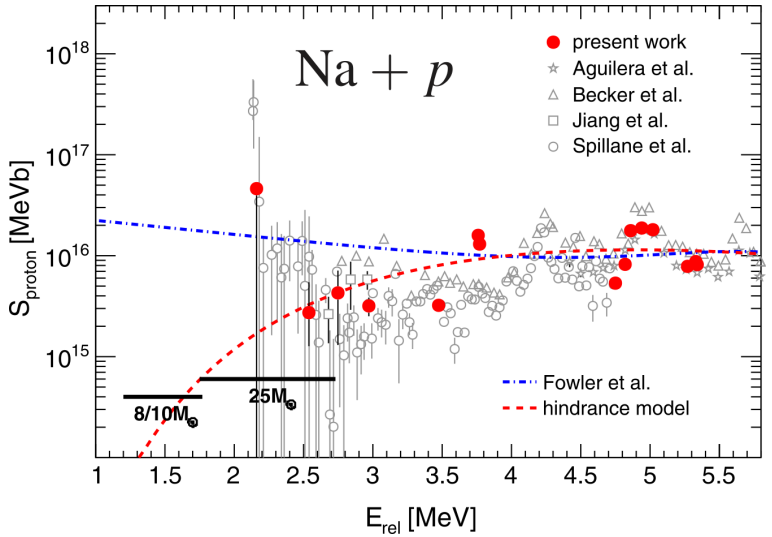
# STELLA measurements of $^{12}C+^{12}C$

- Provides reliable excitation functions over 8 orders of magnitude
- Explore different regimes: hindrance regime, Gamov windows
- At the lowest energies: $\lesssim$ 100 pb cross-sections!
- Latest analysis: improved timing selection
- Input for sensitivity studies: hydrodynamics calculations (stellar evolution)

Fruet *et al.* PRL **124** (2020)

Nippert *et al.* in preparation (2024)



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Nippert *et al.* in preparation (2024)

A&A 660, A47 (2022)
https://doi.org/10.1051/0004-6361/202141858


Astronomy & Astrophysics

**A new $^{12}C + ^{12}C$ nuclear reaction rate: Impact on stellar evolution**

E. Monpribat[1], S. Martinet[2], S. Courtin[1,3], M. Heine[1], S. Ekström[2], D. G. Jenkins[3,4], A. Choplin[5], P. Adsley[6,7], D. Curien[1], M. Moukaddam[1], J. Nippert[1], S. Tsiatsiou[2], and G. Meynet[2]

Monpribat *et al.* A&A **660**, A47 (2022)

Dumont *et al.*, A&A **688**, A115 (2024)

Astronomy & Astrophysics

**Massive star evolution with a new $^{12}C + ^{12}C$ nuclear reaction rate**

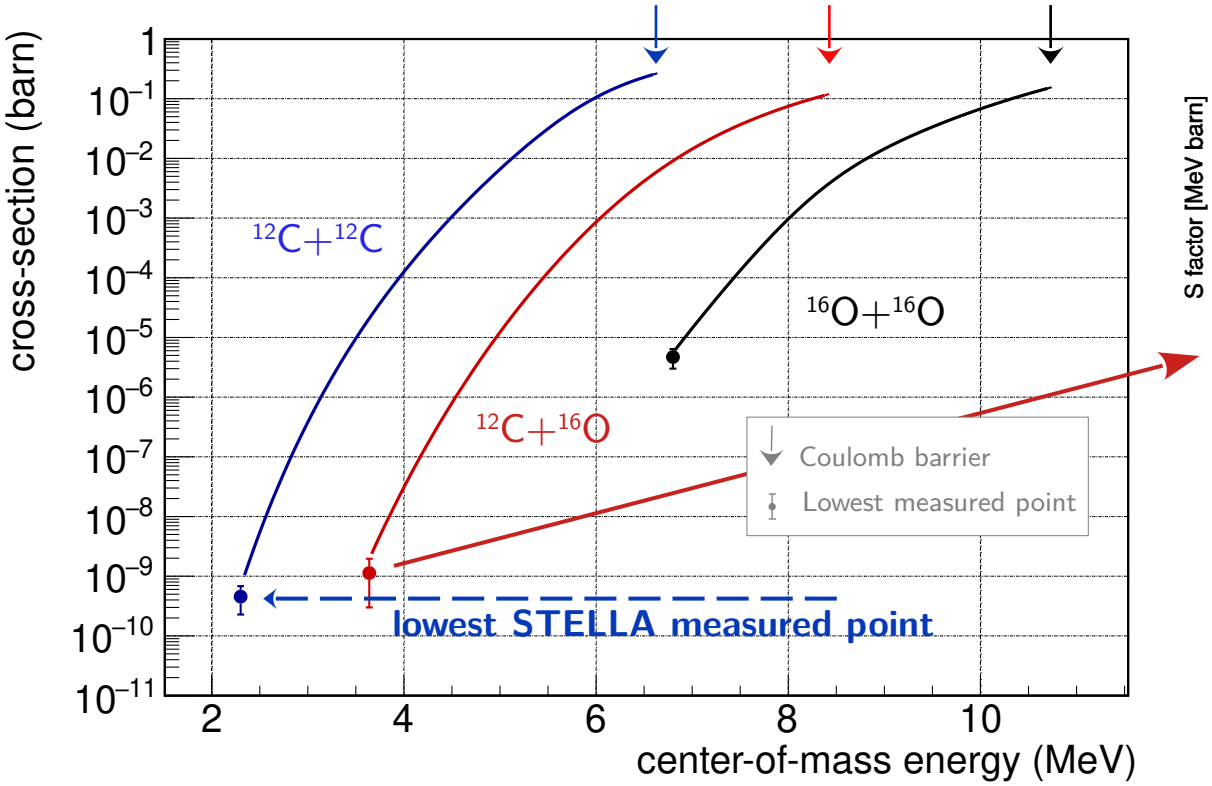
**The core carbon-burning phase**

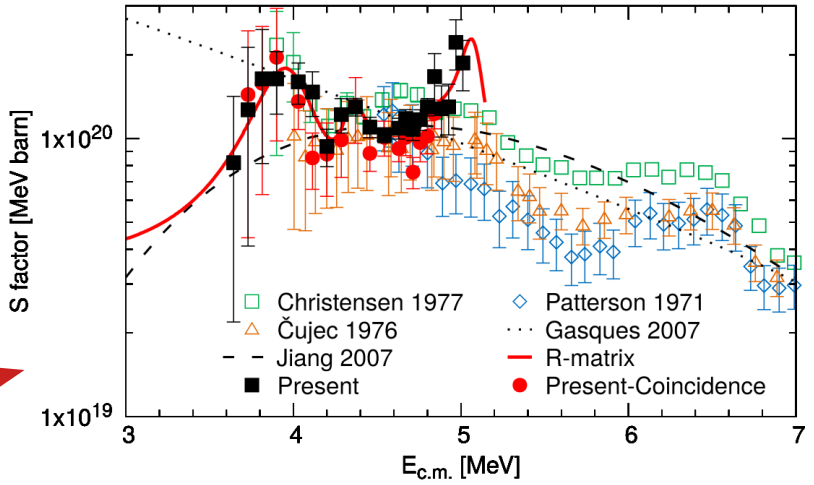
T. Dumont[1], E. Monpribat[1], S. Courtin[1,2], A. Choplin[3], A. Bonhomme[1], S. Ekström[4], M. Heine[1], D. Curien[1], J. Nippert[1], and G. Meynet[4]

# Toward $^{12}C+^{16}O$ and $^{16}O+^{16}O$ with STELLA

Challenging systems: at astrophysical energies of interest: larger number of open channels

$\rightarrow$ experimental upgrade needed




Hints for resonances at low energy

Fang et al. Phys. Rev. C **96** (2017)

supported by recent calculations of $^{12}C+^{16}O$ molecular resonances

Taniguchi and Kimura, PRB **800** (2020)

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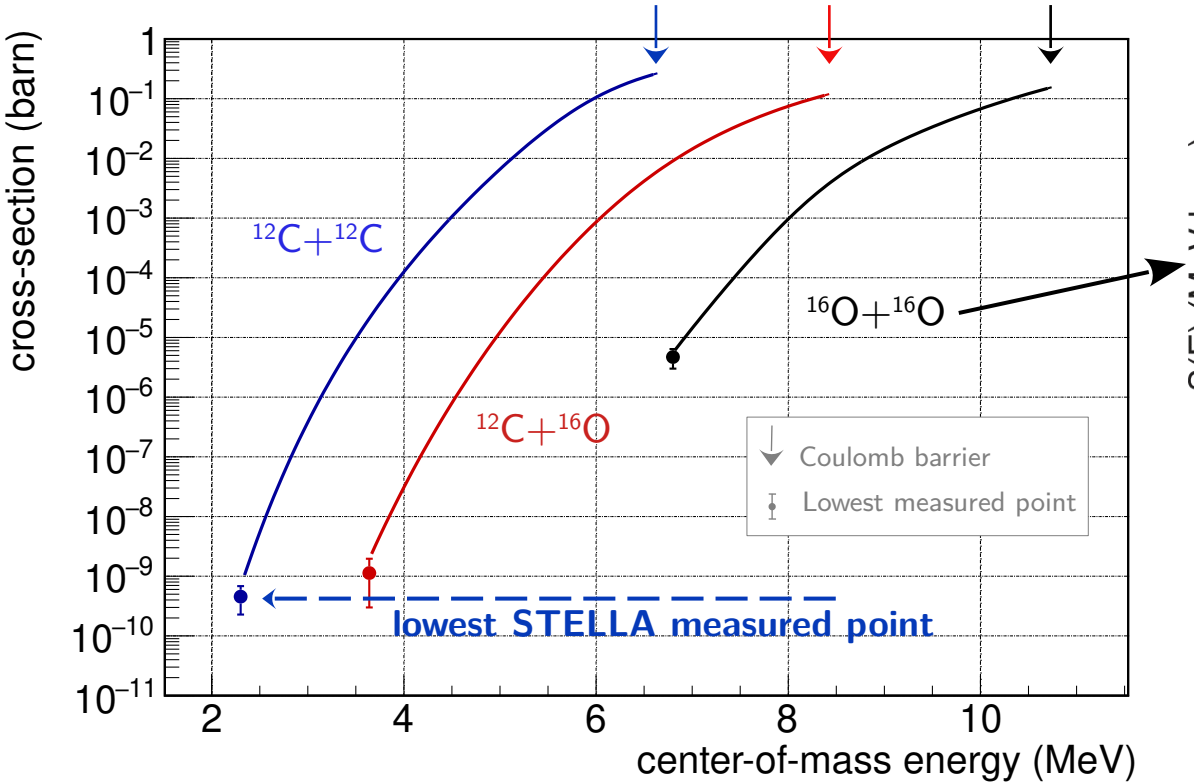
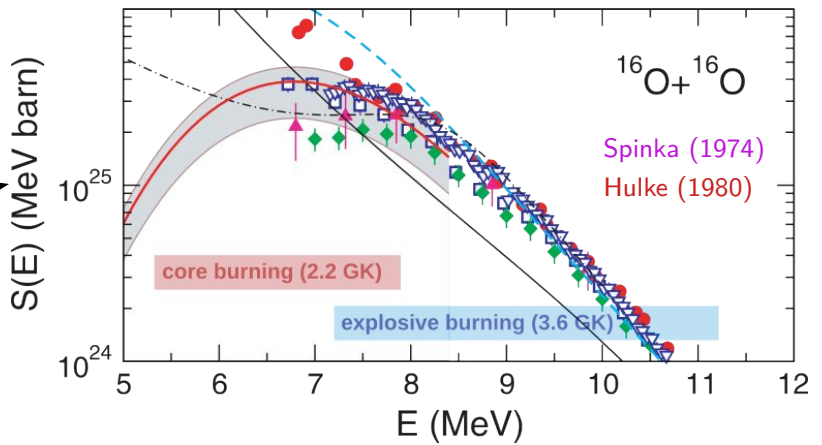



adapted from Jiang et al. Phys. Rev. C **75** (2007)

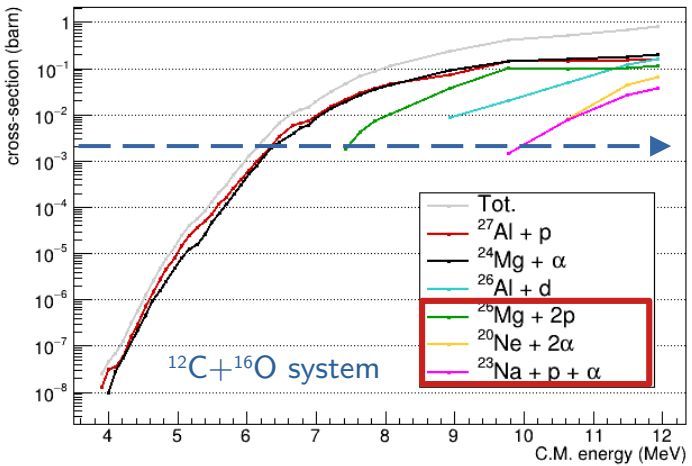



Large discrepancies at low energy

Presence of hindrance?

→ needs further measurements

# Resolving complex final states: the $^{12}C+^{16}O$ case

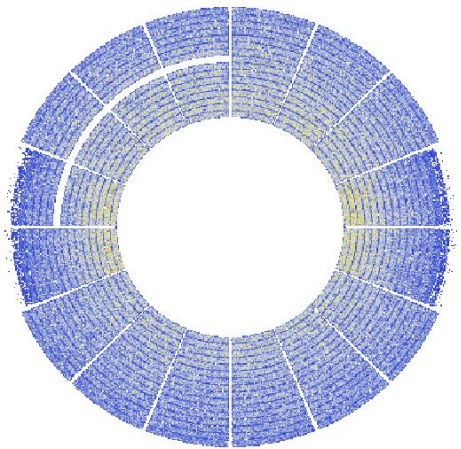


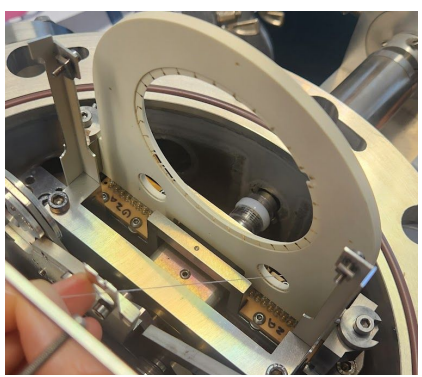

At energies of interest: three-body exit channels are open

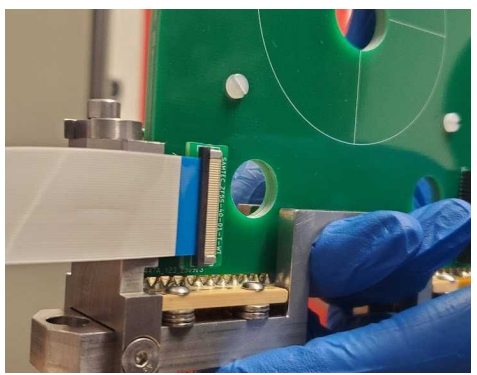
Measured down to ~2mbarn (γ) Christensen Nucl. Phys. **A280** (1977)

→ STELLA Si detector upgrade:

- ✓ full kinematics determination
- ✓ improved angular coverage
- ✓ adapted thickness for $^{12}C+^{16}O$

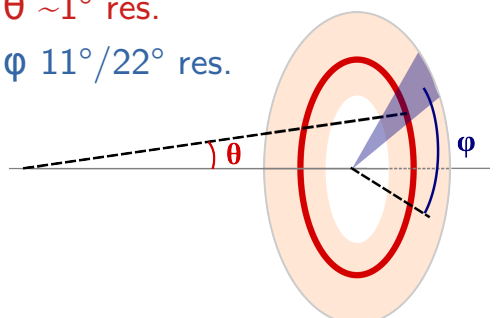






θ ~1° res.

φ 11°/22° res.



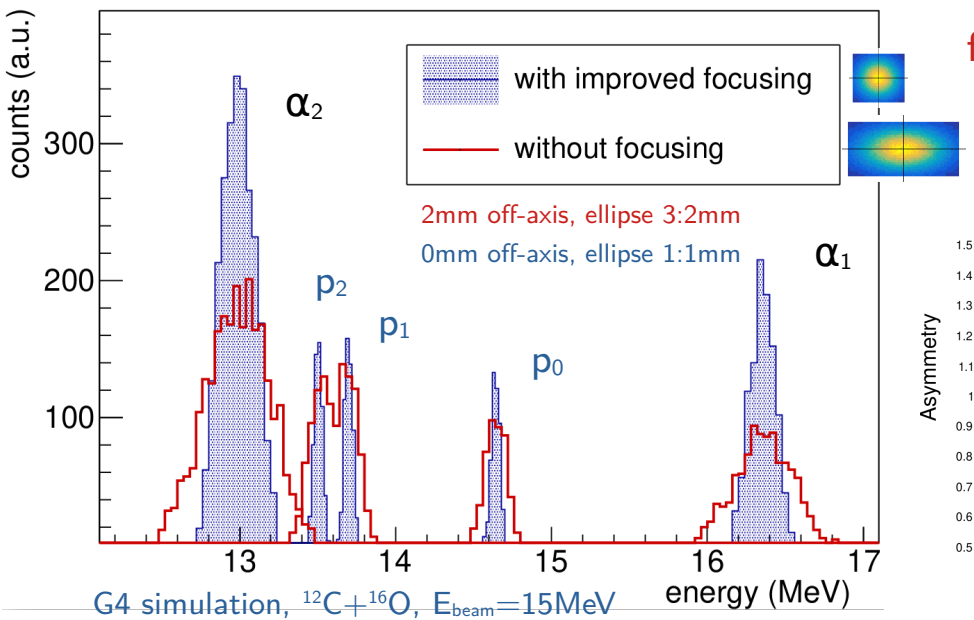

→ Detector design & DAQ upgrade

*Developments in cooperation with Micron Technologies*

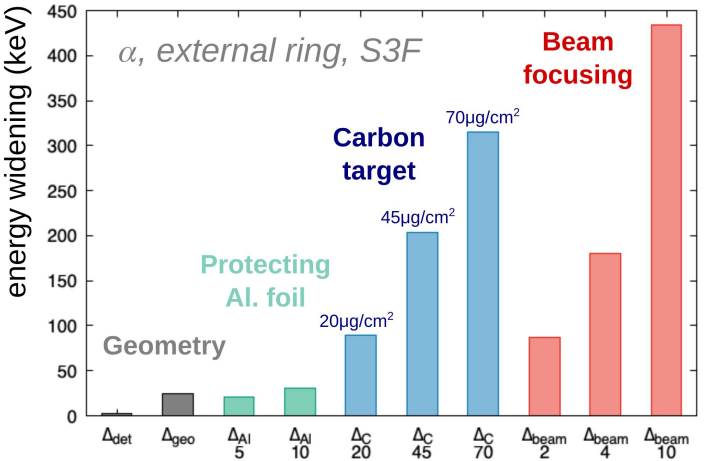
# Improved precision: energy resolution budget

- Optimization target width/protecting aluminium foils
- Beam focusing identified as dominant contribution to energy resolution (size, symmetry)

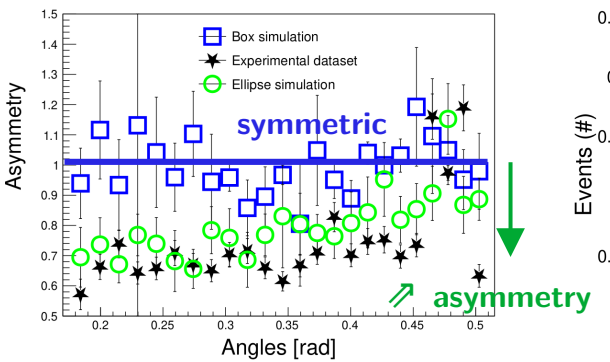
→ 90° line upgrade @Andromède for STELLA

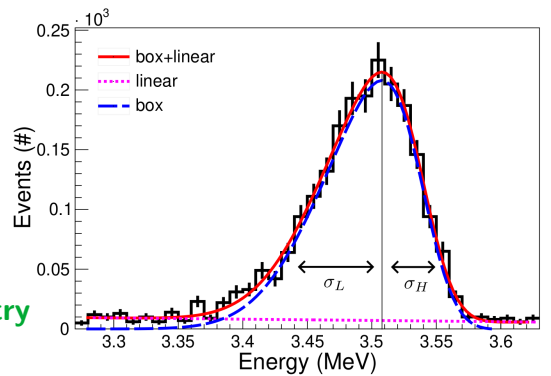



G4 simulation, $^{12}C+^{16}O$, $E_{beam}$=15MeV




Z. Zobundzija, M1 internship



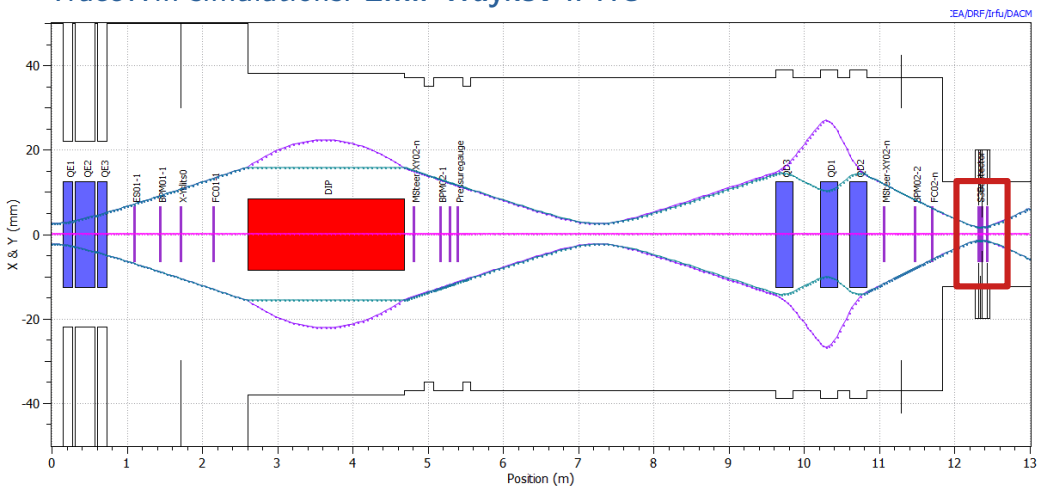




E. Bella, M2 internship

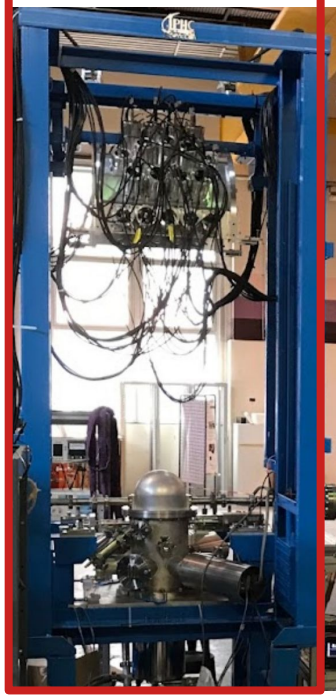
# Upgrade of the beam line at Andromède

- Re-design the STELLA 90° line @Andromède
- Beam optics simulations optimized on STELLA requirements: beam spot in size and symmetry

TraceWin simulations: **Emil Traykov** IPHC



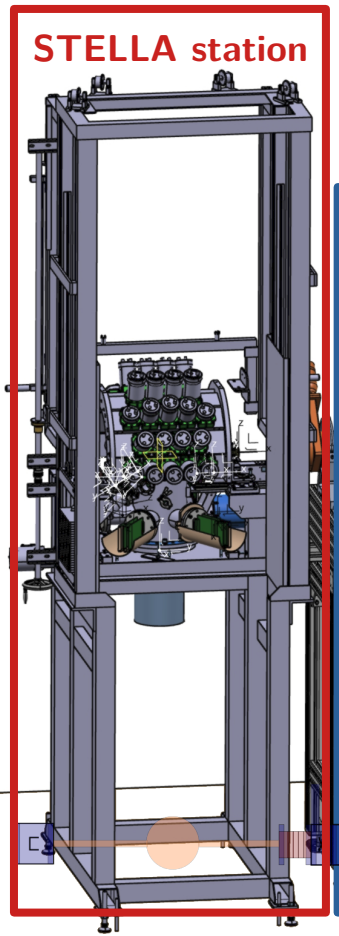

**STELLA station**

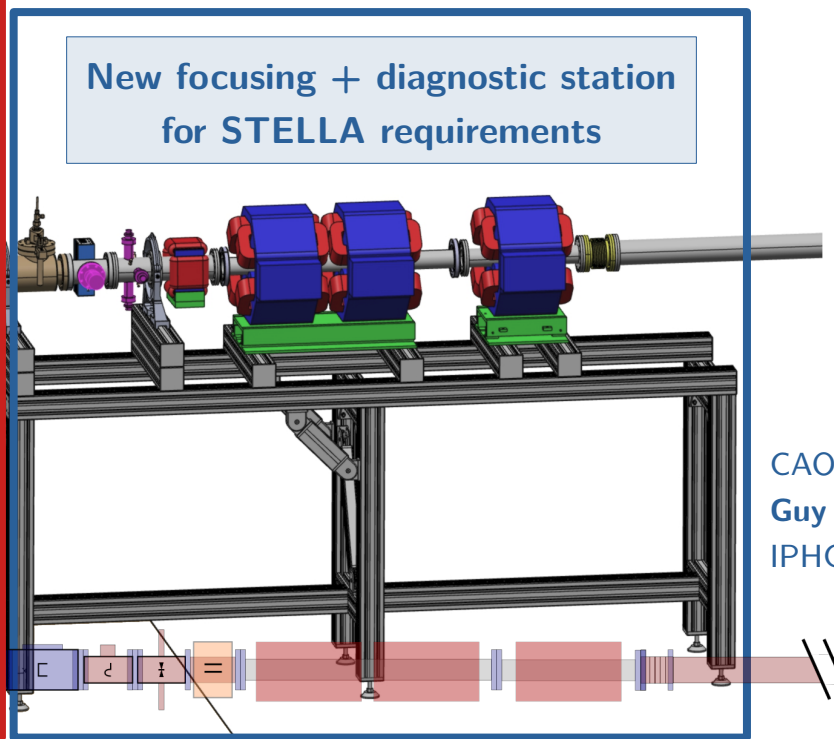


**Existing 90° line**

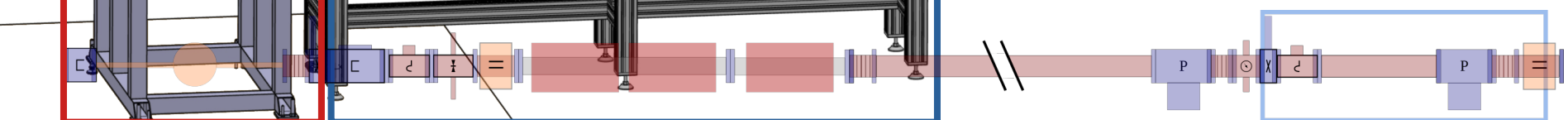
- Measurement of the beam emittance planed on site this autumn

# Upgrade of the beam line at Andromède




CAO:
**Guy Heitz**
IPHC

# Conclusion and perspectives

- STELLA successfully explored fusion cross-sections down to sub-nbarn region for $^{12}C+^{12}C$
  - ✓ virtual background suppression via coincidence and ns-timing precision

- **Explore next fusion systems: $^{12}C+^{16}O$ and $^{16}O+^{16}O$**
  - ✓ upgrade charged-particle detectors and improve beam focusing
  - → **upgrade of the 90°line at ANDROMEDE**
  - ✓ aim: exclusive measurement, full resolution of exit channels

- **Rich physics program:**
  - Nuclear physics: resonances, fusion hindrance?
  - Astrophysical impact for massive stars: structure, nucleosynthesis?
    - → New hydrodynamics calculations on-going for sensitivity studies
      - + inclusion of TDHF calculations

# Thank you for your attention!

J. Nippert,[1,*] P. Adsley,[2] A. Bonhomme,[1] R. Canavan,[3,4] W.N. Catford,[3] P. Cotte,[2] S. Courtin,[1,5,†] D. Curien,[1] S. Della Negra,[2] T. Dumont,[1] E. Gregor,[1] G. Haefner,[2] F. Hammache,[2] M. Heine,[1] D.G. Jenkins,[6] J. Lesrel,[2] E. Monpribat,[1] L. Morrison,[3] M. Moukaddam,[1] S. Pascu,[3] Zs. Podolyák,[3] P.H. Regan,[3,4] I. Ribaud,[2] M. Richer,[1] M. Rüdiger,[3] N. de Séréville,[2] C. Stodel,[7] J.G. Vega Romero,[6] and J. Vesić[8]

(STELLA collaboration)

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**+ @IPHC Strasbourg: Guy Heitz, Cédric Mathieu, Marc Richer, Emil Traykov**