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

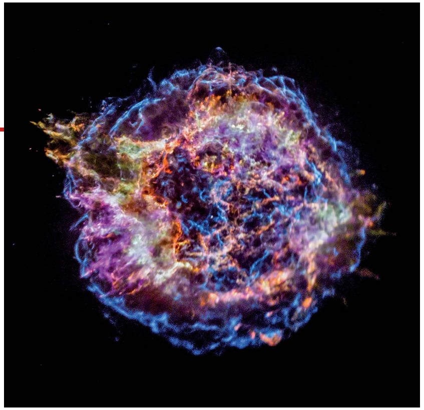
Aurélie Bonhomme
STELLA collaboration
IPHC Strasbourg, France

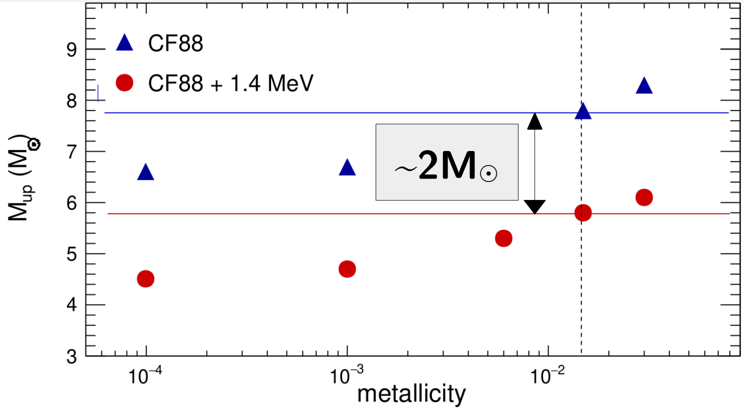
Carbon and oxygen burning in massive stars

- $^{12}C+^{12}C$: first heavy-ion fusion reaction to be considered for $M > M_{up} \simeq 8\ M_\odot$ - $(0.8–1.5) \cdot 10^9$ K
- Next natural reactions of astrophysical relevance: involving ^{16}O
  - $^{12}C+^{16}O$: late burning phases of C/O, shell burning, intershells mixing, SN
  - $^{16}O+^{16}O$: the next binary fusion ($(1.5 - 2.6) \cdot 10^9$ K)

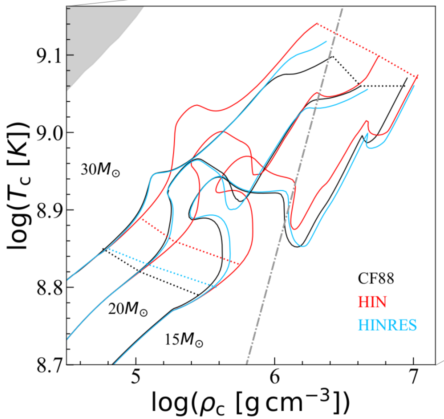
→ impact on limit M_{up}, structure, nucleosynthesis (s-process)

cf. T. Dumont lecture!

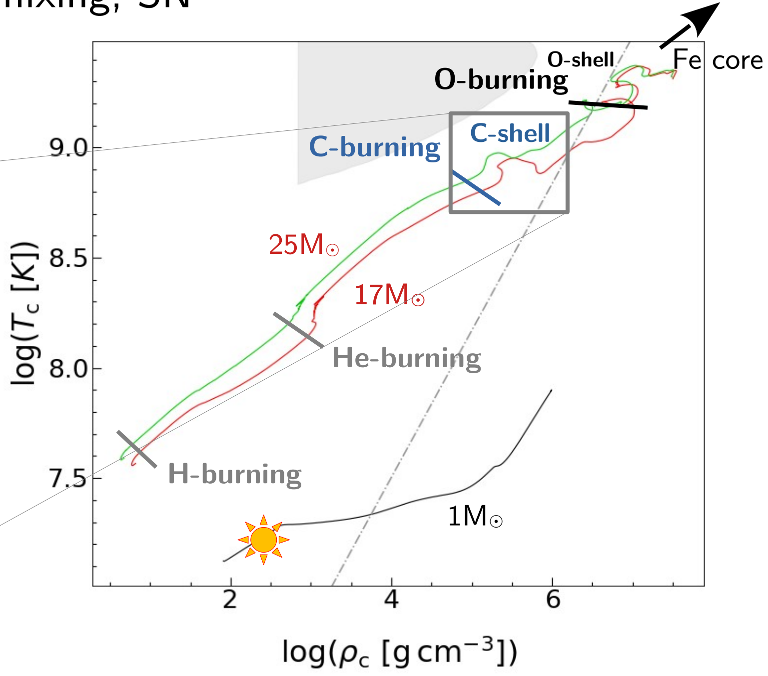




Straniero *et al.* JPC Ser. **665** (2016)

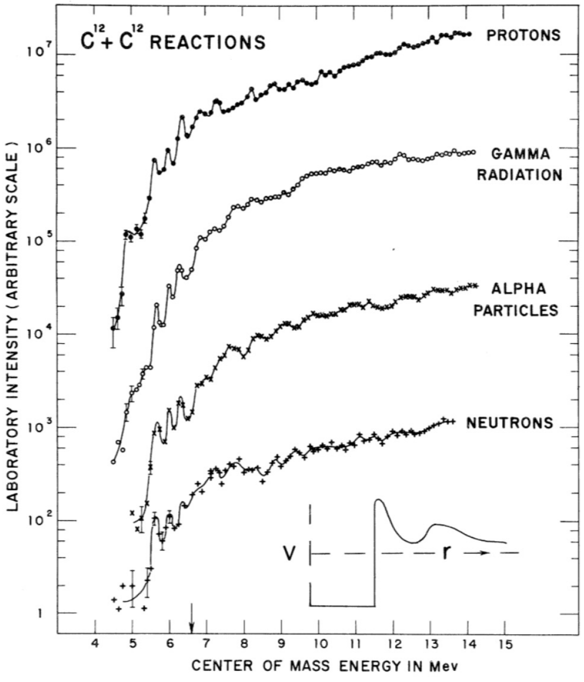


Dumont *et al.* A&A, **688** (2024)

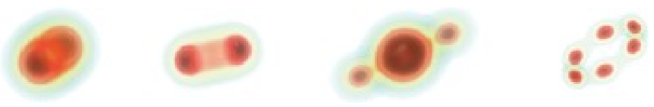


Fusion involving ^{12}C and ^{16}O: nuclear perspective

cf. M. Heine lecture!



Almqvist *et al.* PRL **4** (1960)



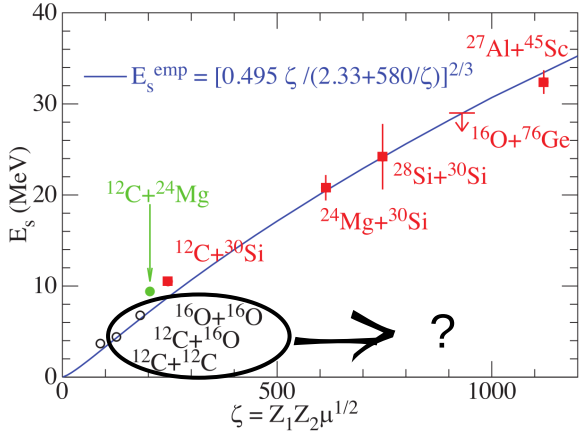
Ebran *et al.* PRC **90** (2014)

- Nuclear structure / resonances
  - Molecular states
  - Alpha-clustering
- Fusion hindrance

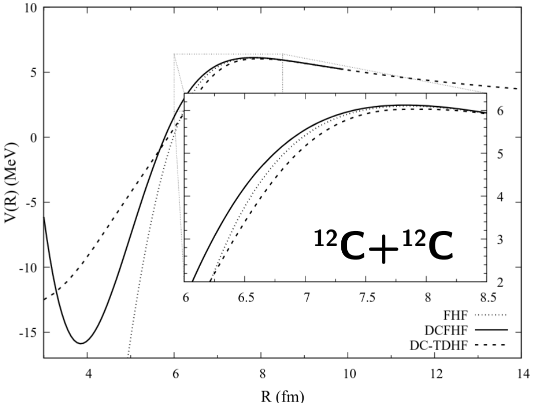
  Observed in medium-mass range

  → ^{12}C and ^{16}O systems?

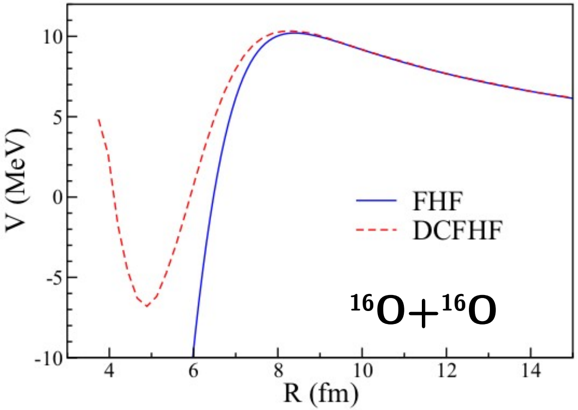
Montagnoli and Stefanini, EPJA **53** (2017)



Godbey et al. PRC **100** (2019)

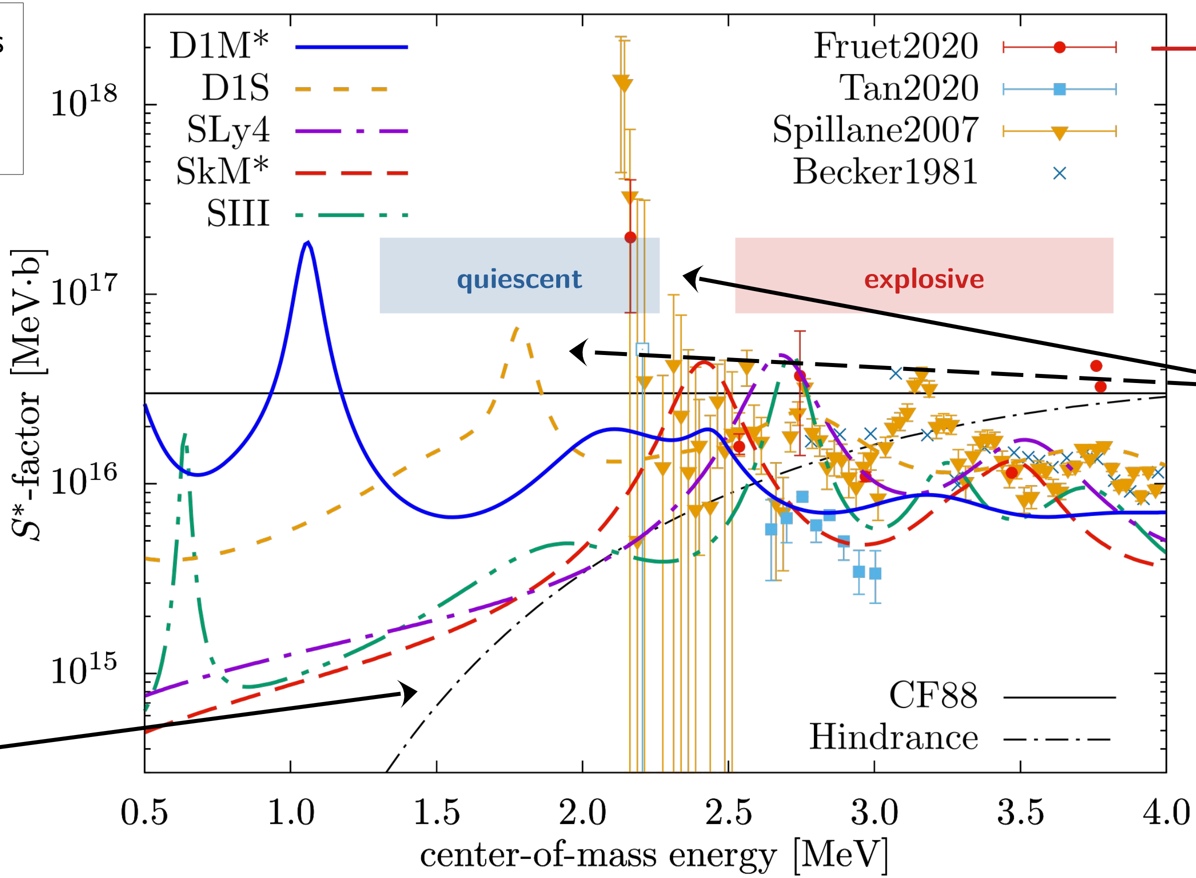


Simenel et al. PRC **95** (2017)



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

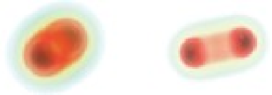
S-factor: 'removes' effects of Coulomb barrier:
S = E.σ(E).exp(2πη)



STELLA 2020!

Presence of resonances?

Presence of fusion hindrance?



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

Direct measurement principle

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

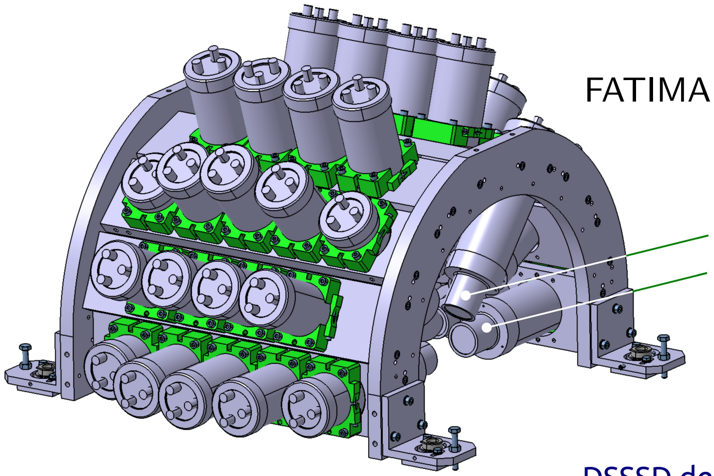
$^{12}C + ^{12}C \rightarrow ^{20}Ne^* + \alpha$, $^{20}Ne^* \xrightarrow{\gamma} ^{20}Ne$

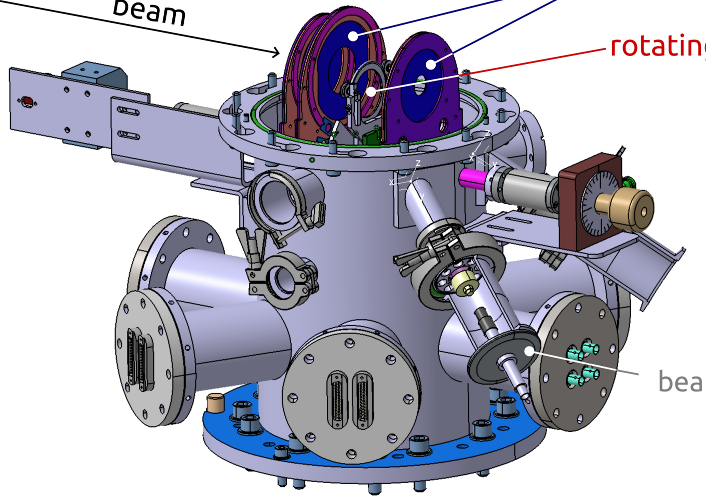
Direct measurements:

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

→ **STELLA setup**

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





Direct measurement principle

$^{12}\text{C}+^{12}\text{C} \rightarrow {}^{23}\text{Na}^{*} + \mathbf{p}$, $\quad {}^{23}\text{Na}^{*} \xrightarrow{\gamma} {}^{23}\text{Na}$

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

Direct measurements:

- Charged particles (p/α)
- De-excitation gamma-rays
- Coincidence measurement → **STELLA setup**

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

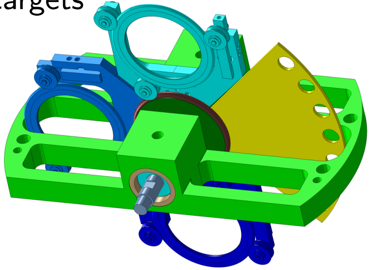
very low cross sections (sub-nb!)

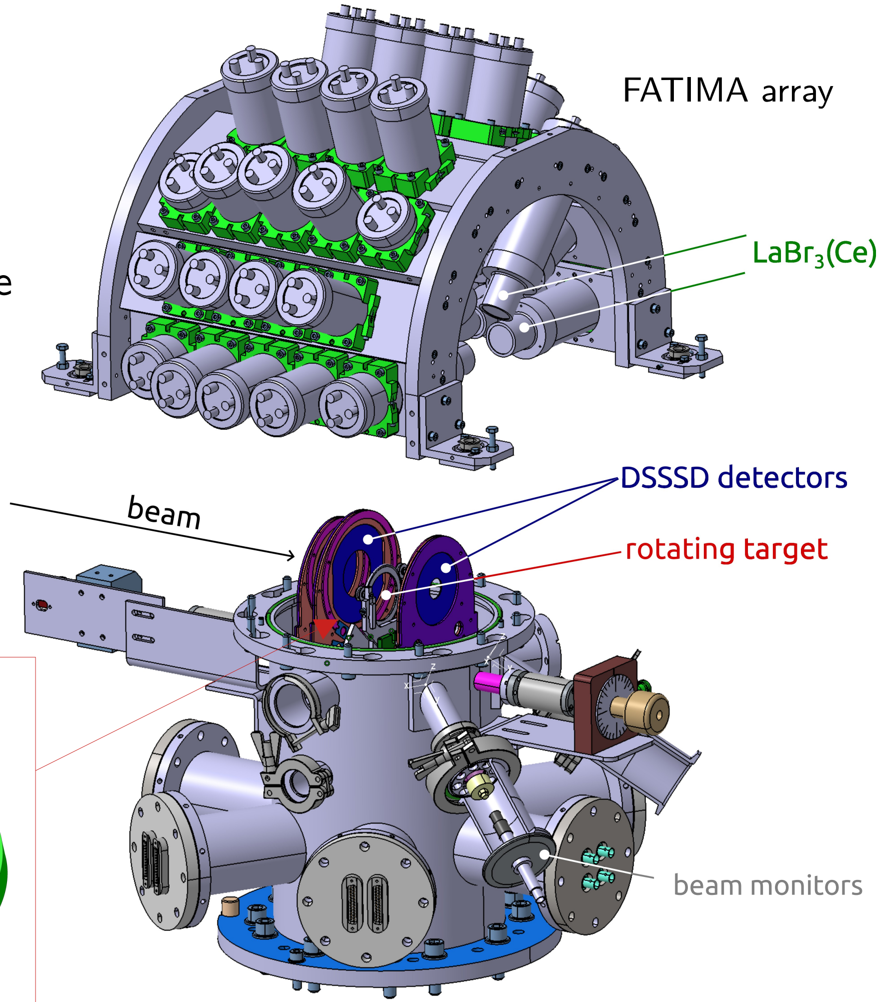
→ 4MV **@Andromède** (ECR source)

→ intensities **up to 3puA**

→ **weeks of measurements!**

Self supporting rotating targets

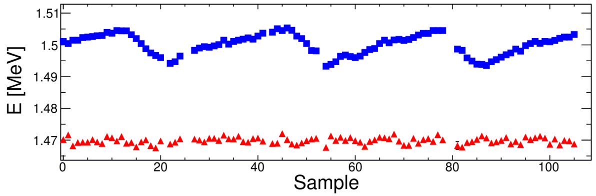




Direct measurement principle

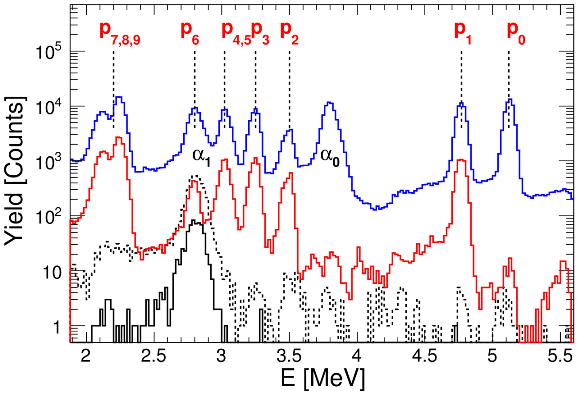
LaBr3 detectors → gamma detection

- ✓2.5 % @ 1.4 MeV – efficiency 2.6%/8.6% (α/p)
- ✓coverage: $d\Omega = 23$ % of 4π
- ✓sub ns-timing
- ✓self-calibration (temperature drifts)

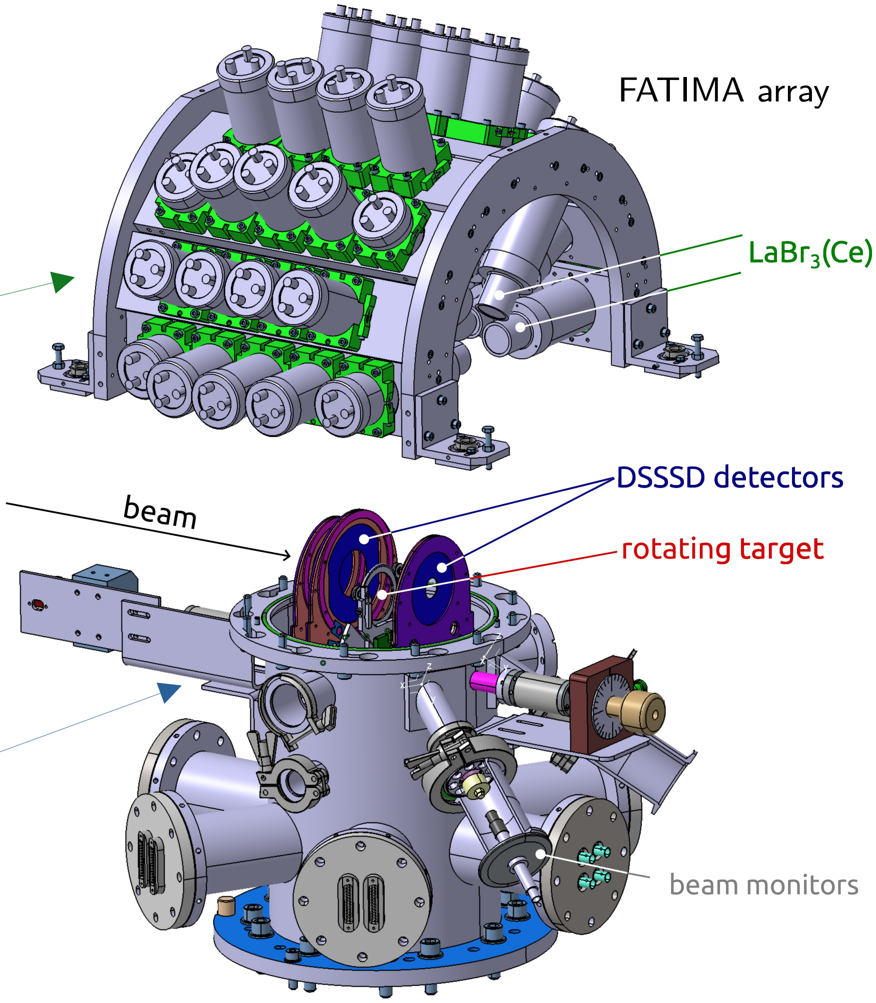


Particle detectors → alpha/protons detection

- ✓annular Si (Micron)
- ✓angular distribution measurements $d\Omega = 24$ % of 4π
- ✓protected by Al foils



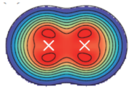
Heine *et al.* NIM A **903** (2018)



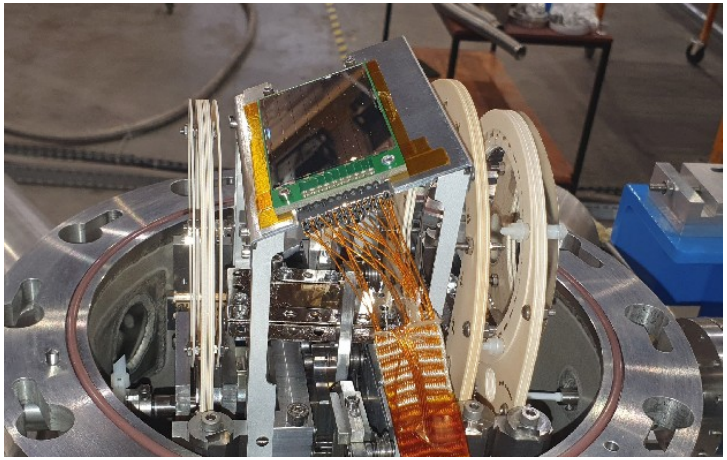
Fruet *et al.* PRL **124** (2020)

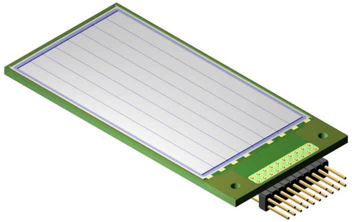
Pixel detectors for angular distributions

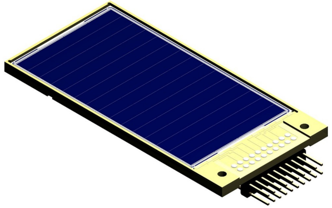
- Additional coverage of steep angles: θlab $= 60°$ - $90°$
- Versatile configuration with two types of detectors (Micron Semiconductors): BB10 (granularity) and SUPER-X3 (timing)
- Unambiguous determination of angular distributions

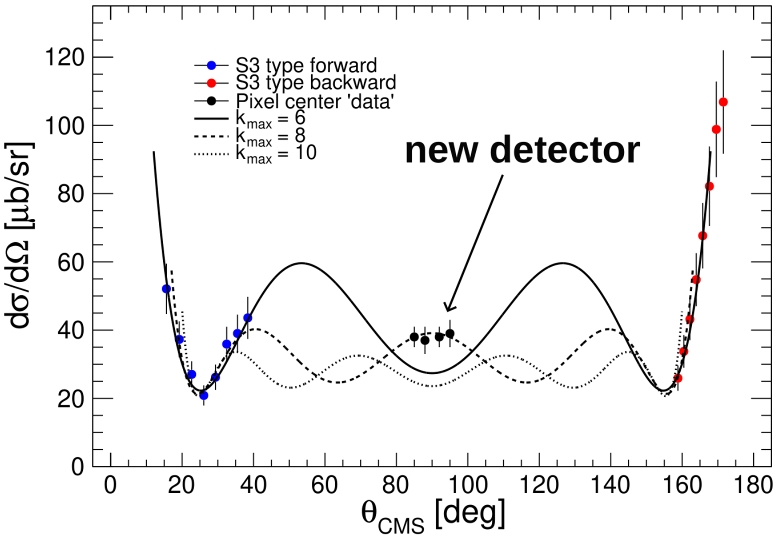


$$^{12}\mathrm{C} + ^{12}\mathrm{C} \to ^{24}\mathrm{Mg}^* \to ^{20}\mathrm{Ne} + \alpha_0 + \gamma$$
$$0^+ + 0^+ \to ?^+ \to 0^+ + 0^+ + \vec{L}_\alpha$$





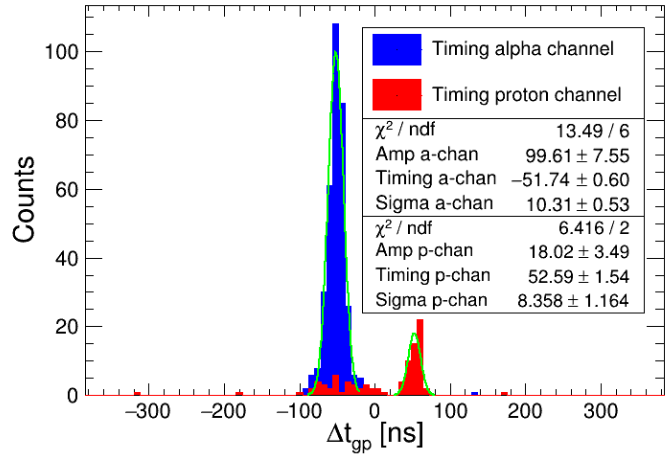




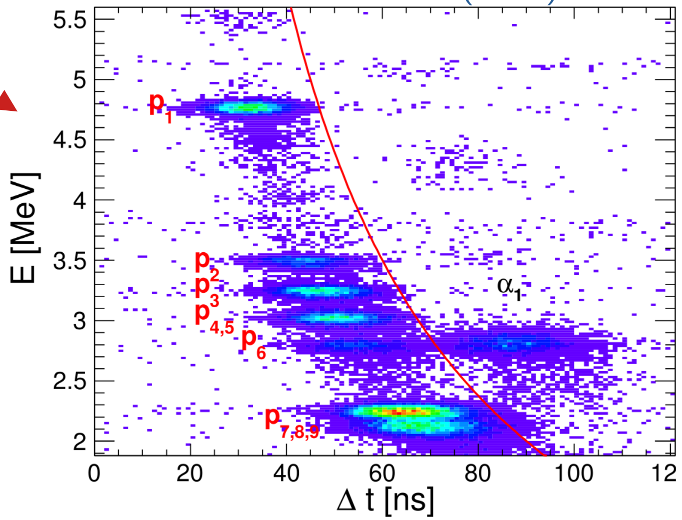
Coincidence method power

- ns-precision timing: resolution γ-particle ∼ 10ns
  random background estimation via delayed windows
- Alpha/proton separation based on timing

Nippert *et al.* submitted to PRC



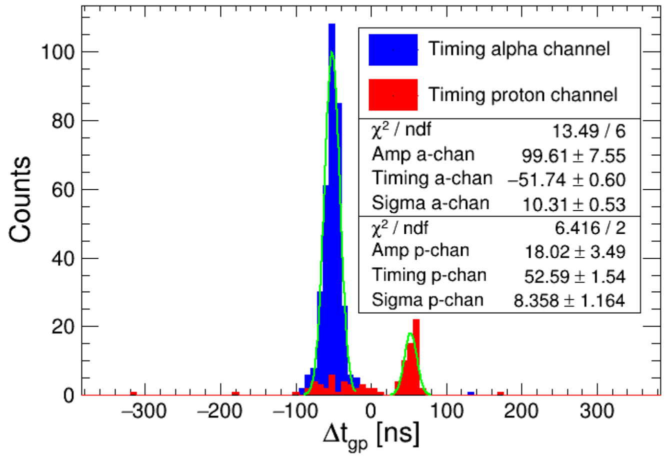
Heine *et al.* NIM A **903** (2018)



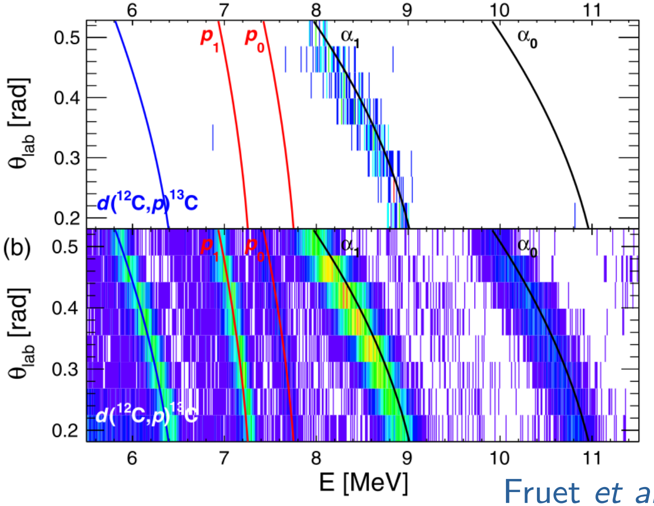
Coincidence method power

- ns-precision timing: resolution γ-particle ~ 10ns
  random background estimation via delayed windows
- Alpha/proton separation based on timing
- 2-3 o.m. background suppression → clean signal

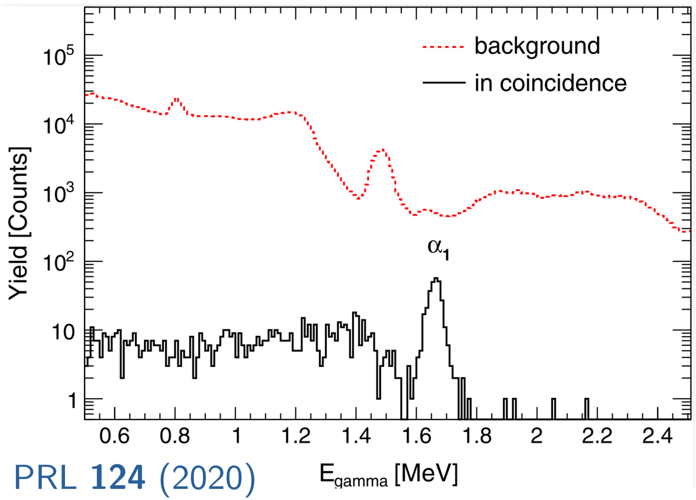
Nippert *et al.* submitted to PRC



Particle spectra

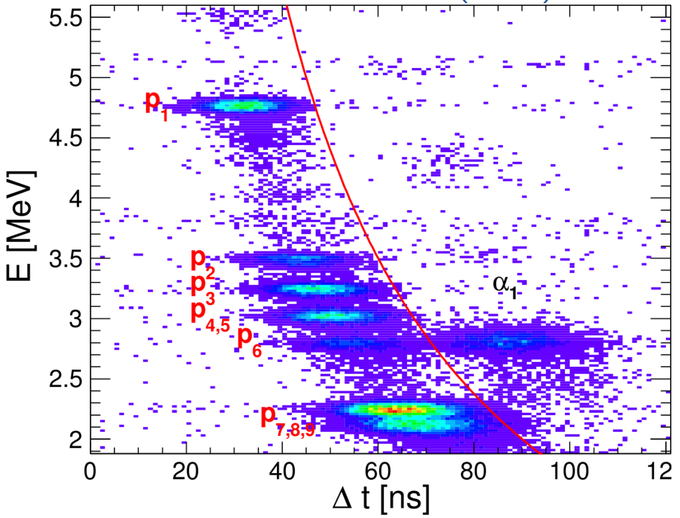


Gamma spectra



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

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

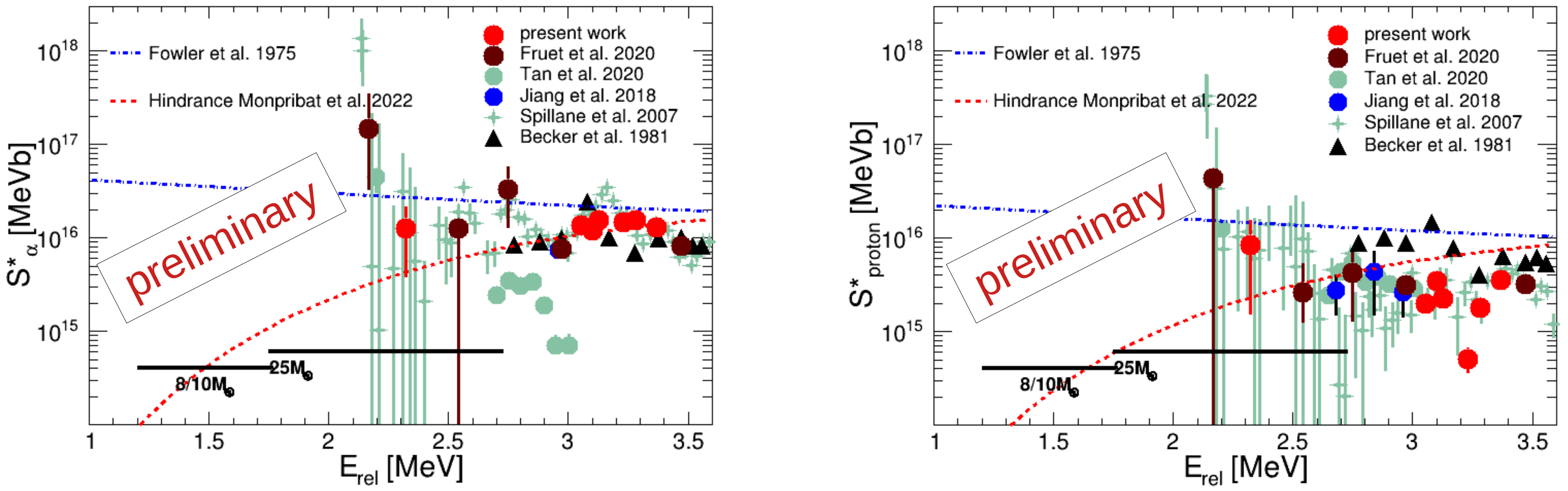


STELLA measurements of $^{12}C+^{12}C$

- Explore different regimes: hindrance regime, Gamov windows
- At the lowest energies: $\lesssim$ 100 pb cross-sections!
- Latest analysis: improved timing selection
- Next: reach the deep sub-barrier regime underground (proposal @Felsenkeller)

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

Nippert *et al.* submitted to PRC (2024)



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

- Explore different regimes: hindrance regime, Gamov windows
- At the lowest energies: $\lesssim$ 100 pb cross-sections!
- Latest analysis: improved timing selection
- Next: reach the deep sub-barrier regime underground (proposal @Felsenkeller)
- Input for sensitivity studies: hydrodynamics calculations (stellar evolution)

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

Nippert *et al.* submitted to PRC (2024)

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

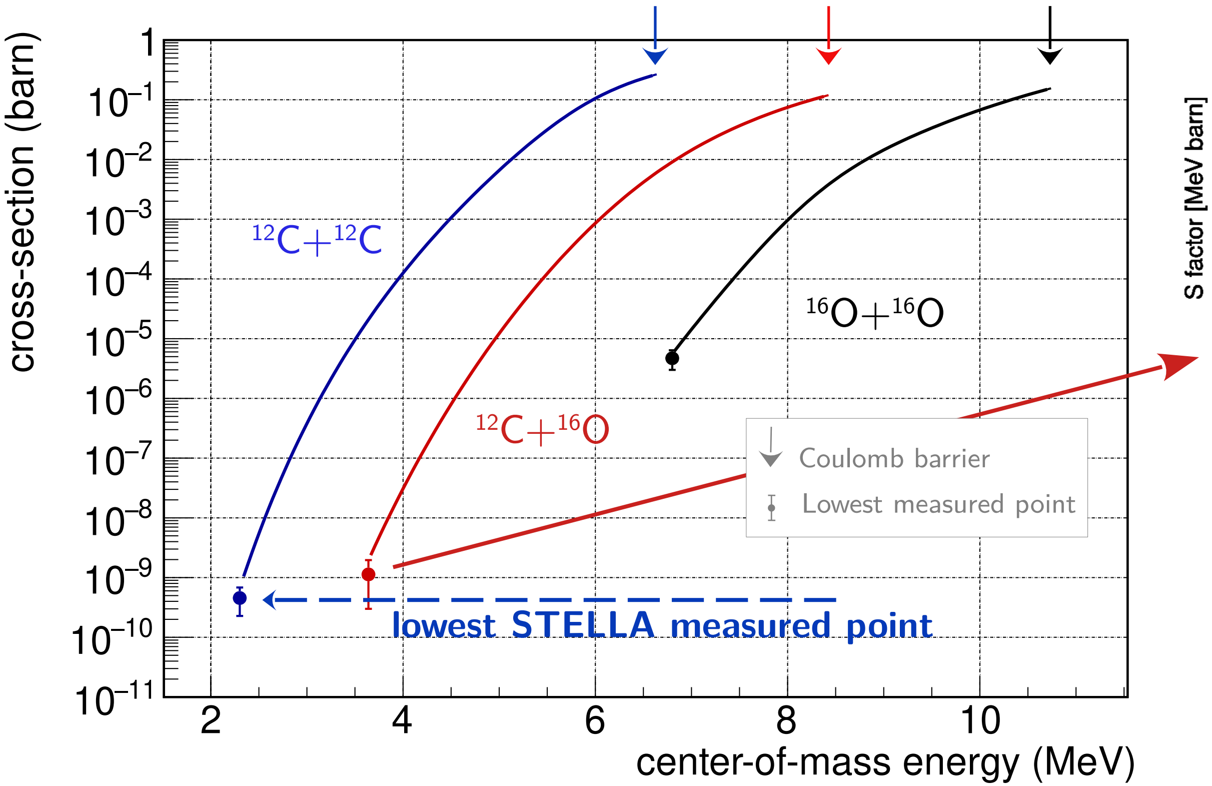
The core carbon-burning phase

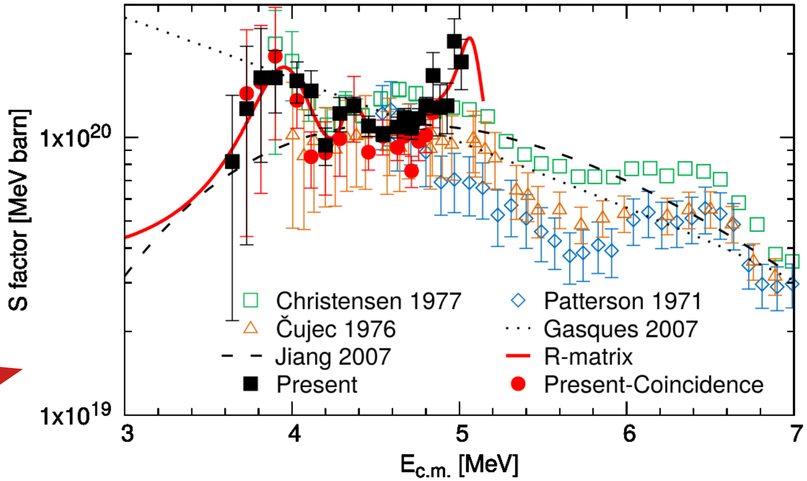
T. Dumont[1], E. Monpribat[1], S. Courtin[1,2], A. Choplin[3], A. Bonhomme[1], S. Ekström[4], M. Heine[1], D. Curien[1], J. Nippert[1], and G. Meynet[4]

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

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

→ experimental upgrade needed





Hints for resonances at low energy

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

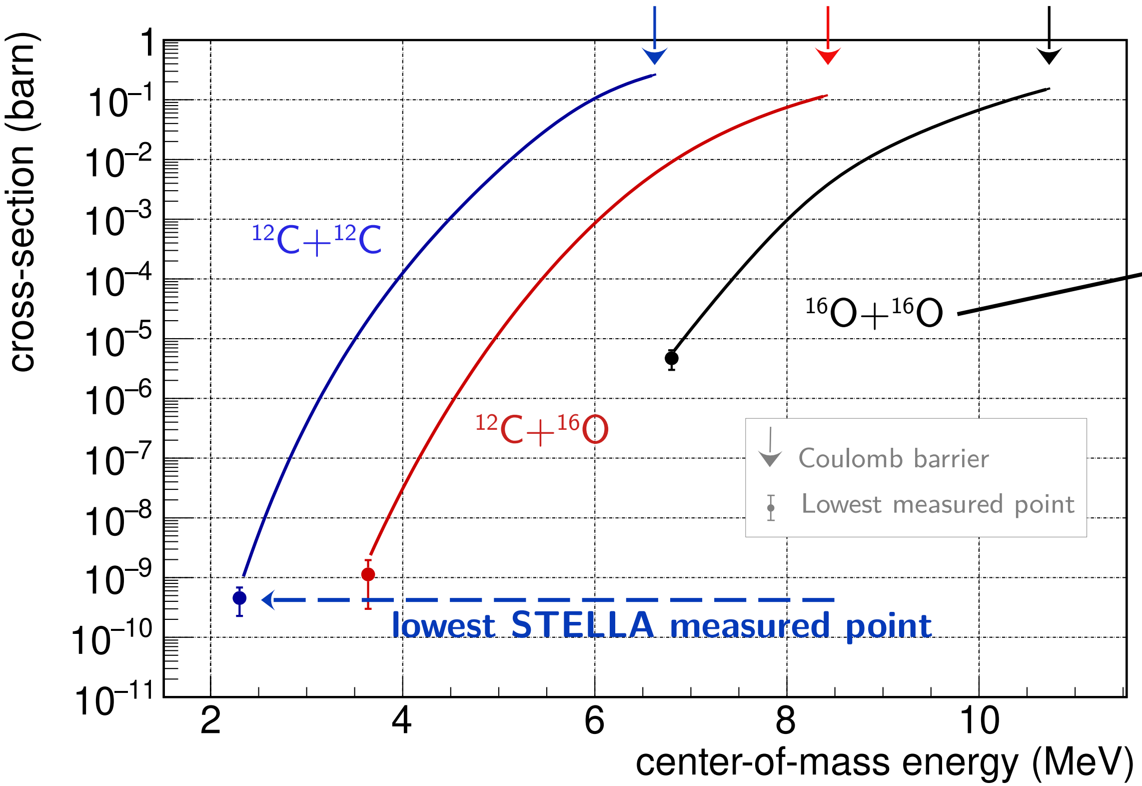
supported by recent calculations of $^{12}C+^{16}O$ molecular resonances

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

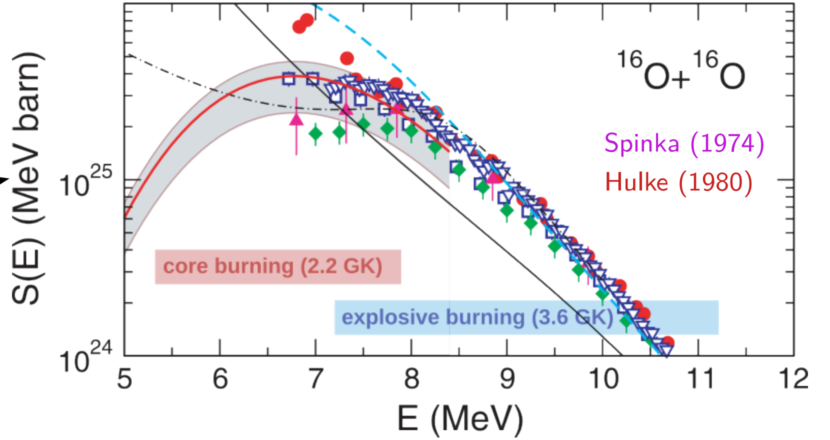
Toward $^{12}C+^{16}O$ and $^{16}O+^{16}O$ with STELLA

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

→ experimental upgrade needed



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

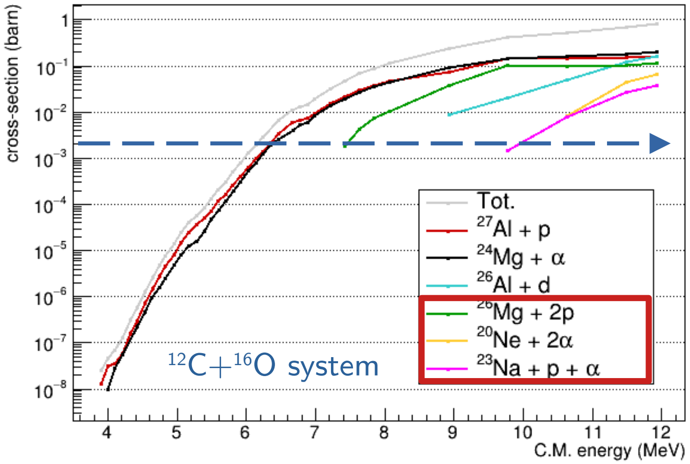


Large discrepancies at low energy

Presence of hindrance?

→ needs further measurements

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

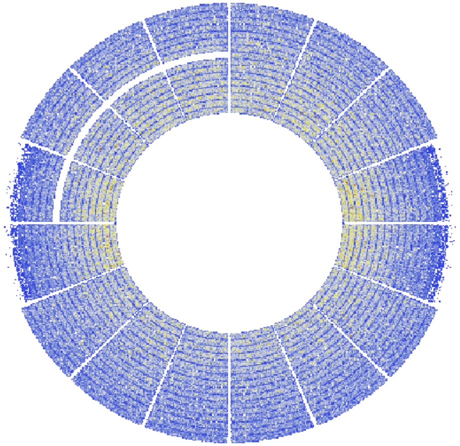


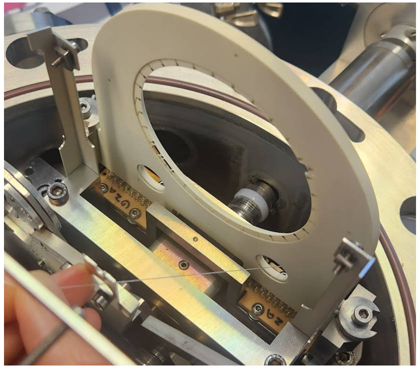
At energies of interest: three-body exit channels are open

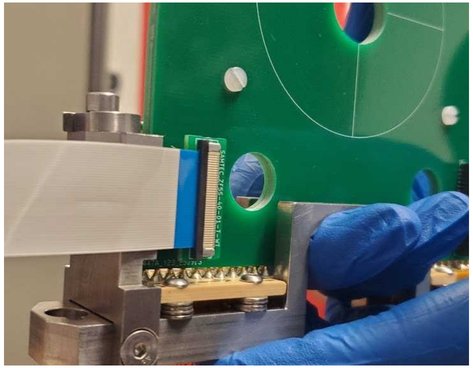
Measured down to ~2mbarn (γ) Christensen Nucl. Phys. **A280** (1977)

→ STELLA Si detector upgrade:

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

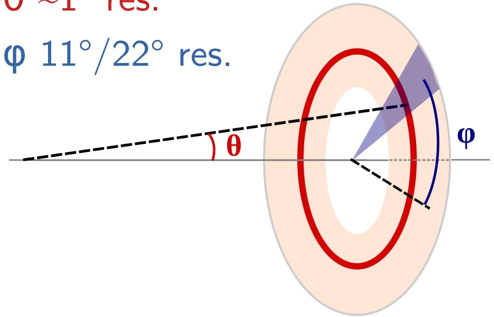






θ ~1° res.

φ 11°/22° res.



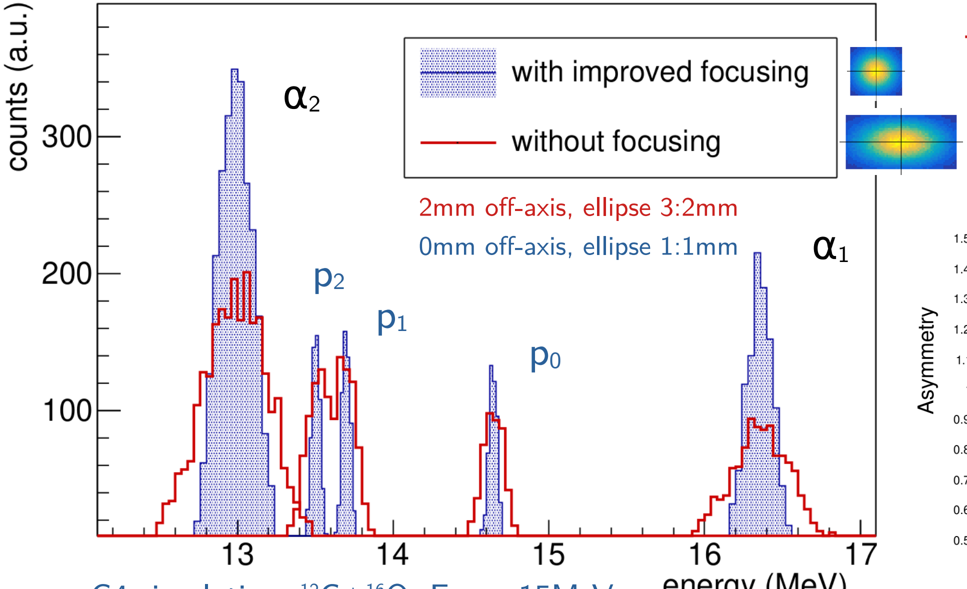
→ Detector design & DAQ upgrade

Developments in cooperation with Micron Technologies

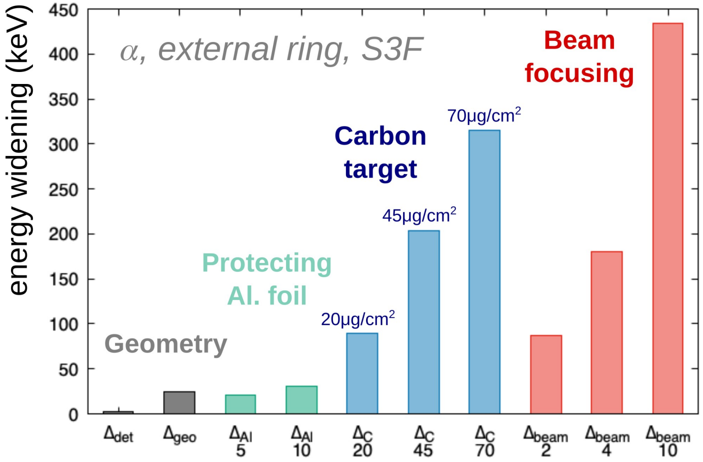
Improved precision: energy resolution budget

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

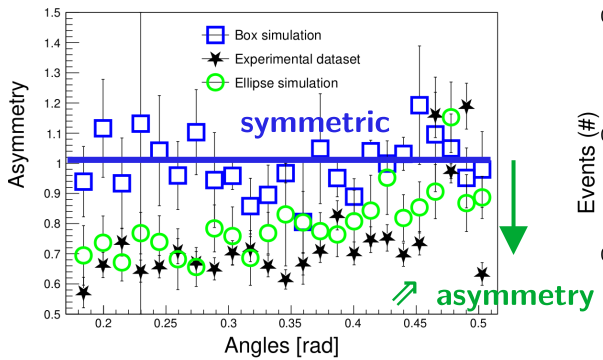
→ 90° line upgrade @Andromède for STELLA

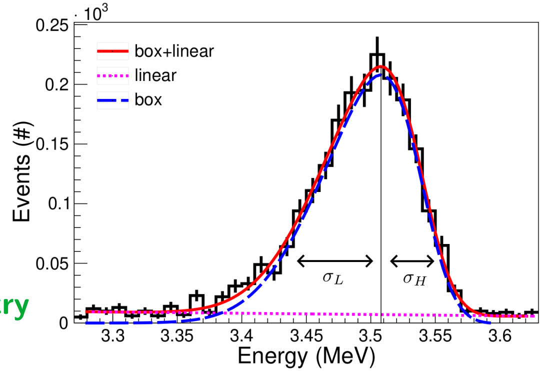


G4 simulation, $^{12}C+^{16}O$, $E_{beam}=15$MeV



Z. Zobundzija, M1 internship



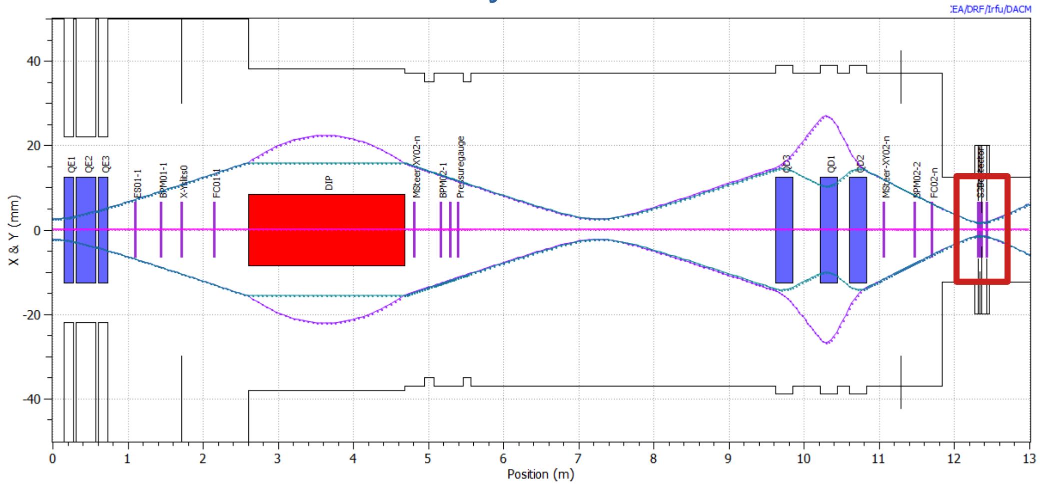


E. Bella, M2 internship

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

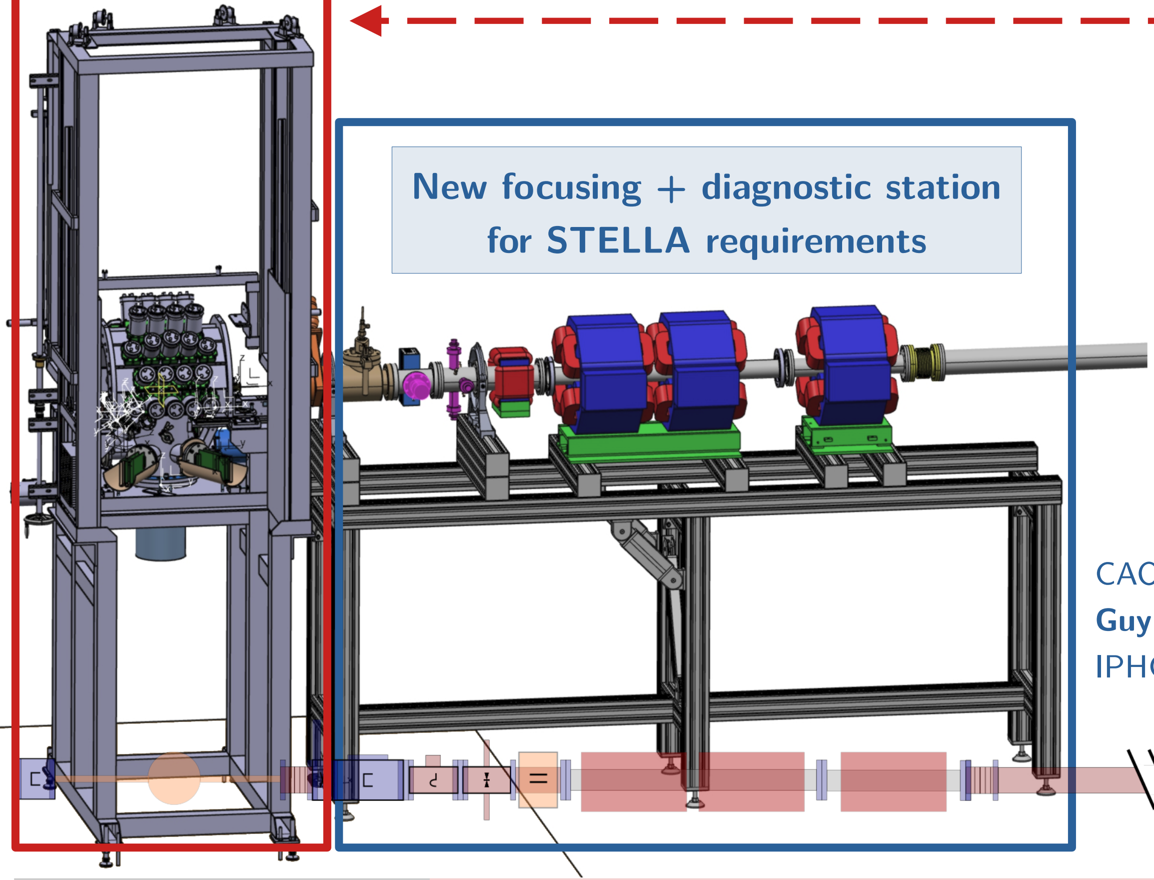
TraceWin simulations: **Emil Traykov** IPHC



- Measurement of the beam emittance planed on site this autumn

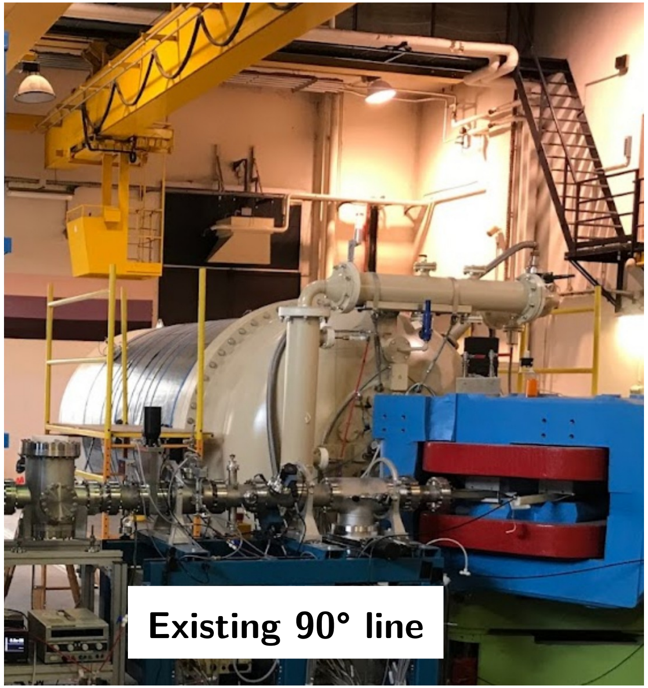
Upgrade of the beam line at Andromède

STELLA station



New focusing + diagnostic station for STELLA requirements

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
  - ✓ 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
  - explore deep sub-barrier energies underground @Felsenkeller (ChETEC-INFRA)

Thank you for your attention!

J. Nippert,[1,*] S. Courtin,[1,2,†] M. Heine,[1] D.G. Jenkins,[3] P. Adsley,[4] A. Bonhomme,[1] R. Canavan,[5,6] D. Curien,[1] T. Dumont,[1] E. Gregor,[1] E. Monpribat,[1] L. Morrison,[5] M. Moukaddam,[1] M. Richer,[1] M. Rudigier,[5] J.G. Vega Romero,[3] W.N. Catford,[5] P. Cotte,[7] S. Della Negra,[7] G. Haefner,[7] F. Hammache,[7] J. Lesrel,[7] S. Pascu,[5,8] Zs. Podolyák,[5] P.H. Regan,[5,6] I. Ribaud,[7] N. de Séréville,[7] C. Stodel,[9] and J. Vesić[10,11]

(STELLA collaboration)

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