



Direct Reaction program

INDRA-FAZIA collaboration

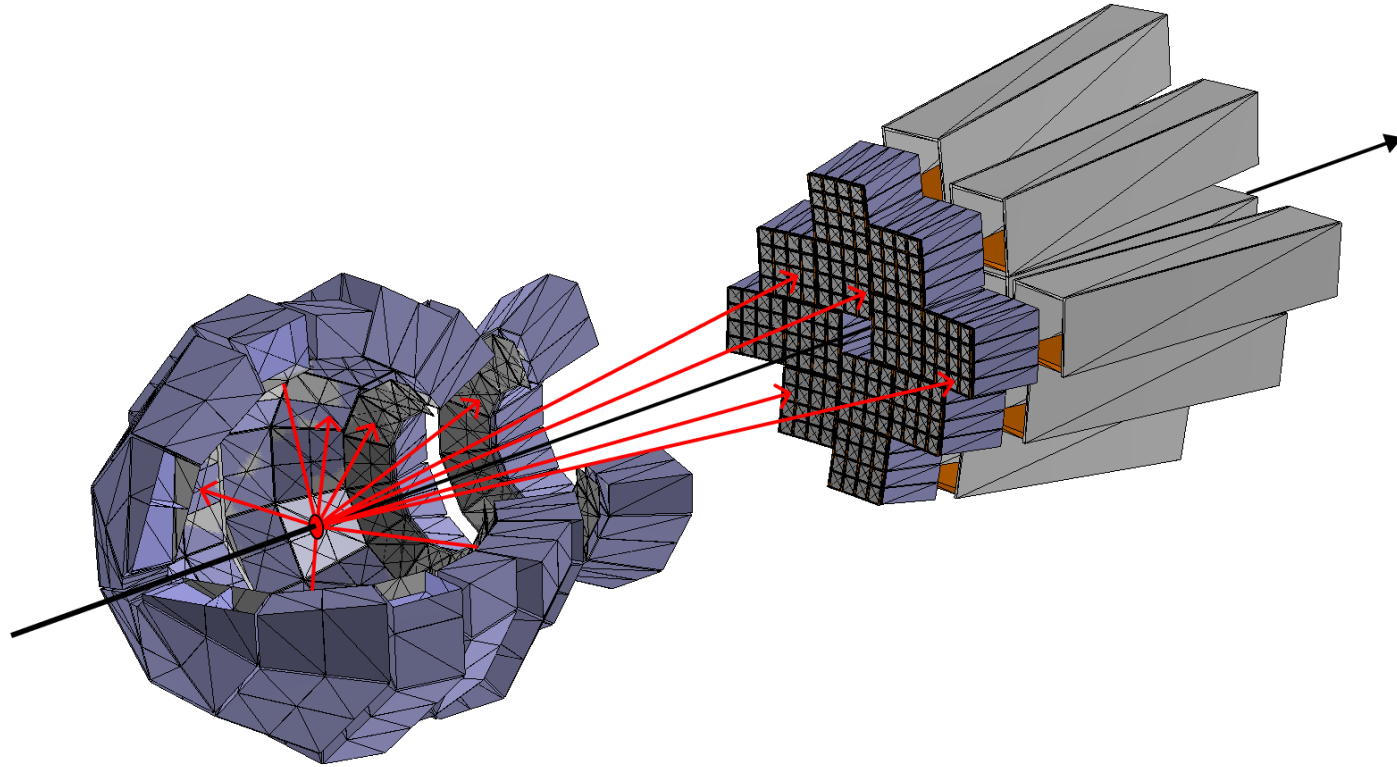
Diego Gruyer, LPC and GANIL

Nicolas Le Neindre, LPC

John D. Frankland, GANIL

INDRA-FAZIA@GANIL

Detector initially designed for high multiplicity events
in heavy-ion collisions

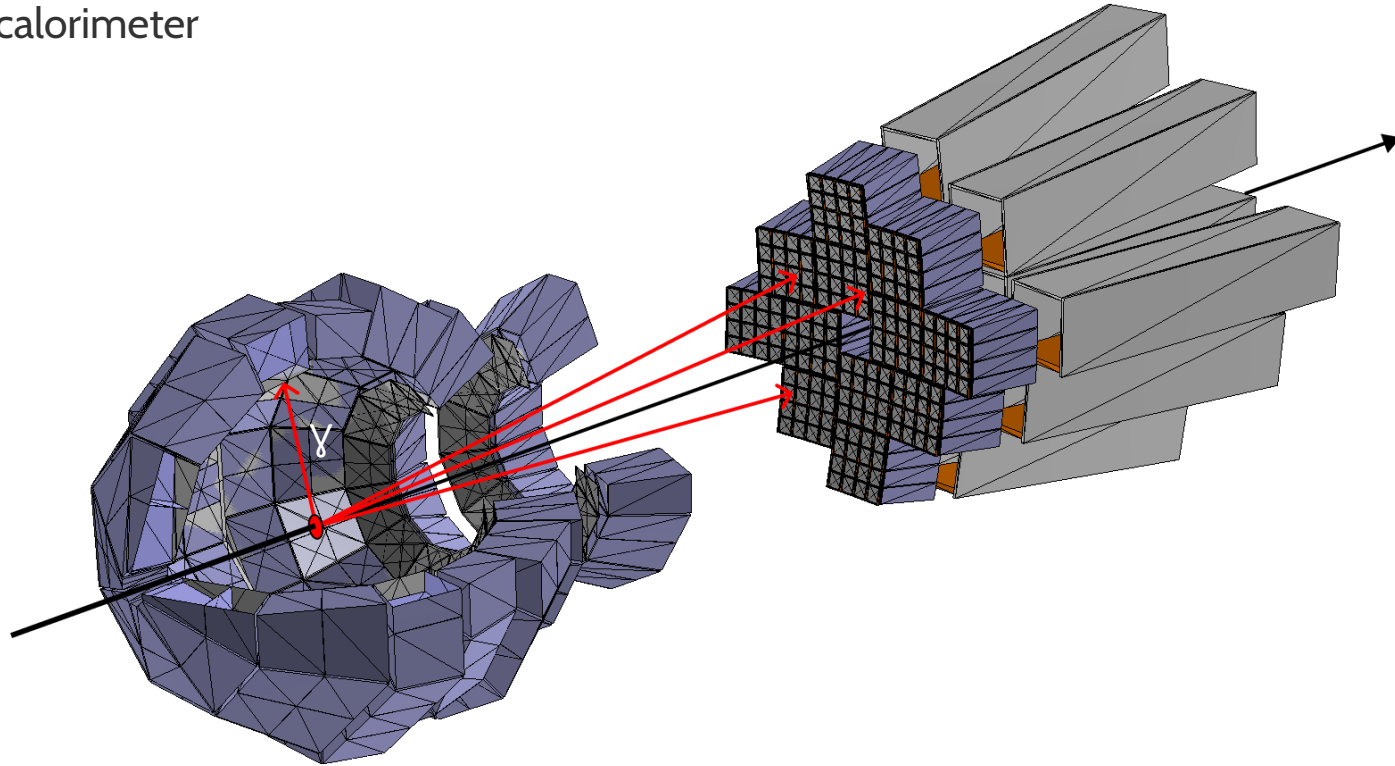


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Detector initially designed for high multiplicity events
in heavy-ion collisions

→ FAZIA : charged particle spectrometer

→ INDRA : gamma calorimeter



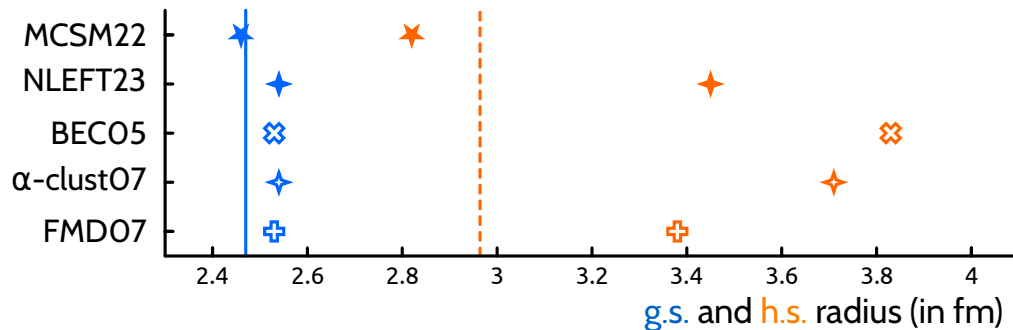
Hoyle state radius

Hoyle state radius experiment

Crutial for understanding ^{12}C formation in stellar nucleo-synthesis. Still very challenging for modern nuclear structure theories.

→ No consensus on the spacial configuration

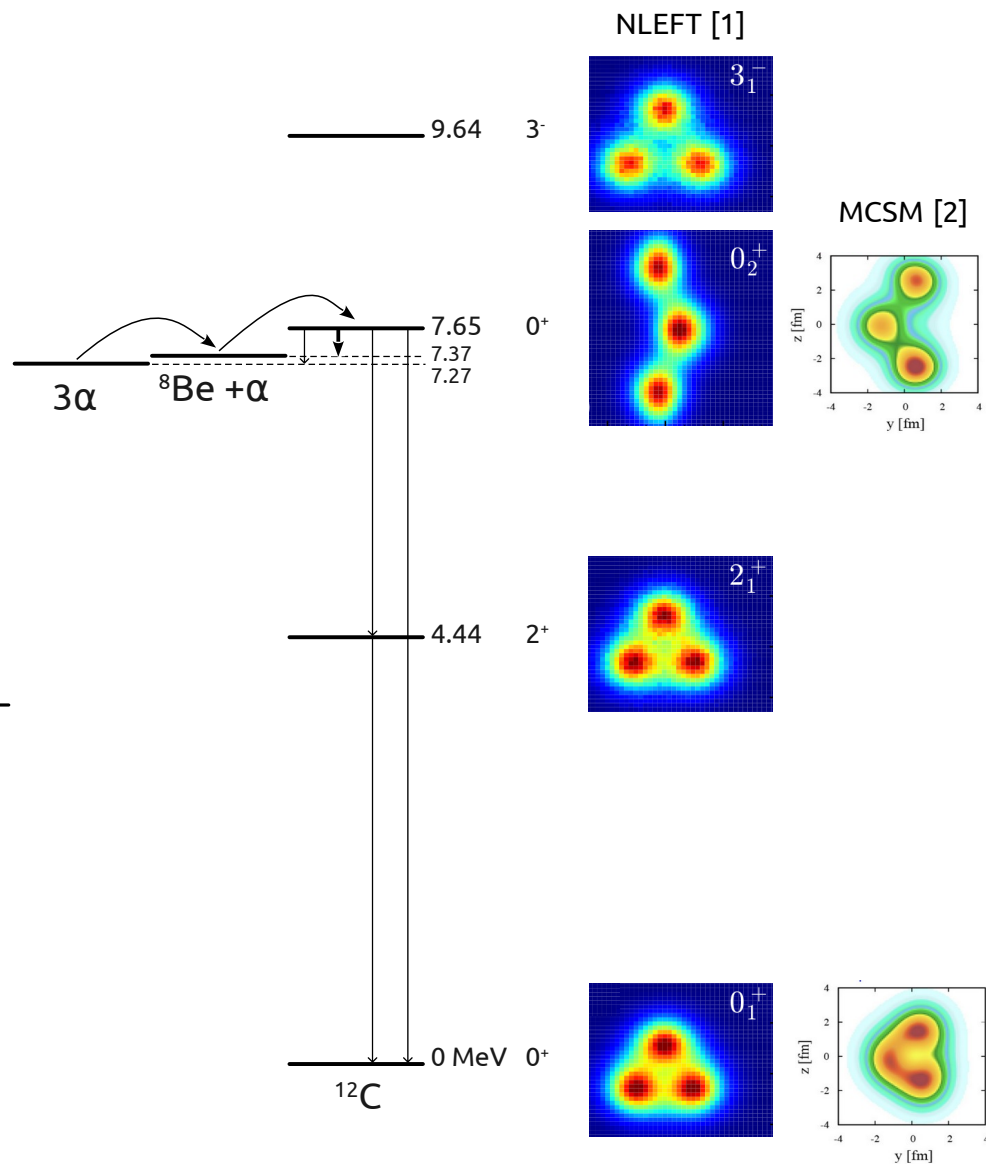
→ Questionable experimental estimate of the radius

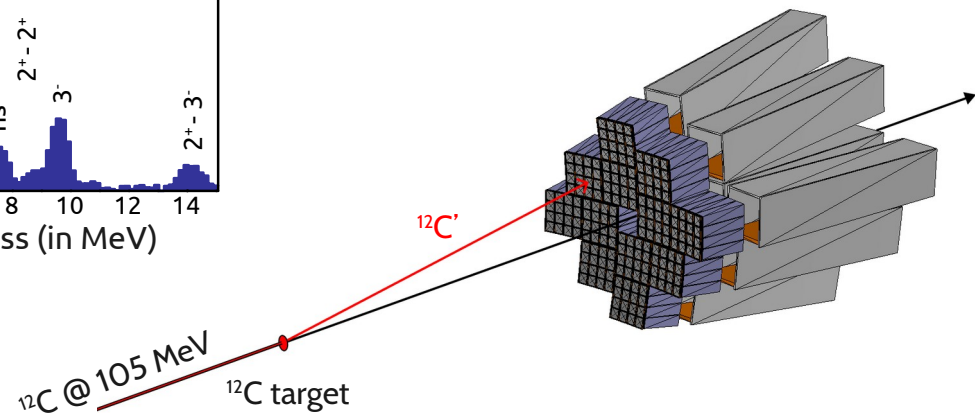
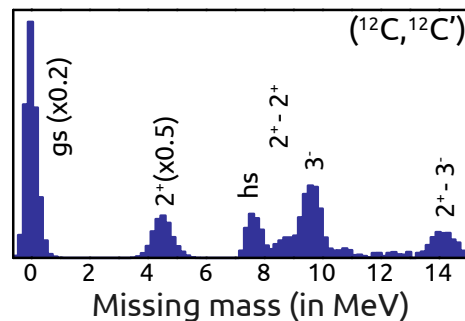
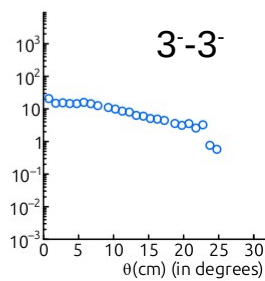
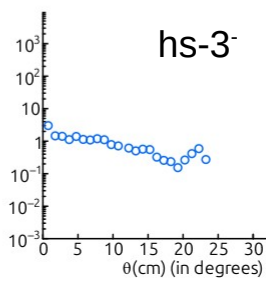
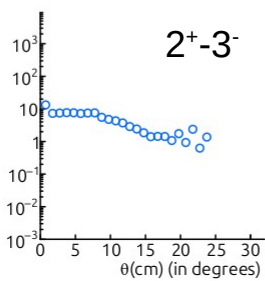
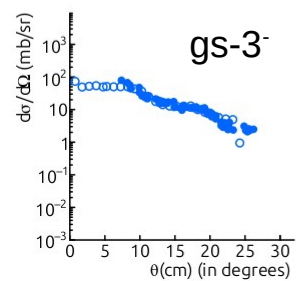
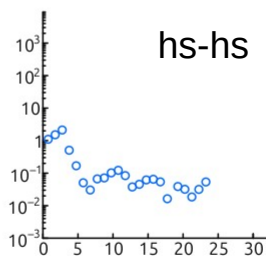
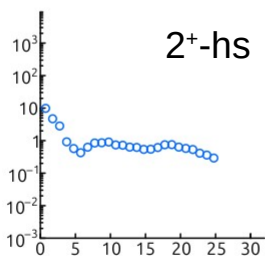
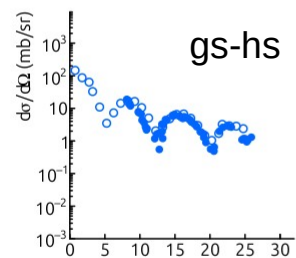
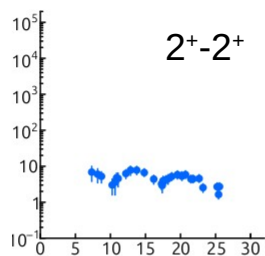
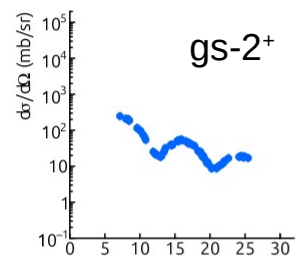
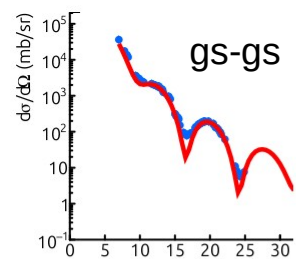


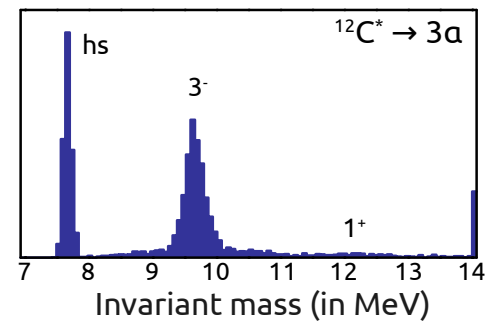
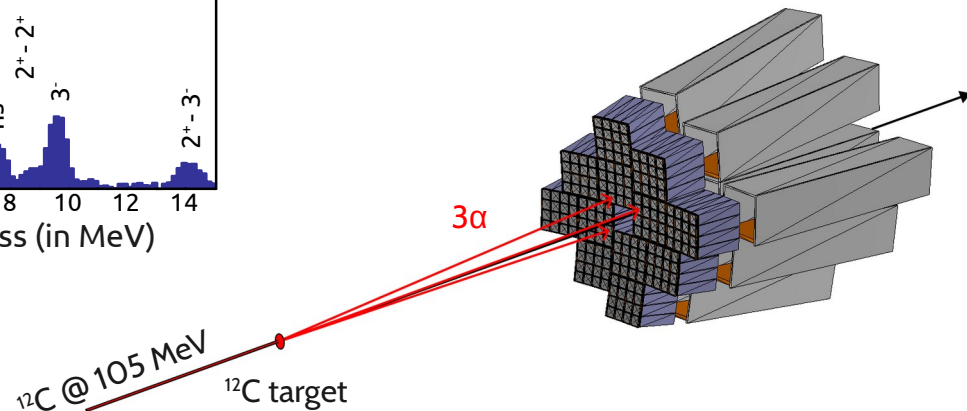
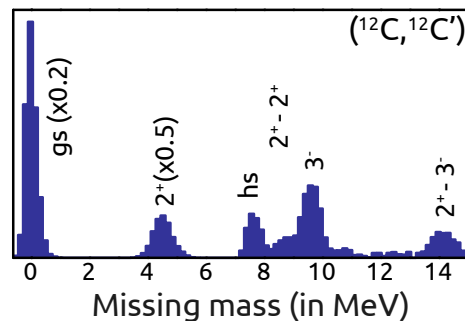
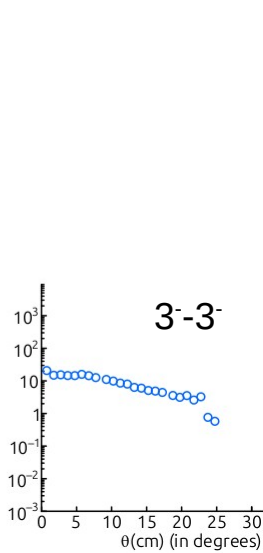
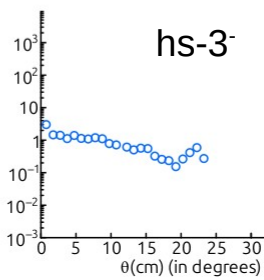
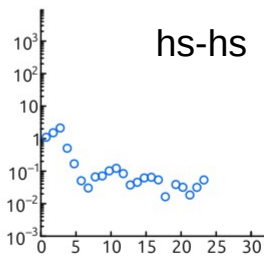
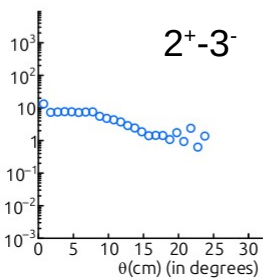
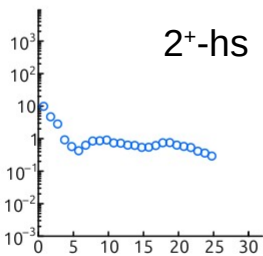
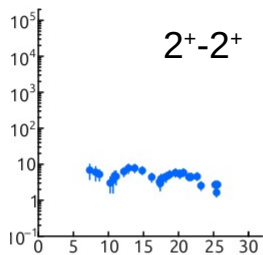
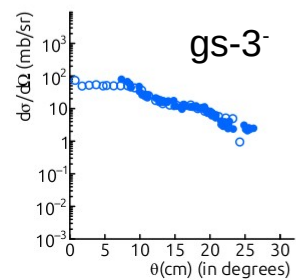
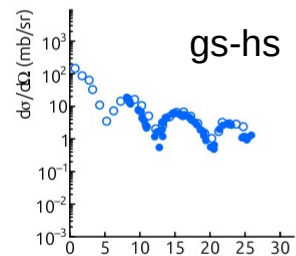
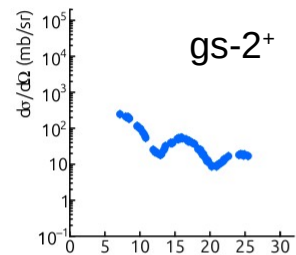
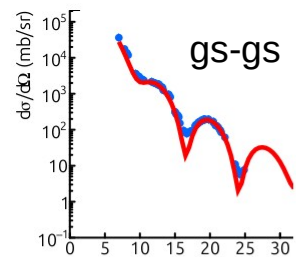
→ Measure the Hoyle state matter radius using elastic and inelastic $^{12}\text{C} + ^{12}\text{C}$ scattering cross sections

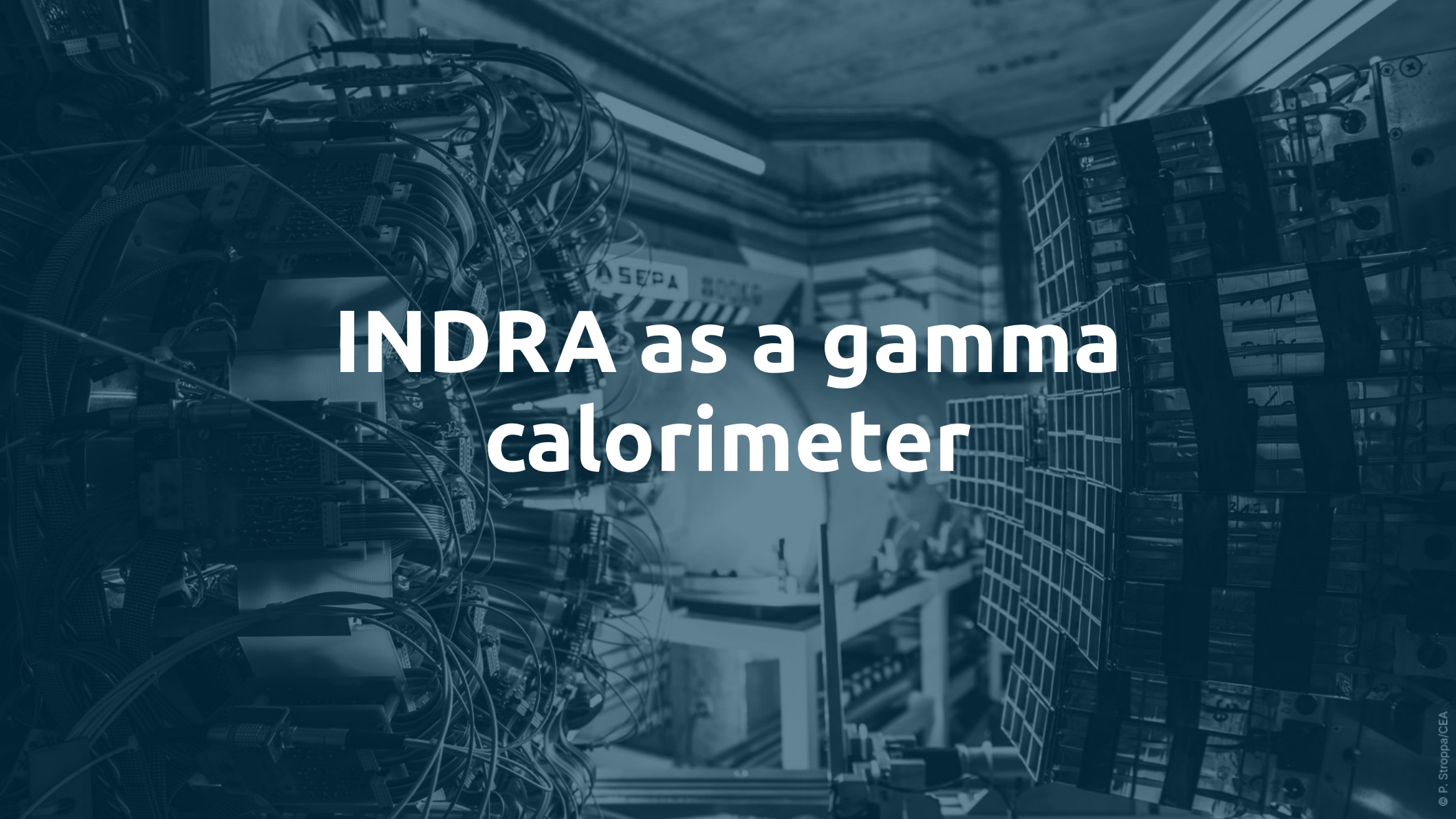
[1] S. Shen et al., Nature Com. 14 (2023) 2777

[2] T. Otsuka et al., Nature Com. 13 (2022) 2234







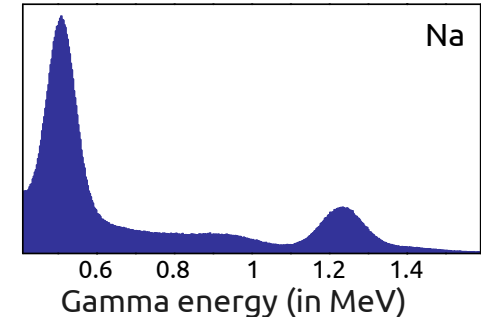
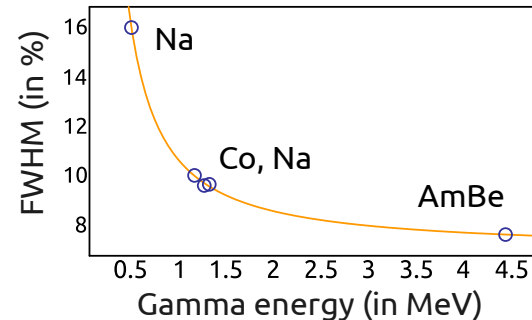
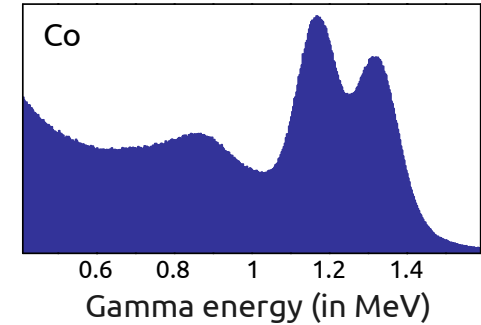
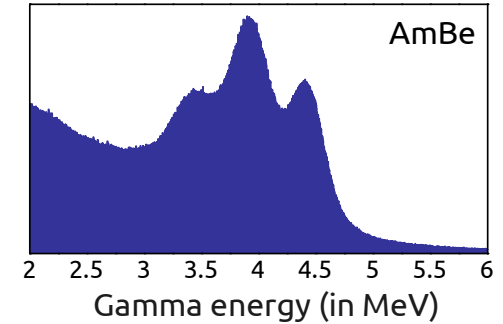
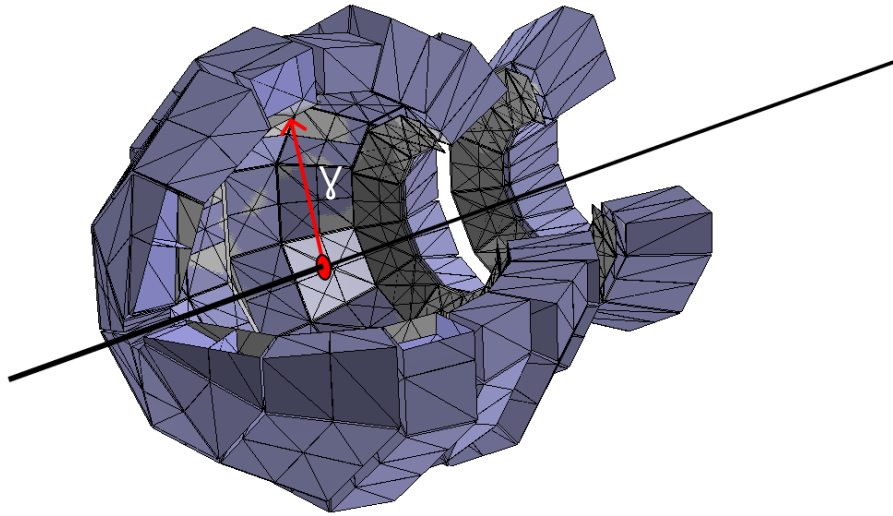


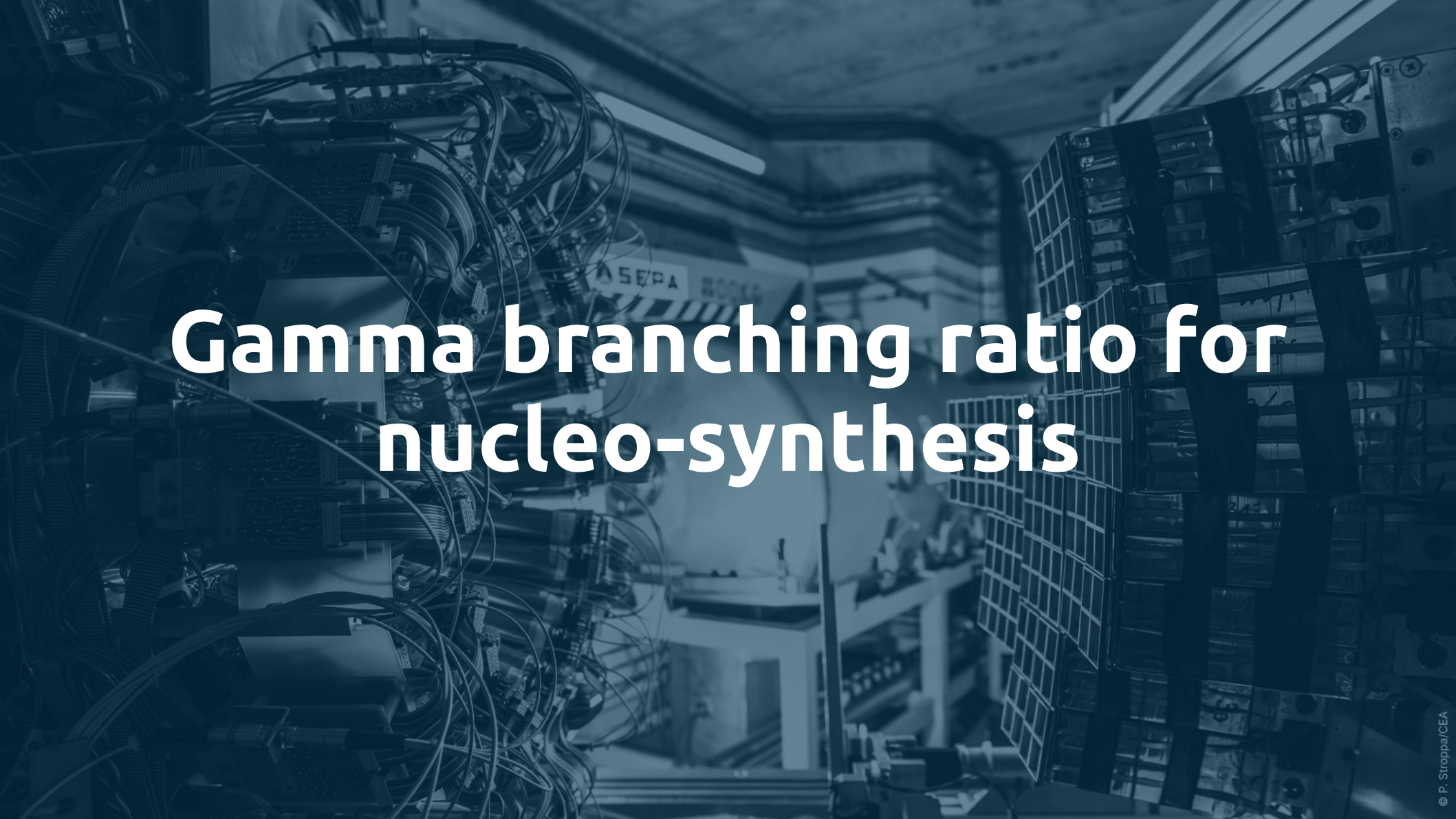
INDRA as a gamma calorimeter

Gamma detection with INDRA

Gamma from the 2^+ state of ^{12}C were detected in INDRA CsI during the Hoyle state experiment.

- Calibration run with Na, Co and AmBe gamma sources
- Decent energy resolution and excellent overall efficiency !





Gamma branching ratio for nucleo-synthesis

High temperature nucleo-synthesis

In normal stars, ^{12}C is mostly produced by the three alpha process through the Hoyle state (7.65 MeV). At higher temperature, the 3^- (9.64 MeV) state might contribute but the poor knowledge of the 3^- gamma decay branching ratio leads to very uncertain rates.

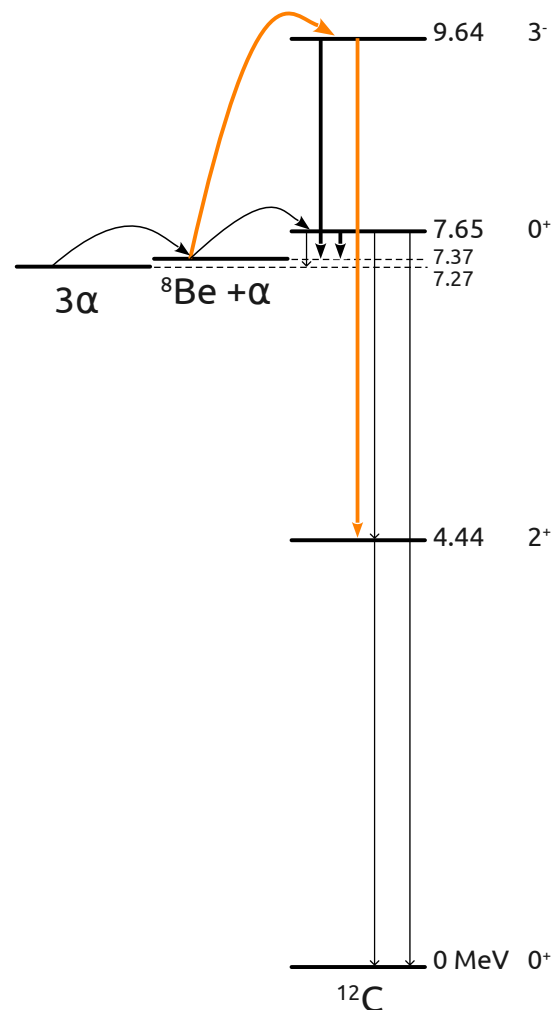
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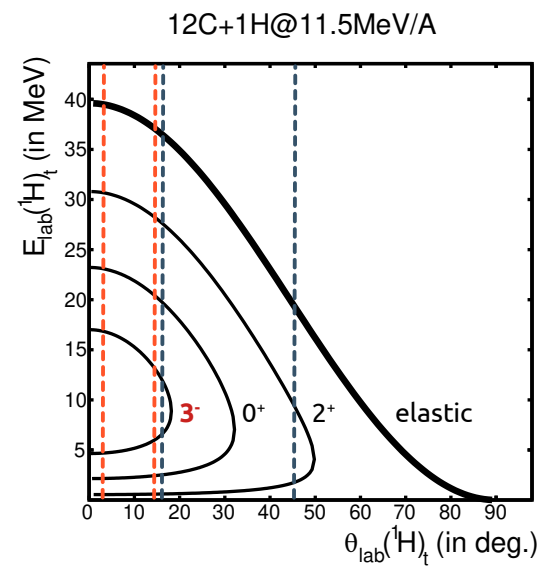
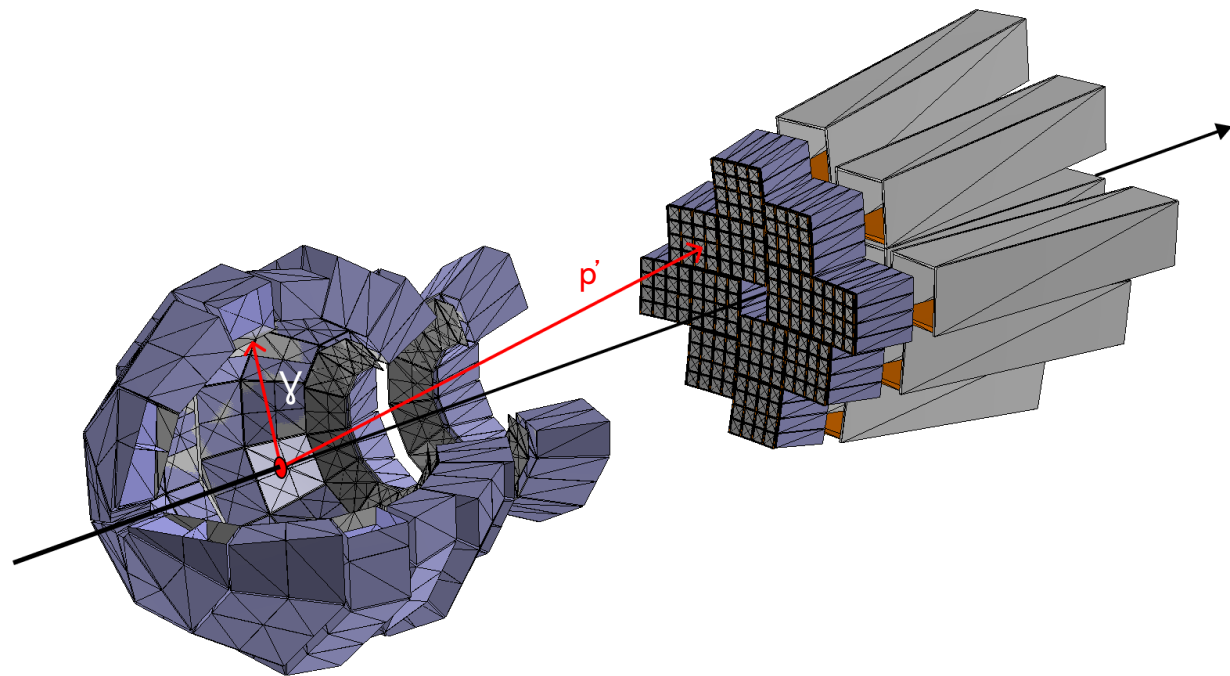
- $\Gamma_\gamma = 0.31 \text{ meV}$: Crannell et al. (1967) (e,e')
- $\Gamma_{\text{rad}}/\Gamma_{\text{tot}} < 10^{-7}$: Chamberlin (1974) (p,p') [$p\text{-}^{12}\text{C}$]
- $\Gamma_{\text{rad}}/\Gamma_{\text{tot}} = 1.3(1.2) \cdot 10^{-6}$: Tsumura (2021) (p,p') [$p\text{-}^{12}\text{C}$]
- $\Gamma_{2\gamma}/\Gamma_{\text{tot}} = 6.4(5.1) \cdot 10^{-5}$: Cardella (2021) (p,p') [$p\text{-}^{12}\text{C}-\gamma-\gamma$]

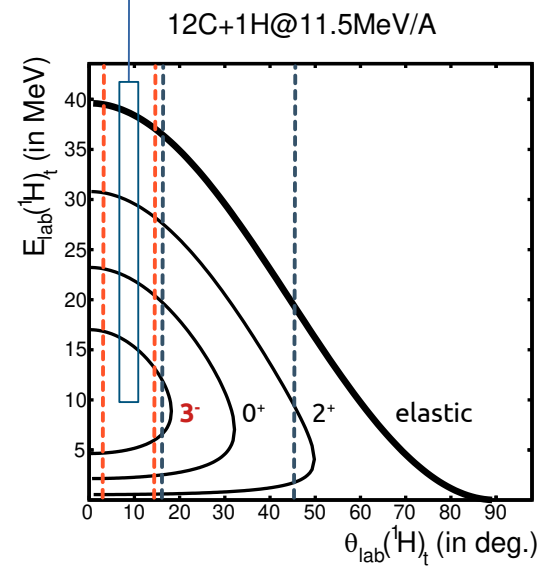
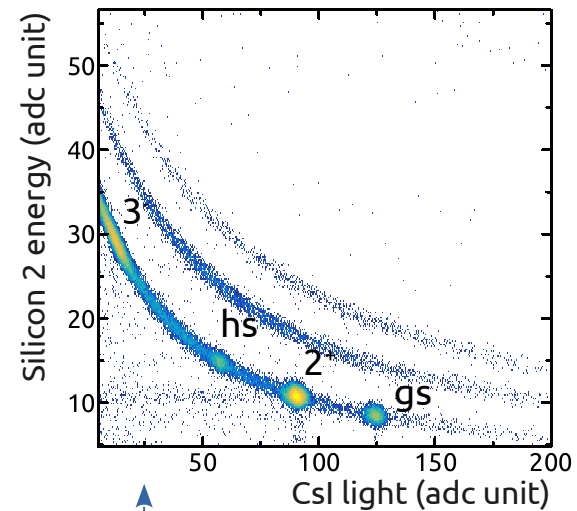
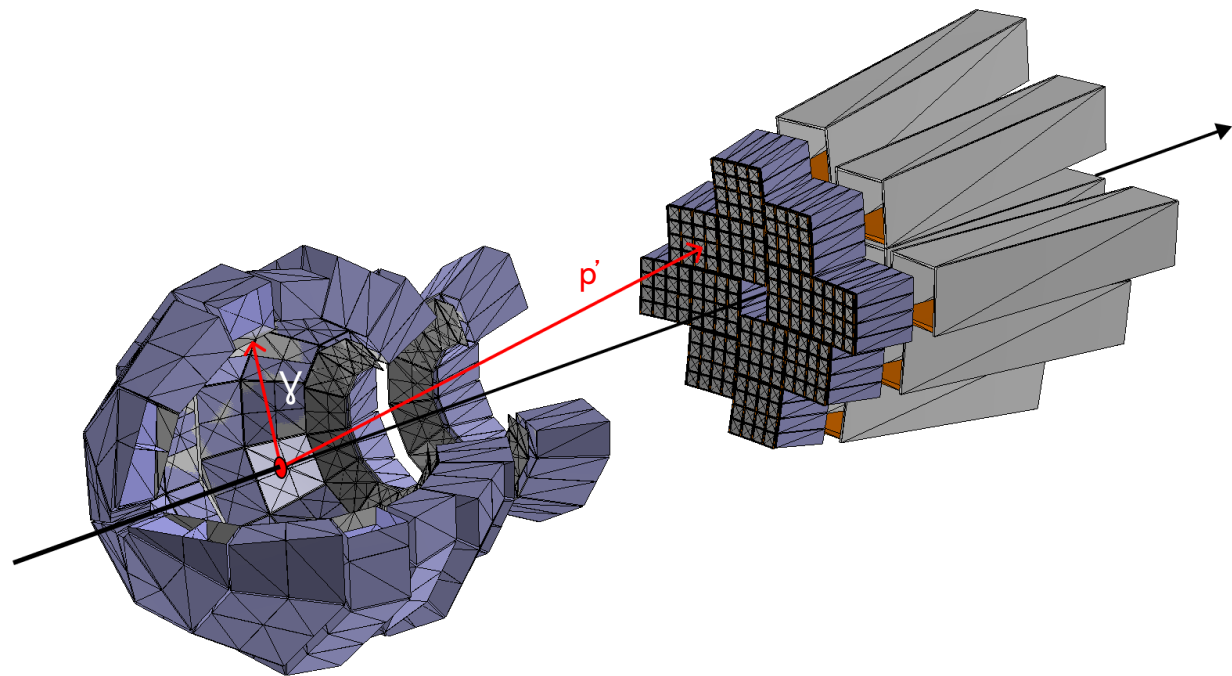
T26-01 (2026)

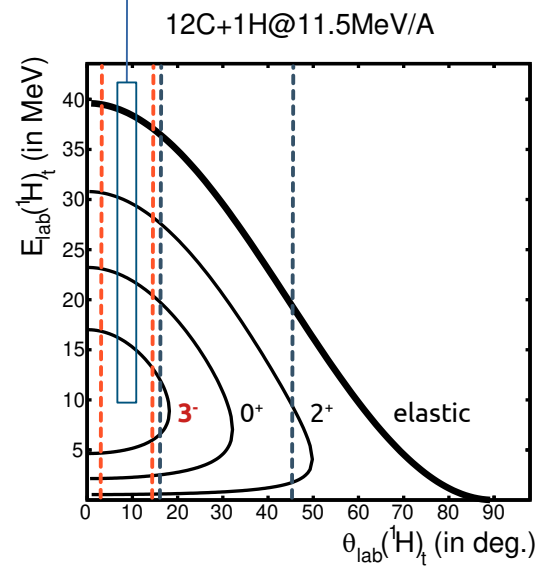
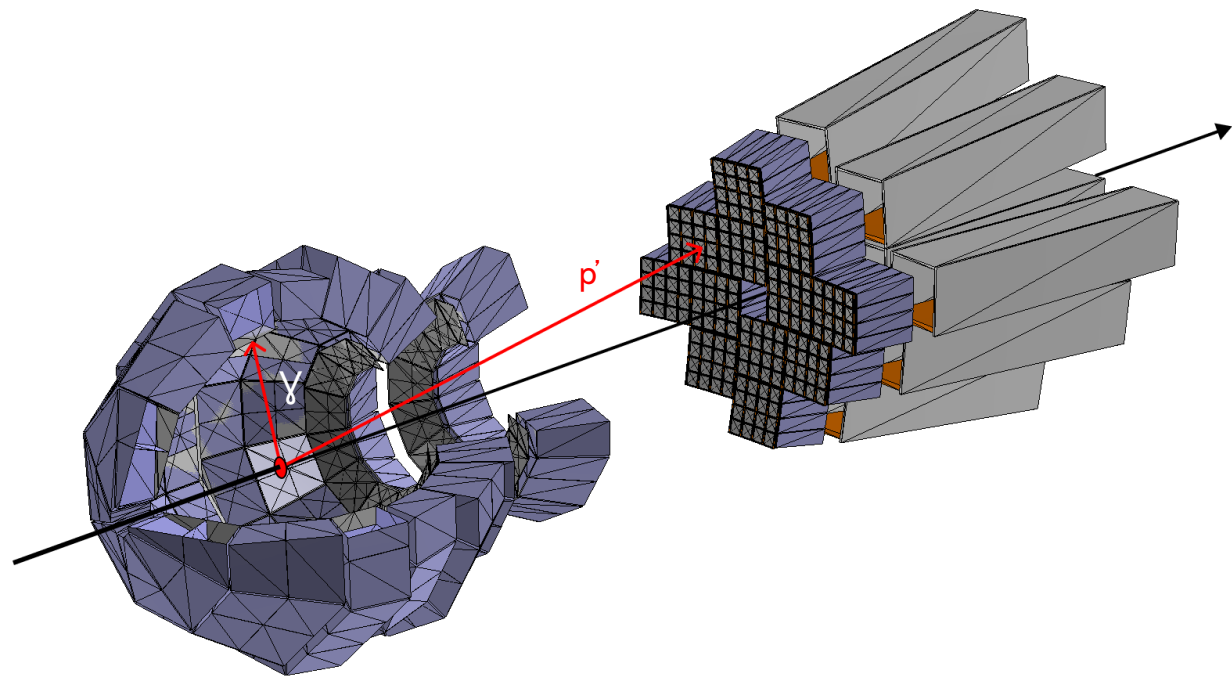
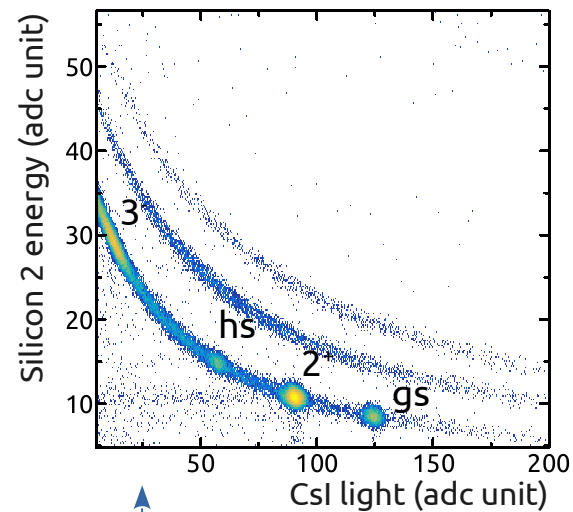
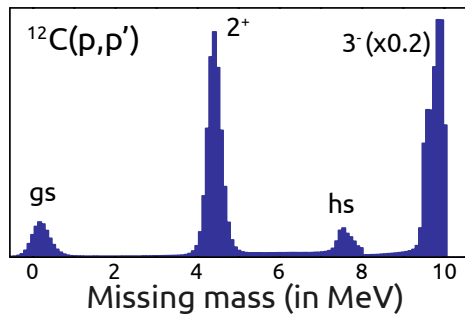
Measure $\Gamma_{2\gamma}/\Gamma_{\text{tot}}$ in (p,p') reaction with [p- γ - γ] coincidences benefiting from the good resolution of FAZIA for detecting the protons and the good efficiency of INDRA for the gamma rays.

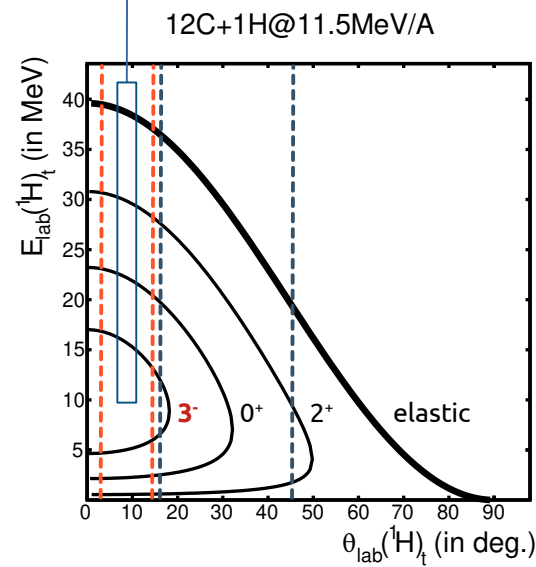
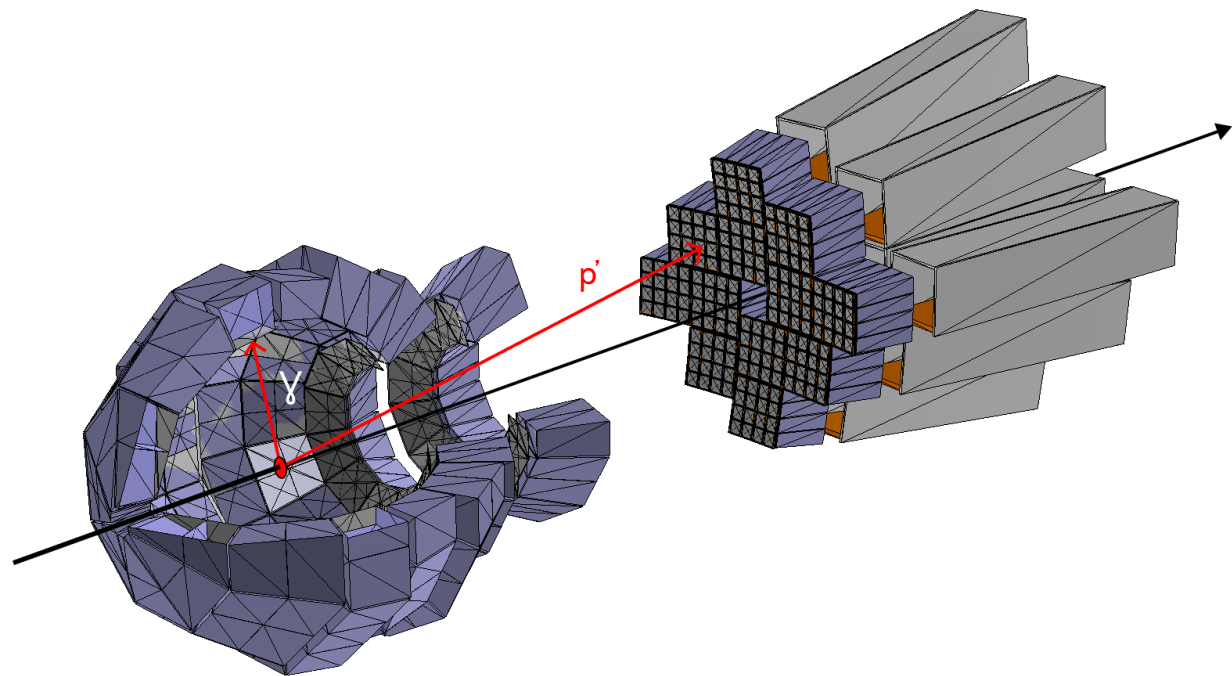
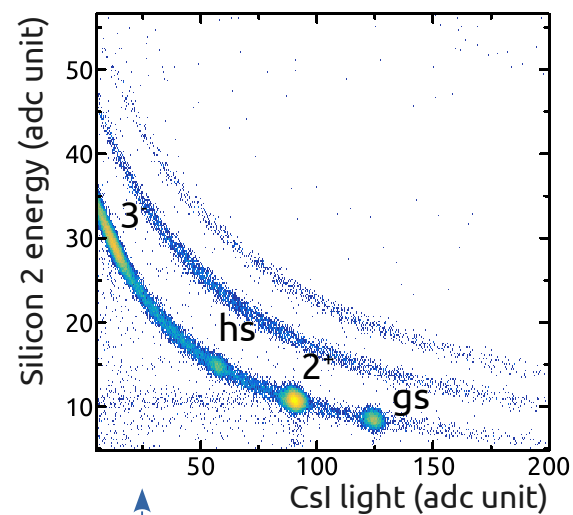
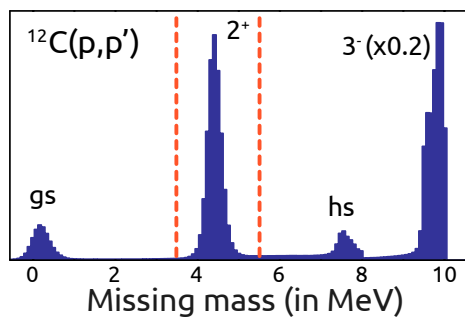
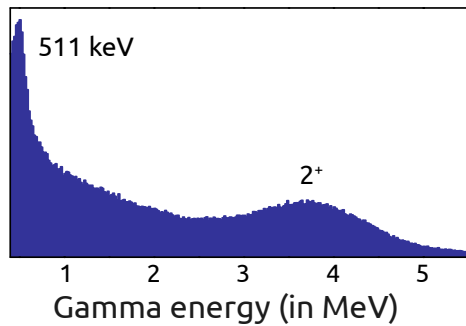
→ 30% relative uncertainty on $\Gamma_{2\gamma}/\Gamma_{\text{tot}}$

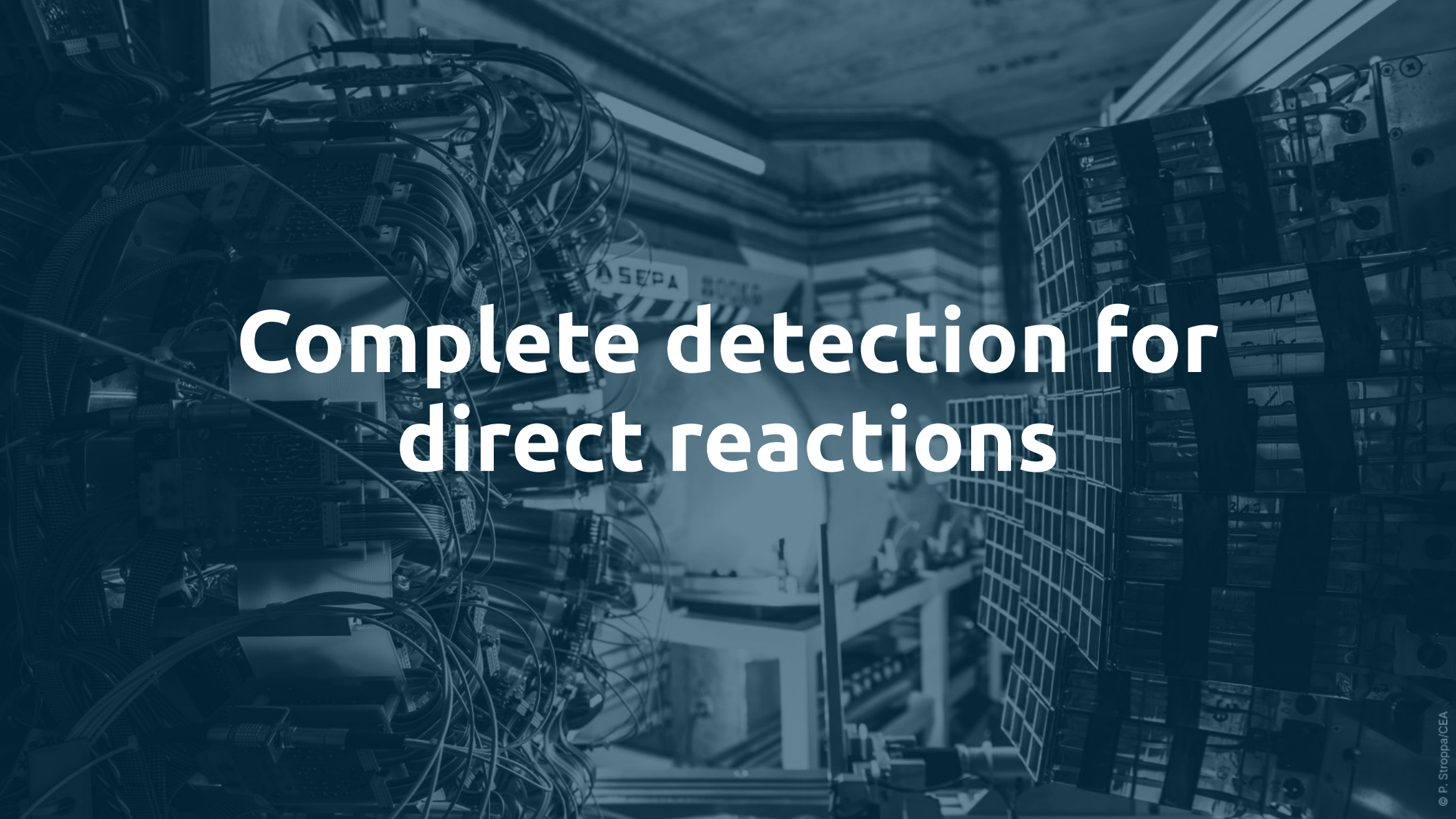
$$\rightarrow {}^{12}\text{C} + \text{CH}_2 @ 11 \text{ MeV/nuc.}$$




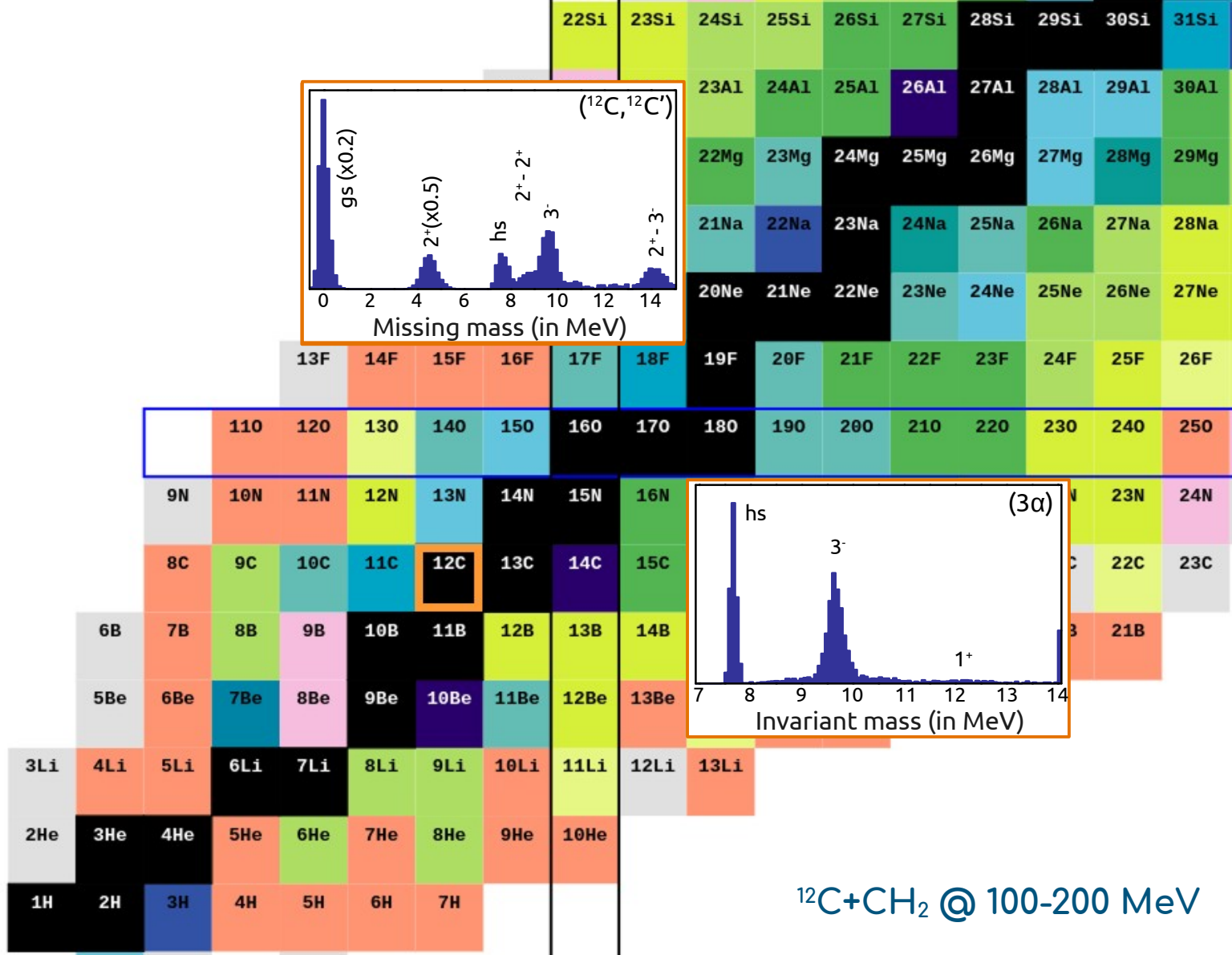




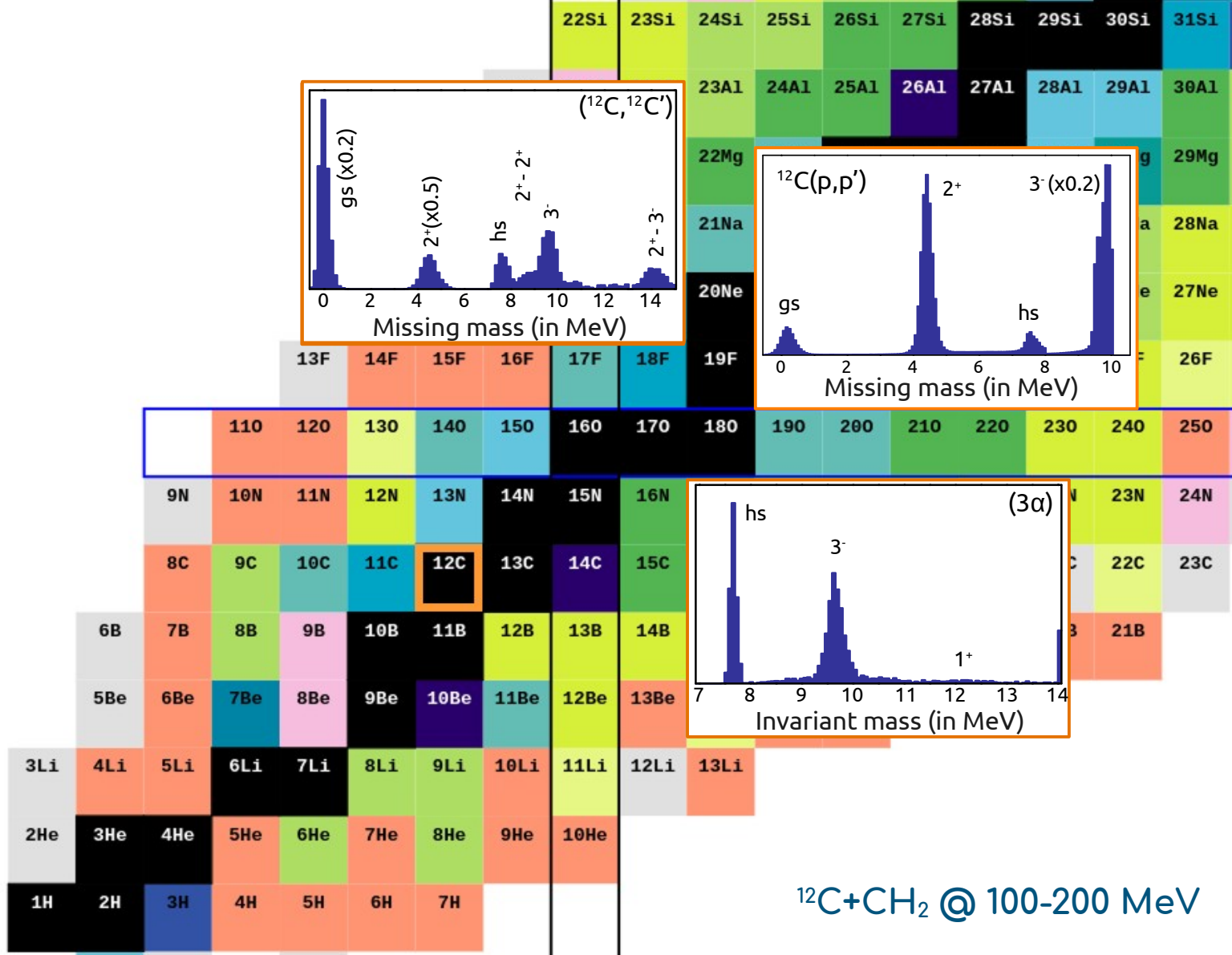


The background image shows a complex particle detector, likely a large-scale scientific instrument. It features a dense network of cables and wires on the left, and a large, grid-like structure on the right. The entire image is tinted with a dark blue color. The text "Complete detection for direct reactions" is overlaid in the center in a white, bold, sans-serif font.

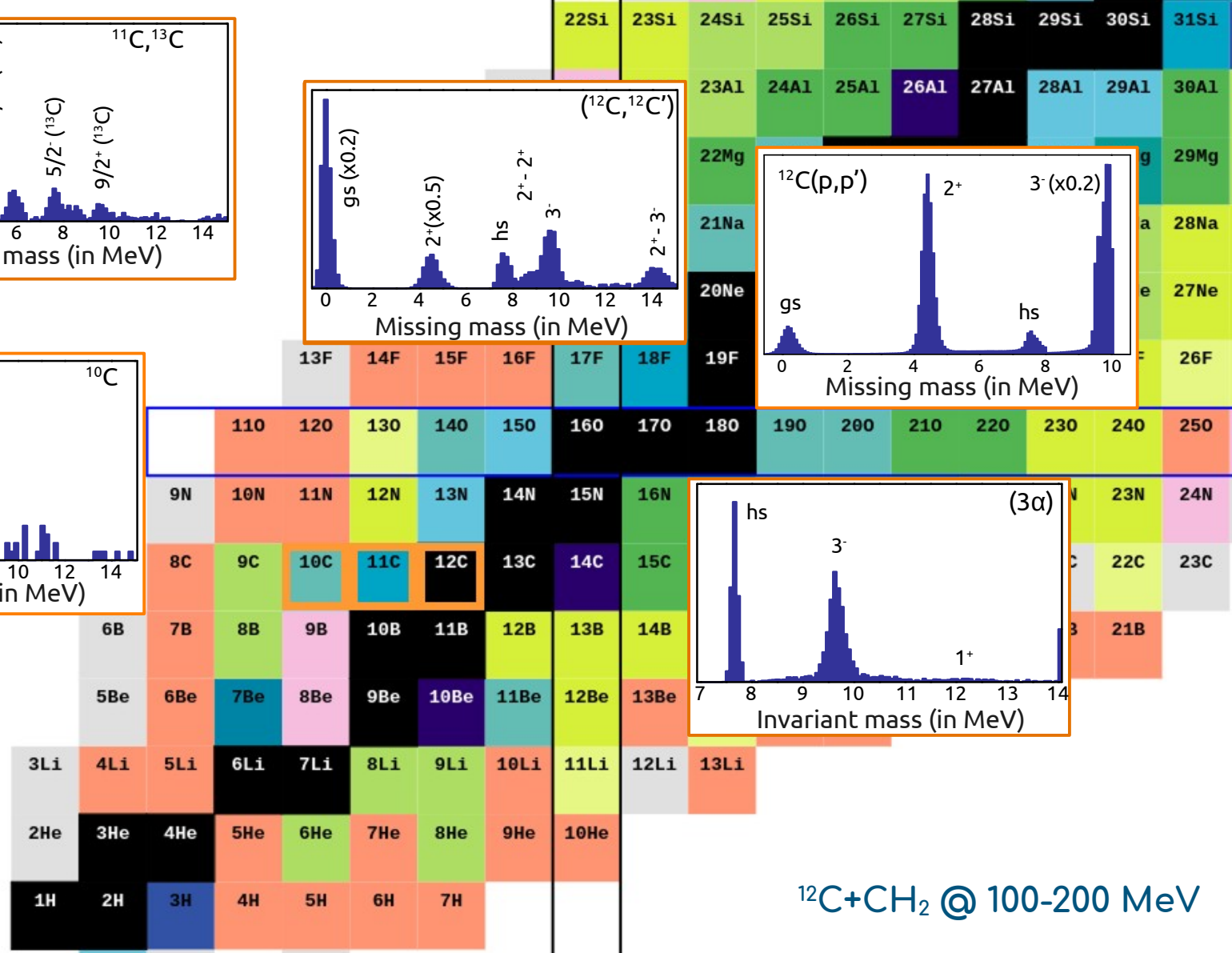
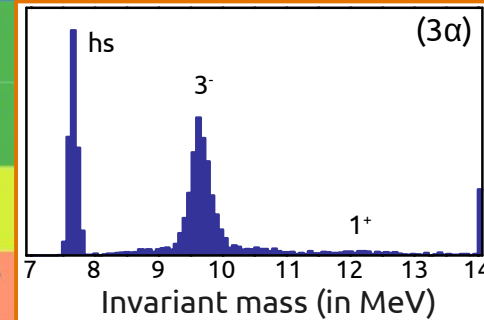
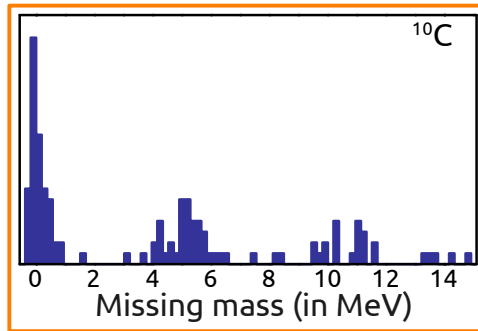
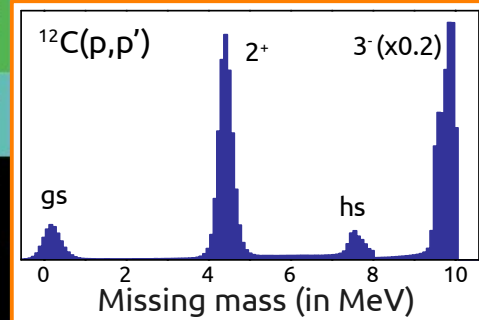
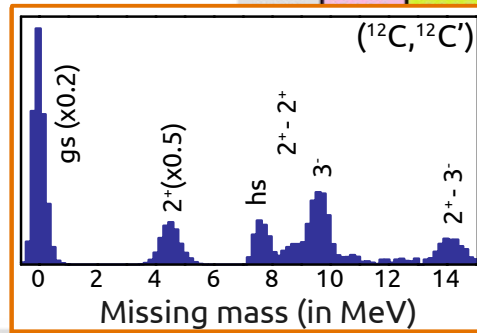
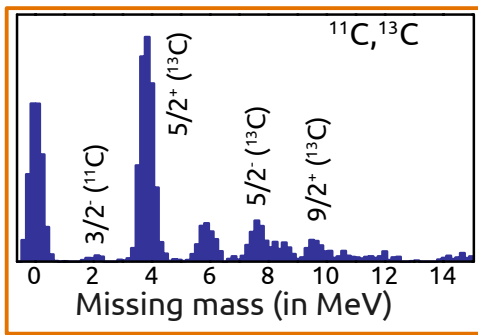
Complete detection for direct reactions



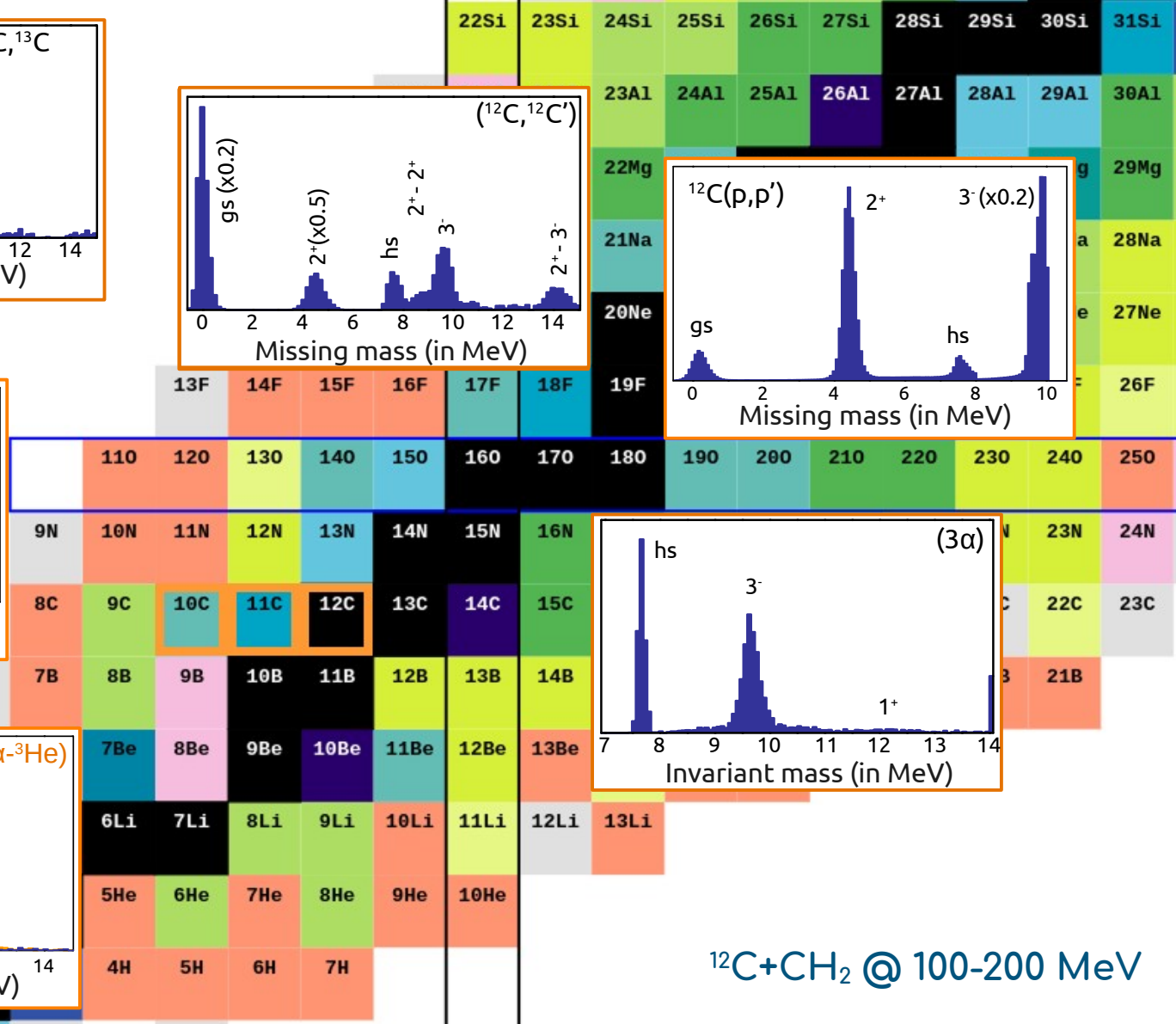
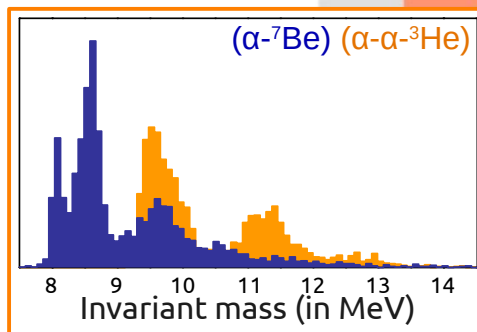
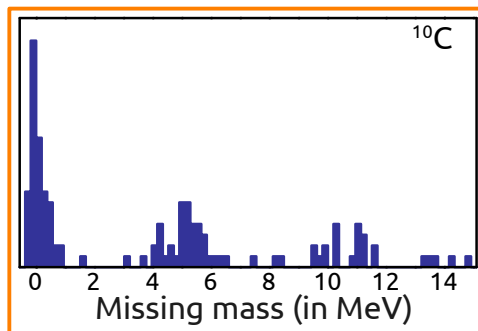
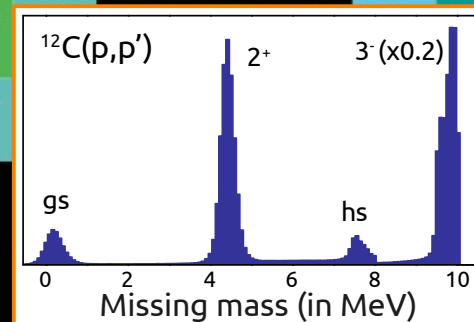
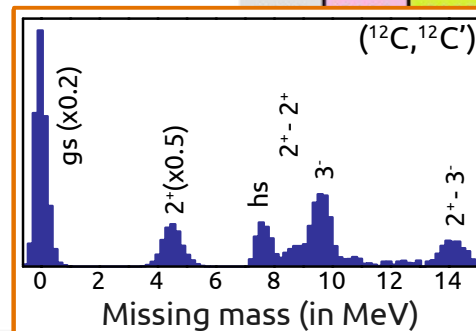
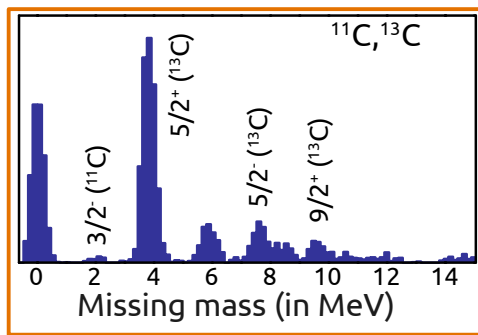
$^{12}\text{C} + \text{CH}_2$ @ 100-200 MeV



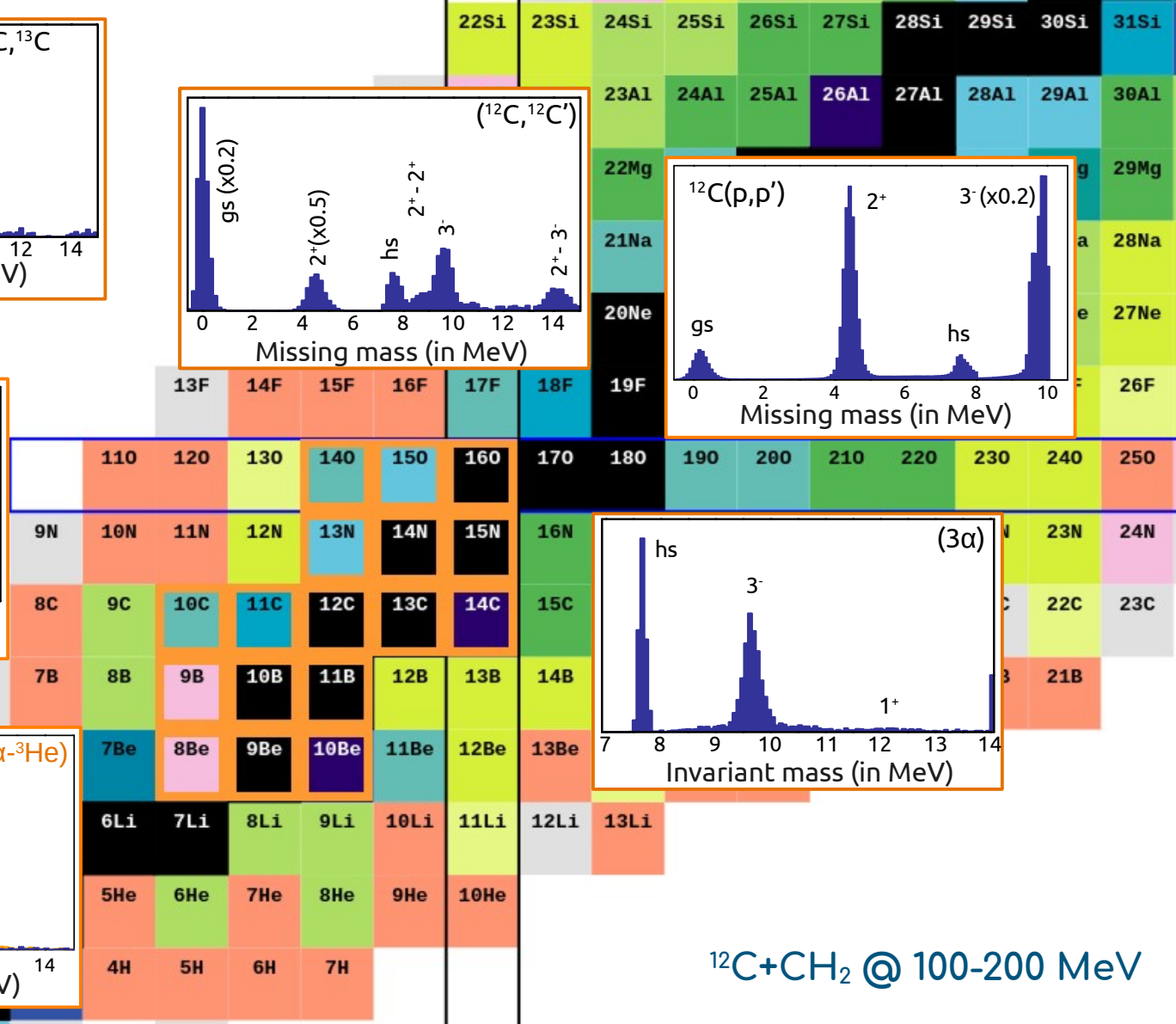
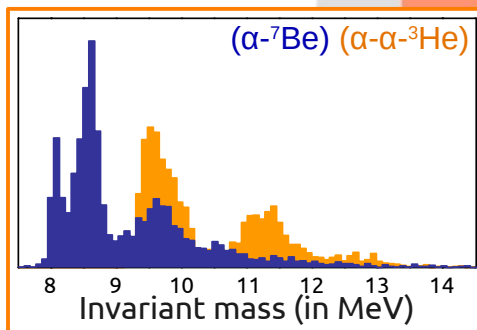
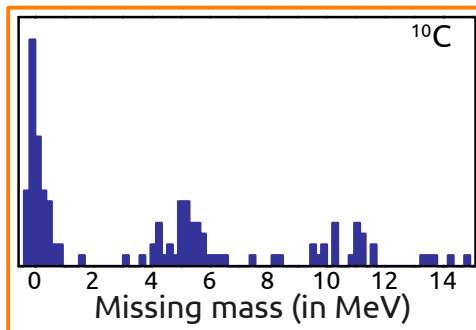
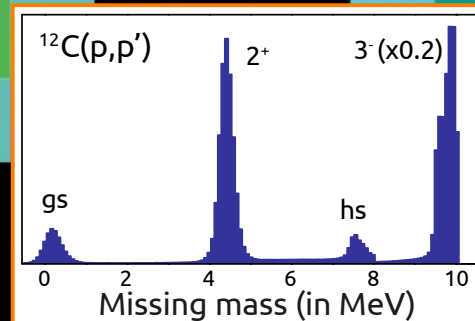
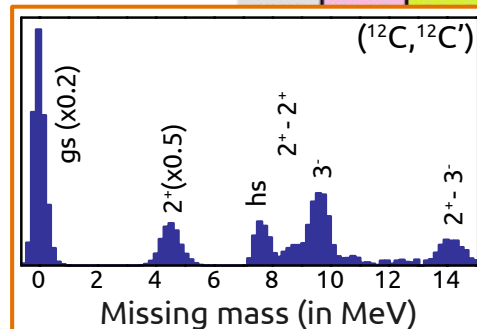
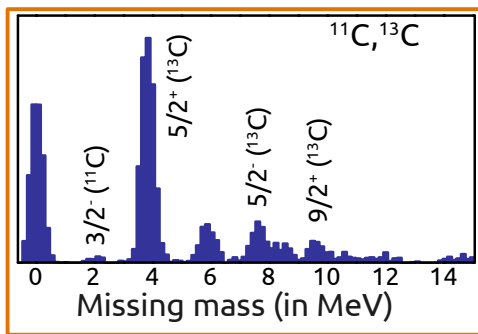
$^{12}\text{C} + \text{CH}_2$ @ 100-200 MeV



$^{12}\text{C}+\text{CH}_2$ @ 100-200 MeV



$^{12}\text{C}+\text{CH}_2$ @ 100-200 MeV



$^{12}\text{C}+\text{CH}_2$ @ 100-200 MeV



Opportunities with SPIRAL1 beams

Hoyle-analog state in ^{13}N

Ying-Yu Cao (曹颖逾)

Key Laboratory of Nuclear Physics and Ion-beam Application (MOE), Institute of Modern Physics,

Fudan University, Shanghai 200433, China

and Center for Fundamental Physics and School of Mathematics and Physics, Hubei Polytechnic University, Huangshi 435003, China

We investigate the cluster structure of ^{13}N using a microscopic $\alpha + \alpha + \alpha + p$ four-body cluster model. The calculated spectra reasonably agree with the observed spectra in the low-lying states. We calculate the reduced width amplitudes and spectroscopic factors to investigate the Hoyle-analog state in ^{13}N . Our calculations show that the $3/2^-$ state at $E_x = 10.8$ MeV is primarily composed of $^{12}\text{C}(0_2^+) + p$ and $^9\text{B}(3/2^-) + \alpha$ components. This finding is generally consistent with the newly observed $3/2^-$ state at $E_x = 11.3$ MeV via the $3\alpha + p$ decay channel. Moreover, considering the calculated root-mean-square radius and isoscalar monopole transition strength, the $3/2^-$ state emerges as a candidate for the Hoyle-analog state with the $^{12}\text{C}(0_2^+) + p$ cluster structure.

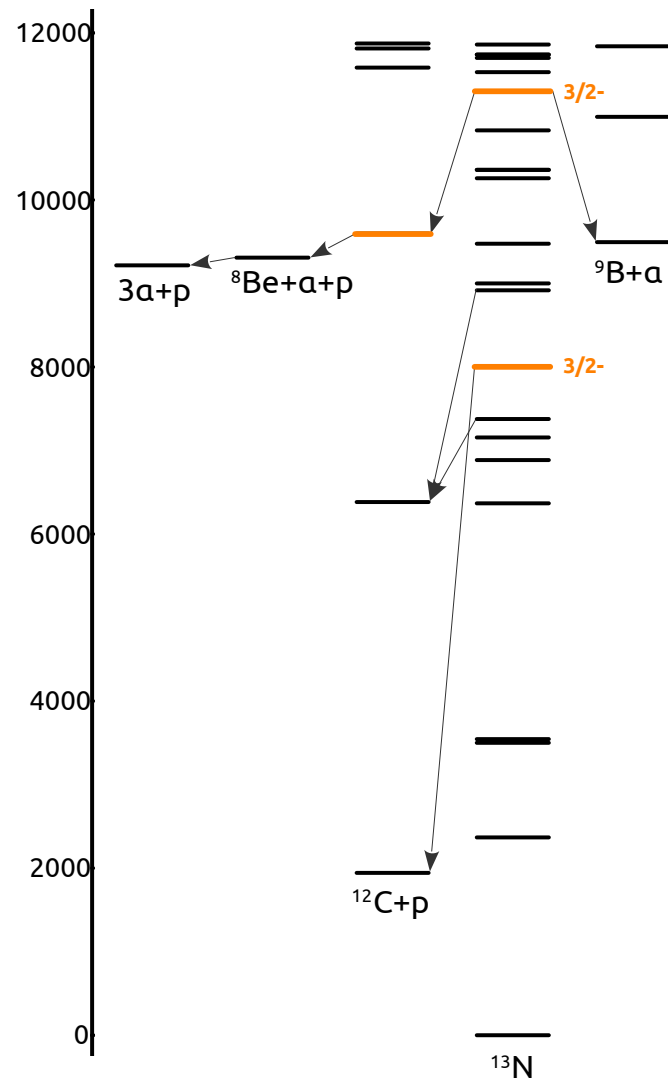
Decay of the proton-unbound superradiant state in ^{13}N

K. Hanselman^{1,*}, I. Wiedenhöver¹, A. Volya¹, L. T. Baby¹, G. W. McCann¹, K. T. Macon²,
E. C. Good², C. M. Deibel², B. Sudarsan² and J. C. Blackmon²

¹Department of Physics, Florida State University, Tallahassee, Florida 32301, USA

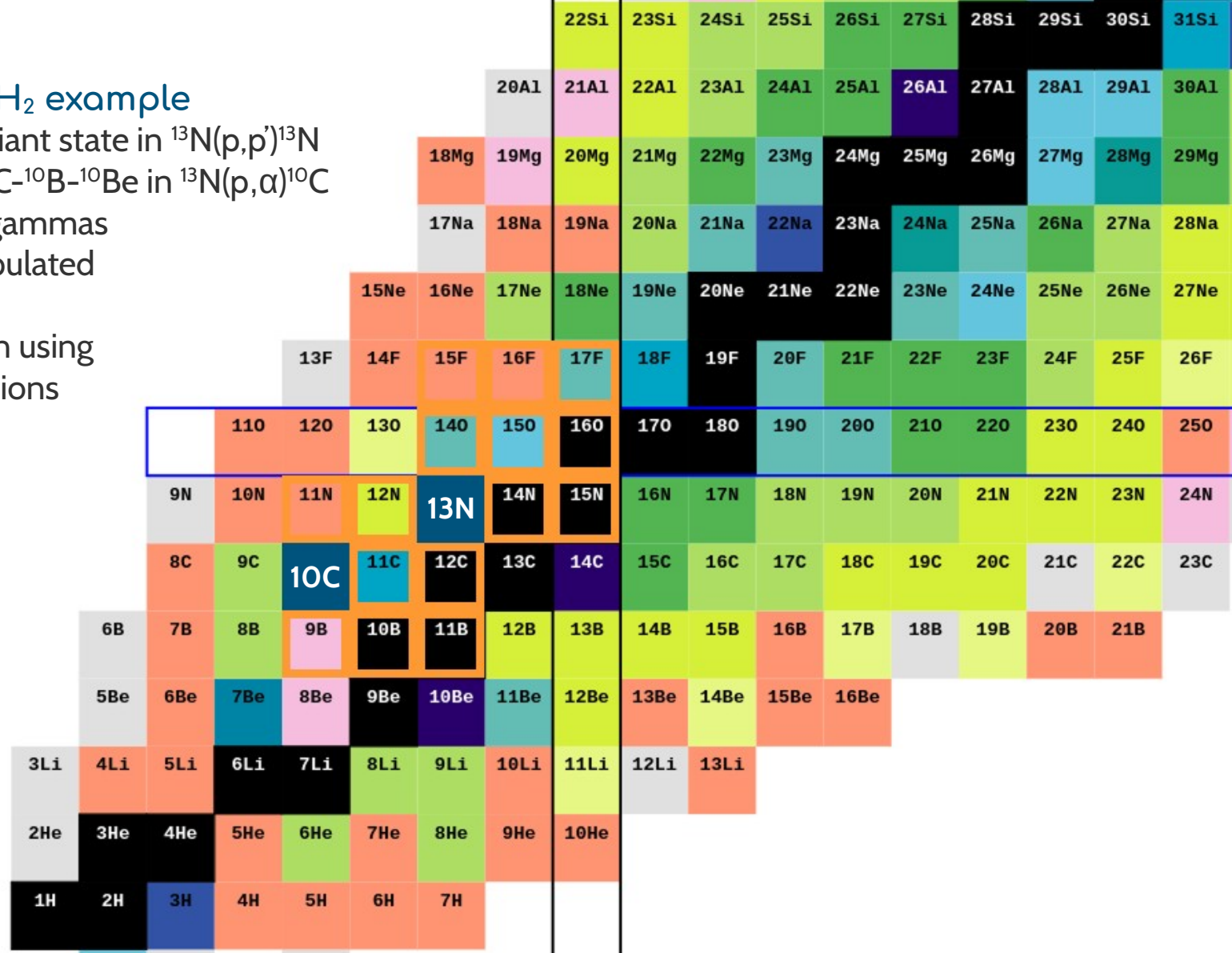
²Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803, USA

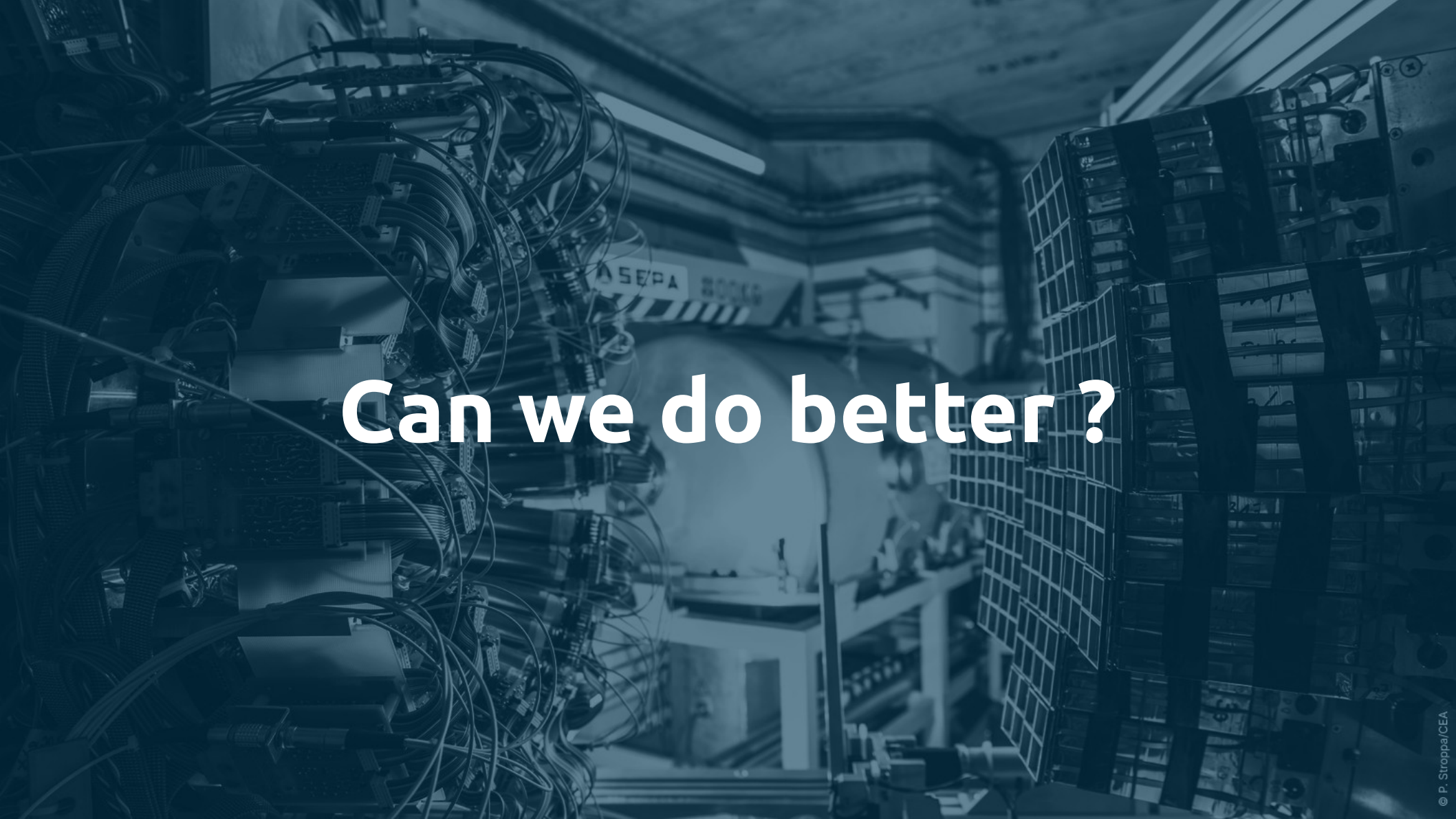
The $^{12}\text{C}(^3\text{He}, d)^{13}\text{N}^*$ reaction is studied in an experiment with a high-resolution magnetic spectrograph, in coincidence with protons detected in silicon detectors near the target. This allows for the observation of angular correlation patterns between the proton transfer and proton decays from populated unbound resonances. A formalism describing the spin polarization of direct reactions is developed to analyze these correlations, and is verified on the known directionally asymmetric decay distributions arising from parity mixing in the $^{13}\text{N}(\frac{3}{2}^-, \frac{5}{2}^+)$ doublet. The same formalism is used to study the decays from the continuum-aligned, broad $3/2^+$ resonance at 7.9 MeV excitation energy, which arises from superradiant coupling. The observed asymmetric angular correlation patterns are approximately reproduced by adding an “artificial” $3/2^-$ resonance with strength equal to that of the reaction formalism. This parity-mixing approach serves as a first approximation to a more advanced reaction model of rapid reaction and decay sequences.



Hoyle analog and super-radiant state in $^{13}\text{N}(p,p')^{13}\text{N}$
 Thomas-Ehrman shift for ^{10}C - ^{10}B - ^{10}Be in $^{13}\text{N}(p,\alpha)^{10}\text{C}$
 Complementary info from gammas
 All transfer channel also populated

→ Excellent detector for cluster studies





Can we do better ?

FAZIA for charged particle spectroscopy

- Excellent missing mass resolution on the heavy projectile-like thanks to good quality **silicon pads**
- Good performances for invariant mass thanks to individual '**pixels**' designed for high multiplicity events but lack of resolution
- Decent performances for (p,p') and (p,α) but lack of resolution

INDRA for gamma calorimetry/veto

- Decent energy resolution for high energy gammas
- Excellent overall **efficiency** at 4 MeV ($\sim 30\%$)

FAZIA for charged particle spectroscopy

- Excellent missing mass resolution on the heavy projectile-like thanks to good quality **silicon pads**
- Good performances for invariant mass thanks to individual '**pixels**' designed for high multiplicity events but lack of resolution
- Decent performances for (p,p') and (p,α) but lack of resolution

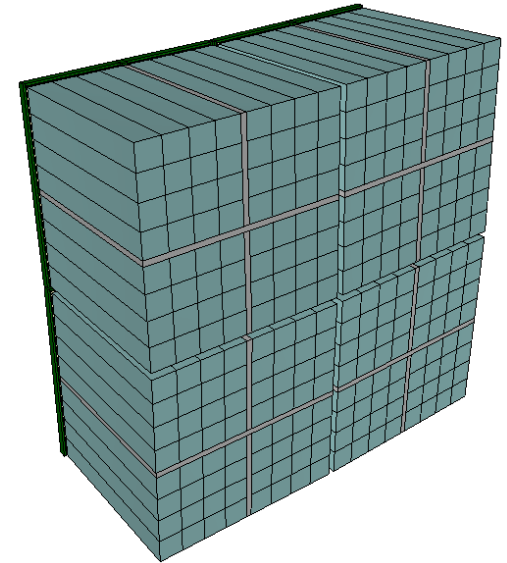
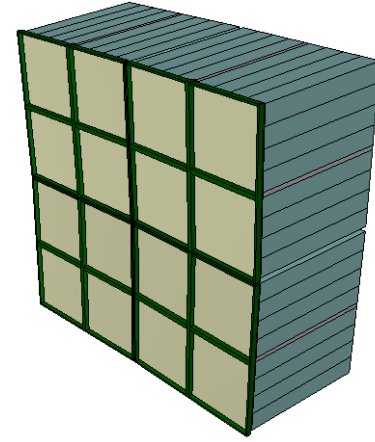
INDRA for gamma calorimetry/veto

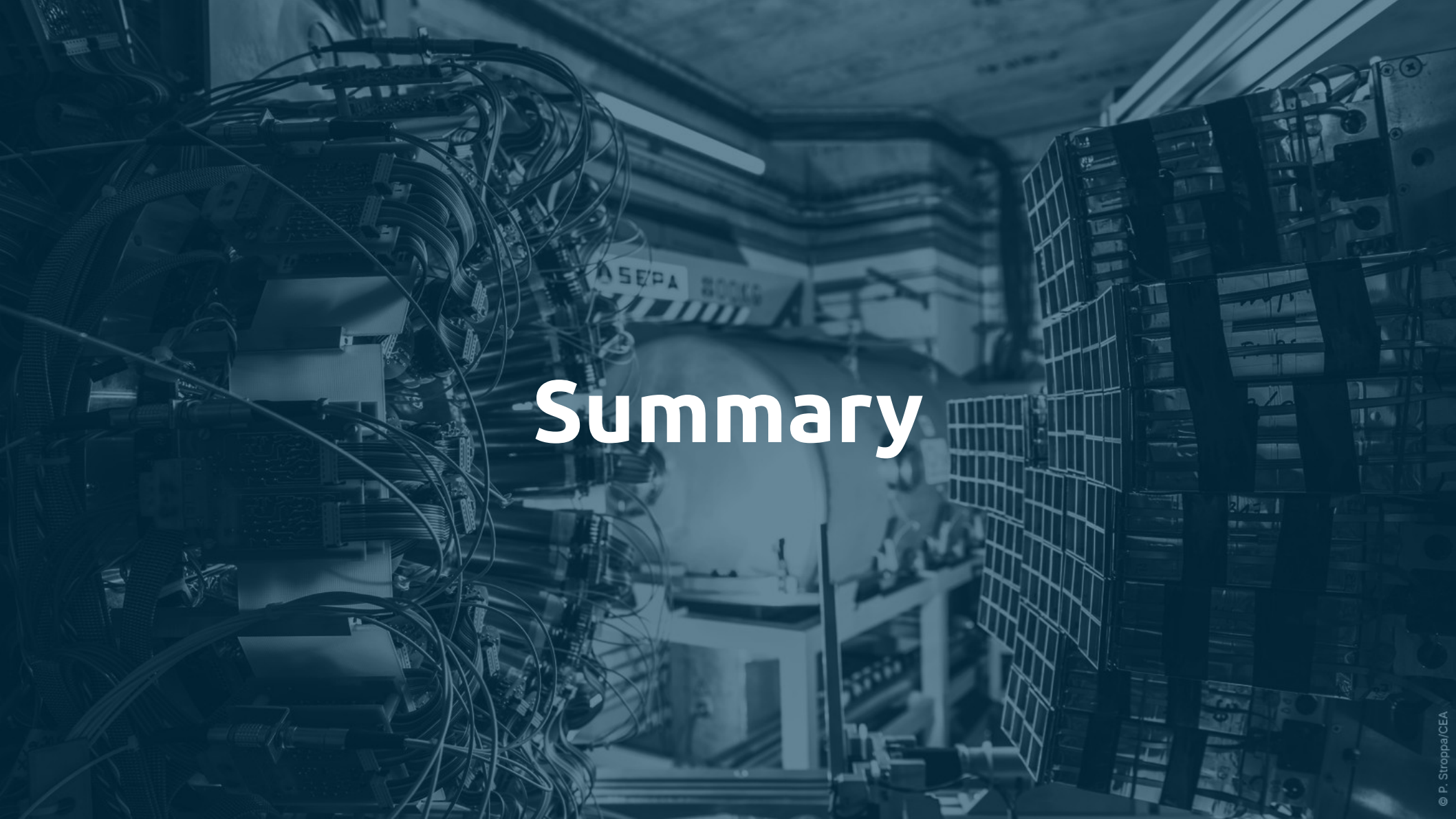
- Decent energy resolution for high energy gammas
- Excellent overall **efficiency** at 4 MeV ($\sim 30\%$)

Potential FAZIA upgrade

Keep the silicon pads for missing mass (heavy) but increase the granularity for invariant mass and (p,p') (light)

- Shorter CsI crystals (10cm $\rightarrow$ 4cm)
- Segmented CsI matrices (4x4?) read by SiPM
- Simplified electronic chain





Summary

