New techniques for direct charged particle measurement for stellar burning

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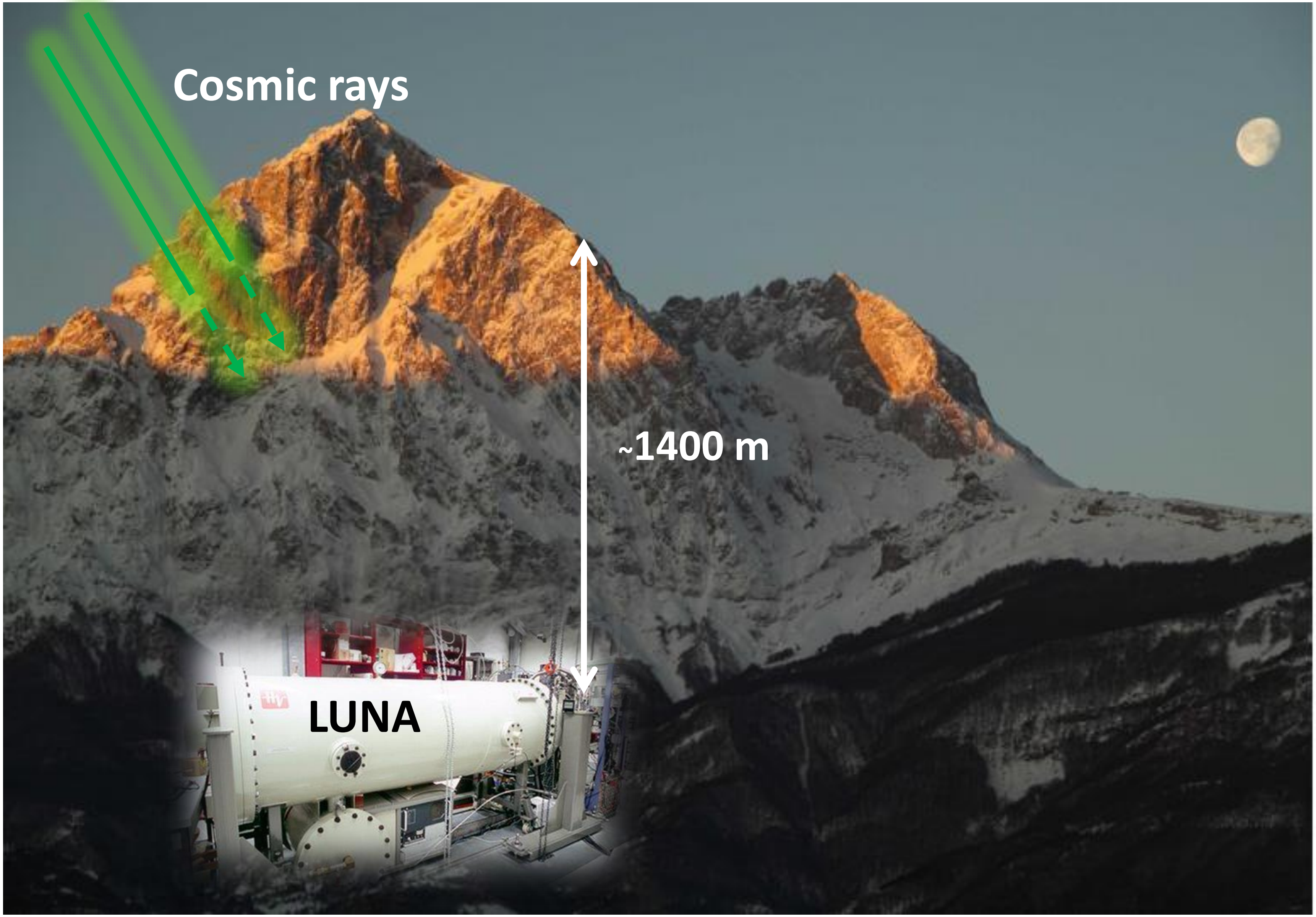
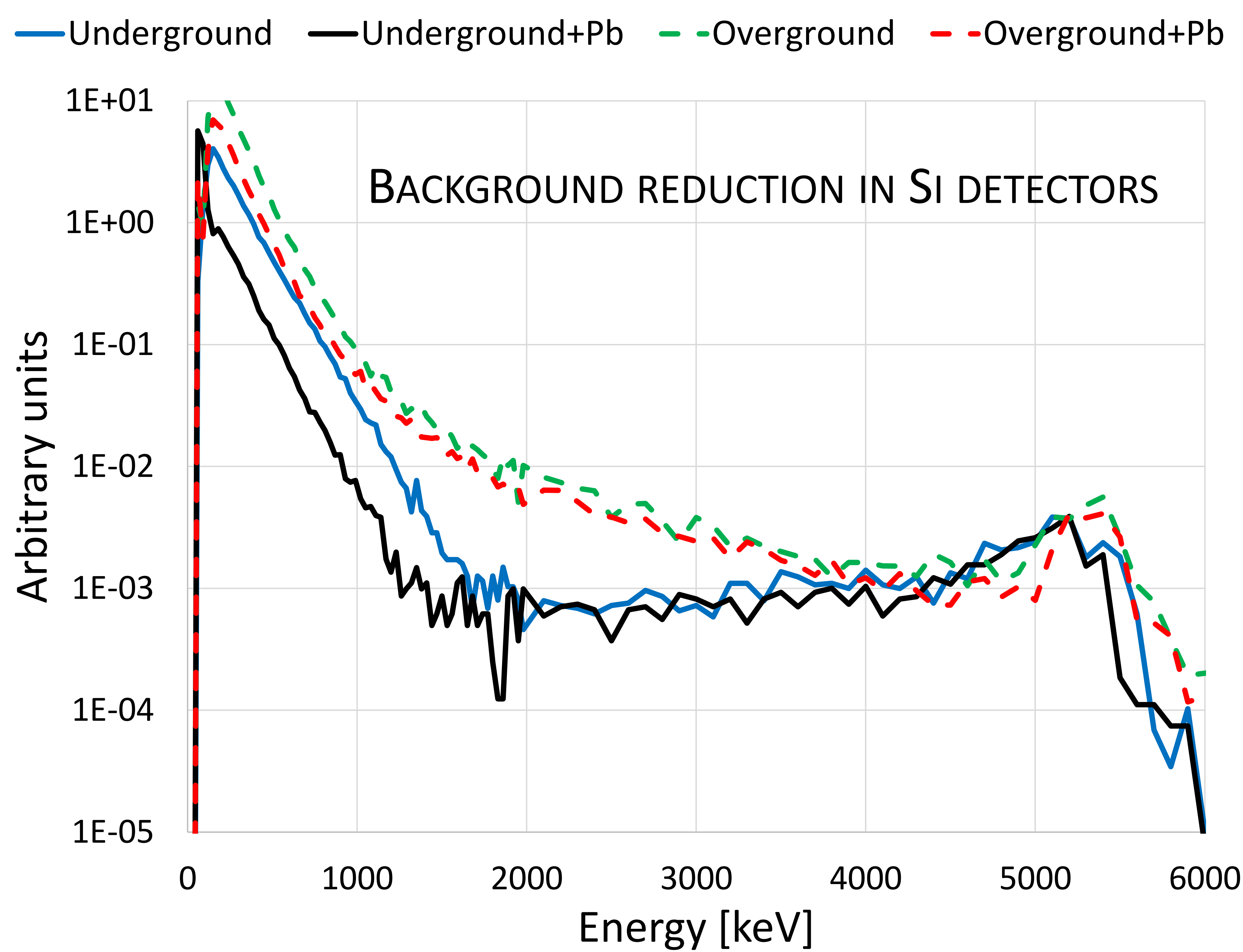
LUNA

(Laboratory for Underground Nuclear Astrophysics)

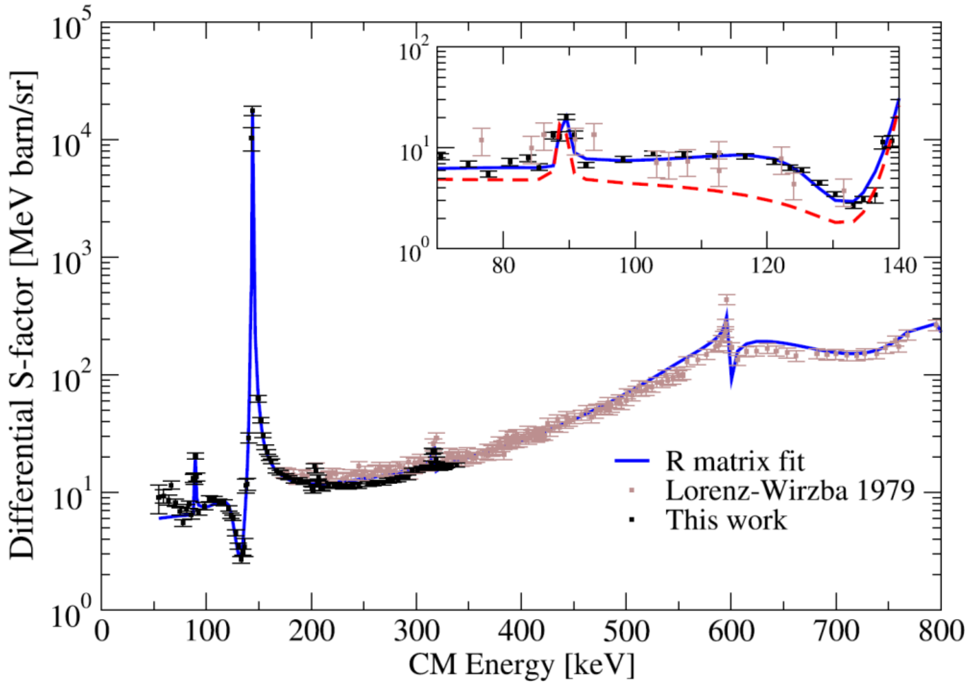


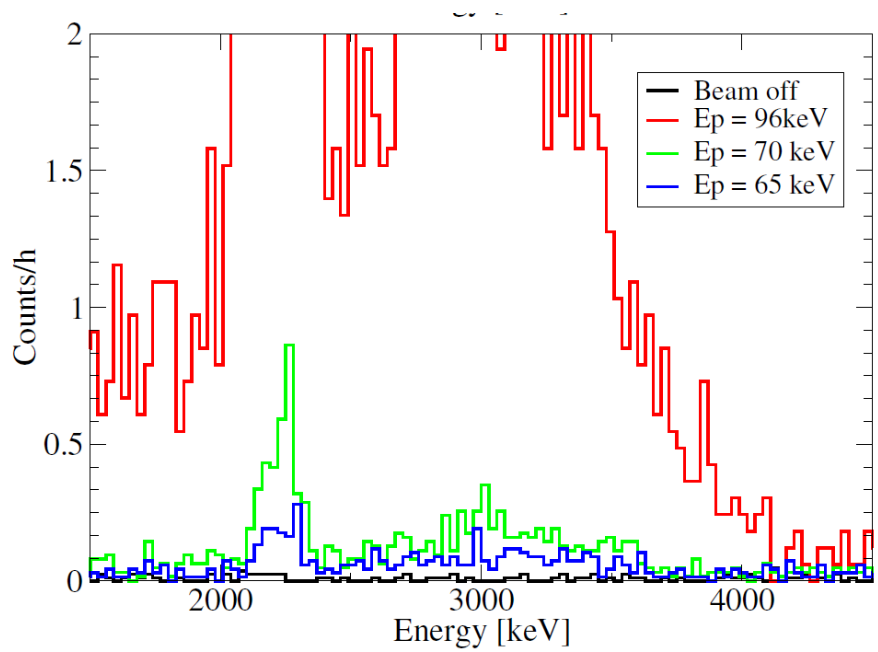


Underground
Underground+Pb
Overground
Overground+Pb
BACKGROUND REDUCTION IN SI DETECTORS
1E+01
1E+00
1E-01
1E-02
1E-03
1E-04
1E-05
Arbitrary units
0
1000
2000
3000
4000
5000
6000
Energy [keV]

$^{18}O(p,\alpha)^{15}N$

- Key CNO cycle reaction influencing isotopic abundances expected in pre-solar grains
- Measured at LUNA down to Ecm=55 keV ($\sigma \sim 10^{-12}$ barn)
- Multi-channel R-matrix fit required to extrapolate to lower energies and reproduce observed resonances





WHAT NEXT?

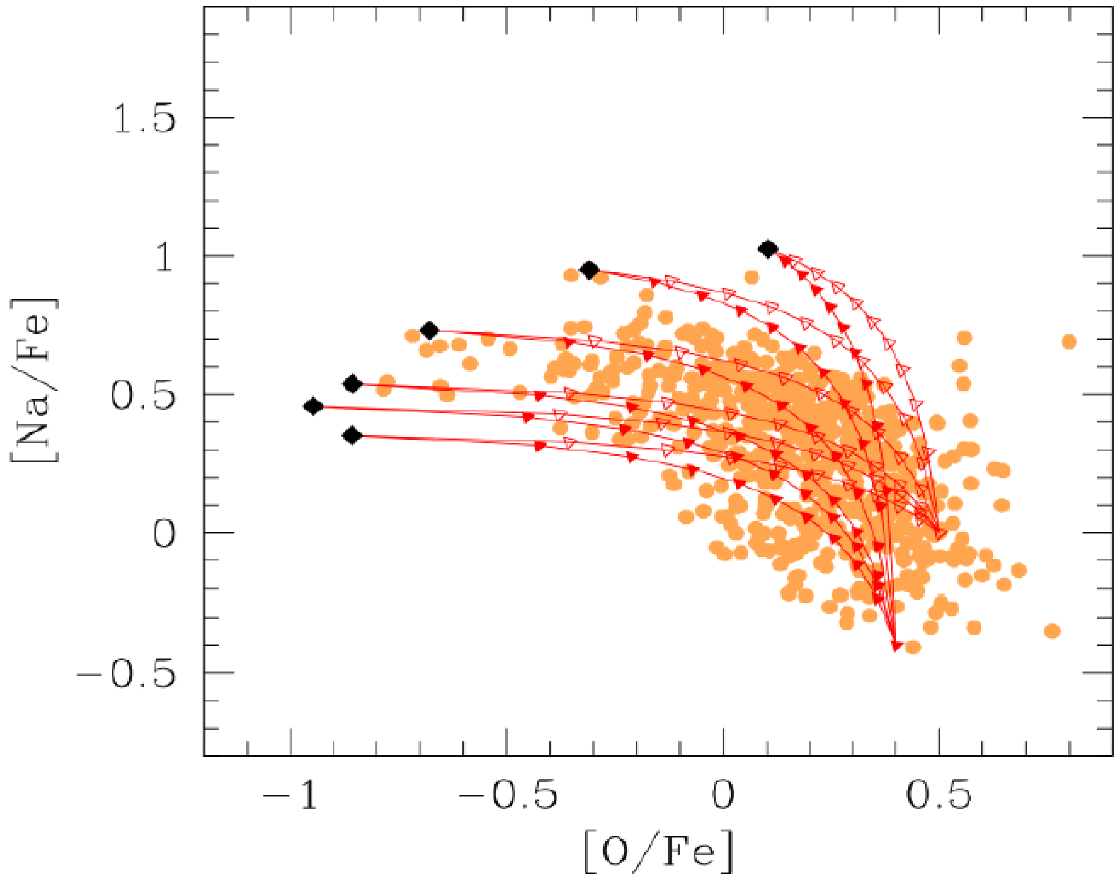
Globular clusters – how do they form?

Globular cluster NGC6441 seen by the Hubble telescope.

Different generations of stars observed. Secondary generations show CNO processing, but *constant* metallicity [Fe/H]!

Clusters are **not** enriched by supernova ejecta. Why? Were the ejecta lost? Do these stars not explode?

OXYGEN-SODIUM ANTI-CORRELATION



Slemer et al., MNRAS, 2017

Globular clusters models that could explain metallicity puzzle exist, but predict O-Na correlation.

However, O-Na are *anti-correlated* in clusters!

$^{23}Na(p,\alpha)^{20}Ne$

One poorly known isolated resonance in this reaction could solve the puzzle, but it is too weak to measure on the surface of the Earth.

Underground at LUNA it would be feasible!

ELDAR ERC Grant

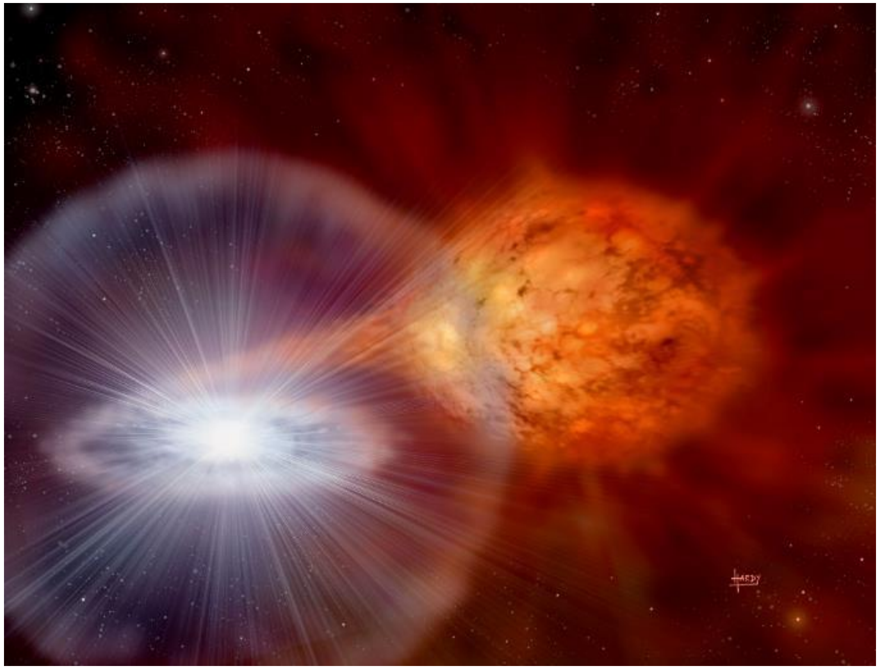
Burning Questions on the Origins of Elements in the Lives and Deaths of Stars

Science and Technology Facilities Council

European Research Council
Established by the European Commission

EXPLOSIVE BURNING

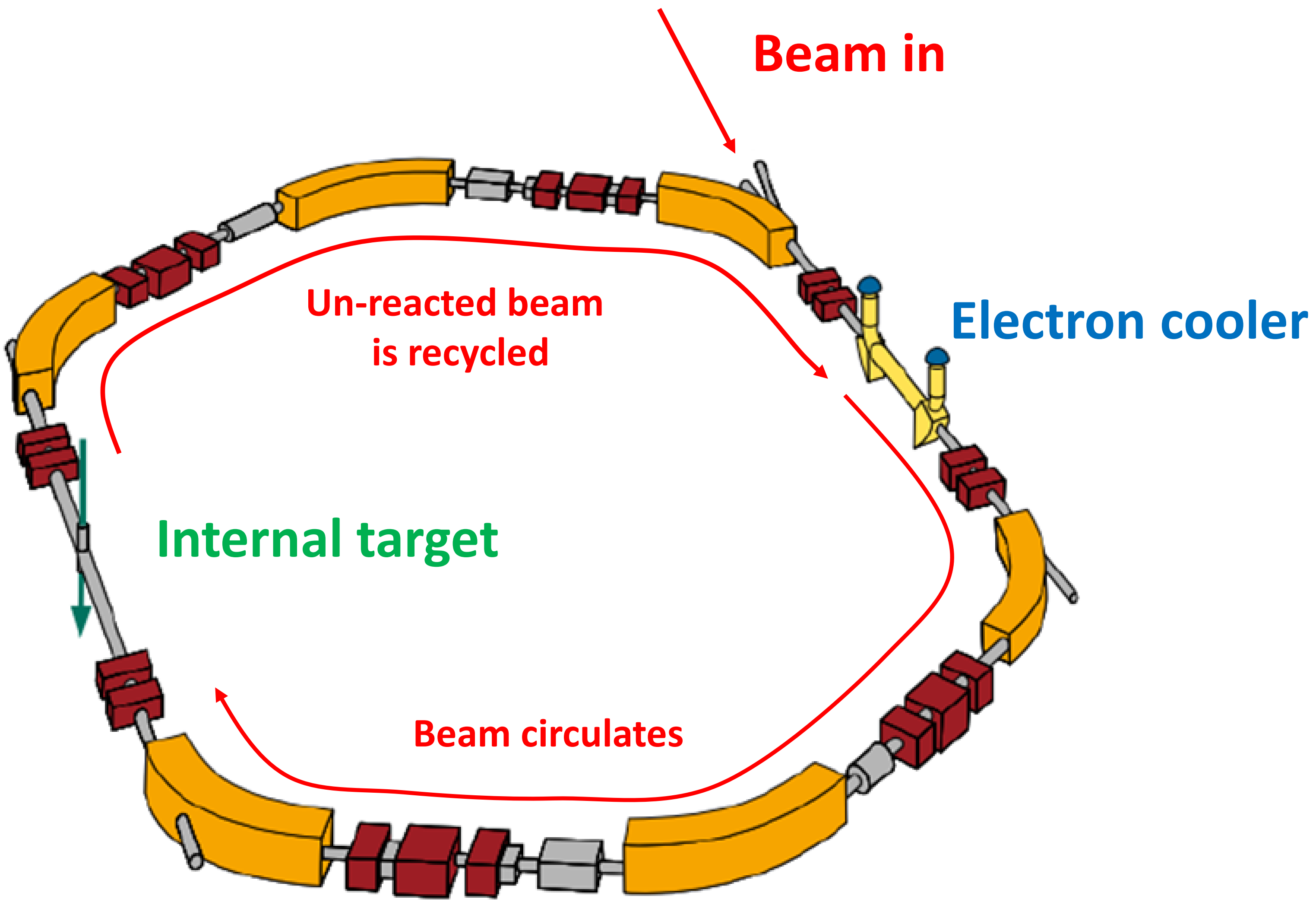
Reactions involve radioactive isotopes



In a laboratory - challenges

- How to produce the radioisotopes of interest?
- Short lifetimes
- Cannot do at LUNA

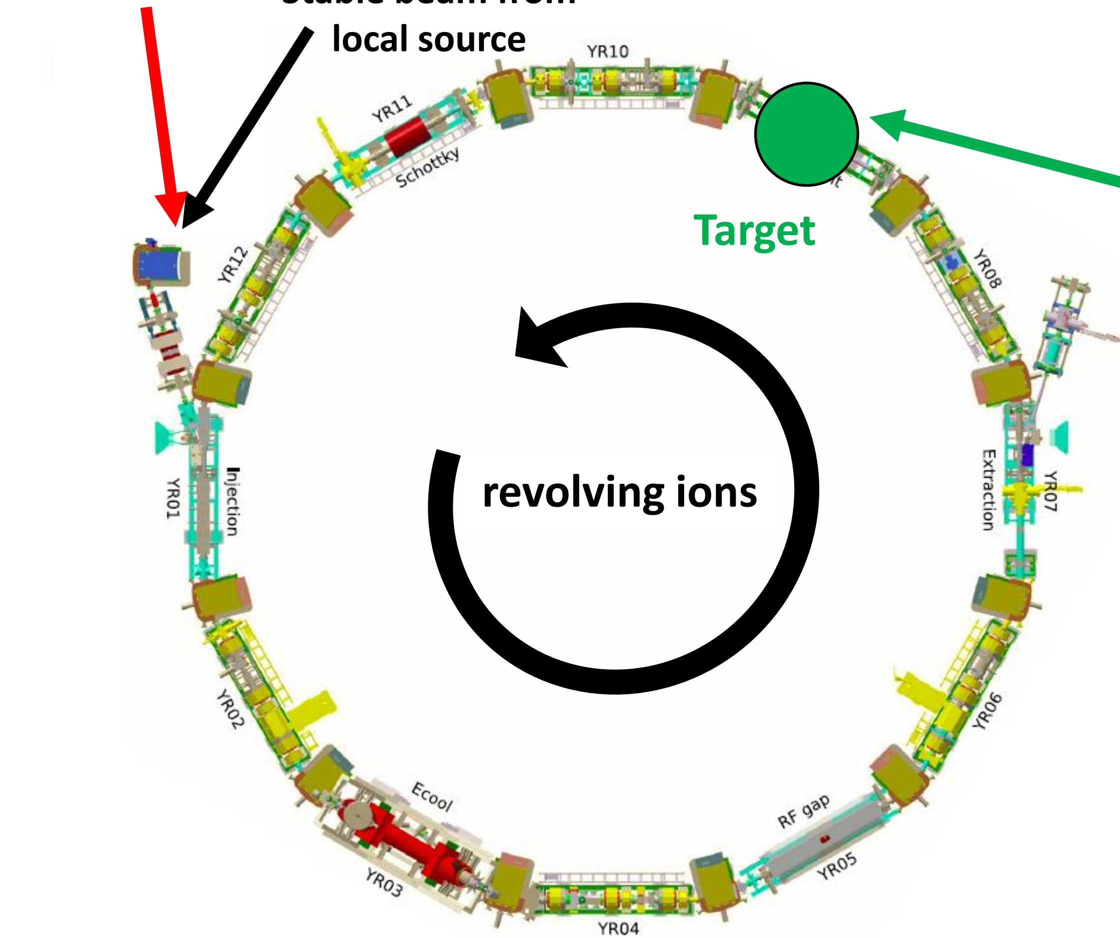
STORAGE RINGS



Picture: Phys. Scr. T156 (2013) 014016

CRYRING – PART OF FAIR PHASE-0

Beam injected via local ion source, or radioactive beam via the ESR



Energy range <10 MeV/A is world-unique and allows **direct measurements** at low energies of stellar interest!

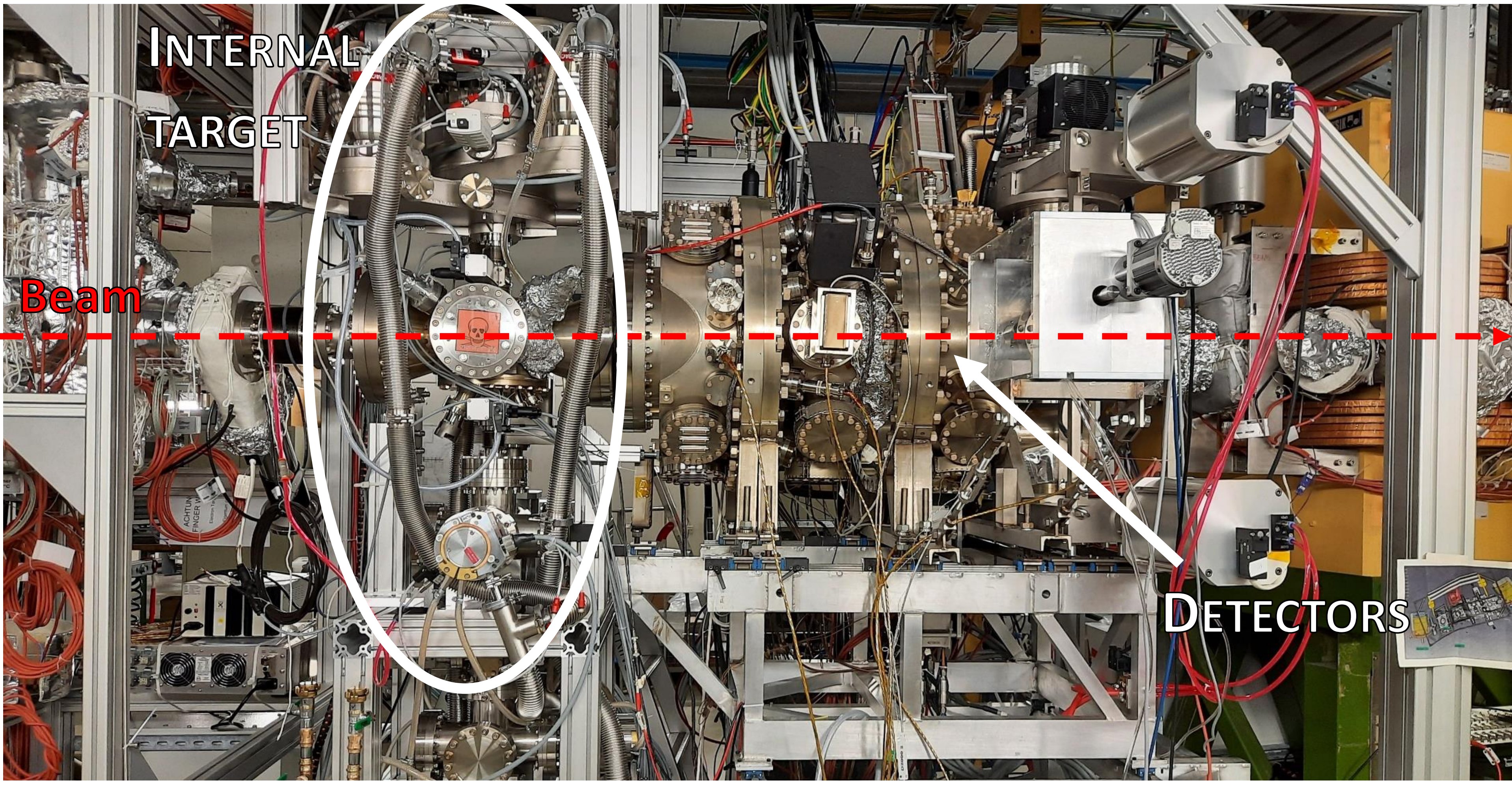
It has one section for experiments with an **ultra-thin** internal cryogenic microdroplet target.

CRYRING must be operated in Extreme High Vacuum (XHV) conditions, i.e. **10^{-12} mbar**. Very challenging!

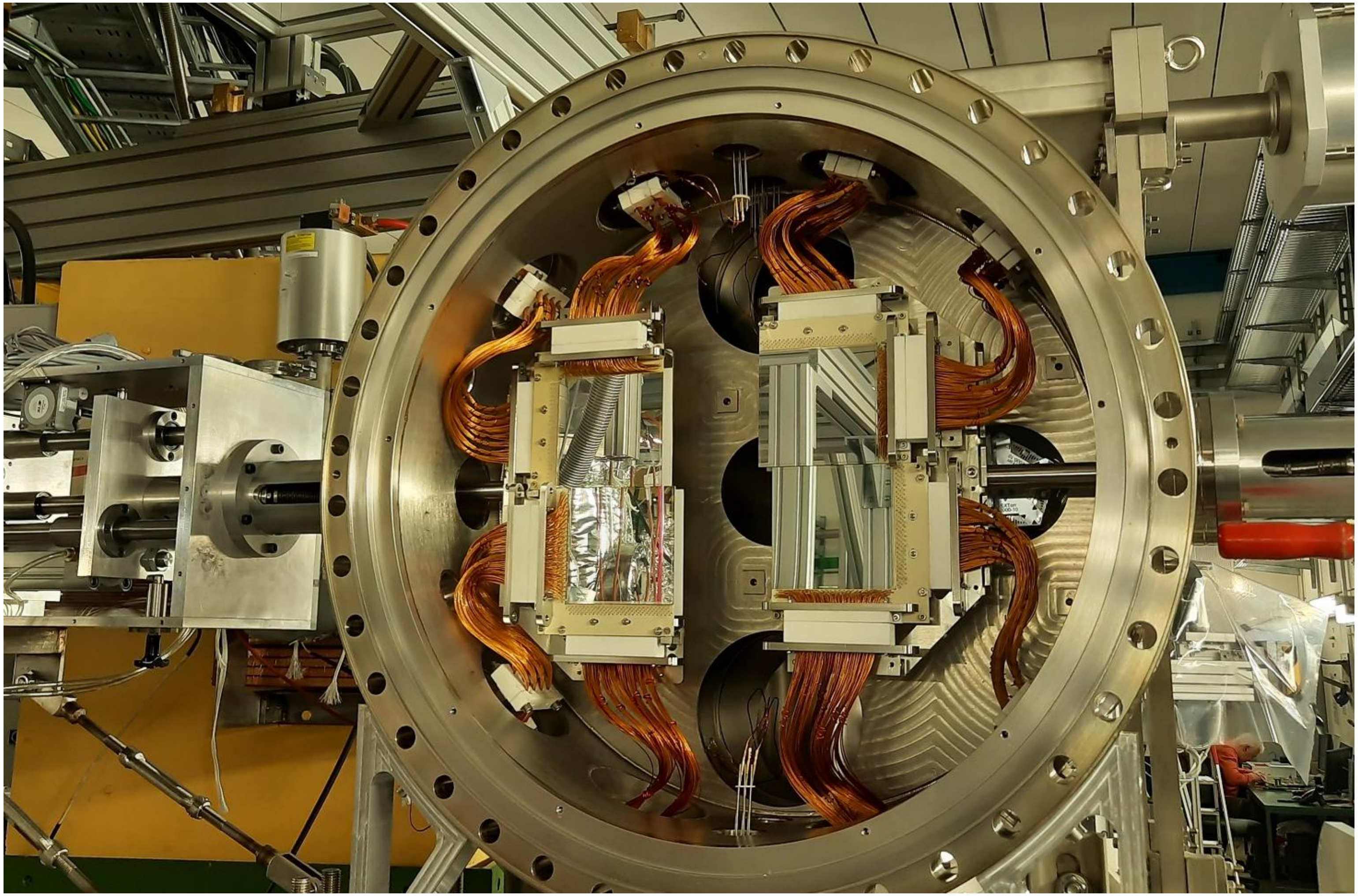
CARME

CRYRING ARRAY FOR REACTION MEASUREMENTS

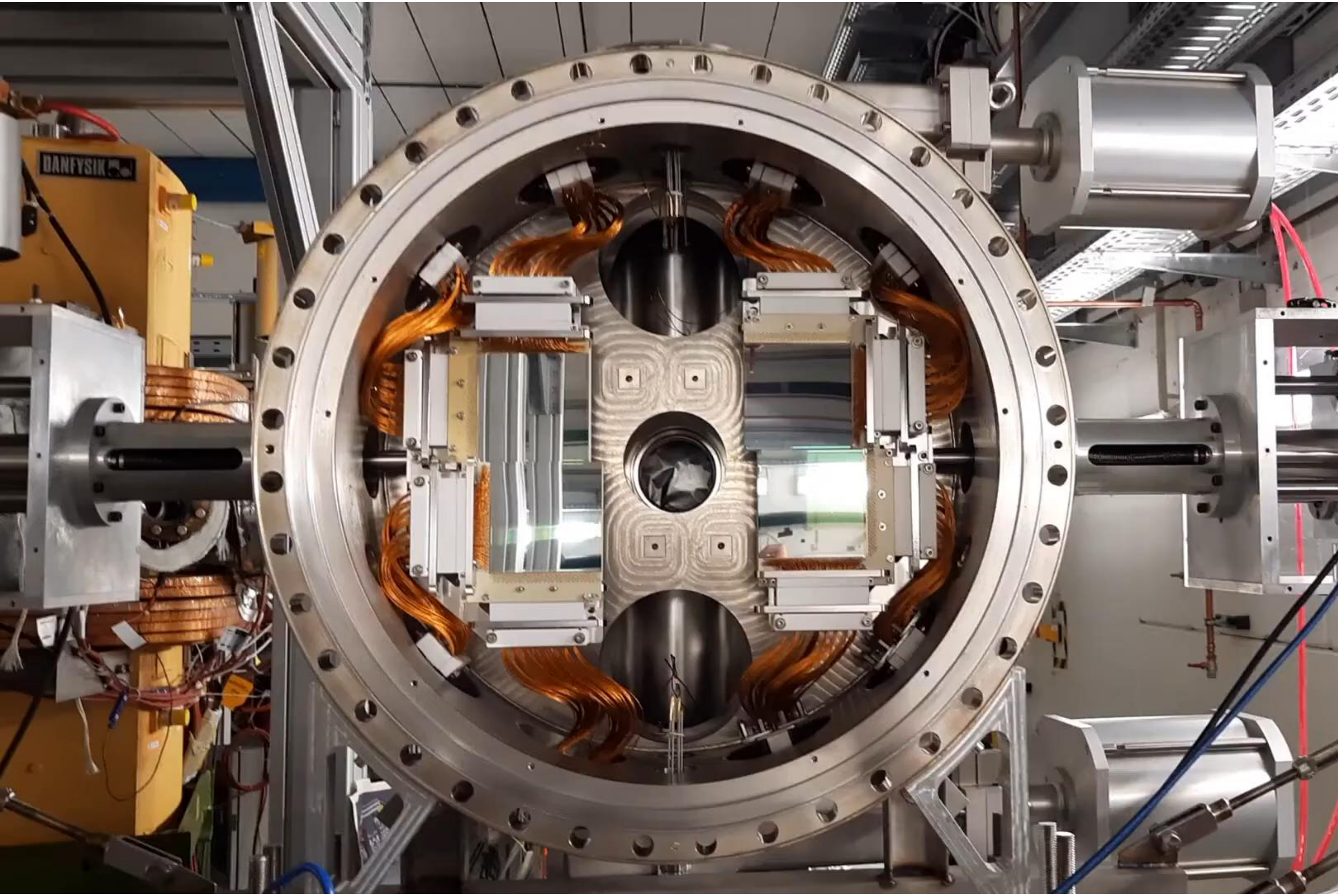
- New charged-particle array mounted **downstream** of target
- Mounted on the CRYRING in 2021, commissioned February 2022



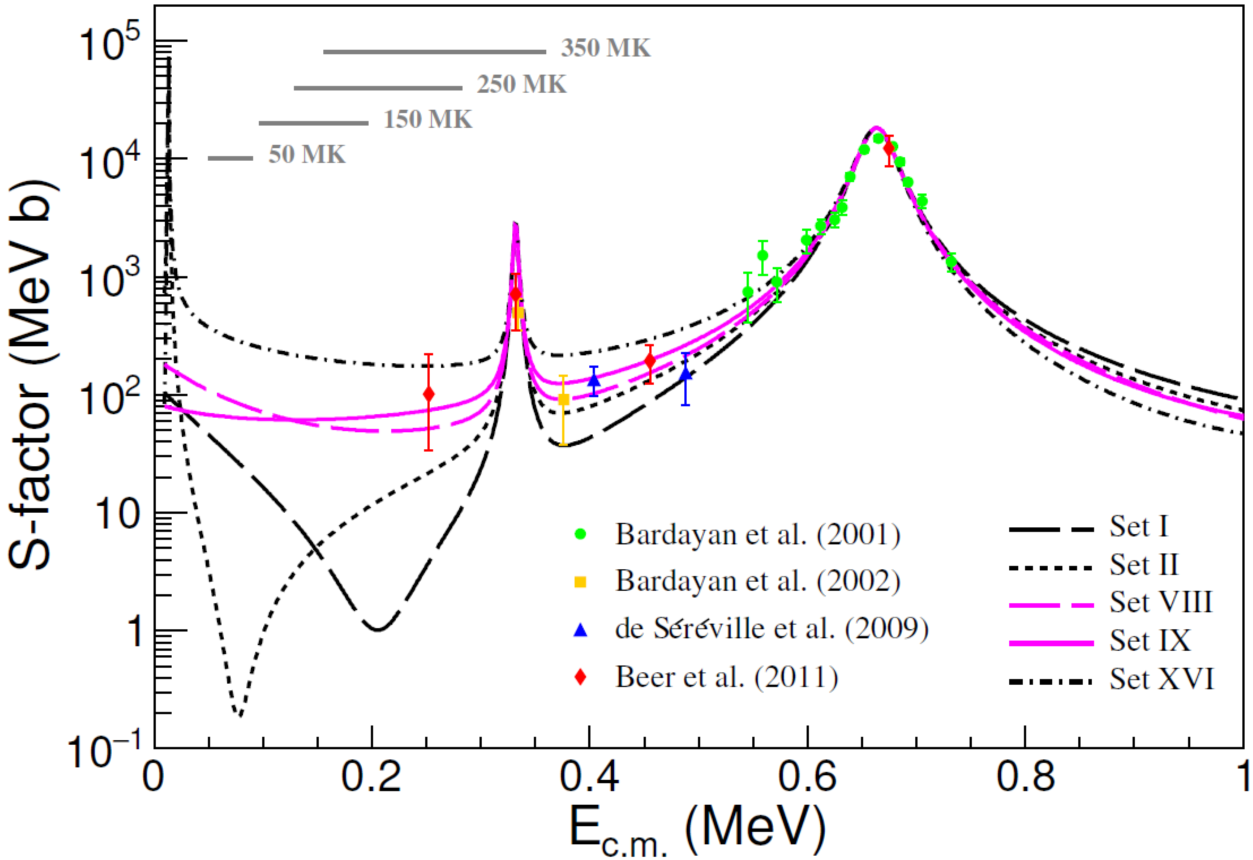
DETECTORS



- Double-sided Silicon Strip Detectors (DSSD)
- Placed directly in XHV
- Can move in XHV – avoid uncooled beam


DANFYSIK

$^{18}F(p,\alpha)^{15}O$

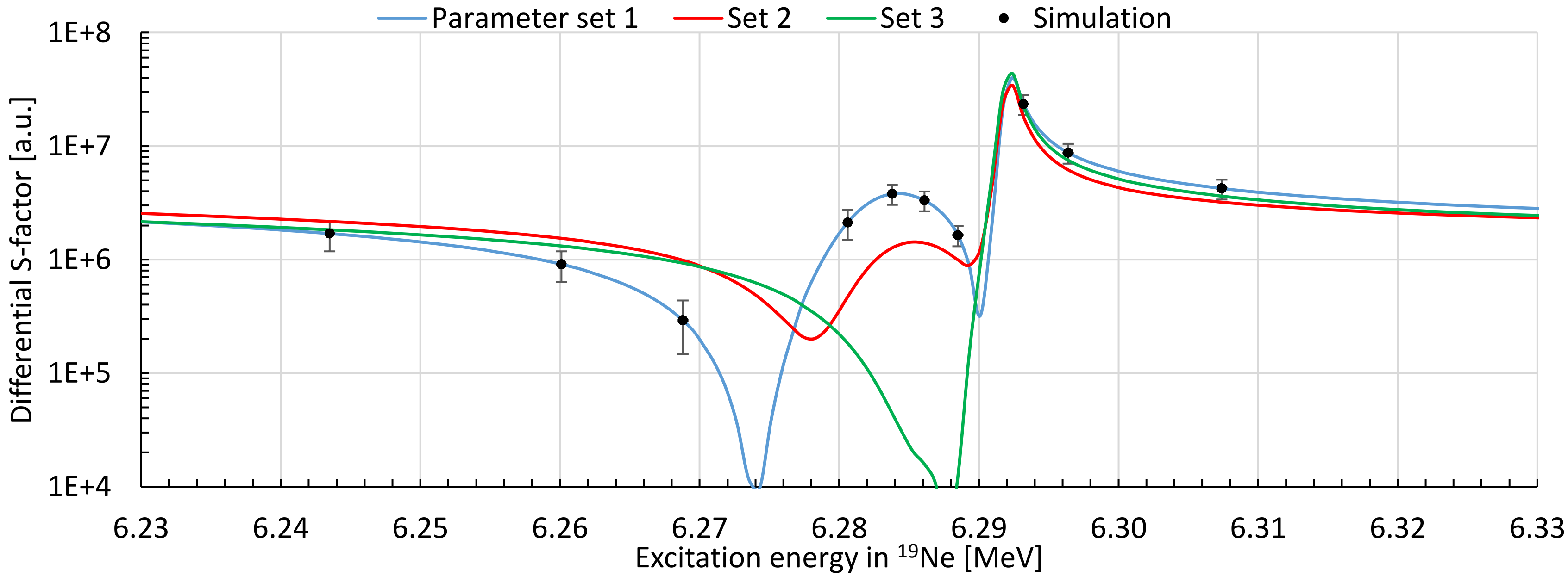


- Key reaction in nova explosions
- Cross-section is affected by interferences between resonances
- **Alpha widths** are key to constrain interference (poorly known)
- **$^{15}O(\alpha,\alpha)^{15}O$** is ideal to probe alpha widths, with good resolution

$^{15}O(\alpha,\alpha)^{15}O$

Traditionally the measurement would be carried out with RIB on extended gas target (~40 keV FWHM). Energy resolution limited by straggling. Multiple excitation energies measured at once.

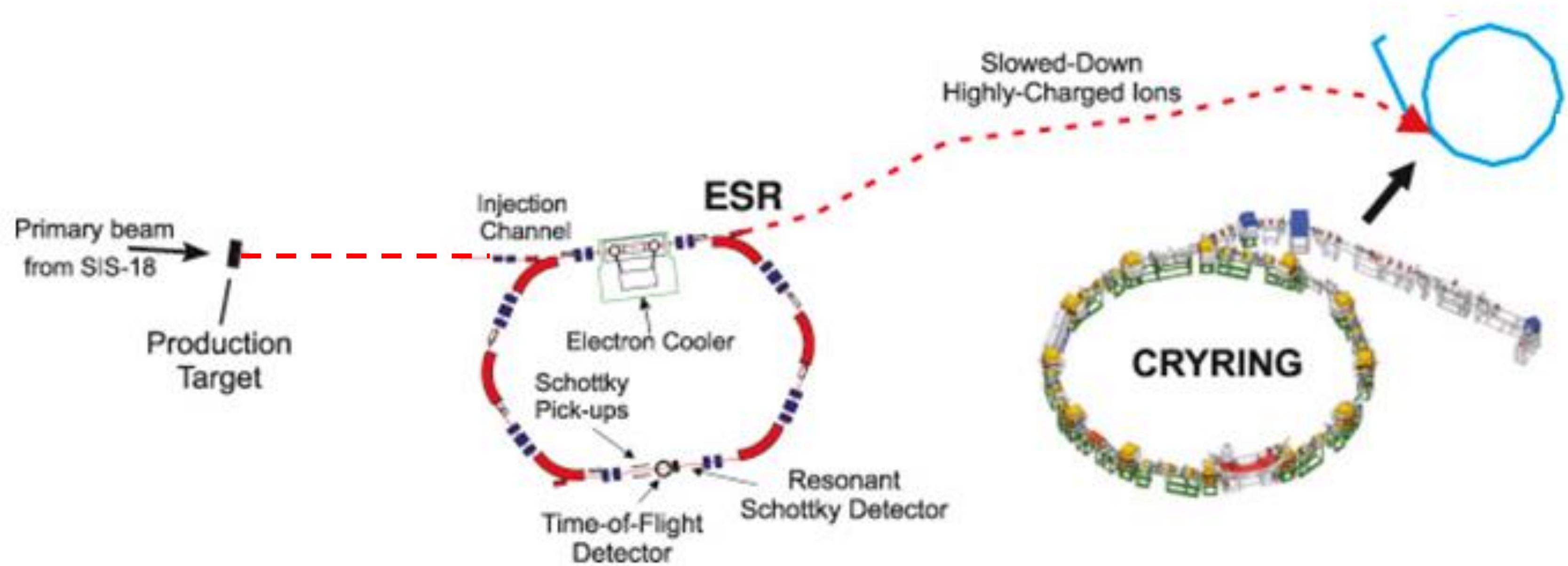
Electron-cooled beams + ultra-thin internal target at CRYRING. No straggling. Unprecedented technique unique to CRYRING: **~1 keV FWHM excitation energy resolution expected.** One energy at a time, stepping through the excitation function.



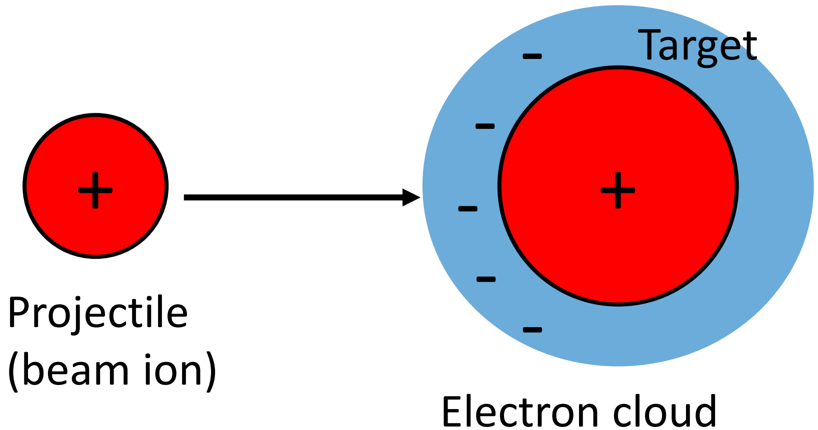
$^{15}O(\alpha,\alpha)^{15}O$

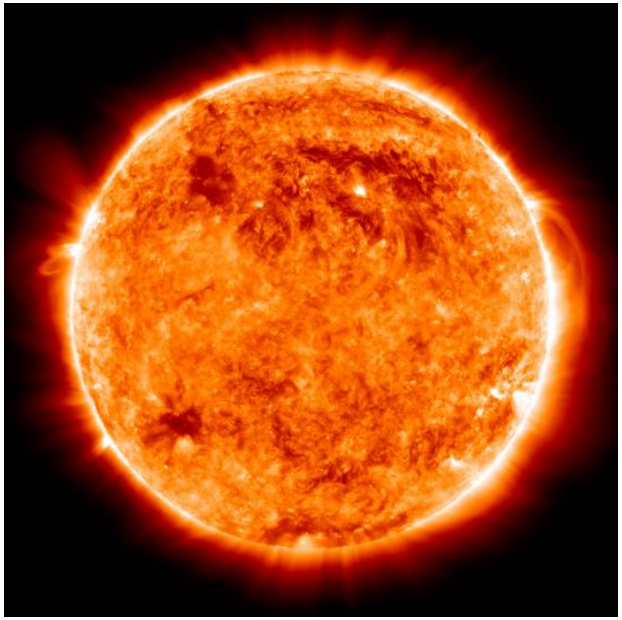
Radioactive ^{15}O beam separated in ESR-> CRYRING. Requires ***two*** paired storage rings.

<u>First test of this new technique early 2024</u>



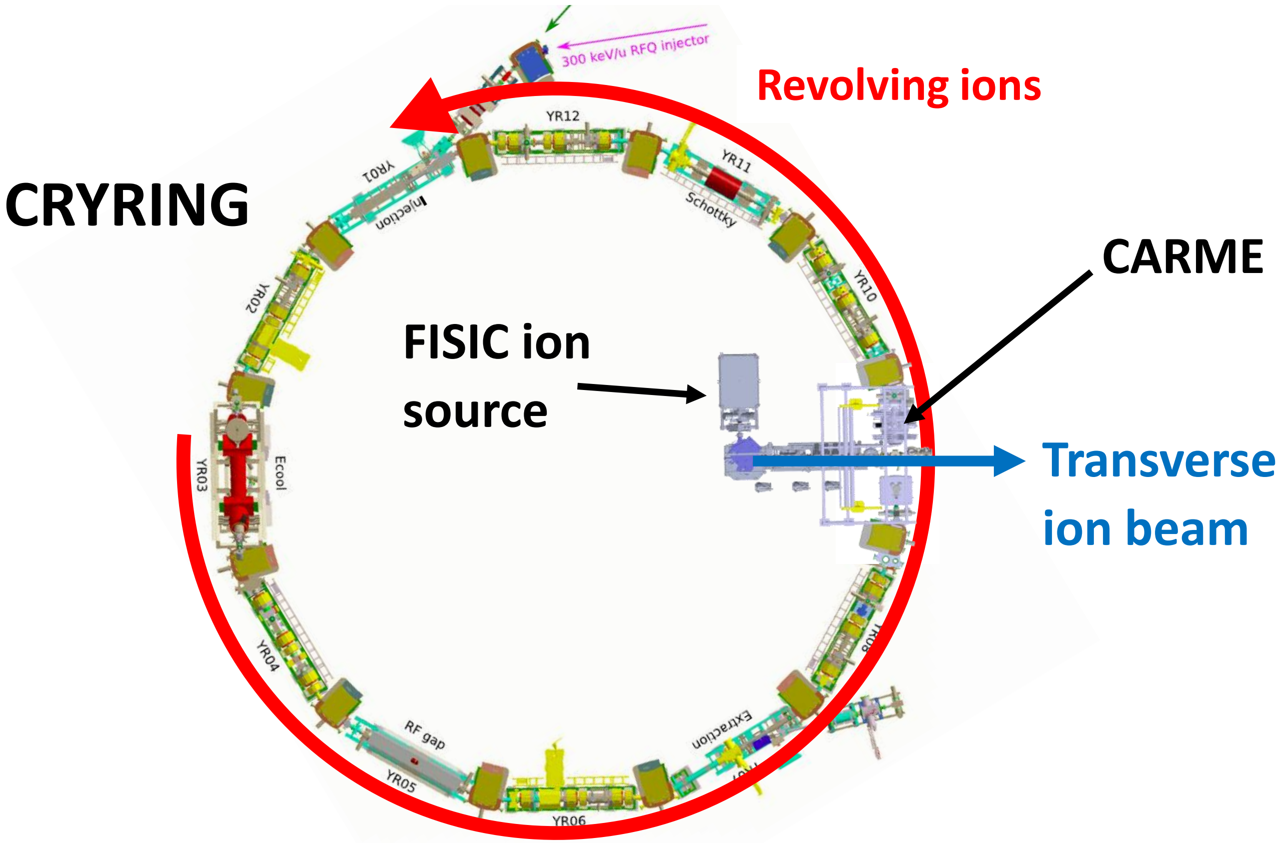
ELECTRON SCREENING





- In the laboratory, target electrons shield nuclear potential
- Orders of magnitude effect!
- No reliable models. Very long standing issue.
- Screening is different in the laboratory vs. a star
- Unknown uncertainty affecting *all* quiescent scenarios including our Sun

First ever bare nuclear reaction studies



FISIC: U. Sorbonne major *atomic* physics project at CRYRING

FISIC+CARME could perform the **first bare cross-section measurements at stellar energies**

Ready in ~2 years

CONCLUSIONS

- Direct measurements of stellar burning reactions are in general extremely challenging
- ELDAR will develop new approaches that are required to face long-standing puzzle in reactions that produce charged particles
- New underground accelerators offer the possibility of scientific breakthroughs via high intensity beams in low-background environments
- Revolutionary techniques such as storage rings can be used to approach long-standing issues in explosive scenarios, but also quiescent burning such as electron screening