Direct measurements of nuclear reactions at stellar burning energies

Carlo G. Bruno

EFB 25, Mainz
31 August 2023

THE UNIVERSITY OF EDINBURGH

UKRI Science and Technology Facilities Council

erc European Research Council
Established by the European Commission

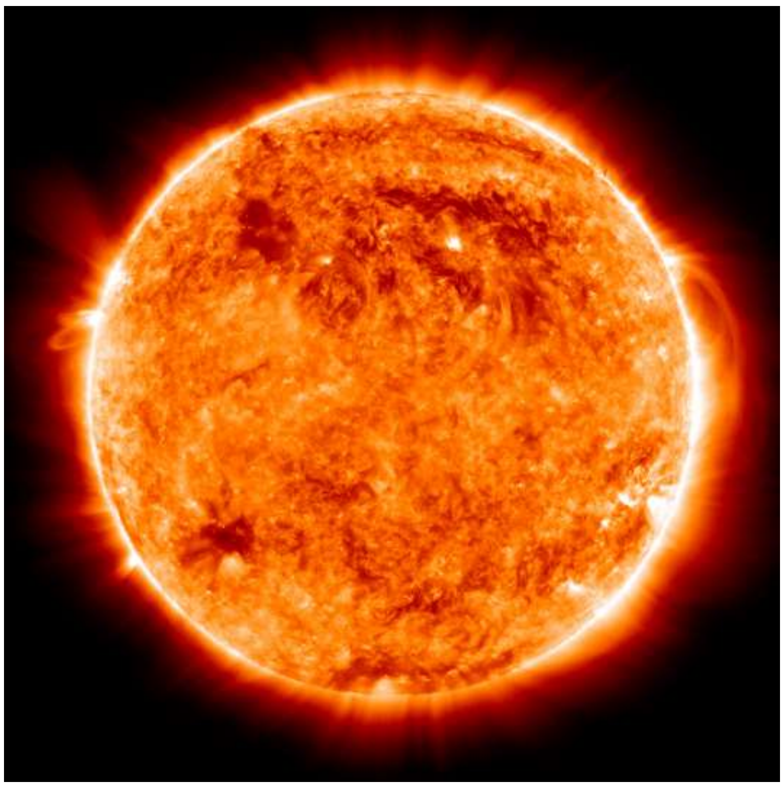
THE CHALLENGE

In a star

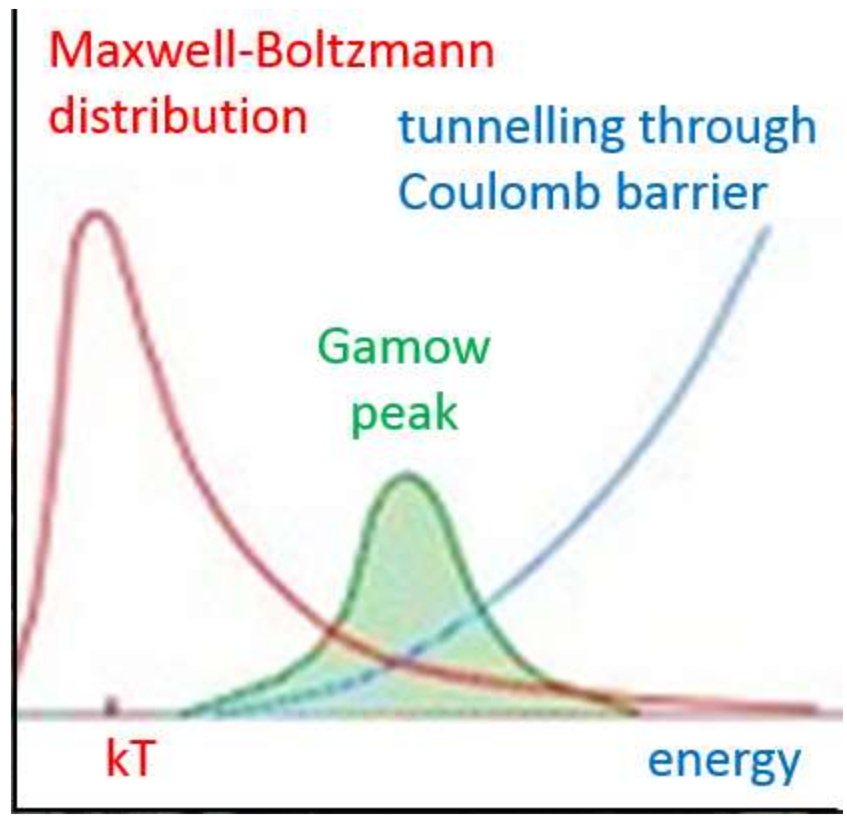
T = 15 x 10^6 K

Energy ≈ 1 keV

Coulomb barrier ≈ 600 keV



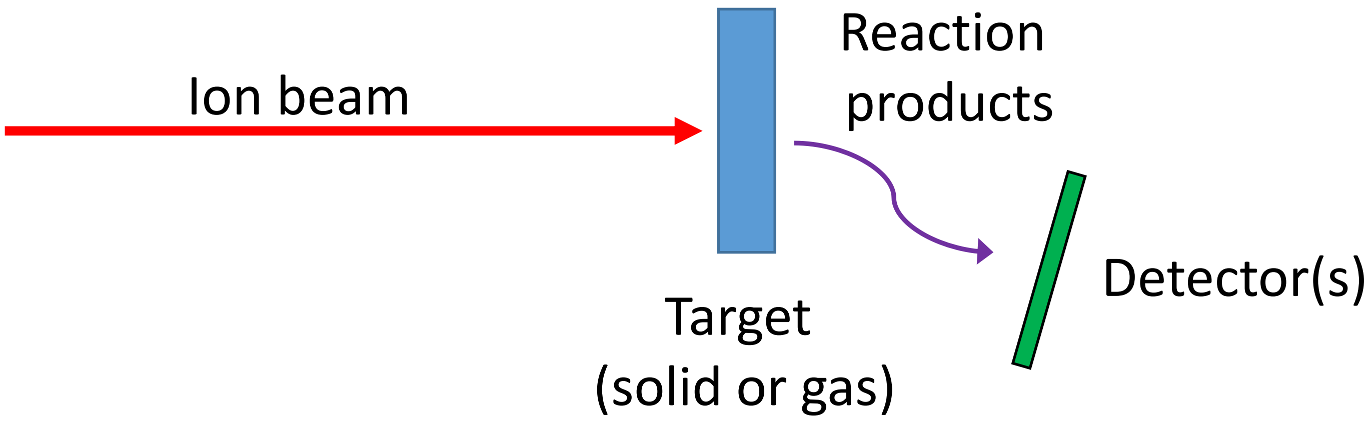
Gamow peak: most significant energy range



THE CHALLENGE

Some typical values

- Cross-section: as low as 10^{-15} barn
- Target thickness: 10^{18} atoms/cm^2
- Beam intensity: 100 μA (10^{15} particles per second)



Yield = $N_{projectiles}$ x N_{target} x Cross-section x Det. efficiency

= 10^{15} pps x 10^{18} cm^{-2} x 10^{-39} cm^2 x 100% (charged particles)

~1% (gamma rays)

= **0.3-30 counts/year**

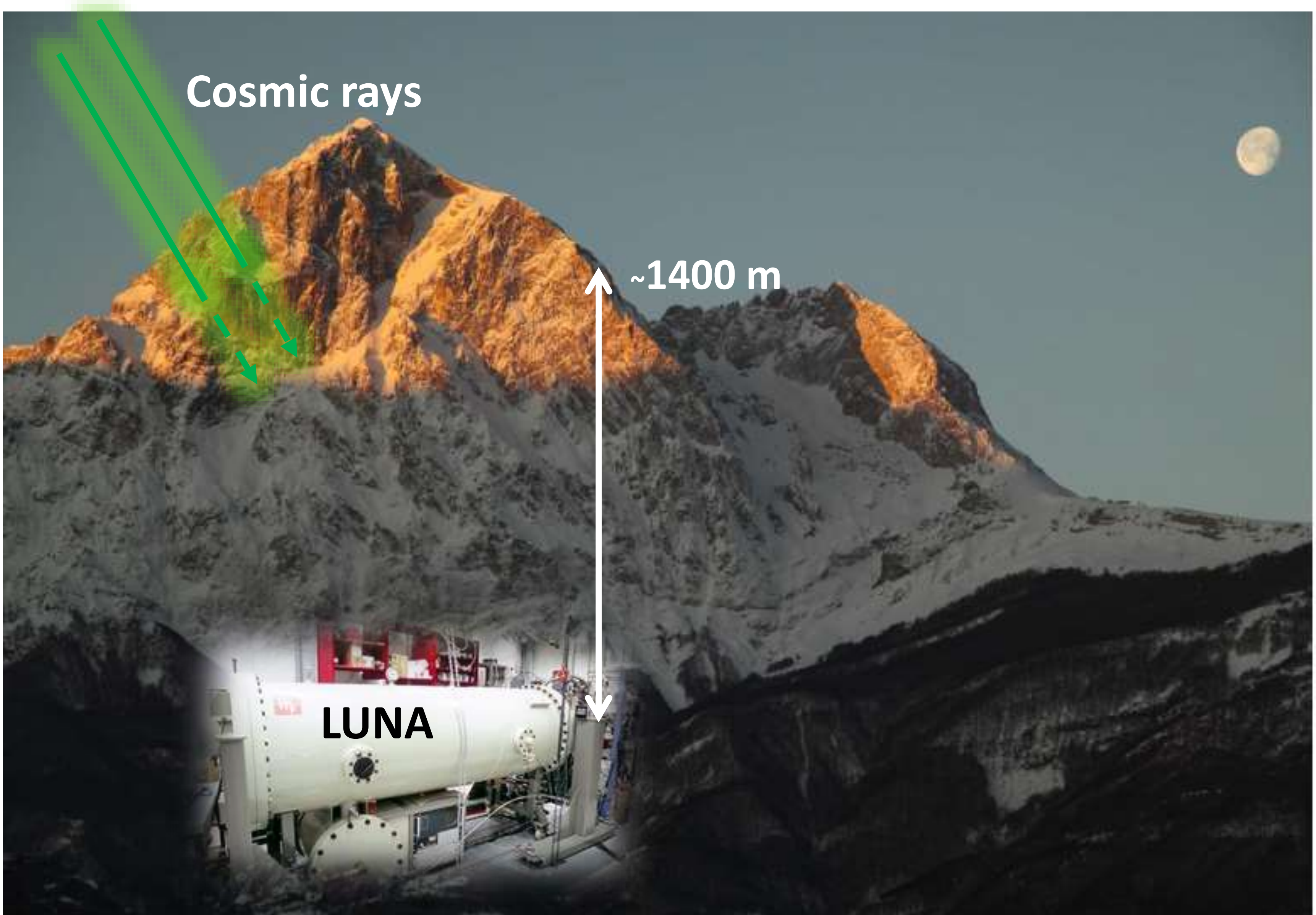
How do we carry out a measurement?

- Improve signal
  Increase beam intensity, increase target enrichment, …
- Reduce background
  Active / passive shielding, background rejection via PSA, …
- Novel measurement techniques

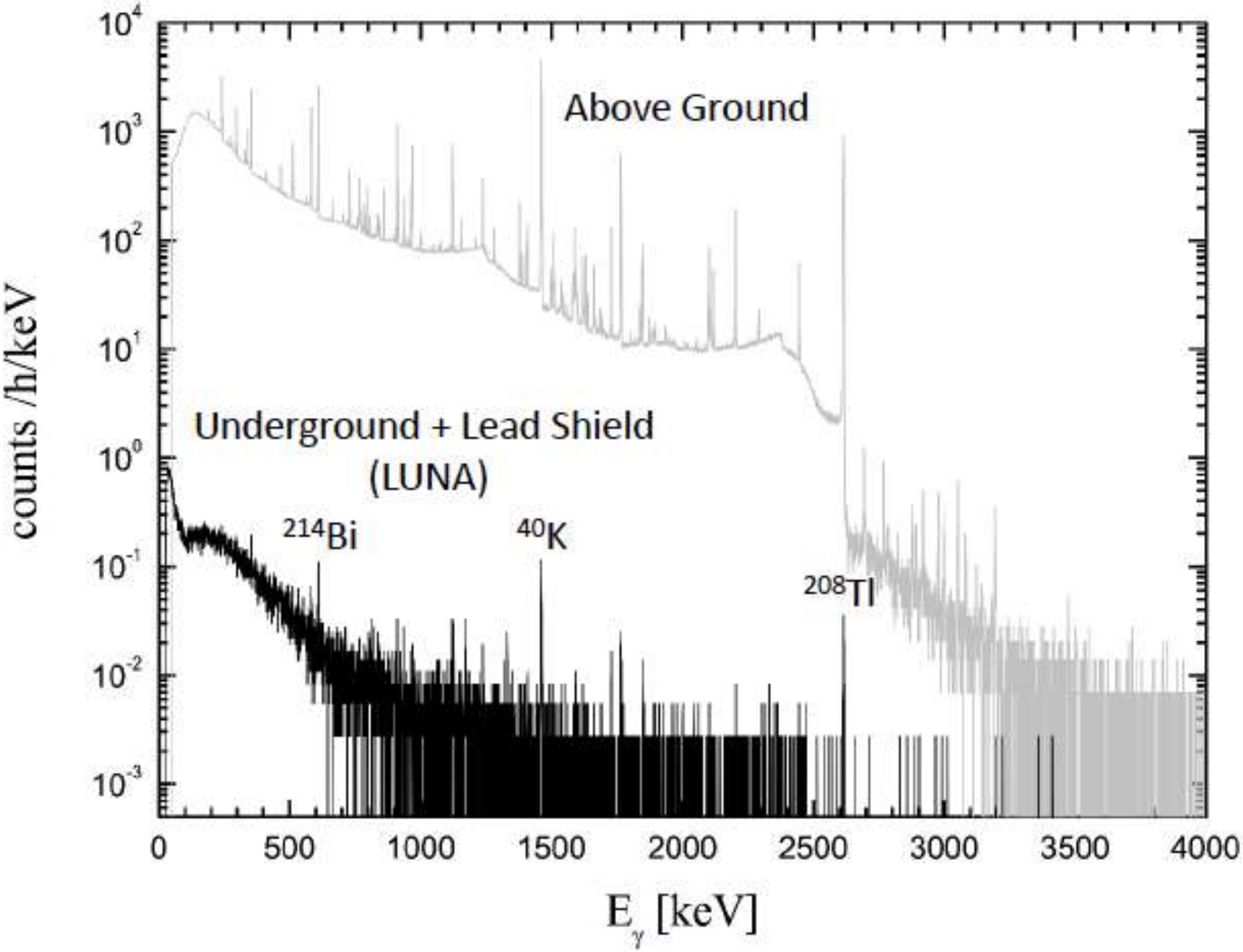
Underground direct measurements

LUNA

(Laboratory for Underground Nuclear Astrophysics)



BACKGROUND REDUCTION IN HPGE



LUNA has traditionally focused on gamma spectroscopy, but background reduction for **charged particles detection** is also significant.

Underground measurement of charged particle reactions can deliver scientific breakthroughs in several scenarios

Example: $^{23}Na(p,\alpha)^{24}Mg$

- Key to understand lifecycle of stars in globular clusters
- Calls to measure it for 15+ years
- Impossible overground.
- Not very hard underground…

… with the right setup!

Globular cluster NGC6441 seen by the Hubble telescope.

ELDAR will fund design and exploitation of new reaction chamber and detection array for particle detection at LUNA.

Expected duration : several months of beam on target

ELDAR ERC Grant

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

Science and Technology Facilities Council

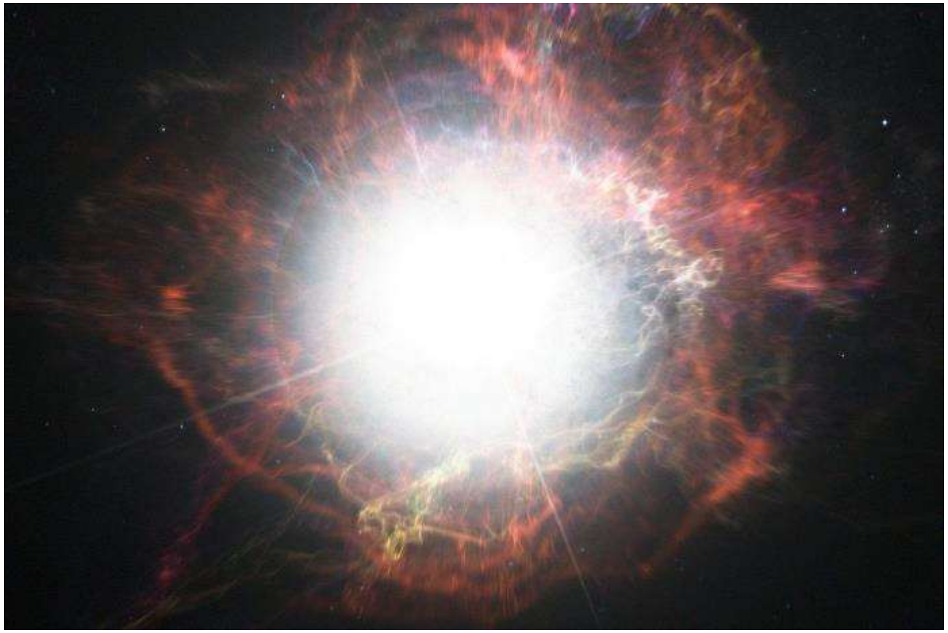
European Research Council

Established by the European Commission

Storage rings

THE CHALLENGE

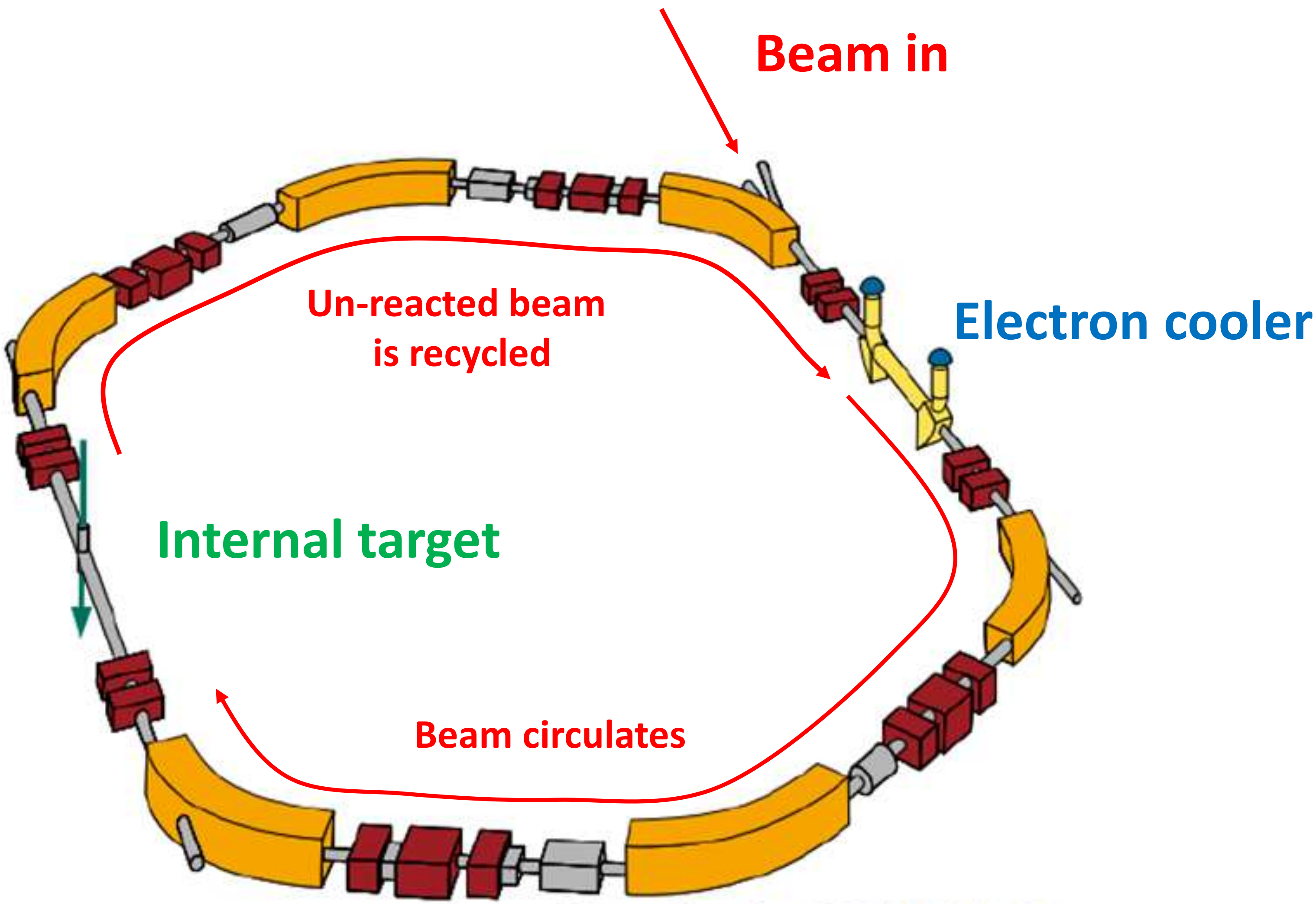
In stellar explosions – reactions involve radioactive isotopes



In a laboratory - challenges

- How to produce the radioisotopes of interest?
- Short lifetimes – cannot make radioactive target

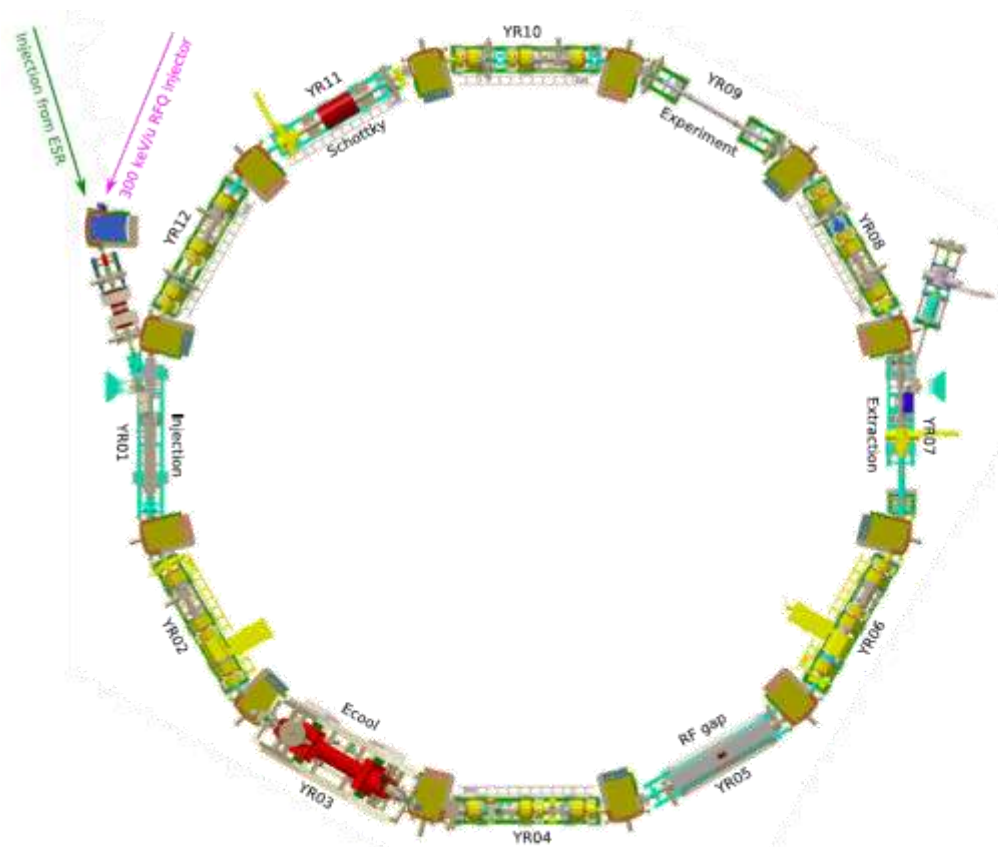
STORAGE RINGS



Picture: Phys. Scr. T156 (2013) 014016

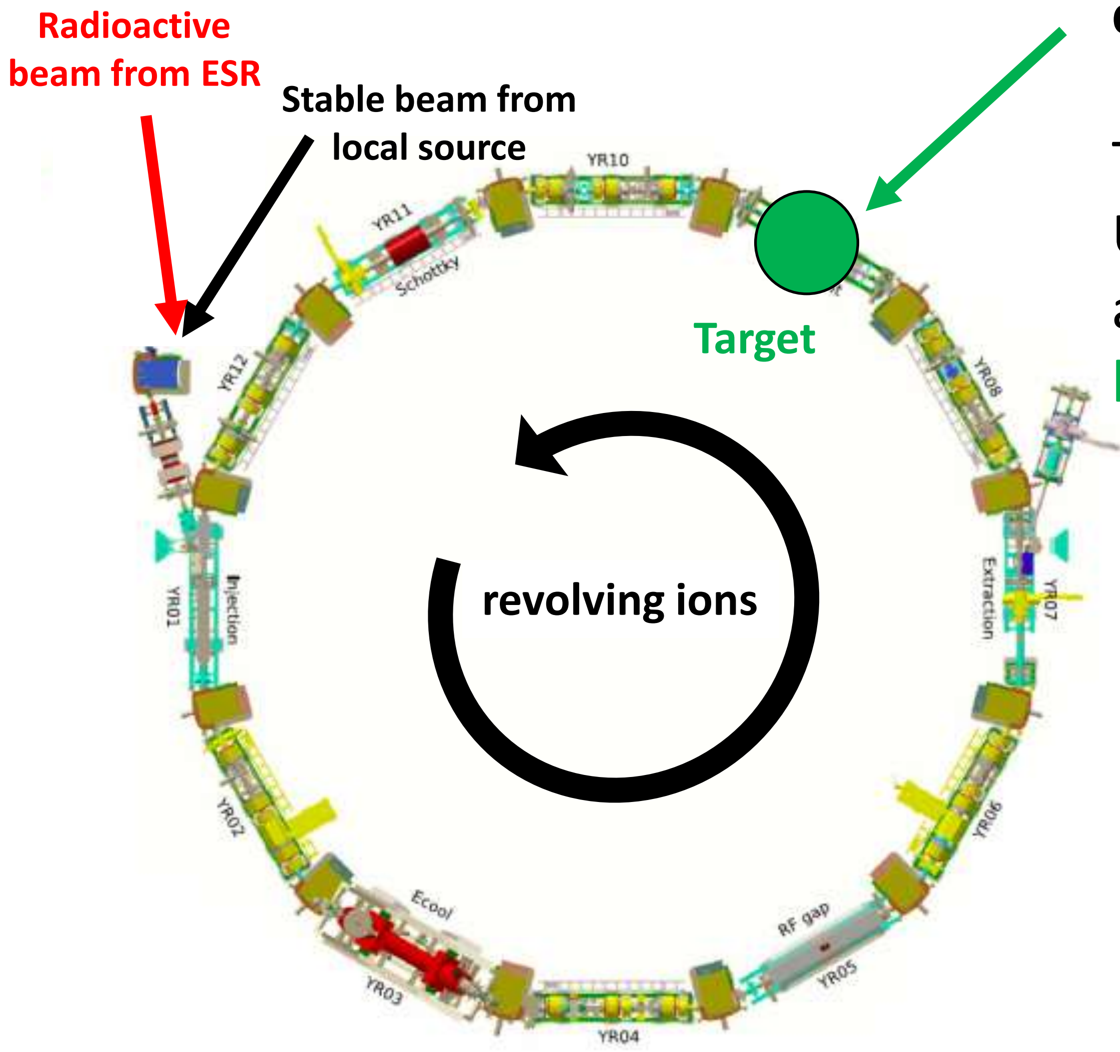
CRYRING
PART OF FAIR

- Energy range: ~hundreds of keV/u to ~10 MeV/u
- Vacuum: $10^{-11} – 10^{-12}$ mbar



CRYRING

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



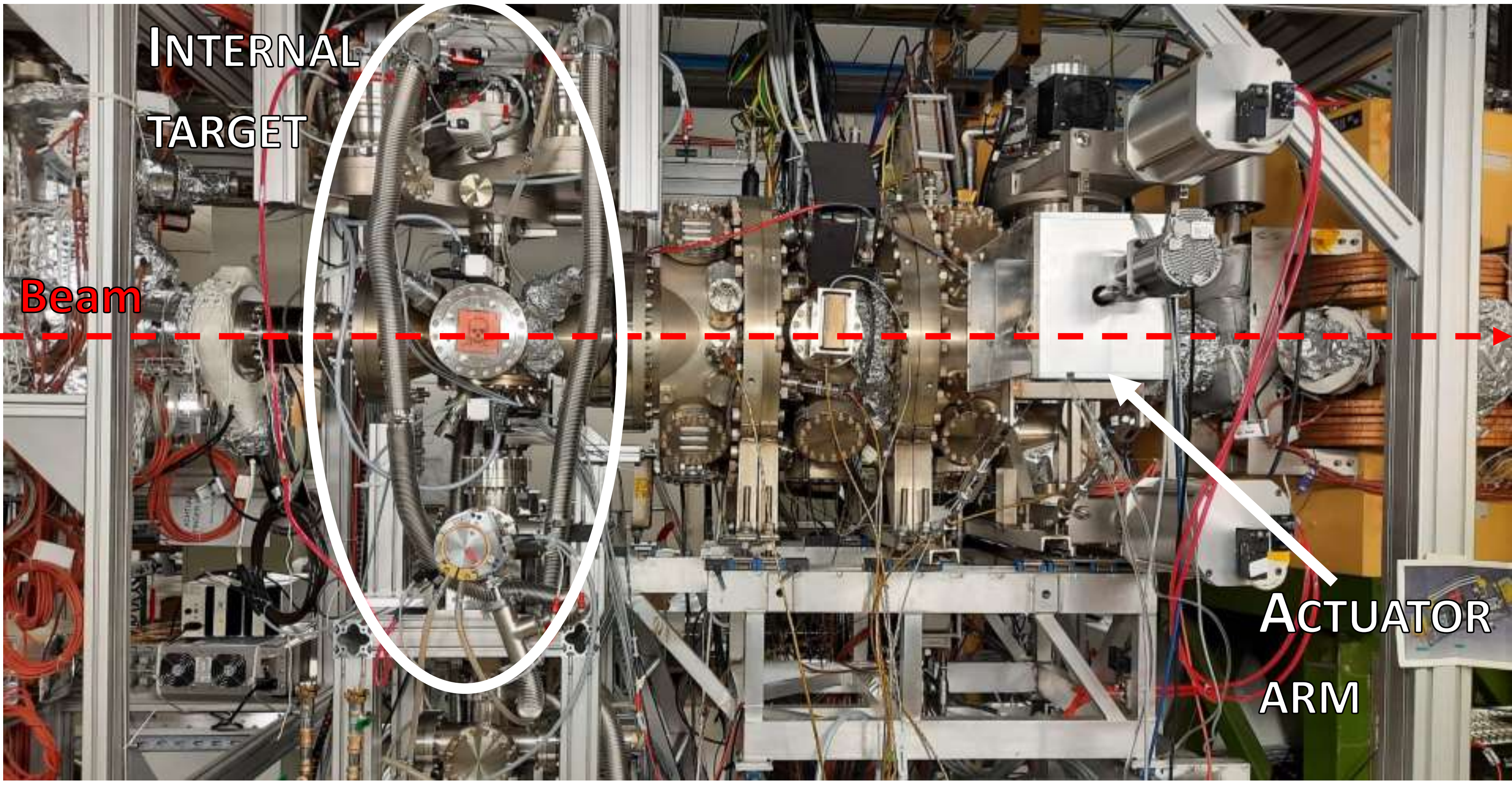
It has one straight section for experiments with an **internal cryogenic microdroplet target**.

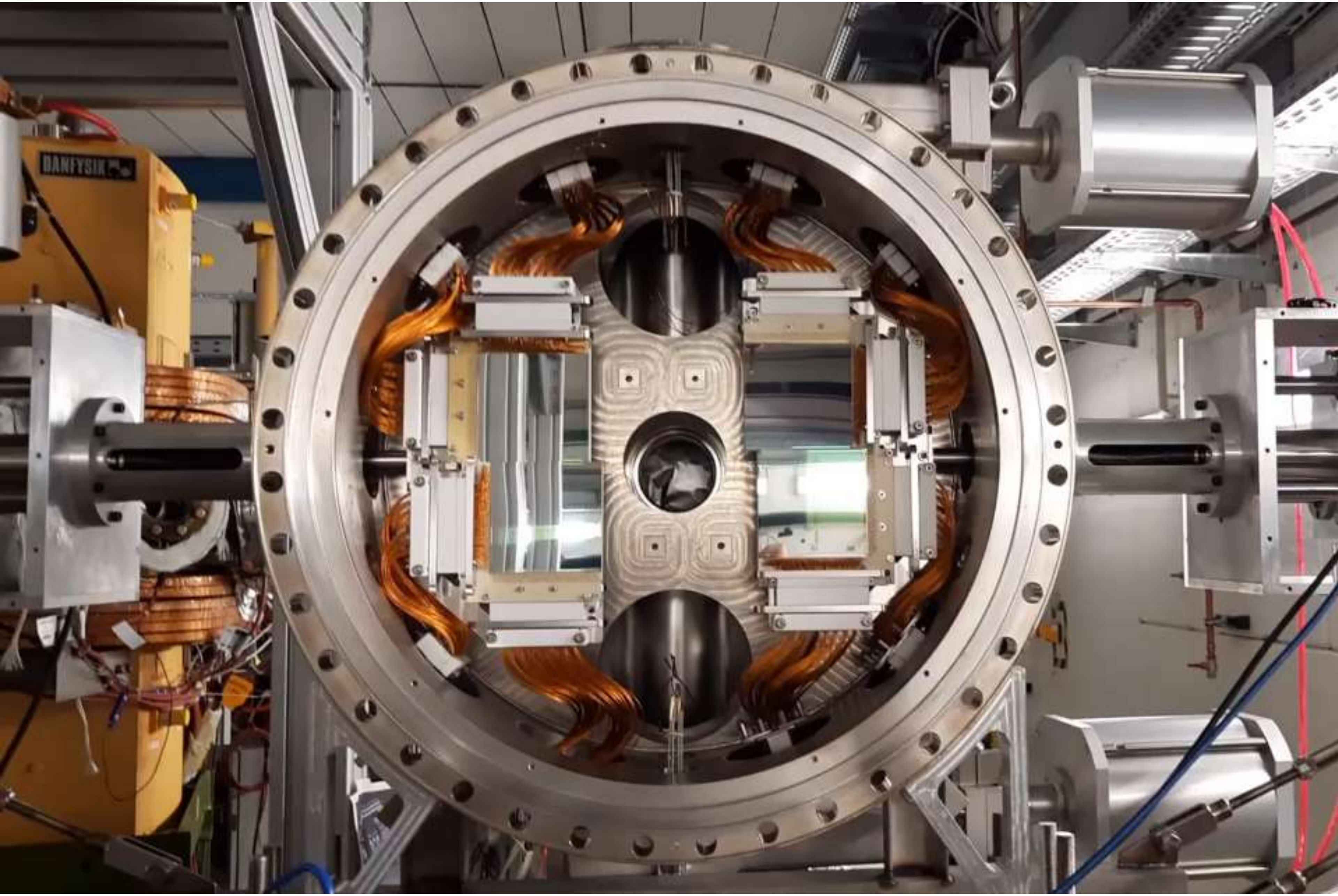
To exploit this novel possibility, UK STFC built a new detection array called CARME, mounted here

CARME

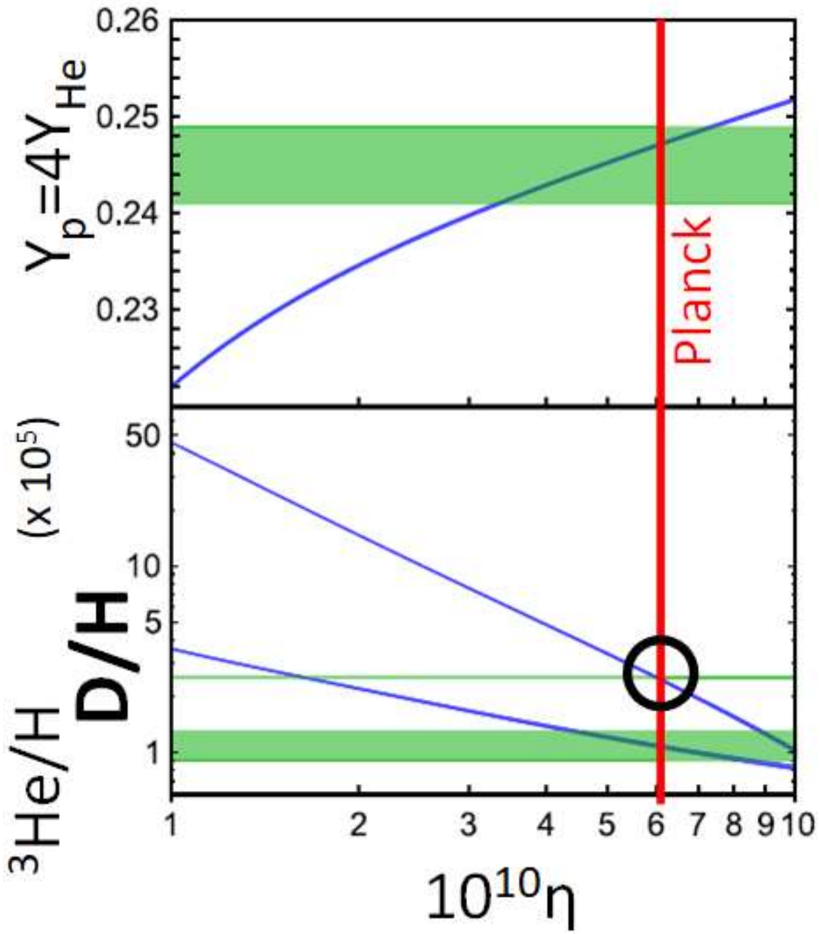
CRYRING ARRAY FOR REACTION MEASUREMENTS

- Reaction chamber mounted **downstream** or upstream of target
- Mounted on the CRYRING in 2021, commissioned February 2022




DANFYSIK

BIG BANG NUCLEOSYNTHESIS



- Elements up to lithium were synthesised during the Big Bang
- Compare astronomical observations in ancient stars vs. Standard Model predictions
- Predictions have a single free parameter

- Comparing results allows for test of the Standard Model
- **Deuterium** has lowest uncertainty

Deuterium burning via $^2H(^2H,^3H)n$ is a key reaction for Big Bang prediction uncertainty

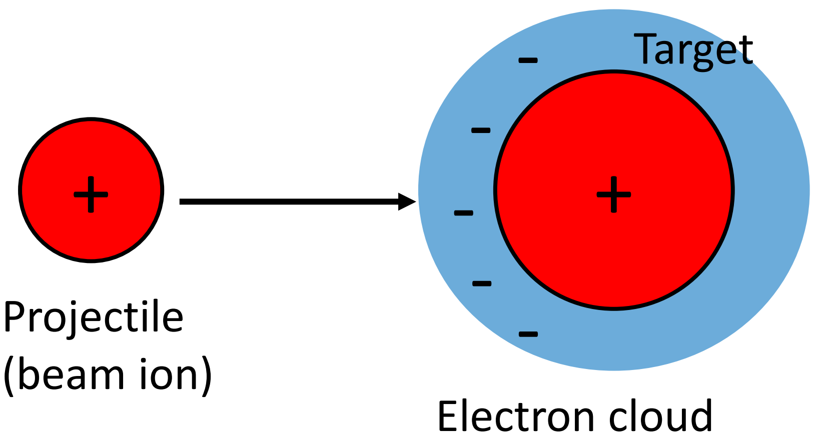
HOW DOES IT WORK?

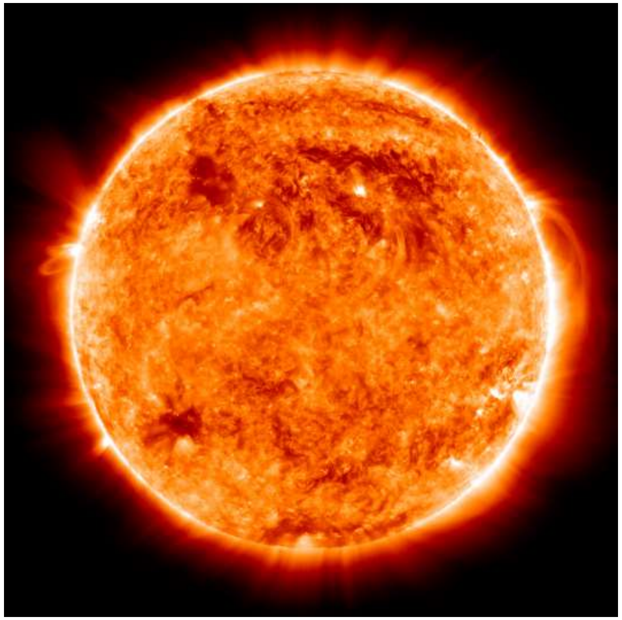
- Deuterium is injected into from local ion source. 10^8 ions per injection, once in 10 seconds or so, filling the ring.

- Beam is accelerated / decelerated as required, and cooled
- Deuterium target turned on (10^{13} atoms/cm2)
- CARME detectors move in
- Measure – beam is lost due to interaction with target

- After a few seconds-minutes (depends on energy!) not much beam left. Dump it.
- Refill, restart

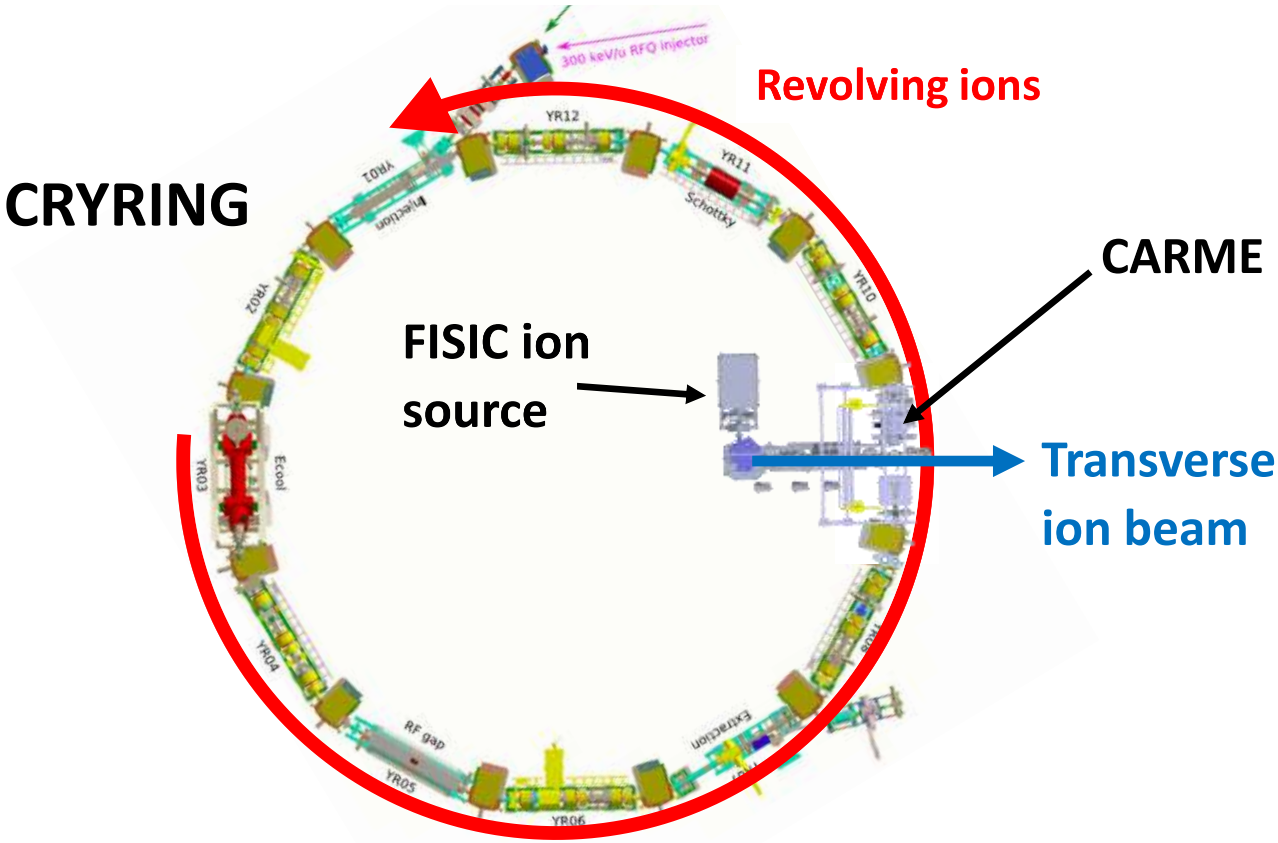
Electron screening





- 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
- New approaches are required

- New underground accelerators (LUNA-MV, JUNA, CASPAR) 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 such as electron screening