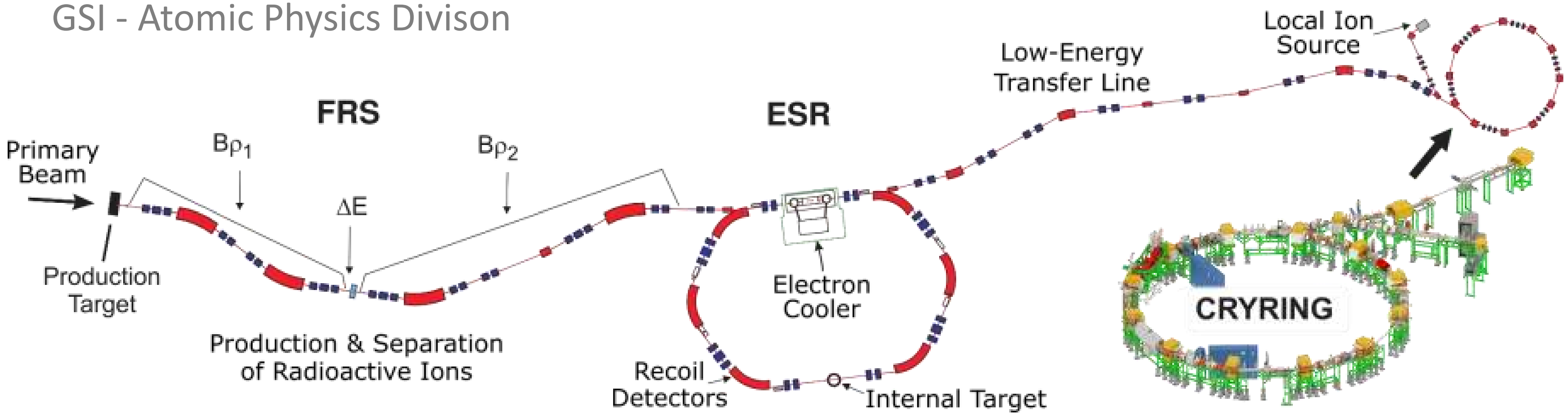
# Low-Energy Nuclear Reactions with Stored and Cooled Radioactive Beams


## Jan Glorius

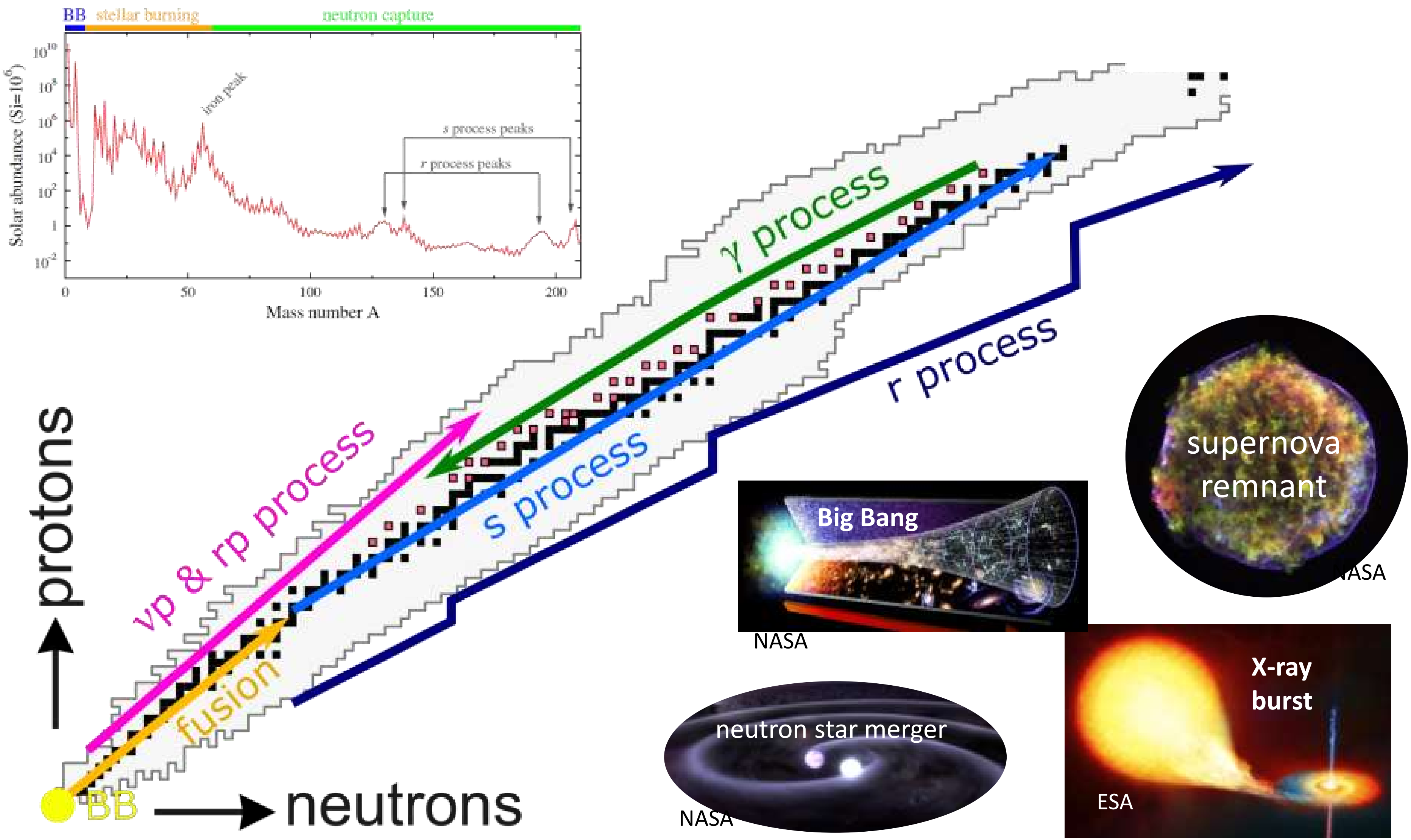
GSI - Atomic Physics Divison

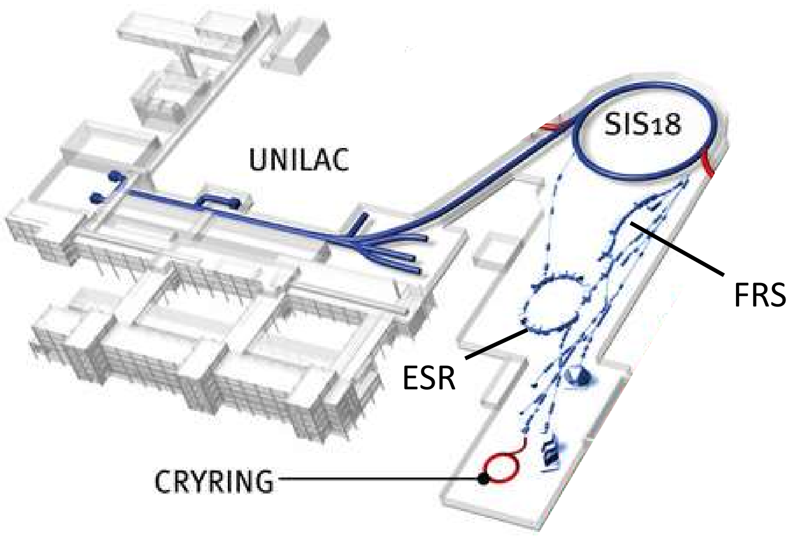


International Symposium on
Stored Ions for Precision Measurement
Fudan University, Shanghai
Nov. 22-24, 2023

# Nuclear Astrophysics – The Big Picture



# The GSI Accelerator Complex



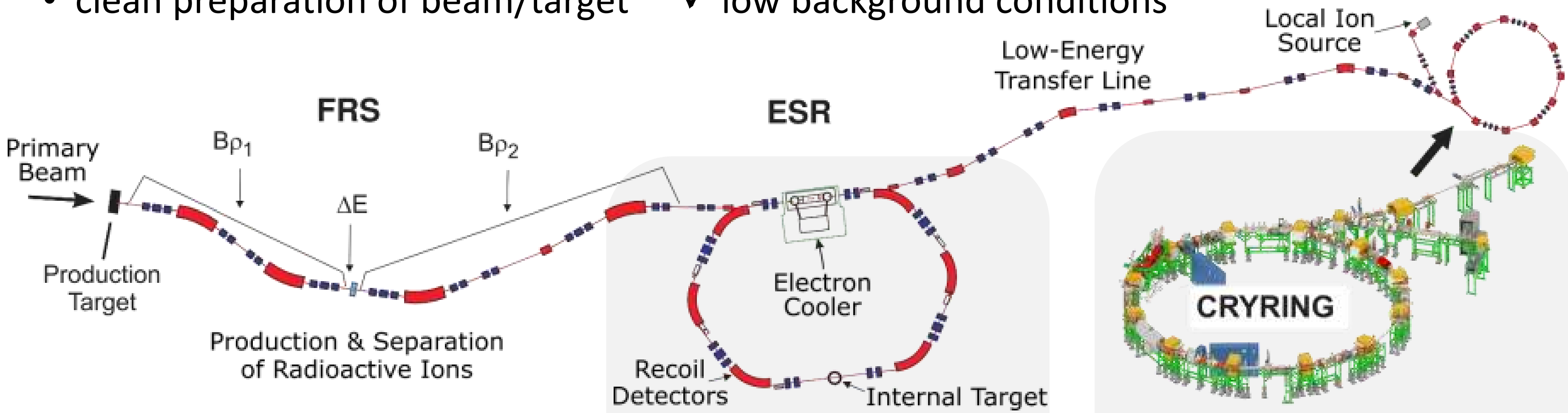

**Helmholtz Center for Heavy Ion Research**

- ion beams from protons to Uranium
- relativistic energies
- in-flight production of exotic beams
- secondary beam experiments

# Exotic Ions at the GSI Storage Rings

- in-flight fragmentation at FRS
- accumulation & recycling of beam
- post-deceleration of ions
- beam cooling & thin gas target
- clean preparation of beam/target

✓ radioactive beams (at high energies)
✓ luminosity boost
✓ Gamow window
✓ high resolution
✓ low background conditions



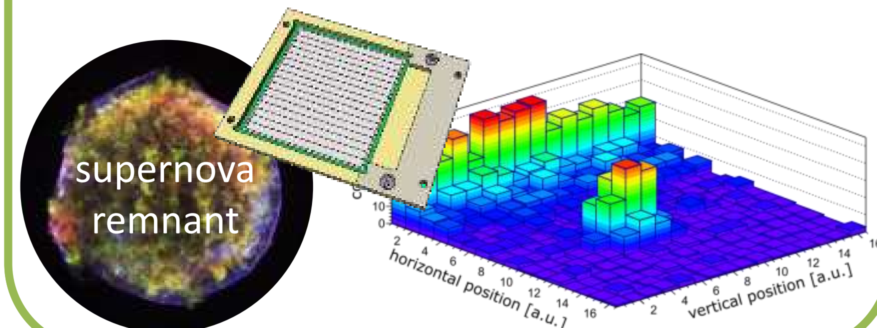

~4 - 550 MeV/u
p = $10^{-11}$ mbar

~0.1 - 15 MeV/u
p = $10^{-12}$ mbar

**very efficient use of exotic beams for high resolution experiments**

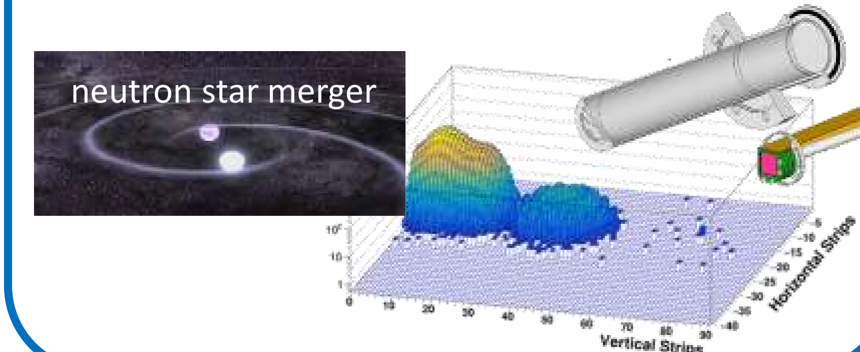
# Overview

## Proton-Capture Reactions for Explosive Nucleosynthesis



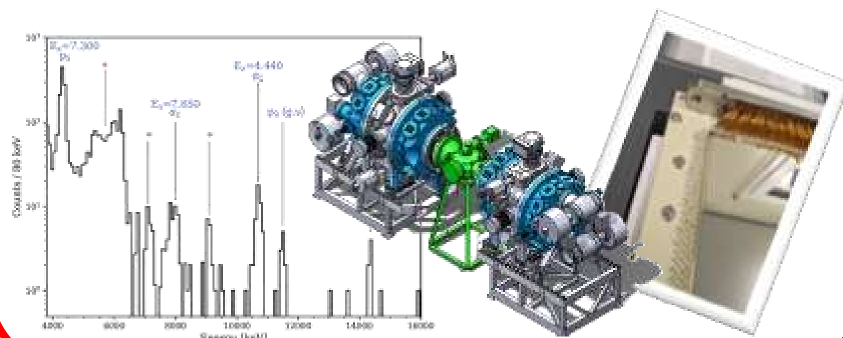

## NECTAR

Nuclear rEaCTions At storage Rings




## CARME

CRYRING Array for Reaction MEasurements



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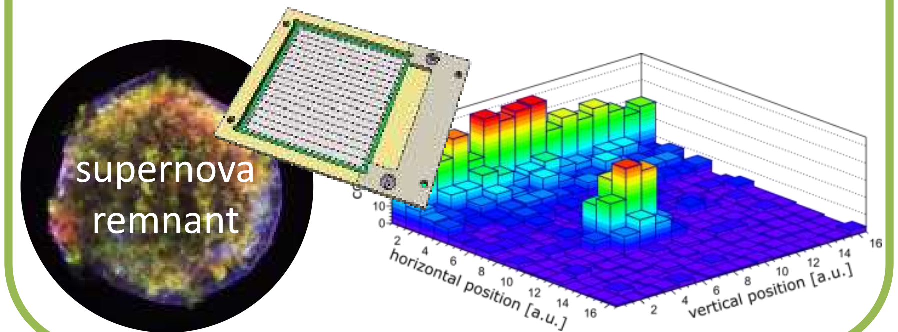


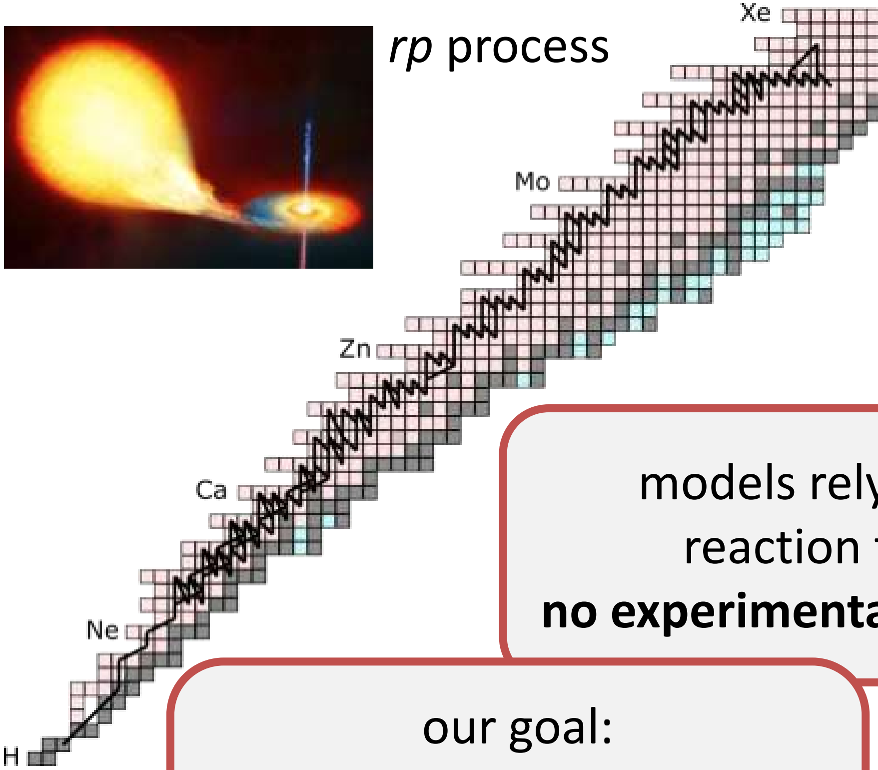

NECTAR
Nuclear rEaCTions At storage Rings




CARME
CRYRING Array for Reaction MEasurements

# Proton-Capture on Stored Radio-Nuclei

*rp* process

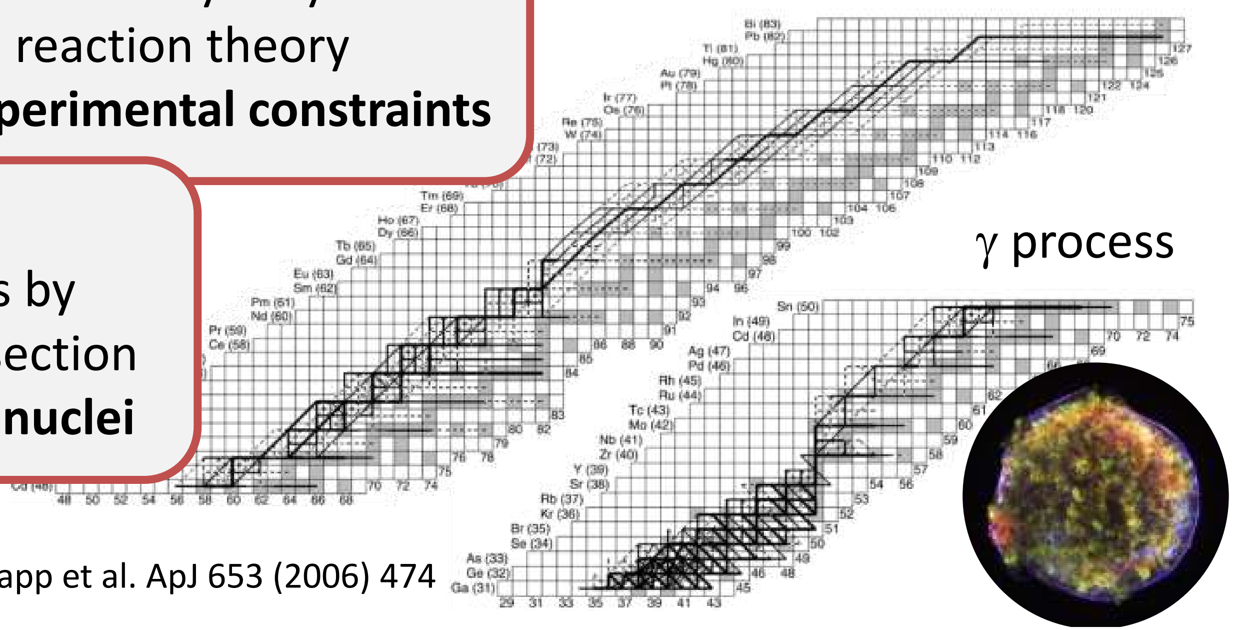



Schatz & Rehm, Nucl. Phys. A 777 (2006) 601

explosive nucleosynthesis
is taking place
**beyond nuclear stability**

models rely fully on
reaction theory
**no experimental constraints**

our goal:
improving models by
experimental cross section
**data on radioactive nuclei**



$\gamma$ process

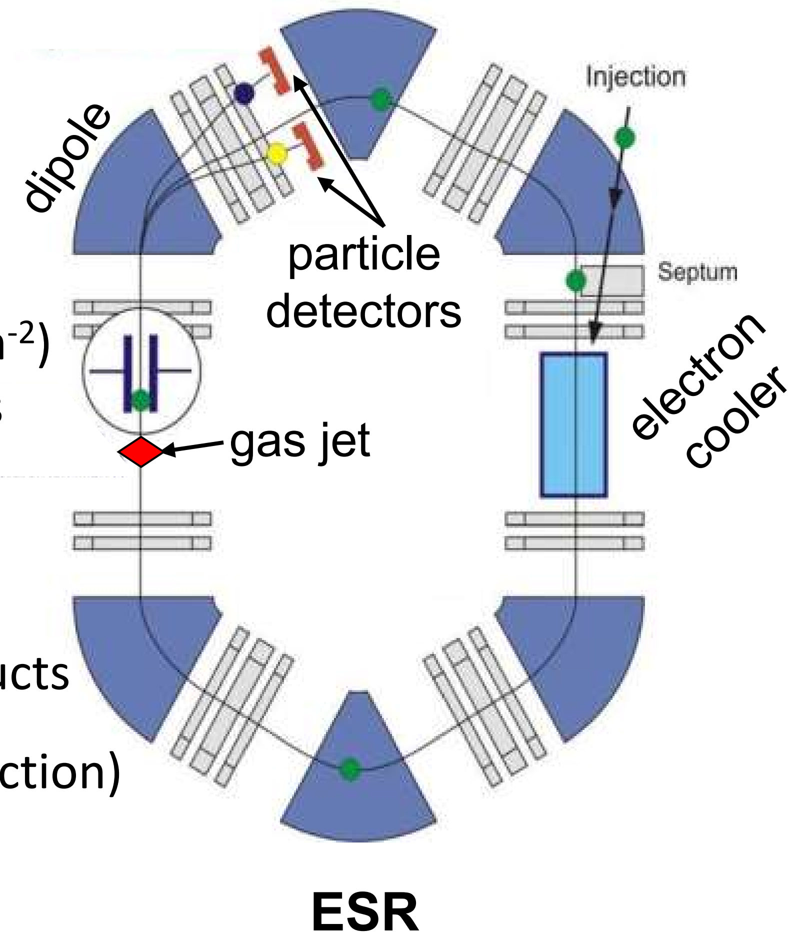
Rapp et al. ApJ 653 (2006) 474

# Proton-Capture Reactions

## Experimental Procedure in ESR

refill ring periodically

- injection of ions @ >100 MeV/u
  - ✓ **fully stripped ions/fragments**
- deceleration & $e^-$-cooling of the beam
  - ✓ **E = 3 - 10 MeV/u**
- activate internal **hydrogen target** ($10^{14}$ $cm^{-2}$)
  - ✓ proton & electron capture reactions
  - ✓ **separated by dipole**
  - ✓ particle detectors on…
    - … inner tracks for (p,$\gamma$) products
    - … outer tracks for $e^-$ capture products
- beam lifetime (residual gas + target interaction)
  - ➢ intensity goes down exponentially



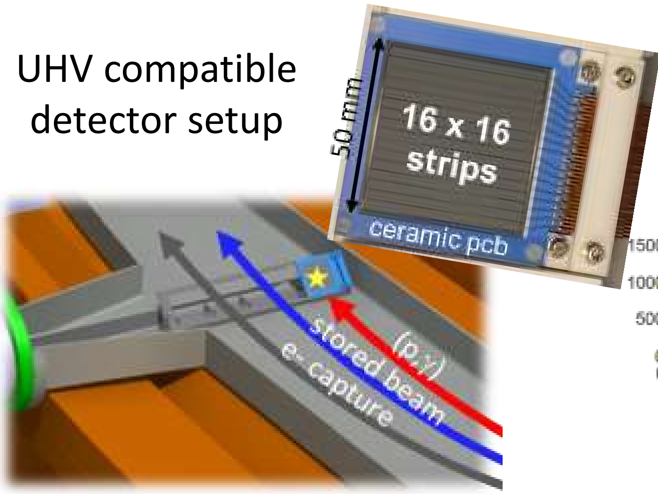

in summary: **a recycling recoil separator**

# Proton-Capture Reactions

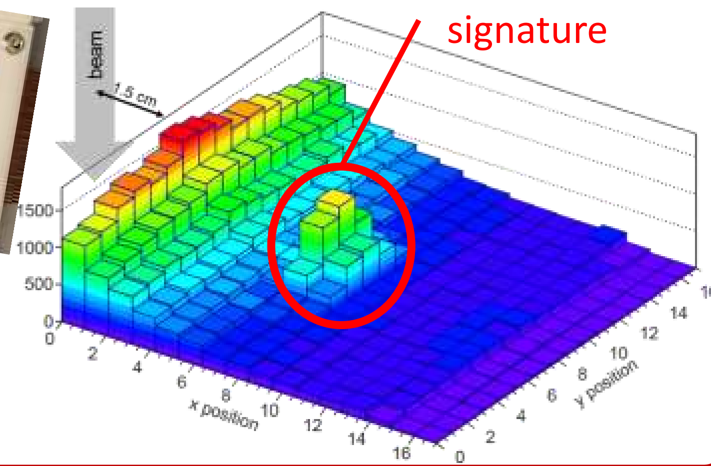
## Experimental Procedure in ESR

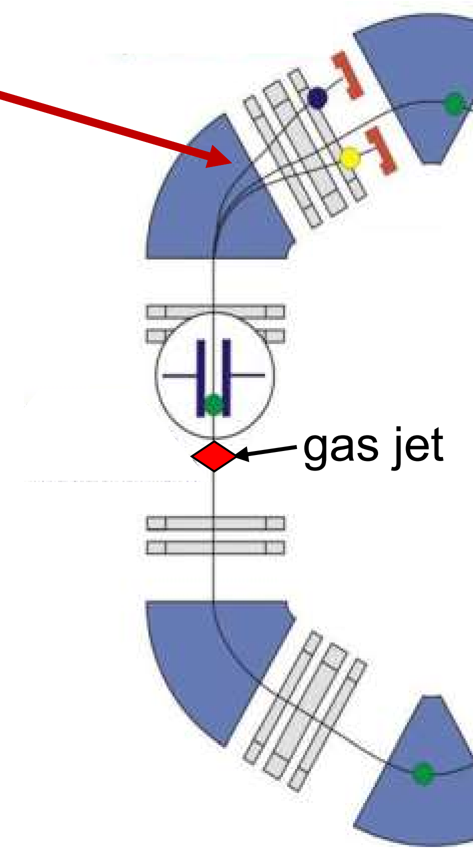
### Nuclear recoil separation & detection

UHV compatible detector setup




proton-capture signature



# Proton-Capture Reactions

## Experimental Procedure in ESR

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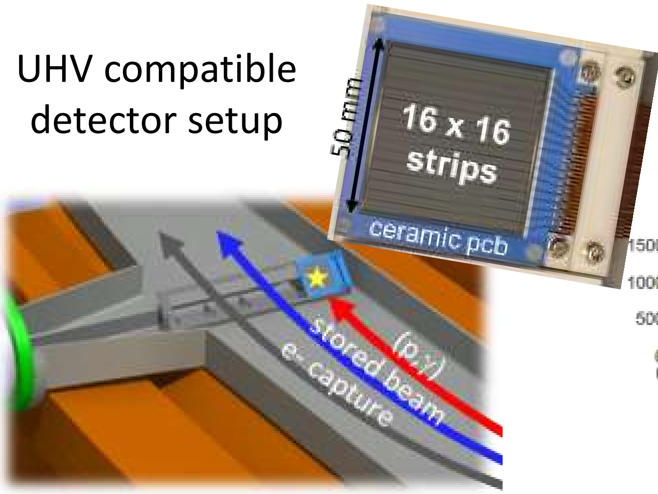
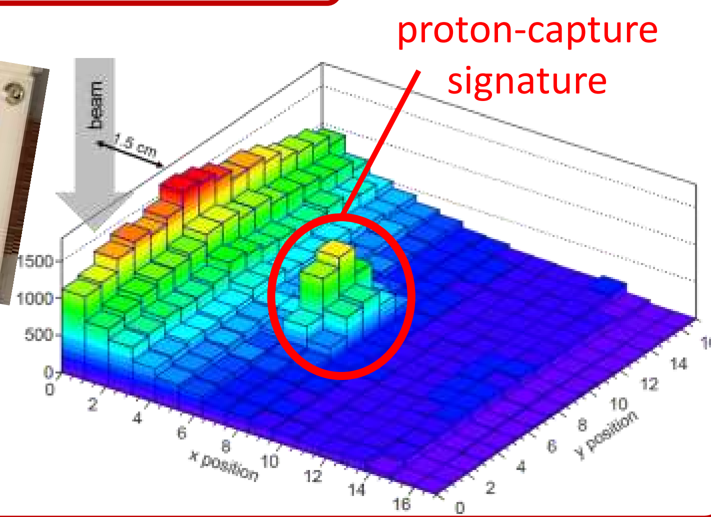
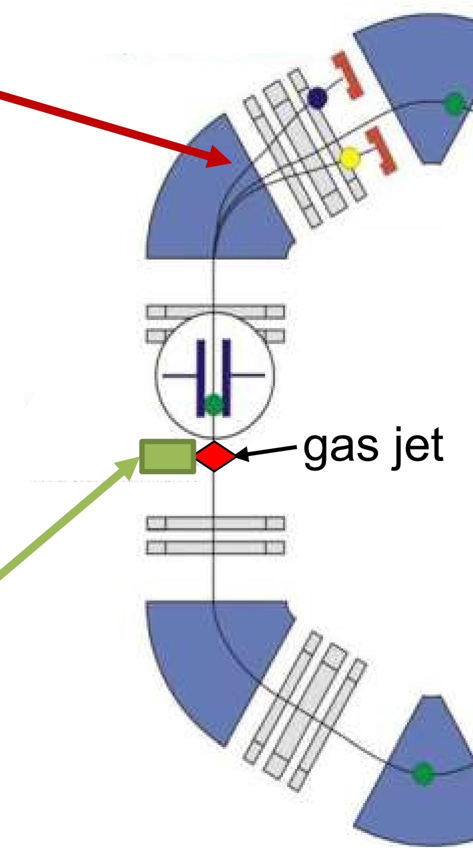
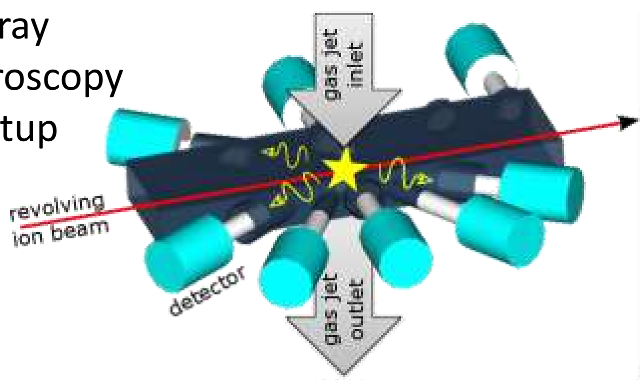


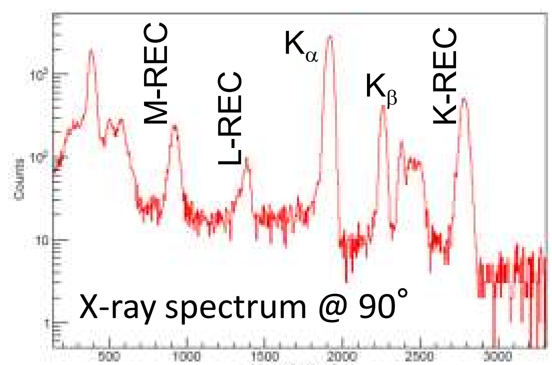




### normalization to atomic processes

X-ray spectroscopy setup



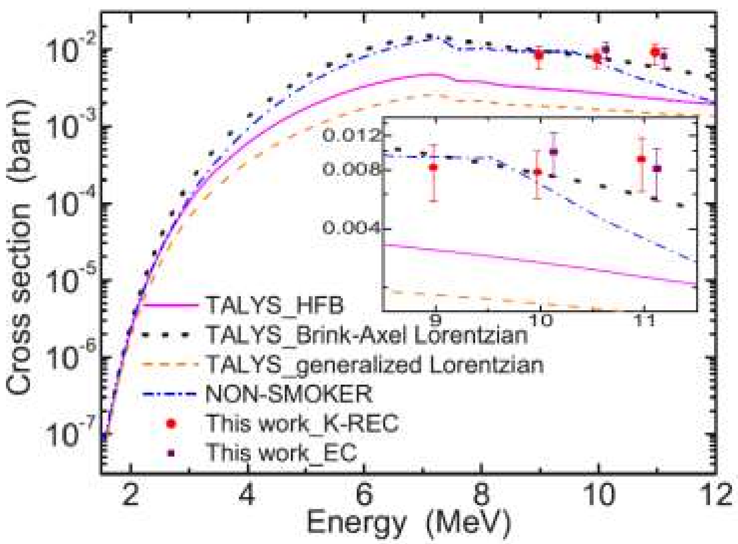
# The Proton-Capture Campaign

## Pioneering with Stable Beams

### $^{96}Ru(p,\gamma)^{97}Rh$

Mei et al. PRC **92**, 035803 (2015)

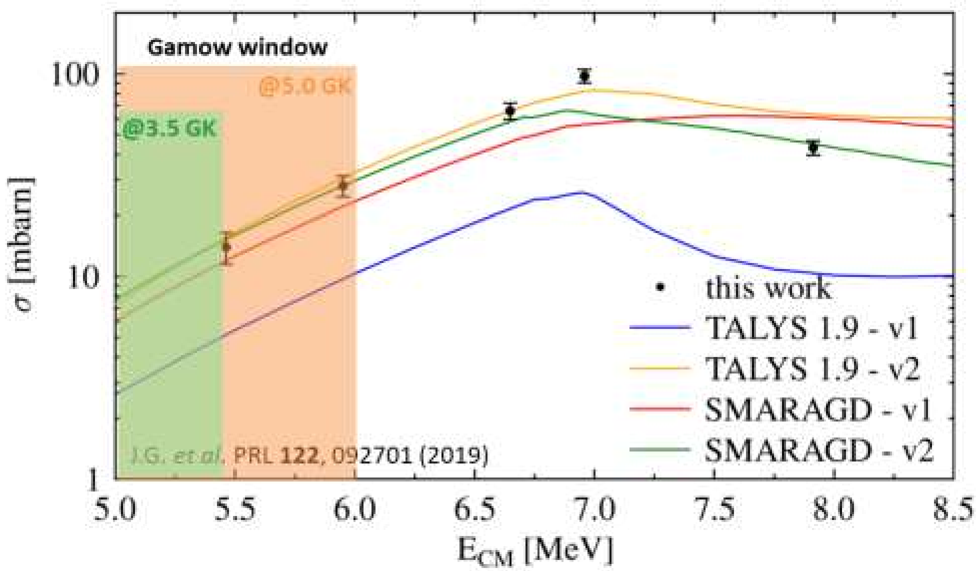
- successful pilot experiment
- Gamow window not reached (detector behind window)




### $^{124}Xe(p,\gamma)^{125}Cs$

J.G. et al. PRL **122**, 092701 (2019)

- UHV compatible Si-setup
- $1^{st}$ meas. inside Gamow window



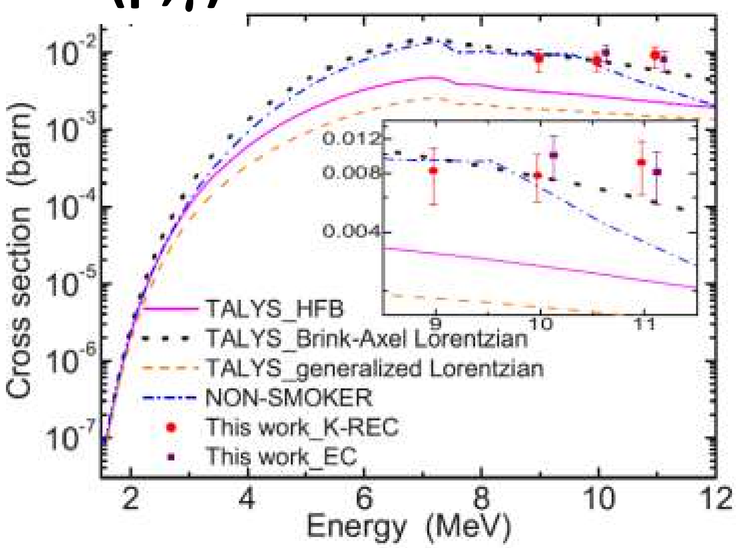
# The Proton-Capture Campaign

## Published Results

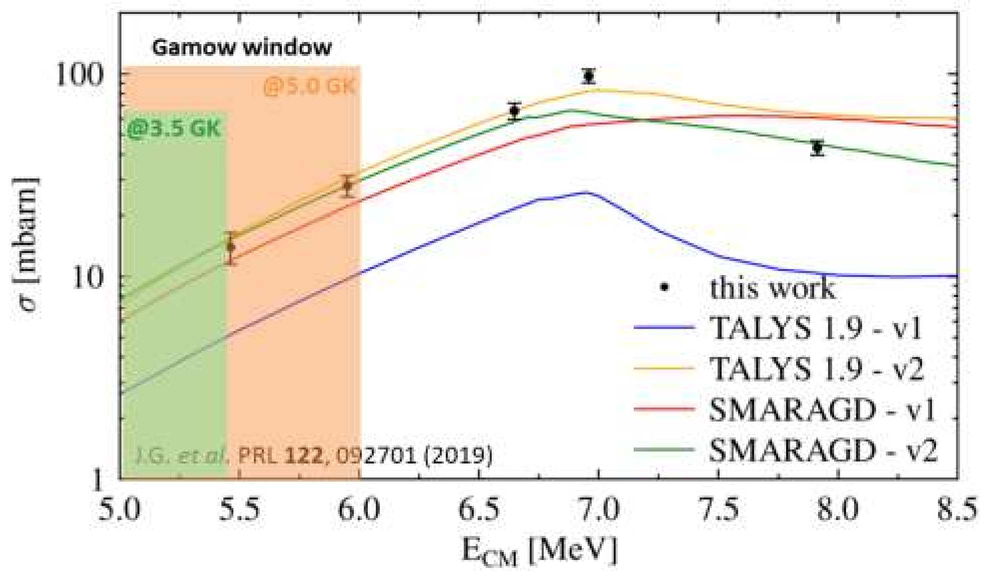
**Testing reaction theory:**

- *local agreement with data* can be reached by tuning nuclear input
  - ✓ pin down key reactions
- a global improvement of the theory needs…
  … constraints at even lower energies
  … data on exotic nuclei

**$^{96}$Ru(p,$\gamma$)**




**$^{124}$Xe(p,$\gamma$)**

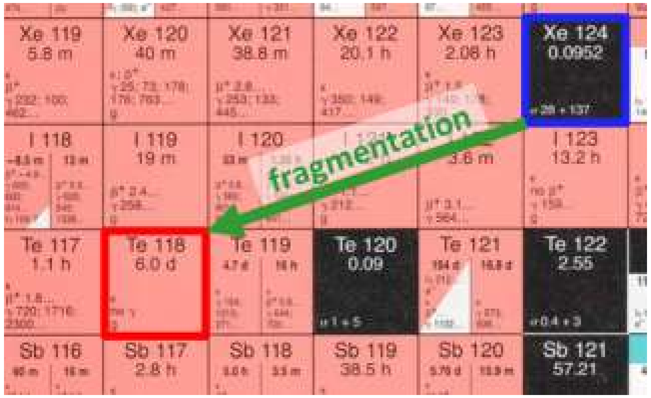


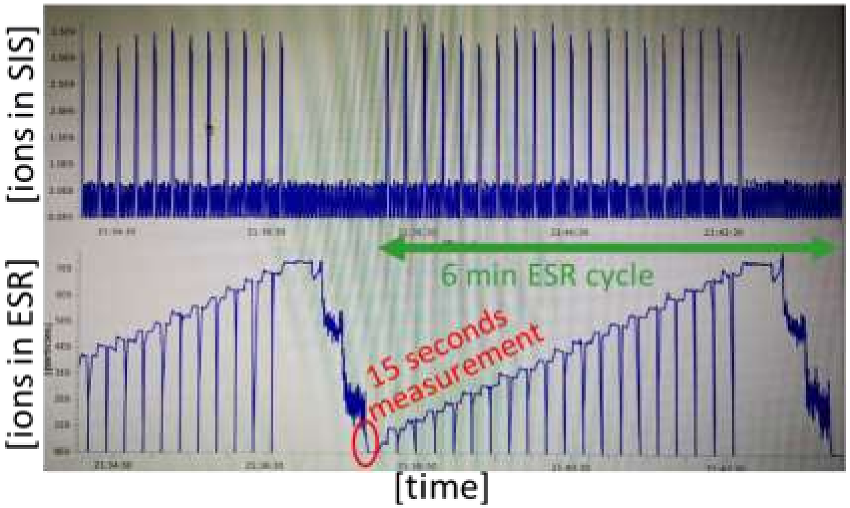
# The Proton-Capture Campaign

## 1st Radioactive Beam Measurement

### $^{118}$Te(p,$\gamma$)

- reaction is part of the $\gamma$ process network
- selected for simplicity of measurement
- production in FRS at 550 MeV/u
- goal: combine accumulation and deceleration of fragments in ESR for the first time




From Synchrotron:

$3.5 \times 10^9$ $^{124}$Xe ions per shot

After FRS:

$3.5 \times 10^5$ fragments per shot

In ESR:

accumulation of 20 shots

**$10^6$ ions left for measurement**

after deceleration

# The Proton-Capture Campaign

1st Radioactive Beam Measurement

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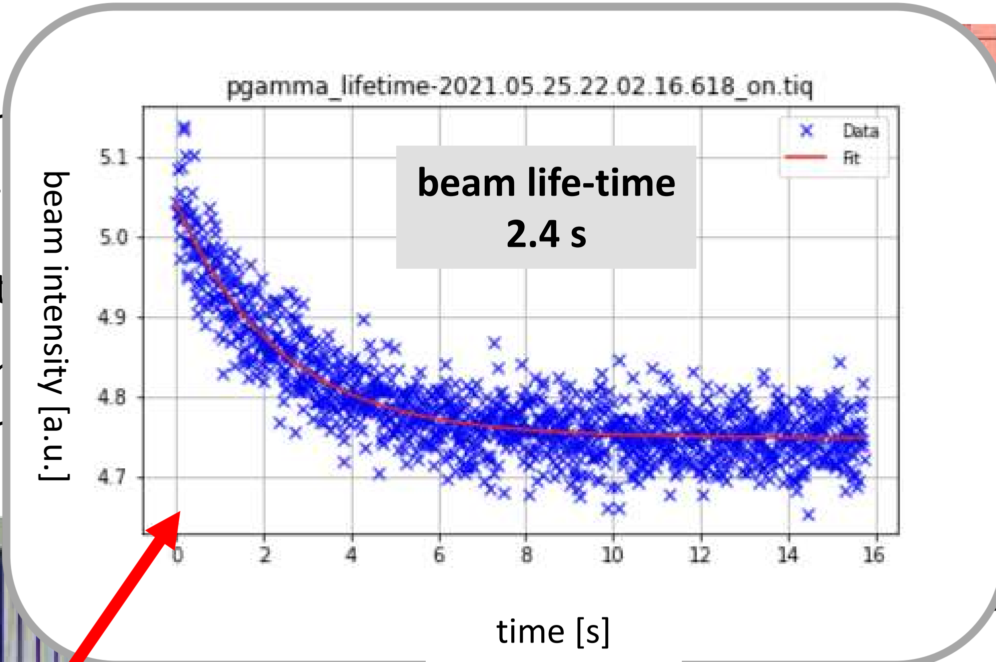
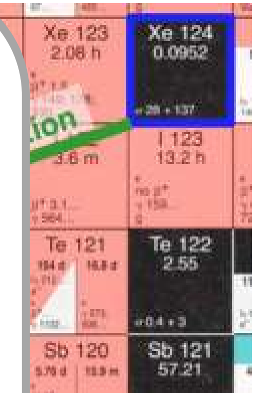
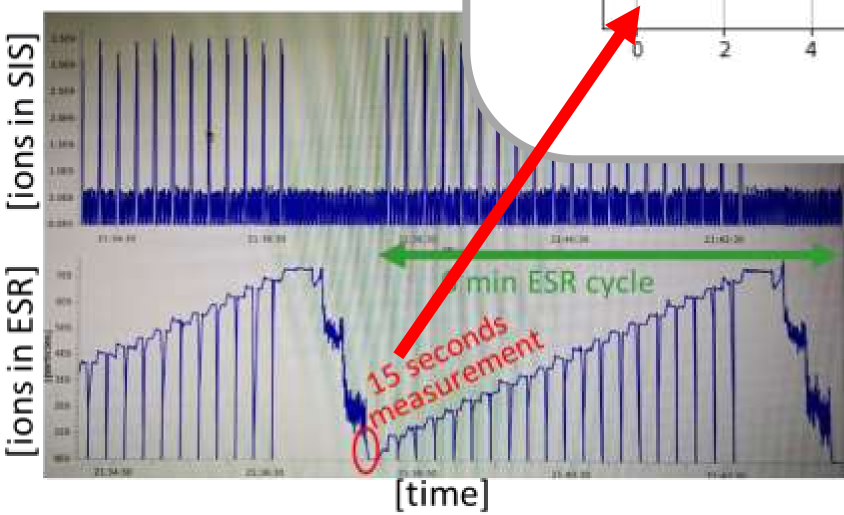



per shot

After FRS:

3.5x10$^5$ fragments per shot

In ESR:

accumulation of 20 shots

**10$^6$ ions left for measurement**

after deceleration

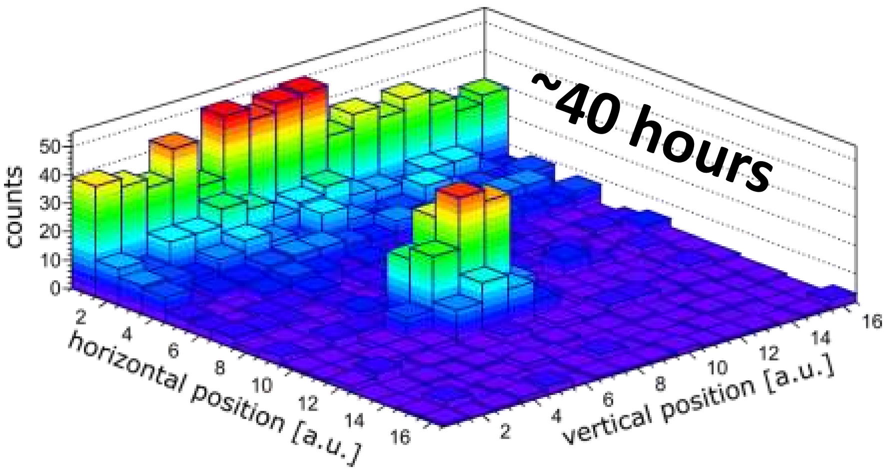
# The Proton-Capture Campaign

## 1st Radioactive Beam Measurement

### $^{118}$Te(p,$\gamma$)

start with measurement at **7 MeV/u**

- ➢ 40 hours of data taking
- ➢ clear proton-capture signature
- ➢ > 300 counts  [≈7.5 counts/hour]



# The Proton-Capture Campaign

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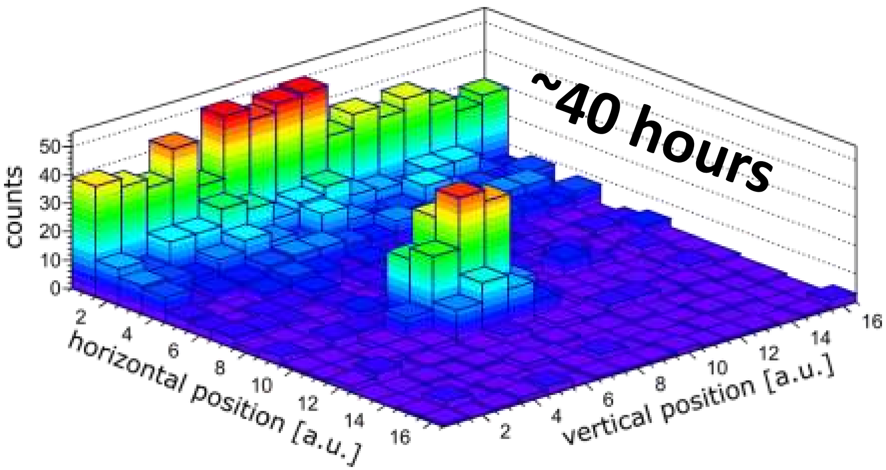
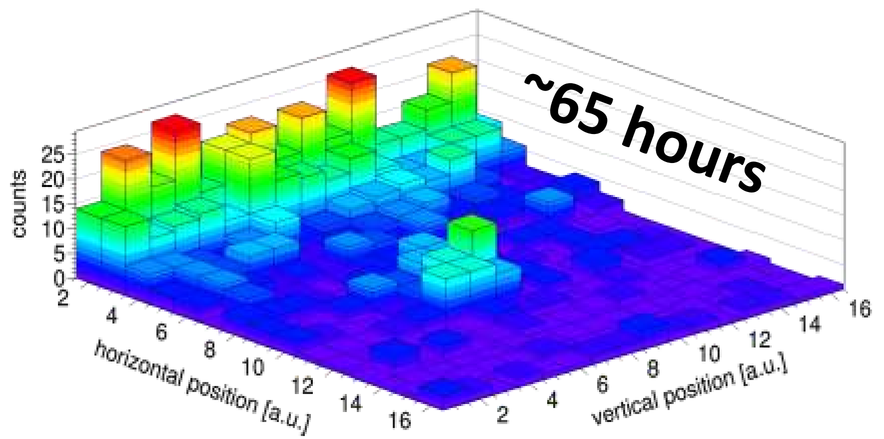



measurement at **6 MeV/u**

- less than $10^6$ ions for measurement
- 65 hours of data taking
- weaker signature
- ≈ 100 counts [≈1.5 counts/hour]



# The Proton-Capture Campaign

## $1^{st}$ Radioactive Beam Measurement

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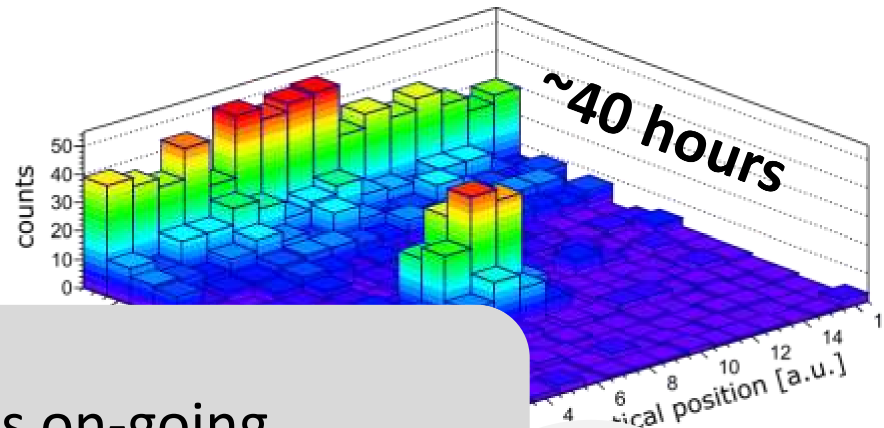



Analysis is on-going

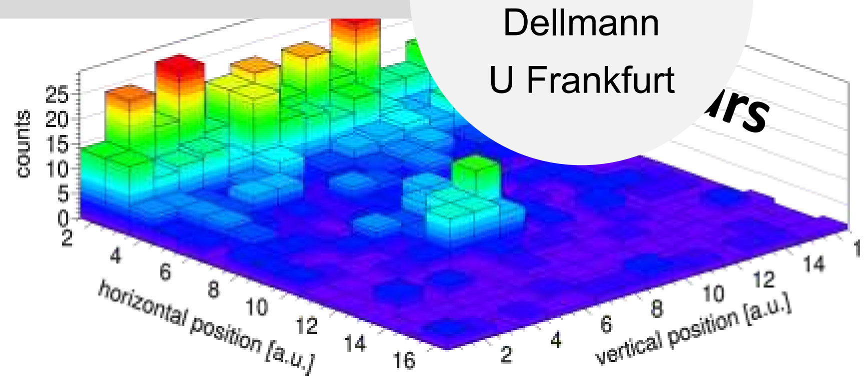
promising preliminary results

another energy pc

- less than $10^6$ ions for measurement
- 65 hours of data taking
- weaker signature
- ≈ 100 counts [≈1.5 counts/hour]

PhD thesis of Sophia Dellmann

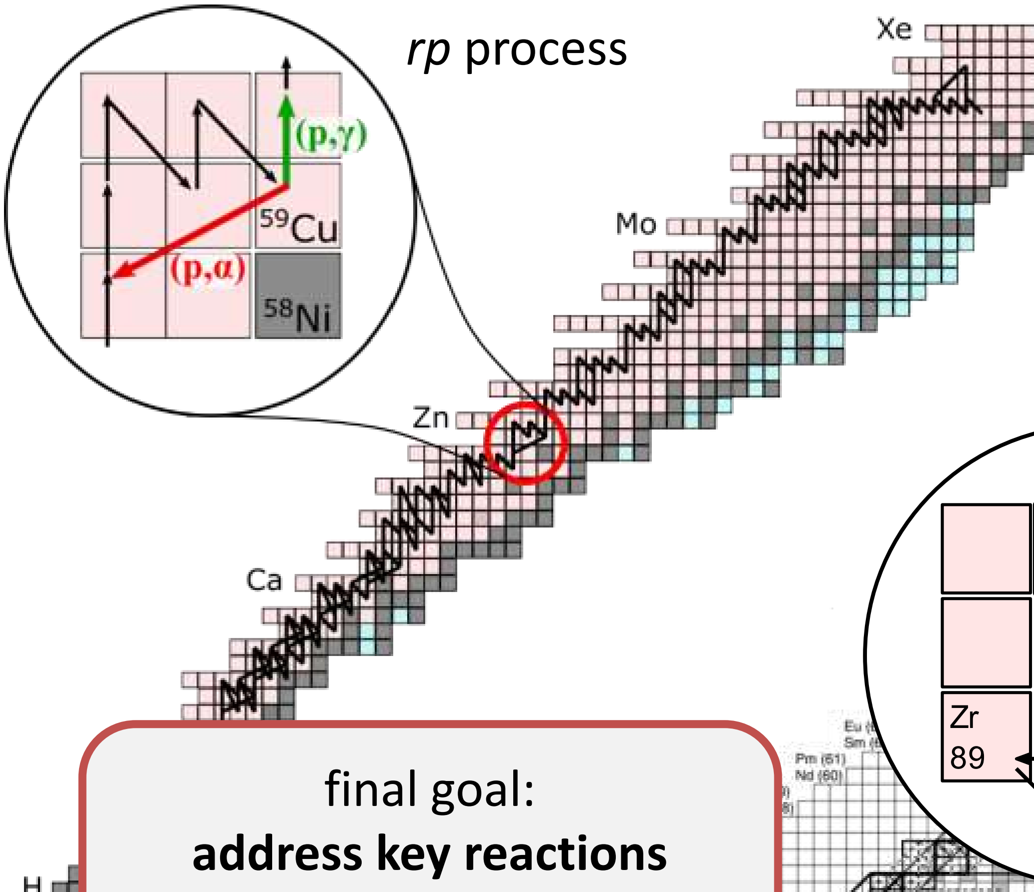
U Frankfurt



# The Proton-Capture Campaign

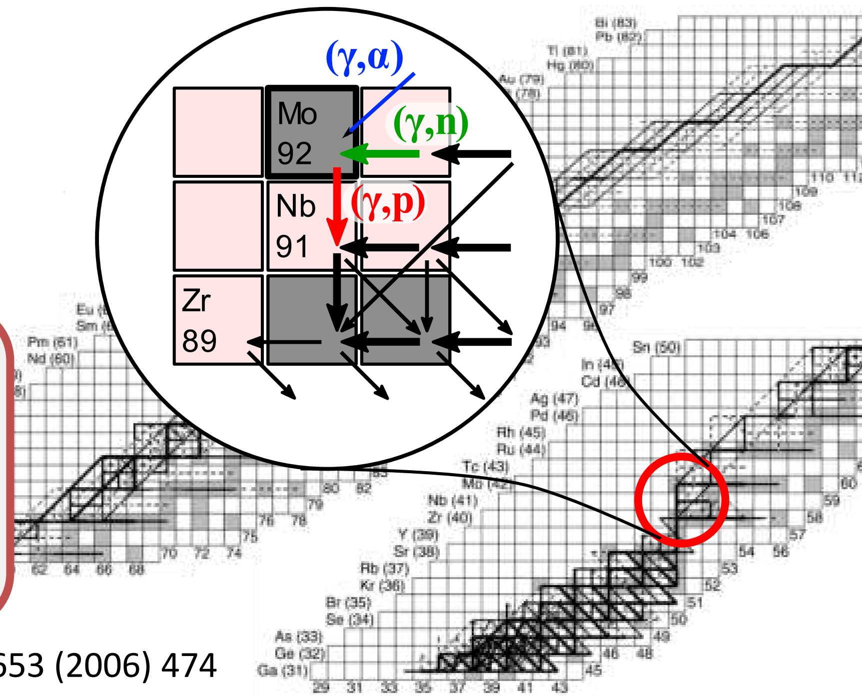
## Future Goals

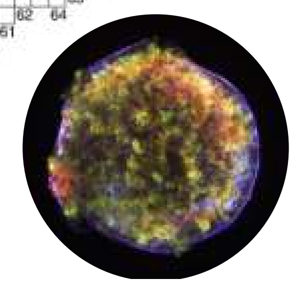
*rp* process




Based on
Schatz & Rehm
Nucl. Phys. A **777** (2006) 601

γ process



final goal:
**address key reactions of explosive nucleosynthesis**

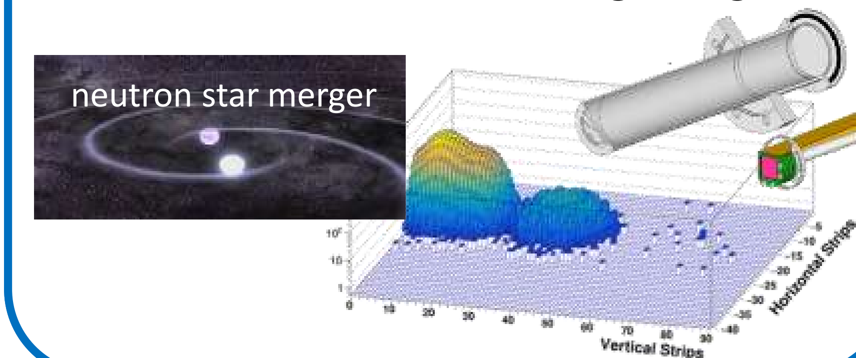
Rapp et al. ApJ 653 (2006) 474

# Overview

Proton-Capture Reactions
for Explosive Nucleosynthesis




NECTAR
Nuclear rEaCTions At storage Rings

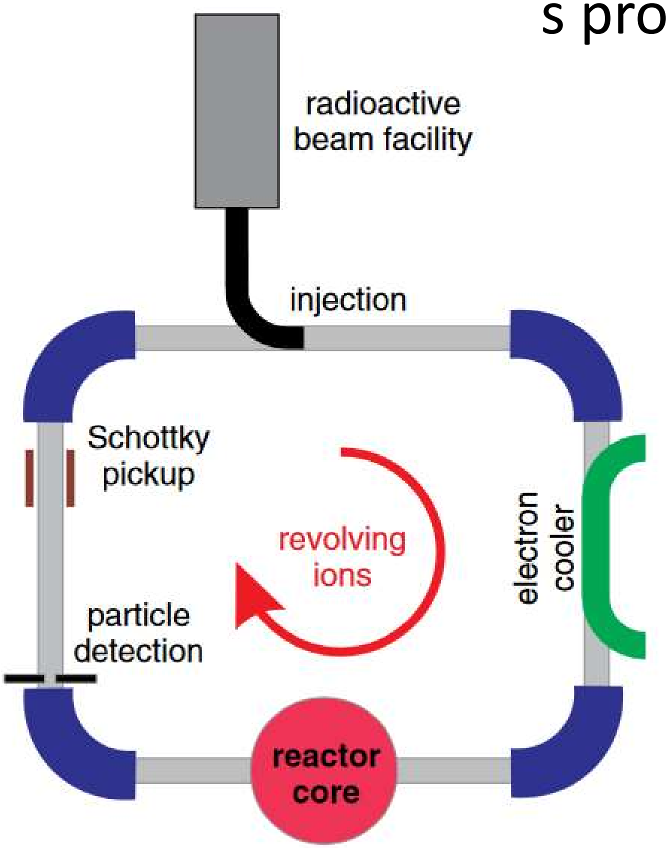



CARME
CRYRING Array for Reaction MEasurements

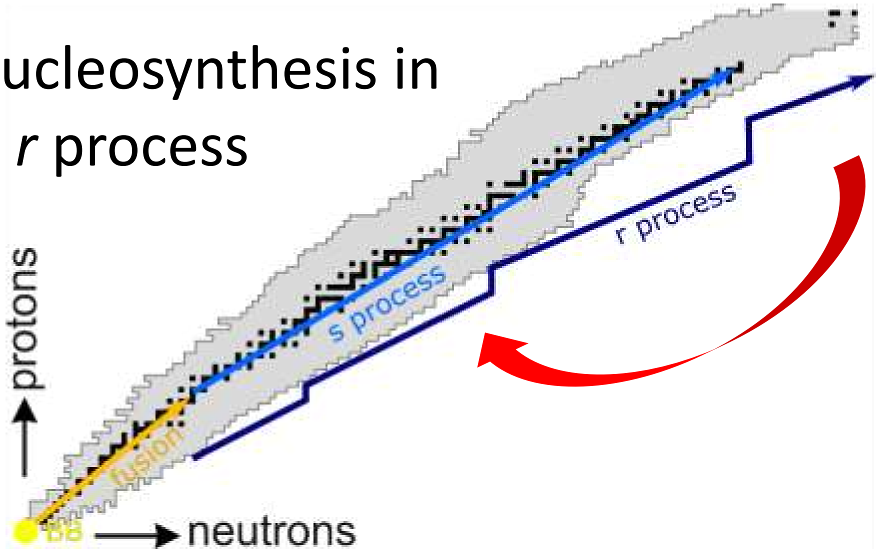
# NECTAR - Nuclear rEaCTions At storage Rings

Neutron-induced reactions in inverse kinematics

neutron-capture nucleosynthesis in
s process & *r* process

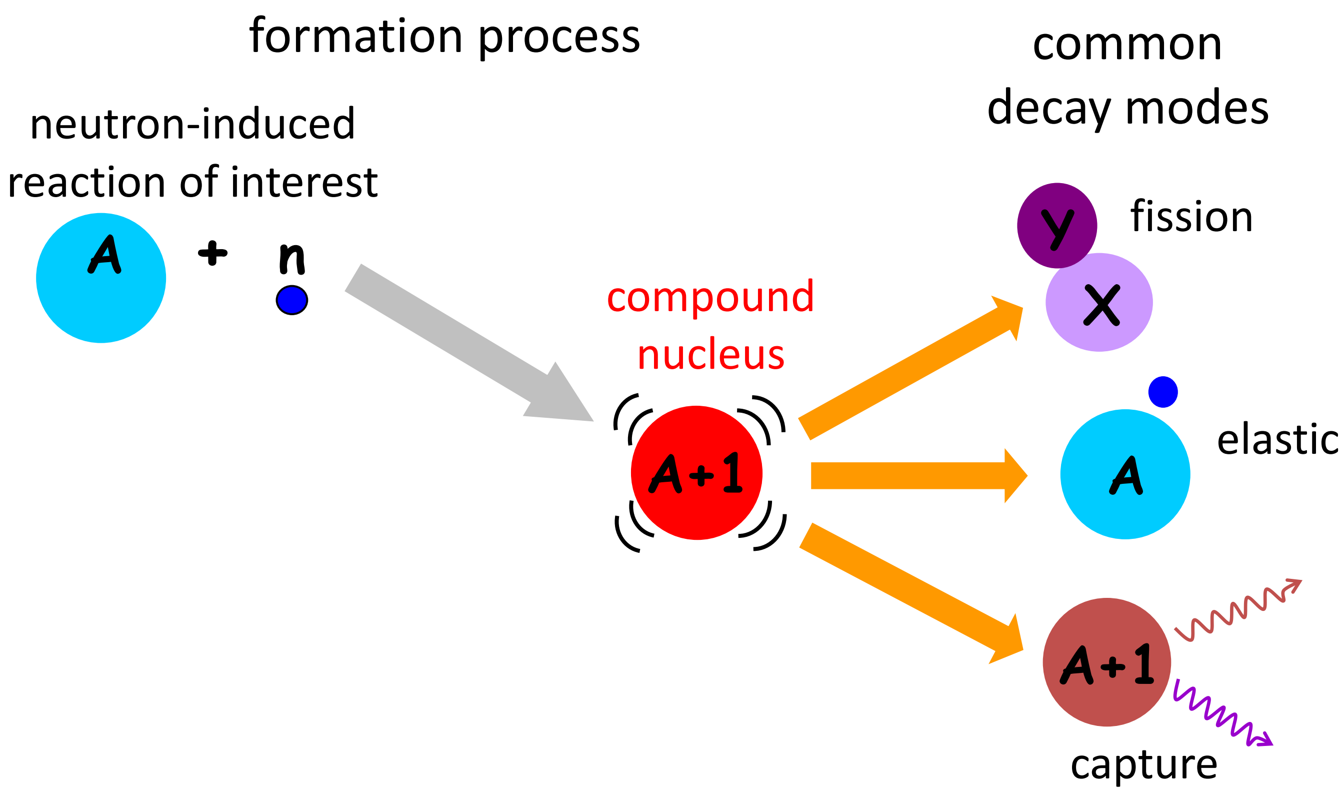



R.Reifarth & Y.Litvinov
*Phys. Rev. ST Accel. Beams* **17**, 014701 (2014)




- the direct approach: build a **neutron target**
  - storage ring & reactor or spallation source
- the indirect approach: the **surrogate technique**
  - NECTAR project (ERC advanced grant)
    PI: B. Jurado, Bordeaux

# NECTAR - Nuclear rEaCTions At storage Rings




$$\underbrace{\sigma^{A}_{n,decay}(E^*)}_{\text{cross section}} = \underbrace{\sigma^{A+1}_{formation}(E^*)}_{\text{theory}} \cdot \underbrace{P^{surro}_{decay}(E^*)}_{\text{measurement}}$$

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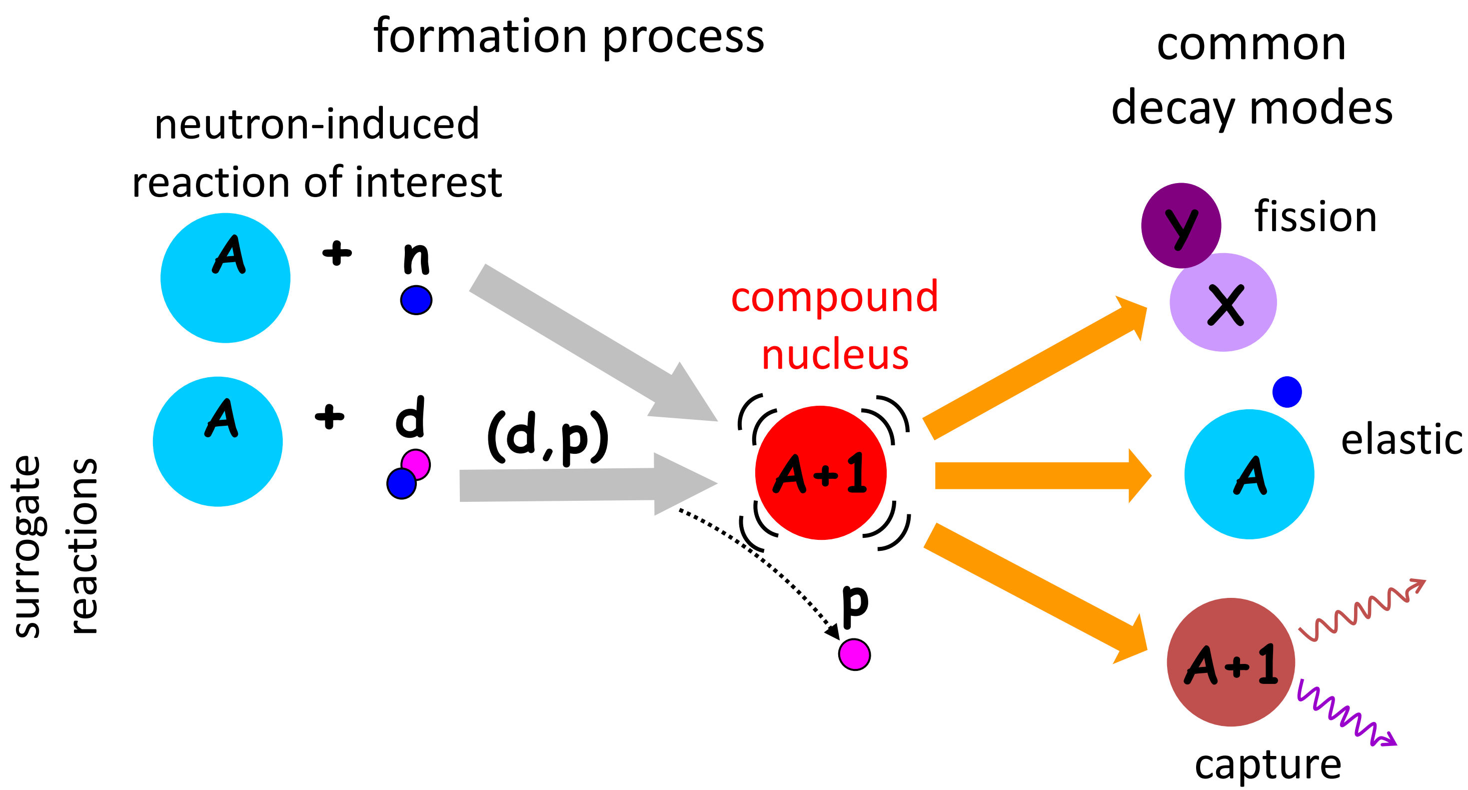


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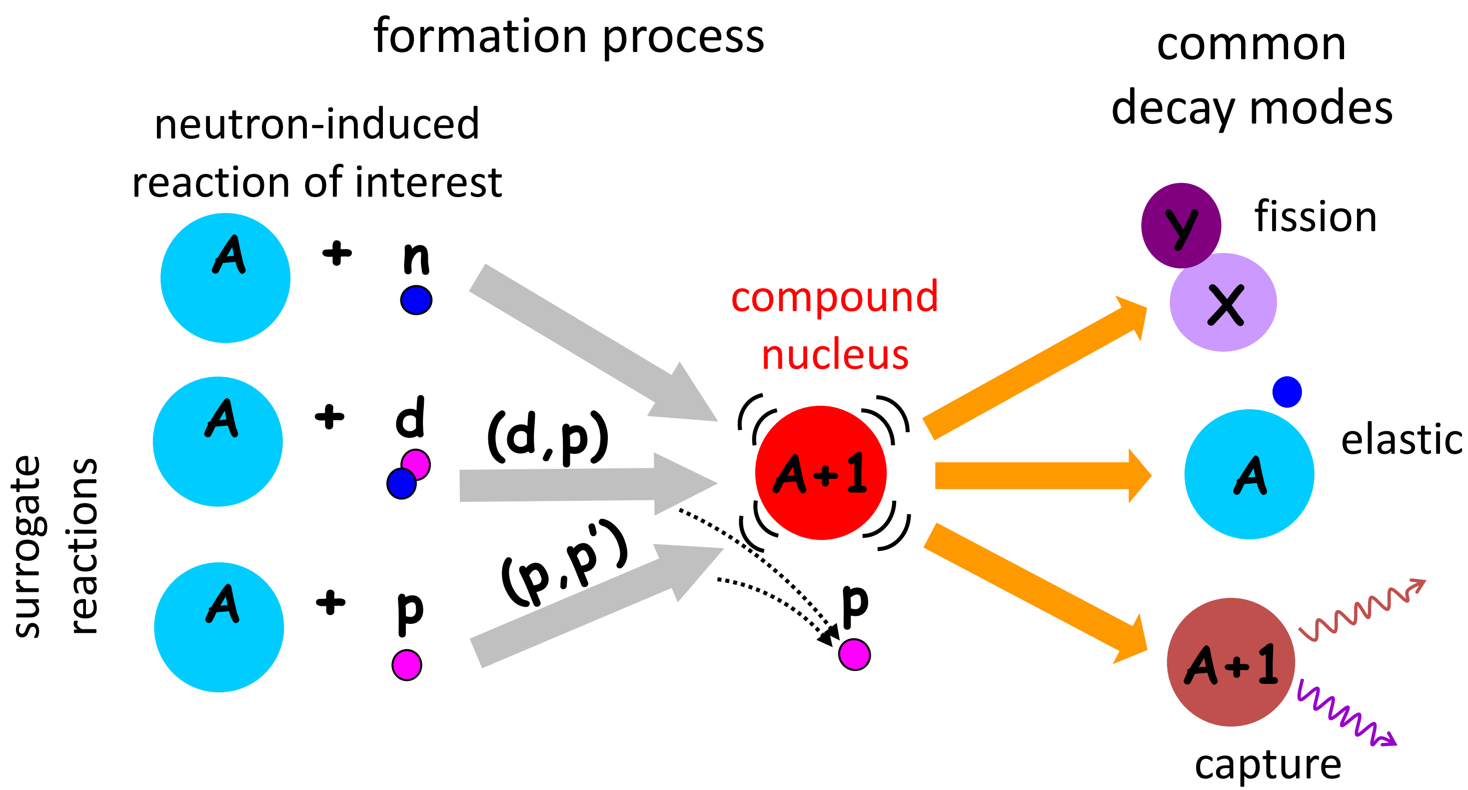


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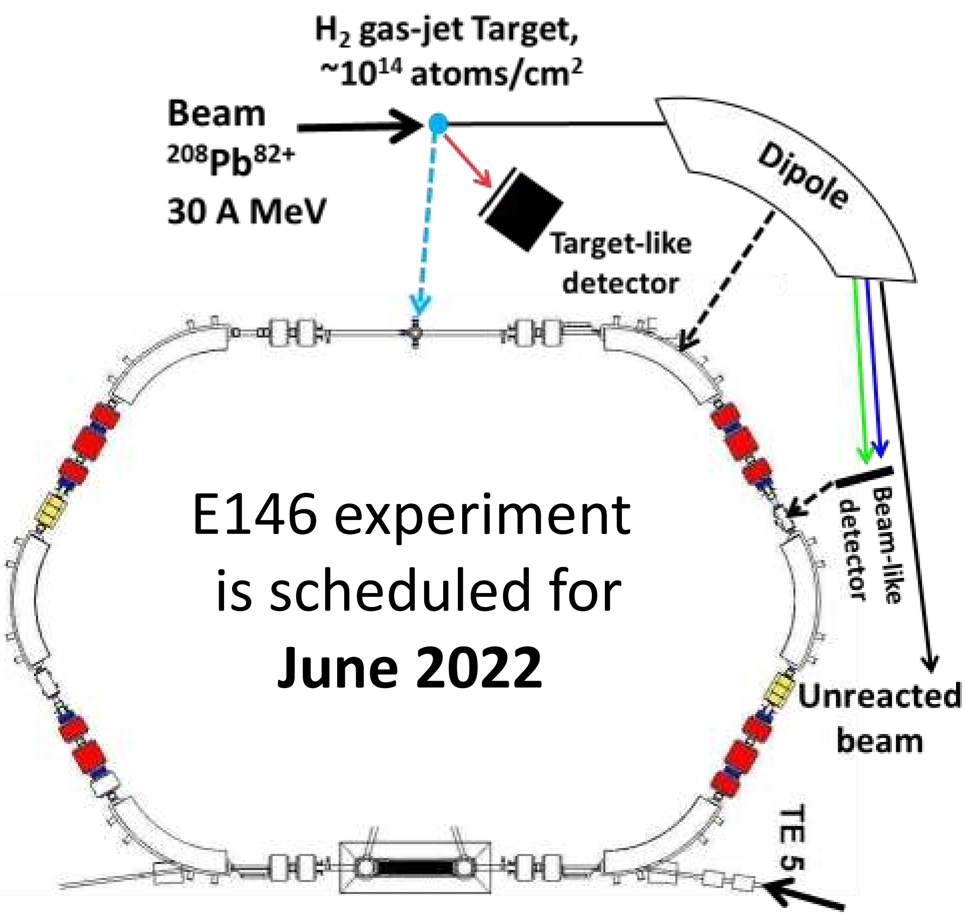
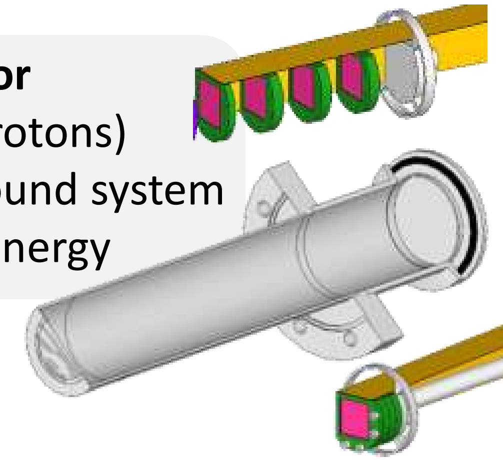
# NECTAR - proof-of-principle in ESR

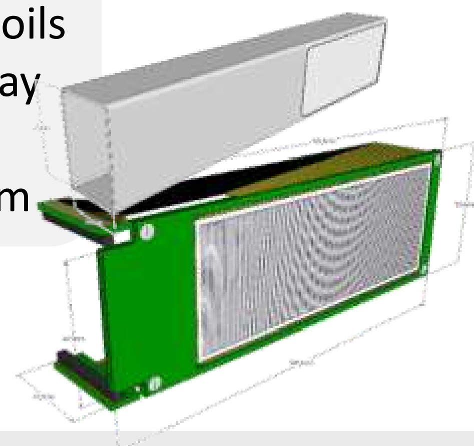
## $^{208}$Pb(p,p') to study $^{208}$Pb(n,n') and $^{208}$Pb(n,$\gamma$)




**Si telescope detector**
for target recoils (protons)
to select the compound system
and the excitation energy



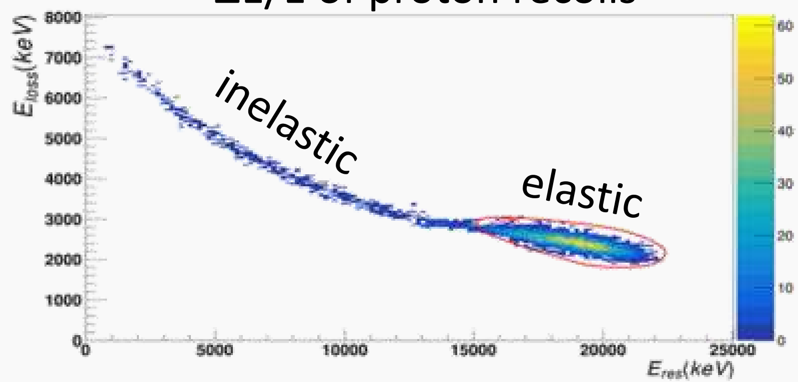
**Si strip detector**
for heavy ion recoils
to select the decay
channel of the
compound system



# NECTAR - proof-of-principle in ESR

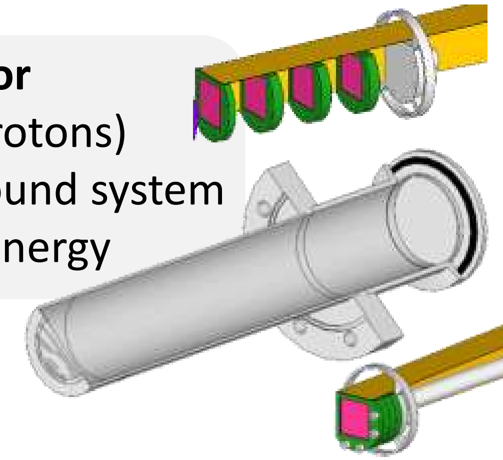
## $^{208}$Pb(p,p’) to study $^{208}$Pb(n,n’) and $^{208}$Pb(n,$\gamma$)

ΔE/E of proton recoils

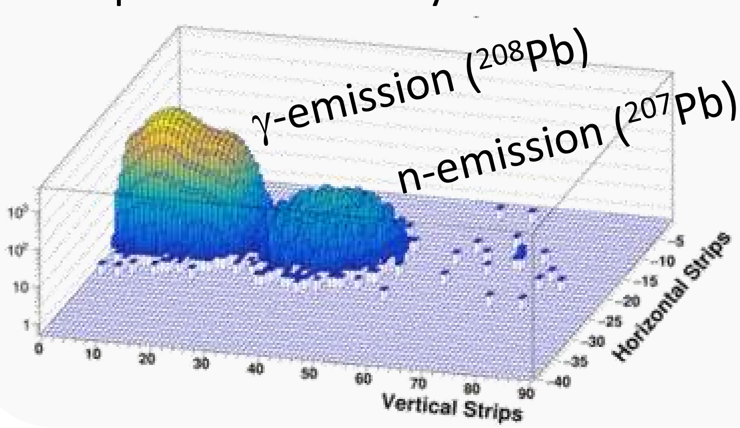



total energy E

**Si telescope detector**
for target recoils (protons)
to select the compound system
and the excitation energy



position of heavy ion recoils

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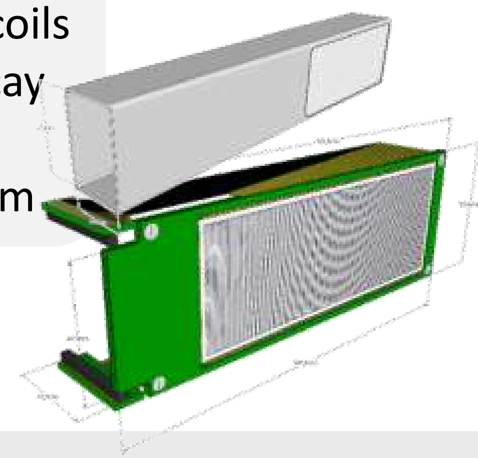


# NECTAR - proof-of-principle in ESR

## $^{208}$Pb(p,p') to study $^{208}$Pb(n,n') and $^{208}$Pb(n,$\gamma$)

## Preliminary Results

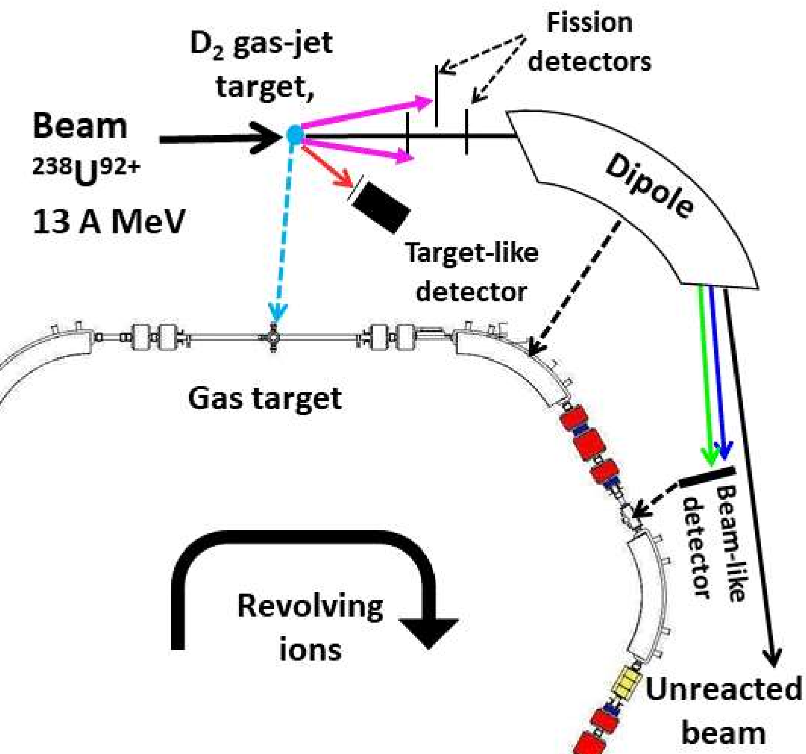
**$^{207}$Pb(n,$\gamma$) cross section**
derived with improved theory

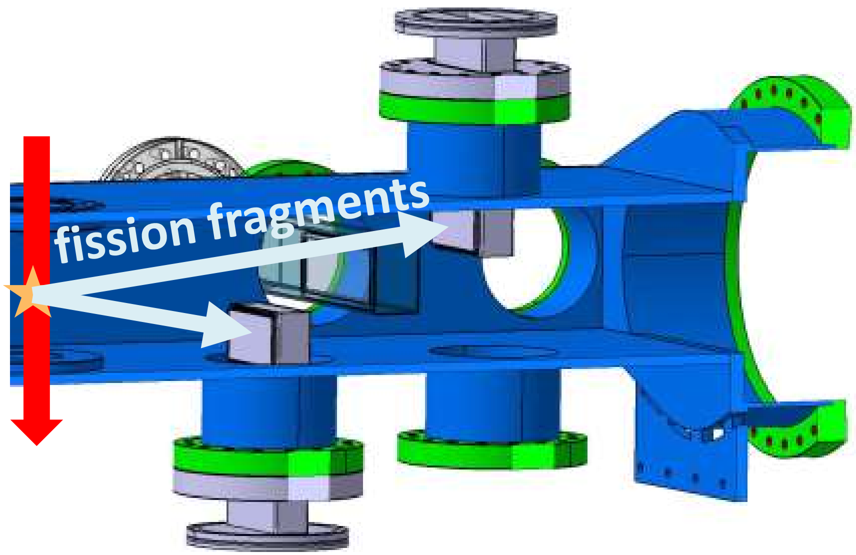
**neutron emission probability**
measured for $^{208}$Pb* compound system

## Successful Proof-of-Concept

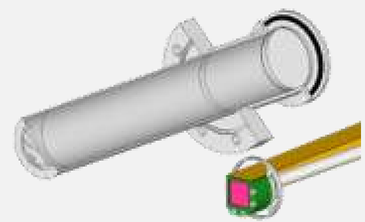
# NECTAR - upgrade for fission channel

accepted proposal: $^{238}$U(d,p) to study $^{238}$U(n,n’) and $^{238}$U(n,γ) and $^{238}$U(n,f)




**Si telescope detector**



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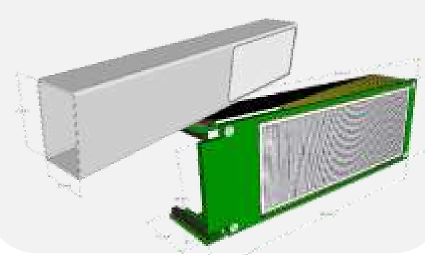

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## Proton-Capture Reactions for Explosive Nucleosynthesis



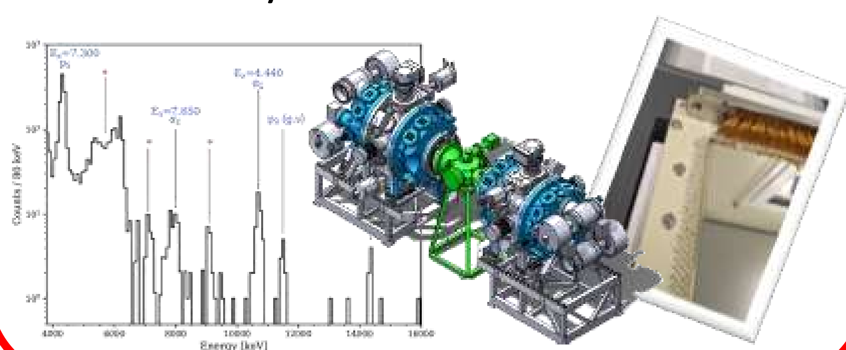

## NECTAR

Nuclear rEaCTions At storage Rings



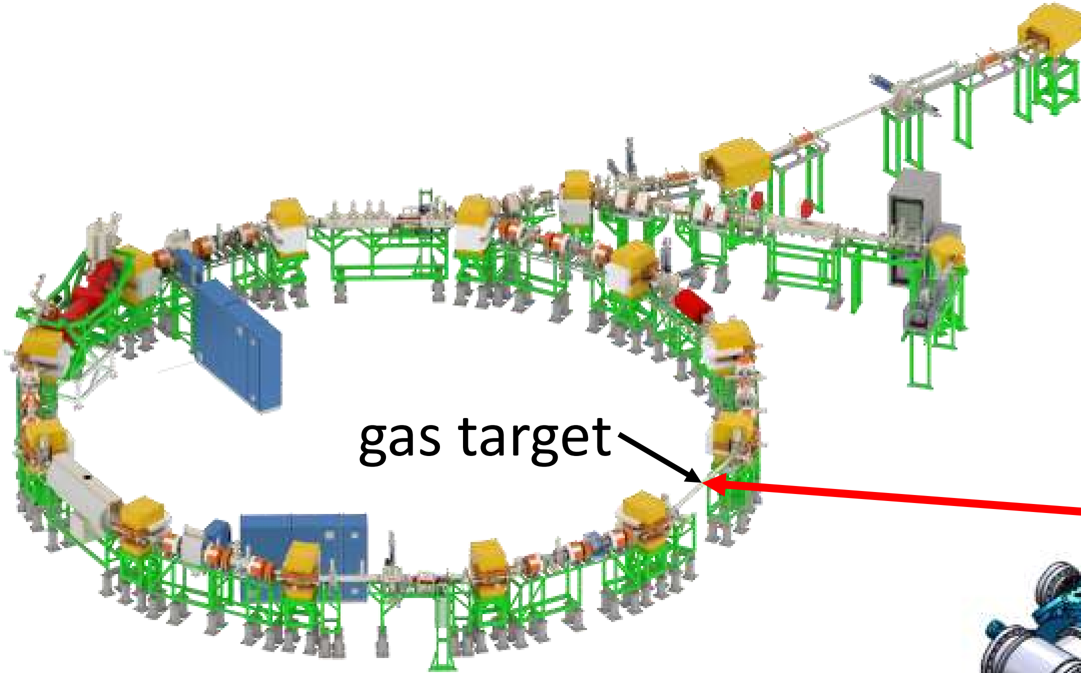

## CARME

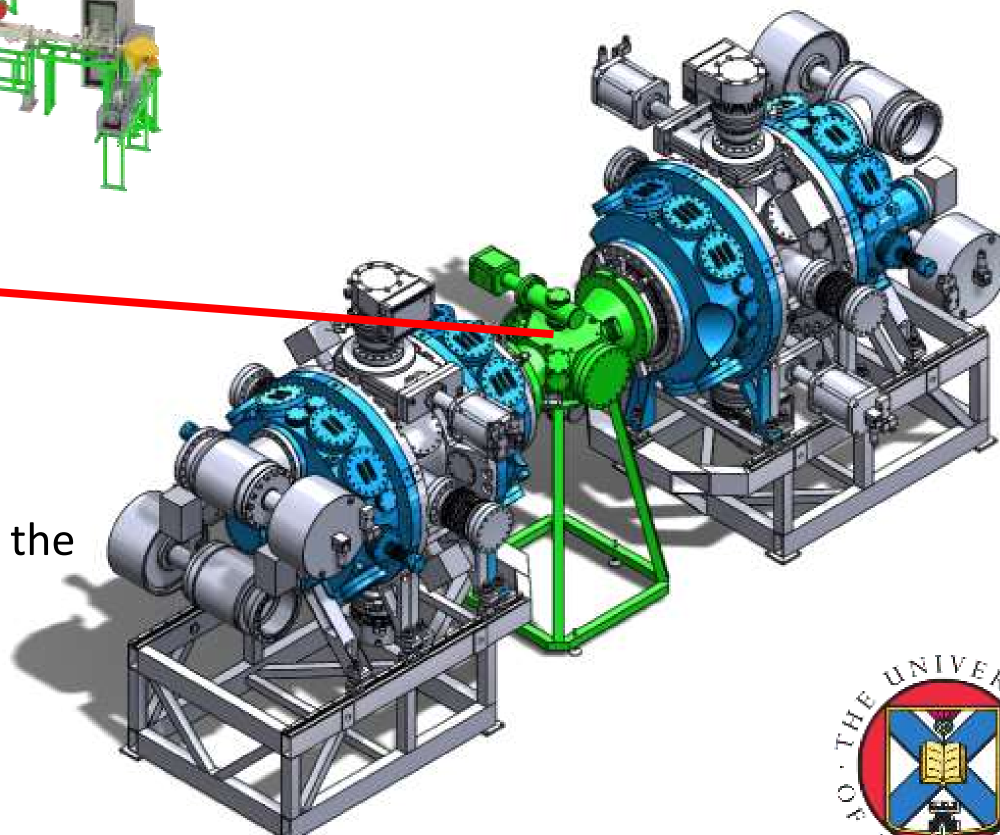
CRYRING Array for Reaction MEasurements



# CARME – Cryring Array for Reaction MEasurement

**UK in-kind contribution to FAIR**
PI: P.J. Woods, Edinburgh



Two reaction chambers mounted around the gas target region.

Versatile tool to study a large spectrum of (nuclear) reactions.

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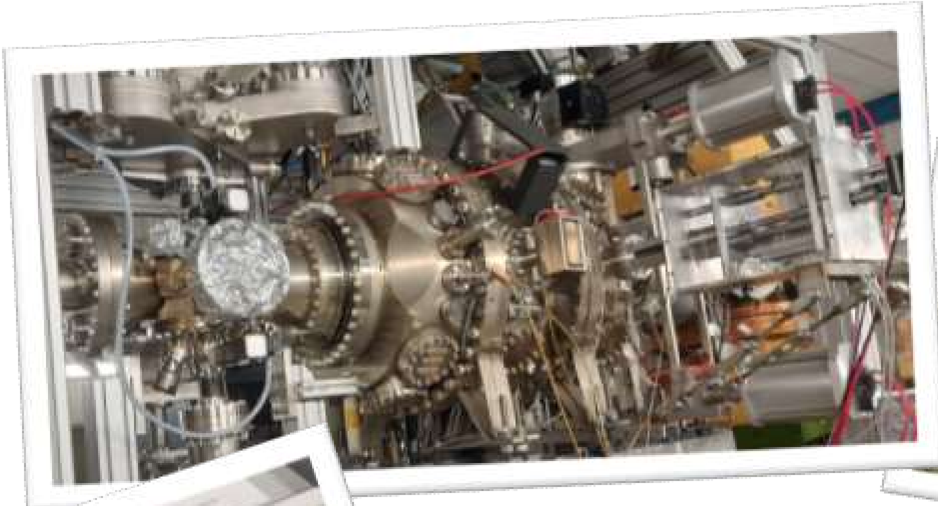
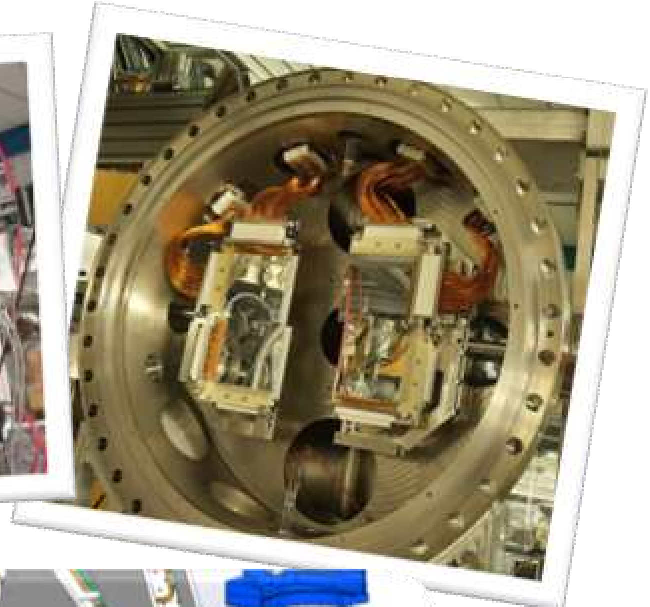
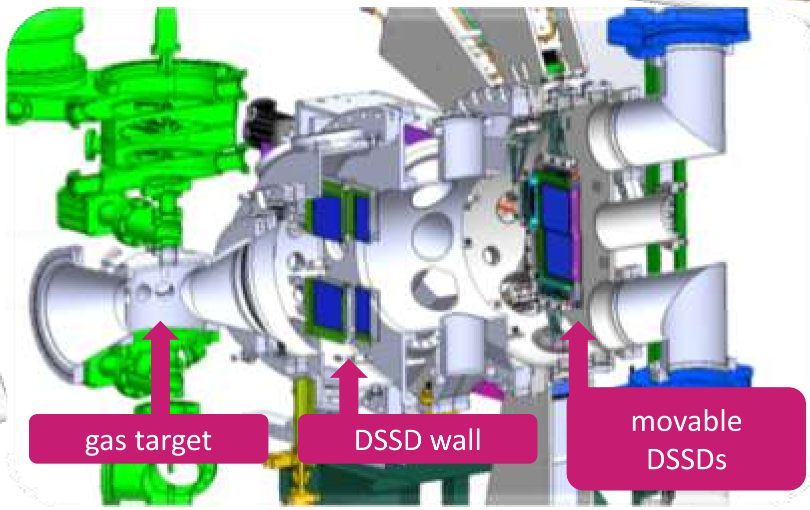






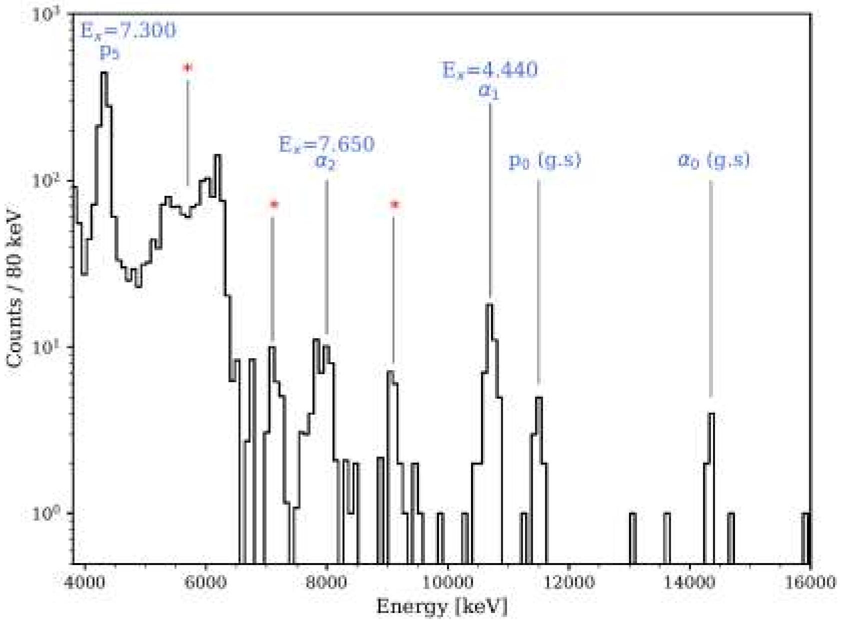

commissioning of CARME & gas target using

$^{14}N$ target

deuterium beam

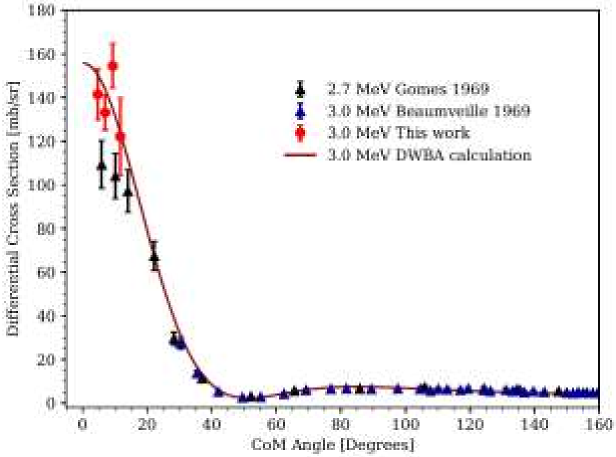
# CARME – Cryring Array for Reaction MEasurement

**energy spectrum**
of light recoils at 1.5 MeV/u




various states *i* populated via
$^{14}N(d,p_i)$ and $^{14}N(d,\alpha_i)$
are identified

**differential cross section**
of $^{14}N(d,p_5)$



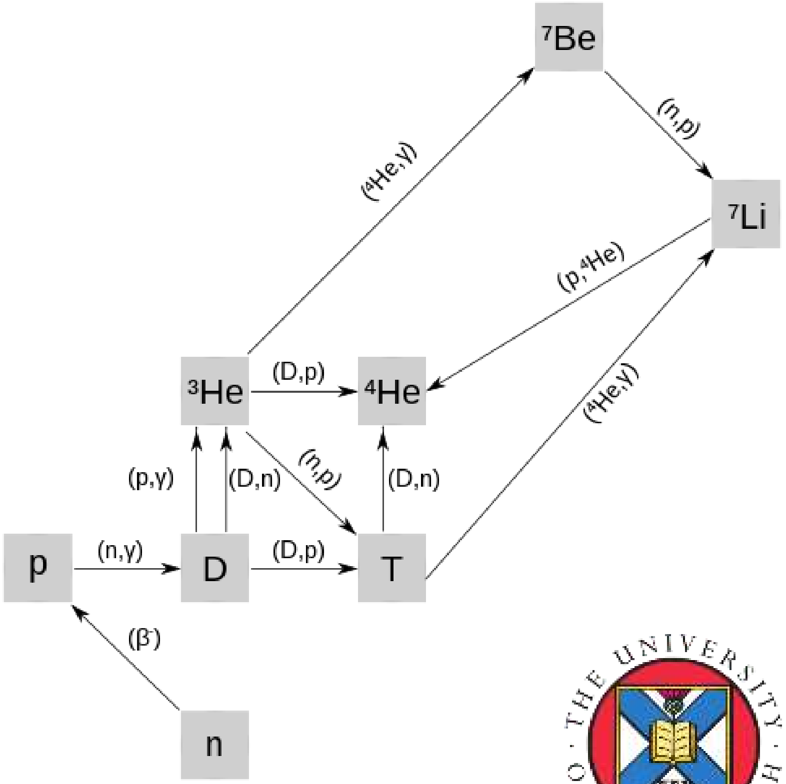

a comparison to older data
and DWBA calculation
shows consistancy

# CARME – Cryring Array for Reaction MEasurement

**Measurement of d+p and d+d fusion for Big Bang Nucleosynthesis**

- BBN calculations deliver predictions for, e.g., isotopic ratios of D/H or 3He/H (blue)
- single free parameter of BBN in the standard model is the barion-to-photon ratio η
- η is measured by, e.g., the Planck mission by mapping the cosmic microwave background
- isotopic ratios are known from observations
- this enables a test of our understanding of the CMB and the Standard Model as a whole
- BBN uncertainties for D/H are dominated by large error bars in d+p and d+d reactions

**Big Bang Nucleosynthesis Nuclear Reaction Network**



# CARME – Cryring Array for Reaction MEasurement

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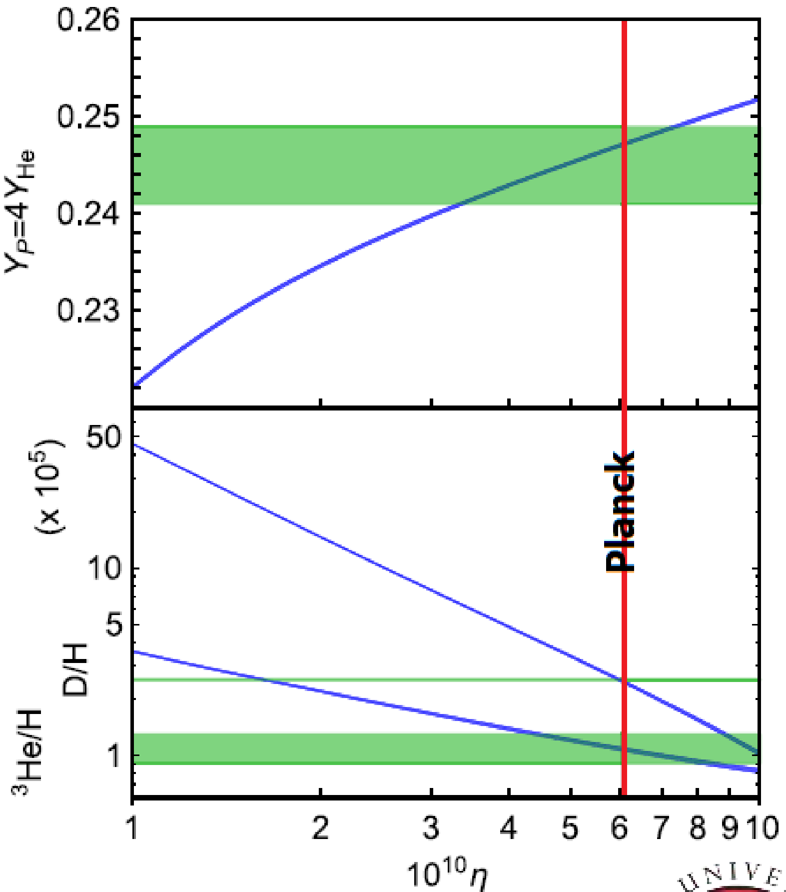


barion-to-photon ratio

# Thank you

The Heavy Ion Storage Rings at GSI provide unique possibilities to study radioactive ion beams at low energies.

This facilitates a rich astrophysics program, which will unfold in the coming years.