Institute Seminar, Institute of Nuclear and Particle Physics
Technische Universität Dresden, October 25, 2018

X-ray bursts and the JENSA gas-jet target

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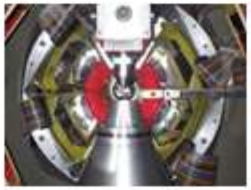
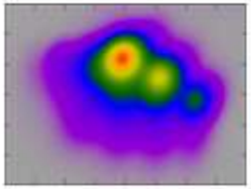
Outline

Part 1
X-ray bursts

Part 2
Rare isotope beams from NSCL and FRIB



Part 3
The JENSA gas-jet target

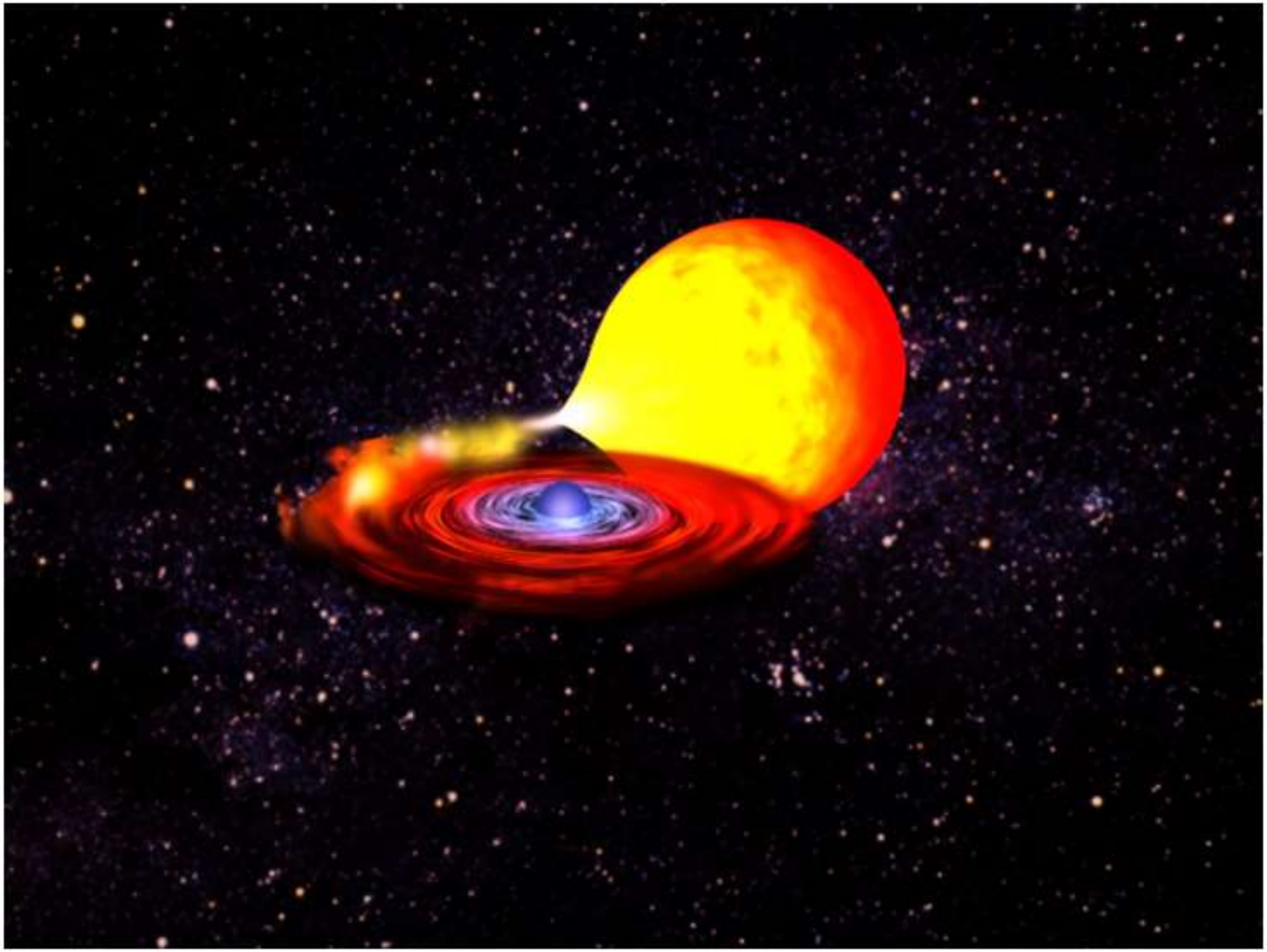


Part 4
First rare isotope beam experiment with JENSA

Part 5
The Recoil Separator for Capture Reactions SECAR

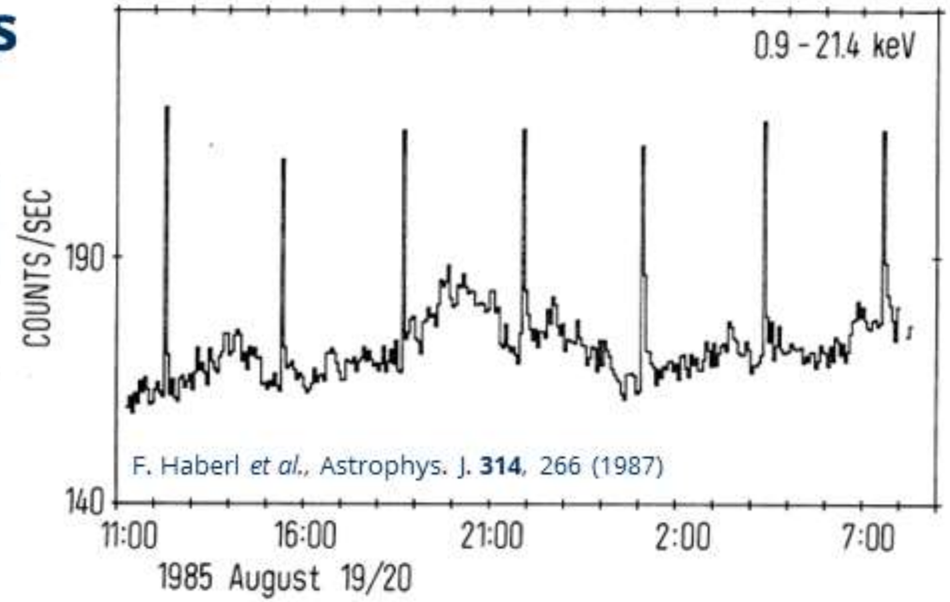
Part 1
X-ray bursts

Model: Accreting neutron star



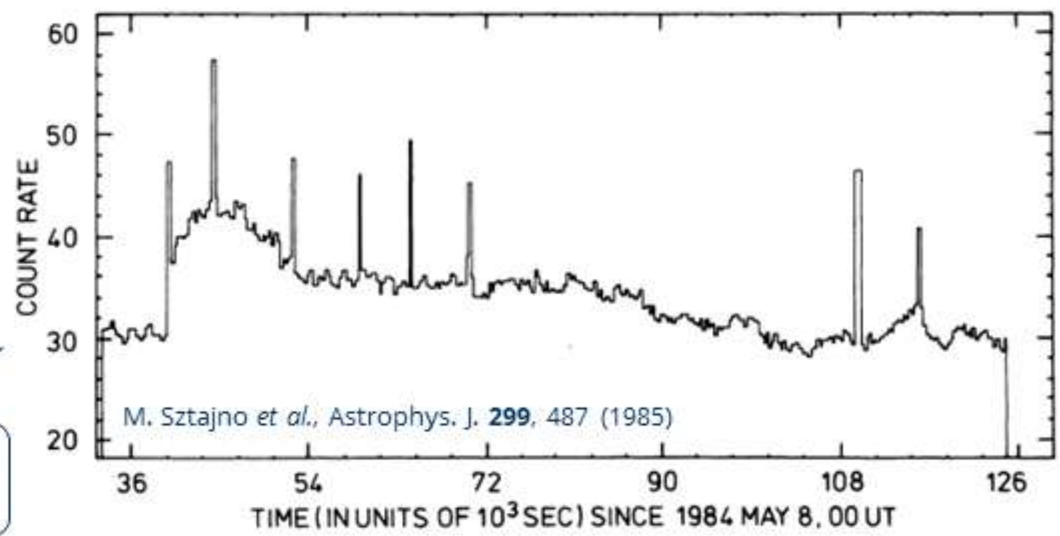
Observation: X-ray bursts

Very regular burst recurrence pattern (from 4U/MXB 1820-30)



F. Haberl *et al.*, Astrophys. J. **314**, 266 (1987)

Frequent and very bright phenomenon	
Brightness	10^{36}-10^{38} erg/s
Duration	10 s to 100 s
Recurrence	hours to days
Observations	~100 sources, ~10^4 bursts
(stars 10^{33}-10^{35} erg/s)	



M. Sztajno *et al.*, Astrophys. J. **299**, 487 (1985)

Irregular burst recurrence pattern (from 4U/MXB 1636-53)

Burst ignition and breakout

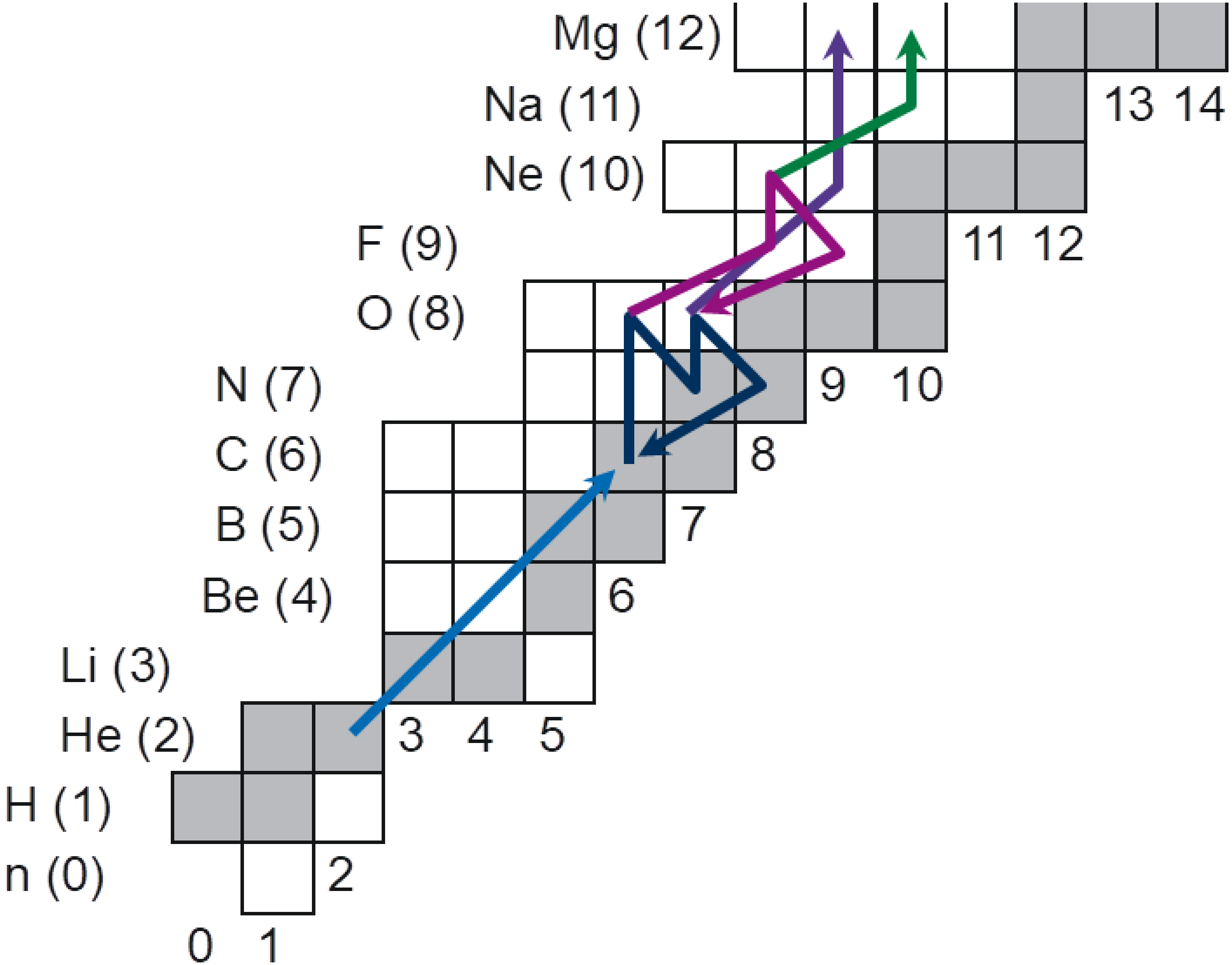
~0.77 GK
breakout 2
$^{18}Ne(\alpha,p)^{21}Na$
(~50 ms after breakout 1)

~0.68 GK
breakout 1
$^{15}O(\alpha,\gamma)^{19}Ne$

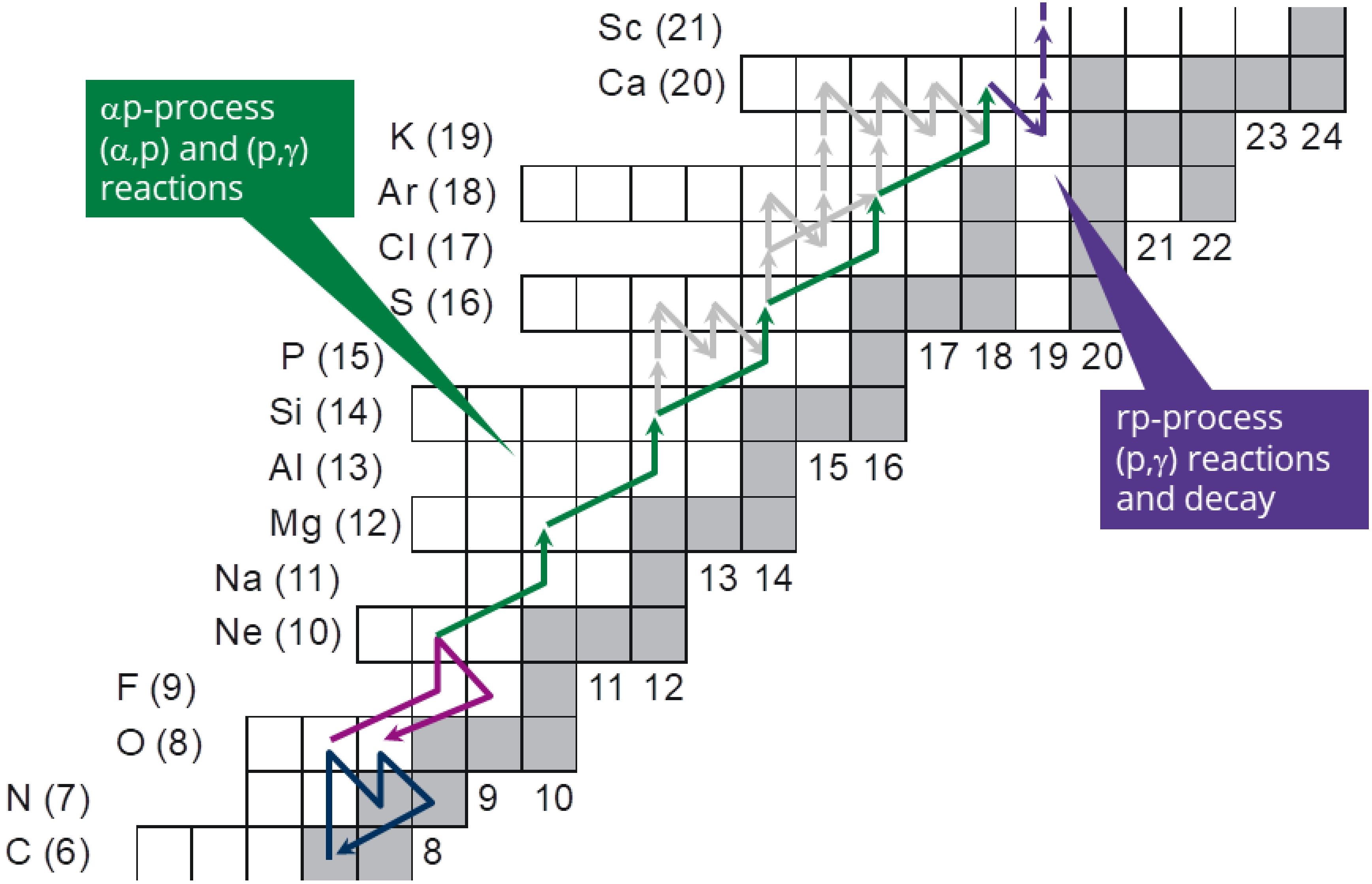
~0.20 GK
Hot CNO cycle II

~0.20 GK
Ignition
3α-process

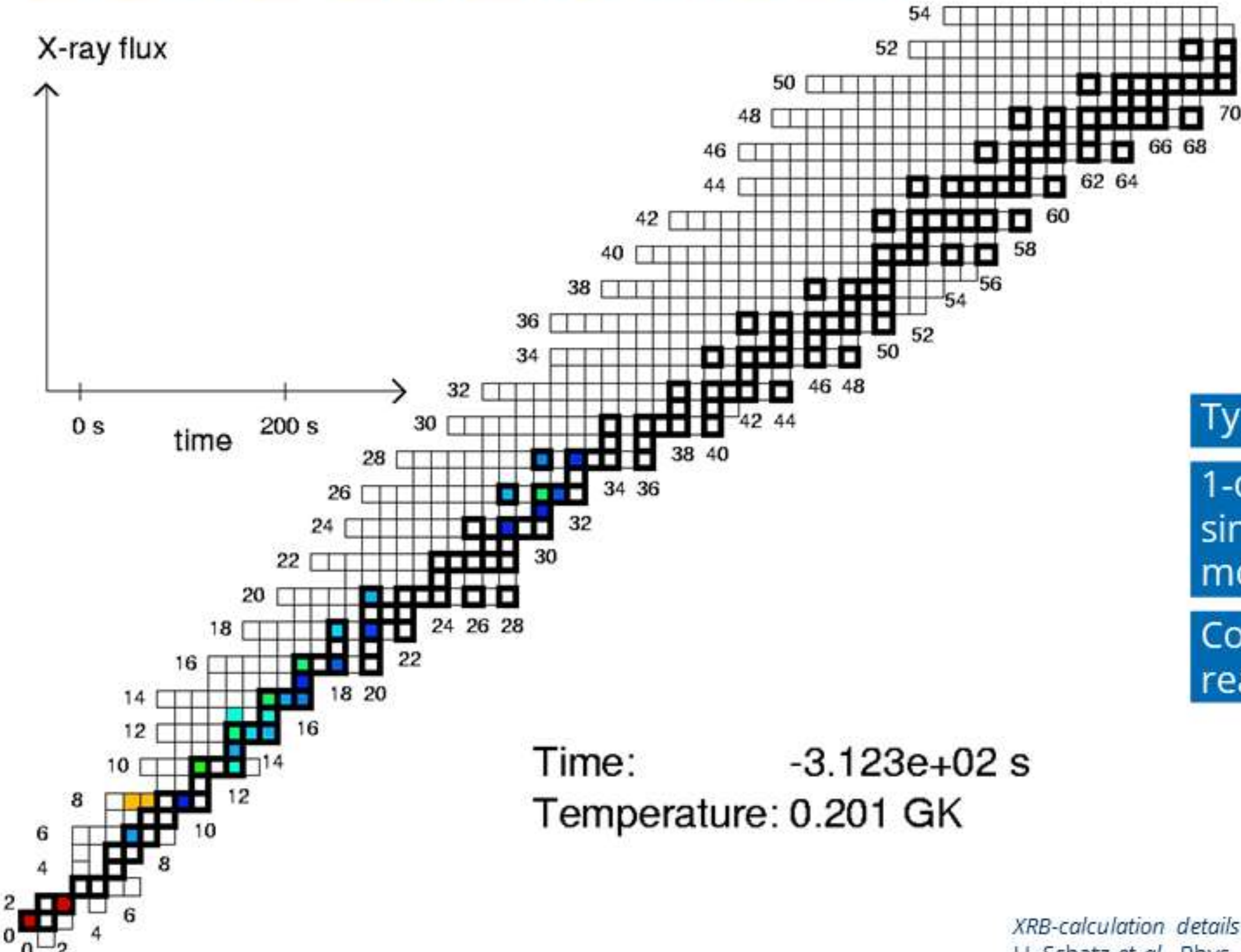
Prior to ignition:
Hot CNO cycle



Burst reactions after the break out



Calculated abundance evolution



abundance

- ■ $\geq 10^{-3}$
- ■ $\sim 10^{-4}$
- ■ $\sim 10^{-5}$
- ■ $\sim 10^{-6}$
- ■ $\sim 10^{-7}$

Type I X-ray burst

1-dimensional single-zone XRB model

Complete nuclear reaction network

XRB-calculation details in:
H. Schatz *et al.*, Phys. Rev. Lett. 86, 3471 (2001)

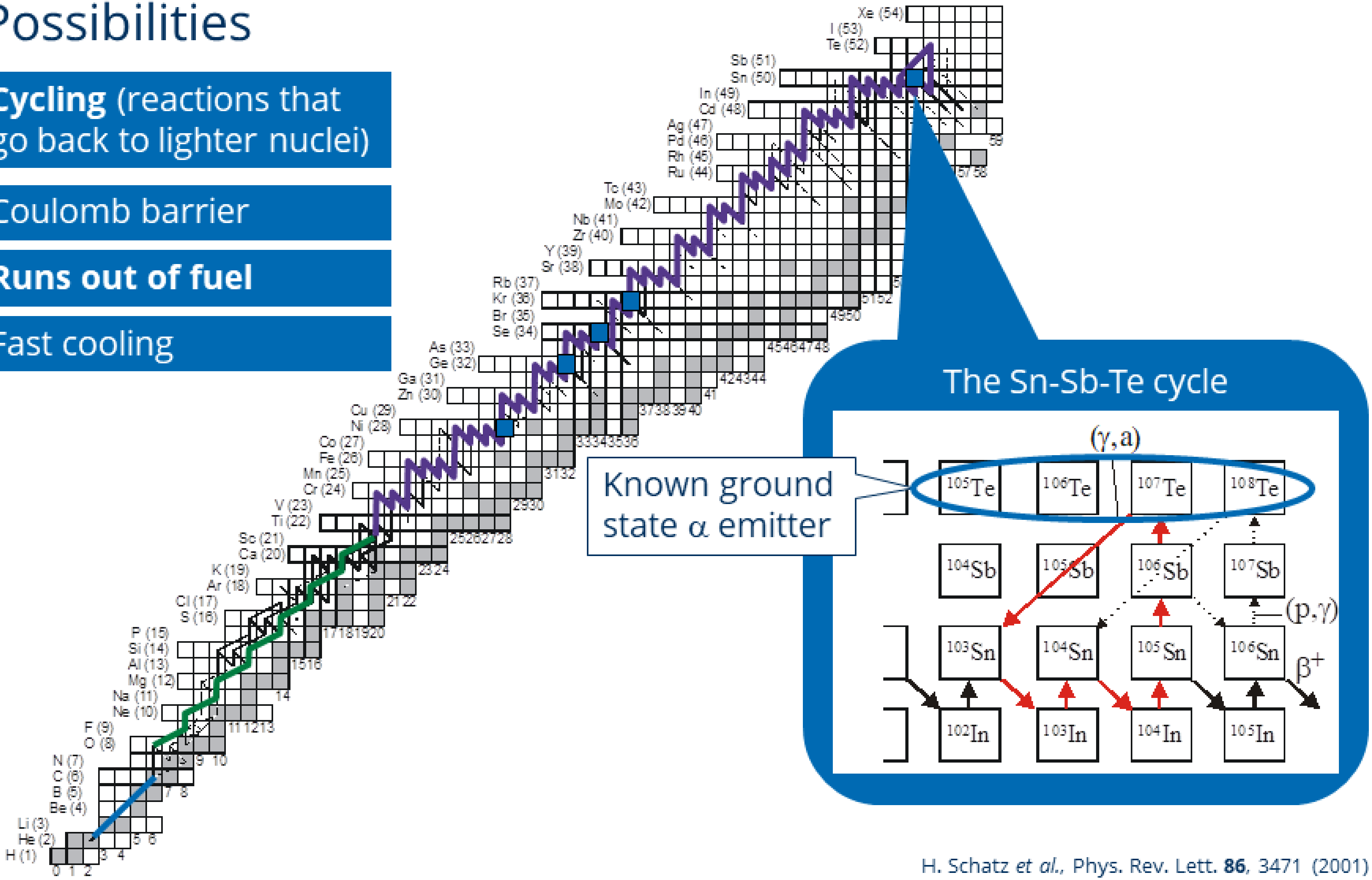
The endpoint of the rp-process
Possibilities

Cycling (reactions that go back to lighter nuclei)

Coulomb barrier

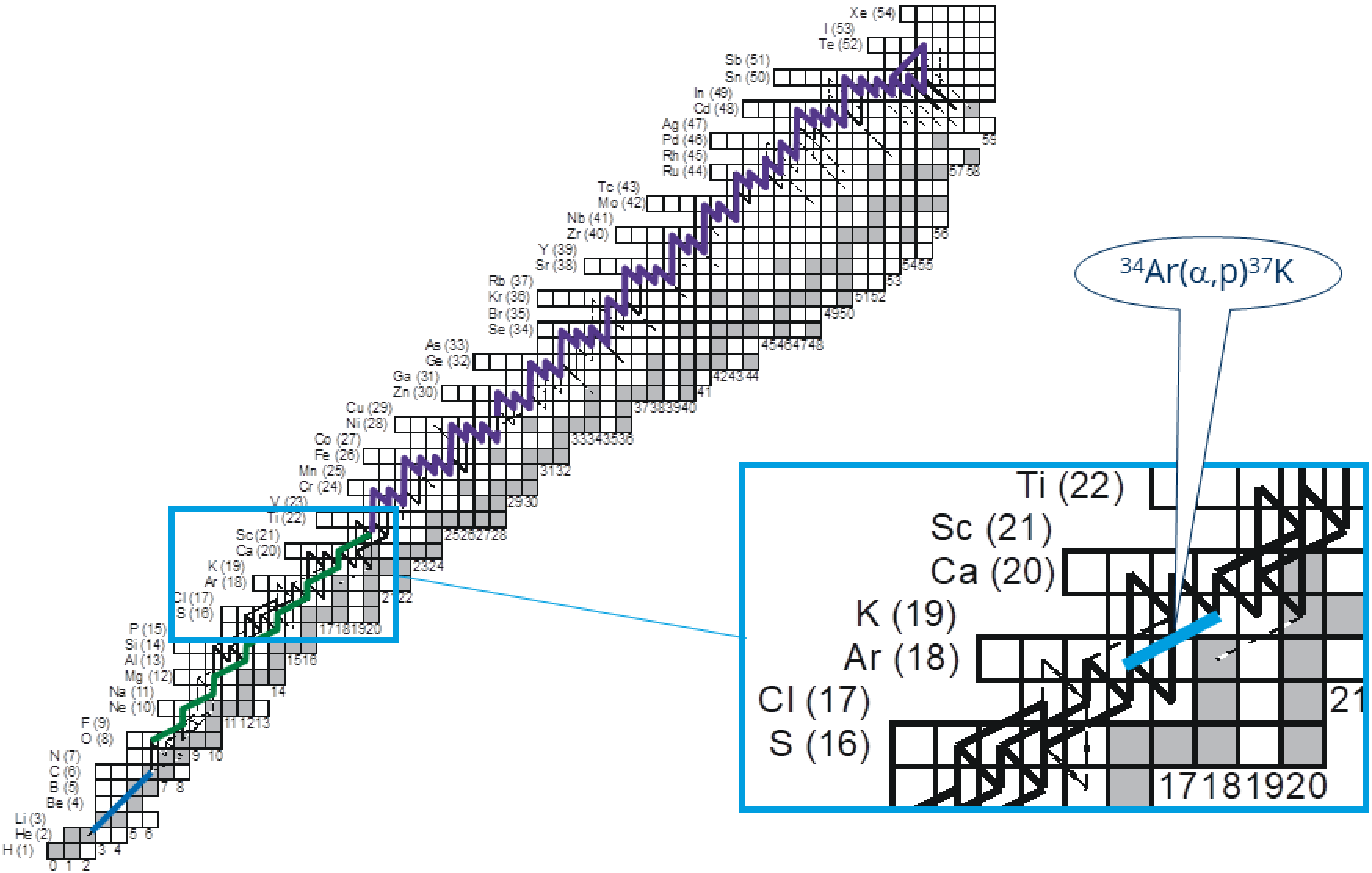
Runs out of fuel

Fast cooling

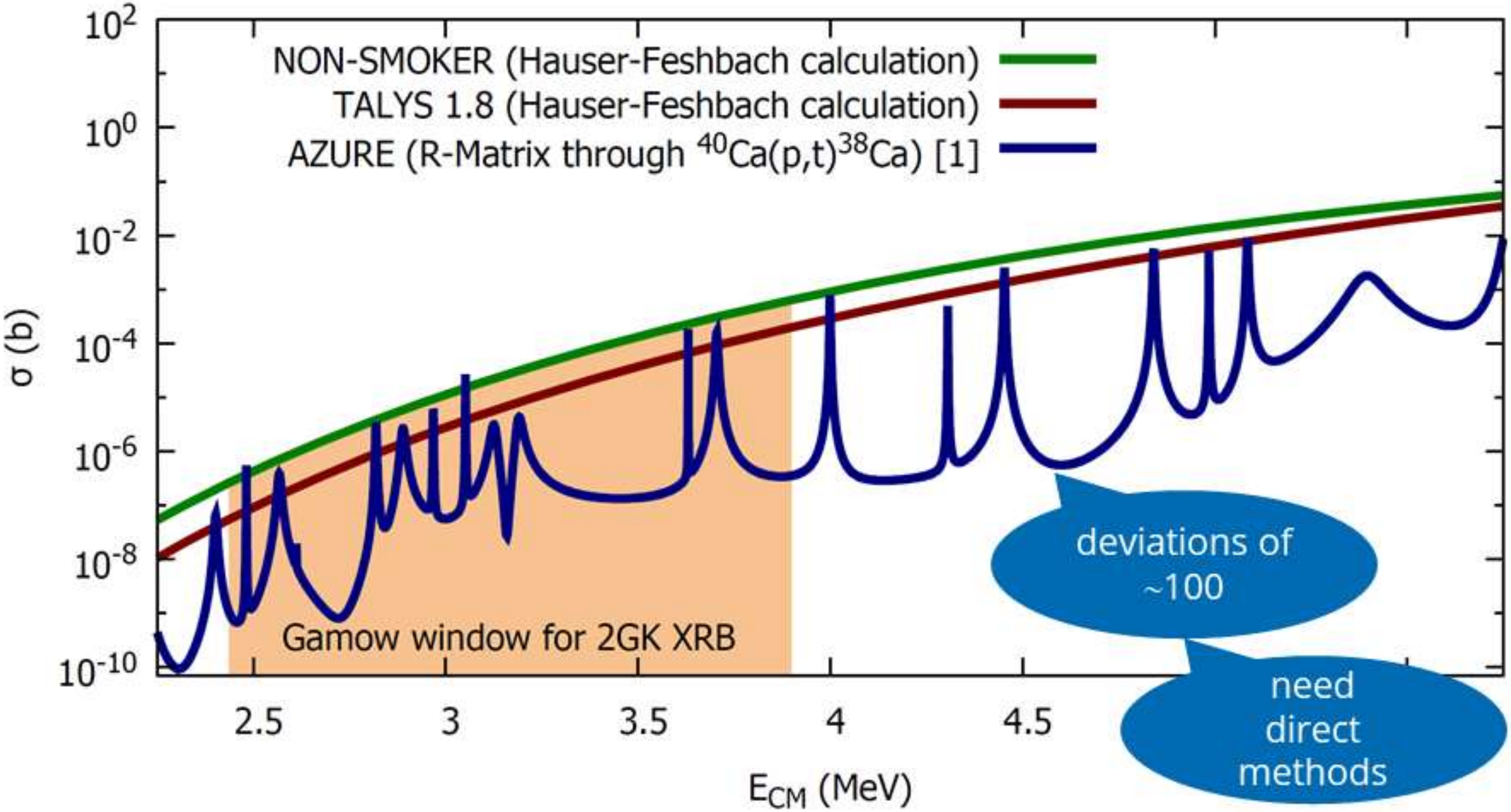


H. Schatz *et al.*, Phys. Rev. Lett. **86**, 3471 (2001)

Bottleneck reactions

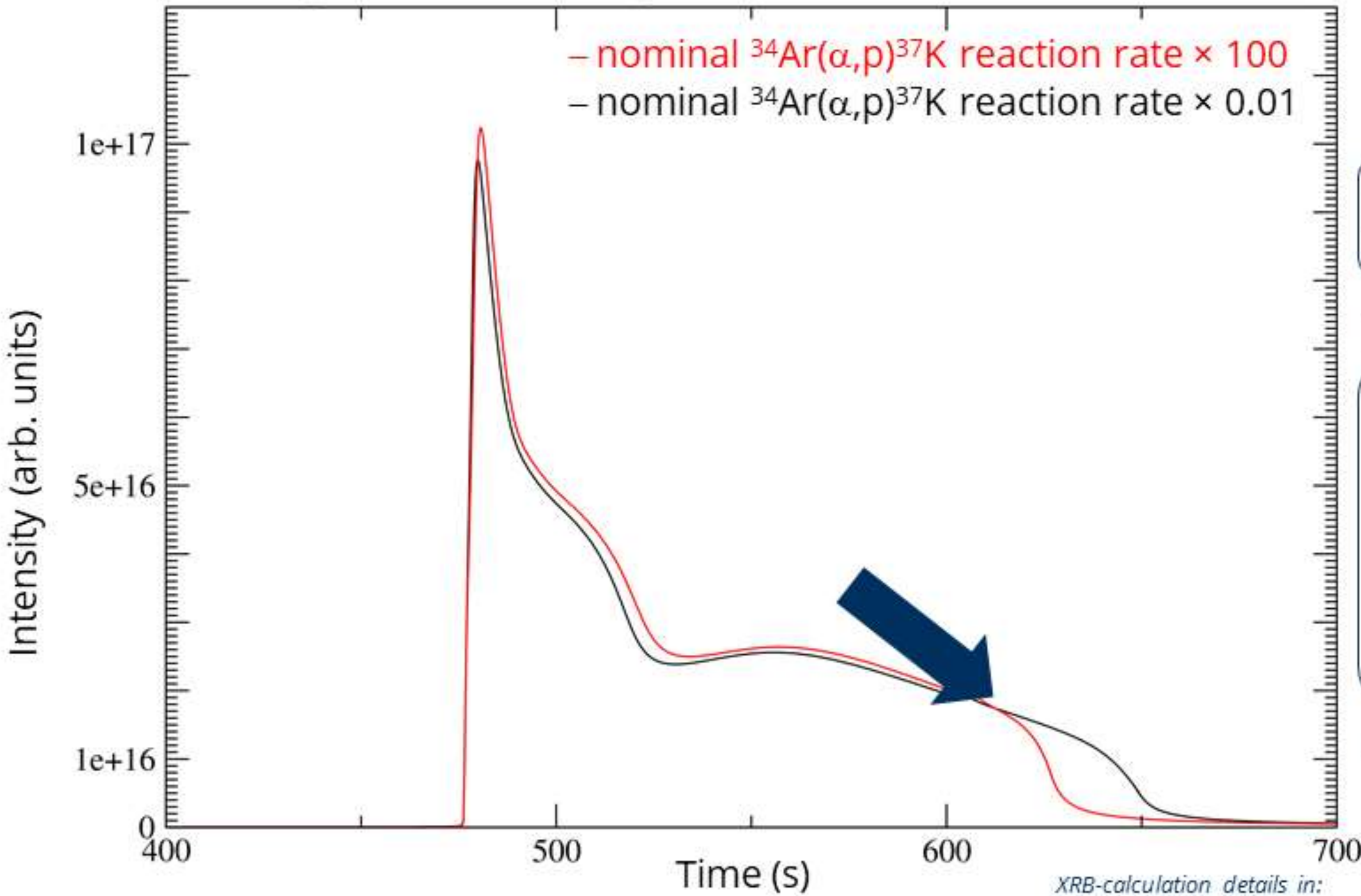


$^{34}Ar(\alpha,p)^{37}K$ cross section



[1] A. M. Long *et al.*: Phys. Rev. C **95**, 055803 (2017).

Light curves
from a single-zone X-ray burst calculation

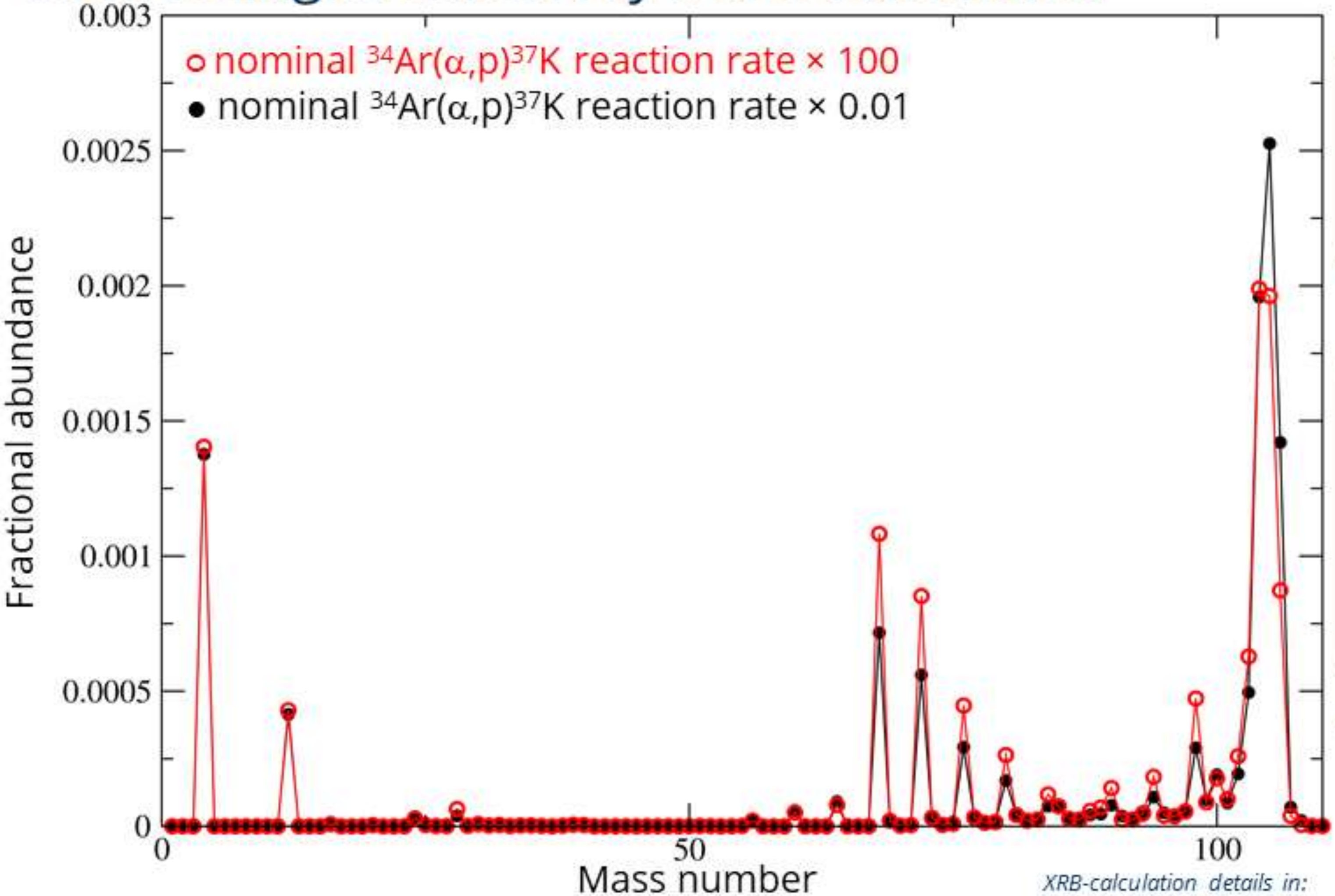


varied **only** $^{34}Ar(\alpha,p)^{37}K$

an increased reaction rate accelerates the reaction flow and the burst burns out faster

XRB-calculation details in:
H. Schatz *et al.*, Phys. Rev. Lett. 86, 3471 (2001)

Final abundance plot
from a single-zone X-ray burst calculation



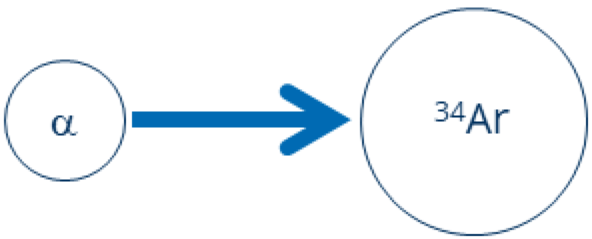
broad effect on multiple species in the burst ashes

higher rate decreases the seed to hydrogen ratio of the subsequent rp-process

XRB-calculation details in:
H. Schatz *et al.*, Phys. Rev. Lett. 86, 3471 (2001)

How to study $^{34}Ar(\alpha,p)^{37}K$ directly?

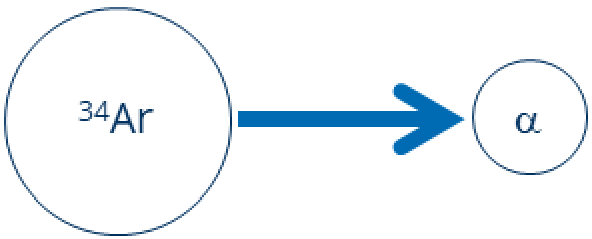
Short half-life of ^{34}Ar ~0,8 s → No targets → Inverse kinematics with radioactive ion beams



$^{34}Ar + {}^{4}He \rightarrow {}^{1}H + {}^{37}K$

$^{34}Ar(\alpha,p)^{37}K$

=

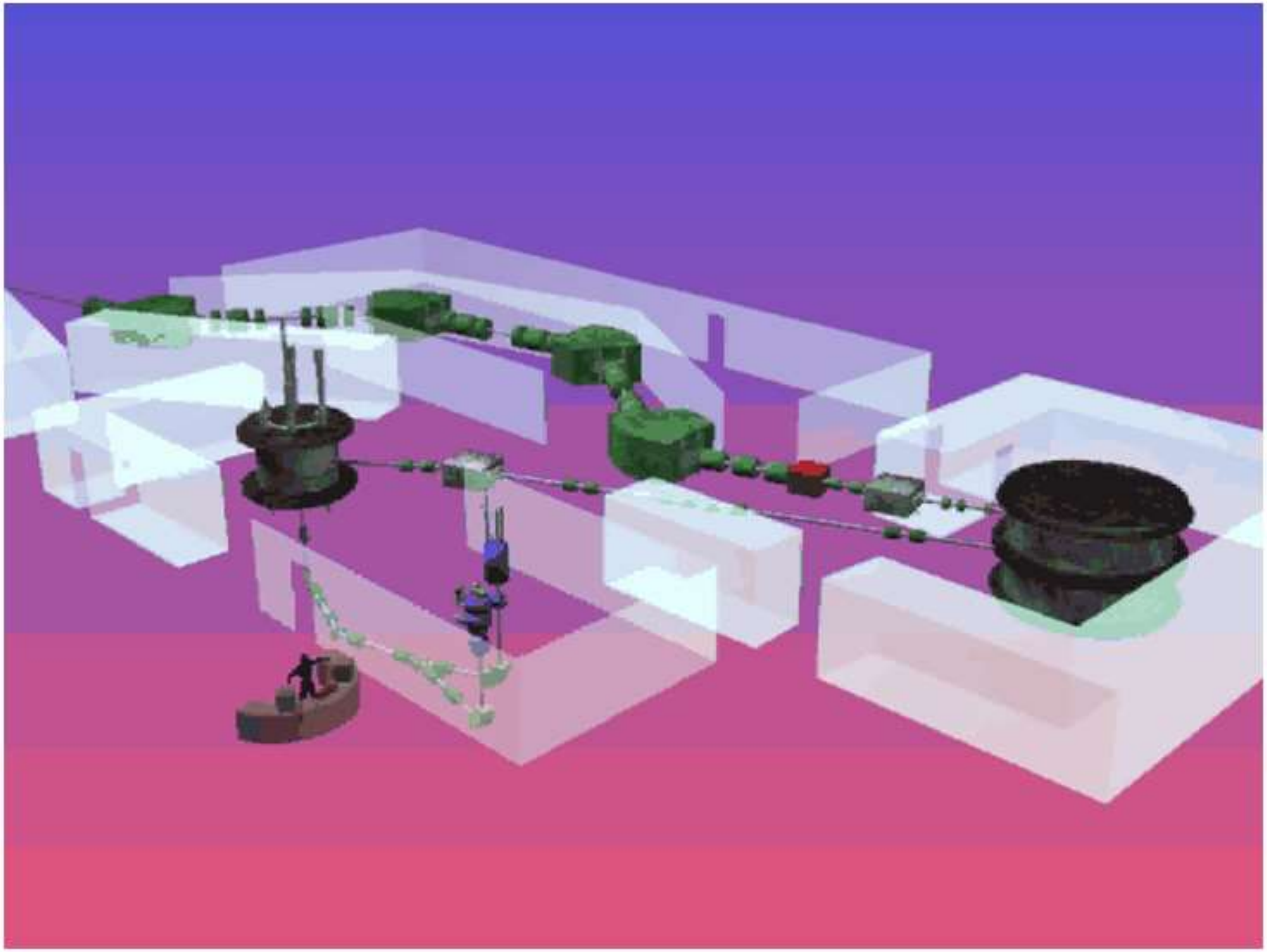


$^{4}He + {}^{34}Ar \rightarrow {}^{1}H + {}^{37}K$

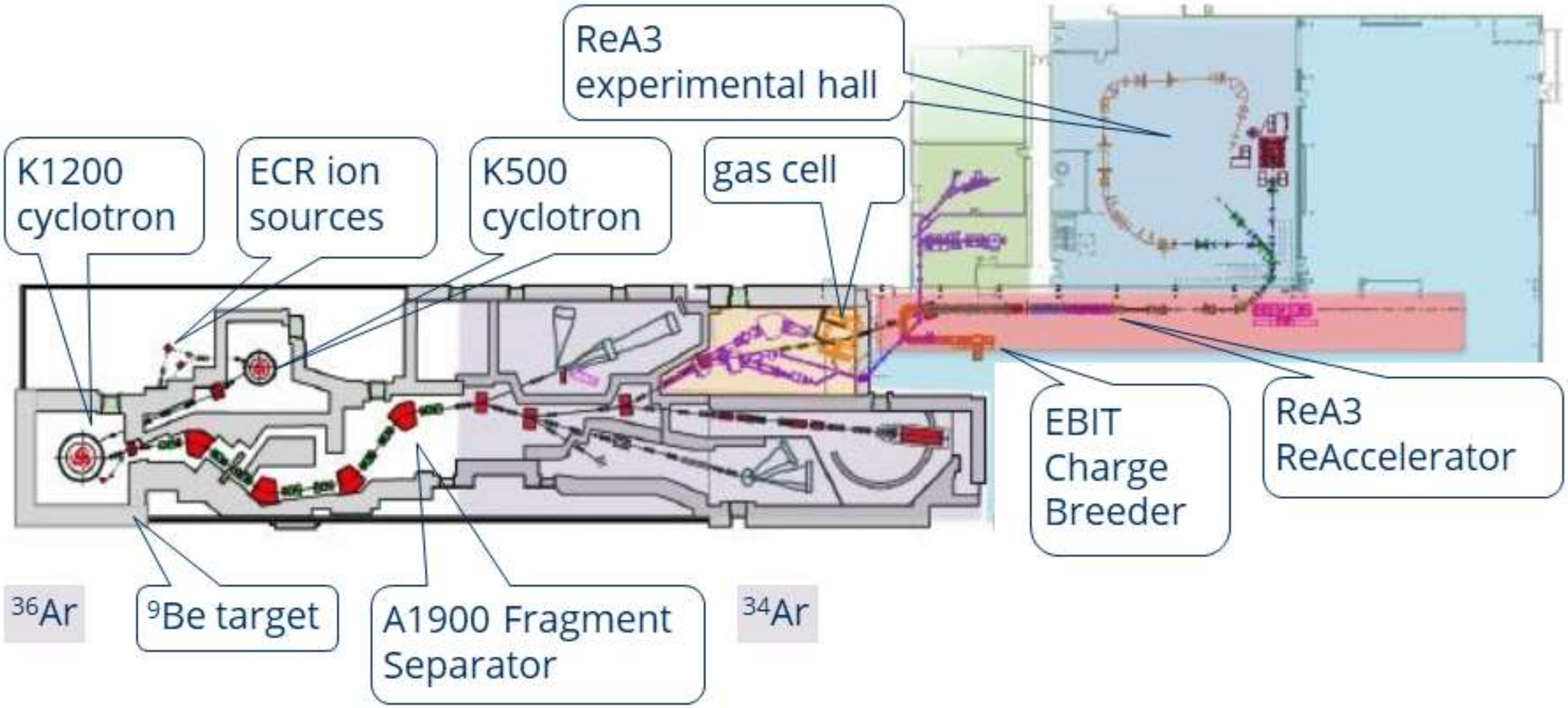
$^{4}He(^{34}Ar,p)^{37}K$

Part 2
Rare isotope beams from NSCL and FRIB

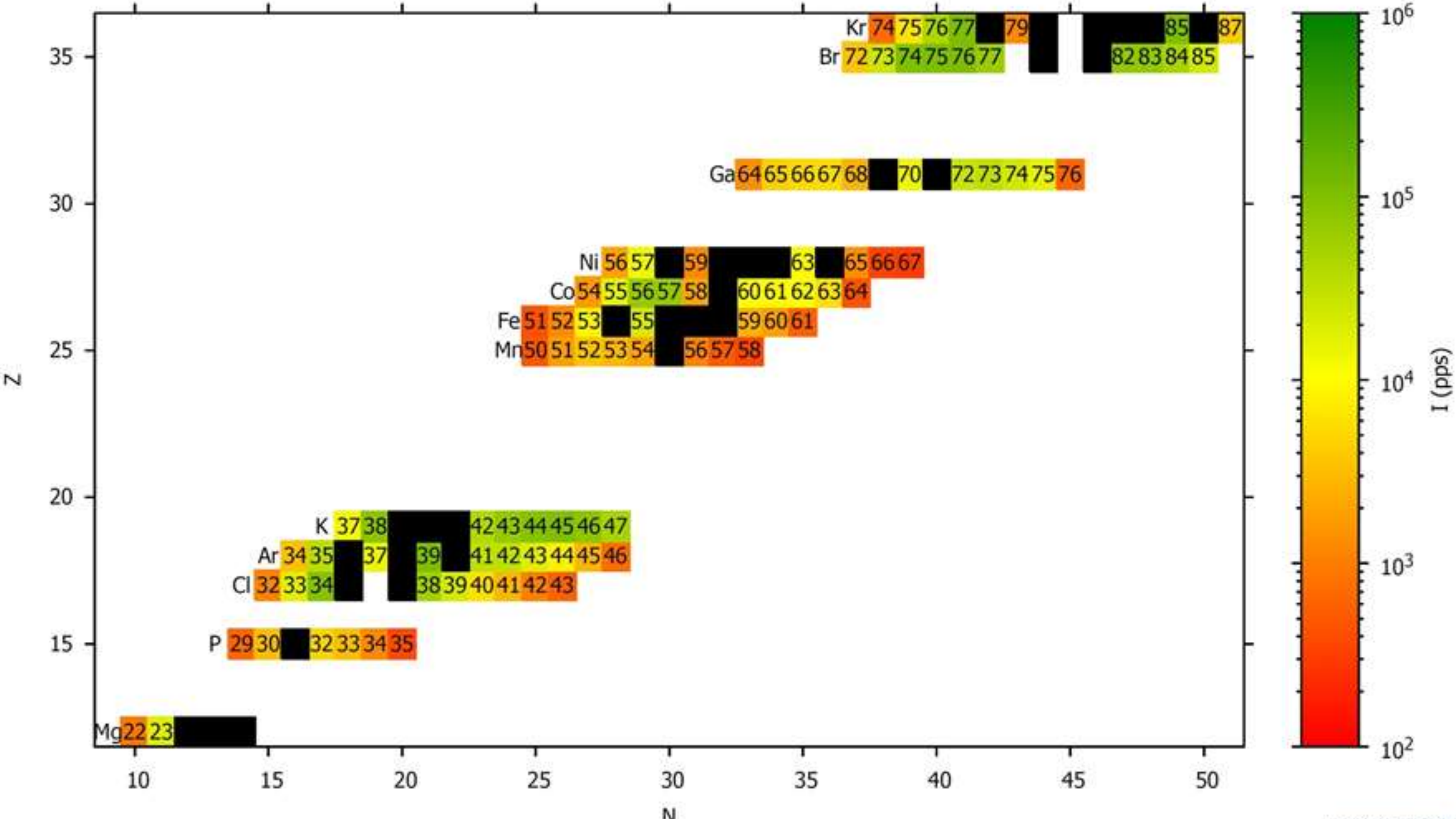
Rare isotope production at NSCL



^{34}Ar beam from ReA3 at NSCL



Available rare isotope beams at ReA3



nscl.msu.edu

FRIB at Michigan State University

- FRIB will be a $730 million national user facility funded by the Department of Energy Office of Science (DOE-SC), Michigan State University, and the State of Michigan
- FRIB Project completion is in 2022, managing to an early completion in fiscal year 2021
- FRIB will serve as a national user facility for world-class rare isotope research

FRIB will enable scientists to make discoveries about the properties of these rare isotopes in order to better understand the physics of nuclei, nuclear astrophysics, fundamental interactions, and applications for society

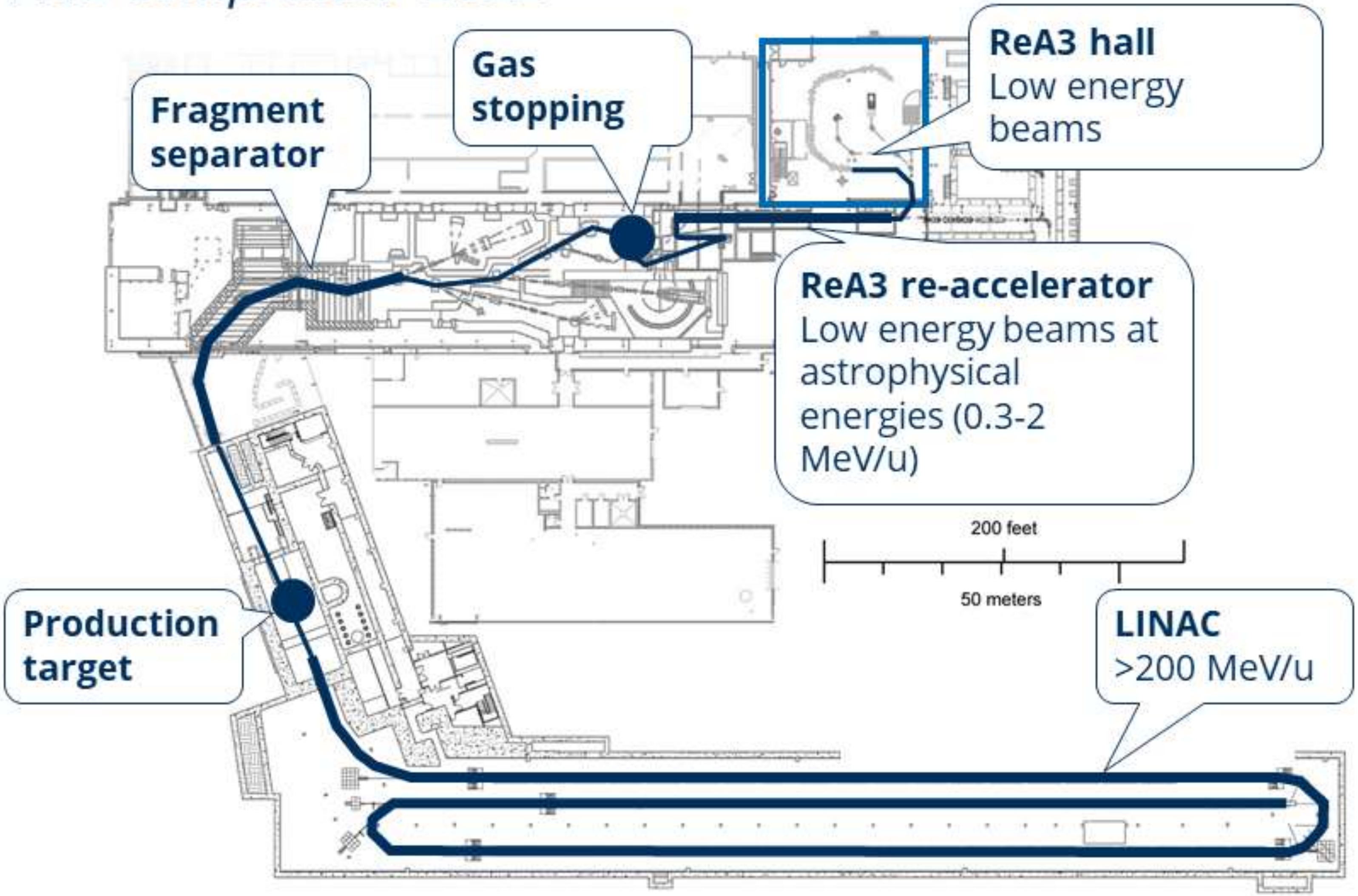
FRIB

Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

frib.msu.edu

Low energy astrophysics at FRIB

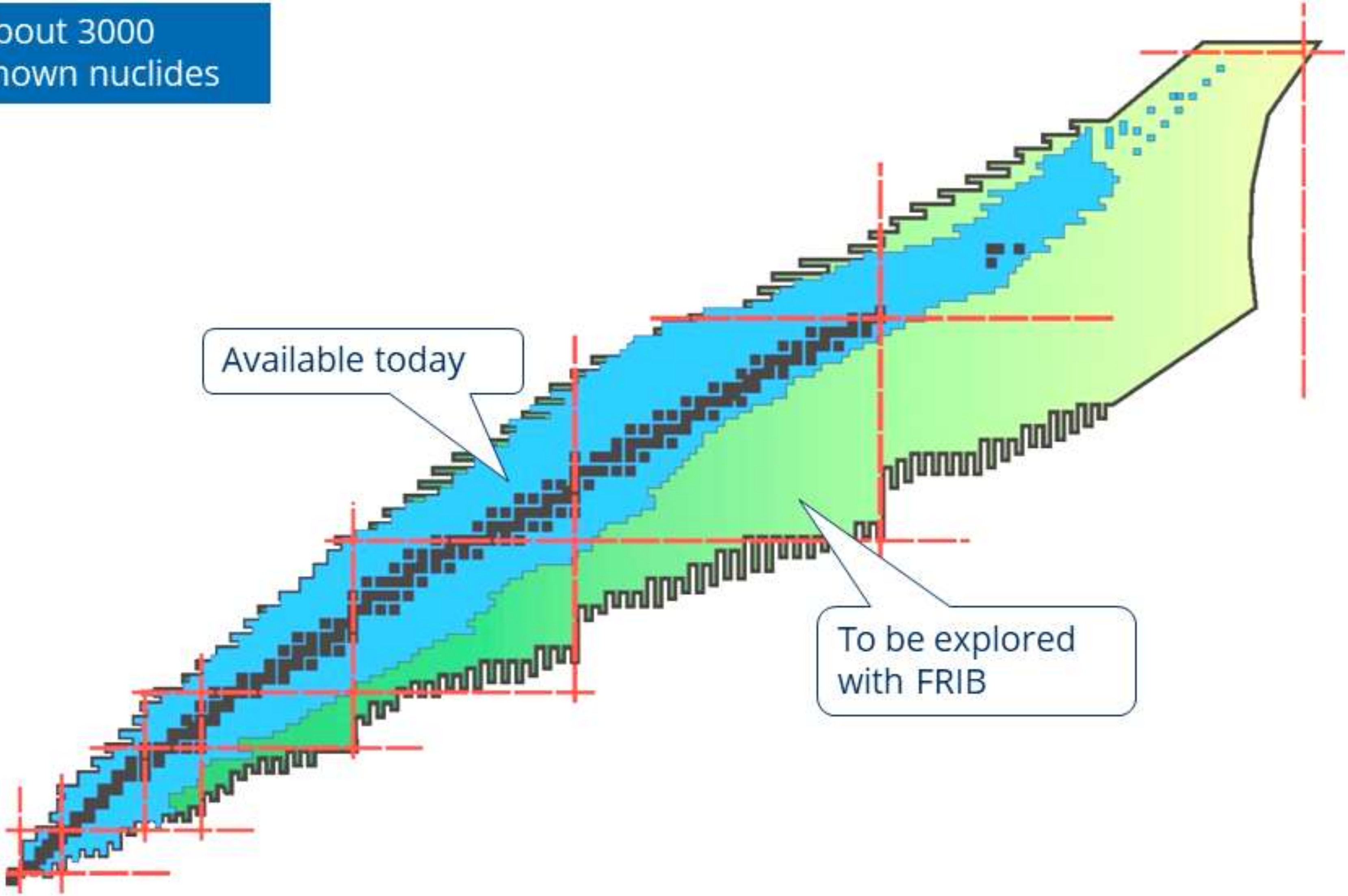
FRIB completion: 2022



frib.msu.edu

Planned beams with FRIB

About 3000 known nuclides

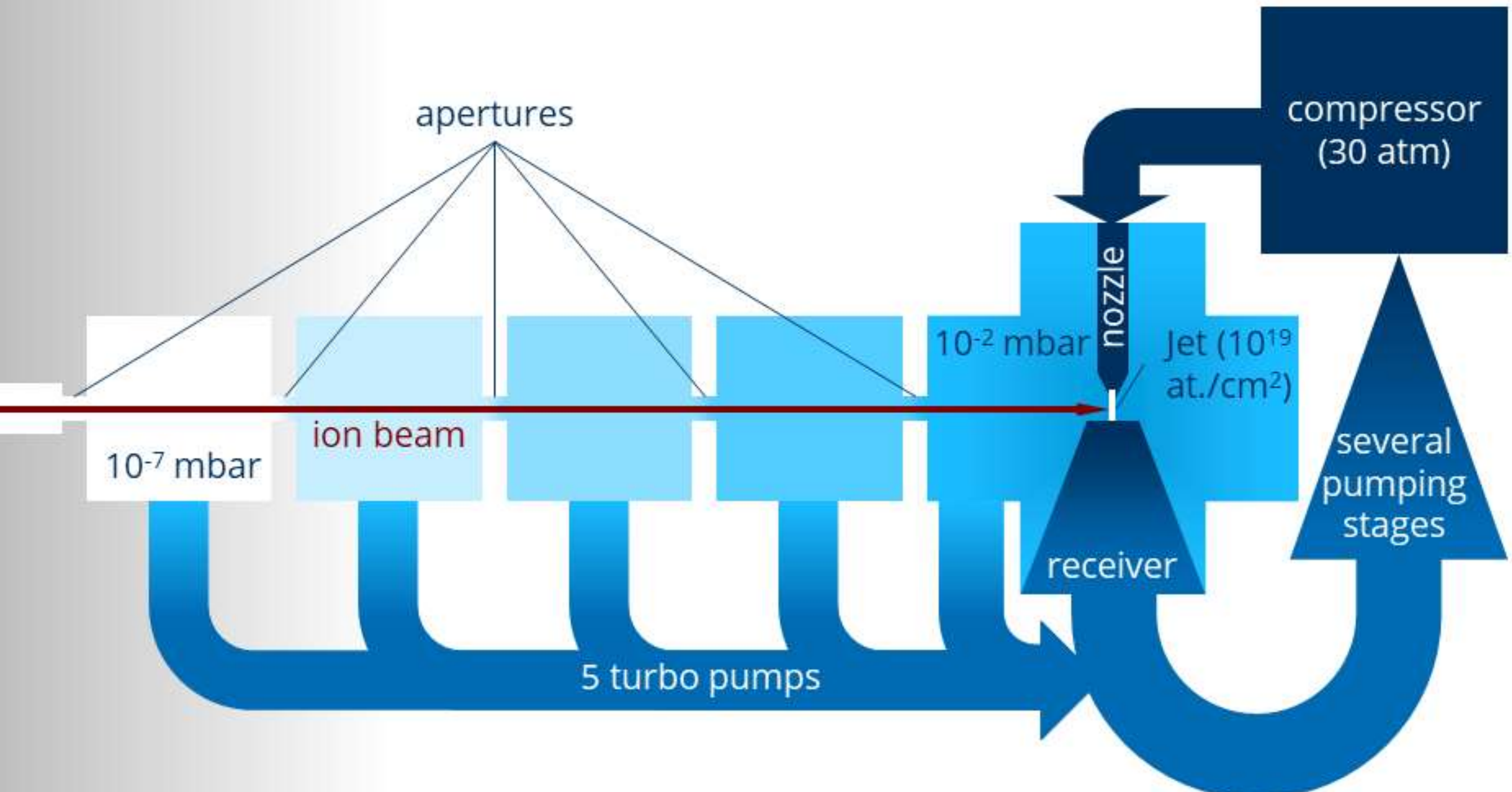


Looking for the best target

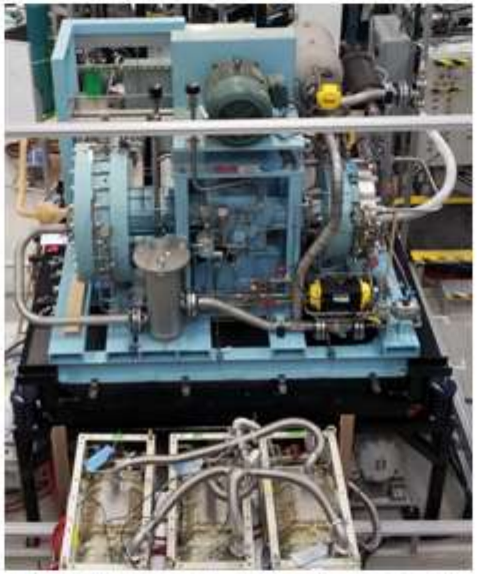
	Solid plastic thin-foil or on backing	**windowless** gas target	**Gas cell** with window	Gas **jet** target
High density	✓	?	✓	✓
Low energy and angular straggling	✓	✓	?	✓
Chemically pure	?	✓	✓	✓
Excellent reaction localization	✓	?	?	✓

Part 3
The JENSA gas-jet target

Recirculating gas system



The JENSA gas-jet target
Jet **E**xperiments in **N**uclear **S**tructure and **A**strophysics

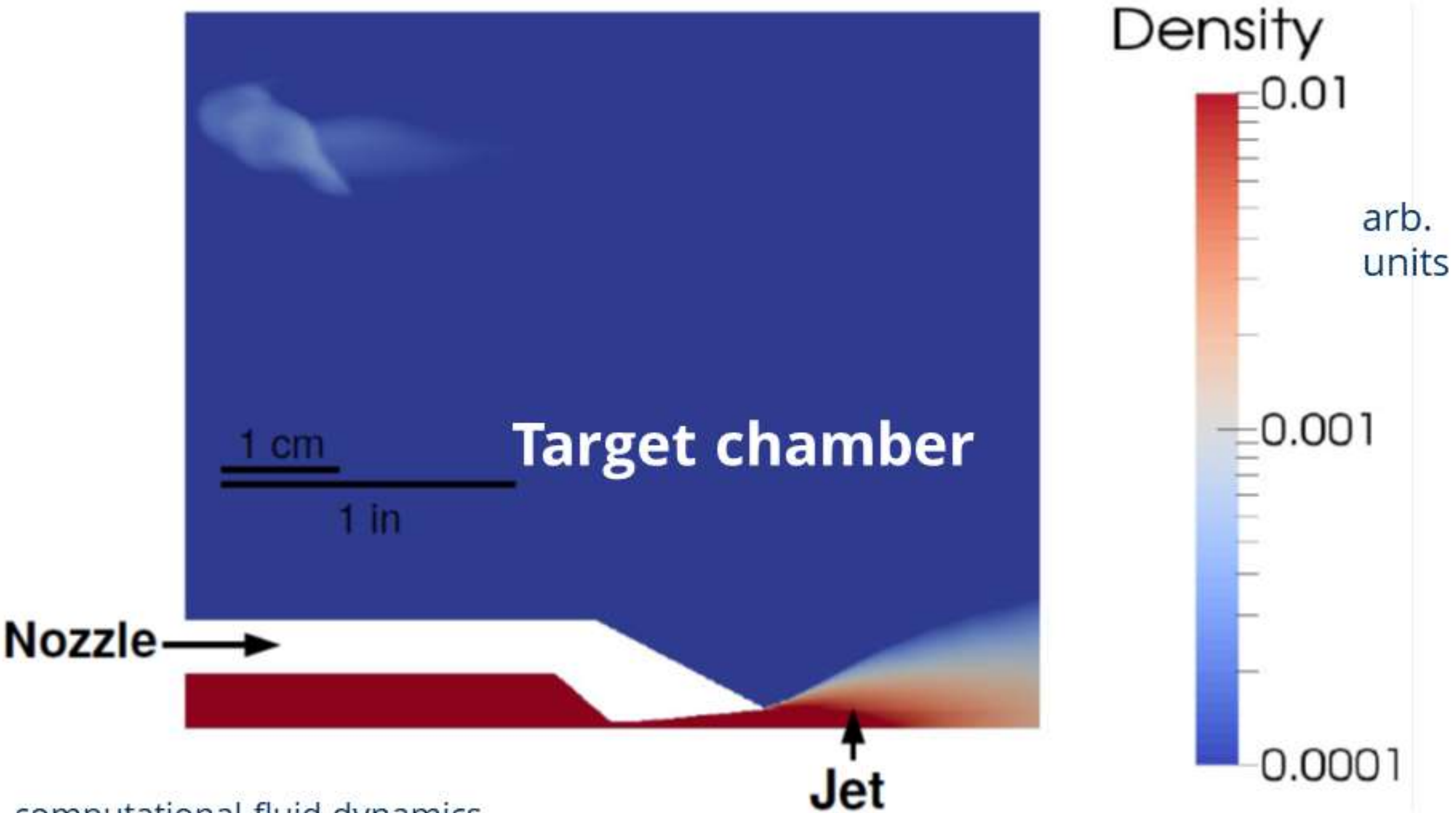


diaphragm compressor

target chamber and pumps

nozzle, receiver and Si detectors

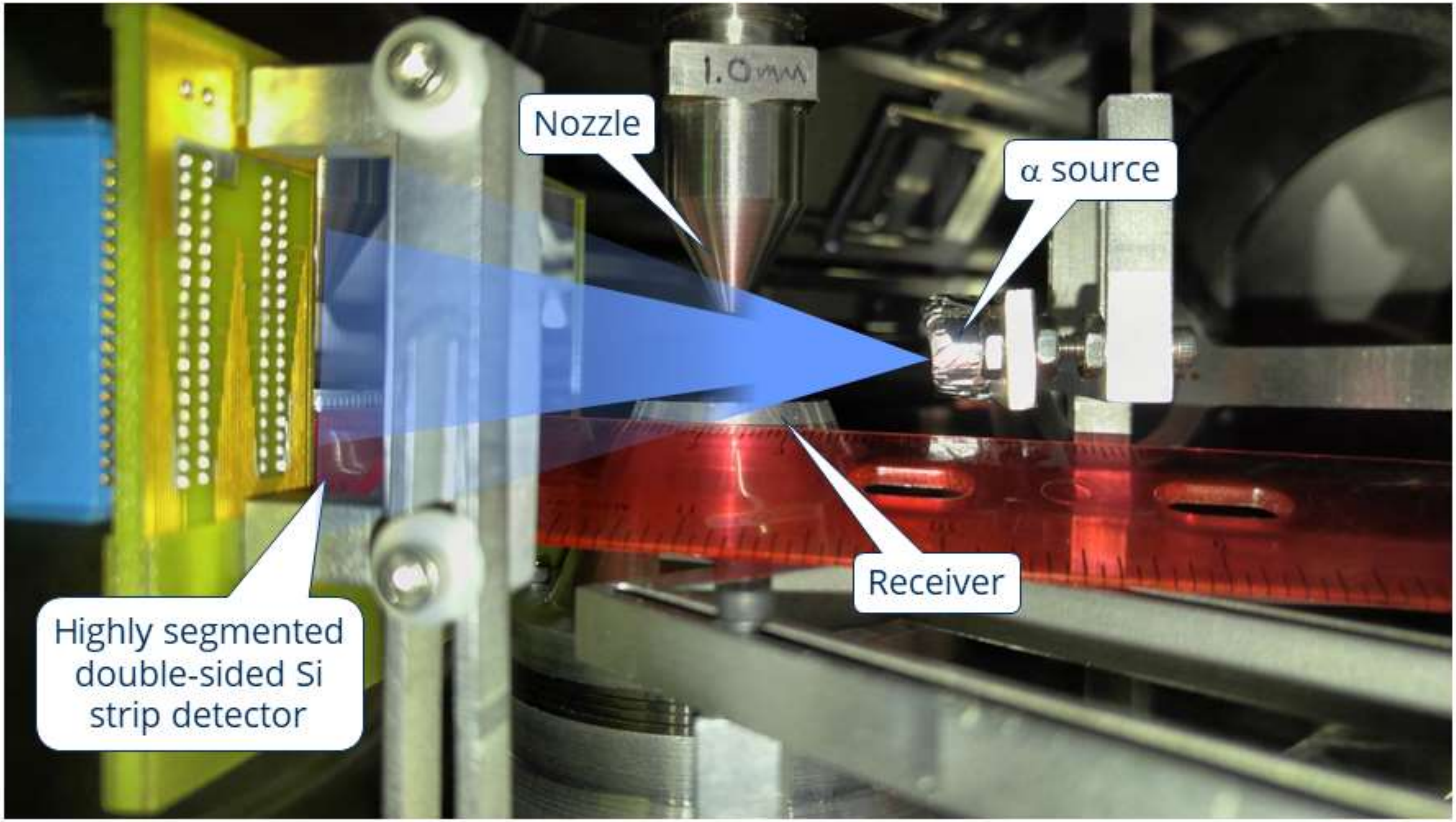
CFD simulation of the jet



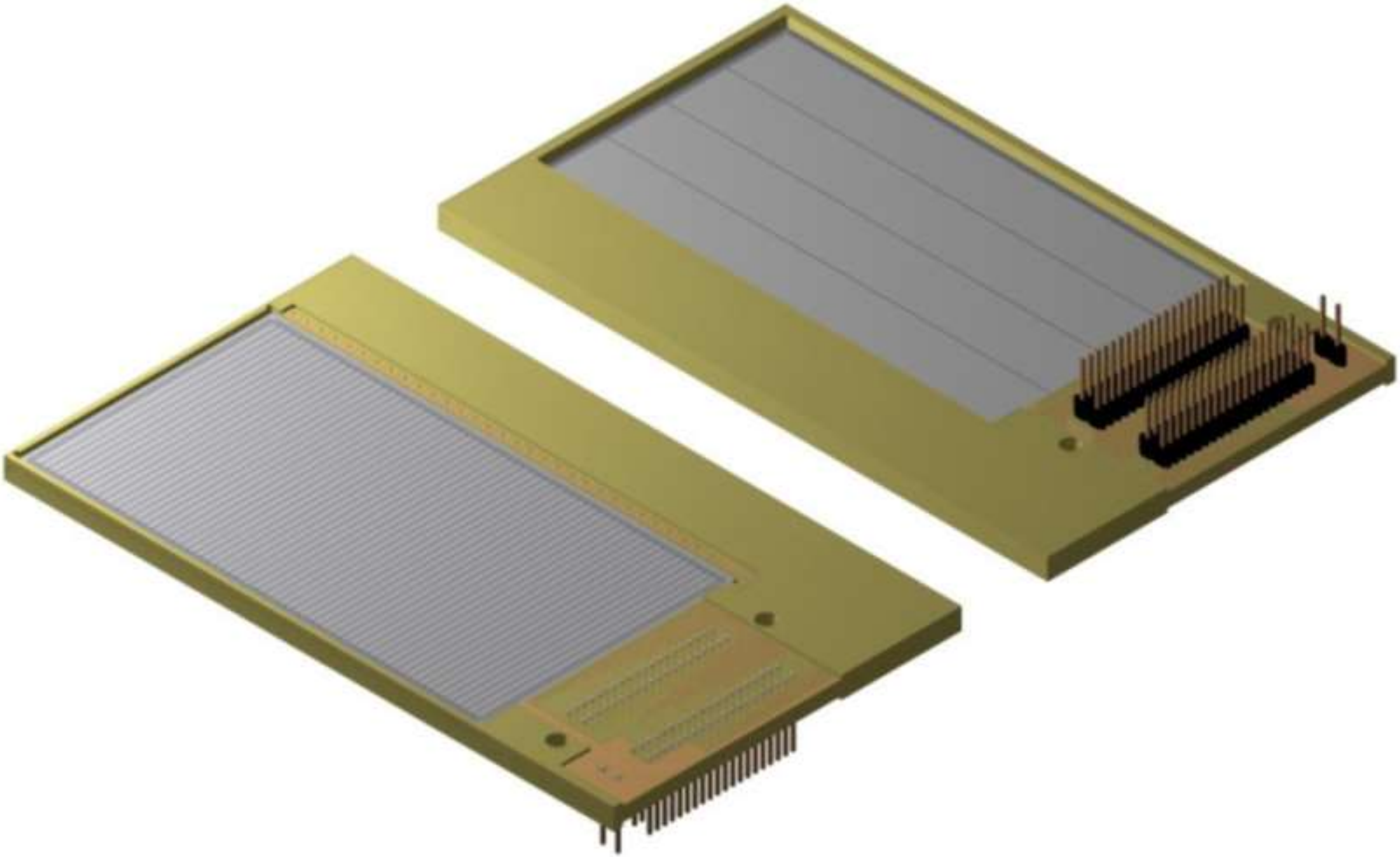
computational fluid dynamics
(CFD) software: WIND-US

Contribution by graduate student Justin Browne

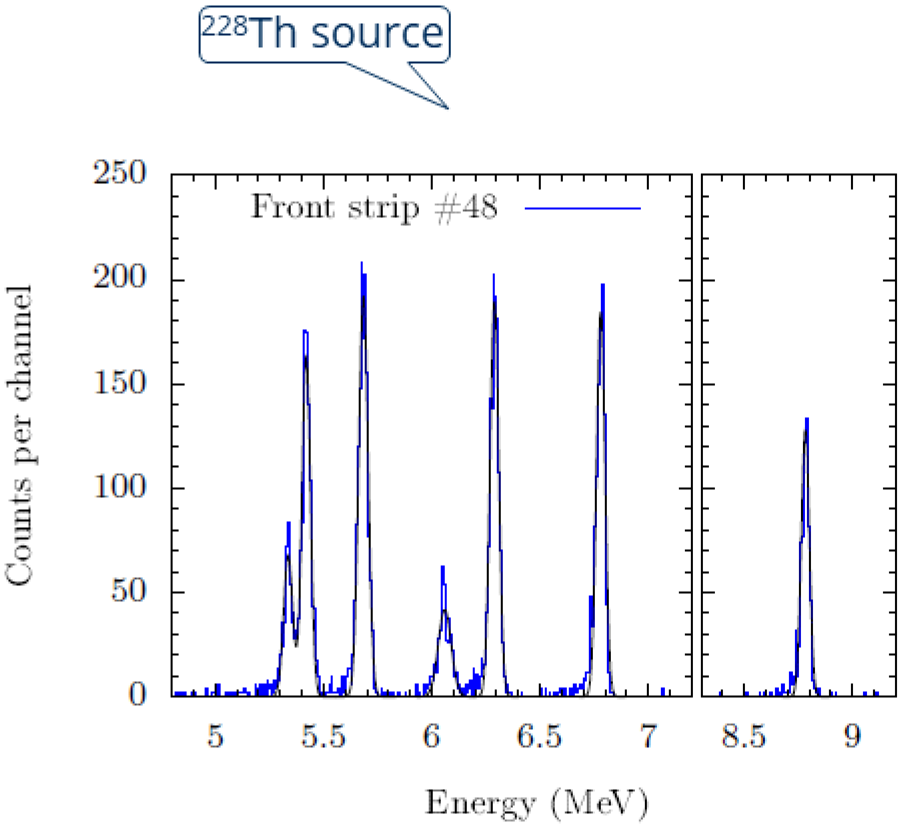
Setup for jet thickness study

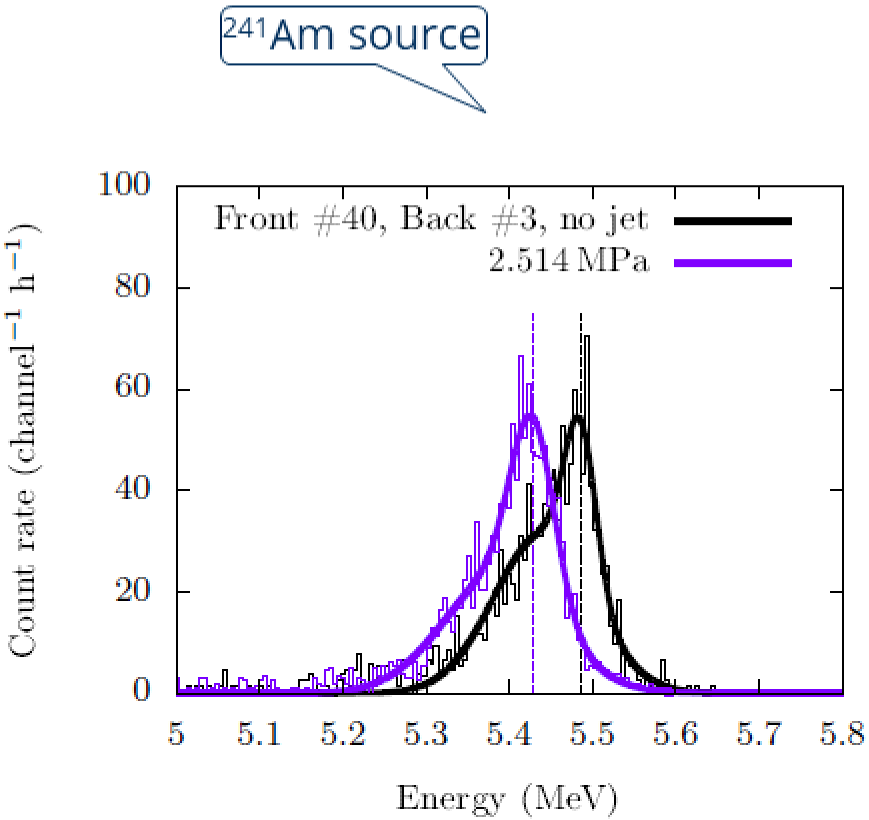


Micron-style BB15 detector



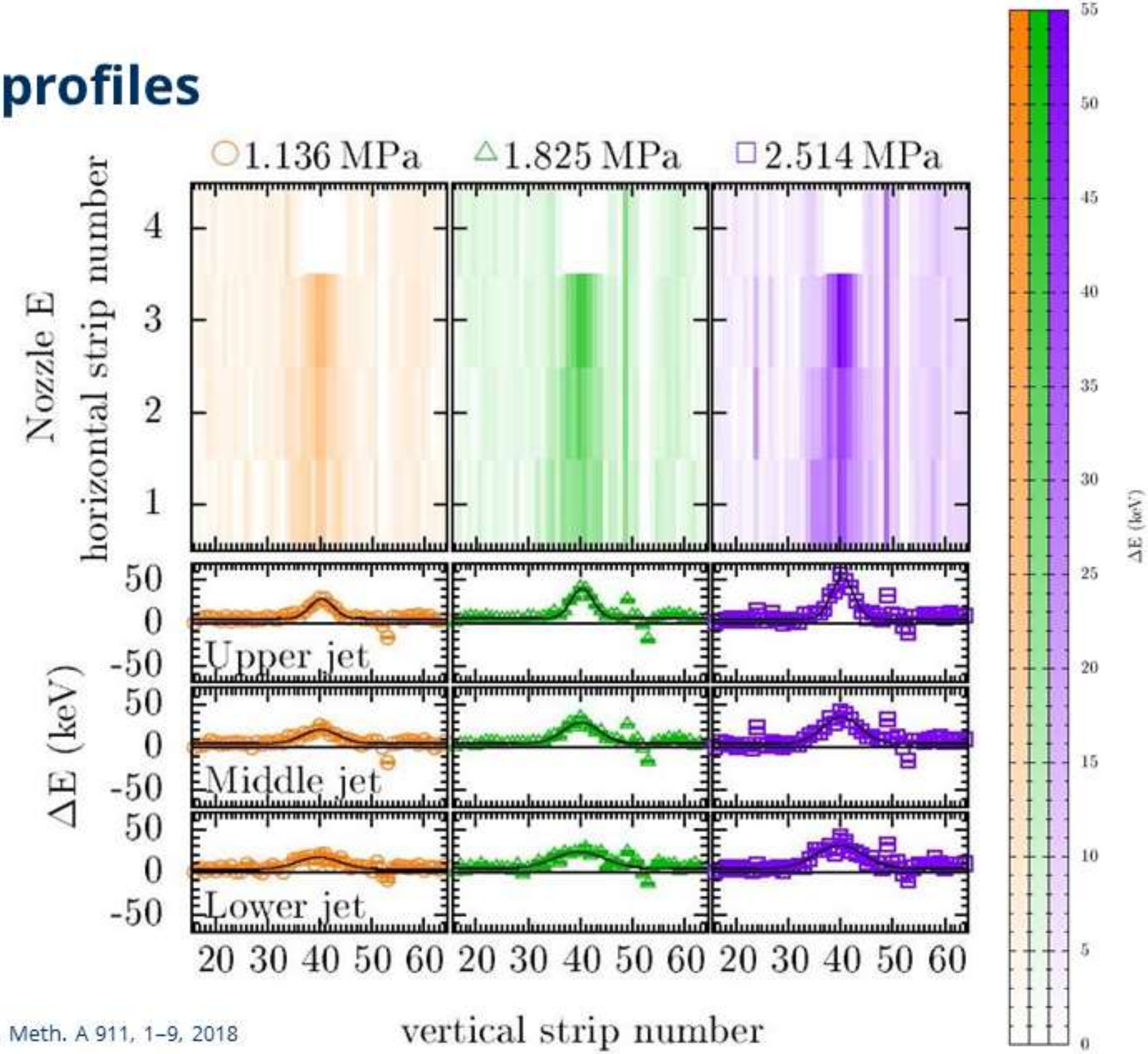
Energy calibration and energy-loss spectrum





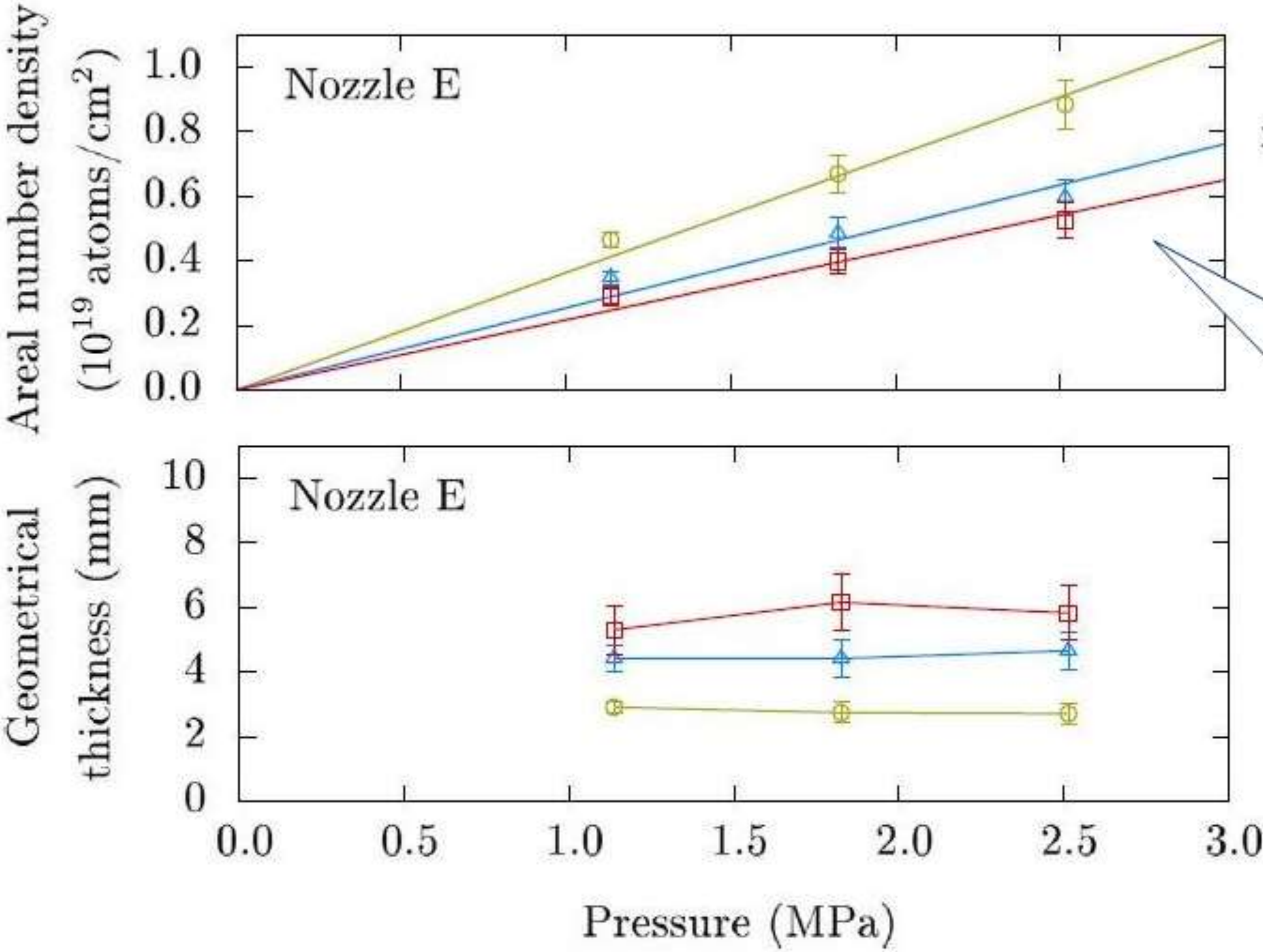
K. Schmidt *et al.*: Nucl. Instrum. Meth. A 911, 1–9, 2018

Energy loss profiles



K. Schmidt *et al.*: Nucl. Instrum. Meth. A 911, 1–9, 2018

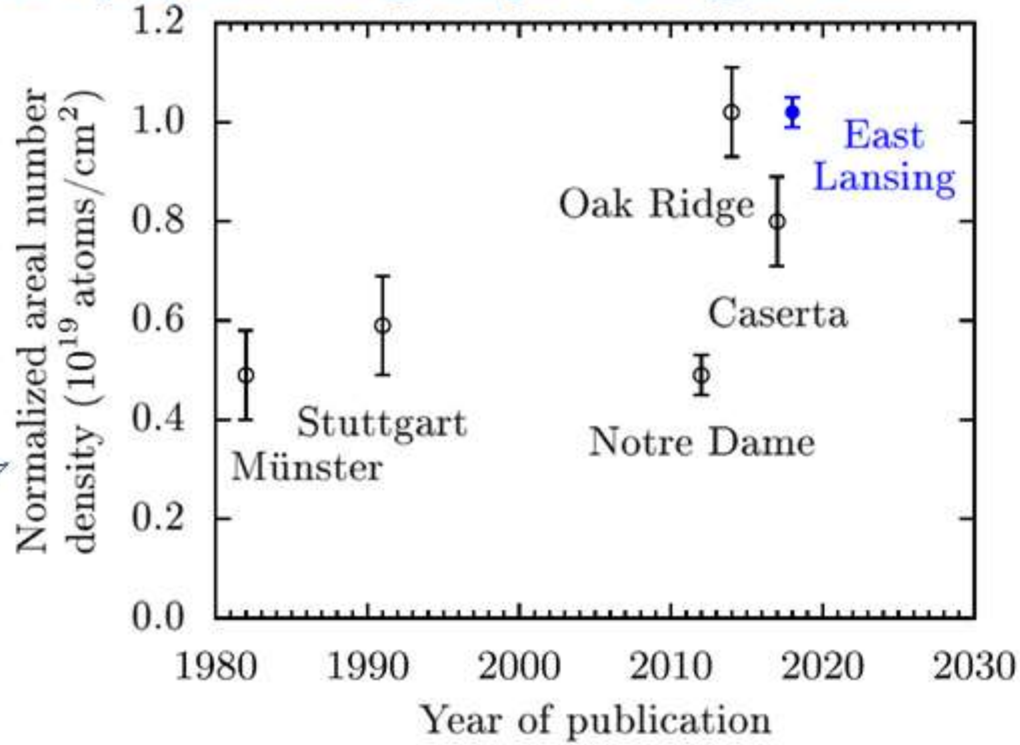
10^{19} atoms/cm² in a 4-mm He jet



Density from measured energy loss and tabulated stopping power

K. Schmidt *et al.*: Nucl. Instrum. Meth. A 911, 1–9, 2018

Comparison with other supersonic gas-jet targets in nuclear astrophysics



Normalized to 2.859 MPa input pressure

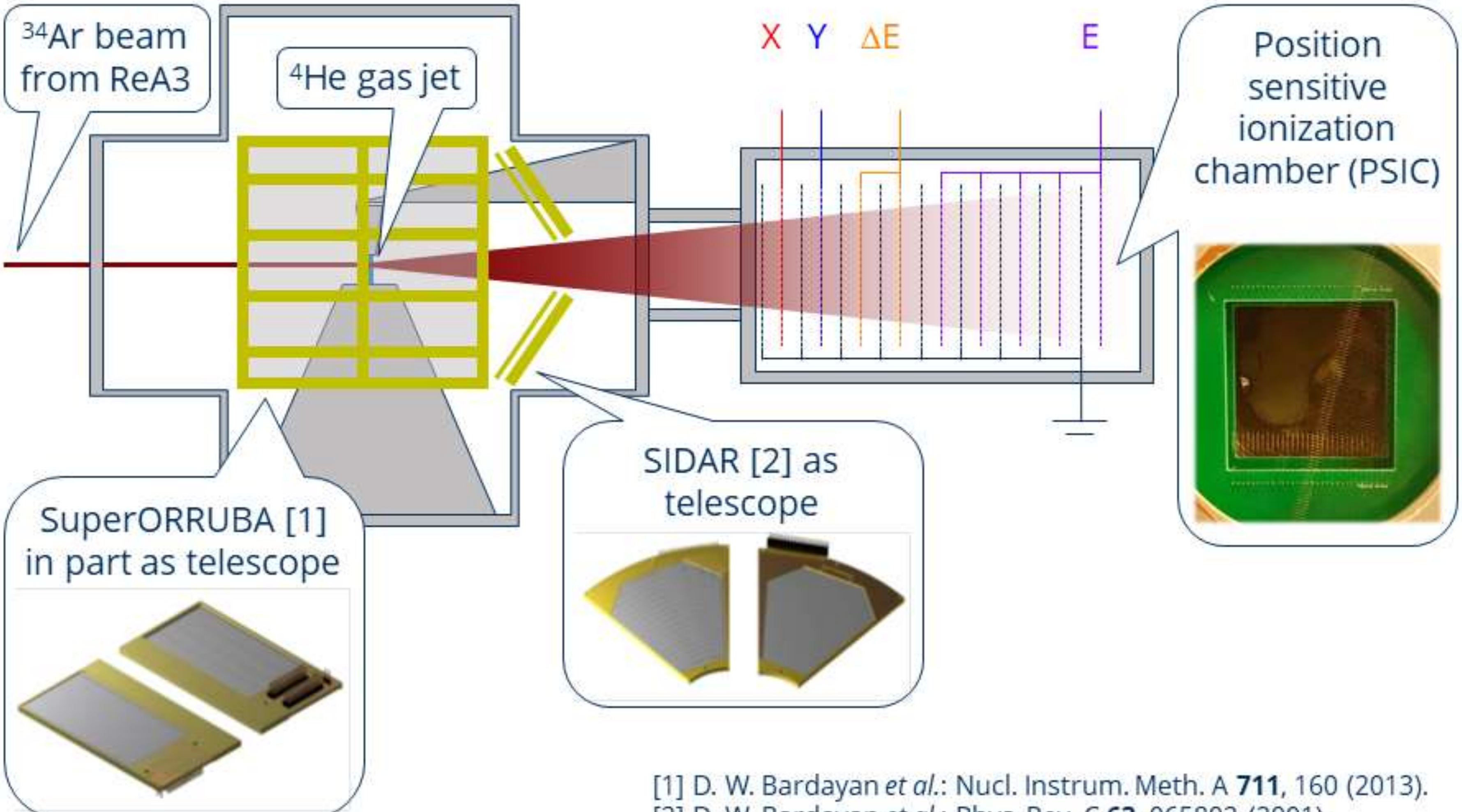
Location	Year	Input pressure (kPa)	^{4}He jet density (10^{18} at./cm^2)	^{4}He jet FWHM (mm)	Distance from nozzle (mm)
Münster	1982	200	0.34 ± 0.06	2.5 ± 0.2	1 to 5
Stuttgart	1991	38	0.078 ± 0.013	2.6 ± 0.2	~1.5
Notre Dame	2012	150	0.259 ± 0.021	2.2 ± 0.2	~4
Oak Ridge	2014	2859	10.2 ± 0.9	5.1 ± 0.3	~1
Caserta	2017	700	1.97 ± 0.21	Not reported	~5.5
East Lansing	2018	2515	9.0 ± 0.3	2.03 ± 0.09	≲4

K. Schmidt *et al.*: Nucl. Instrum. Meth. A 911, 1–9, 2018

Part 4

First RIB experiment with JENSA

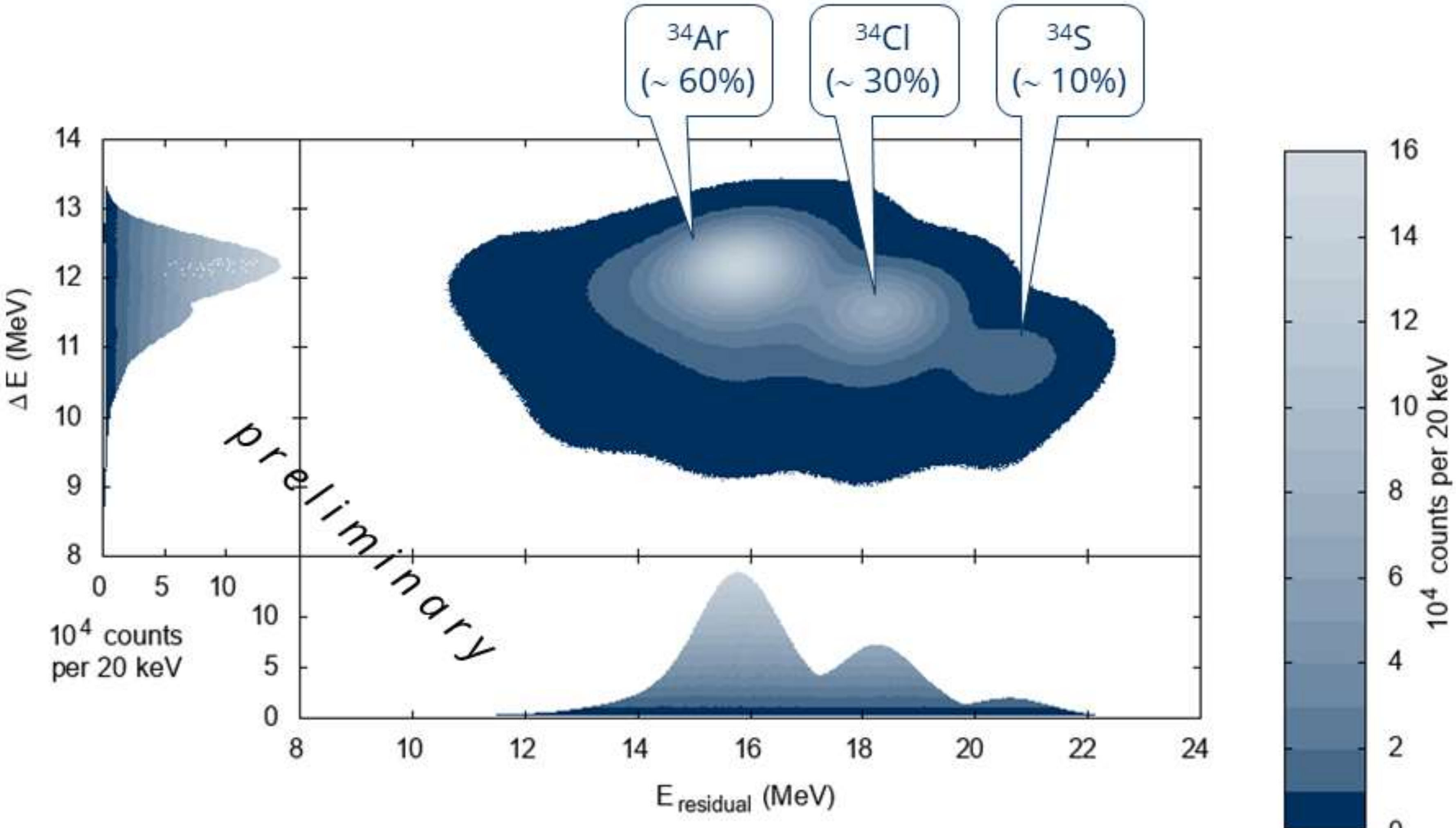
Setup to study $^{34}Ar(\alpha,p)^{37}K$



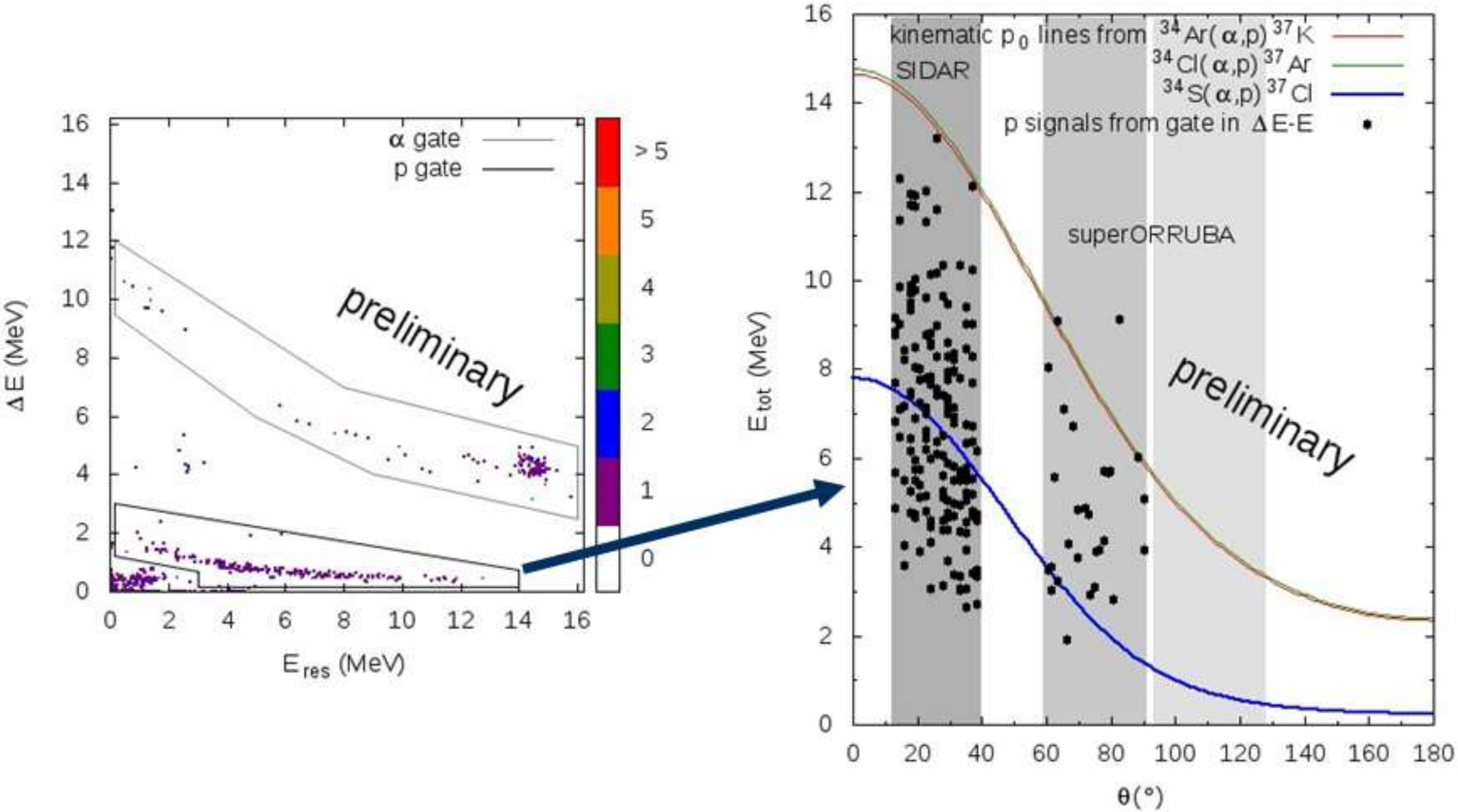
[1] D. W. Bardayan *et al.*: Nucl. Instrum. Meth. A **711**, 160 (2013).
[2] D. W. Bardayan *et al.*: Phys. Rev. C **63**, 065802 (2001).

Rare isotope beam composition measured with PSIC

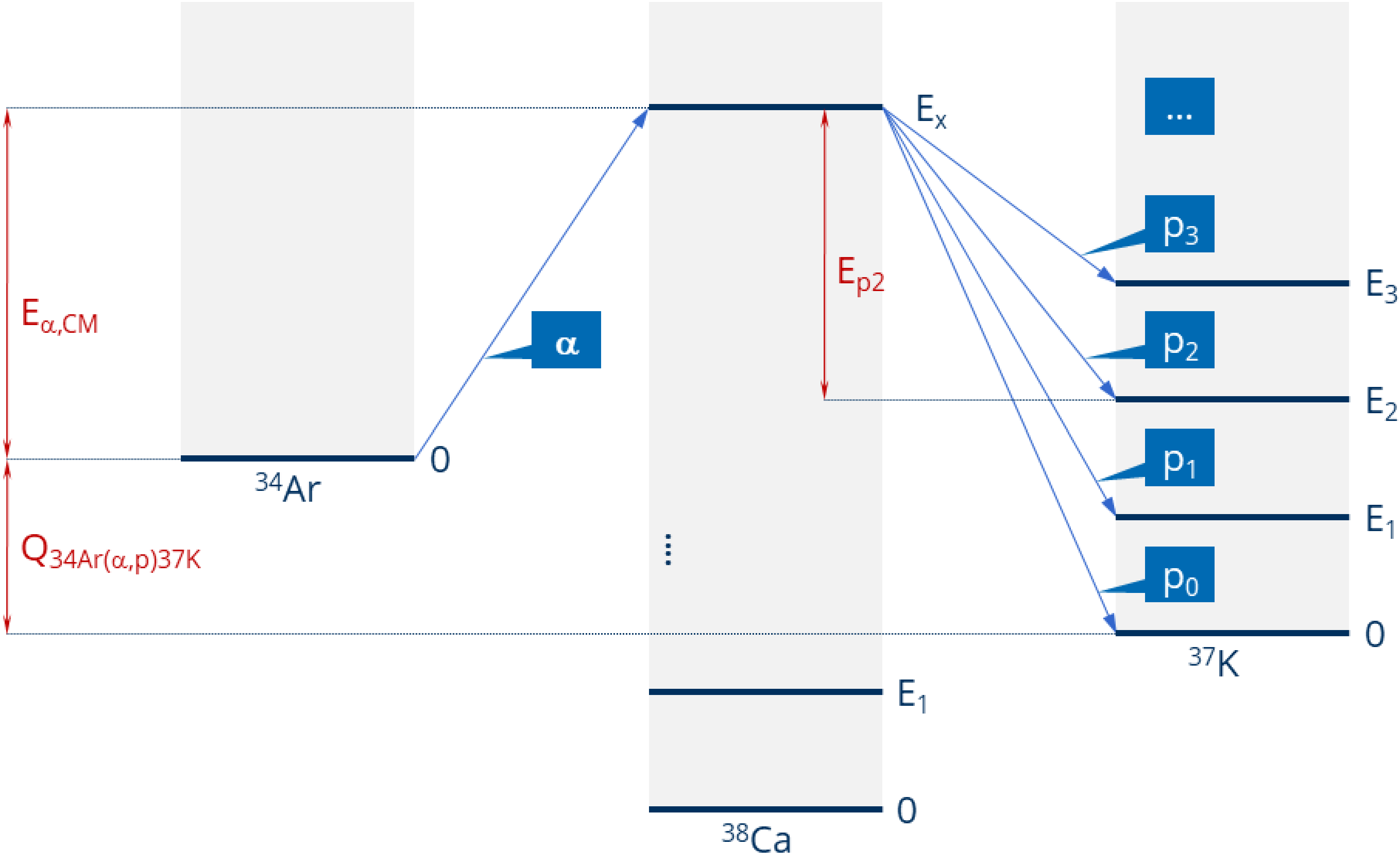
~3000 pps at 1.625 MeV/u for 108 h



Proton signals from $^{34}Ar(\alpha,p)^{37}K$

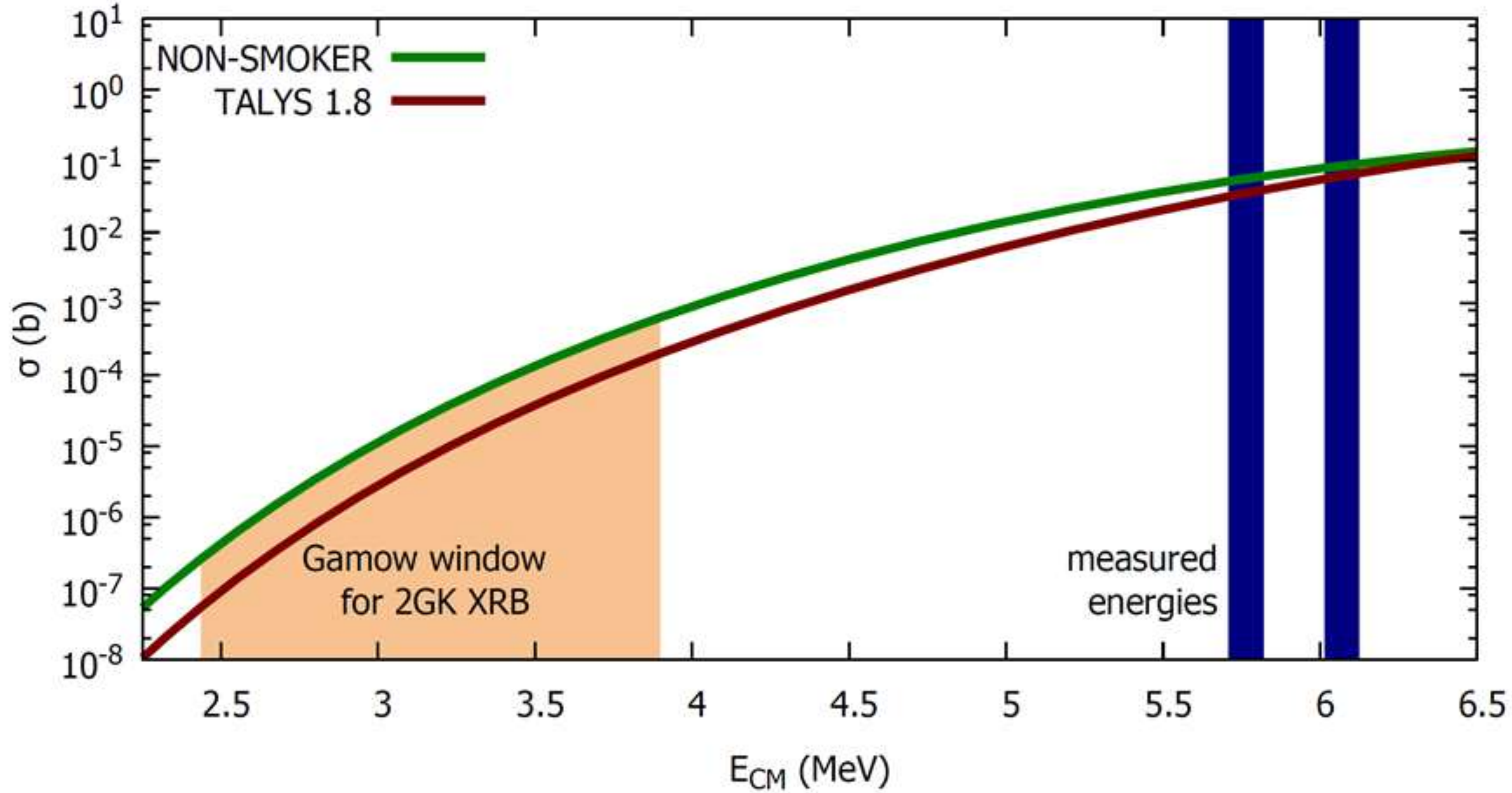


Protons with lower energy



Cross section at E_{CM} = 5.82 and 6.12 MeV

From number of protons and/or recoils, target thickness and effective beam current



Capture reaction studies with JENSA

For (α,p)
Si detectors work

For (α,γ) and (p,γ)
not enough sensitivity with γ-ray detectors

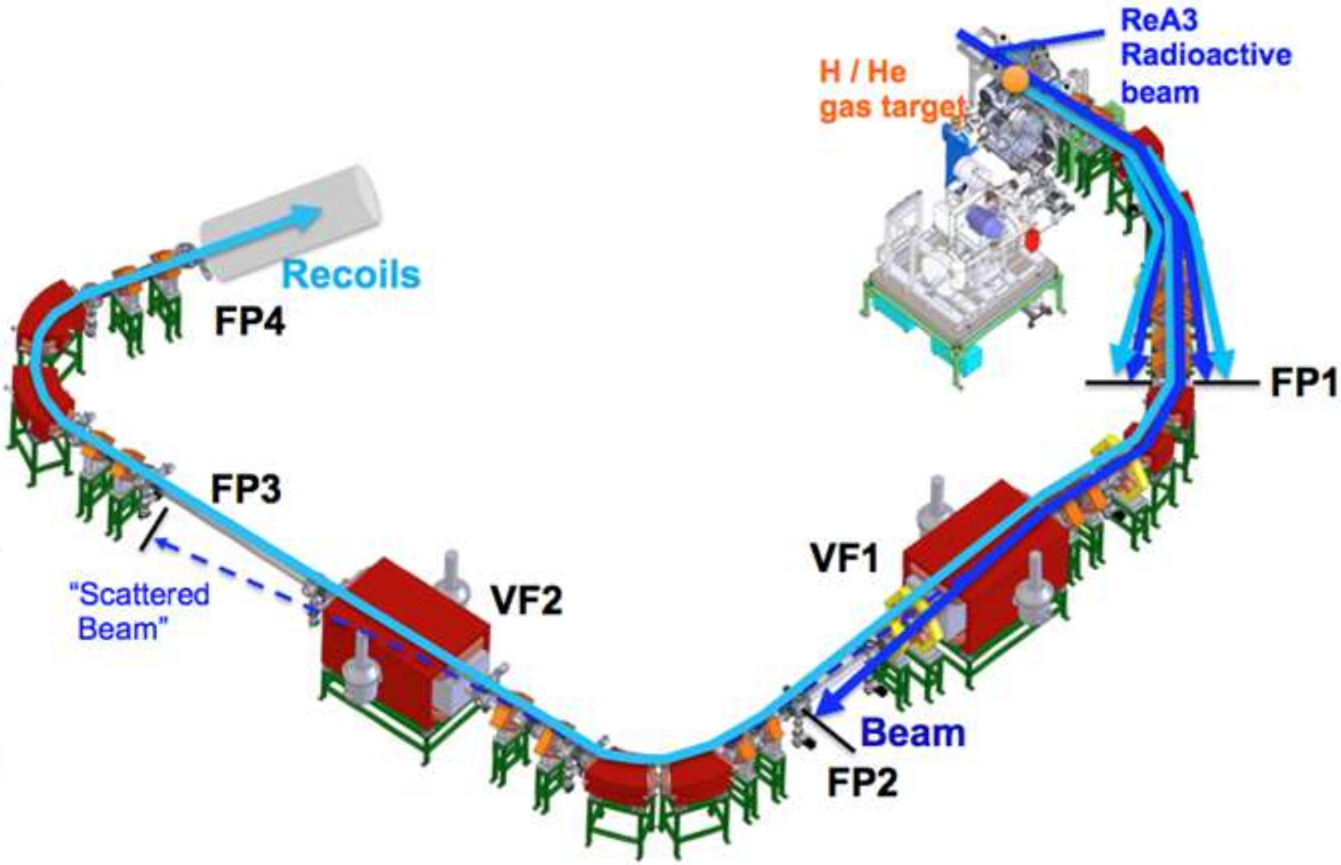
Must use recoil separator with JENSA

Part 5
Separator for Capture Reactions SECAR

SECAR

Recoil **Se**parator for **Ca**pture **R**eactions

- p rich, rare isotope beams
- α and p capture reactions up to A = 65
- rejection: 10^{17}
- energy acceptance: ±3%
- mass resolution: 750

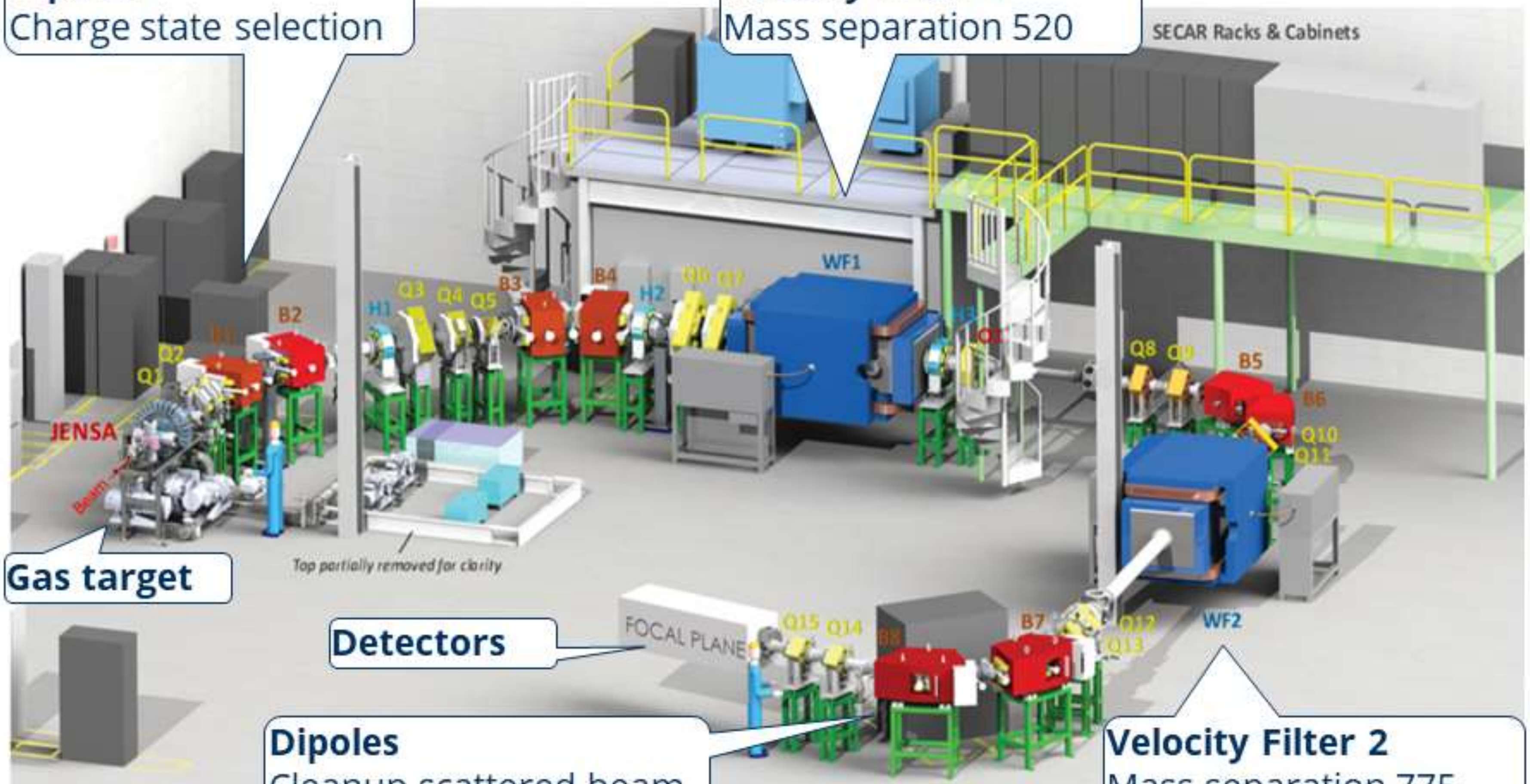


fribastro.org/SECAR/

SECAR layout

Dipoles
Charge state selection

Velocity Filter 1
Mass separation 520



Gas target

Detectors

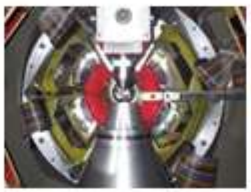
Dipoles
Cleanup scattered beam

Velocity Filter 2
Mass separation 775

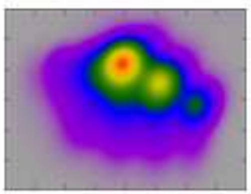
Summary

X-ray bursts are the most common astrophysical thermonuclear explosions observed

Broad range of radioactive beam experiments (together with stable beam experiments) are needed



JENSA in a stand-alone operational mode can measure (α,p) and (p,α) reactions



$^{34}Ar(\alpha,p)^{37}K$ is the first rare isotope beam experiment with JENSA

SECAR will enable (α,γ) and (p,γ) capture reaction measurements

Neutron Star