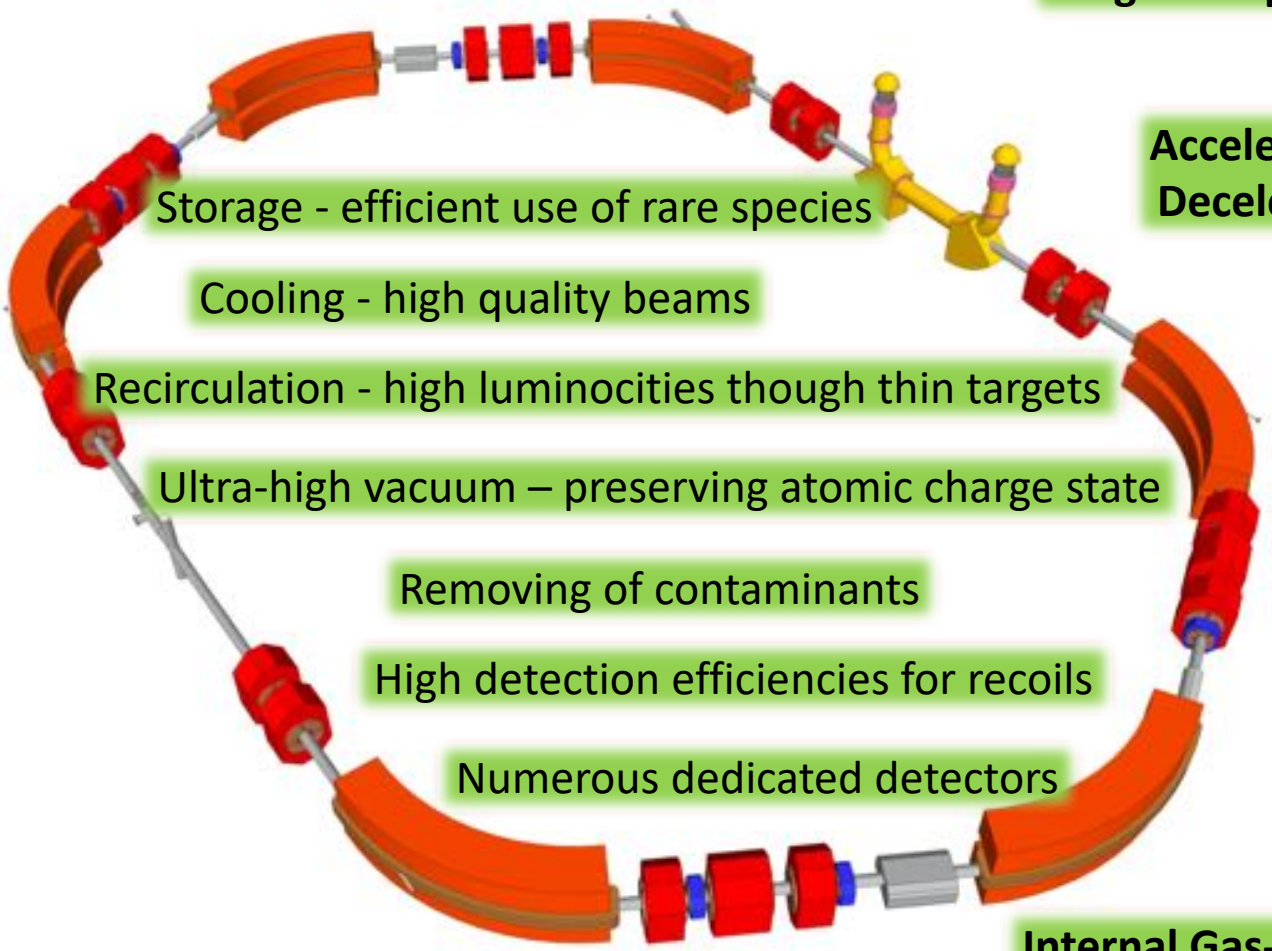
Nuclear astrophysics experiments with stored highly-charged ions: Latest experiments at GSI

Yuri A. Litvinov

Tsukuba Global Science Week 2021
International Workshop on "Universe Evolution and Matter Origin"
11 September 2021

Why storage rings? - Versatile Capabilities



Storage - efficient use of rare species

Cooling - high quality beams

Recirculation - high luminocities though thin targets

Ultra-high vacuum – preserving atomic charge state

Removing of contaminants

High detection efficiencies for recoils

Numerous dedicated detectors

Large Acceptance

Beam Accumulation

Acceleration/ Deceleration

Beam Cooling:
- **Stochastic**
- **Electron**
- **(Laser)**

UHV

Beam Bunching

Various targets:
- **Electrons**
- **Photons**
- **Atoms**
- **(Ions)**
- **(Neutrons)**

Internal Gas-Jet Target

Non-destructive particle detection

Detection:
- **Electrons**
- **Photons**
- **Recoils**

Physics at Storage Rings

Storage rings stay for:
Single-particle sensitivity
Broad-band measurements
High atomic charge states
High resolving power

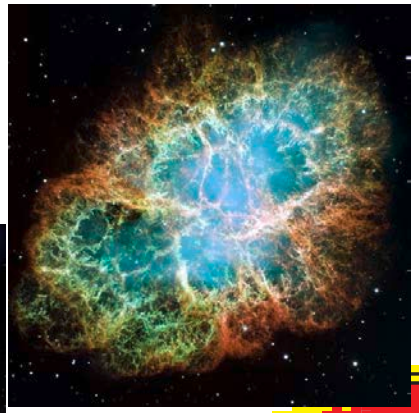
erc ASTRUm

Photos: M. Lestinsky, A. Zschau, GSI; IMP Lanzhou; RIKEN

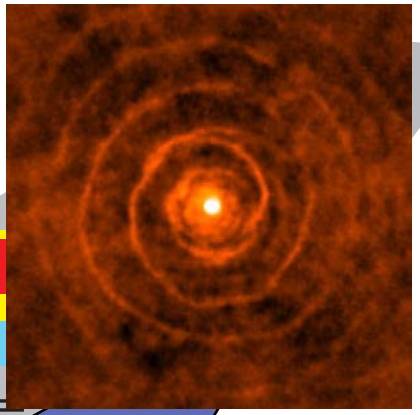
HELMHOLTZ GSI

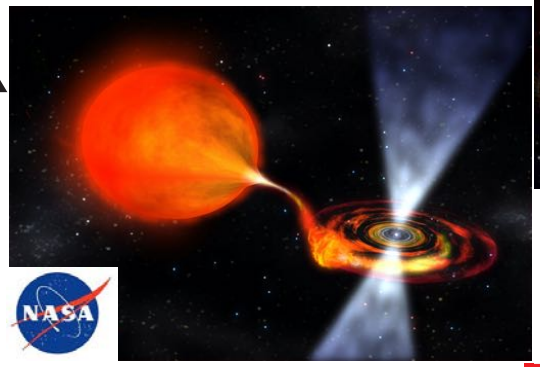
Where and how was gold cooked?

Hubble Gallery
NASA, ESA,
J. Hester, A. Loll



ALMA
(ESO/NAOJ/NRAO)
Hyosun Kim et al.





NASA/Dana Berry

ESA, CC BY-SA 3.0 IGO

Hubble Gallery, NASA, ESA

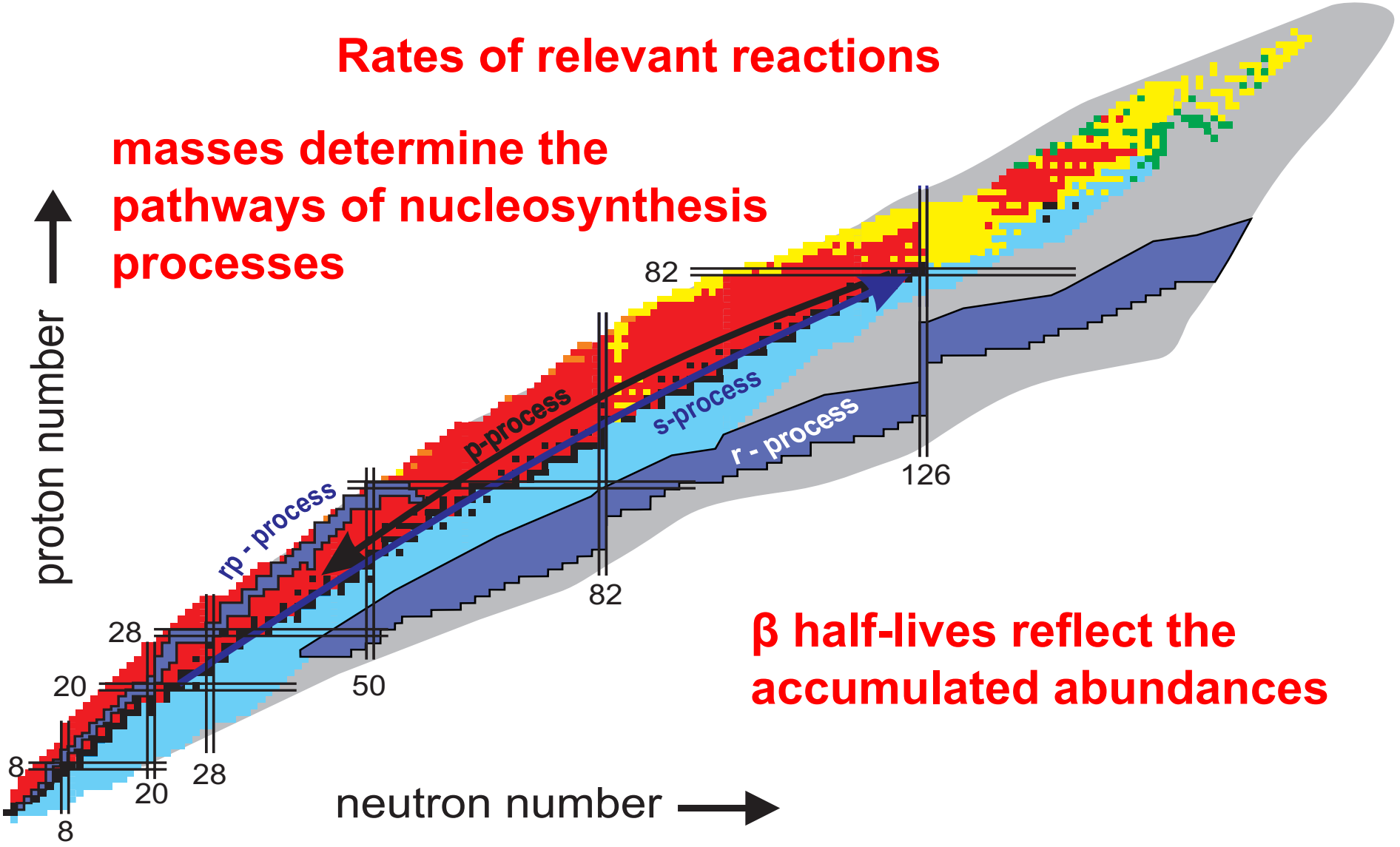
erc ASTRUm

HELMHOLTZ GSI

Where and how was gold cooked?

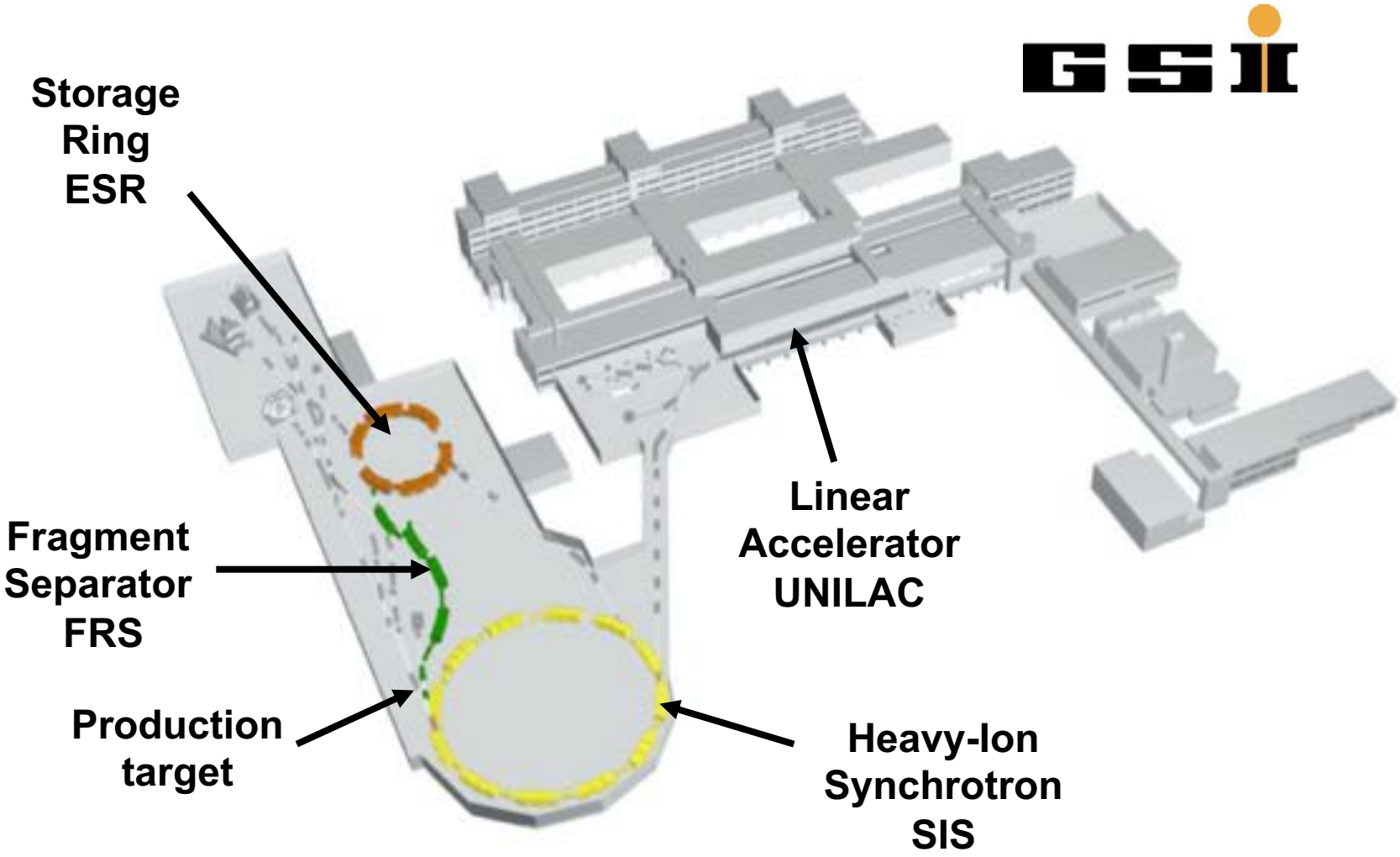
Rates of relevant reactions

masses determine the pathways of nucleosynthesis processes



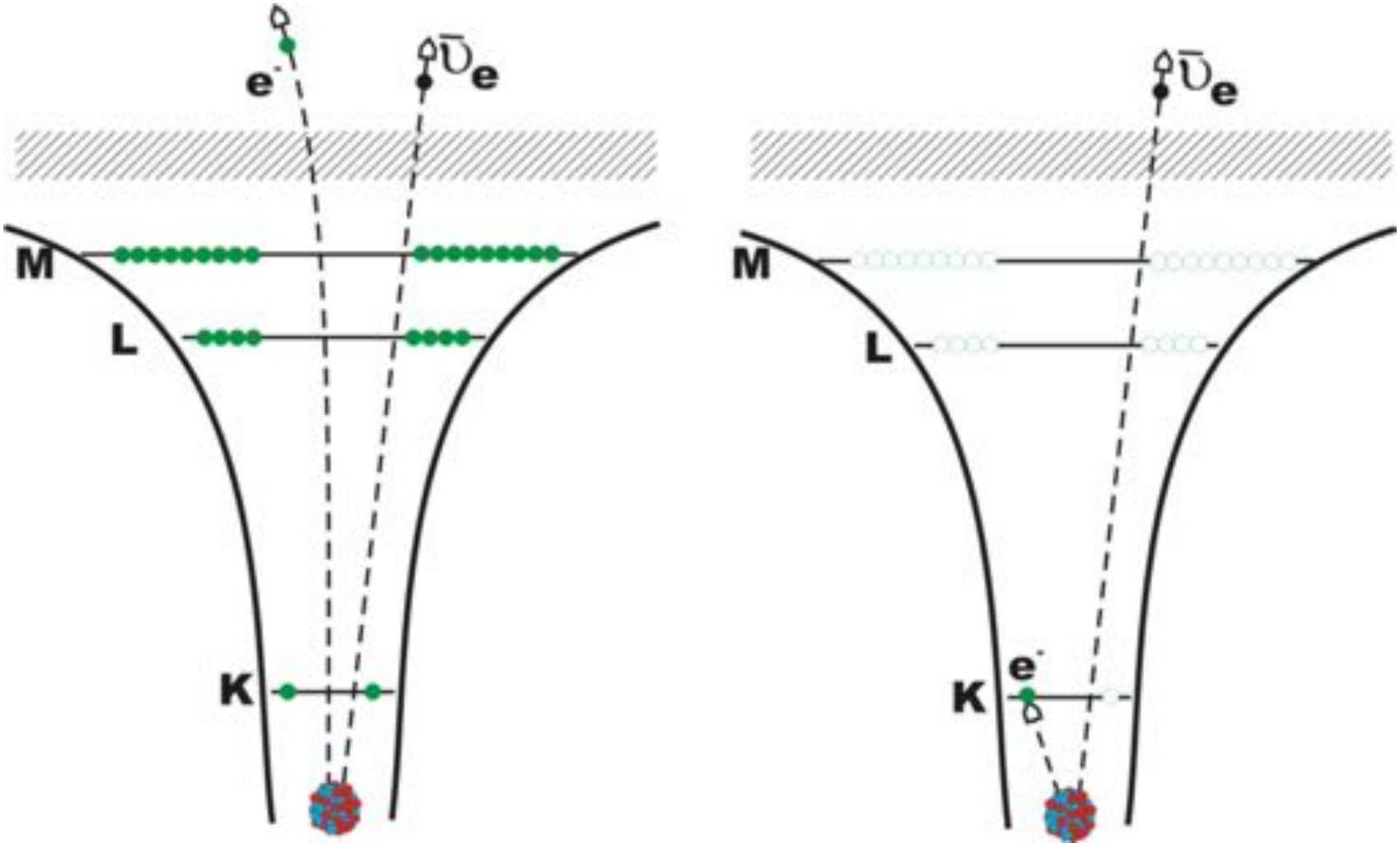
β half-lives reflect the accumulated abundances

Radioactive Ion Beam Facility at GSI



Picture: GSI, Darmstadt

Bound-State β-decay



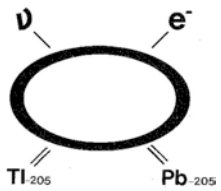
Bound-State Beta Decay of ^{205}Tl Nuclei

Proposal for an experiment to be conducted at FRS/ESR

Measurement of the bound-state beta decay of bare ^{205}Tl ions

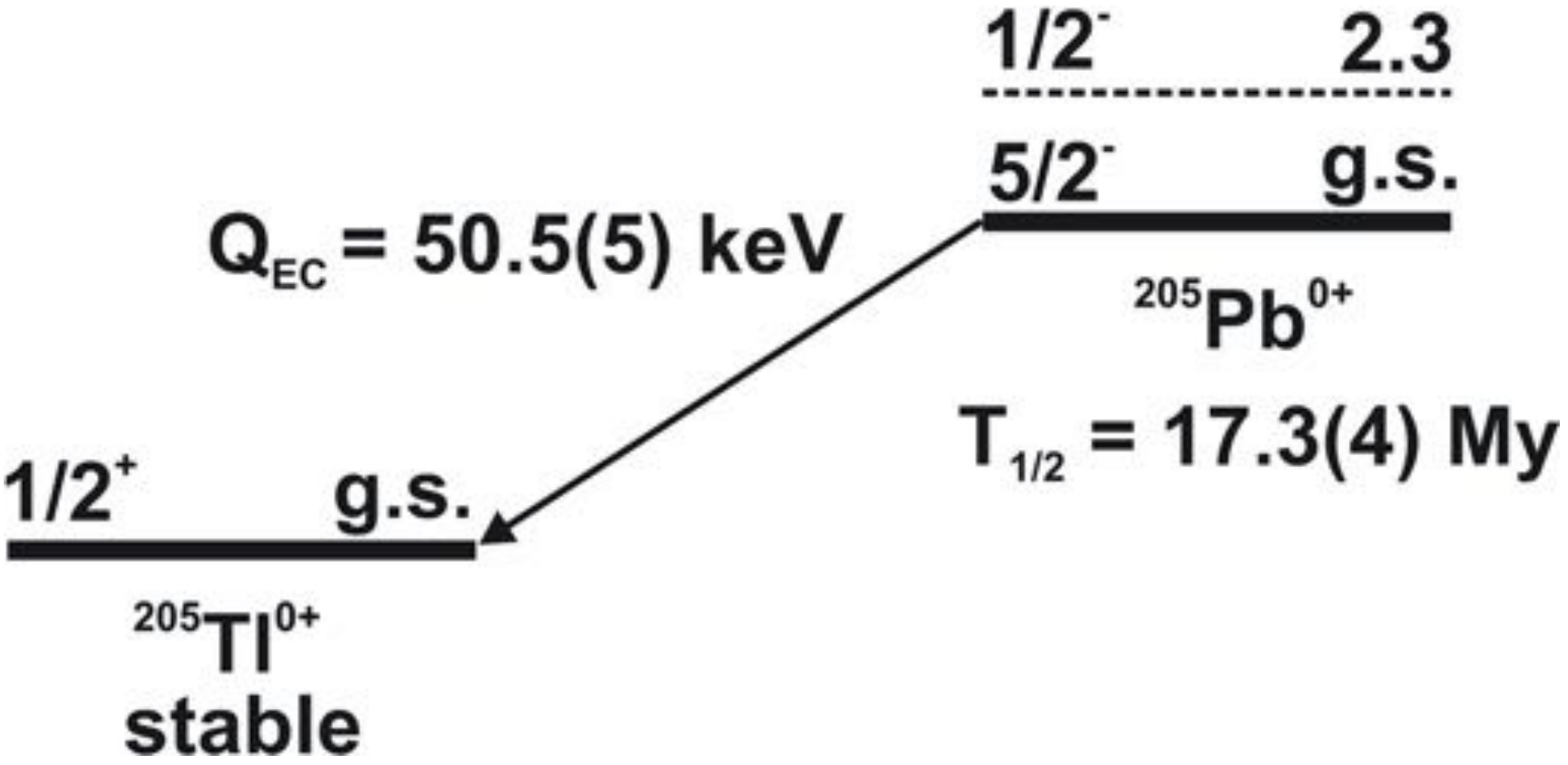
Updated from previously accepted proposal E100

For the LOREX, NucCAR, SPARC and ILIMA Collaborations

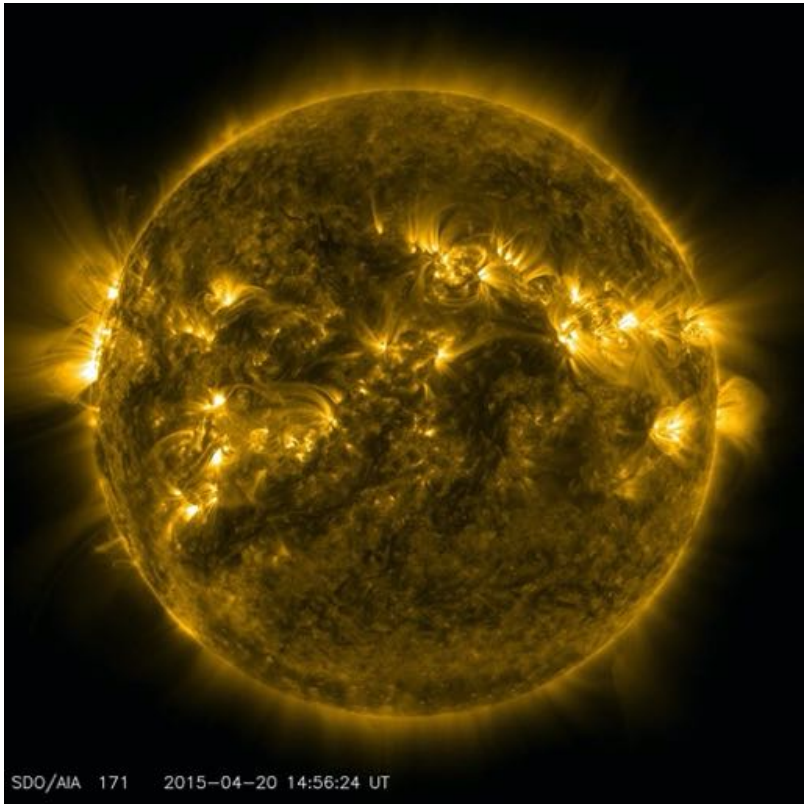


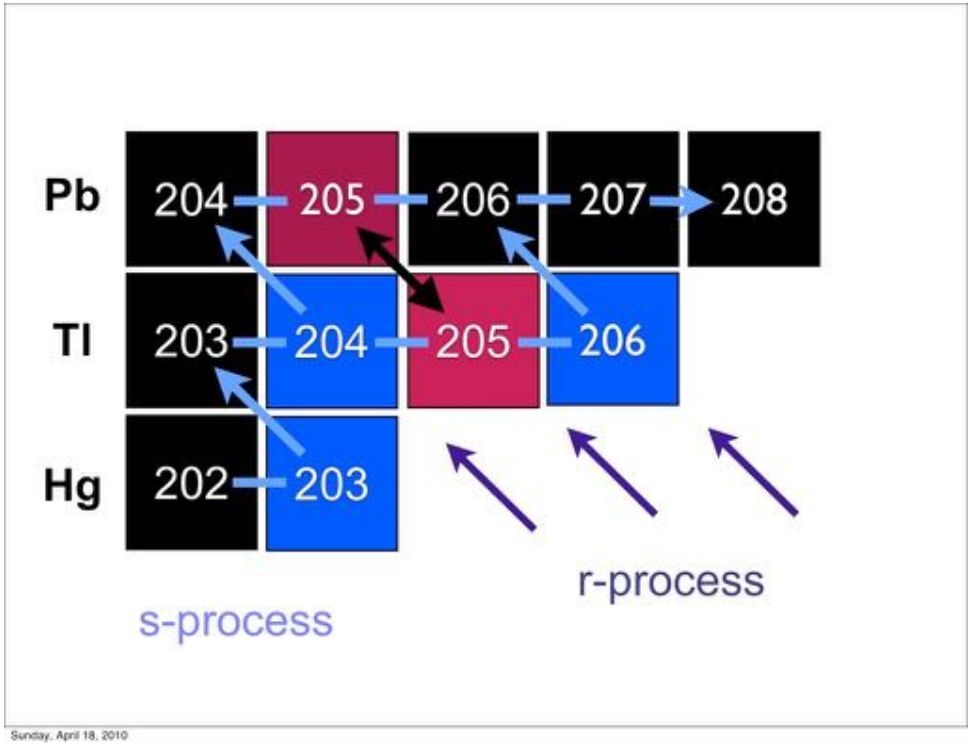
*Regarding the proposal "Measurement of the bound-state beta decay of bare ^{205}Tl ions" (Proposal E121), the G-PAC recommends this proposal with **highest priority (A)** and that **21 shifts of main beam time** be allocated for this measurement.*

Bound-State Beta Decay of ^{205}Tl Nuclei



Bound-State Beta Decay of ^{205}Tl Nuclei





NASA/SDO

Termination of s-process

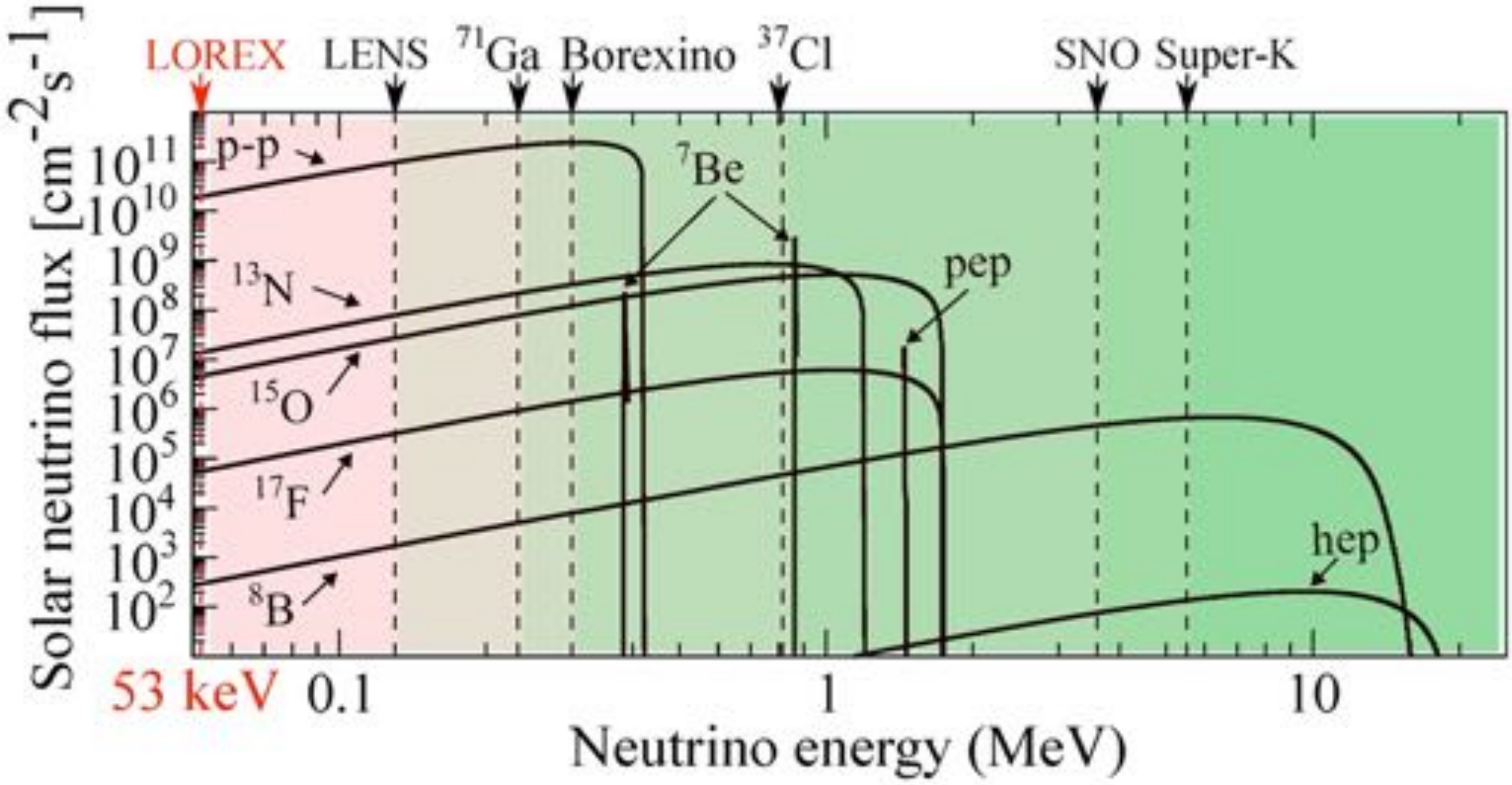
Fate of ^{205}Pb in early Solar system

Detection of Solar pp-neutrinos

erc ASTRUm

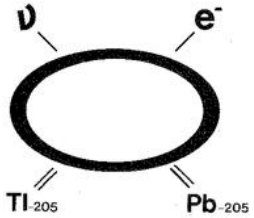
HELMHOLTZ GSI

Solar Neutrino Flux



Lorandite $TlAsS_2$ Mineral

Age = 4.31(2) Ma

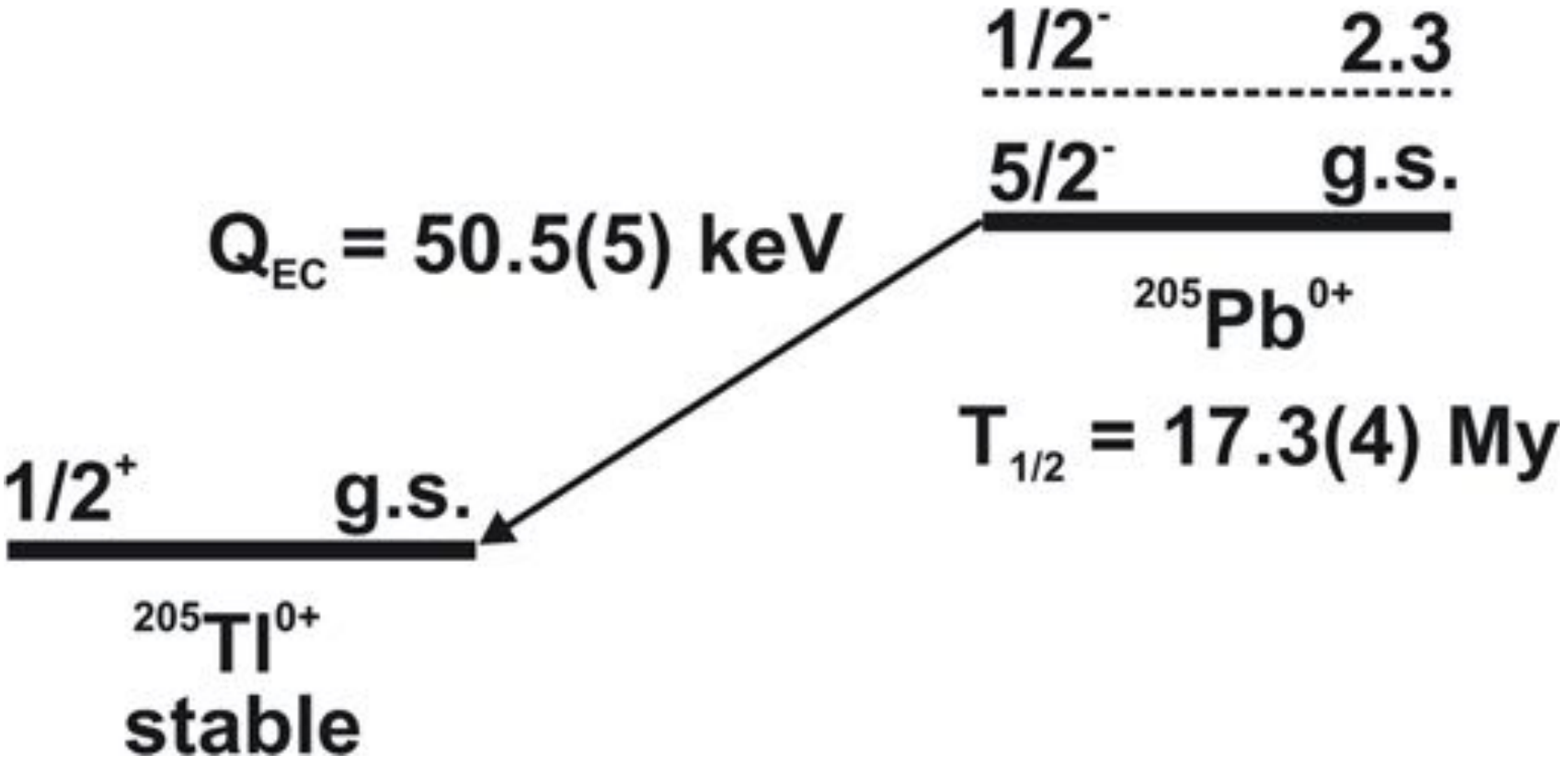


LOREX Project

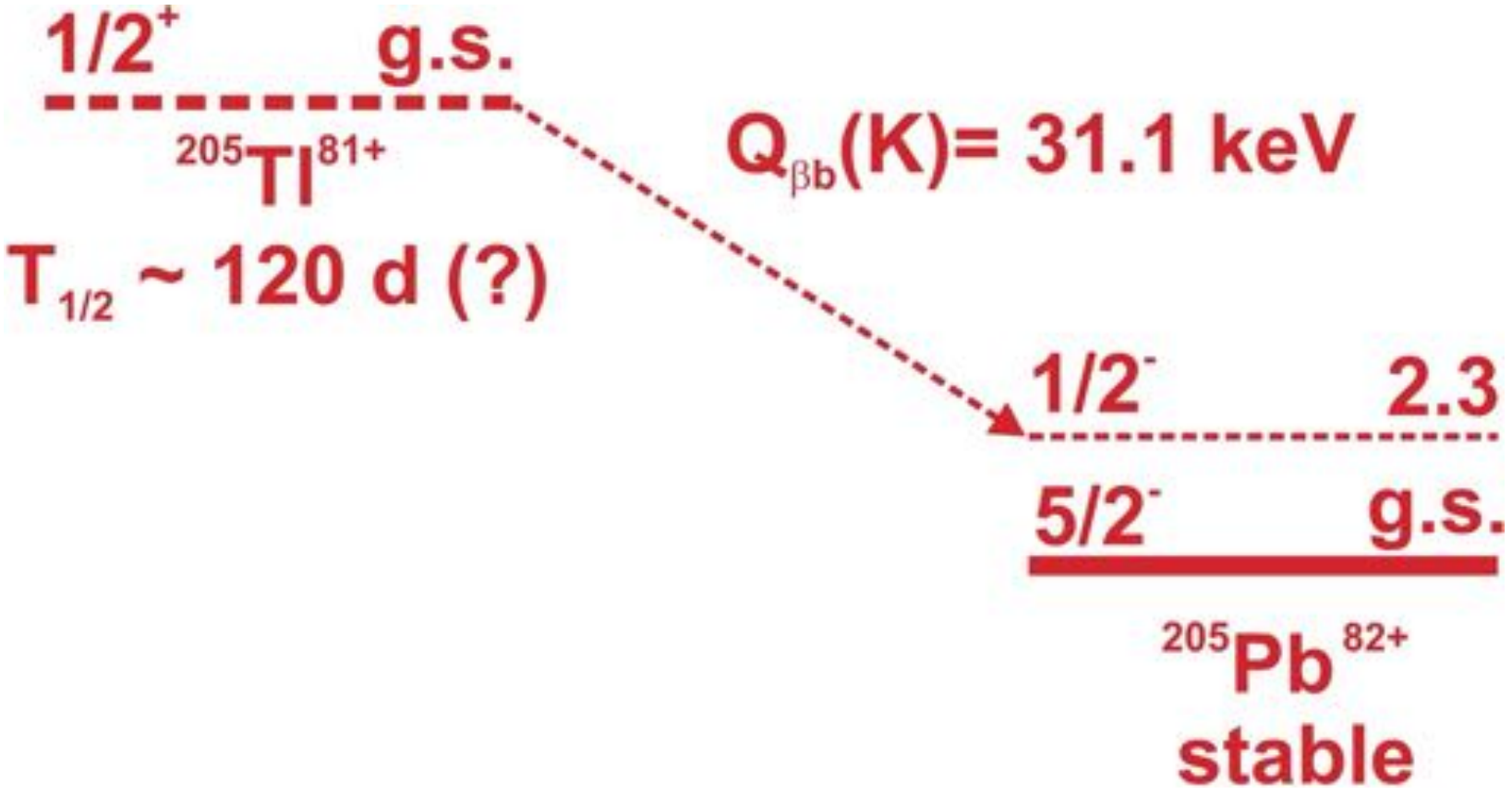
December 2019

EMMI Rapid Reaction Task Force on The LOREX Project

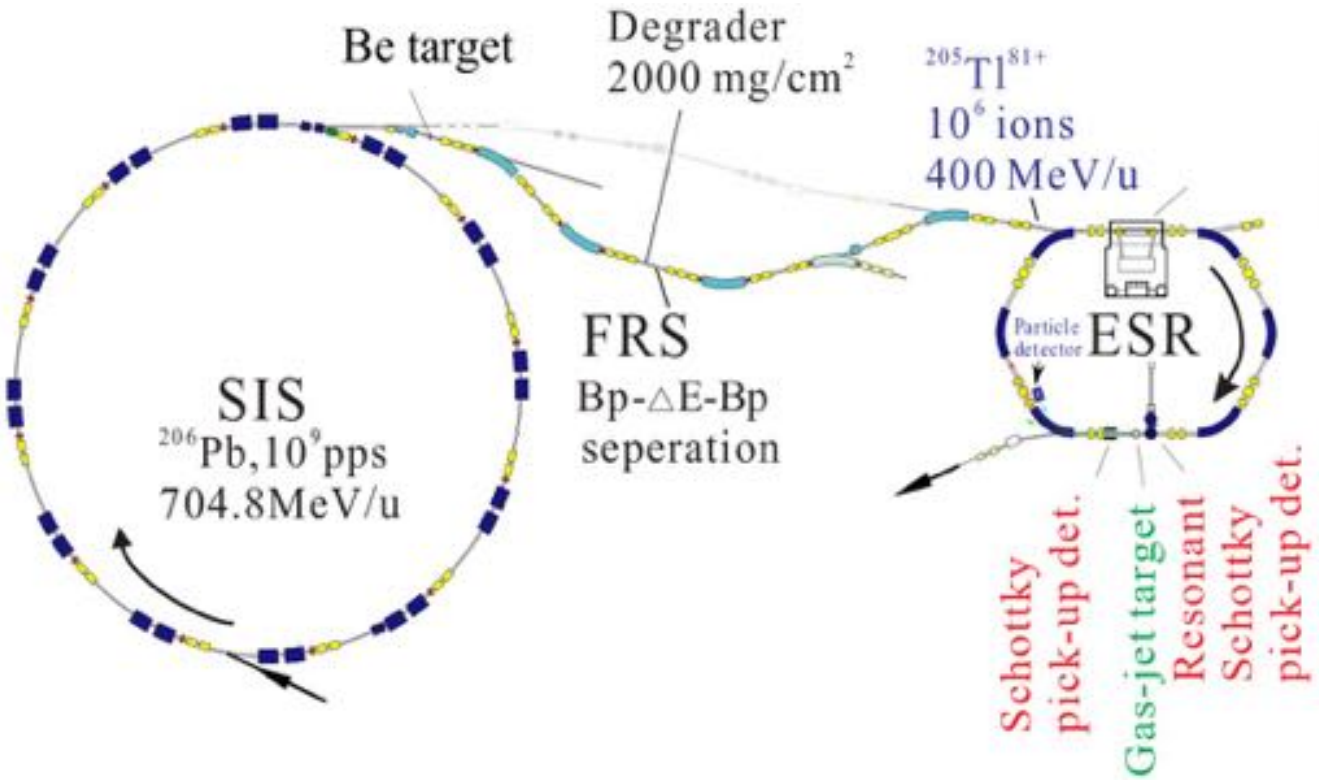
Bound-State Beta Decay of ^{205}Tl Nuclei



Bound-State Beta Decay of ^{205}Tl Nuclei



Experiment during the COVID19
23.03 – 01.04 – 06.04



Enriched ^{206}Pb beam

Separation from $^{205}Pb^{81+}$
$I(^{205}Tl^{81+})/I(^{205}Pb^{81+}) = 1/15$

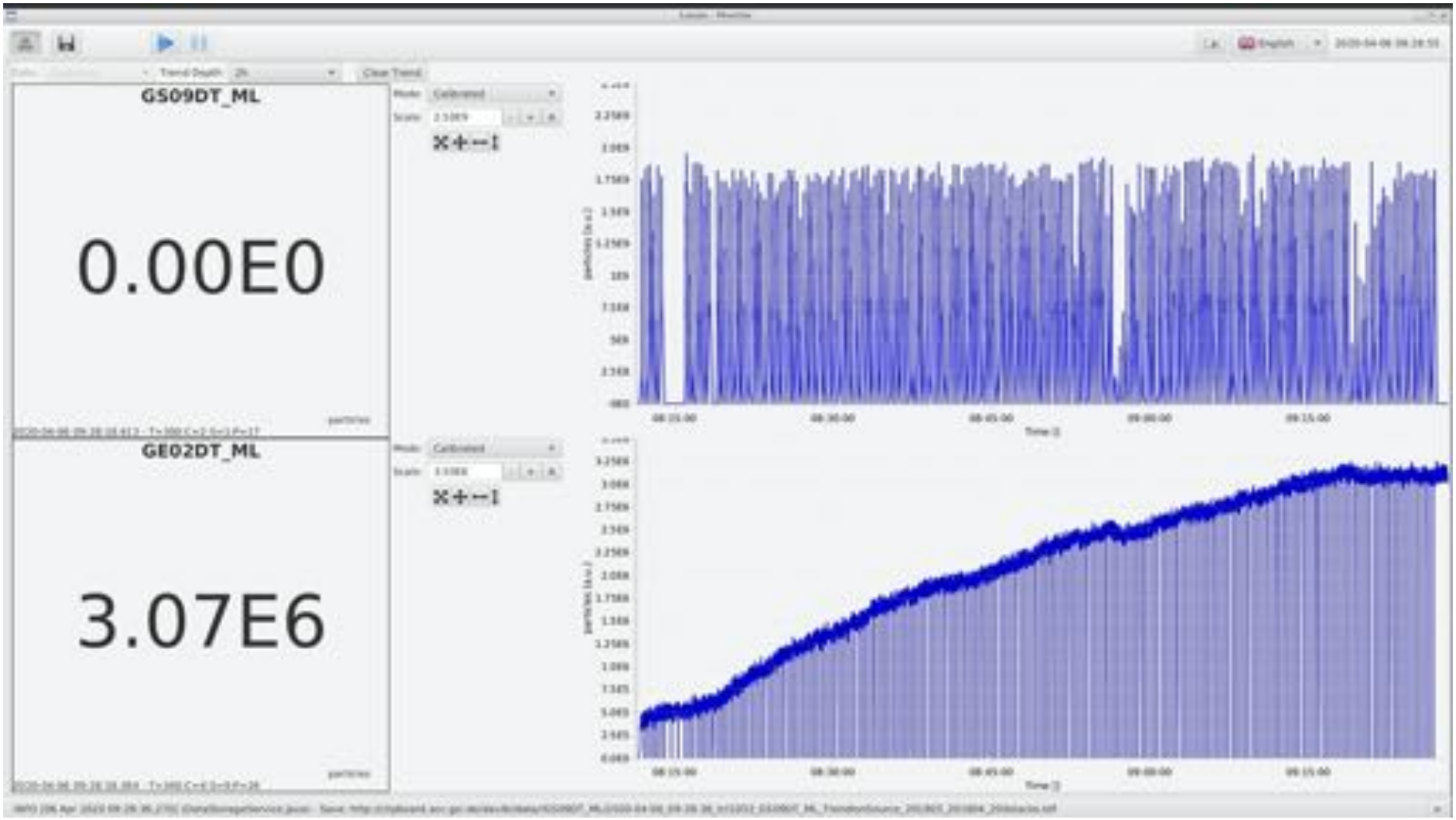
Accumulation

Long breeding time

Separation of decay daughter ions from parent ions

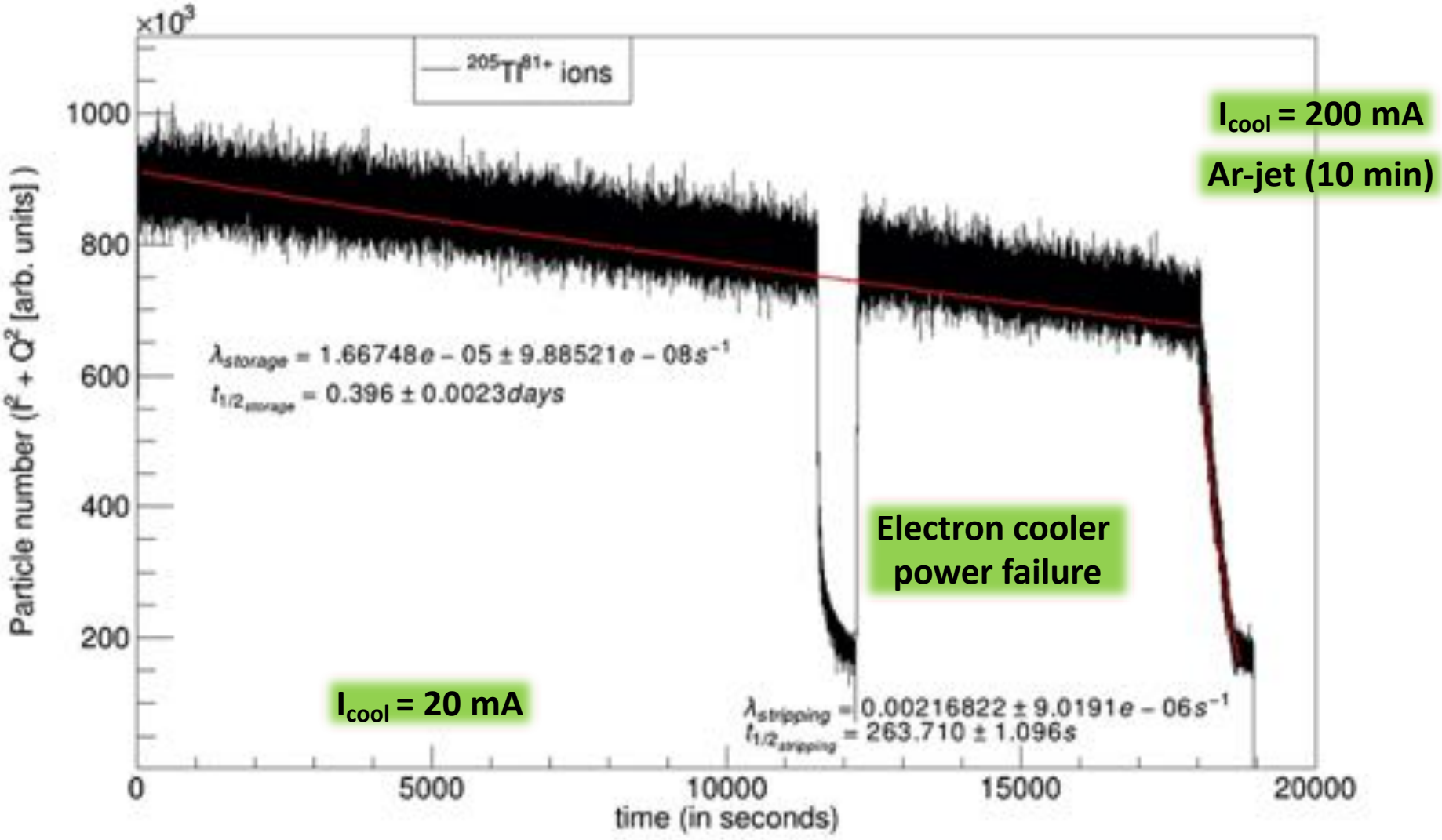
Courtesy R. J. Chen and R. Singh Sidhu

Accumulation of $^{205}Tl^{81+}$ beam in the ESR



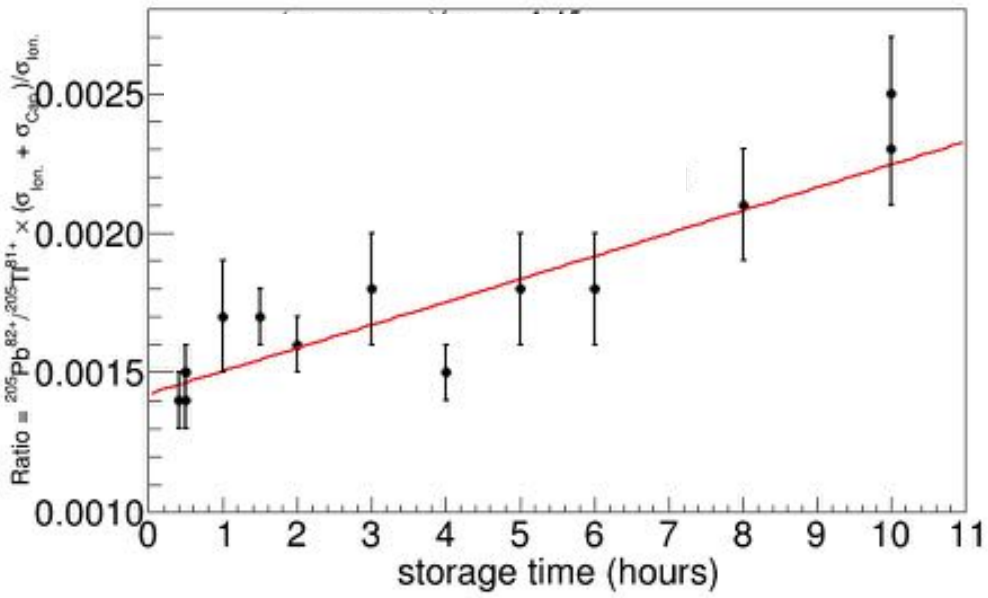
Courtesy R. J. Chen and R. Singh Sidhu

Typical Measurement (5 Hours)



Courtesy R. J. Chen and R. Singh Sidhu

Preliminary Results



ATOMIC DATA AND NUCLEAR DATA TABLES **36,** 375–409 (1987)

BETA-DECAY RATES OF HIGHLY IONIZED HEAVY ATOMS IN STELLAR INTERIORS*

K. TAKAHASHI

University of California, Institute of Geophysics and Planetary Physics
Lawrence Livermore National Laboratory, Livermore, California 94550

and

K. YOKOI†

Kernforschungszentrum Karlsruhe GmbH, Institut für Kernphysik III
D-7500 Karlsruhe, Federal Republic of Germany

PHYSICAL REVIEW C **101**, 031302(R) (2020)

Rapid Communications

Calculated solar-neutrino capture rate for a radiochemical ^{205}Tl-based solar-neutrino detector

Joel Kostensalo* and Jouni Suhonen†
University of Jyvaskyla, Department of Physics, P.O. Box 35, FI-40014, Finland

K. Zuber‡
Institute for Nuclear and Particle Physics, TU Dresden, 01069 Dresden, Germany

(Received 19 December 2019; revised manuscript received 22 January 2020; accepted 19 February 2020; published 4 March 2020)

PHYSICAL REVIEW C **104**, 024304 (2021)

Investigation of bound state β^- decay half-lives of bare atoms

Shuo Liu, Chao Gao, and Chang Xu*
School of Physics, Nanjing University, Nanjing 210093, China

(Received 9 June 2021; accepted 21 July 2021; published 2 August 2021)

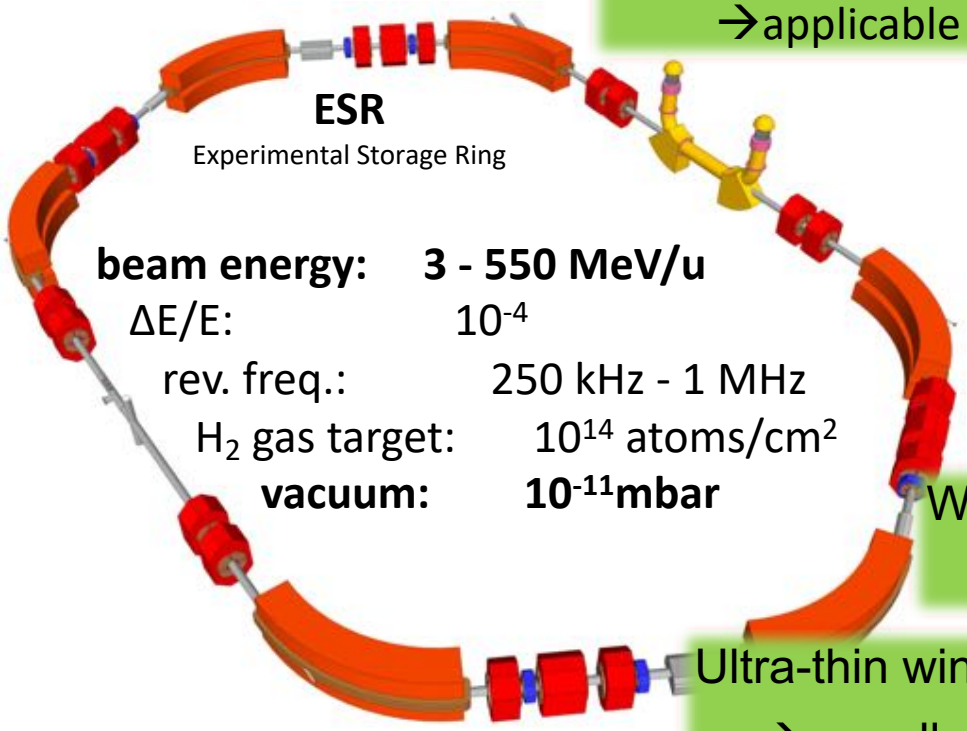
erc ASTRUm

Courtesy R. J. Chen and R. Singh Sidhu

HELMHOLTZ GSI

Nuclear reaction studies in a storage ring

in-flight fragmentation at FRS
→applicable to radioactive nuclei



deceleration of beams
→Gamow window

High revolution frequency
→ high luminosity even with thin targets

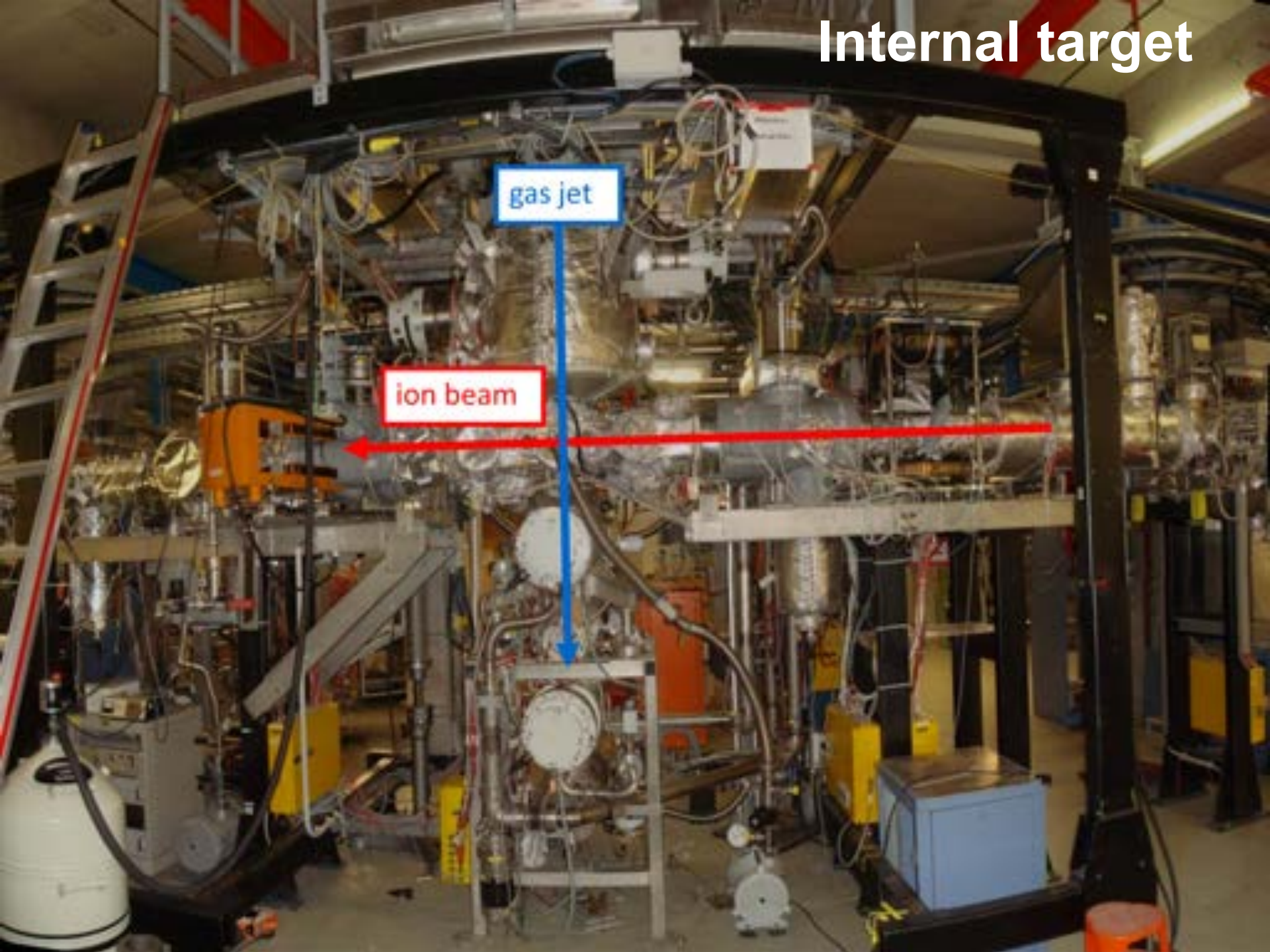
Well-known atomic charge-exchange rates
→in-situ luminosity monitor

Ultra-thin windowless gas targets and electron cooling
→ excellent energy resolution

Detection of ions via in-ring particle detectors, clean beam and target
→low background, high efficiency

very efficient use of exotic beams for high resolution experiments

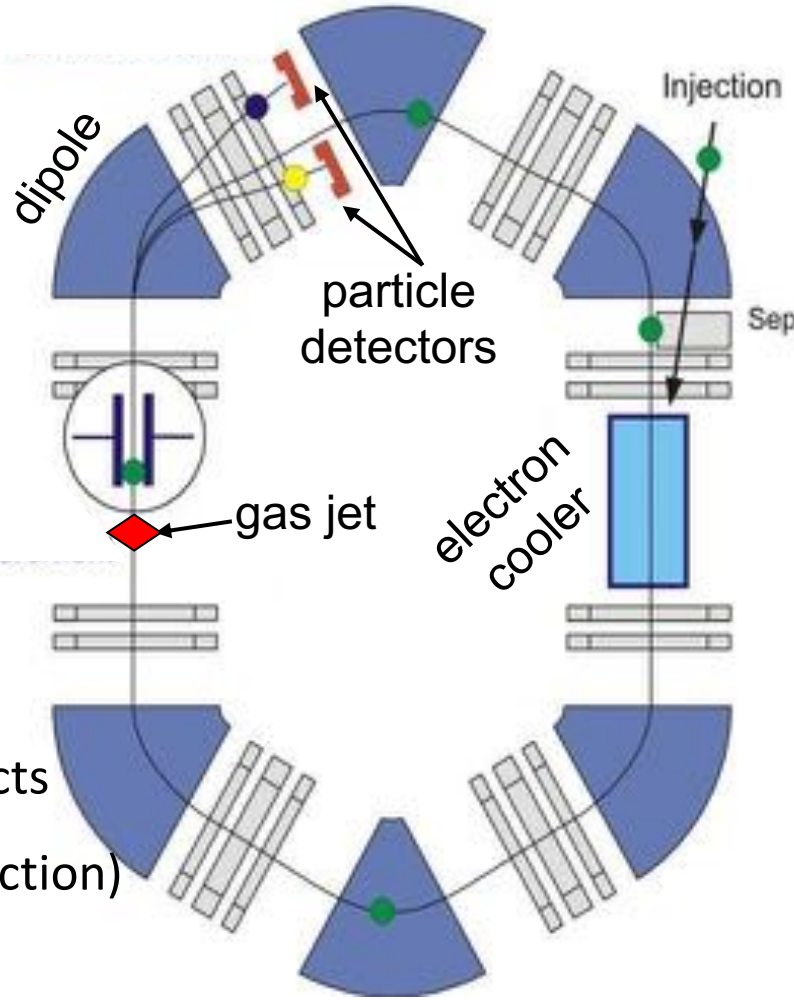
Internal target



Proton-Capture Reactions in the ESR

refill ring periodically

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



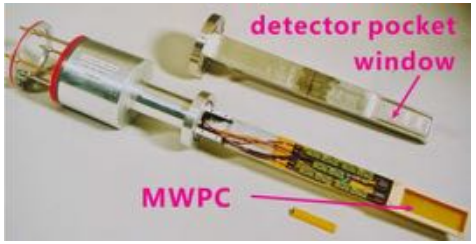
ESR

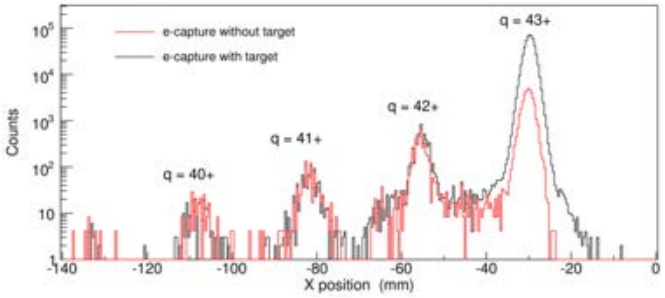
Jan Glorius: "A recycling recoil separator"

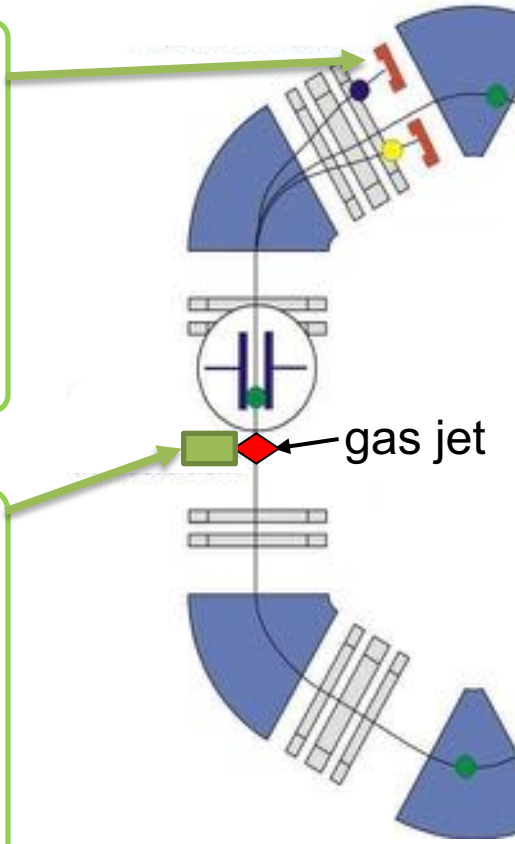
In-Situ Luminosity Monitoring

total e⁻ capture rate [NRC + REC]

measured by particle detection

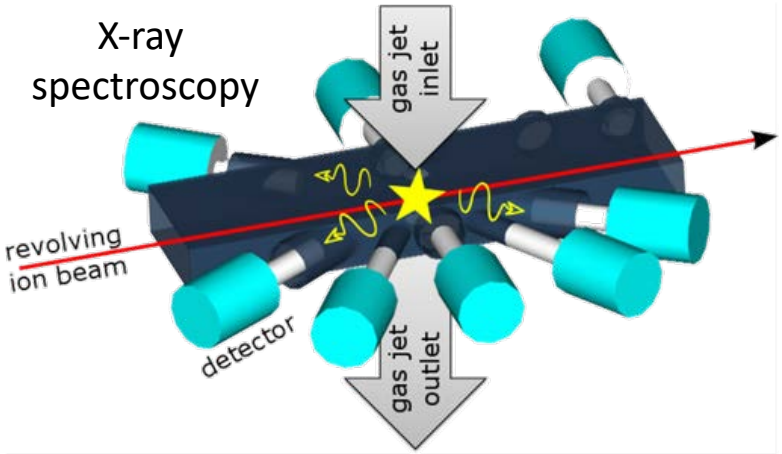


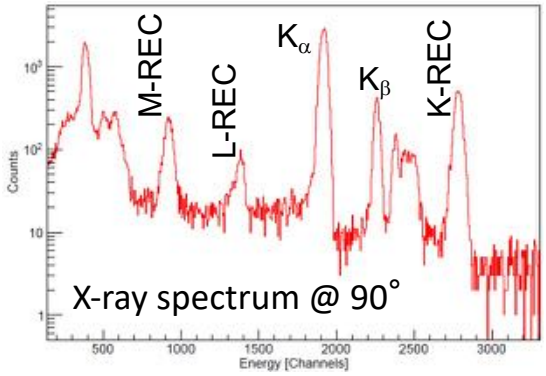




radiative e⁻ capture rate [REC]

X-ray spectroscopy





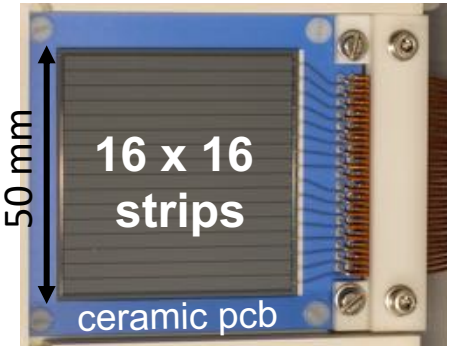
Courtesy J. Glorius

ESR Test Beam Time 2016 ^{124}Xe(p,g)^{125}Cs

Federal Ministry of Education and Research

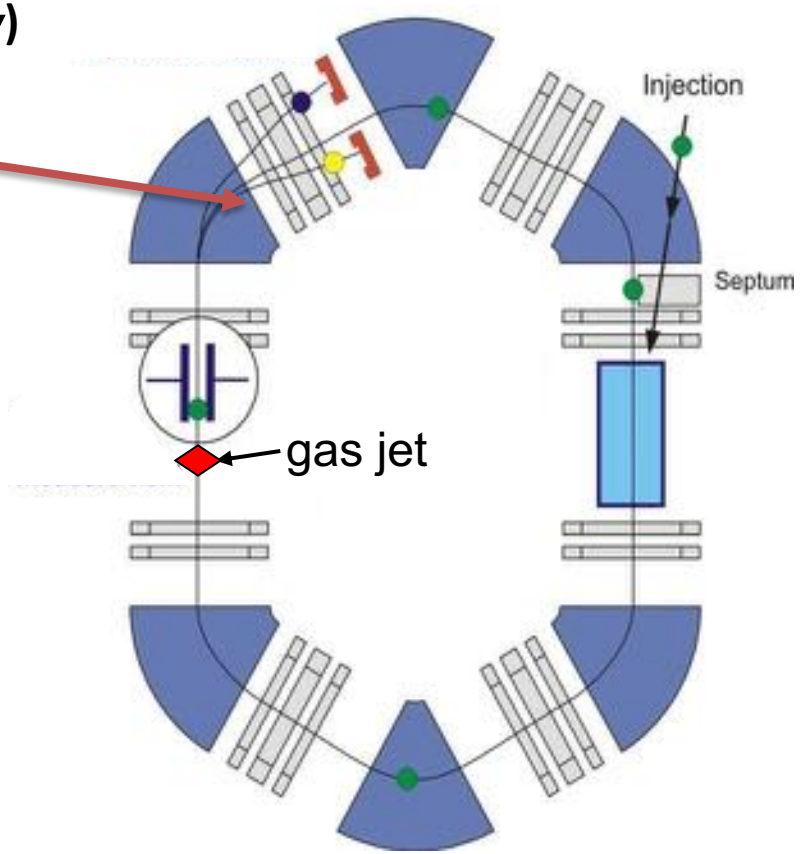
GOETHE UNIVERSITÄT FRANKFURT AM MAIN

2nd generation detectors

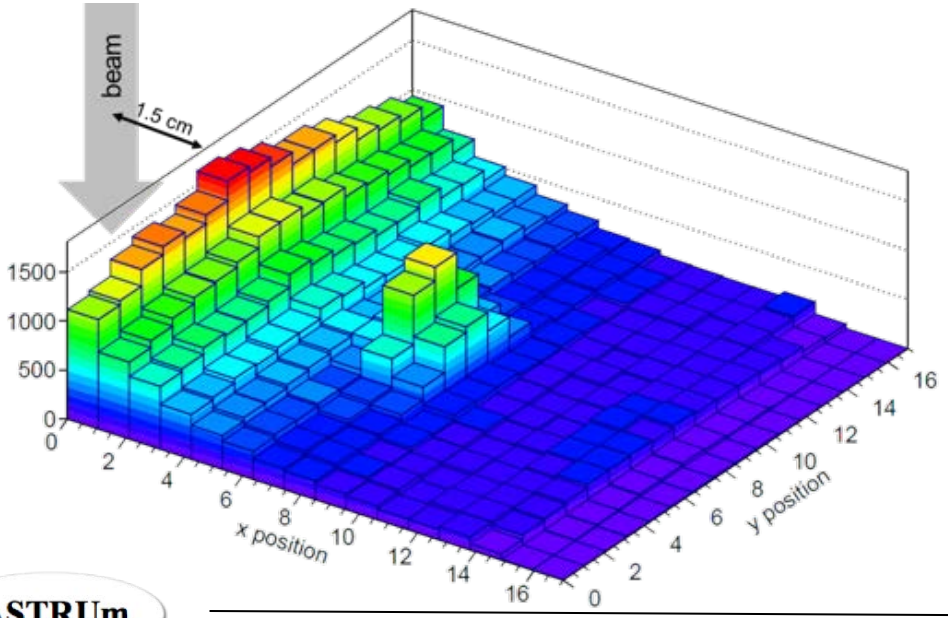


UHV compatible

^{124}Xe(p,γ)



ESR

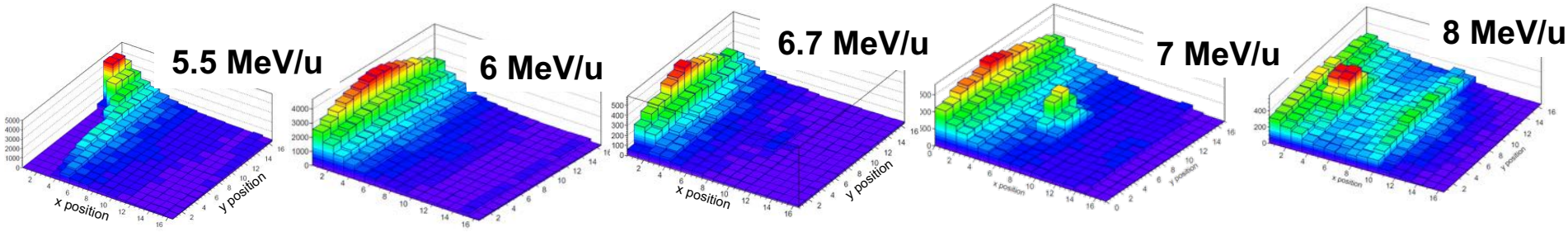


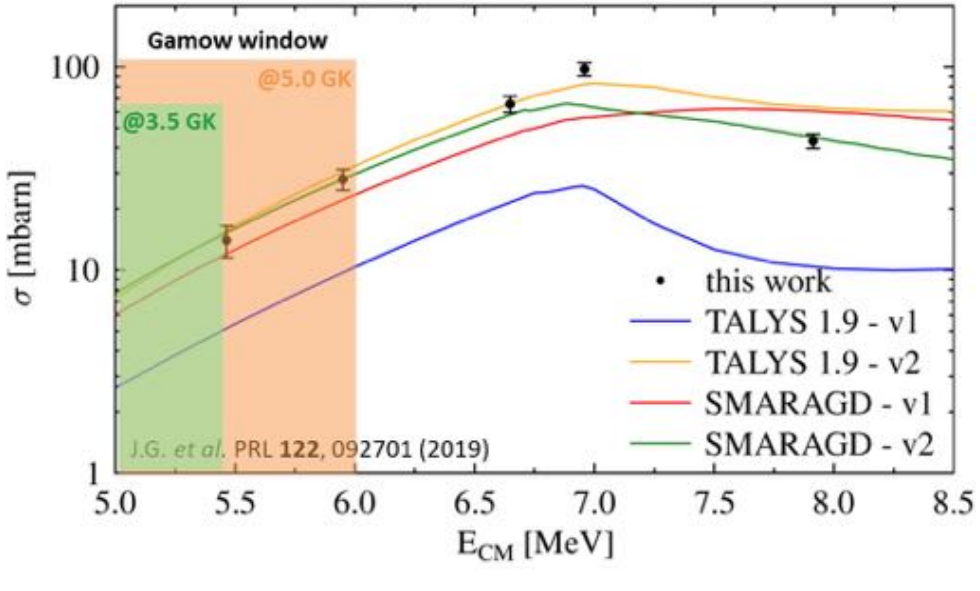
Courtesy J. Glorius

erc ASTRUm

HELMHOLTZ GSI

^{124}Xe(p,g) - Results



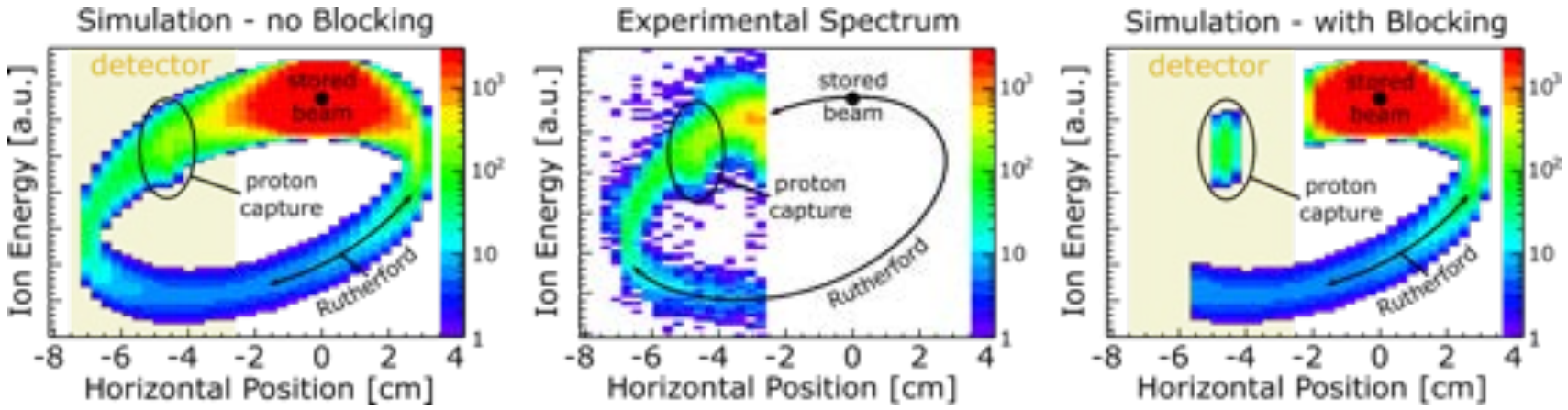


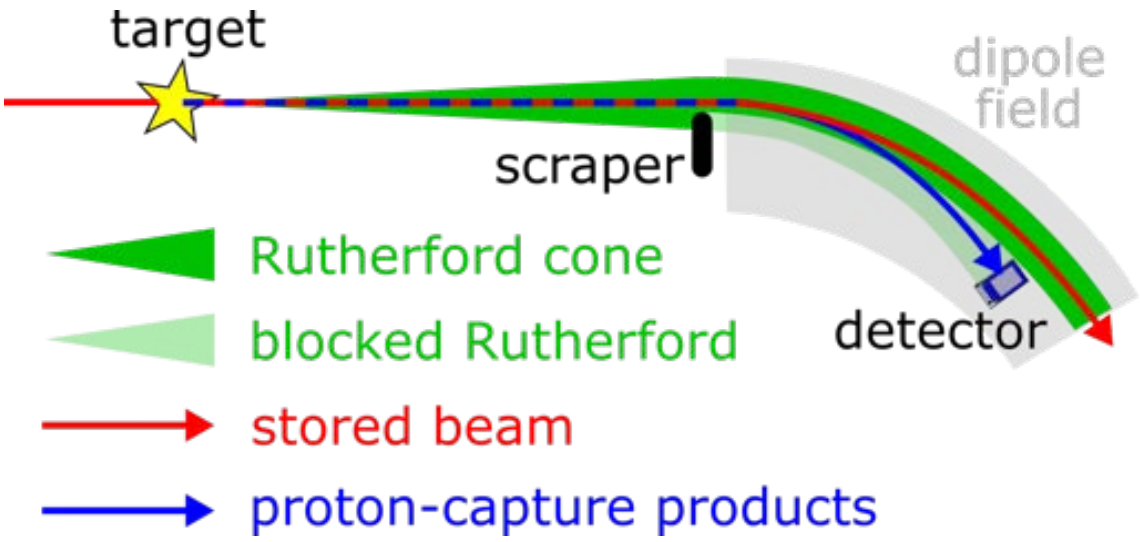
PHYSICAL REVIEW LETTERS **122,** 092701 (2019)

Approaching the Gamow Window with Stored Ions: Direct Measurement of ^{124}Xe(p,γ) in the ESR Storage Ri

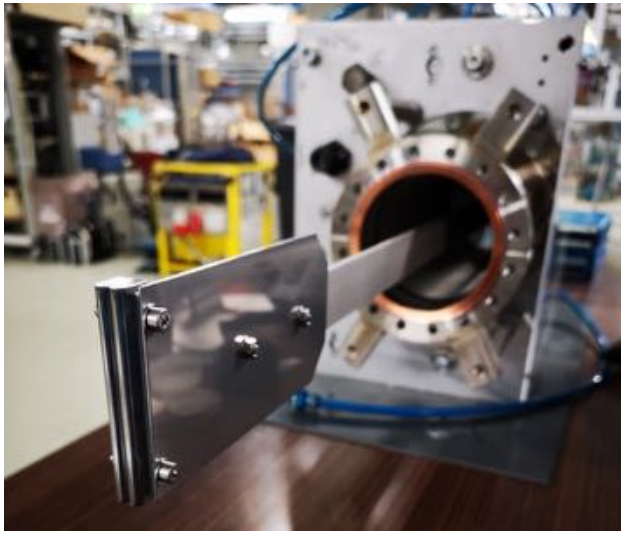
J. Glorius,[1,*] C. Langer,[2] Z. Slavkovská,[2] L. Bott,[2] C. Brandau,[1,3] B. Brückner,[2] K. Blaum,[4] T. Davinson,[7] P. Erbacher,[2] S. Fiebiger,[2] T. Gaßner,[1] K. Göbel,[2] M. Groothuis,[2] A. Gumberidz R. Hess,[1] R. Hensch,[2] P. Hillmann,[2] P.-M. Hillenbrand,[1] O. Hinrichs,[2] B. Jurado,[9] T. Kaus T. Kisselbach,[2] N. Klapper,[2] C. Kozhuharov,[1] D. Kurtulgil,[2] G. Lane,[10] C. Lederer-Woods,[7] M Yu. A. Litvinov,[1] B. Löher,[11,1] F. Nolden,[1] N. Petridis,[1] U. Popp,[1] T. Rauscher,[12,13] M. Reed,[10] R D. Savran,[1] H. Simon,[1] U. Spillmann,[1] M. Steck,[1] T. Stöhlker,[1,14] J. Stumm,[2] A. Surzhykov,[15,16] A. Taremi Zadeh,[2] B. Thomas,[2] S. Yu. Torilov,[17] H. Törnqvist,[1,11] M. Träger,[1] C. Trageser,[1,3] M. Volknandt,[2] H. Weick,[1] M. Weigand,[2] C. Wolf,[2] P. J. Woods,[7] and Y. M.

Towards background free measurement





work of Laszlo Varga



Courtesy J. Glorius and L. Varga

E127: Proton Capture on ^{118}Te (05.2021)

study of radioactive ^{118}Te (6 days half-life)

production, storage, accumulation and deceleration of ^{118}Te in FRS-ESR

up to 1.000.000 $^{118}Te^{52+}$ ions stored

proton-capture measurements realized at 7 MeV/u and 6 MeV/u

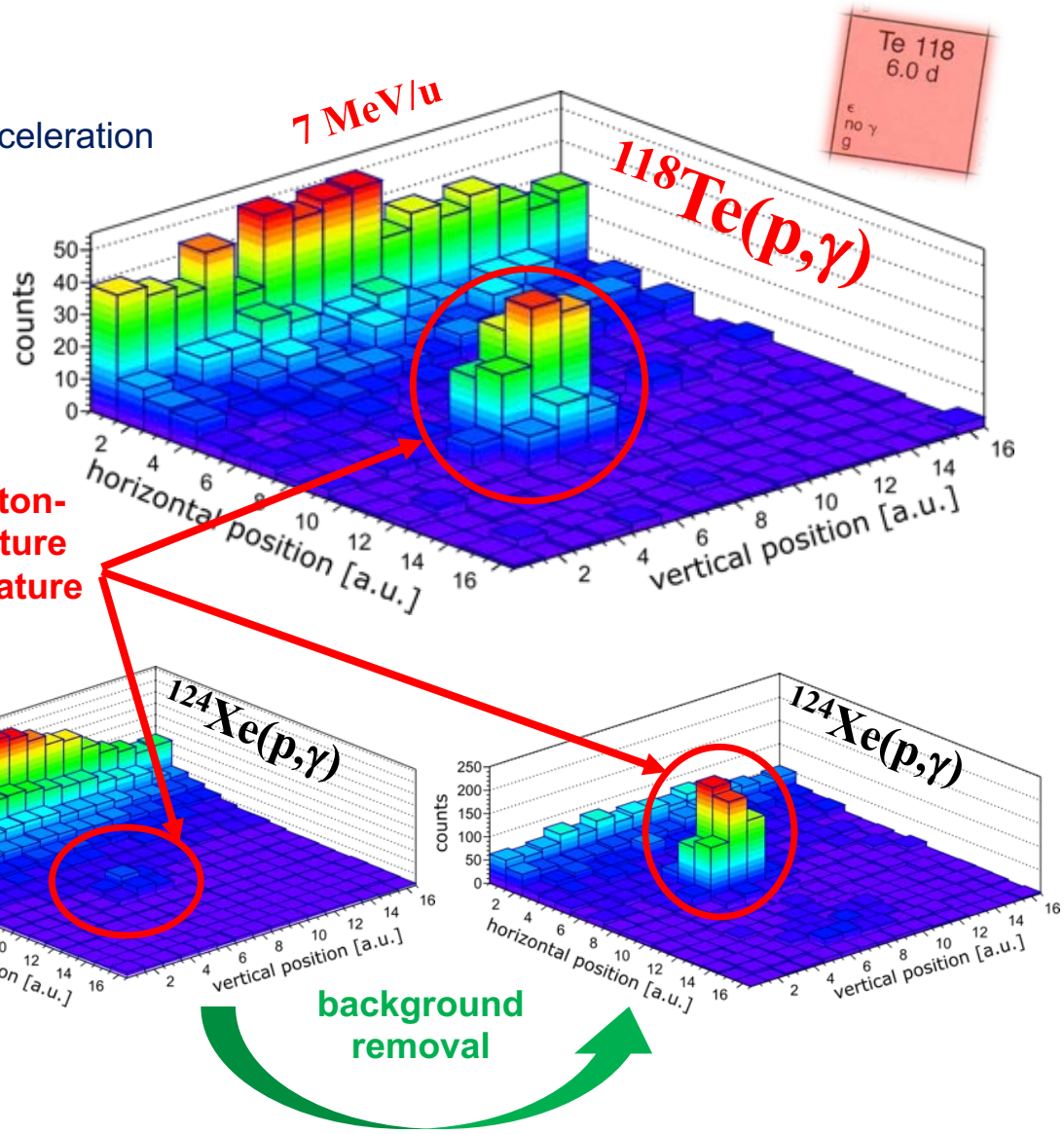
clear signatures with good statistics

new background-free detection method

maximized sensitivity for detection of proton-capture reactions

future prospects:

full access to Gamow window energies in CRYRING



FAIR Phase 0 Research Program

Federal Ministry of Education and Research

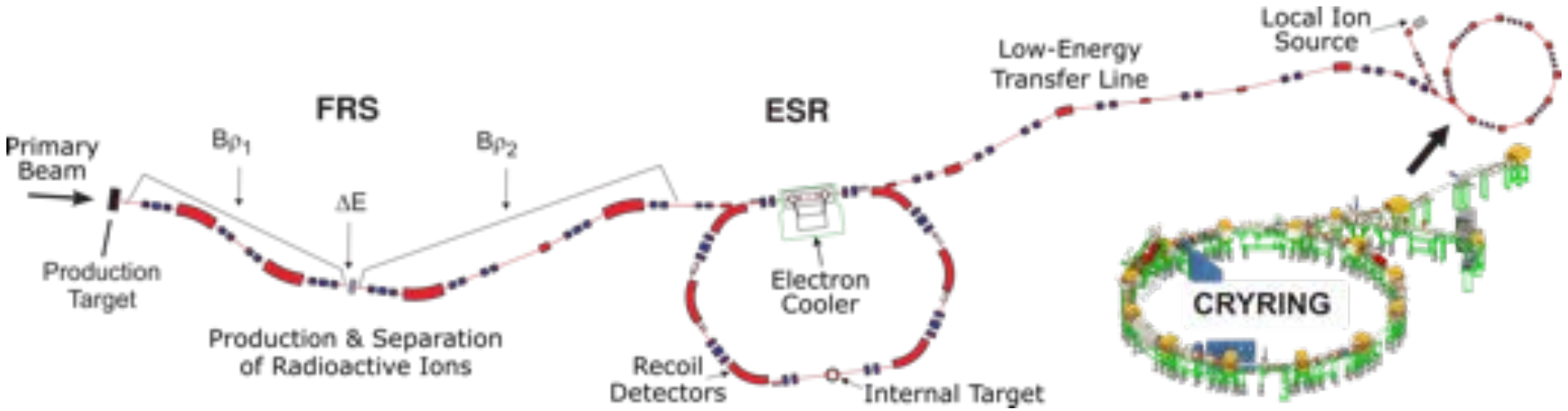
erc

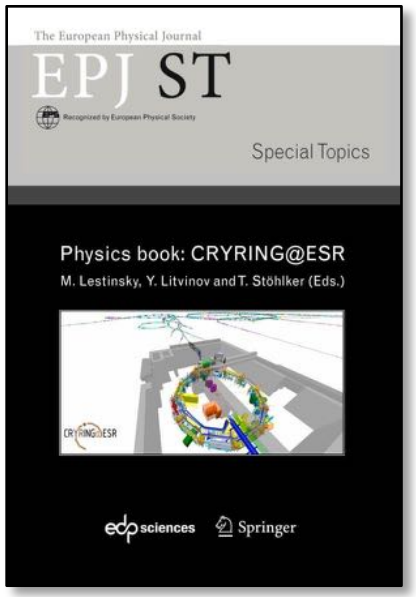
erc ASTRUm

Courtesy J. Glorius and L. Varga

HELMHOLTZ GSI

The CRYRING@ESR facility

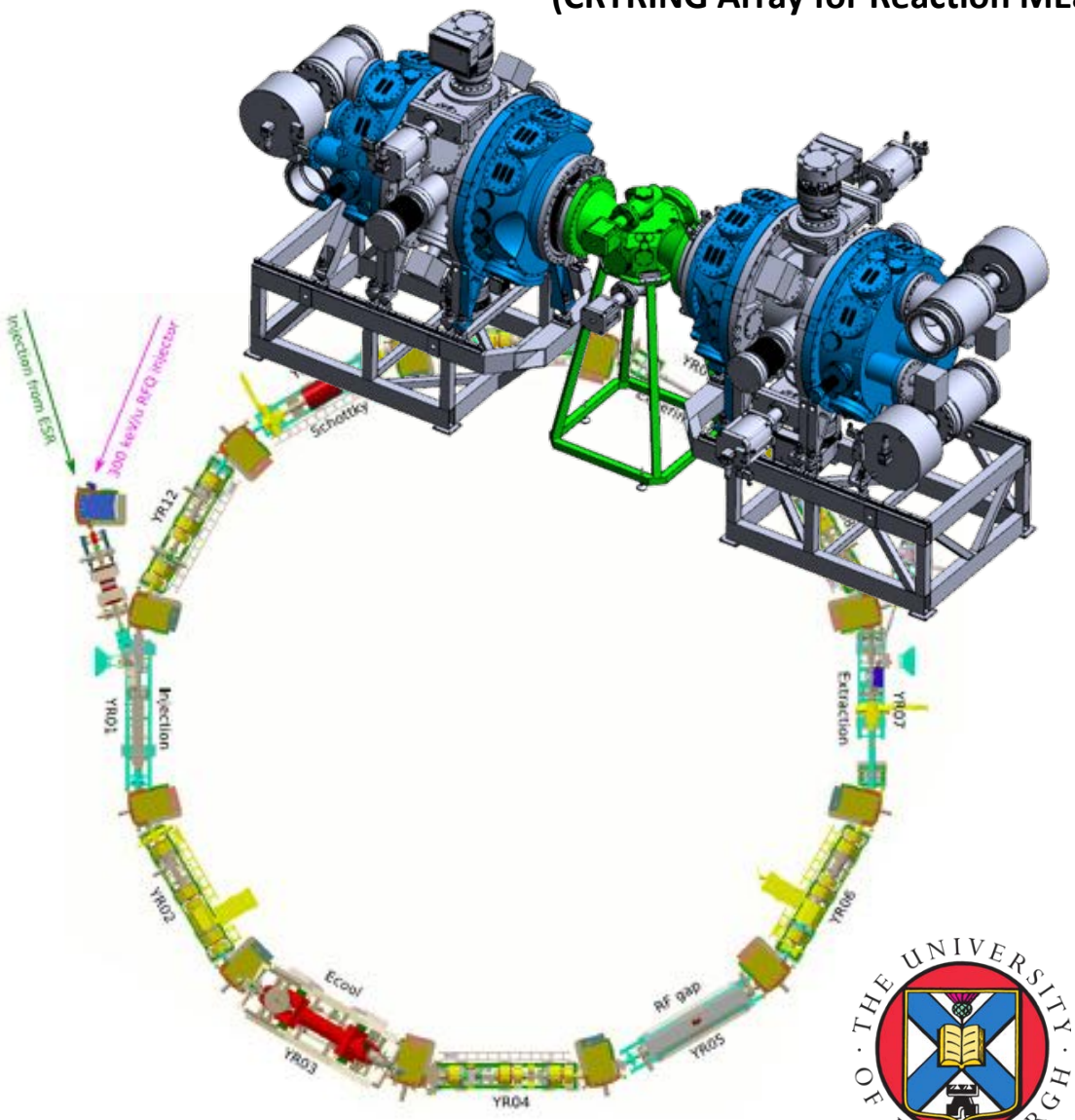




M. Lestinsky, GSI, Darmstadt

CARME @ CRYRING

(CRYRING Array for Reaction MEasurements)



Measure nuclear reactions directly at Big Bang energies

Novae physics

Reactions for p-process

Reactions for rp-process

.....

Neutron-induced reactions (surrogate method)

B. Jurado, ERC AG „NECTAR“

THE UNIVERSITY OF EDINBURGH

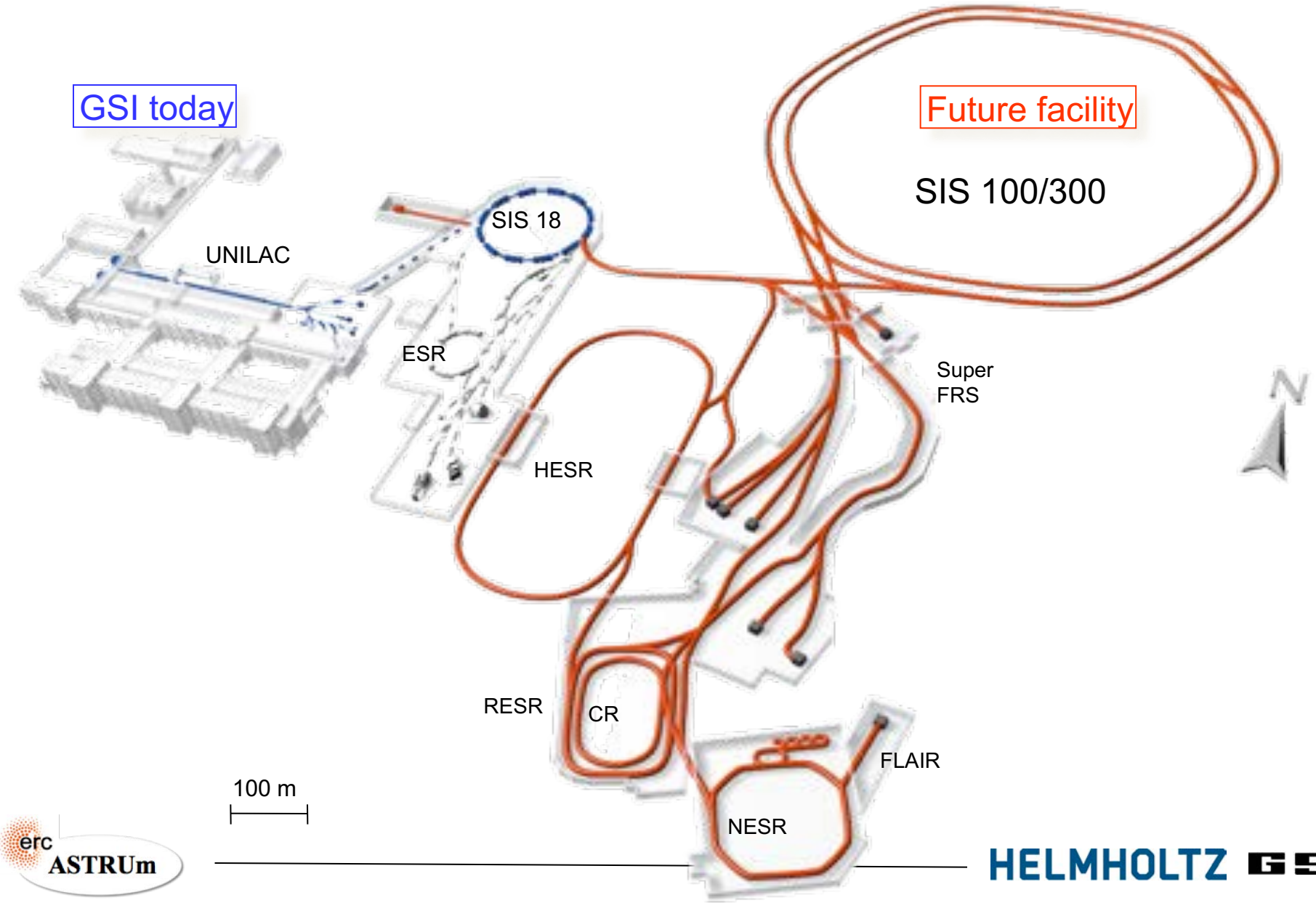
Science & Technology Facilities Council

erc ASTRUm

HELMHOLTZ GSI

Courtesy C. Bruno, T. Davinson, P. Woods

FAIR - Facility for Antiproton and Ion Research



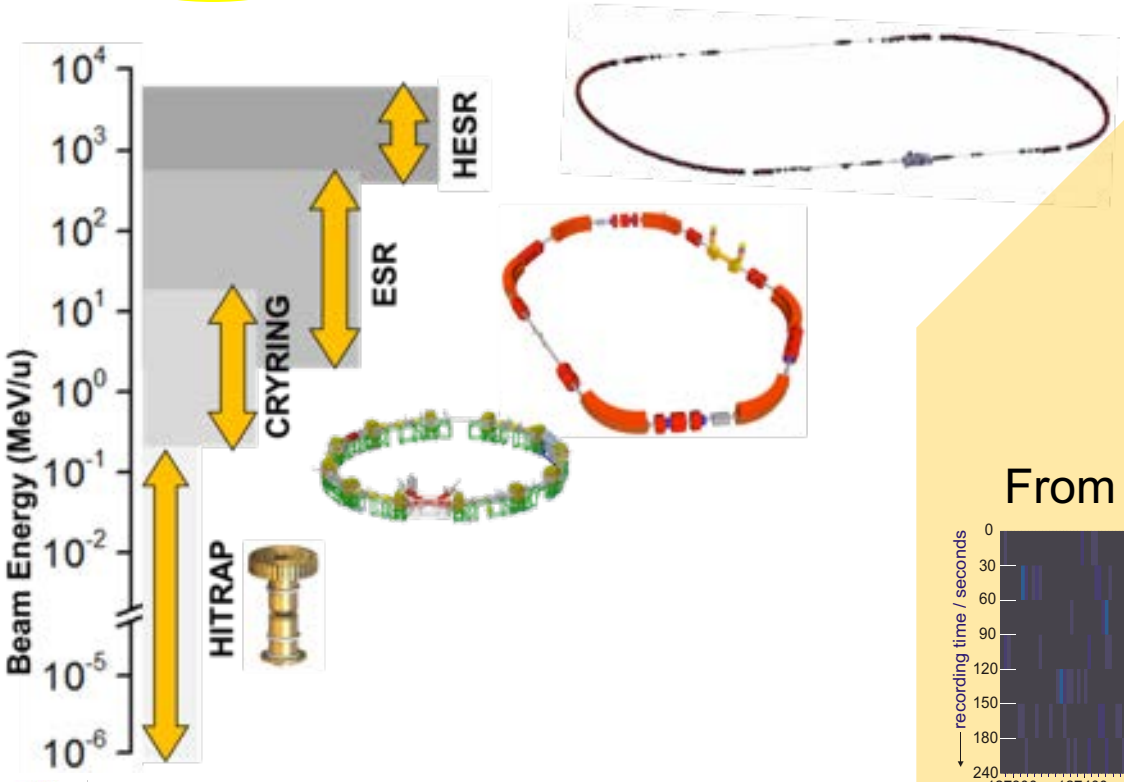
Ion Beam Facilities / Trapping & Storage

Worldwide Unique !

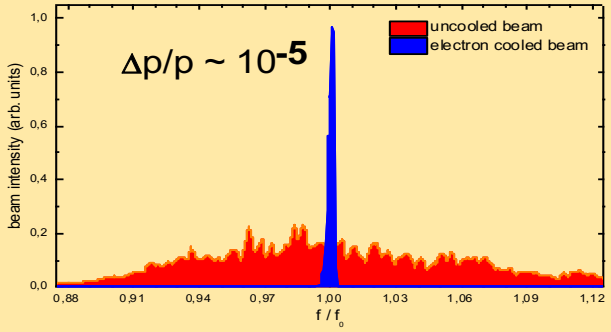
Stored and Cooled

Highly-Charged Ions (e.g. U^{92+}) and Exotic Nuclei

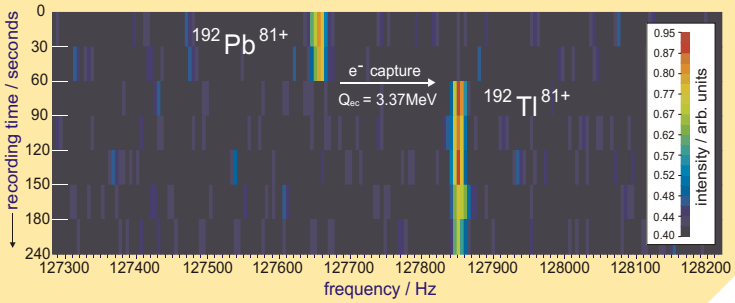
From Rest to Relativistic Energies (up to 4.9 GeV/u)



Cooling: The Key for Precision



From Single Ions to Highest Intensities



erc ASTRUm

HELMHOLTZ GSI

Many thanks to our collaborators from all over the world !!!

We are supported by:

European Research Council
Established by the European Commission

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

Bundesministerium
für Bildung
und Forschung