Future RIB facilities

(RIB= radioactive ion beam / rare isotope beam)

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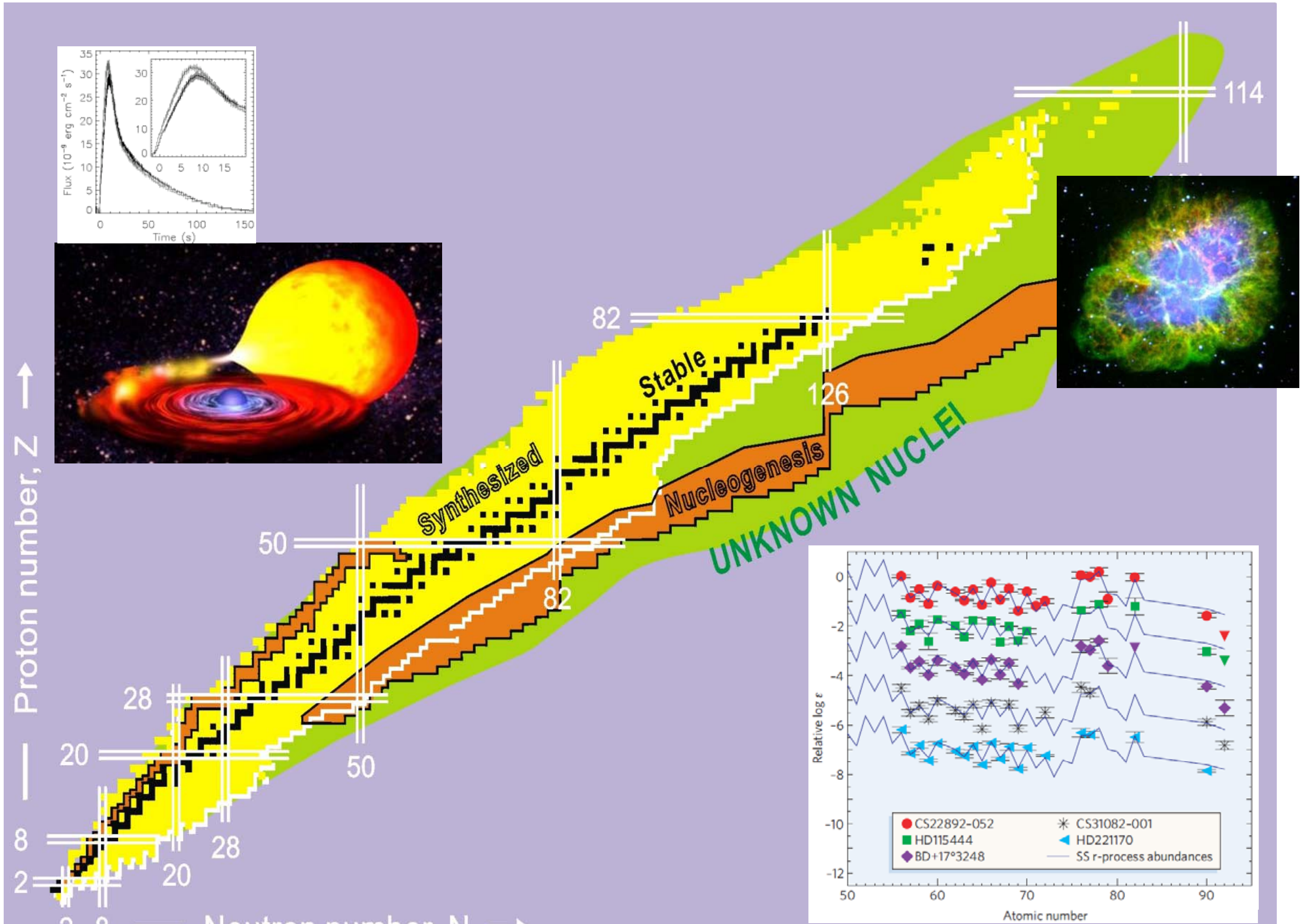
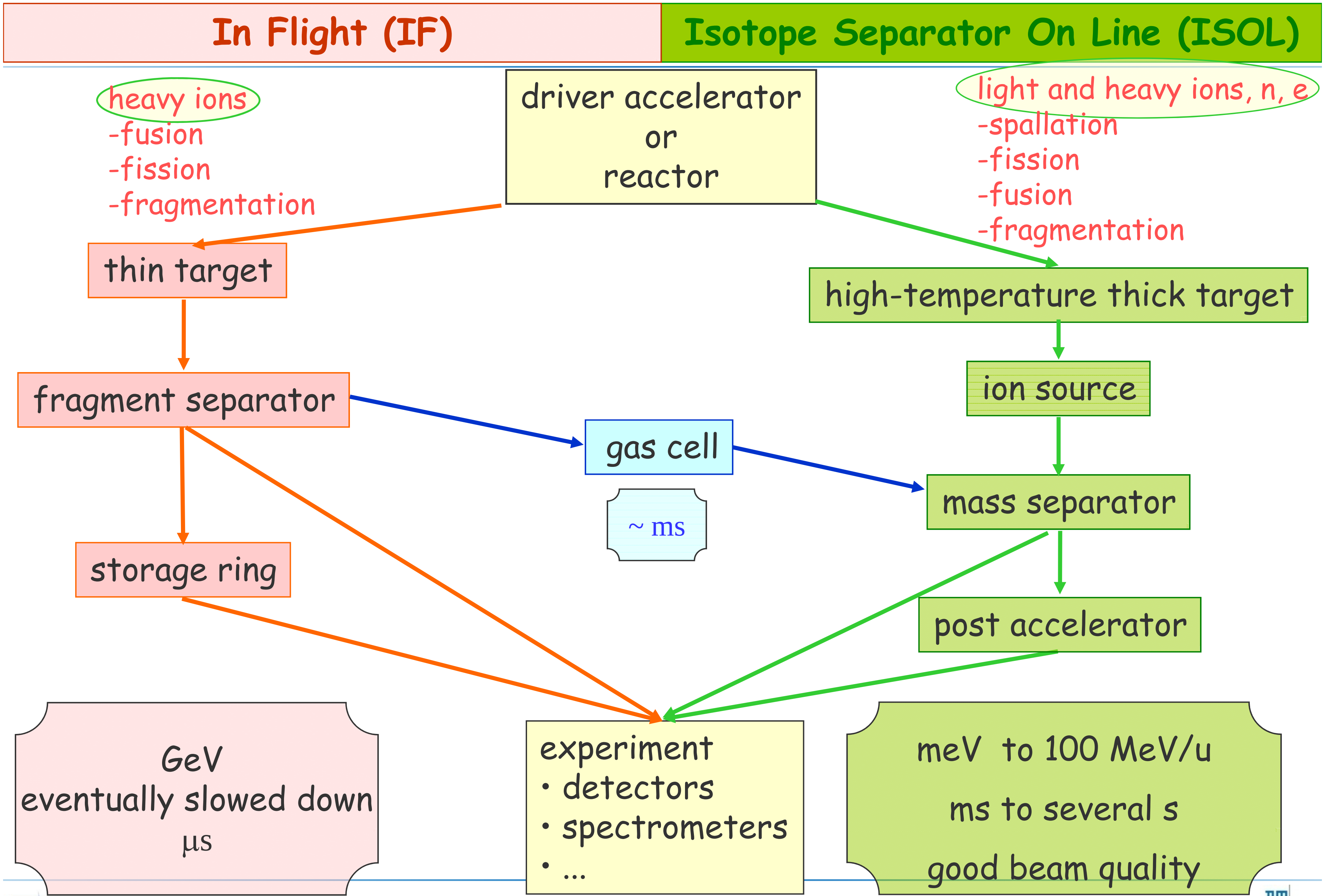
for Nuclear-, Particle-, and Accelerator-Physics

DFG Cluster of Excellence – Origin and Structure of the Universe

Exotic nuclei and explosive nucleosynthesis



J.J. Cowan, C. Sneden, Nature (2006)



From Mark Huyse

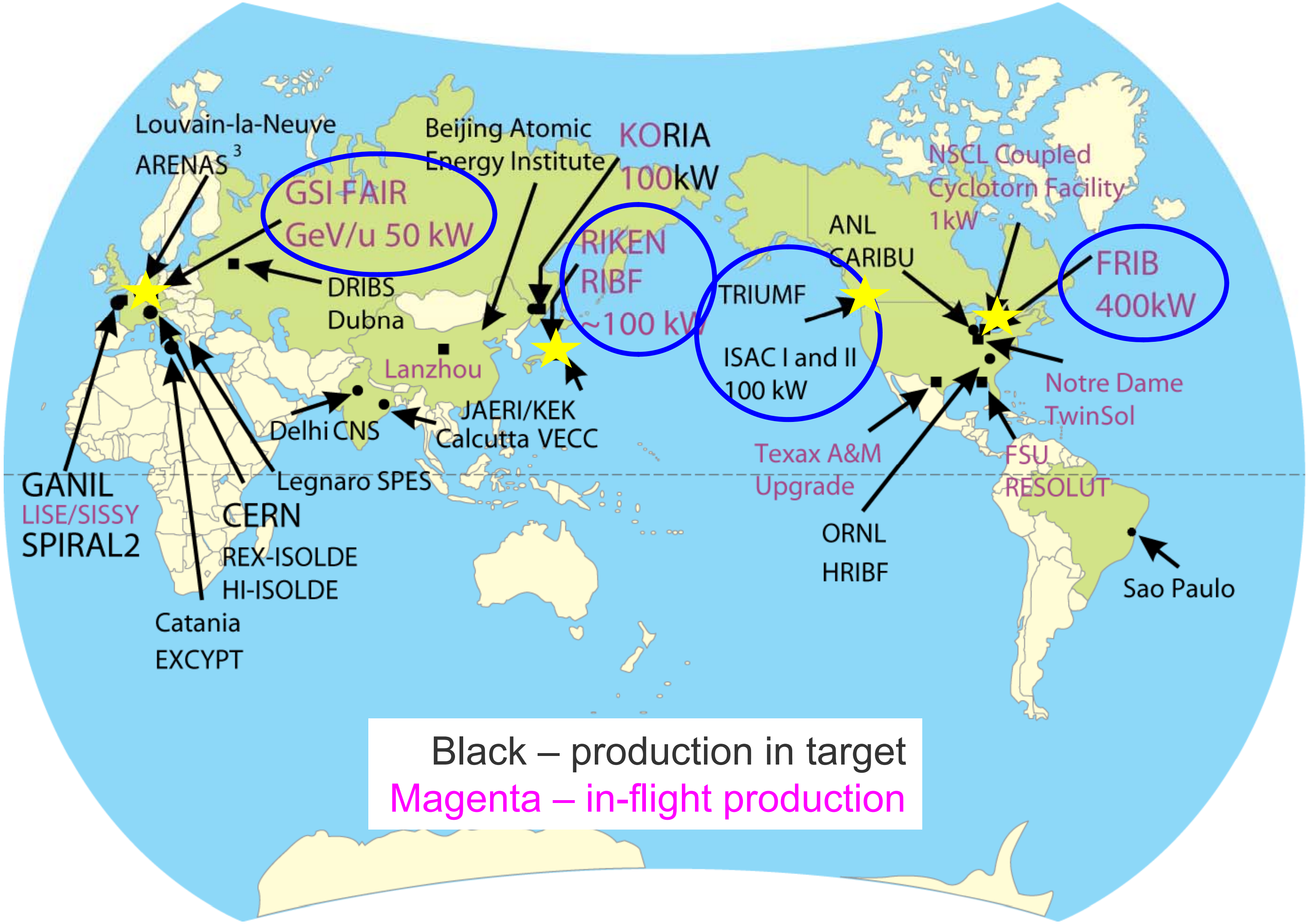
Nuclear Astrophysics at RIB facilities

- **Stopped beams** (all RIB facilities)
  - Ground state properties w/ traps and lasers (Masses, Spins, Moments, charge radii)
  - Decays properties (Half-life, GT-strength, P_n-values, proton decay branch)

- **Reaccelerated beams** (ISAC/ARIEL, HIE-ISOLDE, SPIRAL2, NSCL ReA3)
  - Direct measurement of reaction cross-sections and resonance properties
  - Indirect methods:
    - Trojan horse, surrogate reactions (d,pγ) for (n,γ)

- **Fast beams** (NSCL / FRIB, GSI / FAIR, RIBF, GANIL)
  - **Furthest reach out to very short lived nuclei, e.g. along r-process**
  - Matter radii e.g. via reaction cross-sections
  - GT strength from charge exchange reactions (t,^{3}He), (^{7}Li,^{7}Be)
  - Indirect methods to measure resonance properties and cross-sections
    - Coulomb dissociation (γ,n), (γ,p) and nuclear breakup reactions
  - Storage ring:
    - Masses from single ions, Mass surface
    - Reaction studies: e.g. charge exchange & capture,

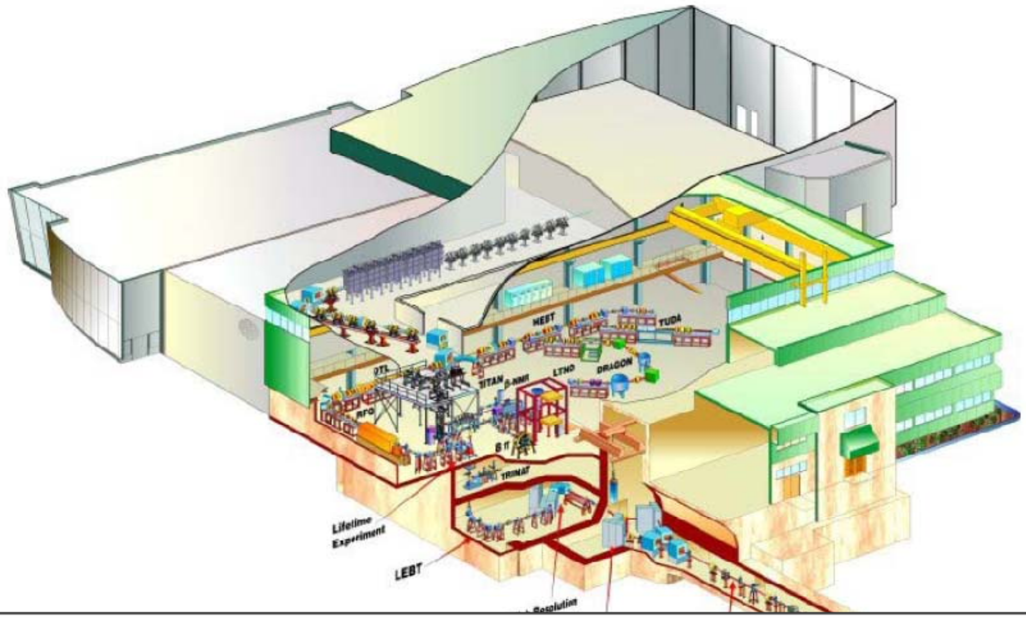
World view of rare isotope facilities



courtesy B. Sherrill

ISAC I & II @ TRIUMF (today)

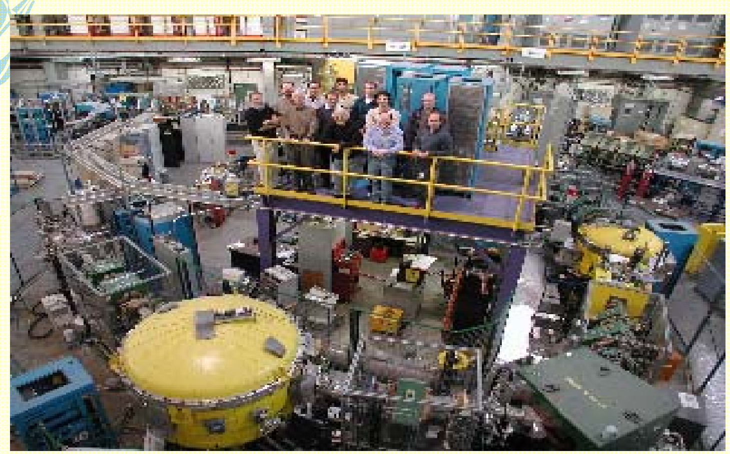
Technische Universität München



ISAC: 2nd generation facility
highest power on target for on-line facilities up to 100μA of 500MeV p
ISAC I: 60 keV & 1.3 AMeV
ISAC II: up to 4.3 AMeV

State-of-the-art facilities for Nuclear Astrophysics, Nuclear Structure, & Fundamental Symmetries:

DRAGON	8Pi
TUDA	HERACLES
EMMA	TIGRESS
TACTIC	Laser Spectroscopy
TITAN	TRINAT
DSL	EDM

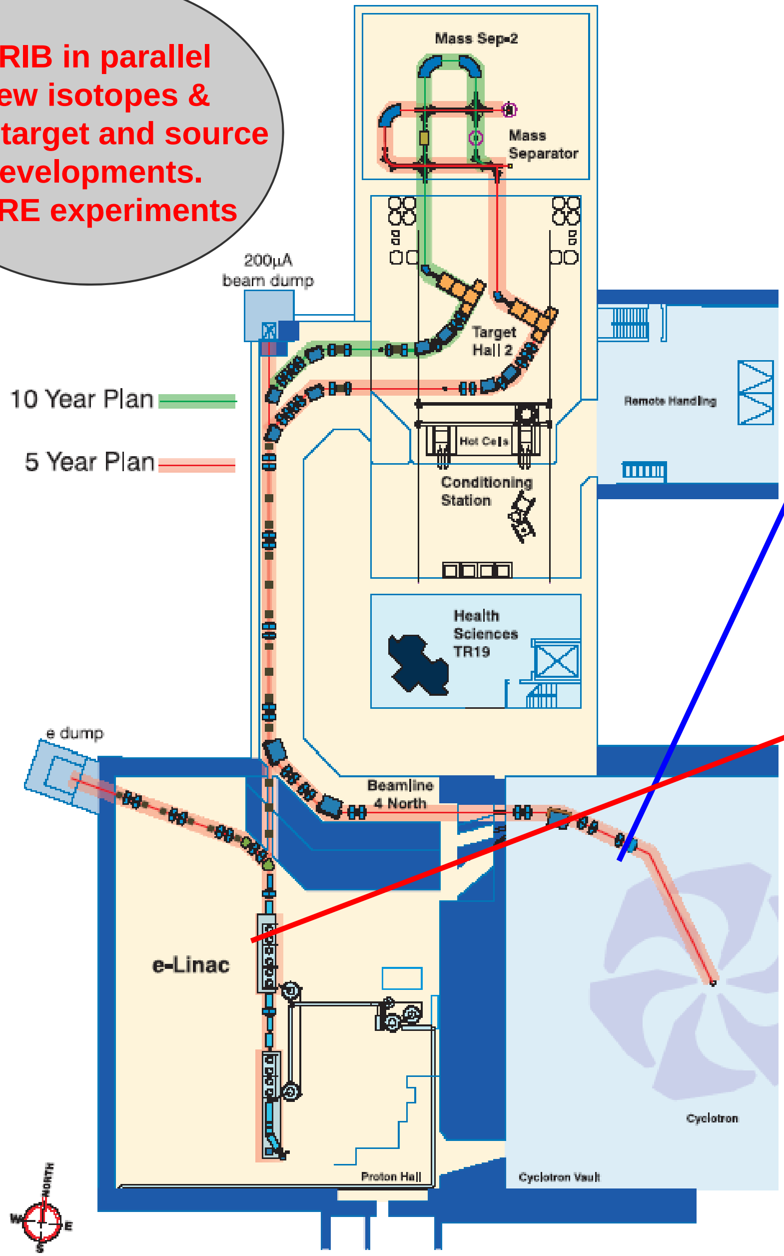


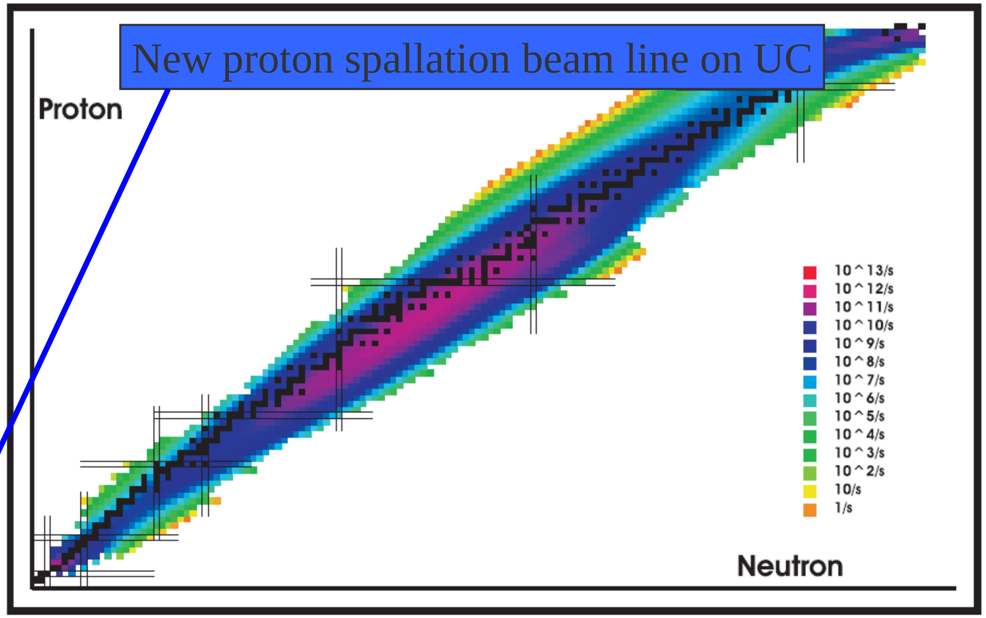
Astrophysics Highlights @ ISAC achieved:

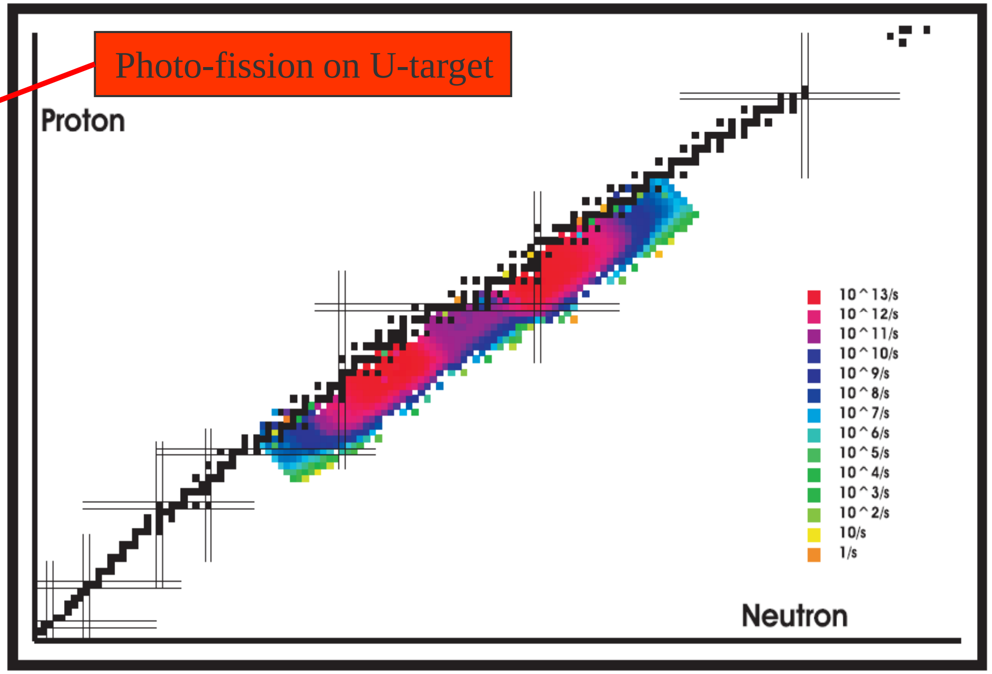
- **DRAGON**: (novae) ^{21}Na(p,γ)^{22}Mg, ^{26g}Al(p,γ)^{27}Si, ^{23}Mg(p,γ)^{24}Al, ^{33}S(p,γ)^{34}Cl (SN) ^{40}Ca(α,γ)^{44}Ti (quiescent) ^{12}C(α,γ)^{16}O *(s-proc.) ^{17}O(α,γ)^{21}Ne*
- **TUDA**: (novae) ^{21}Na(p,p)^{21}Na, ^{18}F(p,α)^{15}O
- **DSL**: (XRB) ^{19}Ne* lifetimes via DSAM
- **TIGRESS**: (novae): ^{20,21}Na Coulex

TRIUMF/ISAC future (2010-2020)

3 RIB in parallel
New isotopes &
more target and source developments.
MORE experiments







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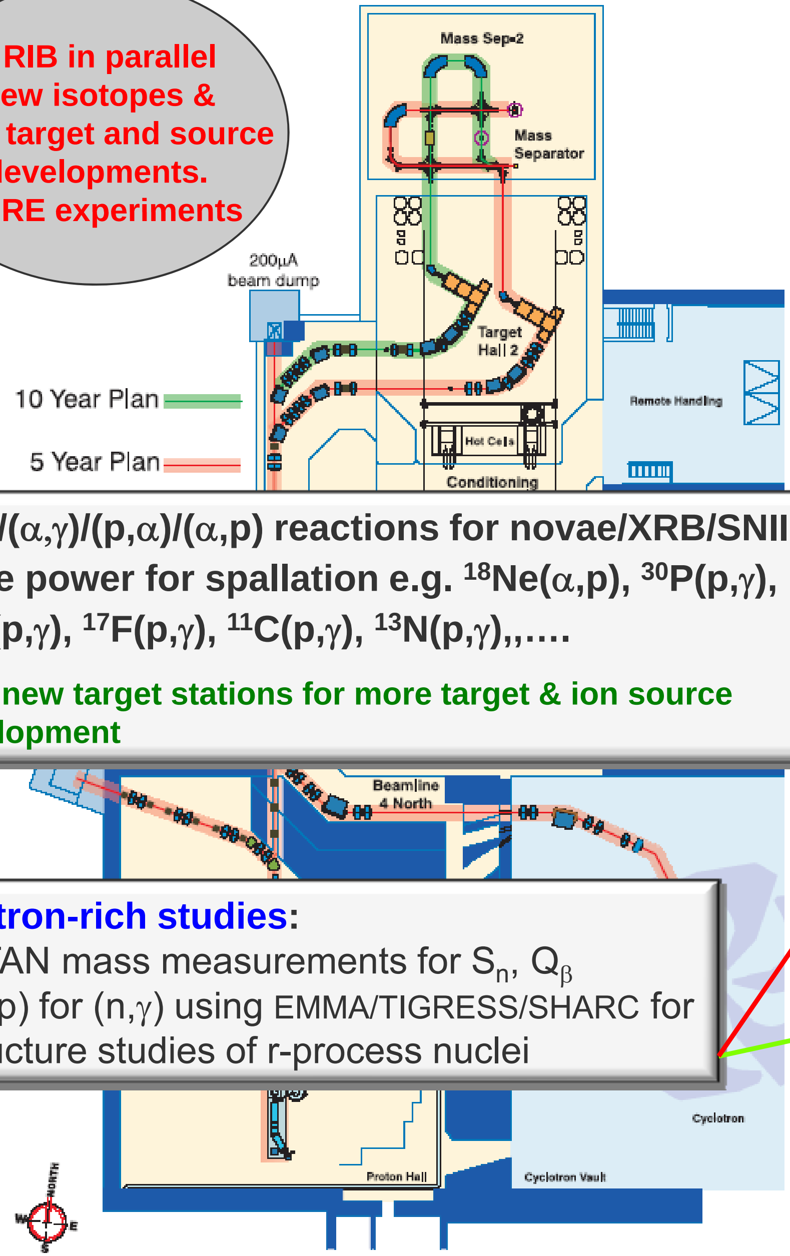
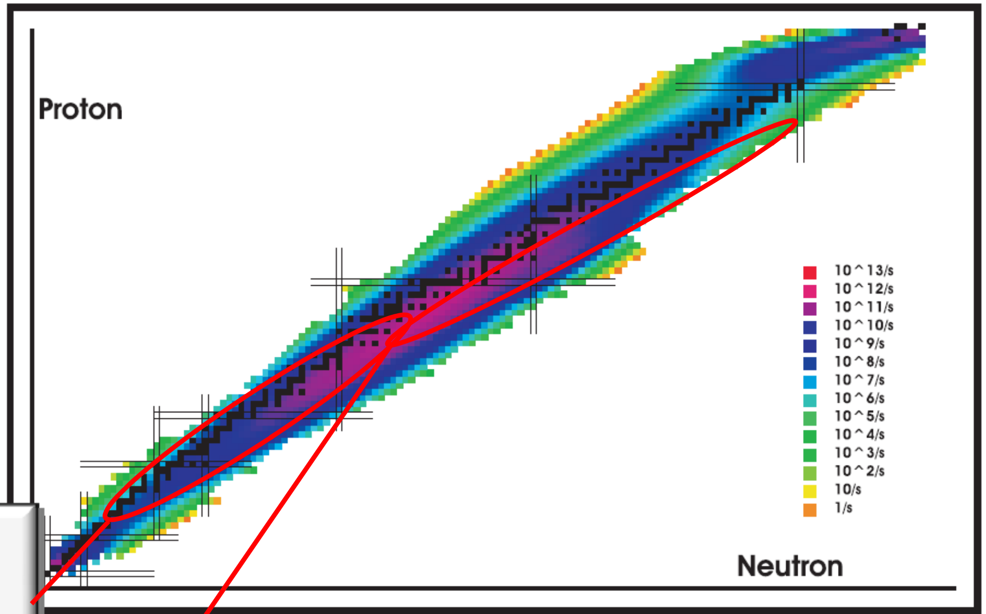
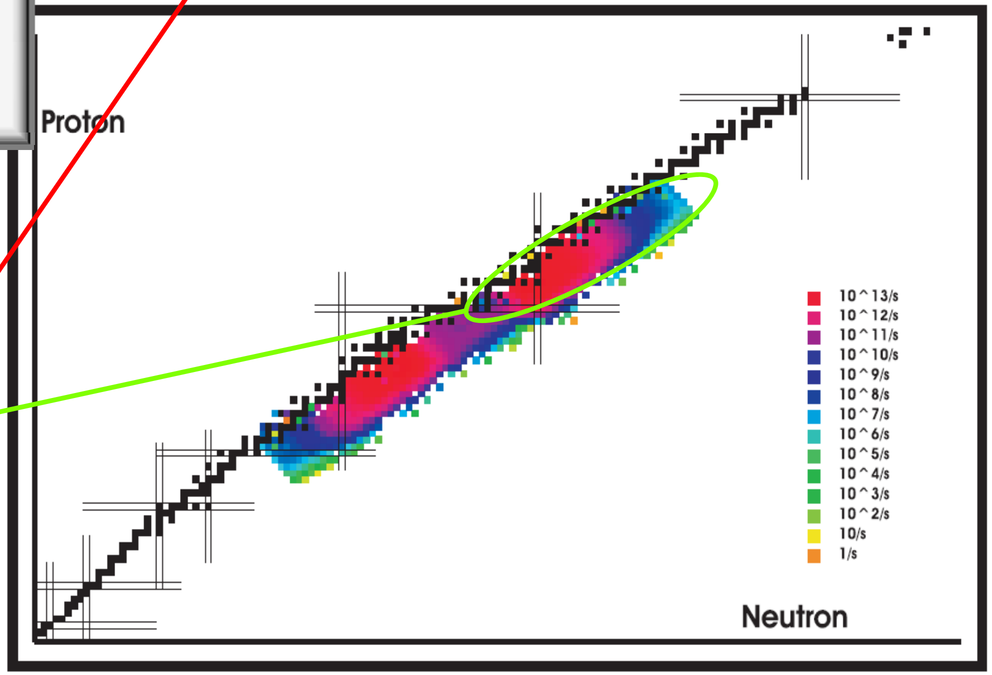


(p,γ)/(α,γ)/(p,α)/(α,p) reactions for novae/XRB/SNII
more power for spallation e.g. ^{18}Ne(α,p), ^{30}P(p,γ), ^{25}Al(p,γ), ^{17}F(p,γ), ^{11}C(p,γ), ^{13}N(p,γ),,….

AND new target stations for more target & ion source development

Neutron-rich studies:
- TITAN mass measurements for S_n, Q_β
- (d,p) for (n,γ) using EMMA/TIGRESS/SHARC for structure studies of r-process nuclei





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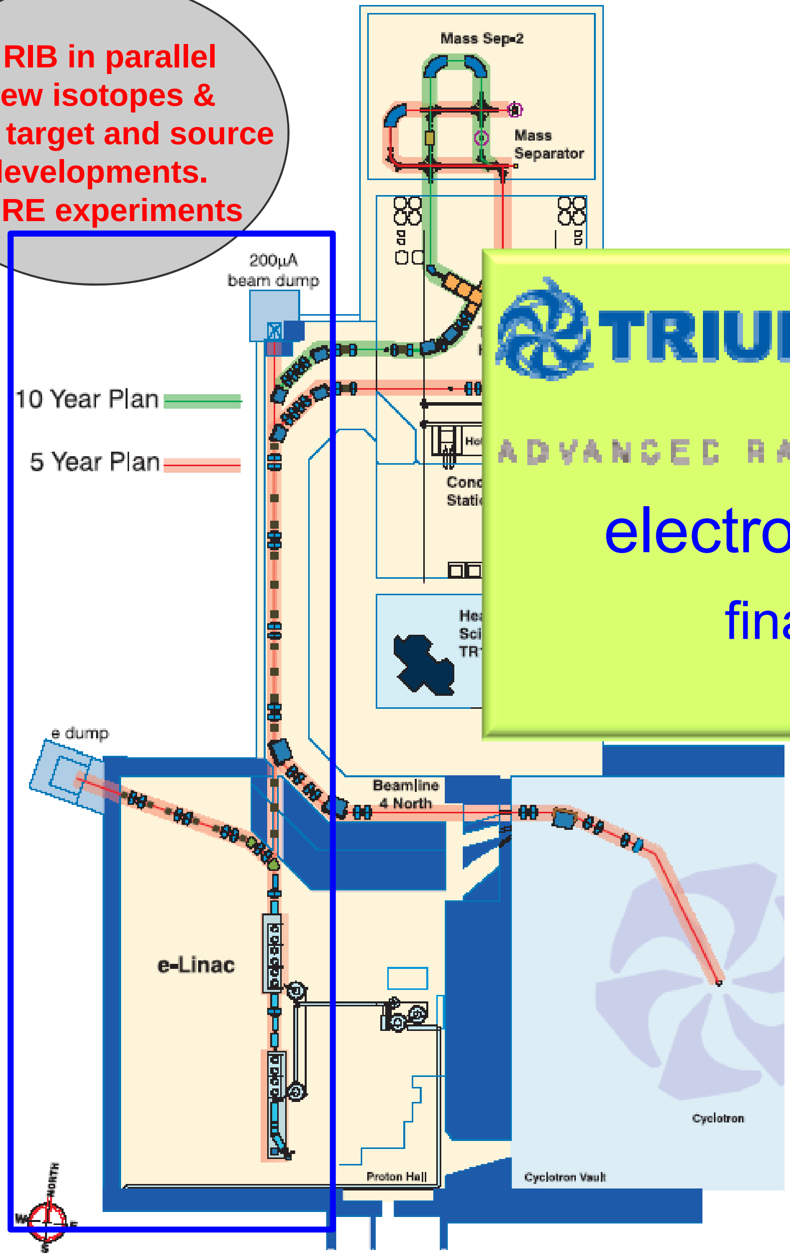
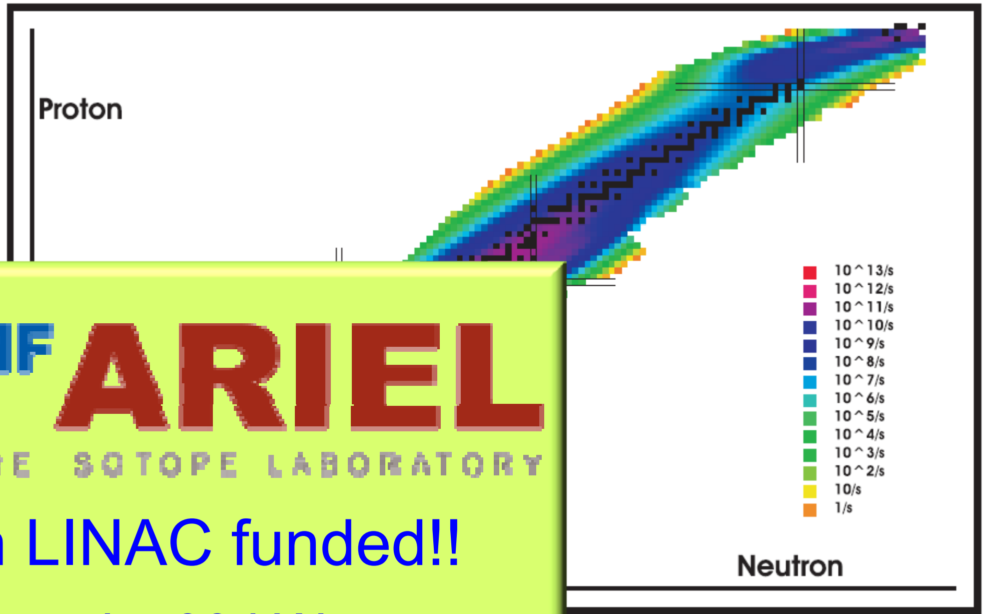
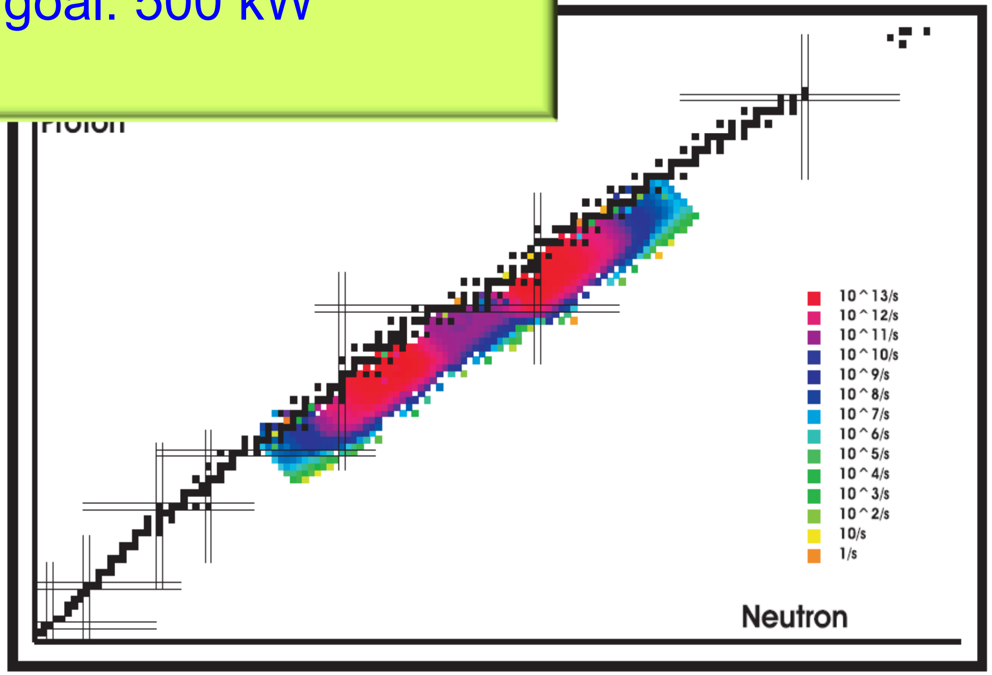


TRIUMF ARIEL
ADVANCED RARE ISOTOPE LABORATORY

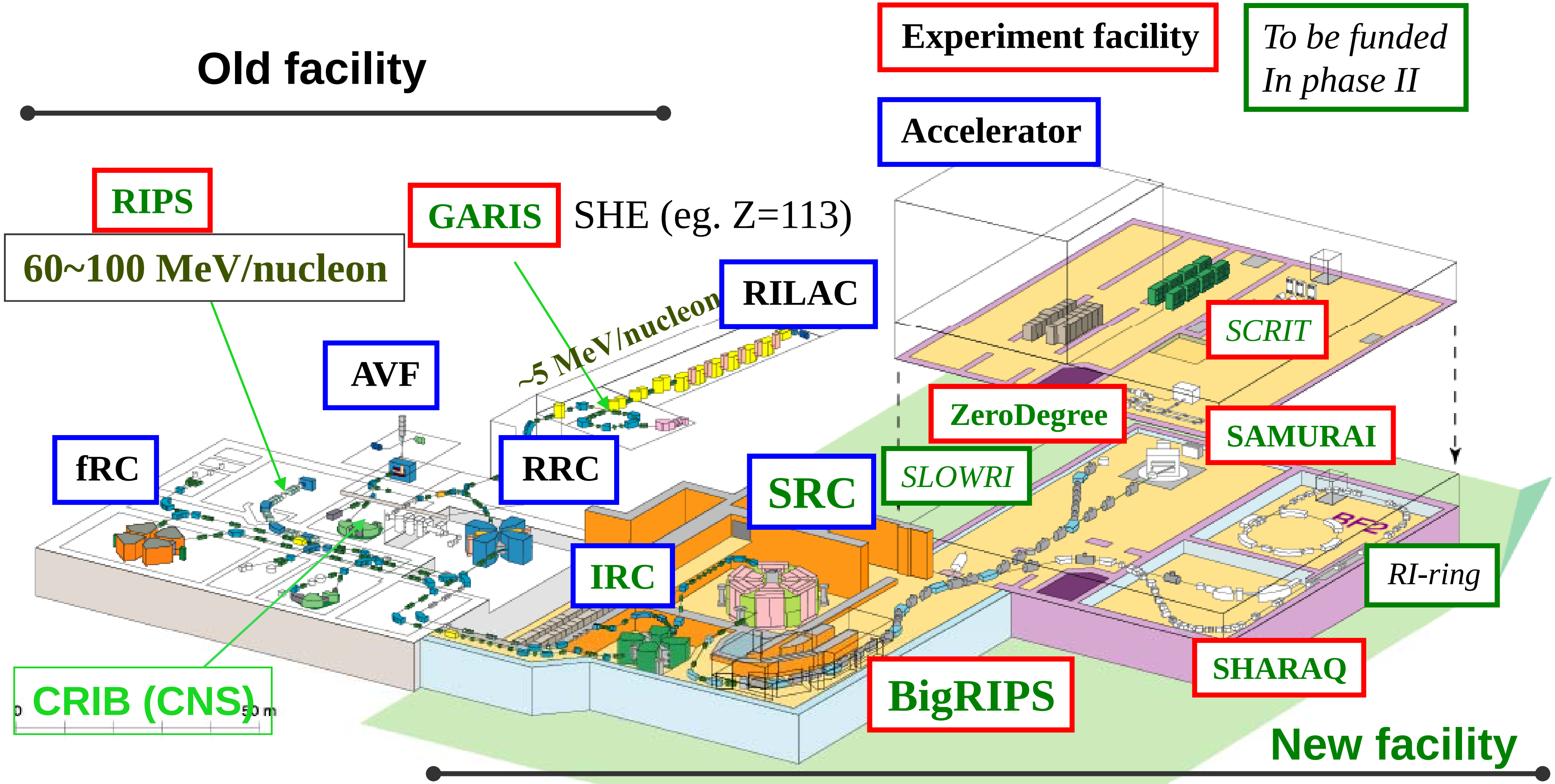
electron LINAC funded!!

final goal: 500 kW





RIKEN RI Beam Factory (RIBF)



- Intense (80 kW max.) H.I. beams (up to U) of 345*A*MeV at SRC
- Fast RI beams by projectile fragmentation and U-fission at BigRIPS
- Operation since 2007

Courtesy T. Motobayashi

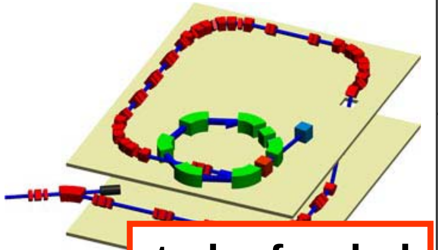
New Devices of RIBF

To maximize the potentials of intense RI beams available at RIBF

for several 100 – 1000 species

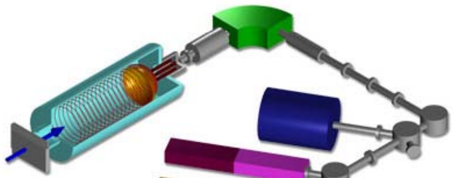
- mass
- half-life
- excited states
- deformation
- charge radii
- matter radii
- charge distribution
- matter distribution
- EM moments
- single particle states
- astrophysical reactions
- giant resonances
- exotic modes
- HI collisions (EOS)

Rare RI ring



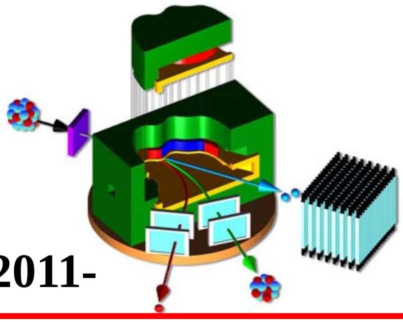
to be funded

SLOWRI



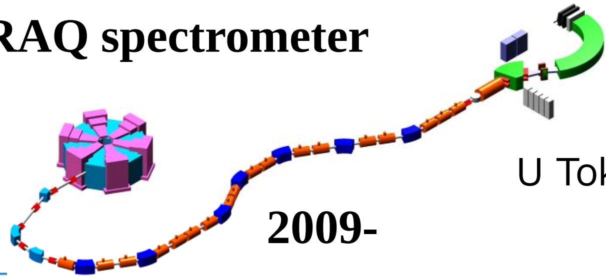
to be funded

SAMURAI



2011-

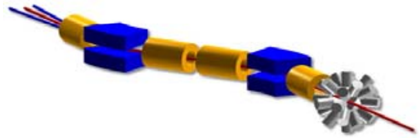
SHARAQ spectrometer



U Tokyo

2009-

ZeroDegree

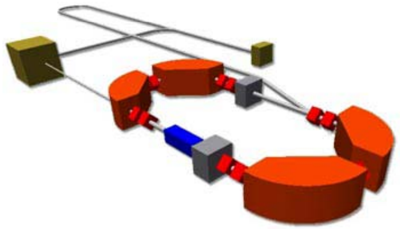


2008-

IRC-to-RIPS BT

to be funded

SCRIT



2010-

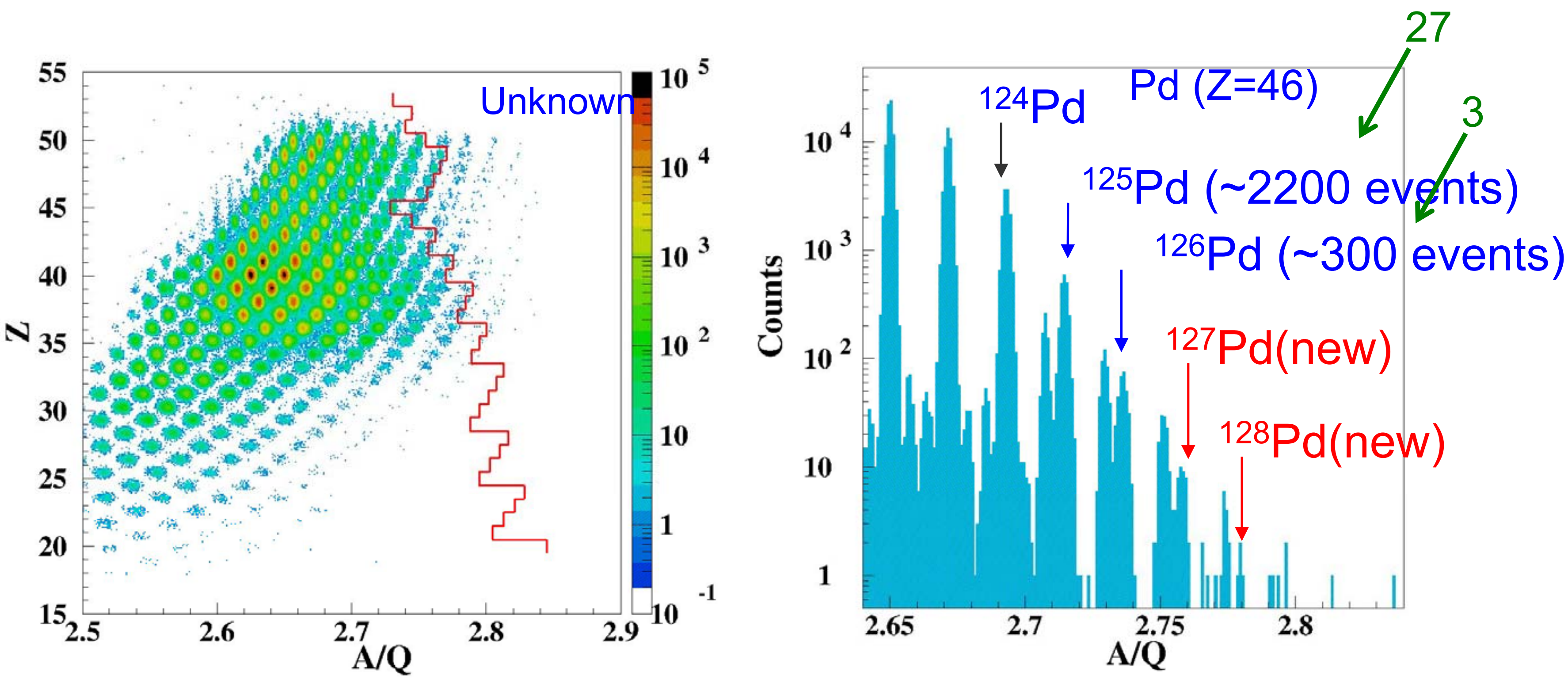
New isotope search using a ^{238}U beam at BigRIPS

Nov. 2008

U-beam intensity (averaged)

~1.8 x 10^9 pps (Nov. 2008) ← 4 x 10^7 pps (2007)

➔ decay studies



Onishi et al., JPSJ 79 (10)

Motobayashi, Kubo

New isotope search using a ^{238}U beam at BigRIPS

U-beam intensity (averaged)

Nov. 2008

27

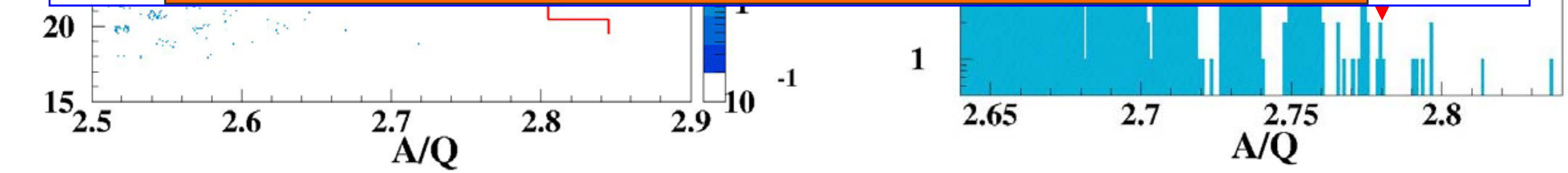
3

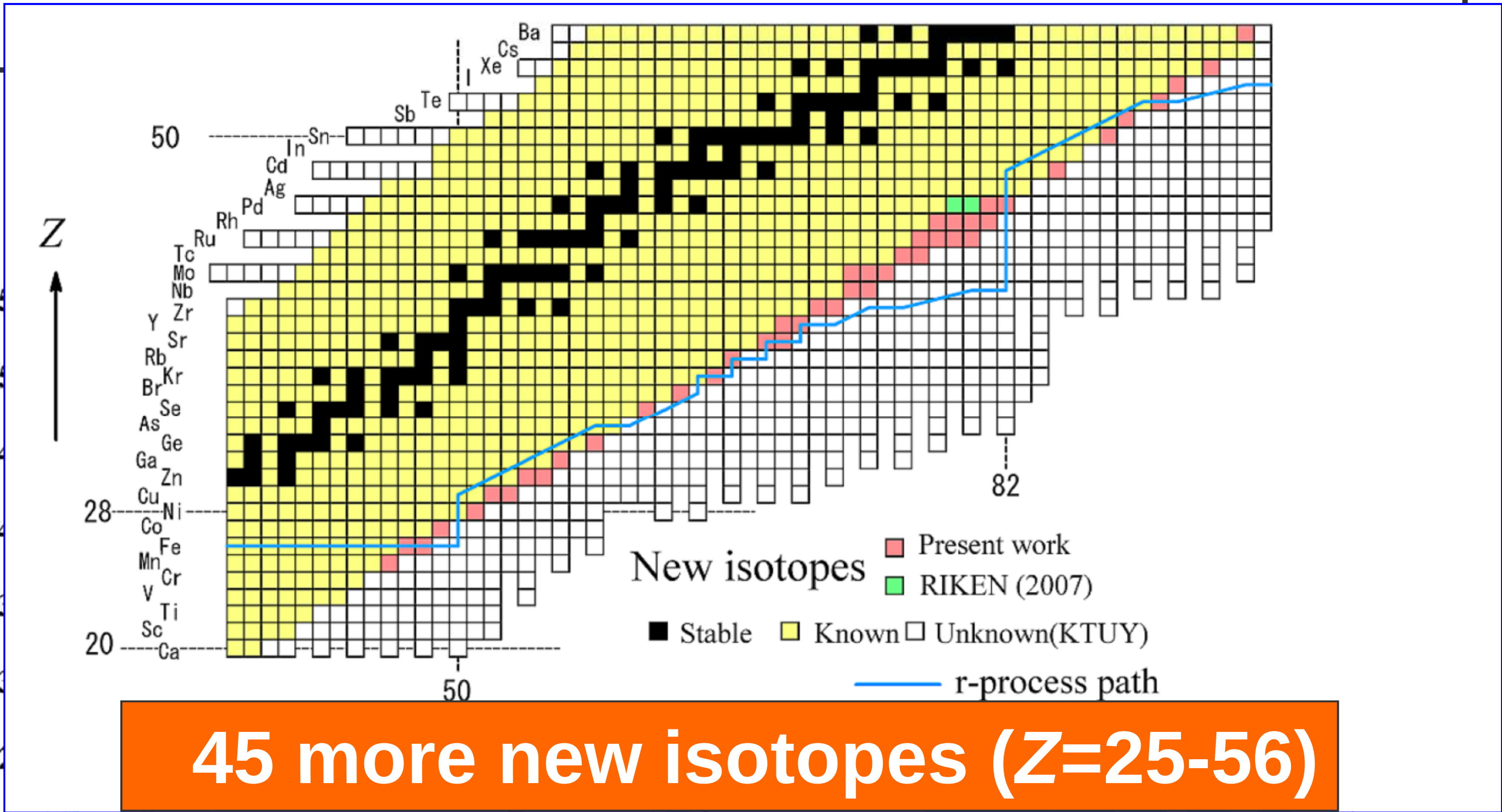
events)

0 events)

)

ew)





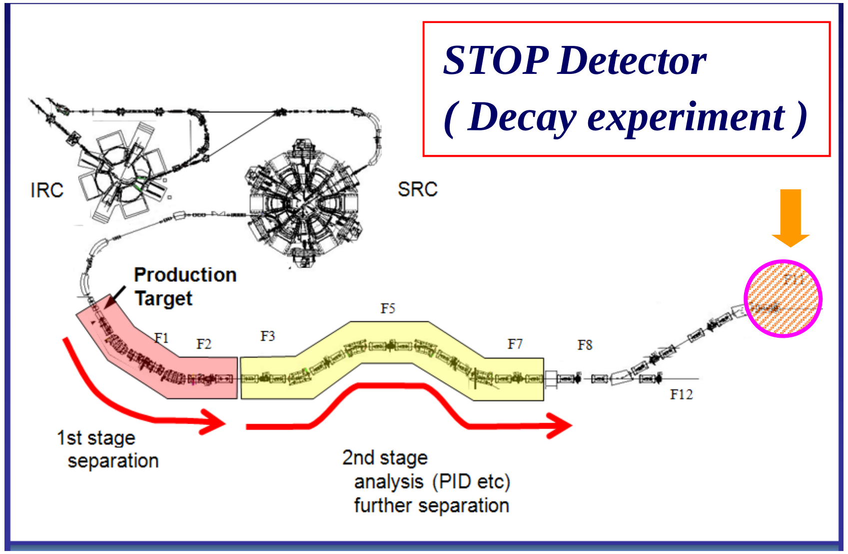
45 more new isotopes (Z=25-56)

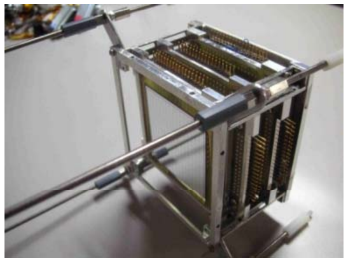
Onishi et al., JPSJ 79 (10)

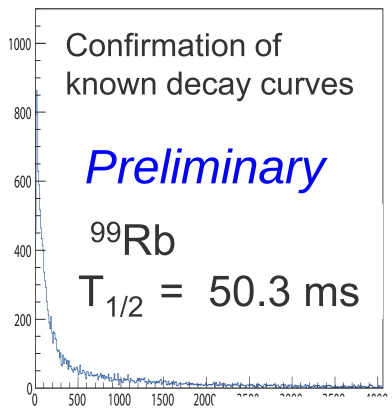
Motobayashi, Kubo

Decay curves & new half-lives

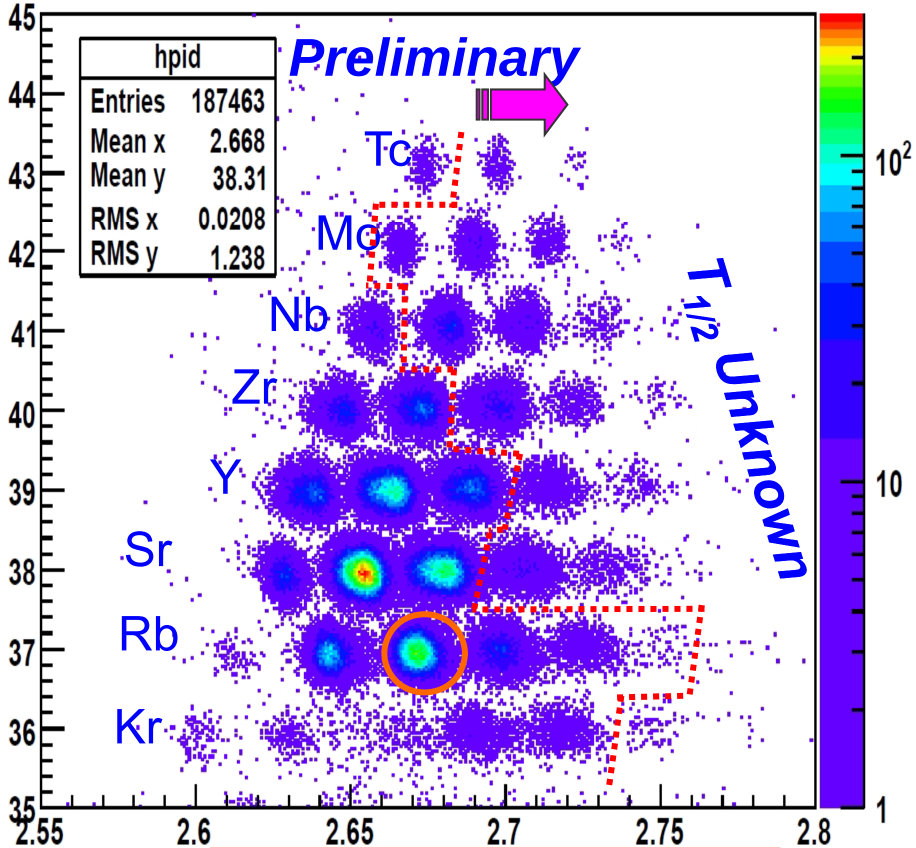
Event by event association
between RI implantation and beta-decay







8 hours
Low implantation rate : 5 ~ 10 cps



Data is under analysis

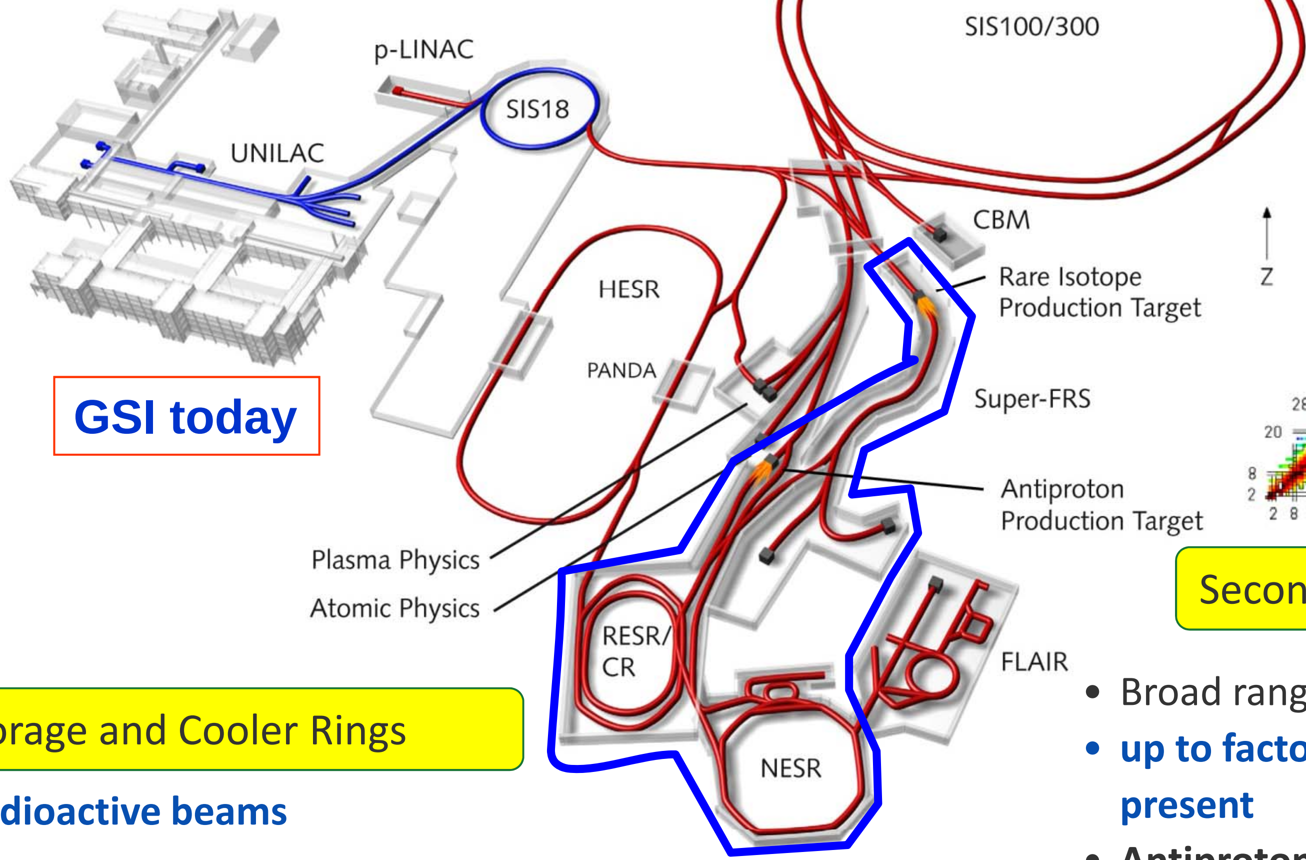
Courtesy T. Motobajashi, S. Nishimura

NuSTAR at the Facility for Antiproton and Ion Research

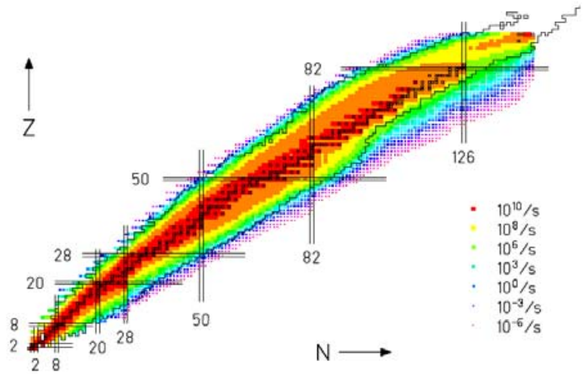
Primary Beams

- **protons to Uranium (5·10^{11} pps)**
- **up to 1.5 A.GeV beam energy**
- **Factor 100-1000 over present intensity**

Future Facility



GSI today



Storage and Cooler Rings

- **Radioactive beams**
- **e$^-$ - nucleus and Antiproton-nucleus collider**

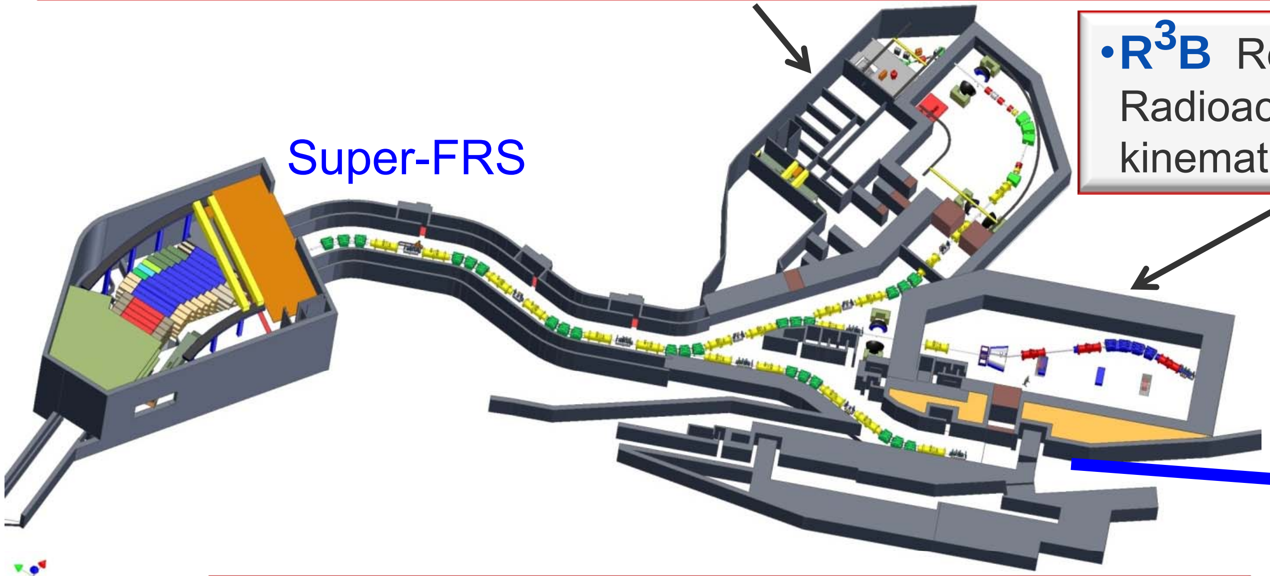
Secondary Beams

- Broad range of **radioactive beams**
- **up to factor 10 000 in intensity over present**
- **Antiprotons**

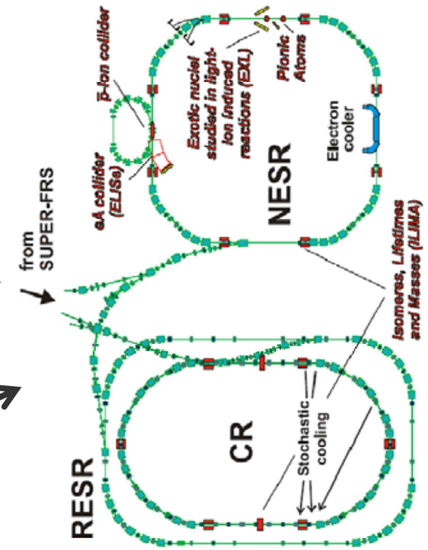
NuSTAR Experiments

LEB experiments:

- **HISPEC:** In-Flight Spectroscopy
- **DESPEC:** Decay Spectroscopy
- **MATS:** Penning trap system (Masses, Trap Assisted Spectroscopy)
- **LASPEC:** LASER Spectroscopy (Spins, Moments, isotope shifts)



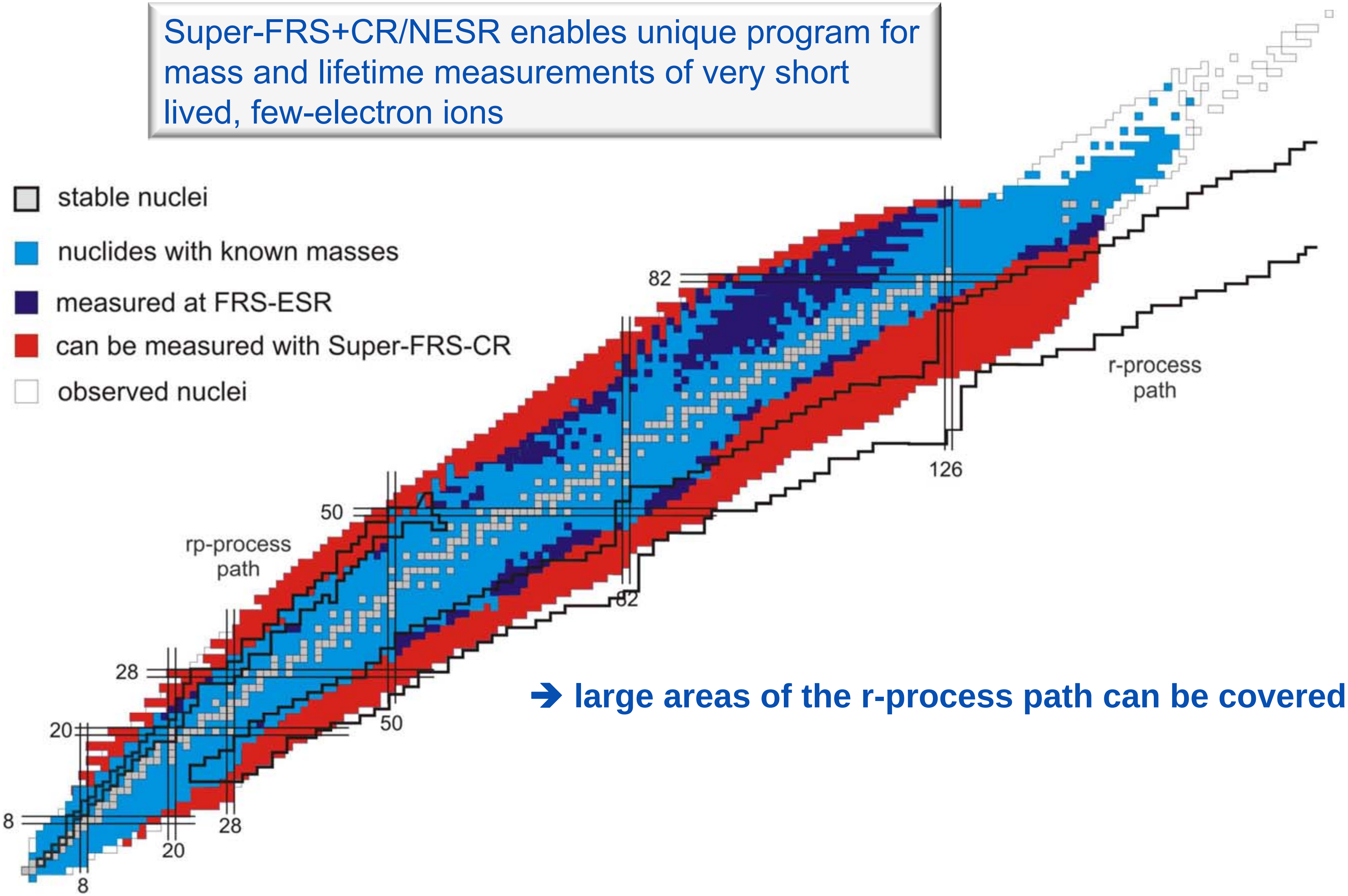
- **R^3B** Reactions with Relativistic Radioactive Beams in complete kinematics



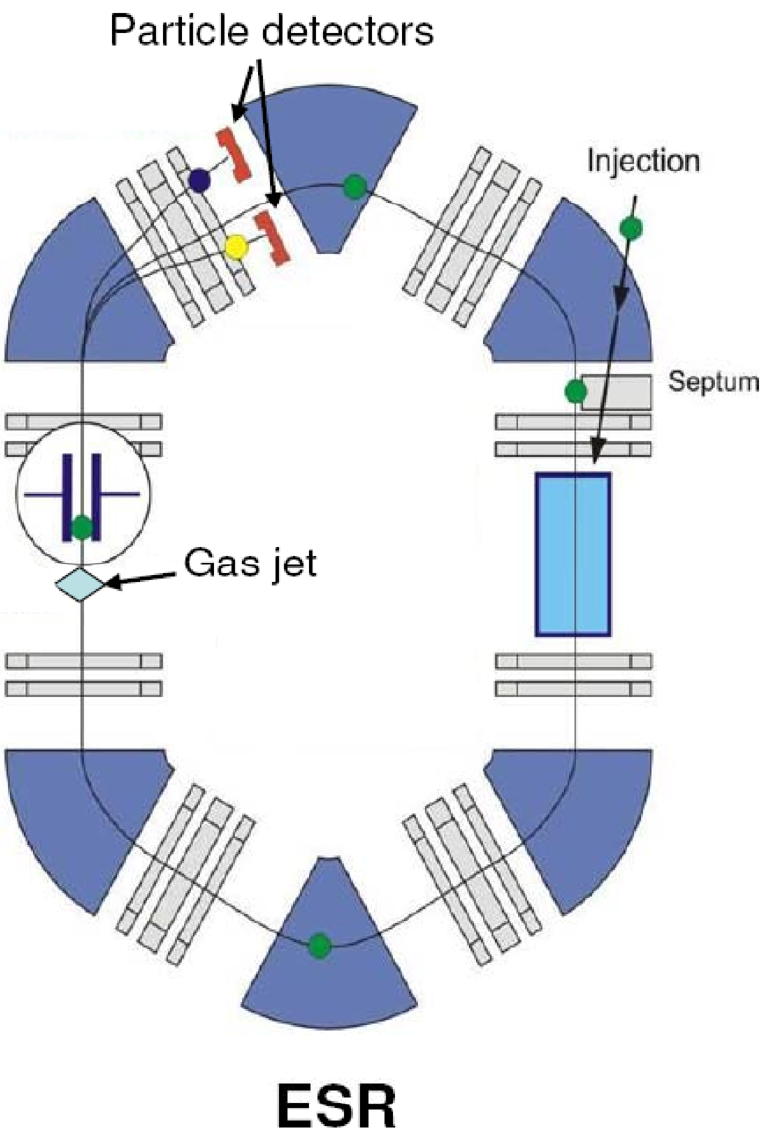
- **ILIMA** Masses and Half-lives for short-lived ions
- **EXL** Reactions on internal target
- **ELISe** Electron Ion Collider

ILIMA

Super-FRS+CR/NESR enables unique program for mass and lifetime measurements of very short lived, few-electron ions

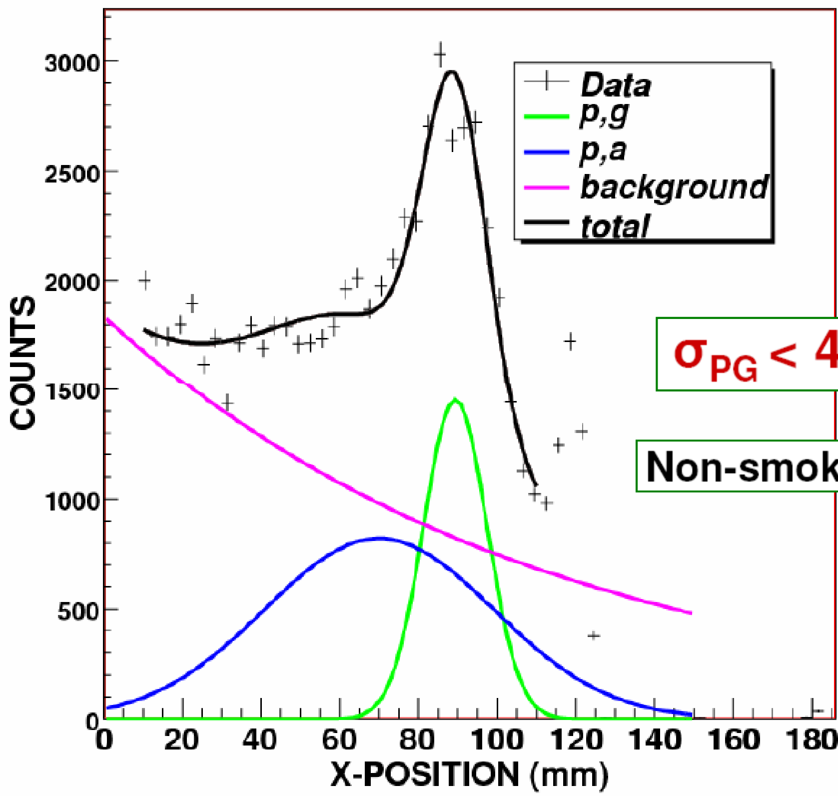


➔ **large areas of the r-process path can be covered**



Measurements of (p,γ) or (α,γ) rates in the Gamow window of the p-process in inverse kinematics.

$^{96}Ru(p,\gamma)^{97}Rh$ 11 AMeV



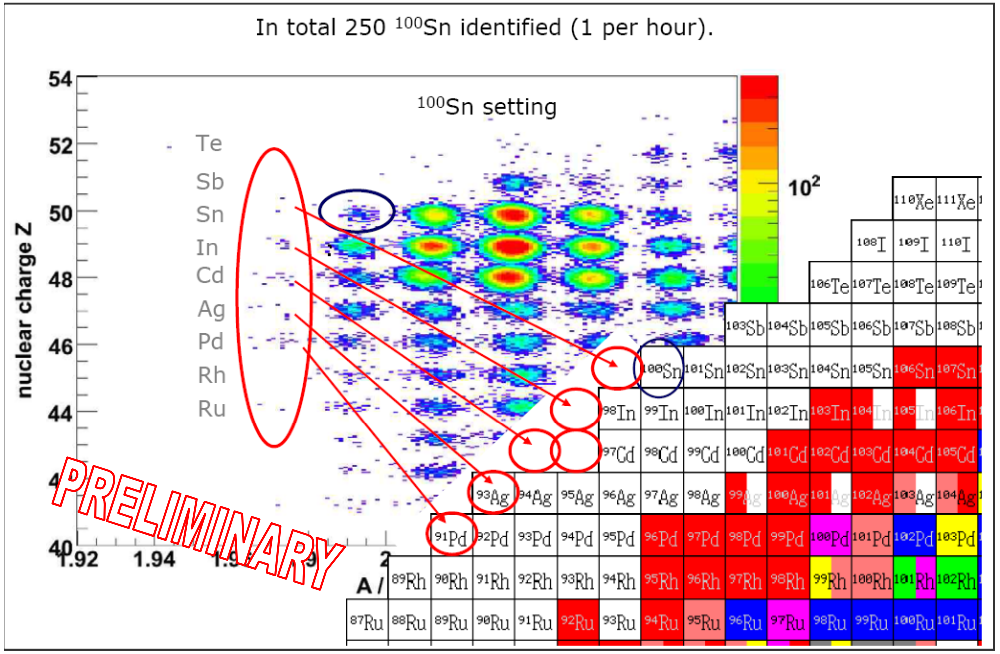
$\sigma_{PG} < 4.0$ mb

Non-smoker: 3.5 mb

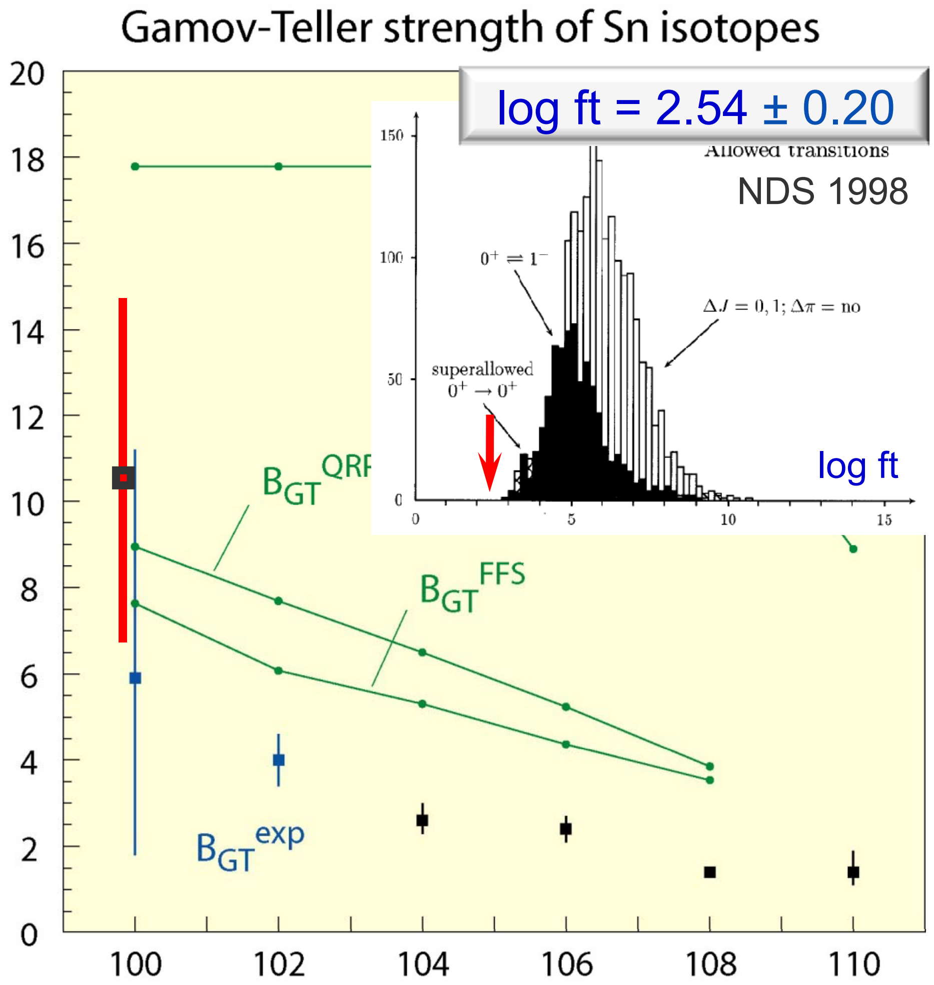
Decay of ^{100}Sn

- ~ 250 ^{100}Sn observed (1/hour)
- Several new isotopes discovered: (^{99}Sn), ^{97}In, ^{95,96}Cd

➔ information on GT strength & rp-process



GSI FRS + RISING gamma spectrometer
+ SIMBA implantation detector (TUM)



A. Stolz et al., 2001 A. Bobyk & W. Kaminski, 2000

Smallest known log ft value!!

Dipole Excitations of Neutron-Rich Nuclei

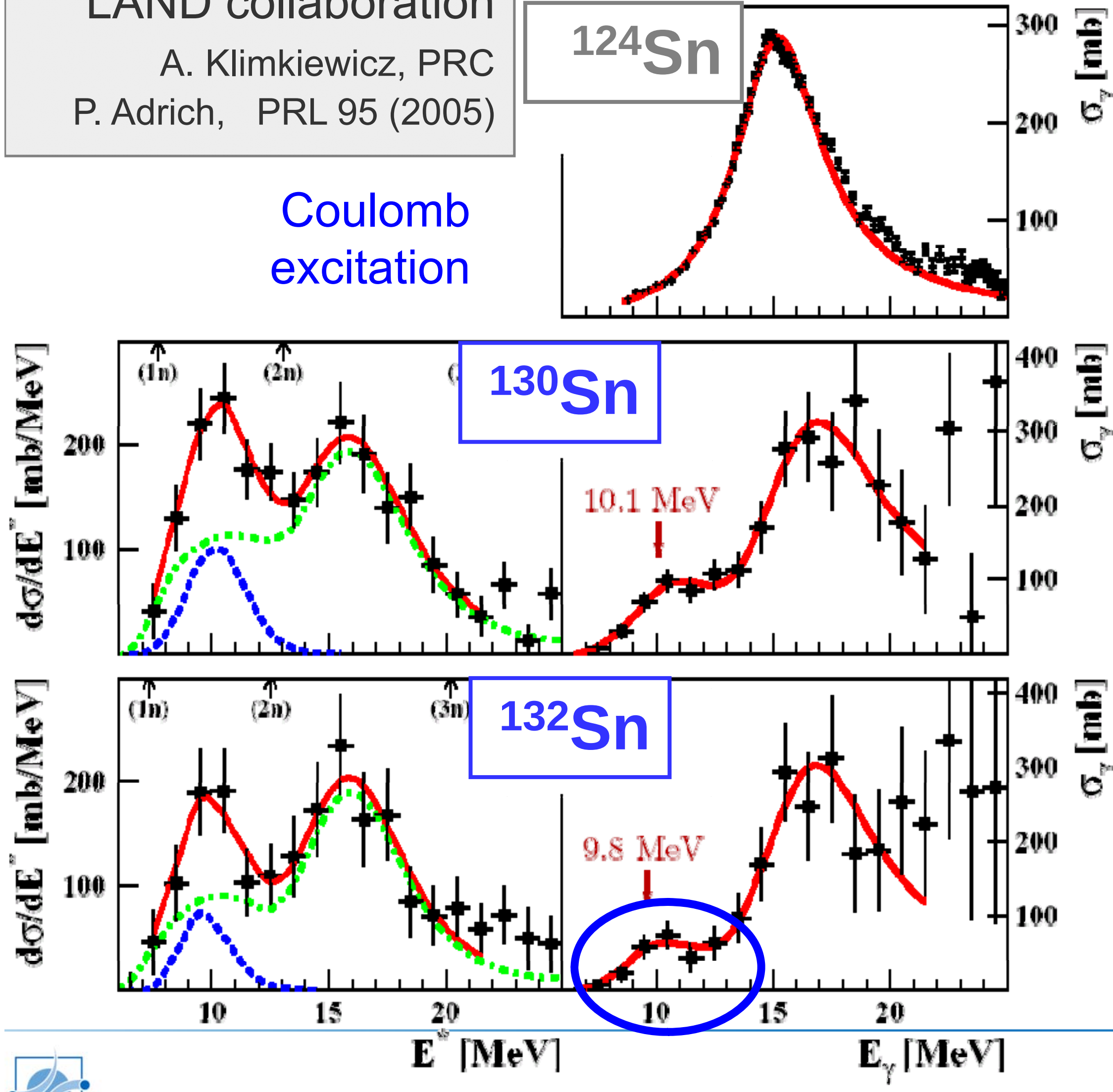
LAND collaboration

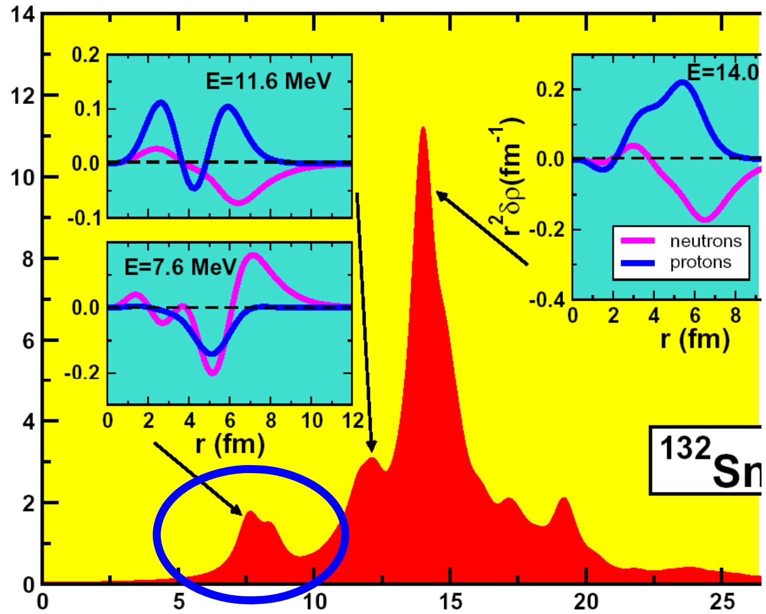
A. Klimkiewicz, PRC

P. Adrich, PRL 95 (2005)

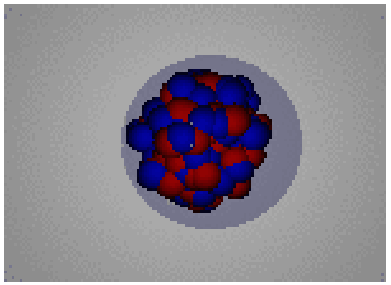
Photoabsorption

Coulomb excitation





P. Ring et al.



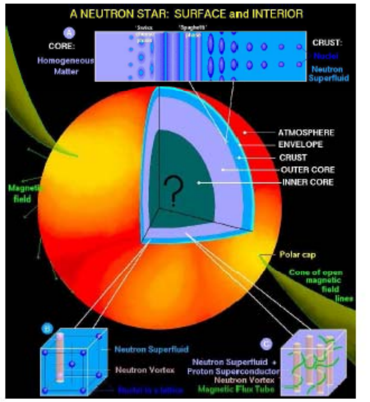
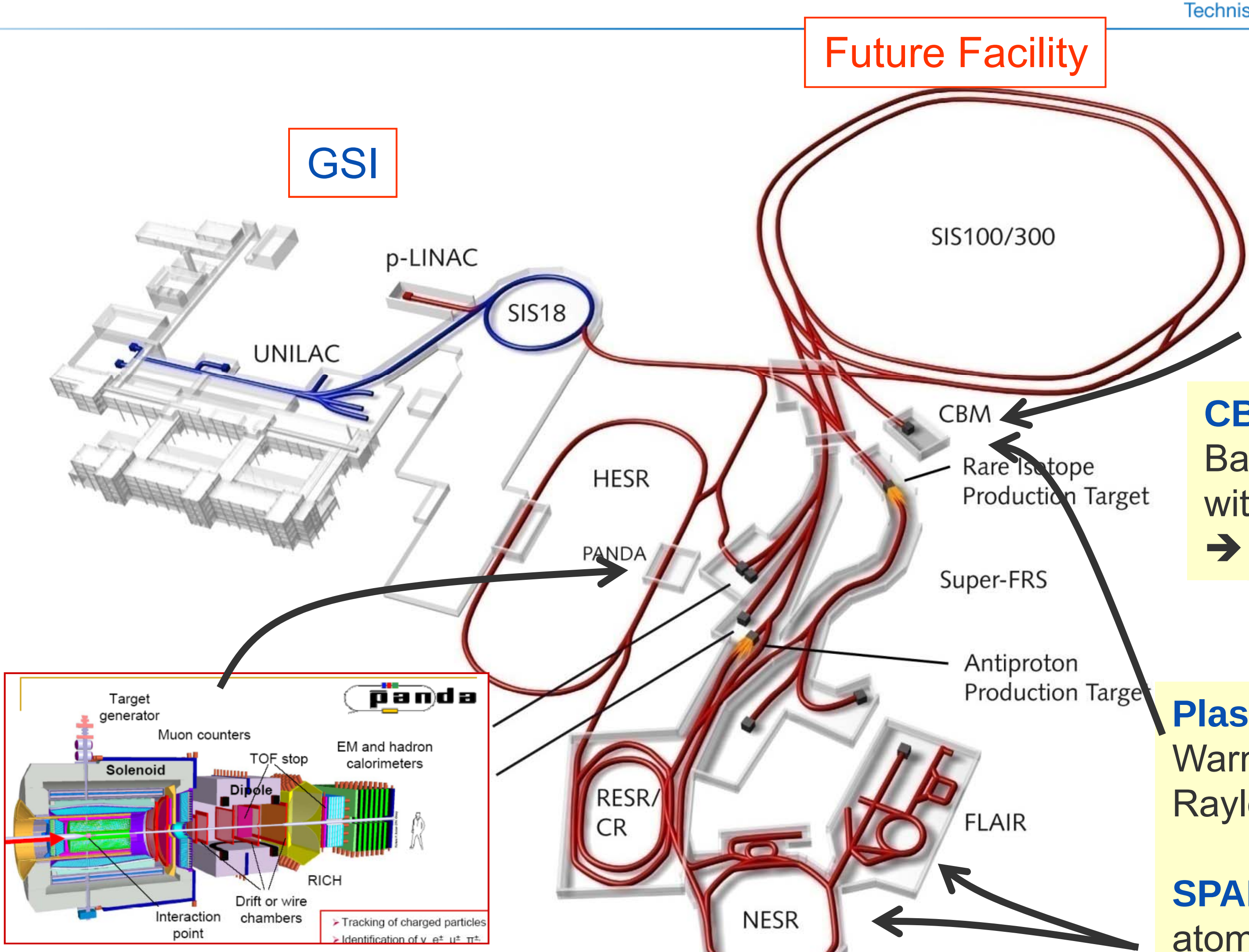
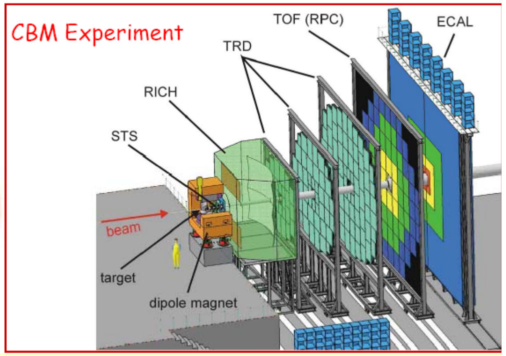


Fig. 3. State-of-the-art rendition of the structure of a neutro star (courtesy of Dany Page).

EOS

The Facility for Antiproton and Ion Research





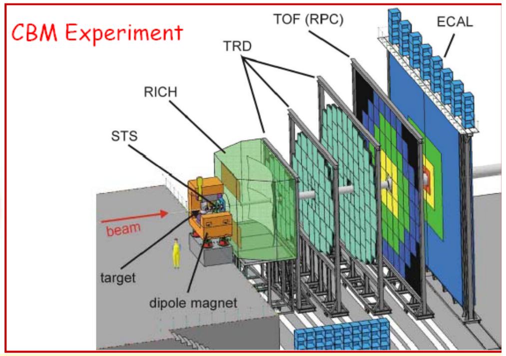
CBM: Compressed Baryonic Matter with heavy ion beams:
➔ **QCD phase diagram**

Plasma Physics:
Warm Dense Plasmas,
Rayleigh-Taylor Instabilities

SPARC:
atomic physics with stored highly charged atoms

PANDA: Hadron Spectroscopy,
Hypernuclei production with high energy Antiprotons

The Facility for Antiproton and Ion Research



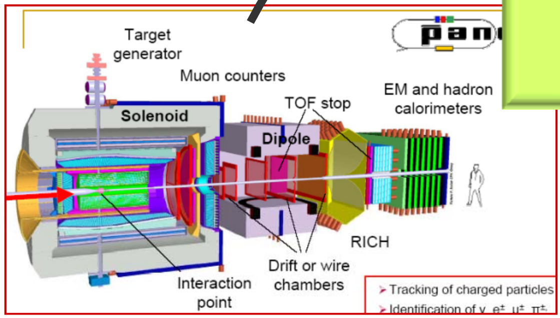
BM: Compressed
aryonic Matter
th heavy ion beams:
QCD phase diagram

October 4, 2010:

Signature of convention

Foundation of FAIR GmbH

Start of Experiments 2017/18



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m Dense Plasmas,
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SPARC:
atomic physics with stored
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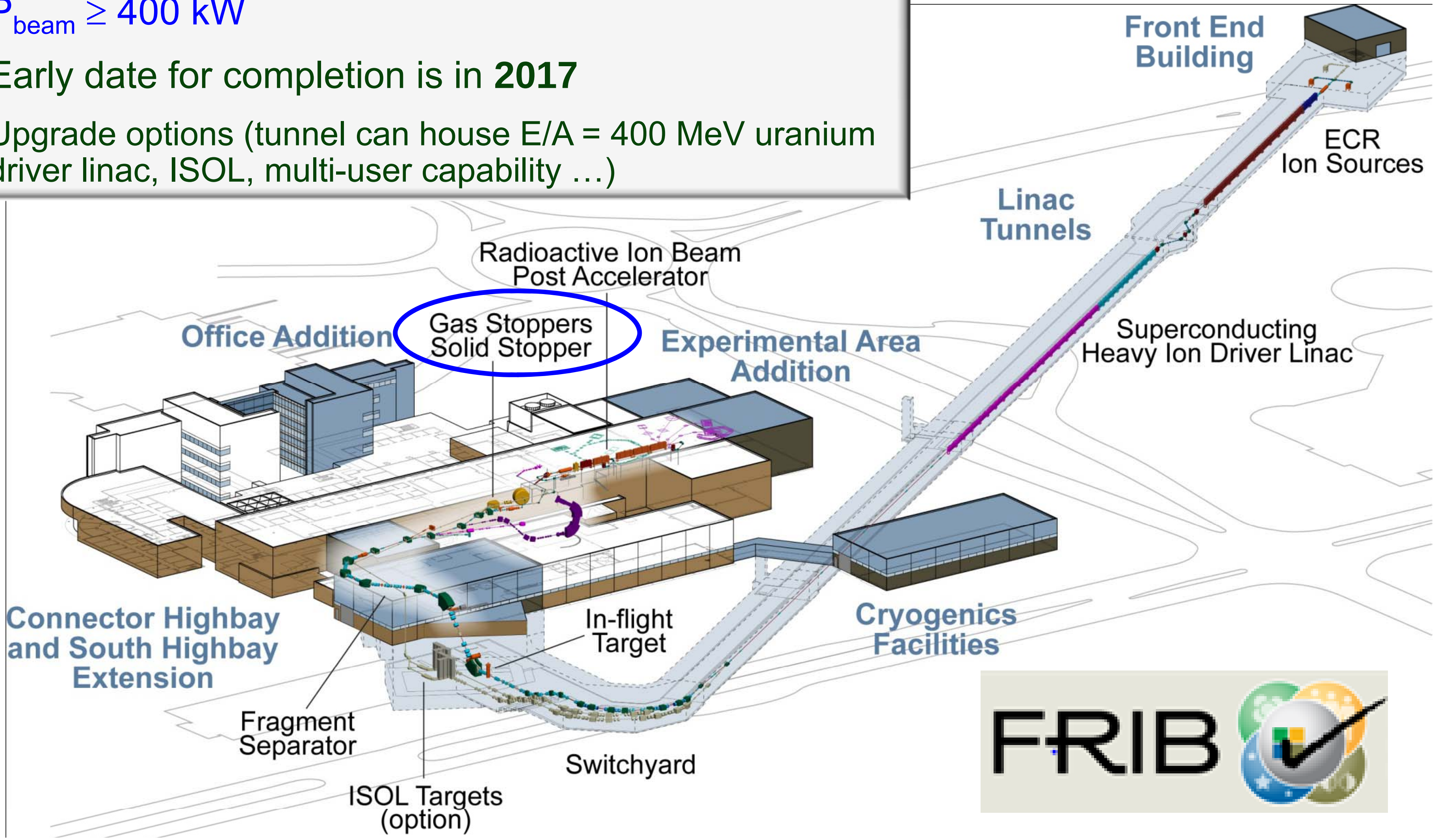
PANDA: Hadron Spectroscopy,
Hypernuclei production with high
energy Antiprotons

Facility for Rare Isotope Beams, FRIB

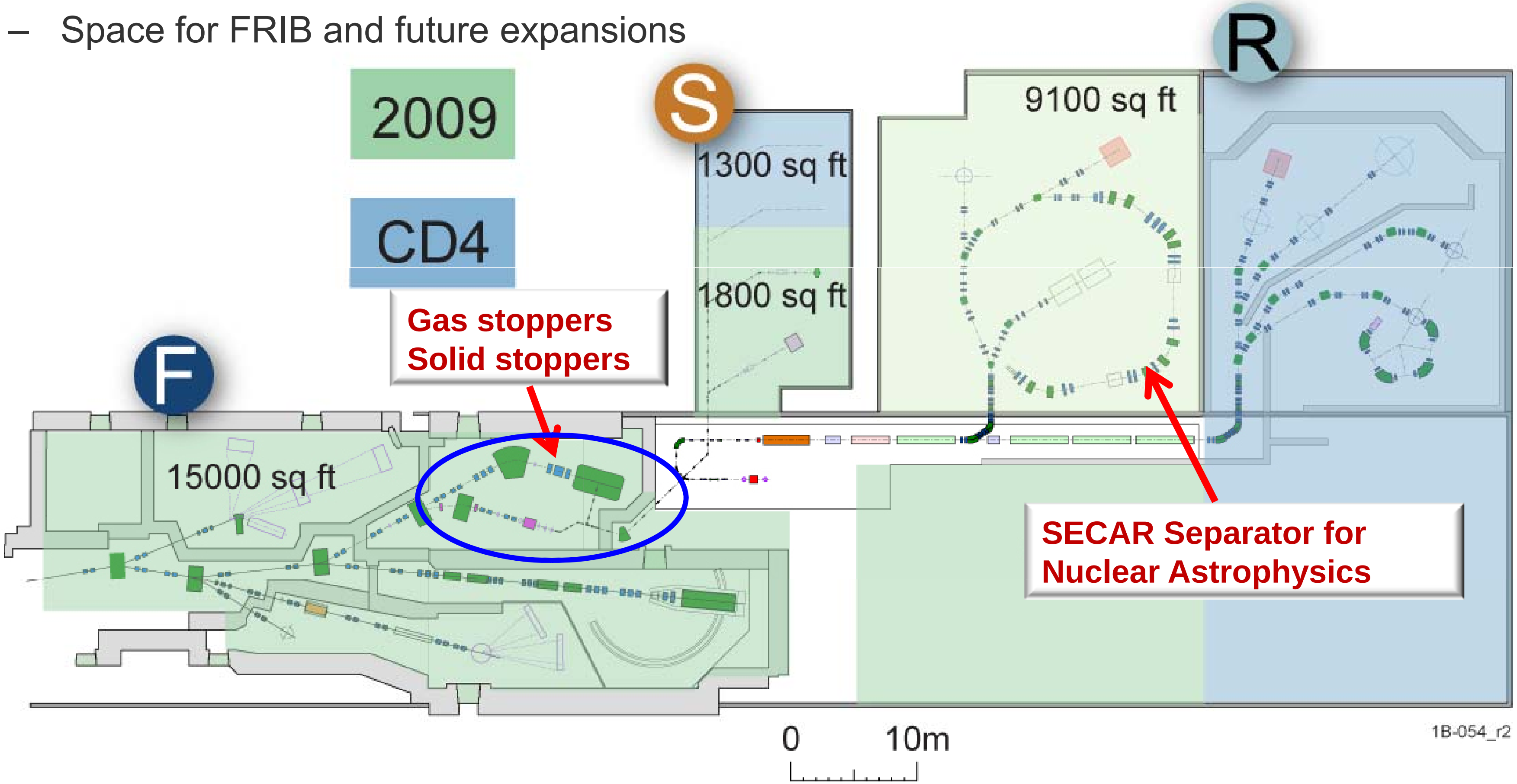
Technische Universität München

- Driver LINAC capable of $E/A \geq 200$ MeV for all ions, $P_{beam} \geq 400$ kW
- Early date for completion is in **2017**
- Upgrade options (tunnel can house $E/A = 400$ MeV uranium driver linac, ISOL, multi-user capability …)



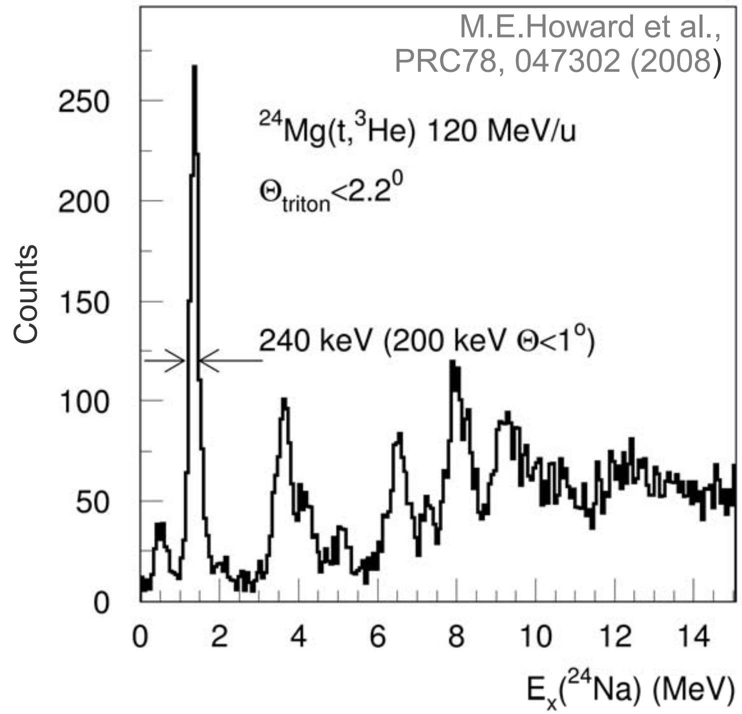
Experimental Areas

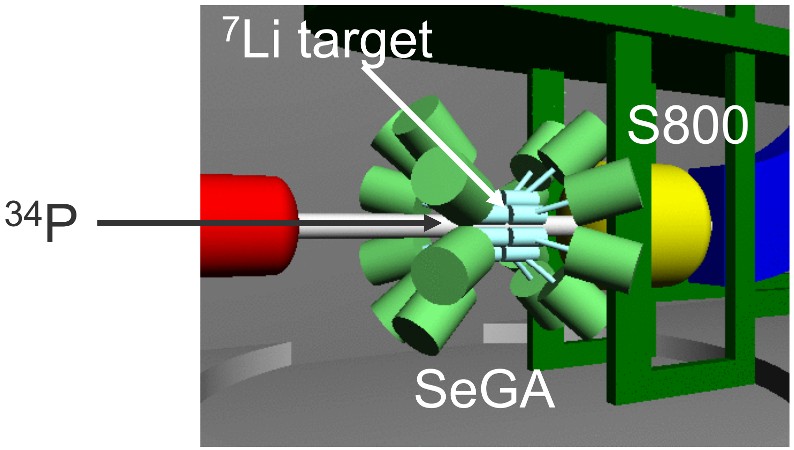
- FRIB experimental areas build on existing NSCL equipment and accelerators
  - **Fast beam experimental areas exist**
  - **Stopped beam area exists** – relocation and expansion in 2009
  - **ReA3 commissioning in 2010** (plus new 9,000 sq ft experimental area)
  - Space for FRIB and future expansions

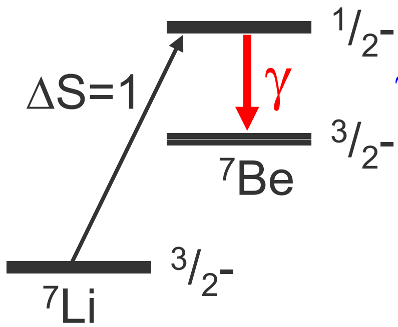


How Do Supernovae Explode?

- Electron capture and beta decay rates play important roles in supernova explosions
  - Core collapse SN: dynamics of collapse, shock energetics
  - SN Ia: nucleosynthesis, flame propagation
- Measure of Gamow-Teller strengths via charge exchange
  - Stable isotopes: (^{3}He,t) or (t,^{3}He)
    - NSCL: ~10^7 t/s from fragmentation of ^{16}O
  - Rare isotopes: inverse kinematics (p,n) or (^{7}Li,^{7}Be)

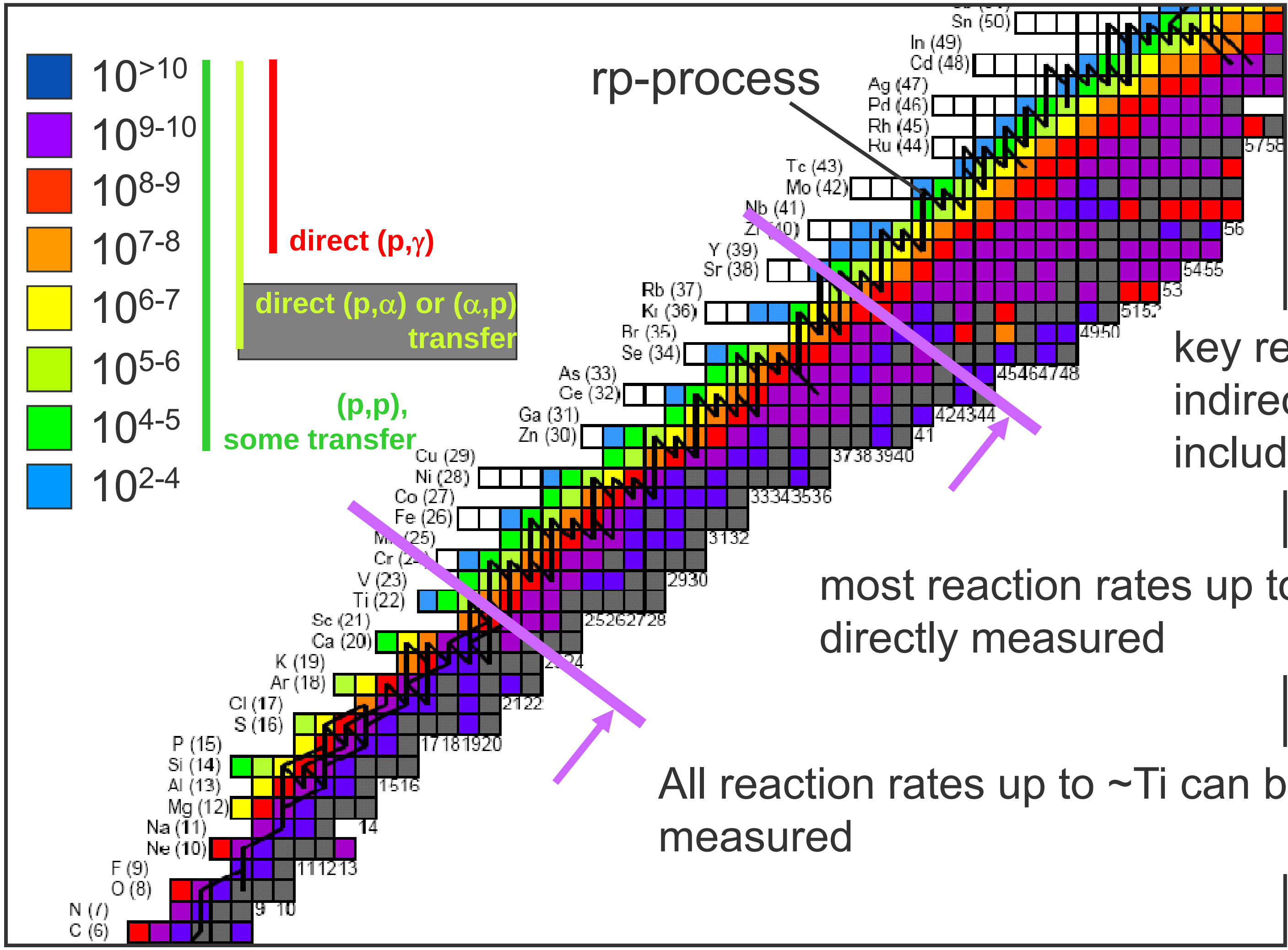






γ-tag spin-flip transition

Reach for X-ray burst reaction rate studies



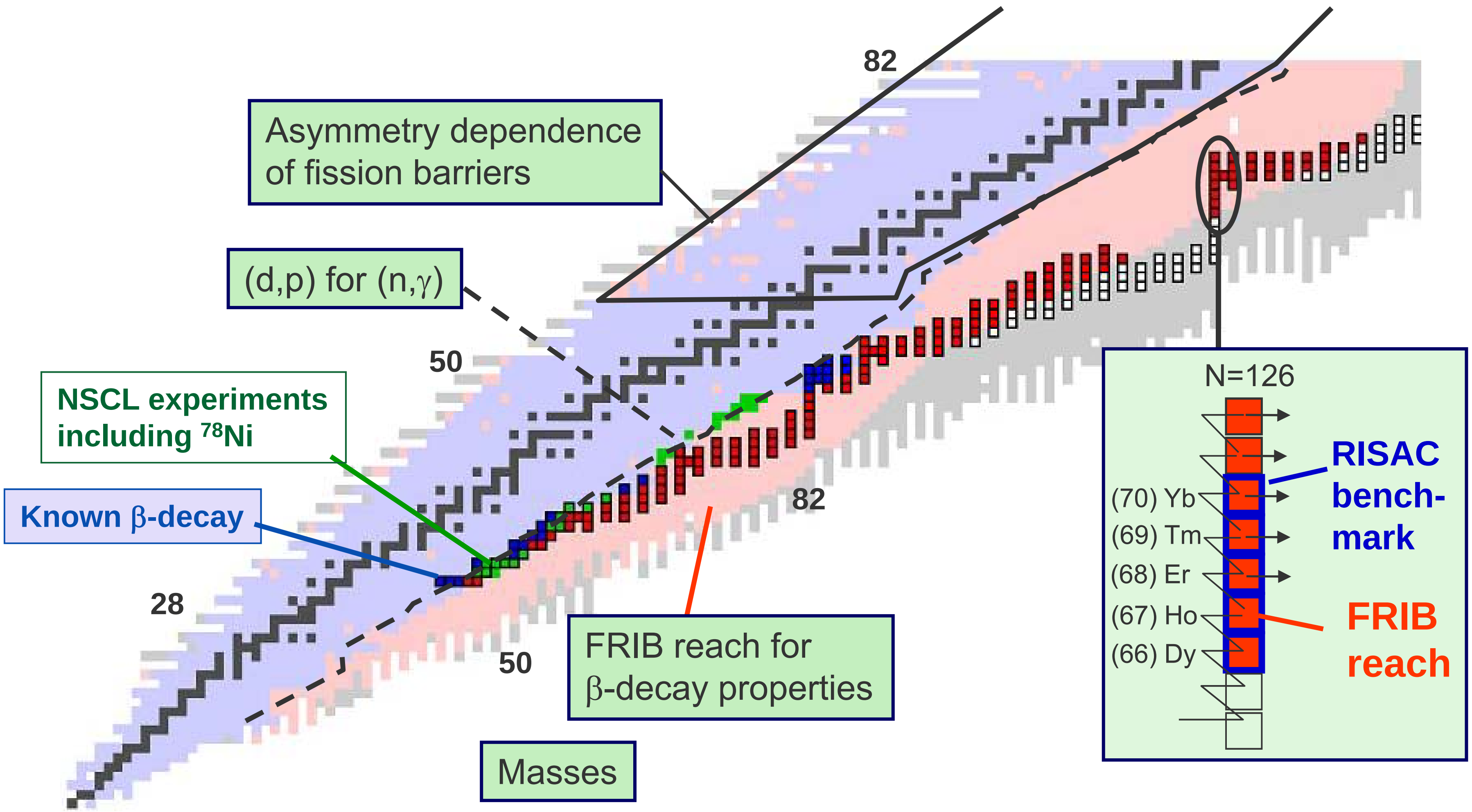
key reaction rates can be indirectly measured including ^{72}Kr waiting point

most reaction rates up to ~Sr can be directly measured

All reaction rates up to ~Ti can be directly measured

courtesy B. Sherrill

FRIB Capability to address r-Process

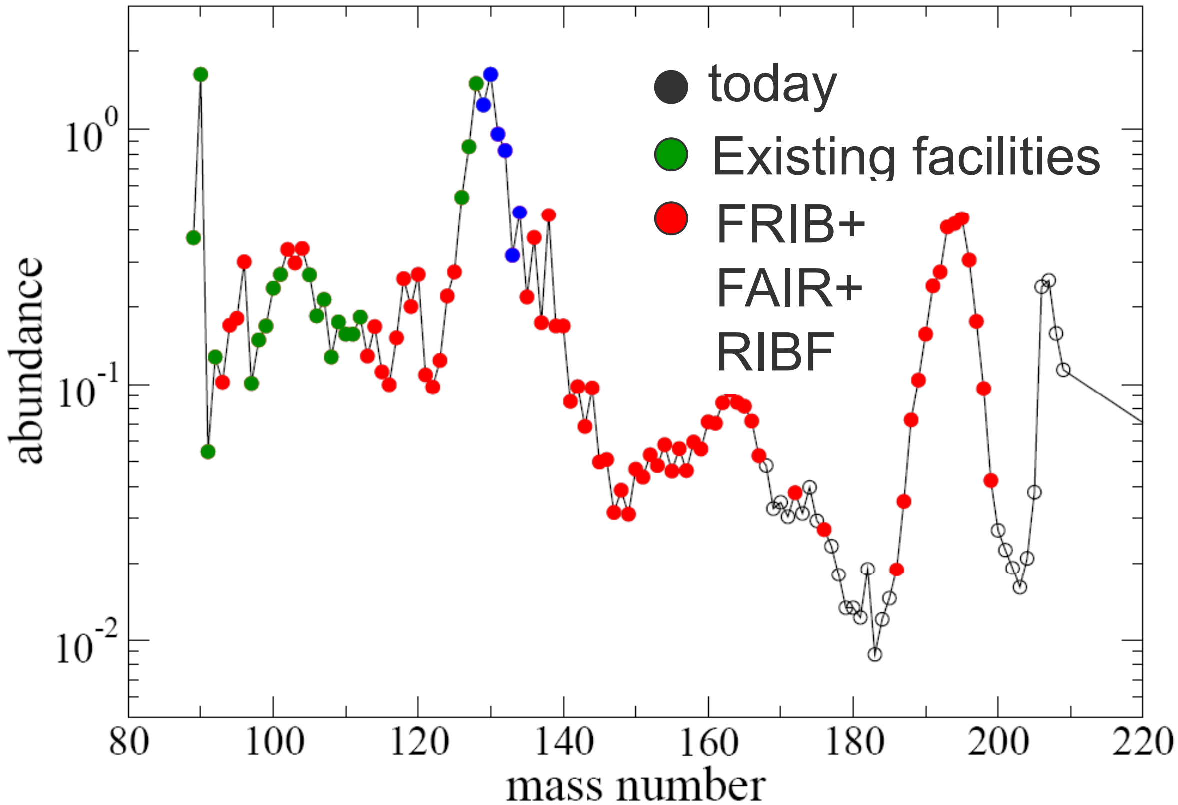


Solar System r-process Abundance Pattern

Today: except in a few cases (blue) can output of models be matched measured abundances.

The next generation RIB facilities will allow one to

- constrain r-process theories using abundance data
- extract full information about r-process (and its environment) from observational data



A colored dot means that the relevant nuclear data (mass, half-life, $P(\beta_n)$) could be measured.

courtesy B. Sherrill

Conclusion

- **Current RIB facilities**

  ➔ substantial contributions to understanding of the origin of the elements

  However:

  limited reach and precision

- **Next generation facilities, in particular RIBF, FAIR, FRIB**
  - Complementary capabilities
  - Reaching the r-process path, in particular in heavy nuclei
  - Higher intensities for precision experiments closer to stability

  ➔ **Breakthroughs in our understanding of the origin of the elements**

- **Exciting progress possible through close cooperation between astronomical observation, astrophysical modeling and nuclear physics theory and experiments**