Nuclear Astrophysics at FAIR

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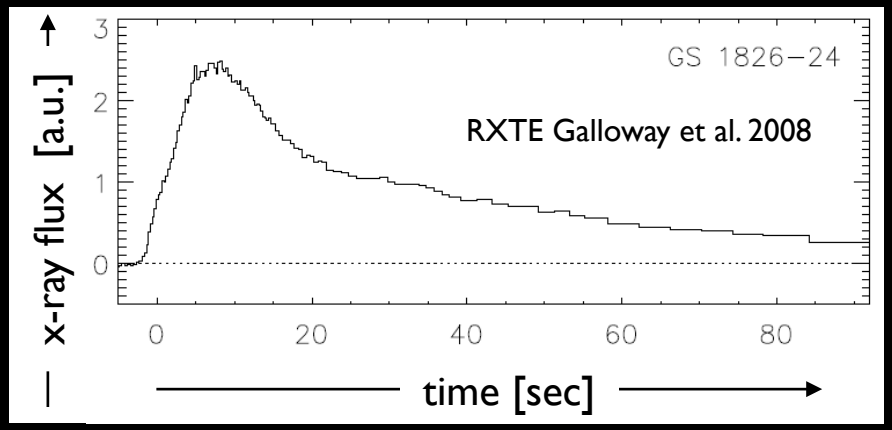
- X-ray binaries
- Rapid neutron capture process (r-process)
- Facility for Antiproton And Ion Research FAIR

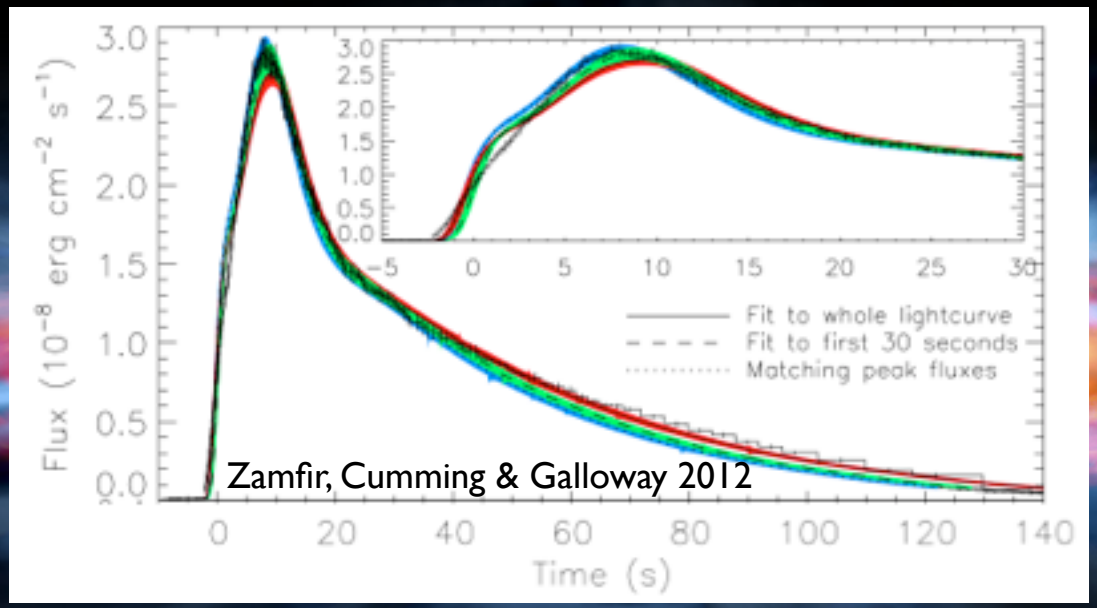
X-ray binaries

- Binary system: neutron star + companion star
- Typical neutron star 1.4M_o, 10km radius
- Explosion more than 1000 more powerful than sun
- Normal burst duration10-100 seconds
- about 90 sources and more than 5000 bursts observed so far

Normal bursts (~minutes)
H, He fuel

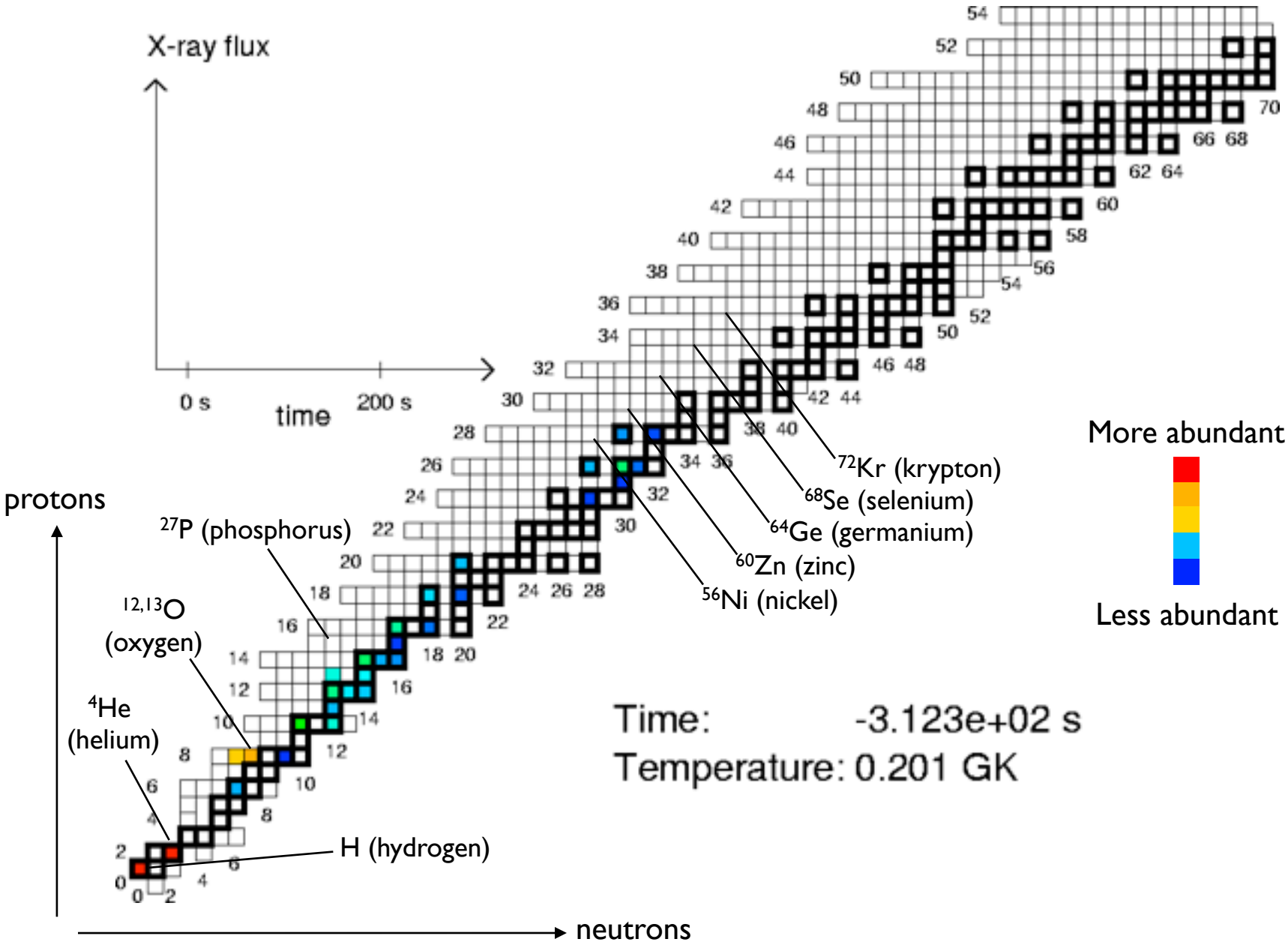


Observations of these events provide information about the properties of matter under extreme conditions: neutron star properties, accretion rate, ignition mechanism, etc.



Mass and radius of neutron star determined based on set of astrophysical parameters that best fit observations

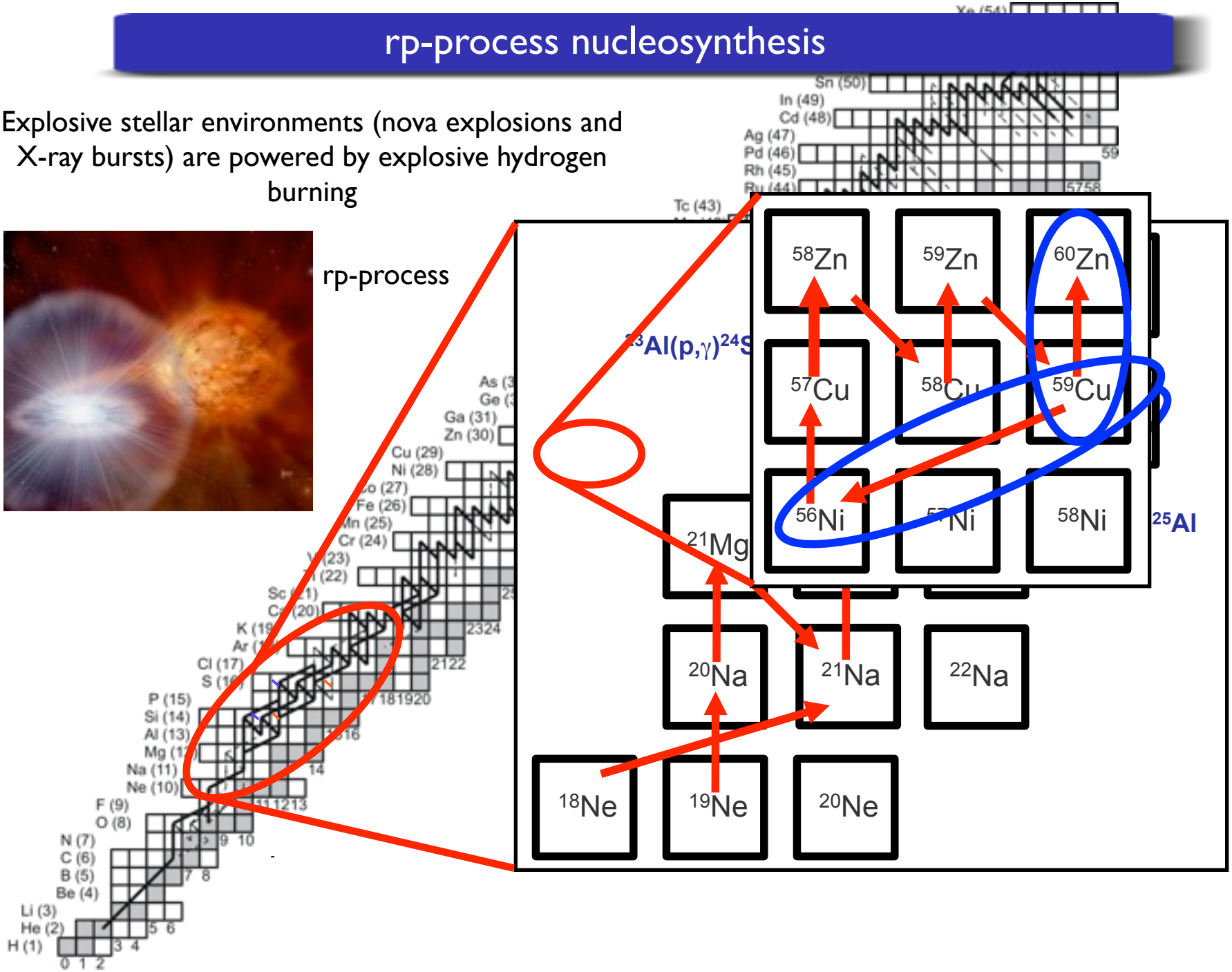
rp-process


X-ray flux
0 s
time
200 s
protons
neutrons
^{27}P (phosphorus)
^{12,13}O (oxygen)
^{4}He (helium)
H (hydrogen)
^{72}Kr (krypton)
^{68}Se (selenium)
^{64}Ge (germanium)
^{60}Zn (zinc)
^{56}Ni (nickel)
More abundant
Less abundant
Time: -3.123e+02 s
Temperature: 0.201 GK

rp-process nucleosynthesis

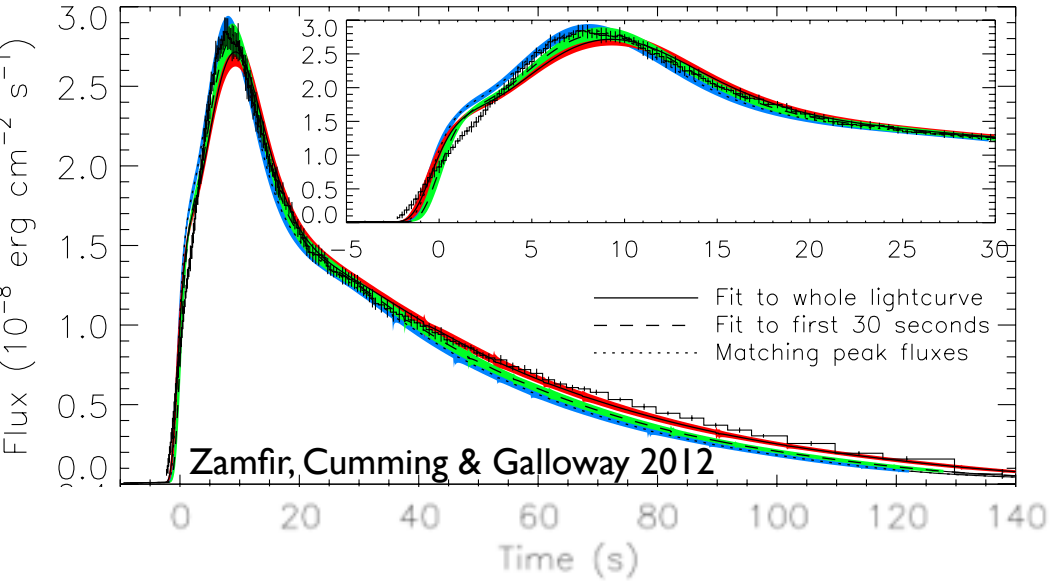
Explosive stellar environments (nova explosions and X-ray bursts) are powered by explosive hydrogen burning

rp-process

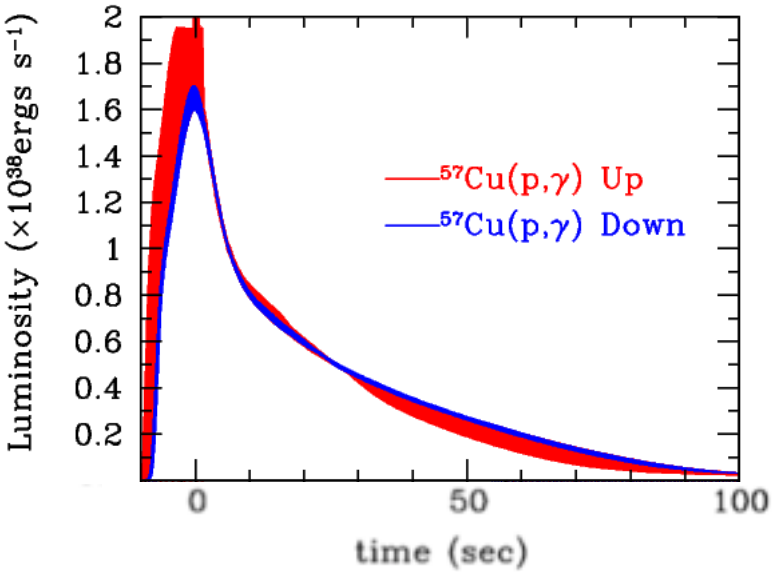


Nuclear physics importance

GS1826-24
X-ray burster

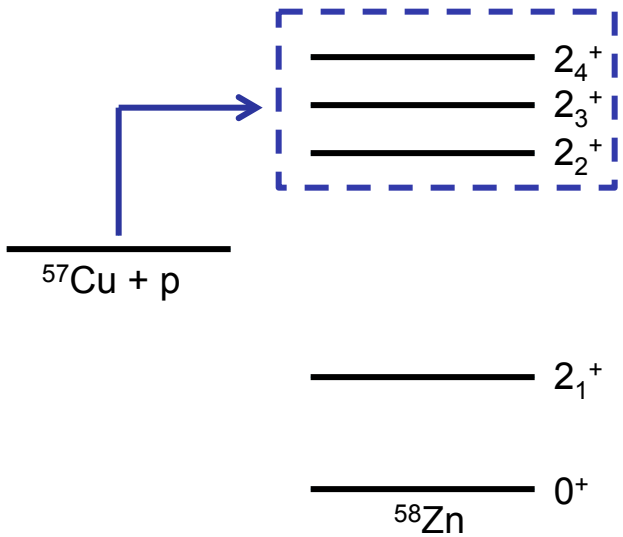


1D multi-zone high
accretion model



Need reliable nuclear physics for full interpretation of observations!
but fortunately not all reactions are important

Nuclear physics - reaction rates



Measure cross section directly
BUT
very low cross sections

OR

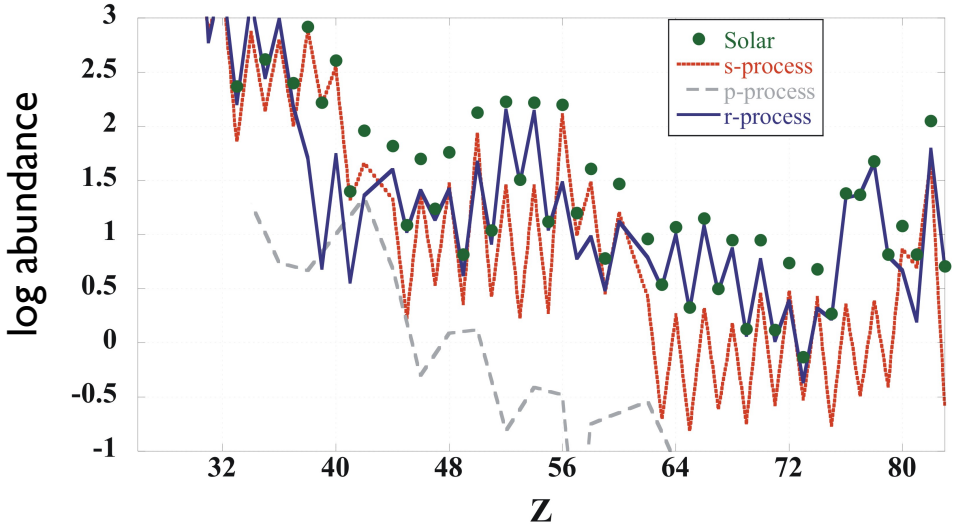
Measure cross section indirectly:
Measure spins, resonance energies, masses, single particle strengths, g-widths and spectroscopic factors

$$\sigma(E) = \pi \lambda\!\!\!^{-2} \frac{2J+1}{(2J_x+1)(2J_y+1)} \frac{\Gamma_x \Gamma_y}{(E-E_r)^2 + (\Gamma/2)^2}$$

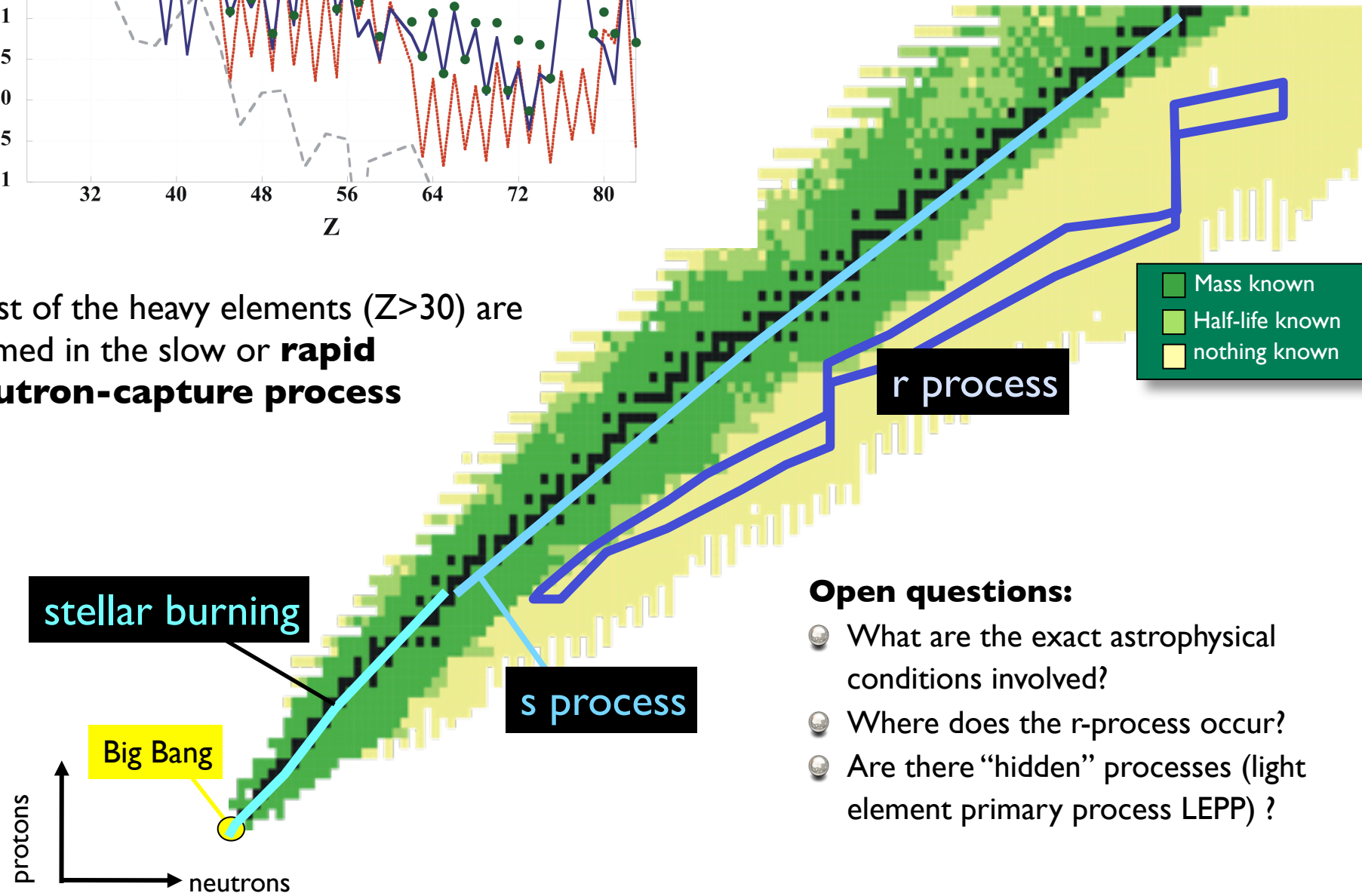
Several important nuclear reactions have high uncertainties!
Measurements are limited by current beam rates

Facility for Antiproton and Ion Research FAIR (Germany)
Facility for Rare Isotope Beams FRIB (USA)
RIKEN Accelerator Research Facility (JAPAN)

Solar system abundances



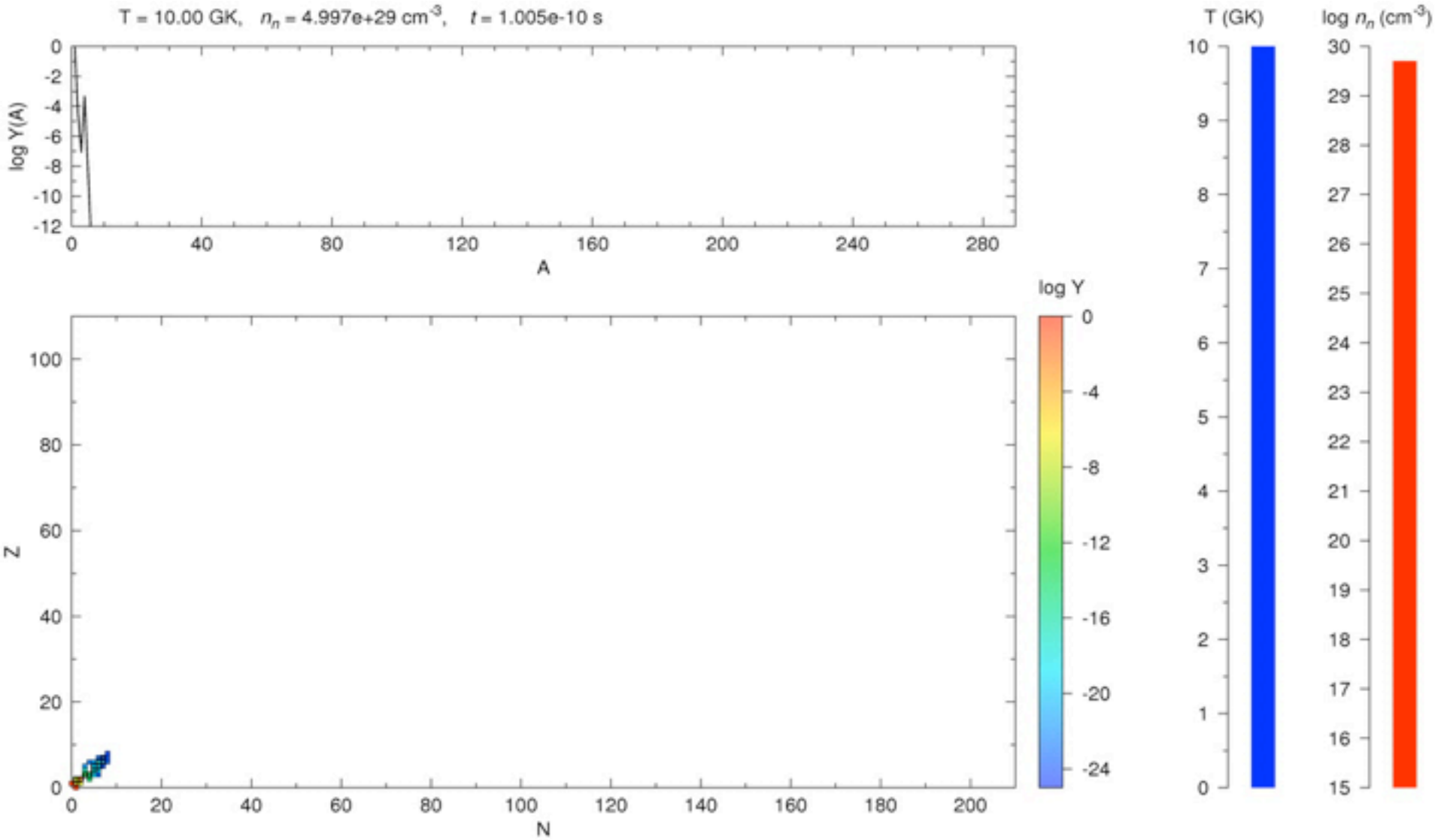
Most of the heavy elements (Z>30) are formed in the slow or **rapid neutron-capture process**



Open questions:

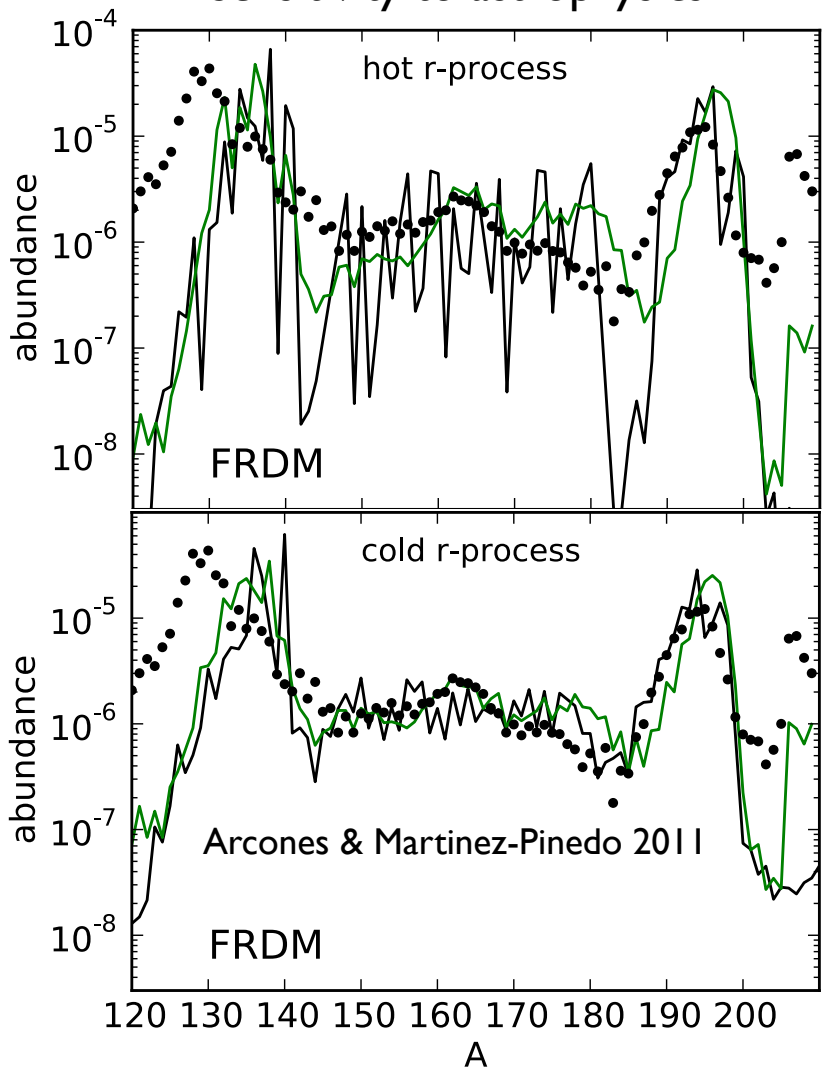
- What are the exact astrophysical conditions involved?
- Where does the r-process occur?
- Are there "hidden" processes (light element primary process LEPP) ?

r-process

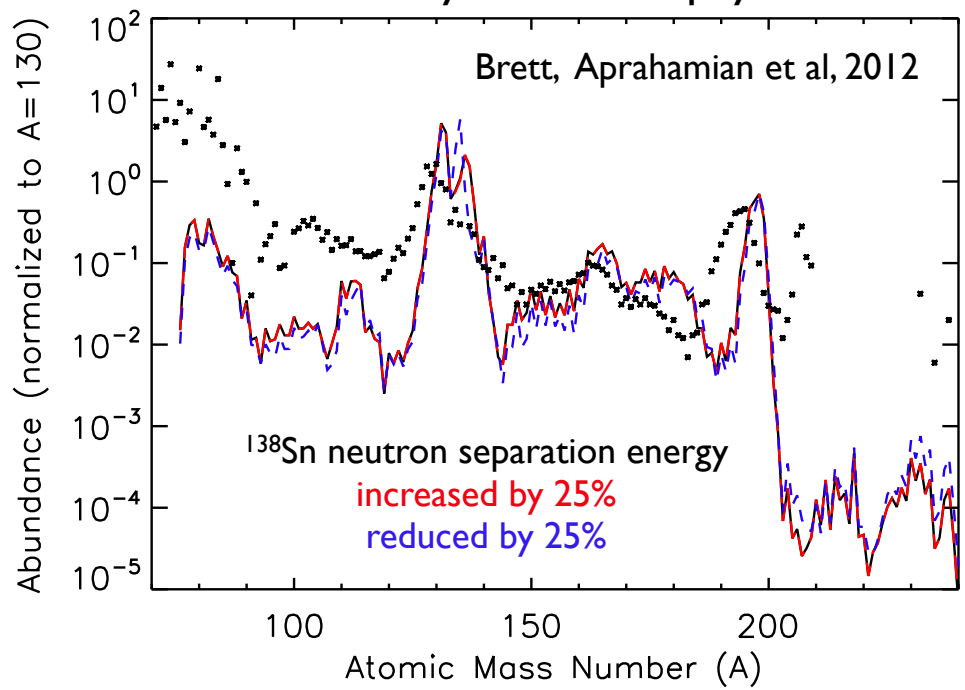

T = 10.00 GK, n_n = 4.997e+29 cm^{-3}, t = 1.005e-10 s
log Y(A)
A
Z
N
log Y
T (GK)
log n_n (cm^{-3})

Sensitivity of r-process to astro and nuclear physics

Sensitivity to astrophysics



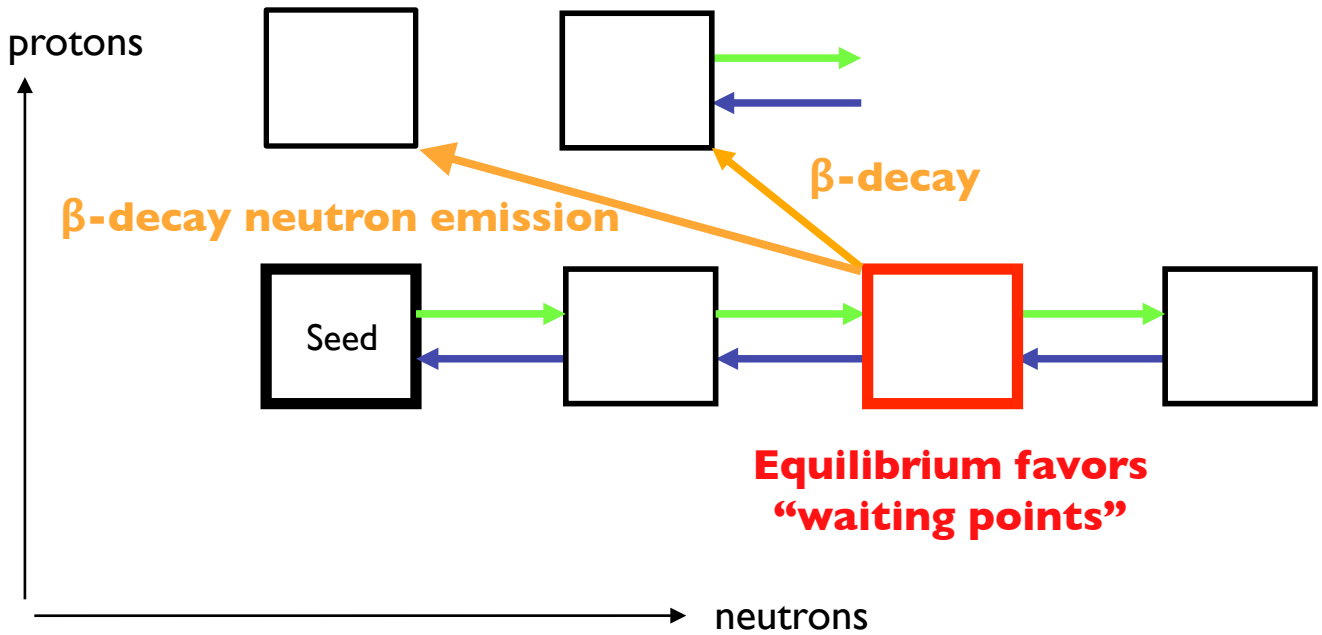
Sensitivity to nuclear physics



Comparison to observations:

- Obtain neutron density, temperature, time
- Determines which model is correct
- Convoluted with nuclear physics

Important nuclear physics r-process



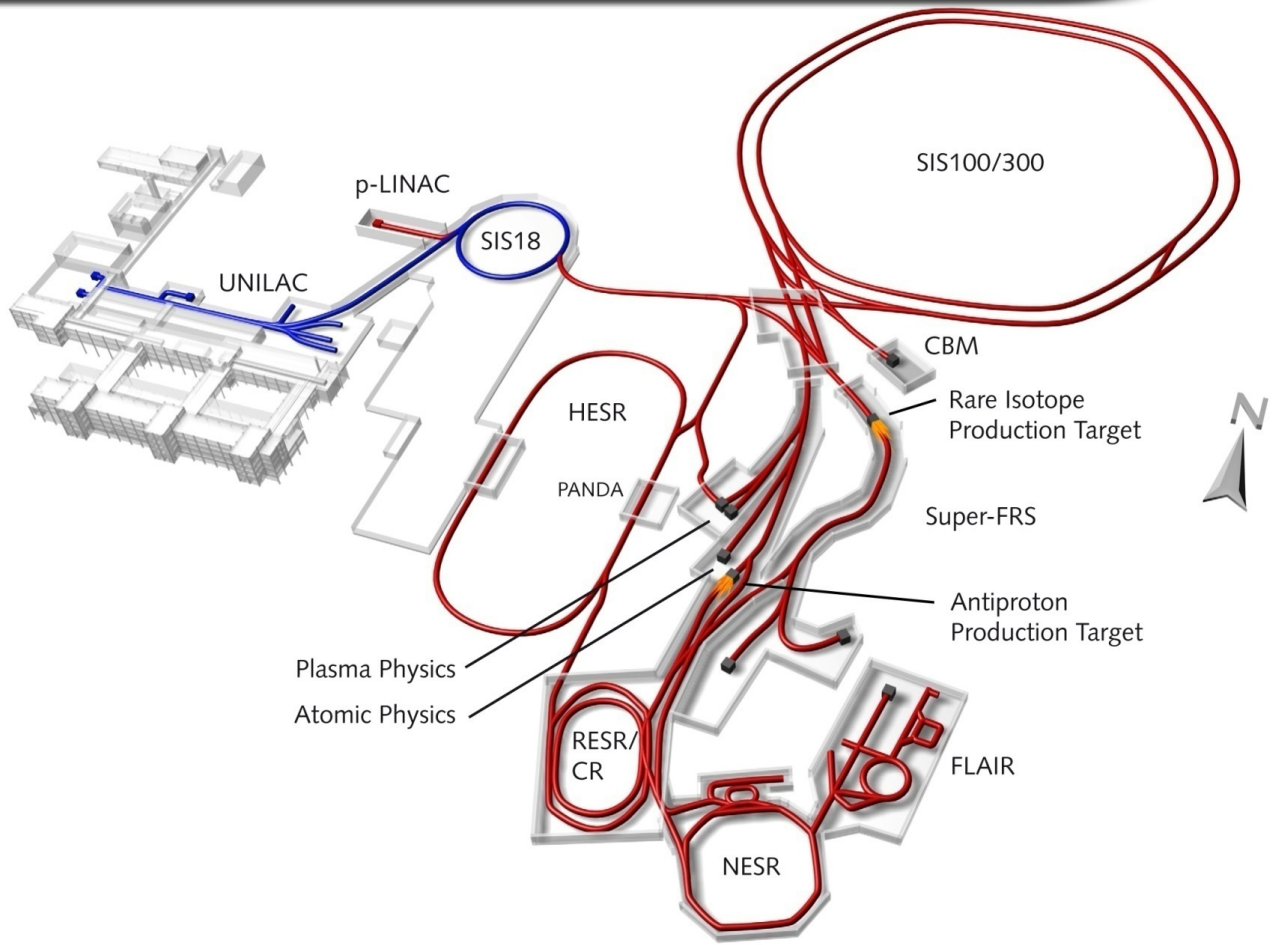
Need:

- Masses
- Half-lives
- Neutron capture rates after neutrons are exhausted
- Neutron emission probabilities
- Maybe fission and neutrino interaction rates

Experimental measurements of these quantities for r-process isotopes is very limited

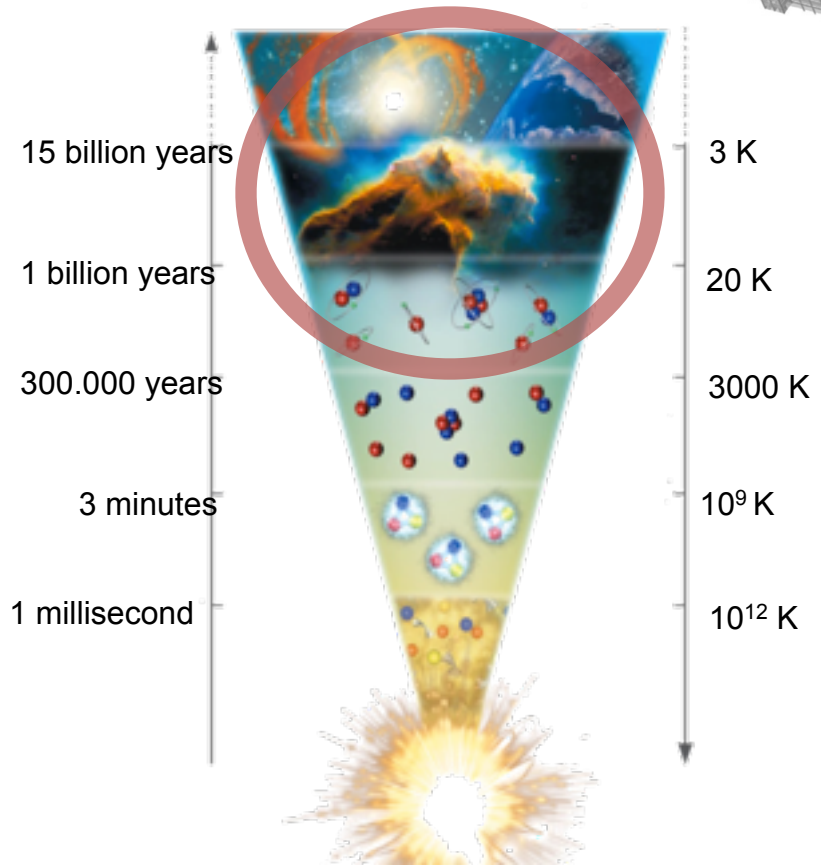
Measurements are limited by current beam rates

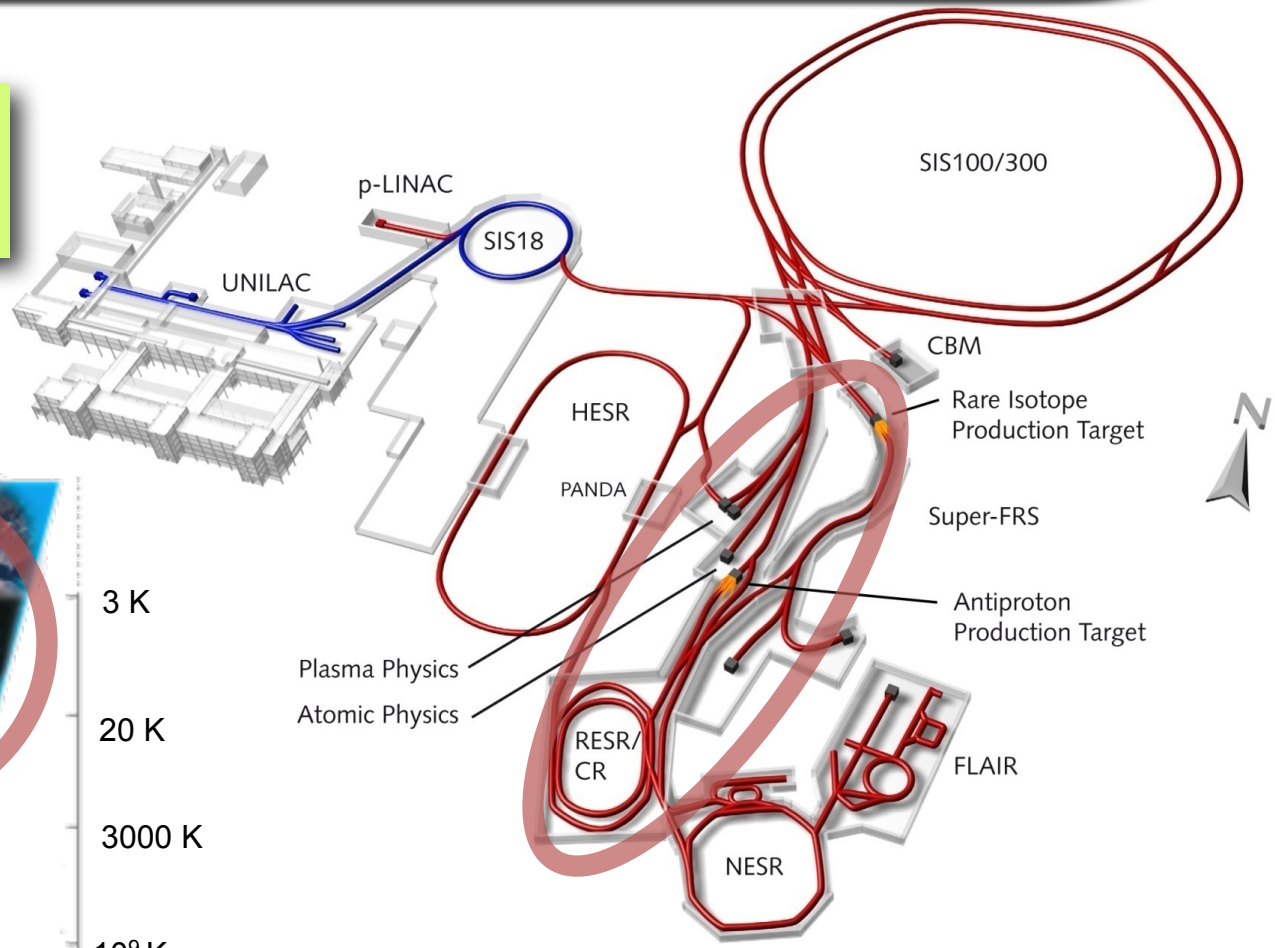
Facility for Antiproton and Ion Research FAIR



Facility for Antiproton and Ion Research FAIR

How are elements heavier than He created? Where are they created?



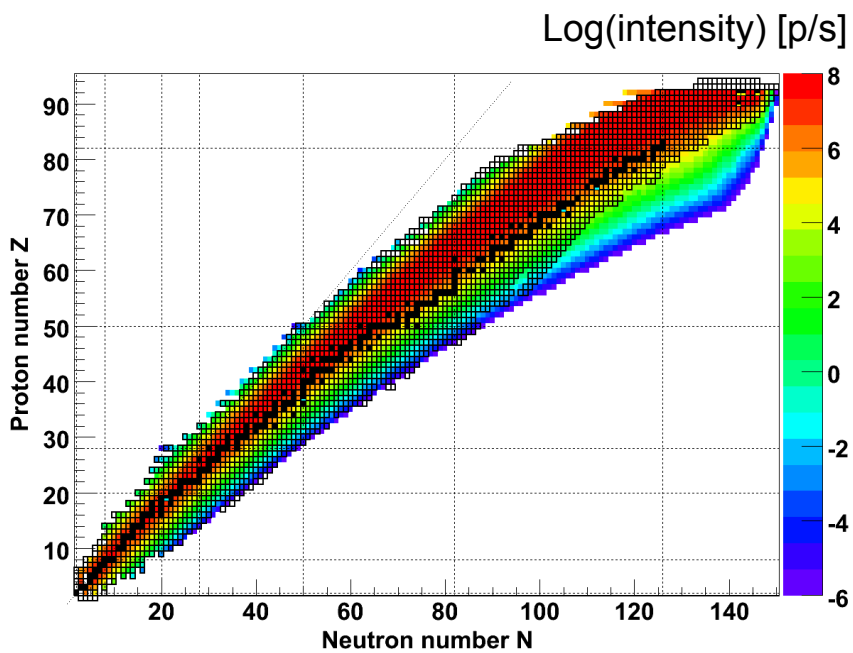


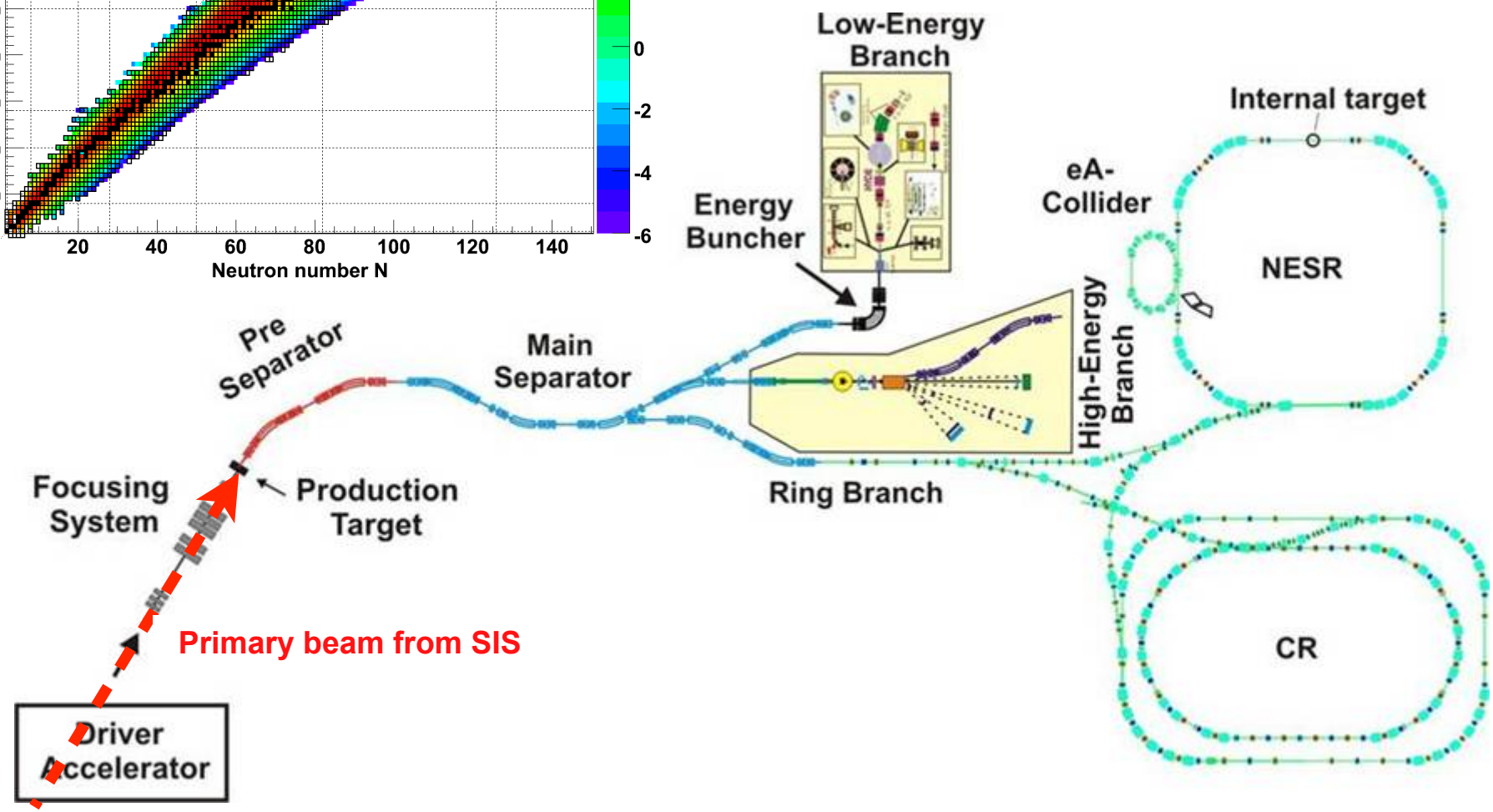
Nuclear Structure, Reactions and Astrophysics

Rare isotope beams (NUSTAR):

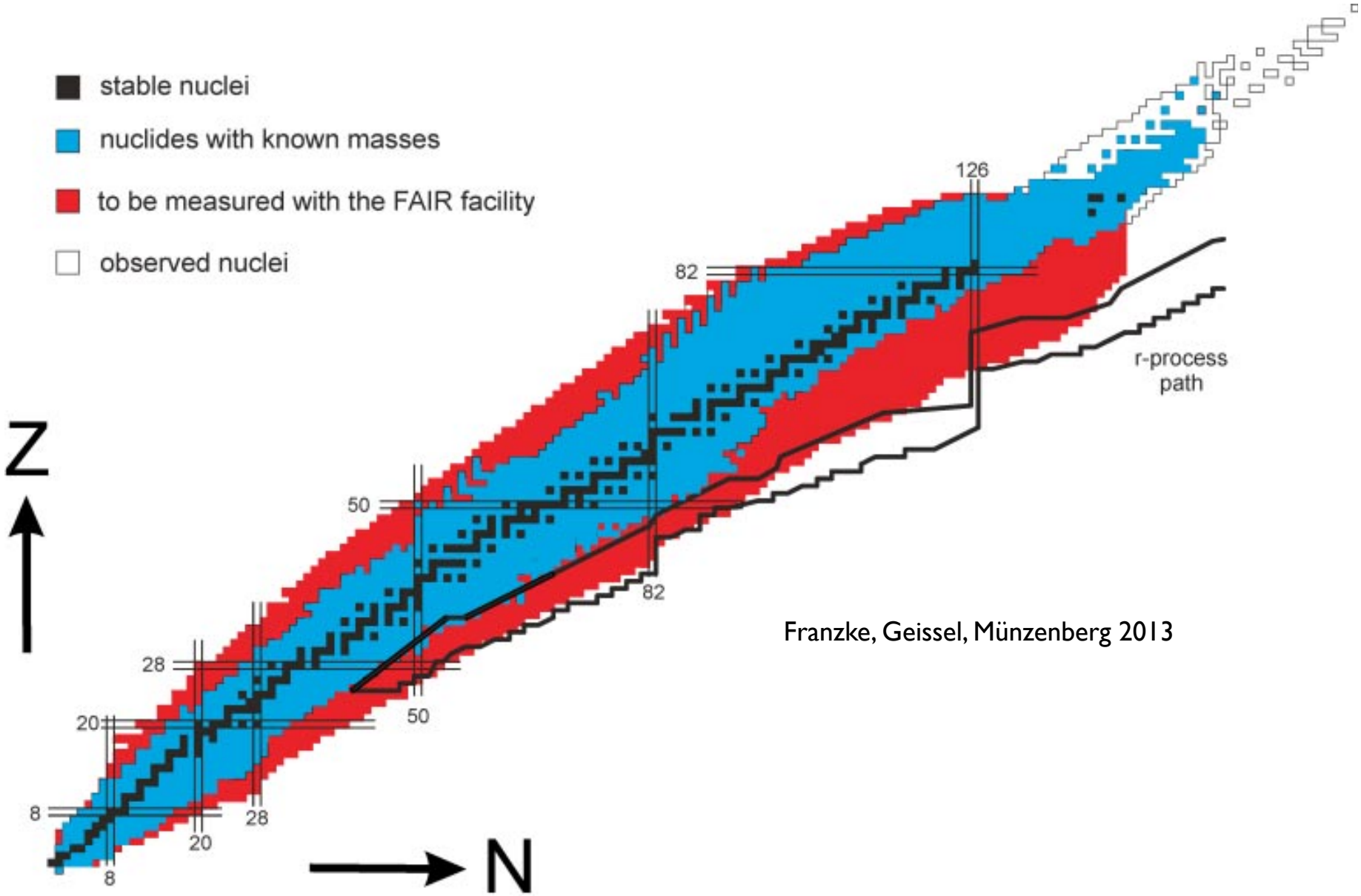
Nuclear structure far off stability, nucleosynthesis in explosive astrophysical events

NUSTAR physics





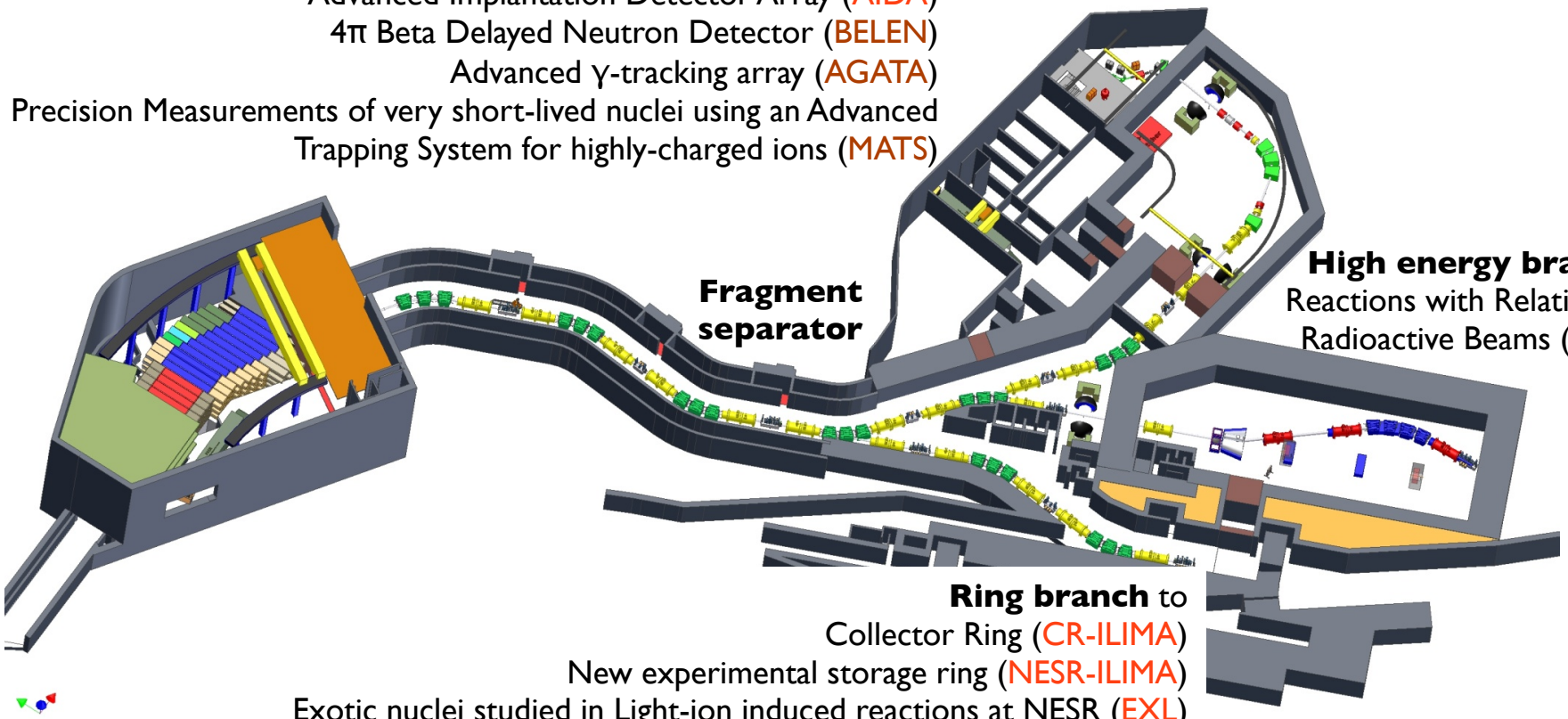
FAIR reach



Franzke, Geissel, Münzenberg 2013

Astrophysics with NUSTAR

Low energy branch
Advanced Implantation Detector Array (AIDA)
4π Beta Delayed Neutron Detector (BELEN)
Advanced γ-tracking array (AGATA)
Precision Measurements of very short-lived nuclei using an Advanced Trapping System for highly-charged ions (MATS)



High energy branch
Reactions with Relativistic Radioactive Beams (R3B)

Ring branch to
Collector Ring (CR-ILIMA)
New experimental storage ring (NESR-ILIMA)
Exotic nuclei studied in Light-ion induced reactions at NESR (EXL)

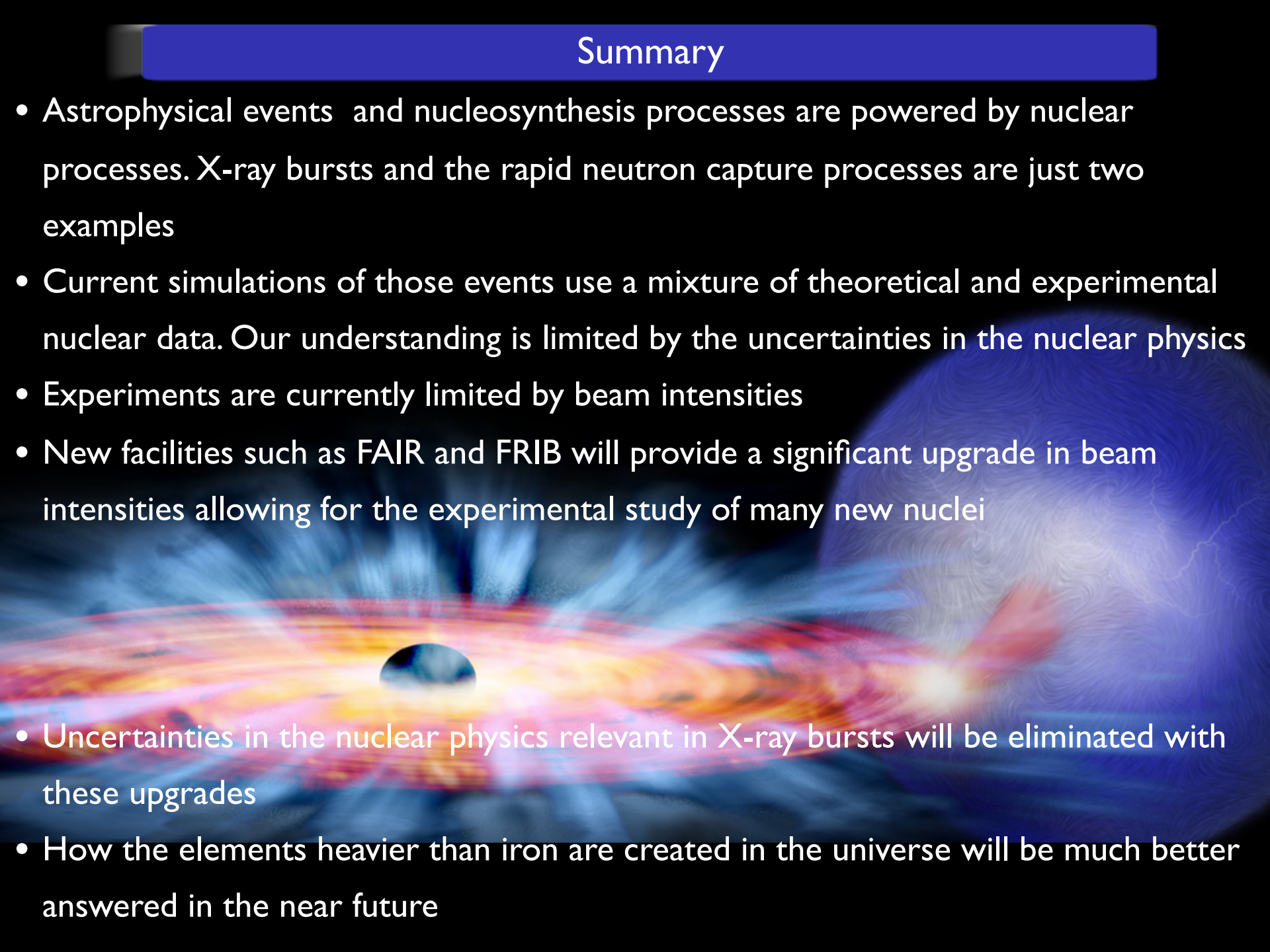
Nuclear spectroscopy
- β-decay (AIDA, BELEN) r-process
- γ-spectroscopy (AGATA) rp-process

Atomic masses
- Masses (ILIMA,MATS) r-process and rp-process

Reaction studies
- Light ion direct reactions (EXL) rp-process and r-process
- Direct (p,γ) reaction measurements (storage ring) rp-process
- Electromagnetic dissociation (R3B) rp-process and r-process

Summary

- Astrophysical events and nucleosynthesis processes are powered by nuclear processes. X-ray bursts and the rapid neutron capture processes are just two examples
- Current simulations of those events use a mixture of theoretical and experimental nuclear data. Our understanding is limited by the uncertainties in the nuclear physics
- Experiments are currently limited by beam intensities
- New facilities such as FAIR and FRIB will provide a significant upgrade in beam intensities allowing for the experimental study of many new nuclei



- Uncertainties in the nuclear physics relevant in X-ray bursts will be eliminated with these upgrades
- How the elements heavier than iron are created in the universe will be much better answered in the near future