Nuclear Astrophysics in EURISOL

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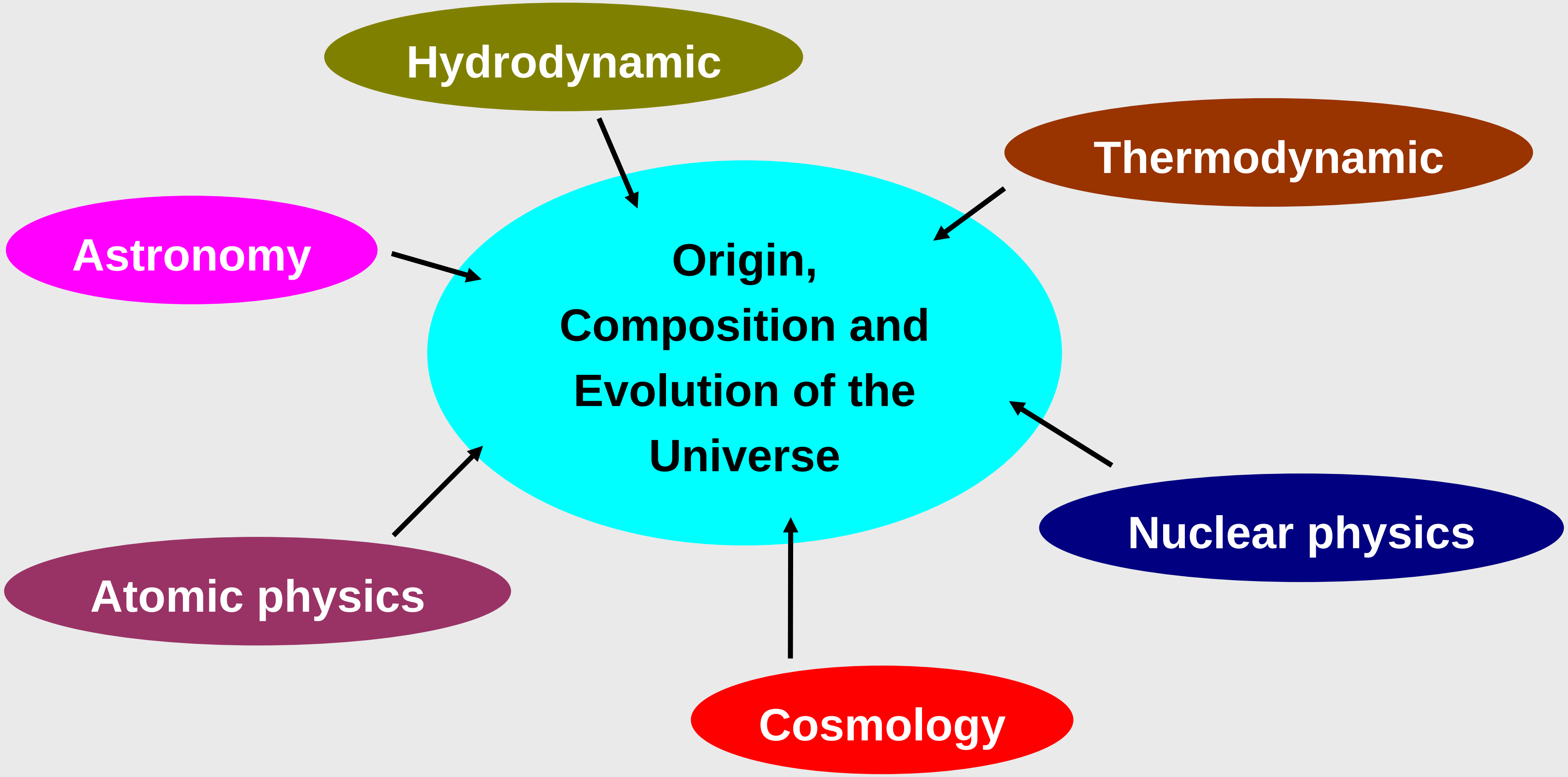
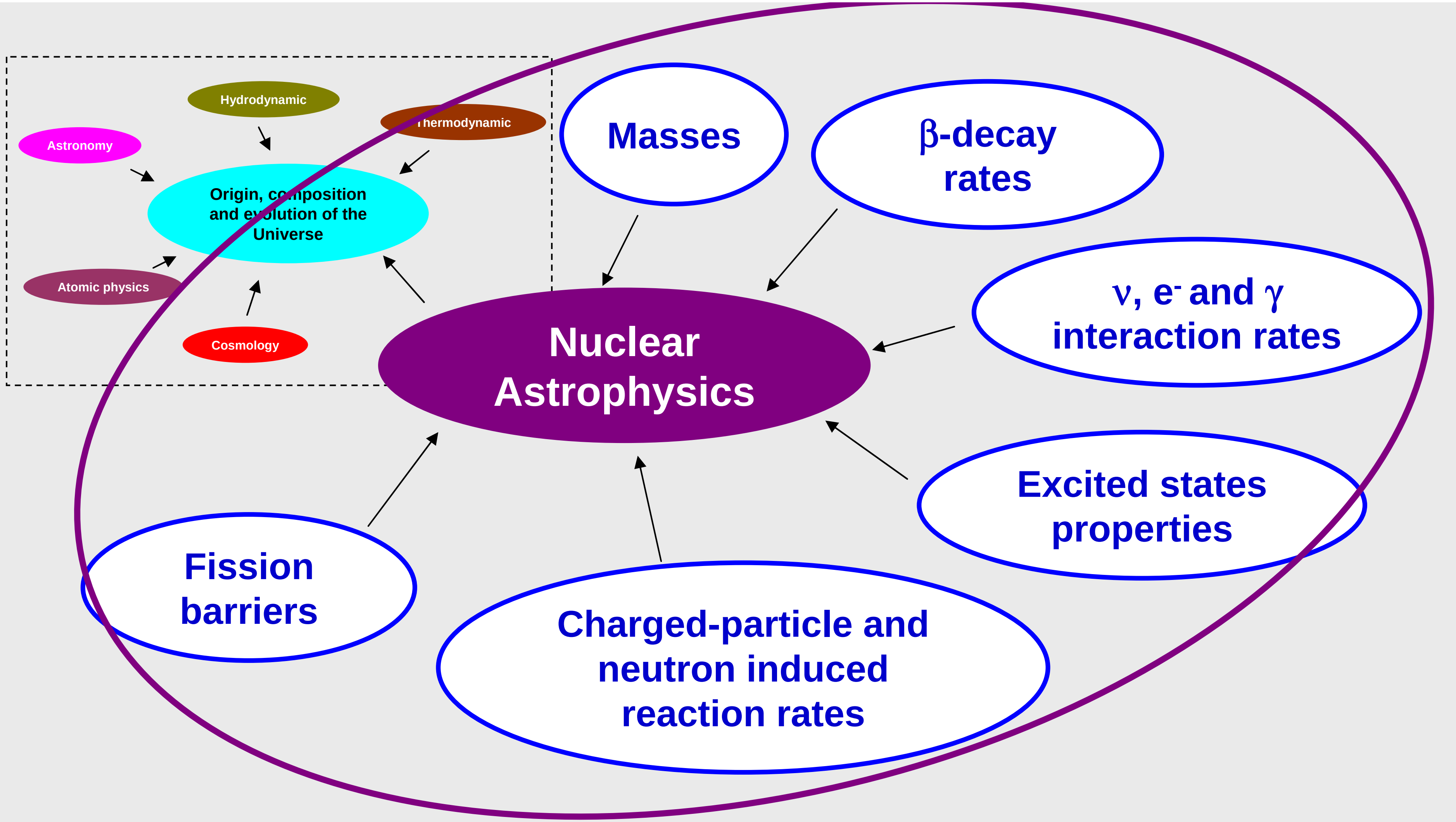
www.cyc.ucl.ac.be/CARINA

In charge of the Subtask "Astrophysics" for EURISOL since January 2006

Understanding the Universe

The structure and the evolution of stars are determined by precise laws and properties involving **many aspects of physics**





Synthesis of elements and energy production in stars

(Stability vs. Collapse)

Explaining the Universe

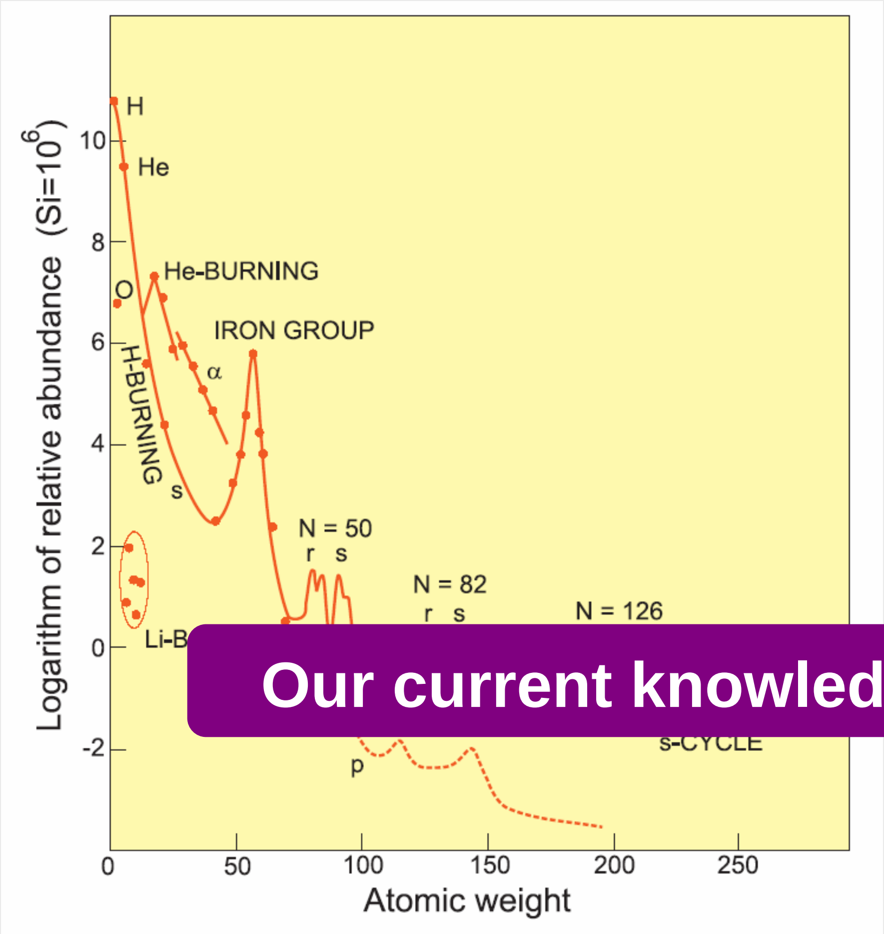


Figure from EURISOL report (based on Suess and Urey, Rev. Mod. Phys.,1956)

Long list of radioactive isotopes observed in the solar system

Explanation of detected amount: test of stellar models and nucleosynthesis calculations

Our current knowledge is very incomplete !

First CARINA workshop (June 2005)

Find the final report at www.cyc.ucl.ac.be/CARINA

Main conclusion

- ***For a coherent program in nuclear astrophysics one needs:***
  - High-intensity, high-purity light- to medium-mass **radioactive beams**.
  - Equipped with a **full range of experimental tools**:
    - **Series of gas targets** *(recirculation for rare gases)*
    - **A multi-stage recoil separator**
    - **A high-resolution magnetic forward spectrometer**
    - **Large-area, fine-granularity solid-state detectors or telescopes** *(on sharing basis; standard electronics and DAQ systems)*
    - **A dedicated high-resolution, high-efficiency gamma-ray detection system**

Nuclear astrophysics in EURISOL

- **Explosive scenarios**: novae, X-ray burst, supernovae, neutron stars…

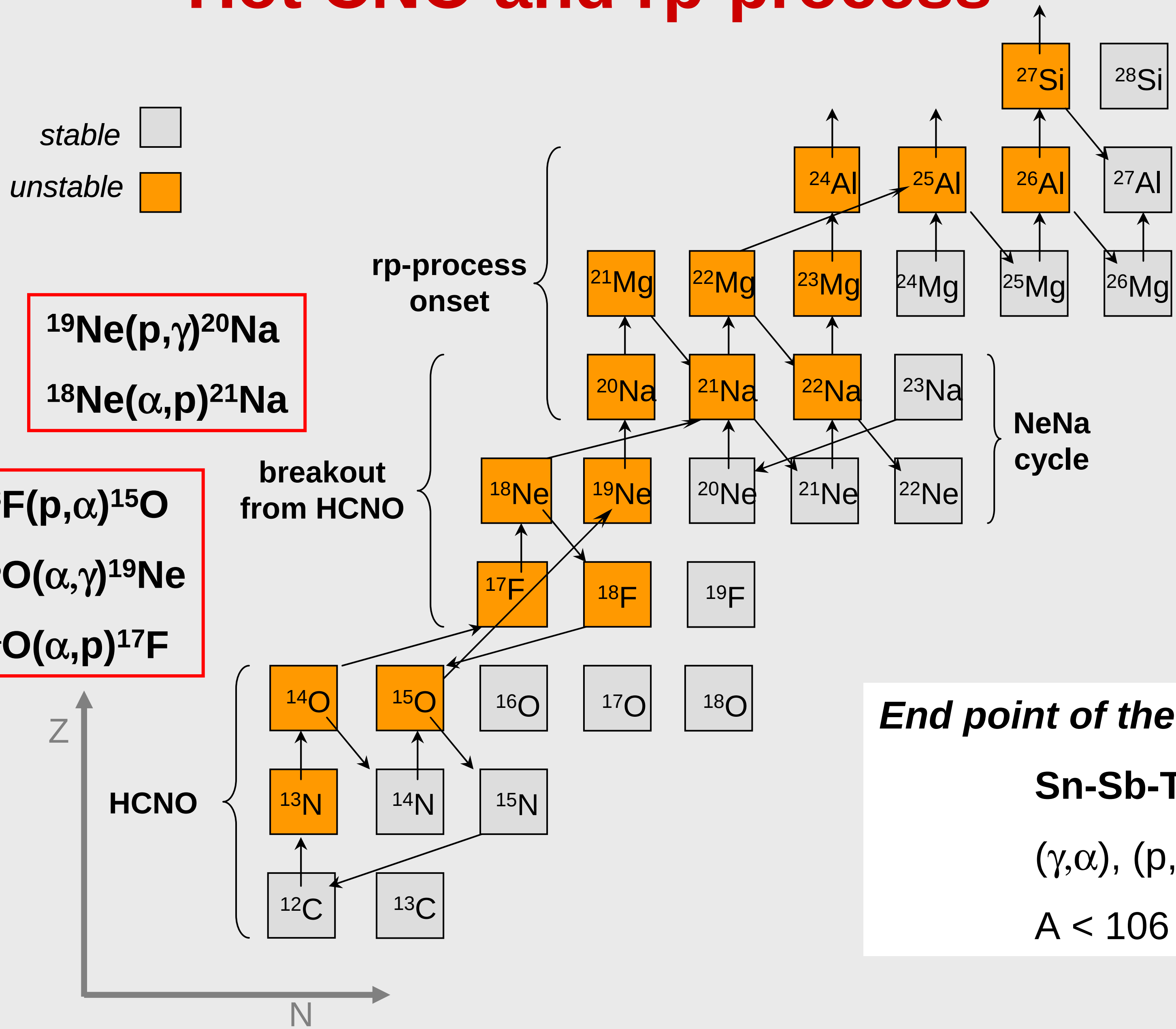
  The Hot CNO cycle and the rp process

  The r-process (the most challenging)

- **Moderate n-rich sites and AGB stars**

  The s-process

Hot CNO and rp-process



^{19}Ne(p,γ)^{20}Na

^{18}Ne(α,p)^{21}Na

^{18}F(p,α)^{15}O

^{15}O(α,γ)^{19}Ne

^{14}O(α,p)^{17}F

^{25}Al(p,γ)^{26}Si

^{26}Al(p,γ)^{27}Si

^{25}Si(α,p)^{28}P

^{30}P(p,γ)^{31}S

***End point of the rp-process*:**

Sn-Sb-Te region

(γ,α), (p,γ), β^+

A < 106

Novae and X-ray bursters

Observables

- Capture and transfer reactions rates on ‘short lived’ nuclei (N to Te)
- Nuclear masses and p-separation energies (near the proton drip-line)
- β-decay half-lives (including decay from excited and isomeric states)

Requirements

Specific cases:
Technical needs to be studied one-by-one

Targets

- Inverse kinematics: proton- and alpha-rich targets
- High intensity beams: need improved technologies
  - Extended-gas targets and gas cells
  - Jet-gas targets (specially suitable for recoil separators)
  - Cryogenic H and He targets

Detectors

- Particles: DSSSD … large solid angles …
- Gamma:
  - Large gamma arrays
  - Recoil separators (preferred)

No single solution for all cases !

$^{18}F(p,\alpha)^{15}O$ and nova gamma-ray emission

Snapshots of a Classical Nova Outburst (cortesy of J. José)

- **Gamma-ray emission from novae is dominated by positron annihilation following beta-decay of the newly synthesized ^{18}F**
- **^{18}F ($T_{1/2}$ = 110 min) → the annihilation radiation will be present after the expanding envelope of the novae becomes transparent.**
- **Current and planned gamma-ray observatories → measurement of ^{18}F abundances**
- **Main destruction reaction: $^{18}F(p,\alpha)^{15}O$**

→ ***Need cross section values at c.m. energies of 200-300 keV***

$^{18}F(p,\alpha)^{15}O$: a long standing problem !

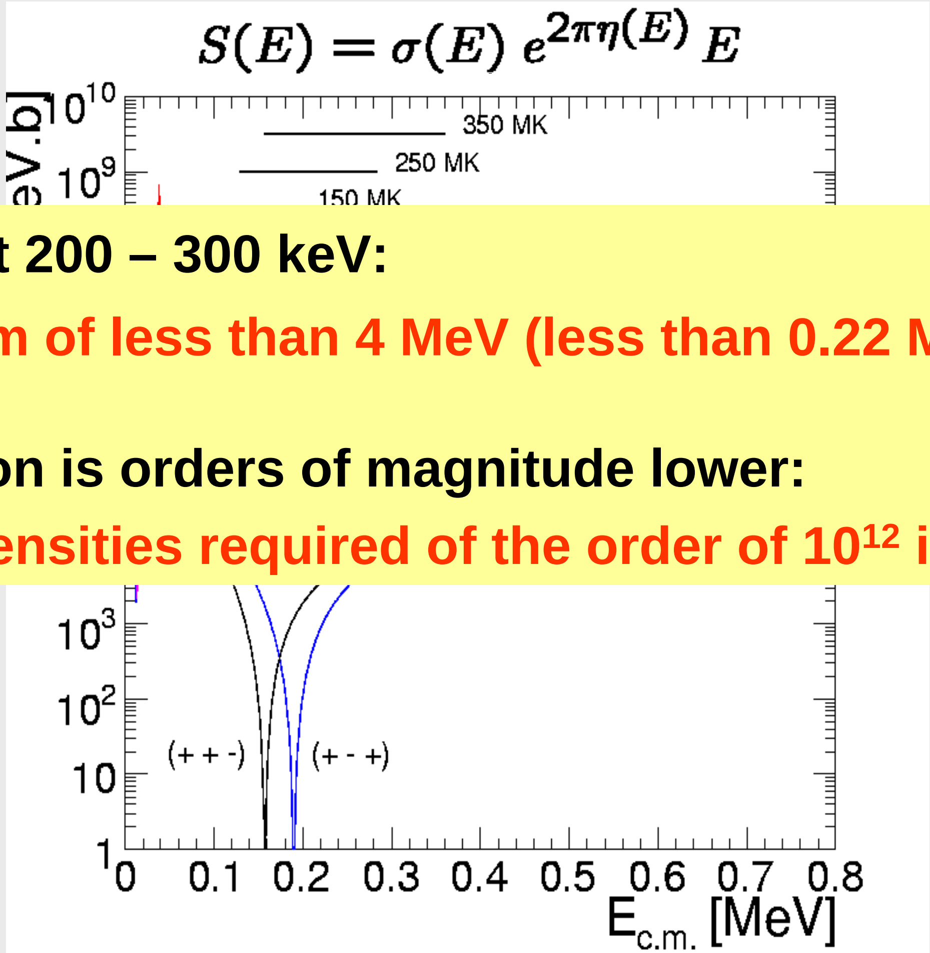
More than 10 years of research:

***Direct measurement*:**	**$^{18}F(p,\alpha)^{15}O$ – done (LLN, Oak Ridge, Argonne)**
***Elastic scattering*:**	**$^{18}F(p,p)^{18}F$ – done (LLN, Oak Ridge)**
***Transfer, DWBA*:**	**$^{18}F(d,p)^{19}F$ – done (LNN, Oak Ridge)**
***Inelastic scattering*:**	**$^{19}Ne(p,p')^{19}Ne$ – done, last week at LLN**
***Elastic scattering*:**	**$^{15}O(\alpha,\alpha)^{15}O$ – accepted at LLN, next year**

Beam (^{18}F, ^{15}O, ^{19}Ne) intensities at LLN: 10^6 – 10^8 ions/s (0.1 – 10 pfA)

^{18}F(p,α)^{15}O: present situation

Rate at novae temperatures is still uncertain by orders of magnitude



Need data at 200 – 300 keV:

→ a ^{18}F beam of less than 4 MeV (less than 0.22 MeV/nucleon)

Cross section is orders of magnitude lower:

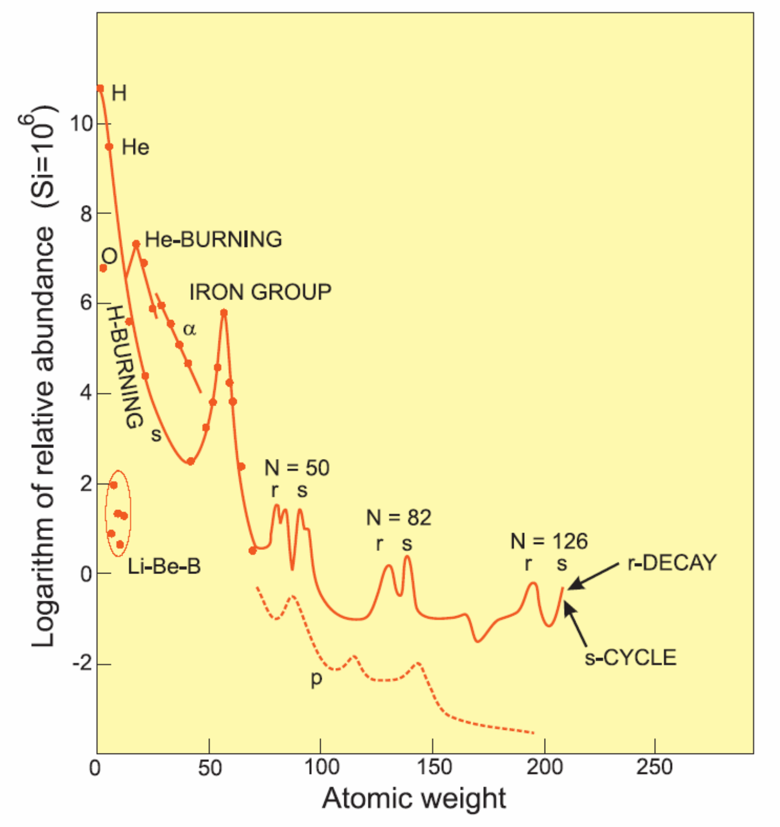
→ Beam intensities required of the order of 10^{12} ions/s (0.2 pμA)

Data from D. Bardayan et al. (Oak Ridge) and N. de Séréville et al. (LLN). Curves: R-matrix model

s- and r-processes

(p,γ) and (α,γ) reactions: inverse kinematics, low energy radioactive beams

Experimental data for (n,γ) reactions are practically missing



Indirect methods?

Accuracy? → astrophysics models

<u>Direct measurements:</u>

→ neutron beams (n_TOF, FRANZ…)

→ **implanted targets > 10^{16} atoms/cm^2**

beams > 10^{10} ions/s (EURISOL?)

The case of ^{60}Fe

→ ^{60}Fe beam : EURISOL?

- Production of ^{60}Fe ($T_{1/2}$ ~ 10^6 yr) in massive stars (pre-supernovae) depends strongly on the very uncertain reactions:

$$^{59}Fe(n,\gamma)^{60}Fe$$

$$^{60}Fe(n,\gamma)^{61}Fe$$

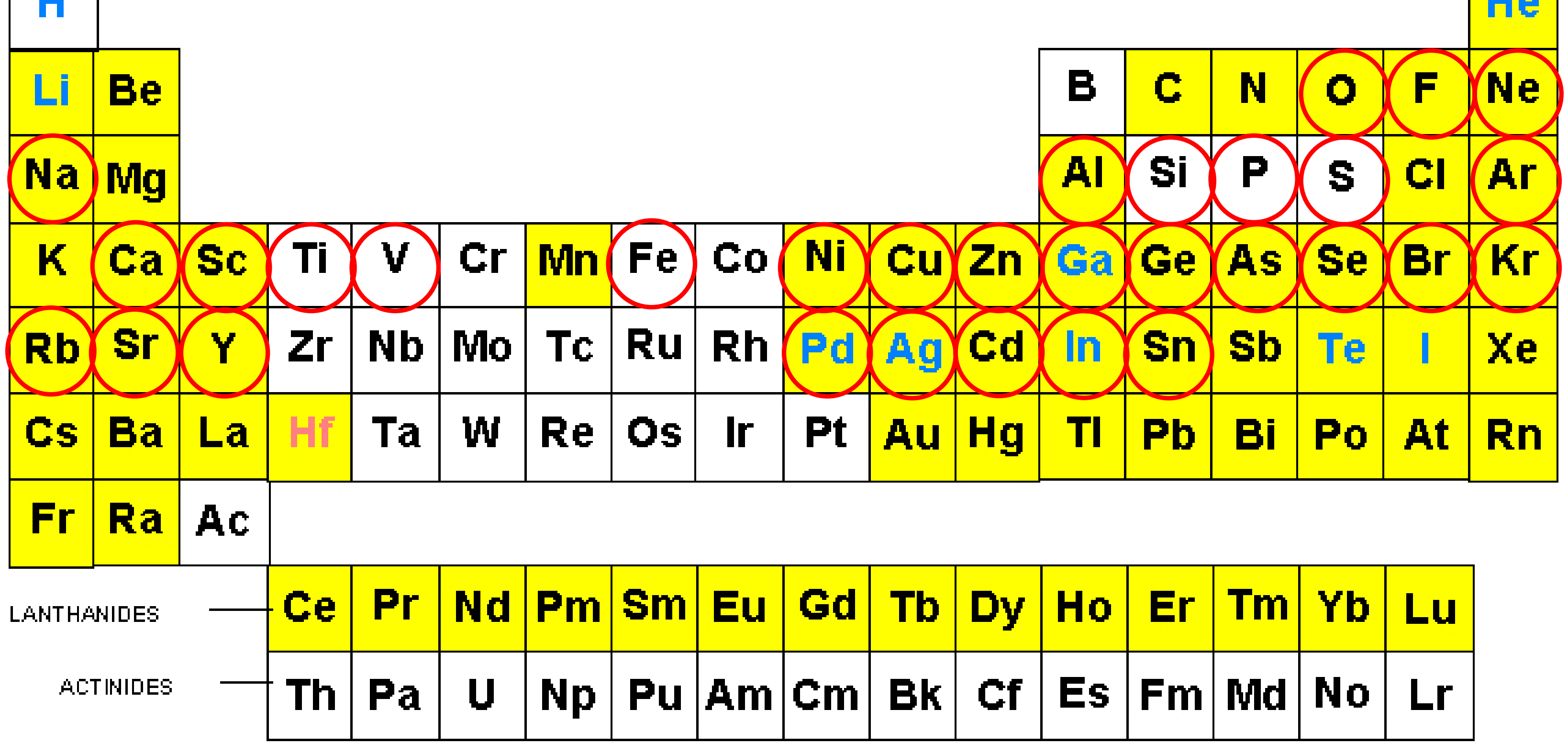
→***Supernova output***

→***Solar system formation triggered by a nearby supernova***

- The ^{60}Fe isotope:
  - detected in deep sea sediments (Knie et al. 2004)
  - observed by INTEGRAL (Harris et al. 2005) – ^{60}Co decay

Required beams

Table from http://isolde.web.cern.ch/ISOLDE/



Required intensities: 10^{10} – 10^{12} ions/s (~ ppA – pμA)

The case of ^{107}Pd

- Spectroscopy observation of elements on the surface of very old metal-poor halo stars (early Universe) – *Sneden et al. 2005*
  - Above barium (A > 138), agreement with solar r-process pattern: ***early robust r-process ?***
  - Below barium, disagreement, underproduction compared to solar system: ***a second r-process ?***

    → ***Ag abundance, specially low***

Mode 1: ^{107}Ag(n,γ)^{108}Ag and ^{109}Ag(n,γ)^{110}Ag are known

Mode 2: ^{107}Pd (β^-)→ ^{107}Ag, $T_{1/2}$ = 6 10^6 yr

But ^{107}Pd(n,γ)^{108}Pd not known

Implanted ^{107}Pd target at EURISOL?

The r-process path

Physics case

- **Nuclear structure properties of n-rich nuclei of paramount importance for understanding and modelling of the r-process**

Proposed experiments

- **Systemati** and
N=82: pos !

Observa

- **Masses, I**
deformati

Does such a research program sound realistic to you?

Requirements

- Low-energy intense beams
- Penning trap mass spectrometer (masses)
- Laser ion source (half-lives)

Requirements for NA Community at EURISOL

EURISOL cater to a broad range of physics interests

How much beam time *can be devoted to* ***nuclear astrophysics experiments*** *(very time-consuming)?*

Yes, if dedicated LE accelerator and target-ion-source

→ *see talk by Nigel Orr*

Call for Ideas for FP7

- From a network to ***Joint Research Projects for NA***

  → For details, please, check the CARINA website:

  www.cyc.ucl.ac.be/CARINA

- Ideas to be discussed in the next CARINA workshop: Spring 2007 in Belgium

  (exact dates and venue to be announced soon)

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For some of the cases discussed here: references are in the EURISOL report