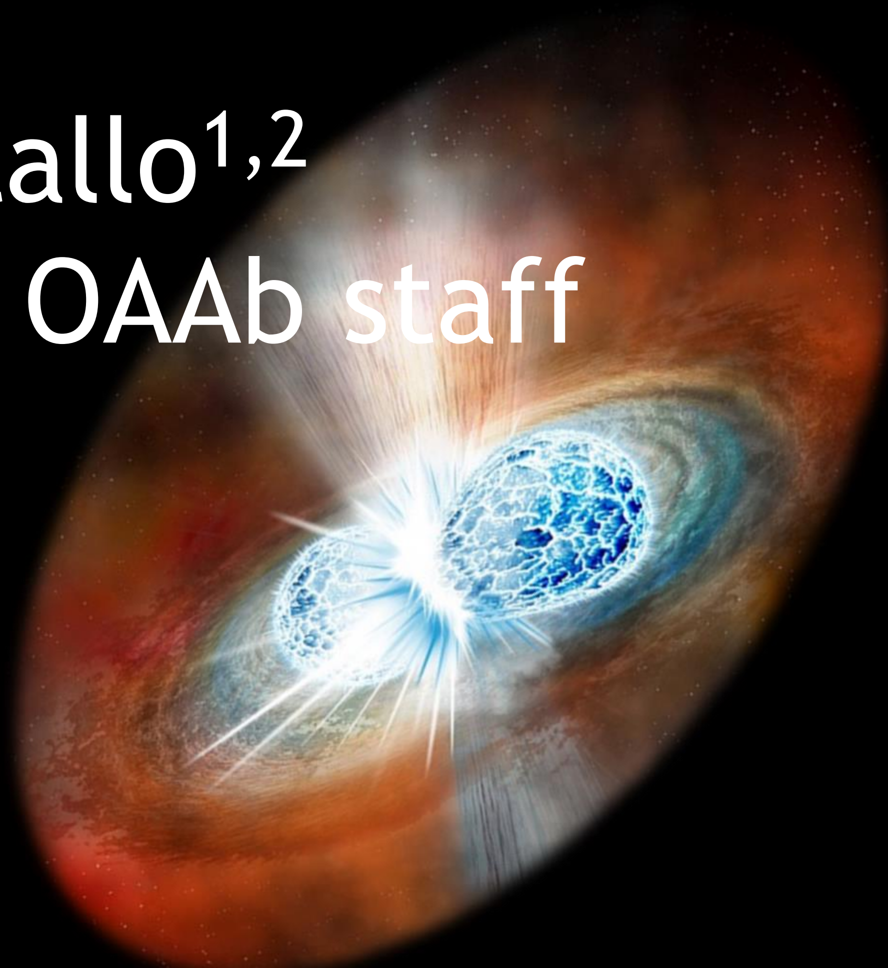
Stellar Cauldrons: heavy elements in the Universe



S. Cristallo[1,2]
on behalf of OAAb staff

1 – INAF, Osservatorio Astronomico d'Abruzzo, Italy
2 – INFN, Sezione di Perugia, Italy

INAF
Osservatorio Astronomico d’Abruzzo

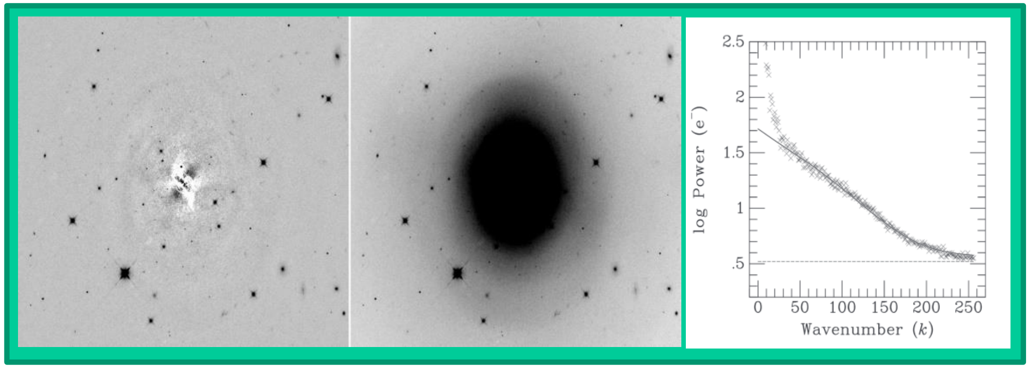
≈ 20 researchers
≈ 10 administratives and technicians
3 PhD students

NGC4993 luminosity distance (before SBF):
D = 44.0 ± 7.5 Mpc (Hjorth et al. 2017)
D = 37.7 ± 8.7Mpc (Im et al. 2017)
both based on Fundamental Plane
With Total error on *D* ~ 20%

SBF distance *D*= 40.7±1.4(ran)±1.9(stat) Mpc
Total error on *D* ~ 6%

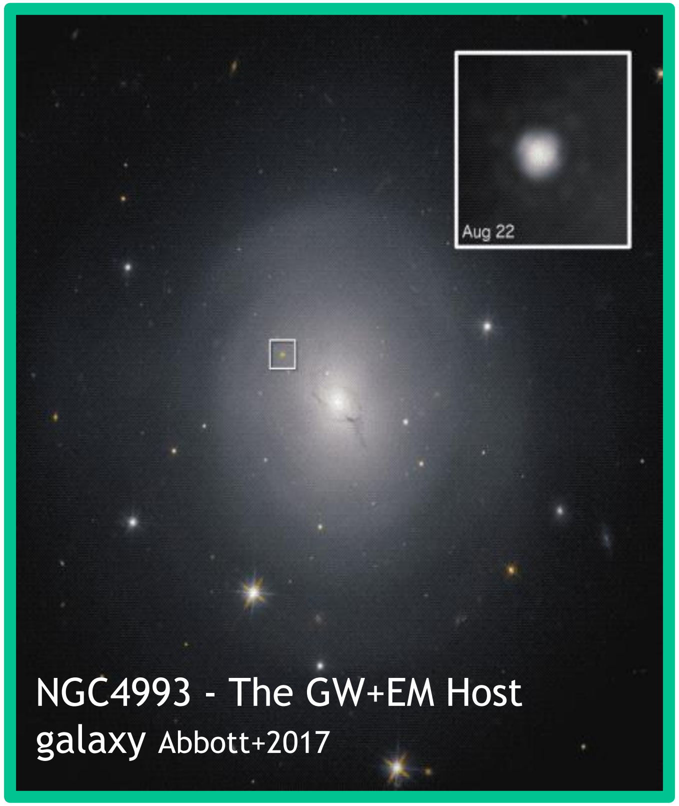
Abbott+18 D from standard sirens:
D=42.4+3.5 Mpc

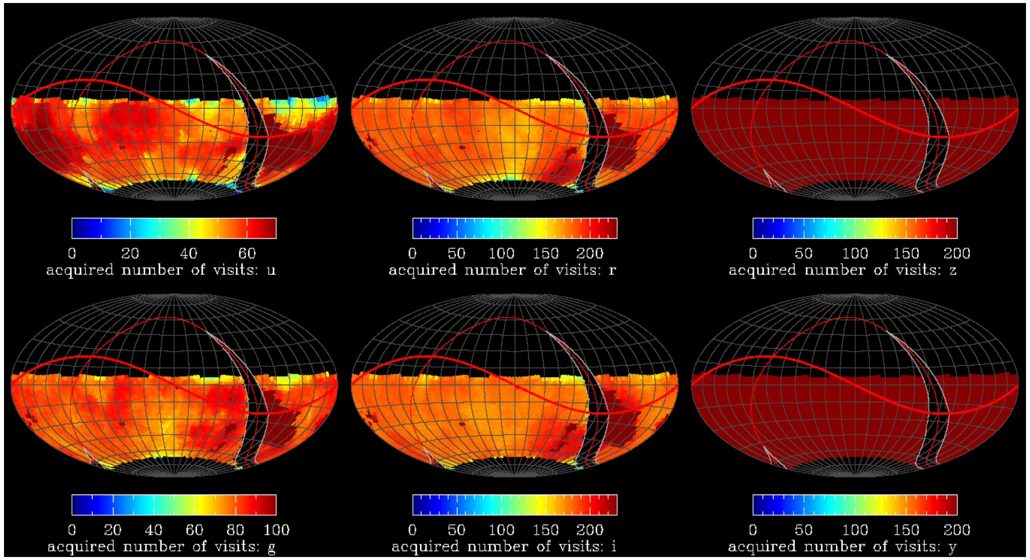
SBF analysis very (very) briefly



INAF-OAAb & GSSI
Cosmology with (SBF) distances

PhD of Nandita Kethan





The LSST perspective

Large Survey of Space and Time
By the Vera Rubin Observatory (LSST)

A INAF-OAAb/GSSI project in progress
PhD student involved: Nandini Hazra

1. INAF-OAAb & GSSI
Transit optical electromagnetic follow-up

Schmidt Telescope at Campo Imperatore

Primary mirror	92cm
Corrector plane	65cm
Field of Views	**1.3° square**
CCD	4096x4096 pix
Pixel scale	**1.0 arcsec/pix**
Filters' system	Sloan (u, g, r, i, z)

Team Members

- Fiore De Luise (INAF-OAAb)
- Francesca Onori (INAF-OAAb)
- Roberta Carini (INAF-OAR)
- Enzo Brocato (INAF-OAAb)
- Mauro Dolci (INAF-OAAb)
- Gaetano Valentini (INAF-OAAb)

1. INAF-OAAb & GSSI
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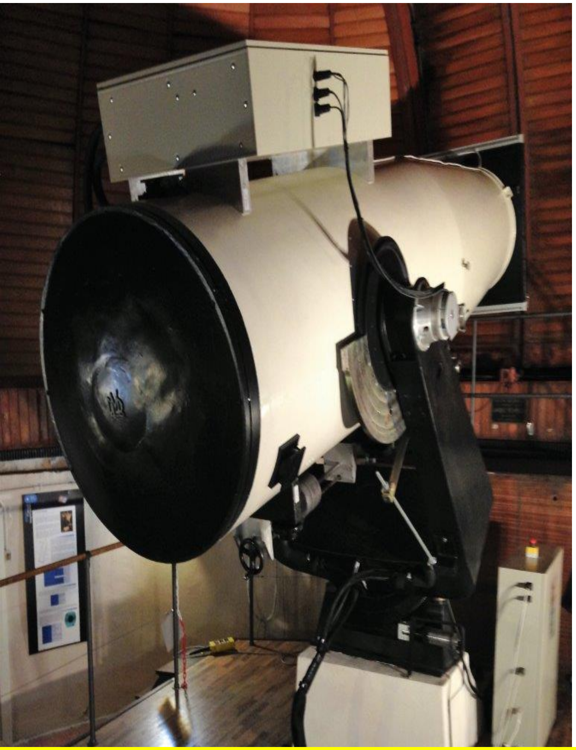

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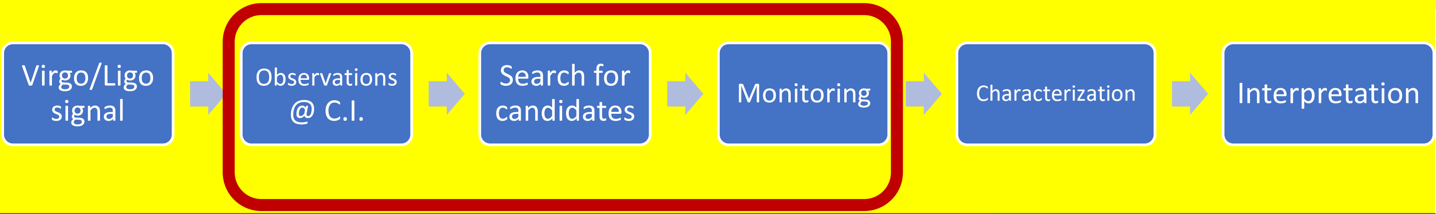
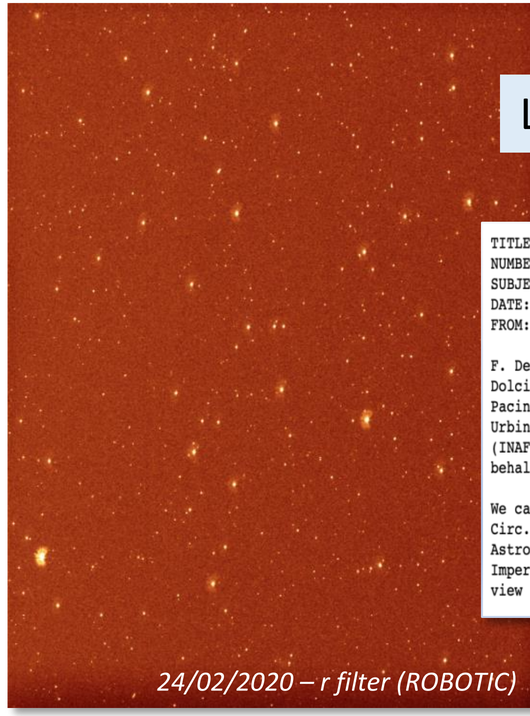
Search of Optical Counterparts of Gravitational Wave Events

Example of research activity @ Schmidt Telescope



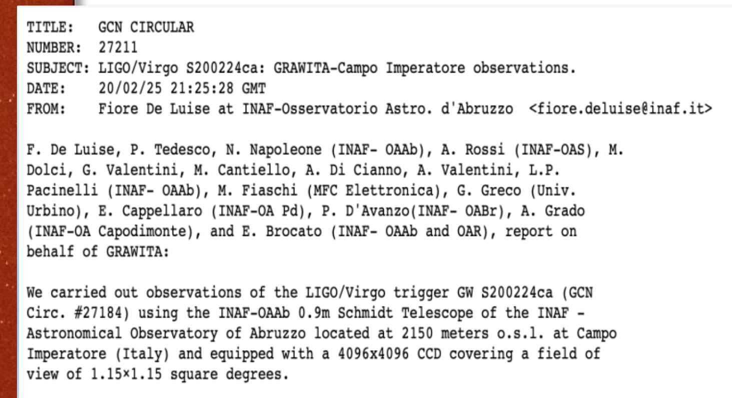
On-going projects:

- **Transients:**
  - **Gravitational waves**
  - **GRB**
  - **Supernovae**
  - **Tidal Disruption Events**
- **Space Debris**
- **Near Earth Objects follow up**

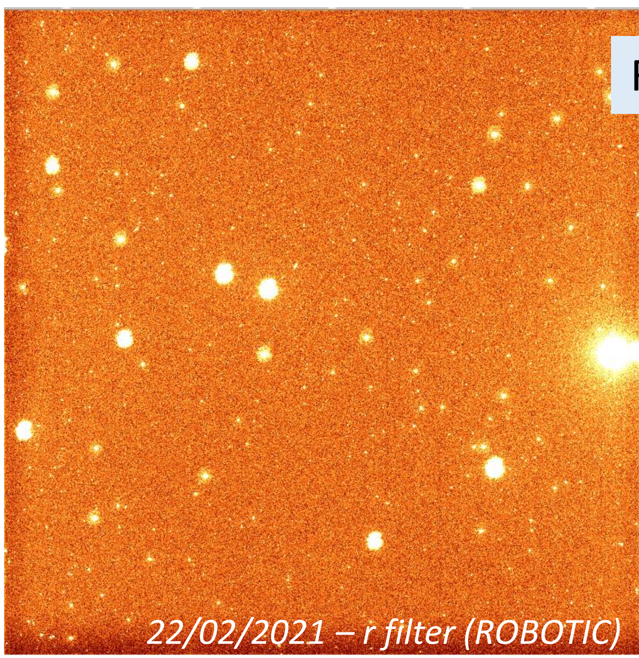


24/02/2020 – r filter (ROBOTIC)

LIGO/Virgo trigger GW S200224ca

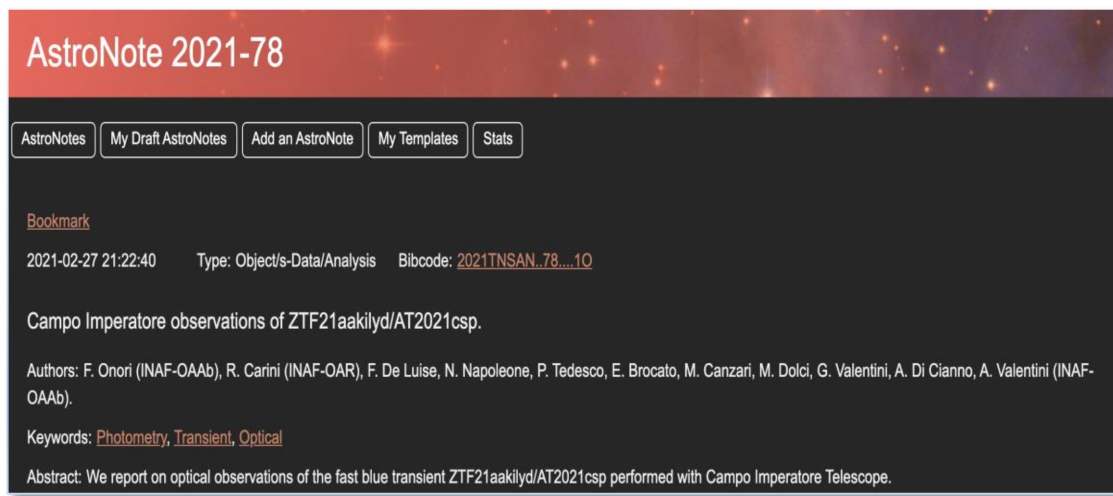


```
TITLE:   GCN CIRCULAR
NUMBER:  27211
SUBJECT: LIGO/Virgo S200224ca: GRAWITA-Campo Imperatore observations.
DATE:    20/02/25 21:25:28 GMT
FROM:    Fiore De Luise at INAF-Osservatorio Astro. d'Abruzzo  <fiore.deluise@inaf.it>

F. De Luise, P. Tedesco, N. Napoleone (INAF- OAAb), A. Rossi (INAF-OAS), M.
Dolci, G. Valentini, M. Cantiello, A. Di Cianno, A. Valentini, L.P.
Pacinelli (INAF- OAAb), M. Fiaschi (MFC Elettronica), G. Greco (Univ.
Urbino), E. Cappellaro (INAF-OA Pd), P. D'Avanzo(INAF- OABr), A. Grado
(INAF-OA Capodimonte), and E. Brocato (INAF- OAAb and OAR), report on
behalf of GRAWITA:

We carried out observations of the LIGO/Virgo trigger GW S200224ca (GCN
Circ. #27184) using the INAF-OAAb 0.9m Schmidt Telescope of the INAF -
Astronomical Observatory of Abruzzo located at 2150 meters o.s.l. at Campo
Imperatore (Italy) and equipped with a 4096x4096 CCD covering a field of
view of 1.15×1.15 square degrees.
```



22/02/2021 – r filter (ROBOTIC)

Recent observations of the fast blue transient ZTF21AT2021csp



AstroNote 2021-78

AstroNotes | My Draft AstroNotes | Add an AstroNote | My Templates | Stats

Bookmark

2021-02-27 21:22:40   Type: Object/s-Data/Analysis   Bibcode: 2021TNSAN..78....1O

Campo Imperatore observations of ZTF21aakilyd/AT2021csp.

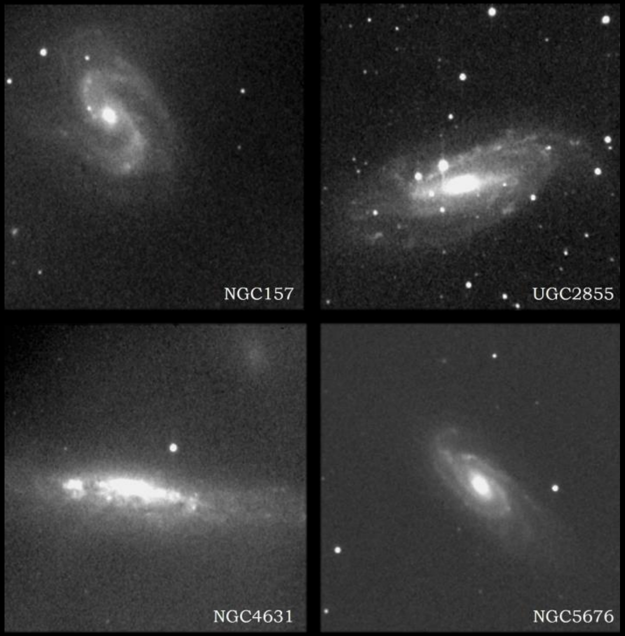
Authors: F. Onori (INAF-OAAb), R. Carini (INAF-OAR), F. De Luise, N. Napoleone, P. Tedesco, E. Brocato, M. Canzari, M. Dolci, G. Valentini, A. Di Cianno, A. Valentini (INAF-OAAb).

Keywords: Photometry, Transient, Optical

Abstract: We report on optical observations of the fast blue transient ZTF21aakilyd/AT2021csp performed with Campo Imperatore Telescope.

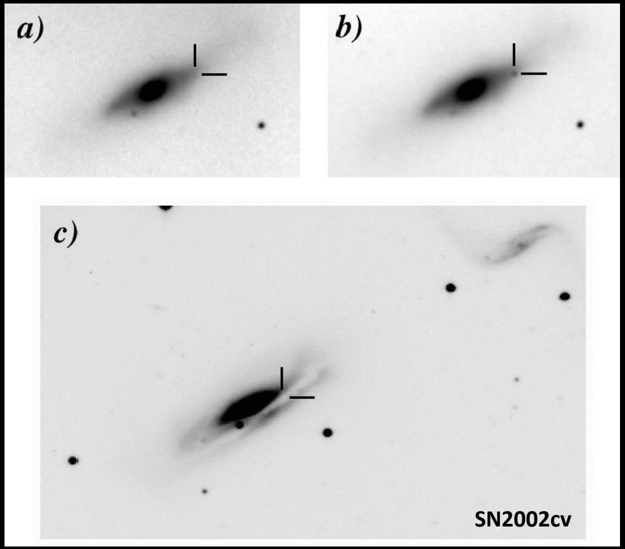
2. INAF-OAAb & GSSI
Near-Infrared Astronomy at Campo Imperatore Observatory

Campo Imperatore observing conditions are excellent thanks to reduced water vapor content (spectral blending from H_2O-lines) and low temperatures (low airglow background, passive cooling of instruments)



- Key science cases for NIR@AZT-24 at Campo Imperatore:

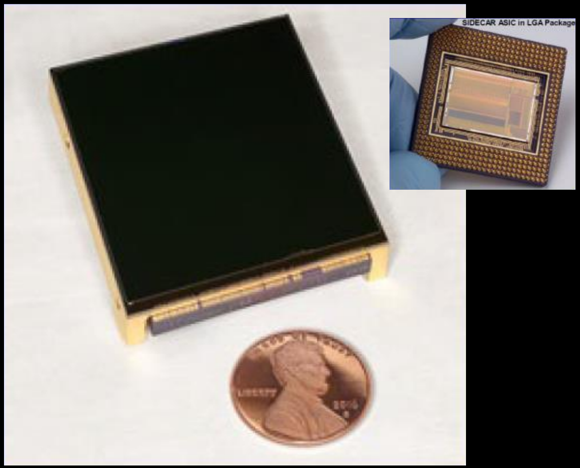
  - **Multimessenger Astronomy: Follow-up of counterparts of Gravitational Wave Events (es.: NIR observations of Kilonovae)**
  - **Supernovae: Follow-up of SNe in nearby galaxies** *(NIR light curves of SN embedded in gas and dust environments. Es. supernova SN2002cv)*
  - **Gamma-Ray Bursts (GRB):** NIR counterparts of Gamma-Ray Bursts
  - NIR observations of AGNs
  - NIR period-luminosity relation of Classical Cepheids
  - follow-up of minor bodies of Solar System
  - Classification and evaluation of Space Debris



Proposal for a new, wider field, AO-assisted NIR camera

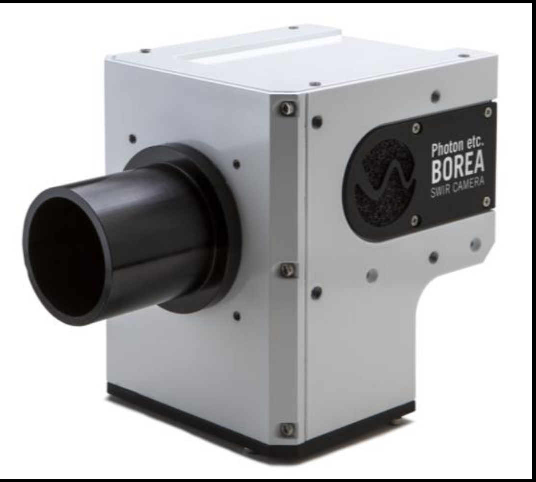
The idea is to exploit the excellent site of Campo Imperatore for NIR observations with the 1.1

➡ by acquiring a new INFRARED, ADAPTIVE-OPTICS facility to be mounted at the AZT-24 a 1.1 m. telescope



Observational advantages:

- Wavelength range of operation: **1 – 2.5 µm**. Imaging in **J, H, K bands** plus a number of narrow bands
- **Near Infrared low-resolution spectroscopy** or narrow-band spectrophotometric imaging
- Perform imaging over a **14.5 x 14.5 arcmin^2 FoV** (New Wide Camera based on 2048 x 2048 HgCdTe detector cooled at 77K) platescale of 0.85 arcsec/pix
- **Adaptive-Optics:** Atmospheric tip/tilt corrector on the telescope focal plane would contribute to a better concentration of the signal coming from the astronomical sources, with an expected increase up to 100%. The new camera could therefore produce a signal-to-noise ratio improvement by a factor up to 3, effectively increasing the limiting performance by at least one magnitude.

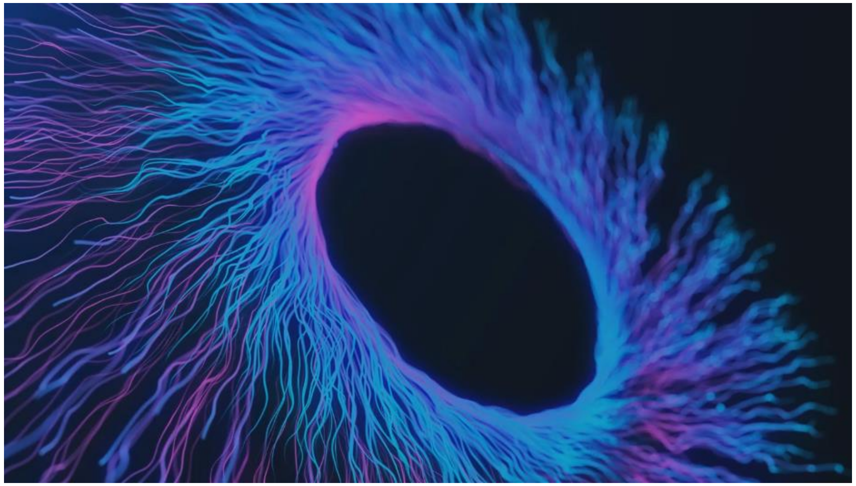


BOREA HgCdTe camera system, cooled at 77 K, from Photon ETC (Canada).

3. INAF-OAAb & GSSI
Stars as laboratories of particle physics

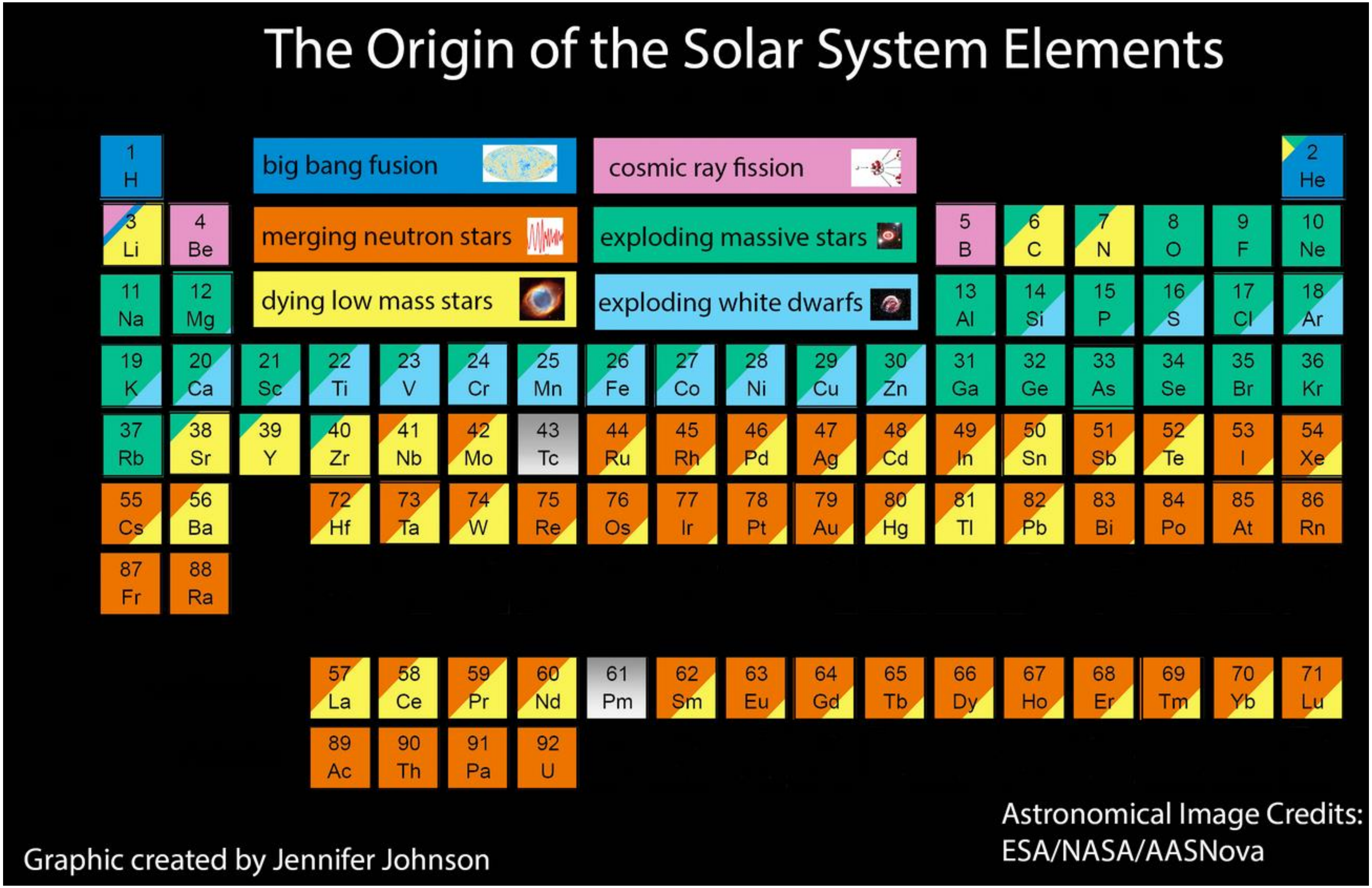
There exist open problems in our understanding the fundamental bricks of our Universe whose solutions require an extension of the Standard Model (SM) and of the related Standard Cosmological Model (SCM).

Many extensions of the SM imply the existence of small particles, such as axions or, more in general, axion-like particles (ALPs).



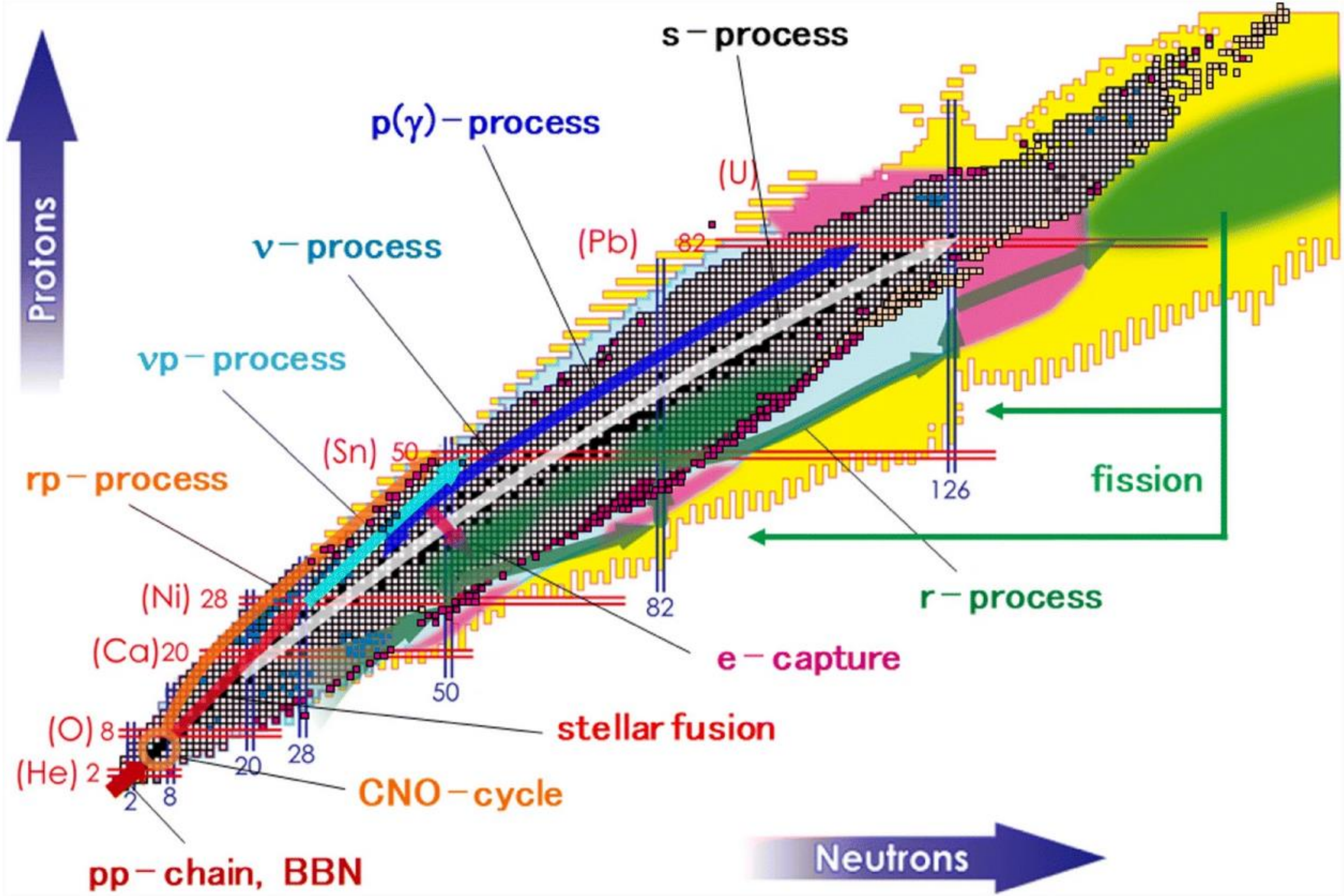
We aim to develop state-of-the-art stellar models that includes the effects of exotic weak interactive particles predicted by the extension of the SM, which will be compared to the growing amount of astrometric, photometric and spectroscopic data are (or will be) provided by the new generation of astronomical facilities (GAIA, JWST, ELT).

Nuclide chart: a stellar perspective



Starting point of my short course “Nucleosynthesis”

Nuclide chart: a stellar perspective



Past thesis @ OAAb + GSSI

GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

- The slow neutron capture process in Asymptotic Giant Branch stars (AGBs):
  - ✓ Mixing triggered by magnetic fields in AGBs

- The rapid neutron capture process in Neutron Stars Mergers (NSMs):
  - ✓ Production of light elements in NSMs

1. Perego, Vescovi, et al. 2022 (ApJ, 925, 22)
2. Vescovi 2021 (Universe, 8, 16)
3. Vescovi & Reifarth 2021 (Universe, 7, 239)
4. Vescovi et al. 2021 (A&A, 652, 100)
5. Vescovi et al. 2021 (JPhG, 48, 5201)
6. Vescovi et al. 2020 (ApJL, 897, 25)
7. Vescovi et al. 2019 (A&A, 623, 126)
8. Vescovi et al. 2018 (ApJ, 863, 115)

GRAN SASSO SCIENCE INSTITUTE

SCUOLA INTERNAZIONALE SUPERIORE DI STUDI AVANZATI

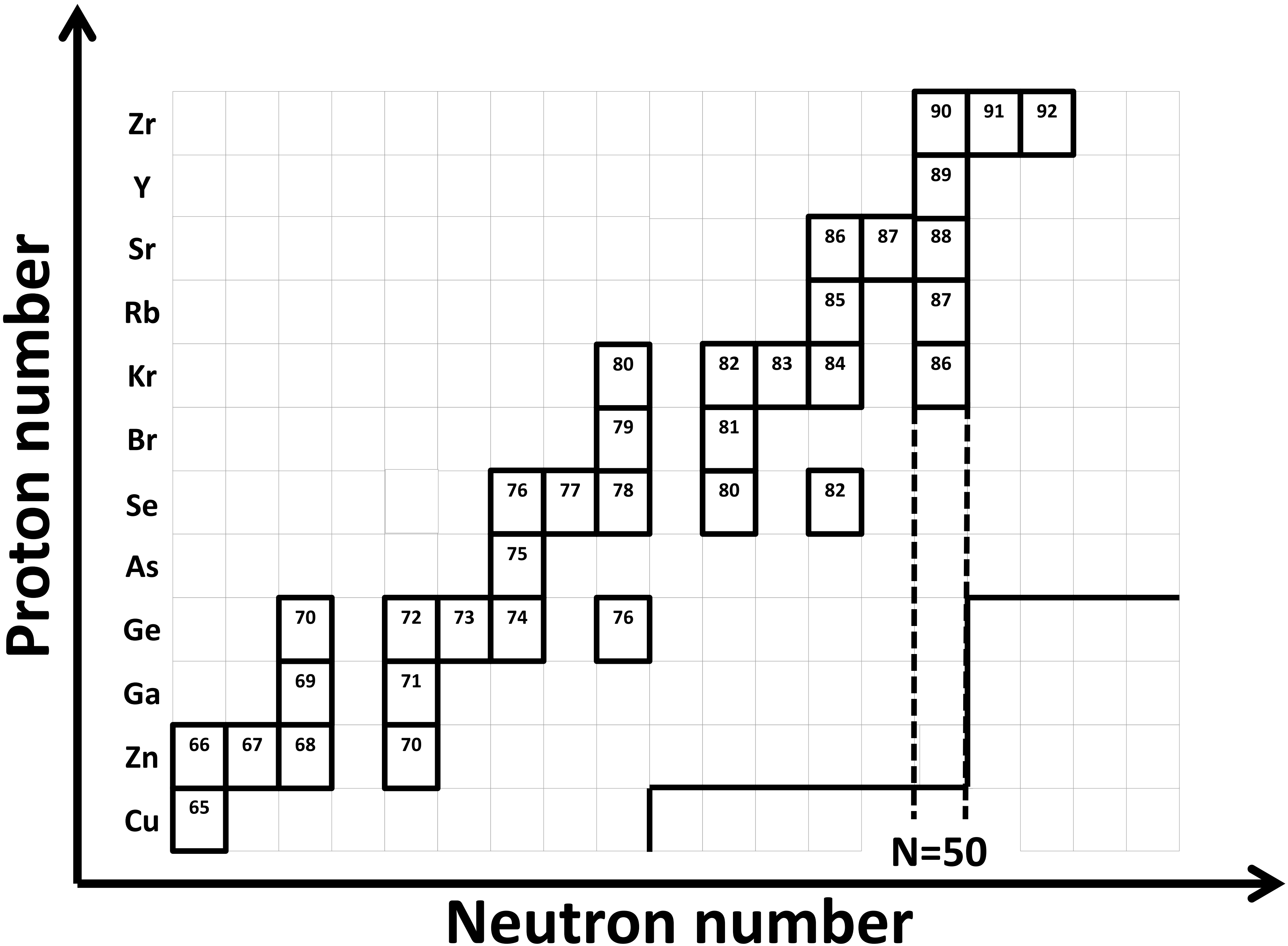
Nucleosynthesis of light and heavy elements across the Galaxy

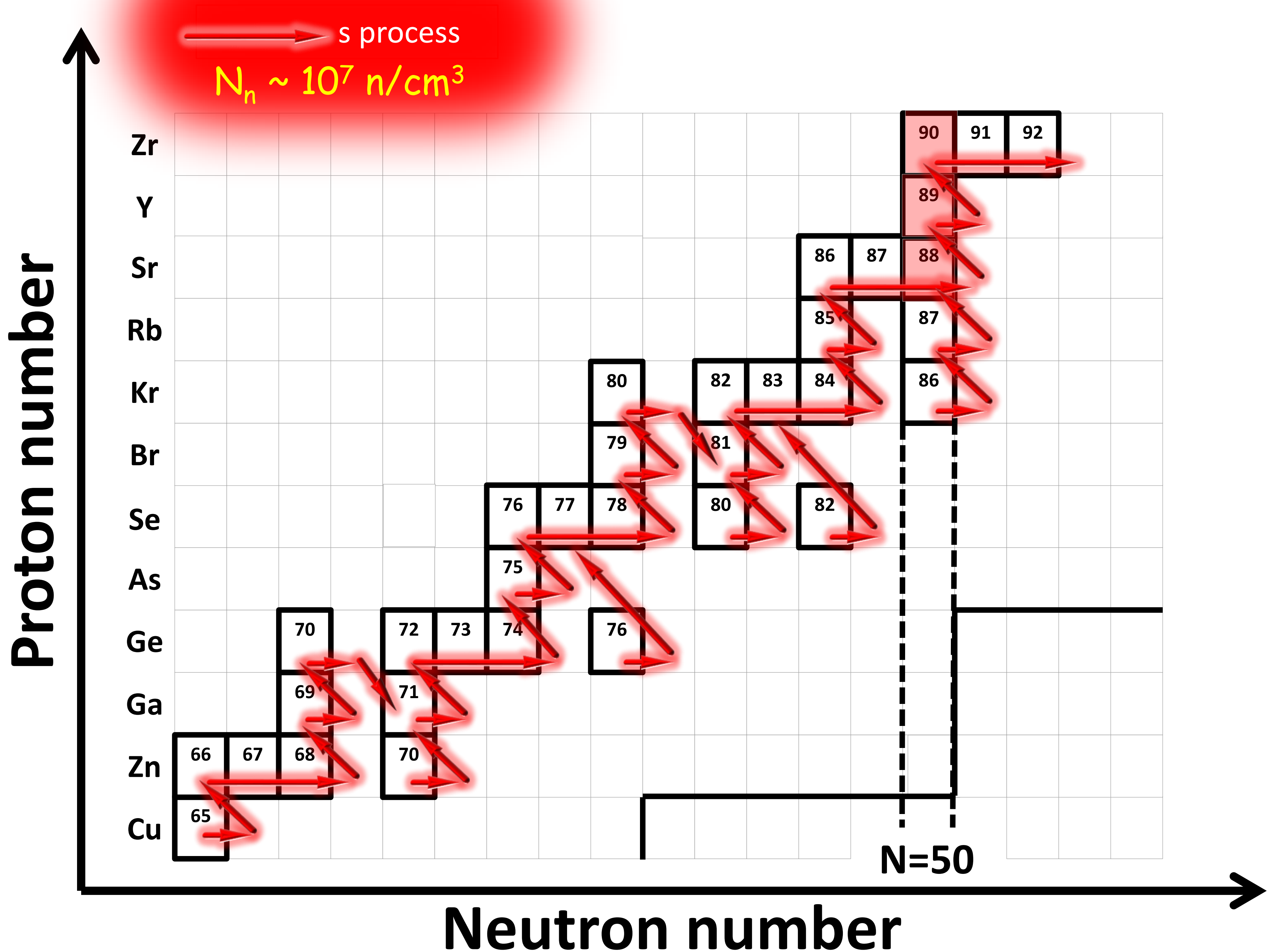
THESIS ADVISOR:
Dr. Sergio Cristallo

CANDIDATE:
Diego Vescovi

THESIS ADVISOR:
Prof. Dr. Marica Branchesi

Diego Vescovi (PhD defense in Oct. 2020)


Proton number
Neutron number
Zr
Y
Sr
Rb
Kr
Br
Se
As
Ge
Ga
Zn
Cu
90 91 92
89
86 87 88
85 87
80 82 83 84 86
79 81
76 77 78 80 82
75
70 72 73 74 76
69 71
66 67 68 70
65
N=50



s process
$N_n \sim 10^7$ n/cm^3
Proton number
Zr
Y
Sr
Rb
Kr
Br
Se
As
Ge
Ga
Zn
Cu
90
91
92
89
86
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85
87
80
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86
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81
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75
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74
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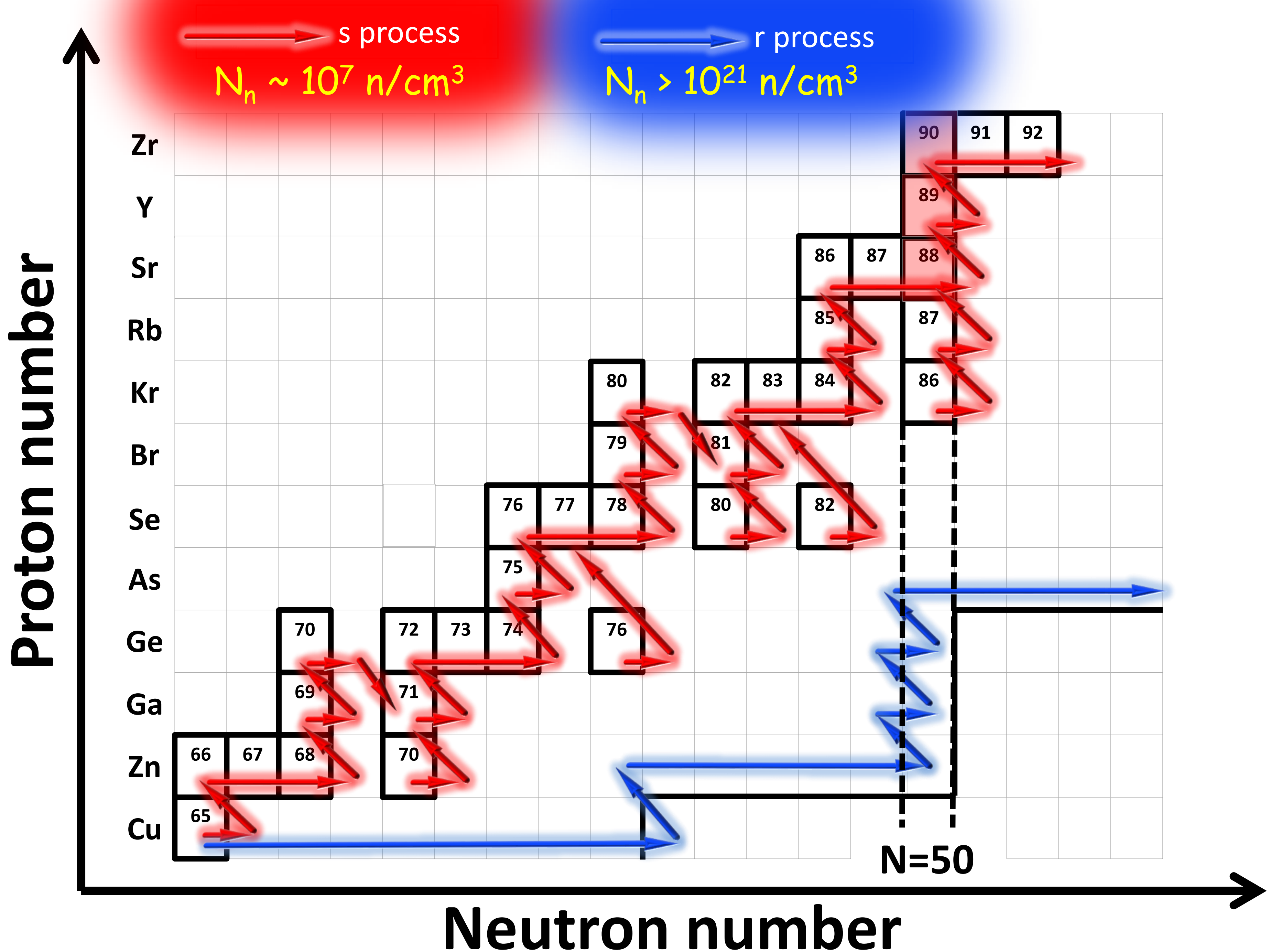
66
67
68
70
65
N=50
Neutron number


s process
$N_n \sim 10^7$ n/cm^3
r process
$N_n > 10^{21}$ n/cm^3
Zr
Y
Sr
Rb
Kr
Br
Se
As
Ge
Ga
Zn
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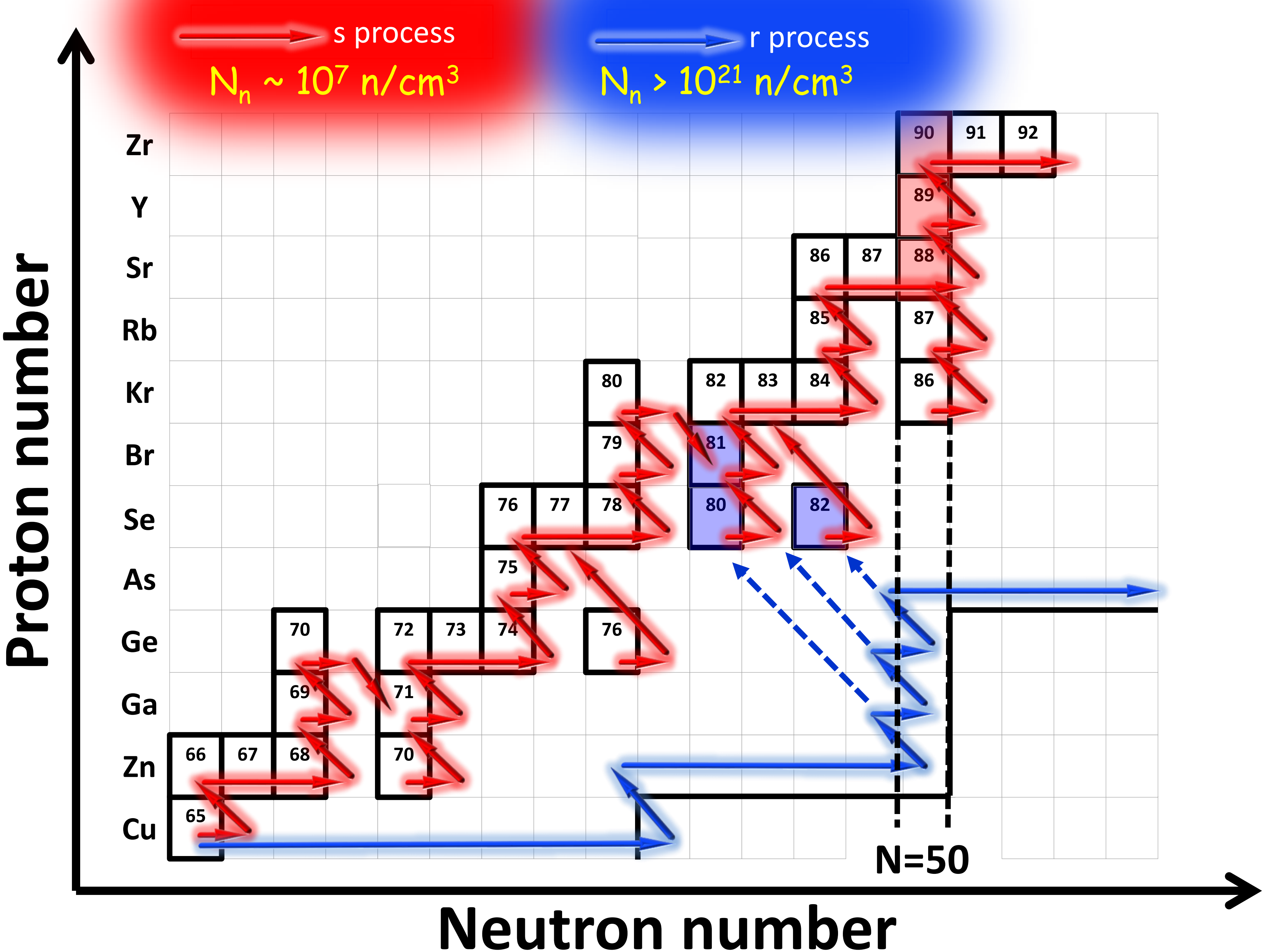
70
65
N=50
Proton number
Neutron number


s process
$N_n \sim 10^7$ n/cm^3
r process
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Zr
Y
Sr
Rb
Kr
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Se
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Ge
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Zn
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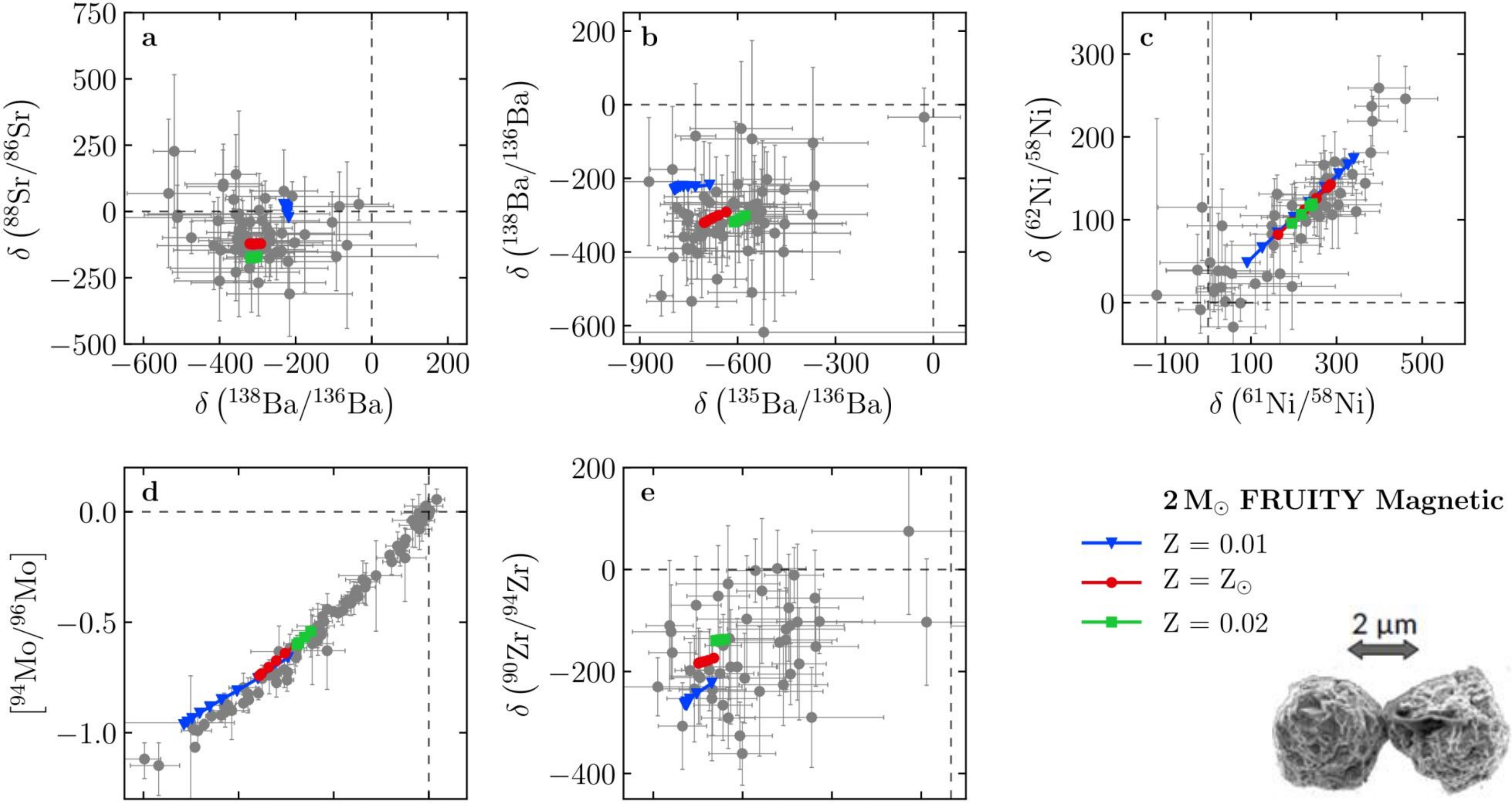
90 91 92
89
86 87 88
85 87
80 82 83 84 86
79 81
76 77 78 80 82
75
70 72 73 74 76
69 71
66 67 68 70
65
N=50
Proton number
Neutron number

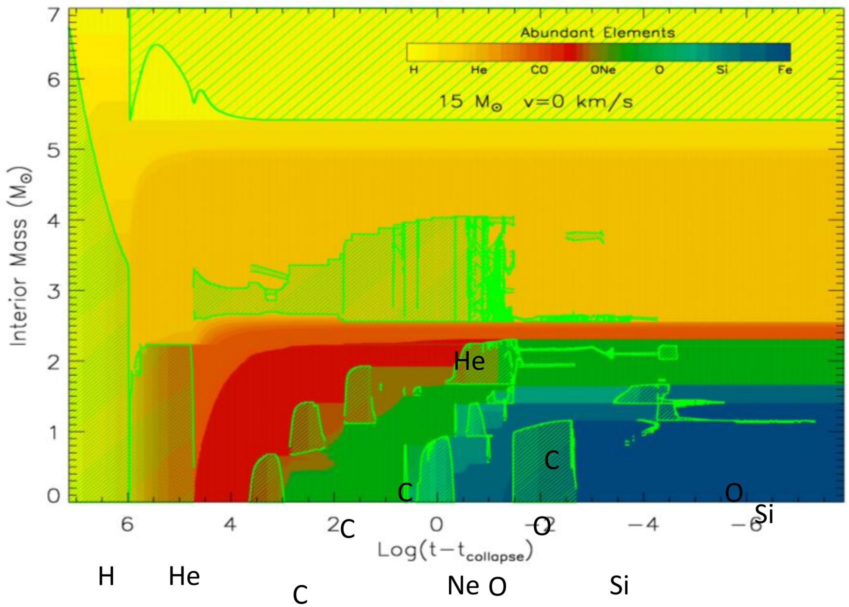
Presolar SiC Grains in Asymptotic Giant Branch (AGB) stars

- Stellar models with **same initial mass** (2 $M_{\odot}$) and **close-to-solar metallicity**
- **Magnetic** contribution



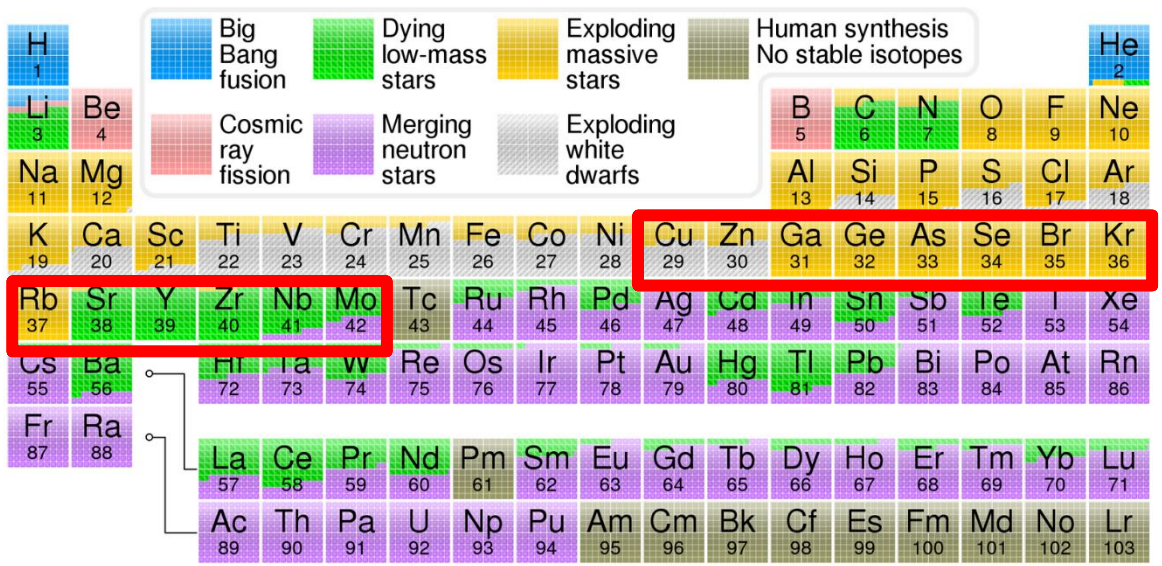
Vescovi+2020

4. INAF-OAAb & GSSI
Slow Neutron Captures in Massive Stars

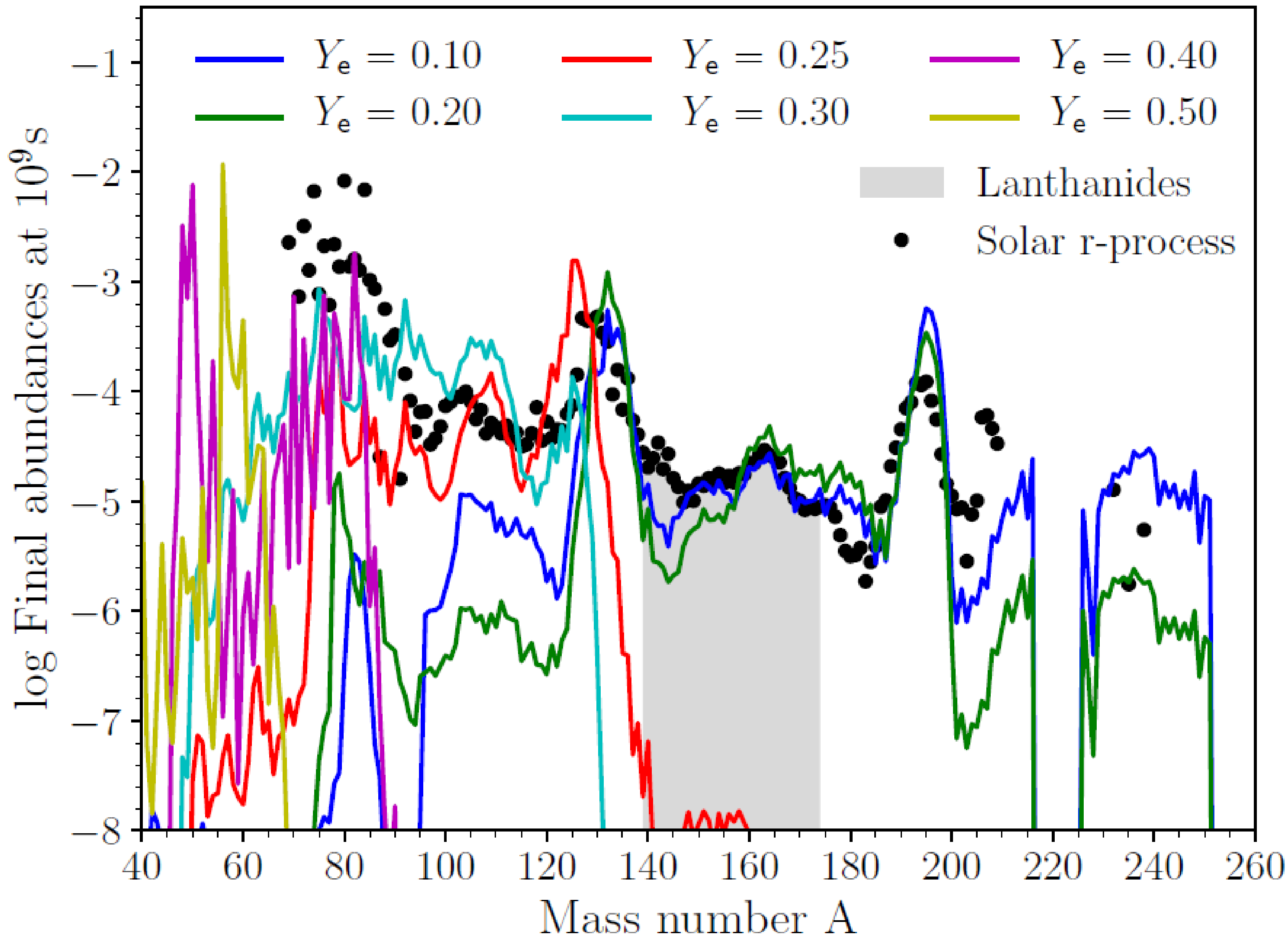


These objects are responsible for the production of light elements, iron-peak elements, but also for light neutron capture elements (from Cu to Sr, and possibly to Mo). This process is known as **weak s-process**.

Many uncertainties related to physical processes (as rotation) and nuclear reaction rates (^{12}C+α, ^{12}C+^{12}C, etc).

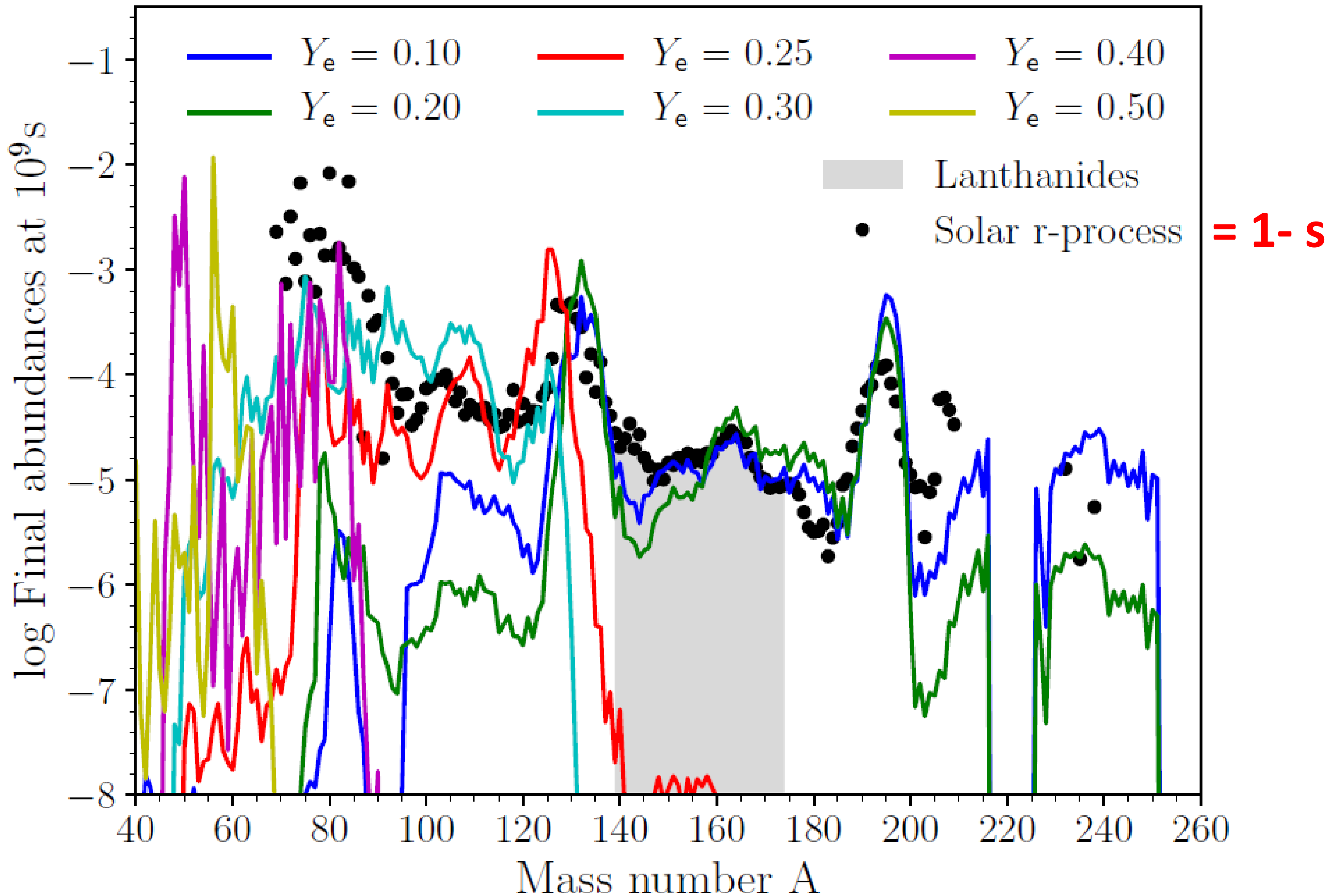


Typical r-process distributions



The **canonical** approach to the r -process is based on an **analytic description** of the phenomenon starting from some **fundamental considerations**.

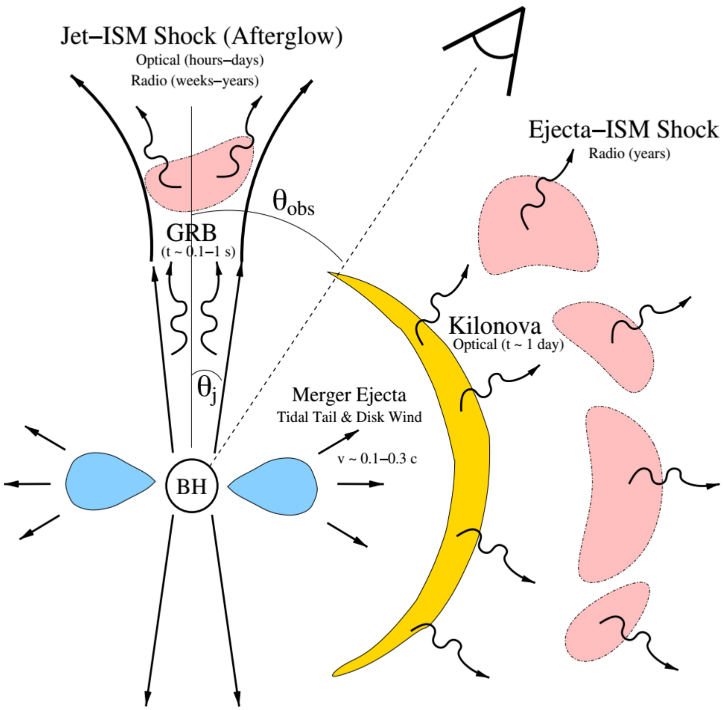
Typical r-process distributions



The **canonical** approach to the r -process is based on an **analytic description** of the phenomenon starting from some **fundamental considerations**.

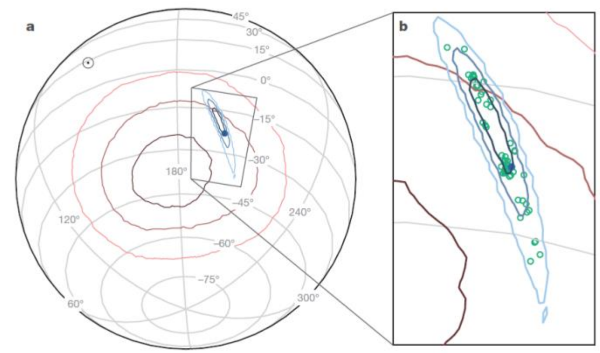
The search for an astrophysical environment suitable for the occurring of the r-process is delicate, as the physical conditions required are extreme.

To date, the only astrophysical site in which the r-process has been demonstrated to occur is a **NSM**. In particular, the electromagnetic counterpart (**AT2017gfo**) of the gravitational wave detection **GW170817** (Abbott+2017) is in agreement with the heating rate and opacity expected from **a distribution of freshly synthesized r-process elements** (see, e.g., Metzger+2019).



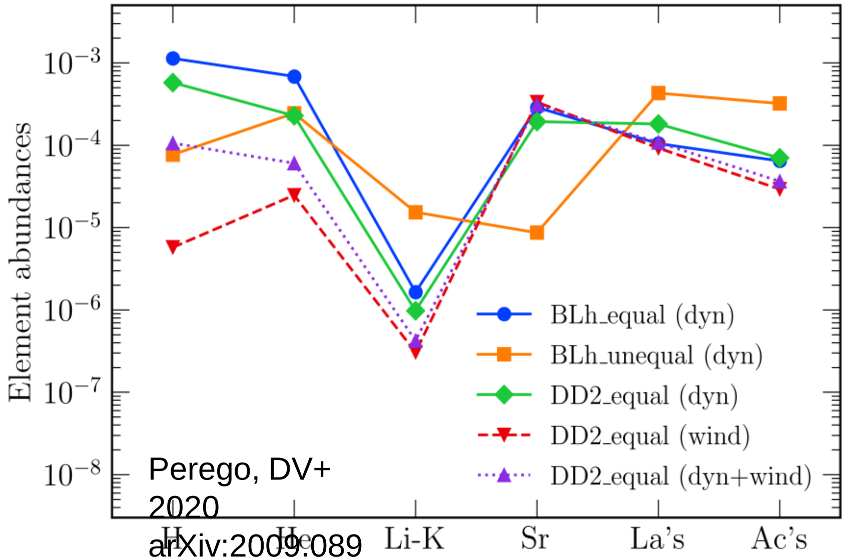
Metzger & Berger 12

Arcavi+2017



A few days after merger the spectrum reveals absorption features, qualitatively compatible with the forest of lines expected for **lanthanides and actinides**.
The analysis at 1.5 days suggested the presence of **strontium (Watson+2019)**.
WHAT ABOUT LIGHT ELEMENTS?

Production of very light elements in kilonovae

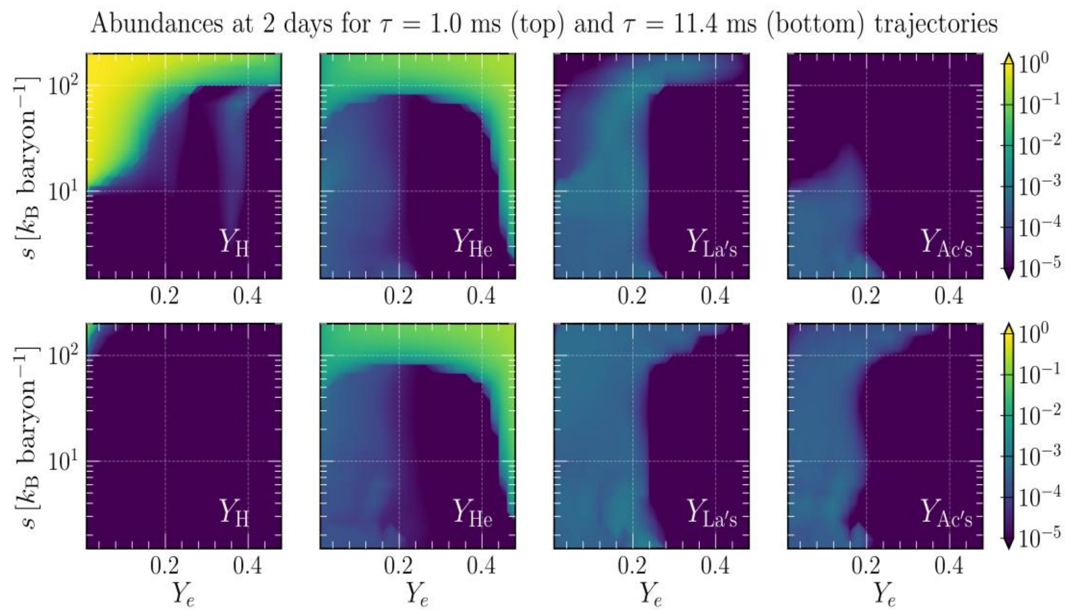


Perego, DV+ 2020 arXiv:2009.08988

H and He are the most abundant species, comparable to Sr, lanthanides, and actinides

Elements between lithium and potassium are usually several orders of magnitudes **less abundant**

Perego, Vescovi,…,Branchesi,…,Cristallo + ApJ(2022)

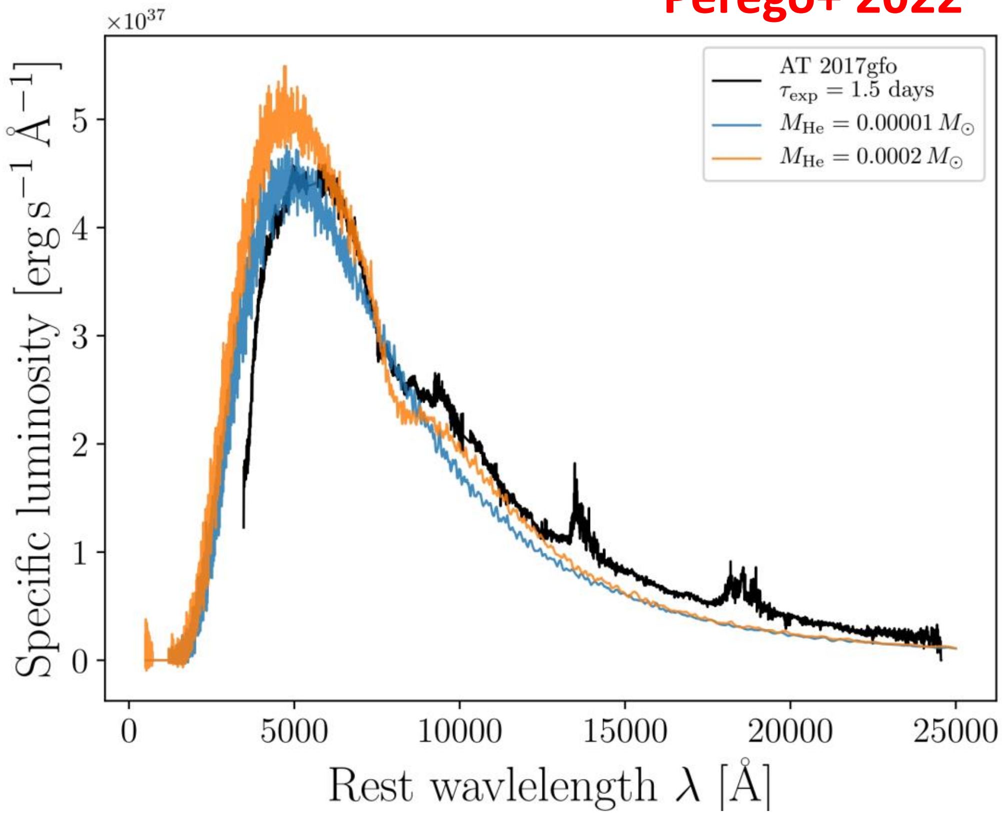


<u>He</u> production <u>can happen both in association or in the absence of heavy elements</u>

Detecting H and He features in kilonova spectra

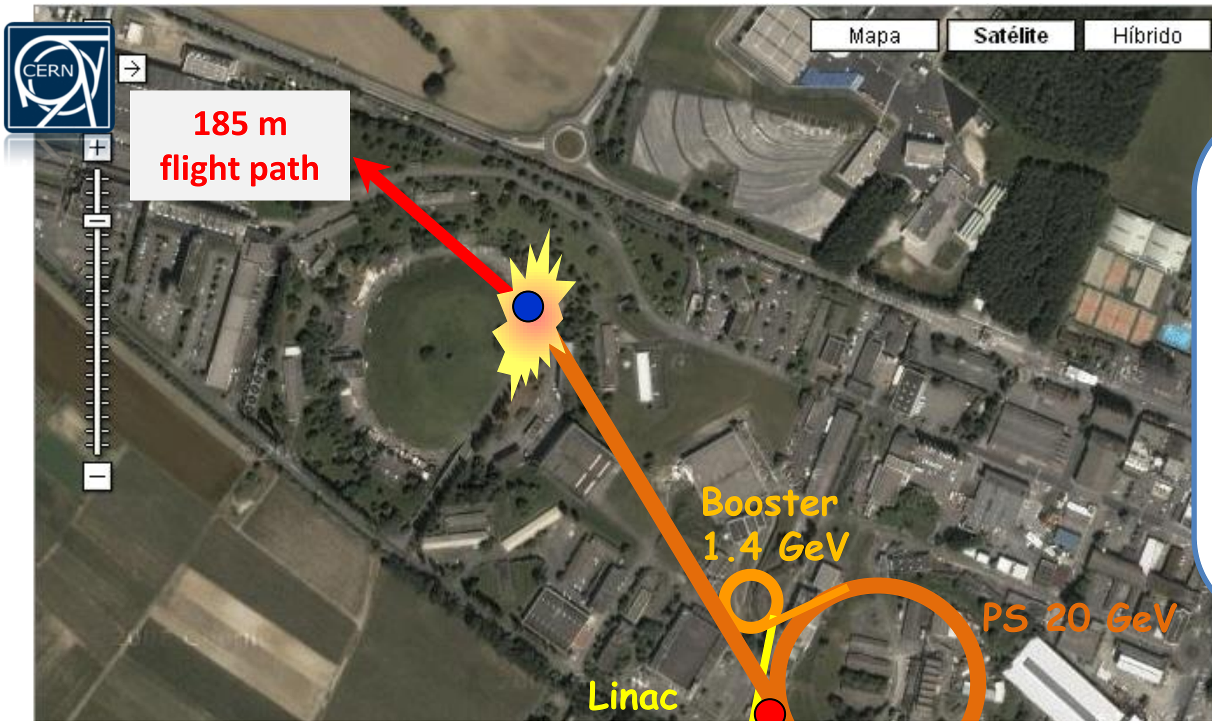
Perego+ 2022

- The spectrum of AT2017gfo at 1.5d shows a broad absorption at 810 nm that was explained by a transition of SrII (**Watson+2019**)
- **TARDIS** used to test whether this feature can be produced by a high velocity He layer in favorable conditions.
- The answer is **YES**, but only with high M_{He} and in non-LTE conditions



He **is likely not responsible** for the observed 810 nm feature, unless non-LTE effects or the He mass are severely underestimated

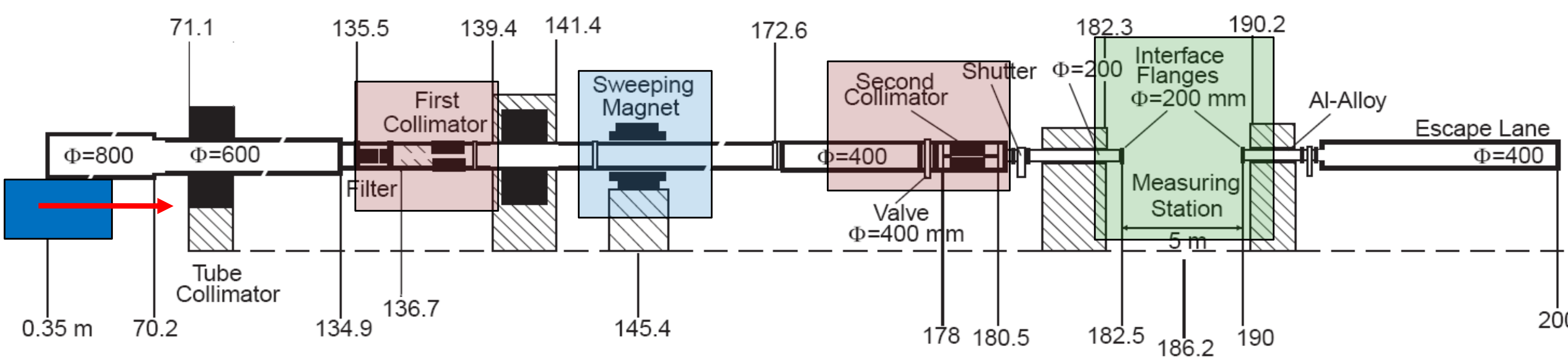
r-process: neutron-induced fission @ n_TOF



n_TOF is a neutron spallation source based on PS at CERN with protons with **20 GeV/c** hitting a lead target (~360 neutrons per incoming proton).

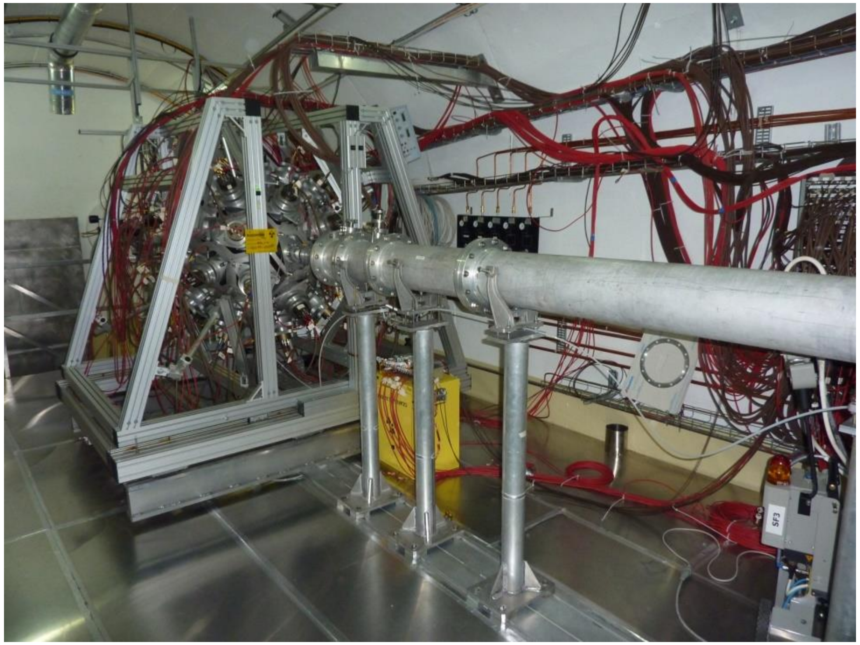
Experimental area at **185 m**.

7×10^{12} protons per burst

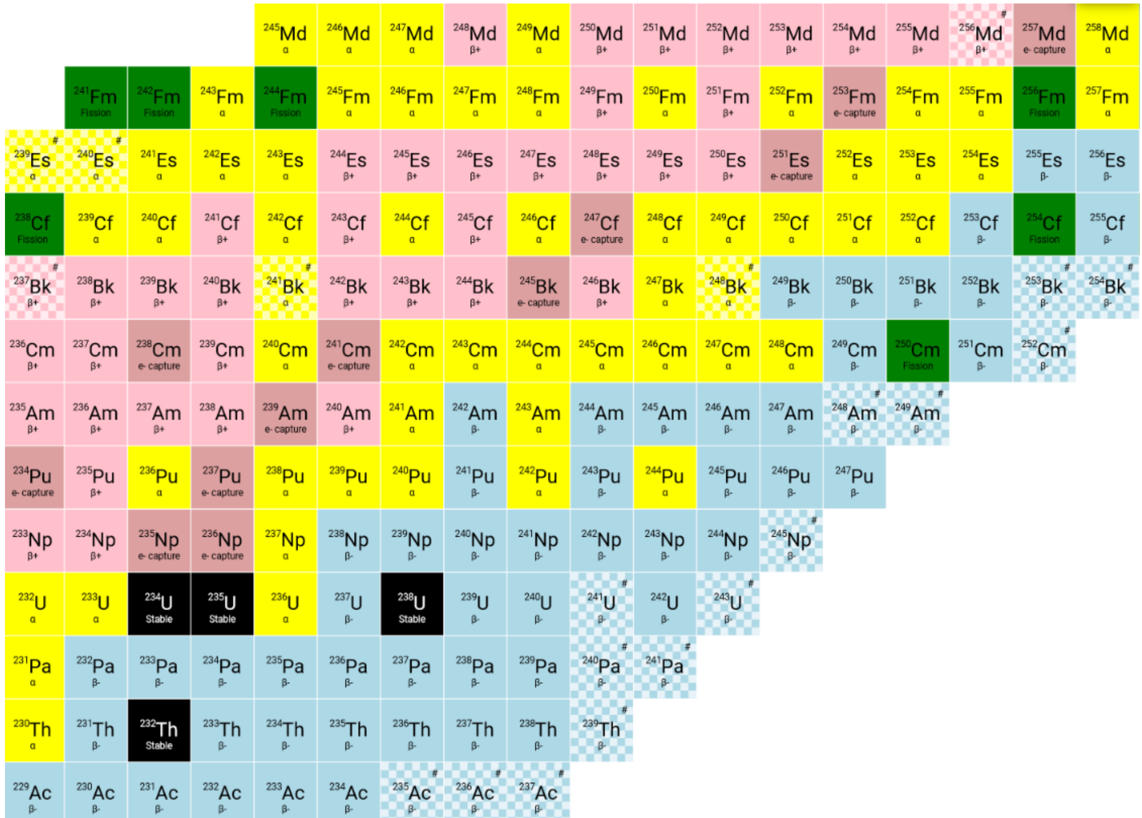


r-process: neutron-induced fission @ n_TOF

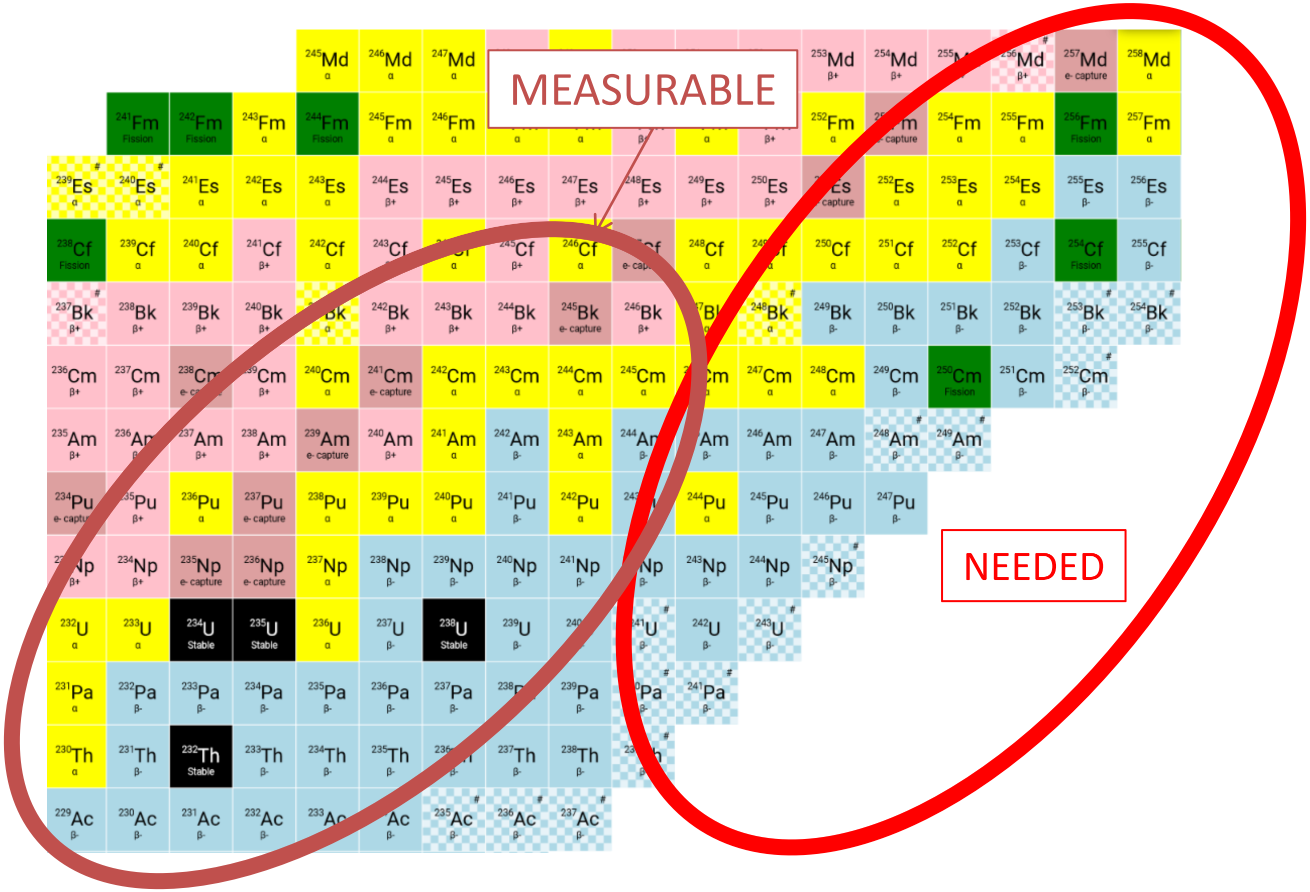


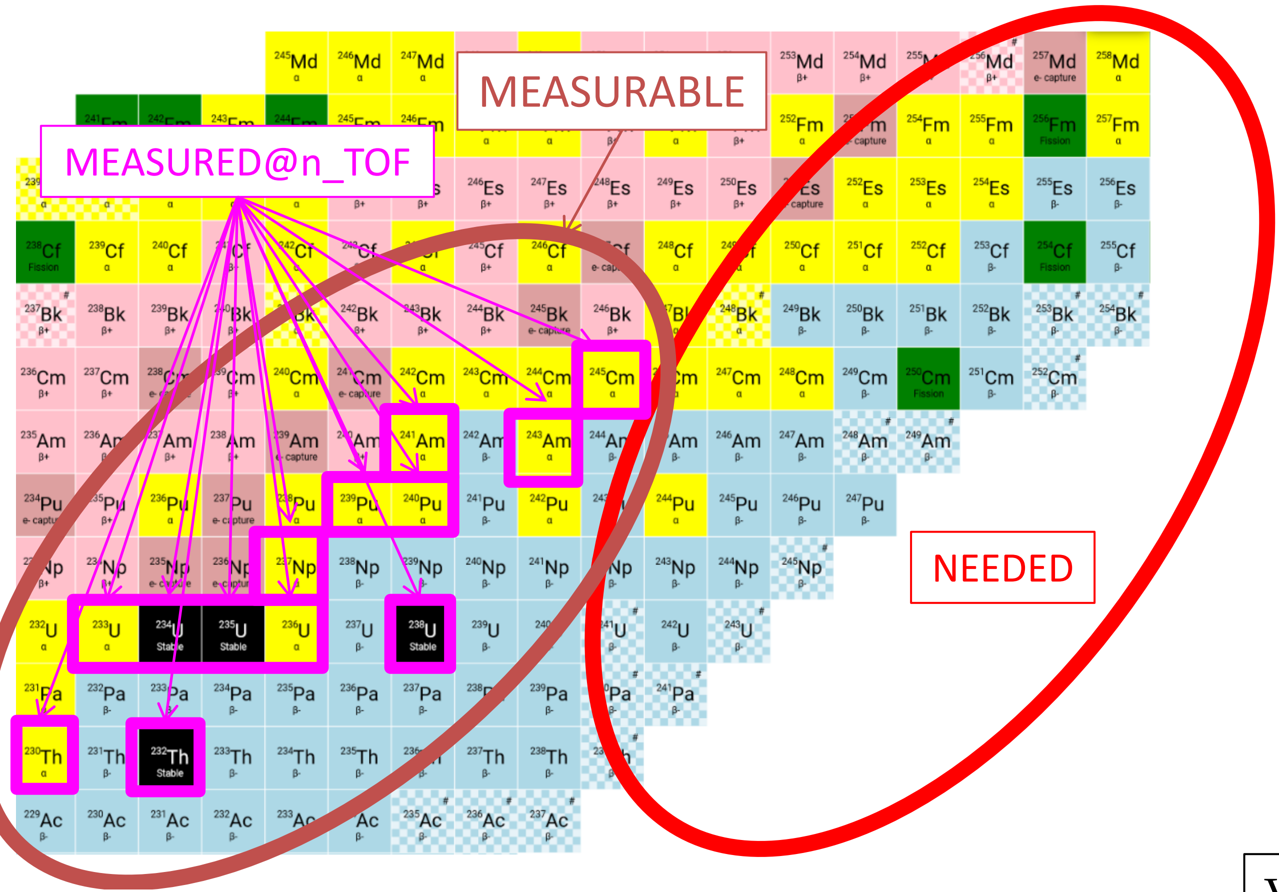

r-process: neutron-induced fission @ n_TOF

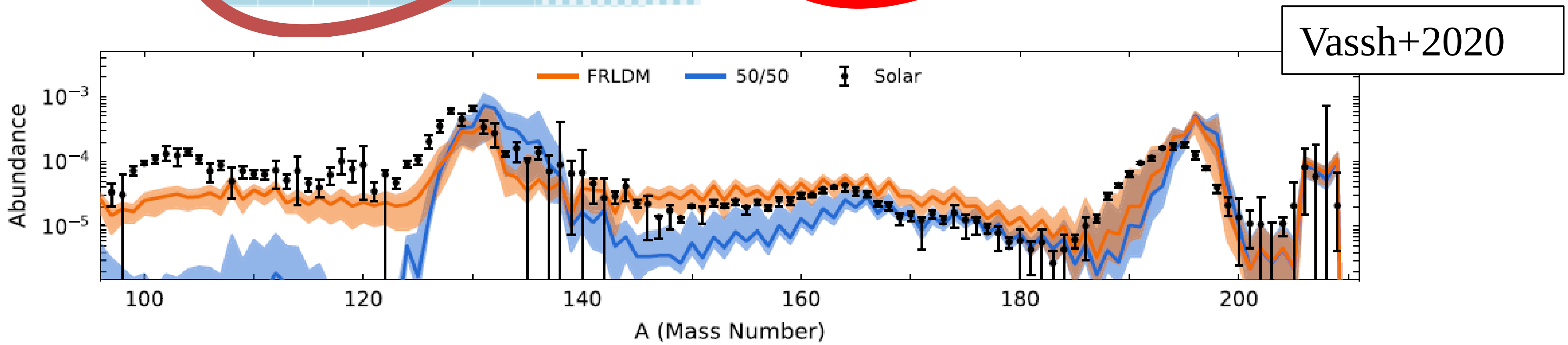


r-process: neutron-induced fission @ n_TOF

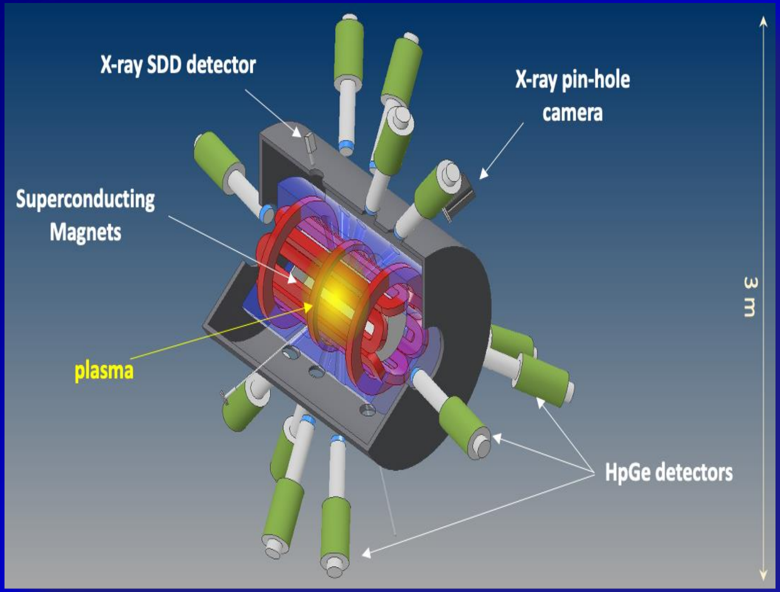


r-process: neutron-induced fission @ n_TOF





PANDORA and Neutron Stars



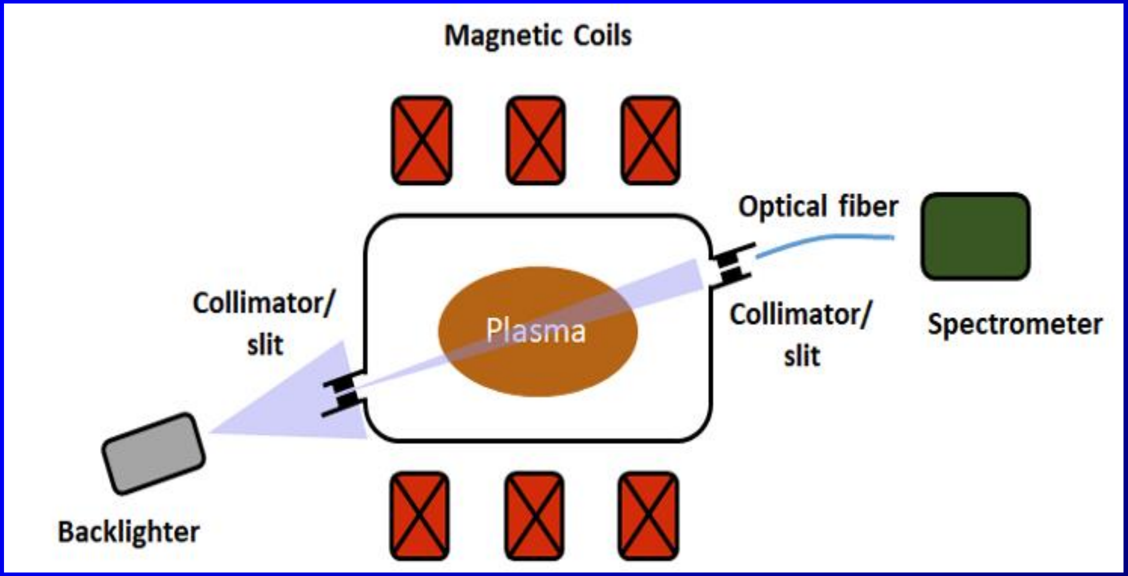
PANDORA consists of:

1) **Superconducting Magnetic Plasma Trap;**
2) **HpGe Array;**
3) **Plasma Diagnostics System.**

Among other things, PANDORA will measure plasma opacity in conditions similar to kilonovae ejecta.

Mascali+ 2022

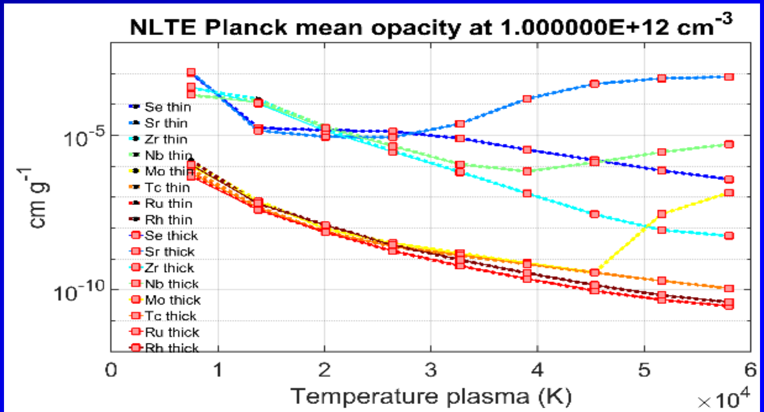
The plasma, enriched with a single heavy element, is irradiated with a (white) calibrated source with an emissivity larger than plasma's one. Then, by means of a spectrometer, the spectral characteristics of the chemical elements are derived.



PANDORA and Neutron Stars

Light r-process elements production dominates for Y_e>0.25, such a large Y_e is expected for early-days blue kilonovae.

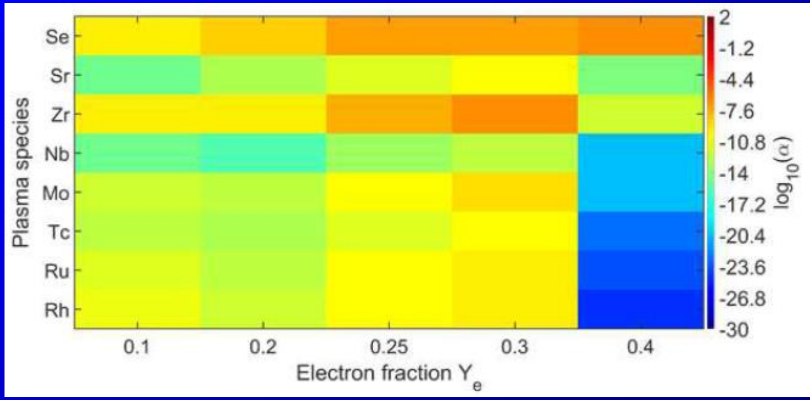
First phase of PANDORA: considered elements going from selenium to rhodium as eligible for our experimental campaign. Thus, single-species self-emitting plasmas made of Se, Sr, Zr, Nb, Mo, Tc, Ru, and Rh have been considered.



Opacity can differ of several orders of magnitudes:

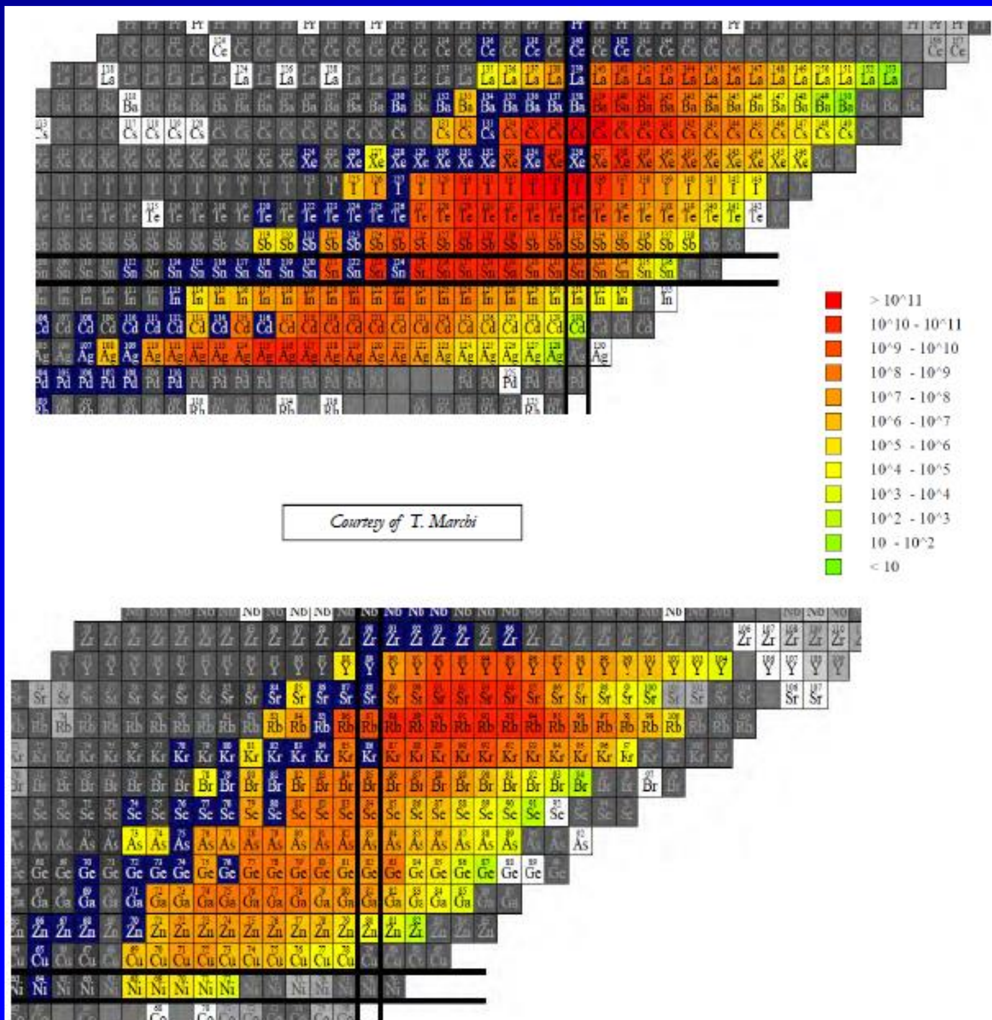
- ejecta enriched in light r-process elements have relatively low opacity (κ<1 cm g^{-1}), radiating optical light that fades in days;
- heavy r-process elements enlarges the opacity ($\kappa \approx$10 cm g^{-1}), with redder light curves lasting even for weeks.

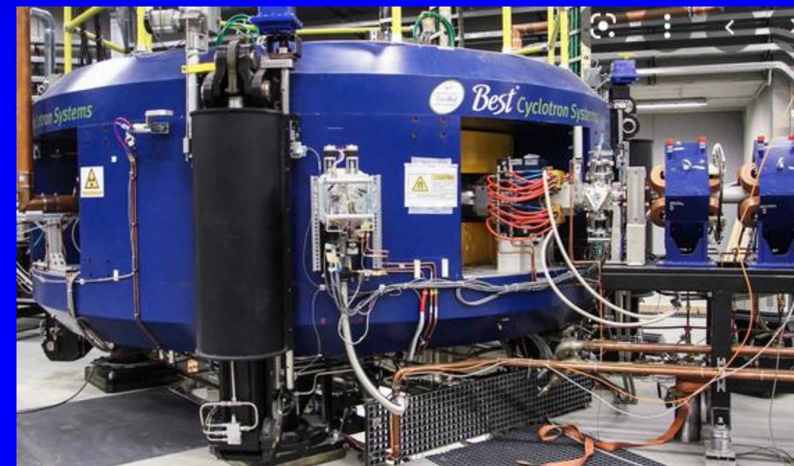
Se, Sr, Zr, and Nb exhibit larger mean opacity at the temperature condition of early-epochs kilonova (<2·10^4 K). In view of these numerical results, it is useful to define a mean opacity weighted on abundances at a given Y_e. For Y_e 0.25 and T typical of blue-kilonova emission, **selenium** plasma as one of the most favoured for the experiment.



SPES@LNL

SPES is the acronym for “Selective Production of Exotic Species”

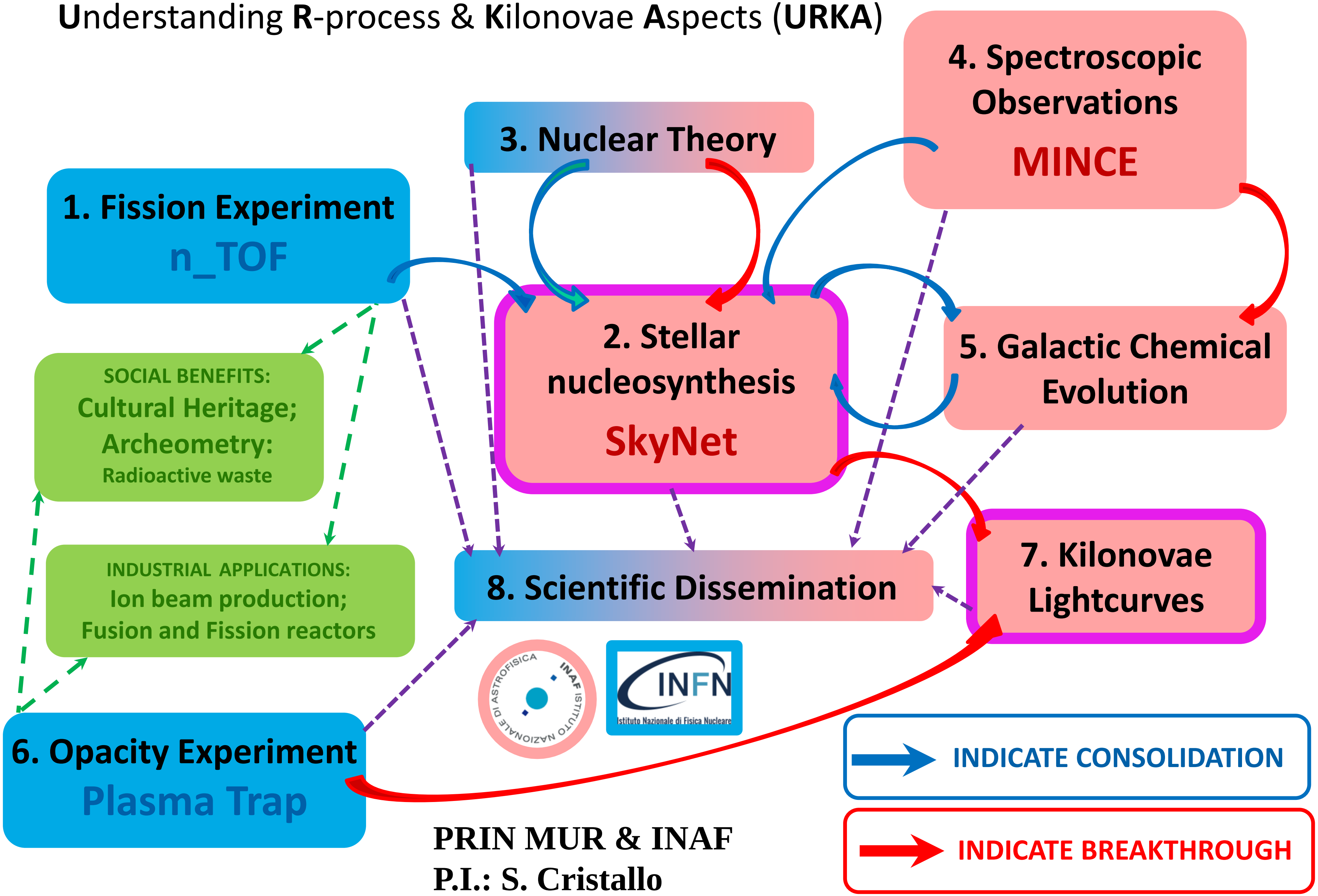




High performance cyclotron with high output current (~0.7 mA) and high energy (up to 70 MeV).
One of the two beams will be dedicated to the nuclear physics facility (producing neutron-rich ions by collisions of protons onto a UCx target).

5. (& 6 & 7 & …) INAF-OAAb & GSSI

Understanding **R**-process & **K**ilonovae **A**spects (**URKA**)



TAKE HOME MESSAGE

- **MANY OPPORTUNITIES TO COLLABORATE WITH PEOPLE @ OAAb**;
- s-process and r-process nucleosynthesis are extremely interesting topics, which received (will receive) a lot of attention in the past (future) years. There are at least 2 nuclear experiments with a consistent Italian participation working on topics related to the r-process. In the next years a 3rd one (SPES@LEGNARO) will be operative;
- Most of this stuff will be presented in my short course "Nucleosynthesis" (GC-3).

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sergio.cristallo@inaf.it (r-process nucleosynthesis, kilonovae lightcurves and experiments)