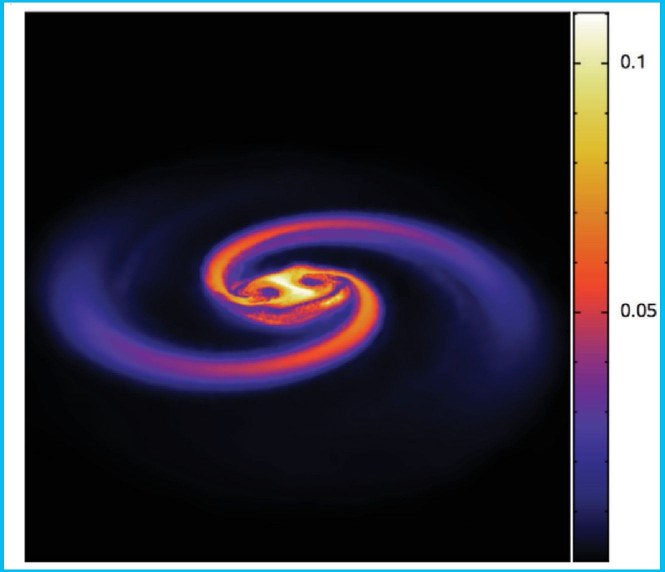
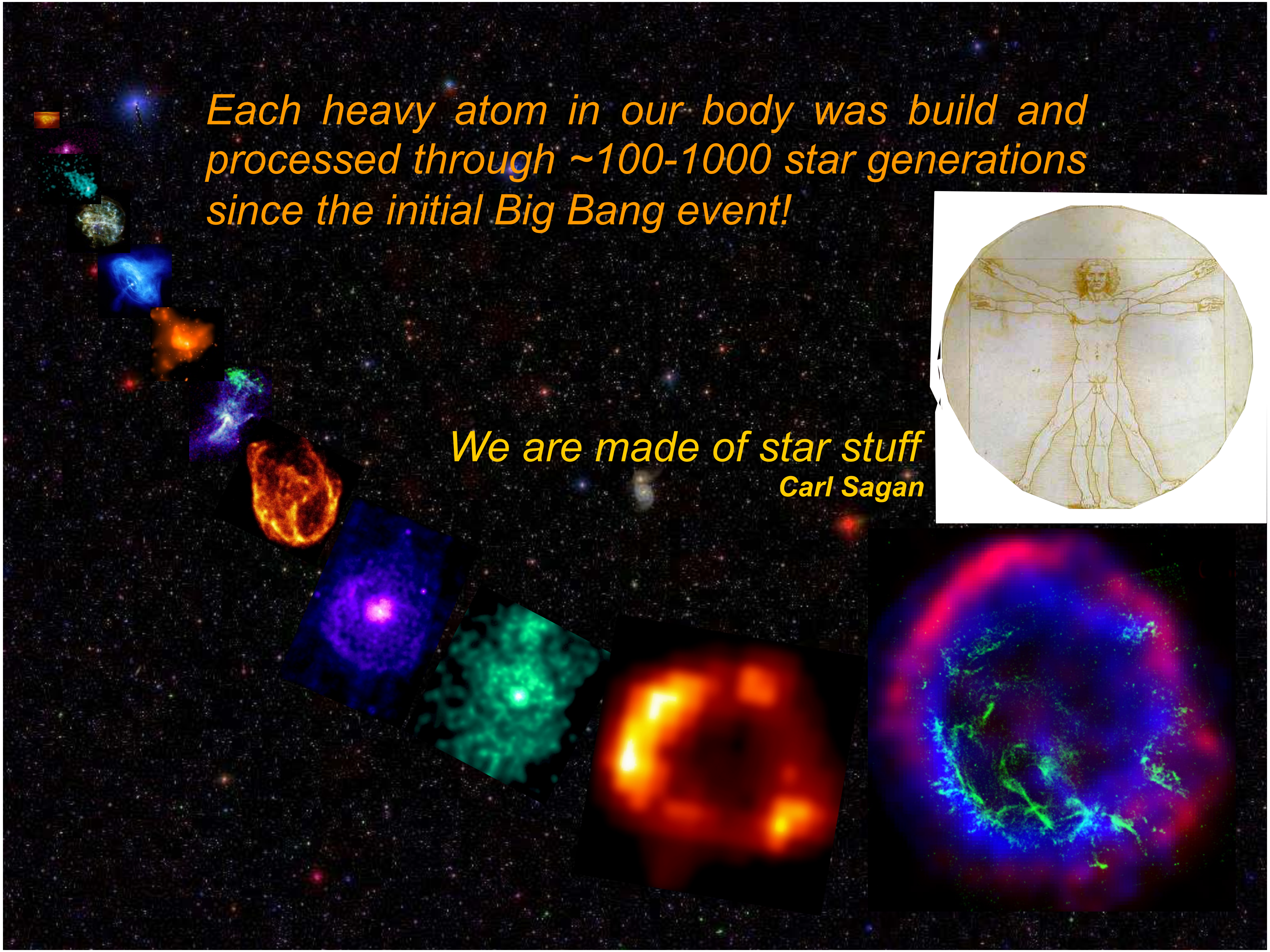
# How Nature makes Gold



*Karlheinz Langanke*
*GSI Helmholtzzentrum Darmstadt*
*Technische Universität Darmstadt*

*,Paco-Yndurain Lecture, Madrid, March 14, 2018*



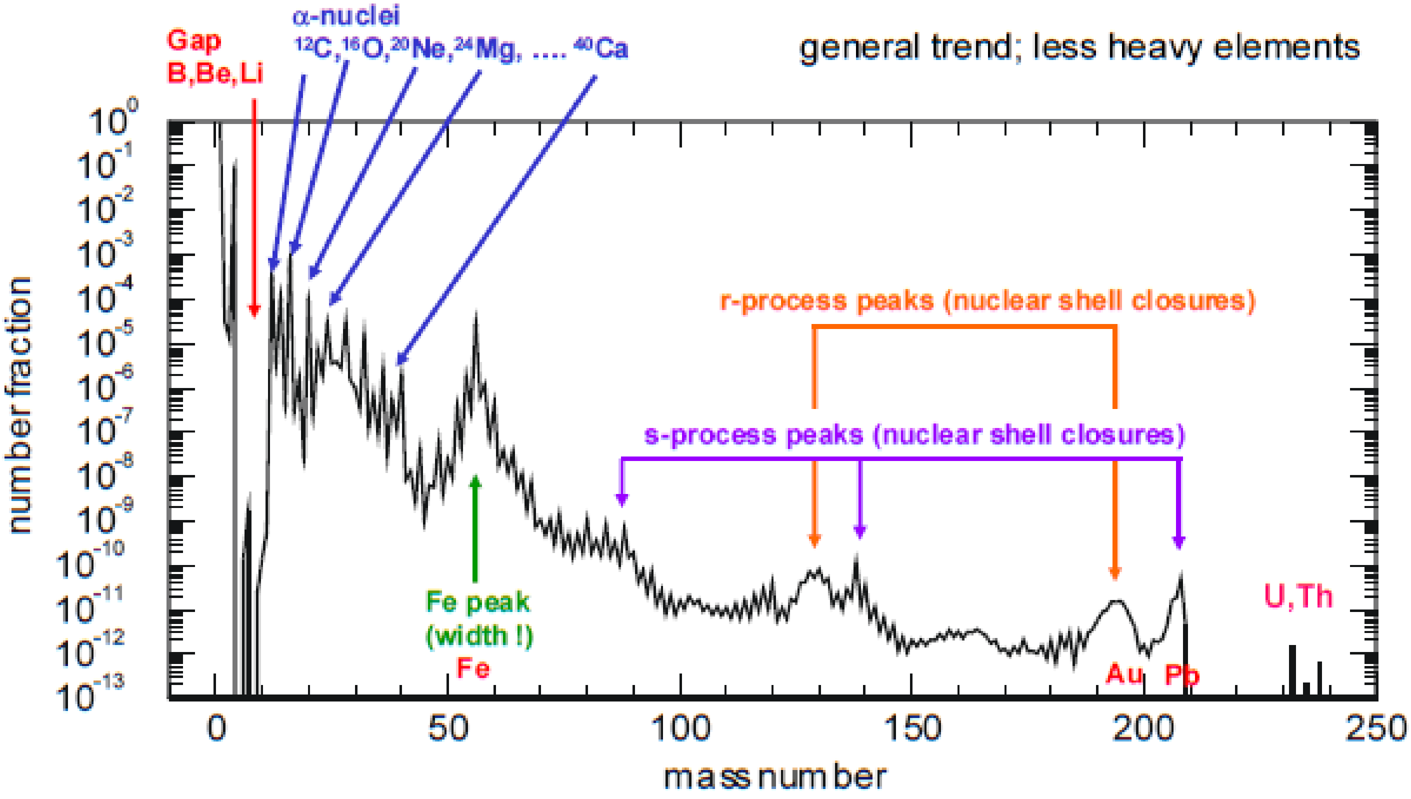
*Each heavy atom in our body was build and processed through ~100-1000 star generations since the initial Big Bang event!*

*We are made of star stuff*

***Carl Sagan***

# Abundances of the elements

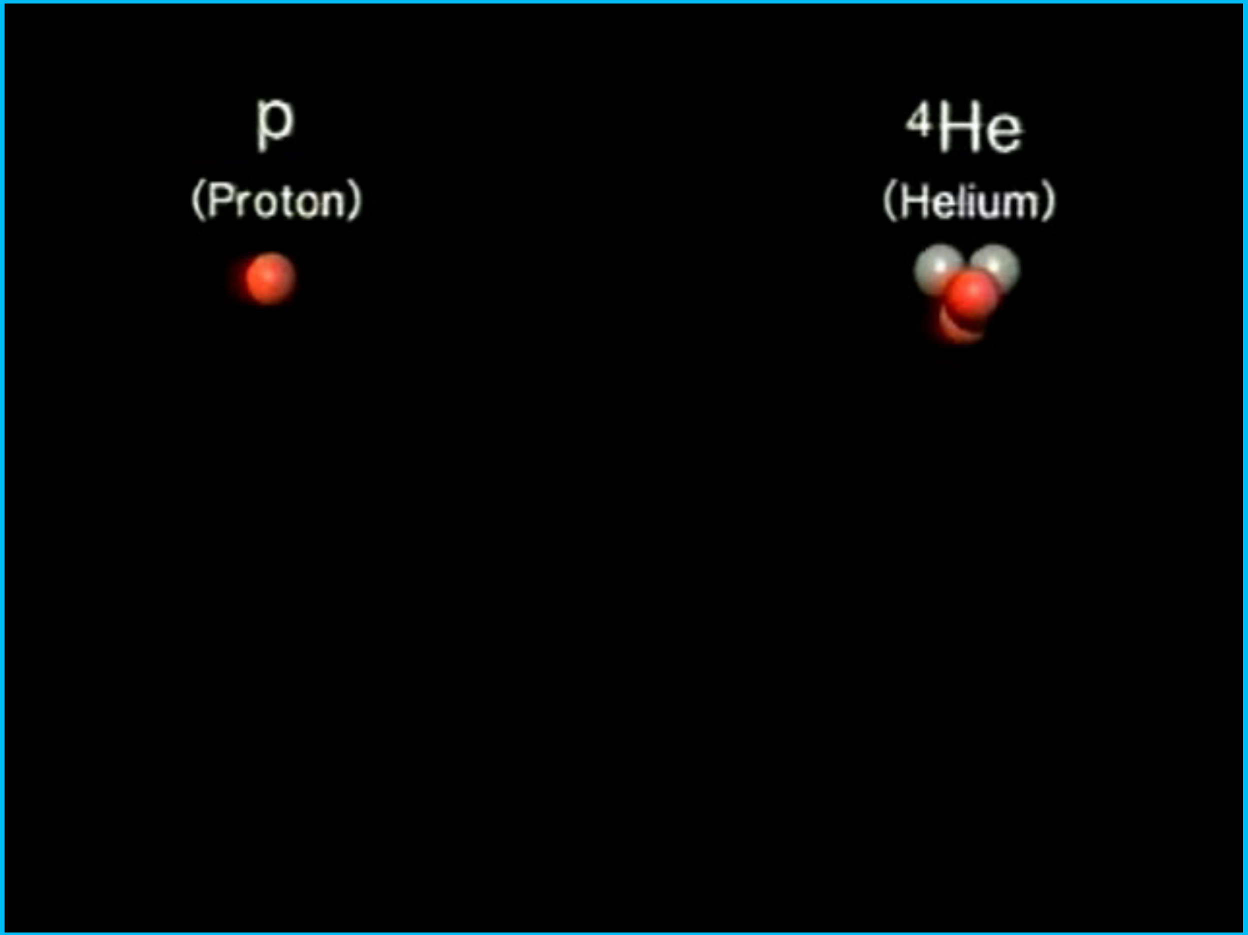
| | |
|---|---|
| Hydrogen mass fraction | X = 0.71 |
| Helium mass fraction | Y = 0.28 |
| Metallicity (mass fraction of everything else) | Z = 0.019 |
| Heavy Elements (beyond Nickel) mass fraction | 4E-6 |



# Where were the elements made?

- the lightest elements (hydrogen, helium, lithium) were created in the first 3 minutes of the Universe
- the heavier elements up to uranium are and have been made in stars
- elements with Z>92 have been artificially produced in labs; the elements with Z=107-112 at GSI

# Nuclear fusion generates energy



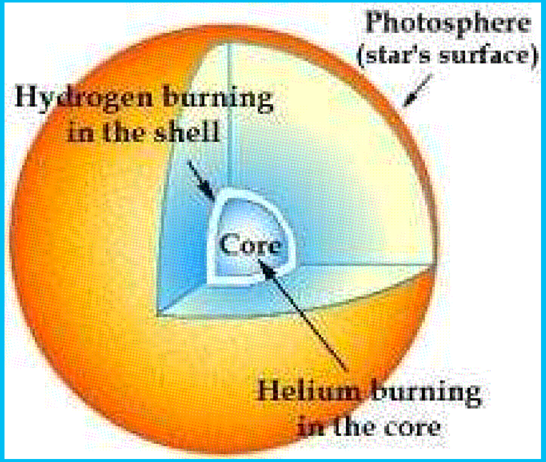
# Solar hydrogen burning

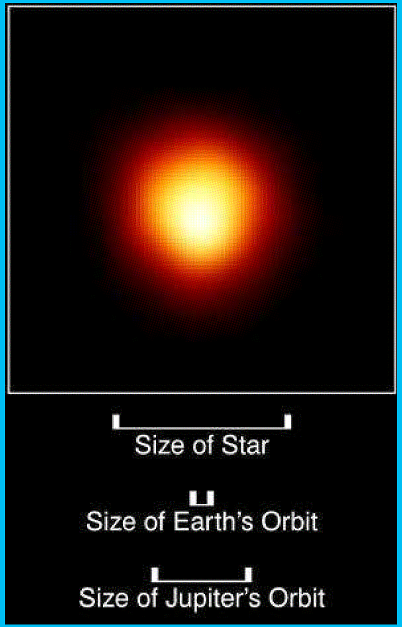
- When a star is born, temperature and density increase in its interior
- matter consists of charged nuclei (and electrons); no free neutrons
- nuclei move fast; nuclei with small charges have the chance  to overcome the Coulomb repulsion (tunnel effect)
- fusion of hydrogen (protons) is the first nuclear energy source


©RIKEN

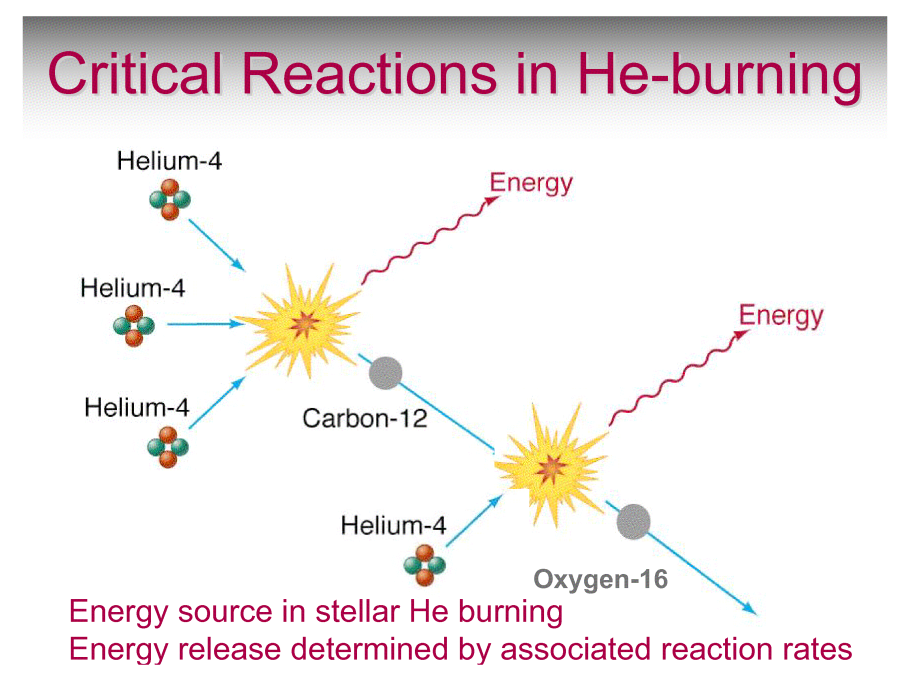
# Helium burning

- At the end of hydrogen burning the star has a helium core. This core contracts under its own gravity and gets hotter.
- Hydrogen continues burning in a shell around the helium core and produces more helium. The core grows and gets denser and hotter.
- The radiation pressure grows. Hereby the outer regions of the star extend. It turns into a Red Giant. Our sun reaches this phase in about 3 billion years. Its radius reaches then up to the earth orbit.
- In the interior it is finally hot enough (100 Millionen Kelvin) that also helium nuclei can fuse.





# Stellar helium burning

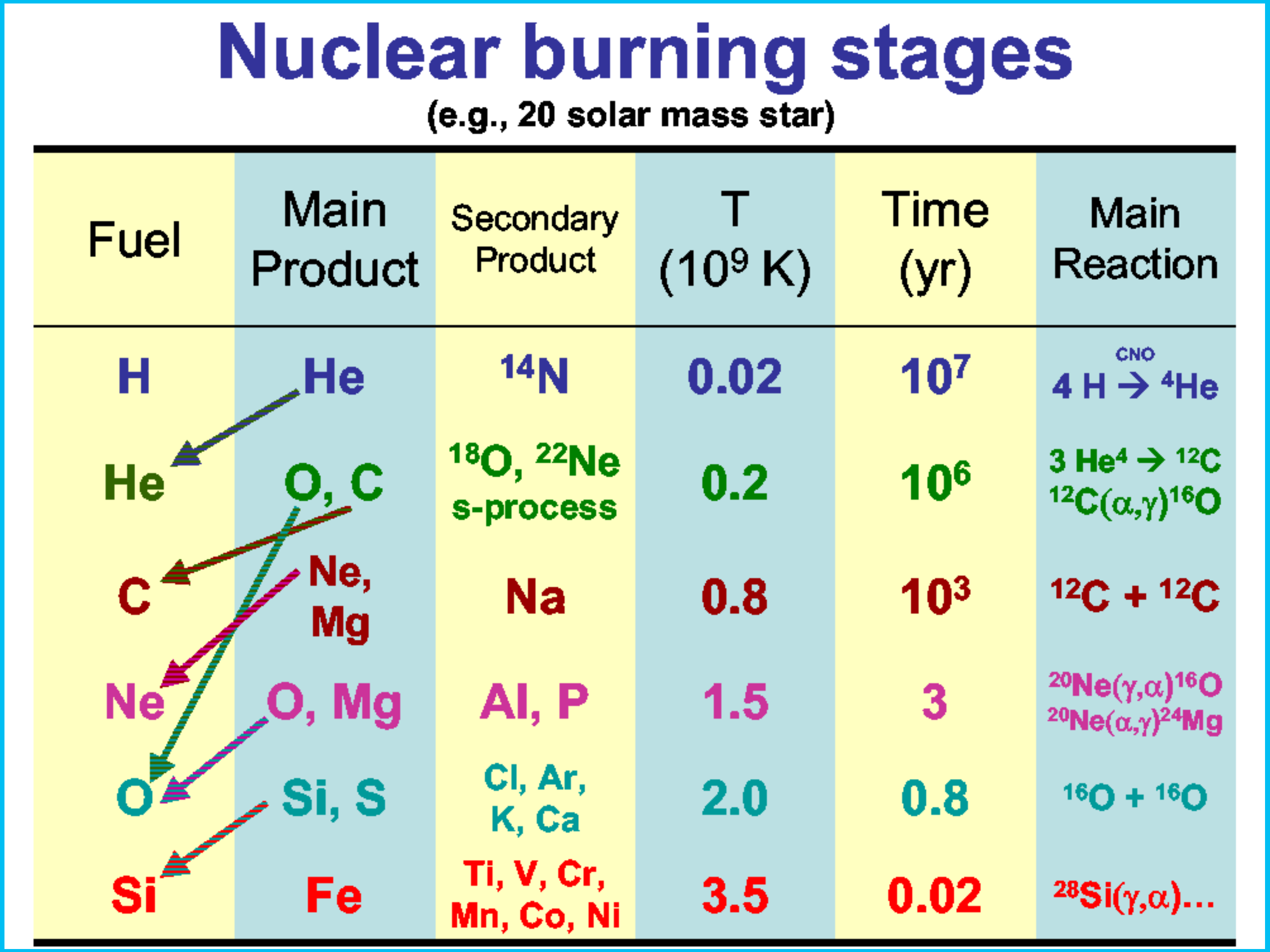


## Critical Reactions in He-burning

Energy source in stellar He burning
Energy release determined by associated reaction rates

- Helium burning decides the ratio of carbon (C) and oxygen (O) in the Universe.
- These are the building blocks of life!

# Advanced stellar burning stages



## Nuclear burning stages

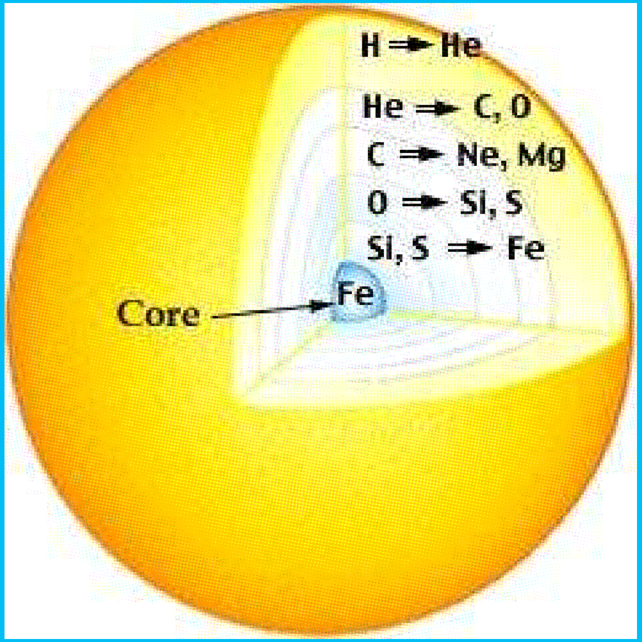
(e.g., 20 solar mass star)

| Fuel | Main Product | Secondary Product | T ($10^9$ K) | Time (yr) | Main Reaction |
|---|---|---|---|---|---|
| H | He | $^{14}$N | 0.02 | $10^7$ | $4\ H \xrightarrow{CNO} {}^{4}He$ |
| He | O, C | $^{18}$O, $^{22}$Ne<br>s-process | 0.2 | $10^6$ | $3\ He^4 \rightarrow {}^{12}C$<br>$^{12}C(\alpha,\gamma)^{16}O$ |
| C | Ne, Mg | Na | 0.8 | $10^3$ | $^{12}C + {}^{12}C$ |
| Ne | O, Mg | Al, P | 1.5 | 3 | $^{20}Ne(\gamma,\alpha)^{16}O$<br>$^{20}Ne(\alpha,\gamma)^{24}Mg$ |
| O | Si, S | Cl, Ar, K, Ca | 2.0 | 0.8 | $^{16}O + {}^{16}O$ |
| Si | Fe | Ti, V, Cr, Mn, Co, Ni | 3.5 | 0.02 | $^{28}Si(\gamma,\alpha)\ldots$ |

*Courtesy: A. Heger and S. Woosley*

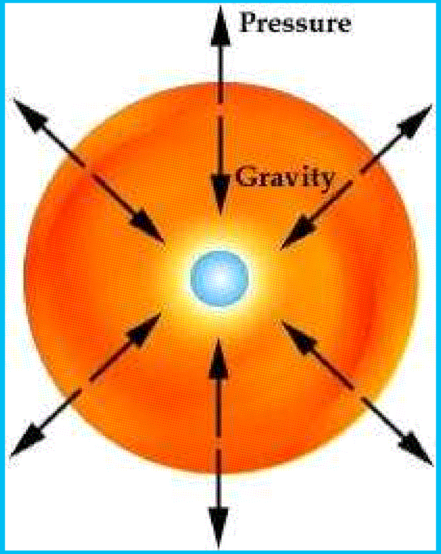
# Final fate of a massive star

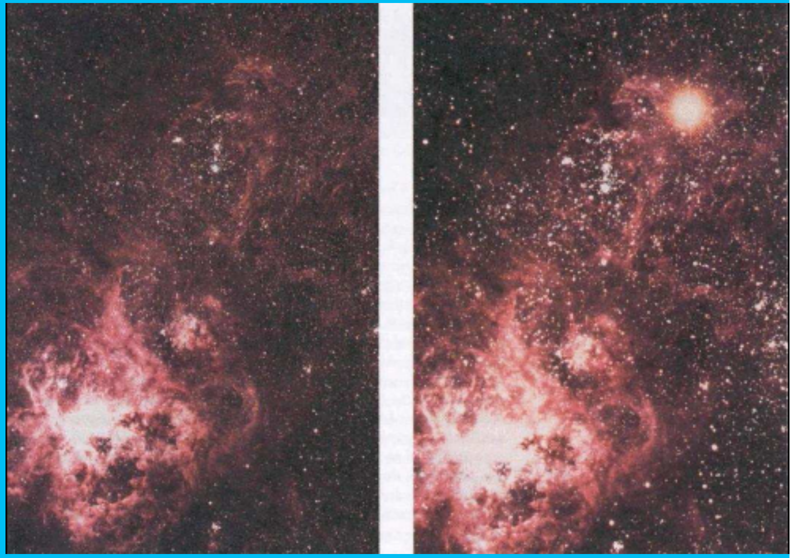
- Star has an onion structure
- Iron is the final product of hydrostatic burning
- The inner iron core grows, gets unstable against its own gravity and collapses
- SUPERNOVA!



# Collapse and explosion of a star

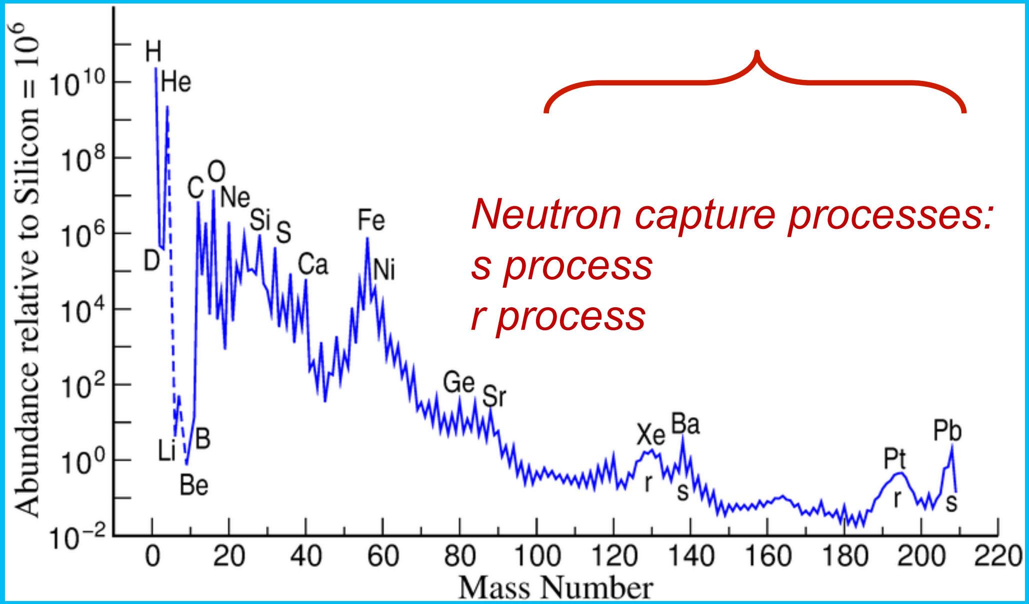
- Stability by pressure-gravity balance
- pressure produced by nuclear reactions
- Balance cannot be kept when iron core grows
- In about 1 second the core radius reduces from 6000 km to 20 km
- Collapse stops, when the core corresponds to a gigantic atomic nucleus. A large portion of the gravitational energy is set free. This energy corresponds to the energy production of 100 suns during its life of about 10 billion years.
- The majority of energy is carried away by neutrinos.



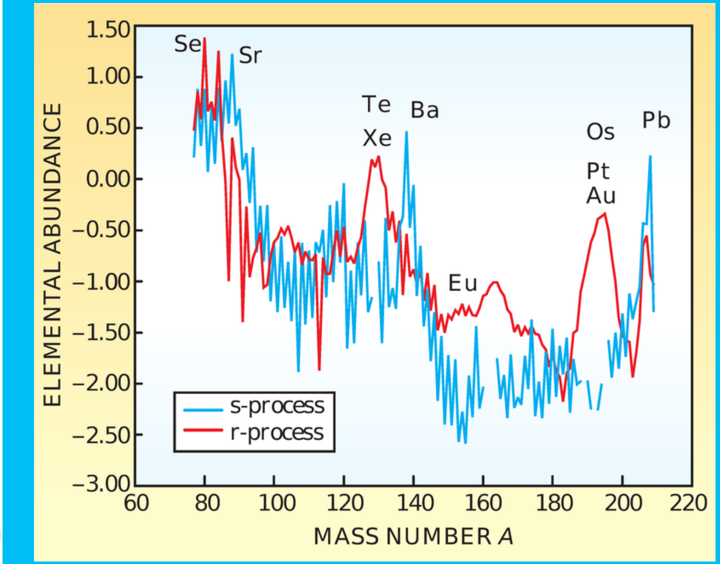


# Making Gold: The R-Process

*National Research Council: one of the 11 greatest unanswered questions in physics*



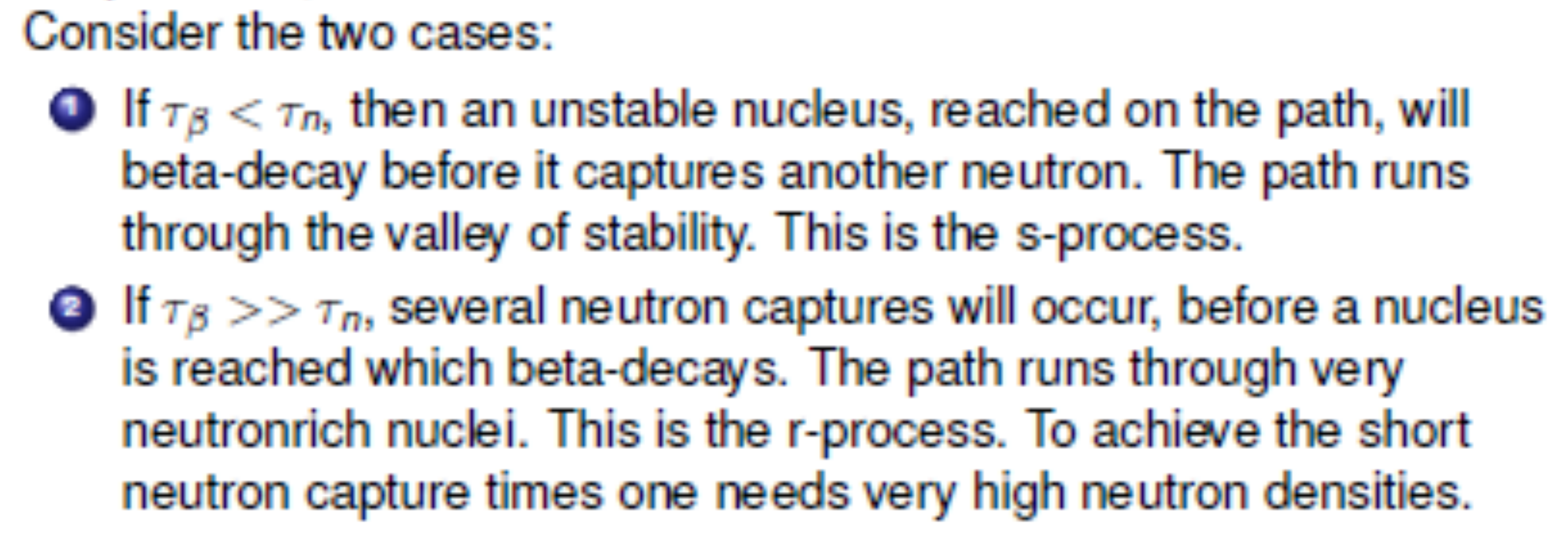
*Neutron capture processes:*
*s process*
*r process*



- *Heavy elements produced in neutron capture processes*
- *R-process operates at early Galactic history*

# Making heavy elements in Nature

*Assume a reservoir of free neutrons and a competition of neutron capture and beta decay:*

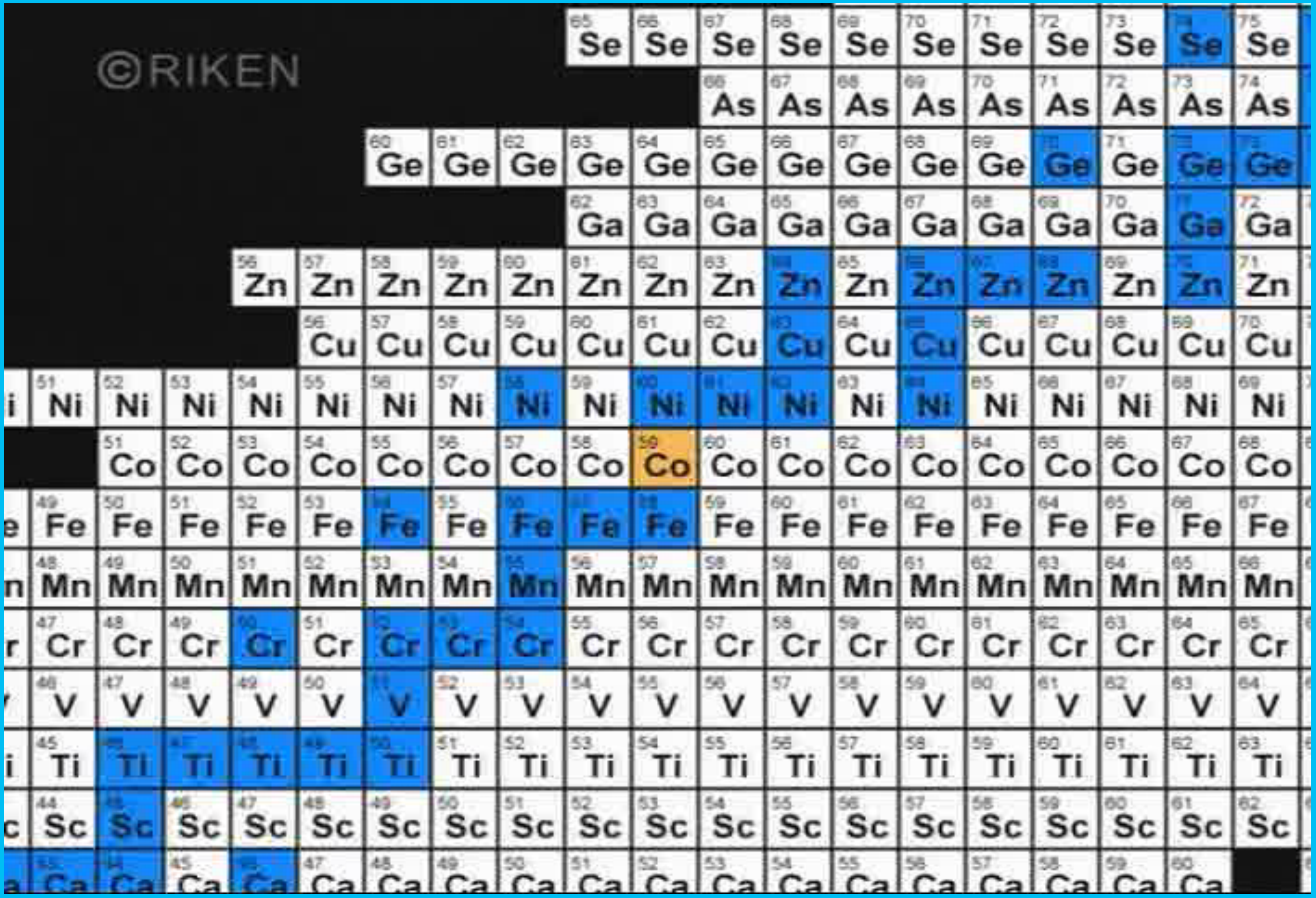


Consider the two cases:

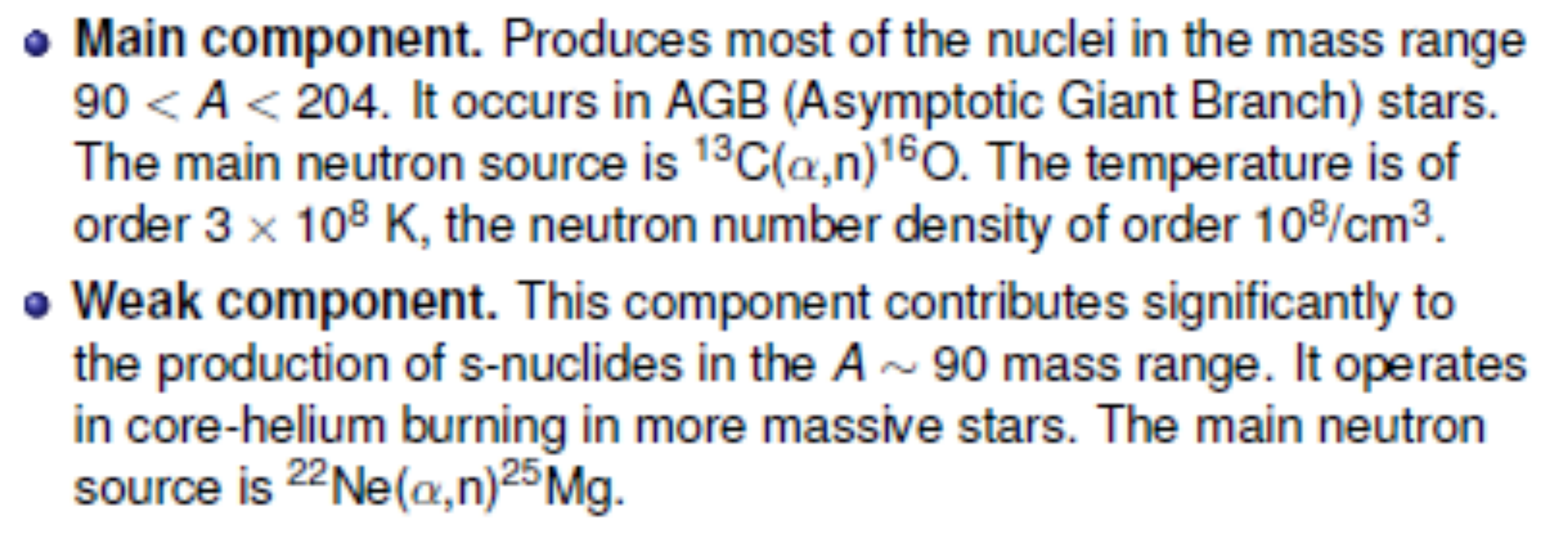
❶ If $\tau_\beta < \tau_n$, then an unstable nucleus, reached on the path, will beta-decay before it captures another neutron. The path runs through the valley of stability. This is the s-process.

❷ If $\tau_\beta >> \tau_n$, several neutron captures will occur, before a nucleus is reached which beta-decays. The path runs through very neutronrich nuclei. This is the r-process. To achieve the short neutron capture times one needs very high neutron densities.

# S-process nucleosynthesis



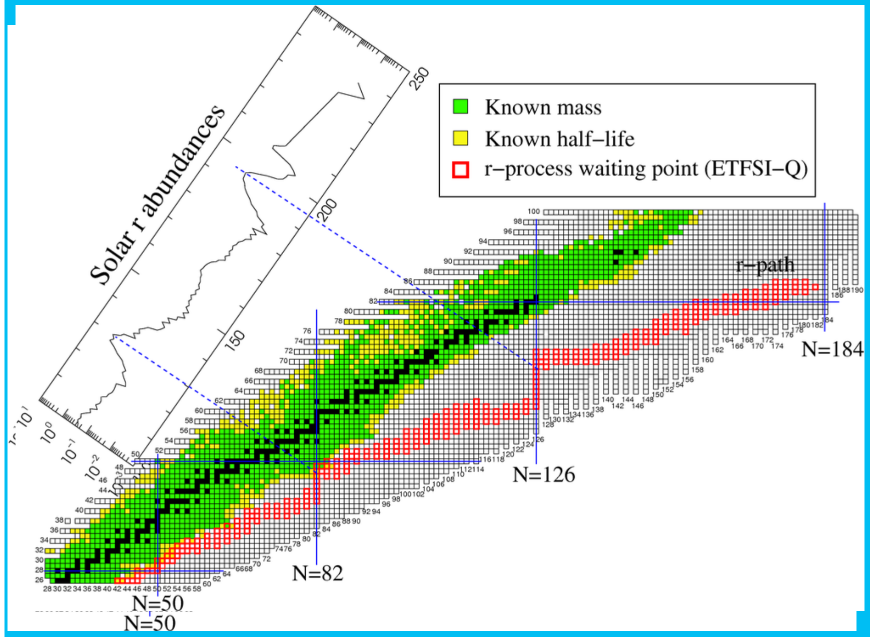
# Astrophysical S-process



- **Main component.** Produces most of the nuclei in the mass range $90 < A < 204$. It occurs in AGB (Asymptotic Giant Branch) stars. The main neutron source is $^{13}C(\alpha,n)^{16}O$. The temperature is of order $3 \times 10^8$ K, the neutron number density of order $10^8/cm^3$.
- **Weak component.** This component contributes significantly to the production of s-nuclides in the $A \sim 90$ mass range. It operates in core-helium burning in more massive stars. The main neutron source is $^{22}Ne(\alpha,n)^{25}Mg$.

*The s-process stops at Pb and Bi, where the s-process path hits the region of alpha instability.*

# *Making Gold! – The r-process*



***Nature***

***vs***

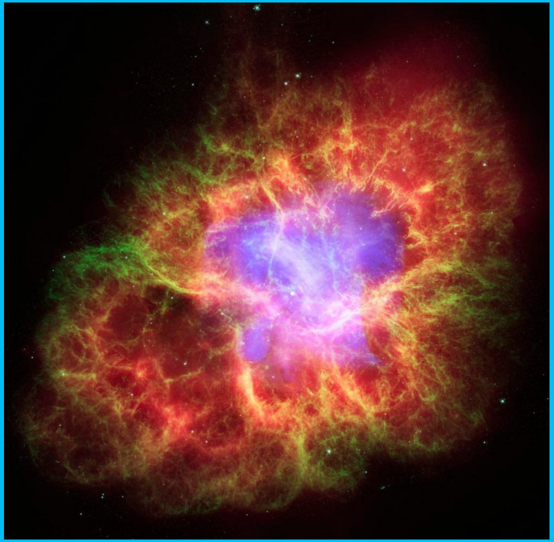
***Humans***

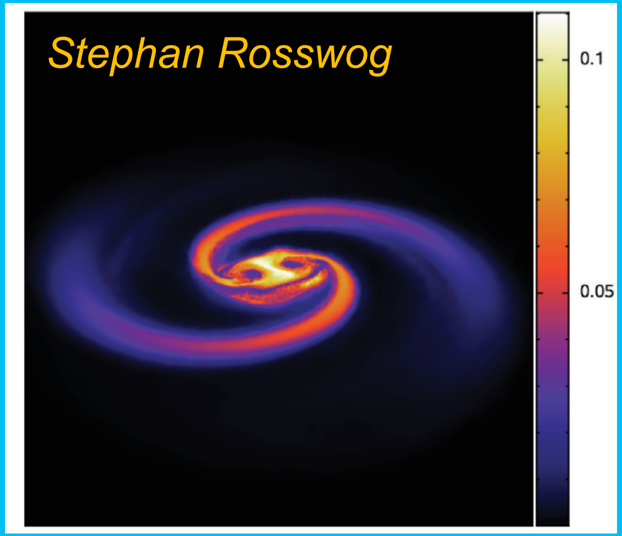
*very fast nuclear reactions in environment with extreme densities of free neutrons Nuclei involved very neutron-rich and short-lived.*

*Johann Friedrich Böttger, Alchemist*
*Inventor of European White China*
*In Meissen, Germany*

# Astrophysical sites

*Core-collapse supernova* *Compact binary mergers*

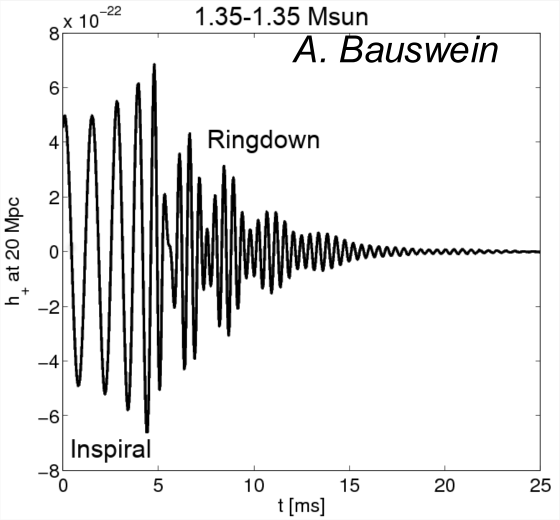




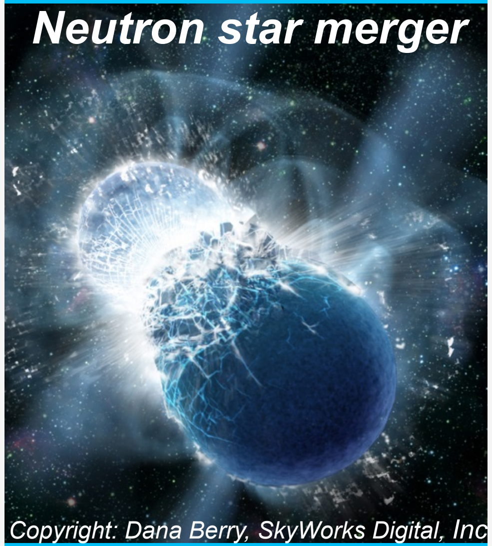
$Y\downarrow e$

| | **Supernova** | **Mergers** |
|---|---|---|
| Optimal conditions | ☹ | ☺ |
| Yield / Frequency | 😐 | ☺ |
| Direct signature | ☹ | ☺ |

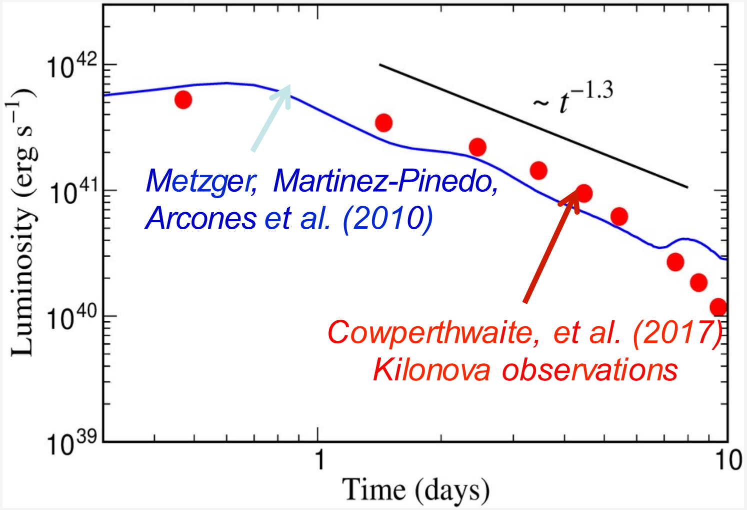
# Neutron Star merger confirmed as astrophysical site of heavy element production



*Gravitational Wave Signal*



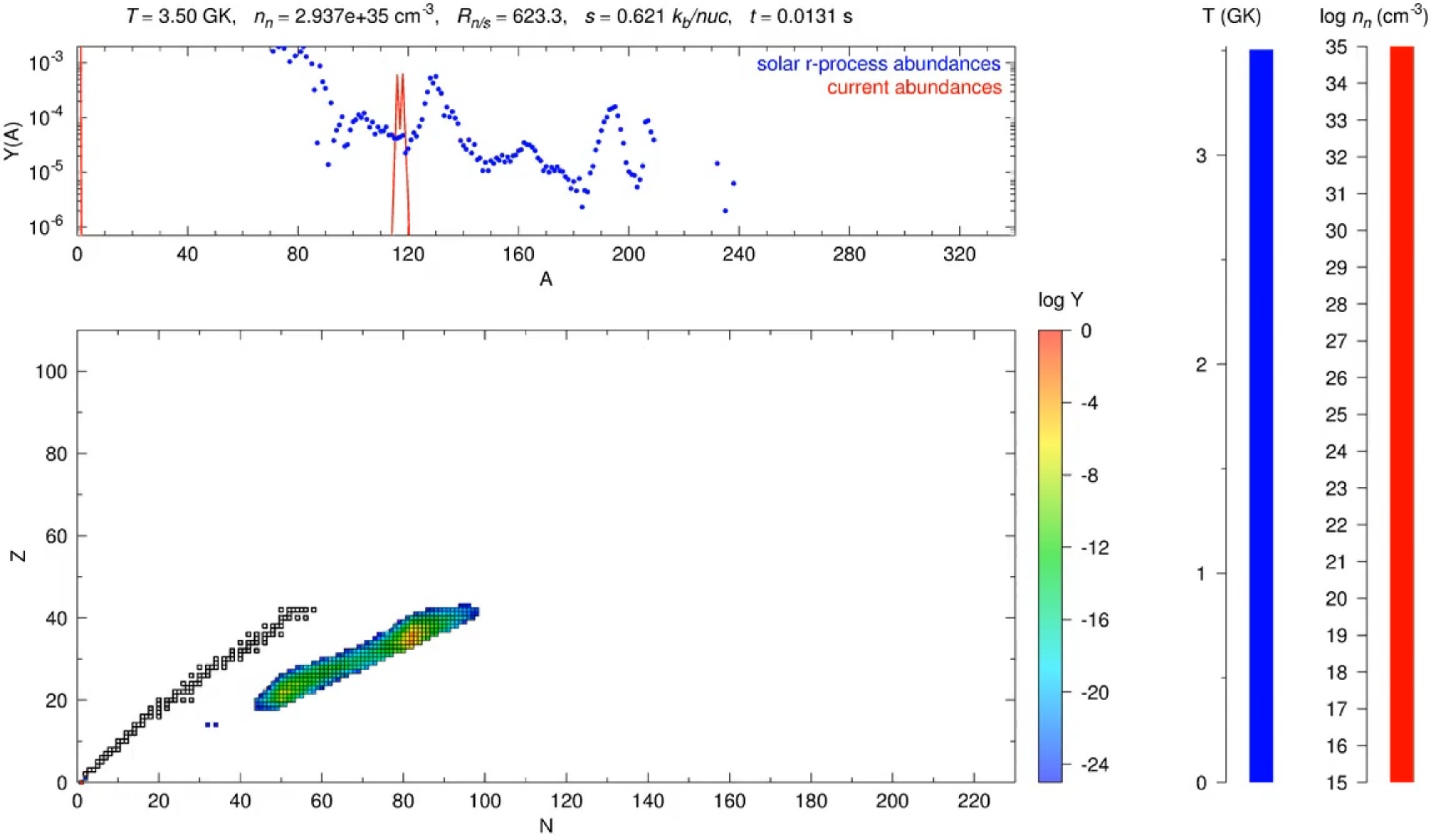
*Copyright: Dana Berry, SkyWorks Digital, Inc*



*Electromagnetic “Kilonova” Signal*

***Electromagnetic “Kilonova” signal due to “r process” in a NS merger has recently been verified by astronomical observations (August 2017)***

# R-Process in NS merger



G. Martinez-Pinedo, M.R. Wu

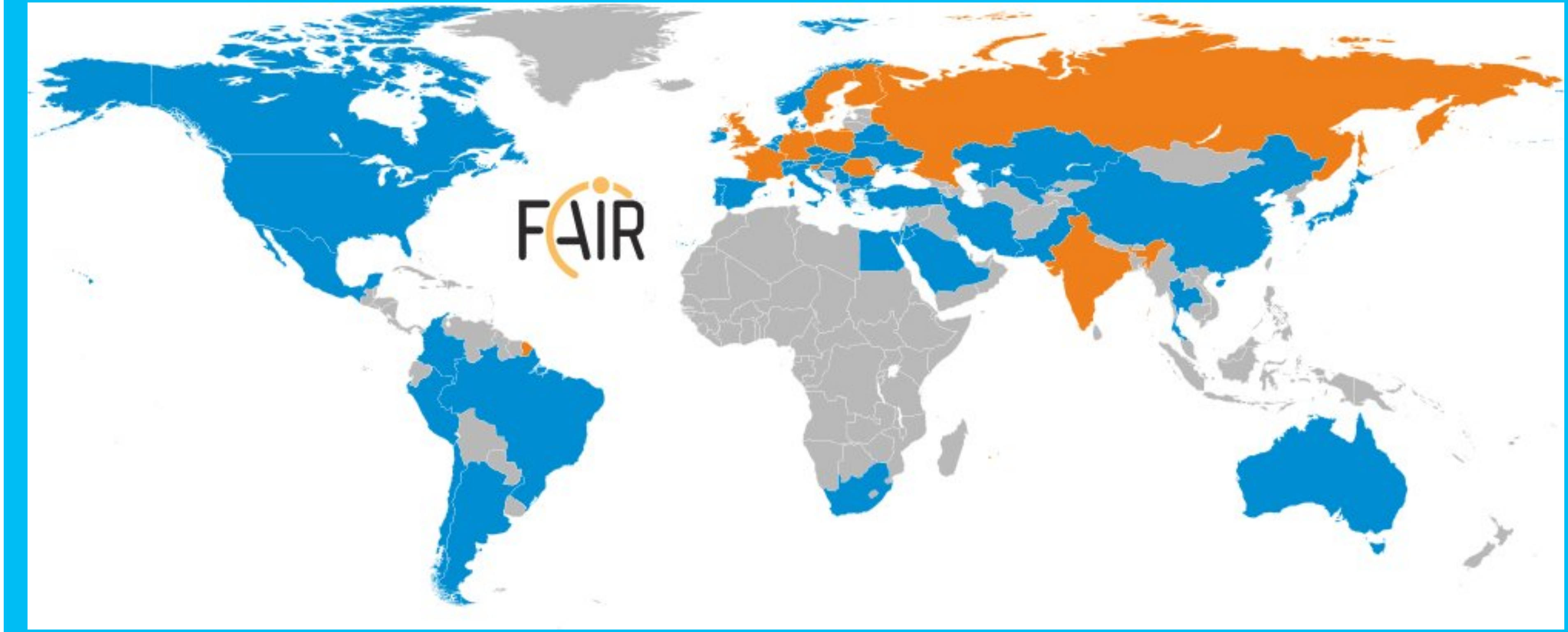
# Nuclear physics needs

- Masses
- Half lives
- neutron capture rates
- fission yields and fragment distributions
- alpha decays

- of nuclei with extreme neutron excess. Most have never been produced yet.
- But this will change -> Radioactive ion Beam Facility

*Facility for Antiproton and Ion Research in Europe*

# International Participation in FAIR

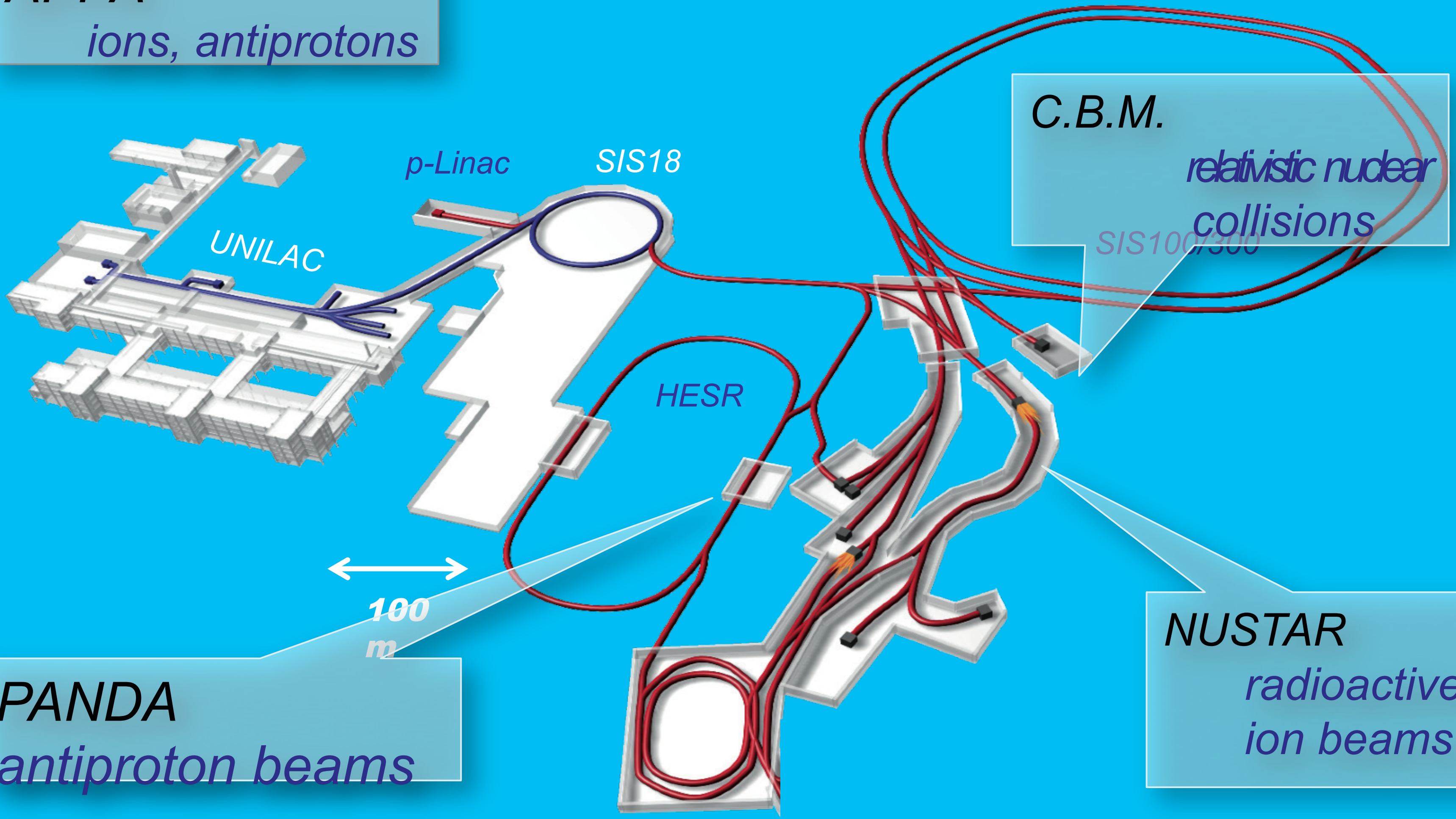


- FAIR governed by international convention
  - 9 shareholders + 1 assoc. partner (orange)
- Scientists from all over the world are engaged
  - More than 200 institutions from 53 countries are involved with their scientists (orange + blue)

# Accelerator complex

**APPA**

ions, antiprotons



**C.B.M.**

relativistic nuclear collisions

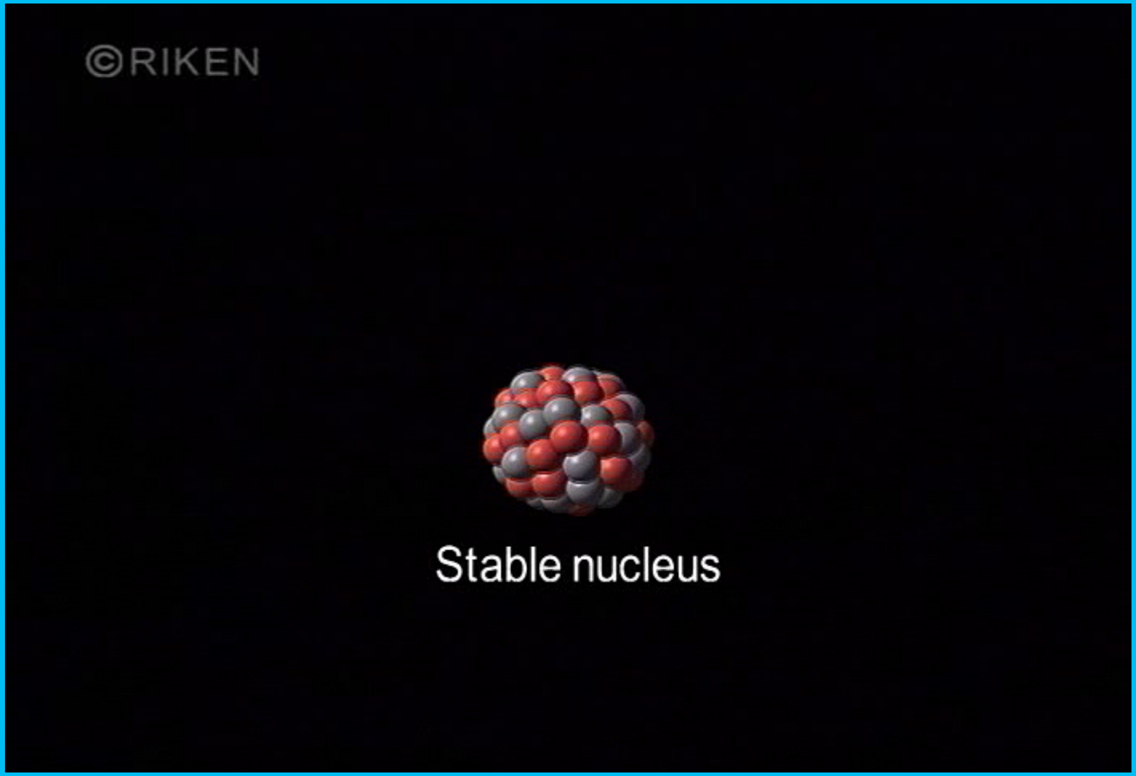
**PANDA**

antiproton beams

**NUSTAR**

radioactive ion beams

# How to create artificial nuclei

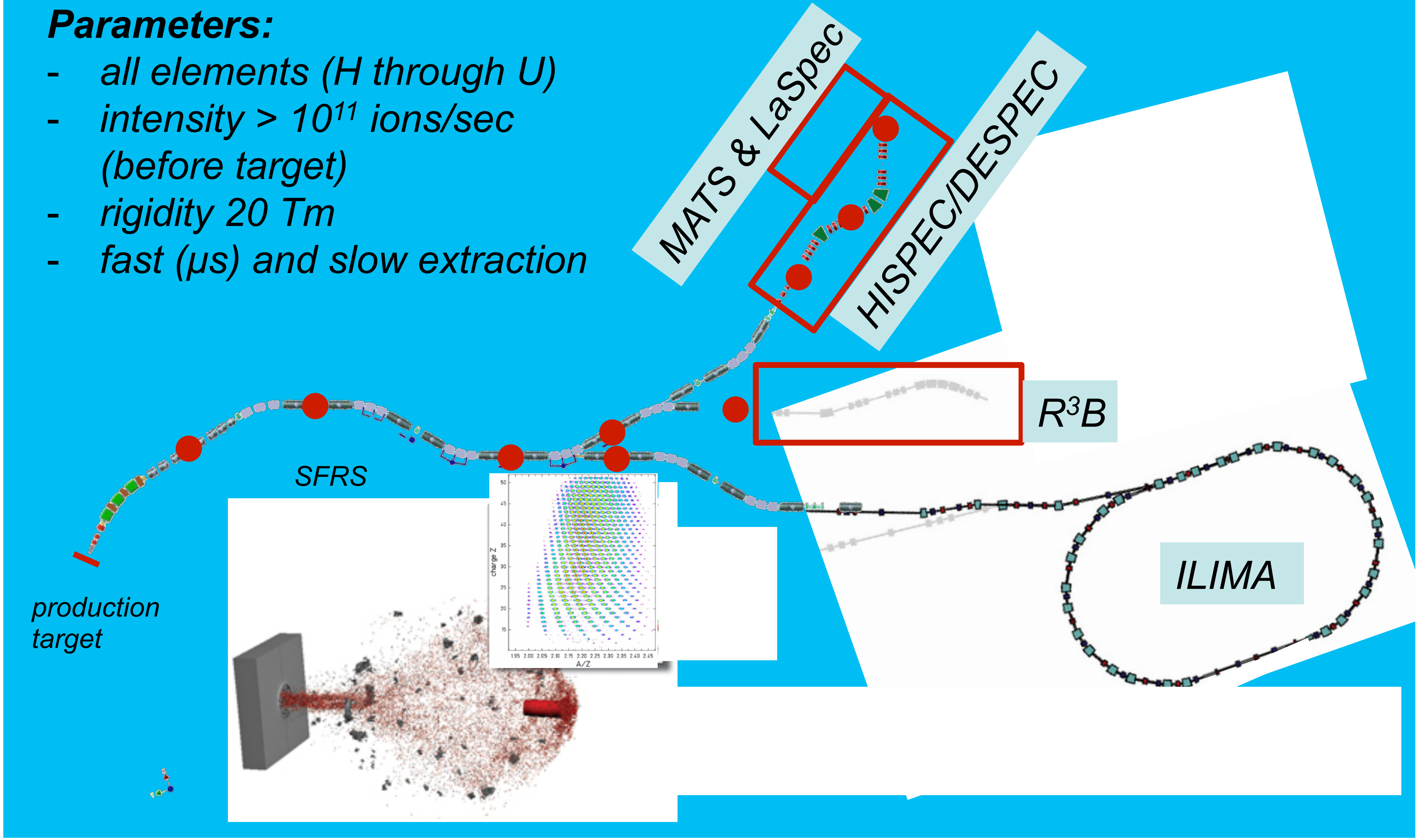


*Billions of collisions per second -> how to fish the exact nucleus one likes to study out of this debris*

# FAIR: rings and instrumentation

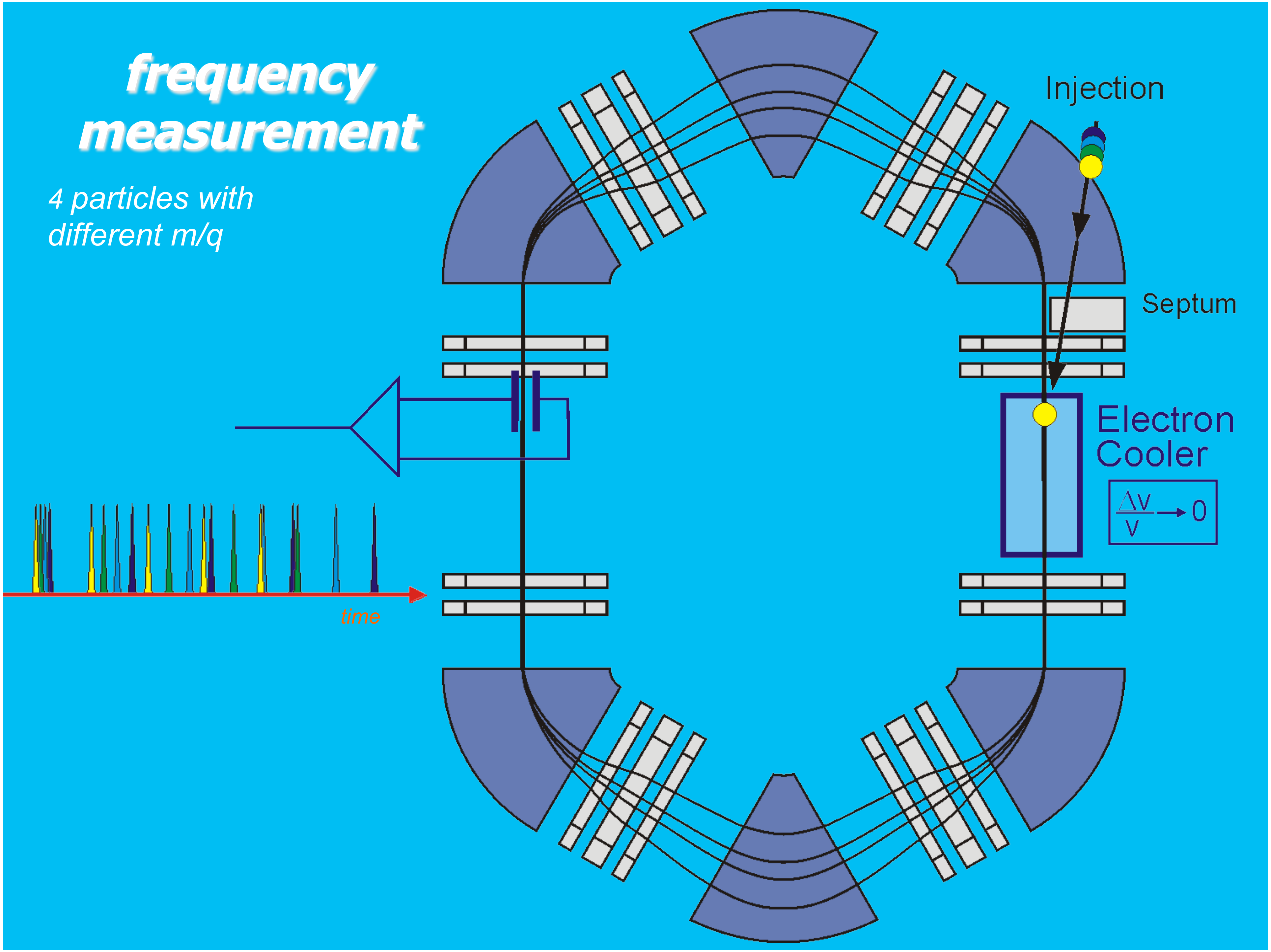
***Parameters:***

- *all elements (H through U)*
- *intensity > $10^{11}$ ions/sec (before target)*
- *rigidity 20 Tm*
- *fast (µs) and slow extraction*

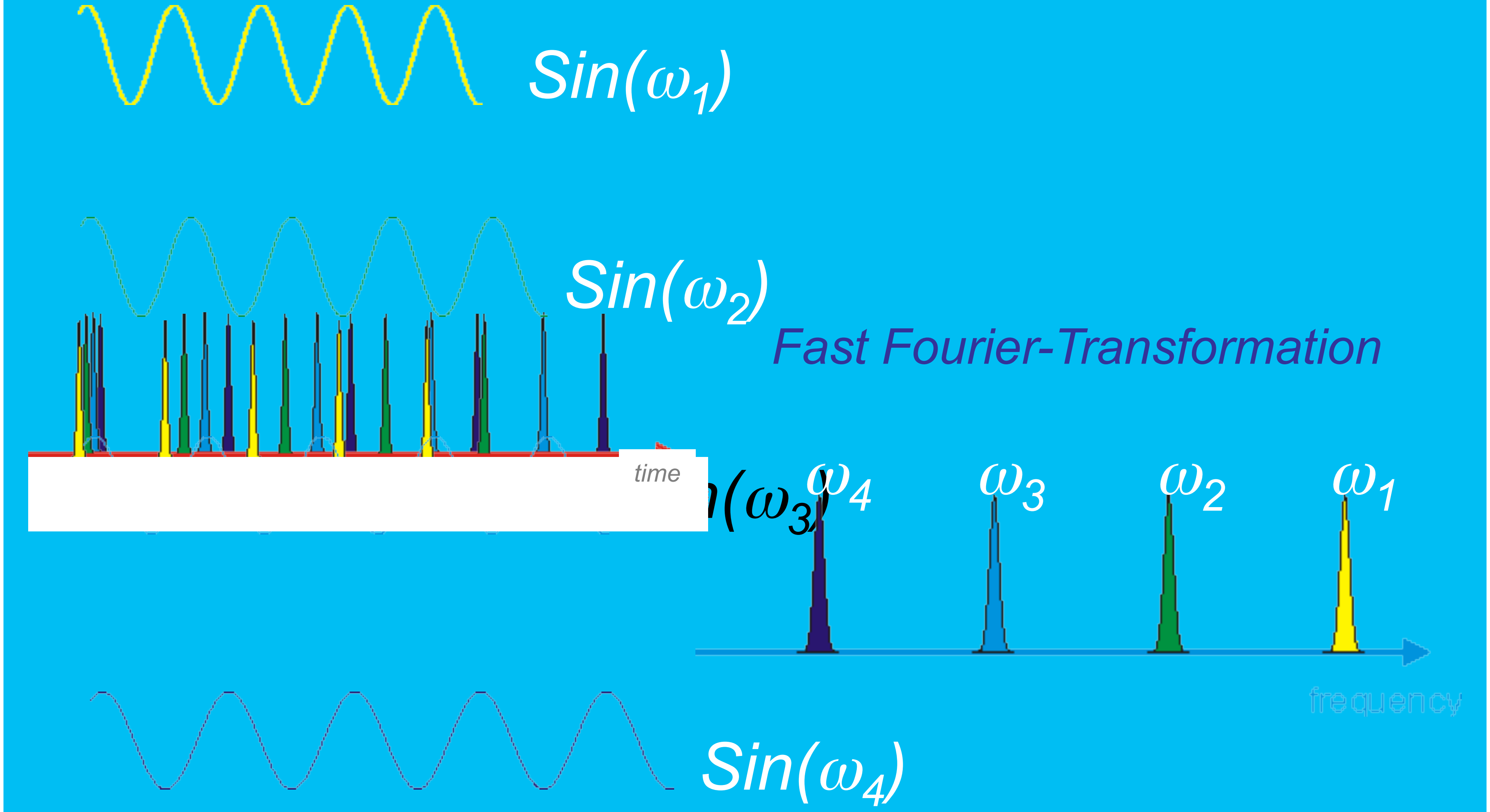


# frequency measurement

*4 particles with different m/q*

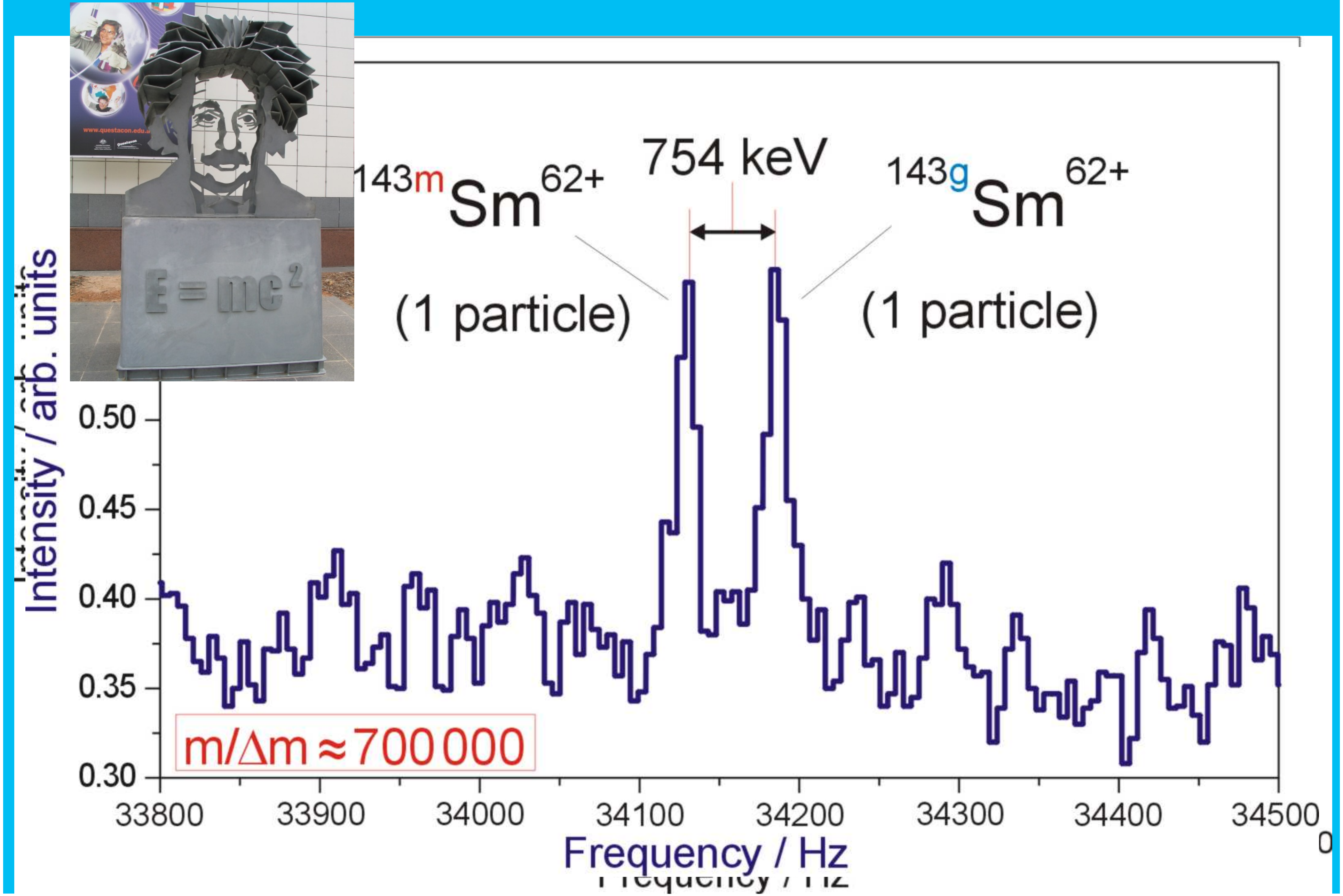


# Frequency measurement



Fast Fourier-Transformation

# Measured mass spectrum



# Precision of mass measurement

*M ~ 160 000 kg*

*M ~ 5 g*

# Neutron star mergers ...
# ... and FAIR – the Universe in the Laboratory

## *Neutron Star Mergers*

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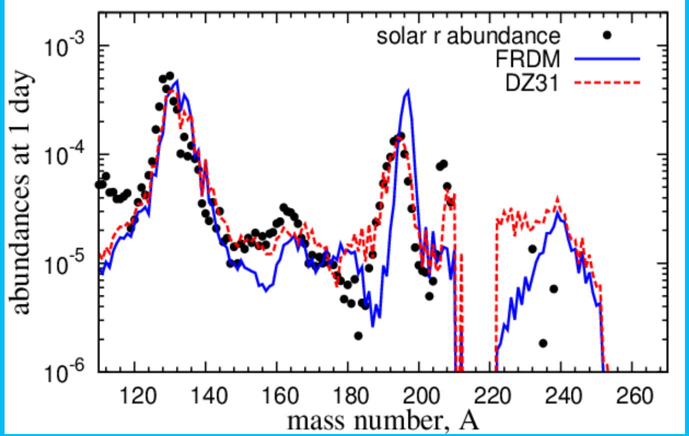
## *FAIR Research Pillars*

- *Equation of State (**Hades, CBM**)*
  - *Gravitational wave signal*
  - *Amount of ejecta*
- *Lambda-nucleon interactions (**PANDA**)*
- *Exotic neutron-rich nuclei (**NUSTAR**)*
  - *r-process nucleosynthesis and abundancies of the heaviest elements gold, platinum and beyond*
- *Plasma and atomic opacities (**APPA**)*
  - *Kilonova electromagnetic transient*

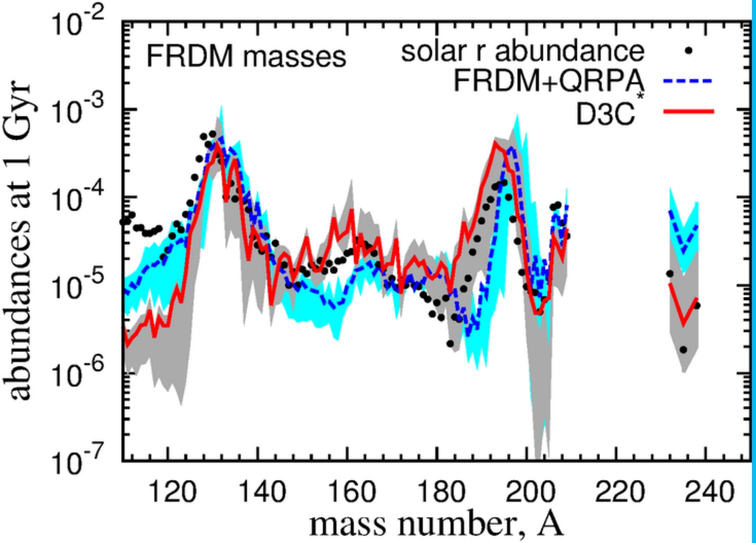
***FAIR offers unique opportunities for studying these fundamental questions related to the STRUCTURE OF MATTER and EVOLUTION OF THE UNIVERSE!***

# Sensitivity to nuclear data

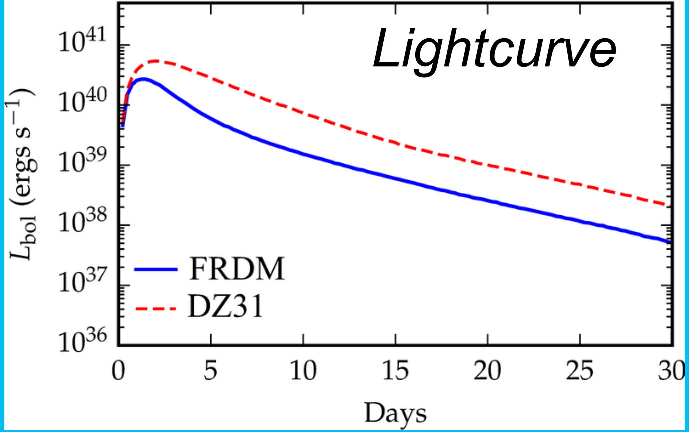
*r-process abundances*



*Masses*

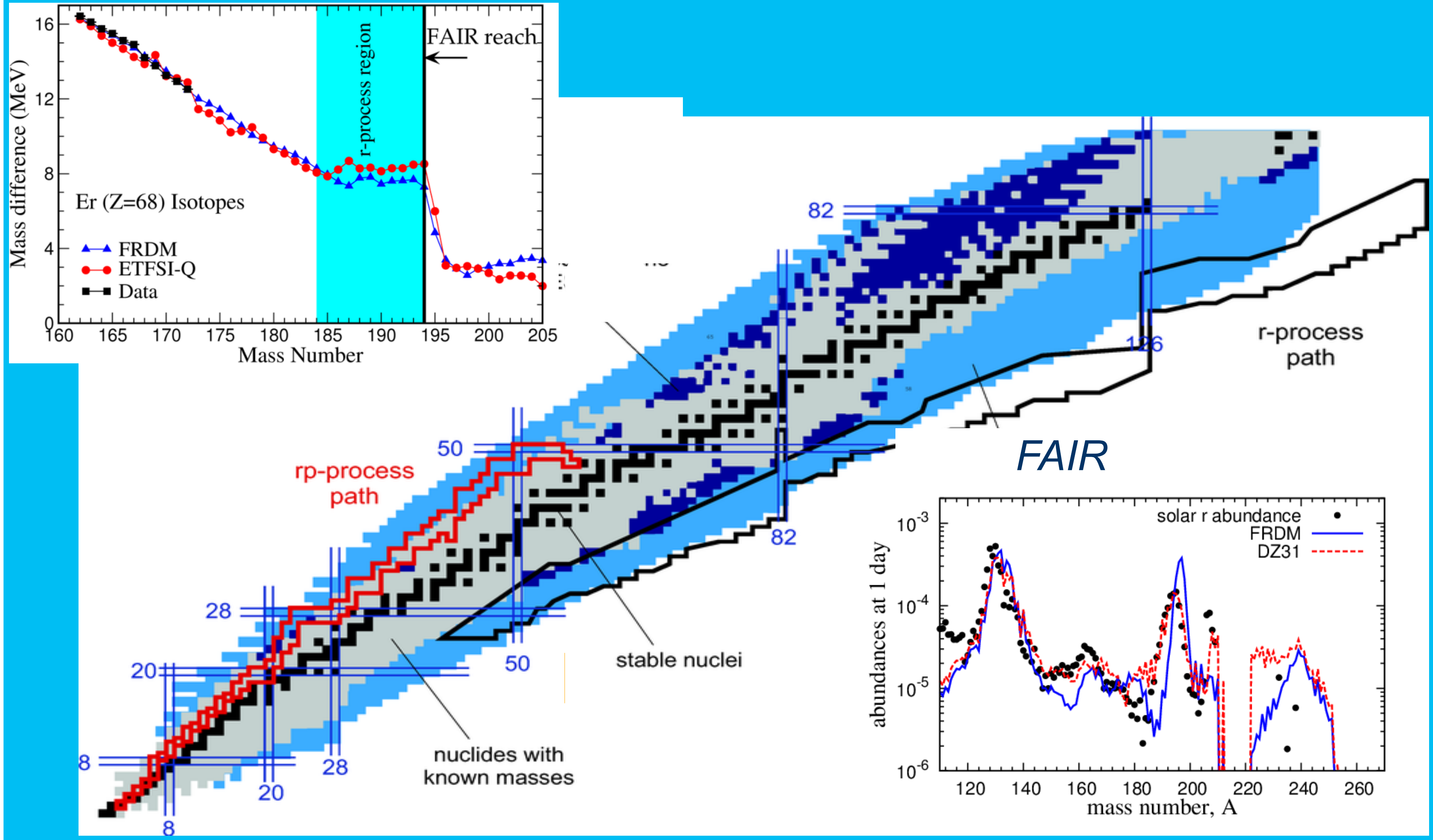


*Half lives*



*Lightcurve sensitive to N=126 halflives -> FAIR range*

# FAIR: nuclear masses

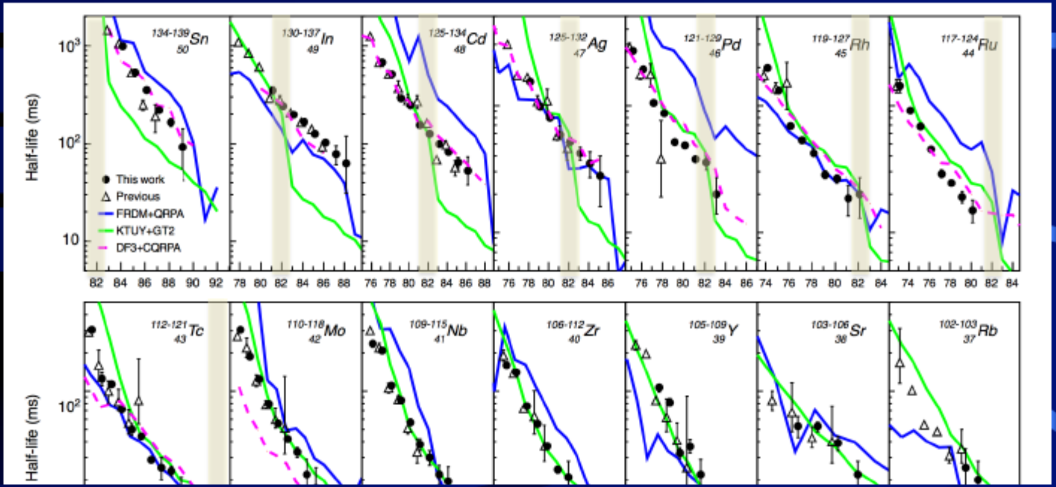


# *Madrid-Strasbourg shell model*

## 110 Half-lives of Very Neutron-Rich Rb to Sn

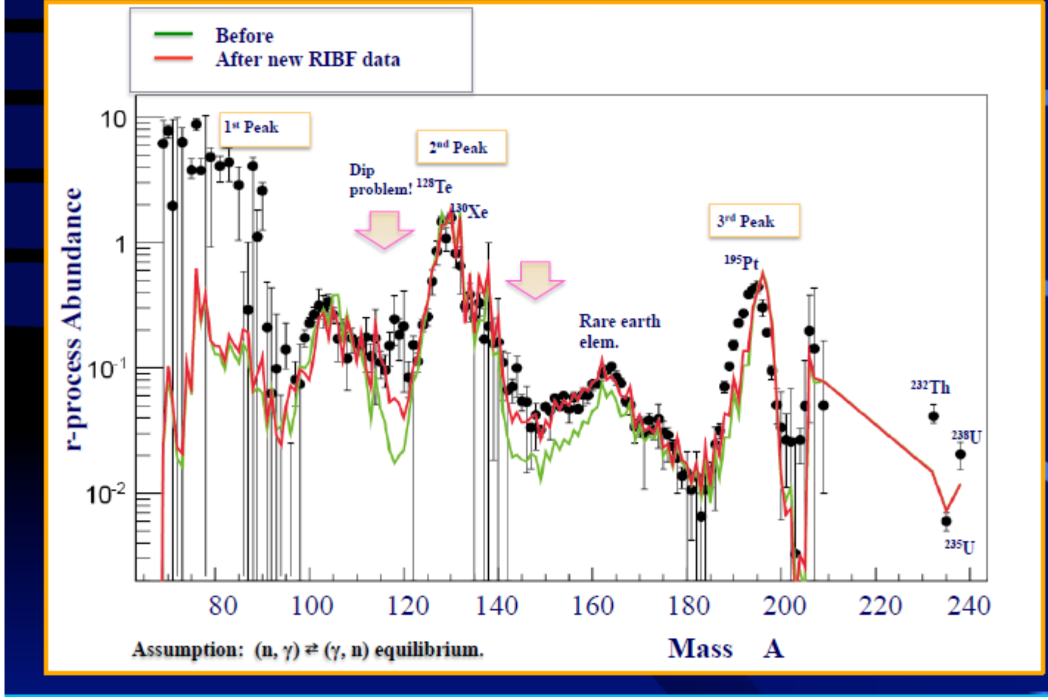
40 new half-lives ! G.Lorusso et al., PRL 114, 192501 (2015)

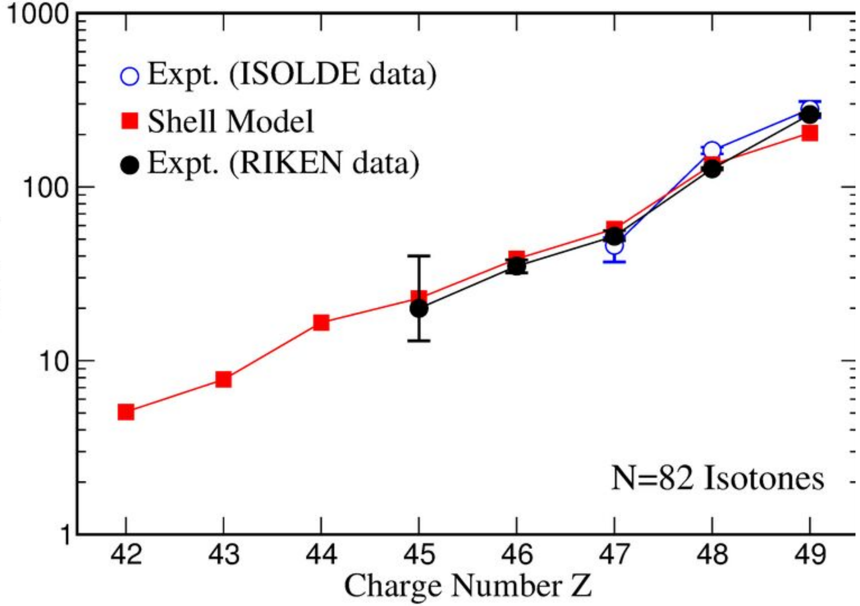
18 new half-lives ! SN PRL 106, 052502 (2011)



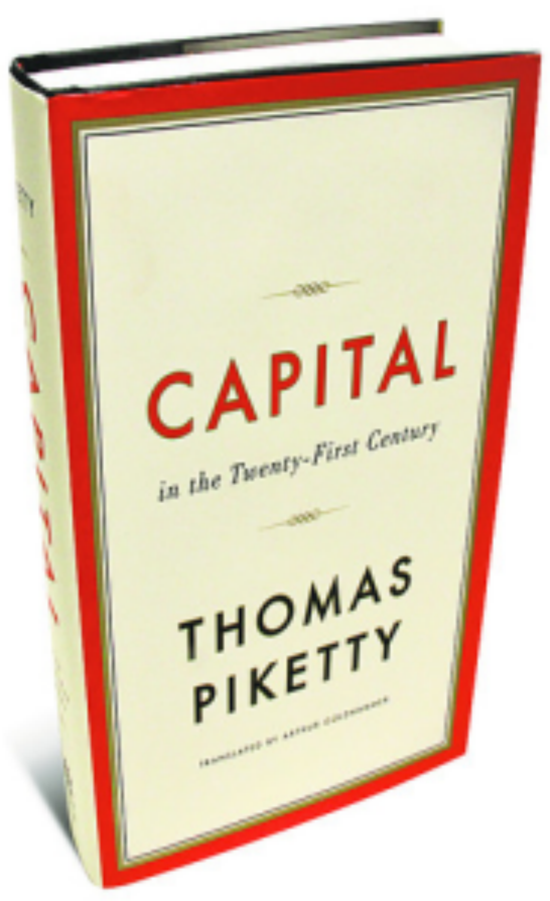
## r-process Abundance with New $T_{1/2}$ (RIBF)

G.Lorusso et al., PRL (2015)





*important progress: halflives from RIKEN*



*Future of society:*

*SKILLS and*
*TECHNOLOGY*

# Educating the next generation

*students learn in interplay of universities and large-scale labs:*

- *exciting science*
- *solving of complex problems*
- *forefront technology and IT*
- *mobility*
- *social skills (working in groups)*
- *internationality, languages*

# HGS-HIRe Graduate Days 2013

5th Anniversary of HGS-HIRe

# The FAIR Chance: New Horizons

# The FAIR Chance: New Horizons