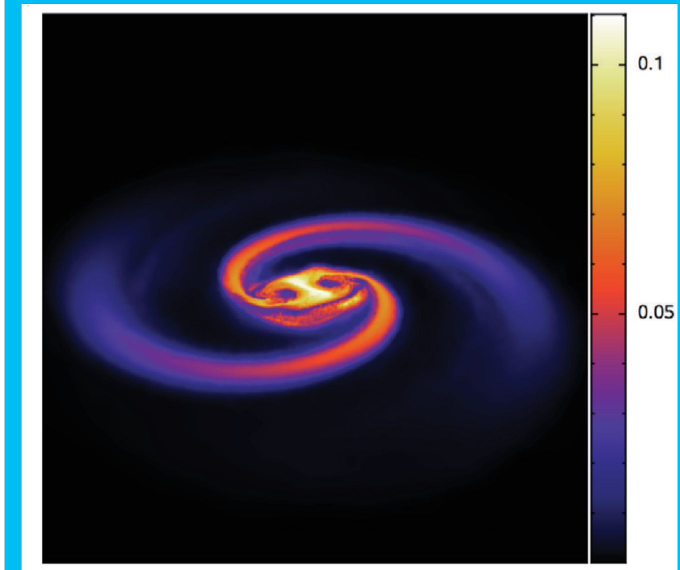
How Nature makes Gold



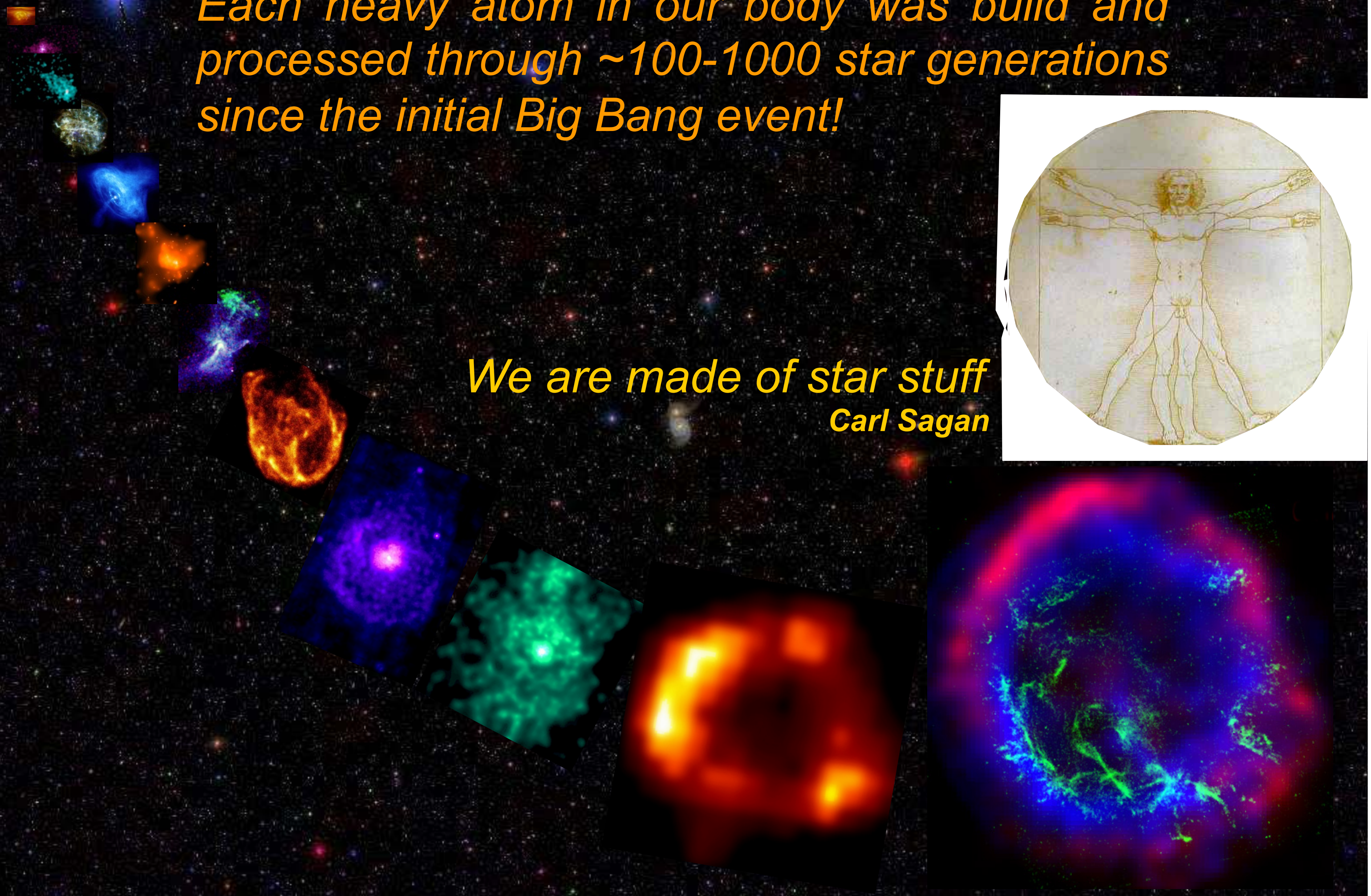
Karlheinz Langanke
GSI Helmholtzzentrum Darmstadt
Technische Universität Darmstadt

HELMHOLTZ ASSOCIATION

GSI

,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!

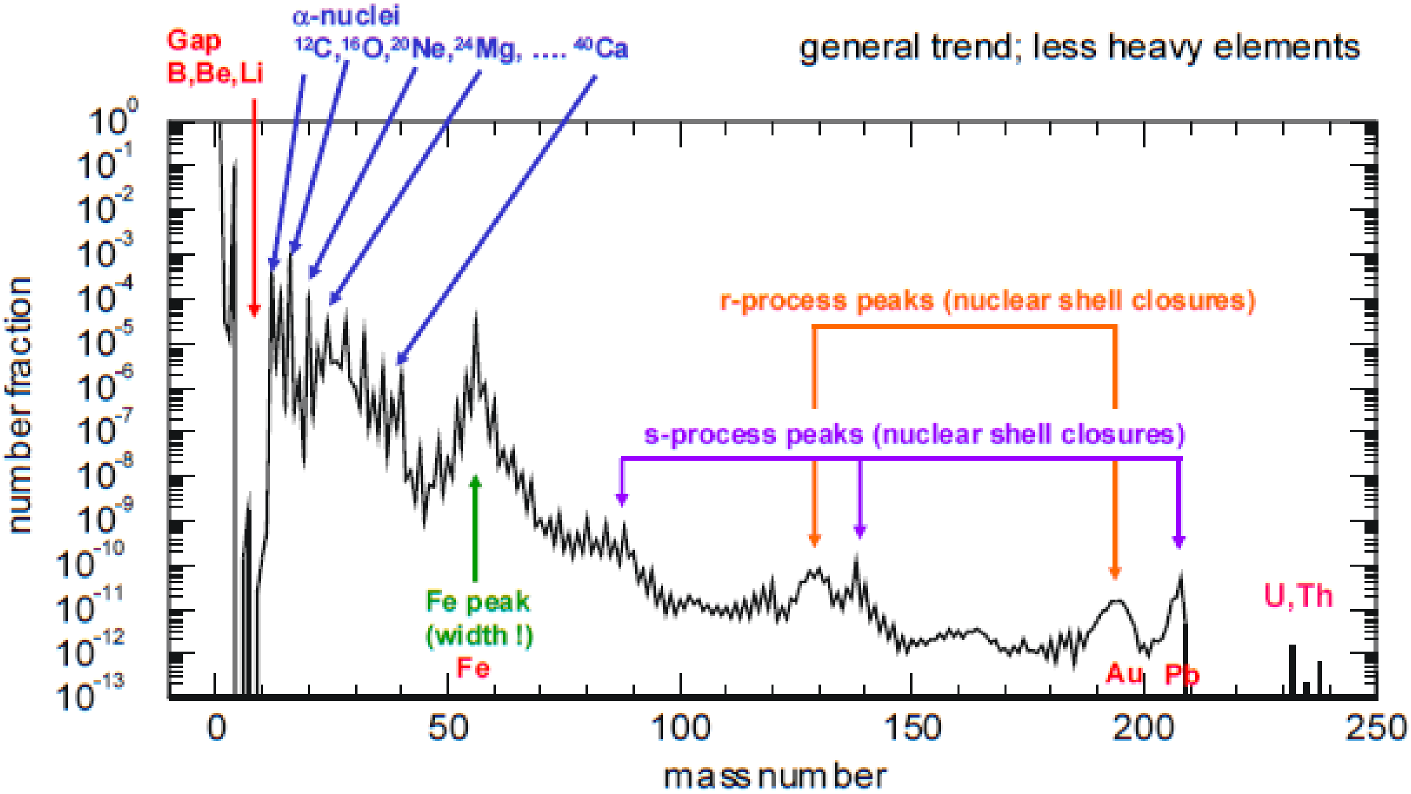


We are made of star stuff

Carl Sagan

Abundances of the elements

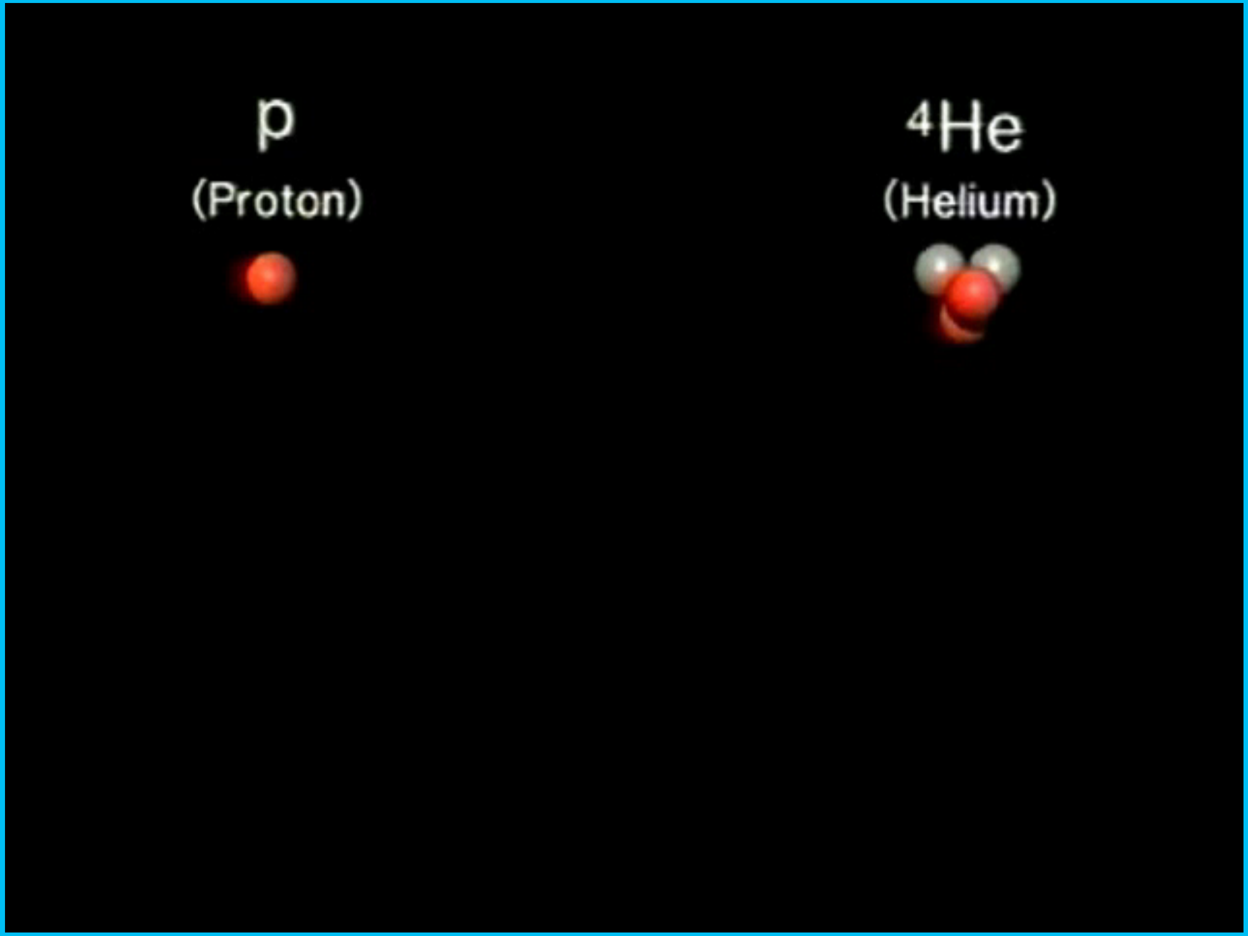
Hydrogen mass fraction	X = 0.71
Helium mass fraction	Y = 0.28
Metallicity (mass fraction of everything else)	Z = 0.019
Heavy Elements (beyond Nickel) mass fraction	4E-6



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

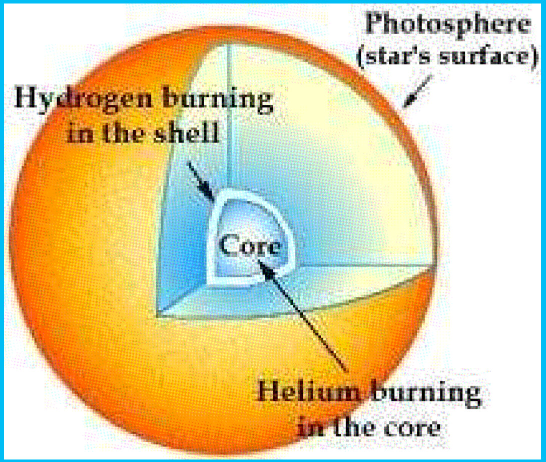


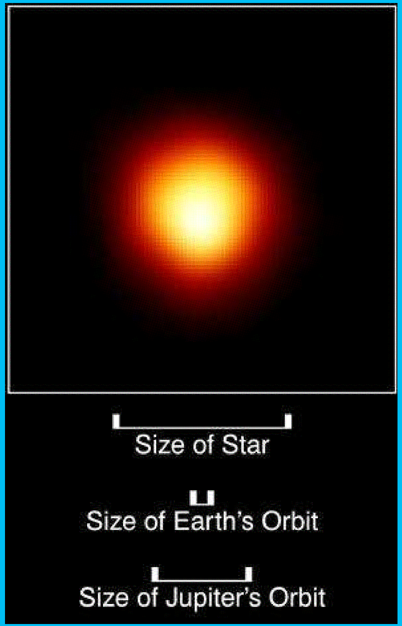
Solar hydrogen burning

- 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

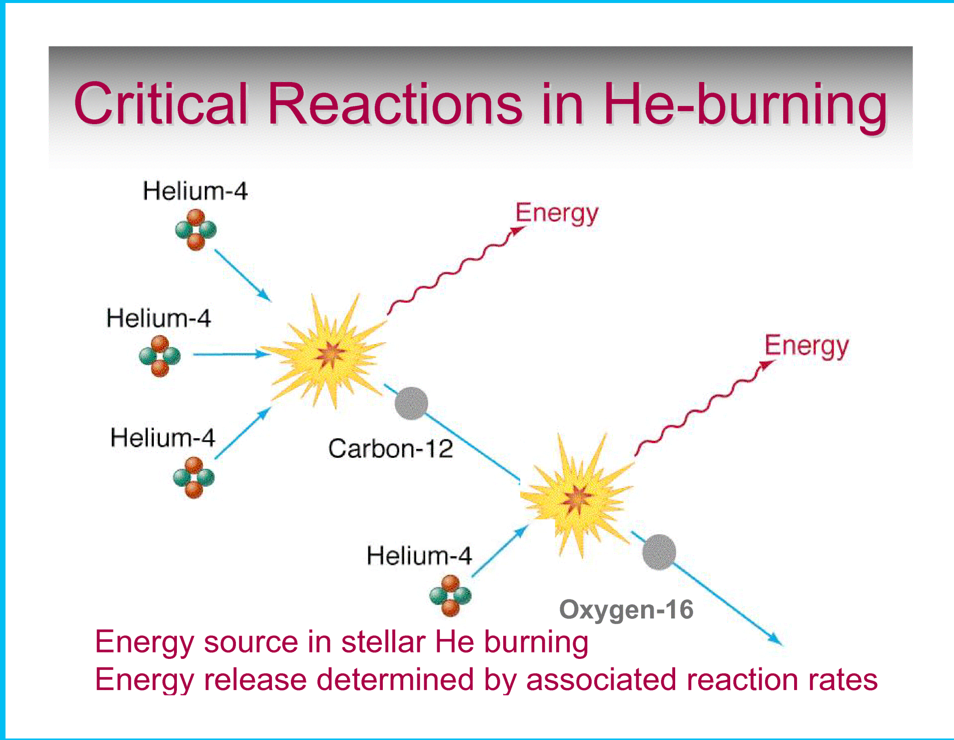
Helium burning

- 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



- 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

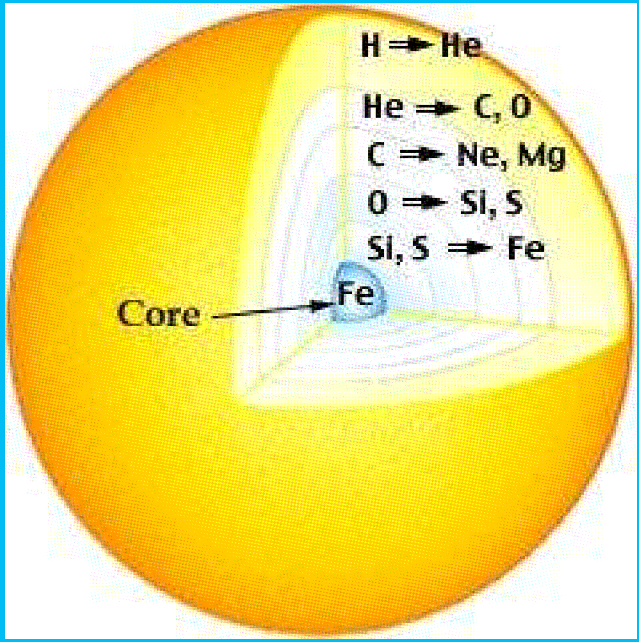
(e.g., 20 solar mass star)

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 s-process	0.2	10^6	$3\,He^4 \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$
C	Ne, Mg	Na	0.8	10^3	$^{12}C + {}^{12}C$
Ne	O, Mg	Al, P	1.5	3	$^{20}Ne(\gamma,\alpha)^{16}O$ $^{20}Ne(\alpha,\gamma)^{24}Mg$
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	$^{28}Si(\gamma,\alpha)$…

Courtesy: A. Heger and S. Woosley

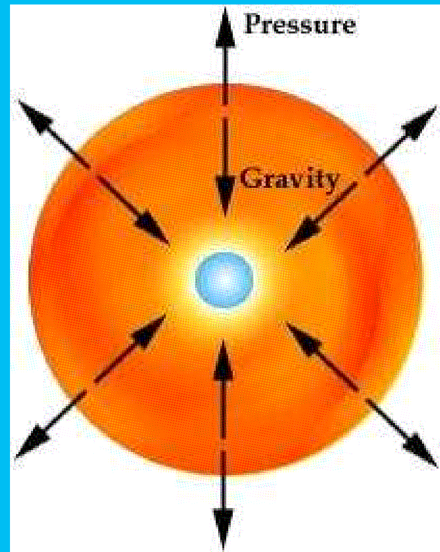
Final fate of a massive star

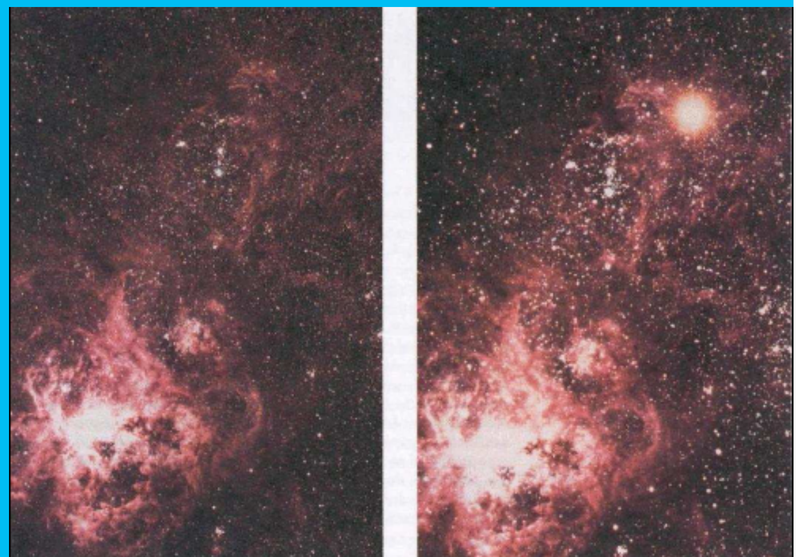
- Star has an onion structure
- Iron is the final product of hydrostatic burning
- The inner iron core grows, gets unstable against its own gravity and collapses
- SUPERNOVA!



Collapse and explosion of a star

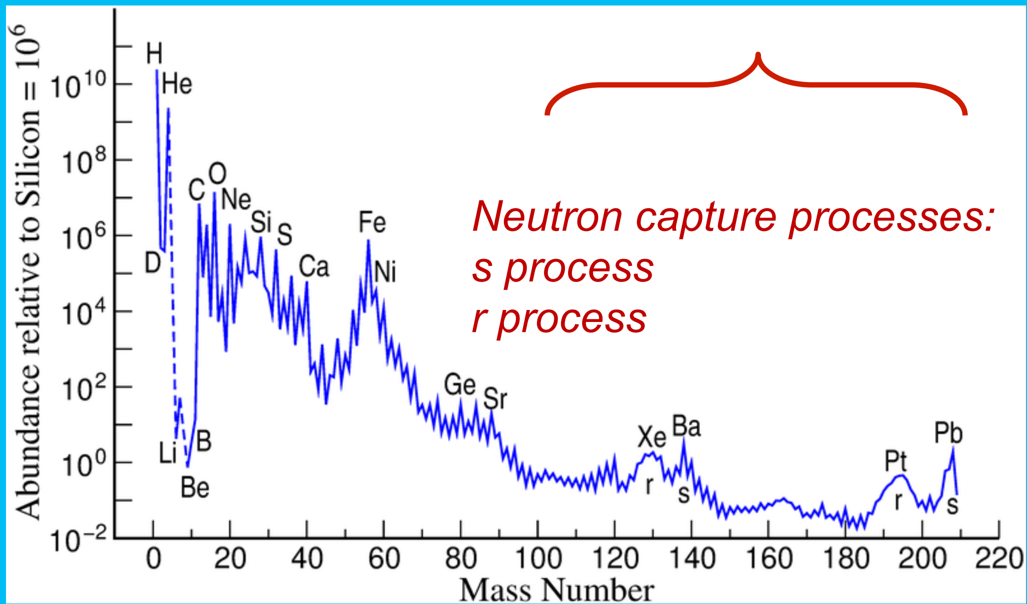
- Stability by pressure-gravity balance
- pressure produced by nuclear reactions
- Balance cannot be kept when iron core grows
- In about 1 second the core radius reduces from 6000 km to 20 km
- Collapse stops, when the core corresponds to a gigantic atomic nucleus. A large portion of the gravitational 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.

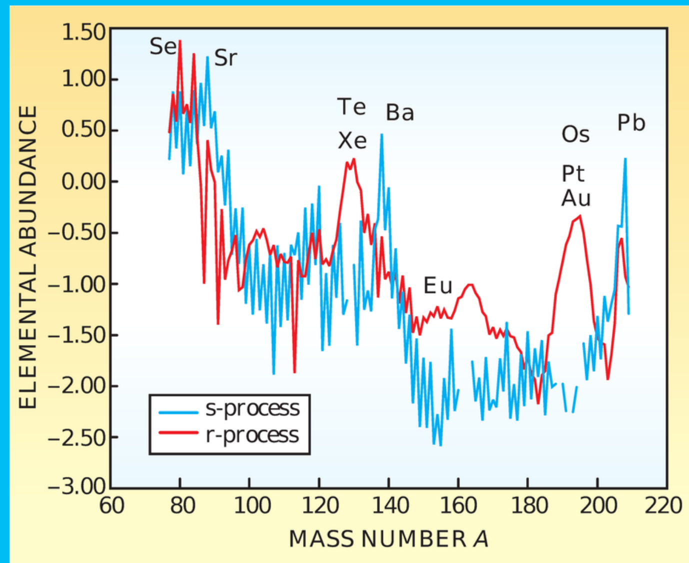




Making Gold: The R-Process

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





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

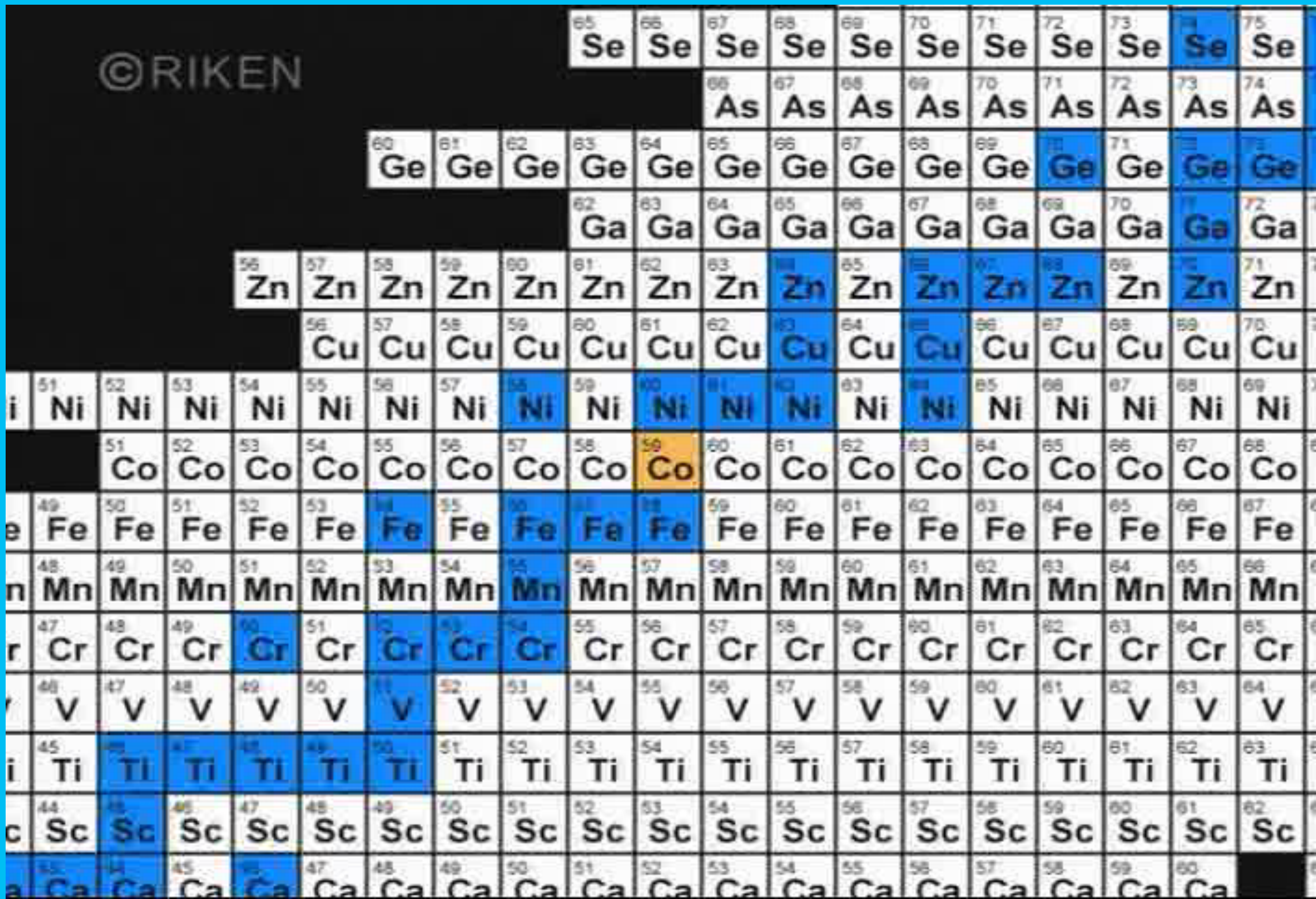
Making heavy elements in Nature

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

Consider the two cases:

1. 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.
2. 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

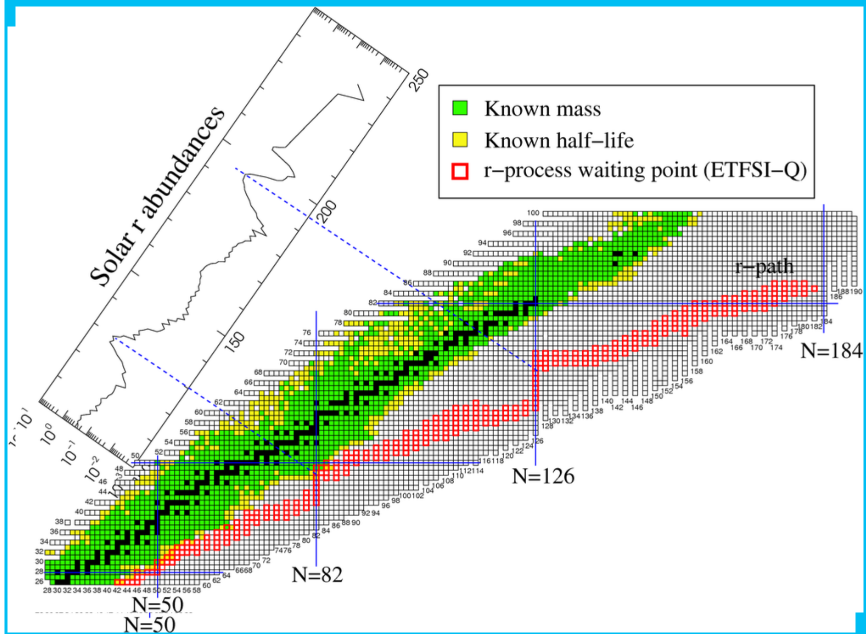


Astrophysical S-process

- **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 3×10^8 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

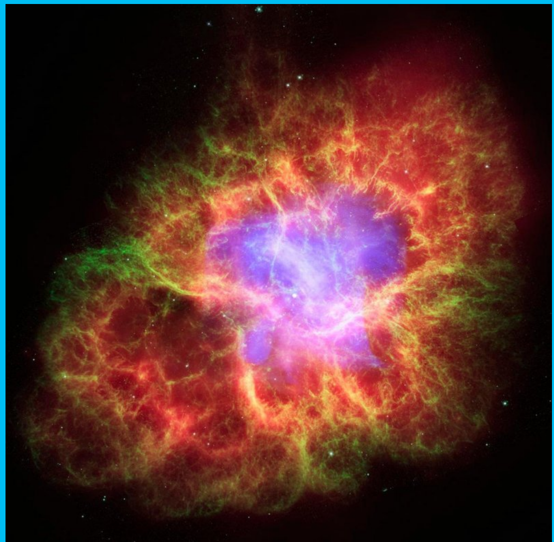
Humans

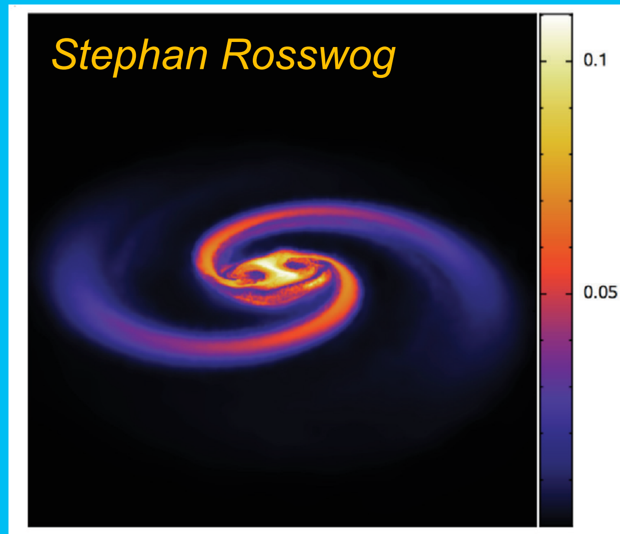
very fast nuclear reactions in environment with extreme densities of free neutrons Nuclei involved very neutron-rich and short-lived.

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

Astrophysical sites

Core-collapse supernova *Compact binary mergers*

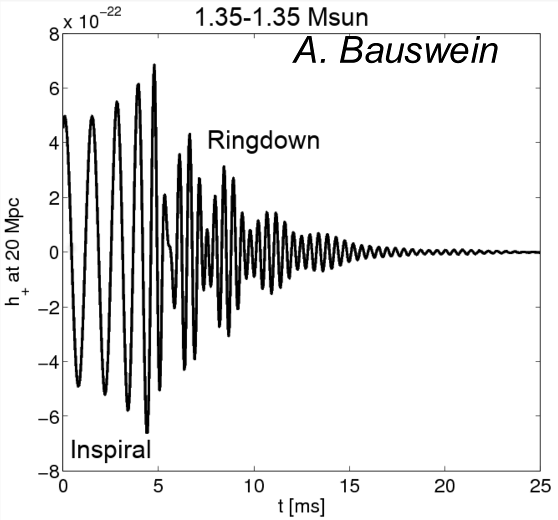




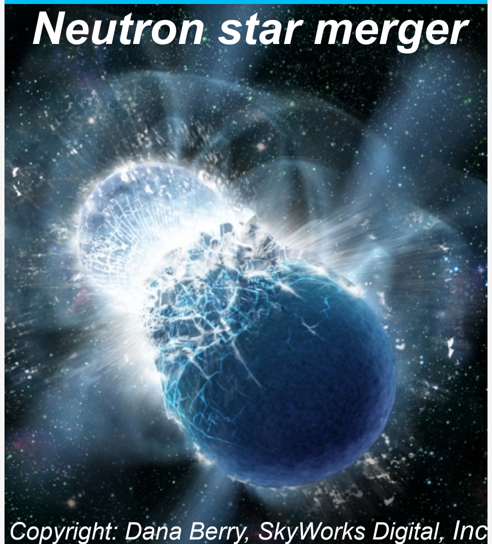
Y_e

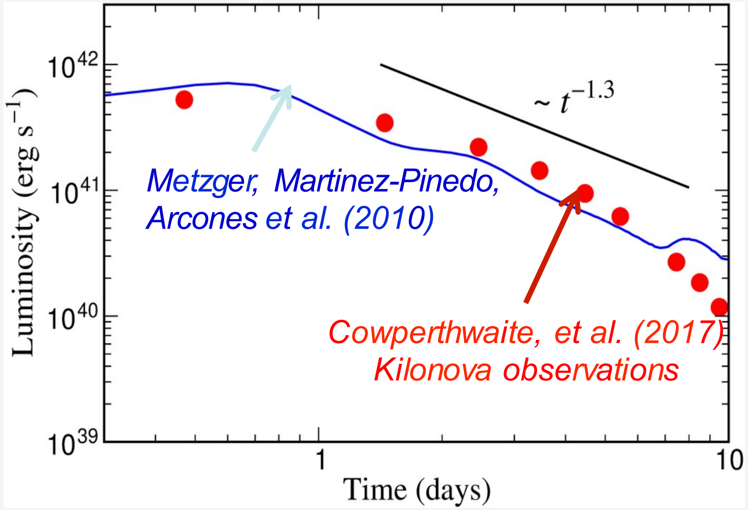
	Supernova	Mergers
Optimal conditions	☹	☺
Yield / Frequency	😐	☺
Direct signature	☹	☺

Neutron Star merger confirmed as astrophysical site of heavy element production



Gravitational Wave Signal

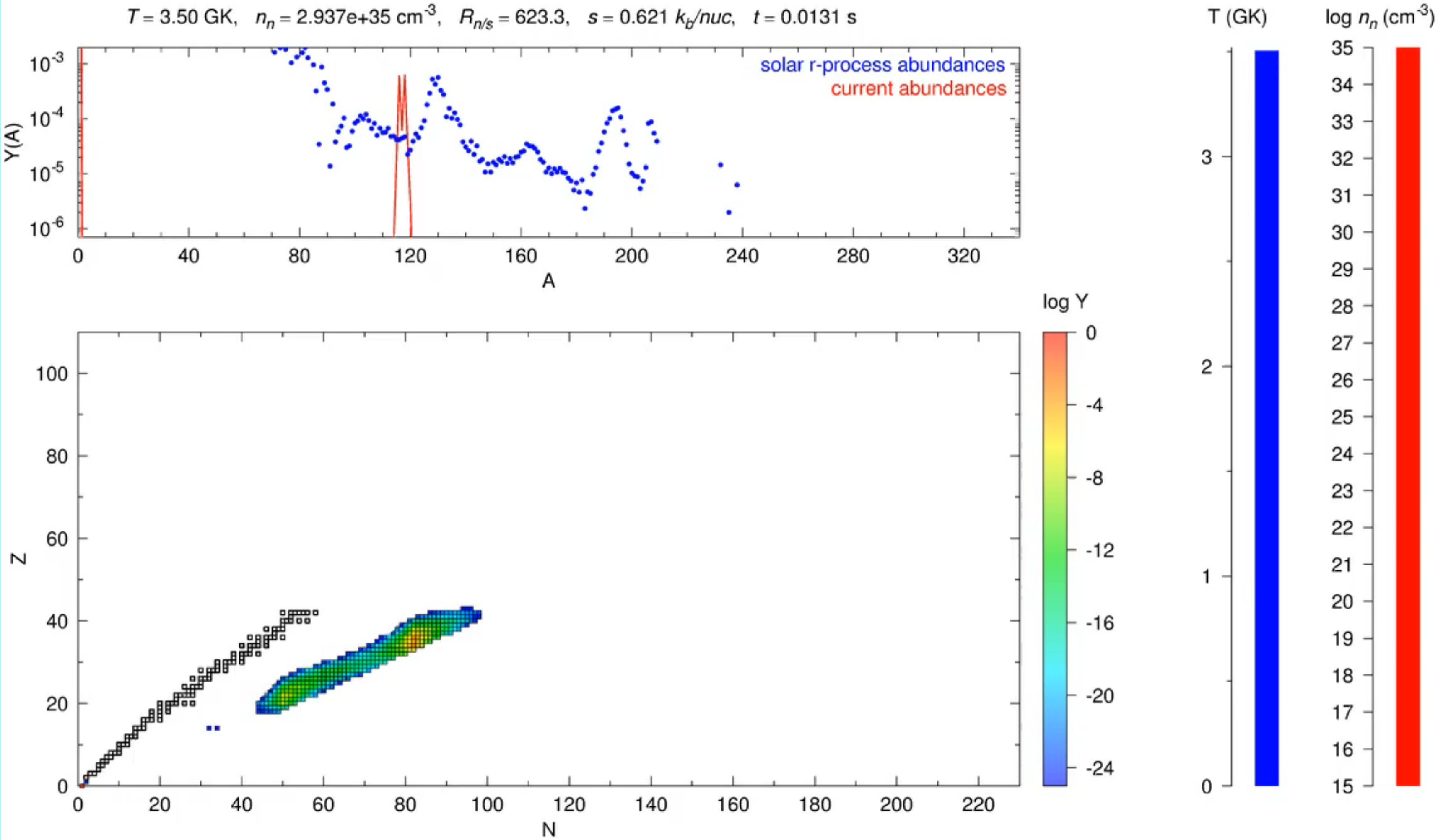




Electromagnetic “Kilonova” Signal

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

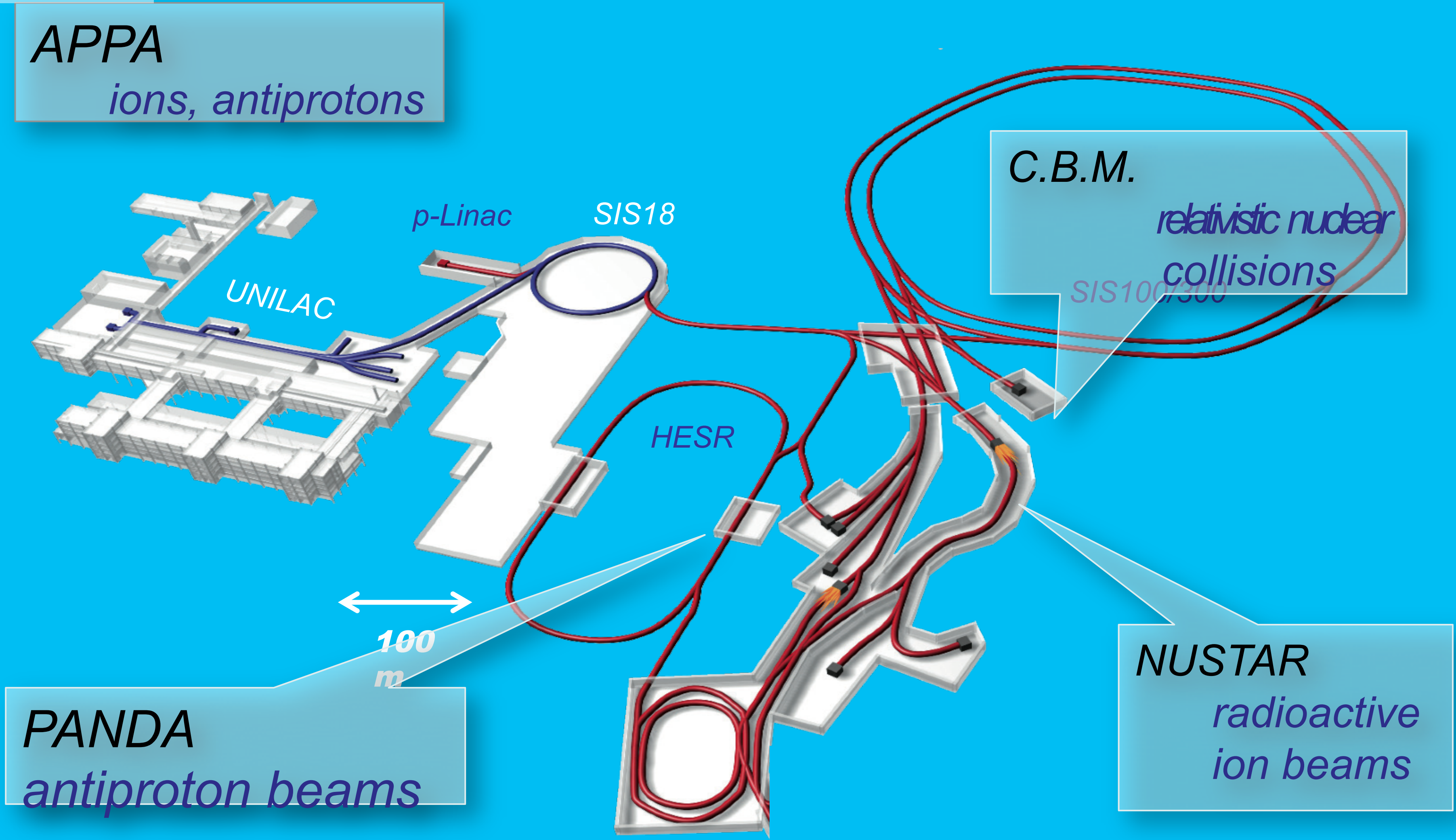
- of nuclei with extreme neutron excess. Most have never been produced yet.
- But this will change -> Radioactive ion Beam Facility

Facility for Antiproton and Ion Research in Europe

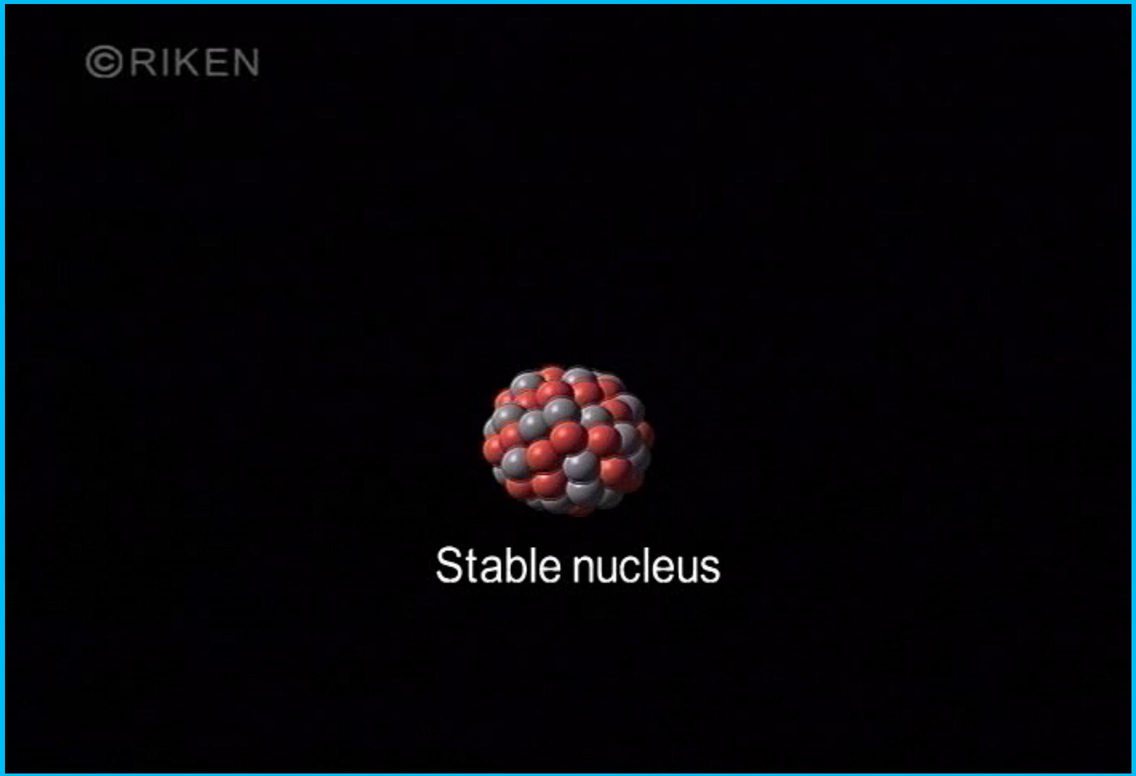
International Participation in FAIR

- 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



How to create artificial nuclei

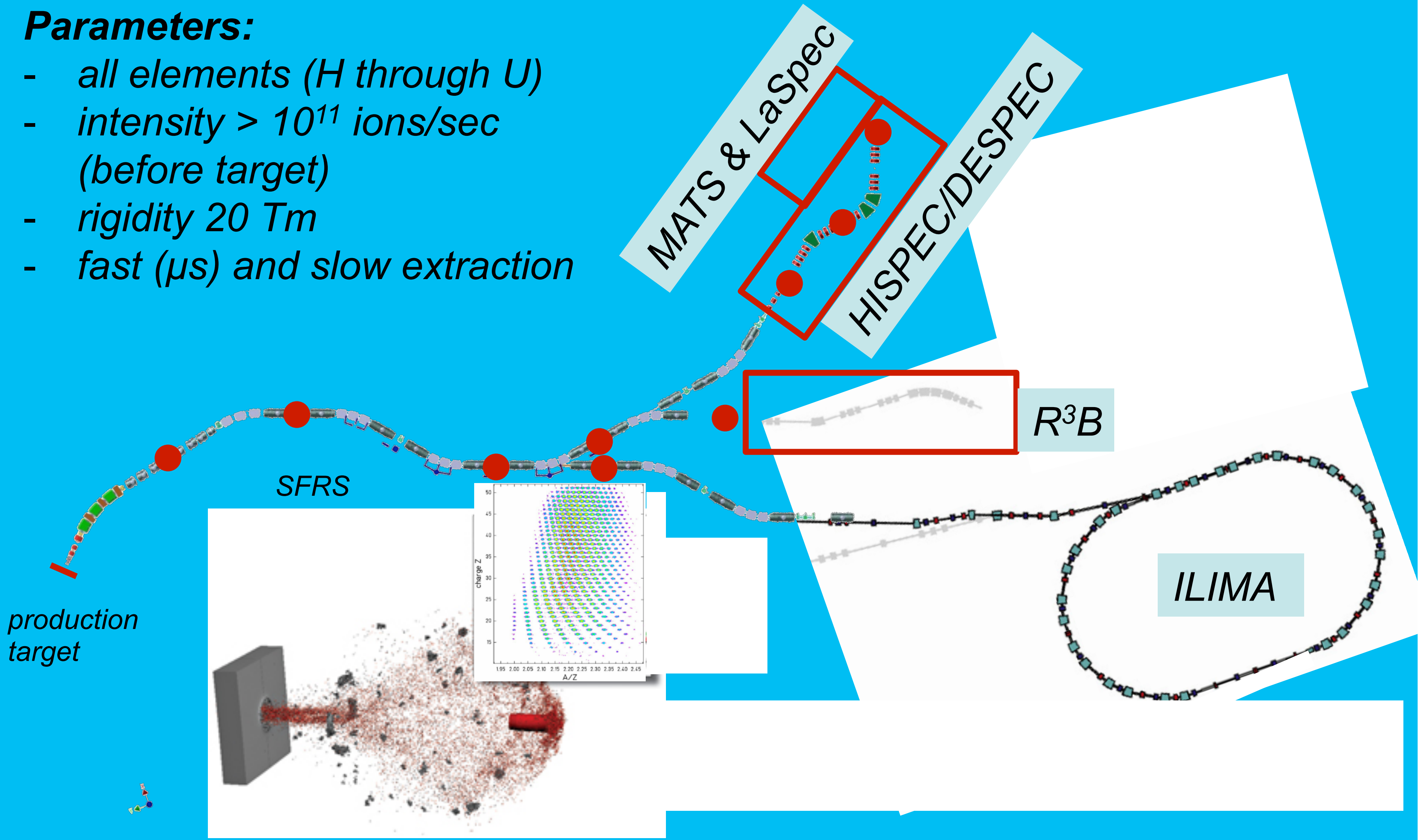


Billions of collisions per second -> how to fish the exact nucleus one likes to study out of this debris

FAIR: rings and instrumentation

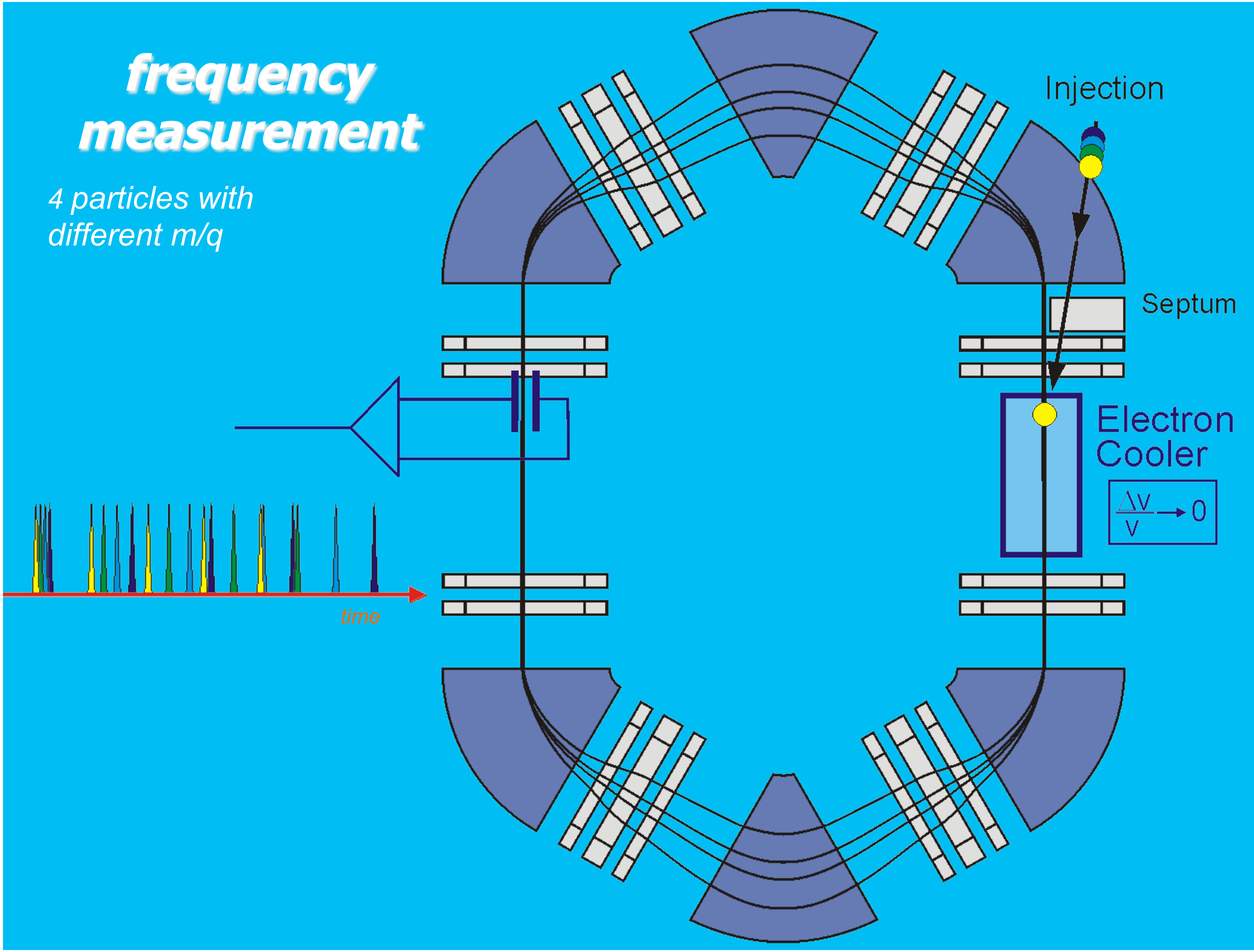
Parameters:

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

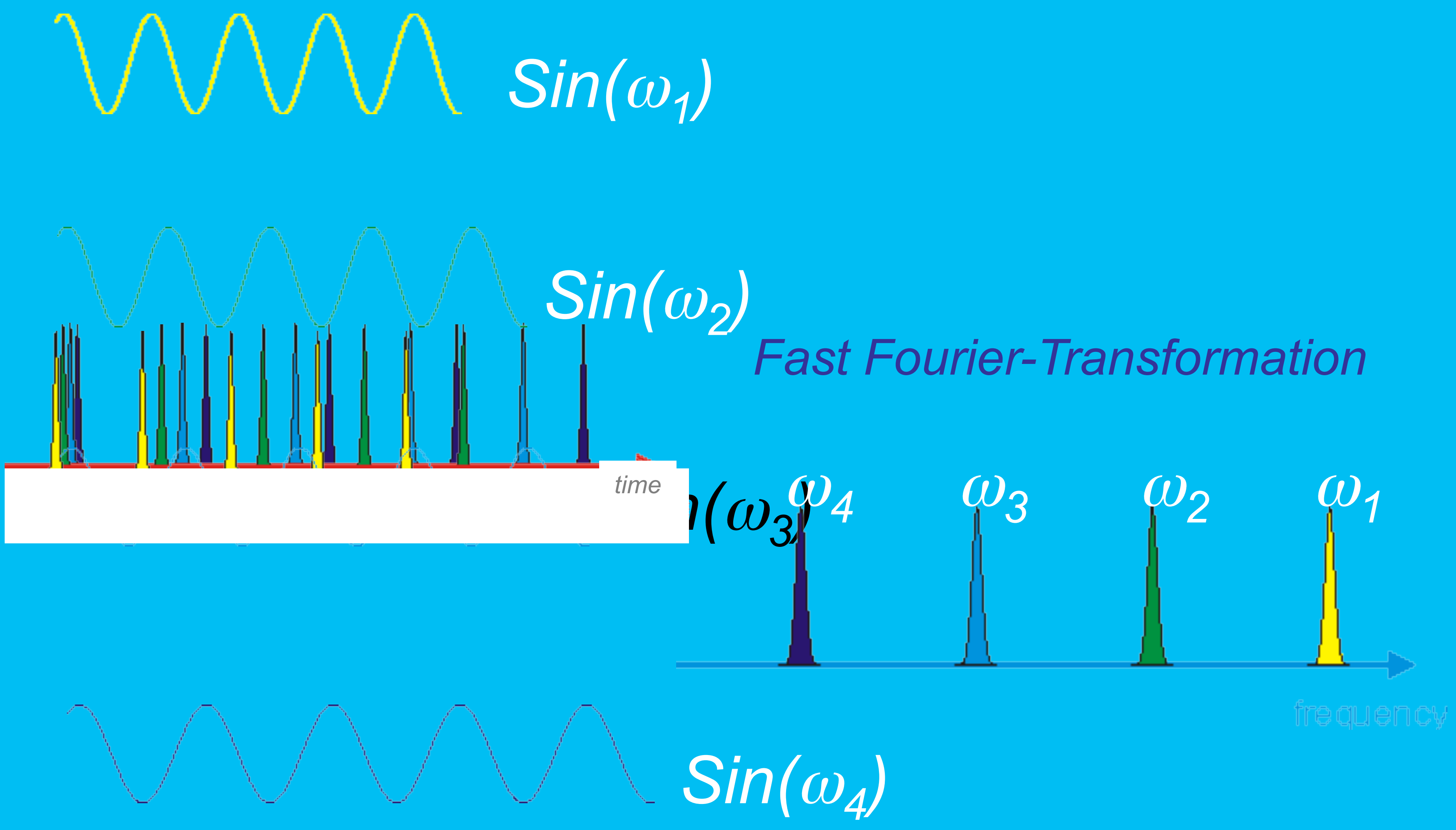


frequency measurement

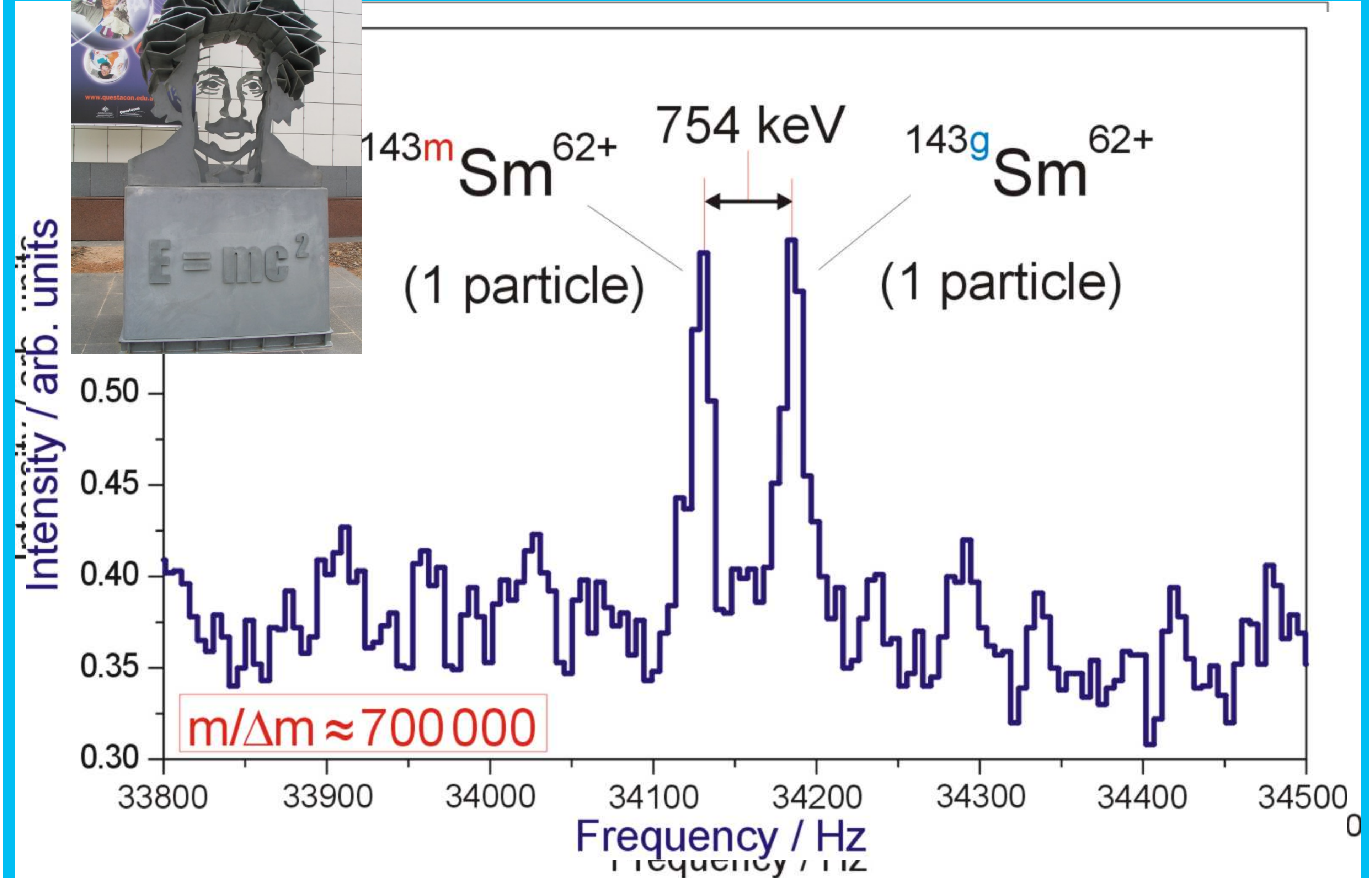
4 particles with different m/q



Frequency measurement



Measured mass spectrum



Precision of mass measurement

M ~ 160 000 kg

M ~ 5 g

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

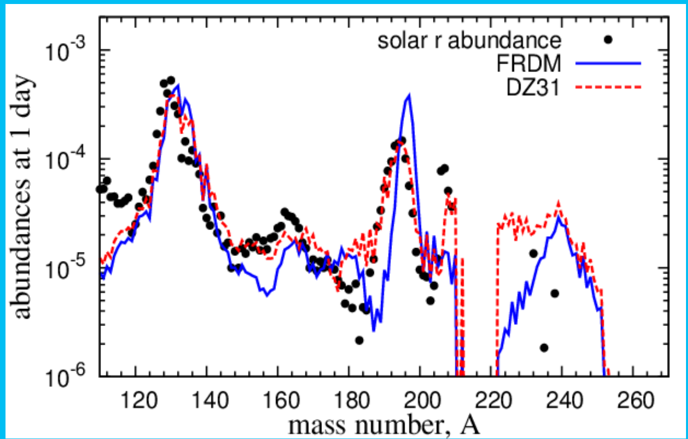
Neutron Star Mergers

FAIR Research Pillars

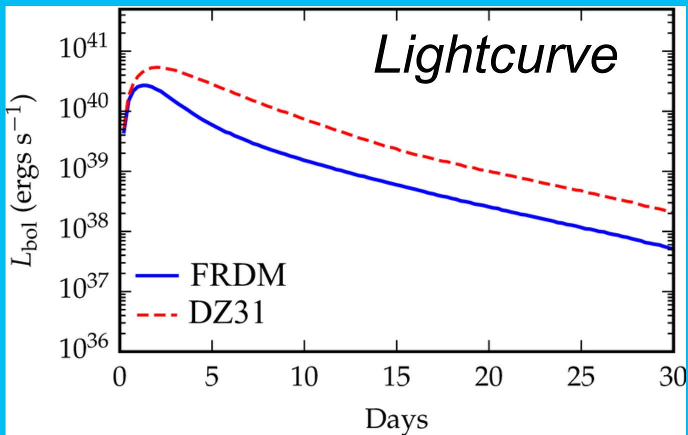
- *Equation of State (**Hades, CBM**)*
  - *Gravitational wave signal*
  - *Amount of ejecta*
- *Lambda-nucleon interactions (**PANDA**)*
- *Exotic neutron-rich nuclei (**NUSTAR**)*
  - *r-process nucleosynthesis and abundancies of the heaviest elements gold, platinum and beyond*
- *Plasma and atomic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

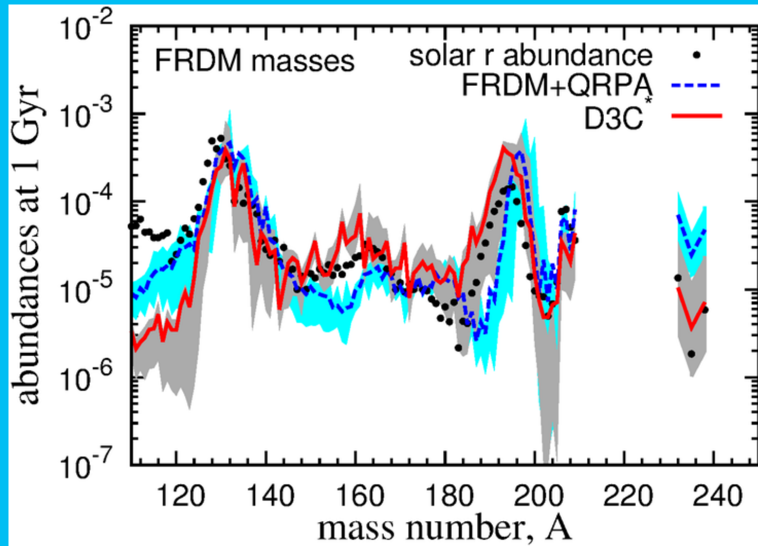
Sensitivity to nuclear data



Masses



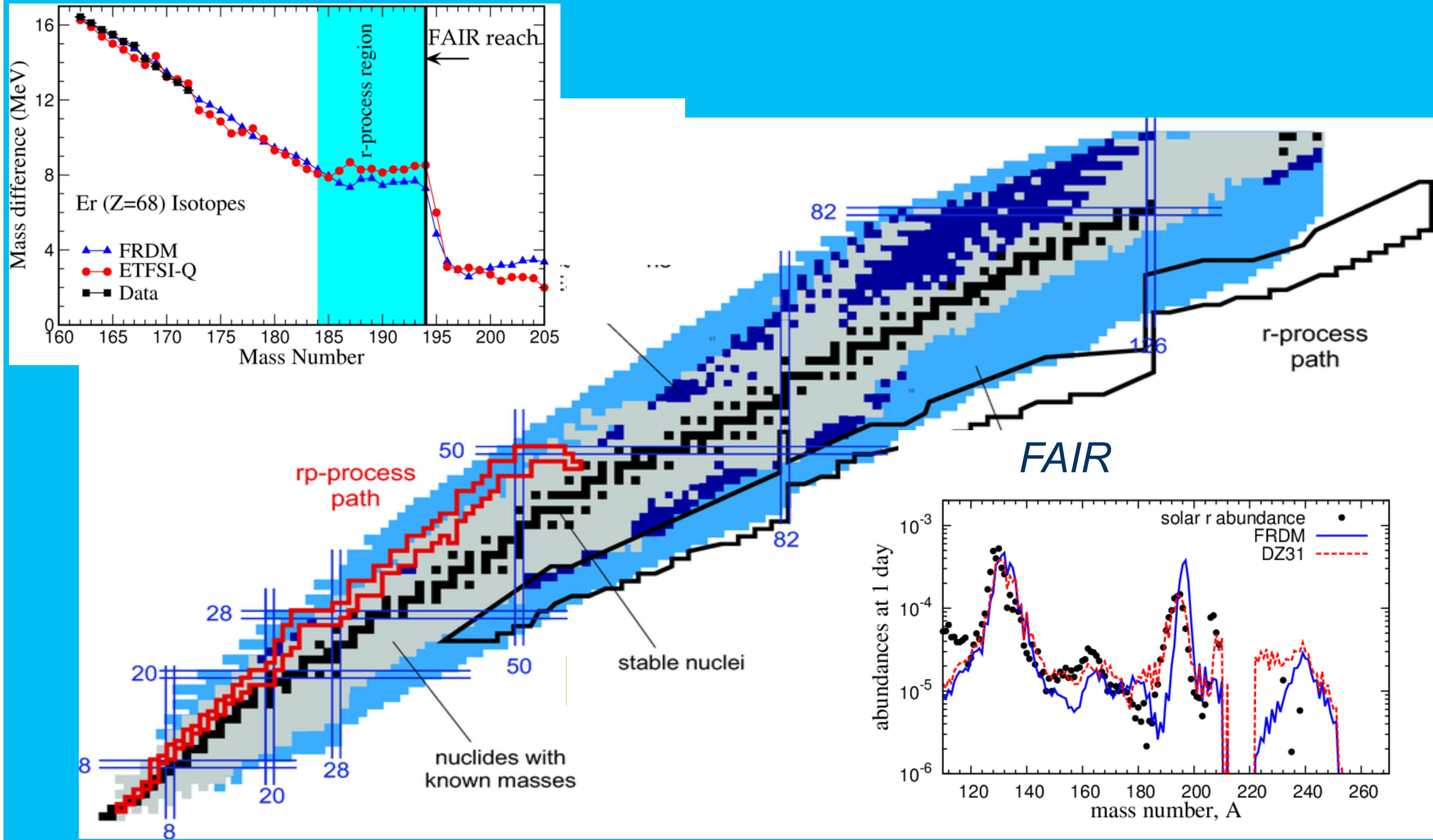
r-process abundances



Half lives

Lightcurve sensitive to N=126 halflives -> FAIR range

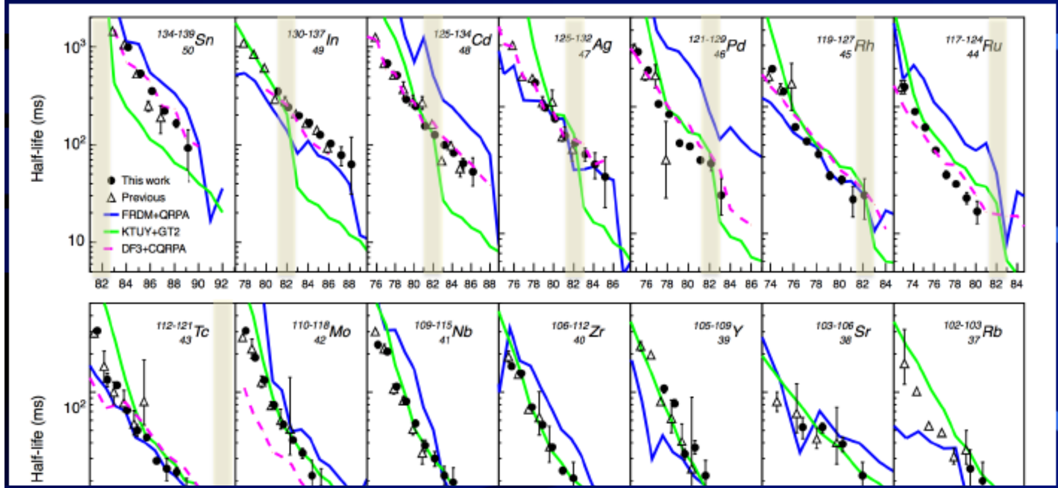
FAIR: nuclear masses



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

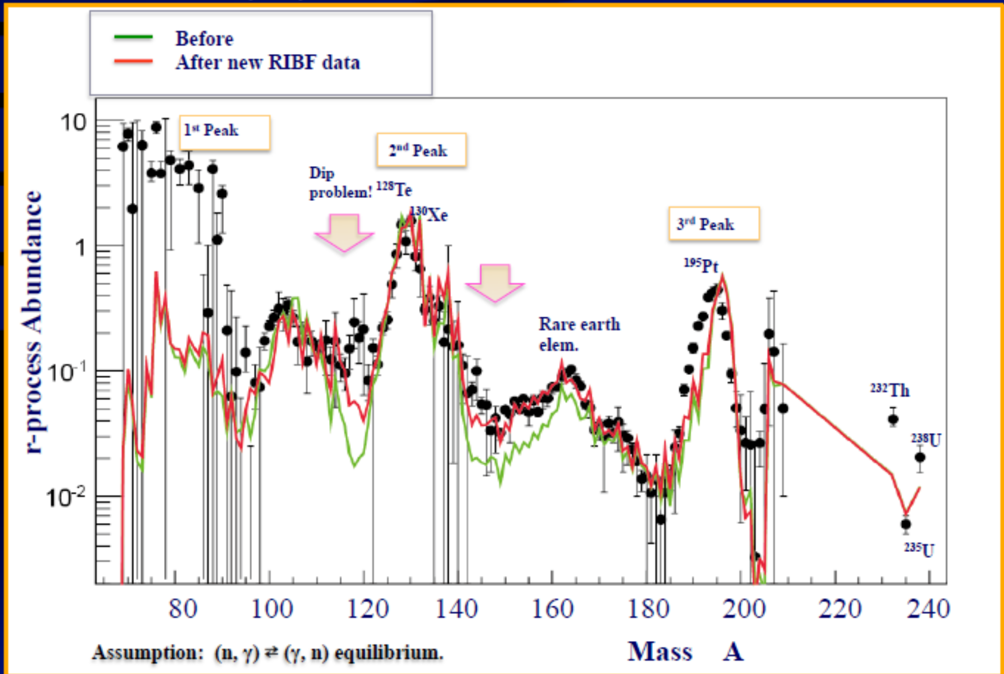
40 new half-lives ! G.Lorusso et al., PRL 114, 192501 (2015)

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

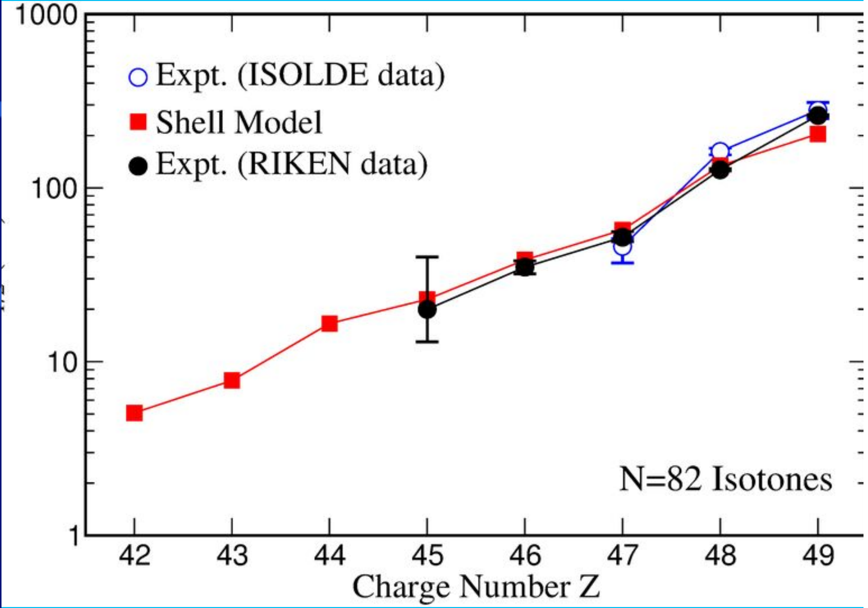


r-process Abundance with New $T_{1/2}$ (RIBF)

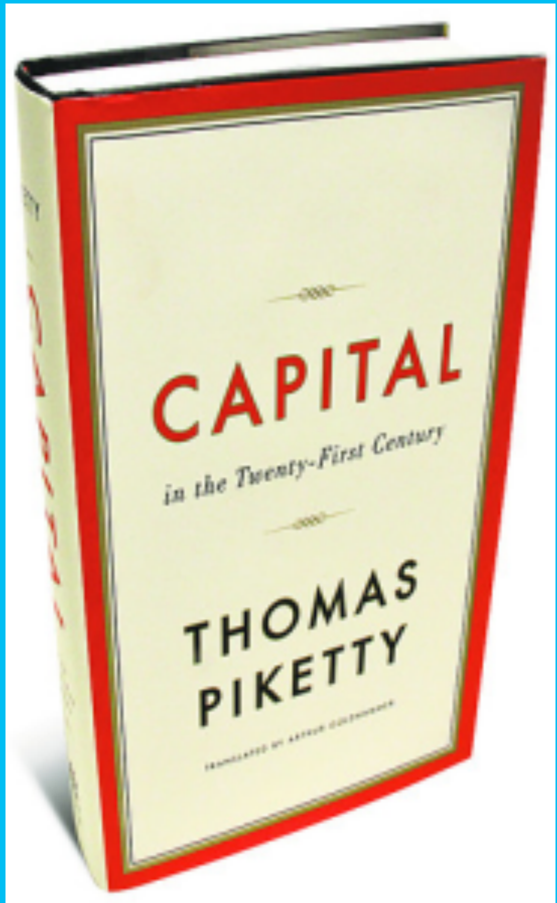
G.Lorusso et al., PRL (2015)



Madrid-Strasbourg shell model



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

The FAIR Chance: New Horizons

The FAIR Chance: New Horizons