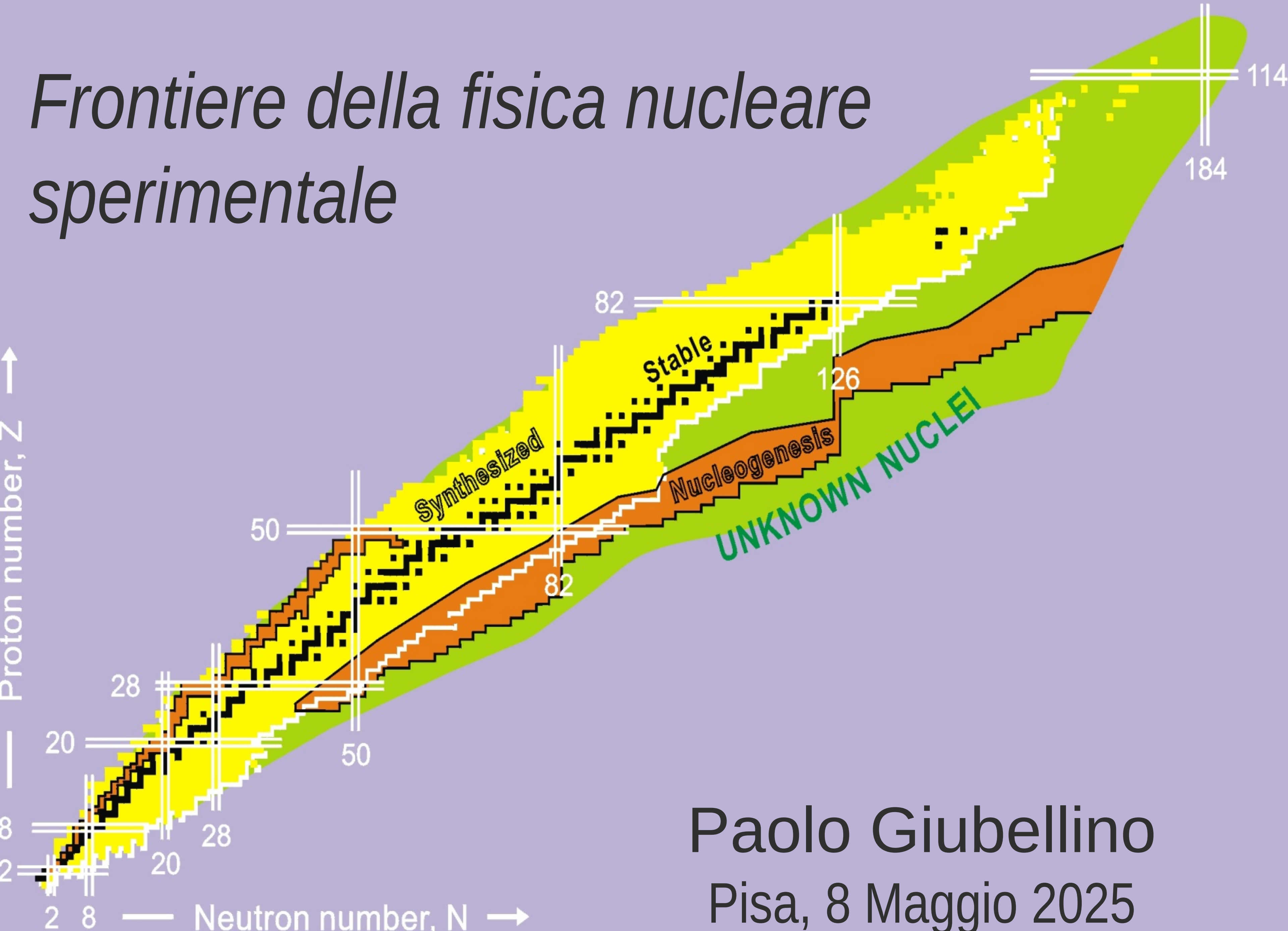
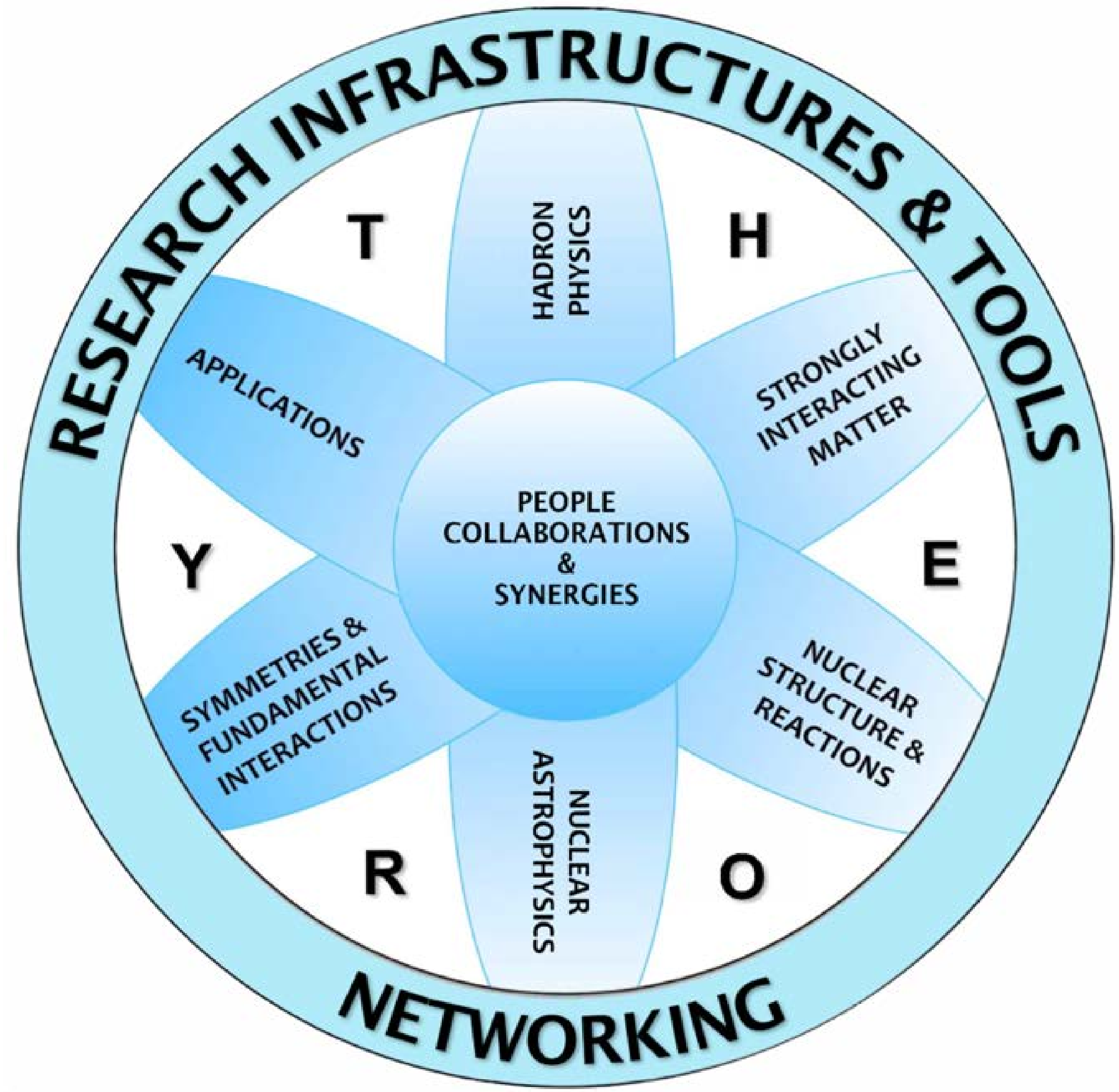
Frontiere della fisica nucleare sperimentale



Paolo Giubellino

Pisa, 8 Maggio 2025

Mission


RESEARCH INFRASTRUCTURES & TOOLS
NETWORKING
T
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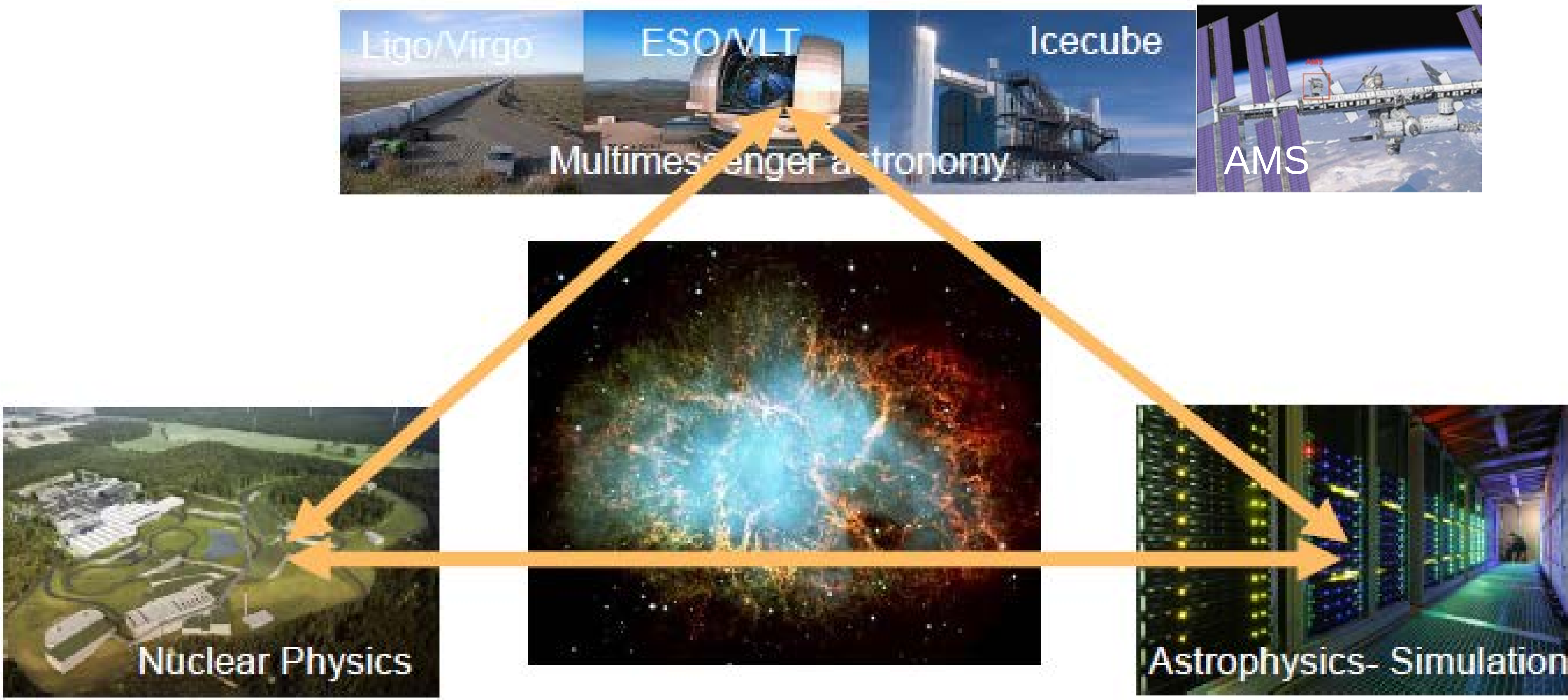
HADRON PHYSICS
STRONGLY INTERACTING MATTER
NUCLEAR STRUCTURE & REACTIONS
NUCLEAR ASTROPHYSICS
SYMMETRIES & FUNDAMENTAL INTERACTIONS
APPLICATIONS
PEOPLE
COLLABORATIONS
&
SYNERGIES

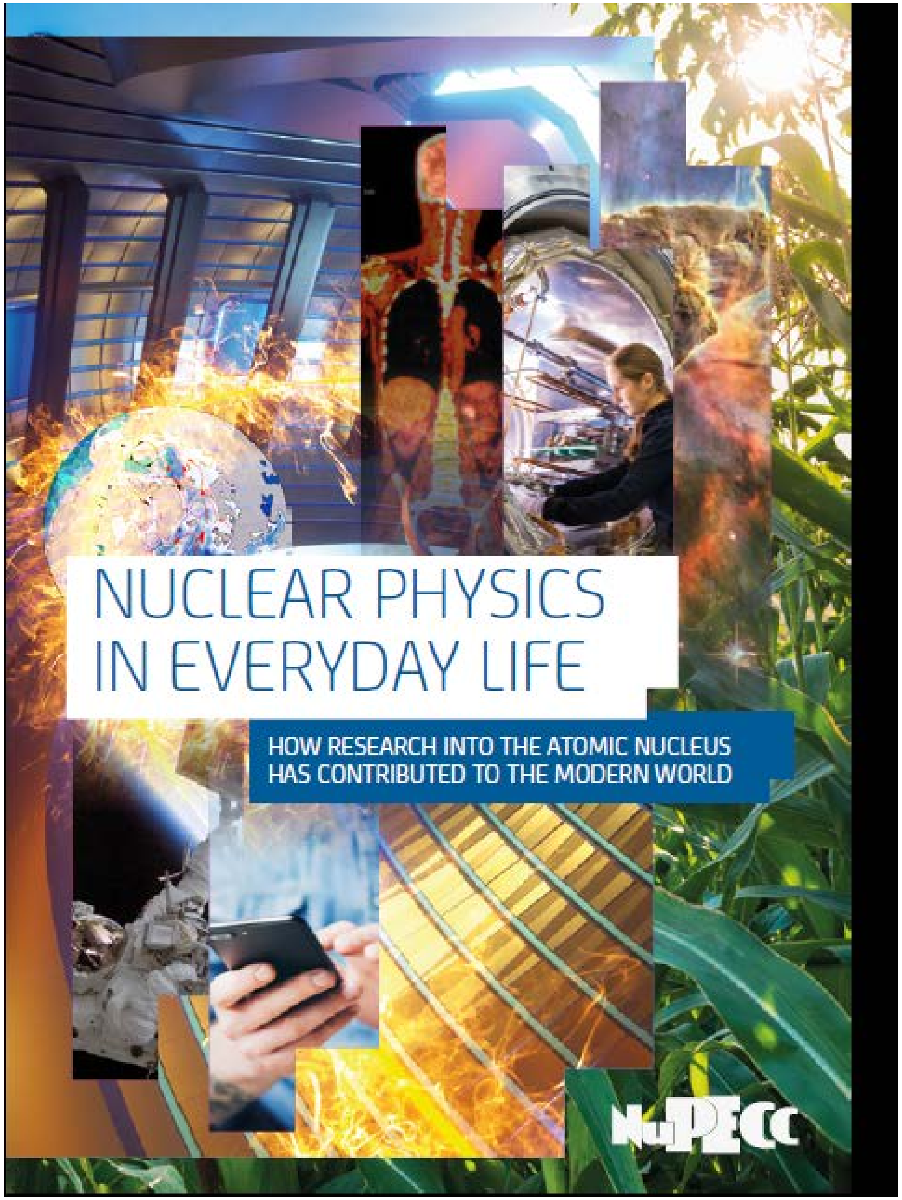

2024
The NuPECC Long Range Plan 2024
for European Nuclear Physics
NuPECC


NuPECC LRP2024
Hadron Physics
Strongly Interacting Matter at Extreme Conditions
Nuclear Structure and Reaction Dynamics
Nuclear Astrophysics
Symmetries and Fund. Int.
Appl. and Societal Benefits
SUSTAINABLE DEVELOPMENT GOALS

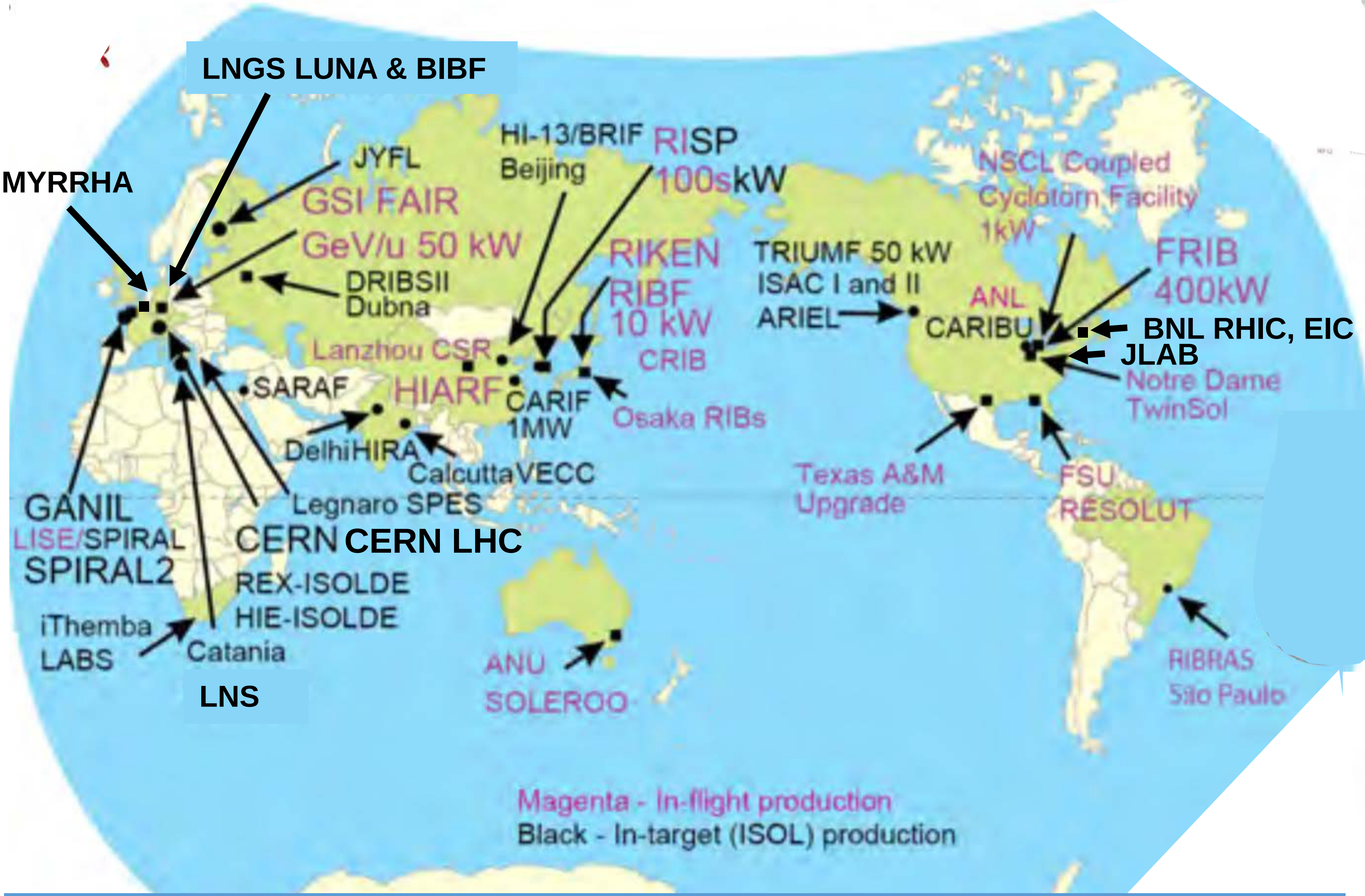
È un momento speciale per la Fisica Nucleare



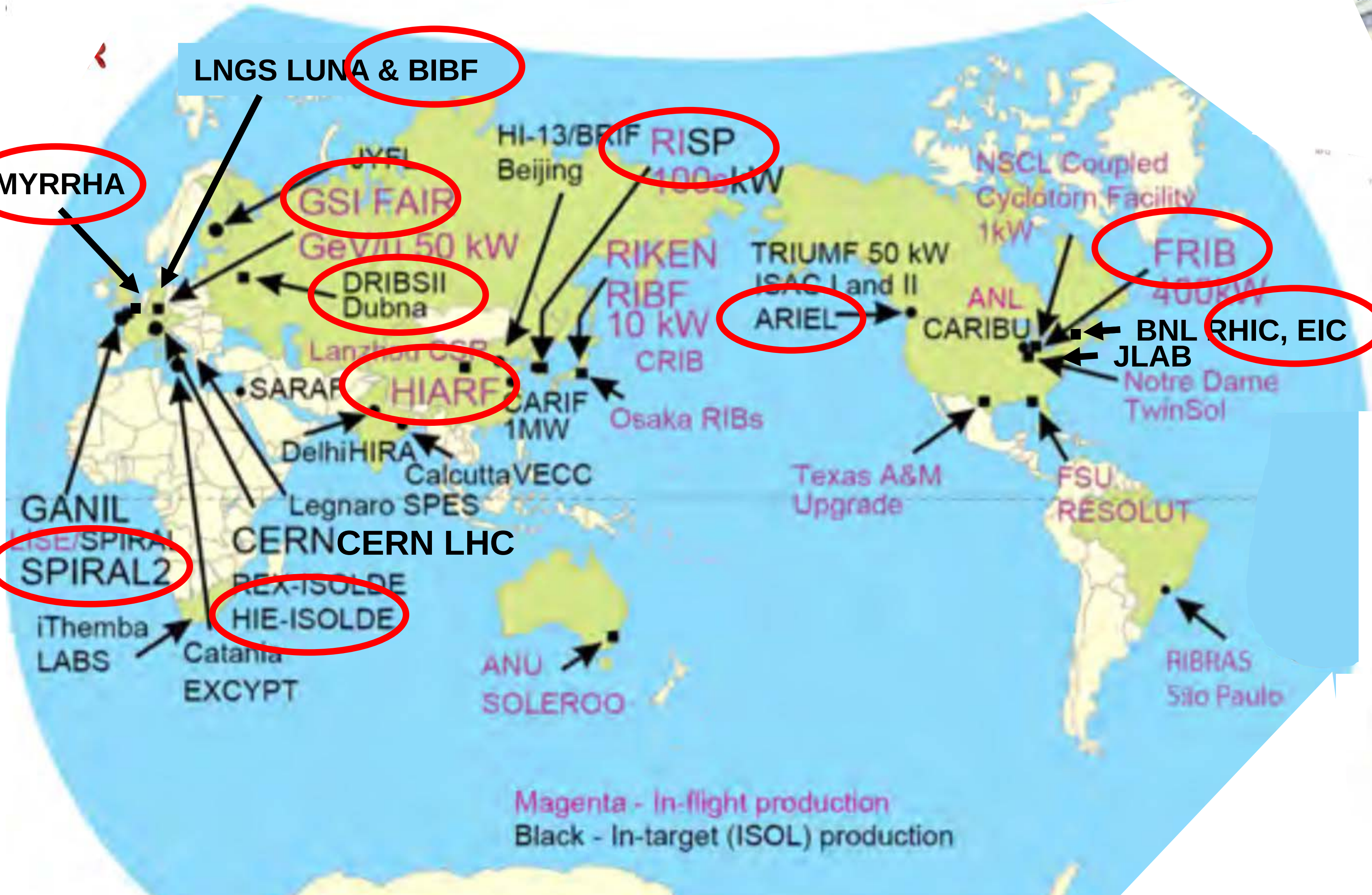
A special moment for Nuclear Physics



- https://www.nupecc.org/pub/np_life_web.pdf



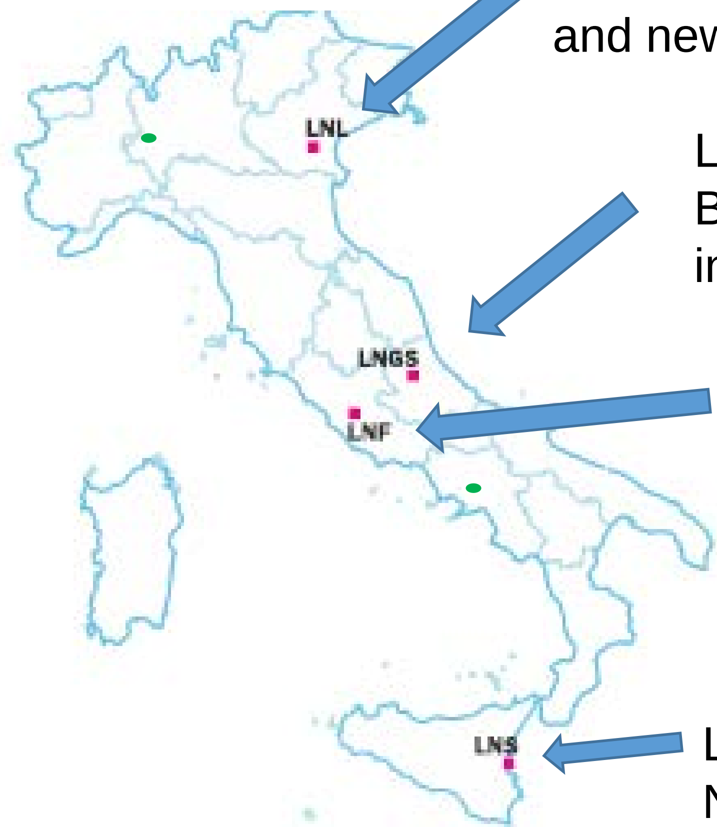
Tante strutture nel mondo, molte NUOVE in costruzione o appena operative



Tante strutture nel mondo, molte NUOVE in costruzione o appena operative

The 4 INFN National laboratories

- All active in world-class Nuclear and Hadron Physics
- **All have major development programs in the future (some just starting, others in construction or under study)**
- In addition: acclerators for Nuclear Astrophysics at CIRCE (near Naples) and a dedicated beamline at CNAO (Pavia) for medical experiments and detector testing

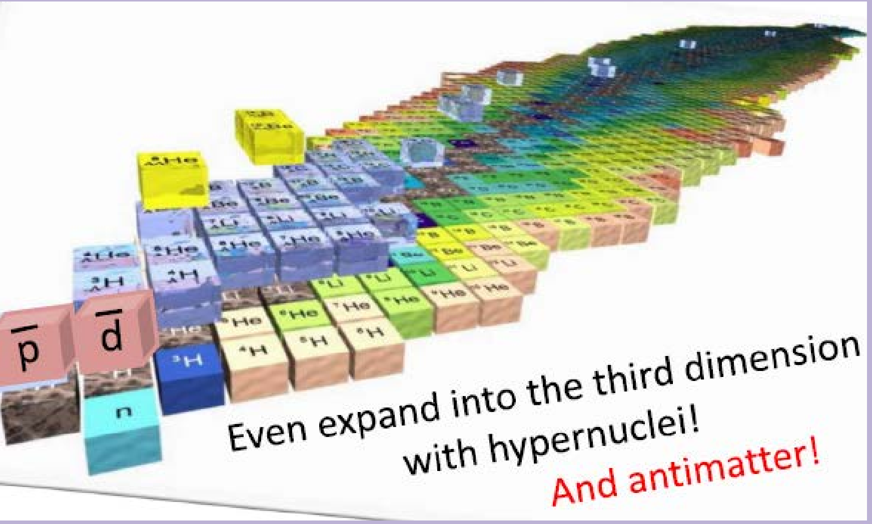


LNL
SPES radioactive beam facility and new radioisotope facility

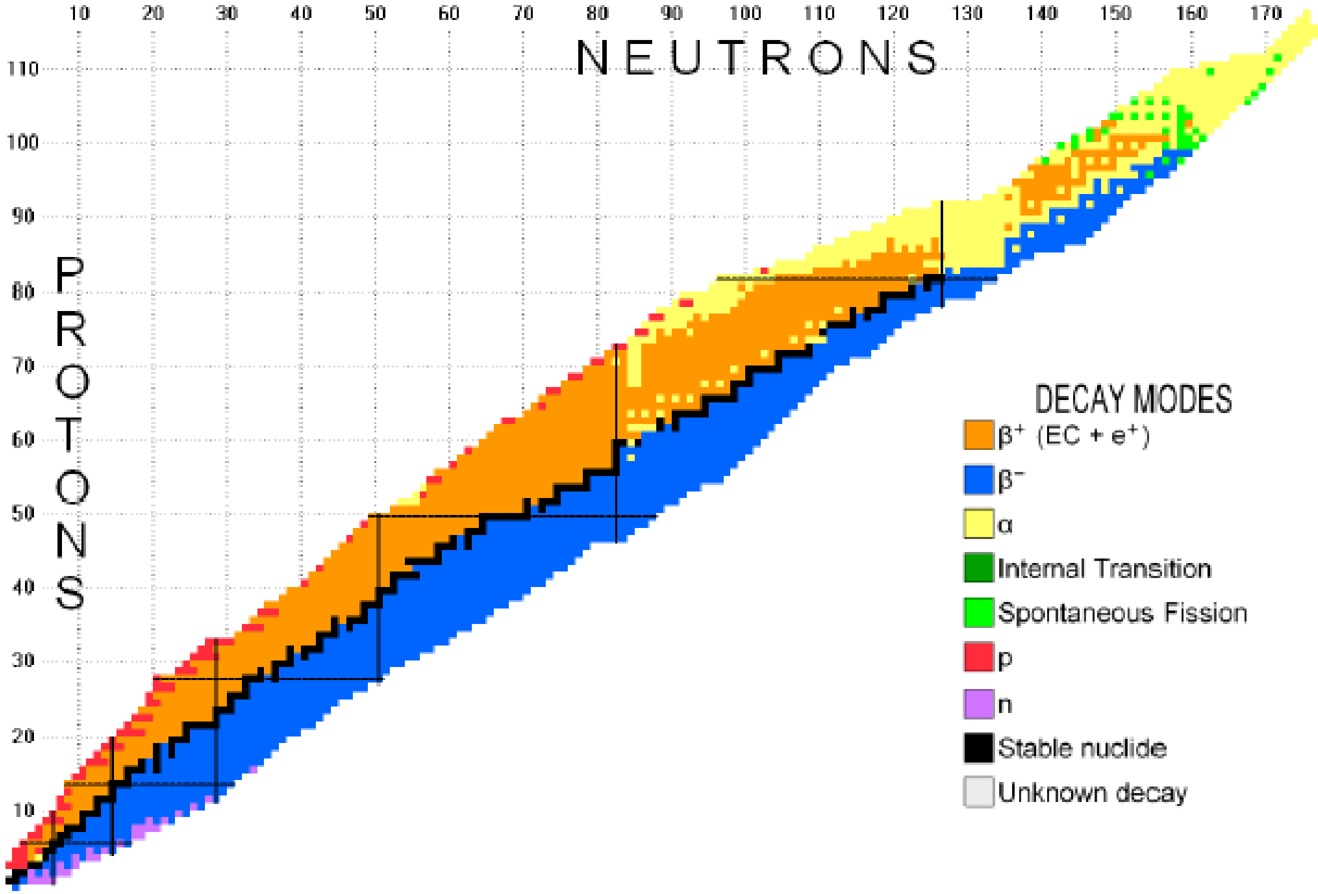
LNGS
Bellotti Ion Beam Facility in addition to LUNA 400

LNF
New EUPRAXIA faciliy opens opportunities for Nuclear Phyiscs experiments

LNS
New facilities and upgrade of Superconducting Cyclotron



Il terreno di lavoro della fisica nucleare

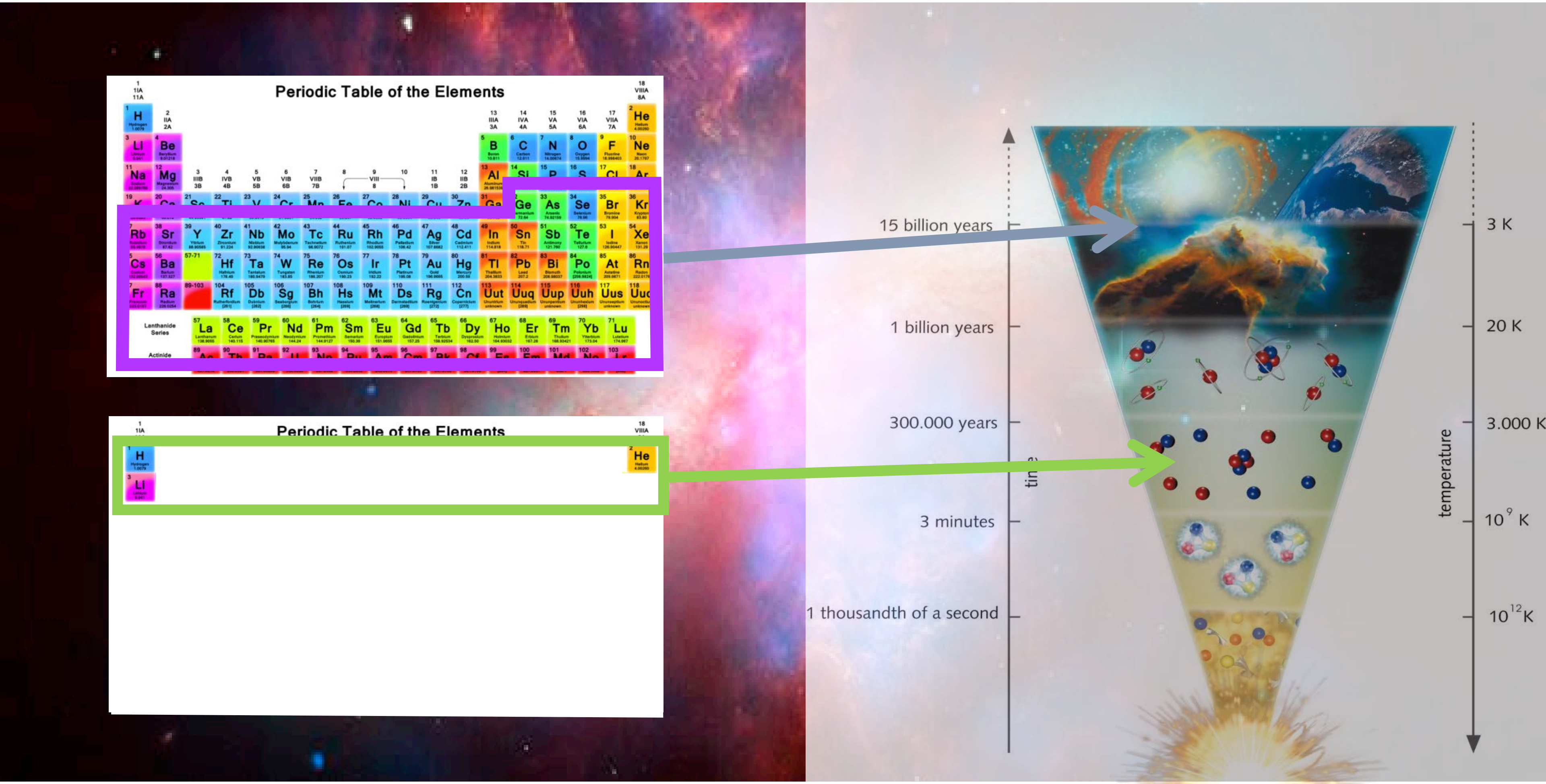


- esistono circa 300 nuclei stabili
- altri circa 3000 sono stati prodotti artificialmente in laboratorio
- sono instabili e decadono con diverse vite medie e diversi modi di decadimento
- Si prevede che esistano circa 7000 nuclei. Sulla maggior parte di essi non si hanno dati sperimentali

Some of the unanswered questions

- How does the vast majority of the universe's visible mass arise from nearly massless quarks?
- What are the properties of the quark-gluon plasma and what is the qualitatively novel state of nuclear matter at extreme conditions?
- How do nuclei and nuclear matter emerge from the underlying fundamental interactions?
- What shapes can nuclei take, how do nuclear shells evolve, and where are the limits of the existence of nuclei?
- What are the limits of fundamental interactions and their symmetries and are fundamental constants constant?

L´origine degli elementi



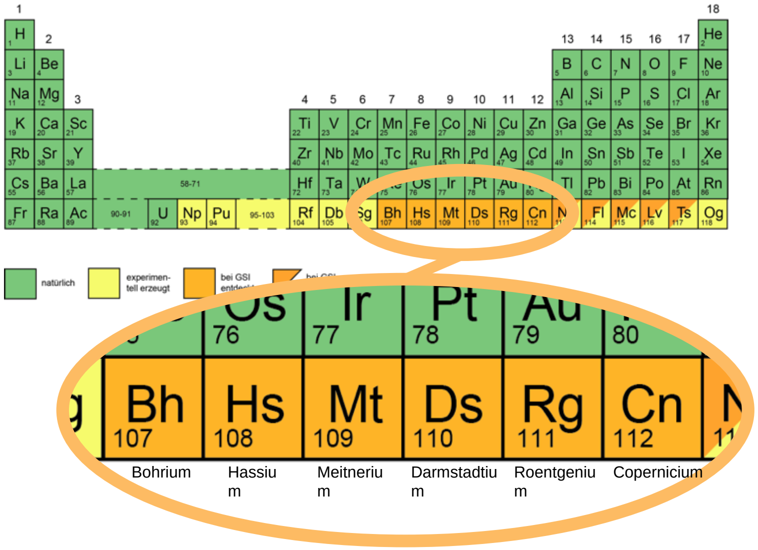
- Dove e come sono stati creati gli elementi? ← ***National Research Council: una delle 11 piu importanti domande in FIsica che attendono una risposta***

Dove e come sono creati gli elementi?

- Gli elementi piu leggeri (Idrogeno, Elio, Litio) sono stati creati nei primi 3 minuti di vita dell´universo

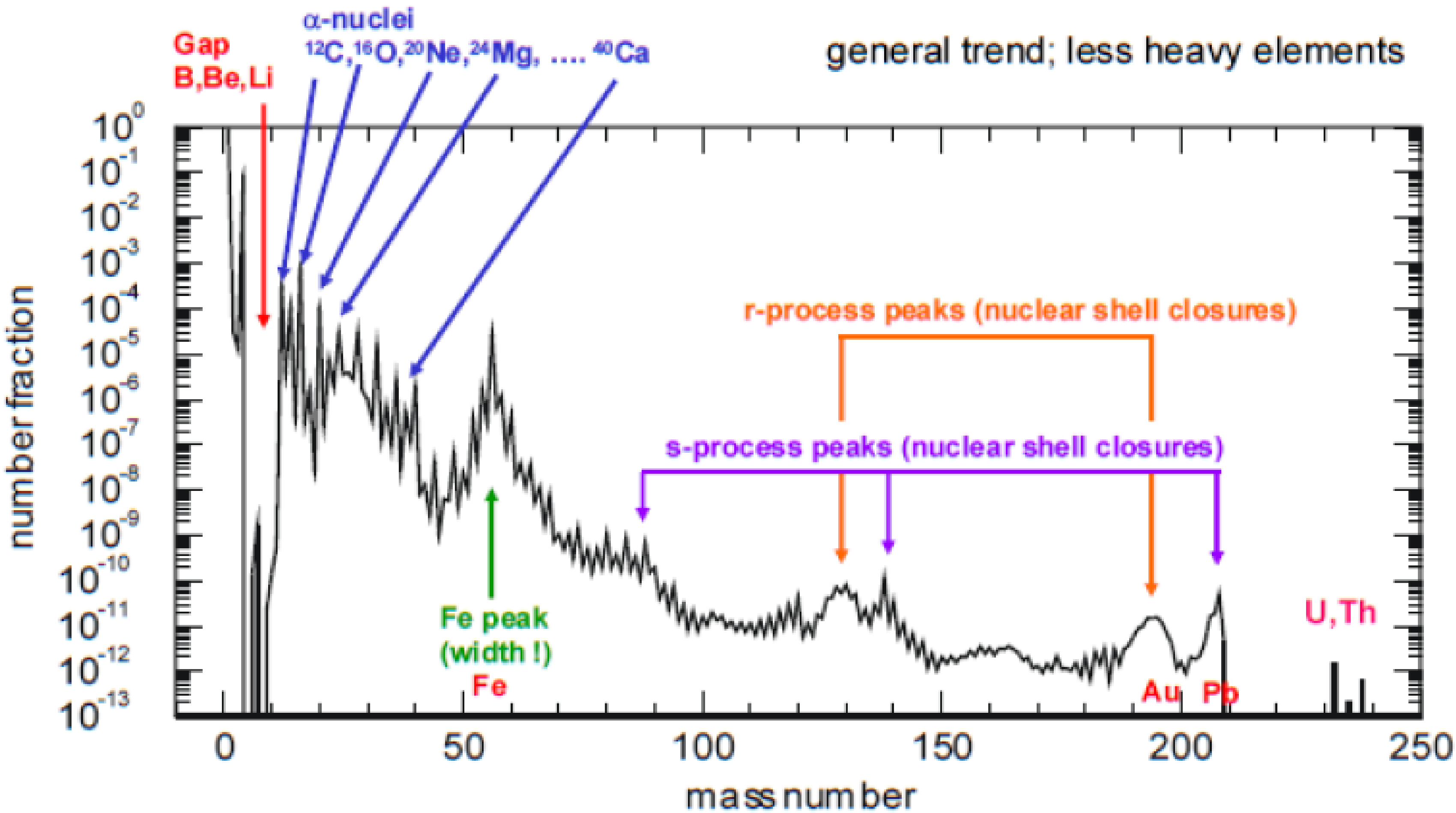
- Gli altri elementi fino all´Uranio sono stati creati e continuano ad essere creati nelle stelle

- Gli elementi piu pesanti dell´Uranio (Z>92) sono prodotti artificialmente in laboratorio.

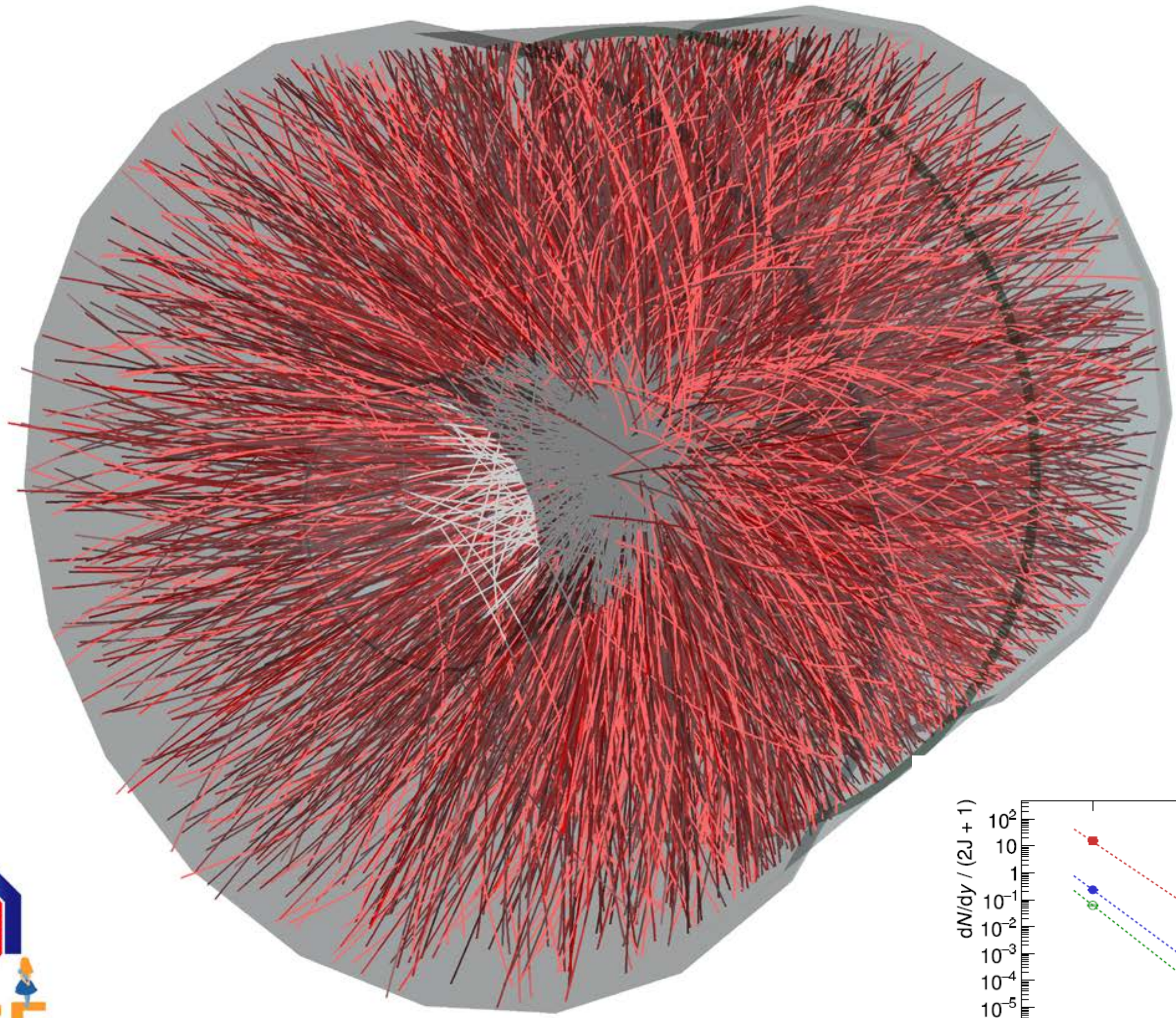


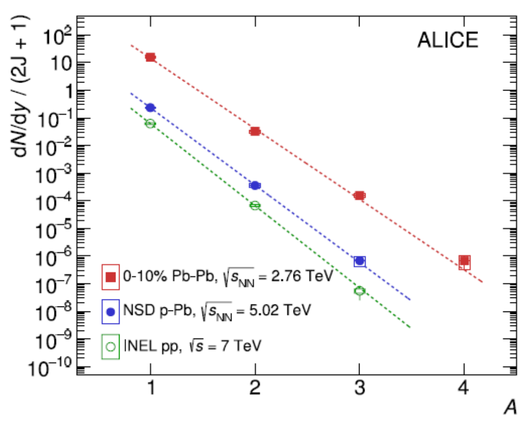
La distribuzione delle abbondanze

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



il Big Bang in laboratorio….

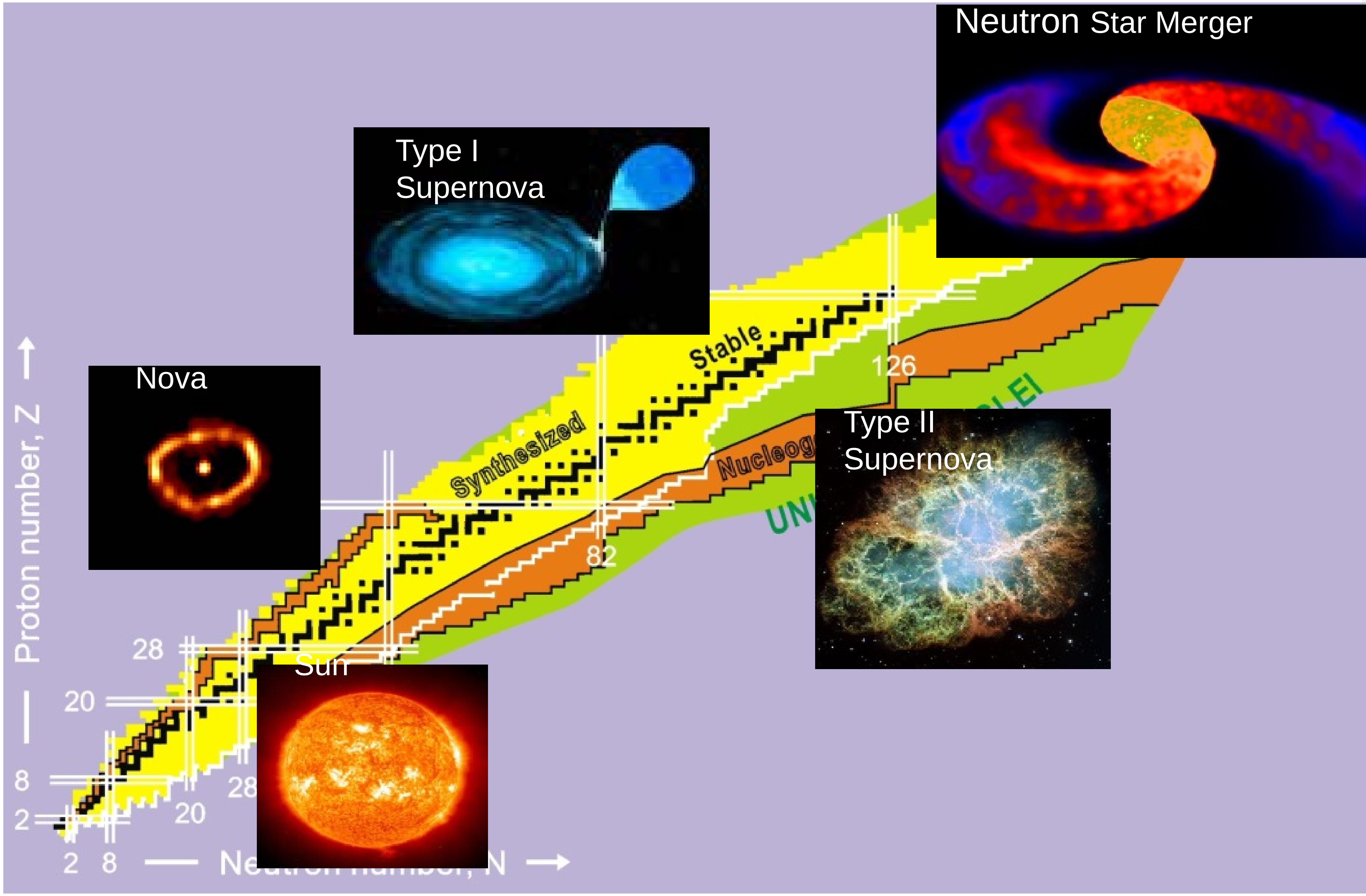




ALICE

- Collisioni di nuclei all´LHC del CERN

Poi, molti processi diversi

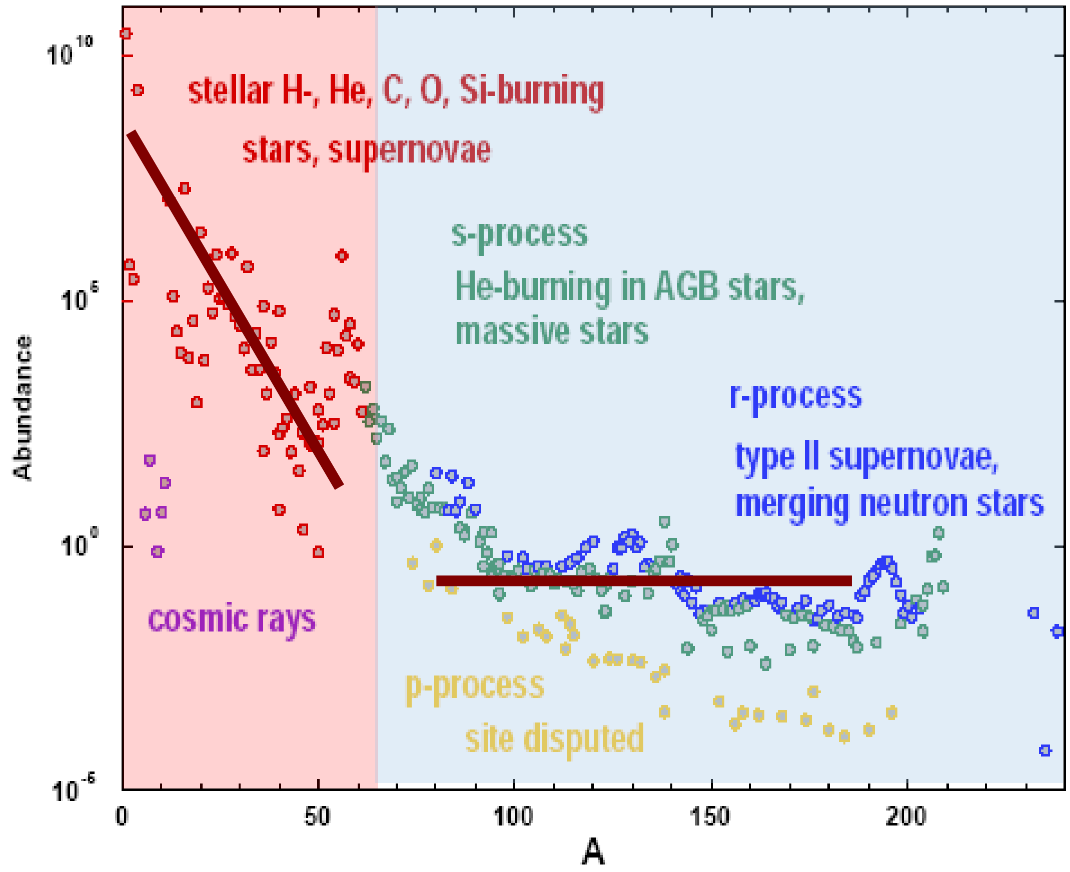


Le reazioni nucleari creano l'energia delle esplosioni stellari e ne determinano la dinamica. Le proprietà nucleari sono quindi importanti! Sfortunatamente quasi tutti i nuclei coinvolti sono instabili e devono essere creati artificialmente per studiarne le proprietà

Stellar Nucleosynthesis

fusion of charged particles

mainly **stable nuclei**



neutron-capture reactions

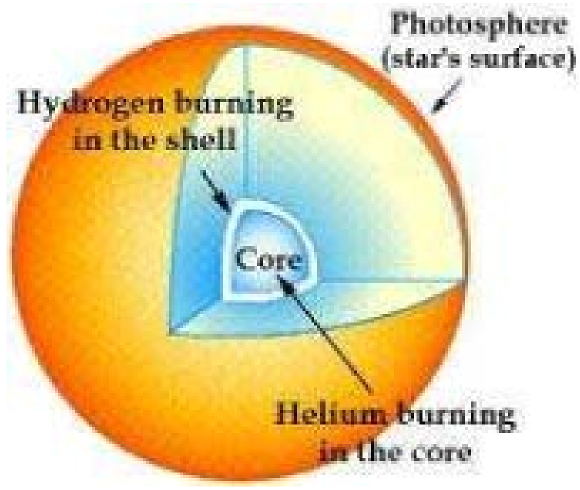
mainly **unstable nuclei**

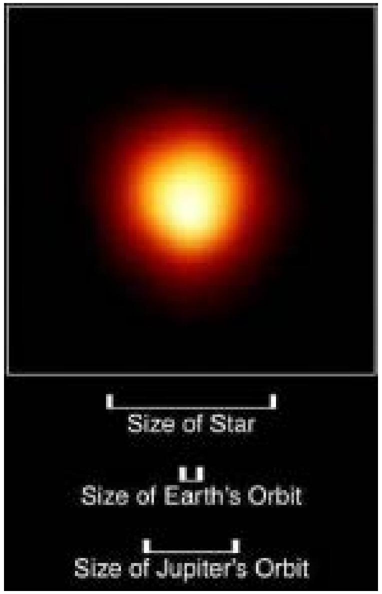
L´inizio… la fusione nucleare

- Quando nasce una stella, crescono progressivamente la densita e la temperatura al suo interno
- La materia stellare consiste di nuclei elettricamente carichi ed elettroni
- i nuclei si muovono velocemente, quando collidono hanno una certa probabilita di superare la repulsione dovuta alla carica elettrica
- la fusione di nuclei di idrogeno (protoni) prima sorgente di energia nucleare

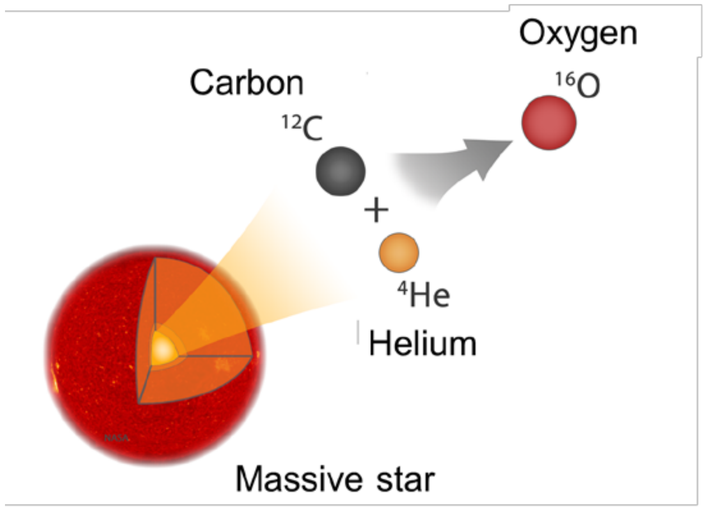
Scondo passo: bruciare Elio

- Alla fine della combustione dell'idrogeno la stella ha un nucleo di elio. Questo nucleo si contrae sotto la sua stessa gravità e diventa più caldo.
- L'idrogeno continua a bruciare in un guscio attorno al nucleo di elio e produce altro elio. Il nucleo cresce e diventa più denso e caldo.
- La pressione di radiazione aumenta. In questo modo le regioni esterne della stella si estendono. Si trasforma in una gigante rossa. Il nostro sole raggiungera questa fase in circa 3 miliardi di anni. Il suo raggio raggiungera quindi l'orbita terrestre.
- All'interno è finalmente abbastanza caldo (100 milioni di Kelvin) che anche i nuclei di elio possono fondersi.

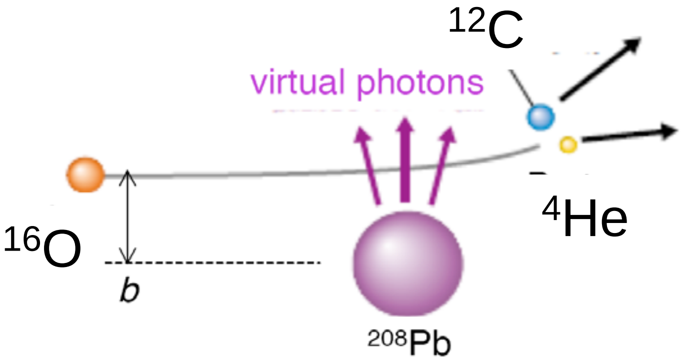




How Nature makes the building blocks of life



rate insufficiently known at astrophysically energies

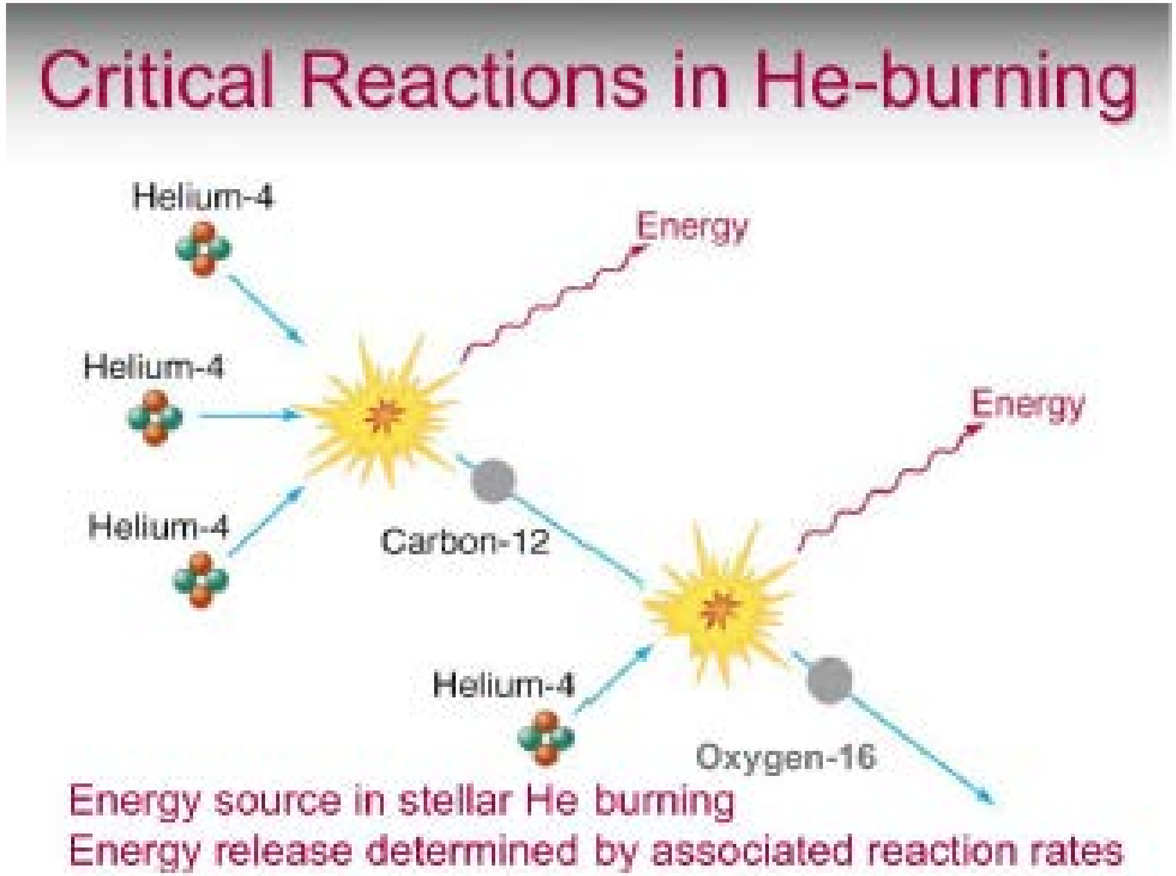


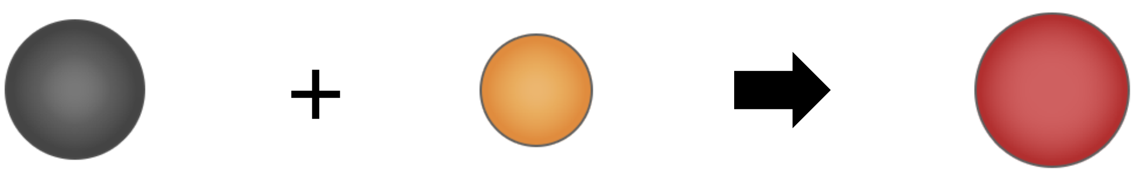
Alpha fusion on 12C is the stellar reaction of paramount importance,

W.A. Fowler, Nobel lecture 1983

Experiment in inverse kinematics (Coulomb dissociation) requires high energies
Difficult measurements … has taken 40 years…

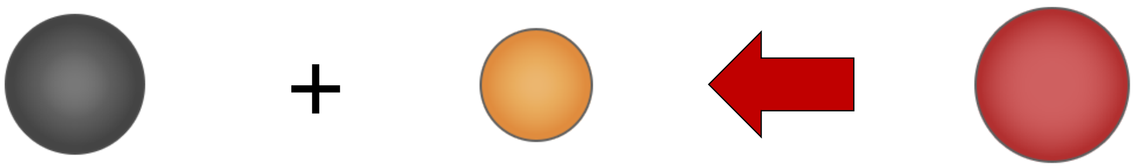
La reazione da studiare





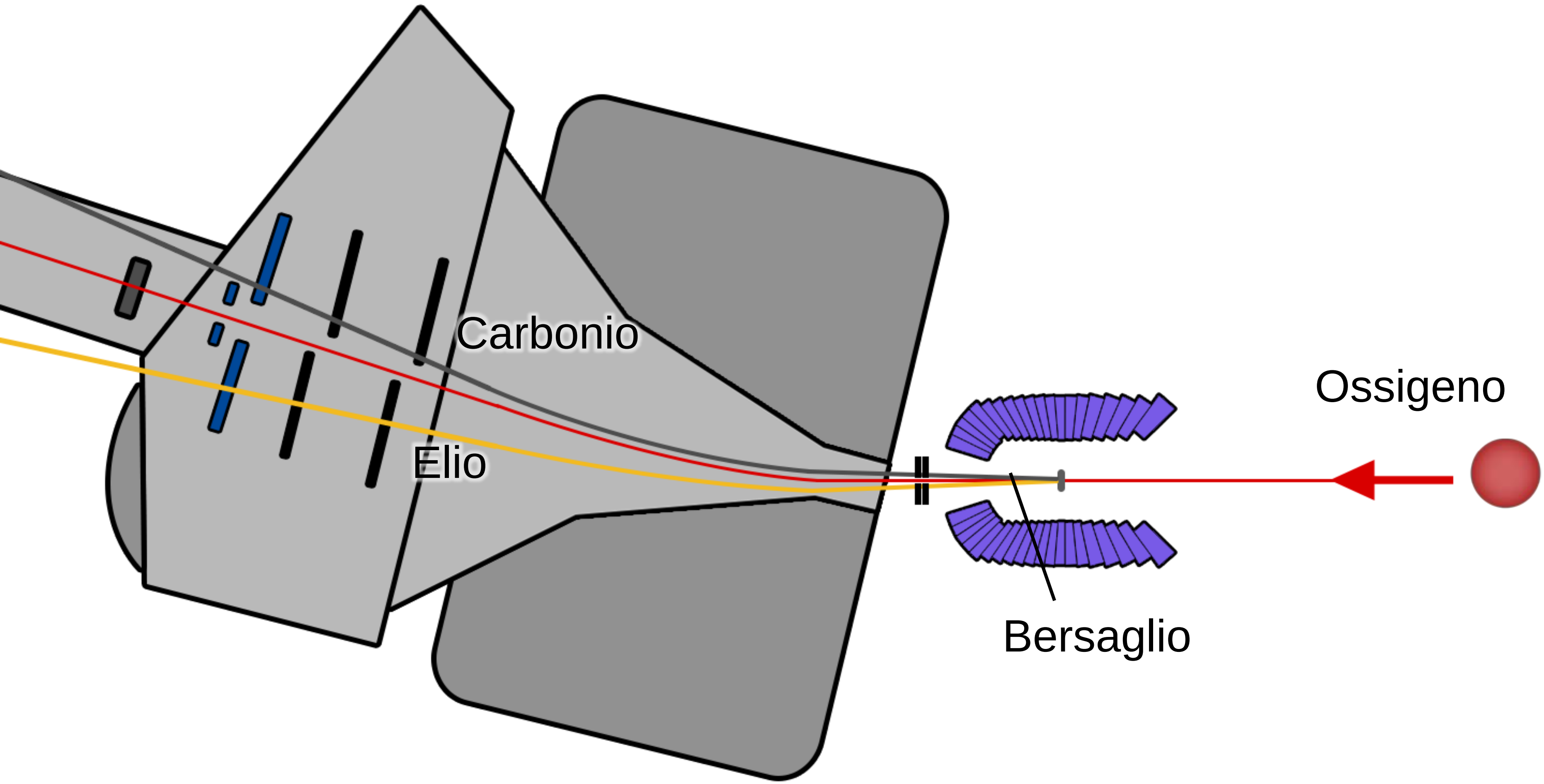
Carbonio Elio Ossigeno

Quella che si PUO studiare



Carbonio Elio Ossigeno

L´Esperimento



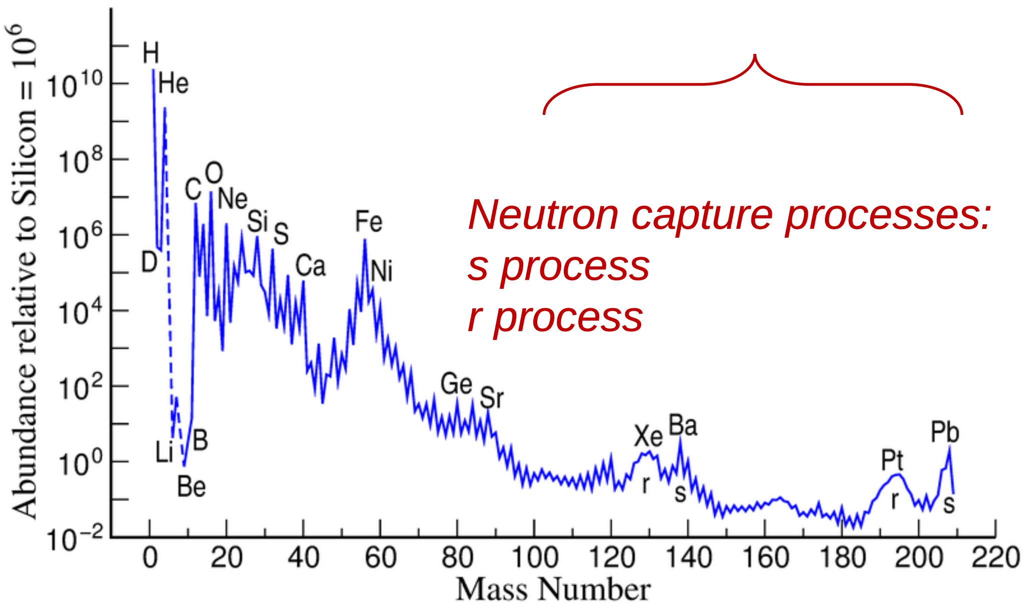
E cosi via….

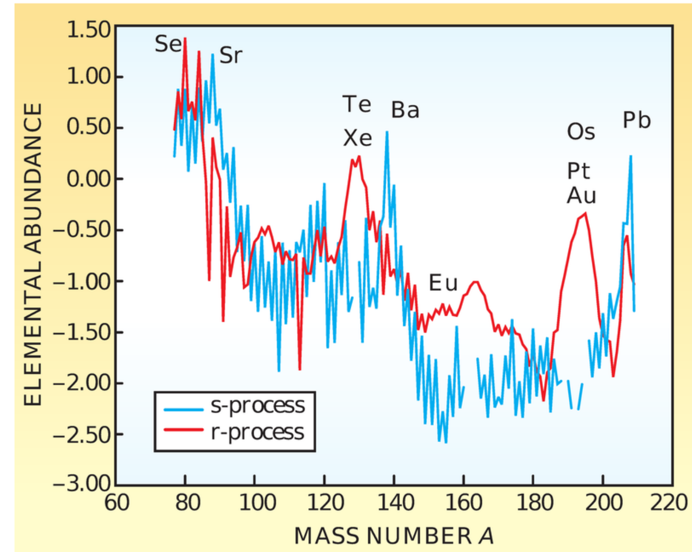
Nuclear burning stages

(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	$4\,H \xrightarrow{CNO} {}^4He$
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	$^{28}Si(\gamma,\alpha)$…

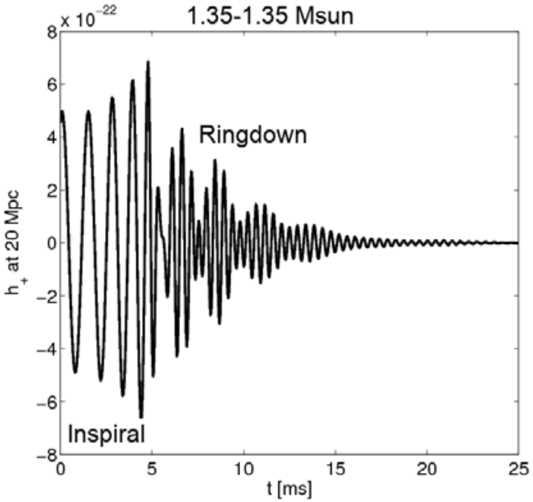
Il sogno degli alchimisti…
Creare l´Oro: l´"R-Process"



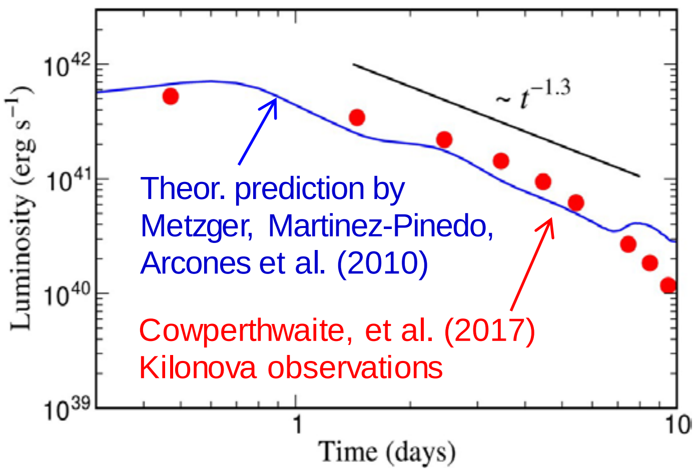


- Gli elementi pesanti sono prodotti in 2 tipi di processi, I cosiddetti s- e r- processes, per lento e rapido
- R-process; eazioni nucleari molto rapide in ambienti con densità estreme di neutroni liberi. I nuclei coinvolti sono molto ricchi di neutroni e hanno vita breve.

Neutron star mergers and their role for the production of heavy elements



Gravitational wave signal



Elektromagnetic "Kilonova"-Signal

Electromagnetic afterglow - "Kilonova-lightcurve" - reveals that heavy elements, e.g. Au and Pt, were produced (r-process), as predicted by nuclear theorists.

Neutron Stars and Mergers vs HI collisions

Neutron stars

Temperature
$T < 10$ MeV

Density
$\rho < 10\ \rho_0$

Lifetime
T ~ infinity

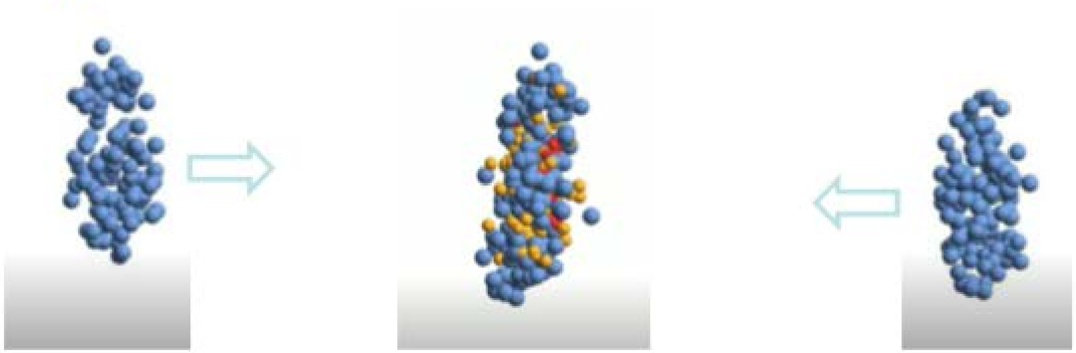
Neutron star merger

Temperature
$T < 50$ MeV

Density
$\rho < 2 – 6\ \rho_0$

Reaction time
(GW170817)
T ~ 10 ms

Heavy ion collisions at SIS100



Compressed Baryonic Matter

Temperature
$T < 120$ MeV

Density
$\rho < 8\rho_0$

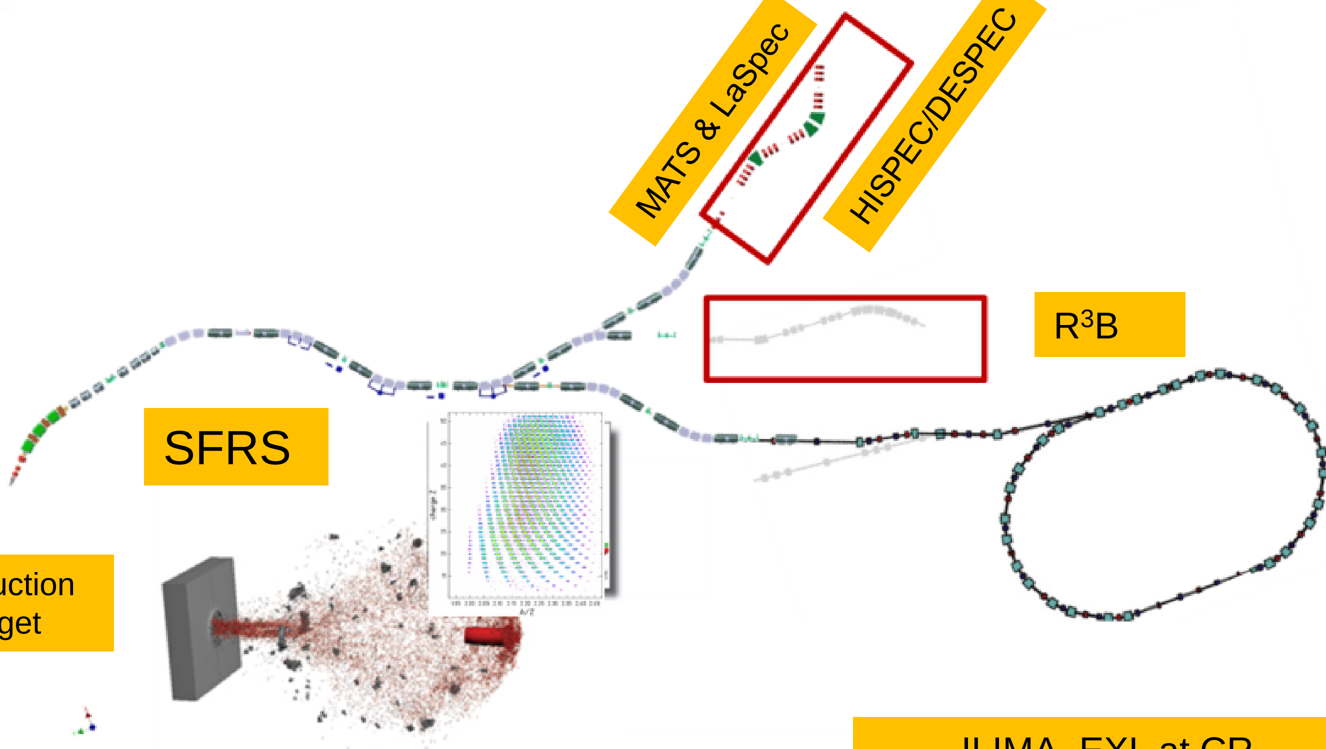
Reaction time
$t \sim 10^{-23}$ s

R-Process in NS merger

G. Martinez-Pinedo, M.R. Wu

GSI and FAIR

„Nucleosynthesis sites” at FAIR



MATS & LaSpec

HISPEC/DESPEC

R^3B

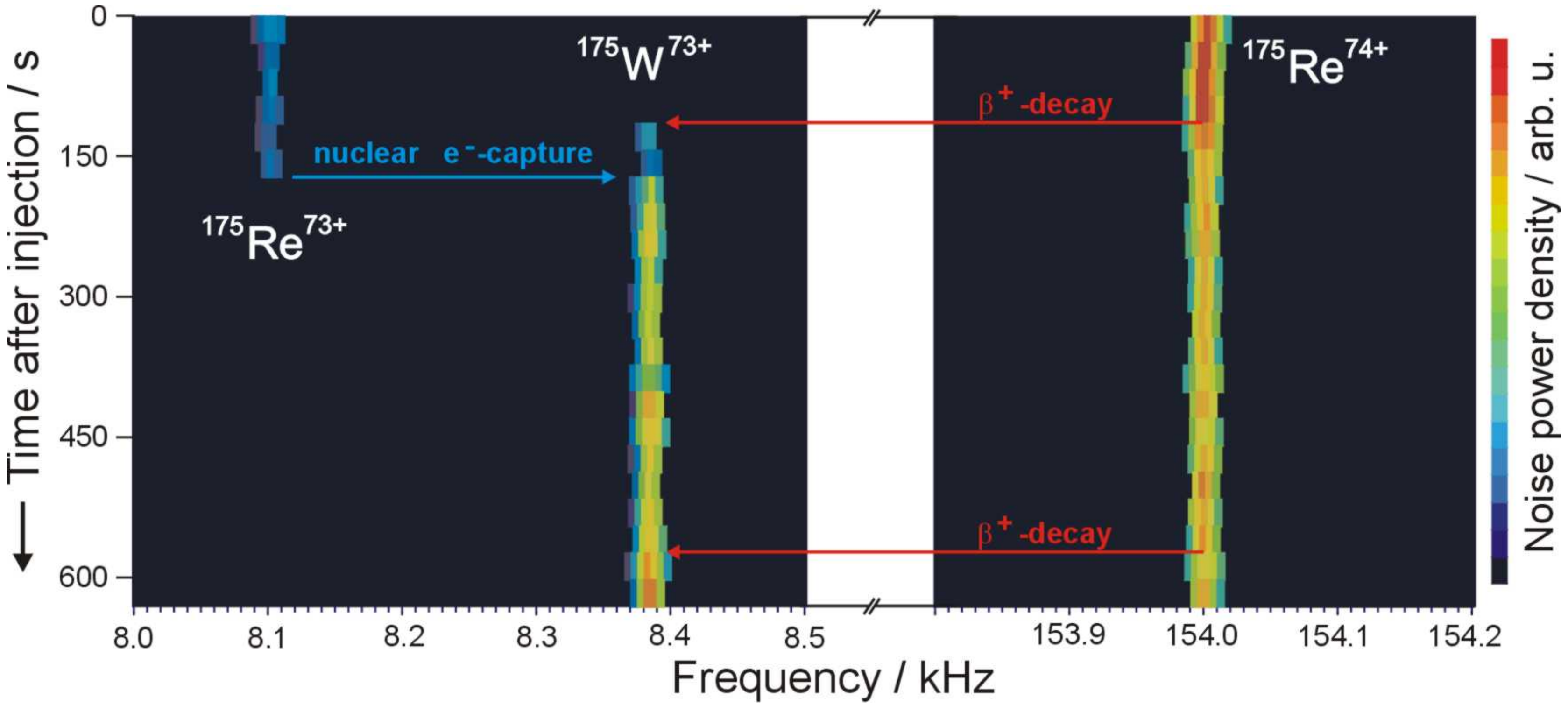
High Intensity Primary Beams (any species up to U)

production target

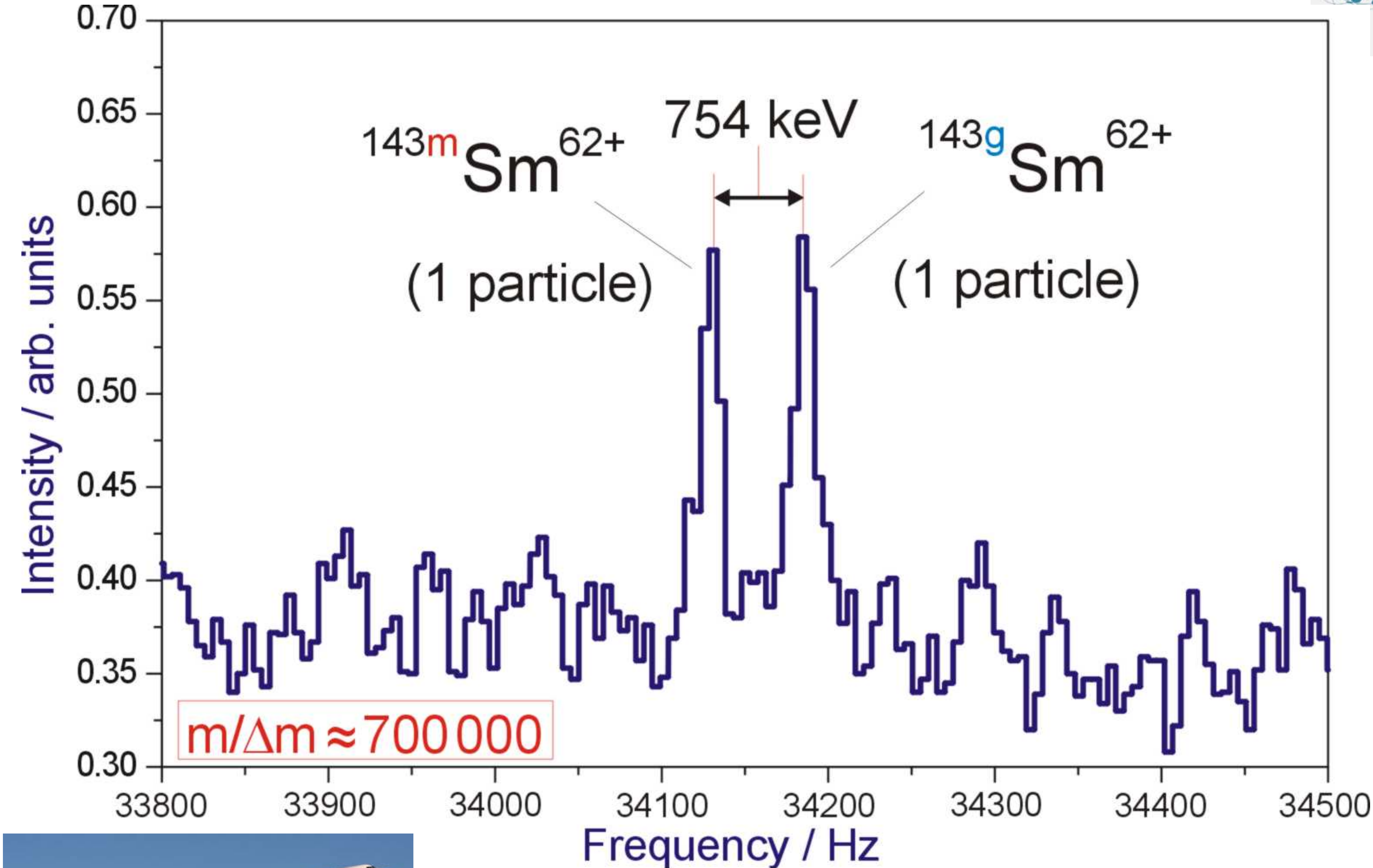
SFRS

ILIMA, EXL at CR
and at ESR, HESR, Cryring

Nuclear decays in a storage ring

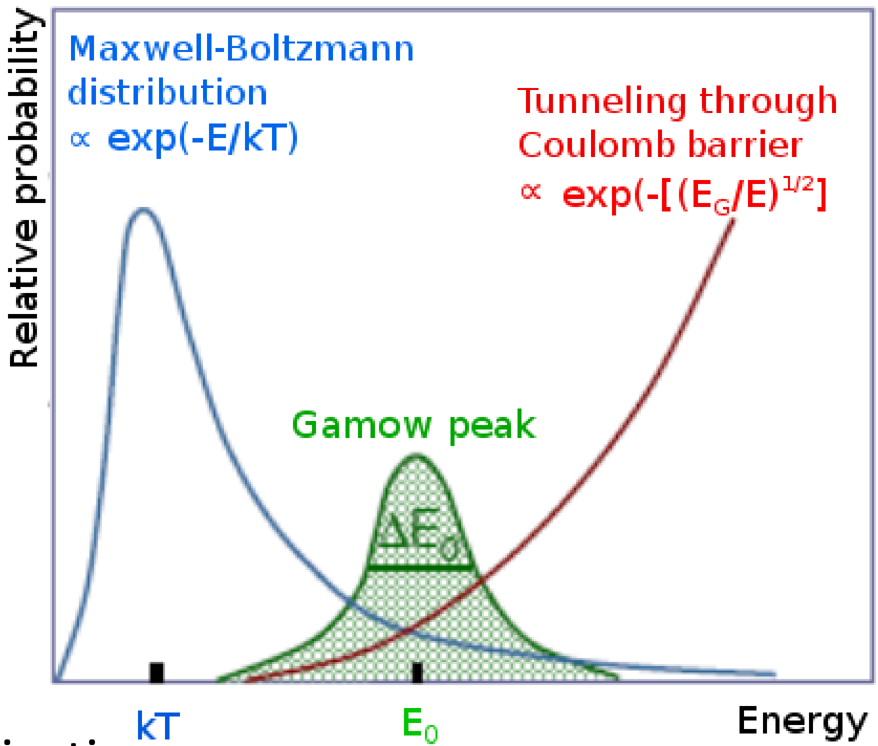


EC, β+,β-, bound-state β, and IT decays
(ESR at GSI)


754 keV
143mSm62+
143gSm62+
(1 particle)
(1 particle)
m/Δm ≈ 700 000
Intensity / arb. units
Frequency / Hz
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
33800
33900
34000
34100
34200
34300
34400
34500

Reazioni stellari in laboratorio: Sfide sperimentali delle misurazioni dirette

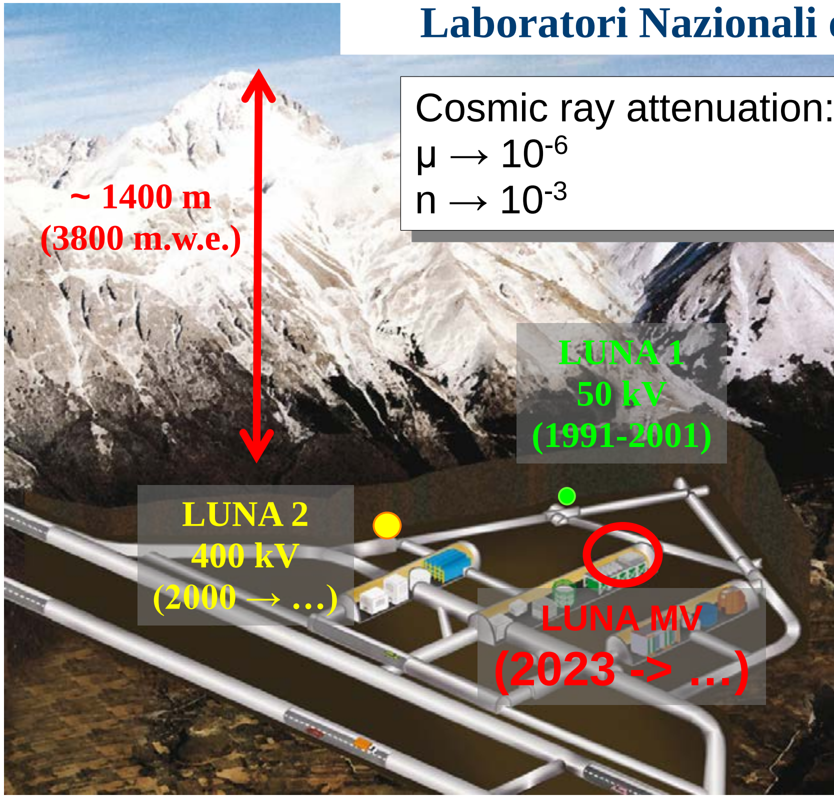
- Energie astrofisiche (finestra di Gamow)
  - << Repulsione di Coulomb tra cariche interagenti
  - sezioni d'urto molto basse, tradizionalmente misurate a energie più elevate ed estrapolate a energie molto basse



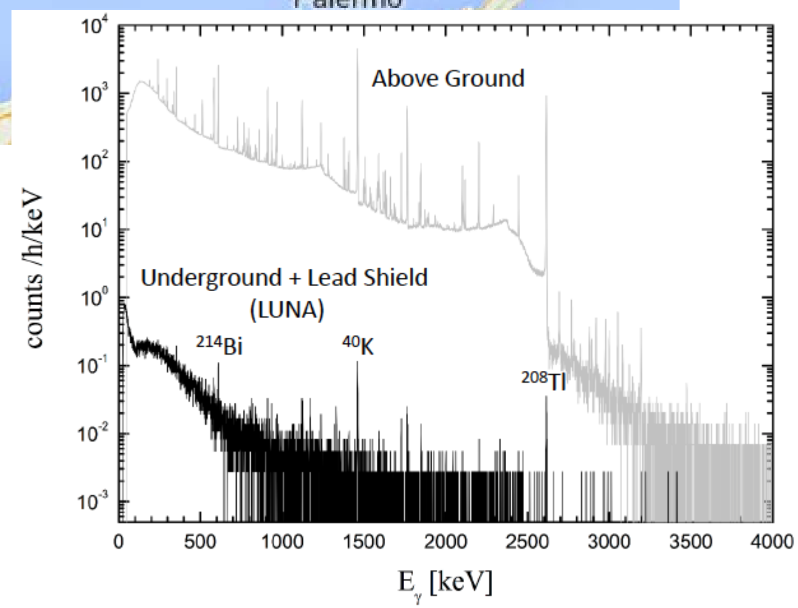
- Si applicano diverse strategie
  - Strumentazione e acceleratori dedicati
- Come ridurre i fondi? Andare sottoterra! (in un laboratorio con bassa concentrazione di U e Th)
- Posizione ideale: i Laboratori Nazionali del Gran Sasso

LUNA: Laboratory for Underground Nuclear Astrophysics (established early 1990s)

Laboratori Nazionali del Gran Sasso, INFN



Cosmic ray attenuation:
$\mu \rightarrow 10^{-6}$
$n \rightarrow 10^{-3}$



400 kV ACCELERATOR:
→ H^+ and He^+ beams
→ I ~ 250 μA

The Future has started:
expanded to the MeV region with the Bellotti Ion Beam Facility

30 years of Nuclear Astrophysics at LUNA (LNGS, INFN)

- **solar fusion reactions**

  $^{3}He(^{3}He,2p)^{4}He$ $^{2}H(p,\gamma)^{3}He$ $^{3}He(\alpha,\gamma)^{7}Be$

- **electron screening and stopping power**

  $^{2}H(^{3}He,p)^{4}He$ $^{3}He(^{2}H,p)^{4}He$

- **CNO, Ne-Na and Mg-Al cycles**

  $^{12,13}C(p,\gamma)^{13,14}N$ $^{14,15}N(p,\gamma)^{15,16}O$ $^{16}O(p,\gamma)^{17}F$ $^{20,21,22}Ne(p,\gamma)^{21,22,23}Na$ $^{22}Ne(\alpha,\gamma)^{26}Mg$ $^{23}Na(p,\gamma)^{24}Mg$ $^{25}Mg(p,\gamma)^{26}Al$

- **(explosive) hydrogen burning in novae and AGB stars**

  $^{17}O(p,\gamma)^{18}F$ $^{17}O(p,\alpha)^{14}N$ $^{18}O(p,\gamma)^{19}F$ $^{18}O(p,\alpha)^{15}N$

- **Big Bang nucleosynthesis**

  $^{2}H(\alpha,\gamma)^{6}Li$ $^{2}H(p,\gamma)^{3}He$ $^{6}Li(p,\gamma)^{7}Be$

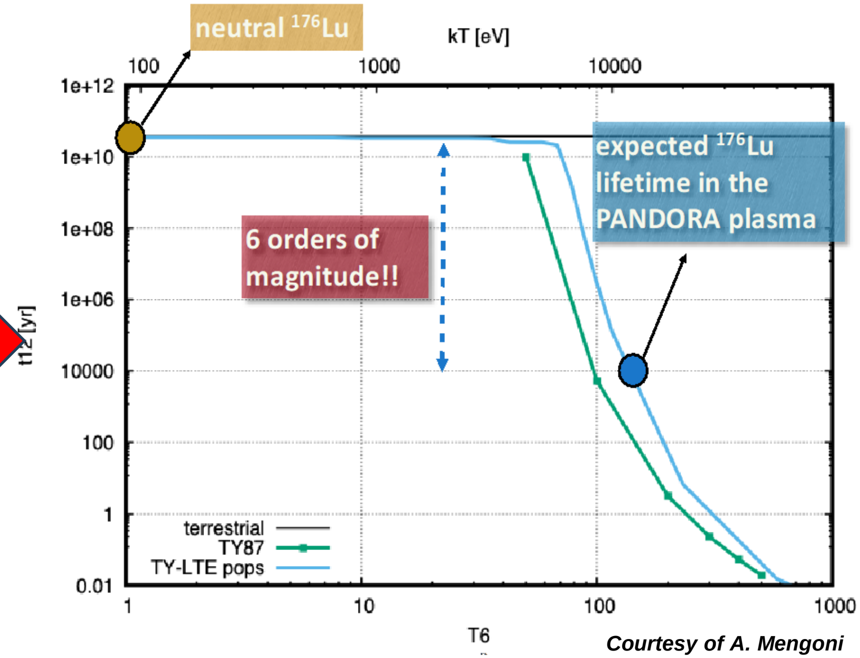
- **neutron capture nucleosynthesis**

  $^{13}C(\alpha,n)^{16}O$

^{176}Lu: lifetime vs. T – theoretical predictions

Stars are made of matter in plasma state where nuclei behaviour could be different

In future, nuclear astrophysics studies will require measurements in extreme conditions different from earth laboratories.

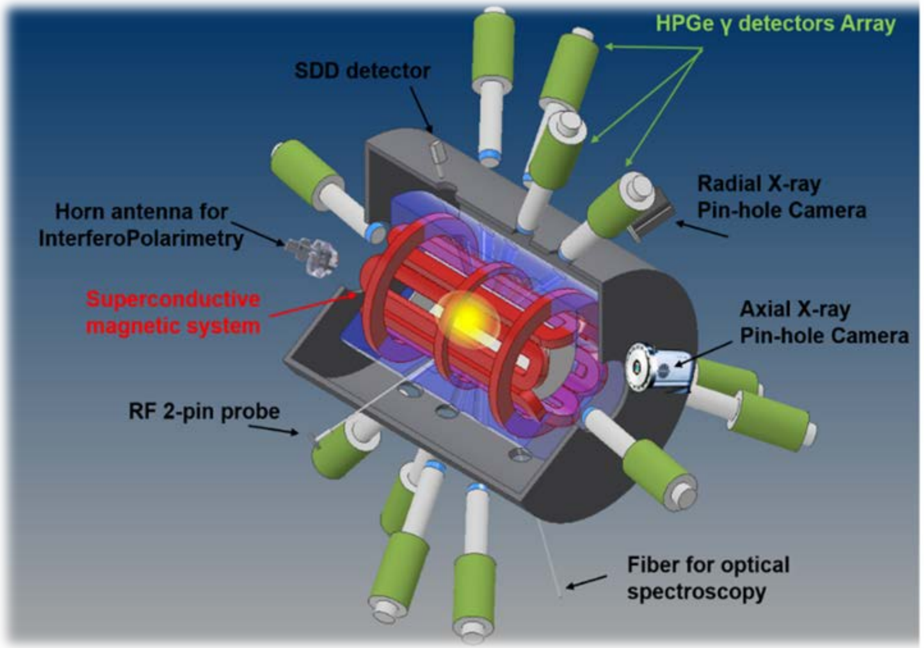


Takahashi et al. 1987, Phys Rev C 36, 1522

The PANDORA experiment (2025)

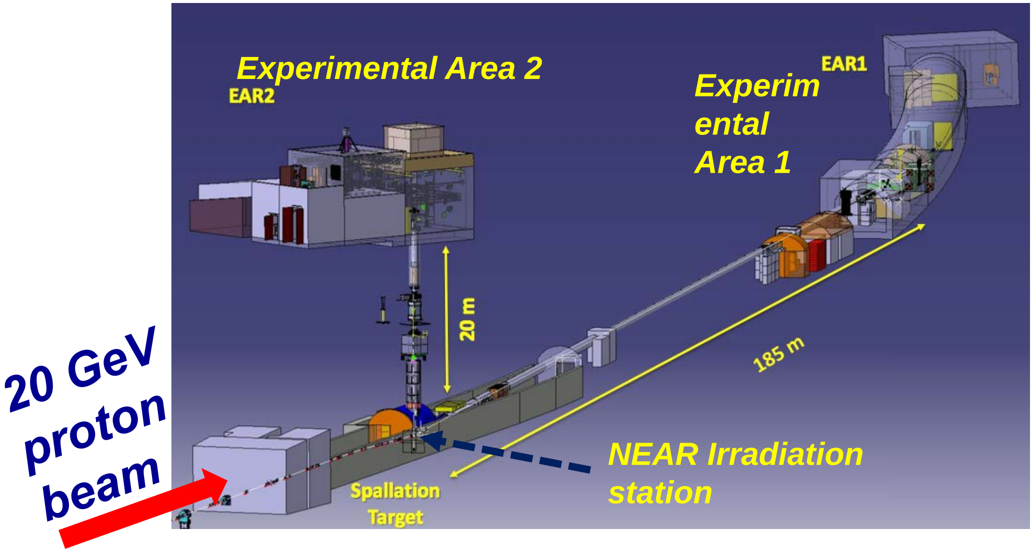
Build a **plasma trap** where ion species are confined in a magnetic field and a plasma is created with:

- Electron density: $10^{12} \div 10^{14}\ cm^{-3}$
- Electron temperature: 0.1 ÷ 100 keV
- Ion density: $10^{11}\ cm^{-3}$ → relies on the radiactive isotope concentration in plasma
- Ion temperature: ~ 1 eV → Ions are cold: no access to the excited states



n_TOF experiment: neutron Time Of Flight

Located at CERN, it is a facility of neutron beams in a wide energy range (from thermal to GeV), aimed to perform high-precision neutron-induced cross section measurements.



Nuclear Technology
- *Advanced Fission reactors (IV Gen and ADS)*
- *Transmutation of nuclear waste*
- *Ageing of structural material in fusion reactors*

Nuclear Astrophysics
- *Big Bang and Stellar Nucleosynthesis*
- *Fission recycling in neutron star merger*
- *Neutron generation in stars*

Fundamental Physics
- *Fission dynamics*
- *Nuclear levels*

Medical Applications
- *Neutron Capture Therapy (BNCT)*
- *Cross sections of human-tissue elements*

Three experimental areas

- **Horizontal** flight-path: **185m** from the target.
  - **Flux: 10^6 n/s, Emax: 1GeV, $\Delta E/E$: 10^{-4}** *Optimal for narrow resonances*
- **Vertical**: **20m**.
  - **Flux: 10^7 n/s Emax: 200MeV, $\Delta E/E$: 10^{-3}** -> *short lived radioactive isotopes, very low cross sections*
- **Near irradiation station: 5m**.
  - **Flux: 10^{10} n/s, Emax: 100MeV** -> *neutron activation / sample irradiation*

Recent Scientific Achievements

$^{140}Ce(n,\gamma)$

Provides evidence for the possible existence of a new stellar nucleosynthesis process known as i-process

PHYSICAL REVIEW LETTERS **132,** 122701 (2024)

Editors' Suggestion Featured in Physics

Measurement of the ^{140}Ce(n,γ) Cross Section at n_TOF and Its Astrophysical Implications for the Chemical Evolution of the Universe

$^{204}Tl(n,\gamma)$

Shedding light on the origin of ^{204}Pb, the heaviest s-only isotope in the solar system

PHYSICAL REVIEW LETTERS **133,** 052702 (2024)

Shedding Light on the Origin of ^{204}Pb, the Heaviest *s*-Process–Only Isotope in the Solar System

$^{235}U(n,f)$

First cross section data above 200MeV.
Extending the upper limit of the only previous measurement up to 440MeV

Phys. Lett. B 860 (2025) 139213

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journal homepage: www.elsevier.com/locate/physletb

ELSEVIER

Letter

New insights on fission of ^{235}U induced by high energy neutrons from a new measurement at n_TOF

$^{246}Cm(n,\gamma)$ and $^{248}Cm(n,\gamma)$

Involved in a collective effort to improve the capture cross-section data for Minor Actinides (MAs), which are required to estimate the production and transmutation rates of these isotopes in light water reactors and innovative reactor systems

Eur. Phys. J. A (2024) 60:246
https://doi.org/10.1140/epja/s10050-024-01453-w

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article

Measurement and analysis of the ^{246}Cm and ^{248}Cm neutron capture cross-sections at the EAR2 of the n_TOF facility at CERN

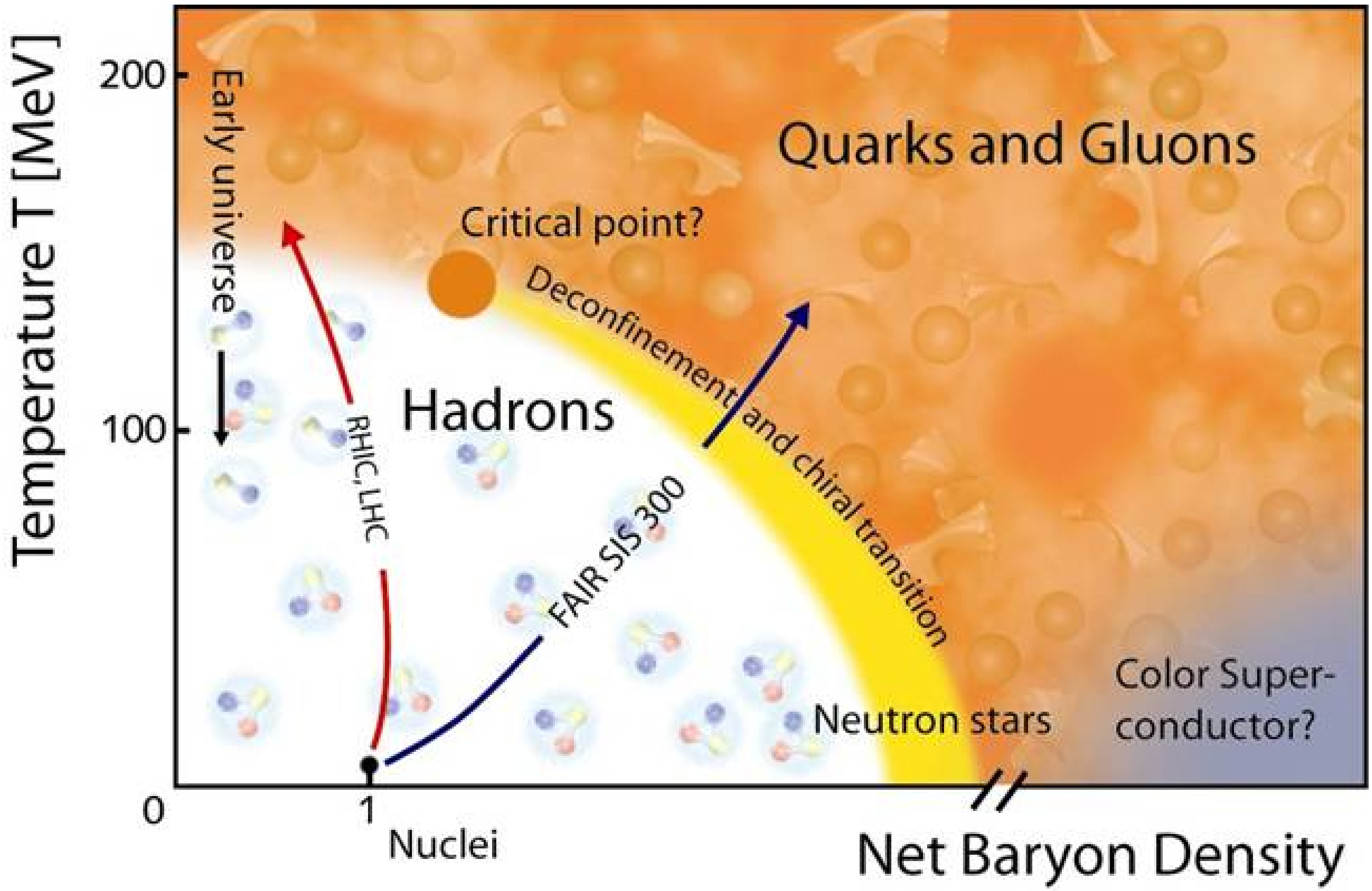
$^{14}N(n,p)^{14}C$

In Boron Neutron Capture Therapy (low energy neutrons), this reaction provides the most important biological dose to healthy tissue

PHYSICAL REVIEW C **107,** 064617 (2023)

Measurement of the ^{14}N$(n,p)^{14}$C cross section at the CERN n_TOF facility from subthermal energy to 800 keV

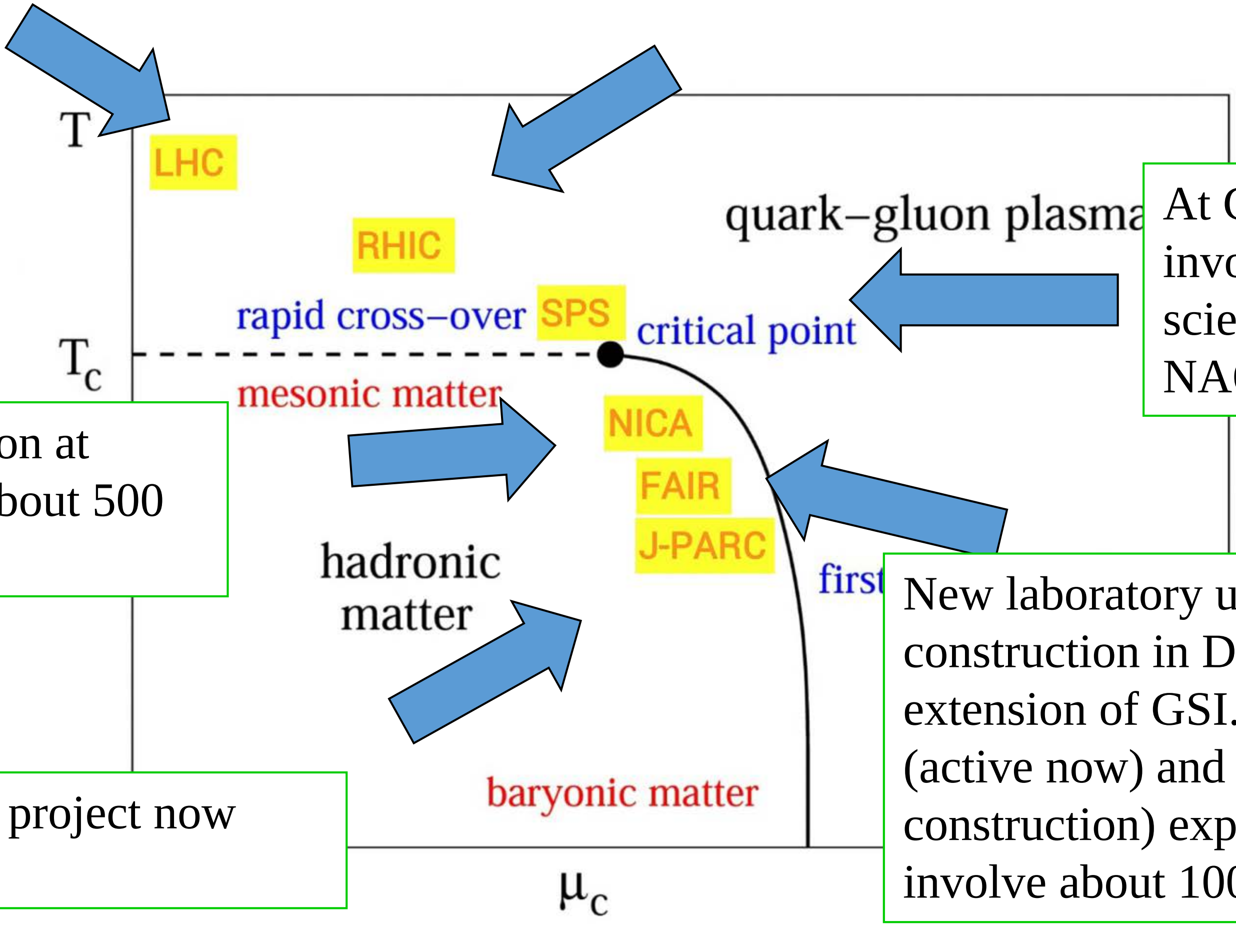
The exploration of the phase diagram of strongly interacting matter



The exploration of the phase diagram of strongly interacting matter with high energy heavy-ion collisisions: a world wide enterprise

At CERN, involves about 1500 scientists in all four large experiments ALICE, CMS, ATLAS and LHCb

At BNL, involves about 1000 scientists in two large experiments (STAR and PHENIX, then SPHENIX)



At CERN, involves about 300 scientists (SHINE, NA60+)

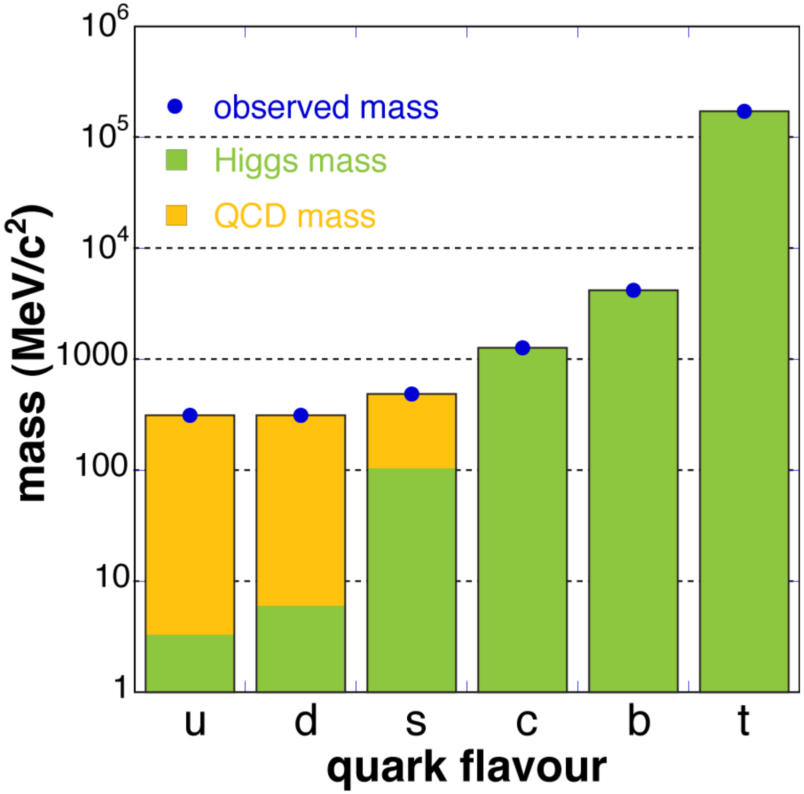
Under construction at JINR, involves about 500 scientists (MPD)

New laboratory under construction in Darmstadt, extension of GSI. The HADES (active now) and CBM (under construction) experiments involve about 1000 scientists.

In Japan, new project now under study

The origin of mass

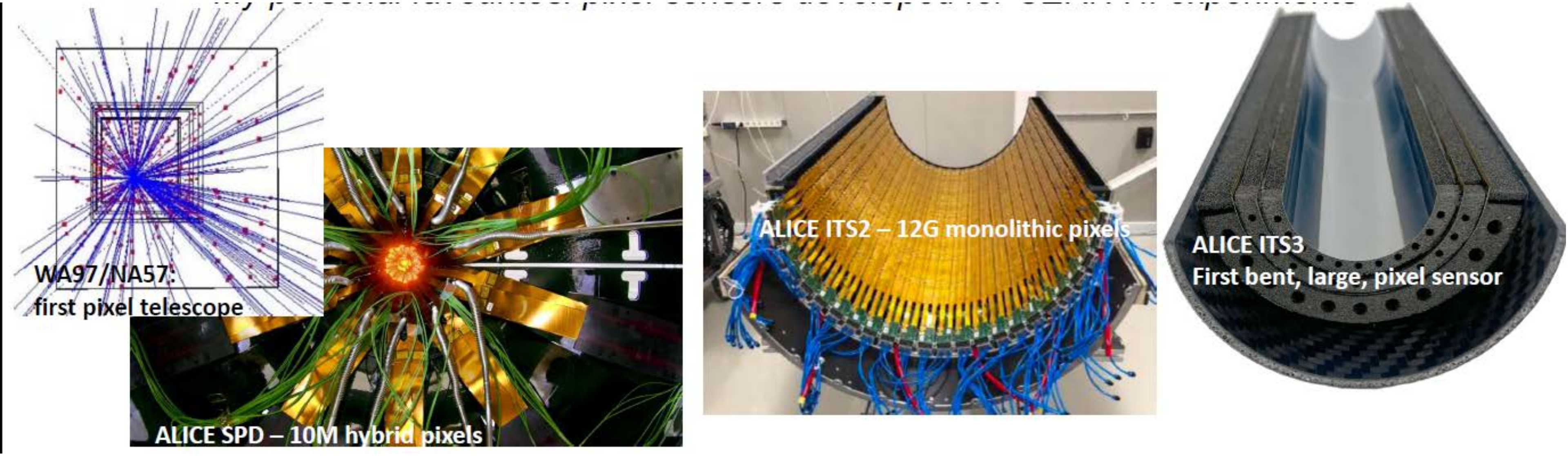
- How hadrons are built from quarks
- Key to understand how the mass of ordinary matter is generated
- Vigorous experimental program in Hadron Physics worldwide
- LHC, JLAB and in the future EIC



Most of the observed mass of light quarks is generated by the spontaneous breaking of chiral symmetry

Heavy-ion physics: a driver of frontier detector R&D

- Requirements: particle identification, precise tracking and vertexing at low *p*T
- Pioneering developments for:
- High-res. time of flight (MRPC), Silicon drift det., continuous readout, tracking on GPUs
- Silicon pixel detectors, in particular low-material sensors (first hybrid, now monolithic)
- TOF and RICH PID detector technologies: now 20 ps Resolution CMOS LGADs and RICH with SiPM readout



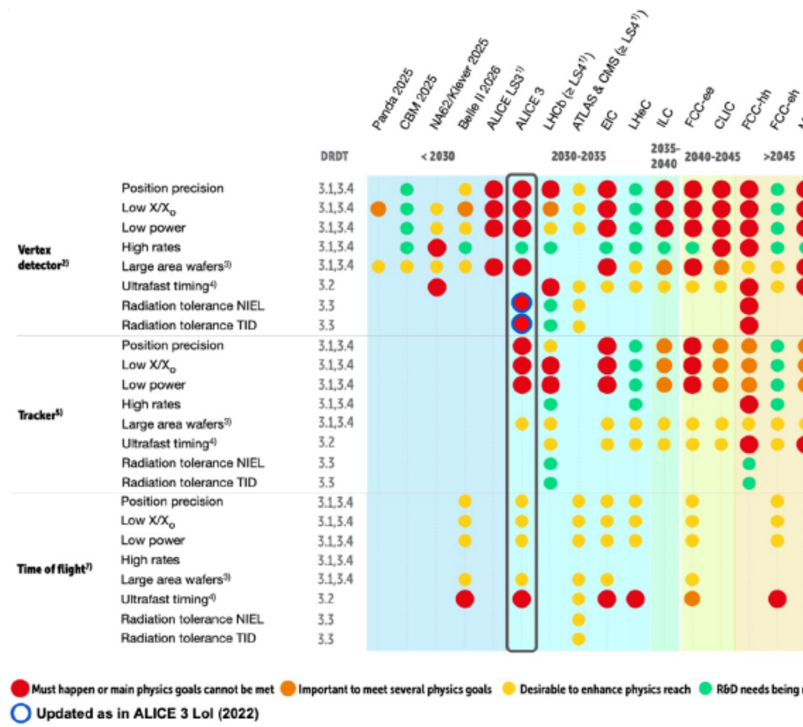
R&D for HI experiments paves the way for future HEP experiments

ALICE 3 and FCC-ee det. have similar pixel vertex specs:

	ITS3	ALICE 3 VTX	FCC-ee
Single point resolution (μm)	5	2.5	3
Time resolution (ns RMS)	2000	100	20
In-pixel hit rate (Hz)	54	94	few 100
Fake-hit rate (/pixel/event)	10^{-7}	10^{-7}	
Power consumption (mW / cm^2)	35	70	50
Particle hit density (MHz/cm^2)	8.5	94	200
NIEL (1 MeV n_{eq})	4×10^{12}	1×10^{16}	10^{14} (per year)
TID (Mrad)	0.3	300	10 (per year)
Material budget (% X_0/layer)	0.09	0.1	˜0.3
Pixel size (μm)	20	10	15-20

ECFA DRD Roadmap:

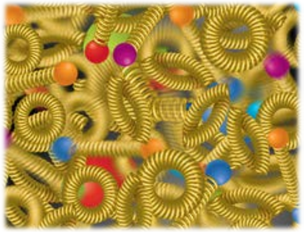
→ **R&D for ALICE upgrades covers a significant part of the long-term strategic R&D lines defined by ECFA**



https://cds.cern.ch/record/2784893

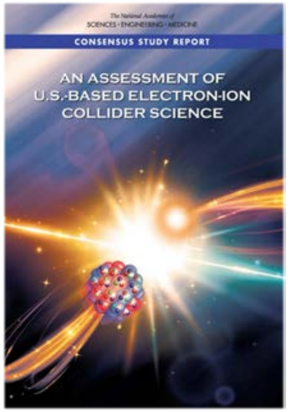
Physics at the EIC: utimate QCD exploration

Aim to investigate with precision the universal dynamics of gluons to understand the emergence of hadronic and nuclear matter and their properties



Main questions to be addressed:

- How does the **mass** of the nucleon arise?
- How does the **spin** of the nucleon arise?
- What are the emergent properties of **dense system of gluons**?
- How are the **quarks and gluon distributed in space and momentum** inside the nucleon and nuclei?

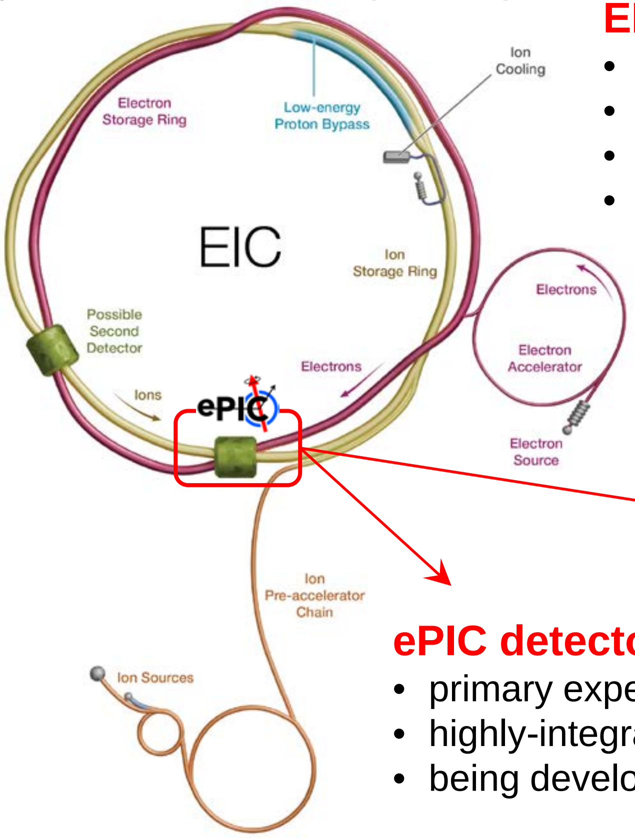


- Most of the visible matter in the universe is made of protons and neutrons
- Basic properties, such as proton mass and spin, emerge from the complex dynamical structure of QCD itself
- The **Science goal of the EIC** is to image quarks and gluons and their interactions to **understand matter at its most fundamental level**

The EIC machine and the ePIC detector

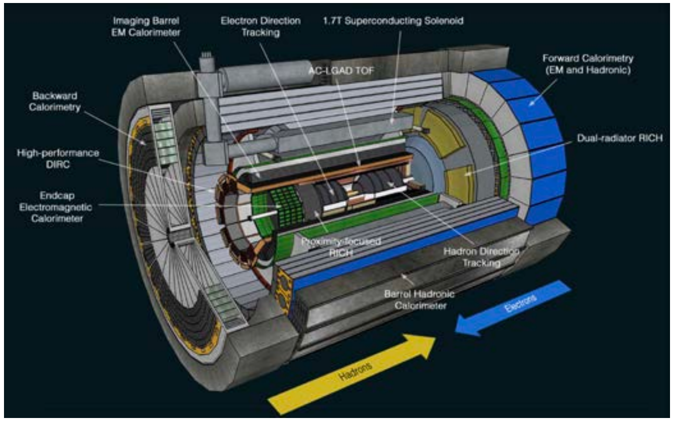
In the current worldwide scenario, EIC is the only novel HE collider in the next 10-20 years

Usage of RHIC tunnel and RHIC p/ion complex



EIC machine:

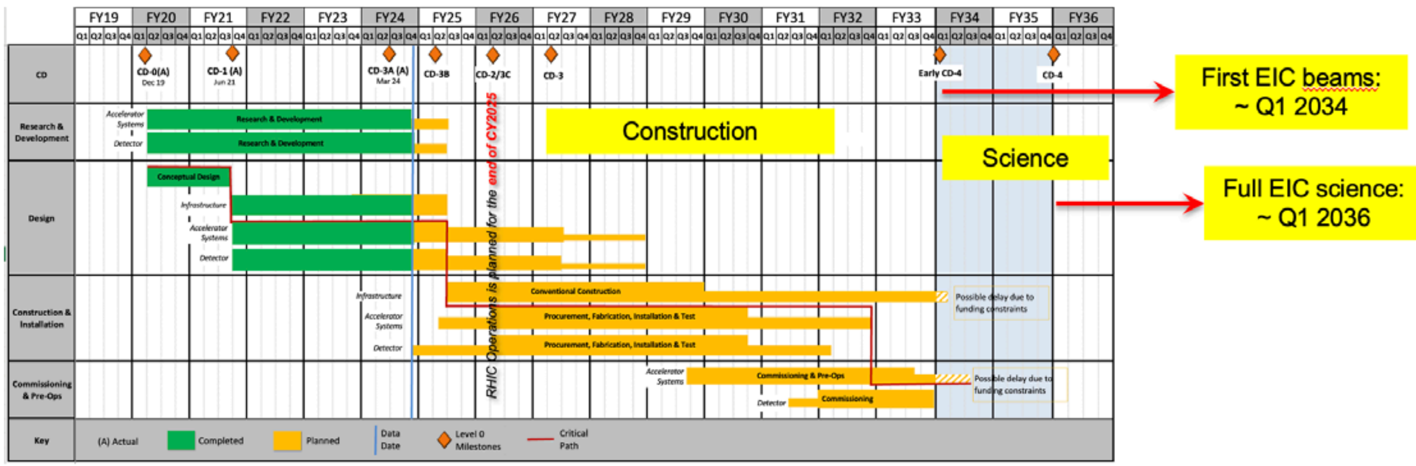
- high luminosity, L ~ 10^{33} – 10^{34} $cm^{-2}s^{-1}$
- broad center-of-mass energy range, $\sqrt{s}$ = 29 –140 GeV
- highly polarized beams (electrons & protons, light ions), ~70%
- heavy ions up to Uranium



ePIC detector:

- primary experiment at the EIC
- highly-integrated, multipurpose detector fully exploiting tracking, PID, calorimetry
- being developed by the ePIC Collaboration in partnership with the EIC project

EIC schedule and INFN contribution to ePIC



INFN main in-kind contributions to the ePIC detector:

- **dual-radiator RICH (dRICH)** → responsibility on mechanics, photosensors, readout electronics, gas and aerogel radiator performance studies (synergies with ALICE 3), full project leadership;
- **innermost layers of the Silicon Vertex Tracker (SVT IB)** → responsibility on Inner Barrel sensor bending/interconnection and (half-)layer assembly, support mechanics development and production (synergies with ALICE ITS3 project);
- **uRWELL-based EndCaps Trackers (uRWELL-ECT)** → responsibility on development and production of the end cap disks to be built with uRWELL technology and integrated in the gas-based tracking system (synergies with JLab12 activities)

NUMEN

NUclear **M**atrix **E**lement for **N**eutrinoless double beta decay

NURE

Extraction from measured cross-sections of *"data-driven"* information on Nuclear Matrix Elements for all the systems candidate for 0νββ

Fotografia di Ettore Majorana dalla tessera universitaria datata 3 novembre 1923

E. Majorana, Il Nuovo Cimento 14 (1937) 171
W. H. Furry, Phys Rev. 56 (1939) 1184

0νββ decay half-life

Phase space factor

contains the average **neutrino mass**

$$\left(T_{1/2}^{0\nu\beta\beta}(0^+ \to 0^+)\right)^{-1} = G_{0\nu\beta\beta}\left|M^{0\nu\beta\beta}\right|^2 \left|f(m_i, U_{ei})\right|^2$$

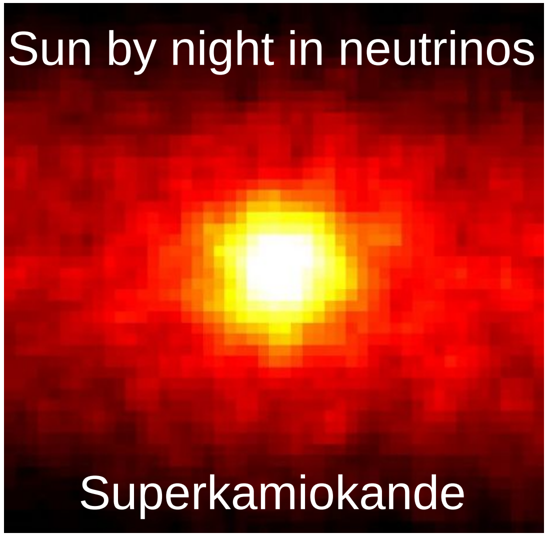
Nuclear Matrix Element (NME)

$$\left|M_{\varepsilon}^{0\nu\beta\beta}\right|^2 = \left|\left\langle \Psi_f \middle| \hat{O}_{\varepsilon}^{0\nu\beta\beta} \middle| \Psi_i \right\rangle\right|^2$$

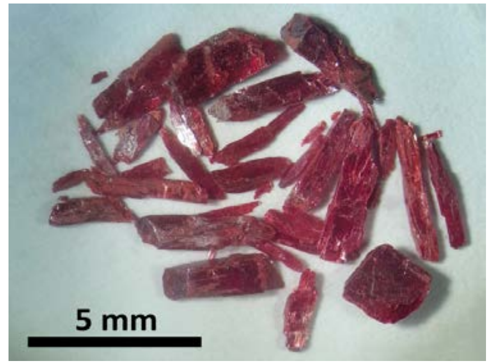
Transition probability of a **nuclear** process

Use of nuclear reactions **(Double Charge Exchange reactions)** to stimulate in the laboratory the same nuclear transition occurring in 0νββ

Neutrinos from the Sun

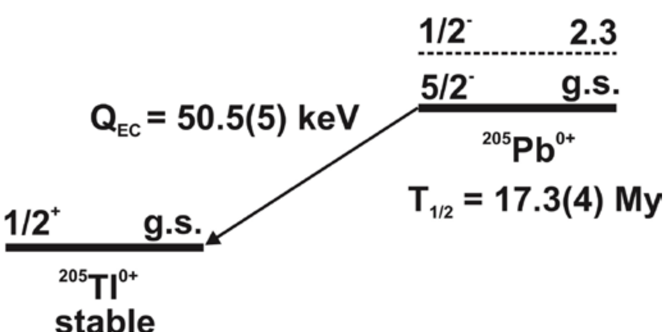


1. Neutrino Physics: The LOREX Project



Lorandite ($TlAsS_2$) as Solar pp-neutrino detector
GSI/FAIR – provides capture cross-section

Did the sun always shine like today? Looking backwars via LOREX project



Measurement unique for storage rings -> GSI/FAIR

LEA (Low Energy Antimatter) Project

Experiments at CERN's AD/ELENA facility (the only low-energy p̄ source):

Physics Goals:

- CPT symmetry tests:

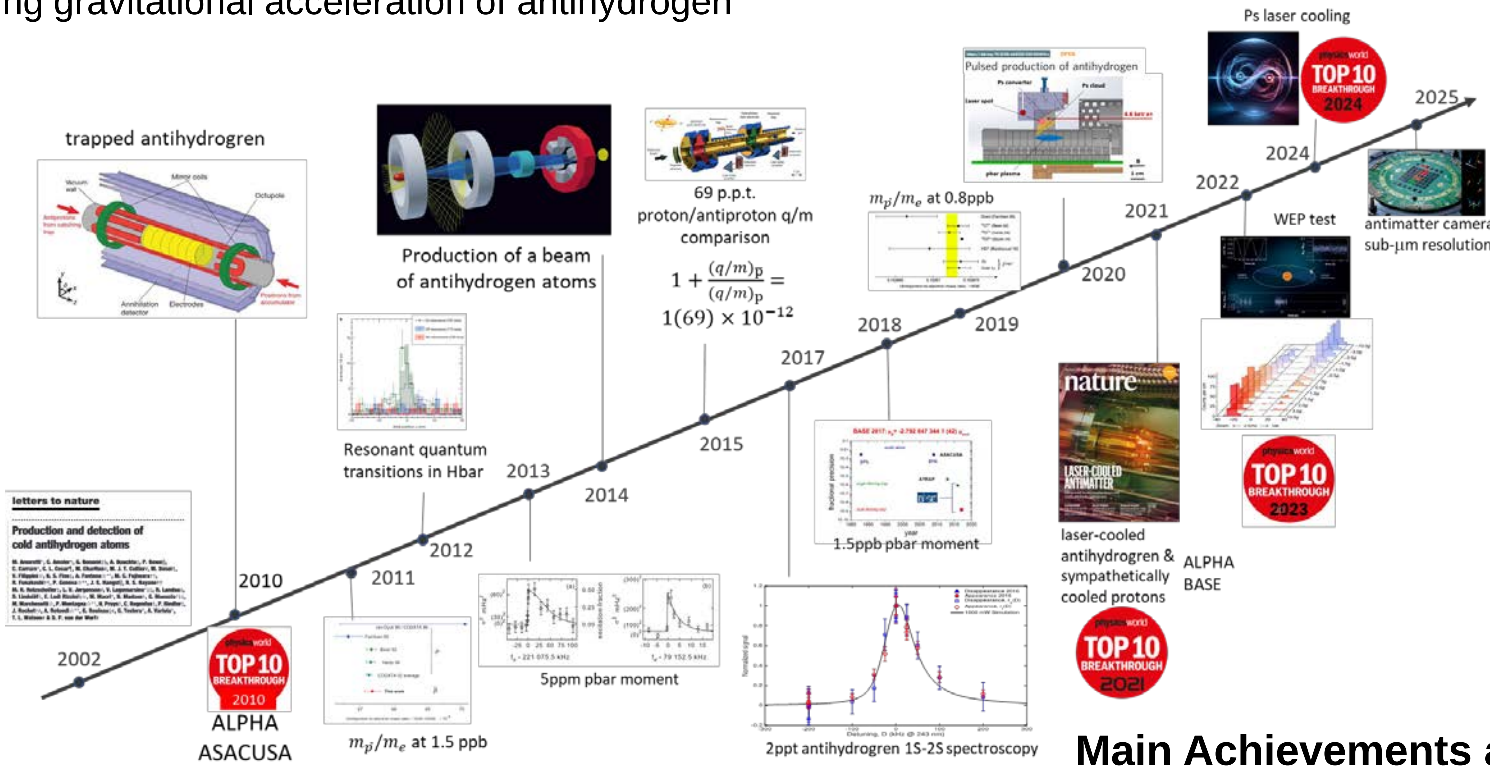
  antimatter scarcity in the Universe and matter-antimatter asymmetry

  ← Antihydrogen laser & MW spectroscopy

- Test of the Weak Equivalence Principle (WEP)

← Measuring gravitational acceleration of antihydrogen

- AEgIS, ALPHA, ASACUSA

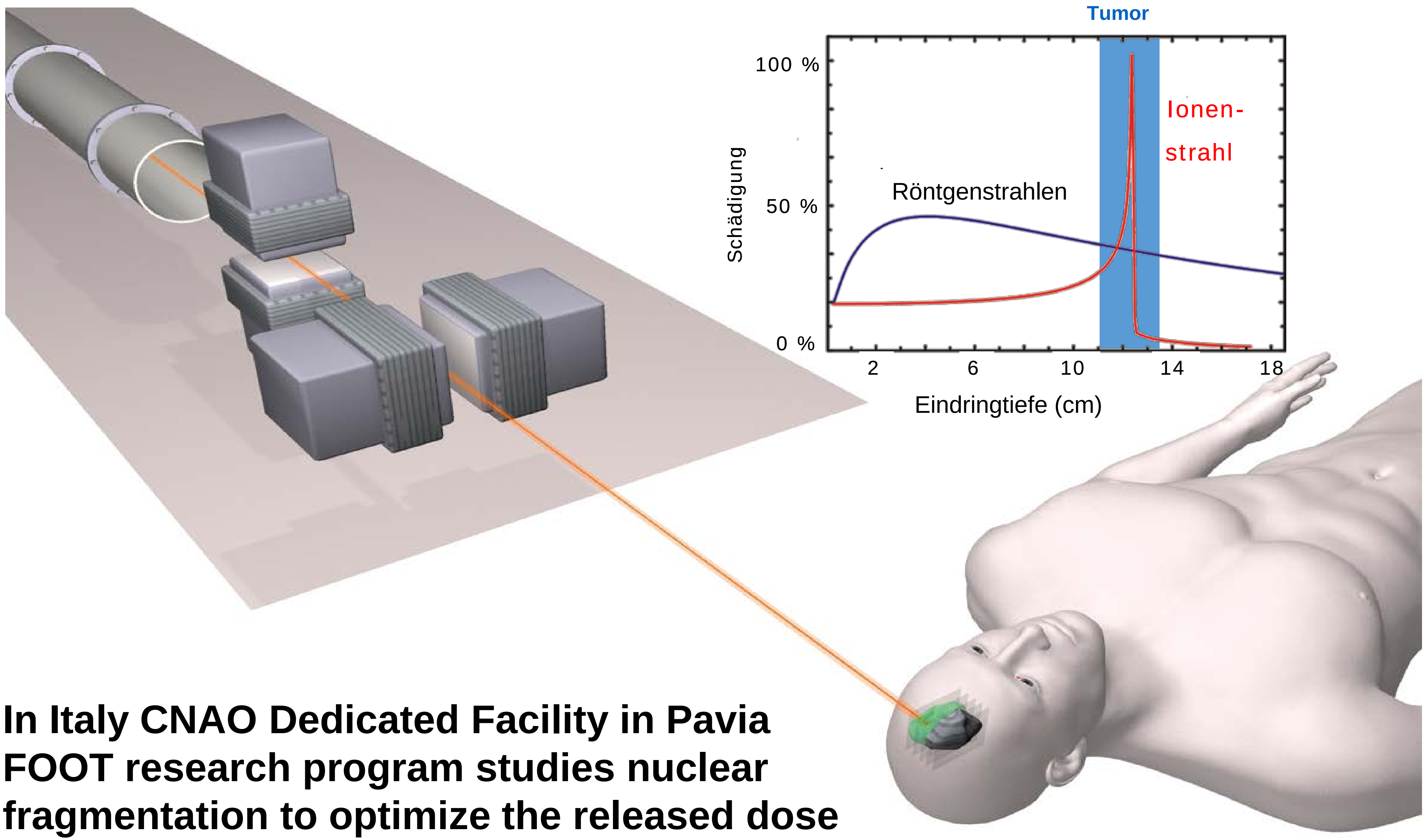


Main Achievements at AD

Societal impact of Nuclear Physics

- Societal benefit can be assessed through the contribution to the 17 **Sustainable Development Goals (SDGs)** published by the United Nations
- Nuclear physics and its applications play a major role in the domains of **energy**, **health** and **space**. Contribute to at least 8 of the 17 SDGs:

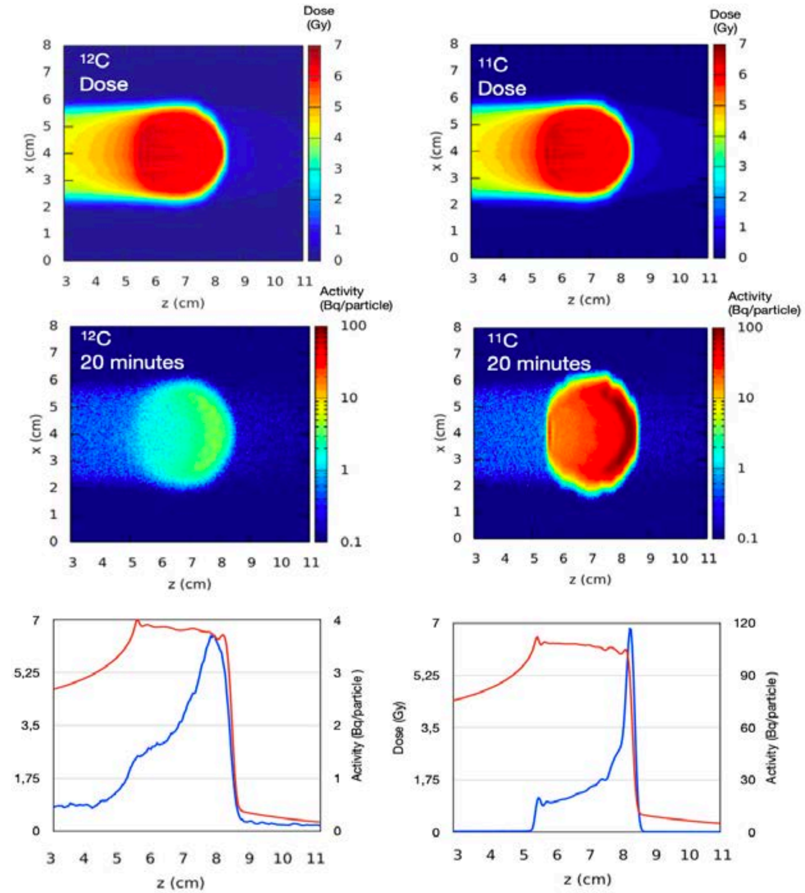
Ion Beam Cancer Therapy: 25 years old yet in full development



In Italy CNAO Dedicated Facility in Pavia
FOOT research program studies nuclear fragmentation to optimize the released dose

Breaktrhoughs continue: RIB in cancer therapy

- Motivation: **PET-based range monitoring: stable ions vs. β+ emitters**



• Uncertainties in CT number conversion
• Quality of the CT
• Anatomical changes and misalignments

↓

RANGE UNCERTAINTY

↓

Adding margins to the tumor contour

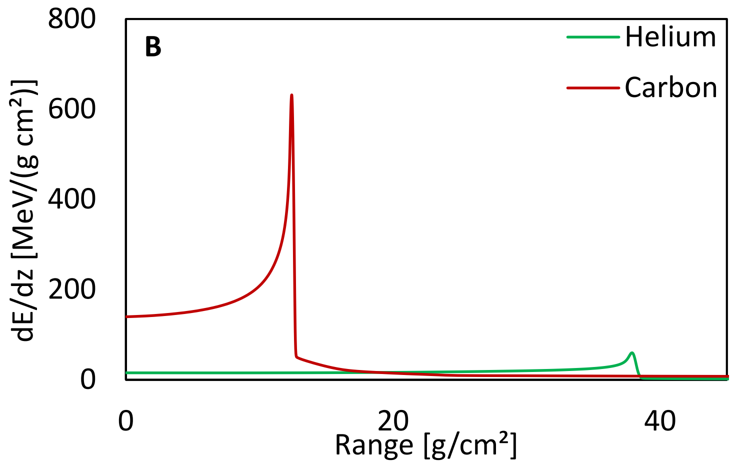
↓

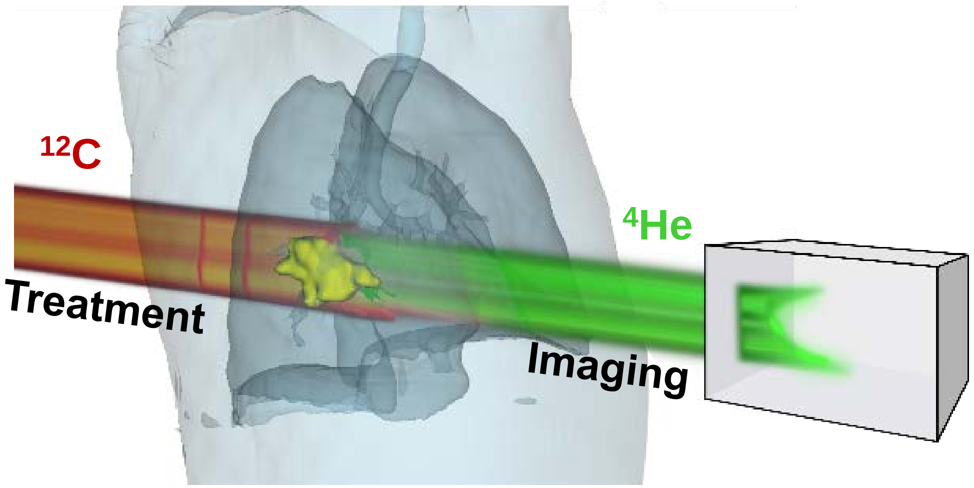
More damage to normal tissue

Boscolo *et al.*, *Front. Oncol*. 2021
Boscolo *et al.*, *NIM-A* 2022

Breakthroughs continue: combined imaging and therapy beams

- PROMISE will result in a new paradigm in carbon ion therapy: **combined imaging and therapy beams**





- Online **image guidance** and **range detection** will reduce uncertainty permitting highly **conformal planning** and **increased tumor control**

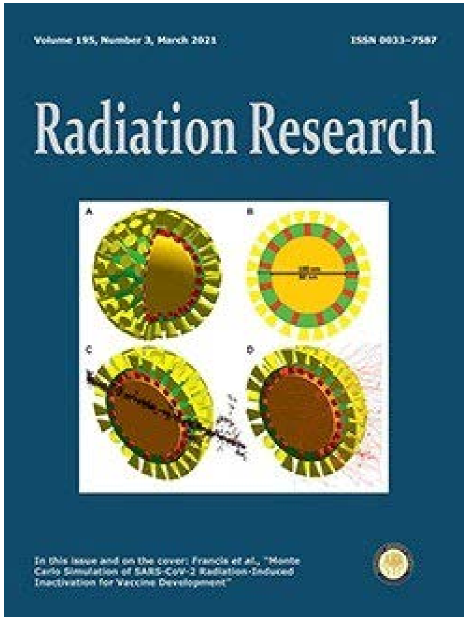
FLASH radiotherapy

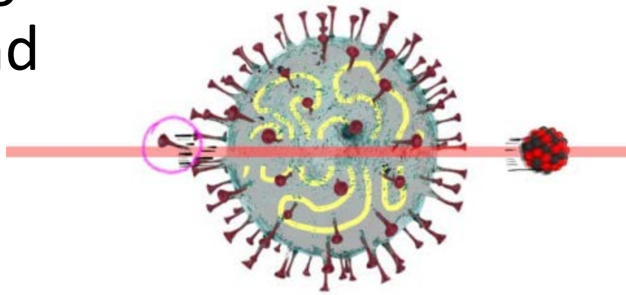
- FLASH Radiotherapy, is a novel approach of RT using ultra-high dose rate aiming to get **unchanged tumor control protection (TCP)** and **decreased normal tissue complication probability (NTCP).**
- GSI has demonstrated for the first time that the FLASH effect can be obtained with accelerated carbon ions (18 Gy in one spill of 150 ms) paving the way to clinical translation in particle therapy

Turn challenges into opportunities:

Use heavy ion beams to inactivate viruses for vaccine development

- Study launched in response to the COVID pandemic
- Energetic ions are able to inactivate the virus by inducing breaks in the viral RNA with minimal membrane damage thus protecting the surface structures.
    - An Influenza virus was irradiated with the iron isotope Fe-56, accelerated at 1 GeV/n
    - Based on the resulting viruses, HZI produced a flu vaccine inactivated with heavy ions and examined it for its ability to promote the formation of virus-binding and neutralizing antibodies after vaccination.
    - Immunization of mice with the inactivated virus resulted in the stimulation of strong, antigen-specific cellular immune responses.





Radiation in space

Space radiation protection

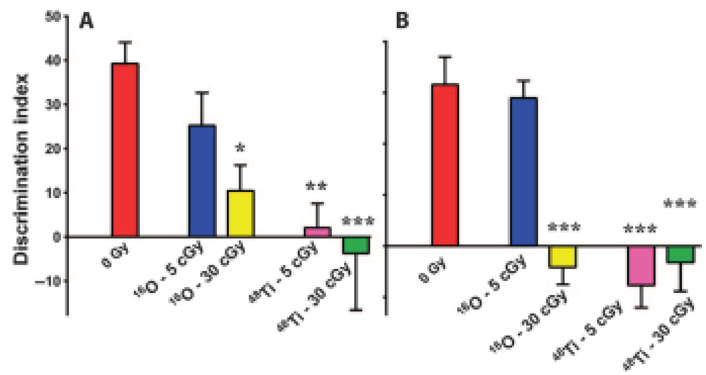
ESA ground-based facility for European studies on space radiation risk and countermeasures (IBER)

RESEARCH ARTICLE

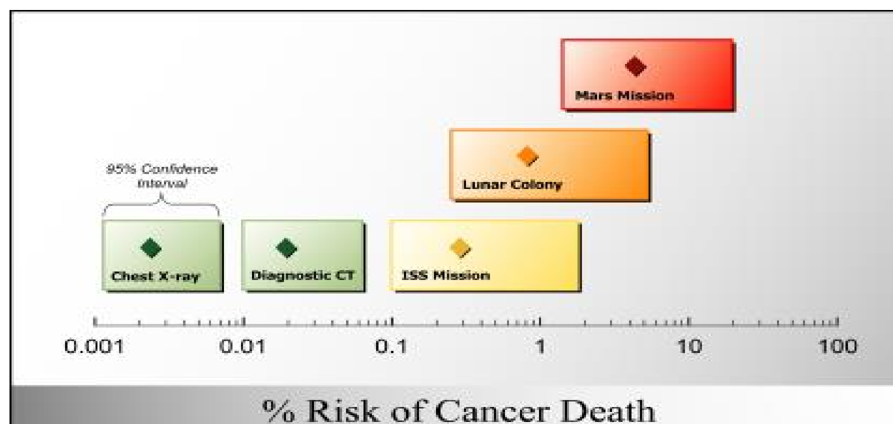
COGNITIVE NEUROSCIENCE

What happens to your brain on the way to Mars

Vipan K. Parihar,[1] Barrett Allen,[1] Katherine K. Tran,[1] Trisha G. Macaraeg,[1] Esther M. Chu,[1] Stephanie F. Kwok,[1] Nicole N. Chmielewski,[1] Brianna M. Craver,[1] Janet E. Baulch,[1] Munjal M. Acharya,[1] Francis A. Cucinotta,[2] Charles L. Limoli[1]*



(**A**) recognition memory (**B**) spatial memory



Durante & Cucinotta, *Nature Rev. Cancer* (2008)

Synthetic hibernation

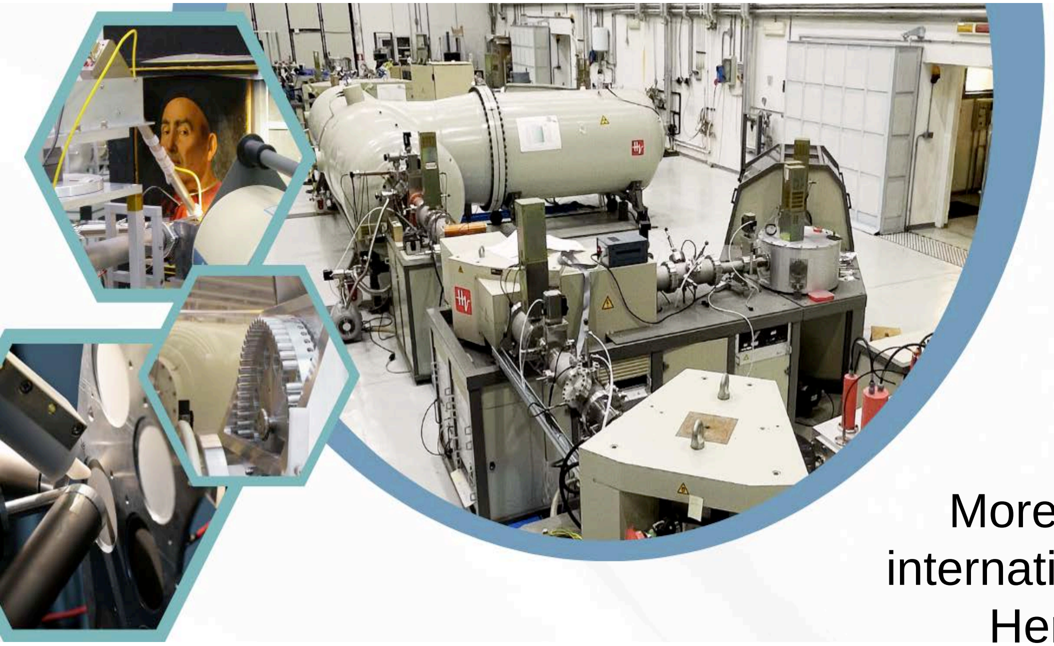
- Astronauts could be put into artificial hibernation to be better protected from cosmic radiation.
- An international research team led by the Biophysics Department of the GSI Helmholtzzentrum in Darmstadt now has found decisive indications of the possible benefits of artificial hibernation for radiation resistance.

- The main results: Synthetic hibernation may have protective effects on a lethal dose of C-ions. In addition, synthetic hibernation reduces the tissues damage from total body irradiation.
- https://www.gsi.de/en/start/news/details/2023/02/09/esa-wissenschaftsprogramm-fair-forschung-winterschlaf
- https://www.gsi.de/en/start/news/details/2022/11/14/schutz-vor-kosmischer-strahlung

ESA VIDEO:

https://www.youtube.com/watch?v=3cTWF6ws450

Nuclear Physics for Cultural Heritage and Environment



LABEC

Laboratorio di tecniche nucleari per l'Ambiente e i BEni Culturali

INFN FIRENZE
Istituto Nazionale di Fisica Nucleare
Sezione di Firenze

UNIVERSITÀ DEGLI STUDI FIRENZE

More than 35 years of experience. High international reputation in both fields (Cultural Heritage and Environmental issues)

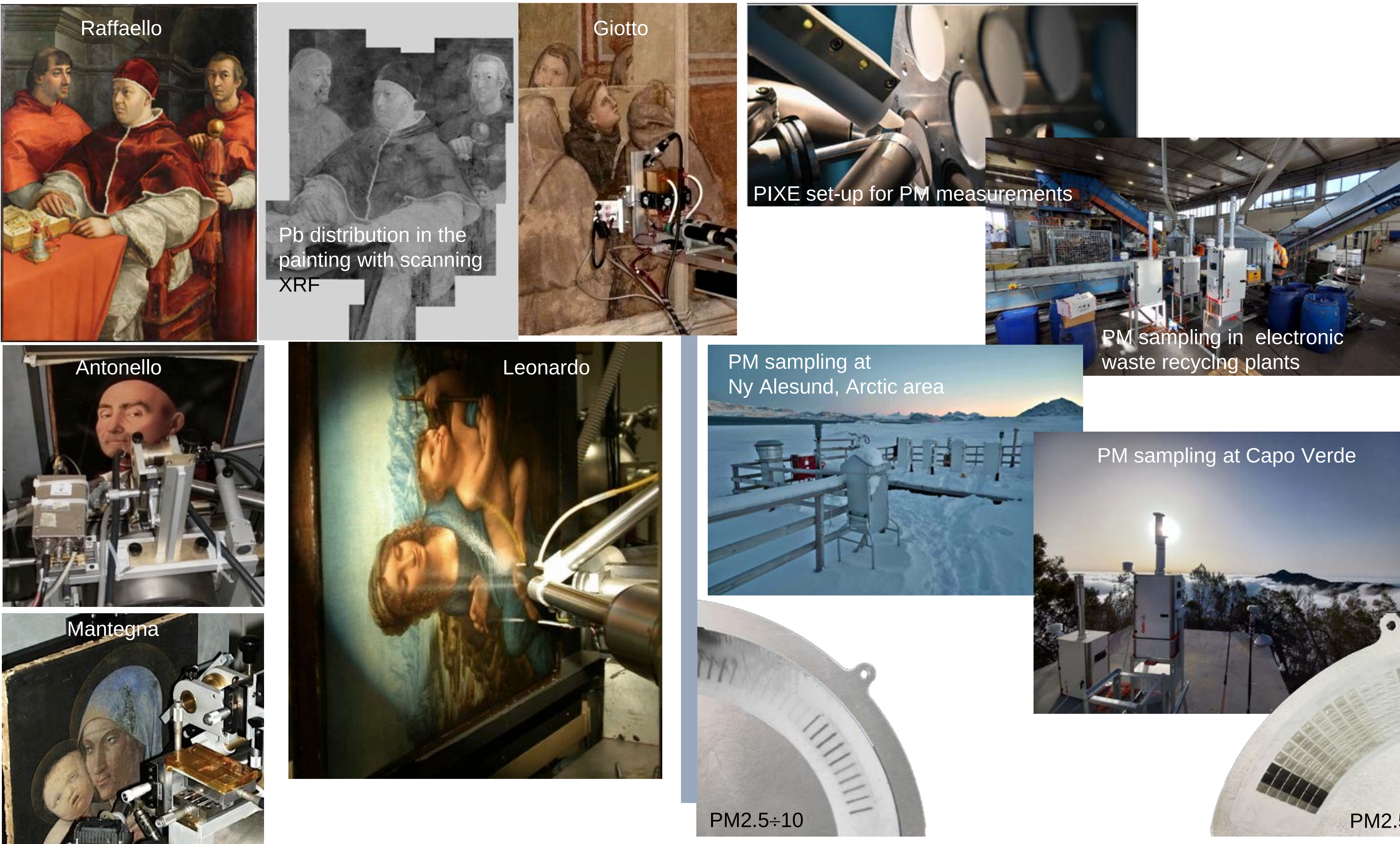
Ion Beam Analysis (IBA) and portable X Ray Fluorescence (XRF) to detect the composition of materials also by scanning techniques to obtain images of elements distribution.

Compositional analysis of paintings by Giotto, Leonardo, Antonello da Messina, Raffaello, Mantegna, Botticelli,, and many other Masters… to provide art historians with "objective" information, also crucial for restauration work

Compositional analysis of the atmospheric particulate (PM_{10}, $PM_{2.5}$, PM_1) and of its variation in time to detect the sources of pollution (discriminating the "natural" from the anthropogenic ones). Analysis of tens of thousand samples, collected in both densely populated areas in Europe and Asia, and in remote sites (e.g. Arctic and Antarctic sites). Important contribution to the understanding of global climate changes, support to the political decisors in taking appropriate mitigation strategies

Accelerator Mass Spectrometry (AMS) for rare isotopes concentration (mainly ^{14}C, not only for dating in the field of Archaeology and Cultural Heritage, but also for environmental issues)

Nuclear Physics for Cultural Heritage and Environment



LABEC

And many many more…

- Nuclear beams as „remote scalpel“ in treatment of non-tumor deseases (Heart Ablation)
- Nuclear Clocks based on Thorium 229
- Early warning of Earthquakes (**artEmis EU project**) using measurements of Radon
- Production of isotopes for medical use
- Measurement of cross sections relevant for Nuclear power plans, both Fission and Fusion
- ….

Summary

- Just a few examples to show that Nuclear Physics is living an exceptional moment
- A wealth of new results contribute to our understanding of many key processes in the Universe from stellar reactions to the properties of the Quark Gluon Plasma
- Innumerable applications have an impact on our quality of life, from medicine to energy
- A number of new facilities all over the world promise very exciting times ahead of us: FRIB, EIC, FAIR, RISP, SPES…

backup

Energy

- Decarbonization goals and security of supply represent critical global challenges. **Nuclear energy** will continue to provide a significant contribution to **energy production for decades to come**
- **Innovation** is vital in the nuclear energy field:
  - Development novel concepts like the Small Modular Reactors (SMR)
  - Advanced nuclear fission systems (e.g. Gen IV program and SNETP/ESNII)
  - Global fusion roadmap projects: ITER and DEMO
  - Nuclear reactor technology and new designs of SMR and larger systems bring progress in passive and inherent safety
  - Projects, such as MYRRHA, focus on our ambition of reducing our current nuclear waste prior to its long-term geological disposal

Energy

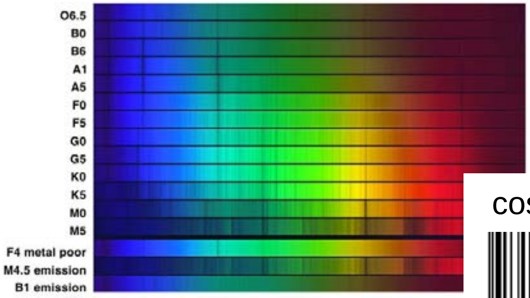
- Development of the next generation of fission reactors and the design of the first fusion reactors is directly linked to several basic nuclear physics research issues:
  - Precise cross section and decay measurements
  - Understanding of nuclear reactions
  - Evaluation of data and their verification and validation
  - Development of reliable databases
  - Irradiation tests of materials

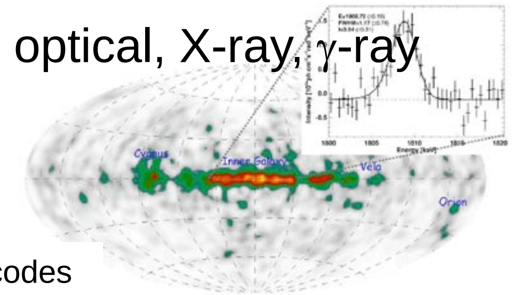
Image: Outline of the MYRRHA facility

The Messengers of the Universe

electromagnetic emissions

radio, microwave, infrared, optical, X-ray, γ-ray





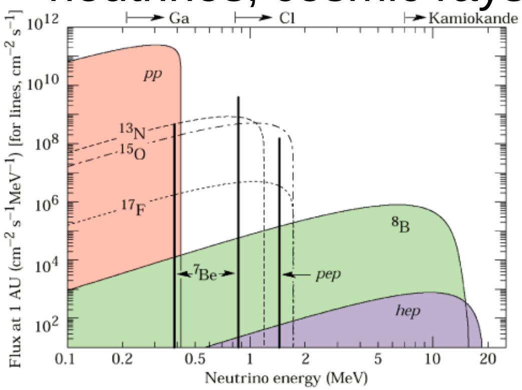
Crab Nebula SN 1054

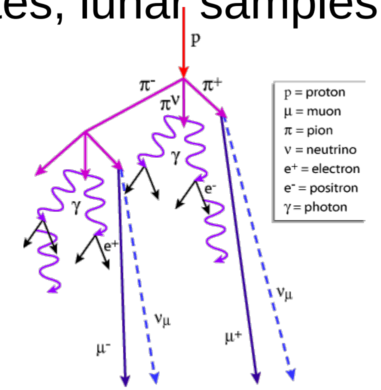
cosmic bar codes

9 771144 875007

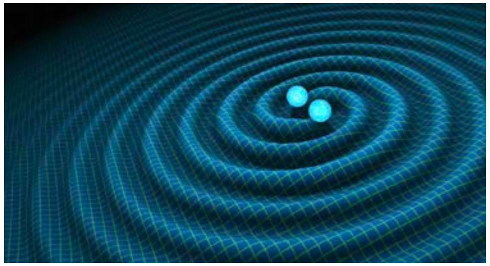
direct messengers

neutrinos, cosmic rays, meteorites, lunar samples, …





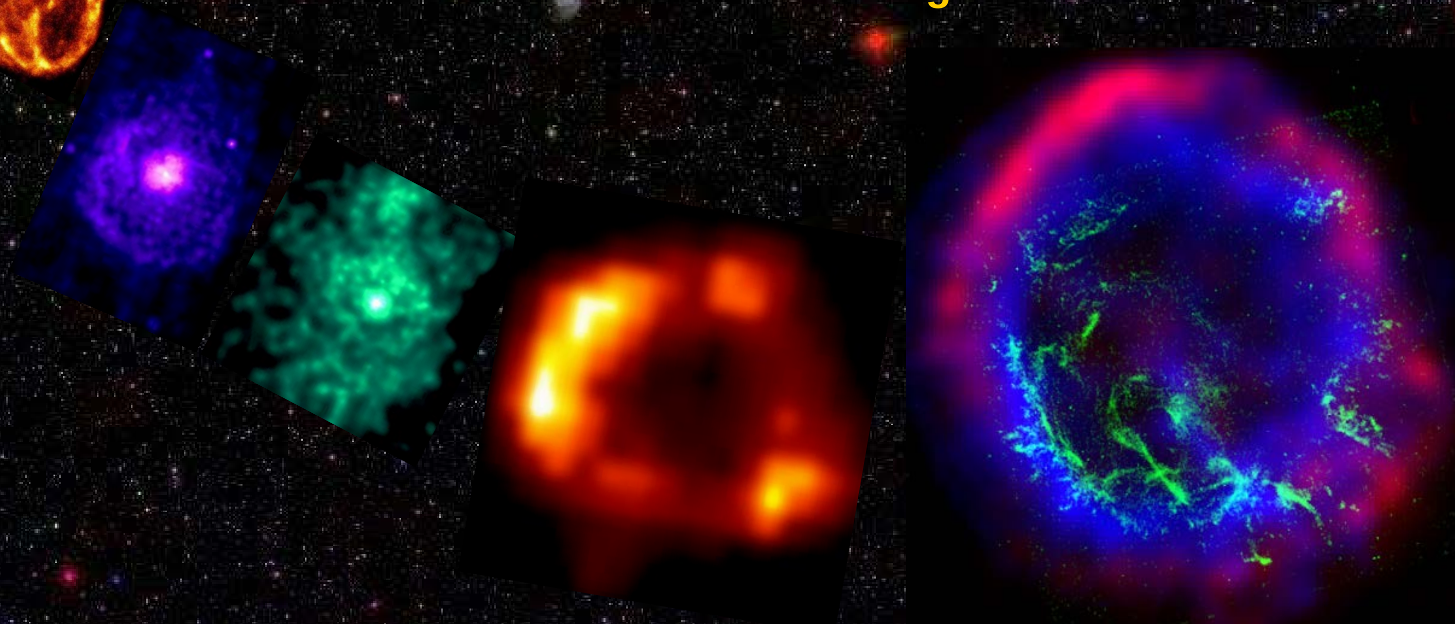
gravitational waves



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

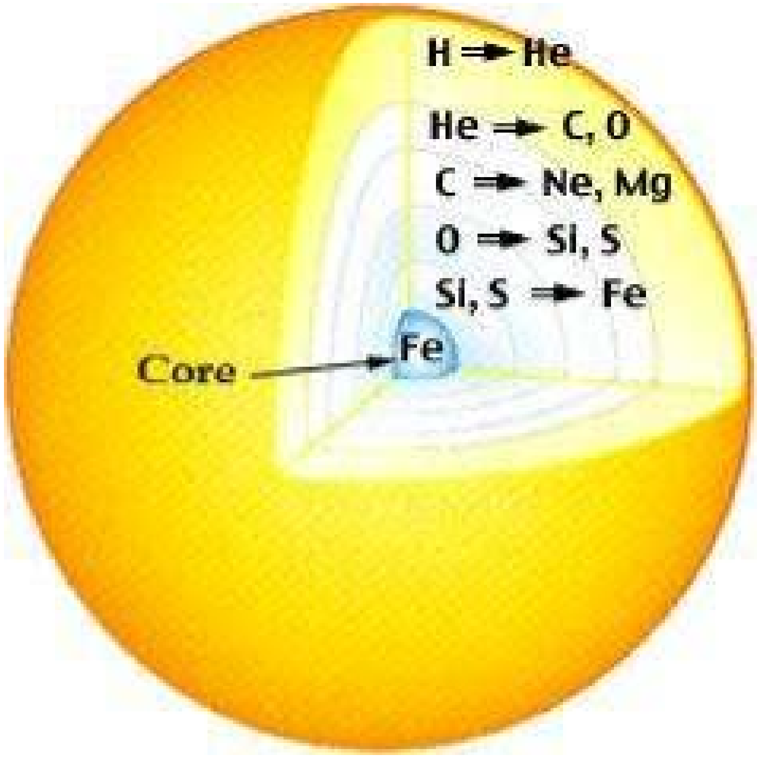
We are made of star stuff

Carl Sagan



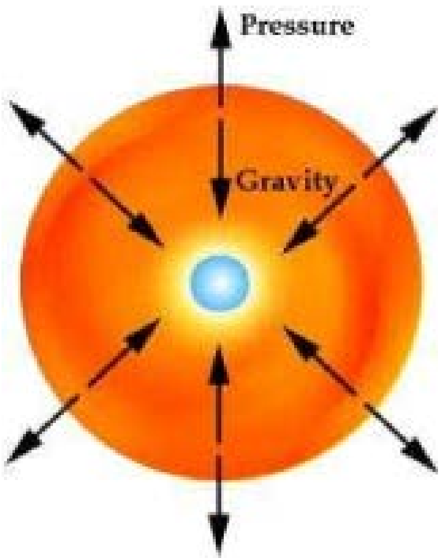
La fine di una stella massiva

- La stella ha una struttura a cipolla
- Il ferro è il prodotto finale della combustione idrostatica
- Il nucleo di ferro interno cresce, diventa instabile rispetto alla sua stessa gravità e collassa
- **SUPERNOVA!**

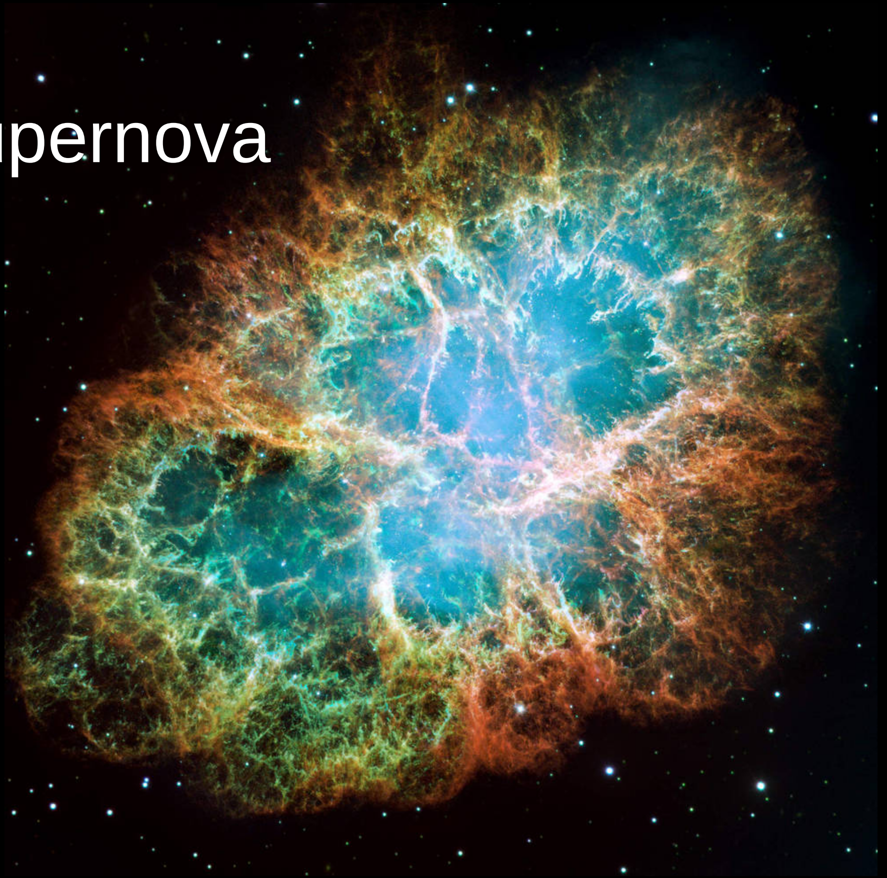


Collasso e esplosione

• Stabilità deriva dall´equilibrio pressione-gravità. La pressione e prodotta dalle reazioni nucleari
• L'equilibrio non può essere mantenuto quando il nucleo di ferro cresce
• In circa 1 secondo il raggio del nucleo si riduce da 6000 km a 20 km
• Il collasso si arresta, quando il nucleo corrisponde a un gigantesco nucleo atomico. Una grande porzione dell'energia gravitazionale viene liberata. Questa energia corrisponde alla produzione di energia di 100 soli durante la loro vita di circa 10 miliardi di anni.



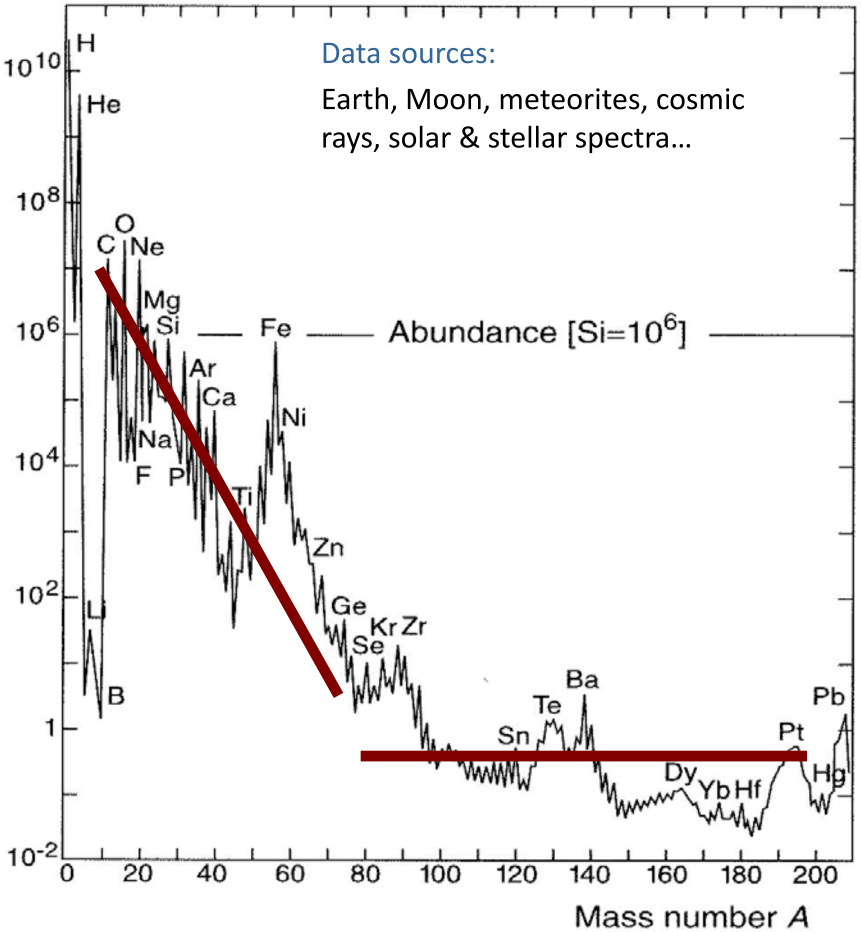
Il destino delle stelle



NASA/CXC/M.Weiss

NASA, ESA, J. Hester and A. Loll (Arizona State University)

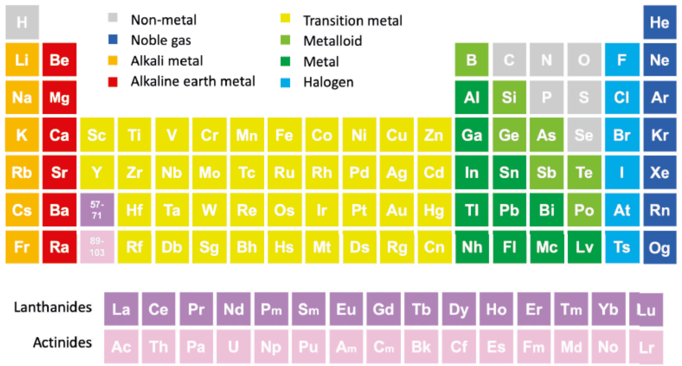
La distribuzione delle abbondanze



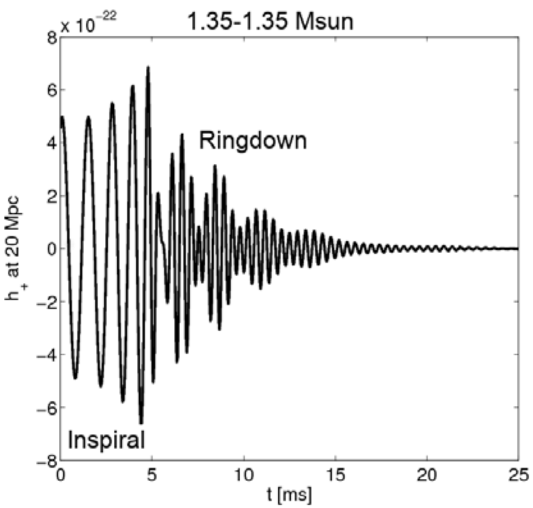
Features:

- distribution spans 12 orders of magnitude
- H ~ 75%, He ~ 23%
- C → U ~ 2% ("metals")
- D, Li, Be, B under-abundant
- exponential decrease up to Fe
- almost flat distribution beyond Fe

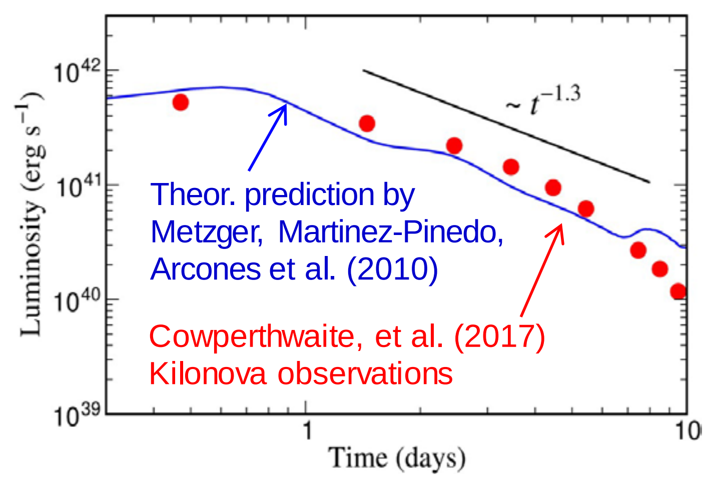
Why these features?
Where do all elements come from?



La fusione di stelle di neutroni confermata come sito astrofisico di produzione di elementi pesanti



Gravitational wave signal



Elektromagnetic “Kilonova”-Signal

August 2017

Electromagnetic afterglow - "Kilonova-lightcurve" - reveals that heavy elements, e.g. Au and Pt, were produced (r-process), as predicted by nuclear theorists.

Si puo studiare in laboratorio, passo dopo passo Neutron Stars and Mergers vs HI collisions

Neutron stars

Temperature
T < 10 MeV

Density
$\rho < 10\ \rho_0$

Lifetime
T ~ infinity

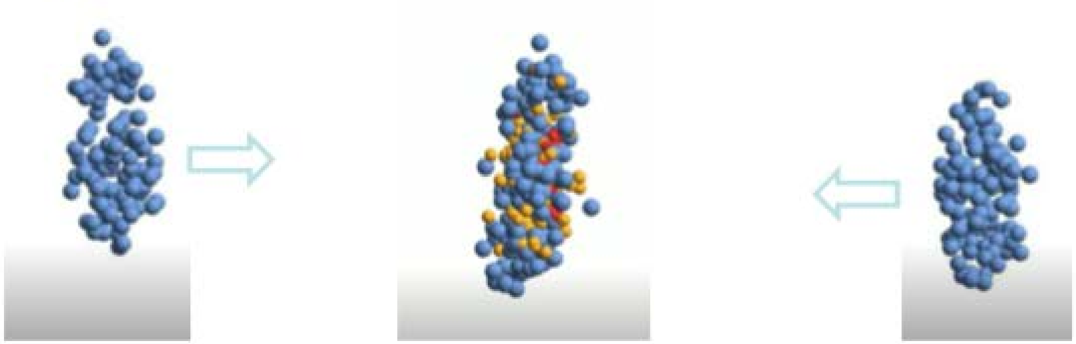
Neutron star merger

Temperature
T < 50 MeV

Density
$\rho < 2 - 6\ \rho_0$

Reaction time
(GW170817)
T ~ 10 ms

Heavy ion collisions at SIS100



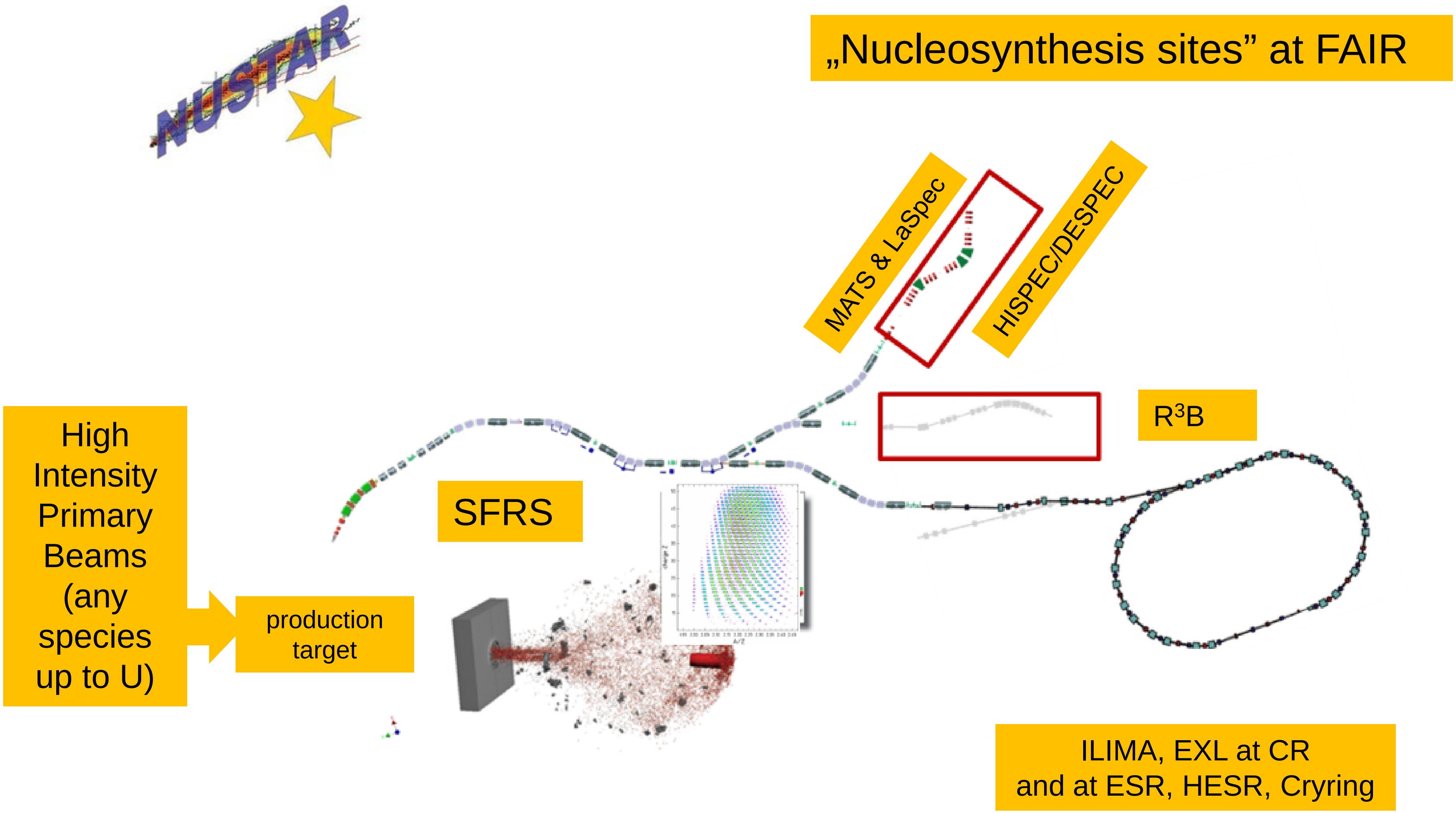
Compressed Baryonic Matter

Temperature
T < 120 MeV

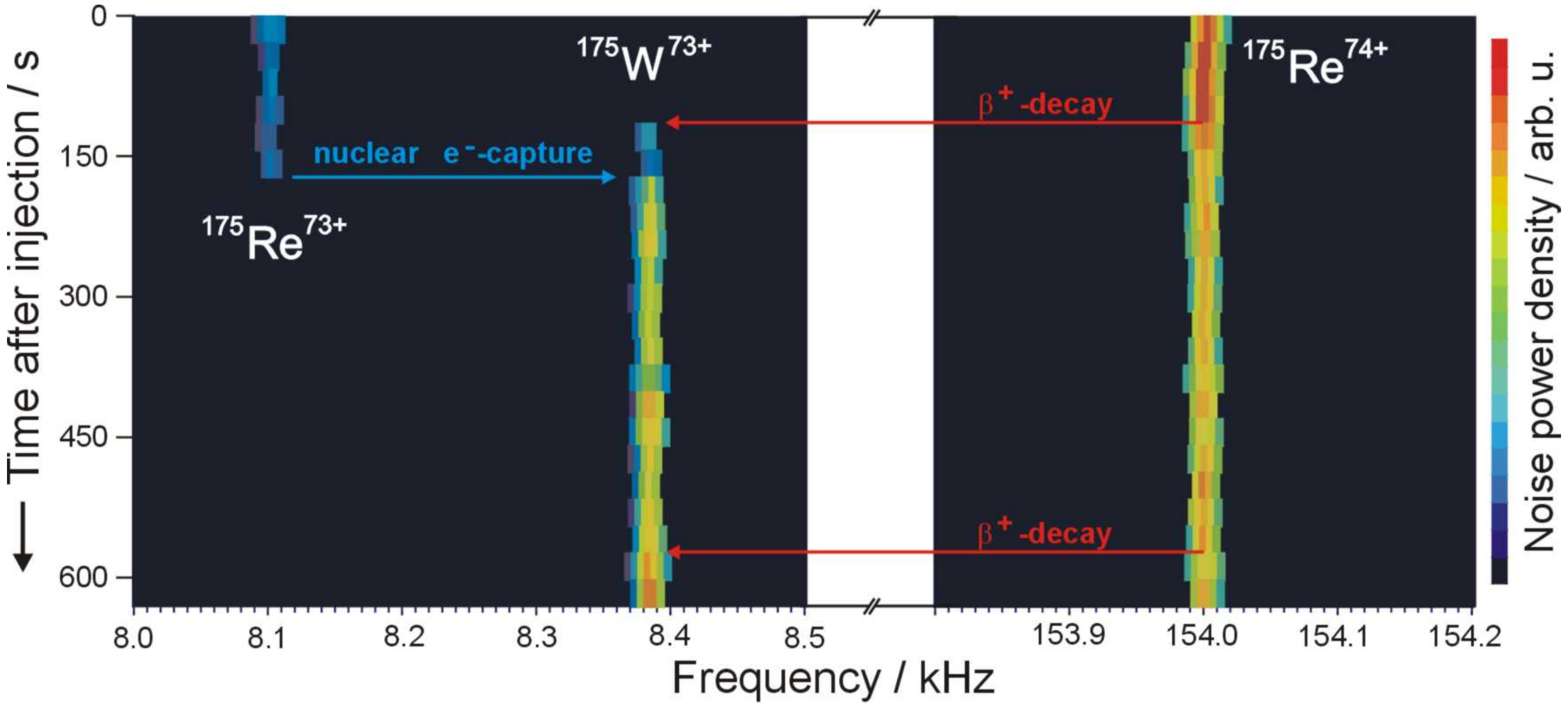
Density
$\rho < 8\rho_0$

Reaction time
$t \sim 10^{-23}$ s

misure di precisione straordinaria



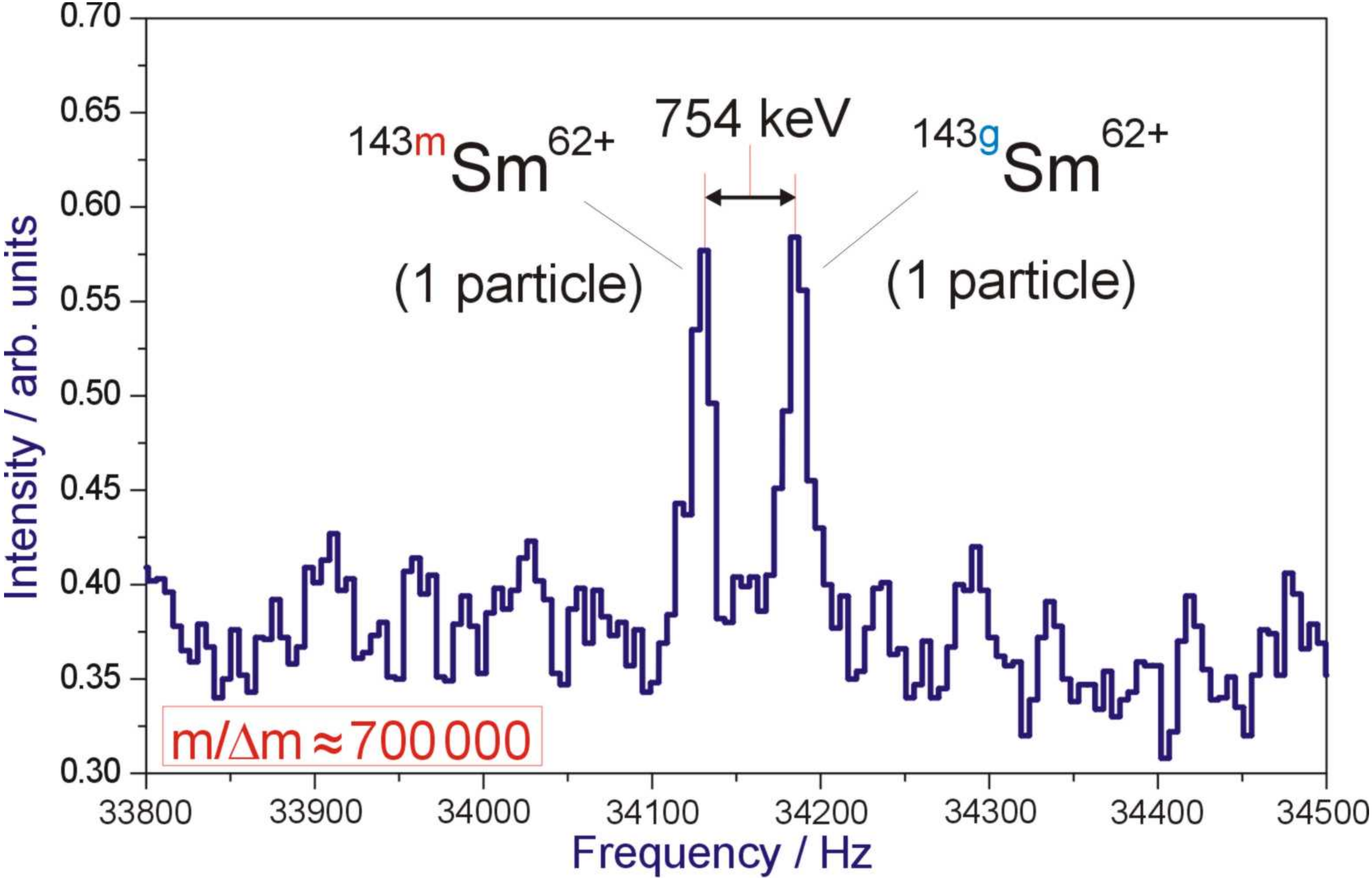
Nuclear decays in a storage ring



EC, β+,β-, bound-state β, and IT decays
(ESR at GSI)

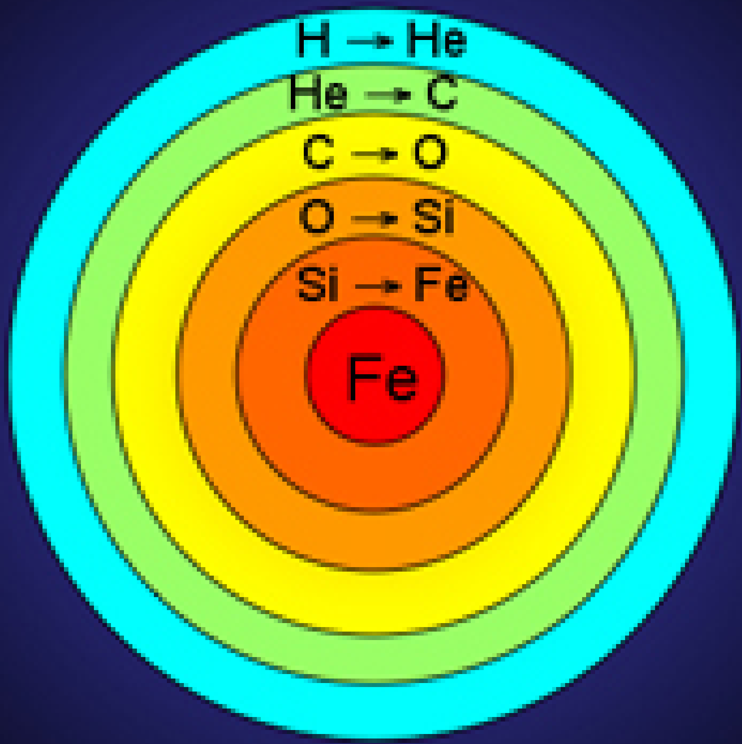
INFN

CSN3 Fisica Nucleare



$$m/\Delta m \approx 700\,000$$

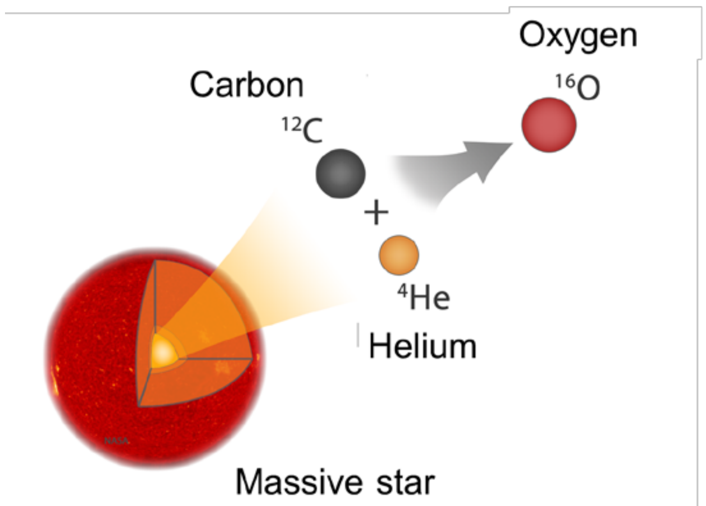
La vita di una stella



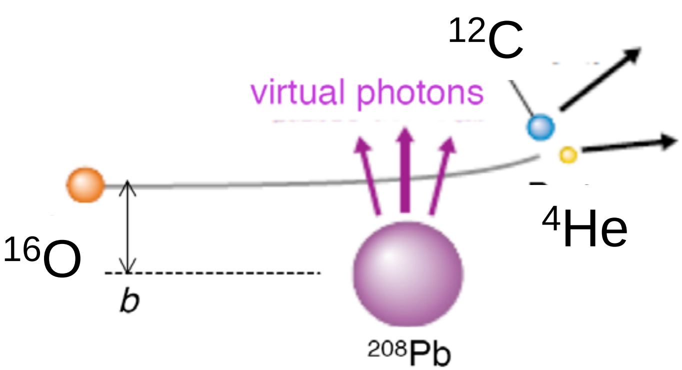
For a 25 solar mass star:

Stage	Duration
H → He	7×10^6 years
He → C	7×10^5 years
C → O	600 years
O → Si	6 months
Si → Fe	1 day
Core Collapse	1/4 second

Dopo l´Elio: come la natura produce I mattoni della vita



la frequenza non e ben nota alle nergie rilevanti in astrofisica

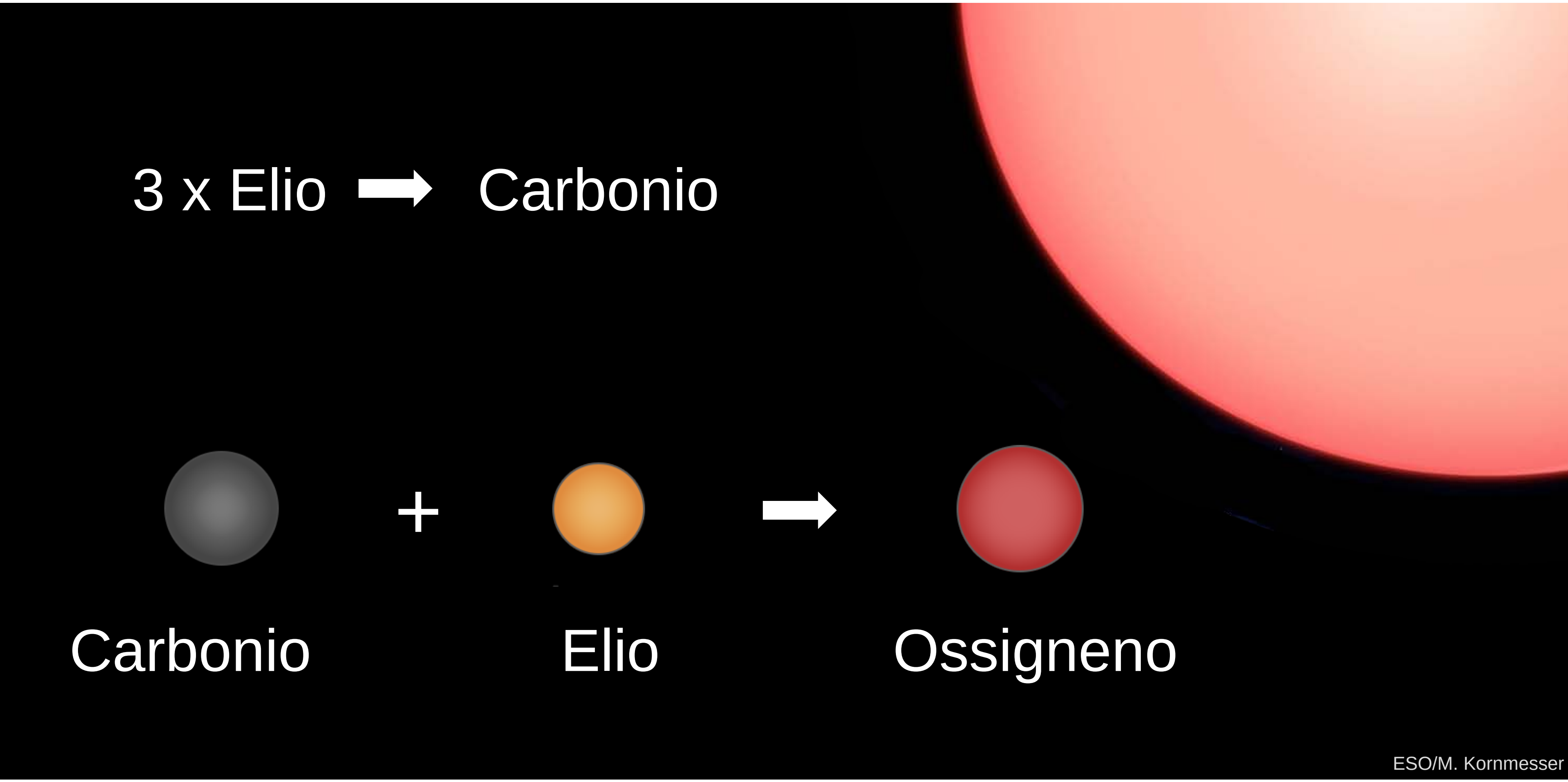


La fusione di particelle Alfa con ^{12}C è una reazione stellare di enorme importanza

W.A. Fowler, Nobel lecture 1983

Ci sono voluti 40 anni…

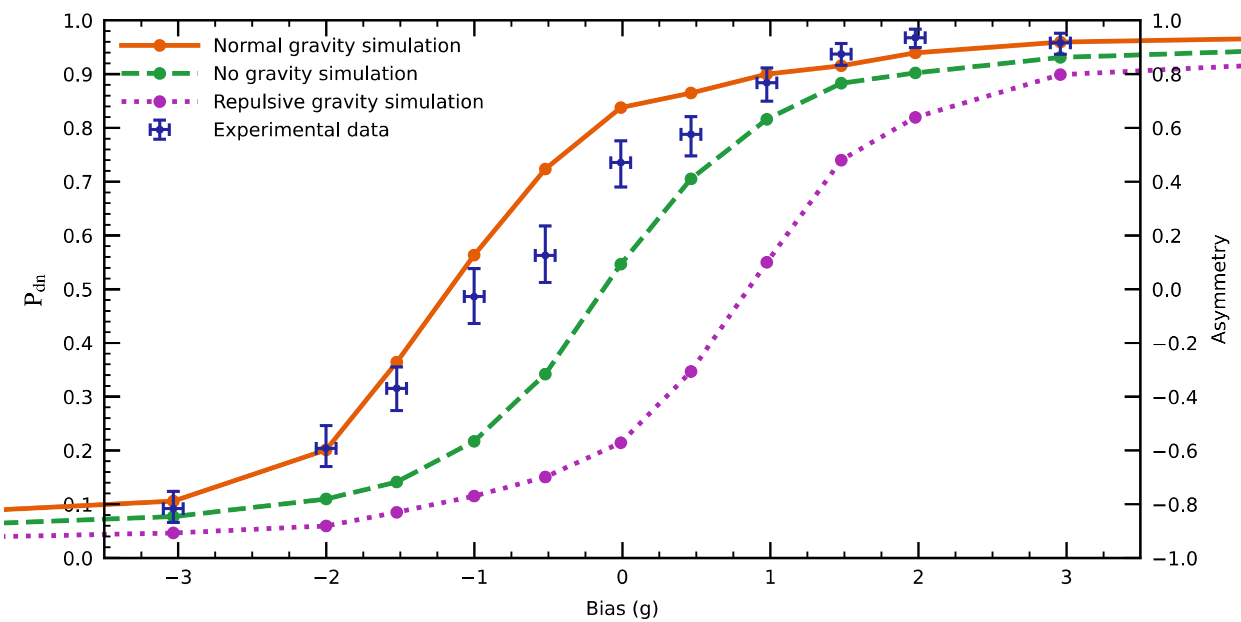
Reazioni di fusione nelle giganti rosse



Gravity on antihydrogen

ALPHA-g experiment at the AD/Elena facility at CERN

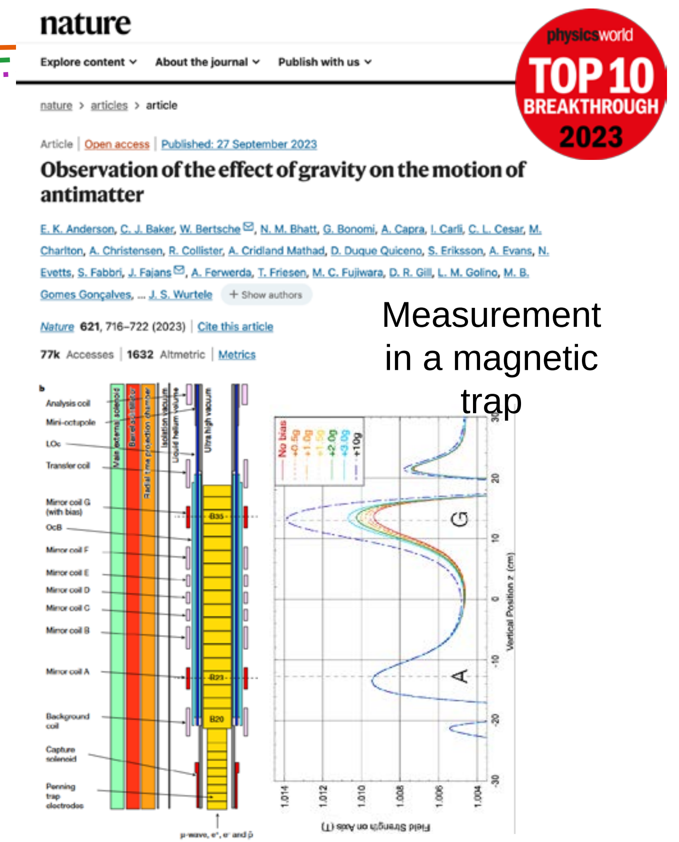
First measurement of the antihydrogen behavior
in the gravitational field of the Earth



$$a_{\bar{g}} = (0{,}75 \pm 0{,}13\ \text{(stat. + syst.)} \pm 0{,}16\ \text{(simulation)}) \cdot g$$

where $g = 9{,}81\ \text{m/s}^2$

Repulsive interaction is excluded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Observation of the effect of gravity on the motion of antimatter

E. K. Anderson, C. J. Baker, W. Bertsche, N. M. Bhatt, G. Bonomi, A. Capra, I. Carli, C. L. Cesar, M. Charlton, A. Christensen, R. Collister, A. Cridland Mathad, D. Duque Quiceno, S. Eriksson, A. Evans, N. Evetts, S. Fabbri, J. Fajans, A. Ferwerda, T. Friesen, M. C. Fujiwara, D. R. Gill, L. M. Golino, M. B. Gomes Gonçalves, ... J. S. Wurtele + Show authors

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Measurement in a magnetic trap