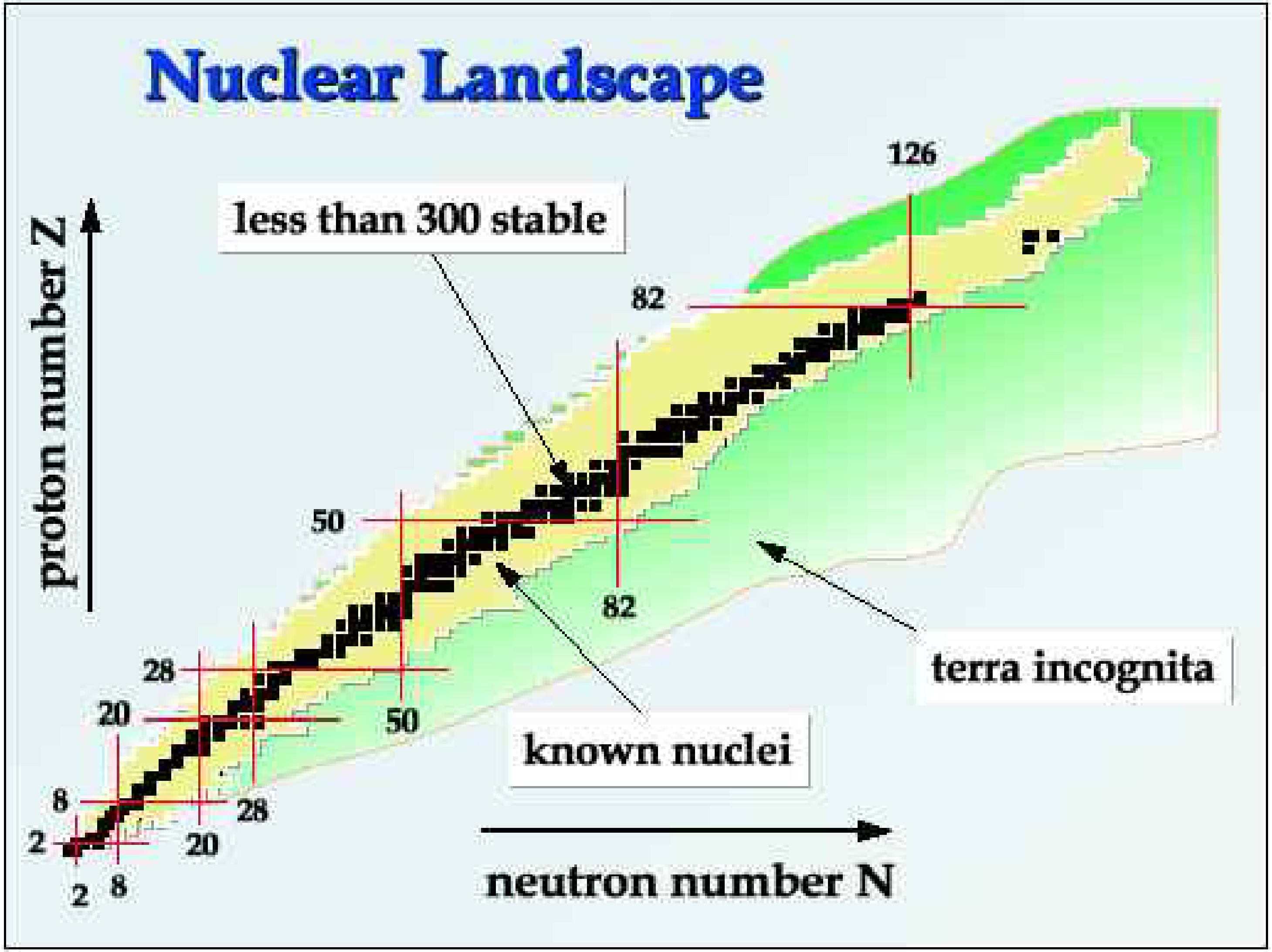
Атомните ядра:
основни градивни клетки на материята и гориво на звездите

- **Основни задачи пред съвременната ядрената физика**

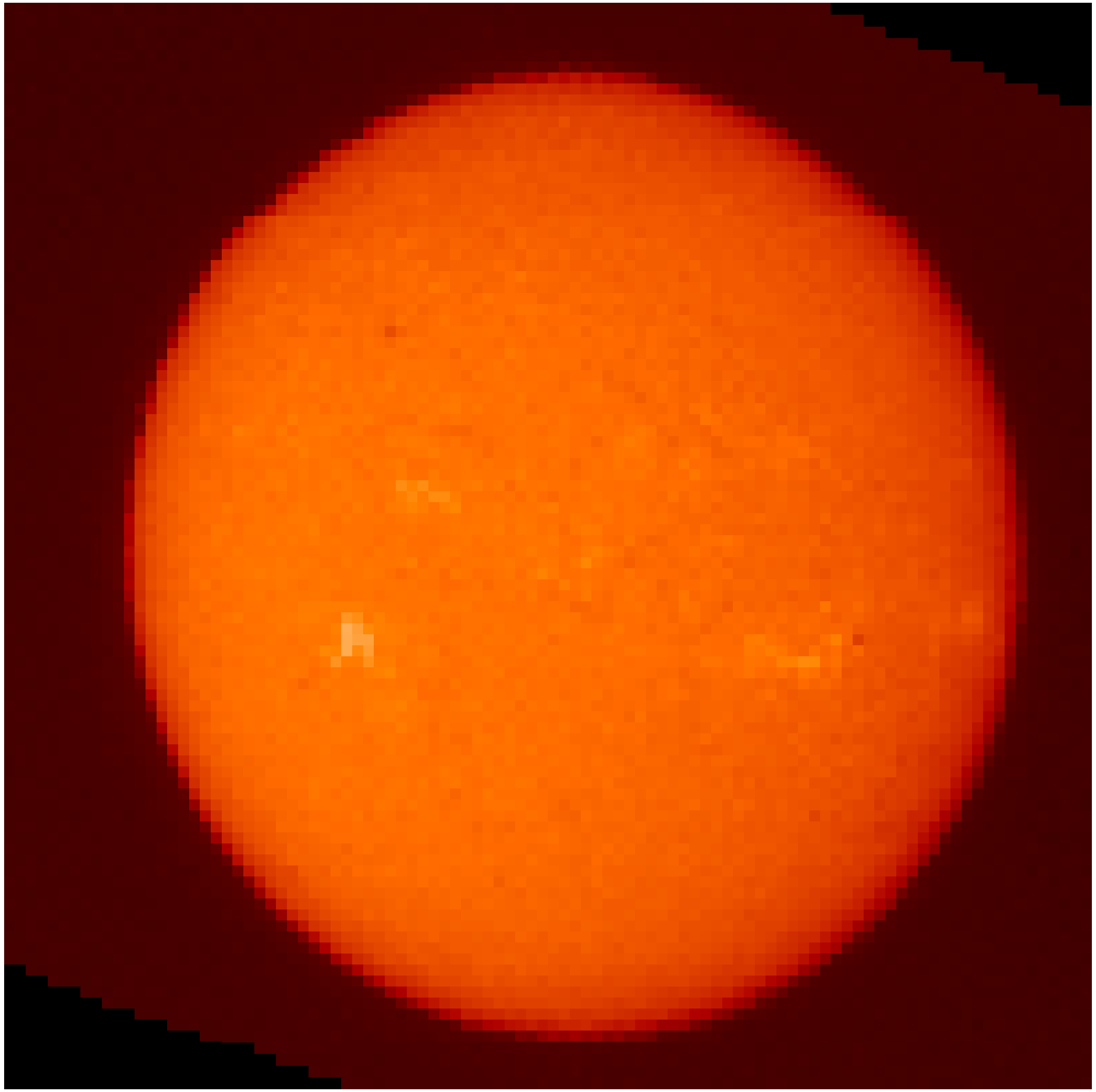
- **Експериментът ИЗОЛДЕ в ЦЕРН: история, резултати, бъдеще**

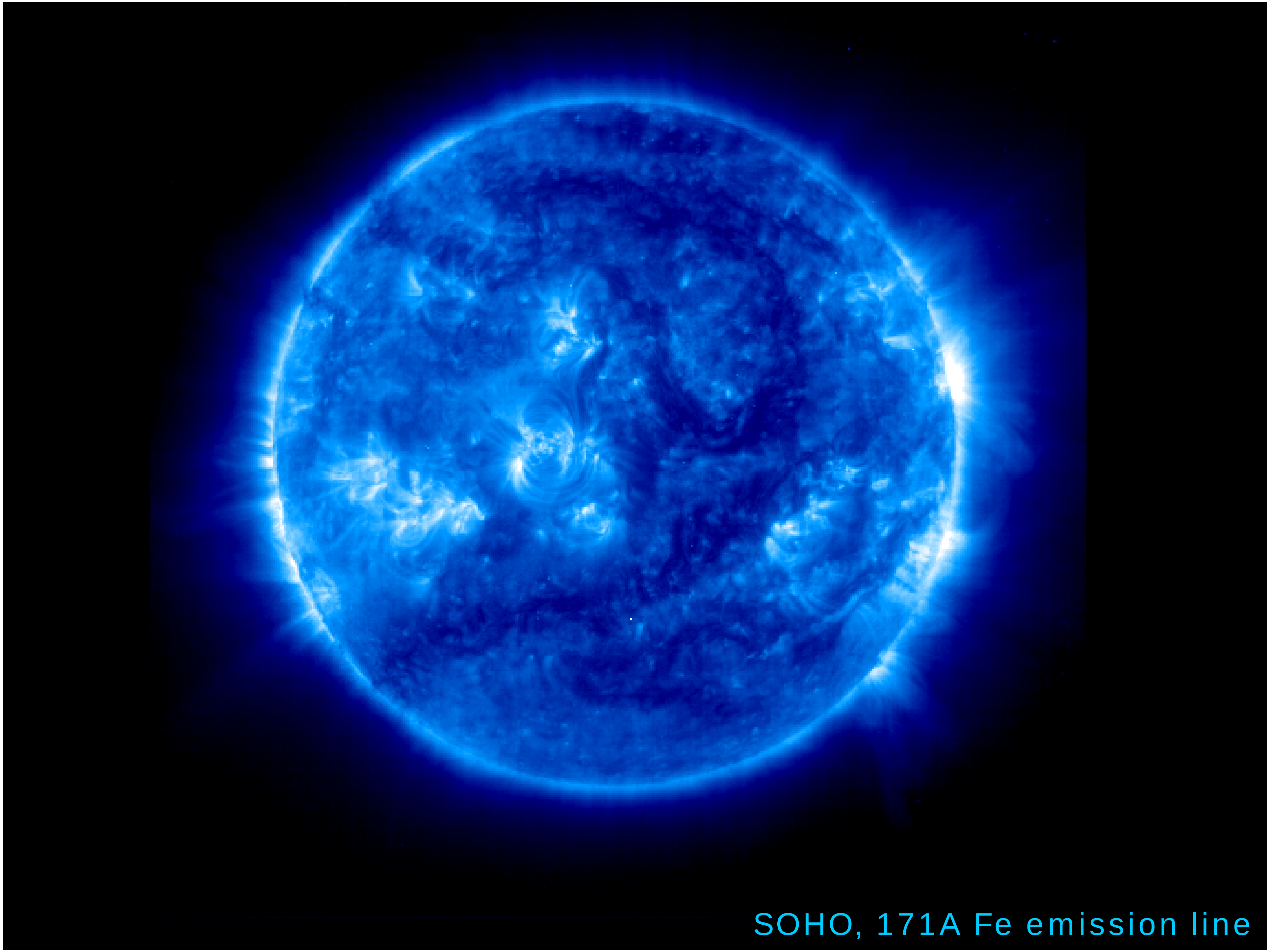
- **Българско участие на ИЗОЛДЕ: постижения и перспективи**



Различни експериментални подходи са необходими за изследване на ядра с различни N и Z. За целта са необходими ускорители работещи в различен режим.

The sun shines 3.85e33 erg/s = 3.85e26 Watts for at least ~4.5 bio years




SOHO, 171A Fe emission line

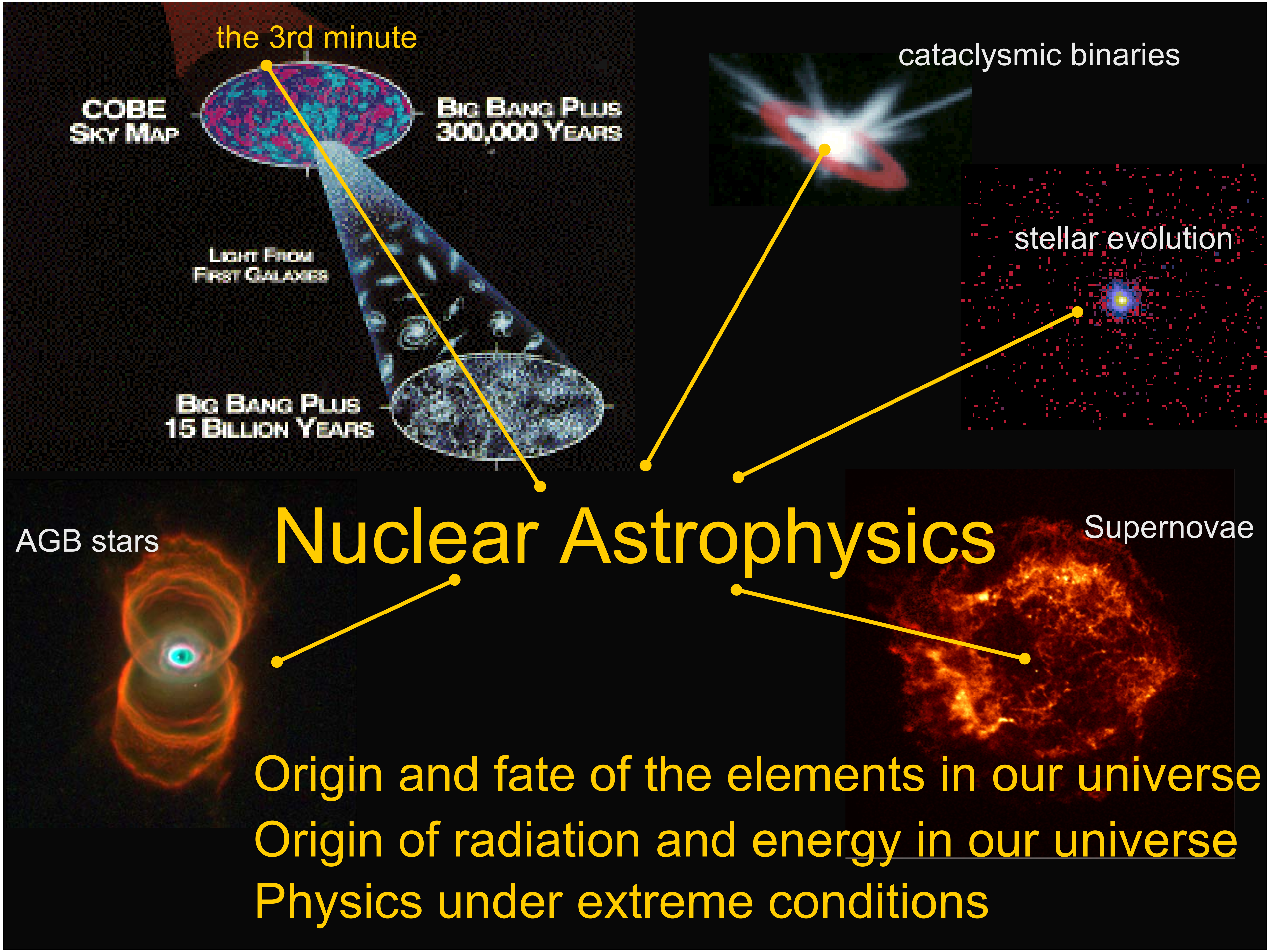
… and its all nuclear physics:

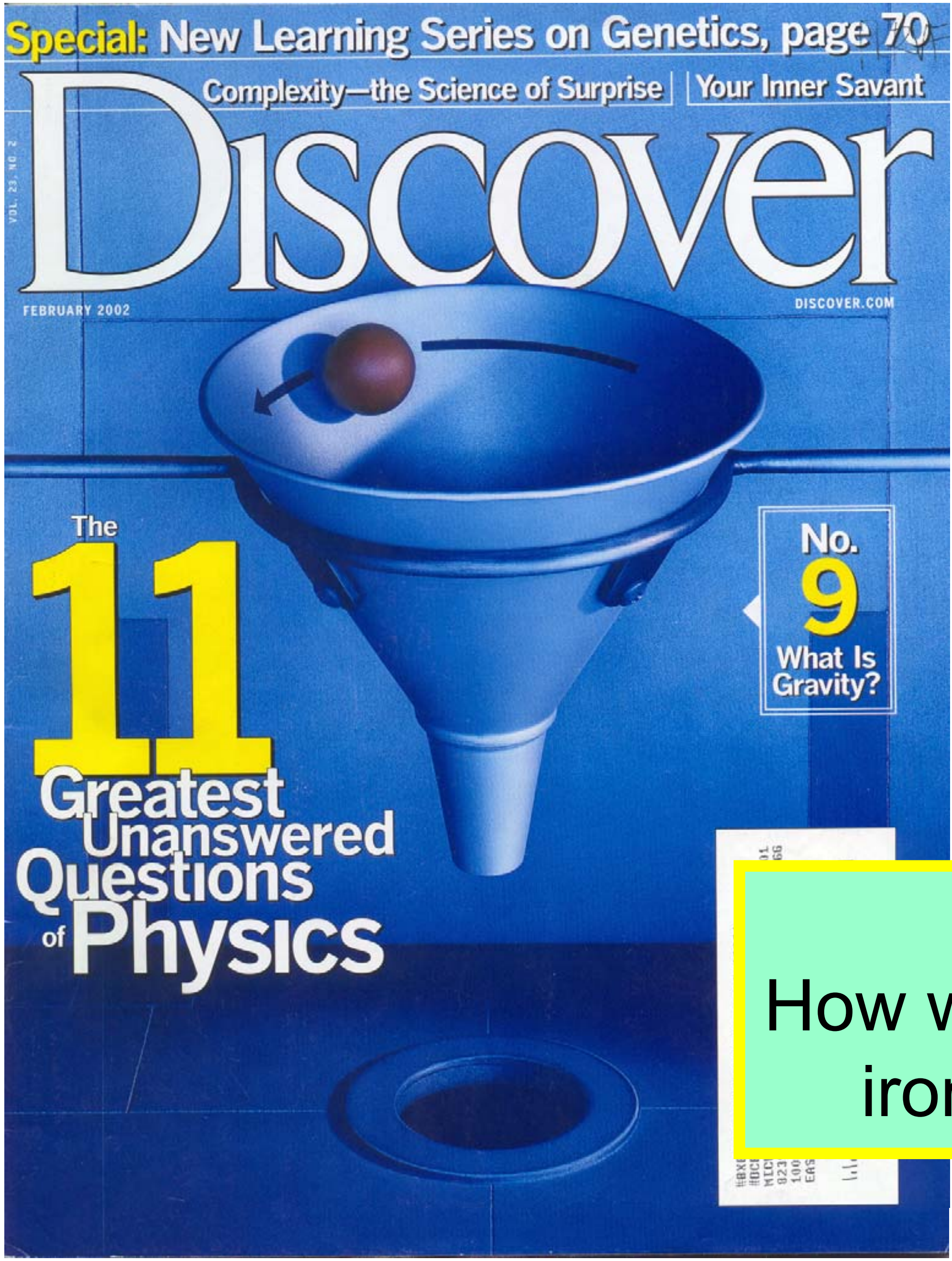
- 1905 Einstein finds $E=mc^2$
- 1920 Aston measures mass defect of helium (α = 4p's)
- 1920 Nuclear Astrophysics is born with Sir Arthur Eddington remarks in his presidential address to the British Association for the Advancement of Science:

> "Certain physical investigations in the past year make it probable to my mind that some portion of sub-atomic energy is actually set free in the stars … If only five percent of a star's mass consists initially of hydrogen atoms which are gradually being combined to form more complex elements, the total heat liberated will more than suffice for our demands, and we need look no further for the source of a star's energy"

> "If, indeed, the sub-atomic energy in the stars is being freely used to maintain their great furnaces, it seems to bring a little nearer to fulllment our dream of controlling this latent power for the well-being of the human race|or for its suicide."

In a 1938 paper, Dr. Bethe explained how stars like the Sun fuse hydrogen into helium, releasing energy and ultimately light. That work helped establish his reputation as the father of nuclear astrophysics, and nearly 30 years later, in 1967, earned him the Nobel Prize in physics.


the 3rd minute
COBE
Sky Map
Big Bang Plus
300,000 Years
Light From
First Galaxies
Big Bang Plus
15 Billion Years
cataclysmic binaries
stellar evolution
AGB stars
Nuclear Astrophysics
Supernovae
Origin and fate of the elements in our universe
Origin of radiation and energy in our universe
Physics under extreme conditions



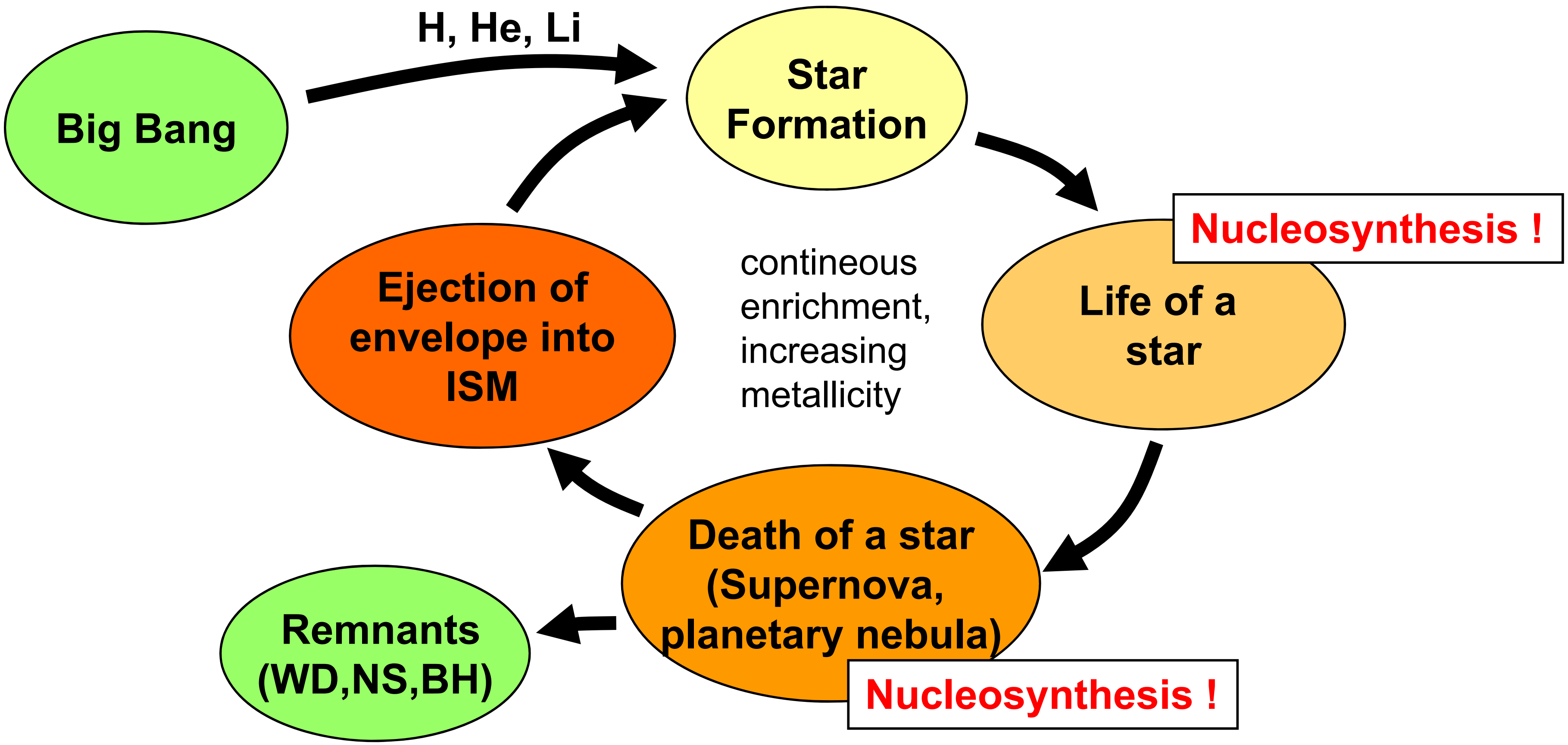
Доклад на Националната академия на науките на САЩ

Комисия по физика на Вселената (CPU)

Question 3

How were the elements from iron to uranium made ?

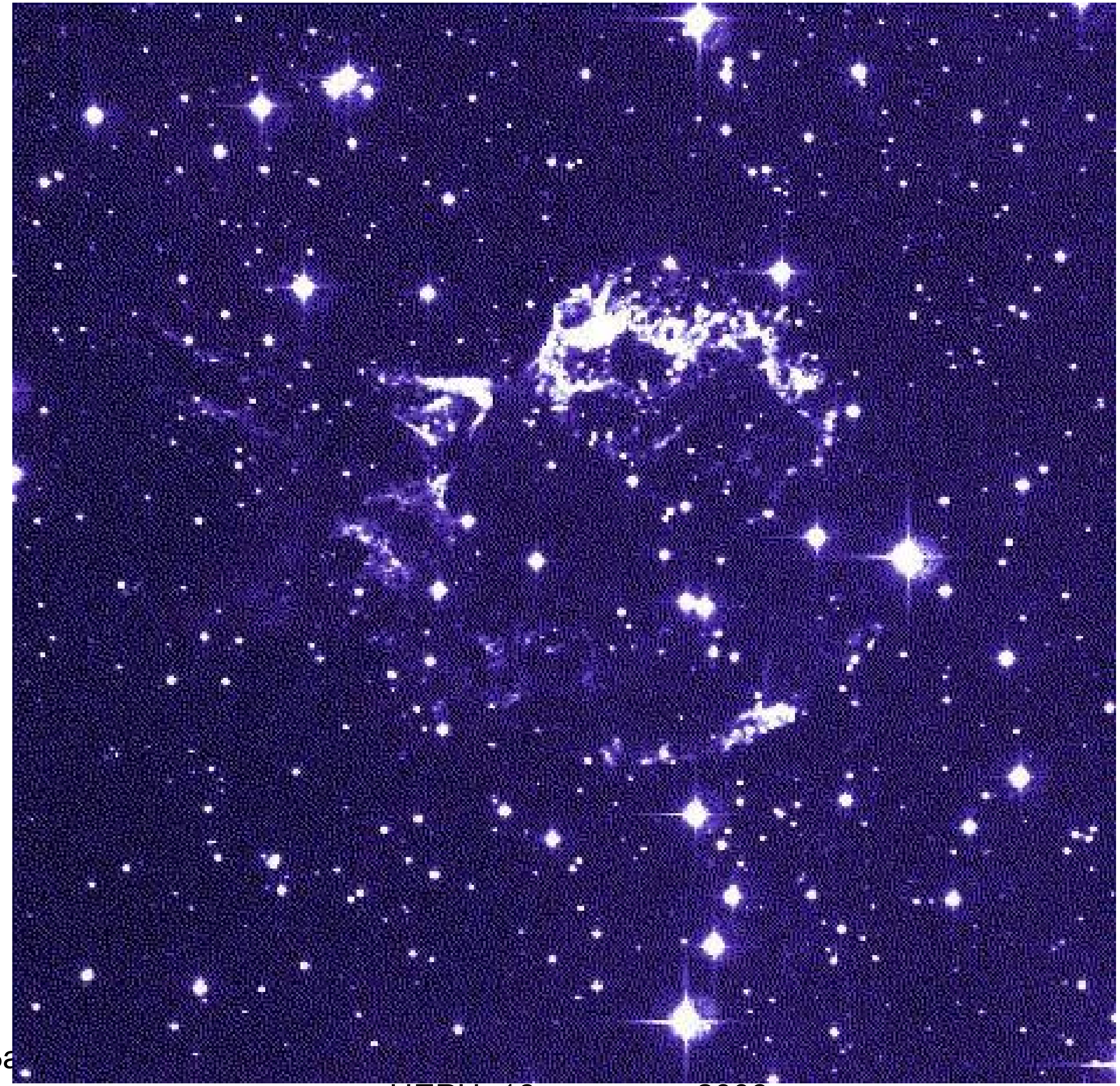
Nucleosynthesis is a gradual, still ongoing process:

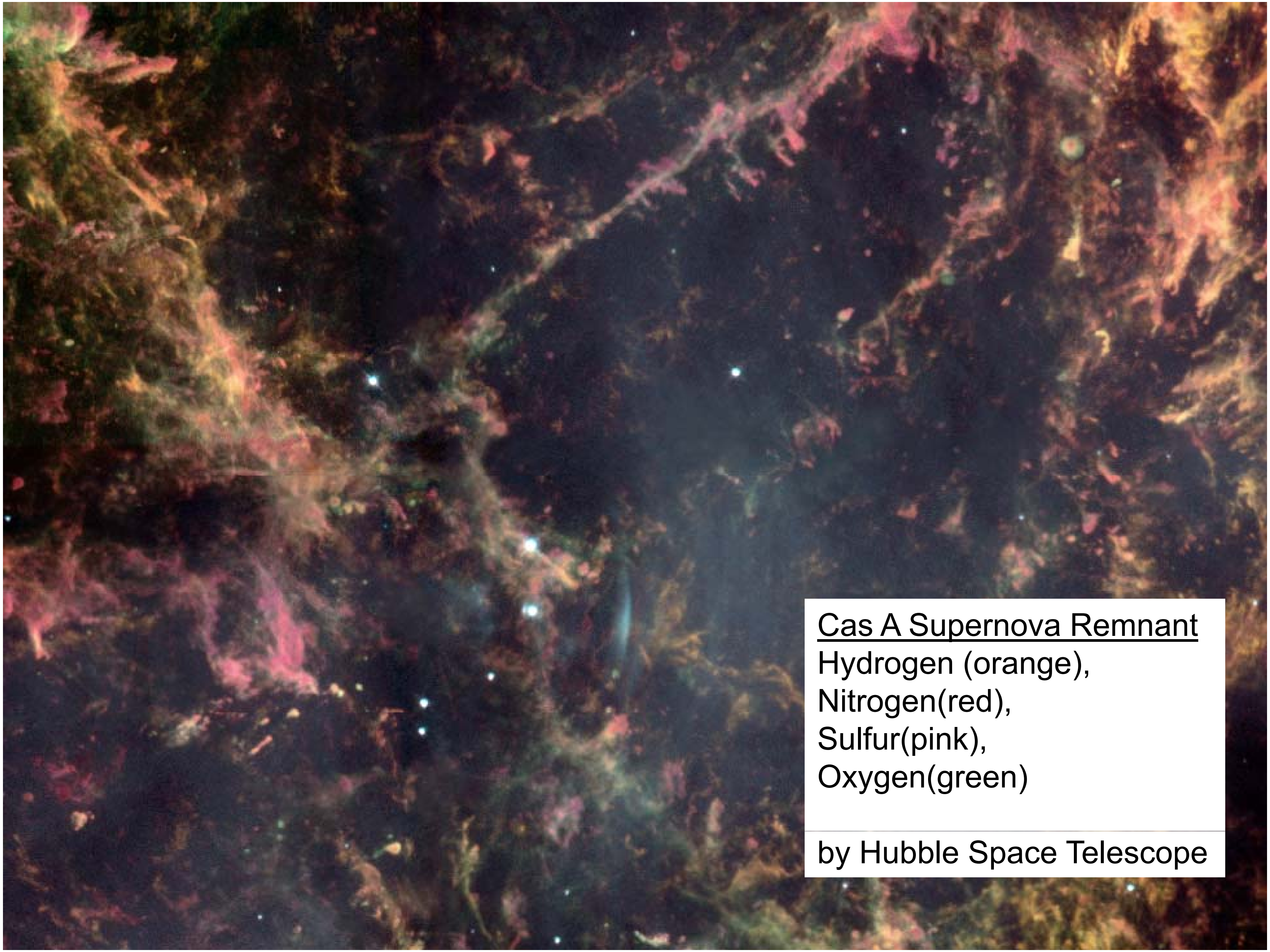


BH: Black Hole
NS: Neutron Star
WD: White Dwarf Star
ISM Interstellar Medium

(b) Supernova remnants - where freshly synthesized elements got ejected

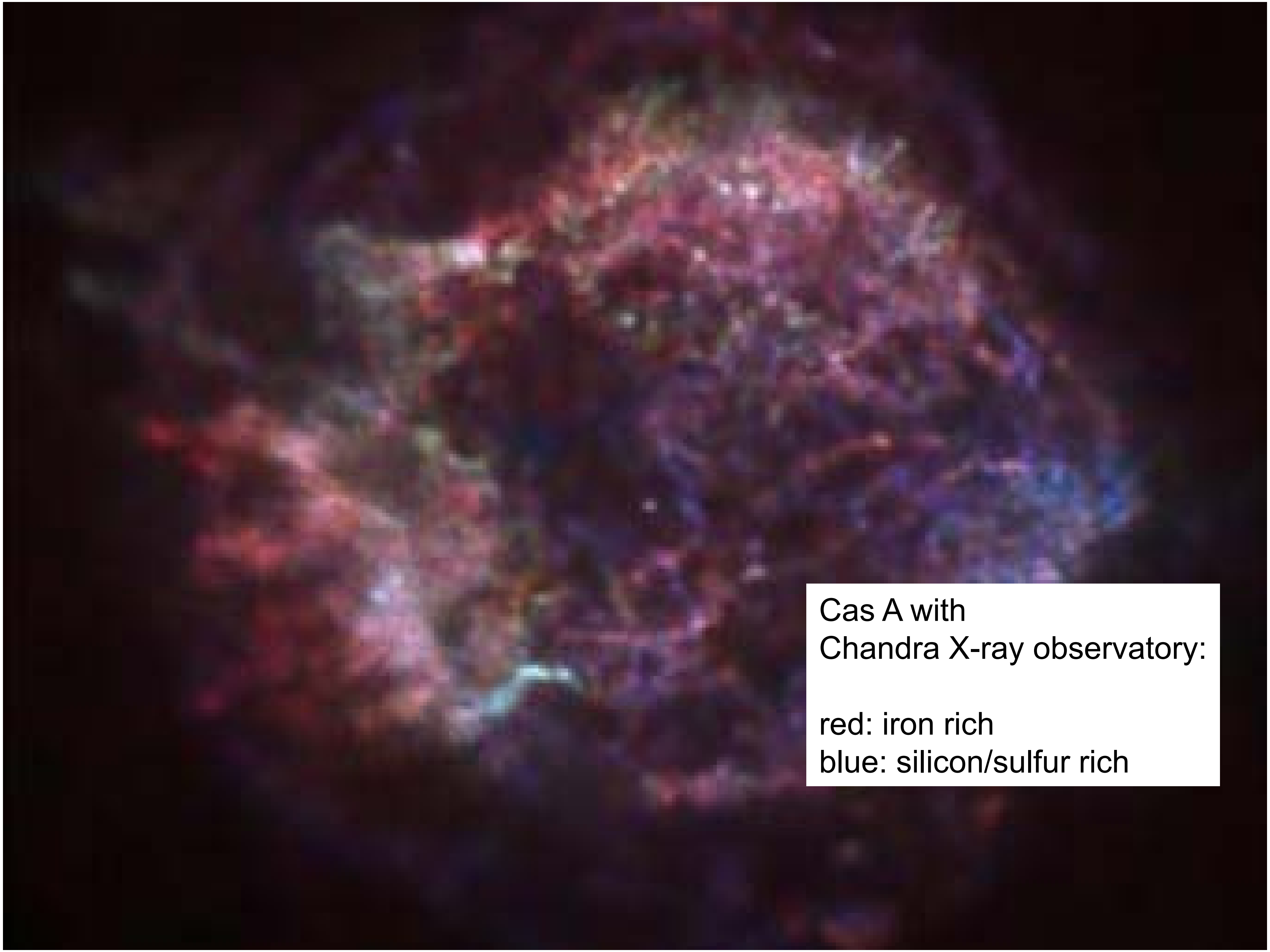
Cas A:





Cas A Supernova Remnant
Hydrogen (orange),
Nitrogen(red),
Sulfur(pink),
Oxygen(green)

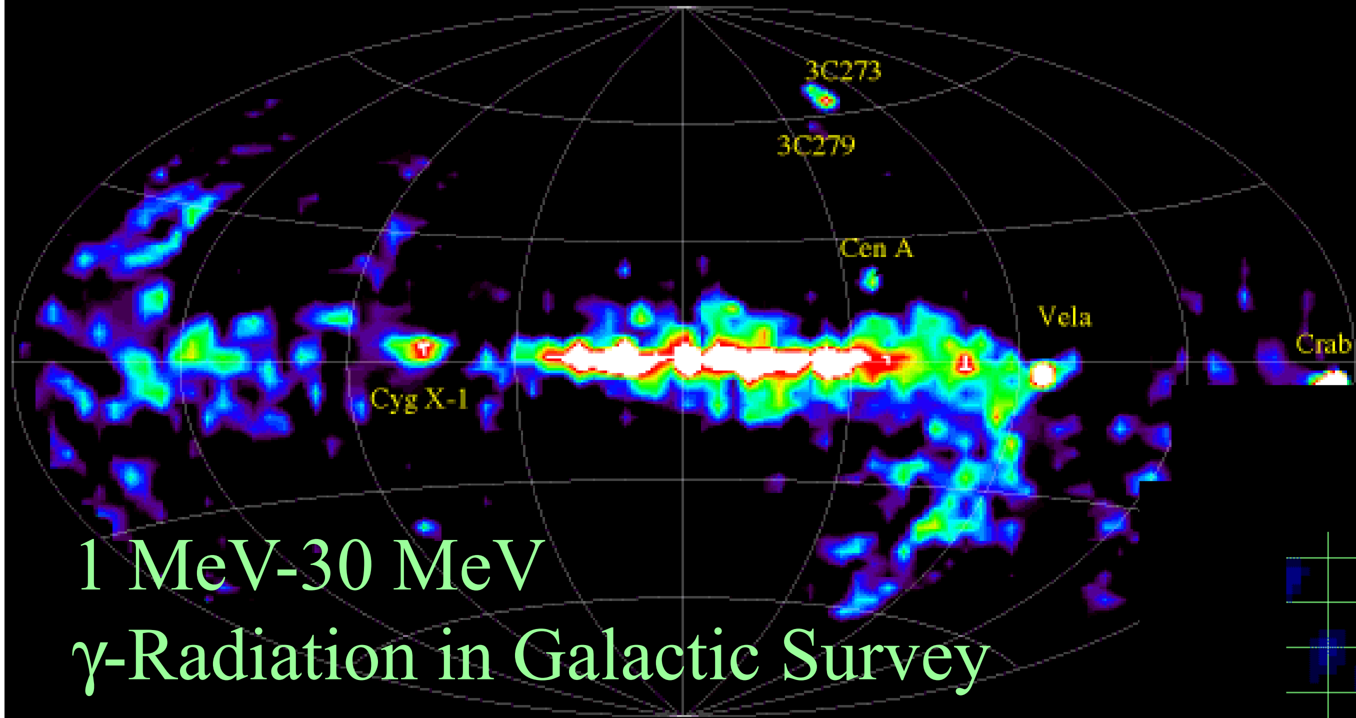
by Hubble Space Telescope



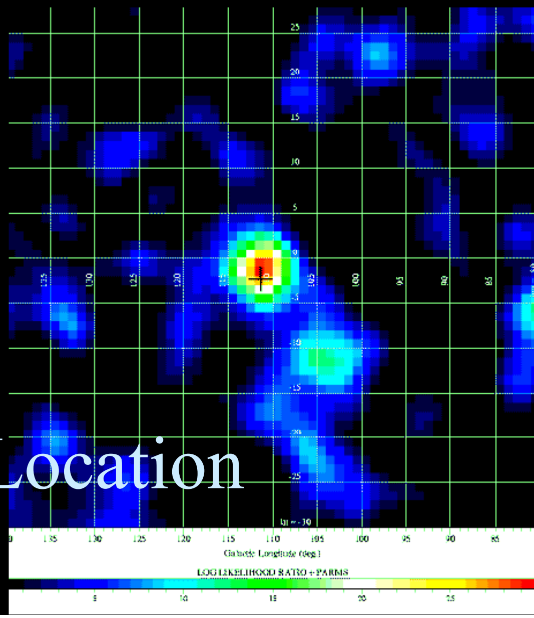
Cas A with
Chandra X-ray observatory:

red: iron rich
blue: silicon/sulfur rich

Galactic Radioactivity - detected by γ-radiation



1 MeV-30 MeV
γ-Radiation in Galactic Survey
(^{26}Al Half life: 700,0000 years)



^{44}Ti in Supernova Cas-A Location
(Half life: 60 years)

Abundances – The Composition of the Universe

Before answering the question of the origin of the elements we want to see what elements are actually there - in other words

What is the Universe made of ? - Answer: We have no clue ….

60% Dark Energy (don't know what it is)
35% Cold dark matter (don't know what it is)
5% Nuclei and electrons (visible as stars ~0.5%)

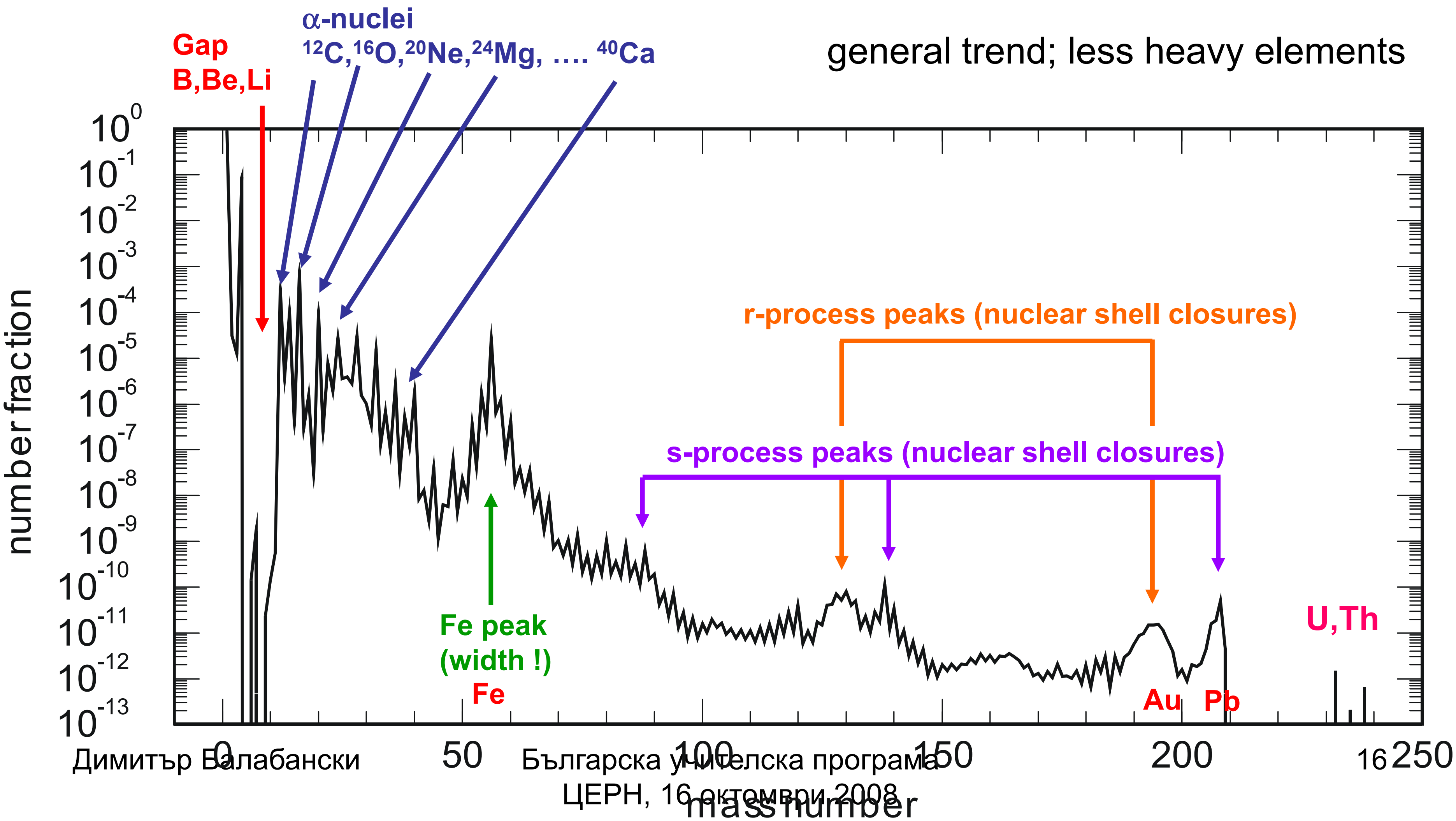
Why bother with 5% ???

Important things are made of it:

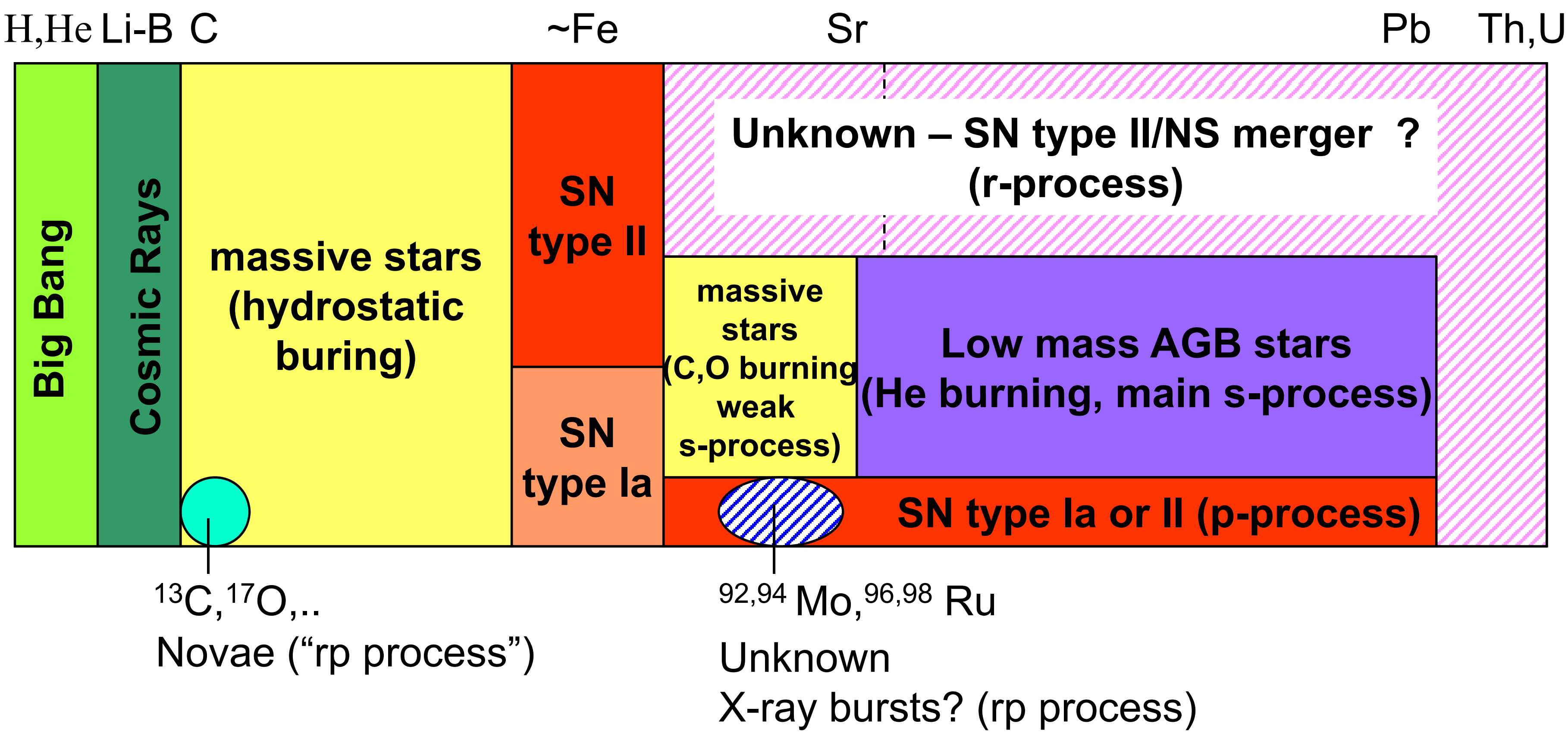
Questions to be answered:

- What kind of nuclei (nuclides) is the universe made of ?
- How abundant is each element ? Each nuclide ?

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

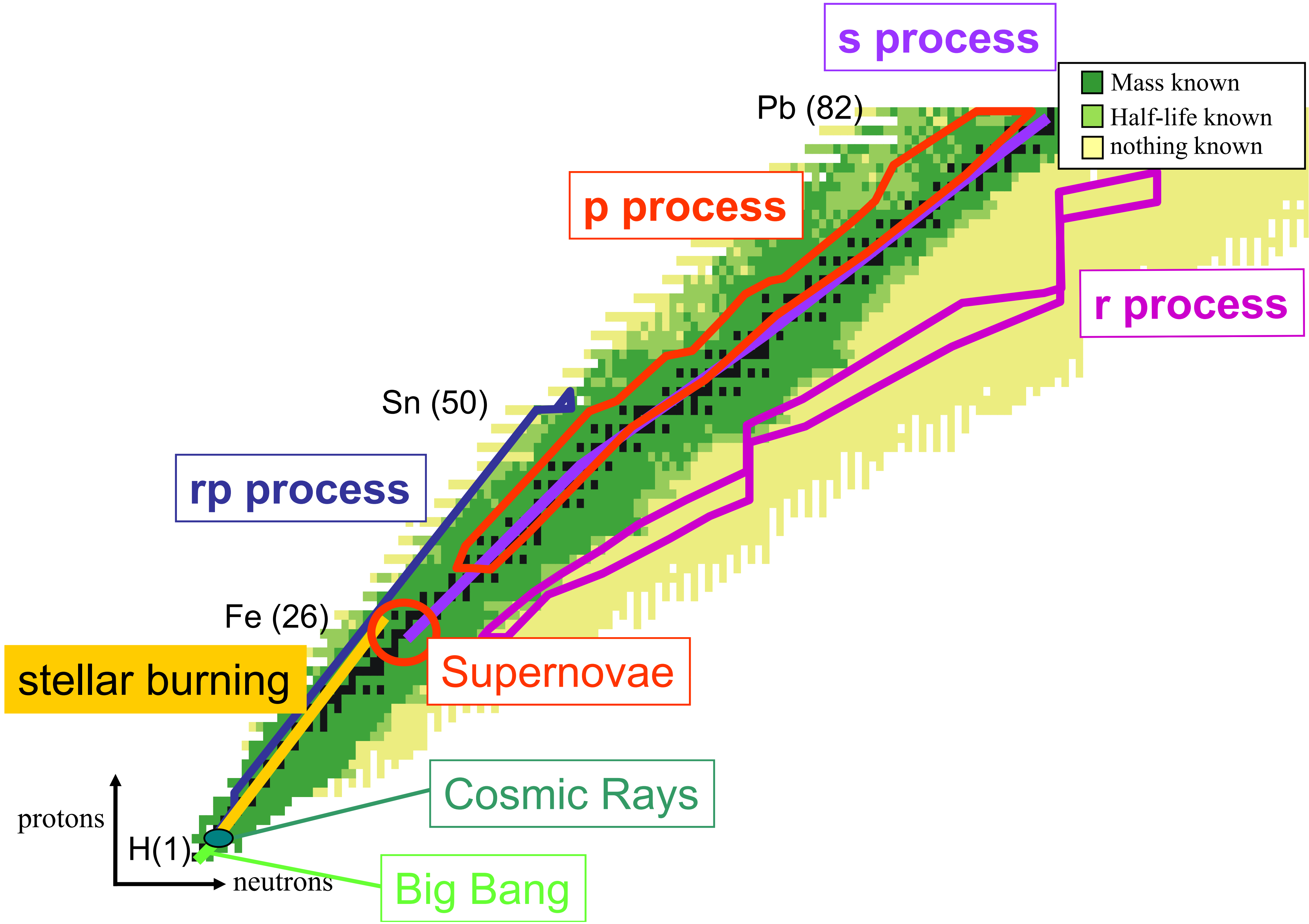


The Origin of the Elements



Possible type II SN (ν-process) contribution to ….

Note: yellow-red all related to massive stars (>8-12 solar masses at ZAMS)


s process
Mass known
Half-life known
nothing known
Pb (82)
p process
r process
Sn (50)
rp process
Fe (26)
Supernovae
stellar burning
Cosmic Rays
protons
H(1)
neutrons
Big Bang

Summary pp-chains:

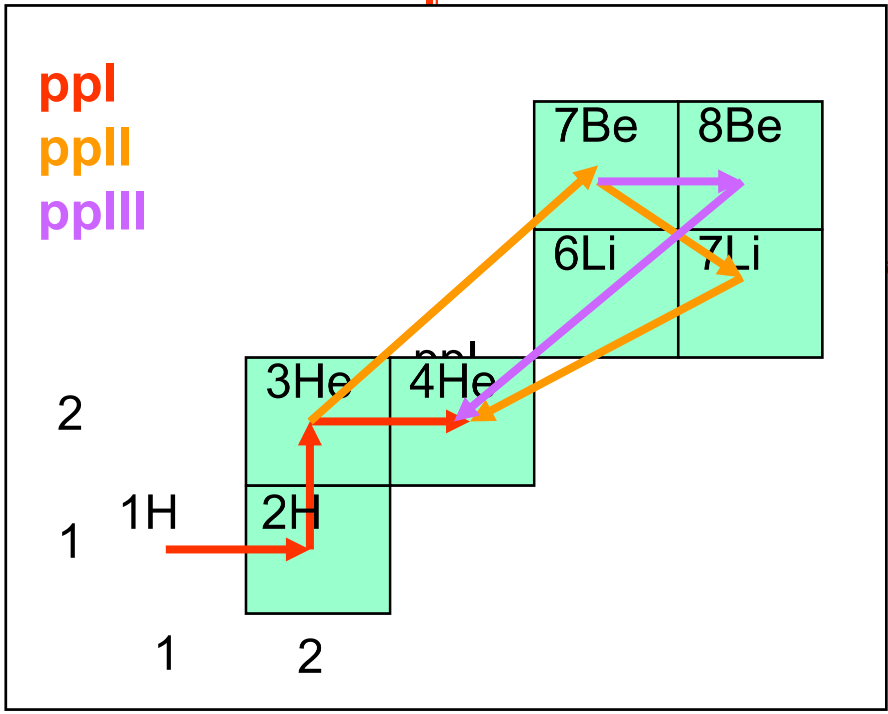
$p(p,e^+\nu)d$

$d(p,\gamma)^3He$

86% → $^3He(^3He,2p)^4He$

14% → $^3He(\alpha,\gamma)^7Be$

- 14% → $Be(e^-,\nu)^7Li$, $^7Li(p,\alpha)^4He$
- 0.02% → $^7Be(p,\gamma)^8B$, $^8B(e^+,\nu)^8Be$, $^8Be(\alpha)^4He$



Why do additional pp chains matter ?

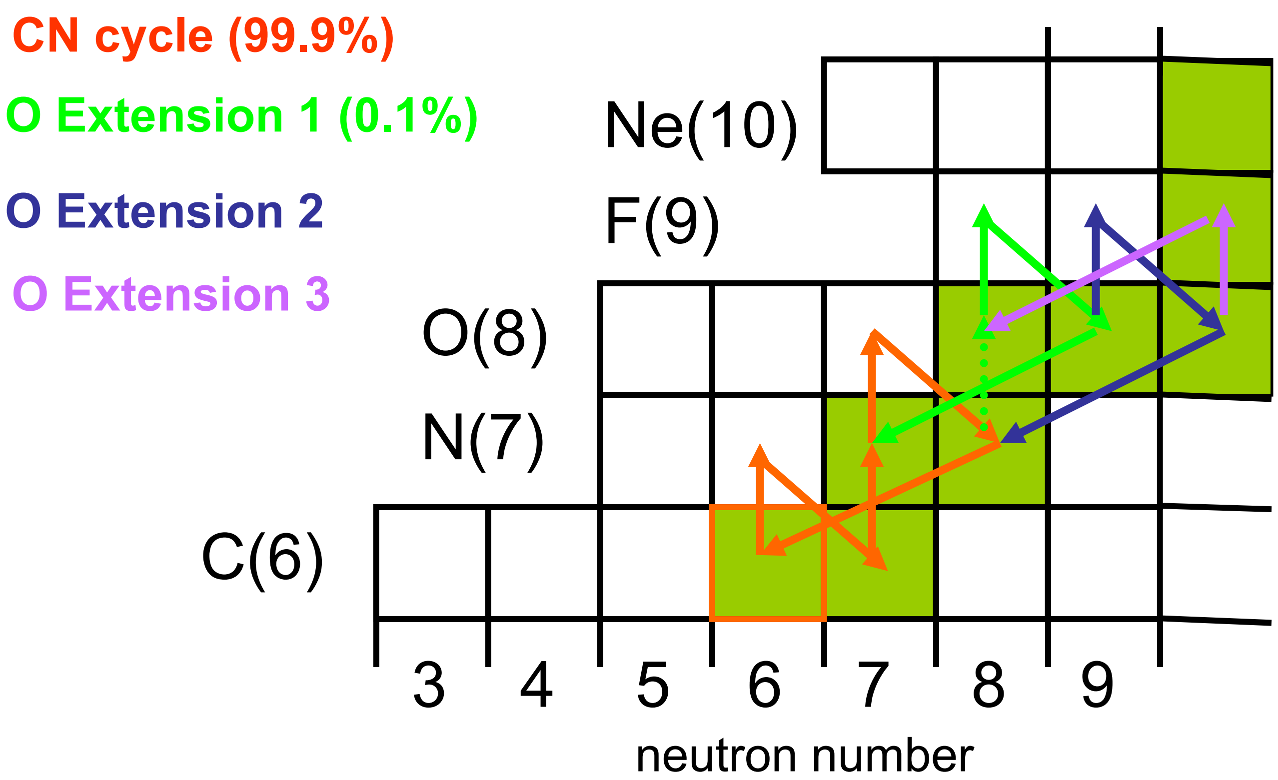
p+p dominates timescale BUT

ppI produces 1/2 ^{4}He per p+p reaction

ppI+II+III produces 1 ^{4}He per p+p reaction

⟶ **double burning rate**

CNO cycle



All initial abundances within a cycle serve as catalysts and accumulate at largest τ

Extended cycles introduce outside material into CN cycle (Oxygen, …)

Hydrogen burning under extreme conditions

Scenarios:

- Hot bottom burning in massive AGB stars (> 4 solar masses)

  ($T_9 \sim 0.08$)

- Nova explosions on accreting white dwarfs

  ($T_9 \sim 0.4$)

- X-ray bursts on accreting neutron stars

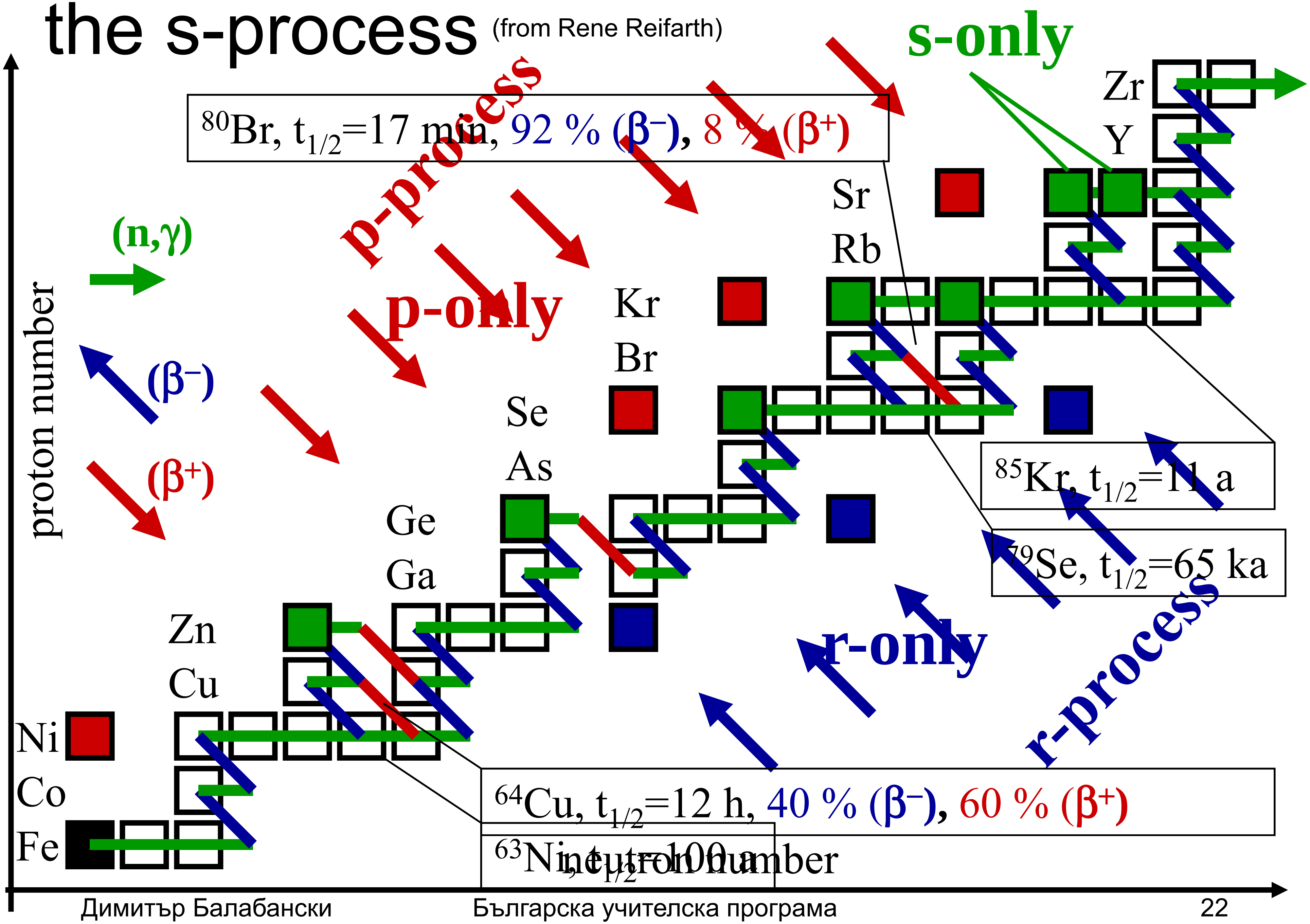
  ($T_9 \sim 2$)

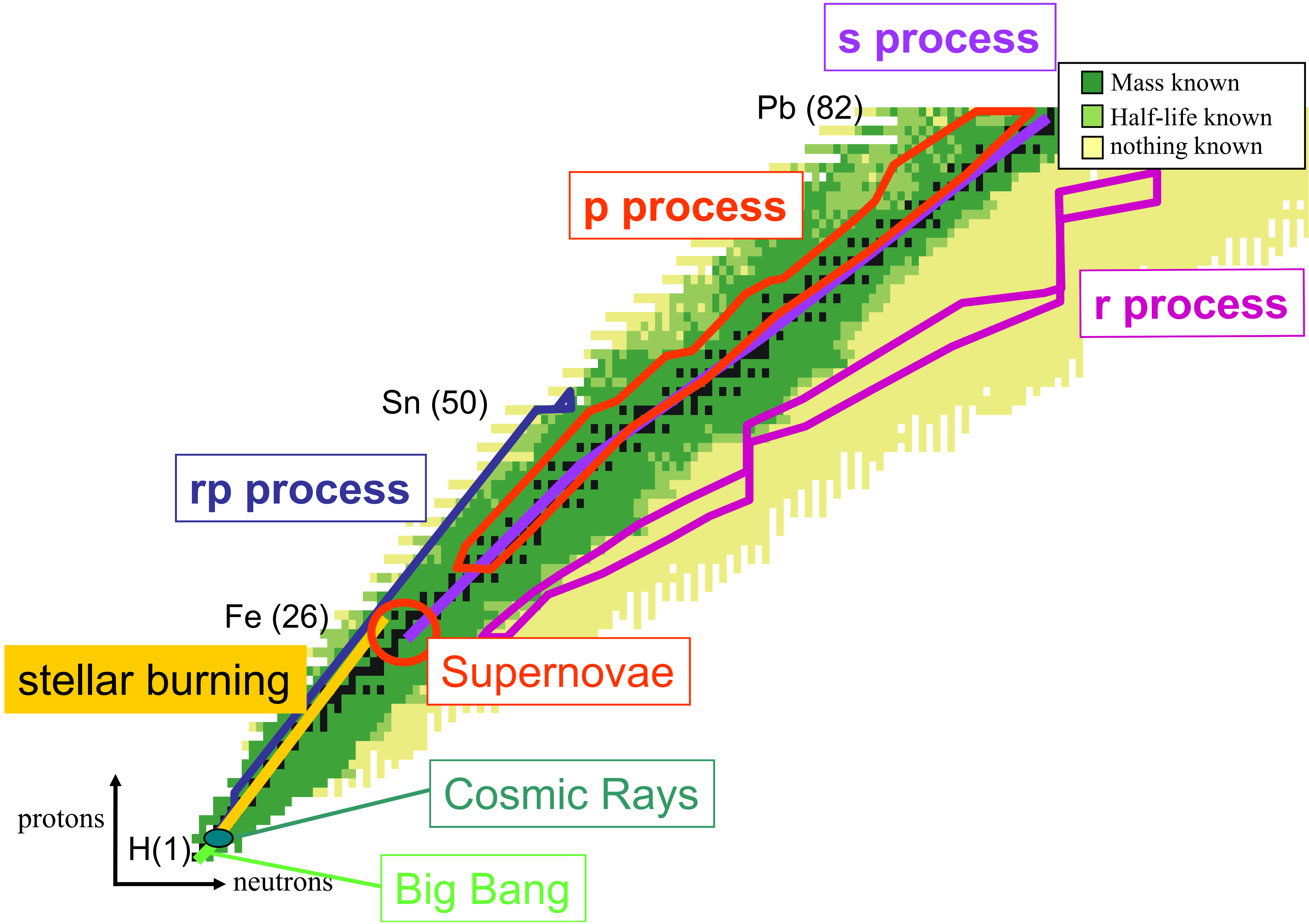
- accretion disks around low mass black holes ?

- neutrino driven wind in core collapse supernovae ?

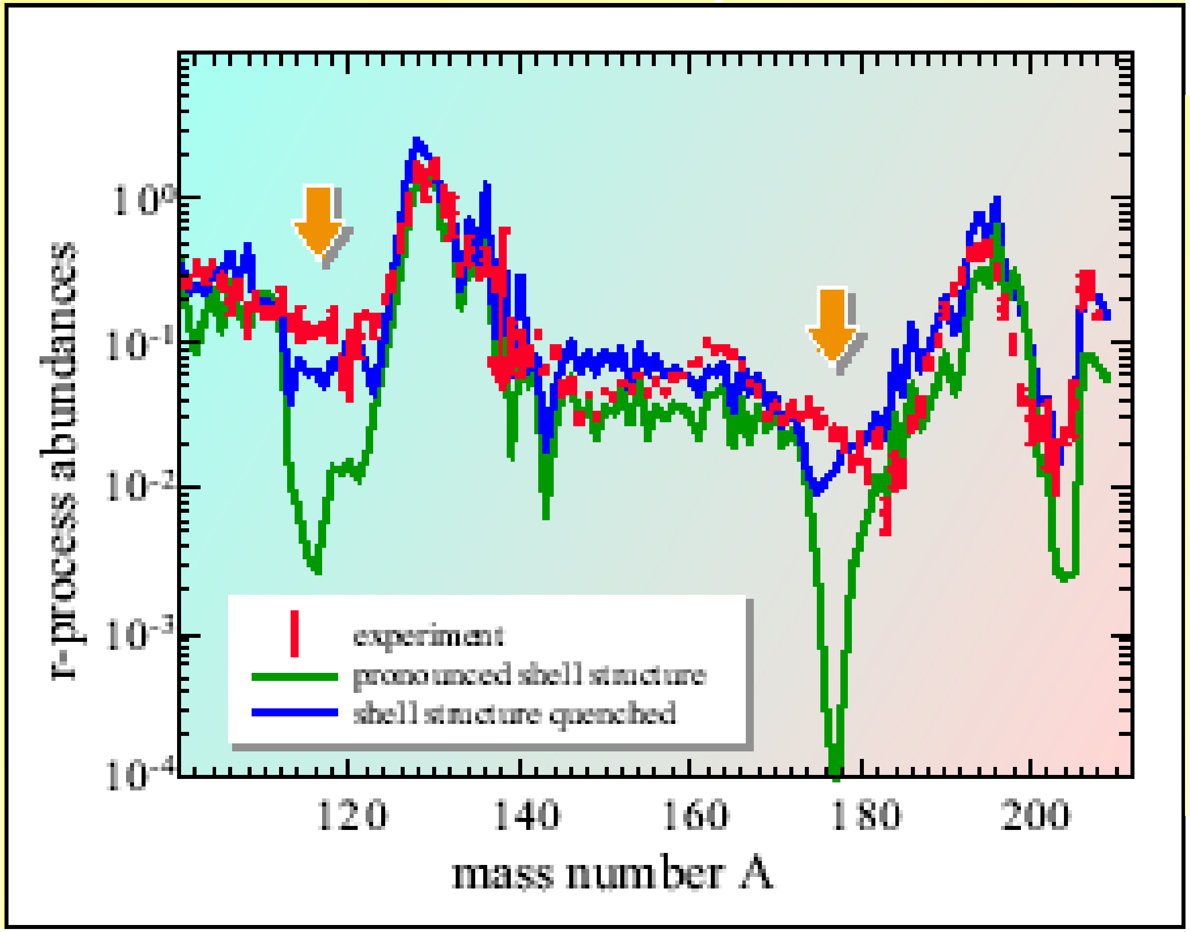
further discussion assumes a density of 10^6 g/cm^3 (X-ray burst conditions)

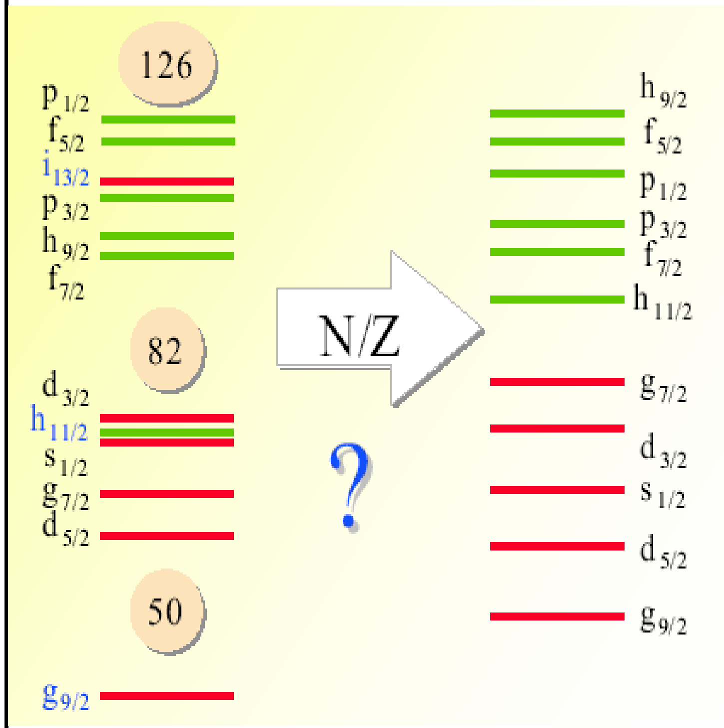
the s-process (from Rene Reifarth)

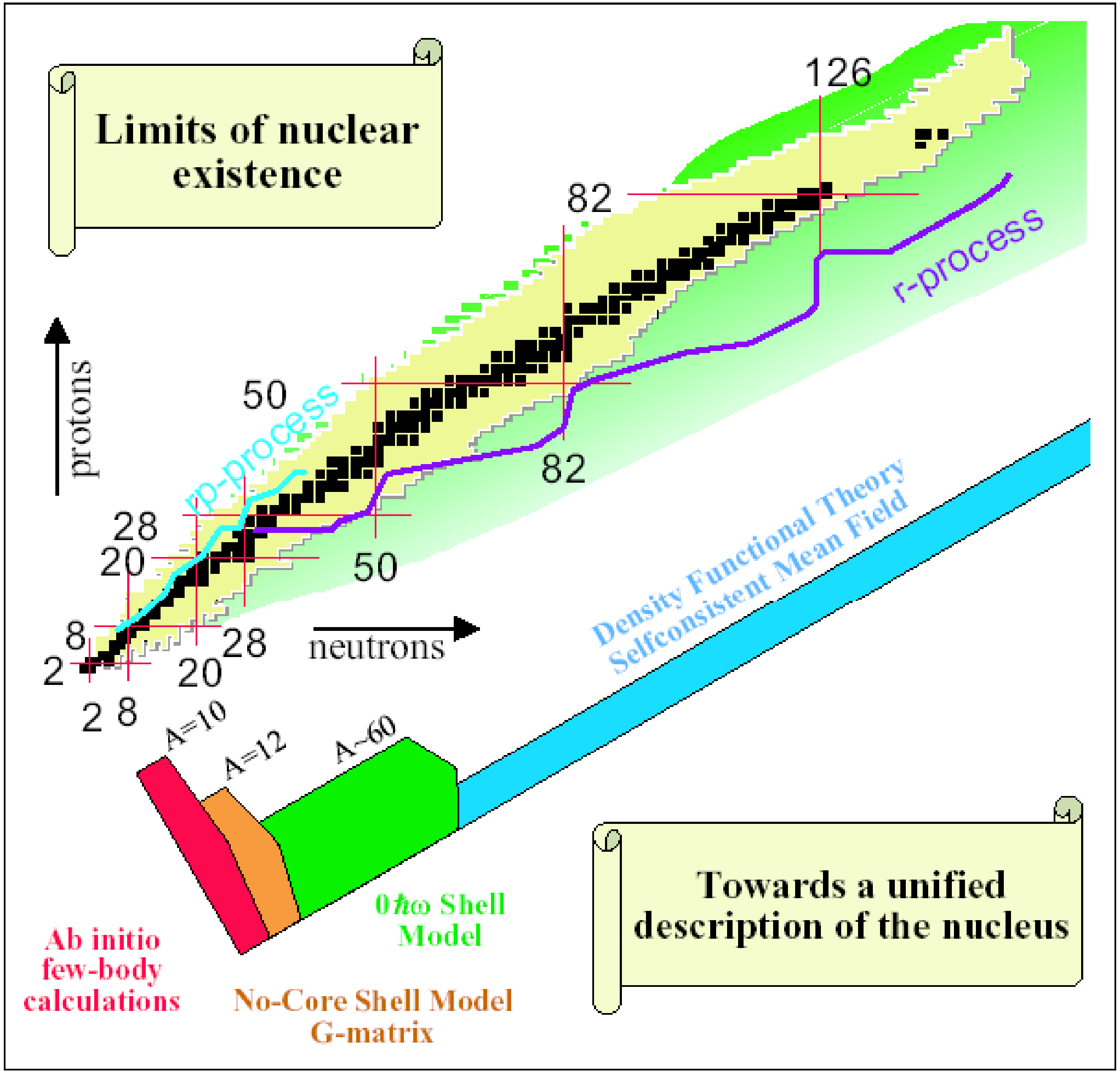



s process
Mass known
Half-life known
nothing known
Pb (82)
p process
r process
Sn (50)
rp process
Fe (26)
stellar burning
Supernovae
Cosmic Rays
protons
H(1)
neutrons
Big Bang

Ядрена астрофизика:
Дали наистина сме наясно с процеса на синтез на елементите ?





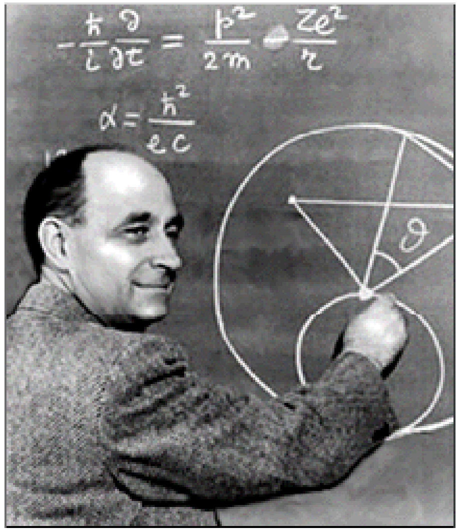


Limits of nuclear existence
126
82
50
28
20
8
2
2 8
20
28
50
82
protons
neutrons
rp-process
r-process
Density Functional Theory
Selfconsistent Mean Field
A=10
A=12
A~60
Ab initio
few-body
calculations
No-Core Shell Model
G-matrix
0ℏω Shell
Model
Towards a unified
description of the nucleus

Closed shells in nuclei

Maria Goeppert Mayer's 1948 theory explained why some nuclei were more stable than others and why some elements were rich in isotopes.

"On closed shells in nuclei" *Phys. Rev.* 74: 235 (1948).
"On closed shells in nuclei II" *Phys. Rev.* 75: 1969 (1949).
"Nuclear configurations in the spin-orbit coupling model.
I. Empirical evidence," *Phys. Rev.* 78: 16 (1950).
II. Theoretical considerations" *Phys. Rev.* 78: 22 (1950).



« Incidentally, is there any evidence of spin-orbit coupling? »

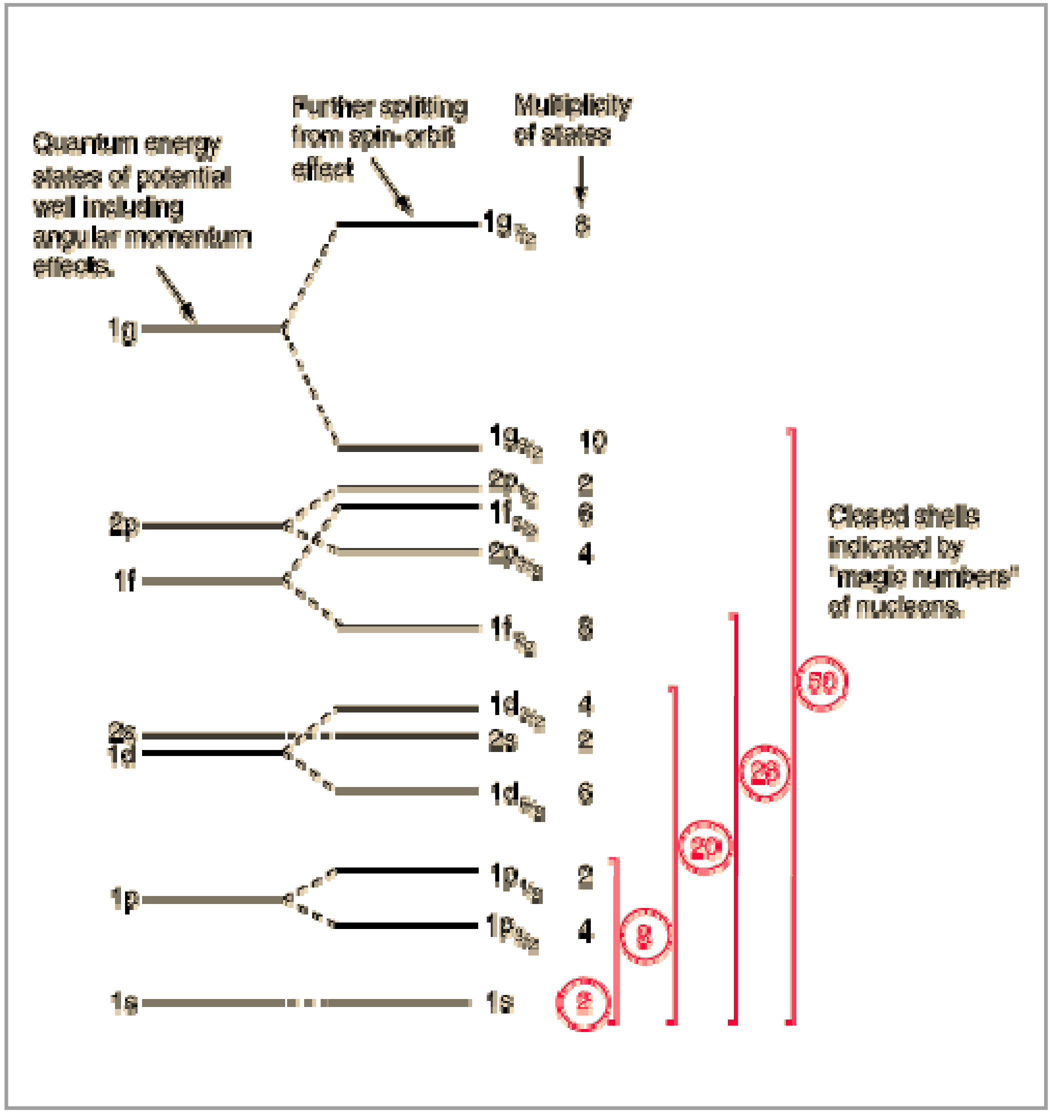
Enrico Fermi

remark on Maria Gepert-Mayer's talk on isotope aboundances, Chicago, 1948

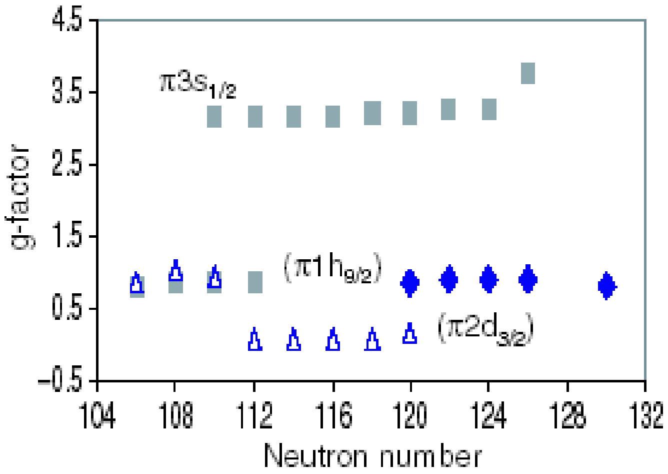
Intruder orbitals

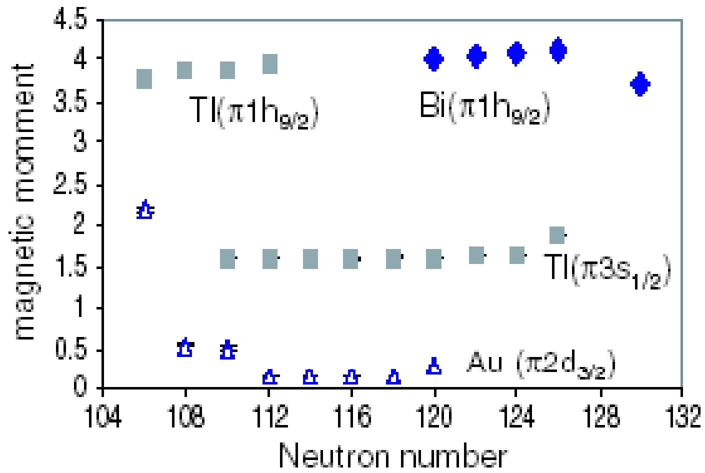
$$V(r) \longrightarrow V(r) + V_{so}$$

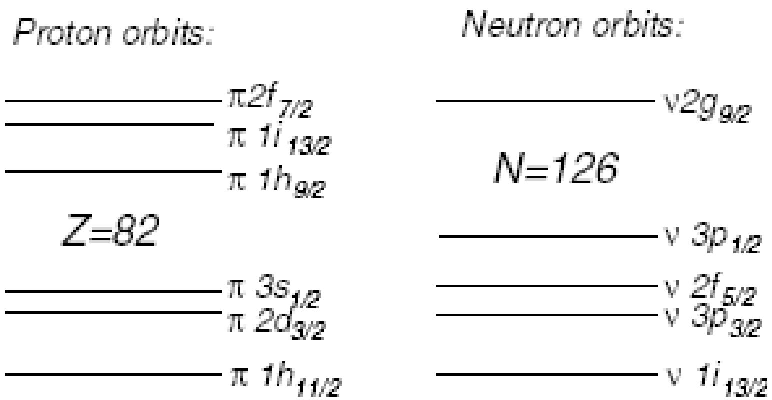
$$V_{so} = f(r)\, \underline{l}.\underline{s}$$



Sensitivity to valence particle configuration

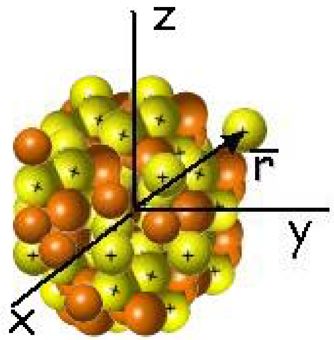


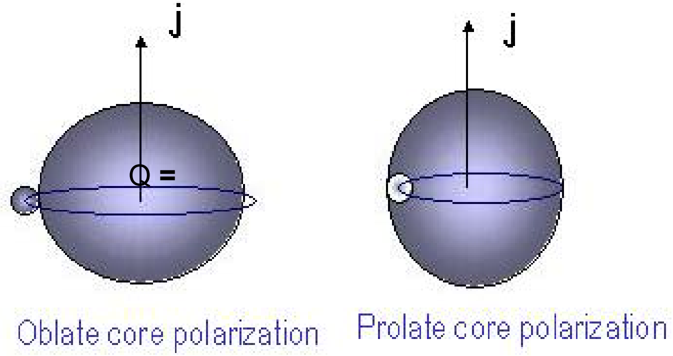




Electric quadrupole moment in atomic nuclei

$$\sum_i e_i(3.z_i^2 + r_i^2) \;=\; \sum_i e_i r_i^2 Y_2(\theta_i, \varphi_i)$$





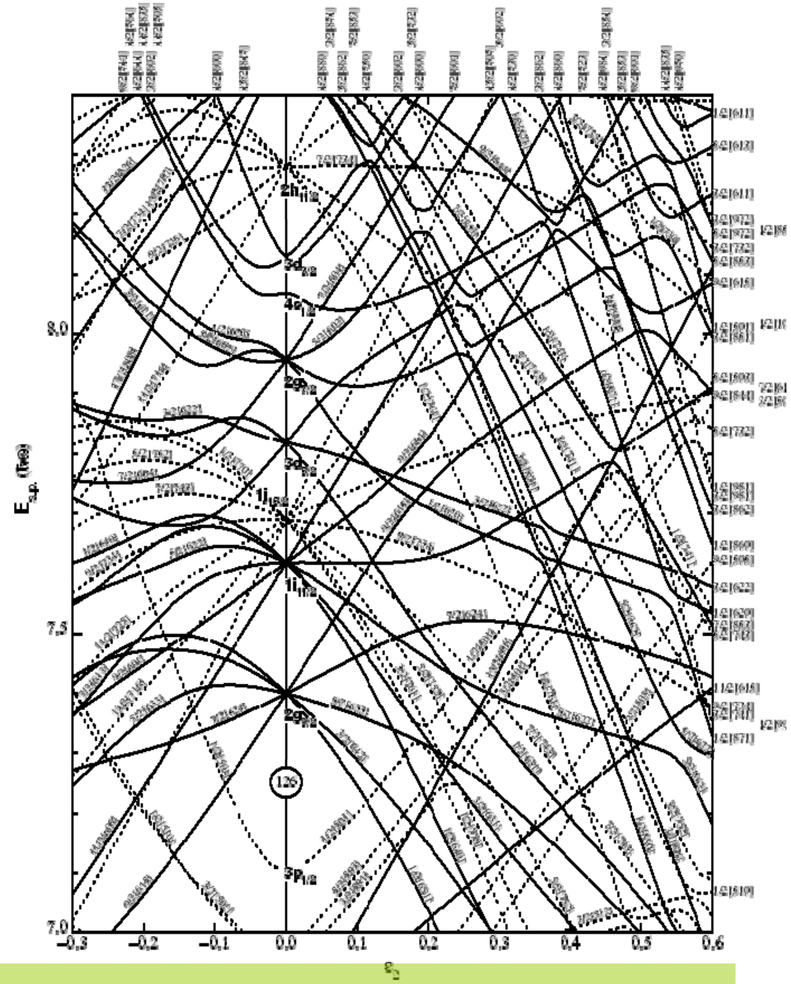
$$Q = \langle I, m = I | \mathbf{Q}_2^0 | I, m = I \rangle$$

$$Q(j) = -e_j \frac{2j-1}{2(j+1)} \langle r_j \rangle^2$$

theory

The Nilsson model

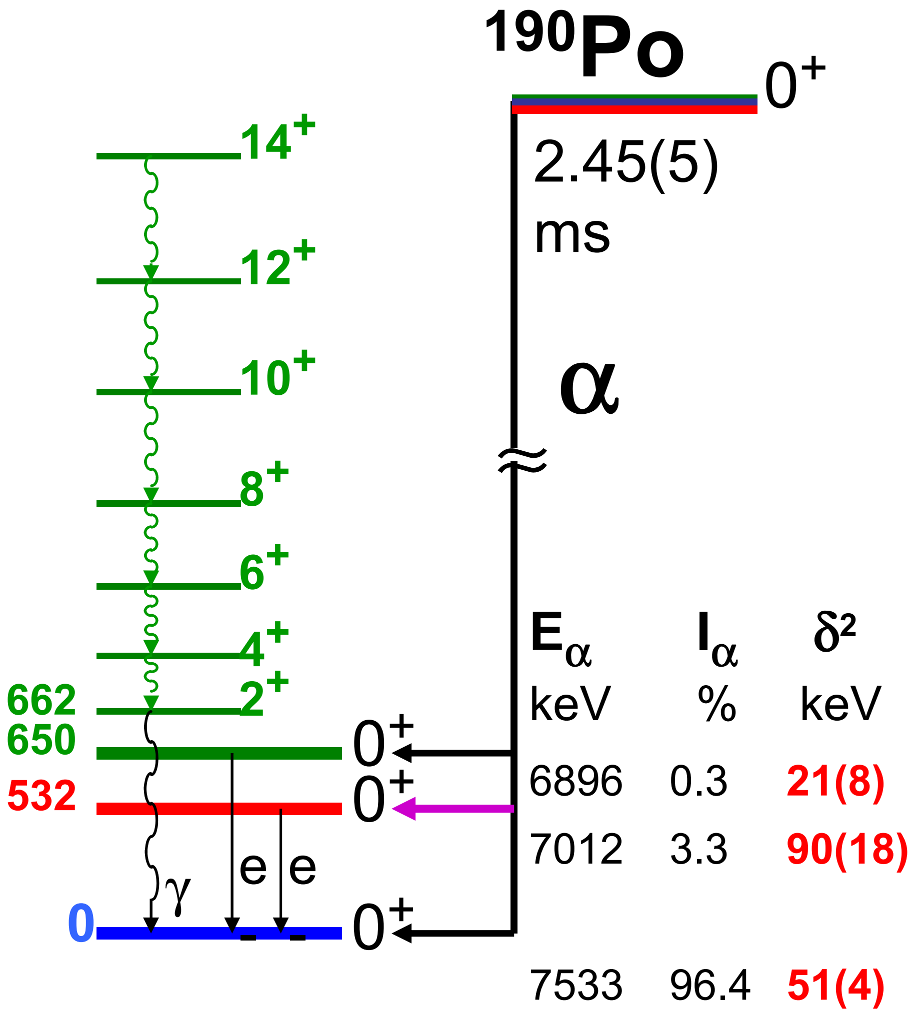
The spherical shell model provides an excellent description of nuclei close to closed shells. However, the large body of evidence that points toward the existence of deformed nuclei necessitates a model that uses a deformed nuclear potential. One such potential is the modified harmonic-oscillator potential, which was first used by Nilsson to investigate the effect of deformation on the single-particle orbits.

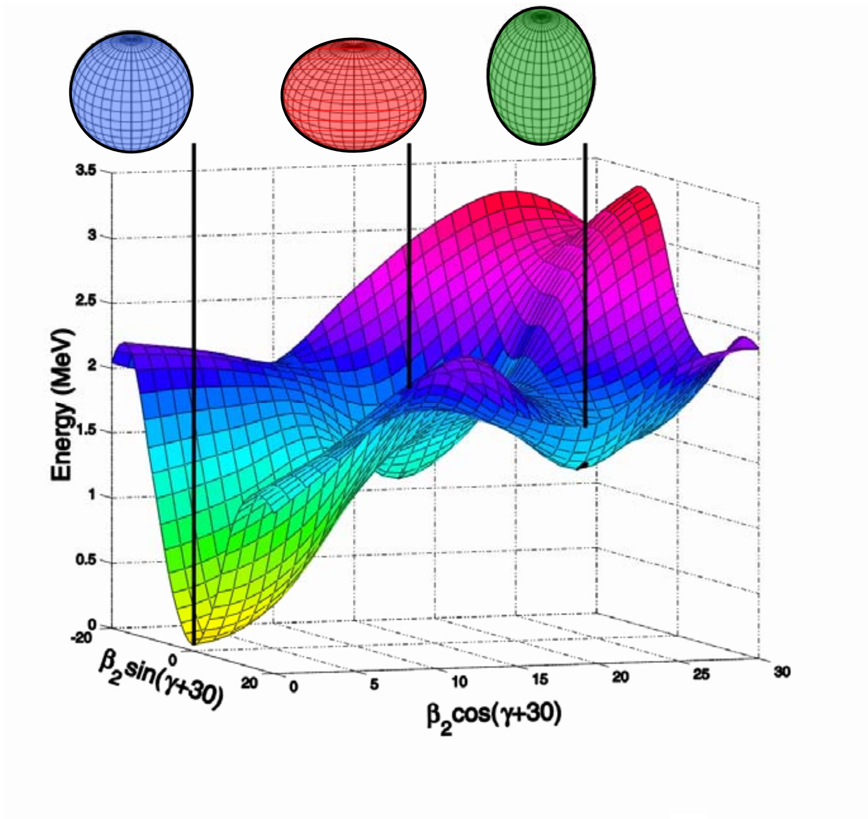


$$H_{N\alpha} = \frac{-\hbar^2}{2m_t}\nabla^2 + \frac{m_t}{2}\left(\omega_x^2 x^2 + \omega_y^2 y^2 + \omega_z^2 z^2\right) - 2\kappa\hbar\omega_0\left[\vec{l}.\vec{s} - \mu\left(l^2 - \langle l^2\rangle_N\right)\right]$$

S.G. Nilsson, Kgl. Dan. Viden. Selsk. Mat. Fys. Medd. **29** No.16 (1955)

Shapes of atomic nuclei





Potential Energy Surface for ^{186}Pb

A. Andreyev et al., Nature 405 (2000) 430

Break down of the nuclear paradigm

from: NuPECC 2004 Long Range Plan

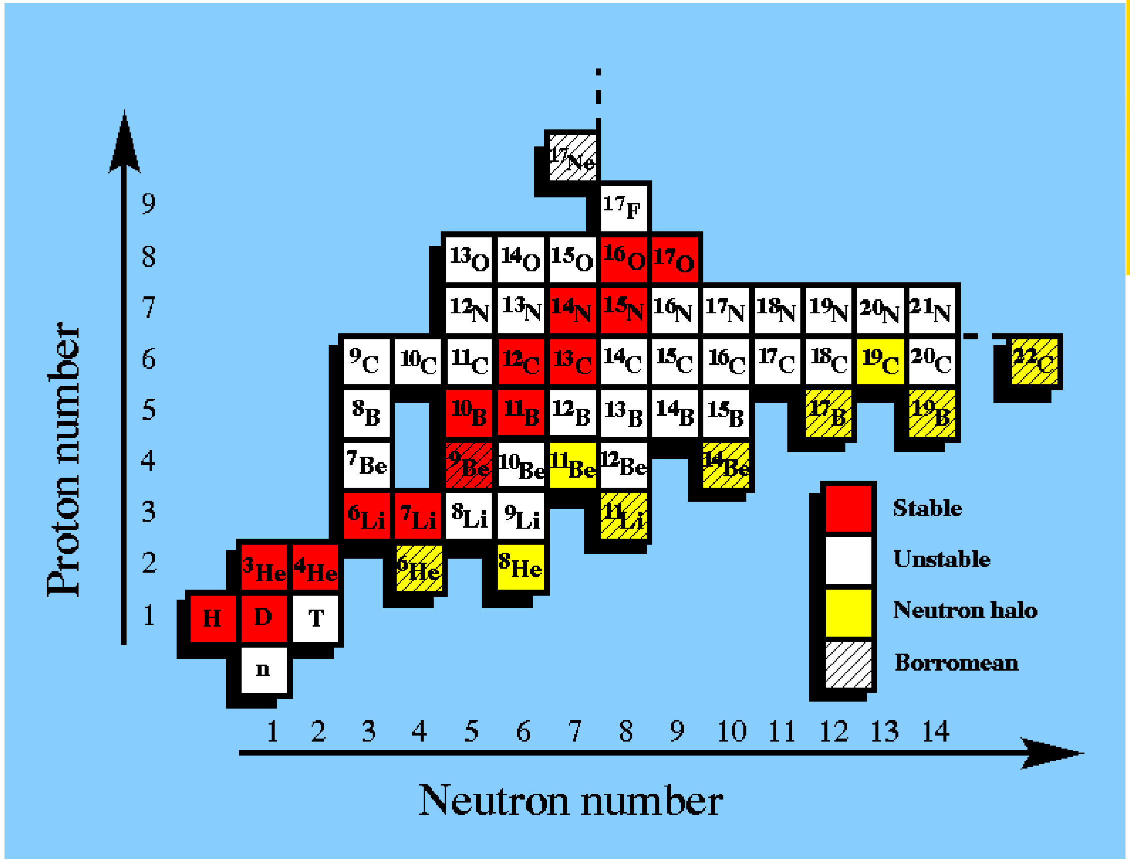
- *Nuclear radii don't go as $A^{1/3}$.*
  For all stable isotopes the density in the atomic nucleus as well as the diffuseness of the surface are nearly constant. Explorations into the far-unstable regions of the nuclear chart have convincingly shown that the diffuseness, and thus the radii of the atomic nuclei, vary strongly.

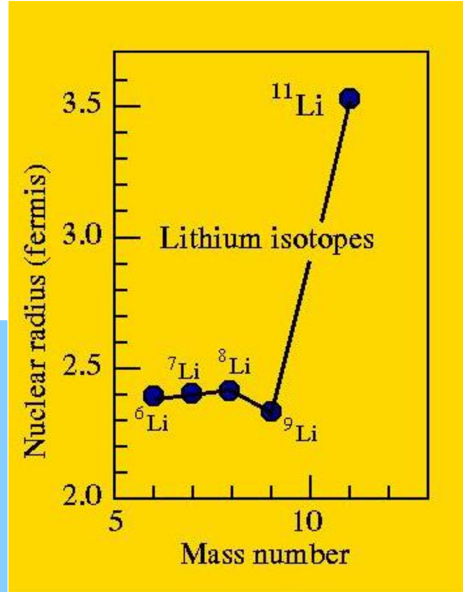
- *Magic Z and N numbers depend on N and Z, respectively.*
  Shell gaps seem to shrink or disappear, and new ones appear when leaving the valley of stability. Also, experimental evidence for new deformed magic numbers is now available.

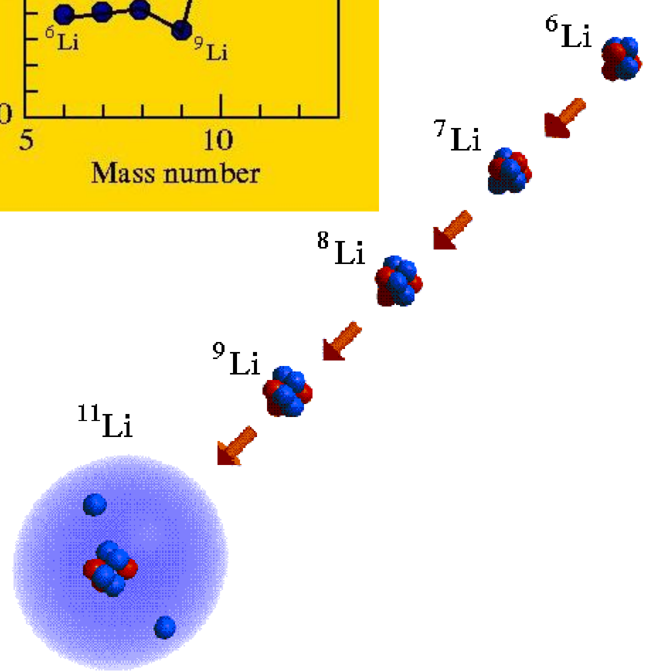
- *Many more bound nuclei exist than anticipated.*
  The neutron drip line is much further out than anticipated twenty years ago. The importance of nucleon correlations and clustering that create more binding for the nuclear system has been underestimated.

Part I: Halo nuclei

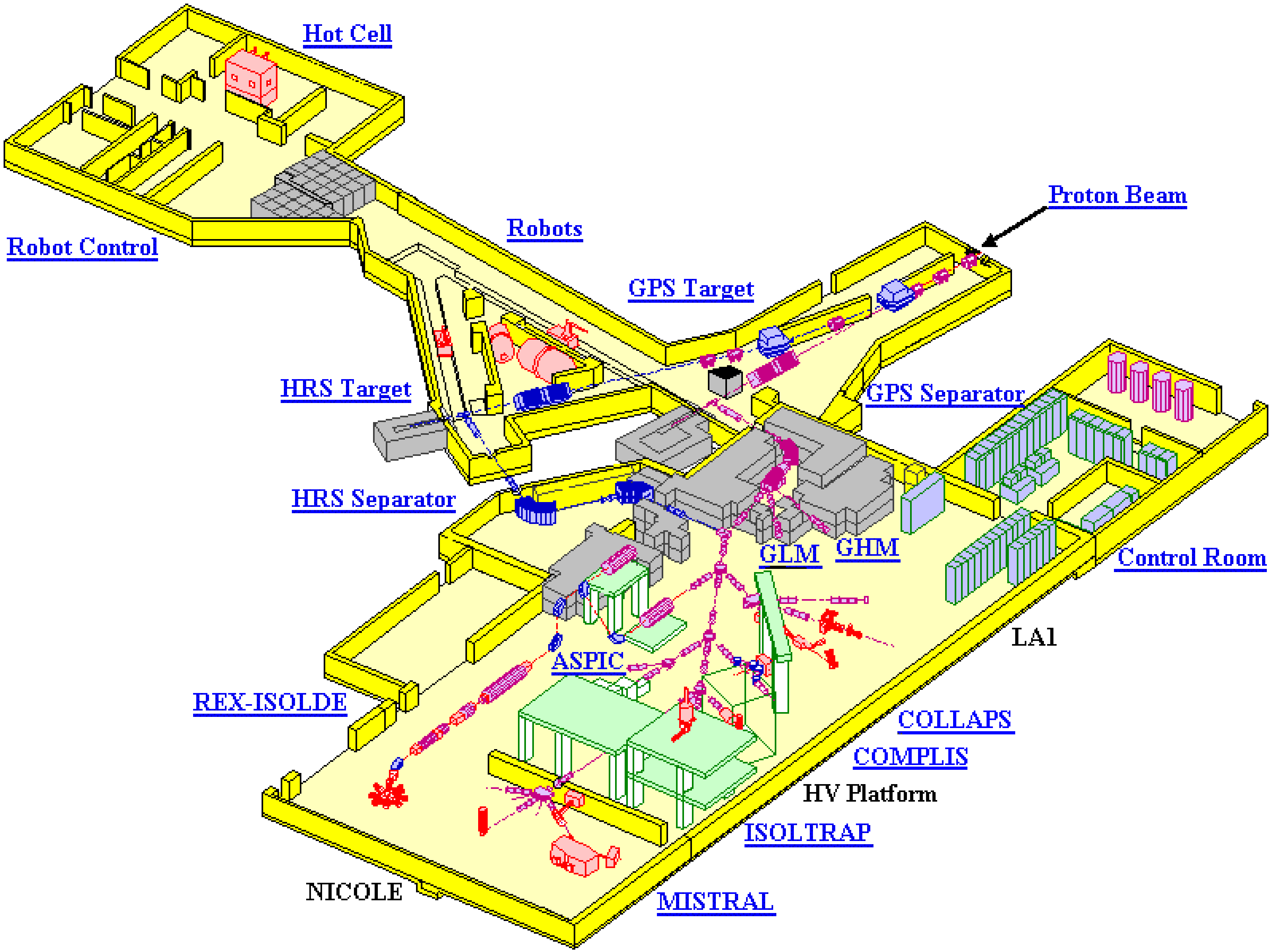
The Li chain





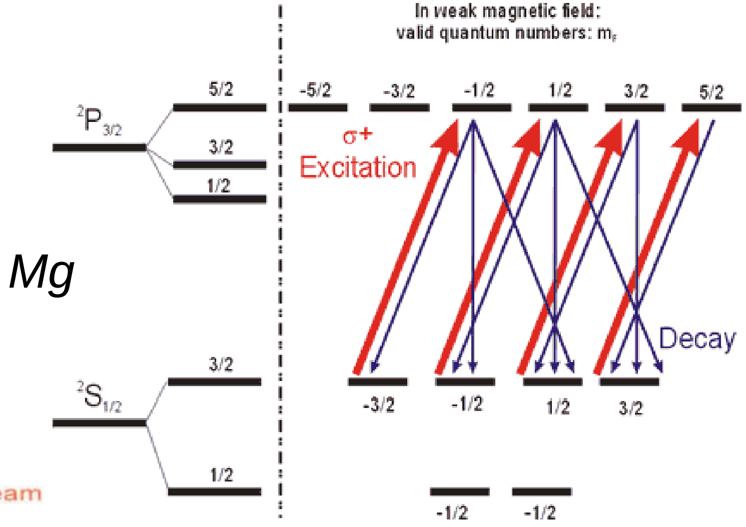


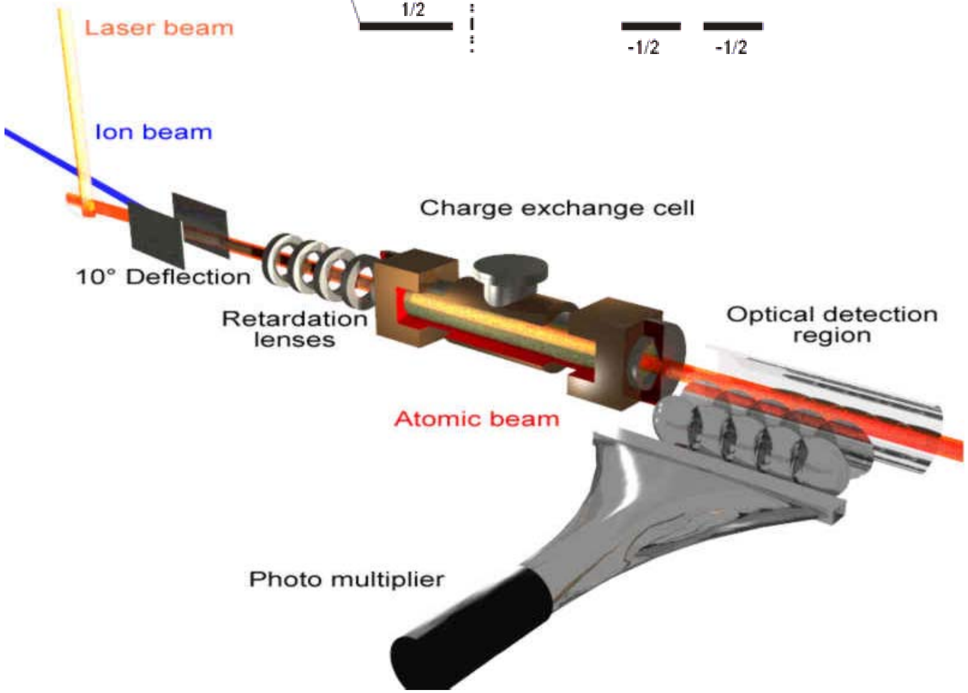
Why is ^{11}Li so big?

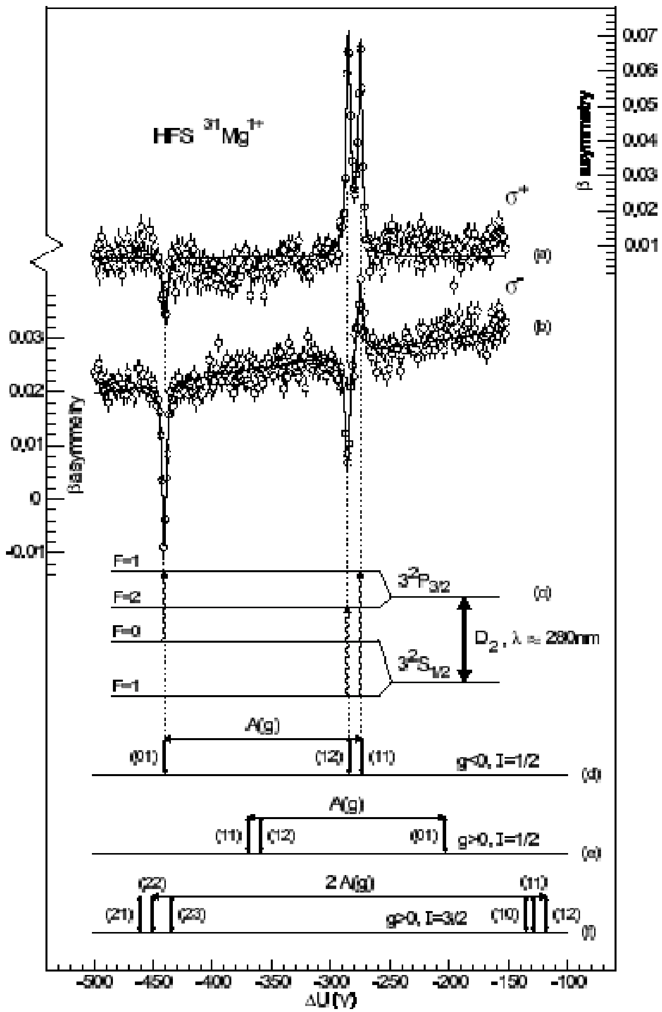

Hot Cell
Proton Beam
Robots
Robot Control
GPS Target
HRS Target
GPS Separator
HRS Separator
GLM
GHM
Control Room
LA1
ASPIC
REX-ISOLDE
COLLAPS
COMPLIS
HV Platform
ISOLTRAP
NICOLE
MISTRAL

COLLAPS: Collinear laser spectroscopy @ CERN

Optical pumping

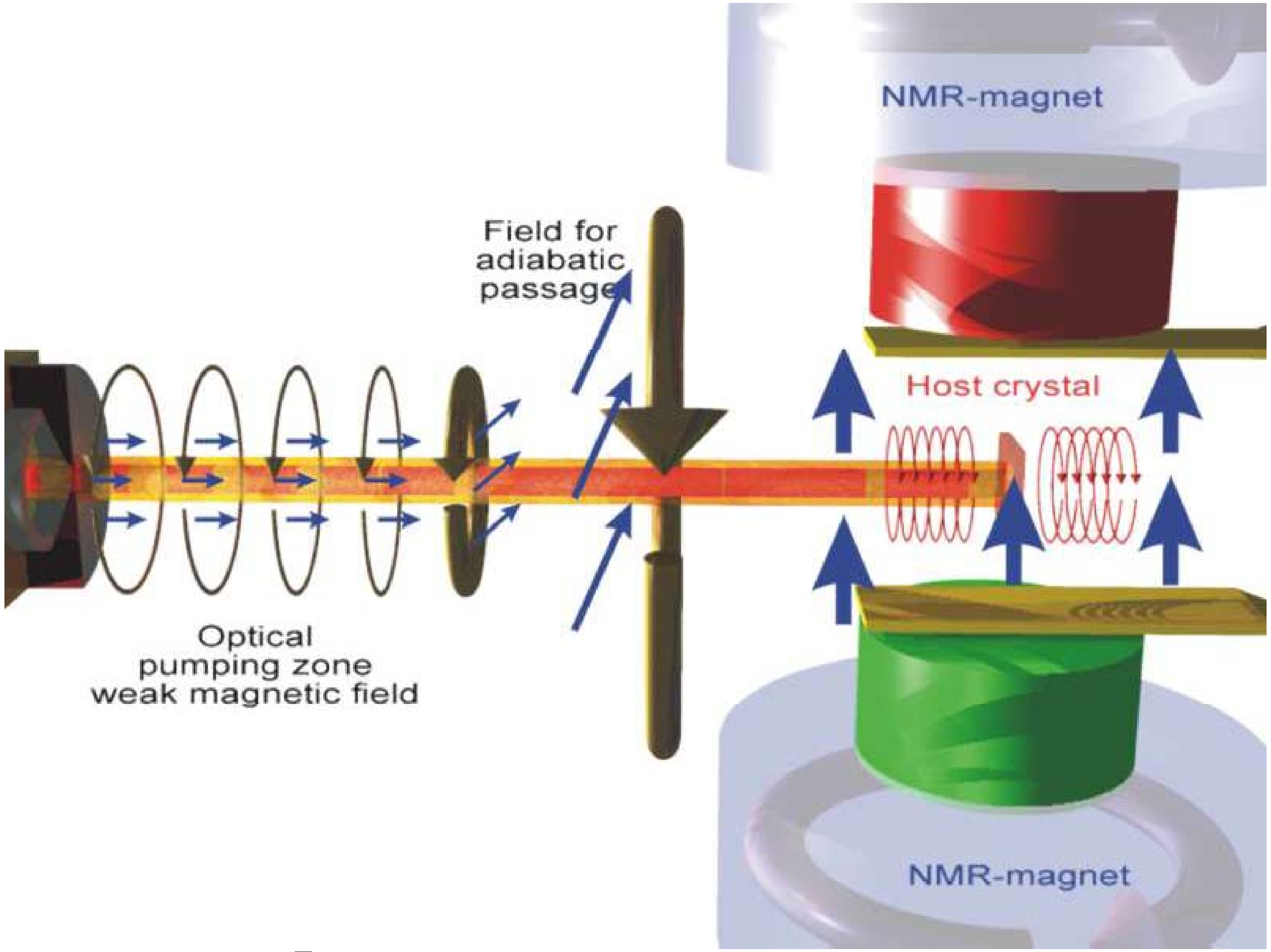




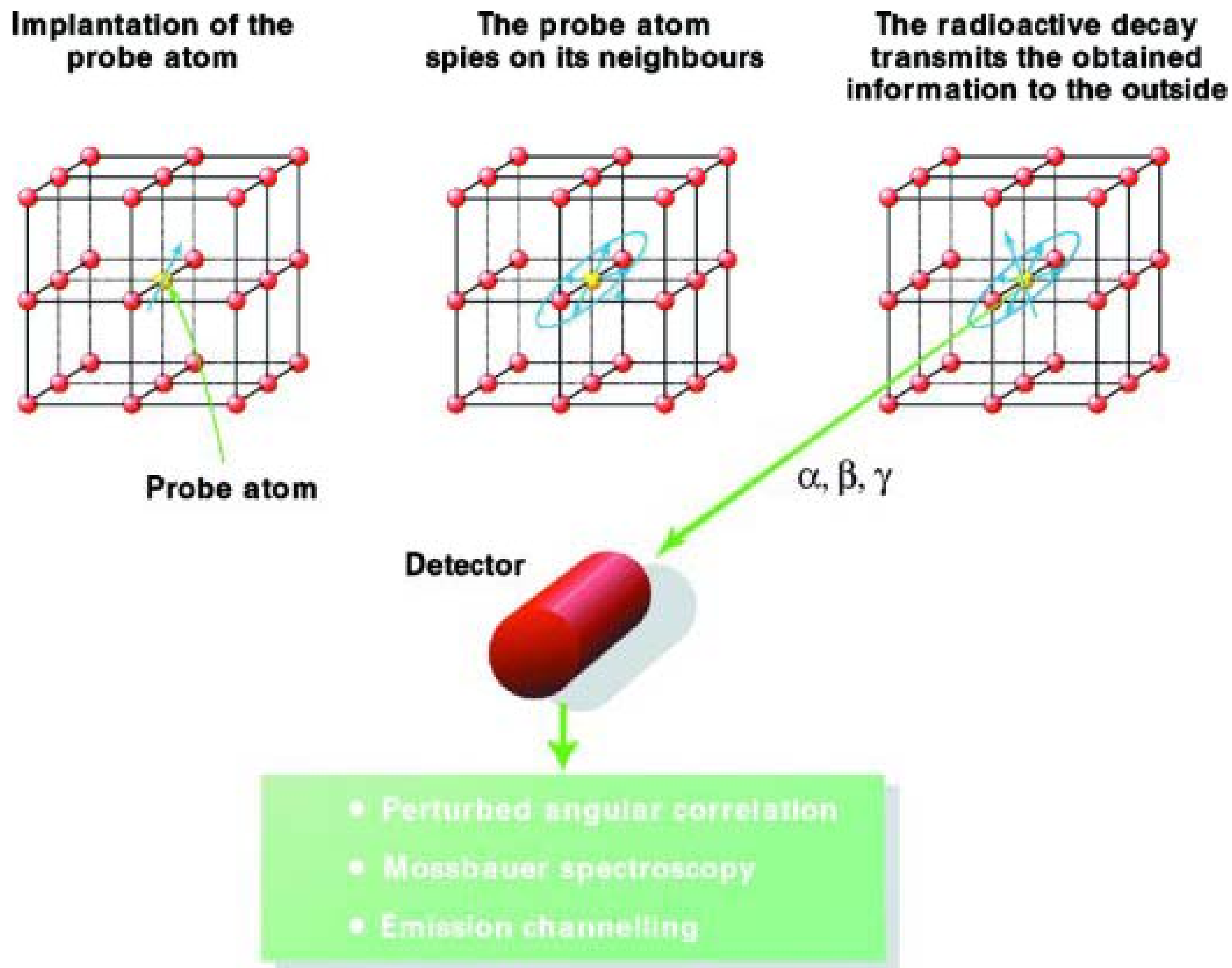


G. Neyens et al, PRL (2005)

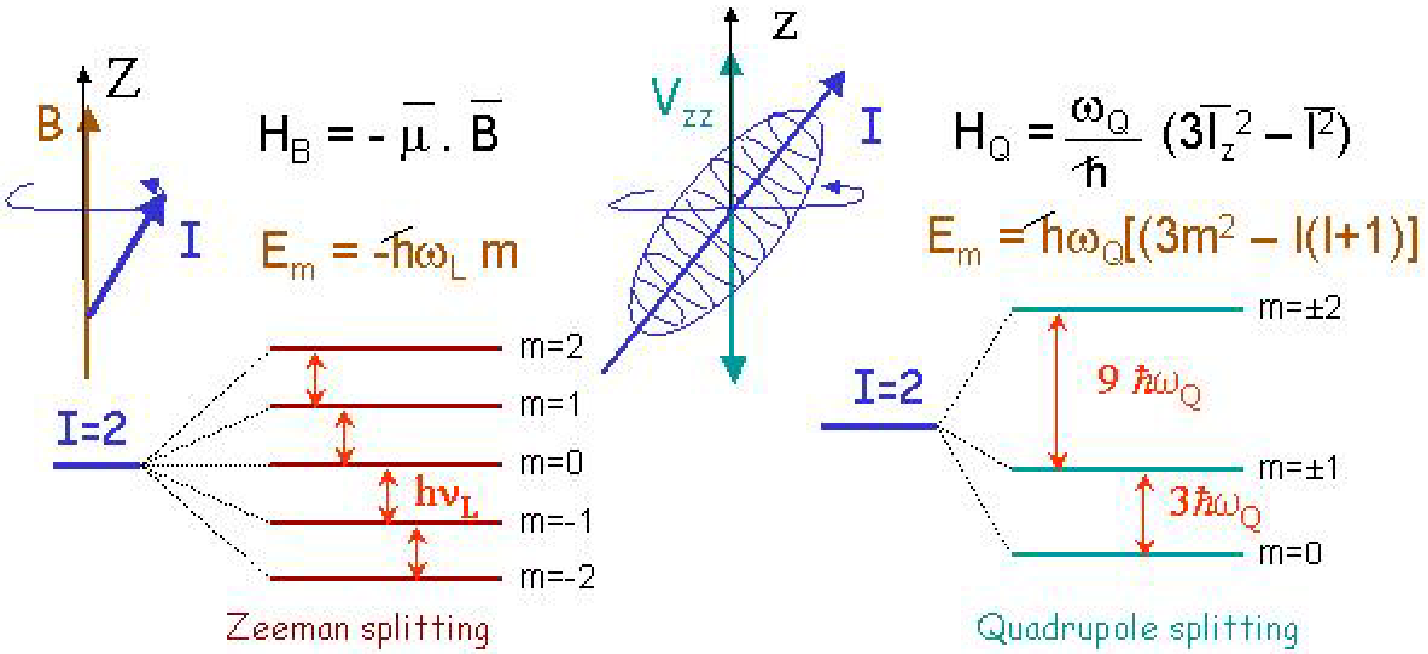
Nuclear magnetic resonance



Hyperfine interactions



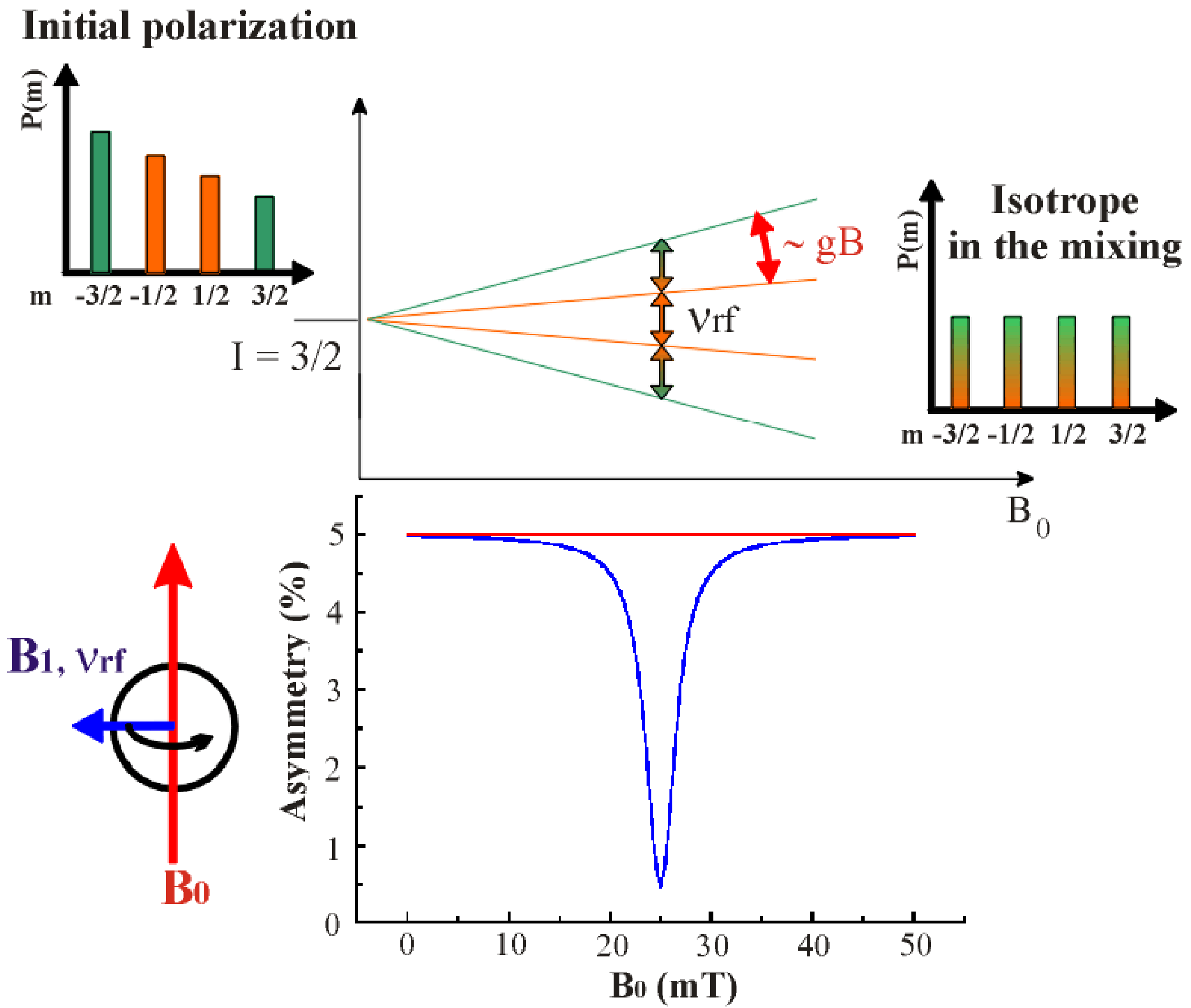
Basic principles for moment measurements



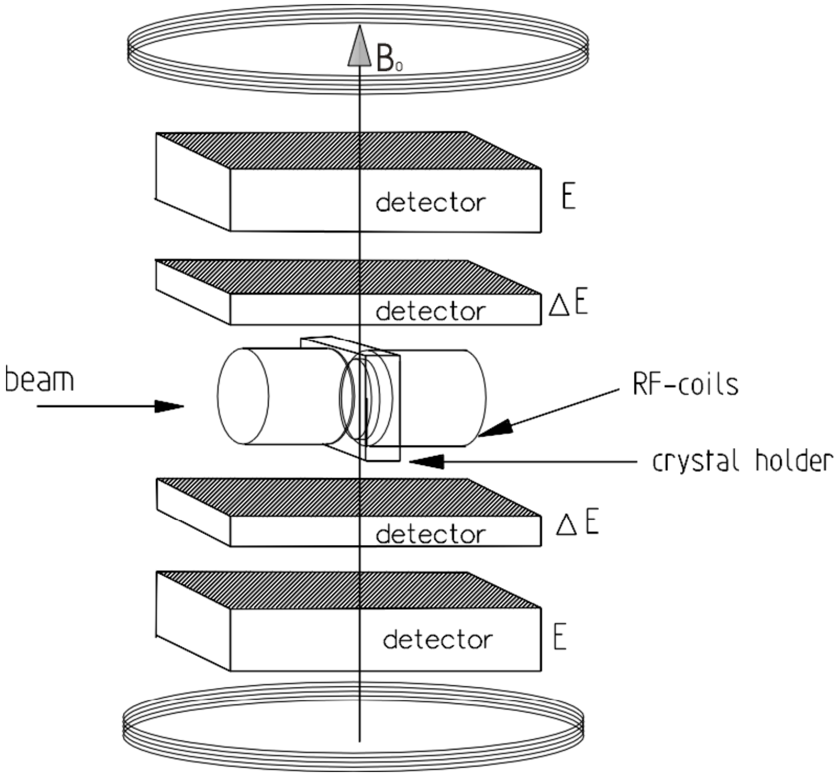
magnetic dipole moments:
experiments in external magnetic fields

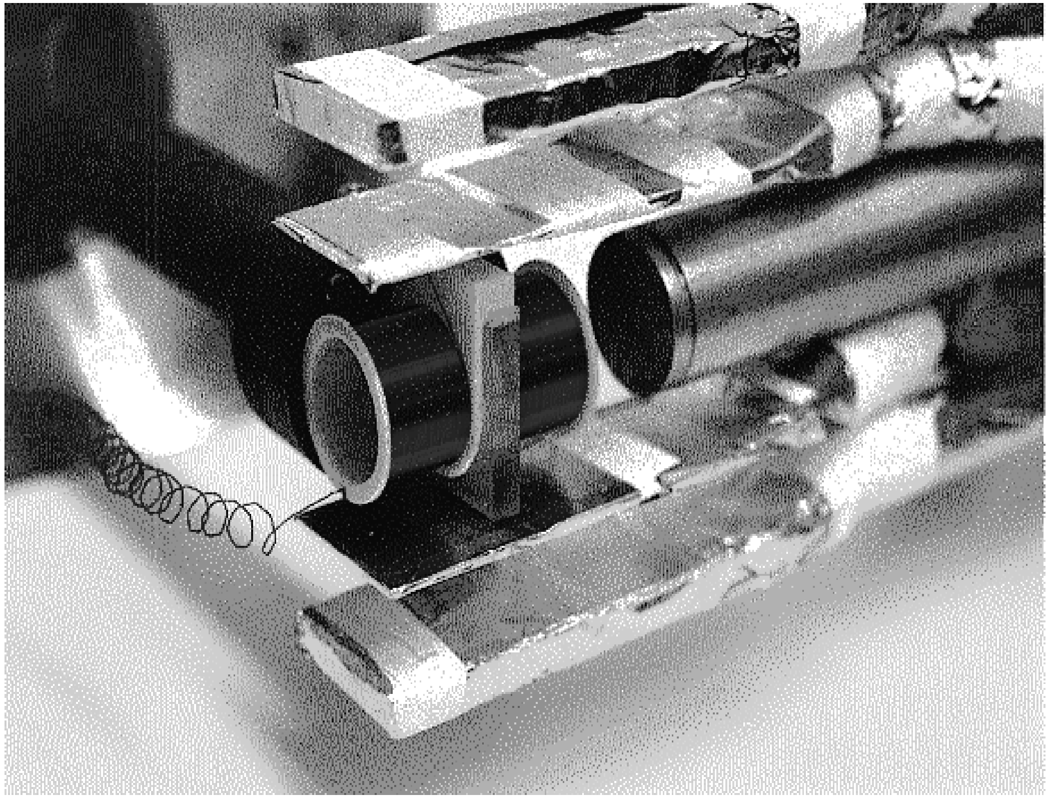
Electric quadrupole moments:
interaction with external electric fields,
e.g. with a lattice field after implantation

Principle of nuclear magnetic resonance

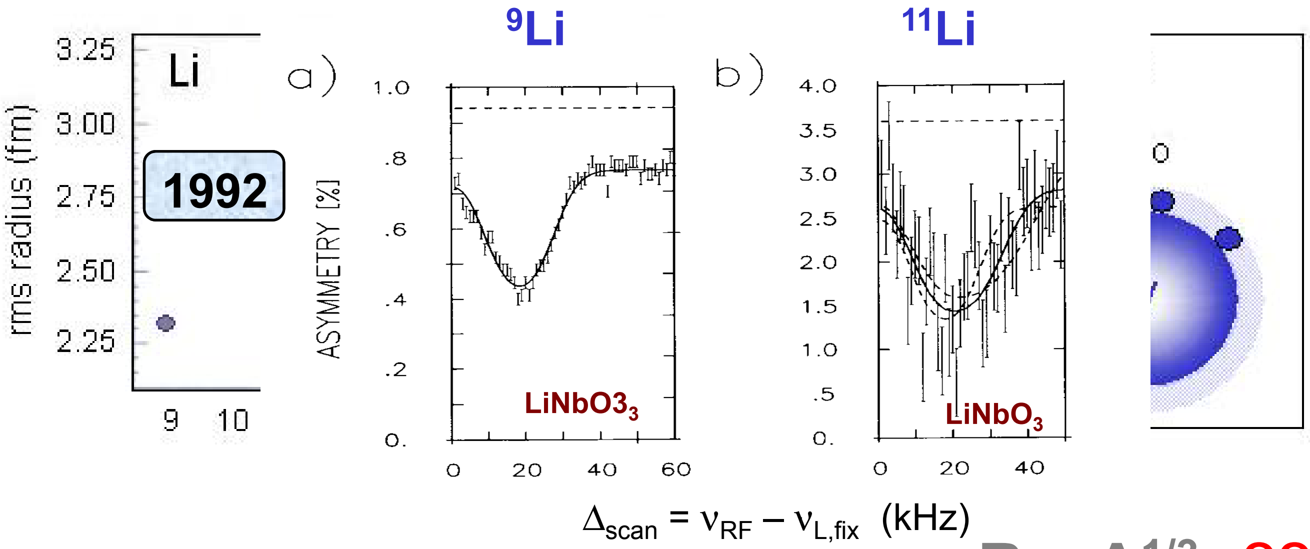


NMR experimental set up

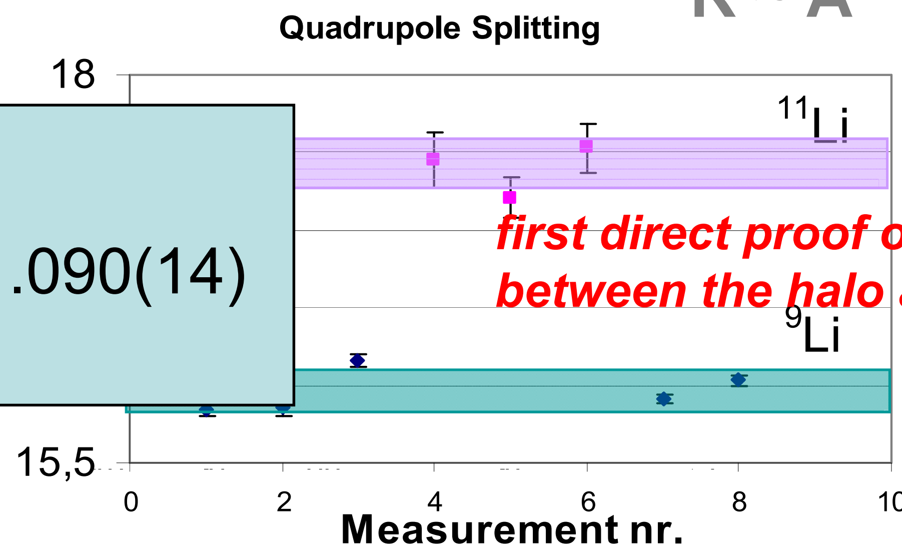




The case of ^{11}Li



R ~ $A^{1/3}$????



$$\frac{Q(^{11}Li)}{Q(^{9}Li)} = 1.090(14)$$

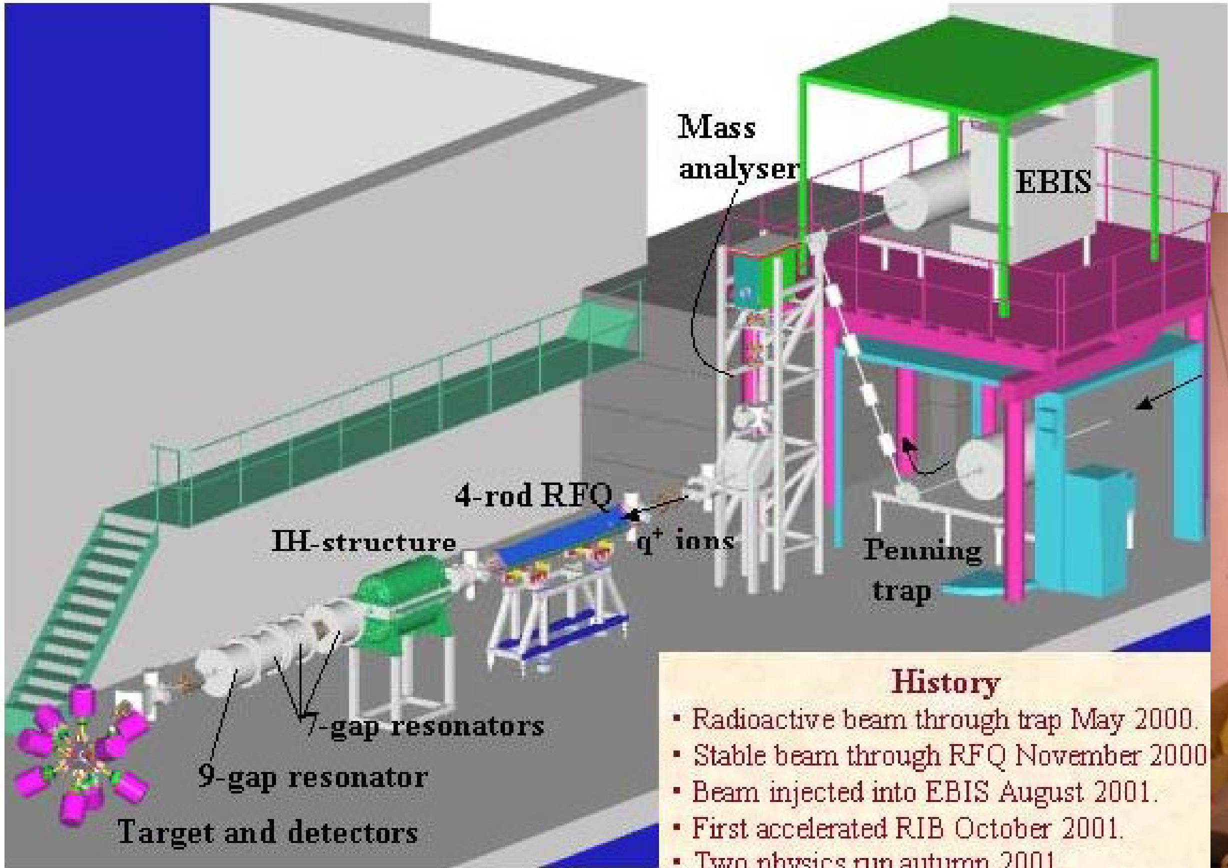
first direct proof of correlations between the halo and the core

Basic questions of modern nuclear physics

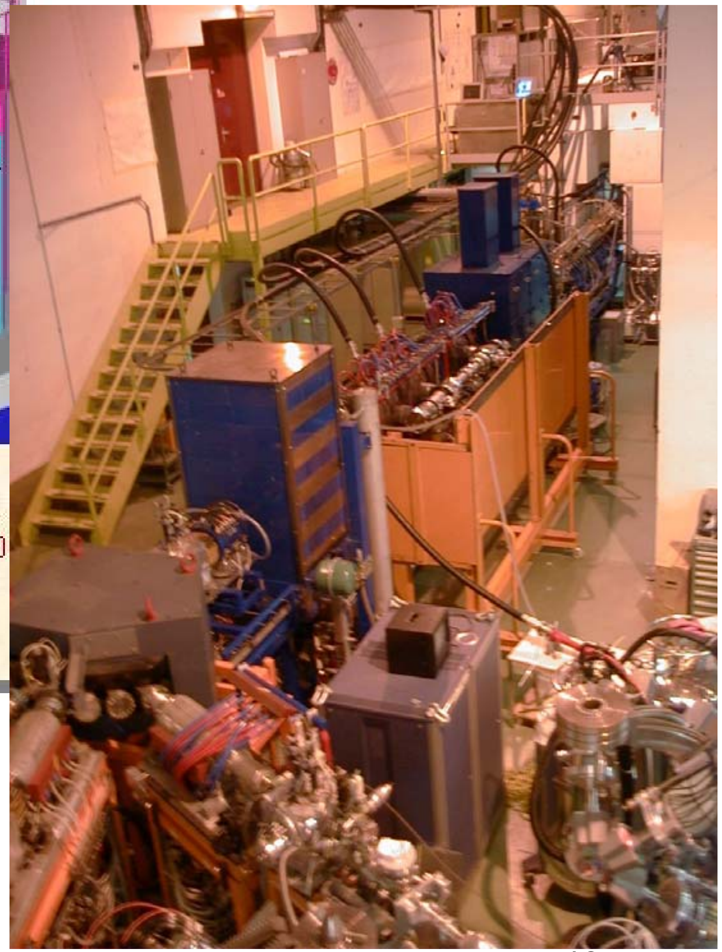
- What are the limits for existence of nuclei? Where are the proton and neutron drip lines situated? Where does Mendeleyev's table end?
- How does the nuclear force depend on varying proton-to-neutron ratios?
- How to explain collective phenomena from individual motion?
- How are complex nuclei built from their basic constituents?

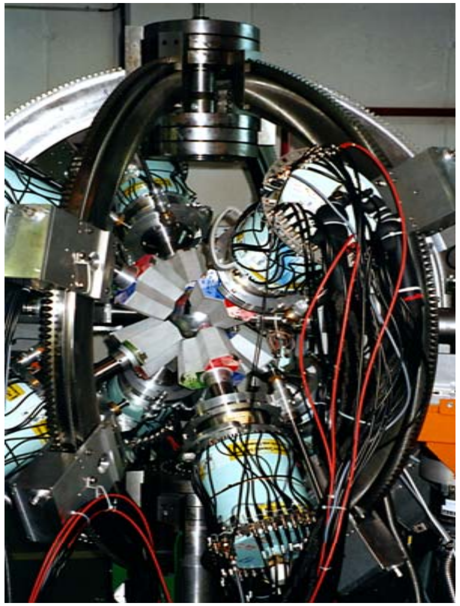
REX - ISOLDE @ CERN

The state-of-the-art instrument

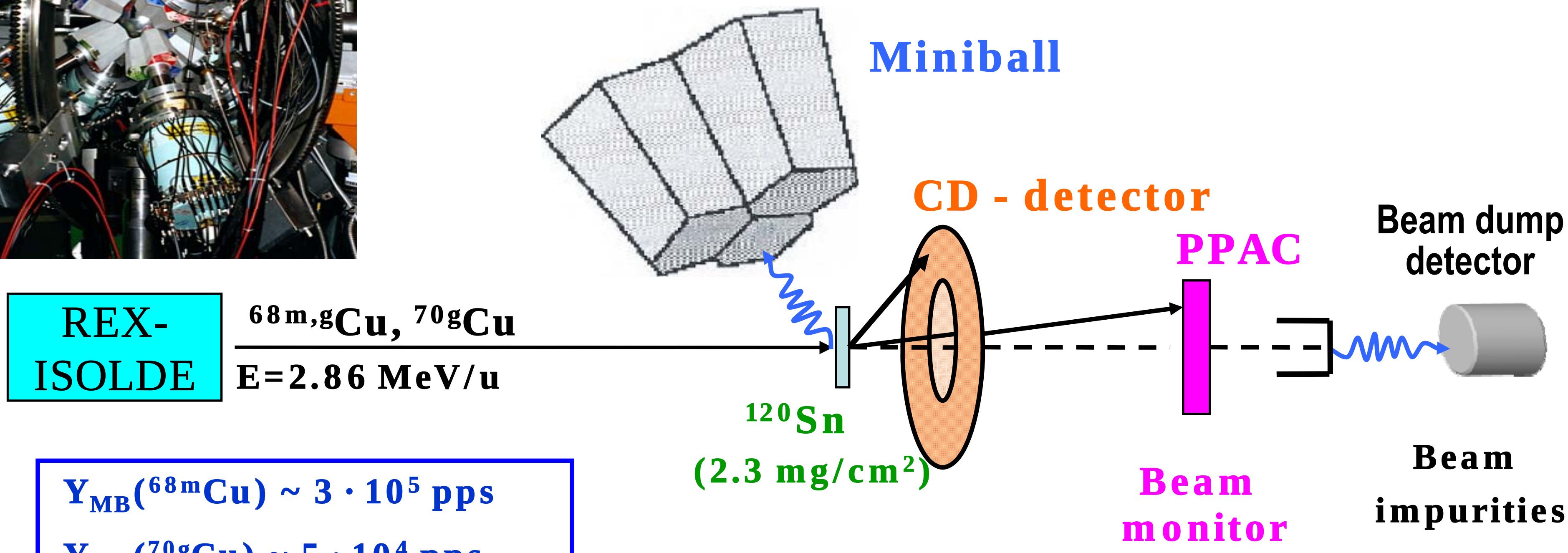


History
- Radioactive beam through trap May 2000.
- Stable beam through RFQ November 2000
- Beam injected into EBIS August 2001.
- First accelerated RIB October 2001.
- Two physics run autumn 2001.





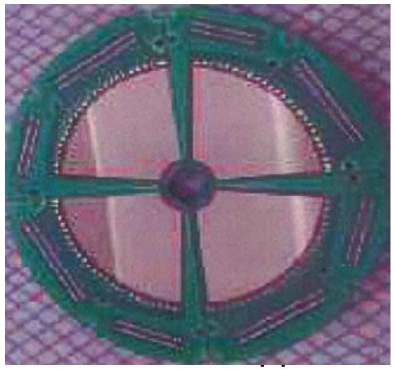
Experimental setup for Coulex @ Isolde



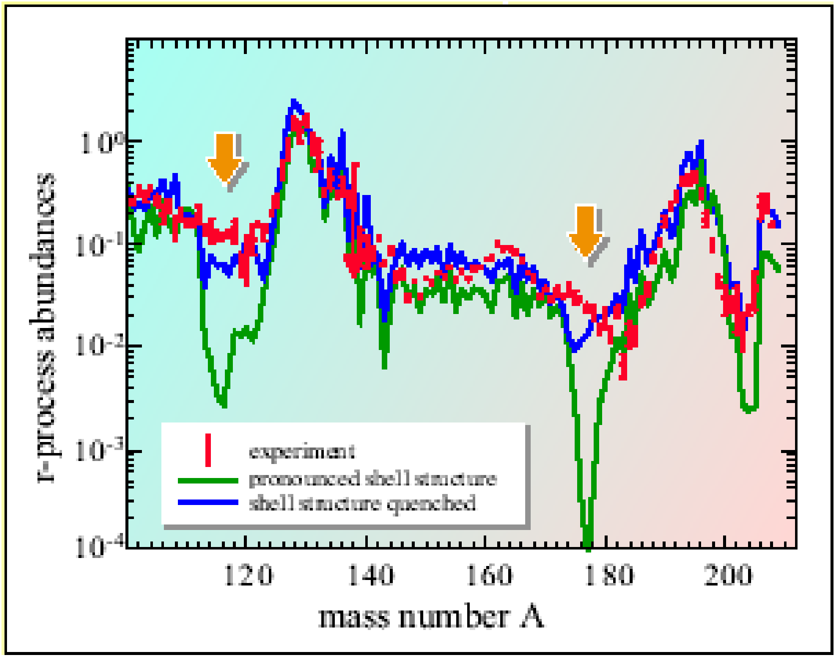
$Y_{MB}(^{68m}Cu) \sim 3 \cdot 10^5$ pps

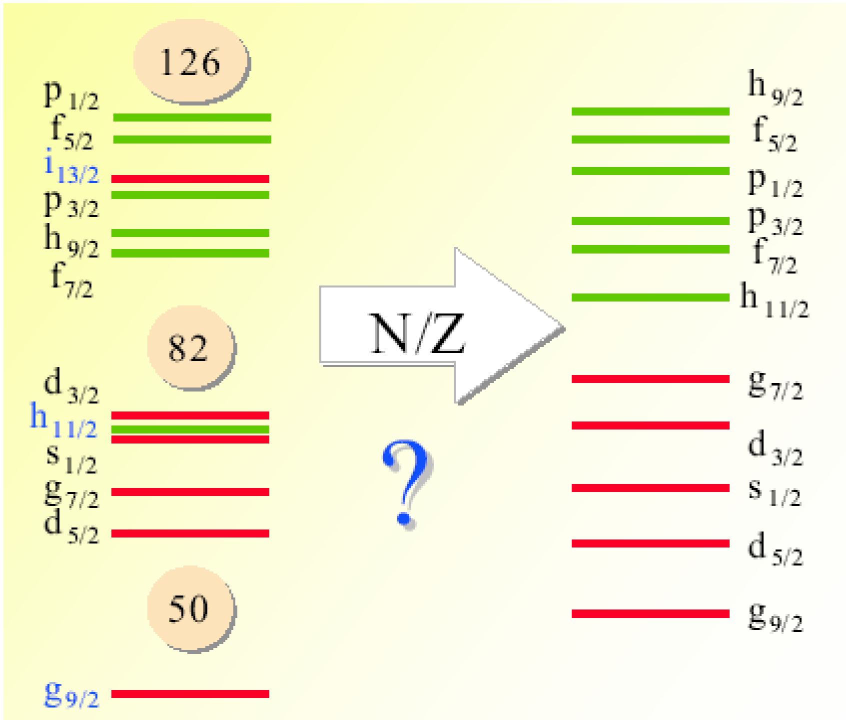
$Y_{MB}(^{70g}Cu) \sim 5 \cdot 10^4$ pps

- particle identification: Double Sided Segmented Silicon Detector;
- detection range: 16°-53° in the laboratory system;
- 4 quadrants, each divided in 16 annular (θ) and 24 sector (ϕ) strips.



Isotope abundances and creation of elements





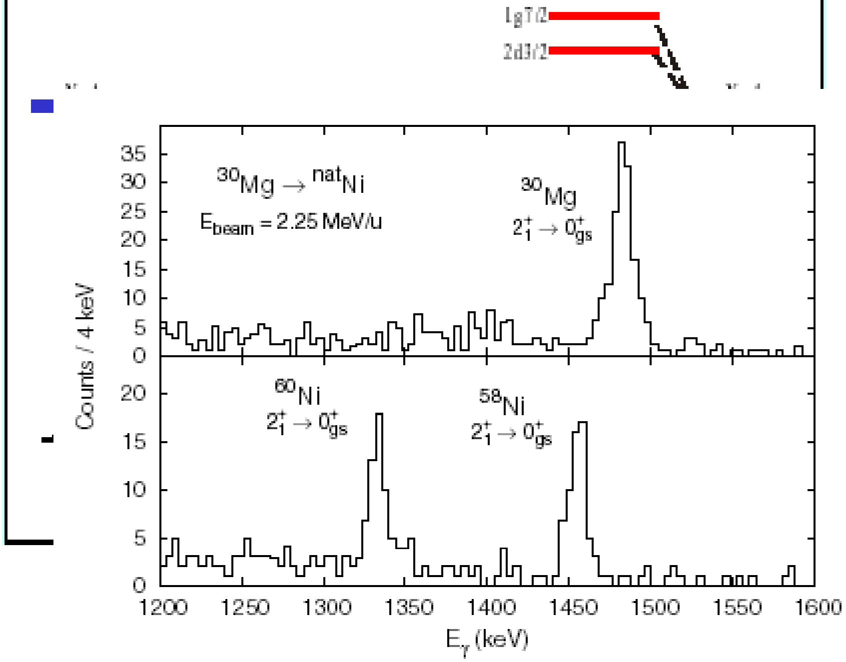
What are the magic numbers far away from stability ?

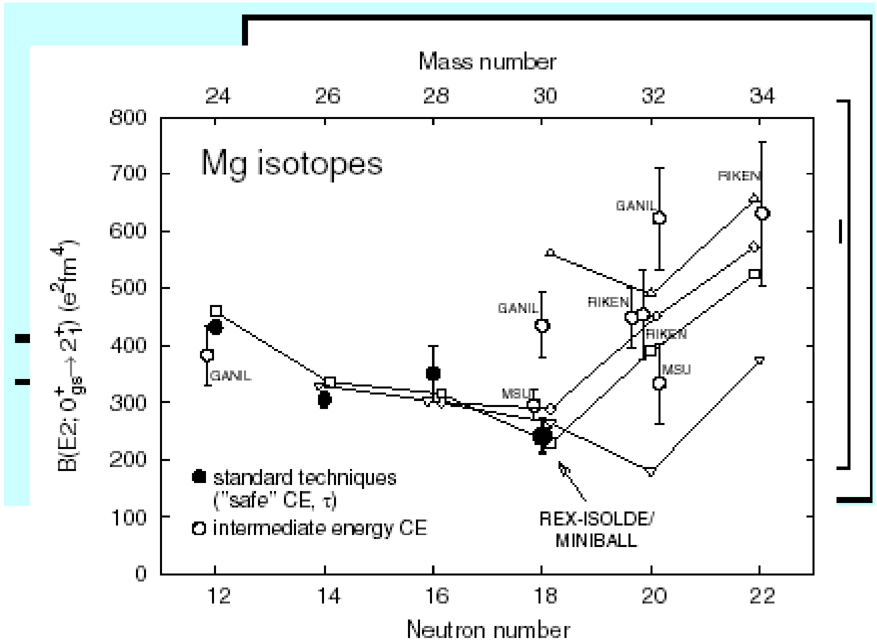
or

- Does the spin-orbit change ?
- Does other terms of the nucleon-nucleon potential play a role?

Migrating magic numbers

"safe" Coulex at the "island of inversion"

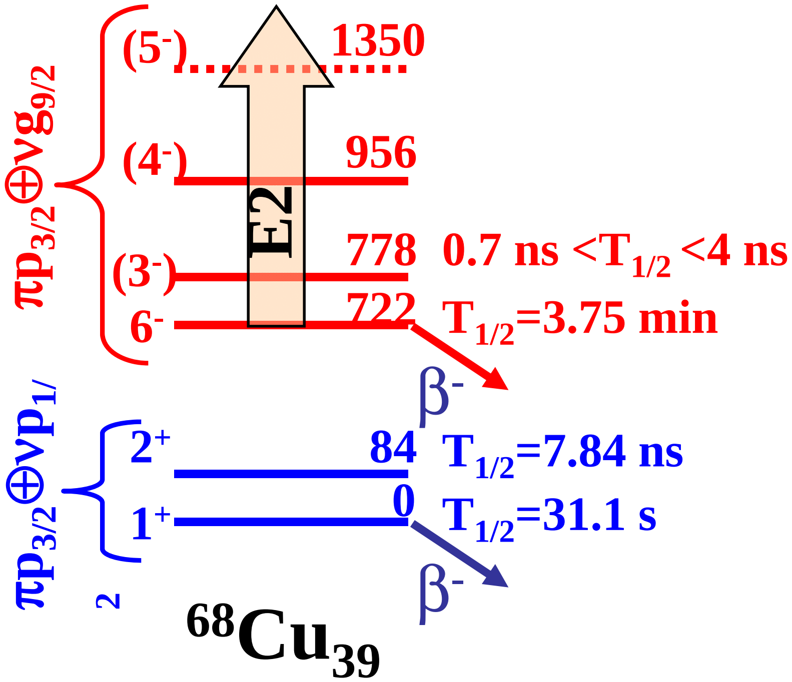


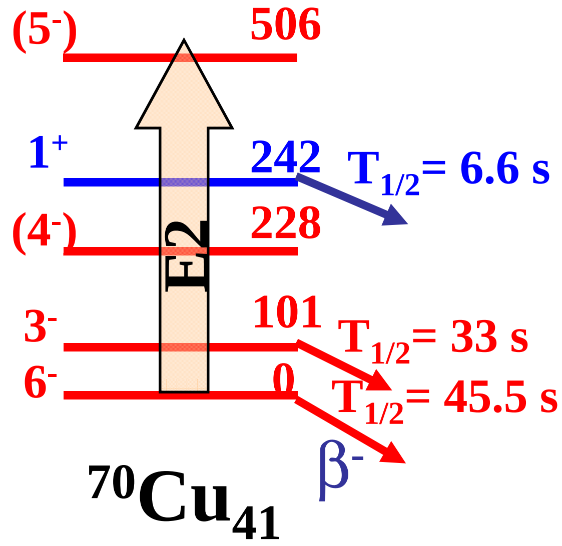


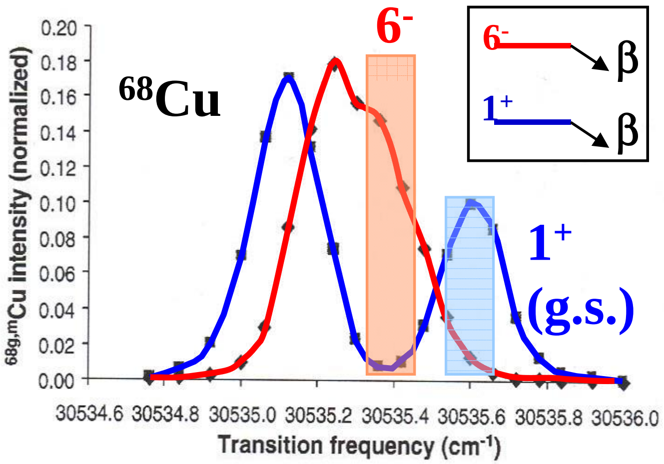
O. Niedermaier et al, PRL 94, 172501 (2005)

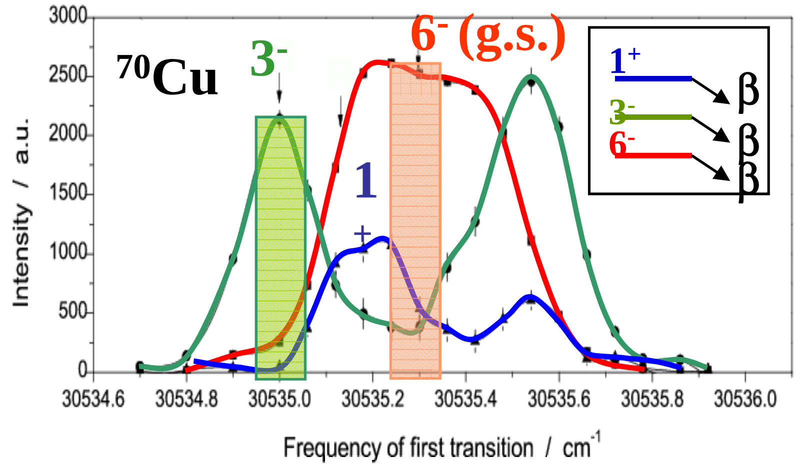
REX-ISOLDE and the Miniball

“Non-standard” Coulomb excitation

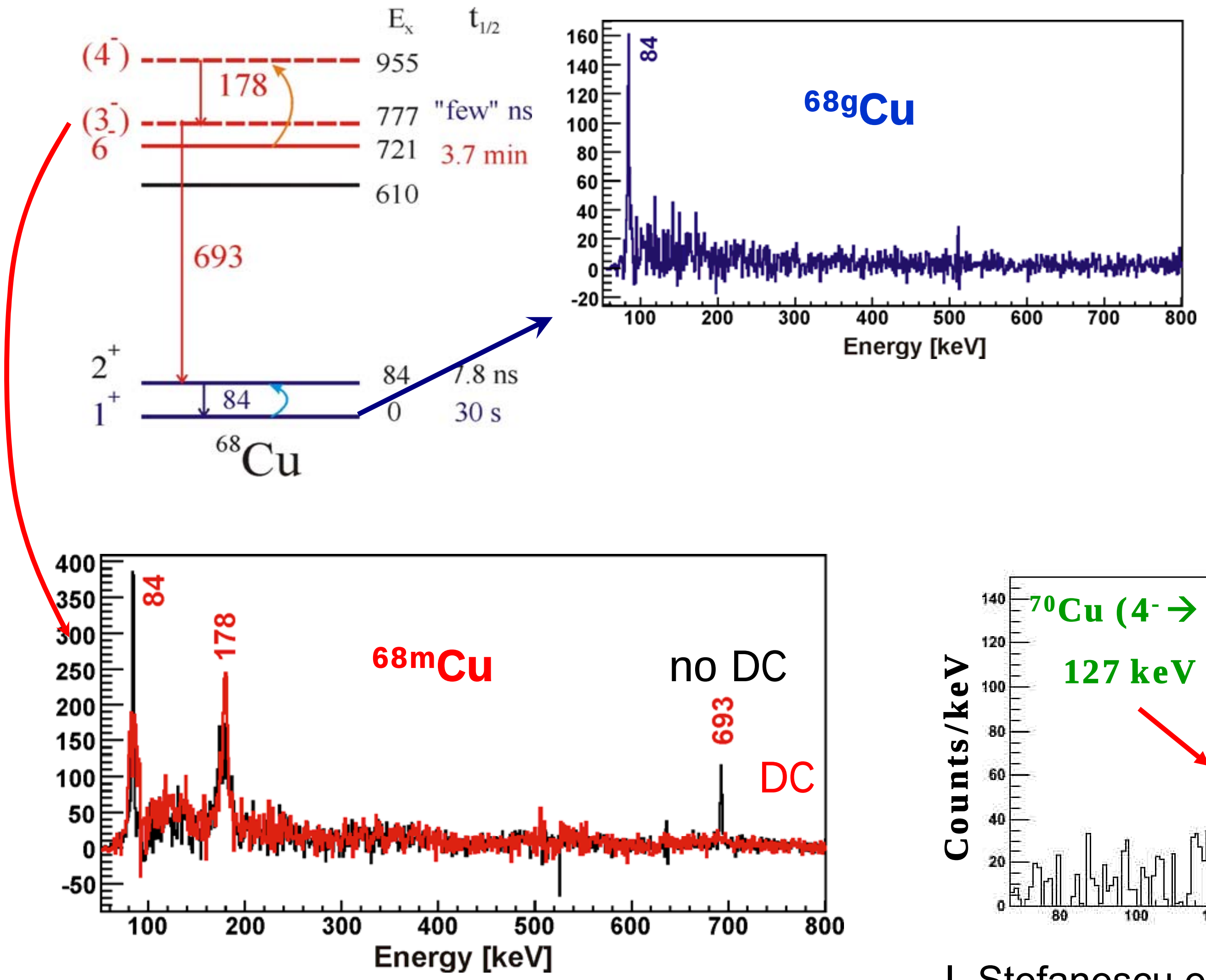


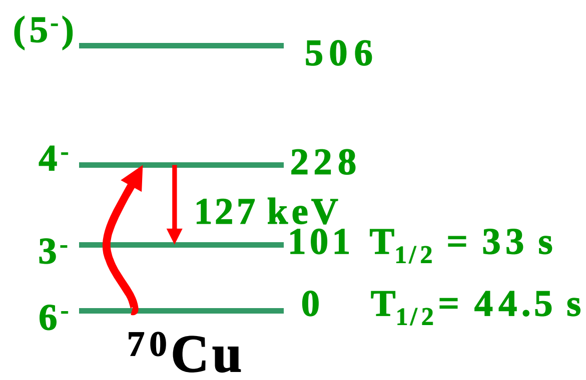


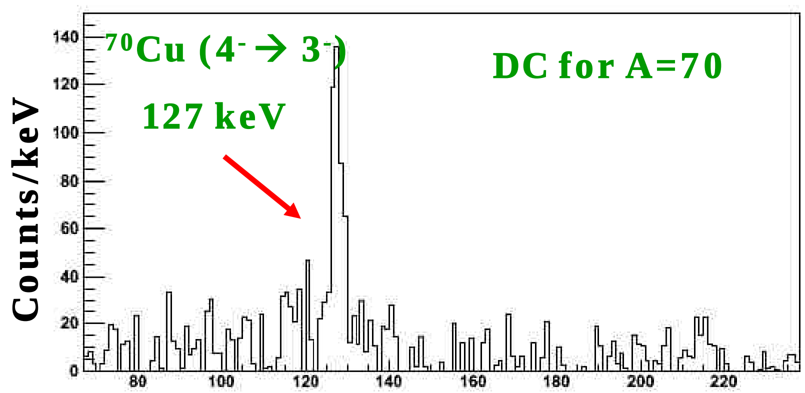




Study of selected structures in the same nucleus

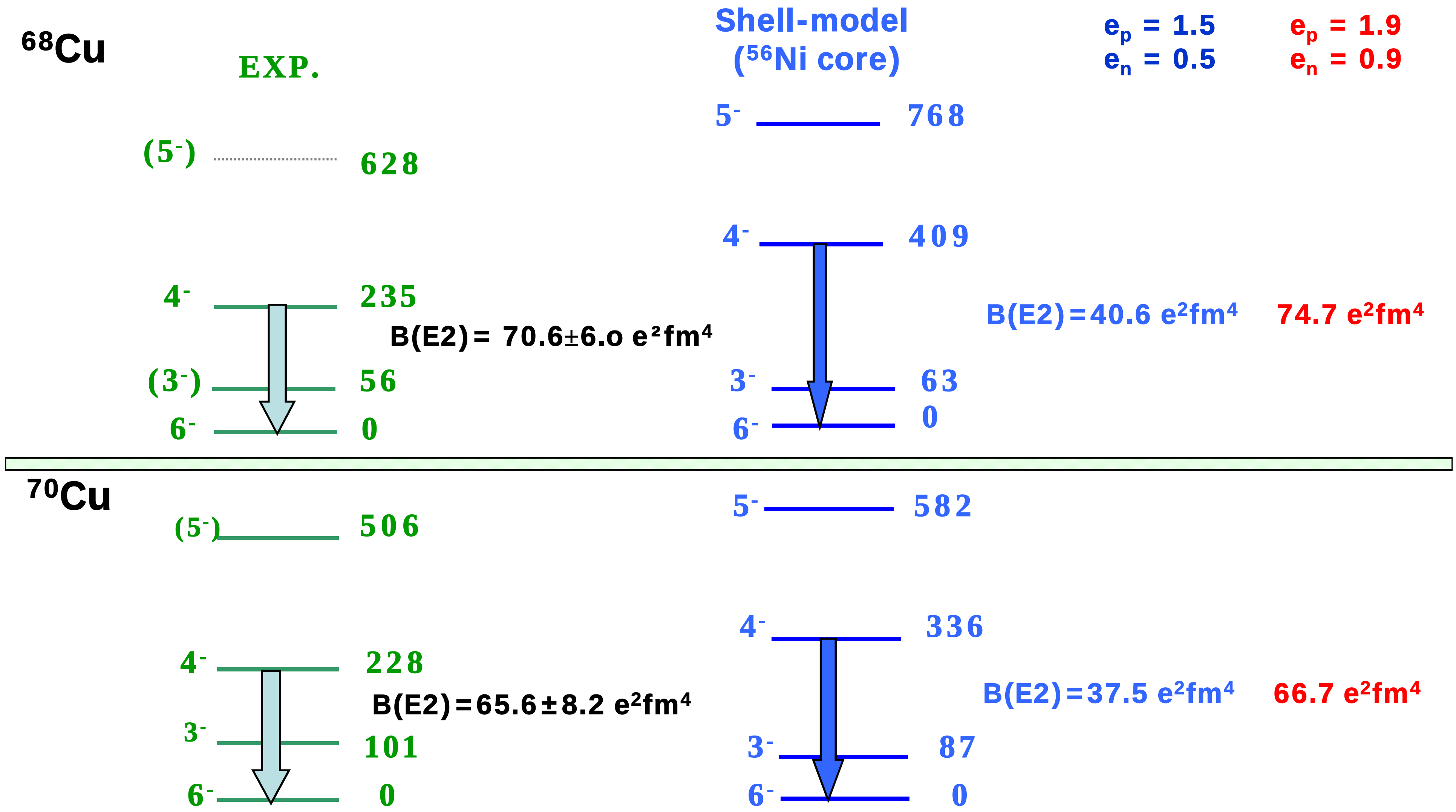






I. Stefanescu et al., PRL 98, 122701(2007).

Comparison to theory



Conclusions and outlook

The present generation of laboratories and instruments allows to keep the European lead in nuclear structure physics on the international arena

NuPECC Roadmap for Nuclear Science in Europe

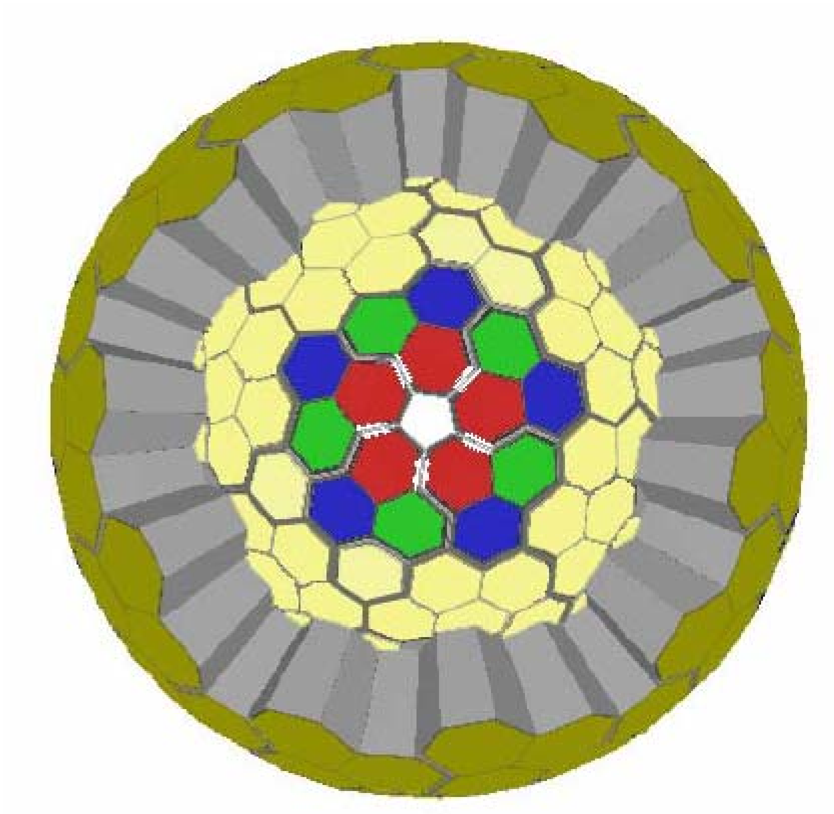
NuPECC recommends as the highest priority for a new construction project the building of the international "Facility for Antiproton and Ion Research (FAIR)" at the GSI, Darmstadt.

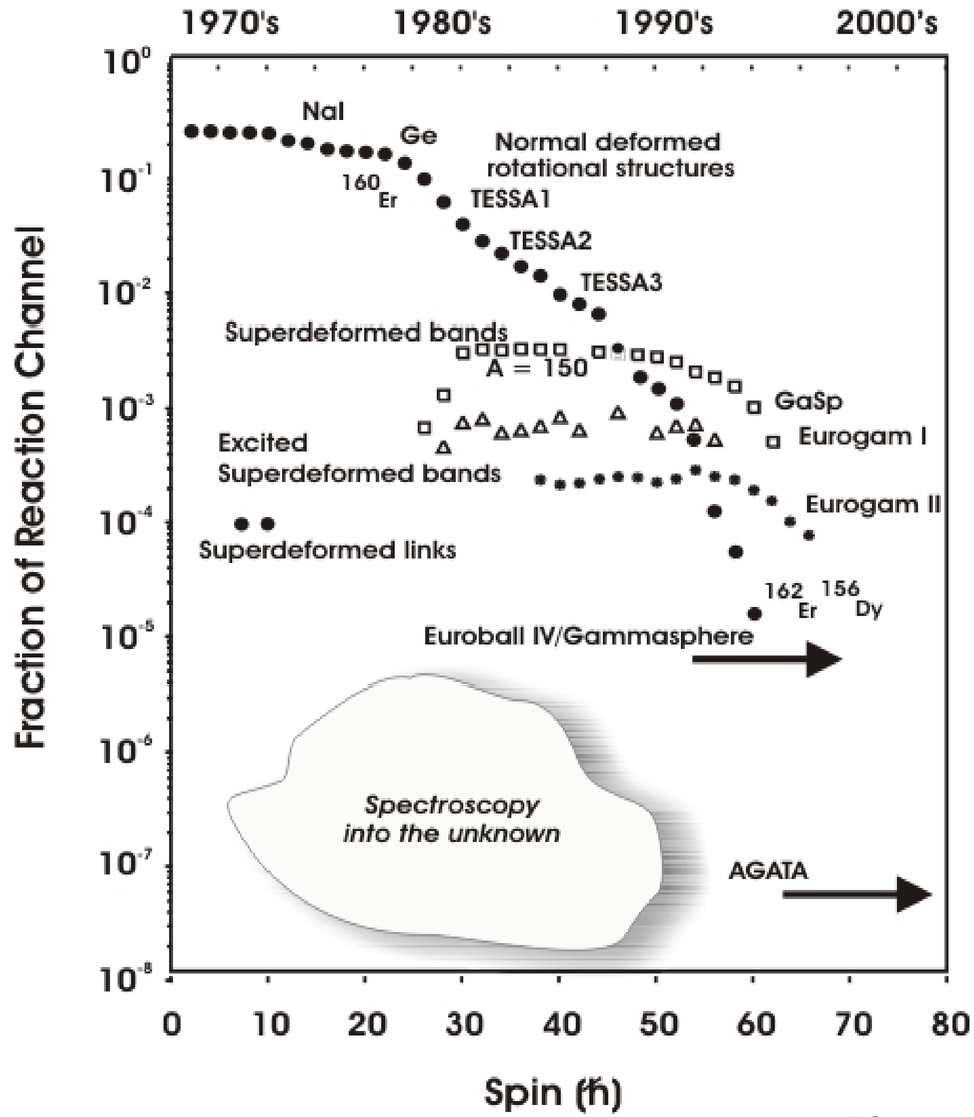
After FAIR, NuPECC recommends the highest priority for the construction of EURISOL.

NuPECC gives full support for the construction of AGATA and recommends that the R&D phase be pursued with vigour.

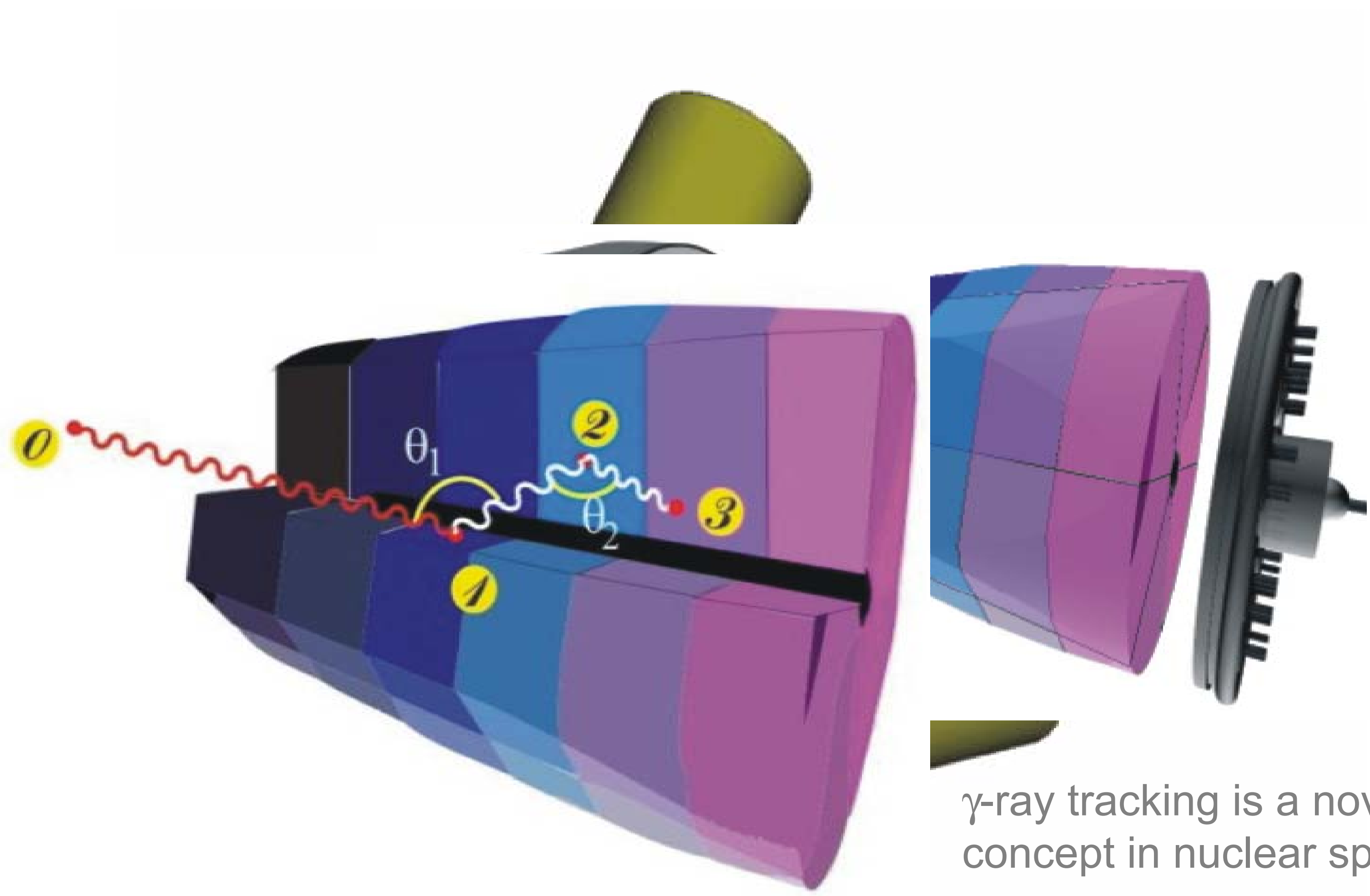
Because of the time-line of EURISOL NuPECC strongly recommends the building of intermediate-generation RIB facilities of the ISOL type. Of these SPIRAL2 meets the criteria of a European large research infrastructure in terms of scientific potential and size of investment and will deliver RIBs in 2009.

The AGATA spectrometer





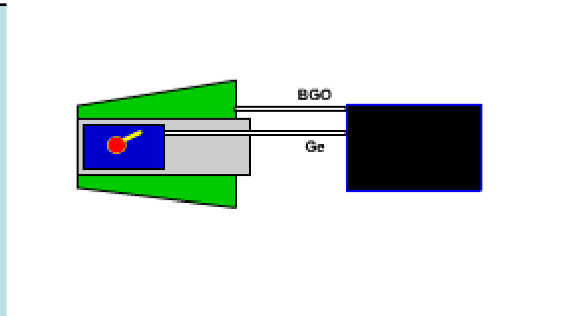
What is AGATA

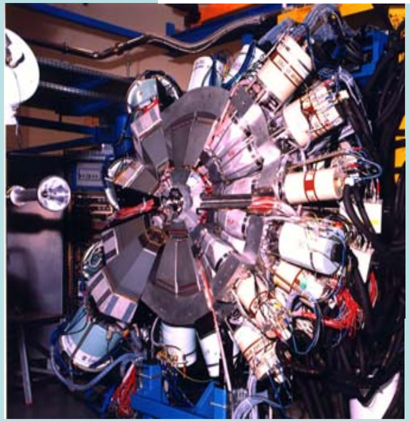


γ-ray tracking is a novel concept in nuclear spectroscopy

Idea of γ-ray tracking

Large Gamma Arrays based on Compton Suppressed Spectrometers



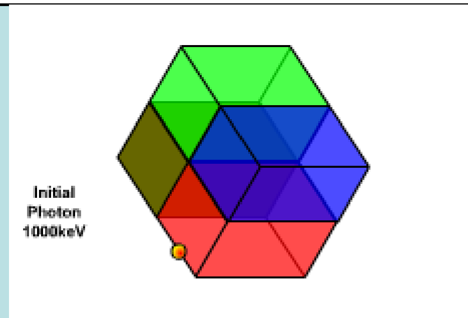


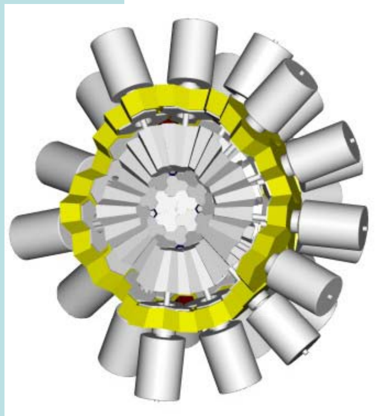
EUROBALL

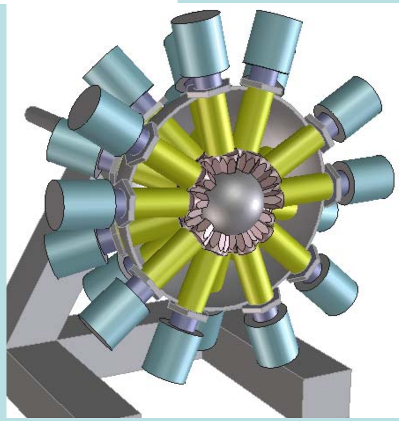
GAMMASPHERE

$\varepsilon \sim$ **10 — 5 %**
(M_γ=1 — M_γ=30)

Tracking Arrays based on Position Sensitive Ge Detectors







AGATA

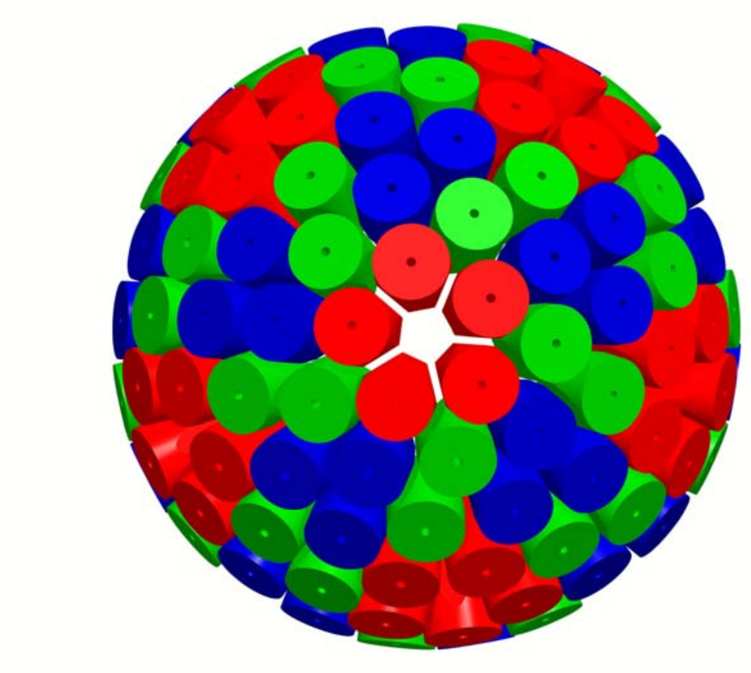
GRETA

$\varepsilon \sim$ **40 — 20 %**
(M_γ=1 — M_γ=30)

Exogam, Miniball, SeGa: optimized for Doppler correction at low γ-multiplicitiy → ε up to 20%

AGATA
(Design and characteristics)

4π γ-array for Nuclear Physics Experiments at European accelerators providing radioactive and stable beams



Main features of AGATA

Efficiency: 43% (M_γ=1) 28% (M_γ=30)
today's arrays ~10% (gain ~4) 5% (gain ~1000)

Peak/Total: 58% (M_γ=1) 49% (M_γ=30)
today ~55% 40%

Angular Resolution: ~1° →
FWHM (1 MeV, v/c=50%) ~ 6 keV !!!
today ~40 keV

Rates: 3 MHz (M_γ=1) 300 kHz (M_γ=30)
today 1 MHz 20 kHz

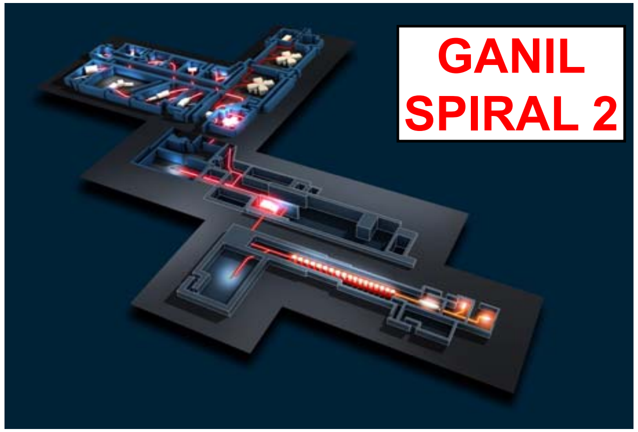
- 180 large volume 36-fold segmented Ge crystals in 60 triple-clusters
- Digital electronics and sophisticated Pulse Shape Analysis algorithms allow
- Operation of Ge detectors in position sensitive mode → γ-ray tracking

The Management of AGATA

FAIR

HIE-ISOLDE

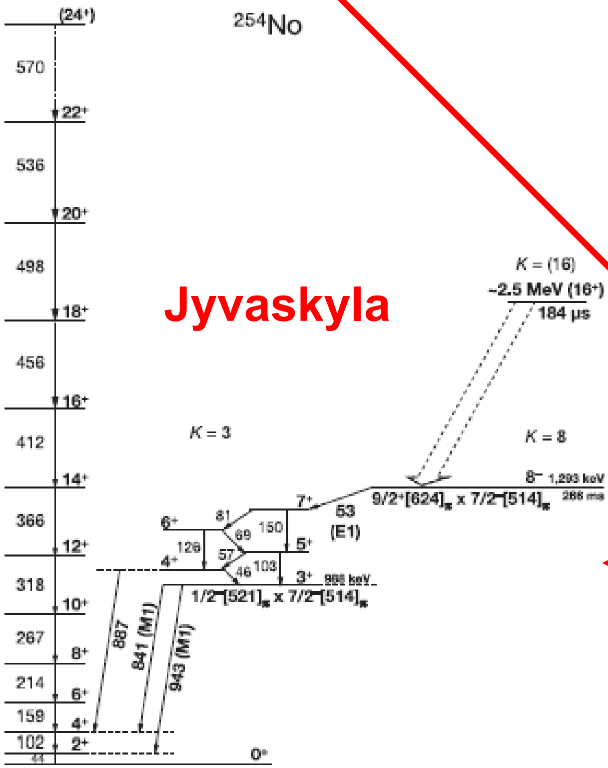
GANIL SPIRAL 2



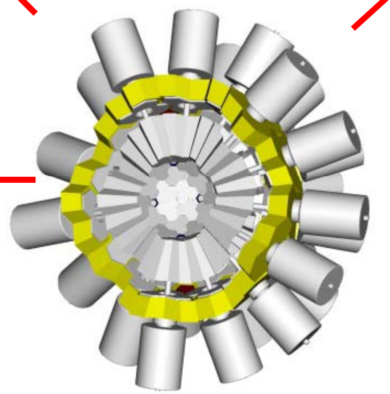
EURISOL
European Separator On-Line
Radioactive Nuclear Beam Facility

INSTRUMENTATION

Jyvaskyla

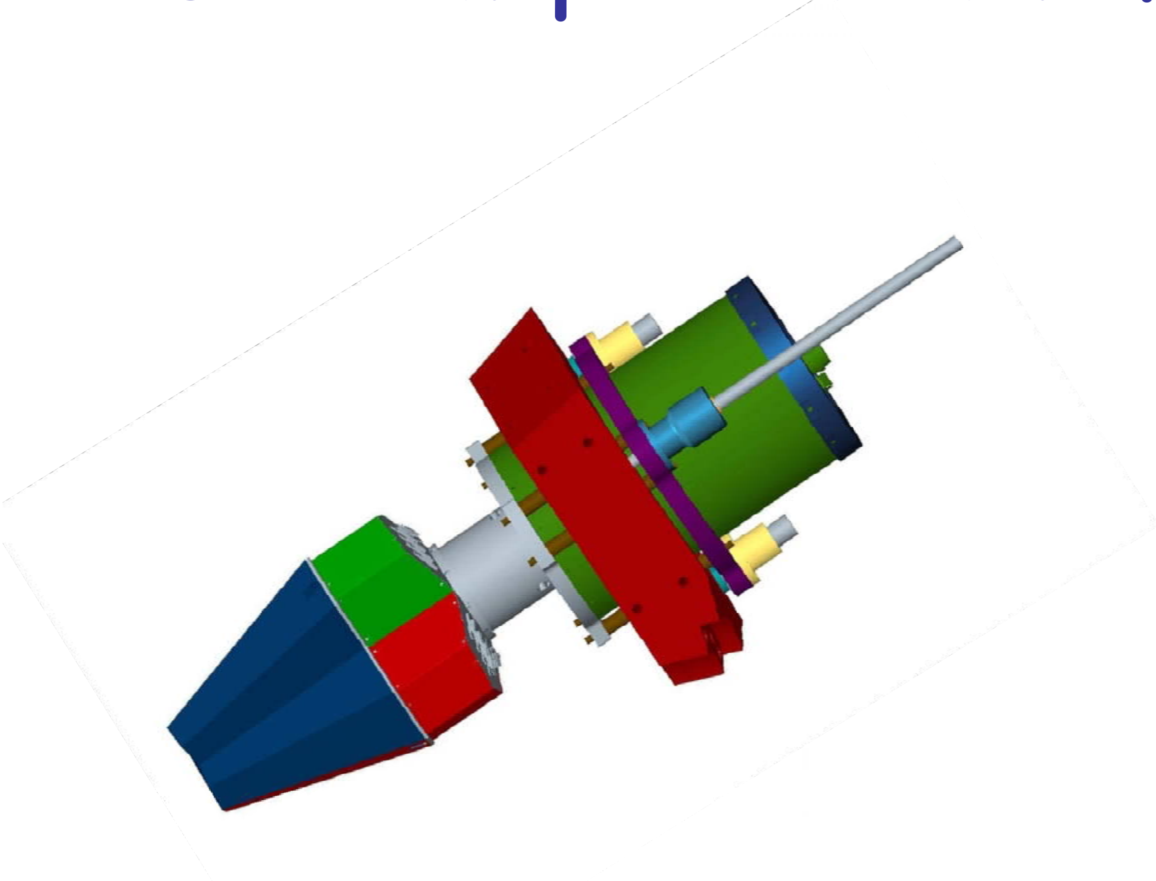


AGATA



LEGNARO

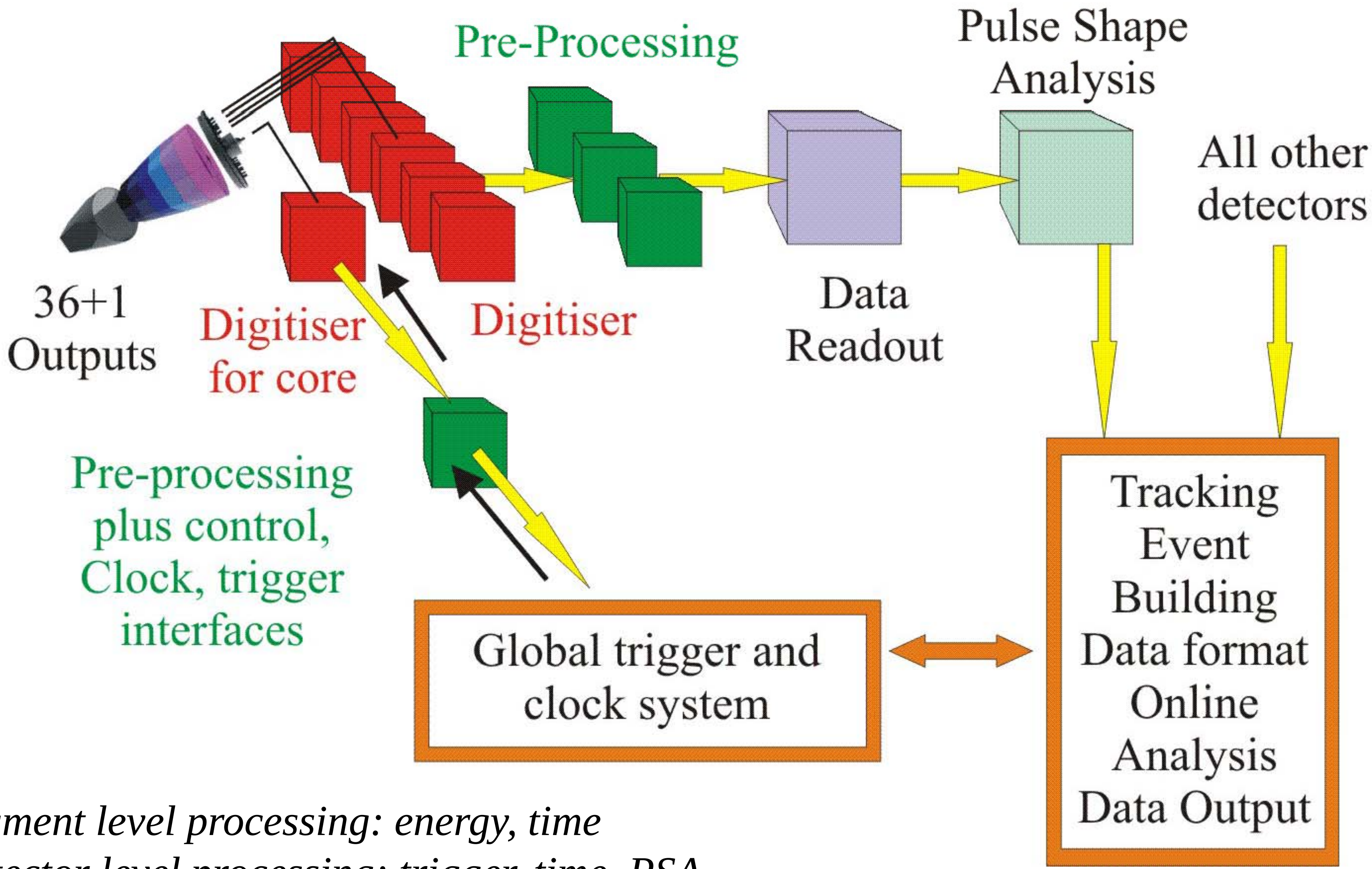
AGATA triple-detector module




First prototype summer 2005

3 encapsulated Ge crystals in one cryostat
111 preamplifiers with cold FET
~230 vacuum feedthroughs
LN_2 dewar, 3 litre, cooling power ~8 watts

Schematic of the Digital Electronics and Data Acquisition System for AGATA



Segment level processing: energy, time

Detector level processing: trigger, time, PSA

Global level processing: event building, tracking, software trigger, data storage

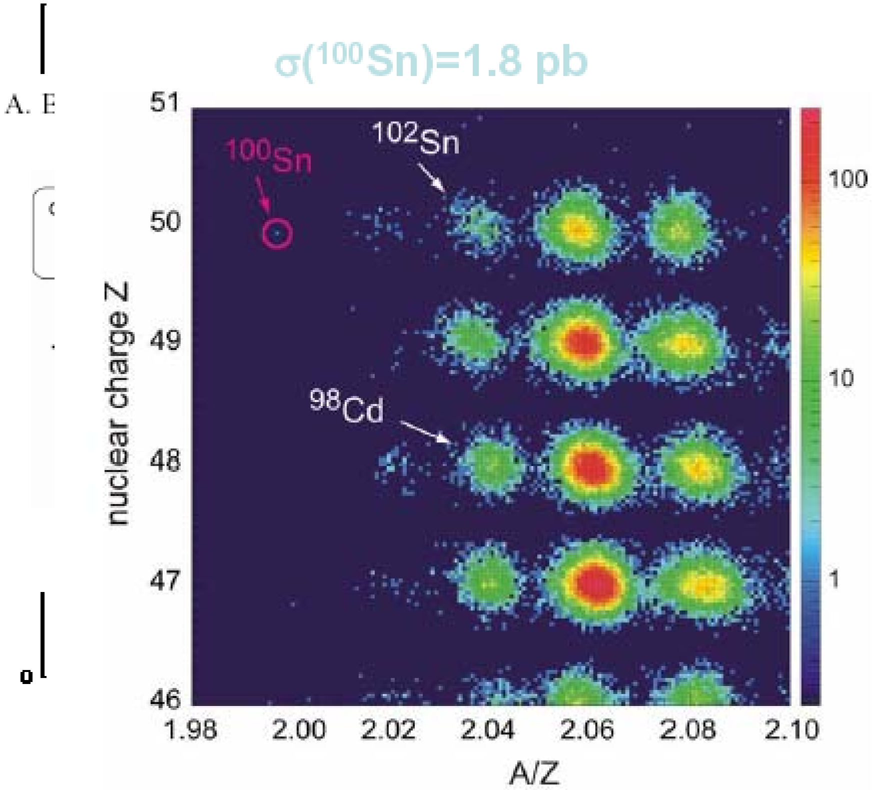
AGATA Digitiser Module

36+1 channels, 100 MhZ, 14 bits
(Strasbourg - Daresbury – Liverpool)

- Mounted close to the Detector *5-10 m*
- Power Dissipation around 400W
- Water Cooling required
- Testing in Liverpool
  (December 2006)
- Production in progress
  (for 18 modules)

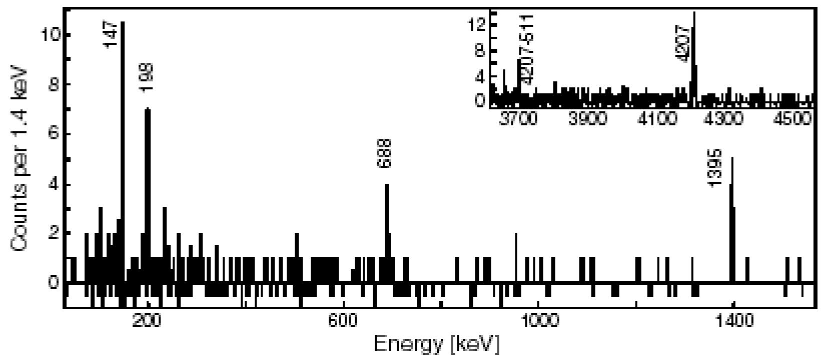
Simulation of state-of-the-art results: Demonstration of the superiority of AGATA

Identification of the Doubly Magic ^{100}Sn



"It is a challenge to the future experiments to verify the predicted $I^{\pi} = 14^{+}$ E6 isomer in ^{98}Cd and $I^{\pi} = 6^{+}$ E2 isomer in ^{100}Sn."

towards spectroscopy of ^{100}Sn



A Blazhev et al, PRC 69, 064304 (2004)

EUROBALL

Българска учителска програма, ЦЕРН, 12 – 18 Октомври, 2008г.

Bulgarian Teacher Programme, CERN, 12 – 18 October, 2008

Проект и реализация

Project and Realisation

European Organization for Nuclear Research

Европейска организация за ядрени изследвания

European Organization for Nuclear Research

ИЯИЯЕ INRNE

Институт за ядрени изследвания и ядрена енергетика, Българска академия на науките

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences

ОБЩЕСТВО НА УЧИТЕЛИТЕ НОВАТОРИ В БЪЛГАРИЯ

Общество на учителите новатори в България

Society of Innovative Teachers in Bulgaria

СЪЮЗ НА ФИЗИЦИТЕ В БЪЛГАРИЯ

Съюз на физиците в България – клон Варна

Bulgarian Union of Physicists – branch Varna

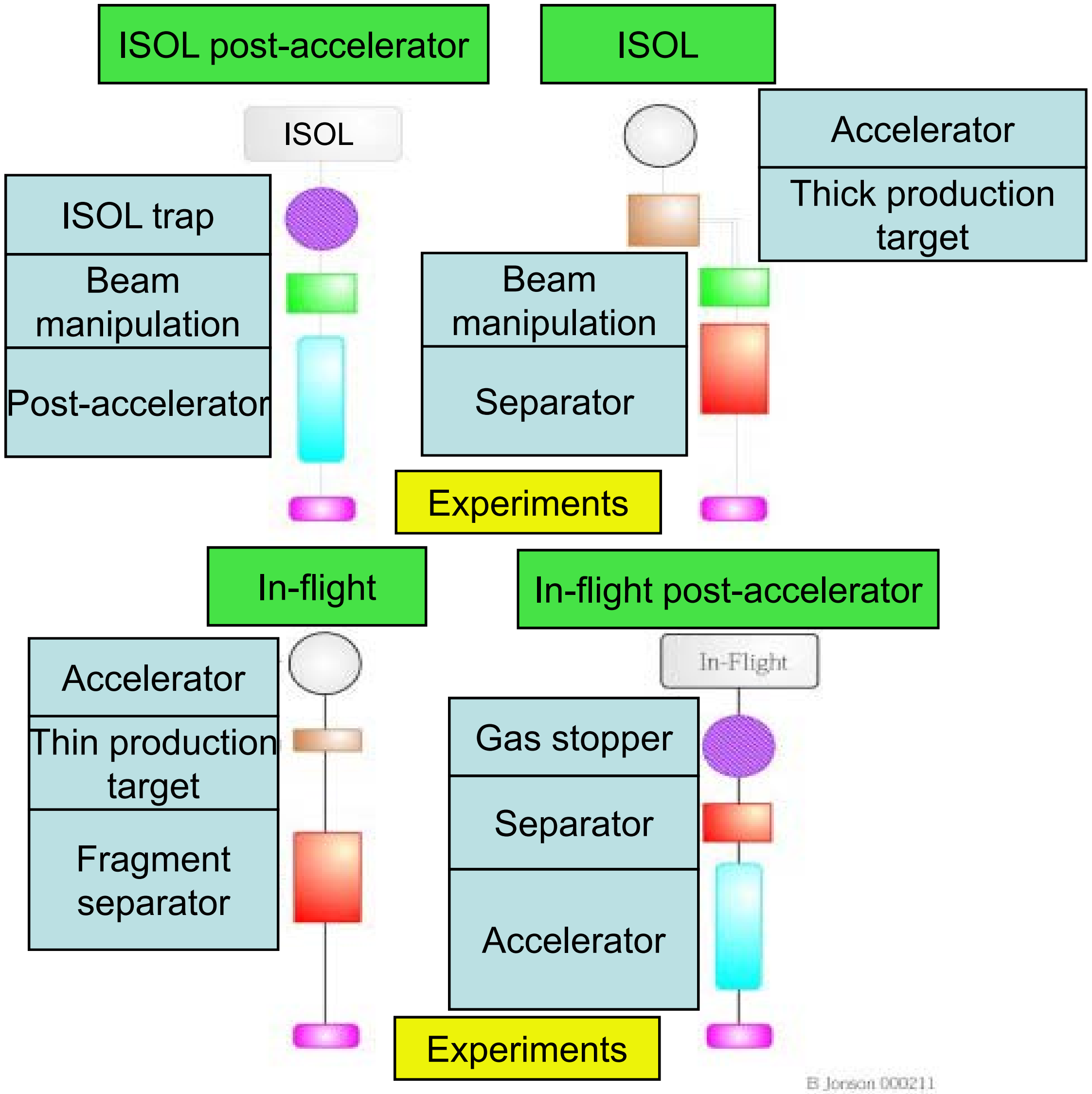
РИО – Варна

Regional Educational Inspectorate – Varna

ВАРНА

Община Варна

Varna Municipality

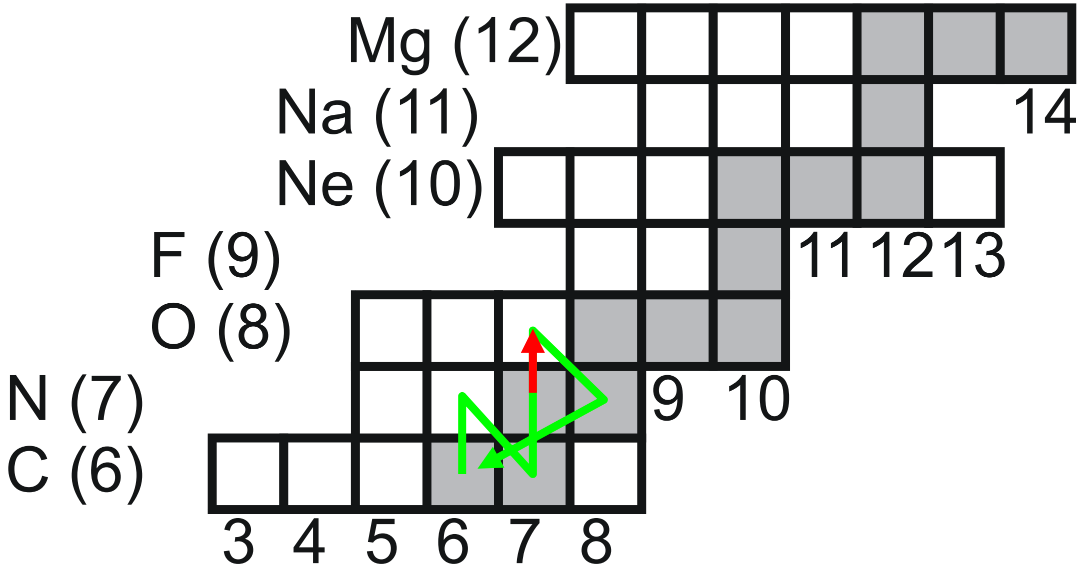


A schematic view of the basic methods of producing radioactive nuclear beams. At the top we see the ISOL method with and without a post-accelerator. Below we see the In-flight method and the proposed hybrid in which fragments are caught in a gas cell and then re-accelerated.

“Cold” CN(O)-Cycle $T_9 < 0.08$

Energy production rate:

$$\varepsilon \propto <\sigma v>_{14N(p,\gamma)}$$



Hot CN(O)-Cycle $T_9 \sim 0.08\text{-}0.1$

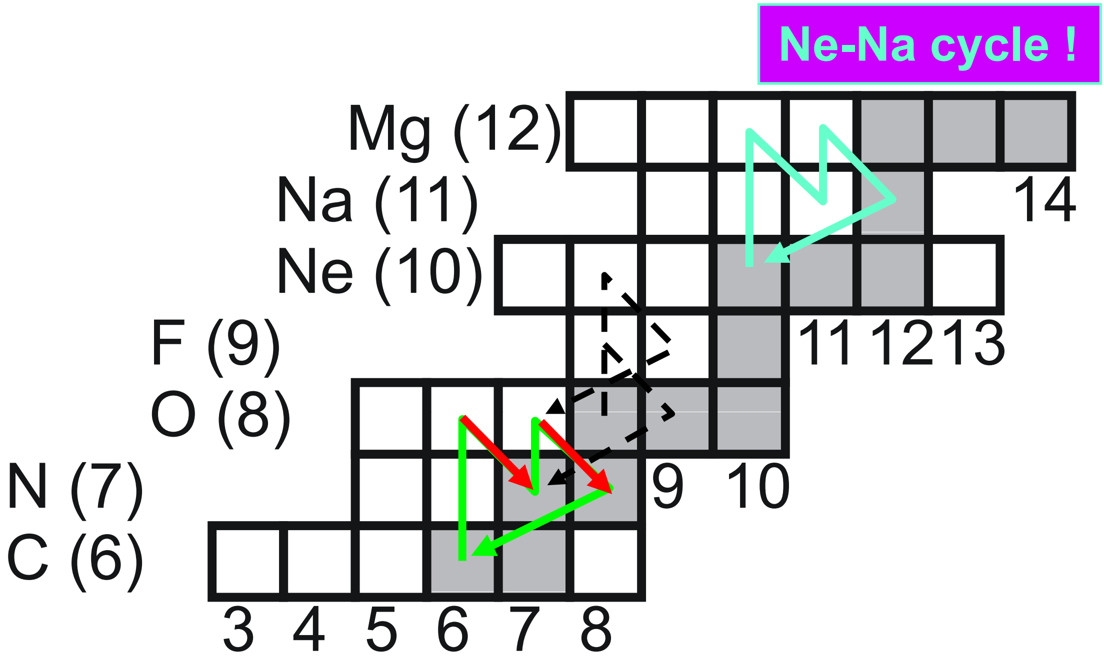
“beta limited CNO cycle”

$$\varepsilon \propto 1/(\lambda^{-1}_{14O(\beta+)} + \lambda^{-1}_{15O(\beta+)}) = \text{const}$$

Note: condition for hot CNO cycle depend also on density and Y_p:

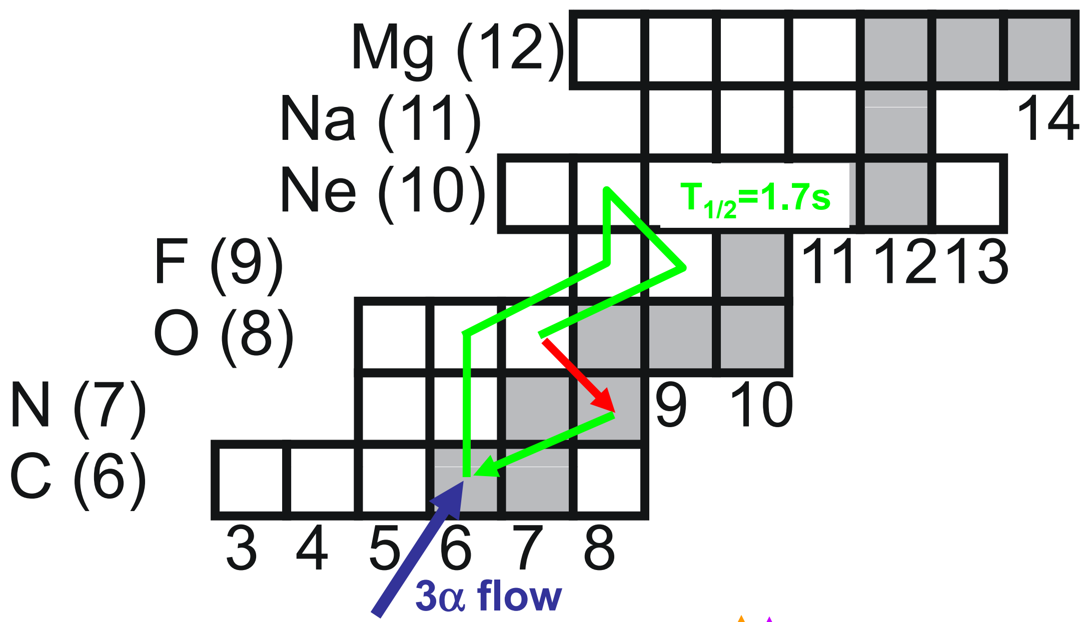
on ^{13}N: $\lambda_{p,\gamma} > \lambda_\beta$

$\Leftrightarrow Y_p \rho N_A < \sigma v > \; > \lambda_\beta$



Very Hot CN(O)-Cycle $T_9 \sim 0.3$

still “beta limited”

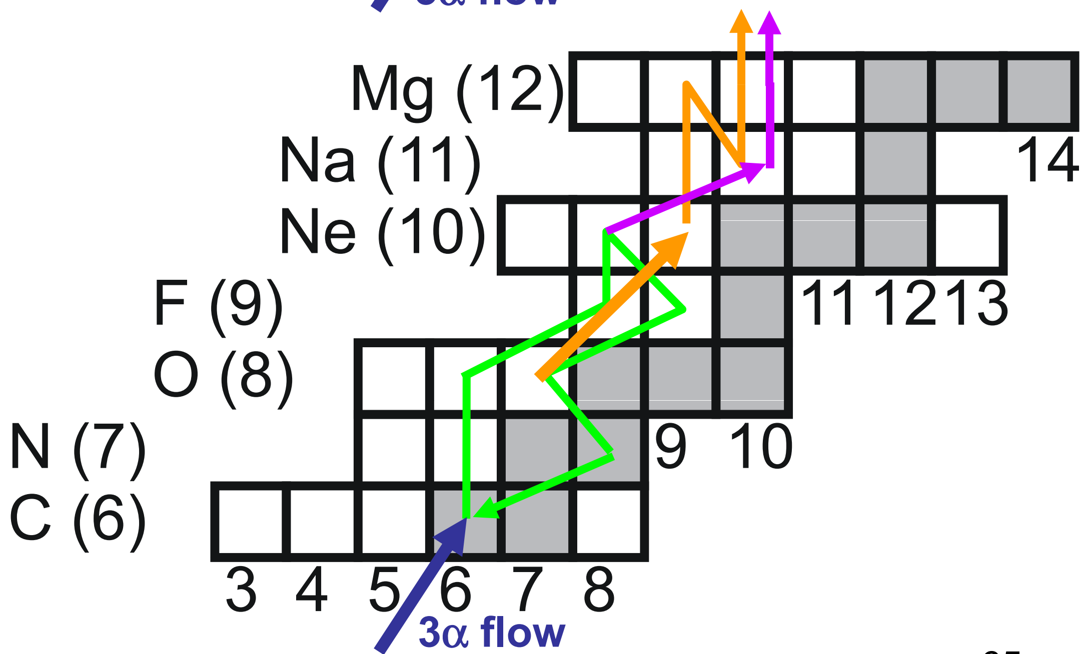


Breakout

processing beyond CNO cycle
after breakout via:

T_9 >~ 0.3 $^{15}O(\alpha,\gamma)^{19}Ne$

T_9 >~ 0.6 $^{18}Ne(\alpha,p)^{21}Na$



The AGATA Organisation
(Many thanks to everybody)

AGATA Steering Committee

Chairperson: W.Korten (and EURONS) Vice Chairperson: P.J. Nolan

**G.deAngelis, A.Atac, F. Azaiez, D.Balabanski, D.Bucurescu, B.Cederwall,
J. Gerl, J.Jolie, R.Julin, W.Meczynski,, M.Pignanelli, G.Sletten, P.M.Walker**

AGATA Management Board

J.Simpson (Project Manager)

D.Bazzacco, G.Duchêne, P. Reiter, A.Gadea, J.Nyberg, Ch. Theisen

AGATA Working Groups

Detector module P.Reiter	Front-end Processing D.Bazzacco	Data Acquisition Ch. Theisen	Design and Infrastructure G. Duchêne	Ancillary detectors and integration A.Gadea	Simulation and Data Analysis J.Nyberg

AGATA Teams

Detector and Cryostat A. Linnemann	Digitisation P.Medina	Data acquisition X.Grave	Mechanical design J.Strachan	Elec. and DAQ integration P. Bednarczyk	Gamma-ray Tracking A.Lopez-Martens
Preamplifiers A.Pullia	Pre-processing I.Lazarus	Run Control & GUI G.Maron	Infrastructure P.Jones	Devices for key Experiments N.Redon	Physics & exp. simulation E.Farnea
Detector Characterisation A.Boston	Global clock and Trigger M.Bellato		R & D on gamma Detectors D.Curien	Impact on performance M.Palacz	Detector data base K.Hauschild
	PSA R.Gernhaeuser/ P.Desesquelles			Mechanical Integration J. Valiente Dobon	Data analysis O.Stezowski