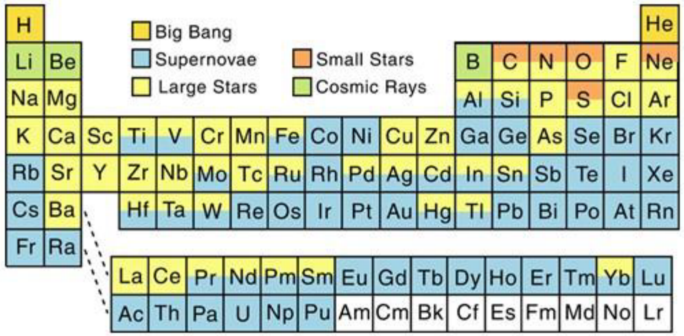
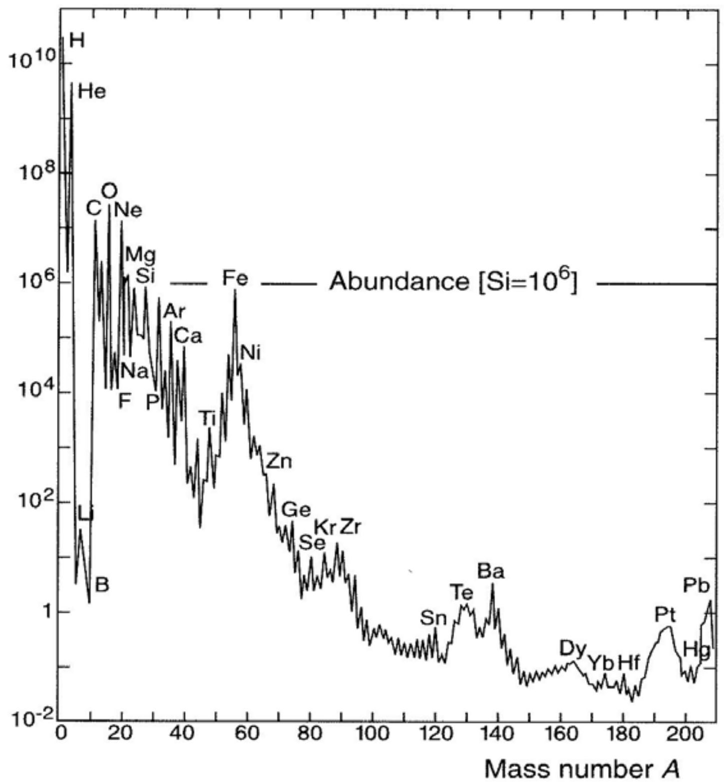
GSI/FAIR
The Universe in the Laboratory

Nuclear Astrophysics: the origin of the elements



periodic table



Data sources:

Earth, Moon, meteorites, cosmic rays, solar & stellar spectra…

Features:

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

How, where and when have the elements been made?

Our place in the Universe

the Earth D ~ $6.4 \cdot 10^3$ km

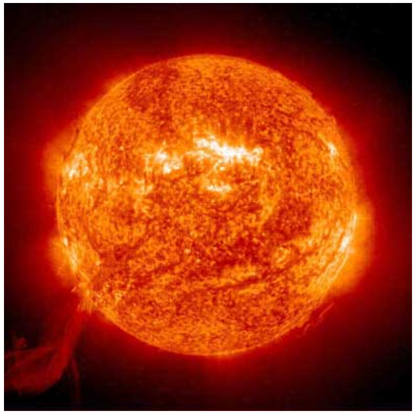
$T \sim 15 \cdot 10^6$ K (our Sun)

$T \sim 10^{10}$ K (Big Bang)

average kinetic energy:

$kT \sim 8.6 \cdot 10^{-8}\, T[K]$ keV

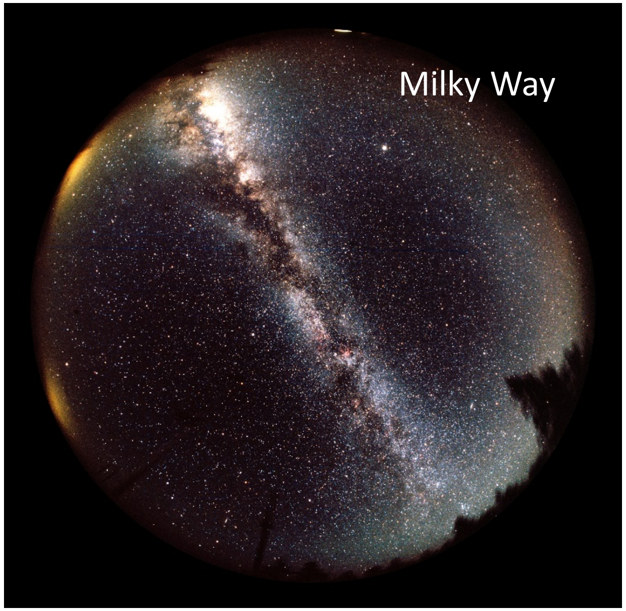
the Sun R ~ $6.9 \cdot 10^5$ km



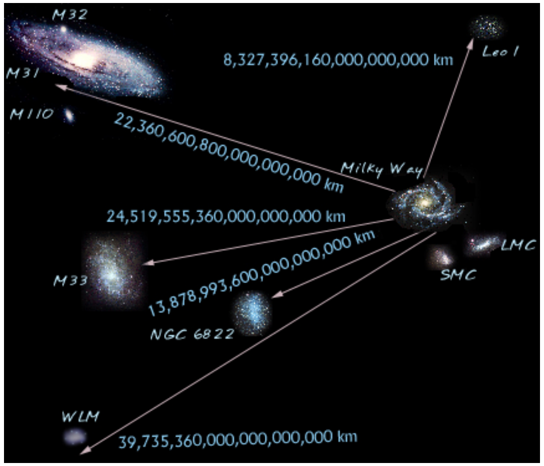
typical star

$M_o = 2 \times 10^{30}$ kg

our Galaxy D ~ $9 \cdot 10^{17}$ km, 10^{11} stars



the local group D ~ $4 \cdot 10^{19}$ km 10-100 galaxies



Zoo of different stars:

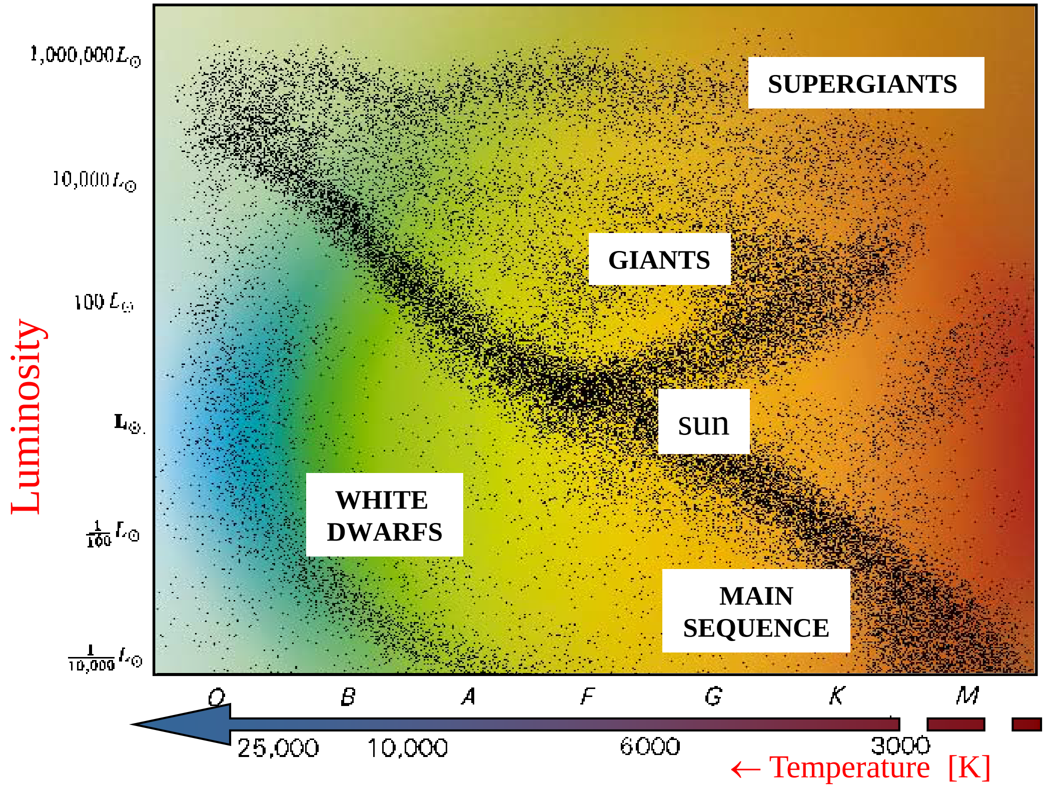
Planetary nebulae
Red giants, Novae
Supernovae, Pulsars…

Zoo of different galaxies:

spherical, elliptical,
spiral, radio, quasars

- How do stars form, live and die?
- What are they made of and what makes them shine?

Hertzsprung-Russell (HR) diagram



No chaos, but order!

~ 95% of all stars in diagonal band called MAIN SEQUENCE

- ➢ highest probability of observing them in this stage
- ➢ longest stage in a star’s lifetime

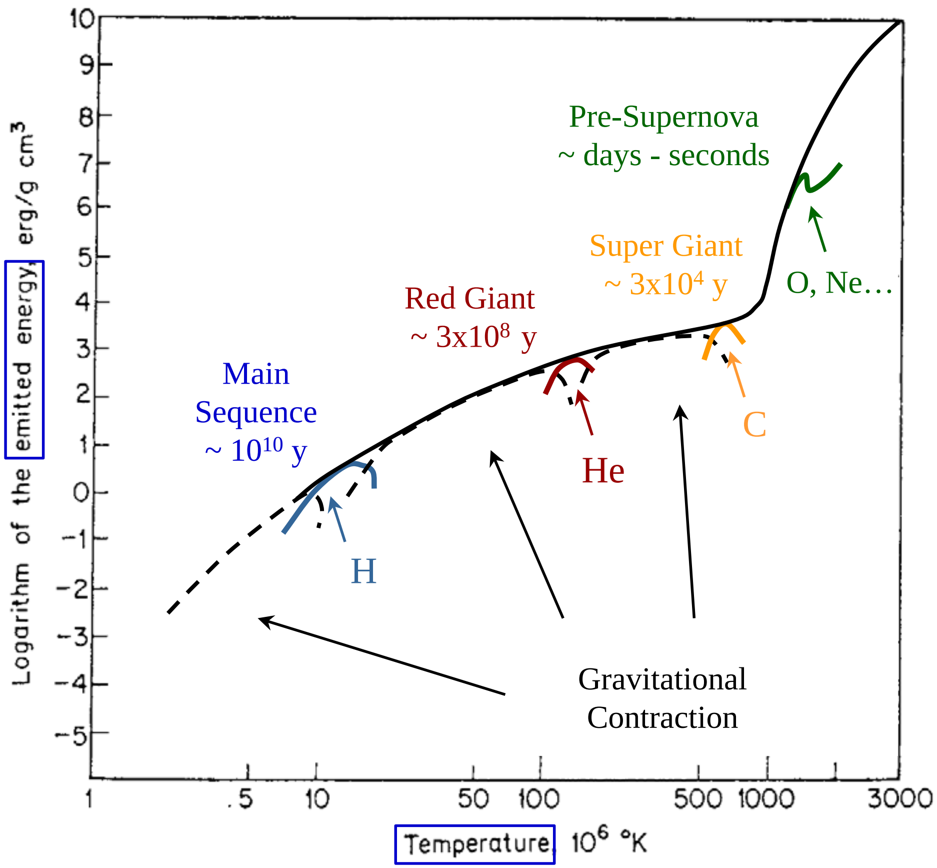
Question: how long do stars live?

Stellar evolution…

Main parameters governing evolution: initial mass & initial chemical composition

Example: evolution stages of a 25 $M_\odot$ star

Quiescent burning



Energy generation rate

$\varepsilon \sim T^n$

n ~ 4 (H-burning)

n ~ 30 (C-burning)

innermost regions only contribute to nuclear burning

e.g. 1/10 M for H-burning
less for subsequent stages

H-burning ≡ MAIN SEQUENCE
longest stage of star's lifetime

… and nucleosynthesis

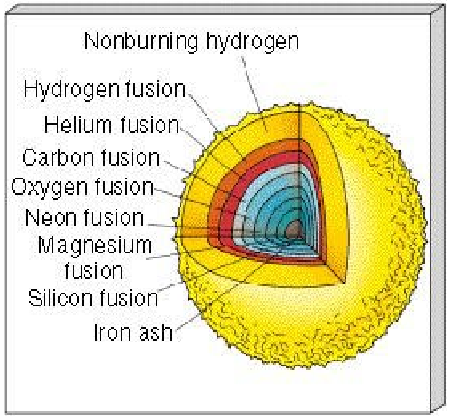
		nucleosynthesis	energy
HYDROGEN BURNING	(1st equilibrium)	$4p \rightarrow {}^{4}He + 2\beta^{+} + 2\nu$ +	26 MeV
HELIUM BURNING	(2nd equilibrium)	$3\alpha \rightarrow {}^{12}C$; ${}^{12}C(\alpha,\gamma){}^{16}O$	+ 8 MeV

${}^{12}C/{}^{16}O$ BURNING

… ${}^{12}C$ ashes = Ne, Na, Mg

… ${}^{16}O$ ashes = Al, … Si

T, ρ



${}^{28}Si$ MELTING

major ash = ${}^{56}Fe$

… A = 40-65

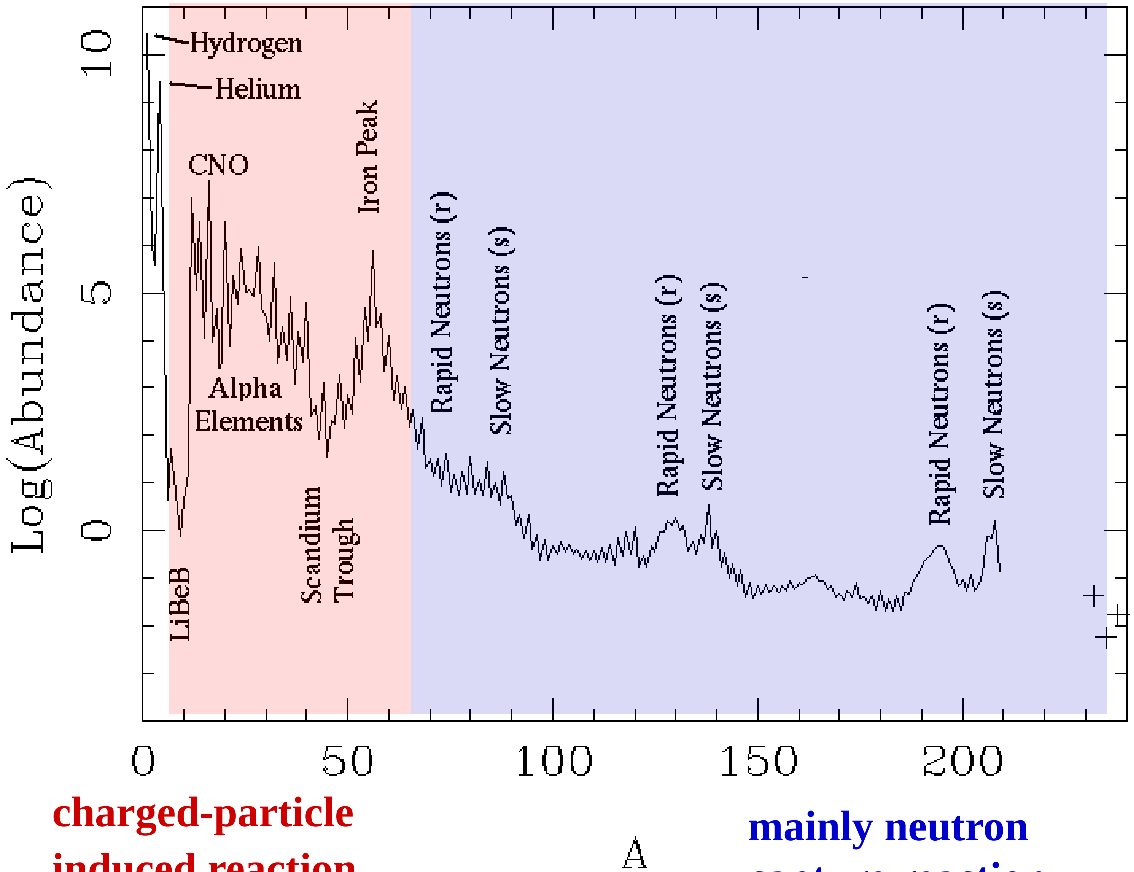
further reactions endothermic gravitational collapse

SUPERNOVA EXPLOSION

neutron star

black hole

Synthesis of the trans-iron elements



charged-particle induced reaction

mainly neutron capture reaction

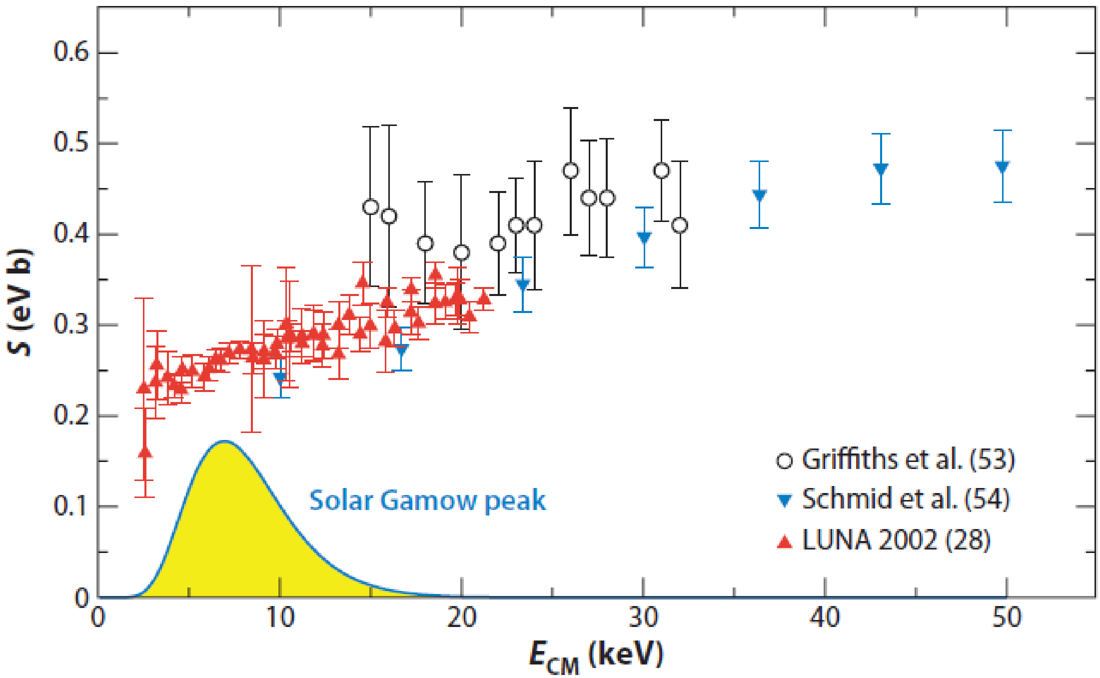
during quiescent stages of stellar evolution

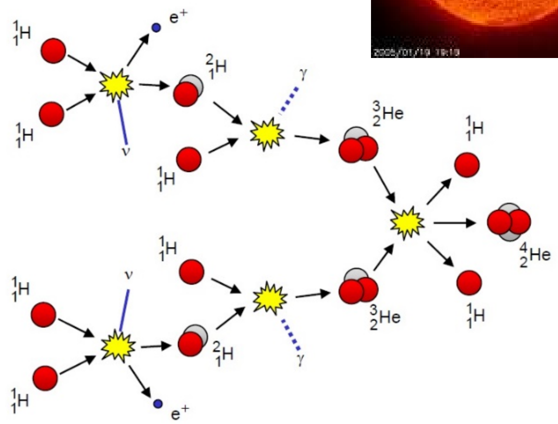
mainly during explosive stages of stellar evolution

involve mainly STABLE NUCLEI

involve mainly UNSTABLE NUCLEI

The $^2H(p,\gamma)^3He$ reaction solar fusion





$$\sigma(E) = S(E) \cdot e^{-2\pi\eta(E)}/E$$

$$\eta = \frac{Z_1 \cdot Z_2 \cdot e^2}{\hbar \cdot v_\infty}$$ Sommerfeld parameter

Laboratory
Underground
Nuclear
Astrophysics

LUNA demonstrate, for the first time, that it is possible to direct study solar fusion in the Gamow window from underground laboratories.

only three reactions studied directly at Gamow peak

LUNA @ Laboratori Nazionali Gran Sasso

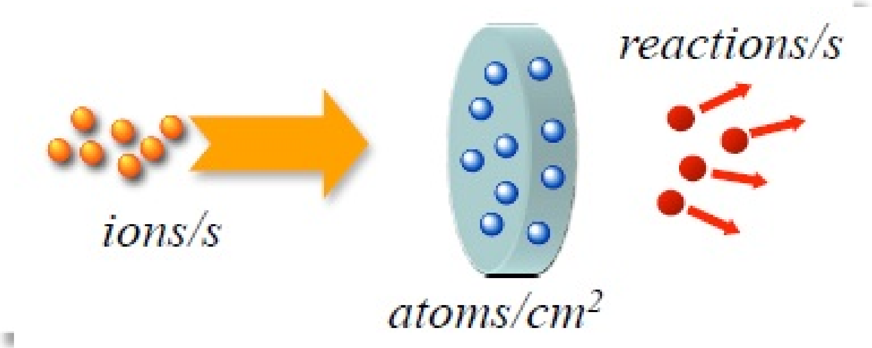
Rock as passive shielding
cosmic ray background
reduction ~ 10^{-4}

4-50 keV accelerator
p-, α-beams ≤ 1 mA

study of pp-chains
e.g. $^{3}He + {}^{3}He$

Nuclear reactions in the laboratory & in space

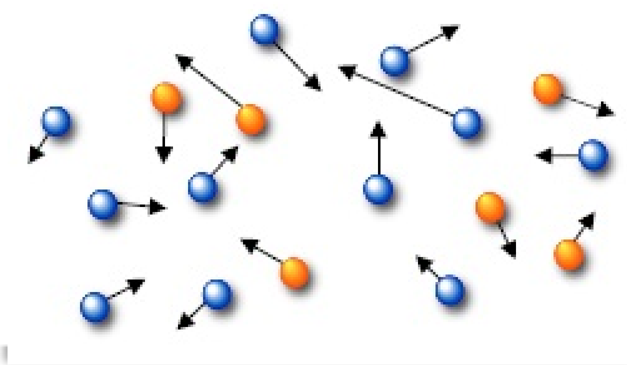
In the lab:



cross section

$$\frac{reactions}{s} = \frac{ions}{s}\,\frac{atoms}{cm^2}\,\sigma$$

In astrophysical events:



reaction rate

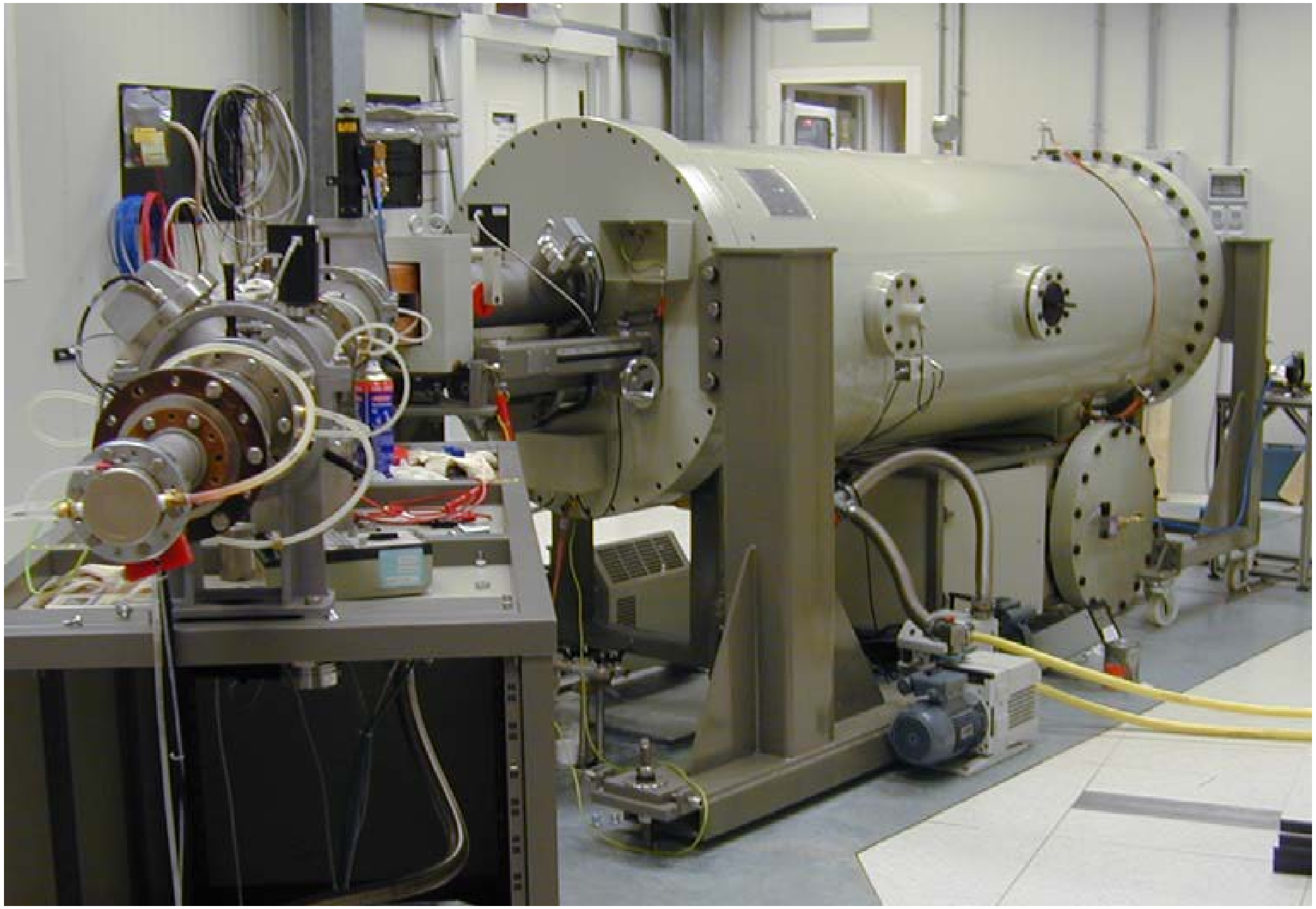
$$\frac{reactions}{cm^3 s} = \int \frac{n_x}{cm^3}\,\frac{n_y}{cm^3}\, v\sigma(v)\phi(v)dv$$

$$\phi(v) = 4\pi v^2 \left(\frac{\mu}{2\pi kT}\right)^{3/2} \exp\left(-\frac{\mu v^2}{2kT}\right)$$

$$\frac{reactions}{cm^3 s} = \frac{n_x}{cm^3}\,\frac{n_y}{cm^3}\,\langle\sigma v\rangle$$

$$\langle\sigma v\rangle = \sqrt{\frac{8}{\pi\mu}}\,(kT)^{3/2}\int_0^\infty \sigma E e^{-E/(kT)} dE$$

LUNA II upgrade



50 – 400 keV

accelerator laboratory

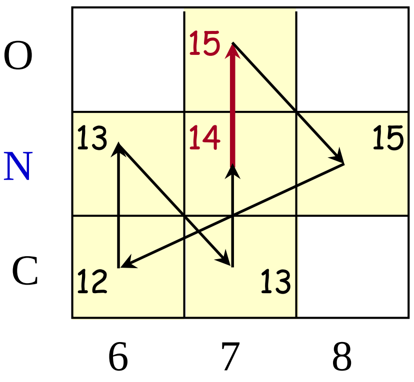
p-, α-beams ≤ 1 mA

Study of p-capture on CNO nuclei (CNO-cycles) and α-capture on light nuclei

Inline-Cockcroft-Walton power supply

$^{14}N(p,\gamma)^{15}O$

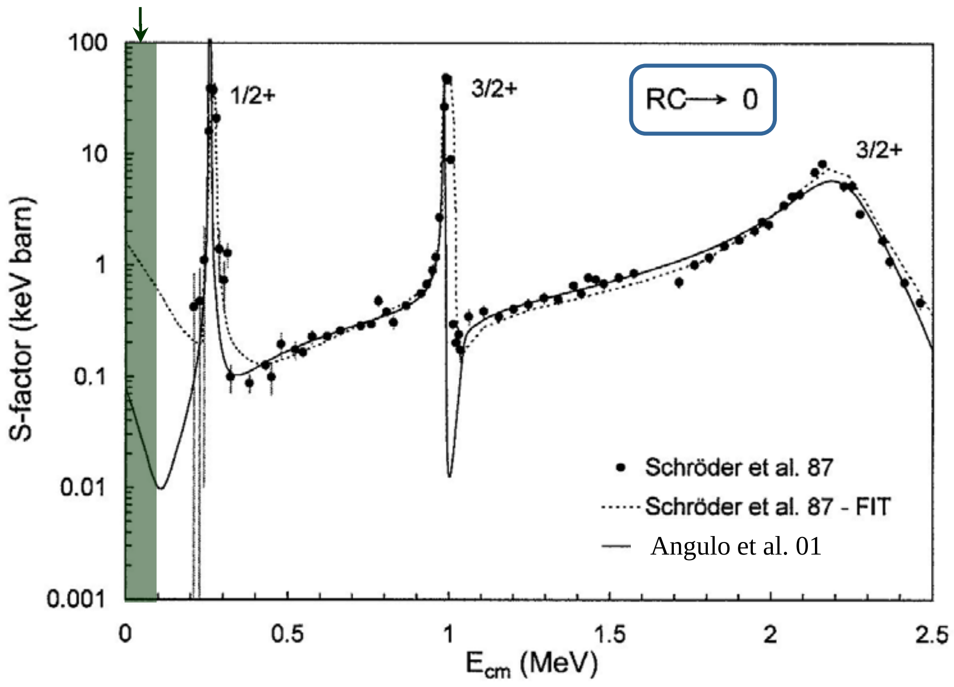
CNO cycle



energy generation rate
in massive main sequence stars

(slowest reaction in CNO cycle)

Astrophysical region:
20-80 keV



$^{14}N(p,\gamma)^{15}O$

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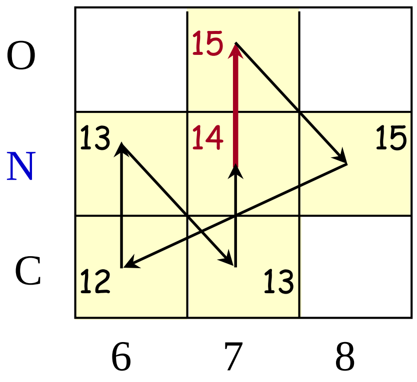
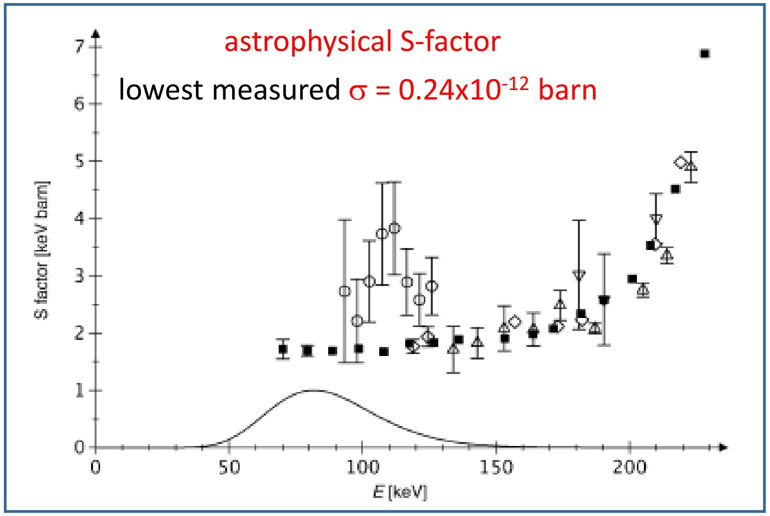
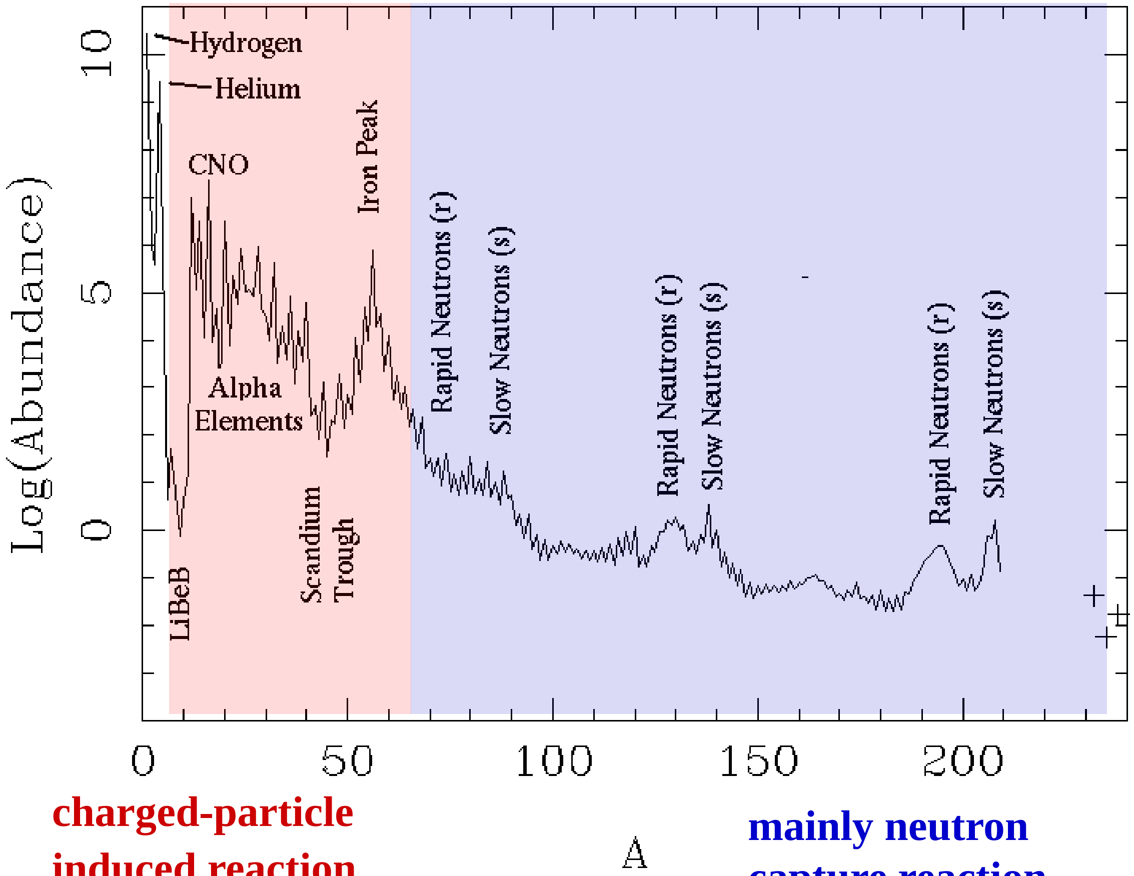
CNO cycle





Synthesis of the trans-iron elements



charged-particle induced reaction

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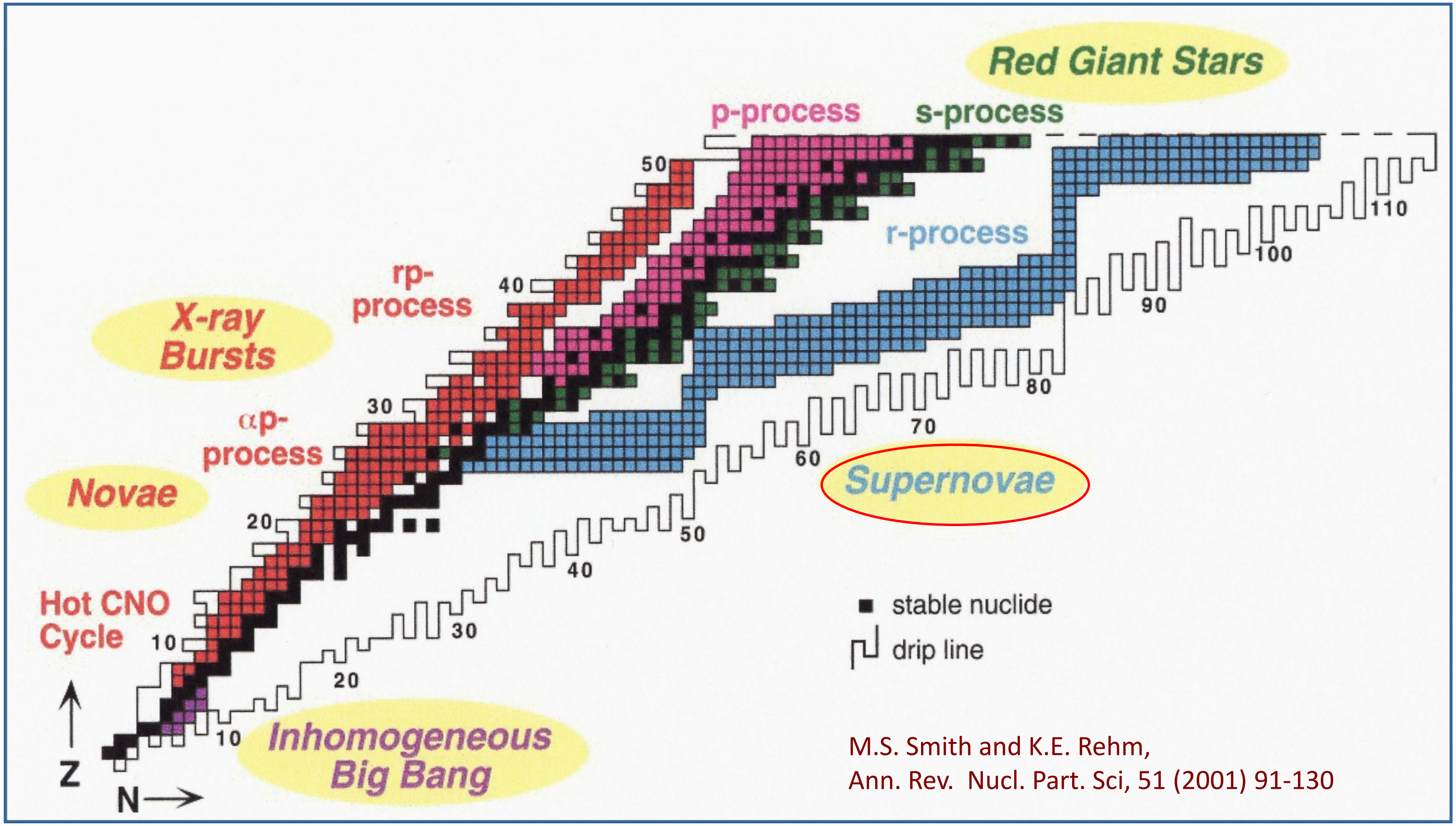
involve mainly STABLE NUCLEI

involve mainly UNSTABLE NUCLEI

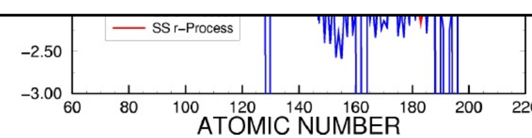
Main nuclear processes and astrophysical sites



- nuclear reaction paths involve UNSTABLE species ⇒ **Radioactive Ion Beams**
- key reactions identified by sensitivity of astrophysical models to nuclear inputs

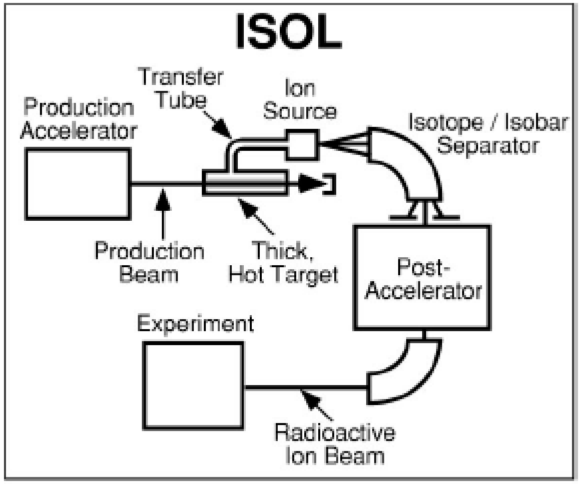
Timescale of the r-process

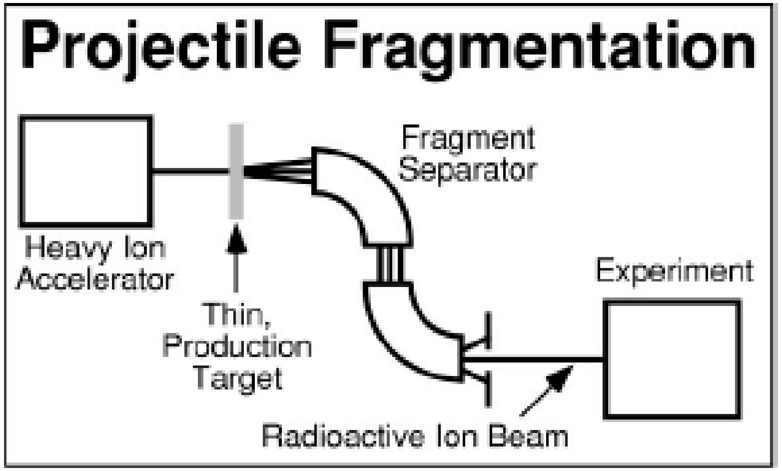
summing up time spent at waiting points: t ~ 0.5 – 10 s



Radioactive Ion Beams production method

- Isotope Separation on Line (ISOL) (CERN, LLN, ORNL, TRIUMF, *ANURIB project*)
- Projectile Fragmentation (PF) (GANIL, GSI, MSU, RIKEN)
- in-flight production (ANL, Notre Dame, TAMU)
- batch mode production (suitable for long-lived species)





☺ excellent quality
high purity
high intensities

☹ limited number of species
different production for different species
limited to nuclei with $t_{½} \geq 1$s (allow for diffusion)

☺ independent from chemical properties
no limitations on $t_{½}$ (fast separation)

☹ typical beam energies too high for NA
poorer beam quality (energy, size)
possible beam contaminations

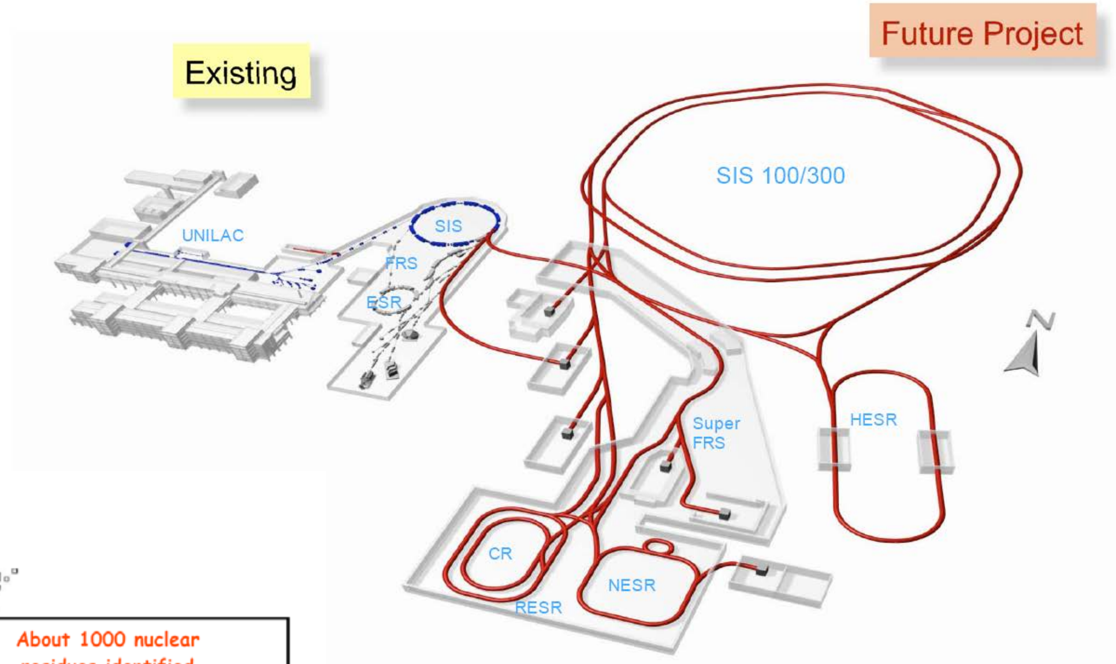
ANURIB: Advanced National facility for Unstable and Rare Isotope Beams

M.S. Smith and K.E. Rehm, Ann. Rev. Nucl. Part. Sci, 51 (2001) 91-130

Radioactive Ion Beams next generation facility

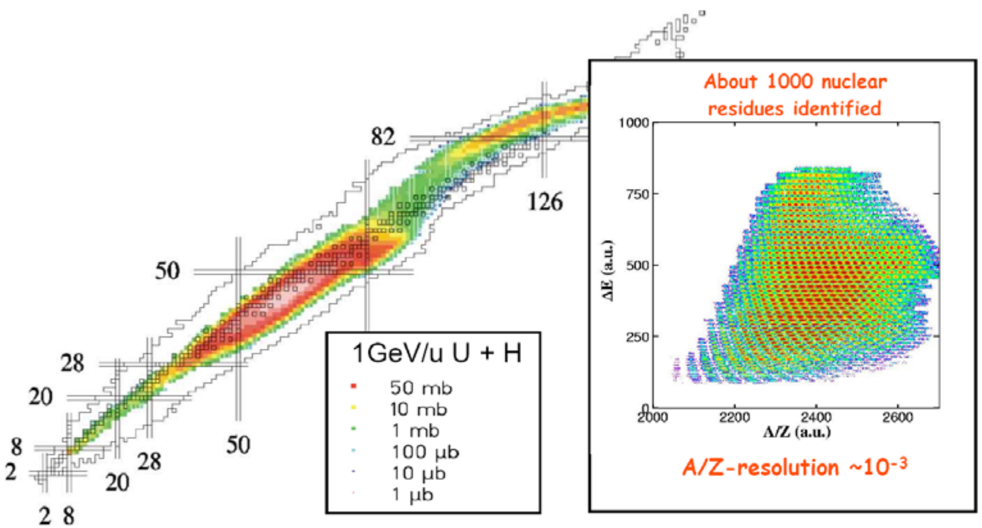
Next generation
RIBs facilities

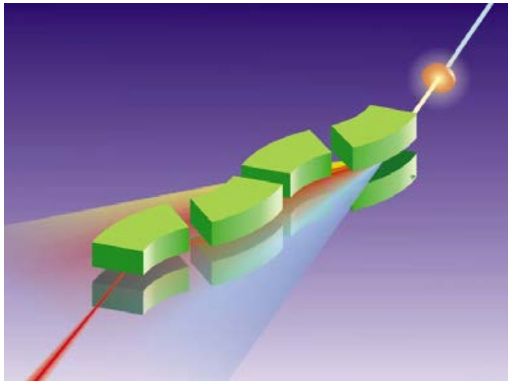
The Future International Facility at GSI:
FAIR – Facility for Antiproton and Ion Research



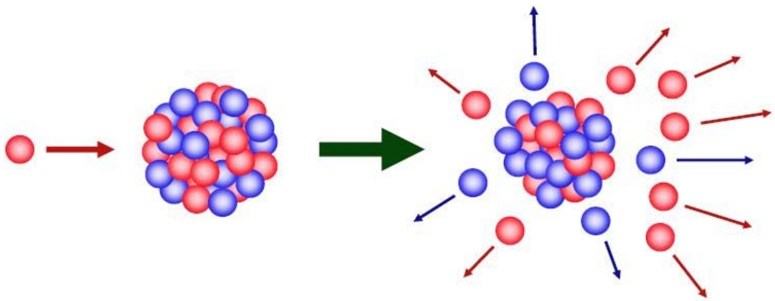
1.0-1.5 GeV/u
all elements up to uranium

P. Armbruster et al.; Phys. Rev. Letters, Jan. 05

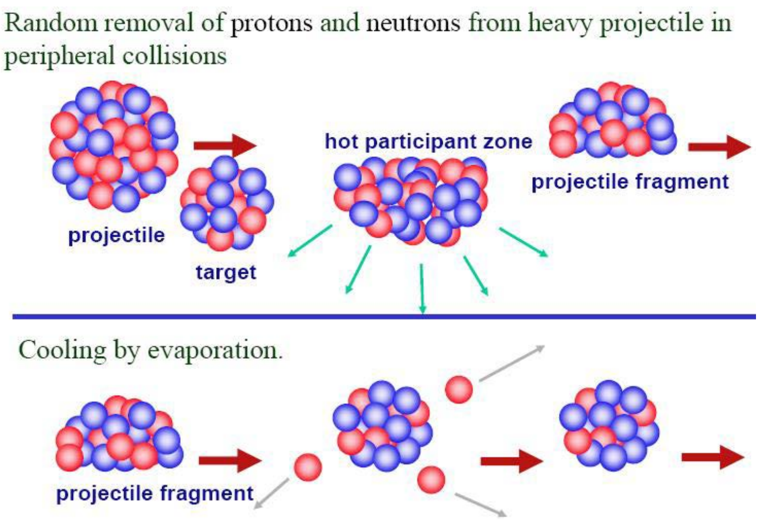




Radioactive Ion Beams production methods



Target fragmentation



Projectile fragmentation

fragmentation invented at LBNL in the 1980´s

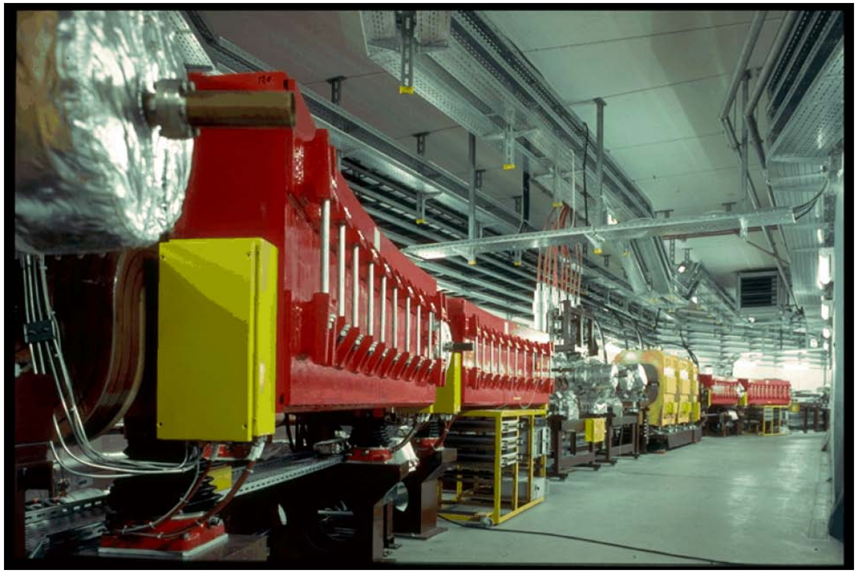
The Universe in the Laboratory

Fast radioactive beams – where?

- GSI since SIS (early 90's)

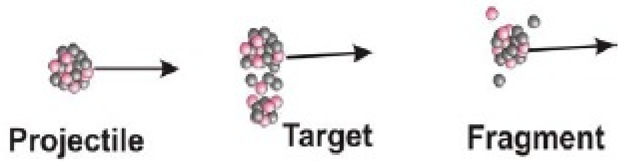
- Intermediate-energy RIBs (tens of MeV/u) since many years at GANIL, MSU, RIKEN

- Future (and current) facilities
  - RIBF@RIKEN
  - FRIB@MSU
  - FAIR-NuSTAR



Production of exotic nuclei at relativistic energies

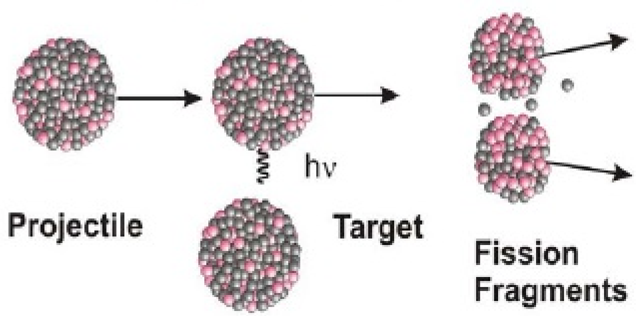
Projectile Fragmentation



Nucleon-nucleon collisions, abrasion, ablation

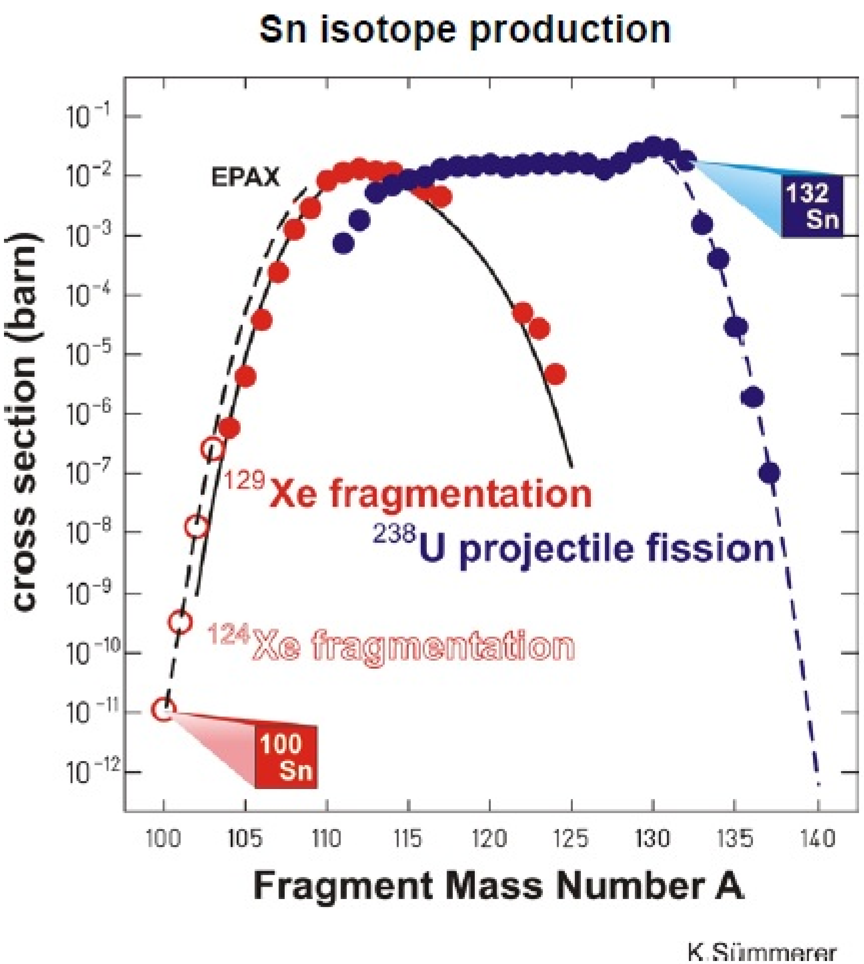
$$\vec{v}_f \approx \vec{v}_p$$

Projectile Fission



Electromagnetic excitation, fission in flight

$$\vec{v}_f \approx \vec{v}_p + \vec{v}_{fission}$$



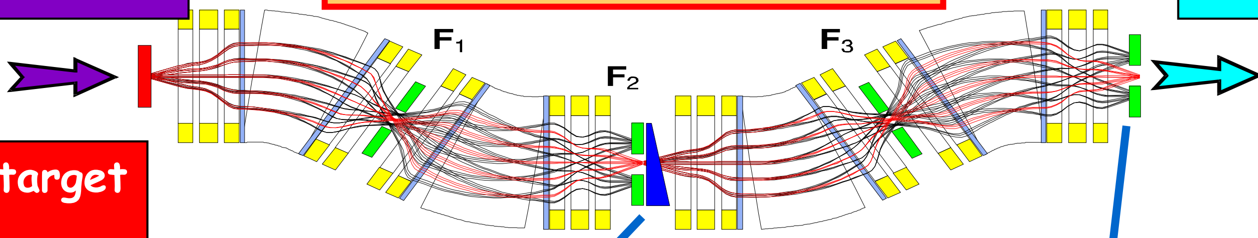
Rare Isotope Selection at FRS: Bρ-ΔE-Bρ Selection

Transmission :
- 20-70 % for fragmentation
- < 2 % for fission

primary beam
^{86}Kr ~700 AMeV

secondary beam
^{78}Ni ~ 100 AMeV

production target
^{9}Be



magnetic dipoles

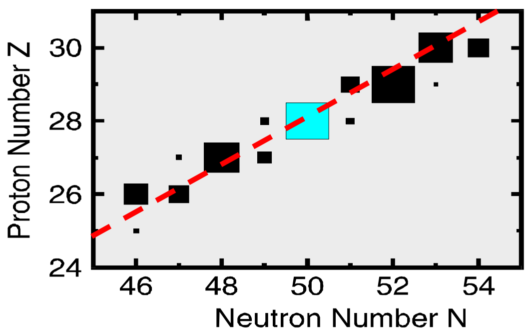
$B\rho \propto \beta\gamma\, A/Z$

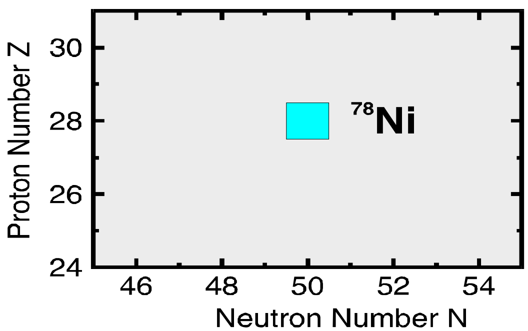
degrader

$\Delta E \propto Z^2 f(\beta)$

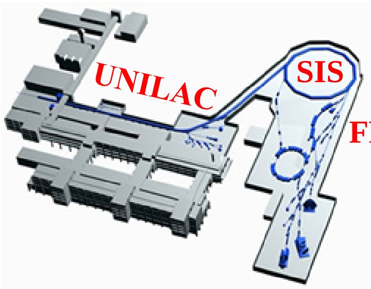
magnetic dipoles

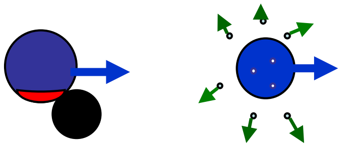
$B\rho \propto \beta\gamma\, A/Z$

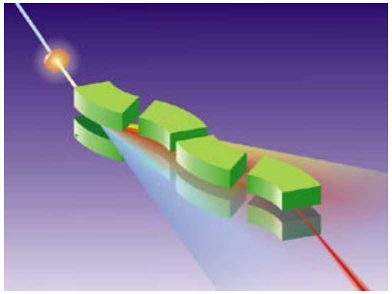




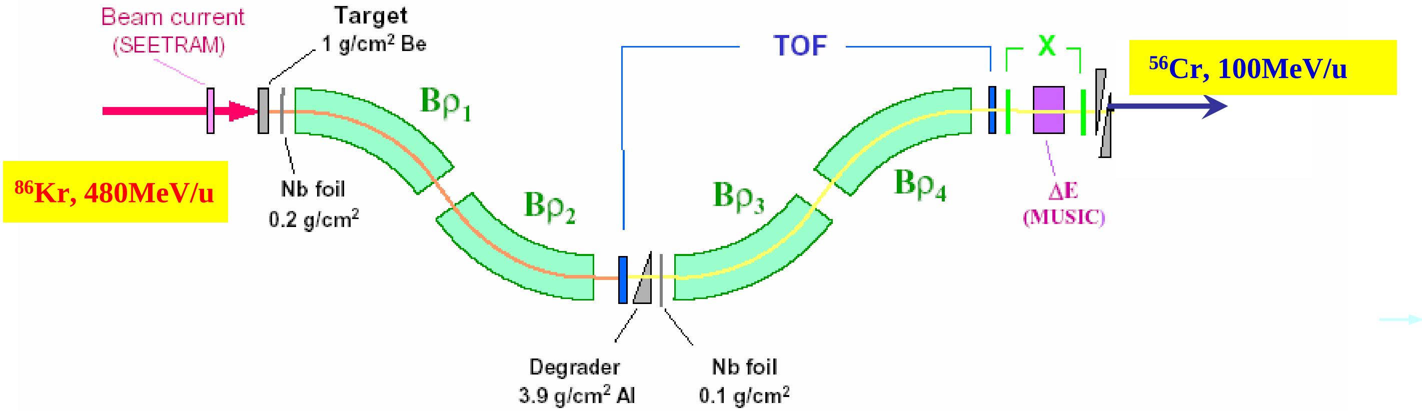
Production, Separation, Identification



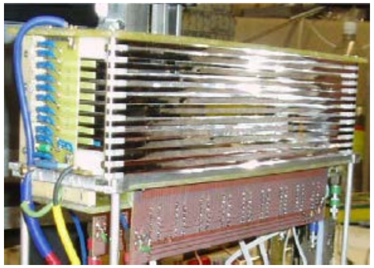




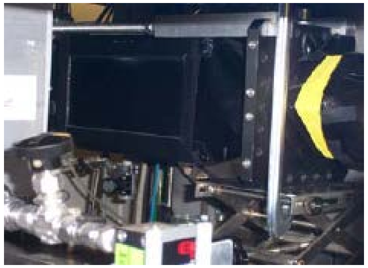
FRagment
Separator



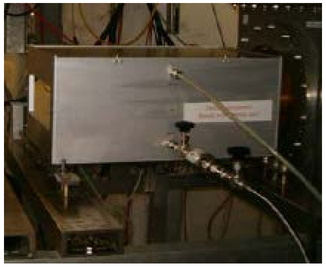
Standard FRS detectors



TPC-**x,y position** @ S2,S4

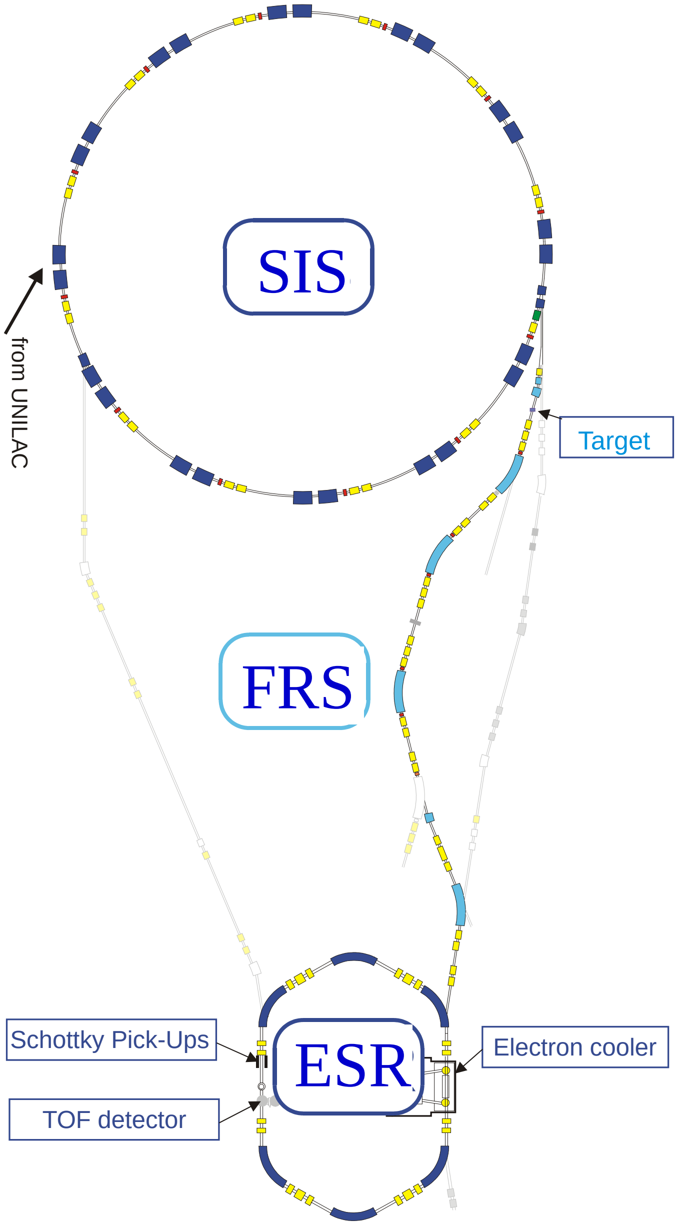


Plastic scintillator (**TOF**) @ S4



MUSIC (**ΔE**) @ S4

Fragment separator and storage ring



Production of highly charged, unstable ions at FRS

In-flight separation at FRS

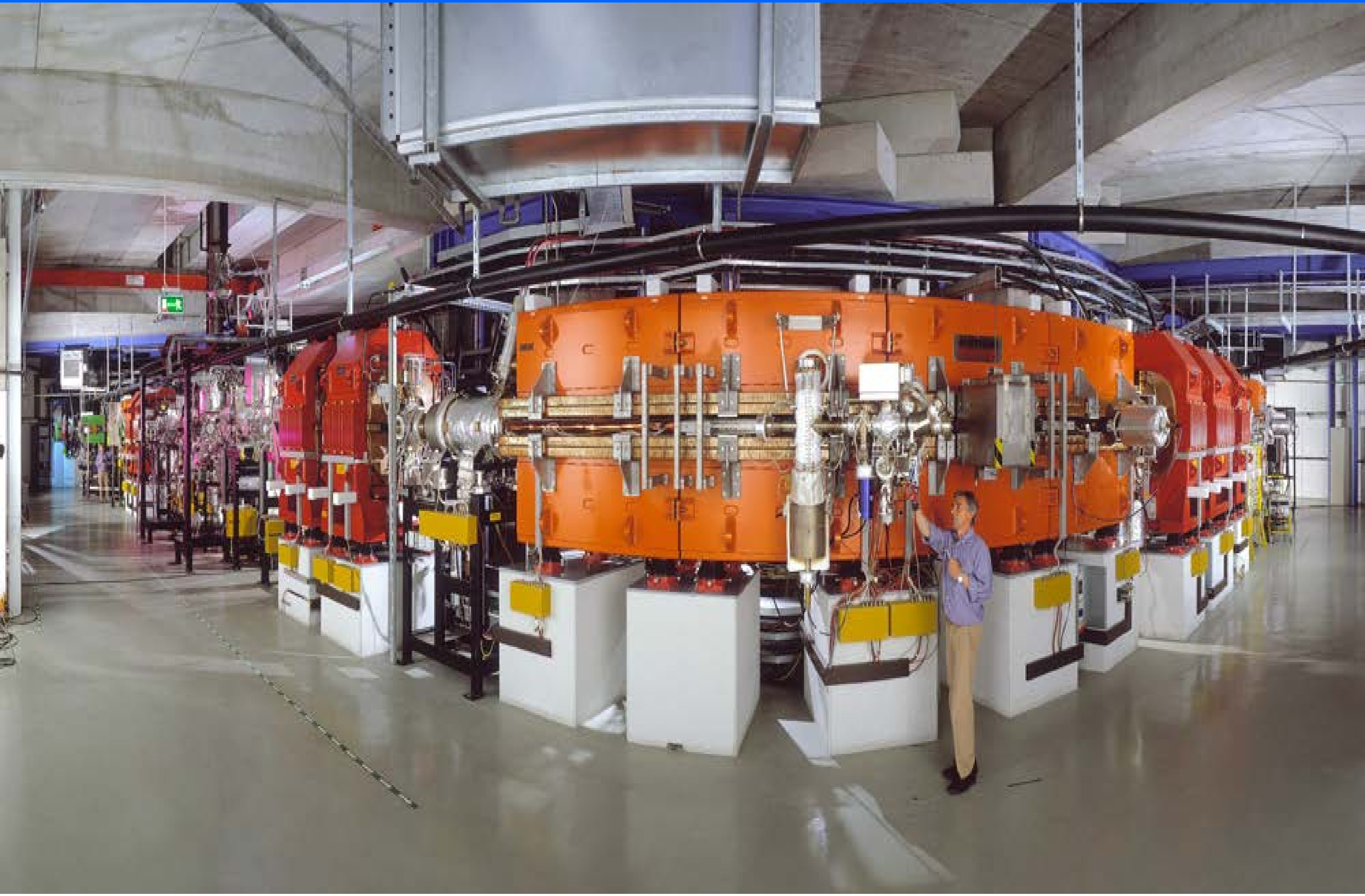
→ Cocktail or mono-isotopic beams

Stochastic and/or electron cooling
→ same velocity for all ions

Schottky analysis

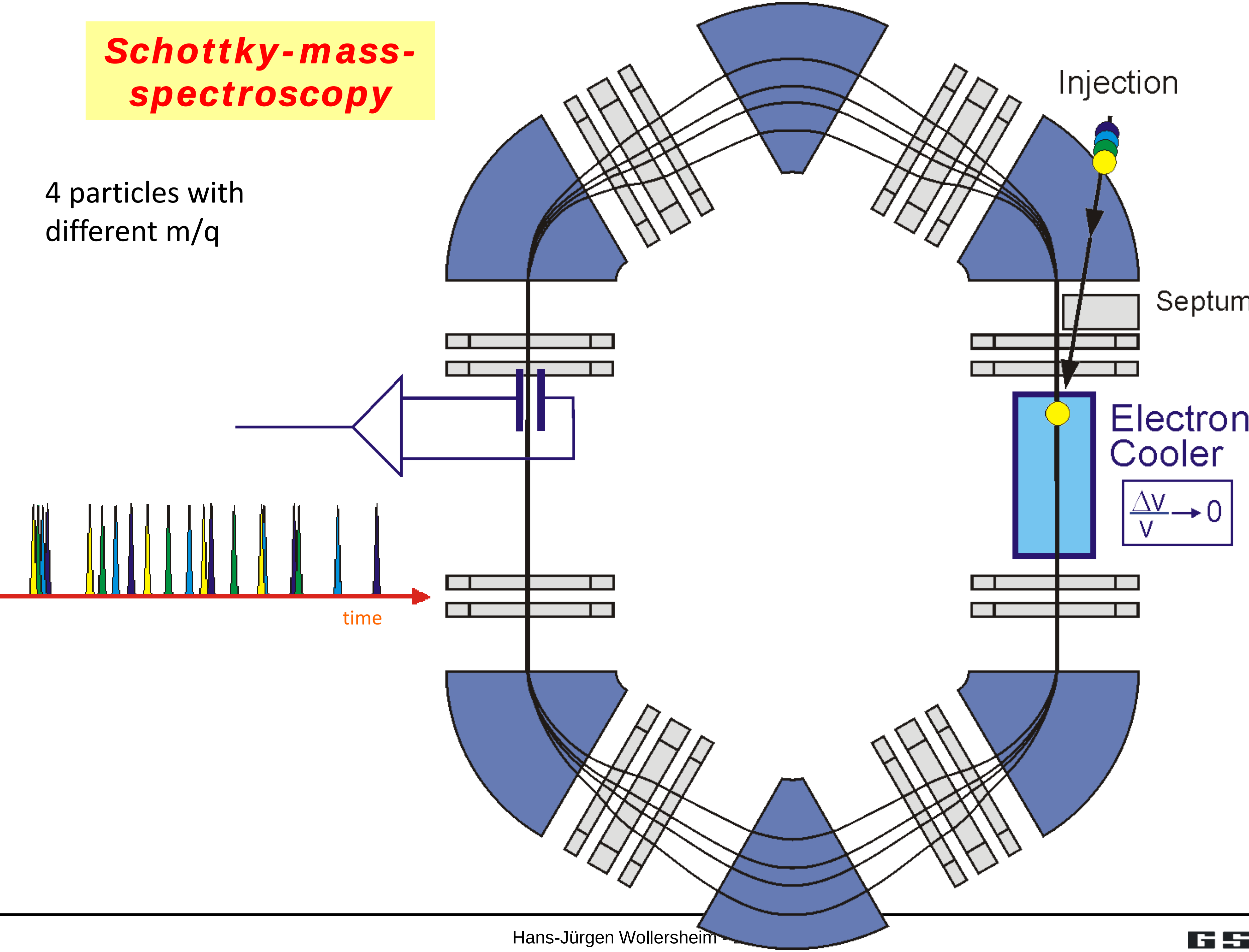
→ Mother and daughter in the same spectrum

The Experimental Storage Ring ESR at GSI



Schottky-mass-spectroscopy

4 particles with different m/q



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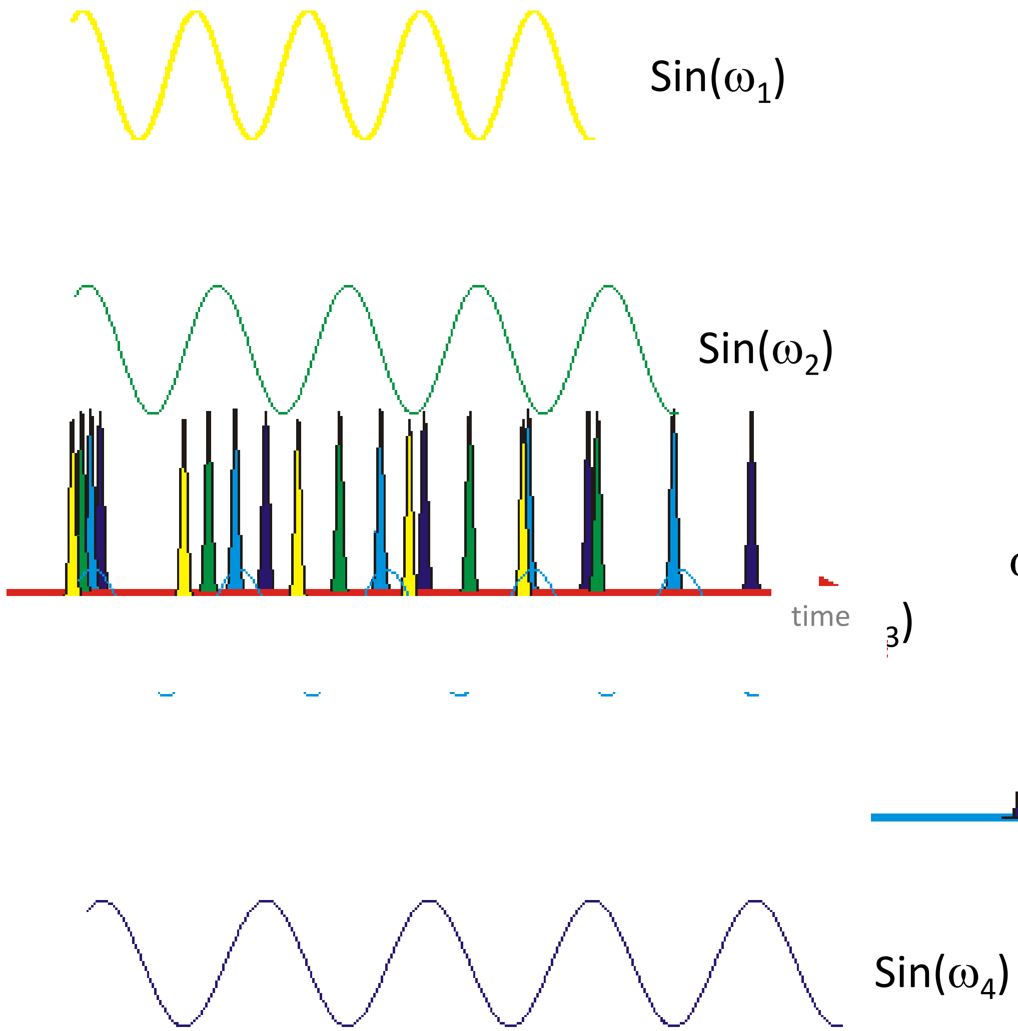
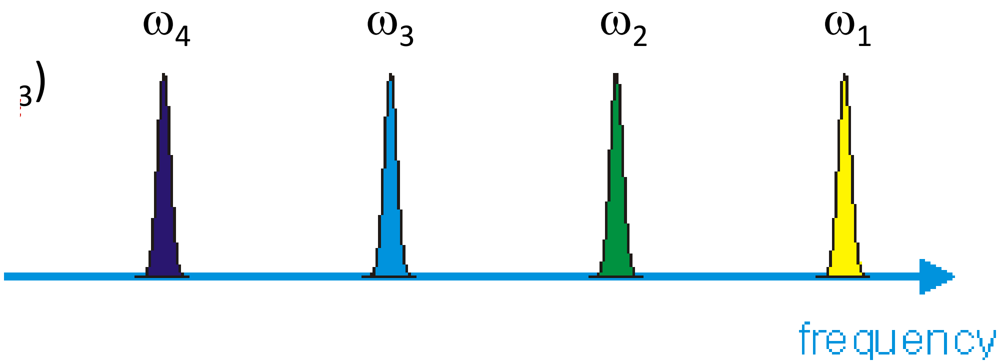
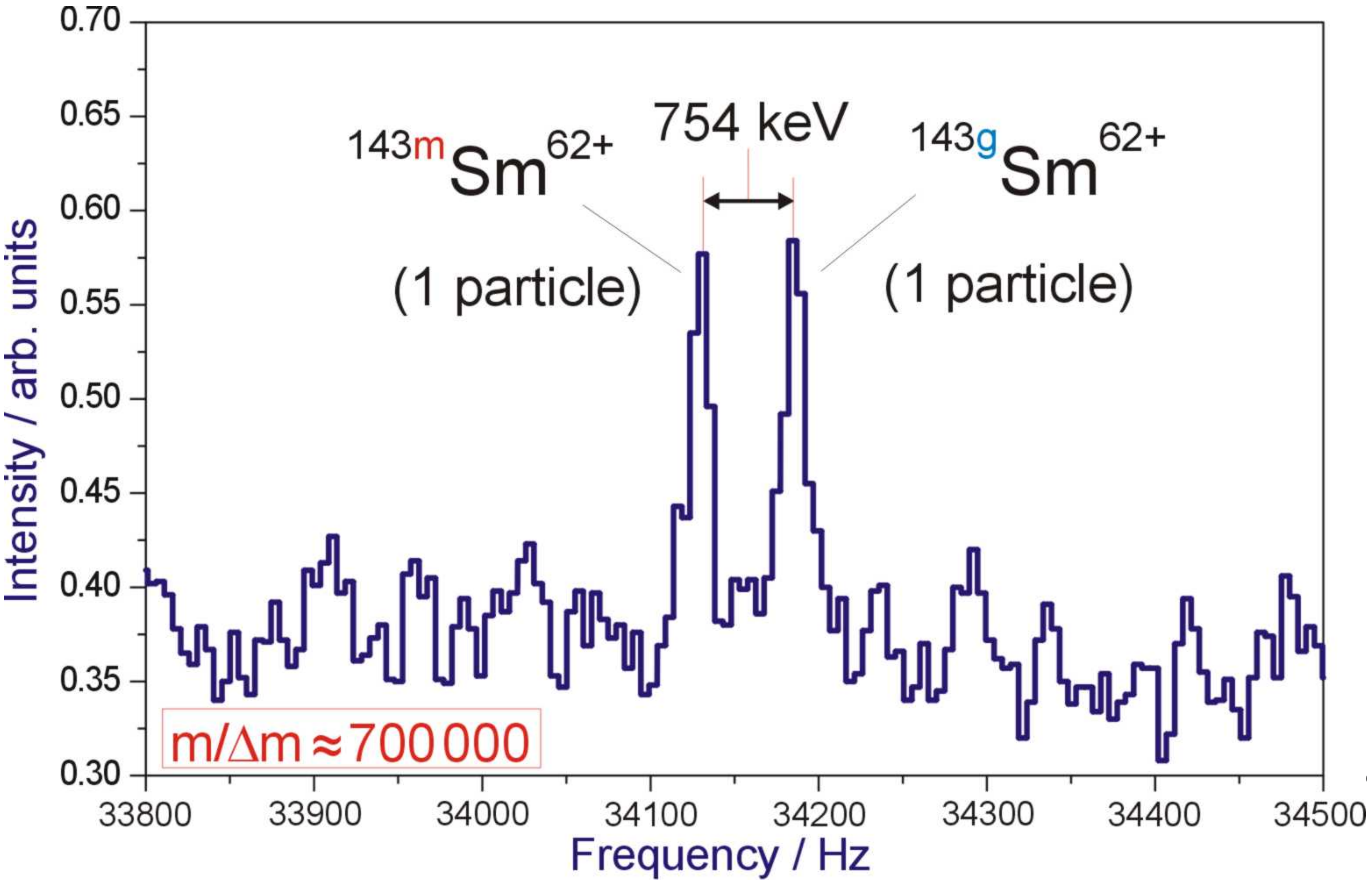


fast Fourier transform



Small-band Schottky frequency spectra

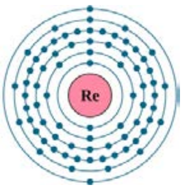


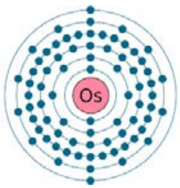
A) Nuclear Cosmic Clock – radioactive dating

How old is the Universe?

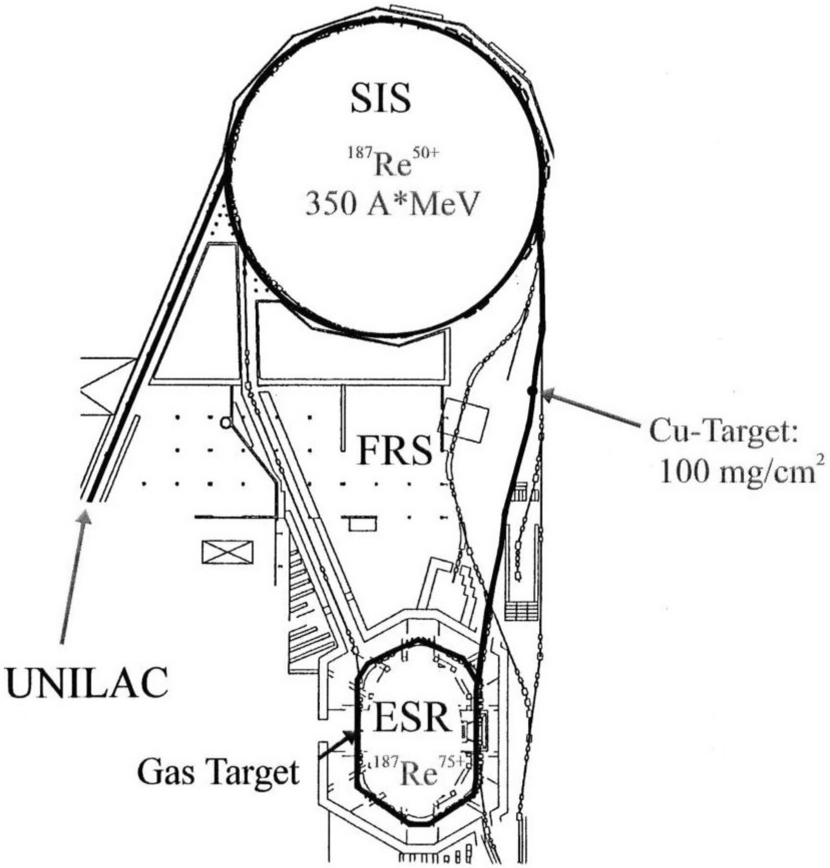
The **7 nuclear clocks** for the age of the Earth, the solar system, the Galaxy and the Universe

nuclei	$T_{1/2}$ [10^9 y]	Q_β [keV]
$^{40}K/^{40}Ar$ (β)	1.3	
$^{238}U…Th…^{206}Pb$ (α,β)	4.5	
$^{232}Th…Ra…^{208}Pb$ (α,β)	14	
$^{176}Lu/^{176}Hf$ (β)	30	1186 ($7^- \rightarrow 0^+$)
$^{187}Re/^{187}Os$ (β)	42	2.6 ($5/2^+ \rightarrow 1/2^-$)
$^{87}Rb/^{87}Sr$ (β)	50	273 ($3/2^- \rightarrow 9/2^+$)
$^{147}Sm/^{143}Nd$ (α)	100	





Fragment separator and storage ring



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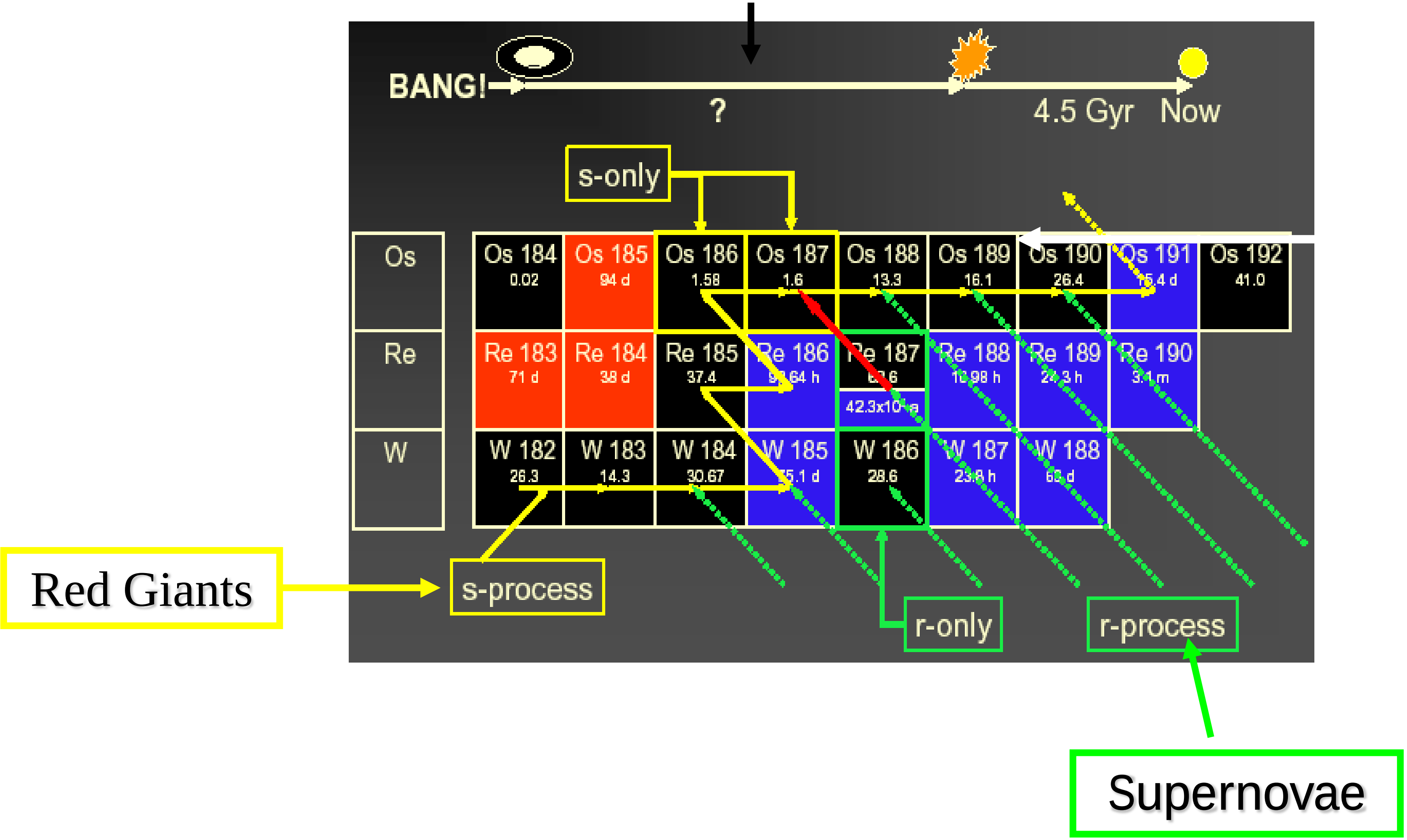
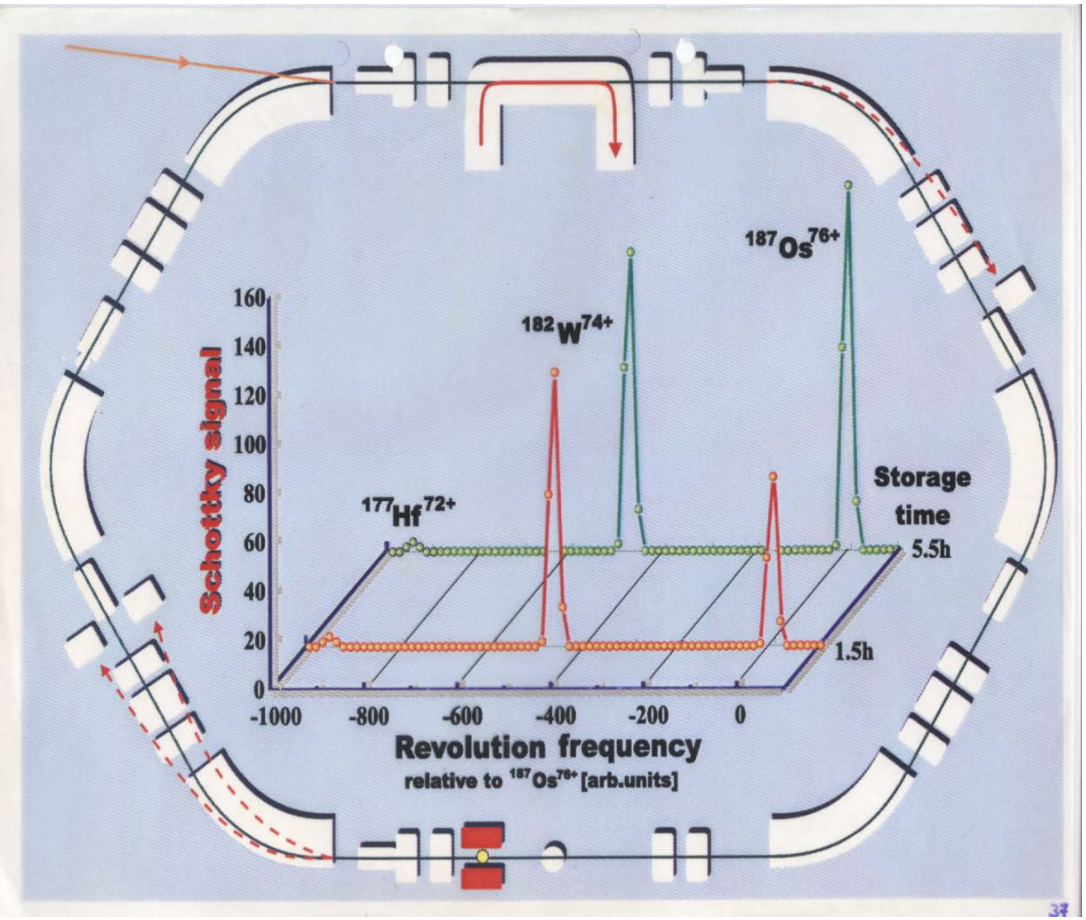
F. Bosch et al., Phys. Rev. Lett. 77 (1996),5190

Re/Os cosmos-chronometer



How to determine a long (33 y) beta half-life?

Os	Os 184 0.02	Os 185 94 d	Os 186 1.58	Os 187 1.6	Os 188 13.3	Os 189 16.1	Os 190 26.4	Os 191 15.4 d	Os 192 41.0
Re	Re 183 71 d	Re 184 38 d	Re 185 37.4	Re 186 90.64 h	Re 187 62.6 / 42.3x10^9 a	Re 188 16.98 h	Re 189 24.3 h	Re 190 3.1 m	
W	W 182 26.3	W 183 14.3	W 184 30.67	W 185 75.1 d	W 186 28.6	W 187 23.8 h	W 188 69 d		



1. store and cool bare ^{187}Re for various times (hours)

2. the β_b daughters, H-like ^{187}Os, are **not resolved** in Schottky spectrum. Q value only 62 keV at the same atomic charge state **q = 75$^+$**

3. after the (long) storage time **strip the one electron** of ^{187}Os in an intense gas jet, acting for a few minutes only

4. the **bare ^{187}Os** ions are **well-resolved** now, at **q = 76$^+$**

5. the number of nuclear reaction products (Hf, W,..) does **not** depend on storage time

F. Bosch et al., PRL 77 (1996) 5

Nuclear cosmic clocks

1. select a long-lived radioactive mother/daughter (β) couple

2. determine **N(m), N(d)** at time **t**

3. $N_m(t) = N_m(t_0) \cdot exp[-\lambda \cdot (t - t_0)]$
   $N_d(t) = N_m(t_0) \cdot \{1 - exp[-\lambda \cdot (t - t_0)]\}$

$$\rightarrow \frac{N_d(t)}{N_m(t)} = exp[\lambda \cdot (t - t_0)] - 1$$

one has to measure 'only'

the relative amount at time t and the **decay probability λ** of the mother

→ nuclear eon clocks
independent on stellar/galactic
evolution models !??

F. Bosch et al., Phys. Rev. Lett. 77 (1996),5190

The ´best-suited´ eon clock: $^{187}Re/^{187}Os$

$T_N > \tau(^{187}Re) \times R(^{187}Os/^{187}Re)_d$

$61.3\ Ga \times 0.137$

= 8.4 Ga

but...

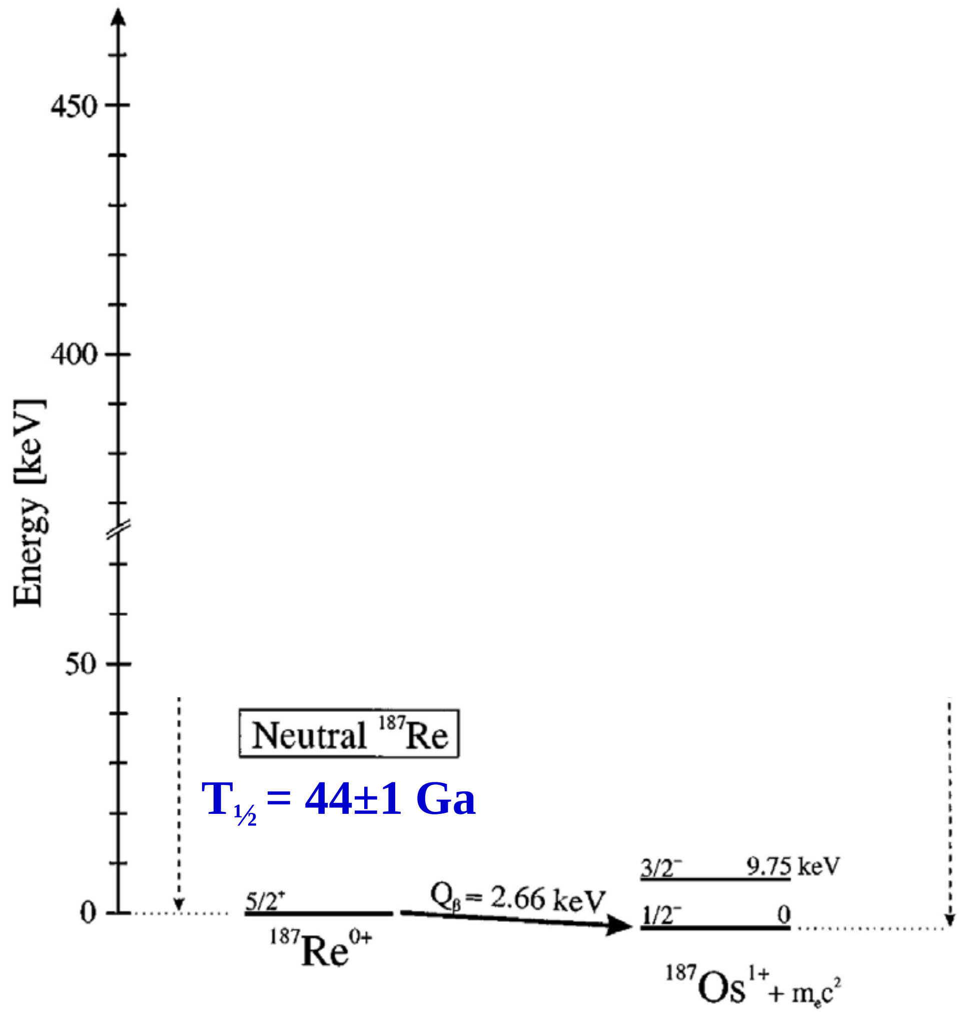
bare and H-like ^{187}Re undergoes β_b decay to the first excited state of ^{187}Os

nuclear matrix element **not** known

measurement of lifetime τ of bare ^{187}Re at the ESR gives

→ **τ (bare ^{187}Re) = (48 ± 3) a**

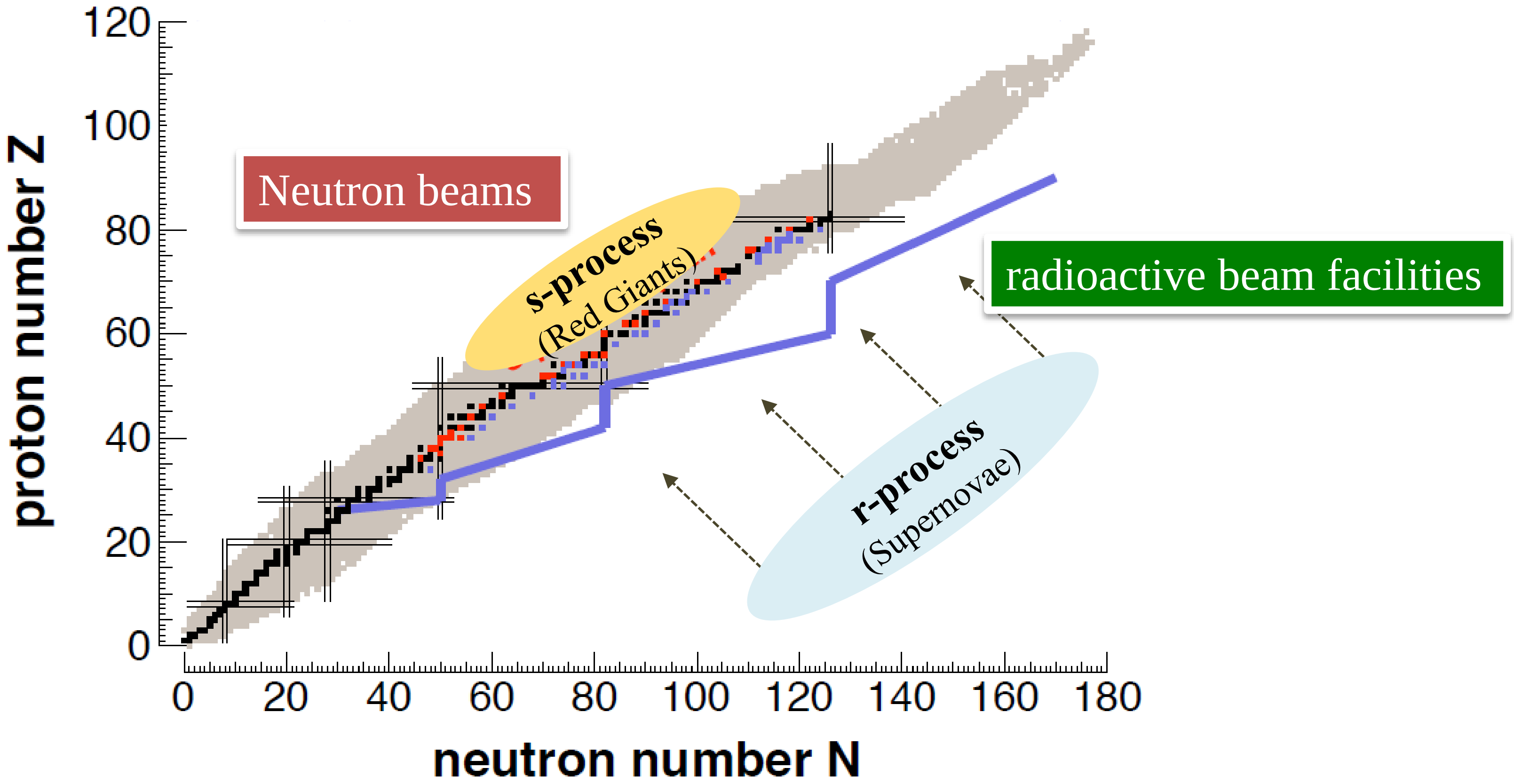
instead of (**61 ± 2) Ga**



The Re/Os cosmic clock is strongly affected by the atomic charge state: nuclear cosmic clocks are not independent on stellar evolution models

$\rightarrow T_G \sim 11$ Ga

B) The stellar nucleosynthesis



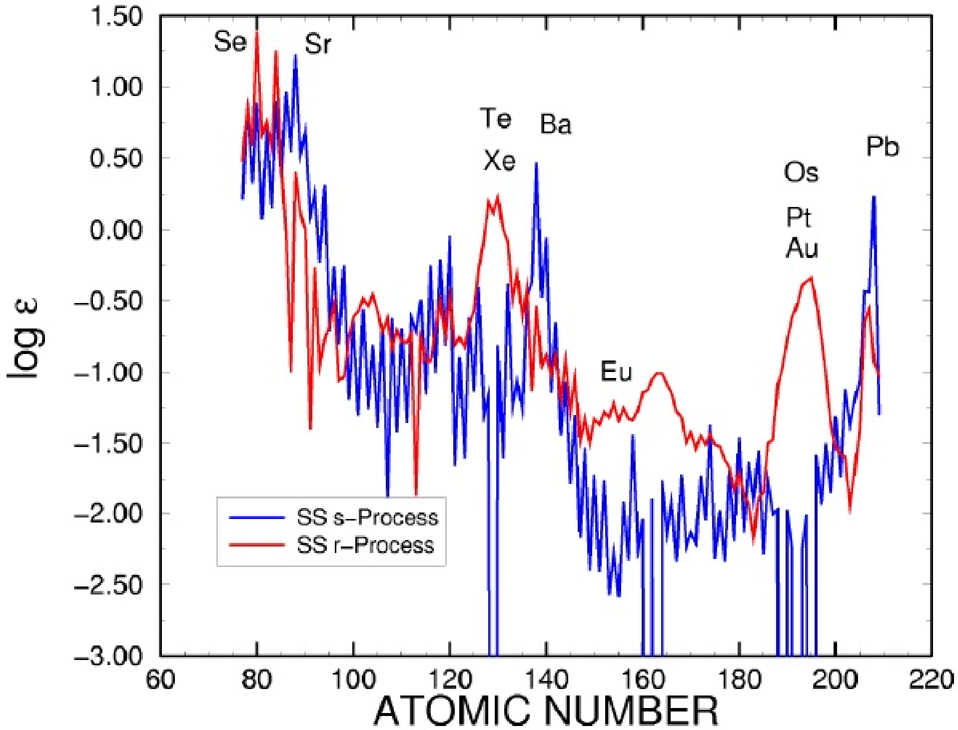
s-process (slow process)**:**

- **Capture times** long relative to decay time
- Involves mostly **stable isotopes**
- $\mathbf{N_n = 10^{6\text{-}12}\ n/cm^3}$, kT = 8 – 90 keV

r-process (rapid process):

- **Capture times** short relative to decay times
- Produces **unstable isotopes** (neutron-rich)
- $\mathbf{N_n = 10^{20\text{-}30}\ n/cm^3}$

Neutron-capture processes



heavy elements are made by

slow $(\tau_\beta / \tau_n < 1)$

and

fast $(\tau_\beta / \tau_n > 1)$

neutron capture events

$\tau_n = lifetime\ against\ neutron\ capture$
$\tau_\beta = lifetime\ against\ \beta^- - decay$

- Sequences of (n,γ) reactions and β^- decays

$$A(Z,N) + n \leftrightarrow A+1(Z,N+1) + \gamma$$

$$A(Z,N) \rightarrow A(Z+1,N-1) + e^- + \bar{\nu}_e$$

- Closed neutron-shells give rise to the peaks at Te, Xe / Ba and at Os, Pt, Au / Pb

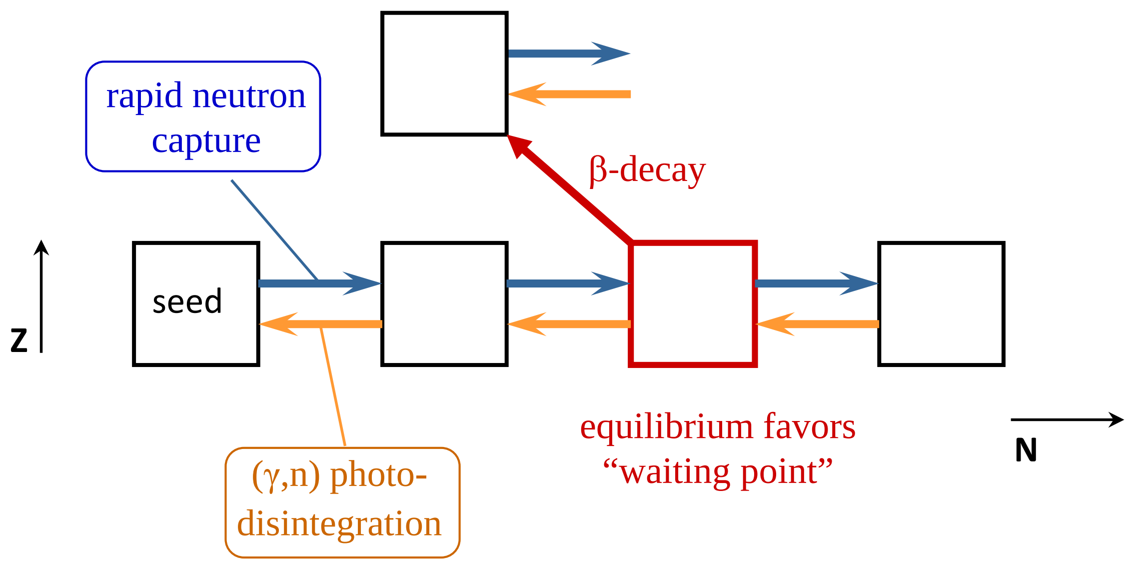
Classical approach of the r-process (n,γ) and (γ,n) equilibrium

waiting point approximation

assume

- (n,γ) ↔ (γ,n) equilibrium within isotopic chain, and
- β-flow equilibrium

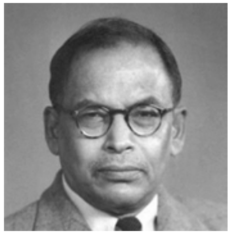
  β-decay of nuclei from each Z-chain to (Z+1) is equal to the flow from (Z+1) to (Z+2)



the nucleus with maximum abundance in each isotopic chain must wait for the longer β-decay time scales

good approximation for parameter studies, BUT steady-flow approximation is not always valid

The „waiting-point“ concept in astrophysics



Nuclear Saha equation:

simplified $\frac{N(A+1,Z)}{N(A,Z)} \propto n_n \cdot exp\left({}^{S_n}/_{kT}\right)$

- high n_n “waiting-point” shifted to higher masses
- low S_n “waiting-point” shifted to lower masses
- low T “waiting-point” shifted to higher masses

Equilibrium-flow along r-process path:

$$\dot{N}(Z) = \sum_A \left\{ \frac{N(Z-1,A)}{\tau_\beta(Z-1,A)} - \frac{N(Z,A)}{\tau_\beta(Z,A)} \right\} = 0$$

- governed by β–decays from isotopic chain Z to (Z+1)

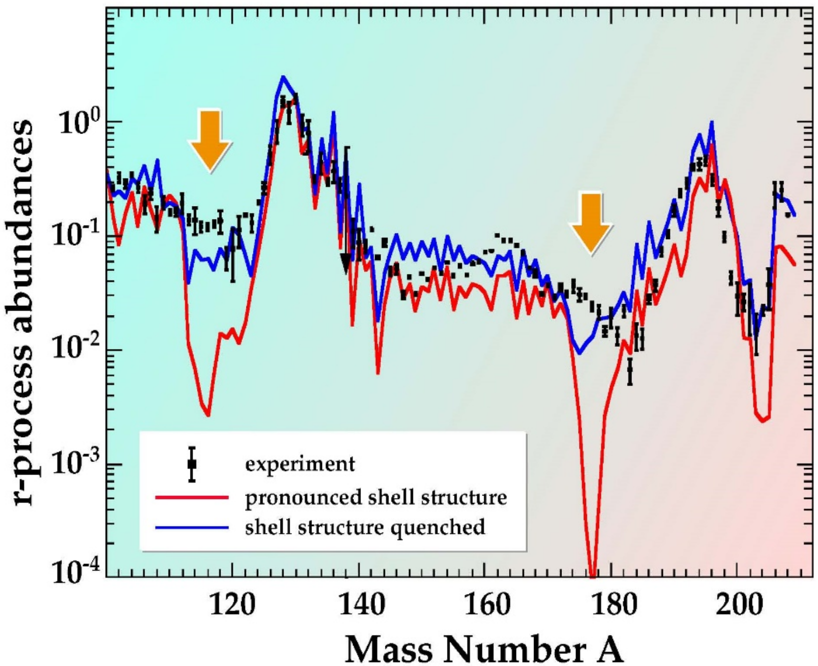
β-decay flow equilibrium implies (n,γ) – (γ,n) equilibrium

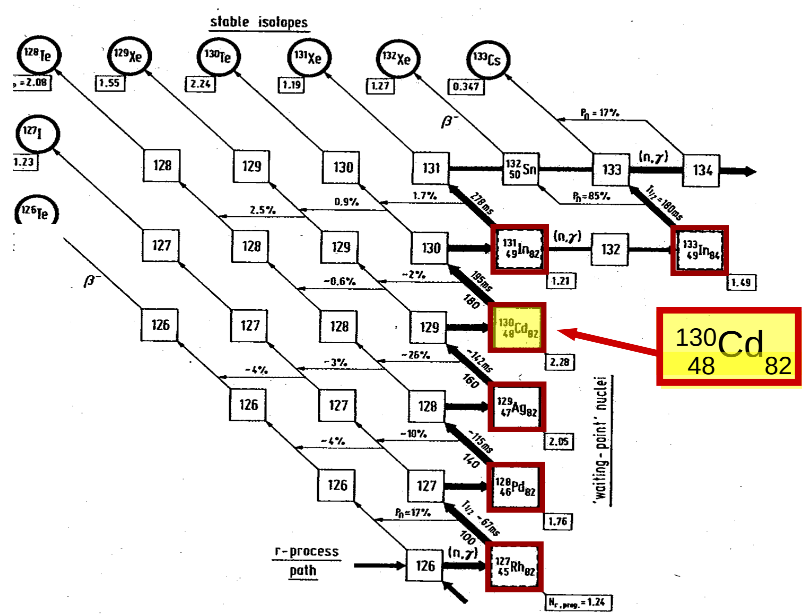
$\tau_\beta > \tau_{n,\gamma}, \tau_{\gamma,n}$

$T_{1/2}$ (“waiting-point“) ↔ $N_{r\text{-process}}$

^{130}Cd – the key isotope at N=82

R - abundances ⇄ **Details of nuclear properties**



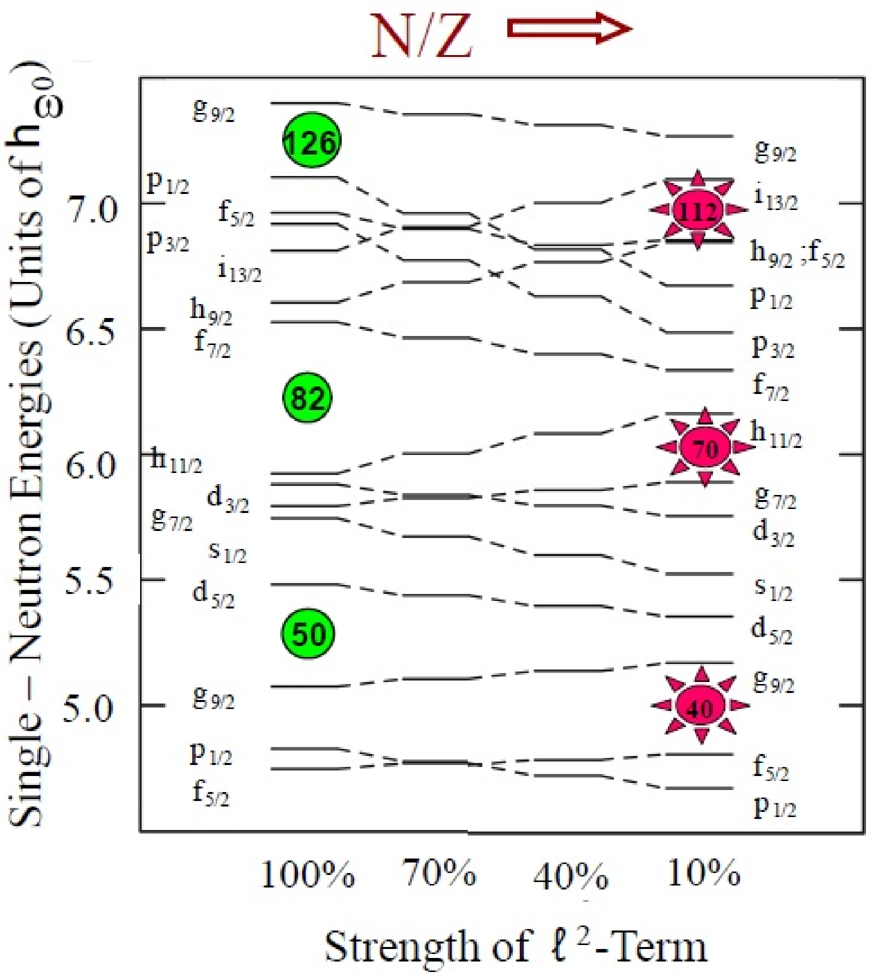


"..the calculated r-abundance 'hole' in the A ≅ 120 region reflects ... the weakening of the shell strength ... below ^{132}Sn "

K-L Kratz

bottleneck at N=82 waiting point near stability?

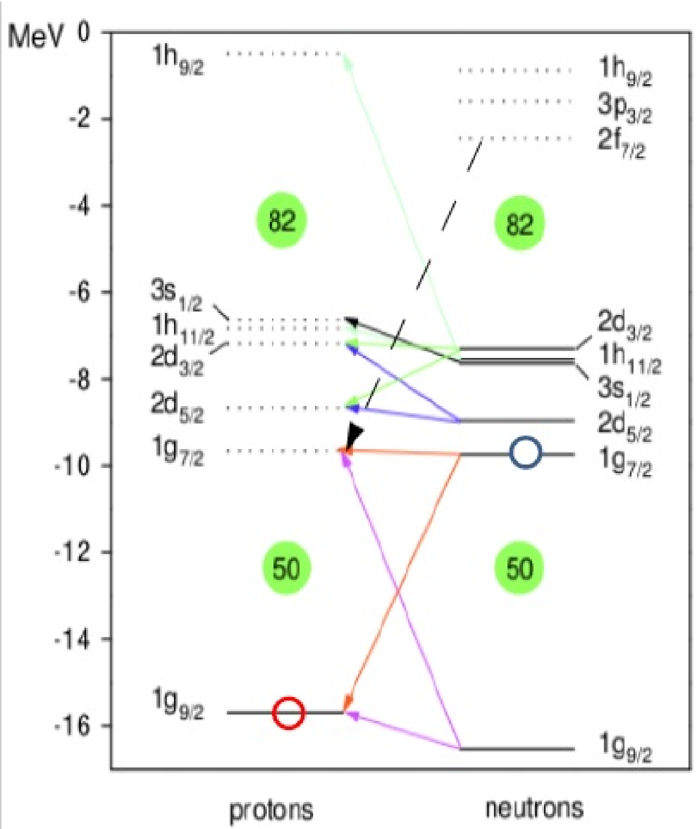
Effects of N=82 "shell quenching"

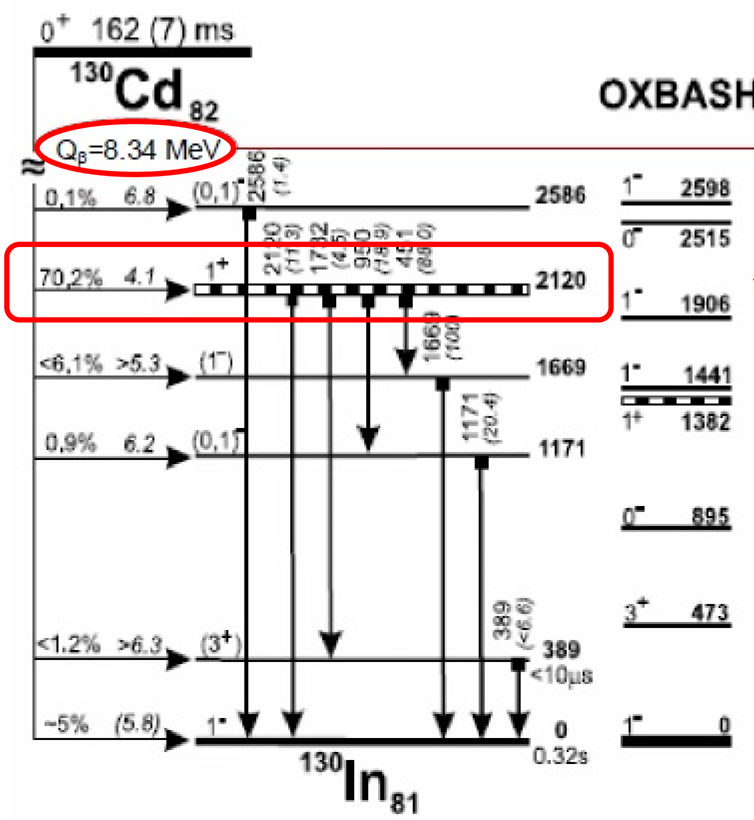


"Shell quenching"

reduction of the spin-orbit coupling strength;
caused by strong interaction between bound and continuum states;
due to diffuseness of "neutron-skin" and its influence on the central potential

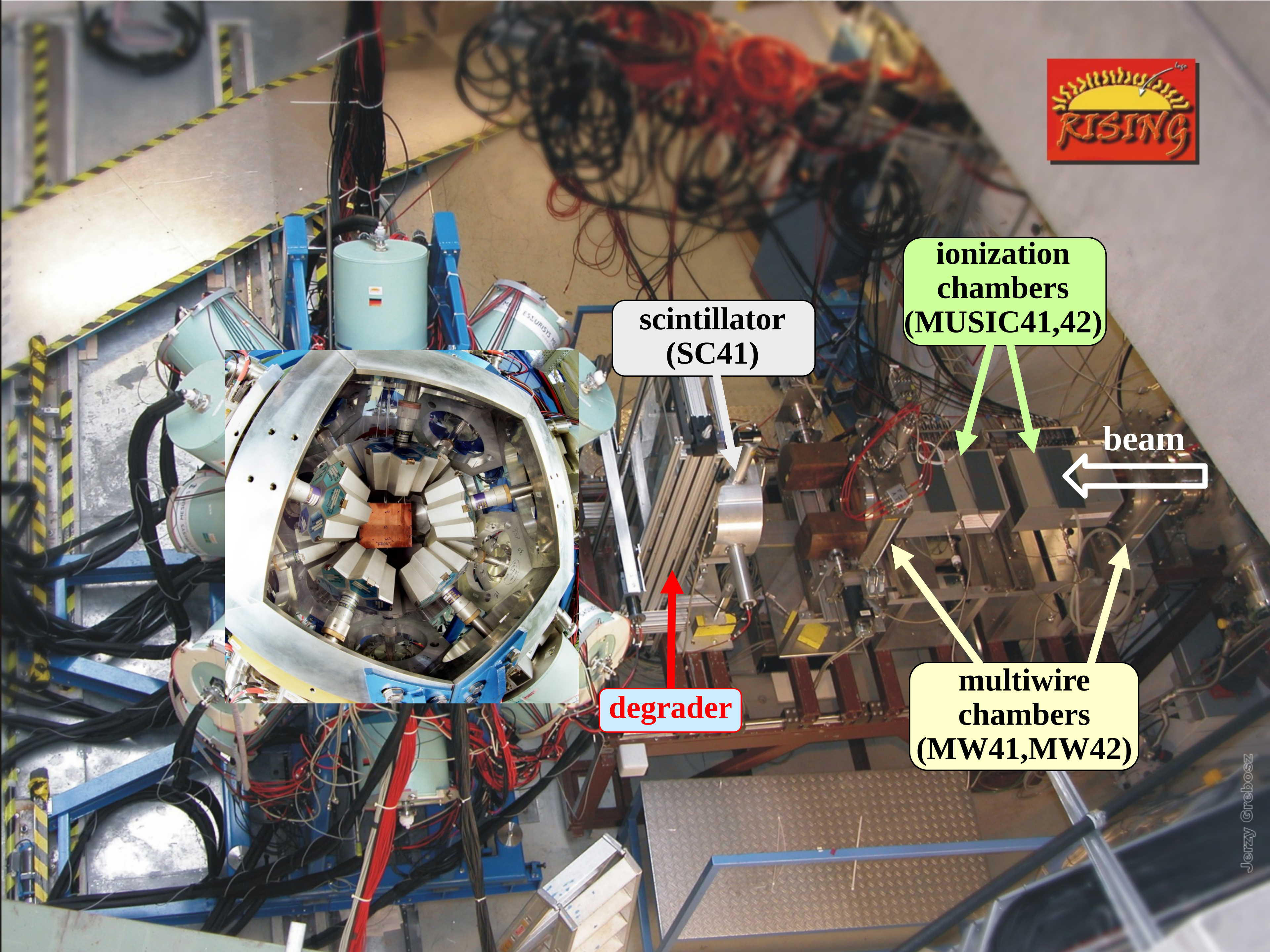
^{130}Cd decay spectroscopy



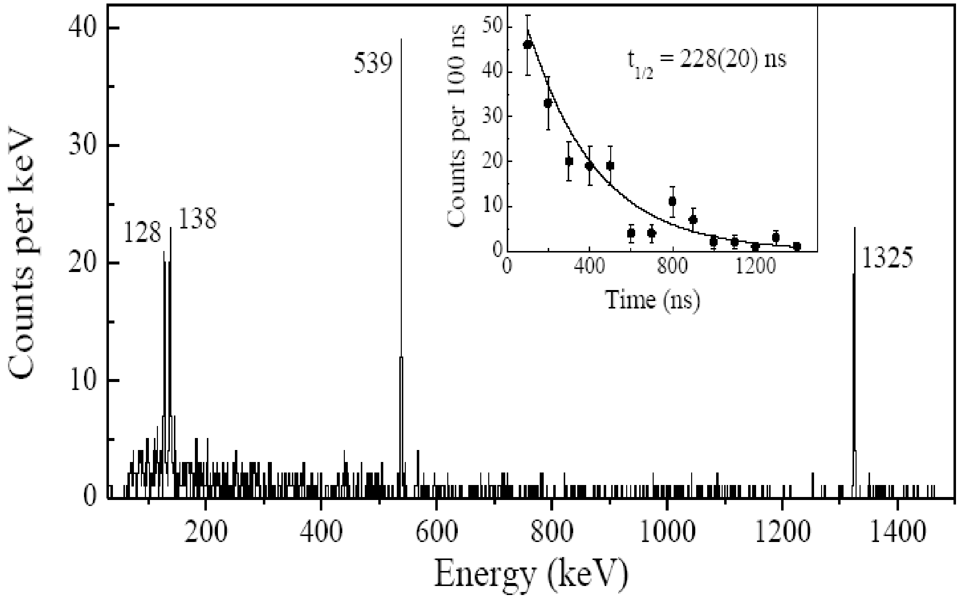


Large Q_β value best reproduced by mass models with N=82 shell quenching

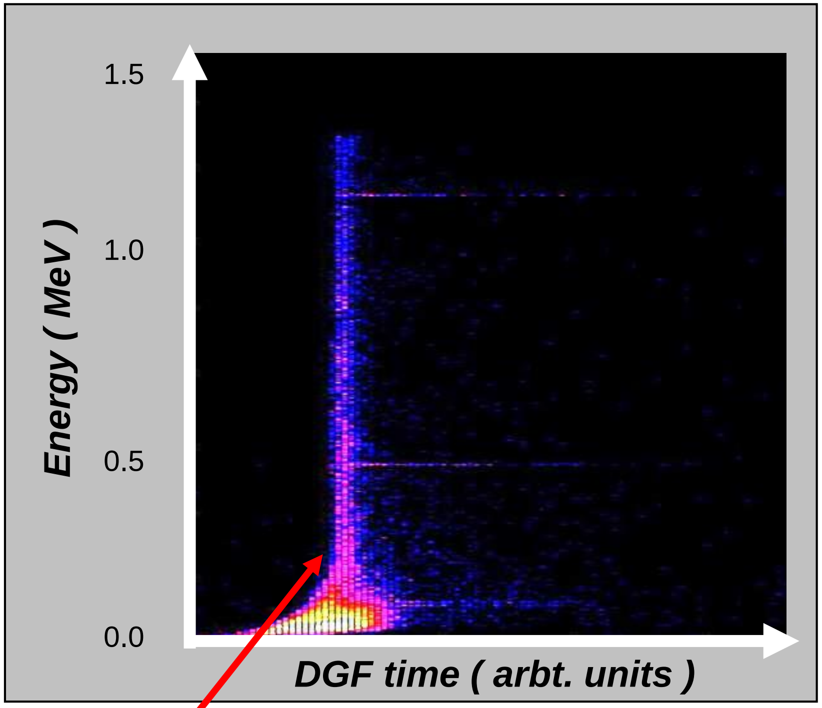
$\pi g_{9/2} \otimes \nu g_{7/2}$


RISING
ionization chambers (MUSIC41,42)
scintillator (SC41)
beam
degrader
multiwire chambers (MW41,MW42)
Jerzy Grebosz

Decay spectroscopy probes shell closures



^{130}Cd: DGF-timing

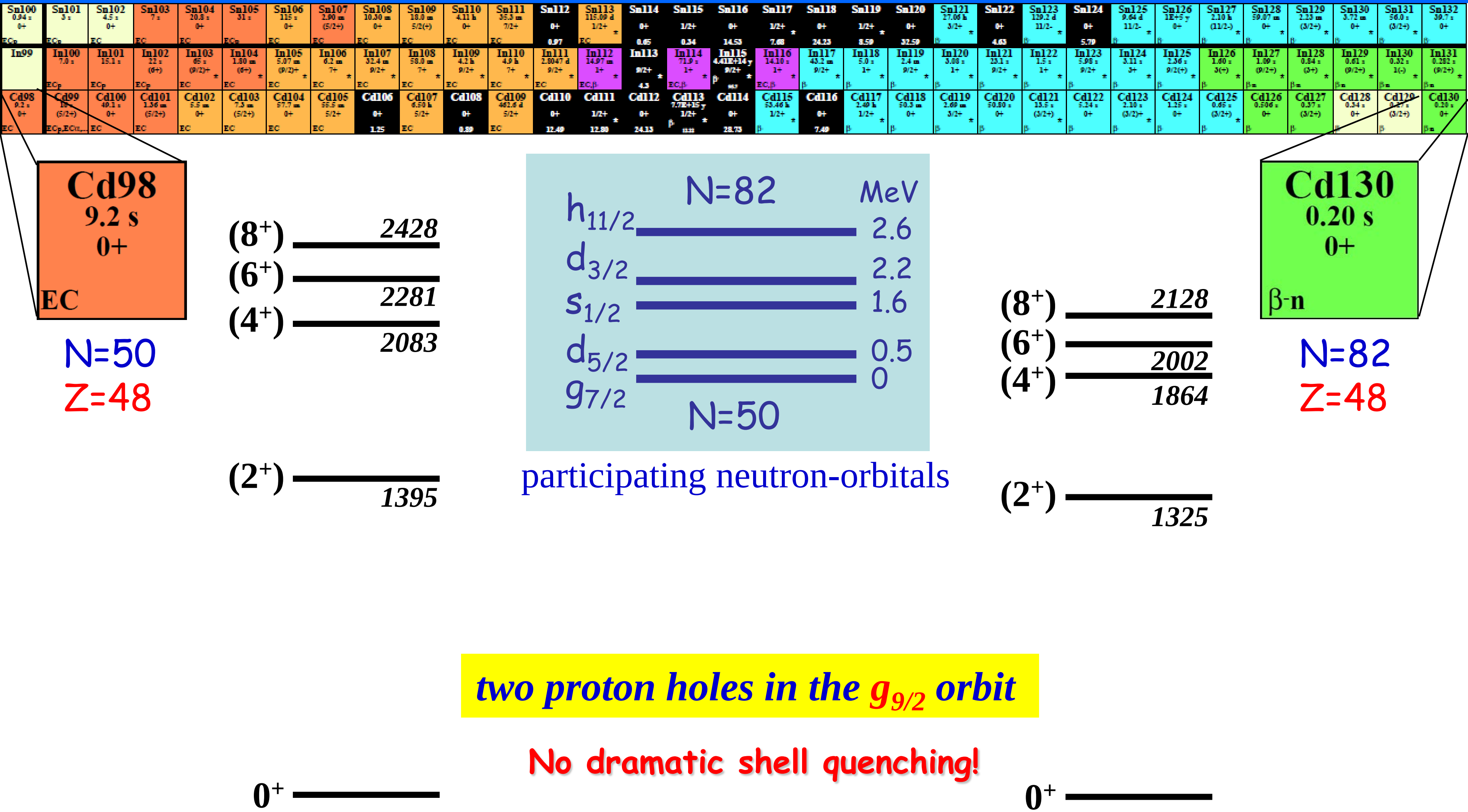


Prompt γ-flash

Decay time range: 20 ns ... 20 μs

A. Jungclaus et al., Phys. Rev. Lett 99, 132501 (2007)

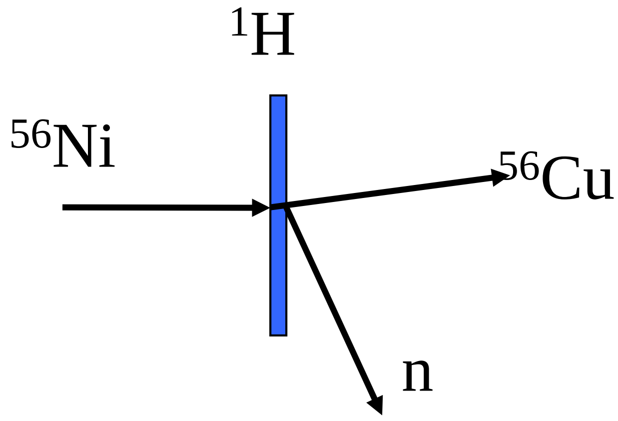
$8^+(g_{9/2})^{-2}$ seniority isomers in ^{98}Cd and ^{130}Cd



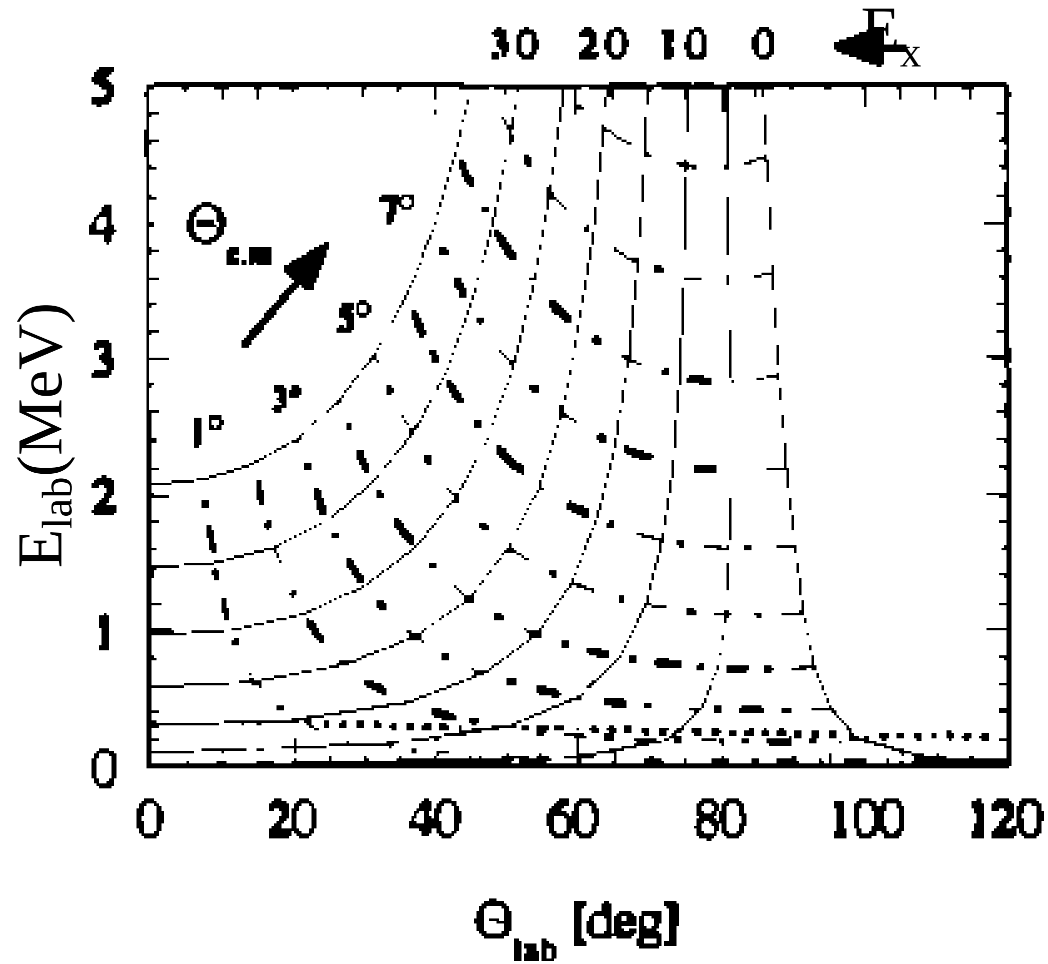
A. Blazhev et al., Phys. Rev. C69 (2004) 064304

A. Jungclaus et al., Phys. Rev. Lett. 99 (2007), 132501

Use Inverse kinematics



$^{1}H(^{60}Co, n)^{60}Ni$

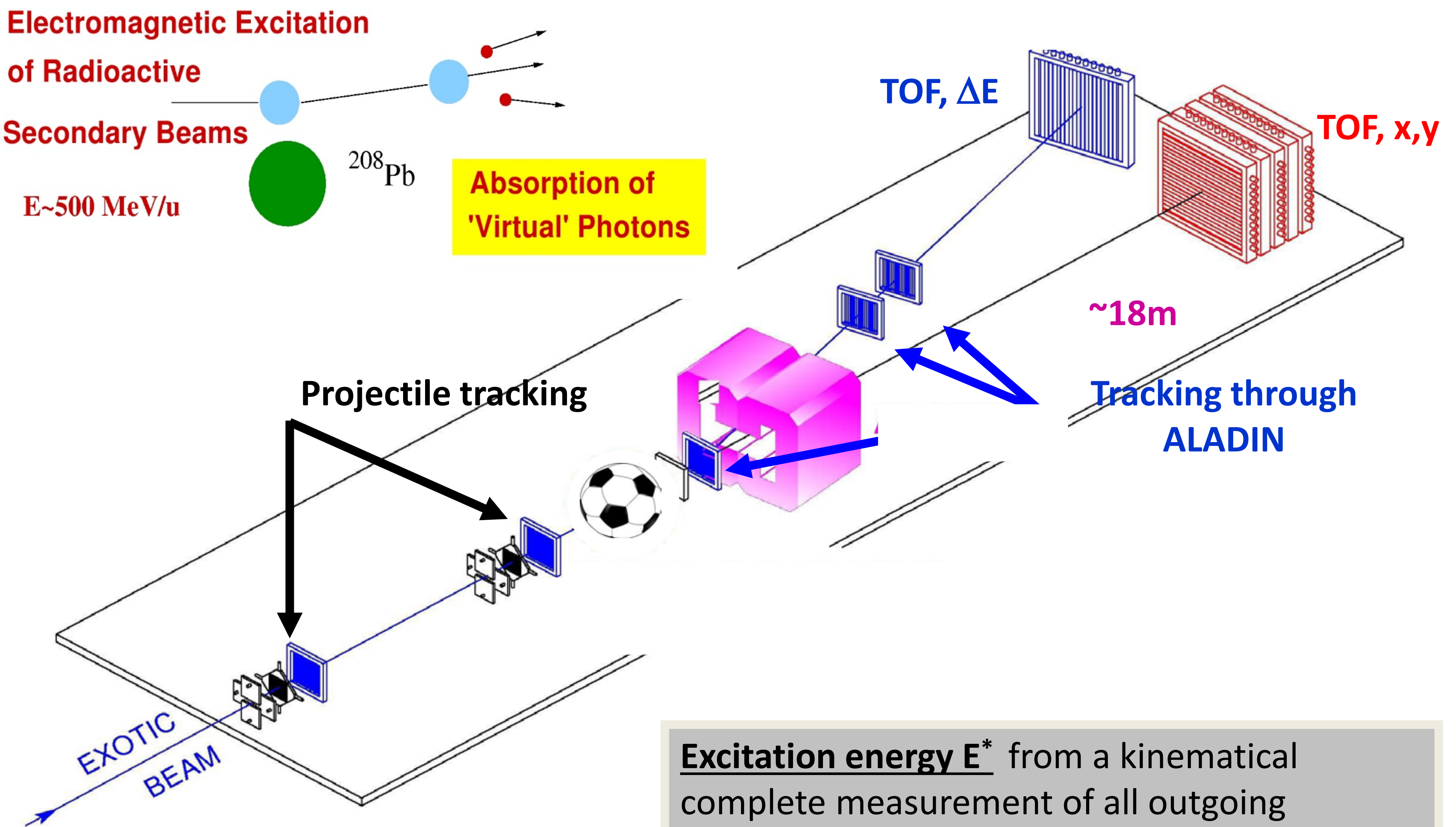


Unusual kinematics

- Light particle has low E, few MeV, angle near 90°.
- Lab angle => $E_{c.m.}$
- Lab E => $\Theta_{c.m.}$

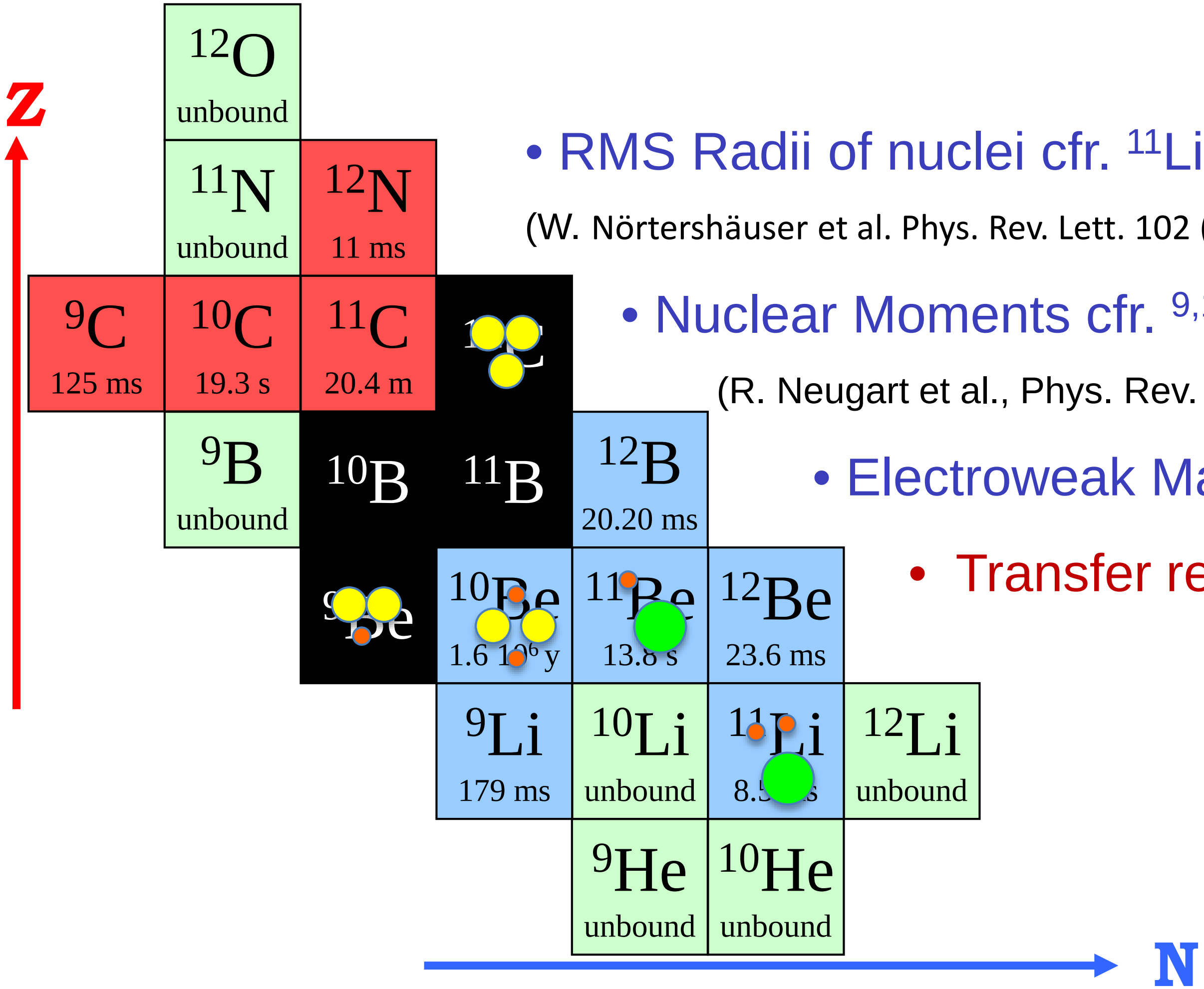
Coulomb break up in inverse kinematics at GSI/LAND

$^{92,93,94,100}Mo(\gamma,n)$ most abundant p-isotopes



<u>Excitation energy E*</u> from a kinematical complete measurement of all outgoing particles.

Testing Ab-Initio Calculations



- RMS Radii of nuclei cfr. ^{11}Li, ^{9,10}Be (abstract ID 96)

(W. Nörtershäuser et al. Phys. Rev. Lett. 102 (2009) 062503)

- Nuclear Moments cfr. ^{9,11}Li (ID 20)

(R. Neugart et al., Phys. Rev. Lett. 101 (2008) 132502)

- Electroweak Matrix Elements

- Transfer reactions

$^{1}H(^{14}Be,2pn)^{12}Li$ lithium isotopes beyond the drip-line

~300 MeV/u ^{11}Li, ^{14}Be + liquid $H_2 \rightarrow {}^{9}$Li + n, ^{11}Li + n, ^{11}Li + 2n

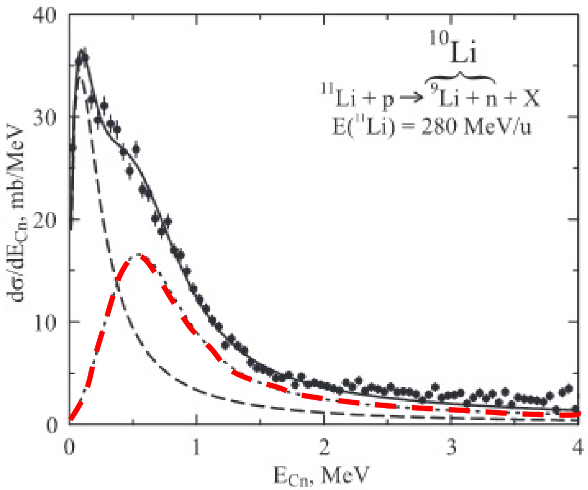
Going beyond the dripline ^{12}Li and ^{13}Li

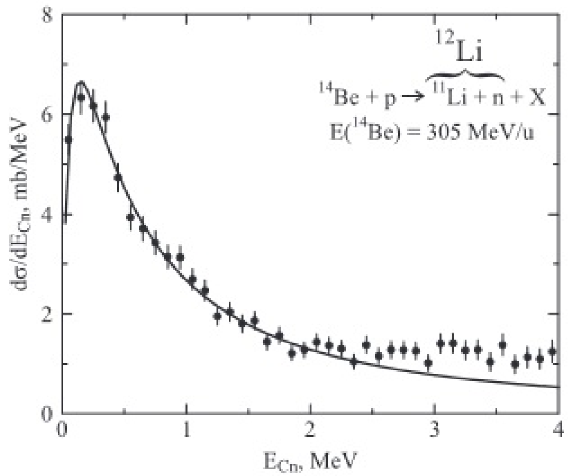
previous results confirmed:

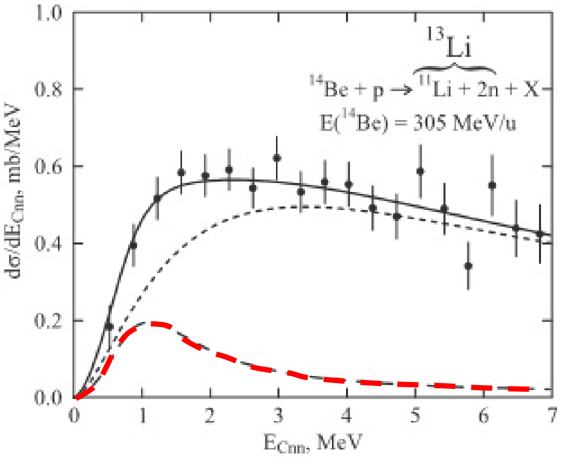
^{10}Li is known as virtual s-state (a = -22 fm) with an excited state at 0.5 MeV and Γ = 0.5 MeV

^{12}Li is observed as a virtual s-state with scattering length a = -11 fm

^{13}Li is seen as a broad 3-body resonance state at 1.5 MeV

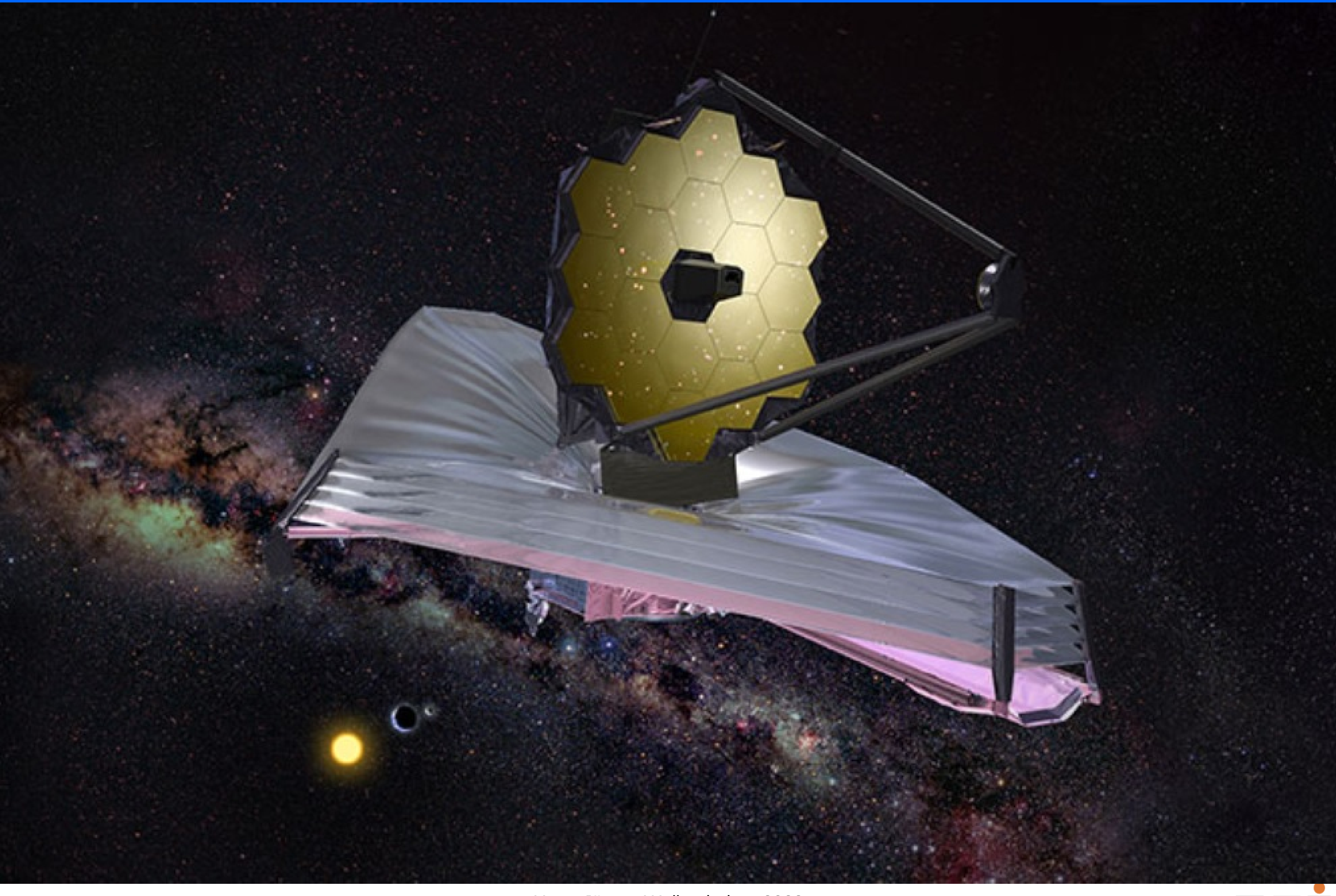






Yu. Aksyutina et al. PLB 666(2008) 430

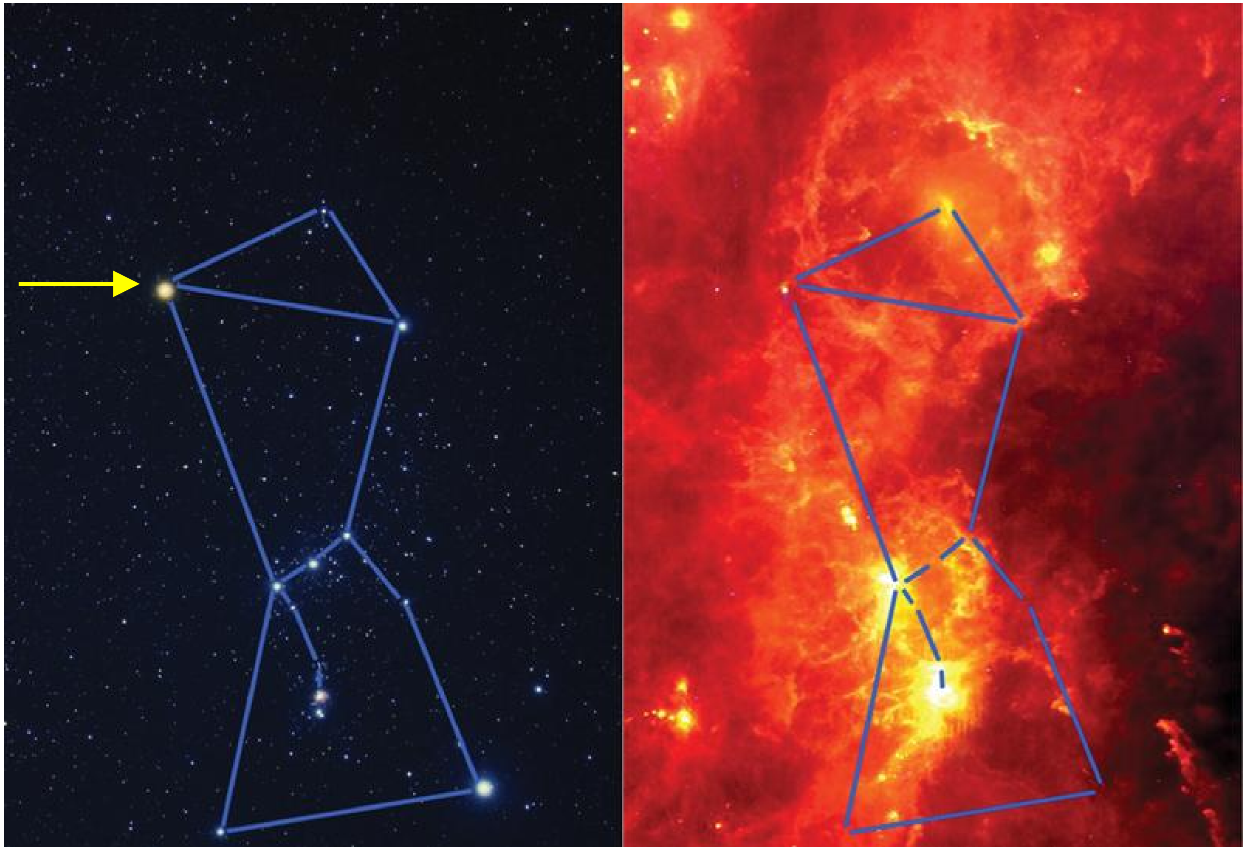
Unveiling the Universe with the James Webb Space Telescope



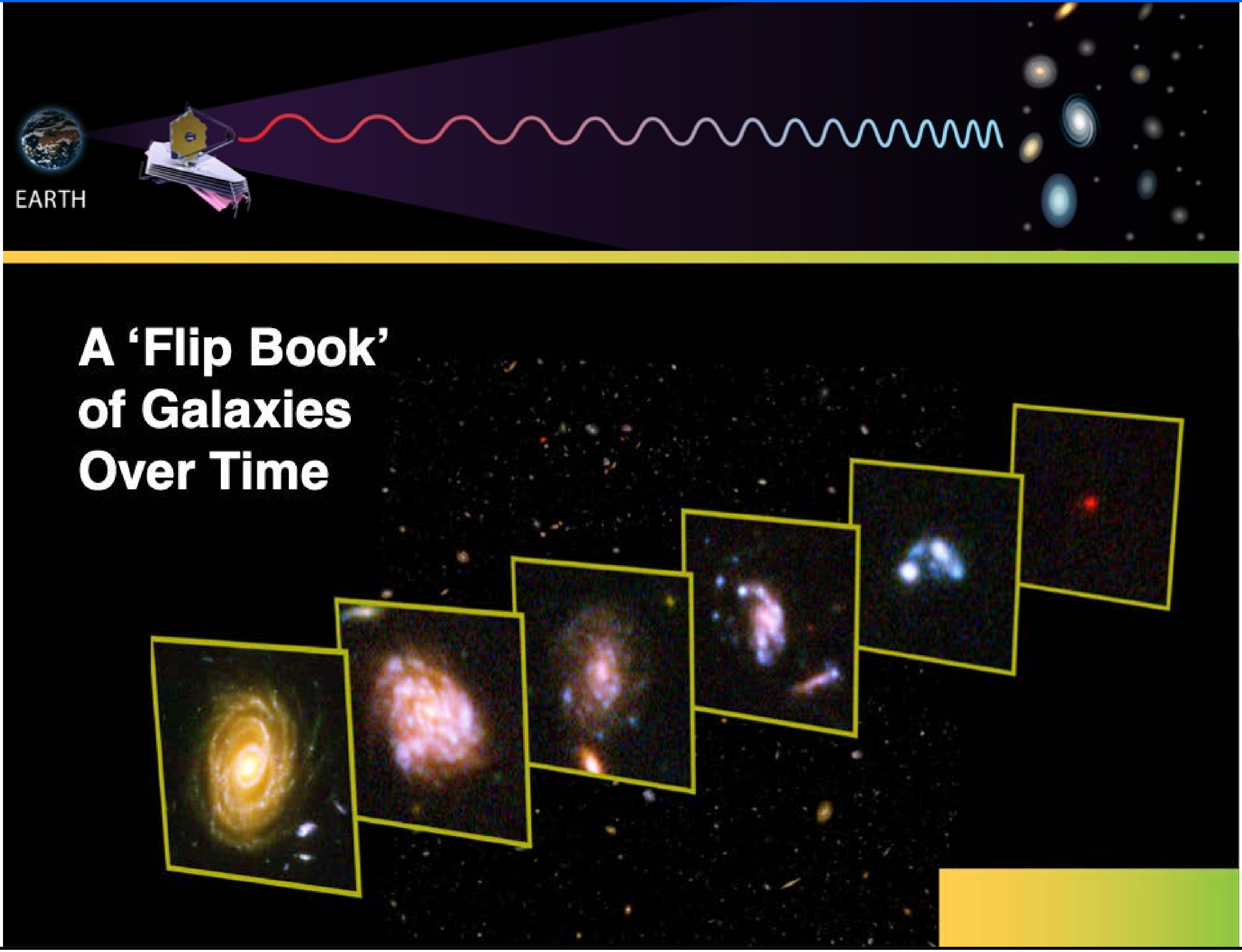
Visible and Infrared Light

Infrared light has the ability to "see" through opaque molecular clouds

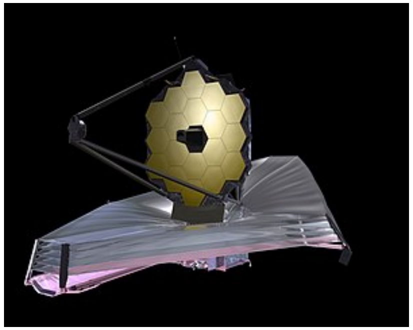
Betelgeuse



Observing the ancient Universe



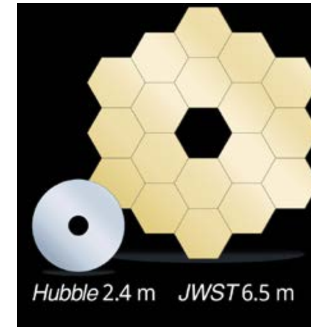
Understanding our Universe

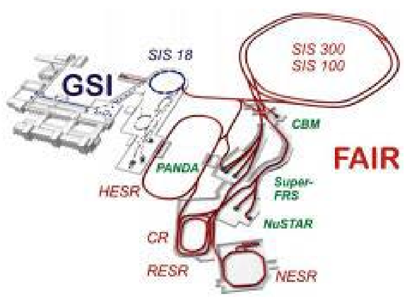


Space based Astronomy

- James Webb Space Telescope

1.5 million km from Earth
mirror 6.6 m diameter
18 mirror segments
5 sunshield layers





Nuclear Physics

- Facility for Anti-proton and Ion Research

all elements from proton to uranium and anti-proton
projectile fragmentation or fission for radioactive ion beams

Finland France Germany India Poland Romania Russia Slovenia Sweden UK Czech

Indian Ambassador H.E. Harish Parvathaneni at FAIR/GSI 17.4.2023

Gururaj Kumar (IUAC, Delhi University)