"Challenges in Nuclear Astrophysics with a next generation ISOL facility"

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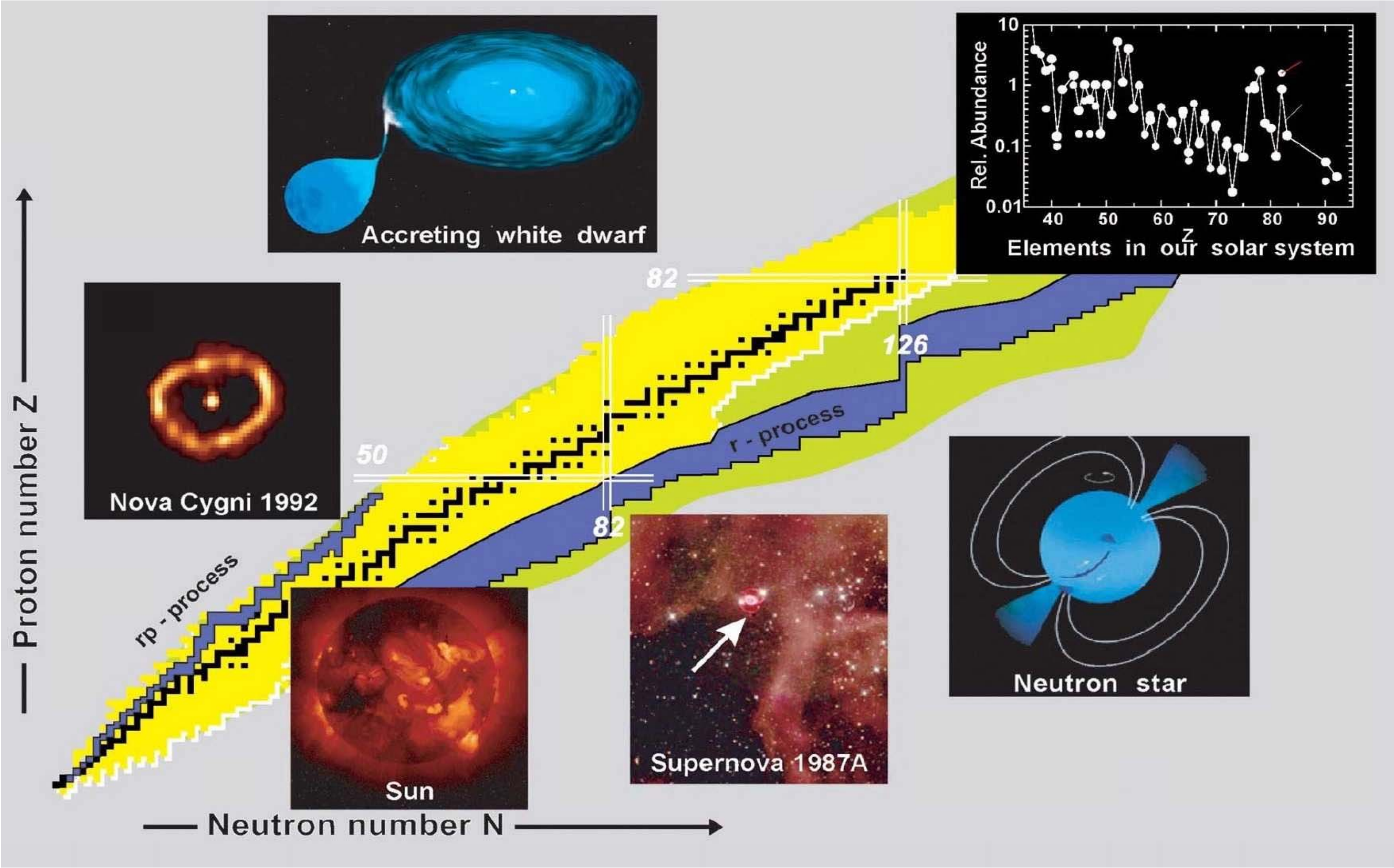


CERN 05/2004

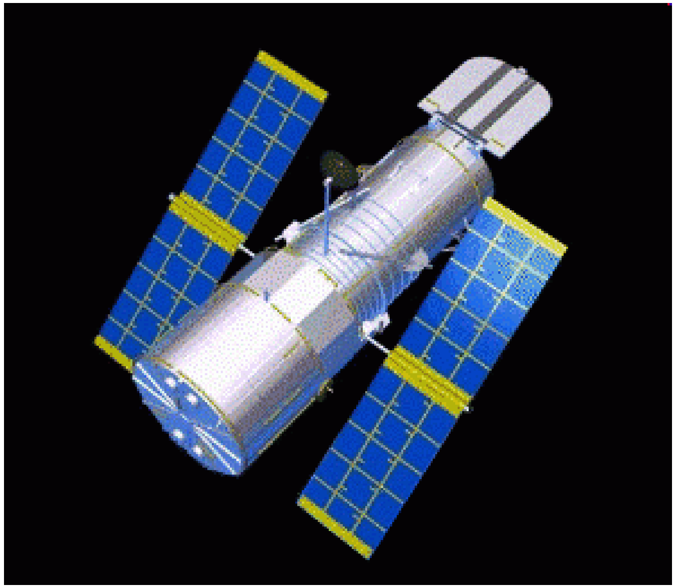
Workshop on *"**Physics at a Multi Mwatt proton source**"*

Historically, nuclear astrophysics has been concerned with

- Interpretation of observed **abundance distributions**, or specific signatures of **luminosity curves**;
- Description of originating **nucleosynthesis processes** (see, e.g. B²FH, 1957!)

Observational instrumentation:

- **meteoric** and overall **solar** abundances;
- ground- and satellite-based telescopes, like *Imaging Spectrograph* (STIS) at **Hubble** or *HIRES* at **Keck I**, and γ-ray satellites like *INTEGRAL* or x-ray observatories *CHANDRA* and *XMM-Newton*



Nuclear Physics in Stellar Binaries

Cataclysmic binaries are potential site for explosive nuclear reaction driven processes
- thermonuclear runaway -

- Nova: thermonuclear runaway burning on accreting white dwarfs
- Supernova type I: cataclysmic burning on white dwarfs
- X-ray bursts: thermonuclear runaway on accreting neutron stars
- X-ray pulsars: steady burning on accreting neutron stars

from Wiescher et al. (2003)

rp-process

at “low” temperatures

Novae

explosive H-burning on surface of white drawfs

cycle pattern due to Cb-barriers;
p-capture and β^+-decay
with similar time scales;
path close to stability

up to $_{19}$K - $_{23}$V
(p,γ); (γ,p); (p,α); $T_{1/2}(\beta^+)$
on odd-Z, T_z = + ½ nuclei
e.g. ^{23}Mg, ^{27}Si, ^{31}S, ^{43}Ti

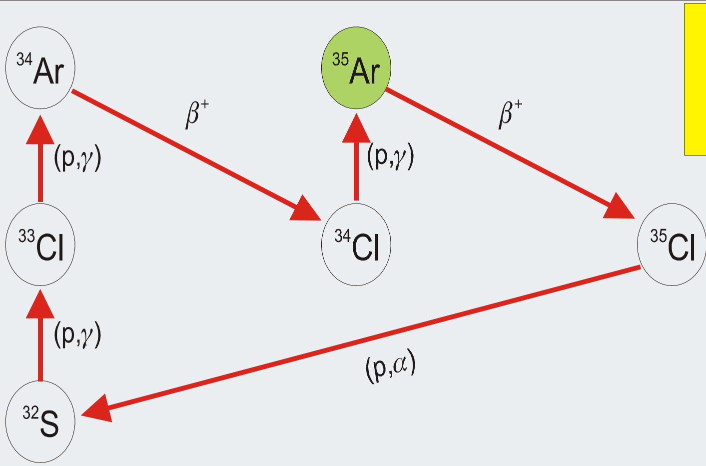
at “high” temperatures

X-ray bursts

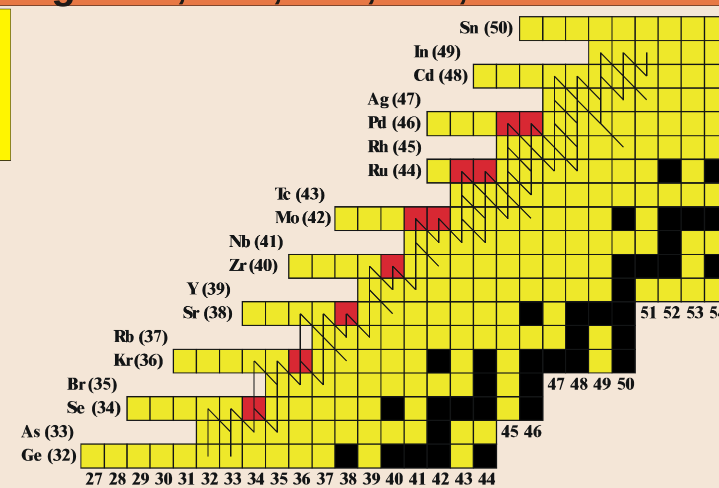
explosive H- and He-burning on surface of accreting neutron stars

(p,γ)-(γ,p) equilibrium; “waiting-point” concept;
sequence of fast p-captures
and subsequent β^+-decay
path far away from stability

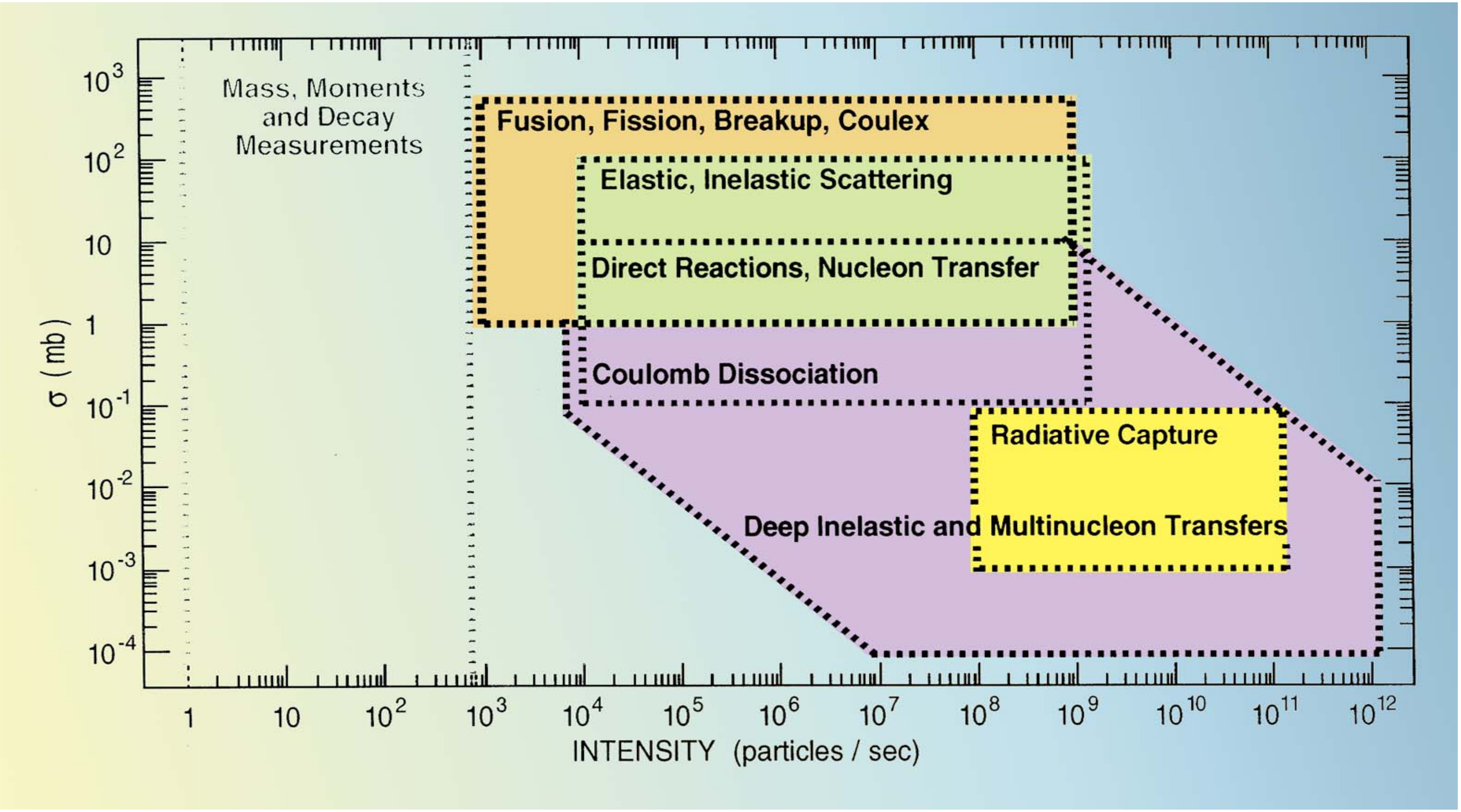
up to $_{46}$Pd - $_{50}$Sn
(p,γ); (γ,p); $(2p,\gamma)$; $T_{1/2}(\beta^+)$
on even Z, T_z = - ½ nuclei
e.g. ^{68}Se, ^{72}Kr, ^{76}Sr, ^{80}Zr, ^{84}Mo ...



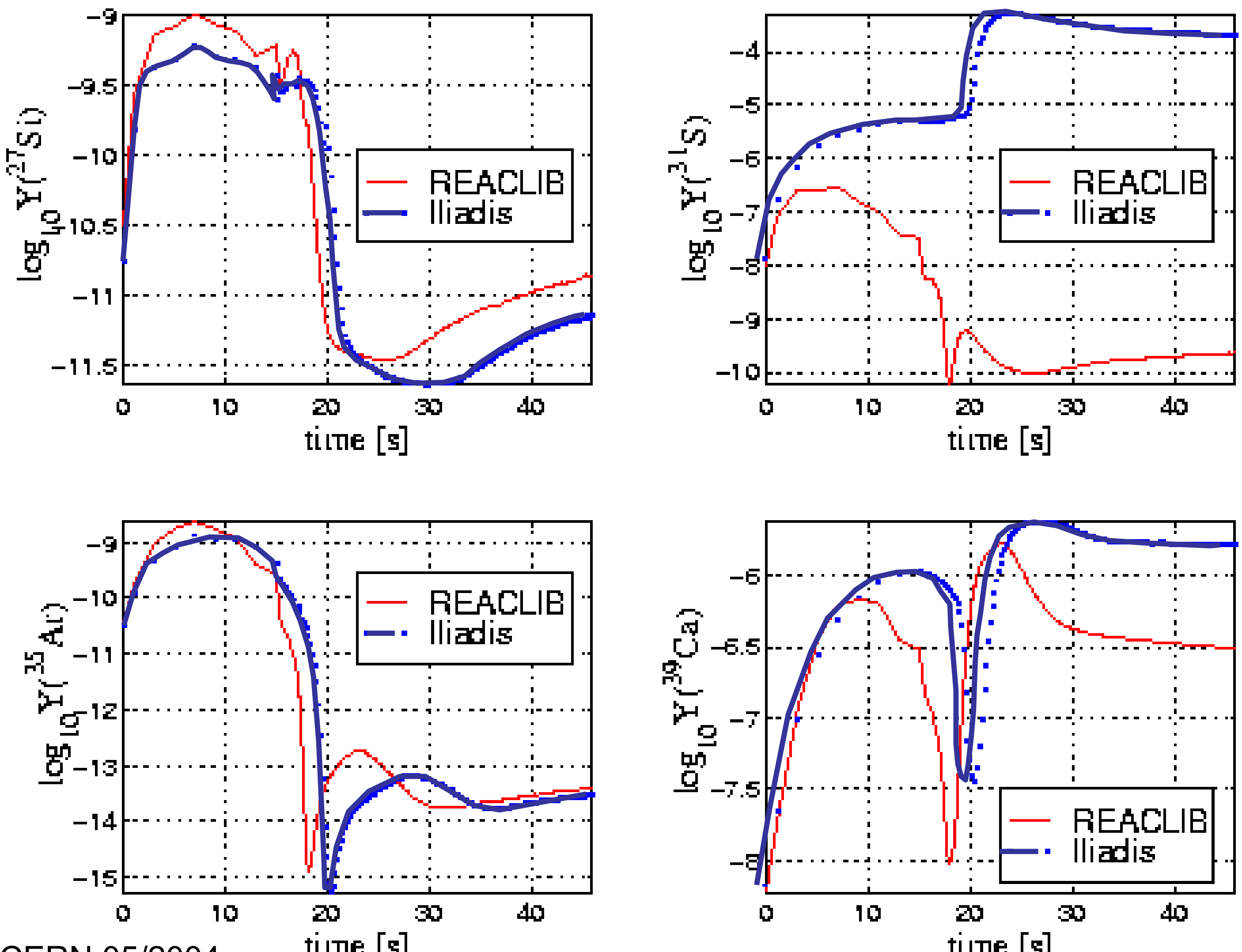
nucl. masses
reaction Q-values



Most relevant Nuclear Structure Experiments



Self consistent calculations
Consequences for isotopic abundances!



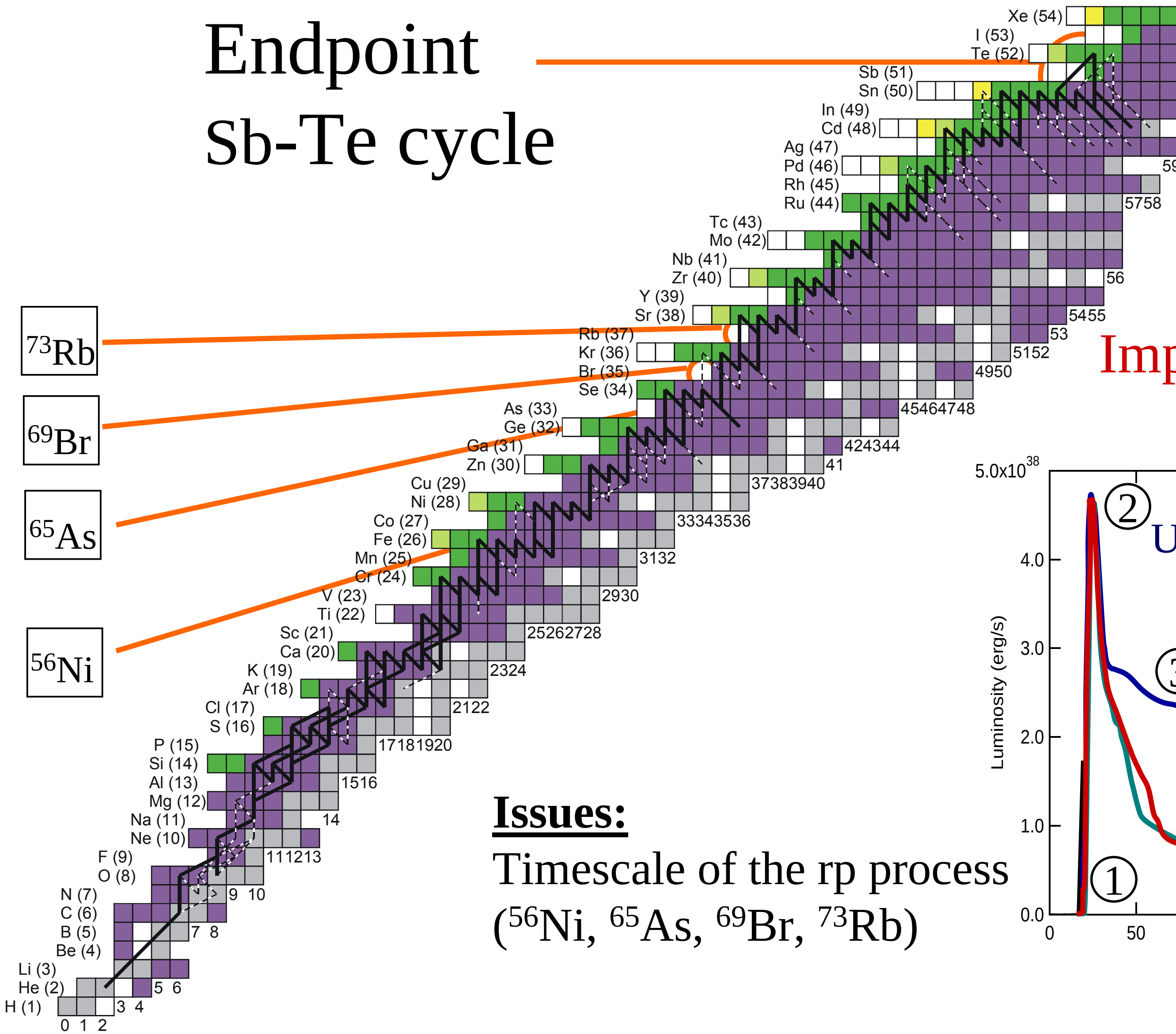
^{31}S, slower depletion
⇒ mixed towards surface

^{39}Ca, slower depletion
⇒ mixed towards surface

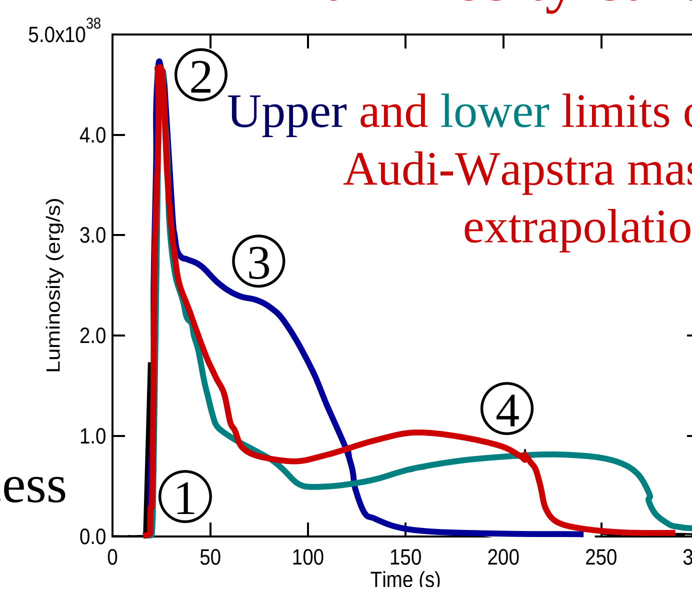
from M. Wiescher 2003

Waiting points in the rp-process

Endpoint
Sb-Te cycle



Impact on X-ray burst luminosity curve



Upper and lower limits of Audi-Wapstra mass extrapolations

Issues:

Timescale of the rp process (^{56}Ni, ^{65}As, ^{69}Br, ^{73}Rb)

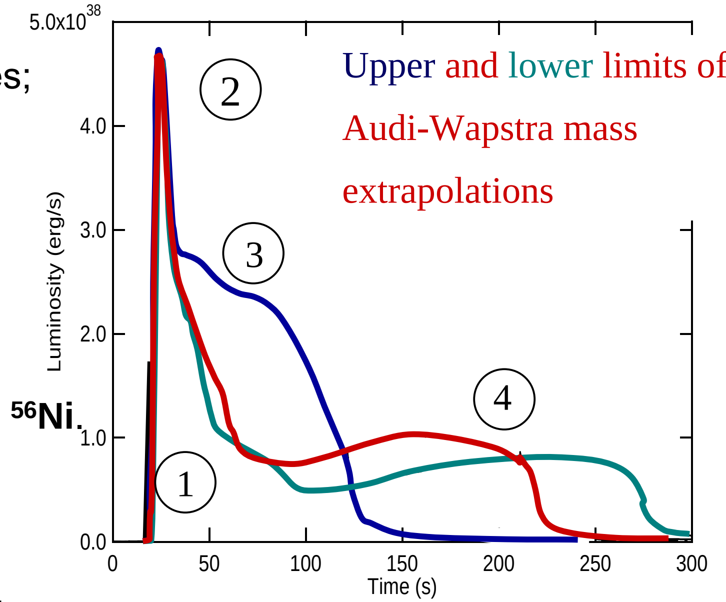
from Wiescher et al. (2003)

The **Energy production in X-ray bursts**

characterized by 4 periods at increasing temperature (2×10^8 - 2×10^9 K):

① ignition phase

Hot CNO-cycles, triggered by p-captures on C, N, O isotopes;
formation of ^{14}N, ^{14,15}O, ^{17}F and ^{18}Ne waiting-point nuclei.

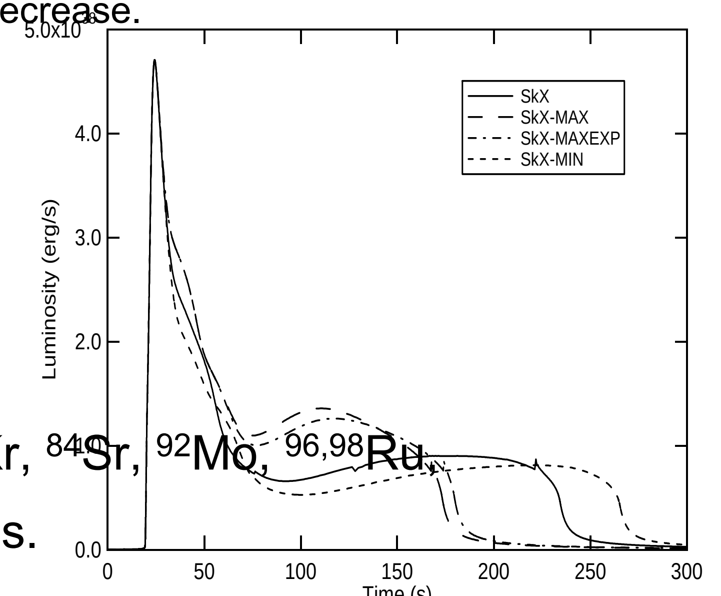


② ignition of triple-α-process

Rapid depletion of ^{14,15}O and ^{18}Ne by α-reactions to ^{24}Si;
further p- and α-captures to waiting-point isotopes ^{29}S, ^{34}Ar;
and subsequent α-captures to **main waiting-point nucleus ^{56}Ni**.

③ dormant period

Here, further processing is halted by (p,γ)-(γ,p) equilibrium;
energy production drops rapidly; and temperature starts to decrease.



④ rp-process beyond ^{56}Ni

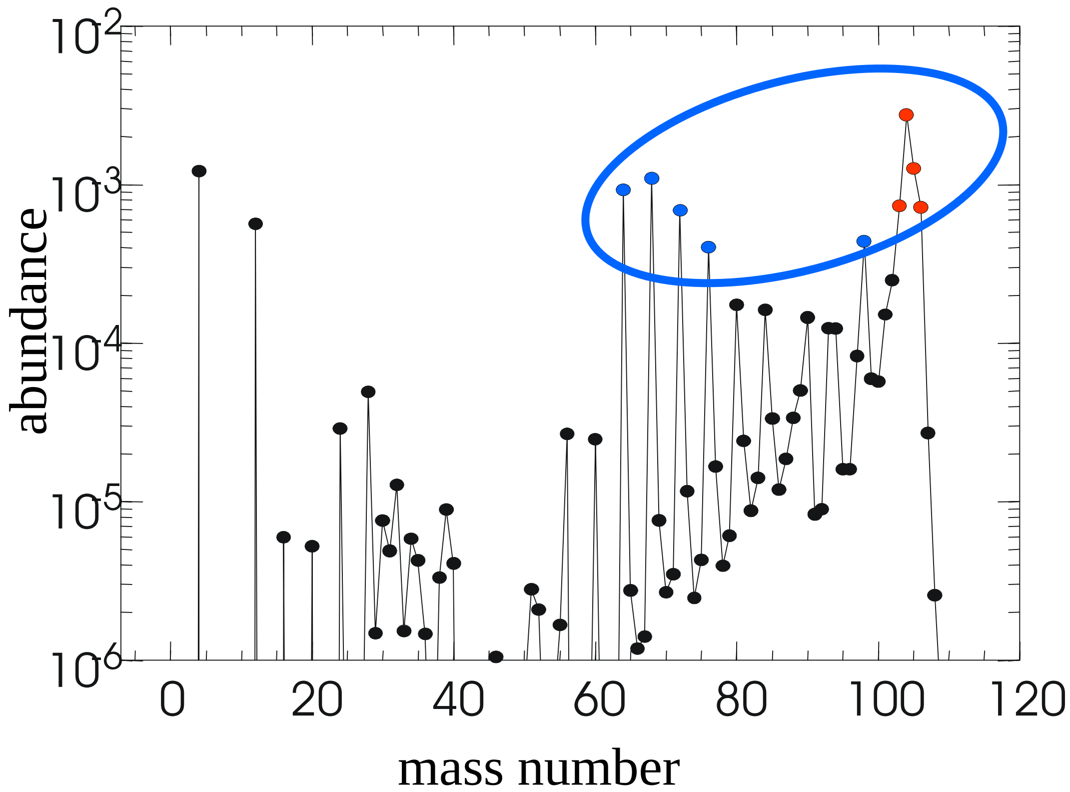
Start at $T_9 = 1.5 \times 10^9$ - 1.0×10^9 K;
cooling phase down to ~ 5×10^8 K;
several even-even waiting-points ^{64}Ge, ^{68}Se, ... ^{100}Sn;
overall time scale ~ 500s.

Clear abundance peaking of light p-nuclei ^{74}Se, ^{78}Kr, ^{84}Sr, ^{92}Mo, ^{96,98}Ru

so far not explained in classical p-process scenarios.

The fate of the processed matter?

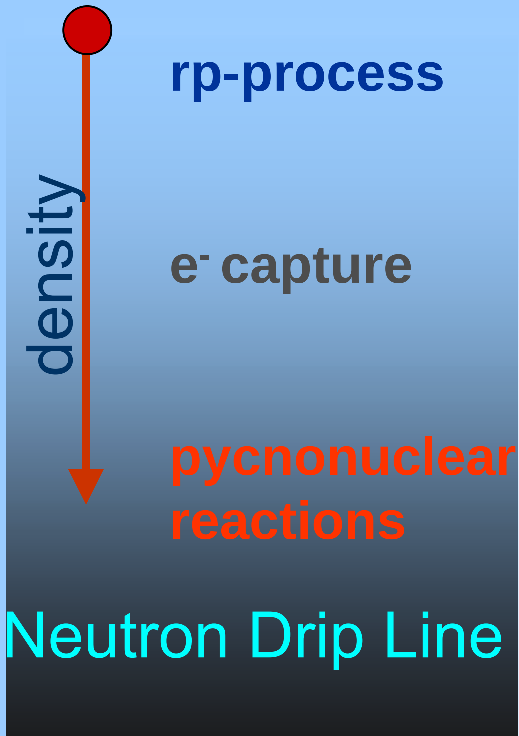
Final abundance distribution

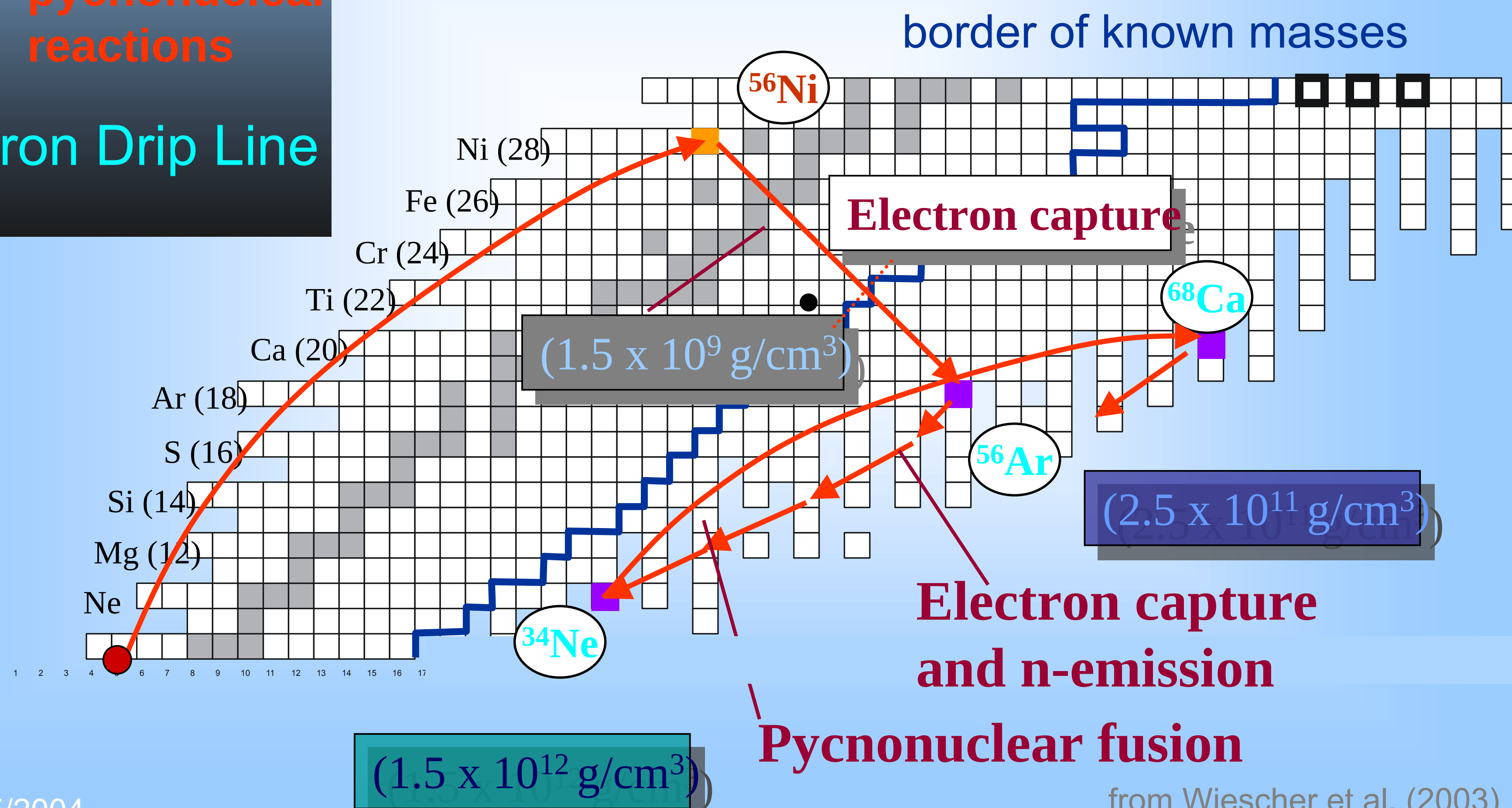


- Ejected out of neutron star grav. potential
  ⇨ contribution to light p-nuclei abundances
- Embedded into neutron star crust
  ⇨ modification of crust composition

from Wiescher et al. (2003)

The fate of matter in the neutron star crust





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from Wiescher et al. (2003)

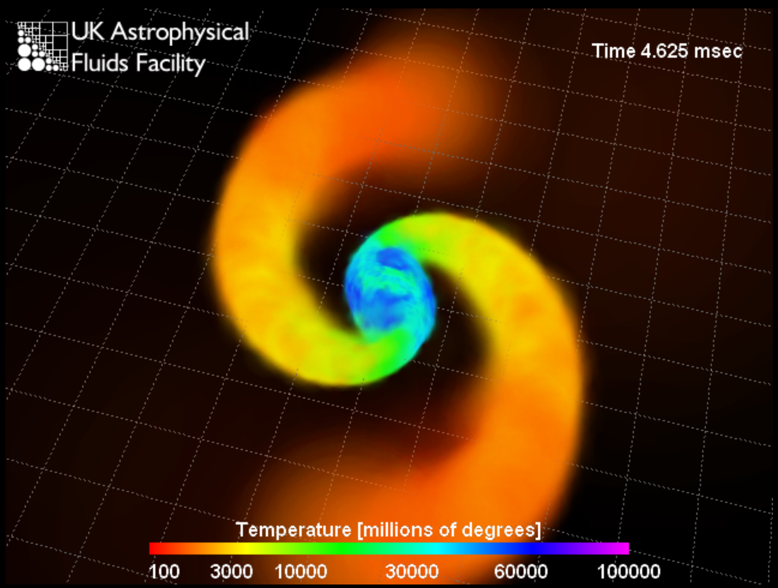
Conclusion

- Nuclear structure along rp-process reaction path (N=Z line) determines abundance distribution in the ashes
- Endpoint is associated with α-unbound nuclei beyond Z,N=50
- Electron capture drives abundance distribution towards the neutron drip line (timescale $>10^5$ y)
- Electron capture induced neutron emission drives abundance distribution towards Z<12
- Pycno-nuclear reactions

from Wiescher et al. (2003)

Nuclear Physics in Neutron-Rich Explosive Environments

High neutron to seed ratio (10 - 150) for rapid neutron-capture processes only in explosive astrophysical sites



- Supernova type II: explosive shell burning (He, C)
  high-entropy neutrino wind ejecta
- Neutron-star (NS) mergers: low-entropy ejecta of NS matter
- Axial jets in SNe: blast ejecta from rotating NS accretion disk

r-process

Supernova II

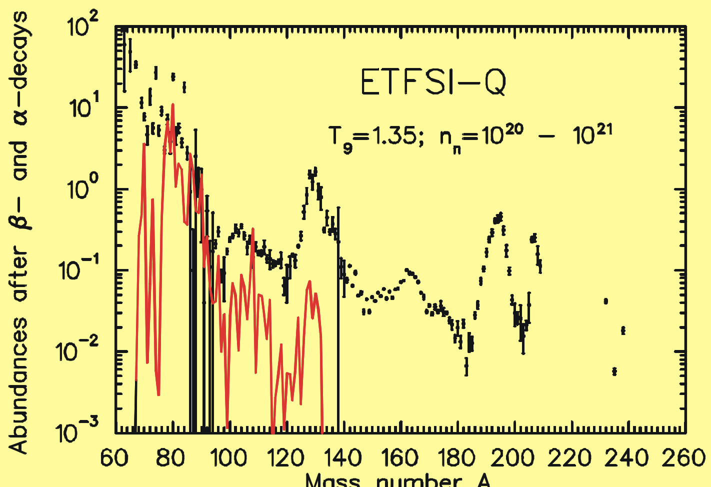
moderate n-densities ($n_n \leq 10^{23}$)
explosive (He, C, Si) shell burning
high-entropy bubble , core scenario

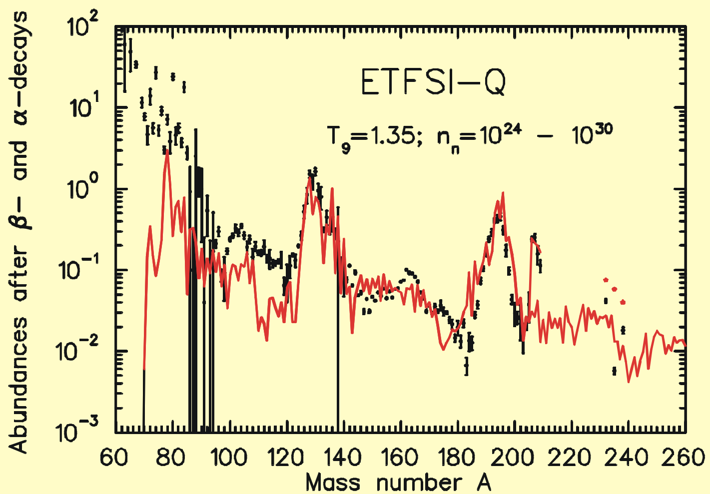
Neutron Star Mergers

high n-densities ($n_n \approx 10^{30}$)
very n-rich ejecta
fission "recycling"

nuclear data needs

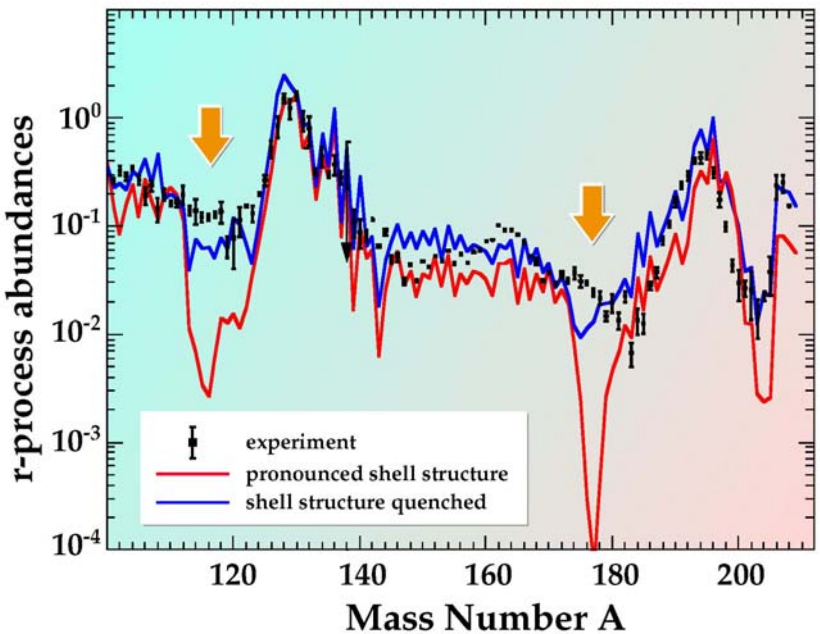
direct: Q_β, S_n, $T_{1/2}$, P_n, $\sigma_{n\gamma}$ of „"waiting-point nuclei" at N_{mag}
indirect: development of nuclear structure with isospin

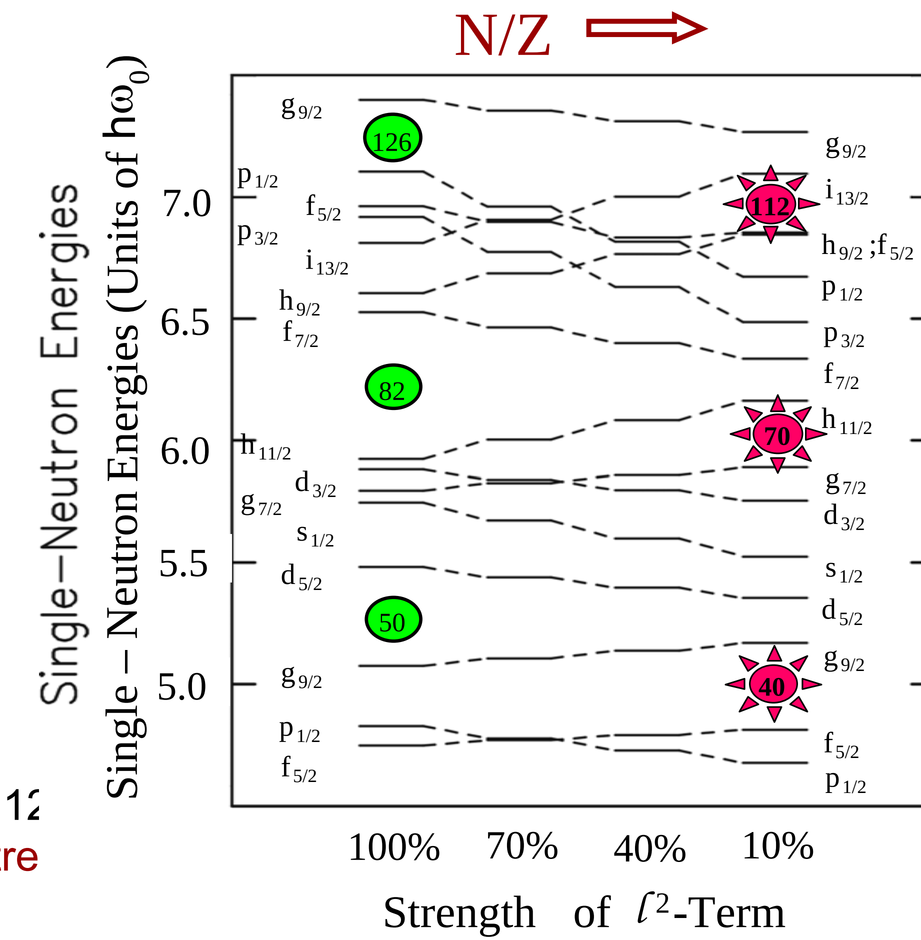




New Nuclear structure at drip-lines, as „shell quenching“?

Defiencies prior to the main peaks were attributed by our group to nuclear structure effects:
- too strong shell strength for extremely neutron-rich magic nuclei far from stability
- nuclear models adjusted to stable nuclides
- new physics far from stability?





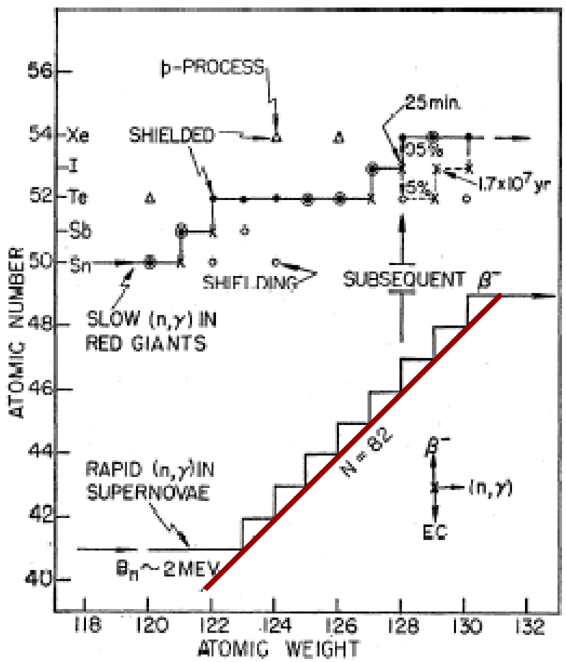
FK²L (Ap.J. 403 ; 1993)
“..the calculated r-abundance ‘hole‘ in the A ≅ 12
region reflects ... the weakening of the shell stre
... below $^{132}_{50}Sn_{82}$“

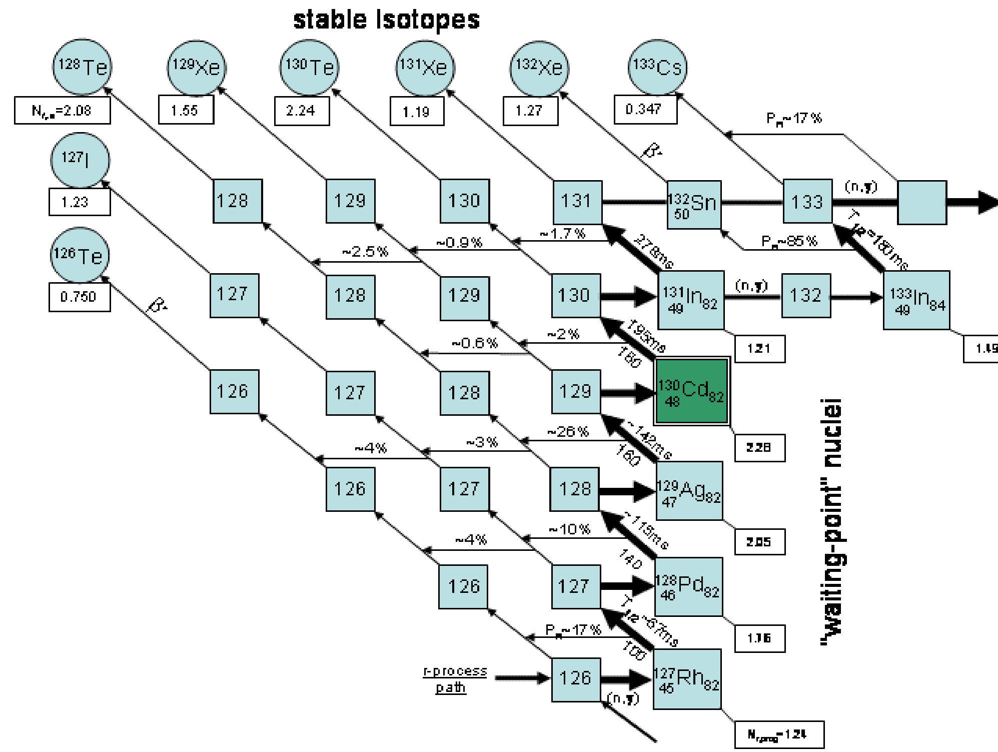
B. Pfeiffer et al.,
Acta Phys. Polon. **B27** (1996)

R-abundance peaks and neutron-shell numbers

already B²FH (Revs. Mod. Phys. 29; 1957)
C.D. Coryell (J. Chem. Educ. 38; 1961)

...still today important r-process properties to be studied experimentally and theoretically.





"climb up the staircase" at N=82;
major waiting point nuclei;
"break-through pair" ^{131}In, ^{133}In;

K.-L. Kratz (Revs. Mod. Astr. 1; 1988)

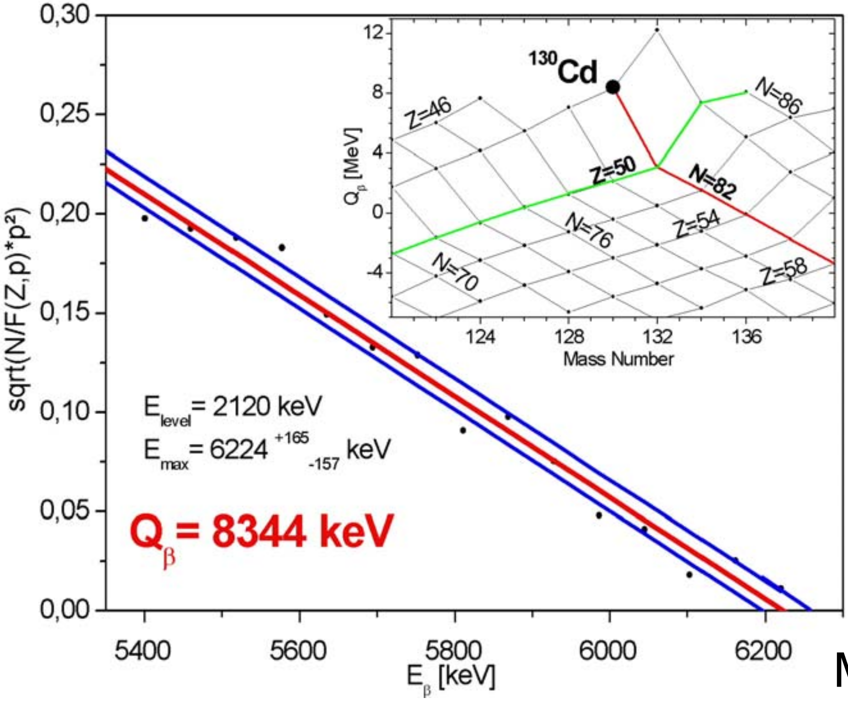
climb up the N= 82 ladder ...

A ≅ 130 "bottle neck"

⇨ **total r-process duration τ_r**

"association with the rising side of major peaks in the abundance curve"

Q_β-value of $^{130}Cd_{82}$

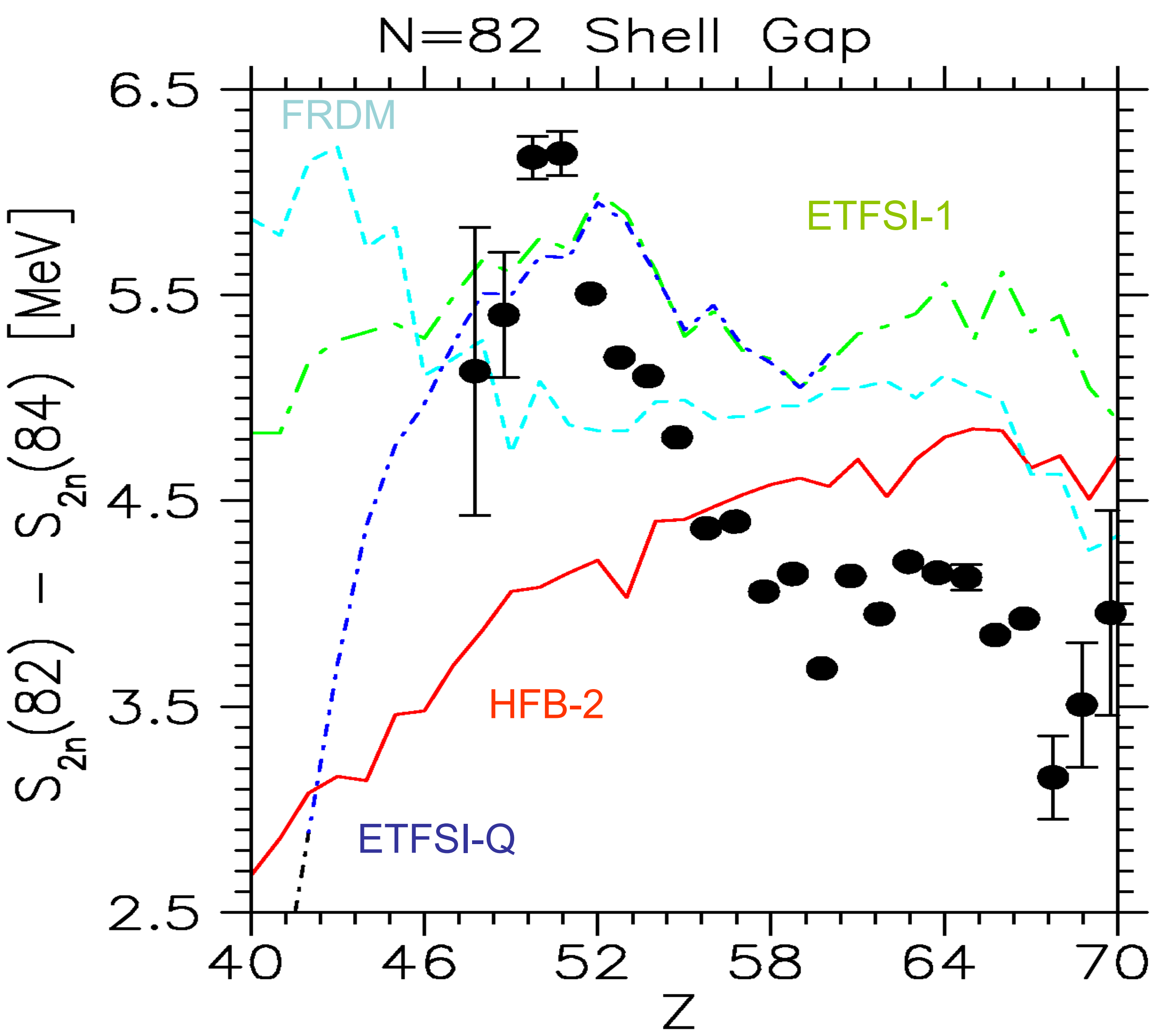


Way-Wood diagram

⇨ Z=50 and N=82 shell closures „visible“

High Q_β-value is a clear signature for an N=82 „shell quenching“ below $^{132}Sn_{50}$

Mass model predictions	Q_β
Hilf et al. (*GTNM*, 1976)	7.57 MeV
Möller et al. (*FRDM*, 1995):	7.43 MeV
Aboussir et al. (*ETFSI*, 1995):	7.87 MeV
Duflo & Zuker (1995)	7.56 MeV
Dobaczewski et al. (*HFB/SkP*, 1996):	8.93 MeV
Pearson et al. (*ETFSI-Q*, 1996):	8.30 MeV
Audi & Wapstra (*Mass Eval.*, 1997):	8.50 MeV
Goriely et al. (*HFBCS*, 2001)	7.00 MeV
Samyn et al. (*HFB-2*, 2002)	7.64 MeV
Brown et al. (*local OXBASH, 2003*):	8.75 MeV


N=82 Shell Gap
FRDM
ETFSI-1
HFB-2
ETFSI-Q
$S_{2n}(82) - S_{2n}(84)$ [MeV]
Z
6.5
5.5
4.5
3.5
2.5
40
46
52
58
64
70

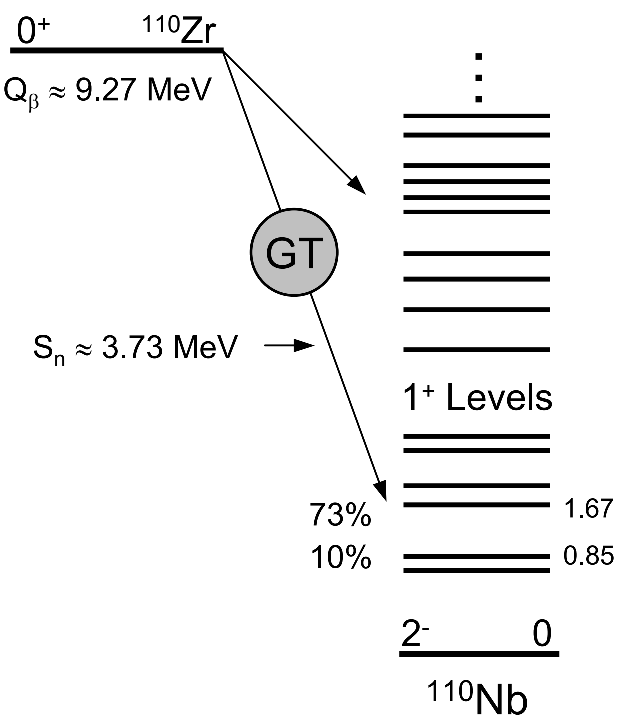
$^{110}_{40}Zr_{70}$

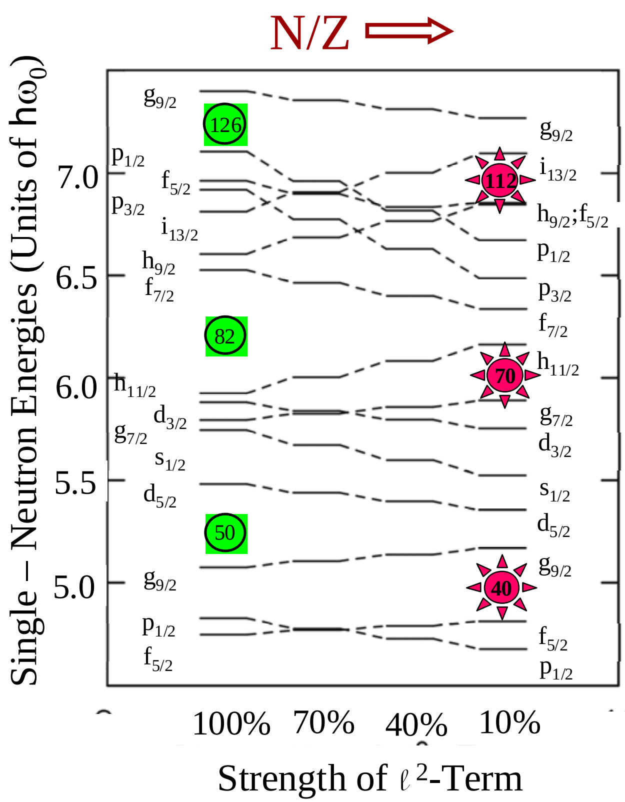
... a new double-magic „waiting-point“ nucleus?

Beta-decay

Normal shell strength
strongly deformed (ε_2=0.31`

$T_{1/2}$	=	88 ms
P_n	=	8 %

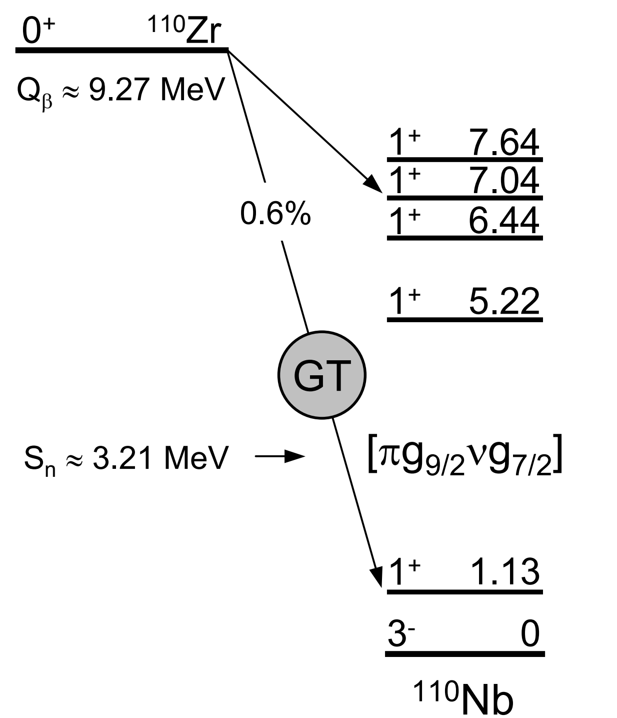




B. Pfeiffer et al.,
Acta Phys. Polon. **B27** (1996)

Shell strength quenched
spherical

$T_{1/2}$	=	14 ms
P_n	=	0.7 %



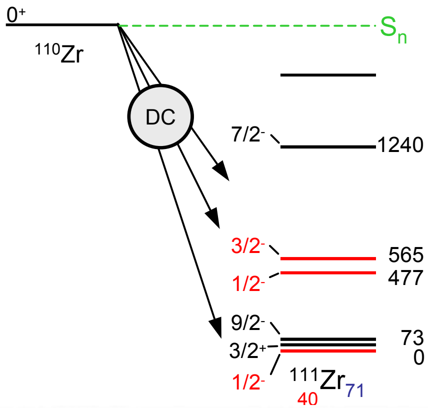
K.-L. Kratz, A. Ostrowski (2004)

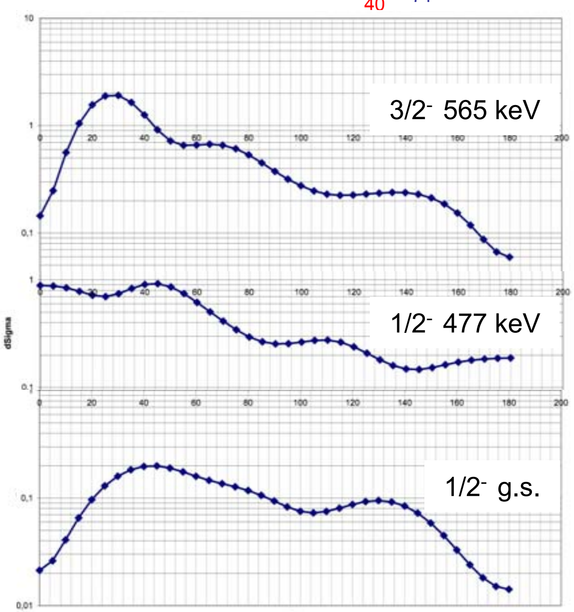
$^{110}_{40}Zr_{70}$

... a new double-magic „waiting-point“ nucleus?

Normal shell strength

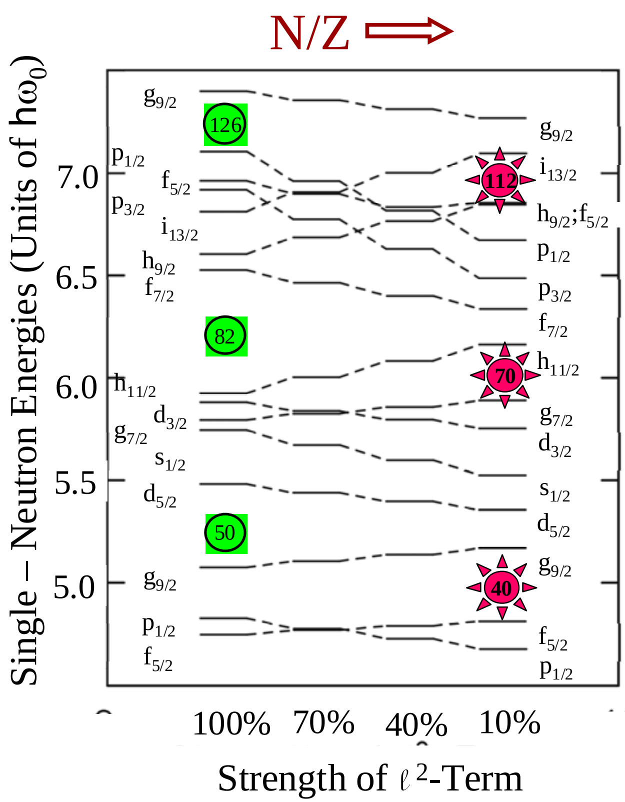
strongly deformed (ε_2=0.34)





Neutron-capture

via (d,p) in inverse kinematics

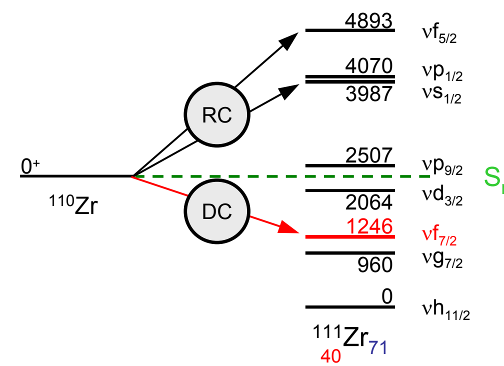


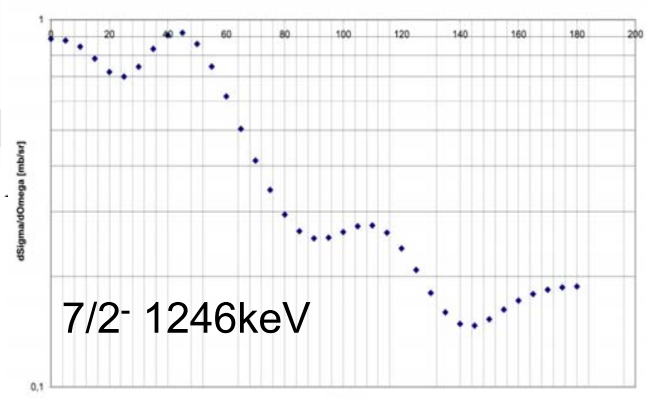
B. Pfeiffer et al.,
Acta Phys. Polon. **B27** (1996)

Shell strength quenched

spherical

$S_n(^{111}Zr) \approx 2.30$ MeV





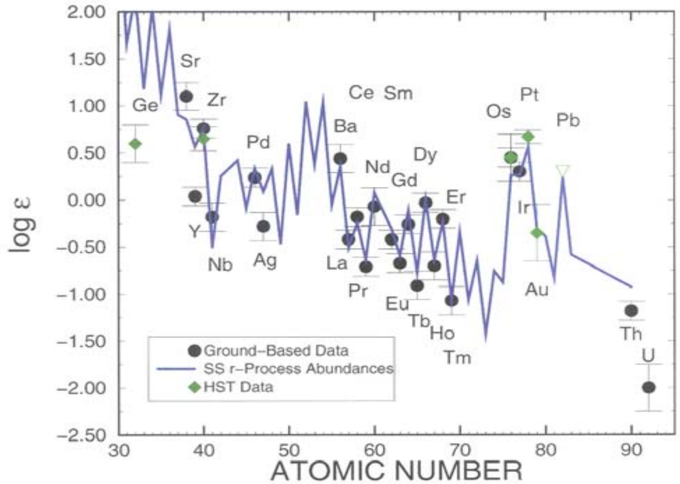
K.-L. Kratz, A. Ostrowski (2004)

Ultra-metal-poor Halo stars

Th-U cosmochronometer

- Th-U chronometer ideal for dating of solar system.
- Lower limit for age of the Universe requires models of Galactic chemical evolution.

- High-resolution optical spectroscopy of ultra-metal-poor, very old Halo red giant stars opens new perspectives:
  - One (or few) nucleosynthesis events seeded ISM.
  - Scaled solar system r-process abundances for $56 \leq Z \leq 79$.
  - Radioactive dating requires „production ratios“.
  - Th/U ratio (hopefully) less affected by extra-polations of nuclear structure

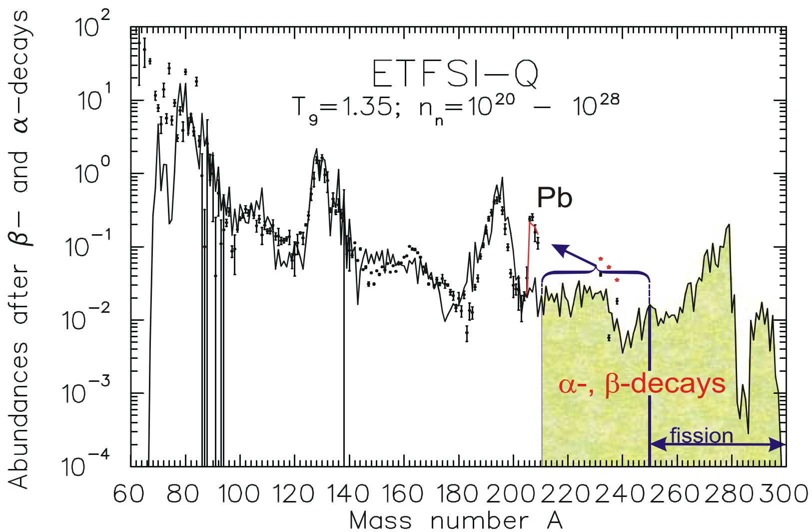


Abundances in BD+17^{o}3248

Calculated abundances of the long-lived actinides test for short-lived isotopes expected in Galactic cosmic rays.

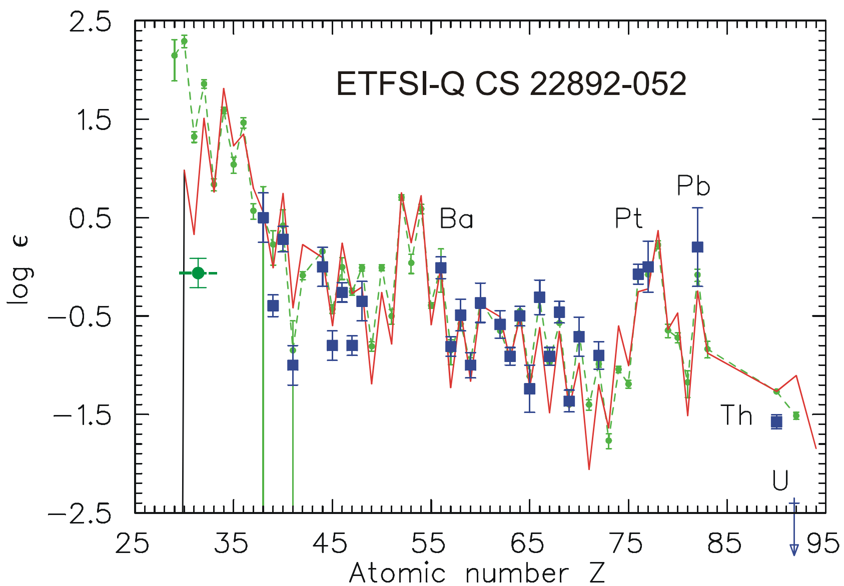
What do we calculate?

Reproduce isotopic $N_{r,\odot}$ distribution using waiting-point approach (lsq-fits; A ⩾ 80, A ⩾ 120)



Pb abundances as reliability criterion for Th, U region!

Convert to elemental $N_{r,\odot}$ curve(–), and scale to halo abundances (■)



↷ comparision to $N_{r,\odot}(Z)$

⇒ excellent agreement above Ba

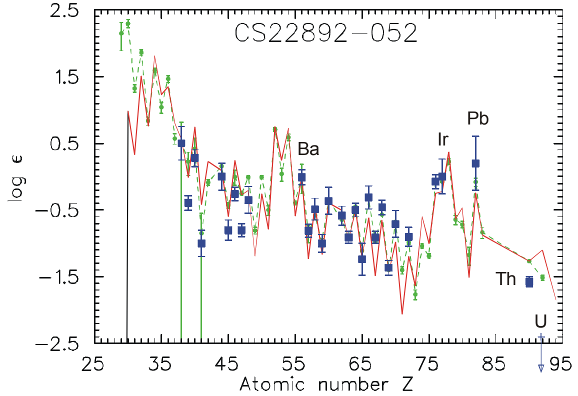
⇒ Th, U cosmo-chronometry

Cosmochronology with Thorium

Several UMP halo stars consistently show solar elemental abundance pattern, among them

CS 22892-052

with 17 elements between Ba and Ir, plus Pb and ^{232}Th ($T_{½} = 14 \cdot 10^9$ a)



⇒ age from average of Th/Ba-Ir

14.6 ± 3.0 Gyr

≈ age of the Universe

Tuning the clock with Uranium

Because of shorter half-life ($T_{½} = 4.5 \cdot 10^9$ a), ^{238}U may yield more precise age.
Recently, first observation of U in CS 31082-001

(Cayrel et al., 2001)

⇒ age from U/Th

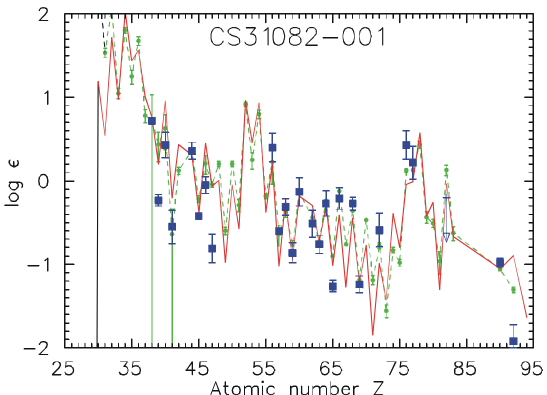
15.0 ± 3.0 Gyr

(Schatz et al., 2002)

In the meantime, second observation of U in BD +17°3248 ⇒ age from U/Th and U,Th/3rd peak

13.8 ± 4.0 Gyr

(Cowan et al., 2002)



Isotope ratios in metal-poor, r-process-rich stars

For a limited number of elements (as Rb, Ba, Eu), not only **elemental** but also **isotopic** abundances have been observed in stars.
This provides crucial information on the timing of the neutron-capture processes, the s- and r-process, in the early Galaxy.

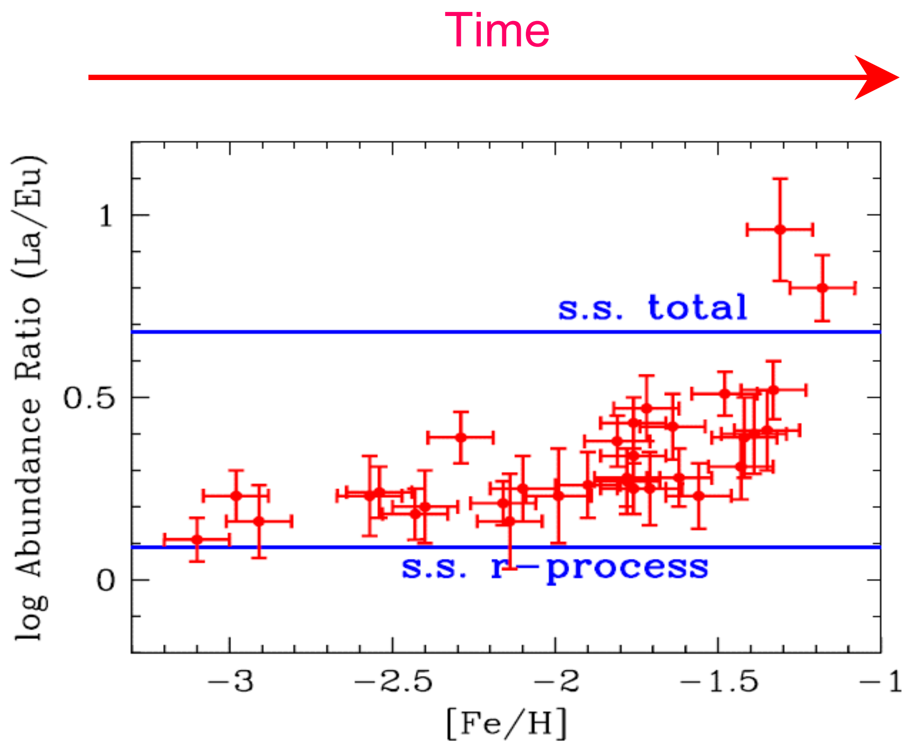


Figure 6: La/Eu ratios for a variety of metal-poor stars as a function of metallicity (*24*). The horizonal lines denote the total and r-process only solar system abundance ratios.

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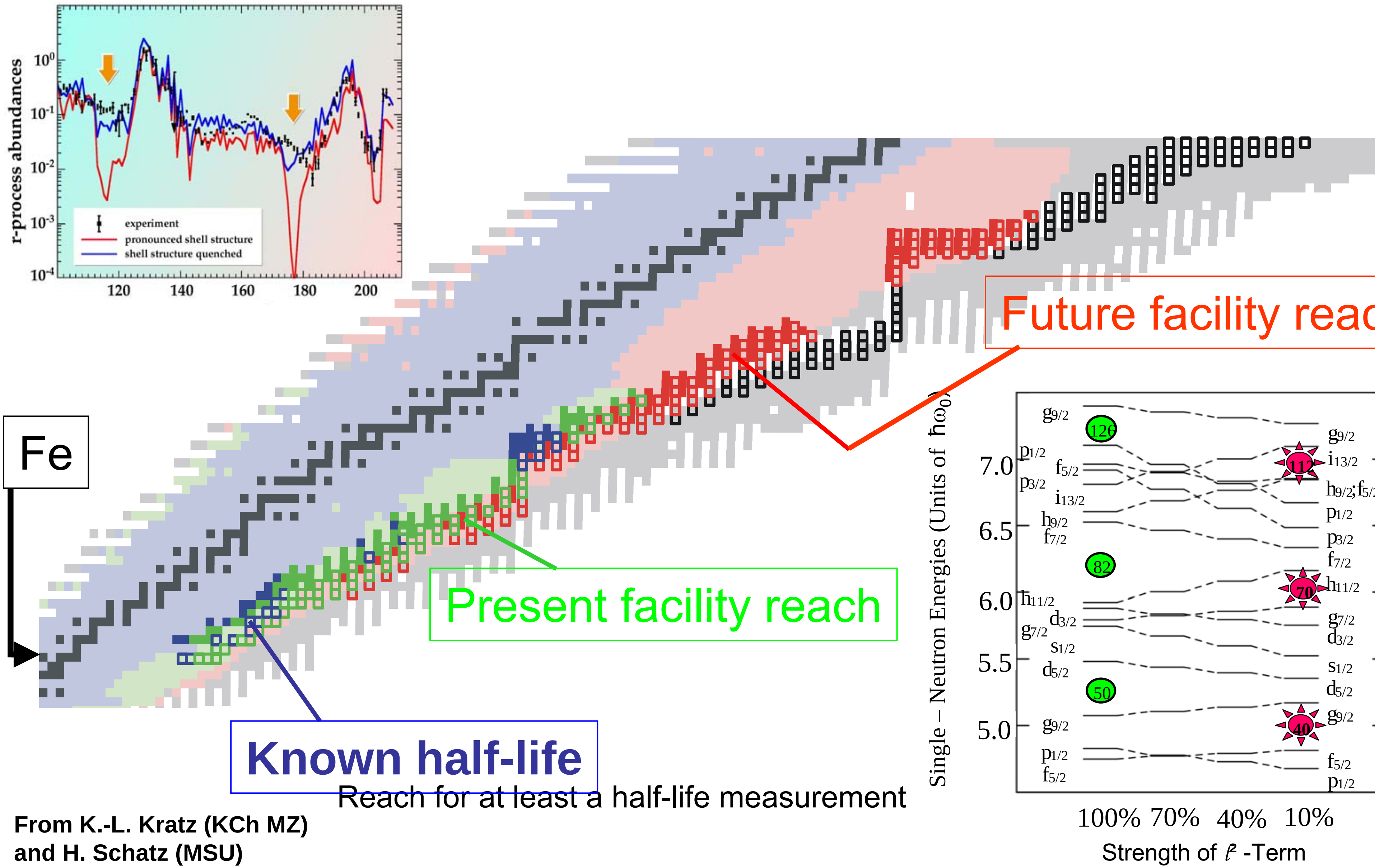
Future developments

- Experimental data for extremely neutron-rich nuclei needed.
- Radioactive Ion Beam facilities
  - extension of the N=50 and 82 regions as close to drip-line as possible
  - N=126 “waiting-point” nuclei

- Ongoing sky surveys detect more metal-poor stars.
- More high-resolution optical spectroscopy in stars of varying metallicity is needed.
- More precise dating of the on-set of s-process nucleosynthesis.

- Scenarios/sites for the r-process
  - Effectively constrain “classical” parameter studies
  - Impact of the network calculations?
- Are there different r-processes?

Reach of radioactive beam facilities



Reach for at least a half-life measurement

From K.-L. Kratz (KCh MZ)
and H. Schatz (MSU)