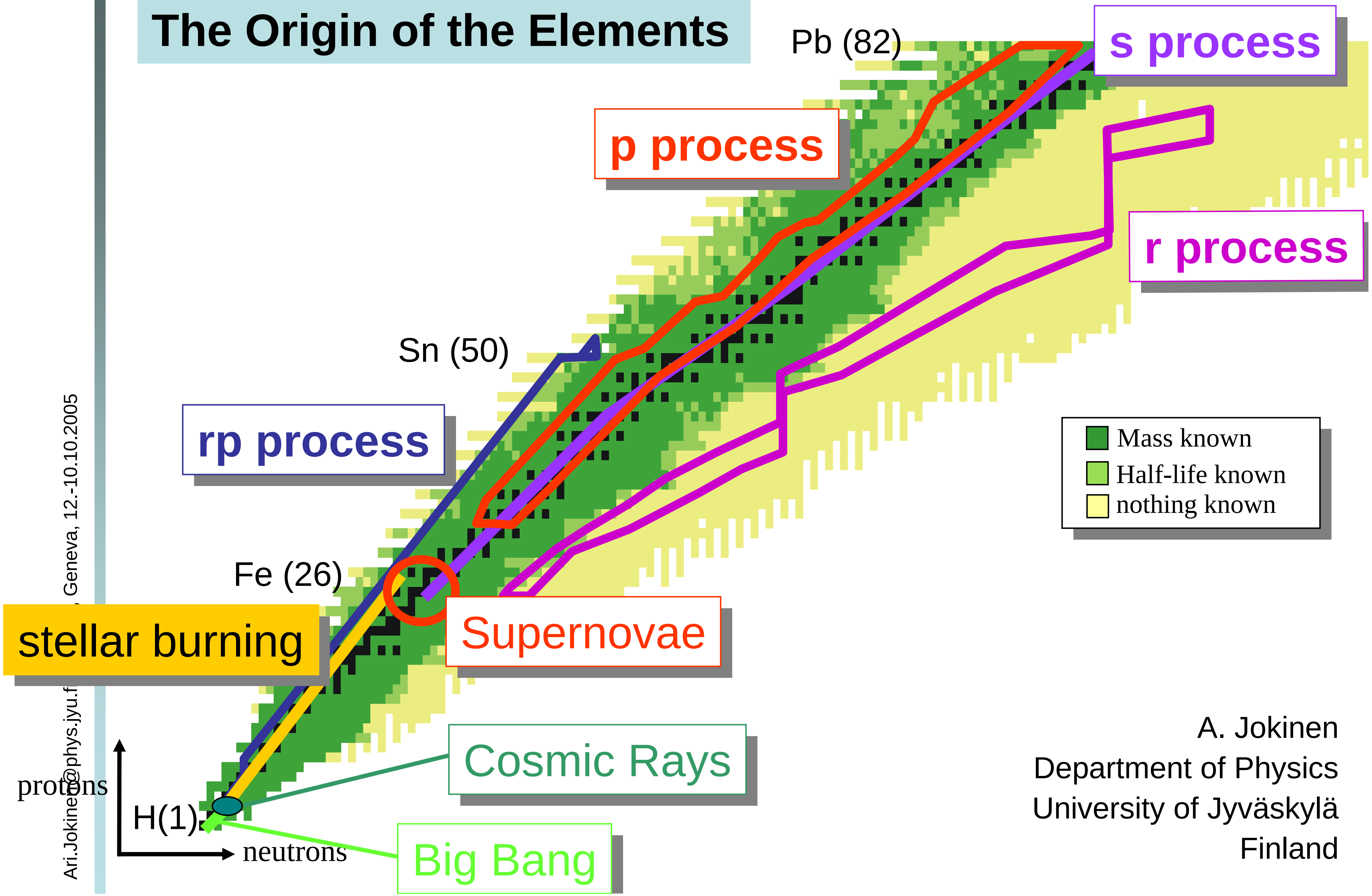
ISOLDE experiments and astrophysics implications

The Origin of the Elements



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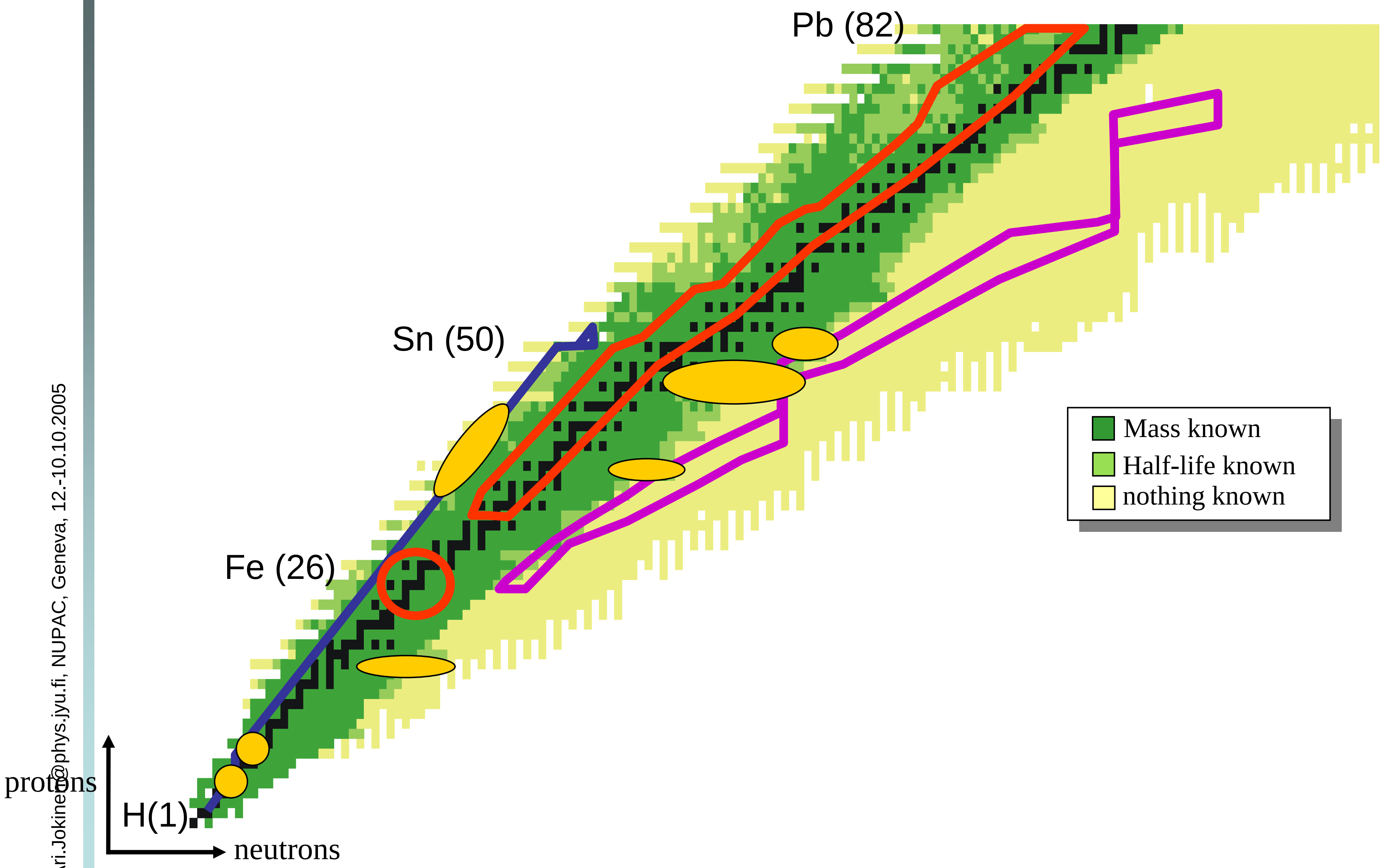
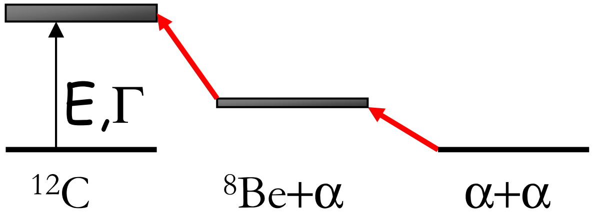
ISOLDE experiments and astrophysics implications



Triple-α process rate

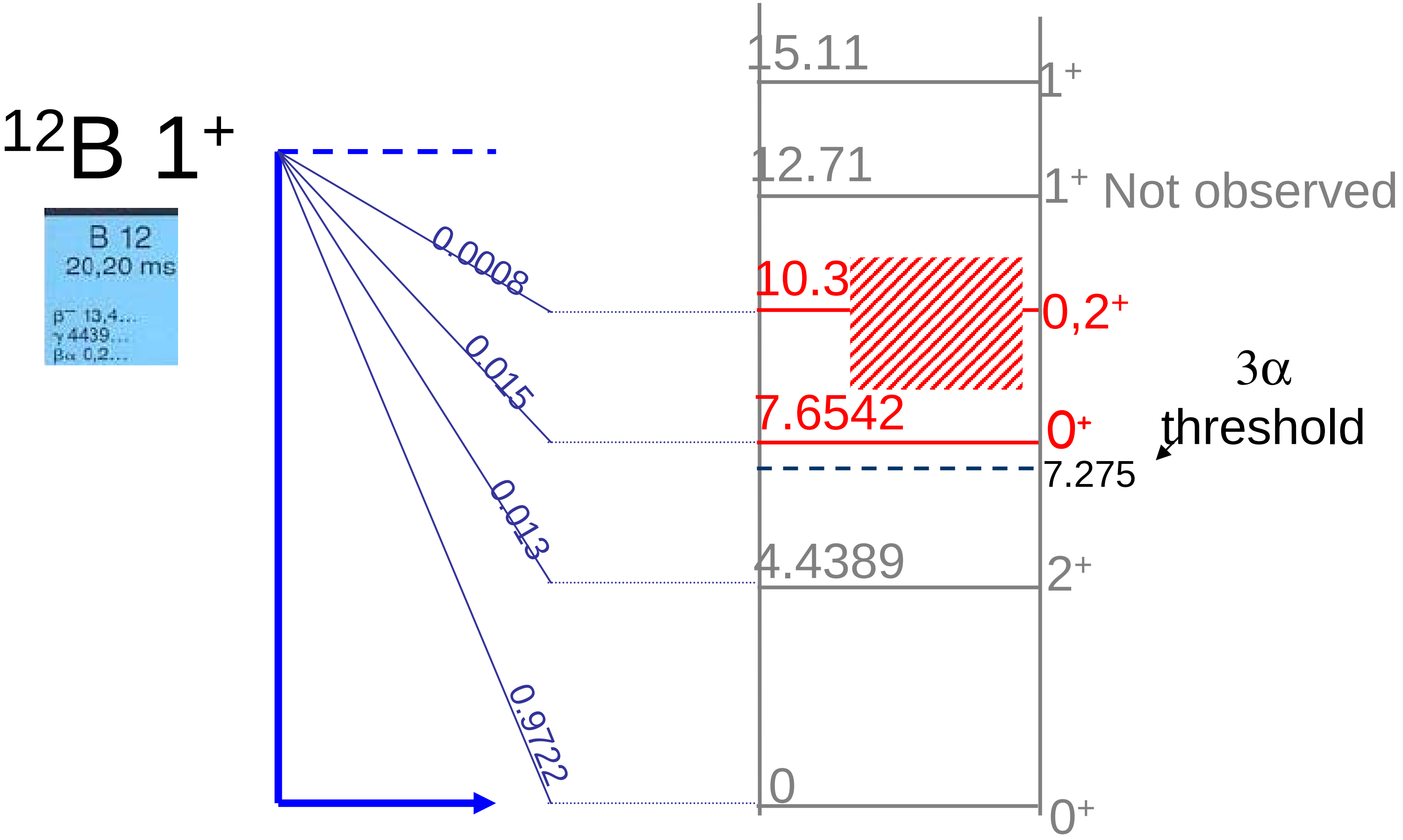


Step I: α+α ⇔ ^{8}Be

Resonant process

Form equilibrium abundance of ^{8}Be

Step II: ^{8}Be + α ⇔ ^{12}C(7.65)



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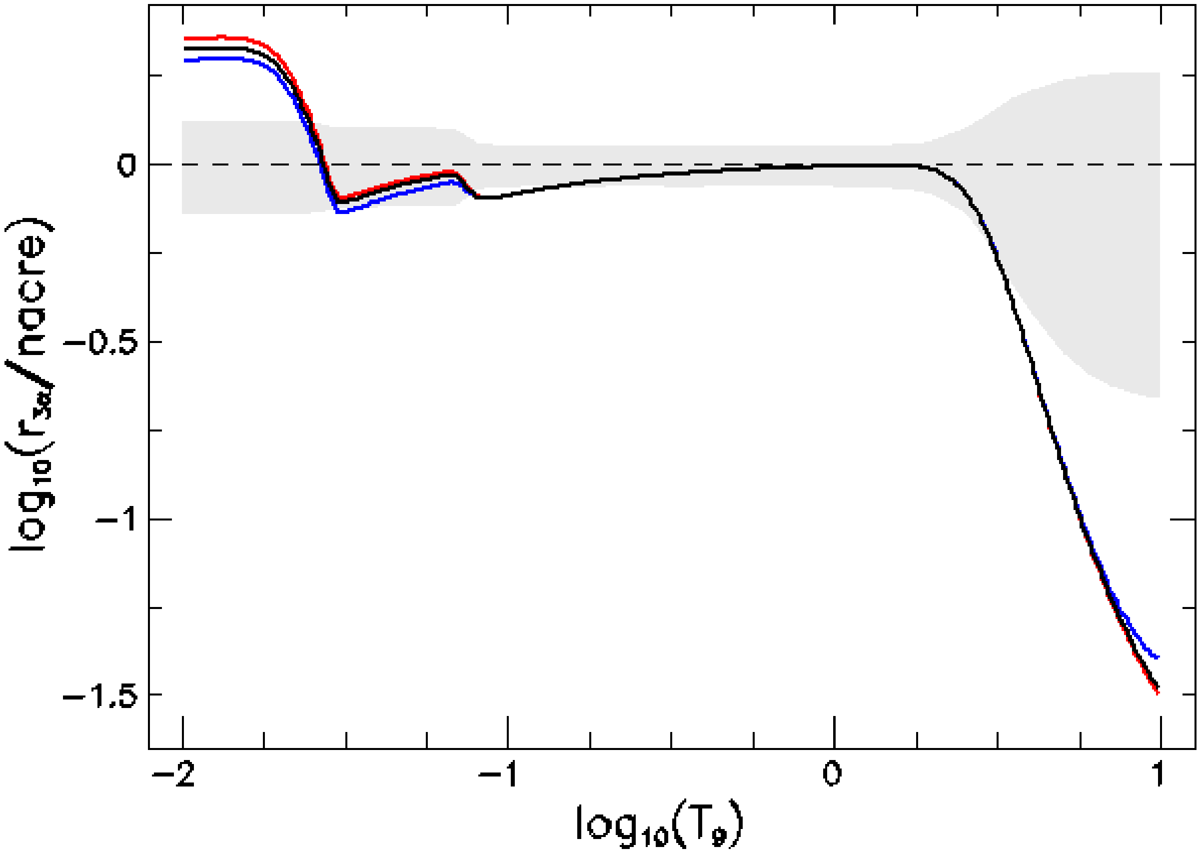
Triple-α reaction rate

H. Fynbo et al., Nature 433 (2005) 136



$r_{3\alpha}$ reaction rate including new interpretation of ^{12}C states,
Nuclear Astrophysics Compilation of Reaction Rates, C. Angulo et al., NPA **656** (1999) 3

Astrophysical implications

- 3α reaction rate is crucial for various astrophysical scenarios and new spectroscopical data on ^{12}C states just above 3α binding energy changes the rates
- At low temperatures, below 10^8 K, evolution of primordial stars (with masses similar to Sun) lacking of the heavy elements depends on 3α rate.
  - New rates implies that the critical level of ^{12}C for an ignition of CNO cycle is reached much faster (even in half time compared to earlier predictions).
- At high temperatures, beyond 10^9 K:
  - Nucleosynthesis in type II supernova shock front
  - X-ray burst, where 3α reaction is one of the trigger reaction in thermonuclear runaways
  - Asymptotic Giant Branch stars
  - New rates implies reduction of the mass fraction of ^{56}Ni → reduction of mass fraction of heavy elements in proton-rich supernova matter
- Together with $^{12}C(\alpha,\gamma)^{16}O$ reaction 3α-reaction determines C and O abundances at the end of He burning in the temperature range 10^8 to 10^9 K:
  - Nucleosynthesis and late-stage stellar evolution
  - New rate and NACRE compilation agrees

^{17}Ne β-delayed particle decay

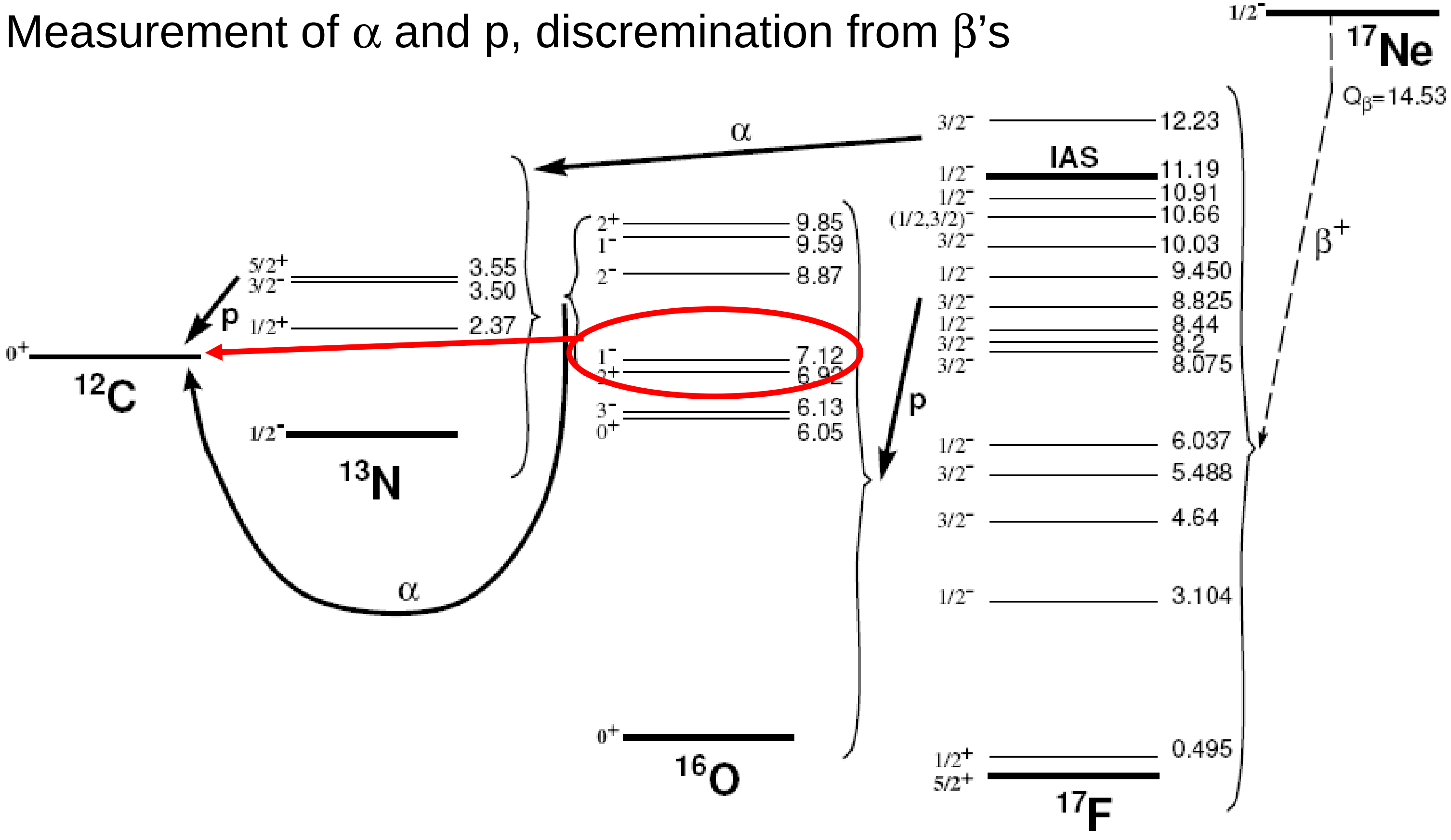
L. Fraile et al., INTC-P-174

Information on ^{16}O states

Effect on the ^{12}C(α,γ)^{16}O reaction

6917 and 7117 keV states, widths

Measurement of α and p, discrimination from β's

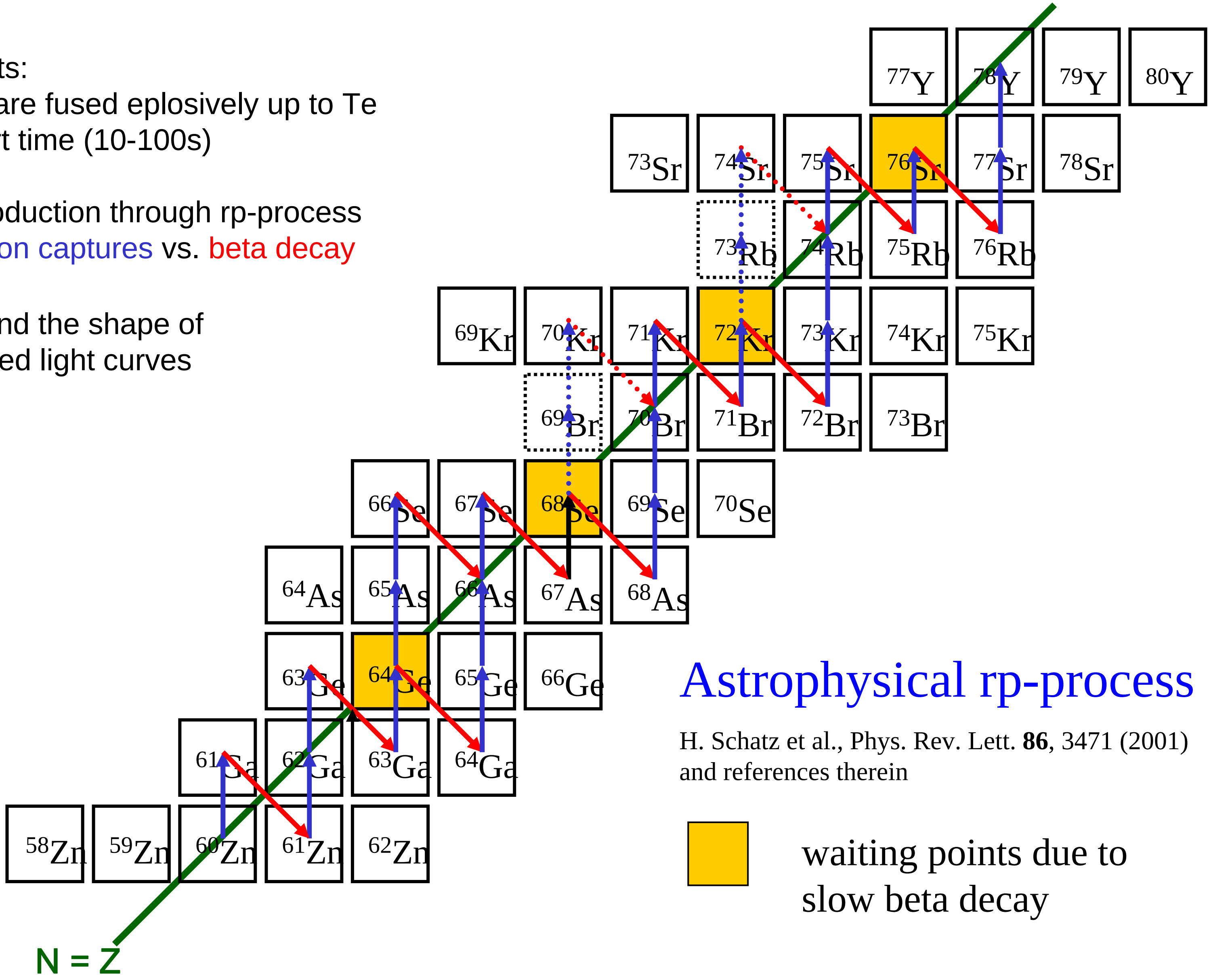


Rapid proton capture process

X-ray bursts:
H and He are fused eplosively up to Te
within short time (10-100s)

Energy production through rp-process
Rapid proton captures vs. beta decay

Duration and the shape of
the observed light curves



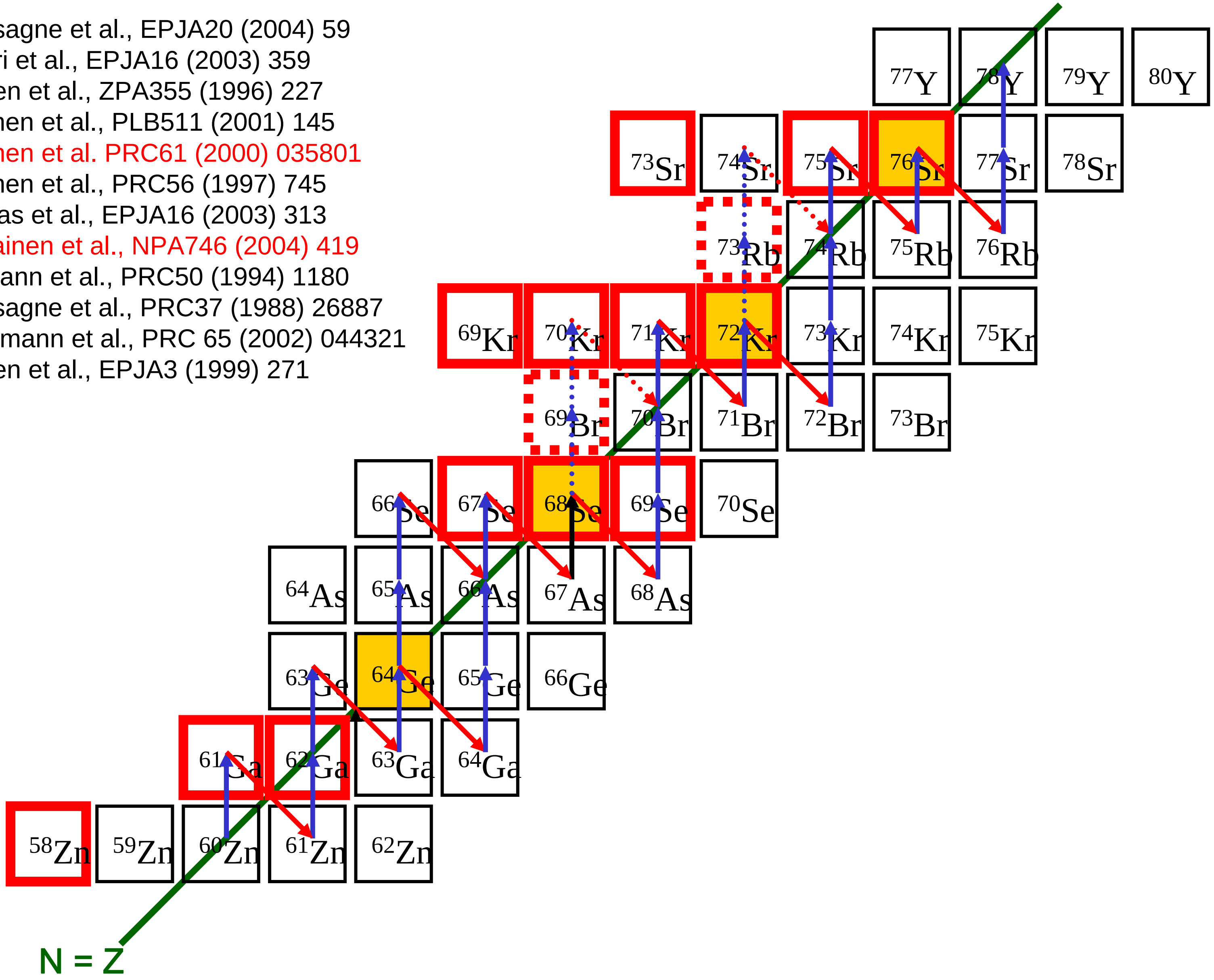
Astrophysical rp-process

H. Schatz et al., Phys. Rev. Lett. **86**, 3471 (2001)
and references therein

🟨 waiting points due to slow beta decay

Rp-process path studies at ISOLDE

^{76}Sr	Ph. Dessagne et al., EPJA20 (2004) 59
^{75}Sr	J. Huikari et al., EPJA16 (2003) 359
^{73}Rb	A. Jokinen et al., ZPA355 (1996) 227
^{74}Rb	M. Oinonen et al., PLB511 (2001) 145
^{70}Kr	M. Oinonen et al. PRC61 (2000) 035801
^{71}Kr	M. Oinonen et al., PRC56 (1997) 745
^{72}Kr	I. Piqueras et al., EPJA16 (2003) 313
^{69}Br	A. Kankainen et al., NPA746 (2004) 419
^{67,68}Se	P. Baumann et al., PRC50 (1994) 1180
^{69}Se	Ph. Dessagne et al., PRC37 (1988) 26887
^{61}Ga	L. Weissmann et al., PRC 65 (2002) 044321
^{58}Zn	A. Jokinen et al., EPJA3 (1999) 271



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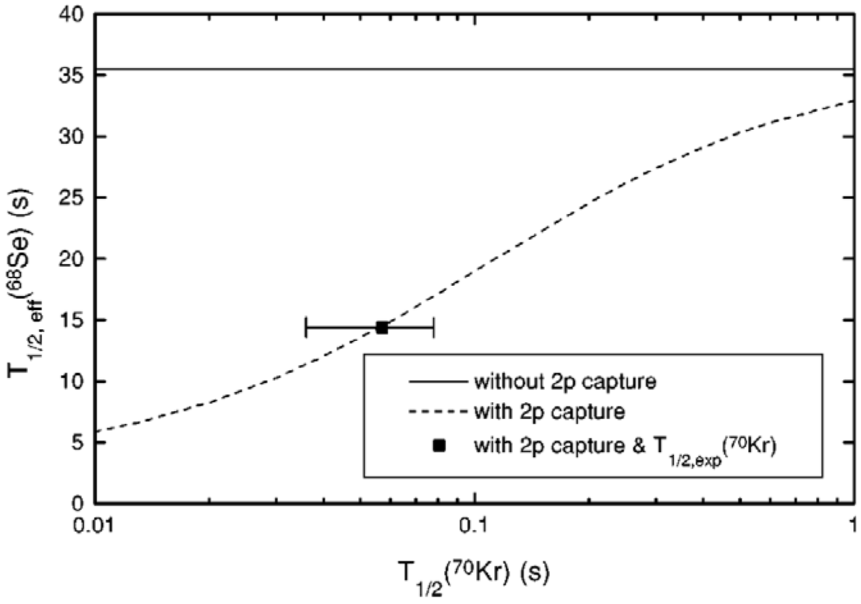
Continuation of rp-process path beyond ^{68}Se

Beta-decay half-life of ^{70}Kr: A bridge nuclide for the rp process beyond A=70

M. Oinonen et al., PRC61 (2000) 035801



$T_{1/2}$ = 57(21) ms

QRPA predictions 390 ms

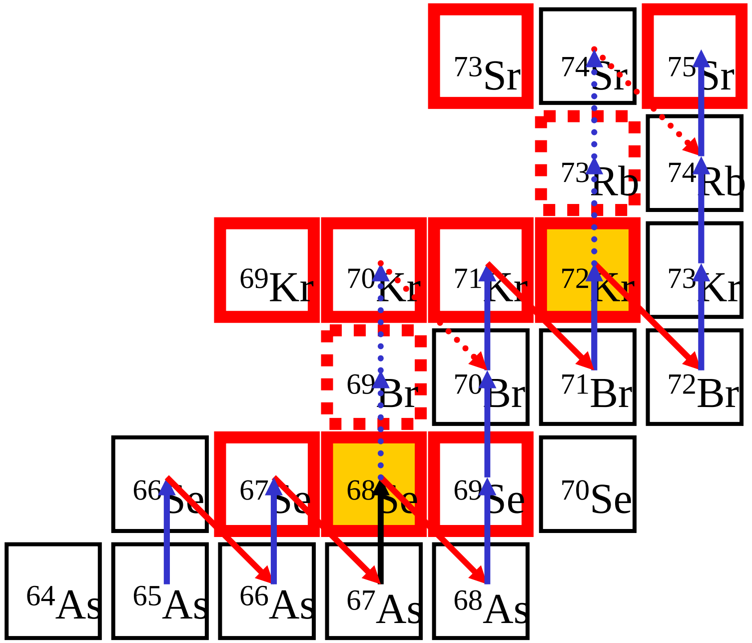
Reaction flow via ^{68}Se(2p,γ) is 2.5 times faster than previously calculated

(T = 1.5 GK and ρ = 10^6 g/cm^3)

Search for proton-decay of ^{69}Br

A. Kankainen, NPA746 (2004) 419

- Populate p-unbound states in ^{69}Br by beta decay of ^{69}Kr
- ^{69}Kr is known to be bound, while ^{69}Br is unbound.
- Continuation of rp-process beyond long-lived ^{68}Se requires 2p-capture on ^{68}Se
- Two step process
- ^{68}Se+p and a resonance in ^{69}Br
- So far, such a study is prohibited by the insufficient intensity of ^{69}Kr
- Target and ion source development



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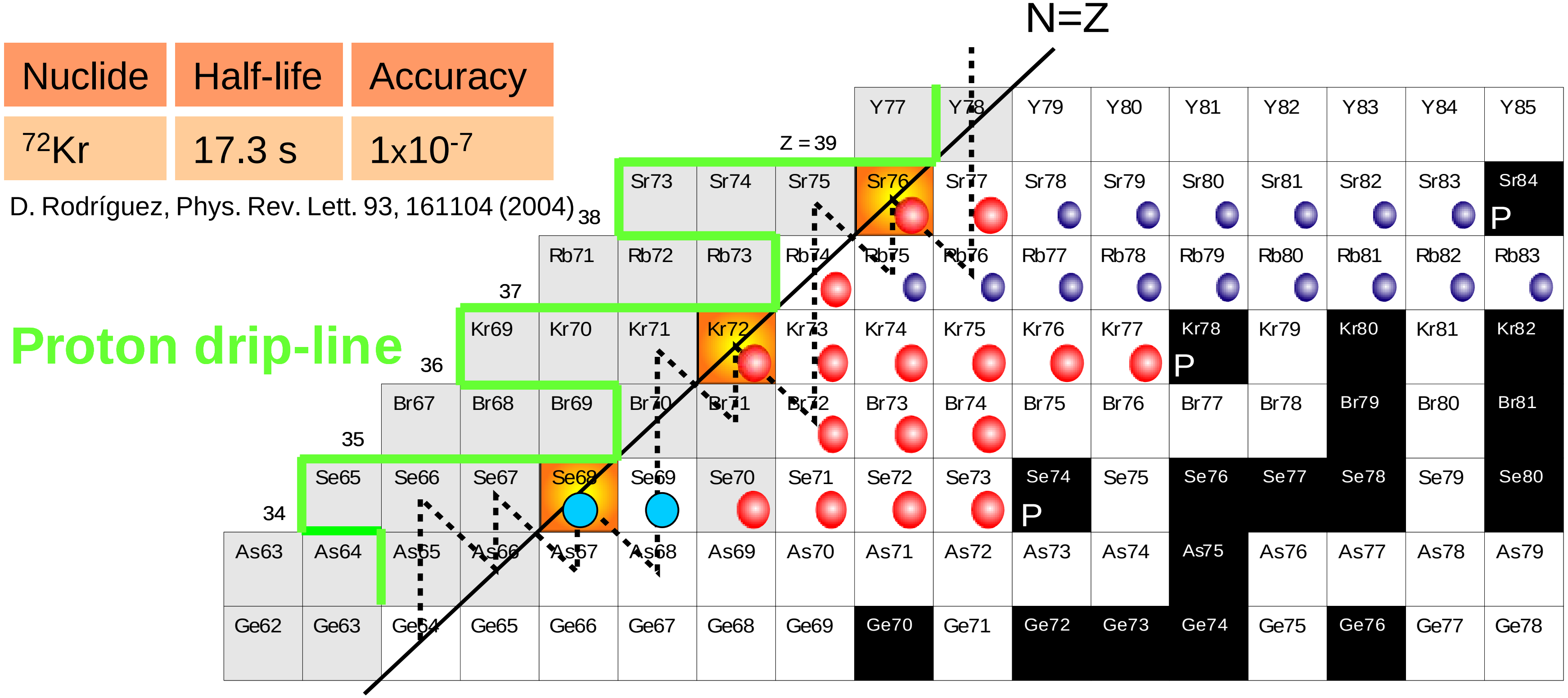
Rp-process above Z = 32

Masses are among the most critical nuclear parameters !

For trap, see presentation by K. Blaum

Nuclide	Half-life	Accuracy
^{72}Kr	17.3 s	1x10^{-7}

D. Rodríguez, Phys. Rev. Lett. 93, 161104 (2004)



----- possible rp - process main path (in type I x-ray bursts)

(H. Schatz et al. Phys. Rep. 294 (1998) 167)

🟧 possible waiting points

▢ mass excess not yet measured

(AME95)

ISOLTRAP measurements

● *2000 - 2002*

● *before 2000*

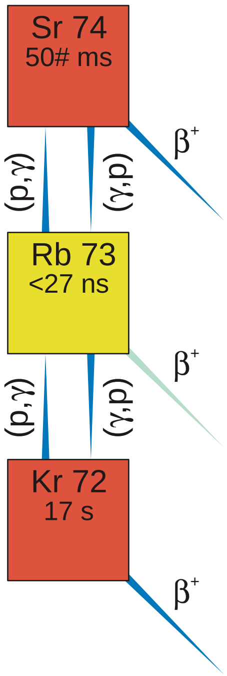
● Canadian Penning Trap

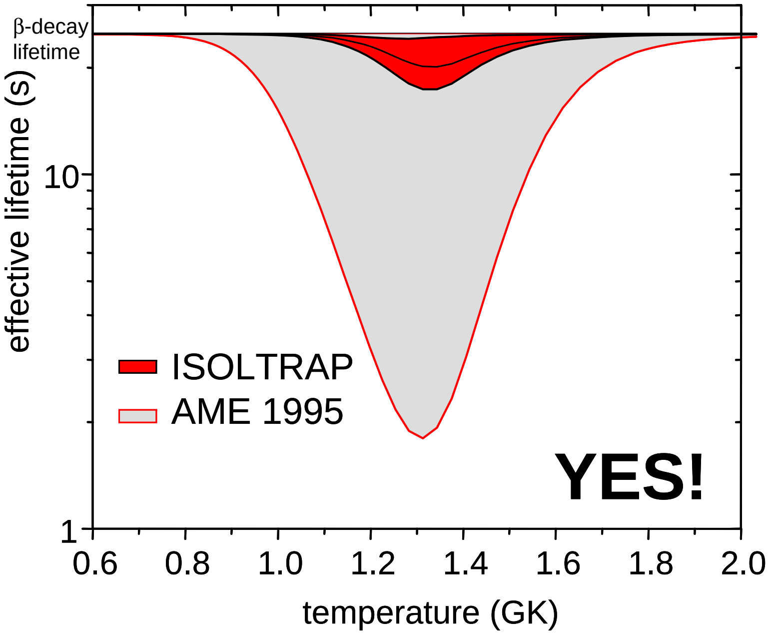
^{72}*Kr = rp-Process Waiting Point?*

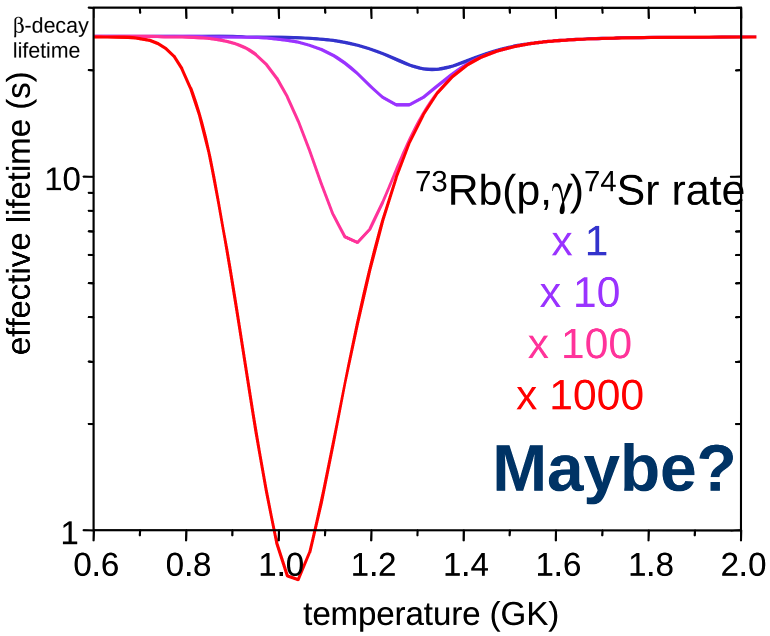
ISOLTRAP mass measurements on ^{72,73,74}Kr

1. Short effective lifetime of ^{72}Kr excluded, but
2. new masses yield a rather high S_p ^{74}Sr, thus
3. there is a room for shortened eff. lifetime with higher ^{73}Rb(p,γ) rate

calculated network







Conclusion: Need now ^{73}Rb(p,γ)^{74}Sr rate within factor 2 to 3.

D. Rodríguez et al., Phys. Rev. Lett. 93, 161104 (2004).

The mass of ^{22}Mg – Astrophysics and CVC

Astrophysics: ^{21}Na(p,γ)^{22}Mg Reaction and Oxygen-Neon Novae

(S. Bishop *et al.*, Phys. Rev. Lett. 90, 162501 (2003))

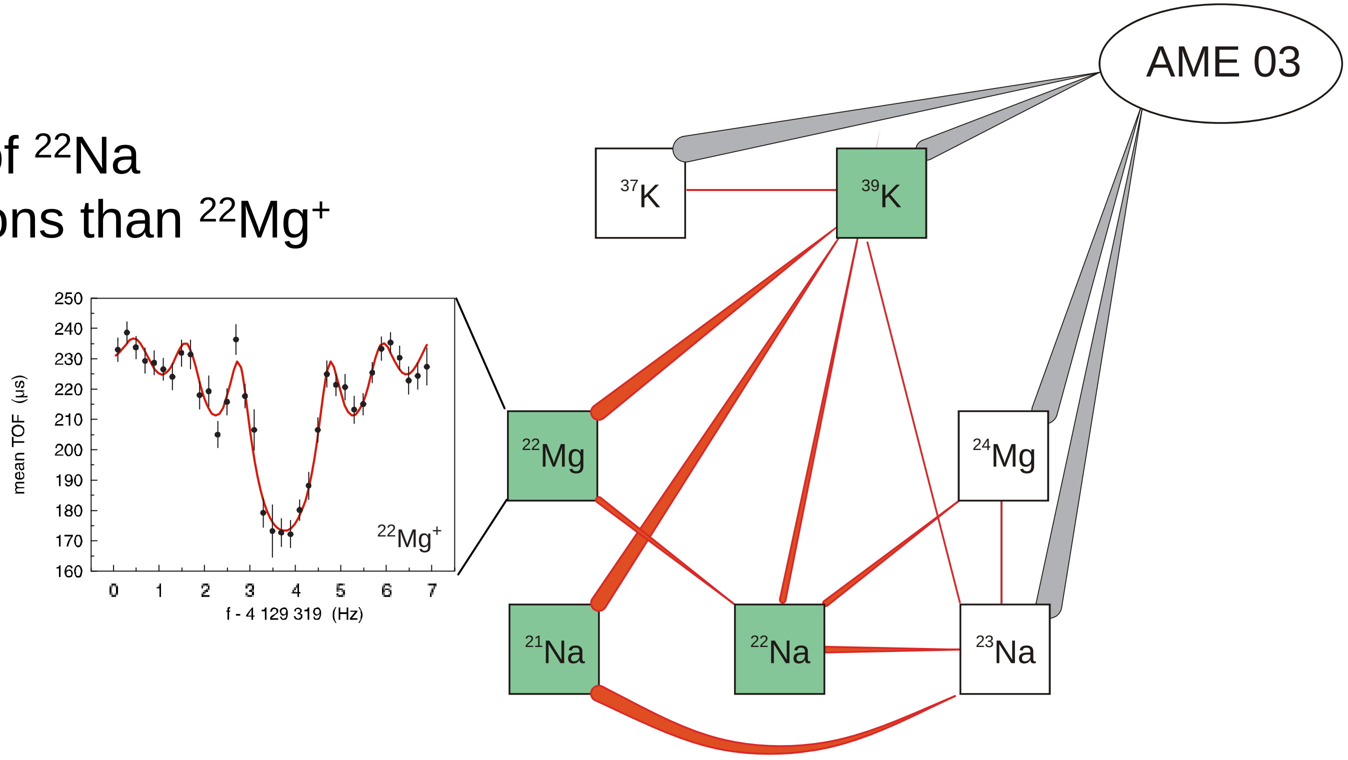
CVC Hypothesis und CKM Unitarity: High Precision Measurement of the Superallowed 0+ → 0+ β decay of ^{22}Mg

(J.C. Hardy et al., Phys. Rev. Lett. 91, 082501 (2003))

Challenge:

Huge background of ^{22}Na

- 10^4 to 10^5 more ions than ^{22}Mg$^+$



Solved by:

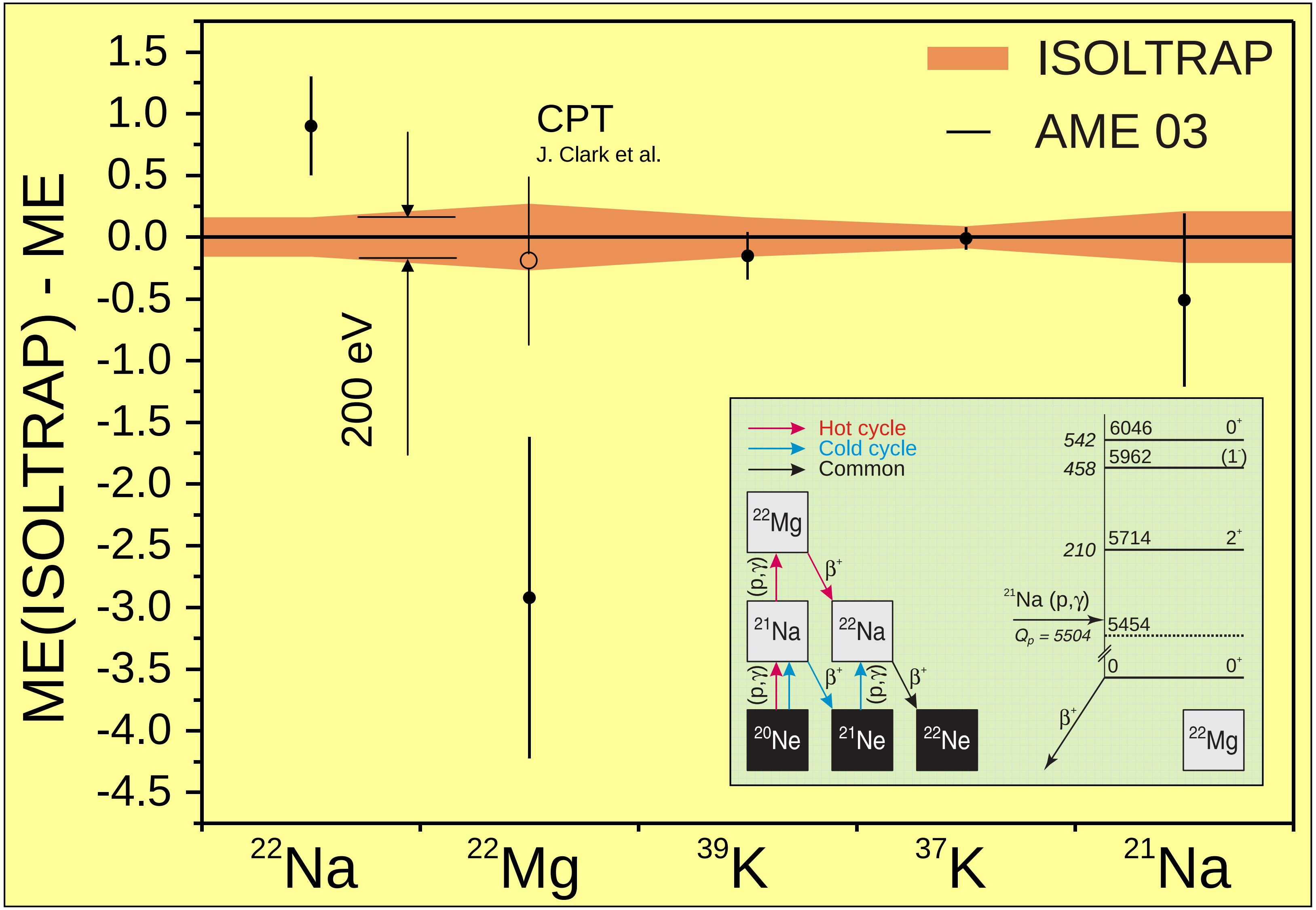
- HRS optimization
- Purification trap optimization

^{22}Mg: $T_{1/2}$ = 3.86 s

🟩 Mass uncertainty reduced by ISOLTRAP

measured frequency ratios and data flow

Solving the mass discrepancy of ^{22}Mg



^{21}Na(p,γ)^{22}Mg resonance energy to 5714 keV state was determined independently and accurately

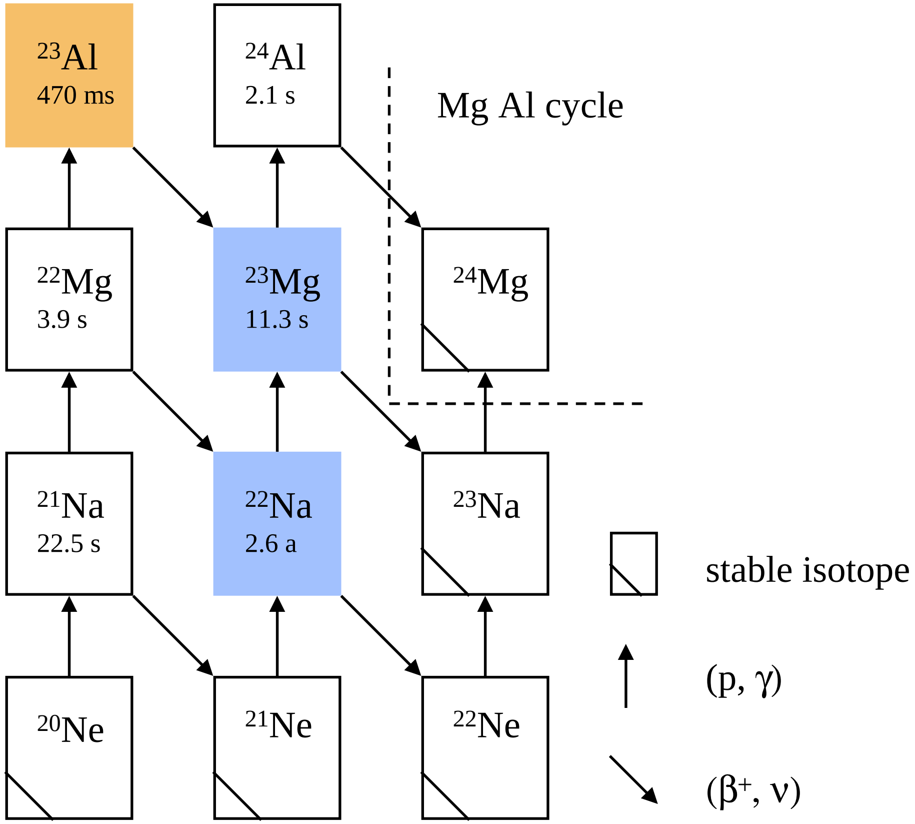
Slightly lower reaction rate compared to J. Bishop et al., PRL 90 (2003) 162501

M. Mukherjee *et al*., Phys. Rev. Lett. 93, 150801 (2004).

Fabrication of radioactive targets

Breakout of the NeNa cycle through the ^{22}Na(p,γ)^{23}Mg capture reaction

Sleuth et al., NPA514 (1990) 471



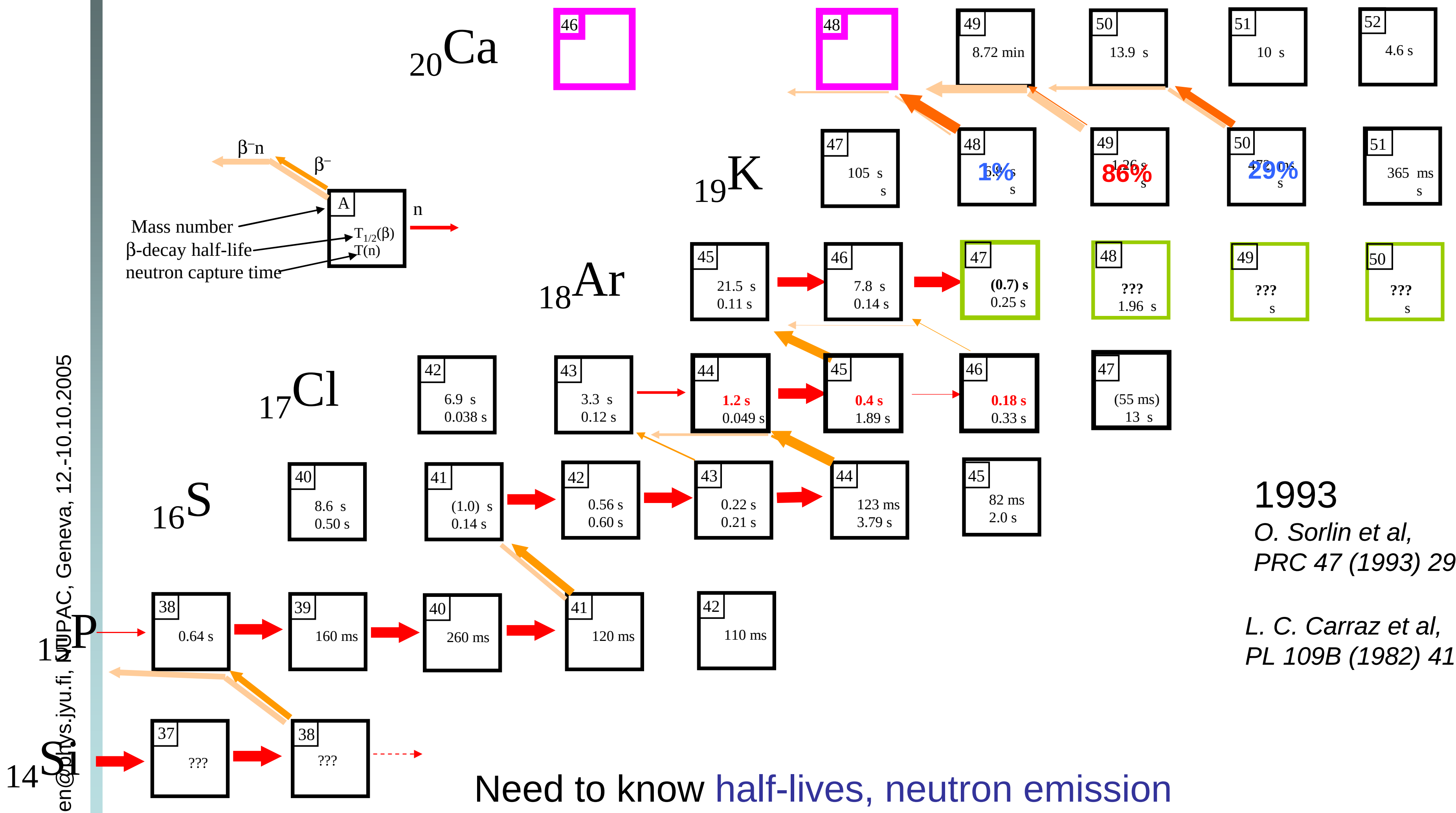
Similar information can be obtained by studying an inverse process – in this case β-delayed proton decay of ^{23}Al

(see decay studies, M. Borge, this meeting)

Precision Measurement of the ^{7}Be(p,γ)^{8}B Cross Section with an Implanted ^{7}Be Target
L.T. Baby et al, PRL90 (2003) 022501
Solar neutrino fluxes

Decay of n-rich Ar isotopes

Calcium isotopic anomalies in the Allende meteorite, F. R. Niederer et al Astrophys J (1980) 240 L73

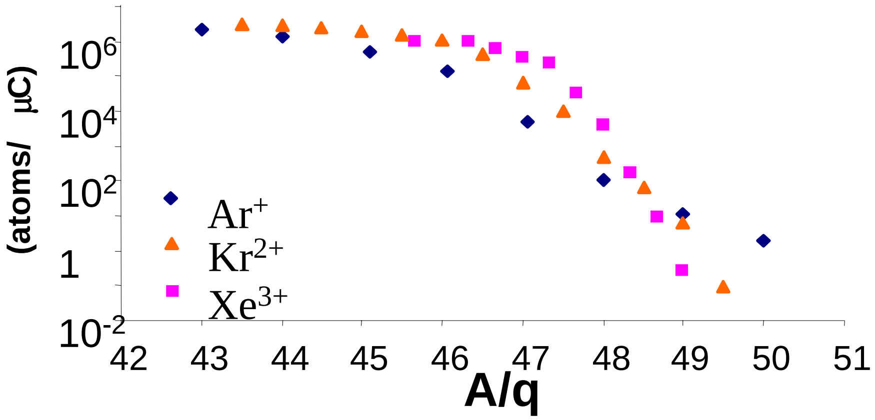


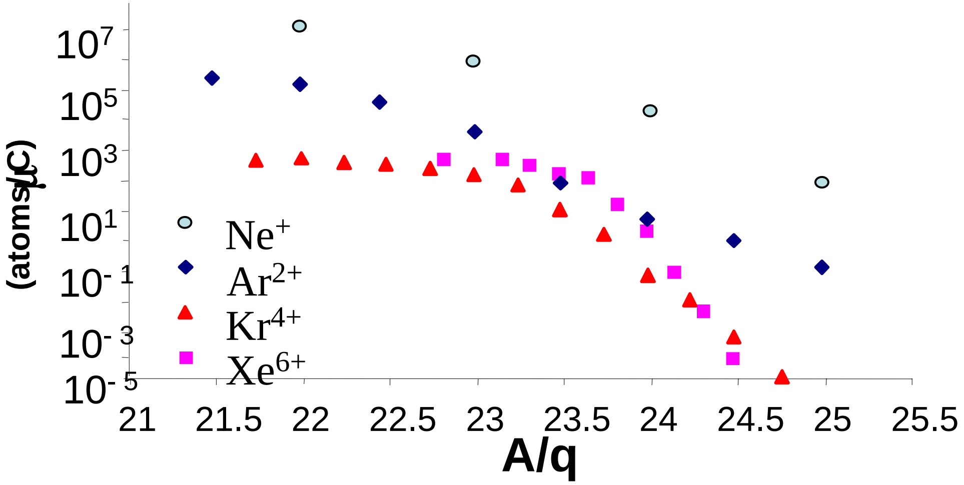
1993
O. Sorlin et al,
PRC 47 (1993) 2941

L. C. Carraz et al,
PL 109B (1982) 419

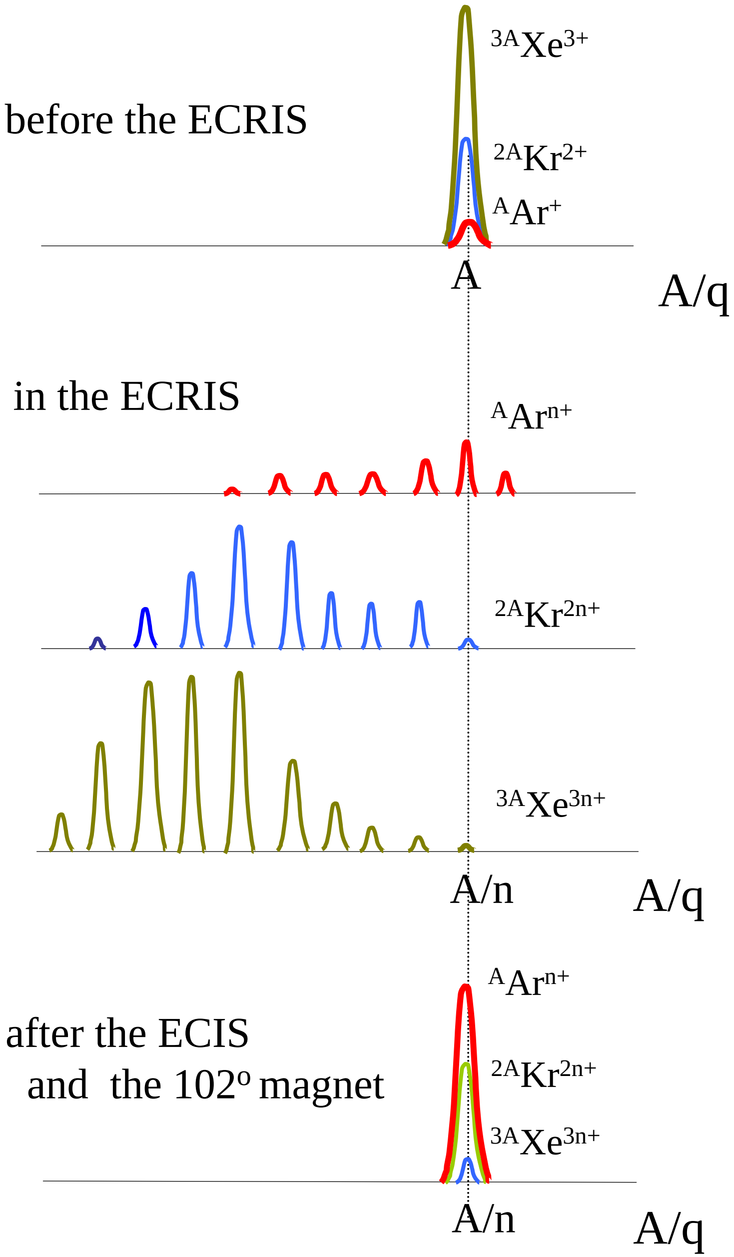
Need to know half-lives, neutron emission probabilities and neutron capture cross-sections

Enhancing Ar by charge breeding (ECR)





L. Weissman et al, PRC67(2003)054314



before the ECRIS

in the ECRIS

after the ECIS and the 102^o magnet

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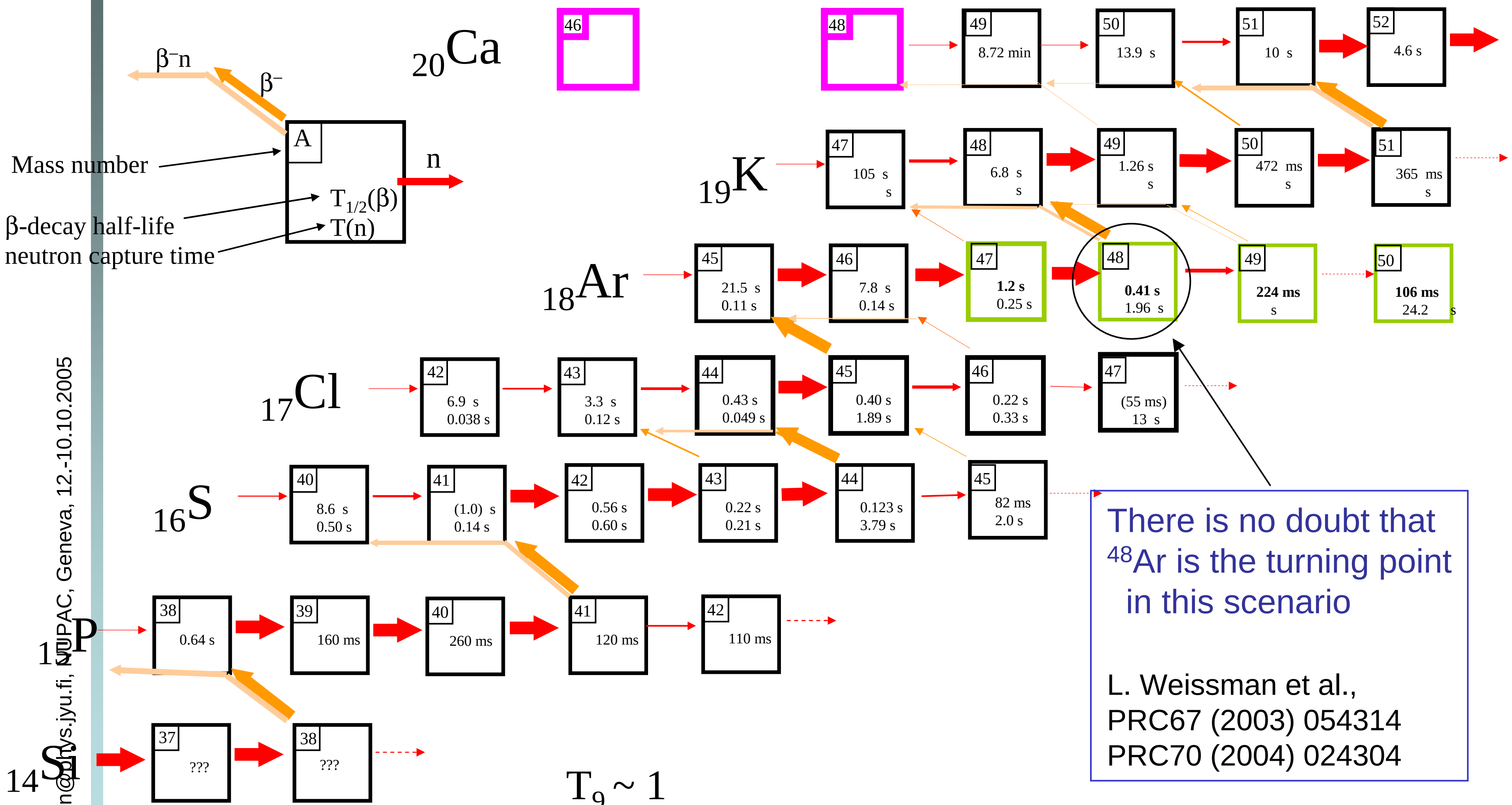
Rapid neutron capture



There is no doubt that ^{48}Ar is the turning point in this scenario

L. Weissman et al.,
PRC67 (2003) 054314
PRC70 (2004) 024304

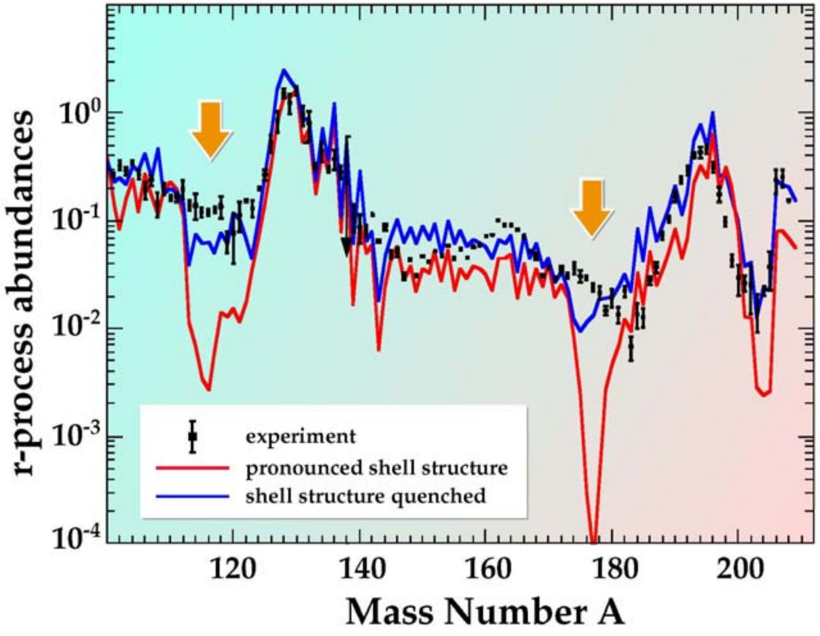
$T_9 \sim 1$

$\rho_n \sim\ 5\ 10^{-5}$ mol cm^{-3}

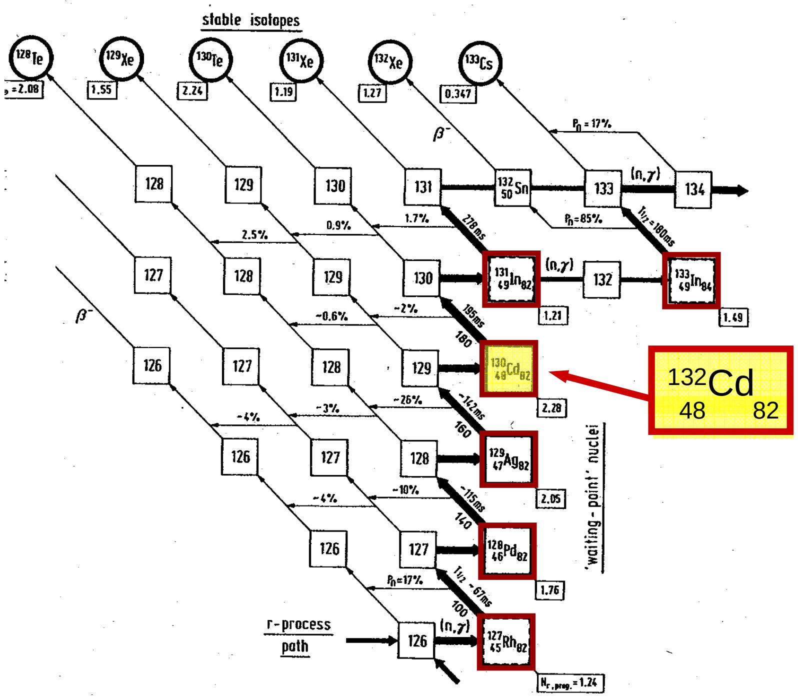
R-process studies

Karl-Ludwig Kratz
Institut für Kernchemie, Univ. Mainz, Germany

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



FK²L (Ap.J. 403 ; 1993)
“..the calculated r-abundance ‘hole‘ in the A ≅ 120 region reflects ... the weakening of the shell strength ... below ^{132}Sn “



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

climb up the N= 82 ladder ...
A ≅ 130 “bottle neck“

⇨ **total r-process duration τ_r**

Nuclear structure consequences

... a number of recent nuclear structure "surprises" in the ^{132}Sn region, e.g.

- low $\nu p_{3/2}$, $\nu p_{1/2}$ SP states in N=83 ^{133}Sn (Hoff et al.; PRL 77, 1996)
- low $E(2^+)$ in ^{134}Sn (Korgul et al.; EPJ A7, 2000)
- trend of low $E(2^+)$, indicating quadropole polarizability in n-rich Cd isotopes up to N=80 (Kautzsch et al.; EPJ A9, 2000)
- low $T_{1/2}$ and P_n in N=83 ^{131}Cd (Hannawald et al.; PR C62, 2000)
- low $\pi d_{5/2}$ SP state in ^{135}Sb (Shergur et al.; PR C65, 2002)
- high $E(1^+)$ and high Q_β in N=82 ^{130}Cd decay (Dillmann et al.; PRL 91, 2003)

↷

① reordering of SP levels
② evidence for neutron-skin effects
③ importance of ff-strength
④ weakening of $\nu g_{7/2}$- $\pi g_{9/2}$ residual interaction
⑤ evidence for N=82 shell quenching

→ Obviously, shell structure around $^{132}_{50}\mathrm{Sn}_{82}$ not yet fully understood !

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Astrophysical consequences:

Dynamic r-process calculations

($T_{1/2}$, P_n from exp. + QRPA

S_n, Q_β from AMDC + ETFSI-Q)

↷ Classical “waiting-point“ concept
$T_{1/2}(N=82) \sim N_{r,\odot}$
too simple!

↷ apart from $T_{1/2}(N=82)$ also effect from
$S_n(N=83)$ on $N_{r,prog} \rightarrow N_{r,\odot}$

...mainly resulting from new nuclear-structure information:
- better understanding of formation and shape of the A»130 Nr,⊙ peak
- as well as r-process matter flow through the A»130 Nr,⊙ peak
- no justification to question waiting-point concept
(Langanke et al., PRL 83, 199; Nucl. Phys. News 10, 2000)

K.L. Kratz, MW-meeting at CERN

Potential of the REX-ISOLDE

- Various nuclear structure studies provide an important nuclear data far from the stability → better extrapolations to nuclei in the regions of astrophysical interest
- Direct methods:
  - Radiative capture reactions [X(p,γ)Y and X(α,γ)Y]
  - Transfer reactions X(p,α)Y and X(α,p)Y
- Indirect methods:
  - Elastic scattering X(p,p)X to investigate resonance properties of CN
  - Transfer reactions: X(d,p)Y to mimic X(n,γ)Y for s- or r-process
- Use of REX for astrophysical reactions starting: Inelastic branch of the stellar reaction ^{14}O(α,p)^{17}F and ^{18}Ne(α,p)^{21}Na (P. Woods, P178) and Studies for rp-process (C. Barton, LoI to INTC)

Summary & Conclusions

- There is a vast amount of nuclear data gathered at ISOLDE which directly contribute to the better understanding of the nuclear processes involved in astrophysical phenomena (rp-process and r-process)
- ISOLTRAP: Accurate mass measurements of key areas for astrophysics. In addition to examples given, one should mention progress in neutron-rich side, where masses are equally important for r-process
- Higher intensities coupled with improved means to purify the beam (and better detection schemes)
- There is a variety of reaction techniques to be applied at REX-ISOLDE.
- The wide variety of intense low-energy radioactive beams available.

Acknowledgements: K. Blaum, M.J.G. Borge, P. Butler, J. Cederkäll, H. Fynbo, M. Oinonen, P. Van Duppen, L. Weissman, P. Woods, J. Äystö and many others …