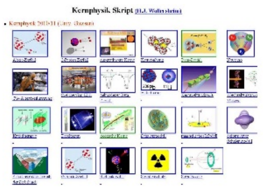
Outline: Experimental Nuclear Astrophysics M. Aliotta

Lecturer: Hans-Jürgen Wollersheim

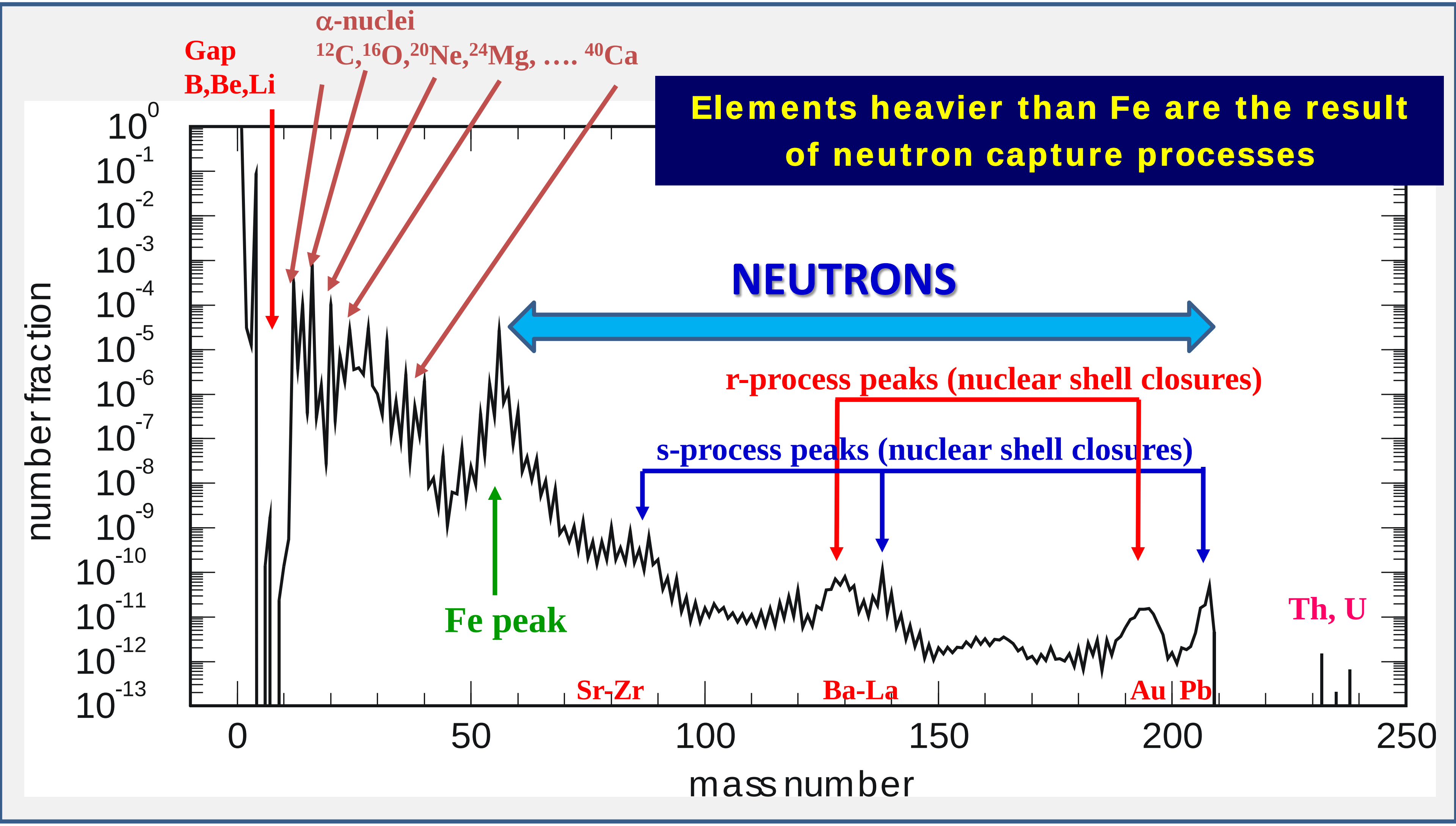
e-mail: h.j.wollersheim@gsi.de

web-page: https://web-docs.gsi.de/~wolle/ and click on



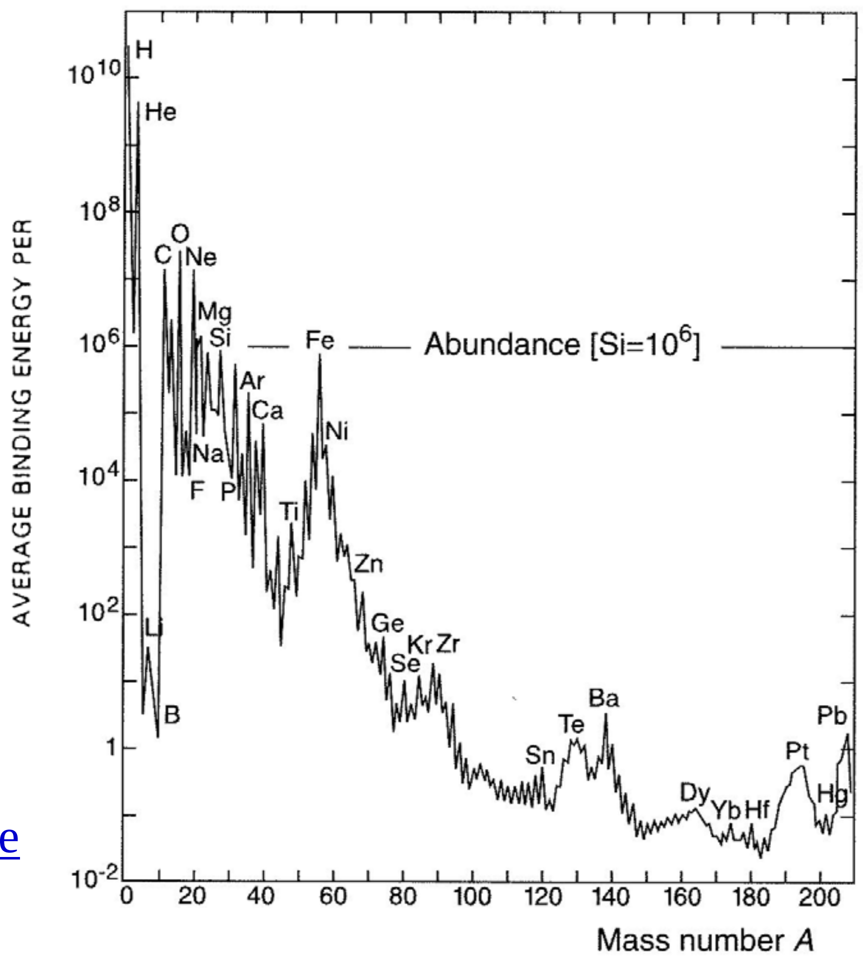
1. neutron capture processes
2. mechanism of s-process
3. mechanism of r-process
4. shell closures

Abundances beyond Fe

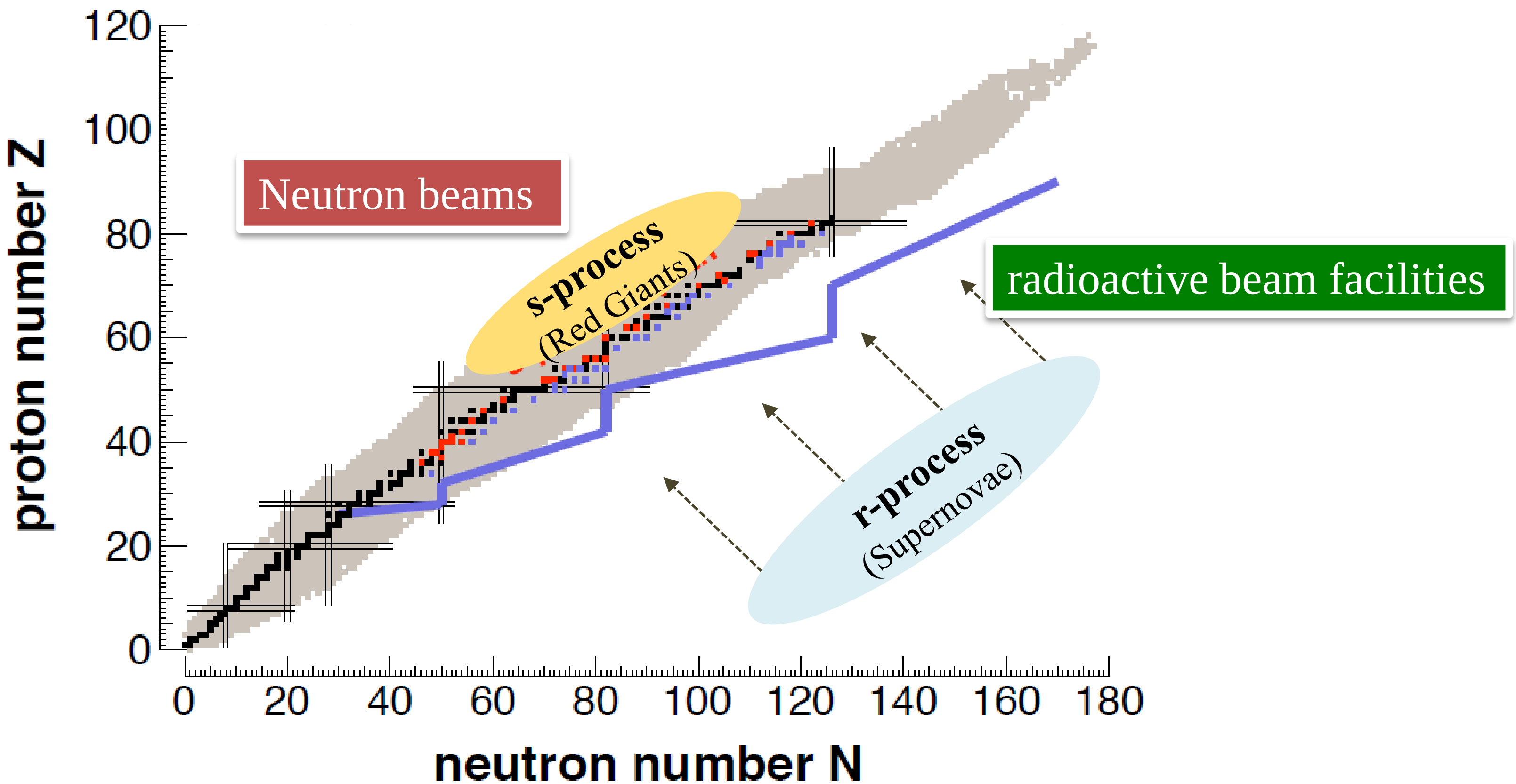


Why neutron capture processes for the synthesis of heavy elements?

- exponential abundance decrease up to Fe
  ⇔ exponential decrease in tunnelling probability for charged-particle reactions
- almost constant abundances beyond Fe
  ⇔ non-charged-particle reactions
- binding energy curve ⇔ fusion reactions beyond iron are endothermic
- characteristic abundance peaks at magic neutron numbers
- neutron capture cross sections for heavy elements increasingly larger
- large neutron fluxes can be made available during certain stellar stages



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)
- $\mathbf{N_n = 10^{20\text{-}30}\ n/cm^3}$

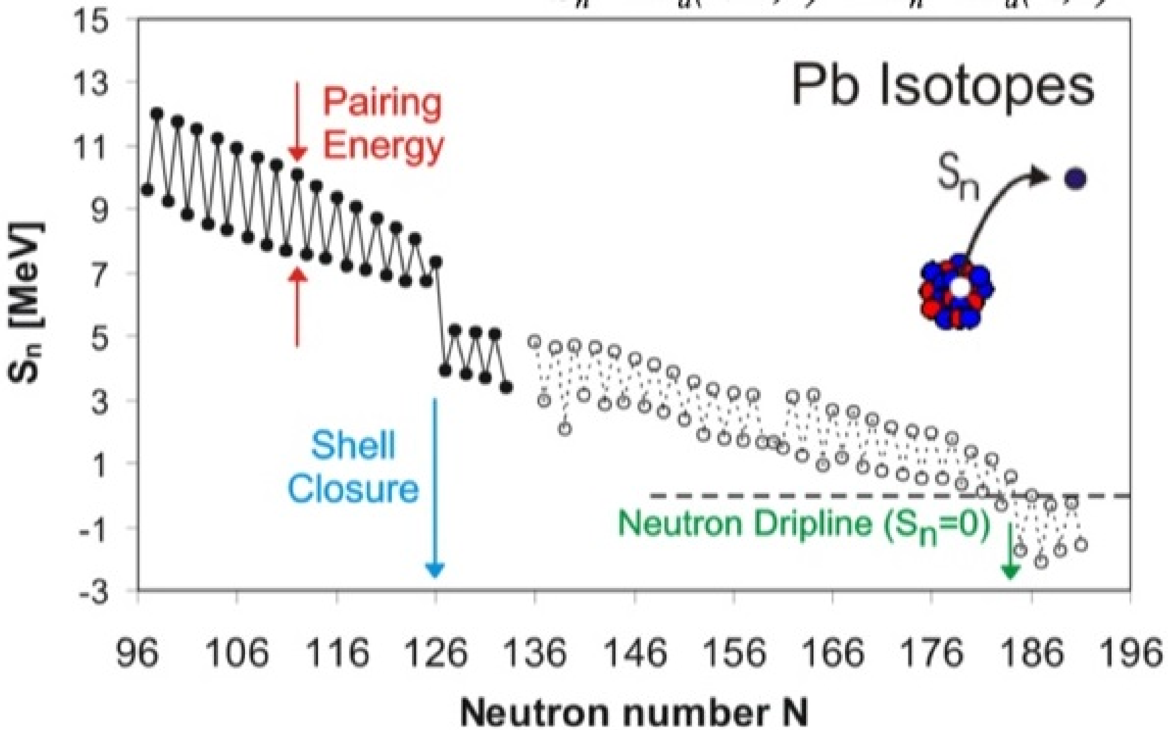
How many neutrons can a proton bind?

The limit of nuclear existence is characterized by the nucleon driplines

B. Jonson: "The driplines are the limits of the nuclear landscape where additional protons or neutrons can no longer be kept in the nucleus – they literally drip out."

P.G. Hansen & J.A. Tostevin: "(the dripline is) where the nucleon separation energy goes to zero."

$$S_n = M_a(N\text{-}1,Z) + M_n - M_a(N,Z)$$



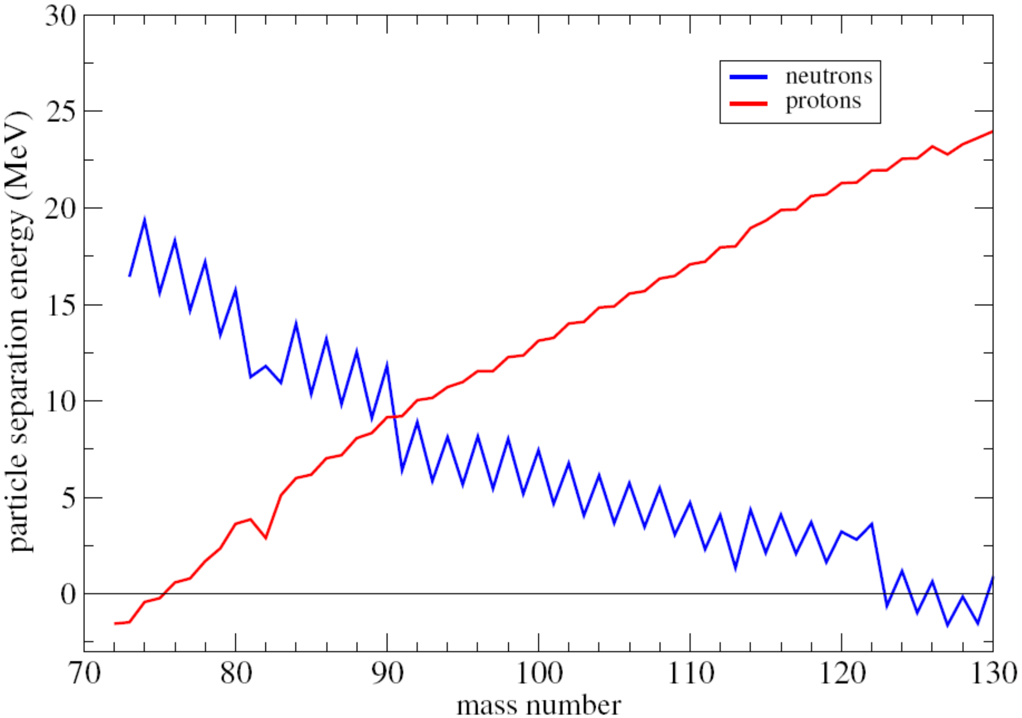
How many neutrons can a proton bind?

The limit of nuclear existence is characterized by the nucleon driplines

B. Jonson: "The driplines are the limits of the nuclear landscape where additional protons or neutrons can no longer be kept in the nucleus – they literally drip out."

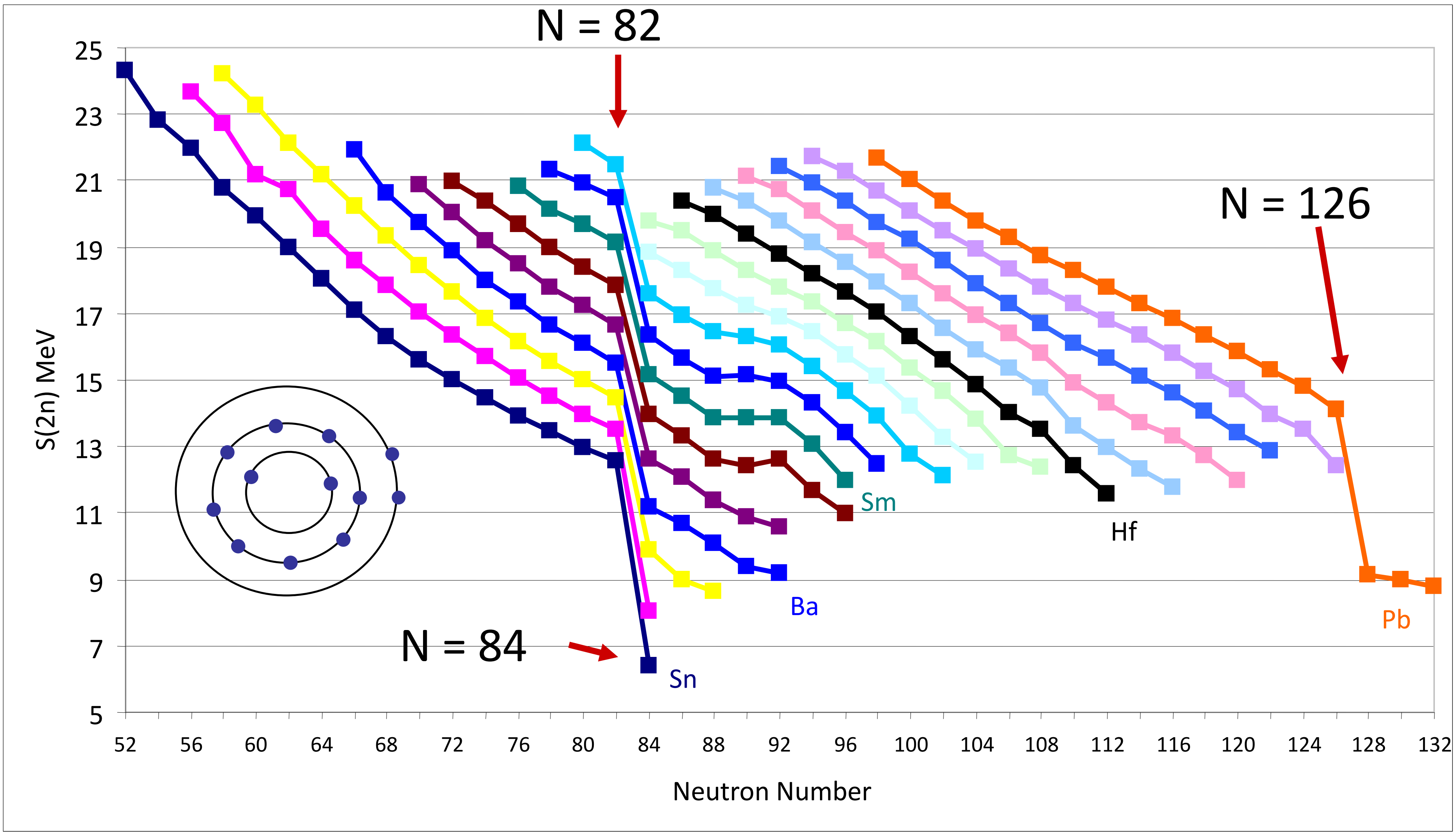
P.G. Hansen & J.A. Tostevin: "(the dripline is) where the nucleon separation energy goes to zero."

Zr isotopes (Z=40, N varies)

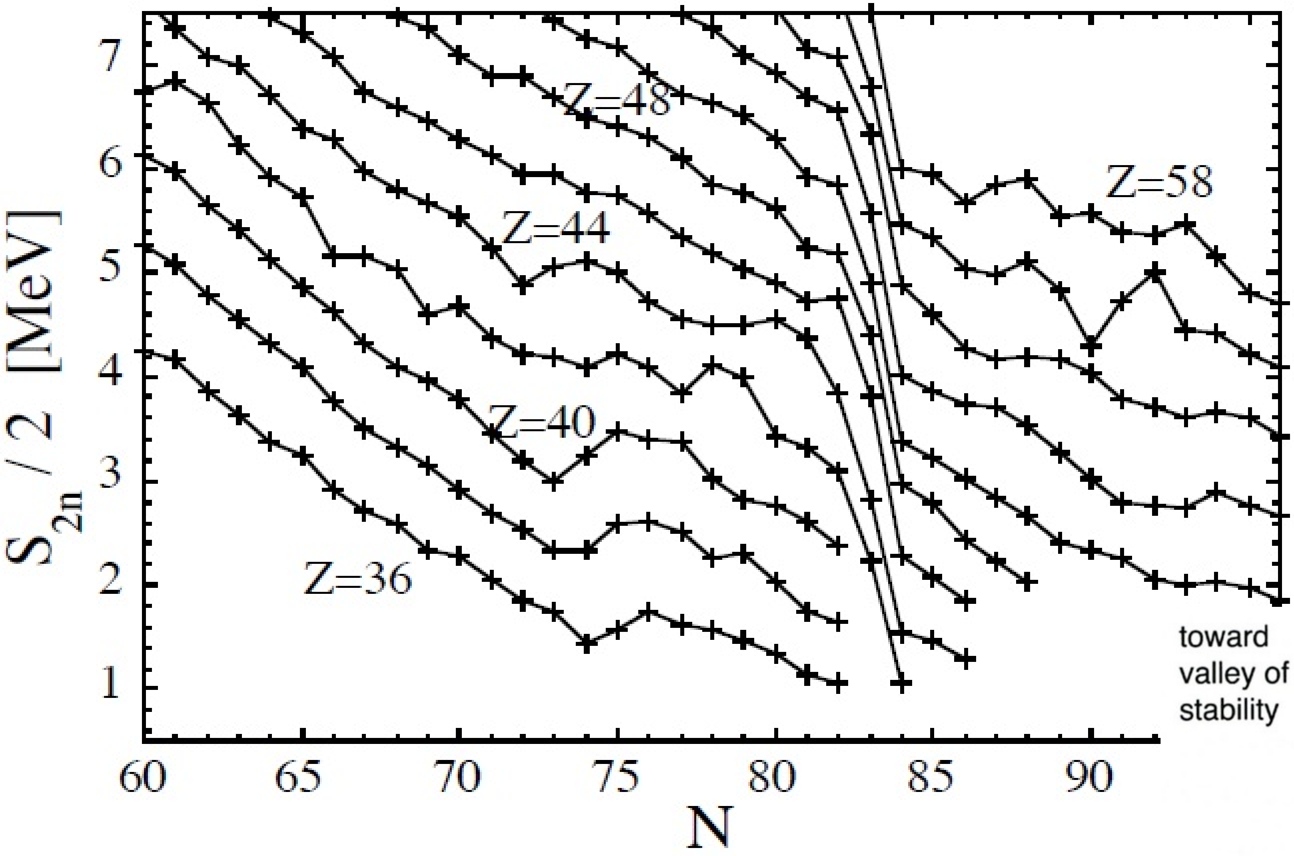


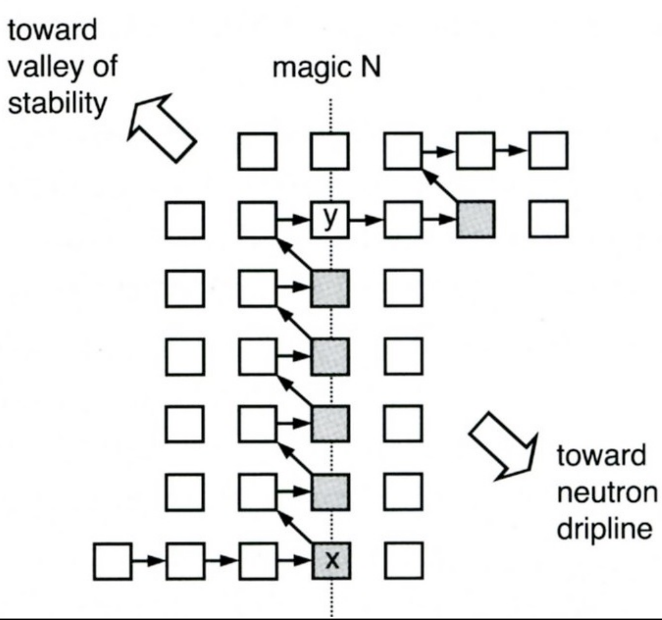
2-neutron binding energies = 2-neutrons separation energies

$$S_{2n} = BE(N,Z) - BE(N-2,Z)$$

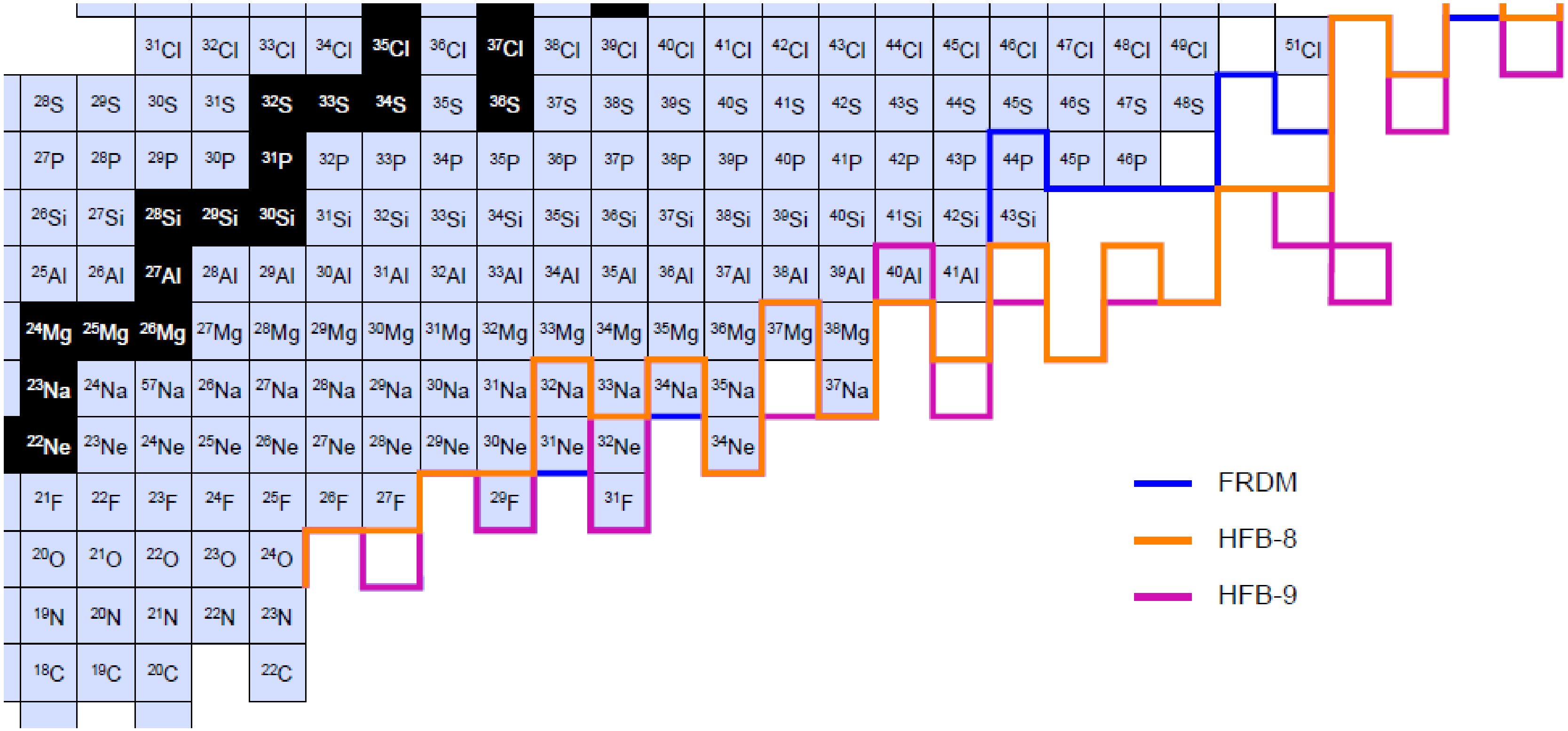


2-neutron binding energies = 2-neutrons separation energies

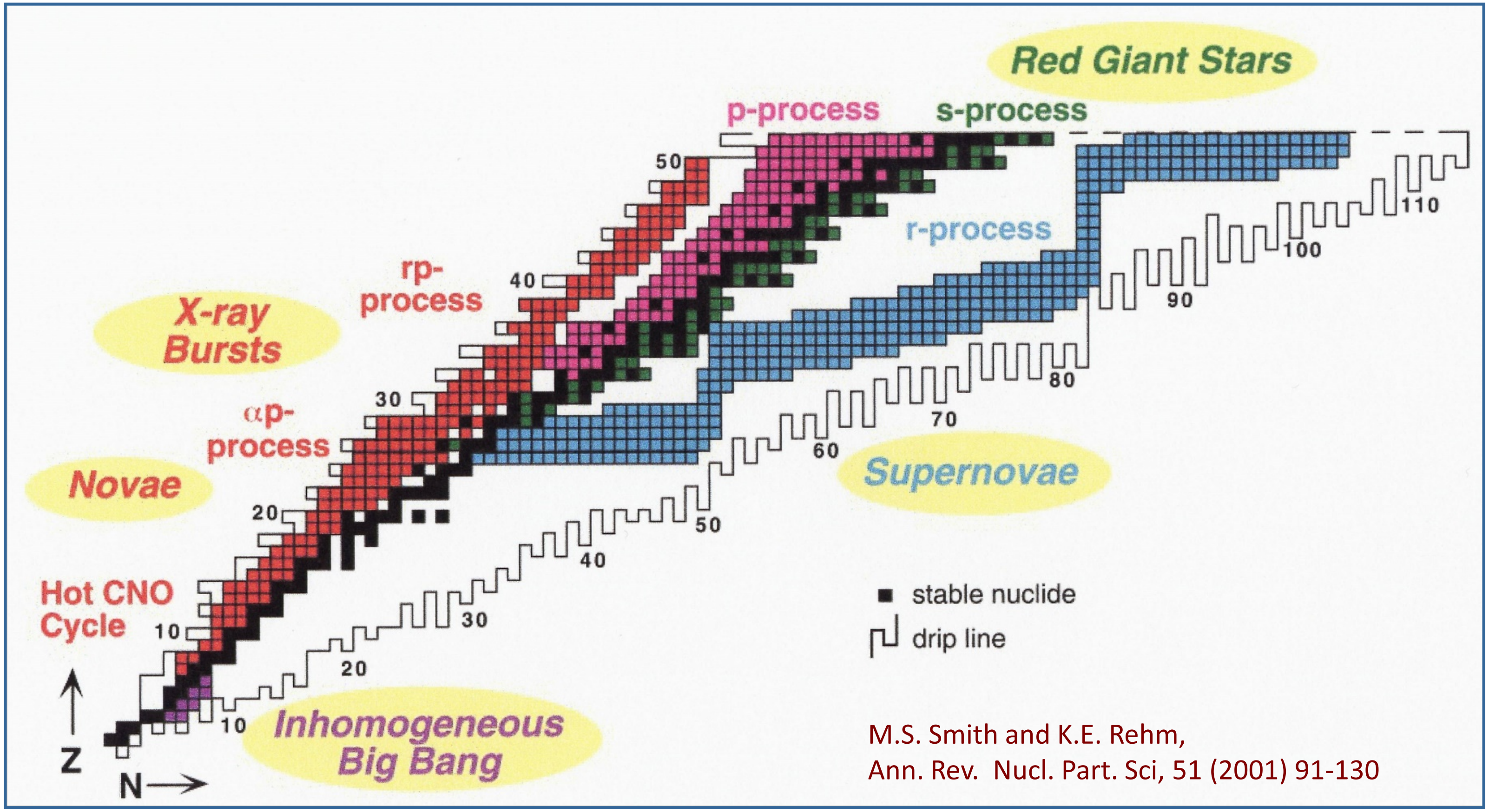




Where is the neutron dripline?

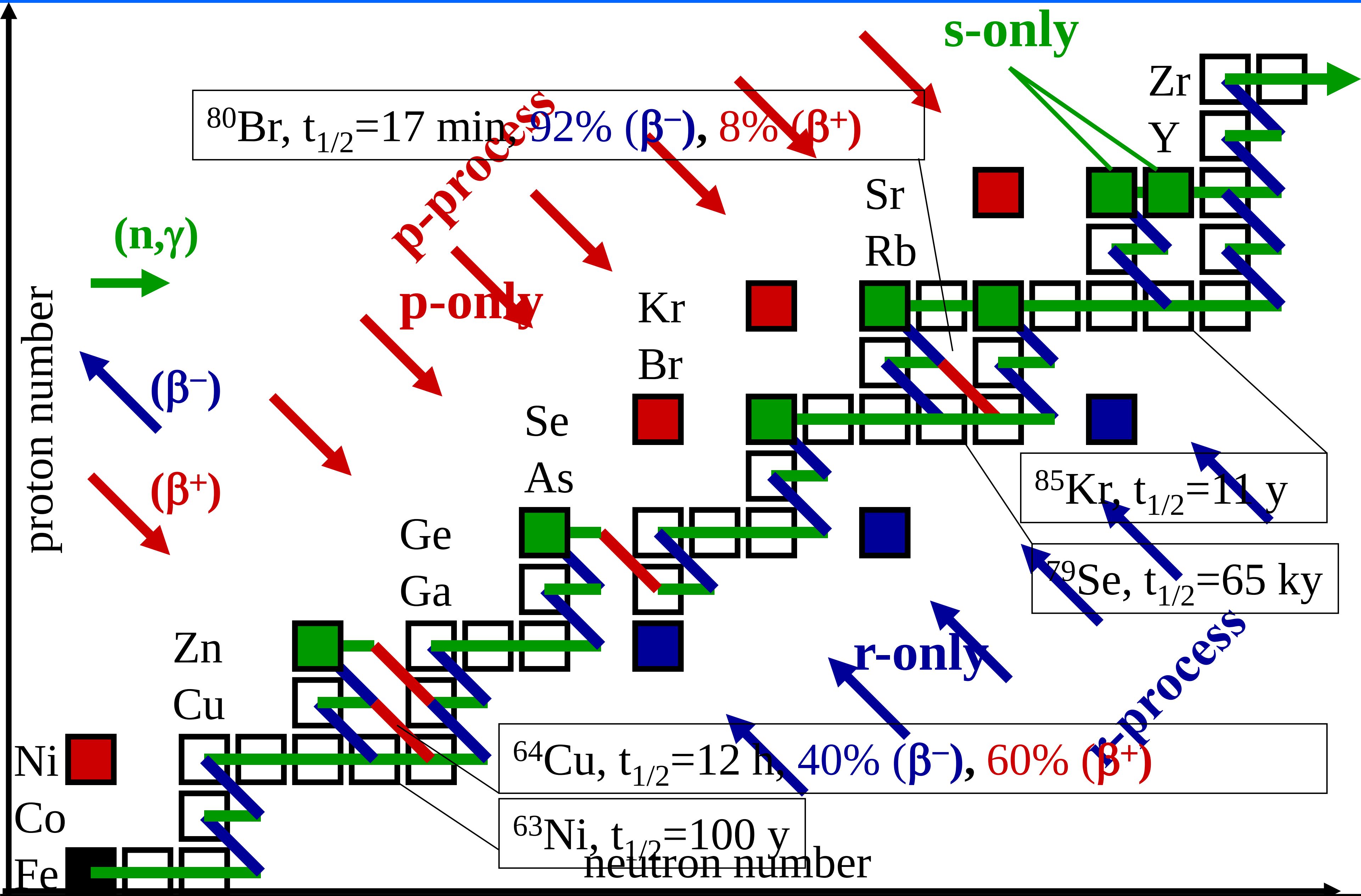


Overview of main nuclear processes and astrophysical sites

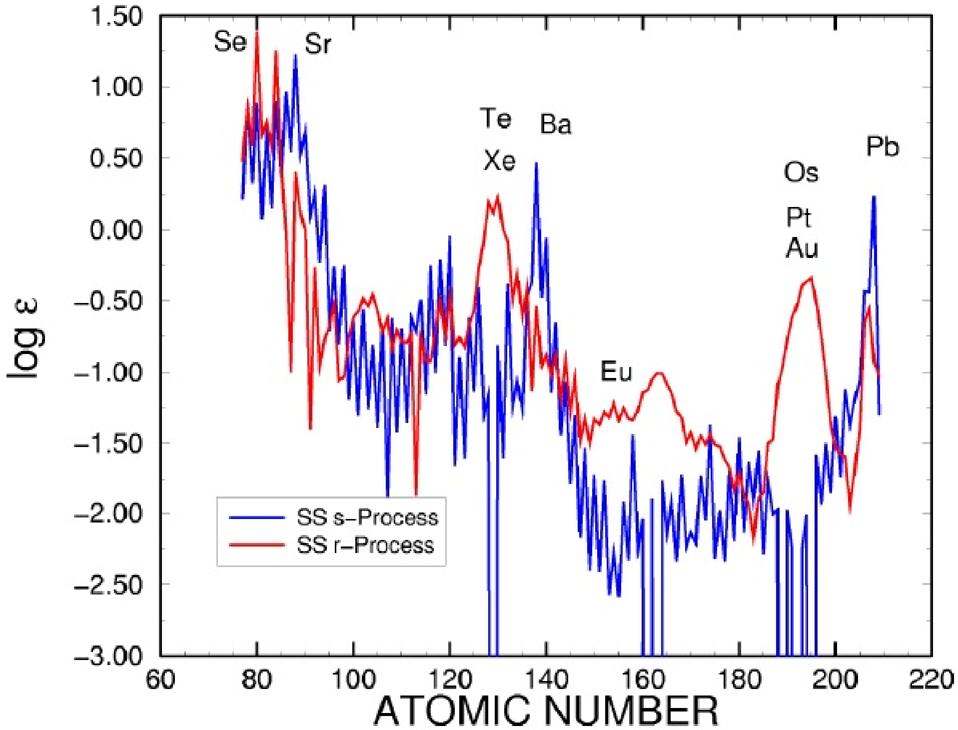


- vast majority of chemical elements produced during explosive phenomena
- nuclear reaction paths involve UNSTABLE species ⇒ **Radioactive Ion Beams**
- key reactions identified by sensitivity of astrophysical models to nuclear inputs

The reaction processes R.Reifarth



Neutron-capture processes



heavy elements are made by

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

and

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

neutron capture events

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

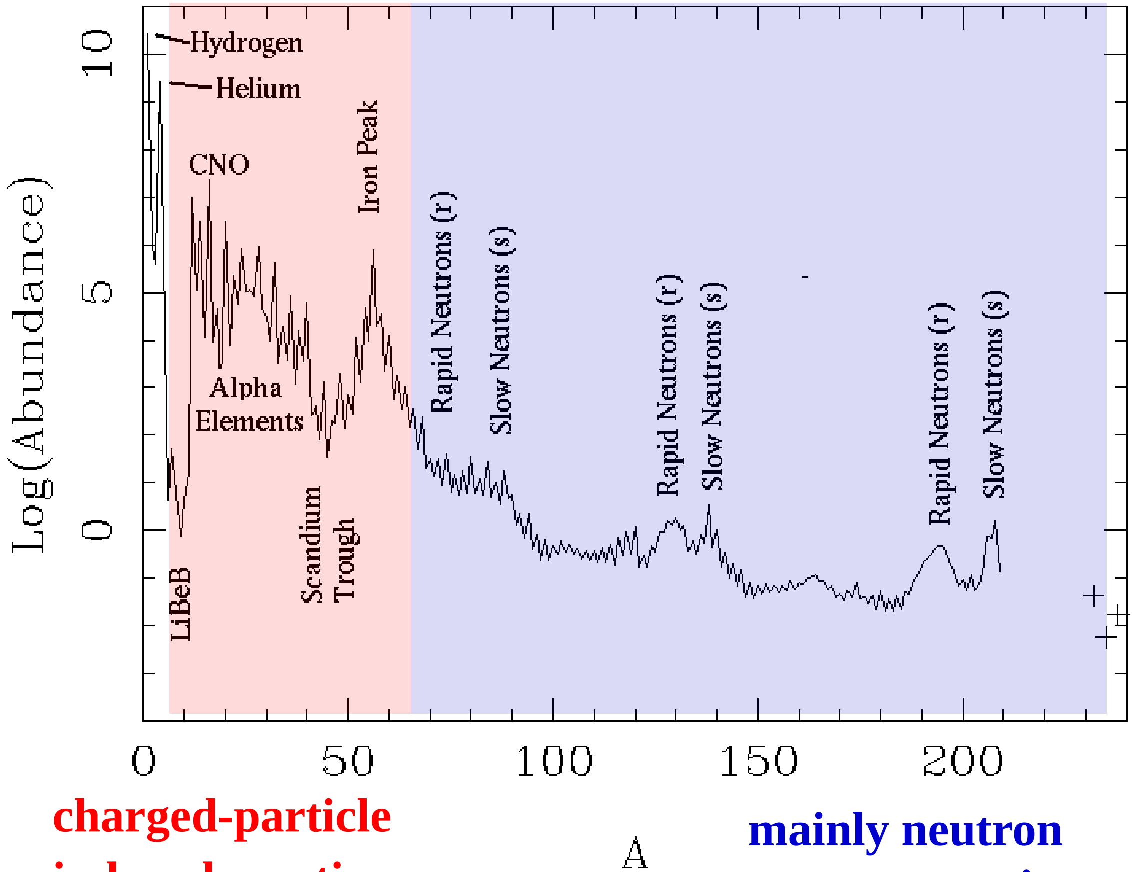
- Sequences of (n,γ) reactions and β^- decays

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

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

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

The synthesis of the trans-iron elements



charged-particle induced reaction

during quiescent stages of stellar evolution

involve mainly STABLE NUCLEI

mainly neutron capture reaction

mainly during explosive stages of stellar evolution

involve mainly UNSTABLE NUCLEI

Nucleosynthesis beyond iron

start with Fe *seeds* for neutron capture

whenever an unstable species is produced one of the following can happen:

- the unstable nucleus decays (before reacting)
- the unstable nucleus reacts (before decaying)
- the two above processes have comparable probabilities

if $\tau_n >> \tau_\beta$ $\Rightarrow$ unstable nucleus **decays**

if $\tau_n << \tau_\beta$ $\Rightarrow$ unstable **reacts**

if $\tau_n \sim \tau_\beta$ $\Rightarrow$ **branchings** occur

with:

$$\tau_n(X) = \frac{1}{N_n \langle \sigma v \rangle}$$

mean lifetime of nucleus X against destruction by neutron capture

$$\tau_\beta(X)$$

mean lifetime of nucleus X against β decay

NOTE: τ_n varies depending upon stellar conditions (T, ρ)

$\Rightarrow$ different processes dominate in different environments

ALSO: τ_β can be affected too by physical conditions of stellar plasma!

factors influencing the β-decay lifetime of an unstable nucleus

- both β^- and β^+ decay are hampered in the presence of electron or positron degeneracy
- β^- and β^+ decays may occur from excited isomeric states maintained in equilibrium with ground state by radiative transitions
- electron-capture rates are affected by temperature and density through population of the K electronic shell

example: ^{7}Be

^{7}Be nucleus can only decay by electron capture with a lifetime: **τ_{EC} ~ 77 d**

in the Sun, $T \sim 15 \times 10^6$ K ⇒ $kT \sim 1.3$ keV ⇒ low-Z nuclei almost completely ionized
e.g. binding energy of innermost K-shell electrons in ^{7}Be: $E_b = 0.22$ keV
⇒ if no electrons available ^{7}Be becomes essentially STABLE!

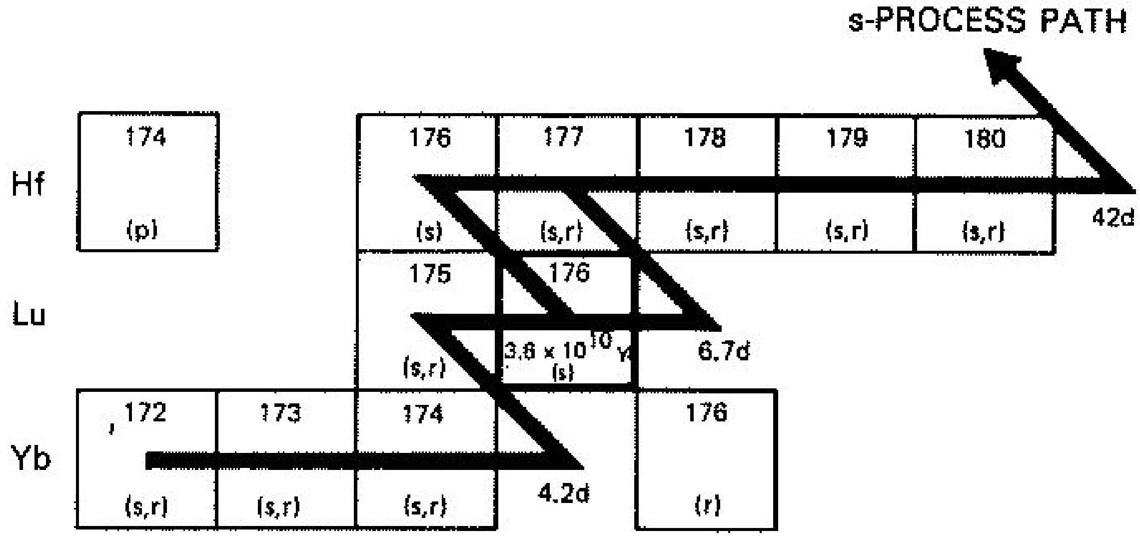
in fact free electrons present in the plasma can be captured
for solar conditions **τ_{EC} ~ 120 d** ⇒ factor **1.6** larger than in terrestrial laboratory

The s-process

- the process
- its astrophysical site(s)
- nuclear data needs
- (experimental equipment and techniques)

The s-process slow neutron capture process

unstable nucleus decays before capturing another neutron ⇔ $\tau_\beta << \tau_n$



how many neutrons are needed?

typical lifetimes for unstable nuclei close to the valley of β stability: seconds → years

assuming: $\sigma \sim 0.1$ b @ E = 30 keV → v = 3×10^8 cm/s

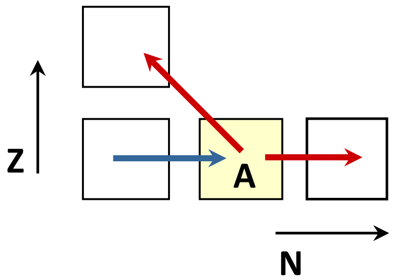
$$\langle \sigma v \rangle = 3 \times 10^{-17} \, cm^3 s^{-1} \quad \Leftrightarrow \quad \tau_n N_n = \frac{1}{\langle \sigma v \rangle} = 3 \times 10^{16} s \frac{n}{cm^3}$$

requiring: $\tau_n \sim 10$ y ⇔ $N_n \sim 10^8$ n/cm^3

Classical approach of the s-process

time dependence of abundance N_A given by:

$$\frac{dN_A(t)}{dt} = \underbrace{N_{A-1}(t)N_n(t)\langle\sigma v\rangle_{A-1}}_{\text{production}} - \underbrace{N_A(t)N_n(t)\langle\sigma v\rangle_A - \lambda_\beta(t)N_A(t)}_{\text{destruction}}$$



assuming:
- T ~ const
- $\tau_n >> \tau_\beta$

$$\frac{dN_A}{d\tau} = \langle\sigma\rangle_{A-1} N_{A-1} - \langle\sigma\rangle_A N_A$$

with: $\langle\sigma\rangle = \frac{\langle\sigma v\rangle_A}{v_T}$ Maxwellian averaged cross section

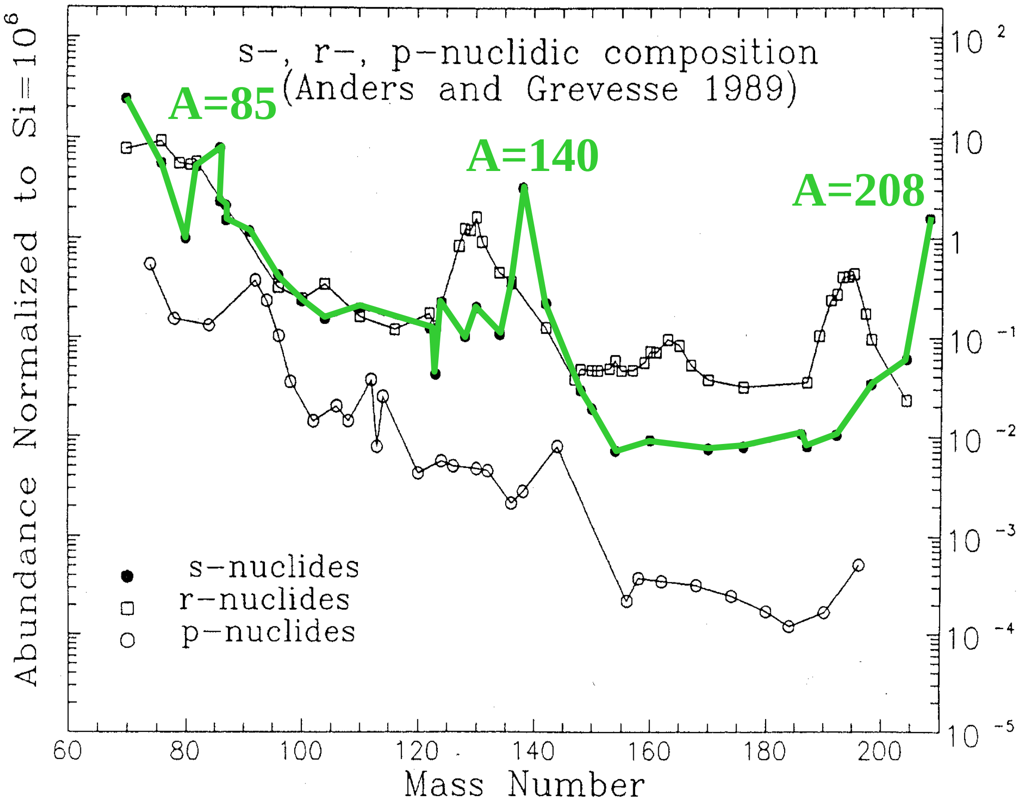
$\tau = \int_0^t v_T N_n(t)dt$ neutron exposure

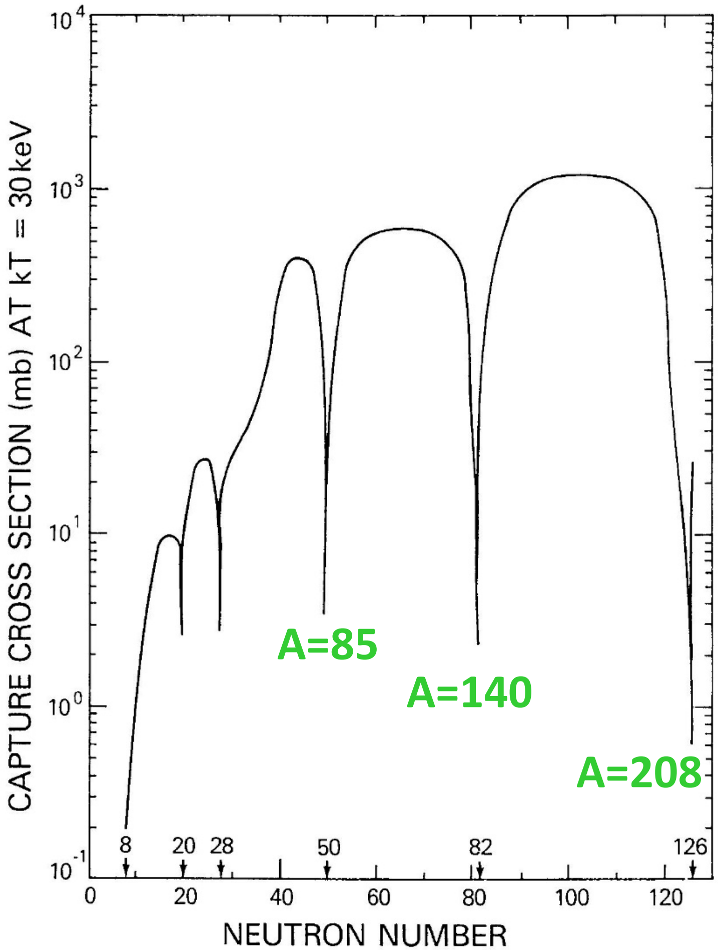
in steady state condition (so-called *local equilibrium approximation*):

$$\frac{dN_A}{d\tau} = 0 \quad \Rightarrow \quad \langle\sigma\rangle_{A\text{-}1} N_{A\text{-}1} = \langle\sigma\rangle_A N_A = \text{constant} \quad \Rightarrow \quad N_A \propto \frac{1}{\langle\sigma\rangle_A}$$

$$N_A \propto \frac{1}{\langle\sigma\rangle_A}$$

small capture cross sections at neutron magic numbers
⇔ pronounced abundance peaks





Rolfs & Rodney: Cauldrons in the Cosmos, 1988

Time-of-Flight technique

applicable to all stable nuclei

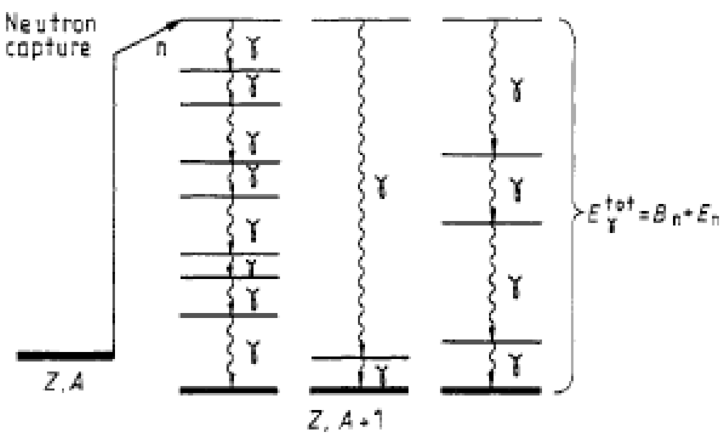
need pulsed neutron source for E_n determination via TOF

signature for neutron capture events

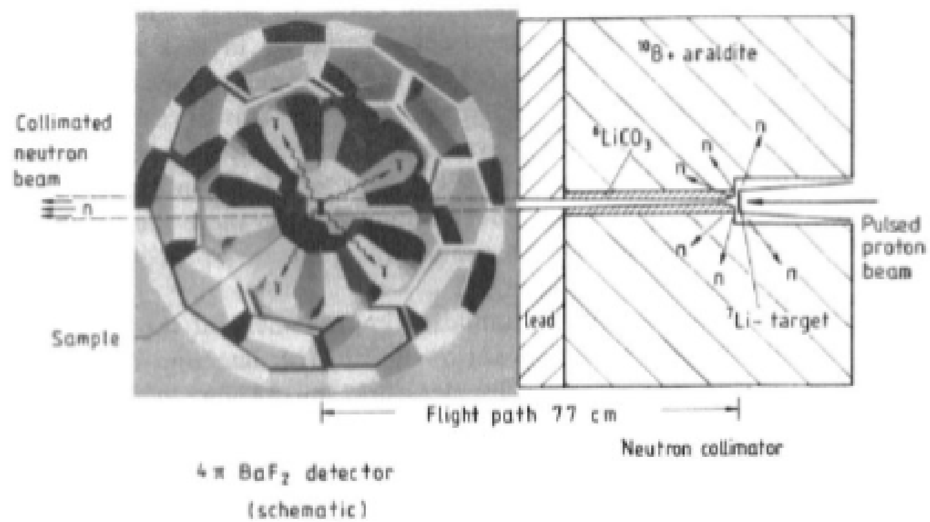
⇕

total energy of γ cascade to ground state

need 4π detector of high efficiency, good time and energy resolution



Karlsruhe: 42 individual BaF_2 crystals



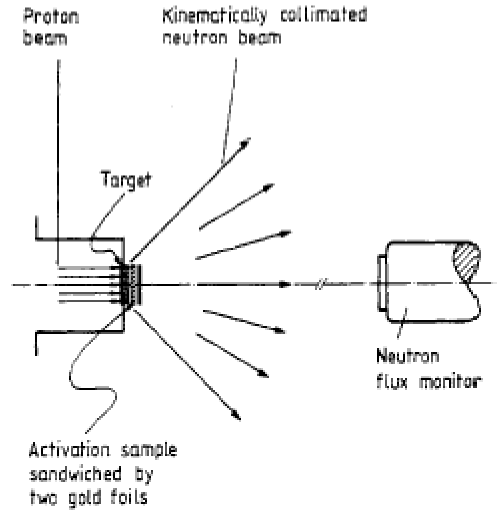
F. Kaeppeler: Rep. Prog. Phys. 52 (1989) 945 – 1013

Capture cross section measurements

activation technique

^{7}Li(p,n)^{7}Be (or ^{3}H(p,n)^{3}He)

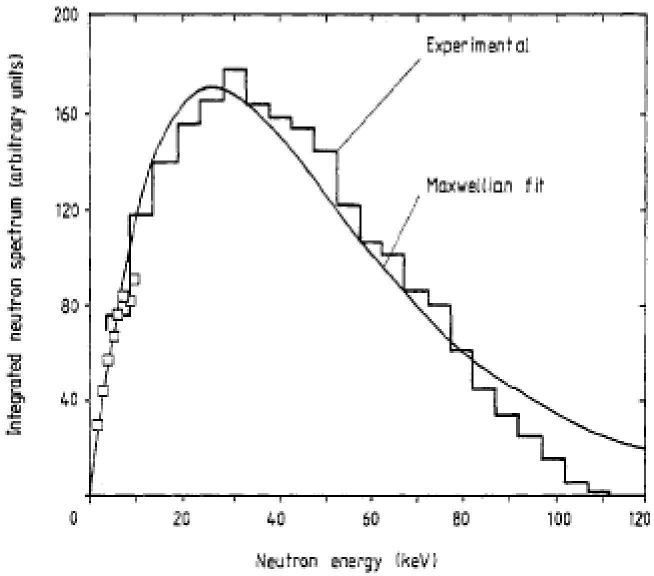
angle-integrated spectrum closely resembles
a MB distribution at kT = 25 keV (52 keV)
reaction rate measured in such spectrum
gives proper stellar cross section



advantages:

high sensitivity ⇒ tiny samples are enough
for (n,γ) mesurements
good for RIBs

high selectivity ⇒ samples of natural composition
can be used



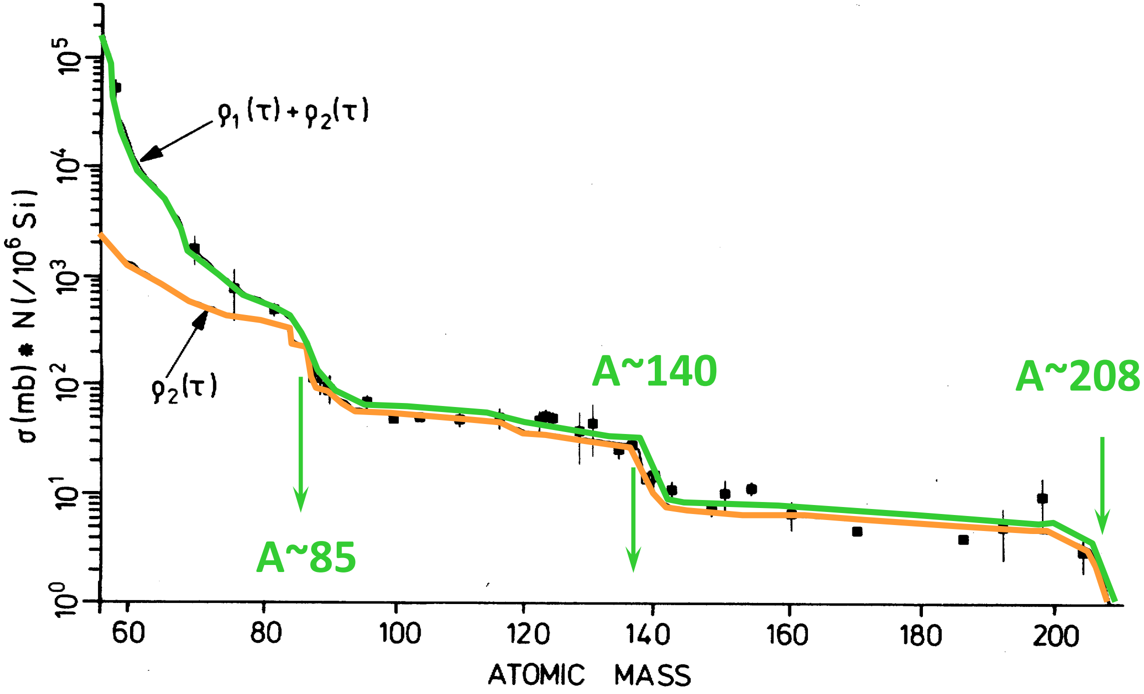
limitations: (n,γ) capture must produce
unstable species
cross section measurements
at E= 25 (and 52) keV only

applications with RIA type facilities: R. Reifarth et al.: NIMA 524 (2004) 215-226

$$\langle \sigma \rangle_A N_A = \text{constant}$$

condition fulfilled between magic numbers of neutrons

sudden drops observed at neutron magic numbers



NOTE

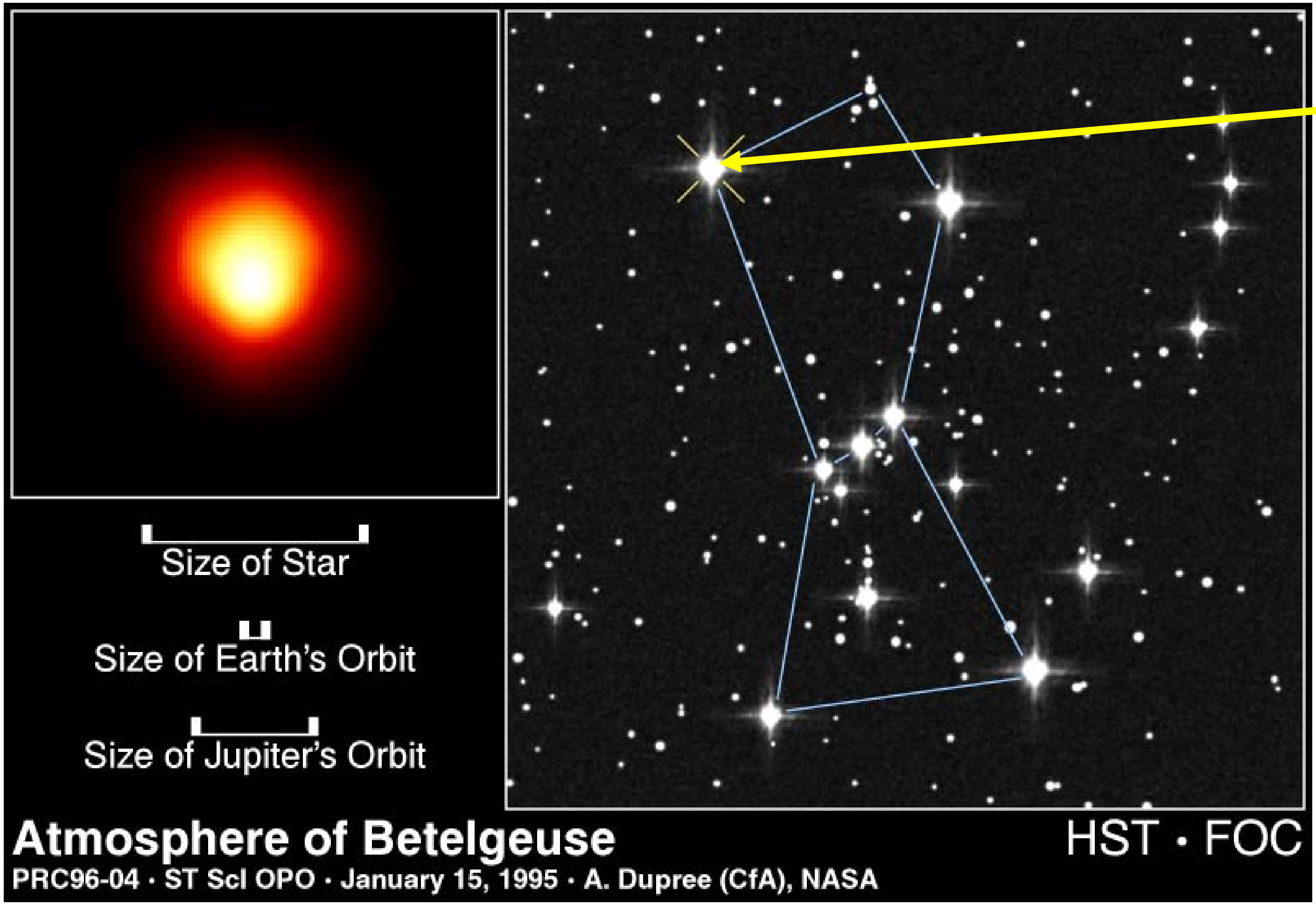
a superposition of many neutron irradiations is needed to correctly reproduce the abundance curve

- **main component (A=88-209)**
- **weak component (A<90)**

s-process: best understood nucleosynthesis process from nuclear point of view

what about the astrophysical site?

Where does the s-process happen?

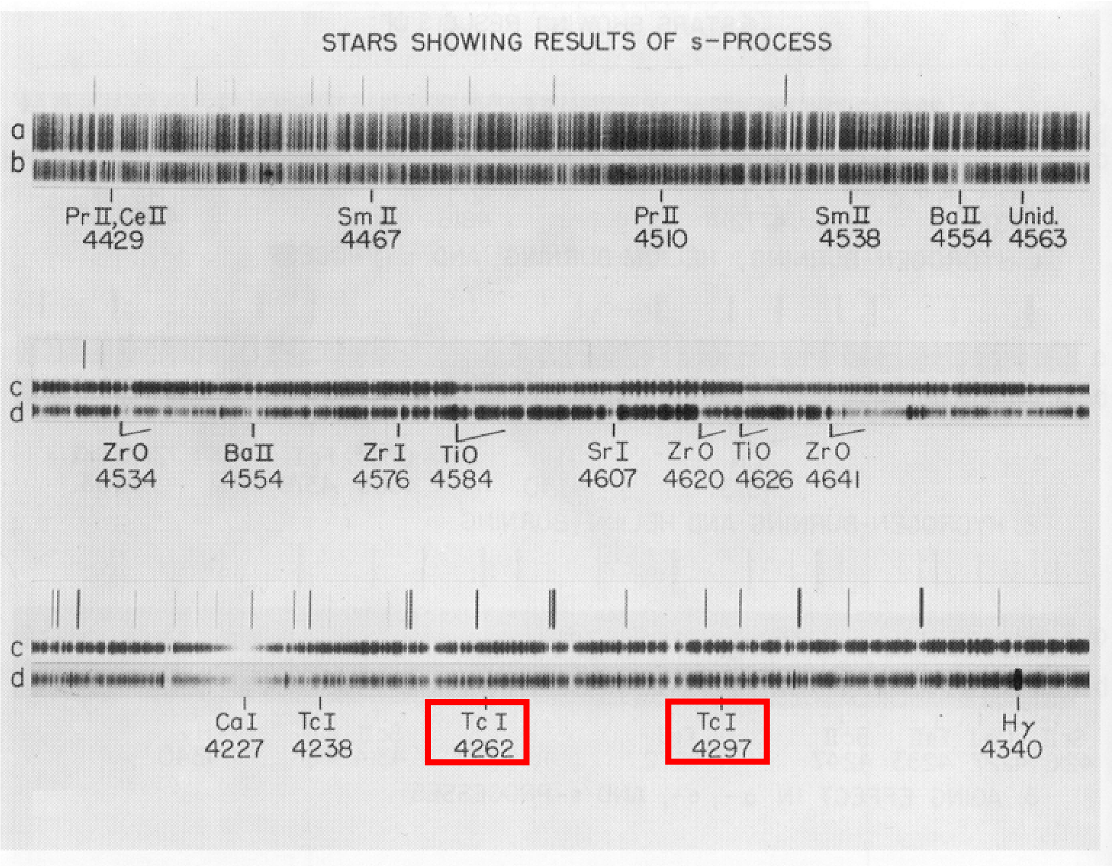


there !

in red giants – and it takes several million years !
(or, more correctly, low mass TP-Asymmetric Giant Branch stars)

How can we tell?

Analyze light from a red giant:



Star contains Technetium (Tc) !!!

(heavy element Z=43, $T_{1/2}$ 4 Mio years, Merrill 1952)

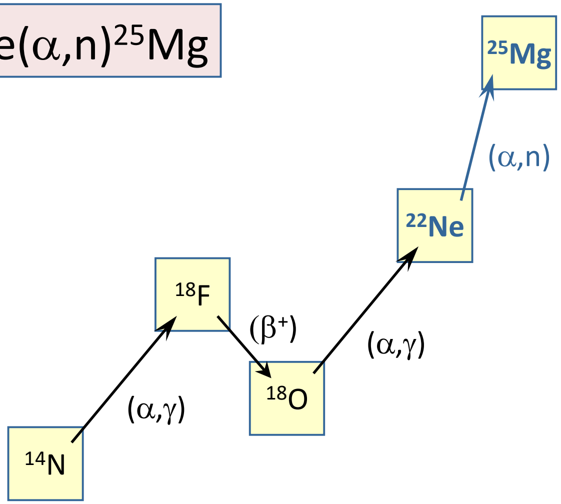
s-process site(s) and conditions

free neutrons are unstable ⇒ they must be produced in situ

in principle many (α,n) reactions can contribute
in practice, one needs suitable reaction rate & abundant nuclear species

most likely candidates as neutron source are:

$^{22}Ne(\alpha,n)^{25}Mg$

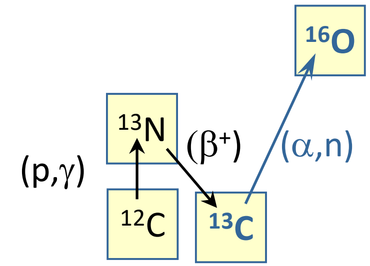


astrophysical site:

core He burning (and shell C-burning)
in massive stars (e.g. 25 solar masses)
$T_8 \sim 2.2 - 3.5$

contribution to weak s-process

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



astrophysical site:

He-flashes followed by H mixing
into ^{12}C enriched zones
low-mass (1.5 - 3 M_{sun}) TP-AGB stars
$T_8 \sim 0.9 - 2.7$

contribution to main s-process

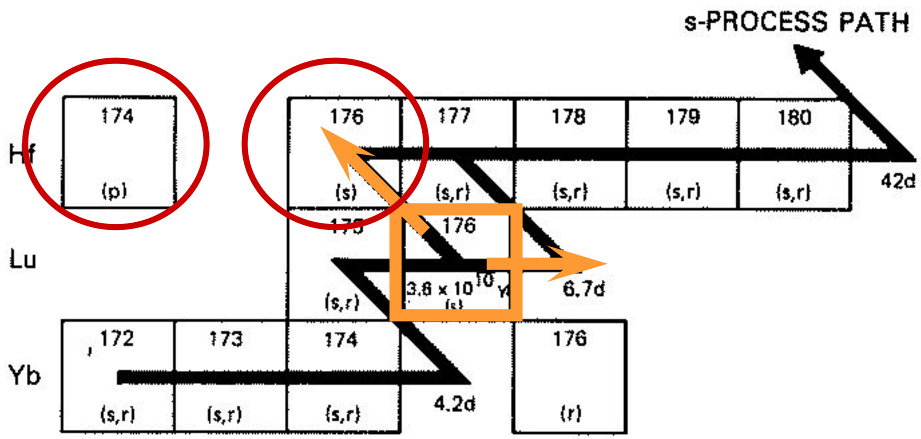
in some cases: $\tau_\beta \sim \tau_n$ $\Rightarrow$ a branching occurs in nucleosynthesis path

example:

$^{176}Lu^{gs} \rightarrow {}^{176}Hf$ $\tau_\beta \sim 5\text{x}10^{10}$ y

$^{176}Lu^{m} \rightarrow {}^{176}Hf$ $\tau_\beta \sim 5.3$ h

for $N_n \sim 10^8$ cm^{-3} $\Rightarrow$ $\tau_n \sim 1$ y



$^{176}Lu^{gs}$ essentially STABLE

$^{176}Lu^{m}$ quickly decays into ^{176}Hf

from abundance determinations:

$$\frac{^{176}\text{Hf}}{^{174}\text{Hf}} = 29$$

(note: ^{174}Hf = p-only nucleus, i.e. not affected by s-process)

$\Rightarrow$ significant amount of s-process branching from $^{176}Lu^{m}$ β-decay is required

$\Rightarrow$ need temperatures $T_8 > 1$ to guarantee that isomeric state is significantly populated

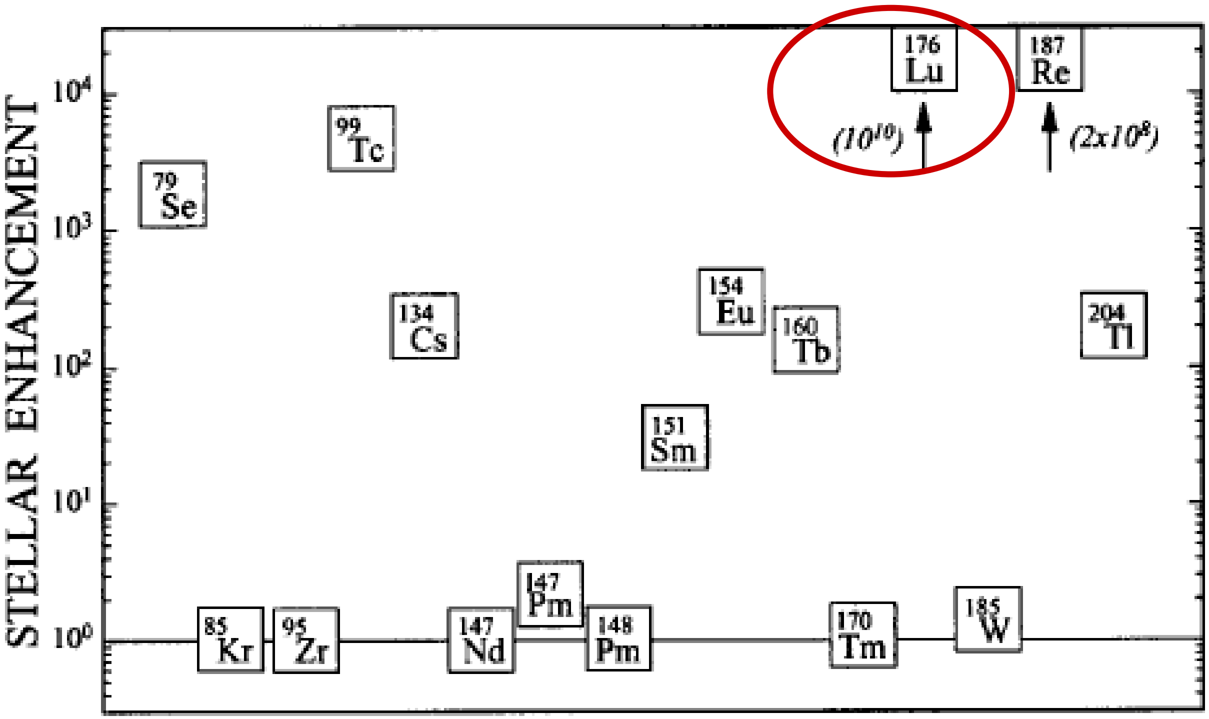
branching points can be used to determine

- neutron flux
- temperature
- density

in the star during the s process

about 15-20 branchings relevant to s process

stellar enhancement of decay (stellar decay rate/terrestrial rate)
for some important branching-point nuclei in s-process path @ kT = 30 keV



F. Kaeppeler: Prog. Part. Nucl. Phys. 43 (1999) 419 – 483

The s-process in a nutshell

	Weak component	Main component
temperature	2.2 – 3.5×10^8 K	0.9×10^8 K
neutron density	7×10^5 cm^{-3}	4×10^8 cm^{-3}
neutron source	^{22}Ne(α,n)	^{13}C(α,n) & ^{22}Ne(α,n)
stellar site	core helium burning in massive stars	TP-AGB stars

- synthesis path *along* valley of β-stability up to ^{209}Bi
- n-source: ^{13}C(α,n)^{16}O and/or ^{22}Ne(α,n)^{25}Mg
- quiescent scenarios: e.g. He burning ($T_8 \sim 1 – 4$; $E_0 \sim 30$ keV)
- branching points: if $\tau_\beta \sim \tau_n$ ⇒ several paths possible

data needs: (n,γ) cross sections on unstable nuclei along stability valley
capture data at branching points

motivation: s-process stellar models; physical conditions of astrophysical site

review: F. Kaeppeler: Prog. Part. Nucl. Phys. 43 (1999) 419 – 483

The r-process

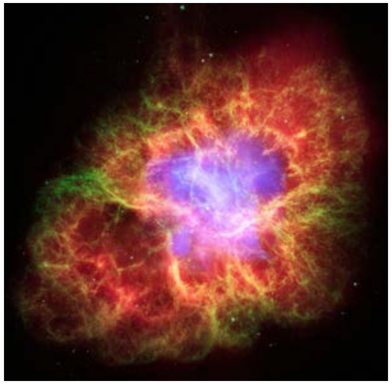
- the process
- its astrophysical site(s)
- nuclear data needs

What is the r-process?

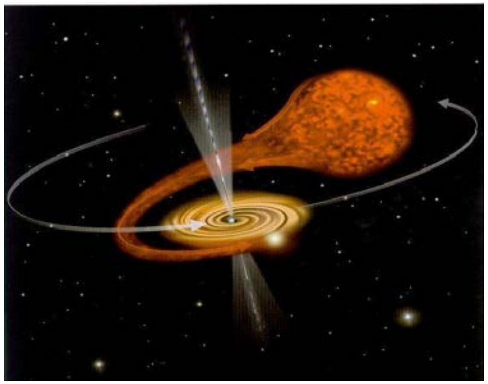
- **Rapid neutron-capture**

- The dominant process through which elements heavier than iron are formed (also s-process or slow neutron capture)

- The exact site of r-process is still unconfirmed however due to the conditions necessary (high neutron density, high temperature) core collapse supernovae and neutron stars mergers are the most likely candidates.



core-collapse supernovae



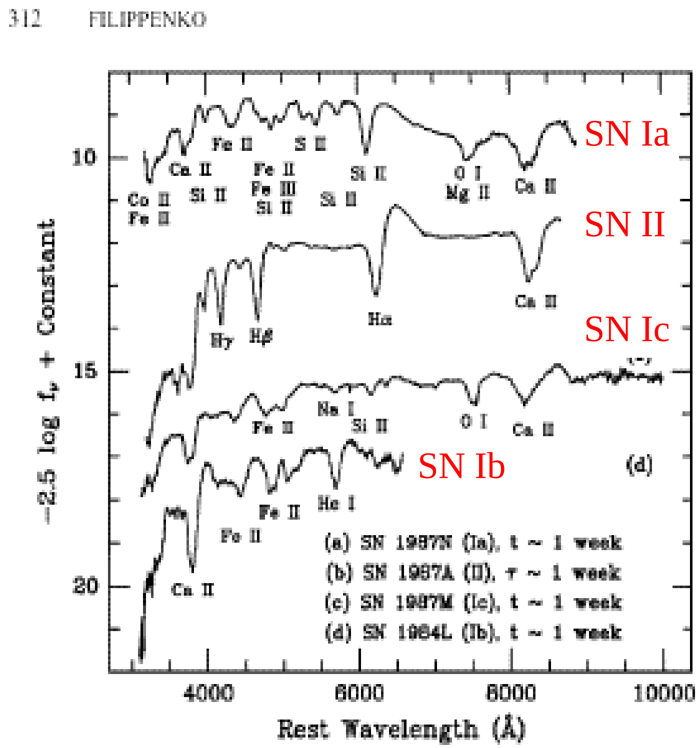
neutron star mergers

- explosion of massive stars ($M \geq 9 \cdot M_{\odot}$)
- site: neutrino-winds from cooling of hot proto-neutron star
- high frequency (~ 0.3 yr^{-1}), low yield ejecta ($10^{-4} - 10^{-5} \cdot M_{\odot}$)
- Observations: not every supernovae produces r-process

- mergers eject around $0.01 \cdot M_{\odot}$ of very neutron-rich material (Ye~0.01). Similar amount of less neutron-rich matter ($Y_e \geq 0.2$) ejected from accretion disk.
- low frequency, high yield
- observational signature: electromagnetic transient from radioactive decay of r-process nuclei

supernovae I: no hydrogen lines in spectrum, supernovae II: hydrogen lines in spectrum

Supernova classification



observational:
- Type I: no hydrogen lines in spectrum
- Type II: hydrogen lines in spectrum

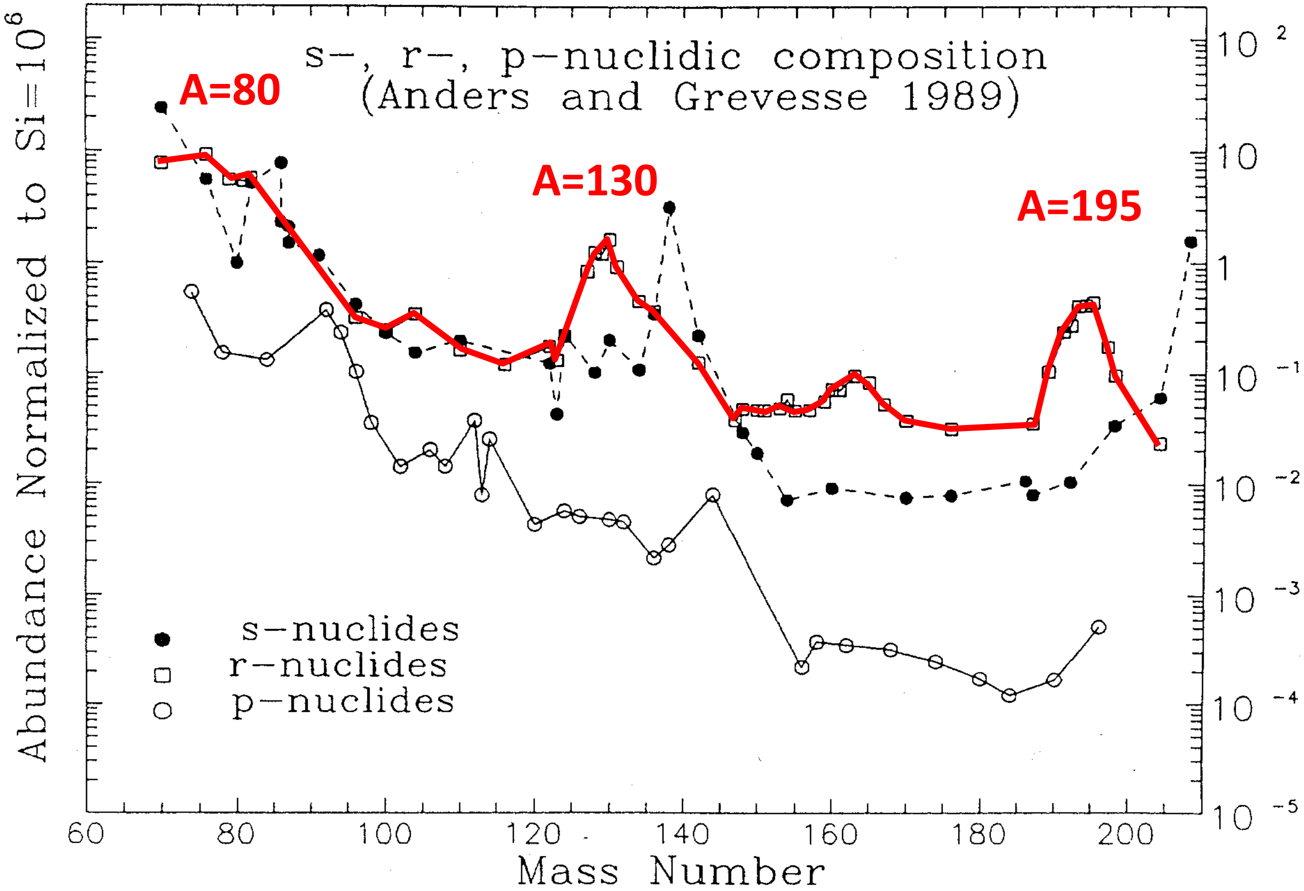
theoretical:
- thermonuclear explosion of degenerate core
- core collapse → neutron star/black hole
  relation no longer 1 to 1 → confusion
- Type Ia (Si lines): thermonuclear explosion of white dwarf
- \Type Ib/Ic (no Si; He or no He): core collapse of He star
- Type II-P: classical" core collapse of a massive star with hydrogen envelope
- Type II-L: supernova with linear light curve
  (thermonuclear explosion of intermediate-mass star? probably not!)

complications
- special supernovae like SN 1987A
- Type IIb: supernovae that change type, SN 1993J
  (Type II → Type Ib)
- some supernova "types" (e.g., IIn) occur for both explosion types ("phenomenon", not type; also see SNe Ic)
- new types: thermonuclear explosion of He star (Type Iab?)

The r-process

r-process abundances N_r can be obtained as the difference between solar abundances N_{solar} and calculated s-process abundances N_s

$$N_r = N_{solar} - N_s$$



Constraints from elemental abundances

Ultra **M**etal **P**oor giant halo stars give info on early nucleosynthesis in Galaxy

example:

CS22892-052

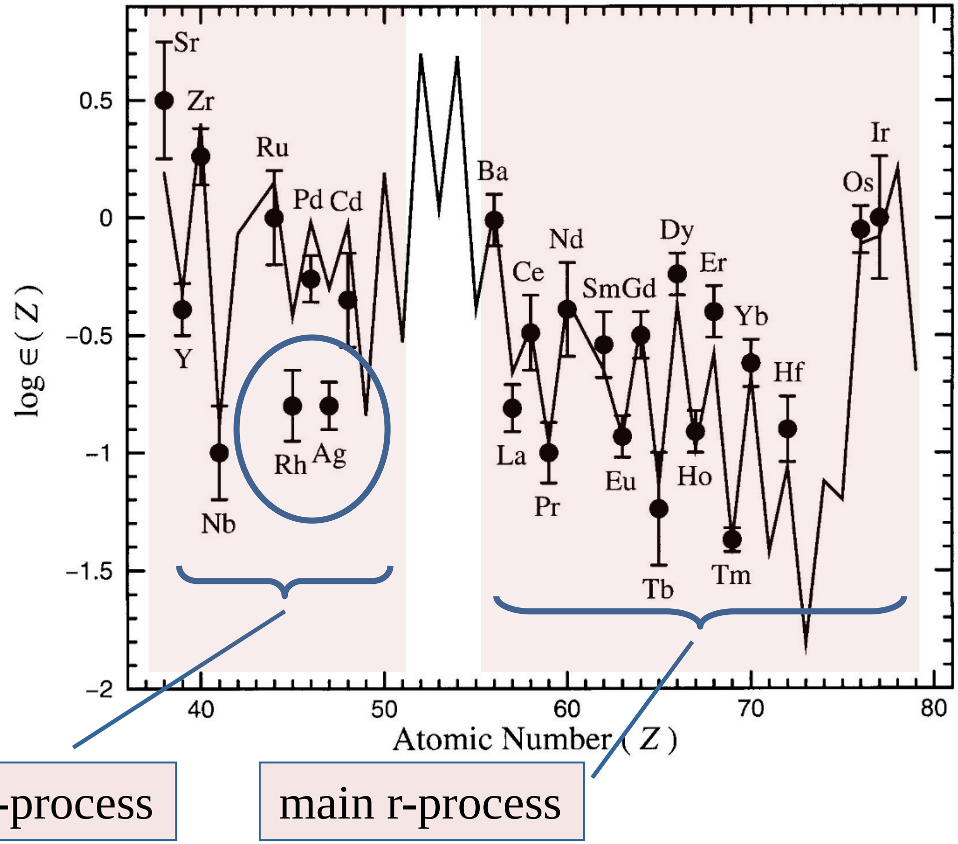
red giant located in galactic halo

[Fe/H]= -3.0

[Dy/Fe]= +1.7

recall:

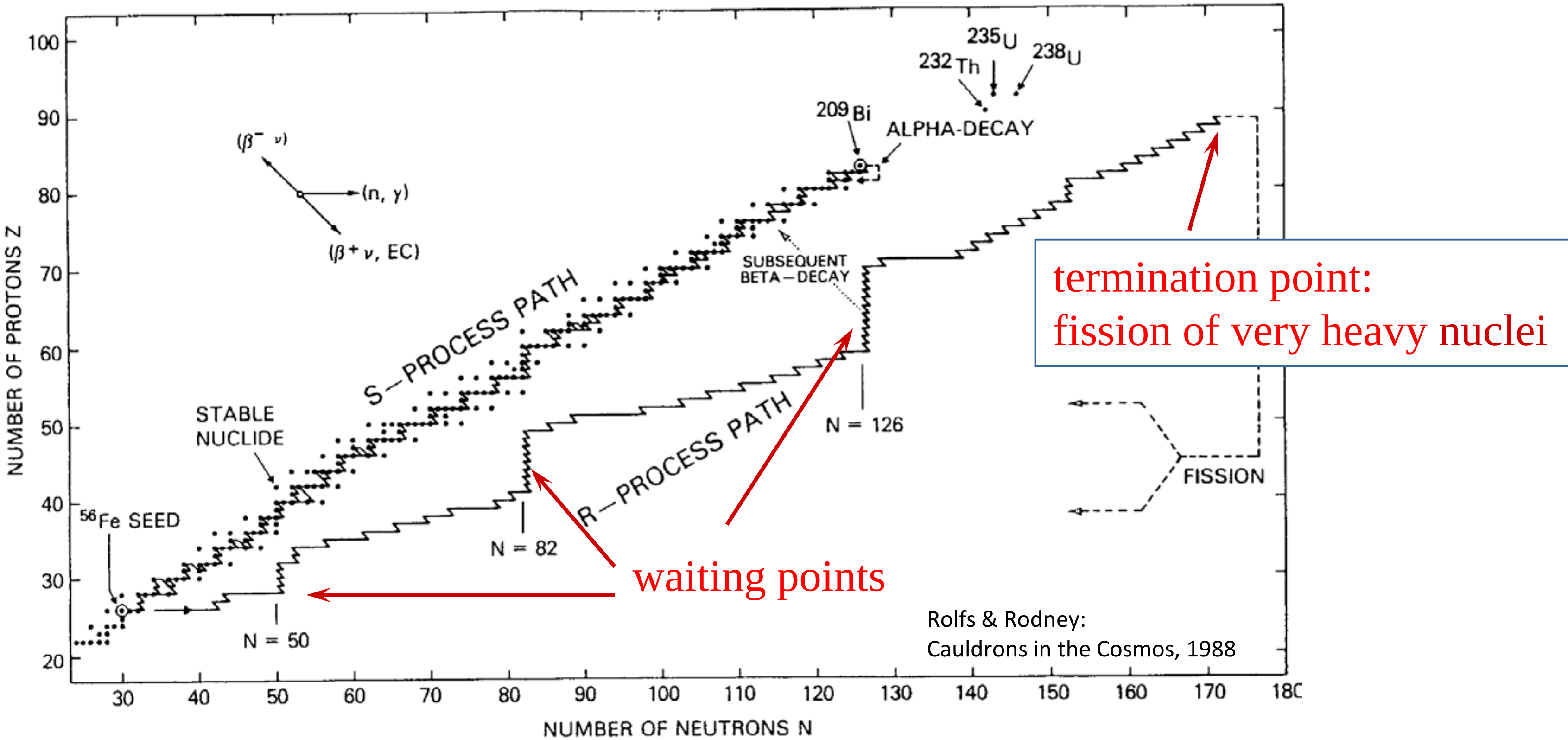
$[X/Y]=\log(X/Y)-\log(X/Y)_{solar}$



- for **A ≥ 130** solar-like abundances even for stars originating from very different regions of Galactic halo
  ⇒ **main r-process** independent of astrophysical site
- for **A ≤ 130** under-abundances ⇒ **weak r-process**

The r-process rapid neutron capture process

unstable nucleus reacts before capturing decay ⇔ $\tau_n << \tau_\beta$

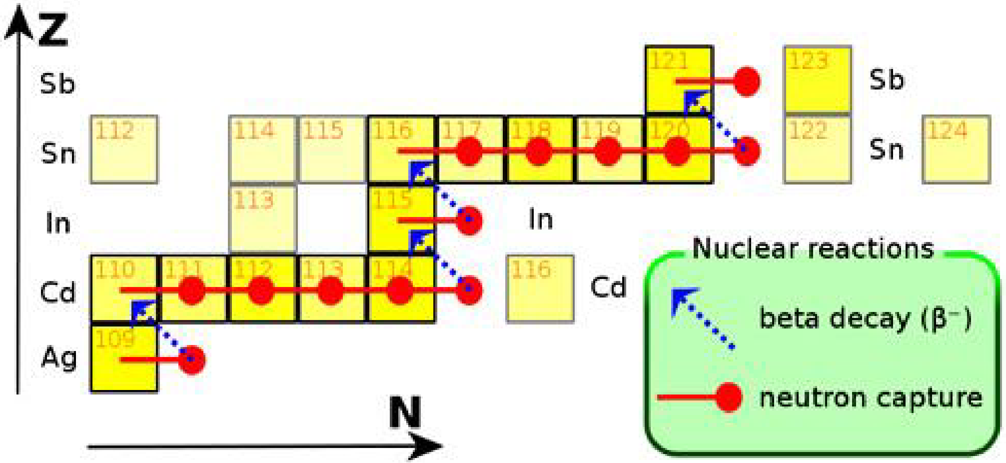


typical lifetimes for unstable nuclei far from the valley of β stability: $10^{-6} – 10^{-2}$ s

requiring: $\tau_n \sim 10^{-4}$ s ⇔ $N_n \sim 10^{20}$ n/cm^3

explosive scenarios needed to account for such high neutron fluxes

Mechanisms of r-process

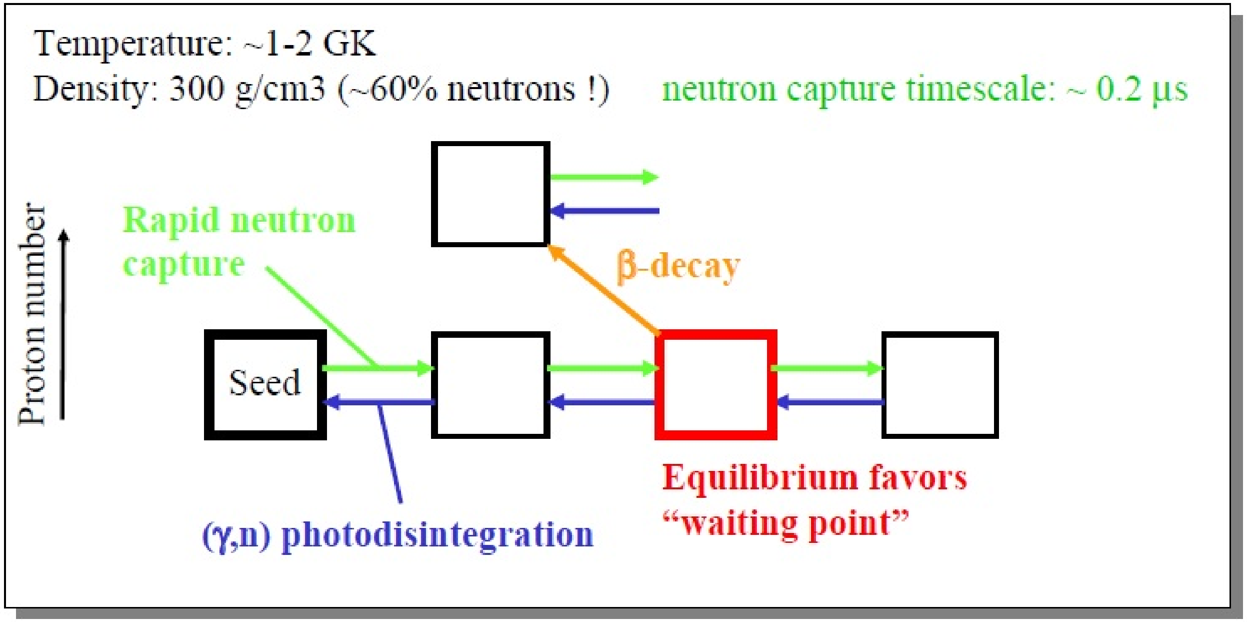


- High T (T > 10^9 K)
- High neutron density ($n_n > 10^{20}$ cm^{-3} $\Rightarrow \tau_n = \frac{1}{n_n\langle\sigma v\rangle} \approx 10^{-1} - 10^{-3}\ s$)
- Nuclei are bombarded with neutrons
- Neutrons can be absorbed until the neutron separation energy is less than zero. This is the neutron drip line
- Neutron rich isotopes are unstable to beta decay
- After beta decay the new nucleus will have a new neutron drip line and in most cases be able to capture more neutrons

(n,γ) and (γ,n) equilibrium

- Photodisintegration can play an important role in the r-process path. In very these hot environments there will be high energy photons.

- The location of “waiting points” in r-process are points where an equilibrium between neutron capture rates and photodisintegration has been reached

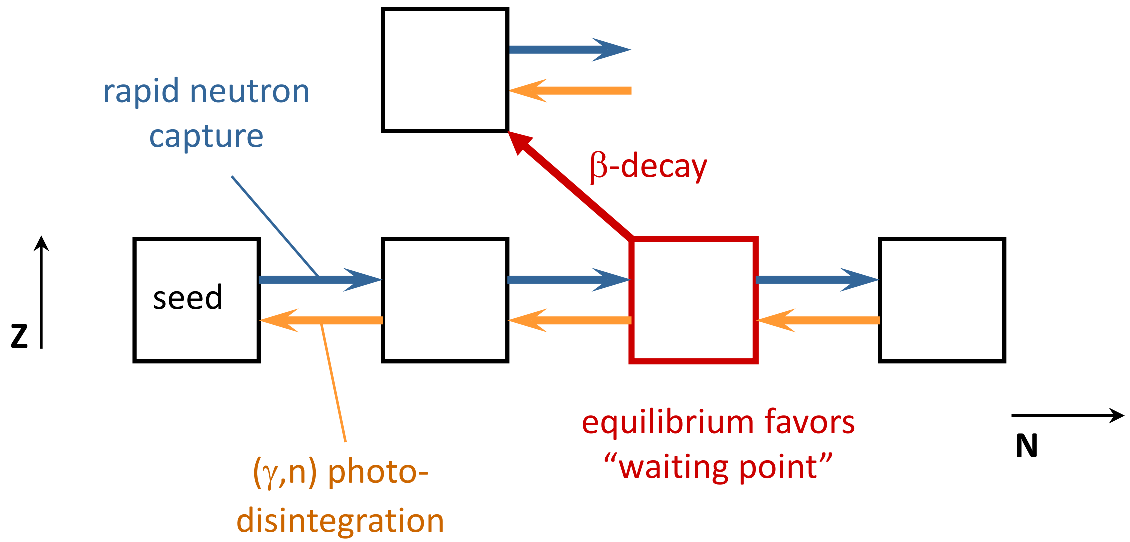


waiting point approximation

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)

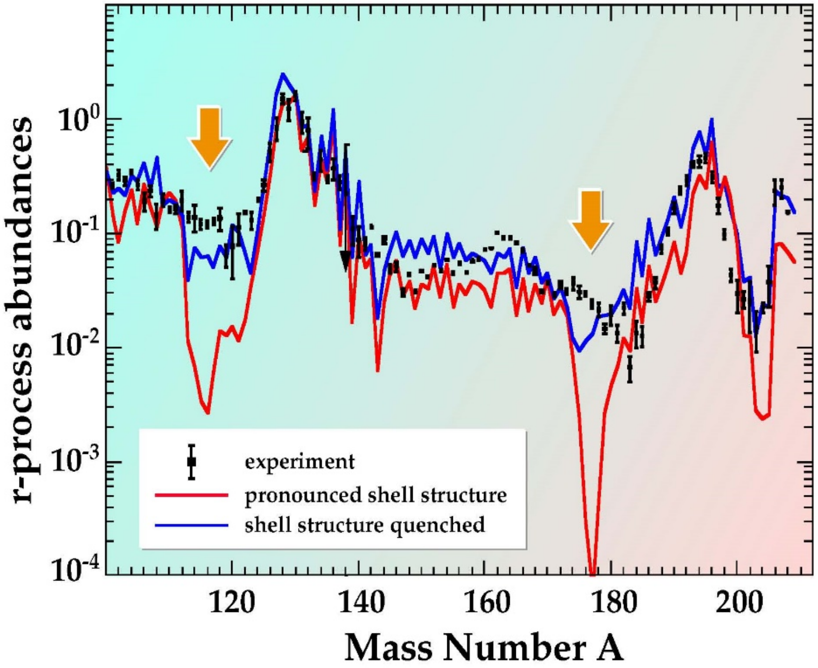


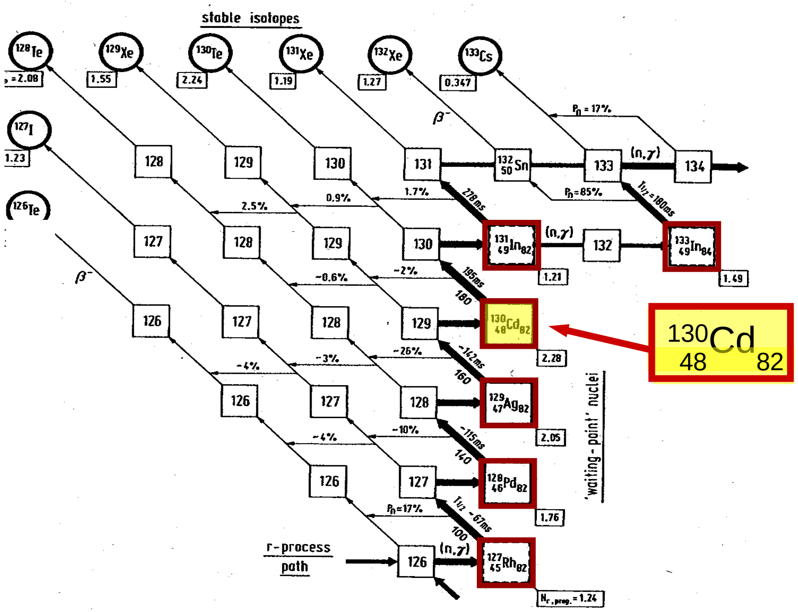
the nucleus with maximum abundance in each isotopic chain must wait for the longer β-decay time scales

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

Imprints of shell effects in r-process?

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?

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

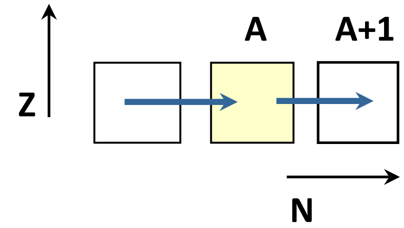
$\tau_\beta > \tau_{n,\gamma}, \tau_{\gamma,n}$

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

Classical approach of the r-process

- abundance ratios of neighbouring isotopes only depends on N_n, T and S_n

$$\frac{Y(Z,A+1)}{Y(Z,A)} = f(N_n, T, S_n)$$

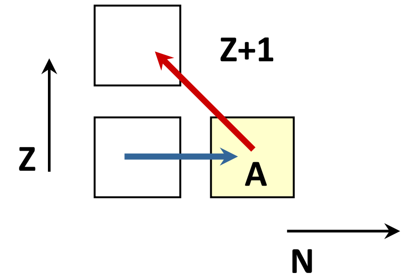


note: neutron capture rates do not play relevant role in most of r-process

- abundance flow from neighbouring isotopic chains is governed by β decays

define:
total abundance in each isotopic chain $Y(Z) = \sum_A Y(Z,A)$

$$Y(Z) \propto \frac{1}{\lambda_\beta(Z)} = \tau_\beta$$

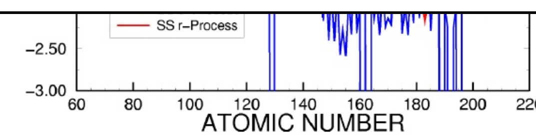


need nuclear masses (S_n) and lifetimes (τ_β) together with environment conditions (N_n, T)

late neutron captures can modify final abundance distribution mainly in region A > 140

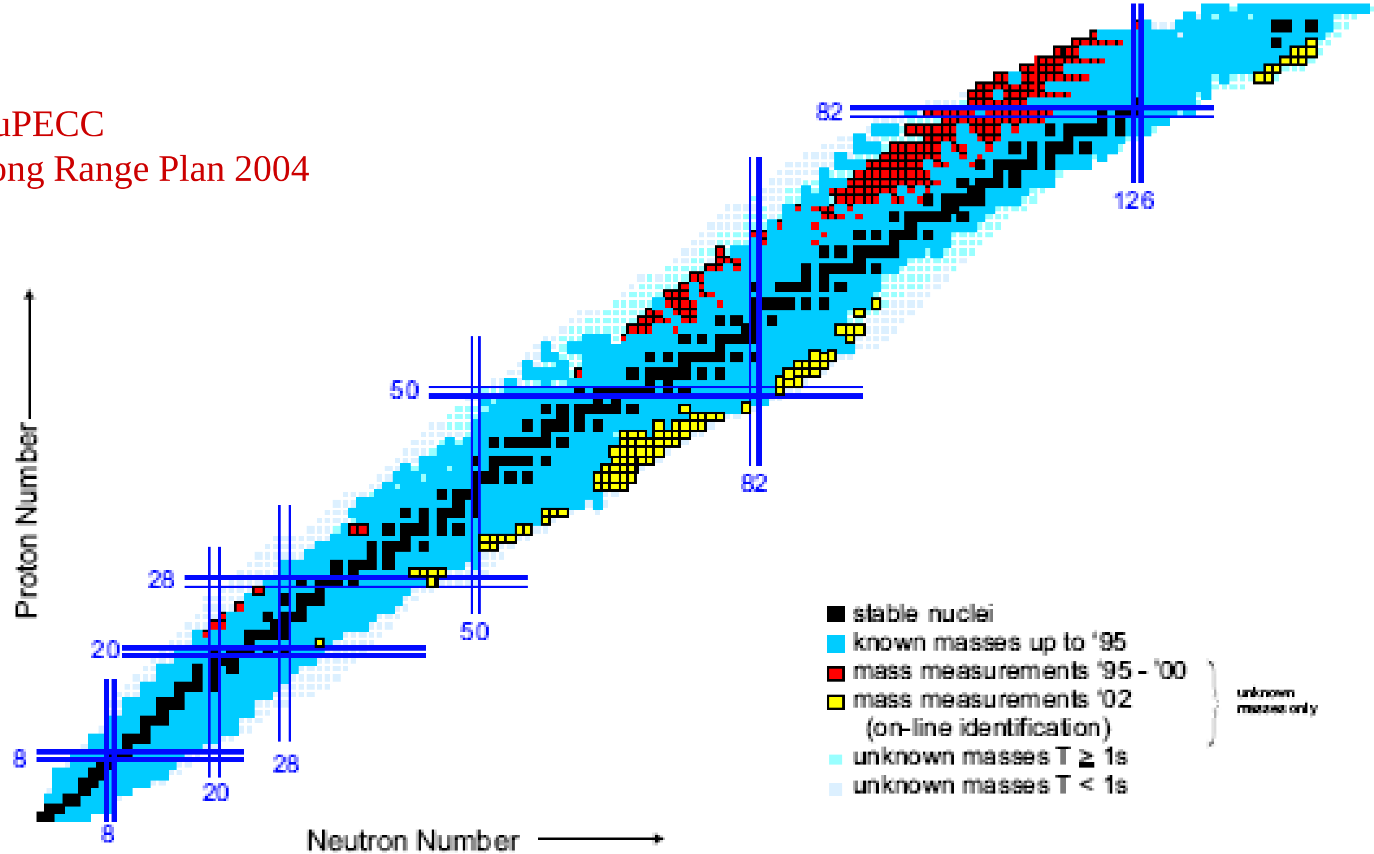
Timescale of the r-process

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



at present very little is known for neutron-rich nuclei very far away from β stability
⇒ must rely on theoretical calculations

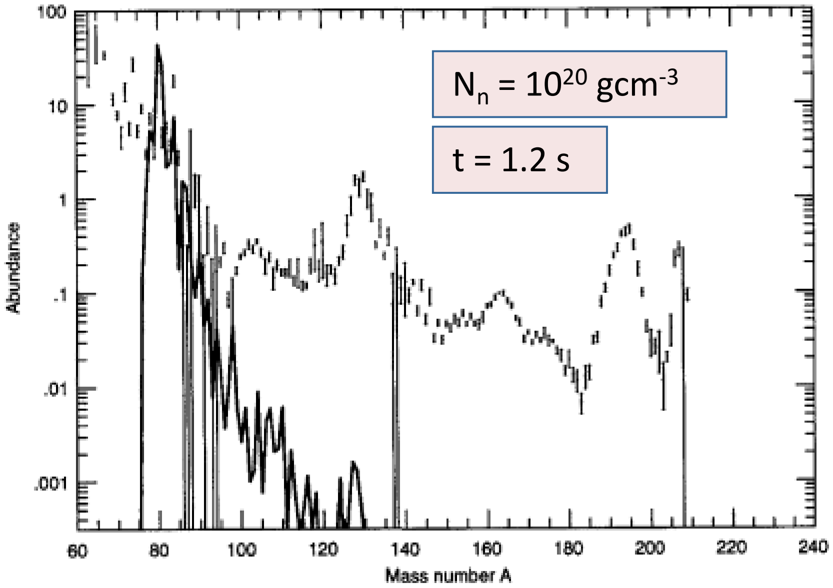
NuPECC
Long Range Plan 2004

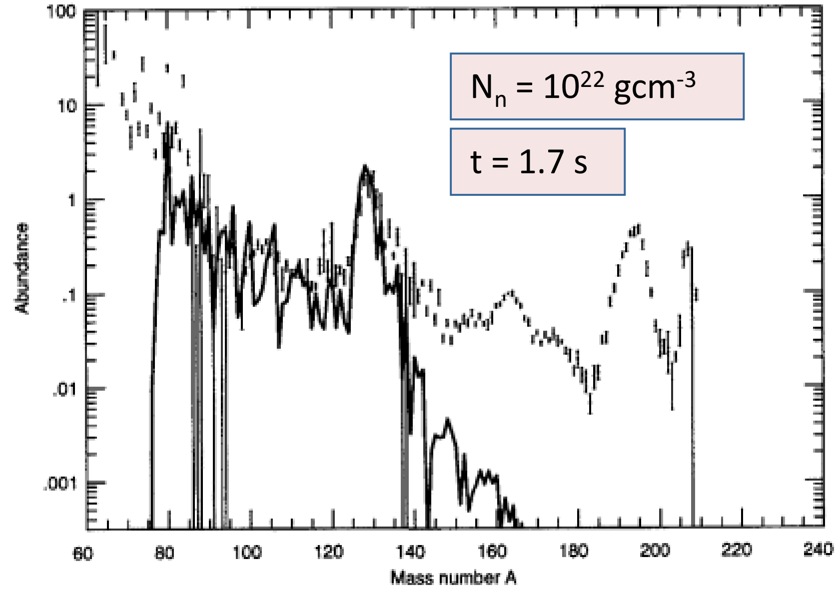


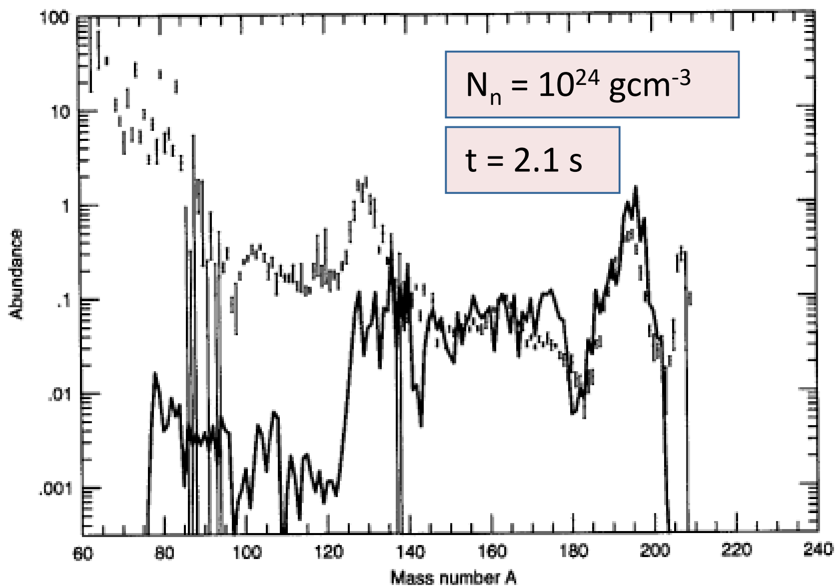
@ ISOLDE β-decays for ~ 30 neutron-rich nuclei have been determined including N=82 waiting points ^{130}Cd & ^{129}Ag

GSI ~ 70 new masses determined recently in region N=50 & 82

Time-dependent r-process calculations







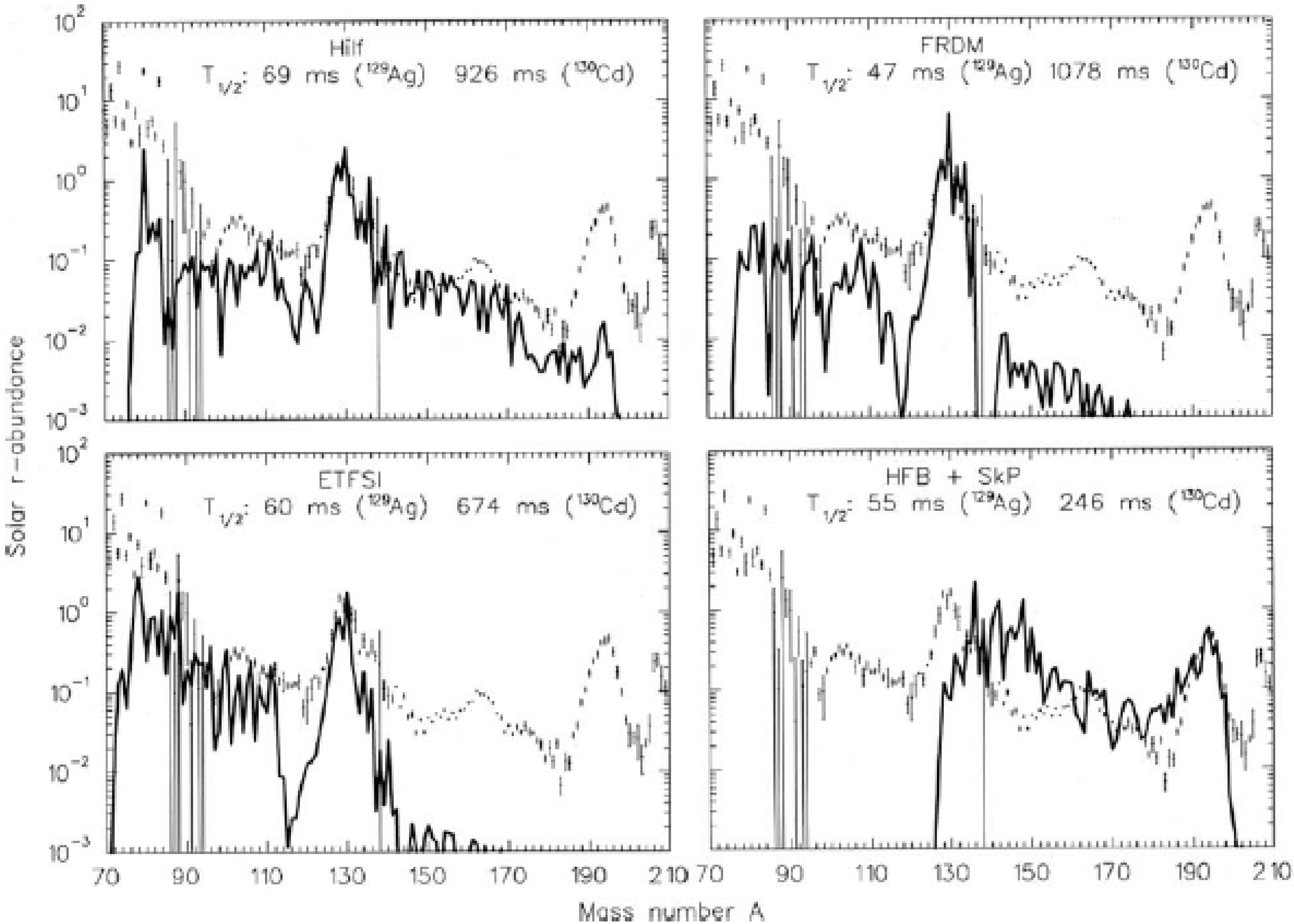
$T = 1.35 \times 10^9$ K

a full fit to the solar r-process abundances requires a superposition of different stellar conditions (not necessarily different sites)

Pfeiffer et al.: Nucl. Phys. A 693 (2001) 282 – 324

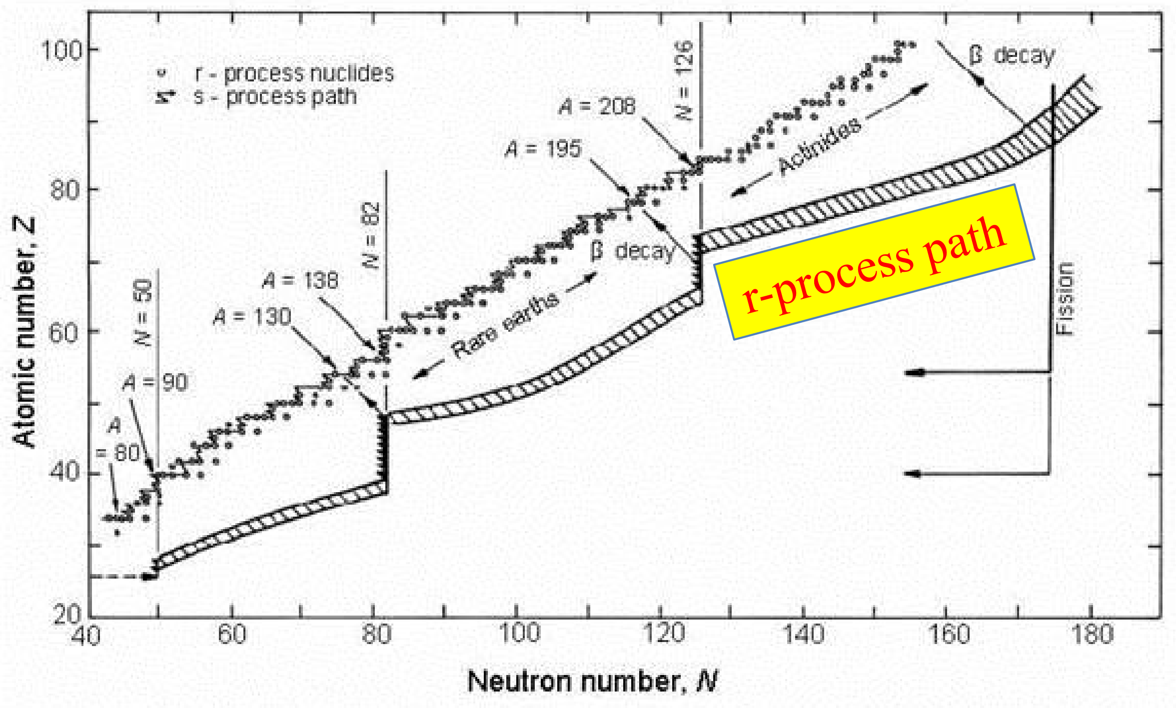
Time-dependent r-process calculations

S_n values from four different mass models; constant astrophysical parameters;
$t_{½}$ for ^{129}Ag and ^{130}Cd calculated according to respective mass values



The end of r-process: fission

- eventually it is possible to make a bigger nucleus. Trying to pack too many protons in a nucleus results in instability to spontaneous fission as well as neutron induced fission
- nuclei in the **N = 175** region typically fission and terminate the r-process
- the fission fragments from the heavy nucleus will re-seed the r-process



H	30,000
C	10
Fe	1
Au	$2 \cdot 10^{-7}$

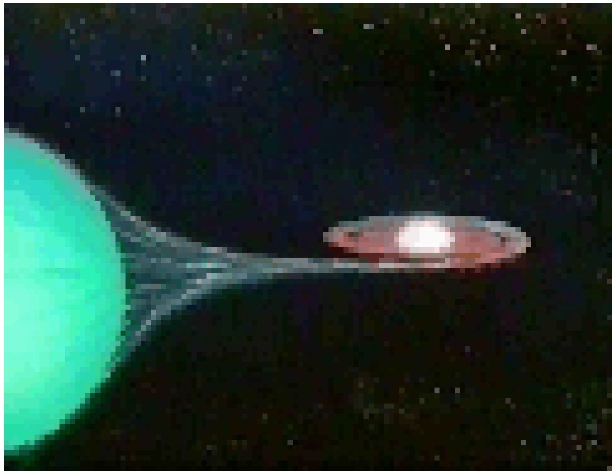
Astrophysical site(s) for the r-process

actual site(s) still unknown

R-process related to environments with
high-neutron density and high temperature.

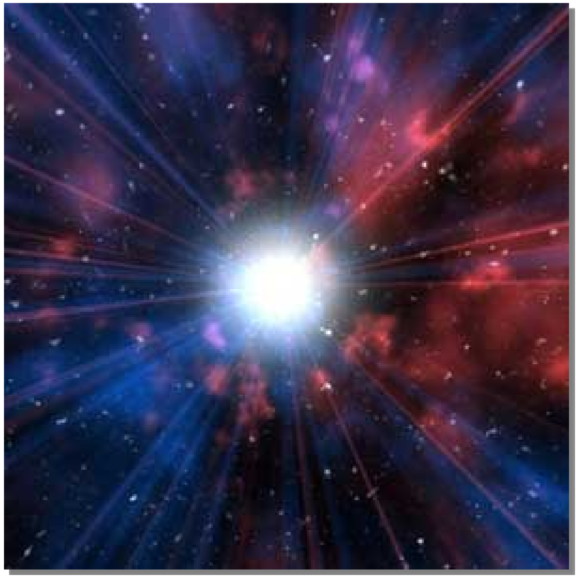
Type II supernovae prime suspects…

Neutron star mergers and accretion disks in g-ray bursts promising alternatives.



Not enough is known at present about the physics to create realistic models

Supernovae

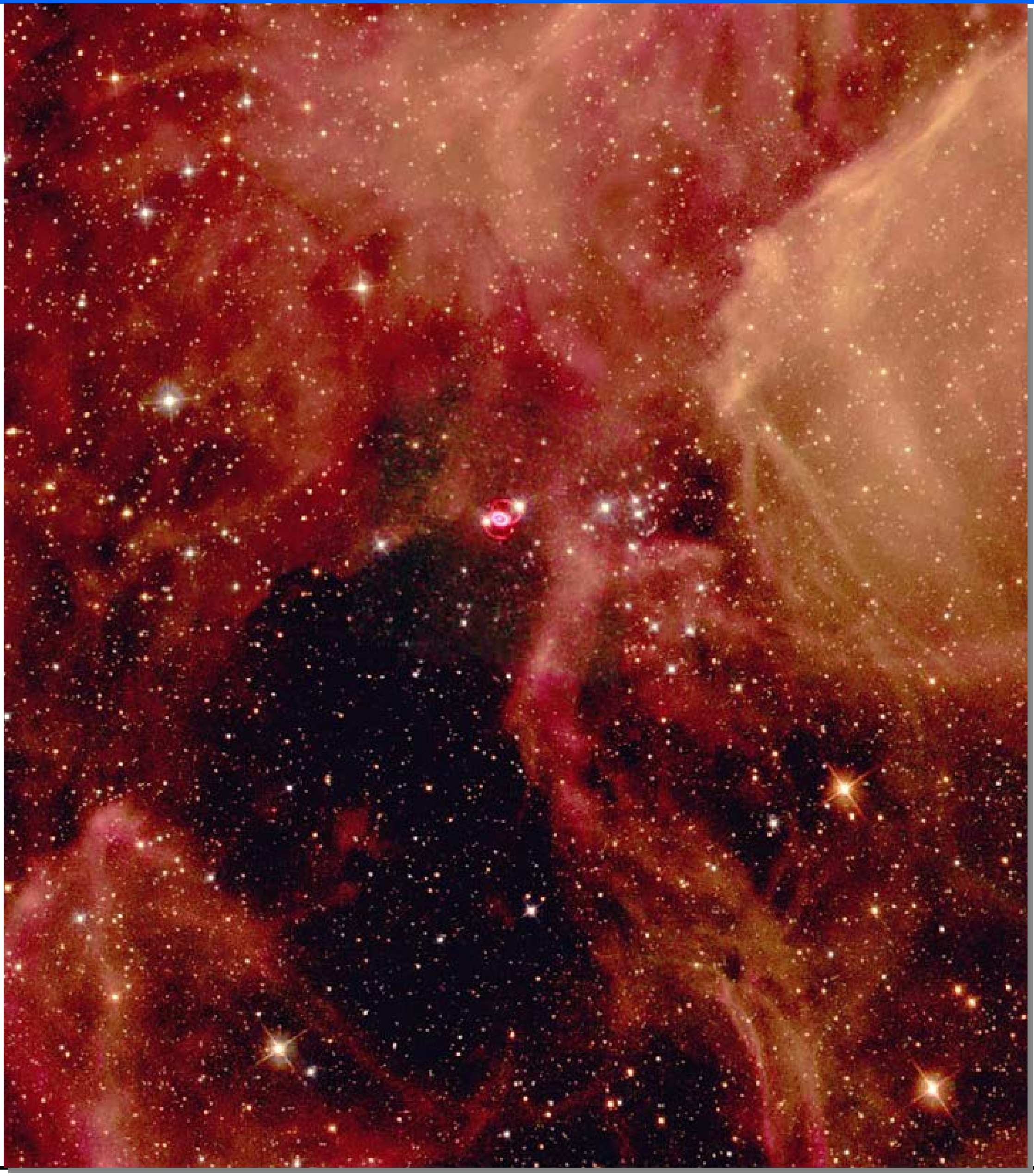


- When the evolved star can burn no more, it collapses
- The core compresses until it becomes the most dense substance known: a *neutron star*
- The rest of the star violently explodes, including even more nuclear burning and spreading all the elements into space
- The material can then form a new solar system, like ours!

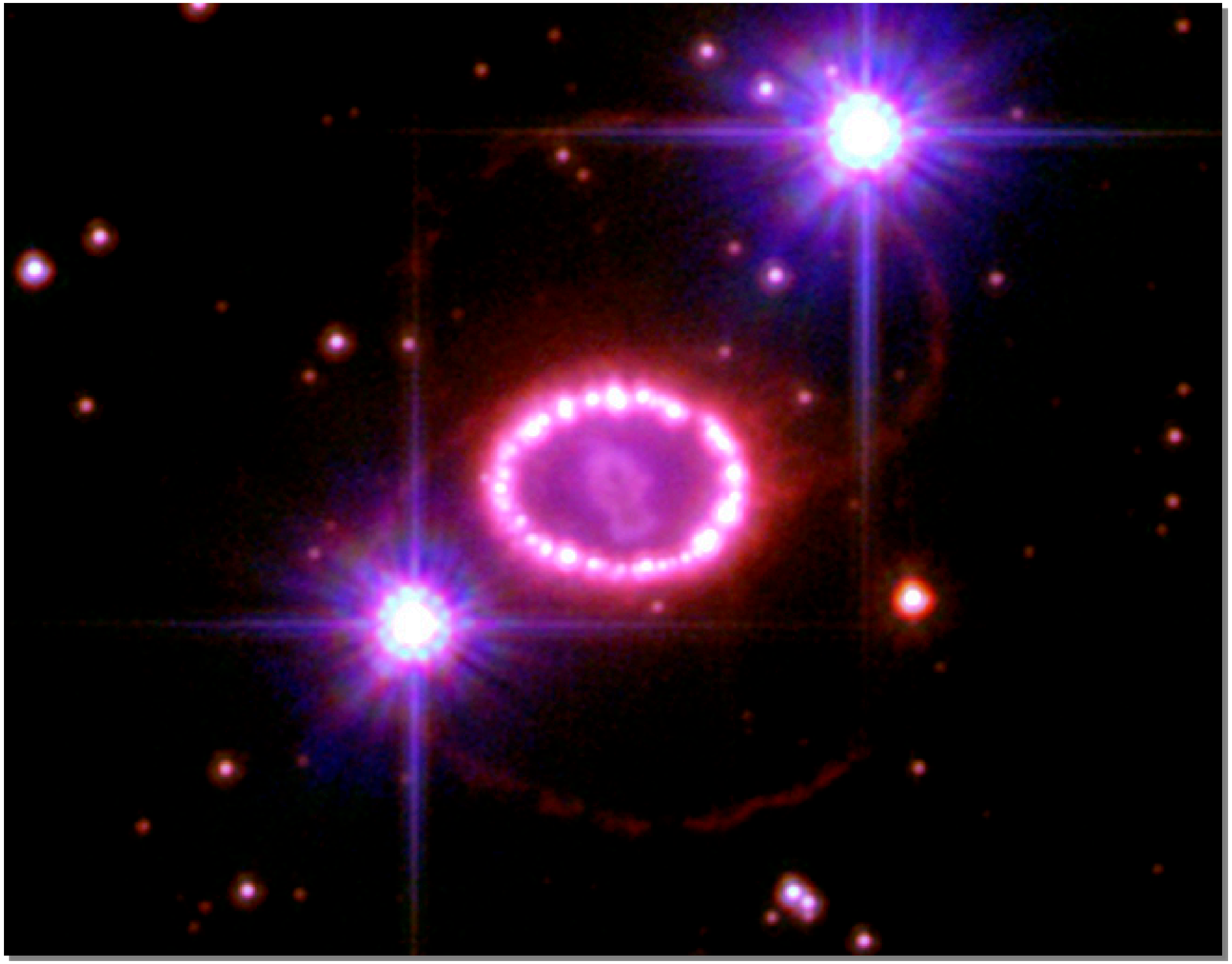
Energy released = 10^{46} Joules (in a matter of seconds) (cup of tea ~600 Joules)
= 30,000 trillion, trillion * *Annual U.S. Energy Consumption*
Can outshine the entire Galaxy it occurs in!
More energy than our sun will generate in its lifetime

Supernovae

Supernovae



Supernovae SN1987A in 2004



The r-process in a nutshell

temperature	**1-2x10^{9} K**
timescale	**~ seconds**
neutron density	**10^{20}-10^{24} cm^{-3}**
neutron source	unknown
stellar site	type II supernovae? neutron star mergers?

- synthesis path far from valley of β-stability
- synthesis of n-rich nuclei
- waiting points: $\tau_\beta << \tau_n$ at closed shells ⇒ abundance peaks (after $\phi_n \to 0$)

data needs: (model dependent)

- neutron separation energies S_n
- nuclear masses far away from stability
- β-decay lifetimes for neutron rich nuclei
- neutron capture cross sections on key isotopes

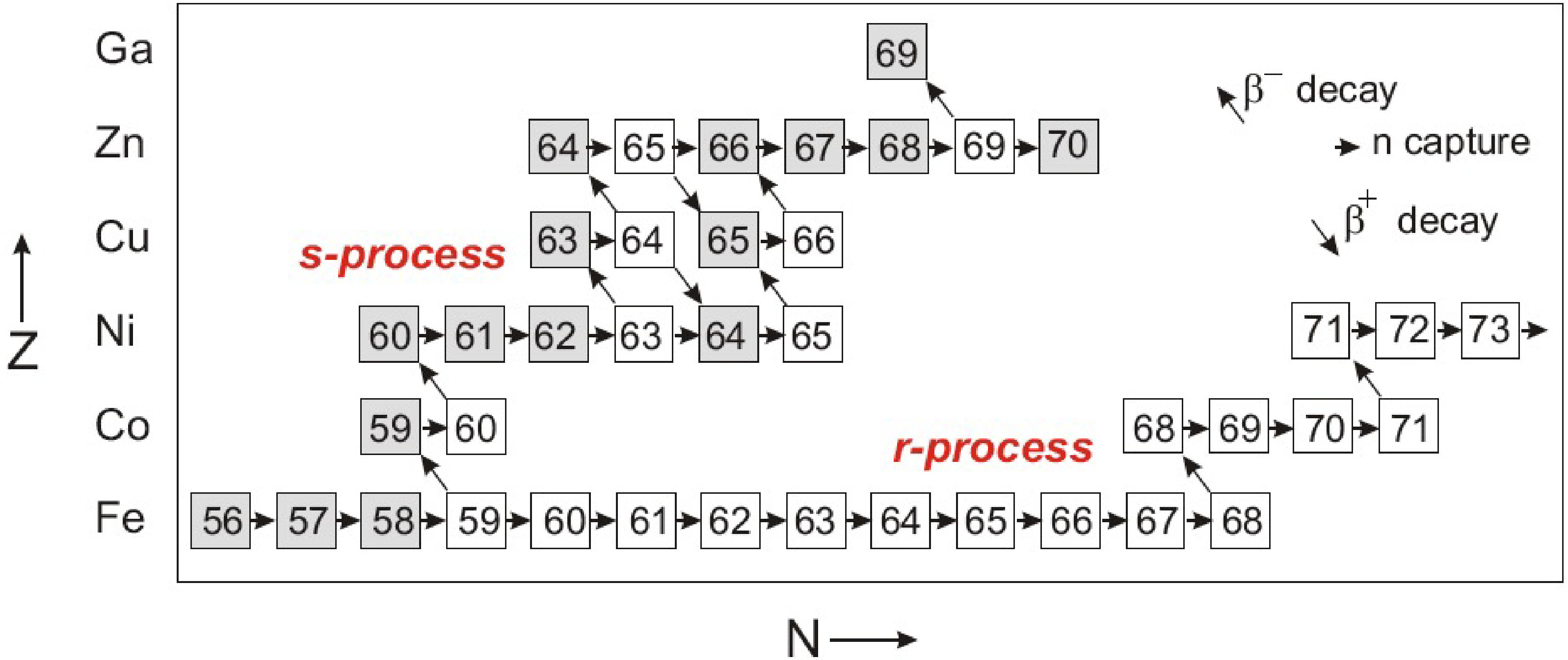
motivation:

- synthesis of heavy elements up to Th, U, Pu
- r-process path(s)
- abundance pattern
- conditions for waiting point approximation

review: Pfeiffer et al.: Nucl. Phys. A 693 (2001) 282 – 324

A schematic representation of the s- and r-process

- If the neutron capture rates are low enough then nuclei have time to beta decay before being hit by another neutron (s-process)
- If the neutron capture rates are high then once an equilibrium between neutron capture and photodisintegration has been reached beta decay will occur (r-process)



A schematic representation of the s- and r-process

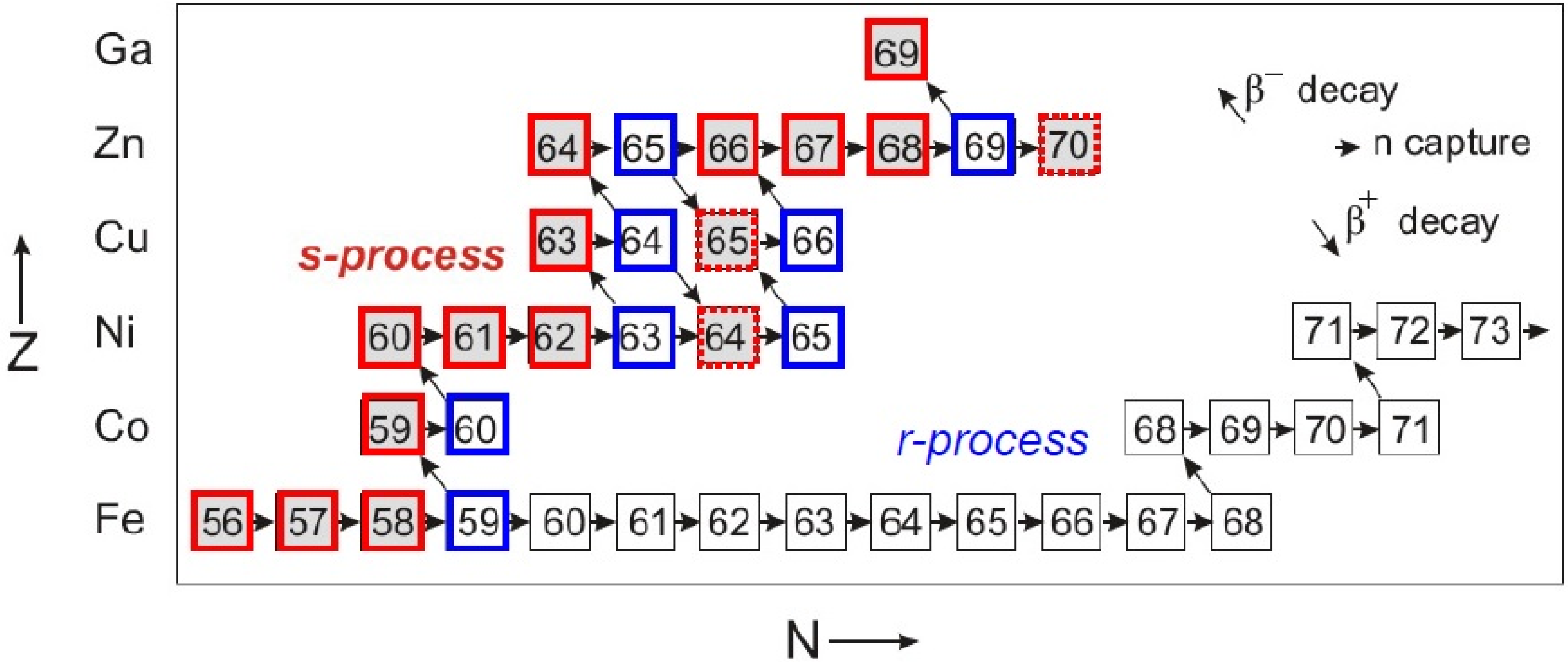
τ_n = lifetime against neutron capture
τ_β = lifetime against β^- – decay

Slow neutron-capture process: $\tau_\beta \ll \tau_n$

$N_n \sim 10^7 - 10^{11}\ cm^3 \quad T \sim 1 - 3 \cdot 10^8\ K \quad t_{irr} \sim 10 - 10^4\ yr$

Rapid neutron-capture process; $\tau_\beta \gg \tau_n$

$N_n \gg 10^{20}\ cm^3 \quad T \sim 1 - 2 \cdot 10^9\ K \quad t_{irr} \sim 1\ s$



A schematic representation of the s- and r-process

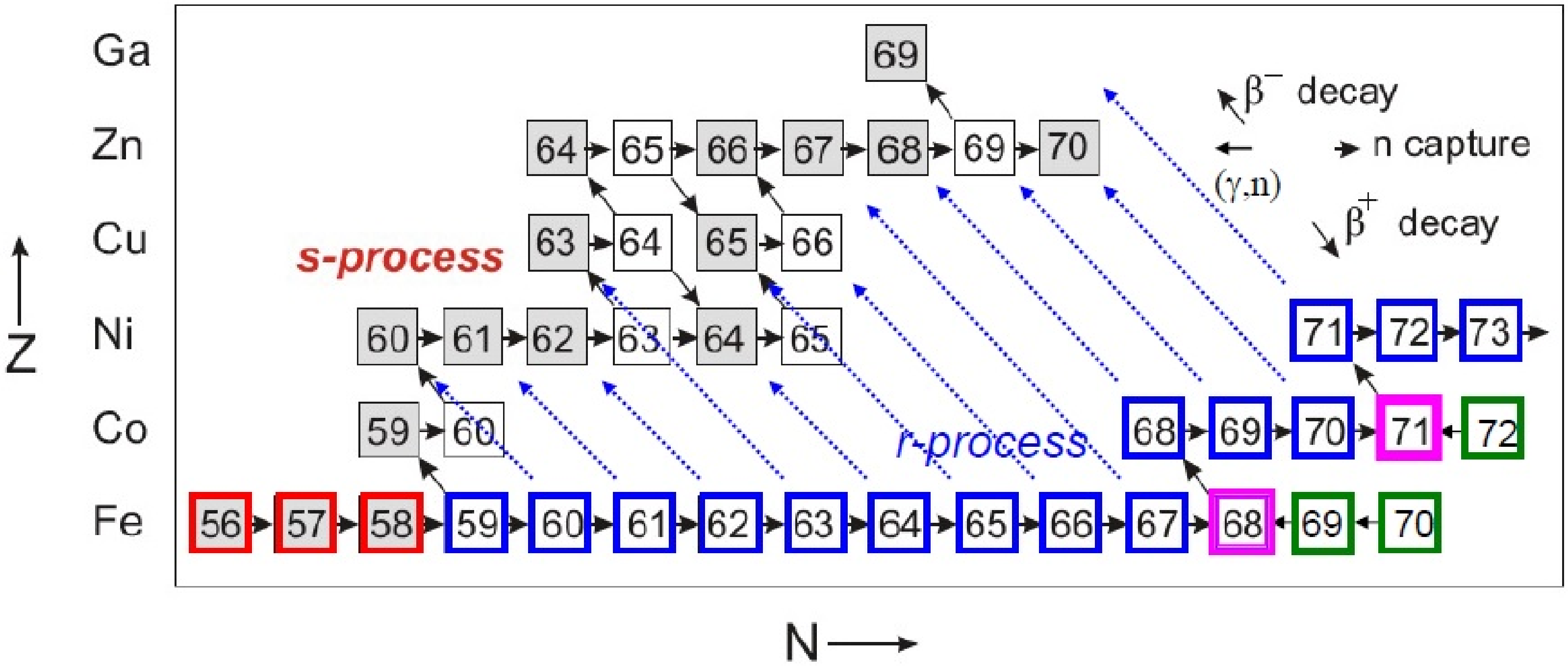
$\tau_n = lifetime\ against\ neutron\ capture$
$\tau_\beta = lifetime\ against\ \beta^- - decay$

Slow neutron-capture process: $\tau_\beta \ll \tau_n$

$N_n \sim 10^7 - 10^{11}\ cm^3 \quad T \sim 1 - 3 \cdot 10^8\ K \quad t_{irr} \sim 10 - 10^4\ yr$

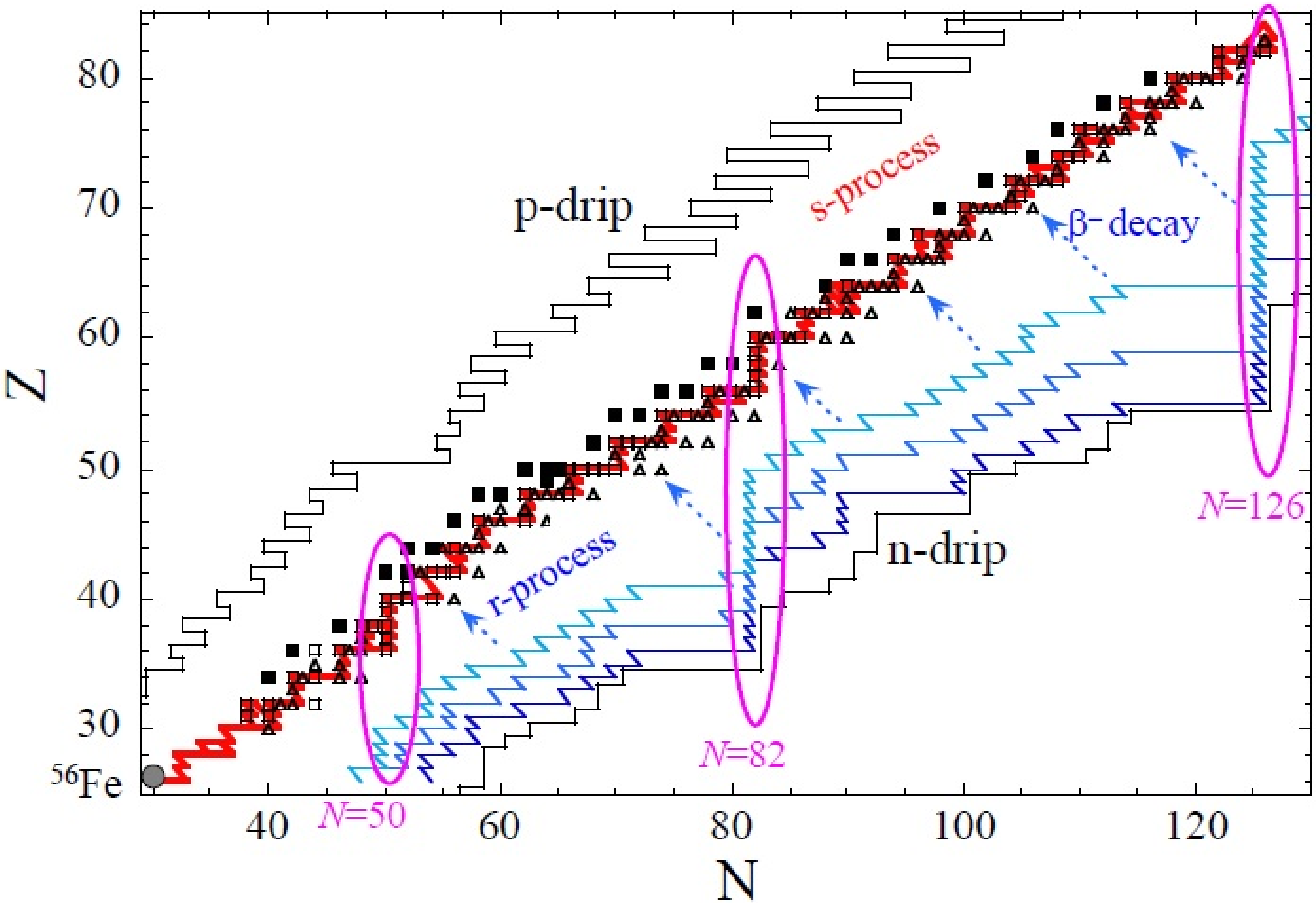
Rapid neutron-capture process; $\tau_\beta \gg \tau_n$

$N_n \gg 10^{20}\ cm^3 \quad T \sim 1 - 2 \cdot 10^9\ K \quad t_{irr} \sim 1\ s$



A schematic representation of the s- and r-process

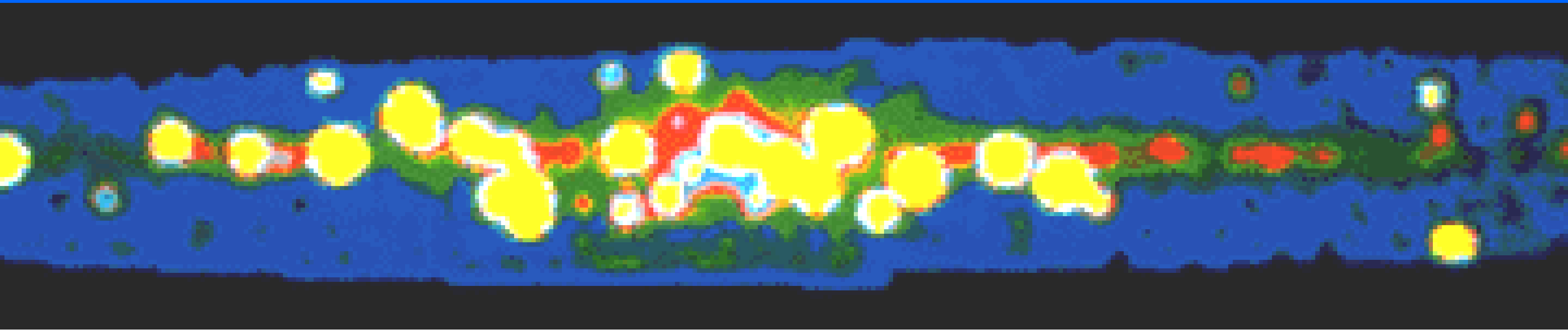
Closed shells at magic numbers N = 50, 82, 126 → slow n-capture



Explosive hydrogen burning

- novae and X-ray bursts
- the rp- and αp-processes

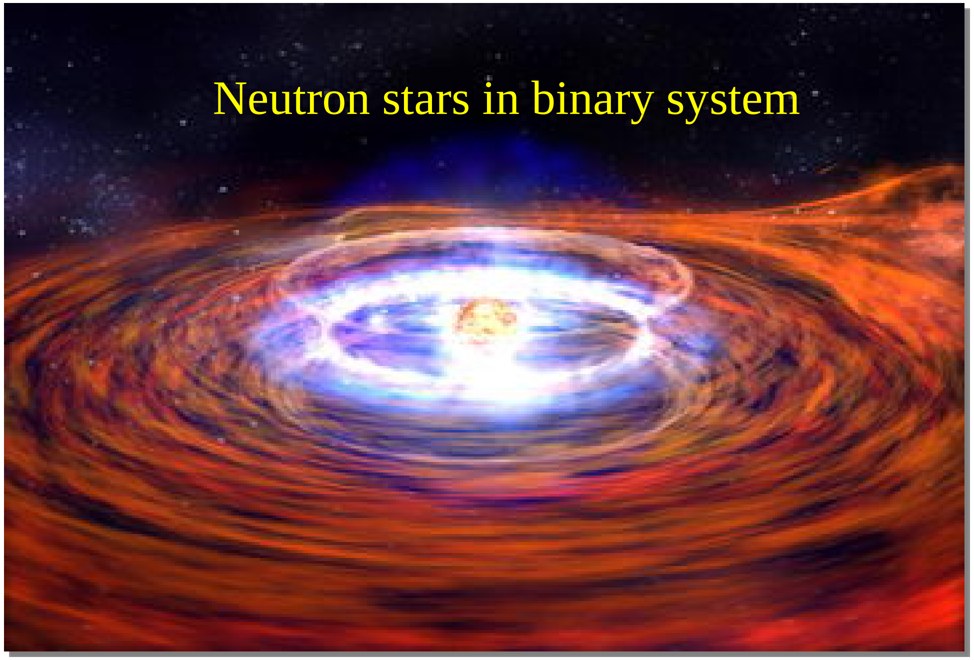
Cosmic X-rays: discovered end of 1960´s



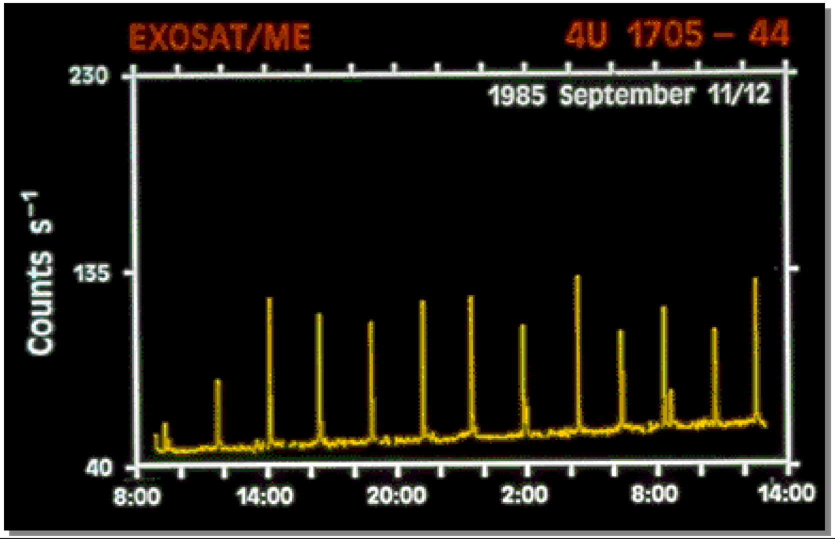
0.5 – 5 keV (T = E/k = 6 – 60 *10^6 K

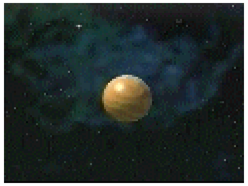
Nobel Price 2002
Riccardo Giacconi

X-ray burst



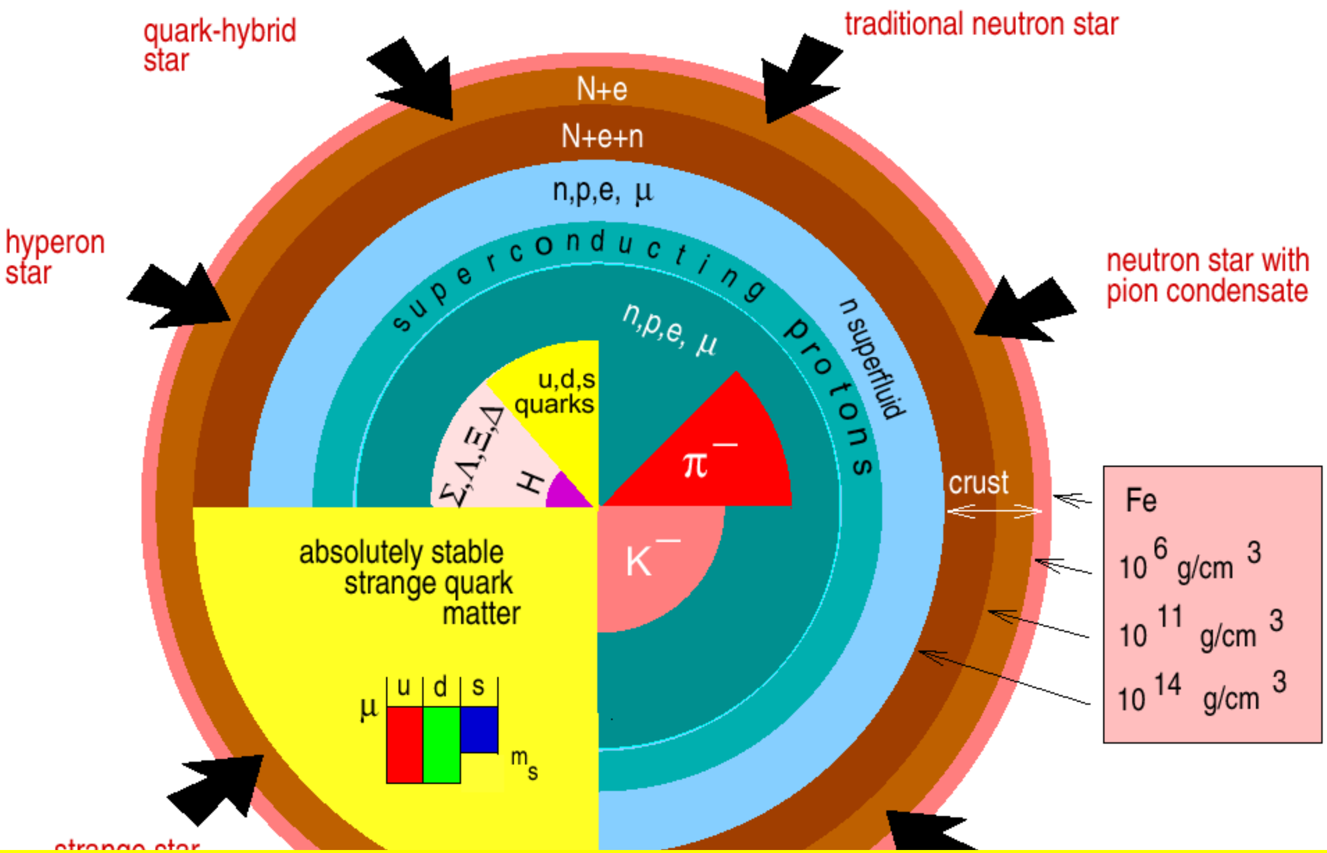
- neutron star has very strong gravitational field
- temperatures and densities reach much higher than novae
- different set of nuclear reactions occur in thermonuclear runaway
- material cannot escape!





X-ray bursts are very interesting: the observations don't quite agree with the theory yet; they are extremely *regular*; no-one quite knows what the composition of the neutron star is!

Possible structure of neutron stars



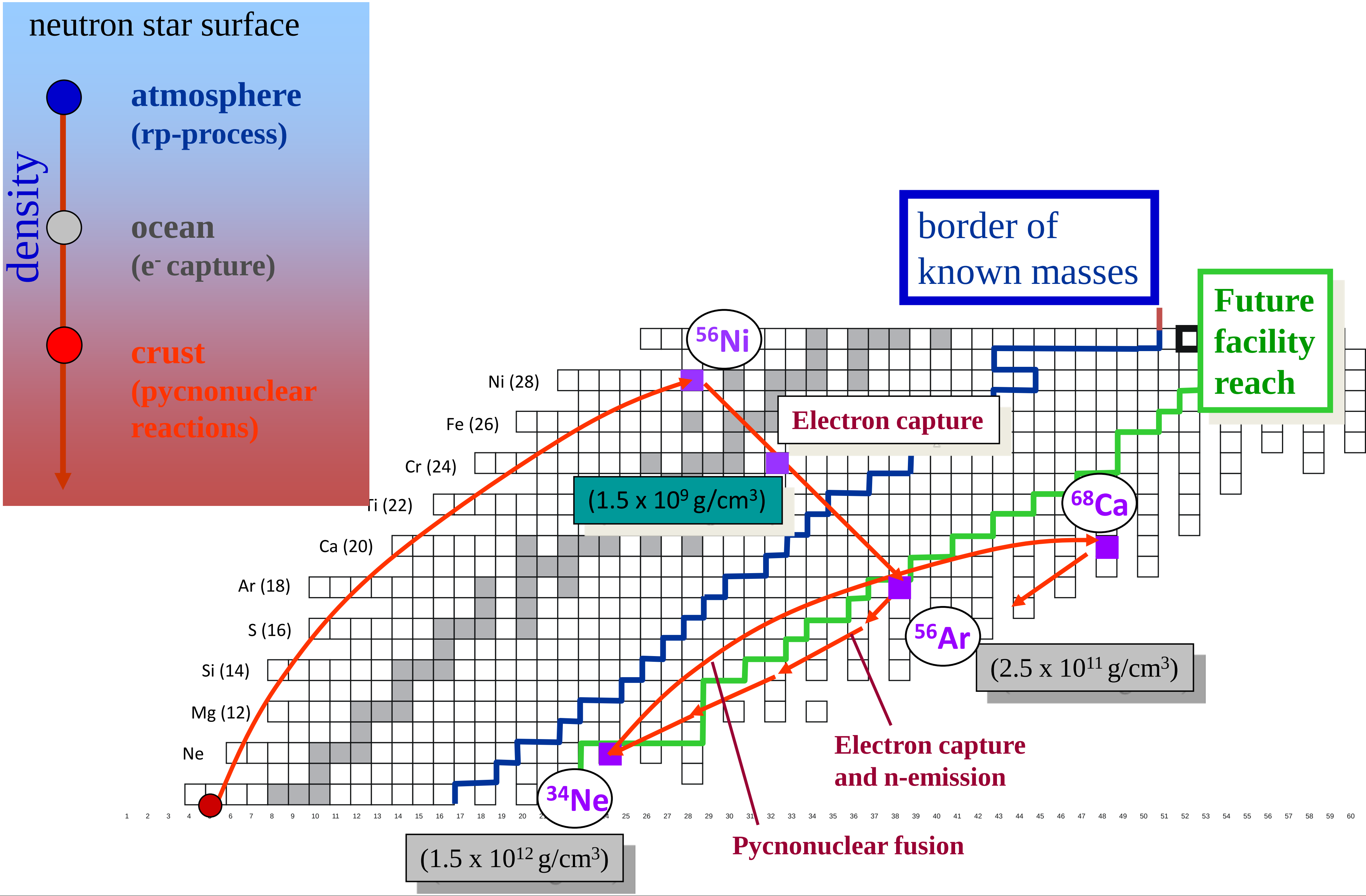
Open questions:

Compressibility of nuclear matter?

How strange is dense matter ?

F. Weber J.Phys. G27 (2001) 465

The fate of matter in the neutron star crust



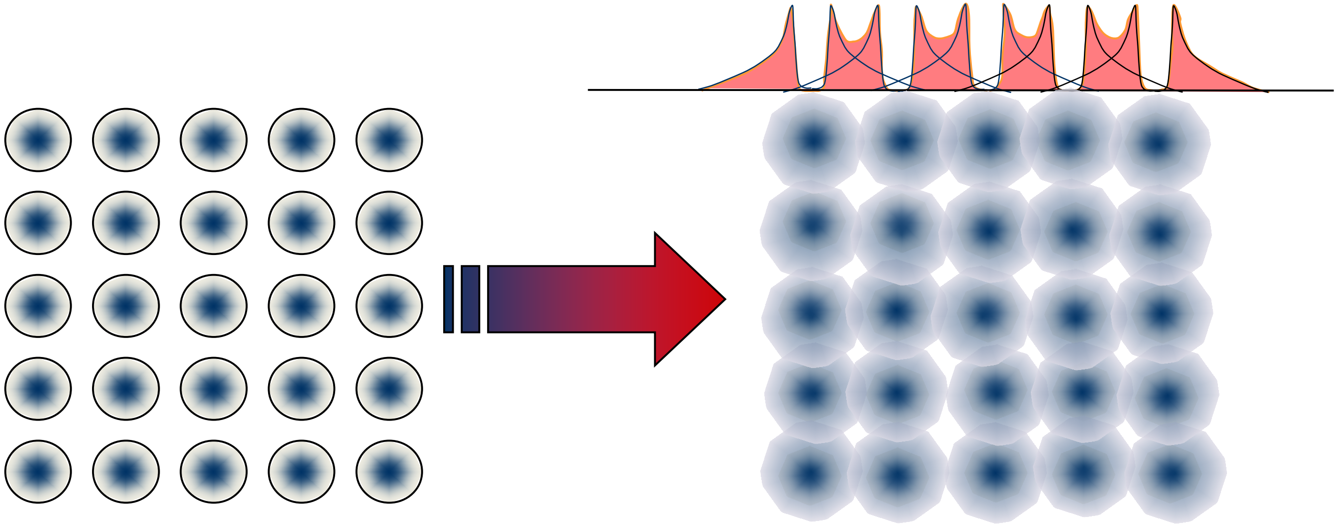
Pycnonuclear reactions

At densities > $\rho = 10^{12}$ g/cm^3 nuclei are densely frozen in lattice position.

Pycnonuclear reactions occur when nuclei vibrate around their frozen lattice position penetrating the Coulomb barrier of the neighbor nucleus.

(Salpeter at al, 1956)

(Koonin, Schramm 1992)



$$R_{pycno} = \left(\frac{\rho}{A}\right) \cdot A^2 \cdot Z^4 \cdot S\ [MeV\text{-}b] \cdot 4.76 \cdot 10^{46} \cdot \lambda^{7/4} \cdot e^{-2.52/\sqrt{\lambda}} \quad [s^{-1} cm^{-3}]$$

$$\lambda \equiv \text{length parameter:} \quad \lambda = \frac{1.95 \cdot 10^{-4} \cdot \rho^{1/3}}{A^{4/3} \cdot Z^2}$$

large Z ⇨ small rate

Hydrogen burning

COLD $\tau_\beta \ll \tau_{part}$	mainly, quiescent stages of stellar evolution	
	pp-chain, CNO, NeNa, MgAl cycles	
HOT $\tau_\beta \gg \tau_{part}$	mainly, explosive stages of stellar evolution	
	Hot pp-chain	super-massive low-metallicity stars novae
	HCNO Hot NeNa Hot MgAl cycles	(novae), X-ray bursts
	rp(αp) process	X-ray bursts & some SNI

proton-proton chain

$p + p \rightarrow d + e^+ + \nu$

$p + d \rightarrow {}^3He + \gamma$

86%

$^3He + {}^3He \rightarrow {}^4He + 2p$

PP-I

$Q_{eff} = 26.20$ MeV

14%

$^3He + {}^4He \rightarrow {}^7Be + \gamma$

99.7%

$^7Be + e^- \rightarrow {}^7Li + \nu$

$^7Li + p \rightarrow 2\,{}^4He$

PP-II

$Q_{eff} = 25.66$ MeV

0.3%

$^7Be + p \rightarrow {}^8B + \gamma$

$^8B \rightarrow {}^8Be + e^+ + \nu$

$\downarrow$

$2\,{}^4He$

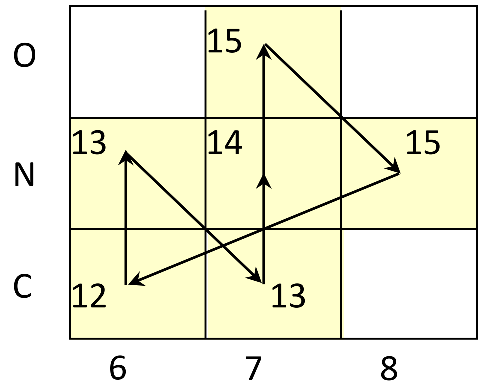
PP-III

$Q_{eff} = 19.17$ MeV

net result: $4p \rightarrow {}^4He + 2e^+ + 2\nu + Q_{eff}$

CNO cycle

cold CNO $T_8 < 0.8$

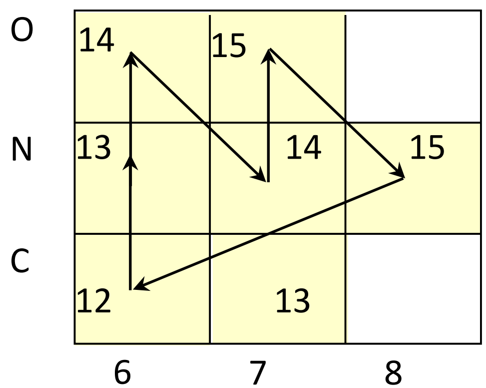


$^{12}C(p,\gamma)^{13}N(e^+\nu)^{13}C(p,\gamma)^{14}N(p,\gamma)^{15}O(e^+\nu)^{15}N(p,\alpha)^{12}C$

cycle limited by β decay of ^{13}N (t ~ 10 min) and ^{15}O (t ~ 2 min)

energy production rate: $\varepsilon \propto \langle \sigma v \rangle_{^{14}N(p,\gamma)}$

hot CNO $T_8 \sim 0.8 - 1$



$^{12}C(p,\gamma)^{13}N(p,\gamma)^{14}O(e+,\nu)^{14}N(p,\gamma)^{15}O(e^+\nu)^{15}N(p,\alpha)^{12}C$

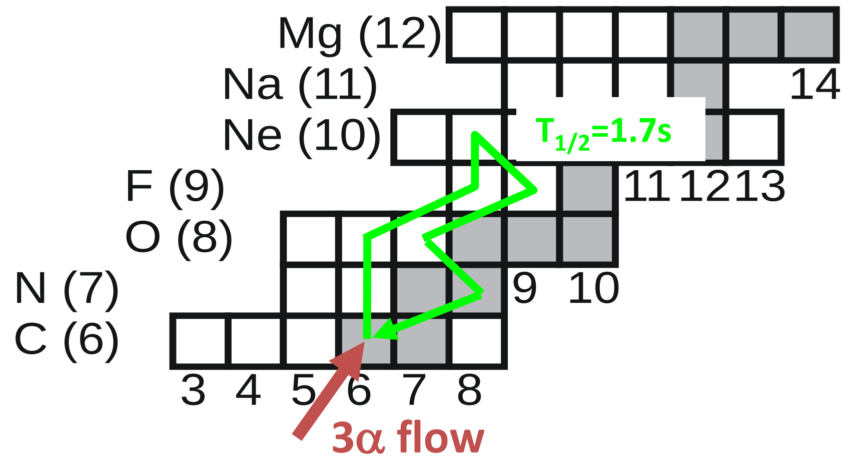
cycle limited by β decay of ^{14}O (t ~ 70.6 s) and ^{15}O (t ~ 2 min)

CNO isotopes act as catalysts and accumulate at largest τ

net result: $4p \rightarrow {}^4He + 2e^+ + 2\nu + Q_{eff}$ $Q_{eff} = 26.73$ MeV very hot CNO-cycle

$T_8 \sim 3$

still “beta limited”



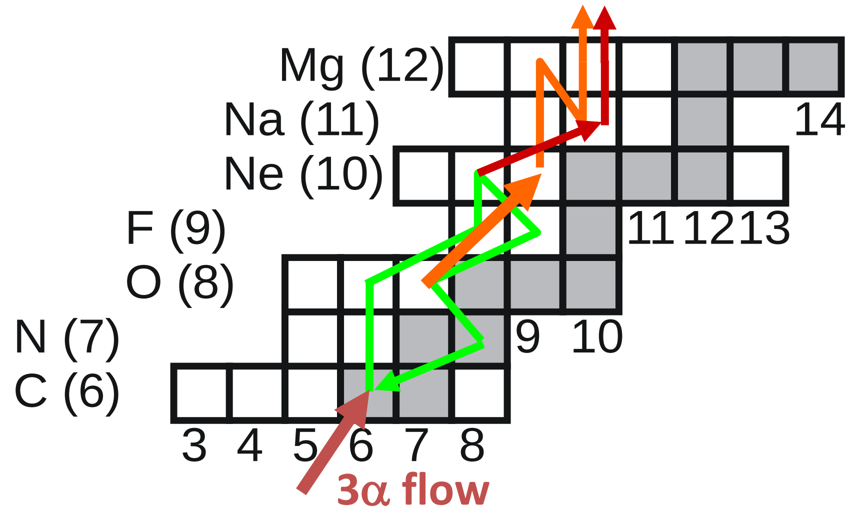
breakout

processing beyond CNO cycle

after breakout via:

$T_8 \geq 3$ $^{15}O(\alpha,\gamma)^{19}Ne$

$T_8 \geq 6$ $^{18}Ne(\alpha,p)^{21}Na$



Explosive hydrogen burning

hydrogen burning under extreme conditions

H burning at temperatures and densities far in excess of those attained in the interiors of ordinary stars is expected to occur on a variety of astrophysical sites:

- hot burning in massive AGB stars (> 4 M_{sun}) (T_9 ~ 0.08)
- nova explosions on accreting white dwarfs (T_9 ~ 0.4)
- X-ray bursts on accreting neutron stars (T_9 ~ 2)
- accretion disks around low mass black holes
- neutrino driven wind in core collapse supernovae

explosive scenarios in binary systems

luminosity, time scales & periodicity properties depend on:

- nature of accreting object
- accretion rate

Observational features of a novae explosions

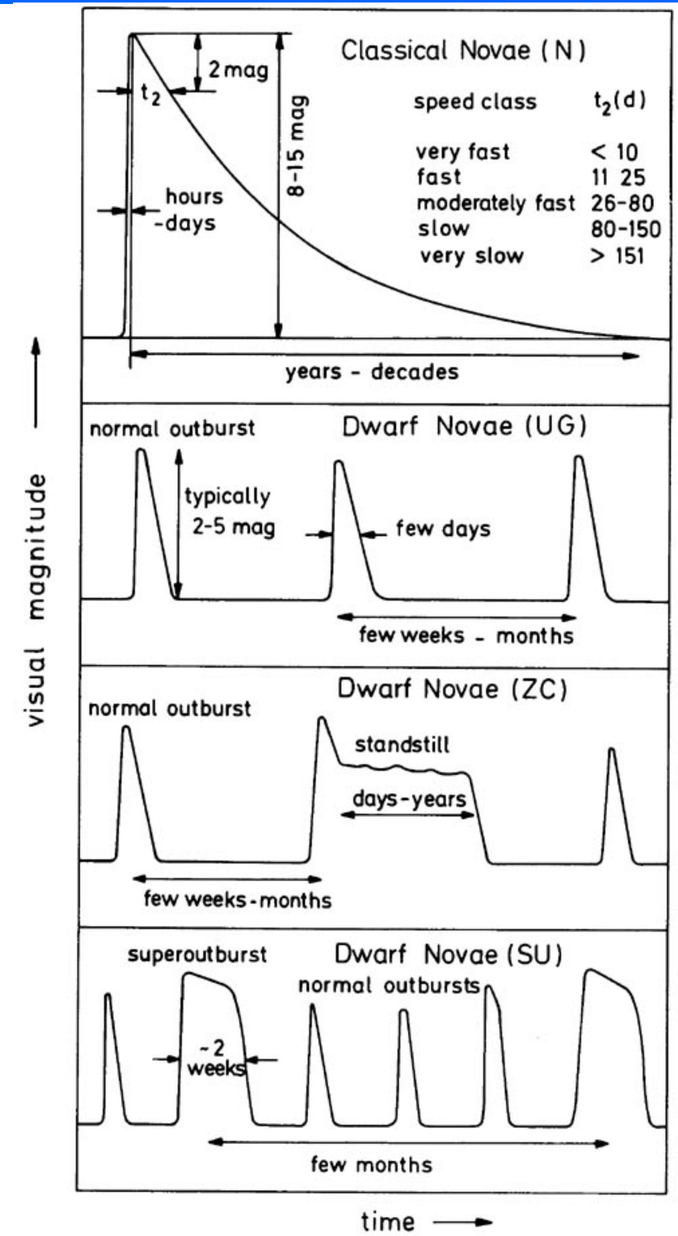
main features of novae explosions

- sudden increase in luminosity by factor $10^4 – 10^6$
- mass ejection (10^{-3} $M_{initial}$)
- energy release (10^{45} erg)
- characteristic spectral lines

very common phenomenon
(about 10 y^{-1} in our Galaxy)

what causes these outbursts?

how to account for observational features?



The model

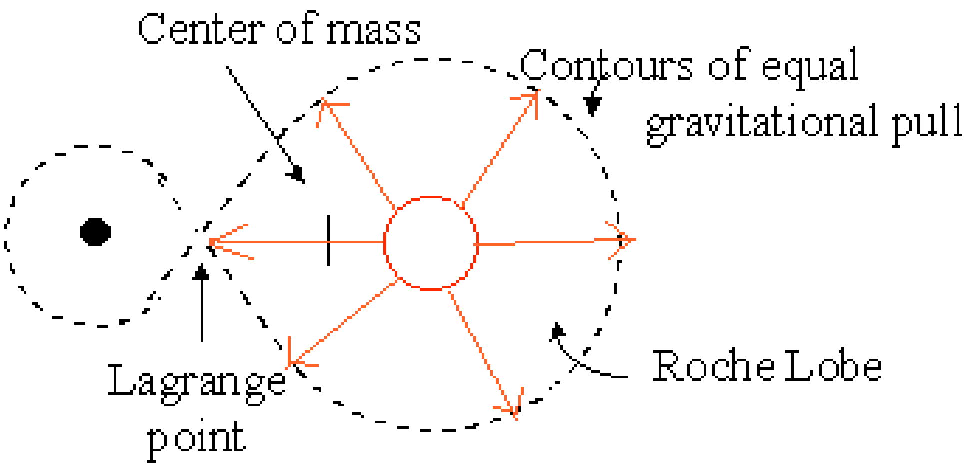
NOVAE semi-detached binary system:

n.b. about 50% of all stars are in binary systems

White Dwarf and less evolved star (e.g. Red Giant)

"dead" star (mainly CO or ONe)
radiating away gravitational energy
maintained by electron degeneracy

H-shell burning
core contraction (possibly He burning)
envelope expansion



assume:

RG completely fills its Roche Lobe while still undergoing expansion;
since no further expansion possible beyond Roche Lobe, matter transfer occurs through Lagrange point

The model

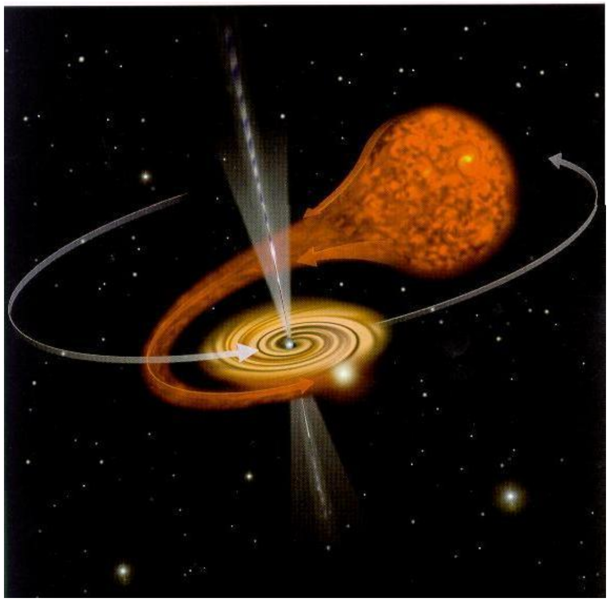
H-rich matter transfer from RG to WD

↓

temperature and density increase on WD's surface

- H-burning ignition at basis of accreted layer
- temperature increase due to energy release
- no expansion on degenerate matter
- no cooling
- further temperature/energy increase
- thermonuclear runaway
- cataclysmic explosion

accretion process - artist's impression



http://hubblesite.org/newscenter/newsdesk/archive/releases/2000/24/video/a

$T \leq 3x10^8$ K
$\rho \sim 10^3$ g cm^{-3}

⇒ (p,γ) and (α,p) reactions on proton-rich nuclei

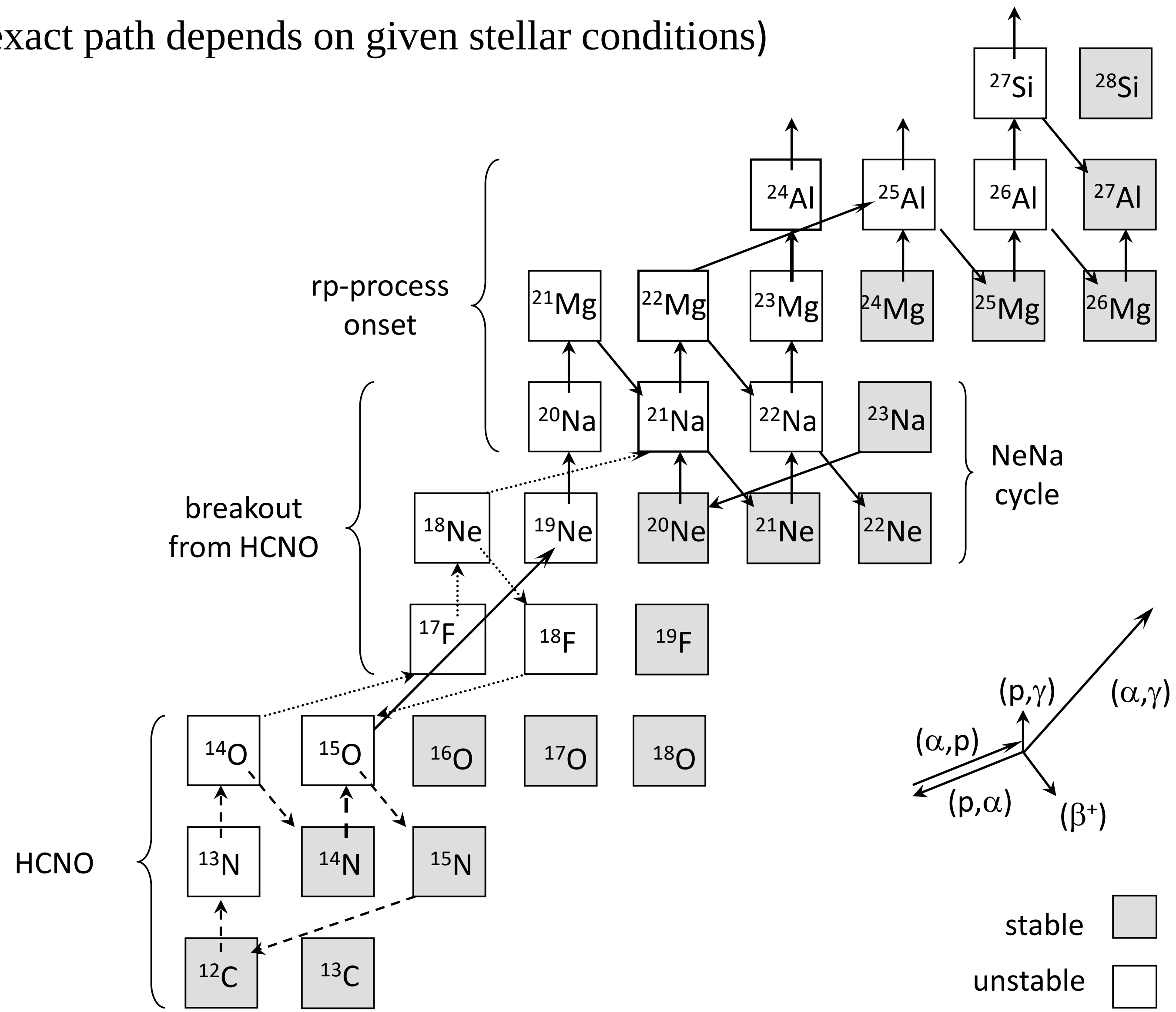
nucleosynthesis up to A ~ 40 mass region

nucleosynthesis path: Hot CNO, NeNa & MgAl cycles (see later for details)

matter ejected ⇒ observations put important constraints on models

Reaction network for explosive hydrogen burning

(exact path depends on given stellar conditions)



Considerations

overall mechanism well understood, however open questions still remain:

- how and when does mixing at bottom of accreted layer occur?
- missing-mass problem (models under-predict mass of ejecta)
- do reactions produce more energy than expected?
- what contribution to Galactic nucleosynthesis? (^{13}C, ^{15}N, ^{17}O & ^{27}Al)
- does a break-out from HCNO cycle (e.g. ^{15}O(α,γ)^{19}Ne) take place?

  (models seem to indicate limited leakage out of HCNO)
- how to explain observed overproduction (vs. solar) of elements in Ne to Ca region?

nuclear data needs

- p-capture reactions on short-lived proton-rich nuclei e.g. ^{25}Al(p,γ)^{26}Mg and ^{30}P(p,γ)^{31}S
- synthesis of e.g. ^{18}F, ^{22}Na, (^{26}Al) very important for their characteristic γ-ray emissions

  INTEGRAL satellite ⇒ γ-ray detection ⇒ constraint on models
- reactions on P and S isotopes for possible flow out of MgAl cycle

Observational features of X-ray bursts

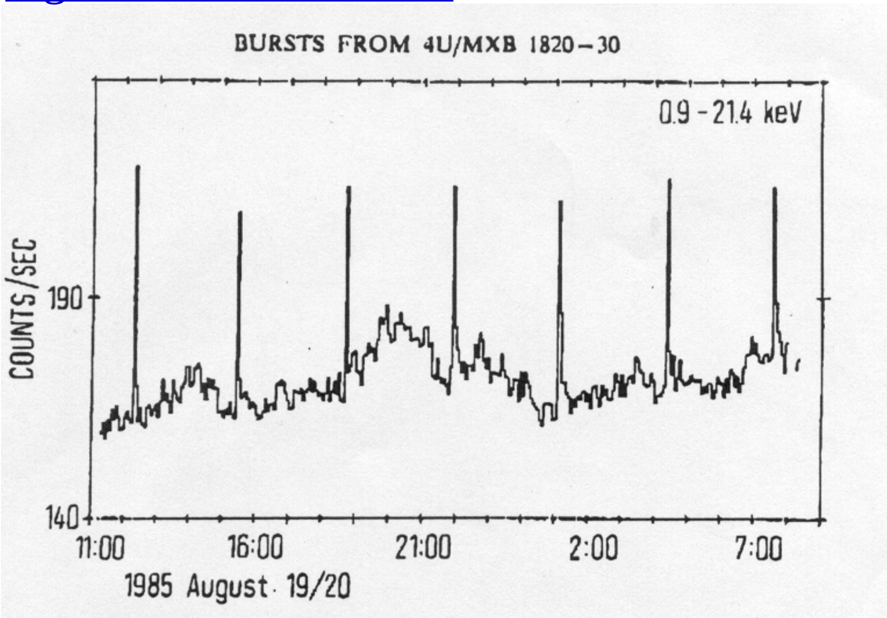
main features of X-ray bursts

- 10^{36}-10^{38} erg/s
  (stars: 10^{33} - 10^{35} erg/s)
- duration 10 s – 100s
- recurrence: hours-days
- regular or irregular

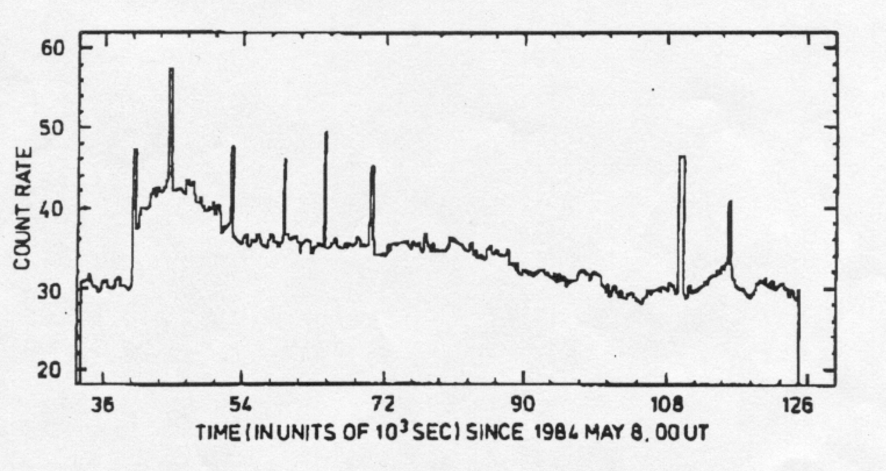
frequent and very bright phenomenon!

total ~230 X-ray binaries known

regular recurrent bursts



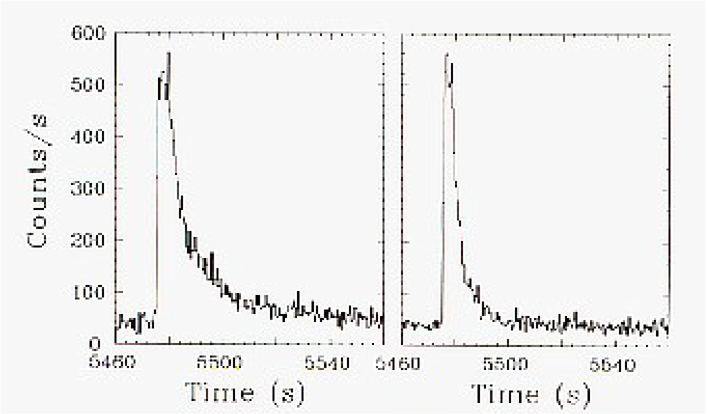
irregular bursts



Observational features of X-ray bursts

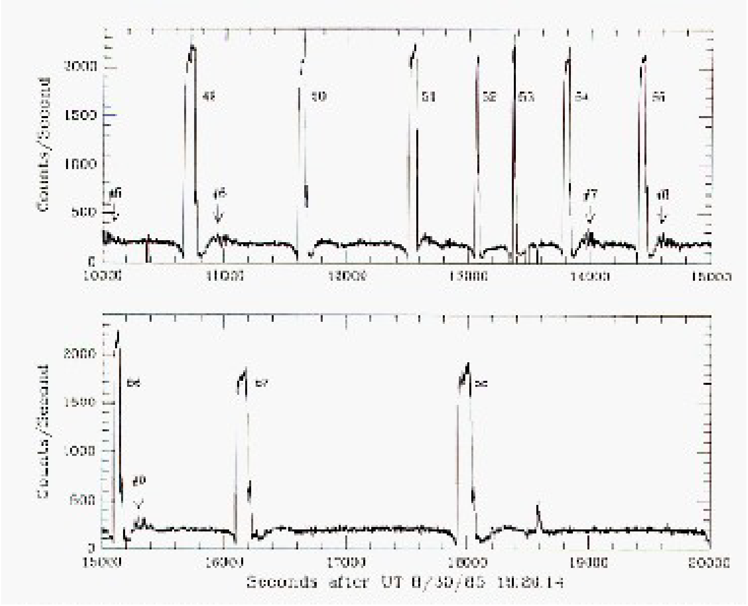
type I X-ray bursts

- 10^{38} - 10^{39} erg/s
- fast rise time (1-10 s)
- duration (~10-100 s)
- some show double peak at max
- spectral softening
- recurrence intervals (several hours)



type II X-ray bursts

- rapid successions of bursts (few minutes interval)
- sudden flux drop without gradual decay from peak values
- no spectral softening in decay



figures from Lewin, W.H.G., van Paradijs, J. & Taam, R.E., 1993, Sp Sci Rev, 62, 223

X-ray binaries

X-ray bursters

frequent outbursts of 10-100s duration with lower, persistent X-ray flux in between

(bursting pulsar: GRO J1744-28)

X-ray pulsars

regular pulses with periods of 1- 1000 s

type I bursts

burst energy proportional to duration of **preceeding** inactivity period

most common type

type II bursts

burst energy proportional to duration of **following** inactivity period

“rapid burster” and GRO J1744-28 ?

The model

X-RAY BURSTERS & X-RAY PULSARS

semi-detached binary system: Neutron star + less evolved star

- explosive ignition of H and/or He (via $3\alpha \rightarrow {}^{12}C$)
- sudden increase surface temperature
- emission of strong X-rays
- cooling down of surface after explosion
- decay of burst profile
- if matter transfer continues process may repeat

$T \sim 10^9$ K
$\rho \sim 10^6$ g cm^{-3}

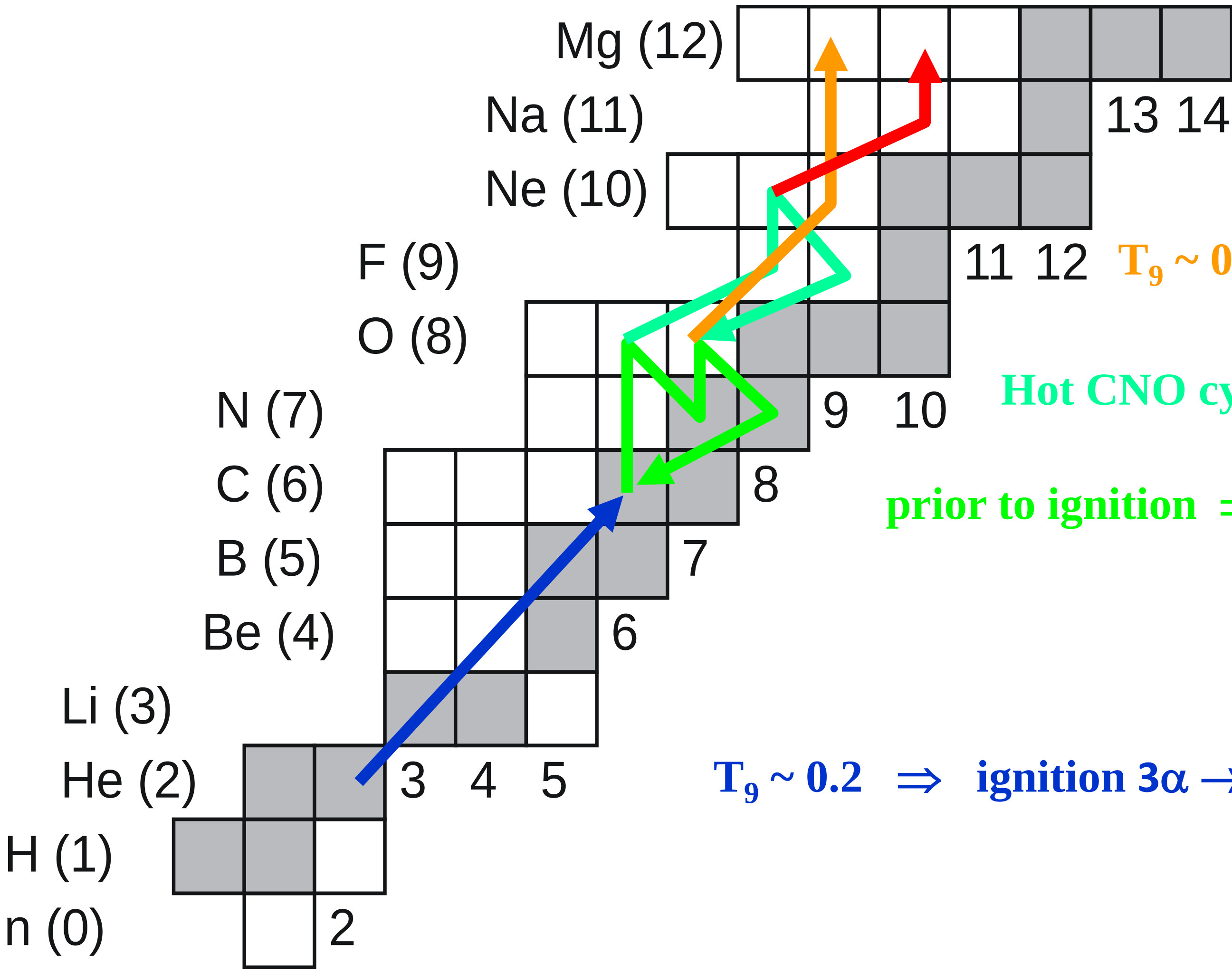
→ (α,p) and (p,γ) reactions on proton-rich nuclei

nucleosynthesis up to A ~ 80-100 mass region

nucleosynthesis path: breakout from Hot CNO, onset of rp-process burst ignition

$T_9 \sim 0.8 \Rightarrow$ **breakout 2: ^{18}Ne(α,p)**

(~50 ms after breakout 1) leads to rp process and main energy production



$T_9 \sim 0.7 \Rightarrow$ **breakout 1: ^{15}O(α,γ)**

Hot CNO cycle II

prior to ignition $\Rightarrow$ hot CNO cycle

$T_9 \sim 0.2 \Rightarrow$ **ignition 3α → ^{12}C**

courtesy: H. Schatz

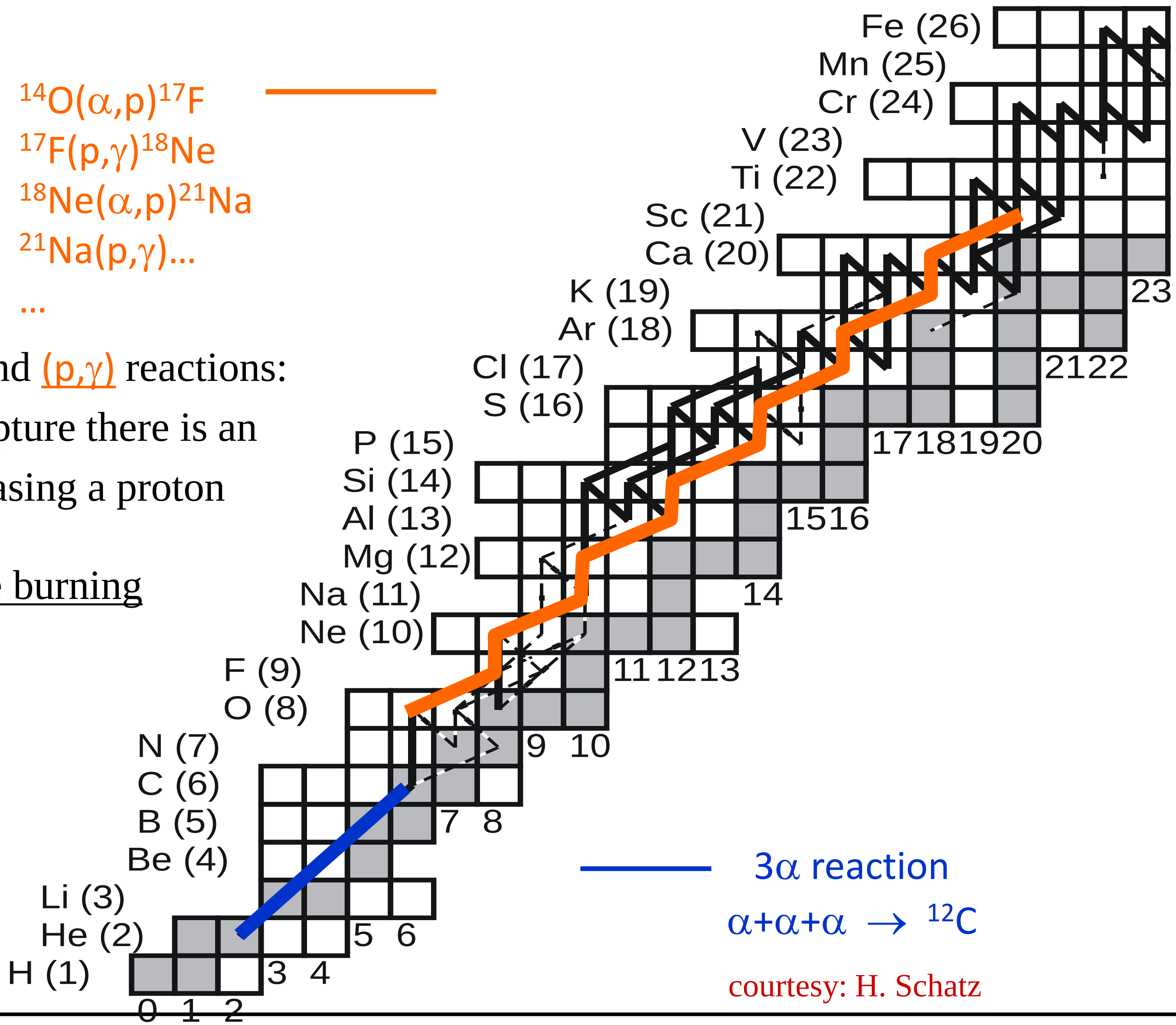
the αp process

αp process:

$^{14}O(\alpha,p)^{17}F$
$^{17}F(p,\gamma)^{18}Ne$
$^{18}Ne(\alpha,p)^{21}Na$
$^{21}Na(p,\gamma)$...
...

alternating (α,p) and (p,γ) reactions:
for each proton capture there is an (α,p) reaction releasing a proton

net effect: pure He burning

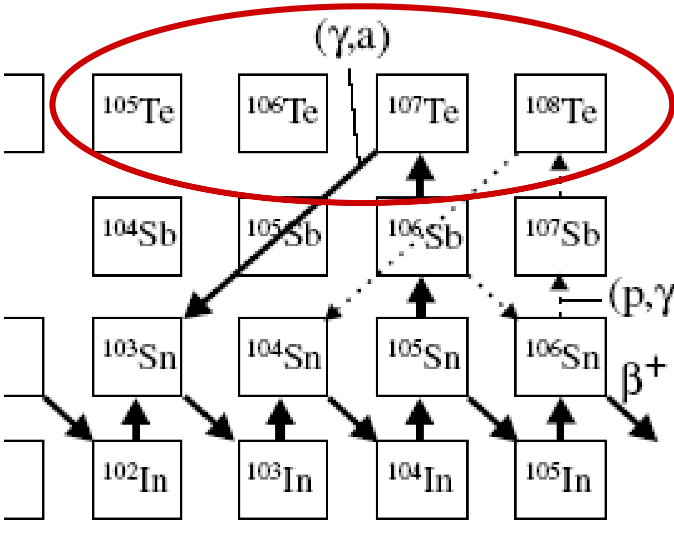


$\alpha+\alpha+\alpha \rightarrow {}^{12}C$

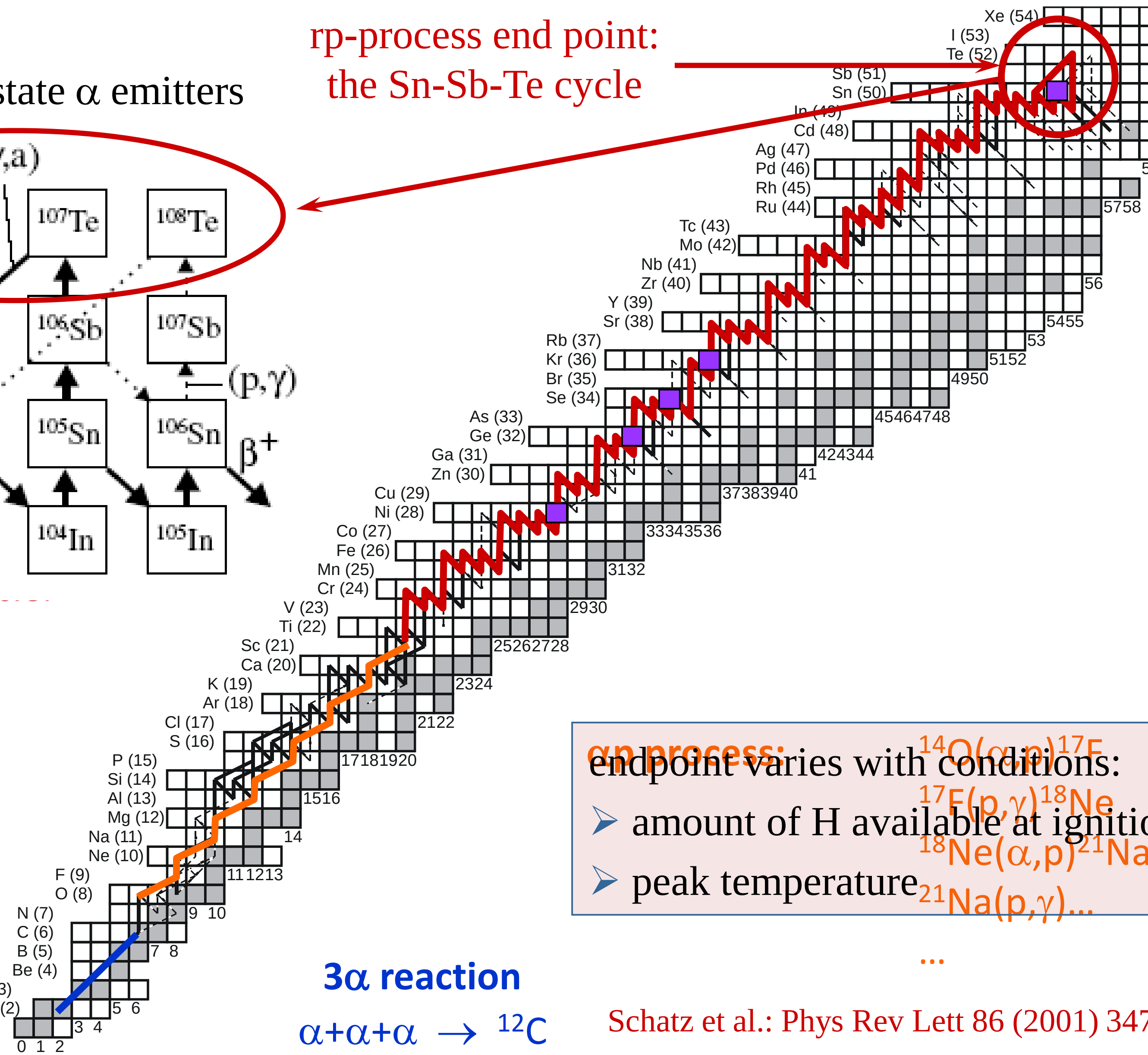
courtesy: H. Schatz

the rp process

known ground state α emitters



rp-process end point:
the Sn-Sb-Te cycle



3α reaction

$\alpha+\alpha+\alpha \rightarrow {}^{12}C$

αp process:
$^{14}O(\alpha,p)^{17}F$
$^{17}F(p,\gamma)^{18}Ne$
$^{18}Ne(\alpha,p)^{21}Na$
$^{21}Na(p,\gamma)$...
...

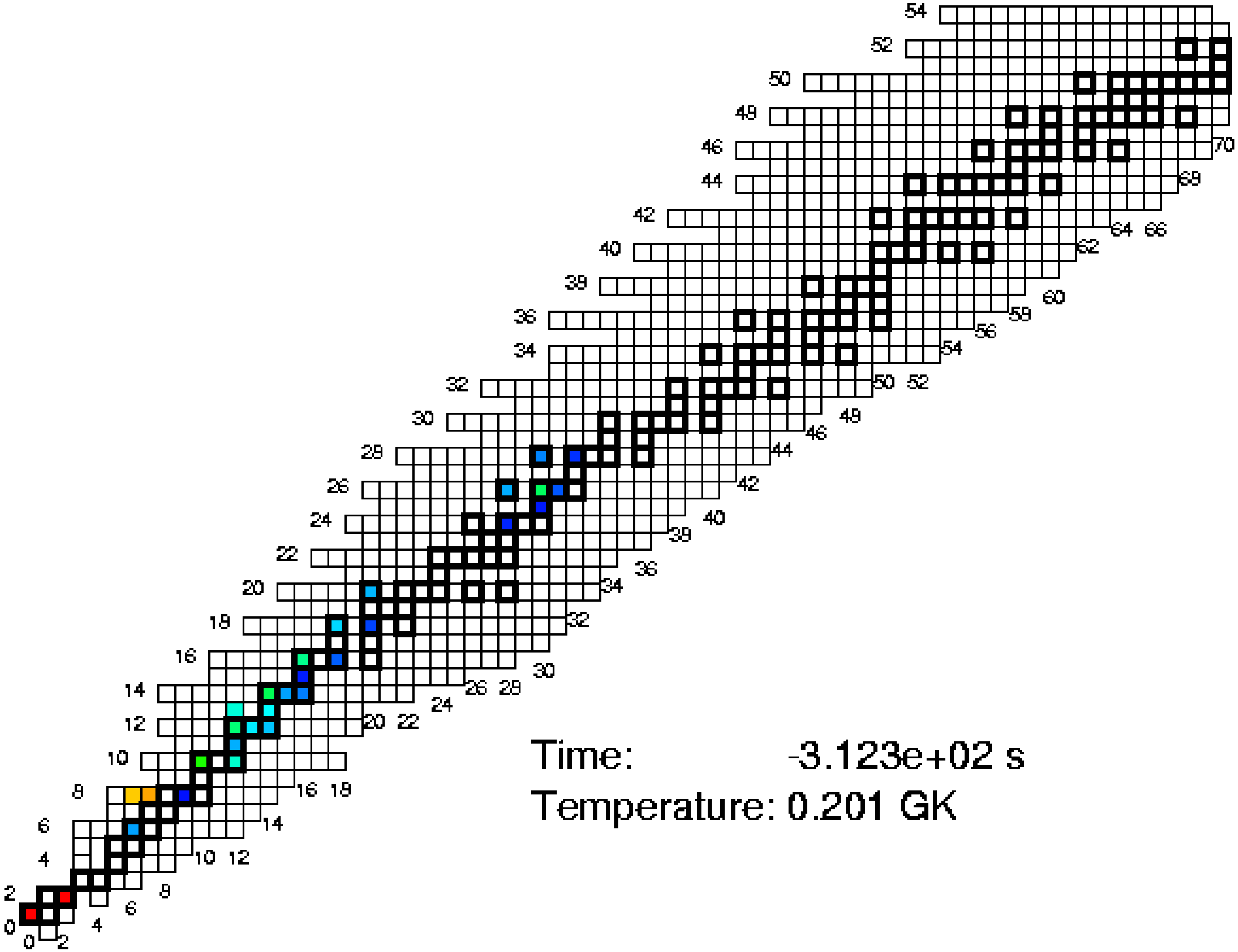
endpoint varies with conditions:

- amount of H available at ignition
- peak temperature

Schatz et al.: Phys Rev Lett 86 (2001) 3471(4)

rp process during type I X-ray burst

H. Schatz, NSCL and Dept. of Physics and Astronomy, Michigan State University



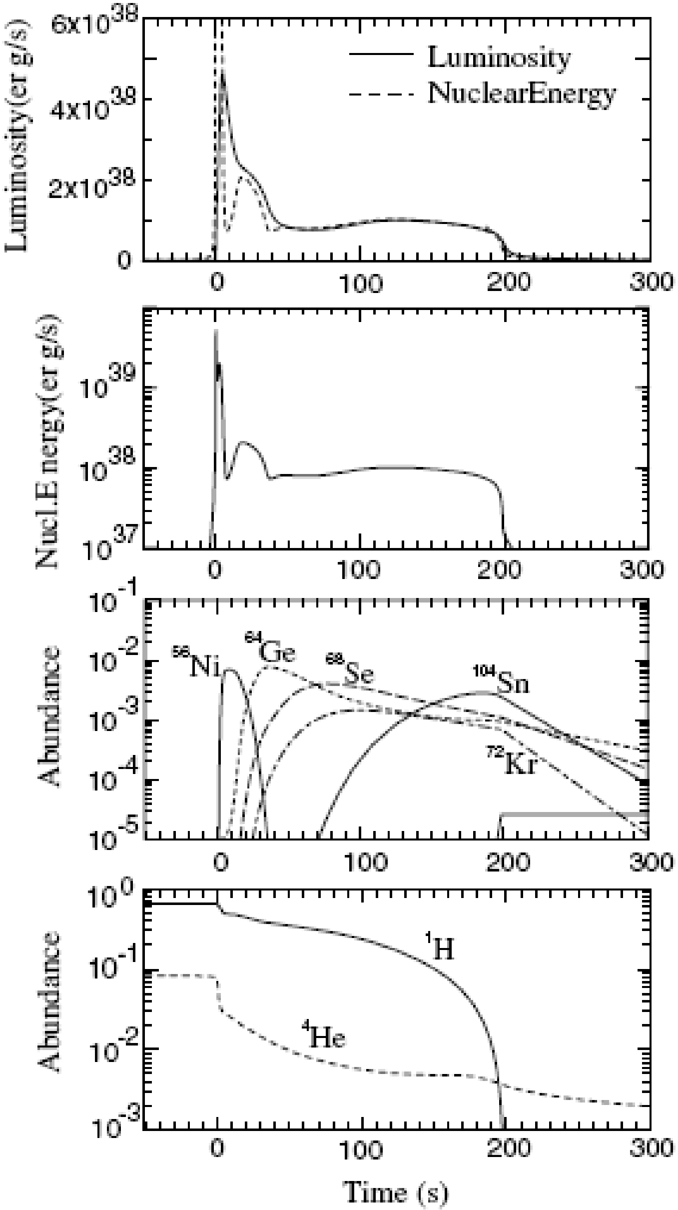
type I X-ray burst

- luminosity

- nuclear energy generation

- abundances of waiting points

- H, He abundance



H. Schatz et al.: Phys Rev Lett 86 (2001) 3471(4)

Considerations

overall mechanism seems well understood, however open questions still remain:

- why are there bursters and pulsars?
- why do burst timescales vary from ~10 s to ~100 s?
- what is the origin of superbursts (10^3 times stronger and longer, t ~ 10^4-10^5 s)?
- what crust composition of neutron star?
- what contribution of X-ray bursts to galactic nucleosynthesis?

observational signatures for X-ray outbursts?

some Type I X-ray bursts show double peak in luminosity separated by a few seconds

possible cause: waiting points in thermonuclear reaction flow ?

waiting points: ^{26}Mg, ^{26}Si, ^{30}S, and ^{34}Ar ?

(α,p) reactions too weak because of Coulomb barrier and
(p,γ)-reaction quenched by photo-disintegration

conclusion: effects of the experimentally unknown ^{30}S(α,p)^{33}Cl and ^{34}Ar(α,p)^{37}K directly visible in the observation of X-ray burst light curves?

Fisker and Thielemann: arXiv:astro-ph/0312361 v1 13 Dec 2003 nuclear data needs

thermonuclear runway driven by αp-process and rp-process

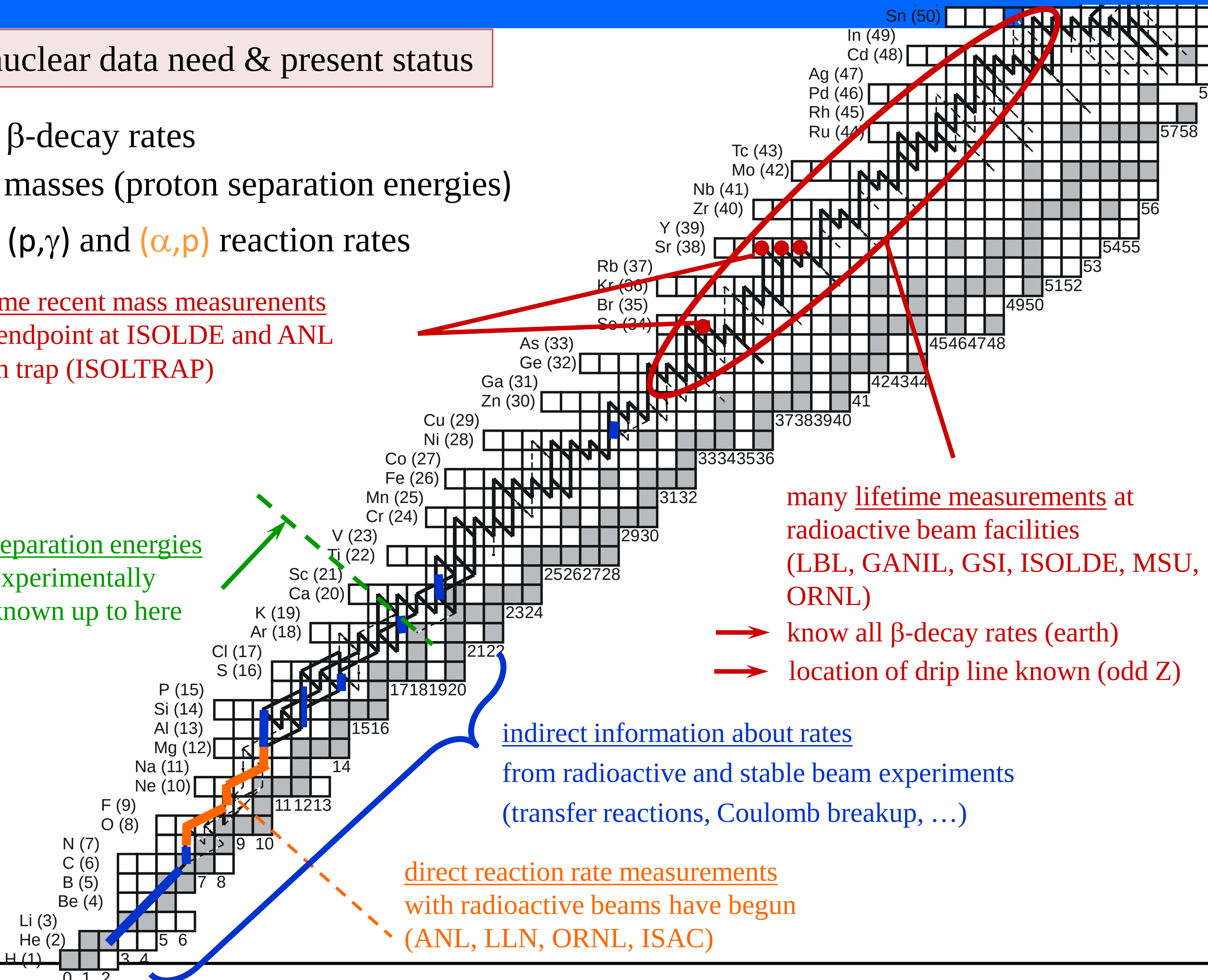
- breakout reactions $\Rightarrow$ critical constraints on ignition conditions + runaway timescale
- proton-capture reactions on short-lived proton-rich nuclei up to proton-drip line

  $\Rightarrow$ influence on temperature and luminosity
- β-decay studies of isomeric and/or excited states
- masses, lifetimes, level structure, proton-separation energies

from: H. Schatz

nuclear data need & present status

- β-decay rates
- masses (proton separation energies)
- (p,γ) and (α,p) reaction rates



some recent mass measurenents
β-endpoint at ISOLDE and ANL
Ion trap (ISOLTRAP)

separation energies
experimentally
known up to here

many lifetime measurements at
radioactive beam facilities
(LBL, GANIL, GSI, ISOLDE, MSU, ORNL)

→ know all β-decay rates (earth)

→ location of drip line known (odd Z)

indirect information about rates
from radioactive and stable beam experiments
(transfer reactions, Coulomb breakup, …)

direct reaction rate measurements
with radioactive beams have begun
(ANL, LLN, ORNL, ISAC)