Towards understanding the origin of *p*-nuclei:

An experimental approach for studying key photonuclear reactions

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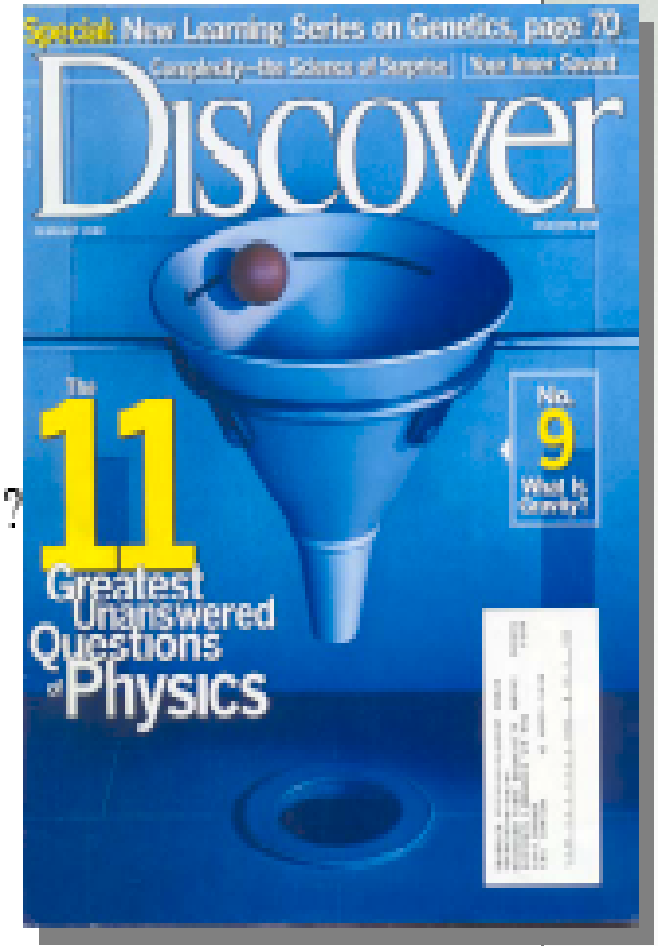
Connecting Quarks to the Cosmos

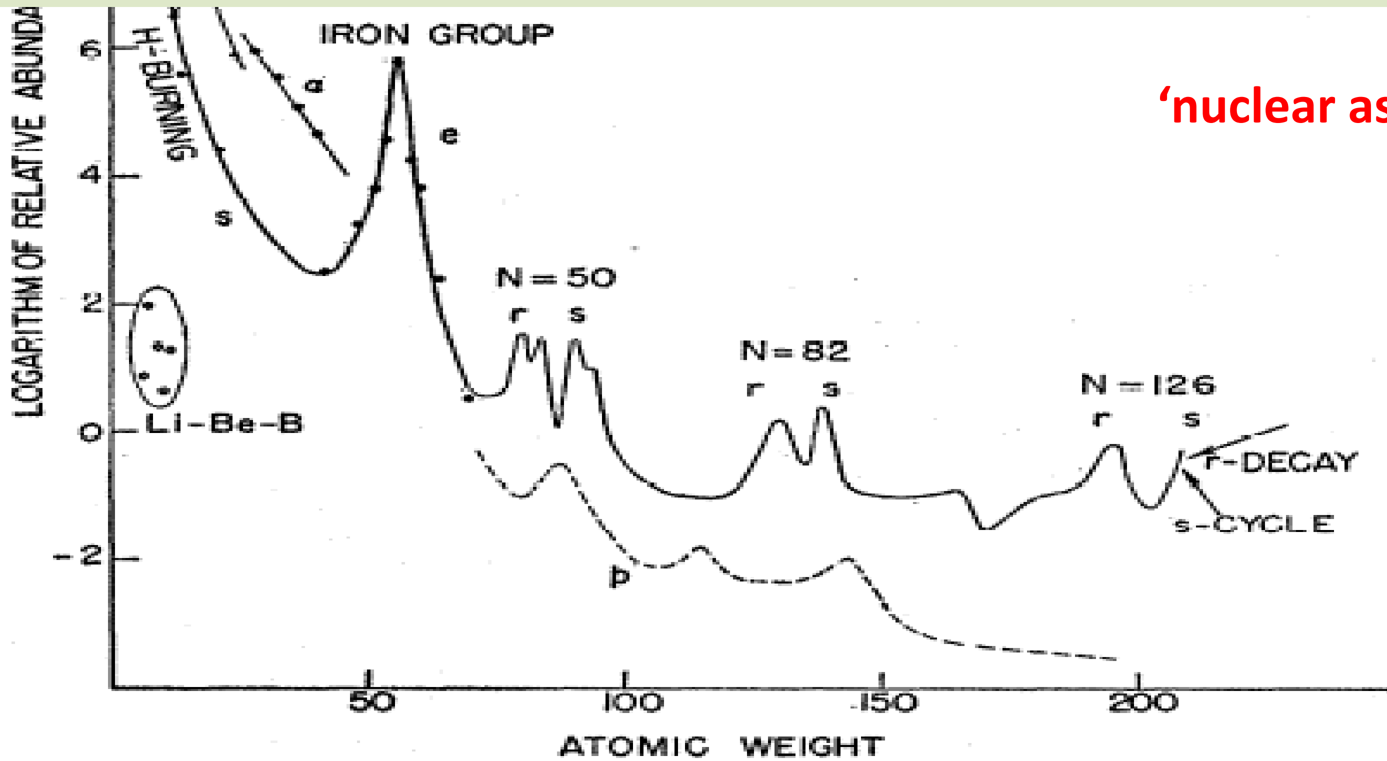
Eleven Science Questions for the New Century (2003) – National Academy Study, Chair M. Turner

- —What is dark matter?
- —What is the nature of the dark energy?
- —How did the Universe begin?
- —Did Einstein have the last word on gravity?
- —What are the masses of the neutrinos and how have they shaped the evolution of the universe?
- —How do cosmic accelerators work?
- —Are protons unstable?
- —Are there new states of matter at exceedingly high density and temperature?
- —Are there additional space-time dimensions?
- ✓ How were the heavy elements from iron to uranium made?
- —Is a new theory of matter and light needed at the highest energies?



What about the nucleosynthetic origin of the 35 trans-iron nuclides , all on the proton-rich side of the valley of stability – the so called *p*-nuclei?

"The first remarkable feature of this process (*p*-process) is the scarcity of the efforts devoted to its understanding. After about 50 years of nuclear astrophysics research, the number of articles devoted to it still remains inferior to the 35 nuclides traditionally classified as *p*-nuclides." ***(Arnould and Goriely (2003))***



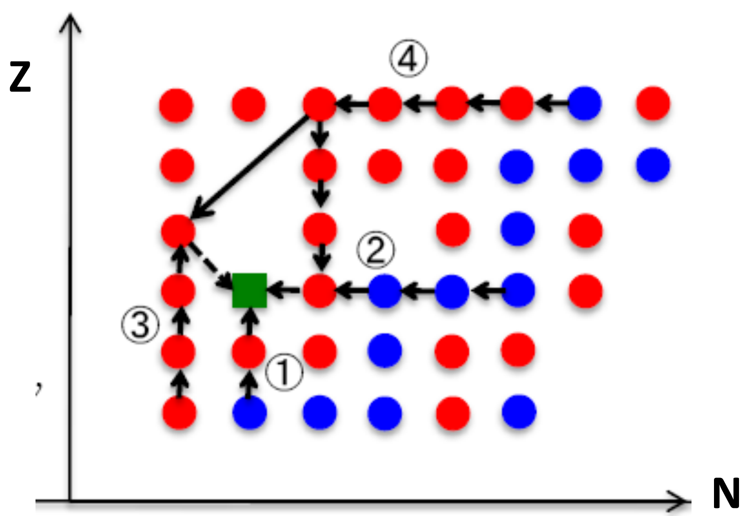
'nuclear astrophysics *p*-nuts'

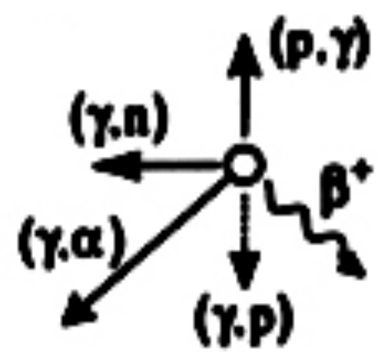
Arnould, Goriely (2003)


KARLSRUHER NUKLIDKARTE

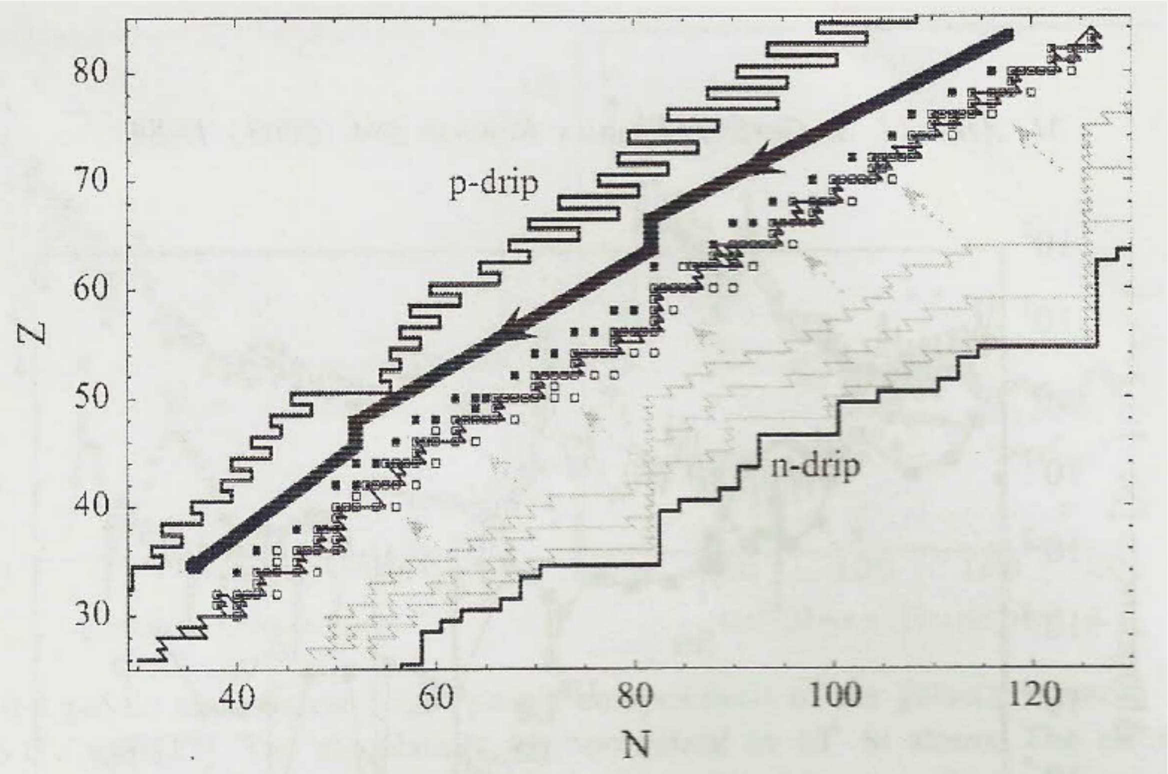
Table 1: The ‘historical’ 35 *p*-isotopes and their relative abundance (%) to the respective elements in the solar system.

Isotope	% Abundance	Isotope	% Abundance	Isotope	% Abundance
^{74}Se	0.87	^{114}Sn	0.66	^{156}Dy	0.0524
^{78}Kr	0.354	^{115}Sn	0.35	^{158}Dy	0.0902
^{84}Sr	0.56	^{120}Te	0.089	^{162}Er	0.136
^{92}Mo	15.84	^{124}Xe	0.126	^{164}Er	1.56
^{94}Mo	9.04	^{126}Xe	0.115	^{168}Yb	0.135
^{96}Ru	5.51	^{130}Ba	0.101	^{174}Hf	0.18
^{98}Ru	1.87	^{132}Ba	0.0097	^{180m}Ta	0.0123
^{102}Pd	0.96	^{138}La	0.091	^{180}W	0.135
^{106}Cd	1.215	^{136}Ce	0.193	^{184}Os	0.018
^{108}Cd	0.875	^{138}Ce	0.25	^{190}Pt	0.0127
^{113}In	4.28	^{144}Sm	3.09	^{196}Hg	0.146
^{112}Sn	0.96	^{152}Gd	0.20		





"P-process studies are among the most complicated nucleosynthesis processes." **(Iliadis, *Nuclear Physics of Stars* (2007))**



- an extended network of some 20000 reactions linking about 2000 nuclei must be followed by an explicit computation
- *p*-process operates far from equilibrium
- concepts of steady flows or reaction rate equilibria cannot be used

Peak temperature, timescale, proton density, seed abundances!

B^2FH+Cameron (1957)

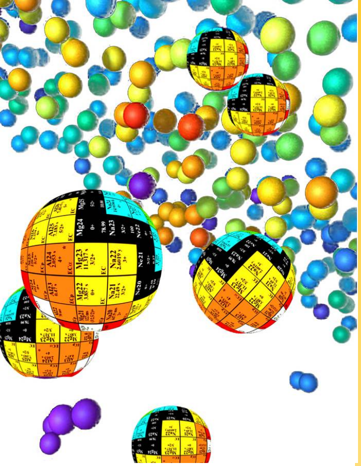
H-rich layers of SNII

(p,γ) and (γ,n) reactions operating on preexisting *s*- and *r*-seed nuclei

Cameron called them '*<u>excluded isotopes</u>*'

Because of the dominant role of played by proton reactions, named these 'p-process' nuclei

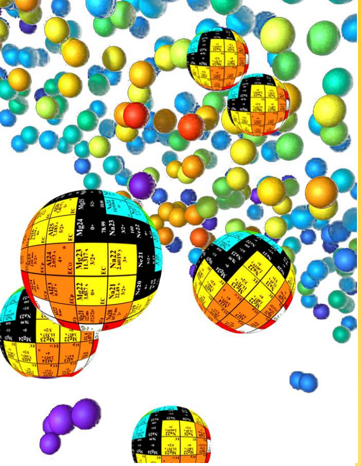
They suggested temperature of the order of $2.5\ 10^9$ K for as high densities as 100 g/cm^3, and timescale of 10-100 s



Arnould (1976)

Synthesis of *p*-nuclei during hydrostatic oxygen burning in the deep O-Ne-rich layers of massive stars in their pre-supernova or supernova phases

A large enhancement of heavy elements, presumably by prior *s*-processing is required. Only *s*-seed nuclei should be enhanced and not *r*-process seeds (recognized to be not important seeds).

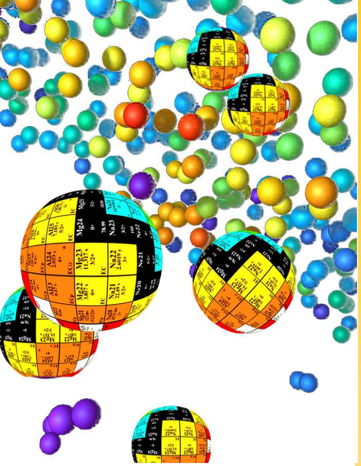


Woosley & Howard (1978)

They found that the (p,γ) chain may require physical conditions that cannot be easily realized in nature. (p,γ) and (p,n) play no role.

Alternatively, they proposed **γ-process**. A distribution of heavy elements subjected to a 'hot photon bath' $((\gamma, n), (\gamma, p), (\gamma, \alpha))$ will be transformed on a timescale of 1s into a distribution of nuclei close to the solar distribution of *p*-nuclei

T optimum conditions for the synthesis of *p*-nuclei in explosive events: $2 - 3.2\ 10^{9}$ K



Howard, Meyer & Woosley (1991)

A new site for the gamma-process: Type Ia supernovae. CO-WD that explodes by deflagration or detonation.

They investigate chains to produce the light-p, and found that

$^{86}Kr(p,\gamma)$ … $^{90}Zr(p,\gamma)^{91}Nb(p,\gamma)^{92}Mo$

is responsible for half of ^{92}Mo (and important for ^{90}Zr as well) and (p,γ) reactions produce also ^{96}Ru. The other half of ^{92}Mo, and ^{94}Mo, come from (γ,n) reaction sequence

• impossible to reproduce the solar abundances of *all* *p*-isotopes using a single process

• several different sites and (independently operating) processes seem to be required

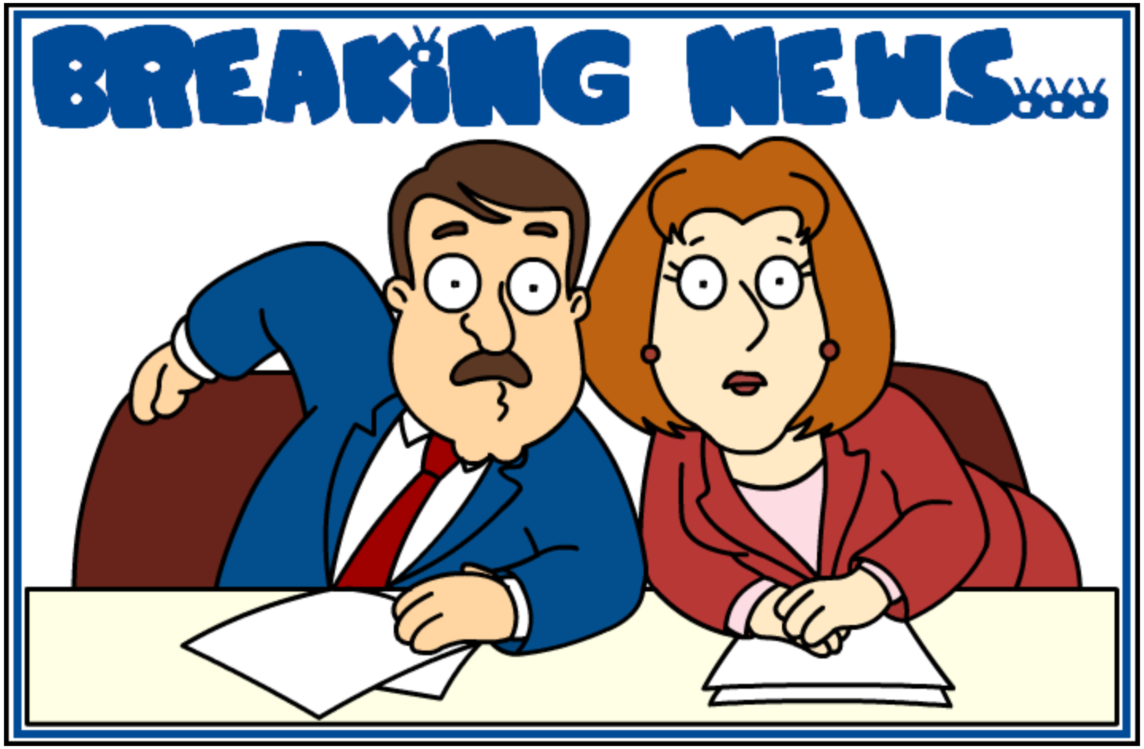
• largest fraction of *p*-isotopes is created by sequences of photodisintegrations and β^+ decays (**the γ-process**)

• generally accepted that the γ-process occurs mainly in explosive O/Ne burning during supernova Type II explosions at temperatures in the range of T ≈ 2-3 GK, but supernovae Type Ia and Ib/c have also been considered

• calculations based on the γ-process concept can produce the bulk of the *p*-nuclei within a factor of ≈ 3 of their solar system (SS) values

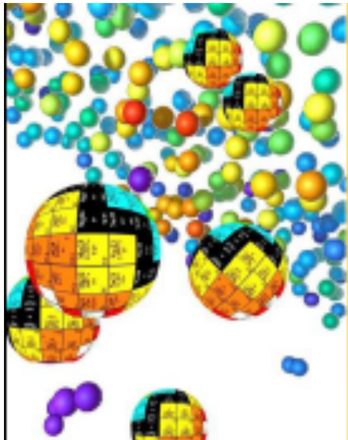
• **BUT**, the most abundant *p*-isotopes, **^{92,94}Mo and ^{96,98}Ru** are notoriously underproduced, making their nucleosynthesis one of *the great outstanding mysteries in nuclear astrophysics*

A process designed to synthesize *p*-nuclei should surely account for the most abundant of these nuclides !!!



A remarkable breakthrough for the endemic problem:

For the first time,
a stellar source has been shown to produce both,
light and heavy *p*-nuclei, at the same level as ^{56}Fe,
including the very abundant Mo and Ru *p*-isotopes!!!

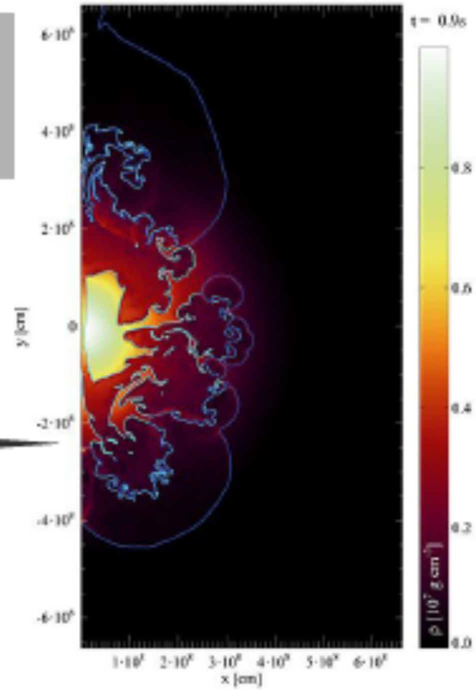


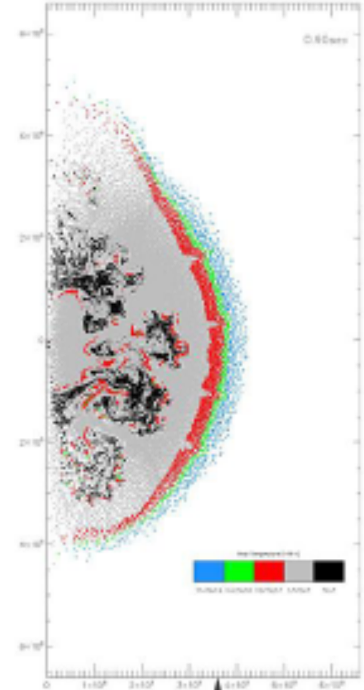
p-process
Claudia Travaglio
Russbach, March 12-16 2012

Travaglio et al. 2011
ApJ 739,93

F. Roepke & W.Hillebtandt

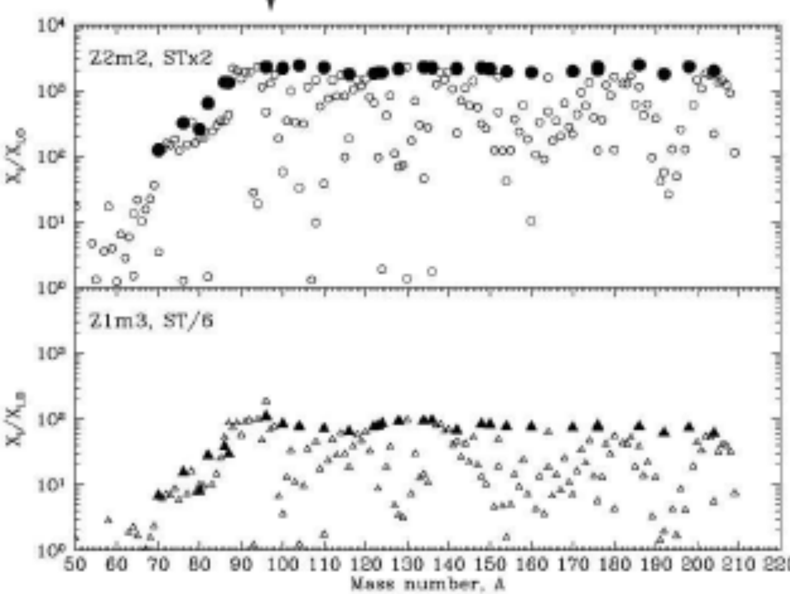
SNIa models





R. Gallino

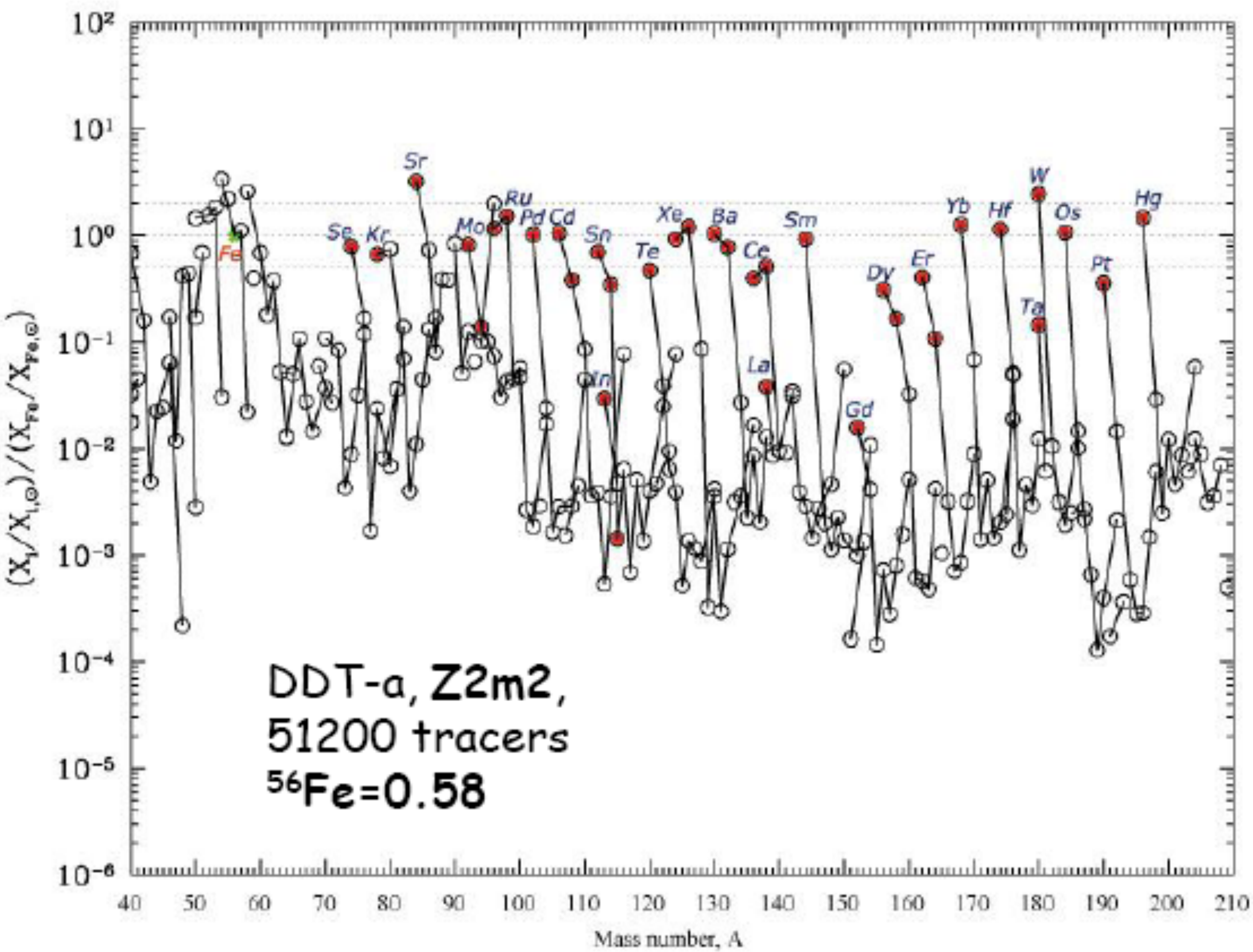
s-process calculations



C. Travaglio

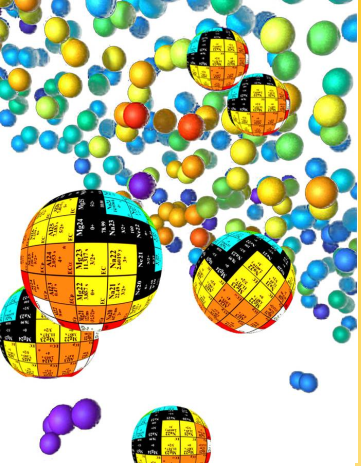
p-process nucleosynthesis

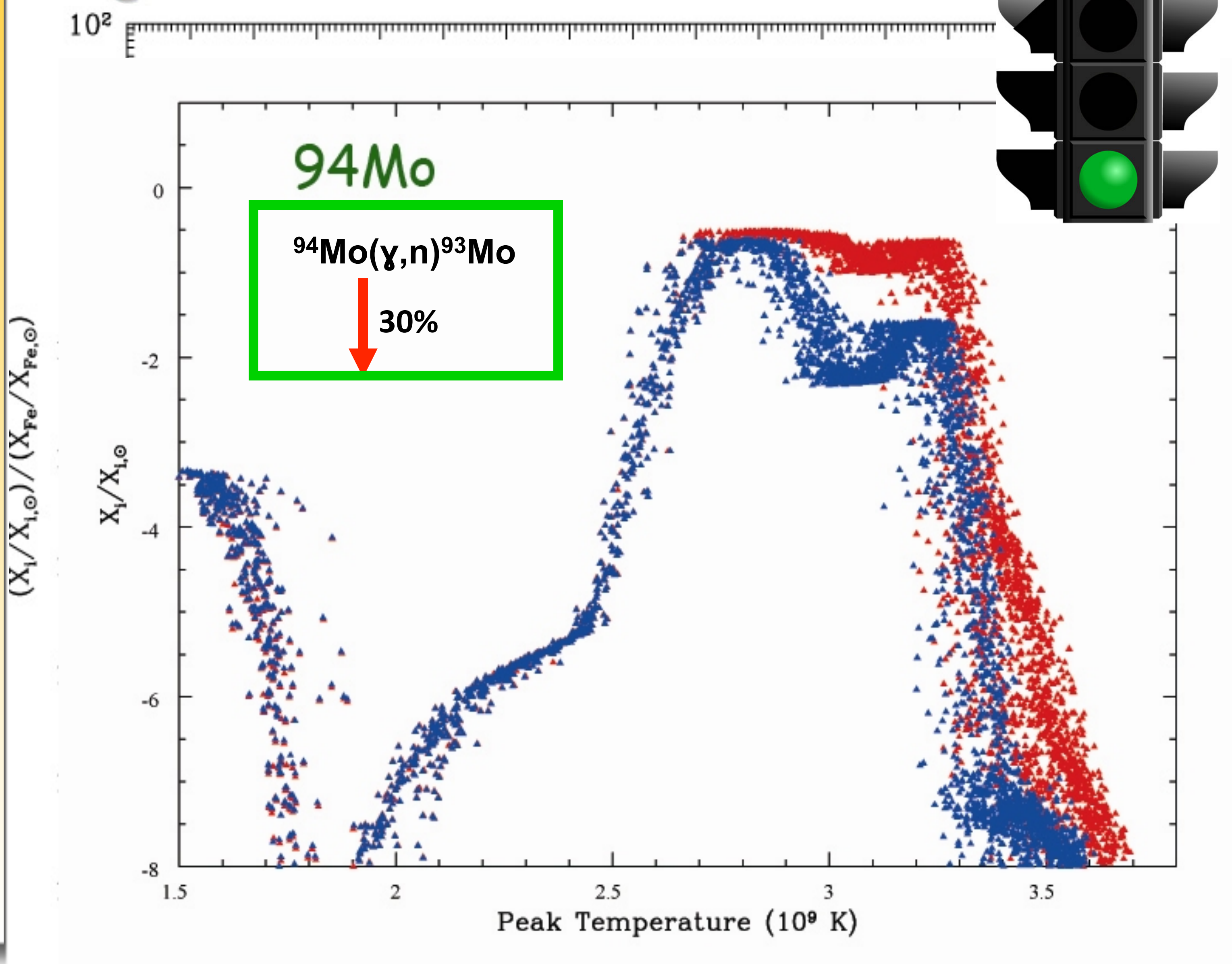
Results: solar metallicity



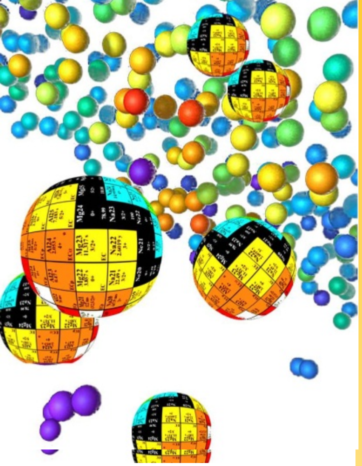
p-process
Claudia Travaglio
Russbach, March 12-16 2012

Looking deeper into p-nuts

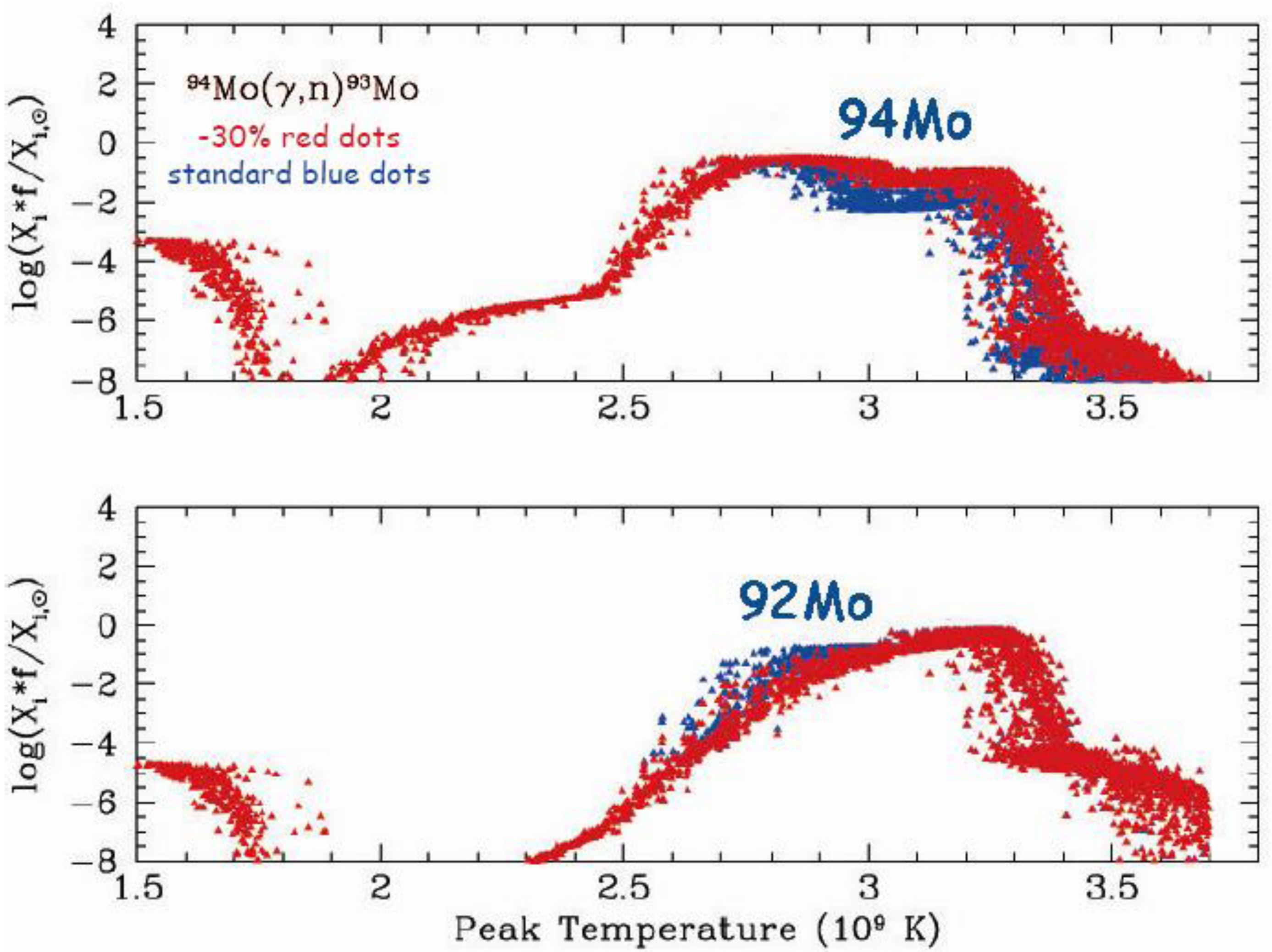




p-process
Claudia Travaglio
Istanbul, May 24-27 2011

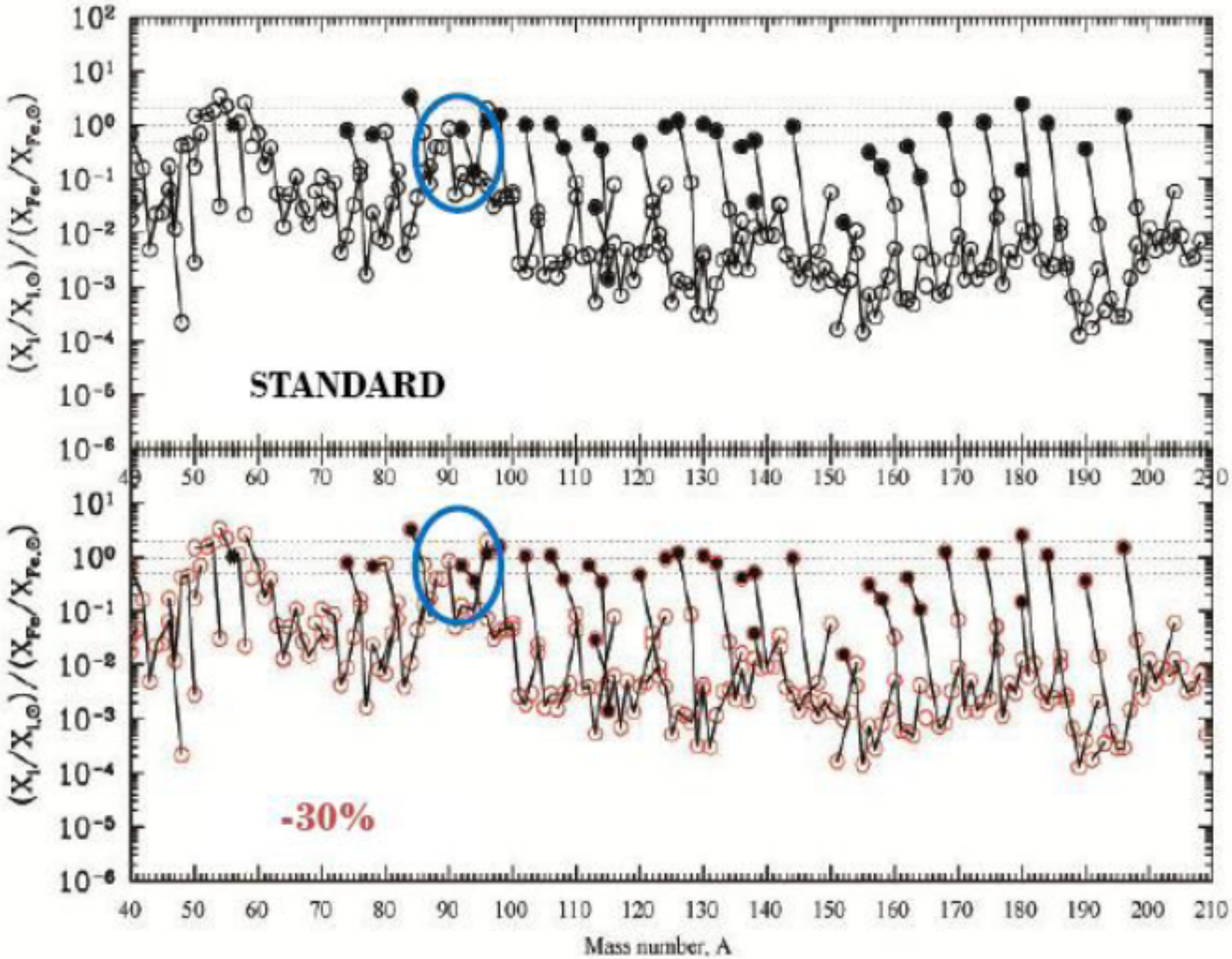


Looking deeper into p-nuts: ^{94}Mo mistery



p-process
Claudia Travaglio
Russbach, March 12-16 2012

Looking deeper into p-nuts: ^{94}Mo mistery fixed, maybe !



P-process nucleosynthesis:
An experimental approach for studying *key* photonuclear reactions

Reactions of interest:

$$^{94}Mo(\gamma,n)^{93}Mo$$

$$^{80}Kr(\gamma,n)^{79}Kr$$ - Key branching point in the γ-process path

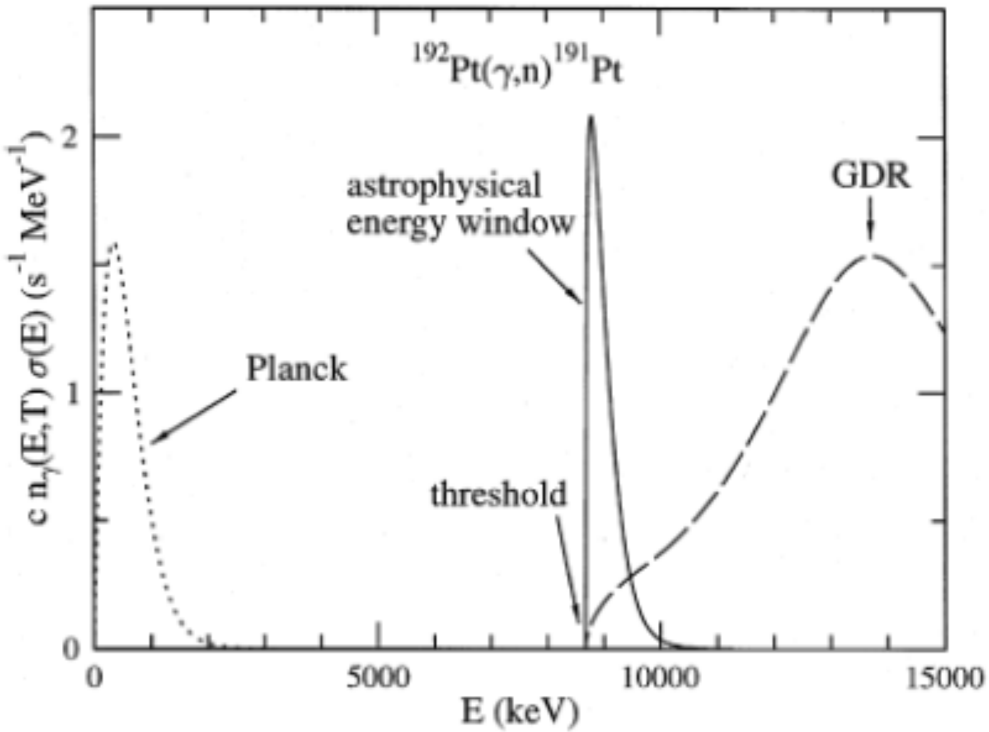
Rauscher (PRC 73, 2006)

^{74}Se(γ,n), ^{78}Kr(γ,n), ^{84}Sr(γ,n)

Experiments with real photons:

Laser Compton Backscattering technique
Bremsstrahlung-induced activation

Photonuclear Reaction Rates



Gamow window:

$$E_\gamma^{eff} = (l + 1/2)kT + Q_{n\gamma}$$

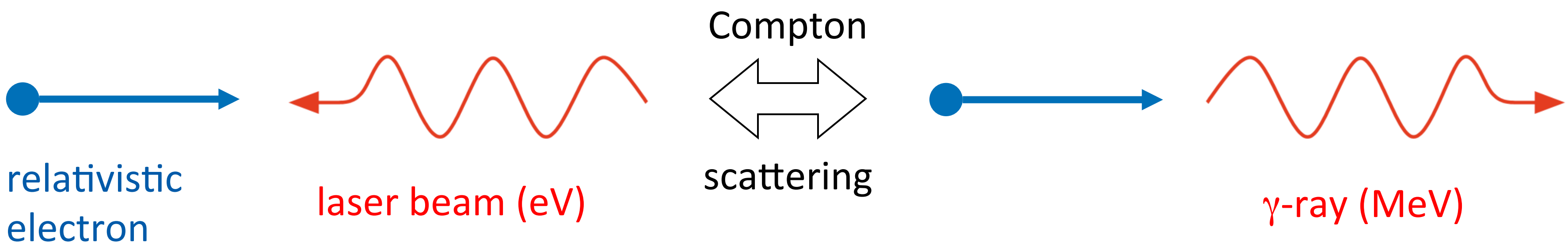
P. Mohr et al. (PLB 488, (2000))

The reaction rate for a photodisintegration reaction

$$\lambda(T) = \int_0^\infty c n_\lambda^{Planck}(E,T)\sigma(E)dE$$

$$n_\gamma^{Planck}(E,T) = \left(\frac{1}{\pi}\right)^2 \left(\frac{1}{\hbar c}\right)^3 \frac{E^2}{\exp(E/kT) - 1}$$

Experimental method: Laser Compton Backscattering (LCB)

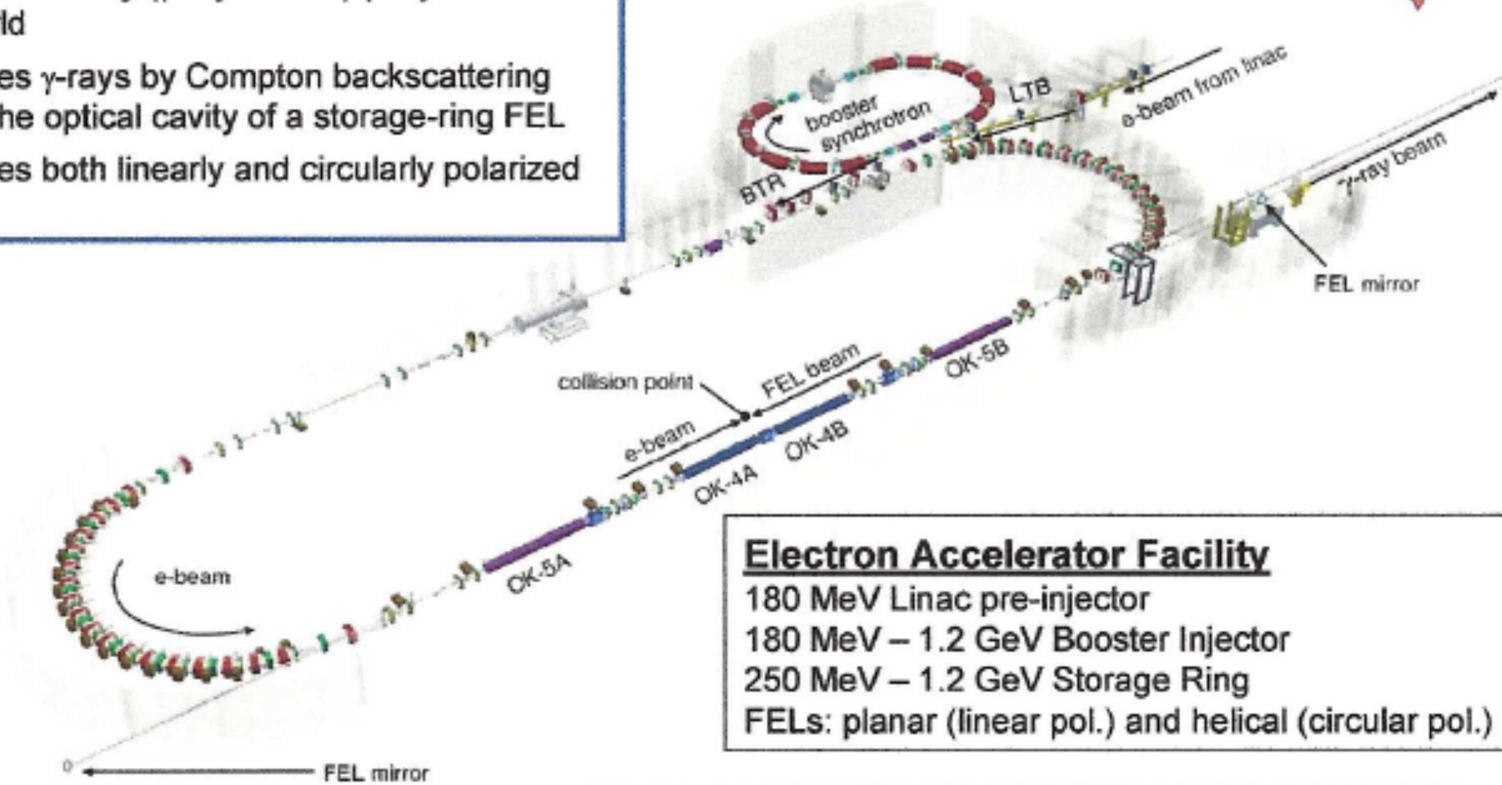


$$E_\gamma = \frac{\hbar\omega \cdot (1 - \beta \cdot \cos\theta_i)}{1 - \beta \cdot \cos\theta_f + \frac{\hbar\omega}{E_{electron}}(1 - \cos\theta_{photon})}$$

- Example: E_{laser} = 3.3 eV, $E_{electron}$ = 450 MeV (γ = 882)
  $\rightarrow$ E_γ = 10 MeV

High Intensity Gamma-ray Source (HIGS) at TUNL

- Highest intensity (γ-rays/s/keV) γ-ray beam in the world
- Produces γ-rays by Compton backscattering inside the optical cavity of a storage-ring FEL
- Produces both linearly and circularly polarized beams



Electron Accelerator Facility

180 MeV Linac pre-injector
180 MeV – 1.2 GeV Booster Injector
250 MeV – 1.2 GeV Storage Ring
FELs: planar (linear pol.) and helical (circular pol.)

γ-ray beam parameters	Values
Energy	1 – 100 MeV
Linear & circular polarization	> 95%
Intensity with 5% $\Delta E_\gamma/E_\gamma$	> 10^7 γ/s

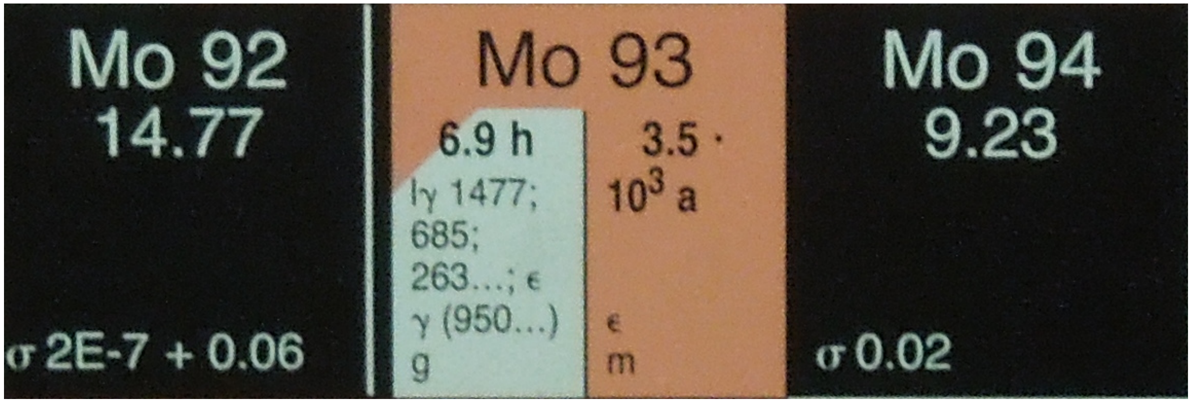
For more details see:
http://www.tunl.duke.edu/higs/

Photoneutron cross section measurements

$$\sigma(E_\gamma) = \frac{N_n}{N_\gamma N_t \varepsilon_n}$$

N_n – number of neutrons detected using ^{3}He counters
N_γ - number of incident photons
N_t – number of target atoms per unit area (enriched target)
ε_n – neutron detection efficiency

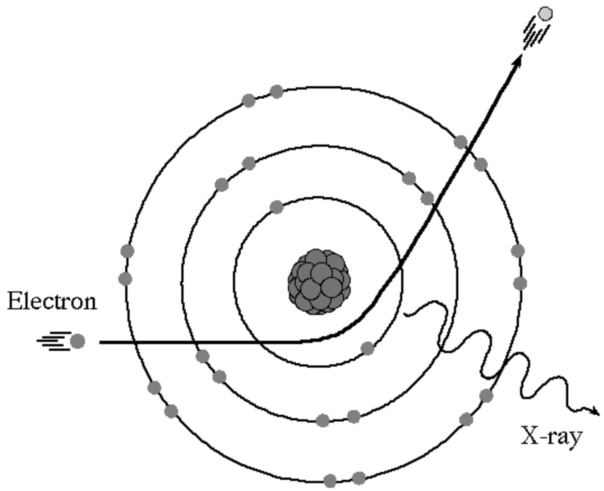
Cross section measurements for $^{94}Mo(\gamma,n)^{93}Mo$ @ HIGS



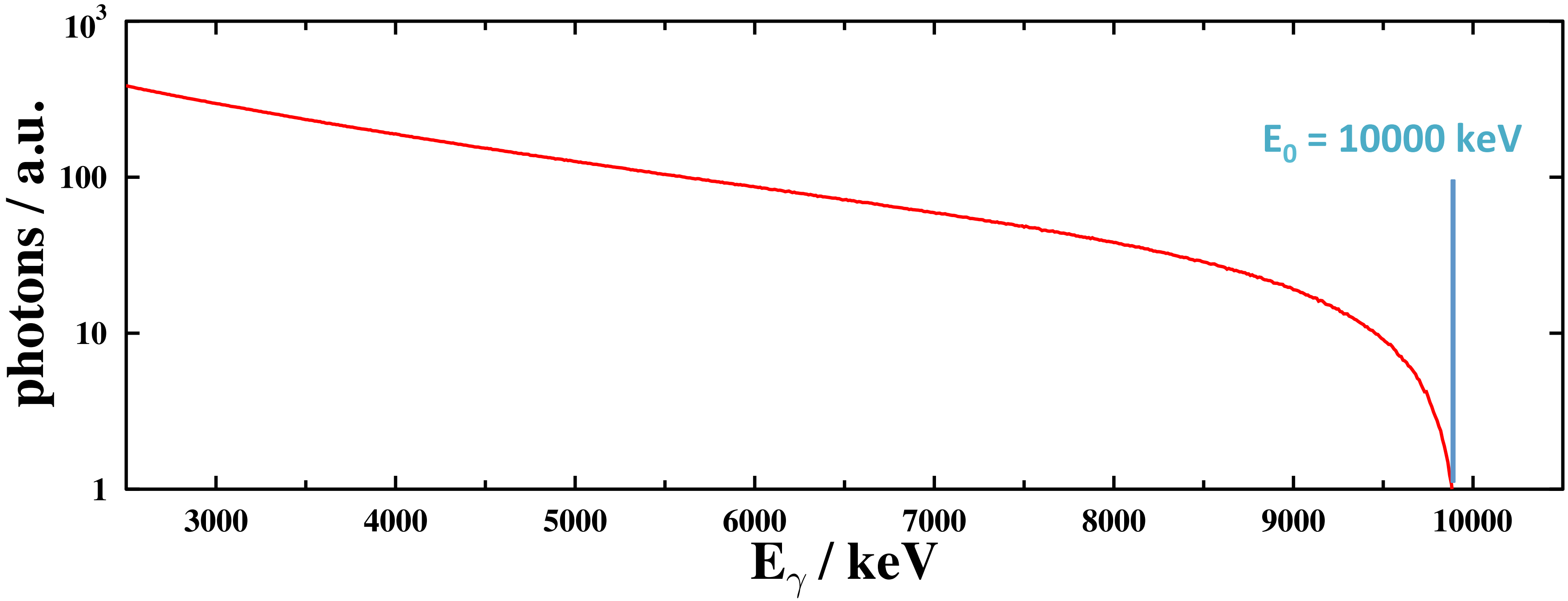
The only way to study experimentally the cross section for $^{94}Mo(\gamma,n)$ in the ground state is by direct neutron counting!!!

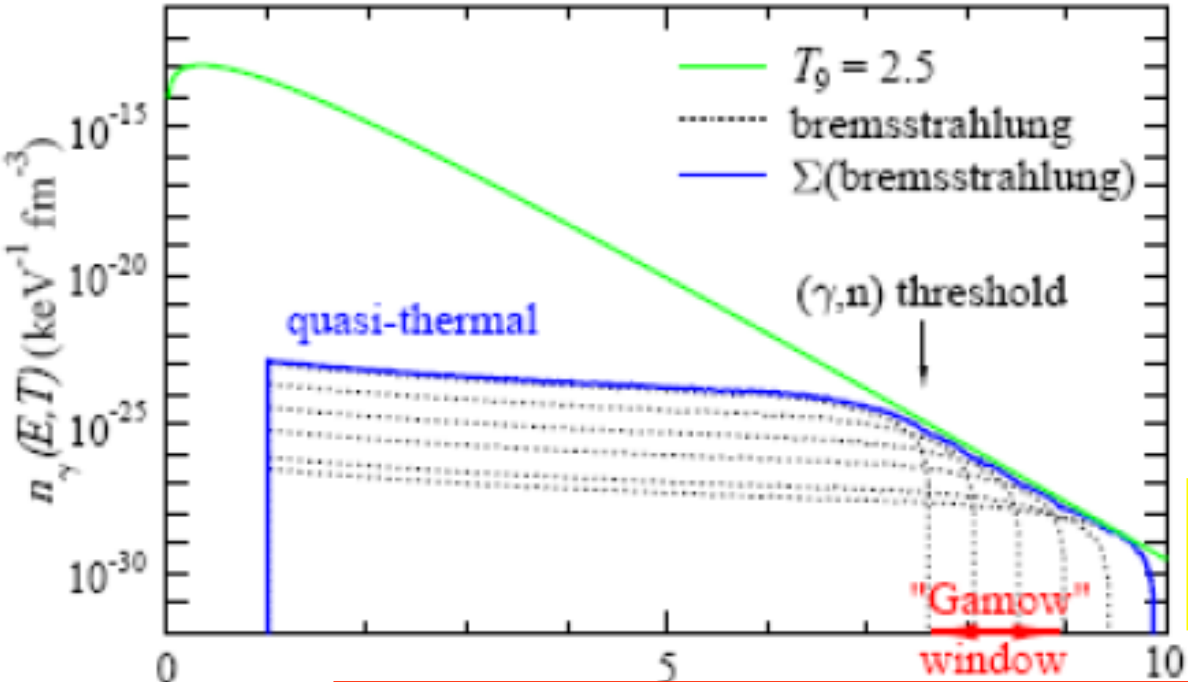
Beam time already approved at HIGS facility!

Experimental method: bremsstrahlung-induced activation



- Production by stopping of electron beam with energy E_0
- Continuous-energy photon spectrum with max. energy E_0





P. Mohr et al. (PLB 488, (2000))

'superposition method'

$$^{A}X(\gamma,n)^{A-1}X^{*}$$

The reaction rate for a photodisintegration reaction

$$\lambda(T) = \int_0^\infty c n_\lambda^{Planck}(E,T)\sigma(E)dE$$

$$c n_\gamma^{Planck}(E$$

$$\lambda_{(\gamma,n)}^{gs}(T) \approx \sum_i a_i(T) \int_{E_{thr}} \Phi_\gamma \quad (E, E_{\max,i})\sigma_{(\gamma,n)}(E)dE$$

$$\lambda_{(\gamma,n)}^{gs}(T) \approx \sum_i a_i(T) I_{\sigma_{(\gamma,n)},i}$$

$$Y_{(\gamma,n)} = N_t I_{\sigma_{(\gamma,n)}}$$

$$A_\gamma = \varepsilon_\gamma I_\gamma f(t_{live}/t_{real}) Y_{(\gamma,n)}$$

Photoneutron reaction rate measurements at astrophysical energies @ JMU - Madison Radiation Facility

Reactions of interest:

^{74}Se(γ,n), ^{78,80}Kr(γ,n), ^{84}Sr(γ,n) with S_n = ~ 12 MeV

Experimental method:

Bremsstrahlung-induced activation

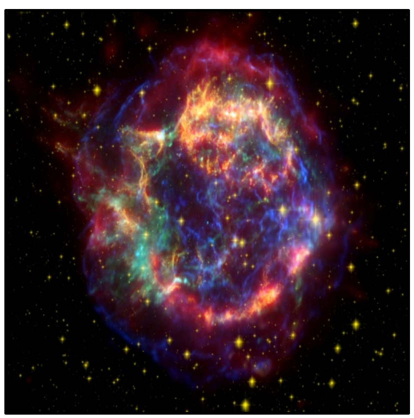
Facility available:

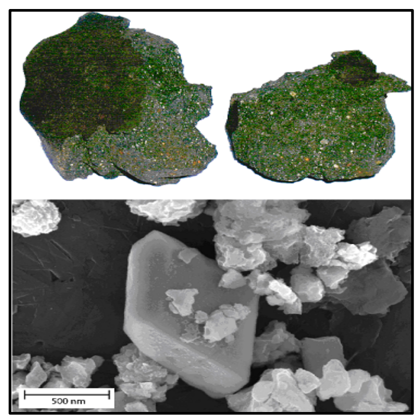
Medical linear electron accelerator manufactured by Siemens to provide X-ray beam energies up to 15 MeV

Co-production of historical *p*-, *s*- and *r*-process isotopes of Zr, Mo and Ru in the neutrino-wind of core-collapse supernovae

Oliver Hallmann and Karl-Ludwig Kratz

Max-Planck-Institute for Chemistry, Mainz





The high-entropy / neutrino-driven wind model

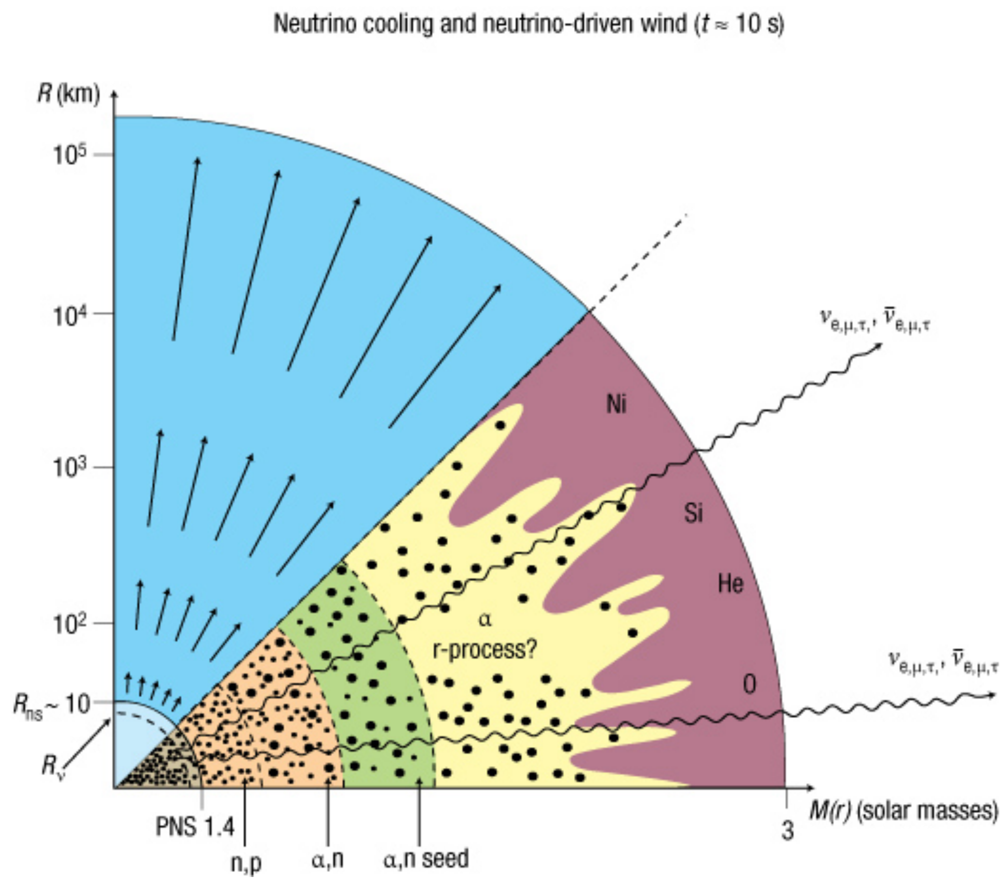
Core-collapse SN "HEW" …still one of the presently favoured scenarios for a rapid neutron-capture nucleosynthesis process

The **neutrino-driven wind** starts from the surface of the proto-neutron star with a flux of neutrons and protons.

As the nucleons cool ($\approx 10 \geq T_9 \geq 6$), they combine to α-particles + an excess of unbound neutrons.

Further cooling ($6 \geq T_9 \geq 3$) leads to the formation of a few Fe-group "seed" nuclei in the so-called **α-rich freezeout**.

Still further cooling ($3 \geq T_9 \geq 1$) leads to neutron captures on this seed composition, making the heavy **r-process** nuclei.



(Woosley & Janka, Nature, 2005)

Historical nucleosynthesis processes vs. HEW

Historical = M. Burbidge, G. Burbidge, W. Fowler, F. Hoyle (1957) until end of ´90s
→ Wallerstein et al. (1997)

	Historical	HEW
p	p-captures (rp), photodesintegration	Charged-particle reactions (CPR)
s	n-captures at stability, $Y_n/Y_{seed} \approx 2$ (Gallino)	CPR, late n-captures
r	n-rich isotopes far off stability	CPR + subsequent n-captures

Two conundrums:

- The SS puzzle: Ratio of the overabundant p-only isotopes ^{92}Mo & ^{94}Mo
- SiC grain puzzle: all 7 Mo isotopes with non-SS peculiar pattern

Mo isotopic abundances in the SS

Particularly **"hot topic"**

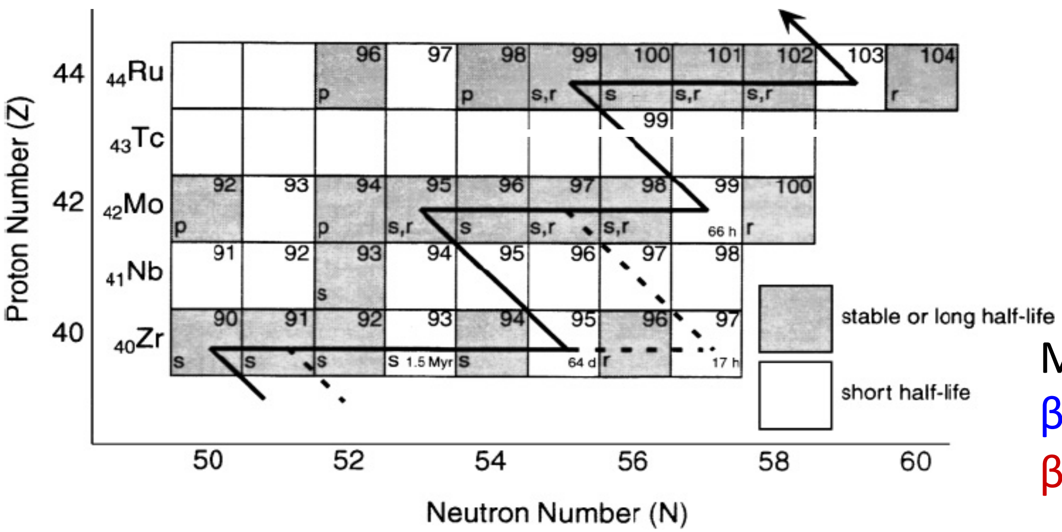
$^{92}Mo/^{94}Mo$

The two most abundant p-nuclei in the SS

	Lodders (2003)	De Laeter (2008)
^{92}Mo	14.836	14.525
^{94}Mo	9.247	9.151
$^{92}Mo/^{94}Mo$	**1.605**	**1.587**

…despite all attempts / scenarios studied up to now,

$^{92}Mo/^{94}Mo$ has remained an "unsolved problem"



7 stable isotopes:

$^{92,94}Mo$ p-only; ^{96}Mo s-only
$^{95,97,98}Mo$ s+r, ^{100}Mo r-only

Mo isotopes "shielded" from both sides:

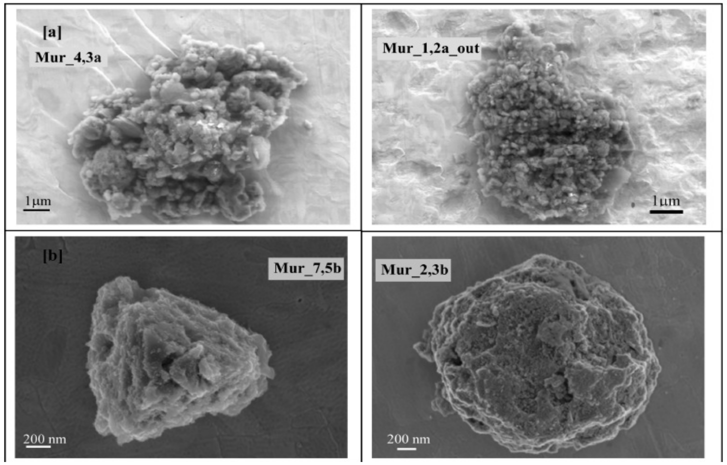
β^- **$^{92,94,96}Zr$** (Z=40)

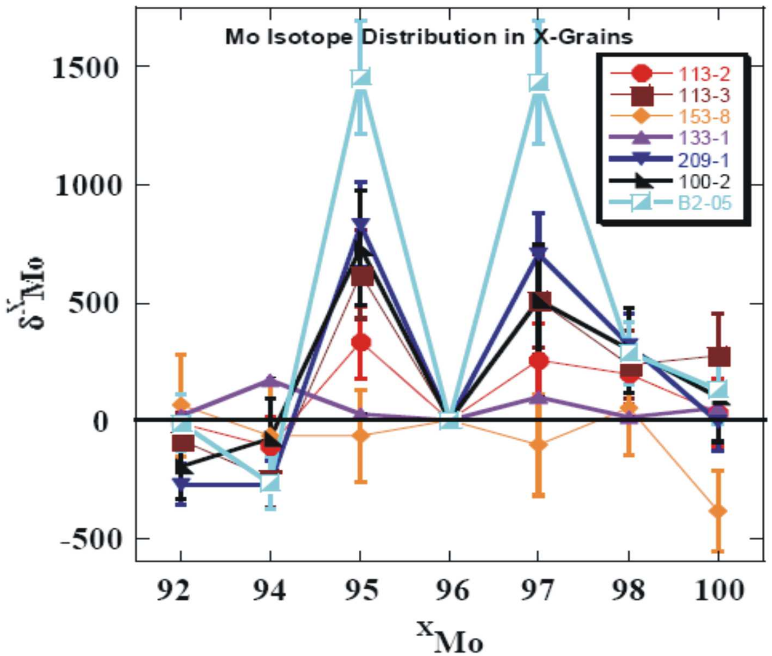
β^+ **$^{96,98-100}Ru$** (Z=44)

Mo isotope distribution in presolar X-grains

M.J. Pellin et al., Lunar and Planetary Science XXXVII (2006) 2041:

Presolar SiC grains, isolated from primitive meteorites, are ejecta of stars that contributed to the protosolar nebula. Among these grains are a rare fraction, called **Type-X**, which are believed to have formed in the stellar outflows of SN II explosions.





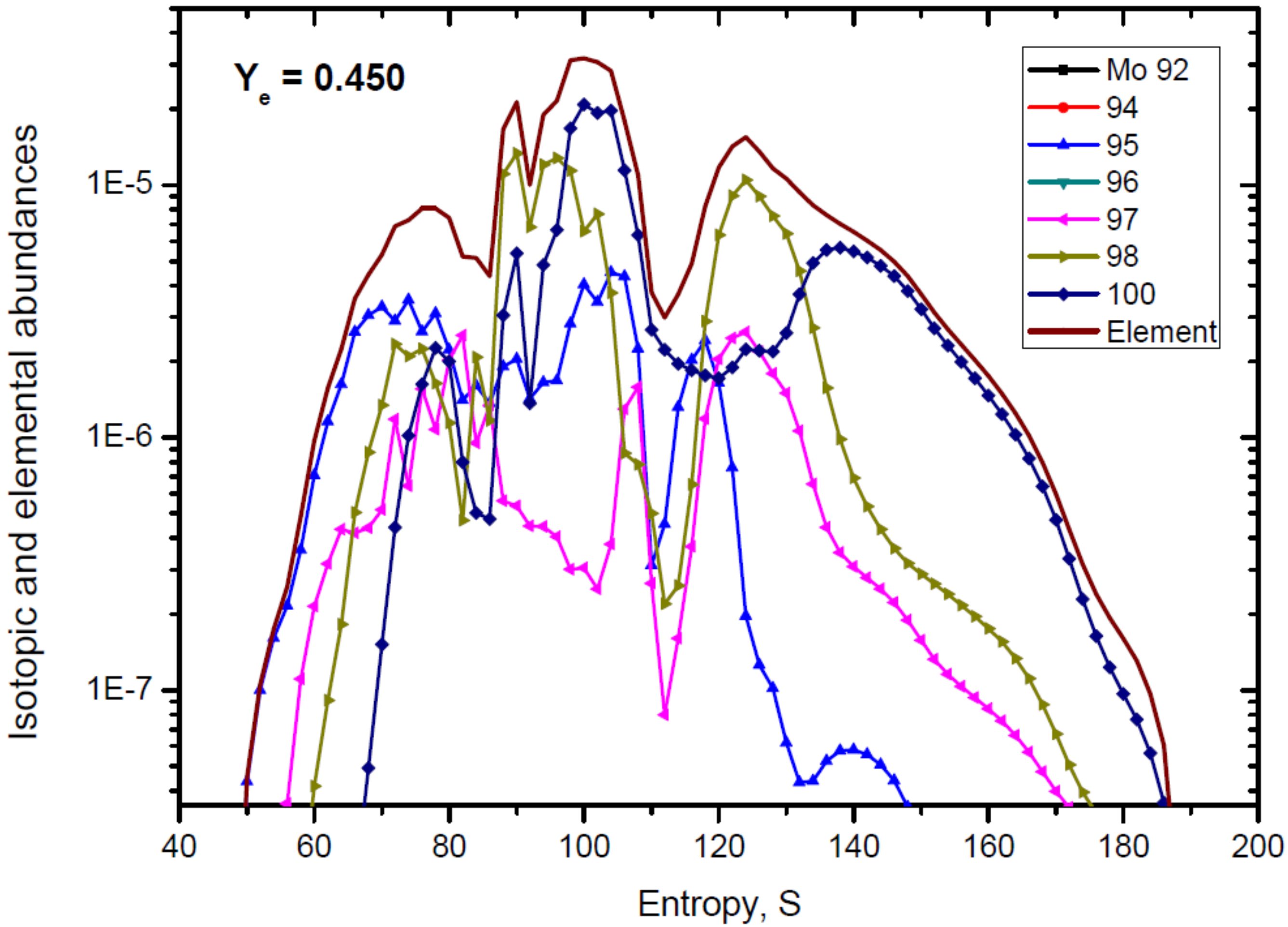
δ notation: deviation in permil from SS

^{X}Mo deviation plotted relative to ^{96}Mo, which is taken as pure s-process isotope ⇨

„unusual isotopic pattern“

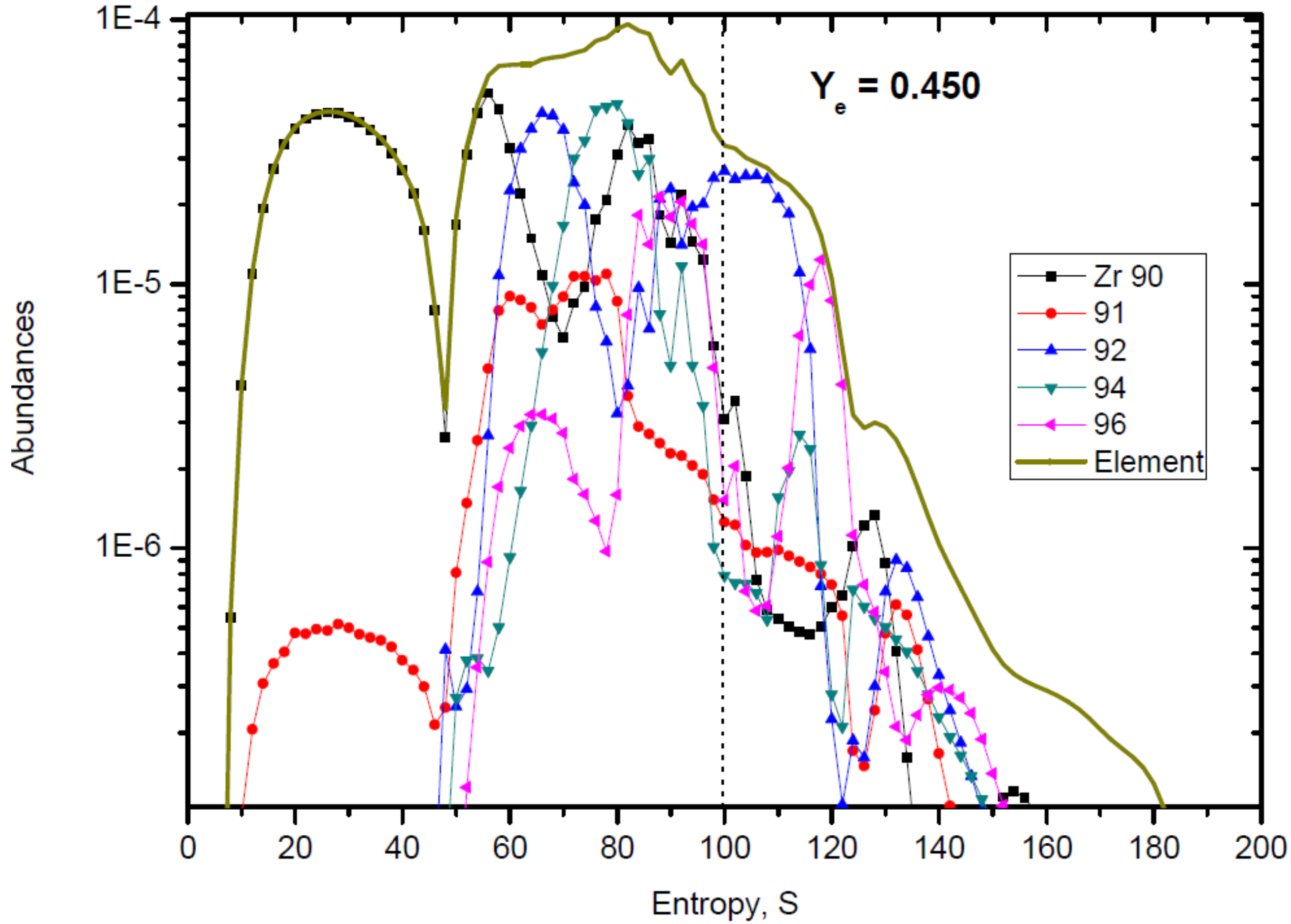
significant enrichment in ^{95}Mo, ^{97}Mo;
smaller enrichment in ^{98}Mo;
no clear signature of ^{100}Mo enhancement.

HEW Mo isotopic abundances



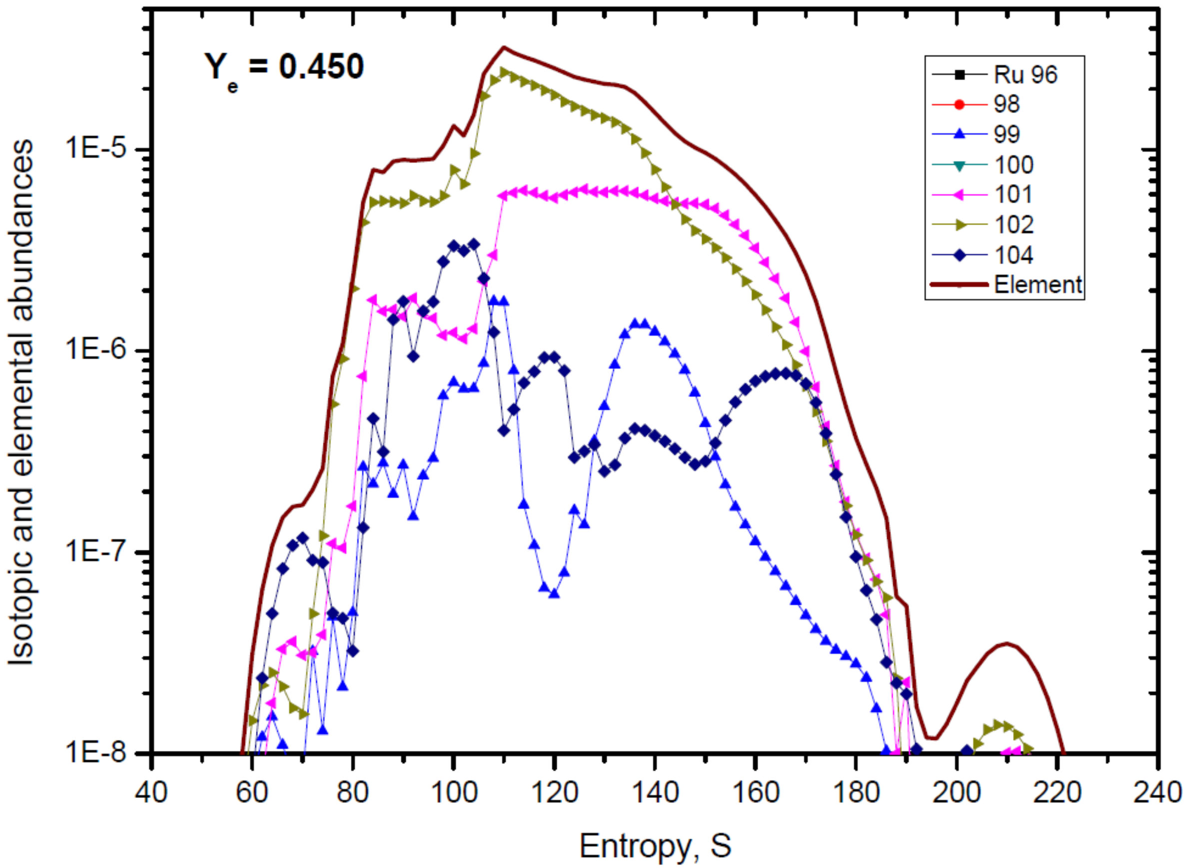
All 7 isotopes are **co-produced** !

Zr isotopic abundances in the HEW



All 5 stable Zr isotopes are **co-produced** !

Ru isotopic abundances in the HEW



Again: All 7 stable Ru isotopes are **co-produced** !

Summary

- The HEW co-produces the historical p-, s- and r-isotopes of Zr, Mo and Ru (in fact: from Zn to Ru) within its charged-particle component
  → **no classical n-capture process required !**

- The HEW charged-particle component can obviously also explain the isotopic anomalies of Zr, Mo and Ru measured so far in presolar dust grains

- More heavy element measurements of stardust samples are needed !

- Finally: **The HEW is the only scenario which can**
  co-produce all Zr, Mo and Ru isotopes
  && reproduce the measured isotopic ratios from SiC-X grains
  && also reproduce the SS value $^{92}Mo/^{94}Mo$

(also see Farouqi et al., PASA 26 (2009) 194 – 202)