nuclear astrophysics – lecture 2

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thermonuclear reaction: narrow resonances

$$\langle\sigma v\rangle \sim \int_0^\infty E\,\underbrace{\sigma(E)}\,\exp\left(-\frac{E}{kT}\right)dE$$

Breit-Wigner formula:

$$\sigma_{BW}(E) \sim \frac{\omega\,\boxed{\Gamma_a\,\Gamma_b}}{(E_r - E)^2 + (\Gamma/2)^2}$$

partial widths of entrance and exit channels

resonance energy

total width

$$\Rightarrow \quad \langle\sigma v\rangle \sim \underbrace{\exp(-E_r/kT)}\,\underbrace{\omega\frac{\Gamma_A\Gamma_B}{\Gamma}}$$

resonance energy: needs to be measured precisely

"resonance strength" ωγ

[broad resonances: widths are energy-dependent → calculate reaction rate analytically]

rare isotopes in stars: supernovae

[Cassiopeia A]

- **Type II, Type Ia**

- **important <u>nuclear physics</u> :**

  r-process: neutron captures

  weak interactions: *e.g.*, electron captures

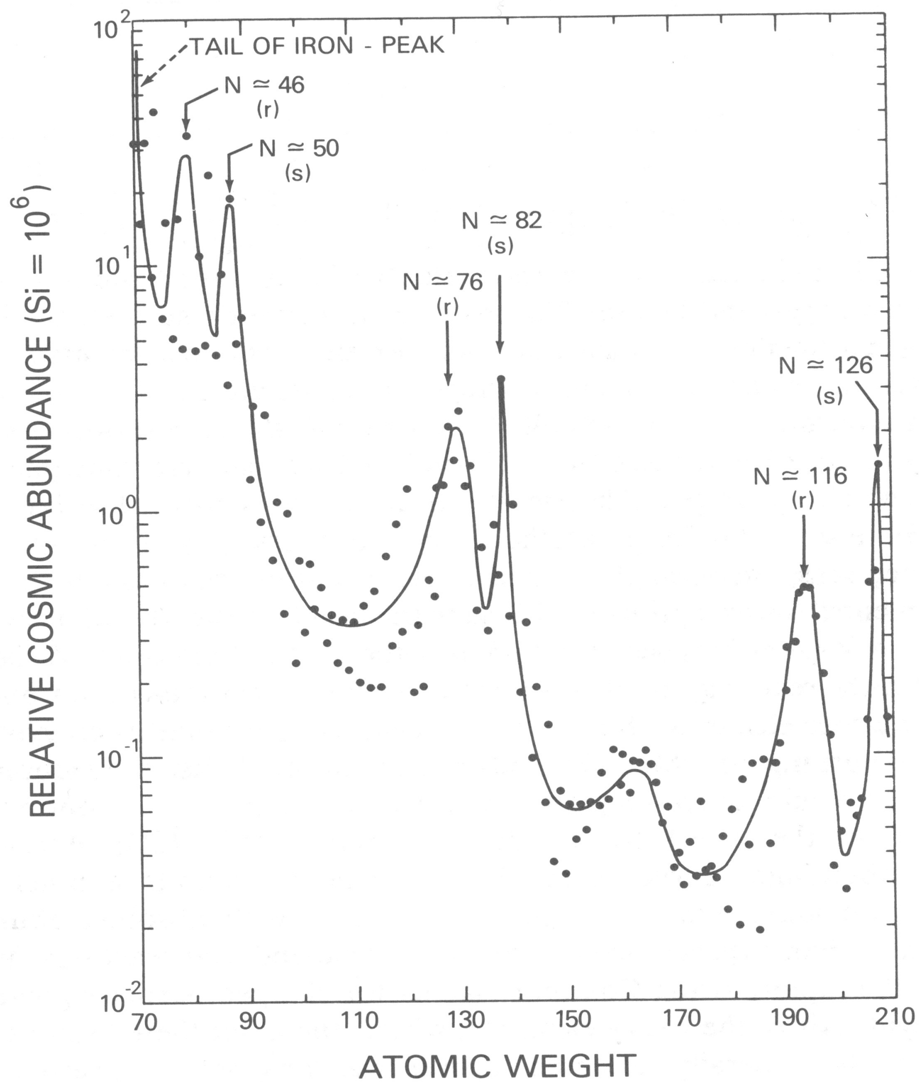
r-process

- **proposed, along with s-process, by Burbidge *et al*. (1957) and Cameron (1957)**

- **accounts for half of the elements that are heavier than iron**

r-process: observations

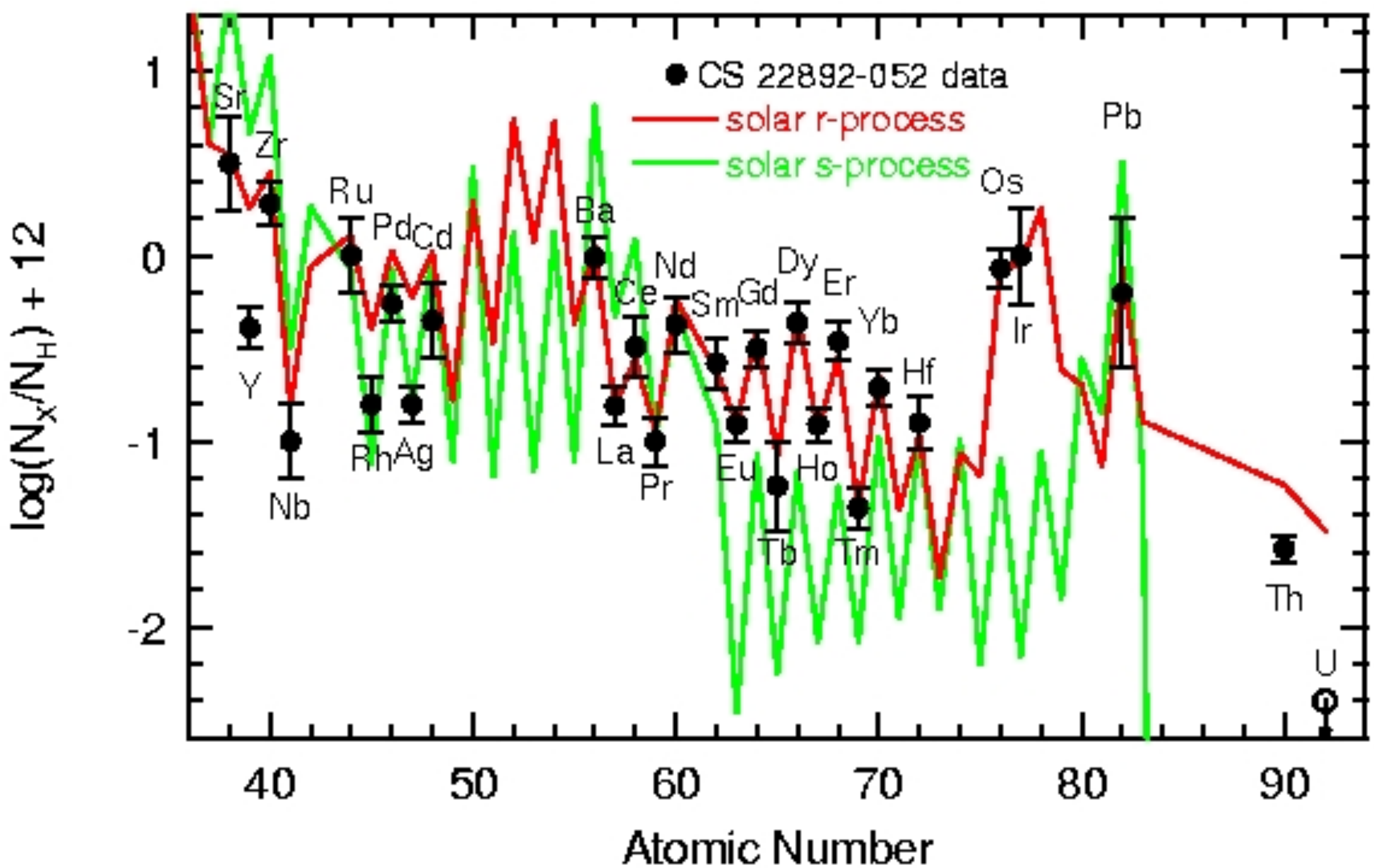
- **abundance peaks at mass 80, 130, and 195**
- **accounts for production of all elements heavier than ^{209}Bi**



[Rolfs & Rodney (1988)]

r-process: observations

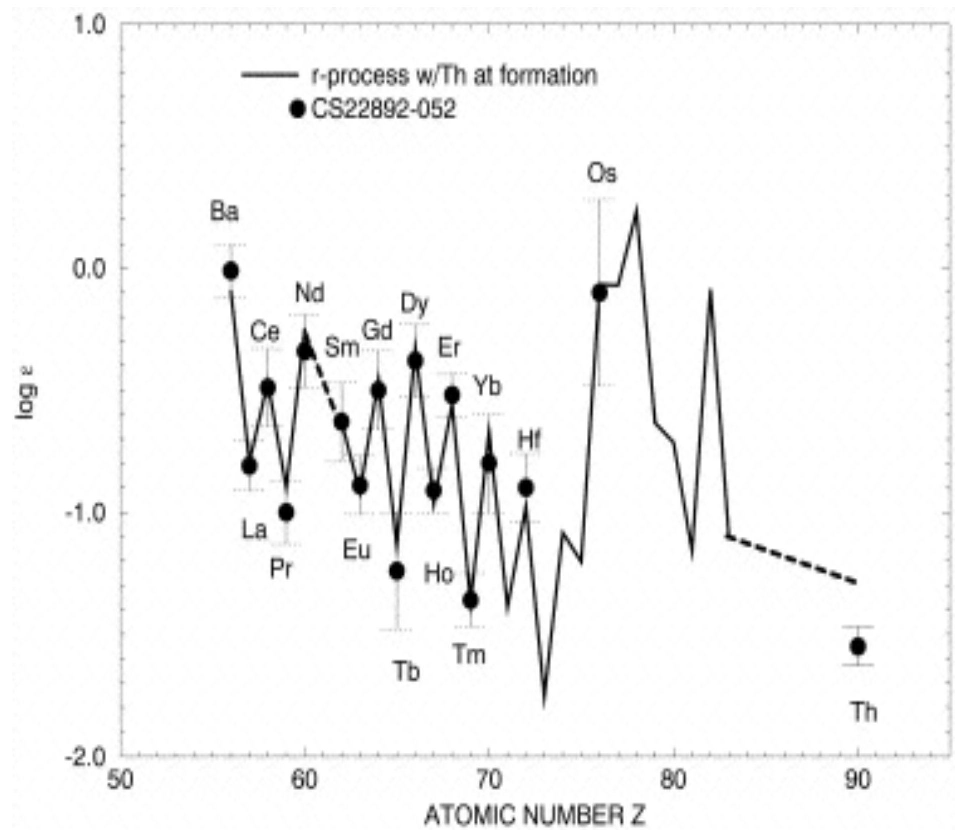
- **abundances in old metal-poor stars:**



[Sneden *et al*.]

r-process: observations

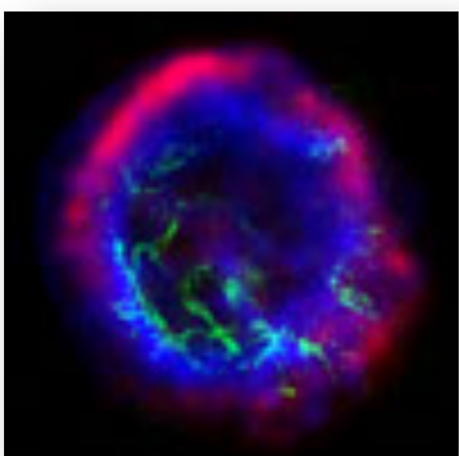
- **From observations:**
  - **agreement with solar abundances for A >130**
  - **r-process insensitive to abundance of pre-existing seed nuclei**
  - **A < 130?**



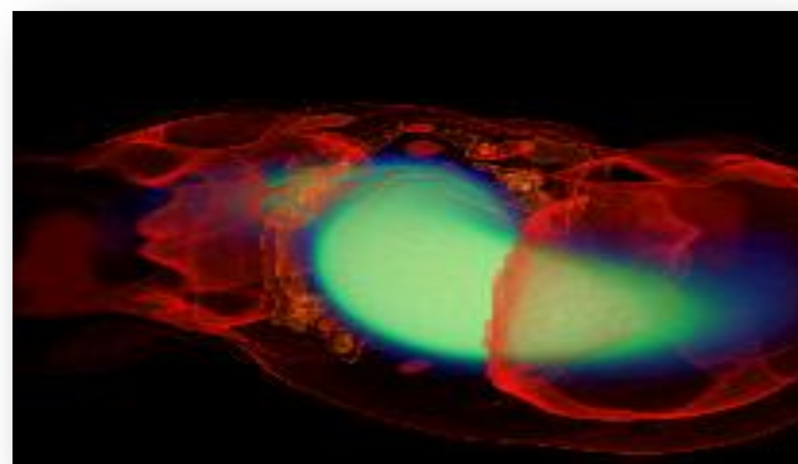
[Sneden *et al*. (1996)]

r-process: models

- possible scenarios:
  - core-collapse supernovae:
    - hot ν-heated bubble: right temperature and neutron density
  - merging neutron stars
- challenge: connect observed abundances to astrophysical environment(s)



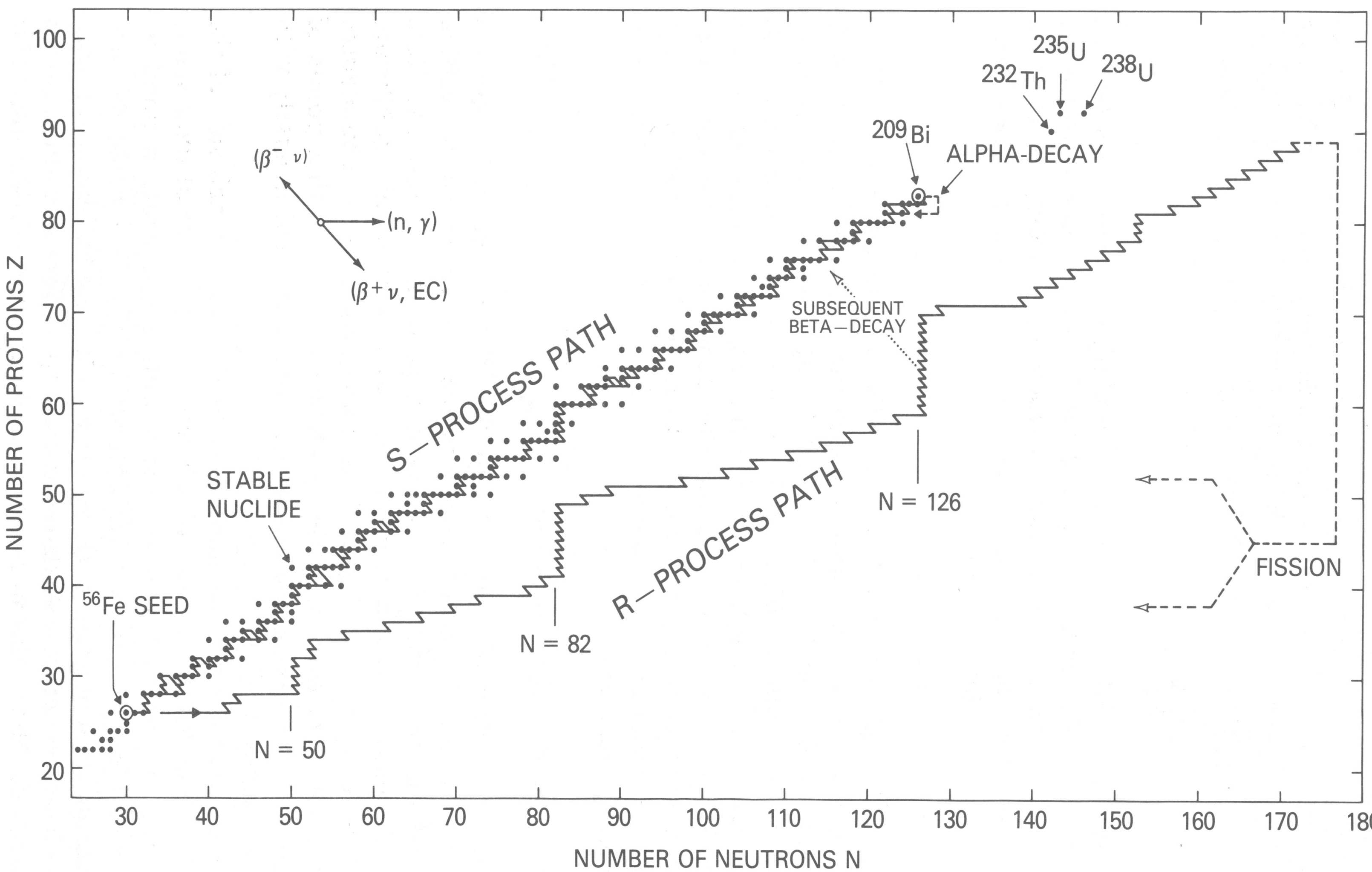
nuclear physics must be understood



r-process: nuclear physics

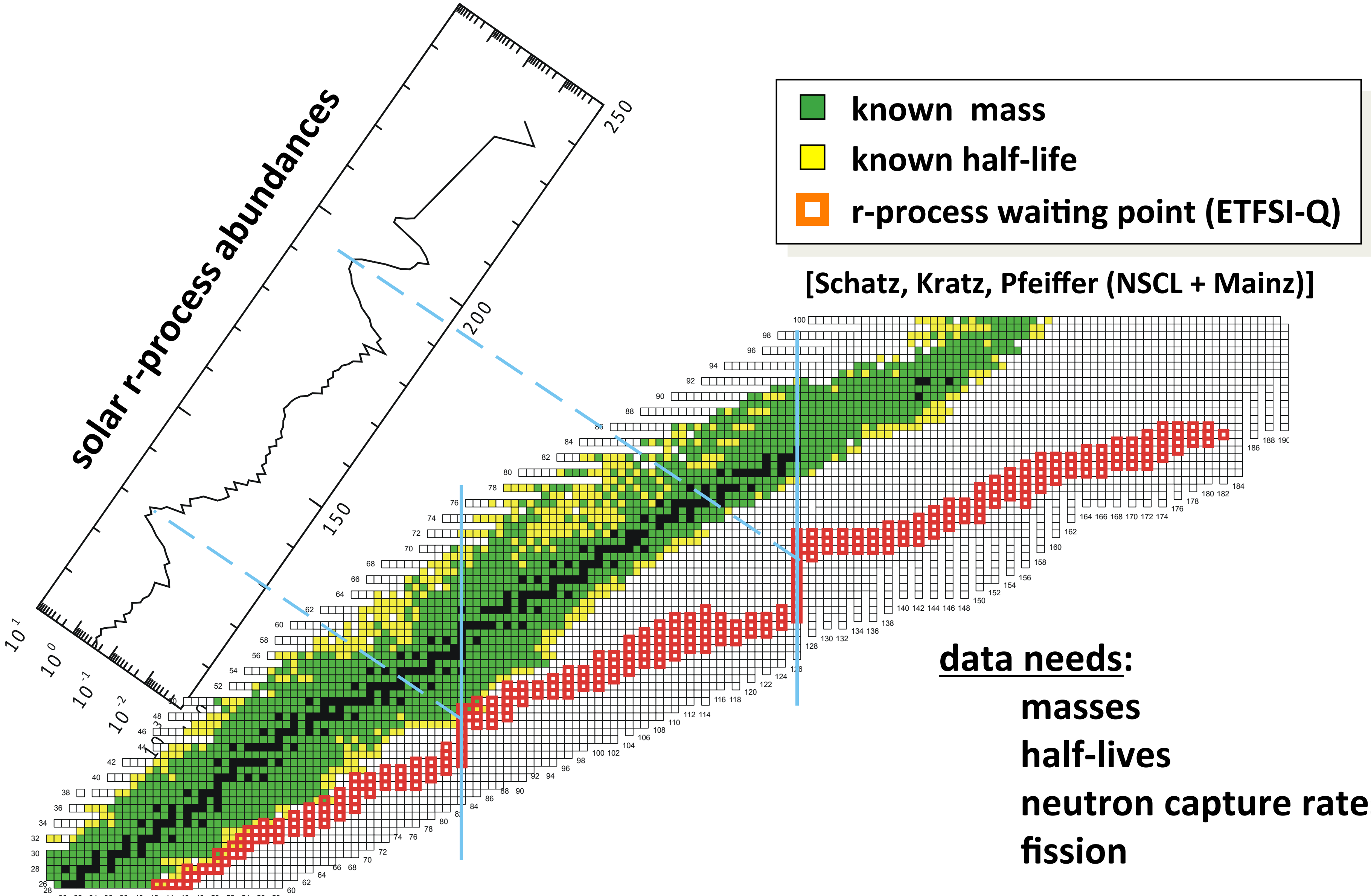
- **general framework:**
  - **neutron captures on "seed" nuclei**
  - **"waiting-point" reached when Q_n low enough for (n,γ) – (γ,n) equilibrium (15 – 30 units away from stability)**
  - **β-decay to next isotopic chain**
  - **neutron closed shells: major impedance to reaction flow**
  - **decay back to stability**

r-process “path”



[Rolfs & Rodney (1988)]

r-process: nuclear physics

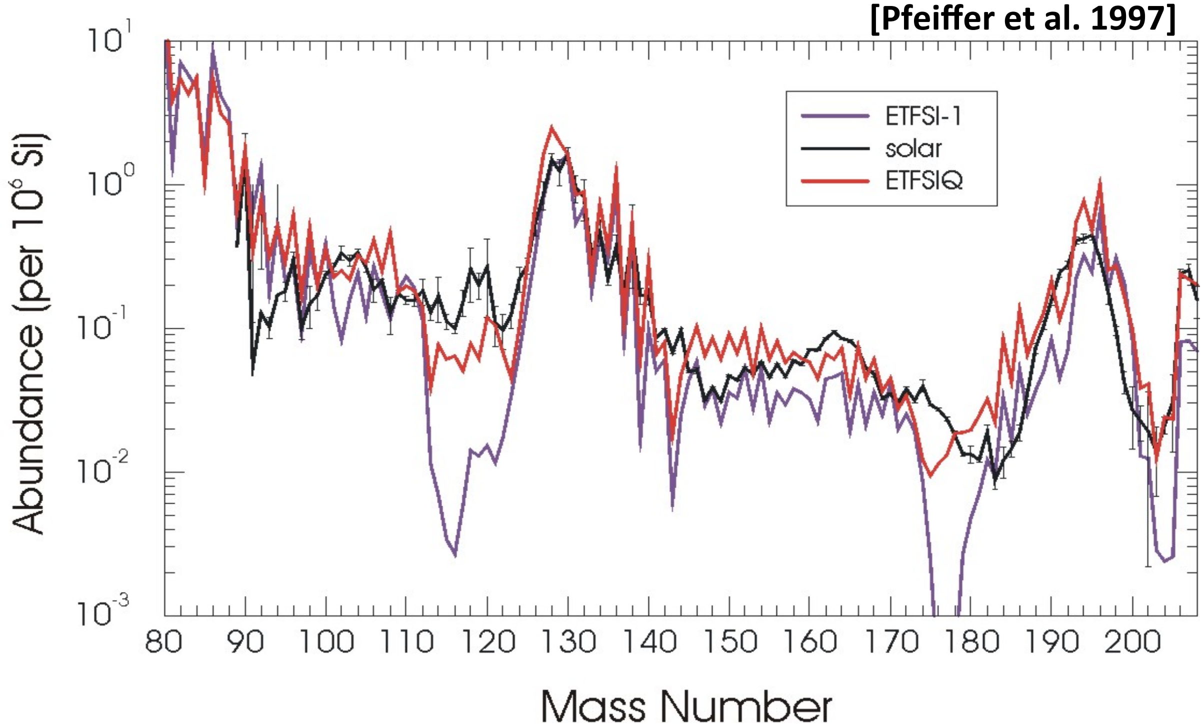


data needs:

- masses
- half-lives
- neutron capture rates
- fission

r-process: nuclear physics

[Pfeiffer et al. 1997]



- **r-process abundances from microscopic mass models with spherical shell gaps: troughs below main peaks**
- **calculations with shell quenching (*e.g.*, N=82): improvement**
- **new measurements needed**

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LETTERS

The magic nature of ^{132}Sn explored through the single-particle states of ^{133}Sn

K. L. Jones[1,2], A. S. Adekola[3], D. W. Bardayan[4], J. C. Blackmon[4], K. Y. Chae[1], K. A. Chipps[5], J. A. Cizewski[2], L. Erikson[5], C. Harlin[6], R. Hatarik[2], R. Kapler[1], R. L. Kozub[7], J. F. Liang[4], R. Livesay[5], Z. Ma[1], B. H. Moazen[1], C. D. Nesaraja[4], F. M. Nunes[8], S. D. Pain[2], N. P. Patterson[6], D. Shapira[4], J. F. Shriner Jr[7], M. S. Smith[4], T. P. Swan[2,6] & J. S. Thomas[6]

First Results from the CARIBU Facility: Mass Measurements on the r-Process Path

J. Van Schelt,[1,2] D. Lascar,[3,1] G. Savard,[1,2] J. A. Clark,[1] P. F. Bertone,[1] S. Caldwell,[2,1] A. Chaudhuri,[4,1] A. F. Levand,[1] G. Li,[5,1] G. E. Morgan,[4] R. Orford,[5] R. E. Segel,[3,1] K. S. Sharma,[4] and M. G. Sternberg[2,1]

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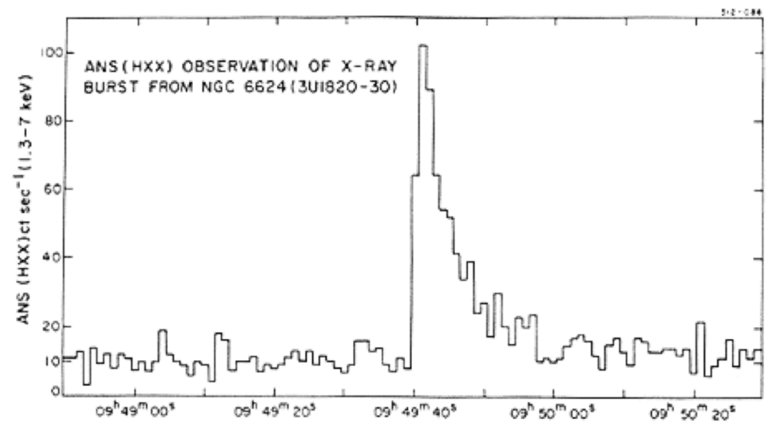
(Dated: July 2, 2013)

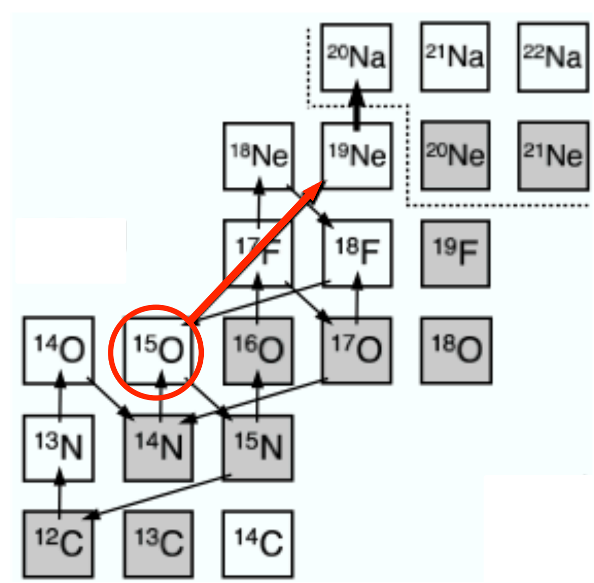
rare isotopes in stars: type I x-ray bursts

- <u>model</u>:
  - binary star system
  - accretion on <u>neutron star</u>
  - thermonuclear runaway



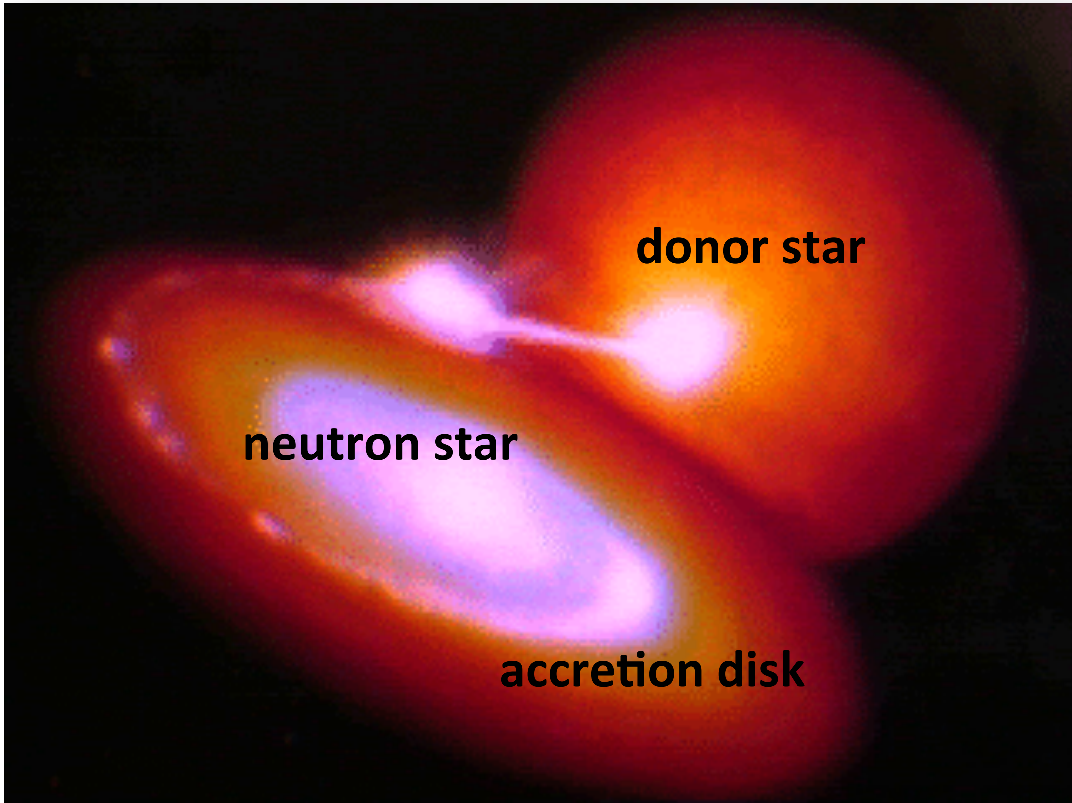
- <u>observations</u>: light curves

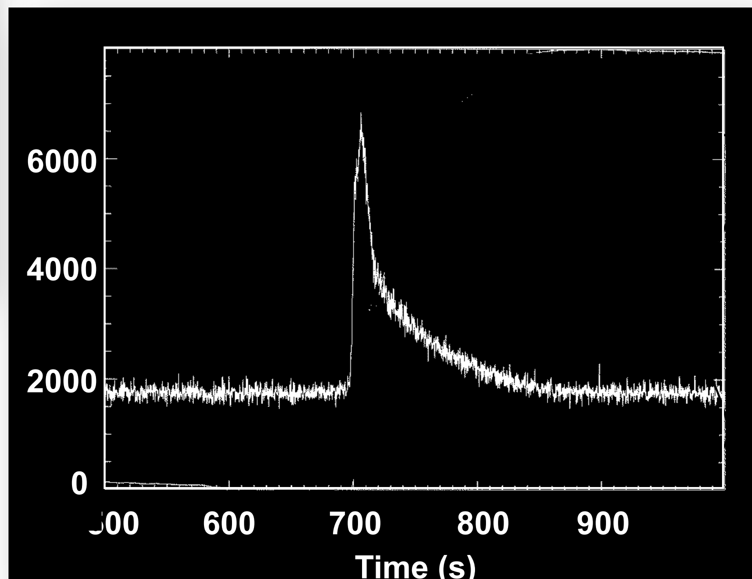
- <u>research areas</u>:
  - Breakout from the Hot-CNO cycles
  - rp-process: path, endpoint, synthesis
  - αp-process → key reactions



- <u>experiments</u>: proton-rich rare isotopes
  - (p,γ) and (α,p) reactions
  - mass measurements

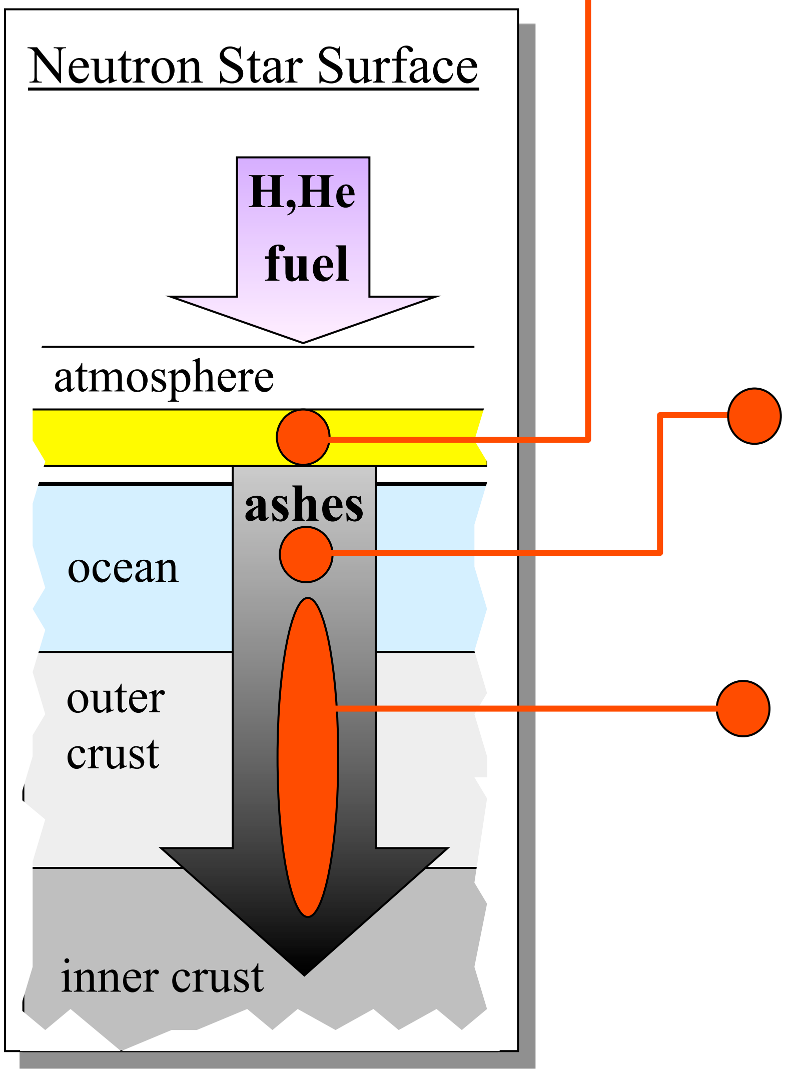
accreting neutron star: x-ray bursts





rp-process on accreting neutron stars

[H. Schatz, NSCL]



thermonuclear burning (rp-process):
burst duration (sec – min)
nucleosynthesis

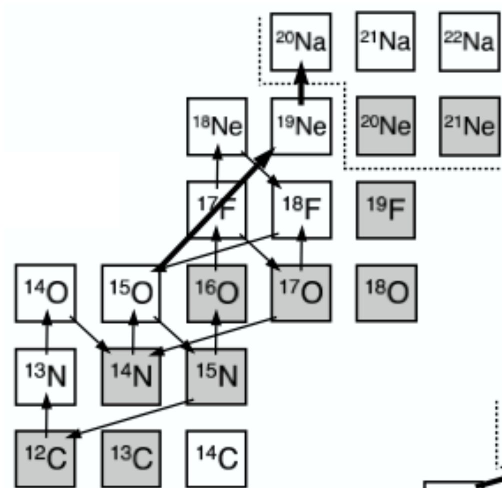
deep hydrogen / carbon burning: superbursts

electron captures / pycnonuclear reactions:
crust heating
dissipation of neutron star's B-field
emission of gravitational waves

rp-process: beginnings

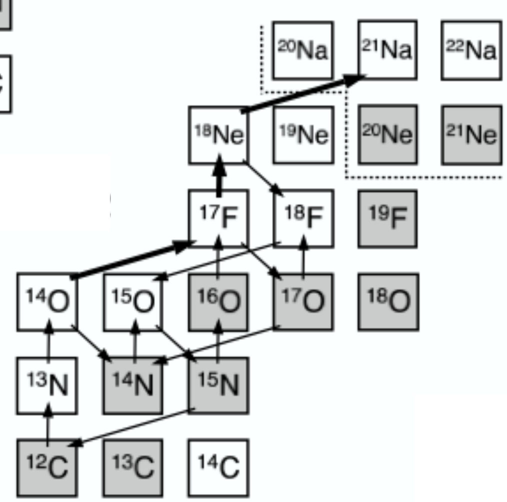
explosive hydrogen-helium burning (T > 0.5 GK)

→ breakout from the Hot-CNO cycles



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

$^{19}Ne(p,\gamma)^{20}Na$



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

$^{14}O(\alpha,p)^{17}F$

$^{17}F(p,\gamma)^{18}Ne$

[figure adapted from C. Iliadis (2007)]

rp-process, cont'd

after breakout from Hot-CNO cycles:

- **(α,p) and (p,γ) on <u>proton-rich</u> nuclei → production of heavier elements**

- **energy generation and timescale set by "waiting-point" nuclei:**

  ***e.g.*, ^{30}S, ^{56}Ni, ^{64}Ge, ^{68}Se**

- **reaction flow: competition between β-decay and reactions**

- **(α,p) and (p,γ) reaction rates:**
  often calculated with statistical models (e.g., Hauser-Feshbach)
  need experimental verification

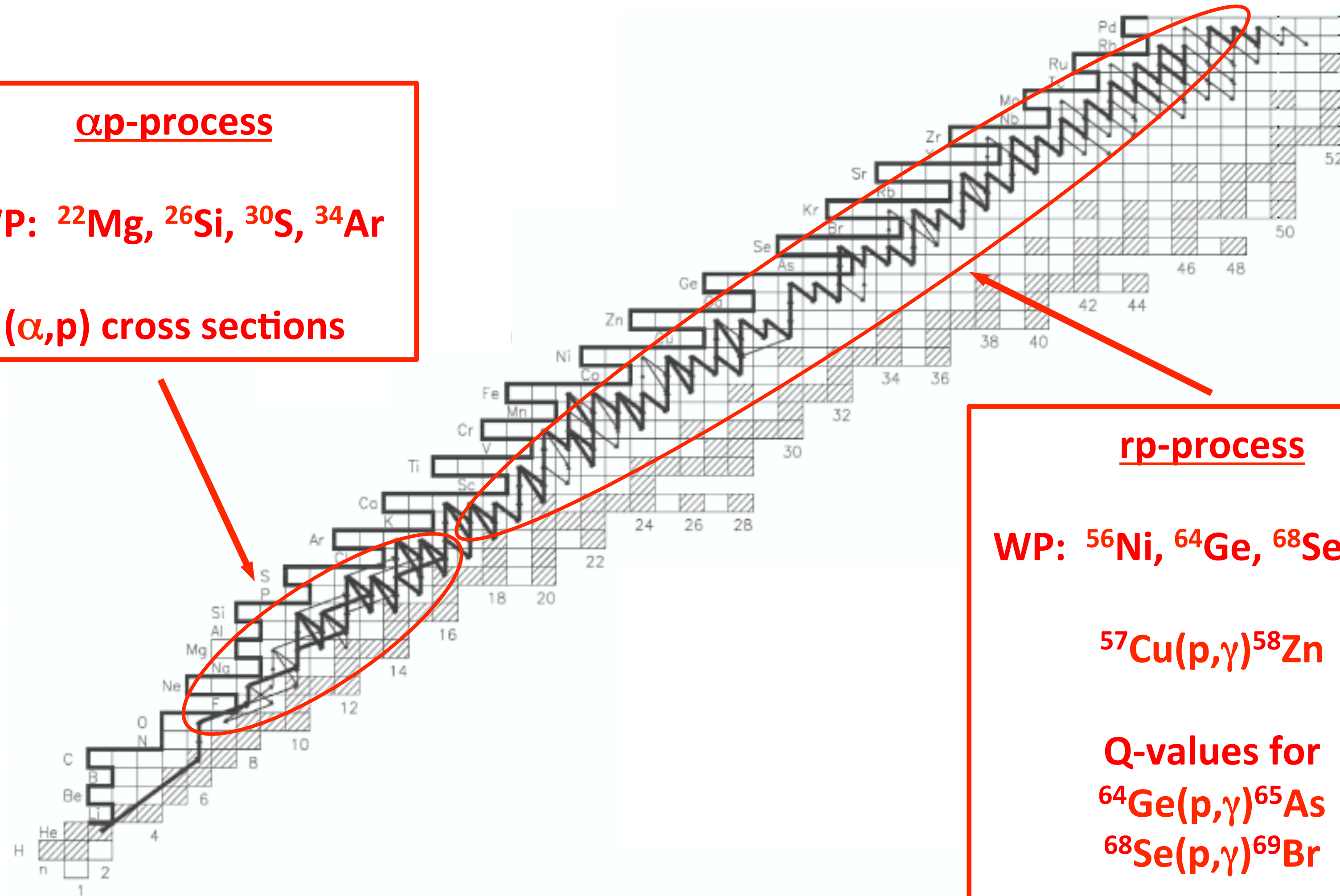
rp-process, cont'd

[type I x-ray burst – neutron star: 1.3M_{sun} , R = 8 km, T_{peak} = 1.4 GK, τ = 100 s]

<u>αp-process</u>

WP: ^{22}Mg, ^{26}Si, ^{30}S, ^{34}Ar

(α,p) cross sections



<u>rp-process</u>

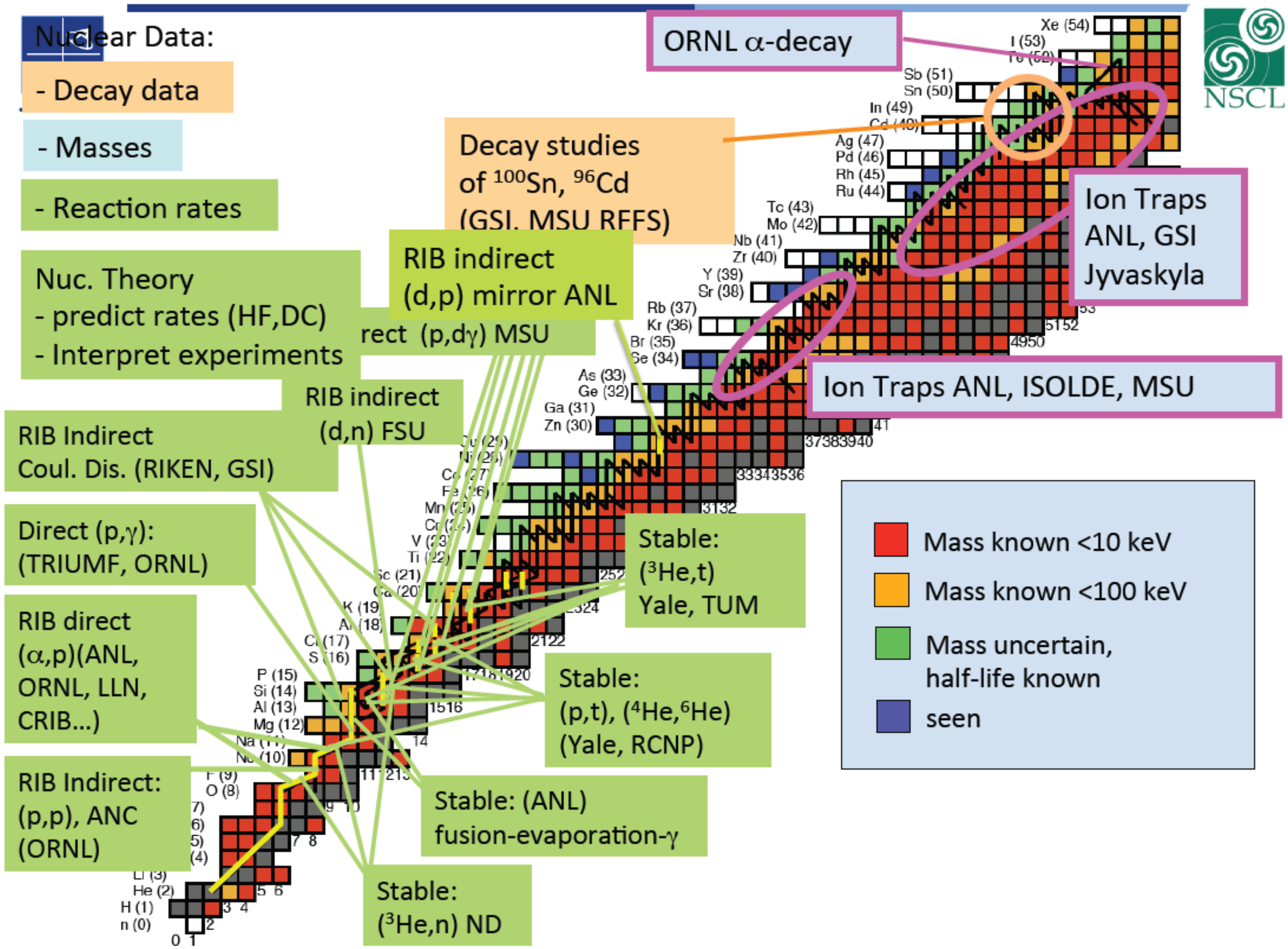
WP: ^{56}Ni, ^{64}Ge, ^{68}Se, ^{72}Kr

^{57}Cu(p,γ)^{58}Zn

Q-values for
^{64}Ge(p,γ)^{65}As
^{68}Se(p,γ)^{69}Br

[nucleosynthesis study: A. Parikh *et al*., Ap.J.Supp. Ser. (2008); PRC (2009)]

rp-process: experiments



[H. Schatz (2012)]

PRL 108, 242701 (2012) PHYSICAL REVIEW LETTERS week ending 15 JUNE 2012

Measurement of the $^{18}Ne(\alpha, p_0)^{21}Na$ Reaction Cross Section in the Burning Energy Region for X-Ray Bursts

P. J. C. Salter,[1] M. Aliotta,[1,*] T. Davinson,[1] H. Al Falou,[2] A. Chen,[2] B. Davids,[2] B. R. Fulton,[3] N. Galinski,[2,4] D. Howell,[2,4] G. Lotay,[1] P. Machule,[2] A. StJ. Murphy,[1] C. Ruiz,[2] S. Sjue,[2] M. Taggart,[3] P. Walden,[2] and P. J. Woods[1]

PHYSICAL REVIEW C 84, 045802 (2011)

First measurement of the $^{33}Cl(p, \alpha)^{30}S$ reaction

C. M. Deibel,[1,2,*] K. E. Rehm,[2] J. M. Figueira,[3,2] J. P. Greene,[2] C. L. Jiang,[2] B. P. Kay,[2] H. Y. Lee,[2] J. C. Lighthall,[2,4] S. T. Marley,[2,4] R. C. Pardo,[2] N. Patel,[2,5] M. Paul,[6] C. Ugalde,[2,7,8] A. Woodard,[2] A. H. Wuosmaa,[4] and G. Zinkann[2]

PRL 106, 252503 (2011) PHYSICAL REVIEW LETTERS week ending 24 JUNE 2011

Ground-State Proton Decay of ^{69}Br and Implications for the ^{68}Se Astrophysical Rapid Proton-Capture Process Waiting Point

A. M. Rogers,[1,2,3,*] M. A. Famiano,[4,3] W. G. Lynch,[1,5,3] M. S. Wallace,[6] F. Amorini,[7] D. Bazin,[1] R. J. Charity,[8] F. Delaunay,[9] R. T. de Souza,[10] J. Elson,[8] A. Gade,[1,5] D. Galaviz,[1,3] M.-J. van Goethem,[11] S. Hudan,[10] J. Lee,[1] S. Lobastov,[12] S. Lukyanov,[12] M. Matoš,[1,3] M. Mocko,[6] H. Schatz,[1,5,3] D. Shapira,[13] L. G. Sobotka,[8] M. B. Tsang,[1] and G. Verde[14]

PRL 106, 112501 (2011) PHYSICAL REVIEW LETTERS week ending 18 MARCH 2011

Direct Mass Measurements of Short-Lived $A = 2Z - 1$ Nuclides ^{63}Ge, ^{65}As, ^{67}Se, and ^{71}Kr and Their Impact on Nucleosynthesis in the *rp* Process

X. L. Tu,[1,2] H. S. Xu,[1,*] M. Wang,[1] Y. H. Zhang,[1] Yu. A. Litvinov,[3,4,1] Y. Sun,[5,1] H. Schatz,[6] X. H. Zhou,[1] Y. J. Yuan,[1] J. W. Xia,[1] G. Audi,[7] K. Blaum,[3] C. M. Du,[1,2] P. Geng,[1,2] Z. G. Hu,[1] W. X. Huang,[1] S. L. Jin,[1,2] L. X. Liu,[1,2] Y. Liu,[1] X. Ma,[1] R. S. Mao,[1] B. Mei,[1] P. Shuai,[8] Z. Y. Sun,[1] H. Suzuki,[9] S. W. Tang,[1,2] J. S. Wang,[1] S. T. Wang,[1,2] G. Q. Xiao,[1] X. Xu,[1,2] T. Yamaguchi,[10] Y. Yamaguchi,[11] X. L. Yan,[1,2] J. C. Yang,[1] R. P. Ye,[1,2] Y. D. Zang,[1,2] H. W. Zhao,[1] T. C. Zhao,[1] X. Y. Zhang,[1] and W. L. Zhan[1]