Which nuclear reactions are important for X-ray bursts?

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Overview of talk

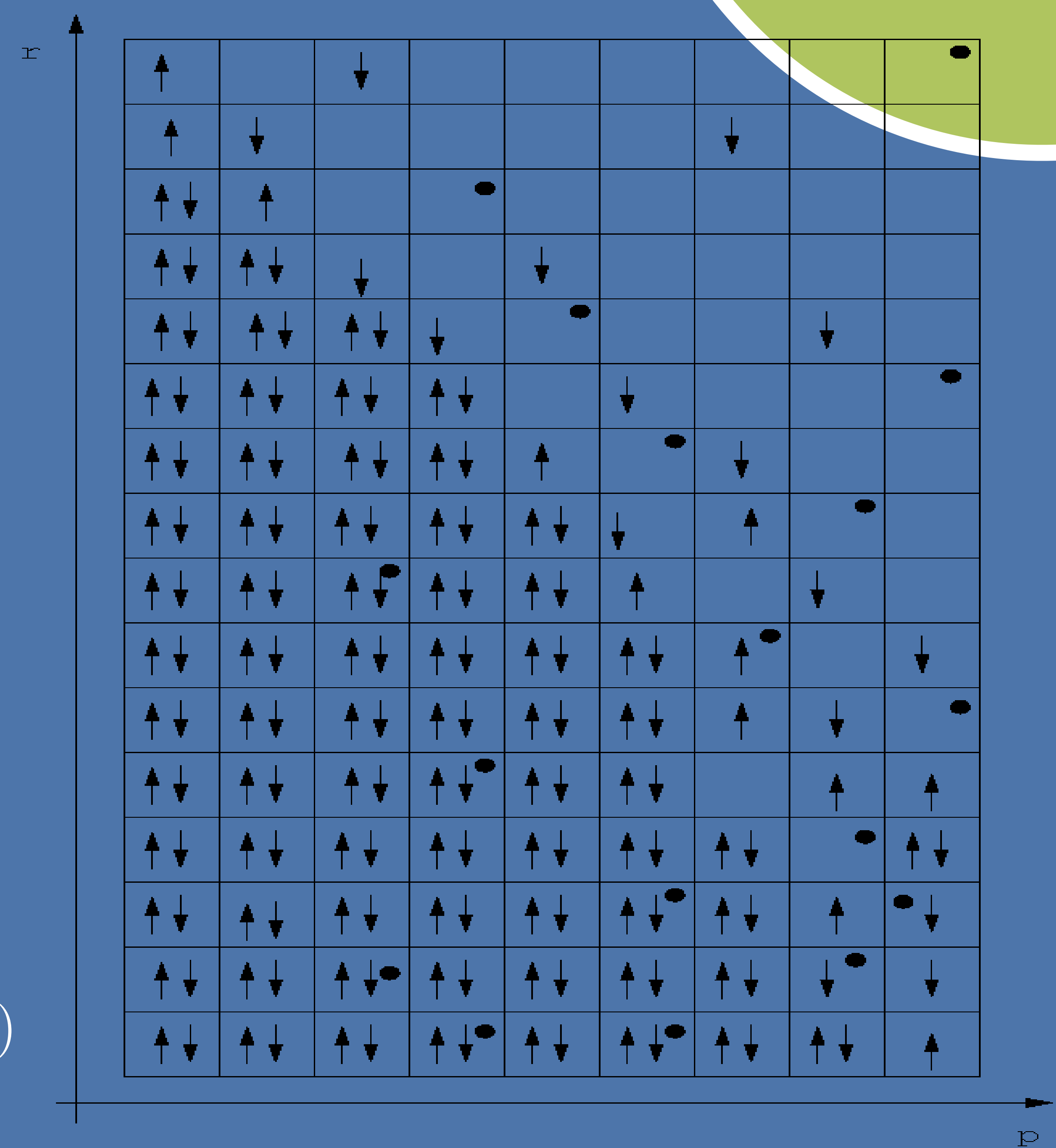
- X-ray burst site.
- X-ray burst theory
  - the thermonuclear flash model.
- Nuclear reaction flow.
- Identifying important reactions.

X-ray burst site

- A binary system with a low mass star and a high mass star.
- High mass star turns into a supernova which leaves a neutron star.
- Roche lobe overflow transfers mass to the neutron star.
- Distance is 100000km but neutron star is 15-20km across so excess angular momentum forms an accretion disk.
- Photospheric impact fully ionizes matter and turns kinetic energy into persistent X-rays.
- Matter accumulates on the surface.

Thermonuclear flash model

- Increasing density the Pauli principle prevents more than two electrons in the same minimum phase space volume
  ➟ **`FD-distribution`**
  ➟ **`High electron pressure`**
- Thermal electrons can't interact much
  ➟ $P_{e^-}(\rho, T) \simeq P_{e^-}(\rho)$
- Equipartion energy: $\overline{E}_{e^-} = \overline{E}_{nuc}$
- $\overline{E}_{e^-} = \overline{E}_{nuc} \rightarrow \overline{p}_{e^-} \ll \overline{p}_{nuc}$
  ➟Nucleons are NOT degenerate
  ➟MB distribution
- $P_{nuc} \ll P_{e^-} \rightarrow P = P_{nuc} + P_{e^-} = P_{e^-}(\rho)$
- But thermal nucleons interact
  ⇨ Runaway!



Runaway!

rp-process

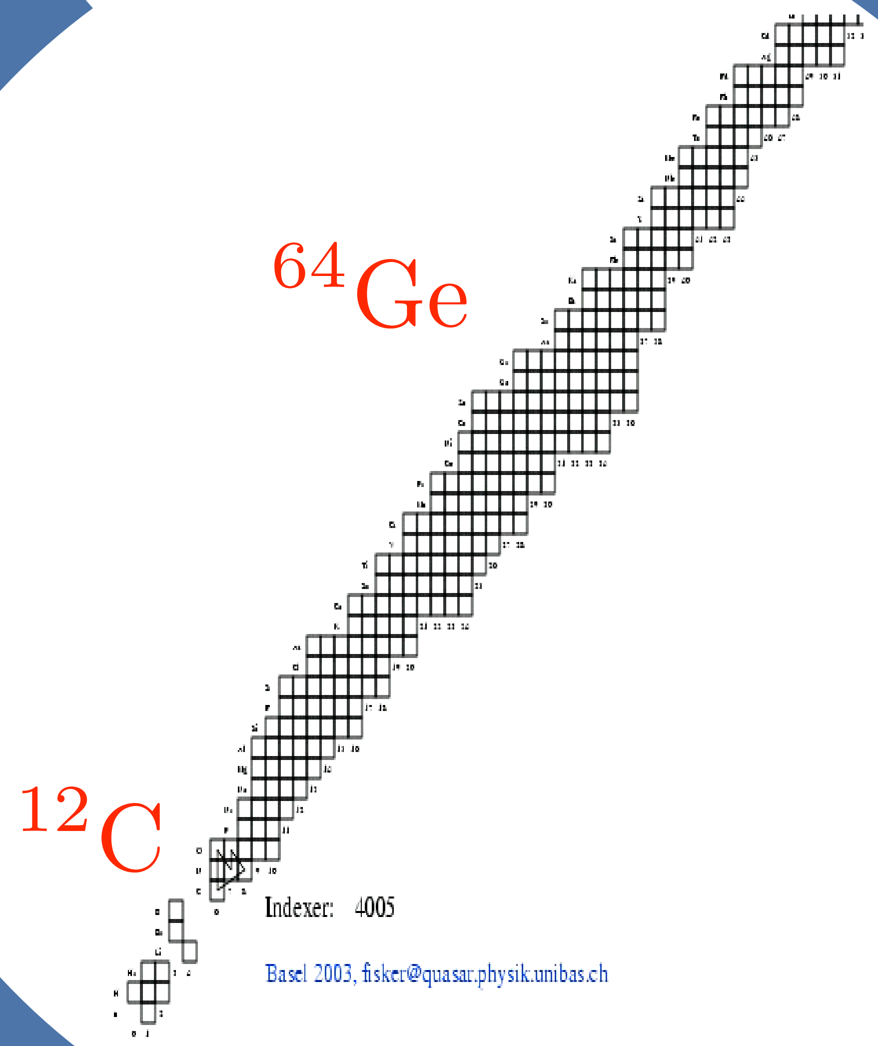
$\beta^+ \quad (p,\gamma)$

αp-process

$(\alpha,p) \quad (p,\gamma)$

photo–disintegration

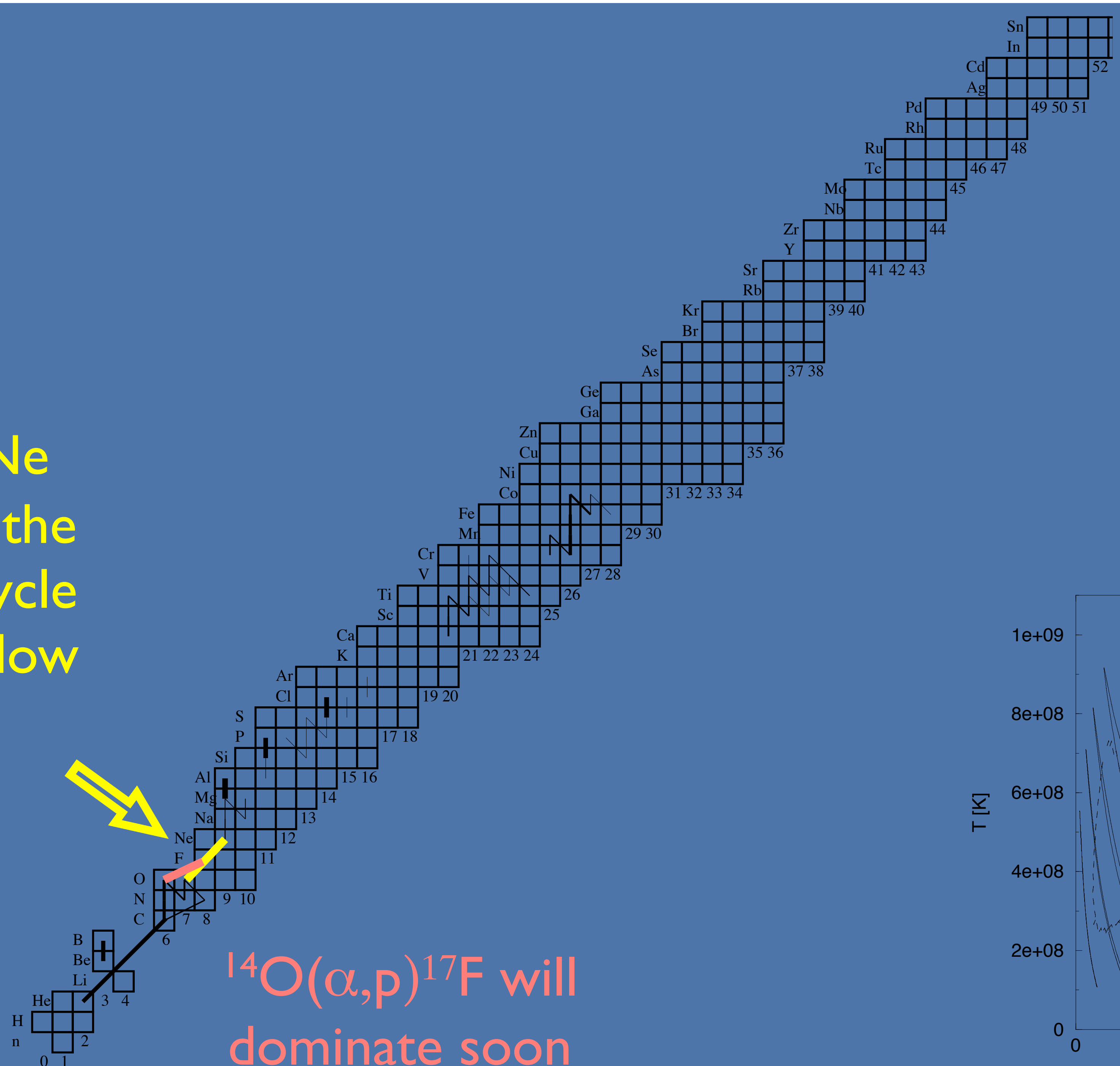
$(p,\gamma),(\gamma,p)$



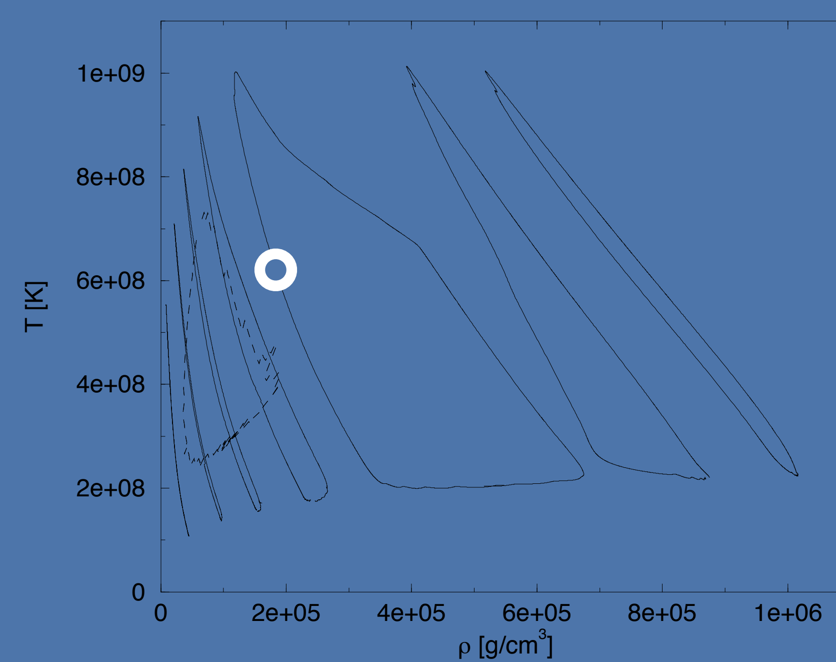
rapid proton-Process

Nuclear reaction flow

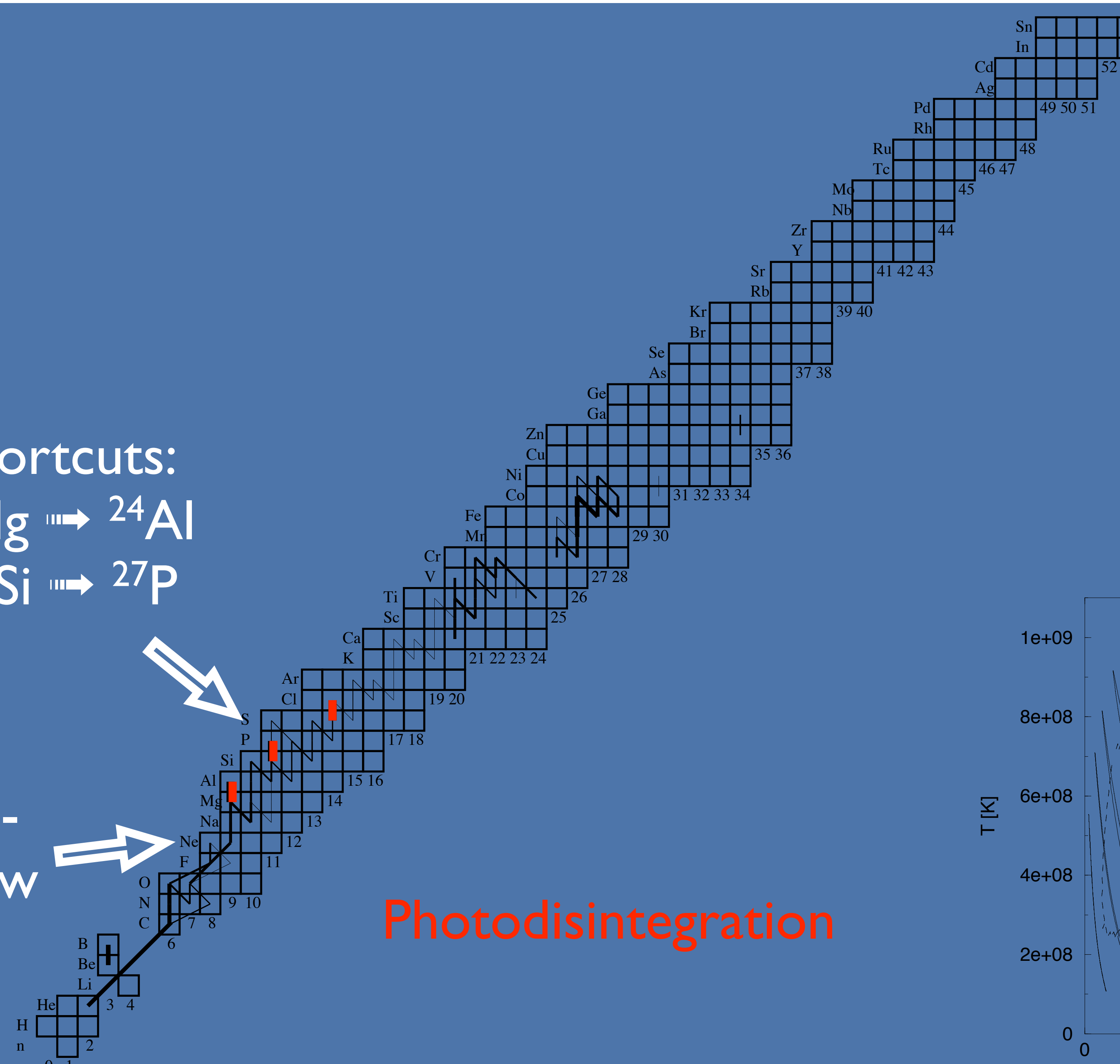
$^{15}O(\alpha,\gamma)^{19}Ne$ breakout of the hot CNO-cycle establishes flow to ^{30}S



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



Nuclear reaction flow



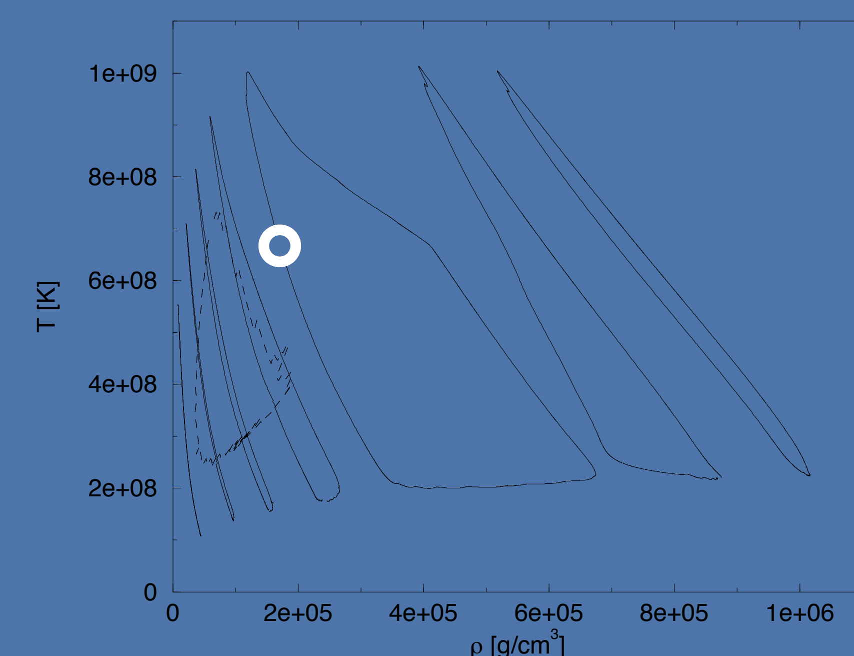
Shortcuts:

^{22}Mg ⇢ ^{24}Al

^{25}Si ⇢ ^{27}P

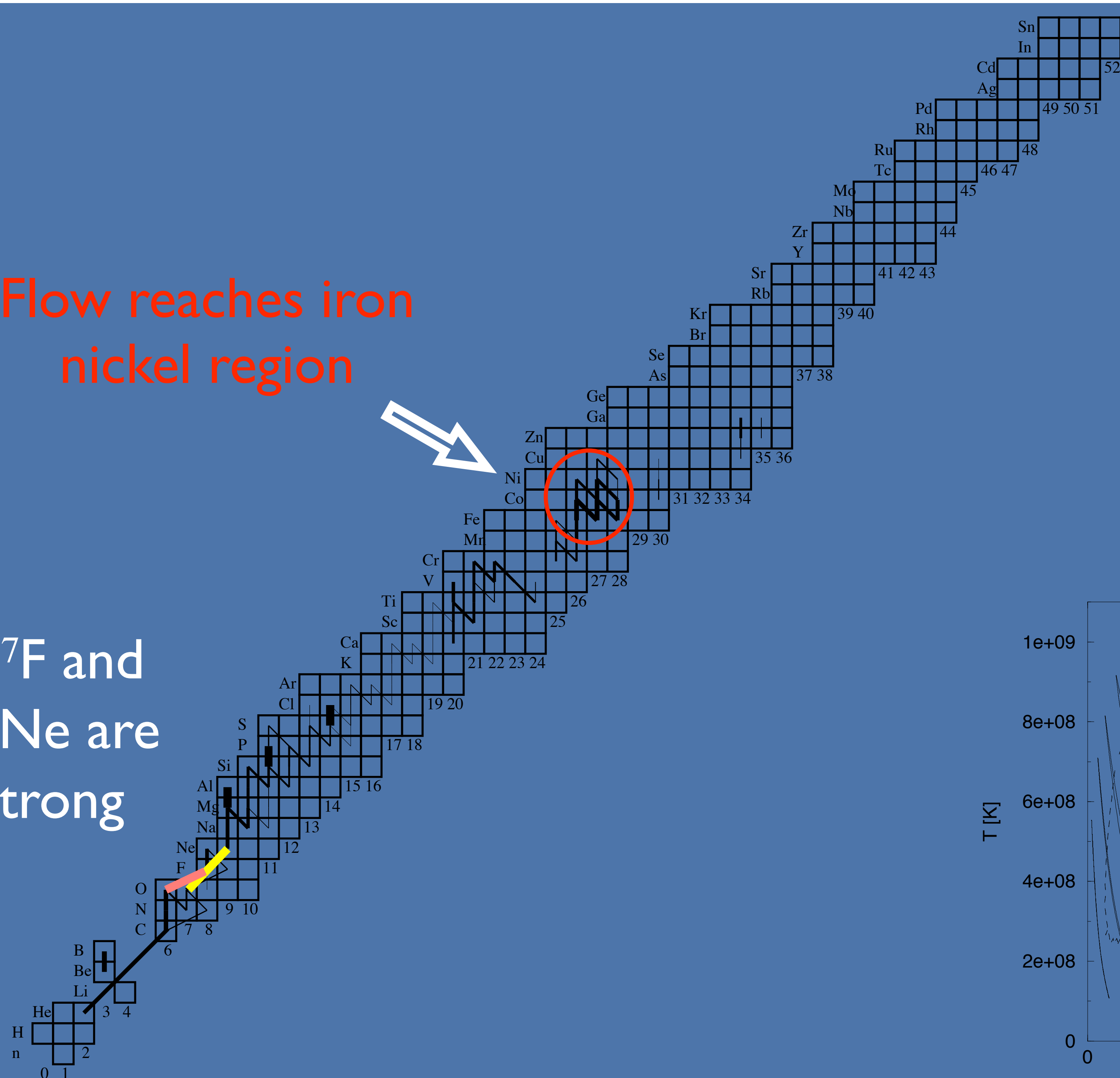
Hot CNO bi-cycle halts flow

Photodisintegration

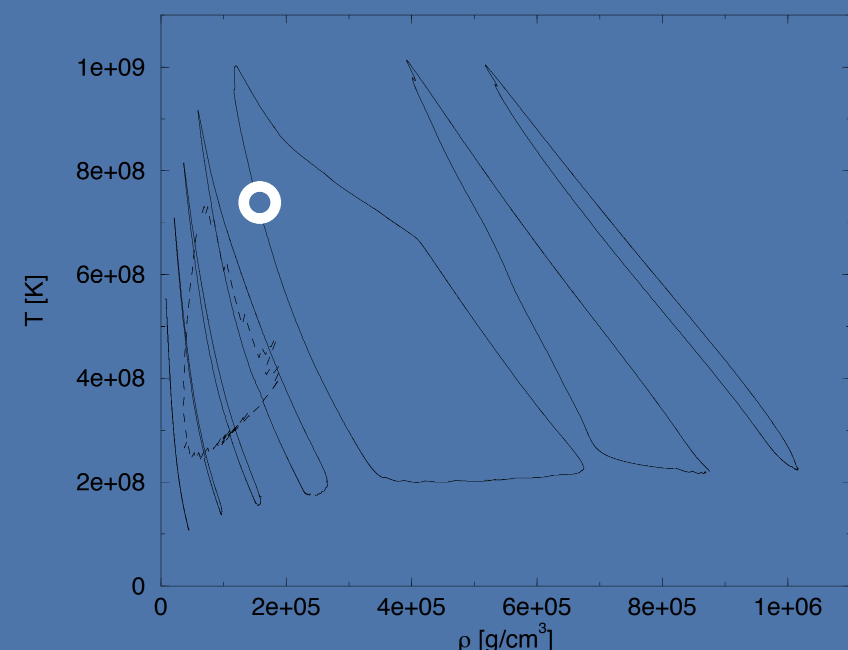


Nuclear reaction flow

Flow reaches iron nickel region



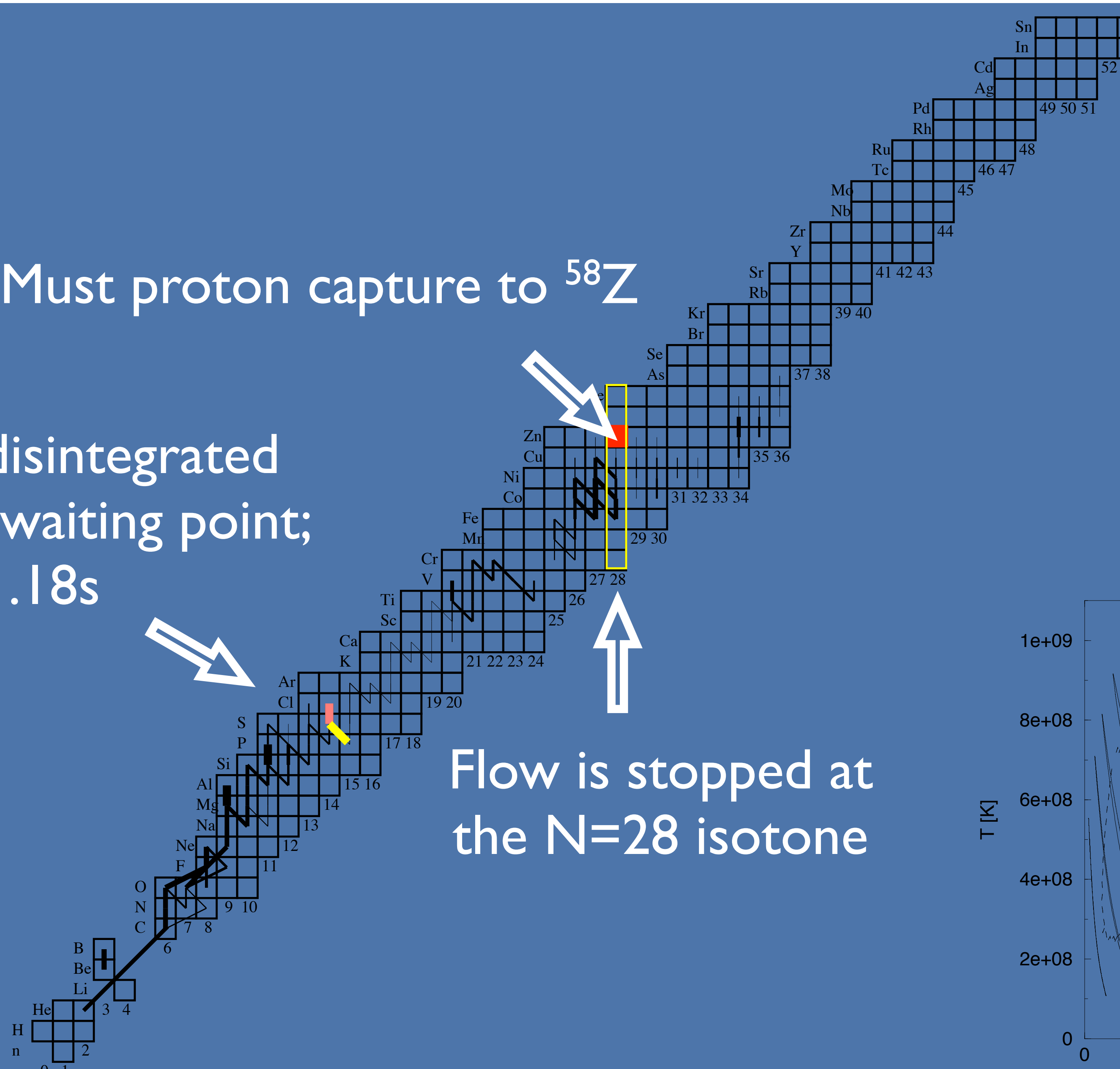
$^{14}O(\alpha,p)^{17}F$ and $^{15}O(\alpha,\gamma)^{19}Ne$ are equally strong



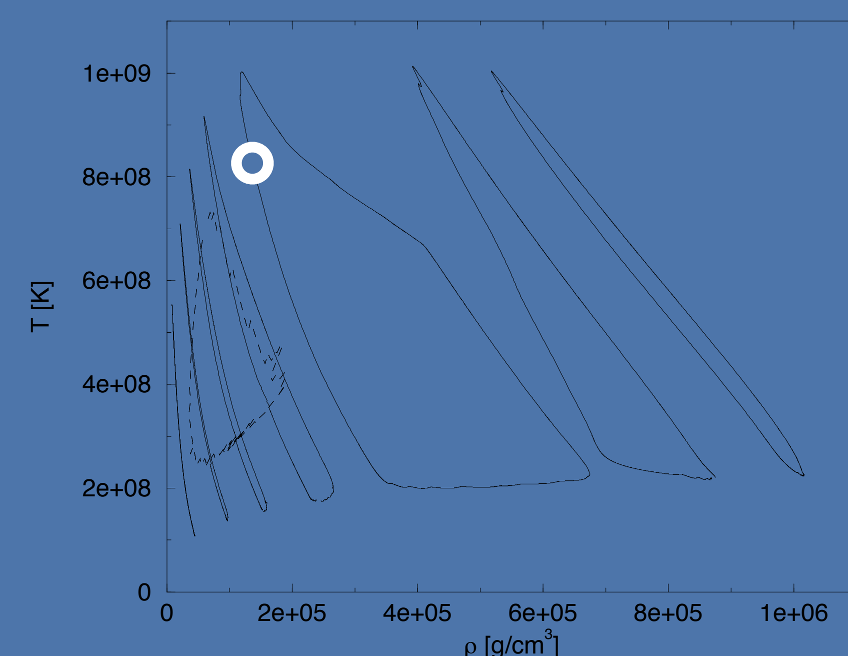
Nuclear reaction flow

Must proton capture to ^{58}Z

^{31}Cl is photodisintegrated
^{30}S becomes a waiting point;
$T_{1/2}$=1.18s

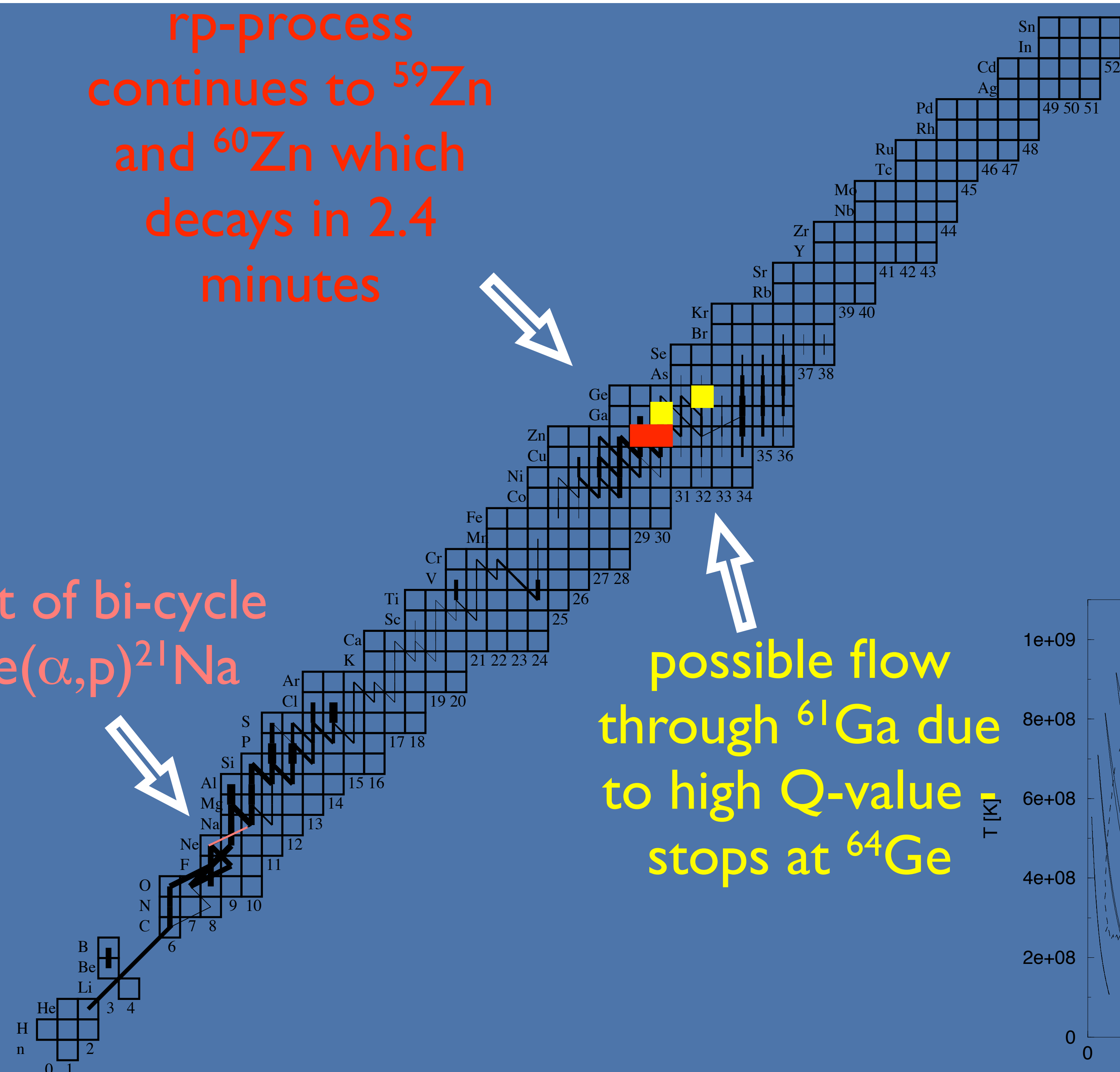


Flow is stopped at the N=28 isotone



Nuclear reaction flow

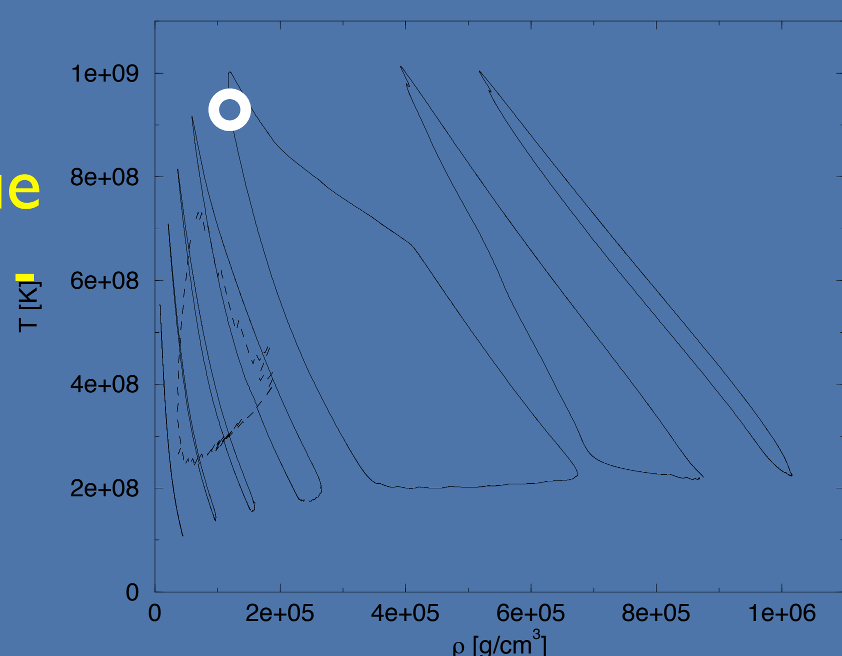
rp-process continues to ^{59}Zn and ^{60}Zn which decays in 2.4 minutes



Breakout of bi-cycle via $^{18}Ne(\alpha,p)^{21}Na$

^{14}O is destroyed immediately upon creation. Formation rate of ^{15}O declines

possible flow through ^{61}Ga due to high Q-value - stops at ^{64}Ge

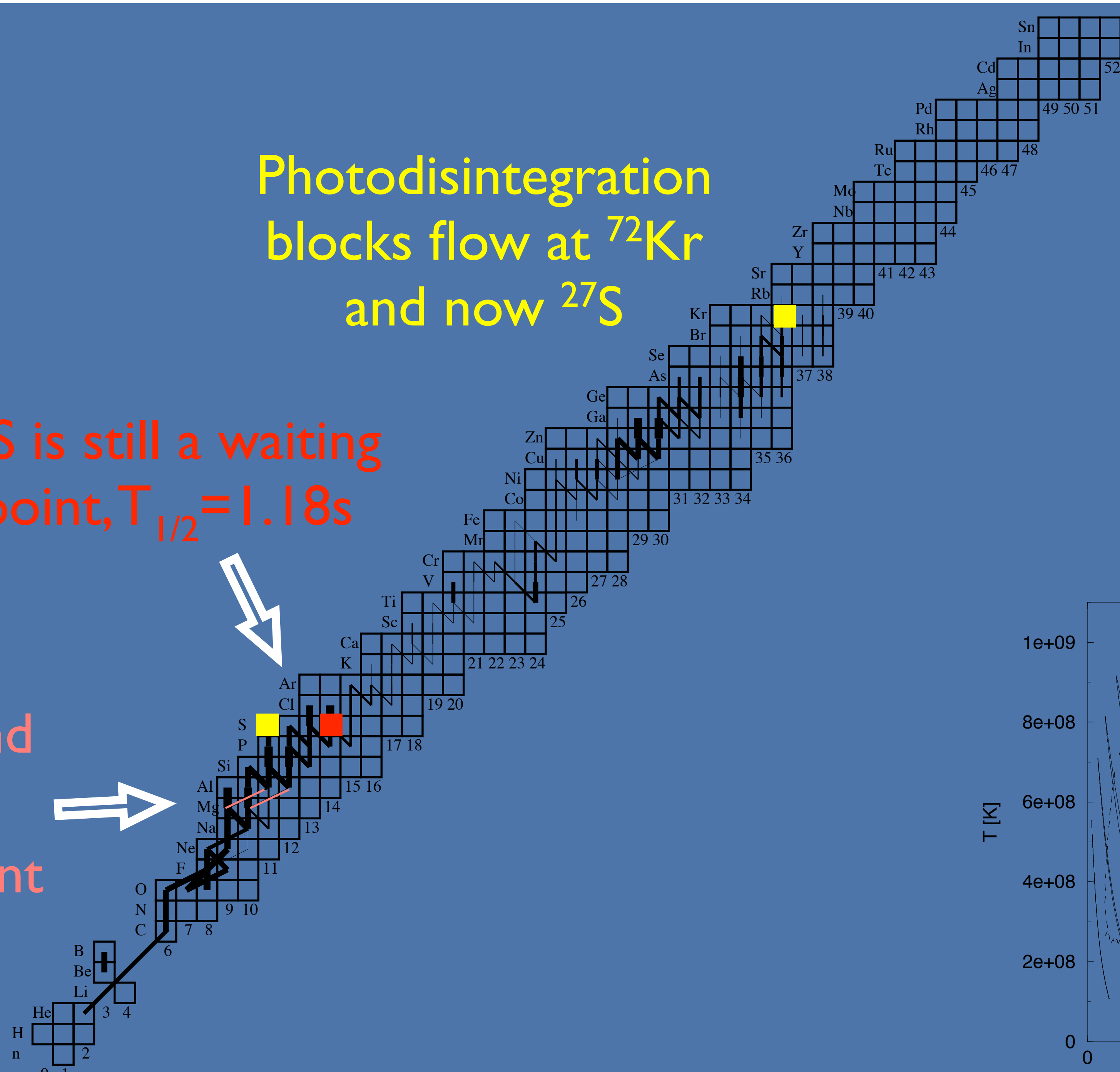


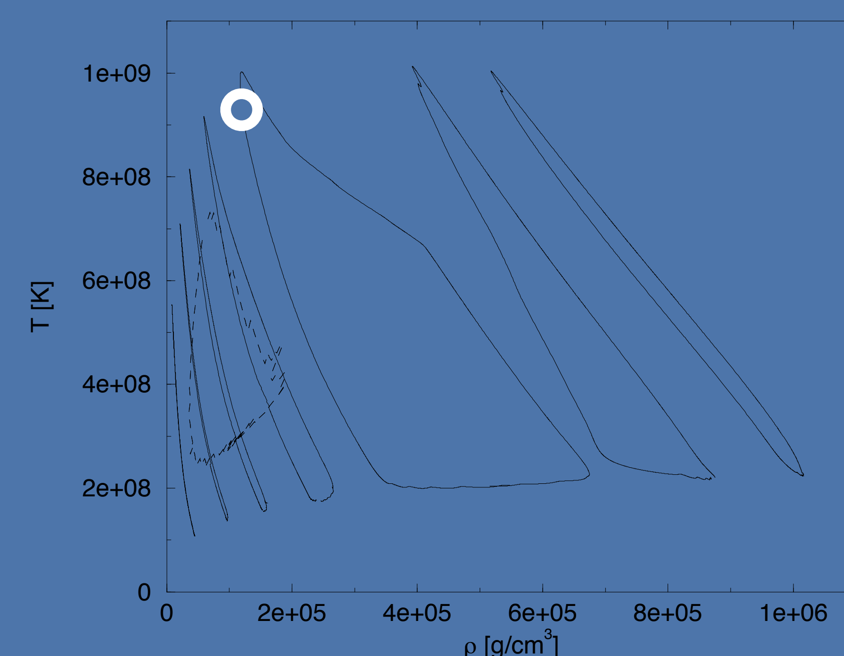
Nuclear reaction flow

Photodisintegration blocks flow at ^{72}Kr and now ^{27}S

^{30}S is still a waiting point, $T_{1/2}$=1.18s

^{21}Mg(α,p)^{24}Al and ^{22}Mg(α,p)^{25}Al, become significant

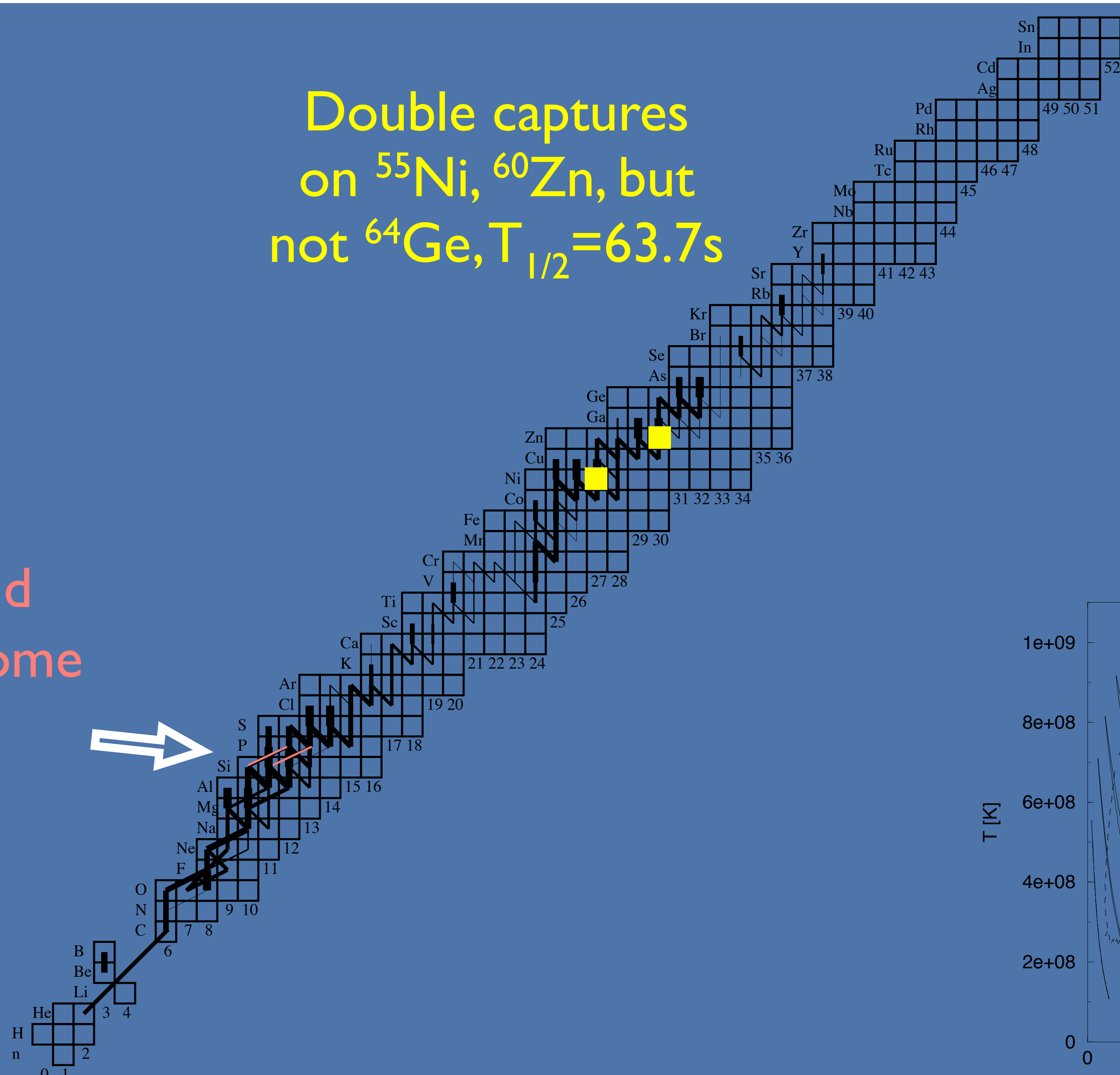


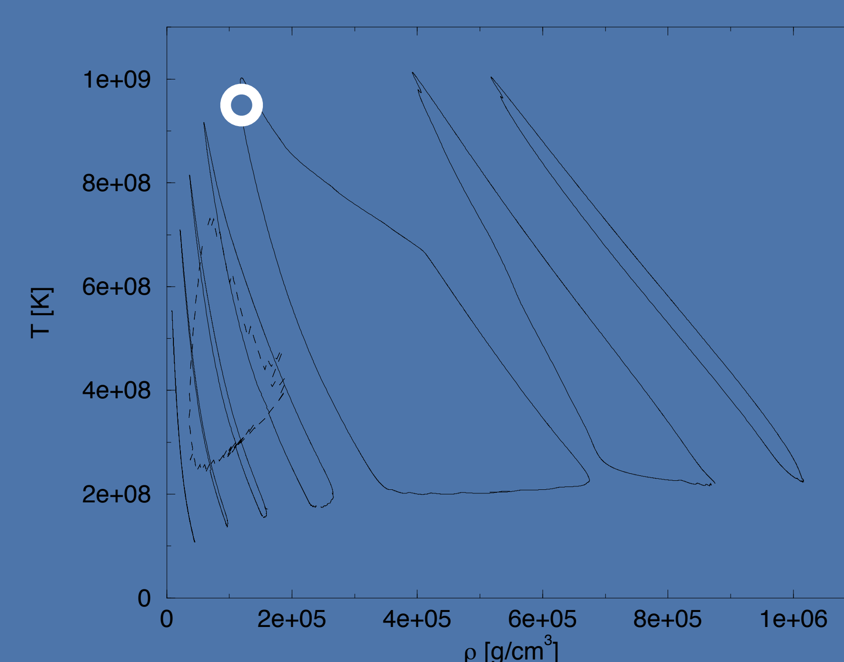


Nuclear reaction flow

Double captures on ^{55}Ni, ^{60}Zn, but not ^{64}Ge, $T_{1/2}$=63.7s

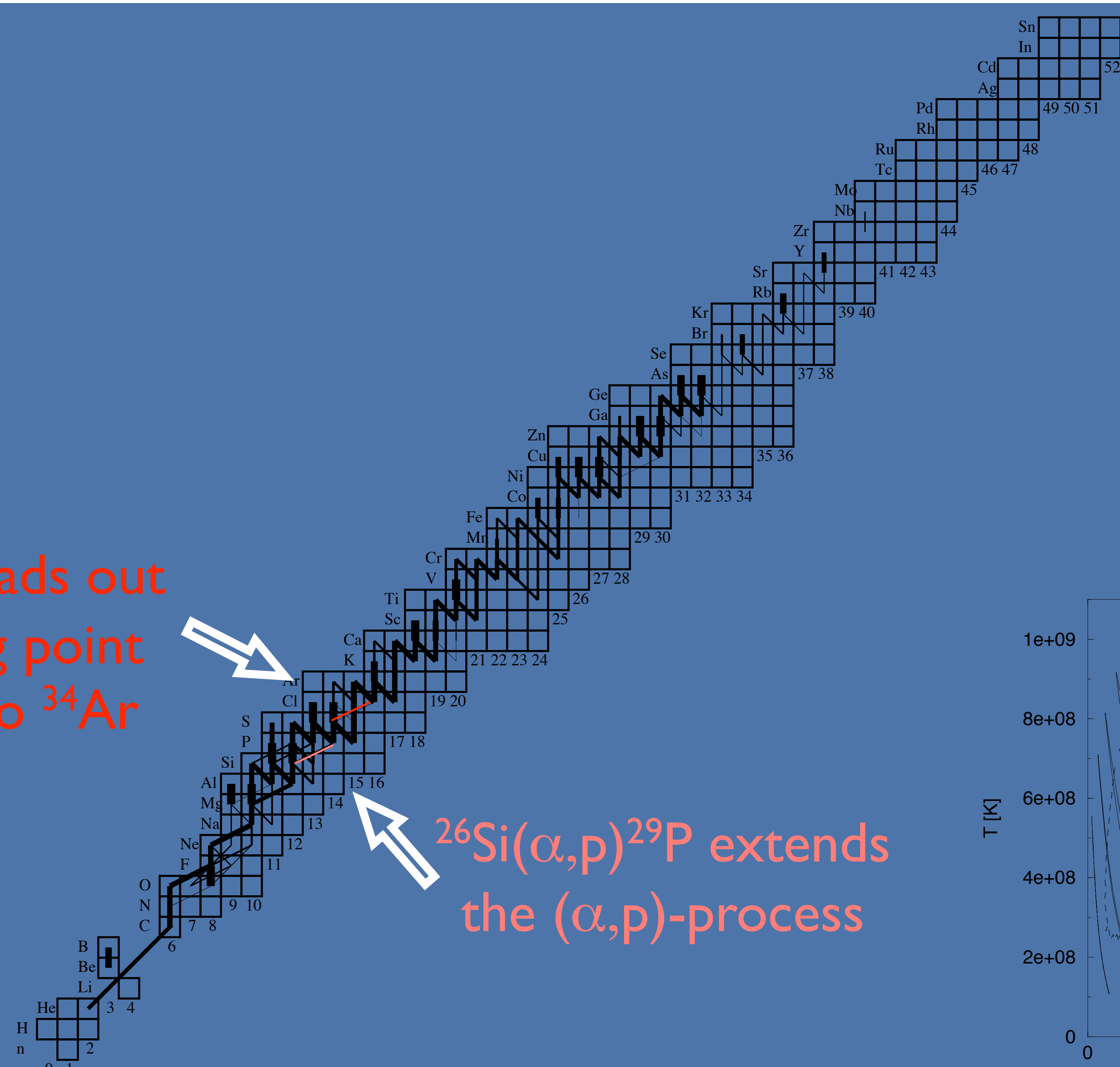
^{24}Si(α,p)^{27}P and ^{25}Si(α,p)^{28}P, become significant



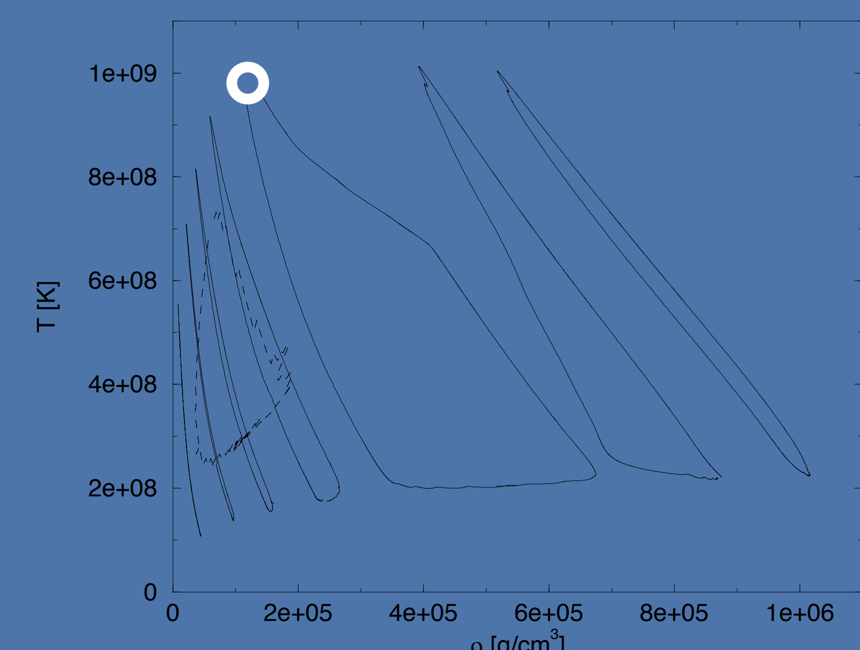


Nuclear reaction flow

$^{30}S(\alpha,p)^{33}Cl$ leads out of the waiting point but only up to ^{34}Ar

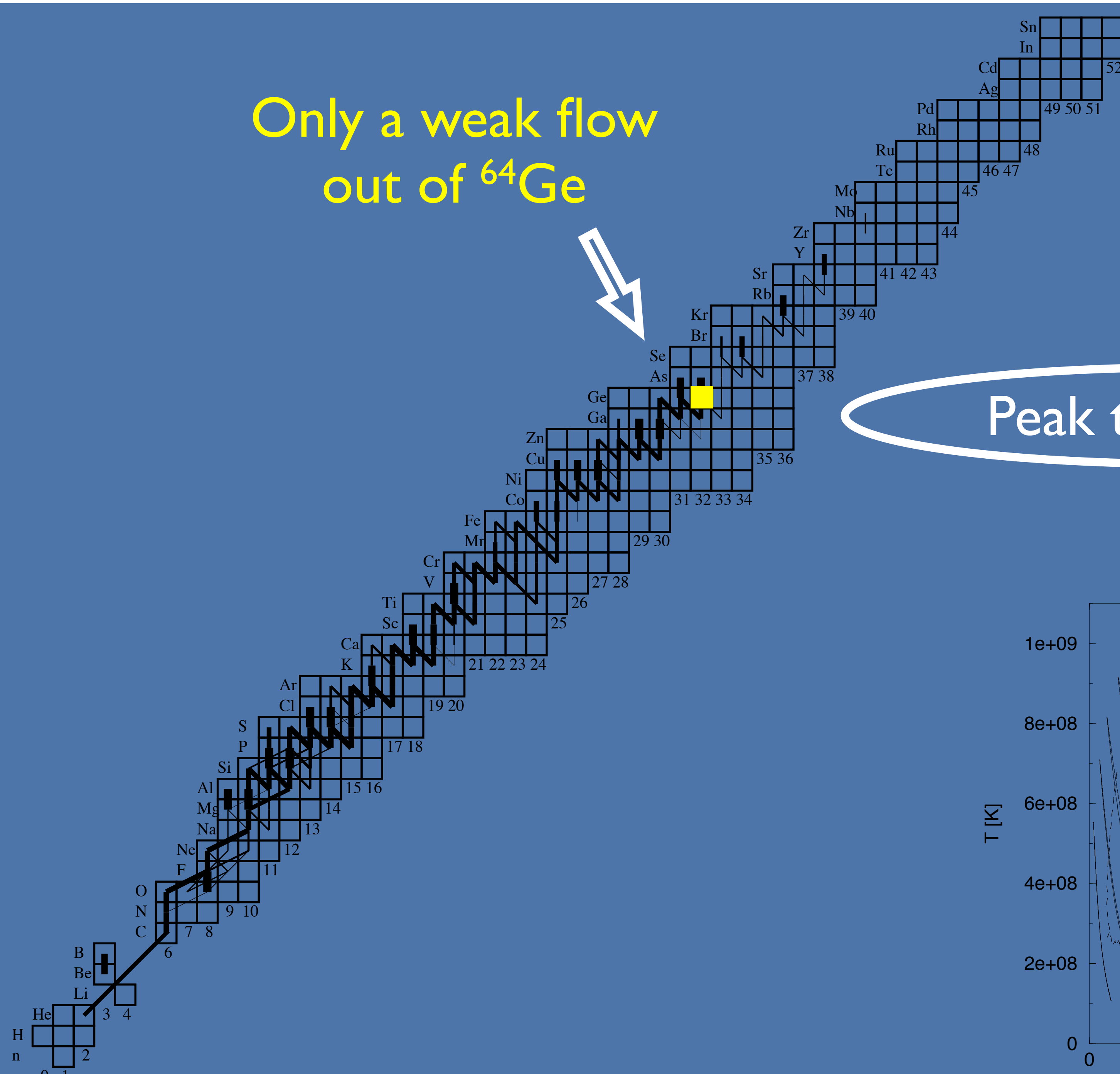


$^{26}Si(\alpha,p)^{29}P$ extends the (α,p)-process

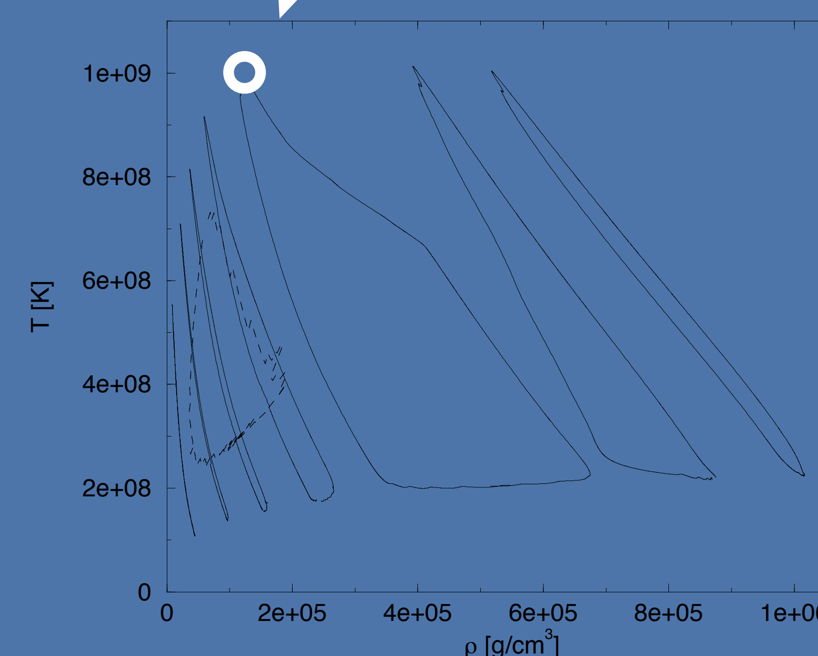


Nuclear reaction flow

Only a weak flow out of ^{64}Ge



Peak temperature

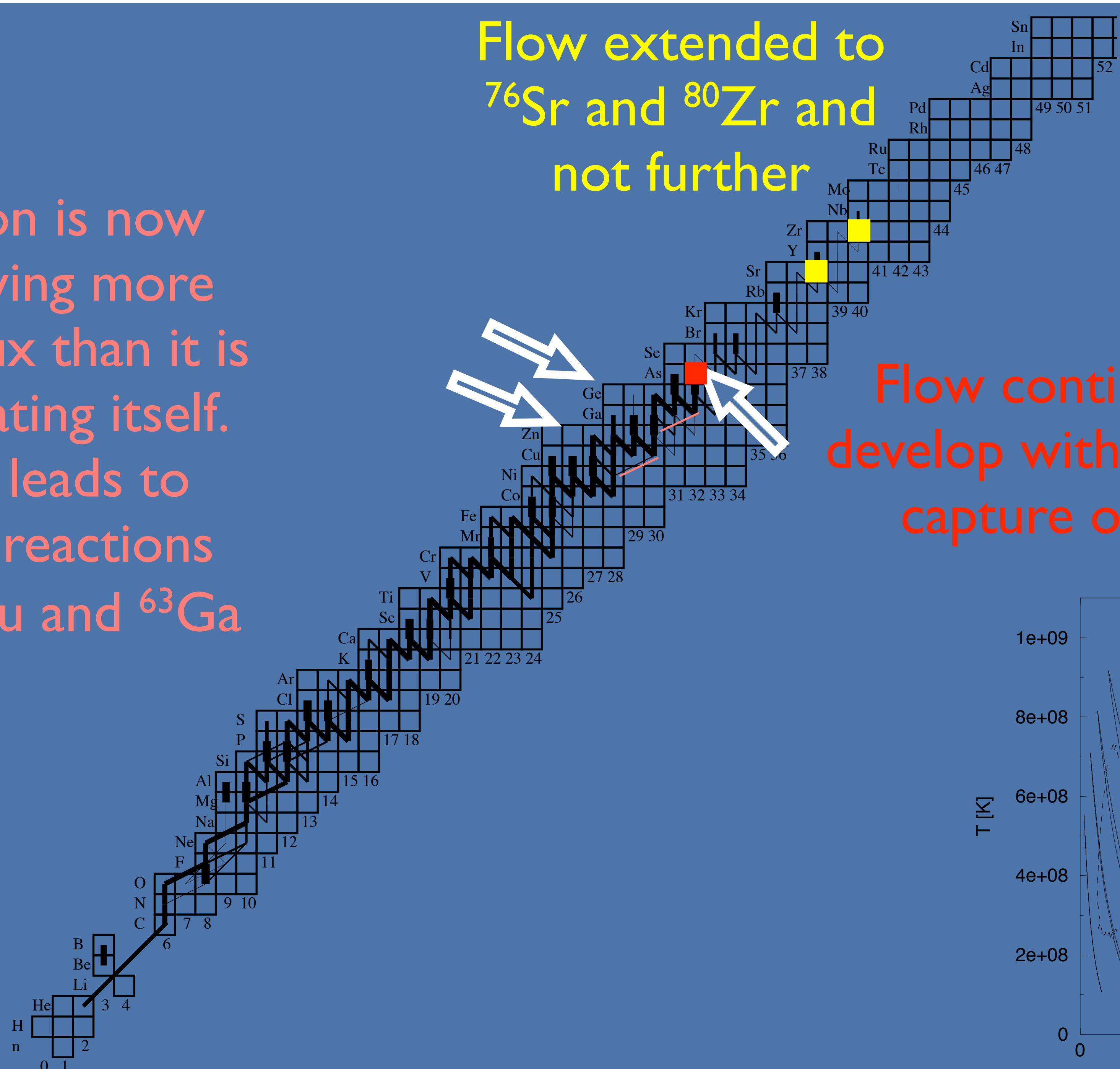


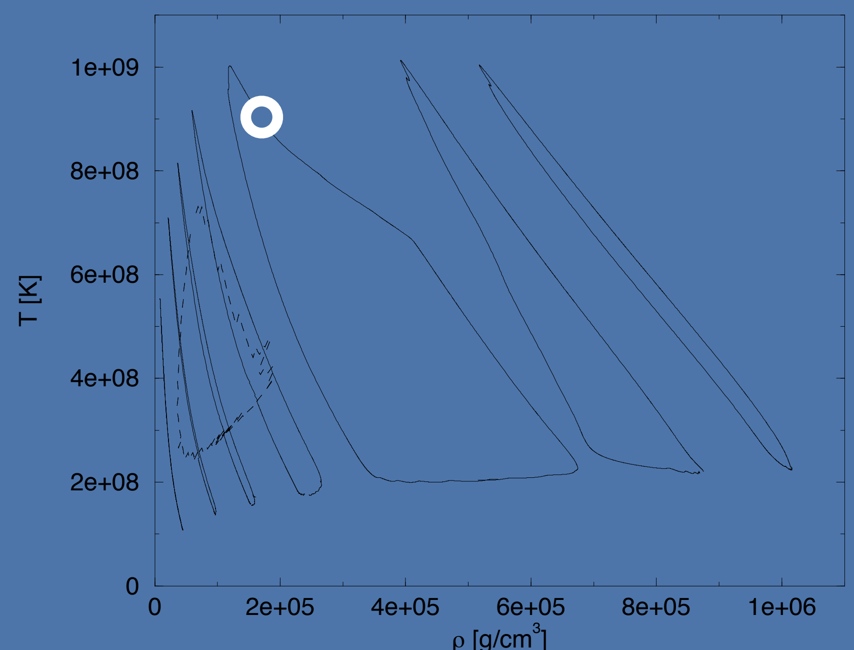
Nuclear reaction flow

Region is now receiving more heat flux than it is generating itself. This leads to (p,α)-reactions on ^{59}Cu and ^{63}Ga

Flow extended to ^{76}Sr and ^{80}Zr and not further

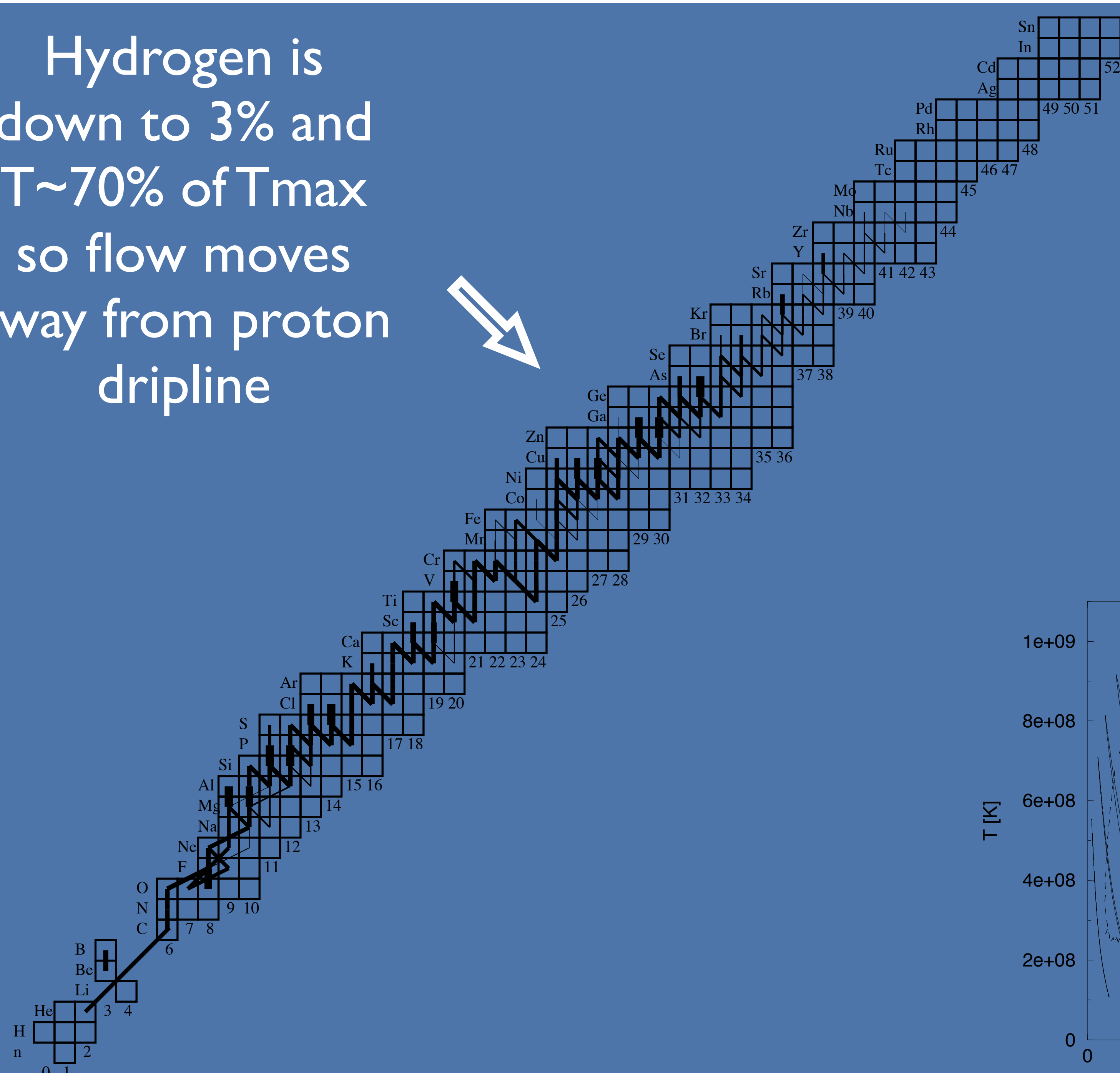
Flow continues to develop with a proton capture on ^{65}As

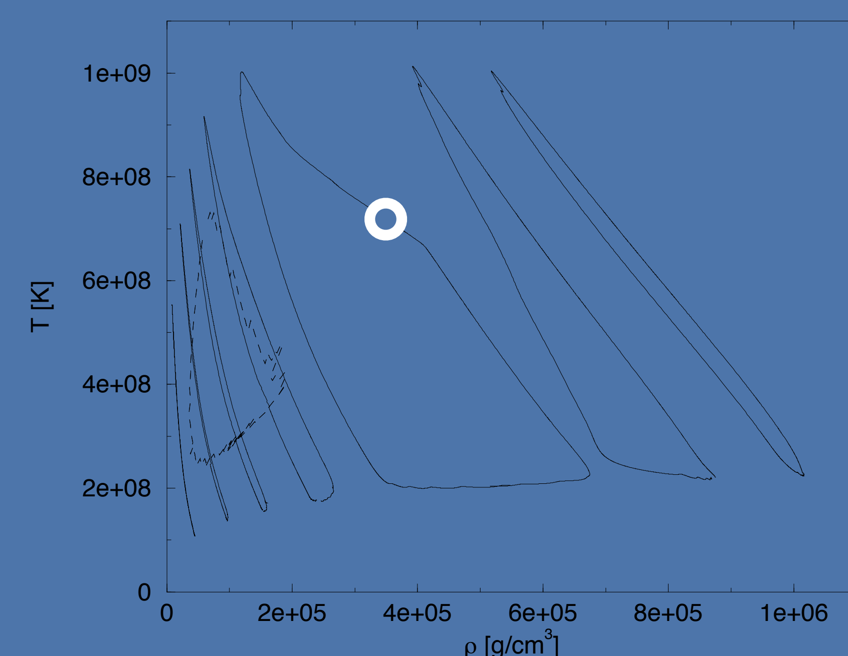




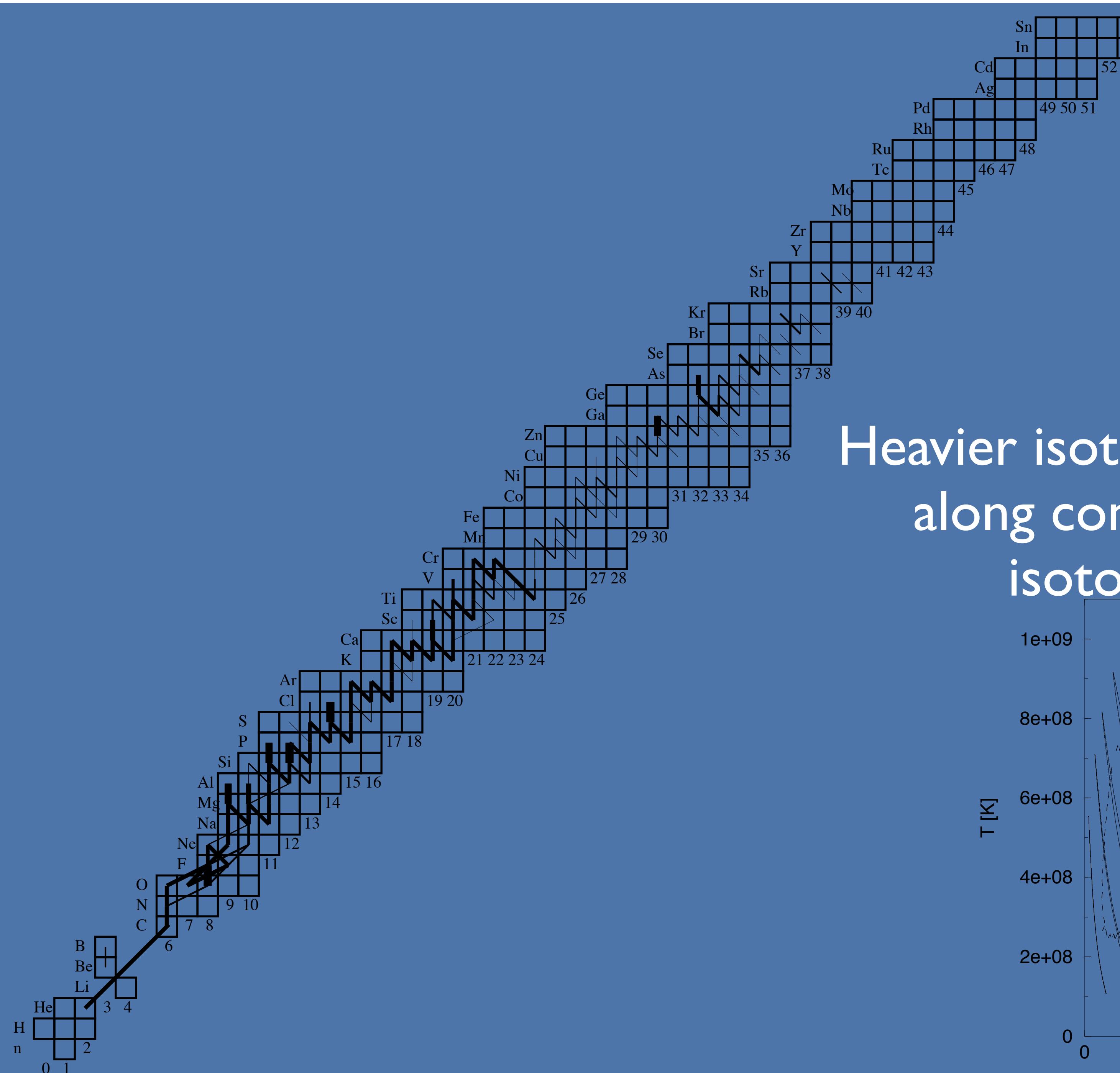
Nuclear reaction flow

Hydrogen is down to 3% and T~70% of Tmax so flow moves away from proton dripline

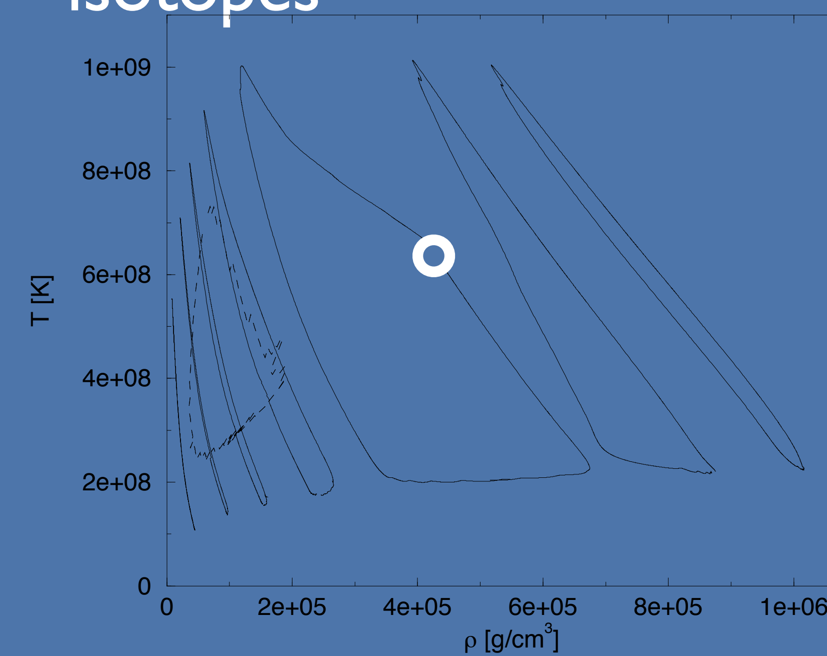




Nuclear reaction flow



Heavier isotopes decay along constant A isotopes



Hydrogen is practically gone

Identifying important rates

- Rates that can be/have been measured.
- Rates that have the largest experimental or theoretical uncertainty.
- Rates that have the largest reaction flow, sit at branching points,... in multi-zone models.
- Monte Carlo methods, one-zone models,...
- (Brute force methods).

Identifying important reactions "How-To"

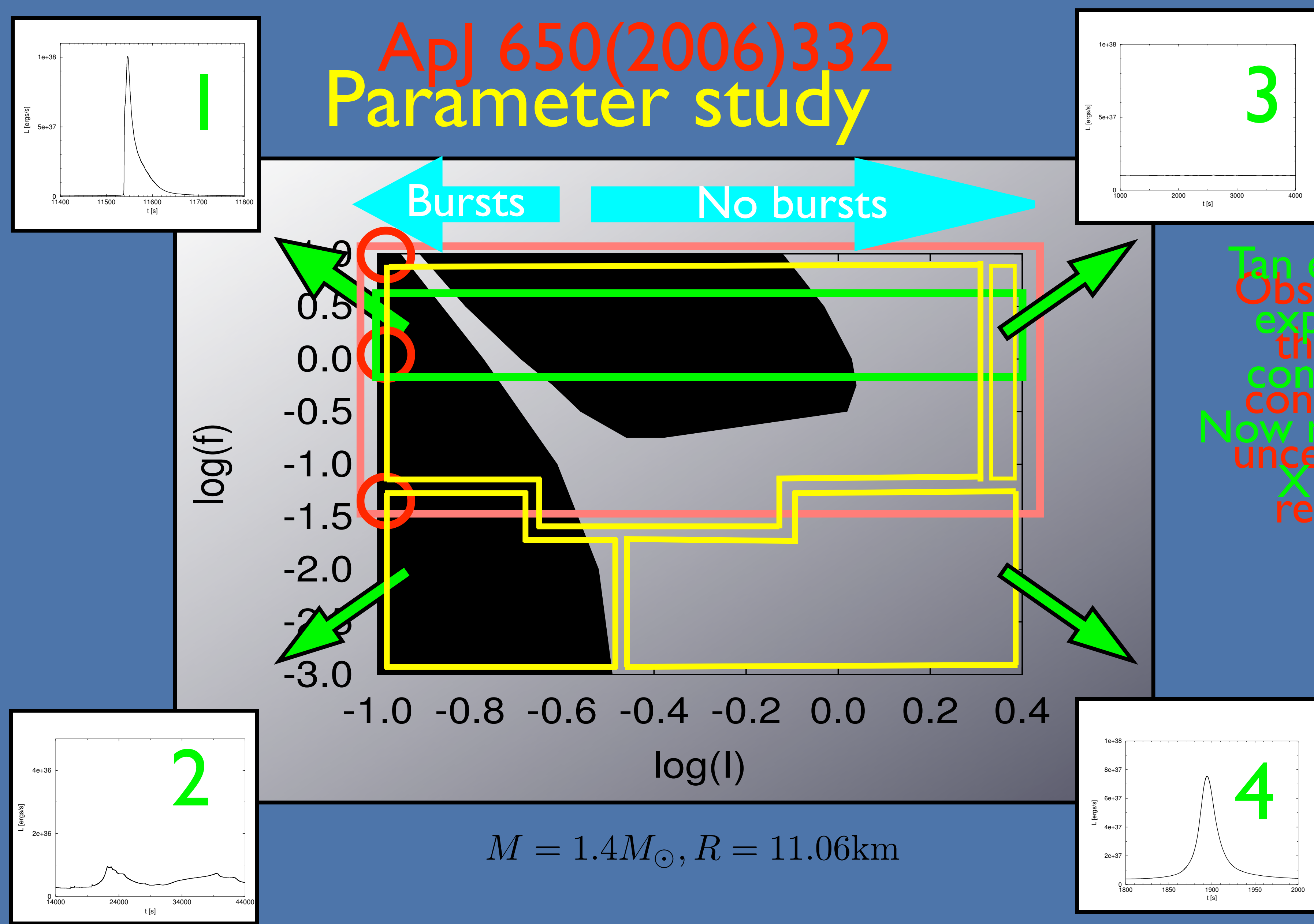
- RXTE and ROSAT (1990s): Excellent timing resolution
  ⇨ identifying bumps in light curves as nuclear reactions.
  Galloway et al., ApJ 601(2004)466
  Fisker et al., ApJ 608(2004)L61
- Chandra and XMM (2000s): Excellent spectral resolution
  ⇨ identifying spectral lines in light curves?
  Weinberg et al. ApJ 639(2006)1018

Investigate the uncertainty of the systemic behavior as a function of the uncertainty of the reaction rates.

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

Fisker, Görres, Wiescher, Davids
ApJ 650(2006)332

Parameter study



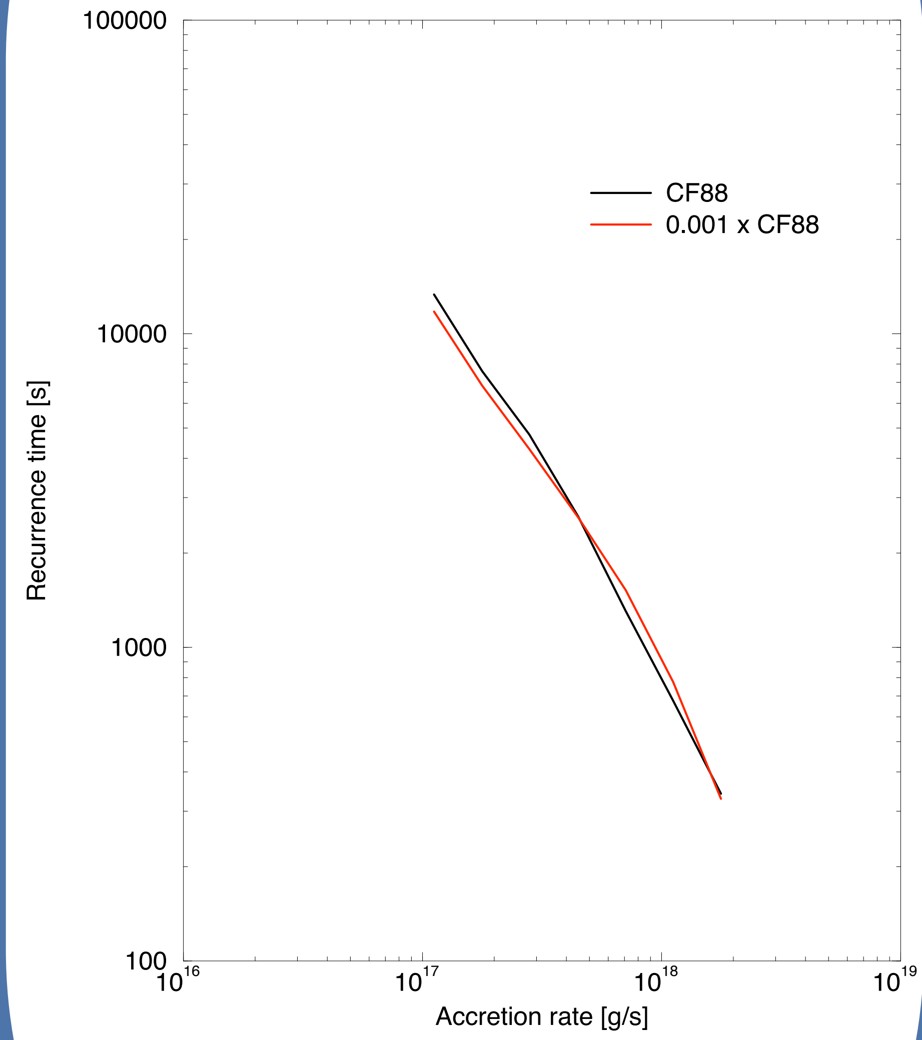
$M = 1.4 M_{\odot}, R = 11.06\text{km}$

Tan et al., in prep. experimentally constrains rate. Now need improved XRB model!

Observations and theory puts a constraint of the uncertainty of the reaction rate.

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

- Reaction follows $^{15}O(\alpha,\gamma)^{19}Ne$ and governs the entry into the rp-process.
- Rate has an uncertainty of "several orders of magnitude"
- Recurrence time changes 10-20%
- Stay tuned for more analysis!



Other candidates?

$^{22}\mathrm{Mg}(p,\gamma)^{23}\mathrm{Al}$

$^{23}\mathrm{Al}(p,\gamma)^{24}\mathrm{Si}$

$^{25}\mathrm{Si}(p,\gamma)^{26}\mathrm{P}$

$^{26}\mathrm{P}(p,\gamma)^{27}\mathrm{S}$

Runaway (rise of the burst)
Recurrence time
Spectral lines

$^{55}\mathrm{Ni}(p,\gamma)^{56}\mathrm{Cu}$

$^{56}\mathrm{Cu}(p,\gamma)^{57}\mathrm{Zn}$

$^{60}\mathrm{Zn}(p,\gamma)^{61}\mathrm{Ga}$

$^{61}\mathrm{Ga}(p,\gamma)^{62}\mathrm{Ge}$

Ashes, crust composition

Conclusion

- Identifying whether a given reaction has an effect on the burst light curve has too many uncontrolled parameters (accretion rate, geometry of burst, other rates) except in a very few cases.
- Observing spectral lines during the peak of the burst has proven difficult and burned isotopes are only convected to the top of the atmosphere in certain types of bursts.
- Therefore: Identify "systemic modes" instead. Use recurrence time, general observations of fluence to accretion luminosity, etc. to constrain the uncertainty of certain reactions.
- Also important: Burst simulations have been done assuming a reaction rate uncertainty of zero. Investigate the uncertainty of the astrophysics given the uncertainty of the nuclear physics.
- Maintain the information flow between modellers and experimentalists!