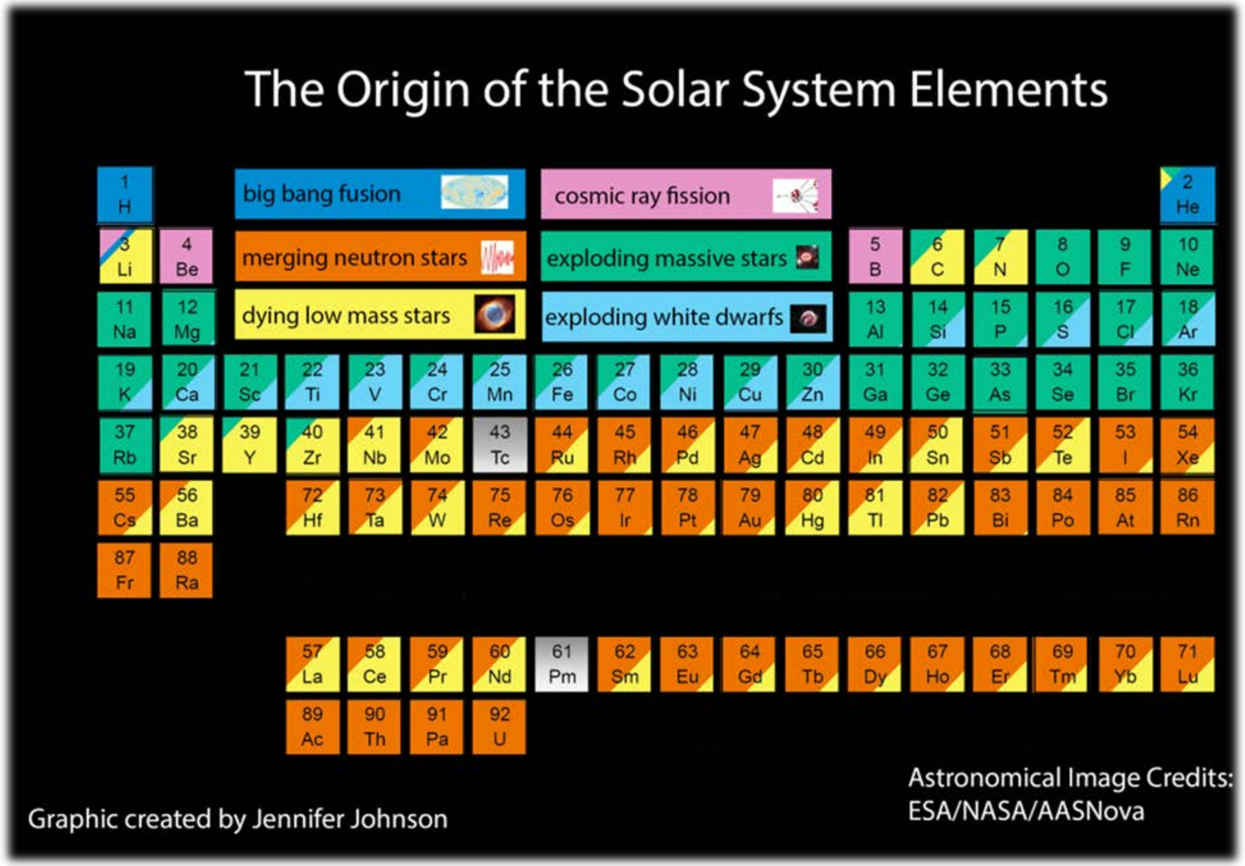
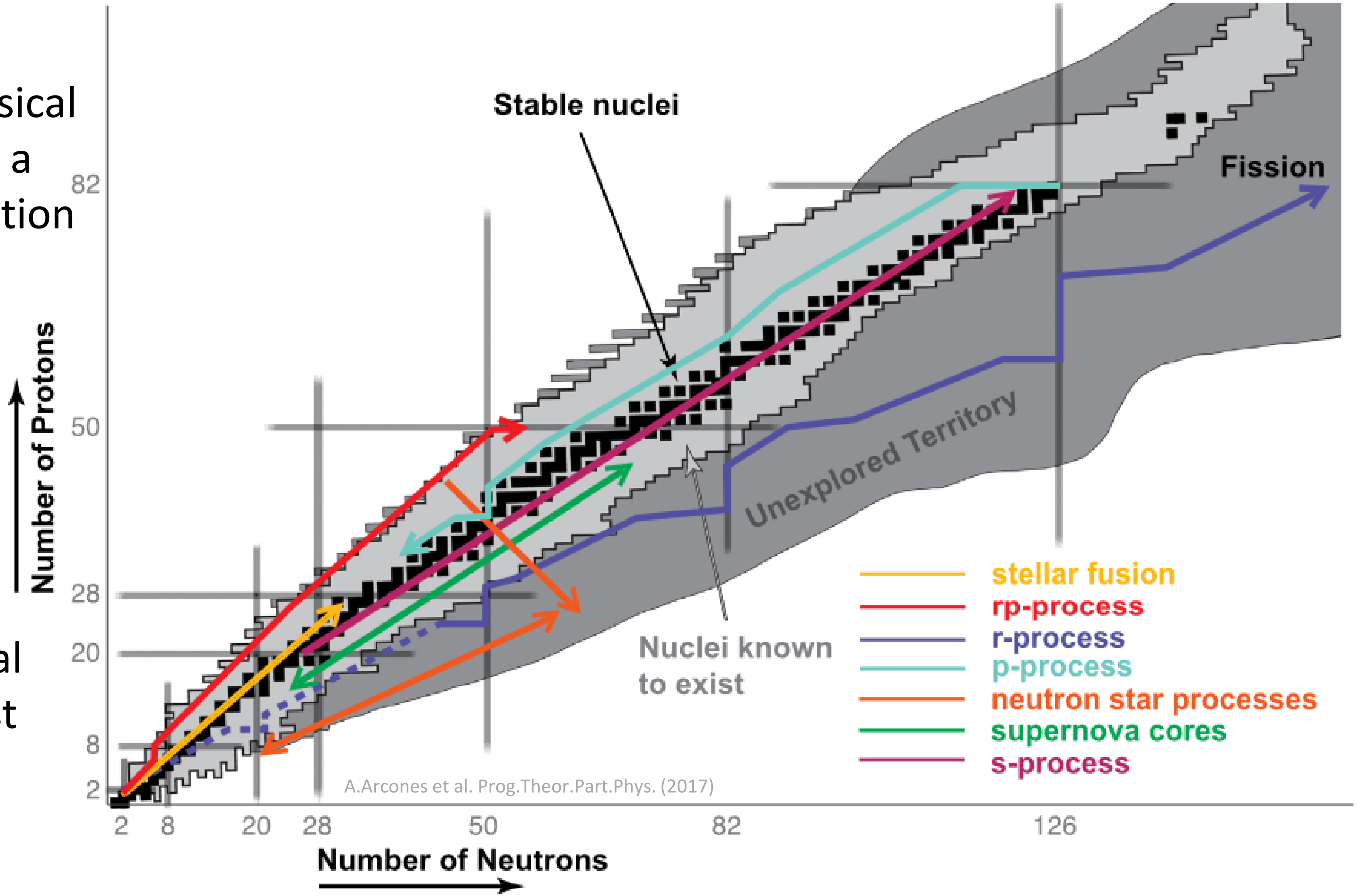
Lecture 21: Nucleosynthesis

- Light element processes
- Neutron capture processes
- LEPP and P nuclei
- Explosive C-burning
- Explosive H-burning
- Degenerate environments



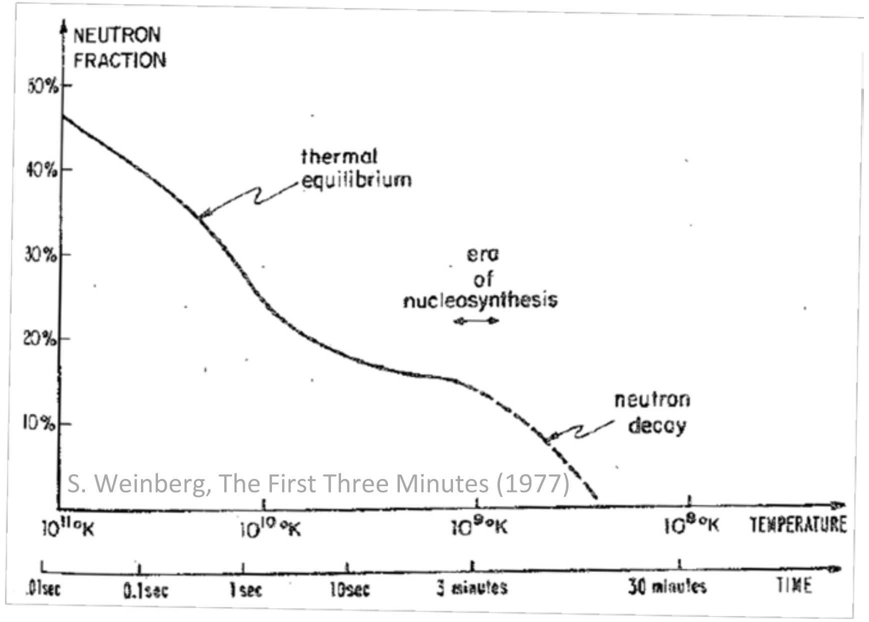
Nuclear Astrophysics: *Nuclear physics from dripline to dripline*

- The diverse sets of conditions in astrophysical environments leads to a variety of nuclear reaction sequences
- The goal of nuclear astrophysics is to identify, reduce, and/or remove the nuclear physics uncertainties to which models of astrophysical environments are most sensitive

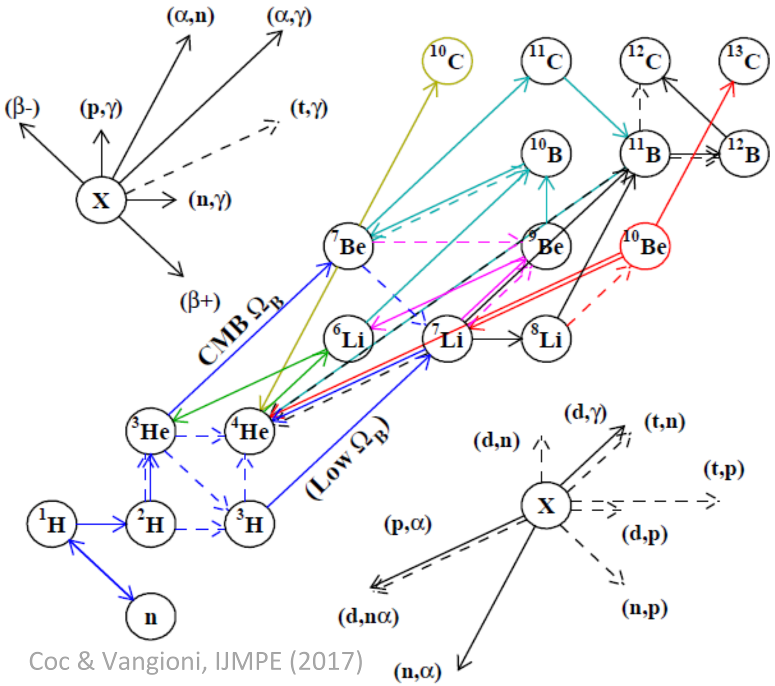


In the beginning: Big Bang Nucleosynthesis

- From the expansion of the early universe and the cosmic microwave background (CMB), we know the initial universe was cool enough to form nuclei but hot enough to have nuclear reactions from the first several seconds to the first several minutes
- Starting with neutrons and protons, the resulting reaction sequence is the Big Bang Nucleosynthesis (BBN) reaction network
- Reactions primarily involve neutrons, isotopes of H, He, Li, and Be, but some reaction flow extends up to C
- For the most part (we'll elaborate in a moment), the predicted abundances agree with observations of low-metallicity stars and primordial gas clouds
- The agreement between BBN, the CMB, and the universe expansion rate is known as the Concordance Cosmology



S. Weinberg, The First Three Minutes (1977)

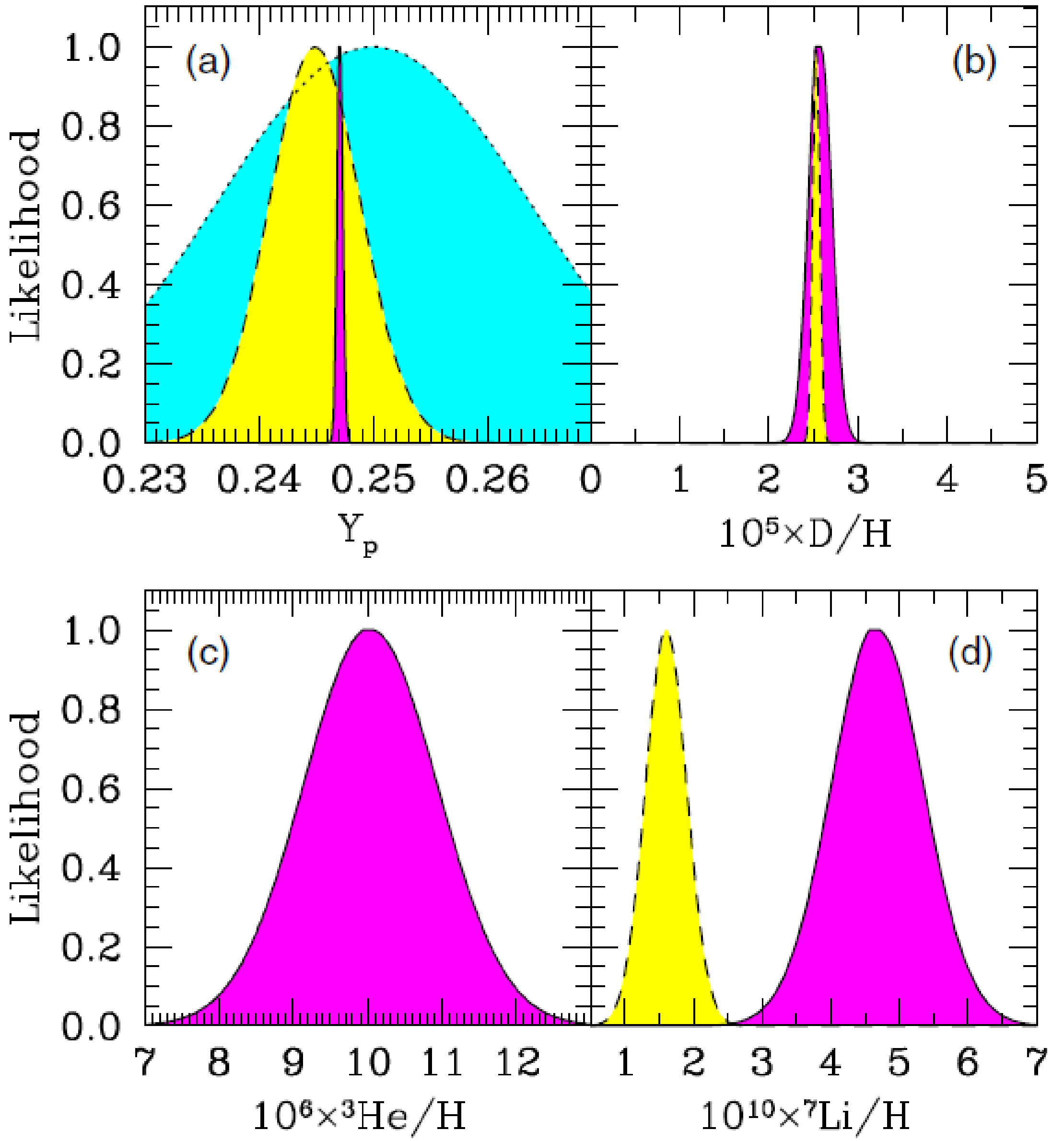


Coc & Vangioni, IJMPE (2017)

BBN open questions

- Notable discrepancies exist between BBN predictions (using constraints on the astrophysical conditions provided by the CMB) and observations of primordial abundances
- The famous "lithium problem" is the several-sigma discrepancy in the ^{7}Li abundance.
  - Alas, a nuclear solution for this problem has been ruled-out, as all relevant reaction rates are well known enough that nuclear uncertainties don't come close to explaining the issue
- The "other lithium problem" was a discrepancy in ^{6}Li predictions and observations, but it was explained by systematics in the observations
- The deuterium abundance, on the other hand, has recently become a more exciting topic
  - Observations are more precise than predictions because of nuclear physics uncertainties!
  - In particular, $d(p,\gamma)$ requires improved constraints

Observations & BBN+CMB Predictions

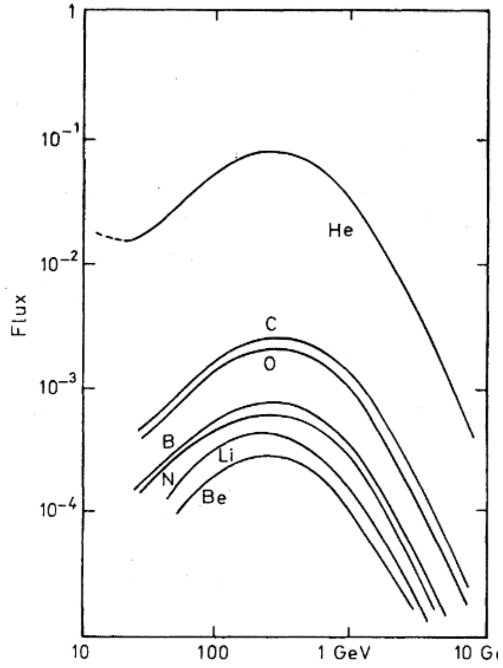


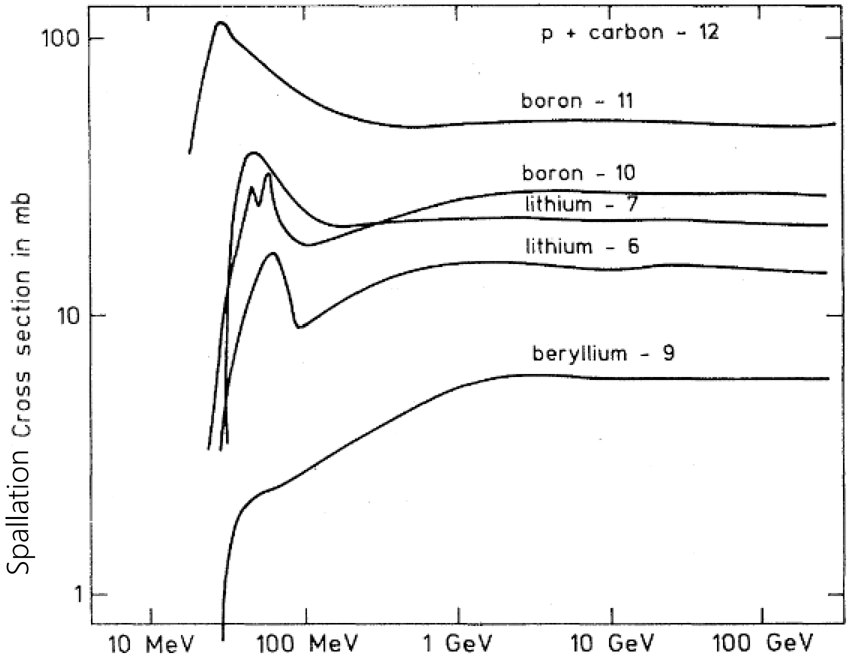
R. Cyburt et al., Rev.Mod.Phys. (2016)

Light elements get a boost, Cosmic ray spallation

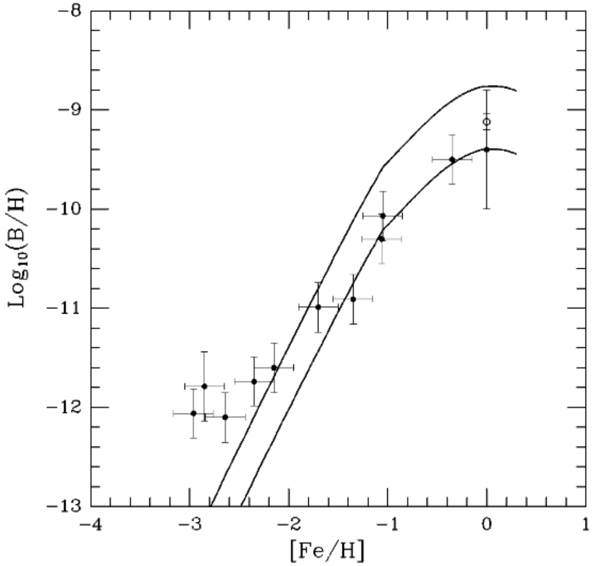
- Due to their low Coulomb barriers and relatively weak binding energies, isotopes of lithium, beryllium, and boron, well as ^{3}He, are easily destroyed in stars and stellar explosions
- And yet, we see abundances of these nuclei which are beyond what can be explained as surviving from Big Bang Nucleosynthesis
- The abundance boost comes from contributions of cosmic-ray induced spallation
- Energetic light ions in space impact abundant isotopes in the interstellar medium, such as ^{12}C, ^{14}N, and ^{16}O, yielding light nuclear products in spallation reactions, steadily increasing their abundances over time

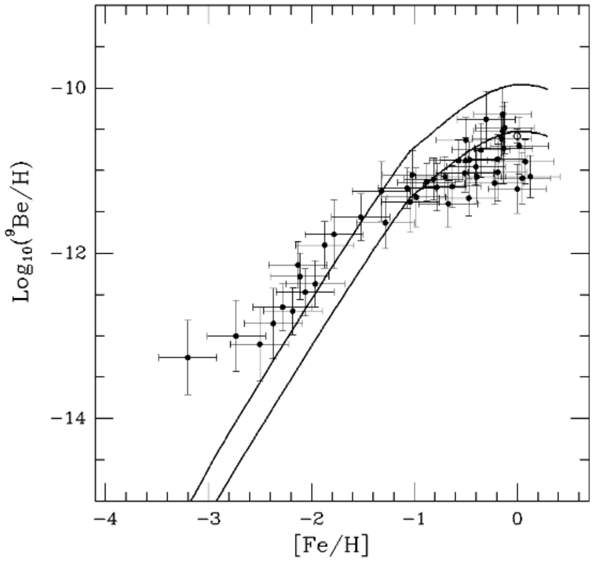
H. Reeves, Rev.Mod.Phys. (1994)





Lemoine, Vangioni-Flam, & Cassé, Astrophysl J. (1998)



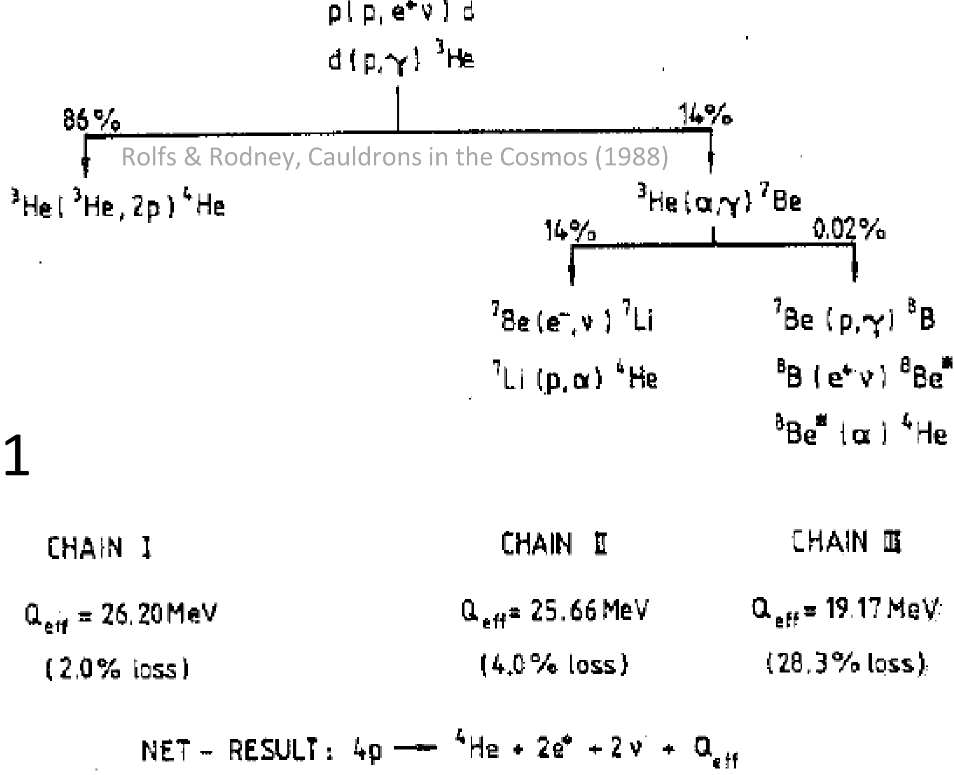


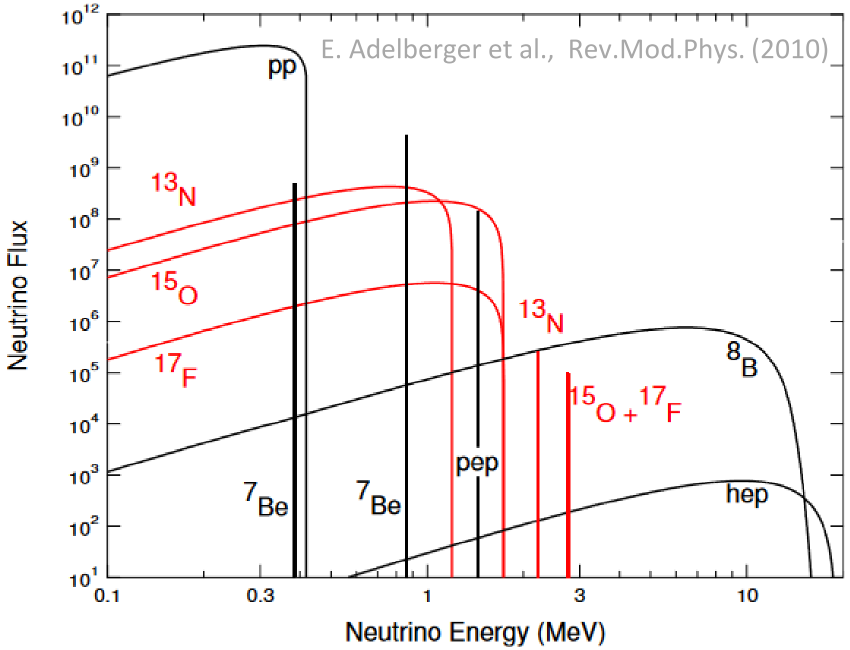
Stars' first ignition: The pp-chain

- For stars as or less massive than the sun, or primordial stars containing only H & He, nuclear burning begins in earnest with the pp-chain(s) [this is preceded by deuterium burning, but the energy generation is negligible in comparison]
- The end result of the pp-chains is to convert 4 protons in to 1 helium nucleus, releasing a total of ~27MeV in the process
- The first step (either $p + p \to d + e^{+} + \nu$ or $p + e^{-} + p \to d + \nu$) requires a weak interaction and so the cross section is roughly $10^{20}\times$ smaller than a typical nuclear cross section and as such unmeasurable

(This is a good thing! Otherwise the sun probably would have burnt out by now.)

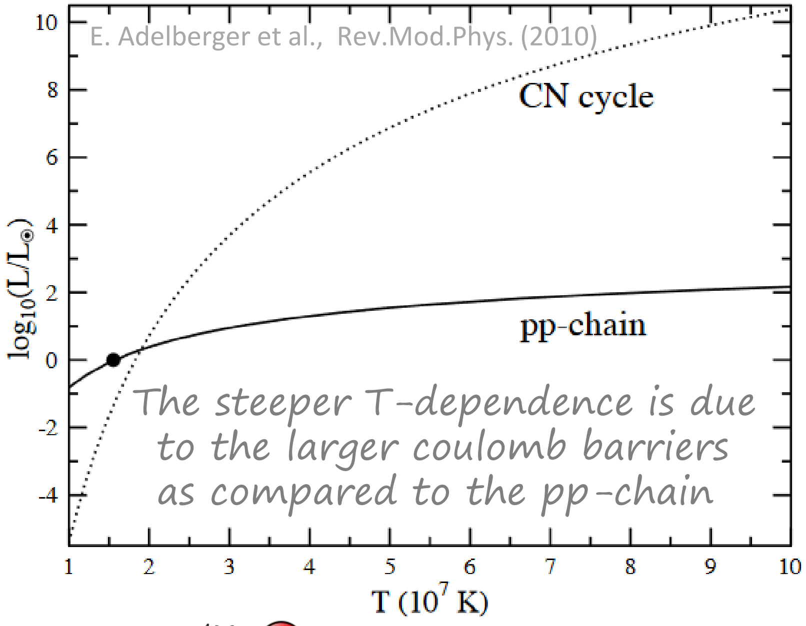
- The low temperature involved makes measuring these cross sections at relevant energies exceedingly difficult, meaning extrapolations of the S-factors are required and electron-screening effects must be taken into account
- The pp-chain rates are of particular interest, since the relative neutrino yields determine the pp-chain branching and therefore the internal temperature of the sun

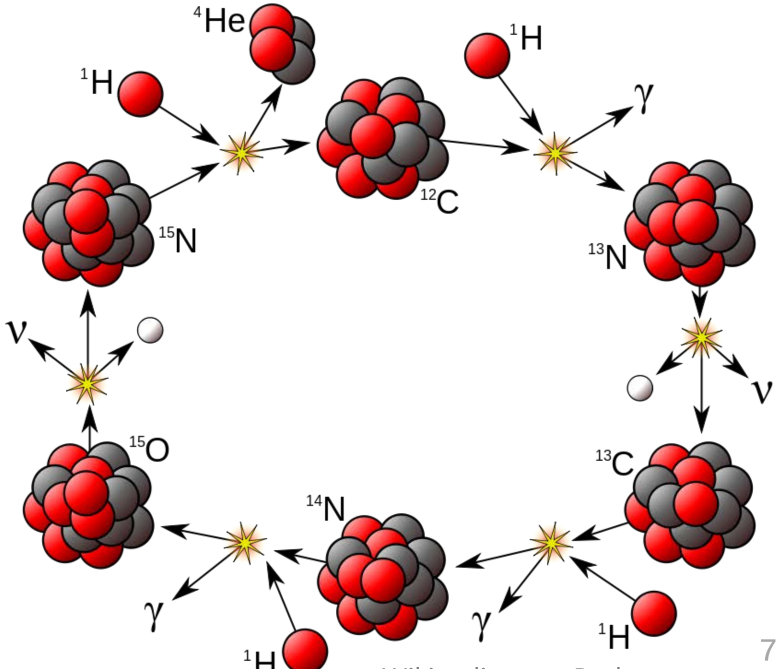




It's getting hot in here, so start the CNO cycle

- For stars just a bit more massive than the sun, more radiation pressure is required to oppose gravitational contraction than the pp-chains can provide. As such, the core contracts until the central temperature is sustains a robust CNO cycle.
- The CNO cycle is another way to convert four protons into one helium nucleus. In this sequence, ^{12}C acts as a catalyst.
- At the modest core temperatures of the sun, ^{14}N(p,γ) is the rate-limiting step in the sequence
 ^{12}C(p, γ)^{13}N(β)^{13}C(p, γ)**^{14}N(p, γ)**^{15}O(β)^{15}N(p,α)^{12}C
 meaning the equilibrium abundance will be concentrated in ^{14}N
- Weaker branches exist to other nuclei, which are the other CNO cycles (identified by different numbers)
- The rates of the CNO cycles play a key role in astrophysics, since they determine how long it takes for massive stars should take to burn through their core hydrogen and therefore provide the age for a globular cluster based on which mass stars (inferred by luminosity) have turned-off the main sequence (the line in the HR diagram [luminosity vs temperature] for core H-burning) yet

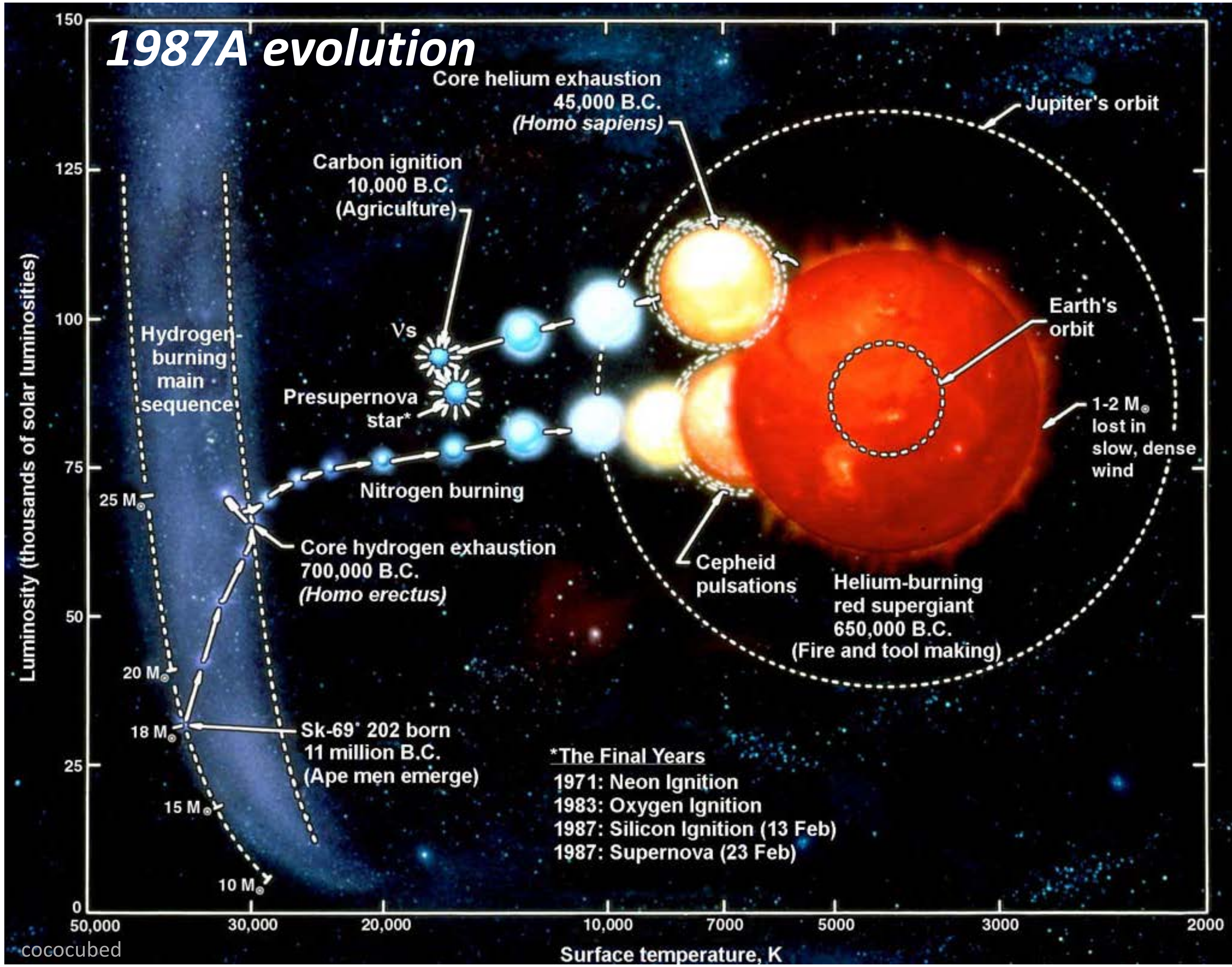




Wikipedia user: Borb

We're going to need another fuel, Helium burning (and beyond)

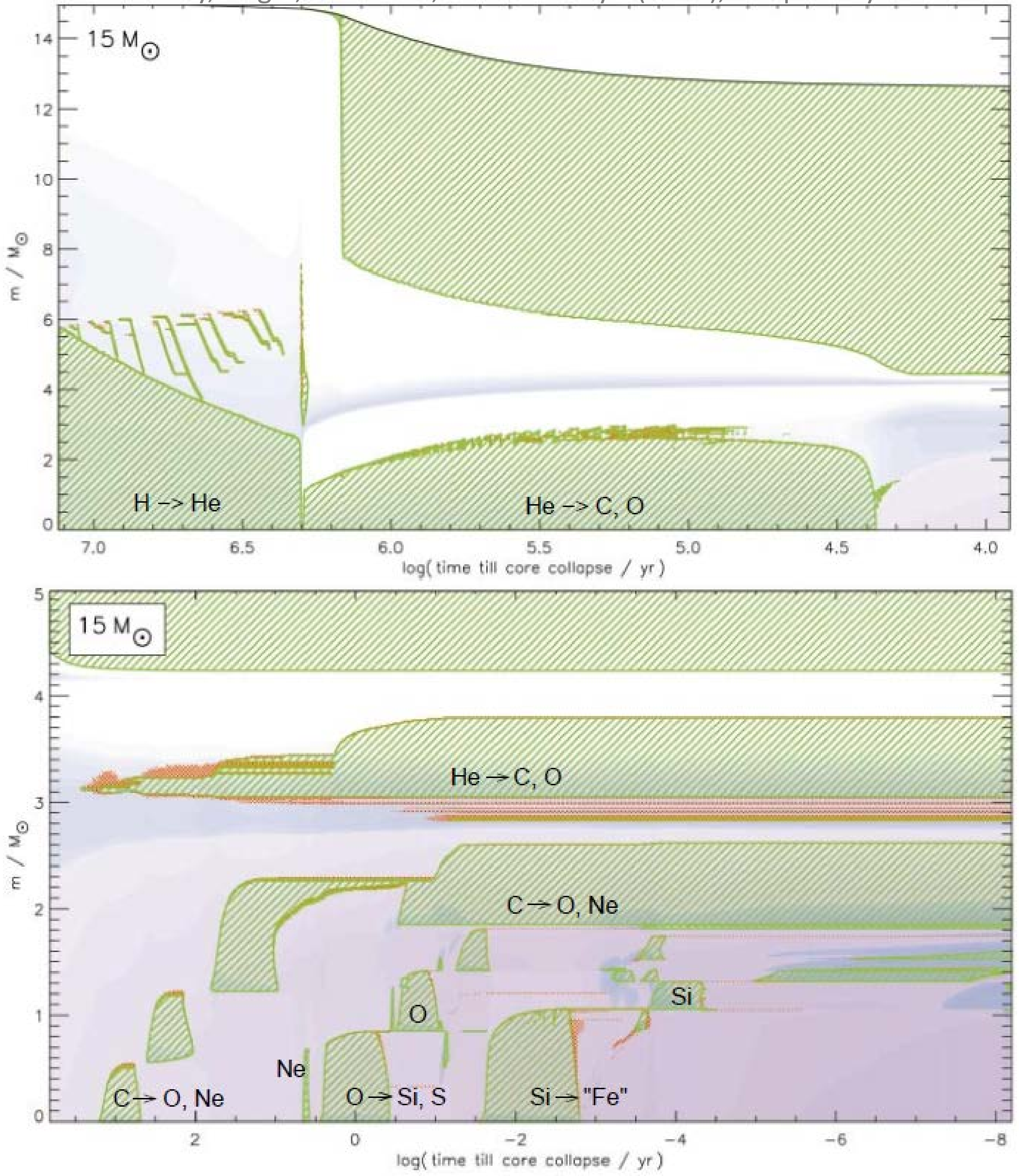
- Once hydrogen in the core has been exhausted, core contraction occurs, raising the temperature. After some shell hydrogen burning grows the helium core, core helium can be burned
- At ~10^8K, the triple-alpha rate ($3\alpha \rightarrow {}^{12}C$) becomes significant
- The 3α rate actually proceeds by an α capturing onto ${}^{8}Be$, which is unbound but has some small equilibrium abundance, into the Hoyle state of ${}^{12}C$
- ${}^{12}C(\alpha,\gamma)$ builds up some ${}^{16}O$ in the core
- Once core He is exhausted, shell He and H burning build the core further, building-up to iron for stars that are initially $\gtrsim 8M_\odot$



Because regular old burning won't do, Advanced burning

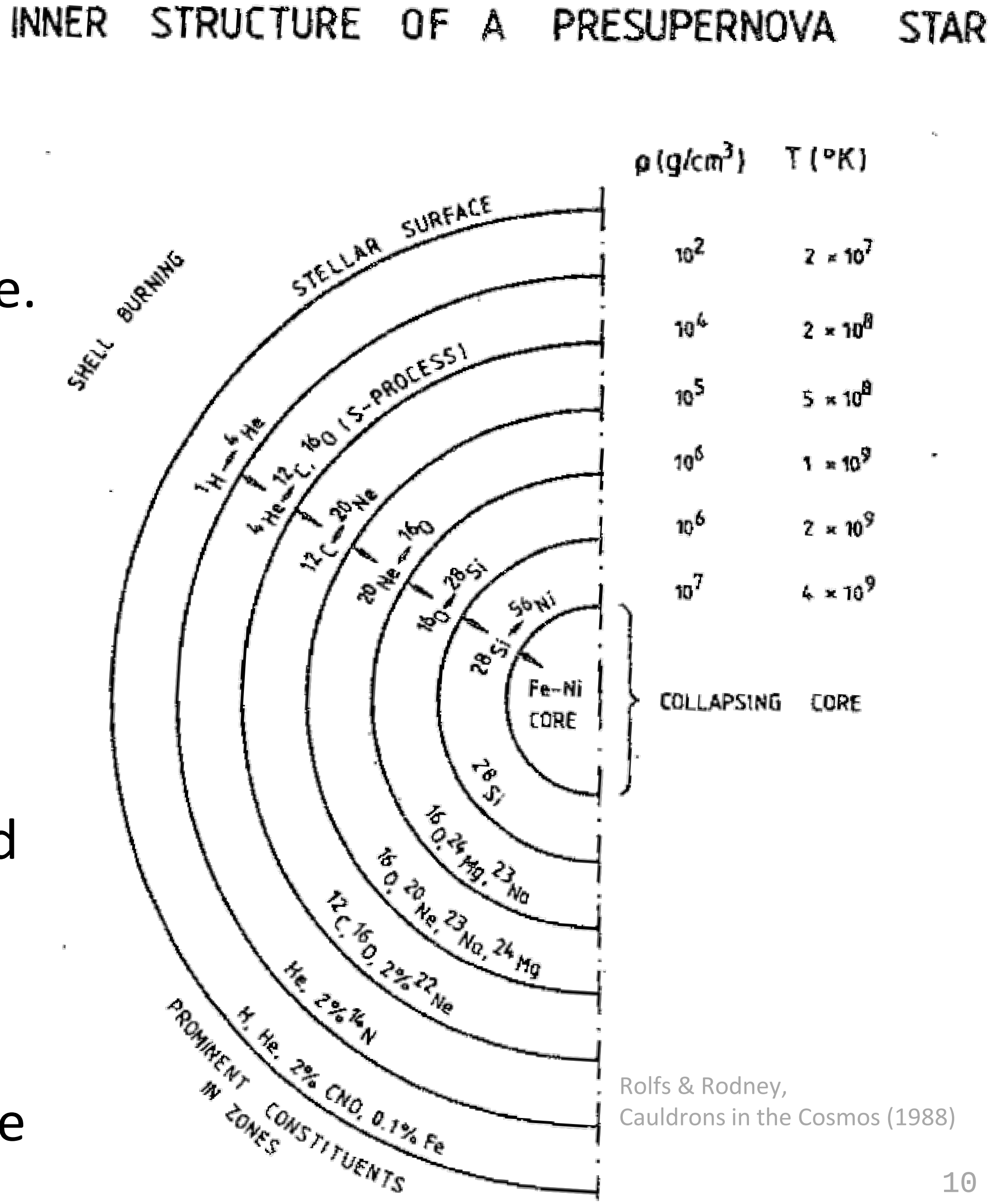
- Subsequent core burning (for massive stars) proceeds via:
  - ***Carbon burning***: $^{12}C+^{12}C$ fusion and captures by the reaction products of produced p & α mostly result in ^{16}O, ^{20}Ne, ^{24}Mg. Stars less than ~ $8M_\odot$ end here
  - ***Neon burning***: Photodisintegration of and α captures by ^{20}Ne converts it to mostly ^{16}O and ^{24}Mg
  - ***Oxygen burning***: $^{16}O+^{16}O$ fusion and captures by the reaction products of produce p & α mostly result in ^{28}Si and ^{32}S, but β-decays of some products results in a slightly neutron-rich composition
  - ***Silicon burning***: Photodisintegration and α captures of ^{28}Si and the reaction products, involving a large range of nuclei. This material is nearly in Nuclear Statistical Equilibrium (all forward & reverse rates equal), so the abundance *distribution* (centered around ^{56}Fe, i.e. the "iron" core isn't just iron) mostly just depends on the temperature and the nuclear masses. This is the end-of-the-road and is followed by core collapse.

Woosley, Heger, & Weaver, Rev.Mod.Phys. (2002), Adapted by O.R.Pols



The onion structure and it's implications

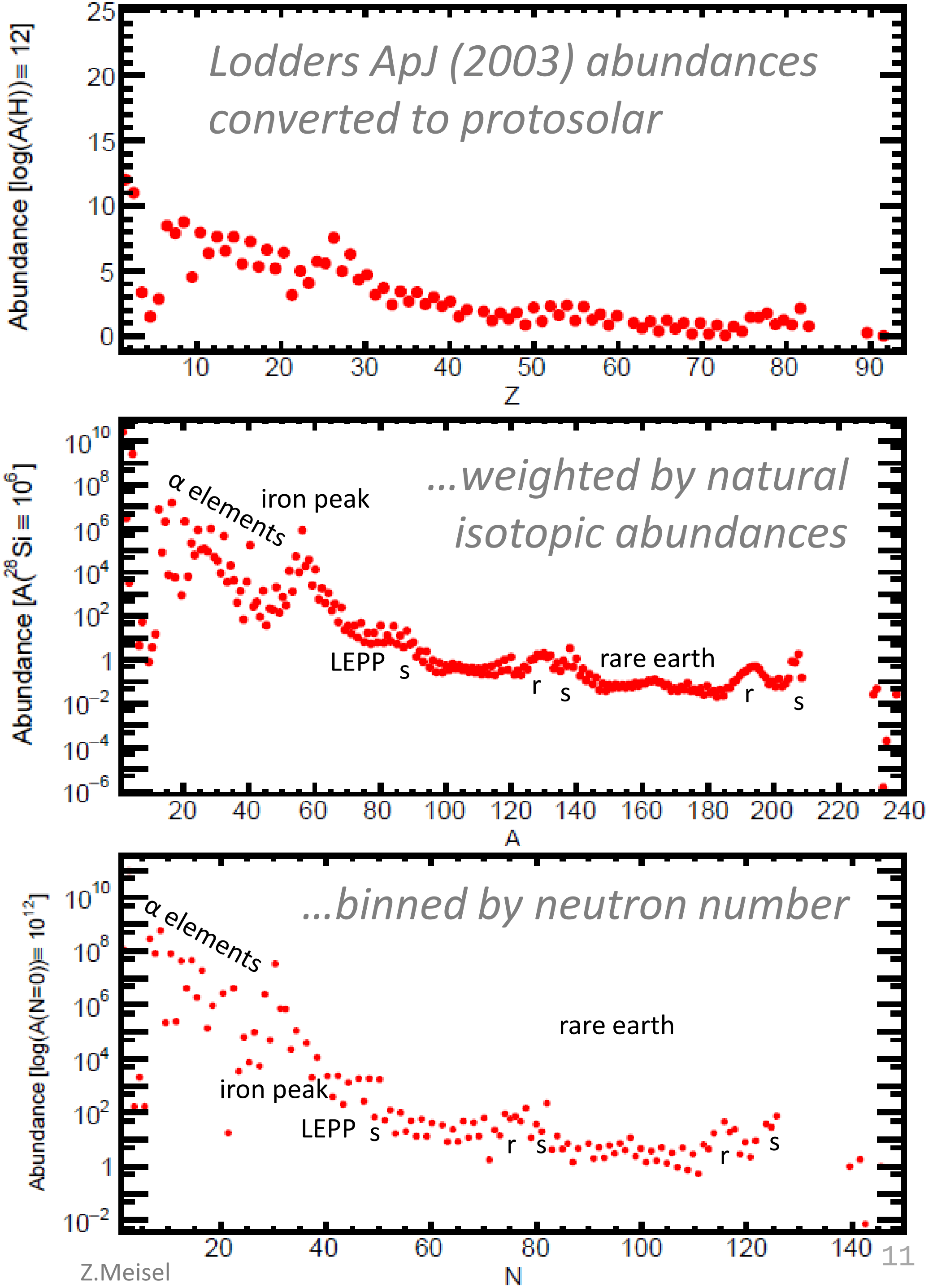
- The aforementioned burning processes also occur in shells (once a given process isn't happening in the core), ultimately resulting in the famous onion structure
- Note that stars can walk and chew gum at the same time. The shell burning can lead to other processes.
  - The main *s*-process (which we'll cover in a moment) occurs near the helium and carbon burning shells
  - The *i*-process (again: patience, grasshopper) may occur near the interface of hydrogen and helium burning
  - When the massive star finally goes supernova, the nuclei in outer shells which aren't fully photodisintegrated can be partially photodisintegrated in the *p*-process (that we'll also get to)
- This material contributes to the chemical enrichment of the universe when it is blown-off as a stellar wind or ejected in the supernova explosion that occurs after core silicon burning ceases



Rolfs & Rodney,
Cauldrons in the Cosmos (1988)

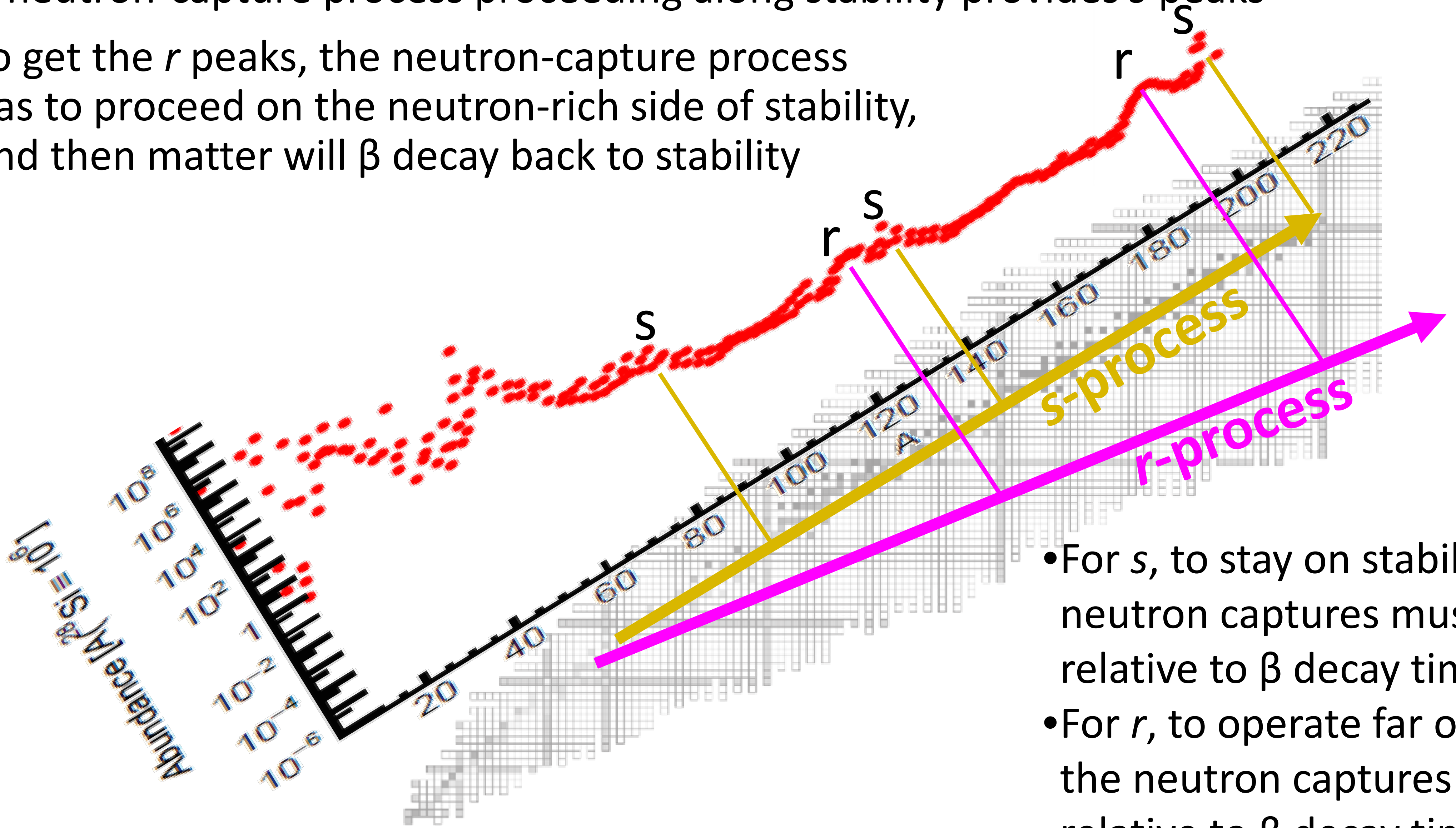
Interlude, the case for neutron-capture processes

- Looking at the solar system abundances in terms of A, we see some pretty interesting patterns
- The α elements and iron peak are consistent with our picture for massive star evolution, but we see several other features beyond iron
- Focusing on the peaks labeled *s* and *r*, we see that the *s* peaks are located at neutron magic numbers 50, 82, 126, with the *r* peaks located just below (at least for 82 & 126)
- Logically, it follows that the processes making the *s* and *r* processes somehow involve sequences of neutron capture reactions that pass through these magic numbers on the nuclear chart. This is because one feature of magic N nuclei is low neutron-capture cross sections relative to neighboring nuclei



We can see where on the nuclear chart the *s* & *r* processes must have occurred by considering where in terms of *Z* pile-up at a magic *N* must have occurred to give the observed peak in *A*

- A neutron-capture process proceeding along stability provides *s* peaks
- To get the *r* peaks, the neutron-capture process has to proceed on the neutron-rich side of stability, and then matter will β decay back to stability



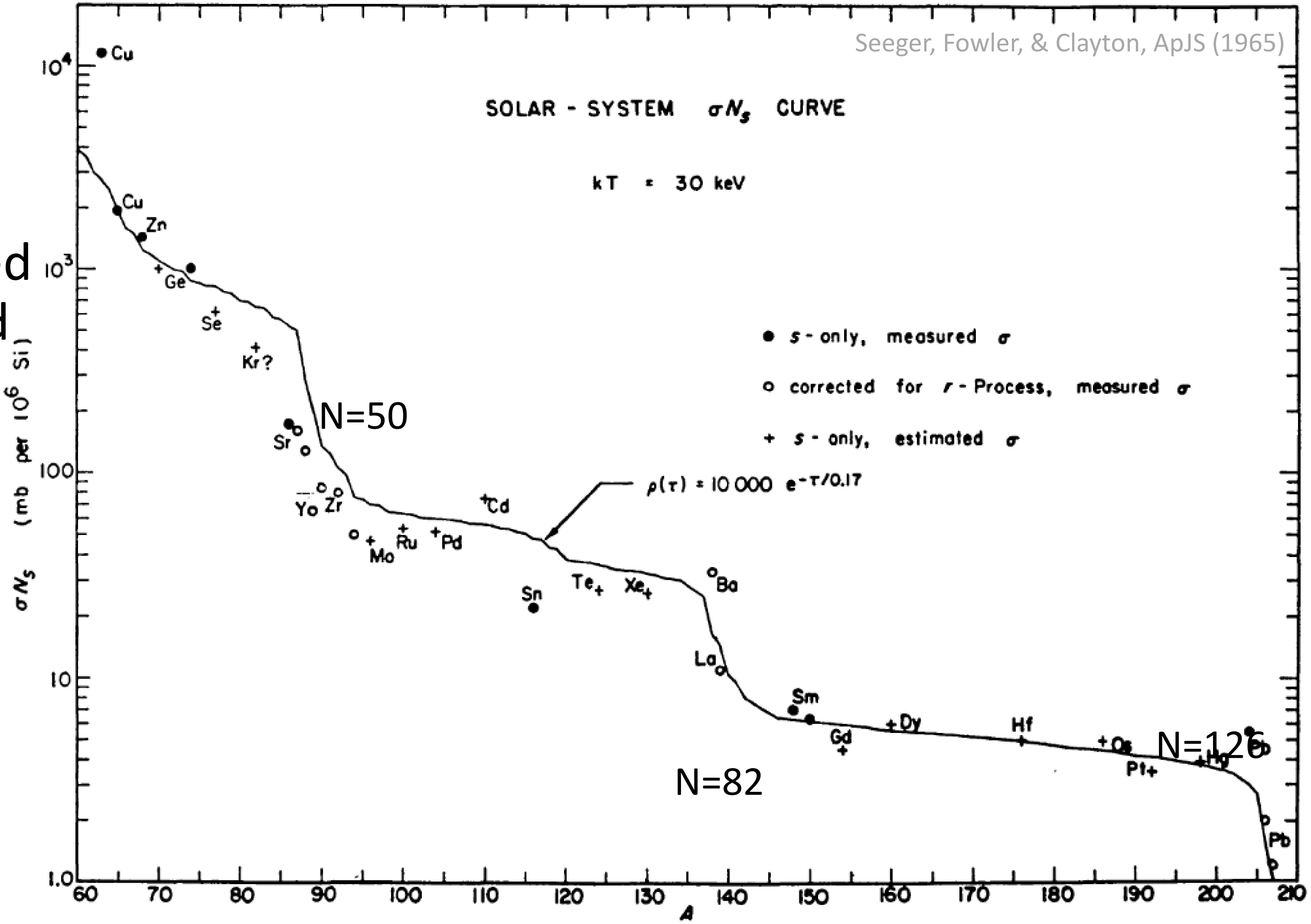
- For *s*, to stay on stability, the neutron captures must be ***s***low relative to β decay timescales
- For *r*, to operate far off stability, the neutron captures must be ***r***apid relative to β decay timescales

Slow and steady, the *s-process*

- For the *s*-process, we need an environment where nuclei can bathe for a long time in a moderate neutron density ($n_n \sim 10^{7-10}\mathrm{cm}^{-3}$). Let's consider the reaction flow for this case.
- For isotope (Z,A), the abundance change is the sum of production & destruction mechanisms, $\frac{dN_{Z,A}}{dt}(t) = n_n(t)n_{Z,A-1}(t)\langle\sigma v\rangle_{Z,A-1} - n_n(t)n_{Z,A}(t)\langle\sigma v\rangle_{Z,A} - \lambda_{\beta:Z,A}n_{Z,A}(t)$
- We'll ignore species with fast β-decays, since they'll just form the more stable isobar more or less instantly, so we can set the last term to zero
- Also, recall $\langle\sigma v\rangle_{n\,cap} \sim constant$, and anyhow we'll assume a constant temperature, so$\langle\sigma v\rangle_i \rightarrow \sigma_i v_T$, where v_T is the thermal velocity for the environment temperature
- As such, our abundance change equation is now $\frac{dN_{Z,A}}{dt}(t) = n_n(t)v_T\left(\sigma_{Z,A-1}n_{Z,A-1} - \sigma_{Z,A}n_{Z,A}\right)$
- Note that $n_n(t)v_T$ is the neutron flux. Integrating this over time gives the neutron irradiation $\tau = \int_0^t n_n(t)v_T\,dt = v_T\int_0^t n_n(t)\,dt$, which is referred to as the neutron exposure
- Re-casting our abundance change in terms of τ, $\frac{dN_{Z,A}}{d\tau} = \sigma_{Z,A-1}n_{Z,A-1} - \sigma_{Z,A}n_{Z,A}$
- In equilibrium, $\frac{dN_{Z,A}}{d\tau} = 0$, so $\sigma_{Z,A-1}n_{Z,A-1} = \sigma_{Z,A}n_{Z,A} = constant$
- So, we can get *s*-process relative abundances based solely on neutron-capture cross sections!

The steady flow approximation

- The steady-flow approximation holds roughly in between magic *N*
- Tests can be performed for elements with multiple isotopes that are shielded from the *r*-process and have measured neutron-capture cross sections, e.g. ^{122,123,124}Te



Reactions of special interest are those with half-lives similar to the neutron-capture time (you'll calculate this time in the group activity). They're called branch-points. They not only alter the abundance pattern, but can be used as s-process thermometers and neutron-density probes, since <σv> isn't exactly constant.

Where do the s neutrons come from?

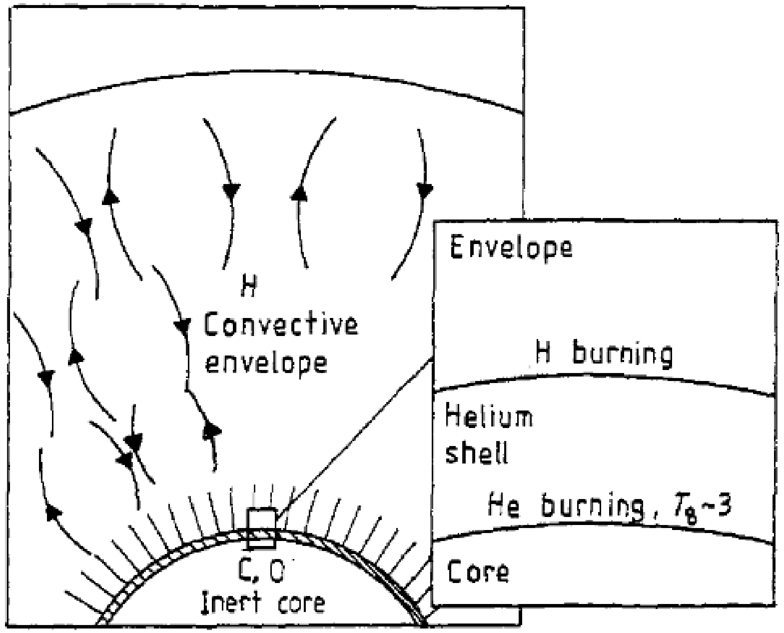
- More careful analyses (e.g. checks with the Te isotopes and branch-points) demonstrate the need for different neutron fluxes for different durations. These are the
  - **Weak**: 60<A<90, near He/C shells in massive stars
  - **Main**: Sr-Pb, thermal pluses in AGB stars
  - **Strong**: Pb enhancement for low-metal AGB stars

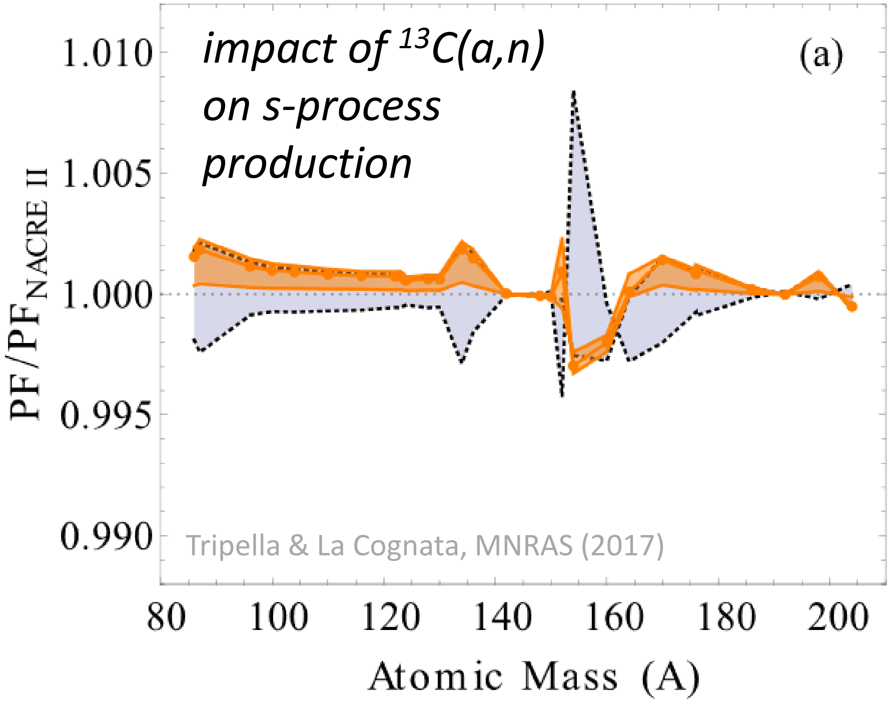
  components. For each kT~30keV or thereabouts.

- No matter, the neutron sources turn-out to be $^{13}C(\alpha,n)$ and $^{22}Ne(\alpha,n)$, where the former only operates for the AGB cases and the latter only operates during brief flashes for the AGB cases

- Other important reactions are the neutron "poisons", light nuclei that swallow-up perfectly good neutrons that would have otherwise been captured by heavier seeds, other exit channels for ^{22}Ne and ^{13}C α-capture which fail to produce neutrons, and reactions producing ^{22}Ne and ^{13}C

Käppeler, Beer, & Wisshak, Rep.Prog.Phys. (1989)





Tripella & La Cognata, MNRAS (2017)

Life in the fast lane, the (hot) *r*-process

- For the *r*-process, a huge neutron density ($n_n \gtrsim 10^{20}\mathrm{cm}^{-3}$, as you'll show in the group activity) is needed in order for neutron capture lifetimes to be much shorter than the ~ms β-decay lifetimes of the extremely neutron-rich nuclei involved
- Neutron-capture will proceed along an isotopic chain until it competes with the photodisintegration rate: $\langle\sigma v\rangle_{3\gamma}/\langle\sigma v\rangle_{12} \approx 1$
- Recalling that $\frac{\langle\sigma v\rangle_{3\gamma}}{\langle\sigma v\rangle_{12}} \approx \left(\frac{\mu_{12}c^2}{k_B T}\right)^{3/2} \exp\left(-\frac{Q_{12}}{k_B T}\right)$, observing $\tau_{n,\gamma} = \frac{1}{n_n\langle\sigma v\rangle_{n,\gamma}}$ and $\tau_{\gamma,} = \frac{1}{n_\gamma\langle\sigma v\rangle_{\gamma,n}}$, and remembering (*how could we ever forget!?*) the Planck distribution $n_\gamma = \frac{8\pi^4}{13c^3h^3}(k_B T)^3$,

$$\frac{1}{\tau_{\gamma,n}} = \lambda_{\gamma,n} \propto (k_B T)^{3/2}\frac{1}{n_n}\exp\left(-\frac{Q_{12}}{k_B T}\right)\lambda_{n,\gamma}$$

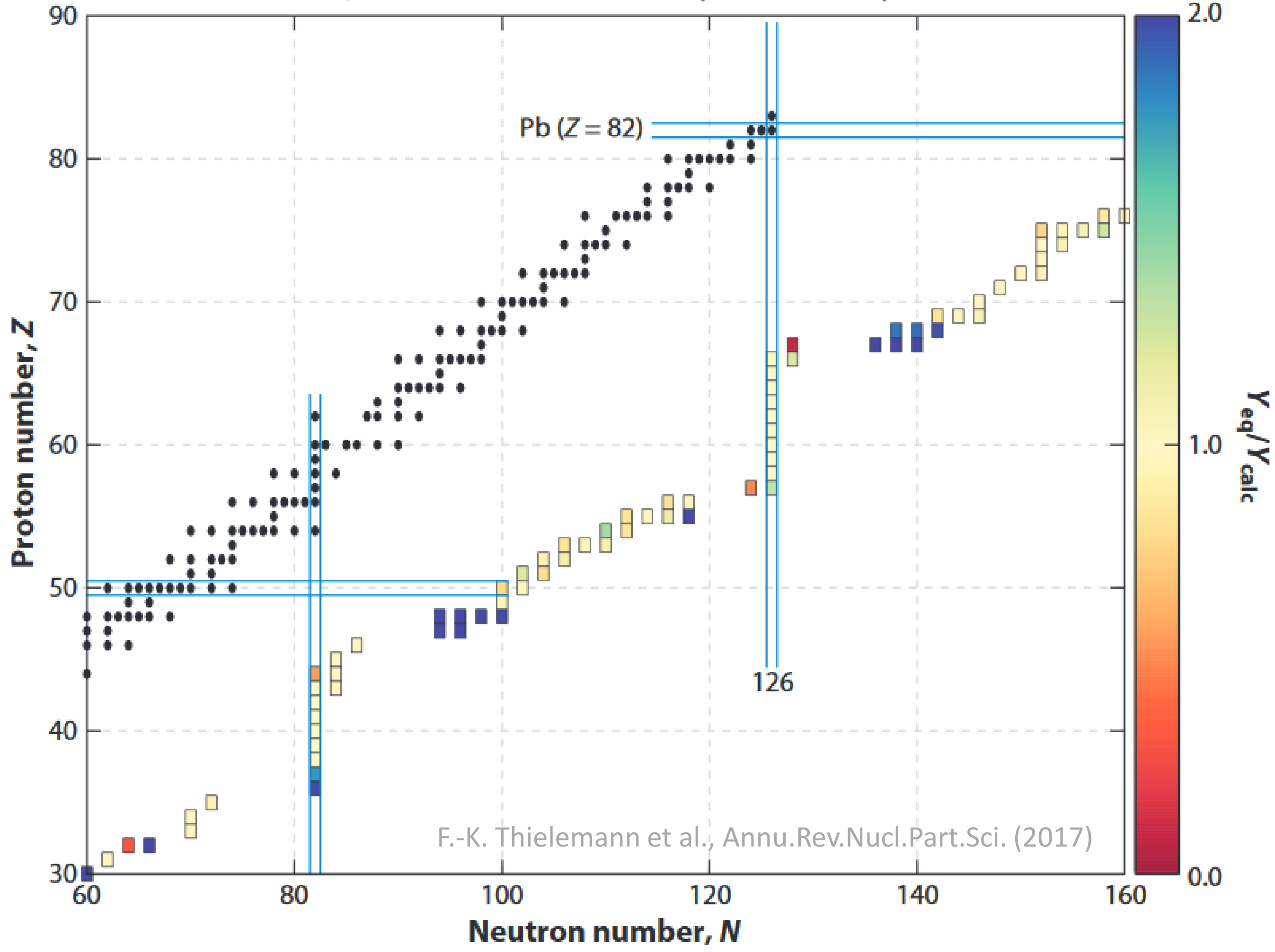
Because we're dealing with (n,γ), Q=S_n

- This means that the *r*-process follows a path with constant neutron-separation energy S_n, where the S_n of the path is determined by n_n and T
(For example, when taking into account all of the proper constants, $S_n \approx 2\mathrm{MeV}$ for $T = 1\mathrm{GK}, n_n = 10^{24}\mathrm{cm}^{-3}$)
- The *r*-process will stall at the isotope of an element with the path's S_n and wait for β-decay.
- Clearly, this implies *r*-process abundances will pile-up at nuclei with long half-lives. Of course, the magic *N* nuclei have relatively long half-lives (and small neutron-capture cross sections), so abundances will pile-up there, resulting in the characteristic *r*-process peaks

A tale of two processes, the hot & cold r-process

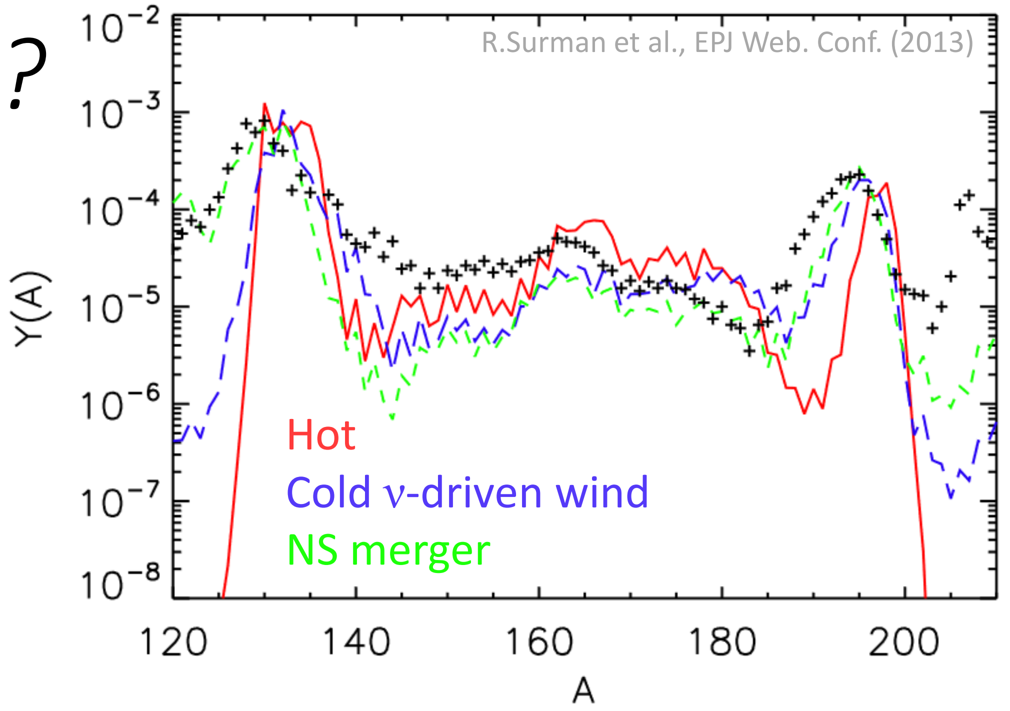
- In the preceding discussion we invoked $(n,\gamma)\rightleftarrows(\gamma,n)$ equilibrium … which isn't always going to be true
- The higher the neutron-density, the lower the temperature can be and still result in an *r*-process
- For those "cold" or colder cases, the individual (n,γ) rates are going to matter
- Even for the hot case, the environment has to cool off eventually, and so neutron-capture rates will matter in the end
- Other interesting details that change the final *r*-abundances are β-delayed neutron emission when the process is ending and fission cycling, which may occur if high-*Z* nuclides are reached

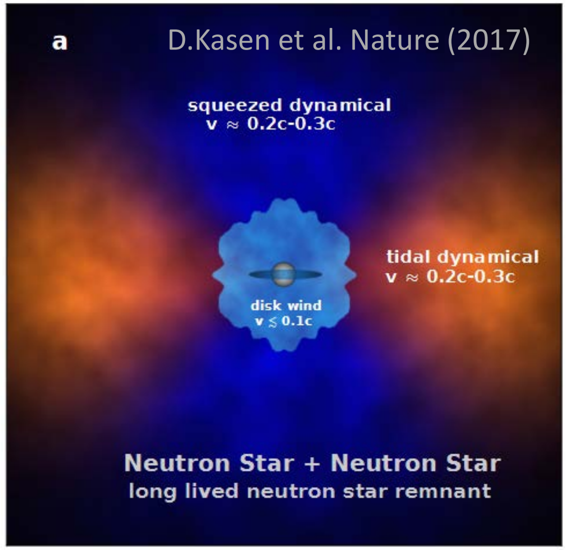
However, $(n,\gamma)\rightleftarrows(\gamma,n)$ equilibrium is a pretty decent first guess for the r-process path location

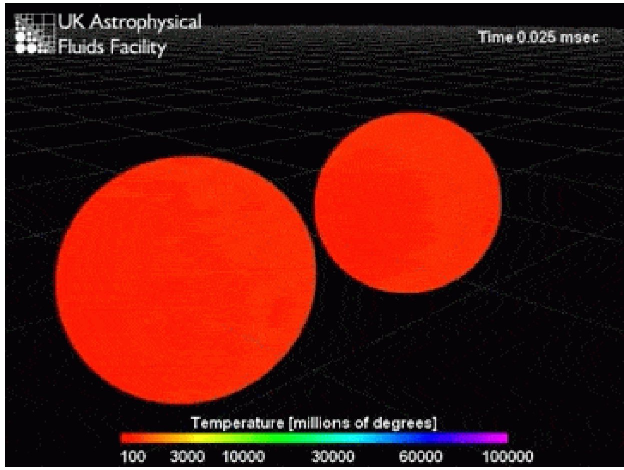


Where do the r *neutrons come from?*

- It turns out that there's potentially more than one way to get large flash of neutrons in a hurry
- Mainstream candidates include core collapse supernovae, neutron star mergers, and black-hole accretion disks
- In the past decade, the deck has become stacked pretty heavily in neutron-star merger's favor
  - CCSN simulations just aren't very neutron-rich
  - Neutron stars can merge quicker than you might think because binary evolution can hasten their inward spiral
  - Galactical chemical evolution simulations show the localized merger yields can get spread far and wide by viscous mixing
  - We've seen a merger make *r*-process material!





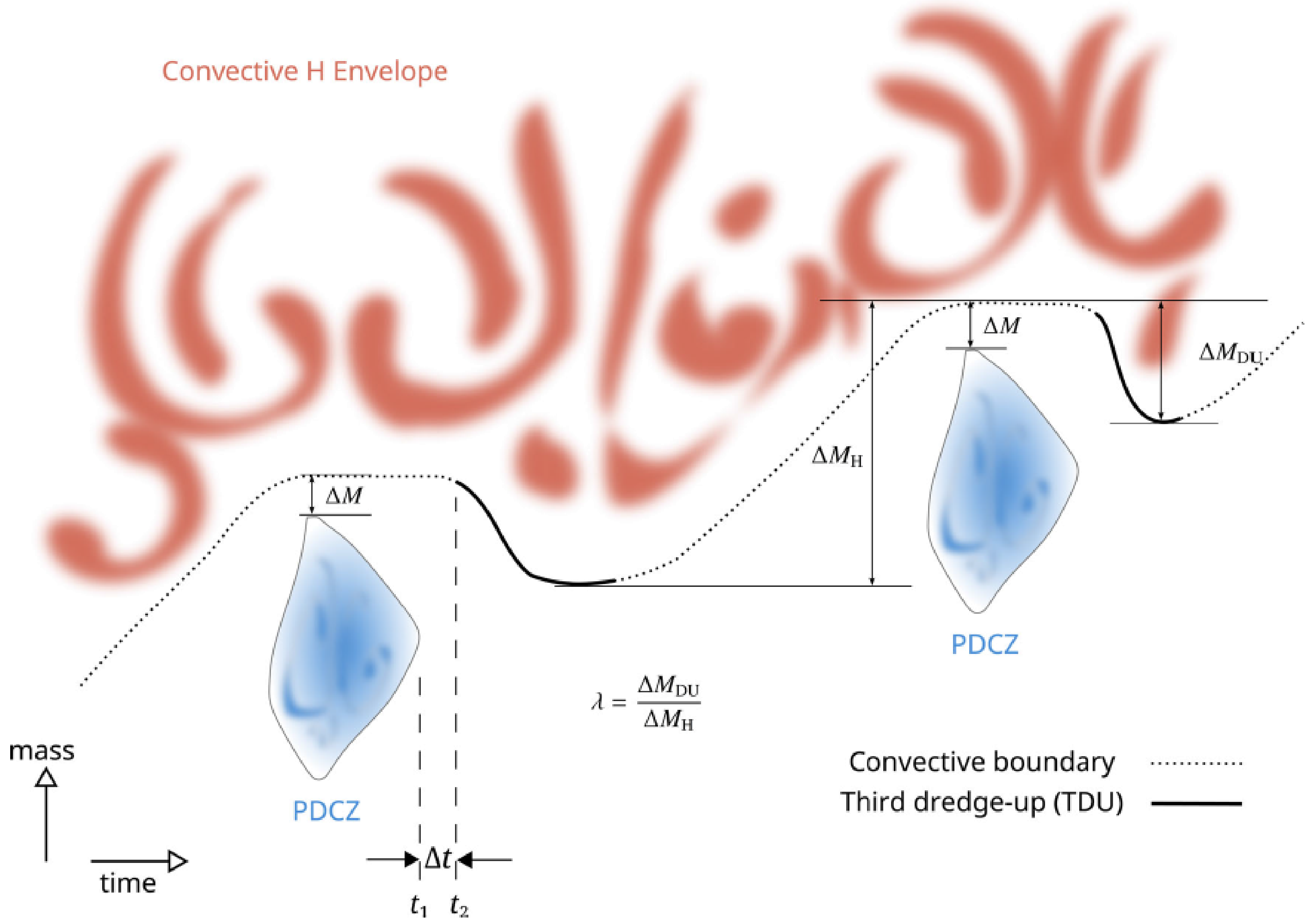


That said, the issue is far from settled. Many modeling and nuclear physics uncertainties exist. Also, this topic has a history of a back & forth and it would be foolish to call the fight too early.

What about moderate neutron fluxes? the i-process

- It turns out, stellar evolution models show that an intermediate neutron flux is possible, so it's been cleverly dubbed the *i*-process
- *i*-process neutrons come from the interface between hydrogen and helium burning shells in high-mass AGB stars. The mixed-in hydrogen results in $^{12}C(p,\gamma)^{13}C$ which then burns via $^{13}C(\alpha,n)$
- The resulting neutron densities are $n_n \approx 10^{15}\mathrm{cm}^{-3}$, which is high enough to drive neutron capture several nucleons off of stability
- Here the individual neutron-capture rates matter. For many the statistical model doesn't apply, so the uncertainties are large

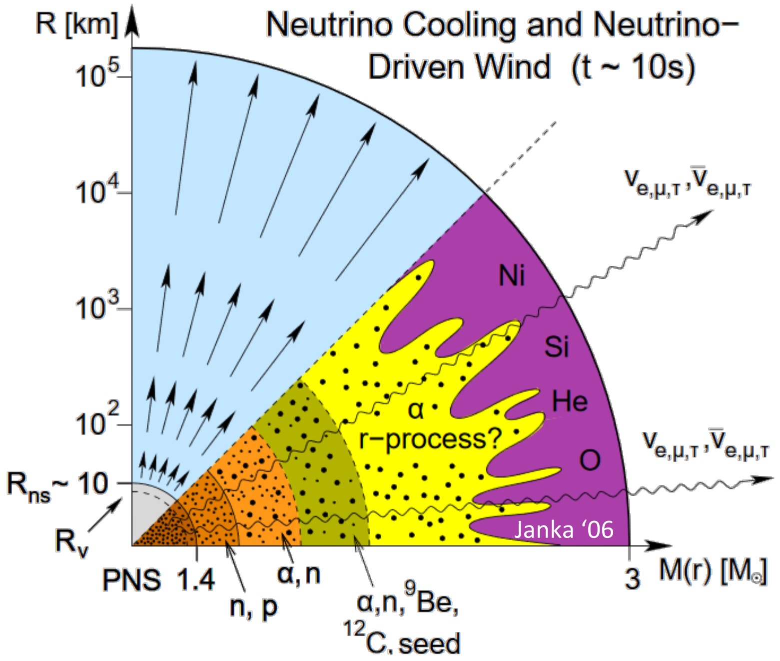
S. Jones et al. *MNRAS* 2016



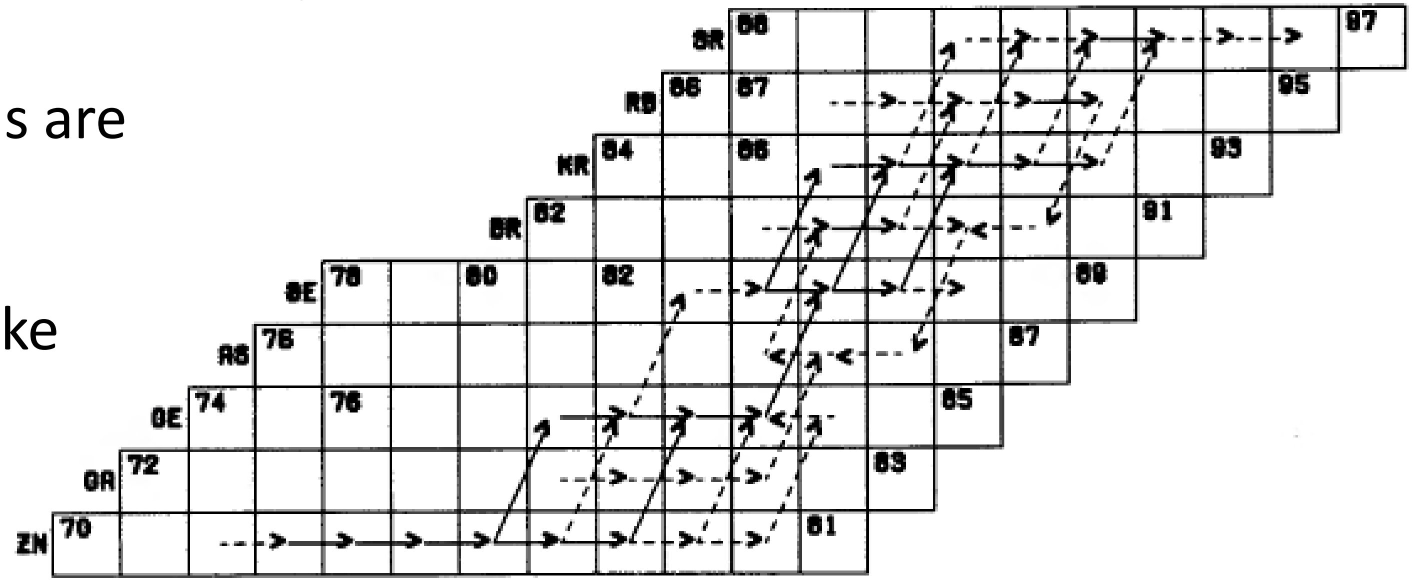
Yay, job security!

What about charged-particles!? the α-process

- As we noted, core collapse supernova simulations seem to not have very neutron-rich conditions
  …so what happens in the explosion then?
- One possibility is α-process nucleosynthesis
- Core collapse supernovae nucleosynthesis starts by photodisintegration of nuclei near the iron core into protons and neutrons. They combine into α particles, which can be captured in (α,n) reactions to form heavier nuclei.
- In the *r*-process, the α-process is just the on-ramp.
  But if there aren't enough neutrons around for the *r*-process, then the α-process is the main event
- The majority of the relevant (α,n) reactions are not known and have sizeable theoretical uncertainties *Yay, job security!*
- Interestingly, the α-process appears to make nuclei in the Zn-Sn region which have an abundance pattern de-coupled from the r-process pattern, known as the LEPP



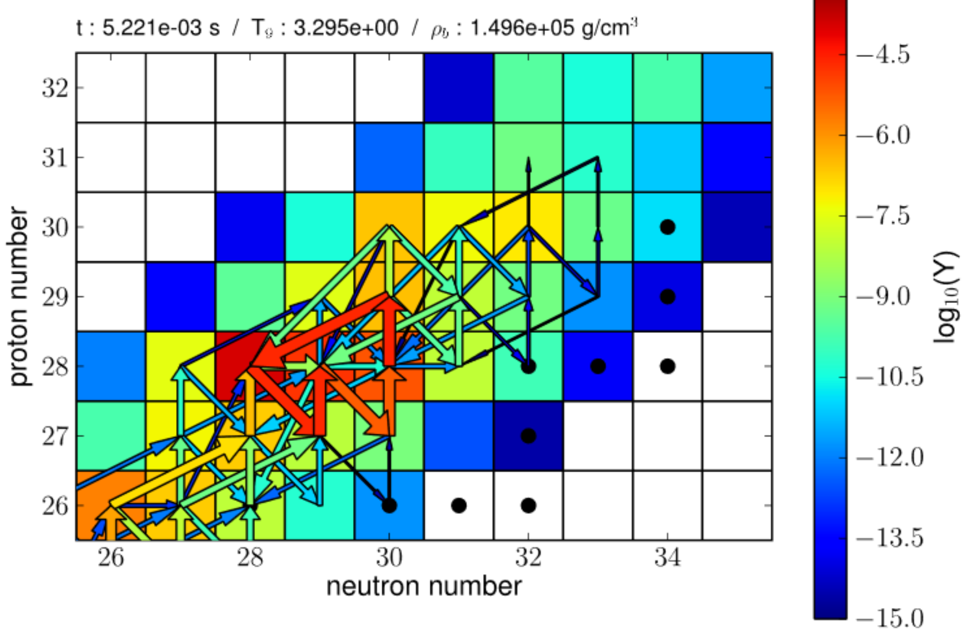
Woosley & Hoffman, ApJ (1992)

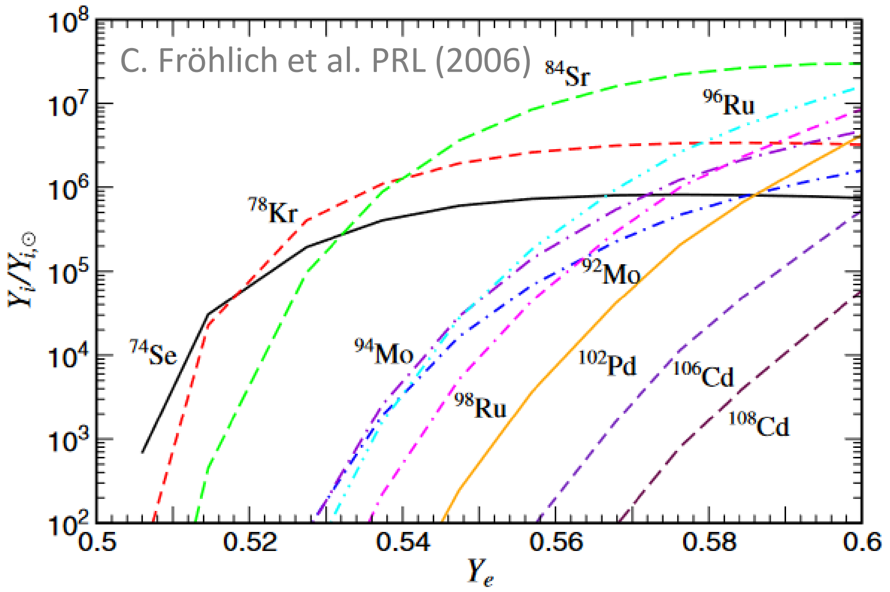


Who says they're neutron-rich!? the νp-process

- An alternative scenario is that the core collapse supernova isn't neutron-rich at all. This is a distinct possibility given the uncertainties in neutrino interactions with matter (the proto-neutron star is a neutrino light bulb)
- For this case, proton and α capture reactions make material around ^{56}Ni at the early high temperatures, but once cooling ensues, a complicated set of reactions takes place.
- Primarily (p,n), (n,p), (p,γ) and (γ,p) reactions
- In models, the νp-process appears to make LEPP nuclei, though many astrophysics and nuclear physics uncertainties remain
- Interestingly, the νp-process may also explain the existence of some of the lower-A *p*-nuclei (*p what!?*)

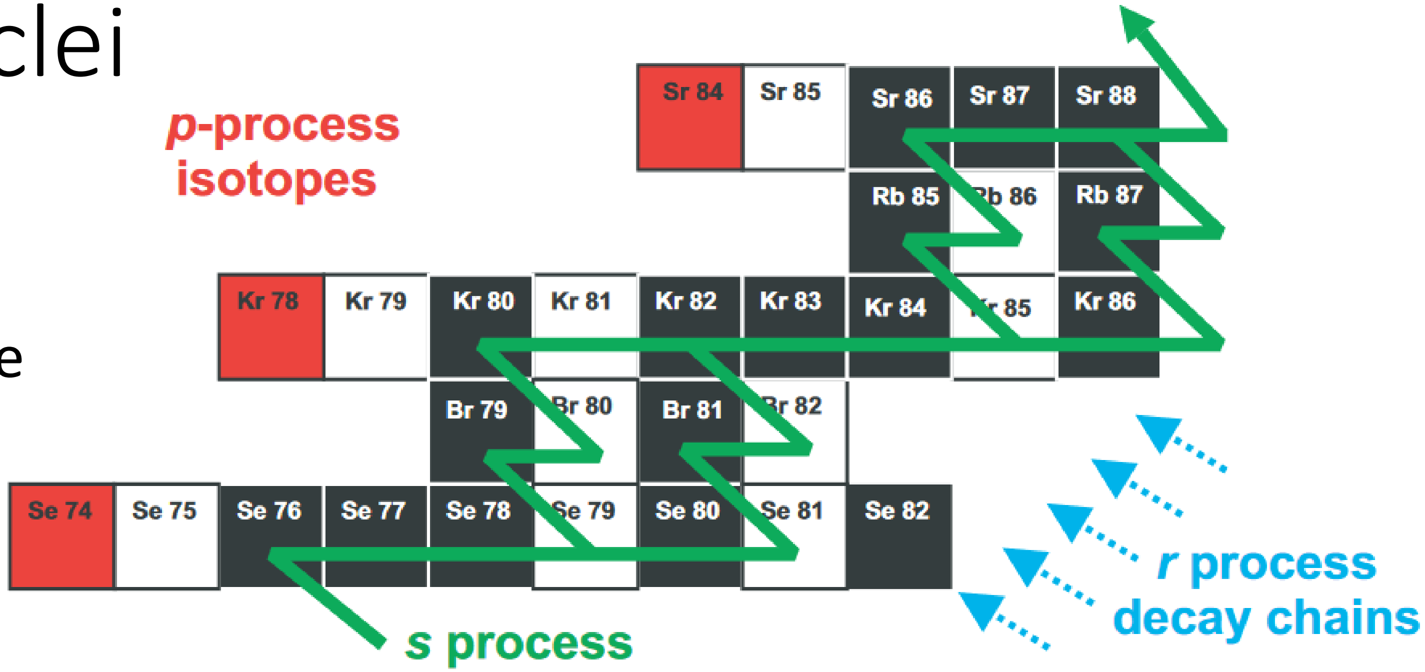
Arcones, Fröhlich, & Martínez-Pinedo, ApJ (2012)



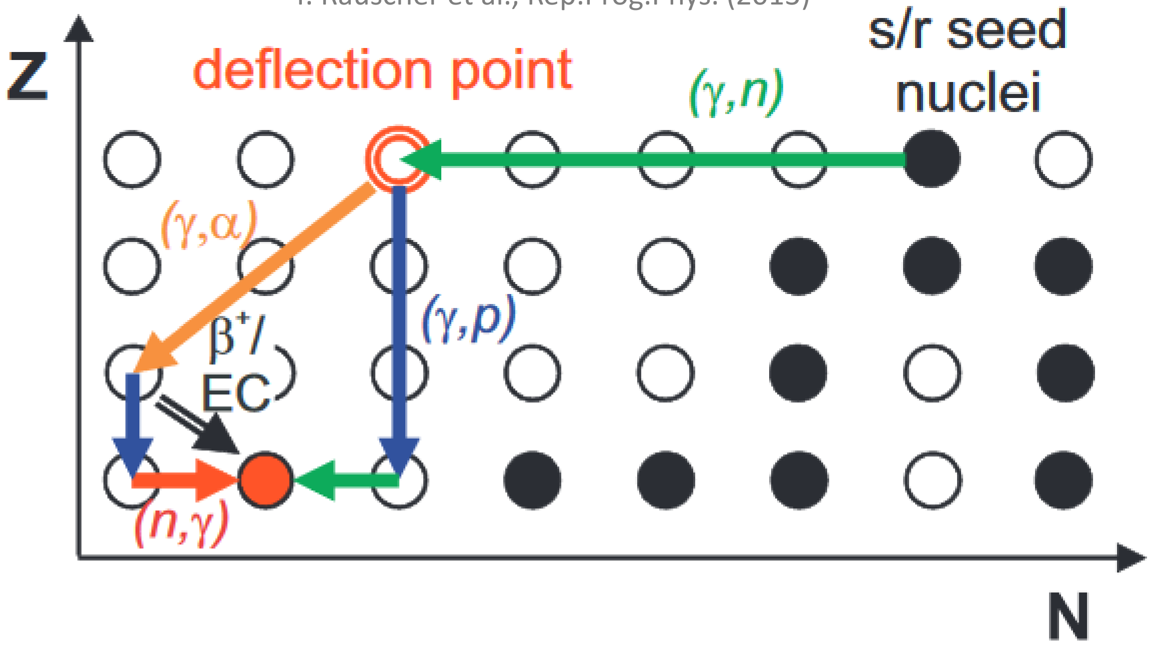


Who ordered these? p-nuclei

- Five minutes ago, when we still had our youth, we were pretty into the idea of neutron-capture producing most of our elements. But how would neutron-capture produce these?
- These nuclides (35 of ‘em) on the proton-rich side of stability need some other explanation
- The νp-process is a possibility for the low-A ones, but it certainly won’t work for A≳70
- Generally, the favored *p*-nuclide production site is the *p*-process in the outer shells of massive stars during core-collapse supernovae. This process comprises photodisintegration reactions of heavy nuclides and some capture reactions of the photodisintegration products

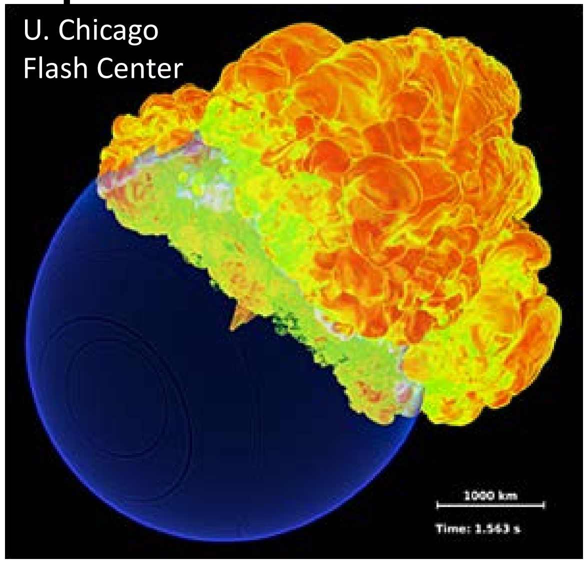


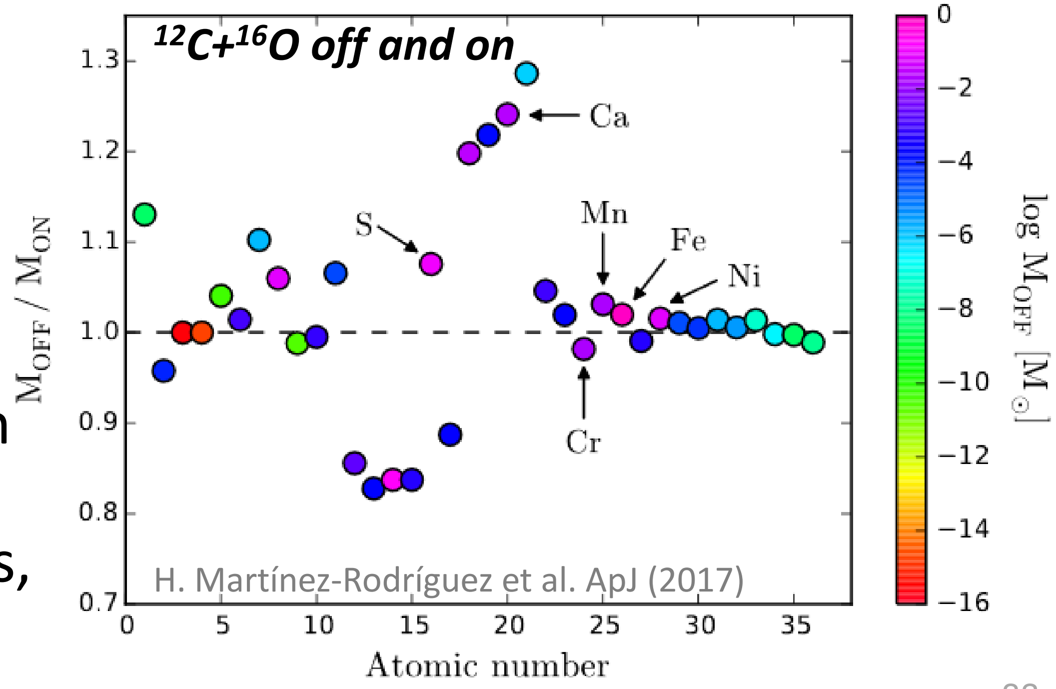
T. Rauscher et al., Rep.Prog.Phys. (2013)



It's not all about core collapse, Type Ia supernovae

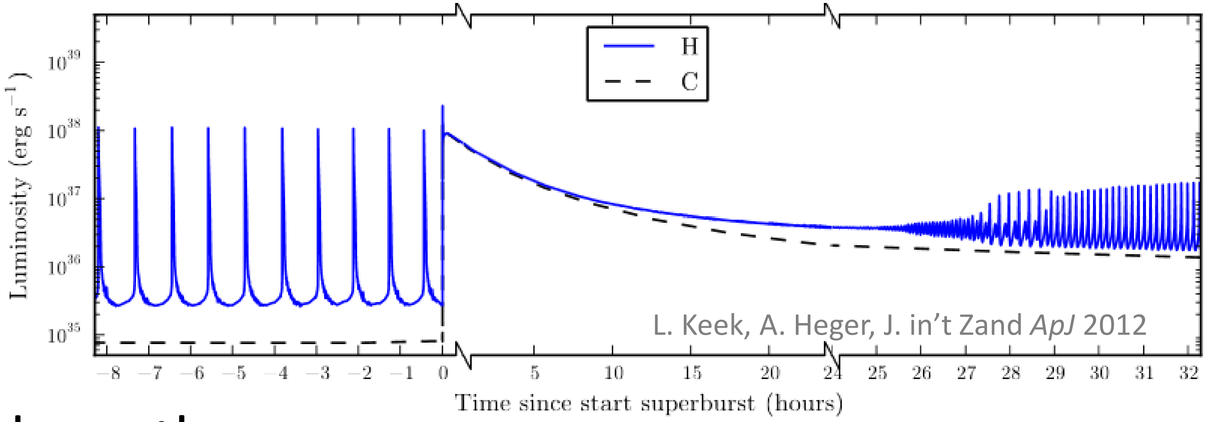
- Supernovae lacking hydrogen in their spectra and clearly producing an absurd quantity of nickel are known as type Ias
- The way to make this happen is to explode a white dwarf (or two) and burn all of the carbon and oxygen which these objects are mostly made of
- No matter whether it's an accreting white dwarf driven over the Chandrasekhar mass or two merging white dwarfs, the end result is $^{12}C+^{12}C$ and $^{12}C+^{16}O$ fuse to release a lot of energy, it's so hot that material is driven into nuclear statistical equilibrium, mostly making stuff near ^{56}Ni
- It's clear that the $^{12}C(\alpha,\gamma)$ rate is critical for setting the C/O ratio that will impact the explosion
- Interestingly, the progenitor choice and nuclear reaction rates appear to affect some isotopic ratios, by way of proton-capture reactions producing proton-rich nuclides, which β-decay and effectively neutron-ize the material that will be photo disintegrated in the explosion





It’s not all about nucleosynthesis, X-ray *super*bursts

- Explosive C burning can occur elsewhere as well
- Energetic explosions, known as x-ray superbursts (we’ll talk about the ho-hum regular ones in a moment) are difficult to explain with anything other than explosive carbon burning



- The idea is that the carbon is accreted onto or made on the neutron star surface until a sufficient density is built-up that $^{12}C+^{12}C$ fusion is triggered
- The reason ^{12}C is favored is that lower-*Z* fuels would burn before enough material is built up to explain the energy of the explosion and higher-*Z* fuels would build up more fuel and be too explosive
- In models, these explosions are so energetic that they lead to nuclear statistical equilibrium, like carbon-burning in Type 1as, and so there isn’t much mystery as to what their mass distributions would be. The outstanding mystery is that the predicted and observed ignition depths for carbon don’t quite line-up

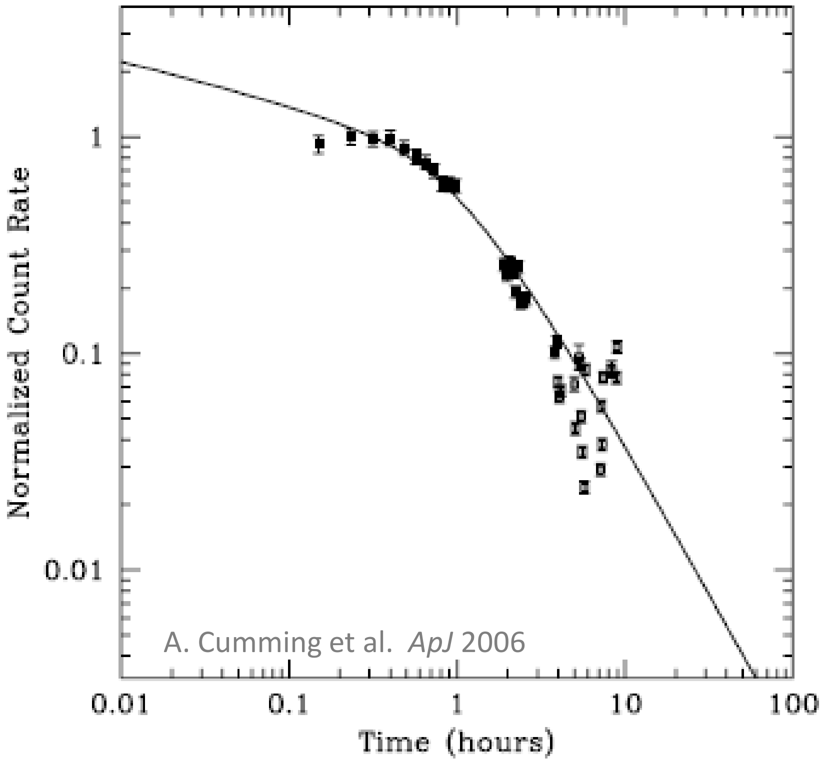
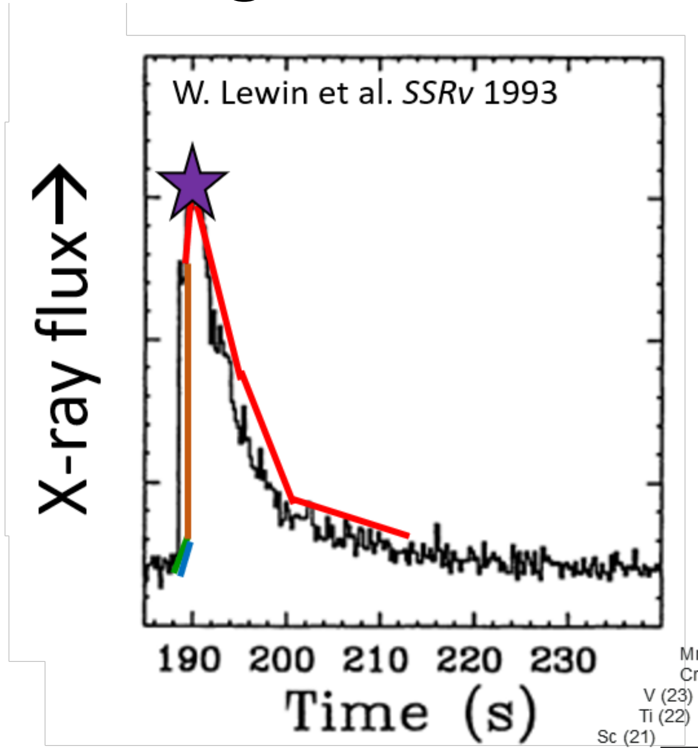
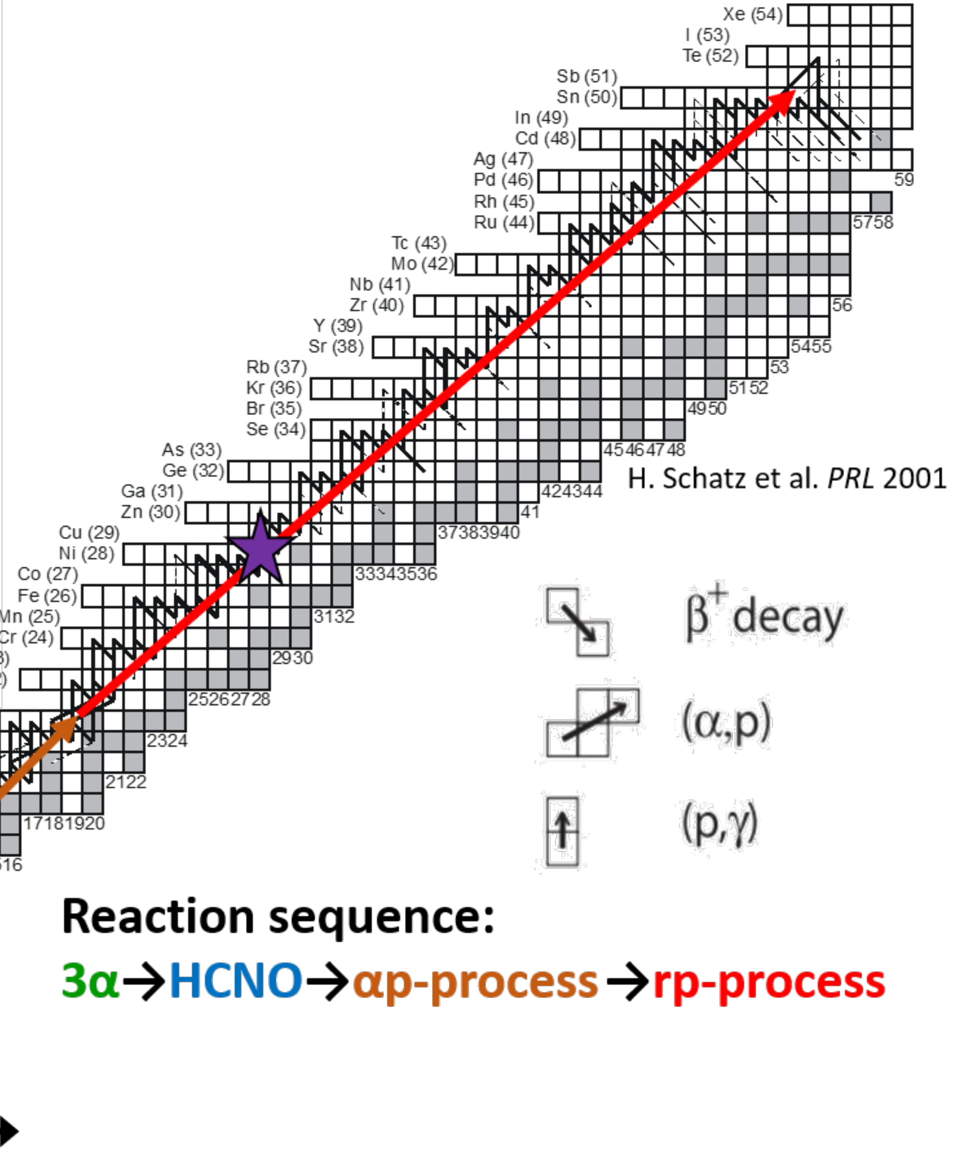
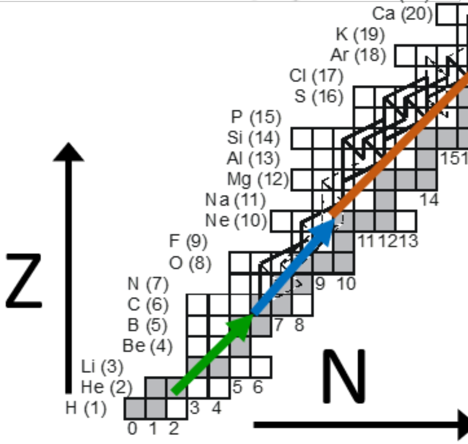


Fig. 9.—Fitted light curve for Ser X-1.

Explosive hydrogen burning's time to shine, X-ray bursts

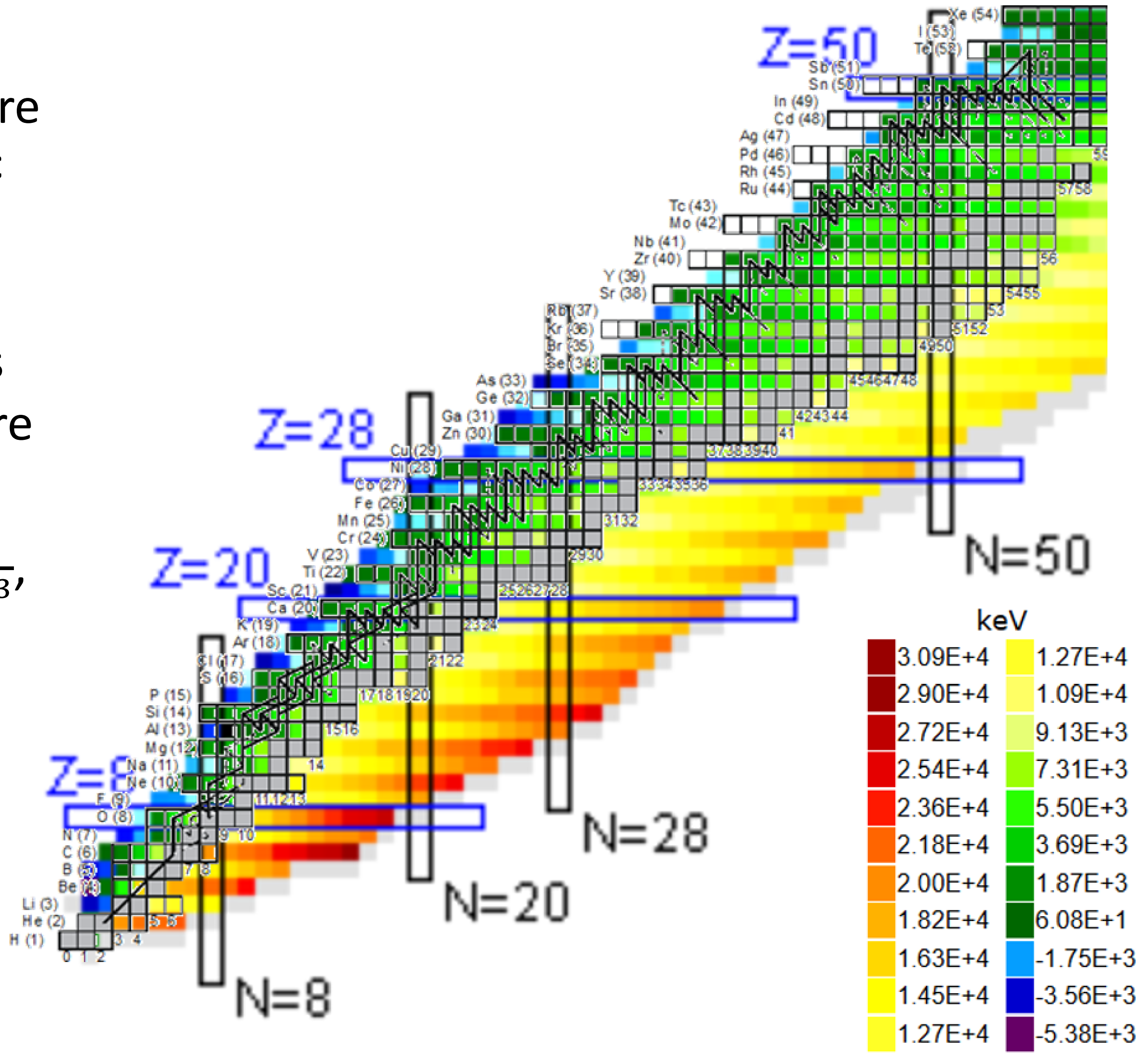
- A more standard scenario for an accreting neutron star is that it's building up hydrogen and helium and one of those materials is going to ignite first, depending on the H/He ratio and the rate material is being dumped onto the neutron star
- The cases where H is stably burned until He ignites and triggers an explosion are the most interesting from a nuclear physics stand-point, as they lead to the (rapid-proton-capture) *rp* -process



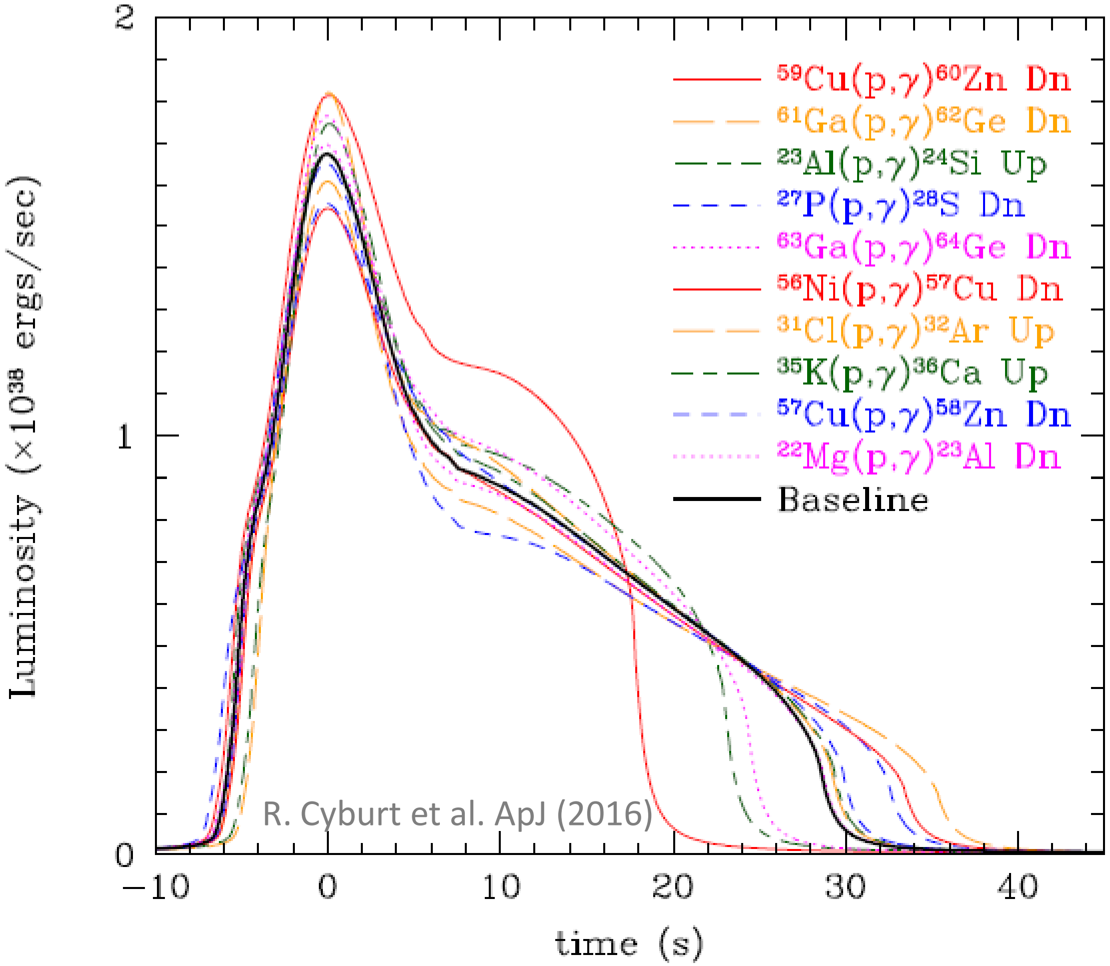
~~Uber~~ the waiting-point approximation, but for proton-capture

- The *rp* -process roughly proceeds in a similar style as the *r*-process, except here proton-captures proceed along isotonic chains until a critical proton-separation S_p energy is reached
- The critical S_p for which $(p,\gamma)\overrightarrow{\leftarrow}(\gamma,p)$ is established depends on the temperature and proton density
- Given the typical conditions, $\rho\sim10^6\,\frac{\mathrm{g}}{\mathrm{cm}^3}$, $X(H)\sim0.7$, and $T\sim1\mathrm{GK}$, it turns out $n_p\sim n_\gamma$ and so just comparing the forward & reverse rates isn't a bad approximation to find the critical S_p
- This turns out to be $S_p\sim1\mathrm{MeV}$
  (as you found in the group activity last class)



Nuclear power, but useless, the rp-process

- As a purely nuclear-powered event, it's not surprising X-ray bursts are sensitive to nuclear physics uncertainties
- Important rates fall broadly into the categories:
  - *Ignition*: Reactions that enable the system to break-out of the stable burning of hydrogen via the CNO cycle. E.g. $^{15}O(\alpha,\gamma)$
  - *Branch points*: Nuclei that have reactions competing, causing matter to evolve to higher-*Z* via one path or another. These reside in the (α,p) process that marks the start of the *rp*-process. E.g. $^{30}S(\alpha,p)$
  - *Waiting points*: Nuclei that have low (or negative) proton-capture Q-values and long half-lives, so (γ,p) competes strongly with (p,γ) and β-decay is slow. These stall the rp-process. E.g. ^{68}Se
  - *Cycles*: Branch-point nuclei that either return material to a repetitive reaction loop or allow the *rp*-process to continue onward to higher-*Z*. E.g. ^{59}Cu

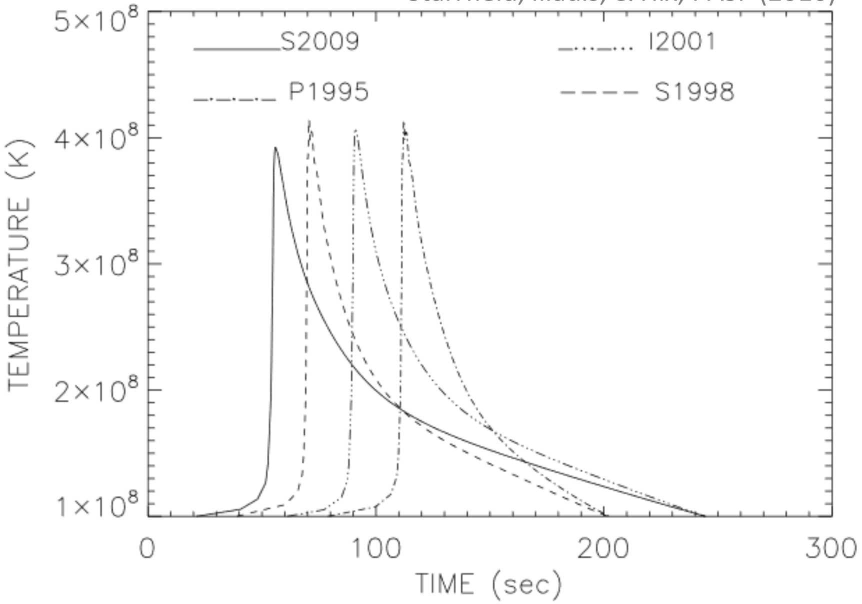


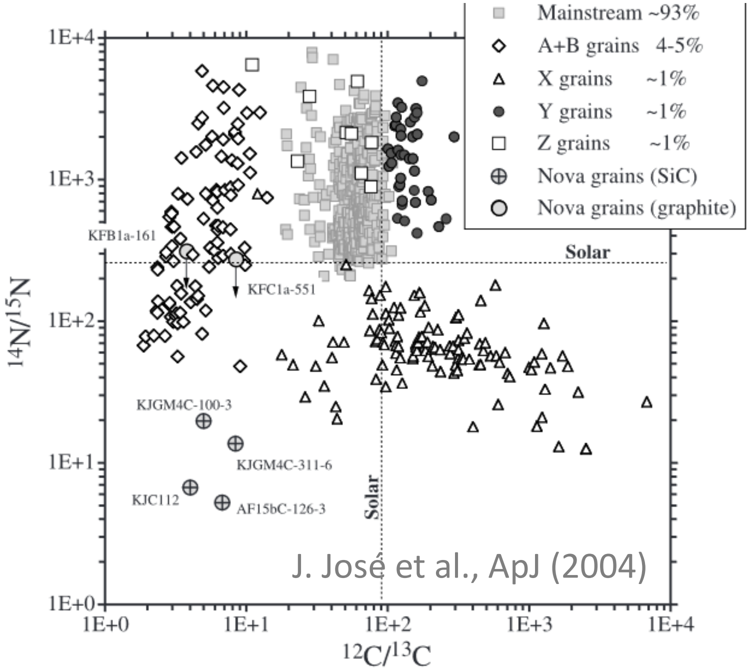
*Neutron stars have very large gravitational binding energies, so the material produced by the rp-process **does not** enrich the galaxy.*

~~Uber~~ *the rp-process, but for white dwarves*, Novae

- A similar sort of process (CNO burning→ thermonuclear runaway → *rp*-process) can also happen on the surface of a white dwarf accreting hydrogen/helium-rich material from a companion star
- The big difference is that the white dwarf has a much smaller surface gravity, which means
  - Lower temperatures are reached in the explosion, since less fuel is needed to spark a runaway. This means that only the proton-capture reactions are relevant (i.e. not α-capture)
  - Material can escape the smaller gravitational potential, so these explosions can enrich the galaxy and contribute to nucleosynthesis. It's thought that the signal of this nucleosynthesis is present in pre-solar grains found in some meteorites

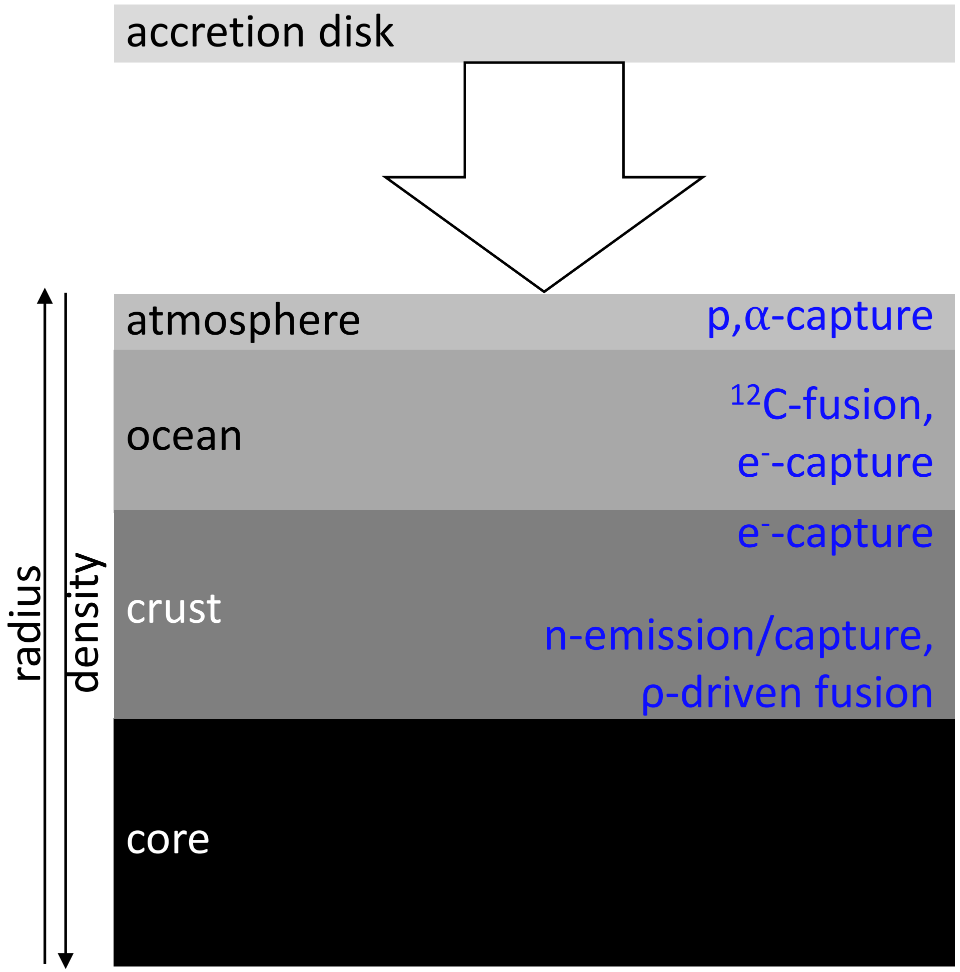
Starrfield, Iliadis, & Hix, PASP (2016)





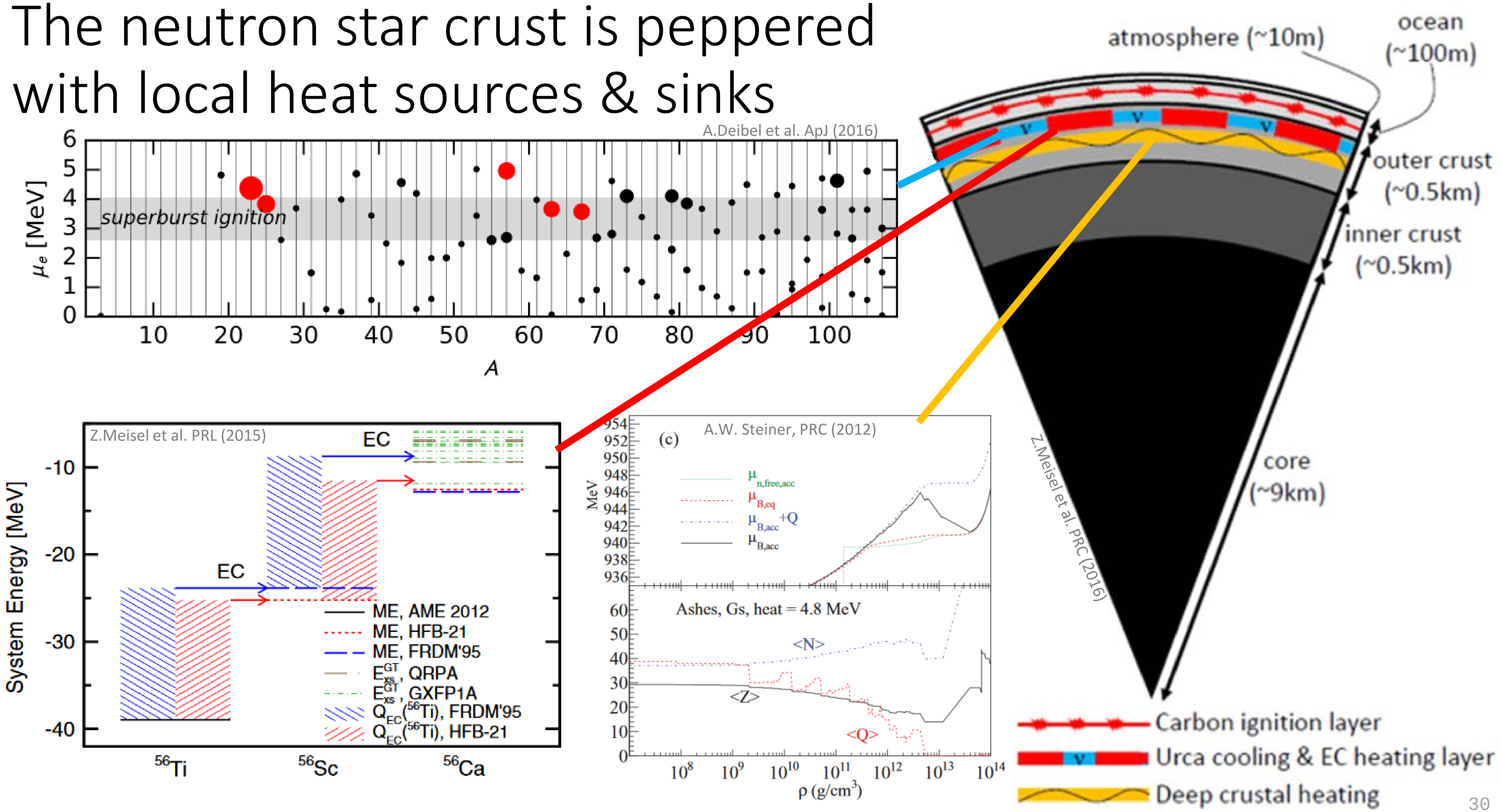
There's more to life than nucleosynthesis, NS crust reactions

- Last episode, on accreting neutron stars, we left-off with the fact that x-ray bursts and superbursts make bright flashes of light and a range of nuclei …but what happens to those nuclei?
- They're buried further into the neutron star ocean and crust, where the density increase substantially with depth. The first interesting consequence is that the electron Fermi energy gets large enough to force electrons into nuclei, converting protons to neutrons
- Electron-capture reactions can either deposit or liberate heat, depending on the nuclear physics specifics
- Deeper in the crust, the neutron-degeneracy pressure rises to the point that neutron-emission/capture occurs, releasing more heat
- Near the point where it doesn't make sense to talk about nuclei any more (because a neutron gas dominates the composition), the density is large enough to fuse nuclei in a process called pycnonuclear fusion



These heating/cooling processes can leave specific signatures in observables from accreting neutron stars, in particular in systems cooling off after prolonged accretion stops

The neutron star crust is peppered with local heat sources & sinks



Further Reading

- Chapter 12: Modern Nuclear Chemistry (Loveland, Morrissey, & Seaborg)
- Nuclear Physics of Stars (C. Iliadis)
- Cauldrons in the Cosmos (C. Rolfs & W. Rodney)
- Lecture Materials on Nuclear Astrophysics (H. Schatz)
- Chapters 10 & 11: Stellar Astrophysics (E.F. Brown)
- Chapter 6,9-13: Stellar Structure and Evolution (O.R. Pols)
- White Paper on Nuclear Astrophysics, Prog.Part.Nuc.Phys (2017)