An introduction to

High Mass Stellar Evolution

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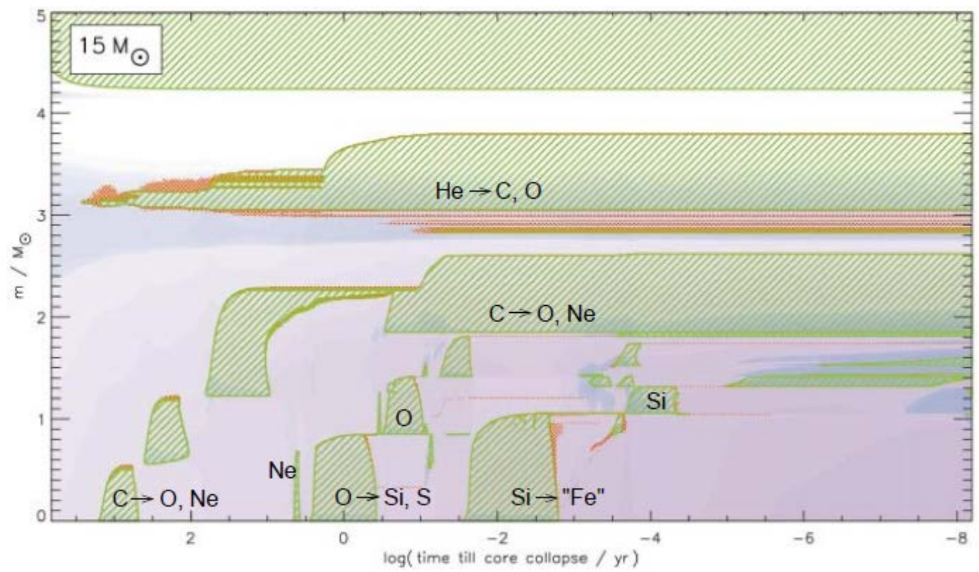
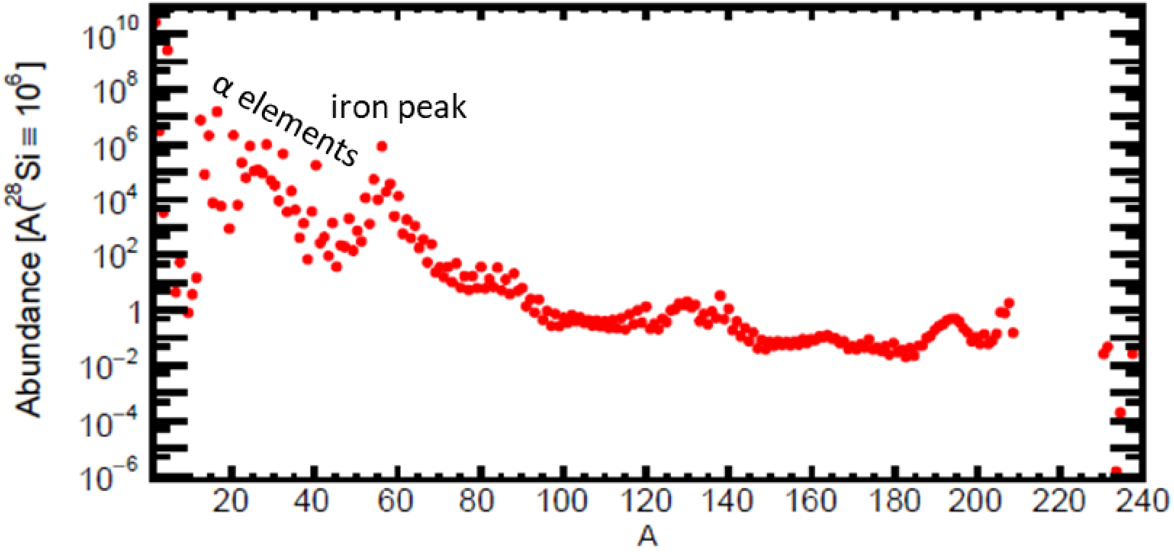
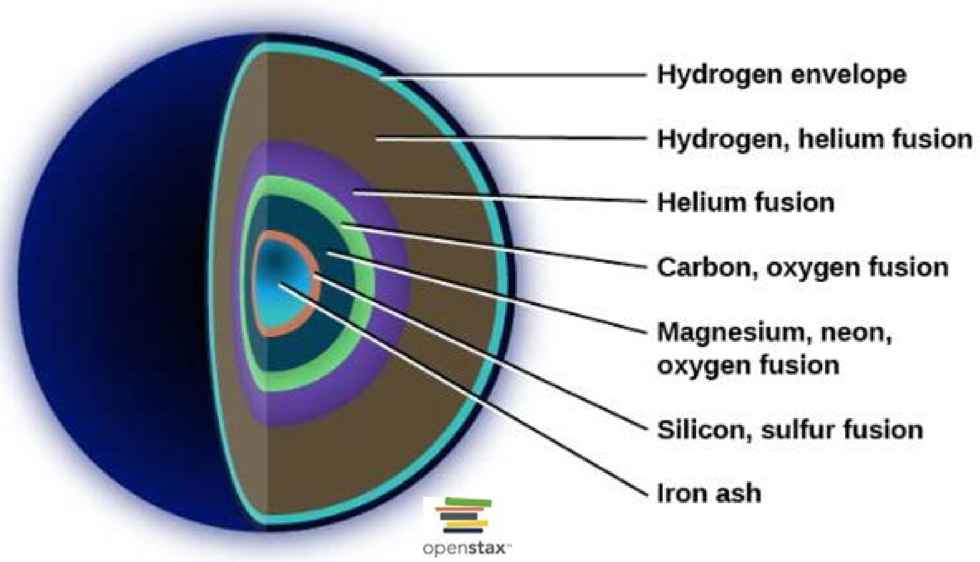
Carbon burning and beyond

- For stars that start at ~$10M_\odot$ or greater, fusion can proceed far beyond carbon
- C burns to make O, Ne, and Mg
- O, Ne, and Mg burn to make elements around Si and S
- Elements around Si and S burn to make elements around Fe, stopping there (see *Introduction to Stellar Nuclear Power*)
- The result is the famous "onion structure"
- This makes a large fraction of elements lighter than iron

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



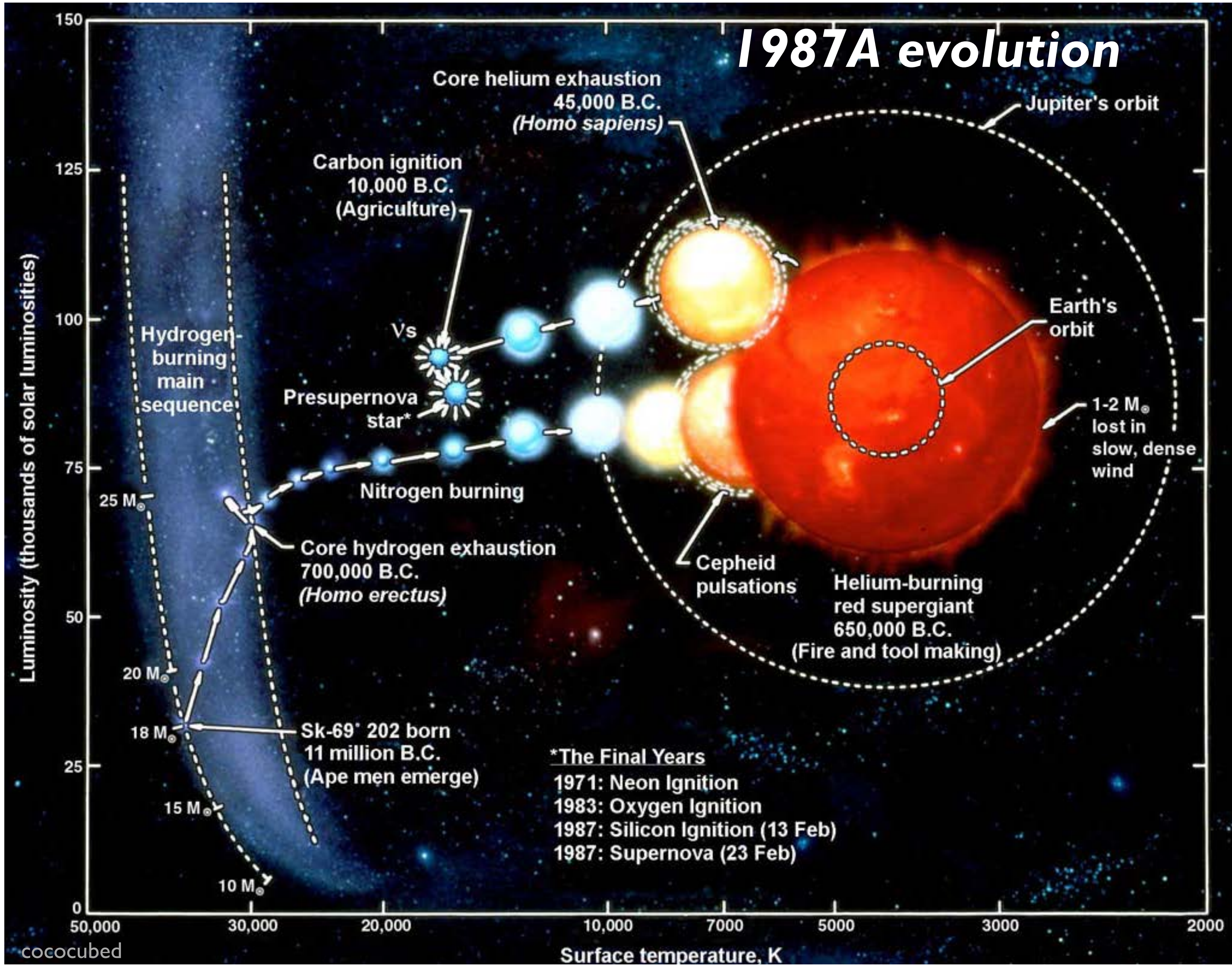




Advanced Burning on the HR Diagram

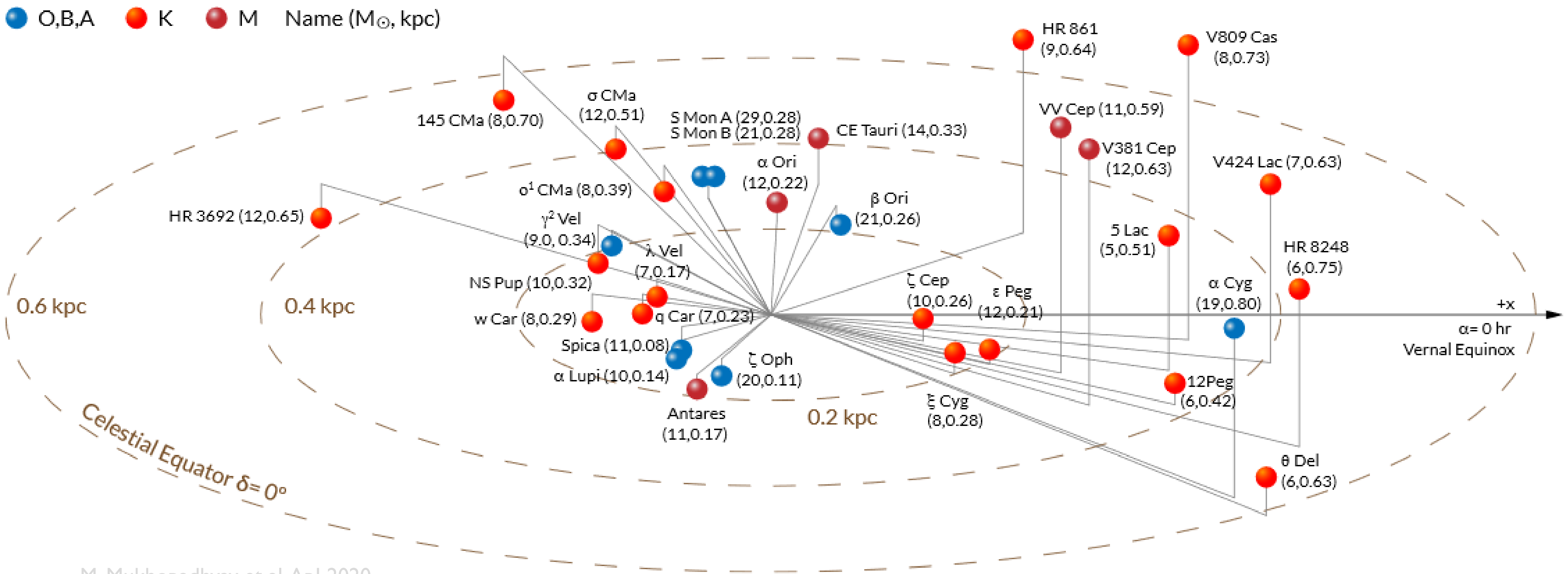
- As we saw in *Introduction to Low Mass Stellar Evolution*, this shell burning will cause the luminosity and radius to increase, producing a “supergiant”
- The timescale for advanced burning stages are relatively short:

Core Fuel	Time, $15M_\odot$	Time, $25M_\odot$
H	11 Myr	7 Myr
He	2 Myr	0.8 Myr
C	2 kyr	0.5 kyr
O	2 yr	0.5 yr
Si	20 days	1 day



How do we know a star is about to go supernova?

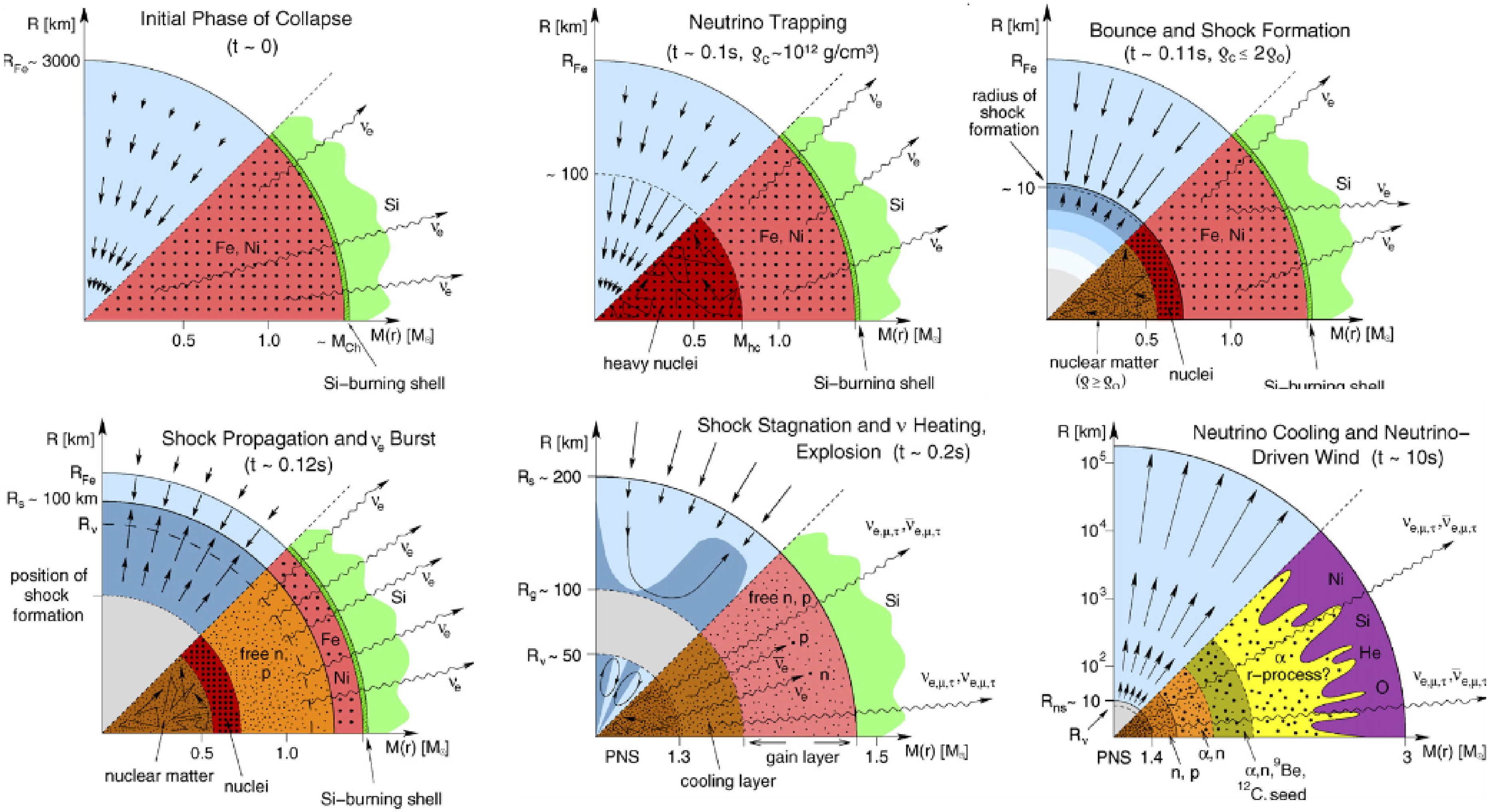
- We don't! The star's structure adjusts too slowly to change the surface properties.
- It may be possible to see a unique neutrino signature in the final hours before collapse



M. Mukhopadhyay et al. ApJ 2020

Core Collapse Supernova

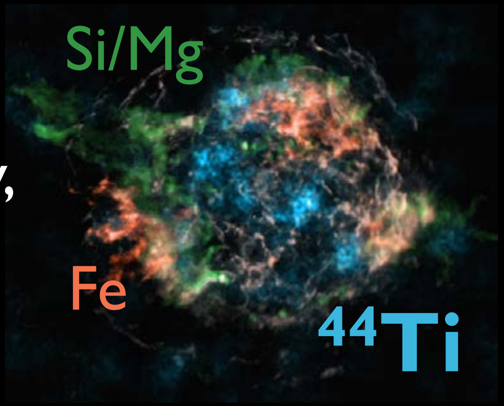
- Once the inert iron core reaches the Chandrasekhar Mass (~1.5$M_\odot$), the core collapses in a free-fall
- Eventually, the material in the core can compress no further and the core bounces, driving a shockwave outward
- A neutron star or black hole is left behind



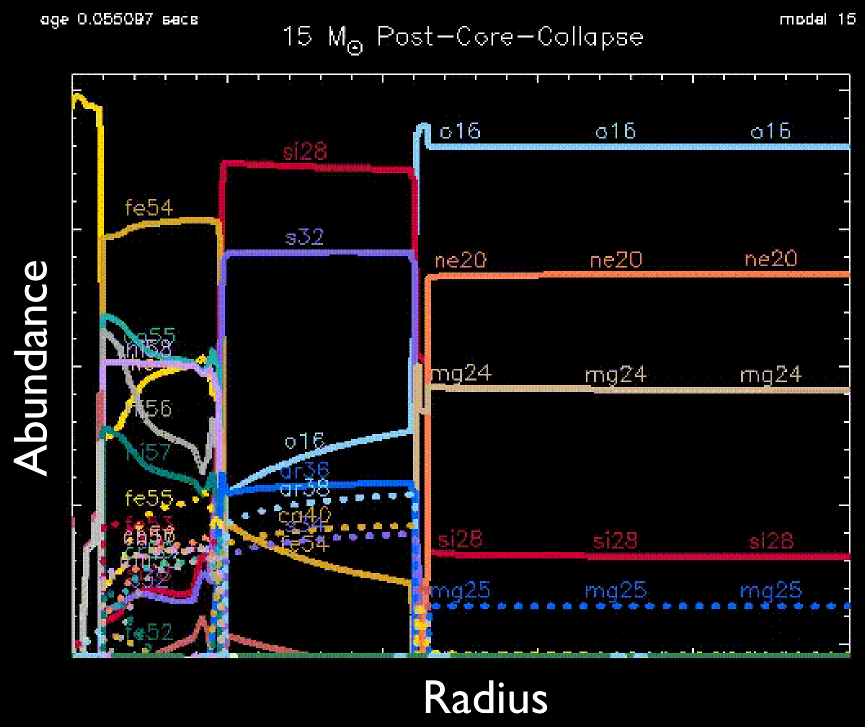
H. Janka et al. Phys. Rep. 2007

Nucleosynthesis in the Supernova Shock

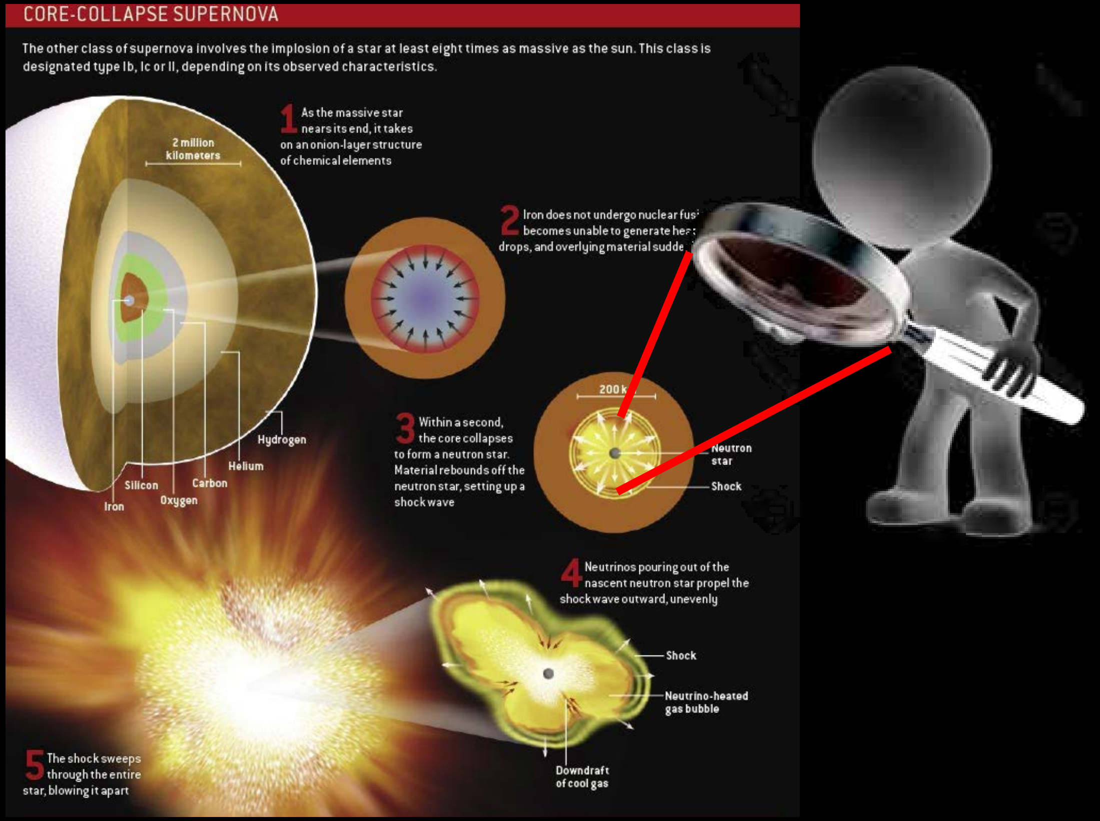
- The outgoing shock following core-bounce raises the temperature & density, where nuclides are mostly made during a freeze-out from equilibrium
- Some radioactive nuclides (e.g. ^{44}Ti) are core collapse supernova diagnostics



B. Grefenstette et al. *Nature* 2014



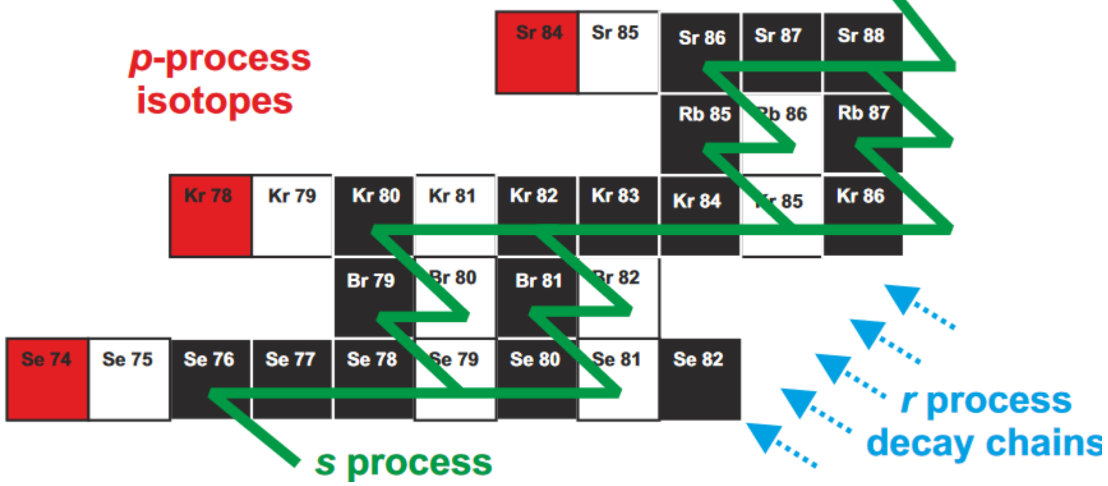
B. Paxton et al. *ApJS 2015*



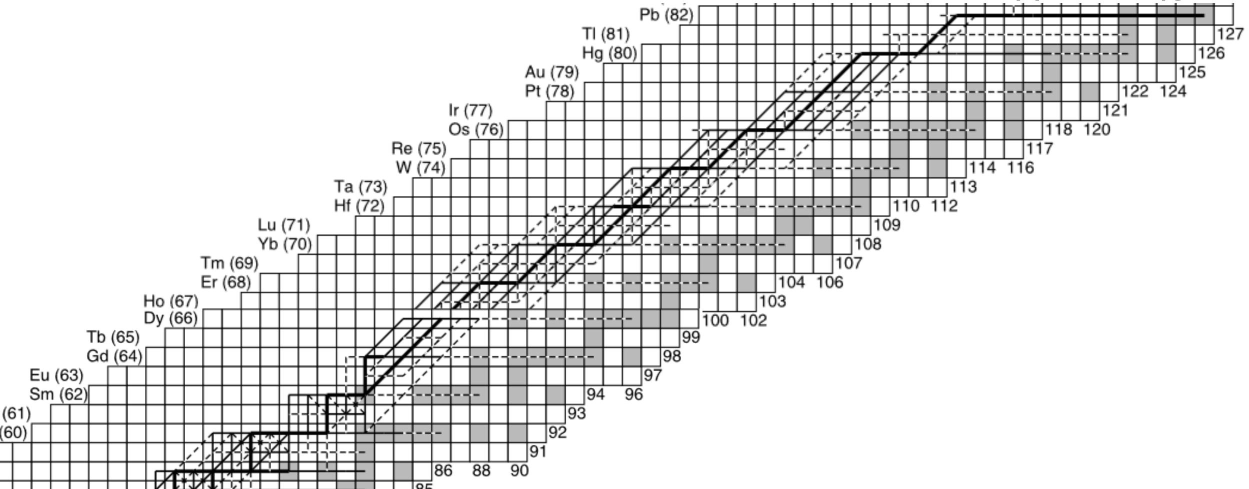
W. Hillebrandt et al. *SciAm* 2006

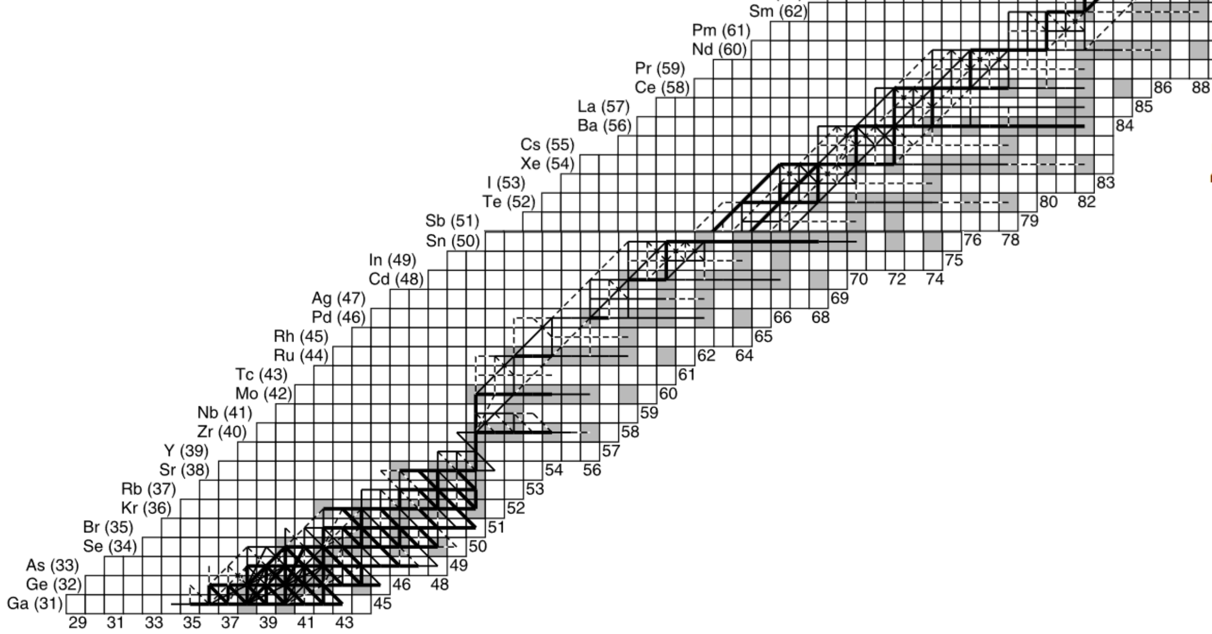
The origins of p-nuclei, in the wake of the CCSN shock

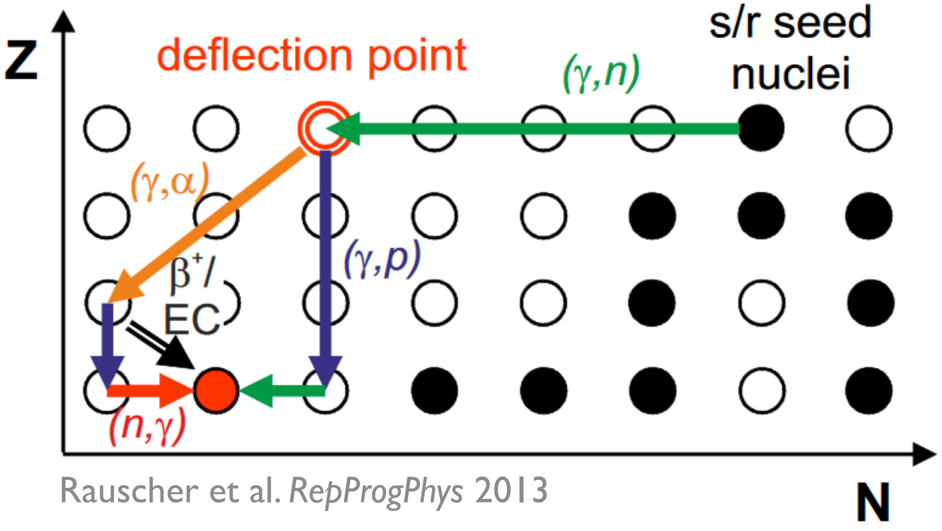
At slightly larger radii, the γ-process in the O/Ne shell is thought to form (most of) the *p*-nuclei, where seed nuclei are destroyed in a massive chain of (γ,*n*), (γ,α), and (γ,*p*) reactions:



Rapp et al. *ApJ* 2006



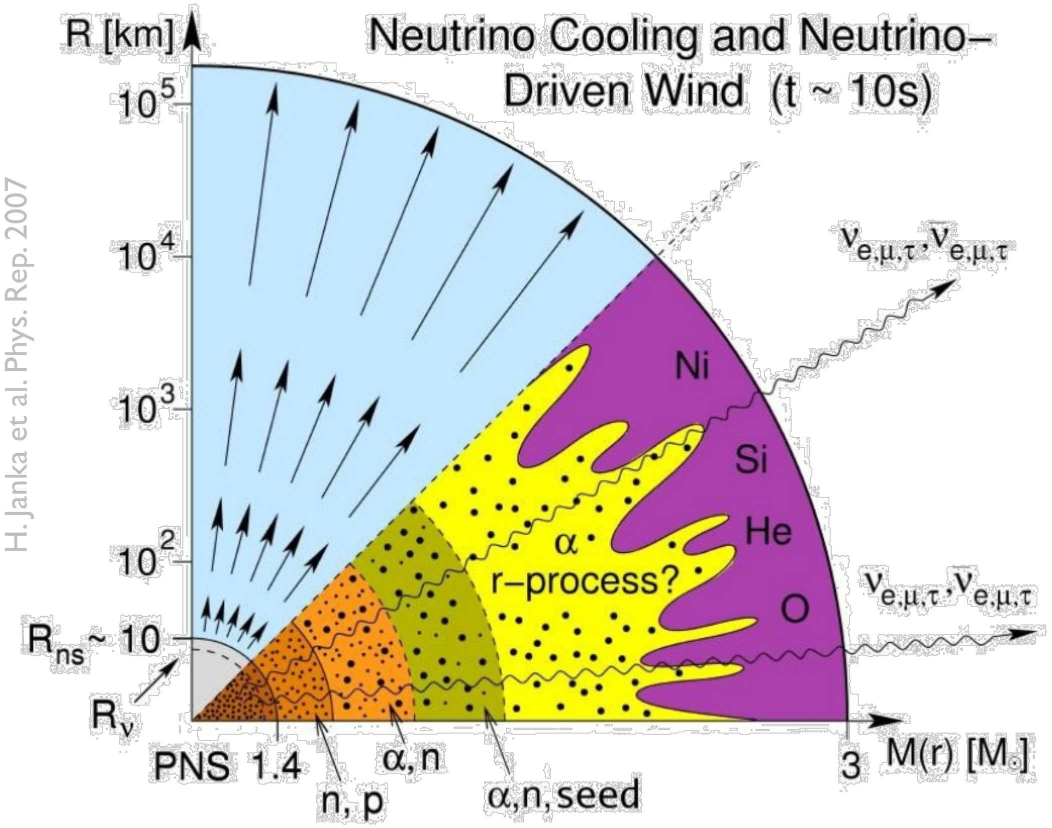




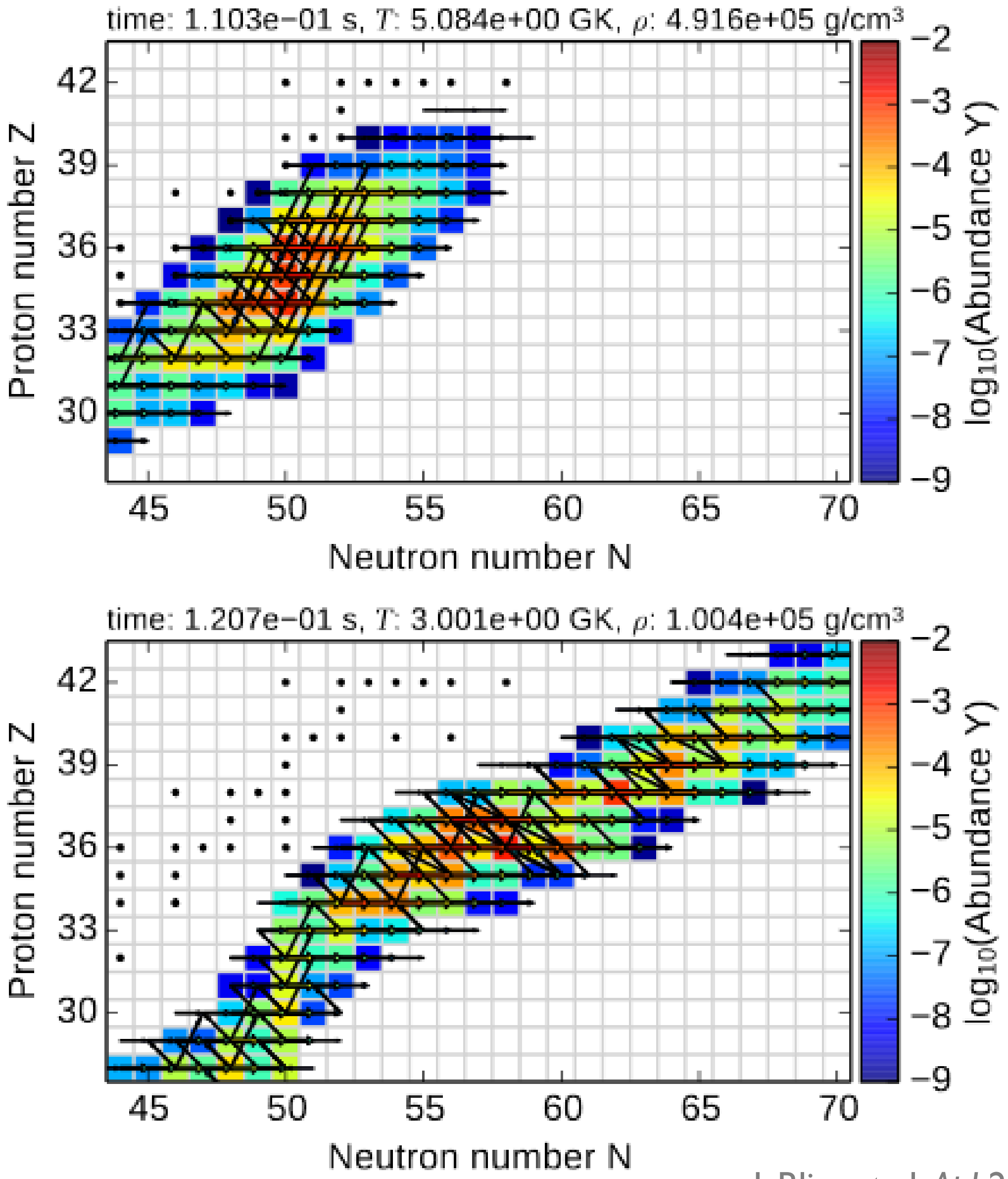
Rauscher et al. *RepProgPhys* 2013

Neutron-rich ν-Driven Wind Nucleosynthesis

For $Y_e < 0.5$, (α,n) reactions drive the flow of nucleosynthesis from seed elements, creating elements from zinc to tin

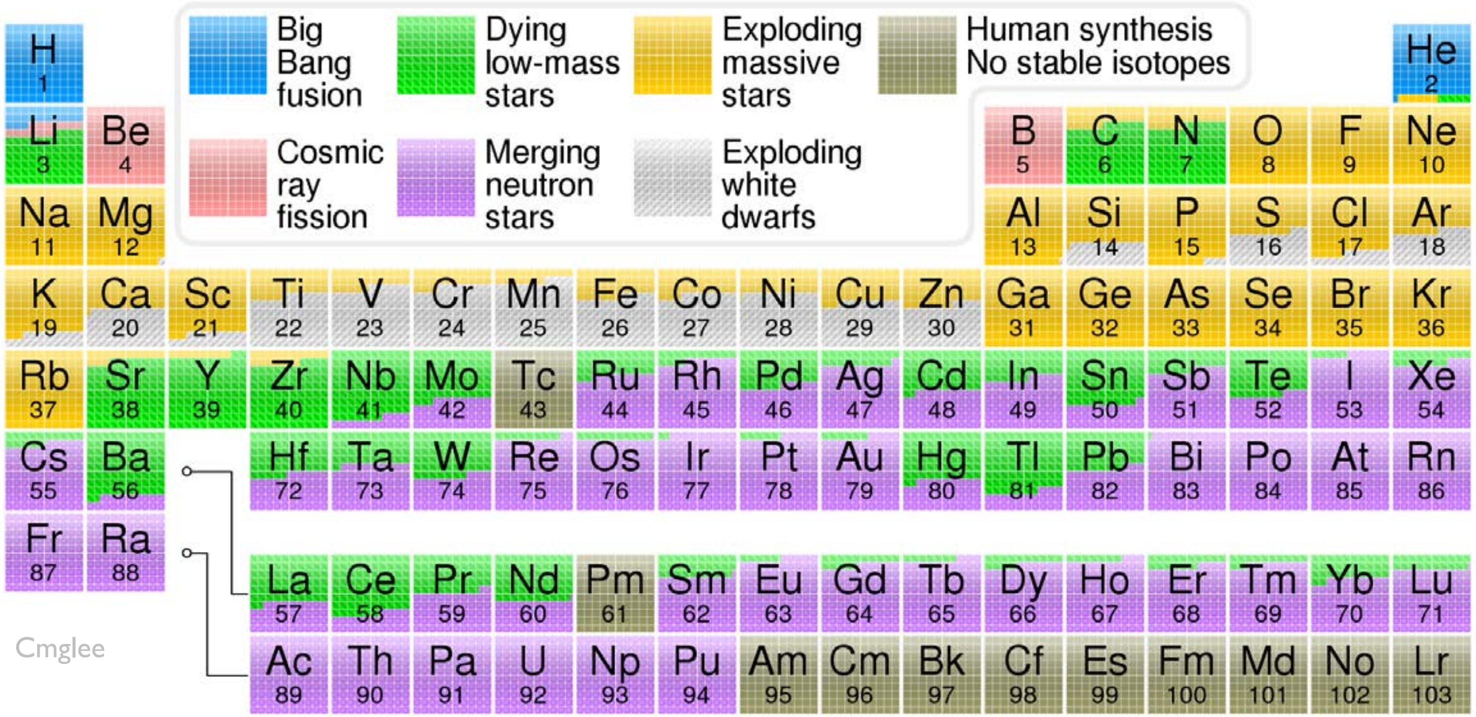


H. Janka et al. Phys. Rep. 2007



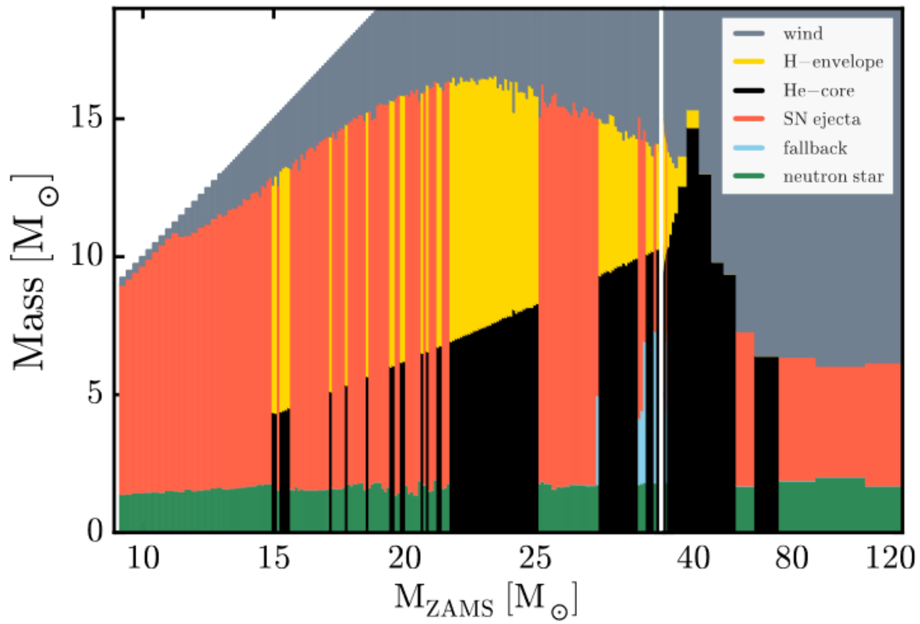
J. Bliss et al. *ApJ* 2018

Core collapse supernovae make a lot of stuff!



Cmglee

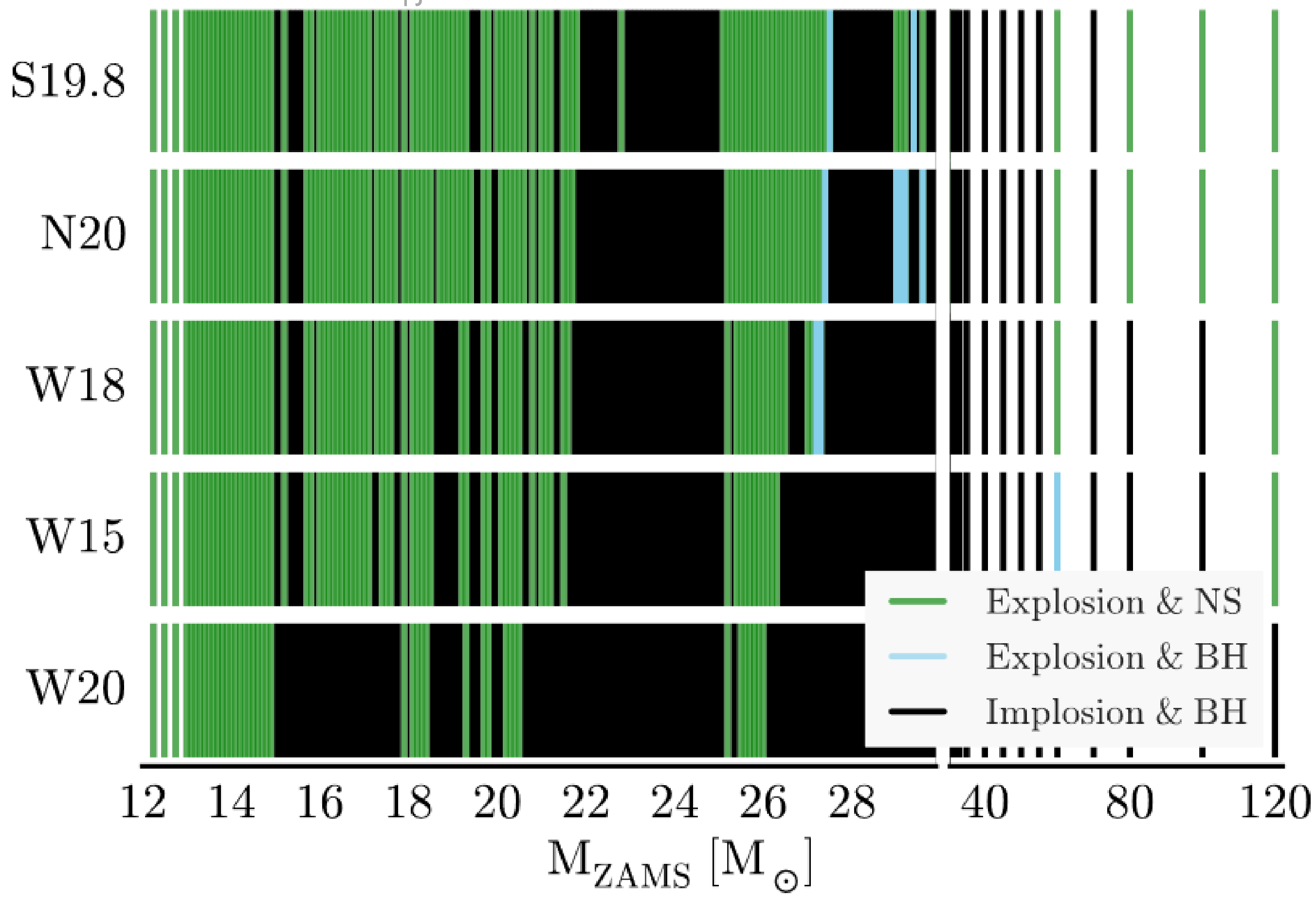
T. Sukhbold et al. ApJ 2016



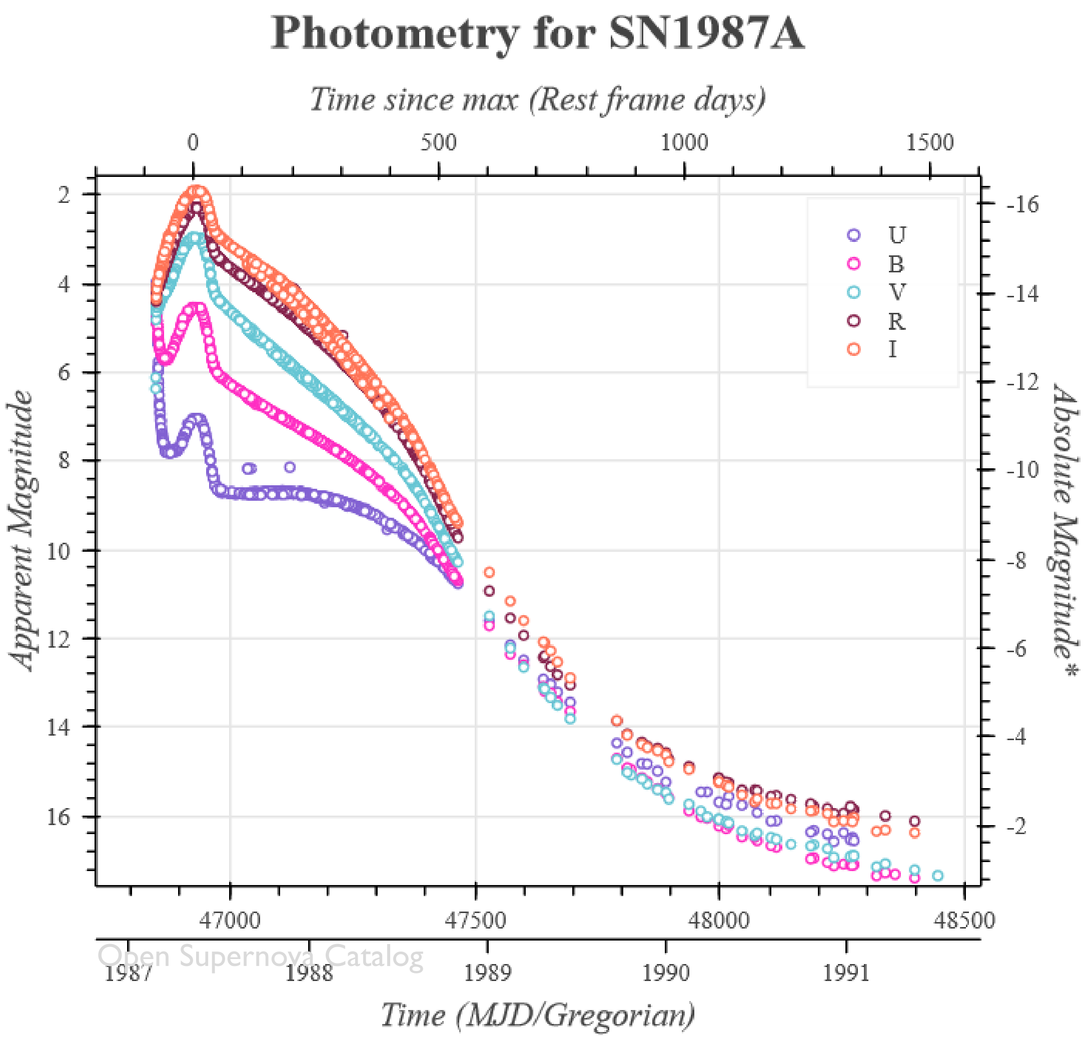
Remnants

- The core collapse supernova will leave behind a compact object
- Lower-mass stars likely produce neutron star, while higher mass stars likely produce a black hole
  (the star may skip the explosion and go straight to black hole and explosions of very massive stars leave no remnant from pair instability supernovae)
- However, the mapping between initial star properties and final remnant isn't straight forward and is an active area of research

T. Sukhbold et al. ApJ 2016

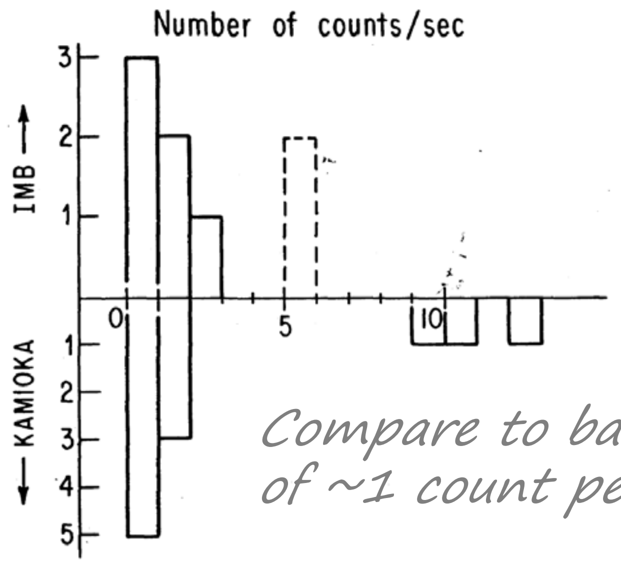


Supernova 1987A, *the celebrity of Core Collapse supernovae*



(Observed as a blue supergiant prior to explosion, so the transition to supernova would be somewhat different than described in this lecture)

Neutrino signature ~2hr before optical detection

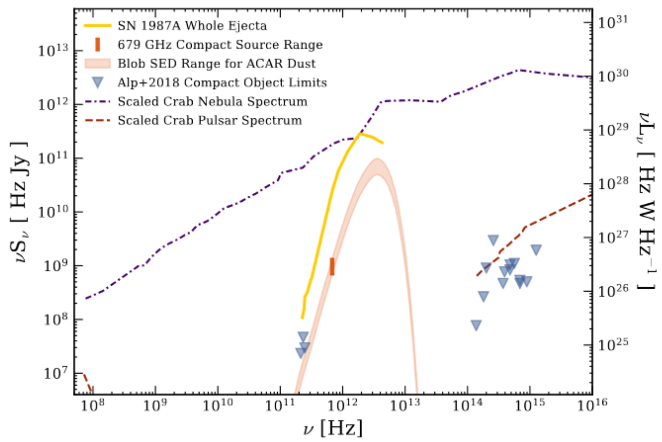


D.Schramm Proc. Int. Symp. Lepton and Photon Int. at High E. (1987)

Compare to background of ~1 count per 10min

Various evidence for a neutron star remnant

Cigan et al. ApJ 2019



Page et al. ApJ 2020