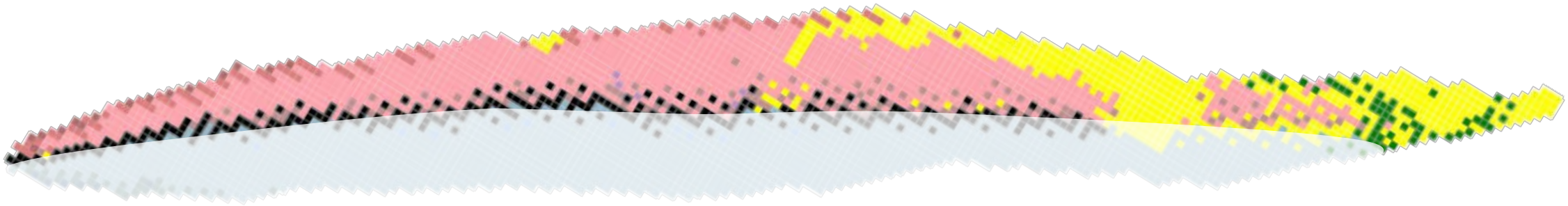
Nuclear Astrophysics Opportunities for Proton-rich Nuclei

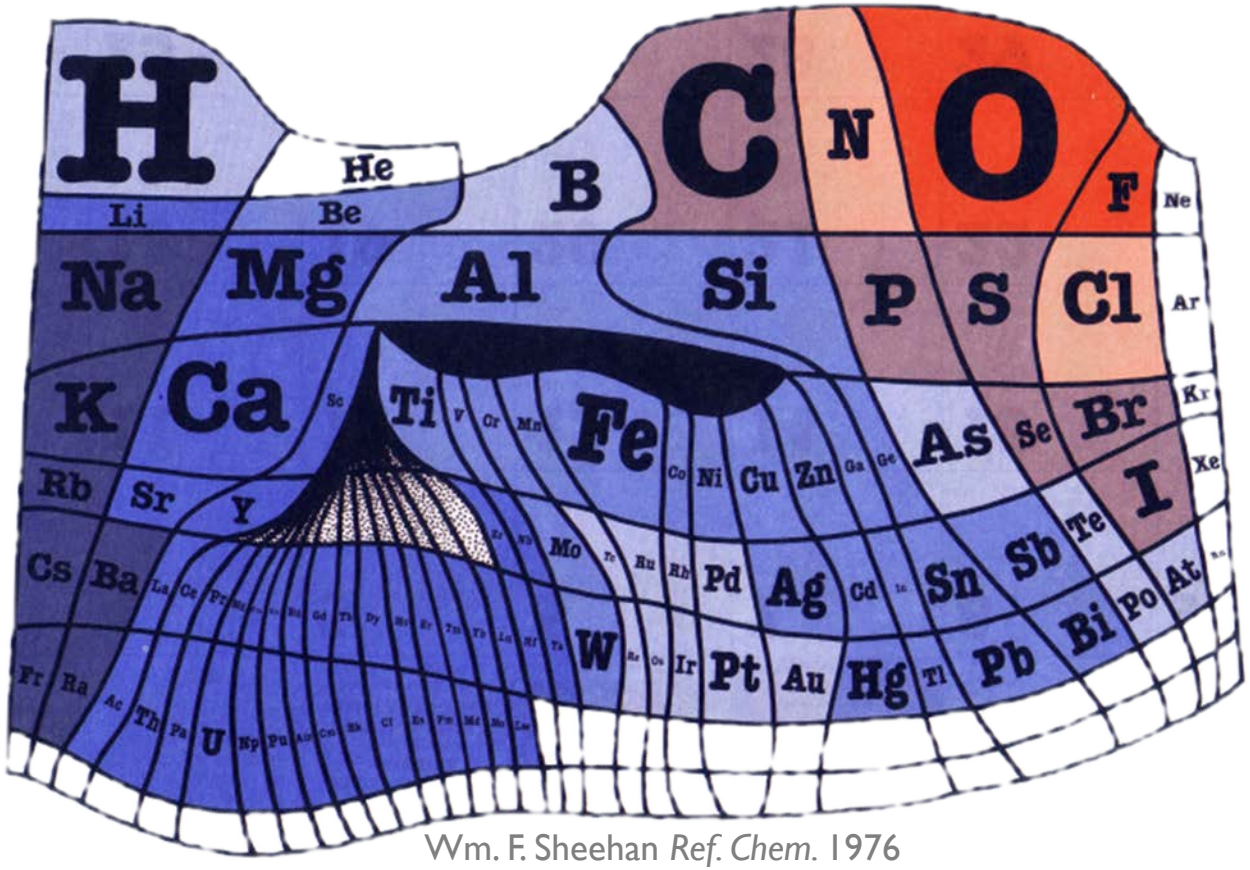


Zach Meisel
Ohio University

Workshop on Nuclear Astrophysics Opportunities at ATLAS 2019

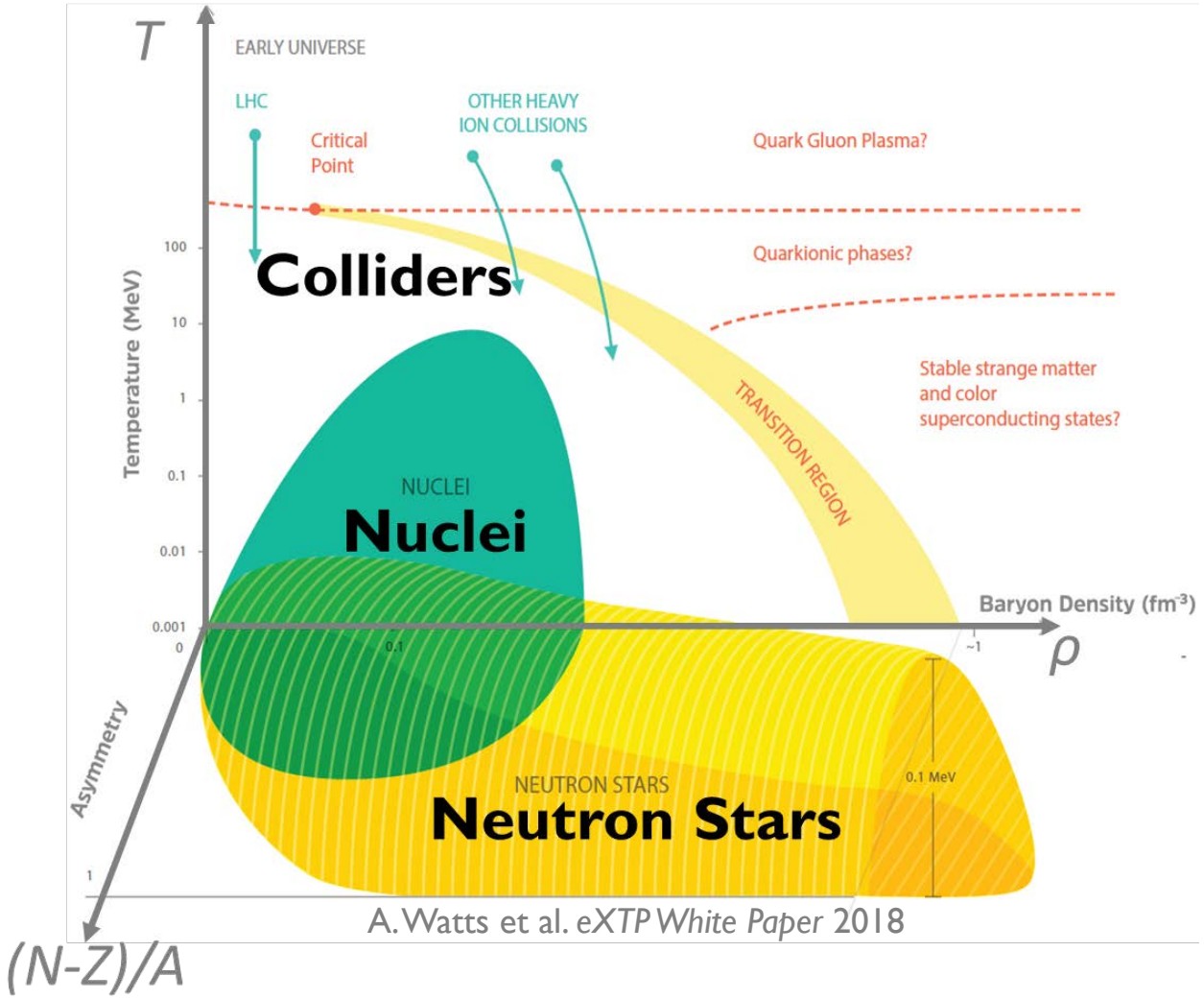
Major Open Questions in Nuclear Astrophysics:

Where were the elements made?



Wm. F. Sheehan *Ref. Chem.* 1976

How does ultradense matter behave?



A. Watts et al. *eXTP White Paper* 2018

Astrophysical Phenomena Impacted by Proton-rich Nuclei

High T and/or ρ drives matter to the extremes.

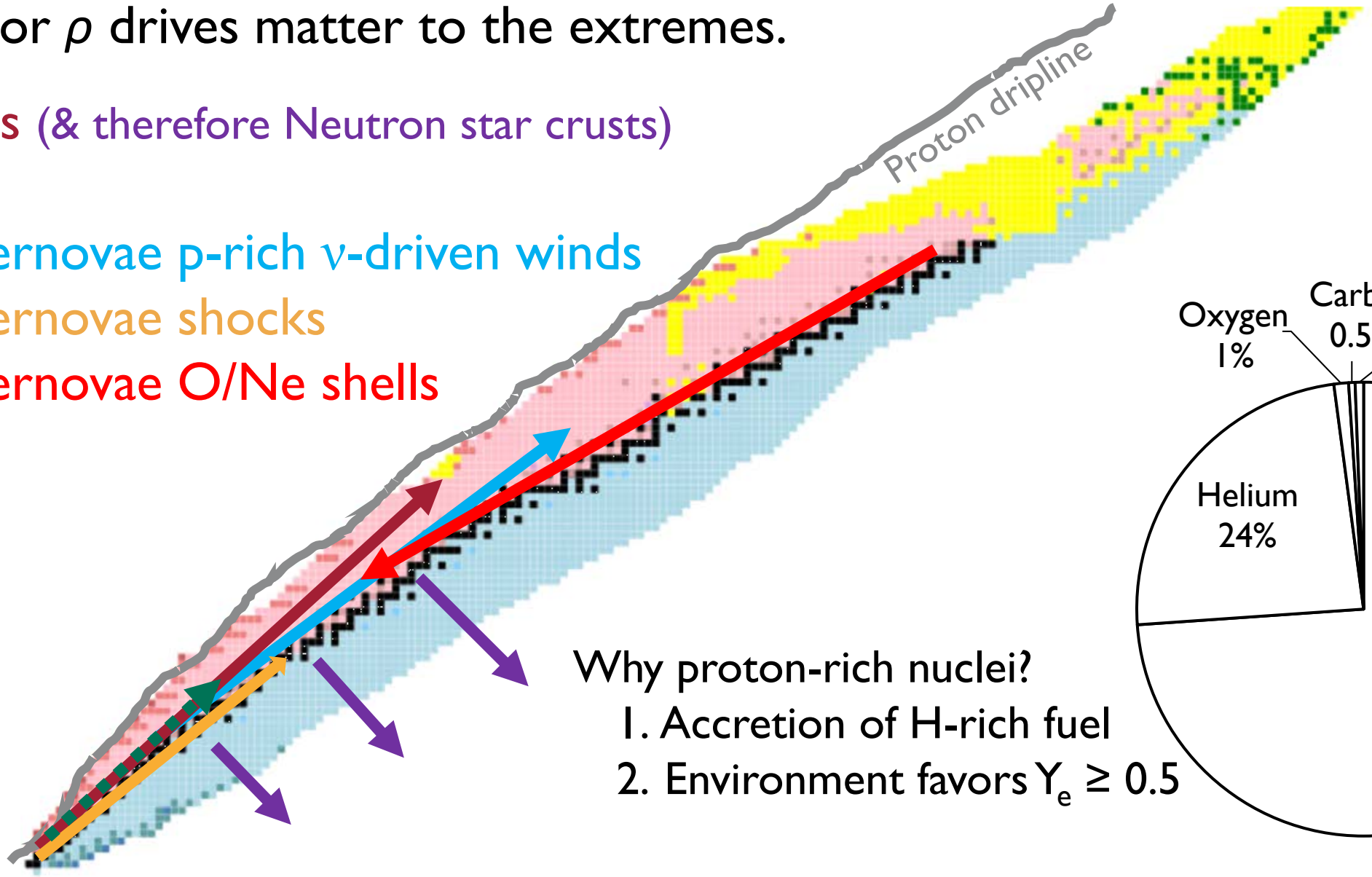
X-ray bursts (& therefore Neutron star crusts)

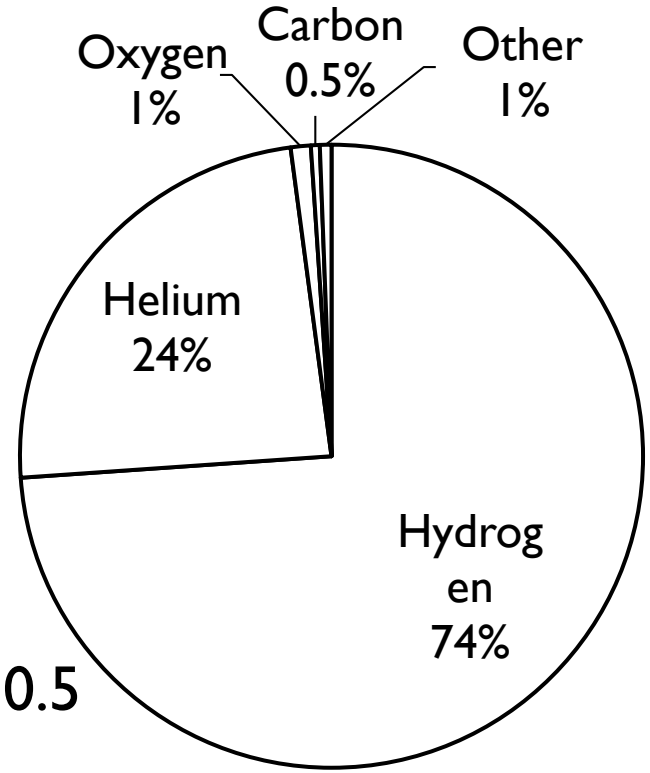
Novae

Type-II supernovae p-rich ν-driven winds

Type-II supernovae shocks

Type-II supernovae O/Ne shells



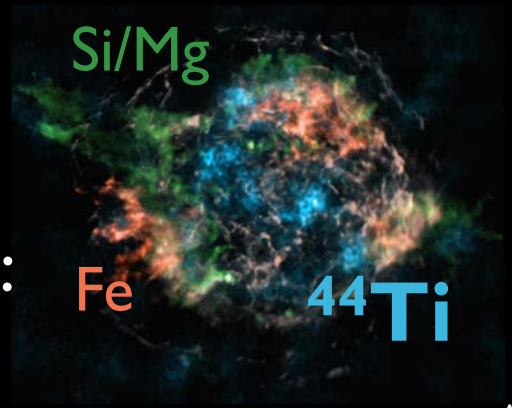


Why proton-rich nuclei?

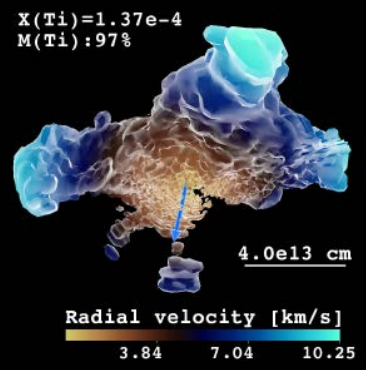
1. Accretion of H-rich fuel
2. Environment favors $Y_e \geq 0.5$

Dense matter & CCSN shock-driven nucleosynthesis

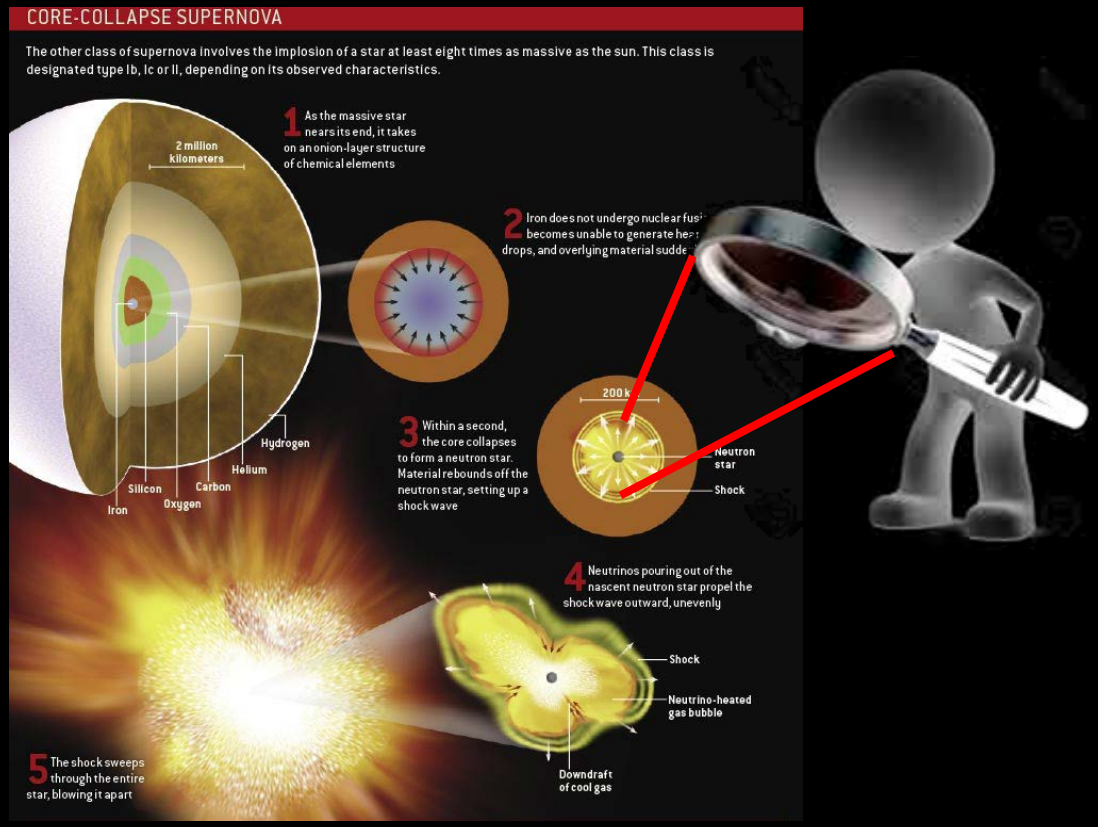
X(^{44}Ti) is a core collapse supernova explosion mechanism diagnostic, where observations can be compared to calculations:



B. Grefenstette et al. *Nature* 2014

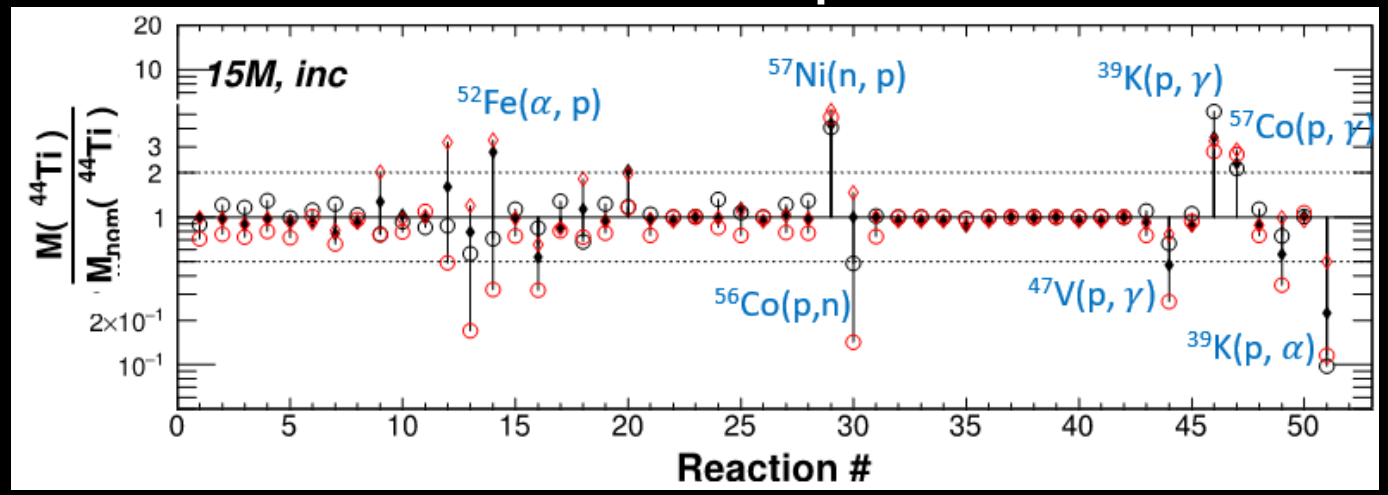


A. Wongwathanarat et al. *ApJ* 2017



W. Hllebrandt et al. *SciAm* 2006

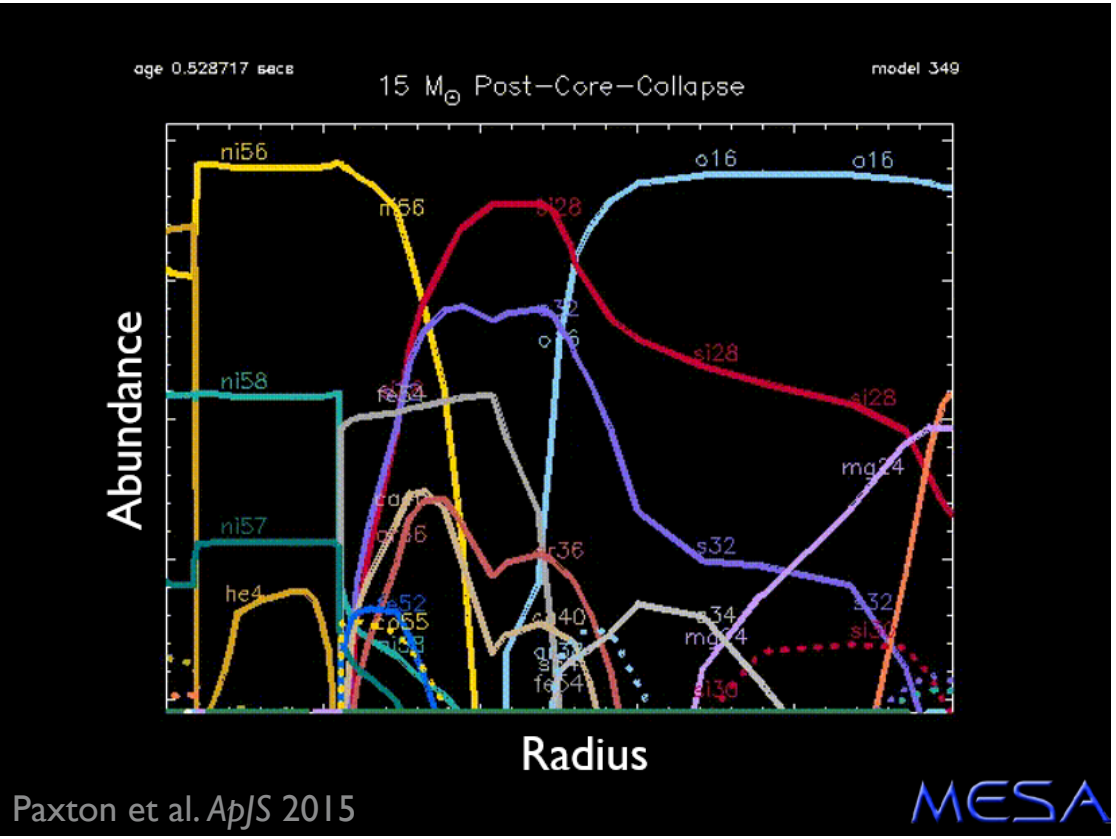
…but X(^{44}Ti) is sensitive to nuclear reactions, often on proton-rich nuclei



Subedi, Meisel, & Merz. *In prep.*

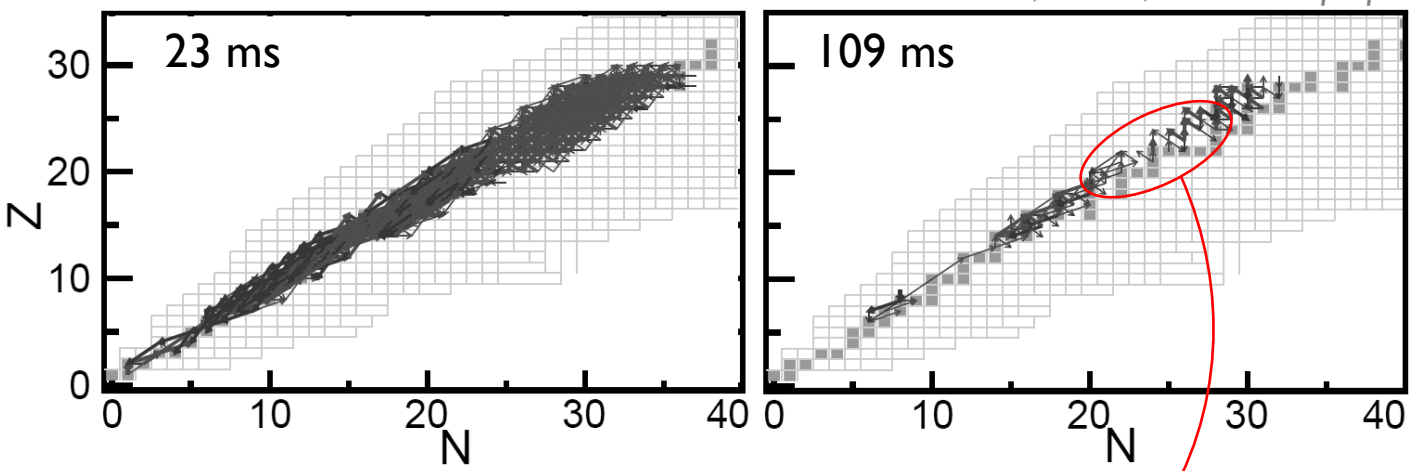
Dense matter & CCSN shock-driven nucleosynthesis

CCSN shock propagation drives a complicated network of nuclear reactions, with X(^{44}Ti) sensitive to *p* and α-burning

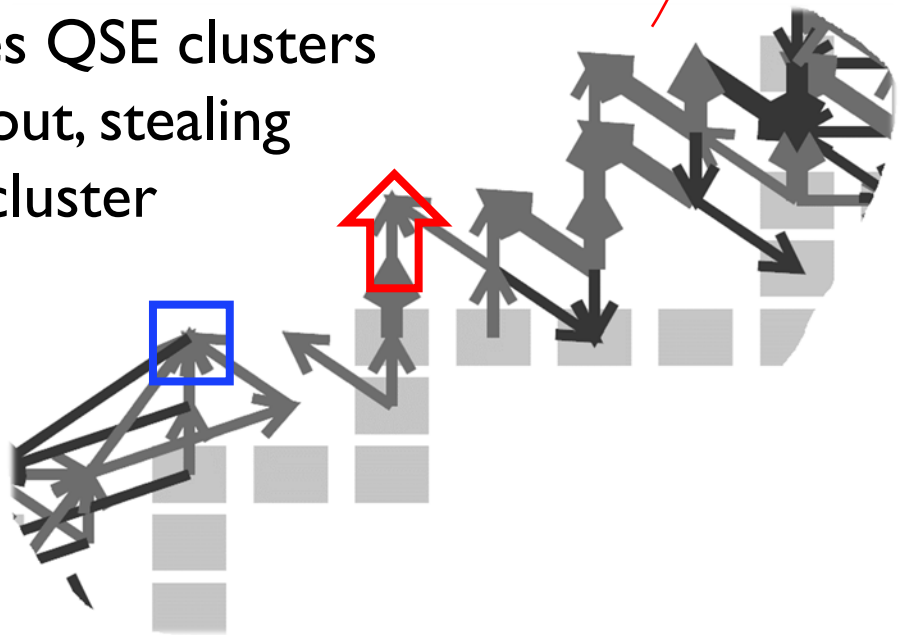


Paxton et al. *ApJS* 2015

Subedi, Meisel, & Merz. *In prep.*

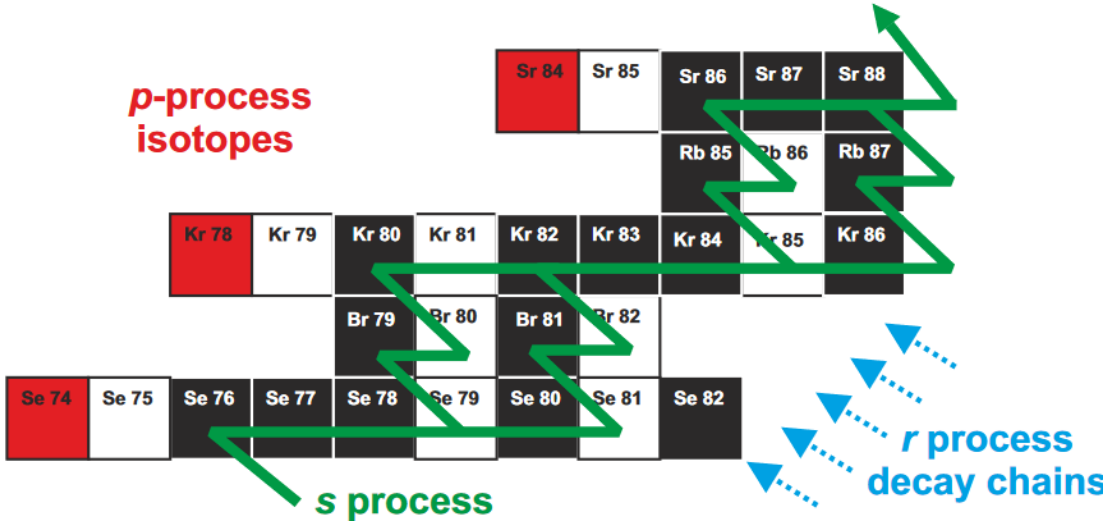


E.g. ^{47}V(*p*,γ) bridges QSE clusters during freeze-out, stealing from the ^{44}Ti cluster

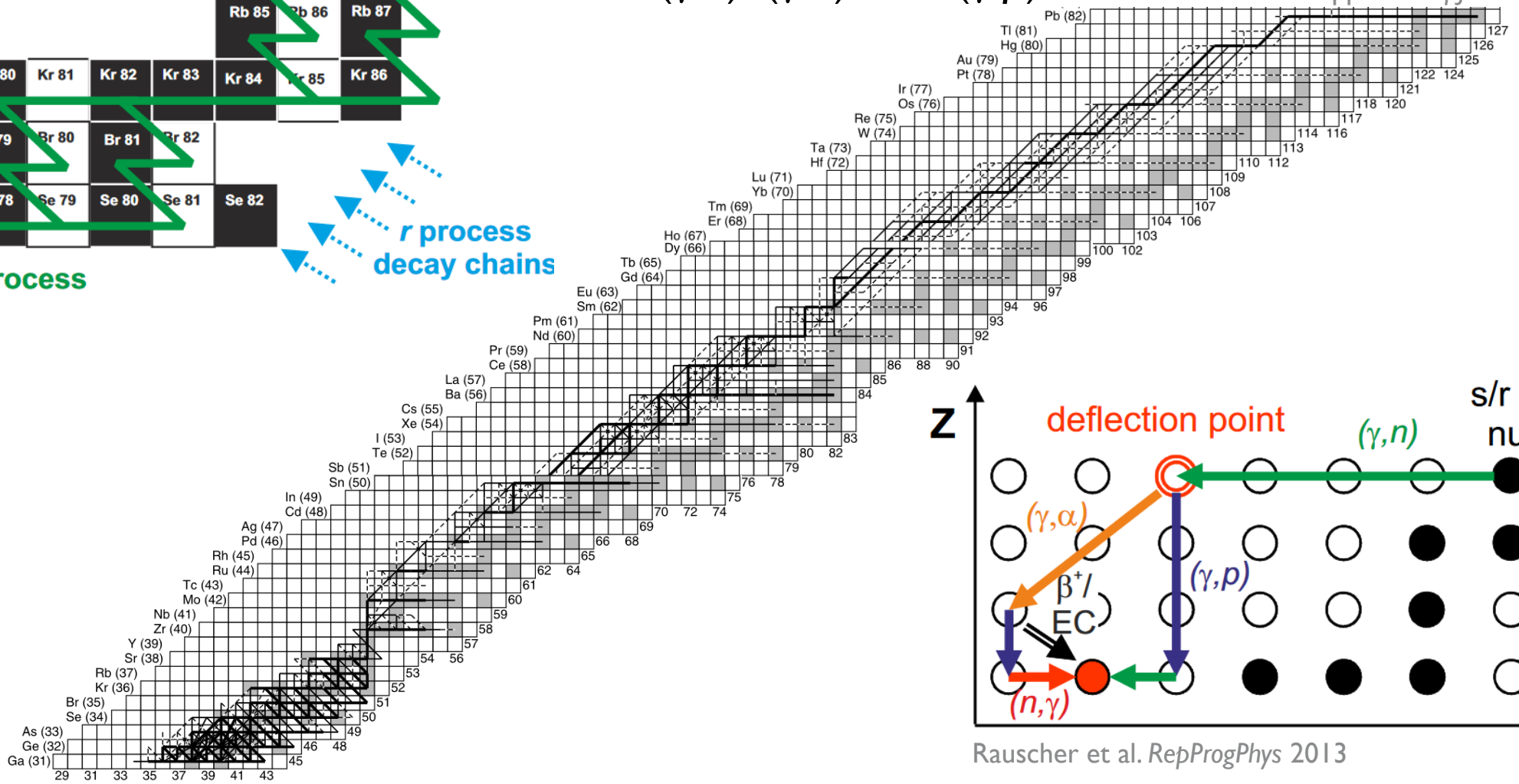


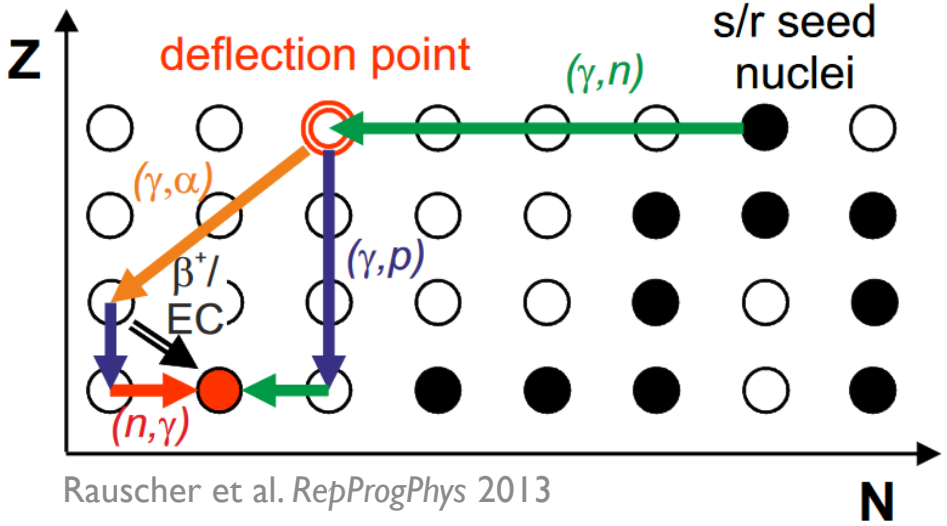
The origins of p-nuclei, in the wake of the CCSN shock

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

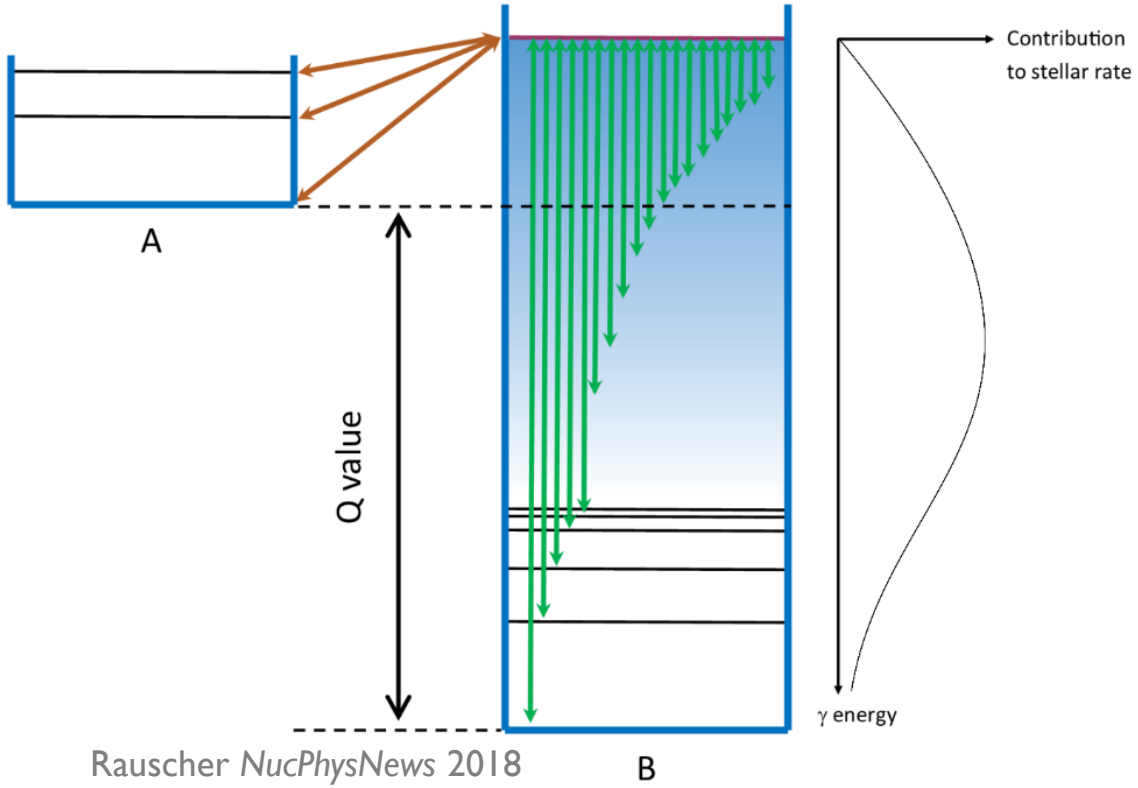




Rauscher et al. *RepProgPhys* 2013

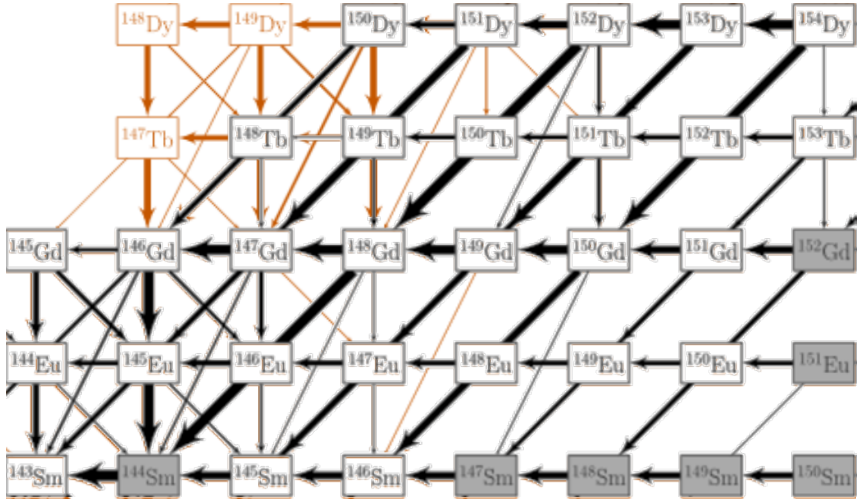
The origins of p-nuclei, in the wake of the CCSN shock

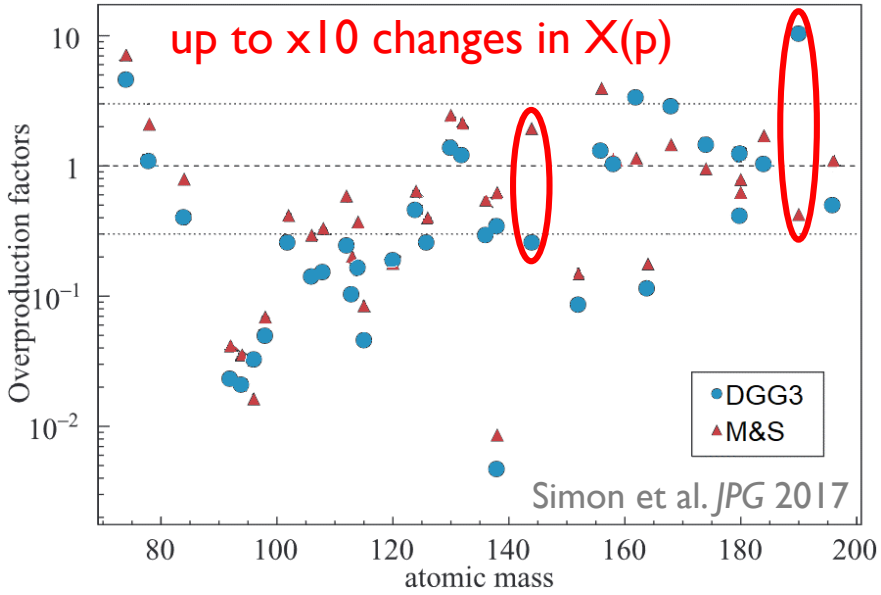
The most useful constraints for γ-induced reactions come from measurements of the inverse, obtaining nuclear properties for HF calculations.



Rauscher *NucPhysNews* 2018

E.g. αOMP impact:

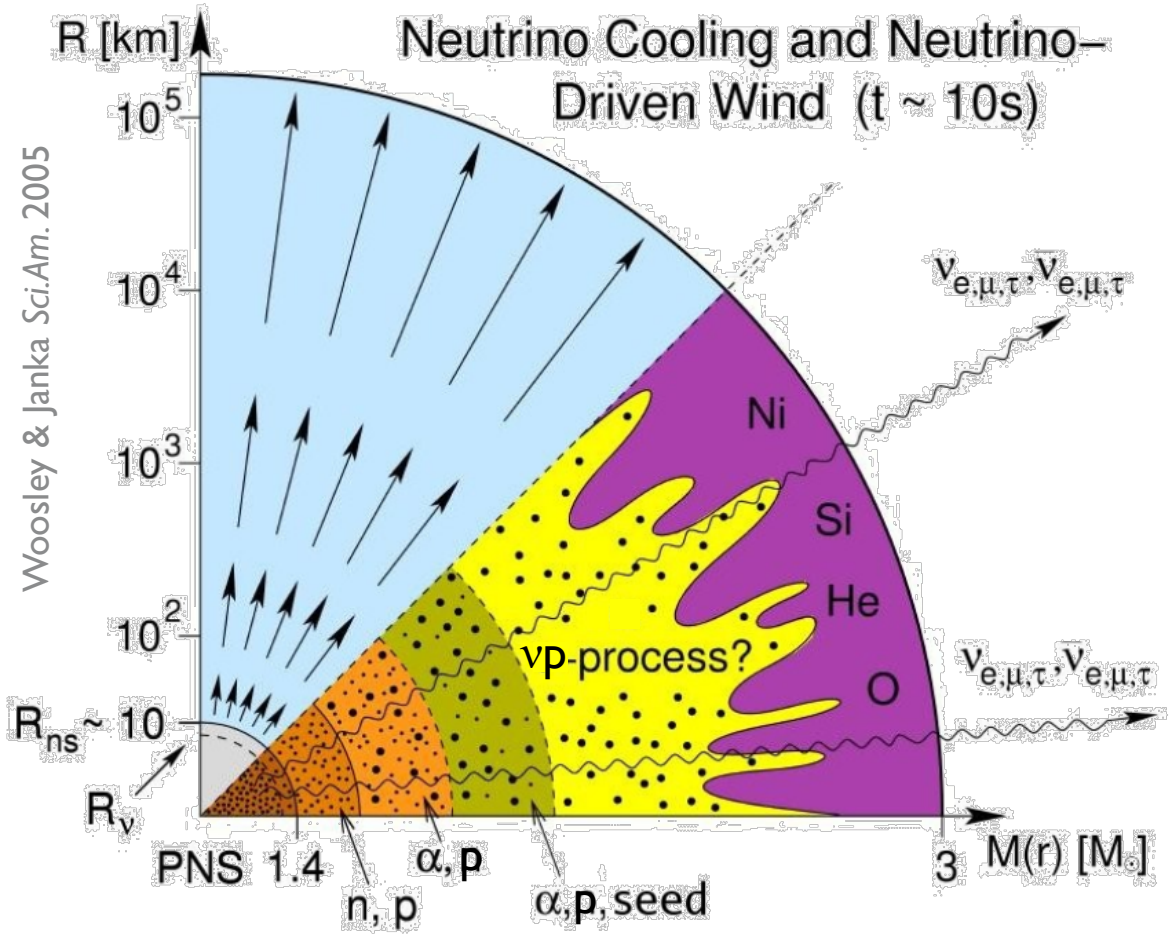




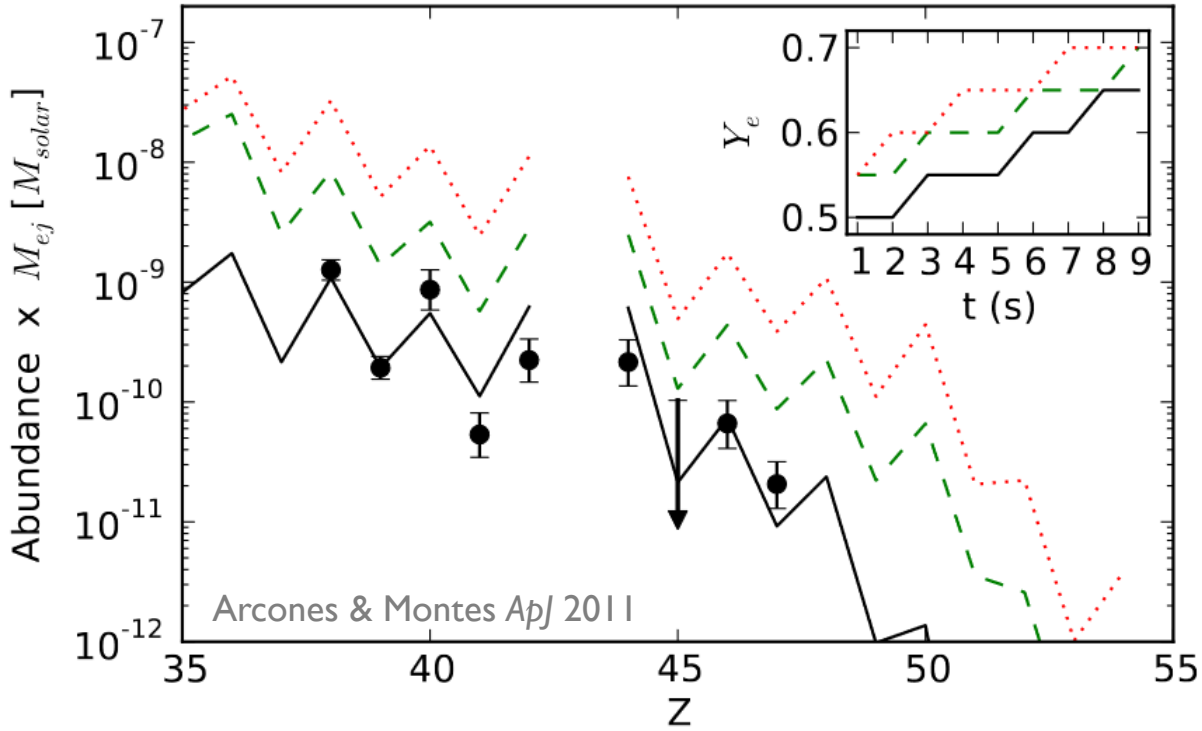
Simon et al. *JPG* 2017

CCSN neutrino-driven wind nucleosynthesis

For $Y_e > 0.5$, *p* and α capture to ~Fe & (n,*p*) reactions short-circuit β-decay to get to higher Z



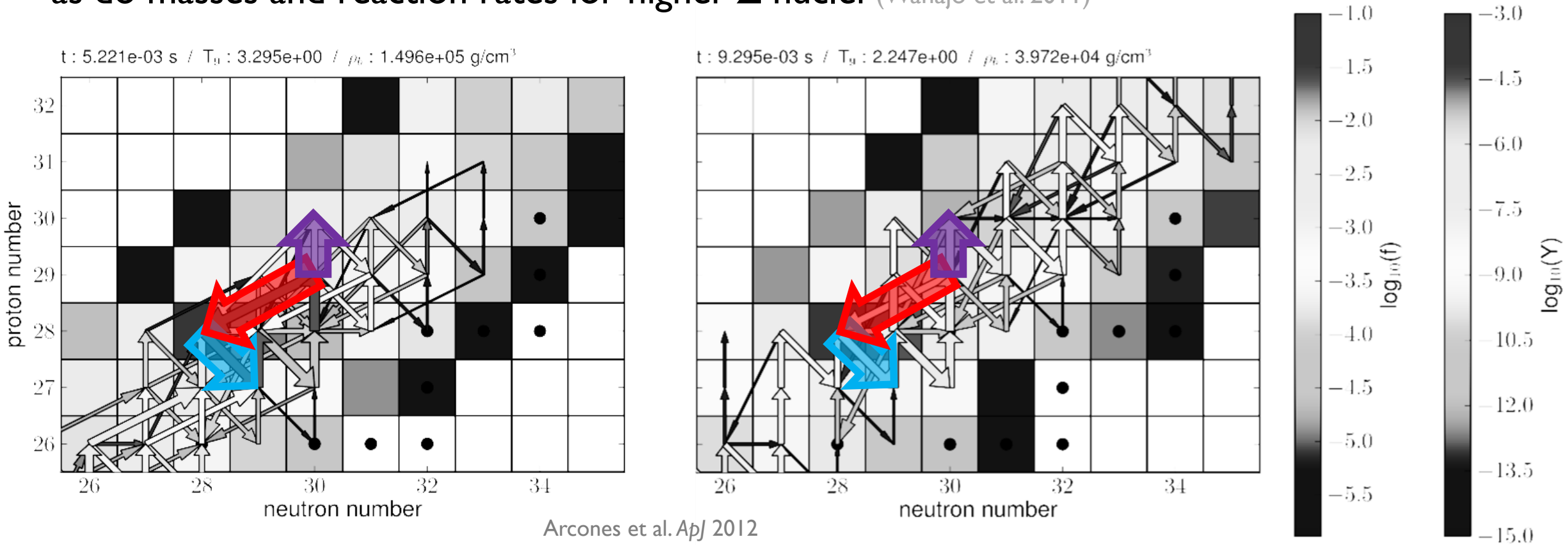
This is a candidate site for "LEPP" elements



…and maybe also light p-nuclei (Mo,Ru)

CCSN neutrino-driven wind nucleosynthesis

The break-out temperature from the **NiCu cycle** strongly influences the νp-process extent, as do masses and reaction rates for higher-Z nuclei (Wanajo et al. 2011)

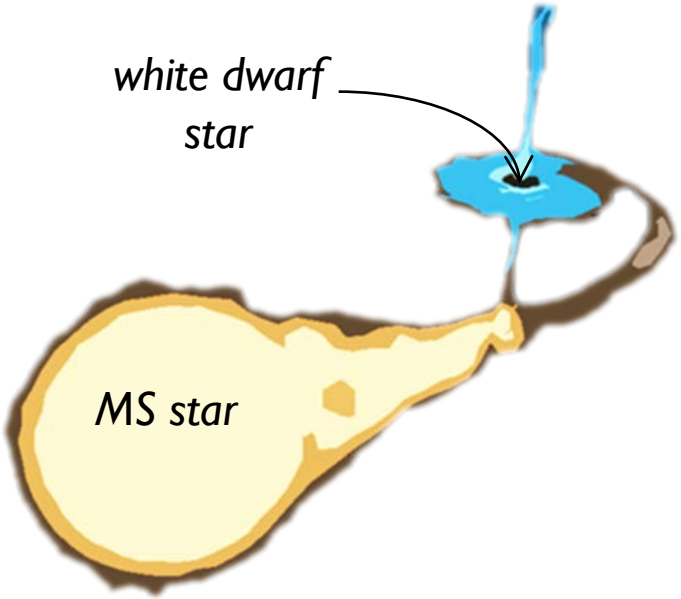


Arcones et al. *ApJ* 2012

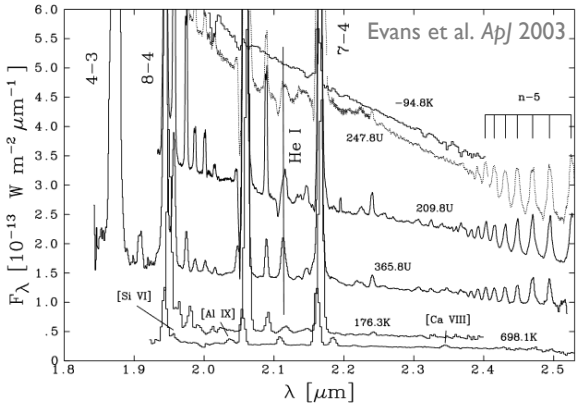
^{56}Ni(*n*,*p*)^{56}Co(*p*,γ)^{57}Ni(*n*,*p*)^{57}Co(*p*,γ)^{58}Ni(*p*,γ)^{59}Cu(*p*,α)^{56}Ni [vs ^{59}Cu(*p*,γ)^{60}Zn]

Nova nucleosynthesis: *dumping H onto a white dwarf star*

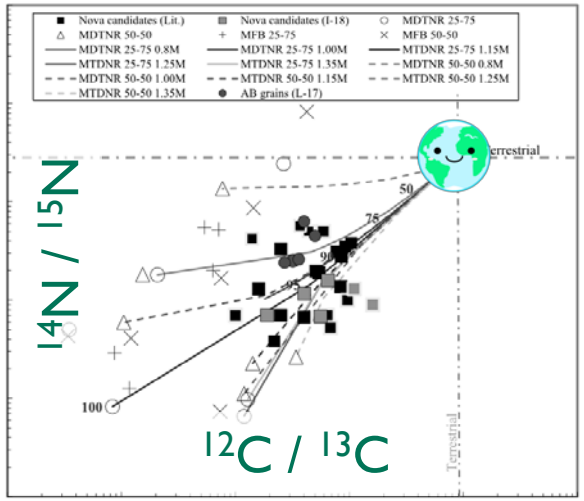
Recurrent explosions synthesize up to ^{40}Ca (and beyond?) with a potentially rich set of observables

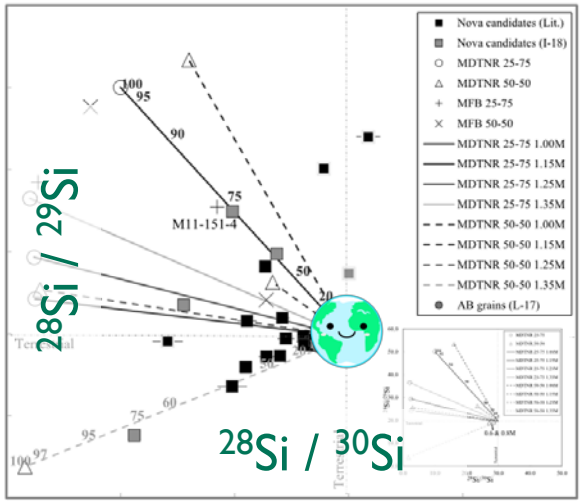


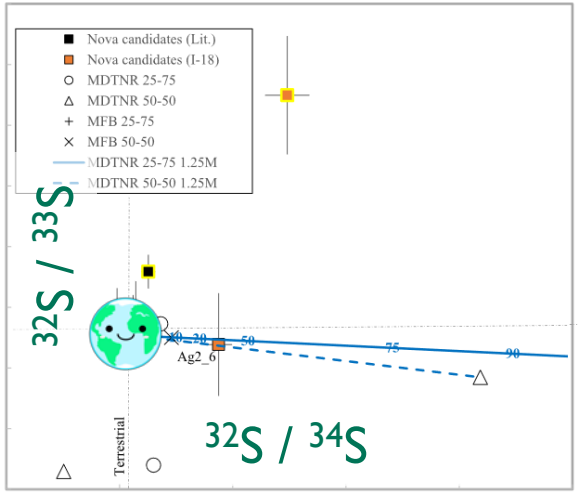
Atomic spectra:

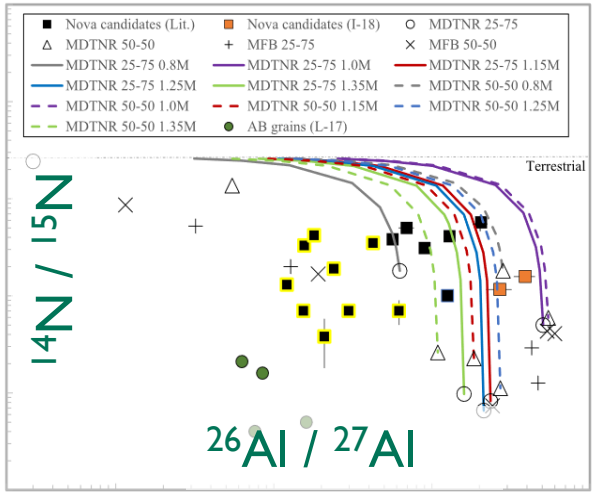


Pre-solar grains:



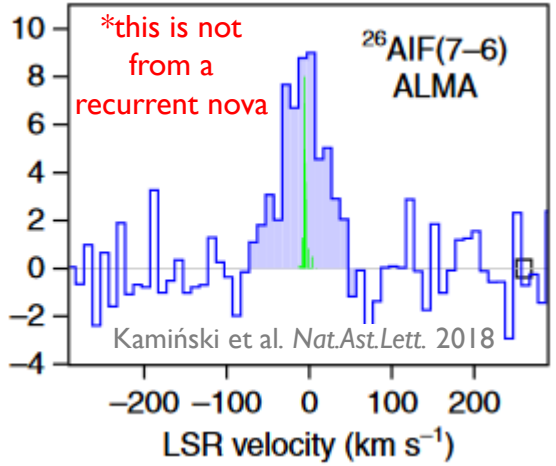




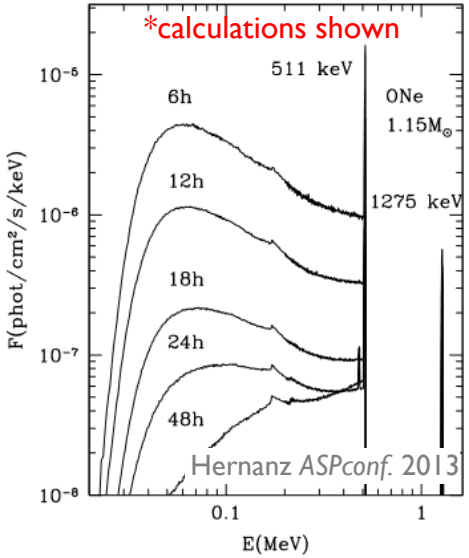


Bose & Starrfield *ApJ* 2019

Maybe* molecular rotations in spectra:

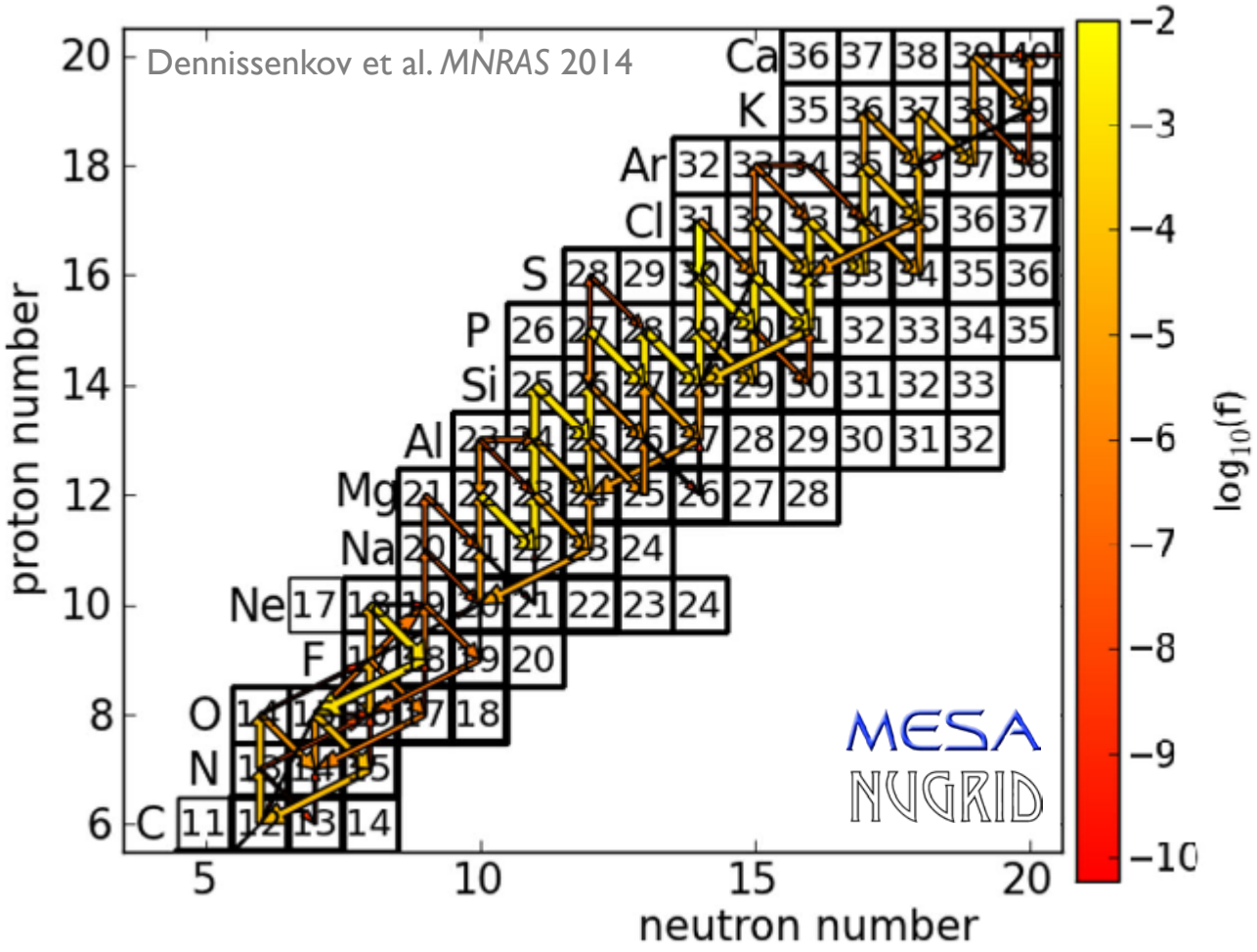


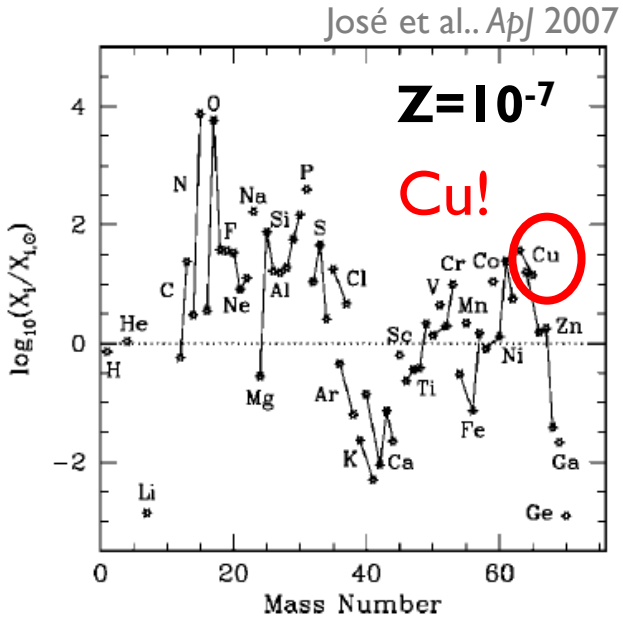
Maybe* γ-rays:

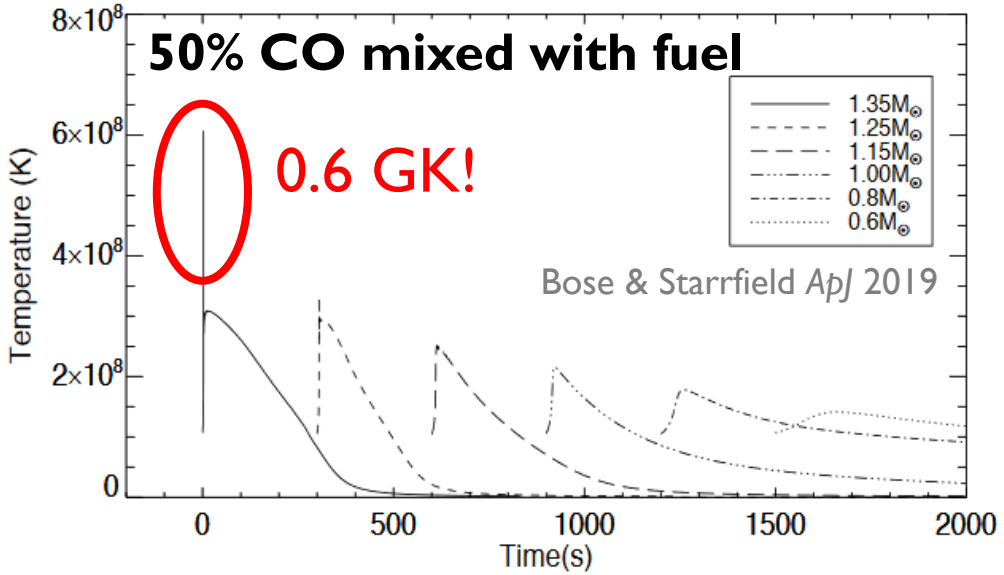


Nova nucleosynthesis: *dumping H onto a white dwarf star*

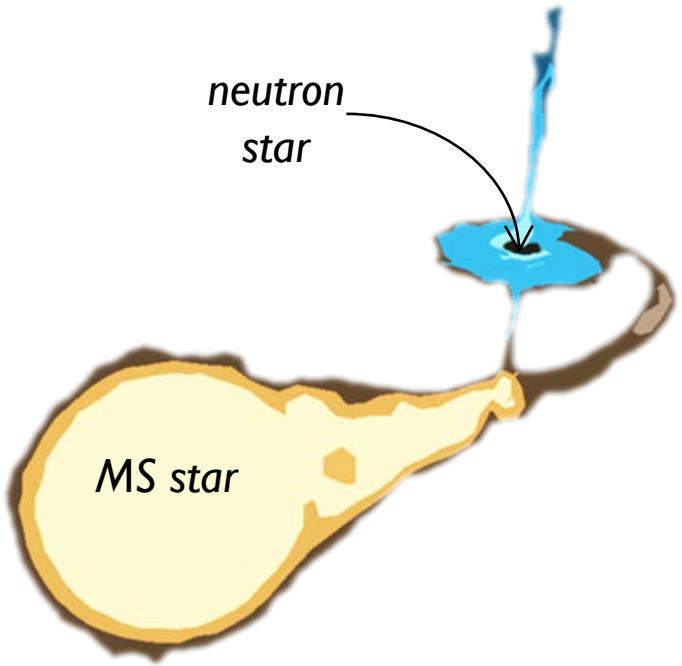
Many rates are well-constrained and mostly known unknowns (Iliadis et al. '02) remain for standard conditions … but lots of phase space remains unexplored for nuclear sensitivities:

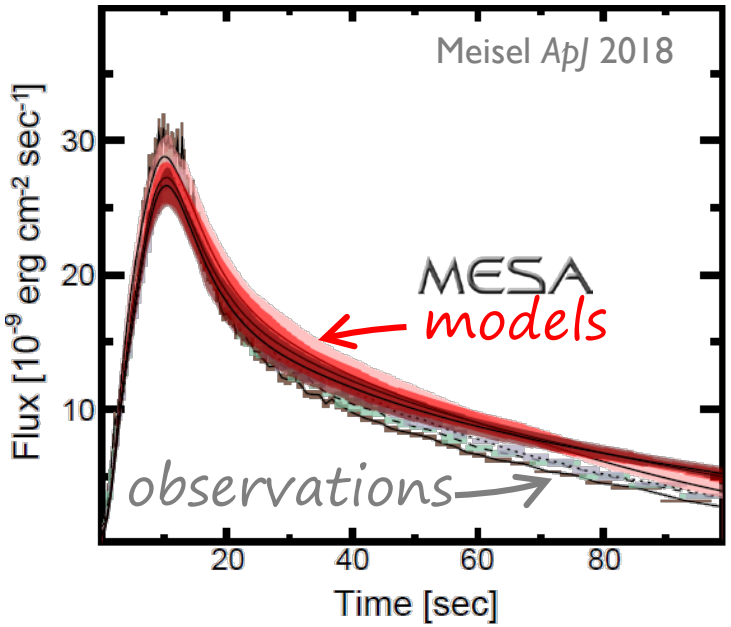


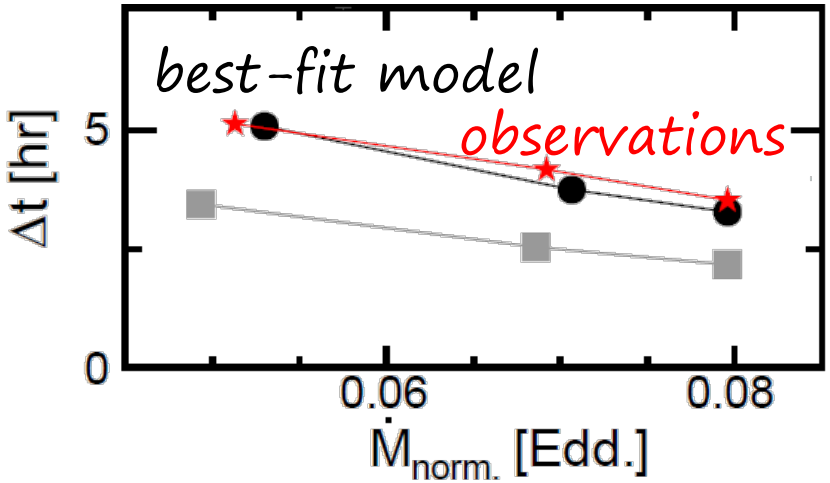




Dense matter & X-ray bursts: *dumping H onto a neutron star*

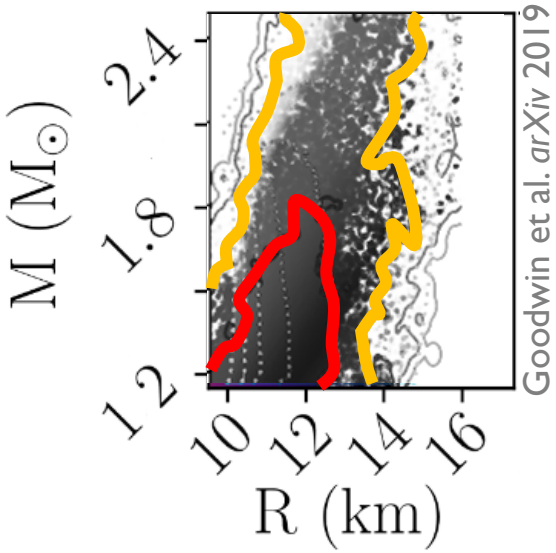


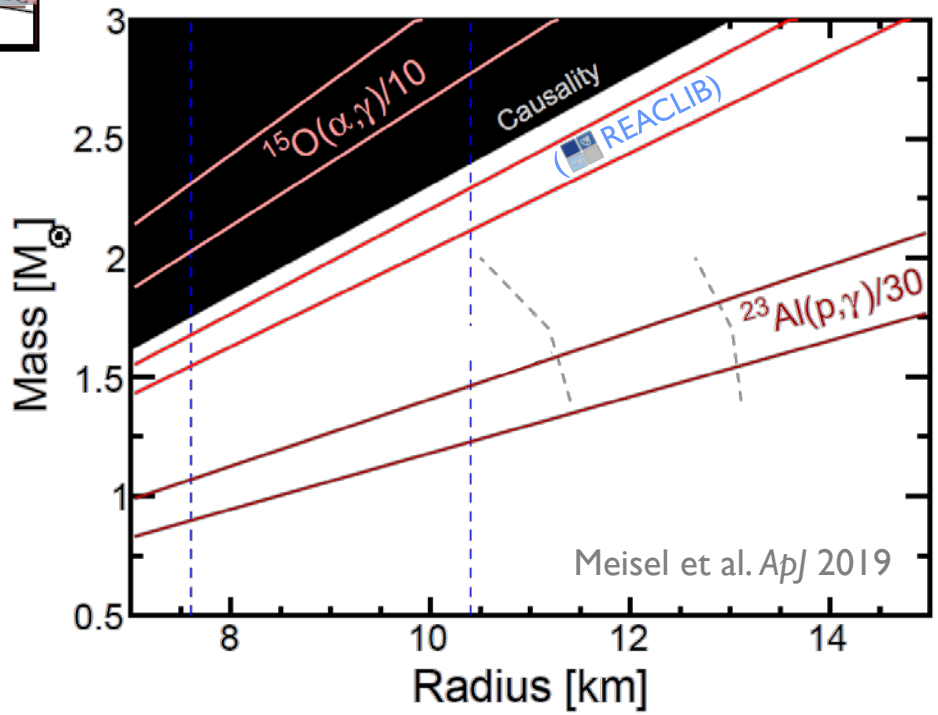




X-ray burst light curves can inform the dense matter EoS by constraining NS Mass & Radii

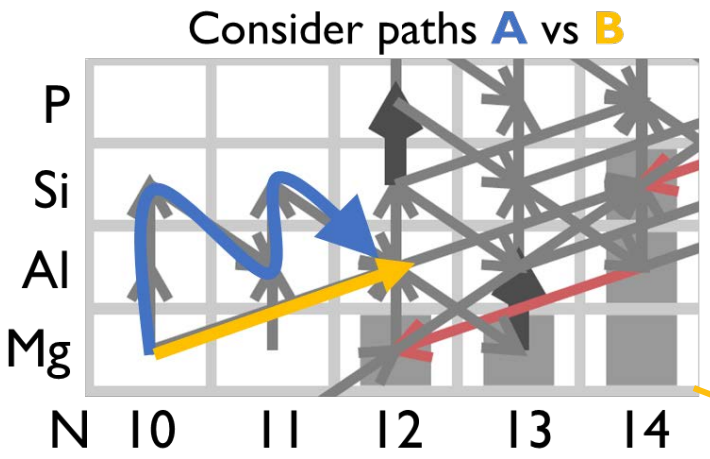
… but this is sensitive to nuclear reaction rates

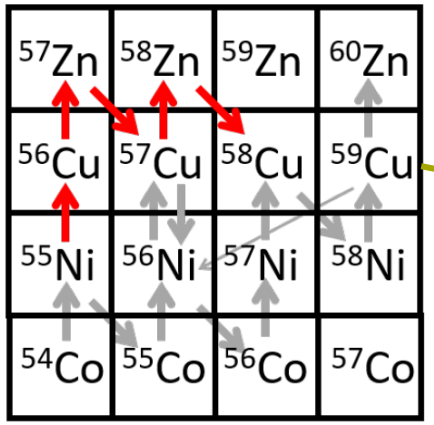


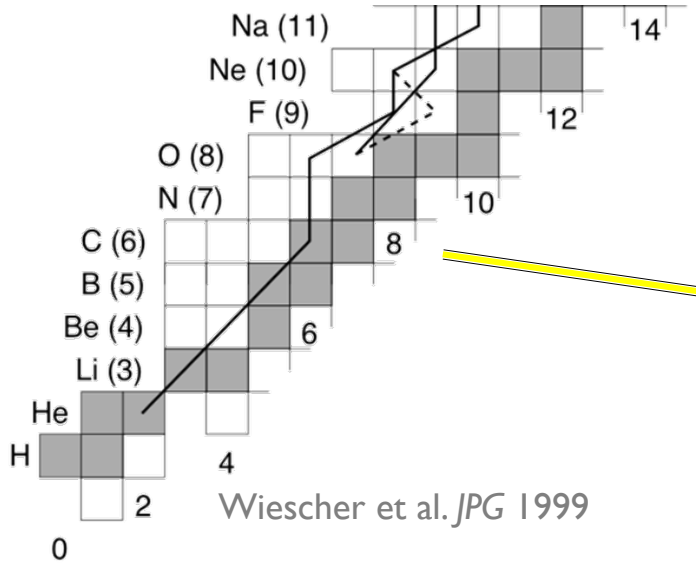


Dense matter & X-ray bursts: *dumping H onto a neutron star*

A well defined (modest) list of priority reaction rates are known …for one set of conditions!







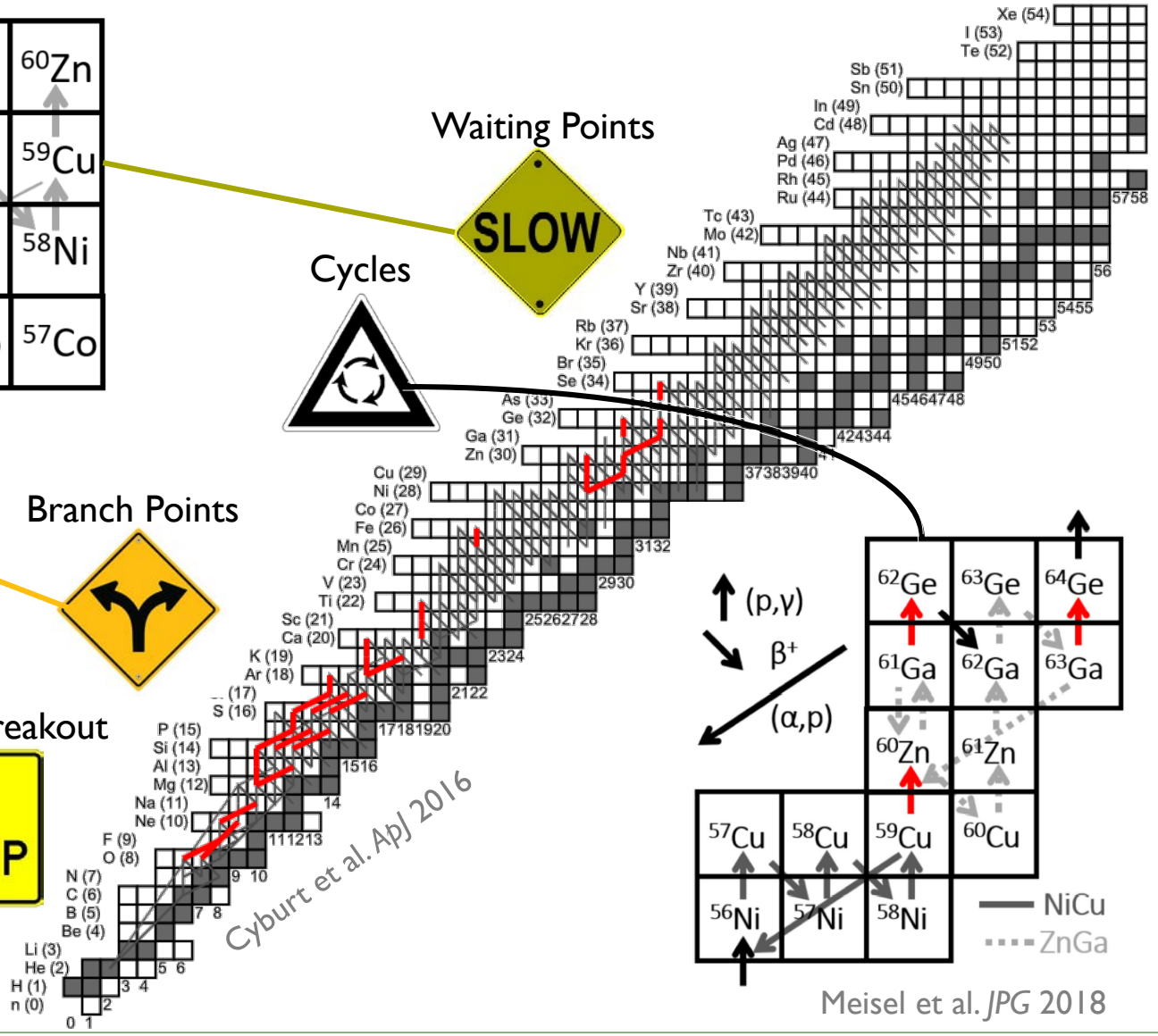
Wiescher et al. *JPG* 1999

Waiting Points

Cycles

Branch Points

Ignition/Breakout

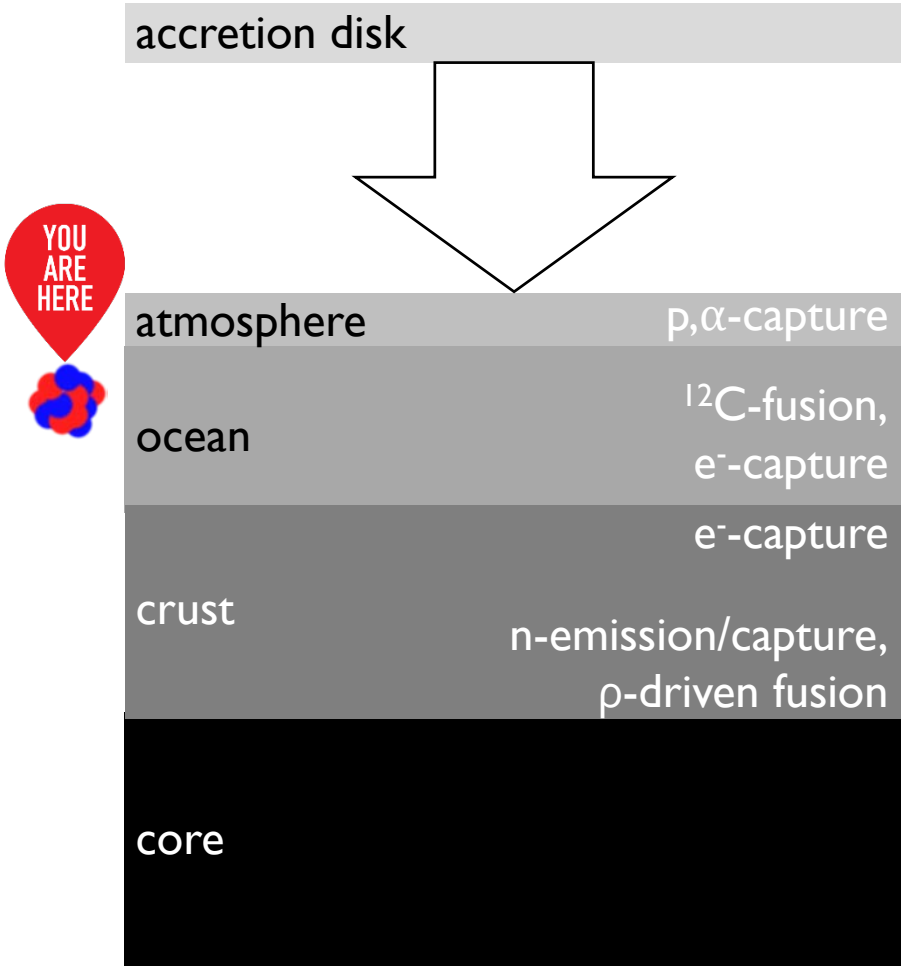


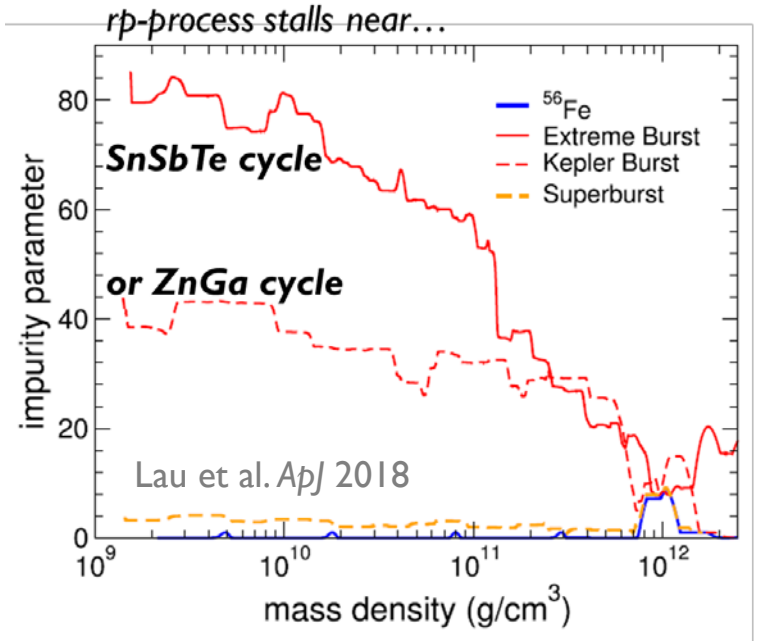
Cyburt et al. ApJ 2016

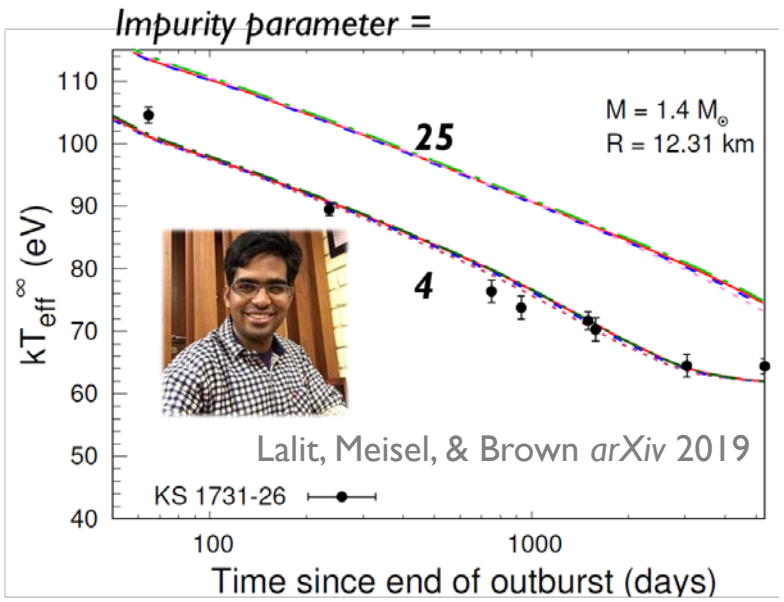
Meisel et al. *JPG* 2018

Downstream effects of XRBs on the neutron star crust

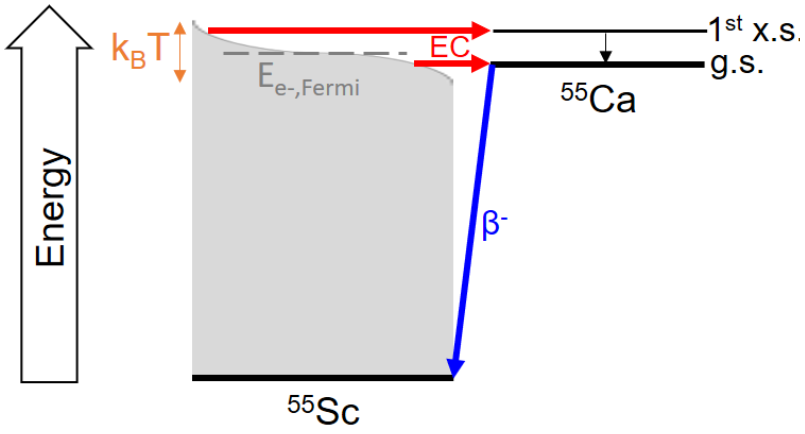
Buried XRB ashes modify the crust composition & thermal structure, impacting other observables

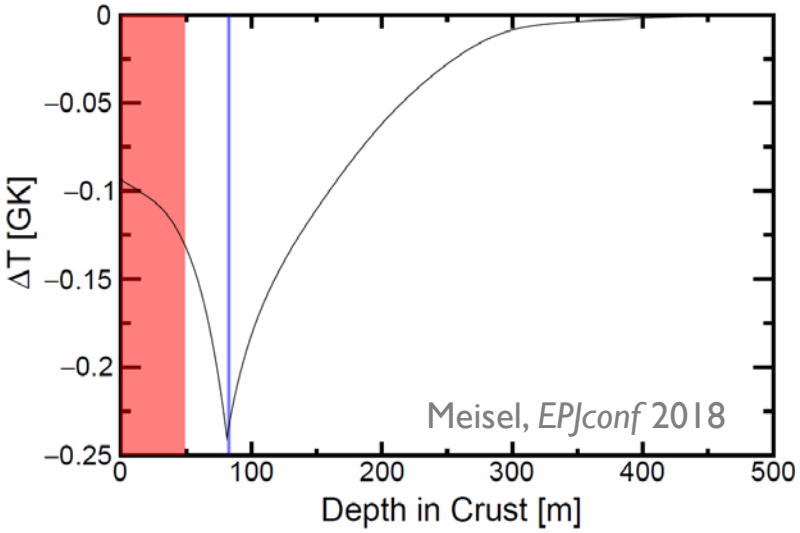






Urca cooling:

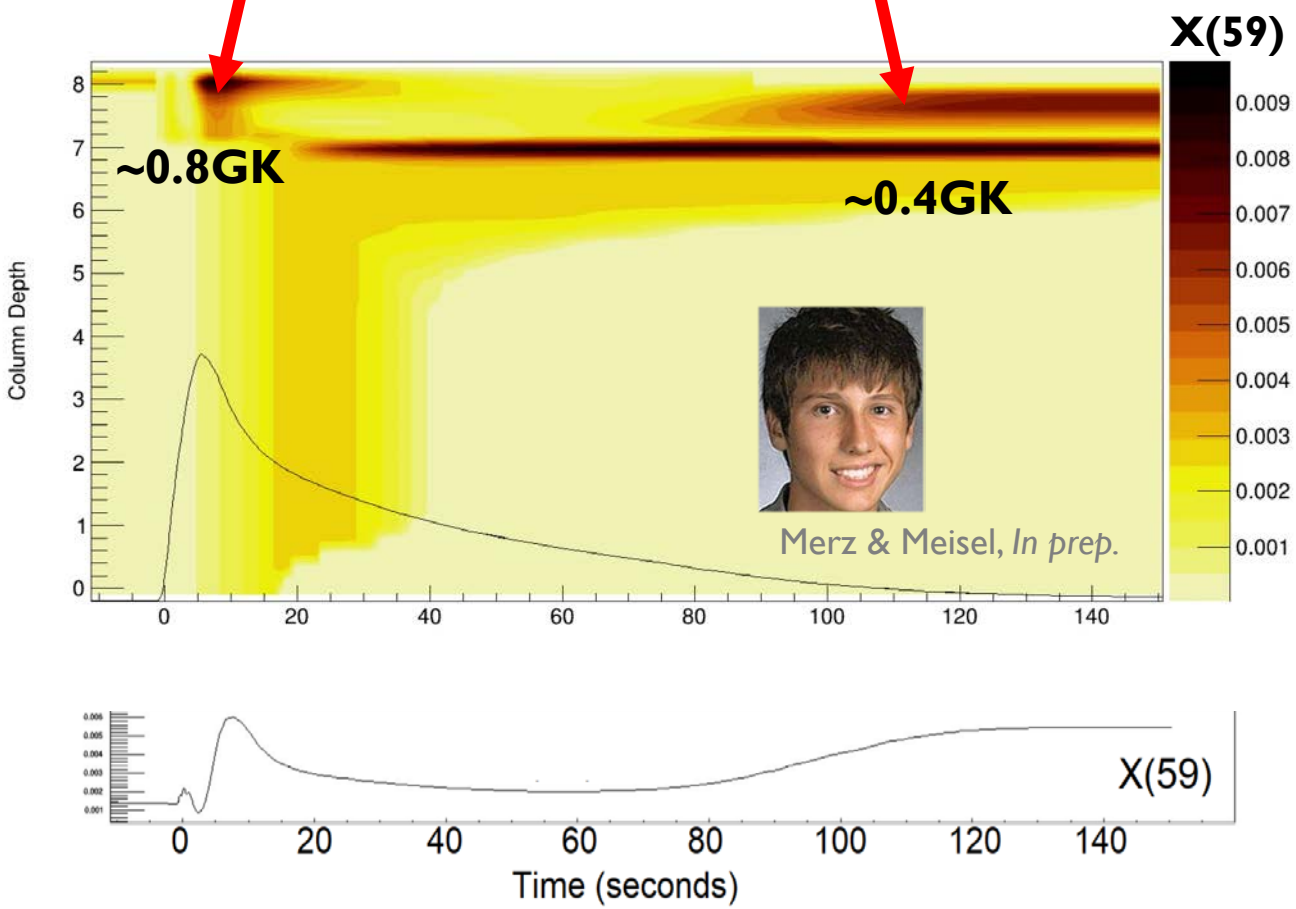




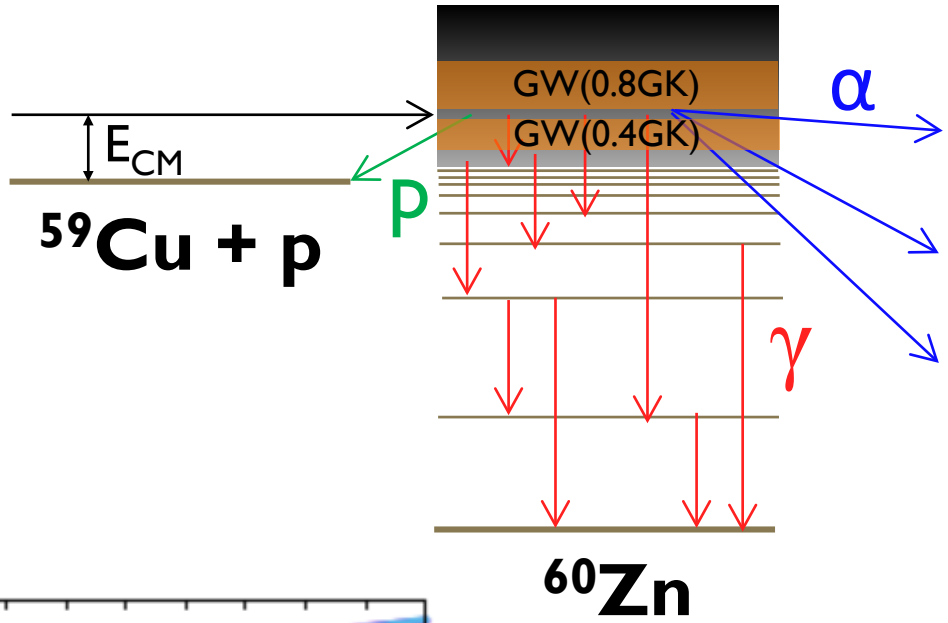
Downstream effects of XRBs on the neutron star crust

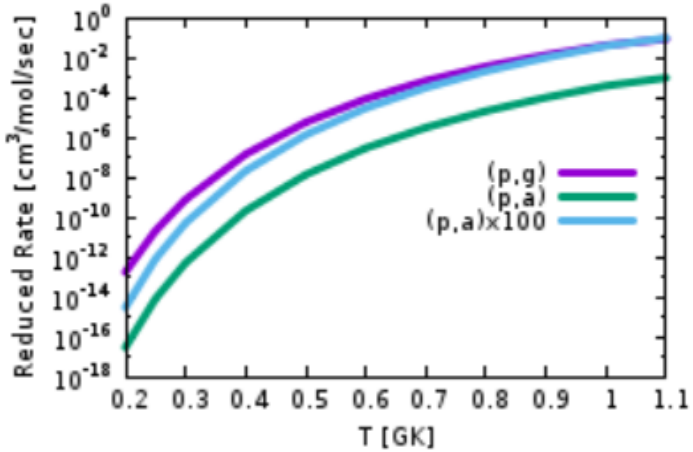
Environment conditions during the light curve impact …

…aren't necessarily the same as for the abundance impact.



So, different excitation energies can be of interest in the compound nucleus …

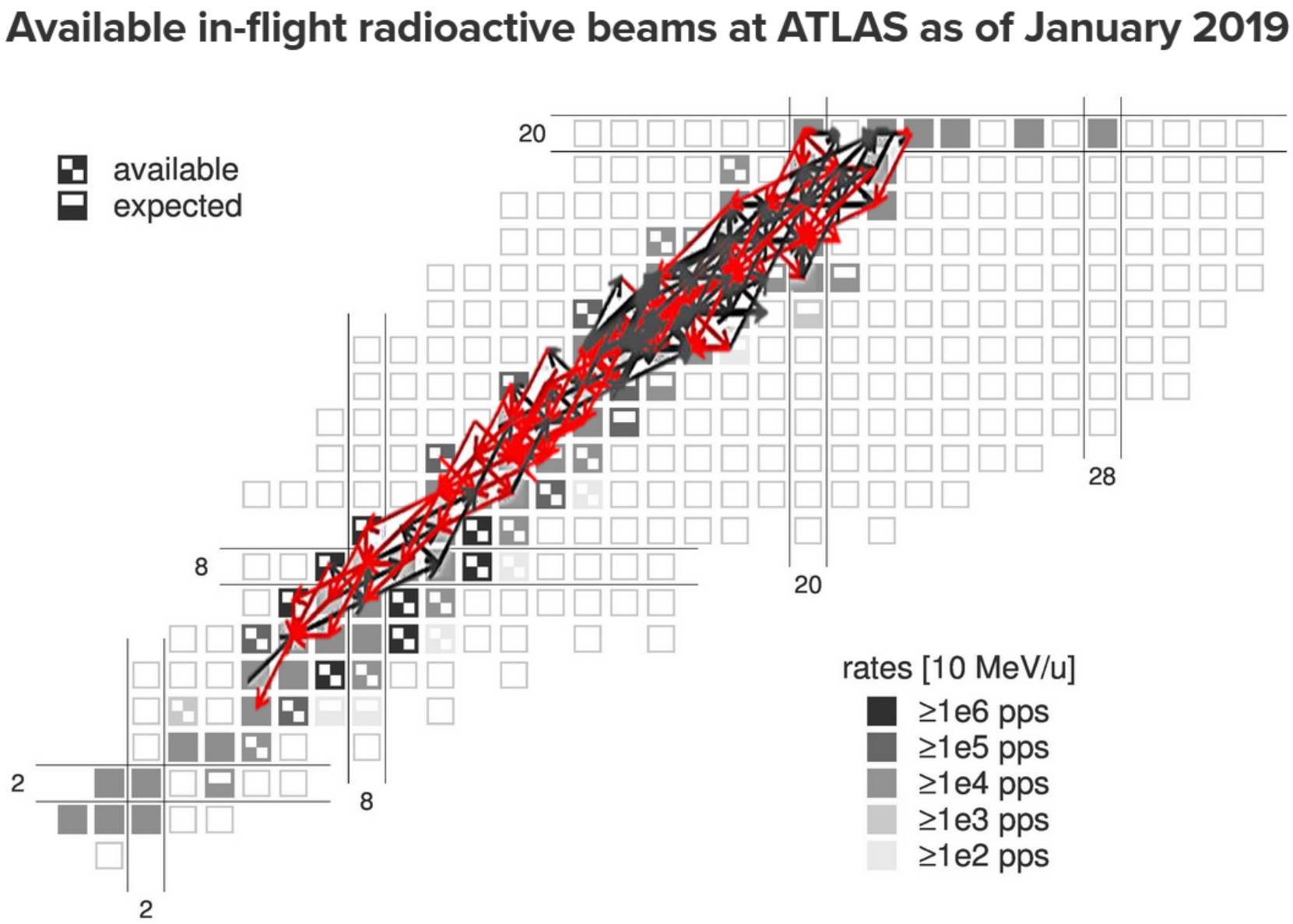




…which explains why an enhanced (p,α) reaction is found* to impact the LC, but not X(59).

*Meisel, Merz, & Medvid, *ApJ* 2019
*Cyburt et al. *ApJ* 2016

No need to "wait for FRIB", there's plenty of exciting work to do *now*



(+complementary work to do later)