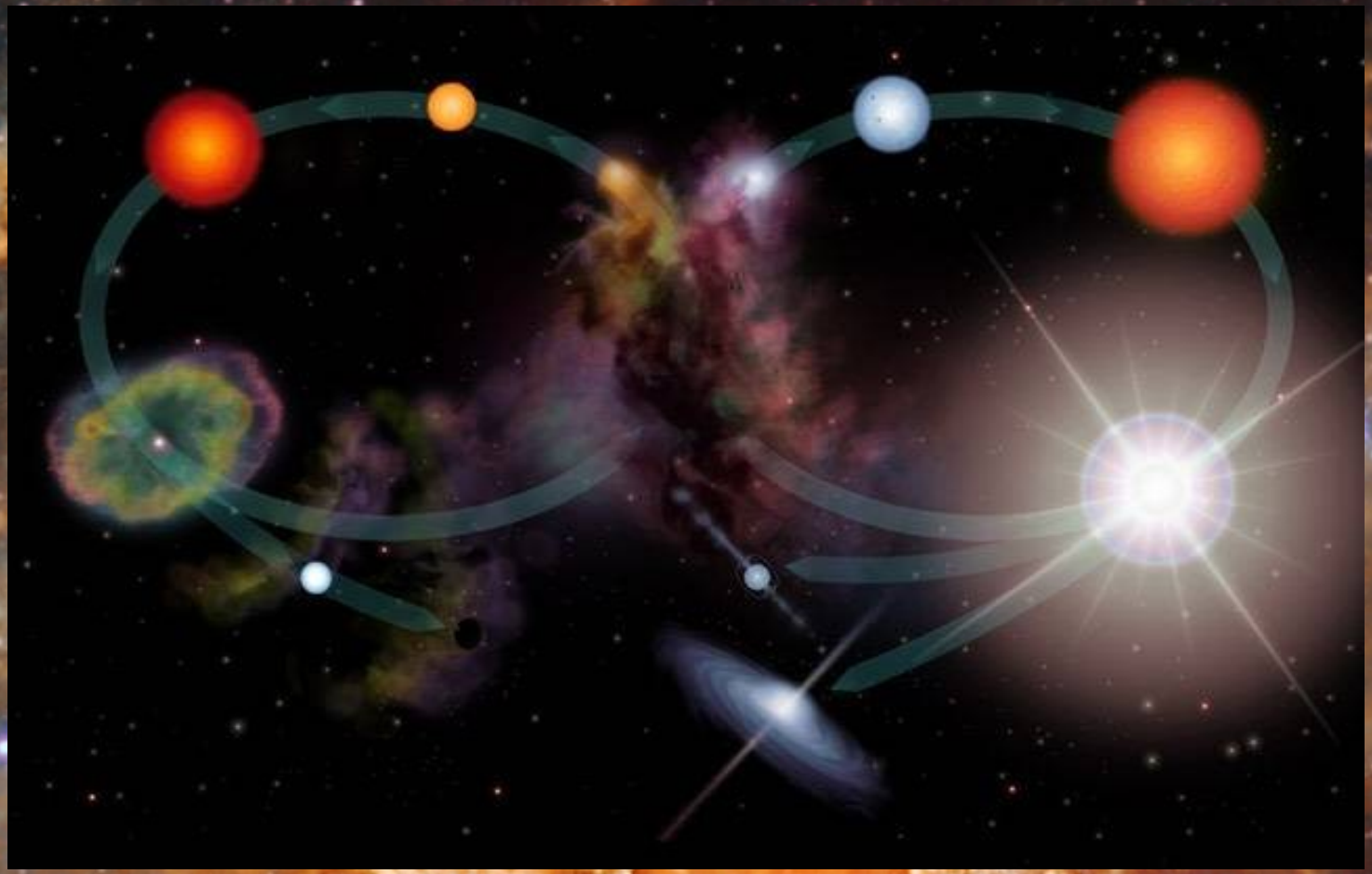
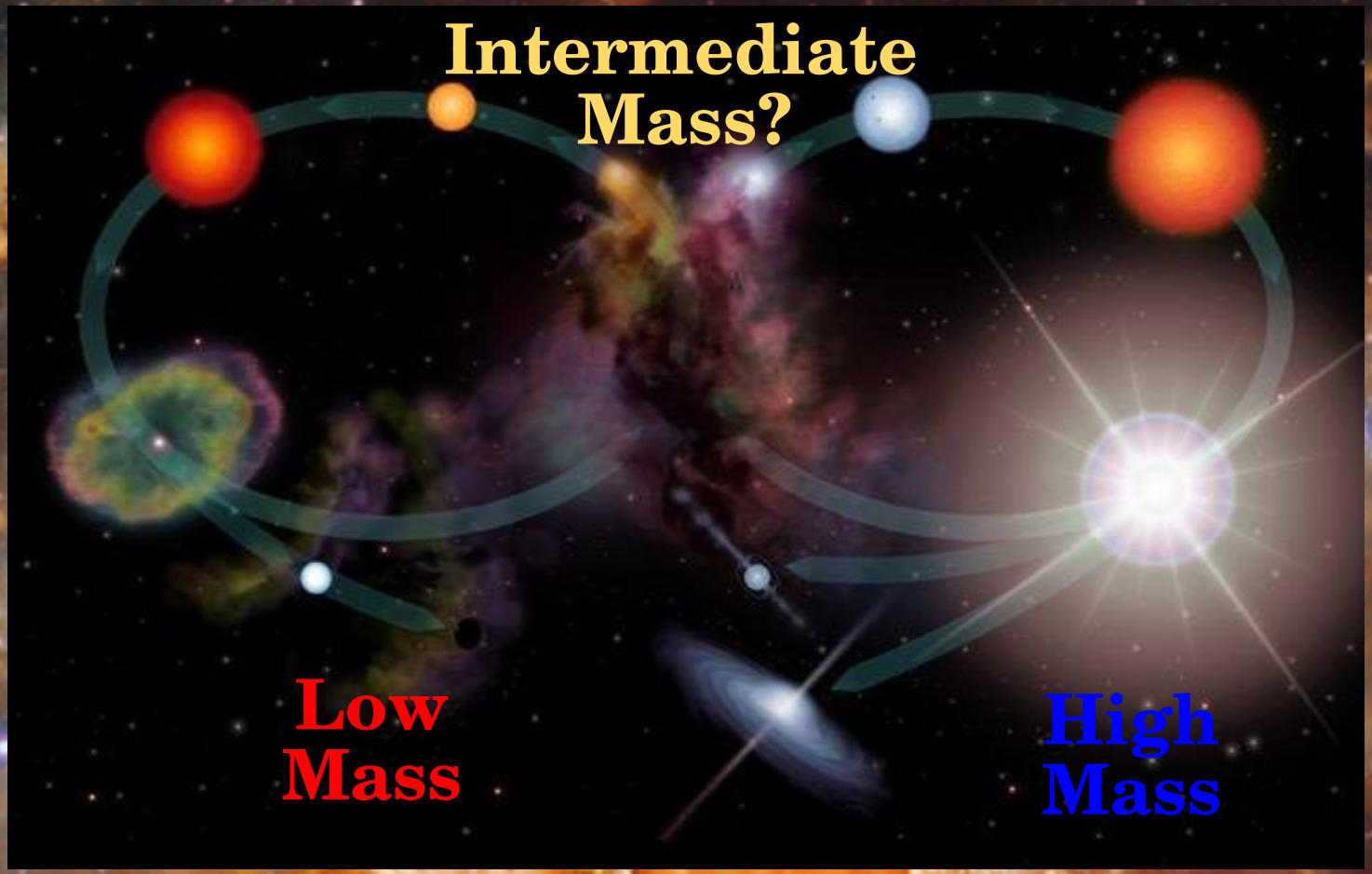


i-process nucleosynthesis in super-AGB stars

Carolyn Doherty (Budapest)

P. Gil-Pons (Barcelona), S.Campbell (Monash), P. Banerjee (Shanghai), J Gutiérrez (Barcelona), A. Heger (Monash), L. Siess (Brussels)



Overview

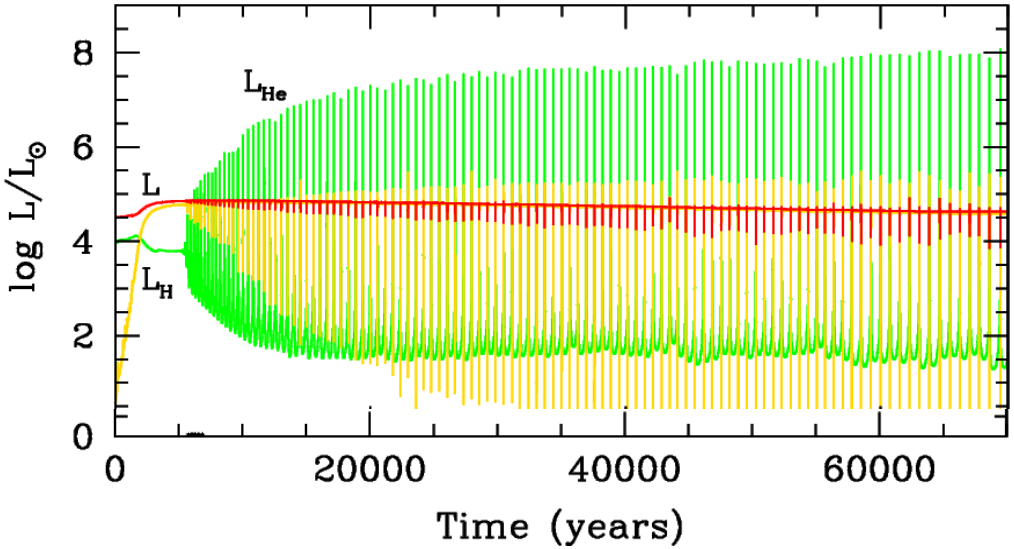
- ★ Super-AGB stars, Red Supergiants & Thorne-Zytkow objects
- ★ “i”-process - neutron densities & potential sites
- ★ Dredge-out nucleosynthesis in super-AGB stars
- ★ Potential to help constrain the the lowest mass supernovae boundary

Super-AGB stars

- ★ Mass range ~6-12 $M_\odot$
- ★ Bridge the divide between low/intermediate-mass and massive stars.
- ★ Off-centre carbon ignition prior to a thermally pulsing phase
- ★ ONe Core vs CO core
- ★ Many 10-1000s of thermal pulses.
- ★ Red, cool (3000-4000K),
- ★ Large envelopes ~ 1000 $R_\odot$
- ★ Very luminous :

Due to efficient Hot Bottom Burning they exceed the Paczynski luminosity limit of Mbol~-7.1

- ★ Low metallicity can reach Mbol~-8.2 (150,000 $L_\odot$)



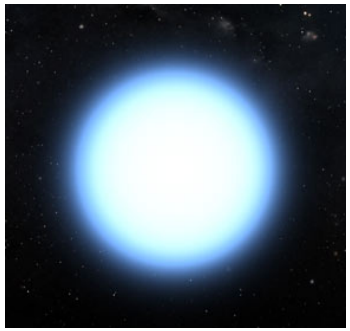
Pioneering evolution models for the first TPs by Garcia-Berro, Iben & Ritossa (1994-1999)

Numerically challenging and only recently have full calculations along TP-Super-AGB phase

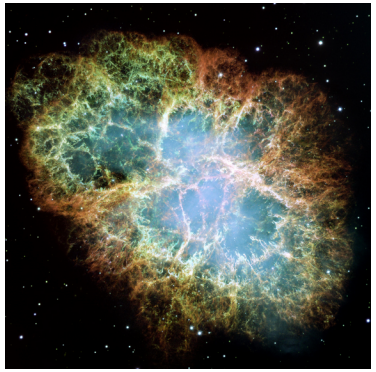
i.e. Siess 2010, Ventura & D'antona 2009/11, Jones+2013/16, Gil-Pons+2013, Doherty+2014/15/17.

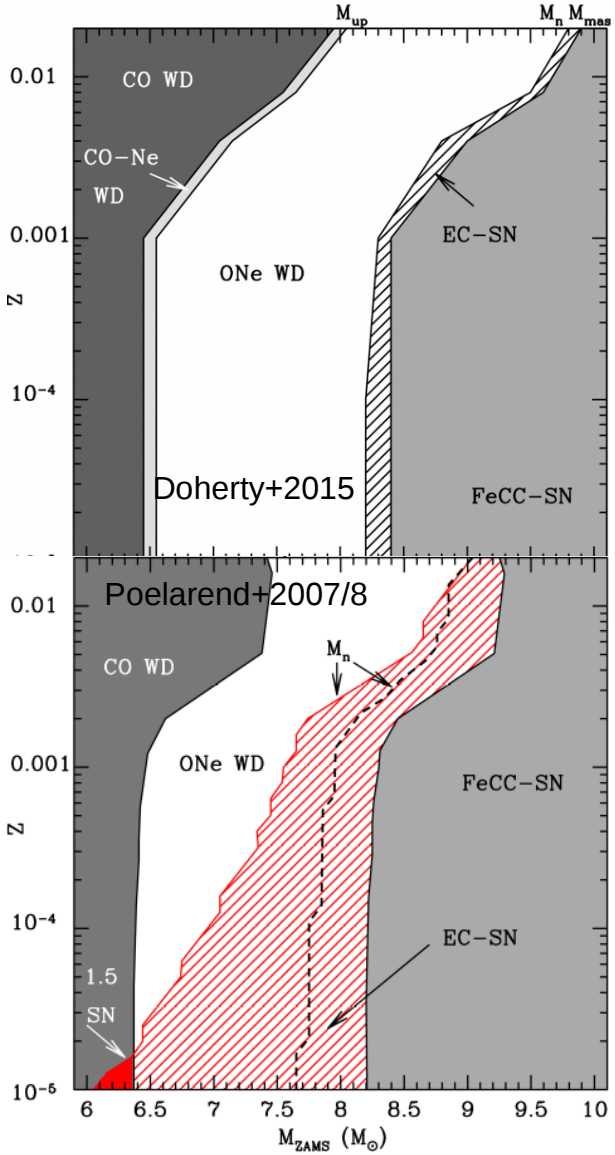
How do super-AGB stars die?

Either as ONe white dwarfs, or as neutron stars* after undergoing an electron capture supernova (EC-SN)?



OR





Competition between between the growth of the core and the mass loss from the envelope during the super-AGB phase determines the stars fate. If the core reaches $M_{EC} \sim 1.375\ M_\odot$ (Nomoto 1987) an EC-SN will occur.

* Debate rages over final fate of an EC-SN either as neutron star or ONeFe remnant (Isern+1991, Canal+1992, Jones+2016)

Review by Doherty, Gil-Pons, Siess & Lattanzio 2017 PASA

Hiding in plain sight?

Super-AGB stars, Red Supergiants (RSG) & Thorne-Zytkow Objects (TZO)

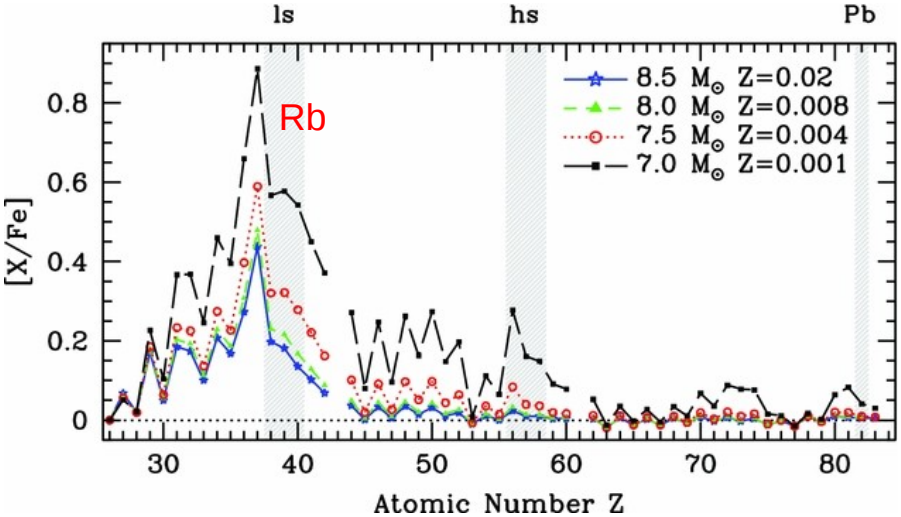
No observationally confirmed Super-AGB star!

How do we find them?

Very similar temperature, luminosity and radius as RSG* & TZO**

Can surface composition help distinguish these types of star?

Only some super-AGB star models find 3DU and s-process enhancement



$[A/B]=\log_{10}(n(A)/n(B))_{\star} - \log_{10}(n(A)/n(B))_{\odot}$

Doherty+2017

*Red supergiant - Late stage of massive star (core He or further burning)

**Thorne-Zytkow Objects

(Thorne & Zytkow 1975/77)

Neutron star at the center of a RSG

irp-process - Mo & Rb (no Ba?)

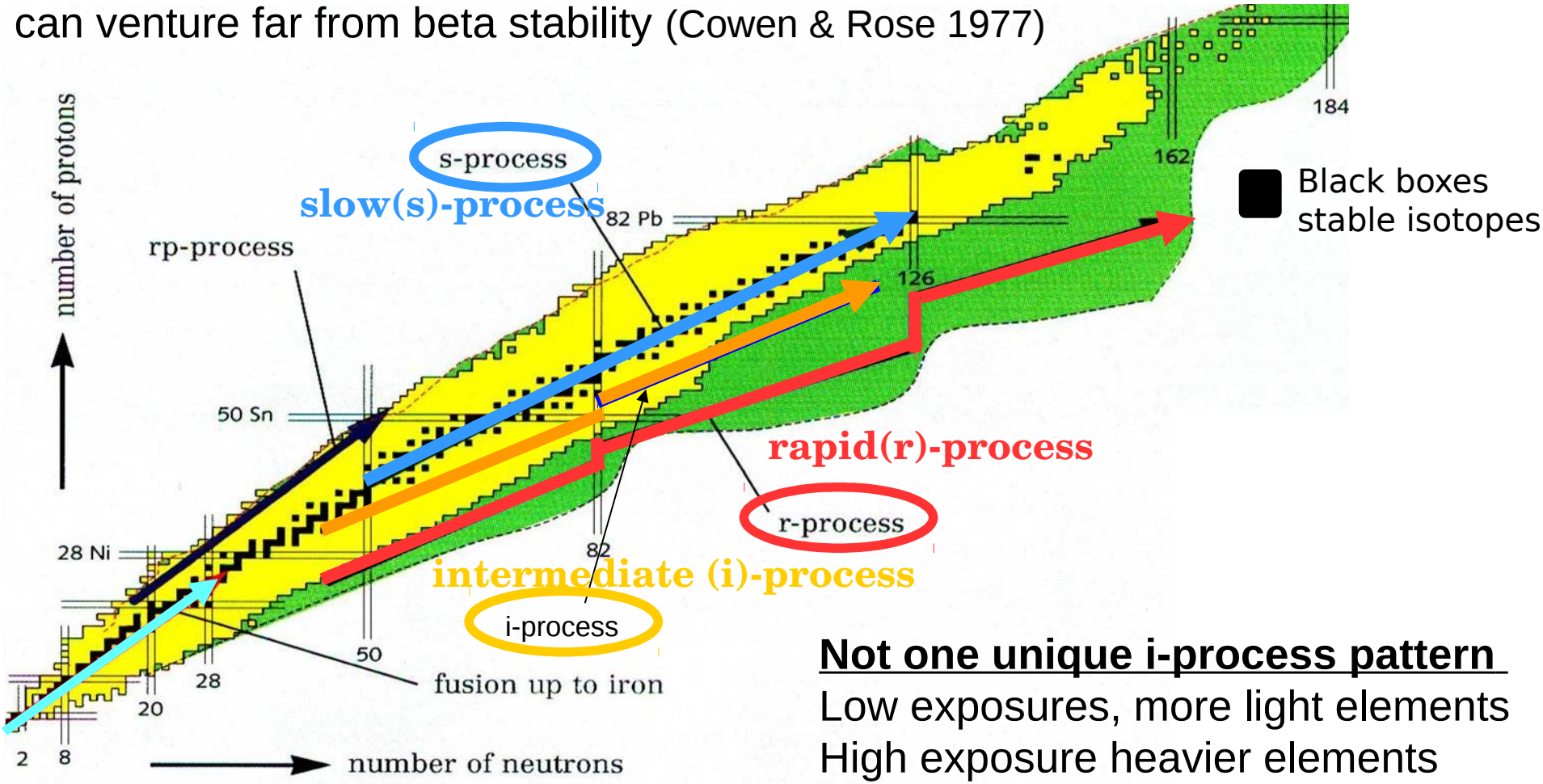
Levesque+2014 HV2112 in SMC

Tout+2014

Beasor+2018

Heavy element production - s, i, r -processes

With "intermediate" neutron densities the abundances can venture far from beta stability (Cowen & Rose 1977)



Not one unique i-process pattern

Low exposures, more light elements

High exposure heavier elements

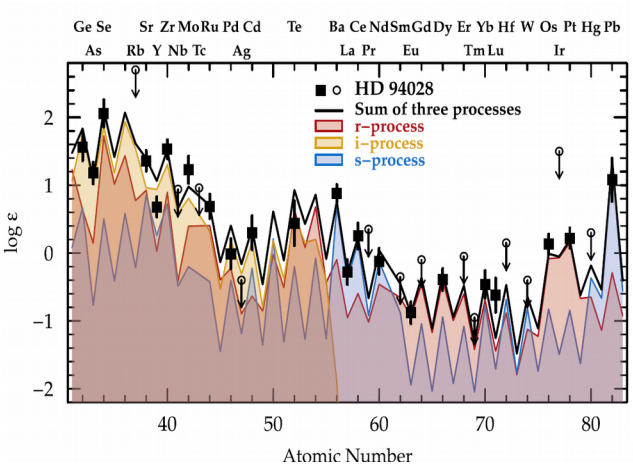
Neutron densities (Nn)
- **s-process** $\sim 10^{8\text{-}13}$ n cm^{-3}
- **r-process** $> 10^{20}$ n cm^{-3}

i-process $\sim 10^{14\text{-}16}$ n cm^{-3}

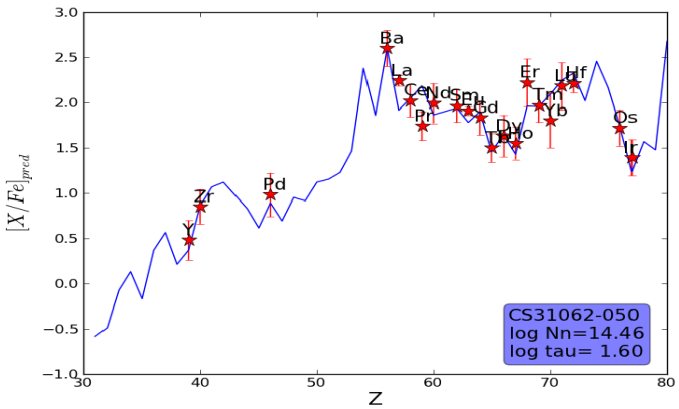
i-process conditions/sites & observations

Selection of studies and proposed sites:

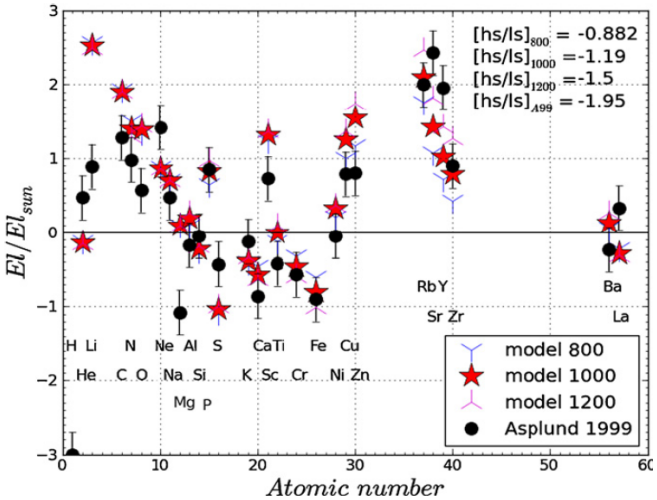
- ★ Red giants undergoing He shell places - Cowan & Rose 1977
- ★ Very late thermal pulses - Herwig+ 2011 (Sakurai's object)
- ★ Carbon-enhanced metal poor stars s/r (i) Dardelet+ 2015, Hampel+2016
- ★ Post-AGB stars Lugaro+ 2015, Hampel+2018 In prep. **(P#49)**
- ★ Low metallicity low-mass stars (proton ingestion episodes) Cristallo+ 2009/16 Campbell+2010
- ★ Rapid accreting white dwarfs Dennisenkov+ 2017
- ★ Low metallicity massive stars - Banerjee+2017, Clarkson+2018 **(P#111)**
- ★ **Super-AGB stars -** dredge-outs Doherty+ 2015, Jones+2016
- ★ **Super-AGB stars** - thermal pulses Jones+ 2016



Roederer et al. 2016



Dardelet et al. 2015



Herwig+2011

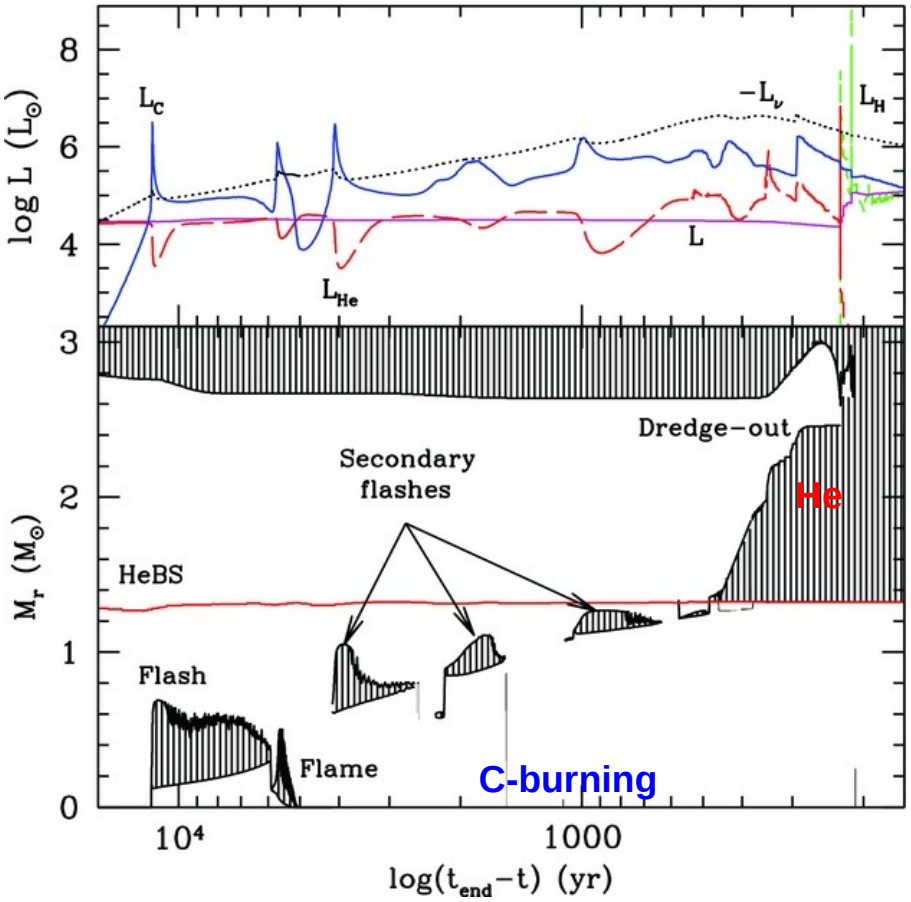
Dredge-out event

- ★ In most massive super-AGB stars ~ 0.3 $M_\odot$ below SN boundary
- ★ Convective He burning region mergers with inward moving convective envelope
- ★ When the zones meet protons are mixed down (proton ingestion episode) to high temperature He (and C) regions
- ★ H flash ~ $10^{6\text{-}9}$ $L_\odot$
- ★ $^{12}C(p,g)^{13}N$ reaction occurs
- ★ $^{13}N(e^+\nu_e)^{13}C$ decays in ~ 10min

Neutron source

$^{13}C(a,\mathbf{n})^{16}O$

- ★ Heavy element production



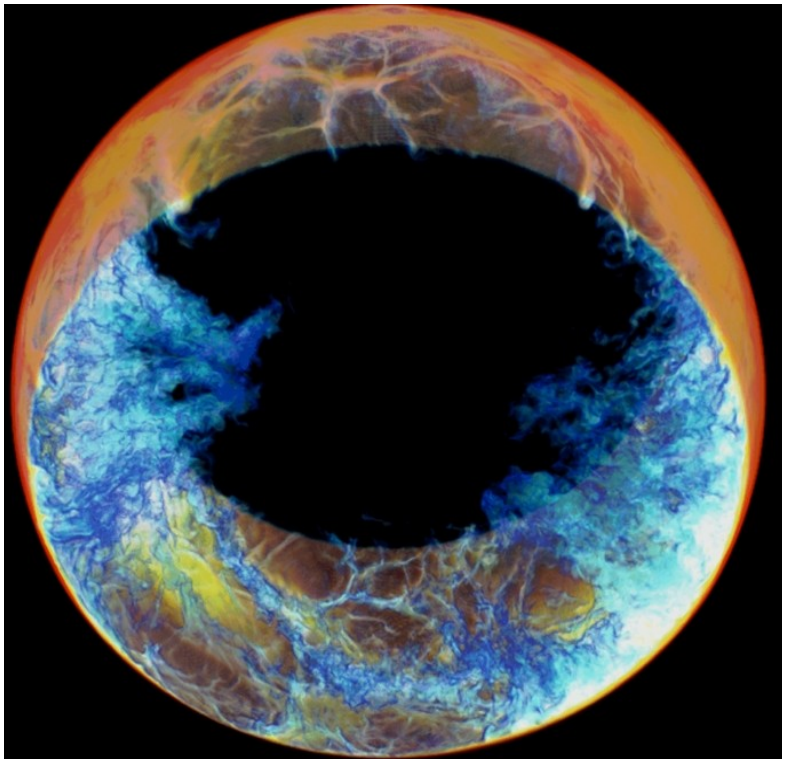
Siess 2007

Dredge-out event - Mass ejection?

- ★ Mixing and burning occur on similar timescales
- ★ 1D calculations may miss important features in this convective/reaction event

- ★ MultiD hydrodynamic models performed for proton ingestion episode (albeit nor dredge-outs)

- ★ Jones+2016 suggested that a dredge-out may cause a global oscillation of shell-H ingestion (GOSH) event (Herwig+2014) which may lead to mass ejection of the entire envelope at this point

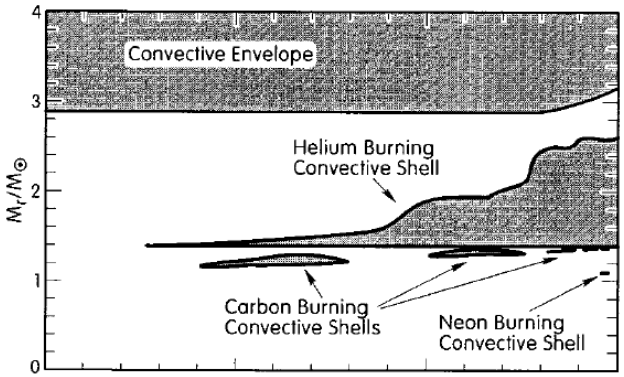


Herwig+2011/14, Woodward+2015

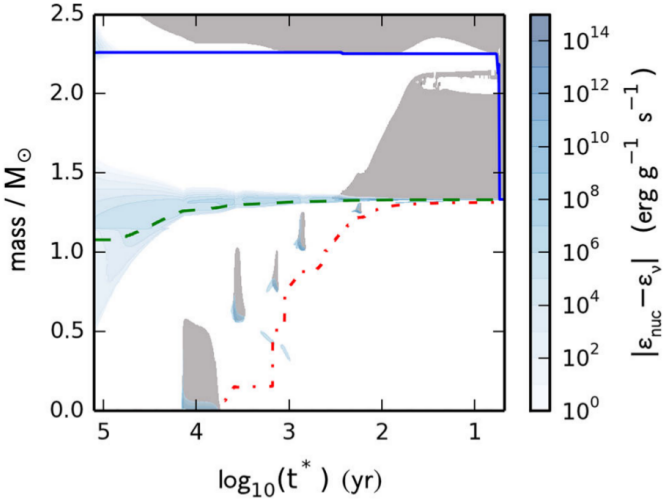
Hydrodynamic picture of H-entrainment into He-shell flash convection near the luminosity peak of the flash for a very late thermal pulse.

Dredge-out events - robust (all codes) + all Zs

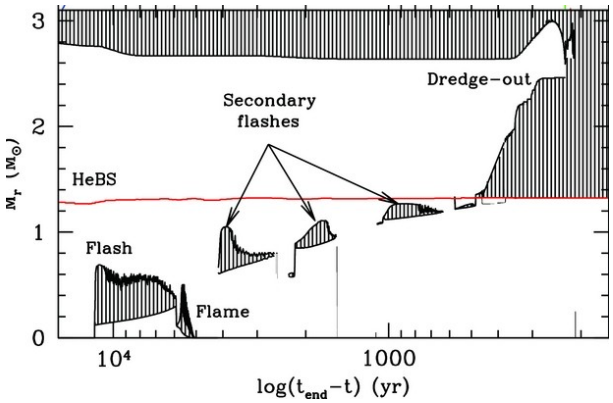
Can these events produce a unique nucleosynthetic signature?



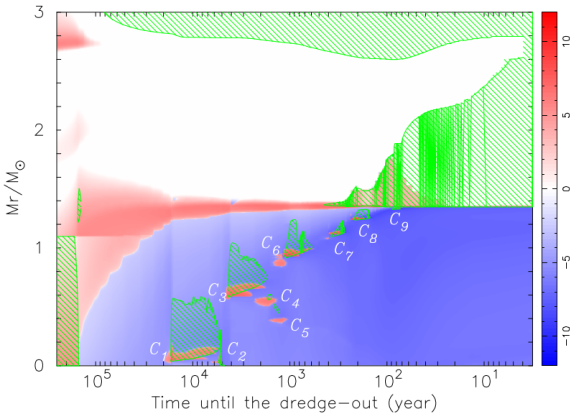
Ritossa+1999 (IBEN CODE)



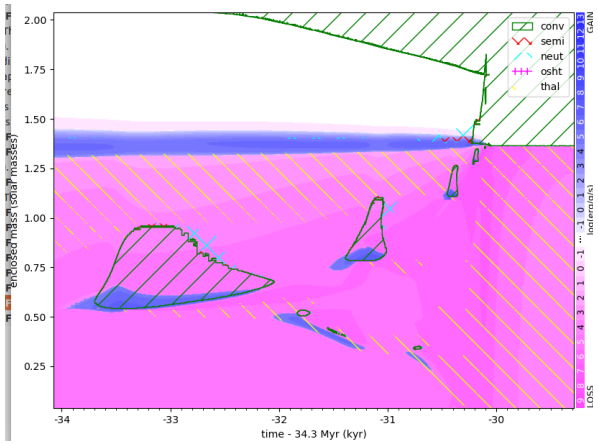
Jones+ 2016 (MESA)



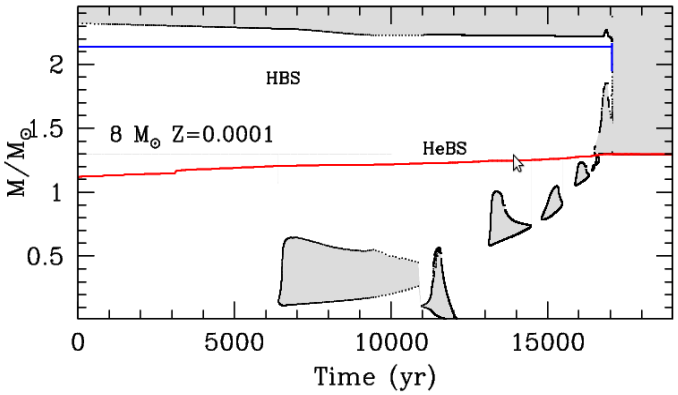
Siess 2007 (STAREVOL)



Takahashi+ 2013



Doherty+ 2018 (in prep) (KEPLER)

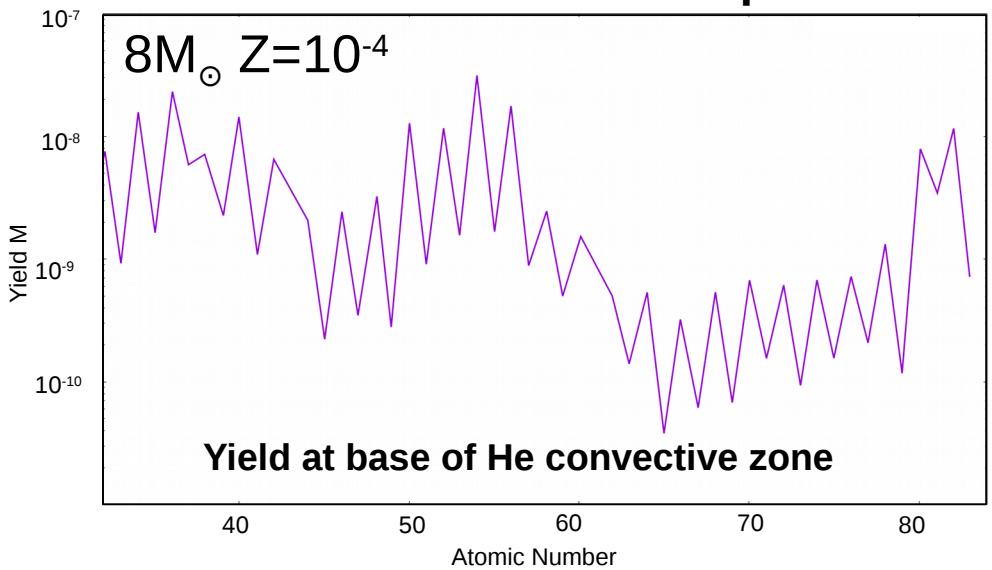


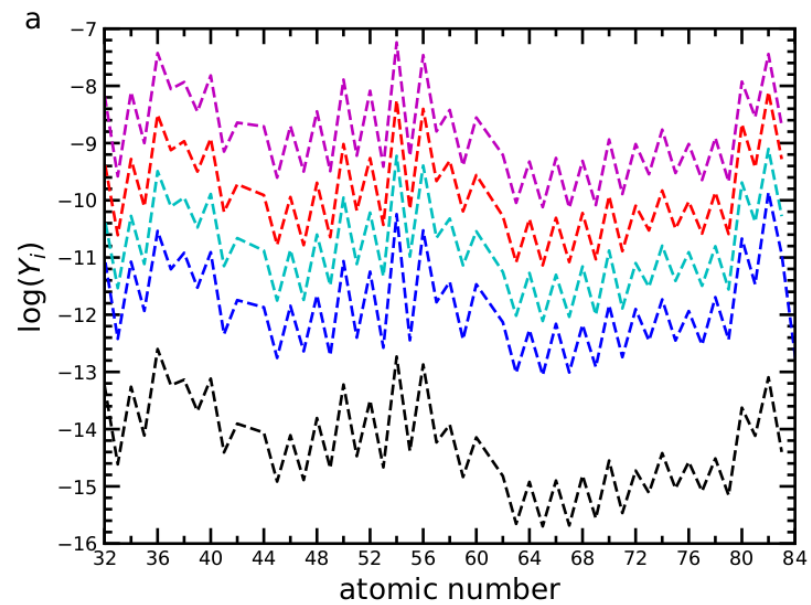
Doherty+ 2015 (MONSTAR)

(Very)Preliminary results

- ★ First heavy element study for dredge-out events
- ★ Using KEPLER 1D stellar evolution code (Heger+)
- ★ Adaptive nuclear network ~ 1000+ species
- ★ Spontaneous ingestion of protons
- ★ Peak neutron densities > 3 x 10^{14} n/cm_3
- ★ Temperature ~ 250MK, Density ~ 500g/cm_3

Elements heavier than Rb produced





Z=0, [Z] = −5, −4, −3,−2.

Banerjee+2017 25Msun Massive star

Different signature than standard thermal pulses

Summary/Future Work

- ★ Dredge-out events in Super-AGB stars make heavier elements (up to even Pb) compared to the (potential) mainly Rb during the thermal pulsing phase
- ★ Heavy element abundances may help us positively identify a super-AGB star compared to other unusual objects such as Thorne-Zytkow Objects
- ★ Currently computing detailed models for a range of metallicities and mixing prescriptions
- ★ Can the dredge-out cause an edjection of the stellar envelope?
- ★ **Multi-dimensional hydrodynamic simulations of this event are crucial!**