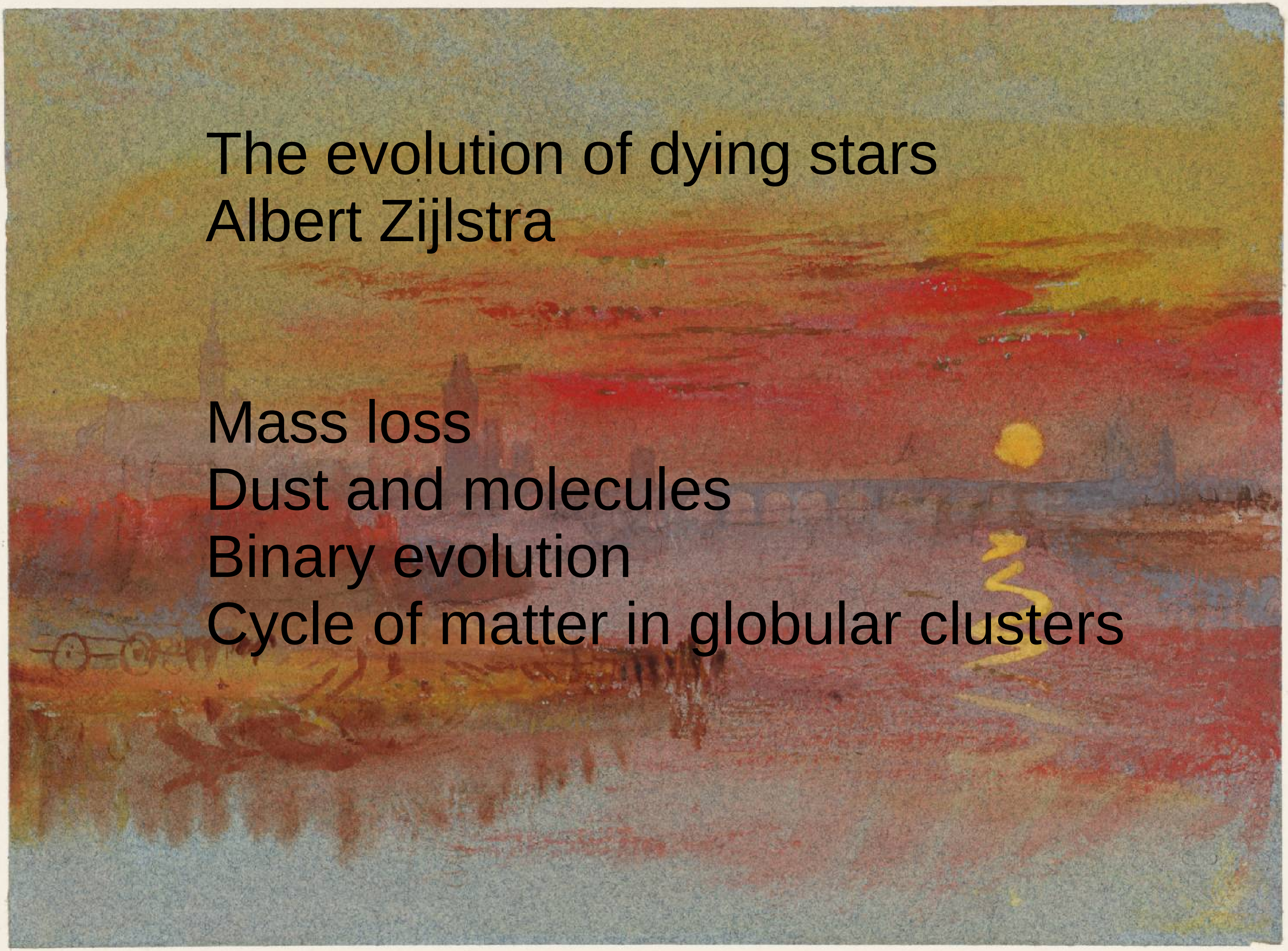


The evolution of dying stars

Albert Zijlstra

Mass loss
Dust and molecules
Binary evolution
Cycle of matter in globular clusters

Mass loss at the end of times

- Stars lose 40%-80% of their mass
- Occurs at end of evolution

  AGB & RGB
- Forms planetary nebulae, white dwarfs, heavy metal, dust, ..

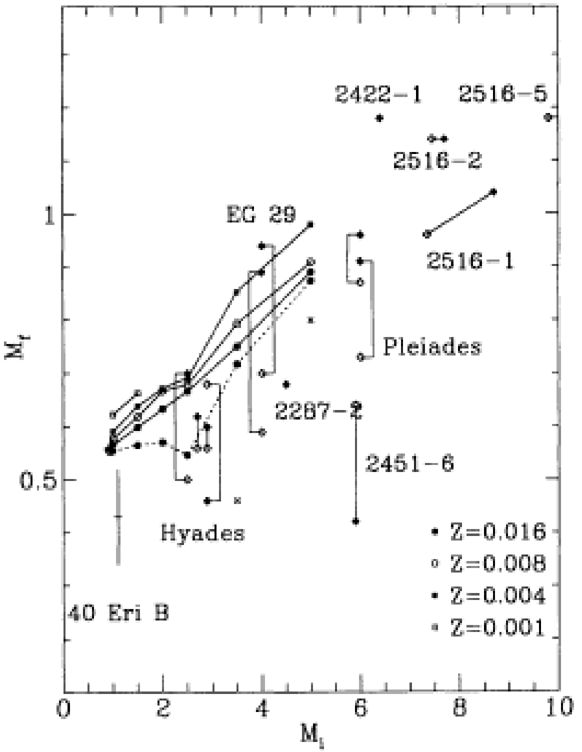
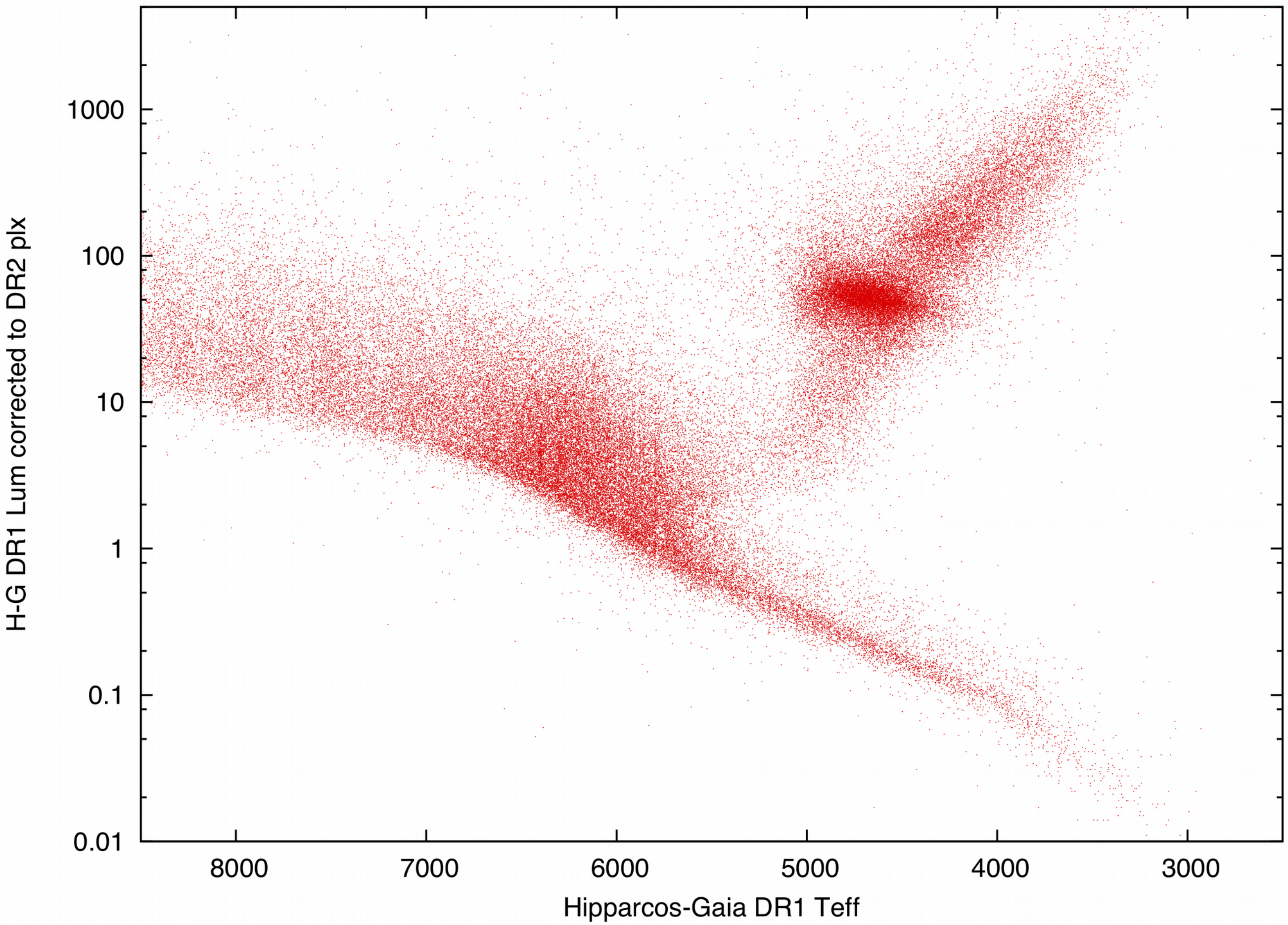


FIG. 21.—Final stellar remnant mass, after AGB mass loss, plotted as a function of the initial mass (*solid curves*). The dashed line represents the core mass at the first helium shell flash for the $Z = 0.016$ calculations. Observational points are taken from Weidemann (1987), and references therein. Annotation of the data points is similar to that presented in Fig. 1 of Weidemann & Koester (1983). Filled diamonds represent masses derived from log g, while open diamonds represent masses derived from the stellar radius. Mass determinations via log g and radius for the same object are joined by a line. The crosses represent the Sanduleak-Pesch binary (Greenstein, Dolez, & Vauclair 1983) where $M_f = 0.8$ was assumed for the primary.

Gaia dr2 HRD


1000
100
10
1
0.1
0.01
H-G DR1 Lum corrected to DR2 plx
8000
7000
6000
5000
4000
3000
Hipparcos-Gaia DR1 Teff

Importance

- 1-10 Msun stars contain as much mass as 10-100 Msun stars

  →equal contributors to mass return

- Life times much longer

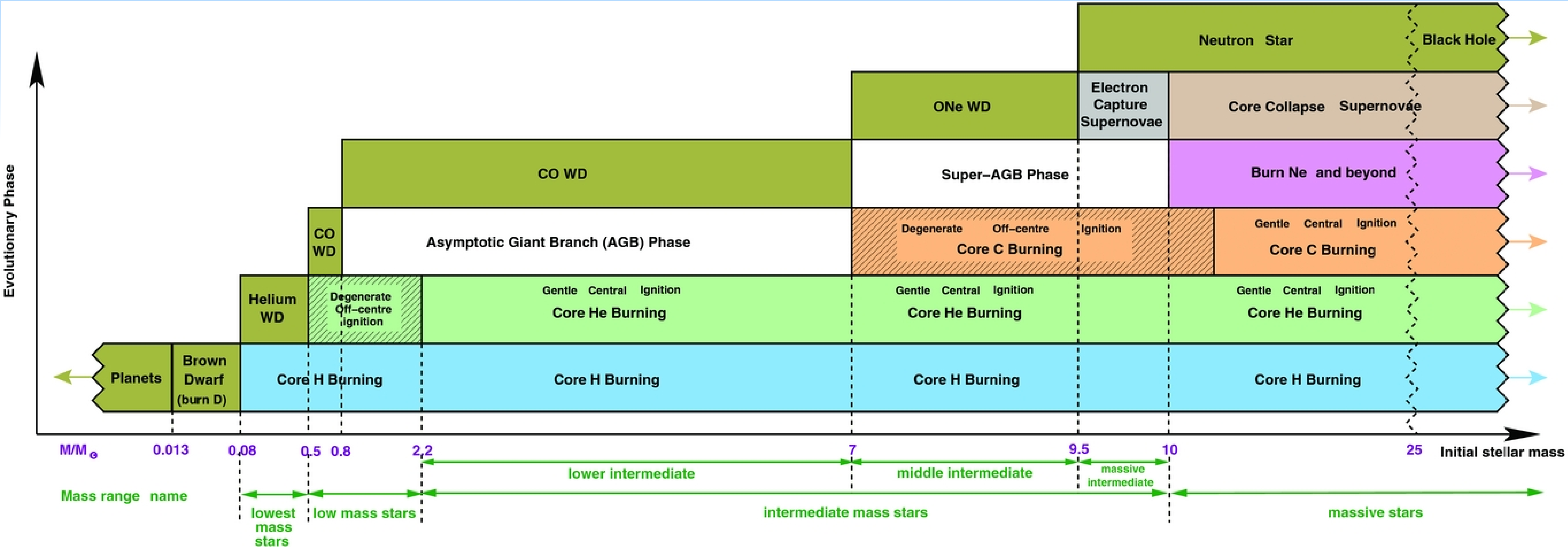
  → Important at late times

- Very efficient dust producers
- Products:

  H,He,C,N,
  s-process elements,
  dust
  com,plex molecules

- Not important for feed back (energy)

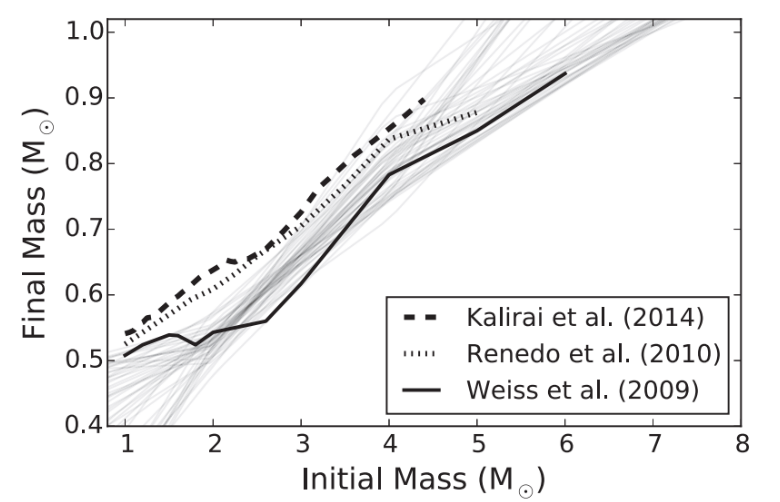
From cradle to grave

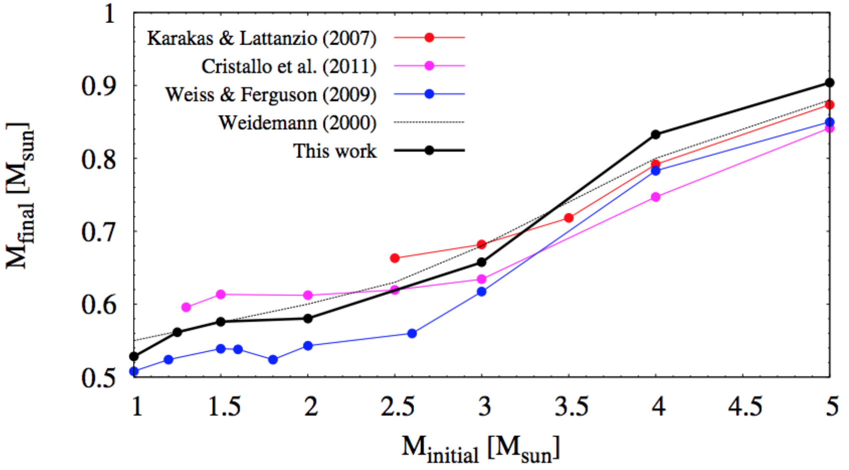


- Karakas & Latanzio 2014, Dawes review

Initial final mass relation

- Measures the total mass return
- Measured from cluster white dwarfs
- Models: fitted with mass loss law
- Significant uncertainties remain in both data and models





Mass loss relations

- Reimers' wind
- Chromospheric
  fast and weak
- $\eta = 0.35$
  (Groenewegen 2010)
  $\eta = 0.48$
  (McDonald & Zijlstra 2015)

$$\dot{M} = \eta 4 \times 10^{-13} \left(\frac{LR}{M} \right)^{\gamma} \mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$$

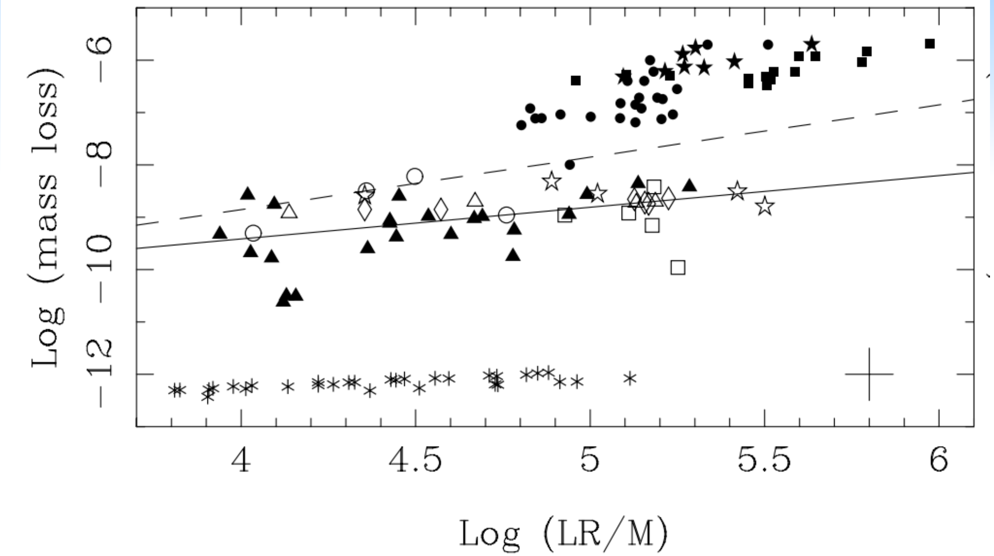
- Schroeder & Kuntz 2005 proposed a modification

$$\dot{M} = 4 \times 10^{-13} \eta_{\mathrm{SC}} \frac{LR}{M} \left(\frac{T_{\mathrm{eff}}}{4000\,\mathrm{K}} \right)^{3.5} \left(1 + \frac{g_{\odot}}{4300 g} \right) [\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}],$$

$$\eta_{\mathrm{Sc}} = 0.2$$

Superwind

- Renzini (1980) proposed an amplified Reimers wind at late stages
- Subsequently confirmed by IRAS observations

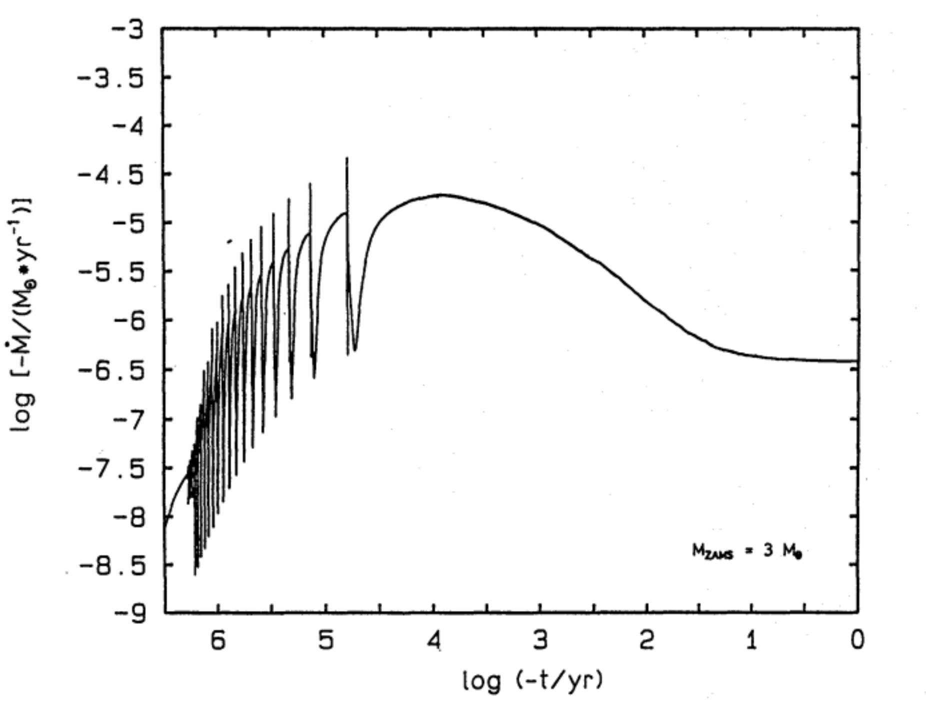


Groenewegen 2010

Superwind formalisms

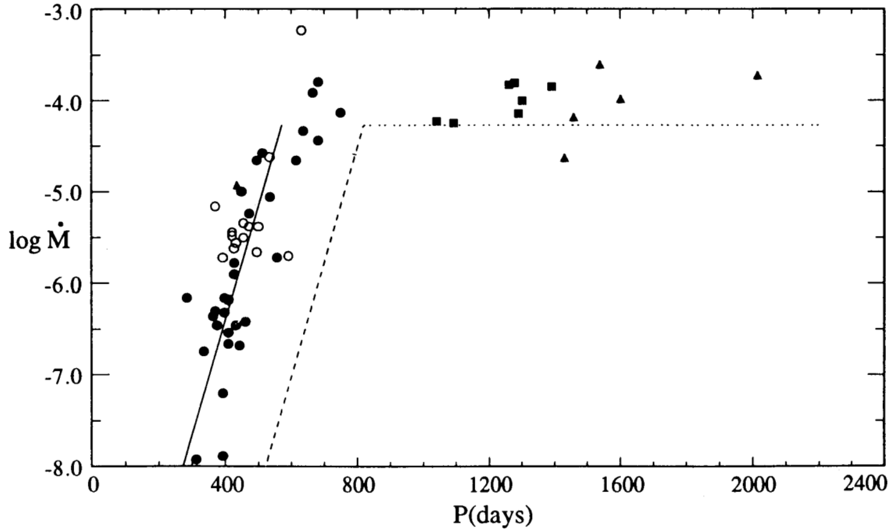
- Bloecker 1995

$$\dot{M}_{\rm B} = 4.83\,10^{-9} M^{-2.1} L^{2.7} \dot{M}_{\rm R}\ [{\rm M_\odot yr^{-1}}]$$



- Vassiliadis & Wood 1993

$$\log \dot{M}_{\rm VW}\ [{\rm M_\odot yr^{-1}}] = -11.4 + 0.0123{\rm P[days]}$$



- Lower mass loss means higher yield

Mass loss: uncertainty

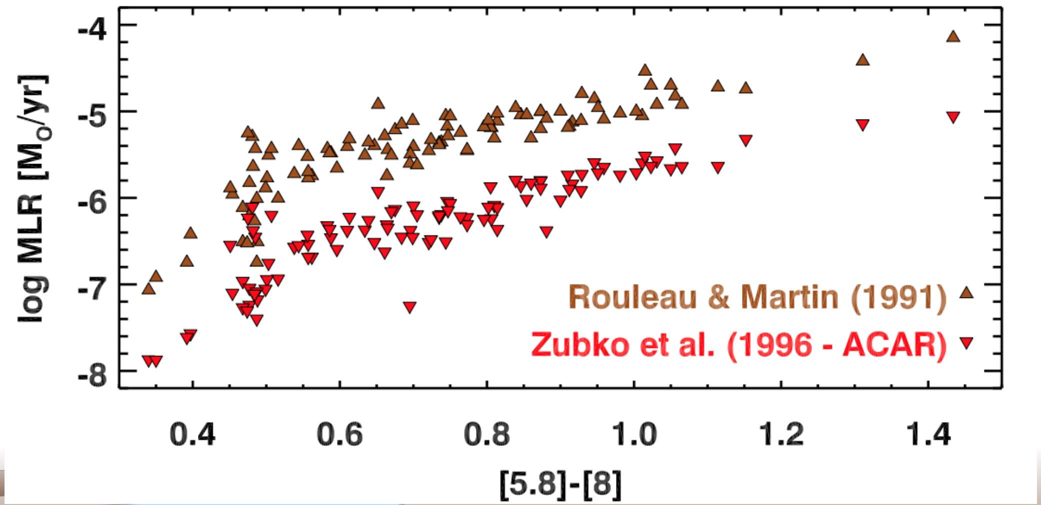
- Measured by tracers

  Dust (unknown constants, Vexp)

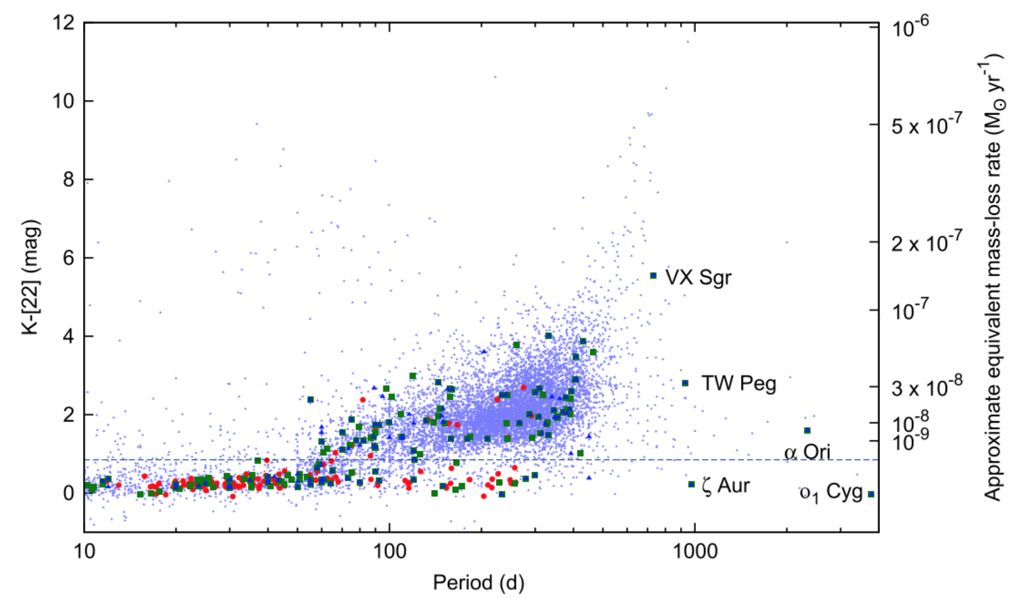
  CO (unknown dissociation radius)
- Assume spherical symmetry
- Lower mass loss means higher yield

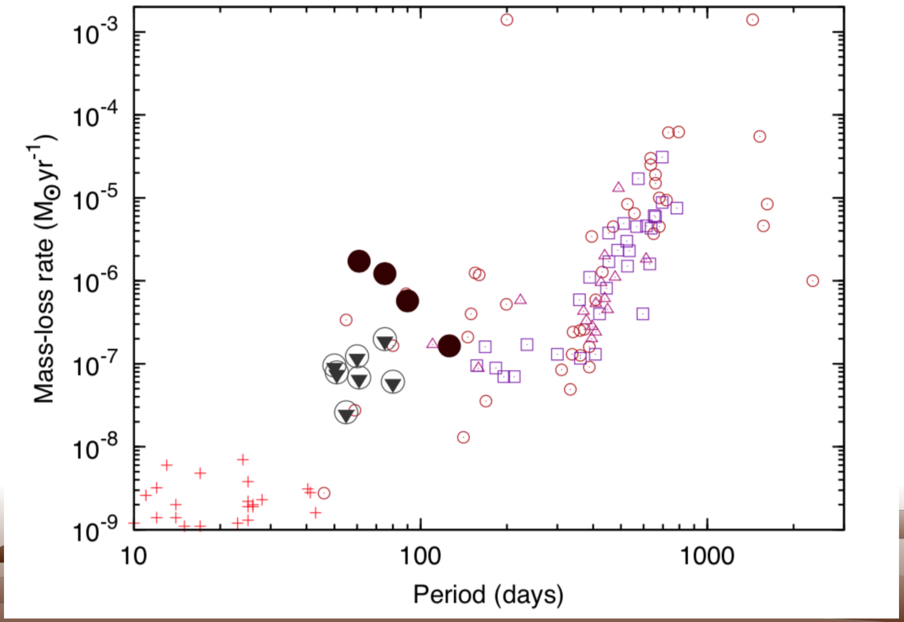
- For amorphous carbon, dust mass varies by a factor of 9 between two common opacities

  Groenewegen & Sloan 2018



Mass loss: step function





- CO, dust excess and Kepler all show a sudden change at P=60 days.

  Glass et al. 2009; Mosser et al. 2013; McDonald & Zijlstra 2016, subm

- Second step up occurs at P=300 days
- Related to pulsation mode and amplitude

Mass loss: the status

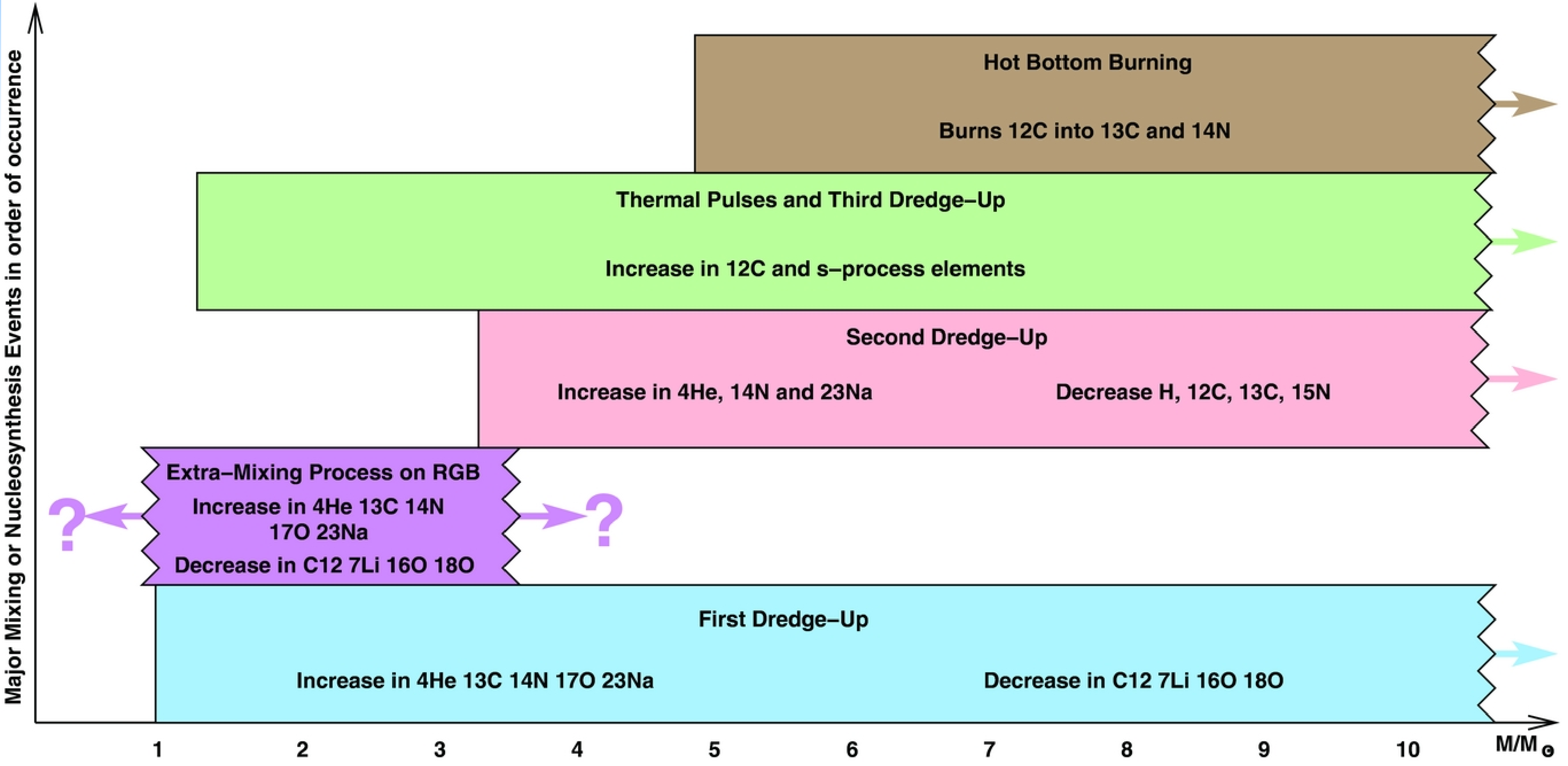
- Reimers law for P<60 days (RGB & EAGB)
- Pulsation-driven wind for P=60-300 days (LAGB),

  Mdot ~ 5 10^-8 Msun/yr
- Momentum-driven wind when P>300 days

  Maximum at a few 10^-5Msun/yr

  (VW93 relation preferred over B95 law)
- Pulsation is crucial – metallicity effects are limited

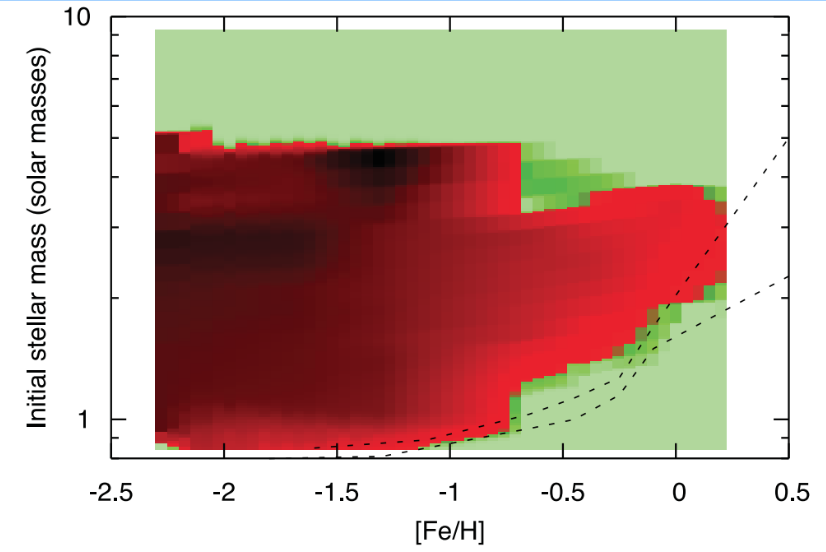
Dredge up



Karakas & Lattanzio 2014

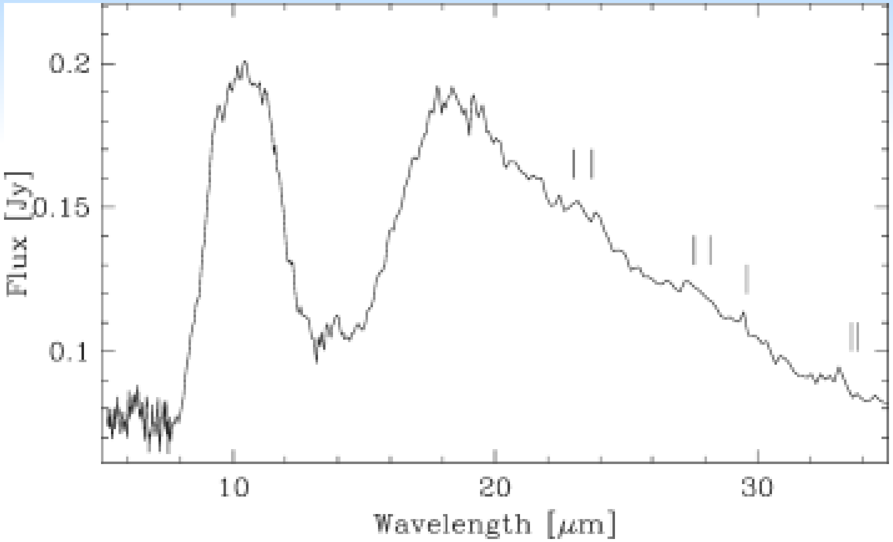
Carbon star formation

- Third dredge-up can cause carbon star formation
- C/O>1: dichotomy to C-rich and O-rich chemistry
- At high Z, carbon stars at 2-4 Msun progenitor mass



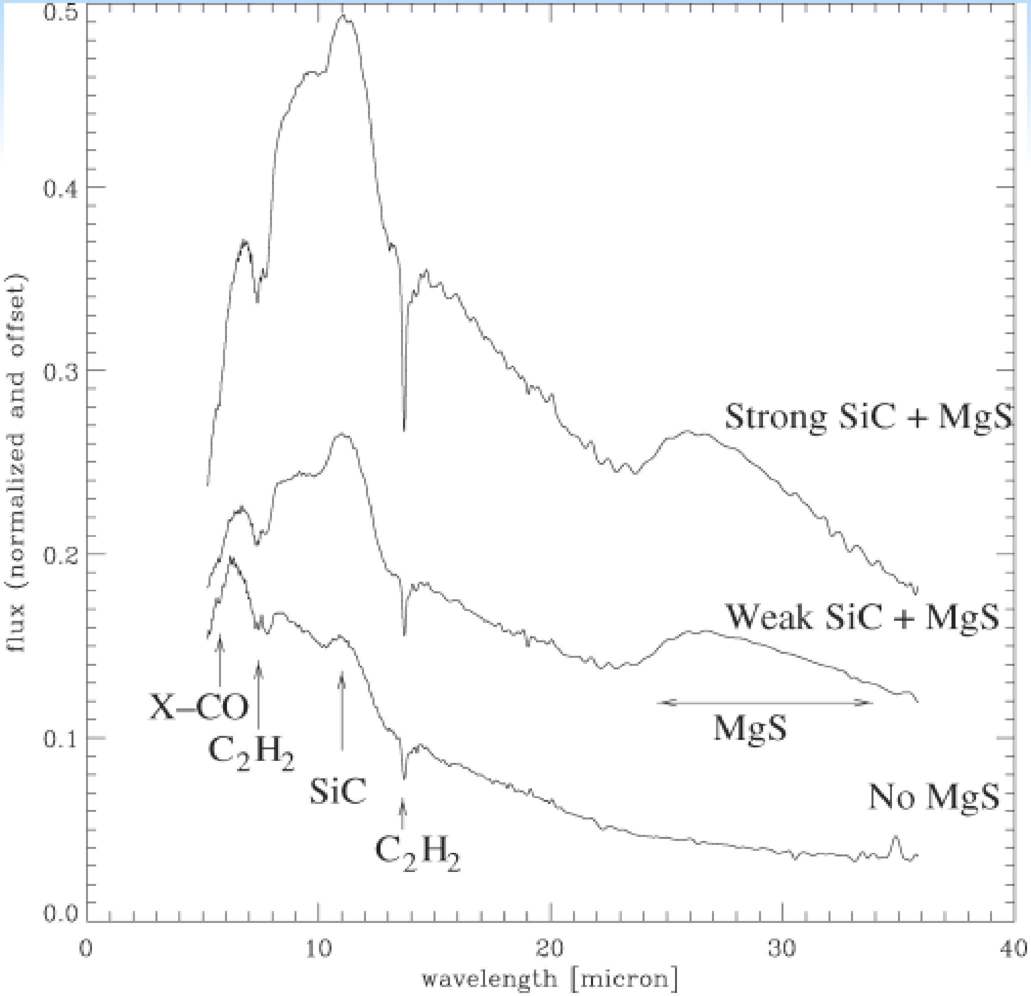
McDonald et al 2012, based on isochrones from Marigo & Girardi (2007)

Dust: oxygen-rich stars



- Alumina (~20%) and silicate production
- Minor component of crystalline silicates (produced in shocks?)
- Higher Z: fosterite (Mg_2SiO_4)
- Lower Z: enstatite (Mg_2SiO_3)

Dust: carbon stars

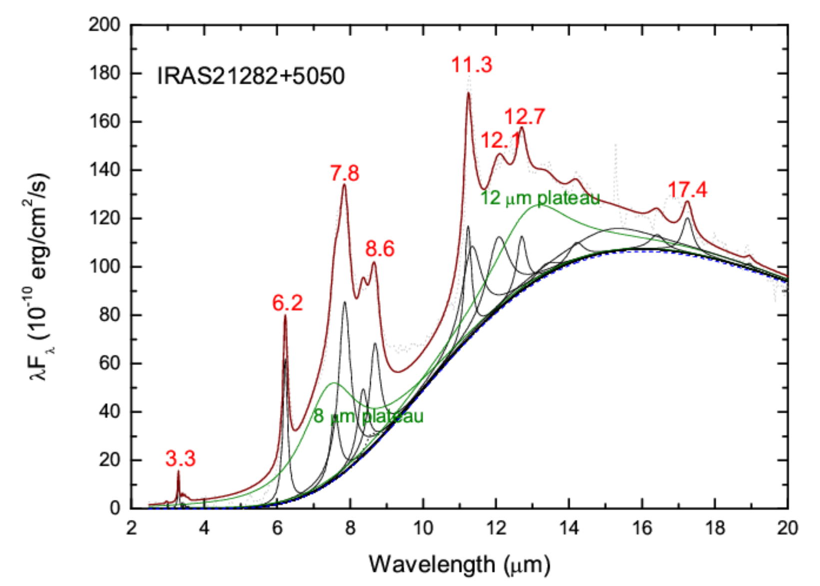


(Low numbers in MW)

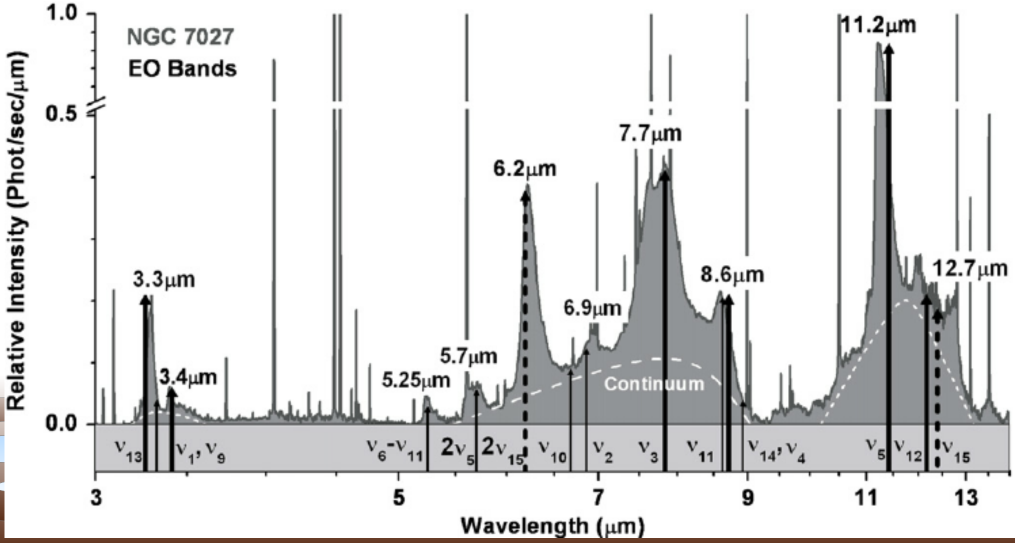
- Copious dust from primary carbon
- Amorphous carbon, graphite
- SiC (seed at higher Z)
- MgS: low-temperature coating

Complex molecules: PAHs/HACs

- Seen in post-AGB stars and PNe
- Also exist in O-rich environments
- Forms from CO dissociation at A_V~4
- Survives in molecular envelopes
- If large PAHs: photostable



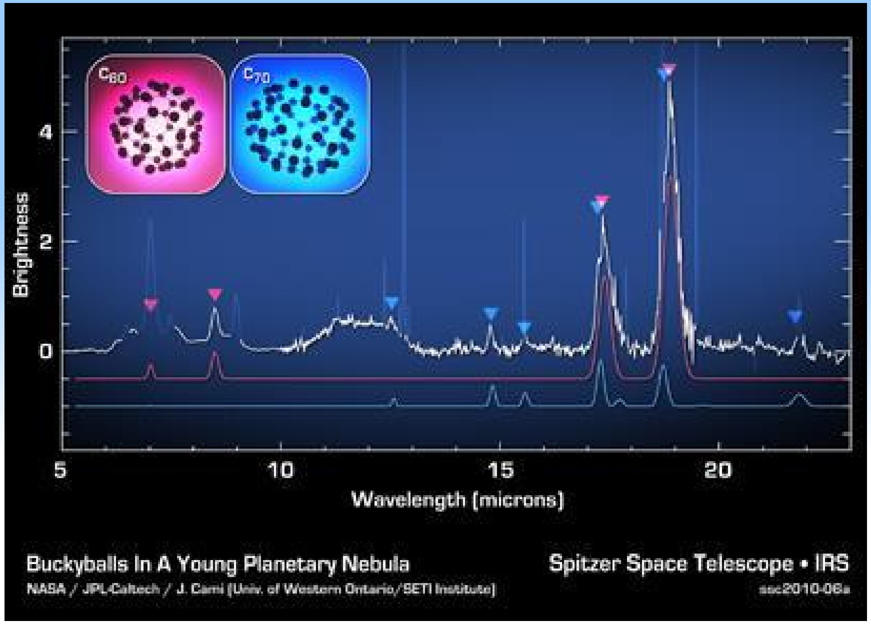
Bernstein & Lynch 2009

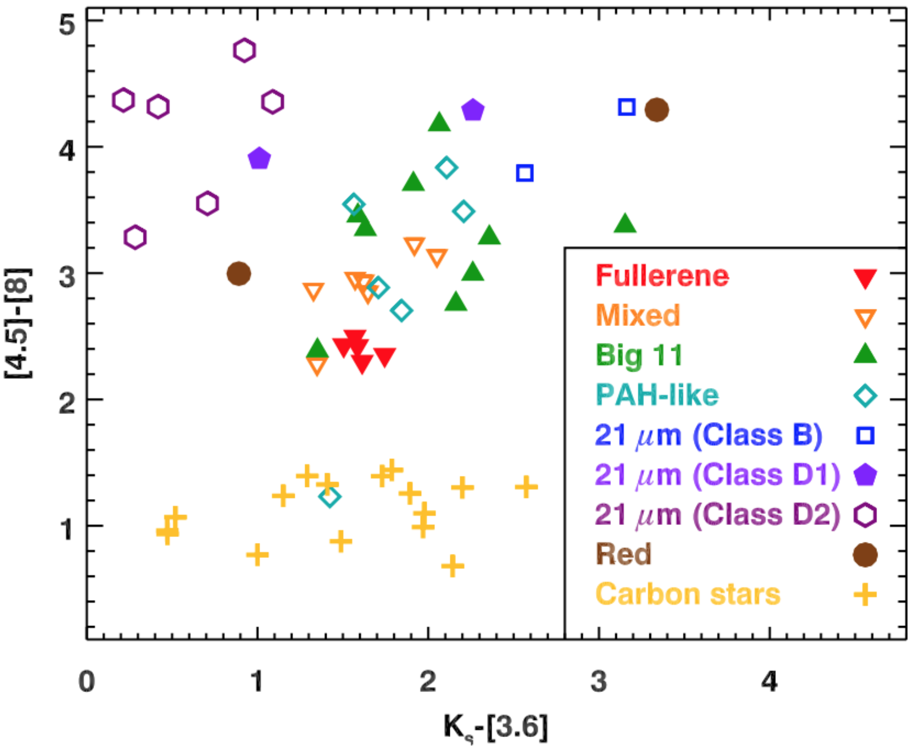


Fullerenes

- Seen in carbon-rich PNe only
- Only cool central stars

  T(star) = 20-40kK
- Low internal reddening
- Forms late, destroys early
- Related to near-infrared dust continuum

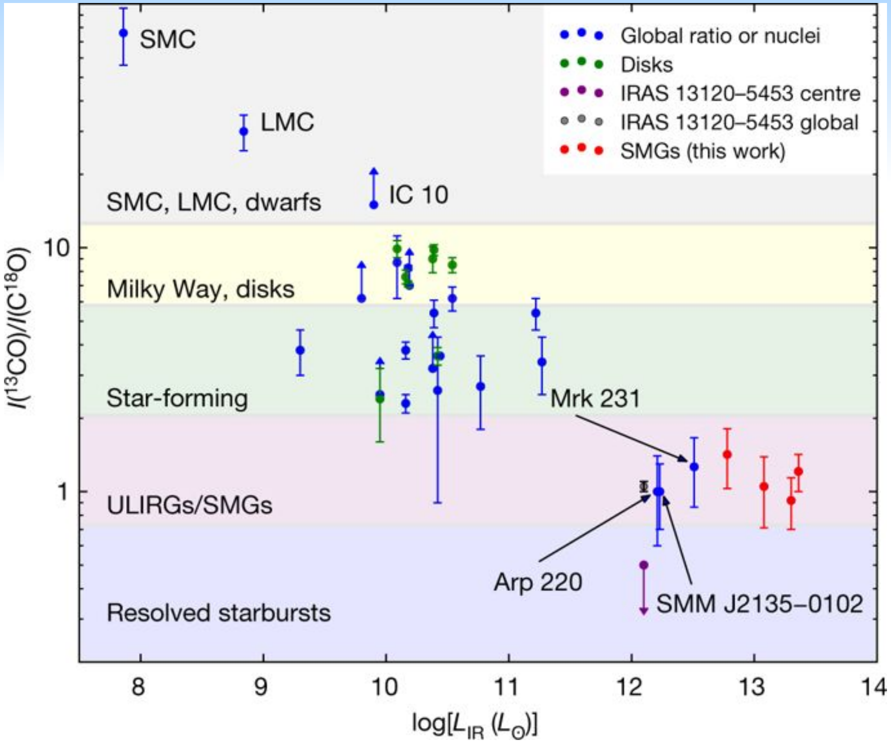




Sloan et al. 2014

Isotopes

- Different isotopes trace different nuclear burning temperatures
- 18O: high temperatures
- Produced in high mass SAGB/SG stars

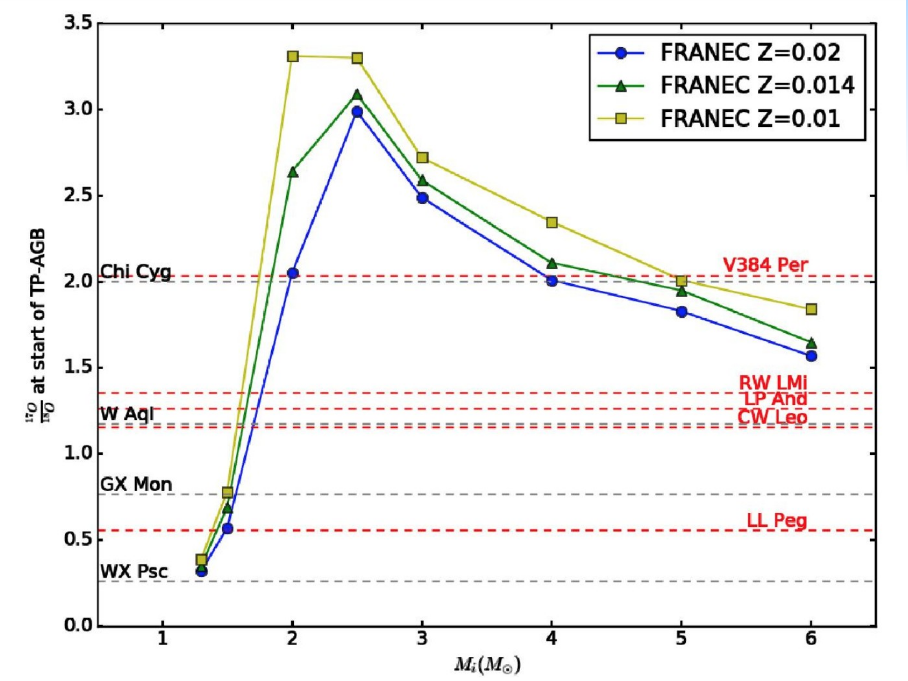


Zhang et al. 2018, Nature

17O/18O

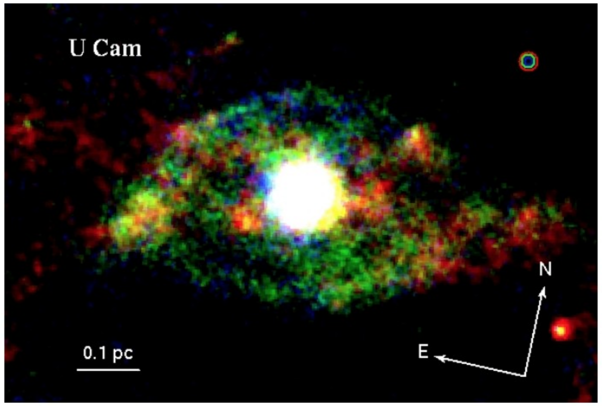
- Sensitive tracer of initial mass
- However, hard to measure

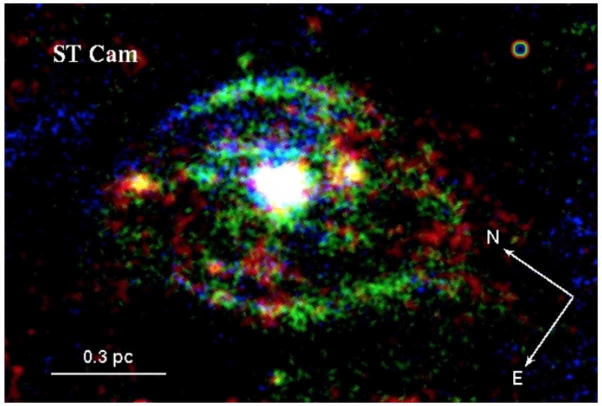
de Nutte et al. 2016, Danilovich et al. 2017

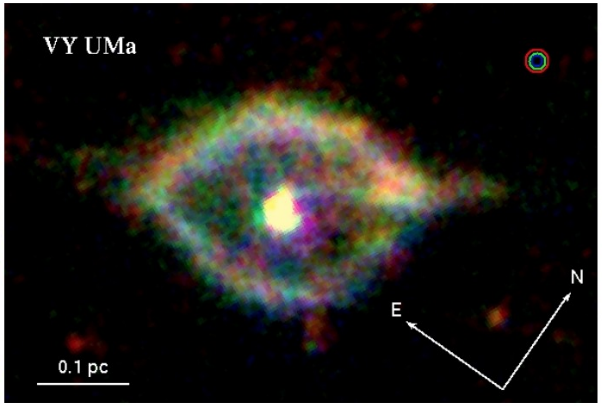


The problem of the asterosphere

- AGB wind sweeps up ISM
- Termination shock 1-4 pc from the star
- ‘wall’ around the star
- Walls tend to be round
- Eye-like shapes may be magnetic shaping Van Marle et al. 2014



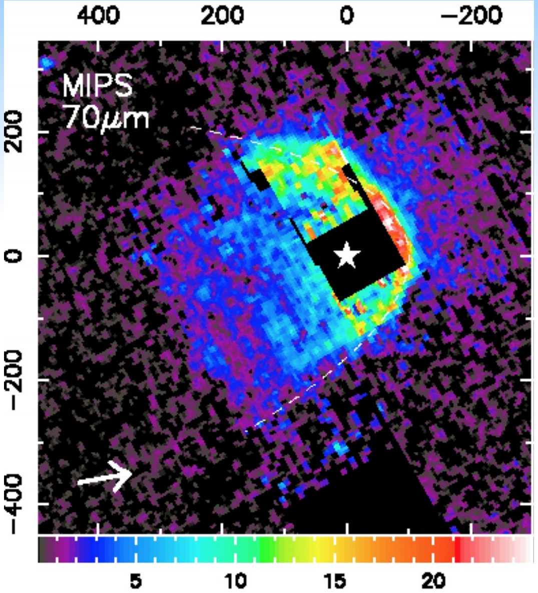


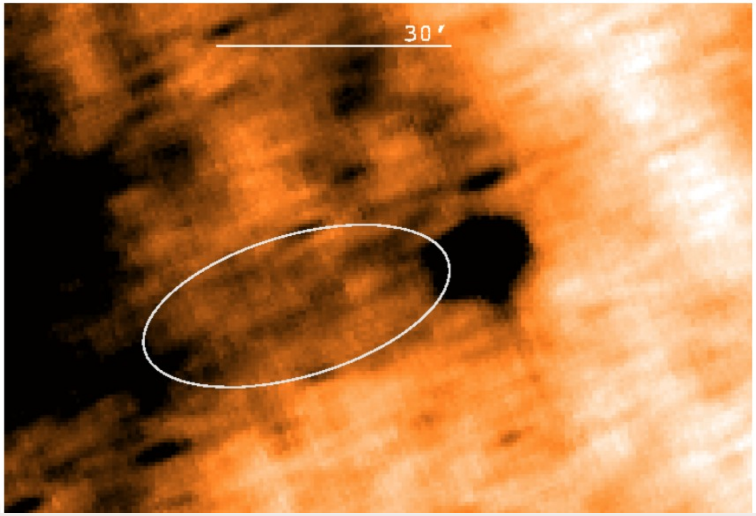


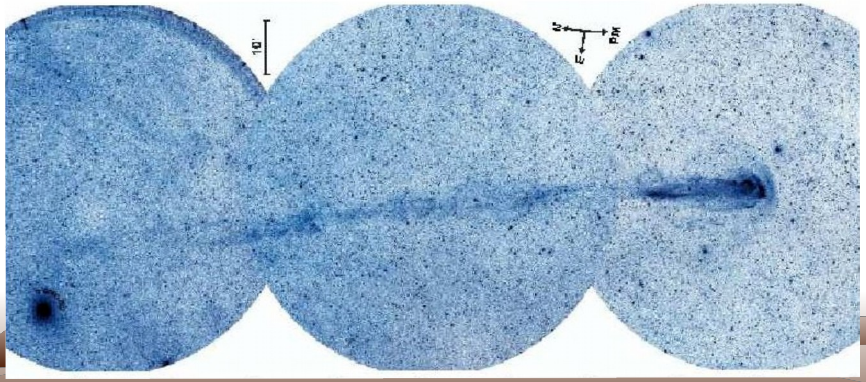
Bows and tails

- Bow shocks and tails are observed
- Majority of their dust and gas is swept-up ISM

R Hya: Ueta et al. 2006, Wareing et al 2006







Post-mass-loss processing

- Photoprocessing from the post-AGB star

  -forms and destroys complex molecules

  -photo-stable PAHs may survive

- Shock processing when entering the ISM
- Removes grains surface layers?
- Cause of disappearance of MgS
- Grain cores (SiC, Silicates) survive

Binary evolution

- Most binaries evolve like single stars
- For separations <~ 1AU, common envelope occurs

  Removes entire envelope

  Early termination of stellar evolution

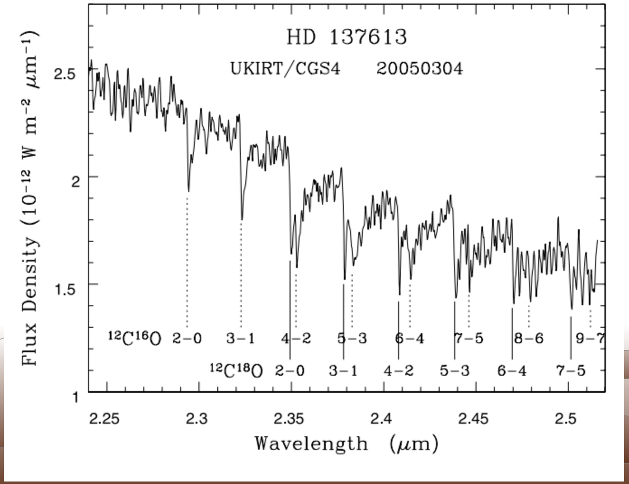
- 5-25% of PNe are post-CE
- Low mass nebulae, H-poor condensations
- The PNe are NOT the CE ejecta
- Trace further mass loss events

  Corradi et al. 2014

Non-standard evolution

RCrB stars

- Highly carbon rich, H-poor
- featureless dust continuum
- 18O/16O ~ 1



- He-CO white dwarf merger: Clayton et al. 2007

14N(alpha)18O but not 13C(alpha)17O

Burning temperature 1.6 10^8 K

- Birth rate one in 500 yr

R CrB stars

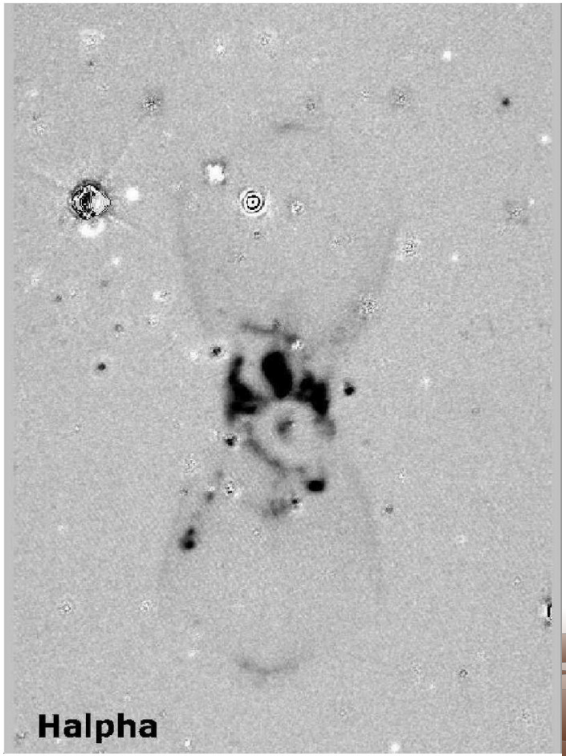
- Karakas et al. 2015

  R CrB stars produce 5 10^-4 Msun/yr of carbon dust in the Galaxy

- Exceeds novae dust production
- An order of magnitude (*est*.) below carbon dust production by Galactic AGB stars

Eruptions: CK Vul

- ‘Nova’ explosion in 1670-1671
- Bipolar nebula was formed



- Kaminski et al. 2017 found molecules

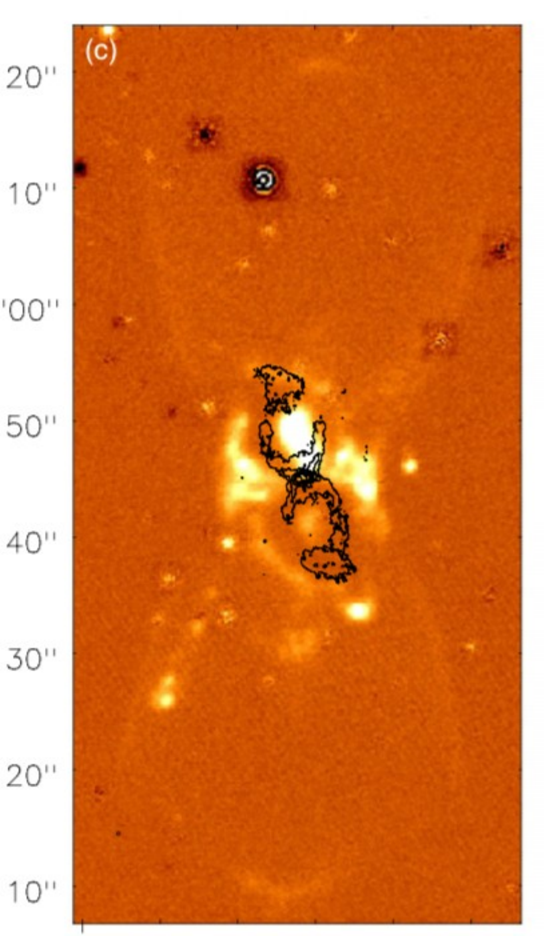
  12C/13C=4

  14N/15N=24

  16O/18O=36
- Extreme Li

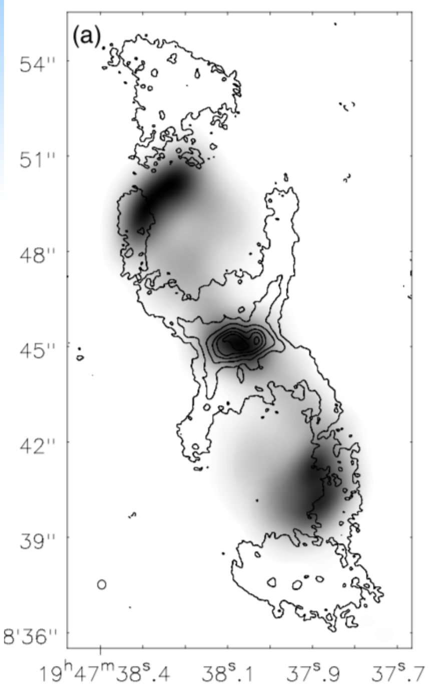
  Hajduk et al. 2013
- Hot CNO burning + partial helium burning ?

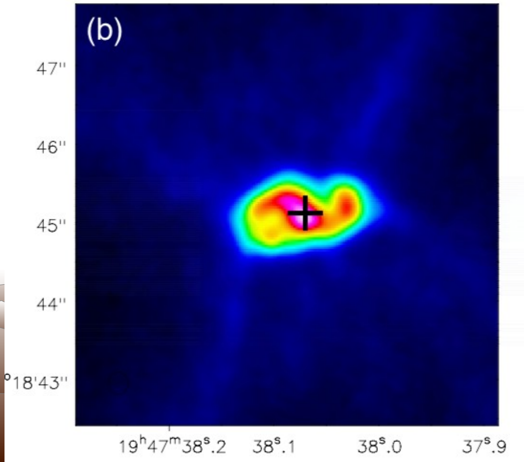
CK Vul



Dust

CH3OH





- ALMA/e-Merlin show multiple precessing lobes, inner disk
  Eyres et al. subm
- Suggested: merger between WD and BD
- Unique or common?

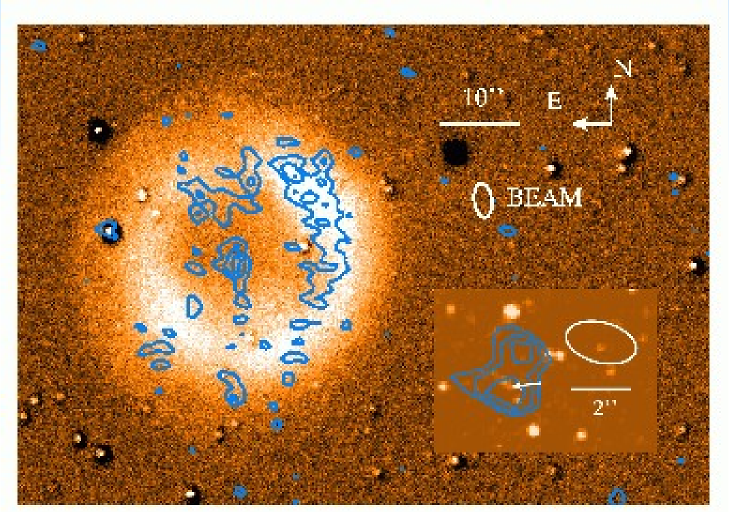
Eruptions: Sakurai's Object

- Very Late Thermal Pulse (VLTP)
- Helium ignition in young white dwarf
- Leading to new mass loss

H-poor, C-rich

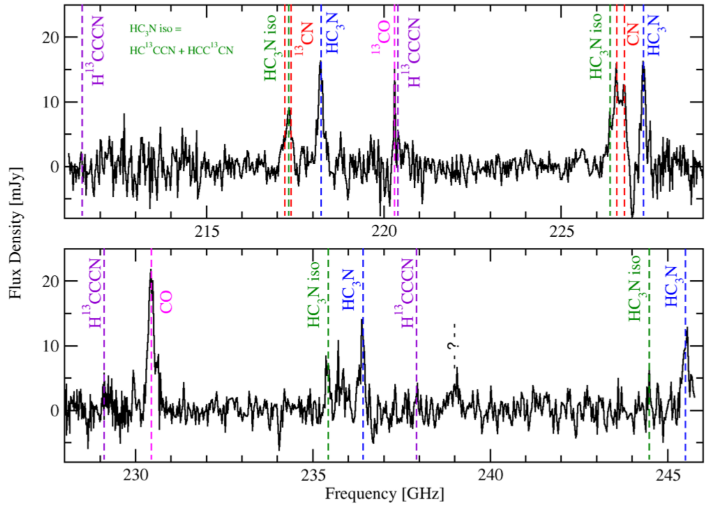
12C/13C ~ 4

very dusty

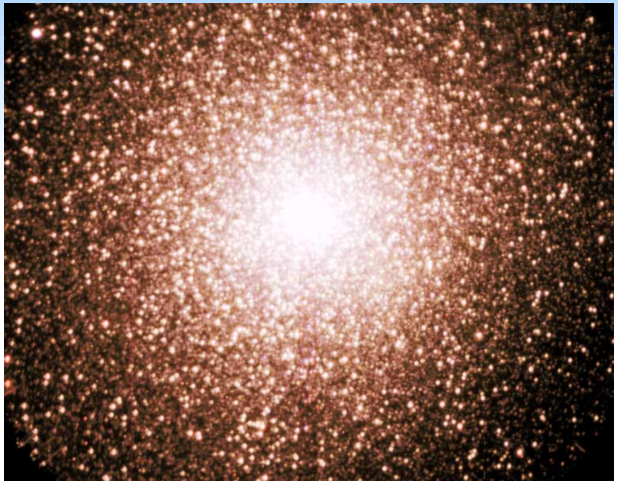


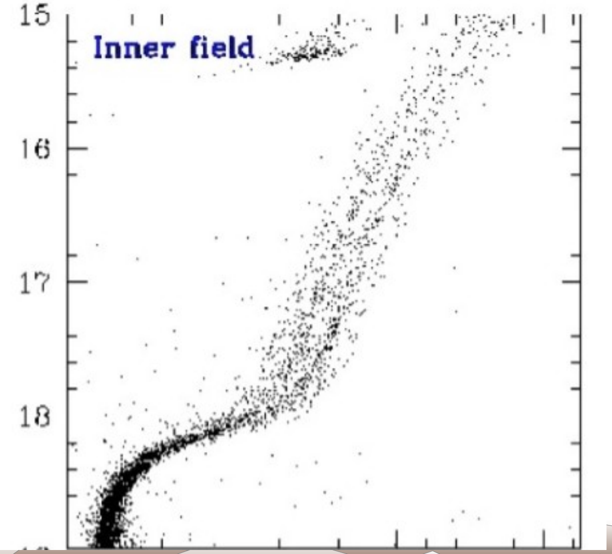
Sakurai

- VLTP occur once per decade
- Eject ~10^-3 Msun (mostly carbon?)
- Carbon production ~0.05 of that of AGB stars
- But may be important for 13C
- However, eruption poorly understood
- Accretion-triggered?



The cycle of matter in globular clusters





NGC2808
Piotto et al. 2007

- Globular clusters are old stellar populations

  10-12Gyr
- Some have multiple populations with AGB(?) enrichment
- Second generation from own stellar ejecta

The cycle of matter in globular clusters

- AGB stars in GCs add ~10^-6 Msun/yr
- Should re-form an ISM
- Only two detections of a mini-ISM in GCs

- Vacuum cleaning?

Various explanations

- Ram pressure from disk passage – too infrequent
- Ionization by millisecond pulsars – too inefficient

AGB stars in 47 Tuc

- 47 Tuc has four dusty AGB stars with mass loss
- We used ALMA to measure their CO
- Non-detections, a factor of 10 below expectations
- Explanation: CO dissociation by UV radiation from cluster post-AGB stars
- CO destroyed at 10-100 AU

McDonald & Zijlstra 2015

- AGB ejecta are already ionized!

Cloudy ionization models on cluster

- Plummer potential

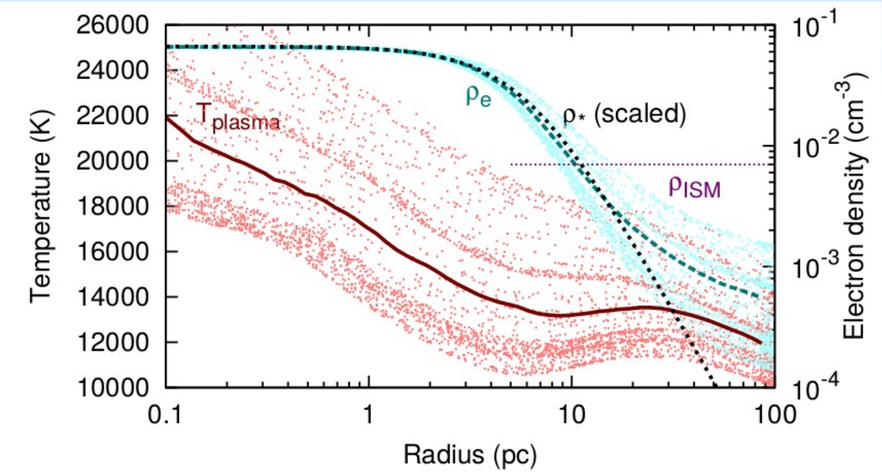
$$\rho(r) = \frac{3M}{4\pi a^3}\left(1+\frac{r^2}{a^2}\right)^{-5/2}$$

- Pressure equilibrium

$$\frac{\mathrm{d}n}{\mathrm{d}r} = -\frac{GMm_{\mathrm{H}}n(r)}{kT(r)}\frac{r}{(r^2+a^2)^{3/2}}$$

$$n_e(0) = 0.067\,\mathrm{cm}^{-3}$$

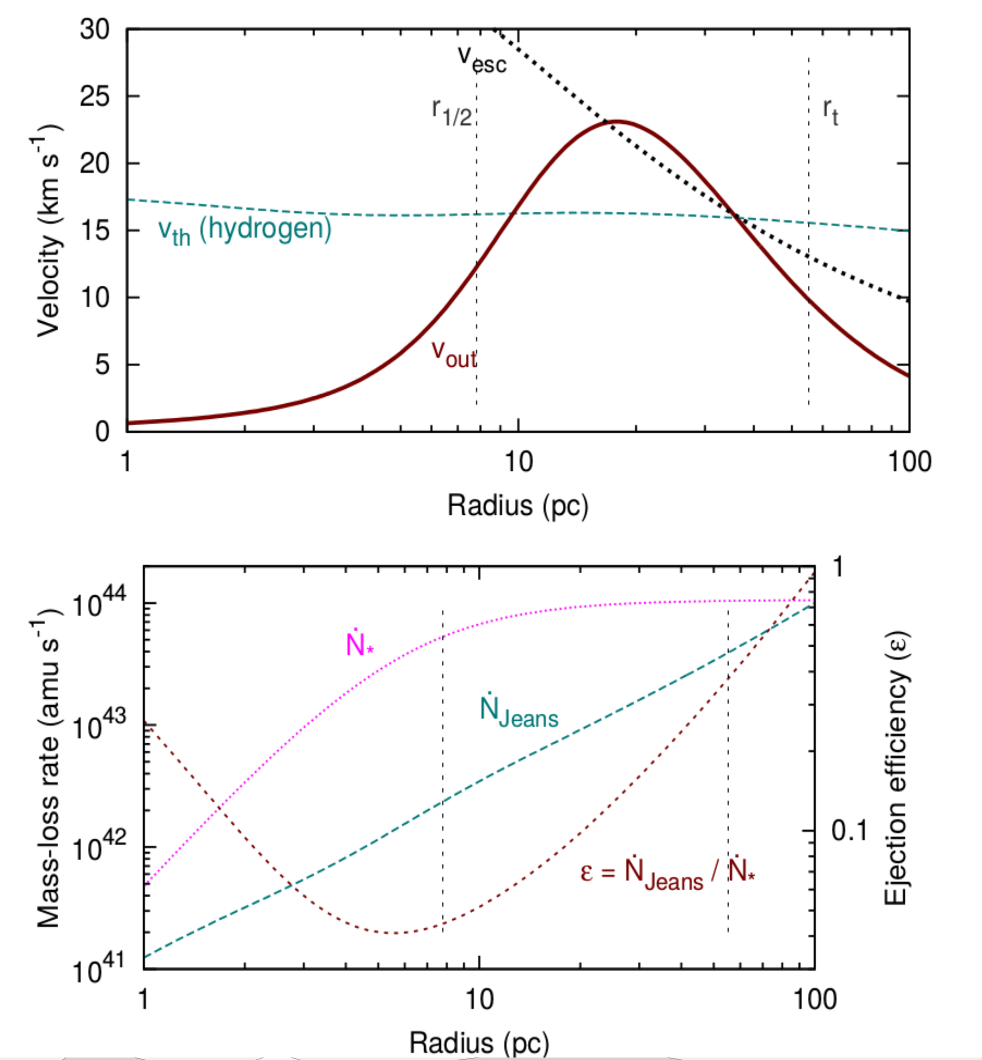
From Freire et al. 2001



- Blue: density
- Red: temperature

Cluster always fully ionized

Gas velocities



- Vesc: escape velocity

  Vth: thermal velocity

  Vout: flow velocity which balances mass loss

- Jeans escape clears the cluster

$$\dot{N}_{\mathrm{Jeans}} = 4\pi r^2 \frac{n_{\mathrm{e}} v_{\mathrm{th}}}{2\sqrt{\pi}} \left(1 + \lambda_{\mathrm{esc}}\right) e^{-\lambda_{\mathrm{esc}}}$$

where:

$$\lambda_{\mathrm{esc}} = \left(v_{\mathrm{esc}} / v_{\mathrm{th}}\right)^2$$

ISM escape fails for

1. Young clusters:

lower ionization rate allows recombination

ICM capture at t<0.25-1Gyr

- Explains multiple stellar generations

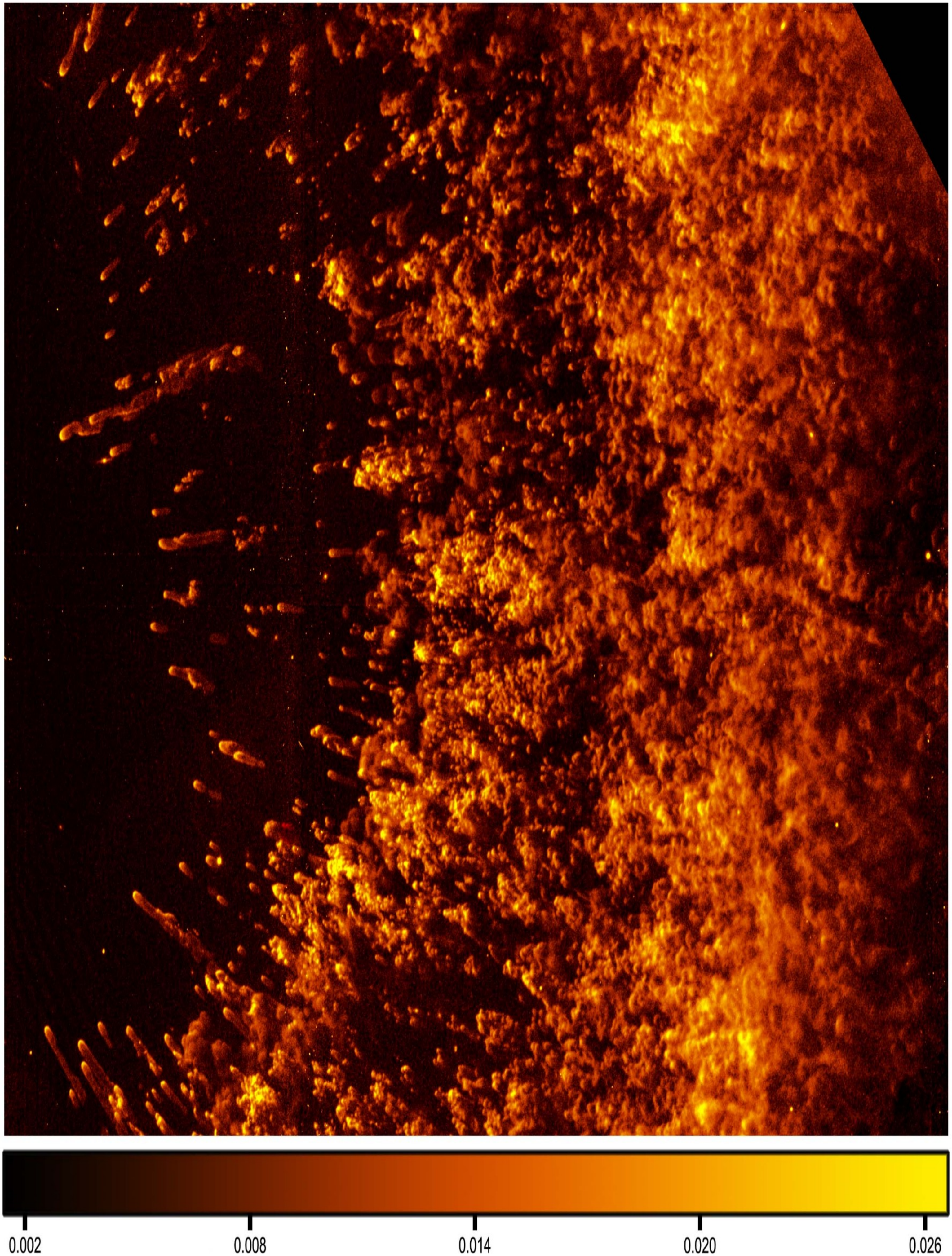
Most in high-mass clusters

2. Massive clusters

- ICM recombination due to higher escape velocity
- Occurs at 3 times the mass of 47Tuc:
  M(GC) < 3 10^6Msun
- Most massive: Omega Cen, 2.4 times 10^6

Summary

- Major uncertainties remain in mass loss and yields from AGB stars and PNe
- Superwind is related mainly to pulsation
- Dust and some PAHs survive the shocks into the ISM. Fullerenes are very short-lived.
- Binary evolution events can be significant contributors to some isotopes
- Globular clusters are cleaned of ISM by their post-AGB stars – old-age energy feedback


0.002
0.008
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