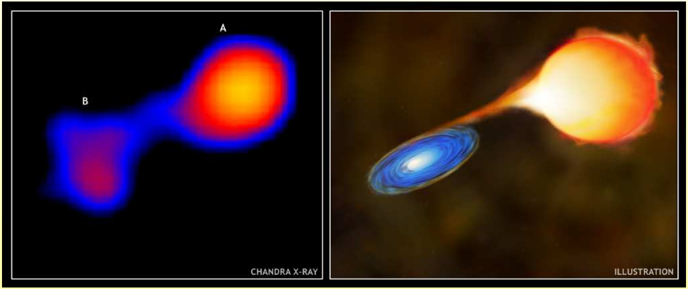
Chemically peculiar stars:
The Binary/CEMP Connection



Robert Izzard

Université Libre de Bruxelles

with Onno Pols, Evert Glebbeek and Richard Stancliffe

Today's excitement

1. Single vs Binary star evolution
2. Chemically Peculiar Stars –
   Carbon Enhanced Metal Poor = CEMP
3. Binary Population Modelling
4. Physics questions
5. Physics (partial) answers
6. The many problems remaining

Binary Stars

International Astronomical Union Symposium:
"Binary Stars as Critical Tools and Tests in Contemporary Astrophysics"

To understand galaxies we need to understand stars, but since most are members of binary and multiple star systems, we need to study and understand binary stars.

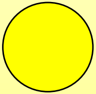
Why are binaries so different?

1. **Single** star evolution

2. **Binary** star evolution

A biased view of the evolution of low/intermediate mass stars

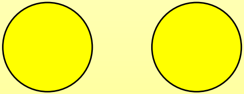
Single Star Evolution



0

Time/Gyr $\longrightarrow$

Single Star Evolution



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Time/Gyr →

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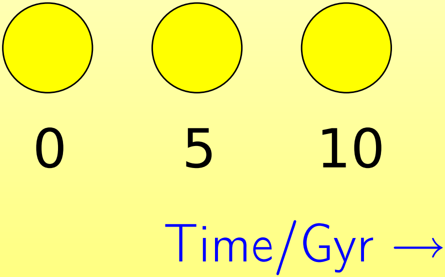
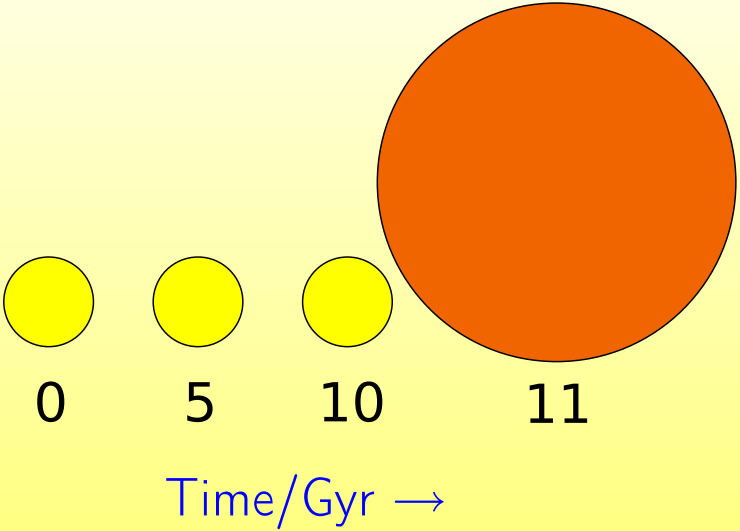


Single Star Evolution



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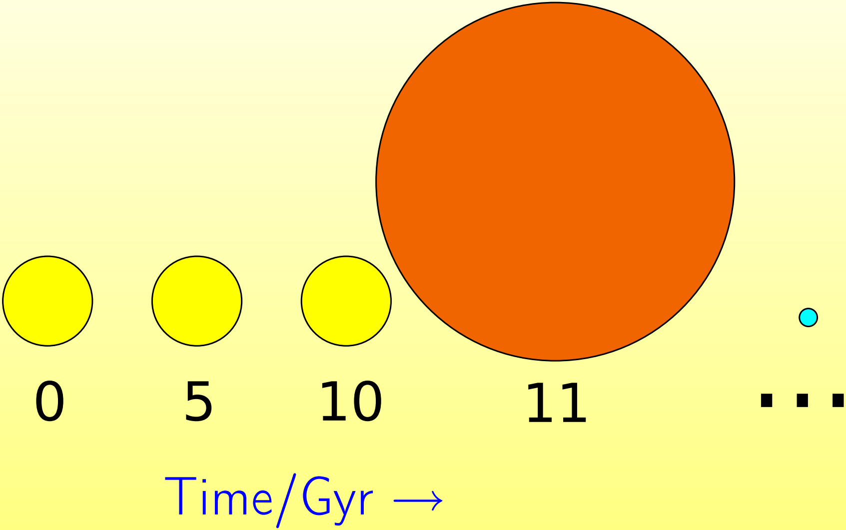
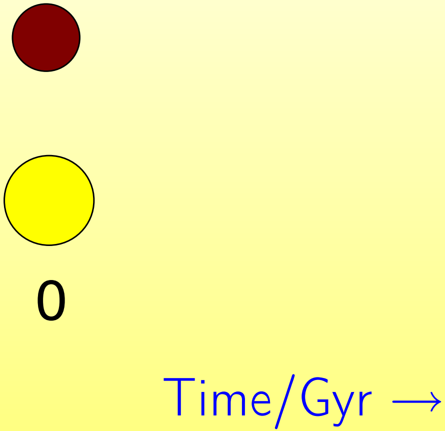


Binary Star Evolution



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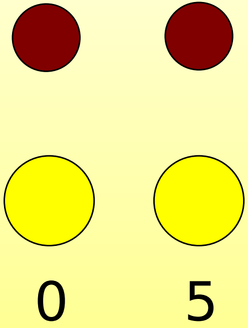

Time/Gyr →

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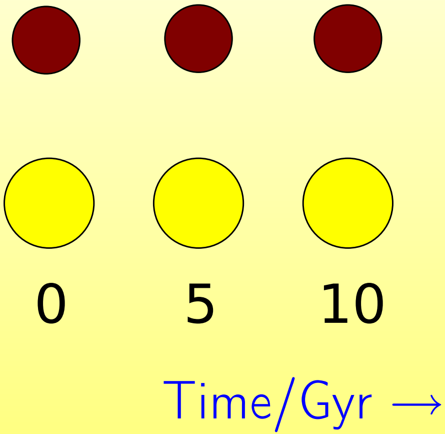

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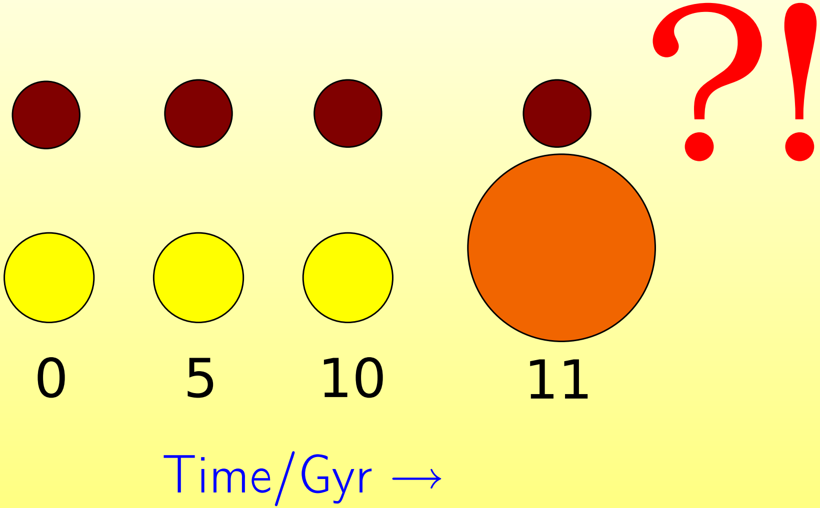


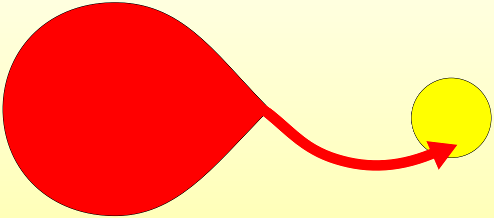
What happens next?

Two cases:

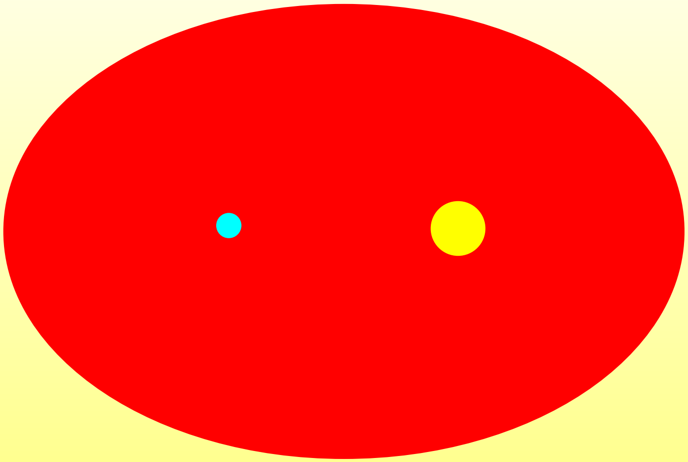
- **Close binary**: Roche-lobe overflow
- **Distant binary**: Wind accretion

Close binary: Roche-lobe Overflow

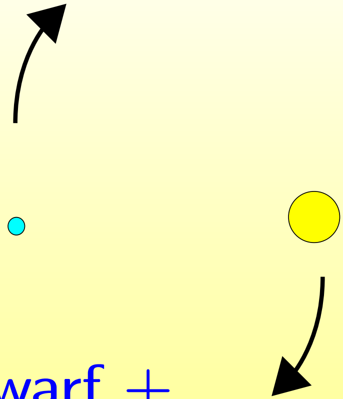
Roche Lobe overflow



Common Envelope (Fast)

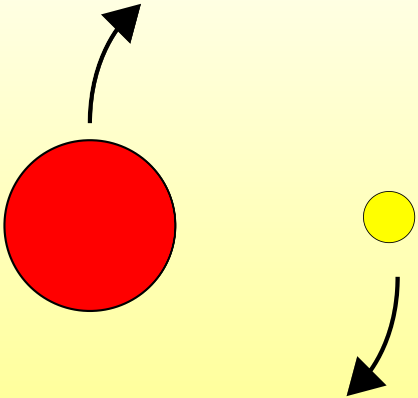


No chemical peculiarities

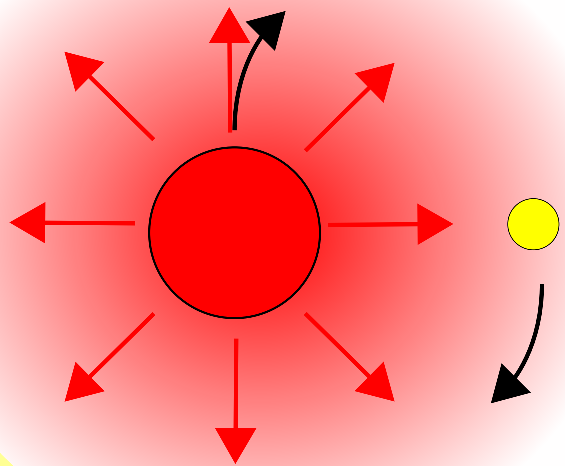


White Dwarf +
Chemically Normal Star

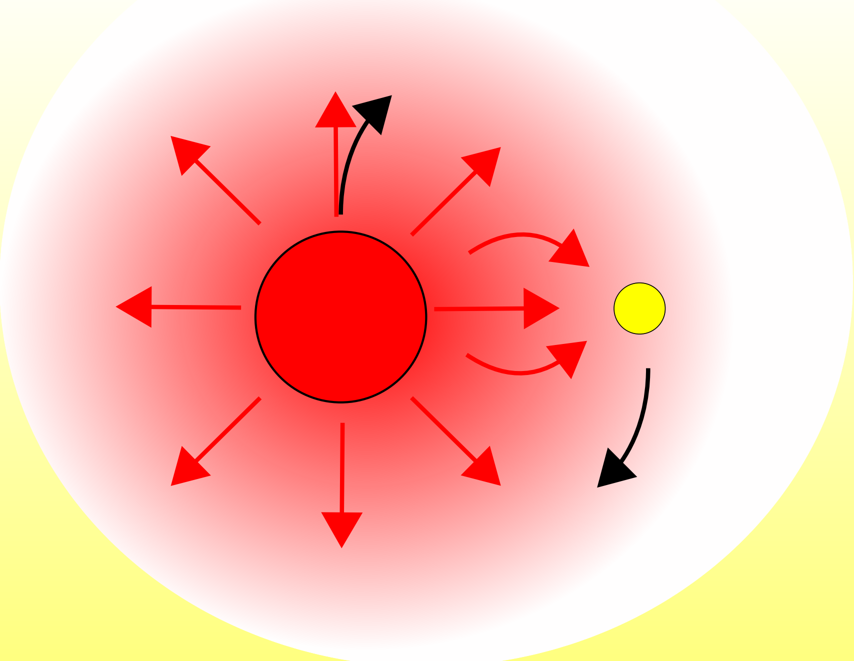
Distant Binary: Wind Accretion



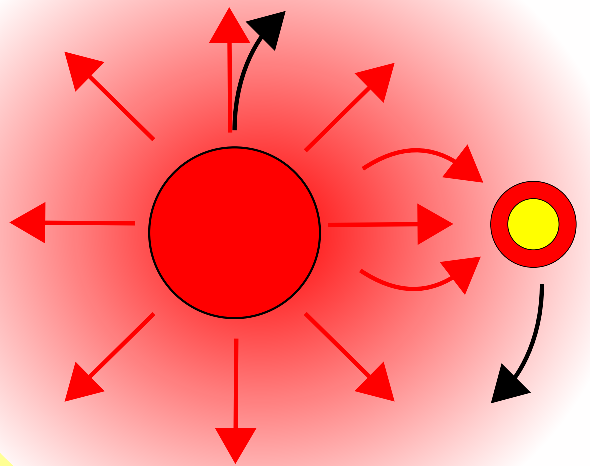
Wind Accretion: Giant Wind



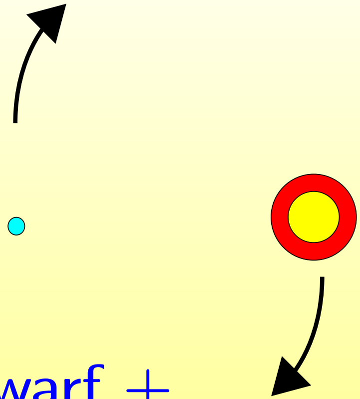
Wind Accretion: Gravitational Focusing



Wind Accretion: Accretion



Wind Accretion 6: Primary Death



White Dwarf +
Chemically Peculiar Star

Do we see chemically peculiar stars?

YES! A family of them:

- Ba stars
- CH stars
- **Carbon enhanced metal-poor stars**

CEMPs

- Metal-poor Galactic halo: **oldest stars**
  $[\mathbf{Fe}/\mathbf{H}] \lesssim -2$
- Binary fraction consistent with **all binaries**
- About 1000 CEMPs known
- Statistically significant number!
- about 20% of all metal-poor stars!
- *Not evolved enough to make their own carbon*
- Must come from a companion star!
- Fashionable… but well-observed because of this

$$[A/B] = \log(A/A_{\odot}) - \log(B/B_{\odot})$$

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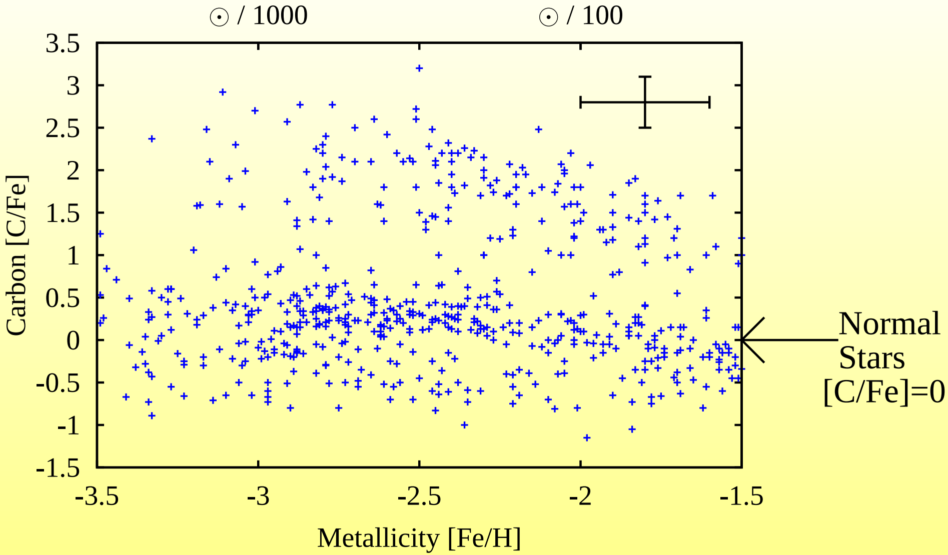
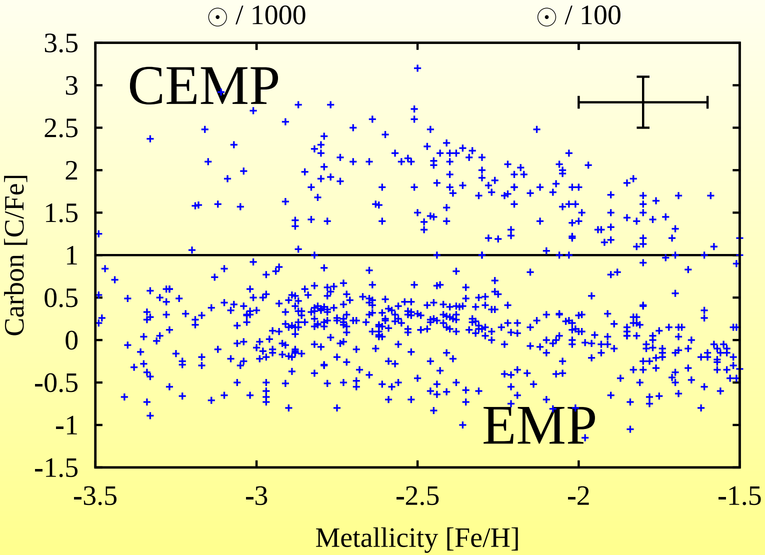
CEMP: Carbon-Enhanced Metal Poor



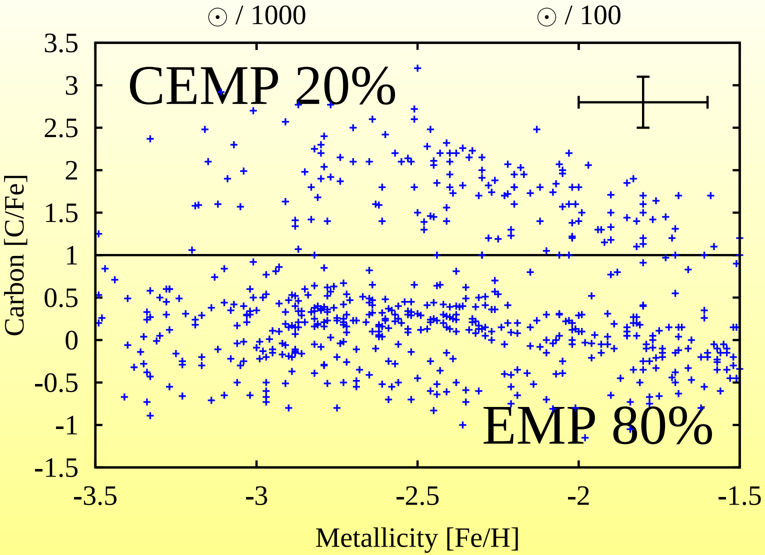
1000 stars from the SAGA database (Suda 2008)

CEMP: Carbon-Enhanced Metal Poor



EMP=Extremely Metal Poor

CEMP: Carbon-Enhanced Metal Poor



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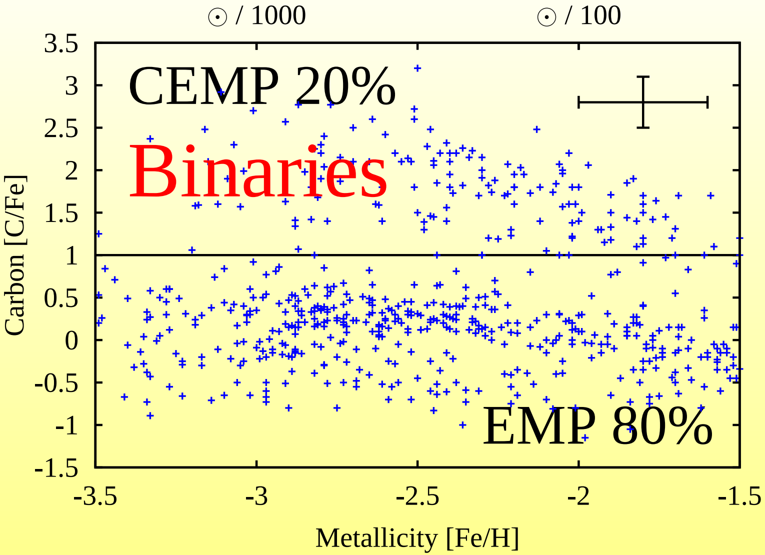


EMP=Extremely Metal Poor

CEMP: Carbon-Enhanced Metal Poor

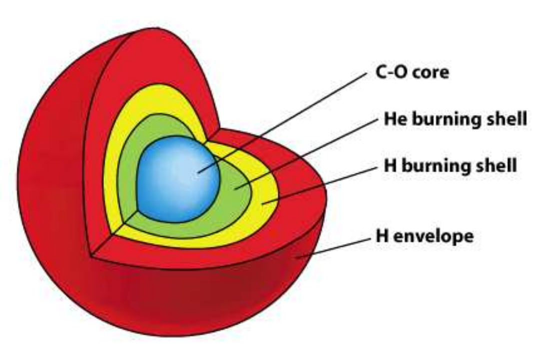
- About 1000 CEMPs known
- Binary fraction consistent with **all binaries**
- Metal-poor Galactic halo: **oldest stars**
- 20% of all metal-poor stars but...

- **Where did the carbon come from?**

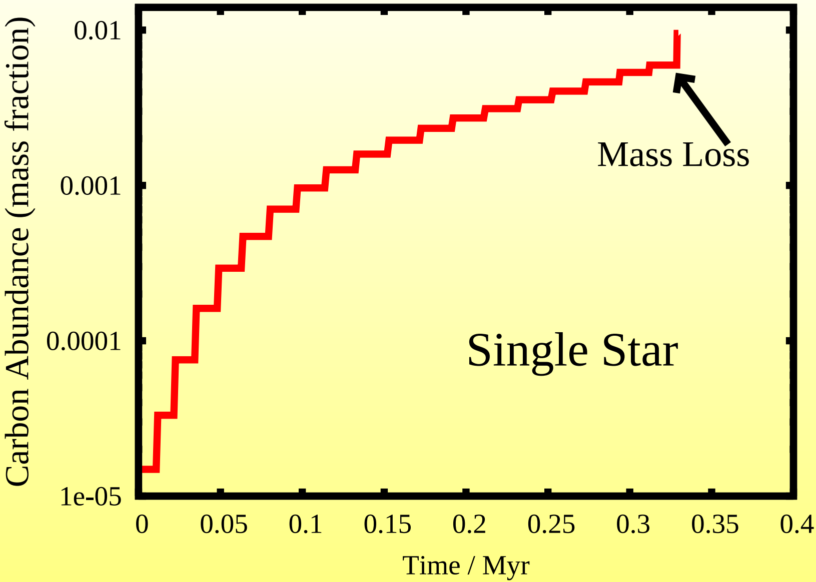
Candidate Primary Star

Primary is *Asymptotic Red Giant* star?

- Make carbon
- and other elements in
  - Ba
  - CH
  - CEMPs
- IDEAL!



Primary Evolution *were it a single star*



Hypothesis

CEMPs are made by Accretion of
Carbon-rich Material
from
Wind of Asymptotic Giant stars

?

How to test the idea?

Binary Star Model

$\downarrow$

Population Synthesis

$\downarrow$

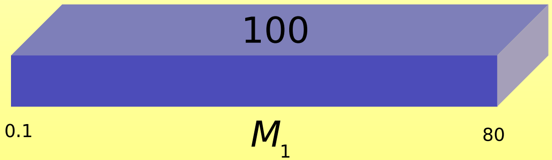
Compare to Observations:

Quantitative Statistical Analysis

Can the model explain 20% CEMP/EMP or other observed properties of CEMPs?

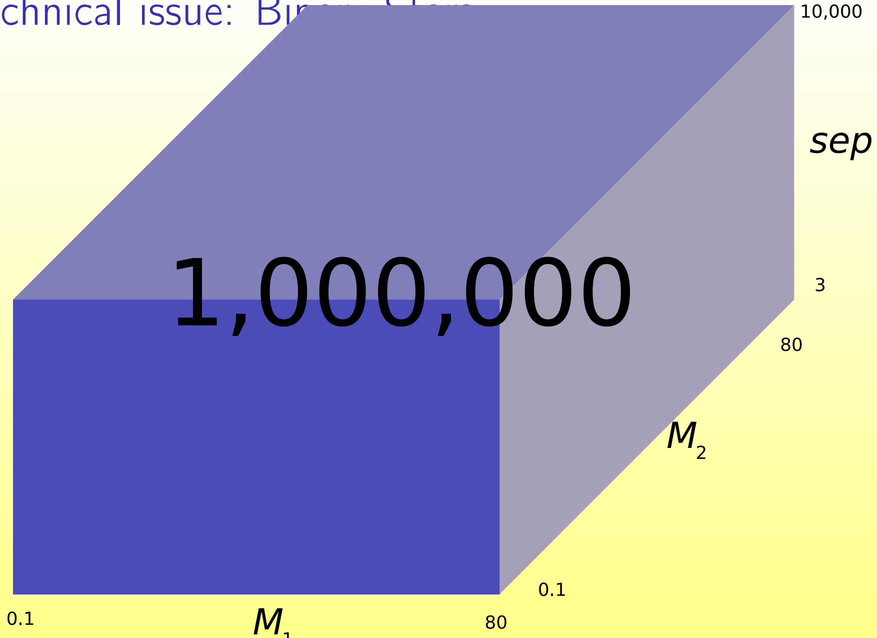
There are technical and physics issues...

Technical issue: Single Stars



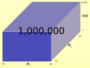
- $10\,\text{h} \times 100 = 1,000\,\text{h} \sim 6\,\text{weeks}$

Technical issue: Binary Stars



$$10\,\mathrm{h} \times 100 \times 100 \times 100 = 10,000,000\,\mathrm{h} \sim 1,000\ \mathit{YEARS}$$

Use a Rapid Code



$$0.1\,\mathrm{s} \times 100 \times 100 \times 100 = 28\,\mathrm{h}$$

Rapid Stellar Evolution Code

Replace many coupled differential equations with

1. fitting formulae
2. tabulated data

based on detailed (single-star) models: R, L, M_{core} etc.

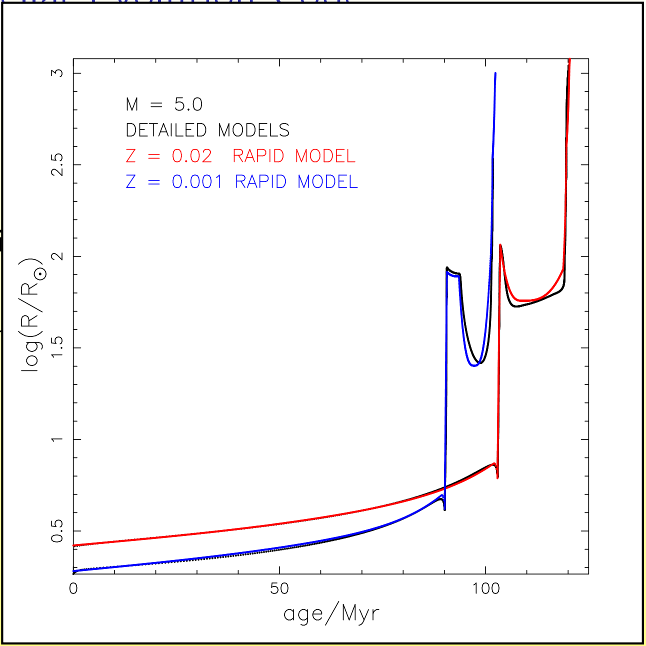
Rapid Stellar Evolution Code

Replace

1. fitti

2. tab

based or

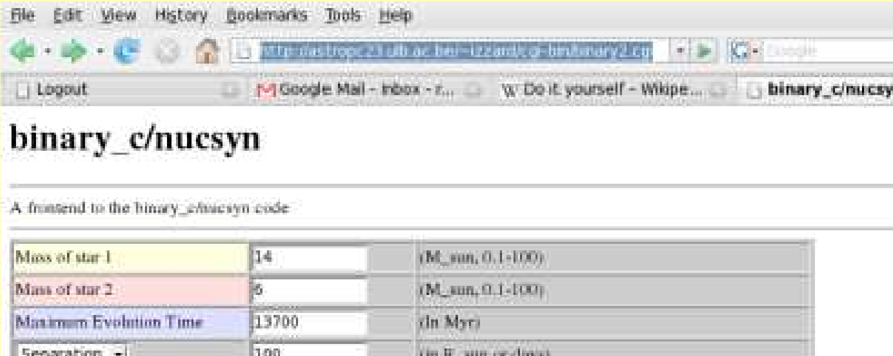


My Code: binary_c/nucsyn

- Rapid single-star model
- Binary-star evolution algorithm
- Coupled nucleosynthesis
- Accurate but $10,000,000\times$ faster

http://www.astro.ulb.ac.be/~izzard/binary_c/

- Try it yourself: Google for ***binary_c frontend***



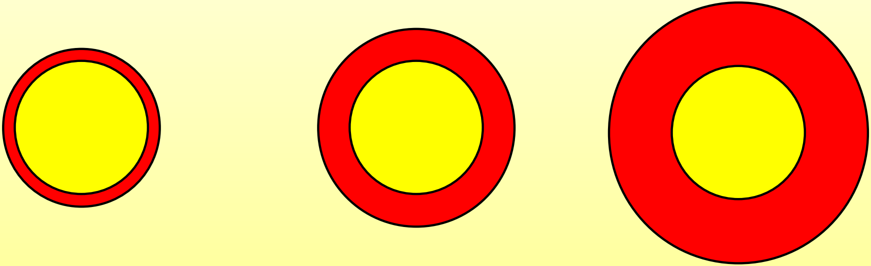
What I do with my code

- Make many populations, each 10^6 stars
- Vary uncertain physics parameters
- Default physics:
  - $[Fe/H] = -2.3$ (solar scaled)
  - Accretion efficiency $= 1$
  - Efficient thermohaline mixing
  - Primary carbon as detailed models (Karakas 2007)
- Tag CEMP, EMP stars, count them
- Compare to observations to find true physics

My Main Physics Knobs

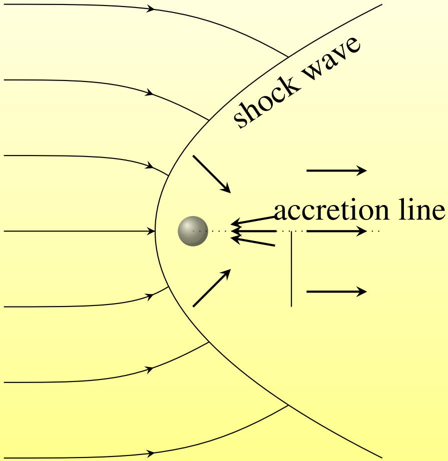
1. Accretion efficiency (onto secondary)
2. Mixing efficiency (in secondary)
3. Composition of accreted material (in primary)

Physics 1: Accretion onto secondary



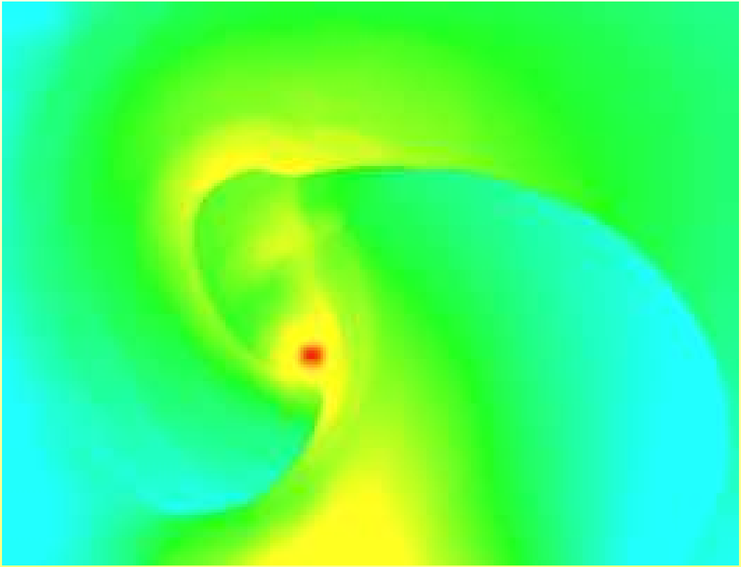
Physics 1: How much Accretion? (onto secondary)

idealised Bondi-Hoyle accretion: Default efficiency 1

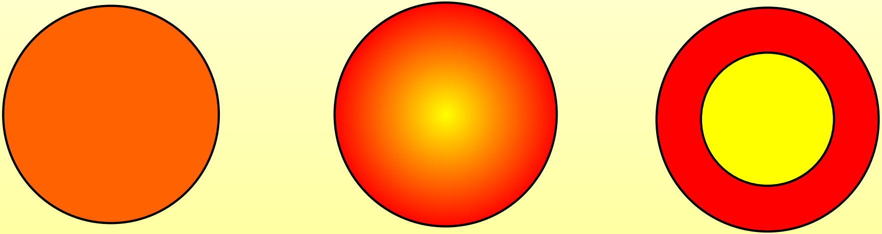


Physics 1: How much Accretion? (onto secondary)

Simulated accretion (val del Borro 2009)



Physics 2: How much Mixing? (In secondary)

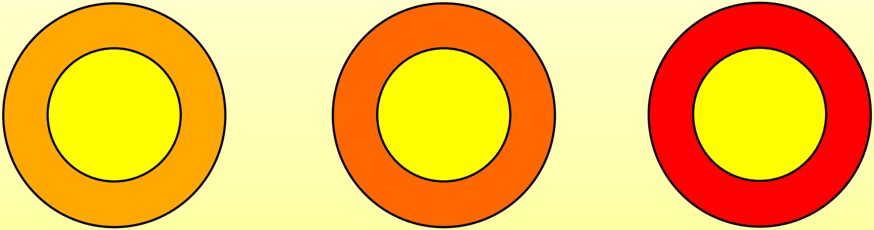


Physics 2: How much Mixing? (In secondary)

Thermohaline mixing: Default model *with* mixing

Courtesy of Matteo Cantiello and Evert Glebbeek

Physics 3: What Composition is Accreted?



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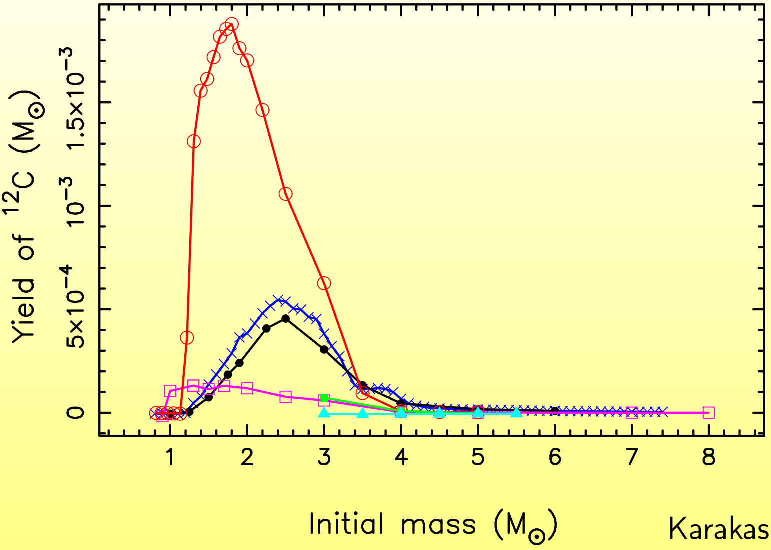


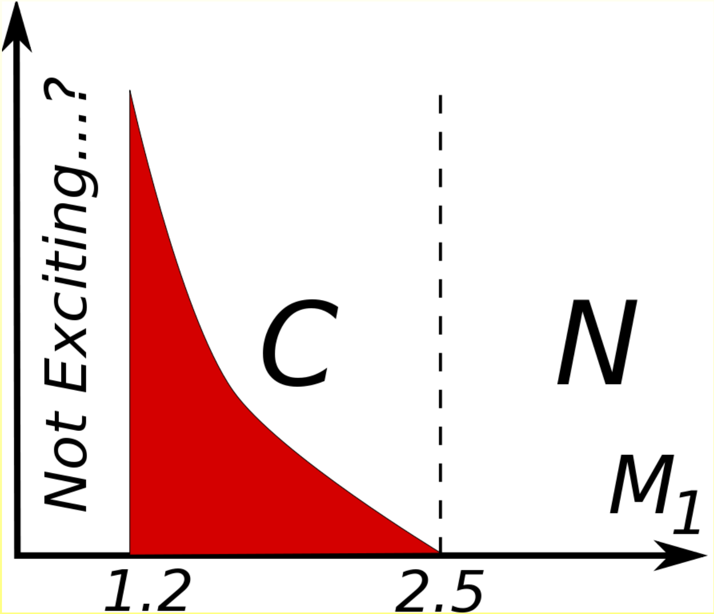
Karakas (2007)

Run the simulations . . .

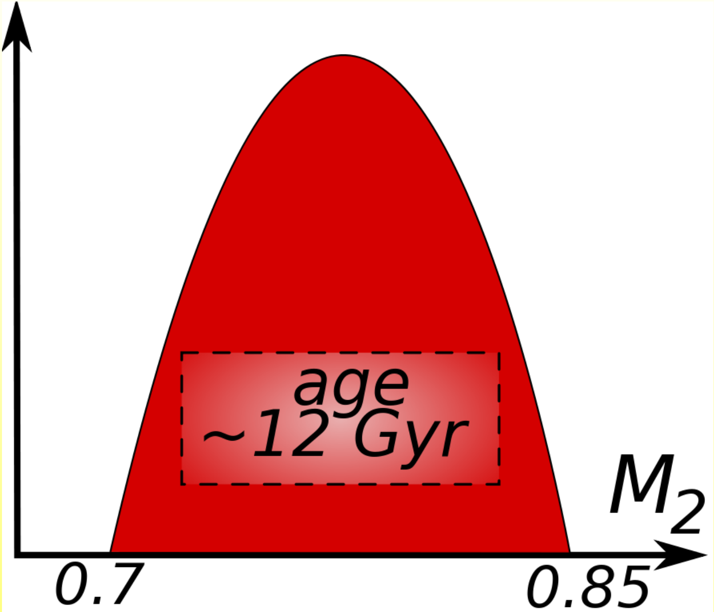
Results

1. Which stars make the CEMPs?
2. What choice of physics knobs gives us 20% CEMPs?
3. What does this tell us about
    3.1 Stellar physics
    3.2 Binary physics
4. What is still broken?

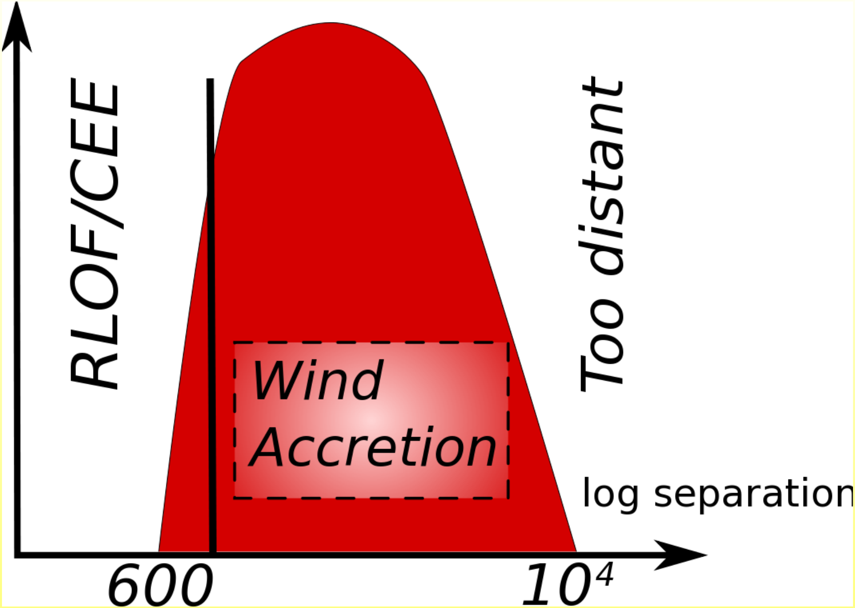
Which stars make CEMPs? M_1



Which stars make CEMPs? M_2



Which stars make CEMPs? *separation*



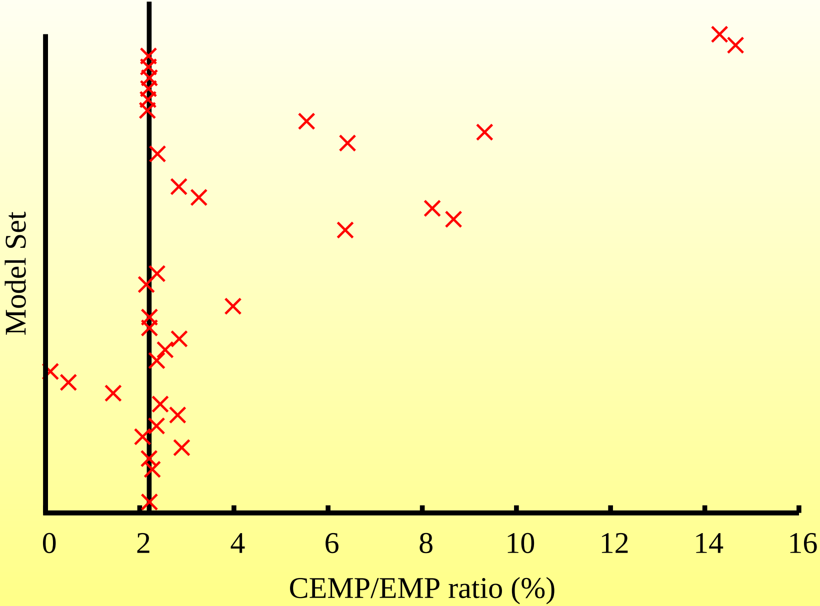
Results

What choice of physics gets us

20% CEMPs?

Izzard, Glebbeek, Stancliffe and Pols
(2009 A&A 508, 1359)

CEMP/EMP ratio (observed $20 \pm 10\%$)



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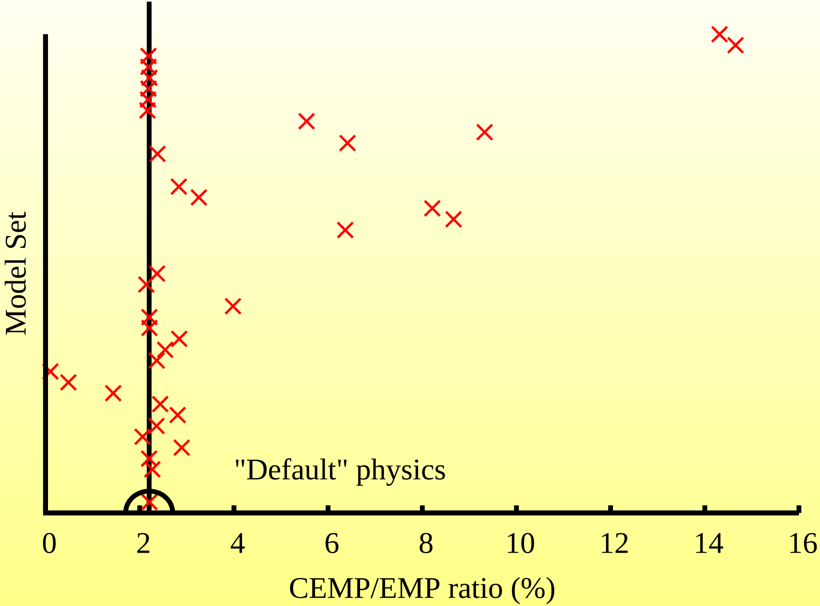
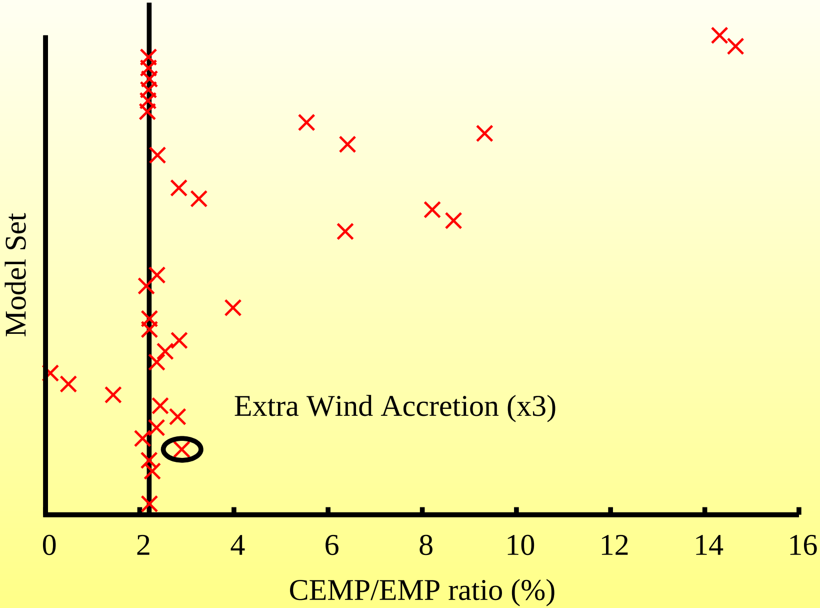


CEMP/EMP ratio (observed 20 ± 10%)



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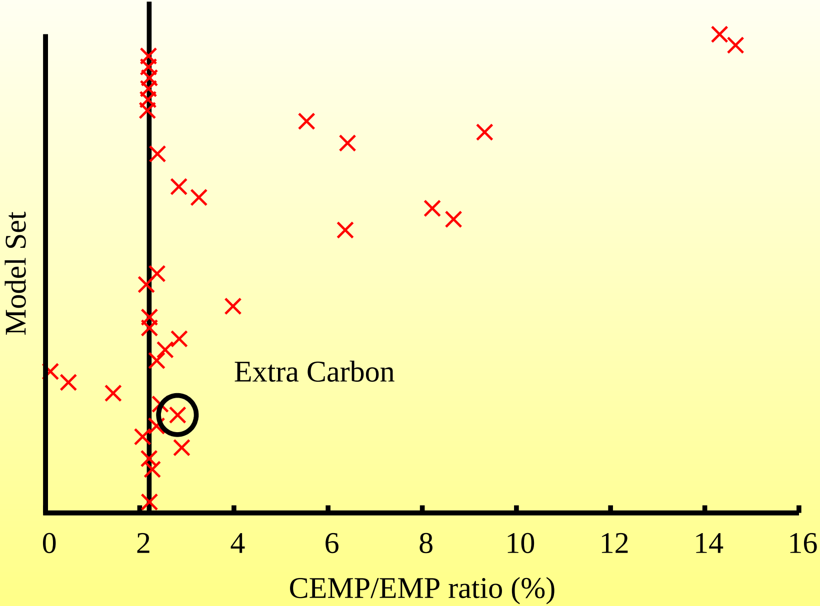

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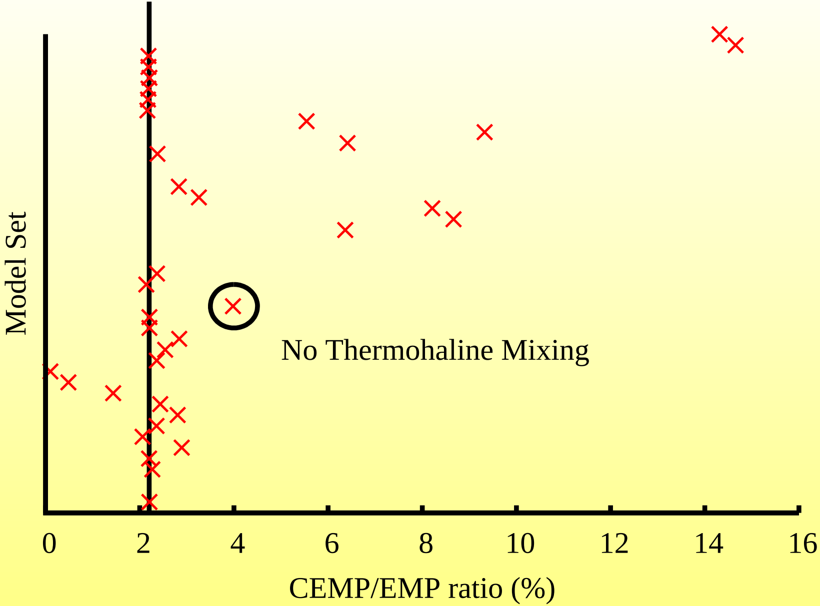

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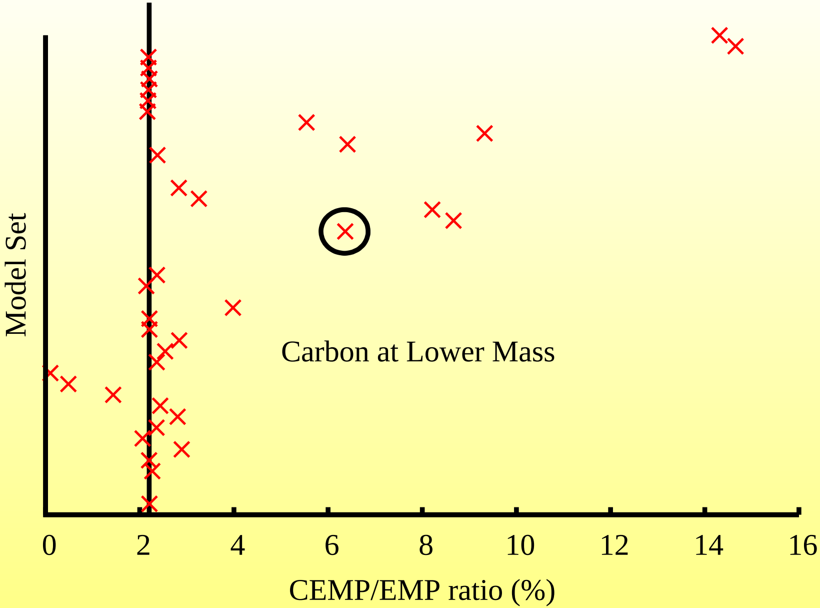

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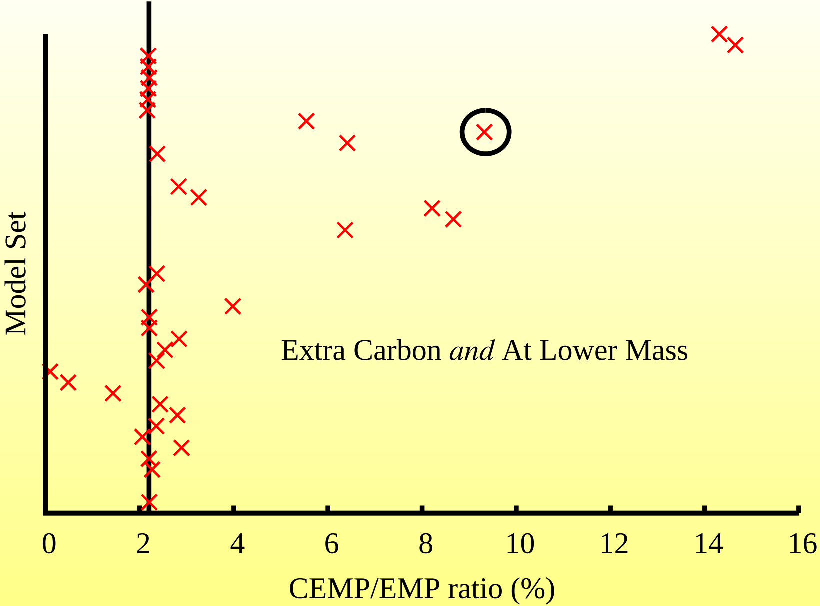

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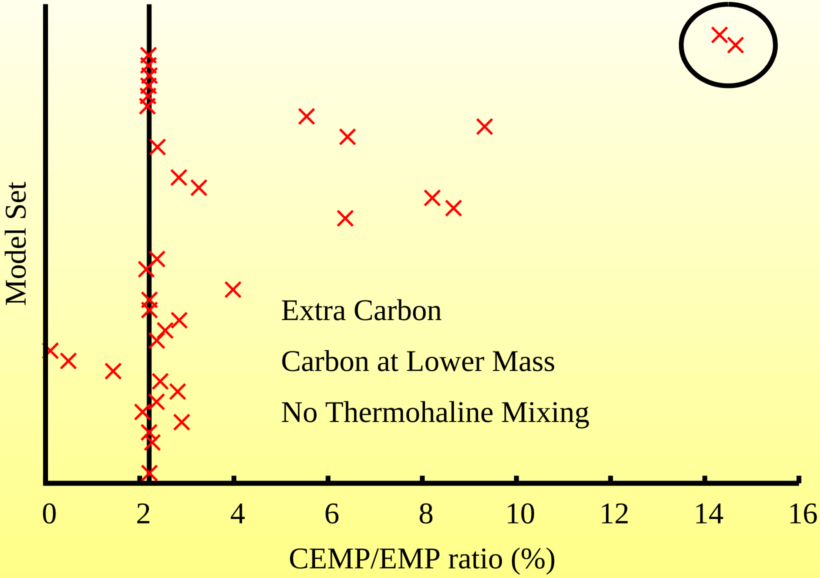

Key Results

1. Need **MORE CARBON** from primary star
   - Found in very low metallicity stellar models [Fe/H] ~ -3
   - My results suggest source still active at [Fe/H] ~ -2
2. Need carbon in **LOW MASS** primary stars
   - *Canonical* Models $M \gtrsim 1.2\,M_\odot$ have carbon
   - My results suggest carbon in $M \gtrsim 0.8\,M_\odot$
   - IMPORTANT because as many stars in 0.8-1.2 $M_\odot$ as 1.2-8 $M_\odot$!
   - *NEW models agree!* (Cristallo-Campbell, Stancliffe-Karakas)
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   - Thermohaline mechanism inefficient?
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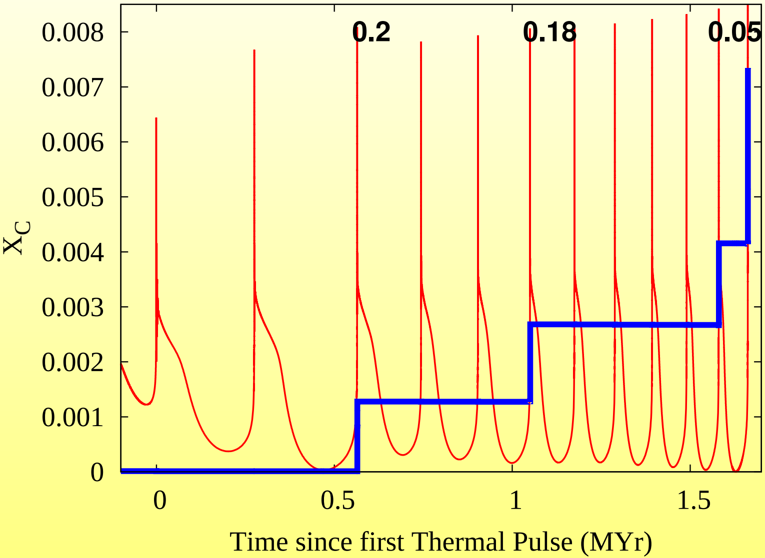
Key Results

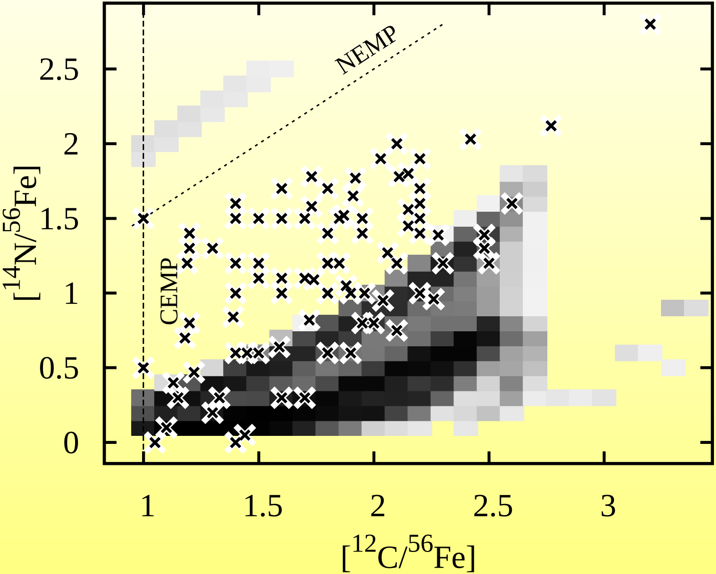
- Asymptotic Giant-accretion scenario works ...
  just about!
- Need some knobs at full for CEMP/EMP$\sim$*15%*
- Other uncertain physics (wind accretion, common envelope efficiency etc) has little effect
- Compatible with lowest observed CEMP/EMP ratio (10%) and high binary fraction
- *Initial mass function* different at low metallicity?
  But then we have a NEMP issue...
- Many other CEMP characteristics to explore

Extra Dredge up – found? $M_{\text{AGB}} = 0.77\,M_\odot$

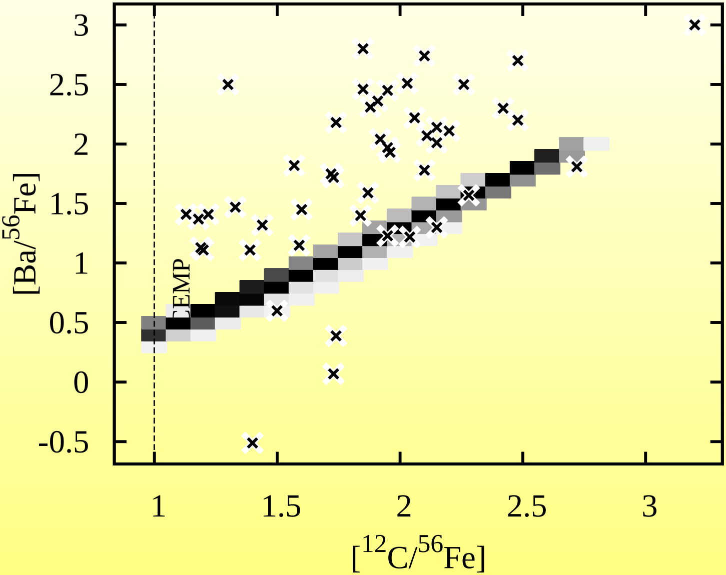
Richard Stancliffe's AGB model



Nitrogen

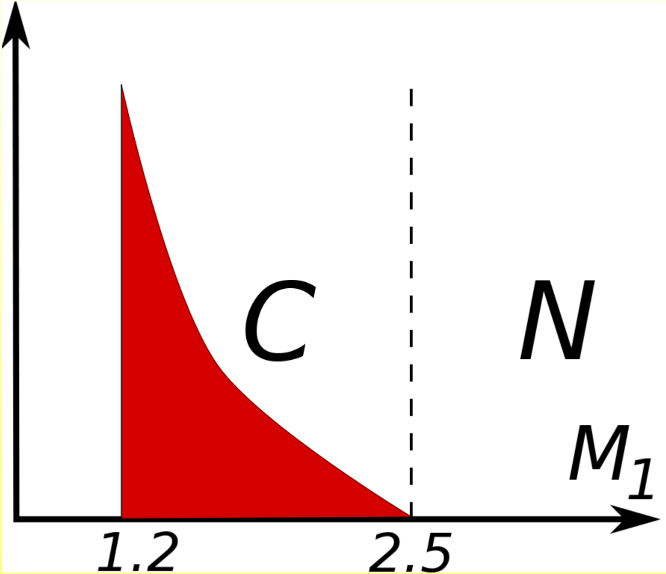


s-process elements



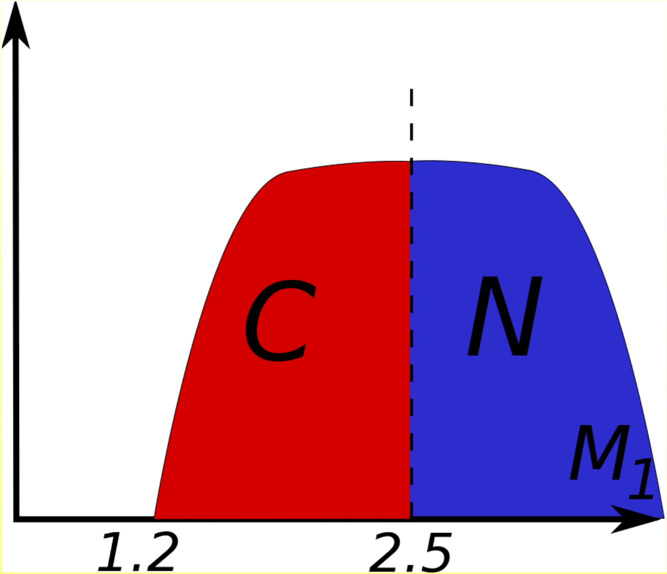
If the IMF were shifted...

Standard IMF



If the IMF were shifted...

Fudged IMF $N_{CEMP} \sim N_{NEMP}$!!!



Conclusions

- By looking at binary CEMPs, we can learn about the evolution of stars:
  - when the Galaxy had just formed
  - at low metallicity
  - in binaries
- In these stars:
  - Donor makes carbon down to low mass: $0.8\,M_\odot$
  - Gainer does not mix much
  - **Challenges for stellar astrophysics!**
  - Challenges for **you**! :)