Thermohaline mixing in metal-poor stars

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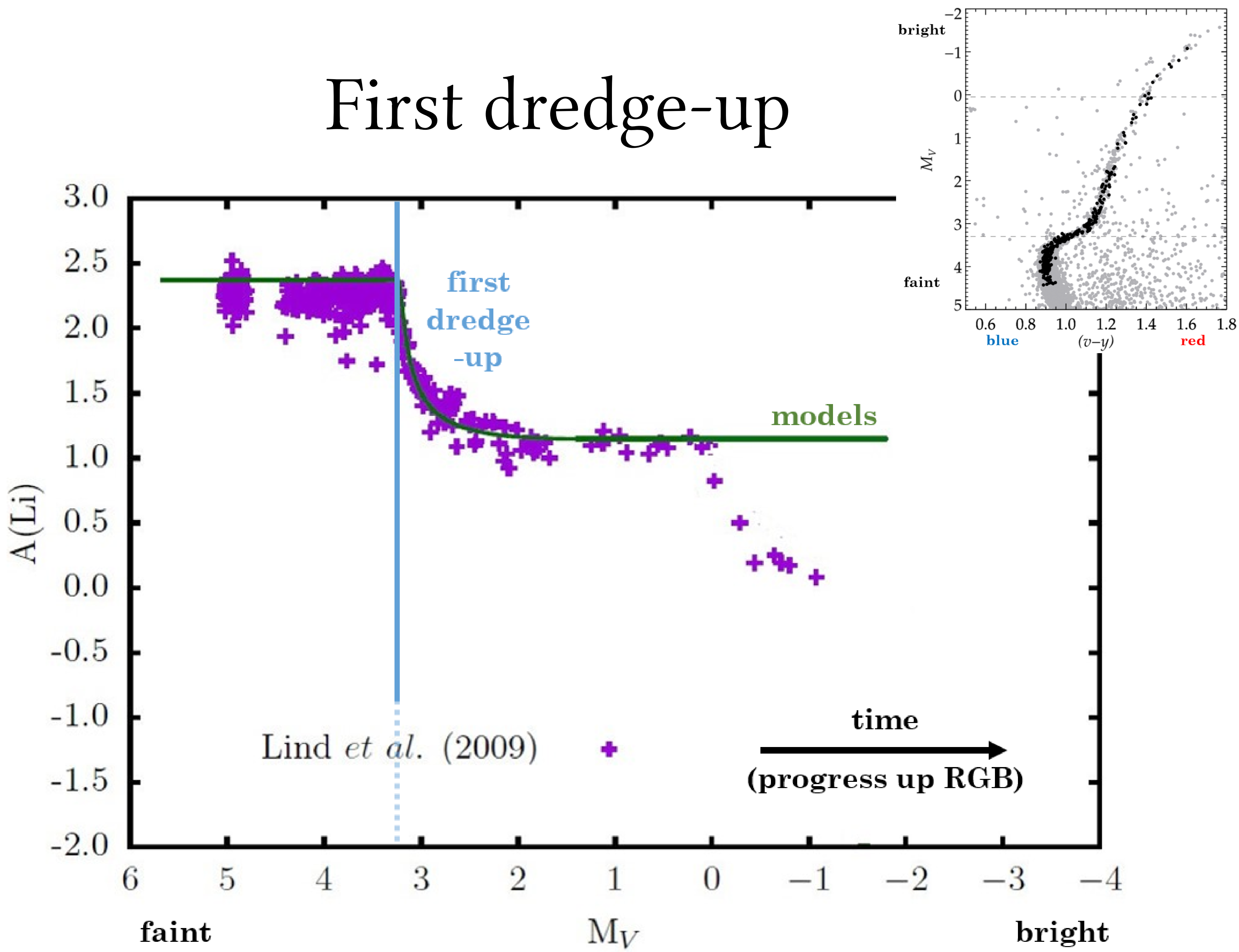
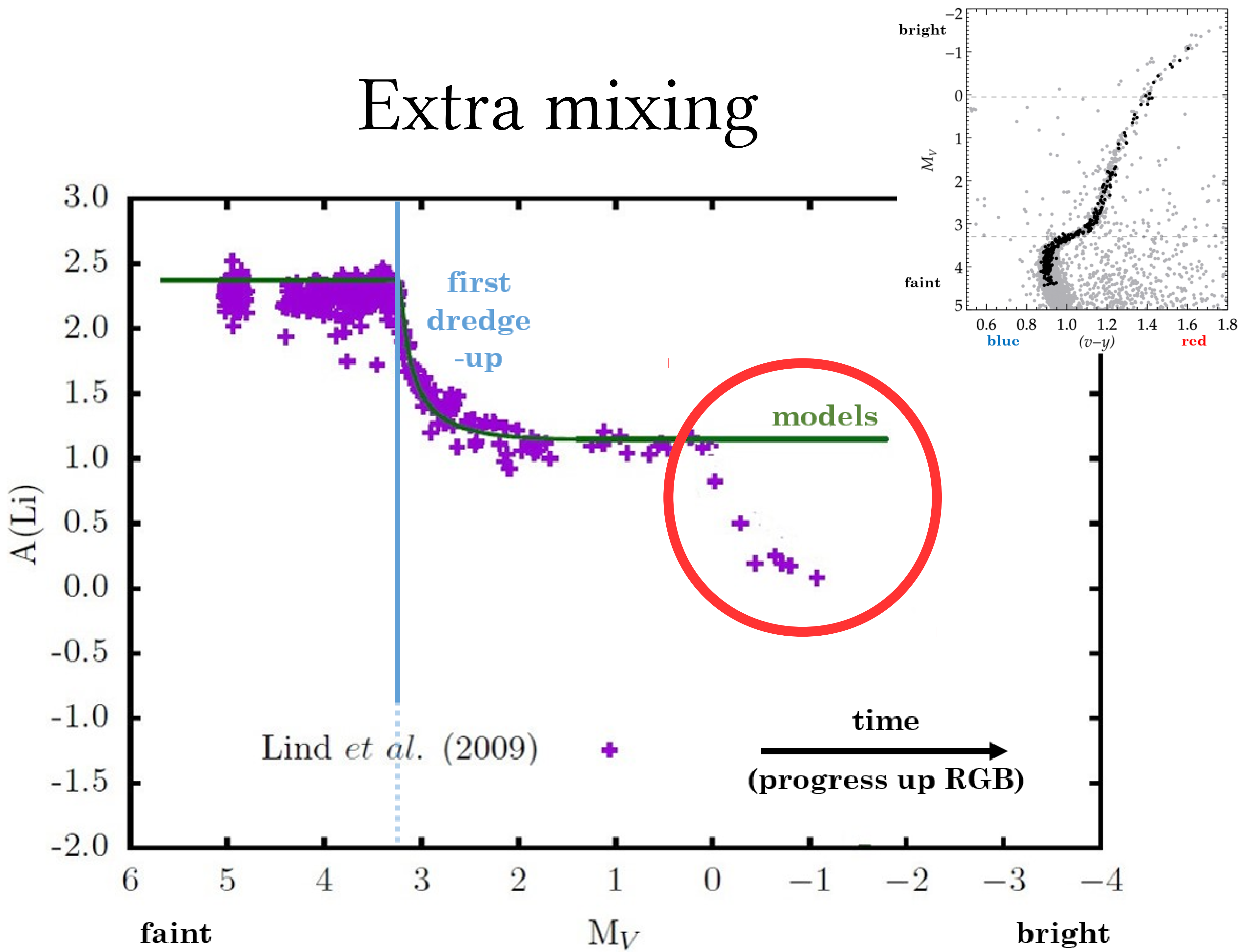
Thermohaline mixing in extremely metal-poor stars

- What is thermohaline mixing?
- Our modification to the standard theory
- Motivation of our implementation to EMP stars
- Results: the carbon offset, CEMP star frequencies

First dredge-up



Extra mixing



Extra mixing

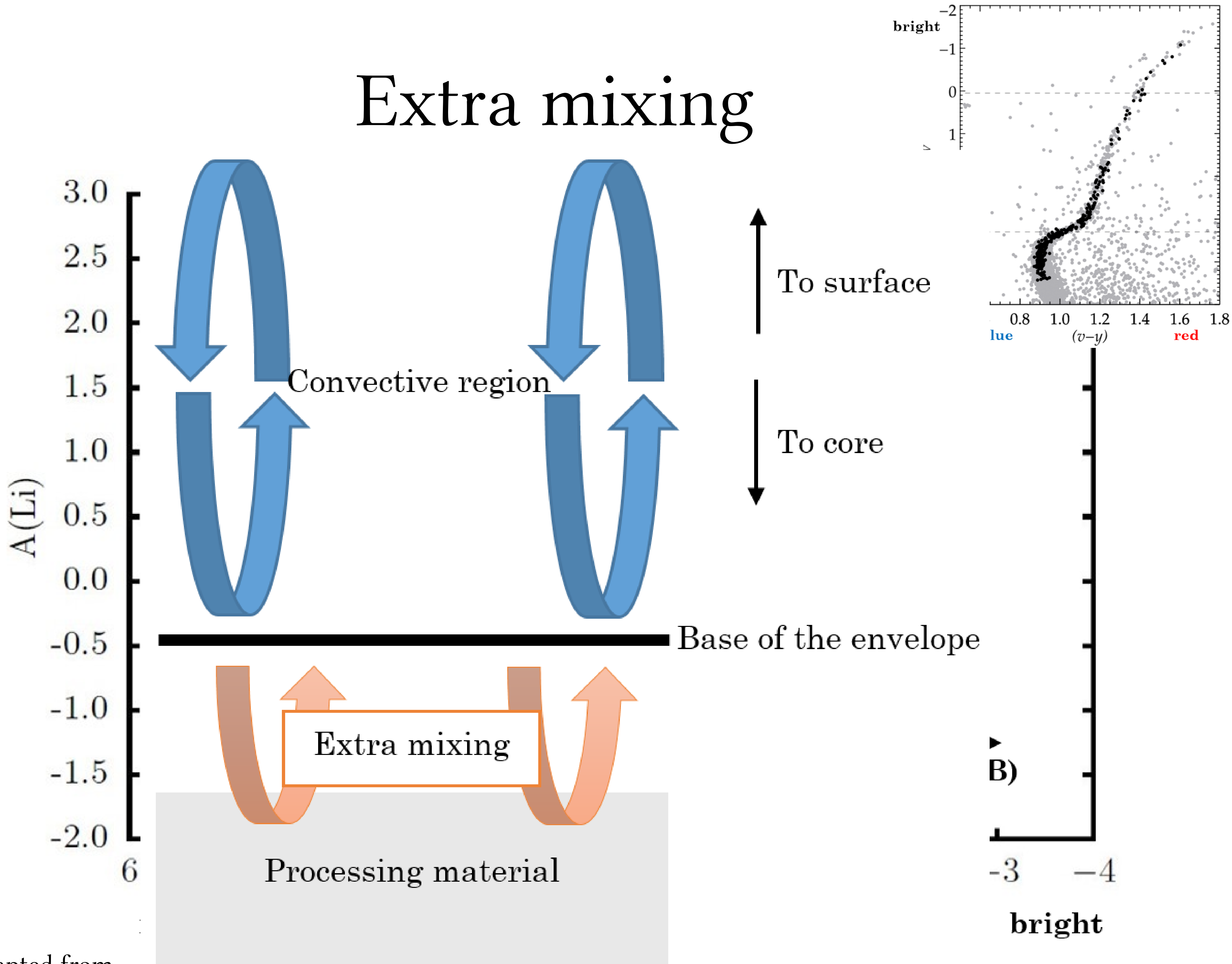
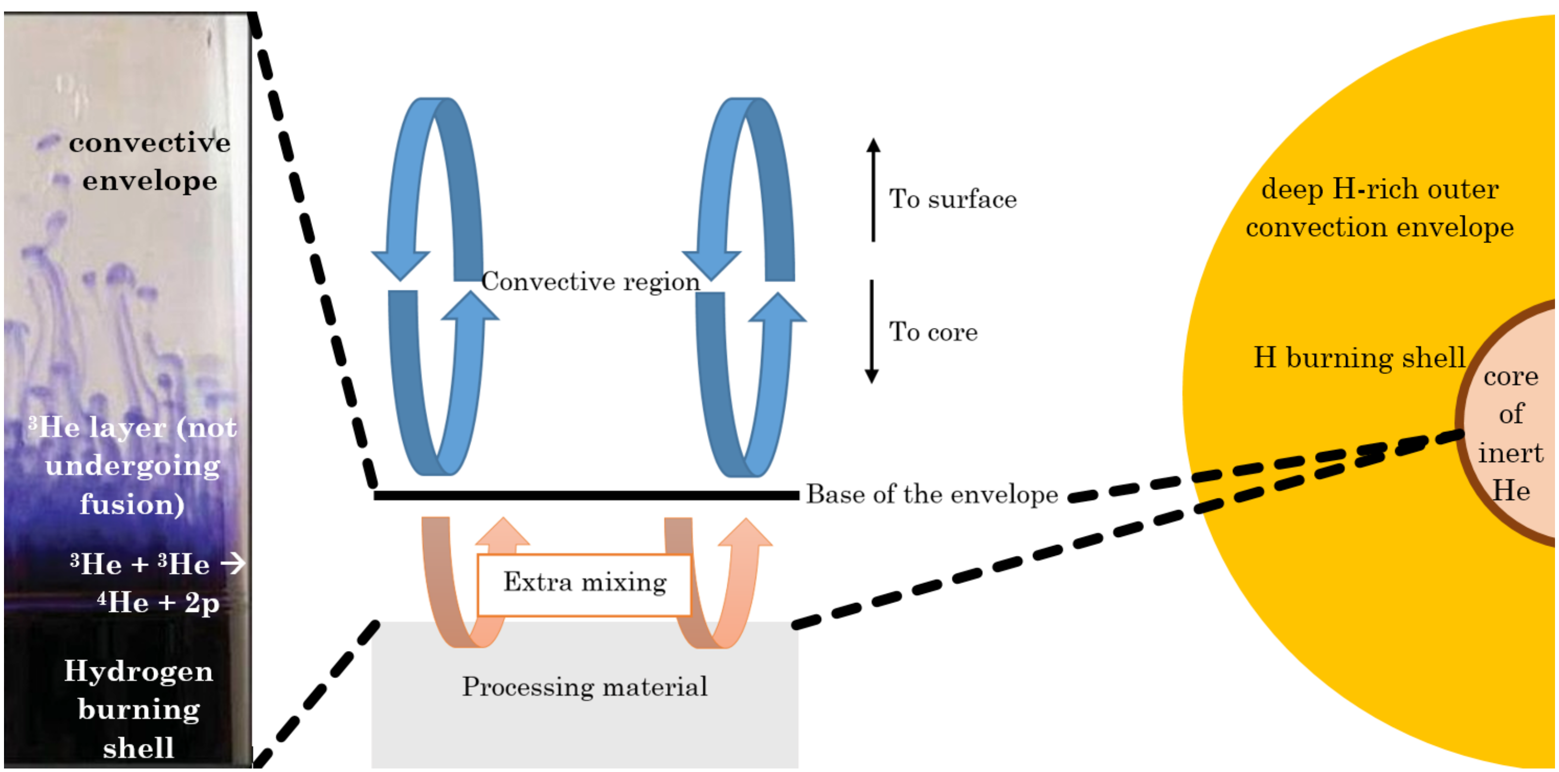


Image adapted from
Lugaro *et al.* (2017)

Thermohaline mixing

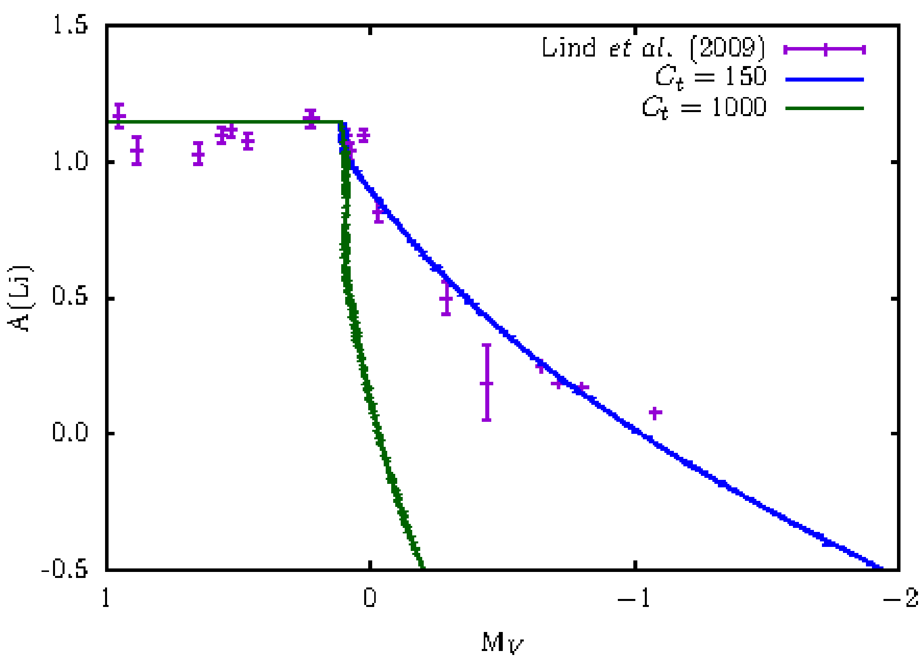
- Occurs in the interiors of low-mass stars (< 2.5 M_{Sun})
- A hydrogen discontinuity is left behind by first dredge-up – it is thought that this creates a barrier to any mixing (Mestel 1953; Kippenhahn & Weigert 1990; Chanamé *et al.* 2005)
- The hydrogen shell advances in mass towards the discontinuity during normal RGB evolution
- Above the hydrogen shell, 3He fusion is occuring via 3He(3He,2p)4He (Denissenkov & Herwig 2004; Eggleton *et al.* 2006)
- This reaction creates a molecular weight inversion, which sets up an environment suitable for thermohaline mixing

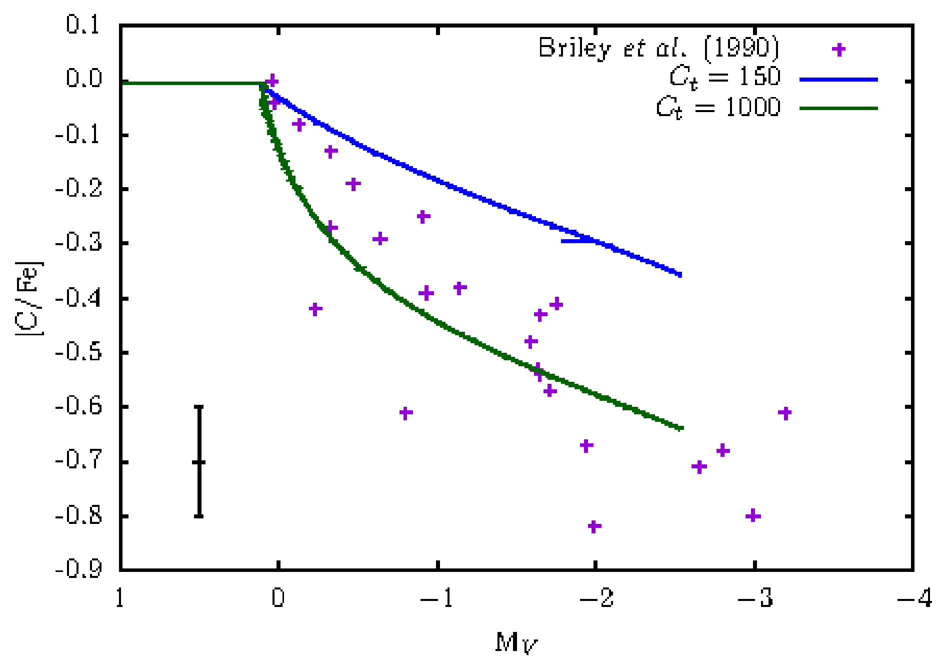
Thermohaline image from Karakas & Lattanzio (2014)



Motivation

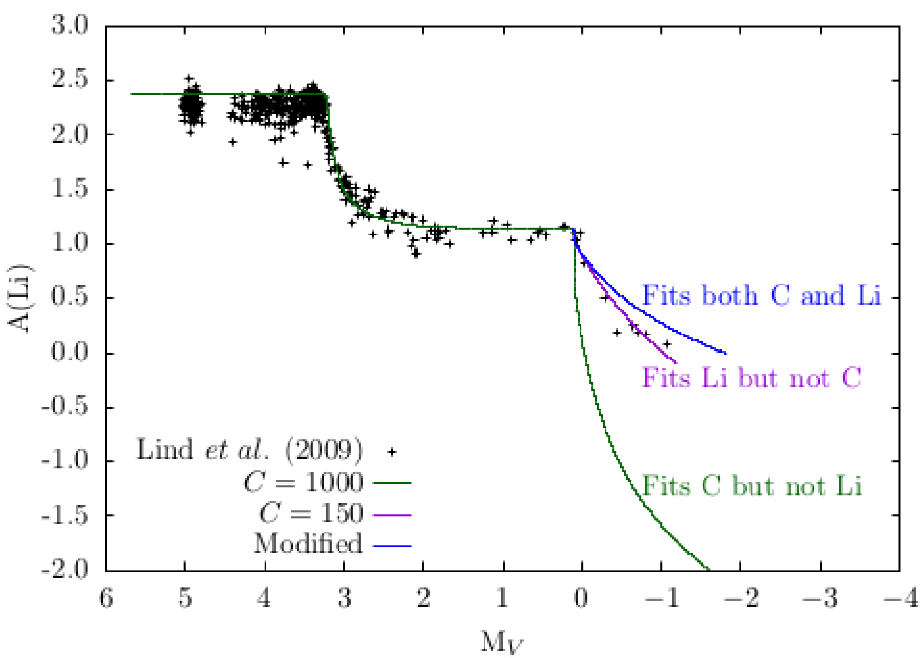
- Ulrich (1972) and Kippenhahn *et al.* (1980) developed a 1D theory for thermohaline mixing that includes a **free parameter Ct**, which is related to the mixing length
- We treat Ct as a free parameter because we do not know the mixing length a priori
- For any value of Ct, we cannot simultaneously match carbon and lithium abundances

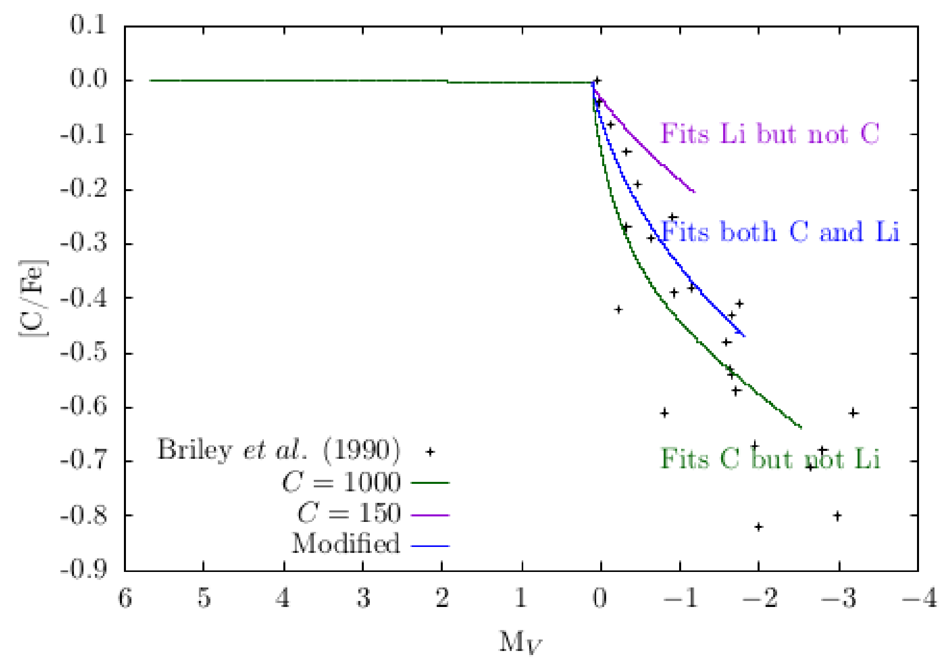




Modification to the standard thermohaline formalism + results

- In Henkel *et al.* (2017), we invoke a temperature dependence that mixes *faster* in hotter regions and *slower* in cooler regions.
- We find we can match carbon and lithium to observations of the metal-poor globular cluster NGC 6397 for the same value of Ct
- This is the first time that carbon and lithium abundances have been simultaneously matched for any set of stars





Application to extremely metal-poor stars

- However, the methodology in Henkel *et al.* (2017) is purely phenomenological; we do not know the physics driving the mechanism and 3D simulations are yet to provide insights.
- We apply this methodology to extremely metal-poor stars.

Why?

- Few metal-poor stellar models exist
- Metal-poor models struggle to match observations
- Determine if our phenomenological model breaks down at low metallicities

Extremely metal-poor stars

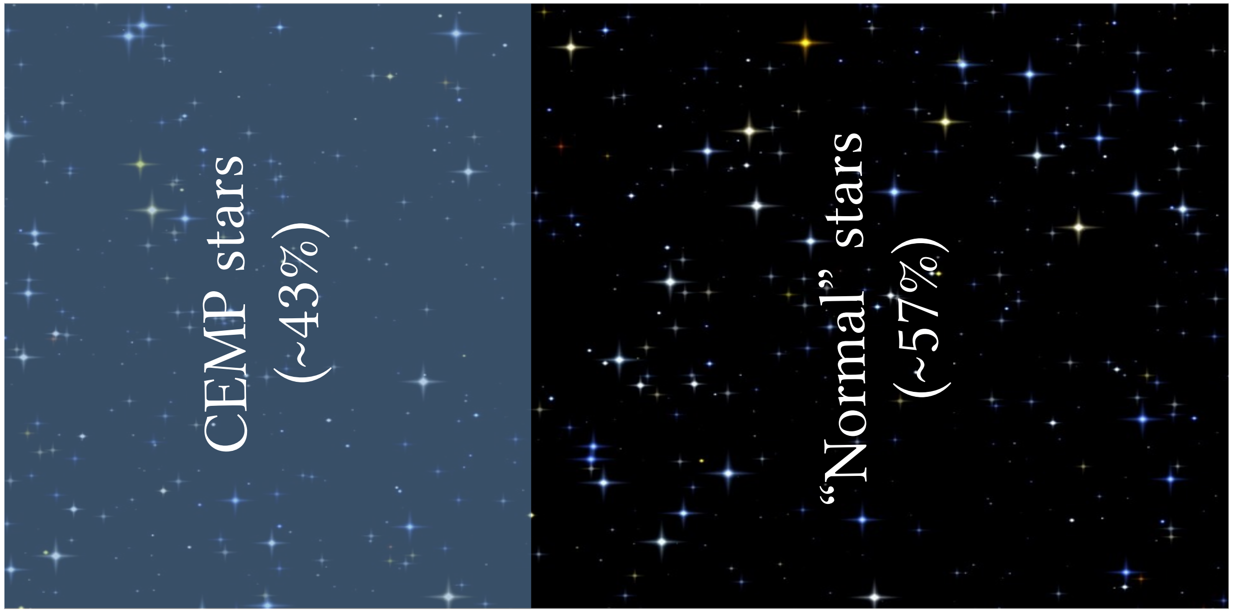
There are several subclasses of EMP stars. The most popular/well-studied are:

1) Carbon-enhanced metal poor (CEMP) stars

2) Nitrogen-enhanced metal poor (NEMP) stars

3) Not enhanced in either carbon or nitrogen (normal?) stars

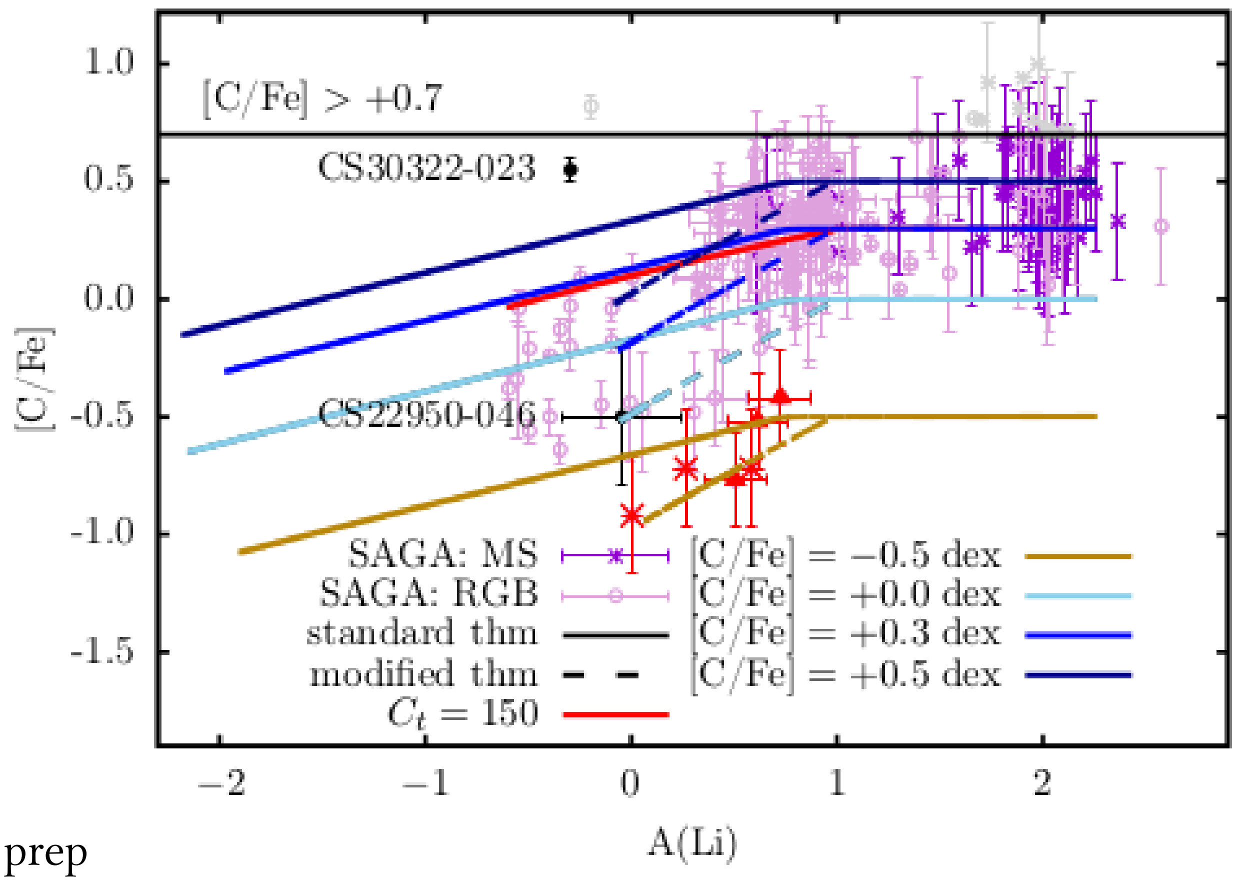
At [Fe/H] ~ -3:



Beers & Christlieb 2005, Norris *et al.* 2013, Placco *et al.* 2014

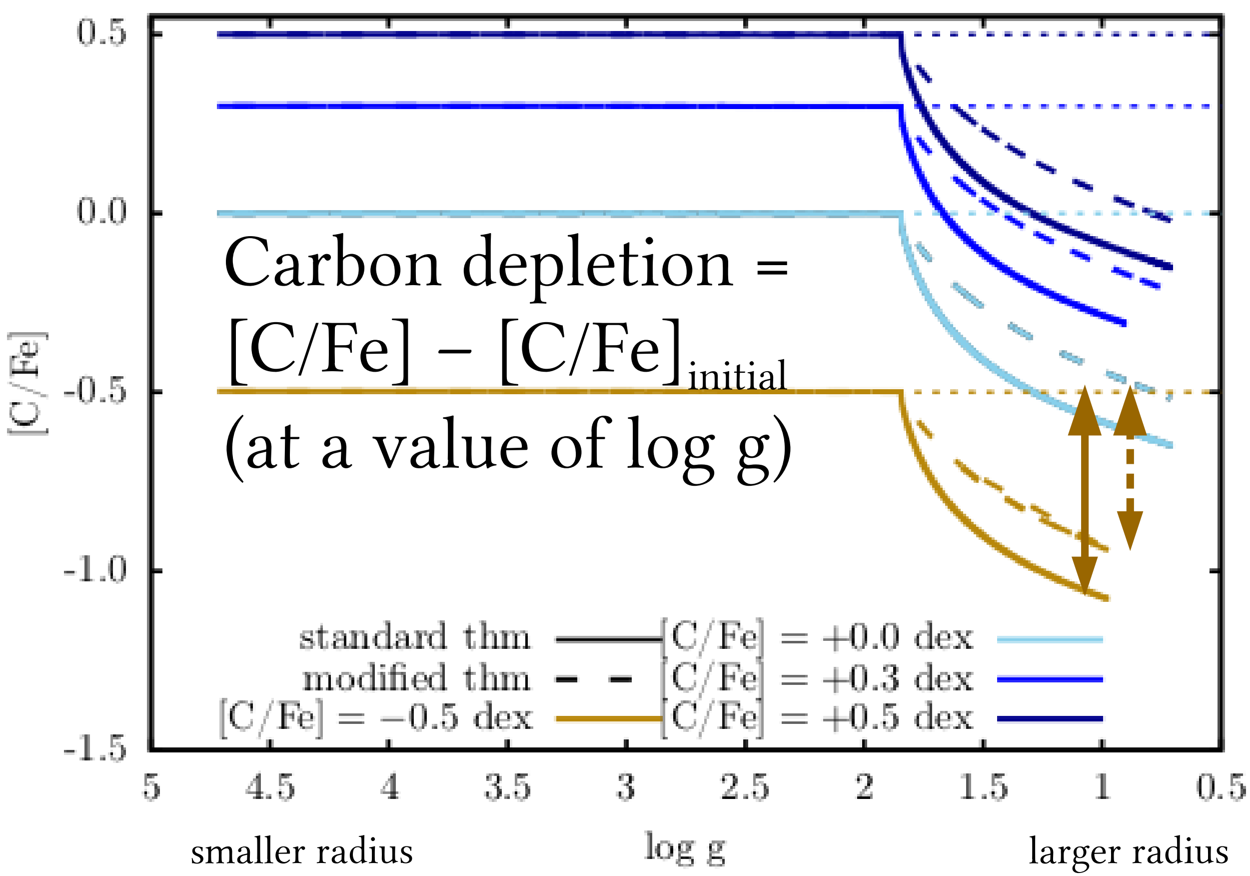
Extremely metal-poor stars

We show that the standard thermohaline mixing models cannot reproduce the downturn in [C/Fe]



Henkel *et al.*, in prep

Extremely metal-poor stars: carbon depletion



At a value of log g (surface gravity), we determine the amount of carbon depletion and compare to the carbon depletions of Placco *et al.* (2014).

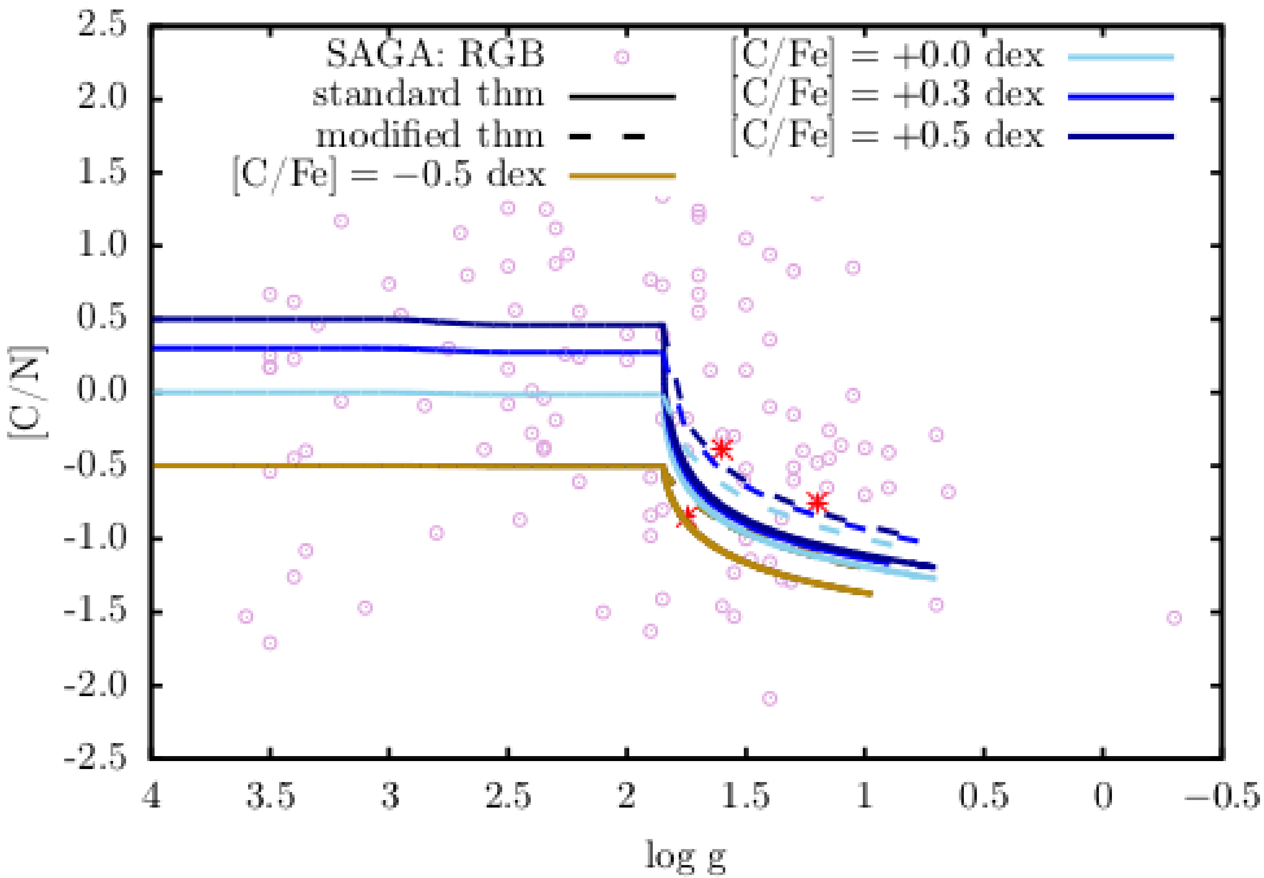
We find the amount of carbon depletion is **lower** in our models compared to Placco *et al.* (2014).

1) Evolutionary status based upon carbon offset **will be inaccurate** if using CEMP star offsets for normal EMP stars

2) Galactic CEMP stars frequencies **will be inaccurate.**

Henkel *et al.*, in prep

Extremely metal-poor stars: carbon depletion



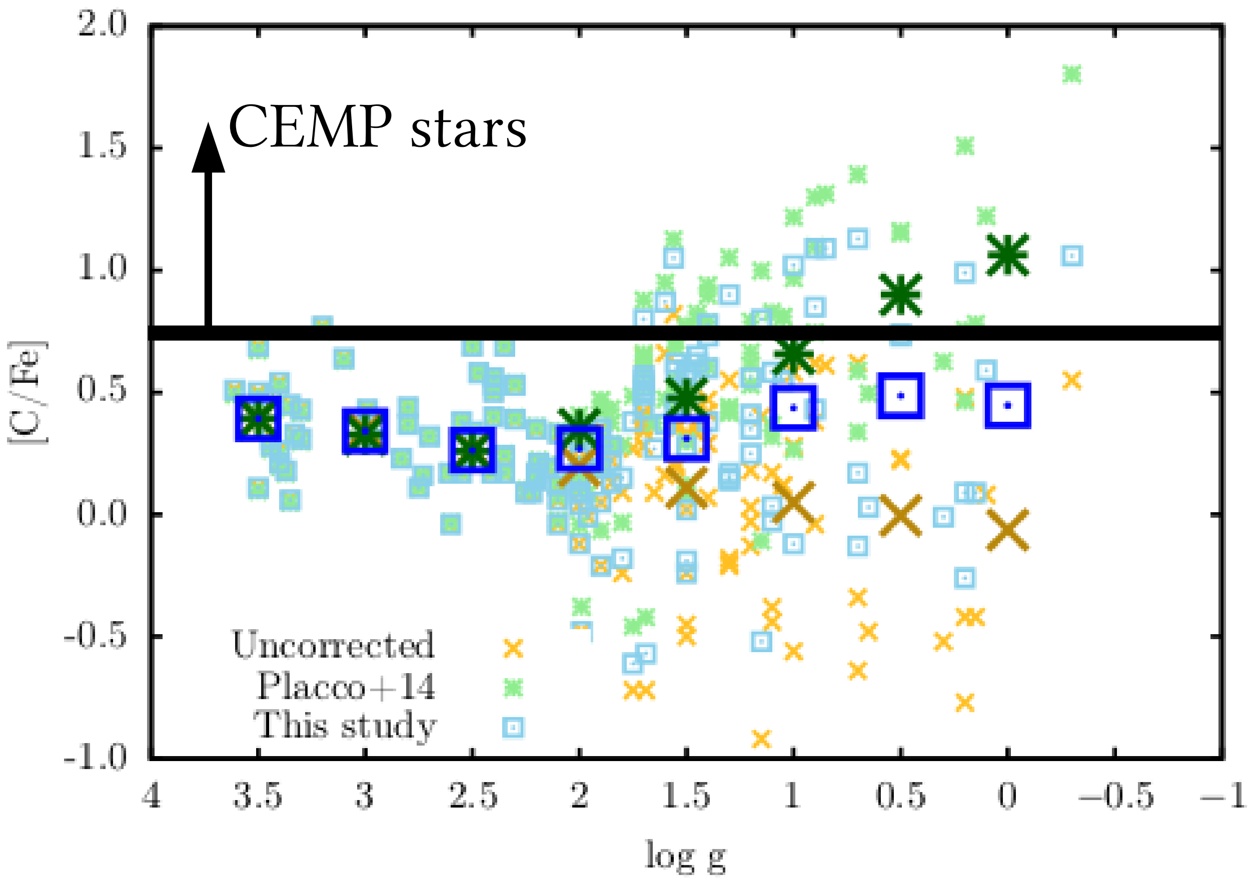
Evolutionary status based upon carbon offset **will be inaccurate** if using CEMP star offsets for normal EMP stars

Masseron & Gilmore (2015) use [C/N] abundances to estimate mass (and hence age) for the Galactic thick and thin disks.

We find that using the standard thermohaline formalism will lead to **inaccurate estimations of mass predictions** of RGB stars.

Henkel *et al.*, in prep

Extremely metal-poor stars: carbon depletion



Galactic CEMP stars frequencies **will be inaccurate.**

We find ~6% fewer CEMP stars in this sample when applying our offsets compared to those of Placco *et al.* (2014).

We find around 14% CEMP stars compared to ~20% for Placco *et al.* (2014).

Binary population synthesis models find **maximum CEMP star frequencies at ~15%** (Izzard et al. 2009a,b; Pols et al. 2009, 2012; Abate et al. 2015).

Henkel *et al.*, in prep

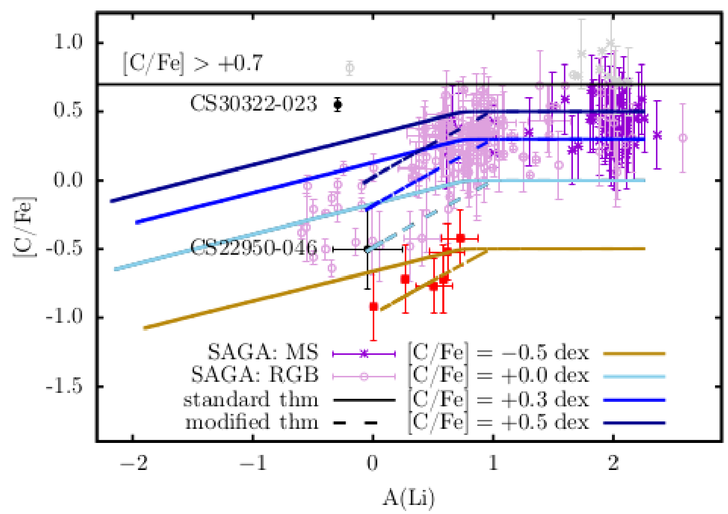
Extremely metal-poor stars

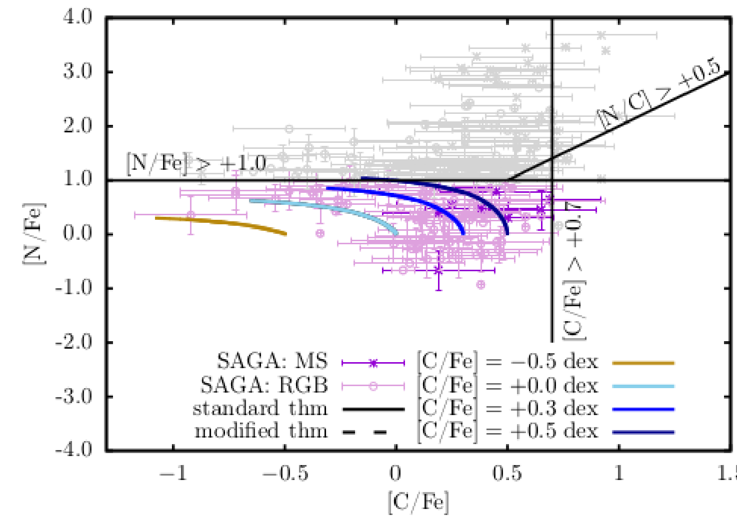
In conclusion:

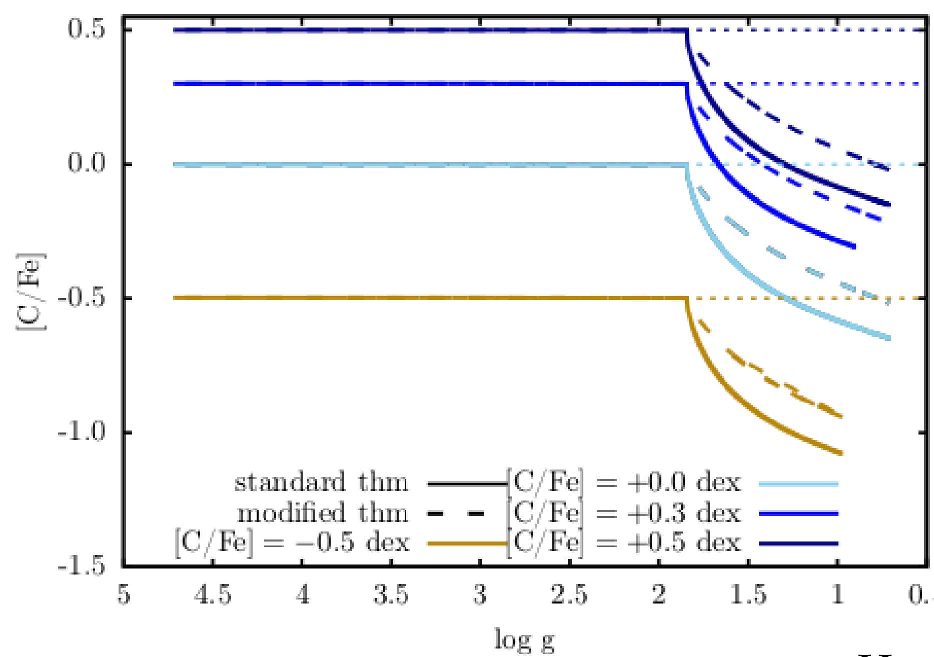
We find that

(1) Our models are a better fit for the observations in the [C/Fe]-A(Li) and [N/Fe]-[C/Fe] planes compared to other available metal-poor stellar models, and

(2) The average carbon depletion is slightly less than models that include standard thermohaline mixing predict.







Henkel *et al.*, in prep

Thank you

Questions?