BSE is not just for cows

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The Many Collaborators (so far. . .)

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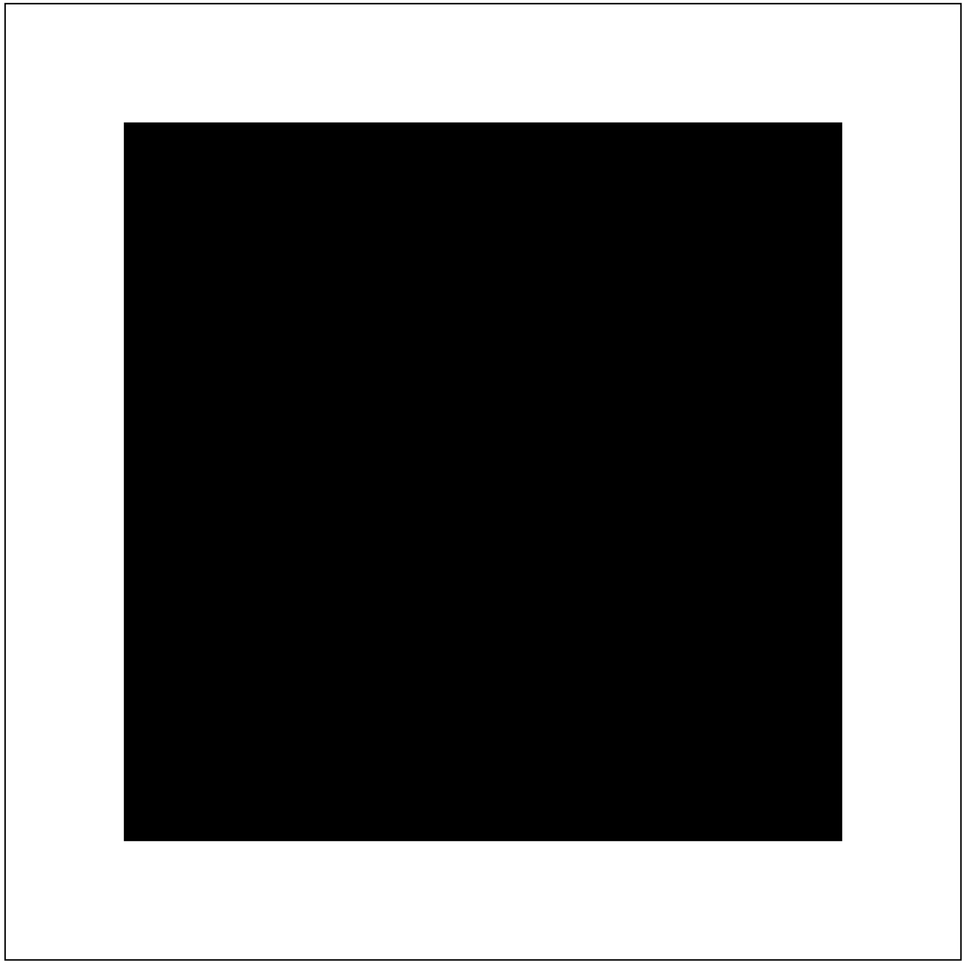
- Maria Lugaro (IoA, soon Utrecht), Onno Pols, Axel Bonačić (Utrecht)
- Amanda Karakas (McMaster, Canada)
- John Lattanzio, Jarrod Hurley (Monash, Melbourne)
- John Eldridge (IAP, Paris)
- Lynnette Dray (Leicester)
- Hilke Schlichting (Caltech)

BSE is for Chemical Evolution

- Brief history of the Milky Way
- Chemical Evolution Model
- Stellar Evolution Uncertainties: e.g. Mass Loss
- One constraint: the solar abundances
- Many constraints: stellar observations
- What About Binary Star Evolution?
- Outstanding problems
- What next?

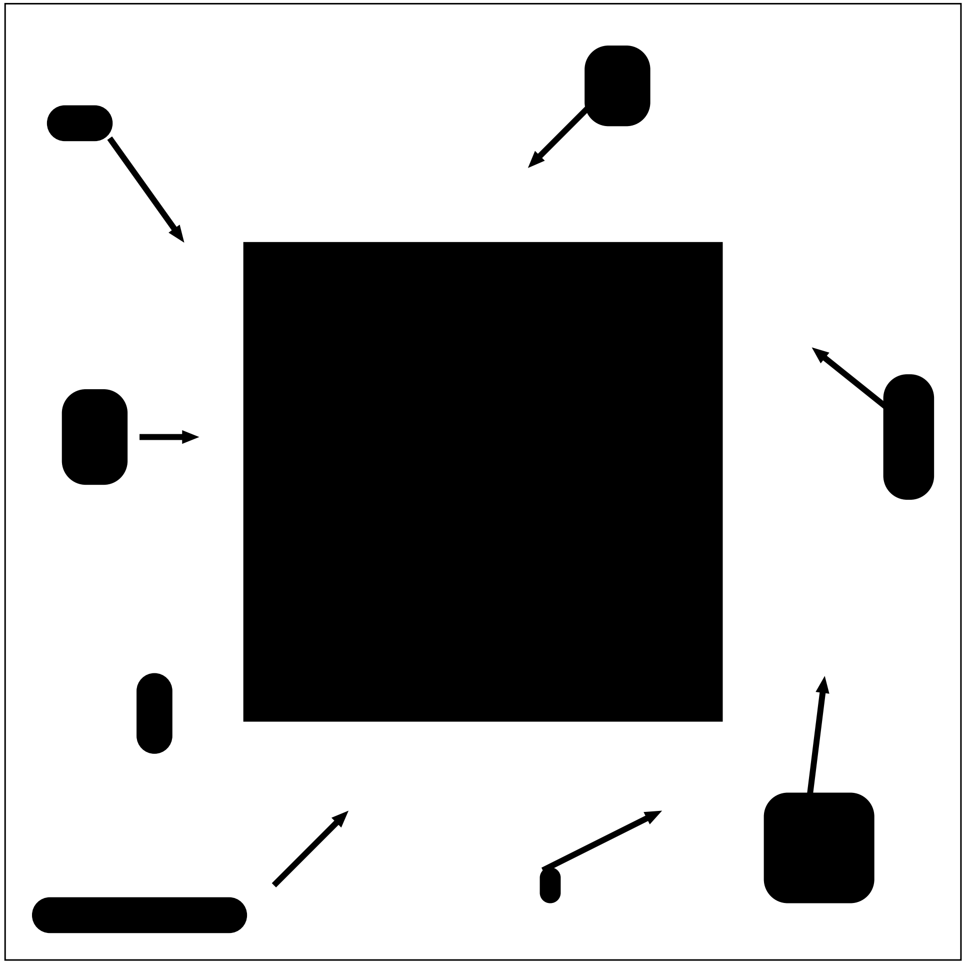
Milky Way Formation…

In the beginning there was just ^{1}H and ^{4}He gas (and dark matter?)



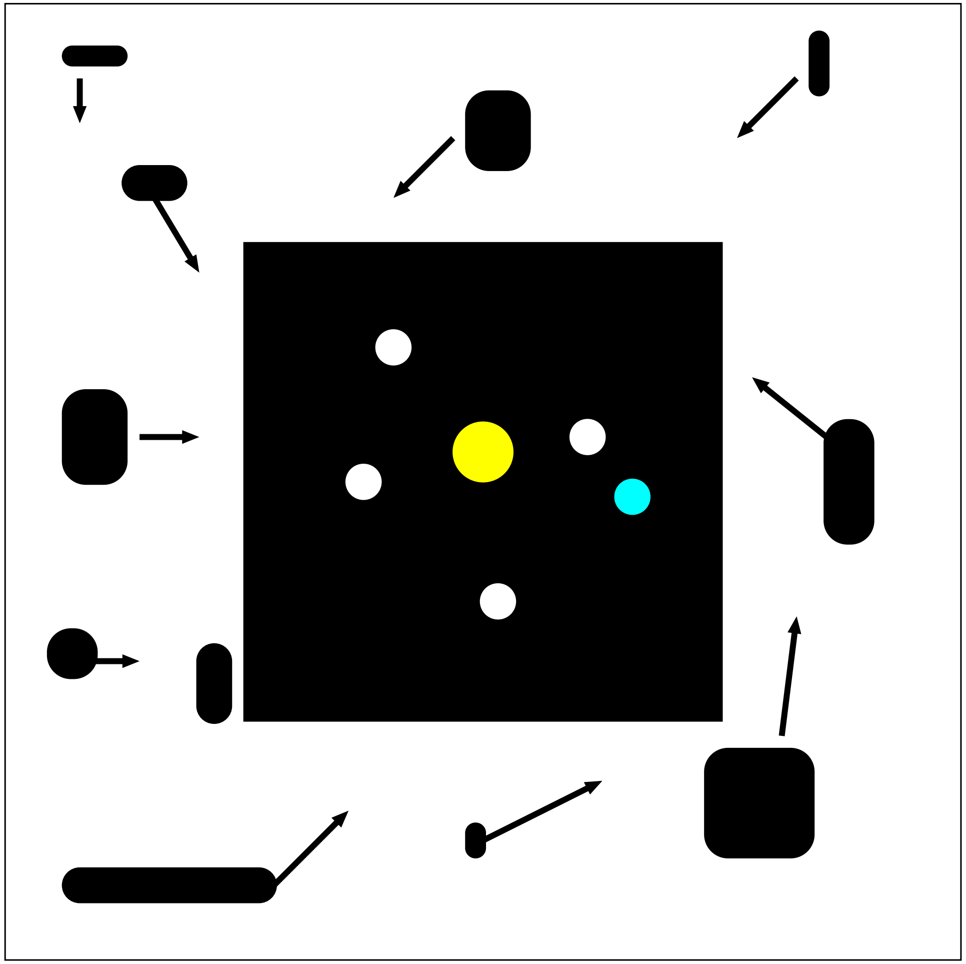
Milky Way Formation…

But gravity leads to collapse and infall of extra mass (somehow!)



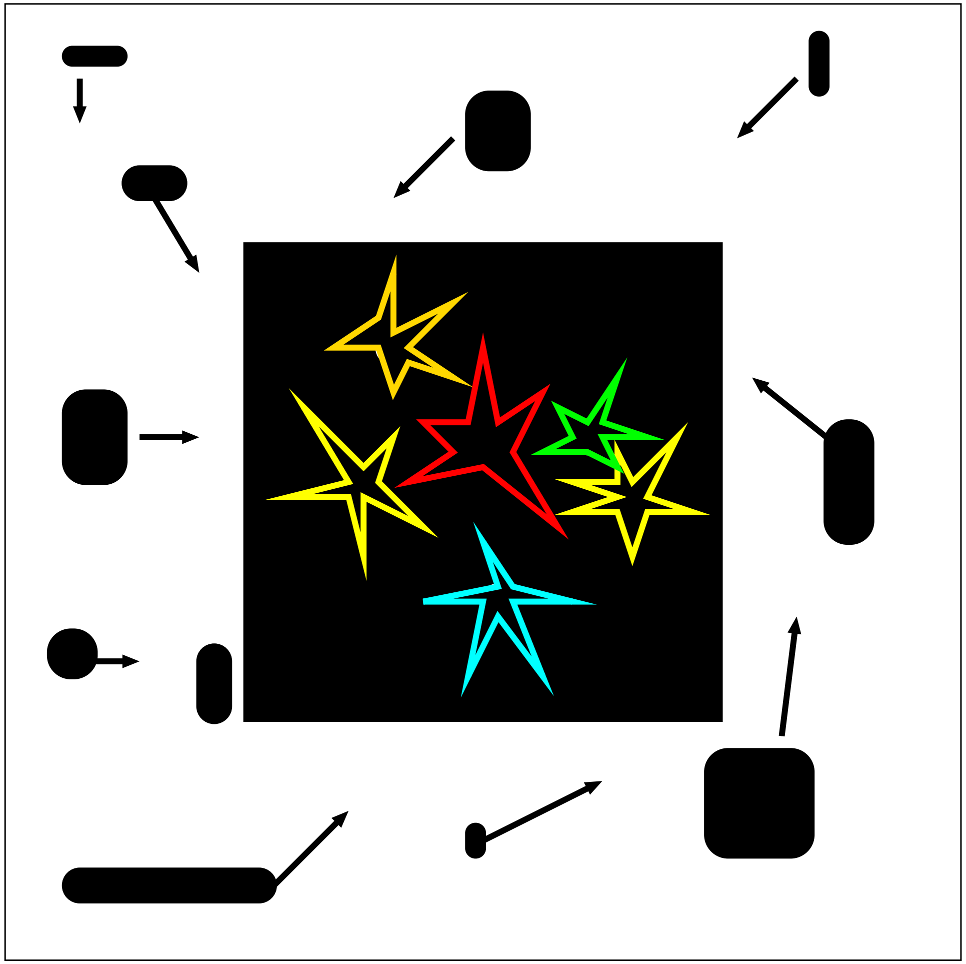
Milky Way Formation. . .

Eventually the density rises enough that stars form
Note these are *zero metallicity stars* ($Z = 0$, “PopIII”)



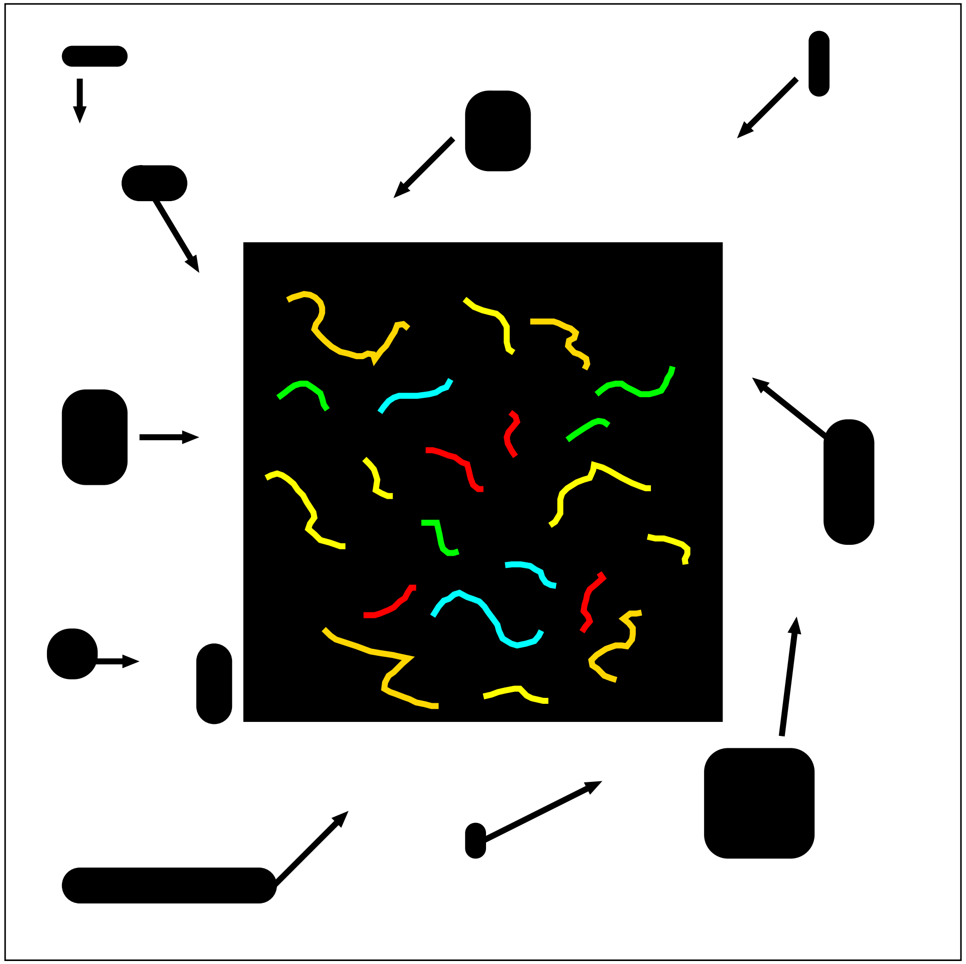
Milky Way Formation…

The first stars explode: ^{12}C, ^{16}O, ^{56}Fe pollution (little ^{14}N)



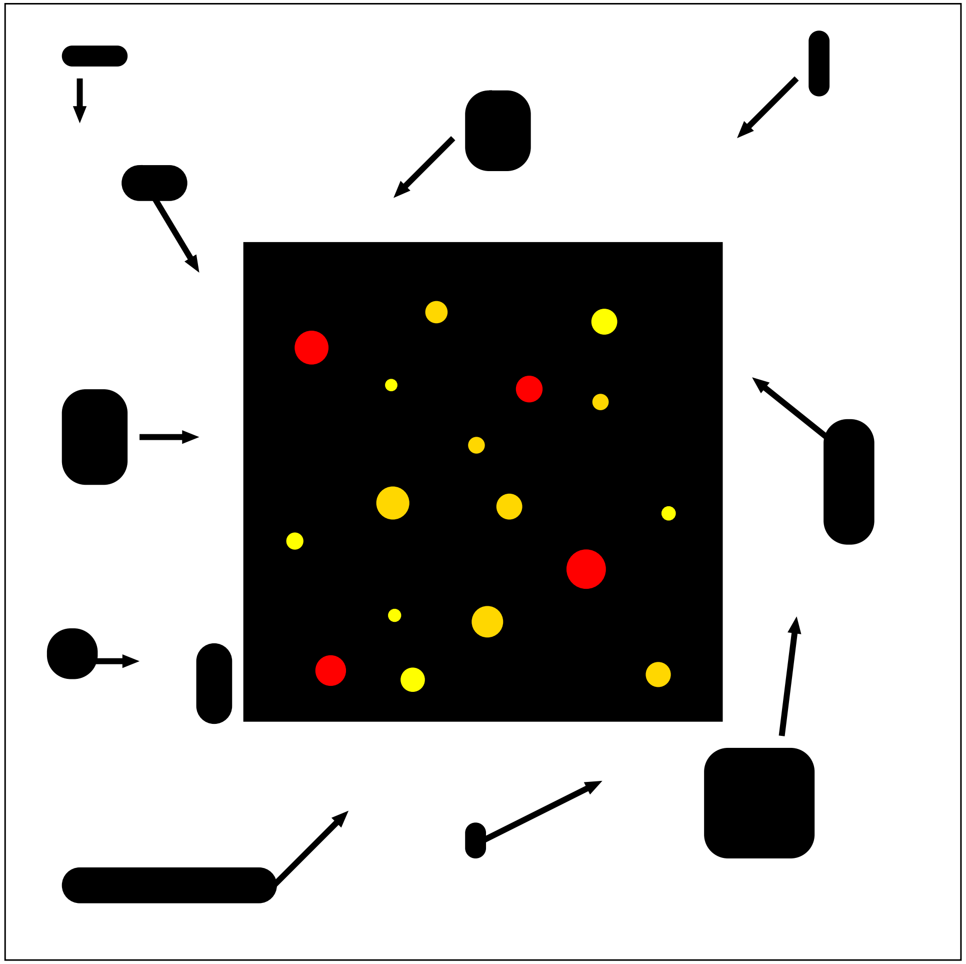
Milky Way Formation…

The environment becomes enriched: $Z > Z_{\text{crit}} \sim 10^{-5}$



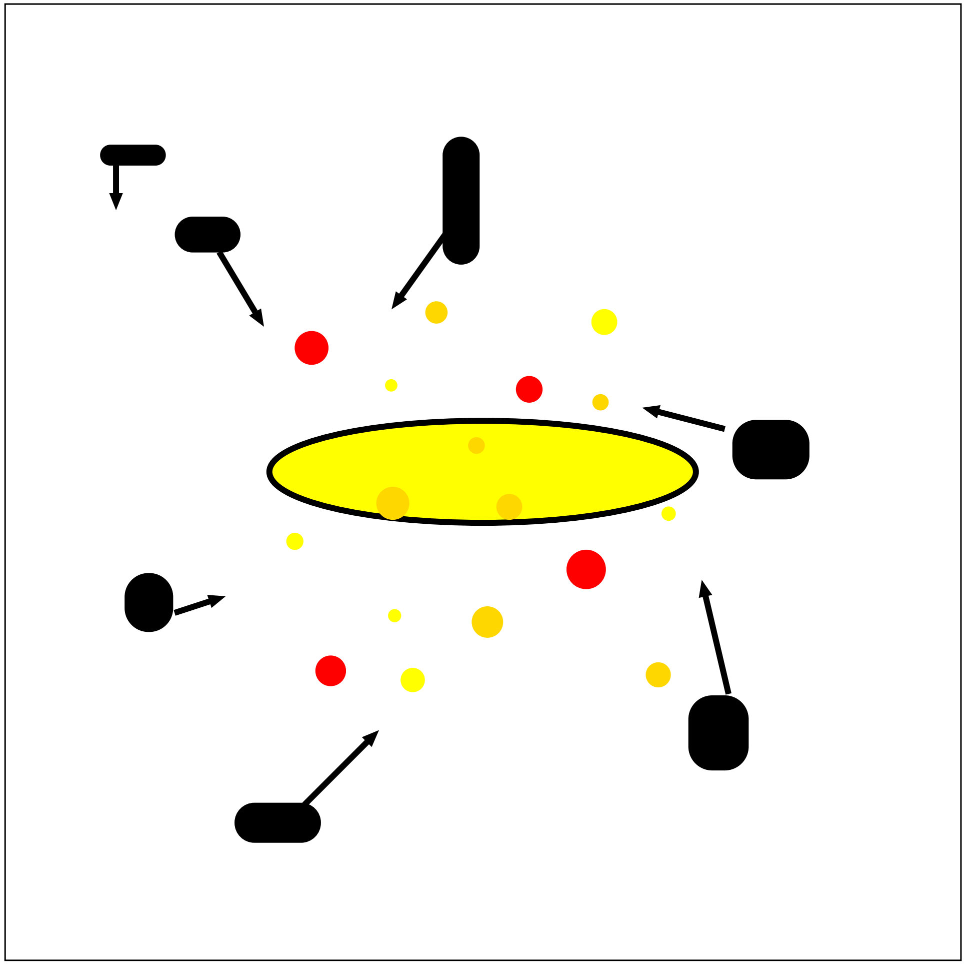
Milky Way Formation…

PopII (low-Z) stars form in the halo with standard IMF (many low mass stars)



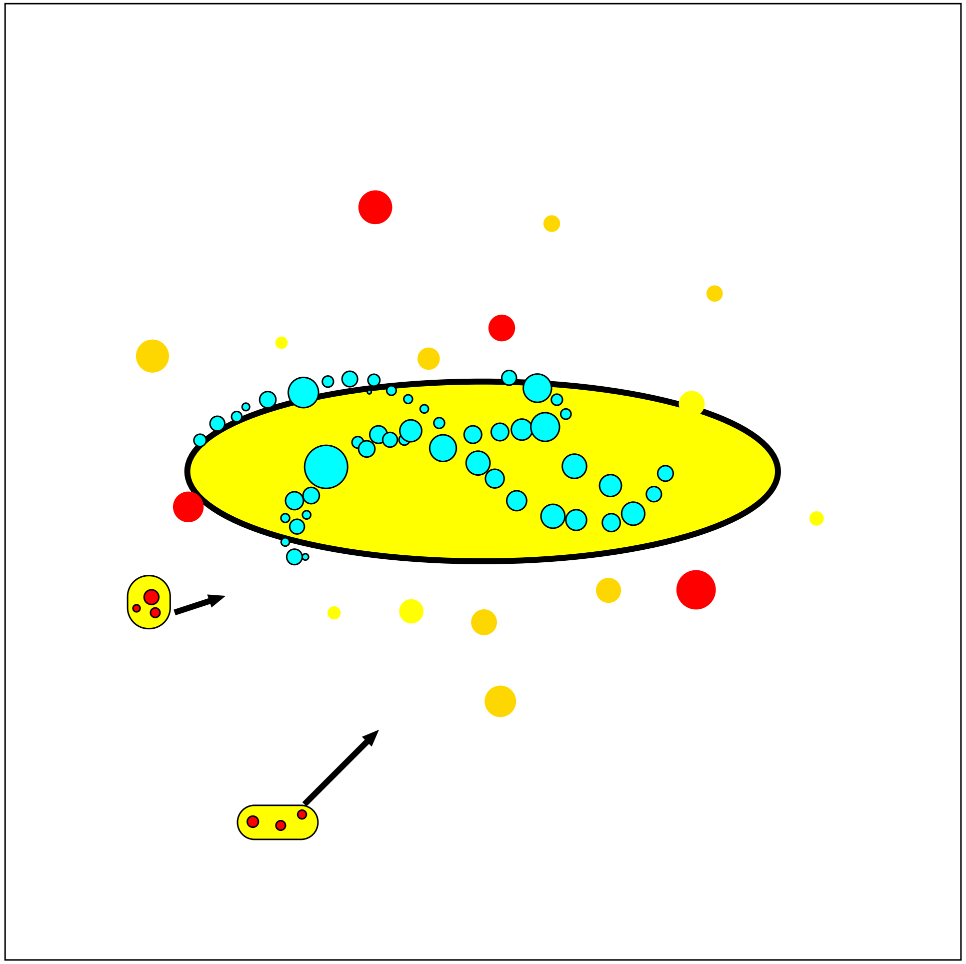
Milky Way Formation. . .

High-angular momentum objects form galactic disk. Star formation and pollution (mainly in the disk), infall continue.



Milky Way Now

Evolution continues to this day.
Star formation mainly in spiral arms.



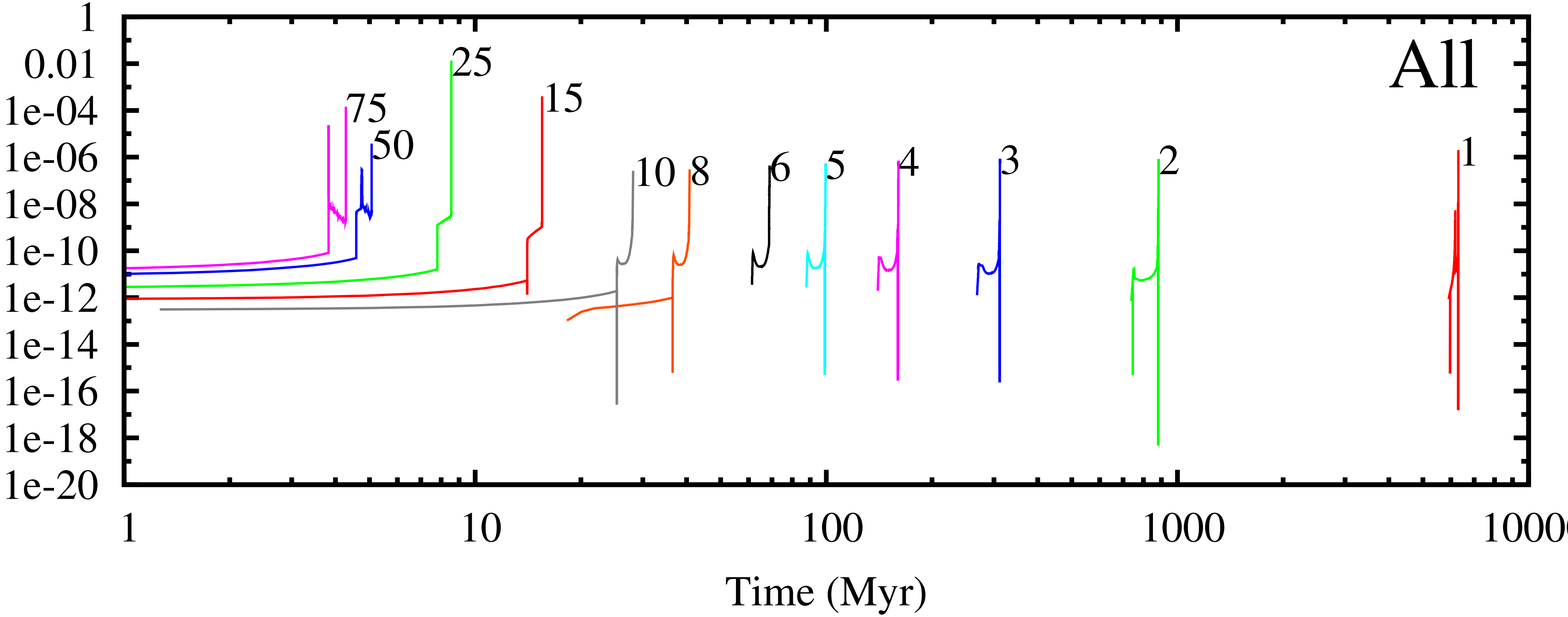
Stellar evolution

Stellar evolution models tell us about chemical processing

- When? High $M \rightarrow t \sim$ Myr, low $M \rightarrow t \sim$ Gyr

Stellar evolution

Mass-loss rate as function of time

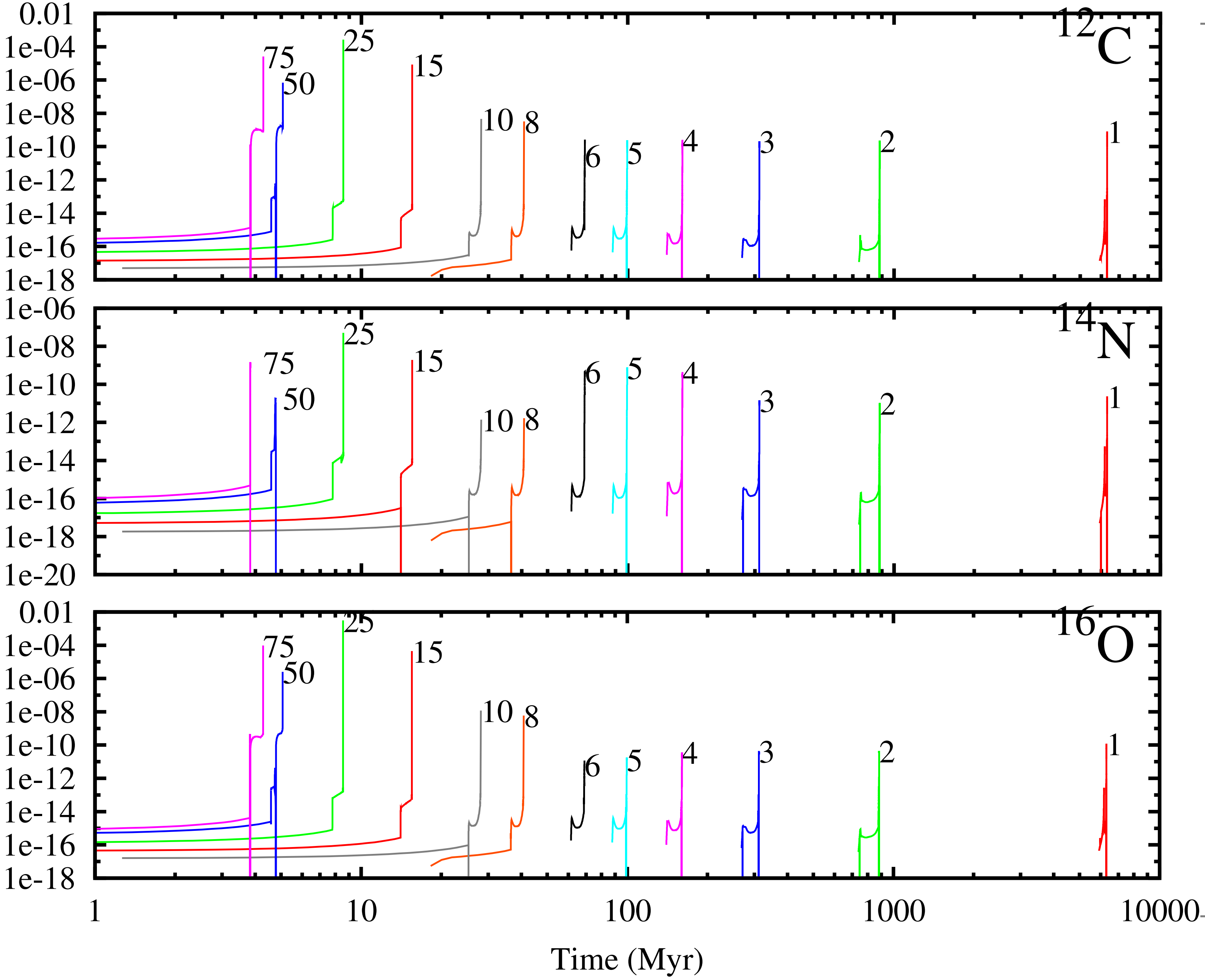


Stellar evolution

Stellar evolution models tell us about chemical processing

- When? High $M \rightarrow t \sim$ Myr, low $M \rightarrow t \sim$ Gyr
- As what? High M supernovae/winds, low M stellar winds.

Stellar evolution



Stellar evolution

Stellar evolution models tell us about chemical processing

- When? High $M \rightarrow t \sim$ Myr, low $M \rightarrow t \sim$ Gyr
- As what? High M supernovae, low M stellar winds.

Is this understood? Reasonably, but many uncertainties in

- Mass loss at all phases of evolution
- Supernova yields (high M)
- 1st, 2nd and 3rd Dredge-up (thermal pulses), hot-bottom burning (intermediate M)
- Binaries (RLOF, SNIa, novae, extras?)
- Initial distributions (IMF etc.)

Rob’s GCE+BSE model

- Mostly stolen from Chiappini/Matteucci et al. (Trieste)
- Closed box with infall at solar radius $8\,\mathrm{kpc}$
- Two phase infall, halo ($\tau = 1\mathrm{Gyr}$) then disk
- SFR $\sim$ gas density^k ($k = 1.5$) if $\sigma_{\mathrm{gas}} > 4 - 7\,\mathrm{M}_\odot\,\mathrm{pc}^{-2}$
- Stellar evolution calculations made *on the fly* with Single Star Evolution (SSE) and Binary Star Evolution (BSE) package (Hurley et al. 2000/2002)
- Nucleosynthesis package bolted on (Izzard et al. 2004/2005?)
- $0.1 \leq M/\mathrm{M}_\odot \leq 100$, $10^{-4} \leq Z \leq 0.03$
- PopIII stars boost Z to 10^{-5}

Why do this?

Advantages

- Dynamic initial abundance mixture based on galactic gas i.e. *not solar scaled*
- Vary stellar evolution: $\dot{M}$, explosive yields, DUP…
- Yield tables not required
- Timescale tables not required: continuous $\dot{M}$
- Binaries if you want

Disadvantages

- Slower than a look-up table of yields/lifetimes, but still only a few seconds for 100 stars
- er…

Does the model work?

- Reproduces solar neighbourhood gas/stellar density
- OK, so the error bars are large… !
- Also can reproduce solar abundances of ^{4}He, CNO and ^{56}Fe *almost* within error bars
- G/K-dwarf metallicity dist. similar to observed
- $[\mathrm{O}/\mathrm{Fe}]$ vs $[\mathrm{Fe}/\mathrm{H}]$ matches observations very well (luck)
- $[\mathrm{N}/\mathrm{O}]$ vs $[\mathrm{O}/\mathrm{H}]$ matches well *with some tweaking*
- $[\mathrm{C}/\mathrm{Fe}]$ vs $[\mathrm{Fe}/\mathrm{H}]$ match is not great, working on it…

So the model works *as well as the one it was based on*. From now on I will assume the model for the star formation and infall is perfect and modify some stellar evolution parameters to determine their effect.

Mass Loss Uncertainty

- One of the greatest problems we have is how to describe mass loss in stars
- Affects high-mass stars (e.g. WR)
- …and intermediate-mass stars (TPAGB)
- …and low-mass stars (GB)
- …and binaries: non-conservative RLOF, colliding winds, extra $\dot{M}$ from tides
- i.e. affects *all* stars and *all* calculations of advanced (interesting) phases of stellar evolution

Massive Star Mass-loss

Consider four different mass-loss prescriptions

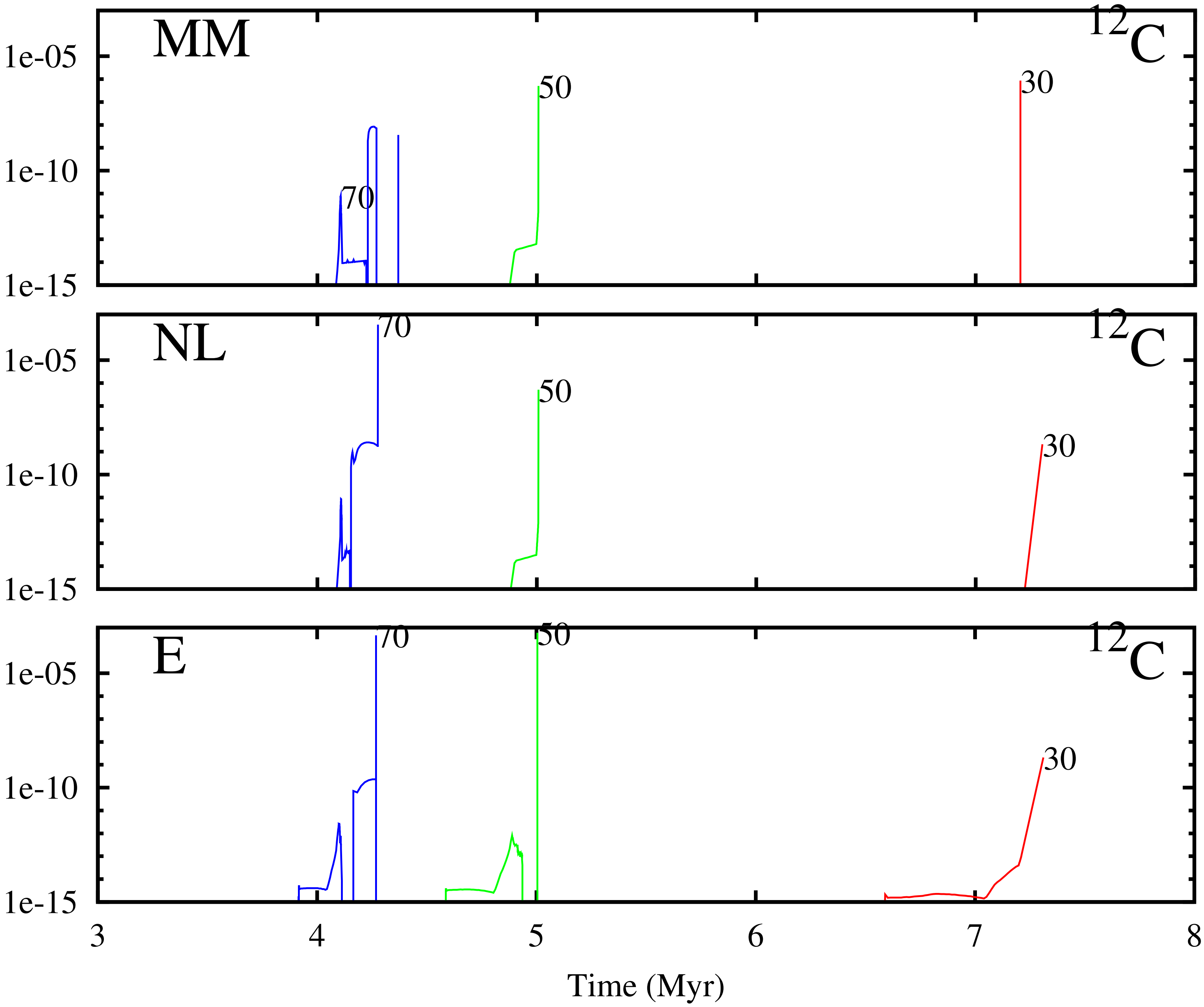
- Hurley et al 2002 (H02 based on Nieuwenhuijzen & de Jager 1990)
- Maeder & Meynet 1994 (MM)
- Nugis & Lamers 2000 (NL)
- Eldridge 2005 (E, as H02 w/$f(Z)$ from Vink's theoretical models)

Massive Star Mass-loss

What effect do we expect?

- $\dot{M}$ affects when and how (much) yield is released
- $\dot{M}$ early means less time for burning
- Which means less ^{14}N and more ^{12}C
- And a smaller core mass when the supernova does happen (more ^{12}C and ^{56}Fe, less ^{16}O according to WW95)

Effect on individual stars ($Z = 0.02$)



Results: At $t_{\text{sun}} \sim 9$ Gyr

Isotope	Obs	H02	MM	NL	E
^{4}He	$0.265 - 0.285$	0.263	0.255	0.254	0.262
^{12}C $\times 10^{3}$	$1.93 - 4.32$	3.56	2.81	2.68	3.36
^{14}N $\times 10^{4}$	$6.60 - 10.9$	9.08	6.54	6.28	8.77
^{16}O $\times 10^{3}$	$4.64 - 8.85$	8.99	10.6	11.2	8.66
^{56}Fe $\times 10^{4}$	$9.35 - 14.2$	9.82	9.70	9.58	9.63

Conclude E is better? (Marginal!)

Mass-loss in AGB stars

AGB mass-loss is also poorly constrained.
Try several prescriptions:

- Vassiliadis & Wood 1993 (H02, original)
- Vassiliadis & Wood 1993 (K02, stronger superwind)
- Reimers with $\eta = 1 - 5$ (R1-R5, $\eta \uparrow$=stronger wind)
- Blöcker 1991 (Bö) with $\eta = 0.5$

Mass-loss in AGB stars

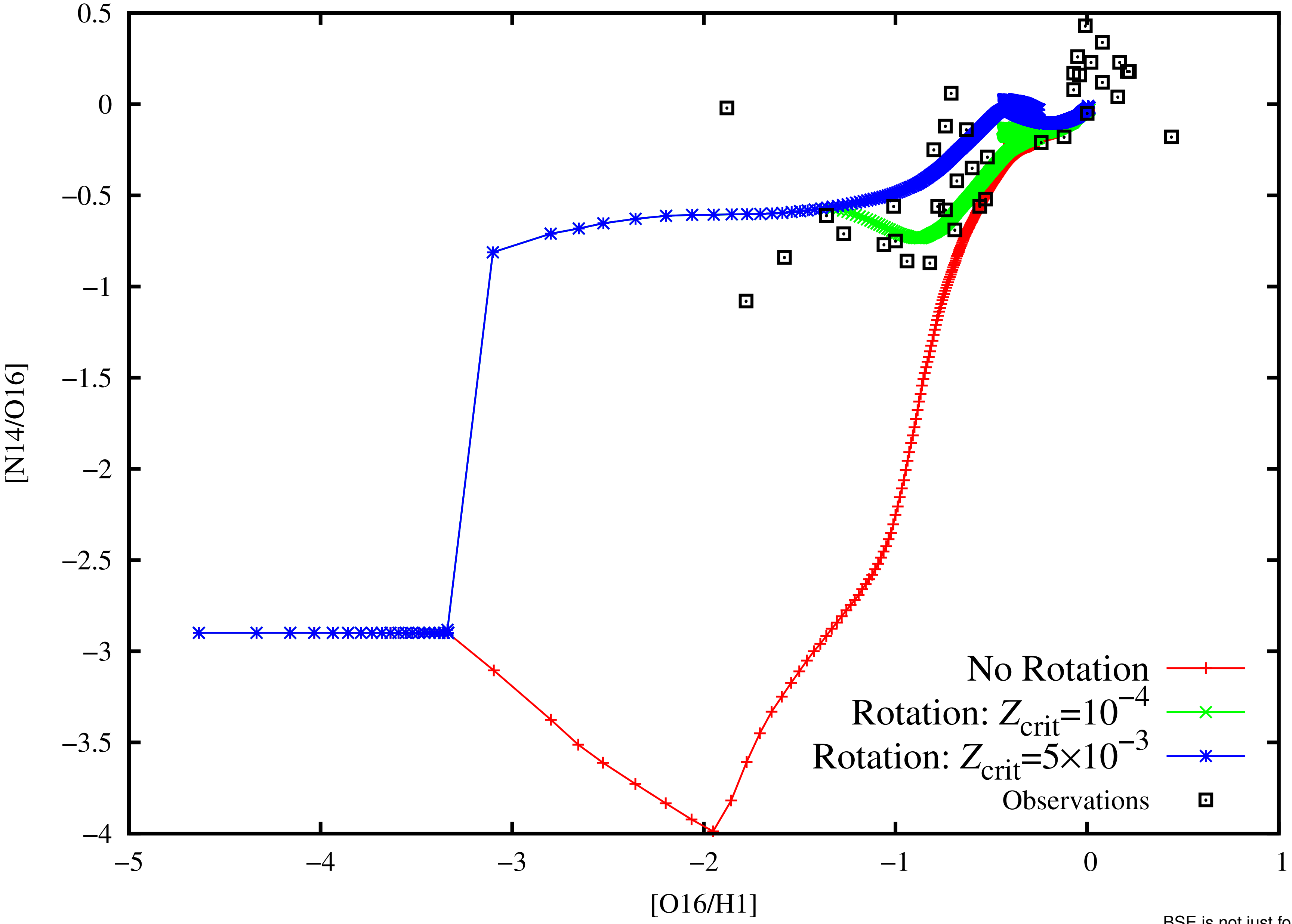
Isotope	Obs	H02	K02	R1	R3	R5	Bö
^{4}He	$0.265 - 0.285$	0.263	0.263	0.265	0.264	0.262	0.261
$^{12}\mathrm{C} \times 10^3$	$1.93 - 4.32$	3.54	3.69	4.37	3.22	2.96	2.64
$^{14}\mathrm{N} \times 10^4$	$6.60 - 10.9$	13.3	9.17	18.7	11.6	9.44	5.62
$^{16}\mathrm{O} \times 10^3$	$4.64 - 8.85$	8.89	8.99	8.78	8.99	9.04	9.16
$^{56}\mathrm{Fe} \times 10^4$	$9.35 - 14.2$	9.76	9.83	9.65	9.85	9.90	9.95

- Only ^{12}C and ^{14}N are really affected
- K02 and R5 give “best” results
- K02 slightly better ^{4}He, still outside 1σ error

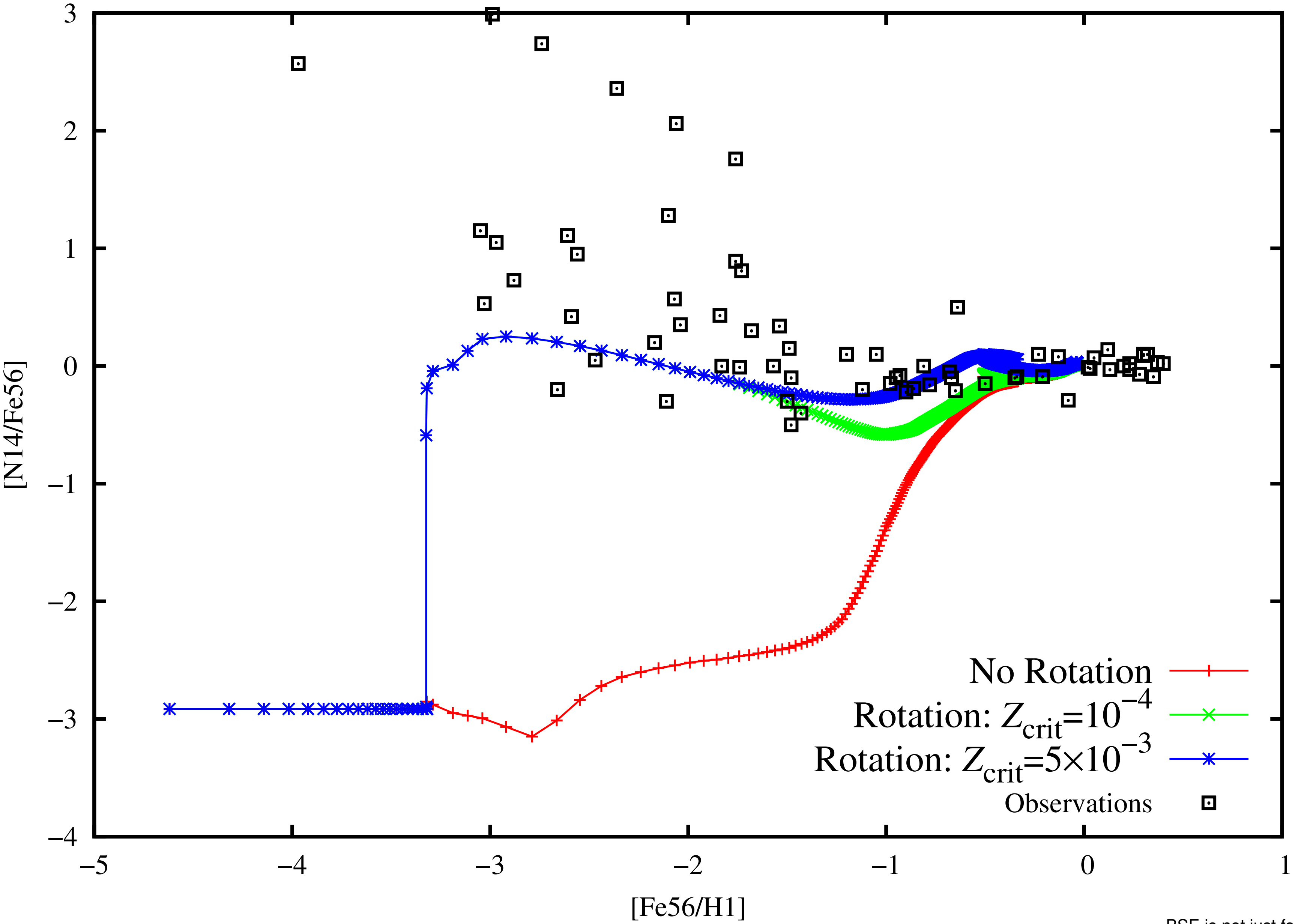
Observations of Many Stars

- We can observe stars of many metallicities locally
- Compare $[\mathrm{X}/\mathrm{Fe}]$ or $[\mathrm{X}/\mathrm{H}]$ to $[\mathrm{Fe}/\mathrm{H}]$
- Tests stellar evolution at early times:
- Nitrogen problem! What is its origin at low $[\mathrm{Fe}/\mathrm{H}]$?
- We need ***primary*** ^{14}N at low metallicity
- Try this: for $Z < Z_{\mathrm{crit}}$ raise surface ^{14}N in core helium-burning stars' envelope to 5×10^{-3} (by mass) to simulate effects of mixing He-burning products into the stellar envelope (perhaps by differential rotation. . . ?)
- NB pre- and post-core-helium burning surface $^{14}N \approx 0$
- Try several Z_{crit}. . .

[N/O] vs [O/H]


0.5
0
−0.5
−1
−1.5
−2
−2.5
−3
−3.5
−4
[N14/O16]
−5
−4
−3
−2
−1
0
1
[O16/H1]
No Rotation
Rotation: $Z_{\text{crit}}=10^{-4}$
Rotation: $Z_{\text{crit}}=5\times10^{-3}$
Observations

[N/Fe] vs [Fe/H]

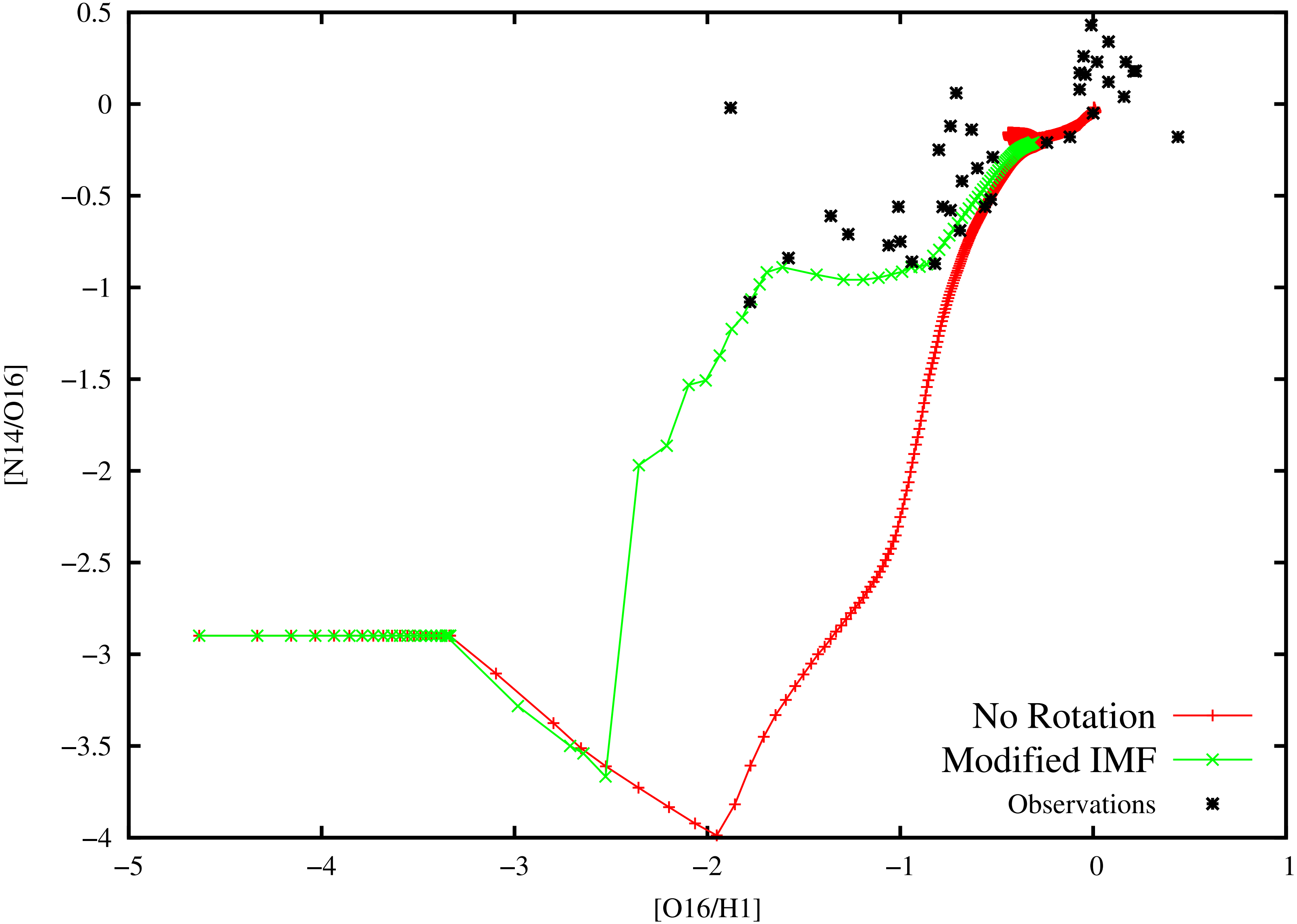

3
2
1
0
−1
−2
−3
−4
[N14/Fe56]
−5
−4
−3
−2
−1
0
1
[Fe56/H1]
No Rotation
Rotation: Z_{crit}=10^{-4}
Rotation: Z_{crit}=5×10^{-3}
Observations

Require primary ^{14}N

Conclude

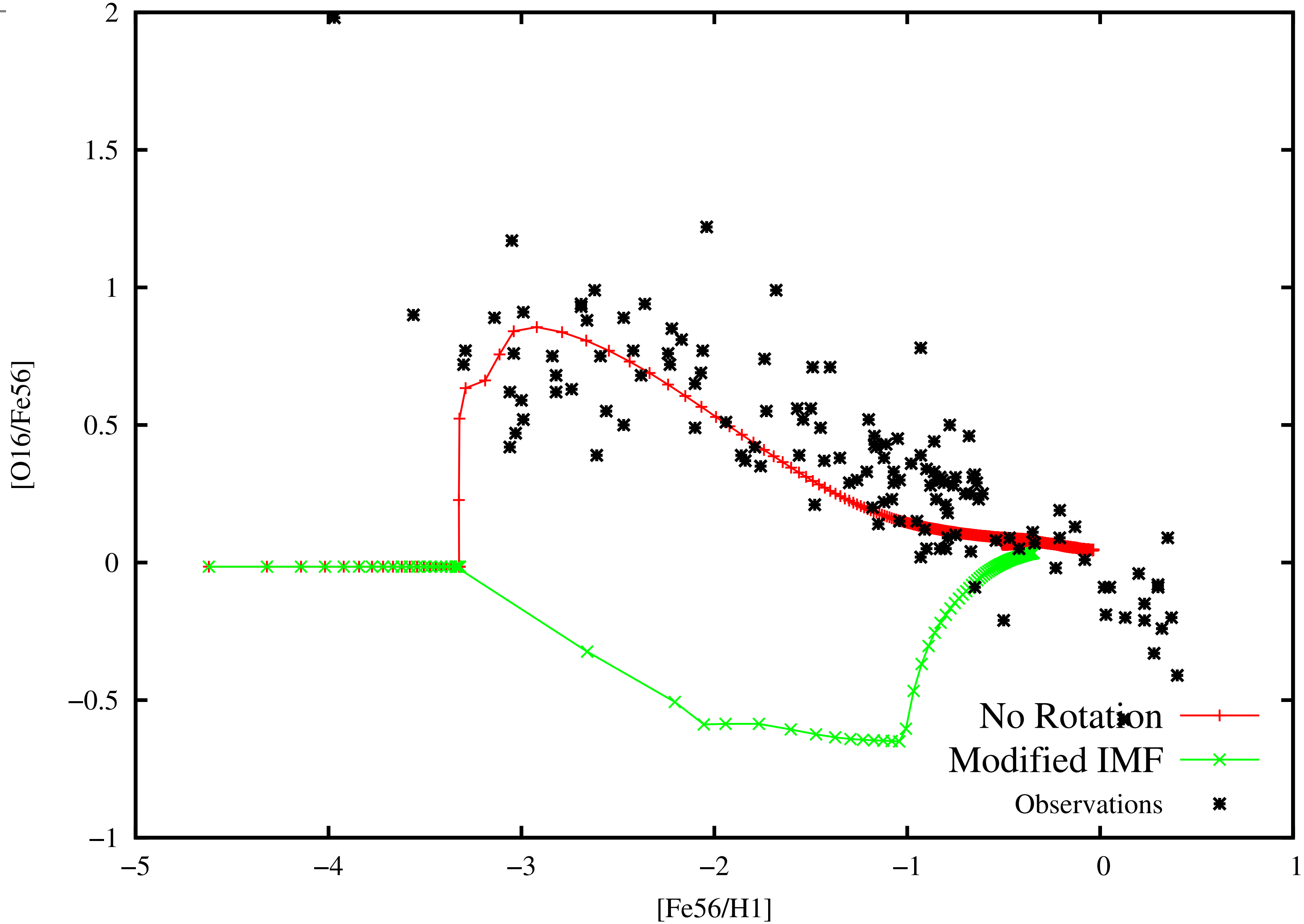
- For $Z \lesssim 5 \times 10^{-3}$ we require extra primary nitrogen
- NB this is *very* early ($\lesssim 50$ Myr) → must be massive stars
- Meynet/Maeder (2002) models sort-of show this, but only for extreme rotation in massive stars and there's still not enough nitrogen
- Yoon and Langer (2005) show something very similar to the prediction (independently of this work!)
- Langer thinks all stars form at high rotational velocity, but…
- Perhaps there is another solution?
- e.g. Try changing the IMF…

IMF is wrong at low-Z?



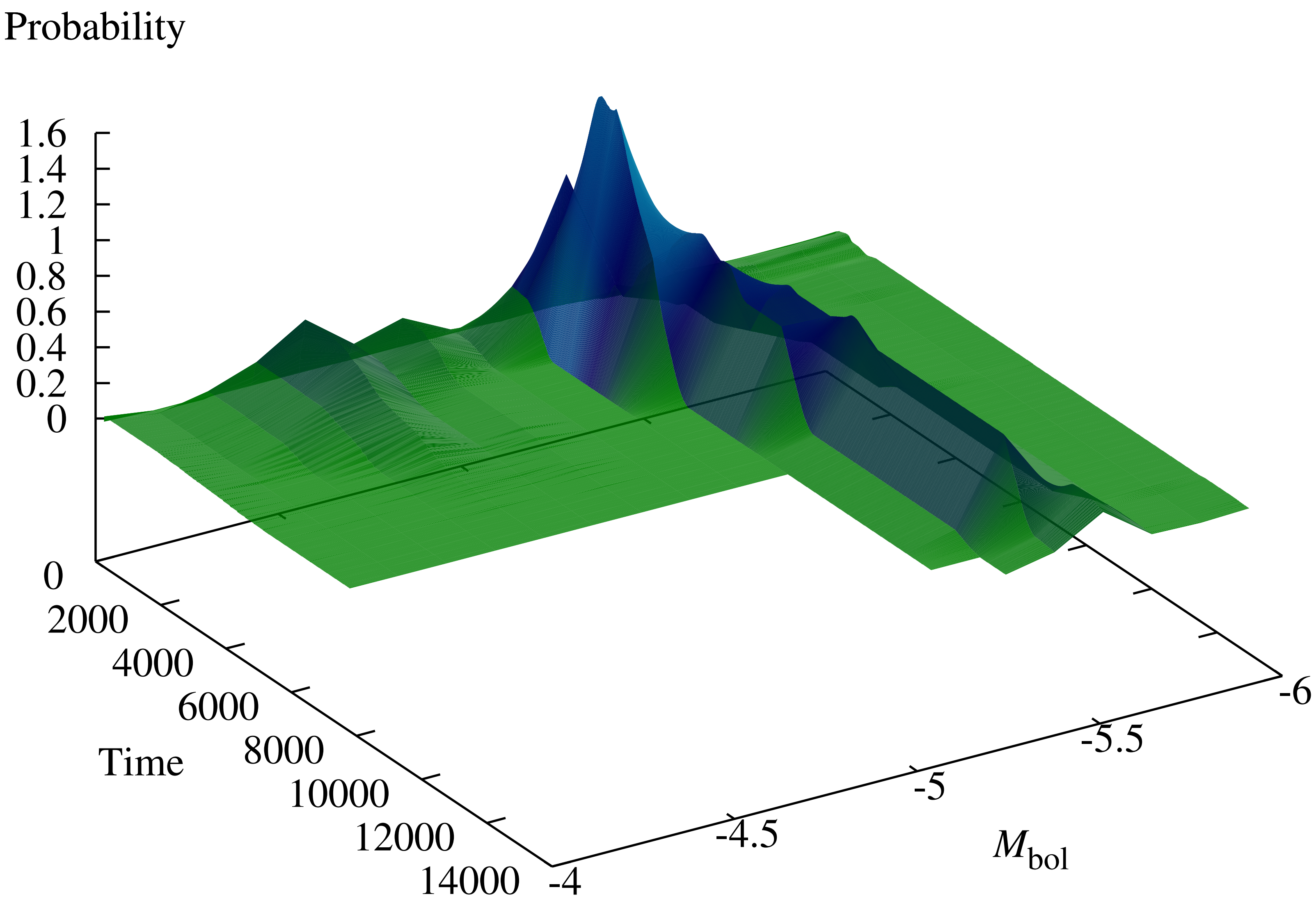
Assumes $M_{\mathsf{max}} = 12\,\mathrm{M}_\odot$ for $Z < 5 \times 10^{-4}$: nice fit!

But this really messes up the oxygen



Assumes $M_{\text{max}} = 12\,\mathrm{M}_\odot$ for $Z < 5 \times 10^{-4}$

Example: stellar populations

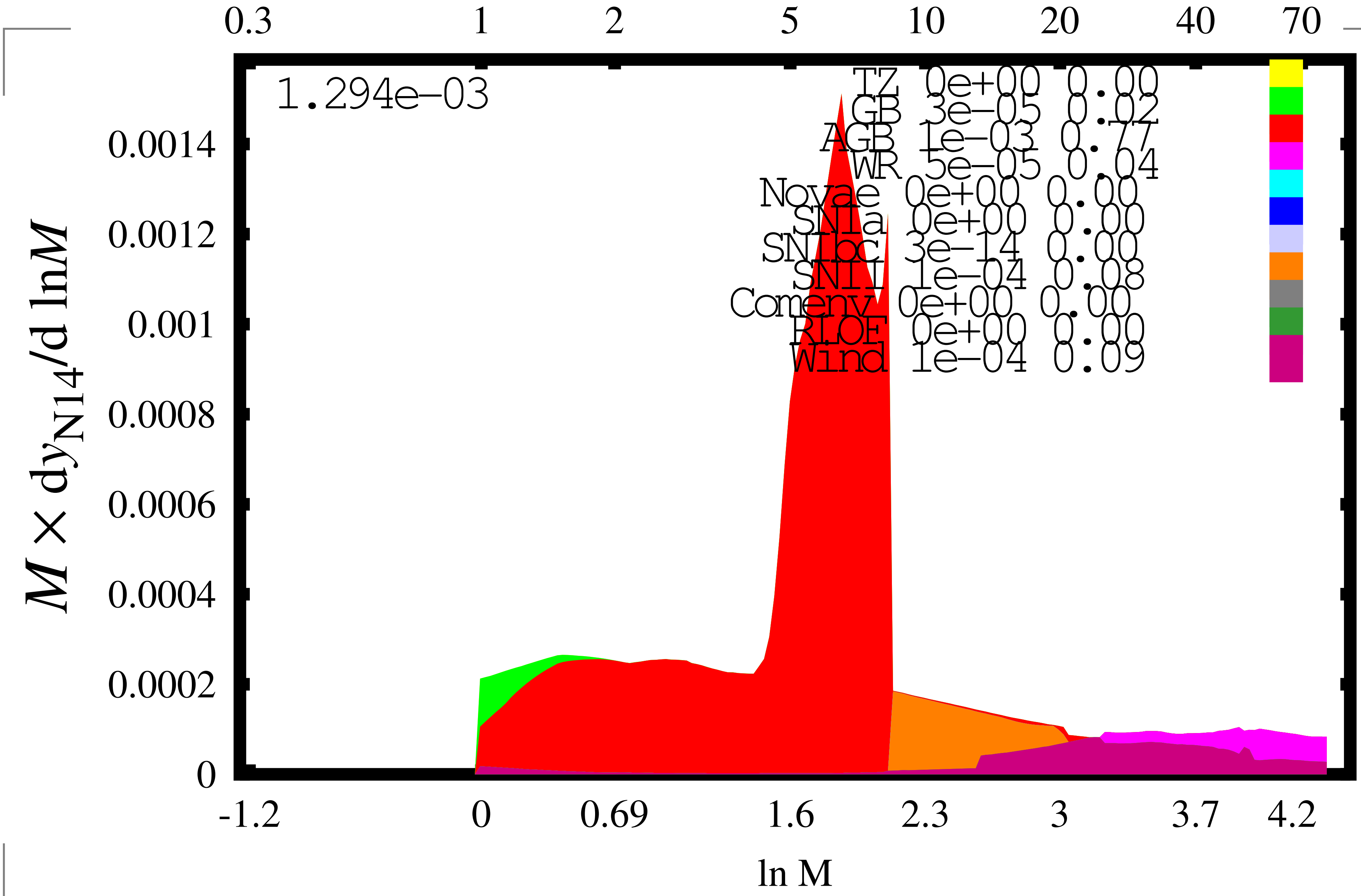


BSE (moo!)

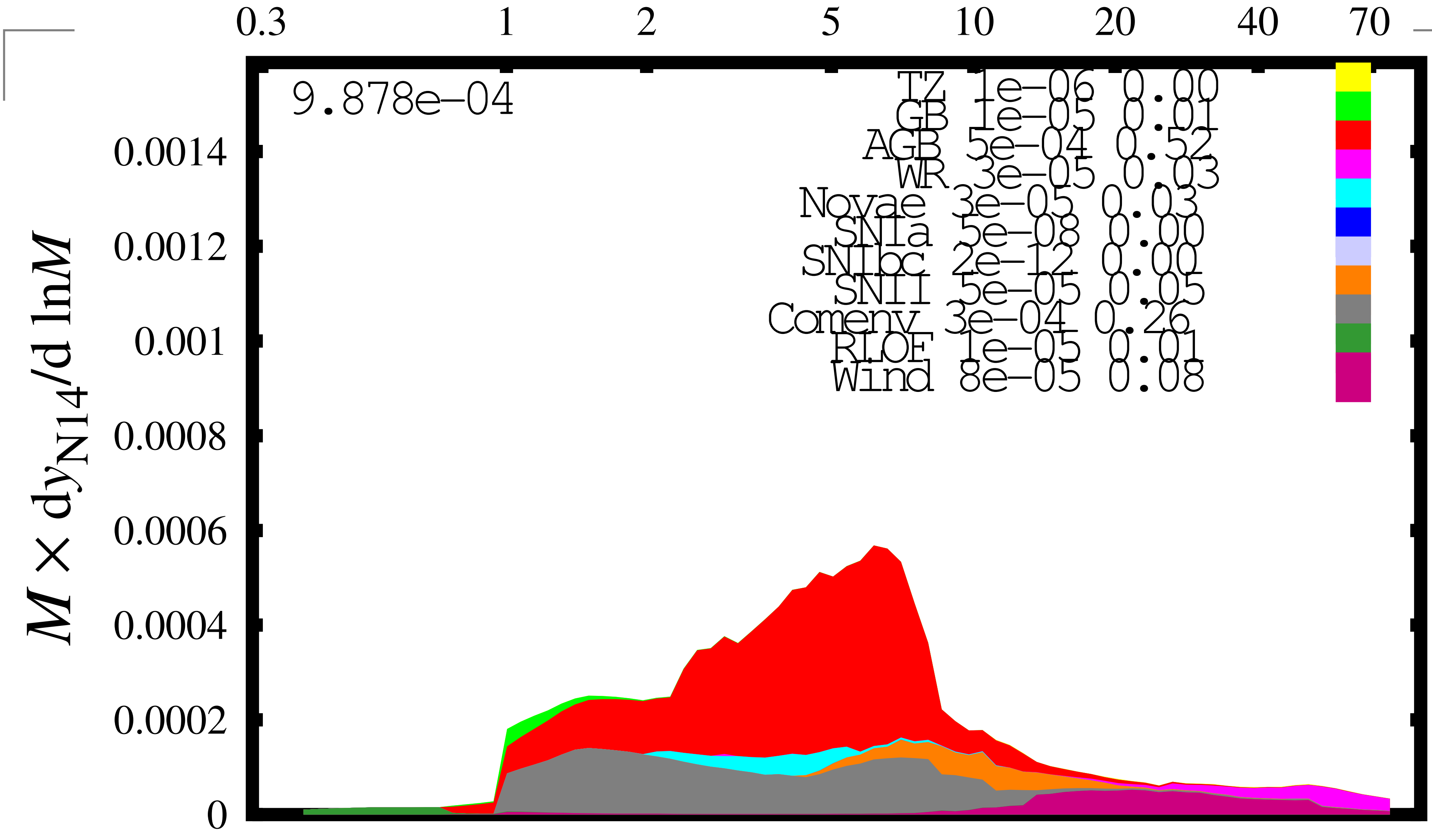
Binary stars are vital for GCE…

- Supernovae (Ia - but what are they?!)
- Novae (accreting WDs)
- Mass transfer (RLOF), pollution, wind collision
- Fewer giants
- Wolf-Rayet stars (SN Ib/c)
- …

Nitrogen Yield (Single Stars)



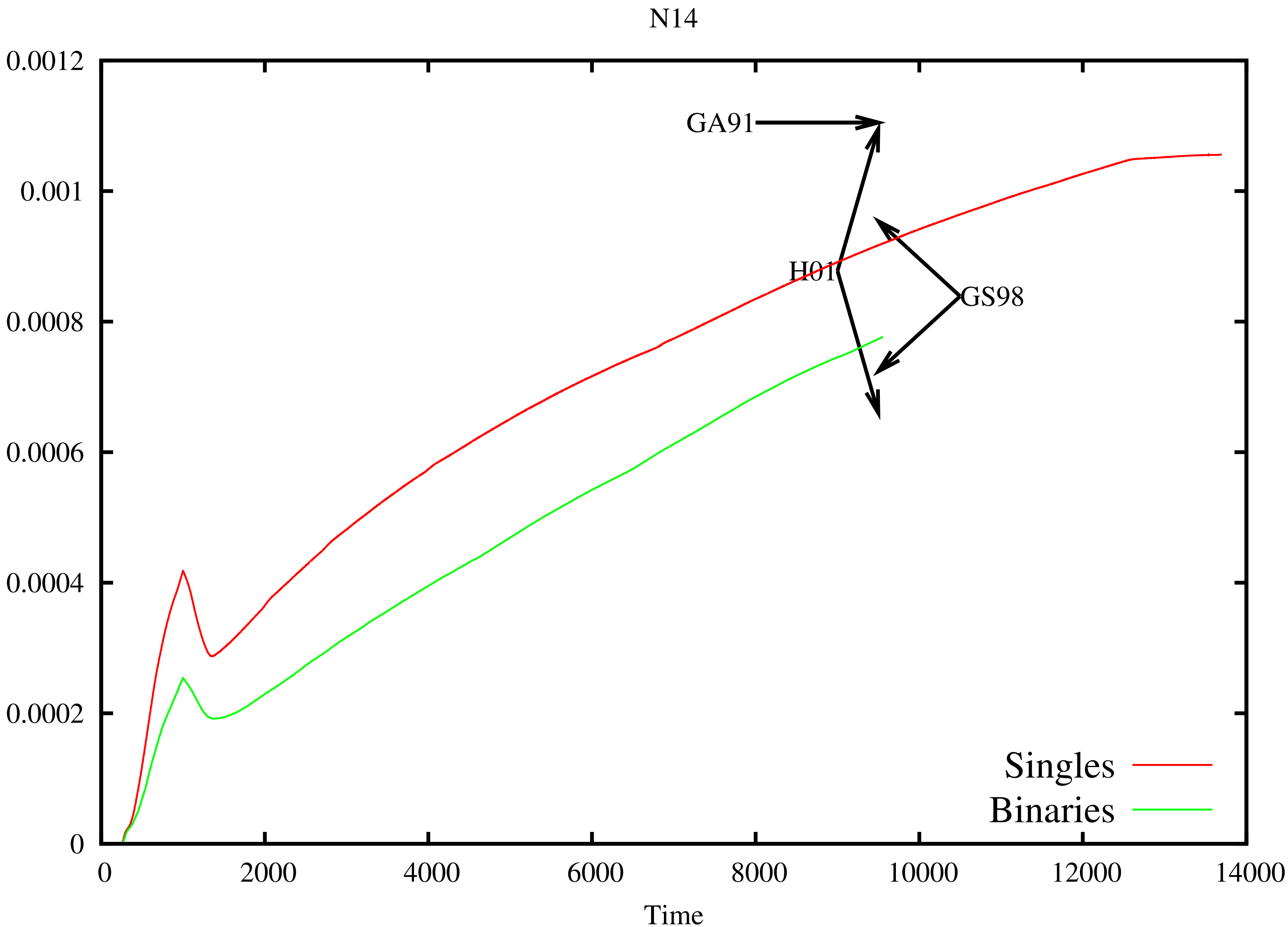
Nitrogen Yield (Binary Stars)



Yields from Single and Binary Stars

Isotope	Single Stars	Binary Stars	Source ($Z = 0.02$)
^{1}H $\times 10$	1.868	1.913	All stars
^{4}He $\times 10$	1.043	1.024	All stars
^{12}C $\times 10^3$	4.155	5.556	SN II,Ibc, WR stars, AGB stars
^{13}C $\times 10^5$	4.987	6.767	AGB stars, novae
^{14}N $\times 10^3$	1.294	0.988	AGB stars
^{15}N $\times 10^6$	1.195	2.069	novae
^{16}O $\times 10^3$	8.325	9.514	SN II, Ibc, WR stars
^{20}Ne $\times 10^3$	1.184	1.191	SN II, Ibc
^{24}Mg $\times 10^4$	3.675	4.208	SN II, Ibc, Ia
^{40}Ca $\times 10^5$	5.275	9.857	SN II, Ibc, Ia
^{56}Fe $\times 10^3$	1.019	2.482	SN II/Ibc ($1/3$), Ia ($2/3$)
Y $\times 10^9$	14.08	8.645	AGB

Effect on GCE: e.g. ^{14}N



Some Conclusions…

I now have

- A working GCE code integrated with single/binary stellar evolution,
- A test-machine which combines single and binary stellar evolution,
- nucleosynthesis,
- galaxy formation and evolution
- and stellar population studies

…and the future

Future plans

- Extend to other isotopes/elements (easy)
- Test other stellar evolution physics
- Extend to galactic radial gradients (perhaps!)
- Test star formation histories, especially in…
- Other galaxies (LMC, SMC, local group, Ly-α clouds?): integrated spectra?
- Explore effect of binarity on stellar populations: Ba-stars, R-stars, in/extrinsic C-stars, SNe Ia progenitors etc.

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