Modeling Fe Enrichment in Galaxy Clusters

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Outline

- Background to the problem
- Initial modeling equations (Standard Model)
- Results from the model
- Changes to the model to match ICM
- Overview of results
- Shortcomings and refinements

Galaxy Cluster Info

- Largest virialized objects in the universe $(>3x10^{14}M\ )$
  - Formed in extreme overdensities
  - Likely different from galaxies in the field
- Retain all (un)processed baryonic matter
  - In the form of stars and 3-10 keV plasma

Overview

- Model the interaction between the galaxies in the cluster and the ICM
  - Fe abundance
  - Star Formation Histories
  - Supernovae

- Prediction of ~0.1*solar Fe enrichment per baryon slightly underpredicts IGM abundances and is too low by about 4 times in ICM

Overview

- Why look at Fe?
  - Fe is created and never destroyed
    - Good tracer of supernovae activity
  - Intracluster plasma conditions make observing Fe abundances easier than other elements
    - Strong absorption lines in the optical
    - Strong emission in the X-ray

- Measurements taken between $z = 0$ and $z \sim 1$

Modeling (1)

$$\frac{d\rho_{\rm stars}}{dt} = \dot{\rho}_{\rm SF} - \dot{\rho}_{\rm MR},$$

$$\frac{d\rho_{\rm ISM}}{dt} = -\dot{\rho}_{\rm SF} + \dot{\rho}_{\rm MR} - \dot{\rho}_{\rm GW},$$

$$\frac{d\rho_{\rm IGM}}{dt} = \dot{\rho}_{\rm GW};$$

$$\frac{d{f^i}_{\rm stars}}{dt} = \frac{\dot{\rho}_{\rm SF}}{\rho_{\rm stars}}({f^i}_{\rm ISM} - {f^i}_{\rm stars}),$$

$$\frac{d{f^i}_{\rm ISM}}{dt} = \frac{\dot{\rho}_{\rm MR}}{\rho_{\rm ISM}}({f^i}_{\rm stars} - {f^i}_{\rm ISM}) + \frac{{\dot{\rho}^i}_{\rm SNIa}}{\rho_{\rm ISM}} + \frac{{\dot{\rho}^i}_{\rm SNII}}{\rho_{\rm ISM}},$$

$$\frac{d{f^i}_{\rm IGM}}{dt} = \frac{\dot{\rho}_{\rm GW}}{\rho_{\rm IGM}}({f^i}_{\rm ISM} - {f^i}_{\rm IGM}),$$

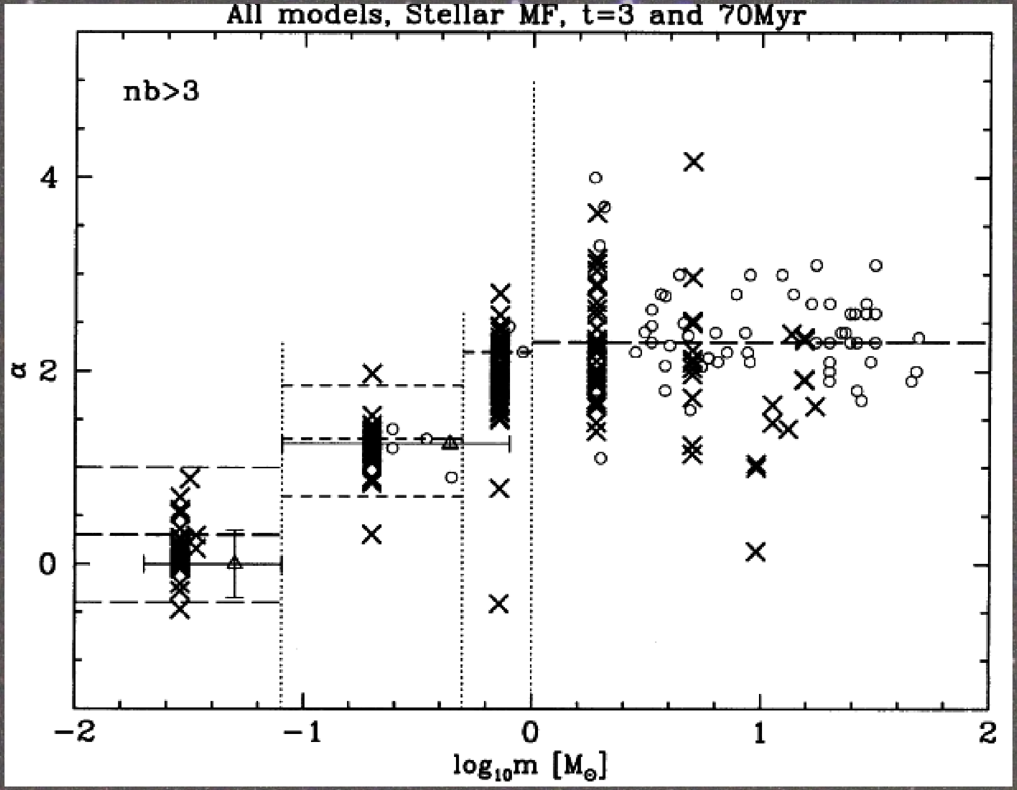
$$\dot{\rho}^i_{\rm SNII}(t) = K_{\rm SNII}\dot{\rho}_{\rm SF}(t)\langle {y_{\rm SNII}}^i\rangle,$$

$$\dot{\rho}^i_{\rm SNIa}(t) = n_{\dot{\rm SNIa}}(t){y_{\rm SNIa}}^i,$$

$$\dot{\rho}_{\rm GW}(t) = K_{\rm GW}(n_{\dot{\rm SNIa}}(t) + K_{\rm SNII}\dot{\rho}_{\rm SF}(t))\rho_{\rm ISM}.$$

Modeling (1)

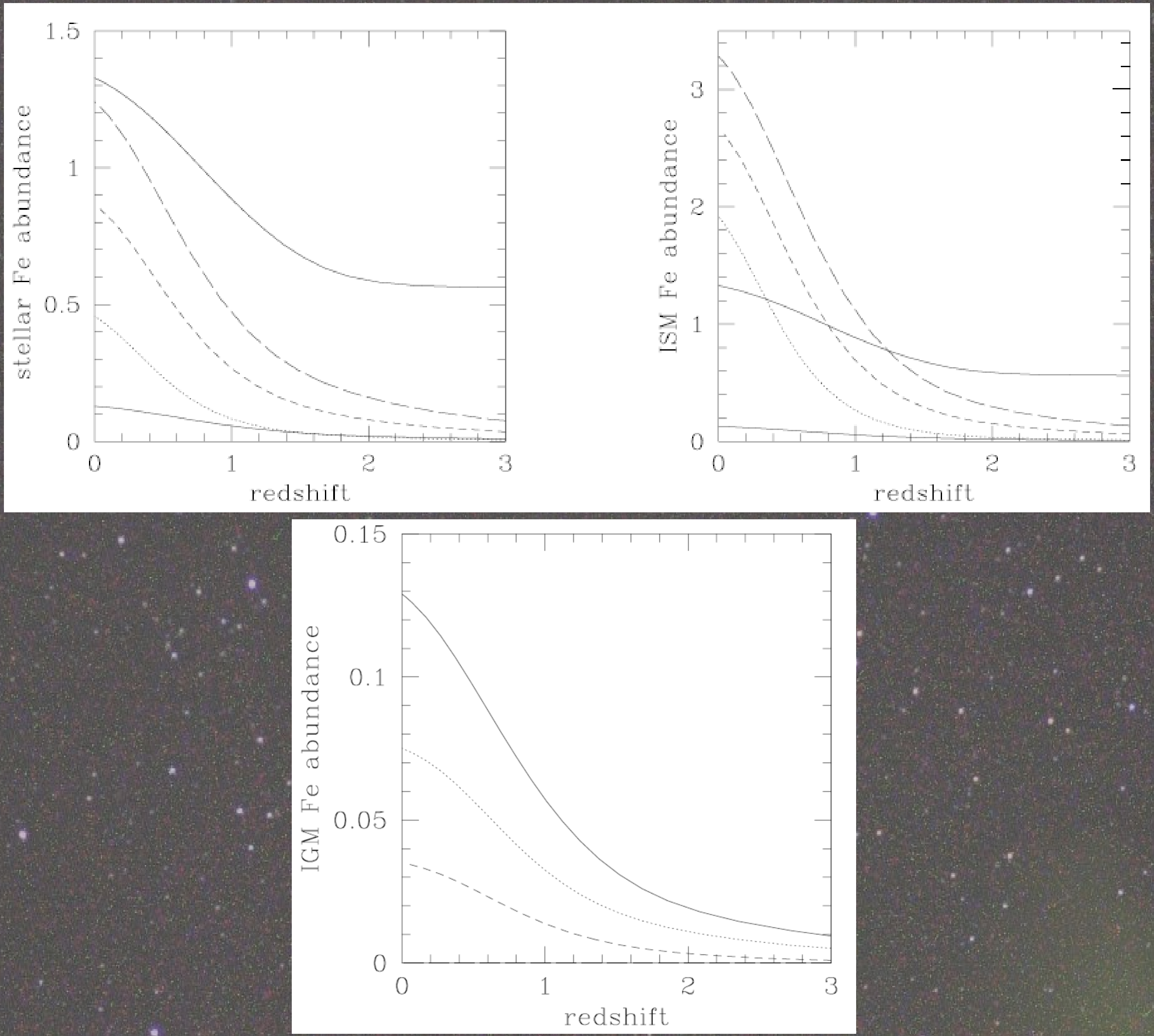
- Initial model of the universe
- 4-part piecewise IMF – Kroupa (2001)



Modeling (1) Results

- The results are given as the fiducial model labeled as 1N2.3
  - Model is integrated over a Hubble time
  - Results give total Fe enrichment yield of 0.13 averaged over all baryons
    - Max wind falls slightly short of observed Fe in IGM
  - Model predicts SNII and SNIa rates consistent with observations
  - Underpredicts abundances seen in ICM by ~4

Modeling (1) Results



Model Changes

How do we change the model to fit cluster data?

- Use top-heavy IMF
  - Enhances formation efficiency of SNII and possibly SNIa
  - Higher average SFR (more SNII and SNIa)
  - Higher average Fe yield per SN
  - Significant enrichment from pregalactic stars

However, we see relative dearth of SN…

Model Changes

How do we change the model to fit cluster data?

- Extend the galactic outflow to transport more Ia metals
  - Ram pressure stripping
  - Efficient winds from galaxy subpopulation
  - Suppression at early epochs of conversion efficiency of SN energy to outflow KE
- Two different long duration winds modeled:
  - Constant wind ‘Wc’
  - Exponential wind ‘Wx’

Model Changes

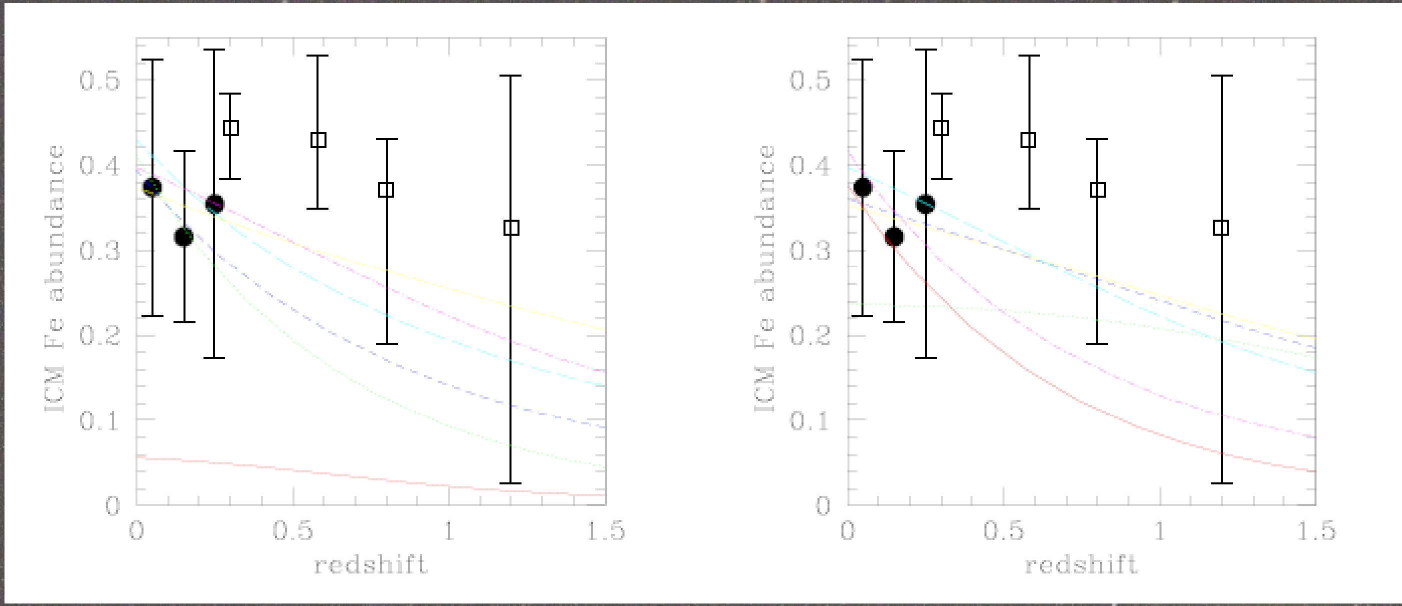
How do we change the model to fit cluster data?

- In clusters, most massive (elliptical) galaxies were assembled and SF completed at $z > 1$
  - SFR enhancement added to some models – rapid mode ‘R’ or hybrid mode ‘H’
  - Models with ‘2’ before ‘H’ or ‘R’ produce twice the universal average of the present-day baryon fraction in stars

Modeling (2) Results

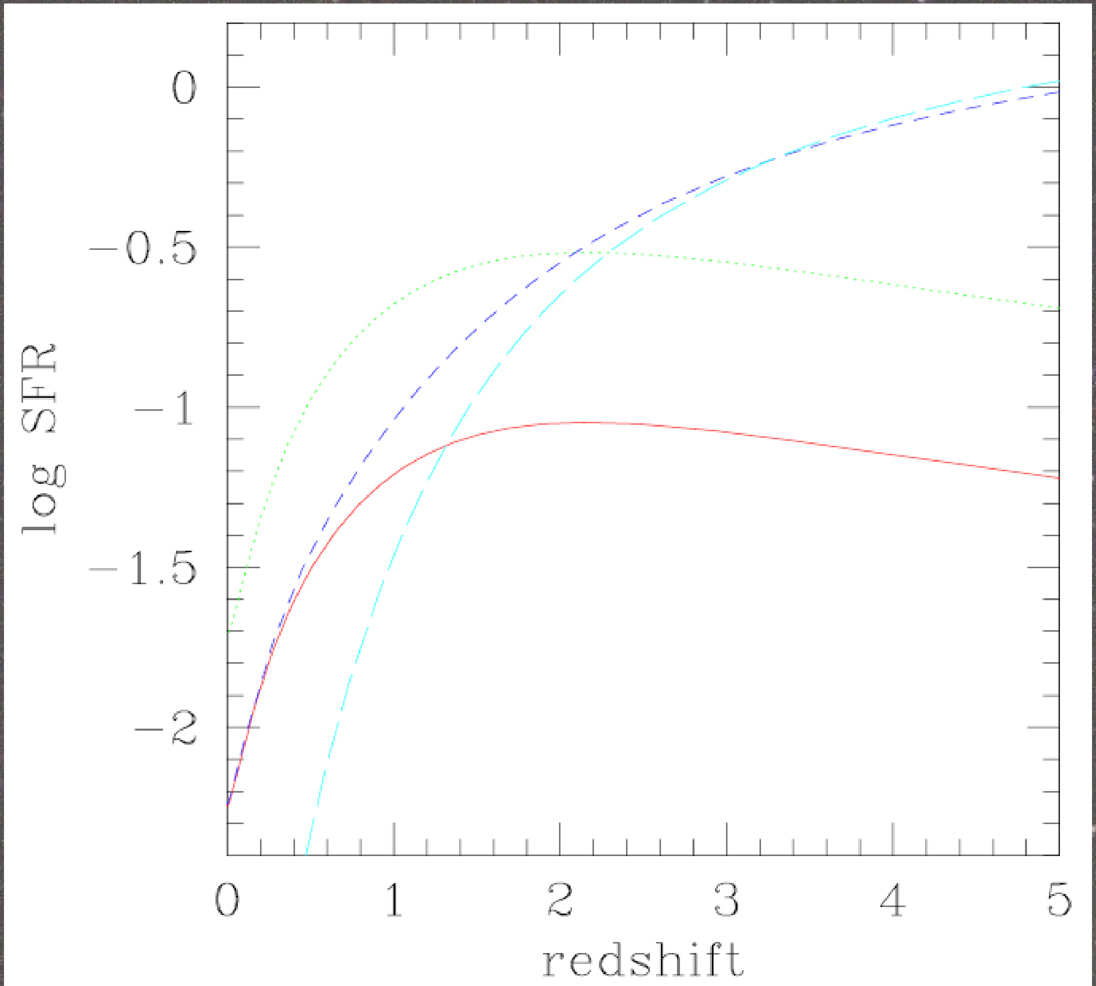
Model shows improvement in abundance trends

- Runs 2H1.3Wx, 2R1.55Wx are best fit
  - Reach ~0.4 Fe abundance measurements in ICM



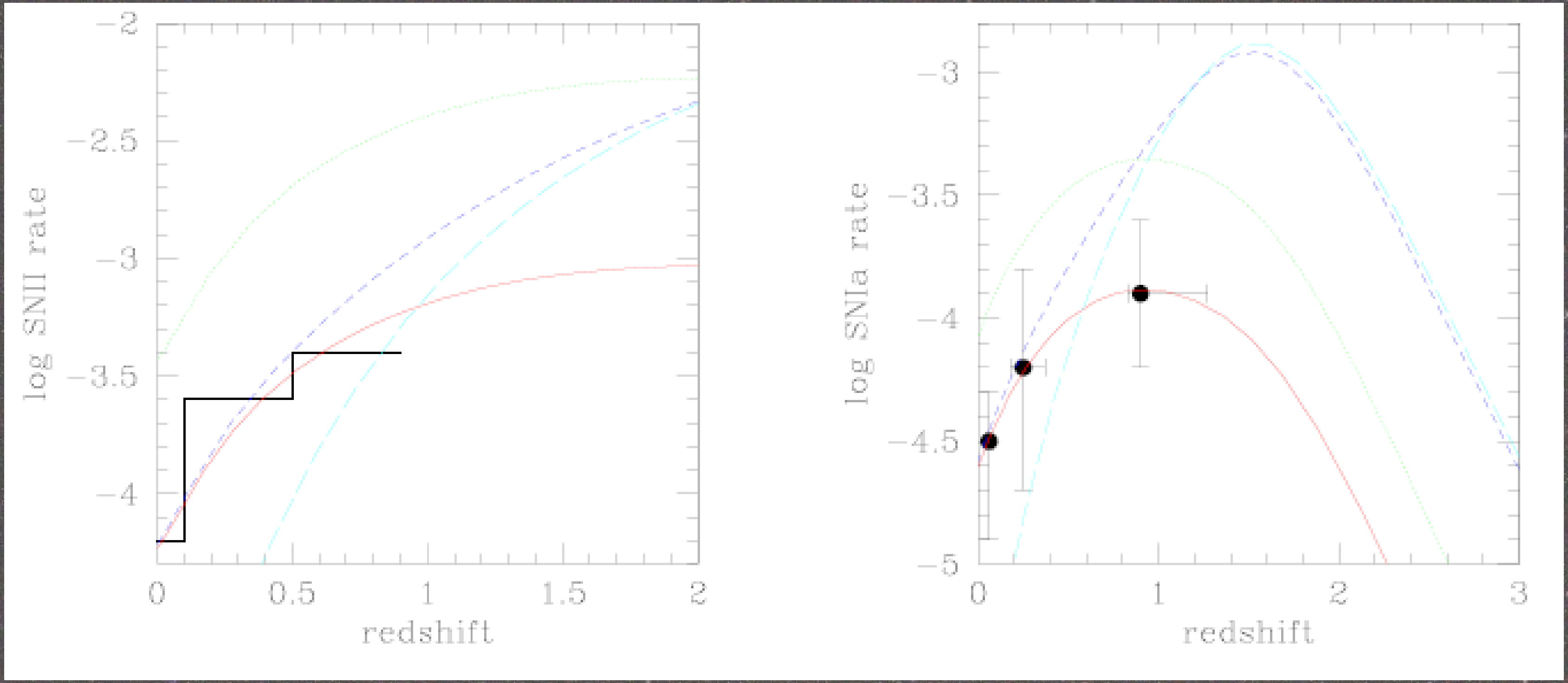
Modeling (2) Results

Model inconsistent with SF rates



Modeling (2) Results

Model inconsistent with SN rates



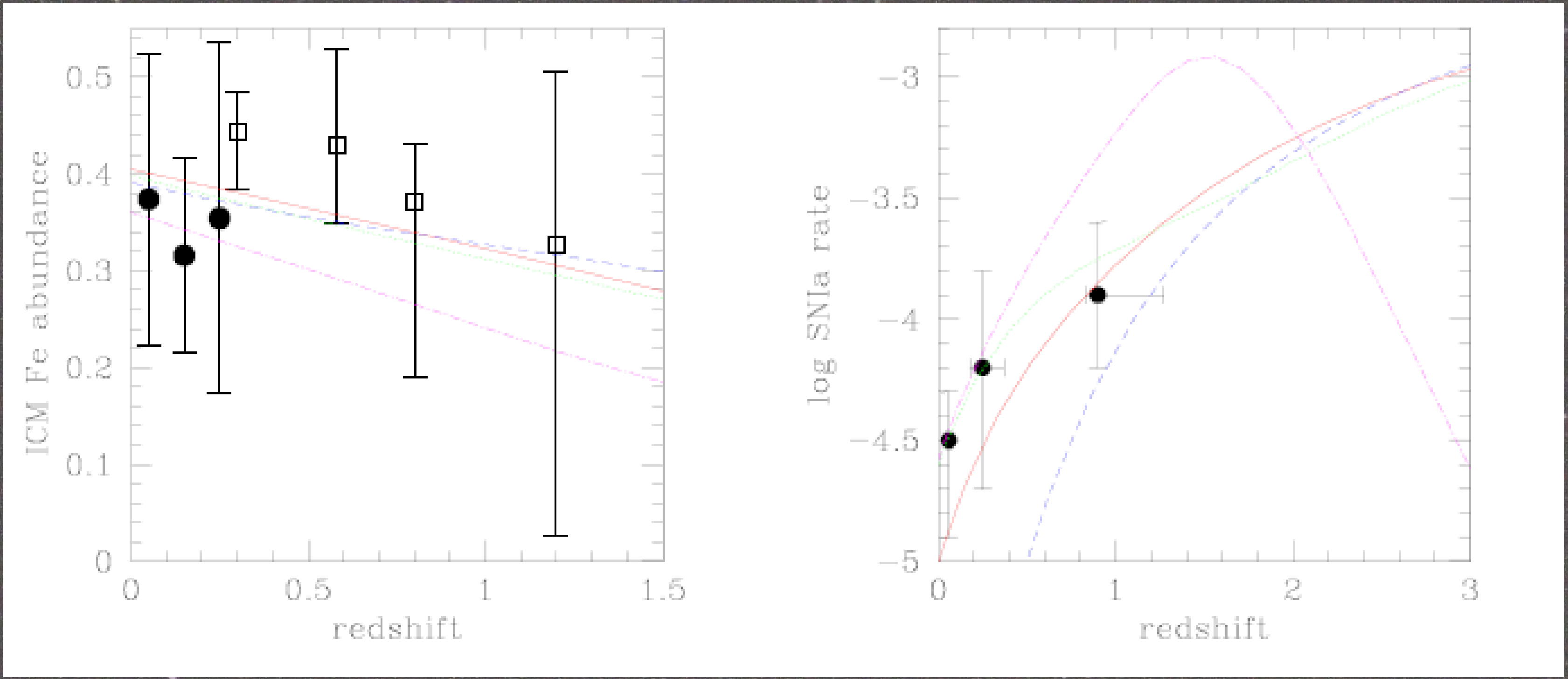
Further Model Changes

How can we fit the SF and SNIa rates better?

- Reduce the SNIa delay time
  - Recall SNIa occur ~3Gy after SF begins (SNII)
  - Change to 0.5 Gy
    - Based on work showing there may be two modes of SNIa (short delay and long delay)
    - Represented by ‘St’ on models

Modeling (3) Results

Hybrid models better fit to Fe abundance and SNIa rates



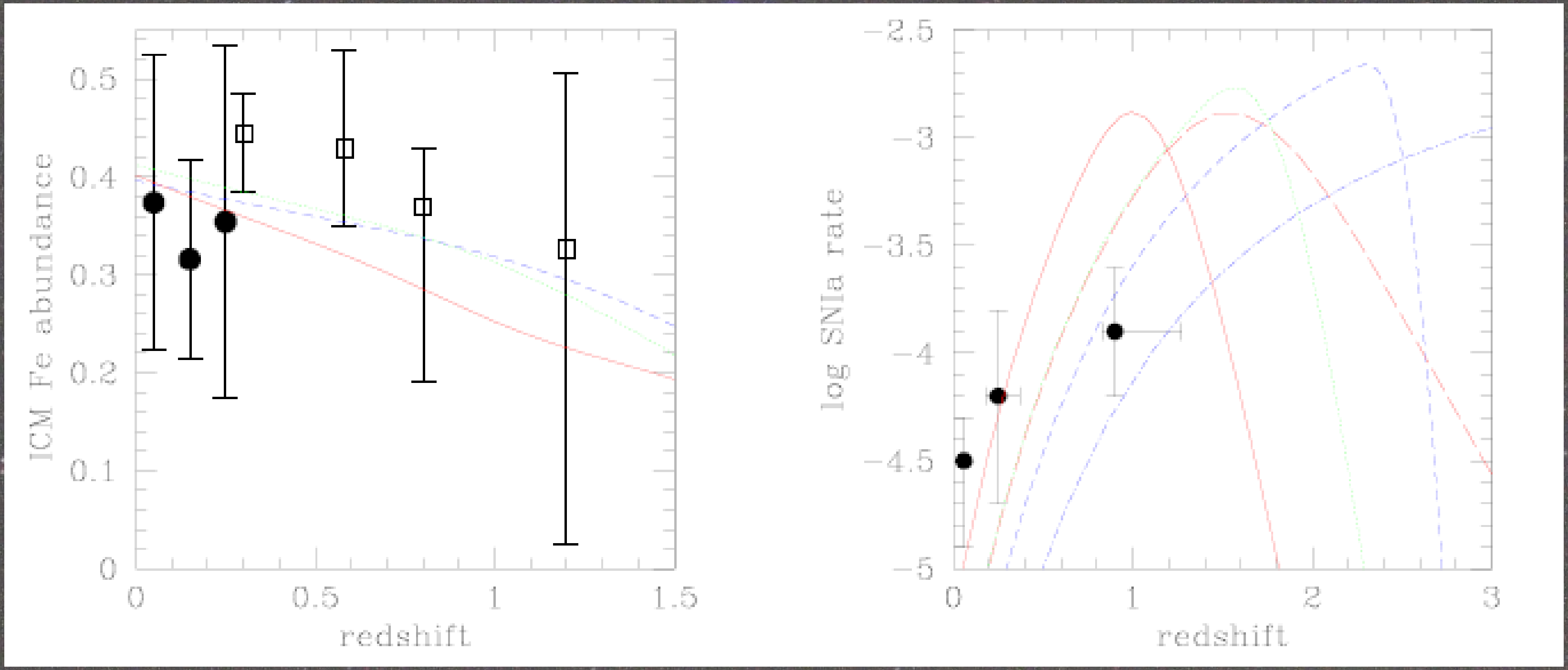
Yet More Model Changes…

How can we improve the rapid mode fits?

- Reduce the formation redshift
  - Allow rapid mode models to initiate SF at z = 3 instead of at z = 10 (for other models)
    - Add ‘z’ suffix to the model runs
  - Try different delay times of 3, 1.5, and 0.5 Gy on these models as well

Modeling (4) Results

Rapid model with 0.5 Gy delay time improves its fit with Fe abundance and SNIa rates



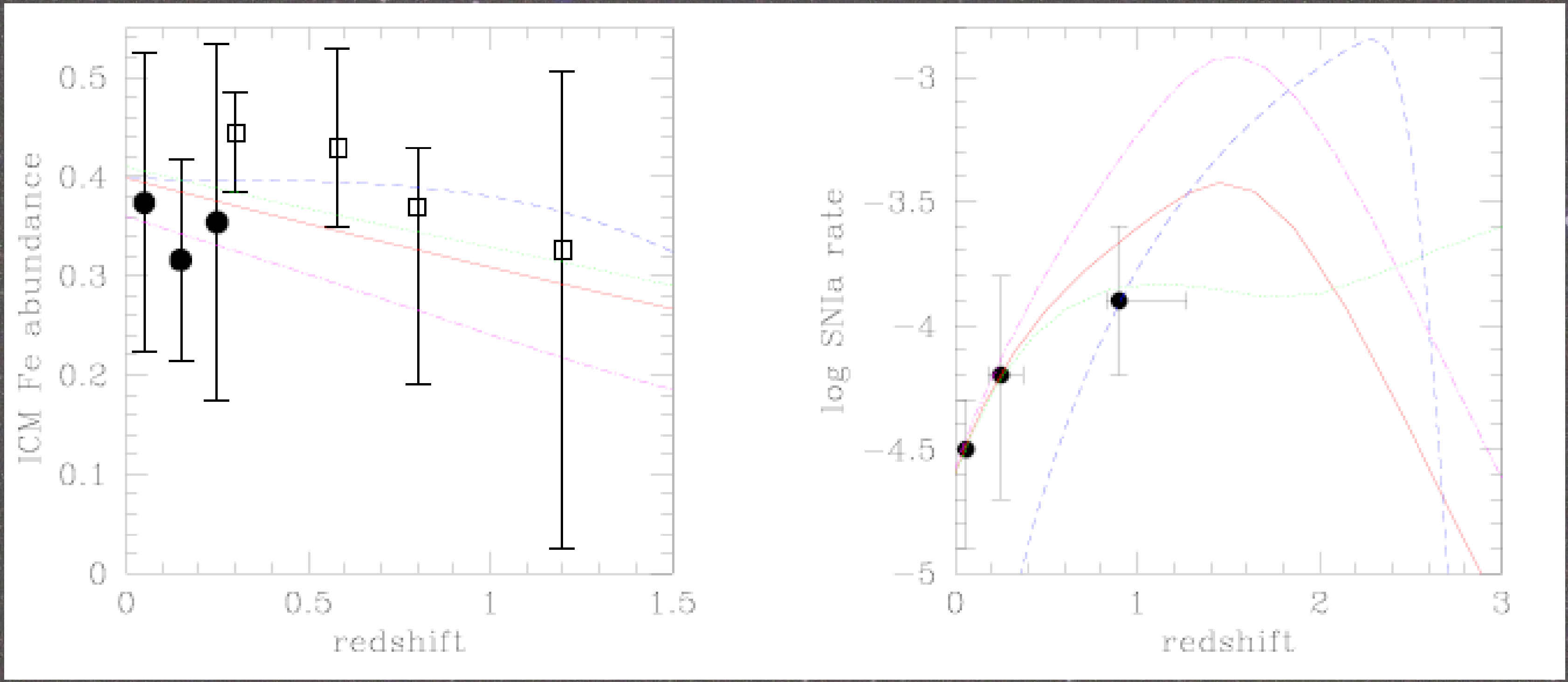
OMG Please Stop With The Model Changes

How can we fit the SNIa rate plot even better?

- Natural reduction of the SNIa rate
  - Assumes that a universal fraction of 3-8M stars form SNIa progenitor binaries
  - Reduce rapid mode SNIa rates in models
    - Add ‘n’ suffix to the model runs
  - Must increase SNII Fe yield from 0.07M to 0.10M to compensate
    - This maneuver not physically justified

Modeling (4) Results

Hybrid models with naturally reduced SNIa rates



Model Results Overview

1. Initial assumption that clusters are representative samples of universe is a bad one
2. Fe enrichment orginates in ~ comparable fractions of SNIa and SNII
3. SNIa delay requires extended duration outflow but not too long
4. Implied SNIa rates are somewhat at odds with observations
5. Best fit models have short time delay with type II domination

Model Results Overview

6. Star formation must be fundamentally different between clusters and the field

7. >25% of Fe must be locked up in galactic ISM to get ICM enrichment

Shortcomings and Refinements

- Fe abundance observations need the error bars reduced
- What happens when infall is considered?
- What is the effect of a dual-phase ISM?
- What is the Fe contribution of Pop. III stars at high redshifts?