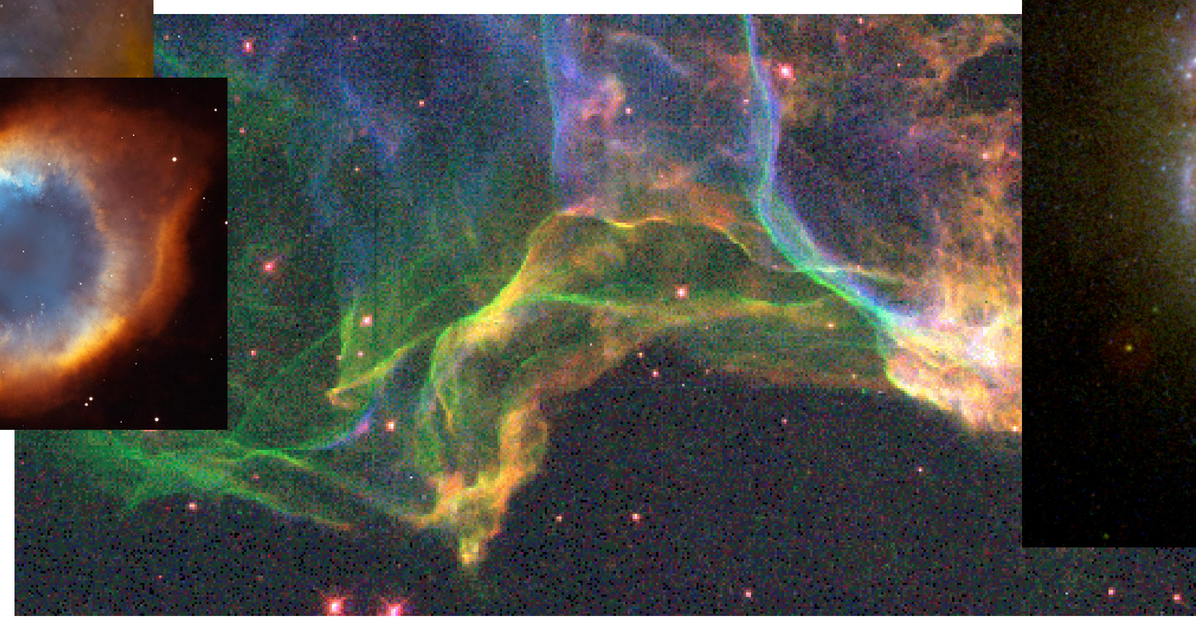
Galactic

Chemical Evolution

For Neophyte Chemical Evolutionists

see also R. Diehl lectures



Brian Fields

U. of Illinois

NIC School, Argonne, July 2008

Collaborators

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Galactic Chemical Evolution

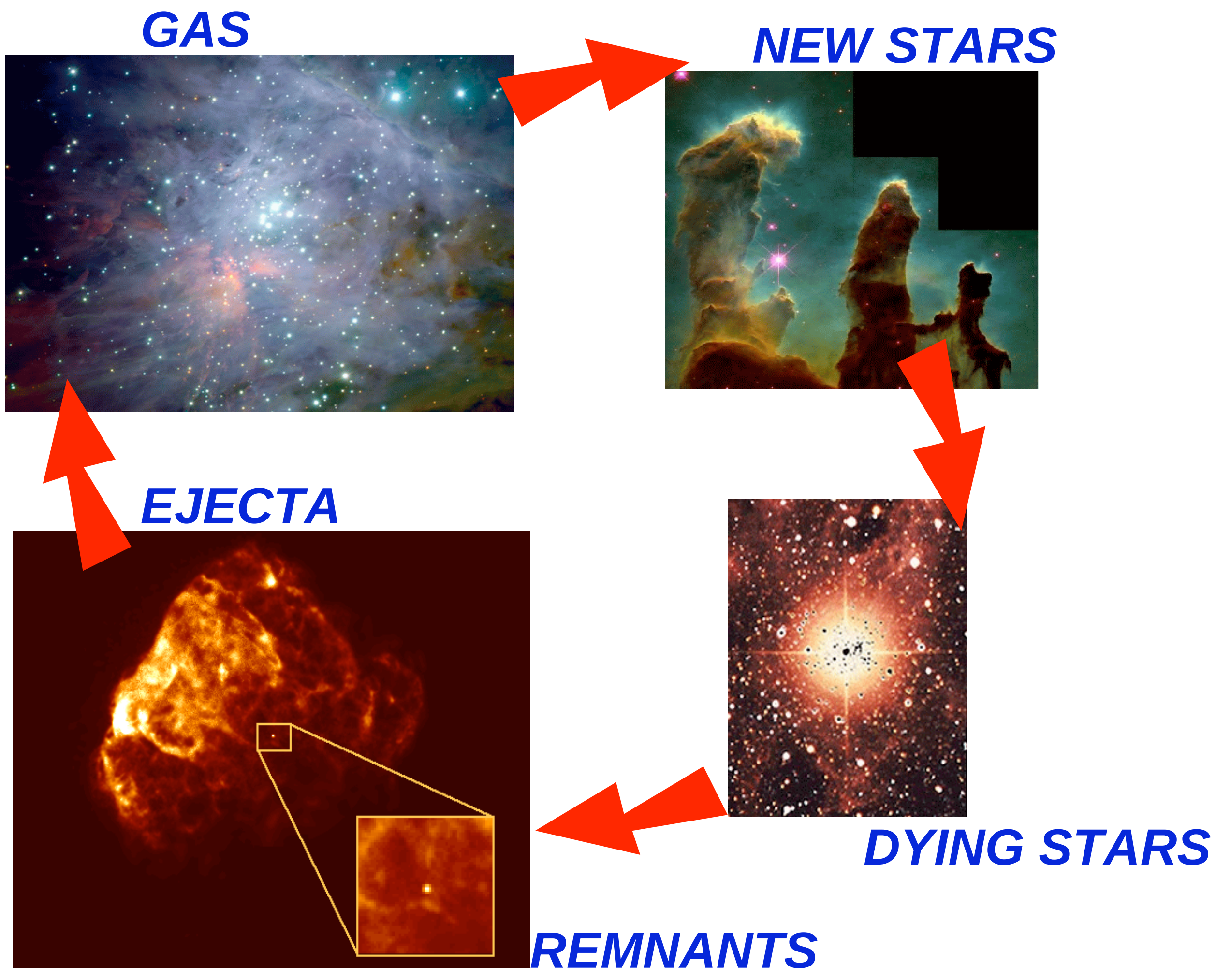
The Cosmic History of Baryonic Matter

- ★ **what's the problem?**
  - how has baryonic matter evolved nucleosynthetically?
- ★ **how will we solve it?**
  - model the cycling of matter from big bang and through generations of stars
- ★ **what are the answers?**
  - predictions for abundance patterns
- ★ **open questions?**

Overview

The Basic Idea

- ★consider a star forming system;
  - e.g., our Galaxy, other galaxies, or a protogalactic subhalo
- ★baryons cycle thru stars: abundances altered by nuke processing
- ★every parcel of baryonic matter records the nucleosynthetic history of cosmic & stellar events



Appropriate Humility

- chem evolution: top of food chain

  lofty goals, but many nontrivial ingreidents

  e.g. galaxy formation and evolution, star formation, stellar evolution and nuke, interstellar chemistry, ...

  significant uncertainties in each, so large uncertaintes in final results

- so what's chem evolution good for?

  IMHO: checking to see if self-consistent scenarios are possible

- caveat emptor

  theory still crude, results model-dependent

  only now beginning to be integrated into larger cosmological framework (hierarchical assembly)

Solar System Abundances

Rosetta Stone of Nuclear Astrophysics

sums cumulative nucleosynthesis up to birth of solar system

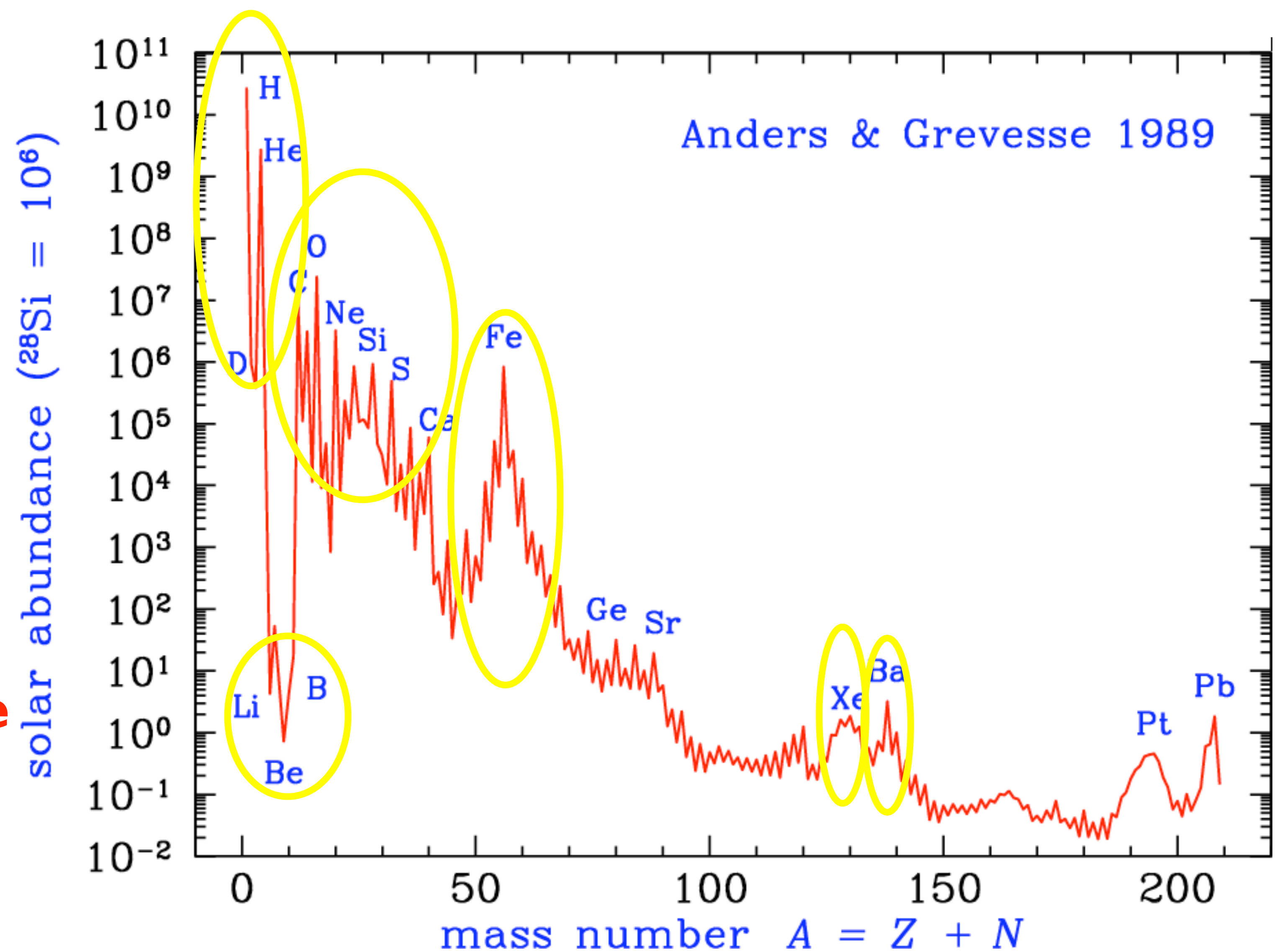
nuclear physics written into the matter around us

- **odd-even effect**
- **max binding at ^{56}Fe**
- **min binding for D, Li, Be, B**

multiple processes at work

- **big bang**
- **cosmic rays (spallation)**
- **alpha elements: core-collapse SN**
- **Fe peak: nuke stat equil**
- **neutron capture: slow, fast**

integrated yields and rates for different sources must give these



Observables:

Abundances in Milky Way Stars

Stellar atmospheres:

- (elemental) abundances *at star birth*

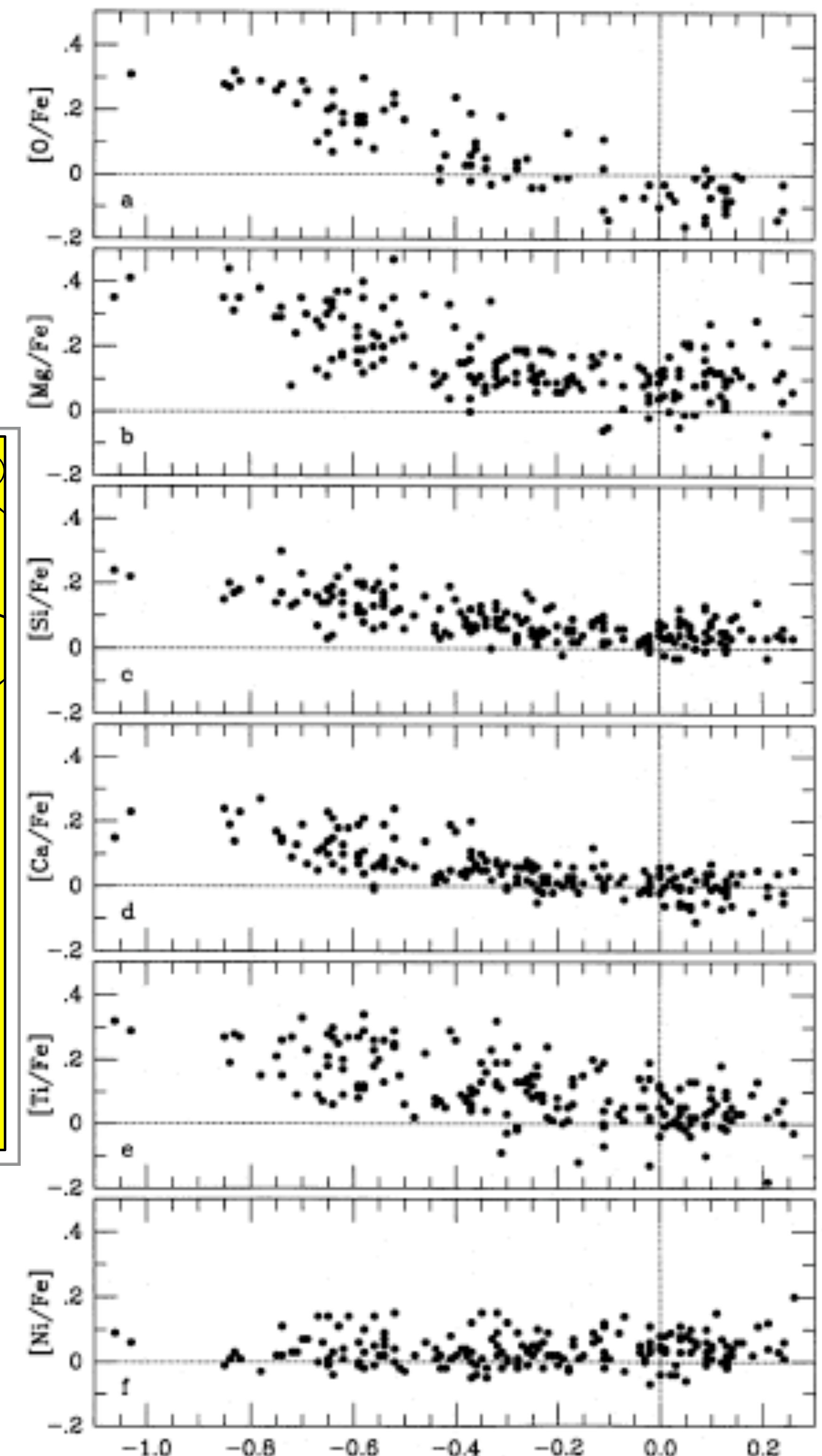
Observable for

- younger stars (disk, Population I)
- olders stars (stellar halo, Population II)

Iron: easy to observe, “metallicity” measure

Clear trends in A/Fe

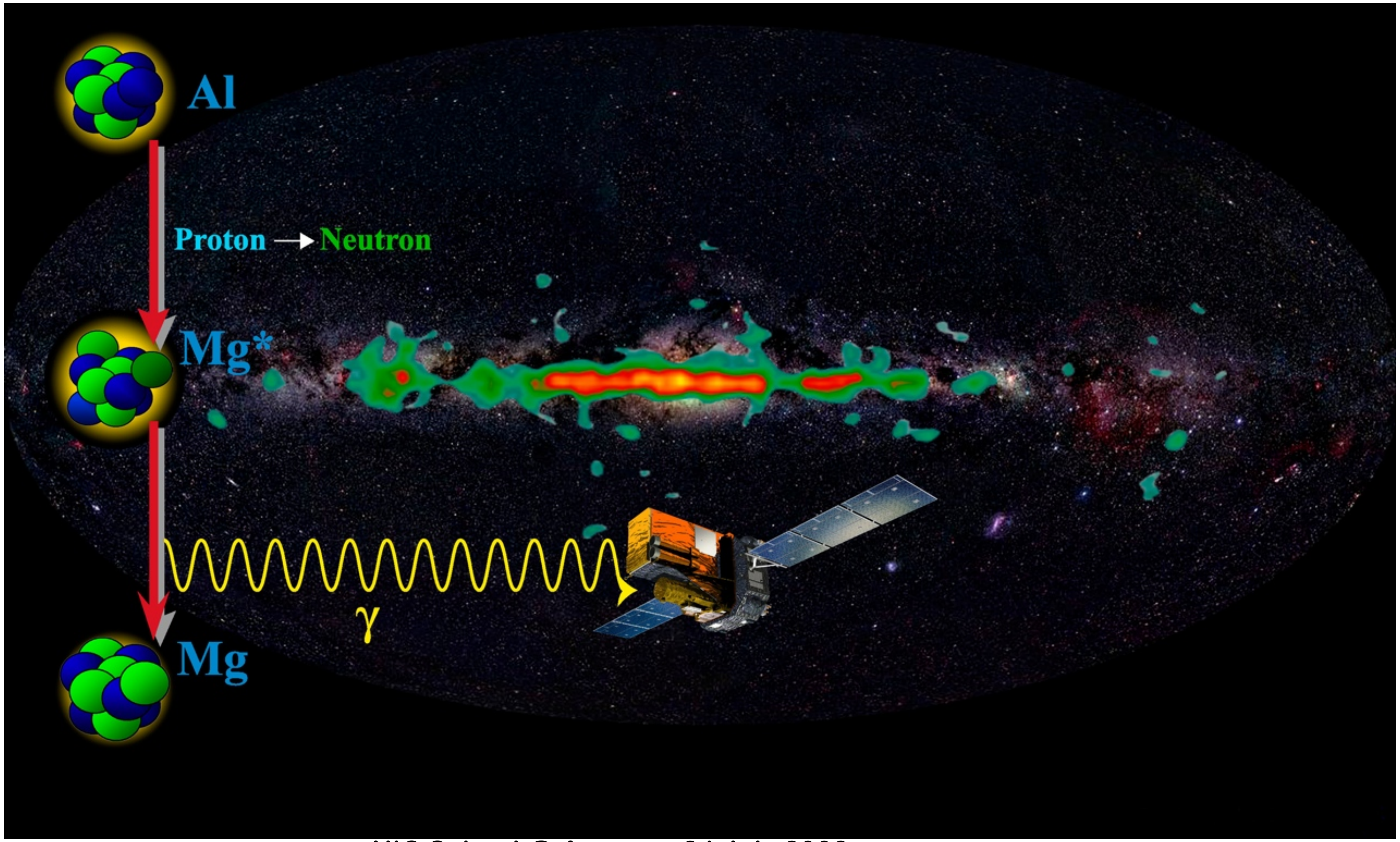
$$[A/Fe] \equiv \log_{10} \frac{(A/Fe)_\star}{(A/Fe)_\odot}$$



$$[Fe/H] \equiv \log_{10}(Fe_\star/Fe_\odot)$$

Observables:
Gamma-Ray Lines
Fresh nucleosynthesis products directly imaged with isotopic sensitivity in real time

see R. Diehl talk



Stellar Physiology: Lifetime & Mass

Stellar fate and lifespan set by *energetics*

Energy output: *radiation*

$$L = dE_{\rm emitted}/dt \sim m^4$$

$$E_{\rm emit,tot} \simeq L\tau$$

Energy reservoir: *mass*

$$E_{\rm nuke,tot} \sim m$$

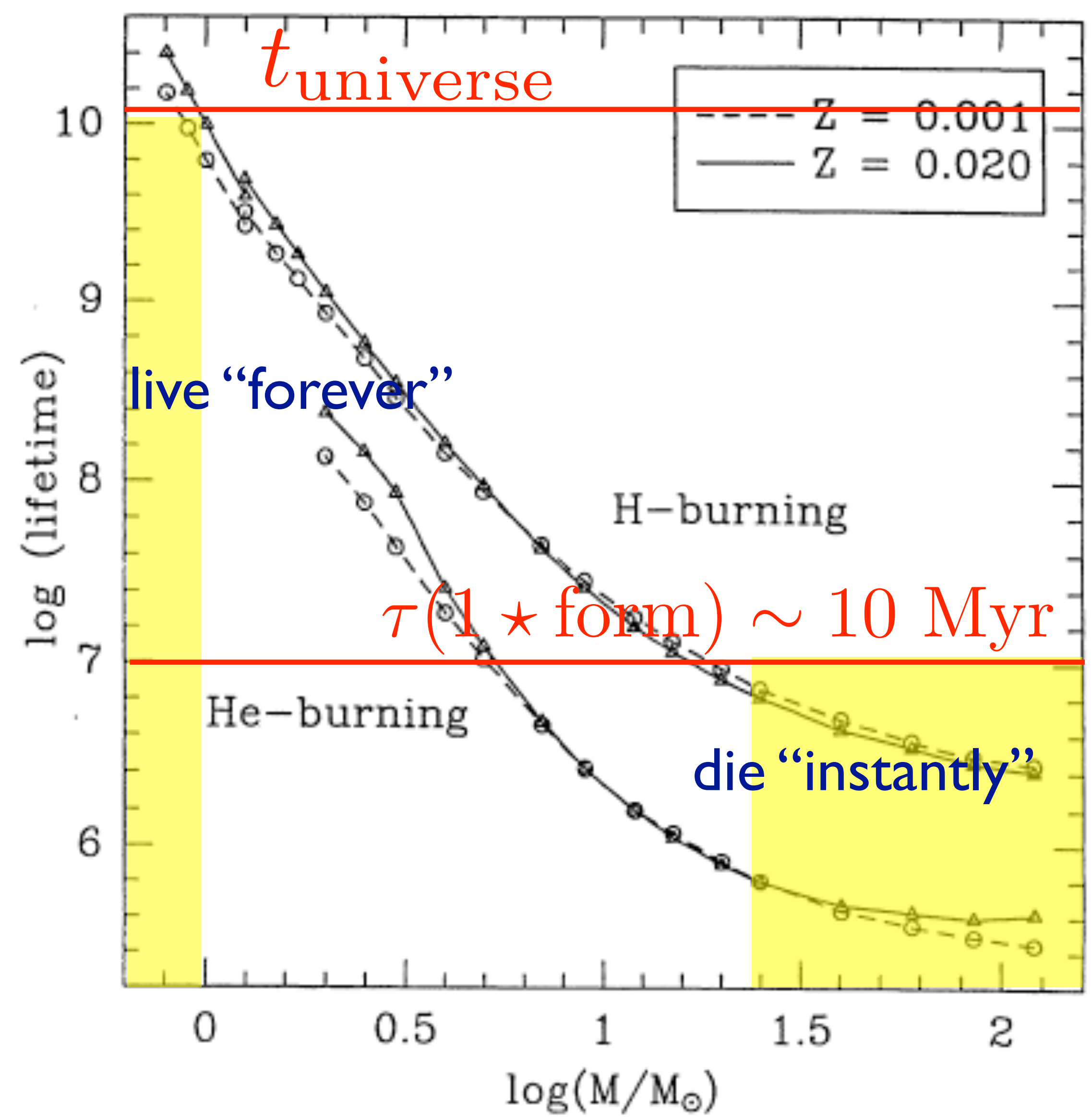
Finite fuel = finite lifetime

Stars must die

Stars have life cycles

Lifespan highly mass-dependent

$$\tau \sim E_{\rm nuke,tot}/L \sim m^{-3}$$



Stellar Sociology:
Initial Mass Function

Star masses range from ~0.1-100 M_{sun}

But not all masses equally likely to be formed

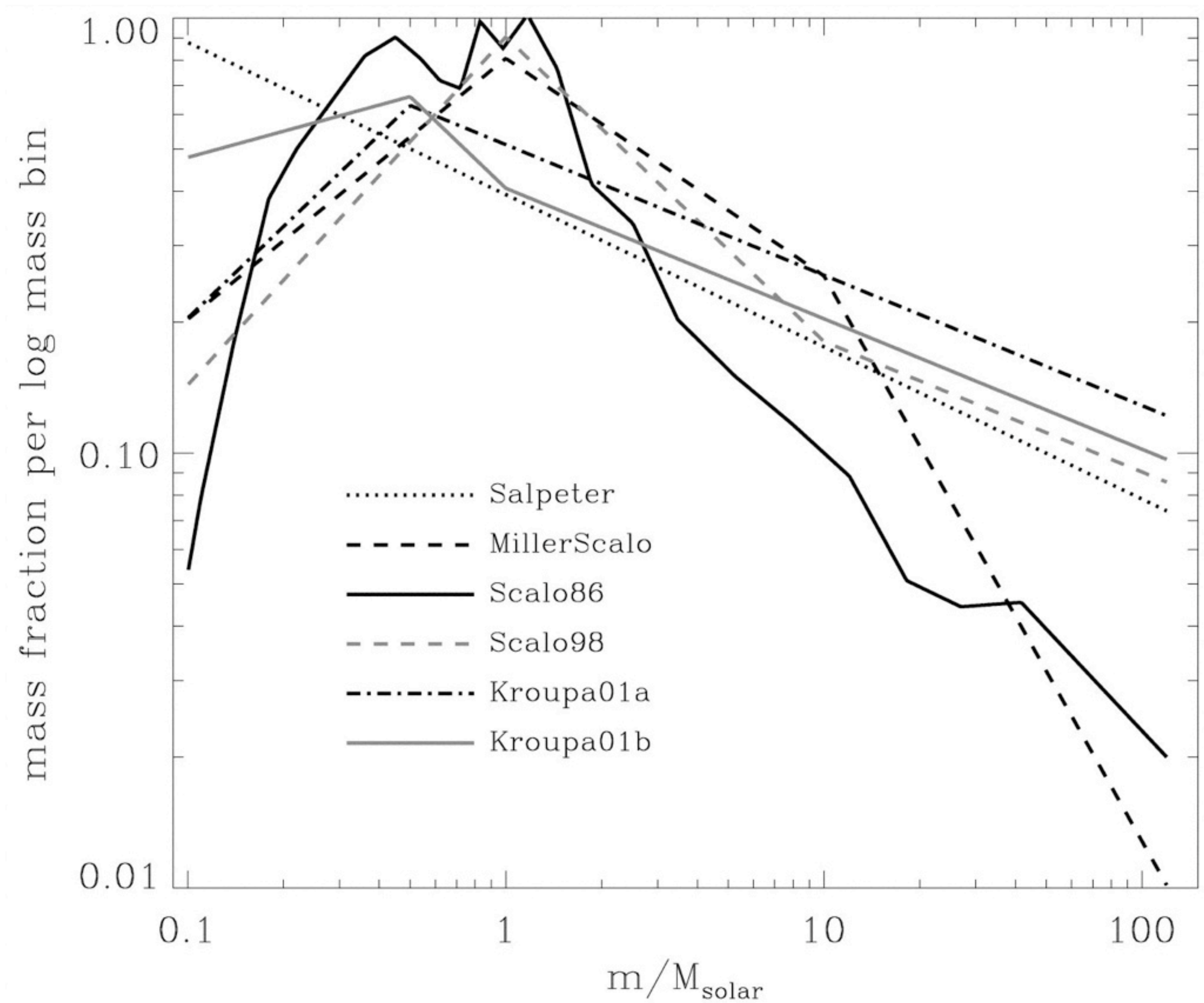
Distribution of masses at birth: ***initial mass function***

Detailed shape highly uncertain

- lowest mass stars very dim
- highest mass stars bright but very rare

General trends clear

- most stars have low mass
- massive stars uncommon



Star Formation Rate

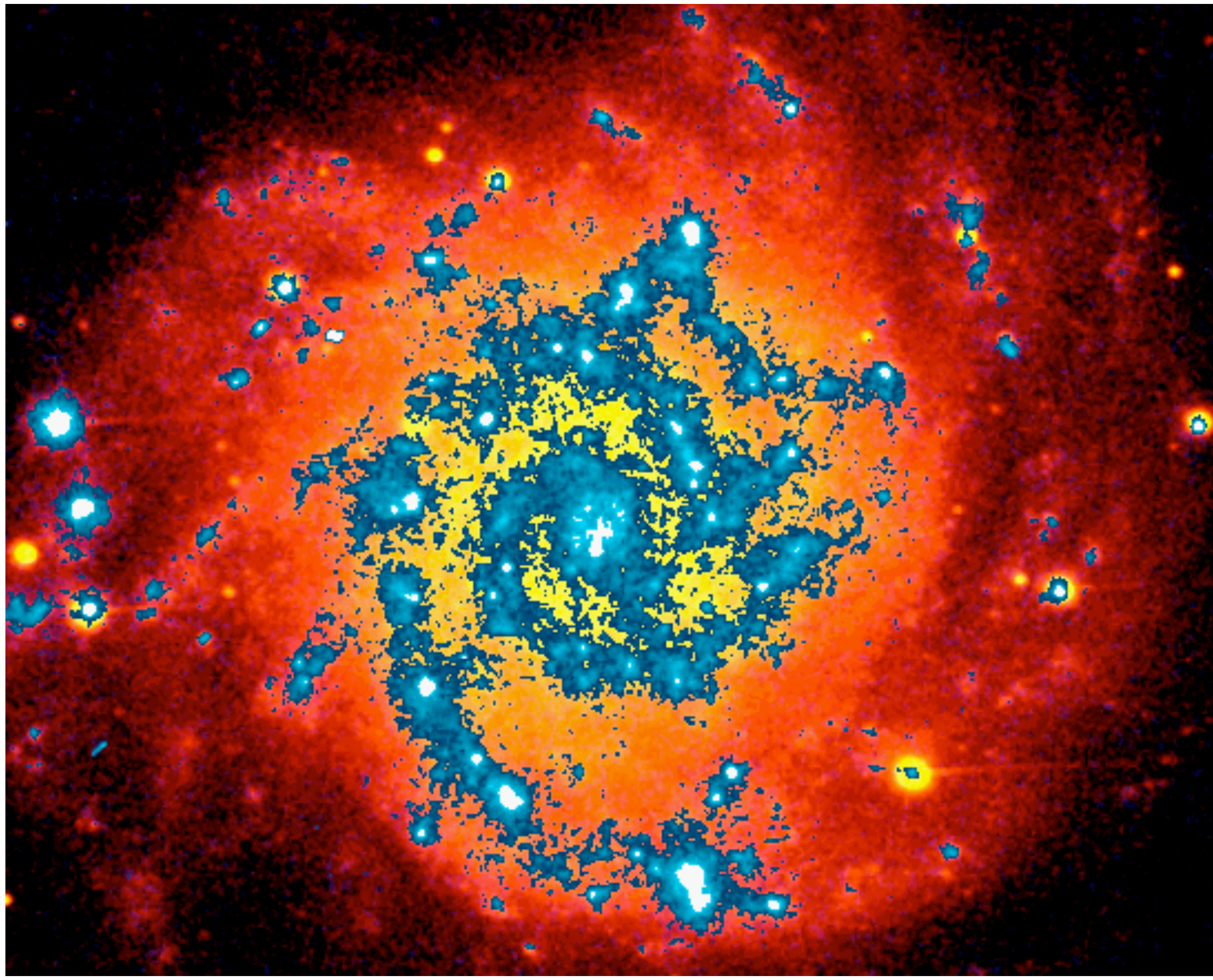
Put it together:

when stars formed,

- **high-mass** stars bright, blue, short-lived, rare
- **low-mass** stars dim, red, long-lived, common

observationally:

- **high-mass** stars trace "instantaneous" star formation rate
- **low-mass** stars trace integrated star formation history



M74: Red and UV

Cosmic Star Formation Rate Present Data

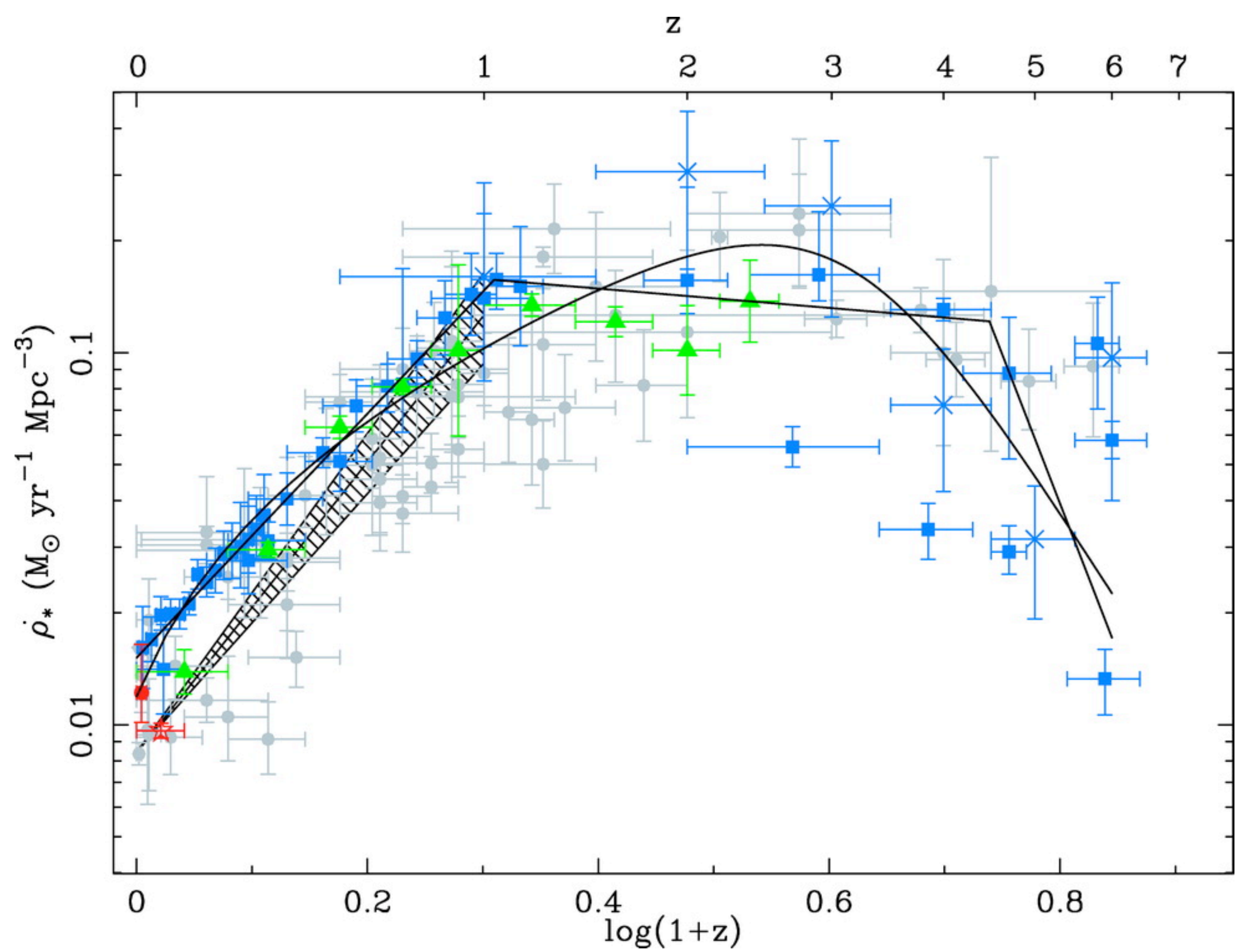
Cosmic average star formation rate per comoving volume

Clear trend:

- rate much higher at redshift z~1-2: t~4 Gyr ago

Not so clear:

- normalization
- high-redshift behavior



Hopkins & Beacom

Cosmic Star Formation Rate Future Prospects

Sky Survey Supernovae

will repeatedly scan large portions of sky

LSST: will discover ~10^5 supernovae per year!

(total recorded from SN1006 to now: ~5000)

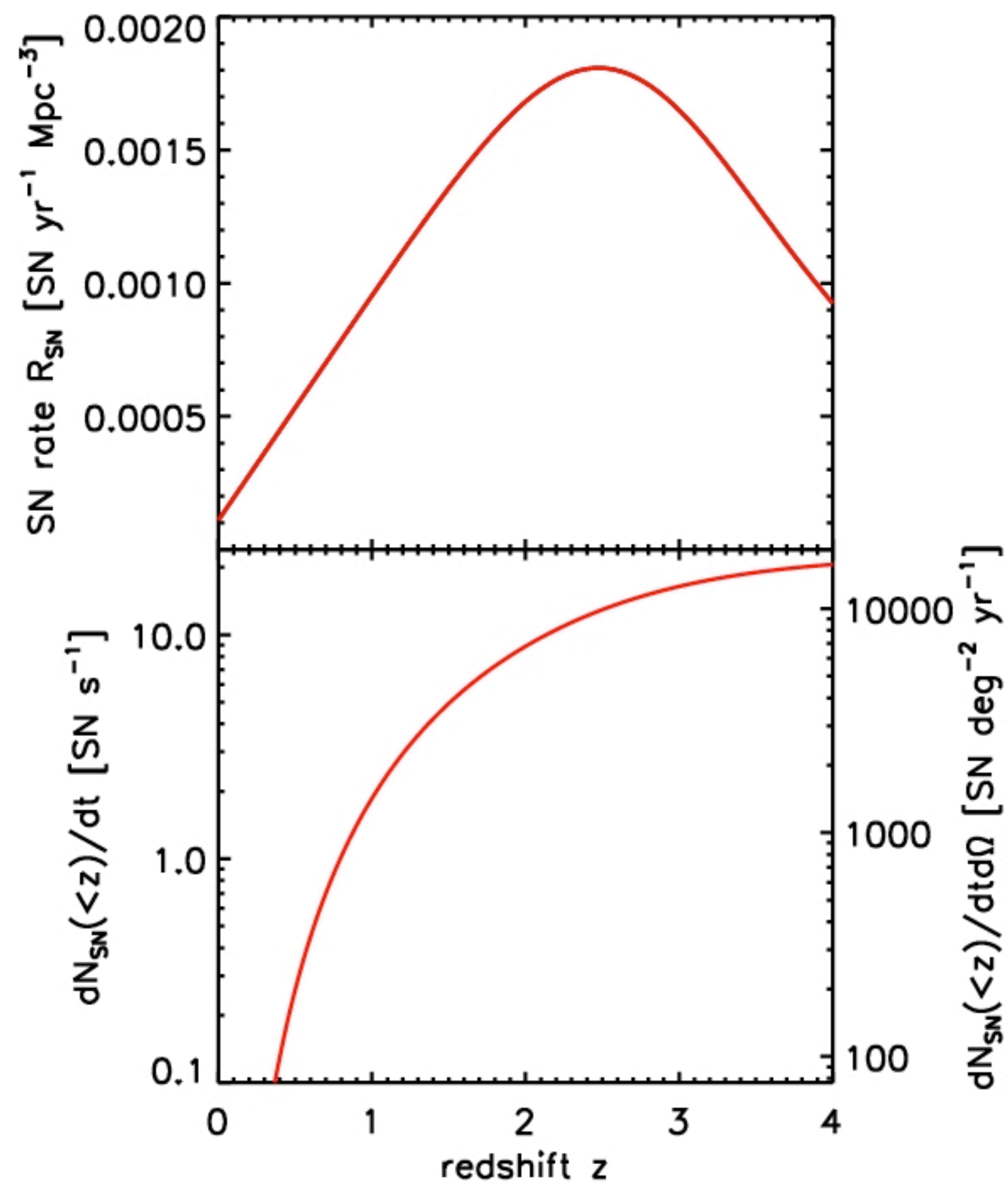
SN rate by direct counting

gives star formation rate normalization

Gamma-Ray Bursts

likely a subset of SNe

if so, cosmic burst rate gives SN rate, SF rate



Lien & BDF

Chemical Evolution Models

Basic Equations: Mass Conservation

divide baryons into gas and stars

$$\dot{M}_{\rm tot} = \text{infall} - \text{outflow}$$
$$\dot{M}_{\star} = \text{star formation} - \text{ejecta}$$
$$\dot{M}_{\rm gas} = \dot{M}_{\rm tot} - \dot{M}_{\star}$$

for each nuclide *i* in gas, with mass fraction $X_i = \frac{M_{{\rm gas},i}}{M_{\rm gas}}$

$$\dot{M}_{{\rm gas},i} = -X_i(\text{star formation}) + \text{ejection}_i$$

results: masses, composition vs time

Results:
Galactic Abundance Trends

Abundance Ratios

if all sources made elements in same ratio, observed values constant

thus changes in ratios reflect differe sources

- mass variation of yields
- new nuke mechanisms

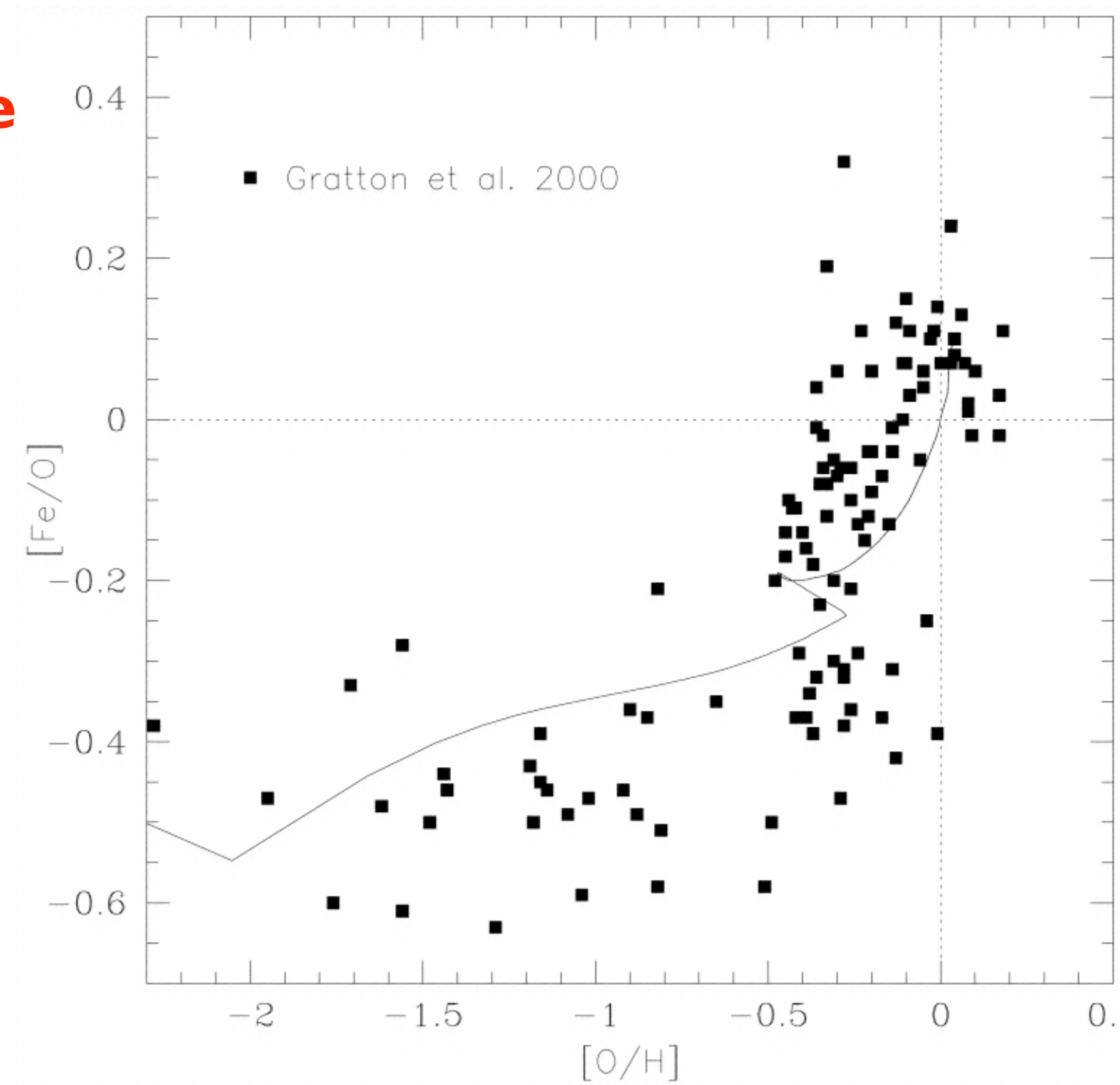
Canonical Example: O/Fe

at low Fe: Fe/O < solar

but low Fe: early times--only SN II

at last times: higher Fe--SN Ia

solar Fe ~ 2/3 from Ia, rest from II



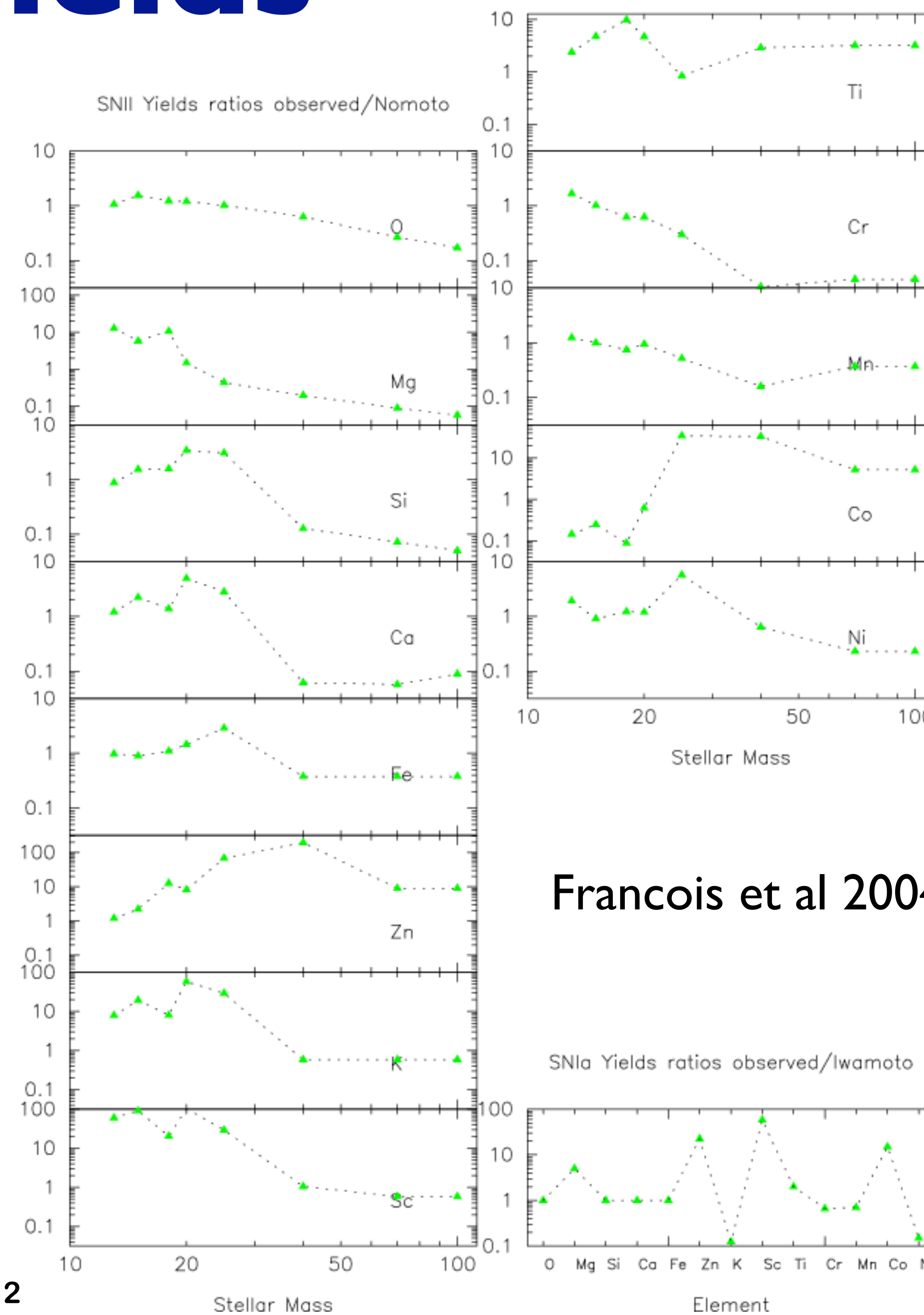
Matteucci et al 2001

Results: Stellar Yields

Try to turn the problem around:

- use SN yields to predict metal abundances and ratios
- compare to large number of stars
- where mismatches occur, adjust yields

Results constrain supernova models



Francois et al 2004

Results:
Deuterium & Galactic Accretion

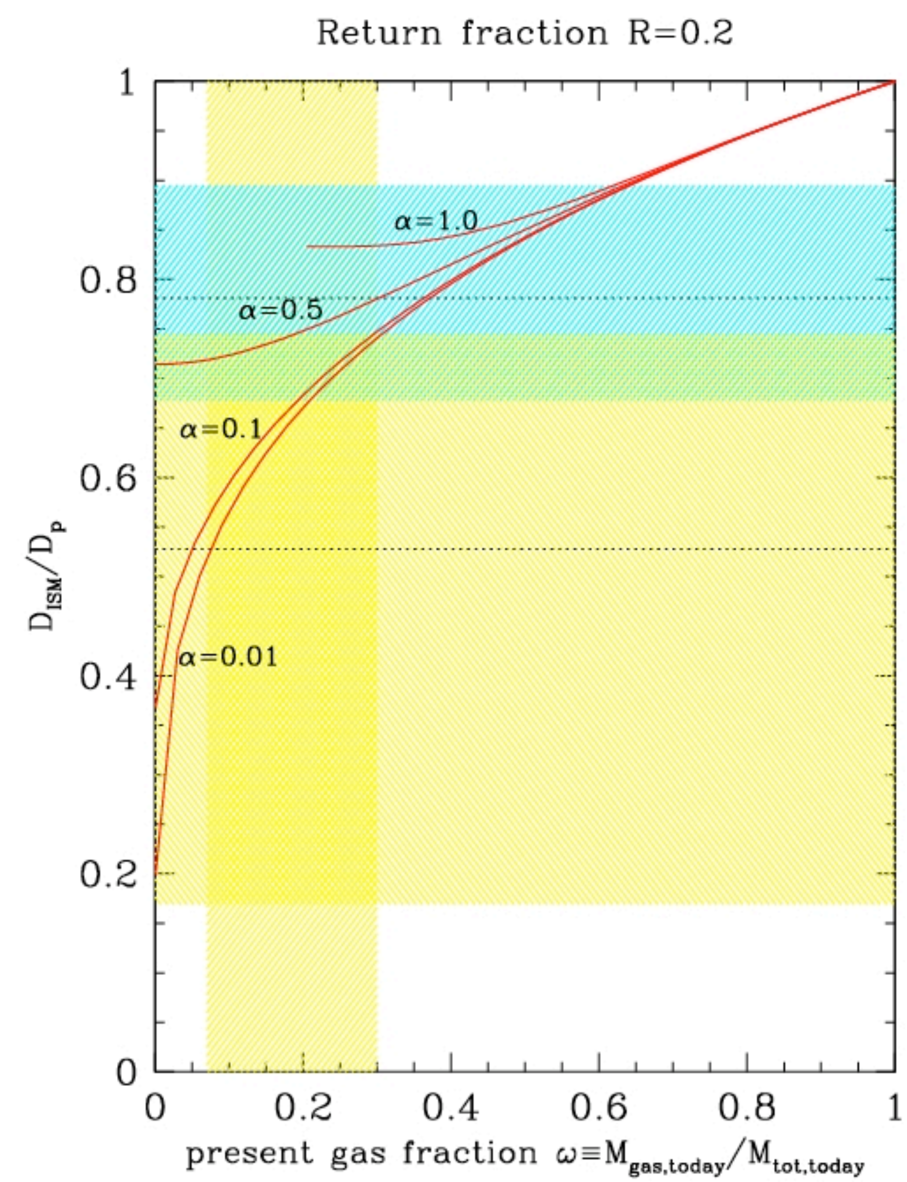
Deuterium is entirely destroyed in stars:

- only made in big bang
- abundance drops with time

Recent observations (FUSE) suggest total interstellar deuterium is very high:

- $D/D_{BBN} \sim 0.8$
- 80% of ISM never in a star!
- but: ISM mass/MW baryons~20%!

implies large ongoing accretion



Prodanovic & BDF

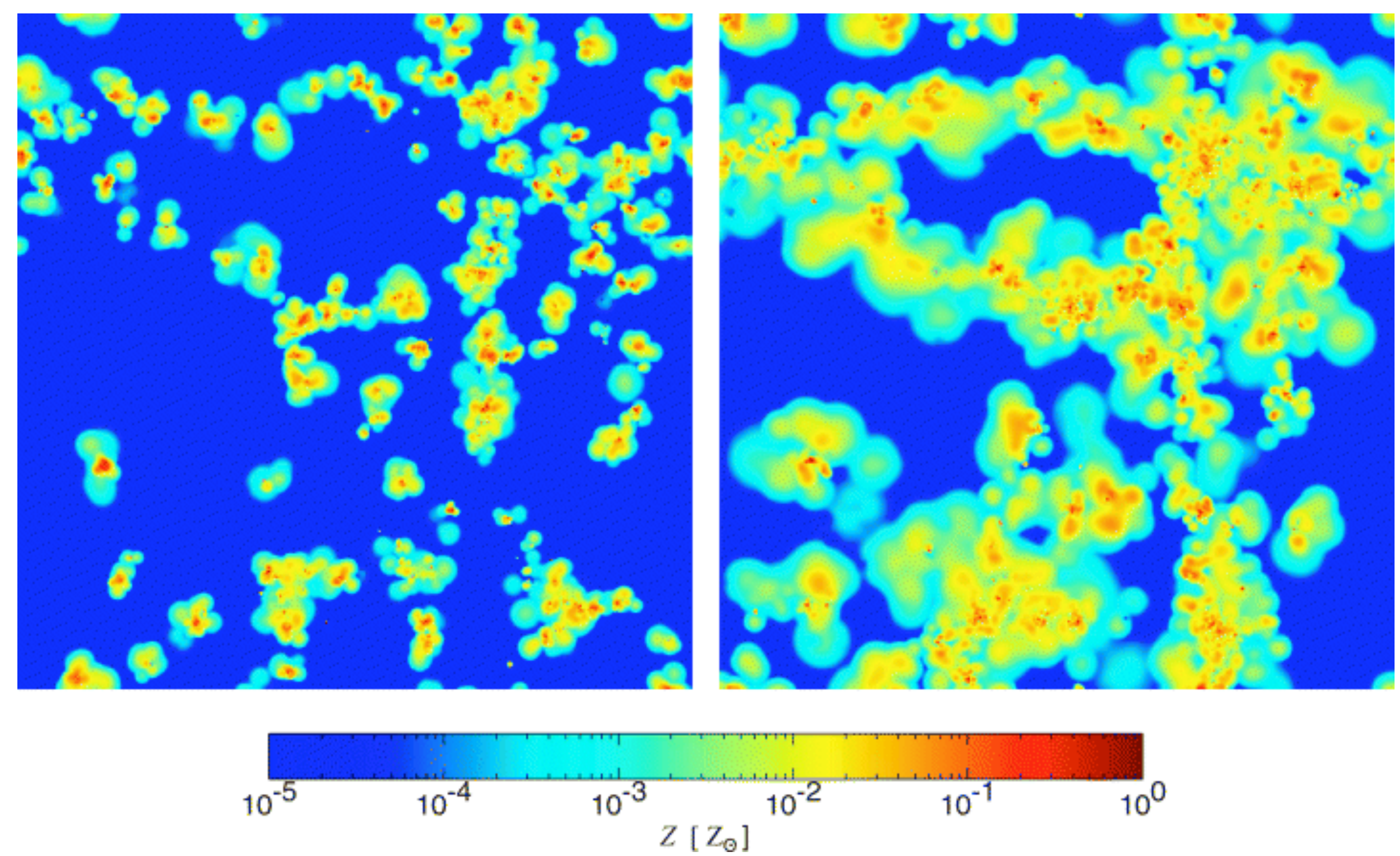
Results: Cosmic Abundance Trends

Simulations of cosmic structure formation now include baryons

- explicit hydrodynamics
- star formation & supernova energy injection via simple prescriptions
- SN ejecta endowed with "metallicity" Z

some models can reproduce cosmic star formation rate

cosmic metal distributions probe galactic winds



Springel & Hernquist 2003

Outlook

Galactic Chemical Evolution is in infancy, high on astrophysial food chain

Classic simple models provide insight into observed abundance patterns

Recently, first serious attempts to place in modern cosmological context, with promising results

Future work will weave together

- **realistic stellar yields**
- **realistic star formation**
- **realistic structure and galaxy formation**

Job security for the chemical evolutionist!