First stars, feedback and dSph: does astrophysical feedback restructure dark matter?

Gerry Gilmore
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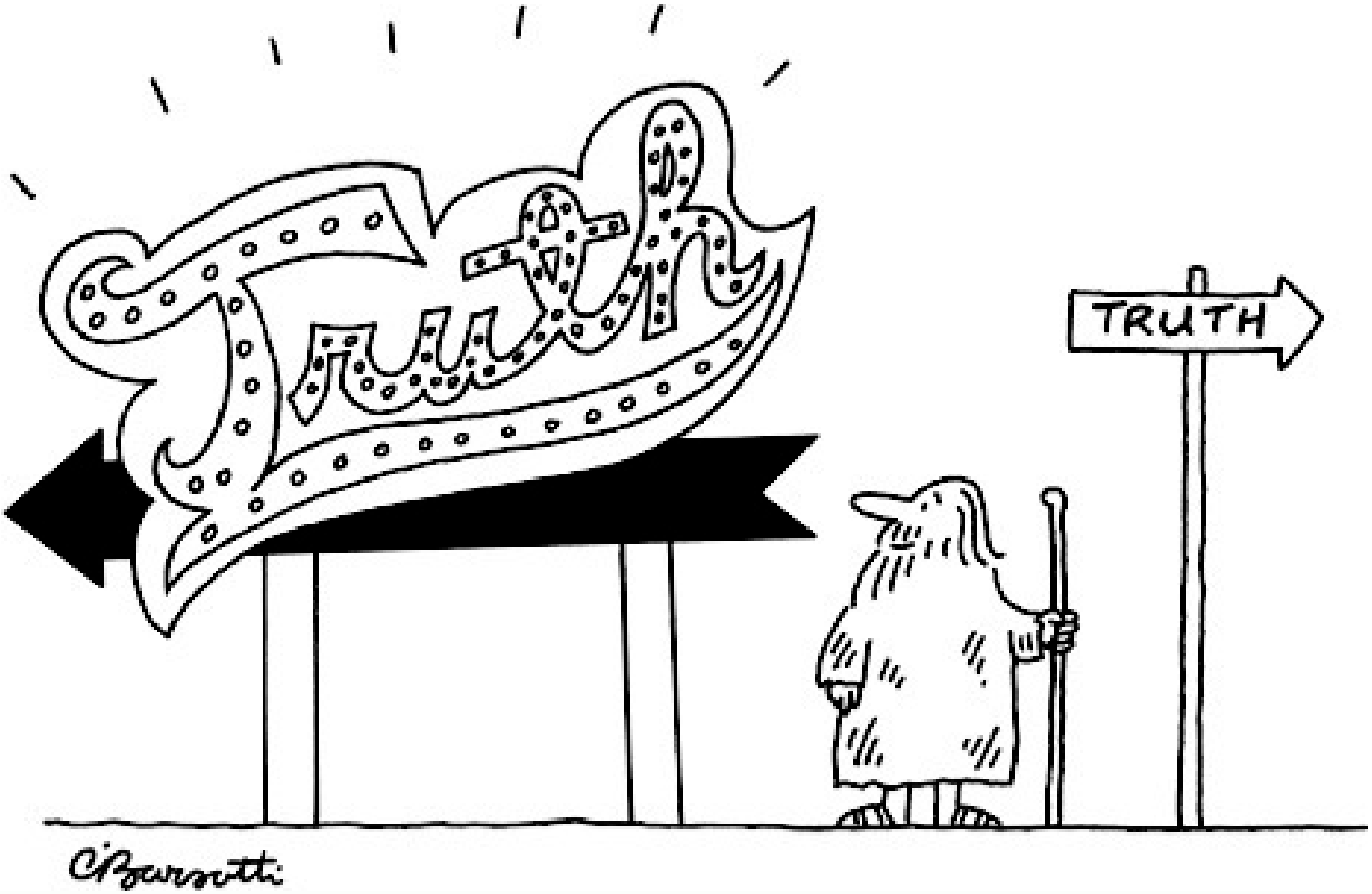
Seeing almost the first stars

quantifying feedback in small DM halos

- Goal: quantify astrophysical feedback in small DM-dominated systems, to try to constrain astroparticle physics – near-field equivalent of LSS neutrino limits. Does feedback remove memory?

- Intro: what do we wish to explain
- Can we define “primordial”? Yes we can!
- Can we quantify star formation rates and feedback before reionisation? Yes we can!

What do we want? Can we have it?



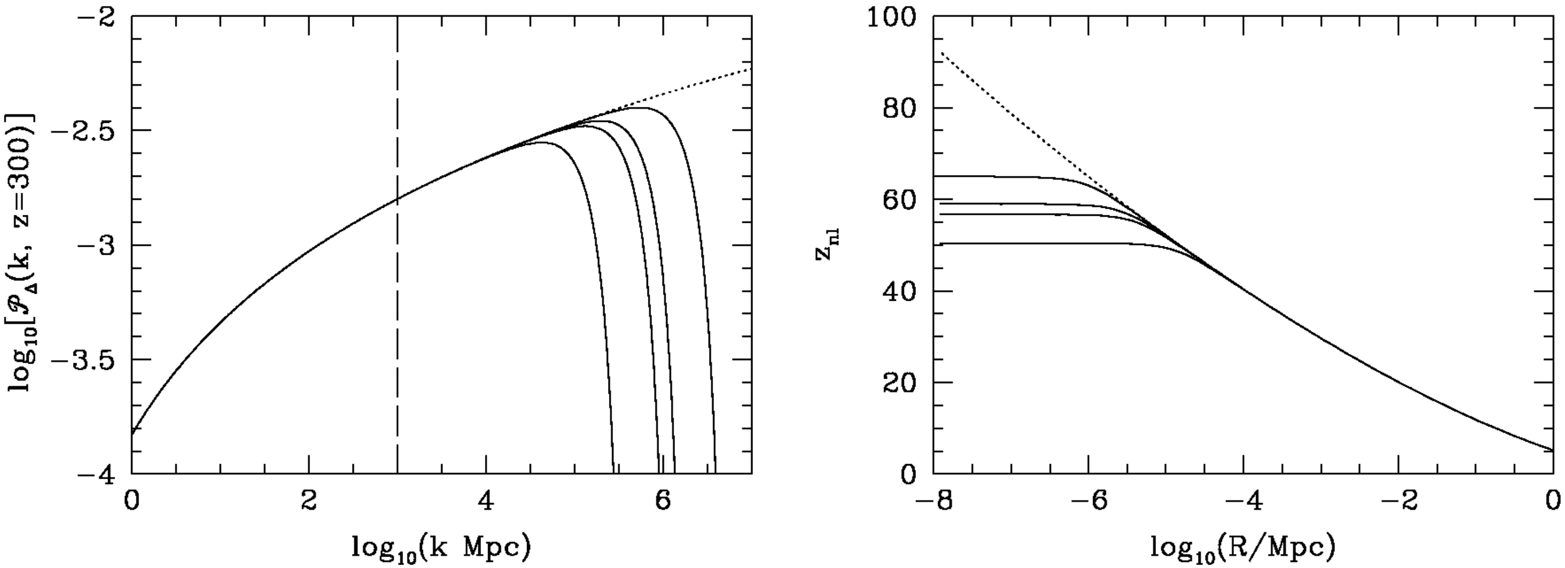
" Examine the objects as they are and you will see their true nature; look at them from your own ego and you will see only your feelings; because nature is neutral, while your feelings are only prejudice and obscurity."

邵雍, *Shao Yong*, 1011–1077

Are there plausible predictions to test?
There is a vast literature, with so far no clear model to test, and only bad news for simple SM extensions from LHC.

Progress will follow new observations

Linear power spectrum at z ~ 300, showing influence of WIMP microphysics:
Physical scales of interest correspond to smallest galaxies
Anticipated DM effects on scales of parsec up ➔ first systems
See also H de Vega talk for a detailed analysis



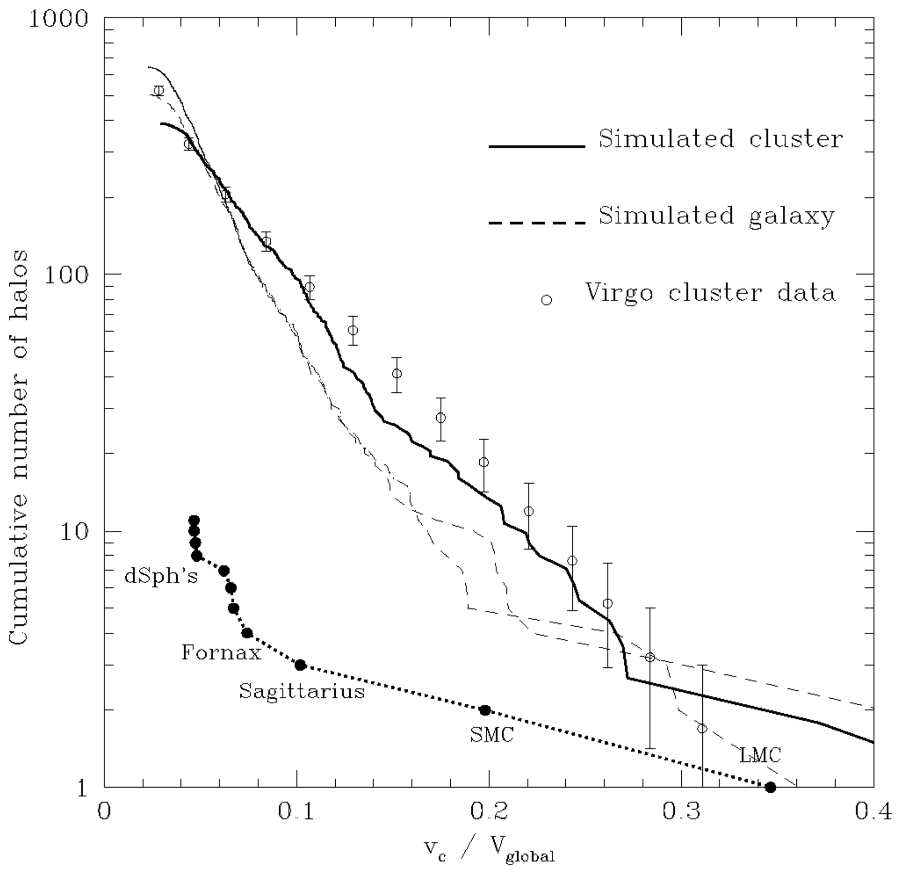
Green, Hofmann & Schwarz 2005

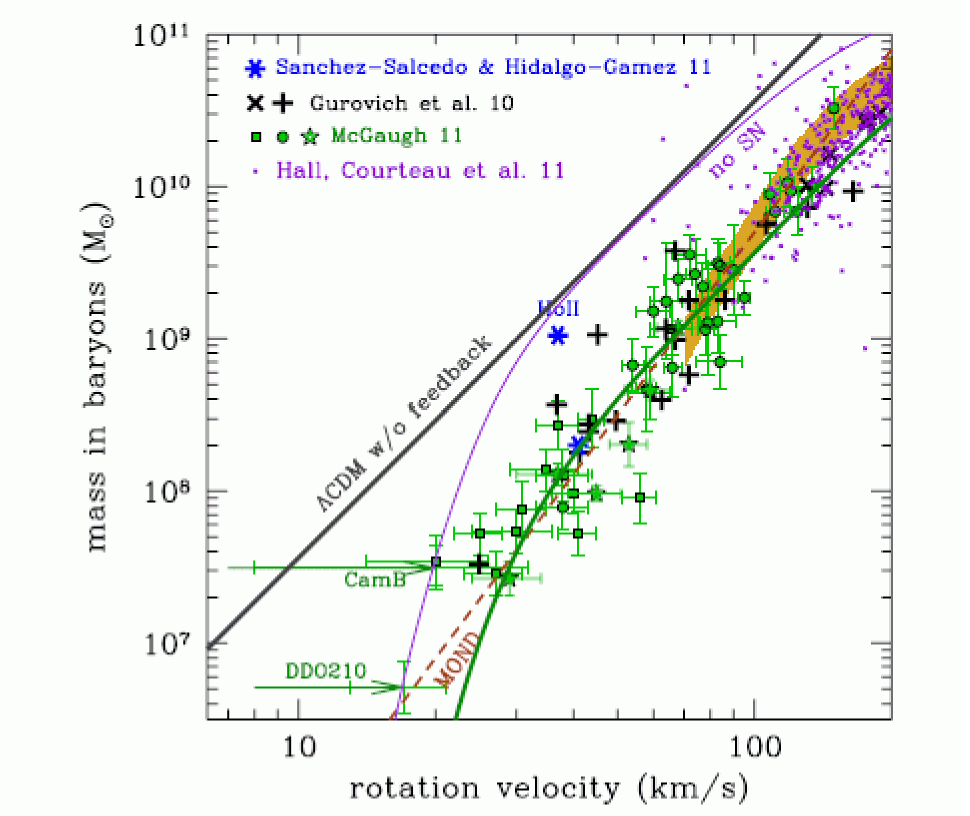
What do we need to explain?

- Galaxy Luminosity function
- Galaxy sizes
- Absence of tidal remnants
- DM cores
- Early evolution of small halos

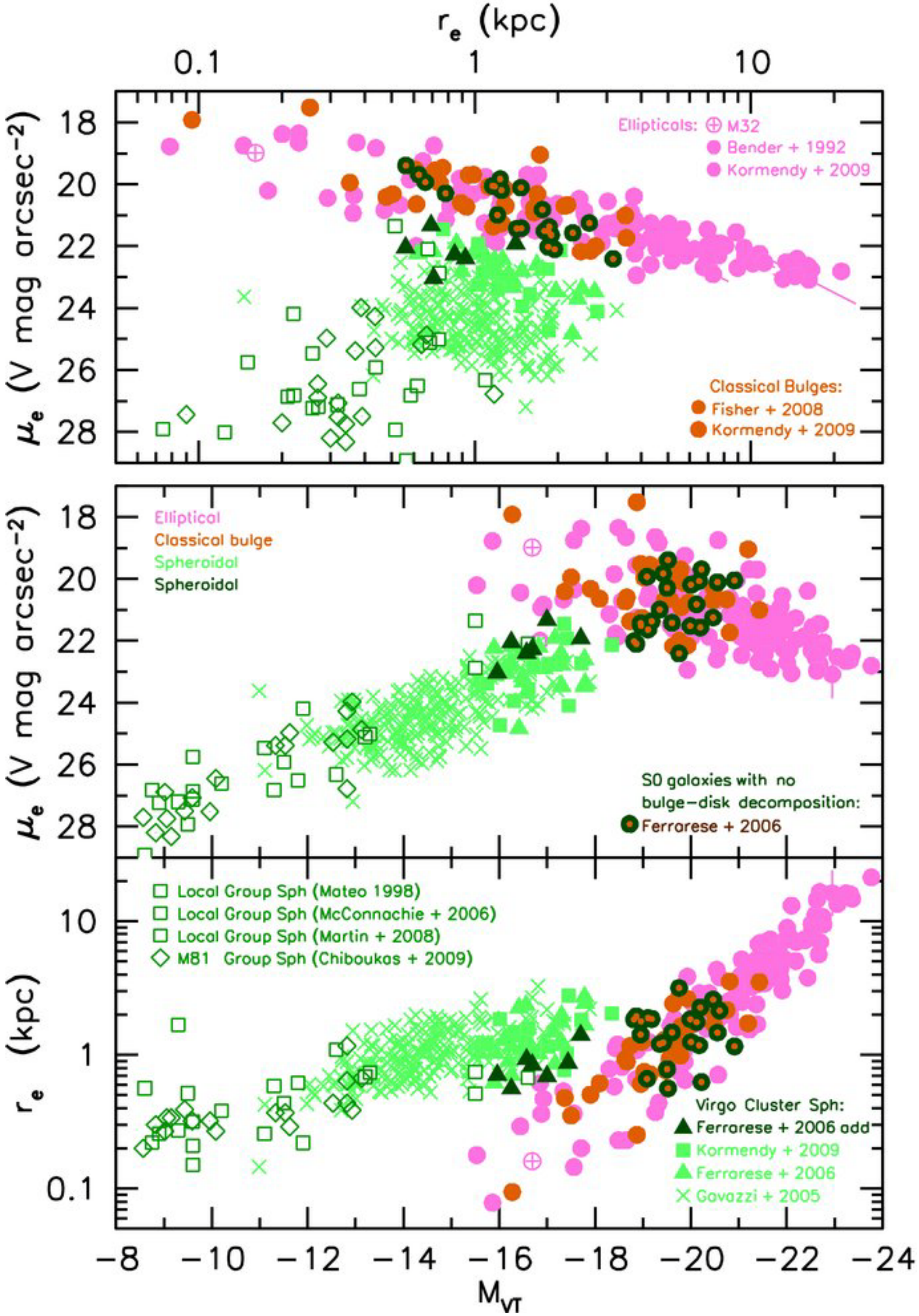
- Can we quantify feedback to see how it works?
- dSph are special since we measure chemistry

Challenge: explaining the luminosity/mass function





Suppression of star formation due to reionization and SN feedback is a semi-analytic fit to the galaxy luminosity function: it is a hypothesis and not a proof



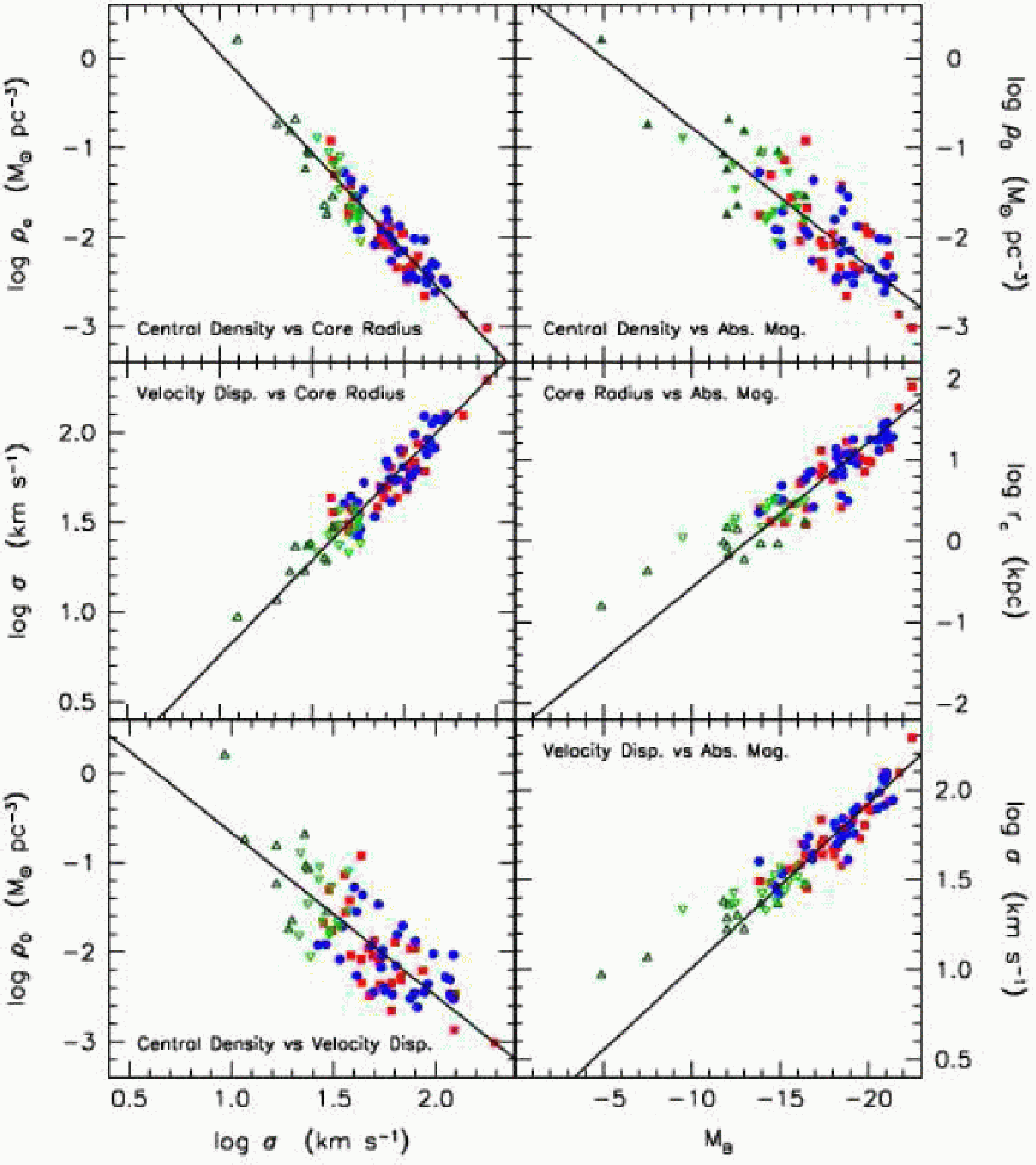
Kormendy & Bender

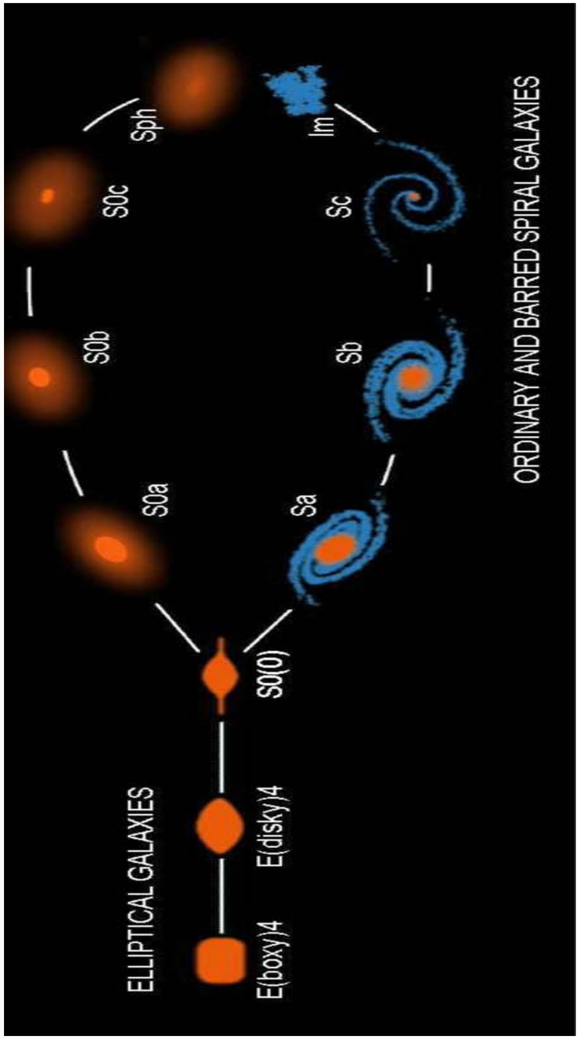
dSph galaxies are the extension of galaxy relations.

Ellipticals are merger remnants

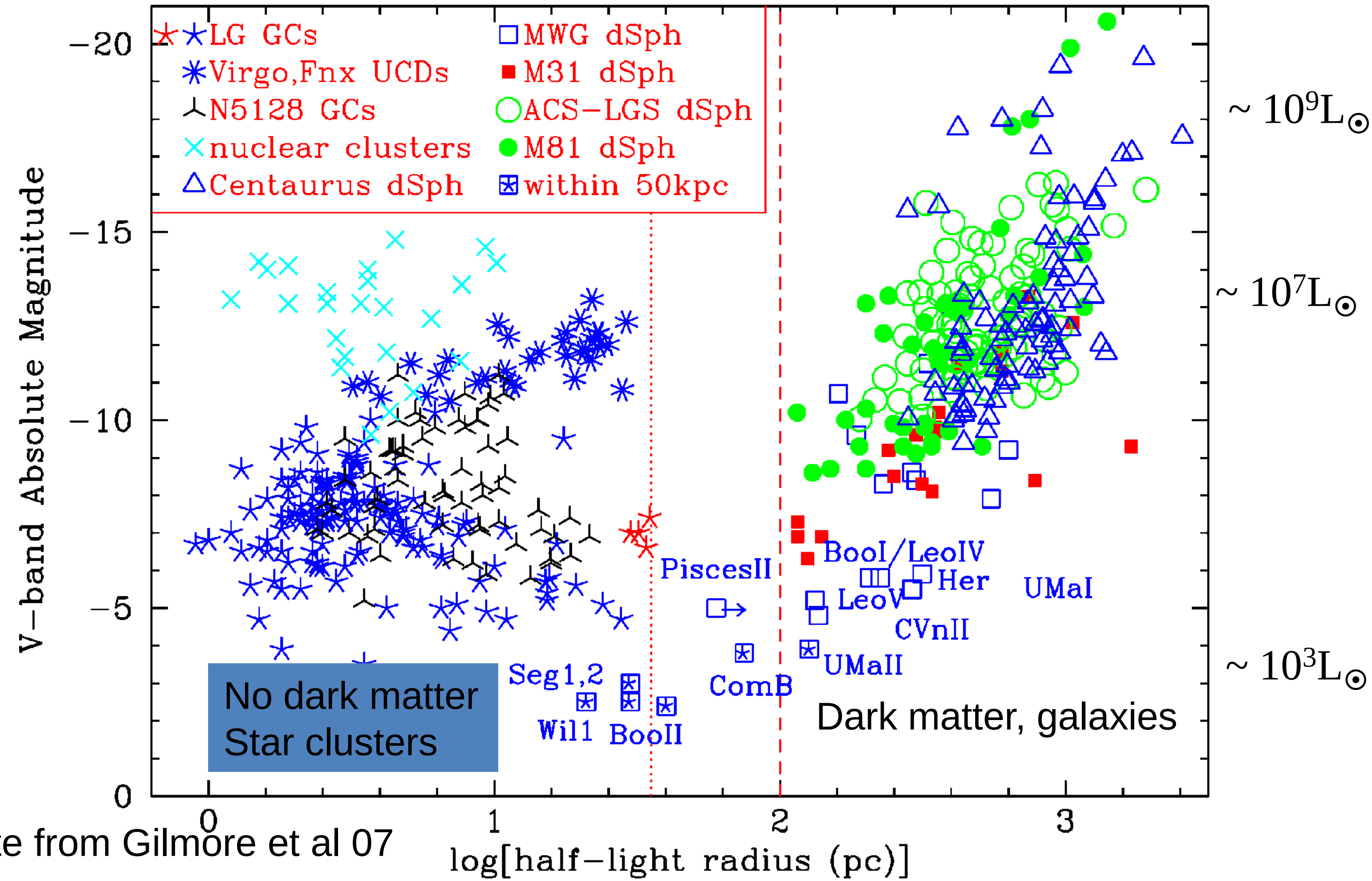
These correlations hold over huge dynamic ranges.

This means the basic physics of galaxy formation must involve common processes, not rare or exceptional events





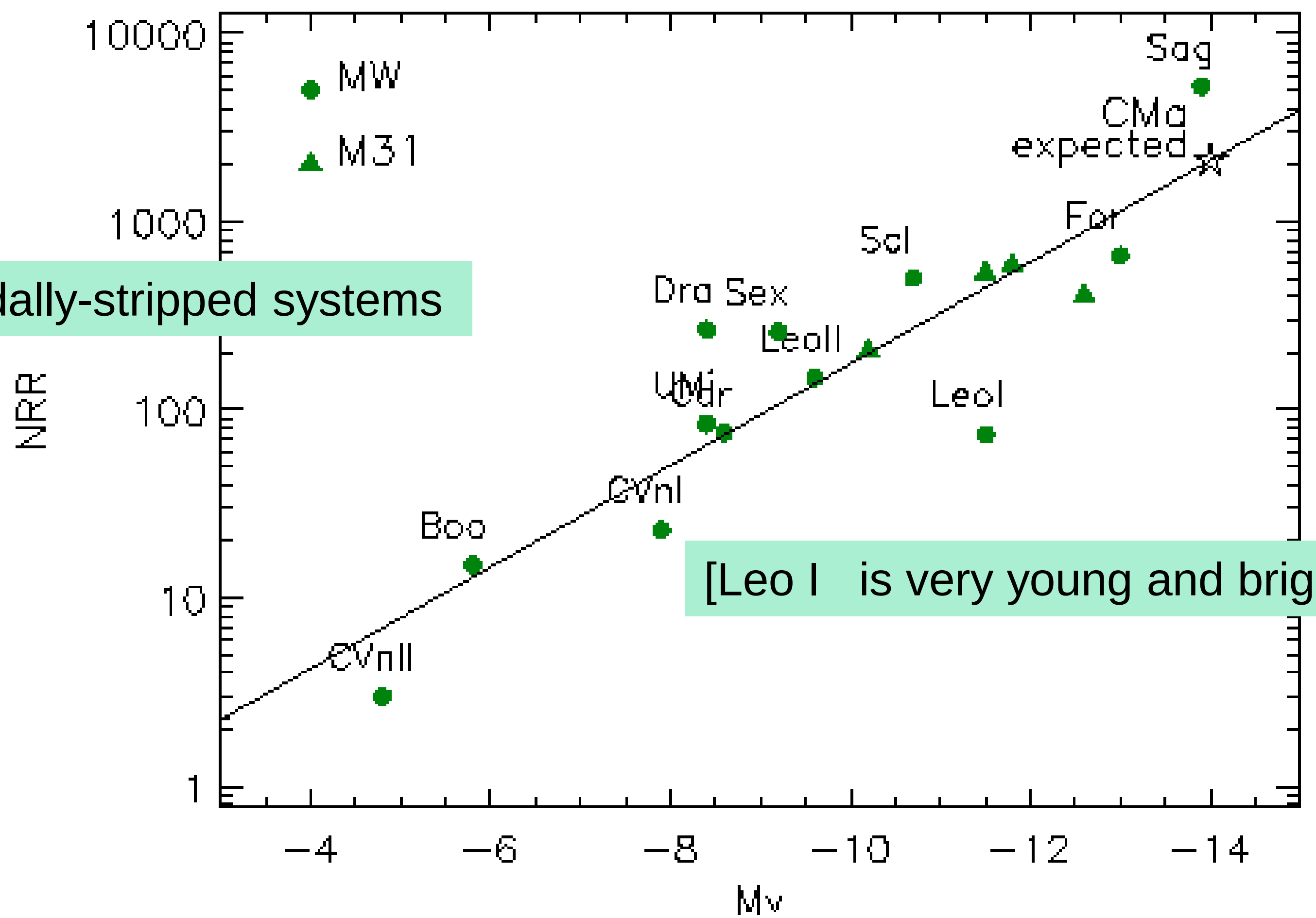
Kormendy & Bender



Update from Gilmore et al 07

Dwarf galaxy half-light radii are of order the DM core size: is this coincidence, or is it the explanation. Why are low luminosity galaxies so very big? If NFW cusps exist, why do stars try so very hard to stay out of them?

PREDICTION 1) dSph galaxies are highly stripped survivors:
RRLyrae numbers vs luminosity for dSph galaxies and CMa candidate
Note – All follow a clear relation, so all are consistent with being very old, being bound and having a tight relation between old star numbers and total stars today – stable?



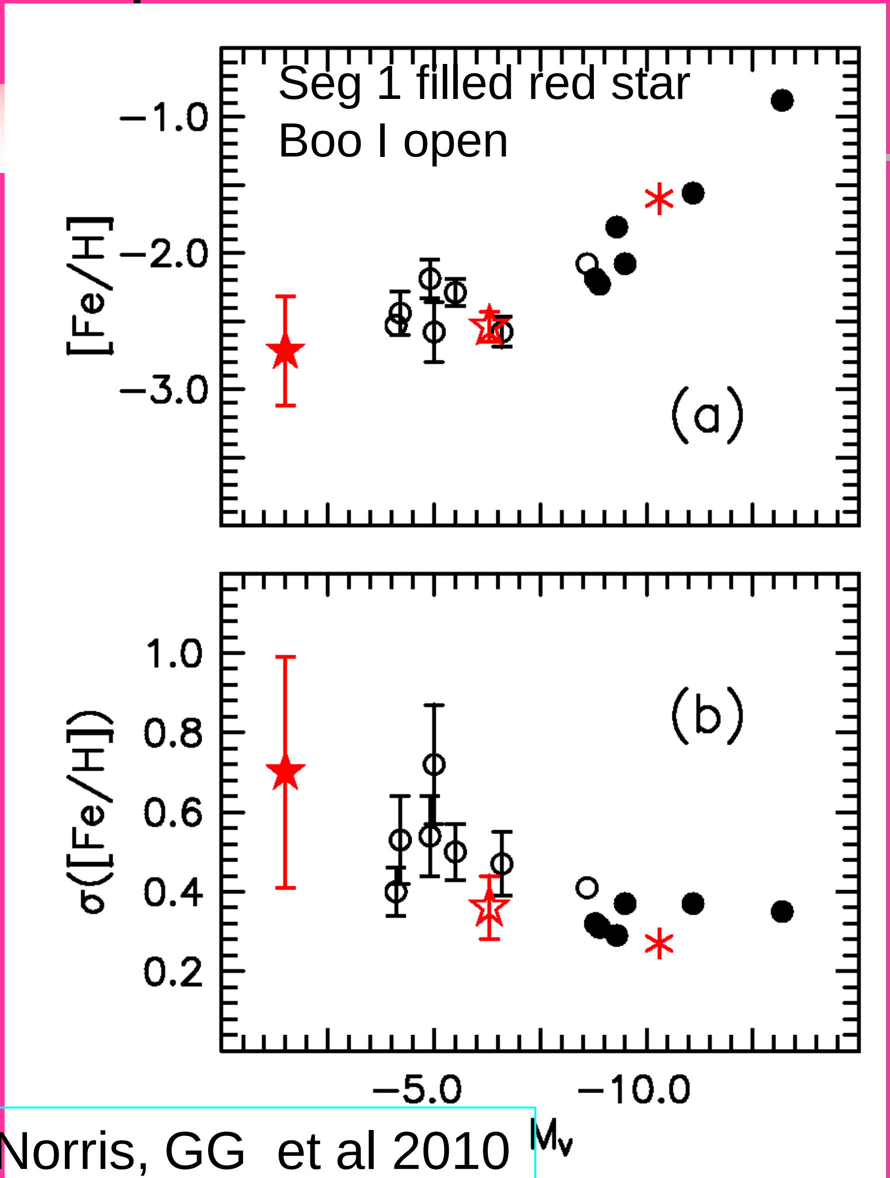
We don’t see a lot of tidally-stripped systems

[Leo I is very young and bright]

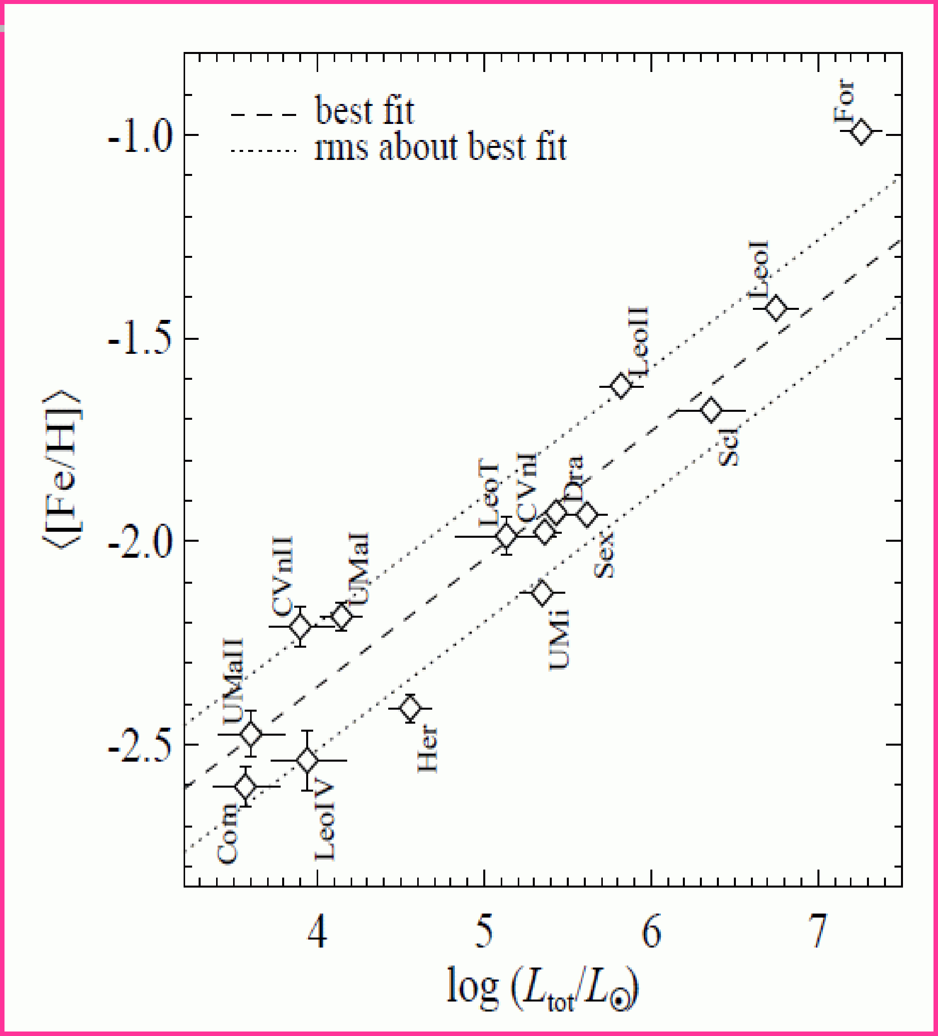
From Cecilia Mateu, QUEST project

CONCLUDE: dSph have not been damaged since formation

Mean iron abundance of member stars against total luminosity of host system: clear trend (also Kirby et al 08; Geha et al 09), hard to maintain if significant loss of stars through tidal stripping



Norris, GG et al 2010



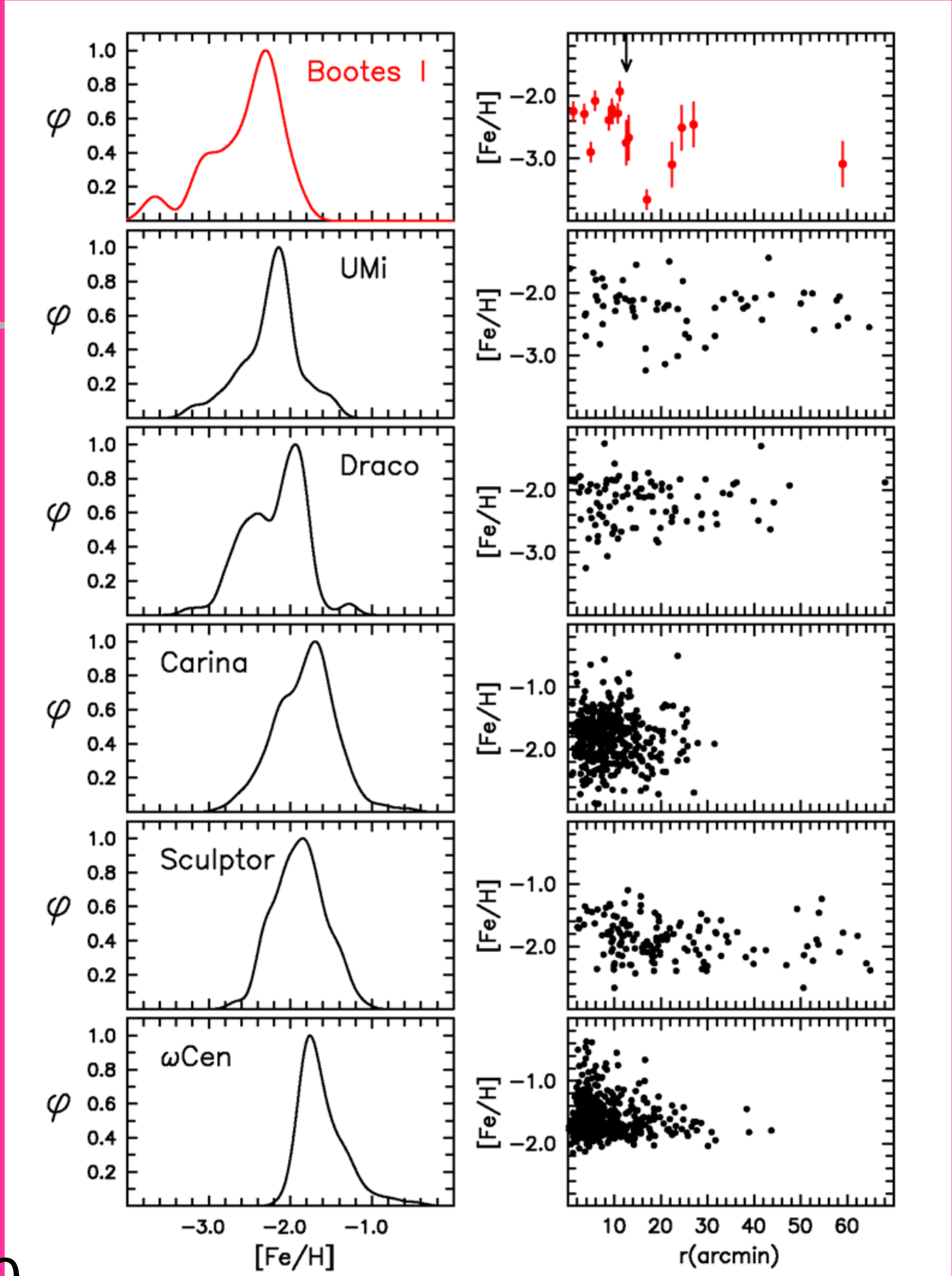
Metallicity distribution functions
are set by enrichment/outflow balance

Essentially, the peak abundance sets the mass-loss fraction

For Boo1 the lost baryon fraction is about 99%

Was that impulsive or slow?

With a closed system – a dSph – we can follow the enrichment history, and know the gas system survived SNe



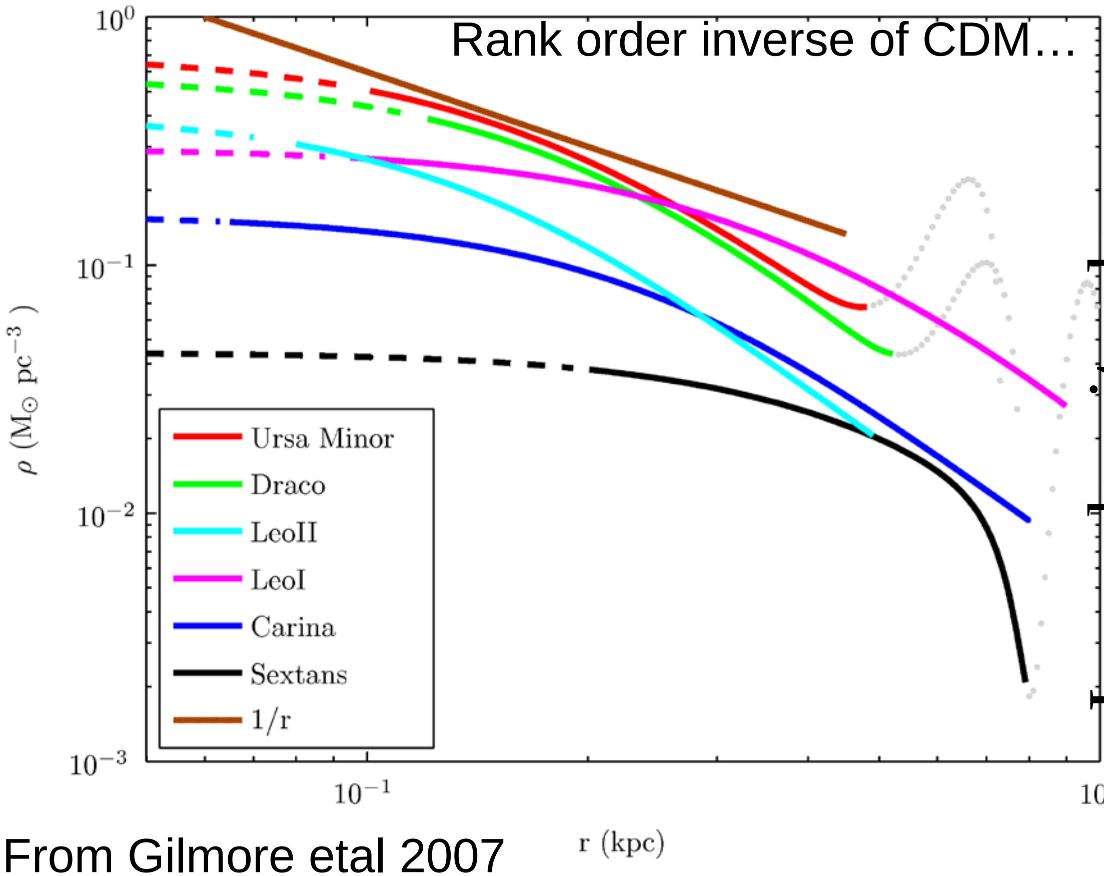
dwarf spheroidals do have low metallicity tails, GCs don't

Norris, et al 2010

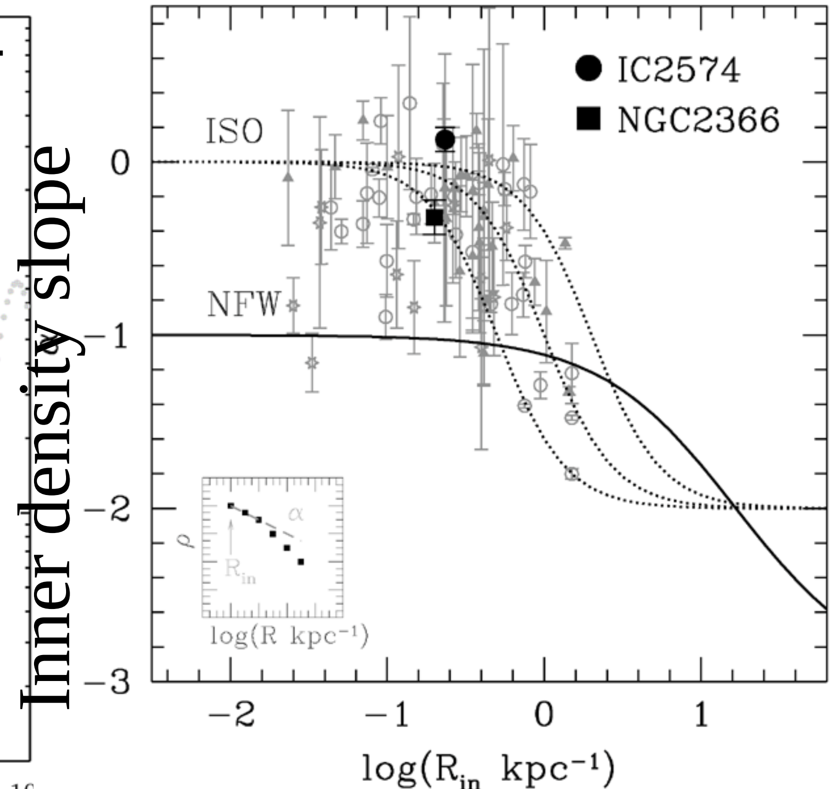
Derived mass density profiles:

See Matt Walker's talk

Jeans' equation with assumed isotropic velocity dispersion:
Now the challenge is to explain,not to refute.



From Gilmore etal 2007



Oh etal 2008 "Things"

- Characteristic Density ~10GeV/c²/cm³
  - DM particles must be extremely dilute (Higgs ~100GeV)

Observations summary one

- There remain major stresses between standard LCDM galaxy formation theory and observations, especially on small scales
- dSph galaxies are a viable test – all the evidence shows they are essentially unchanged since formation
- feedback can only be SNe – no massive BH, and so leaves a memory in chemical abundances
- Can we test the amplitude of SNe feedback in dSph

Very many attempts to model feedback on CDM structure: we can quantify what is needed to affect a LCDM halo

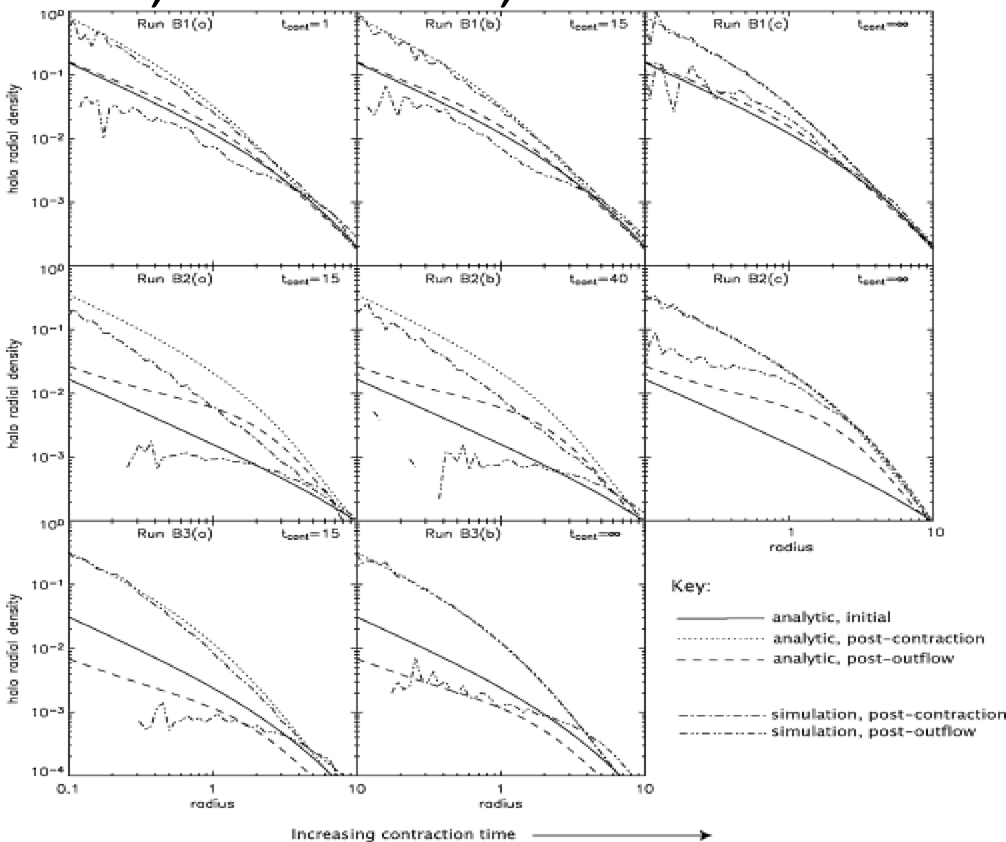
- Some of our examples:
- Read et al 2006 MN 367 387, MN 366 429, 2005 MN 356 107…; Fellhauer etal
- Conclusion:

DM halos certainly respond to tides and mass-loss, but secularly

Mass-loss must happen on less than a crossing time.

Making this consistent with chemical enrichment is hard

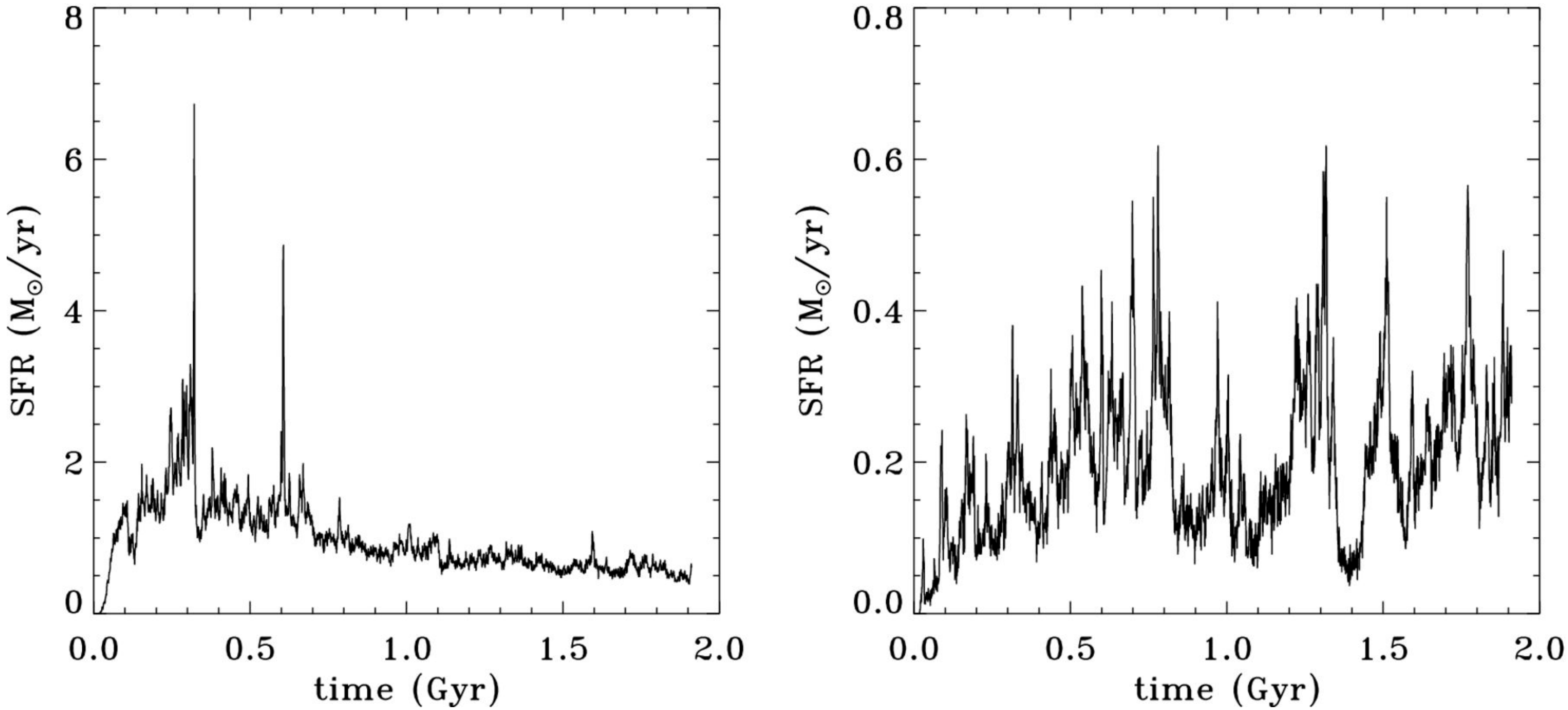
Self-enrichment takes >> T_cross



Early star formation rates:
LHS what is needed for chemical enrichment   RHS what is needed for feedback

Star formation history in the runs without (left-hand plot) and with (right-hand plot) feedback

Continuing bursty star formation with bursts on a local dynamical timescales is essential For dynamical feedback – does that happen?.



Teyssier R et al. MNRAS 2013;429:3068-3078

MONTHLY NOTICES of the Royal Astronomical Society

Summary so far: there are lots and lots of attempts to model feedback to make dSph-like galaxies. Do the models match the evidence?

(2) Dark matter cores are generally inferred in dwarf spheroidal galaxies, whereas ΛCDM theory predicts a cusp, the NFW profile. Strong SN feedback can eject enough baryons from the innermost region to create a core (Governato et al. 2010; Pontzen & Governato 2012), but this requires high early SN feedback and a series of very short bursts of star formation.

(3) The excessive predicted numbers of dwarf galaxies are one of the most cited problems with ΛCDM. The discrepancy amounts to two orders of magnitude. The issue of dwarf visibility is addressed by feedback that ejects most of the baryons and thereby renders the dwarfs invisible, at least in the optical bands. There are three commonly discussed mechanisms for dwarf galaxy feedback: reionization of the universe at early epochs, SNe, and (ram pressure and tidal) stripping. AGN-driven outflows via intermediate mass black holes provide another alternative to which relatively little attention has been paid (Silk & Nusser 2010).

None of these have so far been demonstrated to provide definitive solutions. Reionization only works for the lowest mass dwarfs. The ultrafaint dwarfs in the MW may be fossils of these first galaxies (as checked by detailed models, Koposov et al. 2009; Salvadori & Ferrara 2009; Bovill & Ricotti 2011). It is argued that SN feedback solves the problem for the more massive dwarfs (Macciò et al. 2010). However, this conclusion is disputed by Boylan-Kolchin et al. (2011),

From Silk & Mamon 2011 (RAA)

The information in chemistry

- Abundances define the cooling curve, defining possible star formation rates
- Alpha-elements define the high-mass IMF slope, quantifying the number of SNe
- Alpha-element “break” defines enrichment at 0.3-1Gyr ➔ star/SNe formation rate
- abundances defines gas-loss fraction ➔ impact on IGM chemistry and kinematics: Ly-alpha limit
- Special abundance patterns identify PopIII SNe enrichment ➔ very early stars

Very early baryon assembly and star formation is controlled by the cooling curve
Key points : first cooling by H2 molecules – slow
Later dominated by carbon (&oxygen) excitation level below 13.6eV, 158mu C[II] line

Component	Temperature	Density	Tracers and IR lines
Cold gas	10-100 K	1-1000 cm-3	H2, CO, PAH's
Diffuse HI	100-1000 K	1 cm-3	HI 21cm, [CII], [OI]
HII regions	1000-10000 K	3-300 cm-3	H$ \alpha$, [OII], [OIII]

Signal of first SNe? May be very high C, O, very low Fe

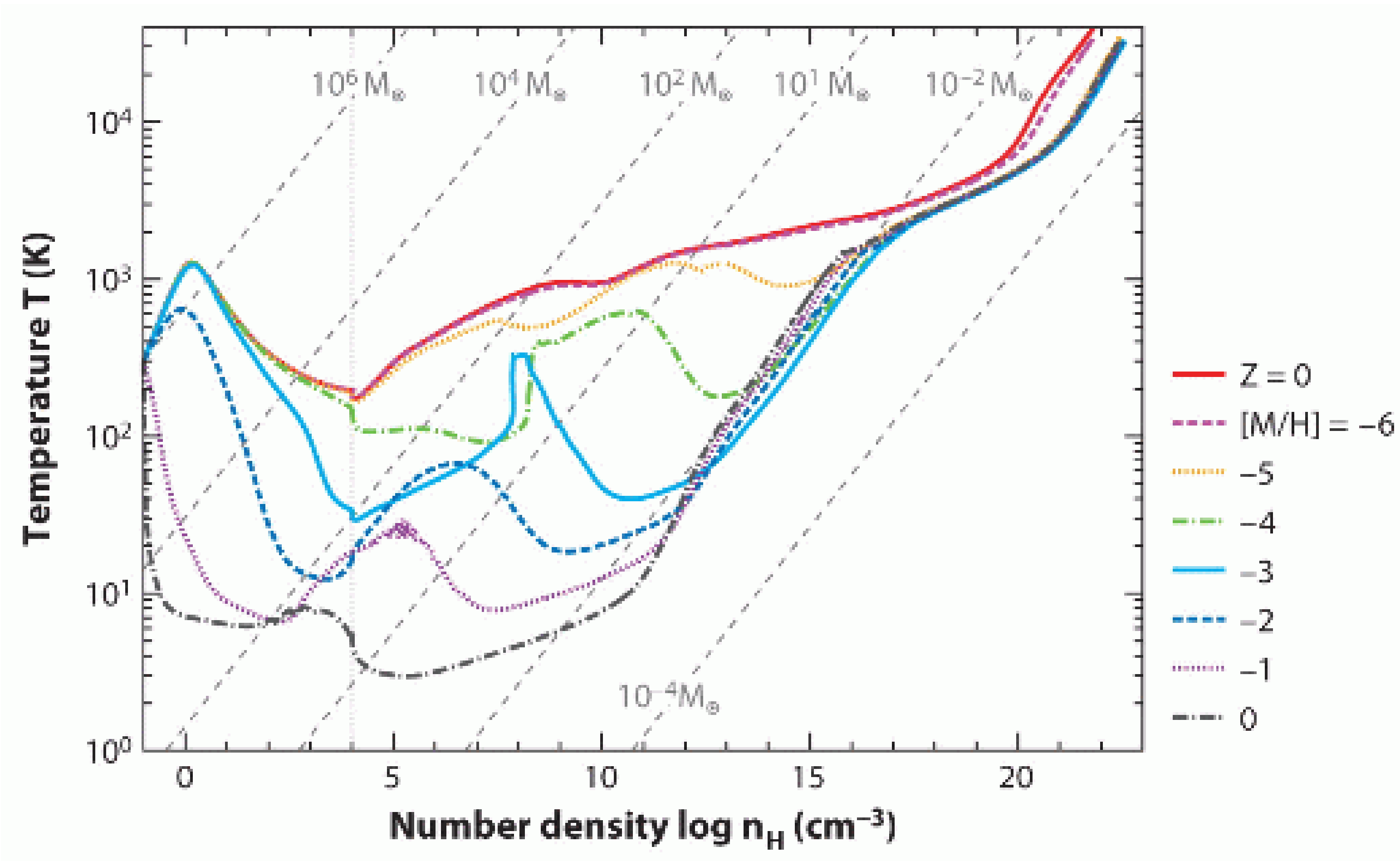
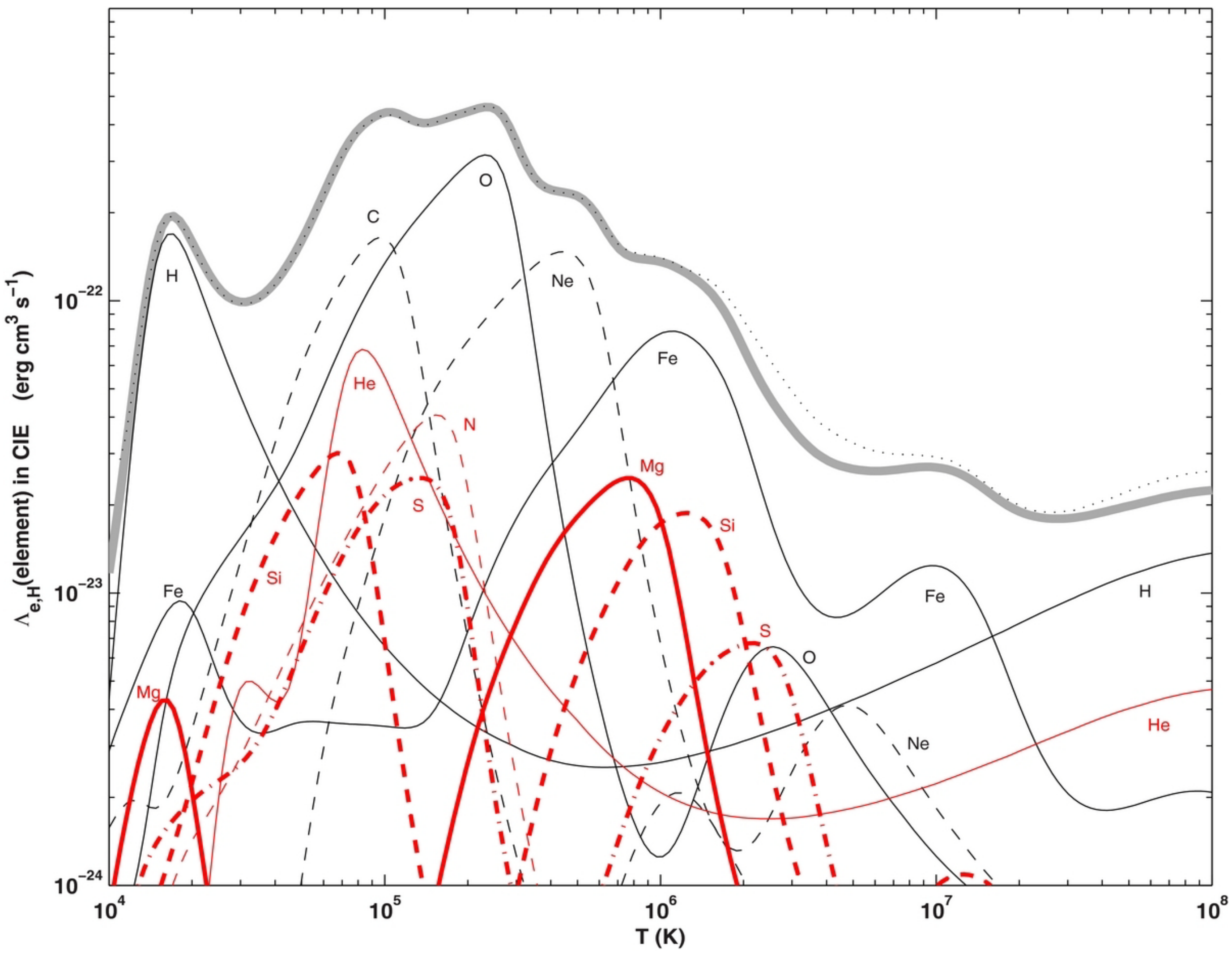


Figure 3 from Ion-by-ion Cooling Efficiencies
Orly Gnat and Gary J. Ferland 2012 ApJS 199 20 doi:10.1088/0067-0049/199/1/20



Cooling is dominated by carbon and oxygen

So what does chemistry tell us

cf Rees 1986 (entropy cooling barrier);
Dekel & Silk 1986 (mass-loss-metallicity)

THE ASTROPHYSICAL JOURNAL, Vol. 157, September 1969

IONIZATION EQUILIBRIUM AND RADIATIVE COOLING OF A LOW-DENSITY PLASMA

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Space Science Department, Rice University, Houston, Texas
Received January 17, 1969

ABSTRACT

The results of calculations of the ionization equilibrium and rate of radiative cooling of a high-tem-
g, Si, and S are con-
re assumed to be the
to be most important
hlung, recombination
smic abundances, the
e cooling curve near

NATURE, VOL. 216, DECEMBER 9, 1967

Molecular Hydrogen in Pre-galactic Gas Clouds

by
WILLIAM C. SASLAW
DAVID ZIPOY
Department of Applied Mathematics and Theoretical Physics, University of Cambridge

During the collapse of pre-galactic gas clouds through a density of about 10^4 particles/cm^3, hydrogen molecules are produced and dominate the subsequent cooling.

IN a plausible picture of galaxy formation, proto-galaxies are produced by the gravitational clustering of many gas clouds[1,2]. Various origins for these clouds have been discussed by Lifshitz[3], Bonnor[4], Saslaw[5] and Harrison[6] among others. In this article, the important, and probably dominant, part that molecular hydrogen plays in the early evolution of large clouds is first investigated, and then the possibility of detecting the radiation they produce is discussed.

The era examined occurs in the conventional big-bang cosmology after matter and radiation have decoupled and before star formation has begun. During this period, $z \lesssim 1{,}000$, the recombination time scale for hydrogen exceeds the Hubble time, and about one hydrogen atom

until the density is too low to produce it. We find, however, that later, in the condensations, charge transfer reactions produce enough H_2 to radiate most of the thermal energy of contraction. General references to the chemistry of charge transfer reactions may be found in ref. 9. Here we consider only those relevant to H_2 (P. Solomon, private communication)

$$e^- + H^+ \rightarrow H \quad (1)$$

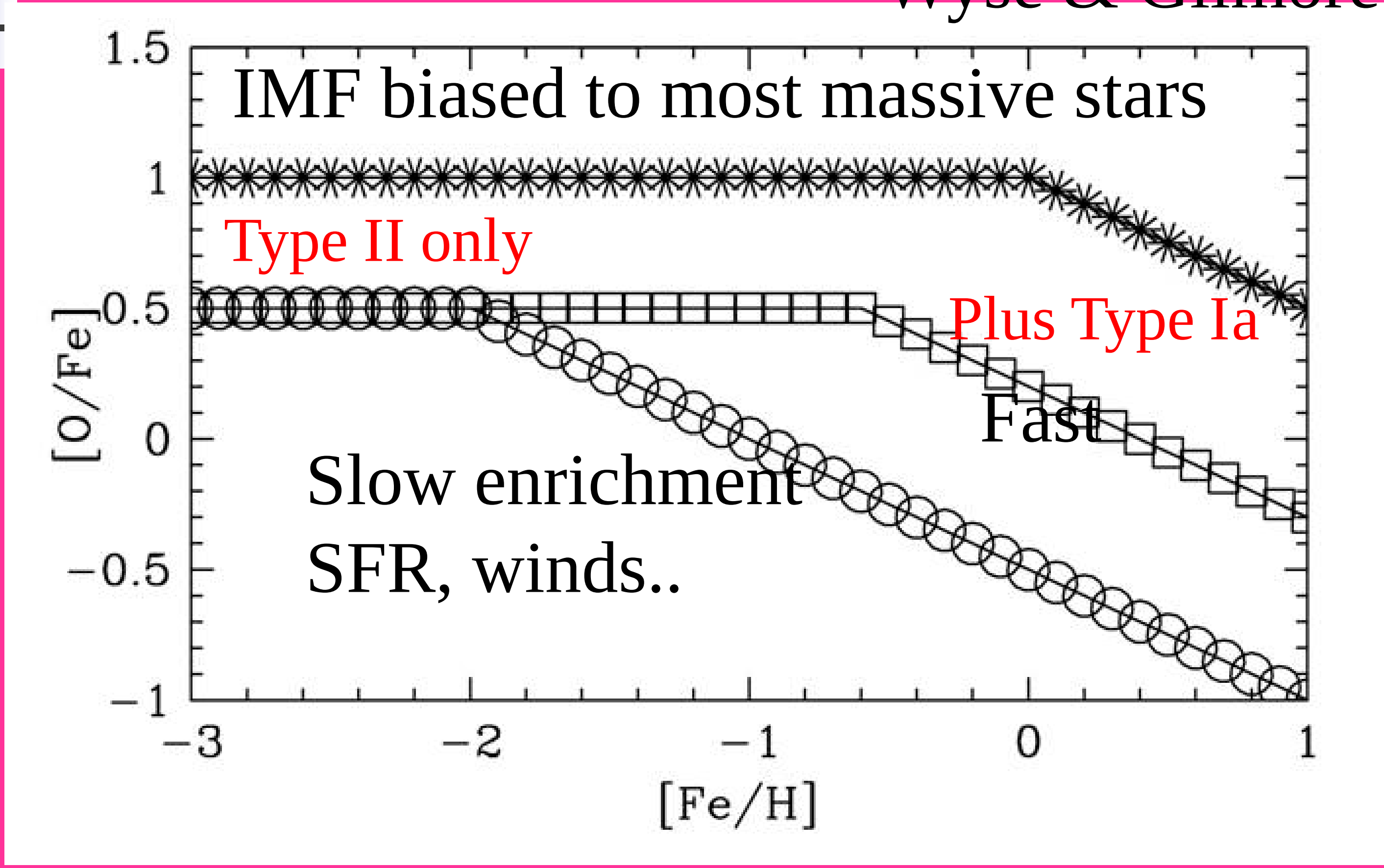
study.

We are grateful to Dr P. Solomon for several helpful discussions about molecular hydrogen. We also thank Dr E. A. Spiegel and Mr M. J. Rees for their comments on the manuscript. One of us (W. C. S.) thanks the US National Science Foundation for a pre-doctoral fellowship during which this work was done. D. Z. was on sabbatical

Alpha Elemental Abundances:

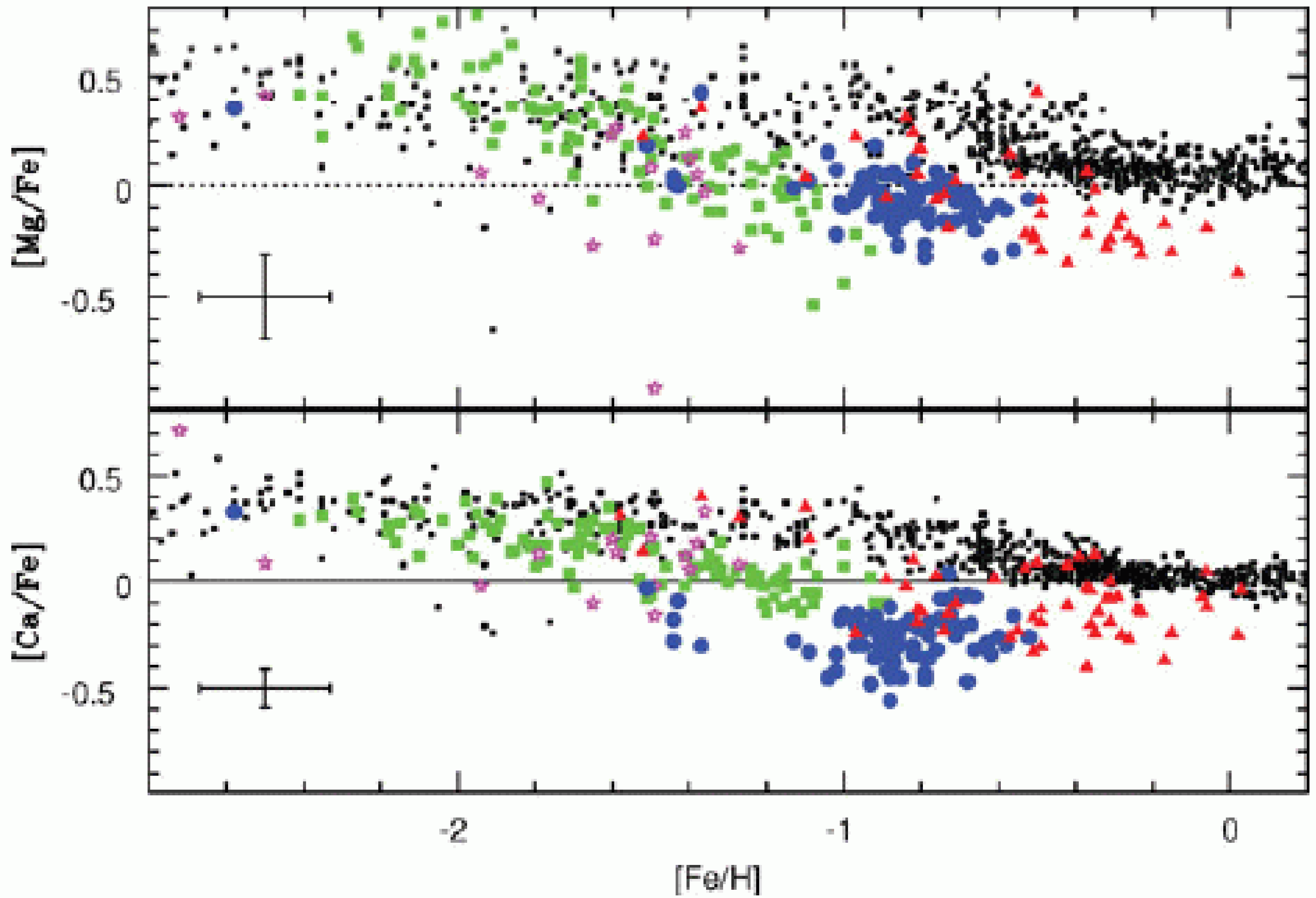
The "break" occurs at fixed time – 1Gyr – after first star formation. It's a clock.

Wyse & Gilmore 1993



Self-enriched star forming region.
Assume good mixing so IMF-average yields

Element ratios in MWG field stars (black) and dSph stars (colours)



Every satellite has slower enrichment than any population in the MWG.
Most satellites have very long-lasting star formation – they survive, and keep their self-enriched gas.

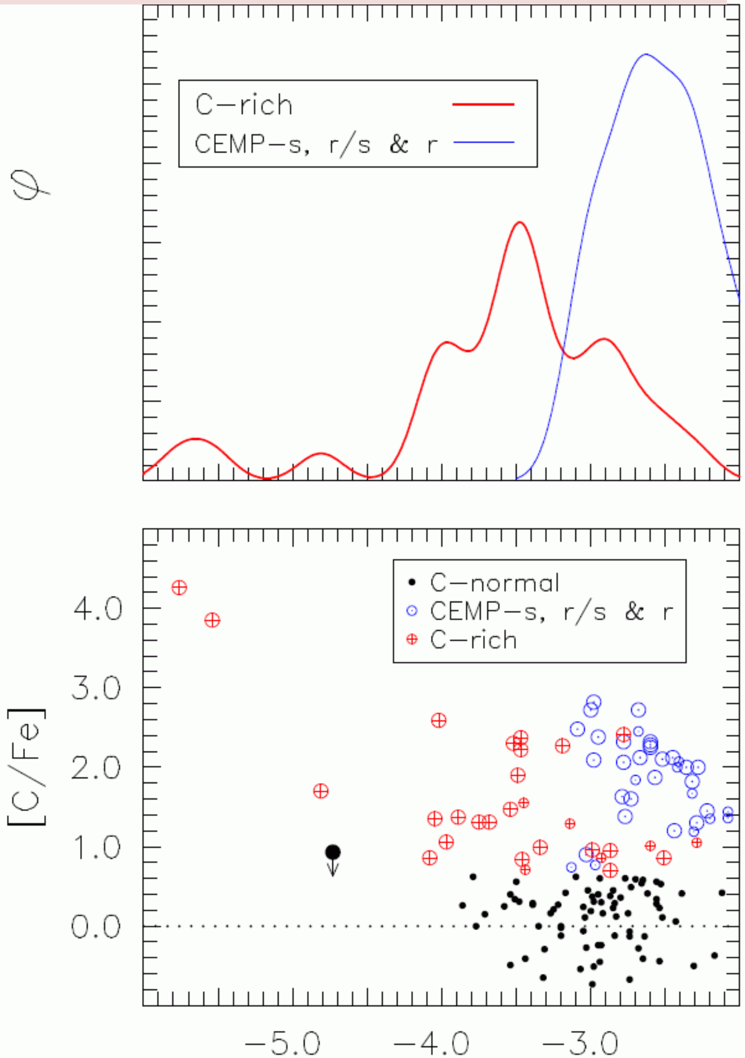
Scatter in element ratios at specific [Fe/H] measures ISM mixing efficiency

etal A+A 465 815 2007

dSph chemical abundance patterns

- Overall chemical abundance patterns from ALL dsph are mutually consistent
- This is robust evidence dSph survived for long times, continued star formation, and retained the chemical enrichment from their Sne
- This simple observations limits feedback to levels too low to have modified the DM potential
- dSph DM mass distributions are primordial.
- Can we find further limits from very early times?

Use the most primitive stars



Now look at lowest abundance stars

3 types: "normal", CEMP-s, CEMP-no
CEMP-s = "normal" + AGB binary
"normal" = weird
CEMP-no = enriched by PopIII SNe?

NB: high-C [Fe/H]>-3.3 is AGB polluted

as emphasized by Masseron et al. (2010), the lack of CEMP-s/rs stars at the lowest metallicities is a "dog that doesn't bark." The CEMP-s/rs go from dominating the C-rich sample (which still includes a large fraction of all stars with [Fe/H] < -2.5) to being absent. Do AGB stars with [Fe/H] < -3 not make the s-process? Not form binaries? Not transfer material?

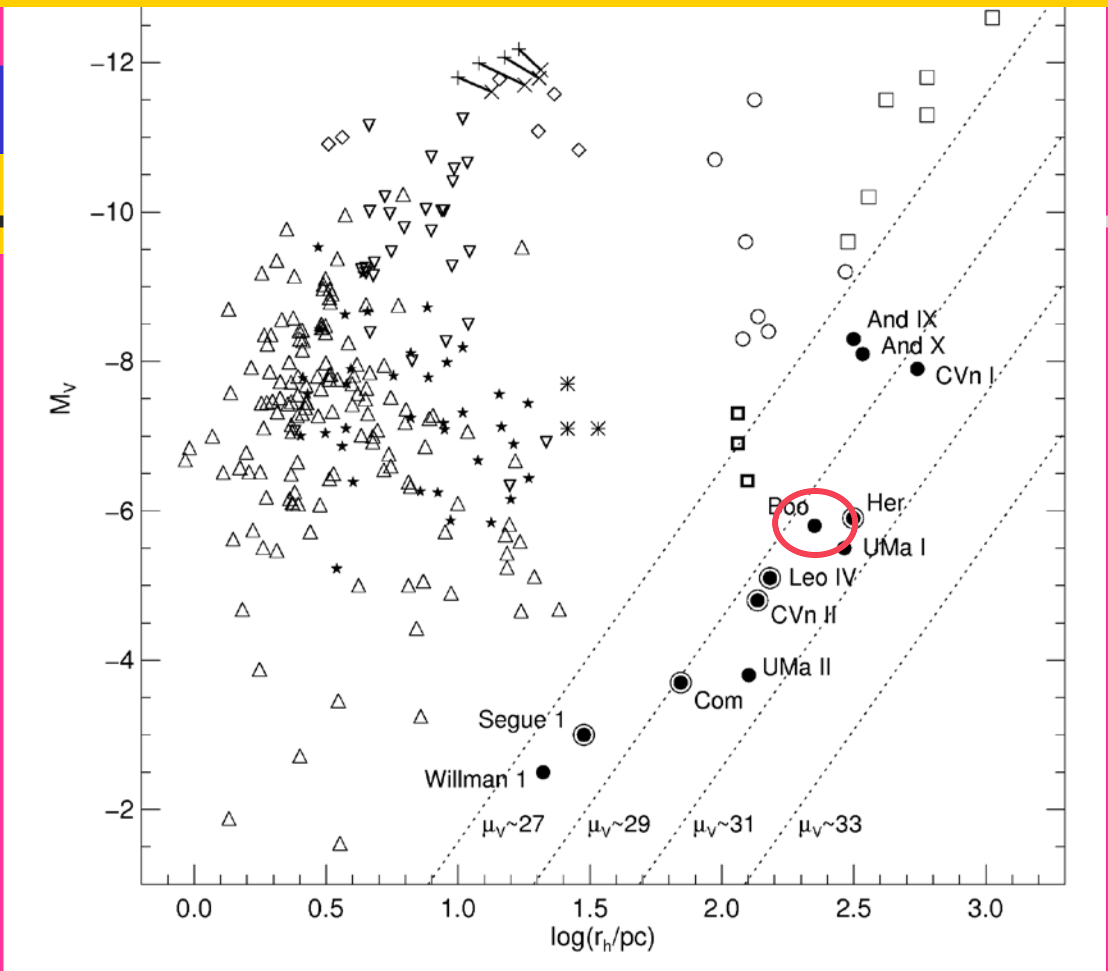
arXiv:1211.3157

THE MOST METAL-POOR STARS. IV. THE TWO POPULATIONS WITH [FE/H] $\lesssim -3.0$

JOHN E. NORRIS[1], DAVID YONG[1], M. S. BESSELL[1], N. CHRISTLIEB[2], M. ASPLUND[1], GERARD GILMORE[3], ROSEMARY F.G. WYSE[4], TIMOTHY C. BEERS[5,6], P. S. BARKLEM[7], ANNA FREBEL[8], AND S. G. RYAN[9]

Belokurov et al. 2007 ApJ, 654, 897 / Martin et al. 2008, ApJ, 684, 1075
Koposov etal (kinematics) ApJ 2011, Norris etal 2010a,b,2011,2012; GG etal 2013 (chem)

Bootes 1: a large, low-luminosity, metal-poor, system with very metal-poor stars. Fainter than a typical GC.
First discovery of CEMP-no stars in a small system allows study of the chemical evolution of a DM-dominated dSph

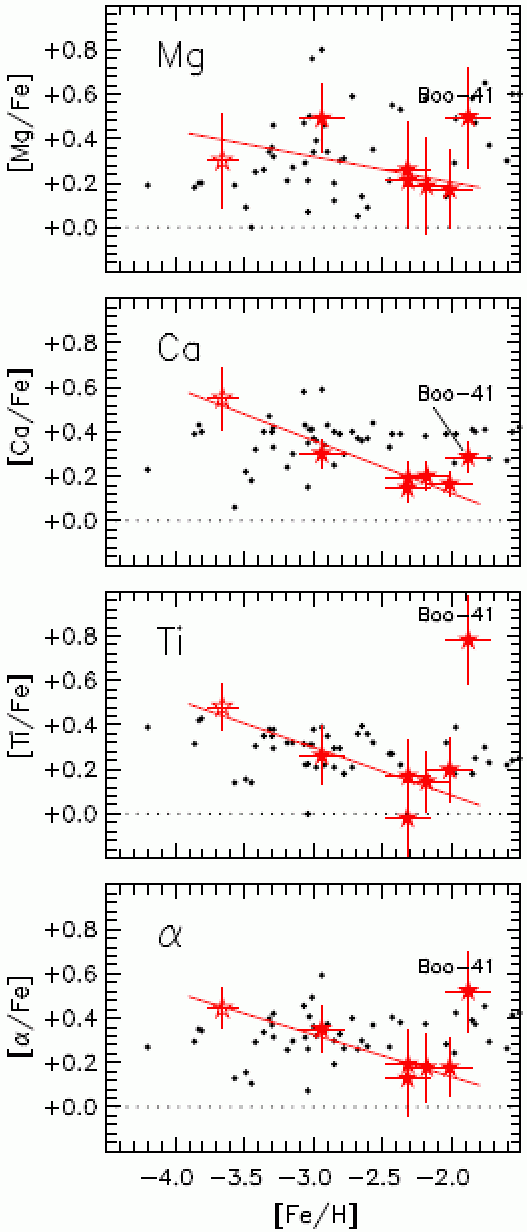


Bootes I
M_v = -6.3
[Fe/H] = -2.5
M = 3-7 $10^4 M_{sun}$
Log Rc = 2.3
Vel dispn ~3km/s

very faint,
very large,
very cold
very metal-poor

Segue1
M_v = -1.5
[Fe/H] = -3.3
M = 600-1300 M_{sun}

The chemical element distribution in this extreme system is very ordinary



The alpha "plateau" is flat or (2-sigma) declining.
➔ Enrichment Duration <~1Gyr

halo amplitude ➔ "standard" stellar IMF

Low-ish scatter ➔ efficient mixing

The element consistency ➔ slow SFR, with time to mix ejecta from several SNe during continuing star formation

Bootes1 had a "standard, gentle" self-enrichment history

ELEMENTAL ABUNDANCES AND THEIR IMPLICATIONS FOR THE CHEMICAL ENRICHMENT OF THE BOÖTES I ULTRA-FAINT GALAXY[1]

GERARD GILMORE[1], JOHN E. NORRIS[2], LORENZO MONACO[3], DAVID YONG[2], ROSEMARY F.G. WYSE[4], AND D. GEISLER[5]

Can we see evidence of the first supernovae?
Consider carbon evolution.

UNDANCES AND THEIR IMPLICATIONS
ICAL ENRICHMENT OF THE BOÖTES I
ULTRA-FAINT GALAXY[1]

OHN E. NORRIS[2], LORENZO MONACO[3], DAVID YONG[2],
MARY F.G. WYSE[4], AND D. GEISLER[5]

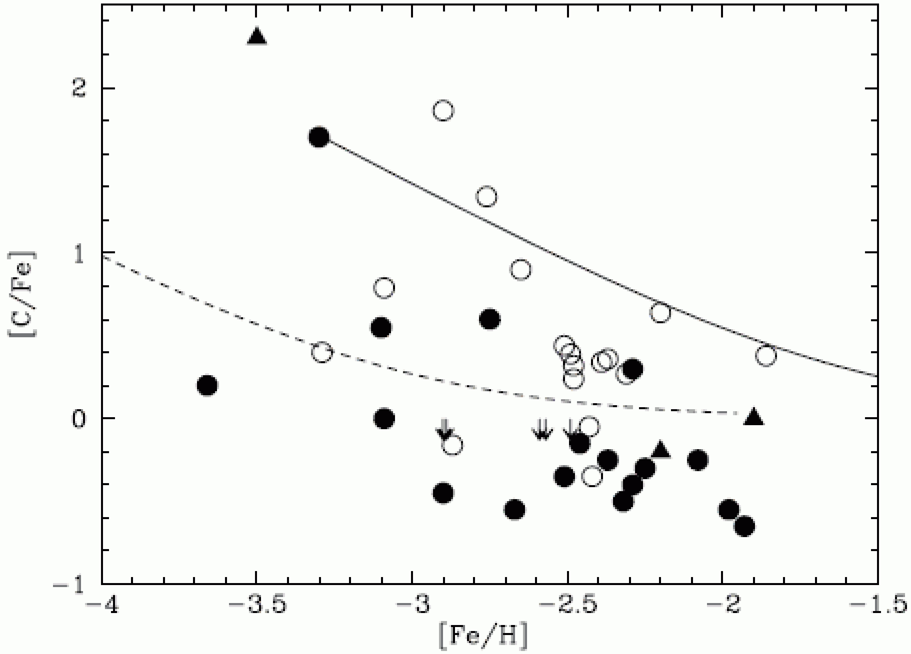


Fig. 11.— [C/Fe] vs. [Fe/H] for stars in the Boötes I dwarf galaxy (filled circles represent data of Norris et al. (2010b), with the exception of the CEMP-no star Boo-119, which has been plotted adopting the carbon abundance from Lai et al. (2011) and the iron abundance from the present work; open circles and upper limits represent data from Lai et al. (2011)) and for the Segue 1 dwarf galaxy (filled triangles, data from Norris et al. (2010b,a)). The smooth curve starts at Boo-119, and tracks the expected evolution due to continuing star formation in gas to which carbon and iron are added in the solar ratio, consistent with normal core-collapse supernovae. As discussed in the text, the data suggest two distinct channels of enrichment, one carbon-rich, and one carbon-normal.

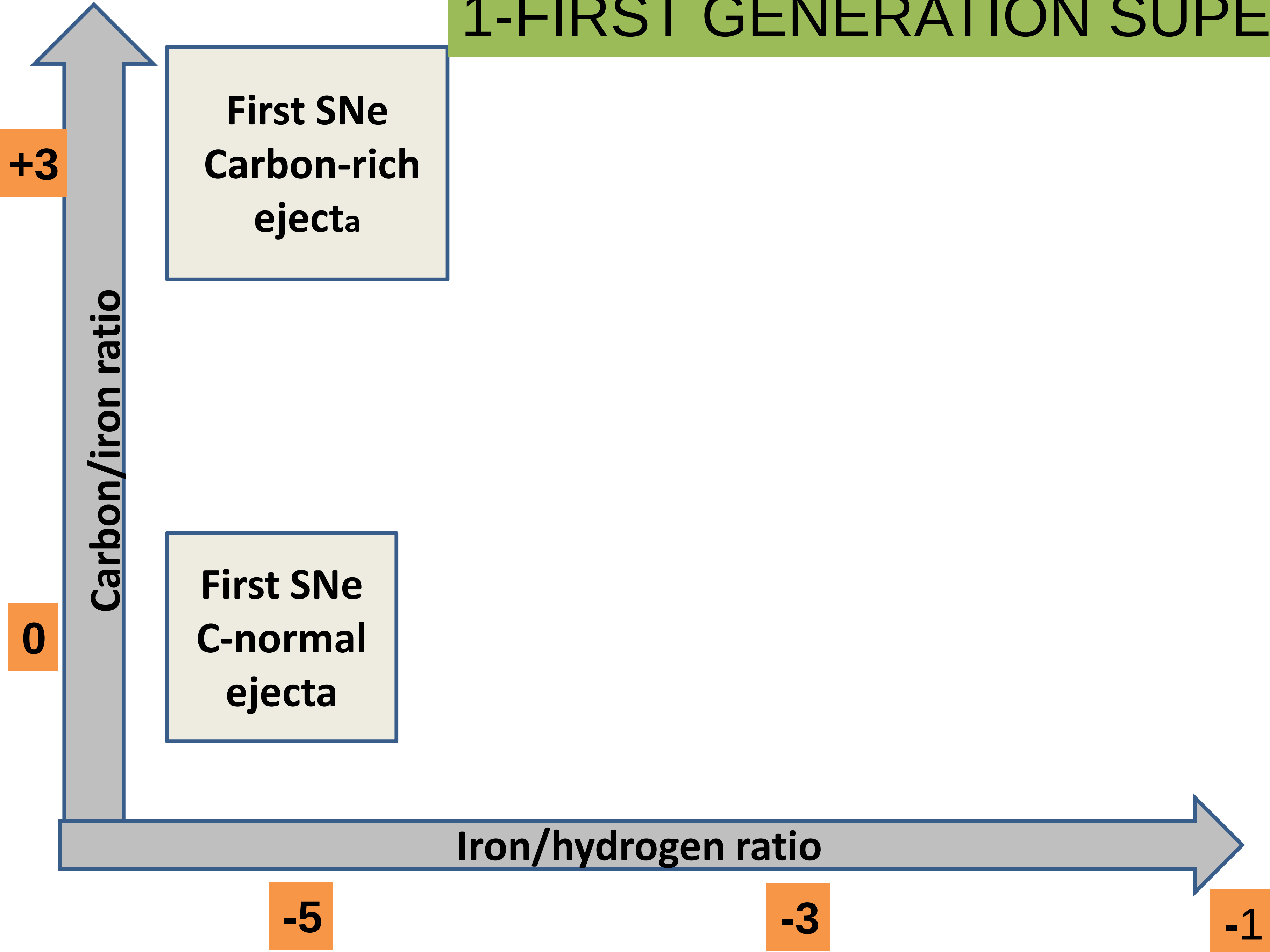
We see two evolutionary paths: C-high & C-low.

Why?

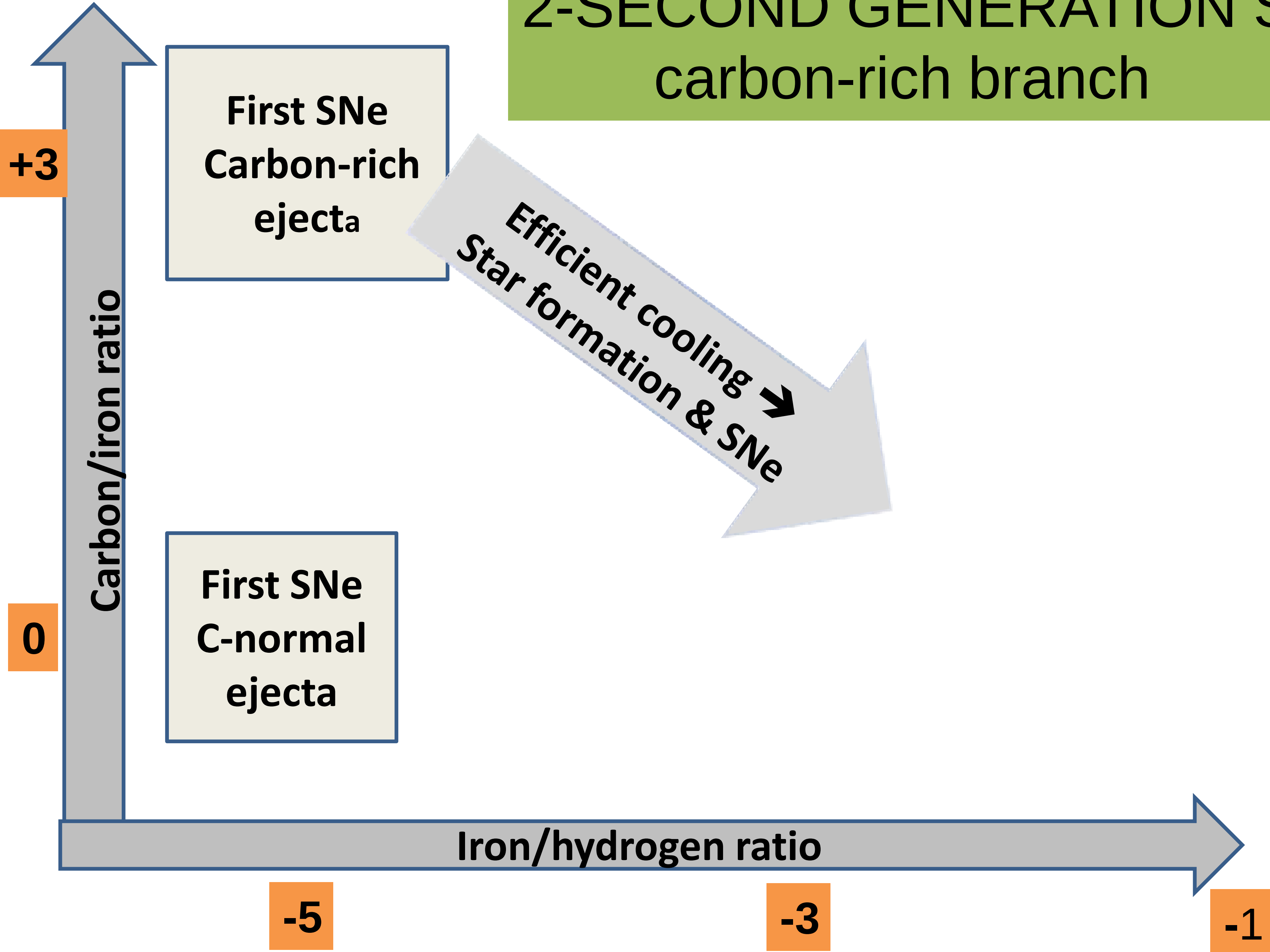
Two early carbon enrichment paths

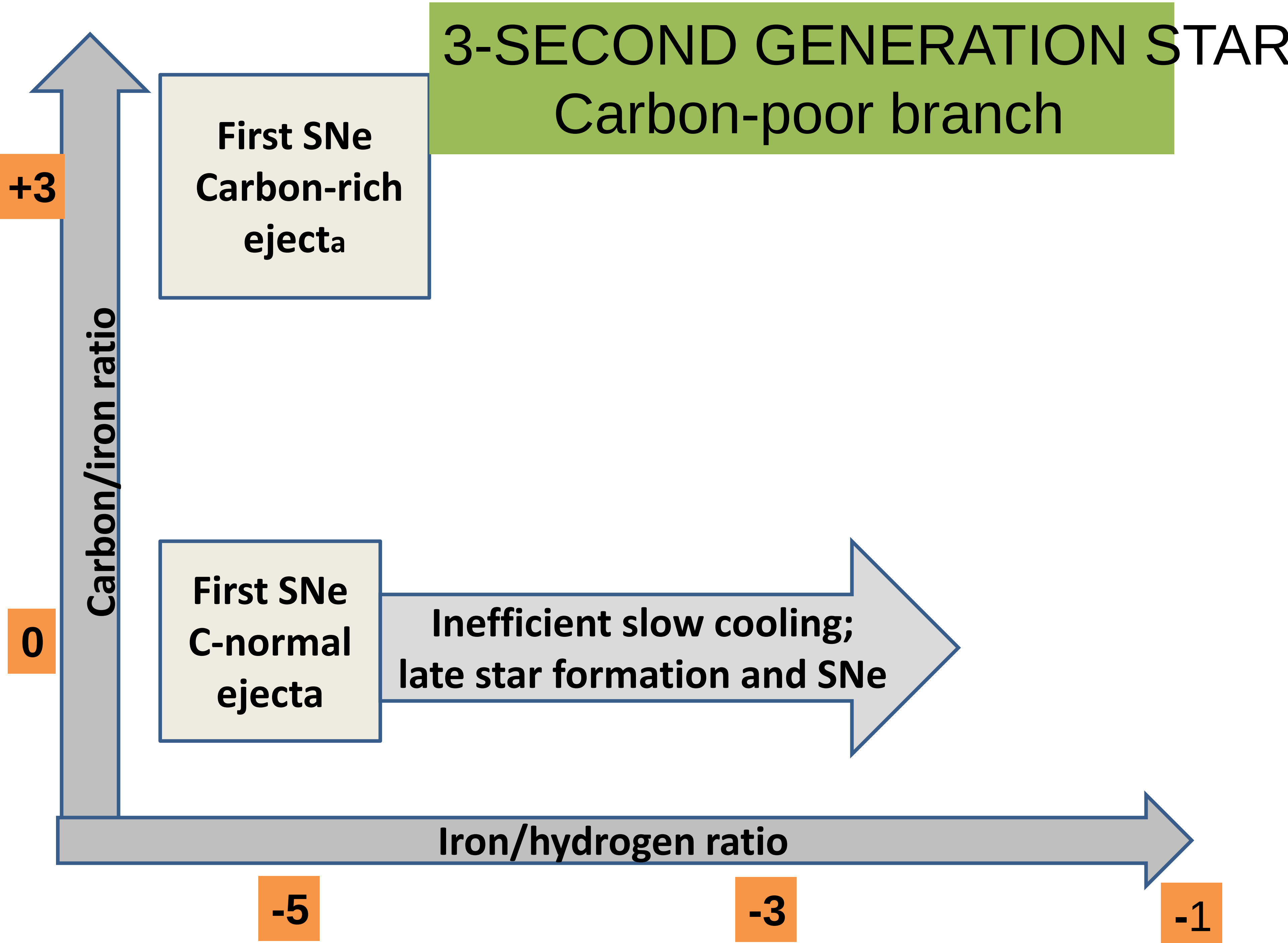
- We see very old stars with carbon abundances either low or high
- There is no chemical enrichment path between these
- There must be two parallel chemical enrichment paths:
- 1) fast, efficient, carbon rich, started by PopIII first SNe
- 2) slow, carbon poor, set by molecular/dust cooling
- The two enrichment patterns do not mix ➔ there is not violent ISM mixing ➔ low SNe rates

1-FIRST GENERATION SUPERN

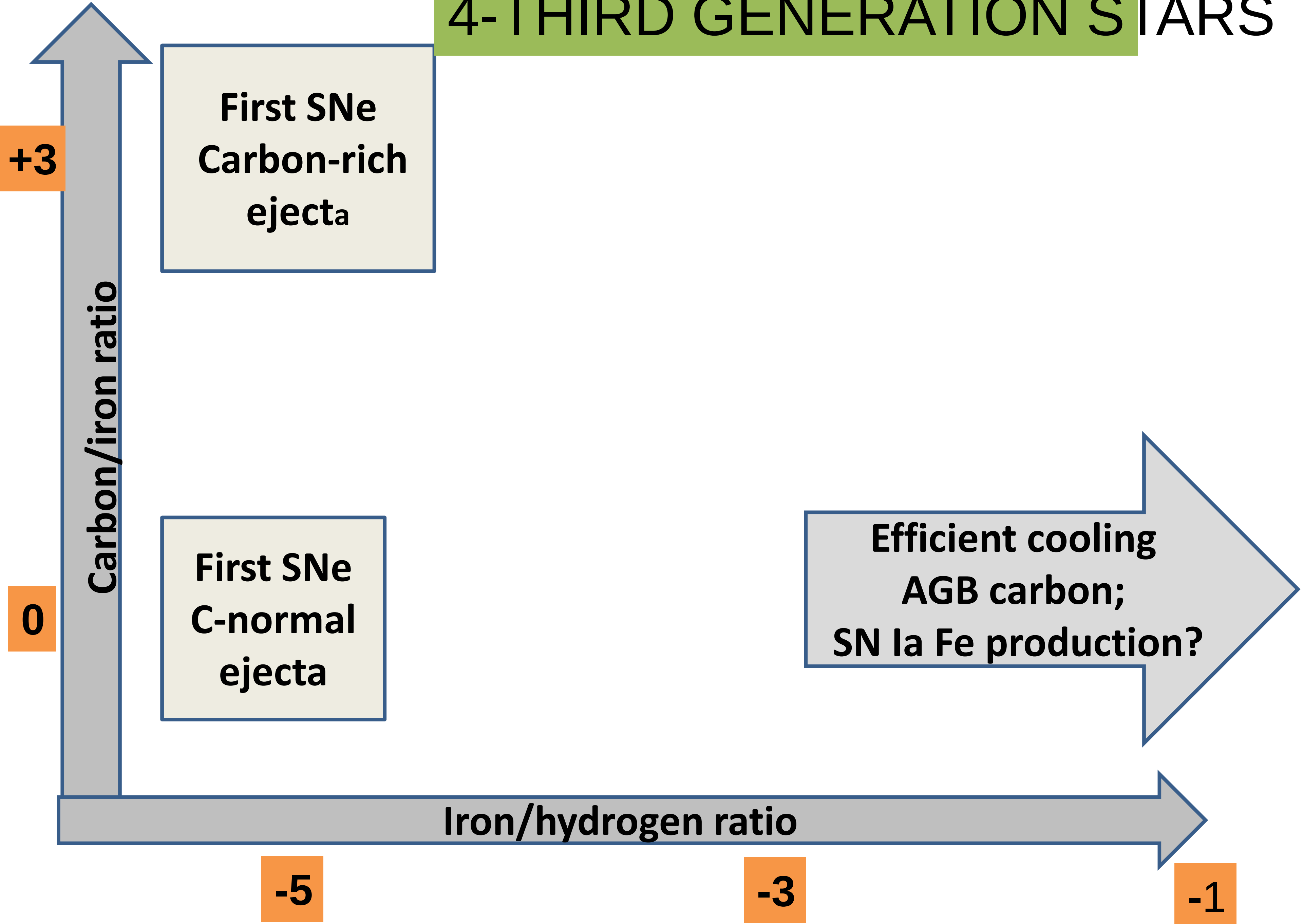


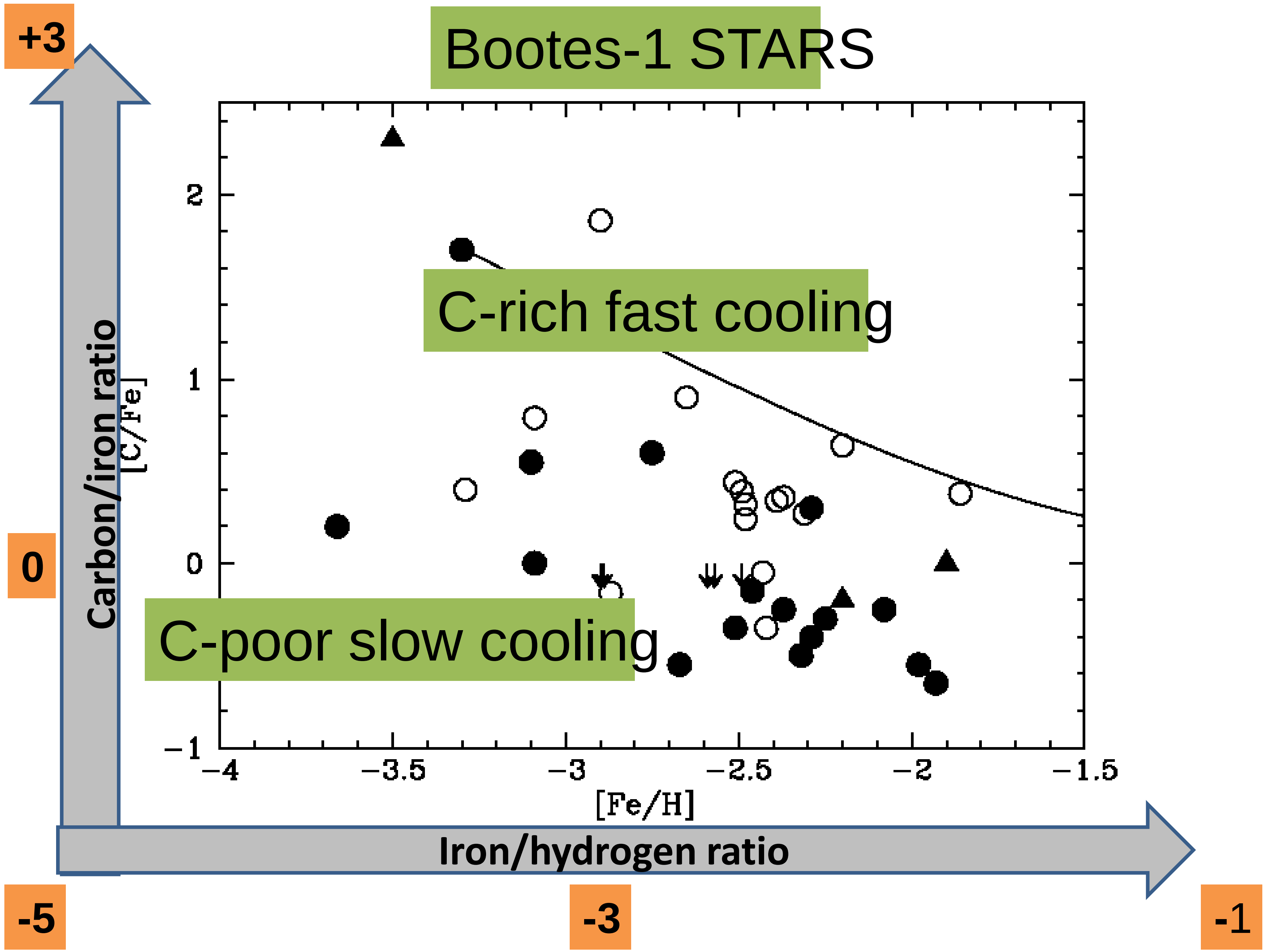
2-SECOND GENERATION STA
carbon-rich branch

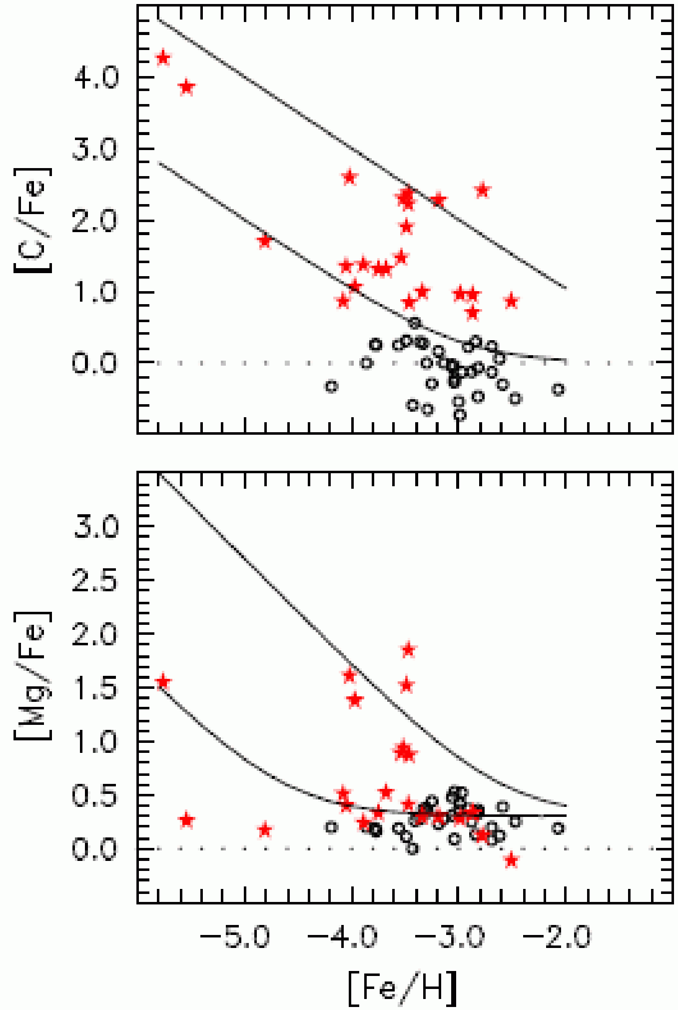



3-SECOND GENERATION STAR
Carbon-poor branch
First SNe
Carbon-rich
ejecta
+3
Carbon/iron ratio
0
First SNe
C-normal
ejecta
Inefficient slow cooling;
late star formation and SNe
Iron/hydrogen ratio
-5
-3
-1

4-THIRD GENERATION STARS




Bootes-1 STARS
C-rich fast cooling
C-poor slow cooling
Carbon/iron ratio
Iron/hydrogen ratio
+3
0
-5
-3
-1
[C/Fe]
[Fe/H]
2
1
0
−1
−4
−3.5
−3
−2.5
−2
−1.5



These two carbon enrichment paths are also consistent with field star abundances in the Galactic halo – but there we cannot know which is older.

dSph self-enrichment system is critical new information

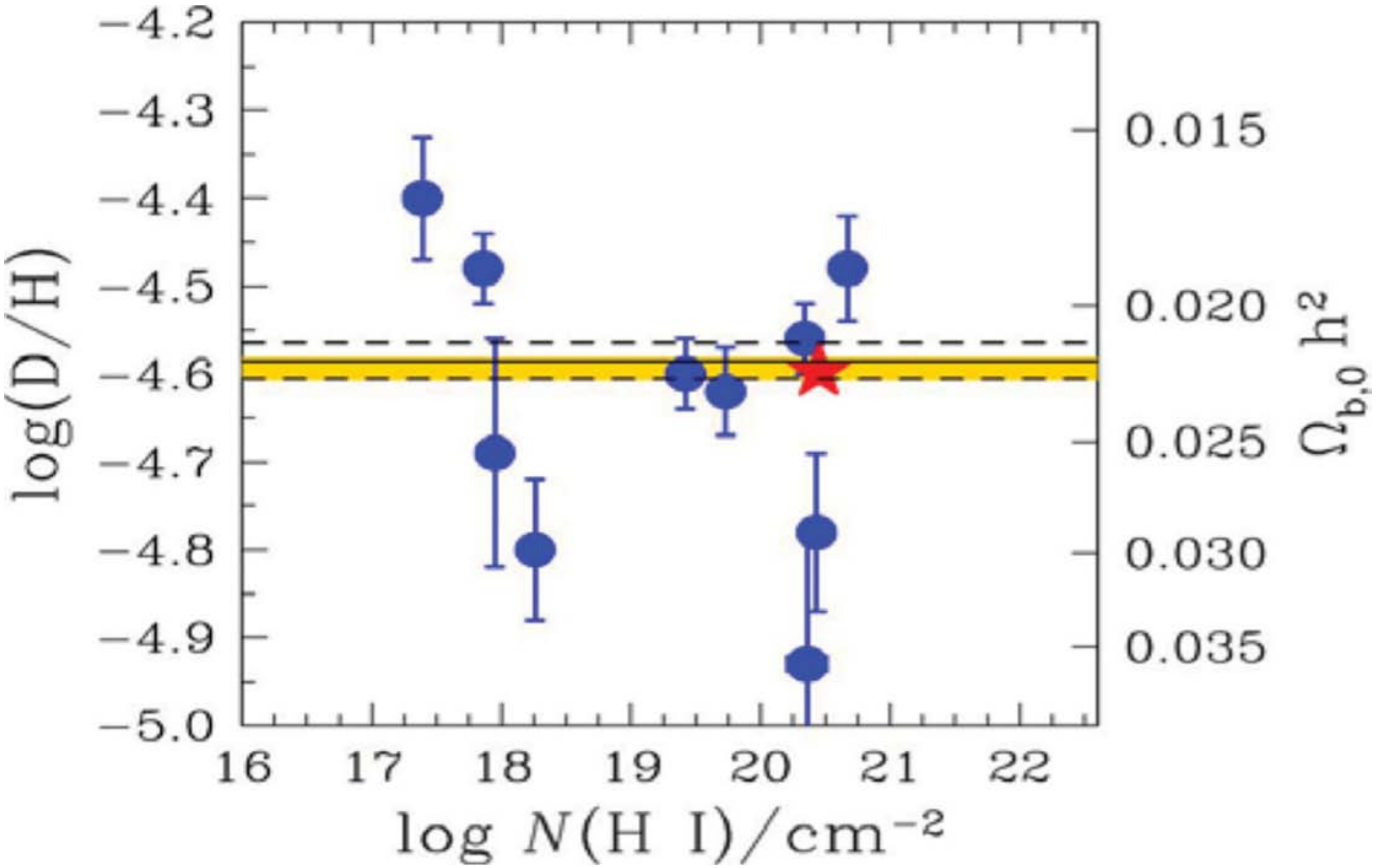
Fig. 12.— [C/Fe] and [Mg/Fe] vs. [Fe/H] for Galactic halo CEMP-no stars (star symbols, from Norris et al. 2012) and C-normal red giants (circles, from Cayrel et al. 2004 and Caffau et al. 2011). The lines represent dilution trajectories, as C-rich and Mg-rich material produced at the earliest times is mixed with C-normal and Mg-normal halo material. As [Fe/H] increases to –2.5, early C-rich and Mg-rich signatures are no longer evident. See text

implication

- Star formation feedback in (at least one!) dSph was far to small to affect the DM potential well ➔ cores are primordial
- We see two channels of star formation, but only at very low [Fe/h} abundances
- Most enrichment is expelled 9gently) from the proto-dSph at very early times
- ➔ this must affect kinematics of IGM/Ly-alpha forest on scales relevant to limits on WDM

Note that the most "primordial" IGM/Ly-alpha systems studied are all very much more metal-enriched than are our dSph stars: these IGM systems are not primordial

Measures of the deuterium abundance in high-redshift QSO absorbers.



Pettini M , Cooke R MNRAS 2012;425:2477-2486

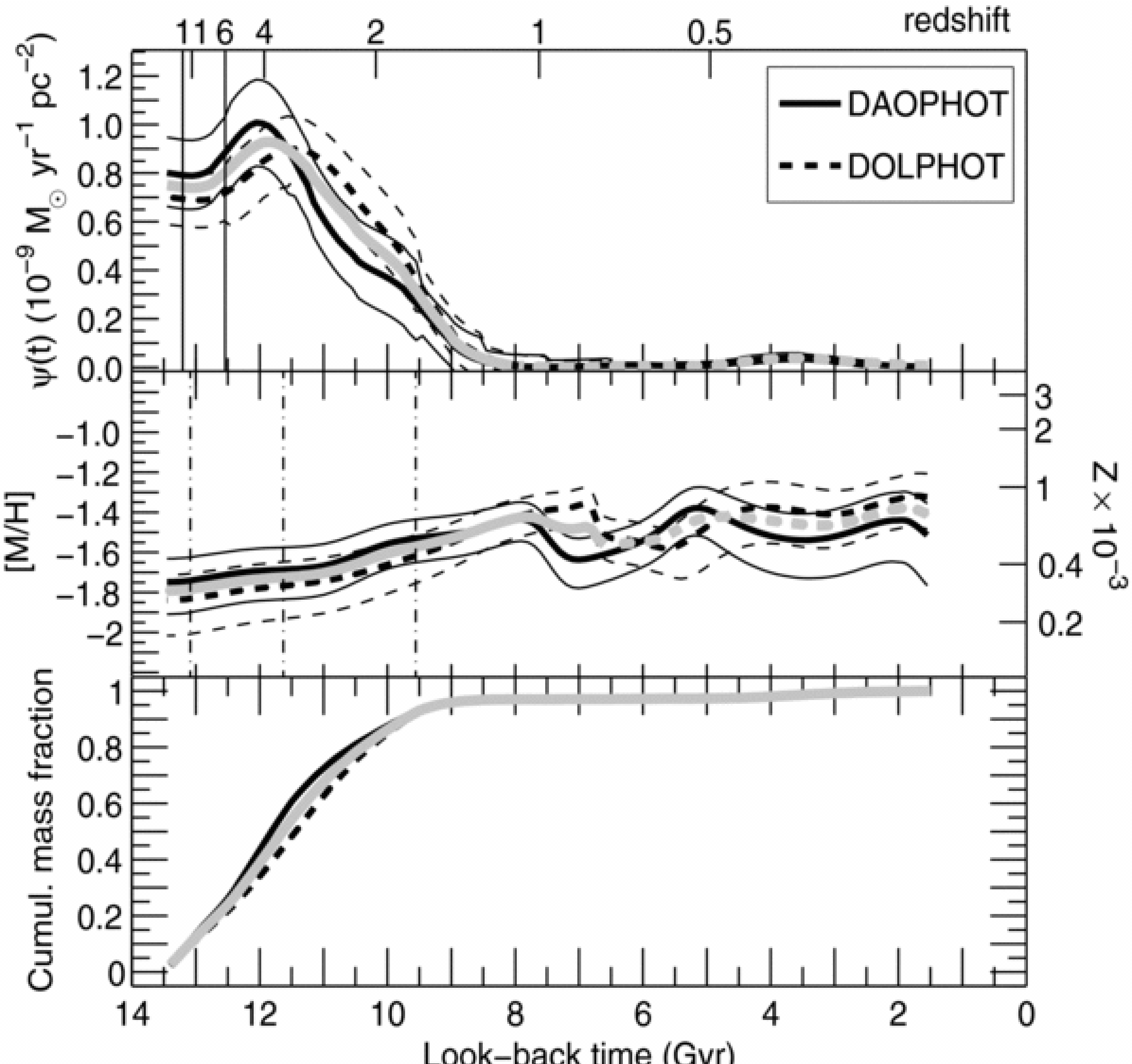
Feedback: what were we testing

- to explain lack of small galaxies (Rees & Ostriker 1977);
- Why so few baryons are in stars (overcooling)
- Why the IGM is metal-rich
- To make galaxy-like galaxies (McCarthy etal MN 2012)
- SNe release a lot of energy, which must drive gas winds (Creasey etal 1211.1395)
- Details are complex (Recchi & Hensler 1301.0812)
- May perturb CDM halo inner structure (Read & GG 2005); Ruiz etal MN 2013; Teyssier etal MN 2013, Penarrubia etal ApJ 2012)
- Major uncertainty is efficiency coupling star formation to mass loss , and SFR(t)

So what does this mean

- Ultra-faint dSph show clear chemical evidence of low rate star formation, with standard IMF, continuing over 10s of crossing times up to many Gyr. Most baryons are blown out, slowly
- Dynamical DM feedback must be unimportant: this isn't forming cores ➔ potential for astroparticle physics
- There are two cooling/star formation channels at low [Fe/H].
- CEMP-no enrichment is created only at extremely low [Fe/H] (= pop3?) then drives rapid cooling
- The high-C IGM with [Fe/H] >-3.3 may be changed by AGB stars – it is not primordial
- Early outflows should be included in IGM modelling

We can derive precise star formation histories directly from stellar CMDs.
Cetus dwarf: Monelli etal 2010 – no sign of reionisation on the SFR(t)
But in all these SFR(t) how can we be sure we are seeing the first stars at Z=20+??



Intermediate-age population dominates in typical dSph satellite galaxies – with very low average SFR over long periods ($\sim 5M_{\odot}/10^5$yr)

Cf Hernandez, Gilmore & Valls-Gabaud 2000

Enrichment history: first PopIII SNe creates high C,O, causes rapid ISM cooling and rapid formation of CEMP-no stars, including high-mass CEMP-no stars, which create standard SNe production. These CEMP-no stars are the surviving first low-mass stars to form. Lower [Fe/H] stars form more slowly, later.
All post-PopIII star formation has standard IMF.

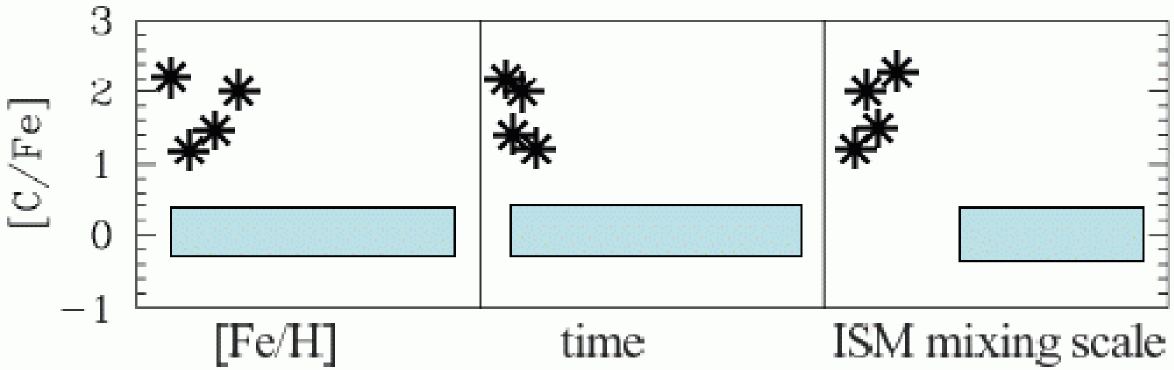


Fig. 13.— Schematic illustration of (i) (left panel) the different iron abundance regimes of the two carbon-enrichment channels; (ii) (middle panel) the different timescales since the onset of star-formation applying to the two separate enrichment channels and (iii) (right panel) the two different spatial scales over which nucleosynthetic material was mixed. The star symbols indicate the CEMP-no channel, while the blue band indicates the carbon-normal channel.

What is an answer?

- No set of experiments can ever establish the `truth` of any theory. Even if theory T predicts outcome O, and O is found, T *is not* proven. If O were outlandish, but seen, many assume T is likely. It remains unproven. Supporting T is the fallacy of ``affirmation of the consequent``.

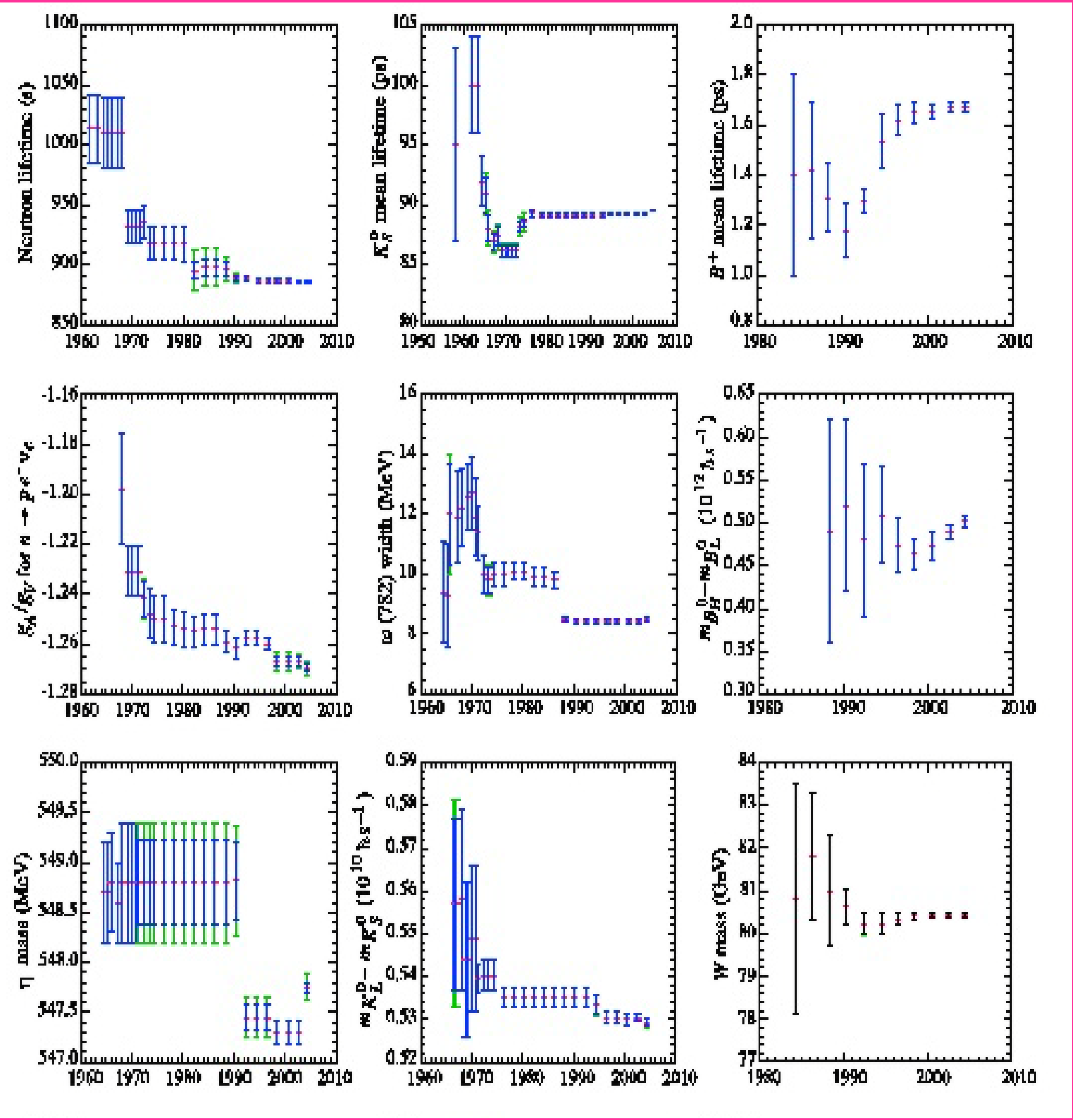
Only if O is not found is anything new learned.

Typically, in astrophysics,
we do not have a theory, in this sense, to test

Consistency does not imply correctness

clearly many scientists like to publish results which agree with their colleagues preconceptions

this isn't just them: think primordial helium



Particle-astrophysics joint challenges

- MSSM has 120+ free parameters…
- neutrino masses and mixing, effective number…
- baryogenesis
  - matter anti-matter asymmetry
- dark matter
- dark energy

Scale invariant power spectrum implies a physical cut-off at some scale, set by particle physics(?):

Is that scale astrophysically relevant?

Can it be deconvolved from feedback?

Can we quantify feedback to learn some physics?