Galactic evolution of D, ^{3}He and ^{4}He

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Outline of the talk

- **Historic overview: D, ^{3}He and ^{4}He evolution before and after *WMAP***
- **Current challenges: (1) true (local) deuterium abundance and galaxy formation scenarios**
- **Current challenges: (2) Galactic evolution of ^{3}He and the need for a new stellar physics**
- **Current challenges: (3) extreme ^{4}He-rich stars: the tip of the iceberg of an '^{4}He problem'?**
- **Conclusions**

Historic overview (I):

D, ^{3}He and ^{4}He in the pre-WMAP era

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High primordial D...

Carswell et al. (1994, MNRAS, 268, L1)
Songaila et al. (1994, Nature, 368, 599)

... or low primordial D?

Burles & Tytler (1998a, ApJ, 499, 699)
Burles & Tytler (1998b, ApJ, 507, 732)
O'Meara et al. (2001, ApJ, 552, 718)
Kirkman et al. (2003, ApJS, 149, 1)

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Low primordial ^{4}He...

Olive et al. (1997, ApJ, 483, 788)
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... or high primordial ^{4}He?

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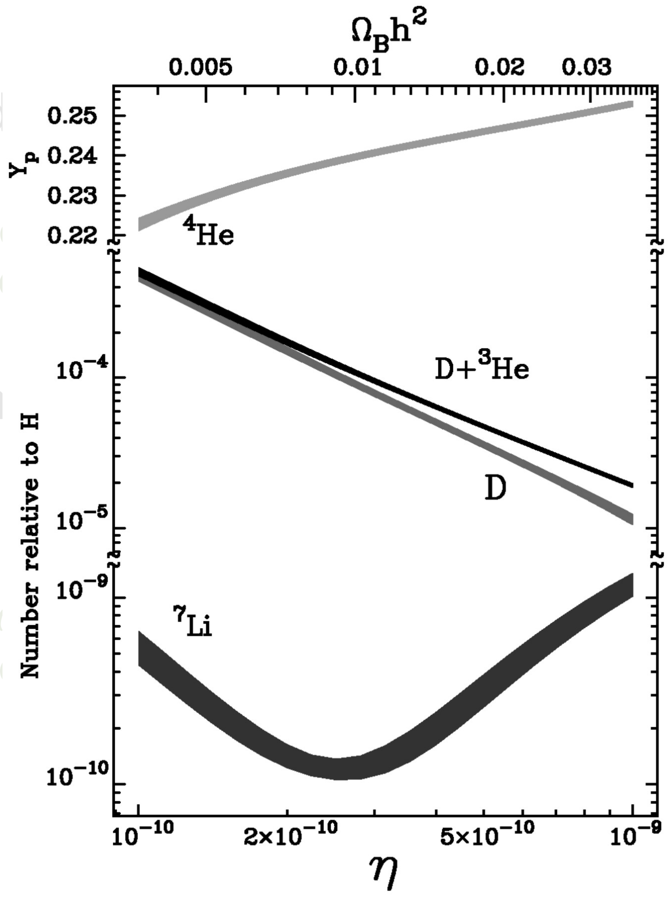

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Figure from Burles et al. (2001)

GCE basics

GCE describes how the abundances of several chemical species and their isotopes evolve in a galaxy, owing to the processes of star formation, infall and/or outflow of gas and return of processed matter from dying stars.

Good models for the Galaxy must reproduce local properties (G-dwarf metallicity distribution, age-metallicity relation, trends of [X/Fe] versus [Fe/H] for several elements, composition of the Sun at birth), as well as radial profiles of gas and stars, rates of SNeII, SNeIa and novae in the disc, and the shape and magnitude of any abundance gradient.

Not a well-sounded astrophysical theory yet !!!

Historic overview (I):

D, ^{3}He and ^{4}He in the pre-WMAP era

Hint from GCE models:

The Deuterium astration factor,

$$f_D \equiv (D/H)_P/(D/H)_{ISM} ,$$

**is modest, of the order of
a factor of 3-2 or even less**

(Audouze & Tinsley 1974, ApJ, 192, 487; Steigman & Tosi 1992, ApJ, 401, 150: Edmunds 1994, MNRAS, 270, L37; Galli et al. 1995, ApJ, 443, 536; Prantzos 1996, A&A, 310, 106; Tosi et al. 1998, ApJ, 498, 226; Chiappini et al. 2002, A&A, 395, 789)

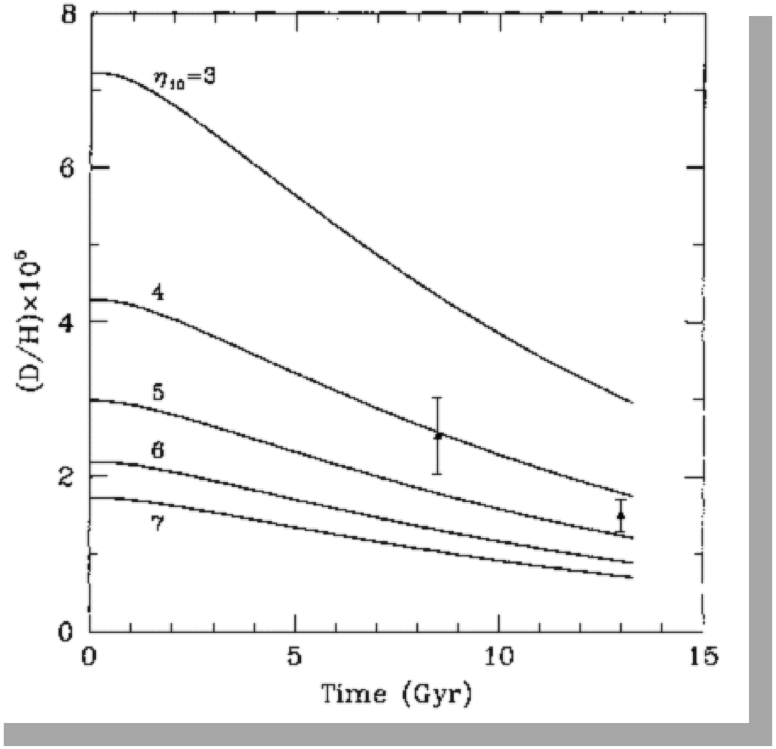

Figure from Galli et al. (1995)

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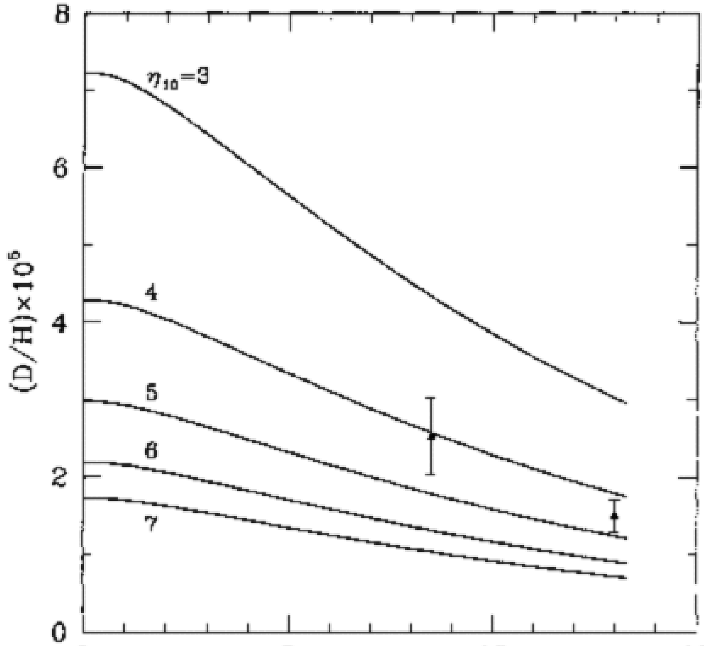


STRONG CASE FOR A LOW PRIMORDIAL DEUTERIUM!!!

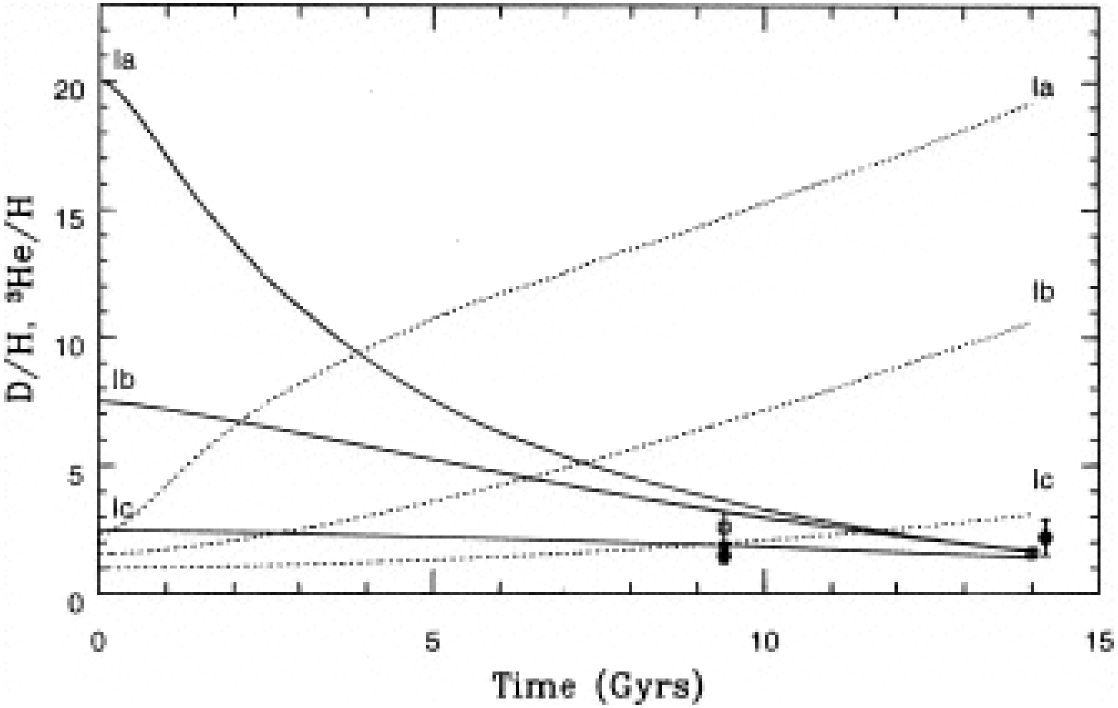
Historic overview (I):

D, ^{3}He and ^{4}He in the pre-WMAP era

Well, there have been exceptions...

Astration factor as high as 10, if an early Galactic wind develops!

(e.g. Scully et al. 1997, ApJ, 476, 521)



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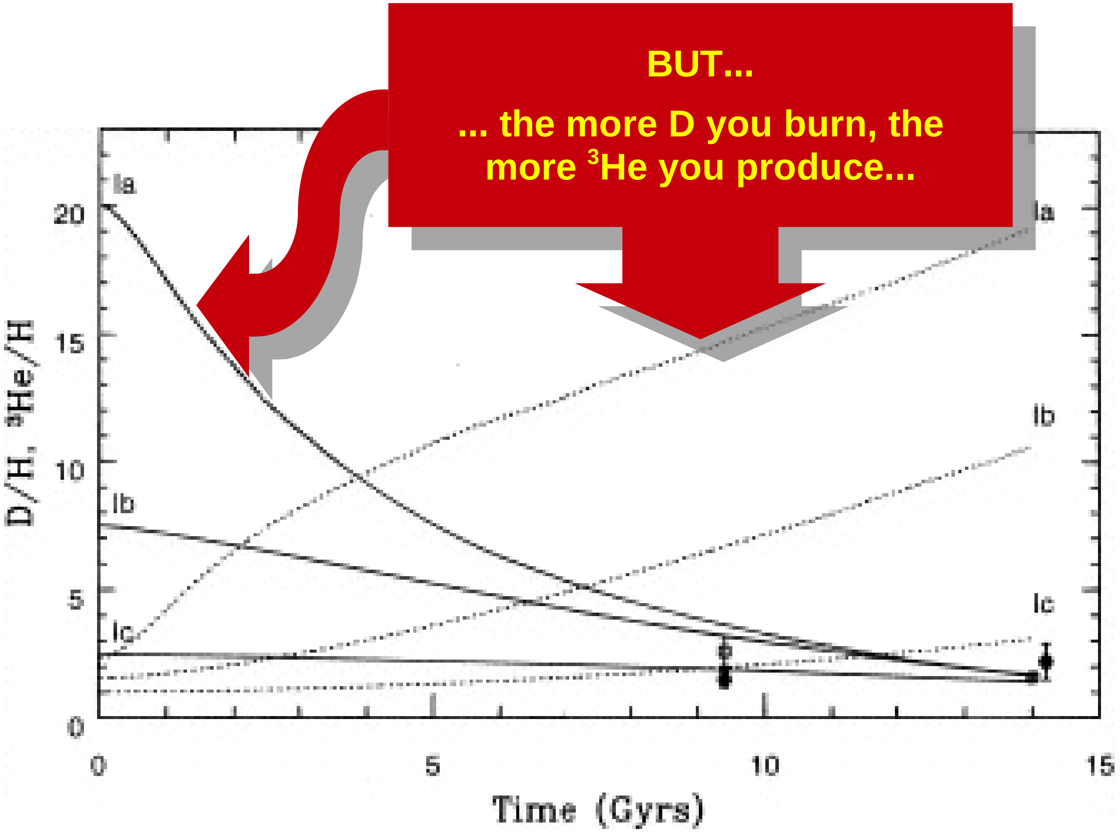

BUT...

... the more D you burn, the more ^{3}He you produce...

Historic overview (I):

D, ^{3}He and ^{4}He in the pre-WMAP era

... and you really don't want to overproduce ^{3}He!

Models:

THICK LINES: Chiappini et al. (2002)
THIN LINES: Tosi (1988)

Assumption: ≥93% of low-mass stars destroy ^{3}He

Data:

Geiss & Gloeckler (1998)
Bania et al. (2002)

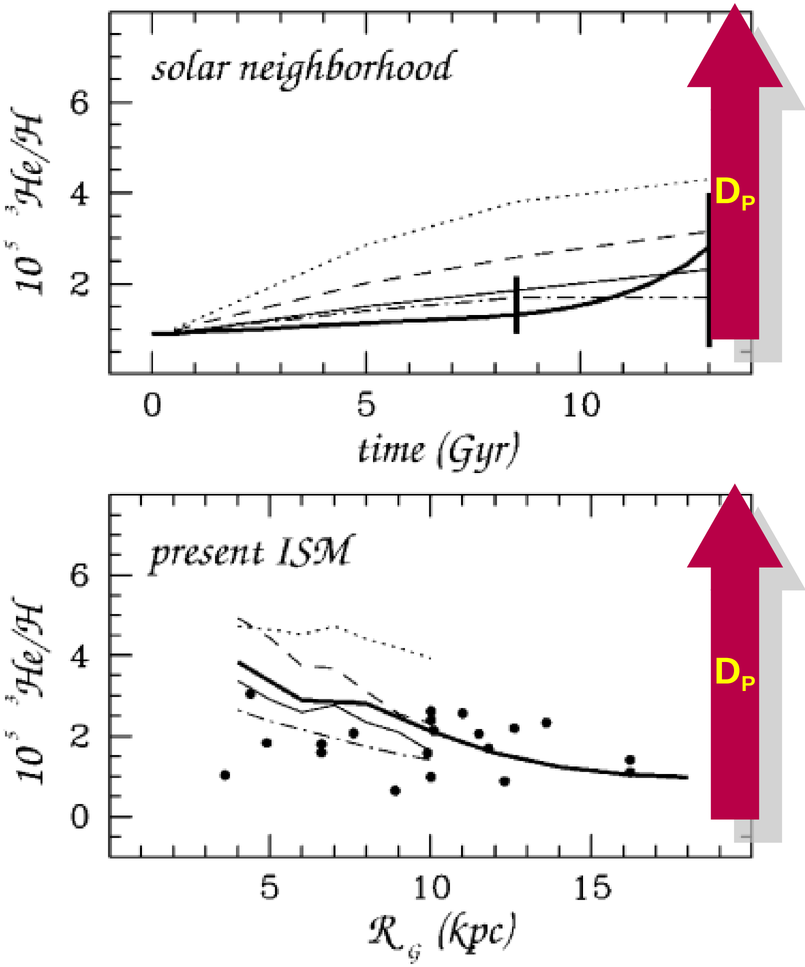

Figure from Romano et al. (2003)

Historic overview (I):

D, ^{3}He and ^{4}He in the pre-WMAP era

... and what about ^{4}He?

Well, it seems that GCE modelers didn't care much about ^{4}He evolution in the Milky Way...

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D, ^{3}He and ^{4}He in the pre-WMAP era

... and what about ^{4}He?

Well, it seems that GCE modelers didn't care much about ^{4}He evolution in the Milky Way...

General consensus that $\Delta Y/\Delta Z$ must lie somewhere in the range 1.5–3

High value for Y_P favored

Historic overview (I):

D, ^{3}He and ^{4}He in the pre-WMAP era

Summary of GCE results:

- **Low $(D/H)_P$**
- **(High Y_P)**
- **Some unknown physical process must destroy ^{3}He in ~93 % of low-mass stars**

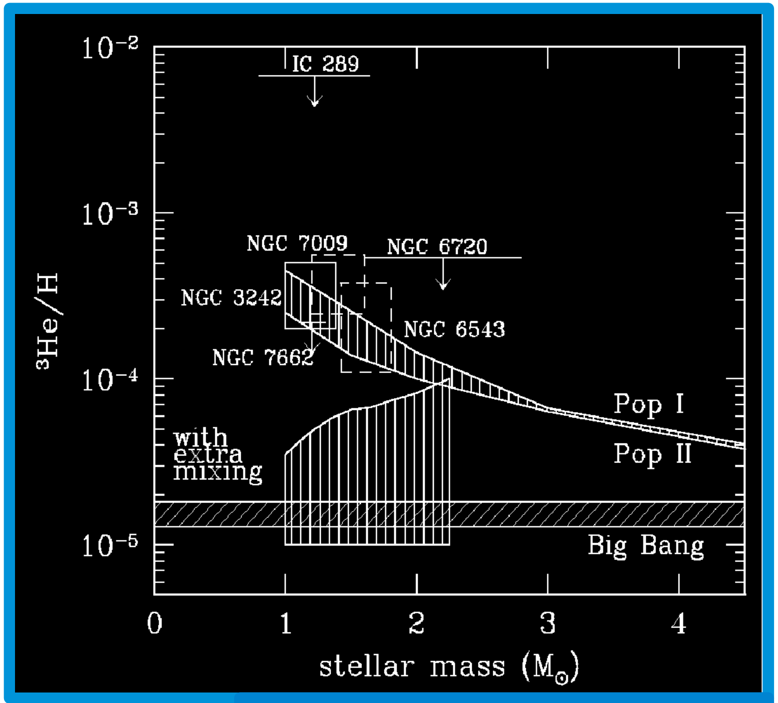
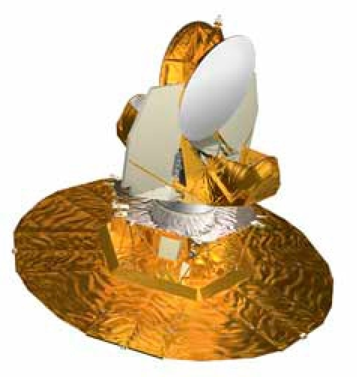


Figure from Galli (2006)

Historic overview (II):

D, ^{3}He and ^{4}He in the post-WMAP era



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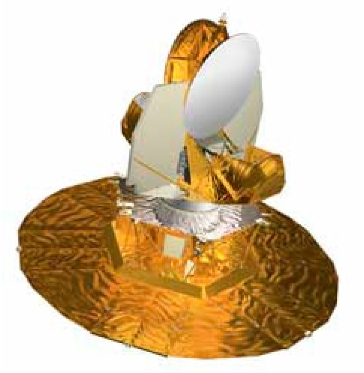


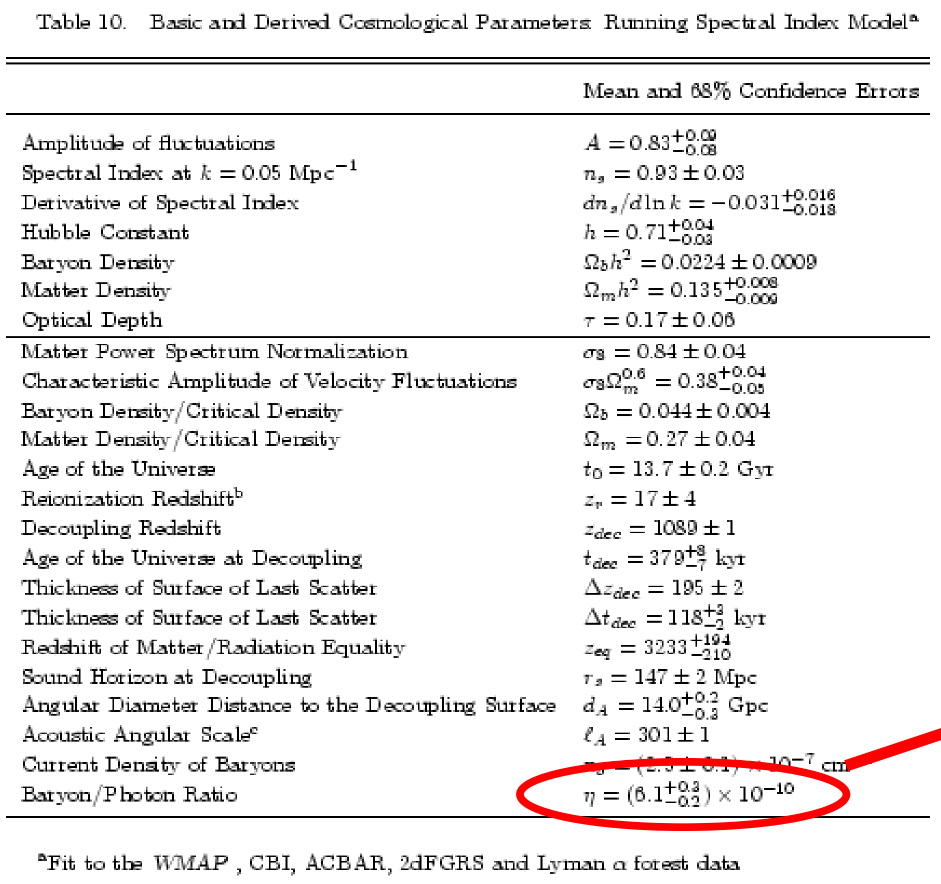


Table 10. Basic and Derived Cosmological Parameters: Running Spectral Index Model[a]

	Mean and 68% Confidence Errors
Amplitude of fluctuations	$A = 0.83^{+0.09}_{-0.08}$
Spectral Index at $k = 0.05$ Mpc^{-1}	$n_s = 0.93 \pm 0.03$
Derivative of Spectral Index	$dn_s/d\ln k = -0.031^{+0.016}_{-0.018}$
Hubble Constant	$h = 0.71^{+0.04}_{-0.03}$
Baryon Density	$\Omega_b h^2 = 0.0224 \pm 0.0009$
Matter Density	$\Omega_m h^2 = 0.135^{+0.008}_{-0.009}$
Optical Depth	$\tau = 0.17 \pm 0.06$
Matter Power Spectrum Normalization	$\sigma_8 = 0.84 \pm 0.04$
Characteristic Amplitude of Velocity Fluctuations	$\sigma_8 \Omega_m^{0.6} = 0.38^{+0.04}_{-0.05}$
Baryon Density/Critical Density	$\Omega_b = 0.044 \pm 0.004$
Matter Density/Critical Density	$\Omega_m = 0.27 \pm 0.04$
Age of the Universe	$t_0 = 13.7 \pm 0.2$ Gyr
Reionization Redshift[b]	$z_r = 17 \pm 4$
Decoupling Redshift	$z_{dec} = 1089 \pm 1$
Age of the Universe at Decoupling	$t_{dec} = 379^{+8}_{-7}$ kyr
Thickness of Surface of Last Scatter	$\Delta z_{dec} = 195 \pm 2$
Thickness of Surface of Last Scatter	$\Delta t_{dec} = 118^{+3}_{-2}$ kyr
Redshift of Matter/Radiation Equality	$z_{eq} = 3233^{+194}_{-210}$
Sound Horizon at Decoupling	$r_s = 147 \pm 2$ Mpc
Angular Diameter Distance to the Decoupling Surface	$d_A = 14.0^{+0.2}_{-0.3}$ Gpc
Acoustic Angular Scale[c]	$\ell_A = 301 \pm 1$
Current Density of Baryons	$n_b = (2.5 \pm 0.1) \times 10^{-7}$ cm
Baryon/Photon Ratio	$\eta = (6.1^{+0.3}_{-0.2}) \times 10^{-10}$

[a] Fit to the *WMAP*, CBI, ACBAR, 2dFGRS and Lyman α forest data

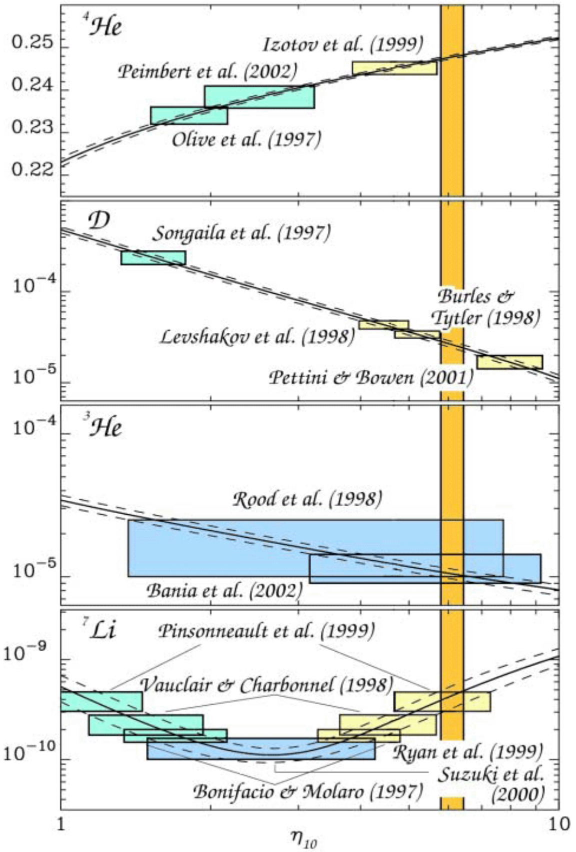
Baryon-to-photon ratio known with unprecedented precision:

$$\eta_{10} \equiv 10^{10}\, \eta = 6.1(+0.3/-0.2)$$

Spergel et al. (2003, ApJS, 148, 175)

Historic overview (II):

D, ^{3}He and ^{4}He in the post-WMAP era



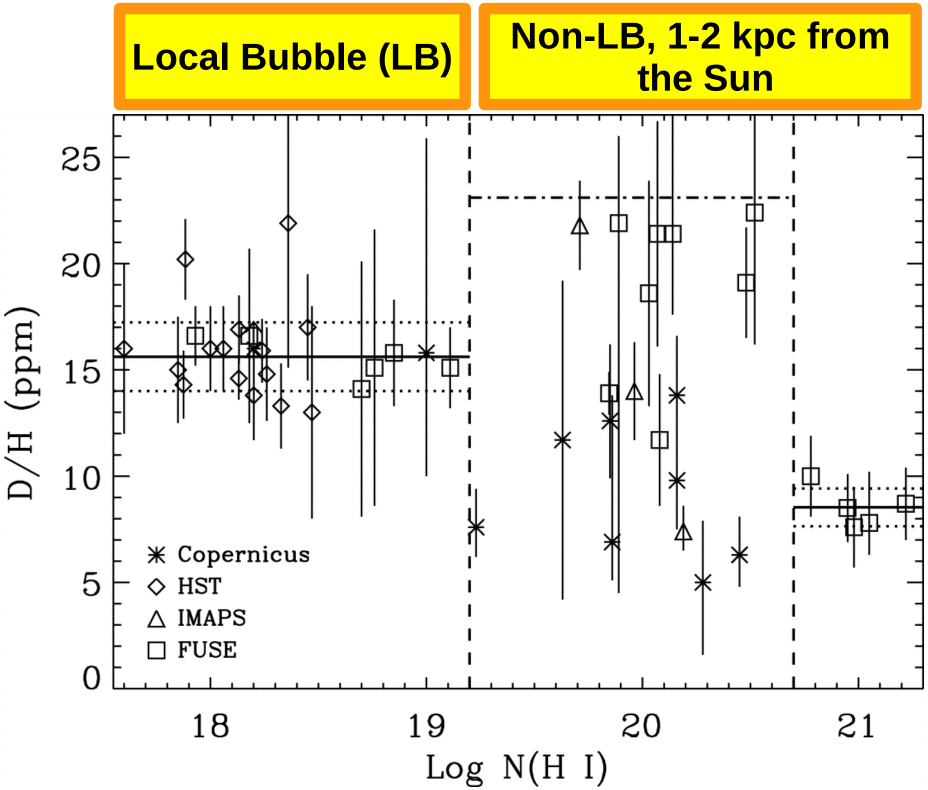
- **Important, independent confirmation of GCE results!**
- **Now, the primordial abundances of the light elements are firmly bound!**

Figure from Romano et al. (2003)

The present (I):

the (un)true local D abundance

Talks by Linsky, Prodanovic and Hébrard + Monday afternoon discussion...



Local Bubble (LB)

Non-LB, 1-2 kpc from the Sun

Figure from Linsky et al. (2006)

What is the local value of the D abundance?

The present (I):

the (un)true local D abundance

Local Bubble (LB)

Non-LB, 1-2 kpc from the Sun

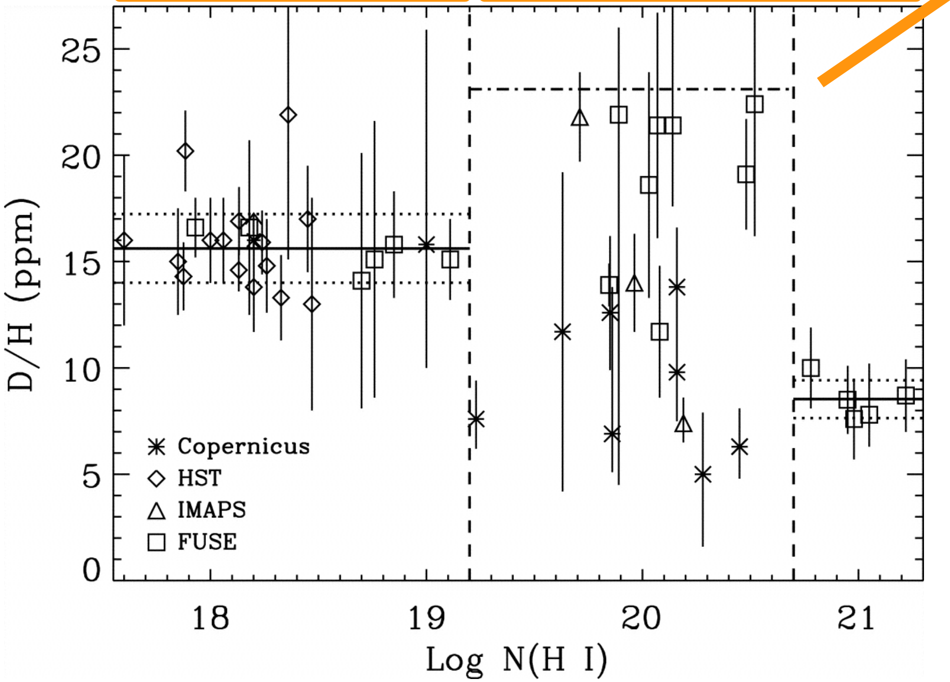
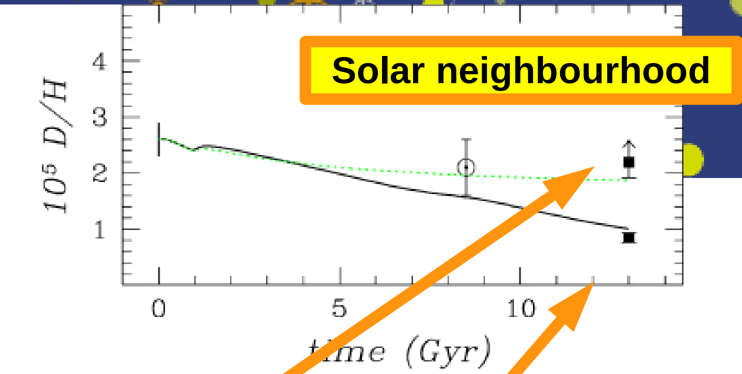
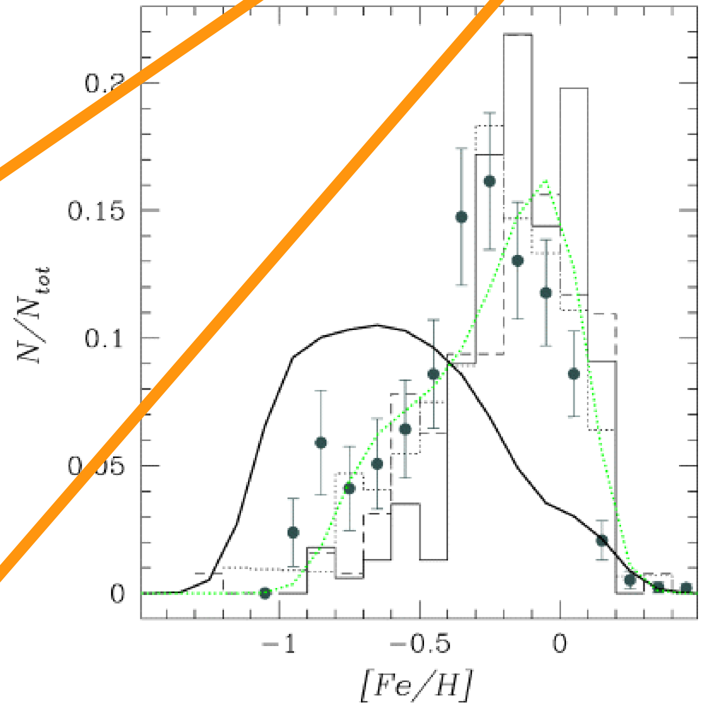


Figure from Linsky et al. (2006)

Solar neighbourhood



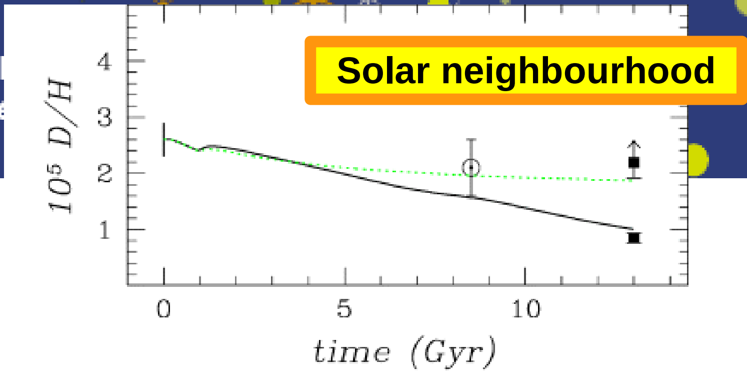


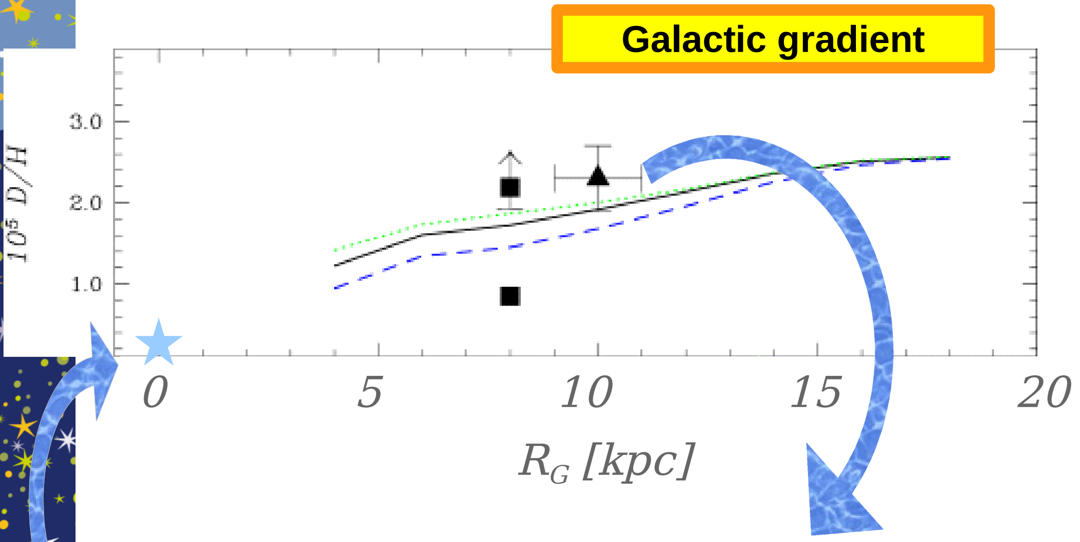
**GCE models point to a high value...
...but not that much high!!!**

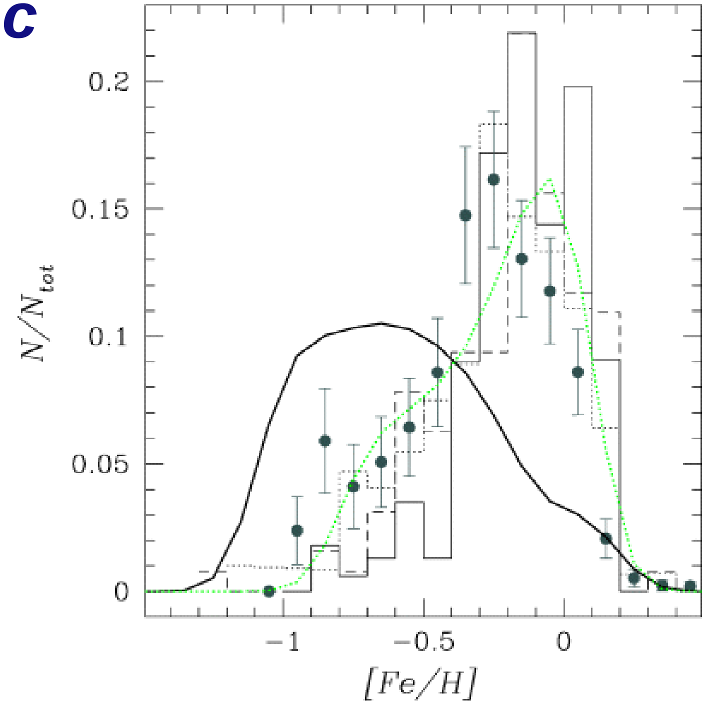
Figure and models from Romano et al. (2006)
See also Tosi et al. (1998, ApJ, 498, 226)

The present (I):

D abundance in the Bulge & Disc







Star: D in the Galactic bulge from DCN lines @72.404, 144.83 GHz (Lubowich et al. 2000)

Filled triangle: D from the 327-MHz D line in the outer disc (Rogers et al. 2005)

GCE models point to a high value...
...but not that much high!!!

Figures and models from Romano et al. (2006)
See also Tosi et al. (1998, ApJ, 498, 226)

The present (II):

^{3}He evolution: the need for a new stellar physics?

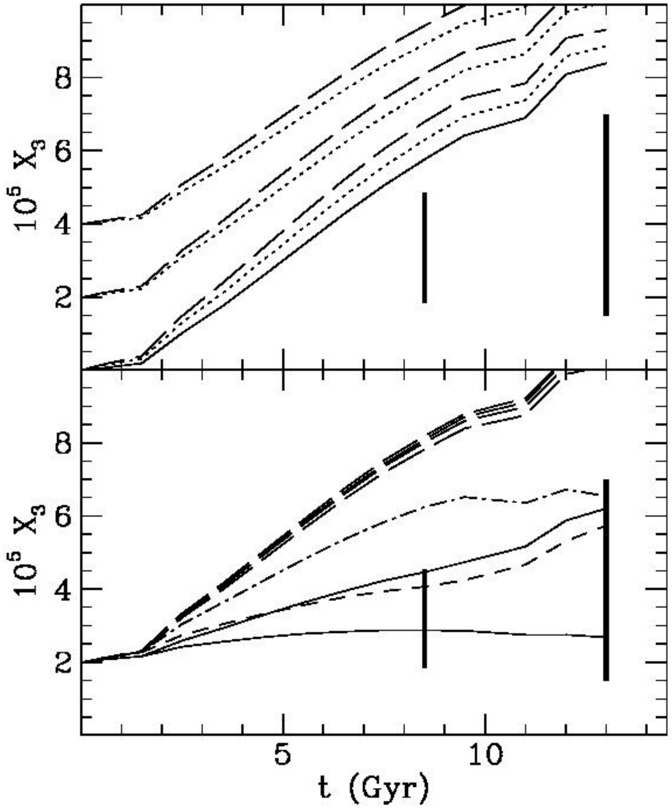


Figure from Dearborn et al. (1996)

Problems raised in pioneering works about ^{3}He evolution in the MW *(Truran & Cameron 1971, Ap&SS, 14, 179; Talbot & Arnett 1973, ApJ, 186, 51; Reeves et al. 1973, ApJ, 179, 909; Tinsley 1974, ApJ, 192, 629)* **still unsolved: some ^{3}He-destruction mechanism must be at work in a fraction of low-mass stars in order not to overproduce ^{3}He in the course of Galactic evolution** *(Galli et al. 1995, ApJ, 443, 536; Dearborn et al. 1996, ApJ, 465, 887; Charbonnel & Do Nascimento 1998, A&A, 336, 915; Sackmann & Boothroyd 1999, ApJ, 510, 217)***... but what is it? One must also explain the existence of PNe with high ^{3}He content** *(e.g. Balser et al. 1999, ApJ, 522, L73)*

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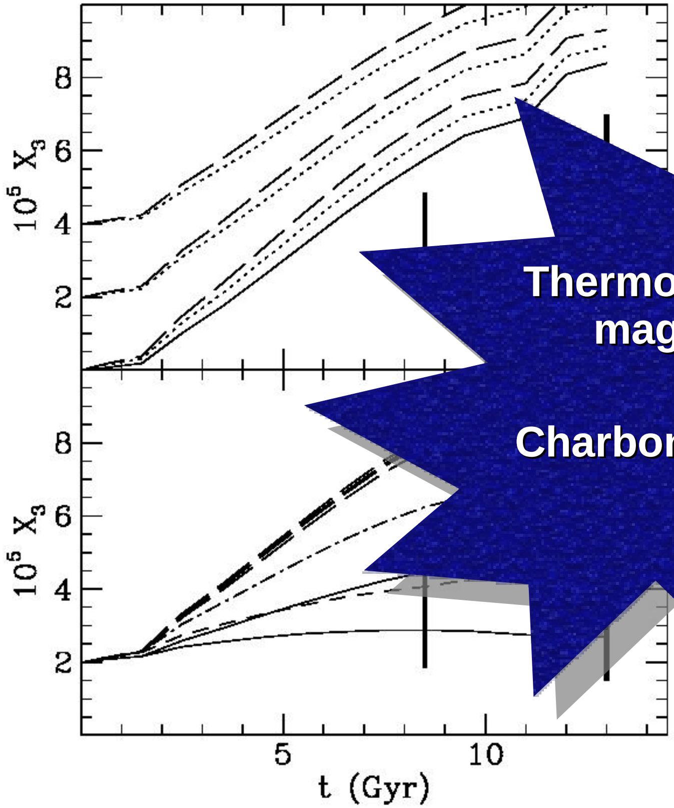

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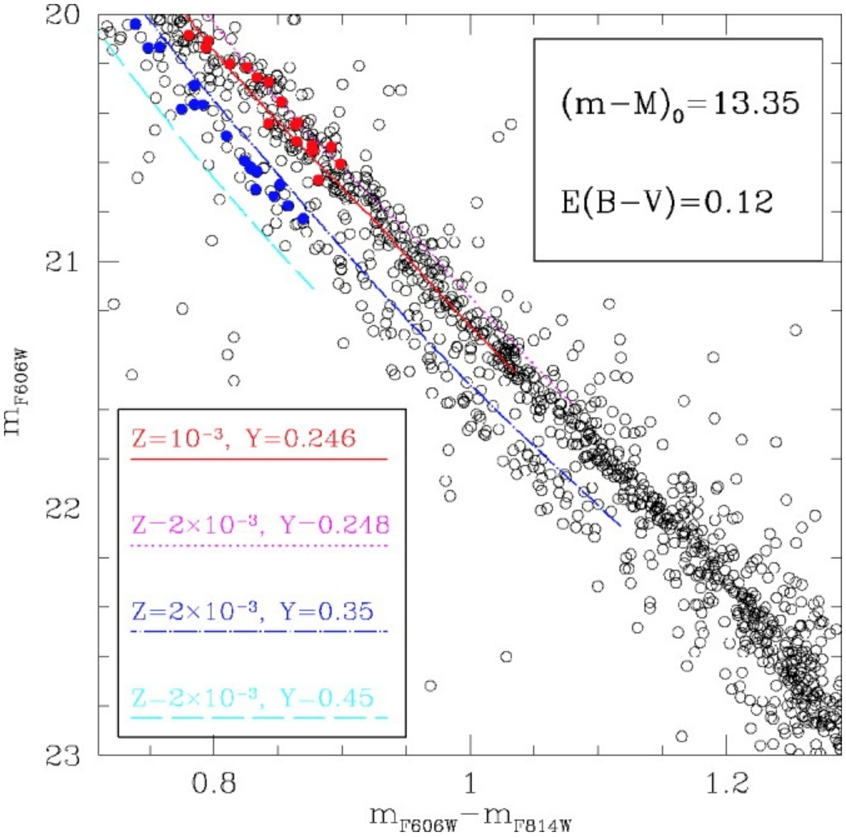
Thermohaline mixing + magnetic fields?

Talk by Charbonnel & Lagarde...

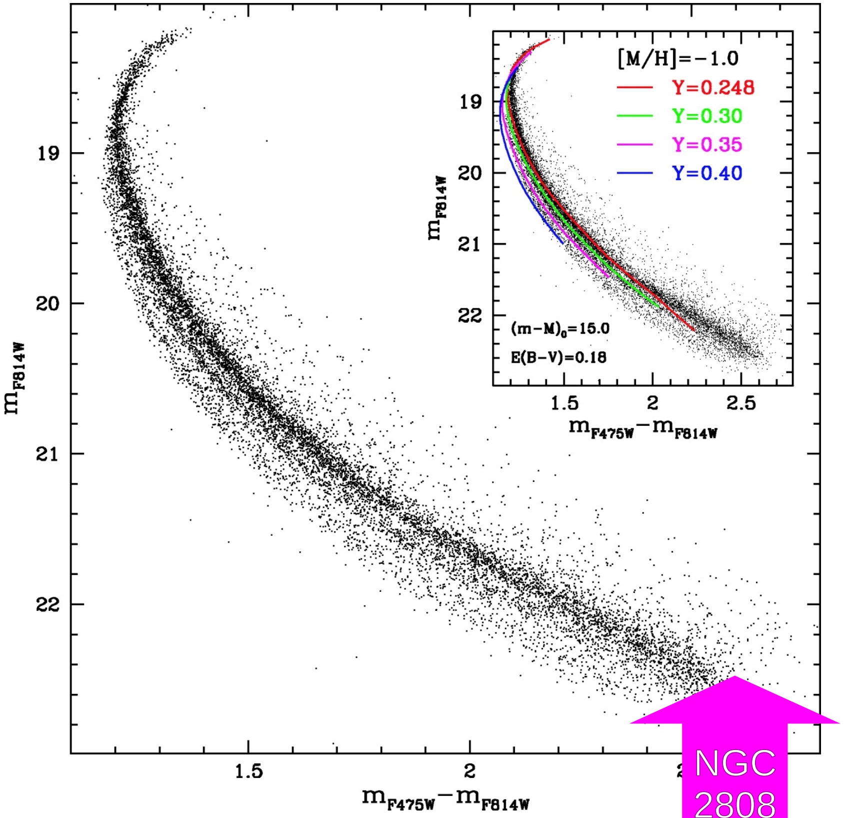
The present (III):

the ^{4}He problem (part I...)



ω Cen

Figure from Piotto et al. (2005)



NGC 2808

Figure from Piotto et al. (2008)

The present (III):

the ^{4}He problem (part I...)

How do you explain ^{4}He abundances as high as ~0.4?

AGB self-pollution scenario

Cottrell & Da Costa (1981, ApJ, 245, L79)
Ventura et al. (2001, ApJ, 550, L65)
D'Ercole et al. (2008, MNRAS, 391, 825)

P. Ventura talk

FRMS self-pollution scenario

Prantzos & Charbonnel (2006, A&A, 458, 135)
Decressin et al. (2007a, A&A, 464, 1029)
Decressin et al. (2007b, A&A, 475, 859)
Decressin et al. (2008, A&A, 492, 101)

T. Decressin talk

The present (III):

the ^{4}He problem (part I...)

How do you explain 4He abundances as high as ~0.4?

AGB self-pollution scenario

Cottrell & Da Costa (1981, ApJ, 245, L79)
Ventura et al. (2001, ApJ, 550, L65)
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P. Ventura talk

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T. Decressin talk

More exotic explanations: Choi & Yi (2007, MNRAS, 375, L1); Marcolini et al. (2009, MNRAS, 395, 719)

The present (III):

the ^{4}He problem (part I...)

A new scenario (only for ω Cen... Romano et al. 2007, MNRAS, 376, 405; Romano et al. 2009, arXiv:0910.1299):

Detailed chemical evolution of the putative ω Cen parent galaxy

($\mathcal{M}_{\mathrm{dSph}}$ = 10^9 $M_\odot$):

- **Strong differential galactic winds reduce the effective metal yields**

SN products easily escape the galactic potential well, whereas elements restored to the ISM through low-energy stellar winds are mostly retained independently of whether they are produced by AGBs or FRMSs

The present (III):

the ^{4}He problem (part I...)

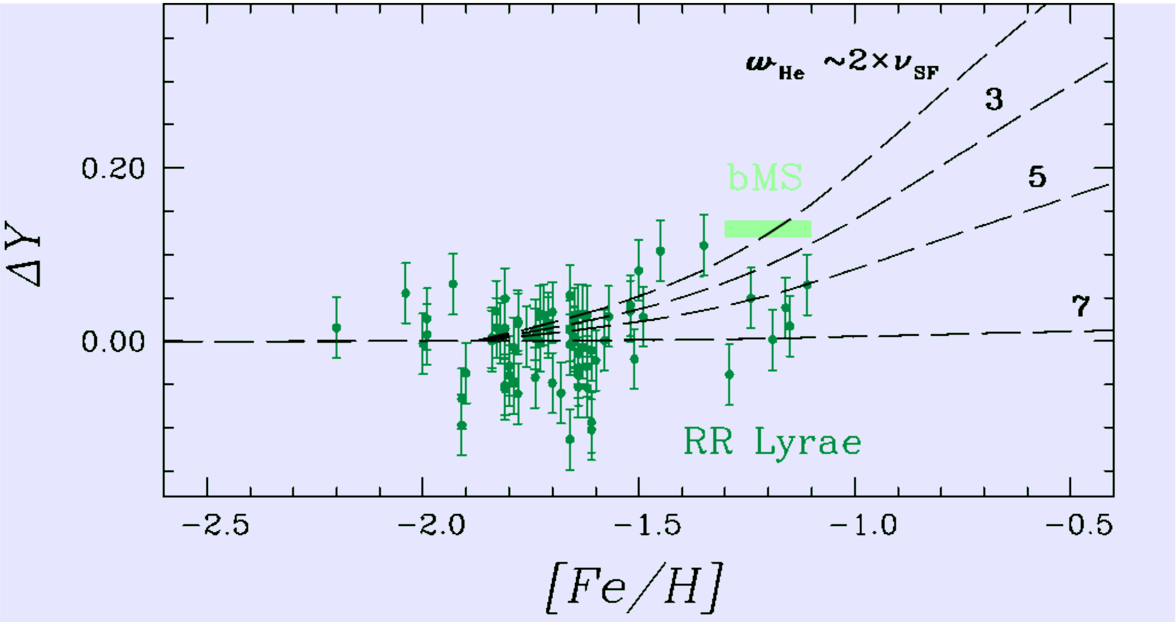
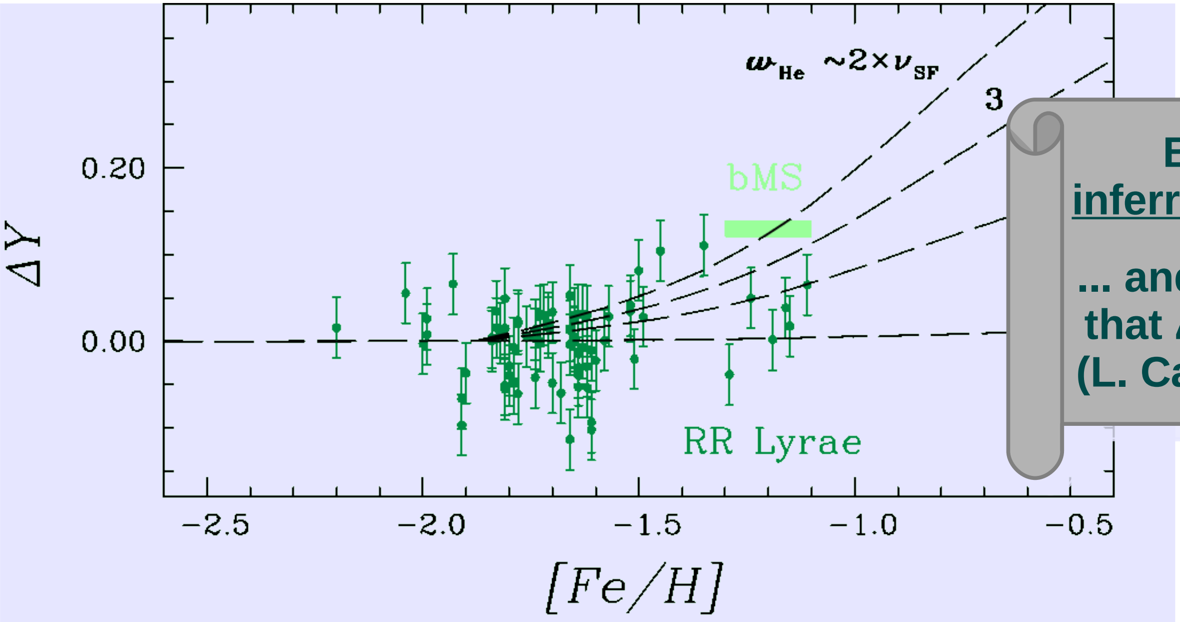


Figure from Romano et al. (2009)

"The answer, my friend, is blowin' in the wind…" *(Bob Dylan, 1962)*

The present (III):

the ^{4}He problem (part I...)



Beware! He is <u>inferred</u>, not <u>measured</u>

**... and it could well be that ΔY = 0.05-0.07...
(L. Casagrande's talk)**

Figure from Romano et al. (2009)

"The answer, my friend, is blowin' in the wind..." (Bob Dylan, 1962)

The present (III):

the ^{4}He problem (part I…)

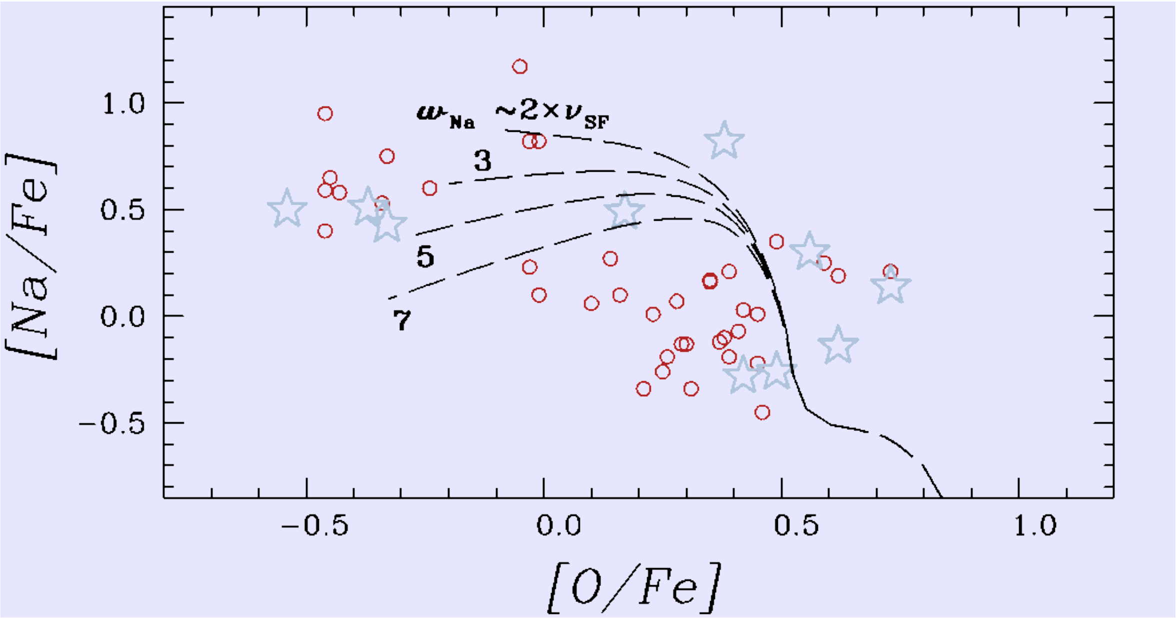
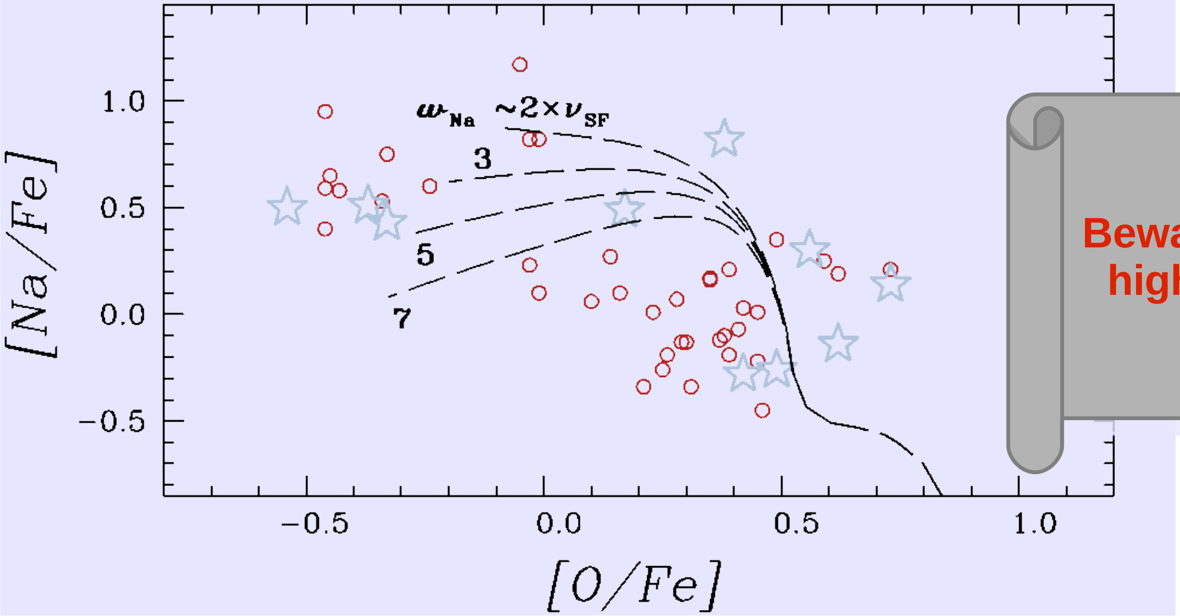


Figure from Romano et al. (2009)

“THE ANSWER, MY FRIEND, IS BLOWIN' IN THE WIND…” *(Bob Dylan, 1962)*

The present (III):

the ^{4}He problem (part I...)



Beware! Na yields are highly uncertain...!

Figure from Romano et al. (2009)

"THE ANSWER, MY FRIEND, IS BLOWIN' IN THE WIND..." (Bob Dylan, 1962)

The present (III):

the ^{4}He problem (part II...)

Mostly indirect estimates of ^{4}He abundances in the Galaxy!

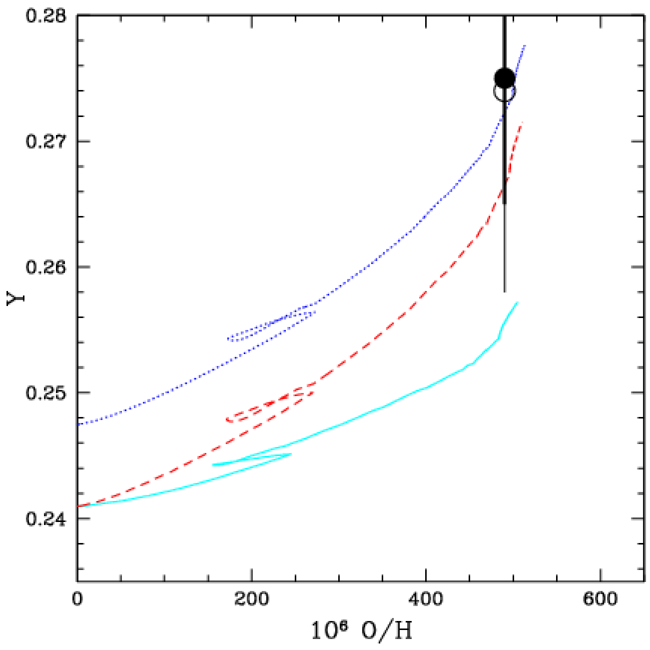


Figure from Chiappini et al. (2003)

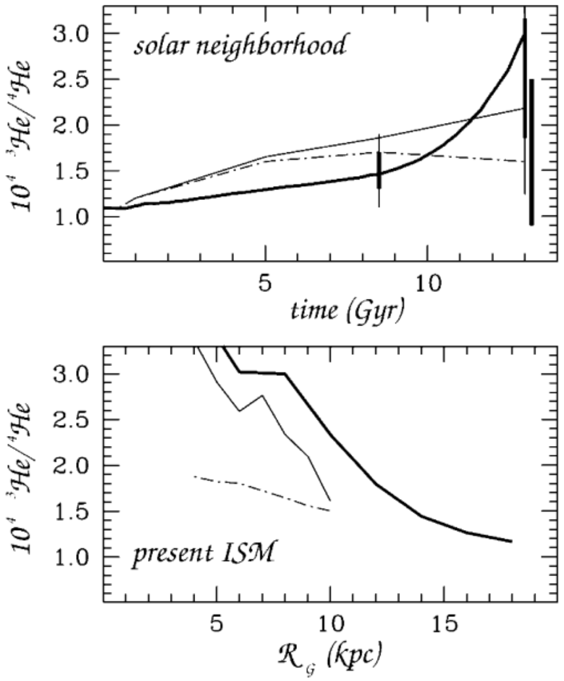


Figure from Romano et al. (2003)

The present (III):

the ^{4}He problem (part II...)

How much ^{4}He in the Sun at birth?

Surface Y = 0.2420 ⇨ initial Y = 0.27250

Surface Y = 0.2285 ⇨ initial Y = 0.26001

Assume different compositions...

... allow for gravitational settling and diffusion...

.. get Y_{ini} in the Sun

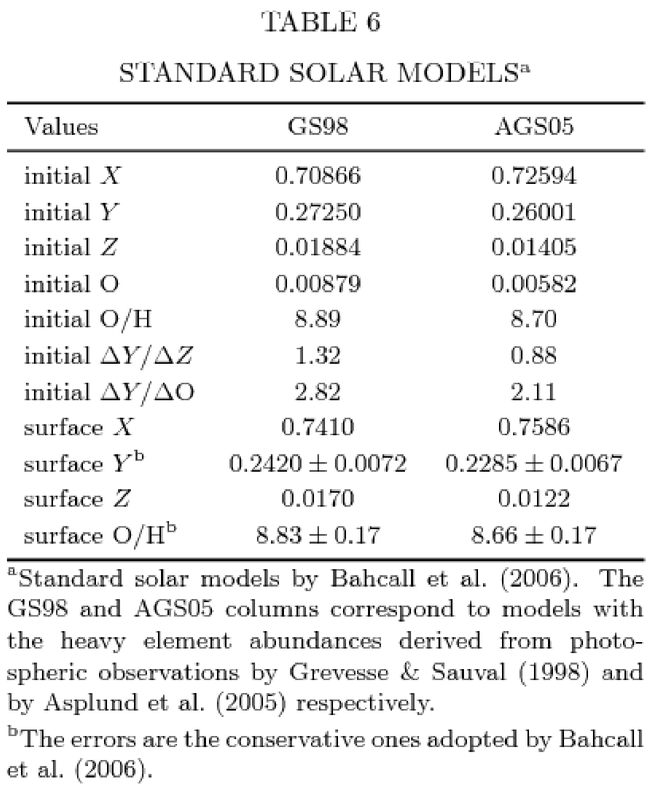


TABLE 6

STANDARD SOLAR MODELS[a]

Values	GS98	AGS05
initial X	0.70866	0.72594
initial Y	0.27250	0.26001
initial Z	0.01884	0.01405
initial O	0.00879	0.00582
initial O/H	8.89	8.70
initial $\Delta Y/\Delta Z$	1.32	0.88
initial $\Delta Y/\Delta$O	2.82	2.11
surface X	0.7410	0.7586
surface Y[b]	0.2420 ± 0.0072	0.2285 ± 0.0067
surface Z	0.0170	0.0122
surface O/H[b]	8.83 ± 0.17	8.66 ± 0.17

[a] Standard solar models by Bahcall et al. (2006). The GS98 and AGS05 columns correspond to models with the heavy element abundances derived from photospheric observations by Grevesse & Sauval (1998) and by Asplund et al. (2005) respectively.

[b] The errors are the conservative ones adopted by Bahcall et al. (2006).

Table from Carigi & Peimbert (2008)

Conclusions

GCE models (at least some of them) are fully consistent with the relatively high value of $(D/H)_{LISM} \sim 2.0 \times 10^{-5}$ suggested by Prodanovic, Steigman & Fields (2009) from their Bayesian analysis of *FUSE* data.

The need for some 'extra mixing' destroying ^{3}He in most (> 90%) of 1–2 $M_{\odot}$ stars came from GCE arguments more than 30 years ago! The way towards the understanding of the underlying physical processes has been a long way, but... see next talk!

It is still debated whether the chemical peculiarities seen in a fraction of Galactic GC stars are due to self-pollution from AGBs or FRMSs. We propose that in very massive GCs (as ω Cen) both stellar categories have polluted the ISM, and that the observed chemical properties have been driven by galactic outflows preferentially enriched in metals.