Primordial Elements: Double Trouble

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Checkpoints

- Abundance basics
- Big Bang Nucleosynthesis (BBN) Overview
- Primordial Element Problem(s)
  - Lithium Problem
  - Deuterium Problem?

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Abundances 101

- Ratio of some element to another (usually H)
- Notations/Representations
  - Mass fraction $X_i = \frac{\rho_i}{\rho_{tot}}$

$$X \equiv X_H \qquad Y \equiv X_{He} \qquad Z \equiv X_{metal}$$

  - Abundance (wrt H, by number) $\frac{i}{H} \equiv y_i \equiv \frac{n_i}{n_H}$

$$y_{He,sol} = 0.1 \qquad y_{Fe,sol} \equiv \left(\frac{Fe}{H}\right)_{sol} = 3.2 \times 10^{-5}$$

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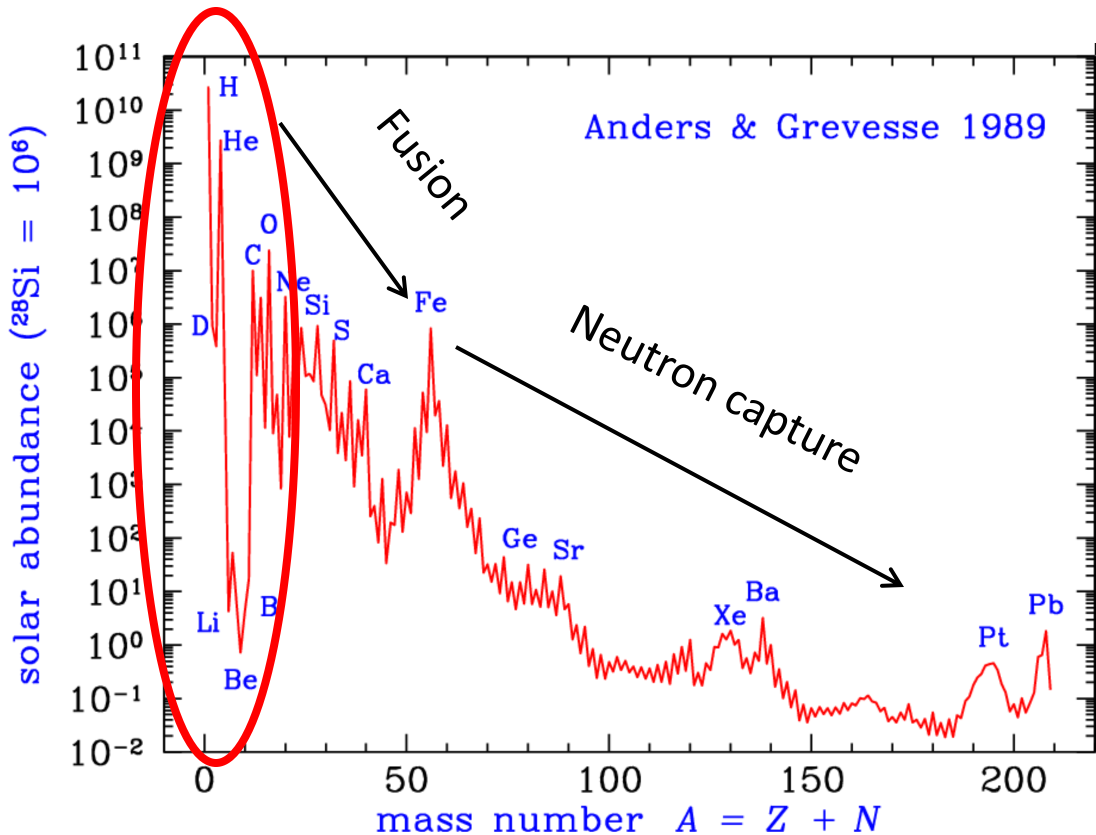
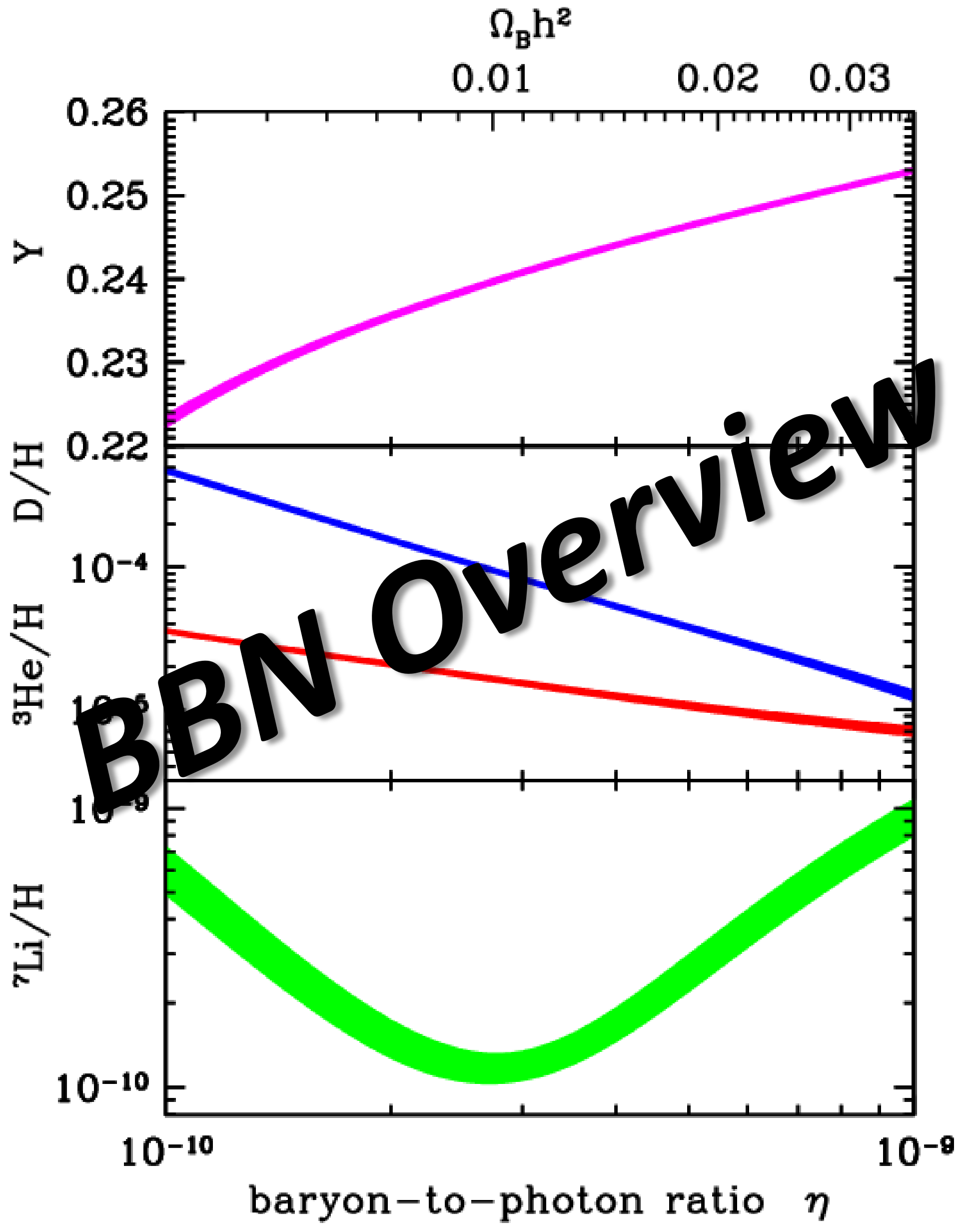
Start: Solar Abundances

- Drop towards high mass numbers
  - Increasing Coulomb barrier
- Zig-zag pattern
  - Odd vs even
- LiBeB drop
  - Inefficient LiBeB fusing in BBN



- Iron peak - equilibrium
- A~130, 200 peaks - s (low) & r(apid) processes (neutron capture)

BBN Overview



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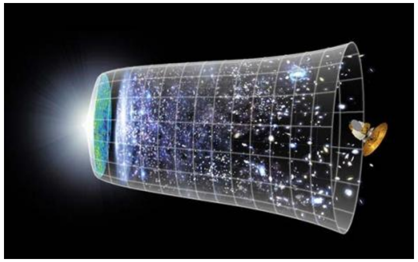
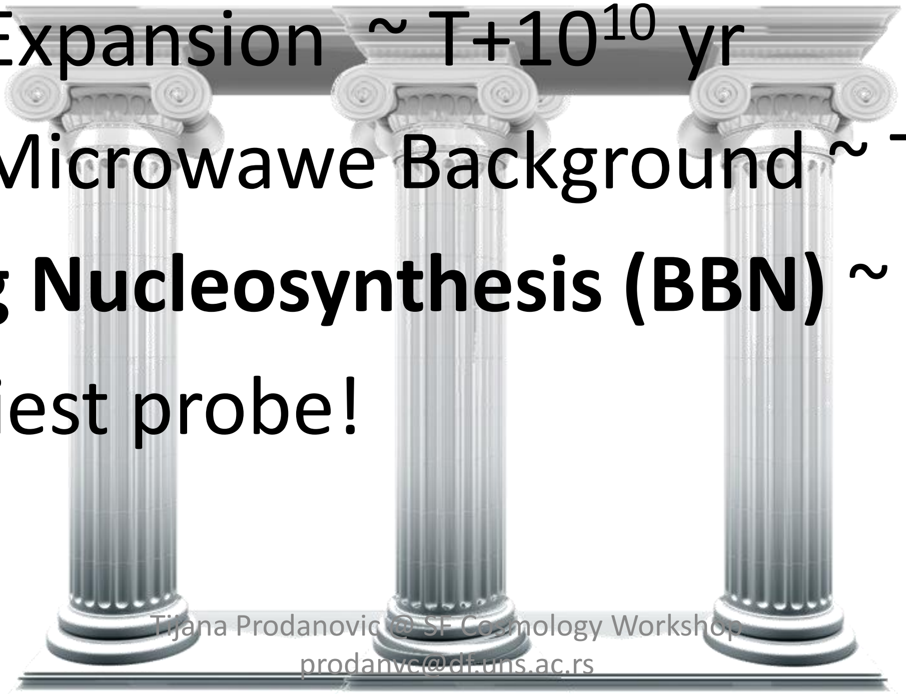
Three Pillars of Cosmology

Observational evidence of the Big Bang Model





I. Hubble Expansion ~ T+10^{10} yr

II. Cosmic Microwawe Background ~ T+4x10^{5} yr

III. Big Bang Nucleosynthesis (BBN) ~ T+1 sec.

The earliest probe!

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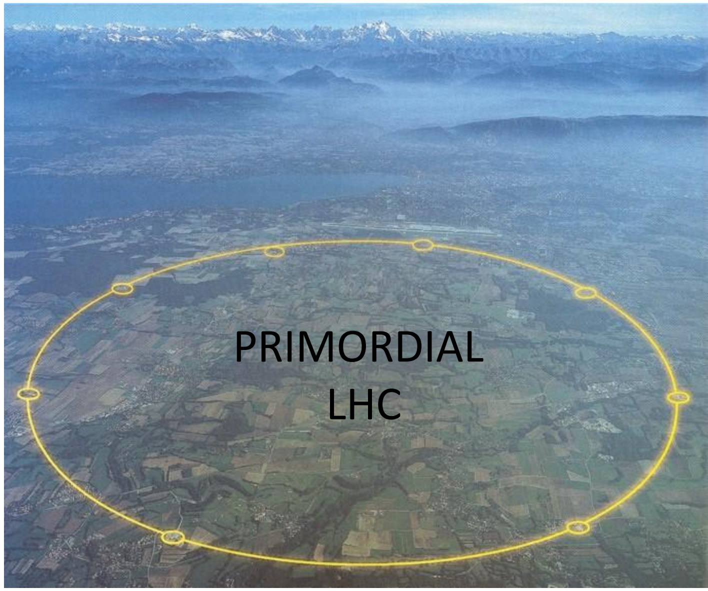
Primordial Nuclear Reactor

- Hot, dense, expanding Universe
  - Sinthesis of lightest elements – D, ^{3}He, ^{4}He, ^{7}Li
  - Race against expansion (faster expansion-less time for BBN!)
- Initial conditions + physics
- Get primordial abundances
- Compare with observations
- Test physics and cosmology!



Standard BBN: Framework

- Standard model of particle physics + ΛCDM cosmology
- General relativity
- Expanding, homogeneous Universe
  - Friedmann equation $$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 = \frac{8\pi}{3} G\rho$$

$$a(t) = \frac{1}{1+z}$$ Cosmic scale factor

$$\rho = \sum_i \rho_i$$ Mass energy density of all cosmic species

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The Key

- Only one free parameter! Controls SBBN!

Baryon-to-photon ratio

$$\eta \equiv \frac{n_b}{n_\gamma} = 2.74 \times 10^{-8} \Omega_b h^2$$

$$\Omega_b = \frac{\rho_b}{\rho_{crit}} \qquad \rho_{crit} = \frac{3H_0^2}{8\pi G}$$

- Constant! BBN determines baryon density!

$$\left.\begin{array}{r} n_\gamma \propto T^3 \\ n_b \propto a^{-3} \propto T^3 \end{array}\right\} \Rightarrow \eta = const. \sim 10^{-9}$$

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Initial Conditions

- T ~ 1 MeV, t ~ 1 sec
- Cosmic radiation
  - Thermal photons and (anti)neutrinos - Relativistic (m<<T)
  - Electrons and positrons – m<T
- Cosmic matter
  - Neutrons and protons – non-relativistic m>>T
- Radiation-dominated epoch
  - Dynamics dictated by radiation species

$$\rho_{rad} >> \rho_{mat}$$

Just before...

- T > 1 MeV, t < 1 sec
- Nucleons in equilibrium
  - Fast ($\Gamma_{n\leftrightarrow p} >> H$) weak interactions

$$n + \nu_e \leftrightarrow p + e^-$$

$$p + \bar{\nu}_e \leftrightarrow n + e^+$$

$$n \leftrightarrow p + e^+ + \nu_e$$

Weak Freeze-out

- Expanding, cooling universe favours lighter protons
- At T ~ 0.8 MeV, t ~ 1 sec.
- Reaction rates not fast enough for expansion

$$\Gamma_{n \leftrightarrow p} << H$$

- Nucleon conversion reactions stop
- Ratio freezes @ $\frac{n}{p} \approx \frac{1}{6}$

$$\frac{n}{p} = e^{-(m_n - m_p)/T}$$

Deuterium Bottleneck

- Must form D before fusion can proceed

$$n + p \leftrightarrow d + \gamma_{2.223\text{MeV}}$$

- But! 2.2 MeV photons destroy D!
- Most photons have T < 1 MeV but still enough of 2.2 MeV photons in thermal tail
- Must wait for deuterium!
- Neutrons keep decaying (~ 10 min) $\frac{n}{p} \rightarrow \frac{1}{7}$

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Fusion time!

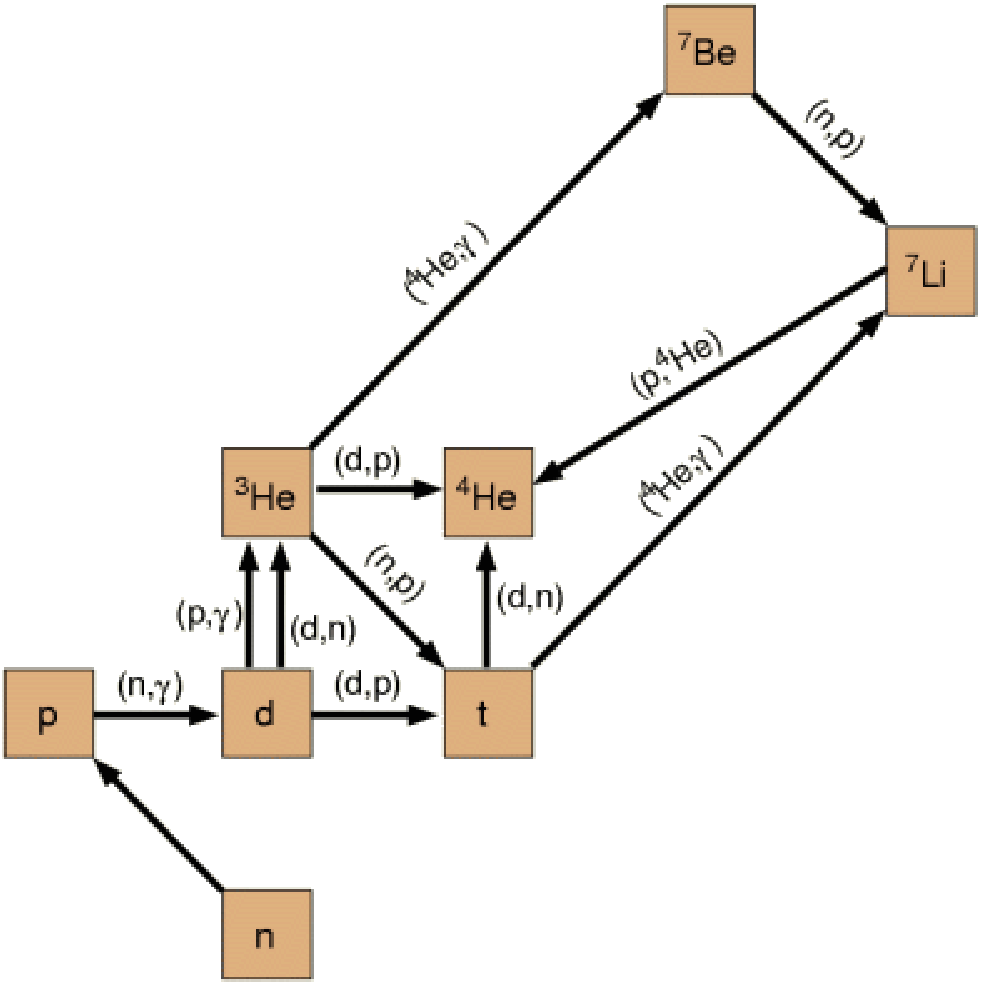
- At t ~ 3 min, T ~ 0.07 MeV
- D abundance rises fast!
- Light elements are fused! Main reactions:

$$^{2}H + {}^{2}H \rightarrow {}^{3}He + n$$

$$^{3}He + {}^{2}H \rightarrow {}^{4}He + p$$

$$^{4}He + {}^{3}H \rightarrow {}^{7}Li + \gamma$$

BBN Reactions Network



The Outcome

- ^{4}He very stable – production favored
- No stable nuclei at A=5 and A=8 - heavier element production suppressed
  - For heavier, must fuse D, T or ^{3}He with ^{4}He
  - Large Coulomb barrier
- Most neutrons go into ^{4}He
  - He not very sensitive to baryon density

$$Y_p \cong 0.24$$

The Outcome

- Incomplete nuke burning
  - Not all neutrons used up
  - Traces of D, ^{3}He and ^{7}Li
  - Trace abundance strongly dependant on nuke freezeout T - baryion density
- BBN stops @ T ~ 30 keV, t ~ 20 min

Nuclear freezeout!

(except for the unstable ones – remaining ^{3}H decays, ^{7}Be + e $\rightarrow$ ^{7}Li)

Primordial abundances vs. Baryon-to-photon ratio

- If higher nucleon (baryon) density
  - BBN starts earlier – more nucleons, higher temp., more complete burning
    - More ^{4}He made
    - Less D and ^{3}He left
    - Li made 2 ways:

$$^3H(\alpha,\gamma)^7Li$$

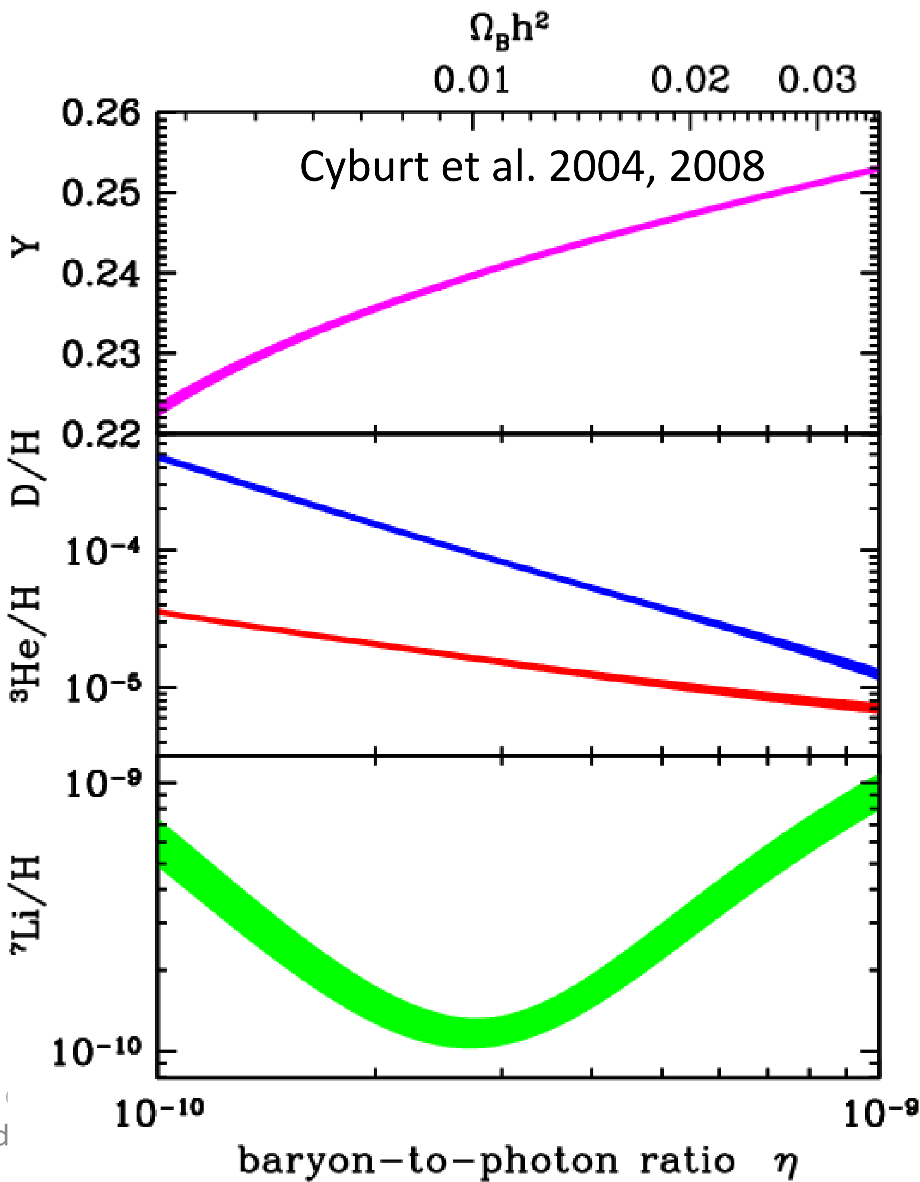
$$^3He(\alpha,\gamma)^7Be \rightarrow ^7Li$$

Less stable under proton collisions
Dominates at low baryon-to-photon

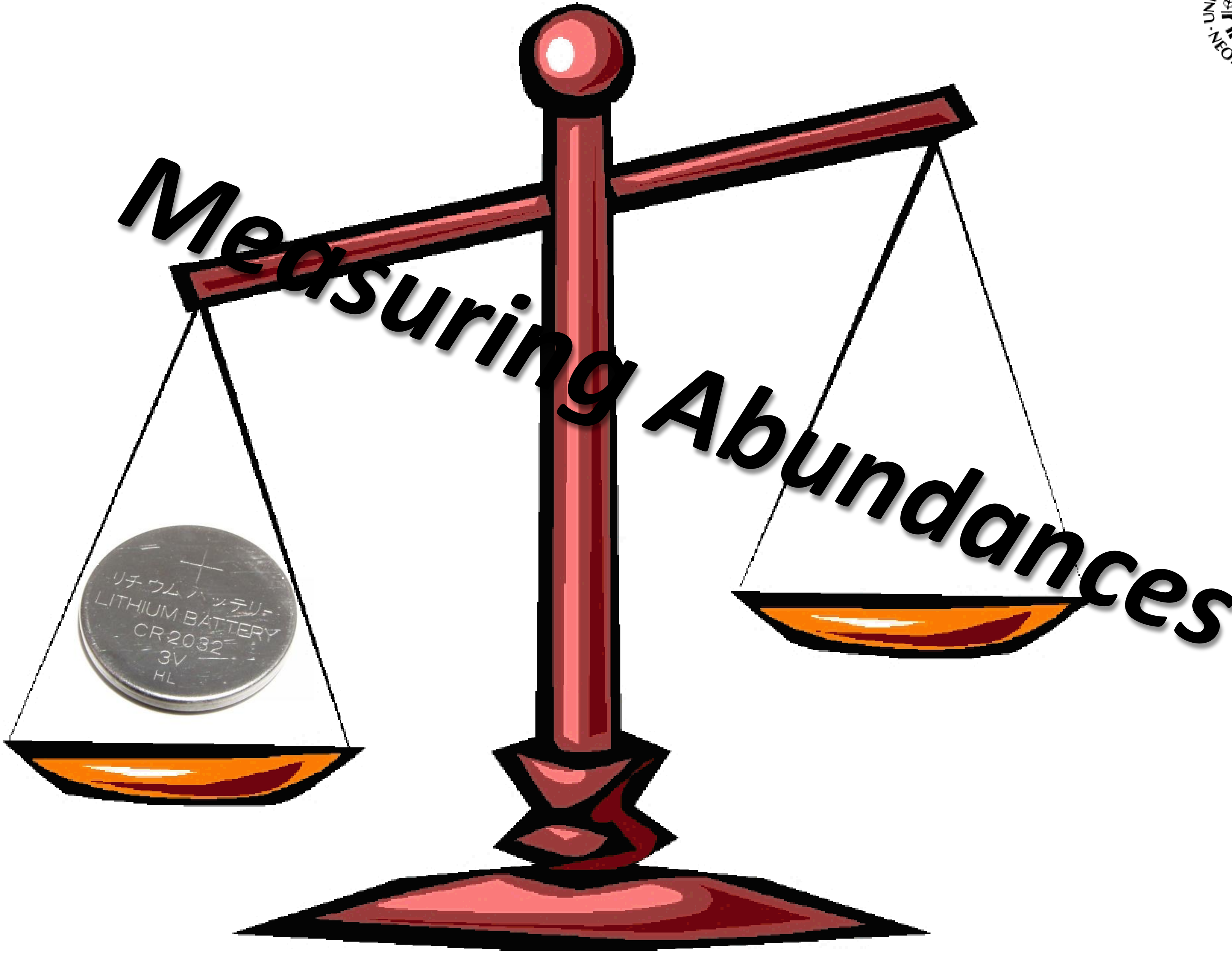
Strongly bound
Dominates at high baryon-to-photon

SBBN Predicted Abundances

- Schramm plot
- Abundance vs. Baryon density
- Curves: SBBN
- 1σ errors – nuclear cross-sections
- Measure abundance!
- Done!



Measuring Abundances



Stuck in the future

- Abundances today not same as after BBN
- Look at (close) to primordial systems – low metallicity
  - Correct for $t_{BBN} \neq t_{obs}$ changes as best as you can
- Where to look?
  - D – apsorption towards QSO (UV)
  - ^{3}He (II) – emission in galactic HII regions
  - ^{4}He (II, III) - emission in extragalactic HII regions
  - ^{7}Li – apsorption in atmospheres of low-metallicity halo stars
- Different systems but look for concordance?

Hopeless ^3He...

- Complicated history
  - Stars burn D to make ^3He, burned to make ^4He
  - More survives in cooler stars
  - Net production...but depends on destruction-production balance
- Only observed in Galactic HII regions – hyperfine transition
- Must extrapolate from today to BBN epoch
- Too model dependant!

Hopefull ^{4}He

- Produced in stars
- Stable – once create, difficult to destroy
- Net increase with time
- Back in time – primordial plateau should exist
- Measured in low-metallicity extragalactic HII regions

- But note...”spherical cow”

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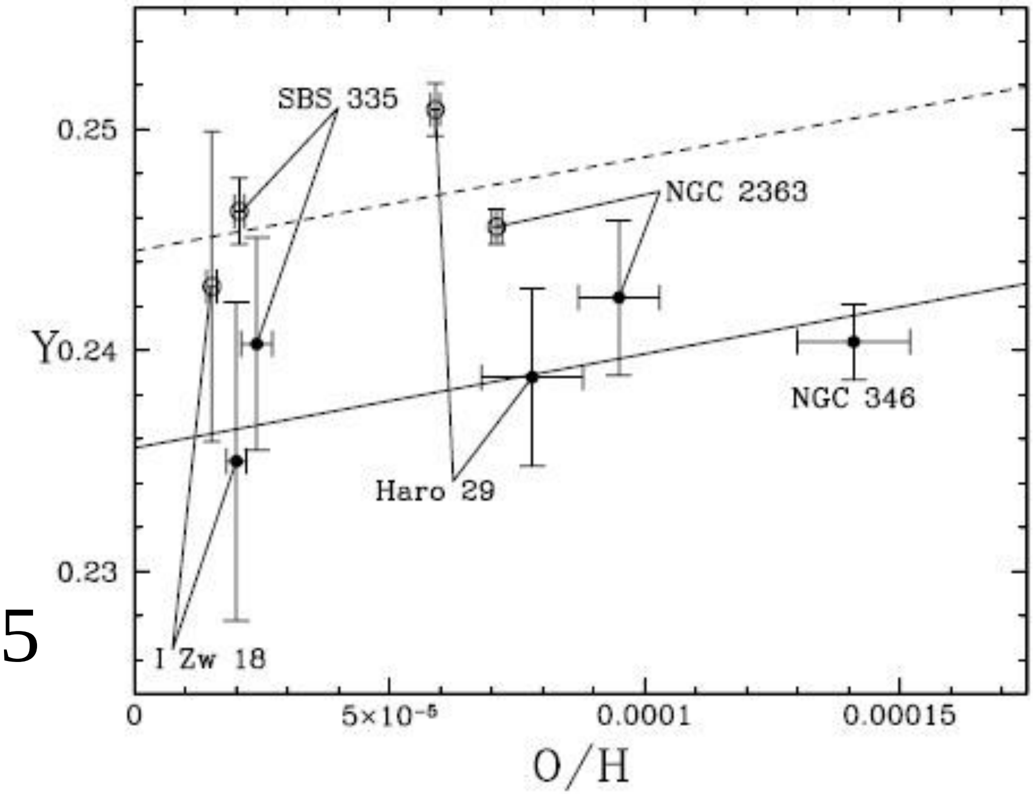
Hopefull ^{4}He

- ^{4}He vs. Metallicity (oxygen)
- Extrapolate to 0 metal.

$$Y_{p,obs} = 0.2384 \pm 0.0025$$



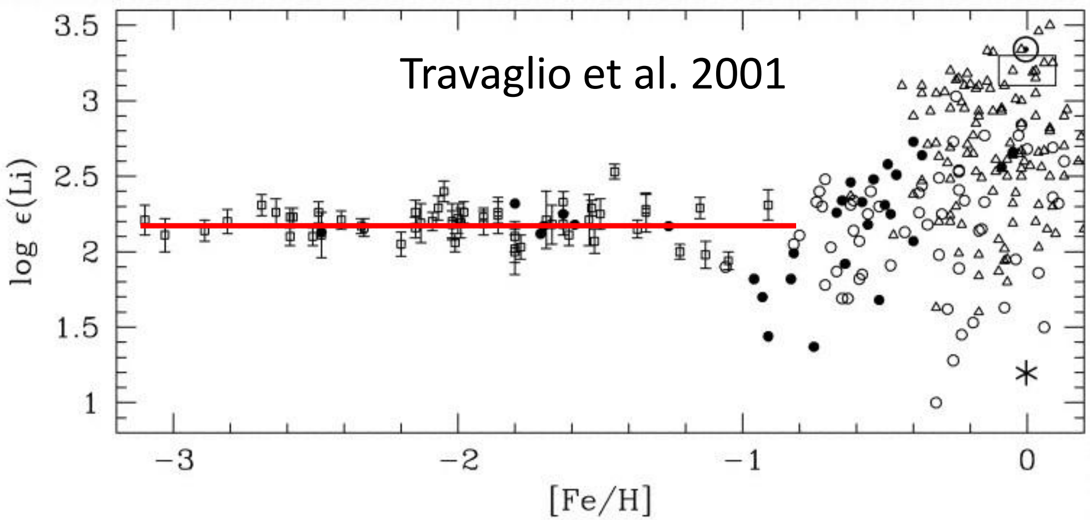
Peimbert et al. 2002

Promissing ^{7}Li

- Fragile, destroyed in stars
- But produced in CR interactions (fusion,spallation) and neutrino-proces in SN
- At low metallicity should see a plateau
- Pop II, low-metallicity, cold halo stars
- Spite plateau

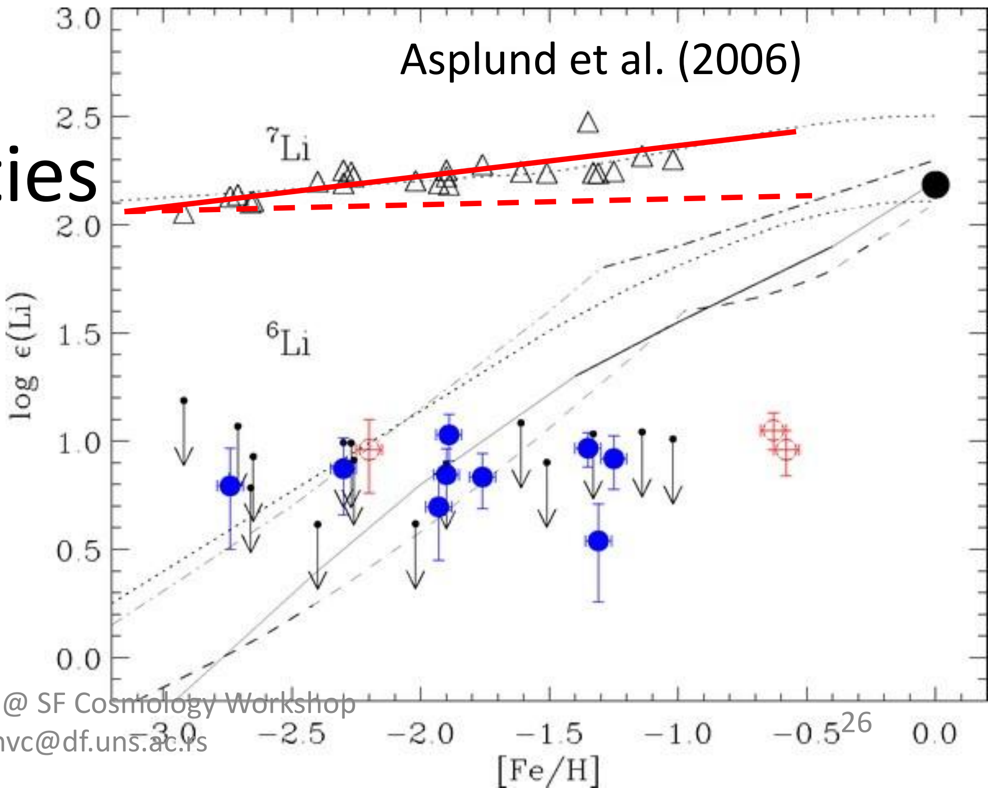
Spite &Spite (1982)

- Primordial Li!



Promising ^7Li

- Spite plateau?
- More data reveal a slope
- Pre-galactic Li (rather than primordial)
- Stellar modeling – systematic uncertainties
  - Temperature scale
  - Mixing (Li fragile!)



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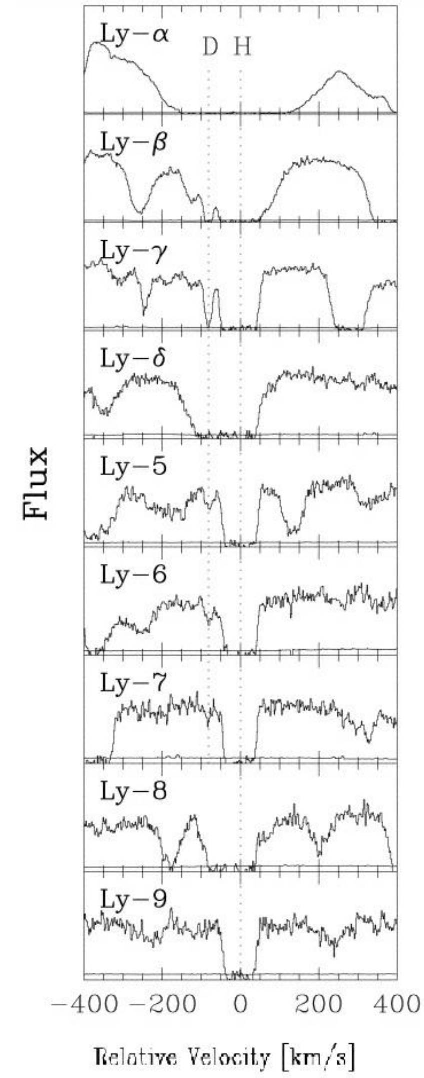
Deuterium - Baryometer of Choice

O'Meara et al. 2001
QSO: HS 0105+1619



- Strong baryon density dependance
- Very fragile – simple history
- Only net destruction (Epstein et al. 1976, Prodanovic & Fields 2003) – stellar processing
- Easy to extrapolate to zero metallicity
- Observe in high-z quasar apsorption Lyα systems
  - Quasars @ z ~ 3 in the background of a cold H cloud
  - D not same as H! Line shifted!

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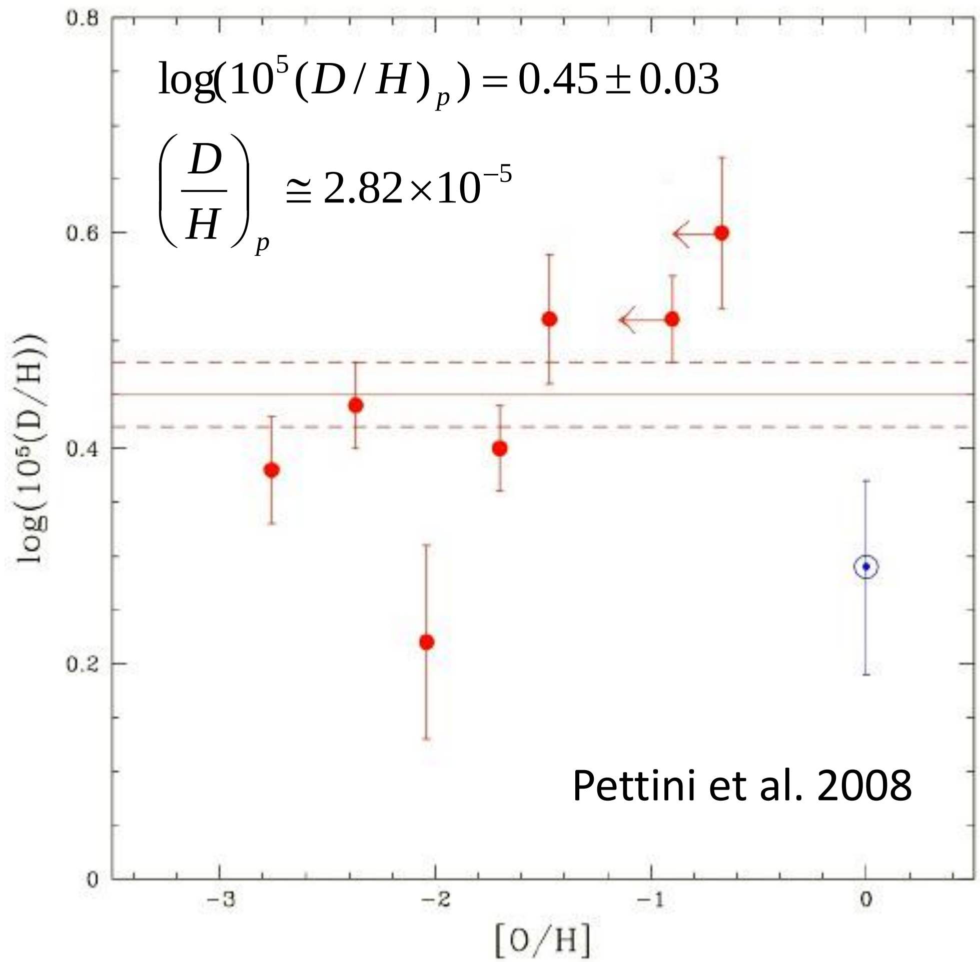
Deuterium - Baryometer of Choice

- Evolution of D with metals

$$D \sim e^{-Z/Z_{sol}} D_p$$

$$Z_{QSO} \sim 0.01 Z_{sol} \Rightarrow D_{QSO} \approx D_p$$

- But scatter!
- Systematics?
- Need more systems! SDSS outlook

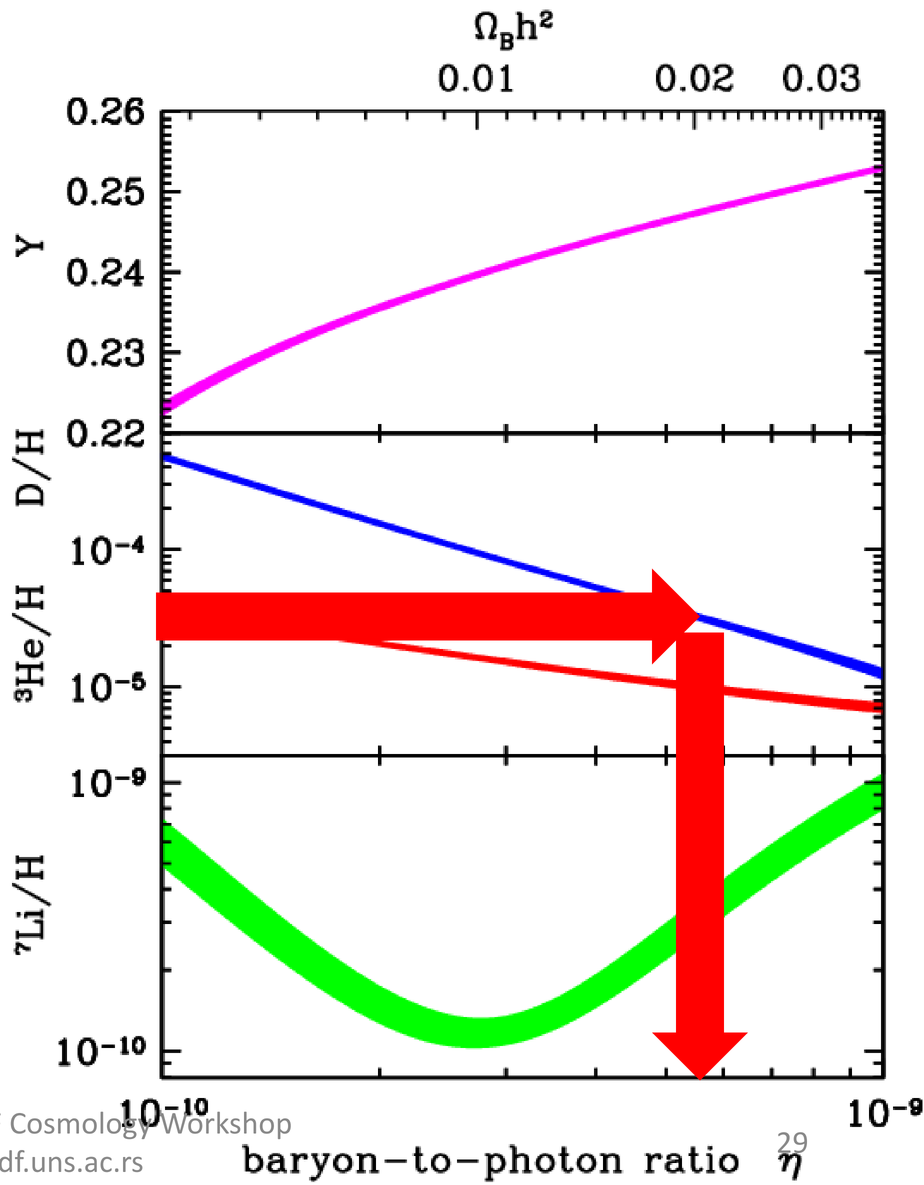


$$\left[\frac{O}{H}\right] = \log\left(\frac{O}{H}\right) - \log\left(\frac{O}{H}\right)_{sol}$$

Simple?

- Have measurements!
- Get baryion density!
- Some uncertainty but consistant
- First indication od dark matter!
  - Deuterium obs. and observed expansion rate not consistent!
  - All matter not baryionic!

All observations

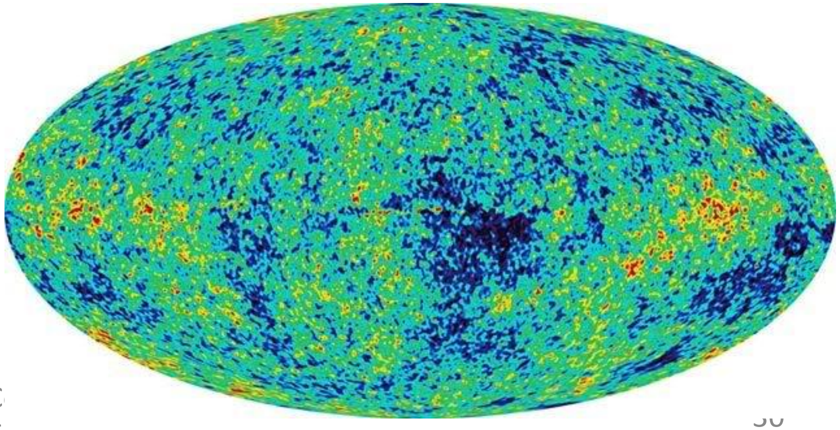


New Light: CMB

- New, independant measurement of baryon density
- WMAP – High-precission cosmology era!
- CMB & BBN – test cosmology!
- WMAP baryon density (Dunkley et al. 2008):

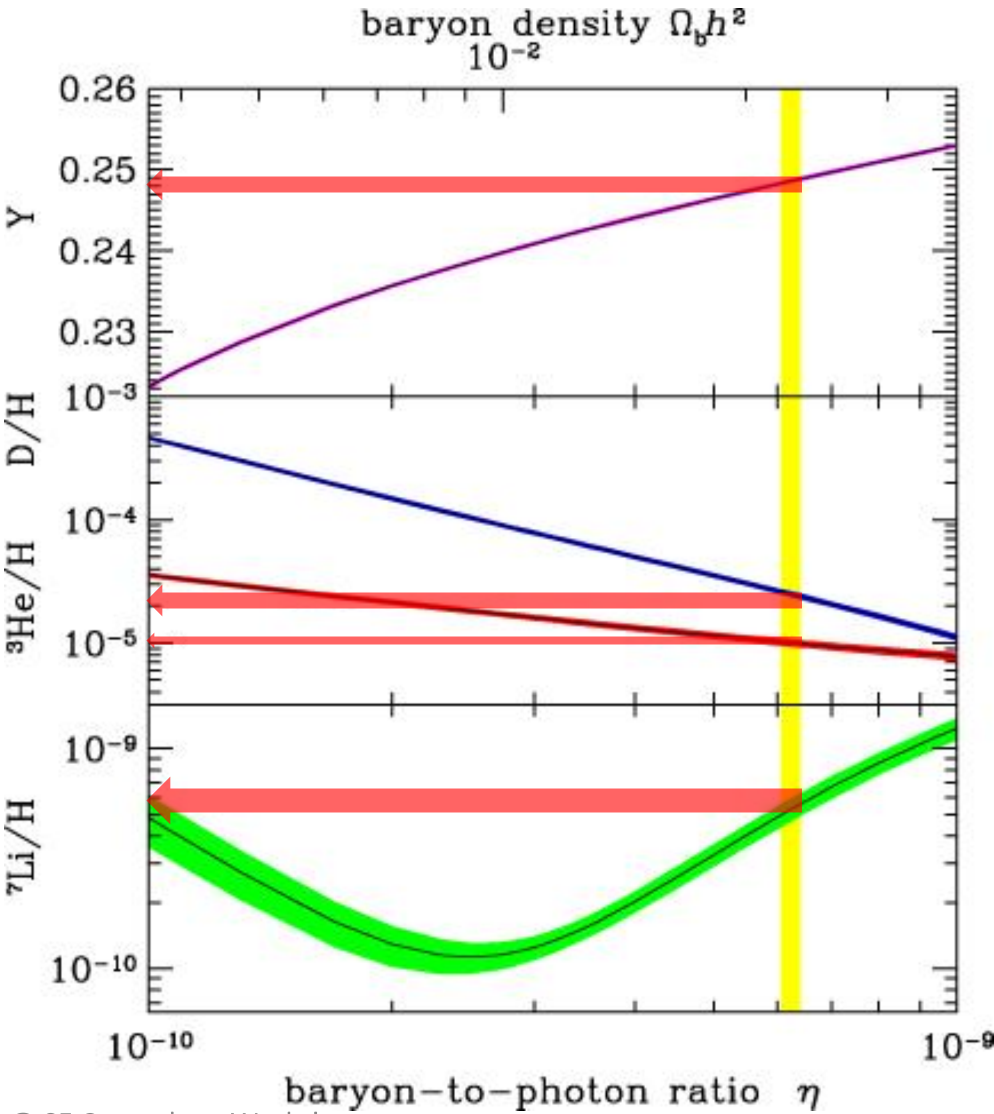
$$\Omega_b h_{100}{}^2 = 0.02273 \pm 0.00062$$

$$\eta = (6.23 \pm 0.17) \times 10^{-10}$$



BBN & CMB

- WMAP – fix baryon density
- Use BBN to predict primordial abundances
- Easy!
- Compare with observations?



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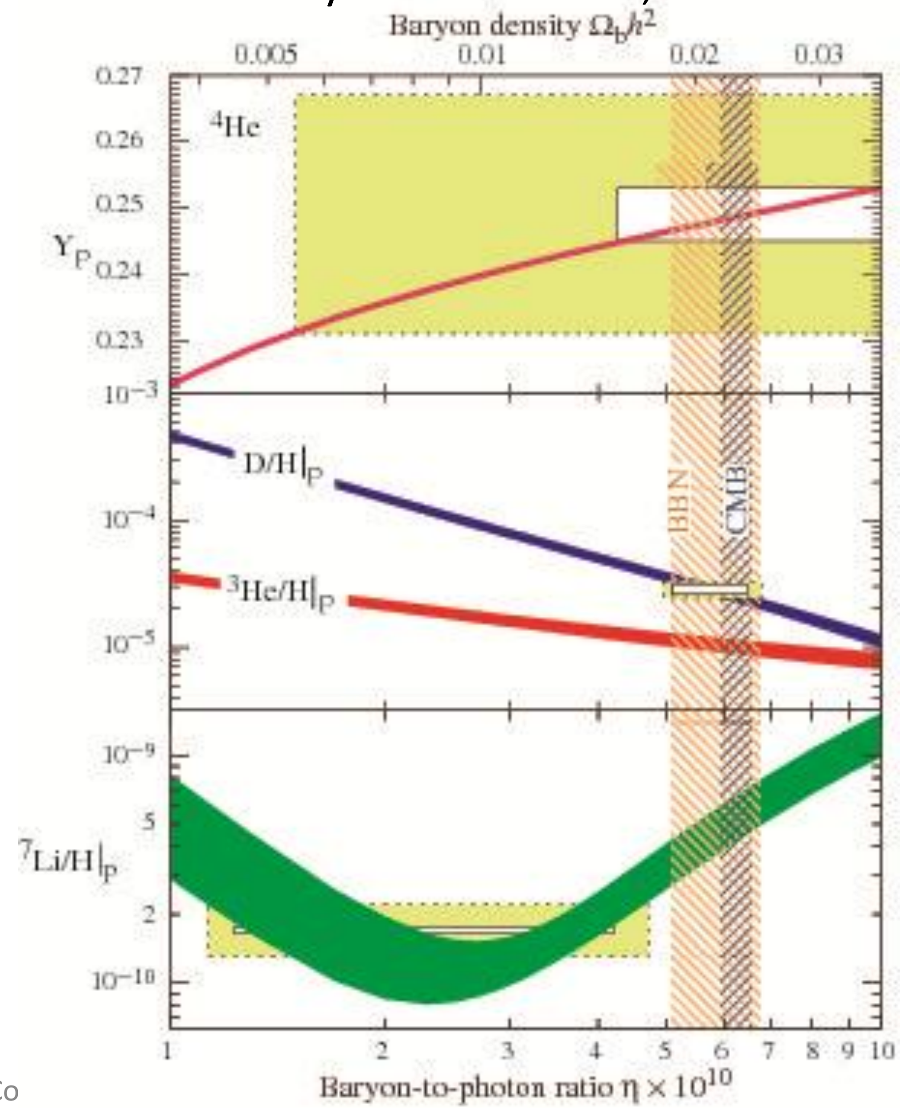
How it all fits?

- BBN theory curves
- CMB – baryon density
- Observation – boxes

- ^{4}He – OK ☺
- D – right on! ☺
- ^{7}Li – in trouble! ☹

Cyburt et al. 2003, 2008



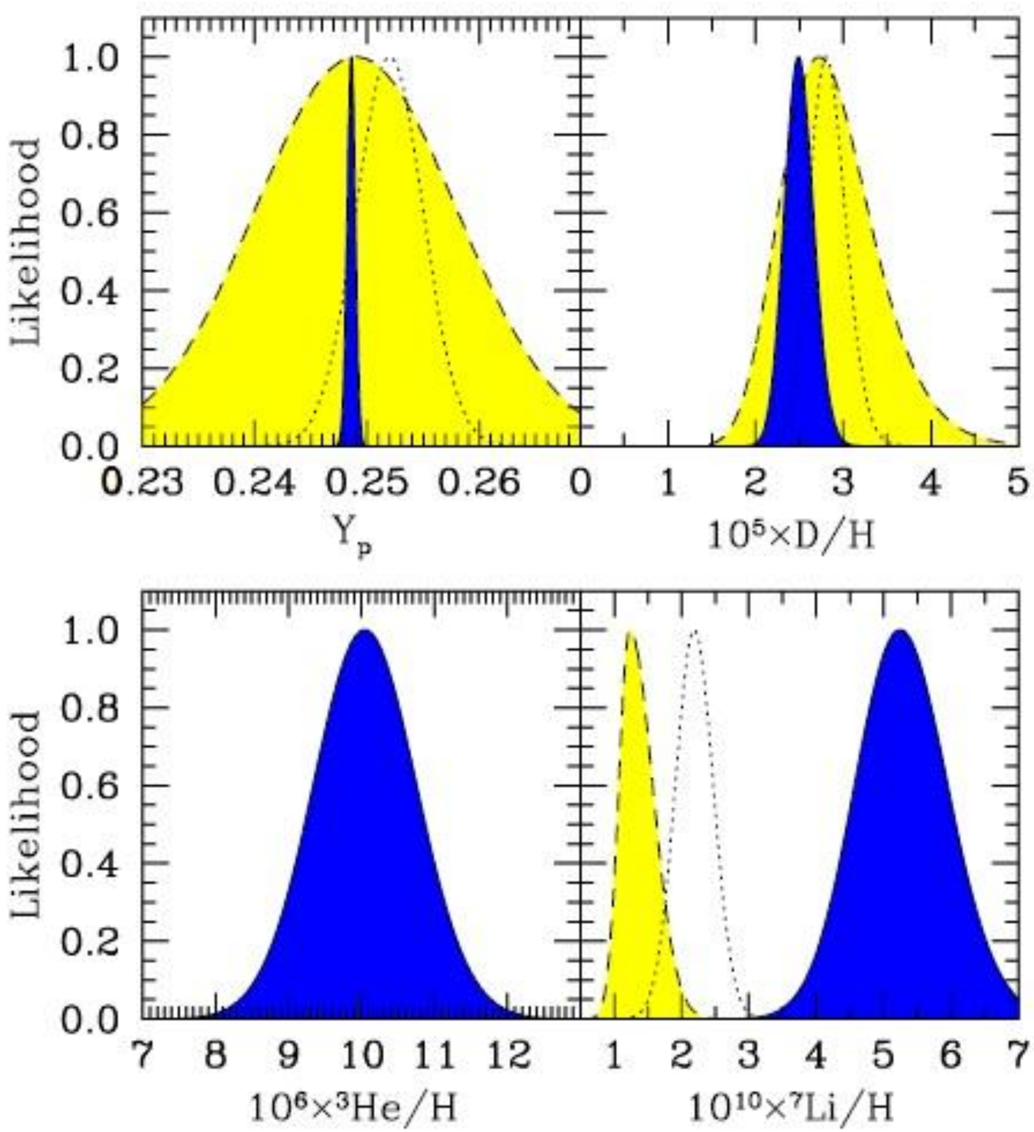
Concordance?

- Cyburt et al. 2008.
- Theoretical (blue)
- Observational (yellow)

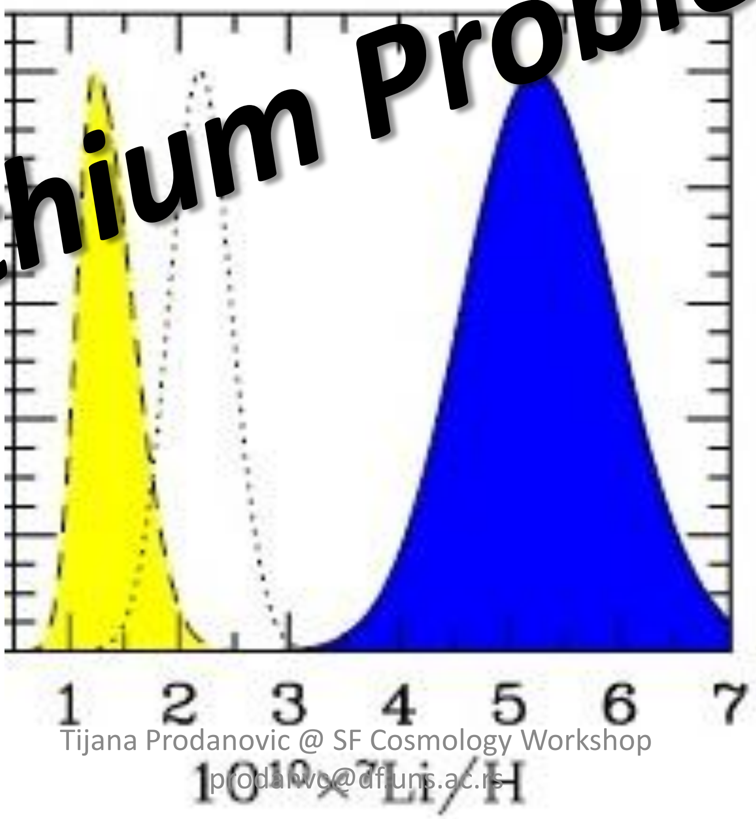
- Lithium way off!

  Factor of 3-4!

PROBLEM!

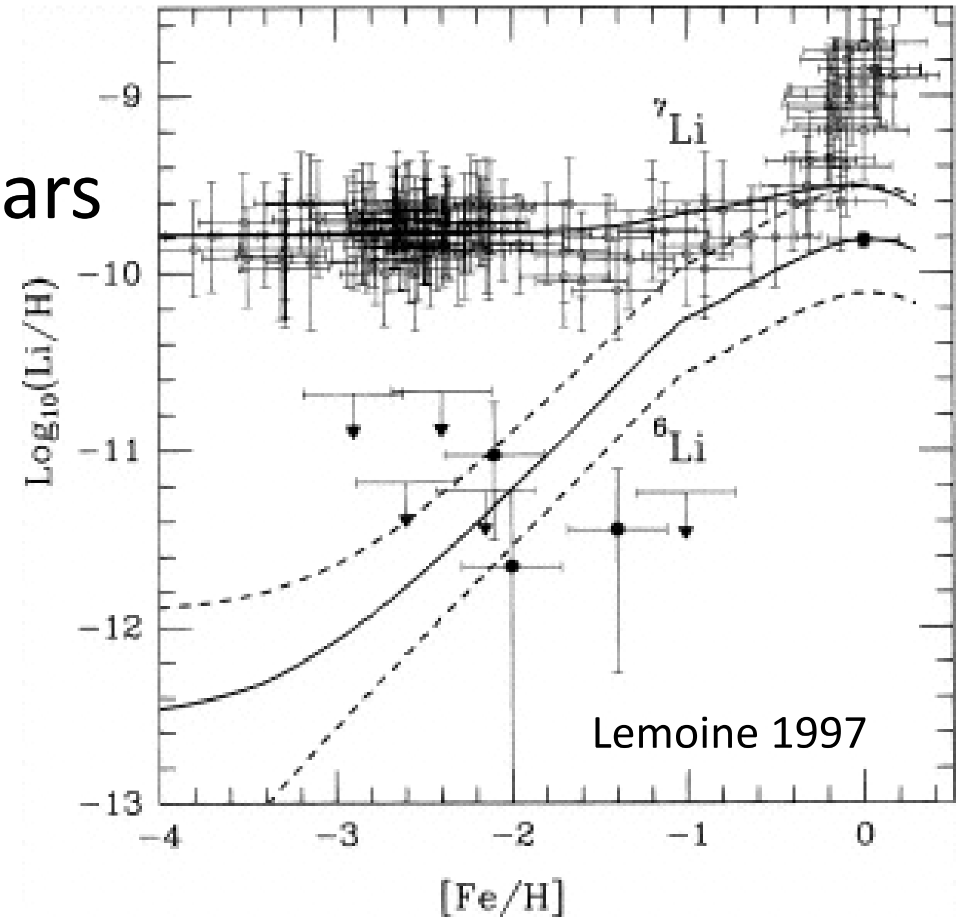


Lithium Problem



Spite Plateau

- Spite & Spite 1982
- Low-metallicity halo stars
- (Close to) Same Li abundance towards lower metallicity
- Very little scatter!
- But different stars
- Primordial plateau?



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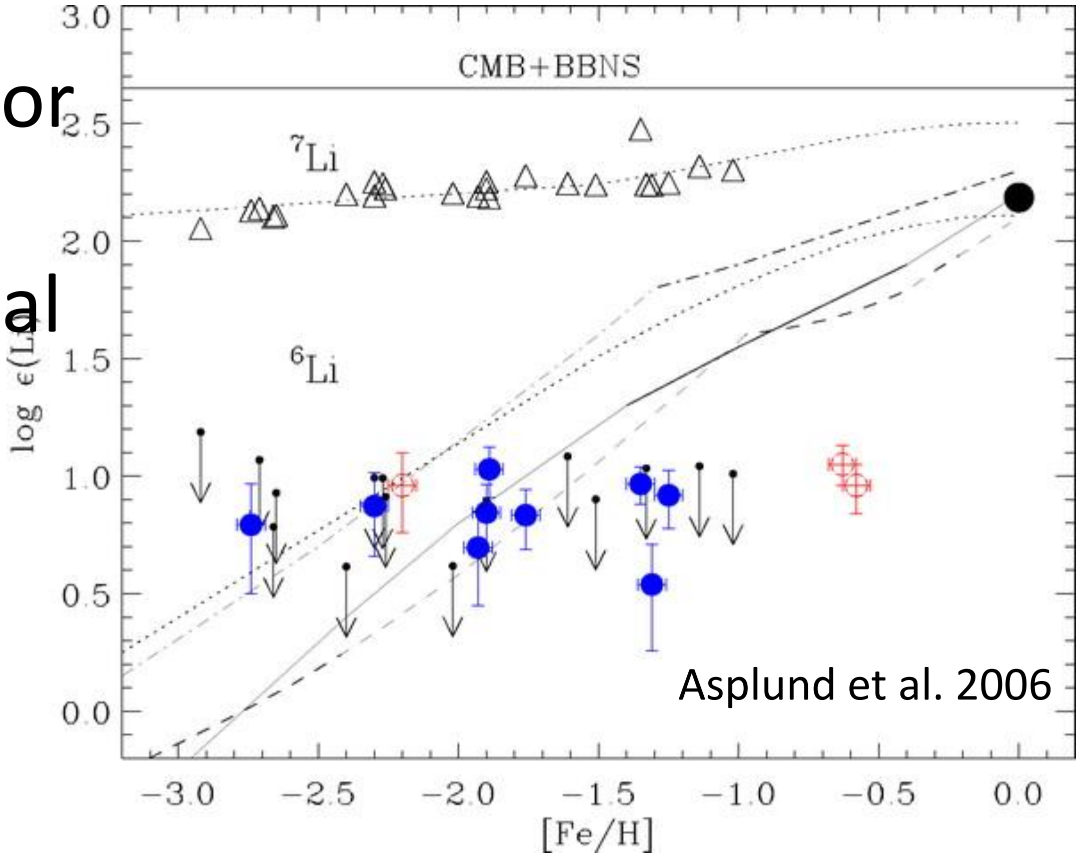
The Lithium Problem

- Spite "plateau" factor of ~ 2-4 **lower** than CMB+BBN primordial Li abundance!

$$\left(\frac{{}^7Li}{H}\right)_p = \left(5.24^{+0.71}_{-0.62}\right)\times 10^{-10}$$

$$\left(\frac{{}^7Li}{H}\right)_{obs} = \left(1.23^{+0.68}_{-0.32}\right)\times 10^{-10}$$



Asplund et al. 2006

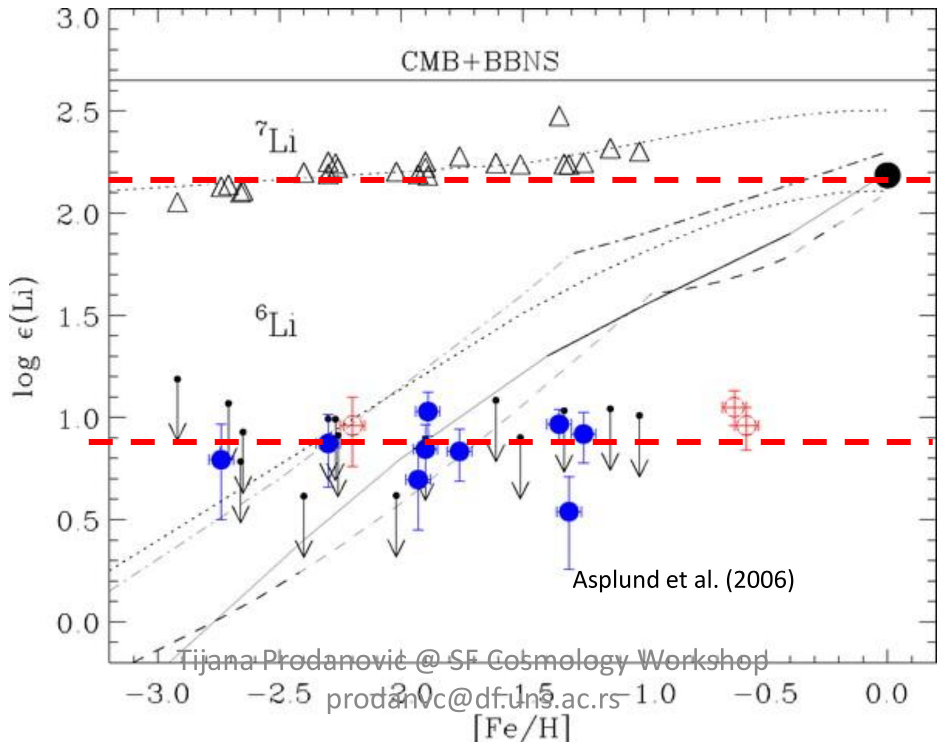
No post-BBN production, but, destruction!?

Lithium Problem Even Worse?

- ^{6}Li "Plateau"? But no BBN source!
- Post-BBN production in cosmic ray interractions
  - Galactic CRs - ^{6}Li increases with metallicity
  - Cosmological CRs? – ^{6}Li constant with metallicity

^{7}Li plateau

^{6}Li plateau

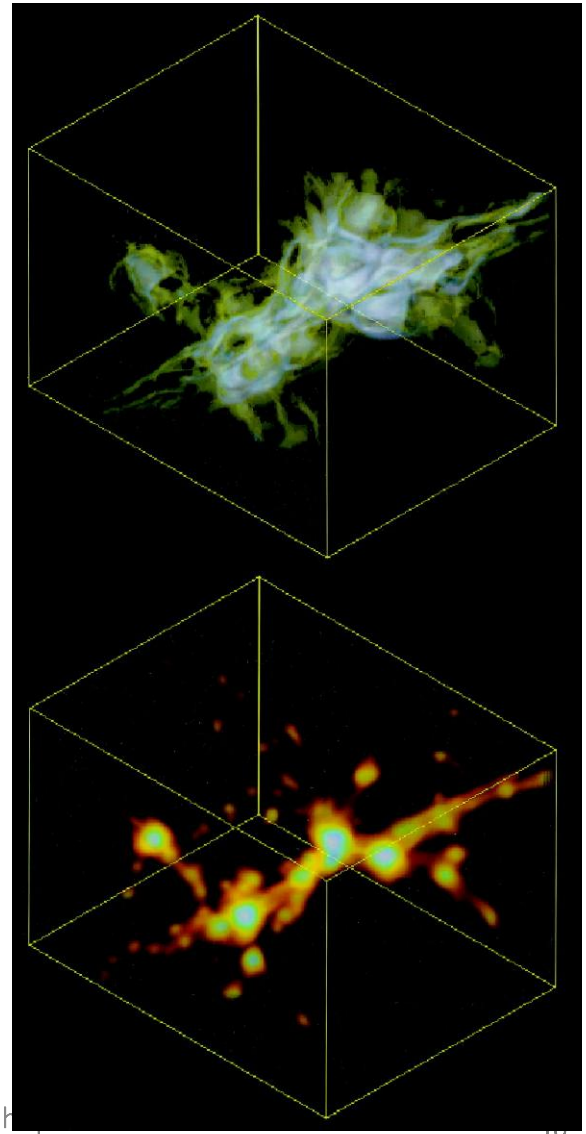


Expected
but inconsistent

Unexpected

Lithium Problem Even Worse?

Miniati et al. 2000



- Cosmological cosmic-rays
  - Structure-formation shocks?
    Note: Non-detection of gamma-rays by Fermi (Ackermann et al. 2010)
  - Primordial in composition – only H & He
  - Make Li (6,7) without other light elements (Be & B)
  - Would contribute to halo-star Li abundance (Suzuki & Inoue 2002)

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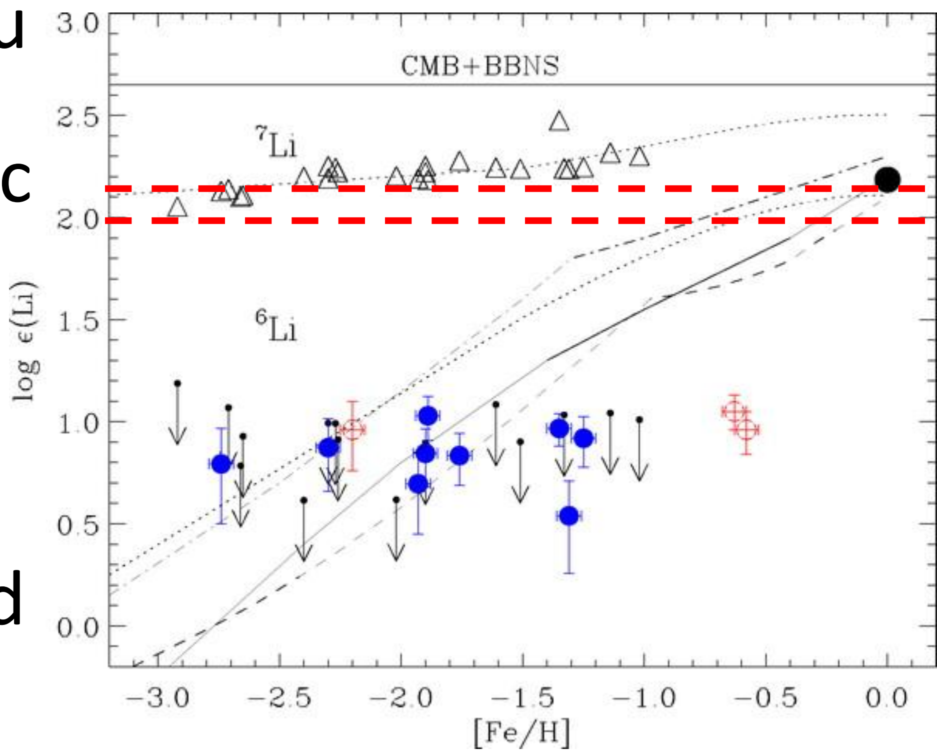
Lithium Problem Even Worse?

- Assume entire ^{6}Li plateau made by cosmological/pre-galactic CRs
- Find ^{7}Li made by same CRs
- ~ 15% of observed Li plateau is pregalactic and not BBN!
- Must correct for it!



- Even larger discrepancy with WMAP+BBN!
- Factor of ~ 5!

Main Problems

- Abundances below predicted observed over a large metallicity range
- How to destroy Li uniformily?
- Is ^{6}Li plateau real?
- What is pre-galactic source of ^{6,7}Li ?

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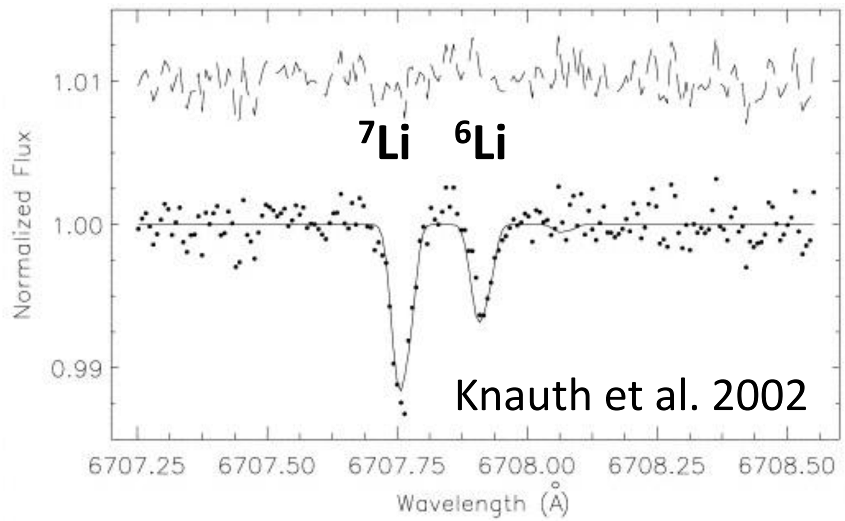
Who is to blame?

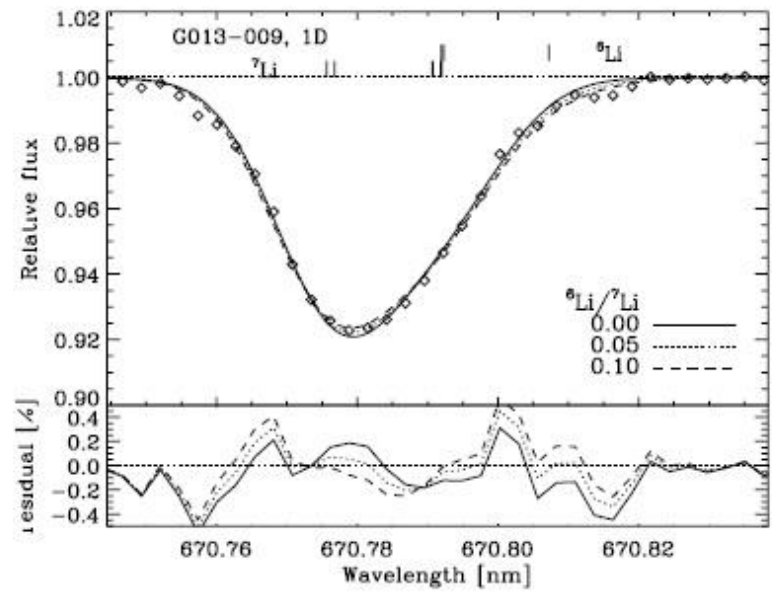
- Observations?
- Inferred abundances wrong?
- Problem with stellar atmosphere modeling?

- Theory?
- Inferred abundances correct?
- Find a way to destroy Li before or in stars

Lithium Observations

- Great in ISM! ☺
  - Both isotopes separated



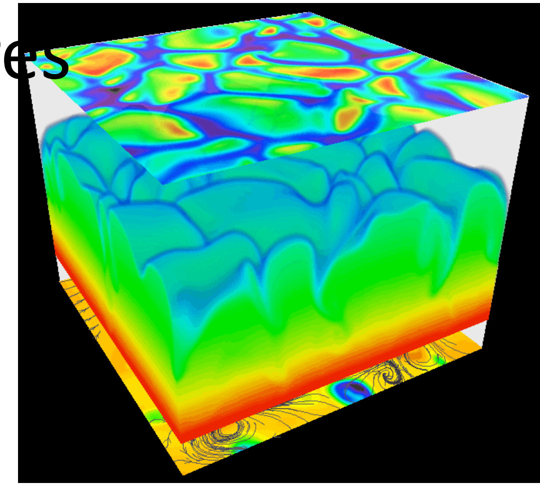


Asplund et al. 2006

- Messy in stars ☹
  - ^{6}Li just a asymmetry kink on ^{7}Li line – get ratio

Lithium observations

- Apsorption lines in stellar atmospheres
- Modeling! Non-LTE, 1D vs. 3D
  - Li mostly ionized in stellar atmosphere
  - Must get the Li II/Li I ratio
  - Must have correct temperature



- To solve Li problem temperature must be much higher!? ΔT ~ 500-600K?
  - Affects other elements (Be, B, O)
  - Casagrande et al. 2010 – new, detailed estimate of T scale gives ΔT ~ 200K

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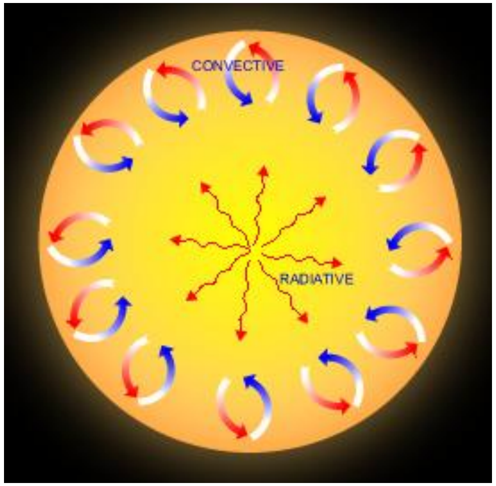
Lithium Theory: Mixing



- Lithium burned easily in stars

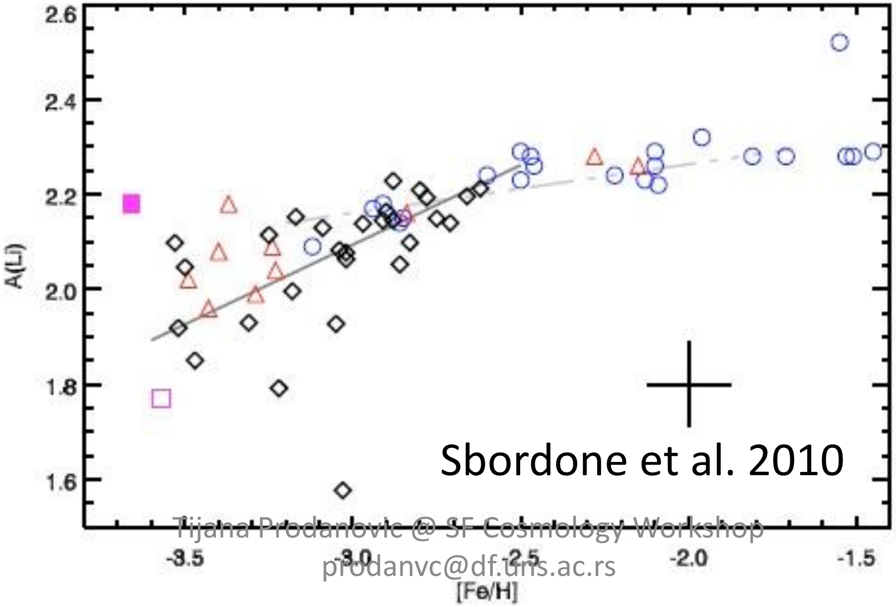
$$T > 2.5\times 10^6 \Rightarrow {}^7Li + p \rightarrow 2\,{}^4He$$

$$T > 2\times 10^6 \Rightarrow {}^6Li + D \rightarrow 2\,{}^4He$$

- Destroyed by convection!
  - Surface material mixes in deeper – Li destroyed
  - If destroy ^{7}Li – destroy ^{6}Li even more!
- But – not enough! Not uniform!
  - Different stars – different convective zones?
  - Would cause scatter!
  - Low-metalliciy stars have shalower convective zones!

Lithium Depletion

- At very low metallicity [Fe/H]<-3
  - Li below Spite plateau
  - Much larger scatter
  - Even more below BBN+WMAP value
- Some depletion must exist!



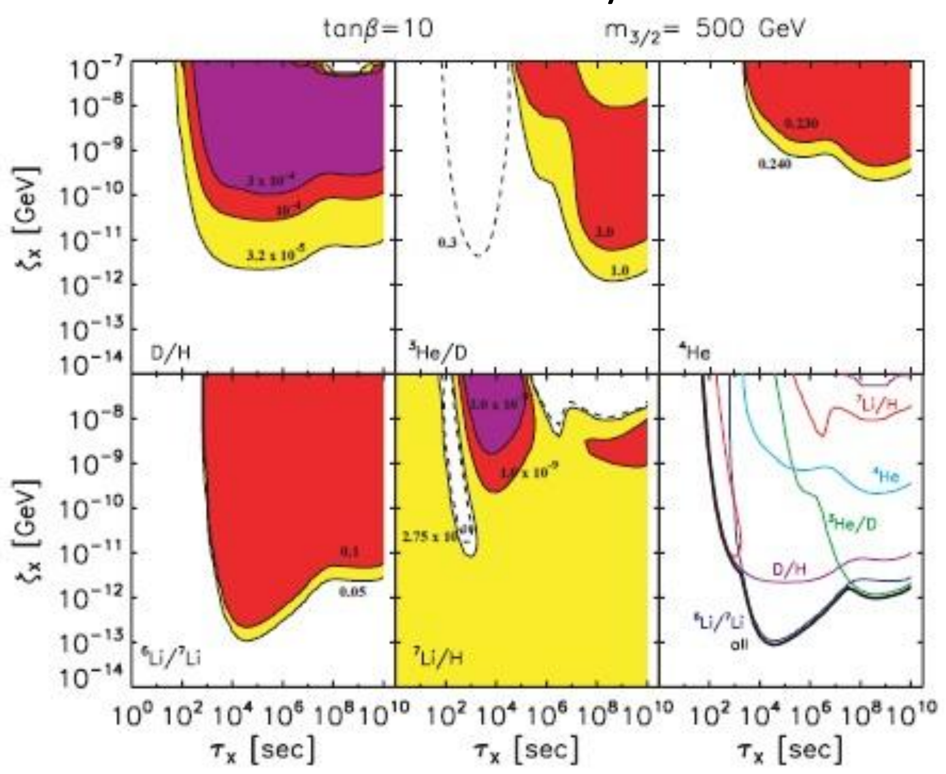
Beyond Astrophysics

- Lithium problem remains
- No conventional solution found...yet
- Must fix ^{7}Li without creating problems with other lite elements!
- Bonus: Same solution a source of ^{6}Li?

Beyond Standard Model

- Lightest SUSY partner - Favorite dark matter
- Hadronic decay of longlived parent (next-to-lightest) SUSY particles during or after BBN
- Changes abundances!
- Spallation
- Narrow parameter space that could fix both ^{6}Li and ^{7}Li !

Cyburt et al. 2009

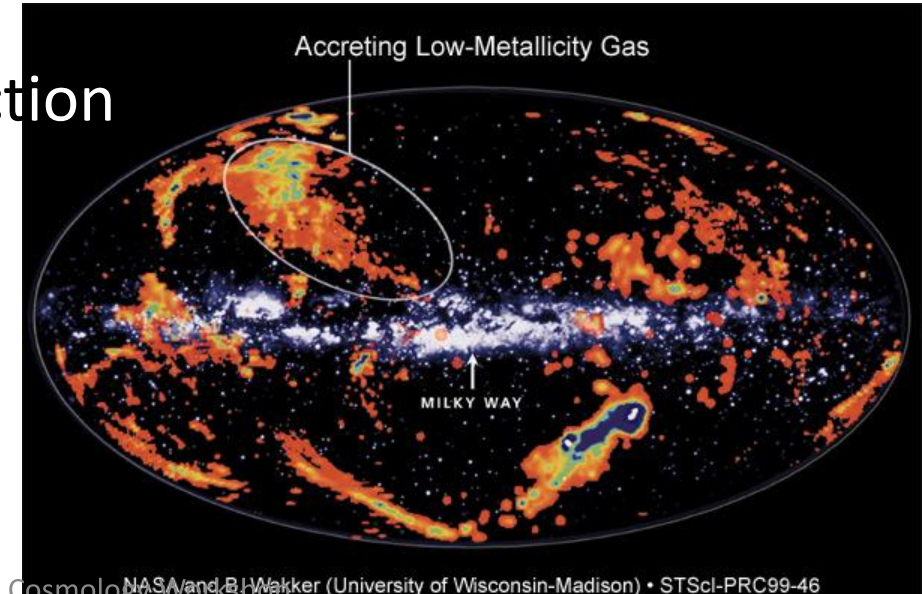


White fields – allowed parameter space
Abundance vs. decay time of particle X

Beyond Standard Model

A Different Approach

- Find another Li site!
- High Velocity Clouds (Wakker & van Woerden 1997)
  - (Some) Low metallicity (~ 10% solar)
  - Low dust
  - No stellar modeling
  - Test pre-galactic Li production
- But photoionisation high, column low, measurement difficult



A Different Approach

- Find another Li site!
- Small Magellanic Cloud (Howk et al 2010 proceedings, 2011 submitted)
  - Metallicity ~ 0.25 solar
  - Measure Li abundance (and 7/6 ratio!)
  - Independant probe
  - Stay tuned!

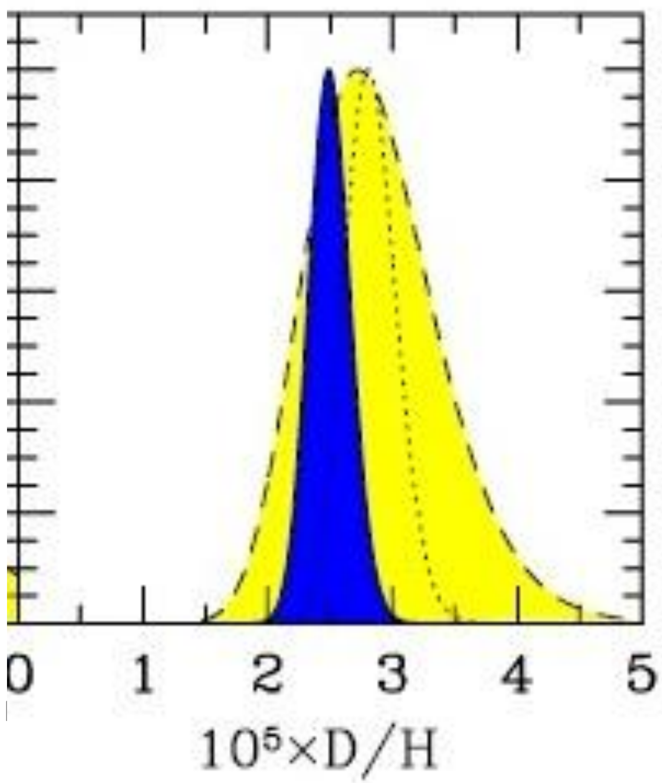
Lithium Problem: Recap

- Factor of ~ 3 discrepancy between BBN+CMB and observed Li abundances in halo stars
- Observational errors – temperature scale? New destruction channels – mixind, relic particle decay?
- Upcomig tests – LHC, low-metal gas observations
- Solution coming soon! < 10 yr

Deuterium Problem

Deuterium Problem?

- BBN & CMB concordance great!
- Primordial D – cosmology success story
- But locally...



(Local) Deuterium Problem

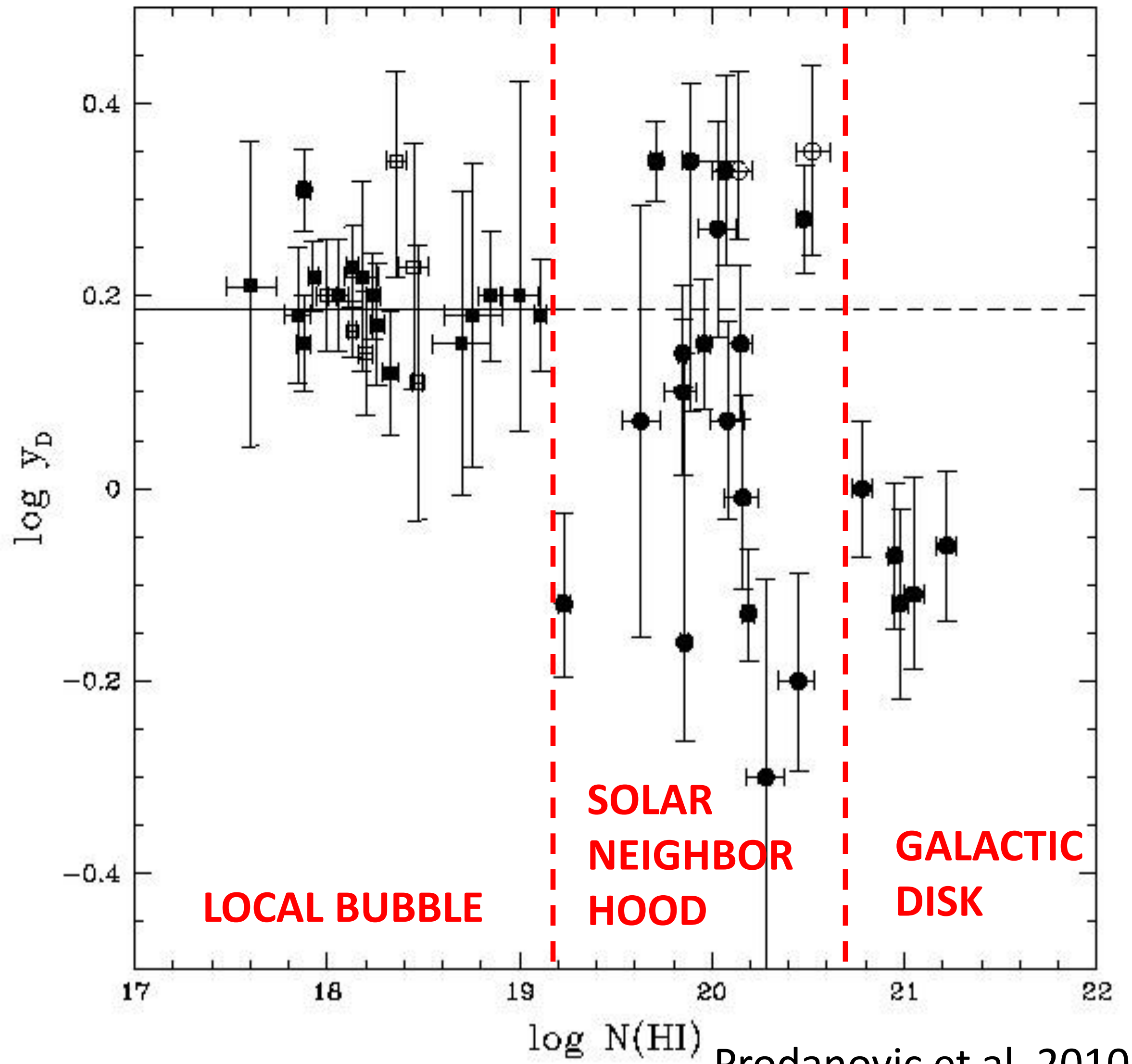
- Simple history
  - Made in BBN $\left(\frac{D}{H}\right)_p \cong 2.82\times10^{-5} = 28.2\text{ppm}$
  - Destroyed everywhere – mostly stellar processing
  - Probes gas "virgin" fraction
  - Great for Galactic Chemical Evolution (GCE)
- But large local variations! Factor ~ 2-3!
  - Both high (~ primordial) and low (Linsky et al. 2006)

$$\left(\frac{D}{H}\right)_{ISM} \cong (0.5-2.2)\times10^{-5}$$

Deuterium Variations

Data:
Linsky et al 2006
Oliveira & Hebrard 2006

$$y_D \equiv 10^5 \left(\frac{D}{H} \right)$$



Prodanovic et al. 2010

Why Care?

- What is the local (ISM) D abundance?
- ISM D very high? (Linsky et al 2006)

$$\left(\frac{D}{H}\right)_{ISM} \geq (2.31 \pm 0.24) \times 10^{-5}$$

- Implications
  - Very low stellar processing? GCE models disagree
  - Large infall/accretion of primordial material?
  - Higher primordial D abundance?

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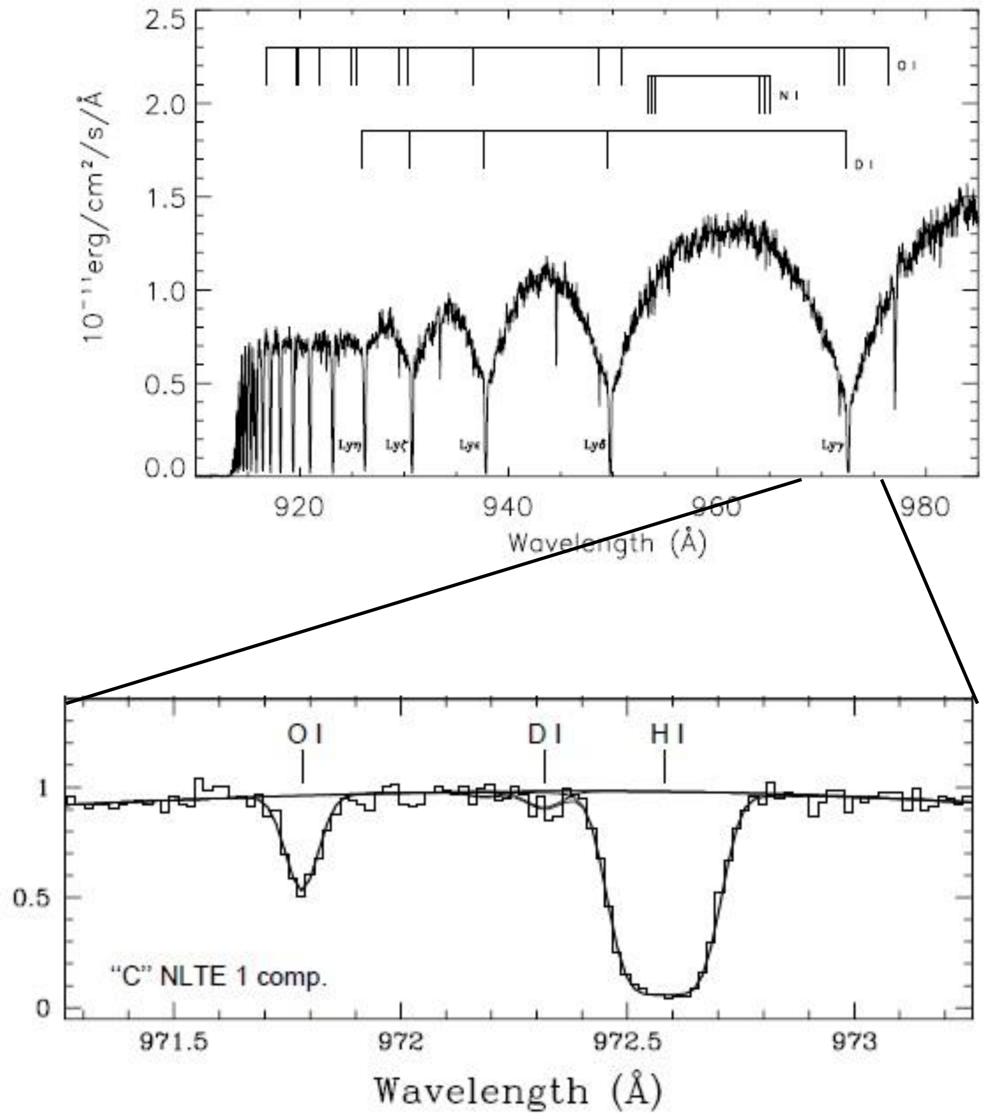
ISM Deuterium Observations

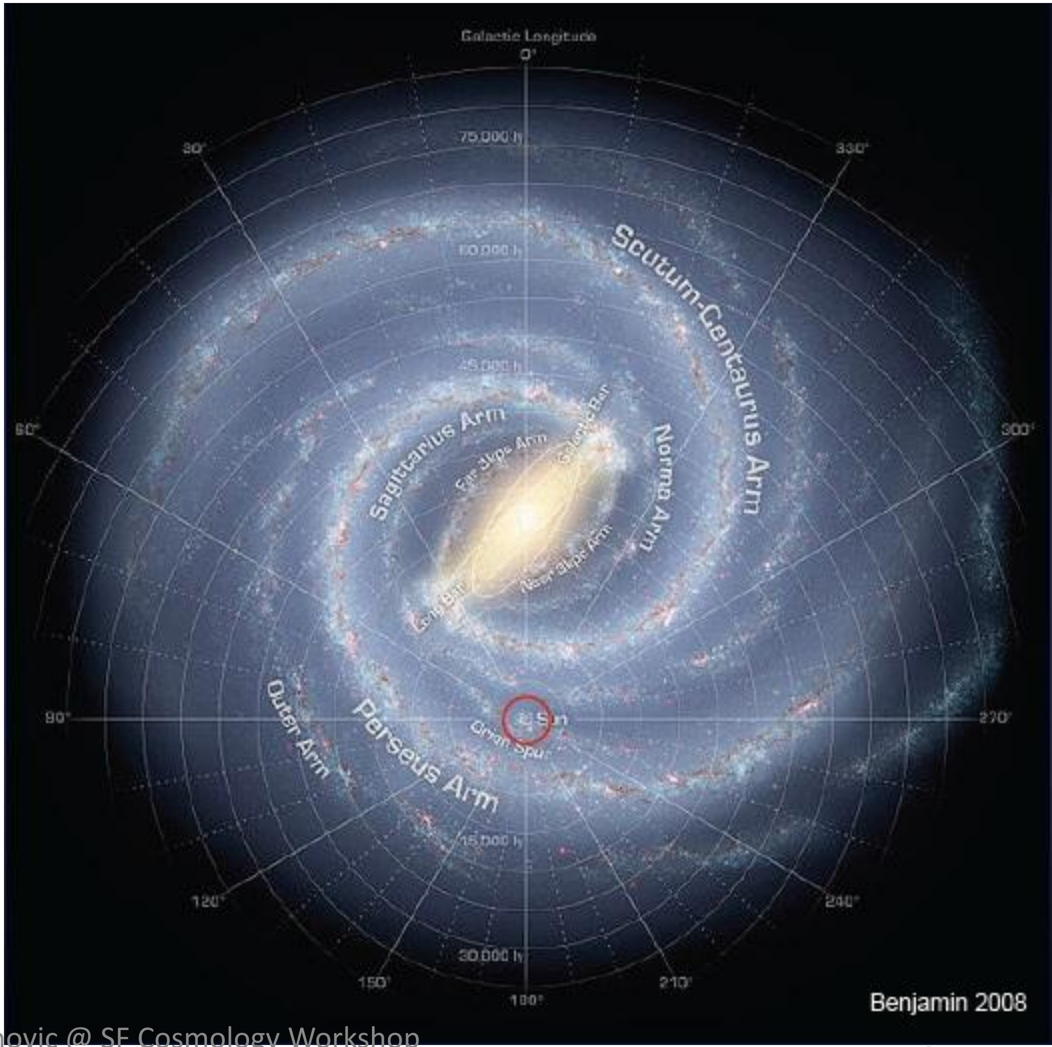
- Neutral interstellar medium
- DI apsorption Lyman series in UV stellar spectra
- Most current observations
  - Hubble Space Telescope - ongoing
  - Far Ultraviolet Spectroscopic Explore (FUSE) – not operational

Lemoine et al. 2002



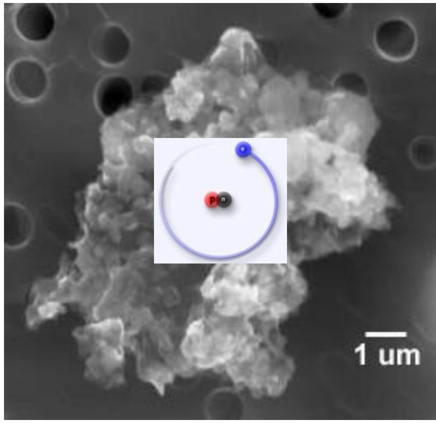
Local Deuterium Observations

- ISM measurements, but in fact very local
- Only up to ~ 500 pc
- Complicated velocity profiles – superposition of clouds
- Deuterium line "invisible" under H lyman apsorption



Solution?

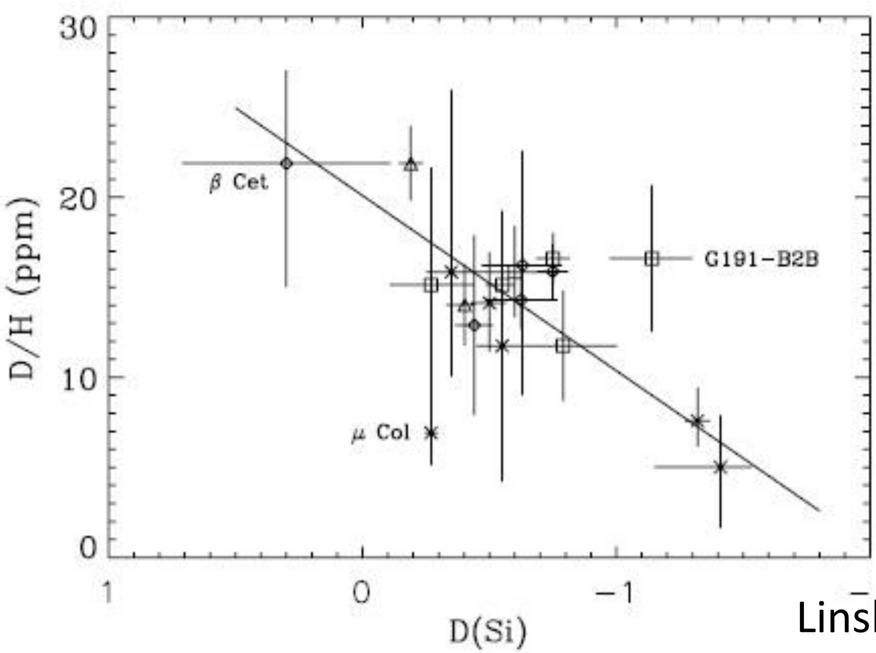
- Deuterium preferentially (compared to H) depleted onto dust! (Jura 1982, Draine 2004, 2006)
- Measure only gas-phase abundance
- Some D fraction locked in dust grains
- Observe – lower bound on "true" abundance
- D should anticorrelate with other refractory elements depletion (Fe, Si, Ti etc.)

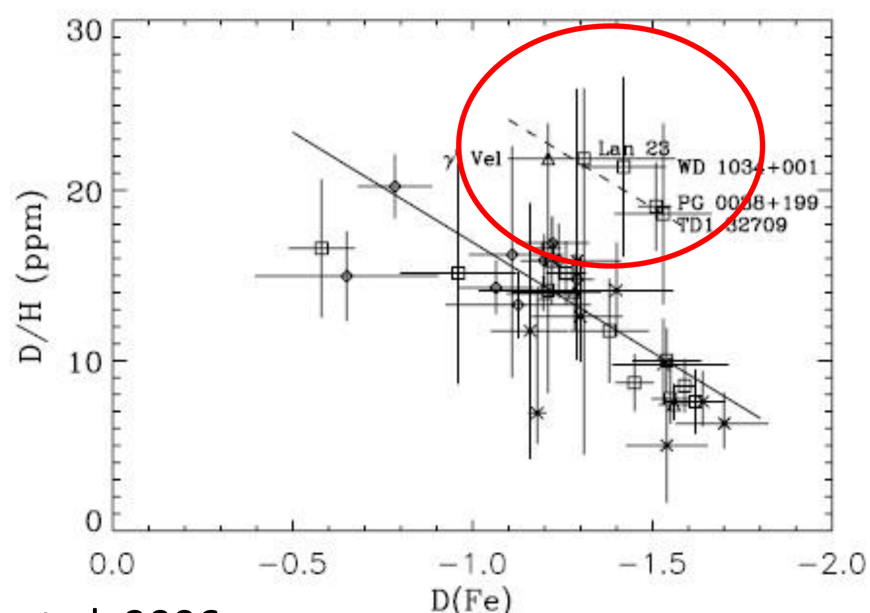


Dust Depletion

- D should anticorrelate with other refractory elements depletion (Fe, Si, Ti etc.)

$$D(\mathrm{X}) = \log[(\mathrm{X/H})_{\mathrm{gas}}/(\mathrm{X/H})_{\mathrm{sol}}]$$

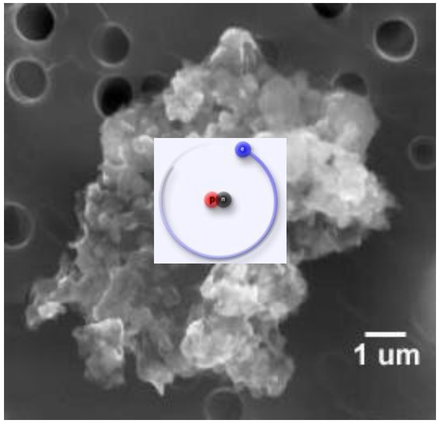




Linsky et al. 2006

"True" ISM Deuterium?

- Measure lower bound on the "true", undepleted D
- Highest measured abundance is closest to true value
- Linsky et al. 2006
  - Take 5 highest values
  - "True" ISM D abundance



$$y_{D,ISM+dust} \geq 2.31 \pm 0.24$$

- "True" ISM D = 82% of PRIMORDIAL!

GCE Objects!

- Deuterium destroyed through stellar cycling
- Astration factor (Steigman et al. 2007) $1.4 \leq f_D \equiv y_{Dp} / y_{DISM} \leq 1.8$
- But new *FUSE* high ISM D $f_D \leq 1.22 \pm 0.15$
- Most gas still unprocessed?
- Gas observations say ~20% of present baryonic mass in ISM
- But D observations say ~80% initial gas unprocessed!

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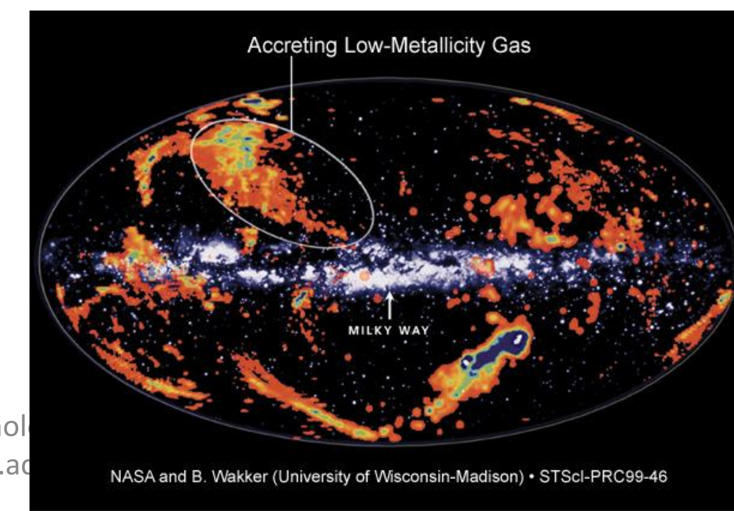
Deuterium Facelift?

- High D but normal stellar processing?
- Need infall of (close to) pristine material
  - e.g. High-velocity clouds with low, ~ 10% solar metallicity
  - Leftover primordial has?
  - Replenish deuterium



Infall Side Effects

- Increase ISM D abundance
- Increase gas content of the Galaxy
- Dilutes metal content of the Galaxy

- **Deuterium and Galactic gas fraction observations powerful constraint of the infall rate**

How much infall?

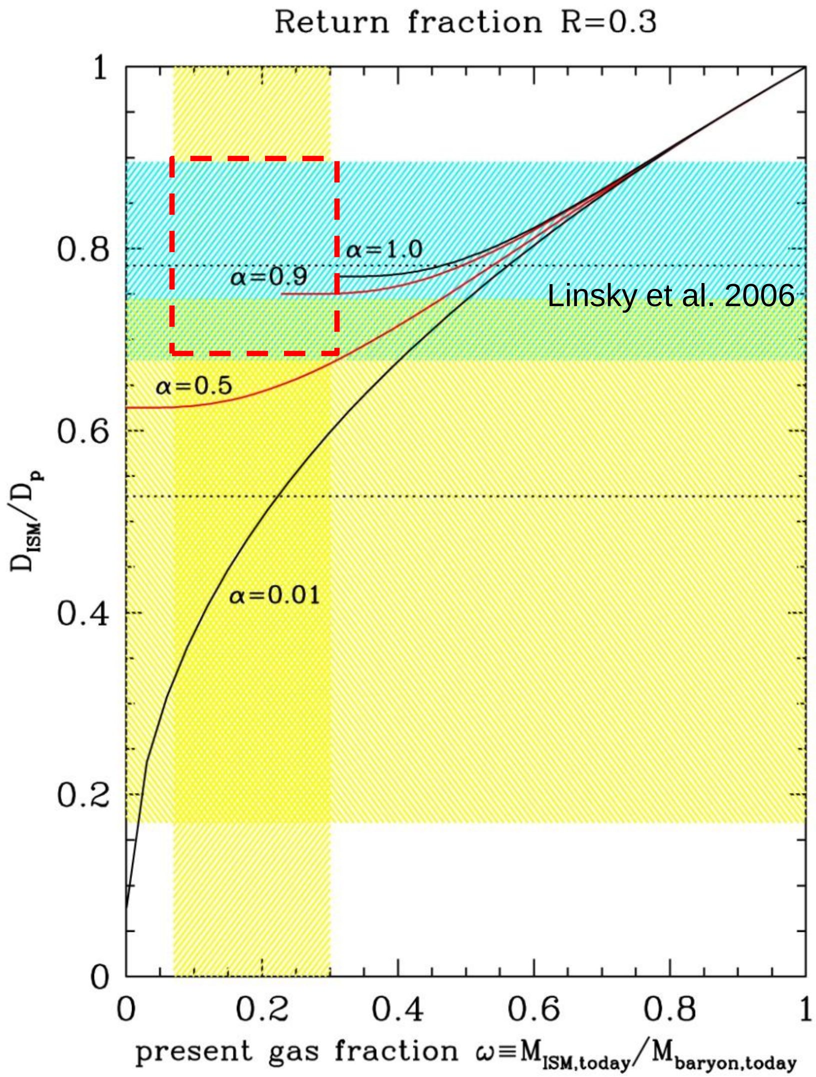
- D *vs.* gas fraction
- Shaded = observations
- Infall ~ star formation rate

$$\dot{M}_{\text{infall}} = \alpha\psi(t)$$

- Allowed infall rate

$$0.5 \leq \alpha \leq 1$$

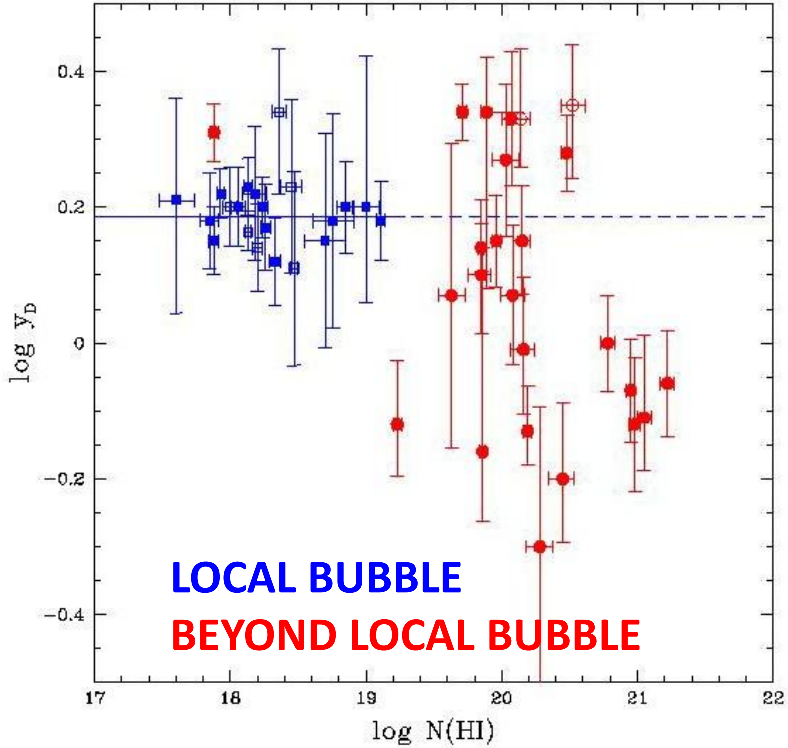
- Almost balances out star-formation!
- Consistent with hierarchical galaxy formation (accretion)
- Still tension with GCE

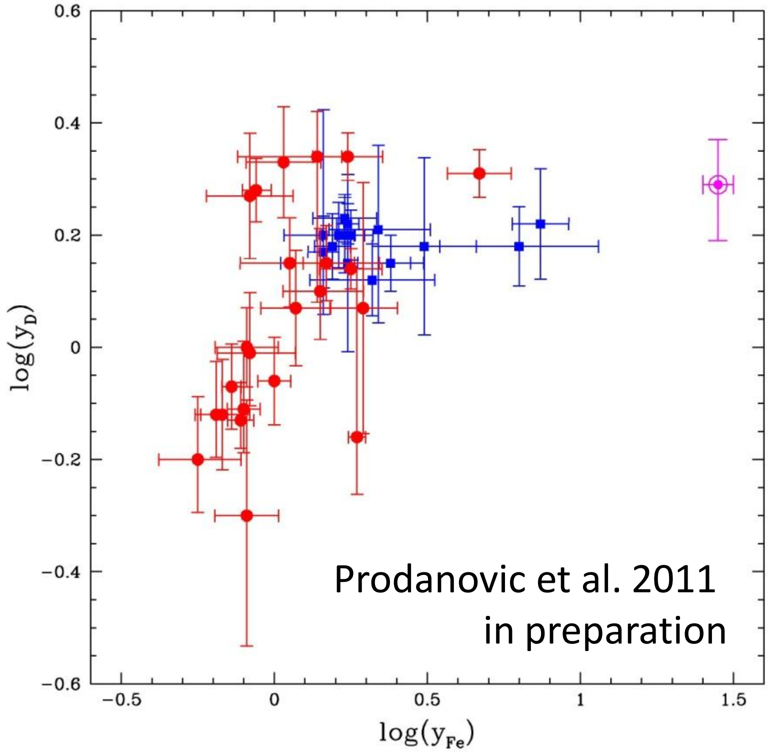


Prodanovic & Fields (2008)

Dust Depletion?

- True at some level, but....
  - Correlation with refractory elements not great
  - D constant in Local Bubble while Fe depleted?





Dust Depletion?

- True at some level, but....
  - Latest “True” ISM D estimate based on 5 highest LOS
  - Might be contaminted by recent infall?
- Need to reevaluate all available data
- Second oppinion: A statistical approach

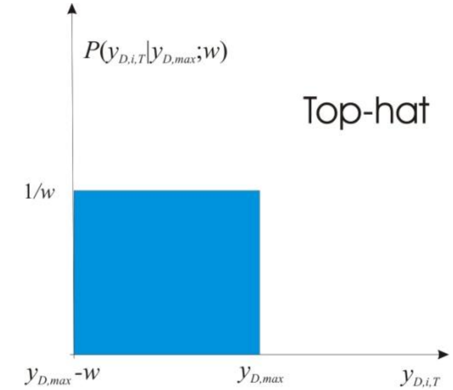
A Statistical Approach

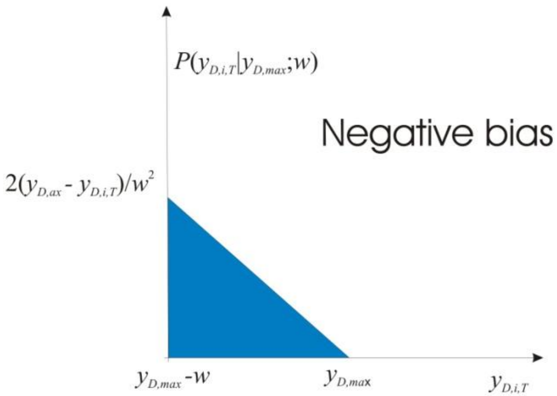
- Hogan et al. (1997) analysis of ^{4}He data
  - Goal: Find primordial ^{4}He
  - Have: post-BBN ^{4}He production contaminated data
  - Assume: There is a post-BBN production
- Take entire deuterium data set – 46 LOS (Linsky et al. 2006)
- Assume nothing about (dust) depletion distribution – only that it exists

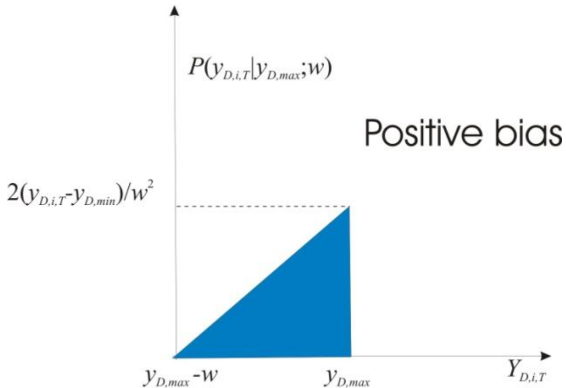
Bayesian Maximum Likelihoon

- Assume there is depletion
- Generic depletion probability distribution:

1) Top hat – all levels of depletion equally probable
2) Negative bias – favors large depletion
3) Positive bias – favors low depletion







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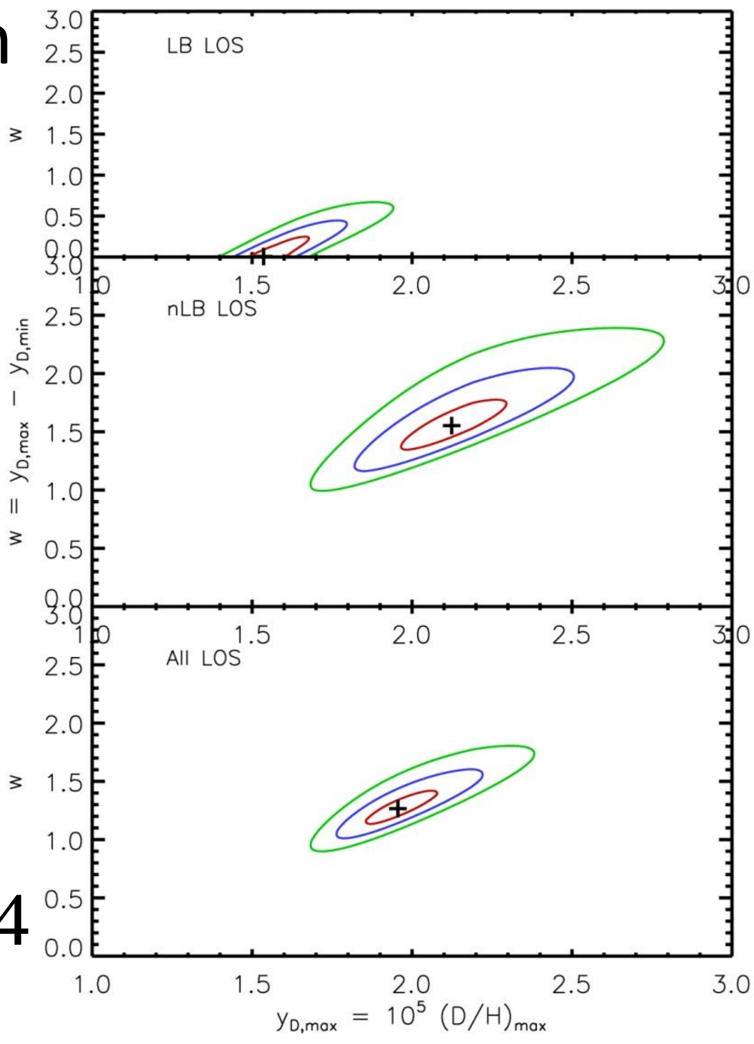
Results: Maximum Likelihood

Prodanovic et al. (2010)



- Top-hat depletion distribution – highest max. likelihood

- 21 Local Bubble LOS

$$y_{D,LB} \cong 1.5 \quad w \cong 0 \quad f_{D,LB} \leq 1.8$$

- 25 non-Local Bubble LOS

$$y_{D,nLB} = 2.1 \quad w = 1.6 \quad f_{D,nLB} \leq 1.3$$

- All 46 LOS

$$y_{D,\max} = 2.0 \quad w = 1.3 \quad f_{D,\max} \leq 1.4$$

True ISM Deuterium Abundance

- Use all 46 LOS
- Top-hat depletion distribution – highest max likelihood value

$$y_{D,ISM} \geq y_{D,\max} = (2.0 \pm 0.1) \times 10^{-5}$$

- Marginally consistent with Liski et al. (2006)

$$y_{D,ISM+dust} \geq (2.31 \pm 0.24) \times 10^{-5}$$

- Releases tension with GCE models and high-redshift measurements

Problems

- Uniform LB D abundance vs. large scatter in nLB?
  - LB - no depletion? $y_{D,LB} = 1.5 \quad w = 0$
  - nLB – large depletion? $y_{D,nLB} = 2.1 \quad w = 1.6$
- Is LB uniformily depleted? Why does Fe vary?
- Is nLB enriched with unmixed infall?
- Is Fe really a good depletion indicator for D?
- Do Fe and D deplete on same types of grains?
- Dust grain physics still unknown territory...

Primordial Element Problem(s)

- Lithium is still a problem
  - Probably too large discrepancy to be observational
  - Need some way to destroy
    - In stars – deeper mixing?
    - Decay of recil particles at BBN epoch – LHC?
  - Need new site! SMC measurements soon!
- Deuterium – BBN + WMAP concordance
  - OK at high-z but locally a pressing problem
  - Can have important cosmological consequences
  - No need to panic...yet

Thank You!

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How much infall needed?

- Build a "keep it simple" model
  - Infall and NO outflow
  - Infall rate proportional to star-formation rate $\psi(t)$

$$\dot{M}_{\mathrm{infall}} = \alpha \psi(t)$$

  - Define gas mass fraction

$$\omega(t) \equiv M_{ISM}(t) / M_{baryon}(t)$$

  - Specify return fraction *R* – fraction of initial stellar mass that is returned to ISM (follows from Initial mass function); e.g. $R = 0.3$ from Salpeter IMF

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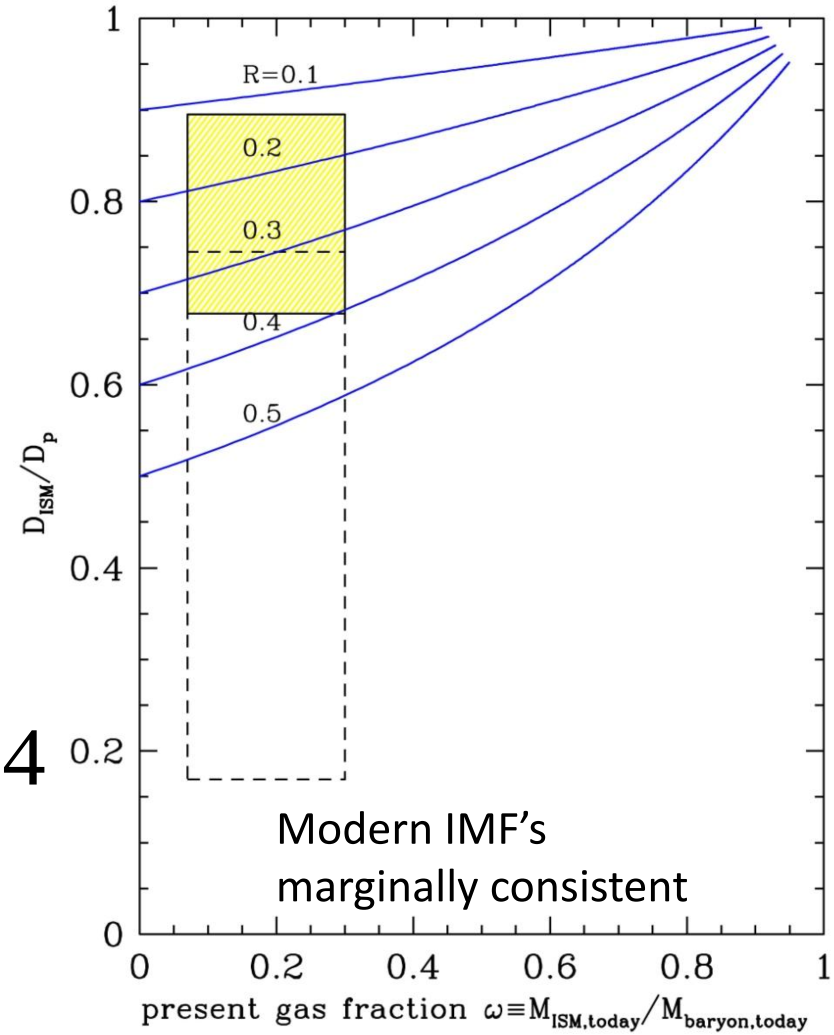
IMF Constraints

- At late times D and gas fraction approach minimum values
- Limiting curves above which no solutions for range of return fractions
- Allowed only $0.1 < R \leq 0.4$
- Modern IMFs demand

$$R = 0.4$$

Prodanovic & Fields 2008



Prodanovic & Fields (2008)

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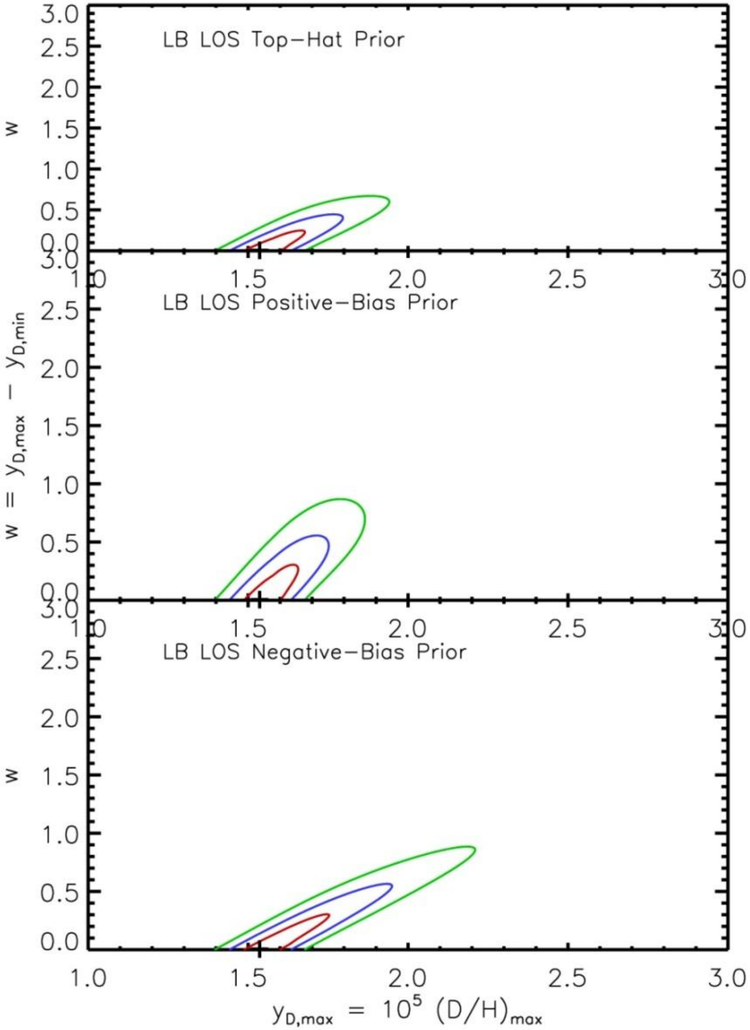
Results: Local bubble

Prodanovic, Steigman & Fields (2009)
arXiv:0910.4961

- 21 Local Bubble LOS
- 1,2,3 σ contours
- All depletion distributions yield

$$y_{D,LB} \cong 1.5 \quad w \cong 0 \qquad f_{D,LB} \leq 1.8$$

- Local Bubble
  - Consistent with no depletion
  - Consistent with GCE



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D vs. Metal yields

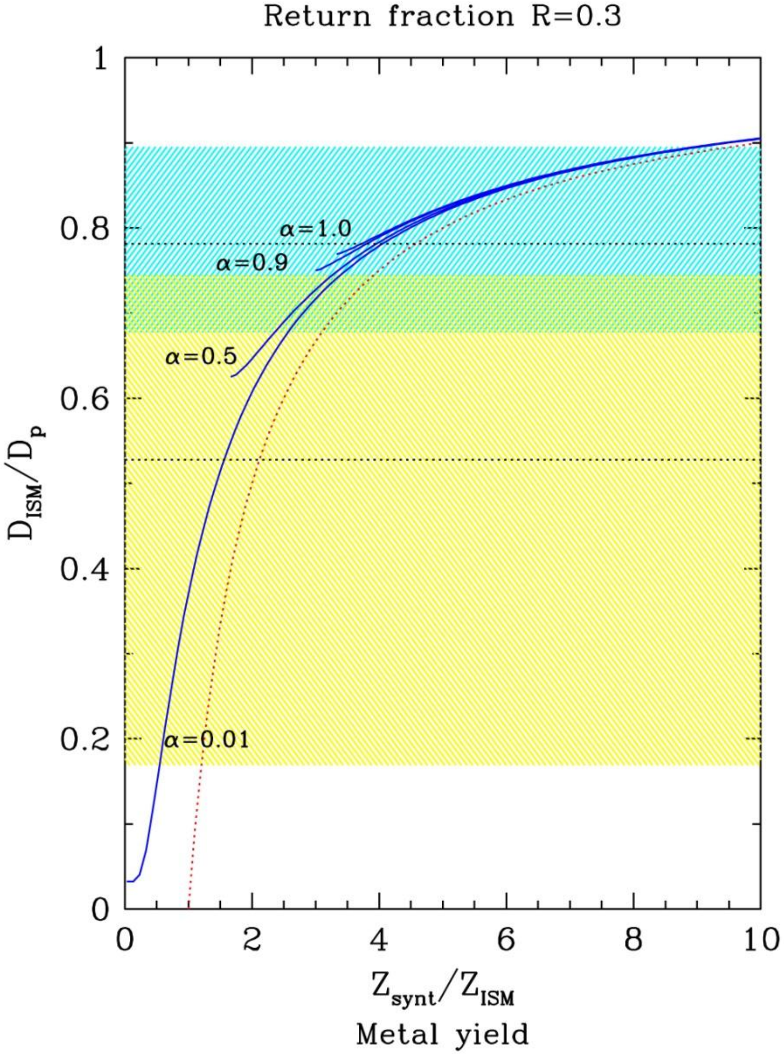
Freshly synthesized metals Z_{synt}

SN metal yield $Z_{SN} \sim 10 Z_{sol}$

Present reasonable estimates

$$Z_{synt}/Z_{ISM} \approx 4$$

consistent with large or no infall since all curves converge.



Prodanovic & Fields (2008)

Model: details

$$\frac{dM_{ISM}}{dt} = -(1-R)\psi + \alpha\psi$$

$$\frac{d}{dt}(DM_{ISM}) = -D\psi + D_p\alpha\psi$$

Where *D* is the deuterium mass fraction defined as: $D \equiv X_D \equiv \frac{\rho_D}{\rho_{baryon}} \simeq 2\left(\frac{D}{H}\right)X_H$

Taking $\mu \equiv M_{ISM}(t)/M_{baryon}(t=0)$ we get:

$$\frac{D(t)}{D_p} = \frac{R}{\alpha+R}\left(\frac{\alpha}{R} + \mu^{\frac{\alpha+R}{1-\alpha-R}}\right)$$

which we can express in terms of the present gas mass fraction by using:

$$\omega(t) \equiv \frac{M_{ISM}}{M_{baryon}} = \frac{1-R-\alpha}{1-R-\alpha\mu(t)}\mu(t)$$

model: details – Return fraction

Approximate: $m_{ej}(m) = m - m_{rem}(m)$

Then, define return fraction for each progenitor mass as: $R(m) \equiv m_{ej}/m$

To find a global return fraction must specify the IMF: $\phi(m) \equiv dN/dm$

$$R = \frac{\int_{m_L}^{m_U} dm \cdot R(m) \cdot m \cdot \phi(m)}{\int_{m_L}^{m_U} dm \cdot m \cdot \phi(m)}$$

For mass ranges $8 \leq m_{SN}/M_{sol} \leq 100$ and $0.8 \leq m_{AGB}/M_{sol} \leq 8$

and Salpeter IMF $\phi(m) \propto m^{-2.35}$

we find return fraction $R = 0.31$

Modern IMFs are flatter in the high-mass regime → more high-mass stars → more ejecta → larger return fractions $R \sim 0.4$

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model: details - envelope

$$\frac{D(t)}{D_p} = \frac{R}{\alpha + R}\left(\frac{\alpha}{R} + \mu^{\frac{\alpha+R}{1-\alpha-R}}\right)$$

$$\omega(t) \equiv \frac{M_{ISM}}{M_{baryon}} = \frac{1-R-\alpha}{1-R-\alpha\mu(t)}\mu(t)$$

For large infall where $R+\alpha \geq 1$

$$\left.\begin{array}{c}\frac{\alpha+R}{1-\alpha-R} < 0 \\ \mu \to \infty\end{array}\right\} \Rightarrow \mu^{\frac{\alpha+R}{1-\alpha-R}} \to 0$$

$$\frac{D_{\min}}{D_p} \to \frac{\alpha}{\alpha + r}$$

$$1-R << \alpha\mu(t) \quad \Rightarrow$$

$$\frac{1-R-\alpha}{1-R-\alpha\mu(t)}\mu(t) \to \frac{1-R-\alpha}{-\alpha\mu(t)}\mu(t)$$

$$\omega_{\min} \to 1 - \frac{1-R}{\alpha}$$

For small infall where $R+\alpha < 1$

$$\mu \to 0 \quad \Rightarrow \quad \left\{\begin{array}{l}\mu^{\frac{\alpha+R}{1-\alpha-R}} \to 0 \quad \Rightarrow \quad \frac{D_{\min}}{D_p} \to \frac{\alpha}{\alpha+R} \\ \omega_{\min} \to 0\end{array}\right.$$

A BAYESIAN approach

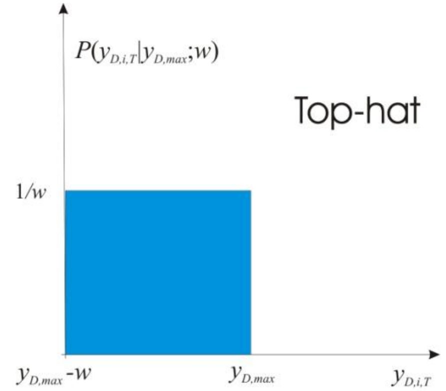
- Finding maximum likelihood $\left\{ y_{D,\max}, w \right\}$

$$L(y_{D,\max}, w) = \prod_i \int dy_{D,i,T} P(y_{D,i} \mid y_{D,i,T}) P(y_{D,i,T} \mid y_{D,\max}; w)$$

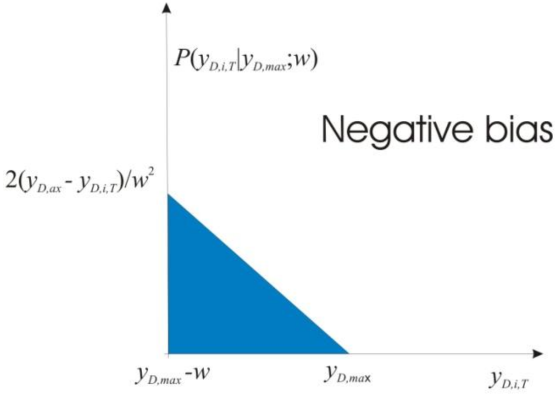
  – $P(y_{D,i} \mid y_{D,i,T})$ - Probability distribution
    - Relates what is measured to what should be measured (true) if it were no errors
    - Assume Gaussian
  – $P(y_{D,i,T} \mid y_{D,\max}; w)$- **Depletion probability distribution**
    - Probability of finding the true, dust depleted ISM D given $y_{D,i,T}$ the max. gas phase D $y_{D,\max}$ and depletion w

Choice: Depletion distributions

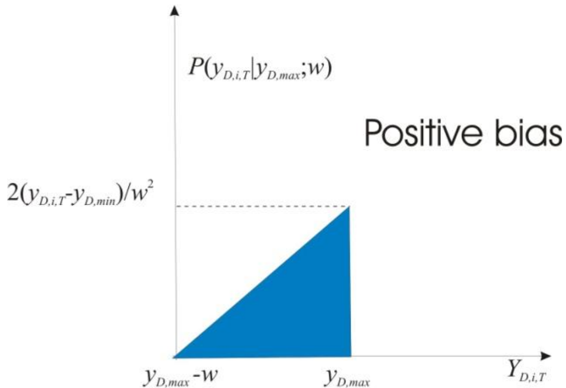
1) Top hat – all levels of depletion equally probable



1) Negative bias – favors large depletion



1) Positive bias – favors low depletion



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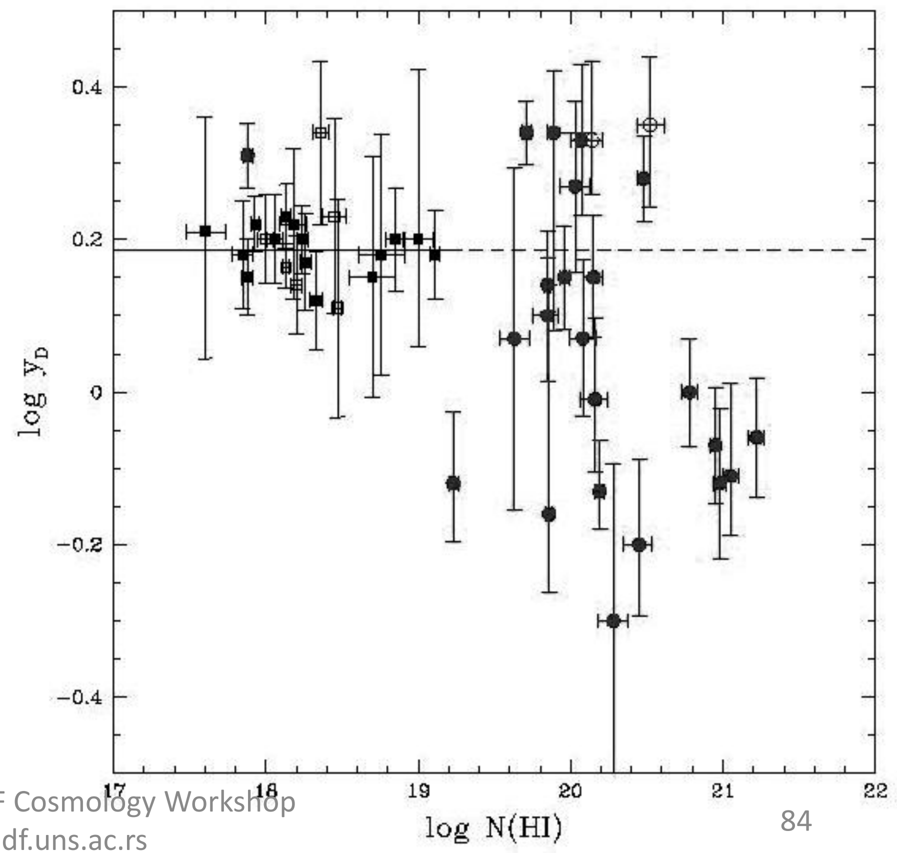
LB vs. Non-LB

- Local Bubble very different from non-Local Bubble
- LB – blue
  - Uniform
- nLB – red
  - Large scatter
- First treat separately

Prodanovic, Steigman & Fields (2009)
arXiv:0910.4961



Results: Depletion Distributions

- All 46 LOS
- Different depletion distribution comparison
  - Top-hat

    $$y_{D,nLB} = 2.0 \quad w = 1.3$$

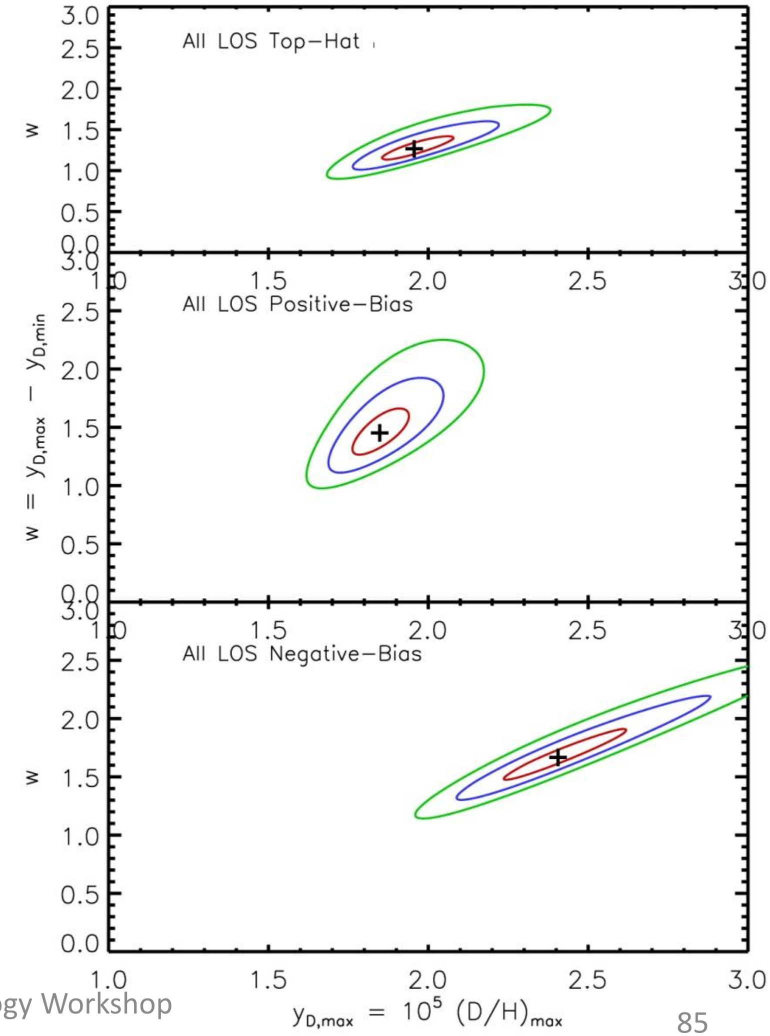
  - Positive-bias

    $$y_{D,nLB} = 1.8 \quad w = 1.5$$

  - Negative-bias

    $$y_{D,nLB} = 2.4 \quad w = 1.7$$

Prodanovic et al. (2010)



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Abundances 101

- Log abundances

$$\log y_i \equiv \log \varepsilon_i = \log \frac{i}{H} + 12$$

$$\log \varepsilon_H = 12$$

Eg. $$\log \varepsilon_{Li} = 2 \Rightarrow \frac{Li}{H} = y_{Li} = 10^{-10}$$

- Elemental ratios relative to Solar

$$\left[\frac{A}{B}\right] = \log\left(\frac{n_A}{n_B}\right) - \log\left(\frac{n_A}{n_B}\right)_{sol}$$

eg. metallicity $\left[\frac{Fe}{H}\right] = -1.0 \Rightarrow y_{Fe} = 3.2 \times 10^{-6}$

Abundances 101

- Ratio of some element to another (usually H)
- Notations/Representations
  - Mass fraction $X_i = \frac{\rho_i}{\rho_{tot}}$

$$X \equiv X_H \qquad Y \equiv X_{He} \qquad Z \equiv X_{metal}$$

$$X + Y + Z = 1$$

Solar values $0.70 + 0.28 + 0.02 = 1$

  - Abundance (wrt H, by number) $\frac{i}{H} \equiv y_i \equiv \frac{n_i}{n_H}$

$$y_{He,sol} = 0.1 \qquad y_{Fe,sol} \equiv \left(\frac{Fe}{H}\right)_{sol} = 3.2 \times 10^{-5}$$

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