Bimodality in Damped Lyα Systems

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Lyman Break Galaxies Properties (Stars)

Comoving SFR Density (z=3)

$$\dot{\rho}_* = 10^{-1.5} - 10^{-0.8} M_\odot yr^{-1} Mpc^{-3}$$

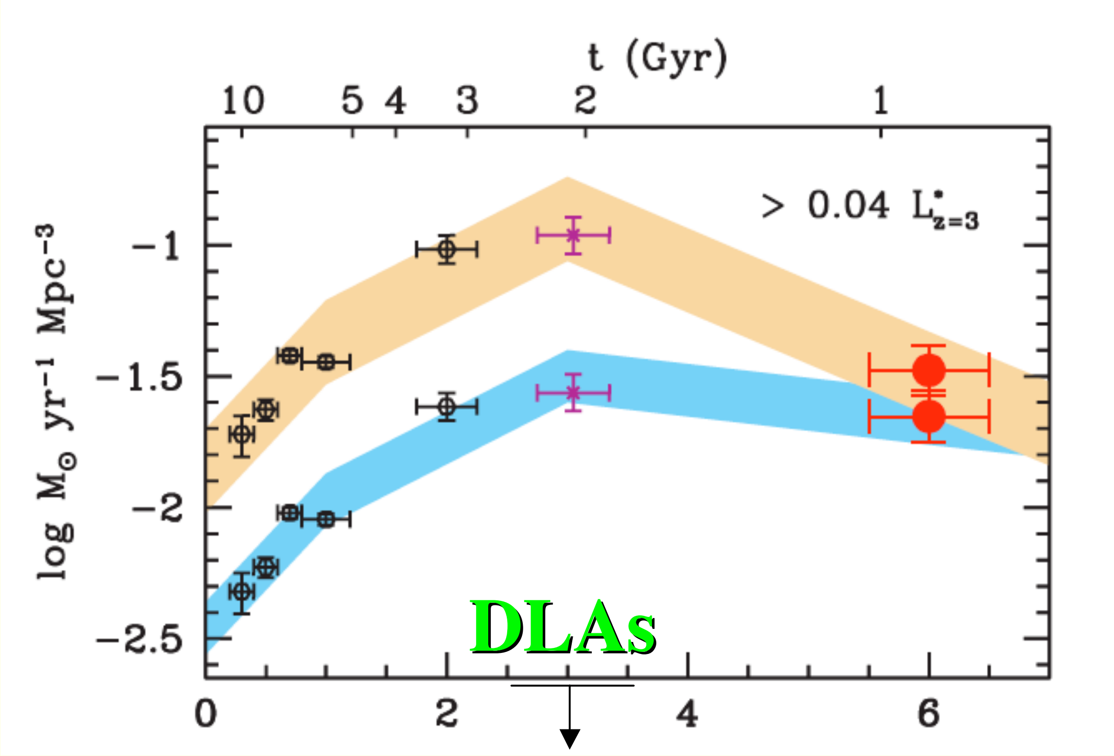
Covering Factor (z=[2.5,3.5])

$$f_A \; < \; 10^{-3} \text{ for } R < 27.5$$

Damped Lyα Absorption Systems (Neutral Gas)

$$f_A \; = \; 0.33 \text{ for } \mathrm{N(HI)} \geq 2 \times 10^{20} \mathrm{cm}^{-2}$$

SFR per unit Comoving Volume due to LBGs and DLAs



- **Comoving SFR density due to *in situ* SF in DLAs is significantly lower than LBG contribution**

$$d\rho_*/dt < 10^{-2.7} M_\odot \mathrm{yr}^{-1} \mathrm{Mpc}^{-3}$$

- **Implied upper limit on average SFR/area per DLA**

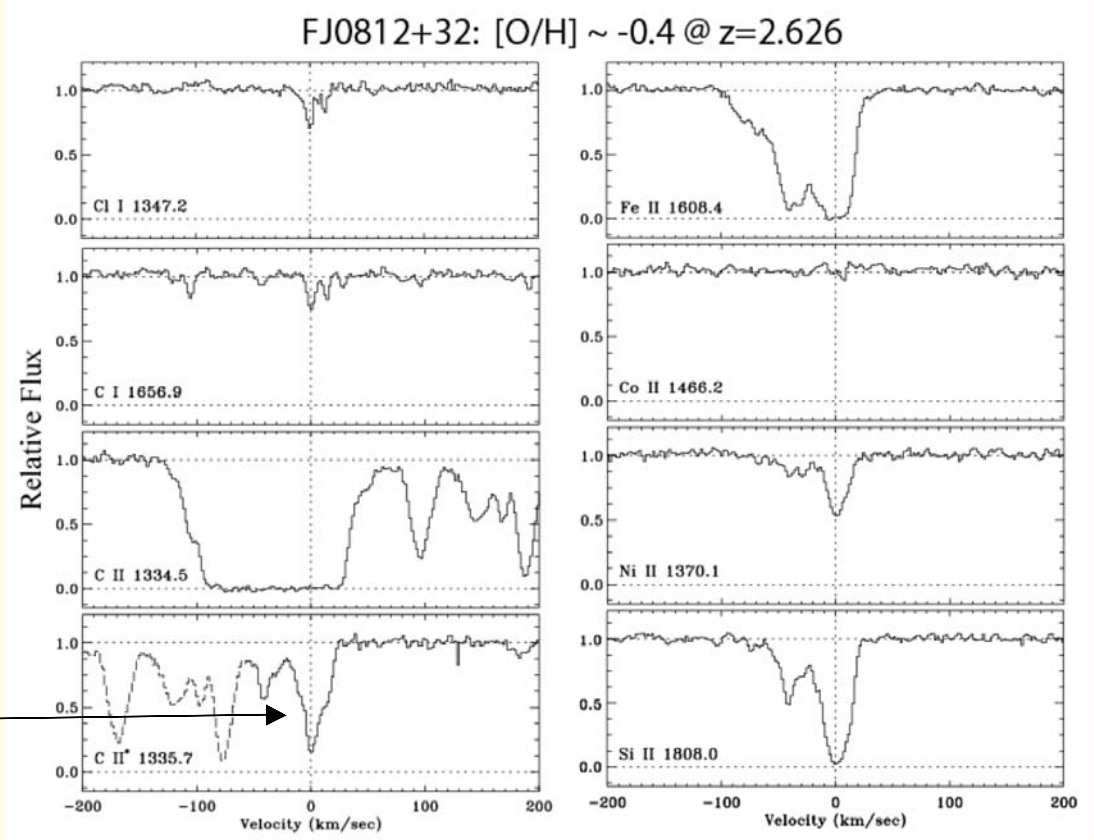
$$< d\psi_*/dt > \, < 10^{-3.6} M_\odot \mathrm{yr}^{-1} \mathrm{kpc}^{-2}$$

Astrophysical Consequences of upper limit $d\rho^{*}/dt < 10^{-2.7} M_{\odot} yr^{-1} Mpc^{-3}$

1. Limit on Metal Production

2. Limit on Gas Heating Rate

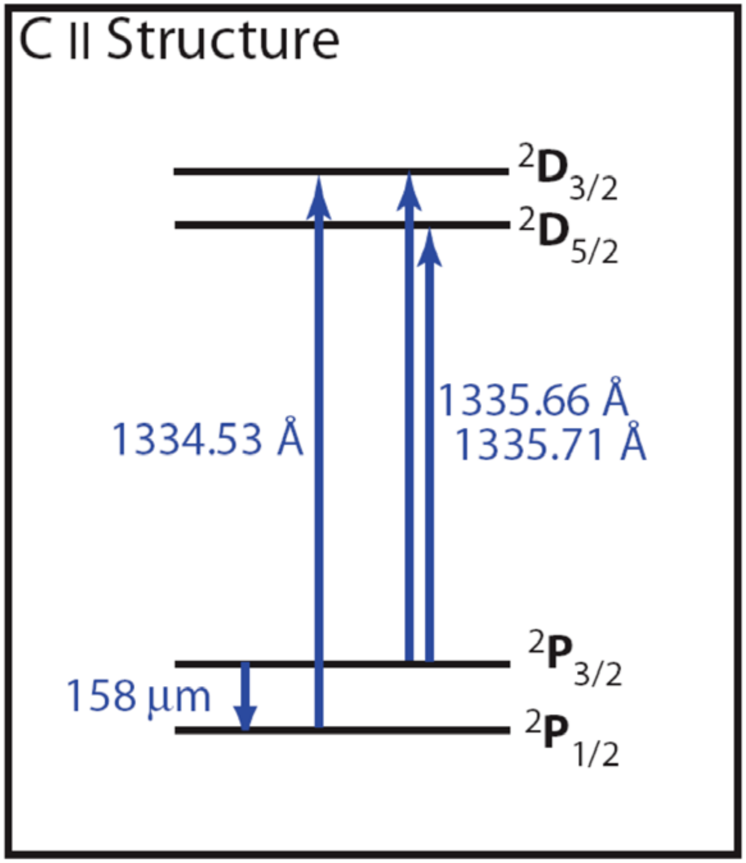
Cooling Rates from HIRES profiles



Cooling Rate Indicator

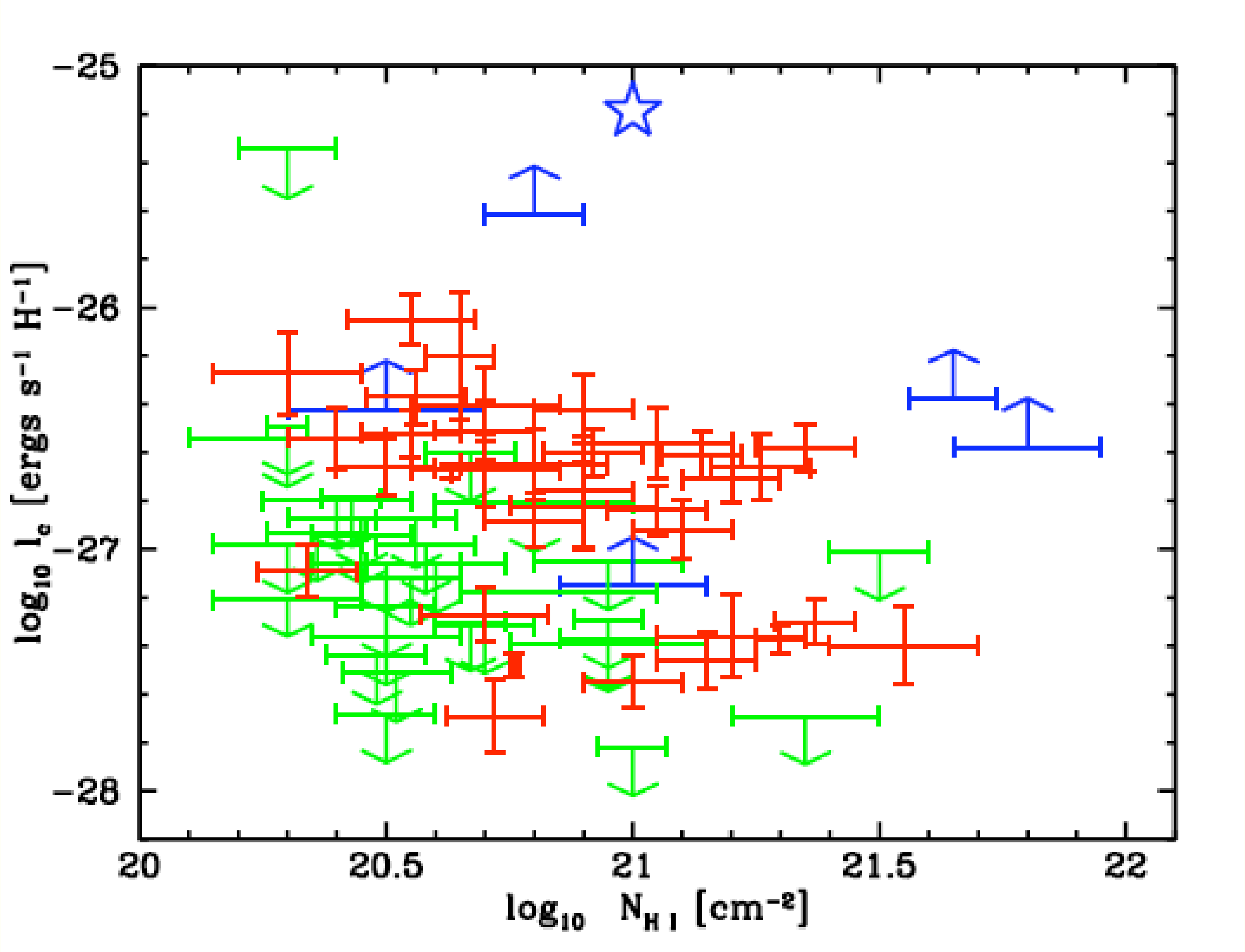
Obtaining Cooling Rates from CII* Absorption

- [C II] 158 micron transition dominates cooling of neutral gas in Galaxy ISM
- Spontaneous emission rate per atom $l_c = n\Lambda_{[CII]}$ obtained from strength of 1335.7 absorption and Lyman alpha absorption
- Thermal balance condition $l_c = \Gamma_{pe}$ gives heating rate per atom



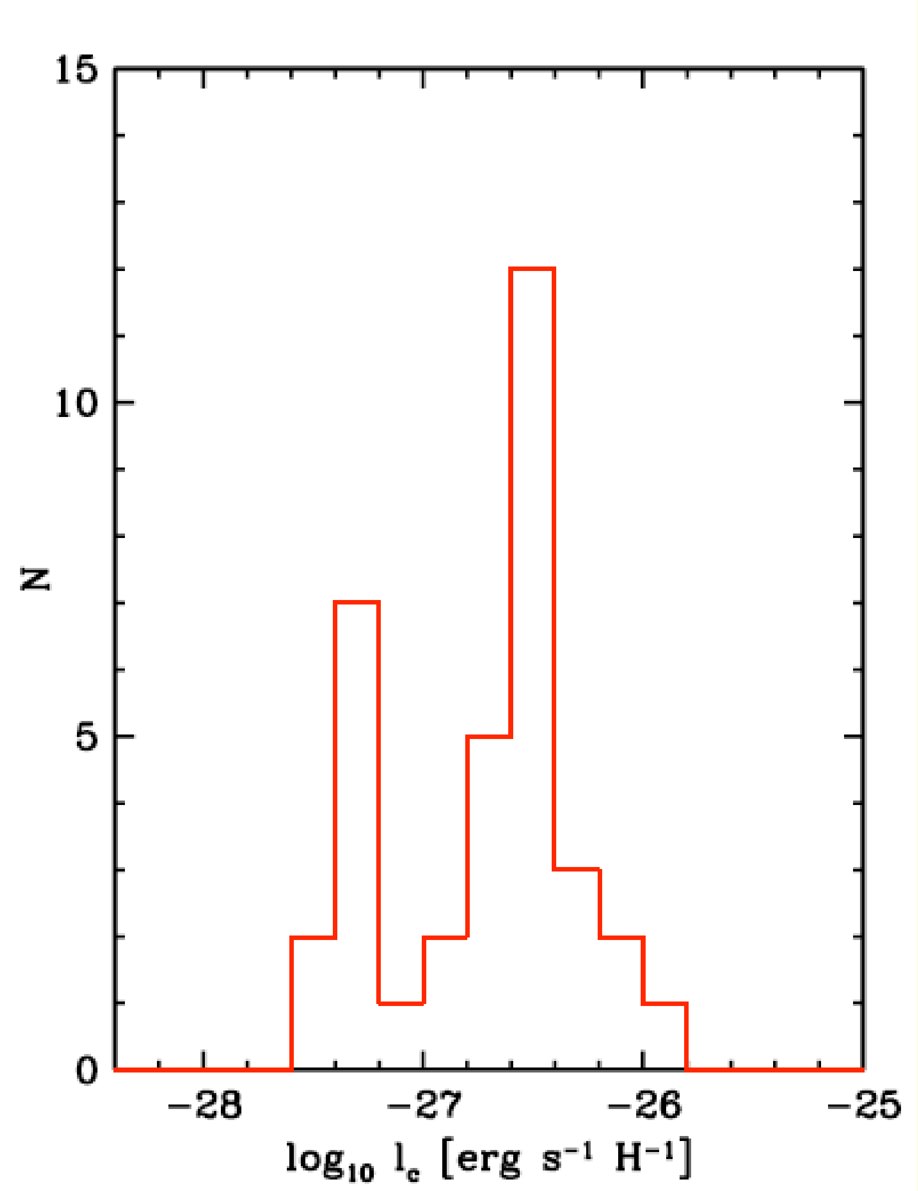
$$l_c = \boxed{n\Lambda_{[C\,II]} \sim \frac{N(\mathrm{CII^*})}{N(\mathrm{HI})} h\nu_{21} A_{21}}$$

[C II] 158 μm Emission Rate (per atom) vs. *N*(H I)



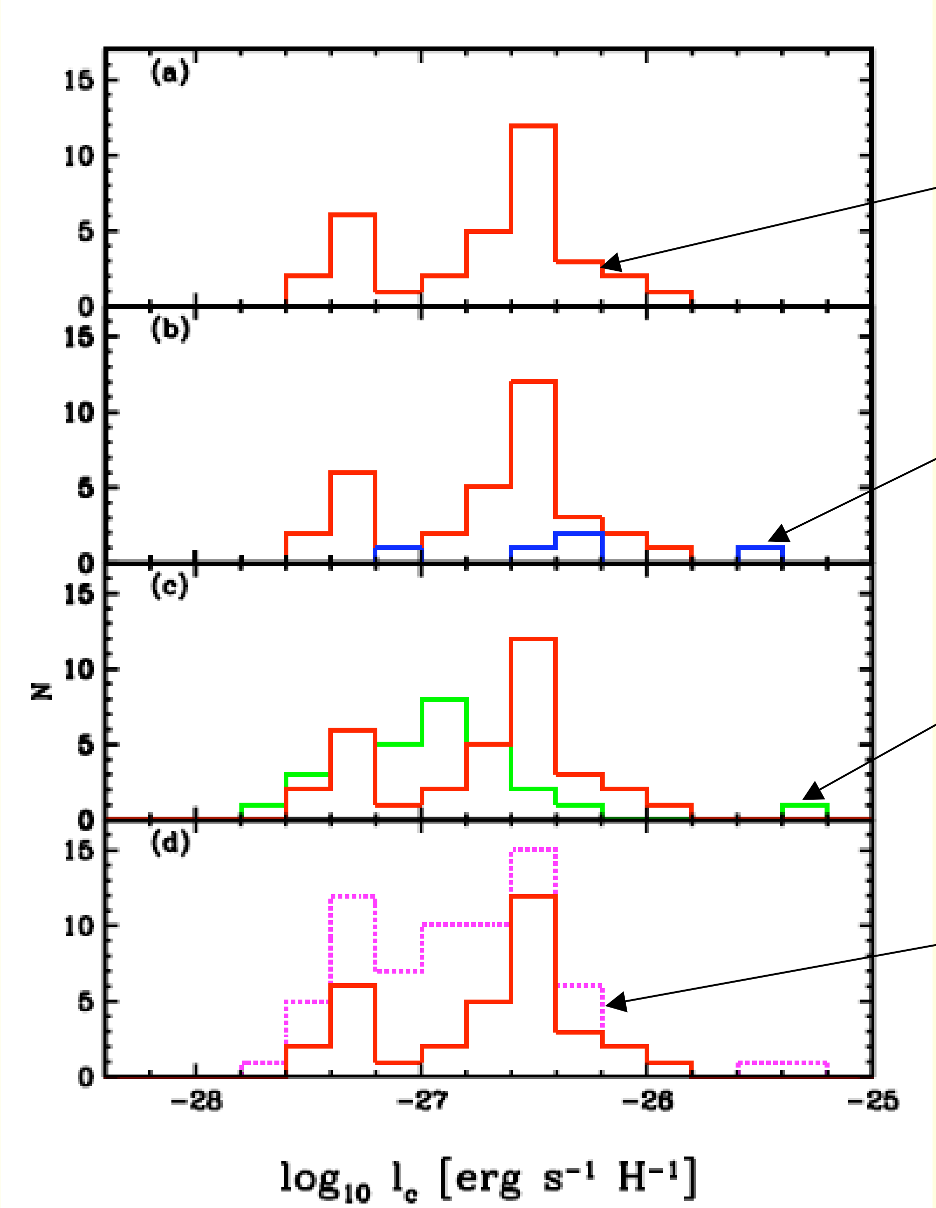
Two Types of DLAs?

Distribution of Detected [C II] 158 μm Cooling Rates



- **Statistically significant evidence for bimodality**

Comparison between Positive Detections and Limits



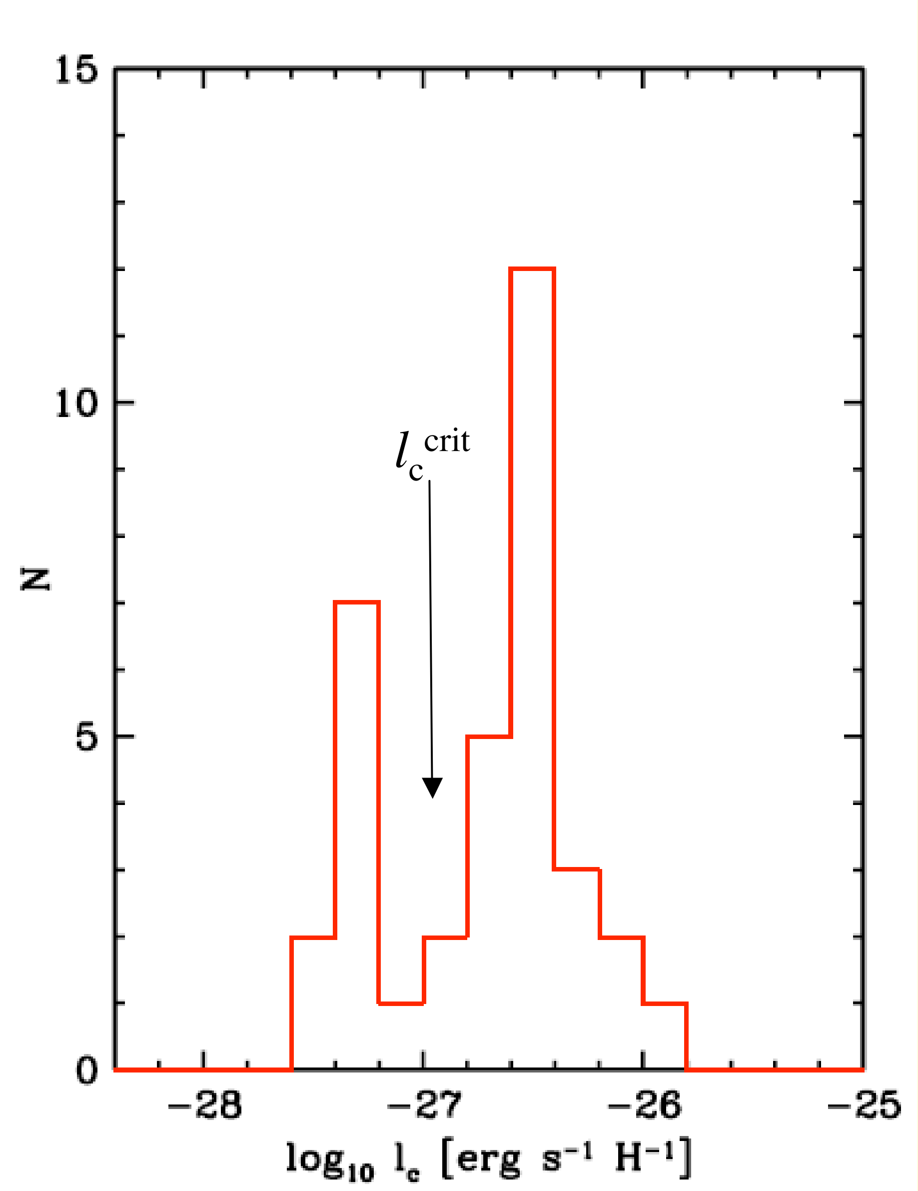
Positive Detections

Lower Limits

Upper Limits

Everything

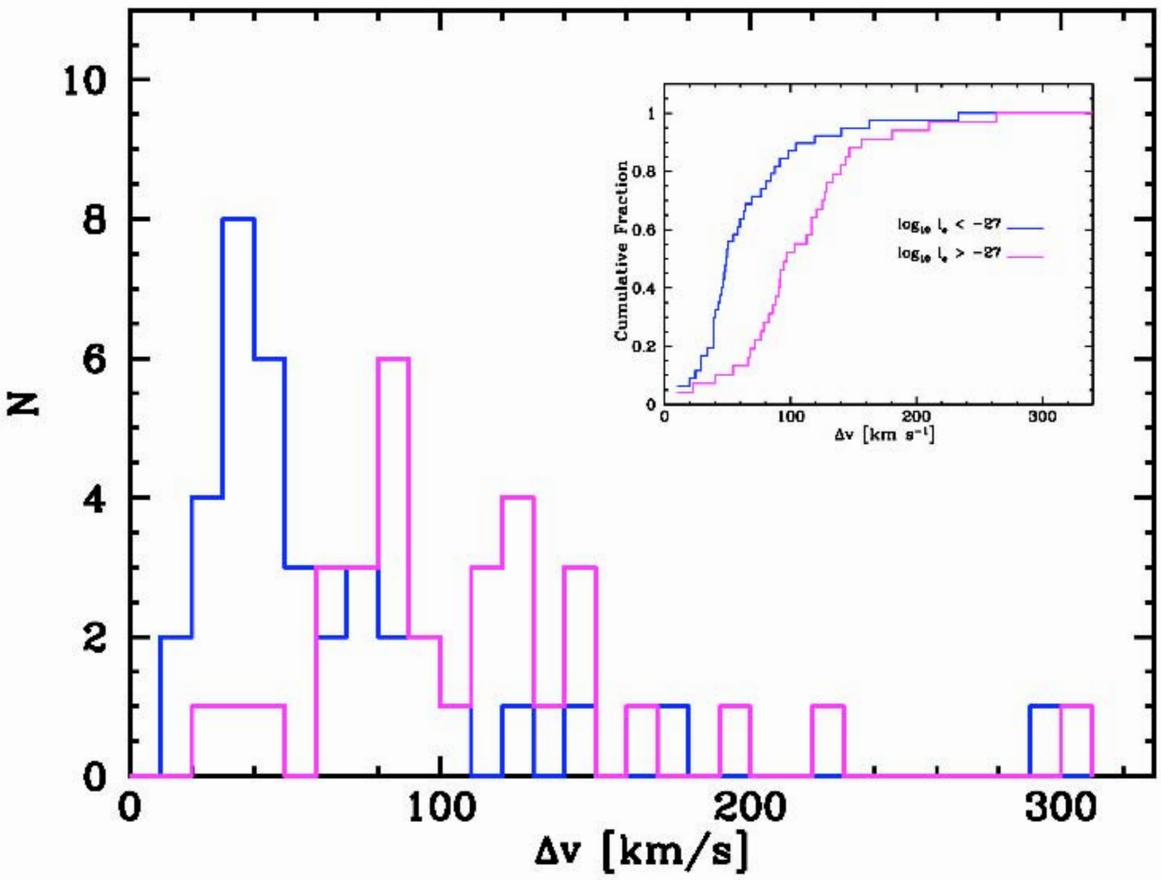
Frequency Distribution of [C II] 158 μm Cooling Rates



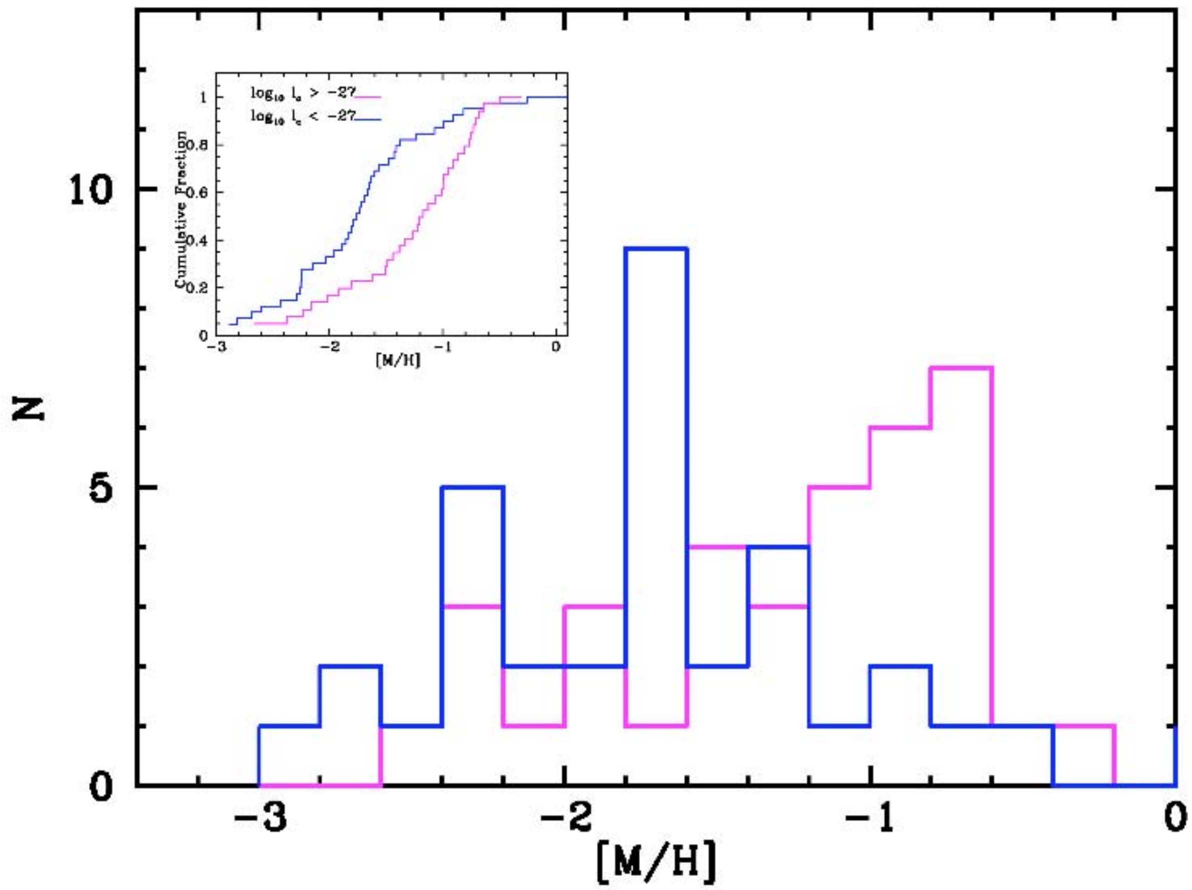
- $l_c^{crit} \approx 10^{-27}$ erg s^{-1}H^{-1}

- Populations separated by l_c^{crit} should have distinct physical properties

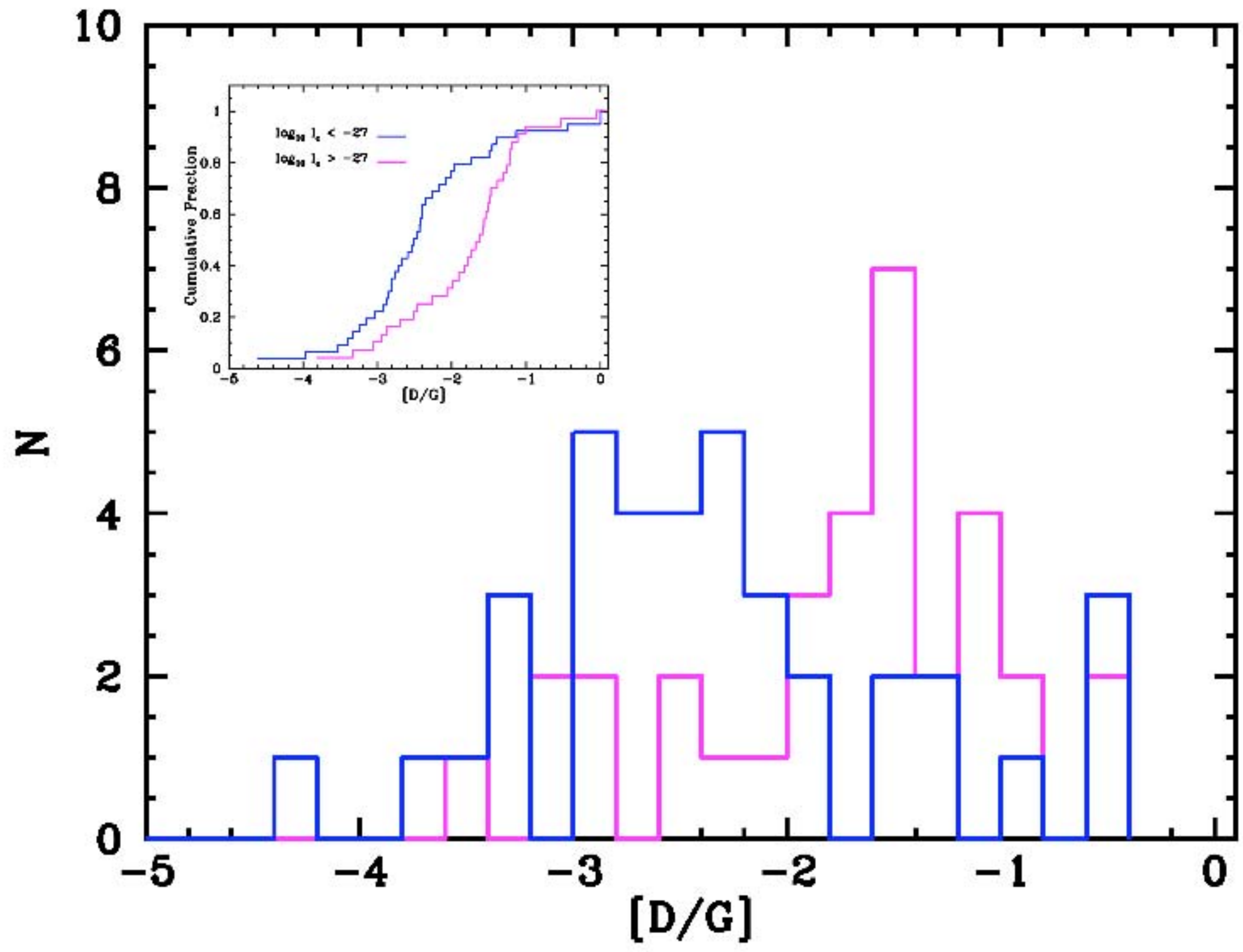
Velocity Interval Distributions



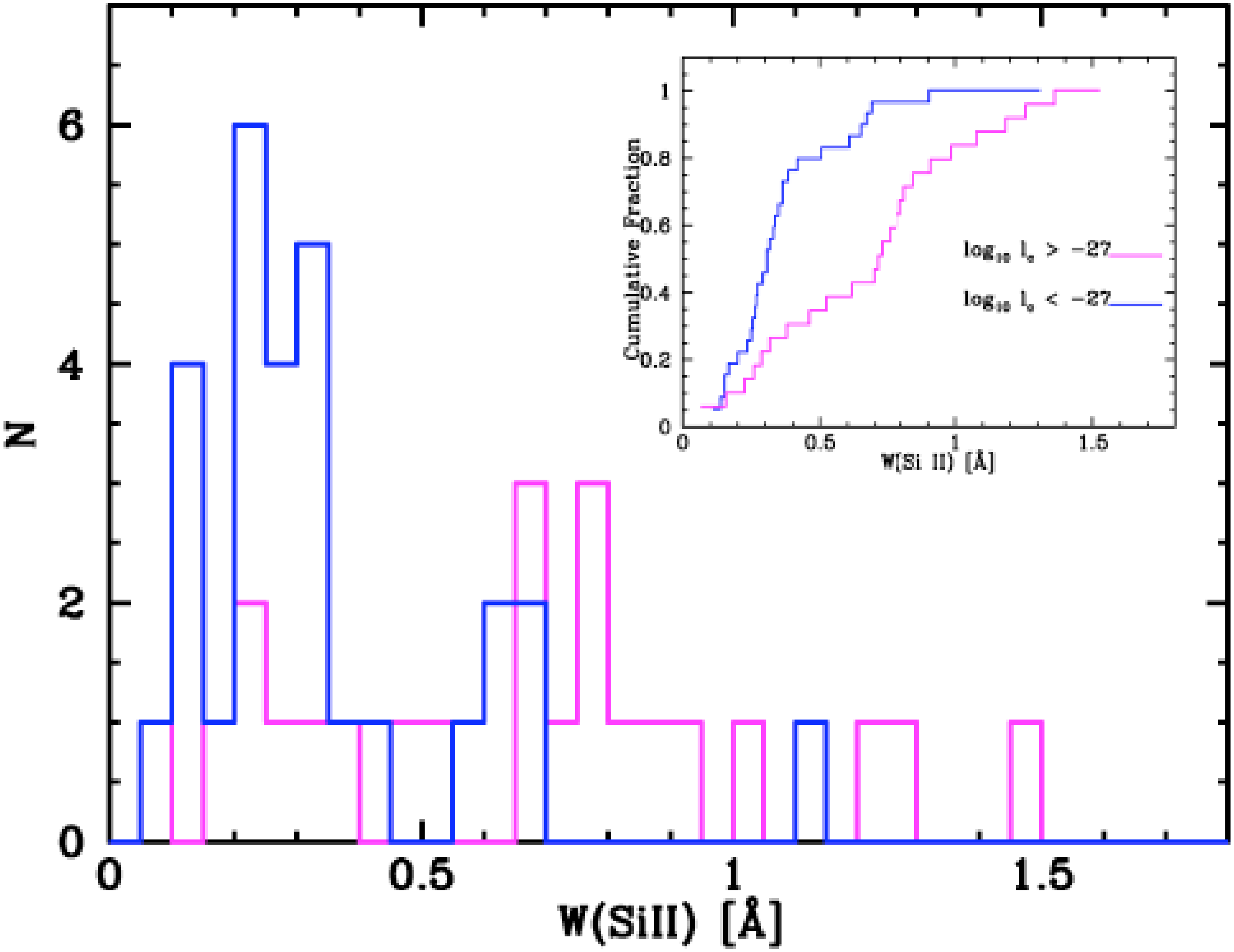
Metallicity Distributions



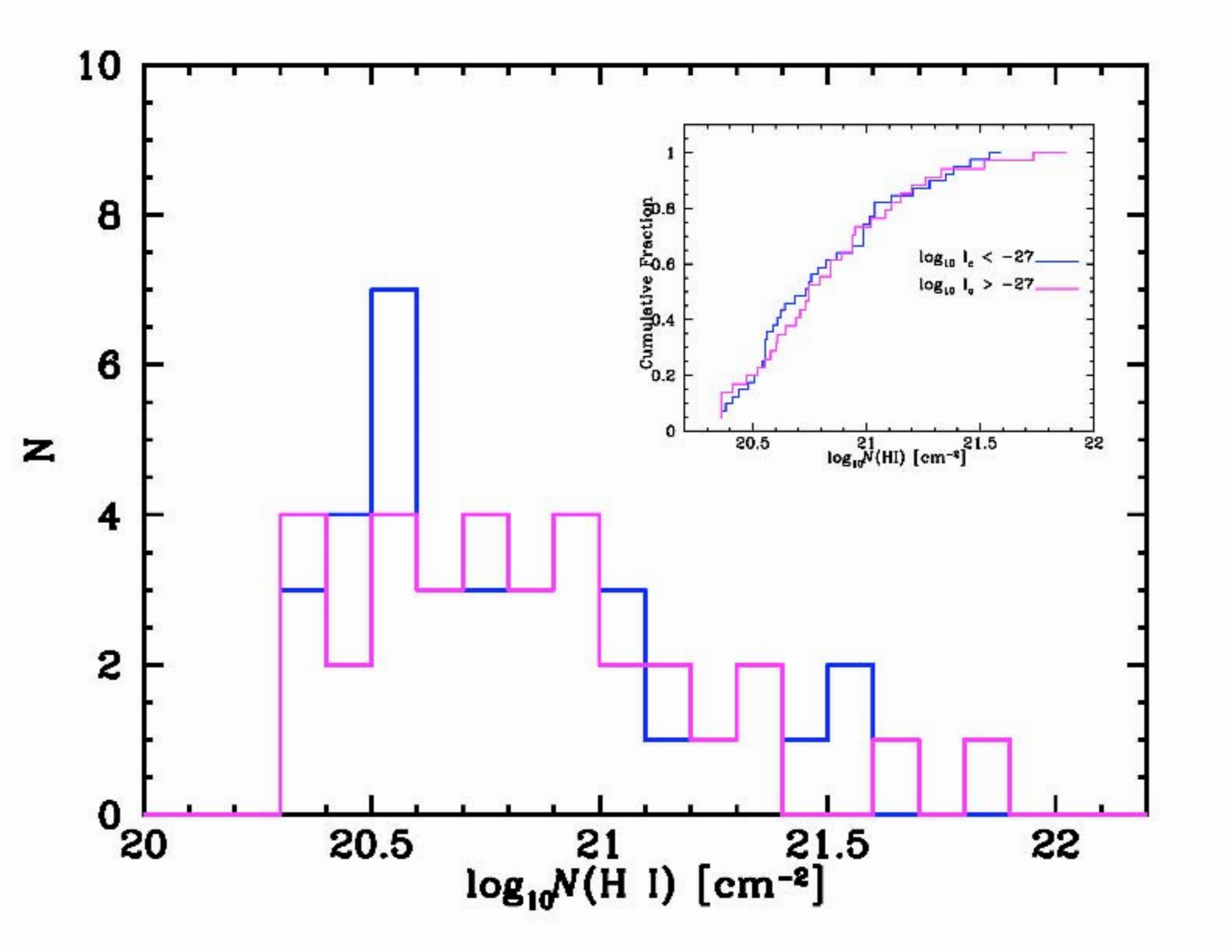
Dust-to-Gas Ratio Distributions



Si II λ 1526 Equivalent Width Distributions



H I Column-Density Distributions

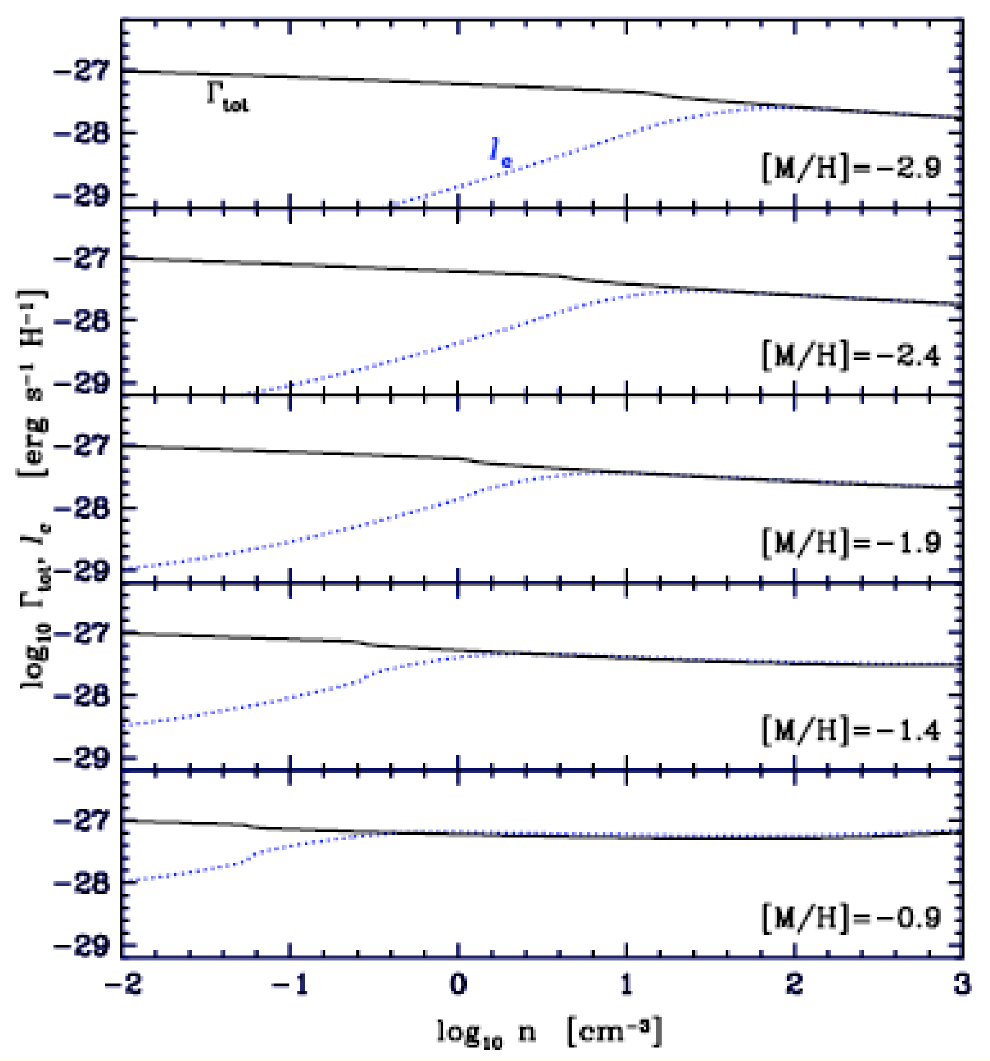


Physical Interpretation of two DLA populations

1. DLAs with $l_c \leq 10^{-27}$ ergs $s^{-1}H^{-1}$

WNM gas heated by X-ray and
FUV Background Radiation

Background Heating and 158 μm Emission rates versus gas density (z=3)



Physical Interpretation of two DLA populations

2. DLAs with $l_c > 10^{-27}$ ergs $s^{-1}H^{-1}$

CNM gas heated by FUV Radiation
Emitted by LBGs embedded in
DLAs

Can *in situ* star formation in DLAs balance cooling in DLAs with $l_c > 10^{-27}$ ergs $s^{-1}H^{-1}$?

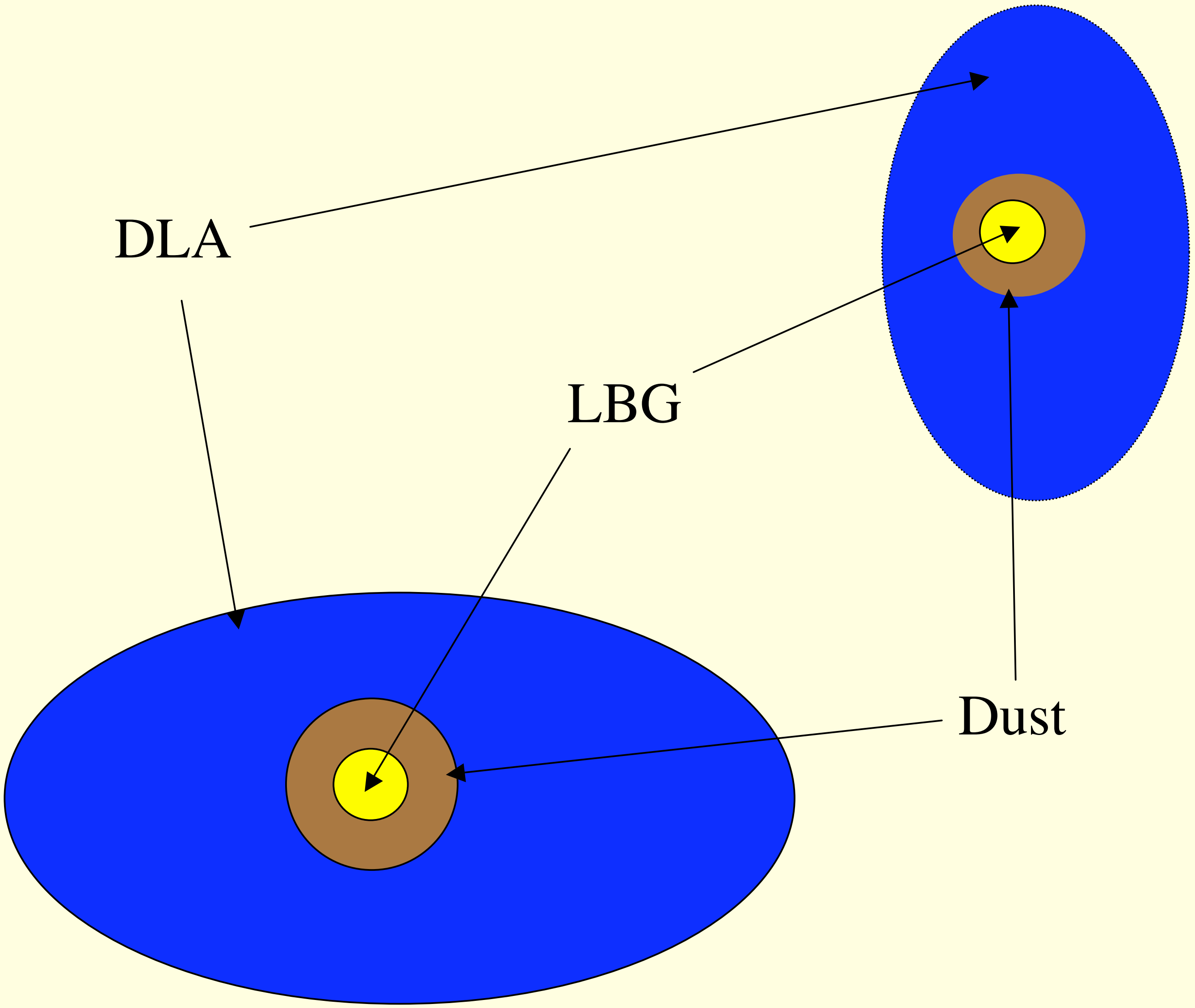
-[C II] 158 μm cooling rate $\mathcal{C}=(2.0\pm0.5)\times10^{38}$ ergs s^{-1} Mpc^{-3}

-Grain photoelectric heating ∝ $d\rho_*/dt$

-Predicted comoving heating rate: $\mathcal{H}_{DLA}<2\times10^{37}$erg s^{-1} Mpc^{-3}

-External energy input required

LBG-DLA Configuration for $l_c > 10^{-27}$ ergs s^{-1} H^{-1}



DLA

LBG

Dust

Solution: Energy and Metal Input from LBGs ($l_c > 10^{-27}$)

-Comoving Heating Rate from attenuated FUV LBG radiation:
$H_{LBG}=(3.0 \pm 1.5)\times 10^{38}$ ergs s^{-1} Mpc^{-3}

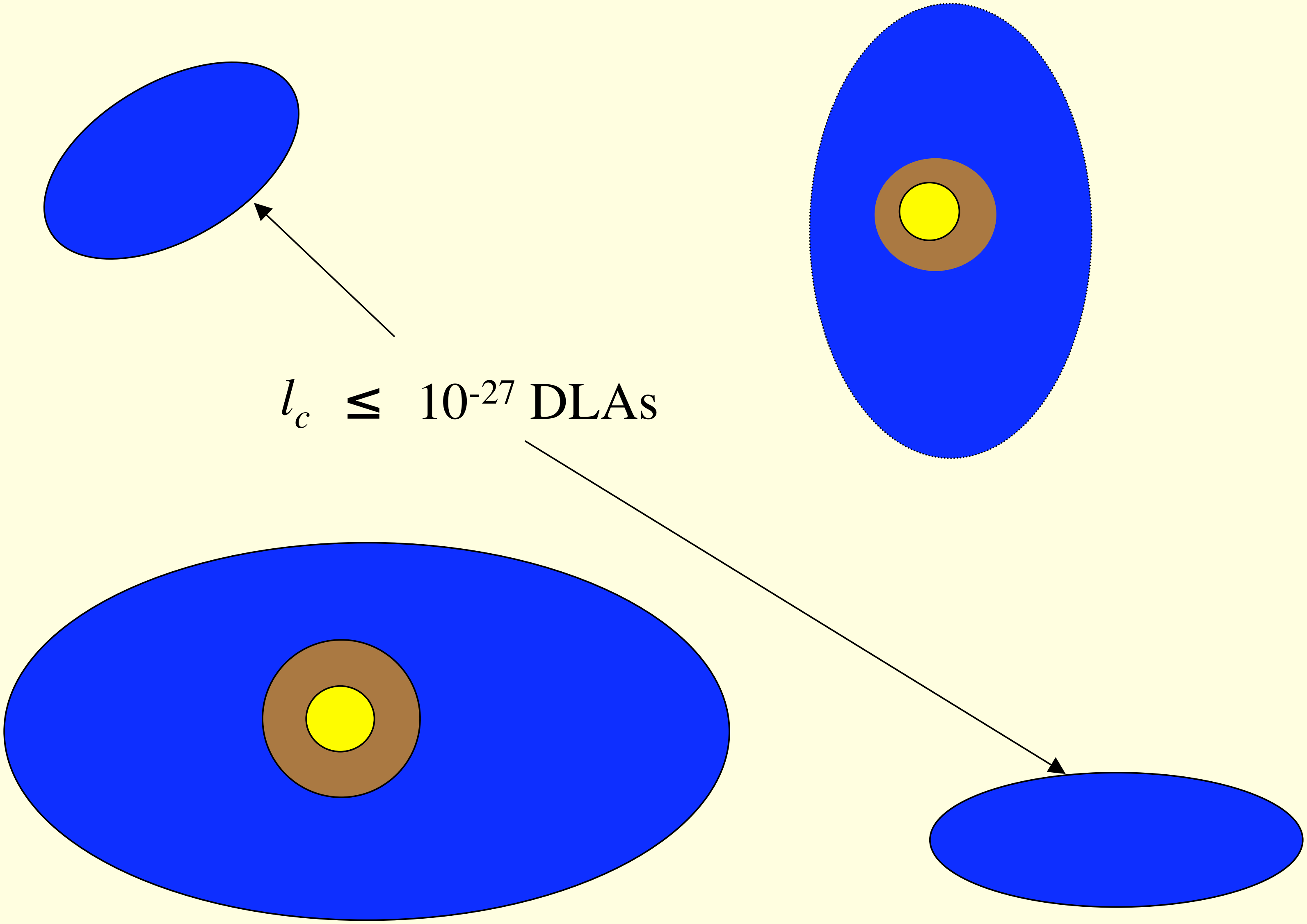
-Metal input due to P-Cygni winds emitted by LBGs a possibility

Solution does not apply to 50% of DLA population

Heated by background radiation alone ($l_c \leq 10^{-27}$)

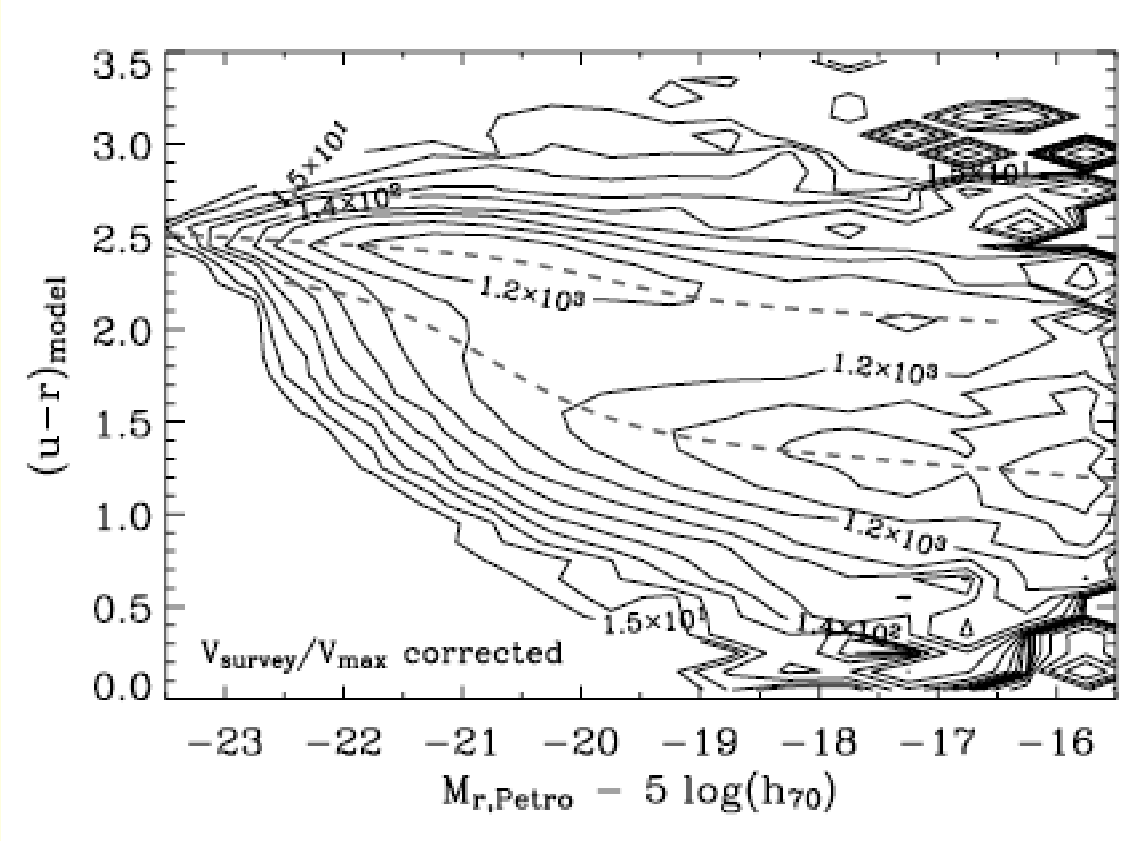
-Embedded LBGs not present in these cases

-Source of metals?

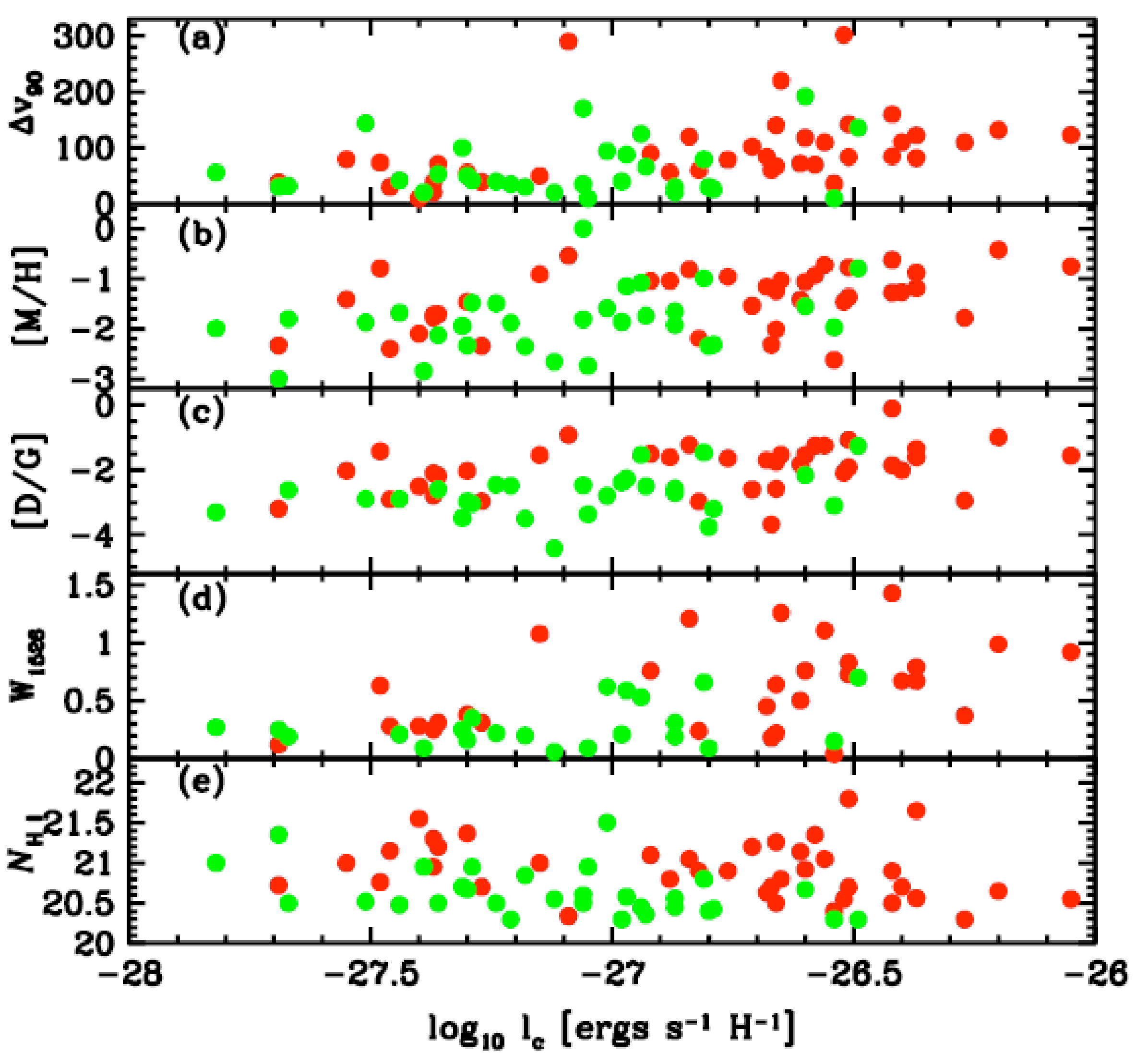


$l_c \leq 10^{-27}$ DLAs

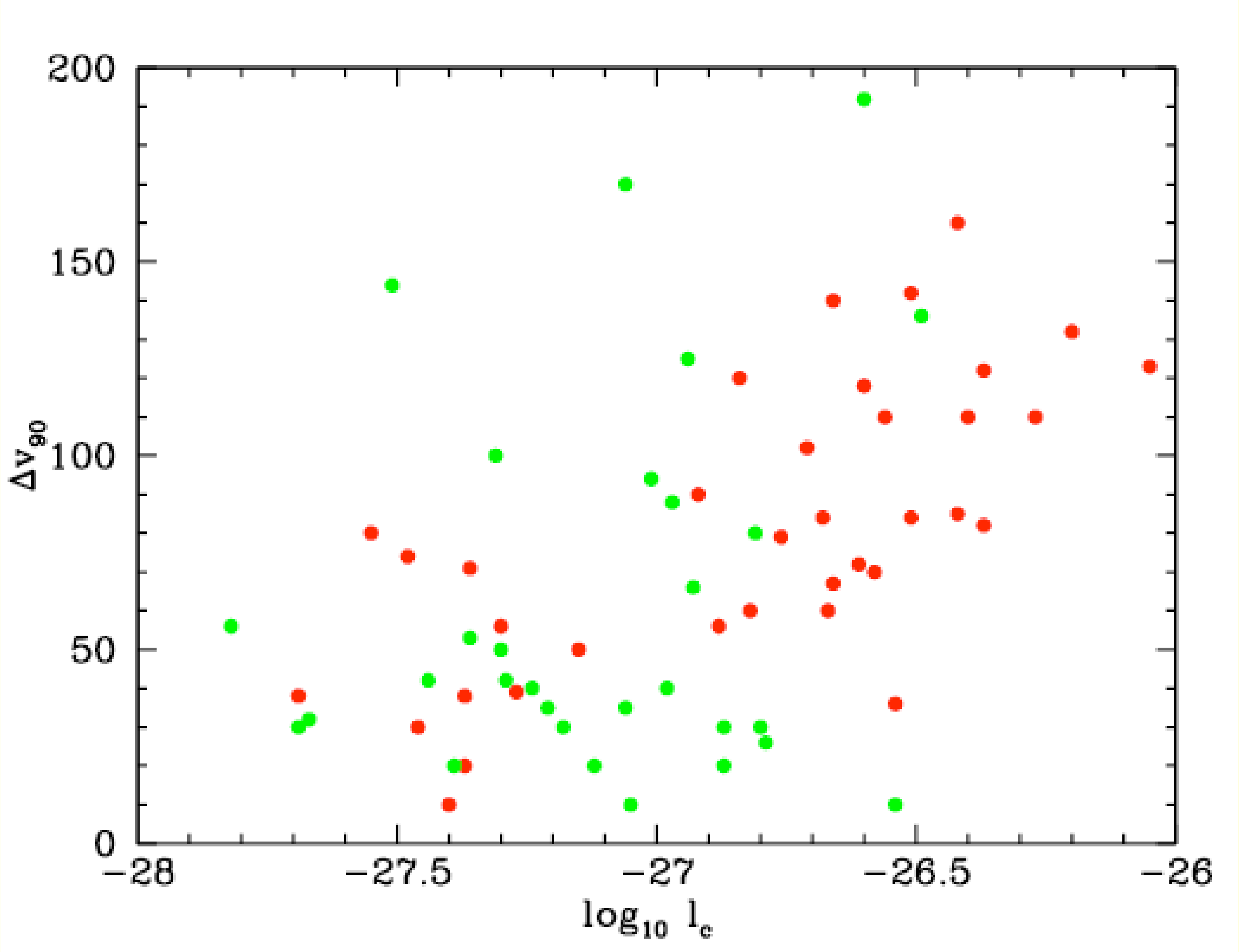
Bivariate Distribution of (u-r,M_r) plane in Nearby Galaxies (Baldry *etal* ‘04)



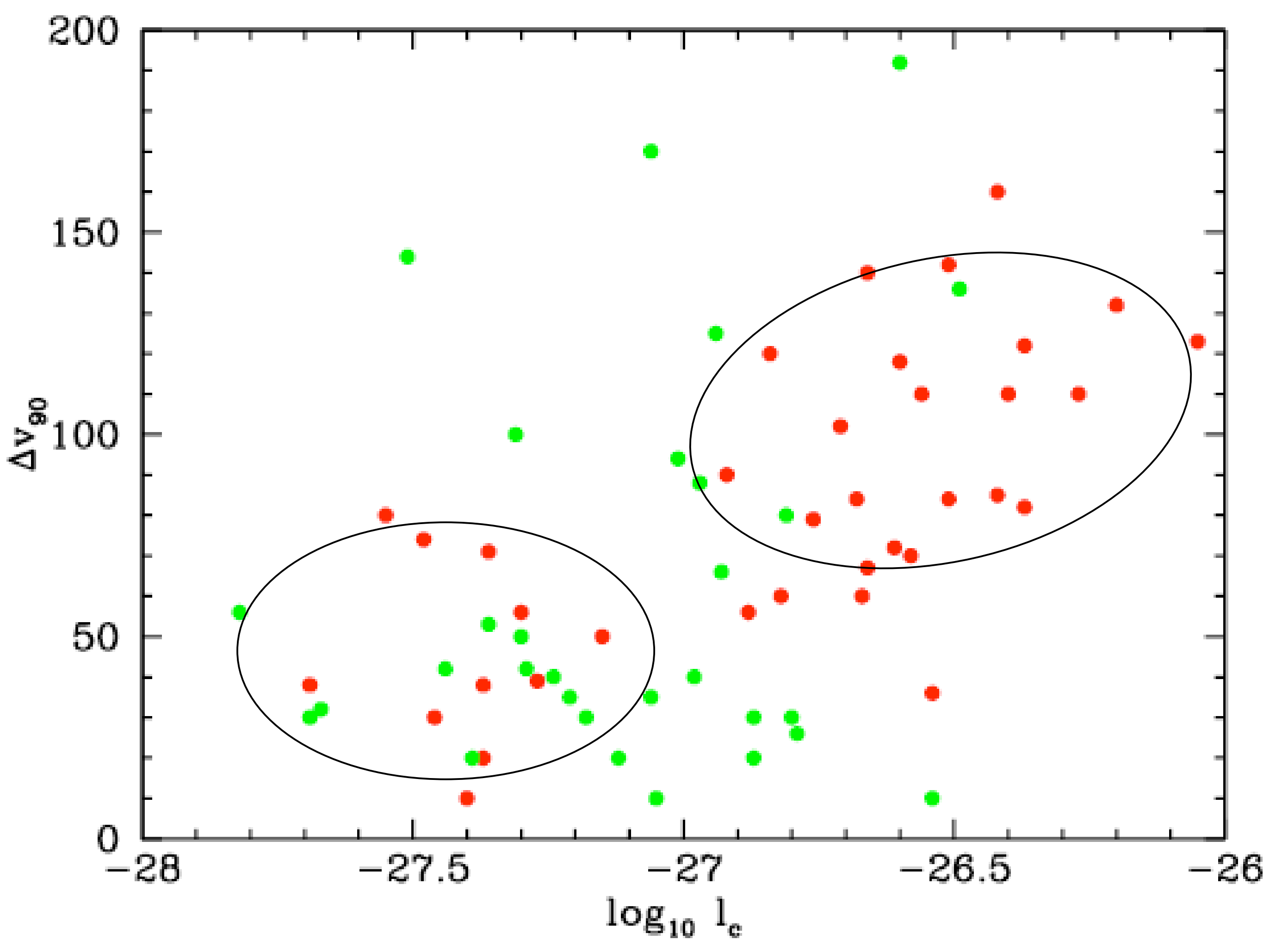
Bivariate Distributions of X versus l_c



Bivariate Distribution in ($\Delta v_{90}, l_c$) Plane in DLAs



Bivariate Distribution in ($\Delta v_{90}, l_c$) Plane in DLAs



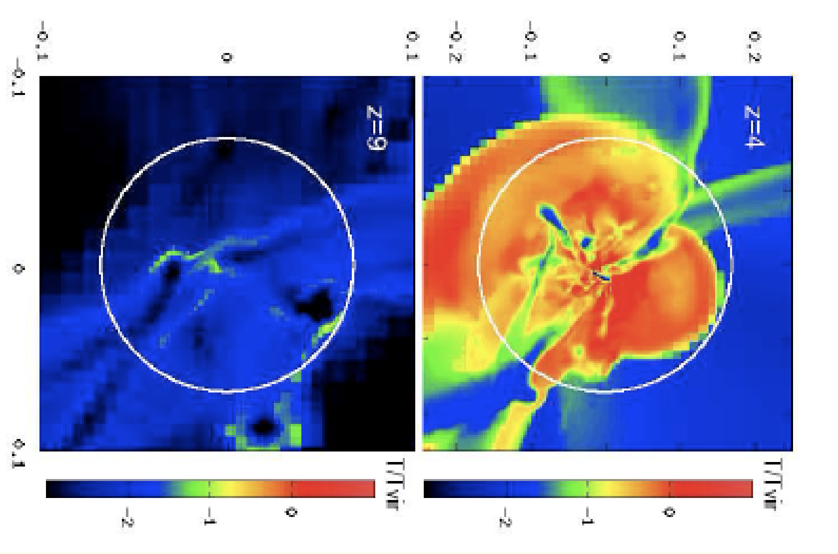
Is l_c a mass indicator?

low l_c	high l_c
$\Delta v = 40$ km s^{-1}	$\Delta v = 91$ km s^{-1}
$[M/H] = -1.81$	$[M/H] = -1.19$
$N_{HI} = 10^{20.7}$ cm^{-2}	$N_{HI} = 10^{20.7}$ cm^{-2}

Predicted $l_c \propto$

$(M/H)\langle n \rangle$	$(M/H) J_\nu$

Origin of Bimodality



Two Modes of DLA Formation (Dekel *etal* ‘05)

1. $M_{\rm DM} > 10^{11.5} M_\odot$: Hot mode, spherical accretion leads to star-forming bulge .

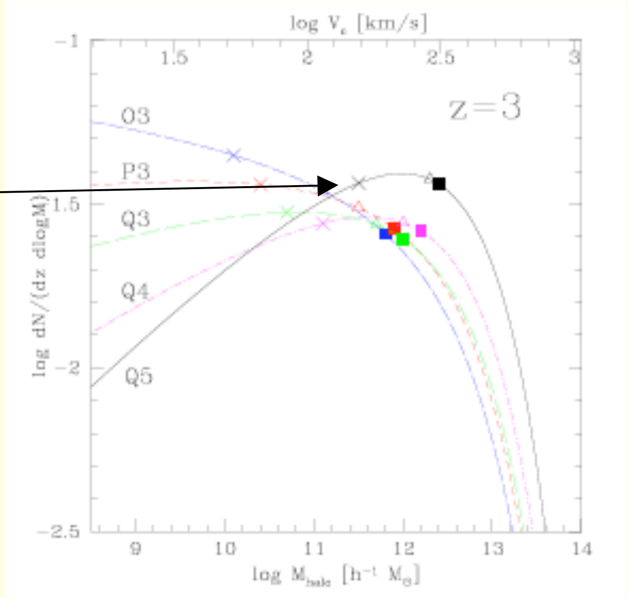
   --Neutral DLA gas accreted along filaments
   --Result is LBG-DLA configuration with high l_c

2. $M_{\rm DM} \leq 10^{11.5} M_\odot$: Cold mode accretion leads to neutral ‘disk’ formation

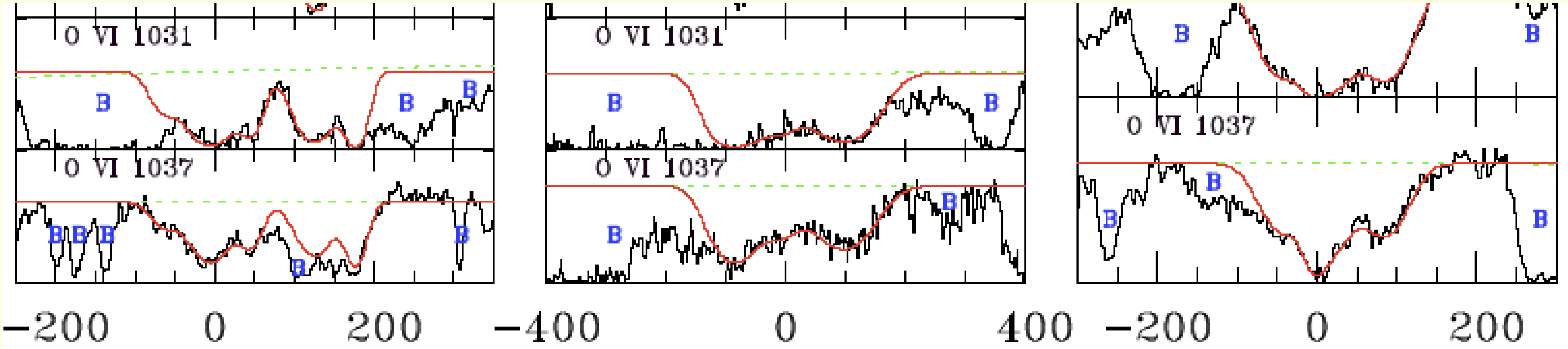
   --Result is pure DLA configuration with low l_c
   --UDF data require low SFRs in DLA gas

Origin of Bimodality (cont.)

- Fraction of DLAs with $M_{\rm DM}>10^{11.5}\,M_\odot$ can be large (Nagamine *etal* ‘07)



- Presence of hot gas (T>3x10^5K) inferred from OVI absorption in > 20 % of DLAs (Fox *etal* ‘07)



Summary: Star Formation in Neutral Gas at High z

- Star formation not distributed throughout neutral gas. Rather it is restricted to bright cores: $R_{gas}/R_{*} \approx 10$

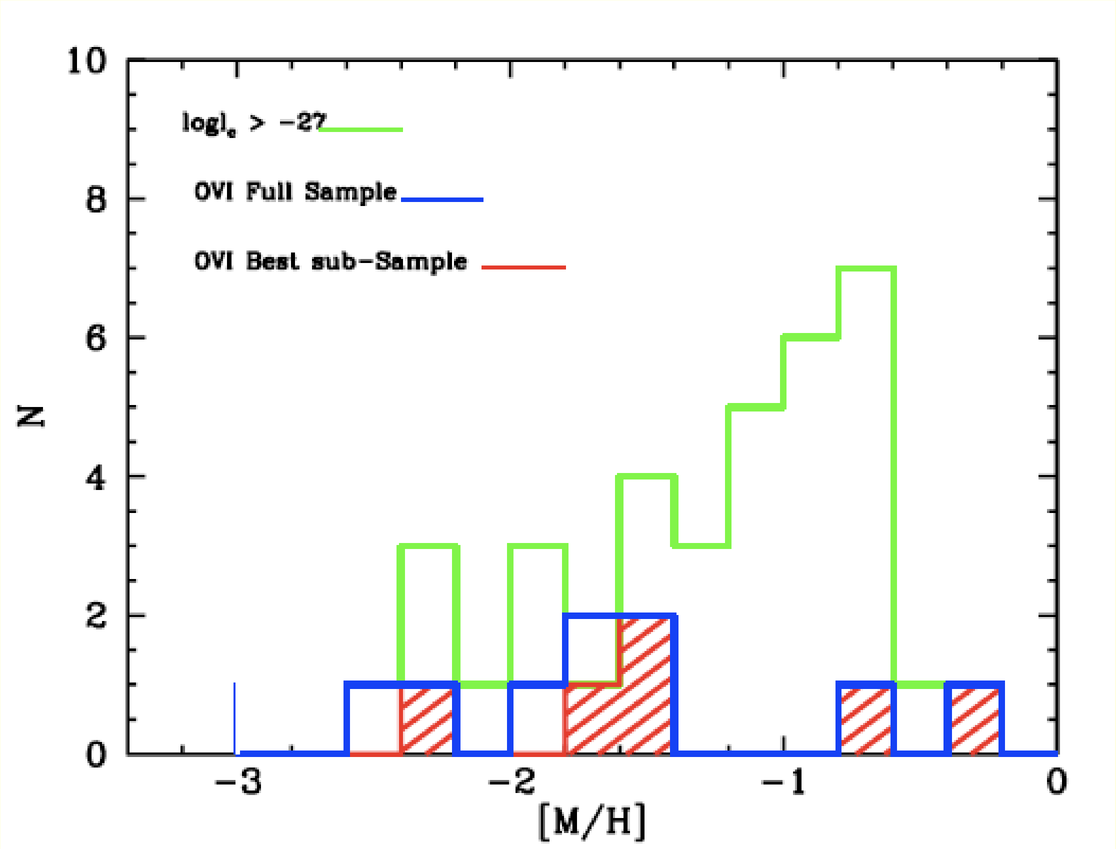
- Bimodality in Damped Lyα Systems
  - --Evidence from two peaks in l_c distribution divided by l_c^{crit}
  - --Support from disjoint Δv_{90}, [M/H], [D/G], W_{1526} distributions

- Interpretation
  - --DLAs with $l_c \leq l_c^{crit}$: WNM gas in low-mass halos heated by X-ray and FUV backgrounds.
  - --DLAs with $l_c > l_c^{crit}$: CNM gas in high-mass halos heated by central ‘bulge’ sources (LBGs).

- Connection to Bimodality in Galaxies
  - --Δv_{90} , [M/H], etc. correlated with l_c
  - -- l_c may be a mass indicator
  - --OVI absorption may may arise in hot gas in massive halos
- Neutral gas in DLAs may fuel star formation in central LBGs

Test: Metallicity Distribution of DLAs with OVI should Resemble that of high l_c DLAs

Results: inconclusive, but consistent with bimodality

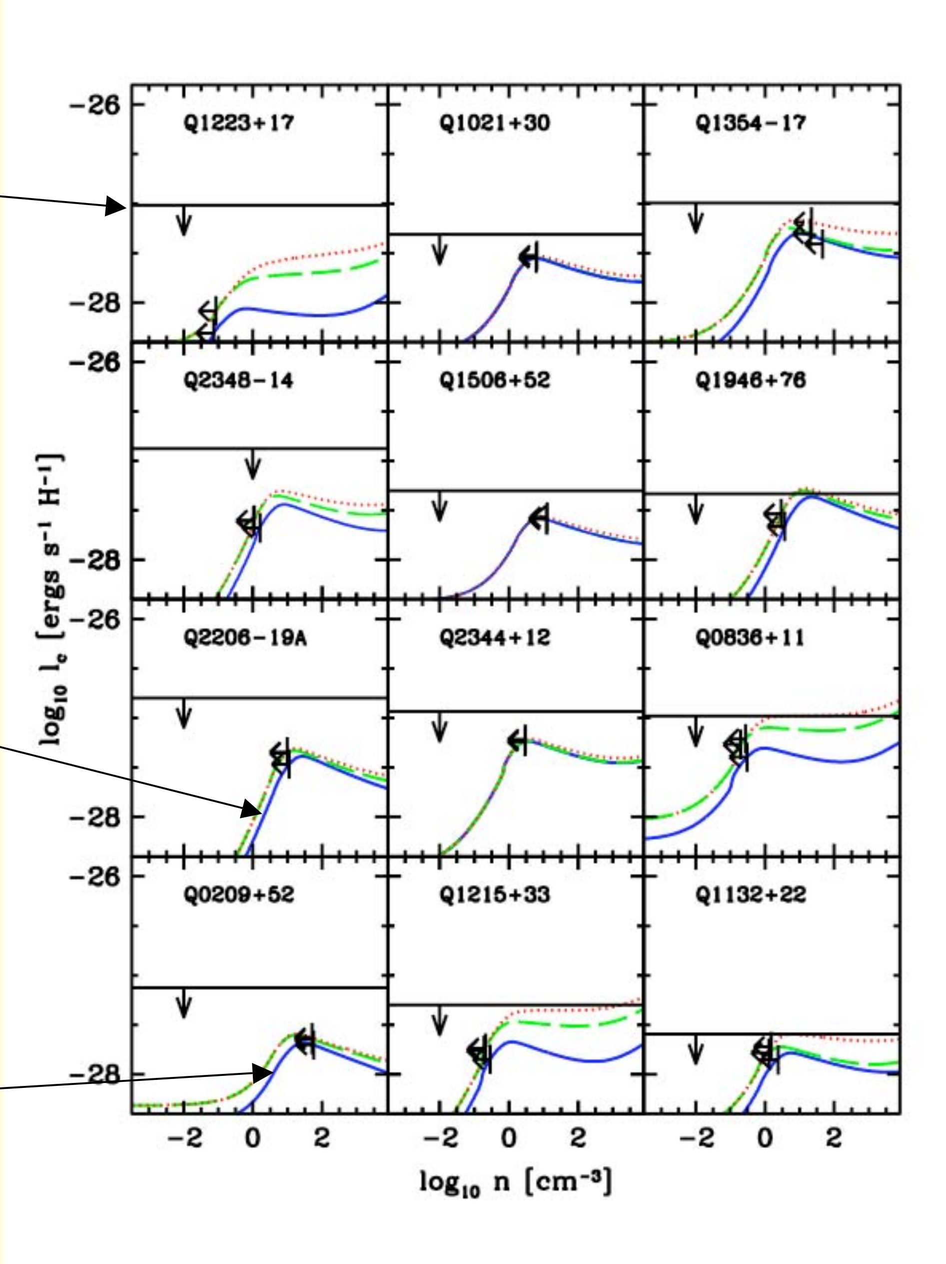


l_c versus n for background heating

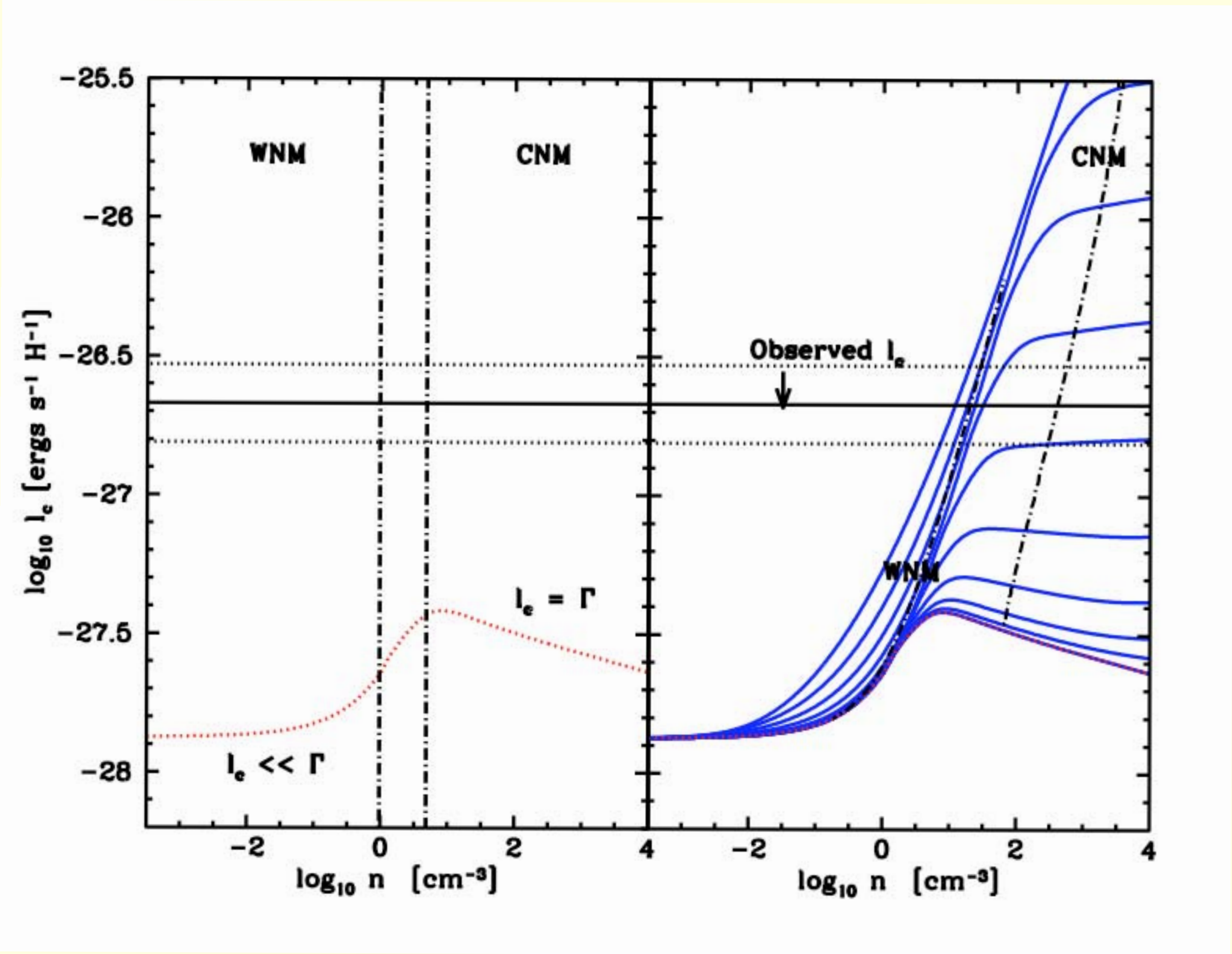
Empirical Upper Limits
on l_c

158 µm emission rate predicted
for gas heated by X-ray and
FUV background radiation

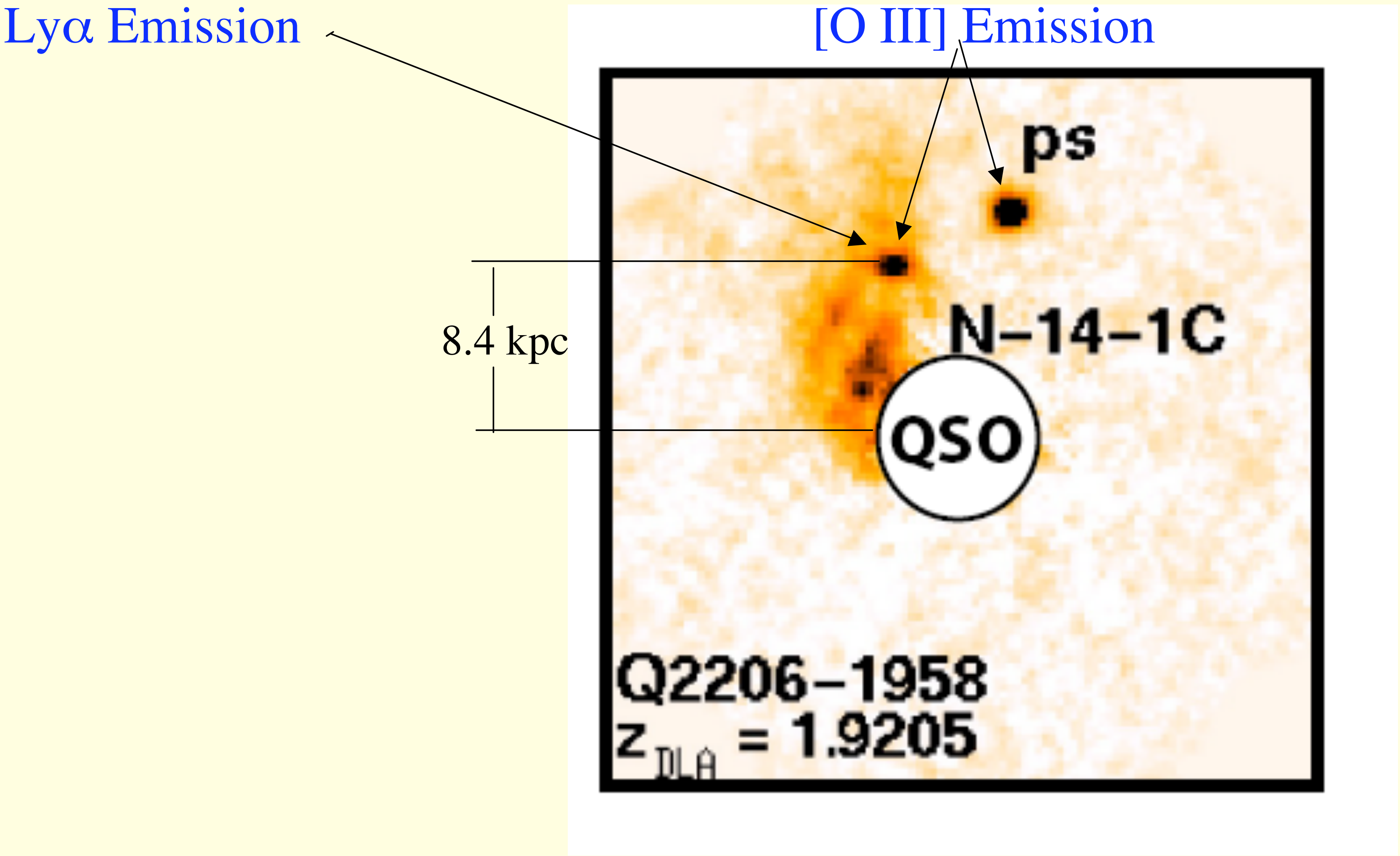
True l_c intersect background curves
In low density WNM



Effect of local heat sources on l_c versus n curves



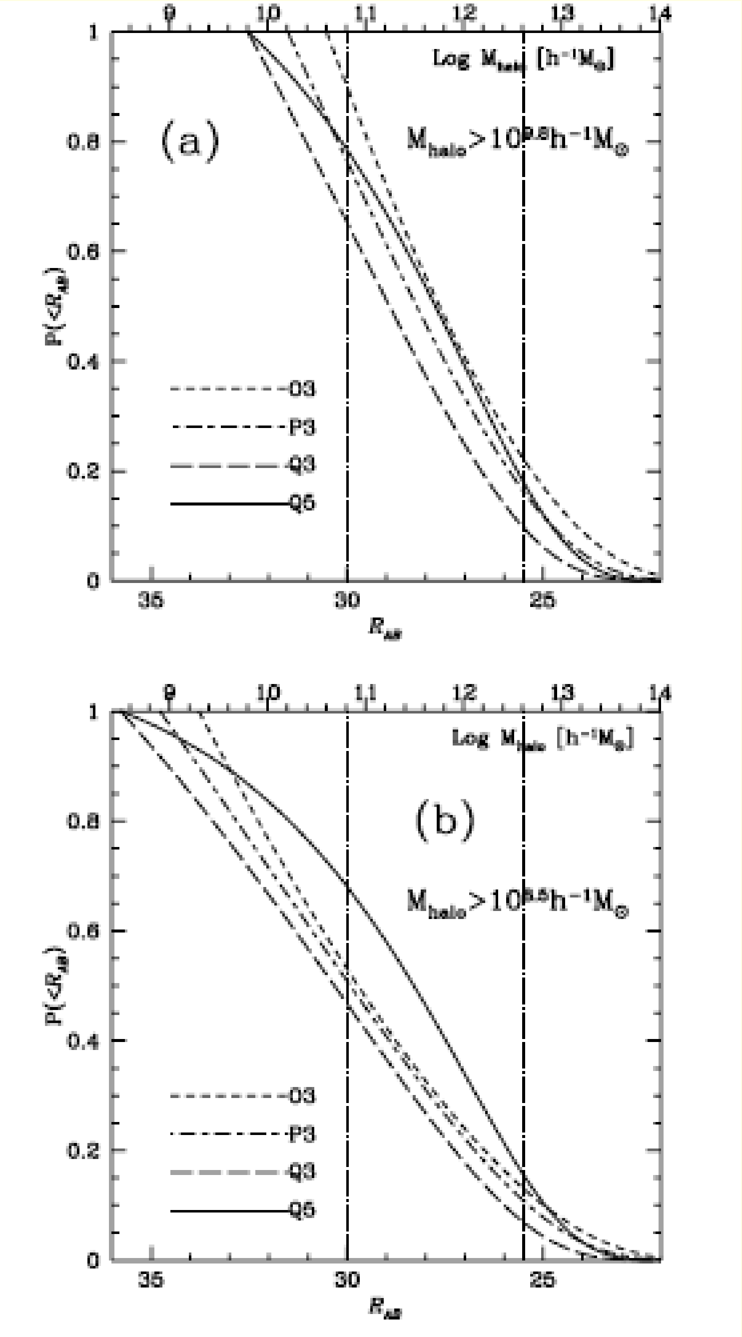
An LBG associated with a DLA (Moller *etal* '02)



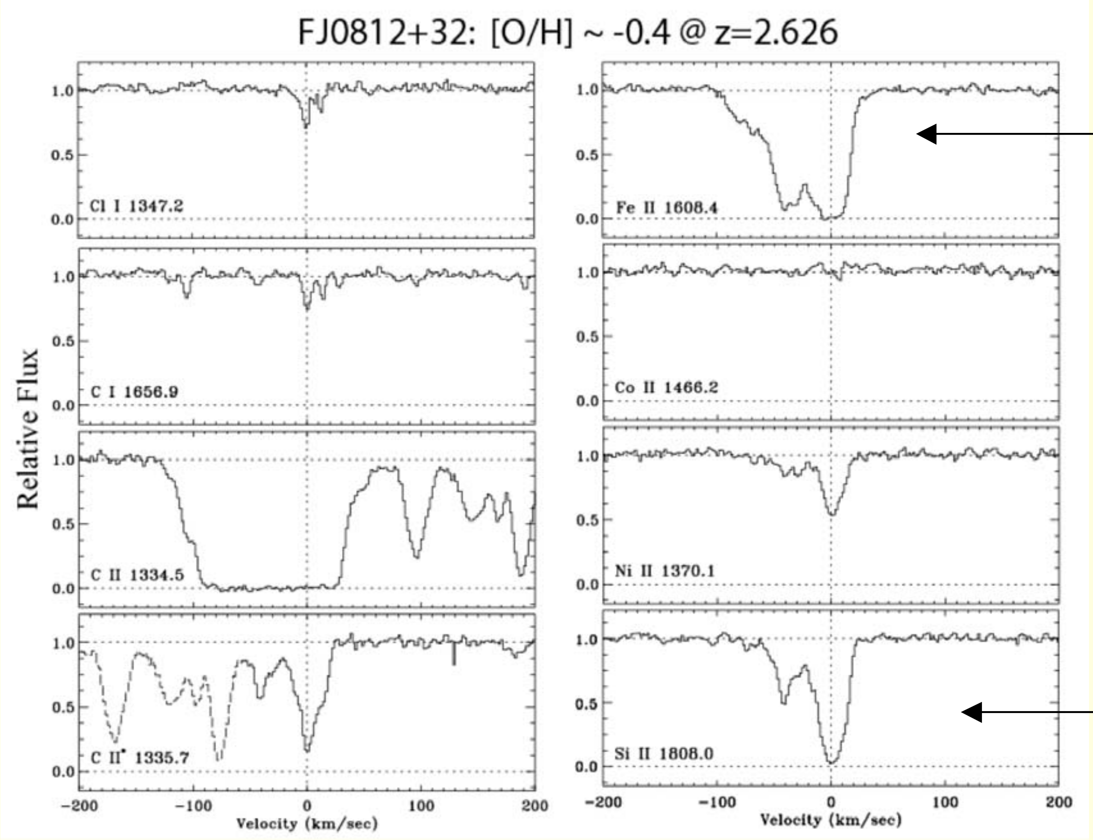
Predicted magnitude distribution for DLAs at z=3

$M_{cut}=10^{9.8}M_\odot$

$M_{cut}=10^{8.5}M_\odot$



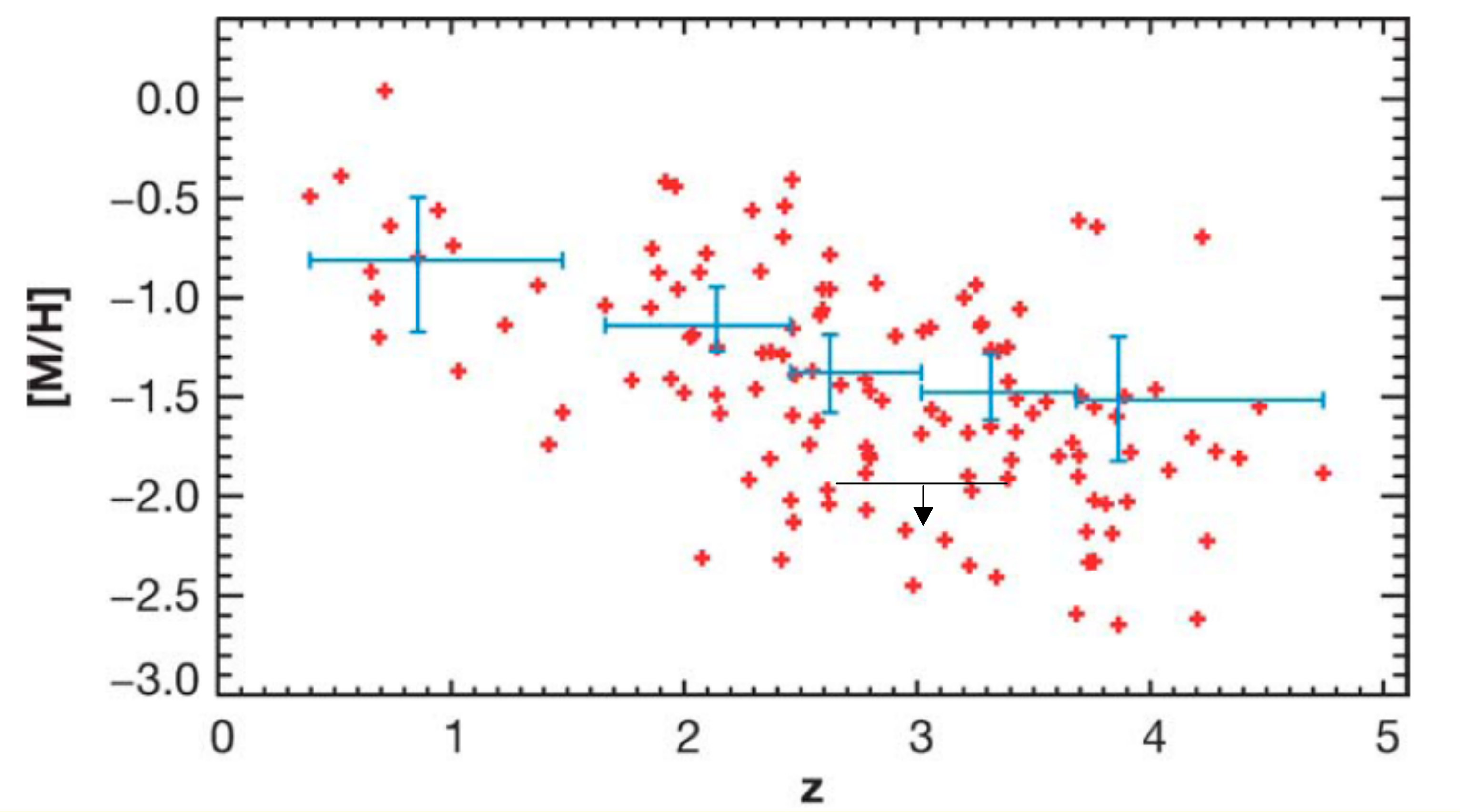
Metal Column Densities from HIRES profiles



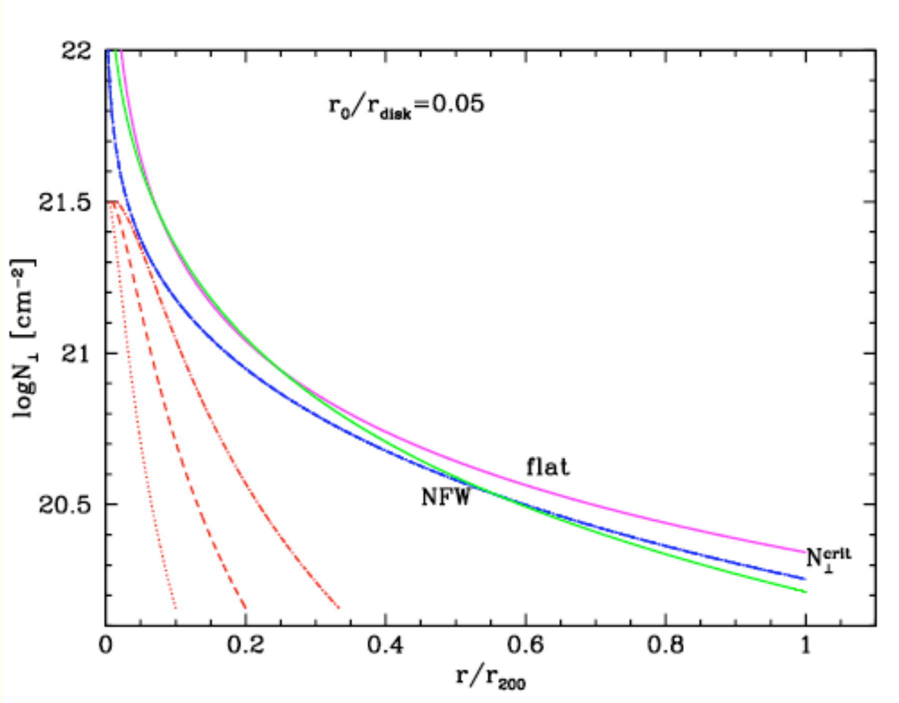
Depletion Indicator

Metallicity Indicator

Comparison between predicted and observed metal abundance



(3) Critical Surface Density larger at high *z*



- $N^{\mathrm{crit}}_{\perp} \propto \kappa\sigma$
- $\kappa \propto (G\rho)^{1/2}$ (epicyclic freq.)
- $N^{\mathrm{crit}}_{\perp} \propto (1+z)^{3/2}$
- Neutral Gas Subcritical

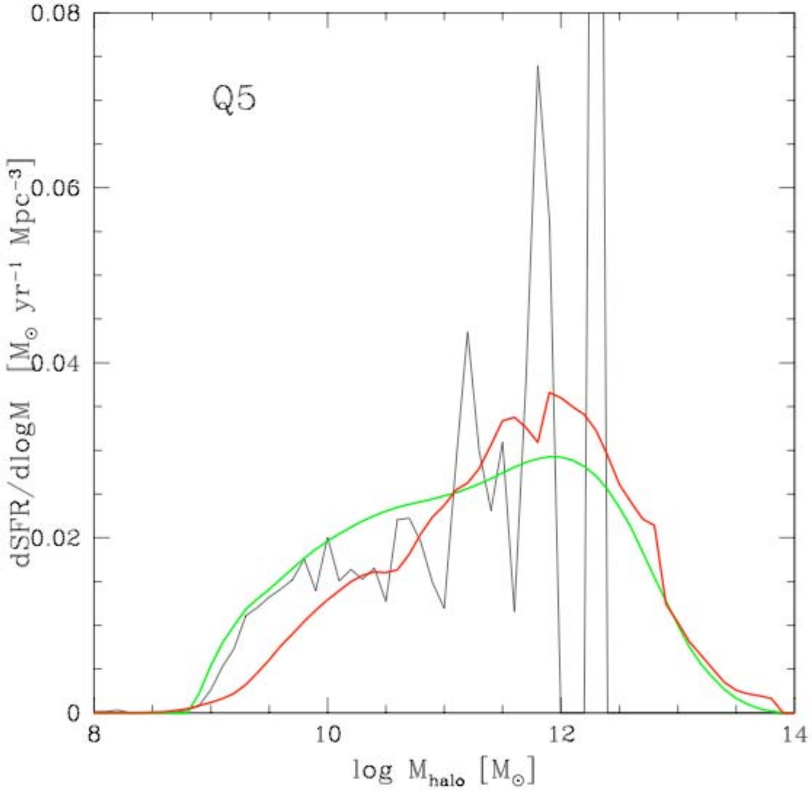
Halo Mass Distribution of Comoving SFR Density

- Correlation between disk size and M_{halo}

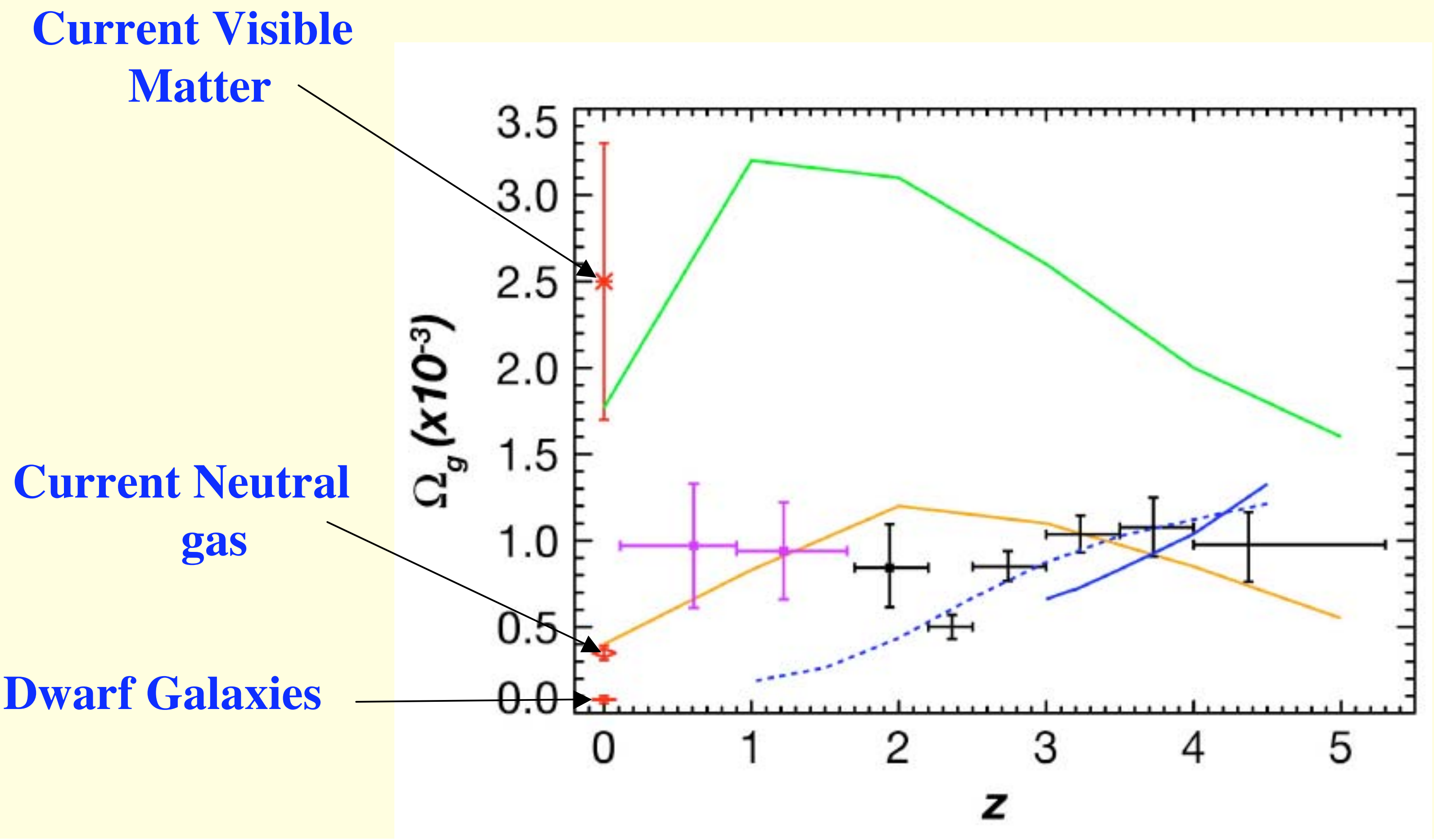
  $\theta_{dla} \approx (1'')(M_{halo}/10^{11} M_{\odot})^{1/3}$

- Kernel angular bandwidth $\theta_{dla} \approx (0.5 \rightarrow 1.5)\theta_{kern}$

- Kernel with $\theta_{kern} = 2''$ sensitive to halos with $M_{halo} = (10^{11.5} \rightarrow 10^{12.5}) M_{\odot}$ which contribute ≈ 40% of total SFR density



Comoving Density of Neutral Gas versus Redshift

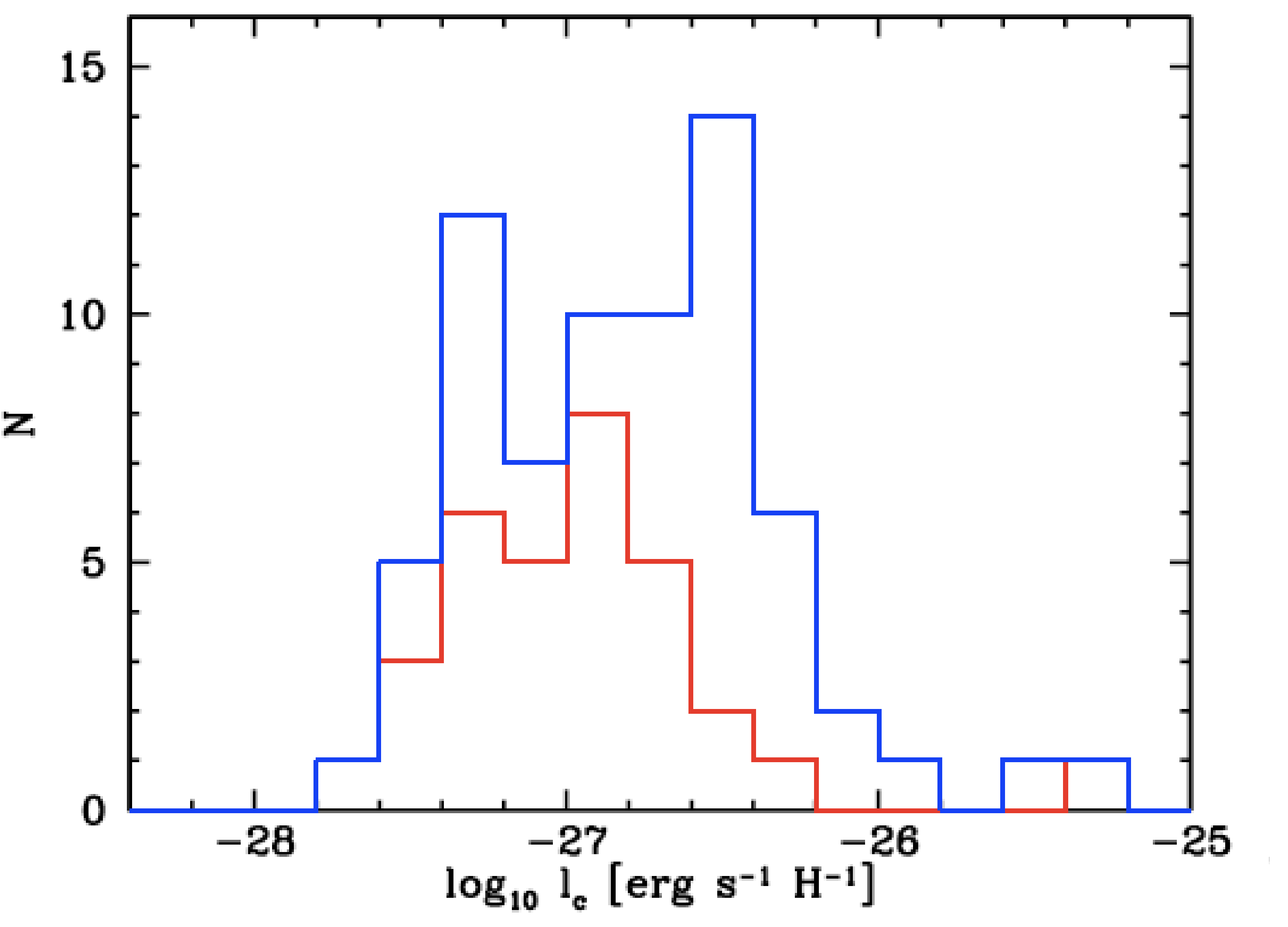


Current Visible Matter

Current Neutral gas

Dwarf Galaxies

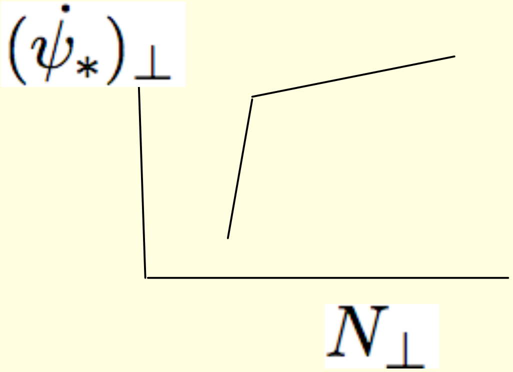
Frequency Distribution of 158 μm Cooling Rates in DLAs



Star Formation in DLAs ?

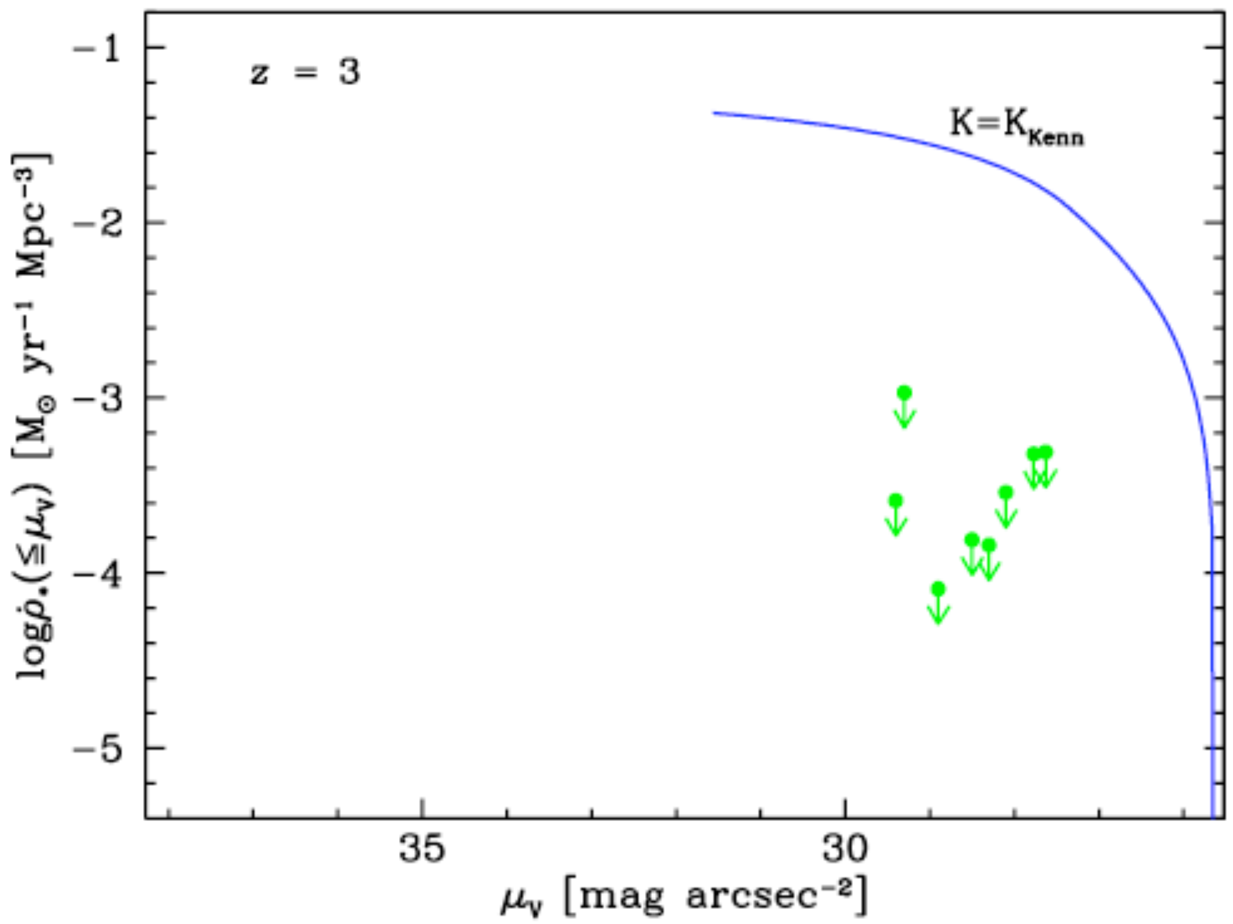
- Do DLAs undergo *in situ* star formation ?
- If DLAs undergo *in situ* star formation, how does the comoving SFR density compare to that of LBGs?
- Or is star formation at high z confined only to compact objects like LBGs?
- In that case, what is the relationship between LBGs and DLAs? Are DLAs the neutral-gas reservoirs for star formation in LBGs?

Connection between Gas and Stars; Kennicutt-Schmidt Law

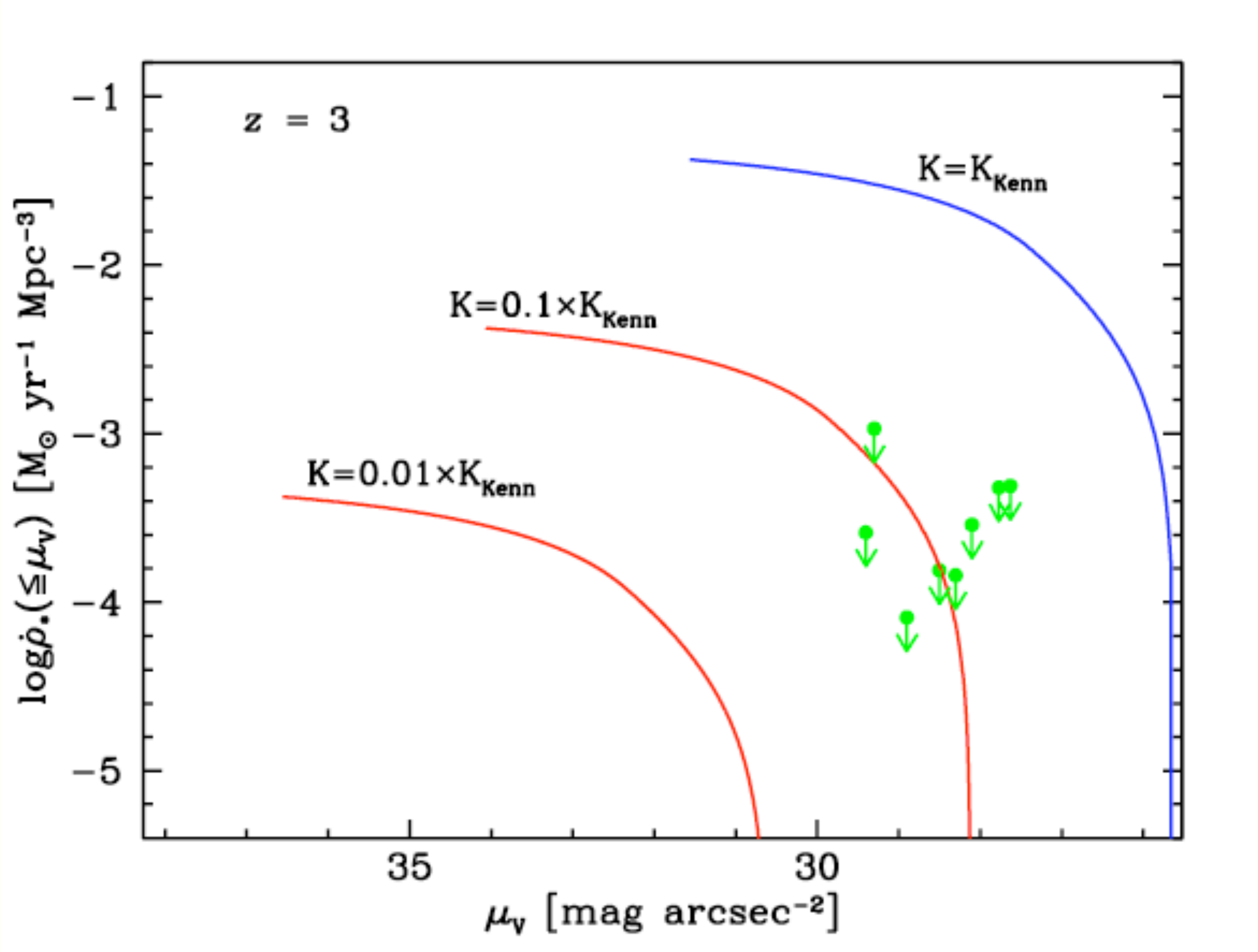


$$(\dot{\psi}_*)_\perp = \begin{cases} 0\ ; N_\perp < N_\perp^{crit} \\ K \times [N_\perp / N_c]^\beta\ ; N_\perp \geq N_\perp^{crit}, \end{cases}$$

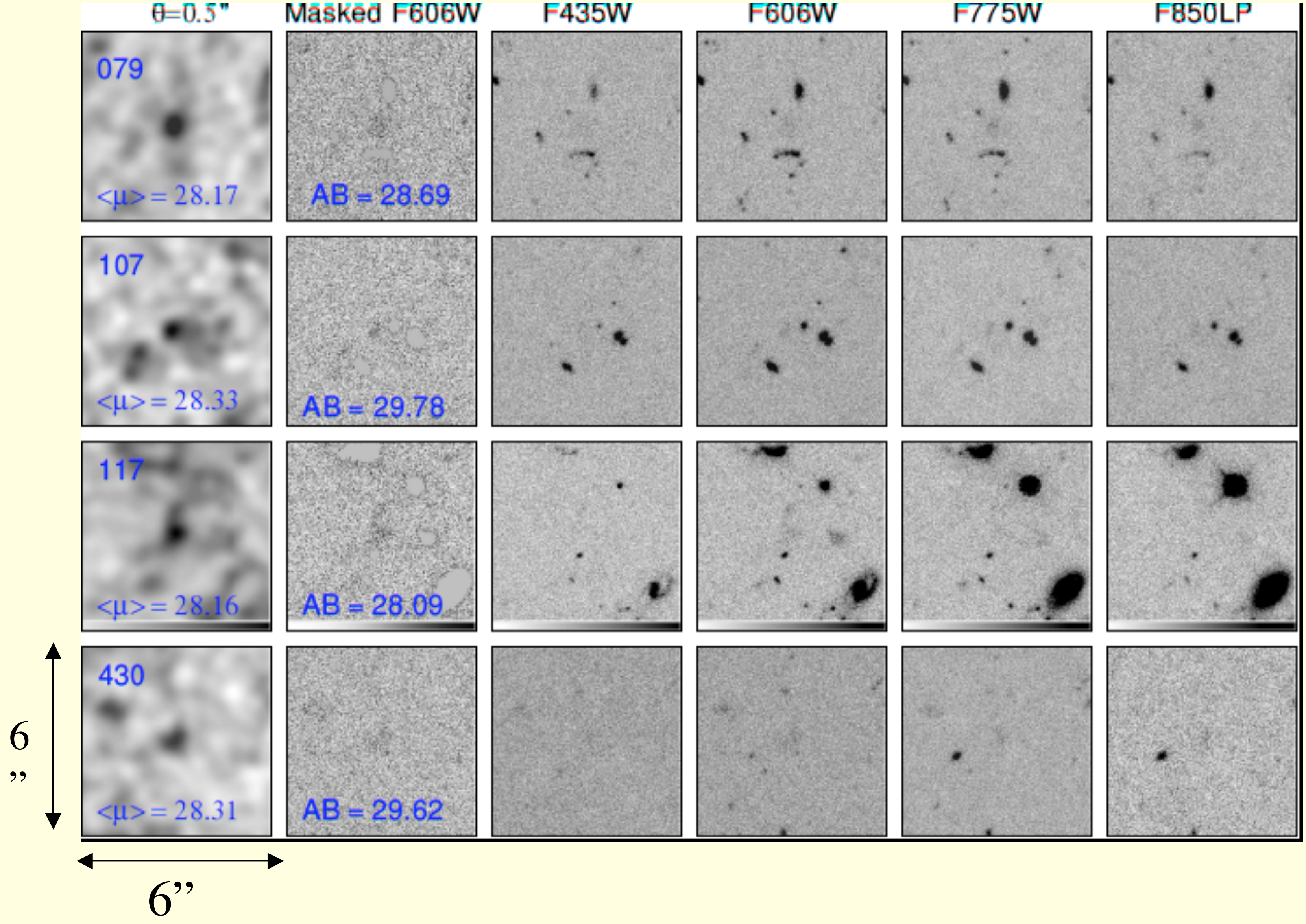
$$\dot{\rho}_*(> N) = (H_0/c) \int_N^{N_{max}} dN' f(N', X) \dot{\psi}_*(N')$$

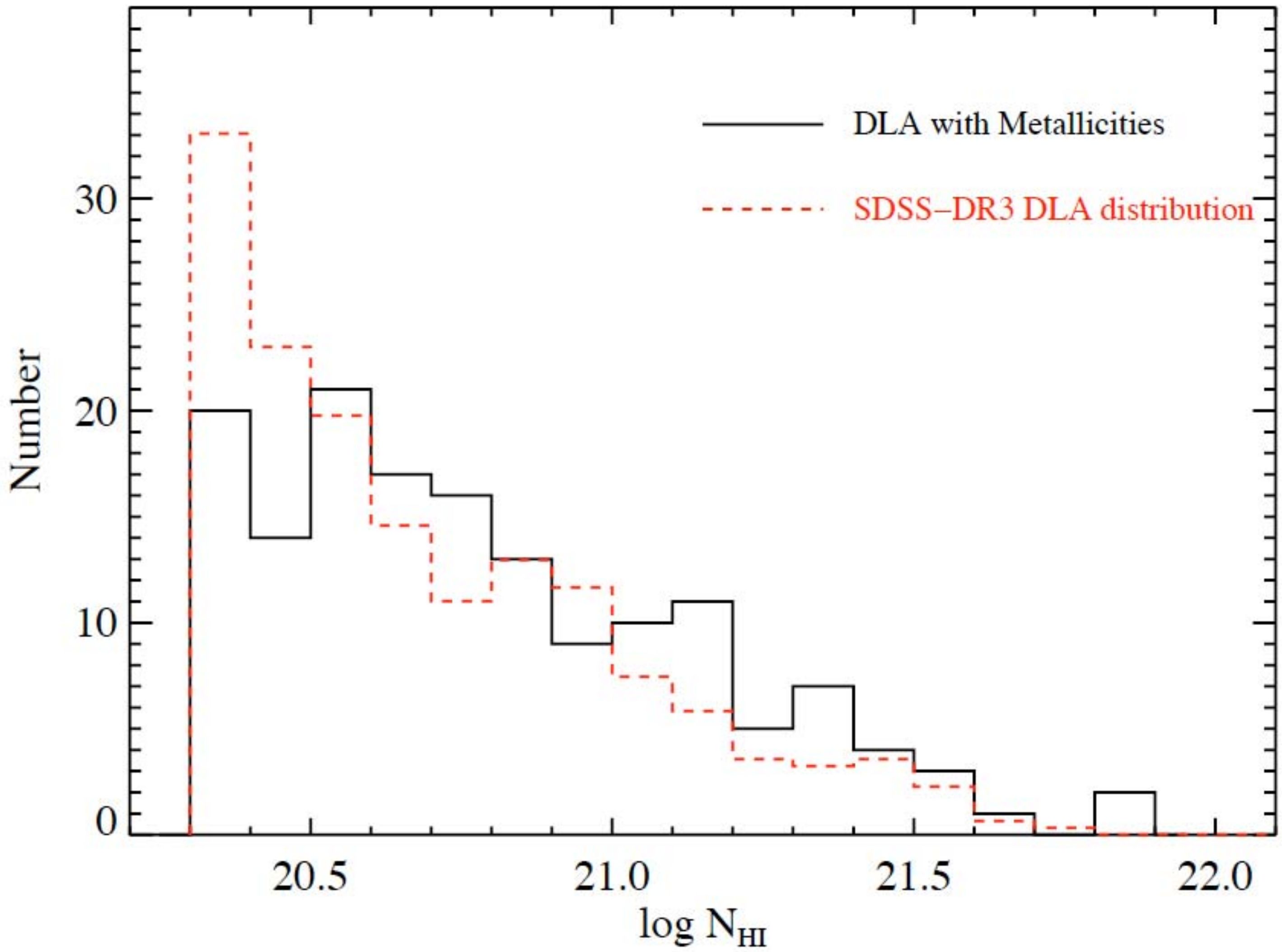


Lower SFR Efficiencies: Effect of Decreasing Normalization K

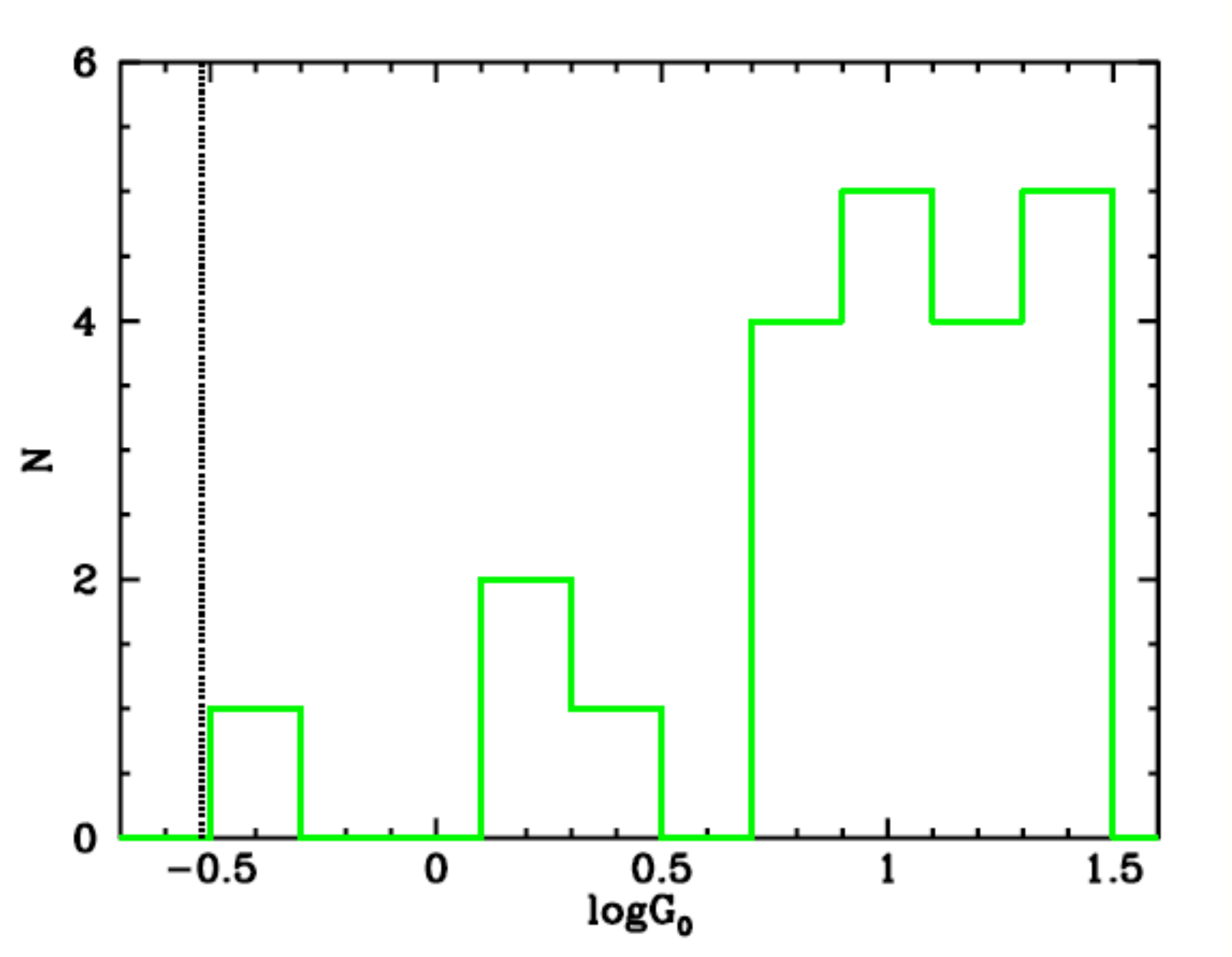


Objects detected in HUDF for θ_{kern}=0.5 arcsec



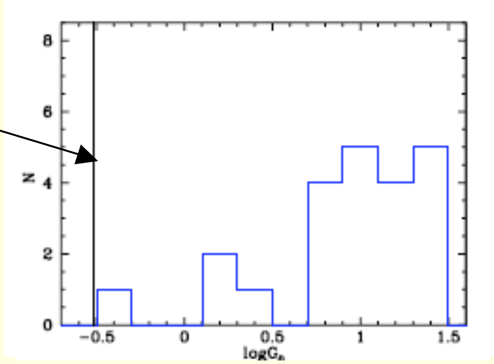

DLA with Metallicities
SDSS−DR3 DLA distribution
Number
log N_{HI}
0
10
20
30
20.5
21.0
21.5
22.0

J_ν distribution inferred for $l_c > 10^{-27}$ population

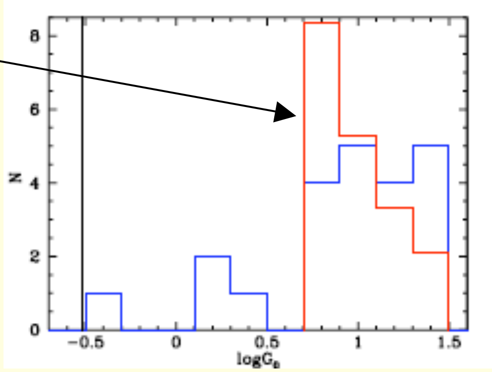


Challenges

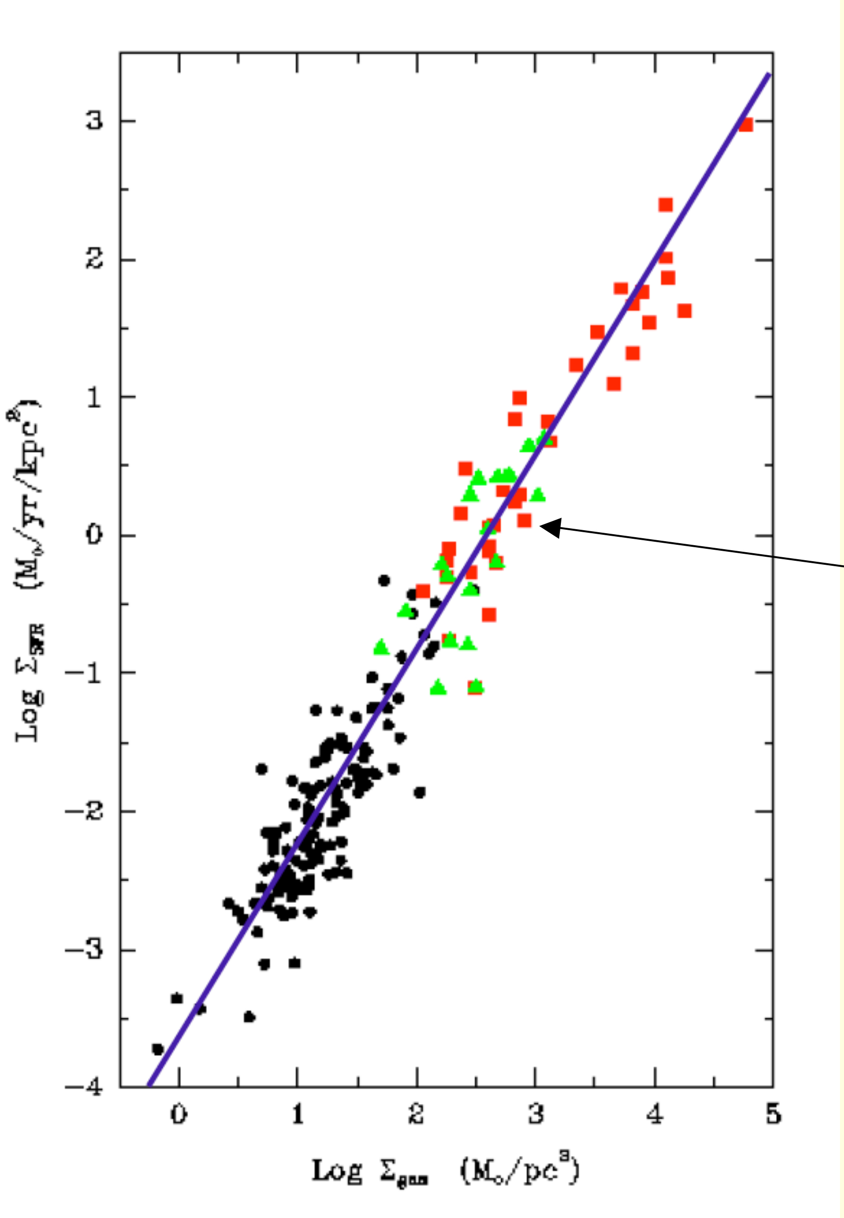
- DLA halo mass distribution continuous
- Lack of emission below $20J_\nu^{bkd}$
- Distribution of J_ν predicted for centrally located LBGs
- But relation between local and bkd. implies $\langle J_\nu \rangle \sim 10J_\nu^{bkd}$



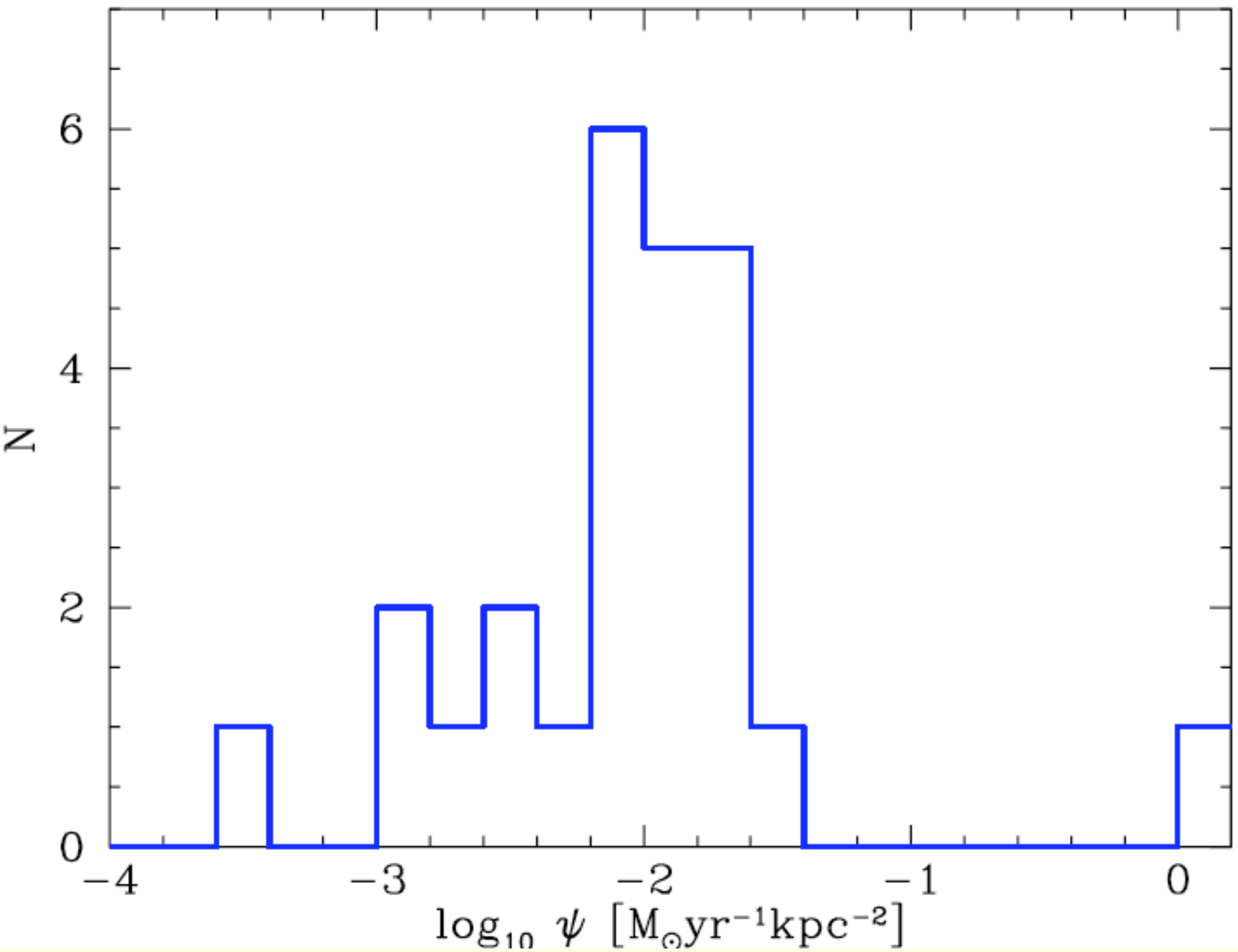
Background



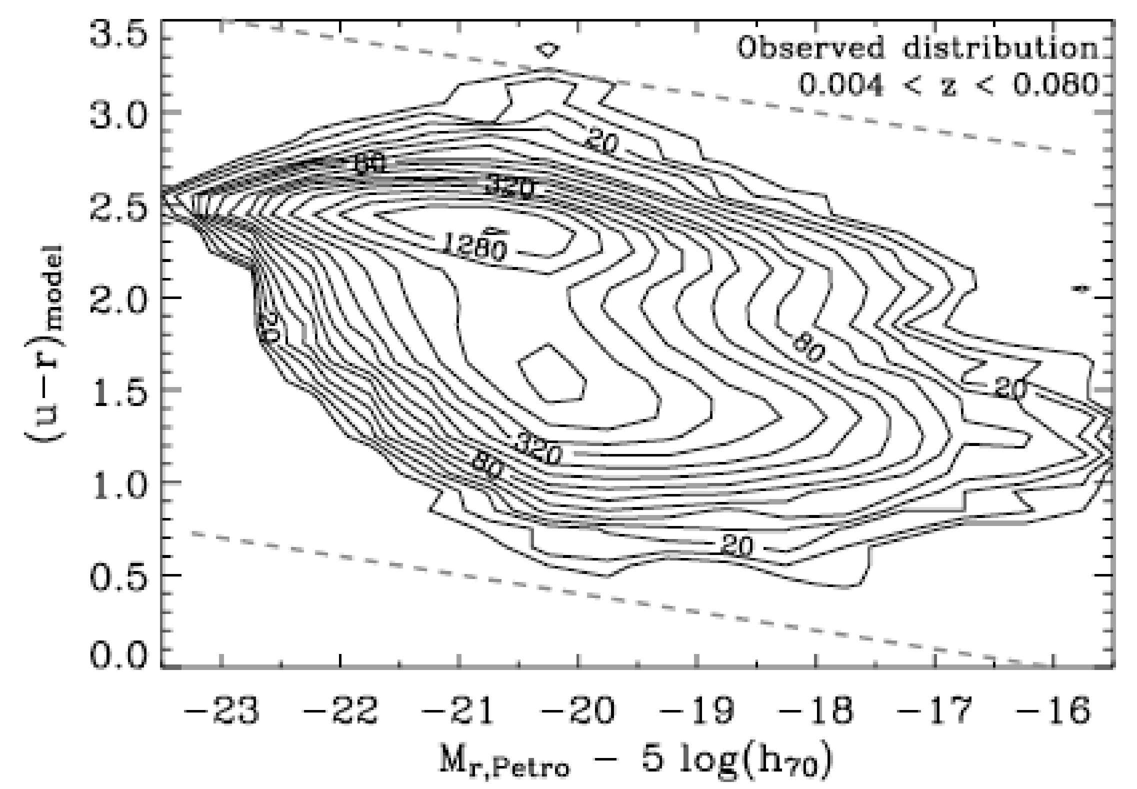
Kennicutt-Schmidt Law for Galaxies



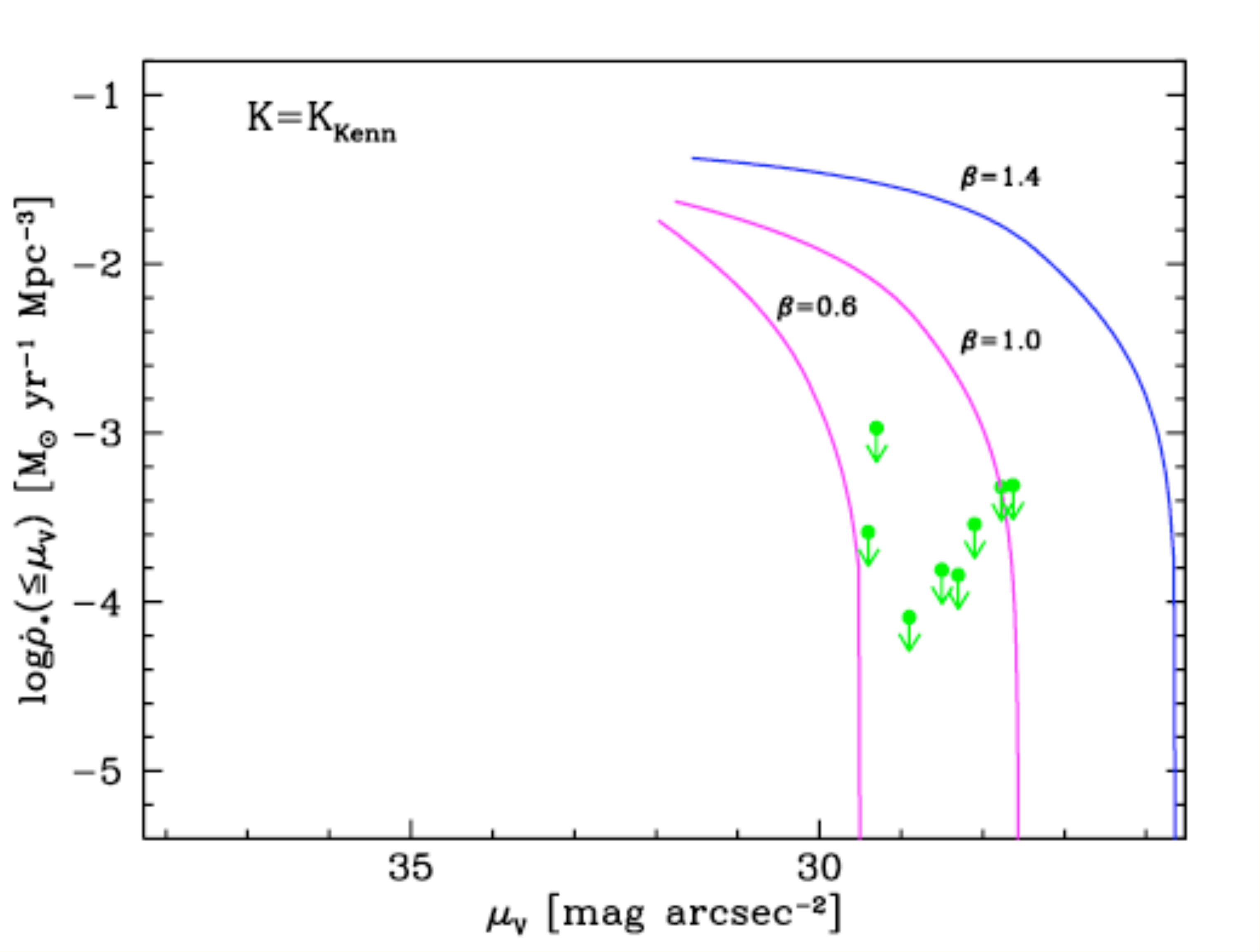
Individual Galaxy


N
0
2
4
6
−4
−3
−2
−1
0
$\log_{10}\,\psi\ [M_\odot yr^{-1} kpc^{-2}]$

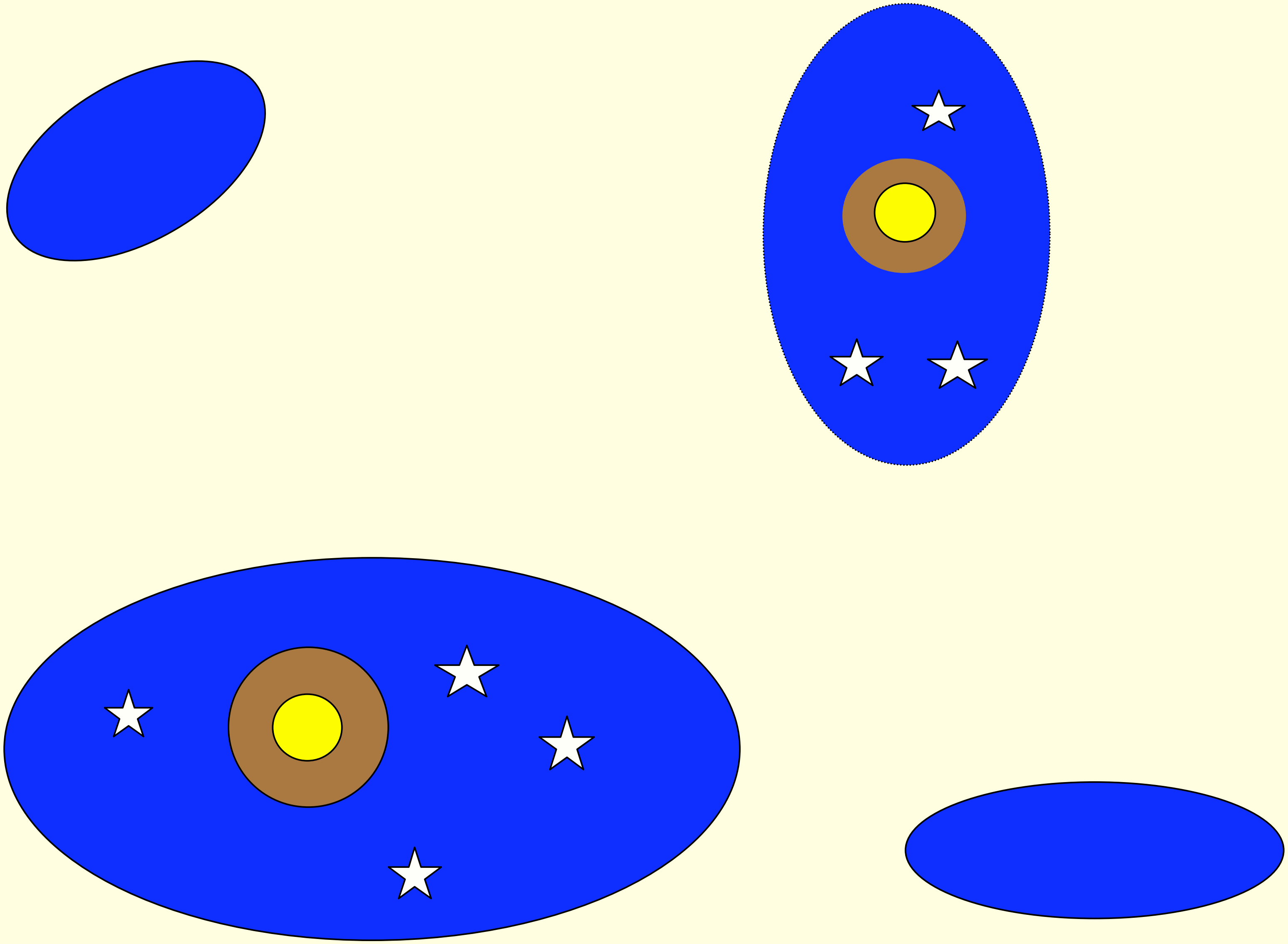
Bivariate Distribution of (u-r,M_r) plane in Nearby Galaxies (Baldry *etal* ‘04)



Lower SFR Efficiencies: Effect of decreasing slope β



Self regulated *in situ* star formation in DLAs with LBG Cores



Consquences of upper limit on comoving star formation Density

Upper limit: $d\rho_*/dt < 10^{-2.7}\, M_\odot\, yr^{-1} Mpc^{-3}$

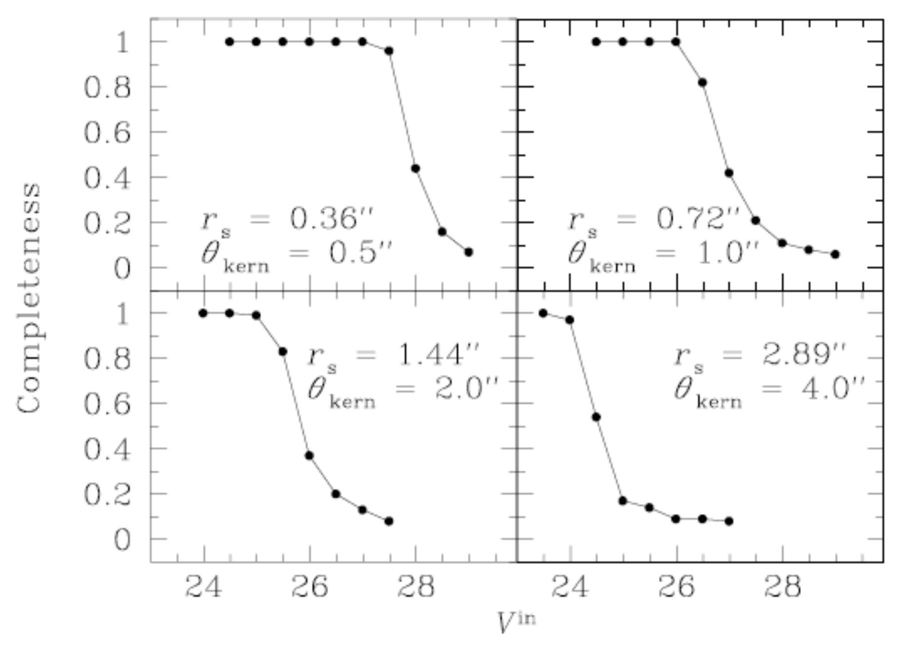
1. ***Limit on Metal Production***

   -Predicted [M/H] <-2.2

   compared to measured [M/H]**=-1.4±0.07**

   -Source of observed metals?

Threshold Determinations from Simulations



1. **Place 10^3 objects with identical exponential brightness profiles, V magnitudes, θ_{DLA} , on UDF image**

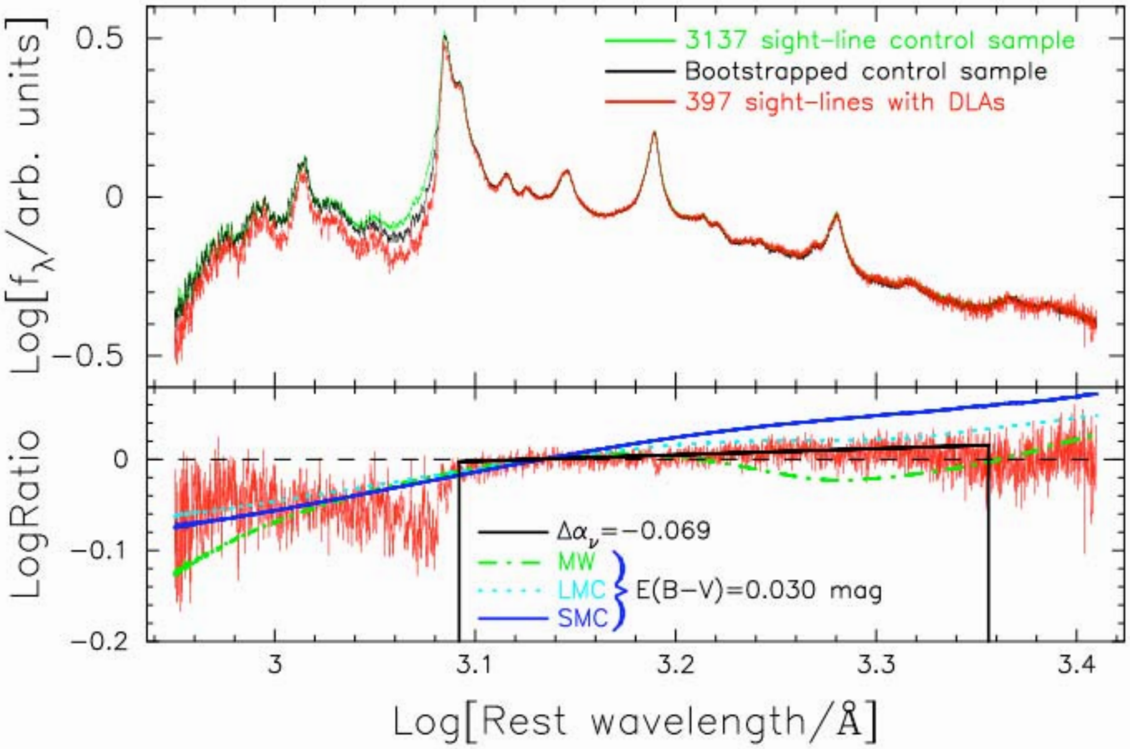
2. **Compute recovery fraction as function of V magnitude**

3. **In principle threshold given by $N_{recover}=N_{95}$**

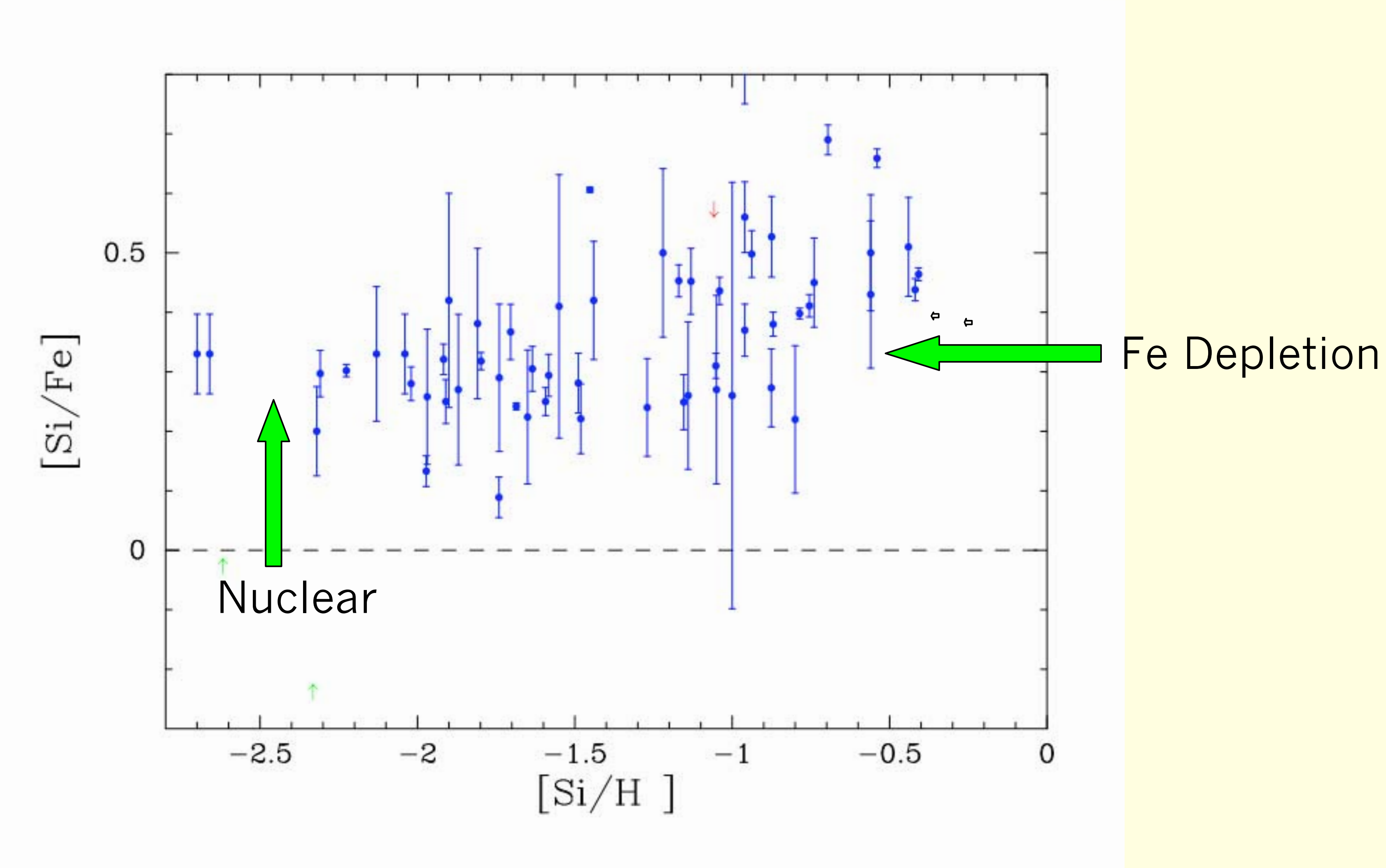
4. **In practice we used more conservative threshold given by $N_{recover}=200$**

Nature of Reddening in DLAs

Murphy etal 2005

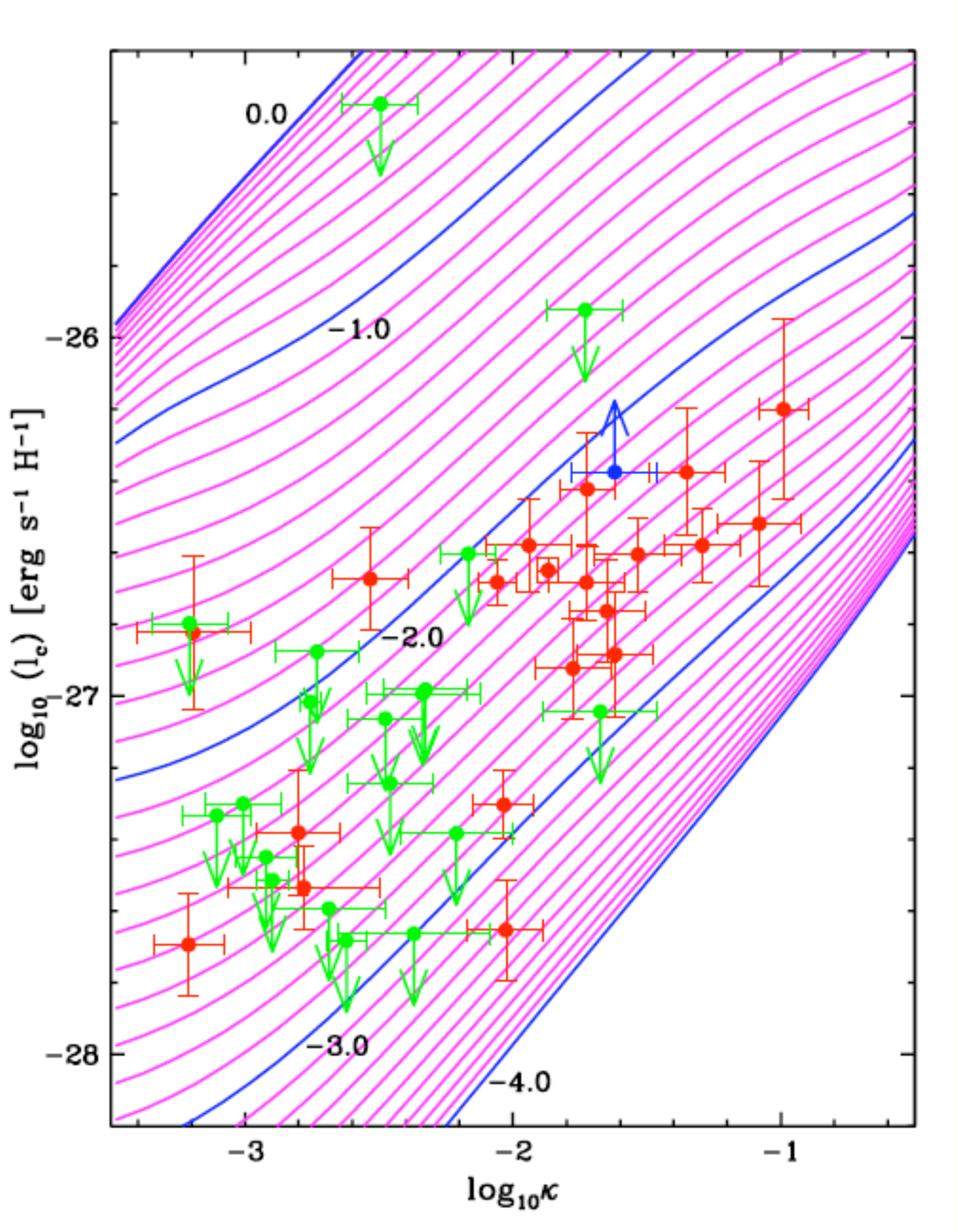


Evidence for Dust Depletion and α Enhancement

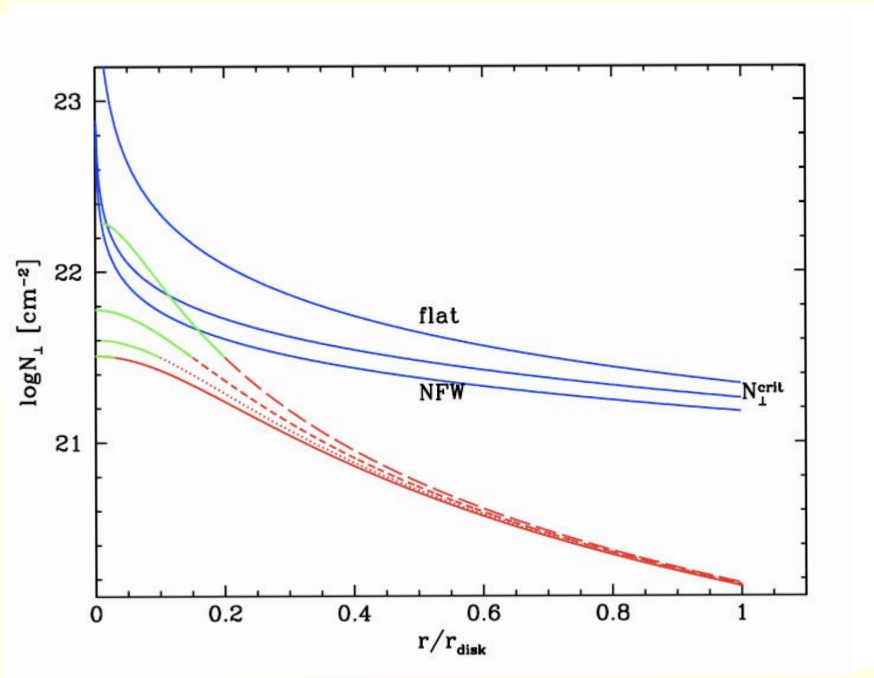


[C II] 158 μm cooling rates versus

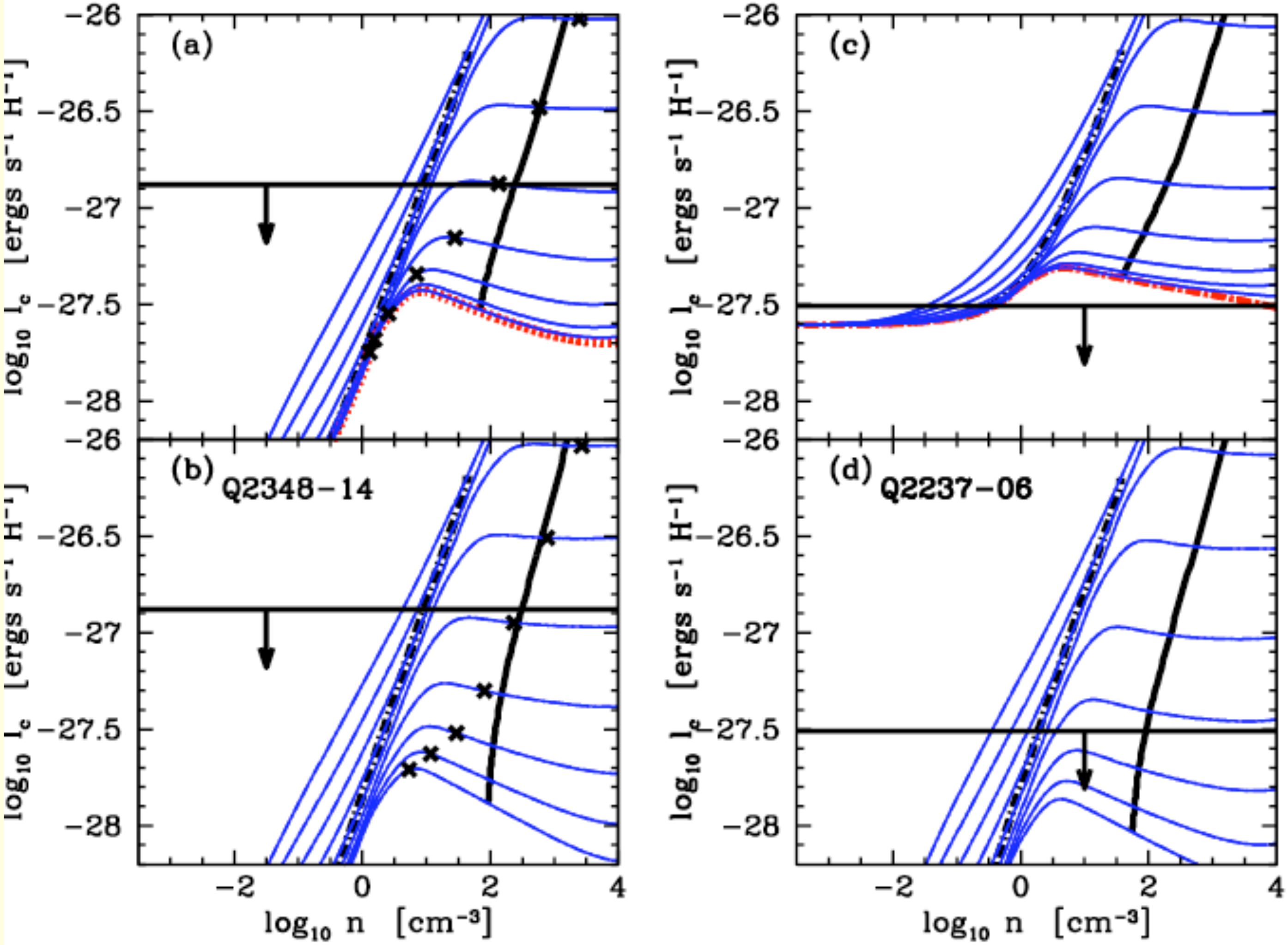
Dust-to Gas Ratio



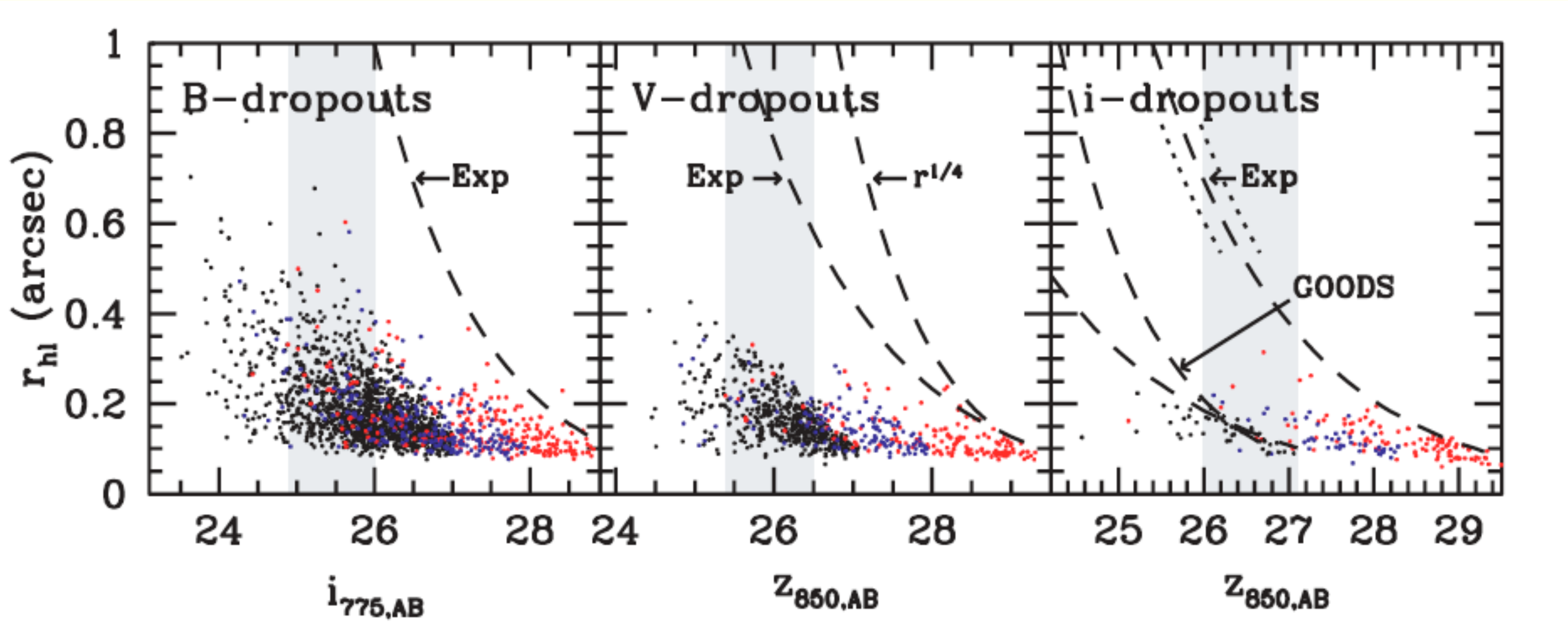
- Star formation in DLAs may be present, but in regions sequestered away from the neutral gas



- Molecular gas may be located at $r < r_{\rm break}$
- Extend $N_\perp$ to $r < r_{\rm break}$
- Molecular gas may be Toomre unstable


(a)
(b) Q2348−14
(c)
(d) Q2237−06
log$_{10}$ l$_c$ [ergs s^{-1} H^{-1}]
−26
−26.5
−27
−27.5
−28
log$_{10}$ n [cm^{-3}]
−2
0
2
4

Magnitude-Size Relation for LBGs (Bouwens etal 2004)



(1) Cumulative Comoving SFR Density Predicted by Kennicutt-Schmidt Relation for z=3

$$\dot{\rho}_*(> N) = (H_0/c)\int_N^{N_{max}} dN' f(N', X)\dot{\psi}_*(N')$$

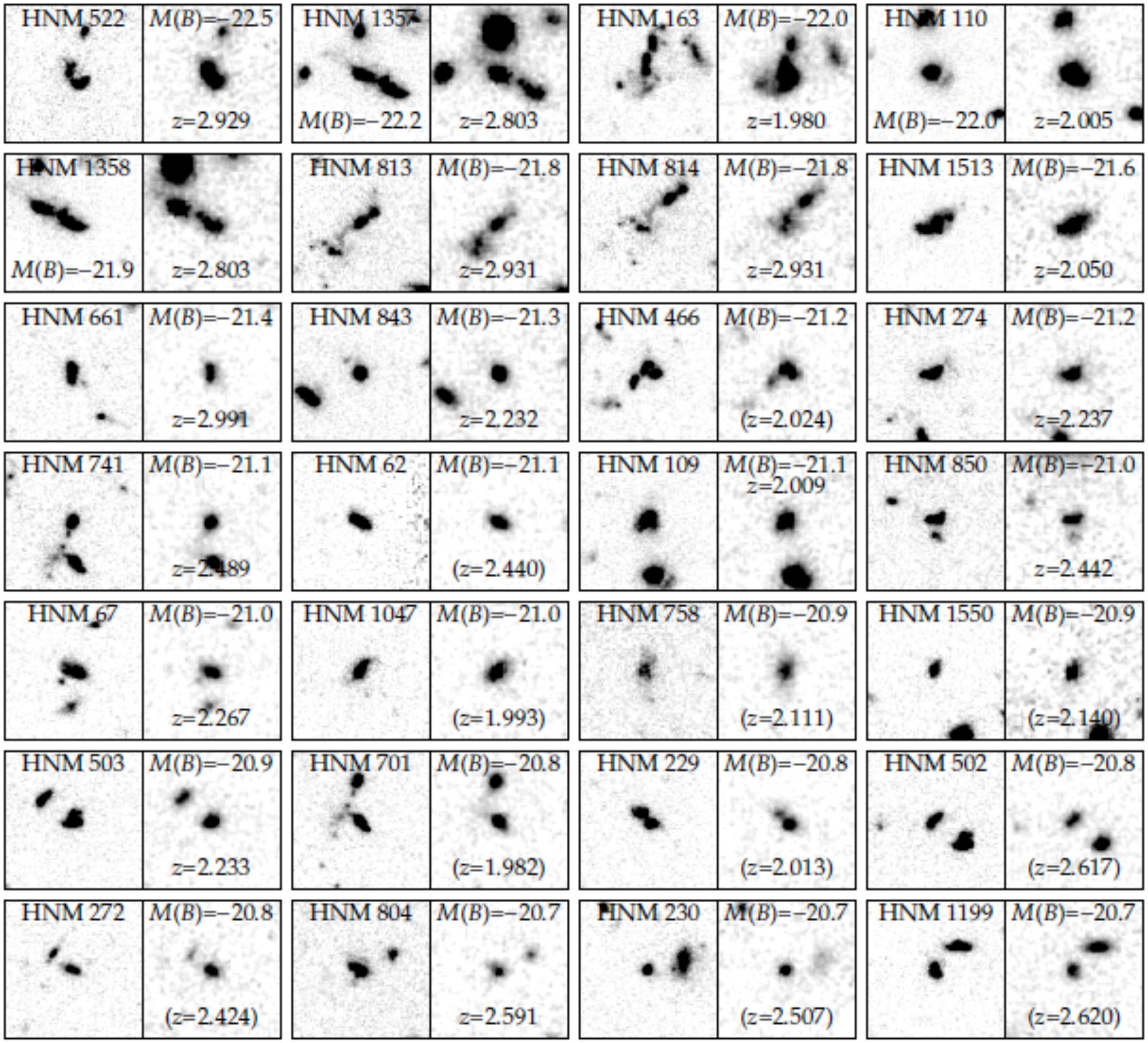
(2) For Randomly Oriented Disks

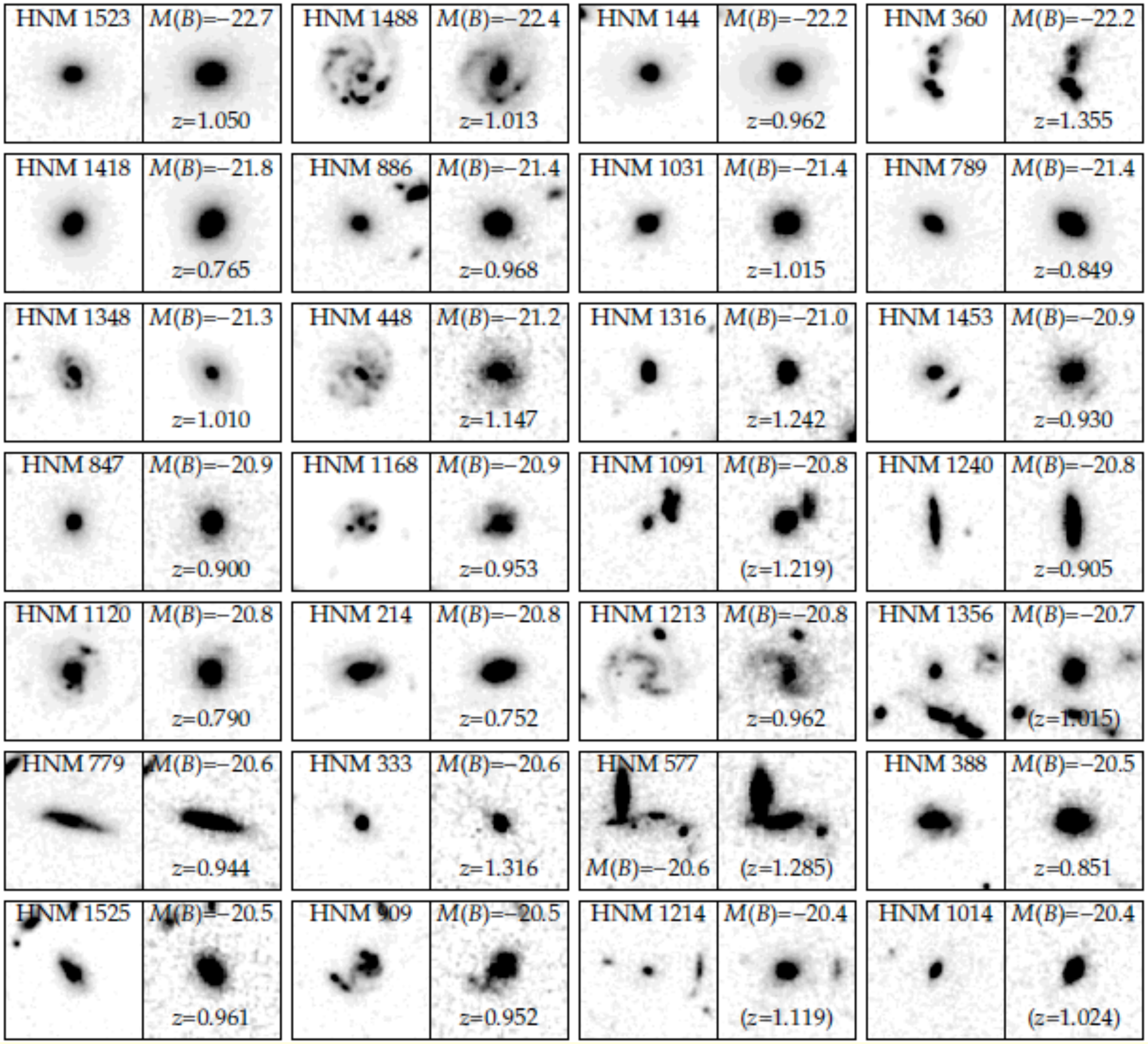
$$\dot{\rho}_*(\geq N, X) = (H_0/c)\int_N^{N_{max}} dN K(N/N_c)^{\beta}\int_{N_{min}}^{\min(N_0,N)} dN_{\perp} g(N_{\perp}, X)(N_{\perp}^2/N^3)(N_{\perp}/N)^{\beta-1}$$

$$f(N, X) = \int_{N_{min}}^{\min(N_0,N)} dN_{\perp} g(N_{\perp}, X)(N_{\perp}^2/N^3)$$

The Gas Content Predicted for the High-Redshift Universe

O’Shea and Norman 2007


HNM 522
M(B)=−22.5
z=2.929
HNM 1357
M(B)=−22.2
z=2.803
HNM 163
M(B)=−22.0
z=1.980
HNM 110
M(B)=−22.0
z=2.005
HNM 1358
M(B)=−21.9
z=2.803
HNM 813
M(B)=−21.8
z=2.931
HNM 814
M(B)=−21.8
z=2.931
HNM 1513
M(B)=−21.6
z=2.050
HNM 661
M(B)=−21.4
z=2.991
HNM 843
M(B)=−21.3
z=2.232
HNM 466
M(B)=−21.2
(z=2.024)
HNM 274
M(B)=−21.2
z=2.237
HNM 741
M(B)=−21.1
z=2.489
HNM 62
M(B)=−21.1
(z=2.440)
HNM 109
M(B)=−21.1
z=2.009
HNM 850
M(B)=−21.0
z=2.442
HNM 67
M(B)=−21.0
z=2.267
HNM 1047
M(B)=−21.0
(z=1.993)
HNM 758
M(B)=−20.9
(z=2.111)
HNM 1550
M(B)=−20.9
(z=2.140)
HNM 503
M(B)=−20.9
z=2.233
HNM 701
M(B)=−20.8
(z=1.982)
HNM 229
M(B)=−20.8
(z=2.013)
HNM 502
M(B)=−20.8
(z=2.617)
HNM 272
M(B)=−20.8
(z=2.424)
HNM 804
M(B)=−20.7
z=2.591
HNM 230
M(B)=−20.7
(z=2.507)
HNM 1199
M(B)=−20.7
(z=2.620)


HNM 1523
M(B)=−22.7
z=1.050
HNM 1488
M(B)=−22.4
z=1.013
HNM 144
M(B)=−22.2
z=0.962
HNM 360
M(B)=−22.2
z=1.355
HNM 1418
M(B)=−21.8
z=0.765
HNM 886
M(B)=−21.4
z=0.968
HNM 1031
M(B)=−21.4
z=1.015
HNM 789
M(B)=−21.4
z=0.849
HNM 1348
M(B)=−21.3
z=1.010
HNM 448
M(B)=−21.2
z=1.147
HNM 1316
M(B)=−21.0
z=1.242
HNM 1453
M(B)=−20.9
z=0.930
HNM 847
M(B)=−20.9
z=0.900
HNM 1168
M(B)=−20.9
z=0.953
HNM 1091
M(B)=−20.8
(z=1.219)
HNM 1240
M(B)=−20.8
z=0.905
HNM 1120
M(B)=−20.8
z=0.790
HNM 214
M(B)=−20.8
z=0.752
HNM 1213
M(B)=−20.8
z=0.962
HNM 1356
M(B)=−20.7
(z=1.015)
HNM 779
M(B)=−20.6
z=0.944
HNM 333
M(B)=−20.6
z=1.316
HNM 577
M(B)=−20.6
(z=1.285)
HNM 388
M(B)=−20.5
z=0.851
HNM 1525
M(B)=−20.5
z=0.961
HNM 909
M(B)=−20.5
z=0.952
HNM 1214
M(B)=−20.4
(z=1.119)
HNM 1014
M(B)=−20.4
(z=1.024)

Evidence for Threshold Surface Densities at z=0

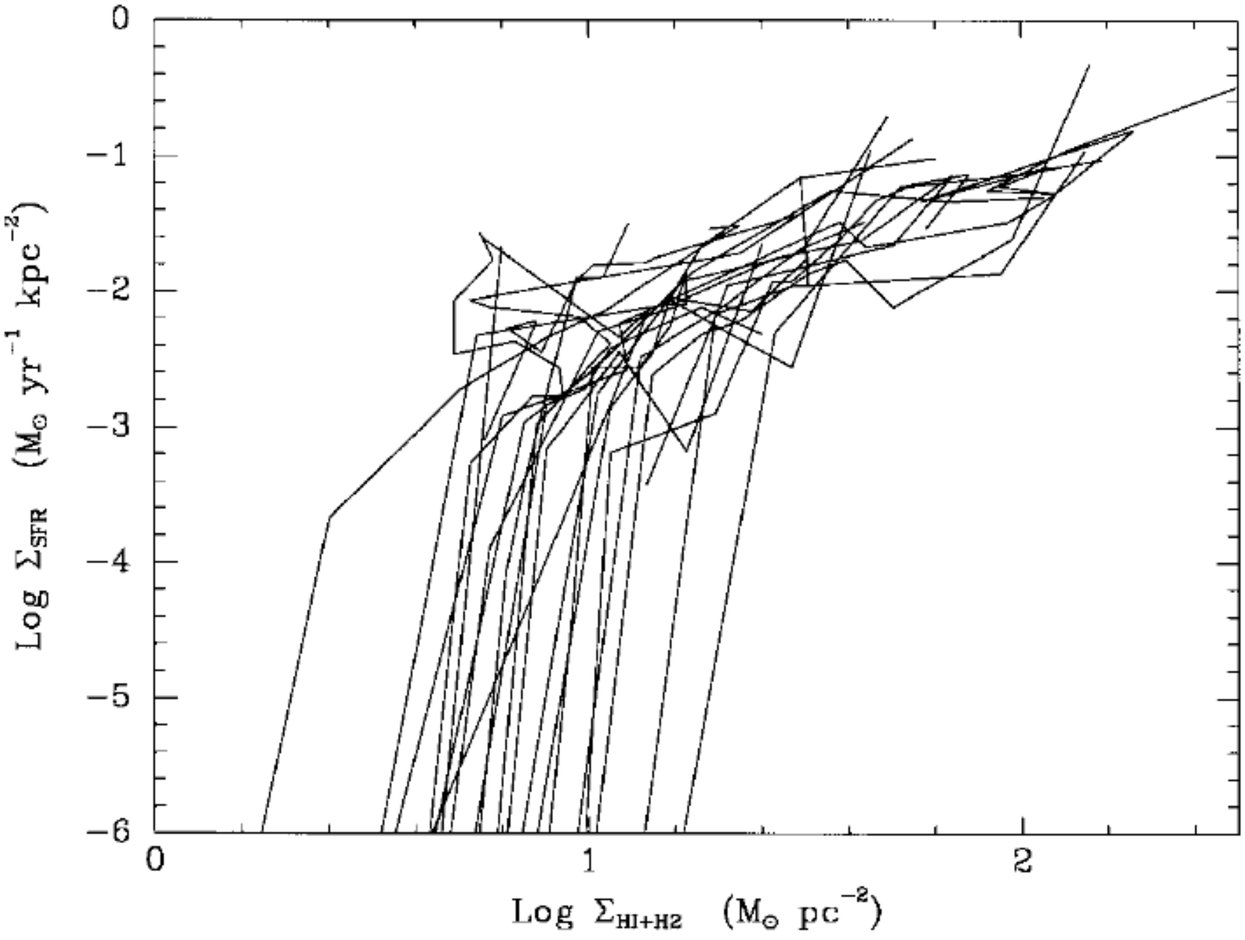
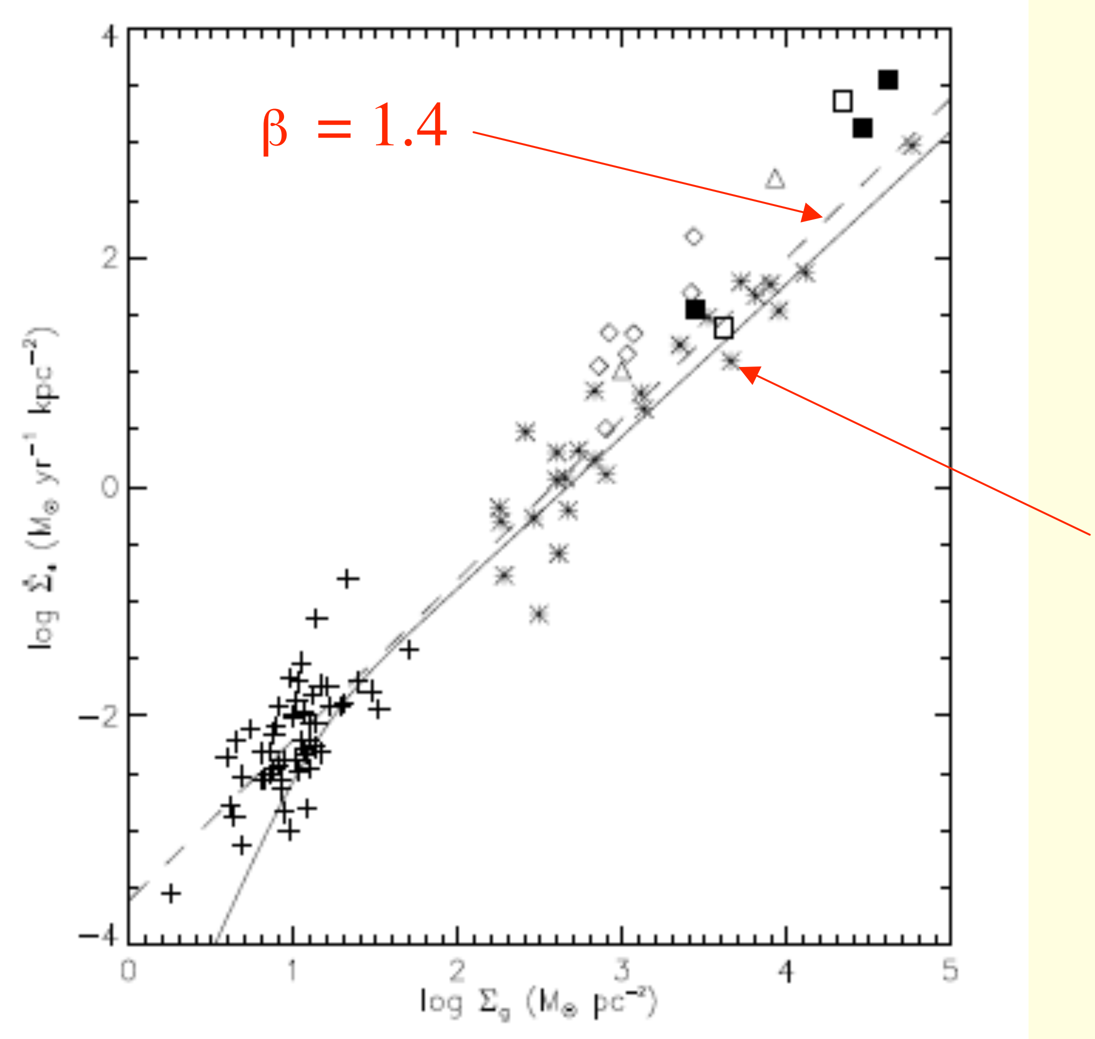


FIG. 3.—Profiles of the azimuthally averaged SFR per unit area as a function of gas density for 21 spirals with spatially resolved Hα data.

Kennicutt-Schmidt Law for Galaxies



$\beta = 1.4$

Individual Galaxy

(2) Effects of Low Molecular Content in DLAs

- Median $f_{H2}=10^{-6}$ in DLAs. By comparison, $f_{H2}=10^{-1}$ in MW
- SFR~f_{H2} in most models for star formation

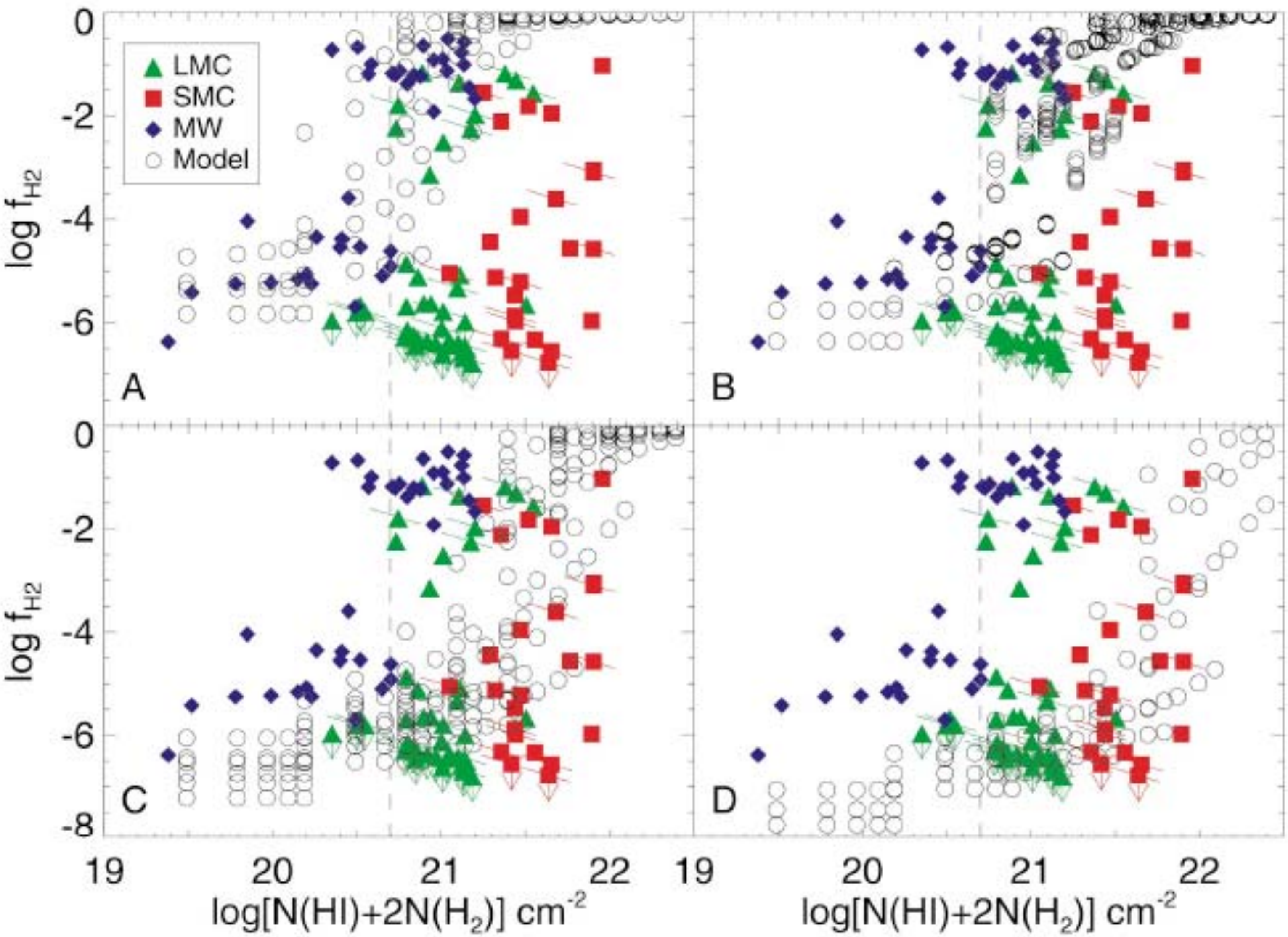
Contrast Between DLAs and MW

•MW: Since $N_{\mathrm{crit}} \sim N_{shield} \sim 10^{20.7}$ cm^{-2}, Toomre instability $N > N_{\mathrm{crit}}$ leads to significant molecule formation, and to star formation

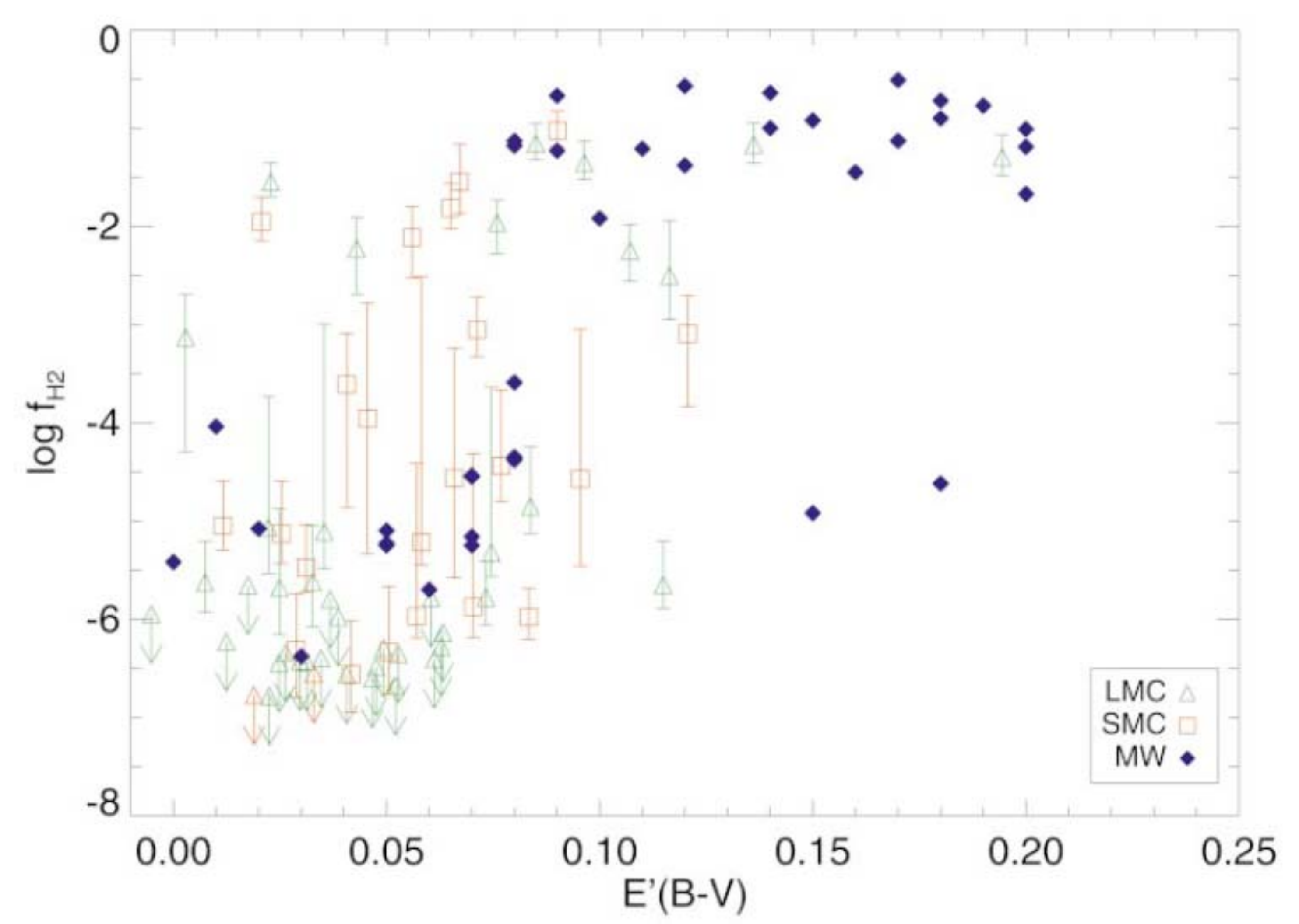
•DLAs: If N_{shield} ($=10^{22}$) > N_{crit} ($=10^{21.5}$), Toomre instability leads to gravitationally bound *atomic* clouds, hence no star formation.

•Reason for high N_{shield} in DLAs is low dust content ($\kappa=0.025$) and high FUV radiation intensities ($G_0 \sim 4$).

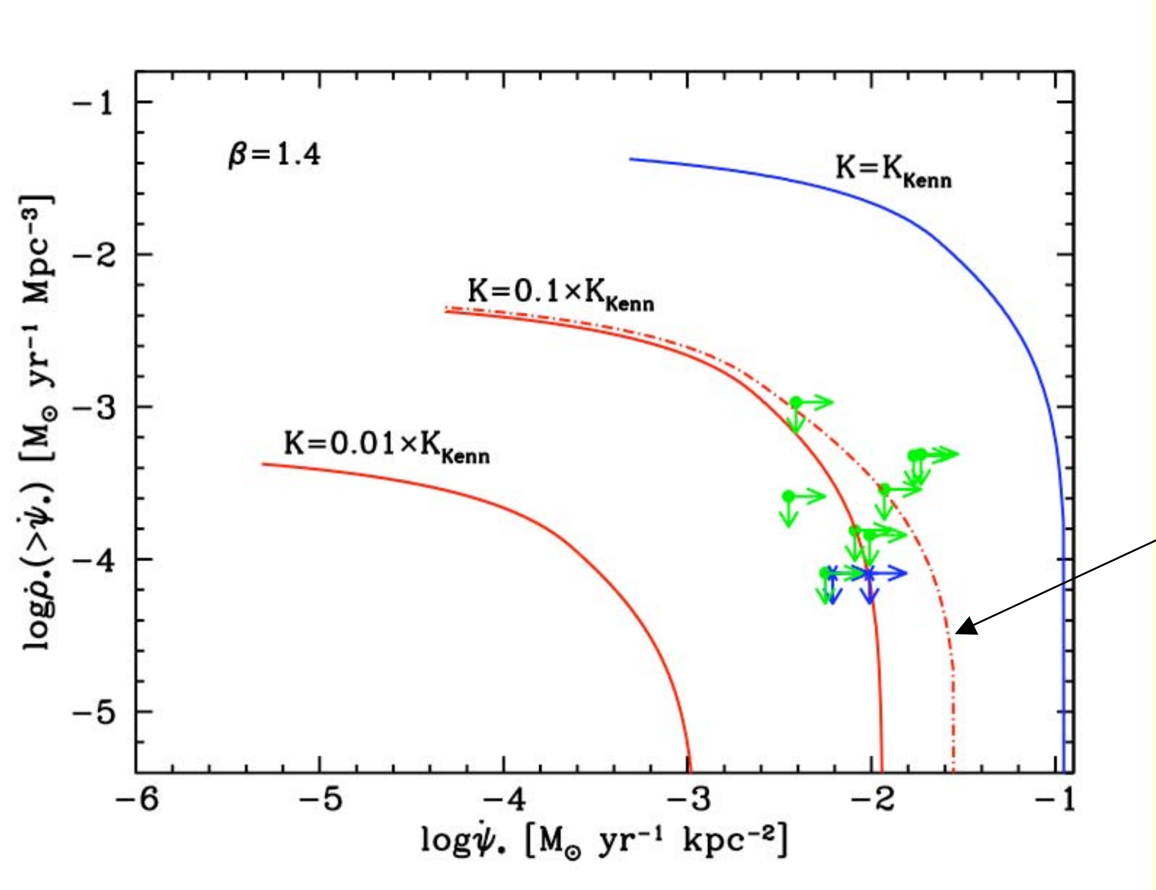
Molecular content versus total proton column density



Molecular fraction versus color excess (Tumlinson etal ‘02)

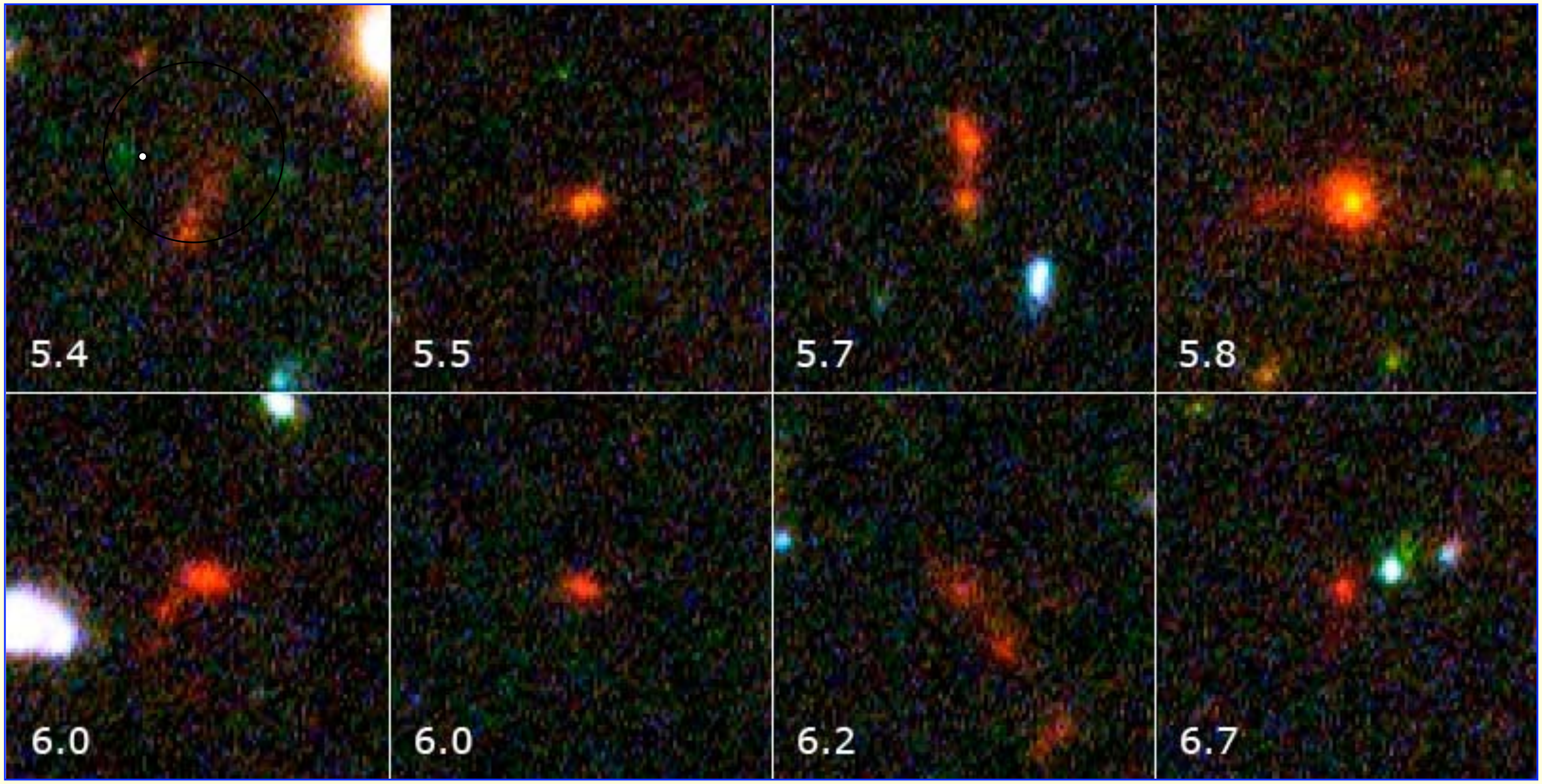


Effect of increasing N_{max}



N_{max}= $2x10^{22}$

Examples of Lyman Break Galaxies

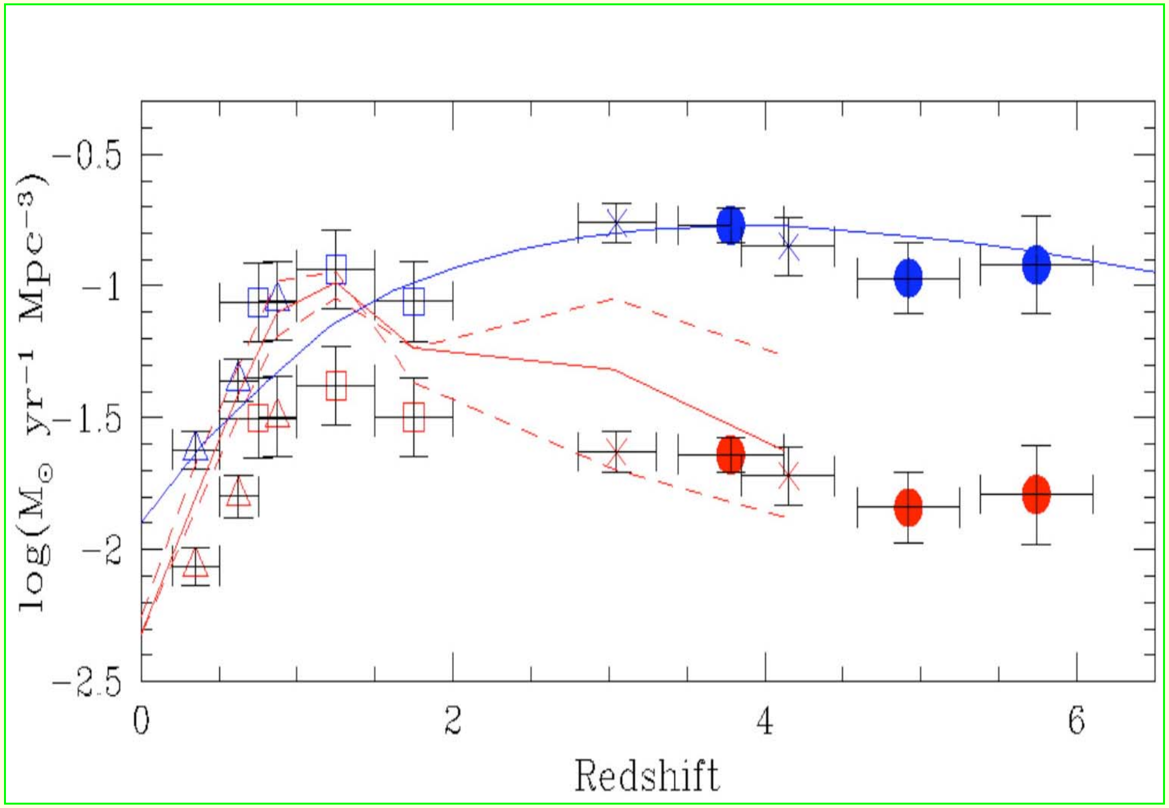


UDF Search with F606W Image

- Central λ matches FUV rest-frame wavelength of 1500Å for z=[2.5,3.5].
- FUV emitted mainly by massive stars, so $L_\nu(t)$ proportional to SFR(t)
- Same technique used to get SFRs for LBGs

- No U-band sensitivity in UDF. Therefore photometric z's unreliable. But technique valuable for obtaining upper limits on comoving SFR densities

SFR or Luminosity per unit Comoving volume



● Observed

● De-reddened

Consequences

- Known star formation occurs in compact objects
- SFRs higher at large redshifts
- 50 % of current stars and metals produced by z~1
- 10 % of current stars and metals produced by z~3

But This Picture is Incomplete

- At high redshifts most baryons were gas

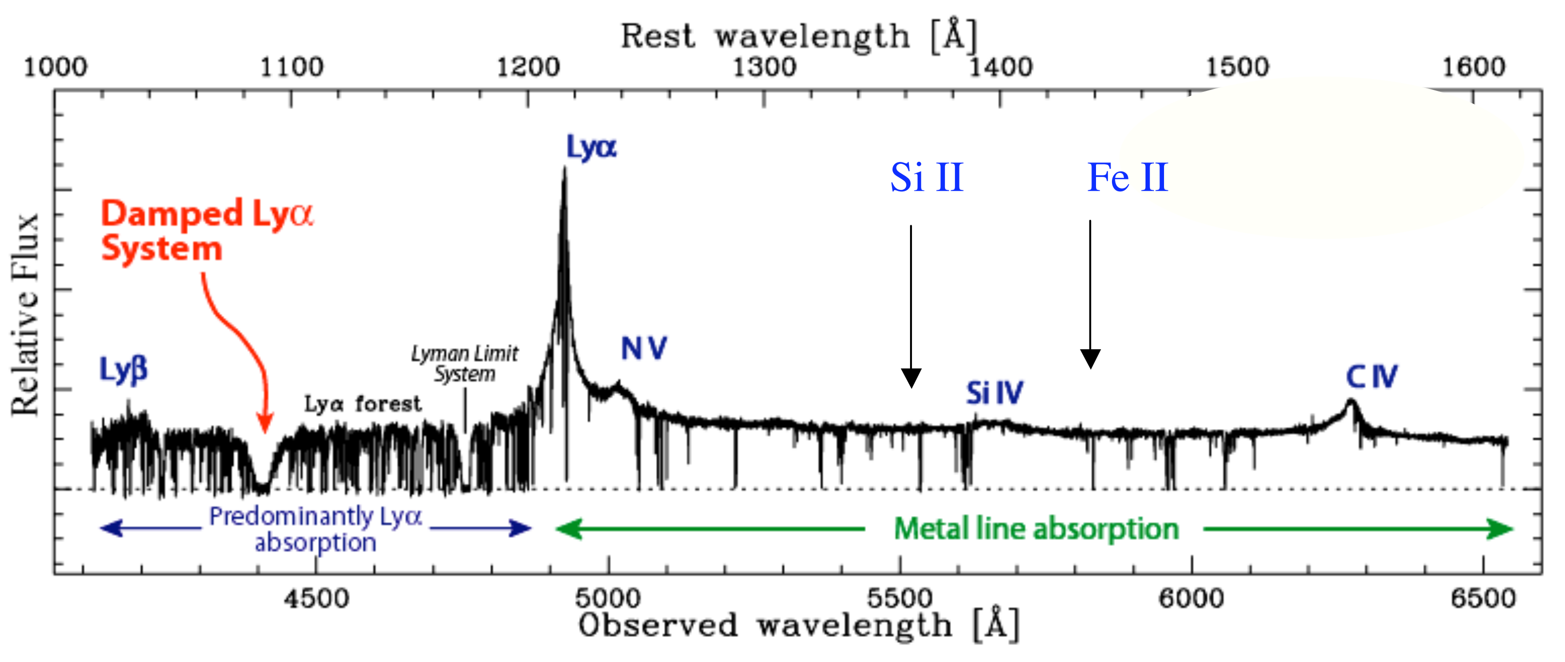
- Since then cold, neutral gas condensed into stars and C and heavier elements formed.
- How did this happen? Throughout gas?

- SFRs of LBGs imply $\Delta\Omega_{gas} = \Omega_{visible}(z=0)$ consumed between z=5 and z=2

- External Neutral gas reservoirs may be needed

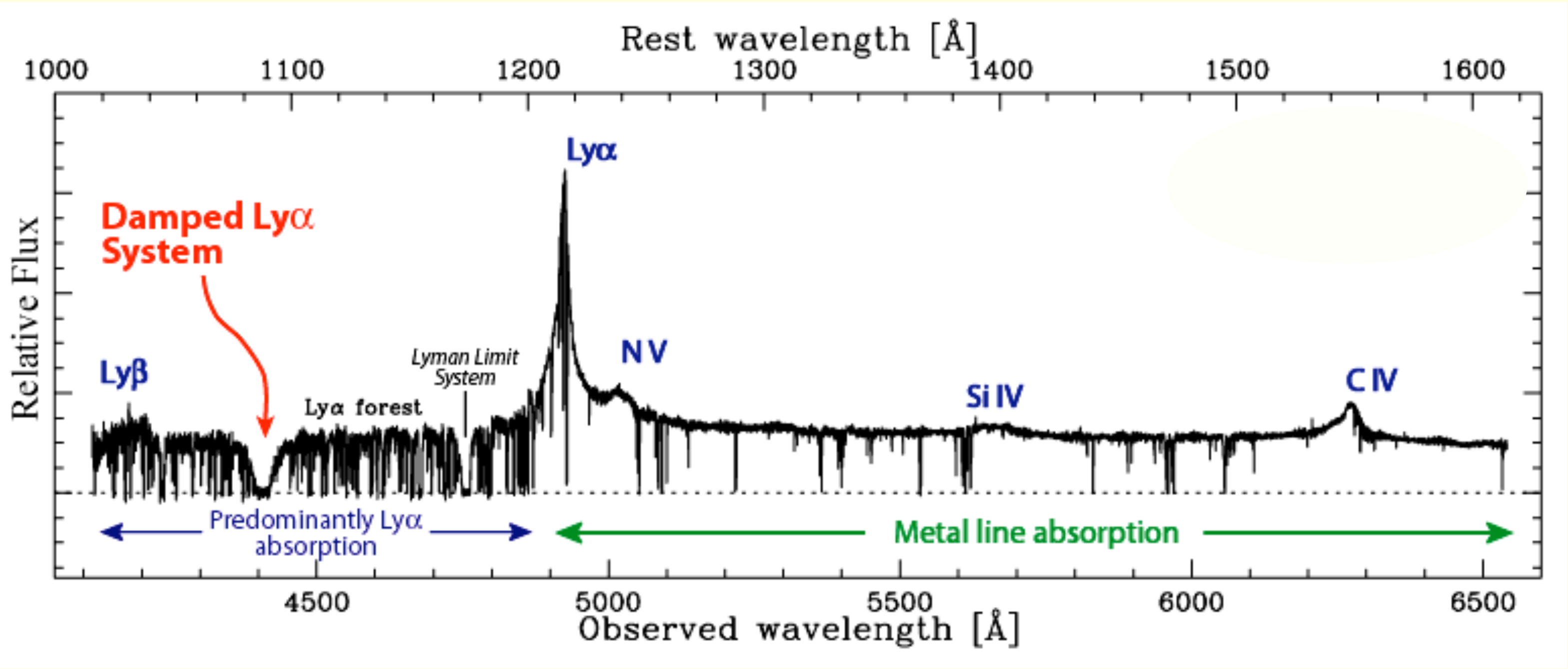
Outline: High-z Neutral Gas Reservoirs

- **Damped Lyα Systems (DLAs)**
- **Evidence for Star Formation in DLA gas**
- **Apply local Kennicutt-Schmidt law for star formation to DLAs**
- **Test predictions by searching for *in situ* star formation in HUDF**
- **DLA-LBG Connection**



- Definition of Damped Lyα System (DLA): $N(HI) > 2x10^{20}\ cm^{-2}$

- Distinguishing characteristic of DLAs : Gas is Neutral



- Definition: N(HI) > 2×10^{20} cm^{-2}

- Distinguishing characteristic of DLAs : Gas is Neutral

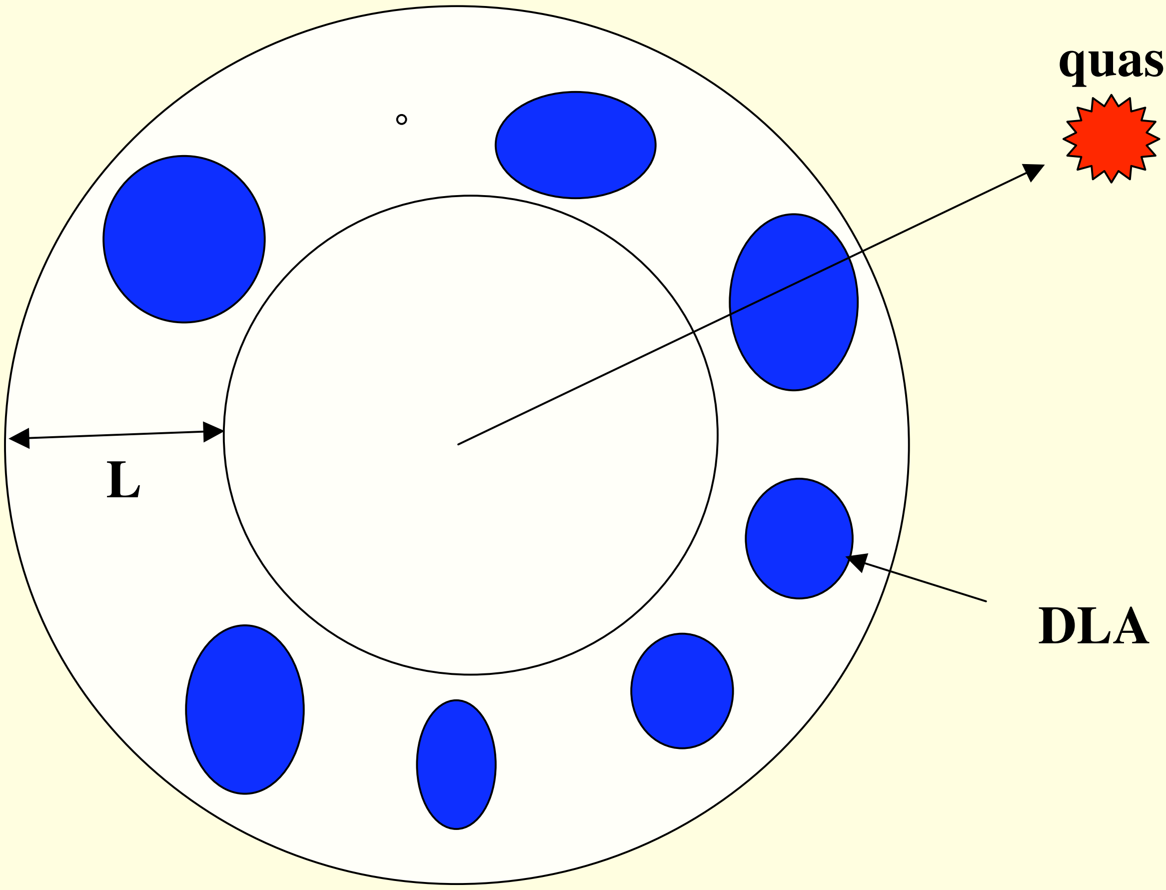
How are DLAs heated?

Stars form out of cold gas

Measuring Mass Density of Neutral gas

- $\rho_{gas}=<\Sigma>*f_A/L$

- **Area covering fraction $f_A=1/3$ for z=[2.5,3.5]**



Evidence for Star Formation in DLAs?

- Evidence from Metal Abundances
- Presence of Dust
- Evidence for Starlight

Metals in DLAs

- ***Most accurate Metal abundances at high-z are for DLAs***

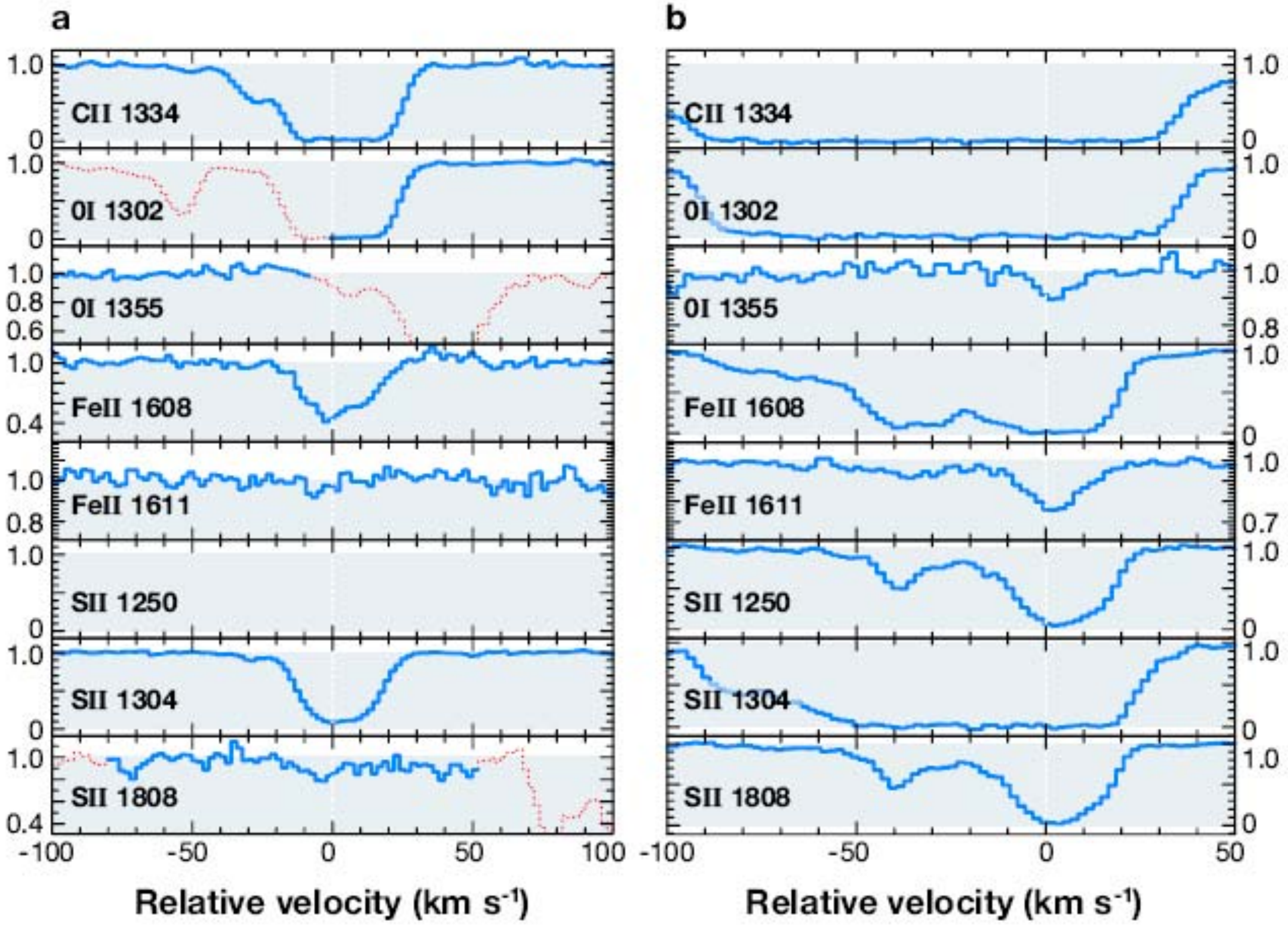
Ionization State of Gas is Accurately Known: H=H^0
Dominant ions are Si^+, C^+, Fe^+, O^0, etc.

Accurate Measurements of Keck Velocity Profiles

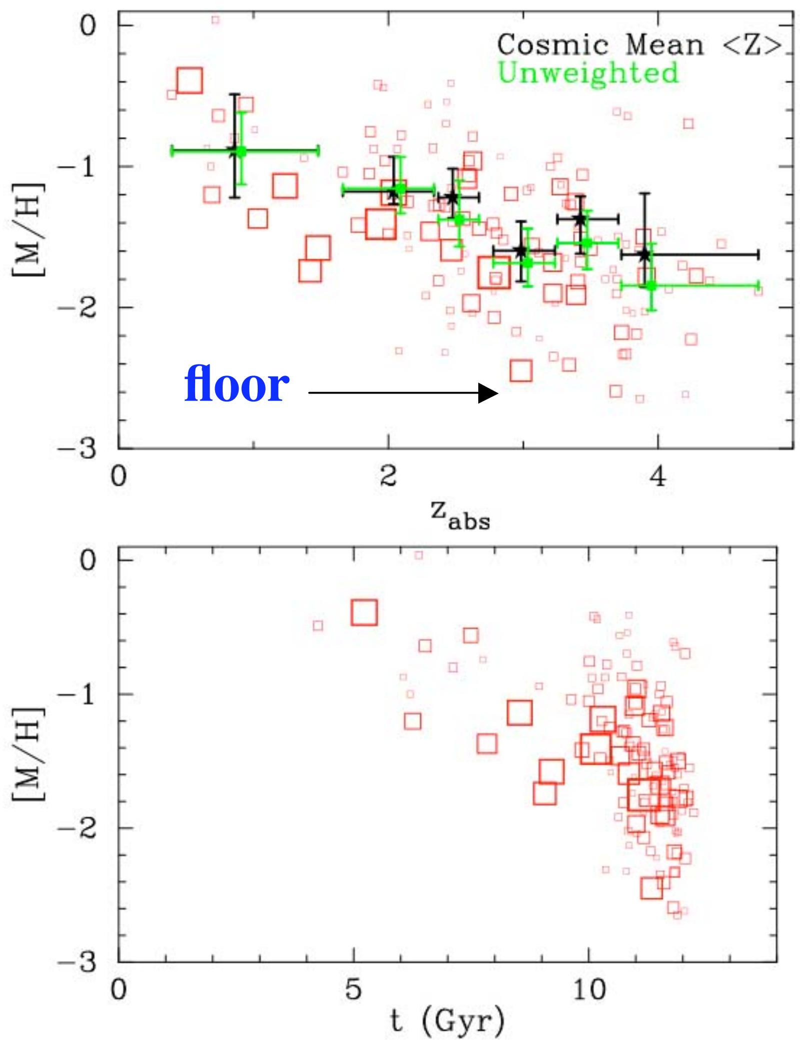
- ***Metals are Byproducts of Star Formation***

- ***Abundance Ratios are Signatures of Star Formation Histories***

Metal Weak **Metal Strong**

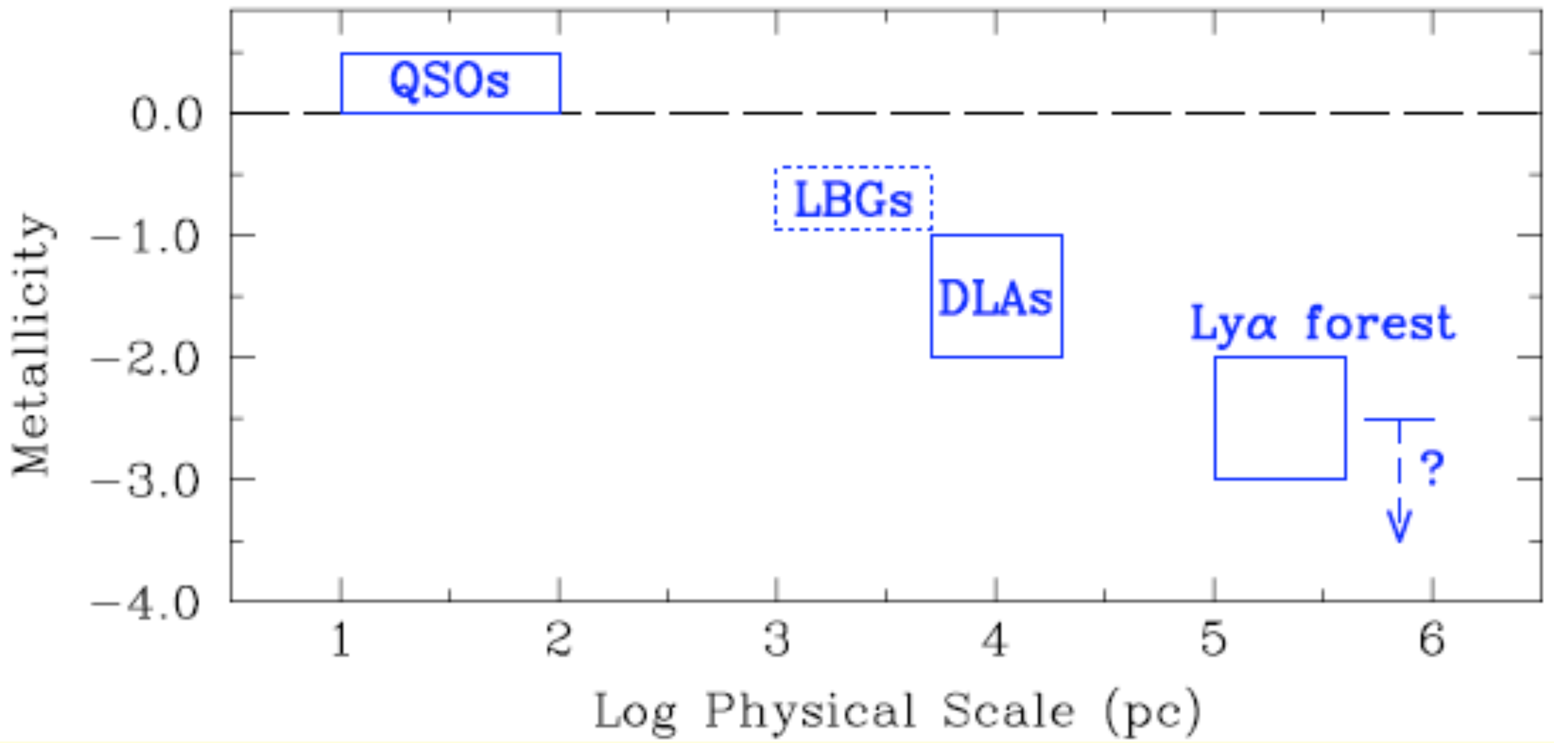


DLA Age-Metallicity Relationship


floor

- Sub-solar metals at all z. But [M/H] underestimated at low z due to undersampling.
- Statistically Significant evidence for increase of metals with time
- Most DLAs detected at epochs prior to formation of Milky Way Disk
- But too many metal-poor galaxies would result if high-z gas turned into stars

Abundances at High Redshift (z = 3)

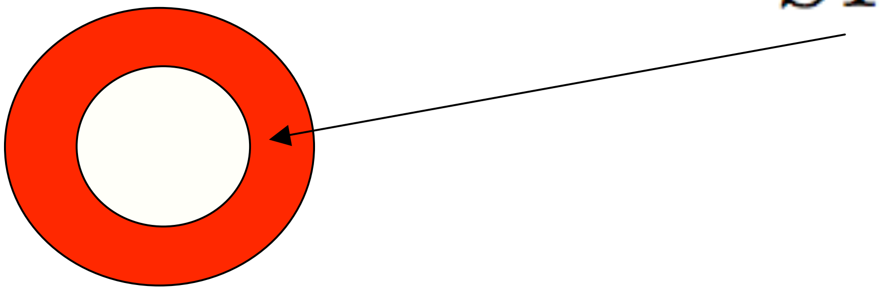


Comoving SFR Density

face-on disks

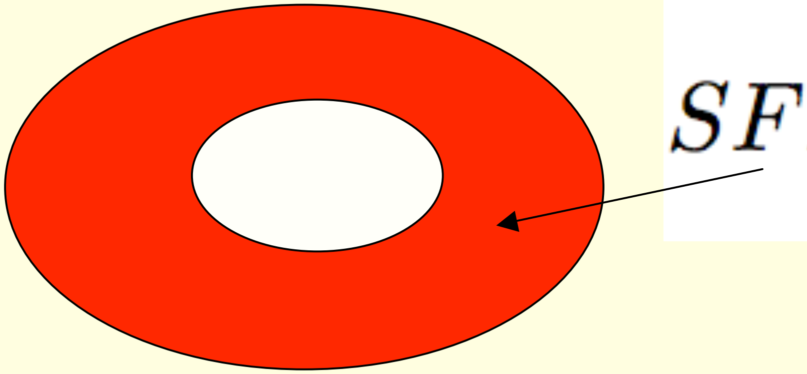
$$\mathbf{d}\dot{\rho}_{*} = \mathbf{n_{co} dA_{\perp}} \times [(\dot{\psi}_{*})_{\perp}] \quad ,$$

$$SFR = dA_{\perp} \times (\dot{\psi}_{*})_{\perp}$$



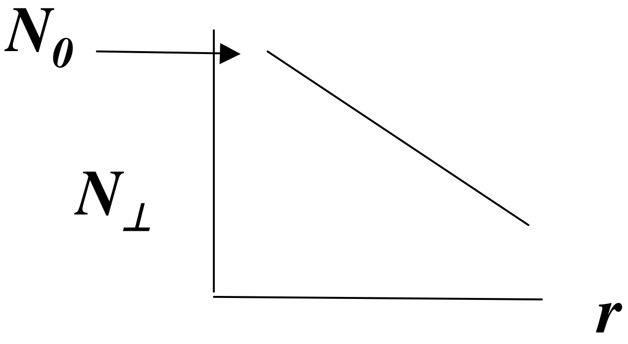
inclined disks

$$\mathbf{d}\dot{\rho}_{*} = \mathbf{n_{co} dA_{\perp} cos(i)} \times [(\dot{\psi}_{*})_{\perp}/\mathbf{cos(i)}] \times \mathbf{sin(i) di} \quad ,$$



$$SFR = dA_{\perp} cos(i) \times \frac{(\dot{\psi}_{*})_{\perp}}{cos(i)}$$

$$\mathbf{f_\perp(N_\perp, X) dN_\perp \equiv (c/H_0) n_\infty dA_\perp}$$



Since $\cos(i) = N_\perp/N$

$$\dot{\rho}_*(\geq N) = \frac{H_0}{c} \int_N^{N_{max}} dN K(N/N_c)^\beta \int_{N_{min}}^{\min(N_0,N)} dN_\perp f_\perp(N_\perp, X)(N_\perp^2/N^3)(N_\perp/N)^{\beta-1}$$

where $f_\perp(N_\perp, X)$ **and** $f(N, X)$ **are related by**

$$f(N, X) = \int_{N_{min}}^{\min(N_0,N)} dN_\perp f_\perp(N_\perp, X)(N_\perp^2/N^3)$$

Observed H I Column-Density Distribution Function