Star Formation Efficiency in Neutral-Gas at High z

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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 Lyman alpha Systems (Neutral Gas)

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

Star Formation in DLAs ?

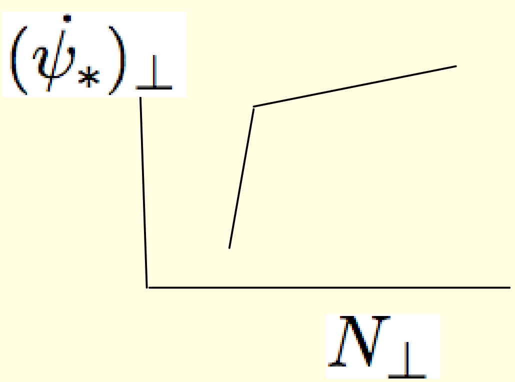
- Do DLAs undergo *in situ* star formation ?

- 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?

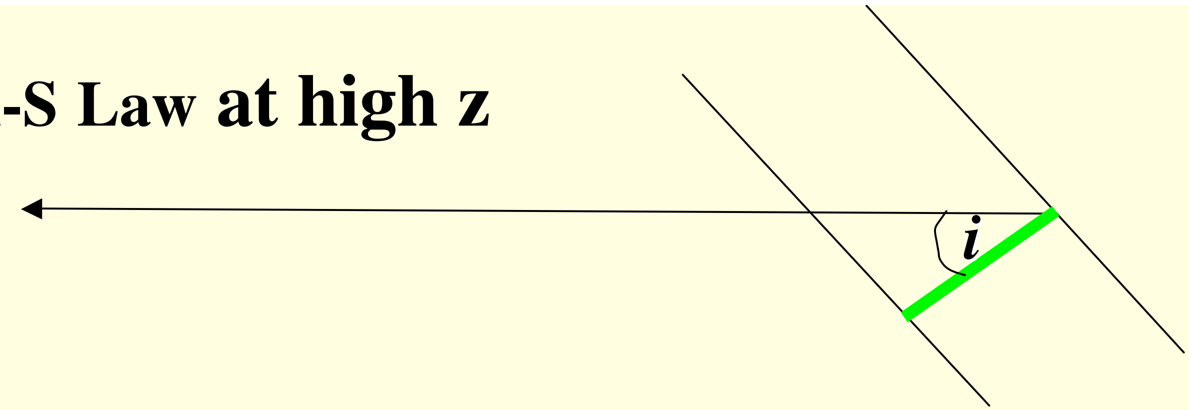
- In that case, what is the relationship between LBGs and DLAs? Are DLAs the neutral-gas reservoirs for star formation in LBGs?

Connection between Gas and Stars; Kennicutt-Schmidt Law



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

K-S Law at high z



Surface Brightness

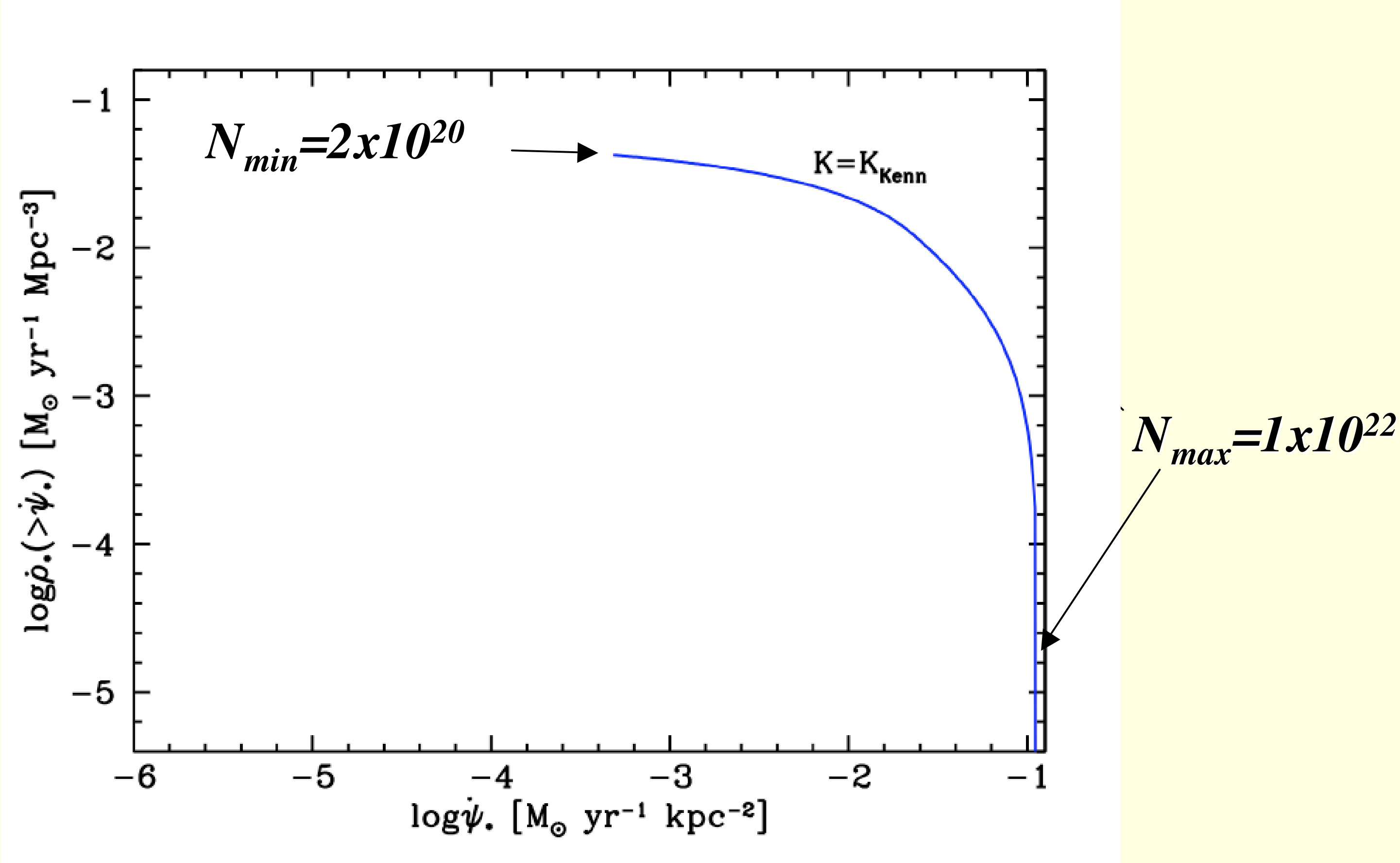
$$\mathbf{<I_{\nu_0}>} = \frac{\mathbf{C}\dot{\psi}_*}{4\pi(1+\mathbf{z})^3\beta} \quad , \dot{\psi}_* \equiv \mathbf{K}(\mathbf{N}/\mathbf{N_c})^\beta$$

log$N$=21.2 cm^{-2} $\Rightarrow$ dψ_*/dt=10^{-2} $M_\odot$ kpc^{-2}yr^{-1}

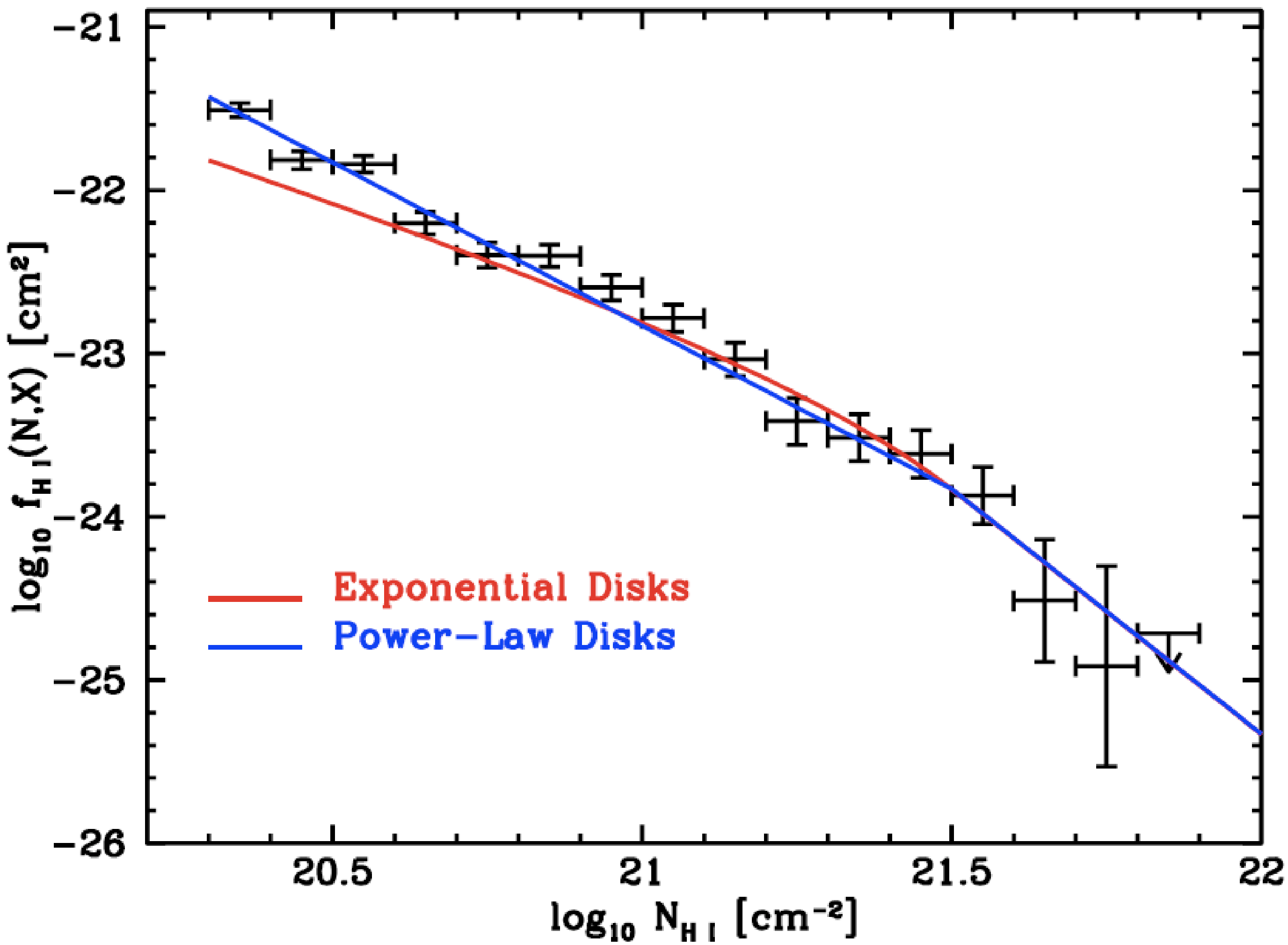
Implied surface brightness at z=3: μ_V=28.4 mag arcsec^{-2}
Measureable in F606W image from Hubble Ultra Deep Field

Cumulative Comoving SFR Density Predicted by the Kennicutt-Schmidt Relation for z=3

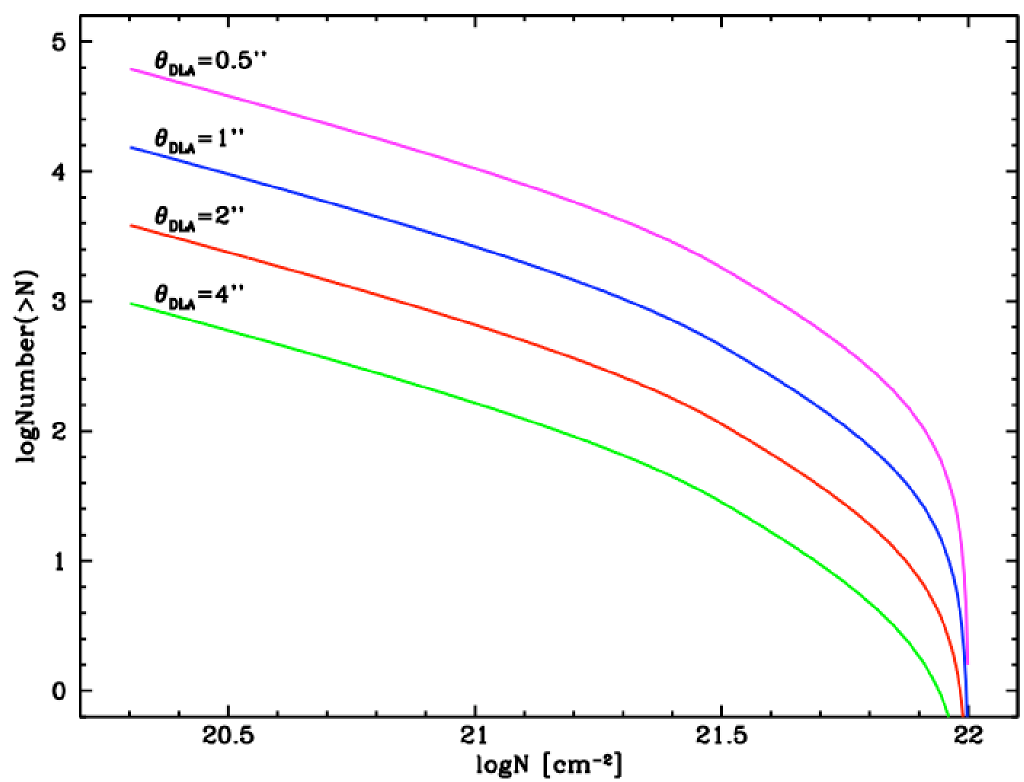
$$\dot{\rho}_*(>N) = (H_0/c)\int_N^{N_{max}} dN' f(N',X)\dot{\psi}_*(N')$$



Observed H I Column-Density Distribution Function



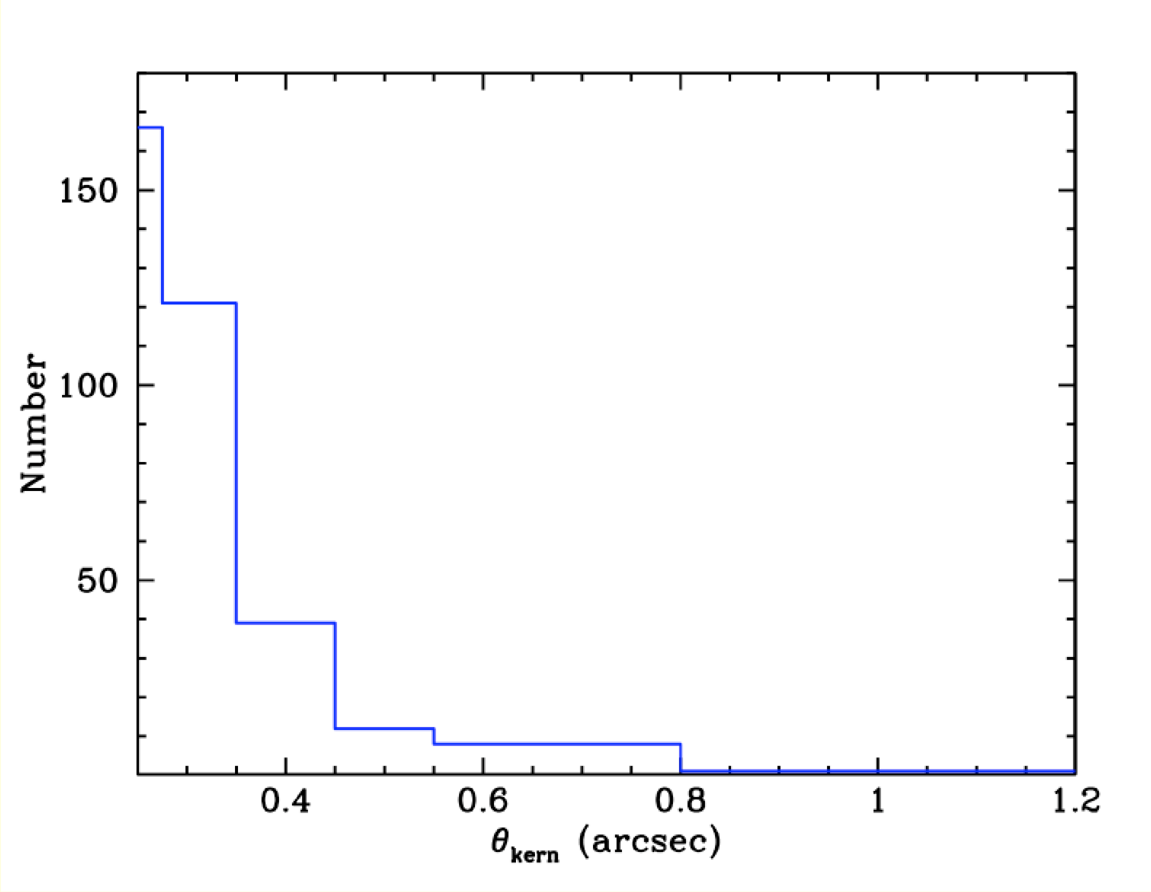
How many DLAs in the UDF with z=[2.5,3.5]?



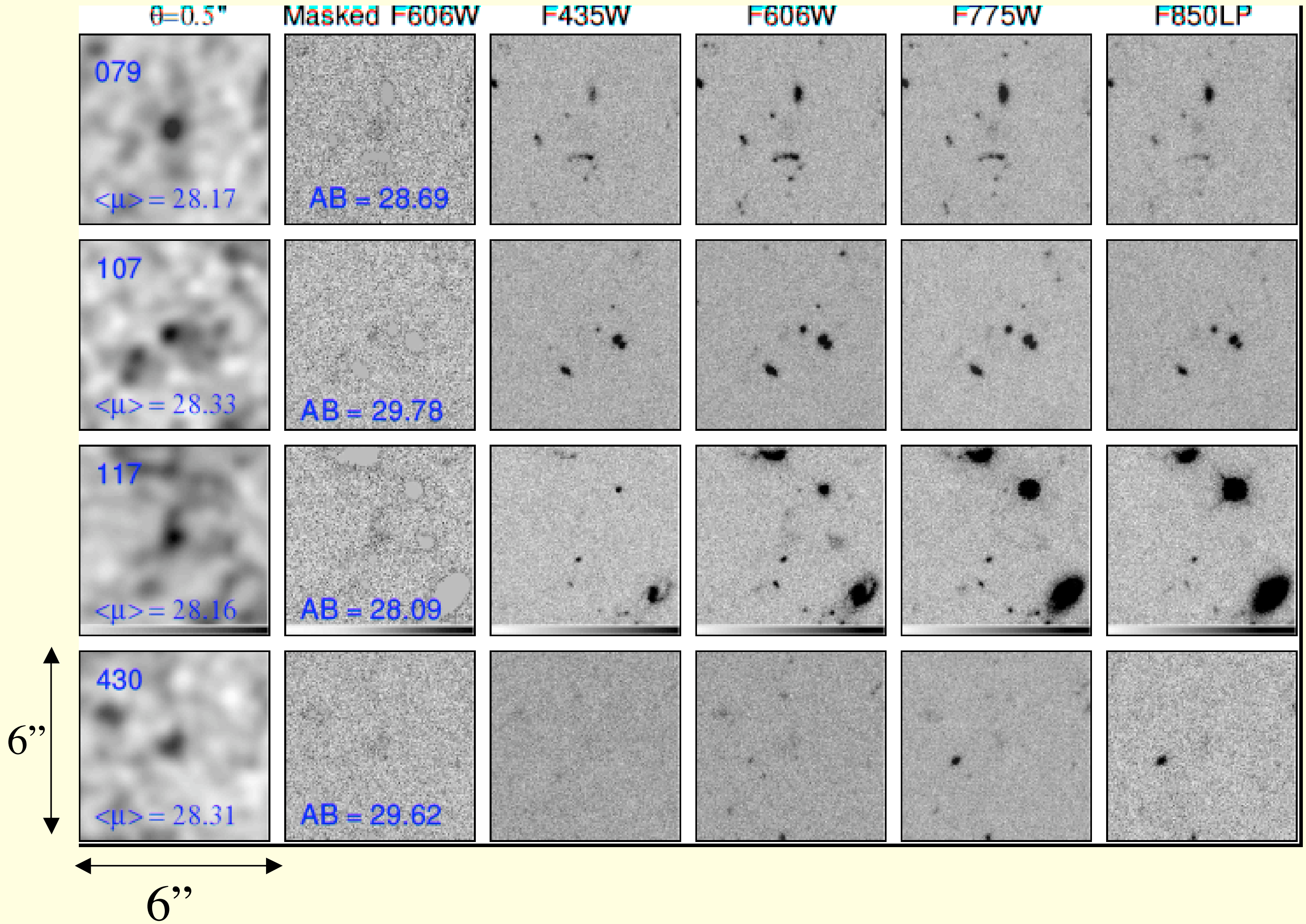
Results of UDF Search with F606W Image

- **Unsmoothed Image (θ_{psf}=0.09”):**
  -Found 11,000 objects with V<30.5
  -None satisfied criteria for *in situ* star formation at Kennicutt rate: i.e. , $\mu_V > 26$, $\theta_{dla} > 0.25''$
- **Smoothed Images:**
  -Removed HSB objects: $\mu_V < 26$
  -Smoothed image with Gaussian kernels with FWHM=θ_{kern} to enhance SNR when $\theta_{kern}=\theta_{dla}$
  -Let θ_{kern}=0.25” to 4.0” or d_{dla}=1.9 kpc to 31 kpc

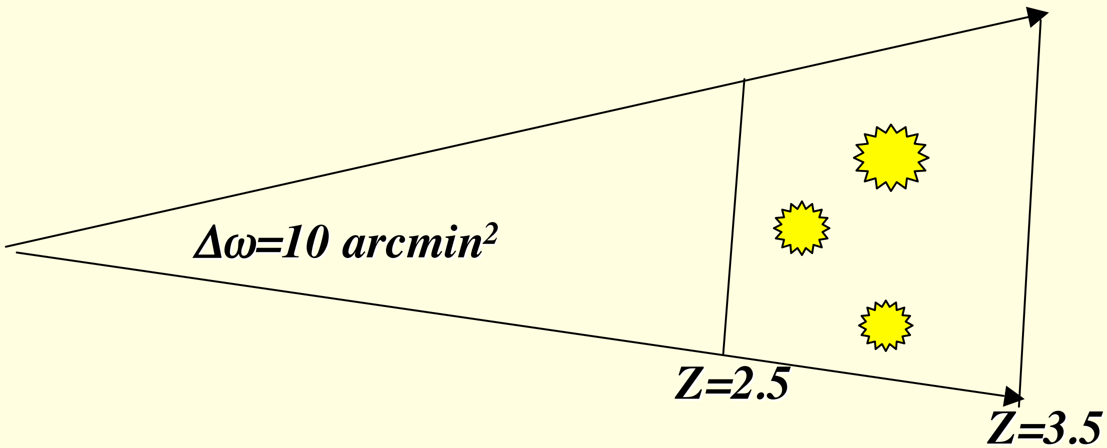
Number of Detected objects versus θ_{kern}



Detected objects for θ_{kern}=0.5 arcsec



Significance of Upper Limits in UDF

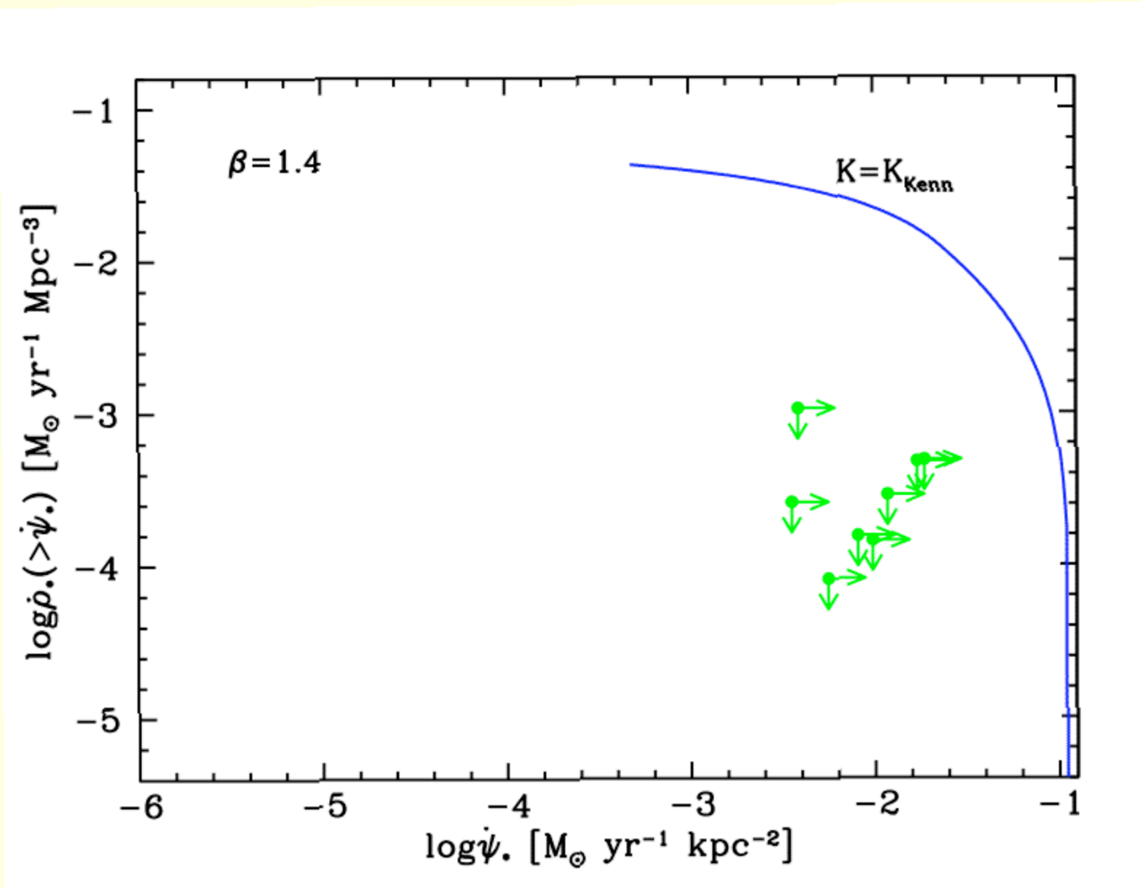


- 95 % confidence upper limit, $n_{co} < N_{95}/\Delta V_{co}$
- Comoving volume $\Delta V_{co} = 3.2\text{x}10^4$ Mpc^3

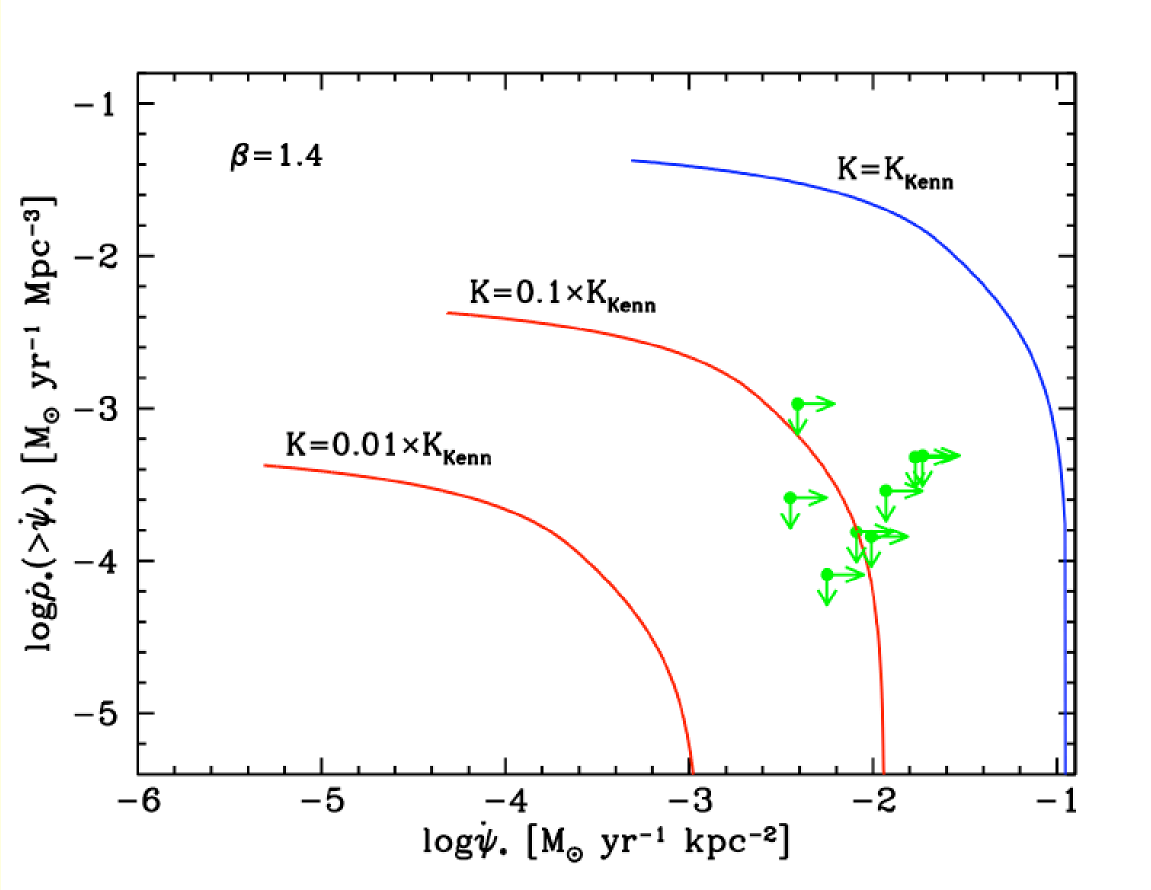
Comoving SFR Density: $d\rho_*/dt = n_{co} \text{x}(\text{ SFR})$

Threshold SFR/Area: $(d\psi_*/dt)_{threshold} \, \alpha \, (I_{\nu 0})_{threshold}$

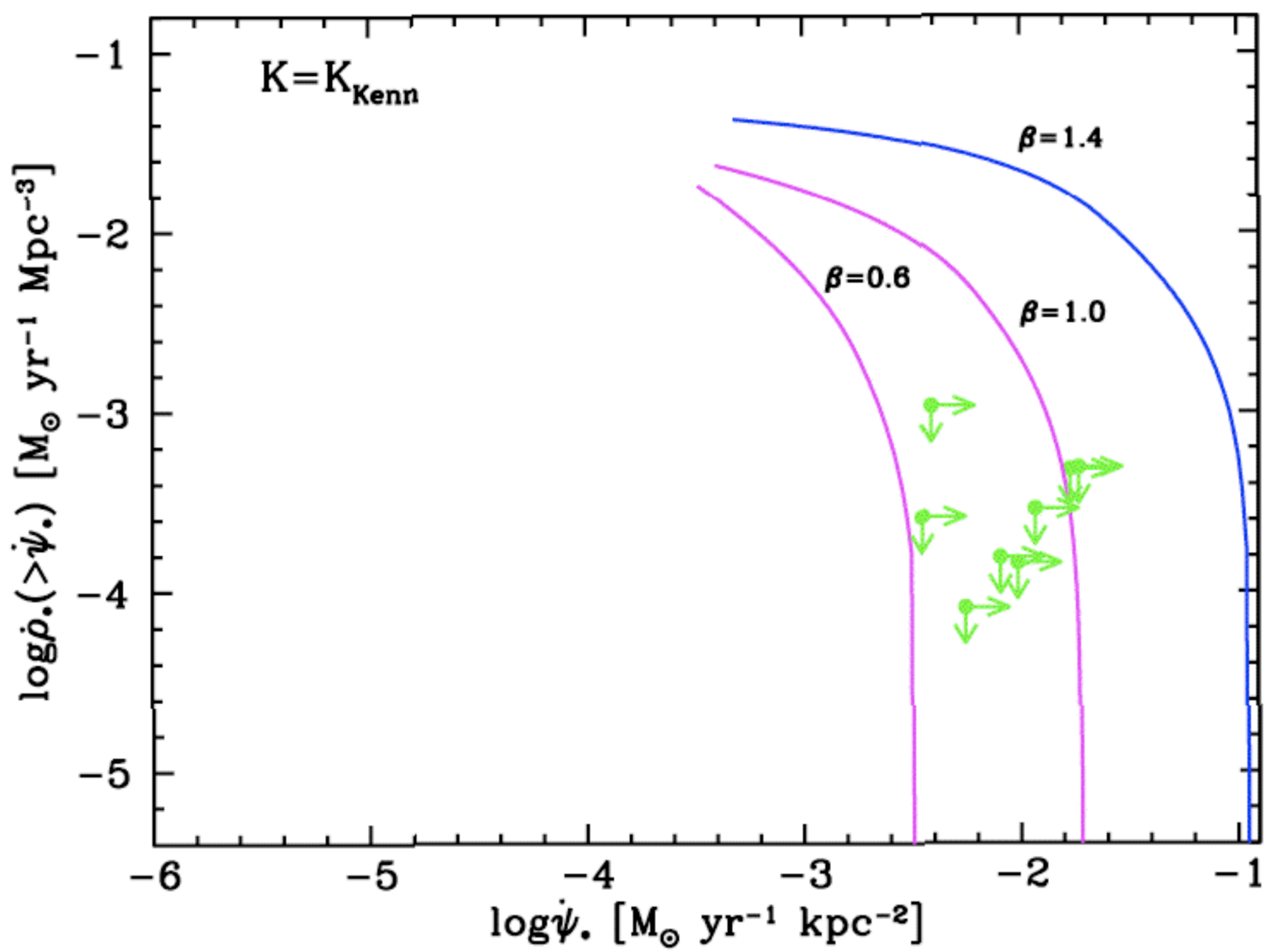
Cumulative Comoving SFR Density: Theory vs Data



Lower SFR Efficiencies: Effect of Decreasing Normalization K



Lower SFR Efficiencies: Effect of decreasing slope β



(1) Lower SFR efficiency due to low Molecular Content of DLAs

- Toomre instability produces gravitationally bound clouds: $N_\perp > N_\perp^{crit}$

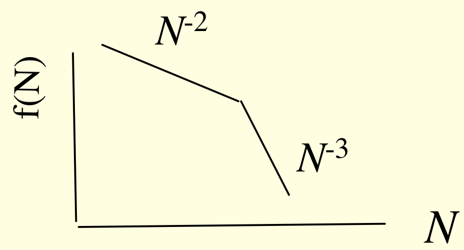
- But clouds cannot cool below ≈ 50 K due to low molecular content of DLA gas

  - DLA Median $f_{H2}=10^{-6}$
  - Galaxy Median $f_{H2}=10^{-1}$

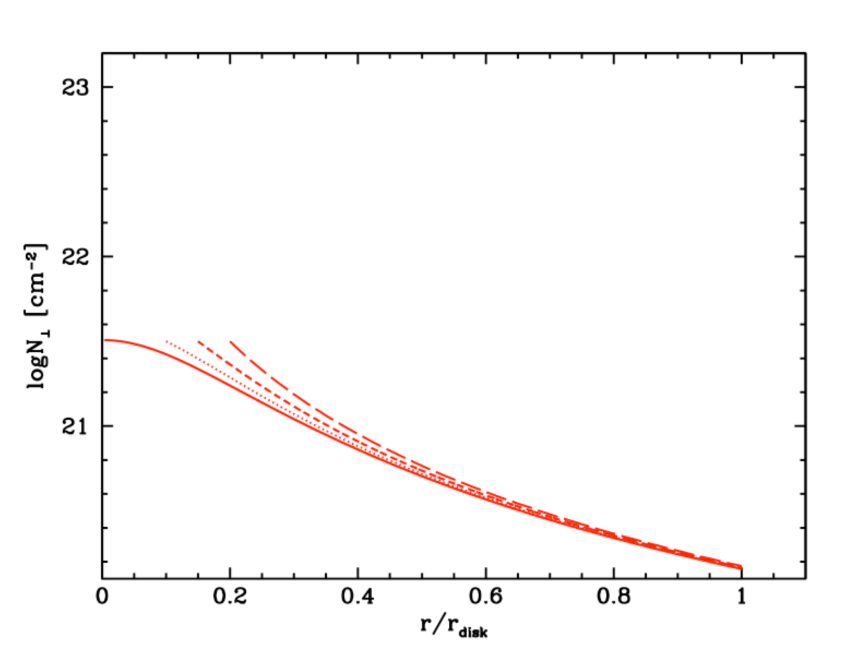
- In most models $\dot{\psi}_* \propto f_{H2}$

- Thus, gravitationally bound atomic clouds do not collapse to form stars

(2) But DLA disks may be sub-critical (Toomre stable)



• *f(N)* exhibits break at $N_{\text{break}}=10^{21.5}$ cm^{-2} . If DLAs are randomly oriented disks, N_{break} equals maximum $N_{\perp}$.



•Infer $N_{\perp}$ versus r from f(N)

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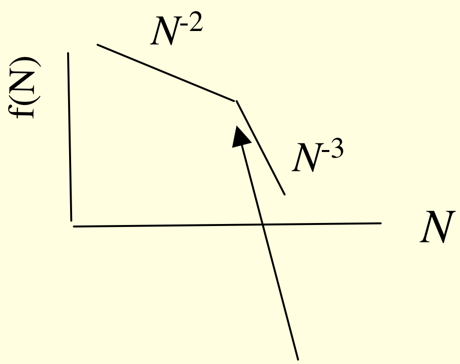

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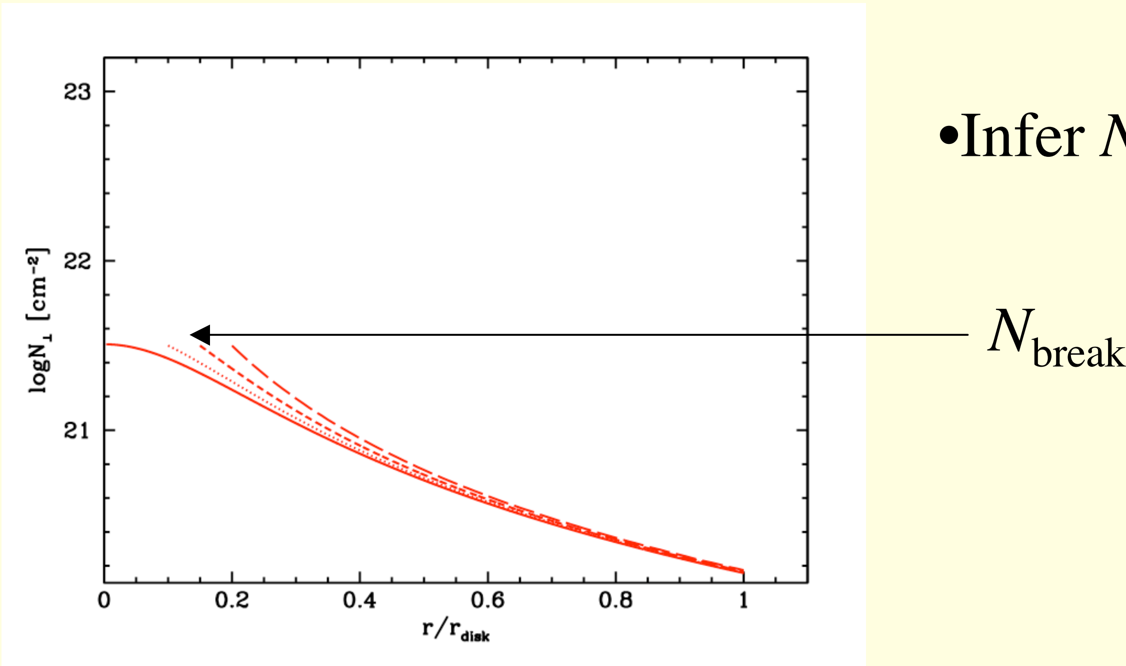

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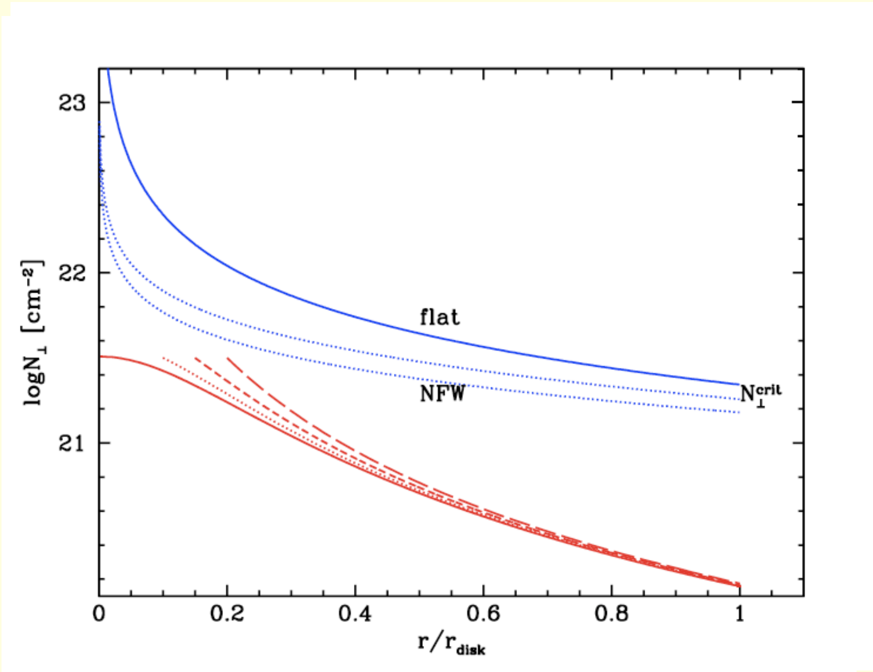
(3) Critical Surface Density Increasing function of z



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

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?

2. ***Limit on Energy Input from in situ star formation into neutral gas***

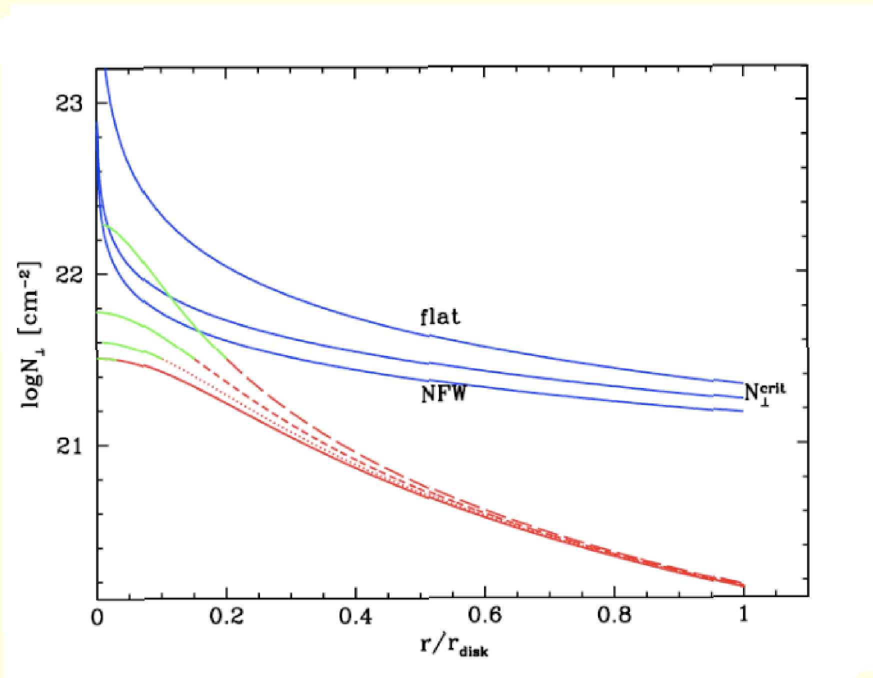
   -[C II] 158 μm cooling rate $\mathcal{C}$=(2.0±0.5)x10^{38} ergs s^{-1} Mpc^{-3}

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

   -Predicted comoving heating rate: H_{DLA}<2x10^{37}erg s^{-1} Mpc^{-3}

   -Source of Inferred Energy Input?

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

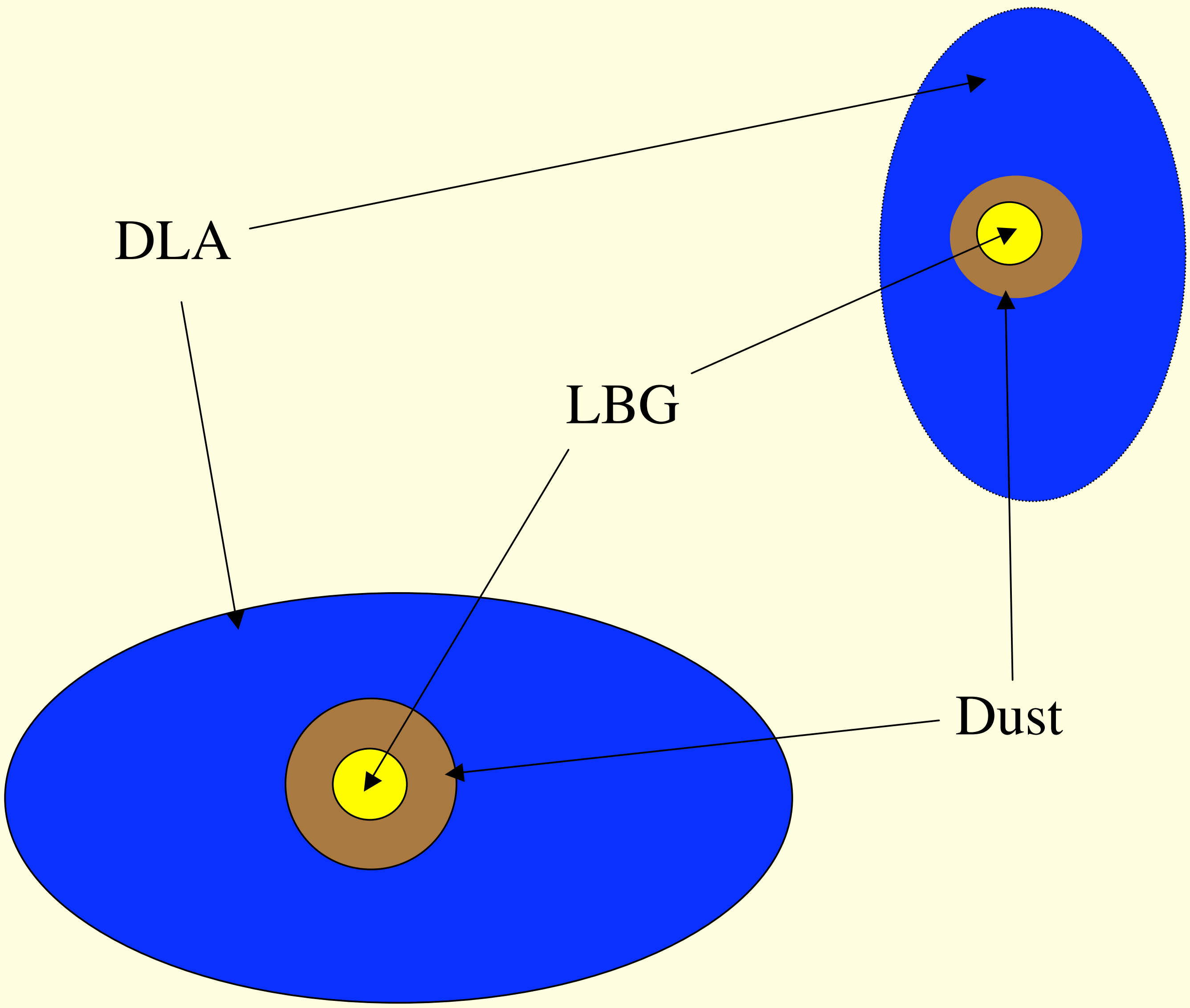


•Molecular gas may be located at $r < r_{\mathrm{break}}$

•Extend $N_\perp$ to $r < r_{\mathrm{break}}$

•Molecular gas may be Toomre unstable

Suggested LBG-DLA Configuration



Solution: Energy and Metal Input from LBGs

-Comoving Heating Rate from attenuated FUV LBG radiation:
$\boldsymbol{H_{LBG}}$=(3.0 ±1.5)x10^{38} ergs s^{-1} Mpc^{-3}

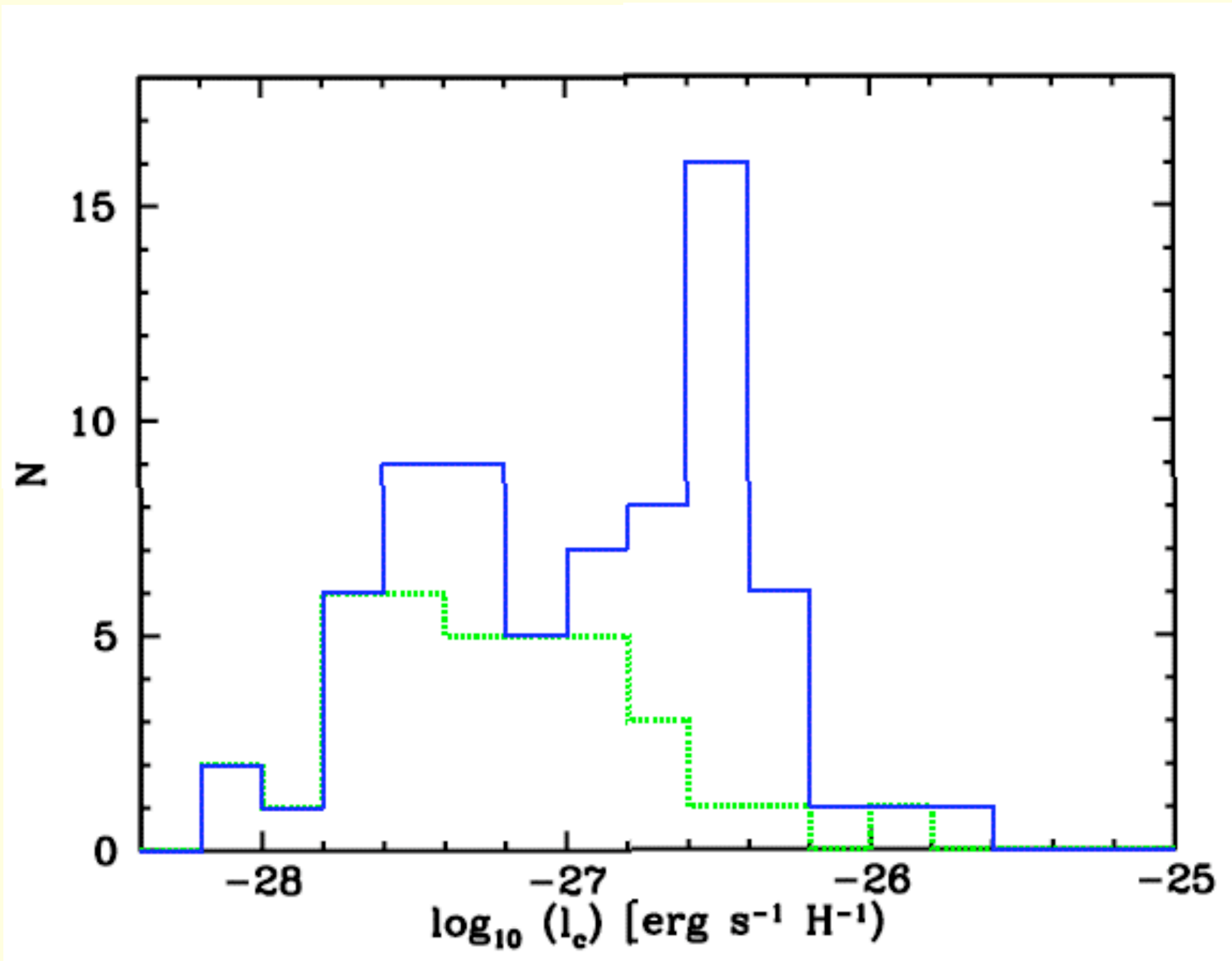
-Metal input due to P-Cygni winds emitted by LBGs a possiblity

Solution does not apply to 50% of DLA population Heated by background radiation alone

-Embedded LBGs not required in these cases

-Source of metals?

Frequency Distribution of [C II] 158 μm Cooling Rates



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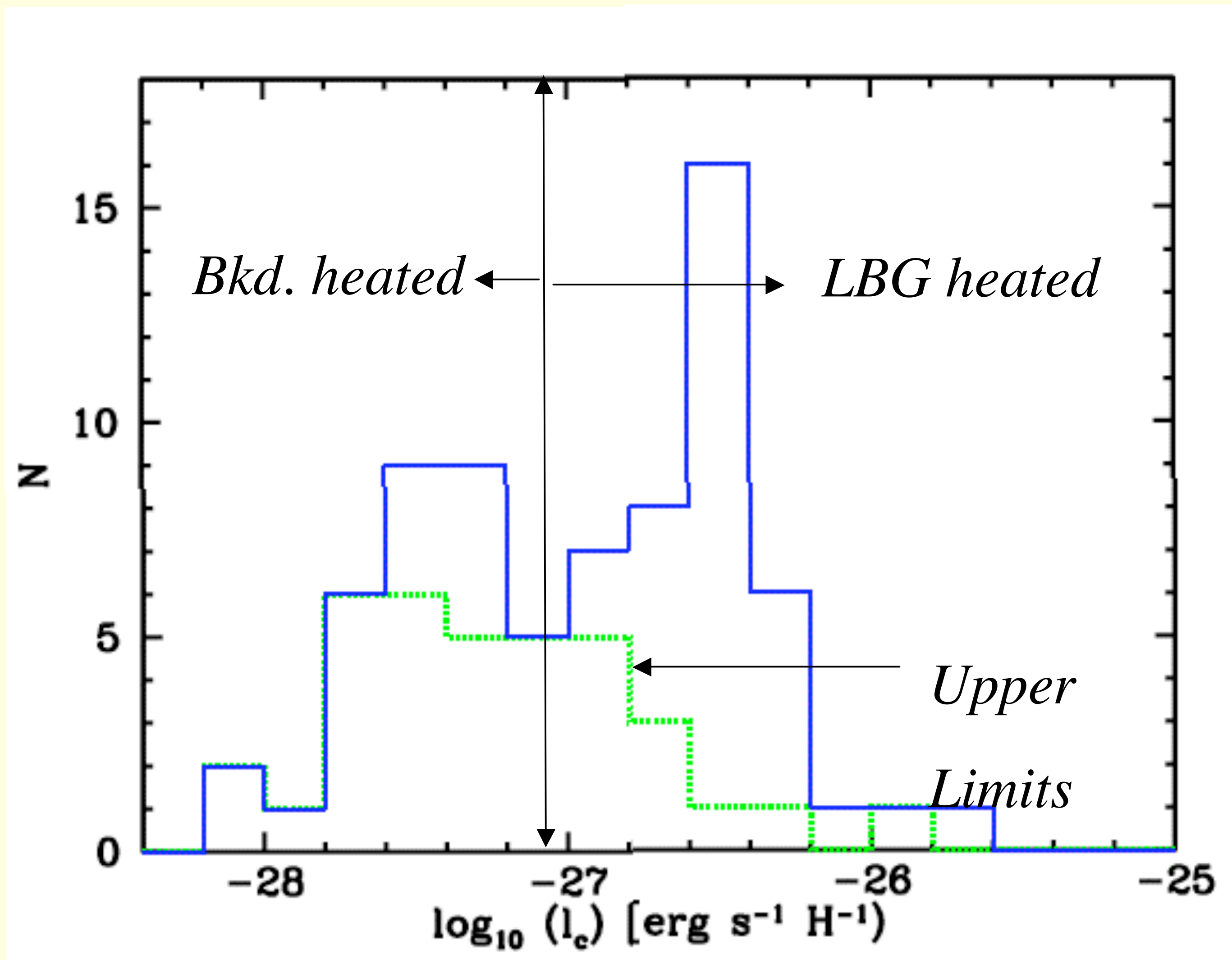

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•Suggested Scenario

-DLAs with higher [C II] cooling rates powered by centrally located LBGs, which may also supply required metals

-1/2 of DLA population heated by background radiation:no LBGs