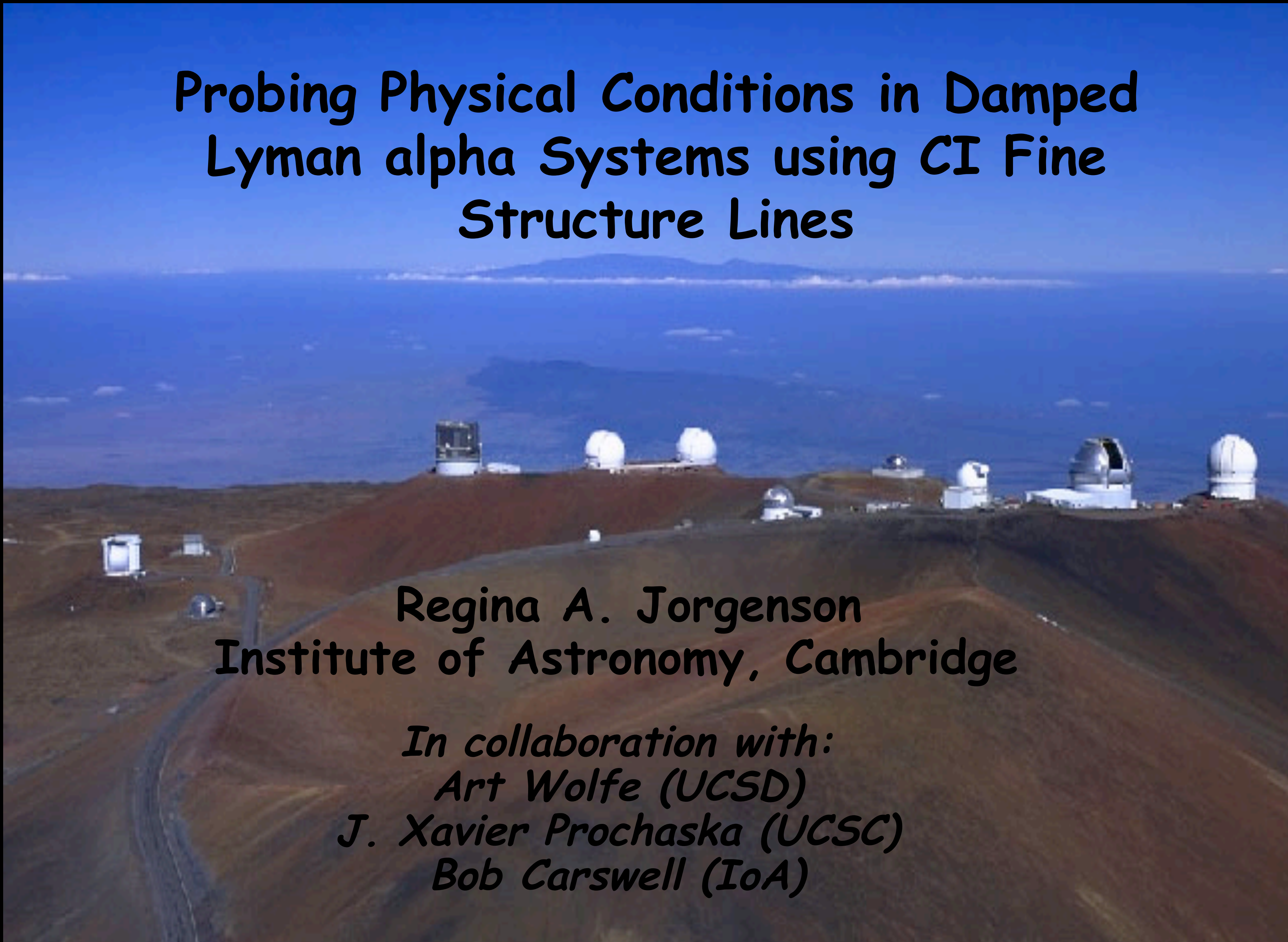

Probing Physical Conditions in Damped Lyman alpha Systems using CI Fine Structure Lines

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In collaboration with:
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Bob Carswell (IoA)

DLA Temperature ‘Controversy’
WNM vs CNM

- 21-cm data ➔ Gas mostly warm:
- Kanekar & Chengular, 2003: Searched for 21-cm absorption towards 10 DLAs. Found none.
  - Place lower limits : T > 1,000 K ; sometimes T > 9,000 K.
- Kanekar et al., 2007: In the few cases of positive detections they argue that the cold gas (CNM) fraction must be low (~17%).

- Wolfe CII* technique ➔ Gas mostly cold:
- Wolfe et al. 2003, 2004: DLAs containing strong CII* absorption must be CNM to avoid violating observed bolometric background limit.
- CII* absorption measured in ~50% of unbiased sample of DLAs, implies covering fraction of CNM ~50%.

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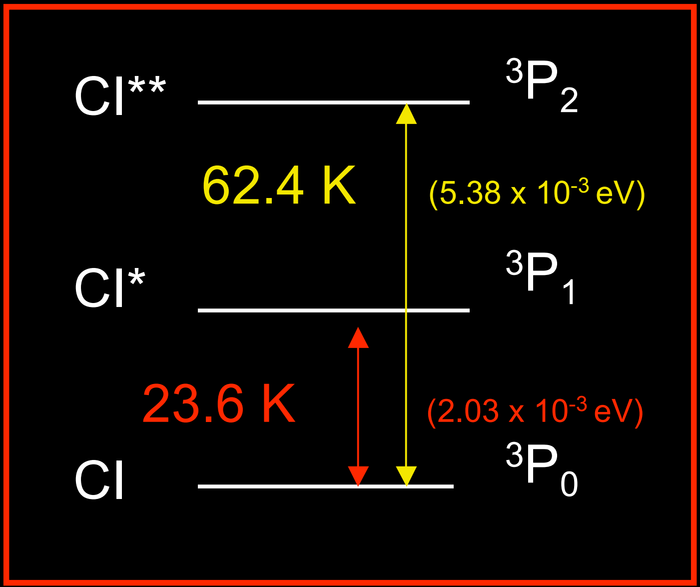
Constraining Physical Conditions (density, temperature, pressure) in DLAs Using Neutral Carbon (CI) Fine Structure Lines

- CI is a sensitive probe of conditions in cold gas.
  - Energy separation between the fine structure states is *extremely* small
- Relative amounts of C in the fine structure states is determined by gas pressure and temperature
  - Levels are populated primarily by collisions
  - Direct excitation by the CMB is significant at high z



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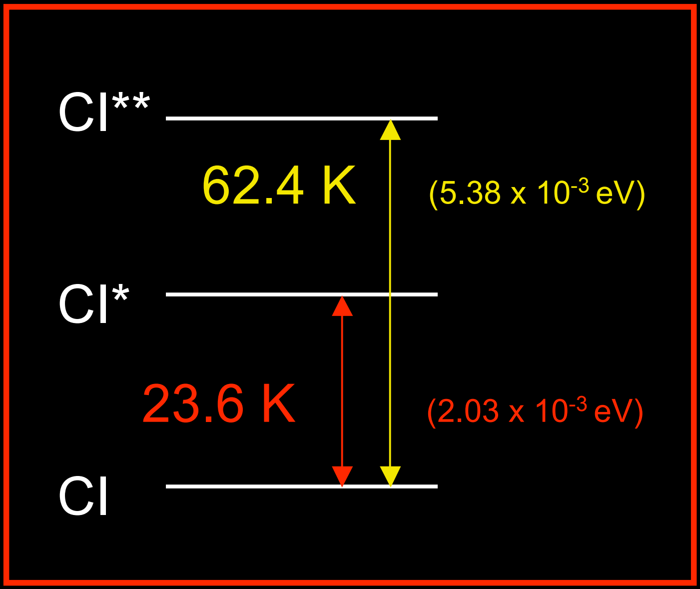
Steady State Solution

$$\sum_j n_j \left(A_{ji} + B_{ji} u_{ji} + \sum_k n^k q_{ji}^k \right) = n_i \sum_j \left(A_{ij} + B_{ij} u_{ij} + \sum_k n^k q_{ij}^k \right)$$

- Include spontaneous radiative decay, excitation by radiation fields (CMB, Haardt-Madau, stellar), collisions (HI, e-, p+)



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Radiative decay

Steady State Solution

$$\sum_j n_j \left(A_{ji} + B_{ji} u_{ji} + \sum_k n^k q^k_{ji} \right) = n_i \sum_j \left(A_{ij} + B_{ij} u_{ij} + \sum_k n^k q^k_{ij} \right)$$

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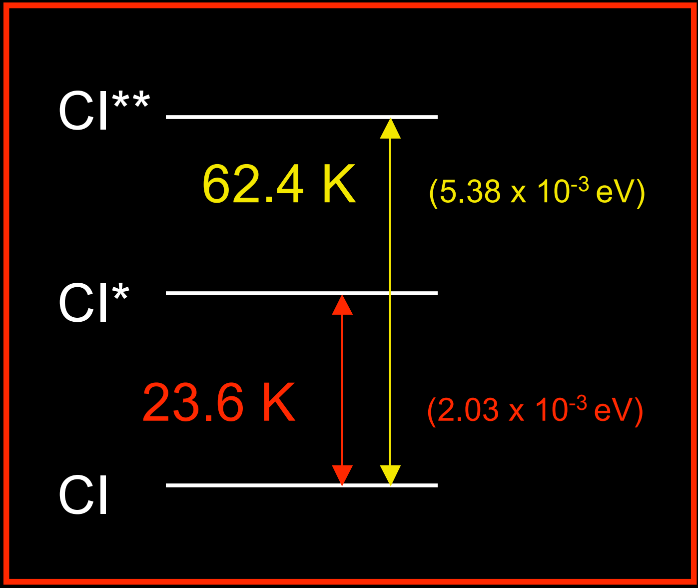

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Radiative decay

Radiation Field

Steady State Solution

$$\sum_j n_j \left(A_{ji} + B_{ji} u_{ji} + \sum_k n^k q^k_{ji} \right) = n_i \sum_j \left(A_{ij} + B_{ij} u_{ij} + \sum_k n^k q^k_{ij} \right)$$

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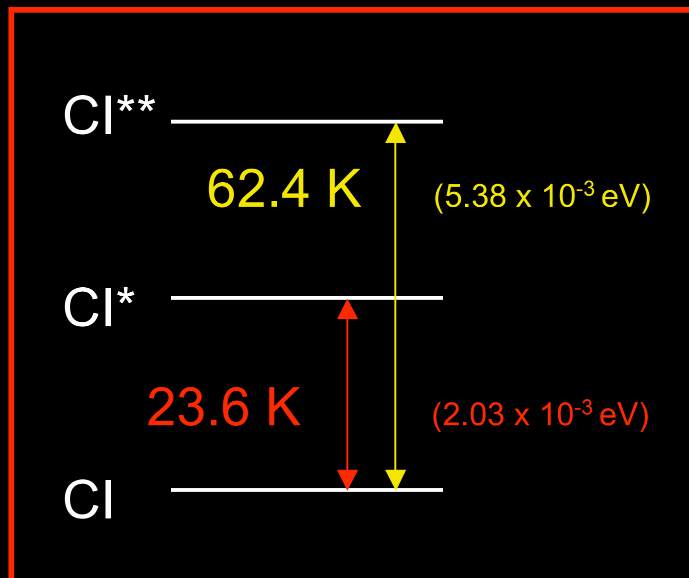

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Radiative decay

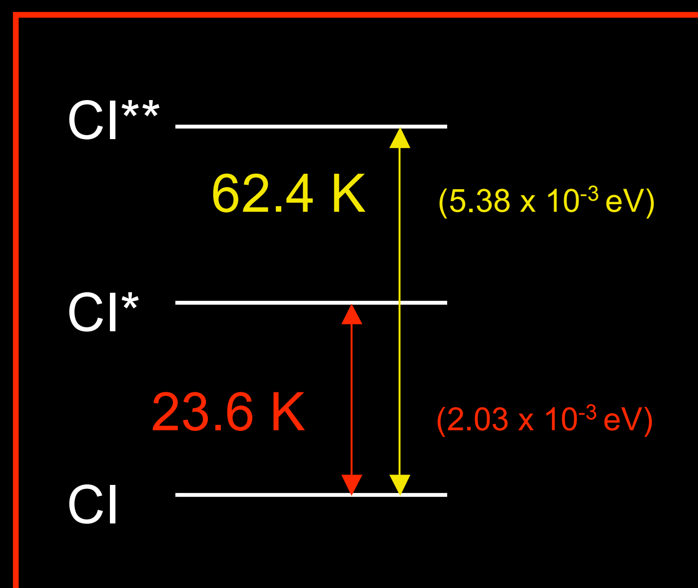
Radiation Field

collisions

Steady State Solution

$$\sum_j n_j\left(A_{ji}+B_{ji}u_{ji}+\sum_k n^k q_{ji}^k\right)=n_i\sum_j\left(A_{ij}+B_{ij}u_{ij}+\sum_k n^k q_{ij}^k\right)$$

- Include spontaneous radiative decay, excitation by radiation fields (CMB, Haardt-Madau, stellar), collisions (HI, e-, p+)



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Radiative decay — Radiation Field — collisions

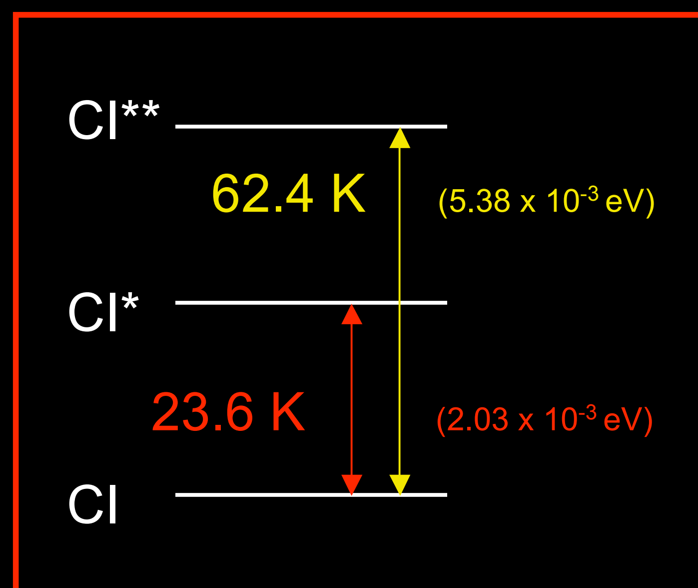
Steady State Solution

$$\sum_j n_j \left(A_{ji} + B_{ji} u_{ji} + \sum_k n^k q^k_{ji} \right) = n_i \sum_j \left(A_{ij} + B_{ij} u_{ij} + \sum_k n^k q^k_{ij} \right)$$

- Include spontaneous radiative decay, excitation by radiation fields (CMB, Haardt-Madau, stellar), collisions (HI, e-, p+)
- 3 levels ➔ 3 homogeneous equations and 3 unknowns:
  - Solve for three levels simultaneously
  - Solve for ratios of the density of each level as a function of n(HI) and T:

$$\frac{n(CI^*)}{n(CI)}(n(HI),T)$$

$$\frac{n(CI^{**})}{n(CI)}(n(HI),T)$$



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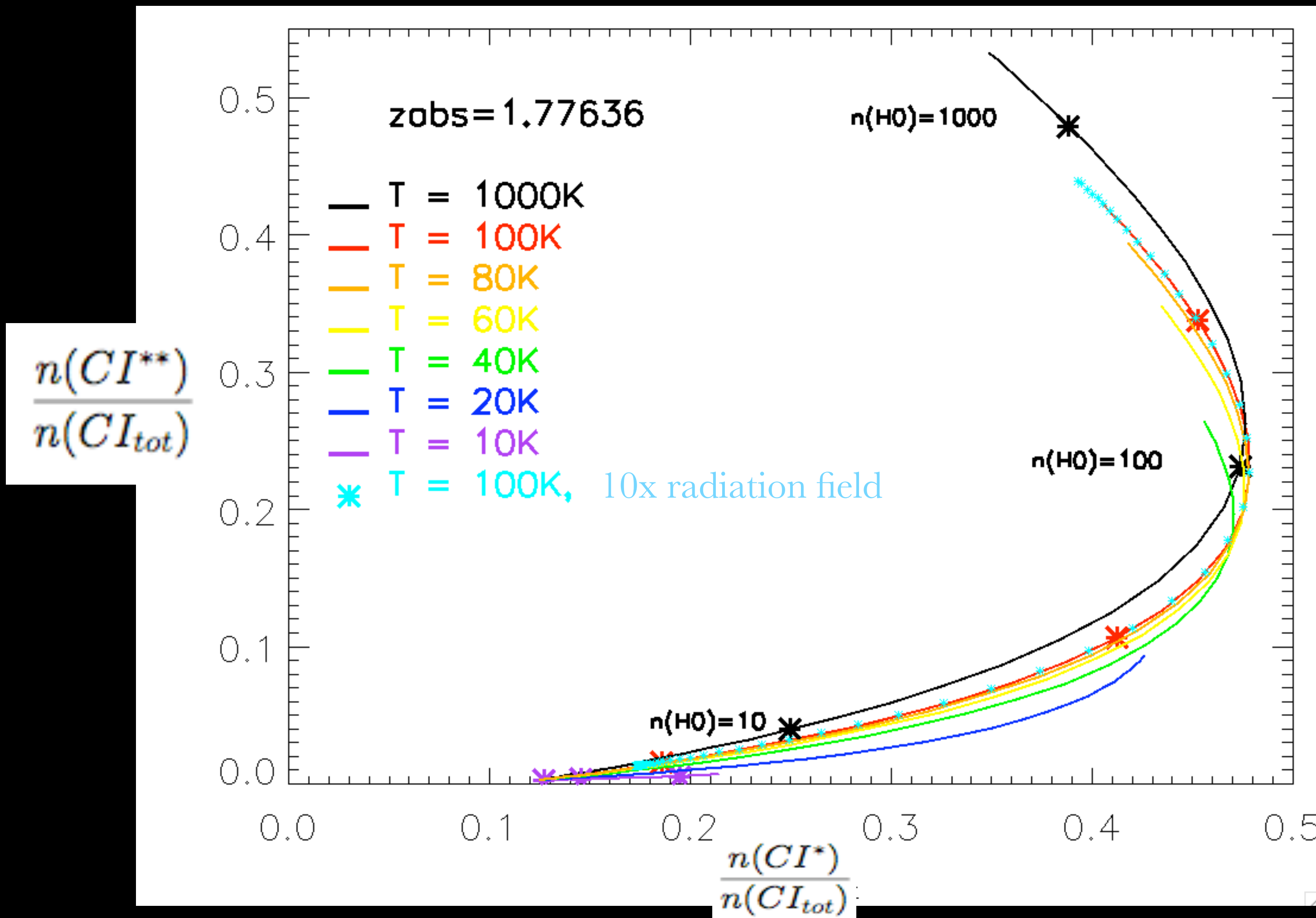
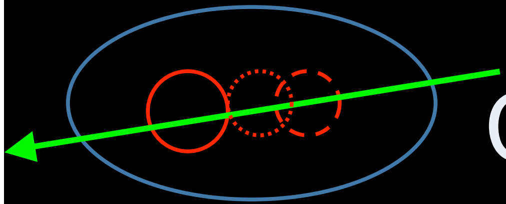
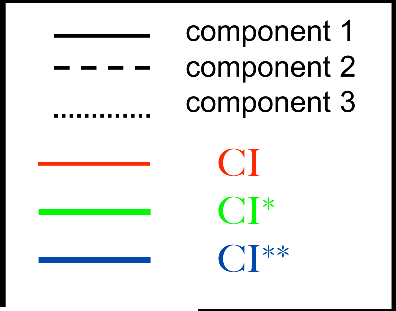
Theoretical Solutions

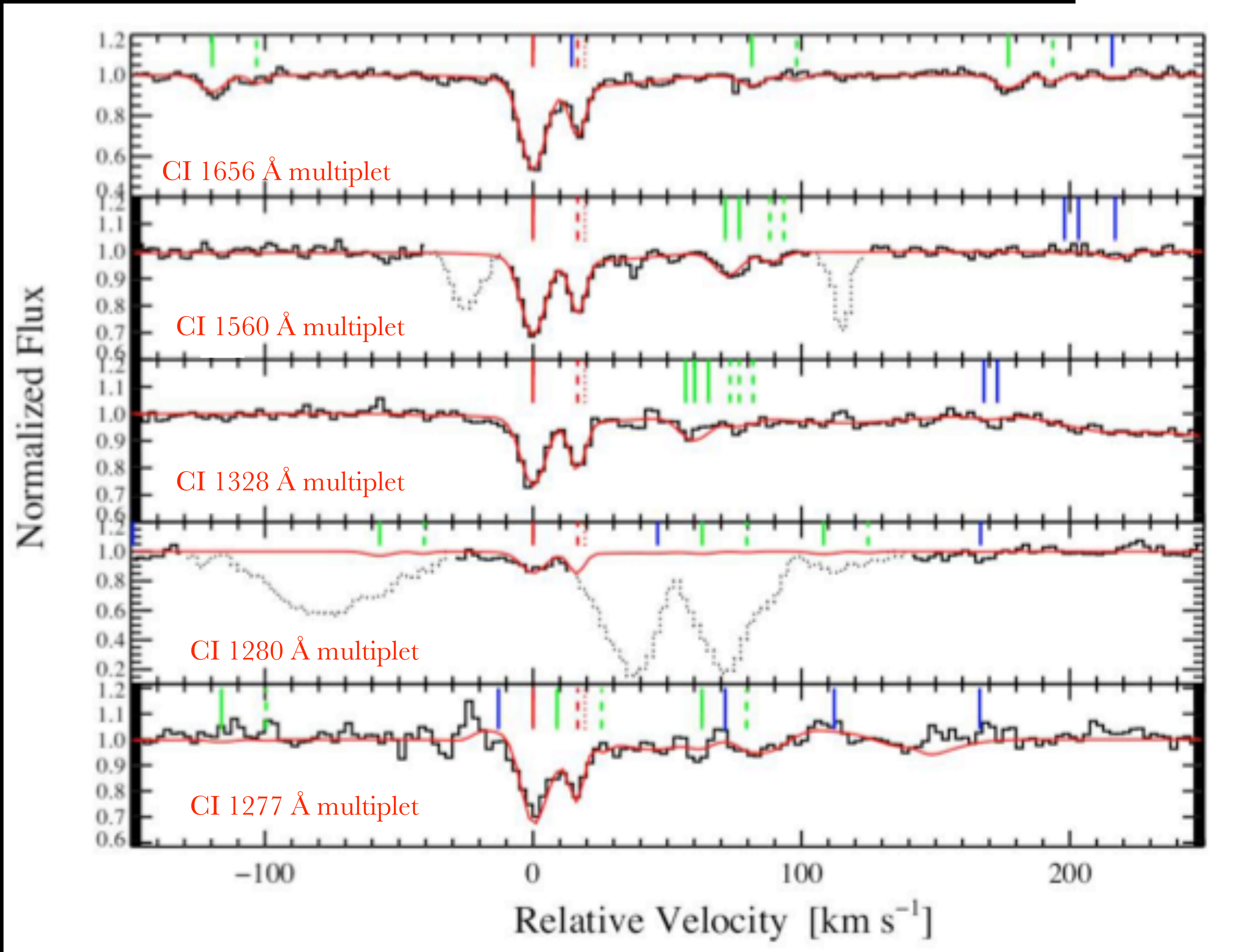


$$n(CI_{tot}) = n(CI) + n(CI^{*}) + n(CI^{**})$$



CI data: DLA1331+17





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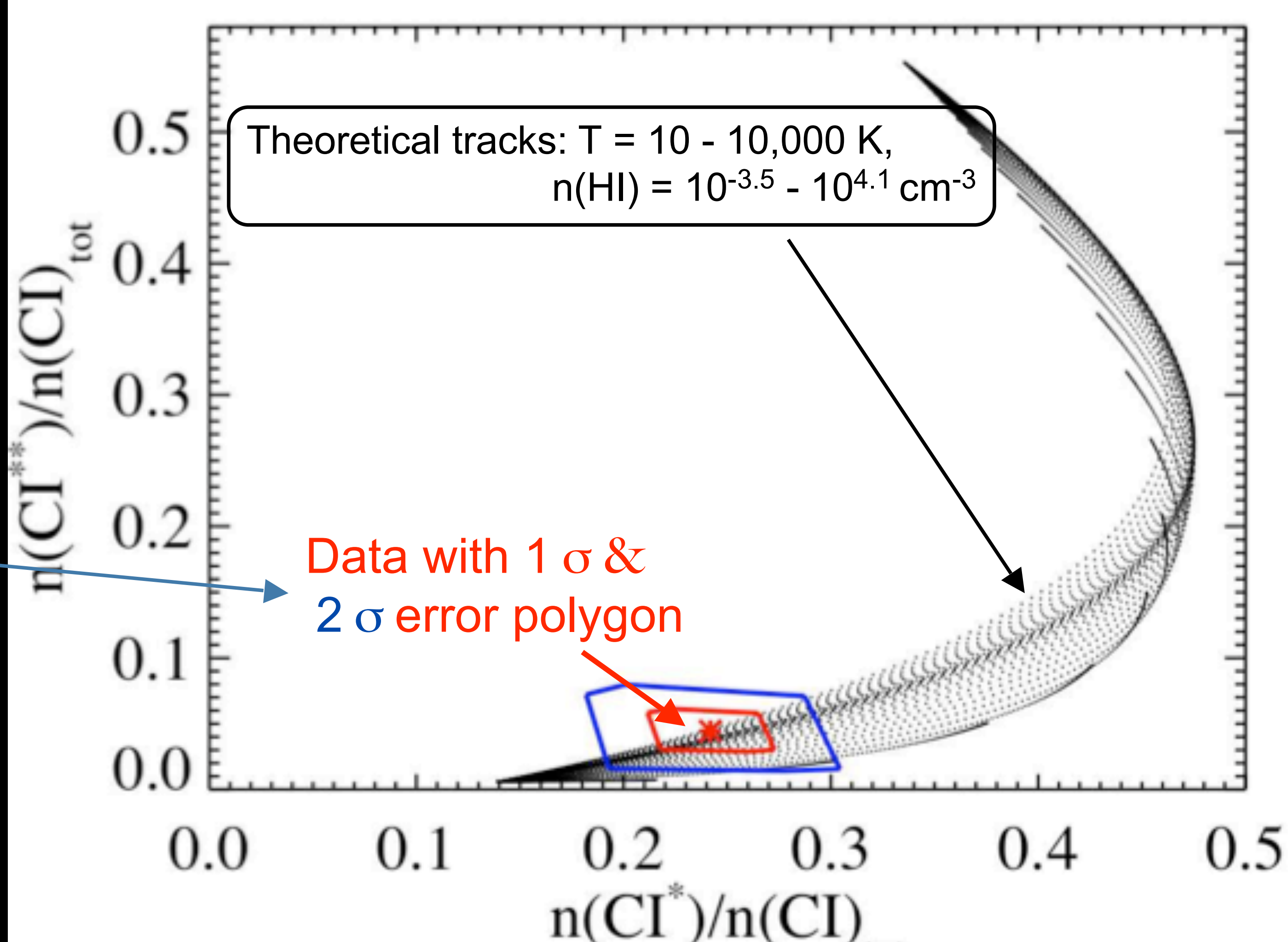
CI Data: constraining n and T

Component 1:

- z_{abs}=1.77636
- **log N(CI)= 13.00 +- 0.01**
- **log N(CI*) = 12.53 +- 0.05**
- **log N(CI**) = 11.80 +- 0.15**



$n(CI_{tot}) = n(CI) + n(CI^{*}) + n(CI^{**})$

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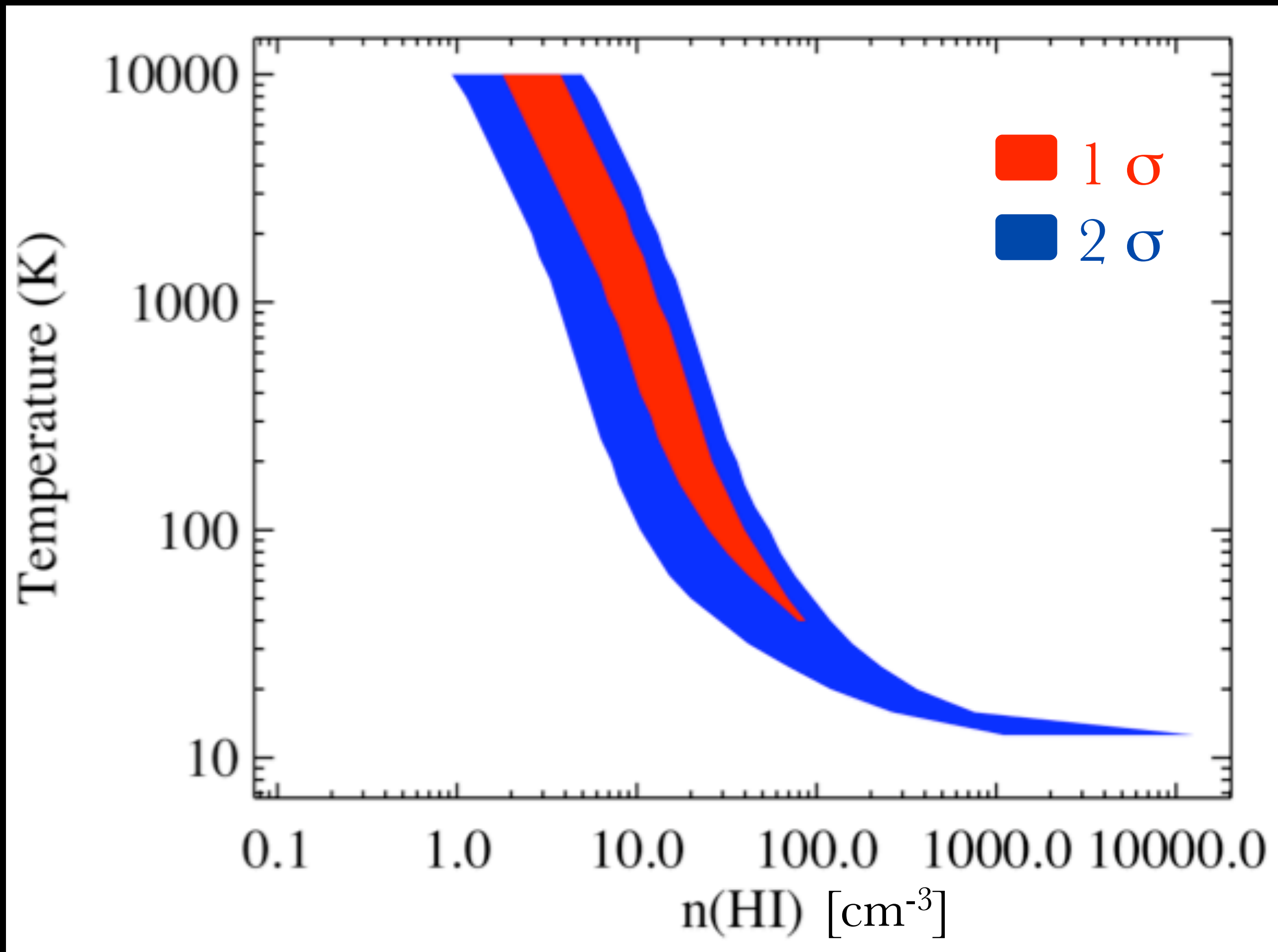
CI Data: n(H I) versus T



➔ Constrains n, but T is degenerate

Include Ionization Equilibrium

- Determines CII/CI for a given radiation field (J_ν) and Temperature.

$$\frac{CII}{CI} \propto \frac{J_\nu}{\alpha_{CI} x n}$$

- Radiation Field determined by CII* technique:
  - i.e. For DLA 1331+17: $J_\nu \approx 3 \times 10^{-19}$ ergs cm^{-2} s^{-1} Hz^{-1} sr^{-1}
- CII/CI is also an observed quantity

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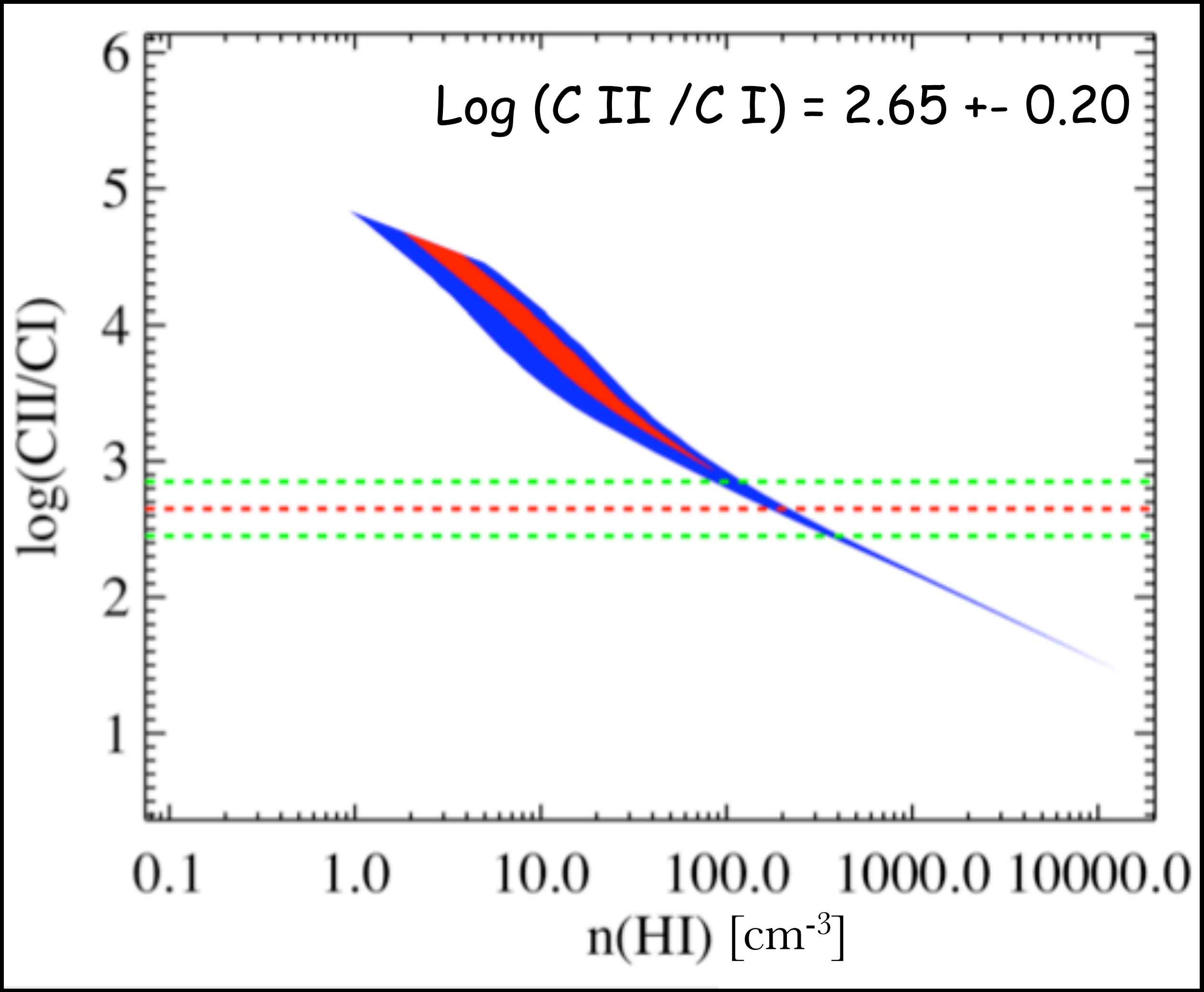
Data: CII/CI ➔ measured ratio constrains results



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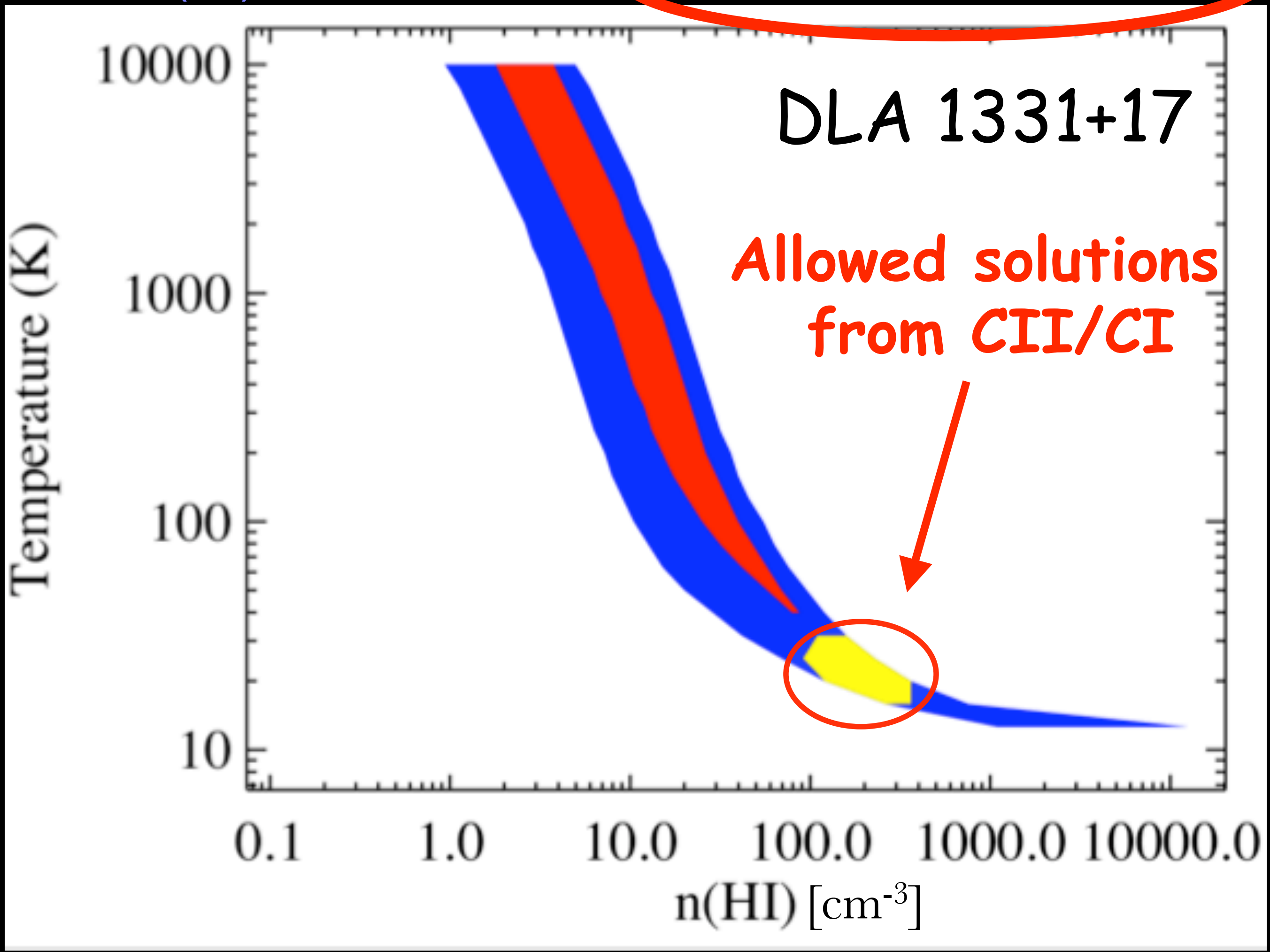
Results:

☑ Constraint on temperature and density

n(HI) ≈ 90 - 360 cm^{-3}, T ≈ 16 - 32 K → CNM



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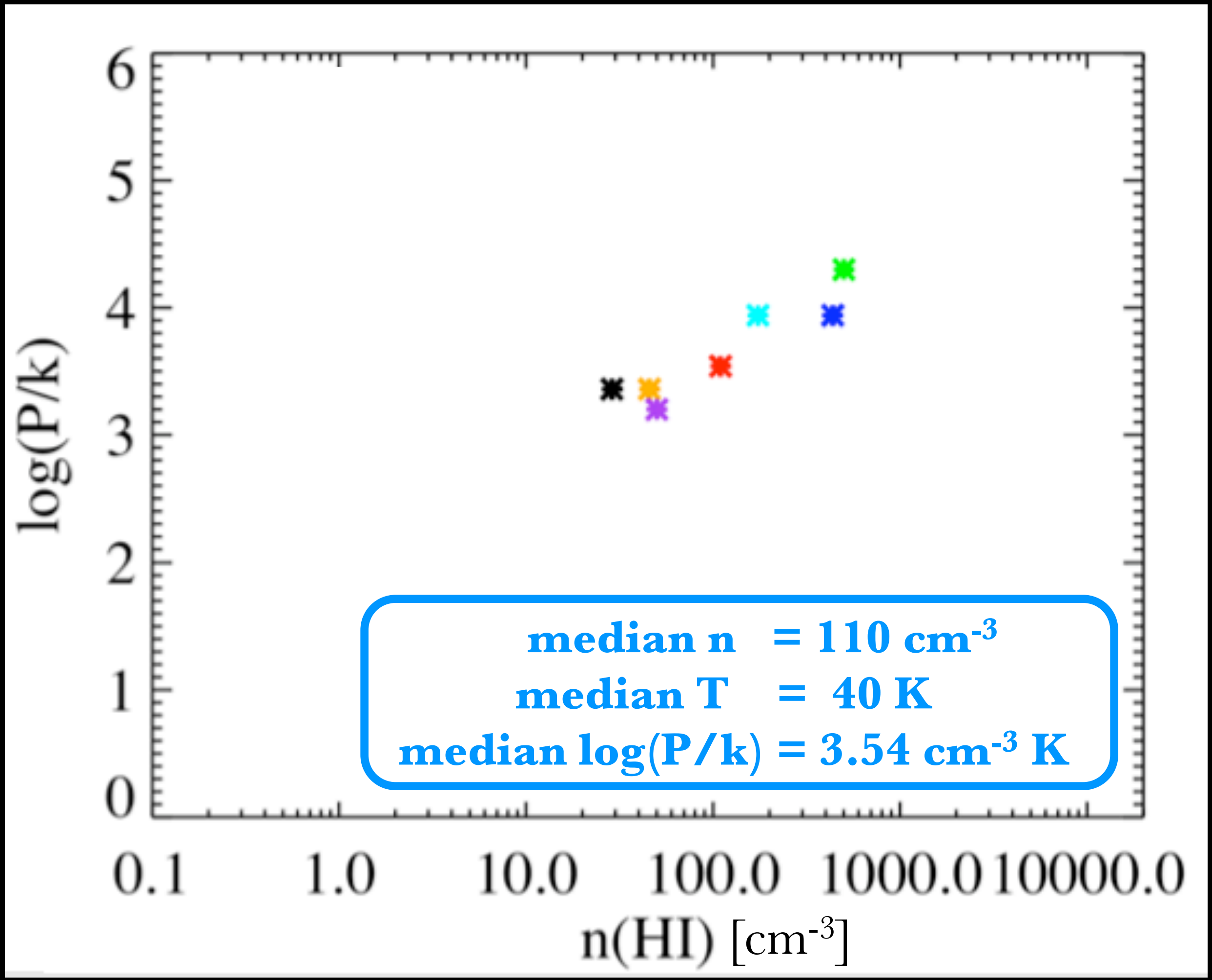
Summary of CI-bearing DLAs

Pressure
(= n x T)



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Pressure
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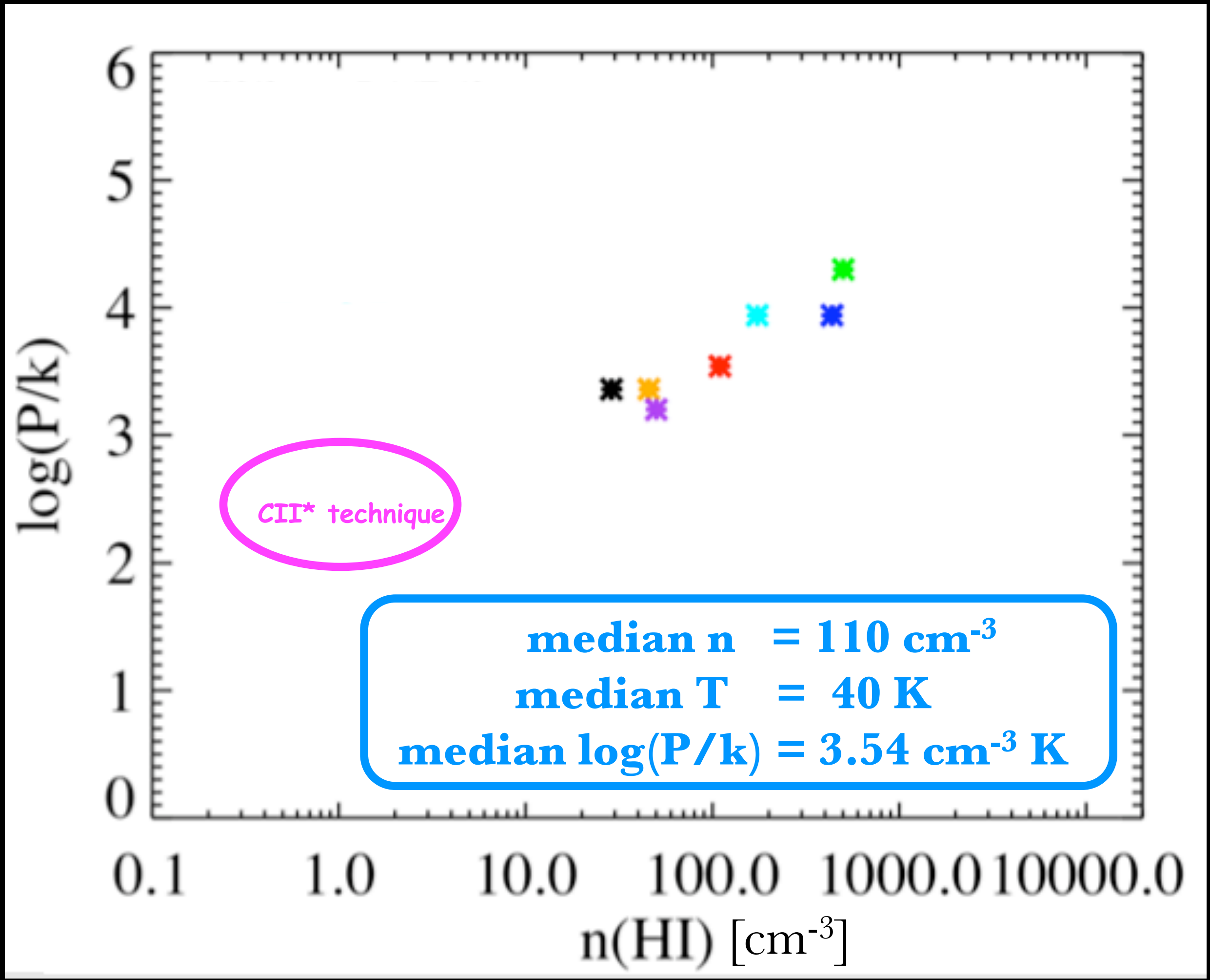

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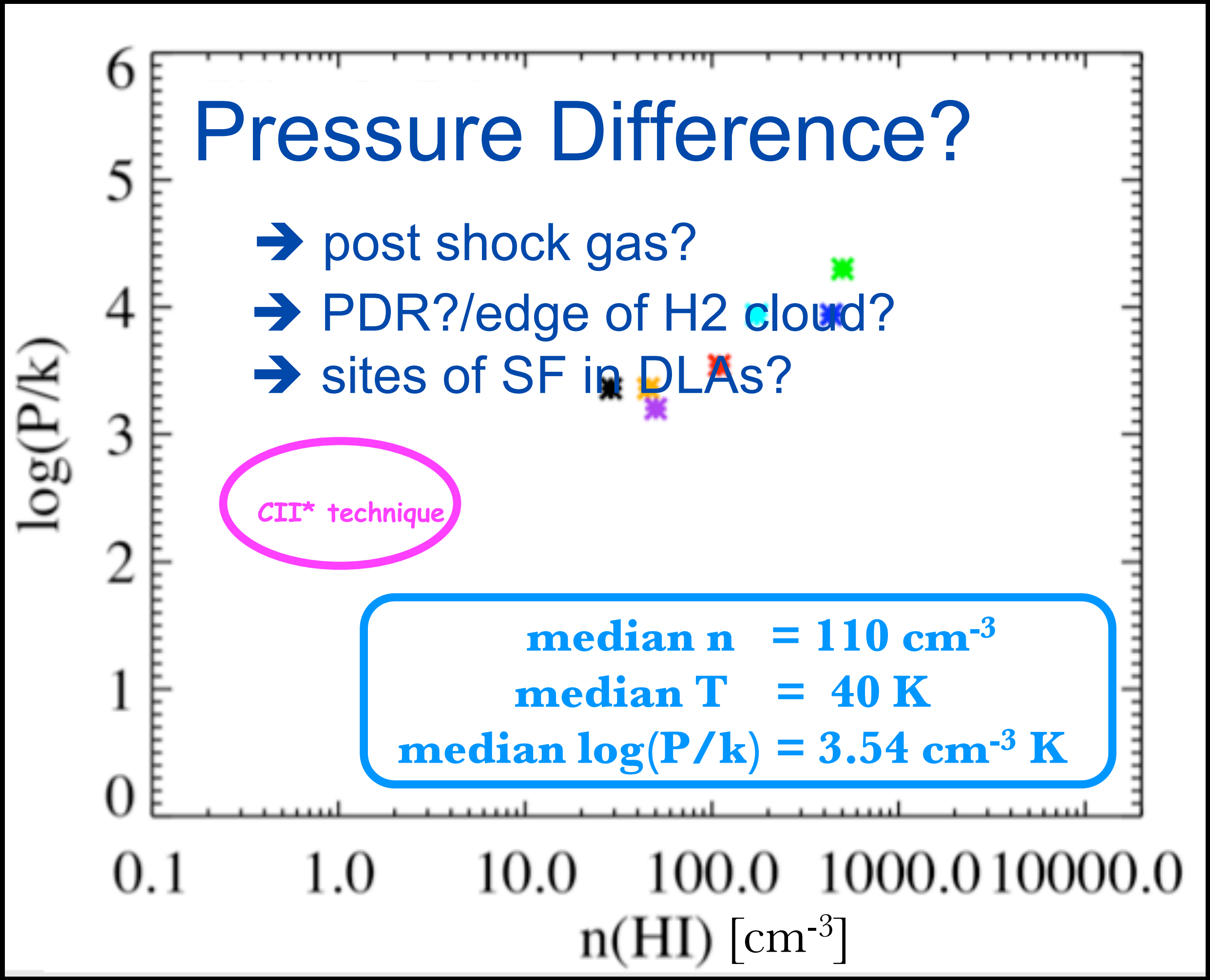

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Summary of CI-bearing DLAs

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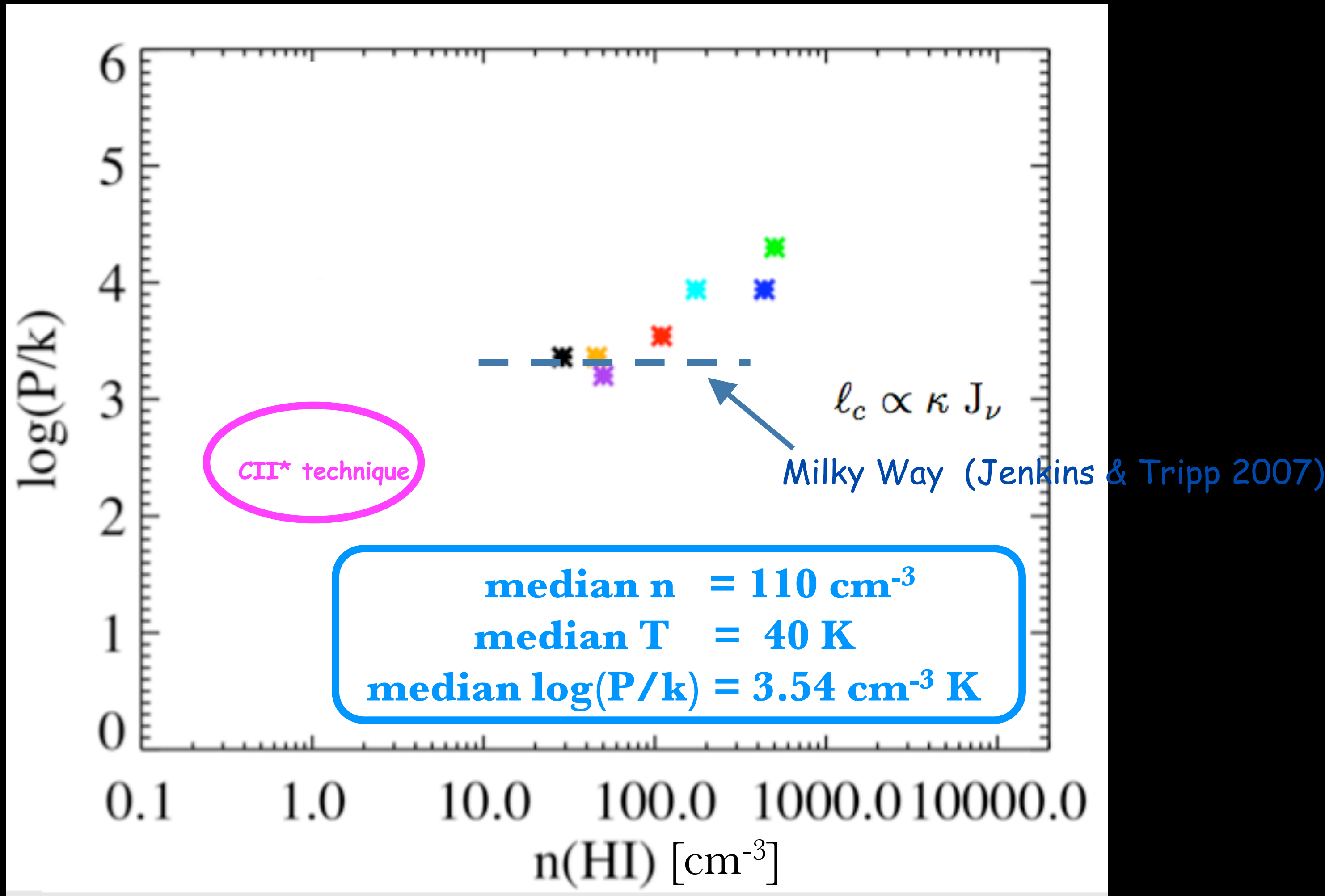
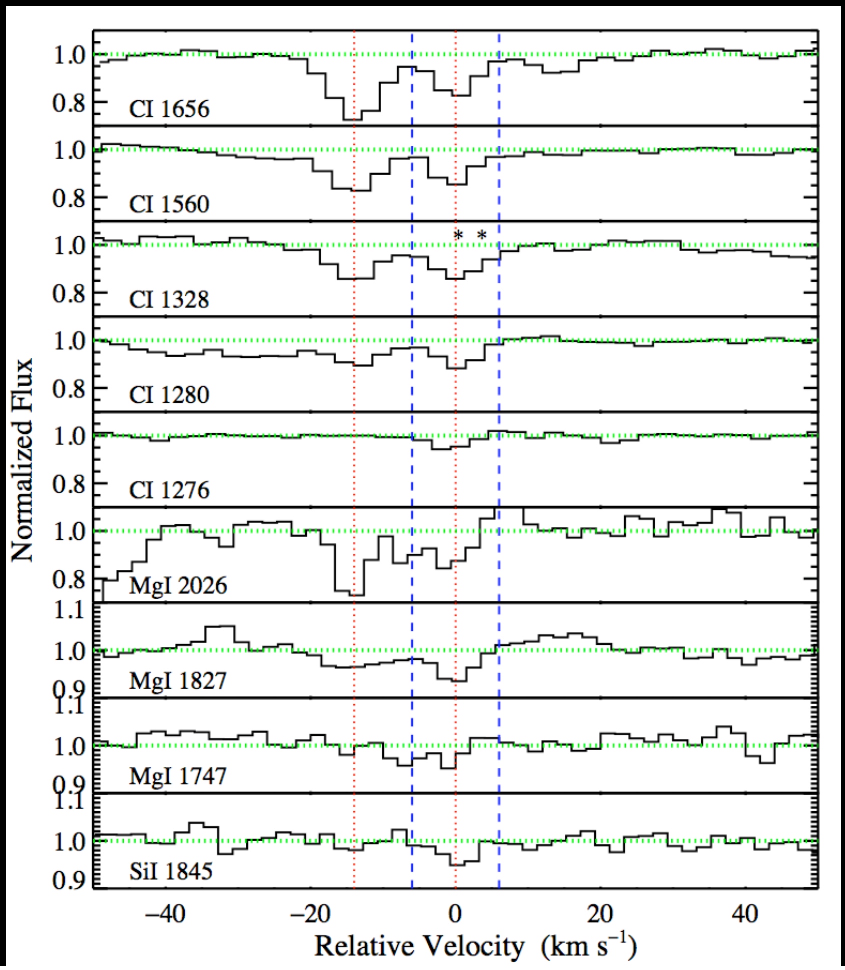


Direct Detection of Cold Gas in DLA 0812+32B

(Jorgenson, et al. *ApJ*, submitted)

- Discovery of sub-resolution, sub-1 km/s component



$$b = (2)^{1/2}\ \sigma$$

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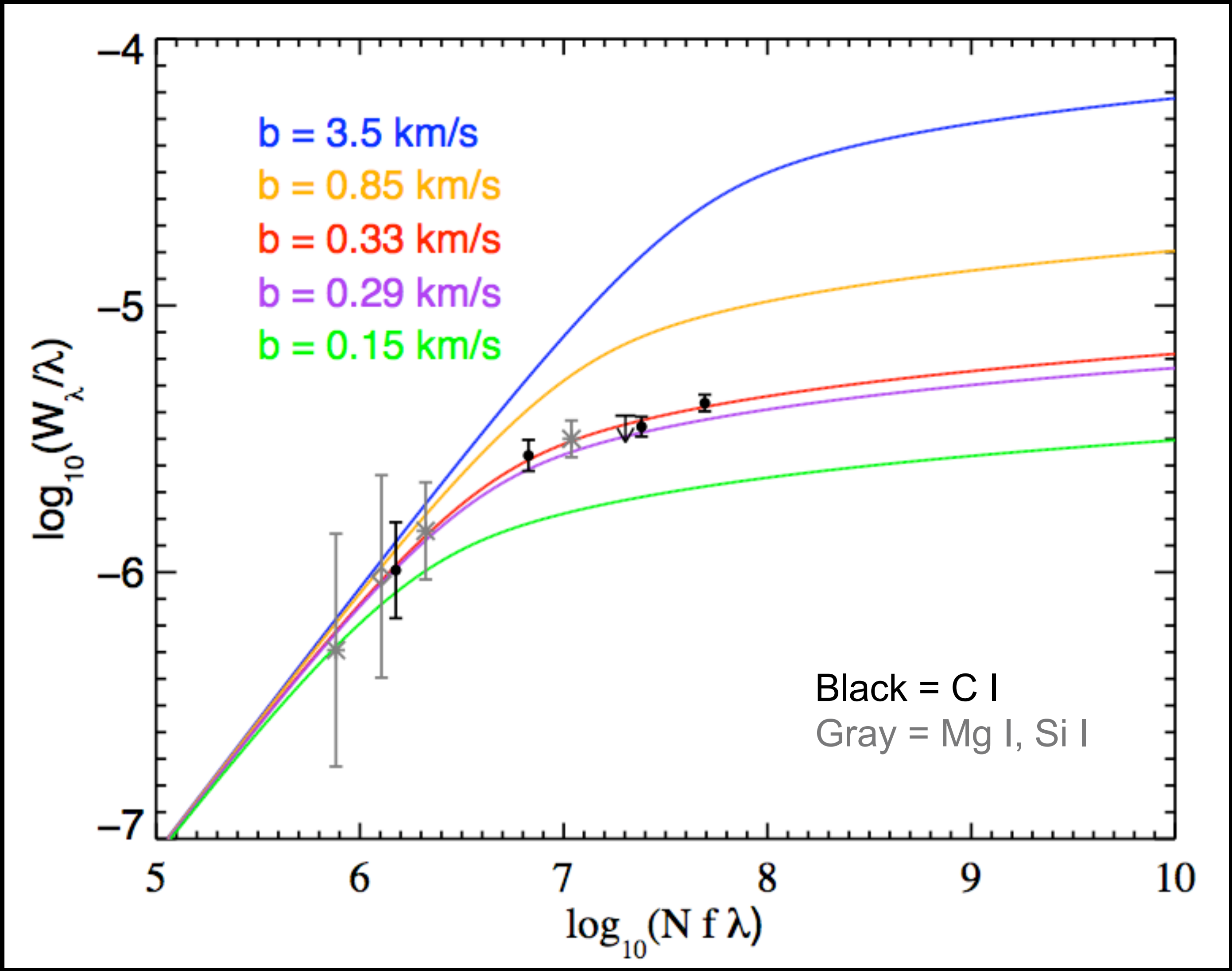
Curve of Growth



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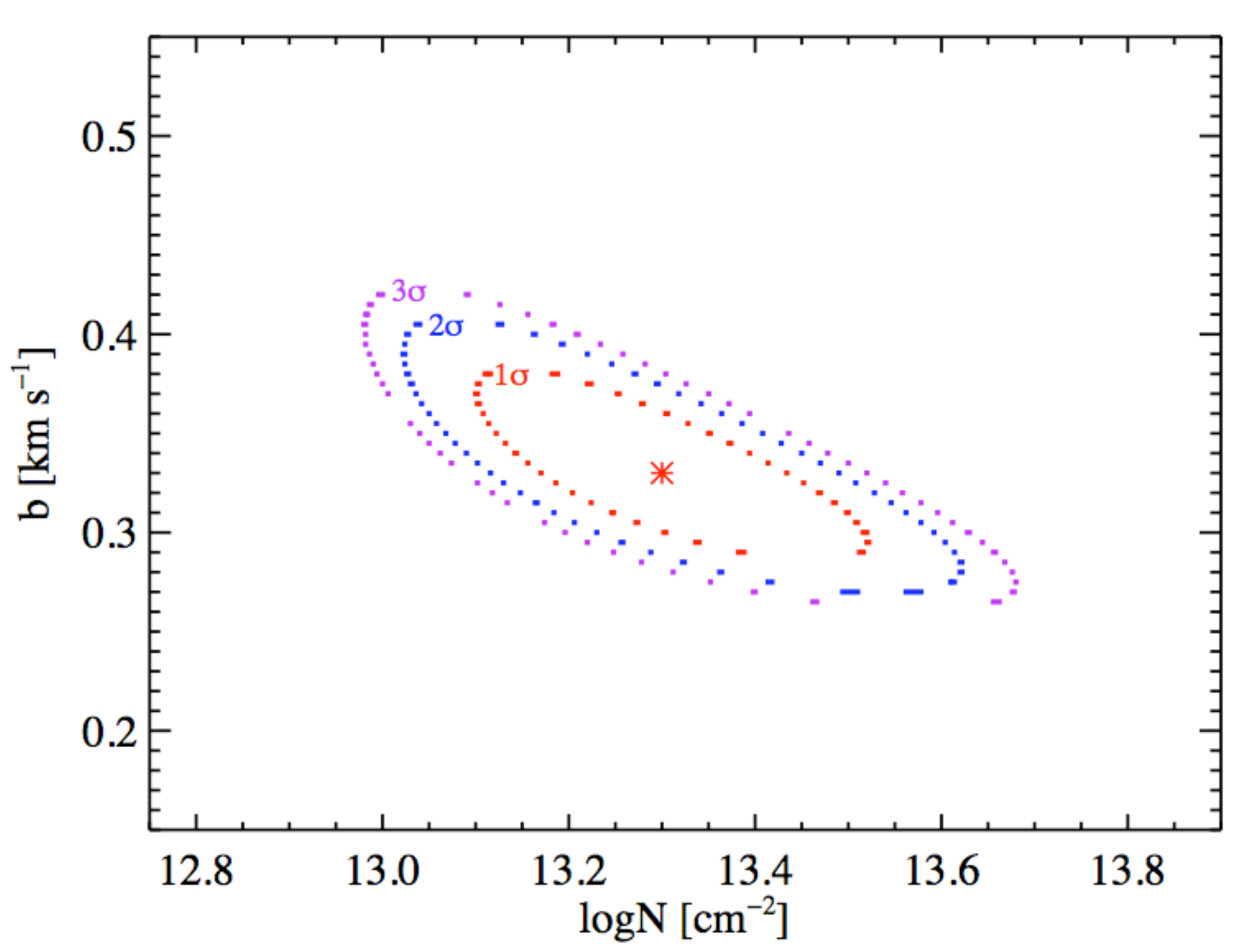
$\Delta\chi^2$ test:

$b = 0.33^{+0.05}_{-0.04}\text{km s}^{-1}$, and $\log N(\text{C I}) = 13.30 \pm 0.2\ \text{cm}^{-2}$



Use narrow component to constrain temperature of gas

$$b^2_{thermal} = \frac{2kT}{m} = \frac{T}{60A} \; km \; s^{-1}$$

$$T_{thermal} \leq 78 \; K \; (\leq 115 \; K, 2\sigma)$$

→ CNM

Cold cloud confirmed by…

- C I fine structure lines COG
- Mg I COG
- Molecular hydrogen (H_2)
  - – T_{ex} = 42 K
    - Log $N(H_2)_{total}$ = 19.88 cm^{-2}, f_{H2} > 0.06

Cloud parameters:

- n (H I) = 40 - 200 cm^{-3}
  - – P/k = 2500 - 16,000 cm^{-3} K
    - size >= 0.6 - 0.1 pc
      - – (using N(H2) as lower limit estimate of column density)

Discussion

- Carswell et al. 2009, in prep: Another narrow, cold component:
  - b = 0.54 +- 0.08 km/s, T < 200 K (2 sigma: T< 350 K)
- At least 2 out of ~ 20 DLAs with CI/H_2 have narrow cold components. ==> covering fraction >~10% of CI-DLAs
- Are these cold components common?
- Could they be self-gravitating?

Conclusions

- DLAs are key components for understanding star and galaxy formation at high redshift
- CI-bearing gas exists in higher density and pressure knots than the surrounding DLA gas.
- Are we beginning to probe the sites of star formation in high z DLAs?
- Narrow CI components reveal unambiguously cold gas (T ~ 100 K)
- Are these cold components ubiquitous?