Understanding The X Factor in Molecular Clouds

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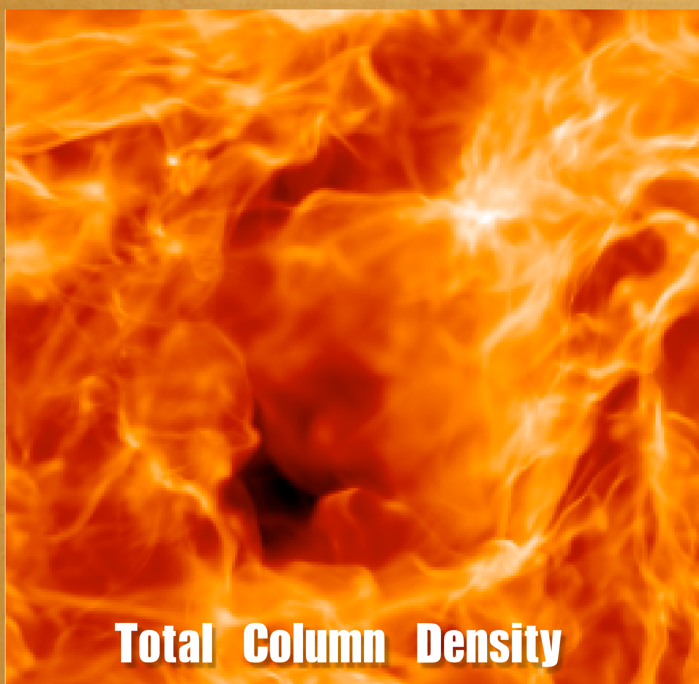

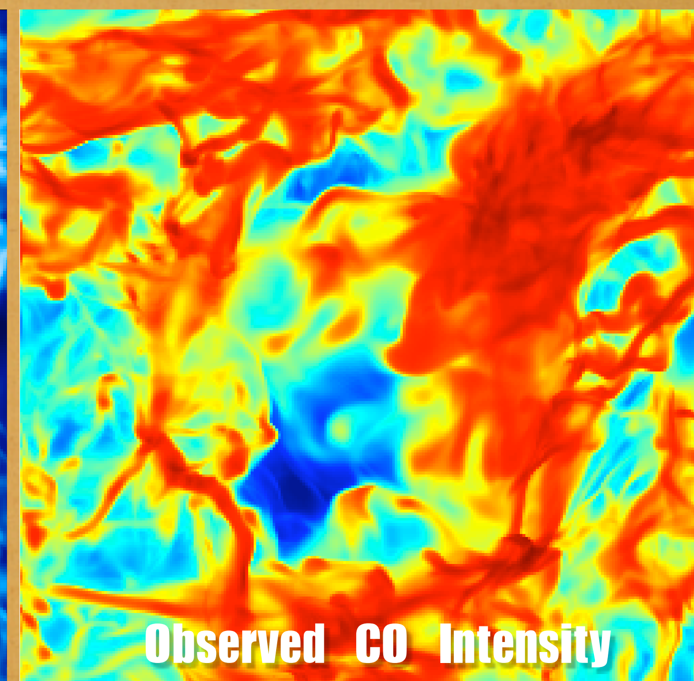

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Göttingen - 9 October, 2012

Overview

- Background: X Factor & Star Formation Law
- Radiative Transfer in MHD-Chemical Models of Molecular Clouds
- Results: The X Factor in various environments
- Results: The Star Formation Law
- Summary

The X Factor

- Ratio of H_2 column density to ^{12}CO intensity found to be ~ constant in Galactic Molecular Clouds
  ➪ $X = N_{H2} / W = 2x10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$
  (Dickman 1978, Solomon et al. 1987)
- Virialized molecular Clouds (Larson 1981, solomon et al. 1987)
- ϒ-ray observations (Strong & Mattox 1996)
- Dust Based Observations (Dame et al. 2001, Pineda et al. 2008)

- Lower Metallicity (e.g. Small Magellanic Cloud):
- Galactic X when CO observations combined with Assumption of Virialized Clouds (Bolatto et al. 2008)
- Varying X due to large quantities of H_2 untraced by CO (Rubio et al. 2004, Israel 1997, Leroy et al. 2009, 2010)

Observationally Derived X Factor

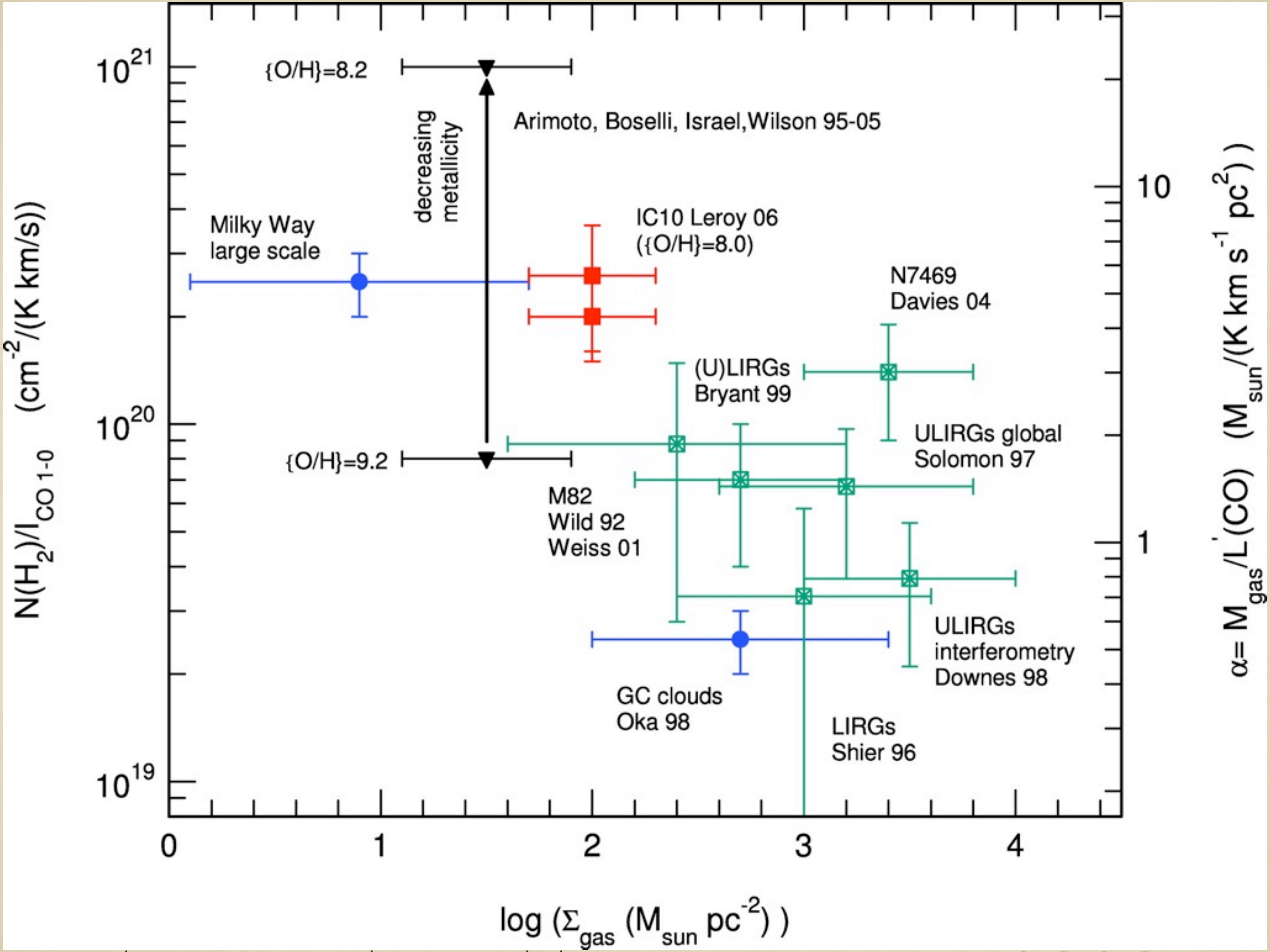

Figure From Tacconi et al. 2008

SF: Observations

- $\Sigma_{SFR} \propto \Sigma_{gas}^N$

Schmidt '59
Buat + '89
Kennicutt '89
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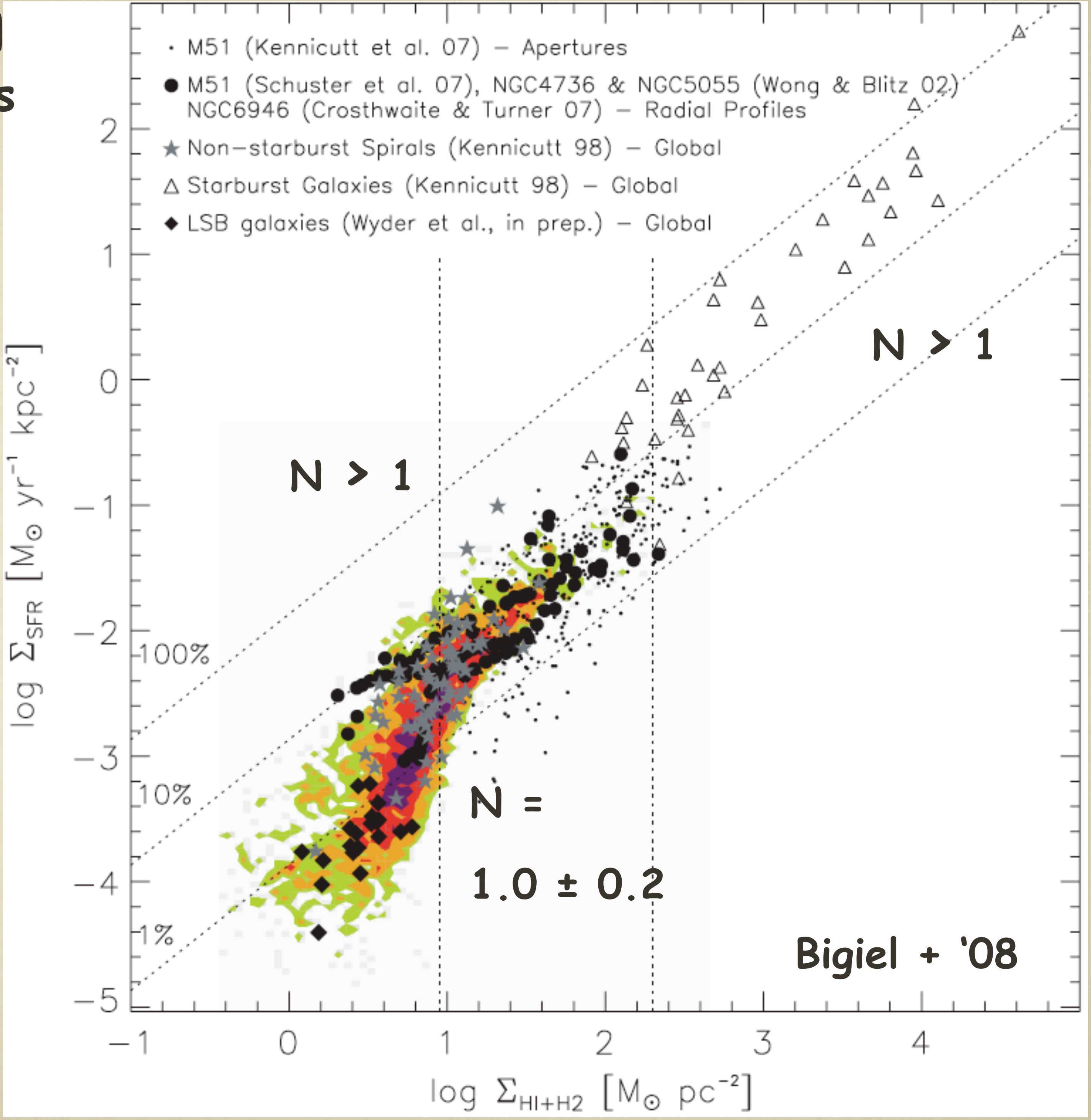
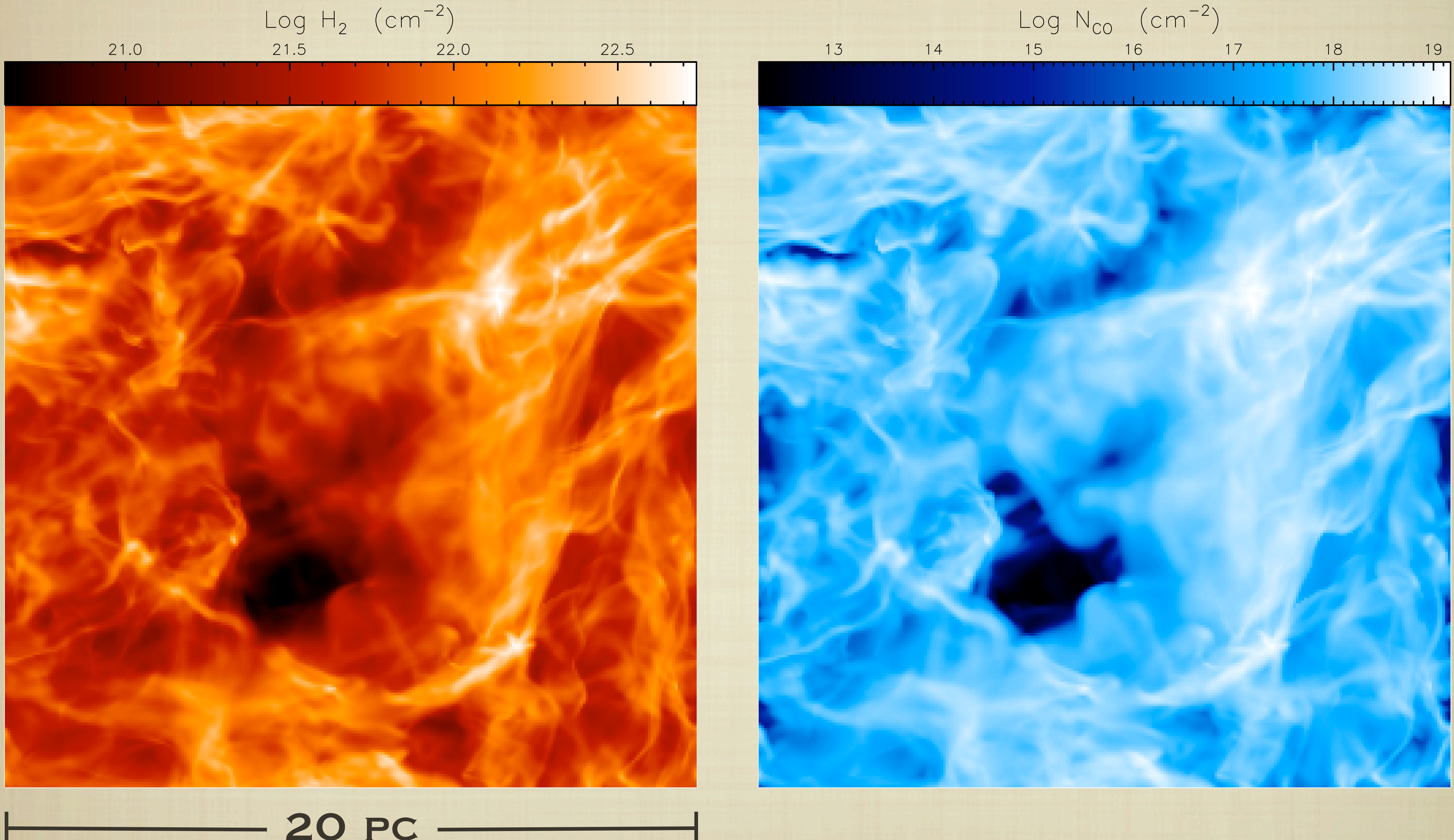


Modeling CO Formation

- Glover et al. 2010: Self-Consistent Treatment of Chemistry in MHD Molecular Cloud Simulations
  - MHD (B_0 = 1.95 μG); Driven Turbulence
  - Track 218 reactions of 32 species
  - CO formation very sensitive to MC properties: background radiation Field, density and metallicity (van Dishoeck & Black 1988, Maloney & Black 1988)
  - H_2 formation mainly dependent on Cloud Age (Glover & Mac Low 2011)
- LVG Radiative Calculations to Model CO intensity, and the X factor (Shetty et al. 2011a,b)

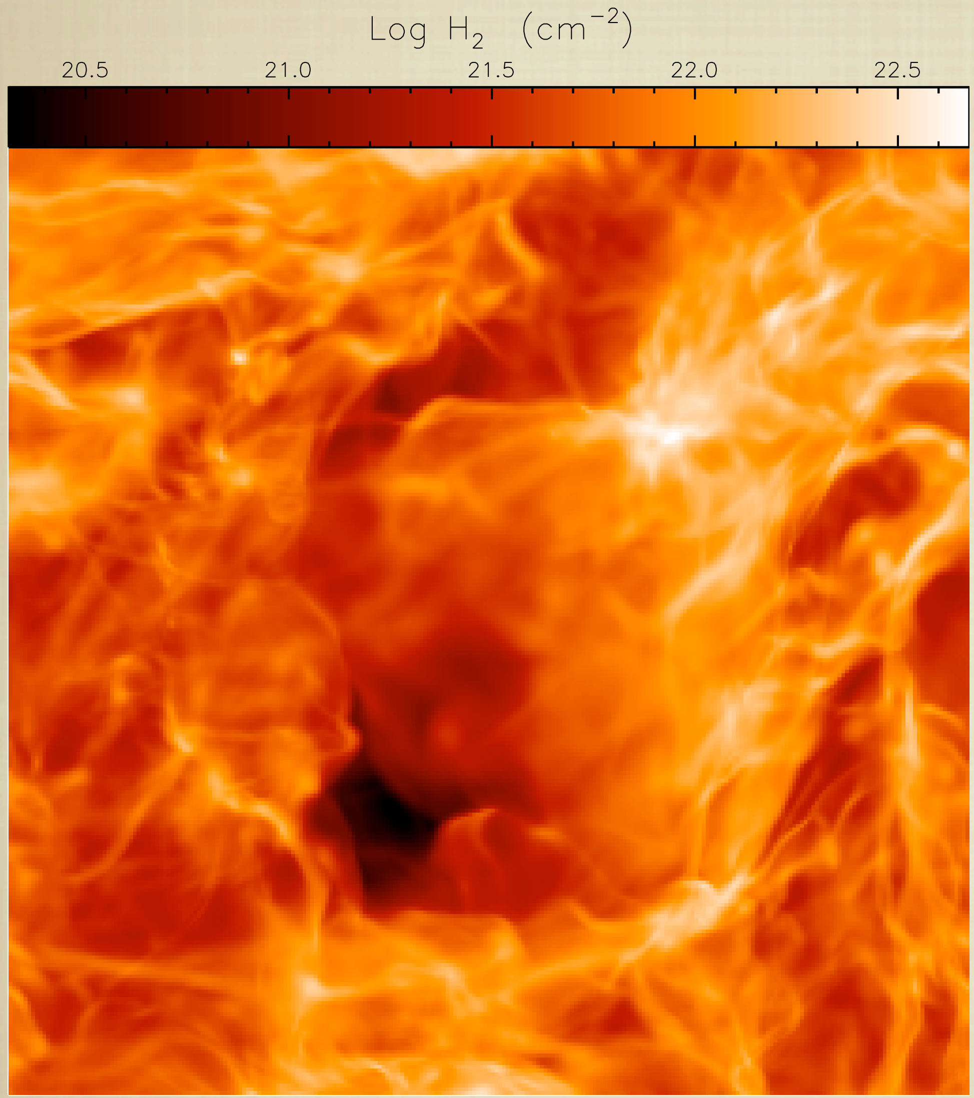
CO in MCs

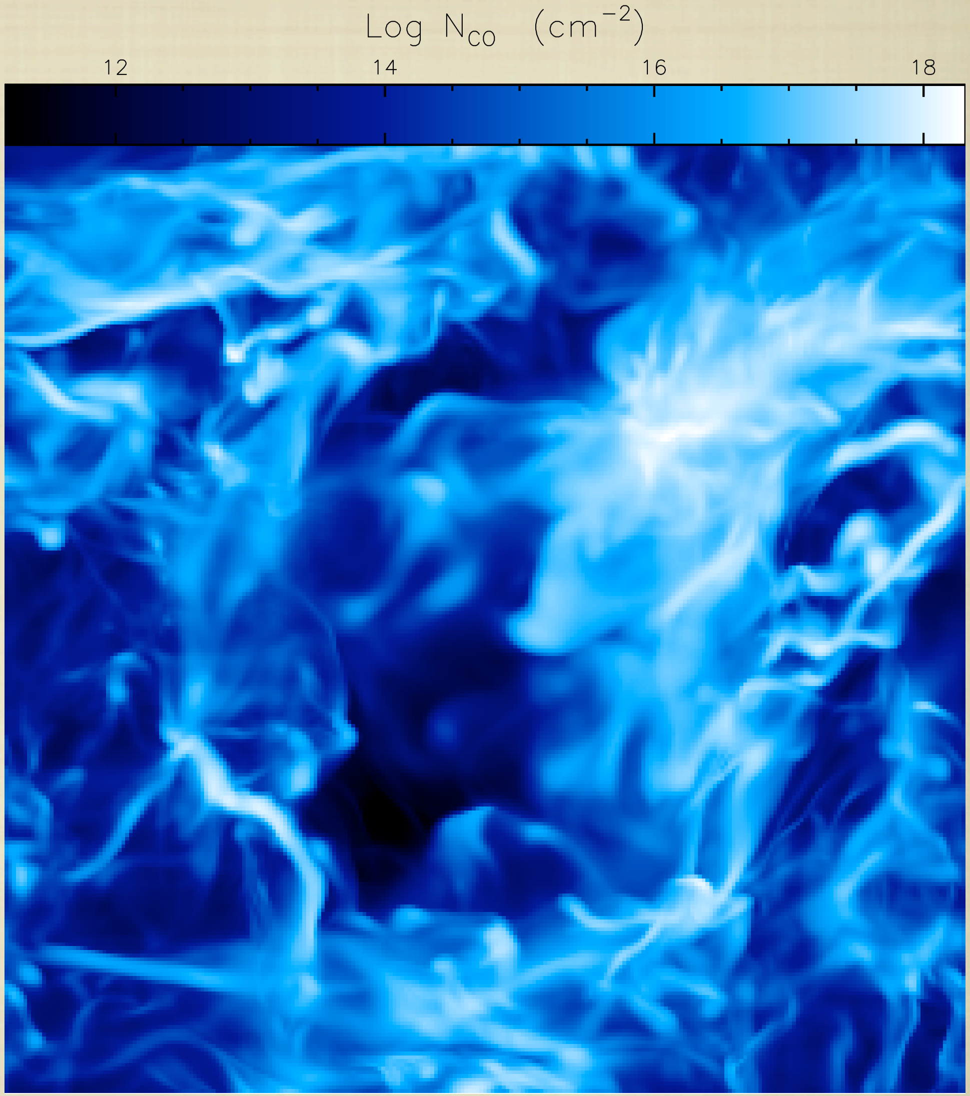
Model Milky Way Cloud: n_0=300 cm^{-3}, Z=Z$_\odot$



Glover et al. (2010)

CO in Low Metallicity MCs Z=0.3 $Z_\odot$





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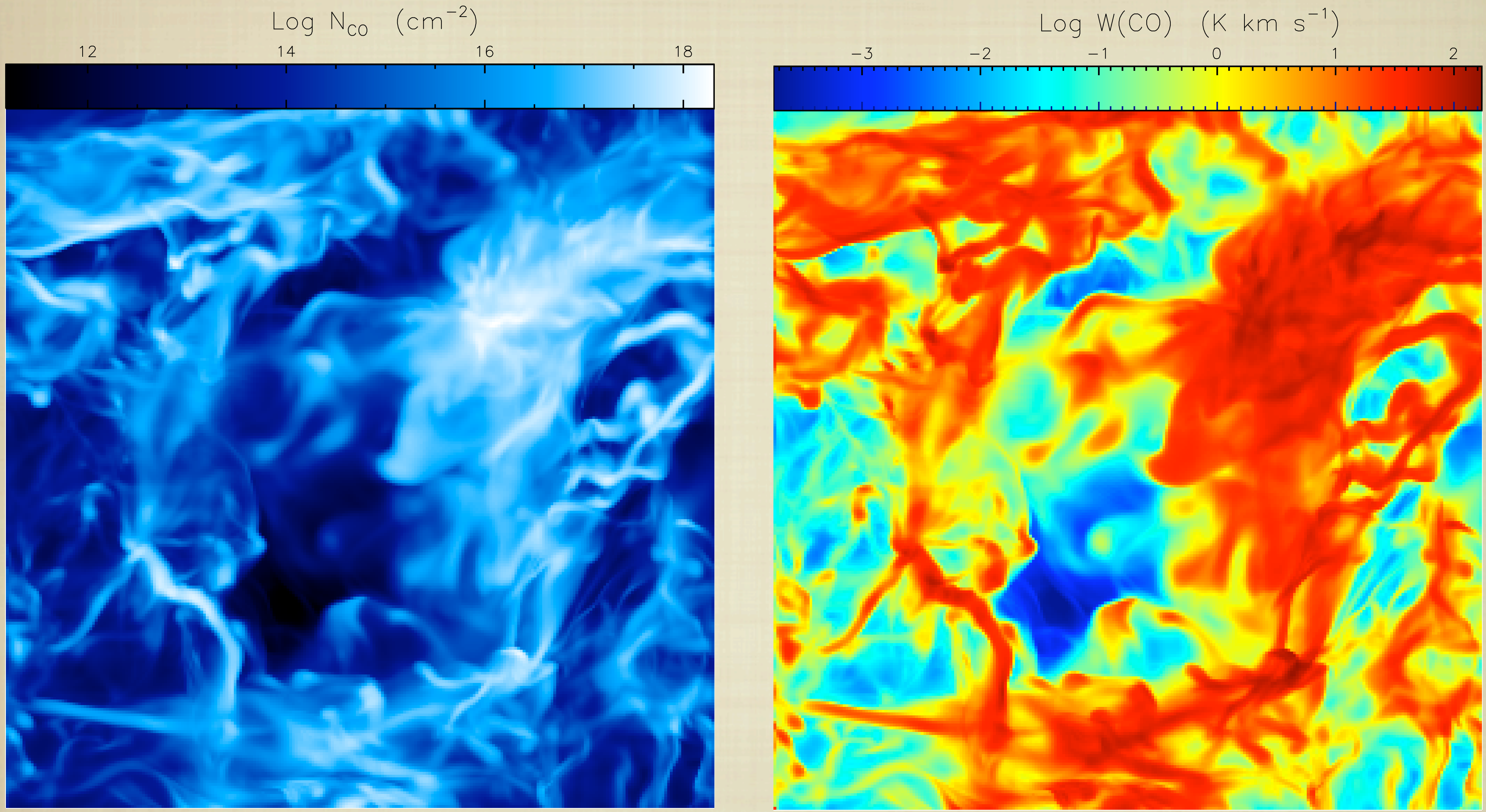
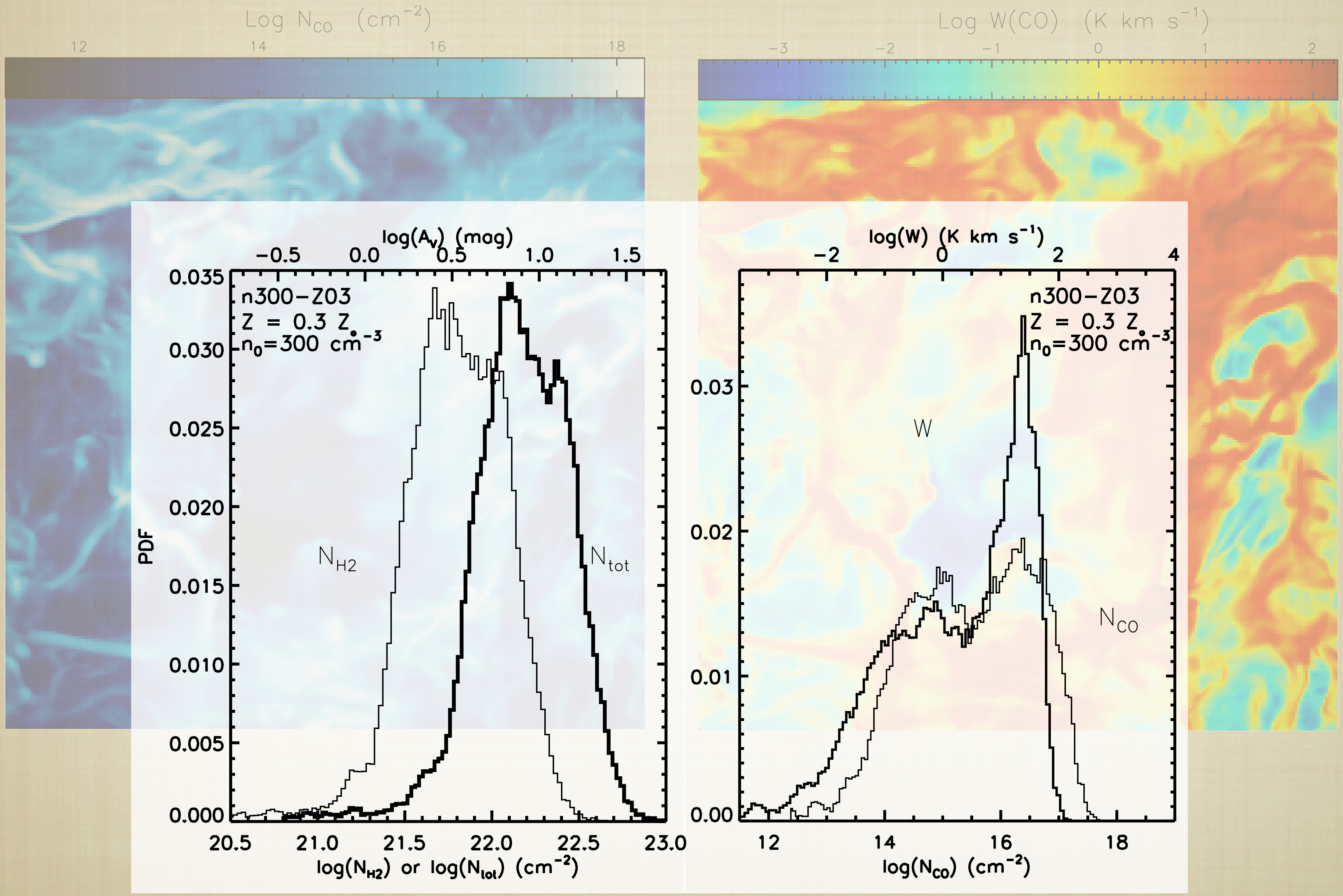


CO in Low Metallicity MCs Z=0.3 Z ⊙



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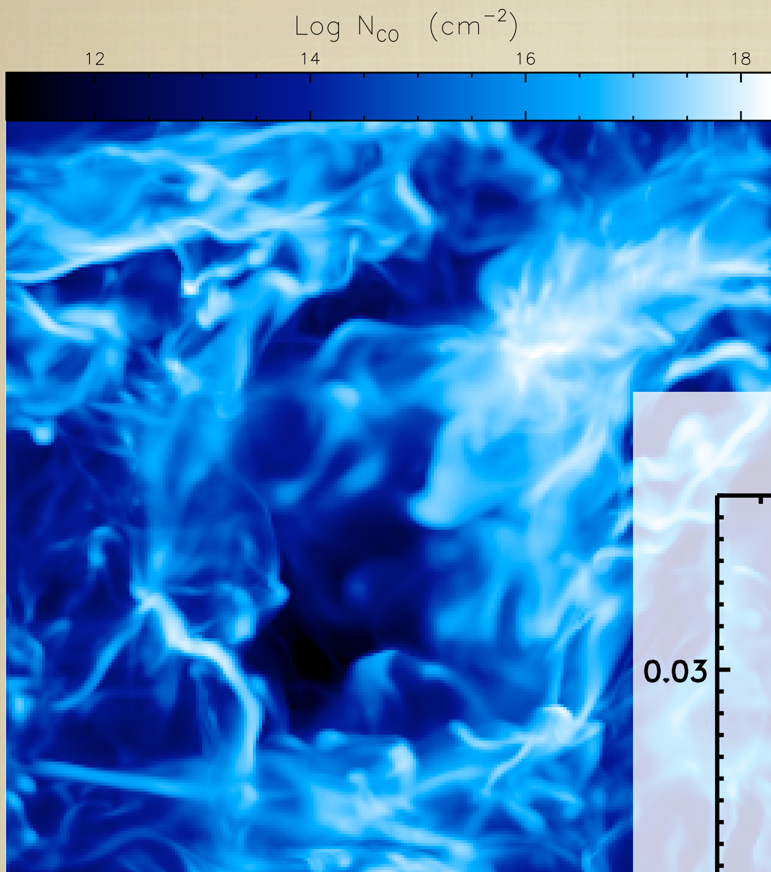

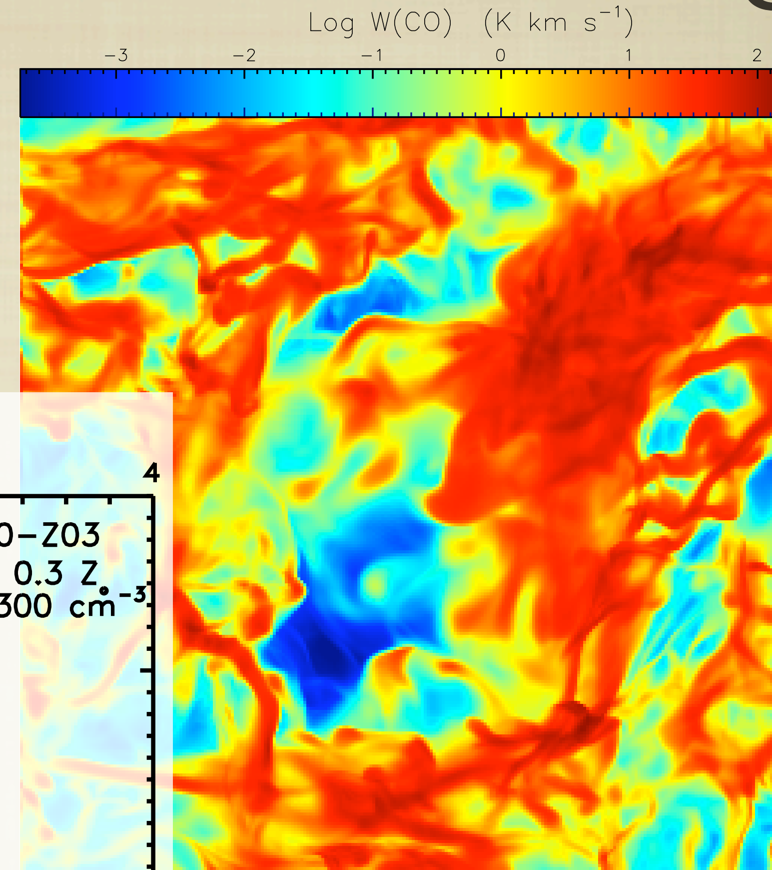

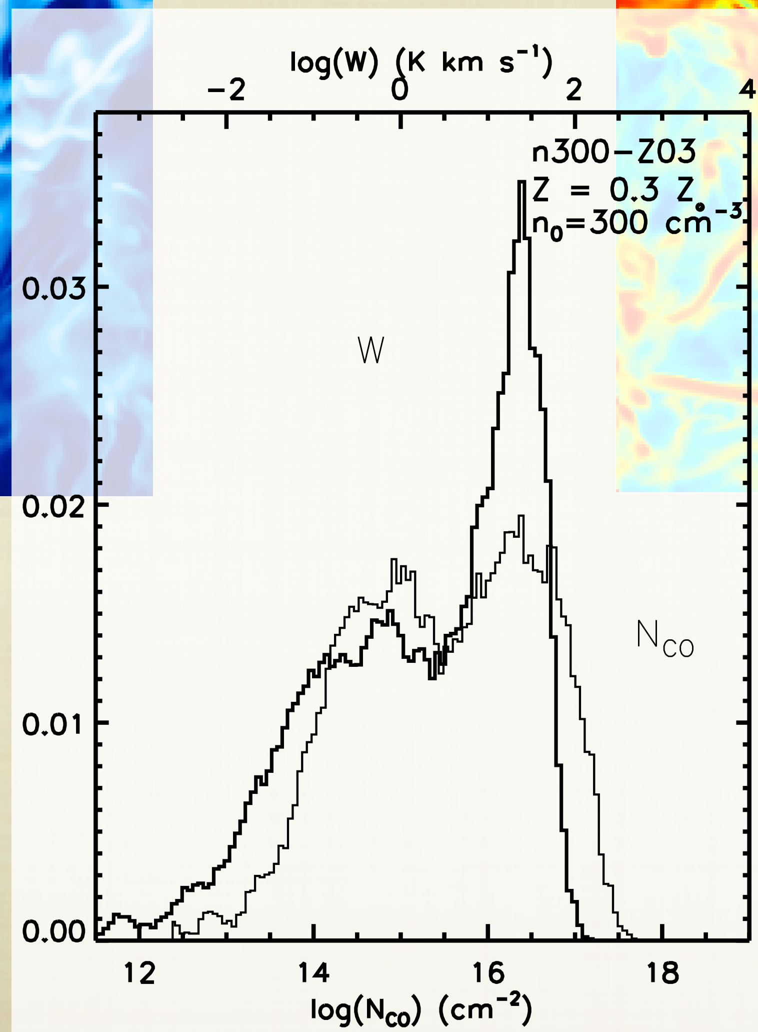

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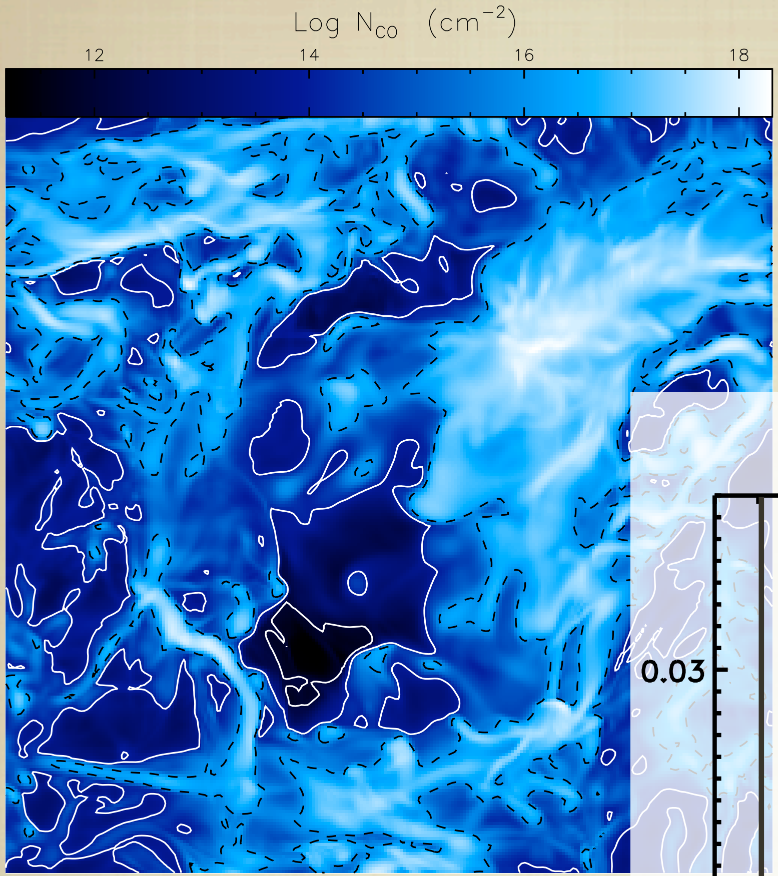
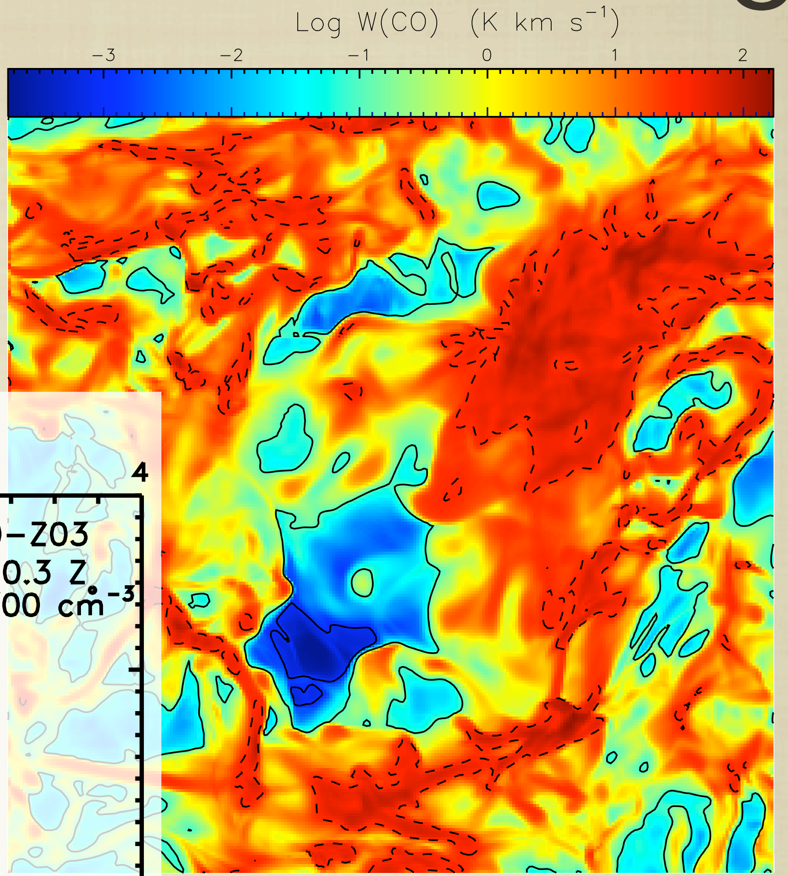
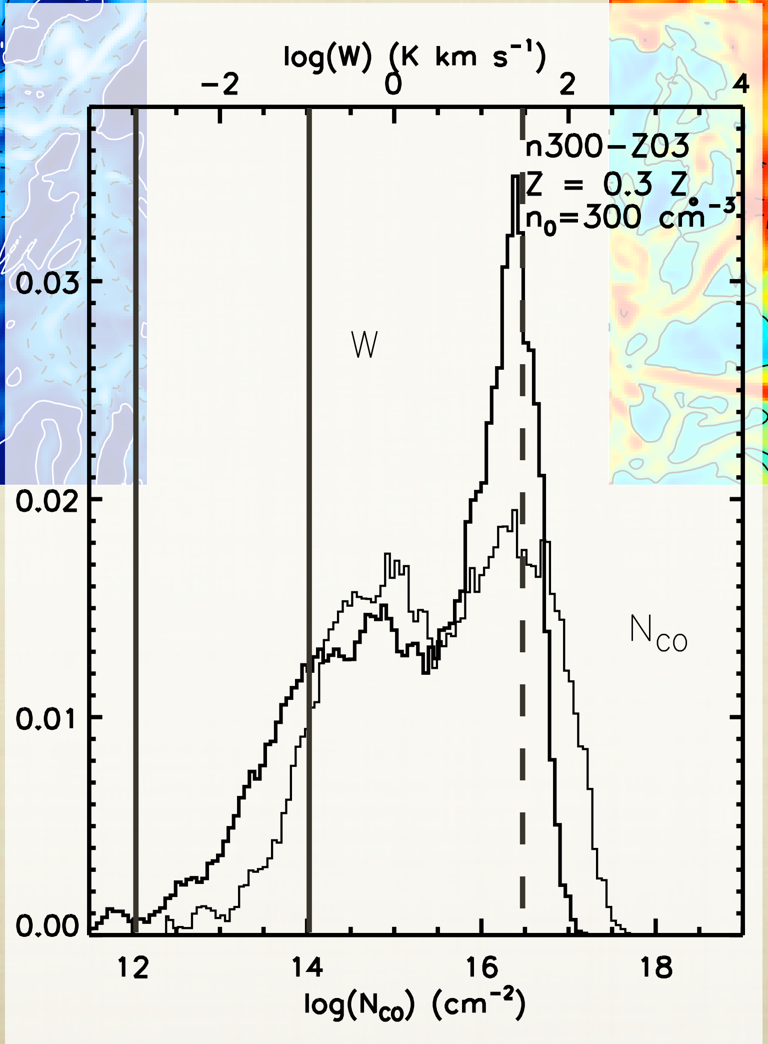
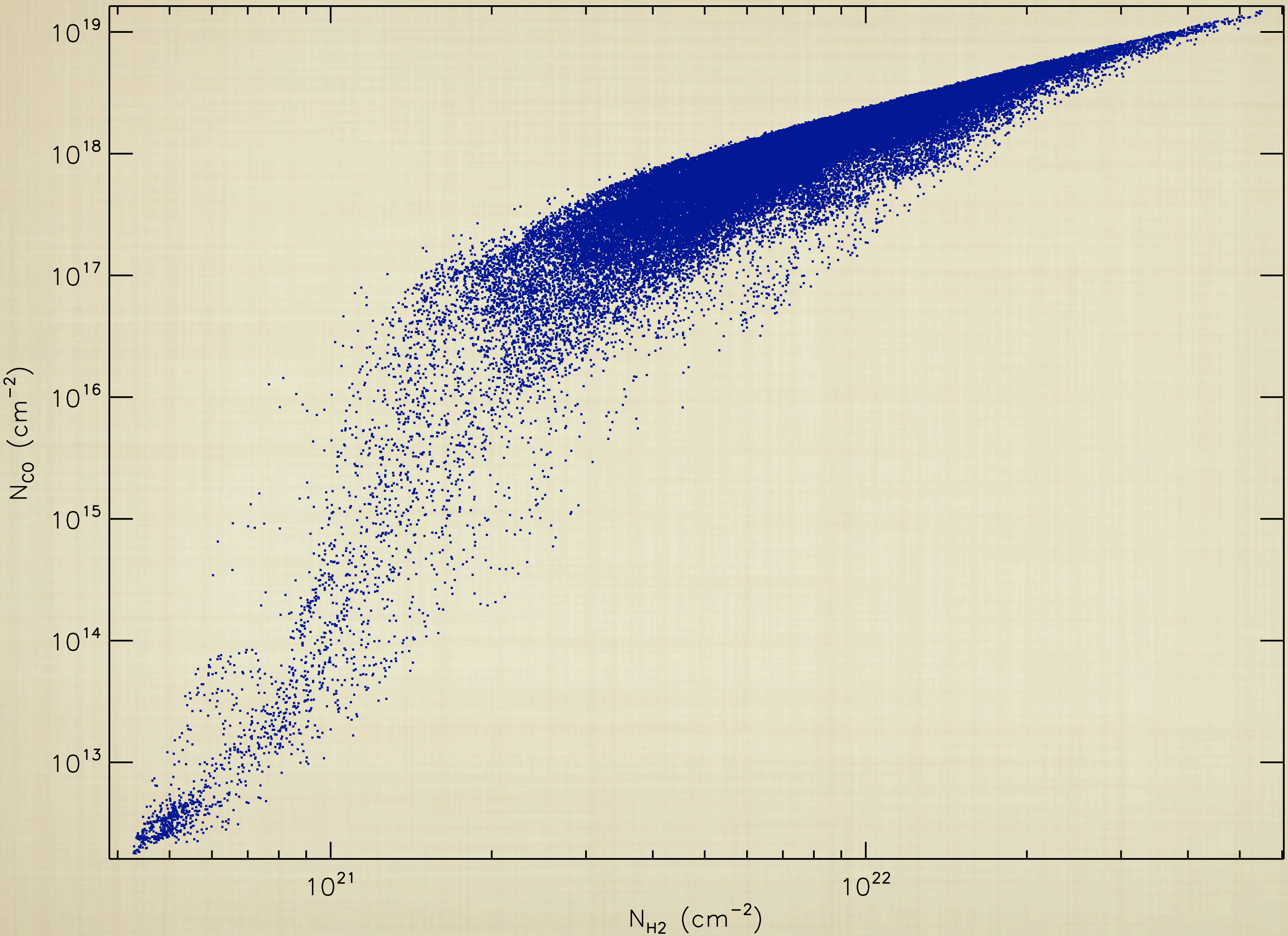






The X Factor = N_{H2}/W



Shetty et al. (2011a)

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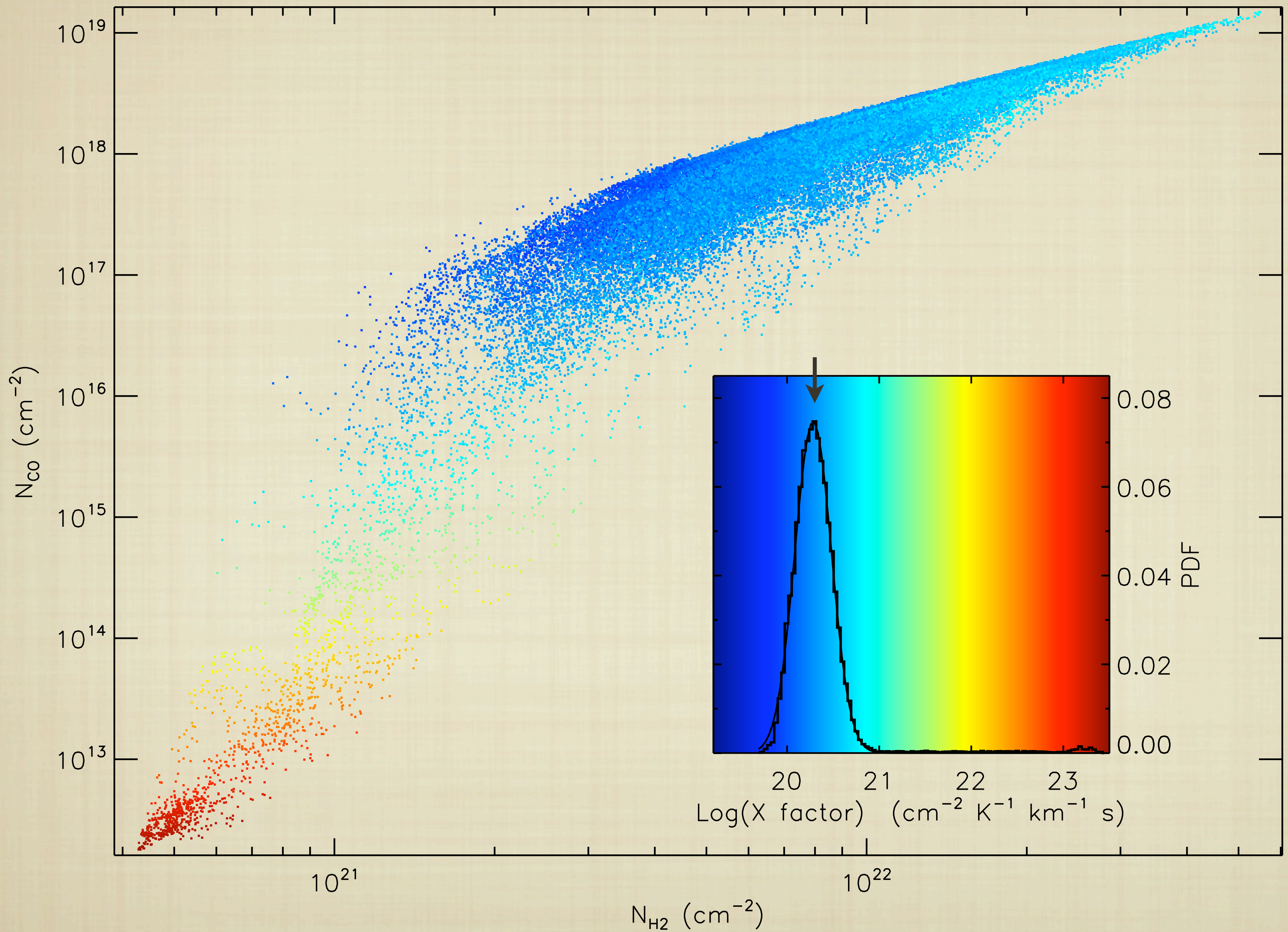

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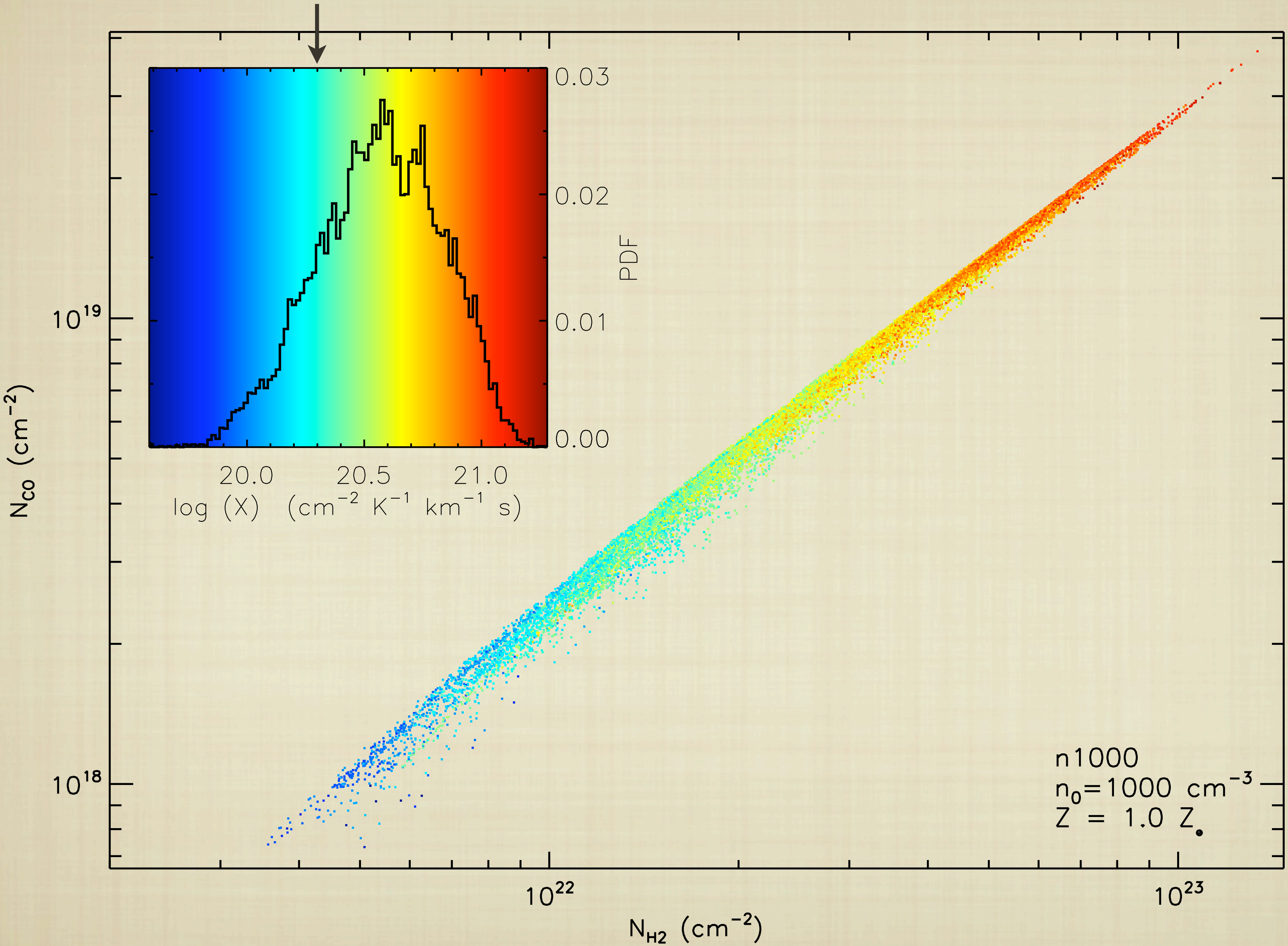

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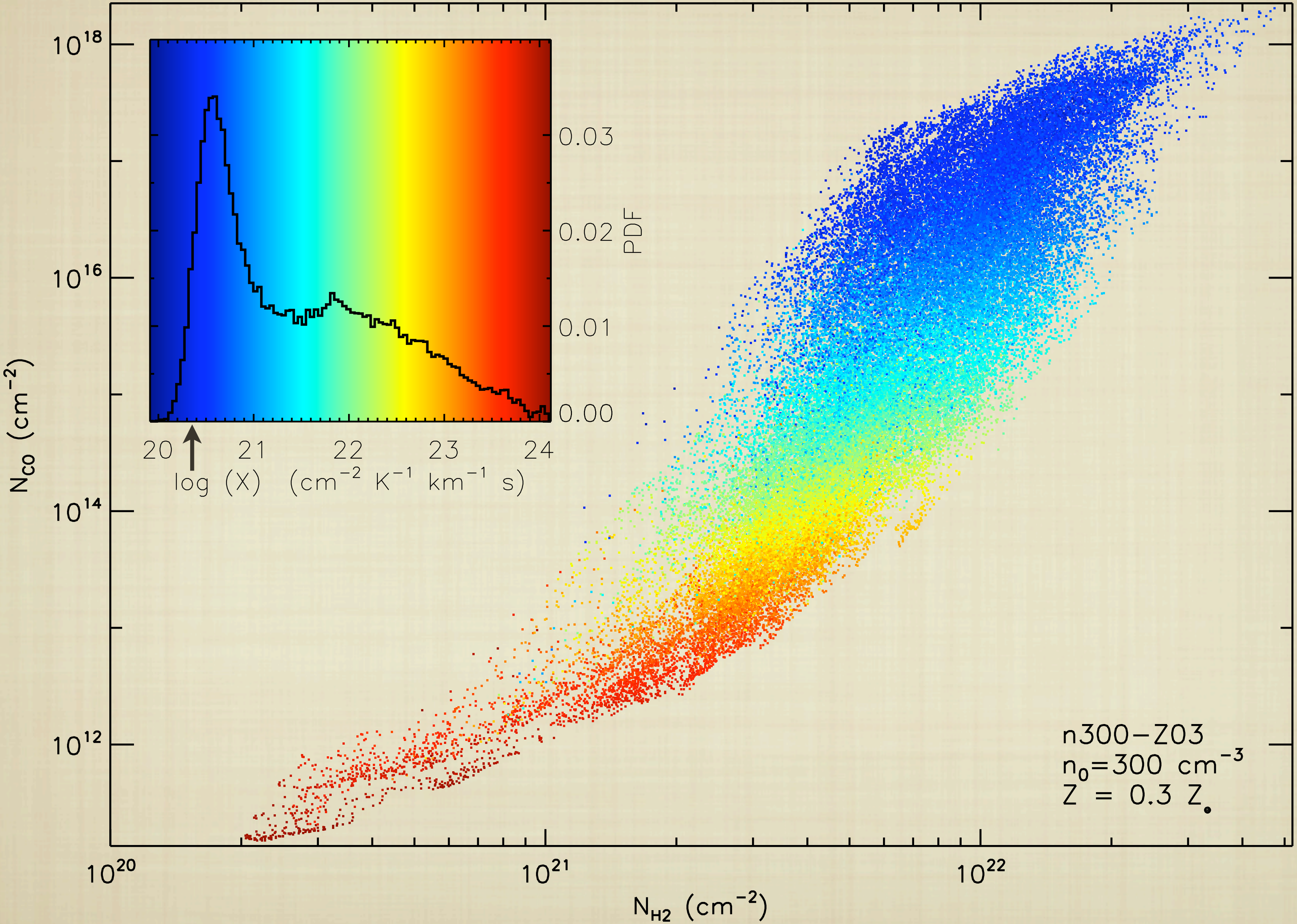

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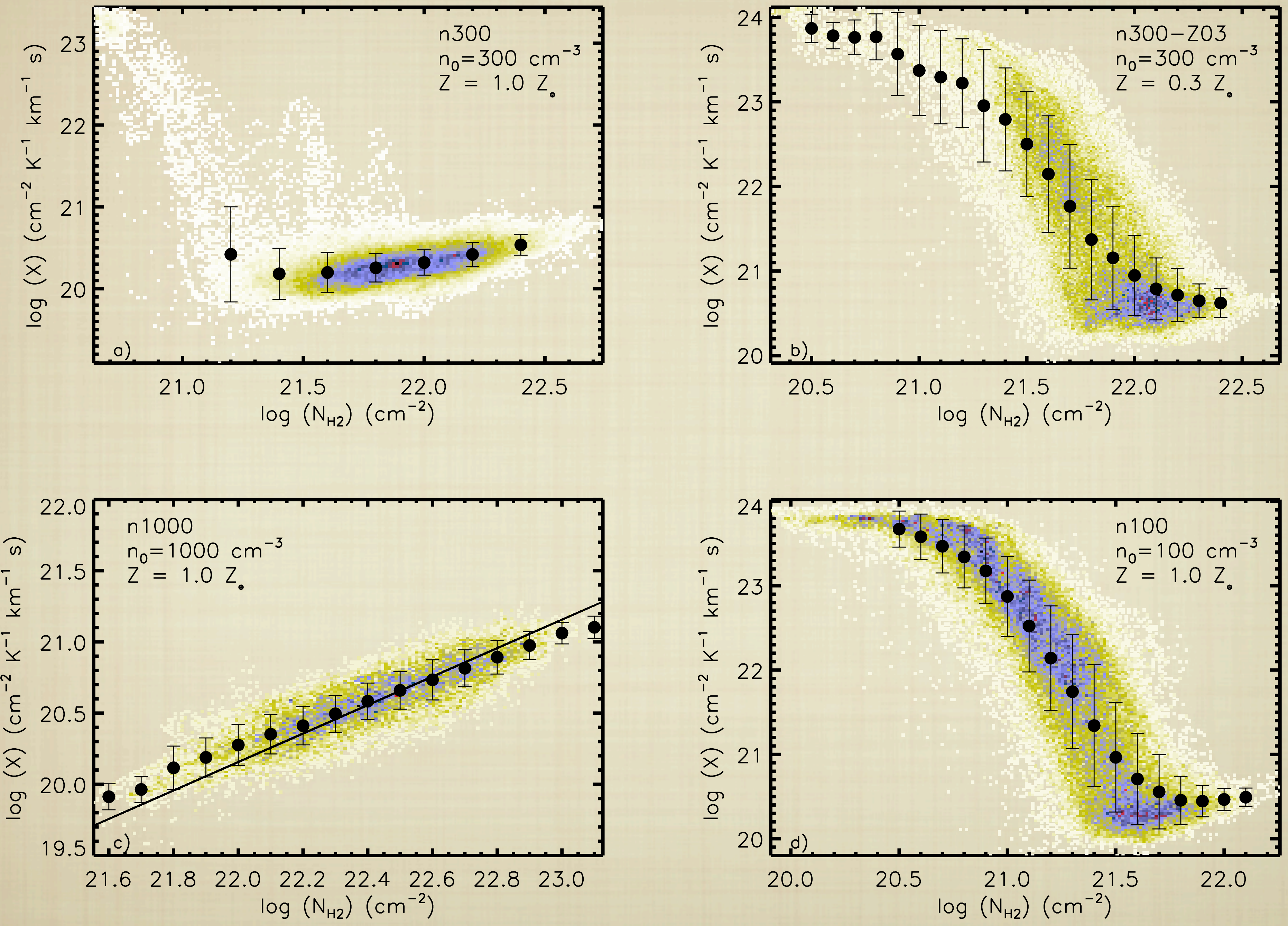

Observationally Derived X Factor

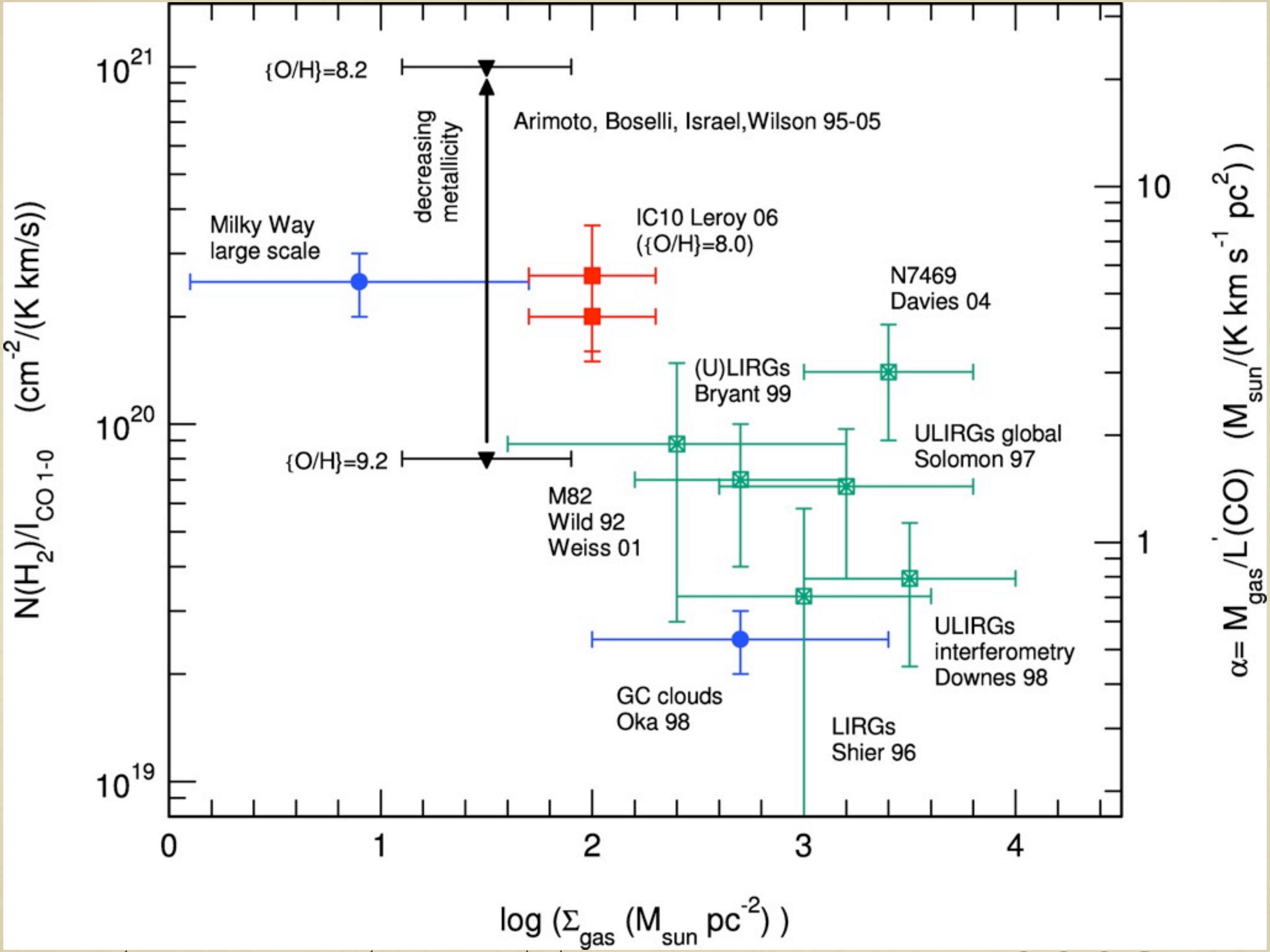

Figure From Tacconi et al. 2008

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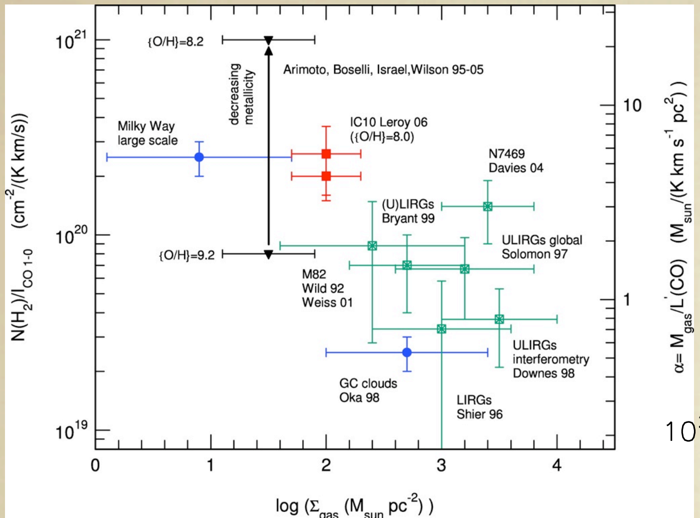
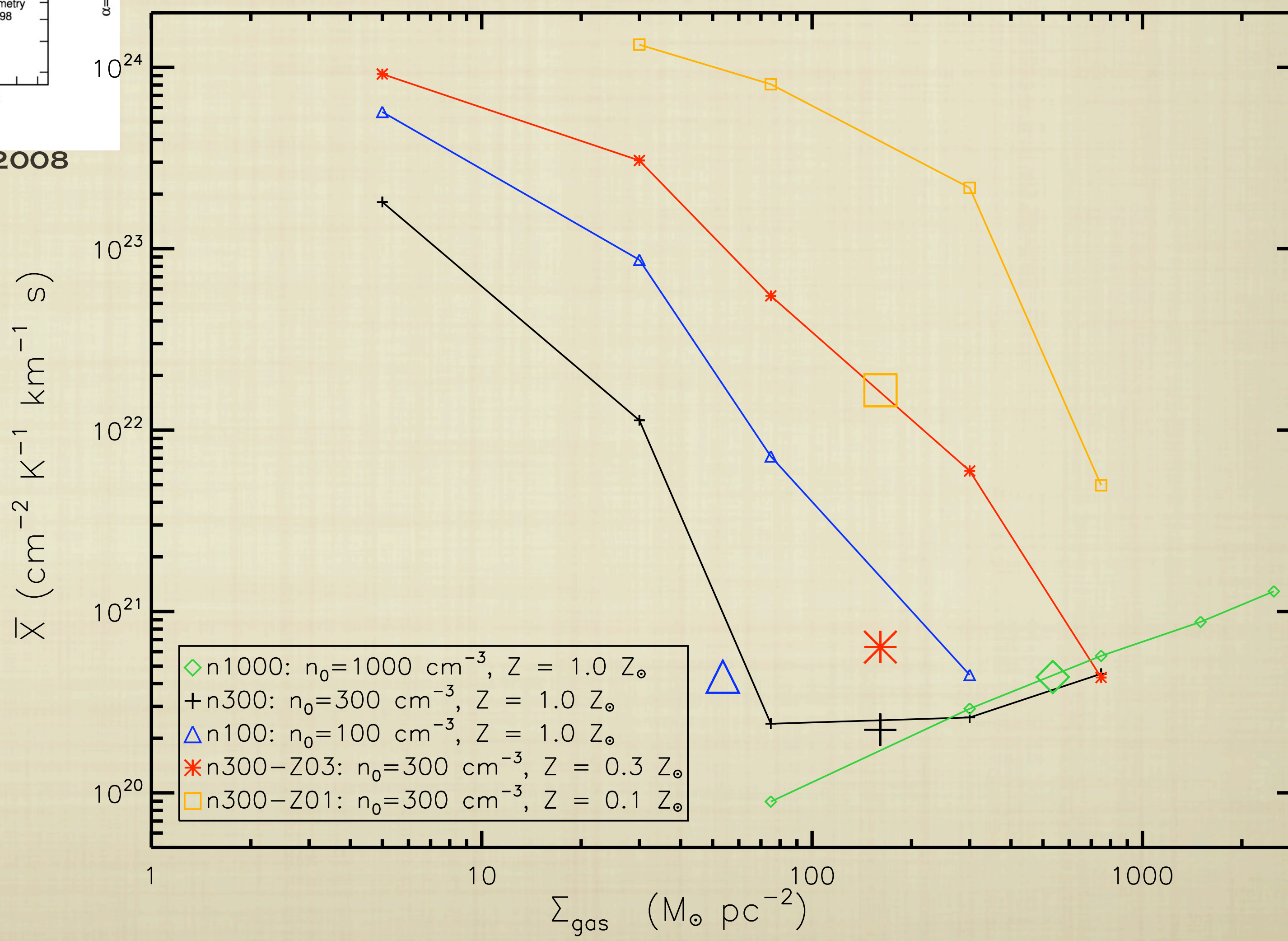


Figure From Tacconi et al. 2008



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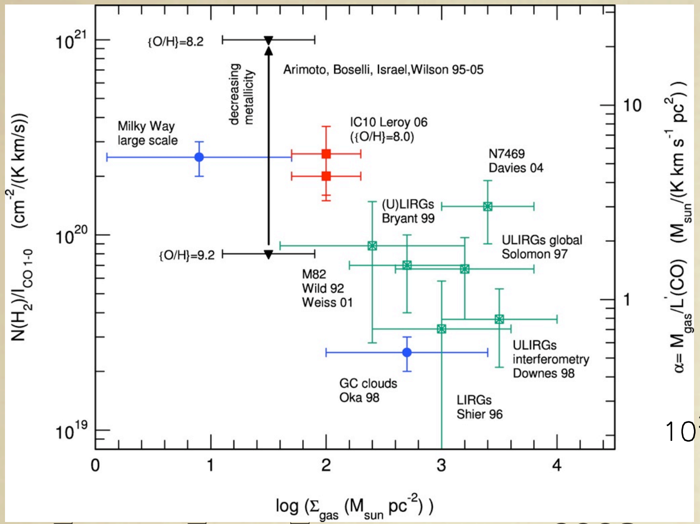

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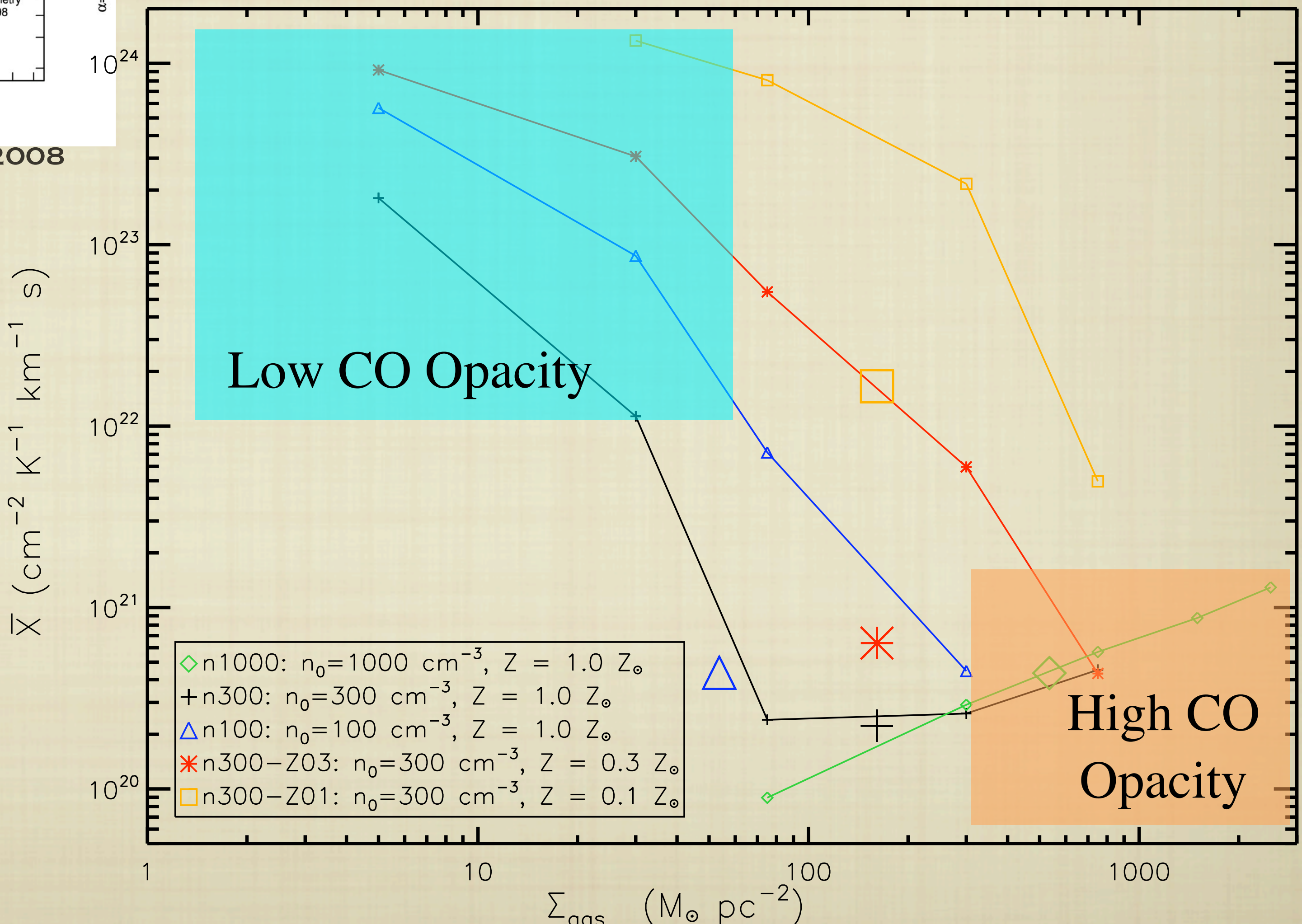

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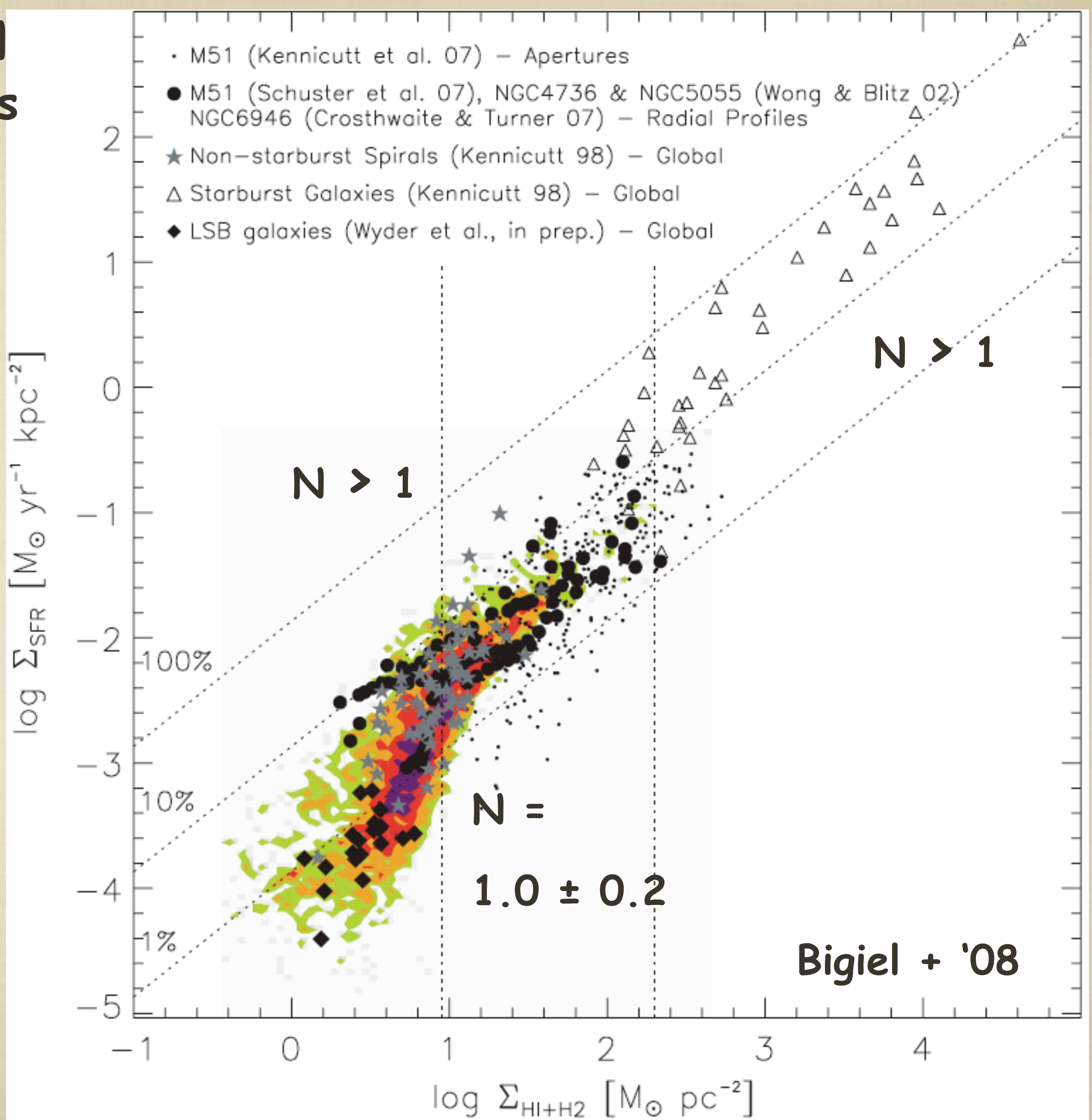
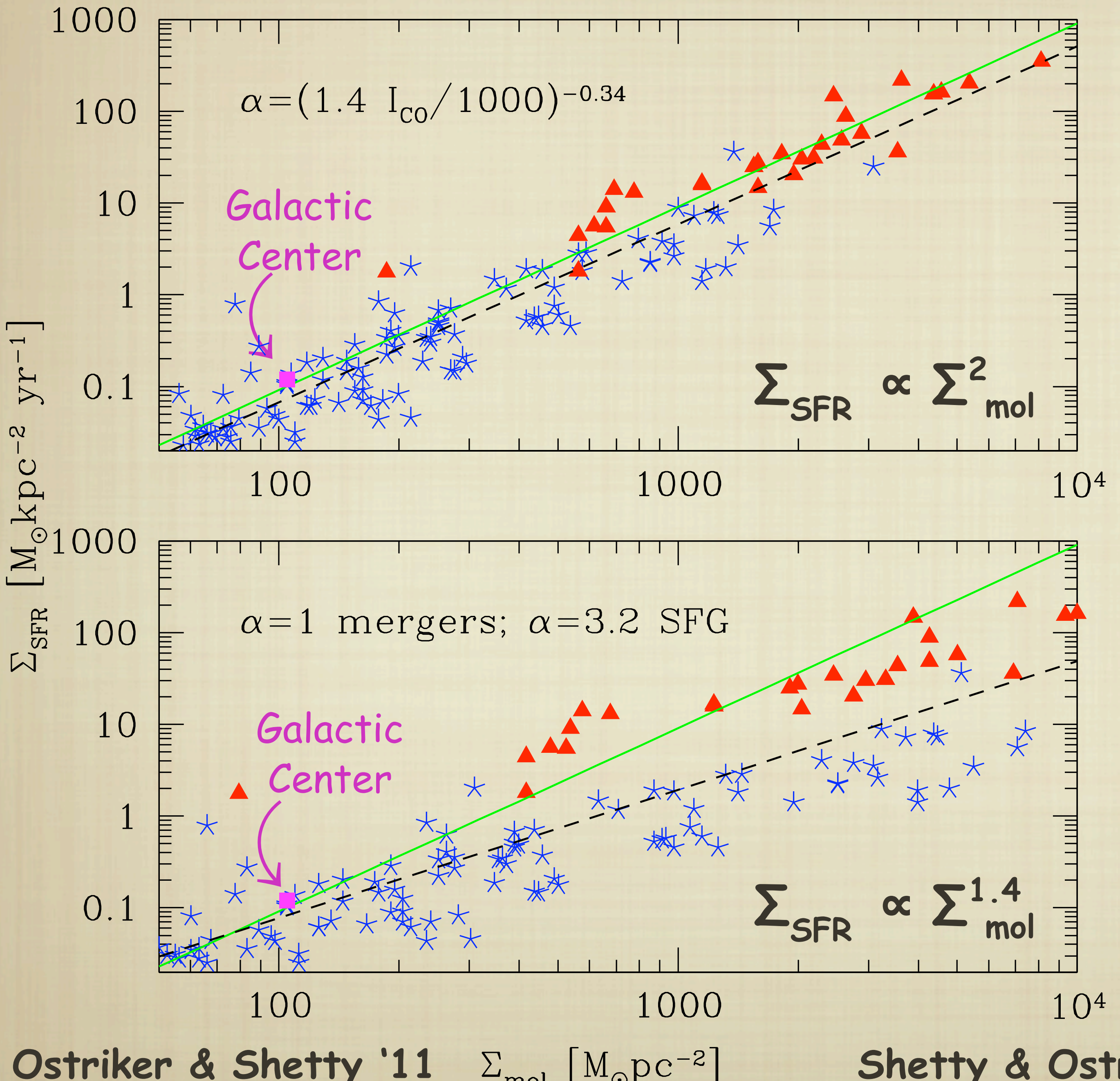


Self-Regulation in Observed Systems?



Star forming galaxies and merger systems from Genzel + '10

Galactic Center from Yusef-Zadeh +'09

Continuous X factor? (Shetty + 11a,b, Narayanan + 11, 12, Feldmann + '12)

Ostriker & Shetty '11

Shetty & Ostriker '12

Inferring the Kennicutt-Schmidt Law

- Measurement uncertainties and intrinsic scatter may lead to biases in fitting a model to data (e.g. Weiner+2006, Kelly 2007).

- Hierarchical models allow for estimating the model parameters of individuals and for the group

- Bayesian inference is ideally suited for fitting hierarchical models, and accounting for uncertainties, through MCMC methods

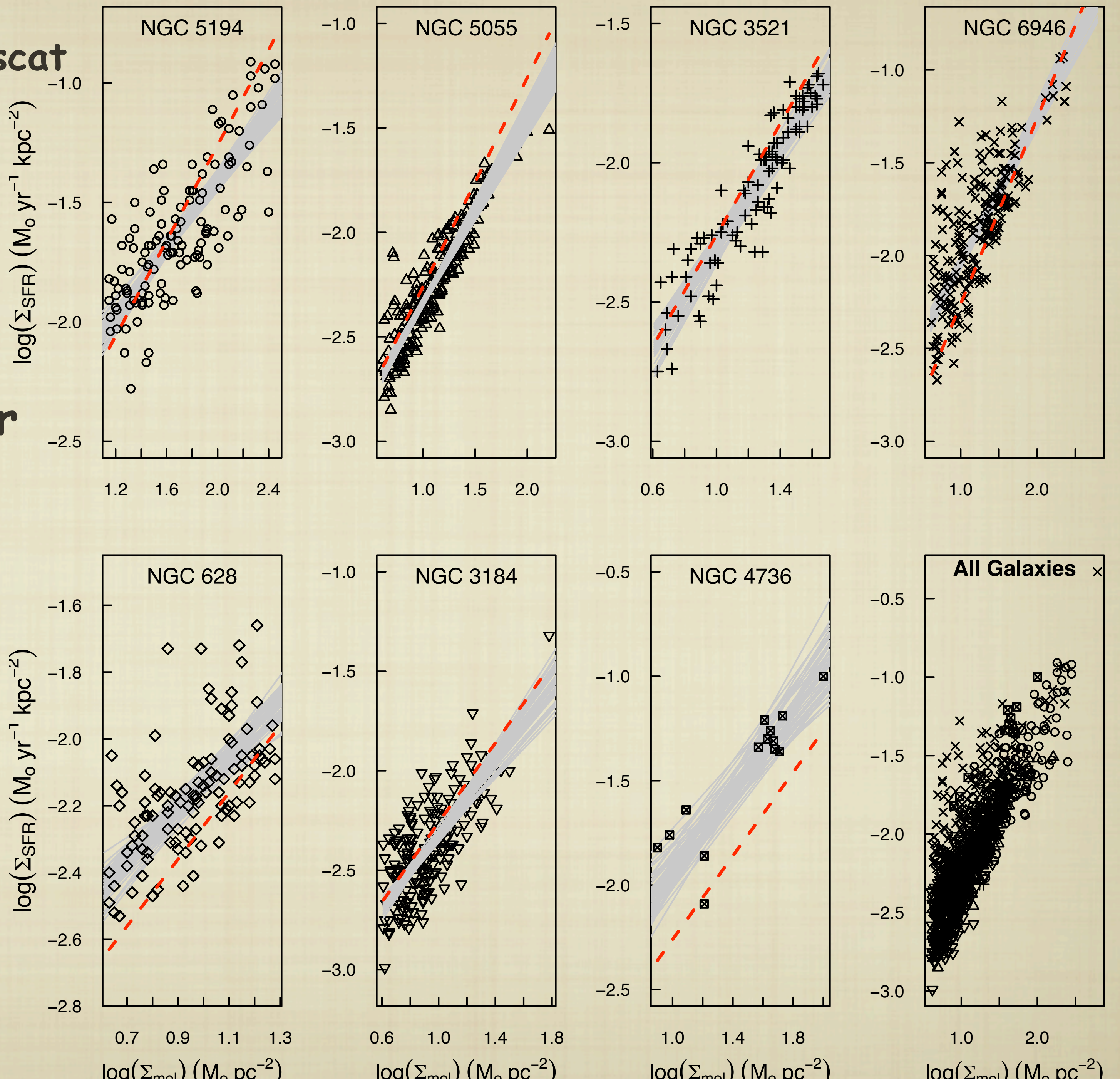
- Employ a hierarchical Bayesian method, with a full treatment of uncertainties to estimate Kennicutt-Schmidt law parameters from the Bigiel + 2008 sample

Hierarchical Bayesian Fitting of the KS Law

- $\Sigma_{SFR} = A\Sigma^{N}_{mol} + \varepsilon_{scat}$

fit individual and "group" parameters, with uncertainties

Posterior is a PDF of each fit parameter



Bigiel+'08, '10
Shetty, Kelly, Bigiel
MNRAS submitted,
arXiv1210:1218

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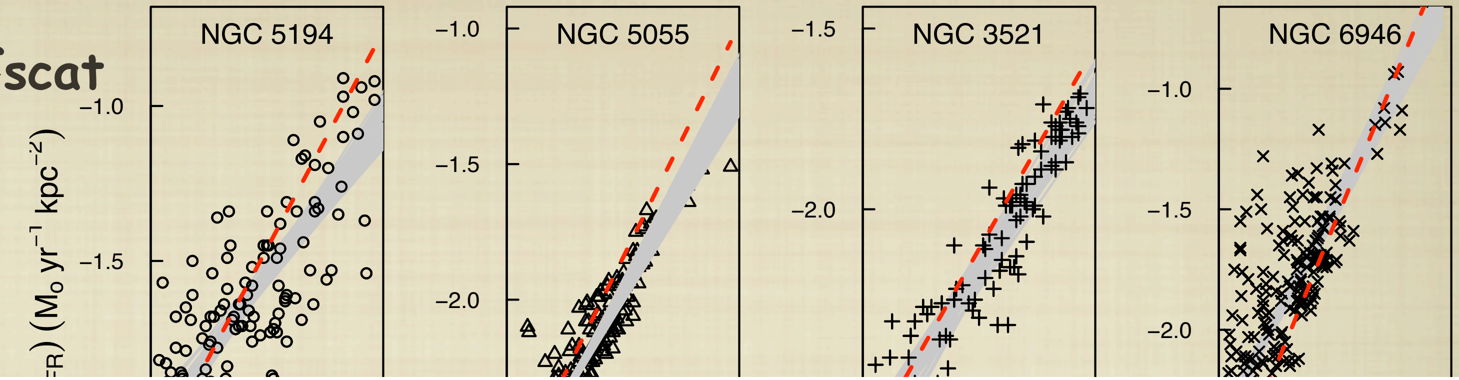
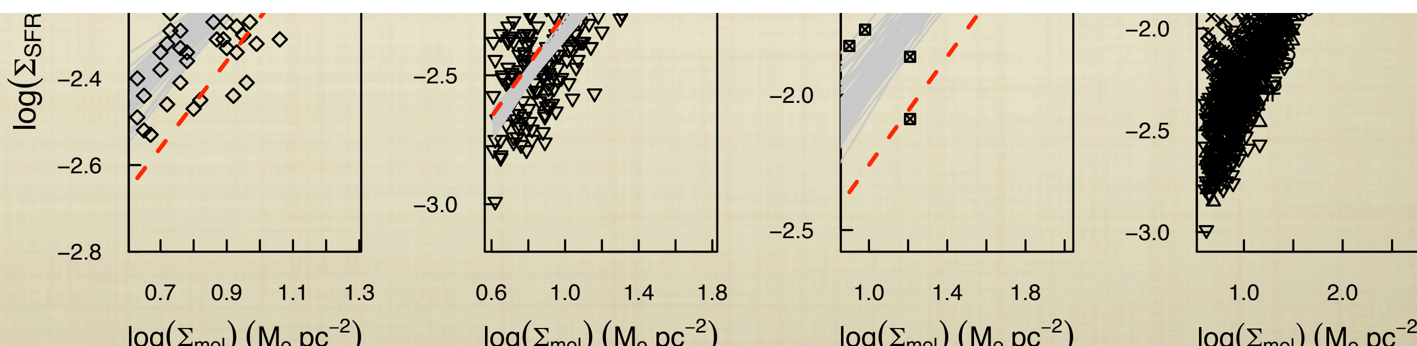


Subject	Bayes A	Bayes $2\sigma_A$	Bayes N	Bayes $2\sigma_N$	Bayes σ_{scat}
NGC 5194 (M51)	−2.84	[−3.0, −2.7]	0.72	[0.62, 0.83]	0.06
NGC 5055	−3.20	[−3.3, −3.1]	0.87	[0.79, 0.95]	0.04
NGC 3521	−3.20	[−3.4, −3.0]	0.90	[0.76, 1.03]	0.05
NGC 6946	−2.81	[−2.9, −2.7]	0.78	[0.70, 0.86]	0.11
NGC 628	−2.89	[−3.1, −2.6]	0.76	[0.51, 0.95]	0.05
NGC 3184	−3.24	[−3.4, −3.1]	0.92	[0.79, 1.10]	0.05
NGC 4736	−2.83	[−3.2, −2.4]	0.92	[0.67, 1.20]	0.08
Group Parameters	**−3.00**	**[−3.3, −2.7]**	**0.84**	**[0.63, 1.0]**	0.14



Bigiel+'08, '10
Shetty, Kelly, Bigiel MNRAS submitted, arXiv1210:1218

Summary

- X Factor varies with Environment, depending on Metallicity, Mean density, Ambient UV field, etc...
- at low metallicity, need a higher X factor
  ⟶ more "Dark Gas"
- Kennicutt-Schmidt Relationship strongly dependent on X factor
- Super-linear KS index at high surface densities (e.g. starbursts) due to self-regulation
- In Normal Galaxies, no Universal KS Law
- Sub-linear KS relationship from Hierarchical Bayesian Fit, suggestive of CO emission from gas unassociated with star formation

Interpretation of The X Factor

- Constant X due to "Virialized" Clouds? (Solomon et al. 1987)

$$X \propto \alpha_{VT} \equiv \frac{M_{VT}}{L_{CO}}$$

- Velocity - Mass Relationship for clouds in Virial equilibrium (Bertoldi & McKee 1992):

$$\sigma_{VT}^2 \equiv \frac{GM_{VT}}{5R}$$

- Cloud Averaged Spectra are Gaussian:

$$L_{CO} = \sqrt{2\pi} T_{B,0} \sigma_v \pi R^2$$

- Taken Together

  (& assuming $\sigma_V = \sigma_{VT}$):

$$\alpha_{VT} \equiv \frac{M_{VT}}{L_{CO}} \propto \frac{\sigma_v / R}{T_{B,0}}$$

- Equivalently:

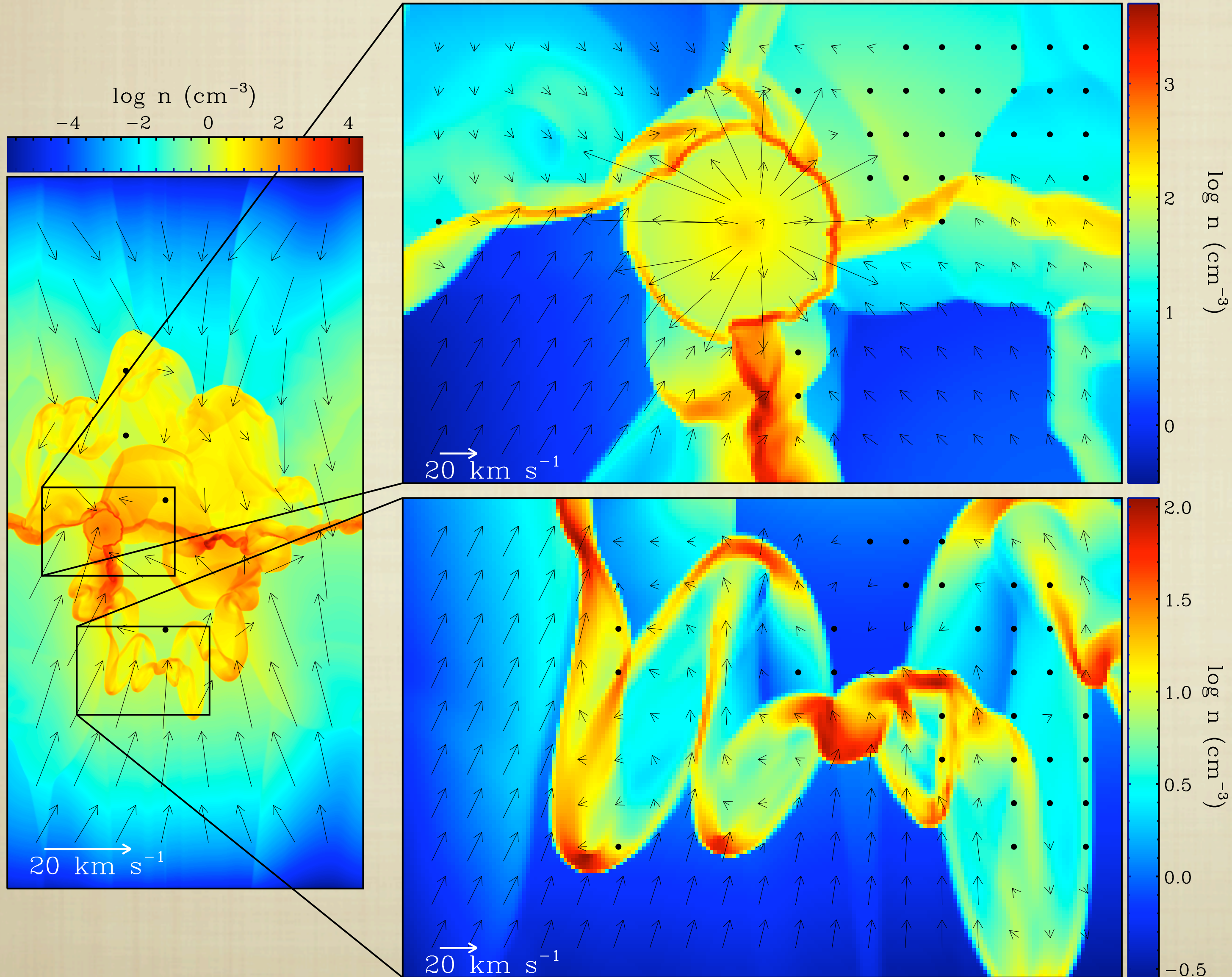
$$\alpha_{VT} \equiv \frac{M_{VT}}{L_{CO}} \propto \frac{\rho^{1/2}}{T_{B,0}}$$

- Virialized Clouds also invoked to explain "Larson's (1981) Laws": $M \propto R^2$ and $\sigma_V \propto R^{1/2}$

In Starbursts:

Dynamic Equilibrium: $W_{tot} \approx P_{drive} \approx P_{turb}$

$$\pi G \Sigma^2/2 \approx f_p \,(p_* / 4m_*)\, \Sigma_{SFR} \approx \rho \sigma^2_z$$



Ostriker & Shetty '11

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