Variations in Star Formation Scaling Relations: Evidence for diffuse molecular gas

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B. Kelly, F. Bigiel, A. Bolatto, C. Brunt, P. Clark, D. Cormier, M. Heyer, S. Hony, R. Klessen, L. Konstandin, T. Loredo, E. Pellegrini, N. Rahman, J. Roman-Duval, & D. Ruppert

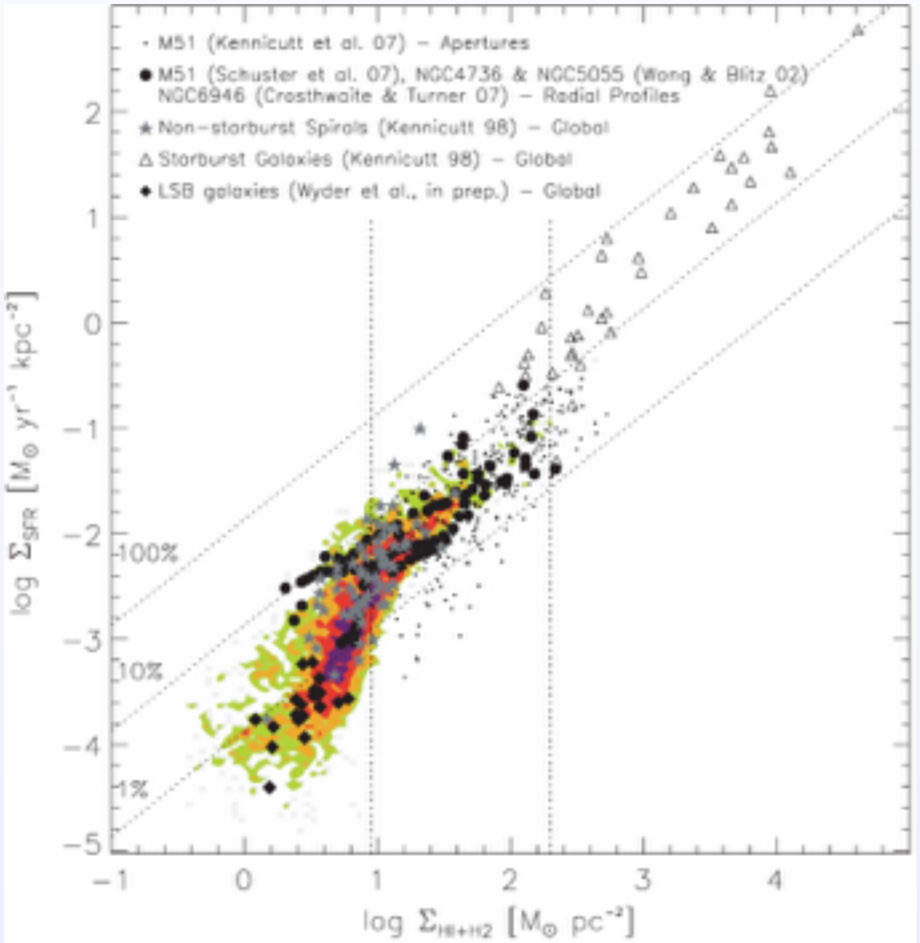
3/09/15 Local Gas2015; ASTRON

Overview

- Molecular Gas - Star Formation (SF) relation
    - Background / Assumptions
    - Implications
    - Fitting the Kennicutt-Schmidt (KS) relation
        - Hierarchical Bayesian fitting
        - Assessing fits, including "by eye"
- Results: Non-universality and sub-linearity of KS relation
- Implications and additional evidence of diffuse molecular gas
- Summary

KS Estimates

- At intermediate 10 $M_\odot$ $pc^{-2} < \sum_{gas} <$ 100 $M_\odot$ pc^{-2}, Bigiel +'08 find N~1



- A linear relationship from resolved galaxies: STING, HERACLES, though with significant scatter (e.g. Bigiel + '08, Rahman + '12, Schruba + '12, Leroy + '13, etc...)

- Super-linear N~1.5 KS relationship from unresolved disks (Kennicutt '89, '98) and resolved observations (e.g. Kennicutt + '07, Liu + '11, Momose + '13)

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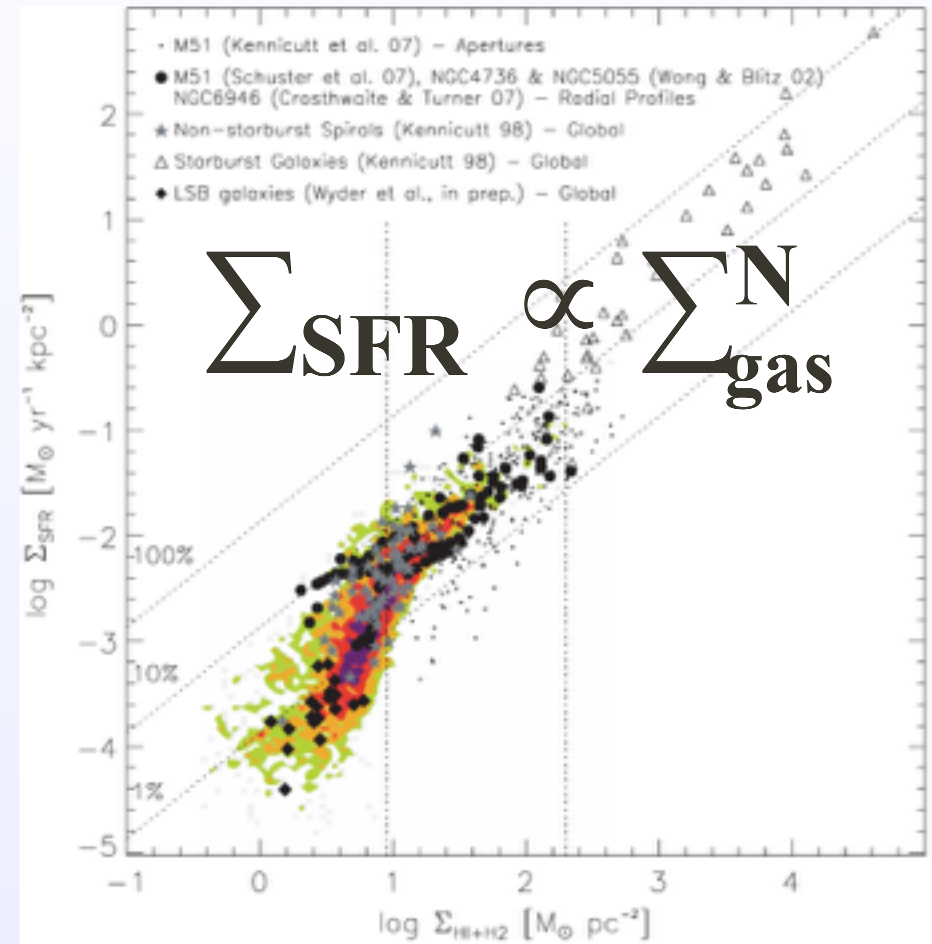

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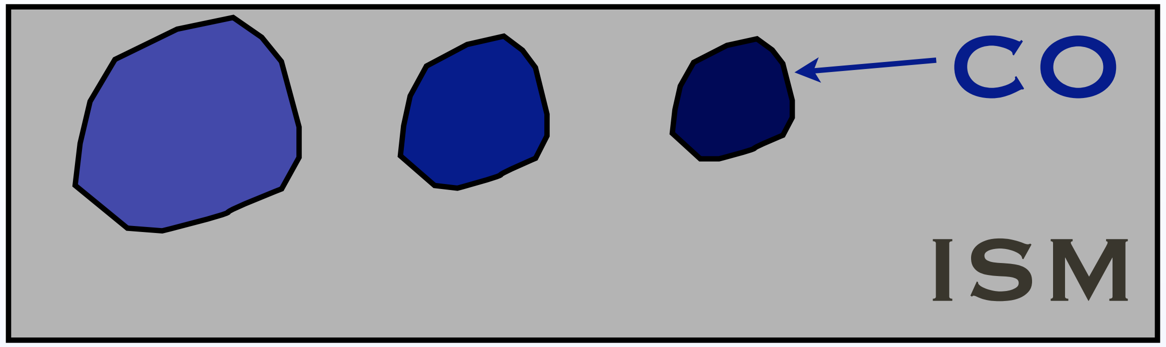
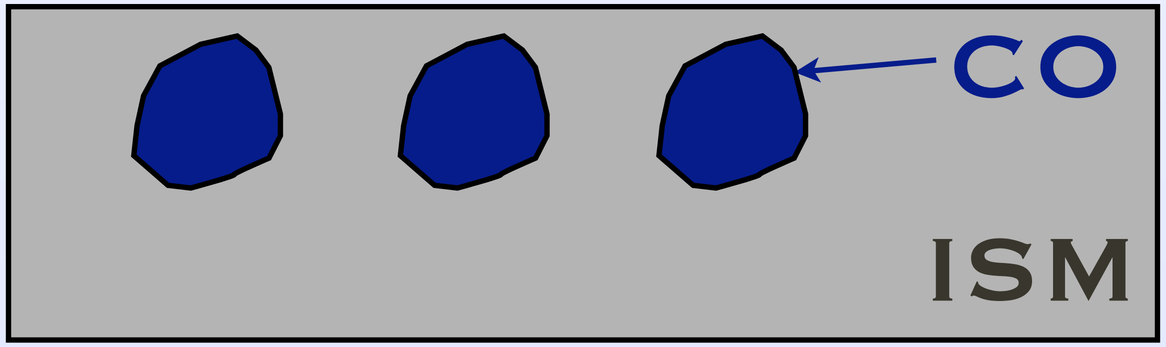
Key Assumptions of KS relation

- **Star Formation Rate $\sum_{SFR}$ tracers: FUV (extinction corrected), mid-IR, and/or Hα**
  - Normal galaxies: 24 μm or TIR
  - Kennicutt & Evans 2012 Review
- **HI and CO lines, assuming an appropriate X_{CO} factor, trace total gas surface density:**
  - $\sum_{gas} = \sum_{HI} + \sum_{H2}$
- **Results *strongly* depend on chosen conversion factors**
- **Focus on $\sum_{SFR} \propto \sum_{H2}^{N}$** (see S. Roychowdhury talk for HI)

Interpreting the KS Slope



Super-linear KS slope (N~1.5)



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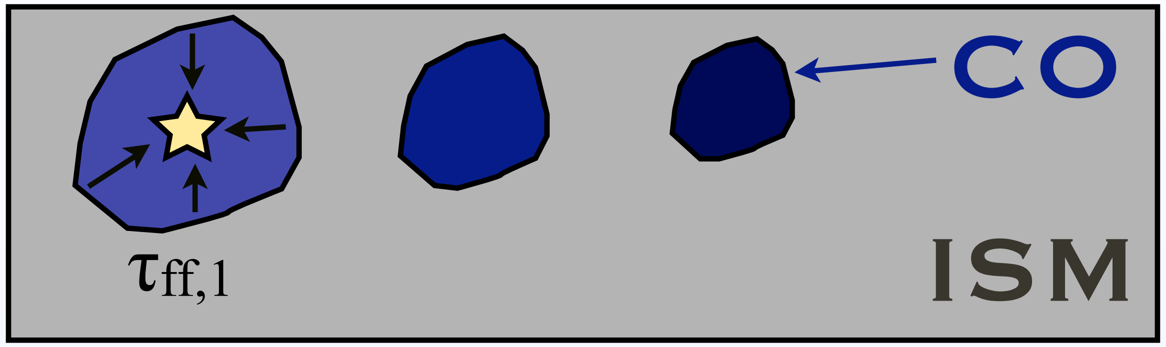

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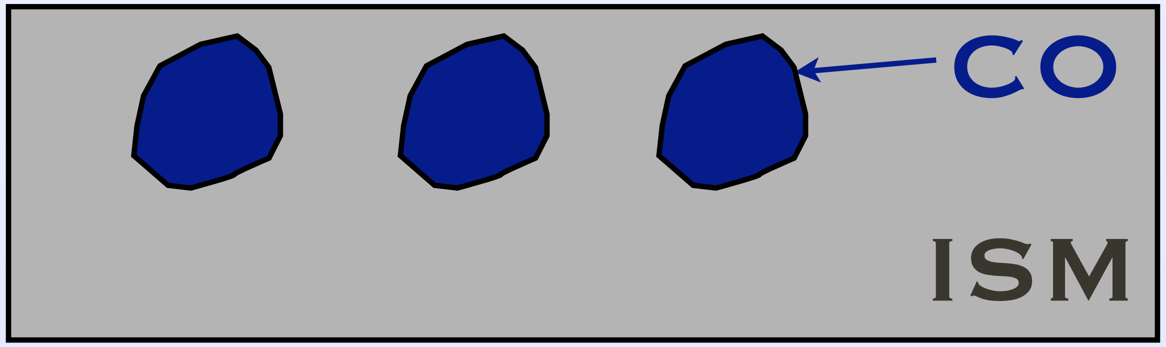

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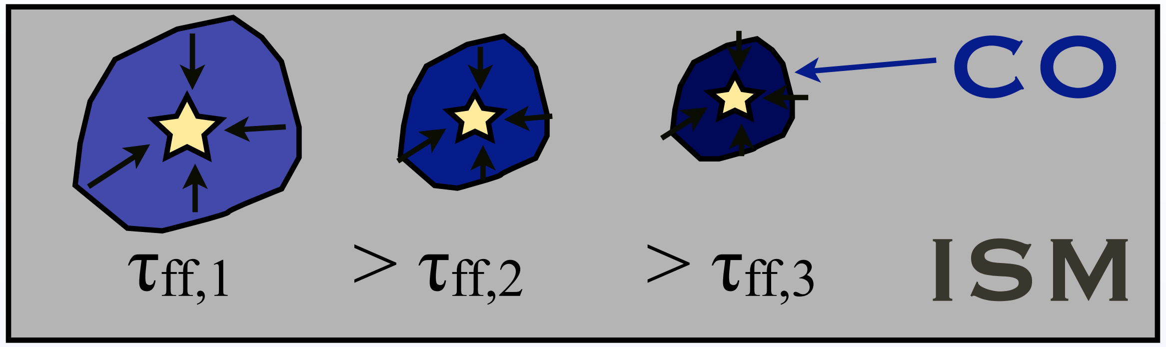

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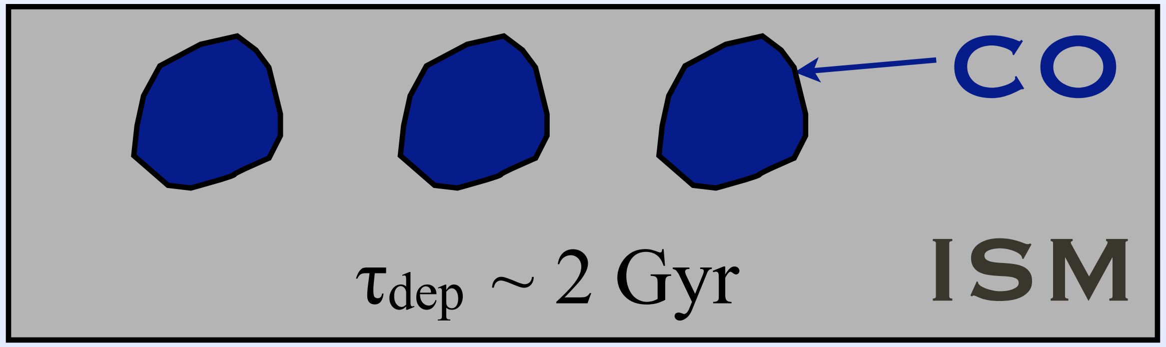

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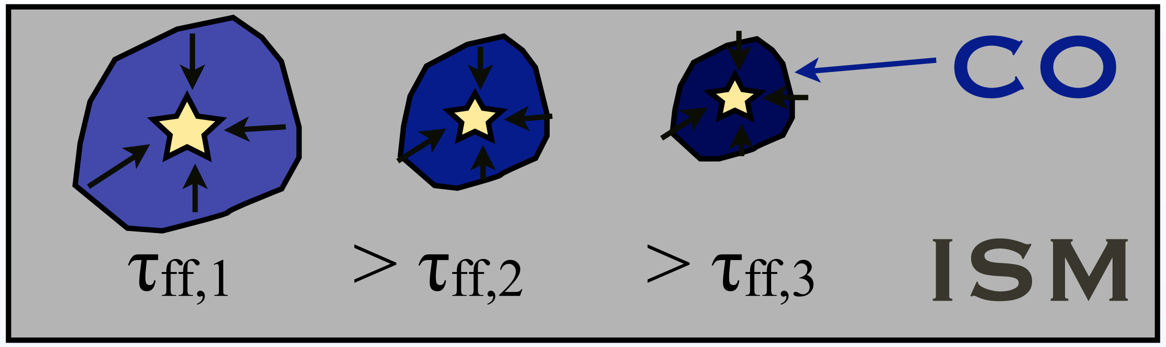

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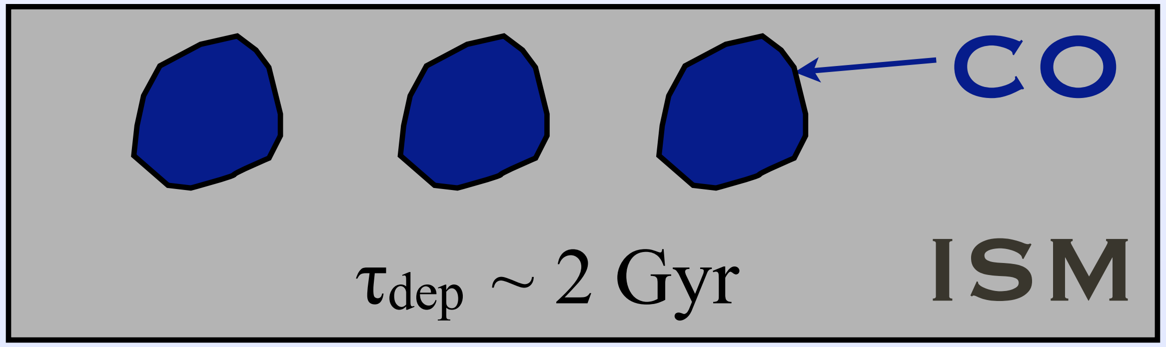
⇒ decreasing gas depletion time, or higher efficiency, with increasing GMC density



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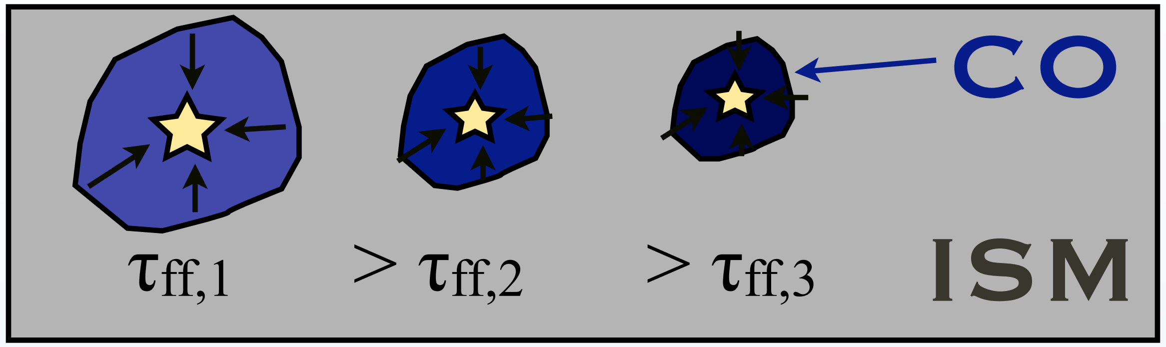

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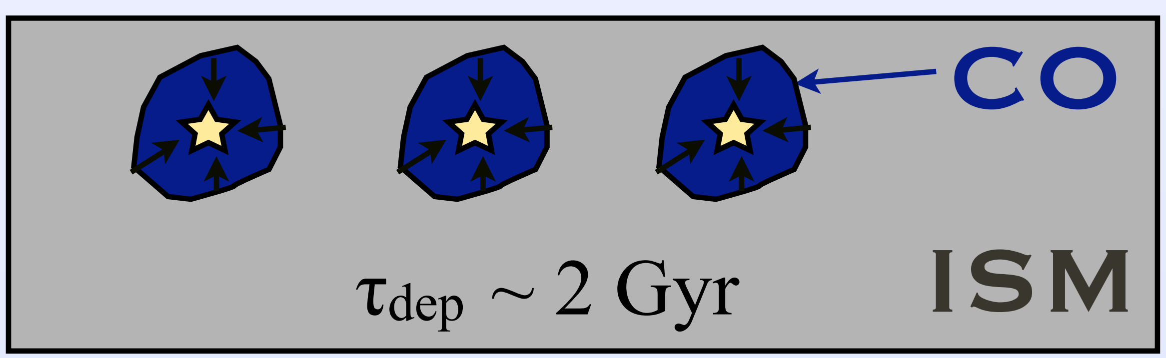

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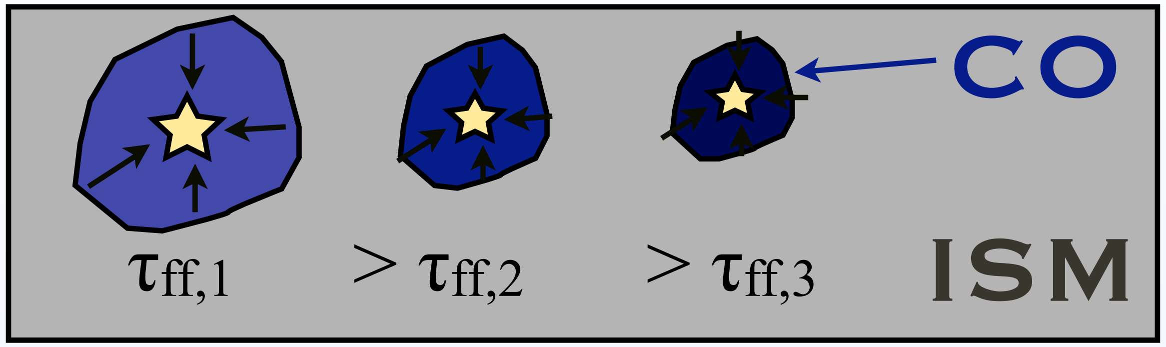

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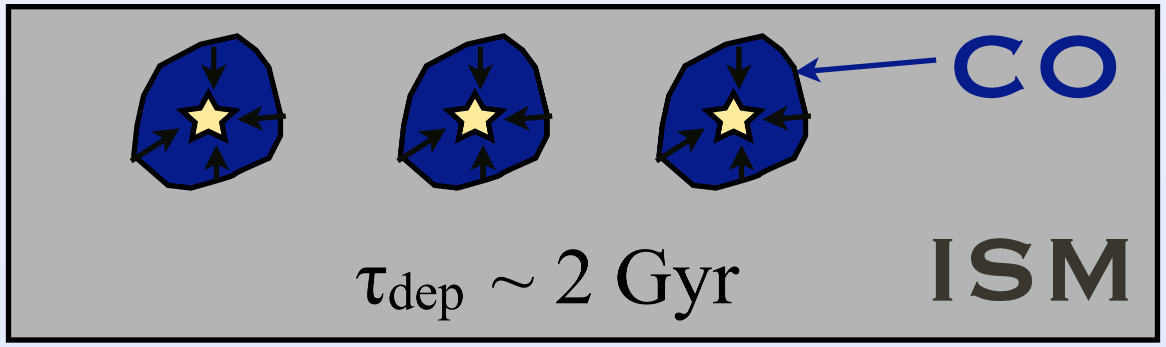

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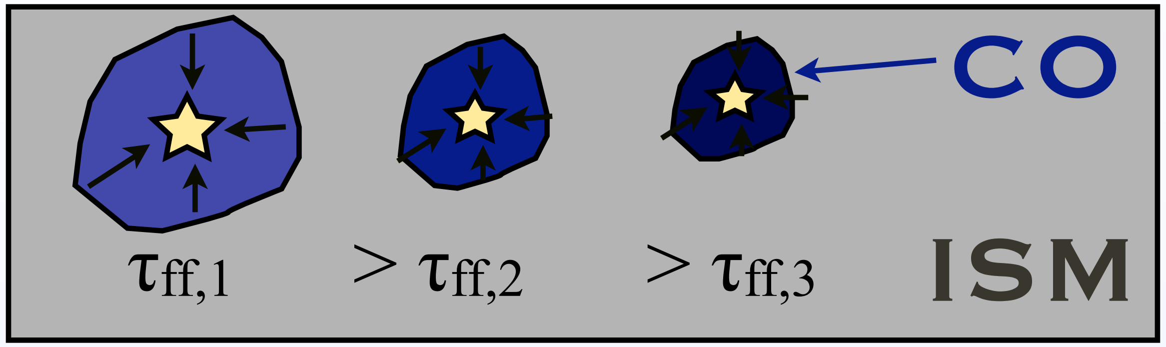

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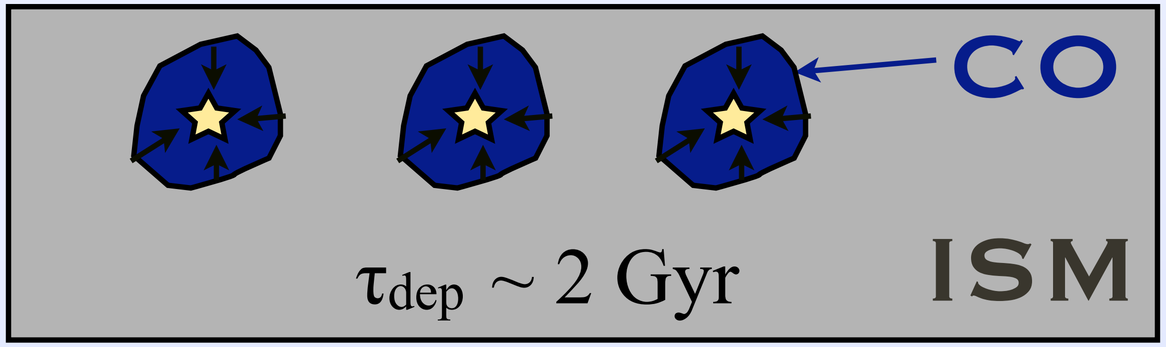
⇒ decreasing gas depletion time, or higher efficiency, with increasing GMC density

In both paradigms, CO traces star forming 'GMCs'

Depletion time $\tau_{\rm dep}$ a key parameter for theories of star formation (Ostriker+, Dobbs+, Krumholz+, Hopkins+, ...)



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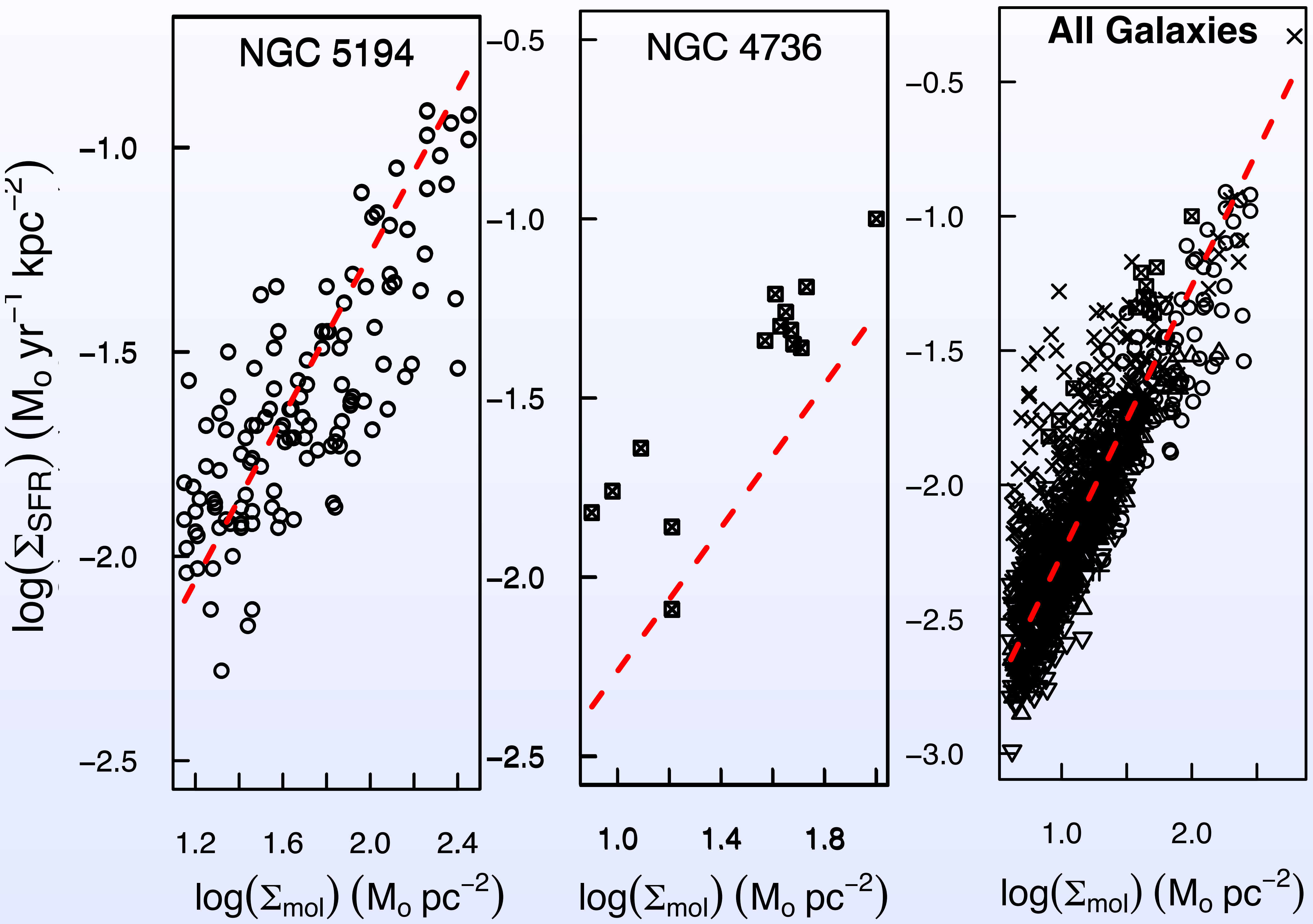
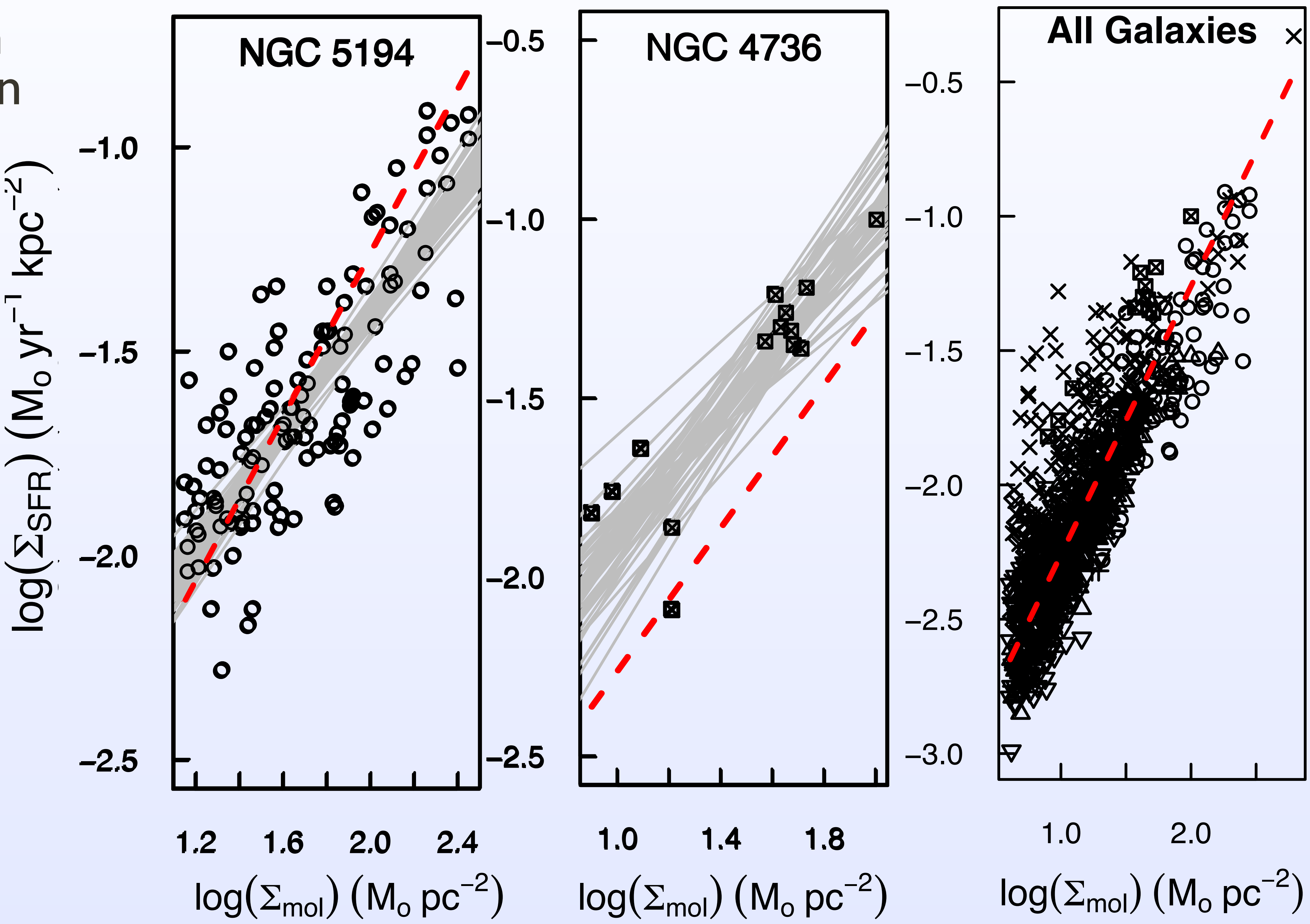
The KS Relationship of the Bigiel + ’08 Sample



Bigiel + ’08
Shetty, Kelly, Bigiel ’13

The KS Relationship of the Bigiel + '08 Sample

Gray lines: 50 random draws from the Bayesian posterior



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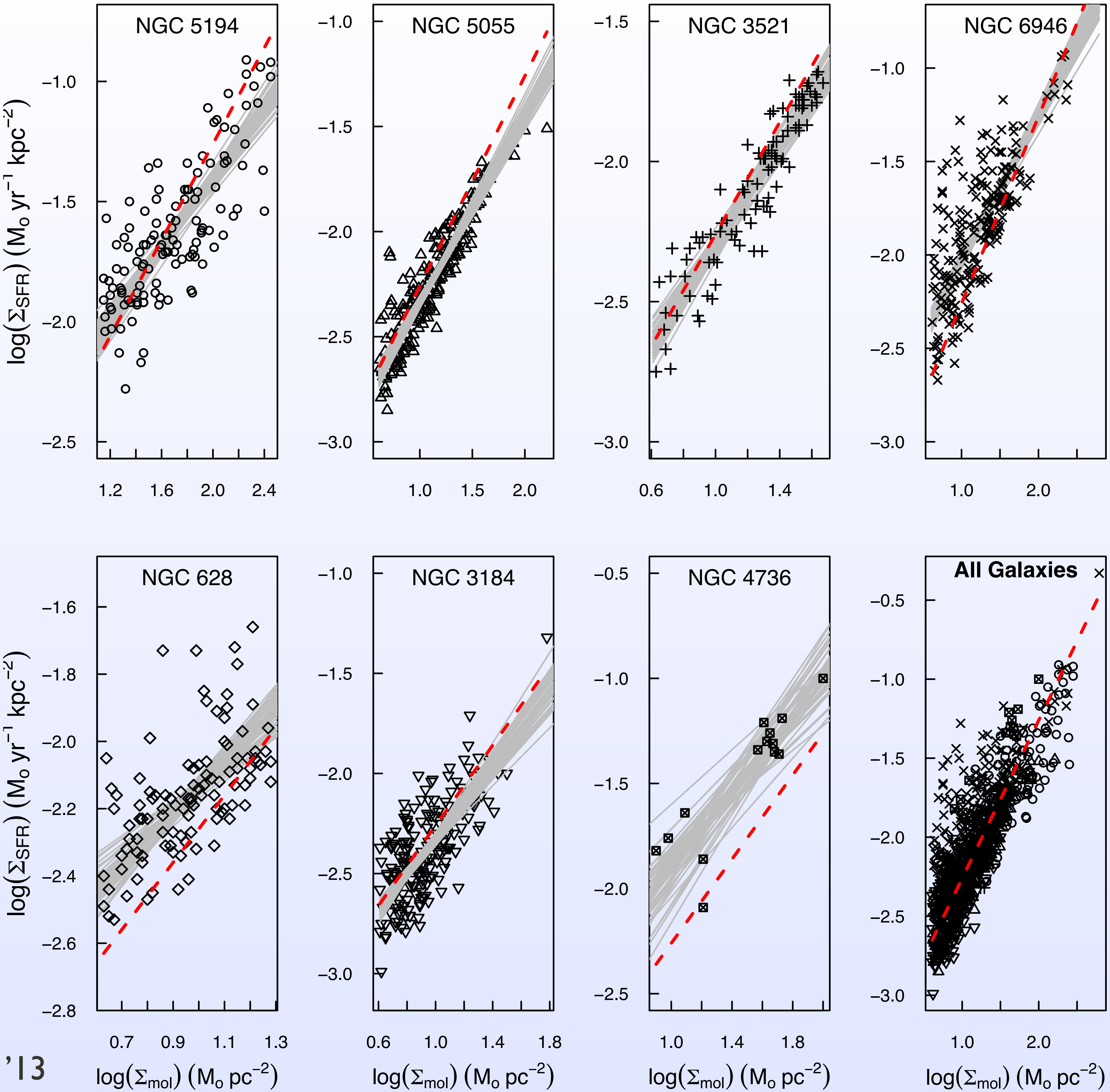

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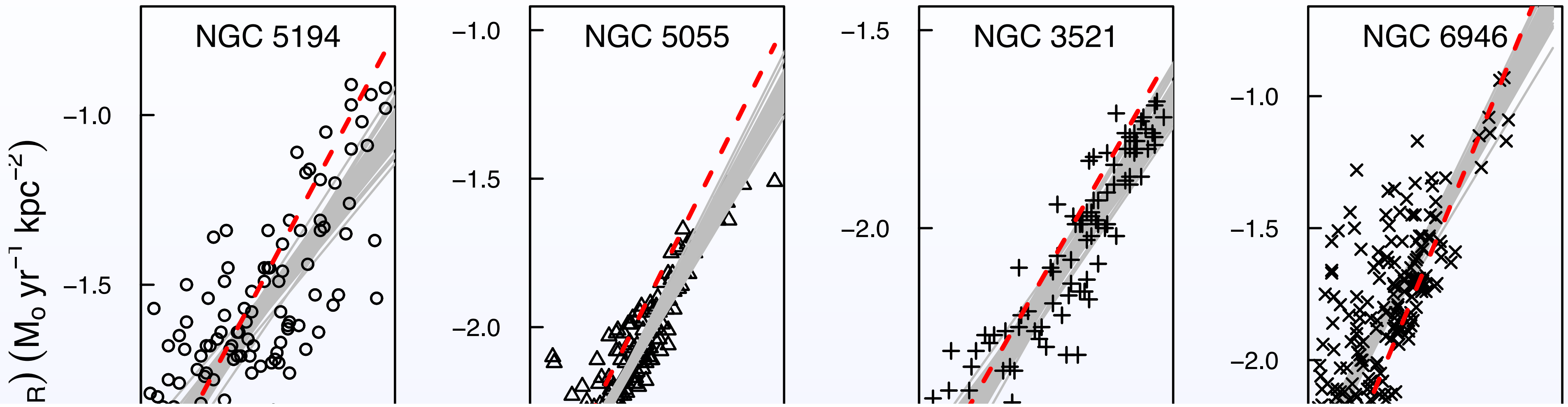
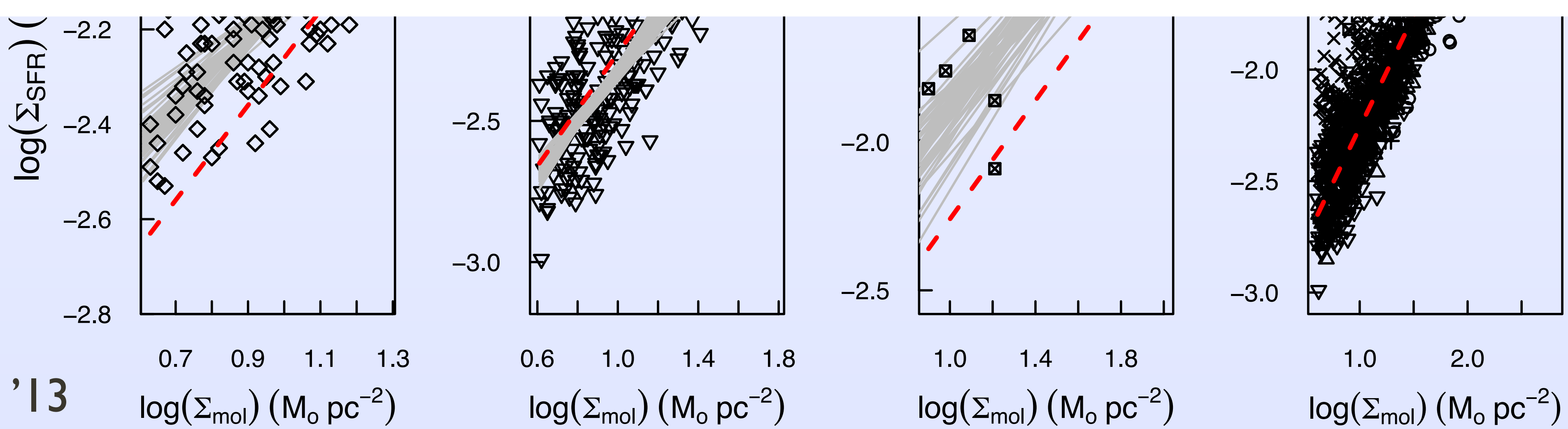


Subject	Bayes A	Bayes $2\sigma_A$	Bayes N	Bayes $2\sigma_N$	Bayes σ_{scat}
NGC 5194 (M51)	−2.84	[−3.0, −2.7]	0.72	[0.62, 0.83]	0.06
NGC 5055	−3.20	[−3.3, −3.1]	0.87	[0.79, 0.95]	0.04
NGC 3521	−3.20	[−3.4, −3.0]	0.90	[0.76, 1.03]	0.05
NGC 6946	−2.81	[−2.9, −2.7]	0.78	[0.70, 0.86]	0.11
NGC 628	−2.89	[−3.1, −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



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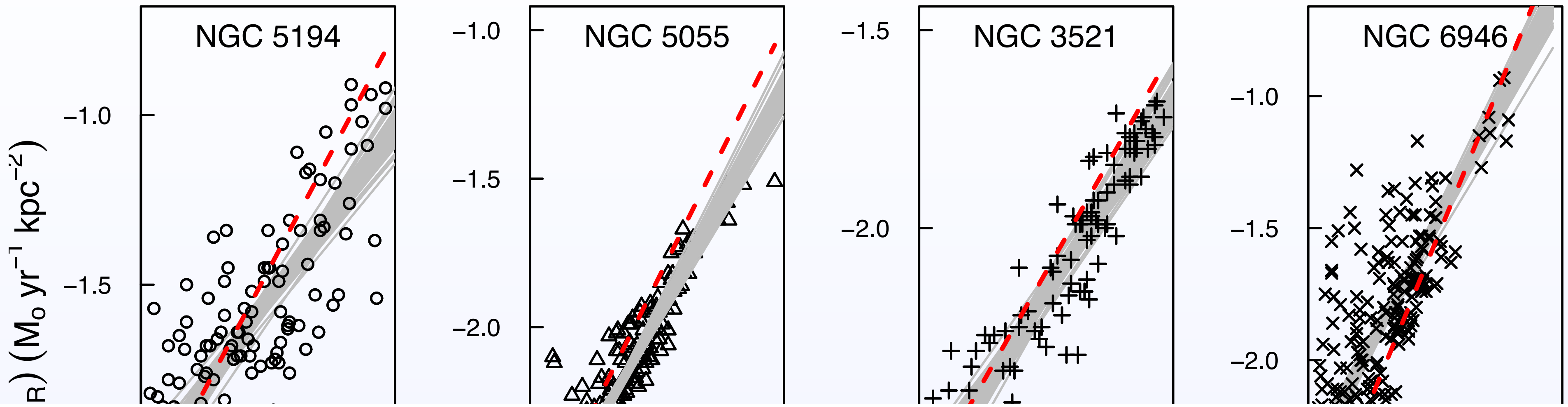

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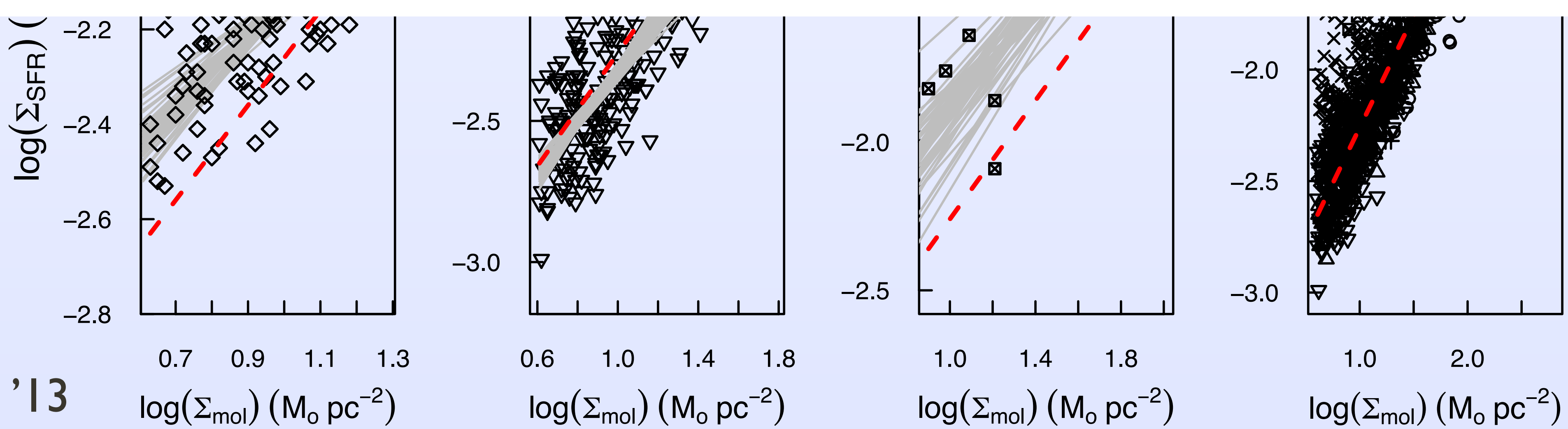

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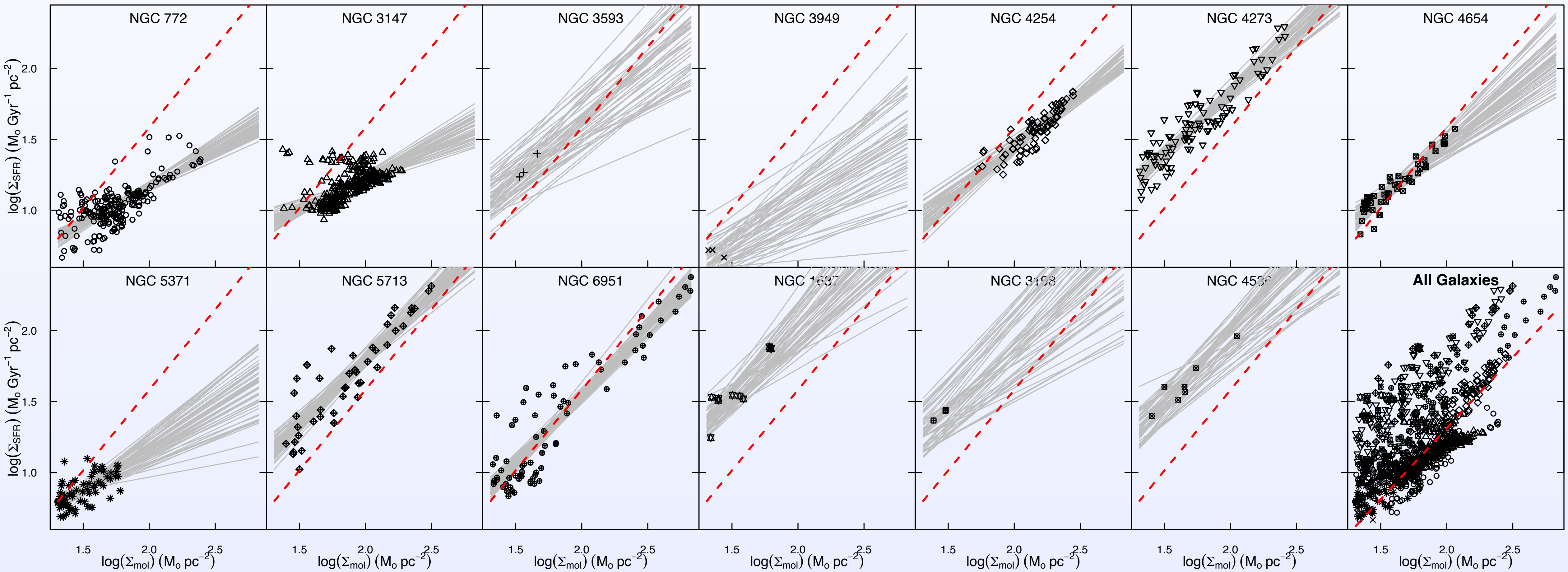

Rahman +'11, '12,
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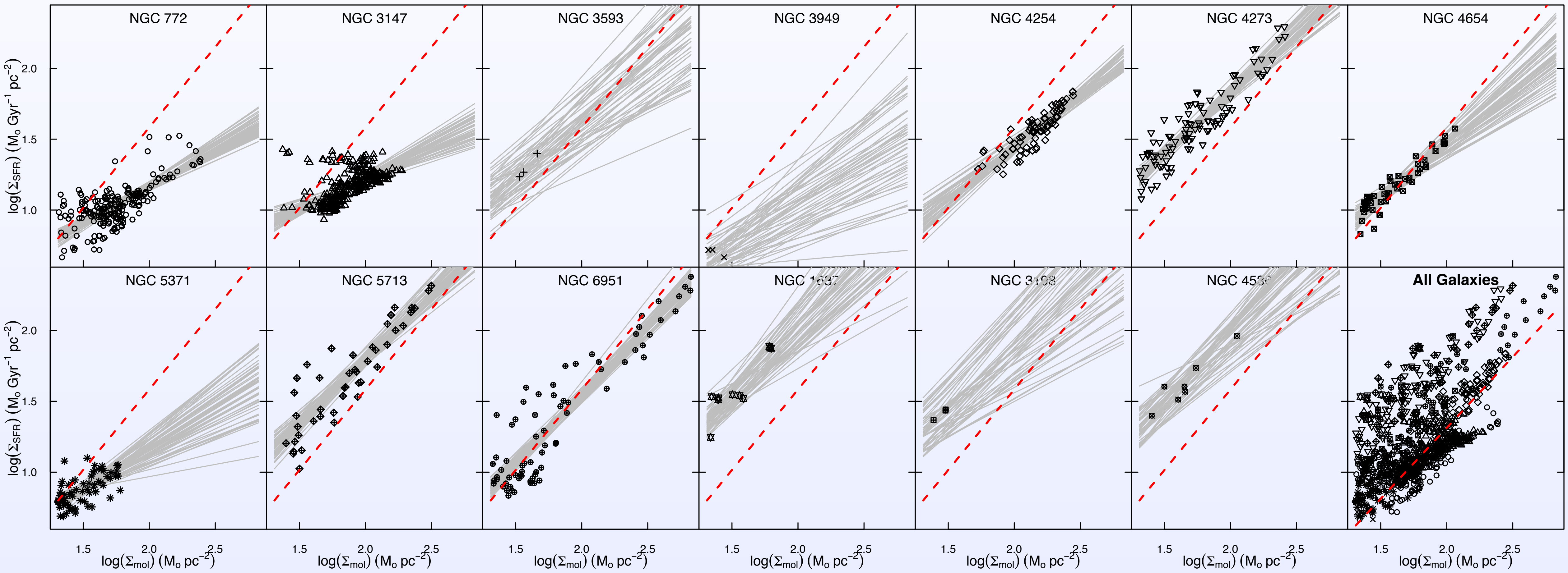

Individual slopes range from 0.42 - 0.95

Mean Slope = 0.76; 2σ=[0.58 - 0.94]

Rahman +'11, '12,
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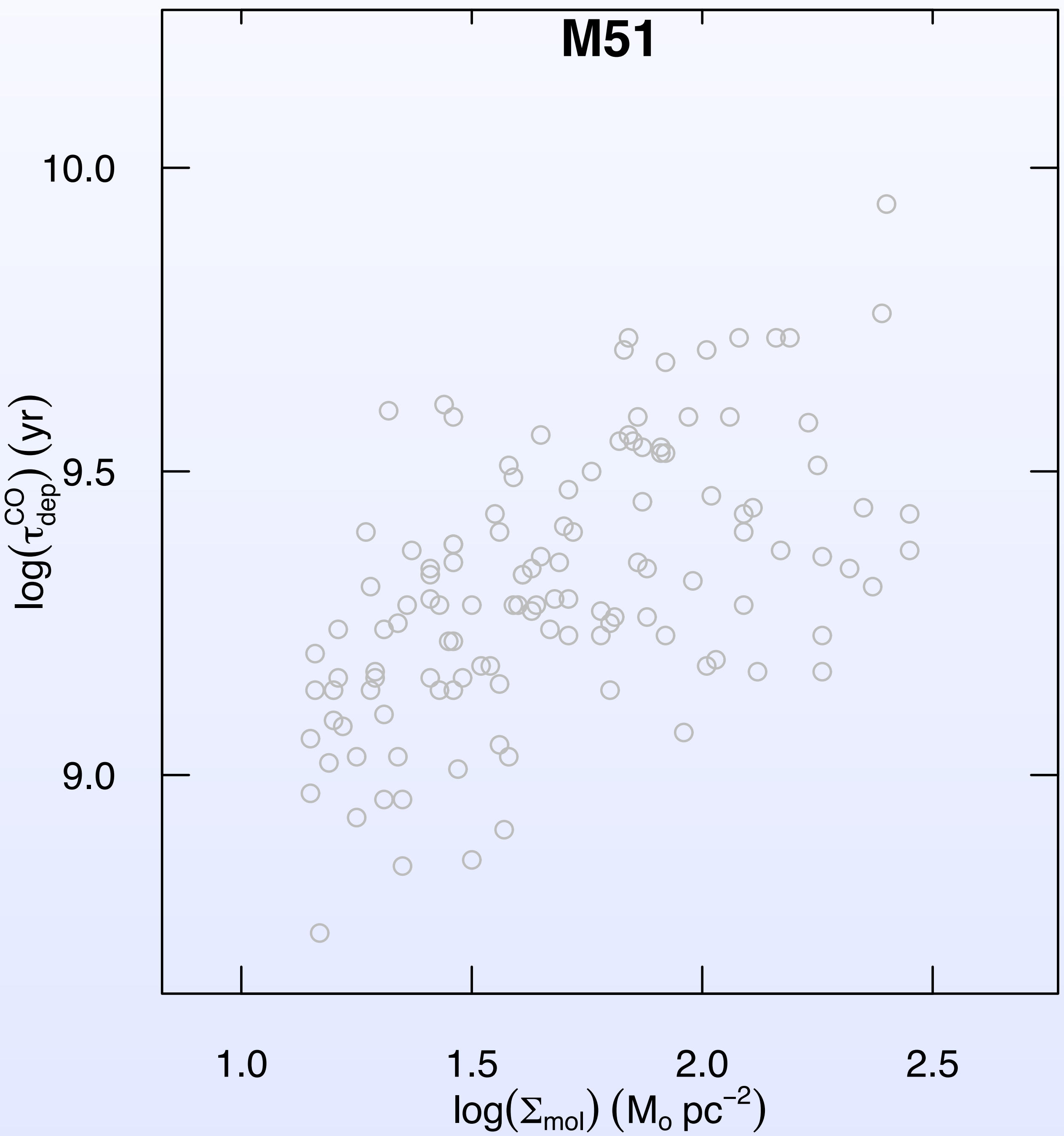
Implications of a sub-linear KS relationship: $\tau_{dep}^{CO} = \Sigma_{gas} / \Sigma_{SFR}$



Data from Bigiel + ‘08, ‘10
Shetty, Clark, Klessen ‘14b

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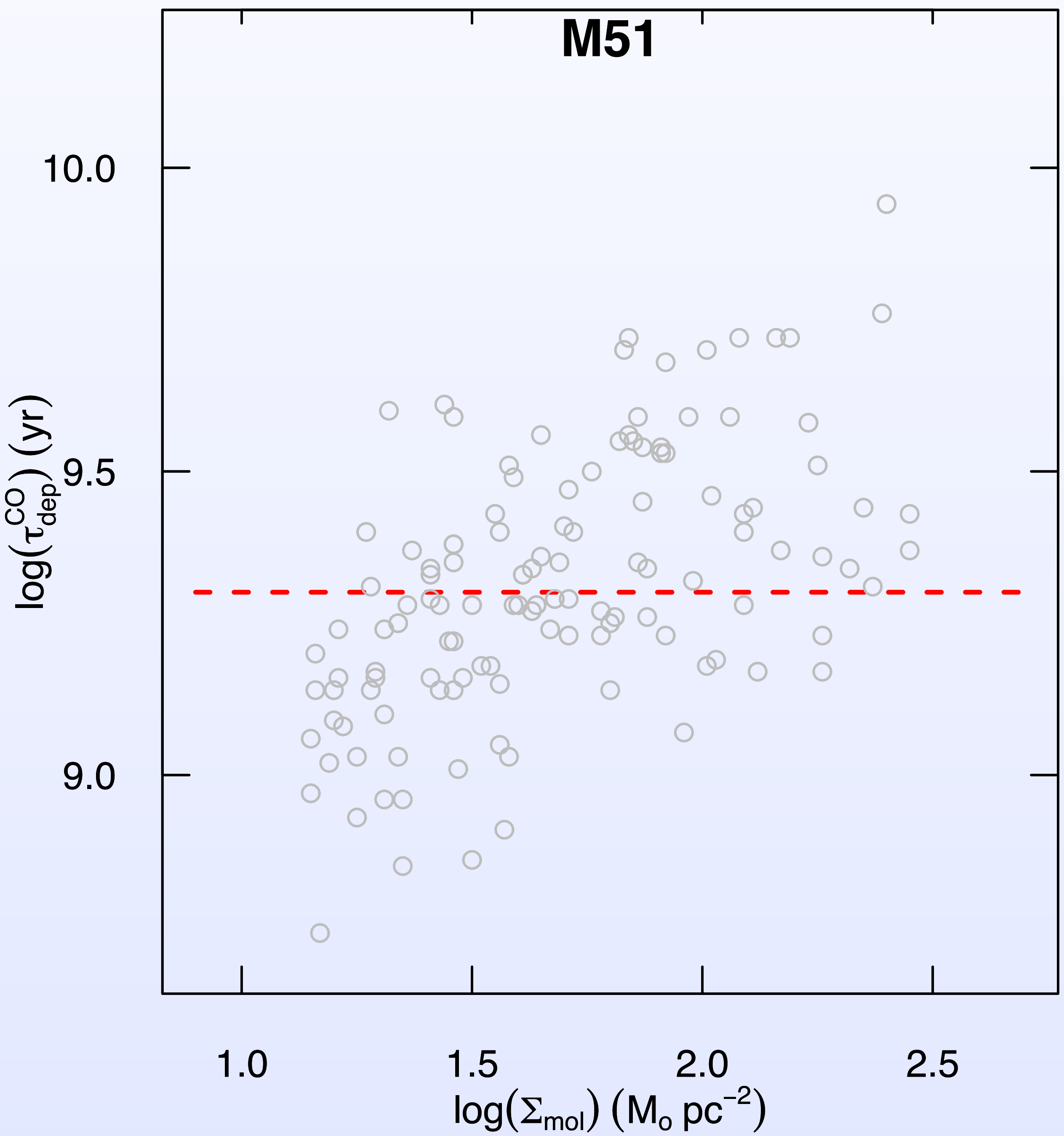

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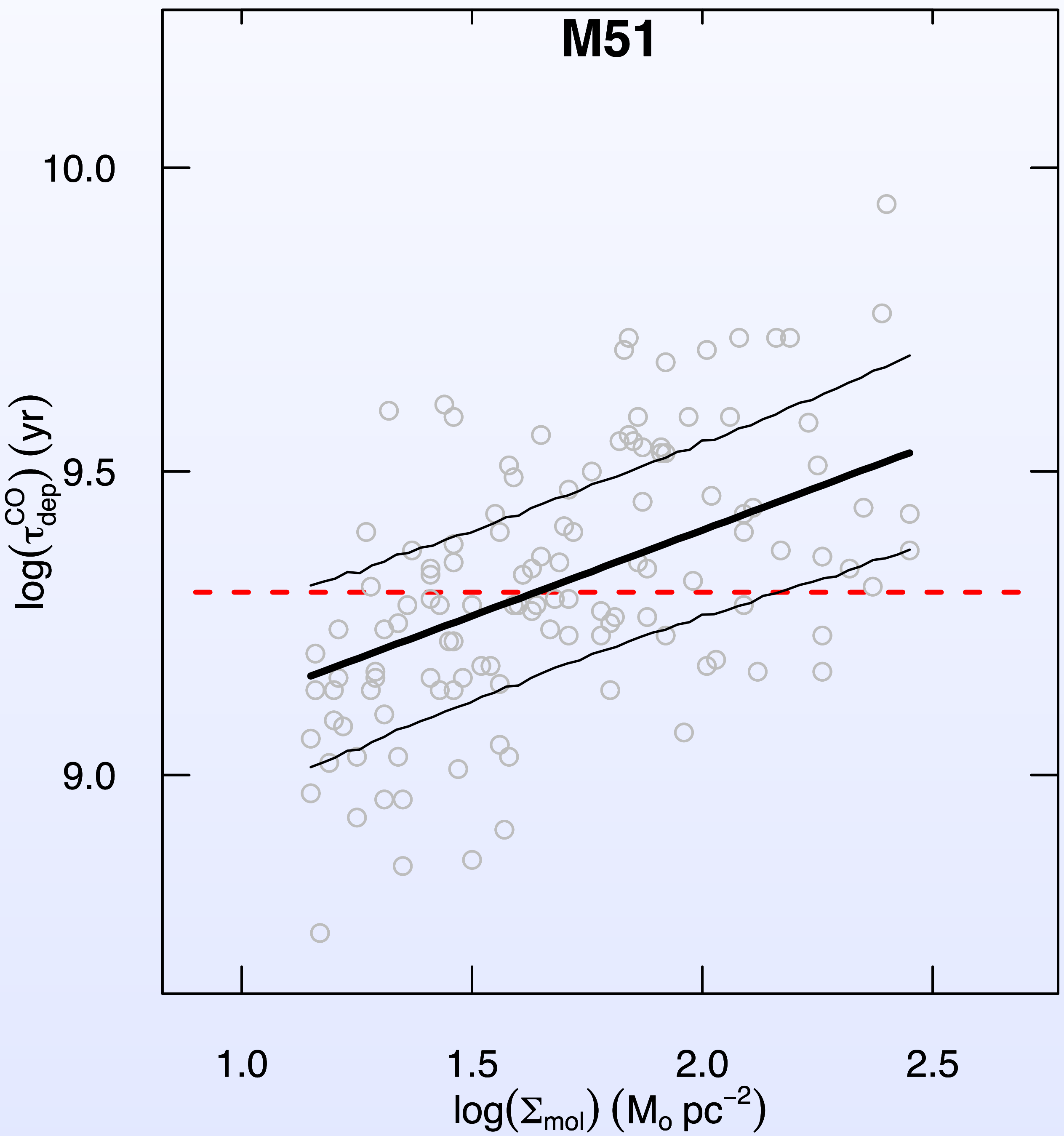

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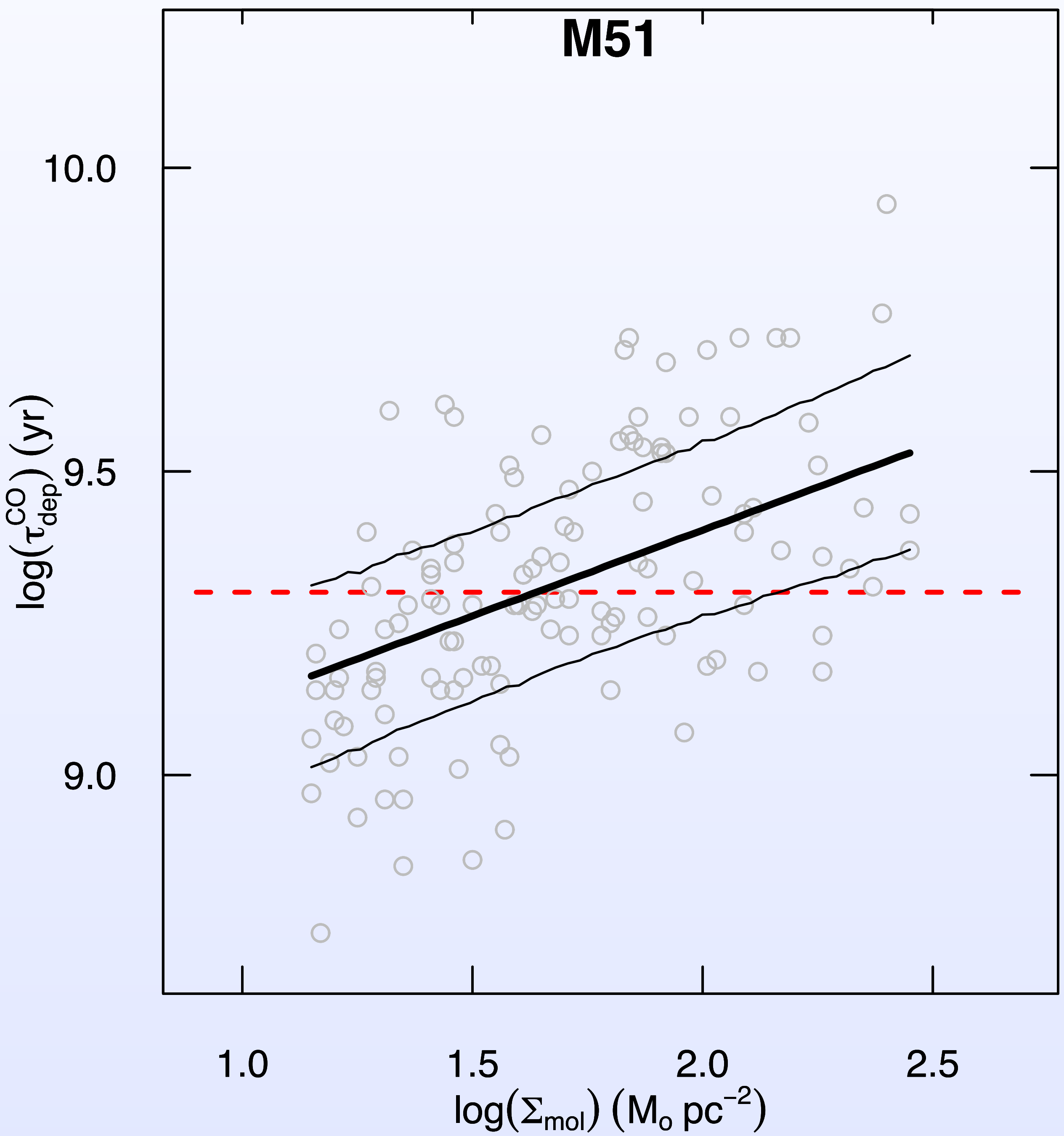

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- If CO is solely tracing clouds, then clouds have different properties, such as densities or SFRs
- X_{co} varies? X_{co} decreasing with Σ_{mol}. X_{co} - Σ_{mol} relationship must vary between galaxies...
- Other Observations: $\Sigma_{SFR} \propto \Sigma_{dense}$ ...? (Gao & Solomon '04, Heidermann+'10, Lada+'10, 12)

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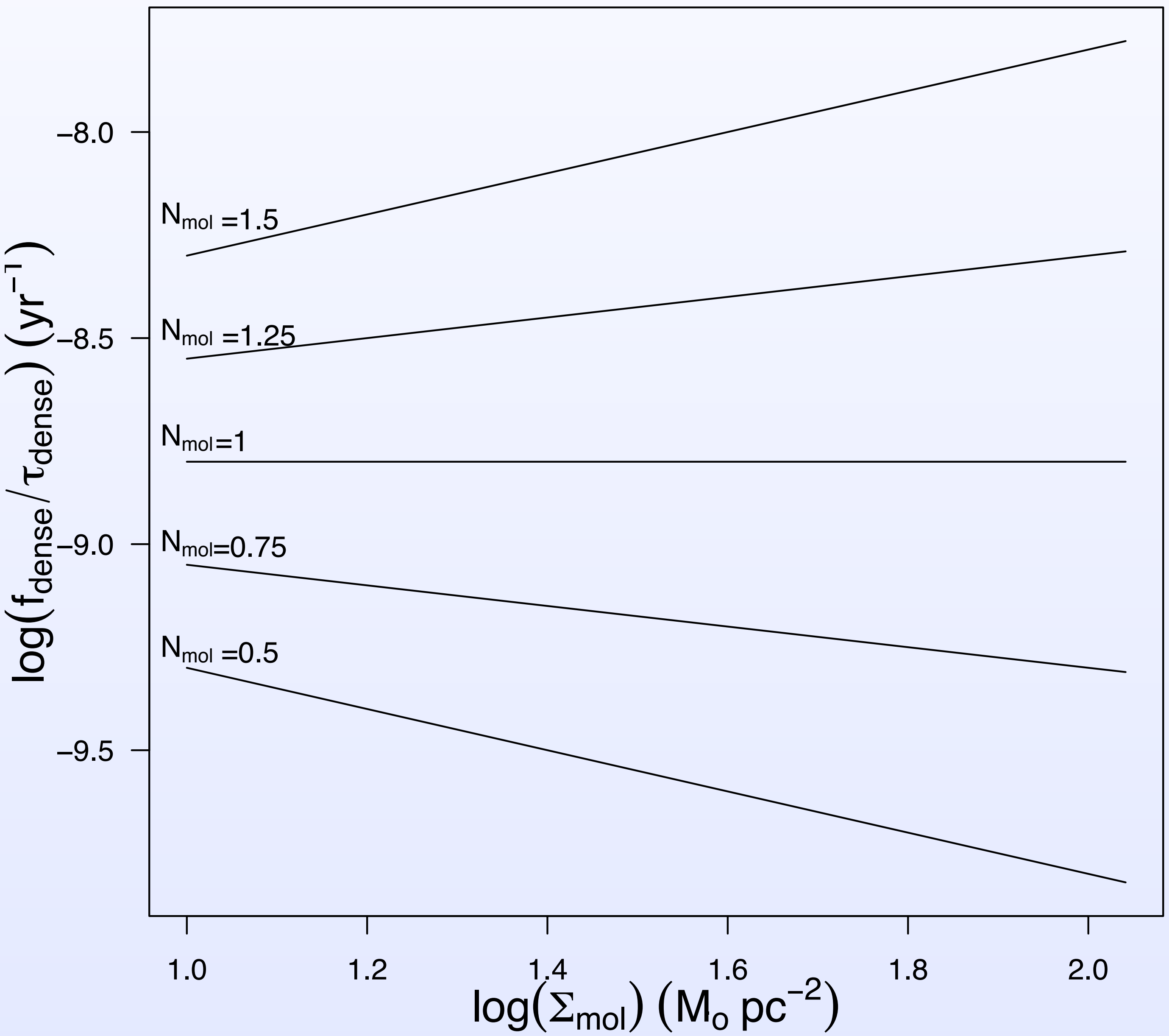

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Interpreting the variable & sub-linear KS Slope

- No "Universal" KS slope: **B** fields, stellar content, metallicity, molecular gas fraction all affect SF properties of given galaxy

Shetty, Clark, Klessen '14b

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Shetty, Clark, Klessen '14b

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ISM

Shetty, Clark, Klessen '14b

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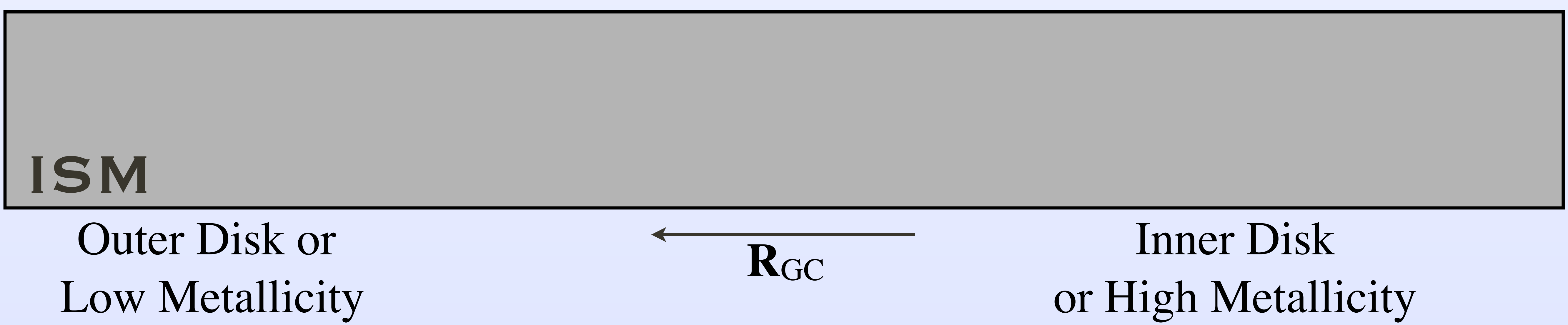

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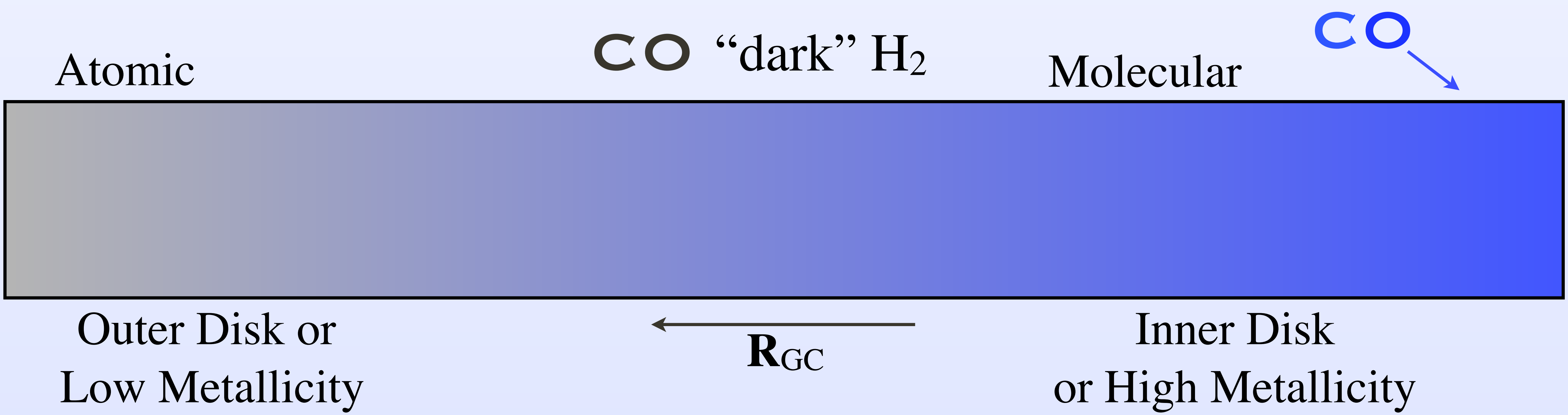

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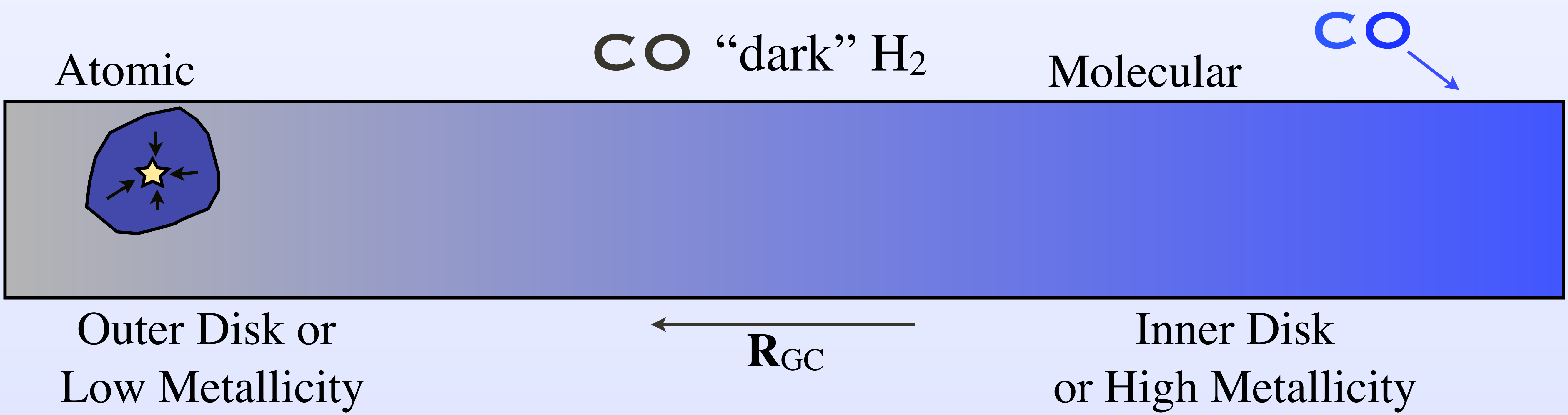

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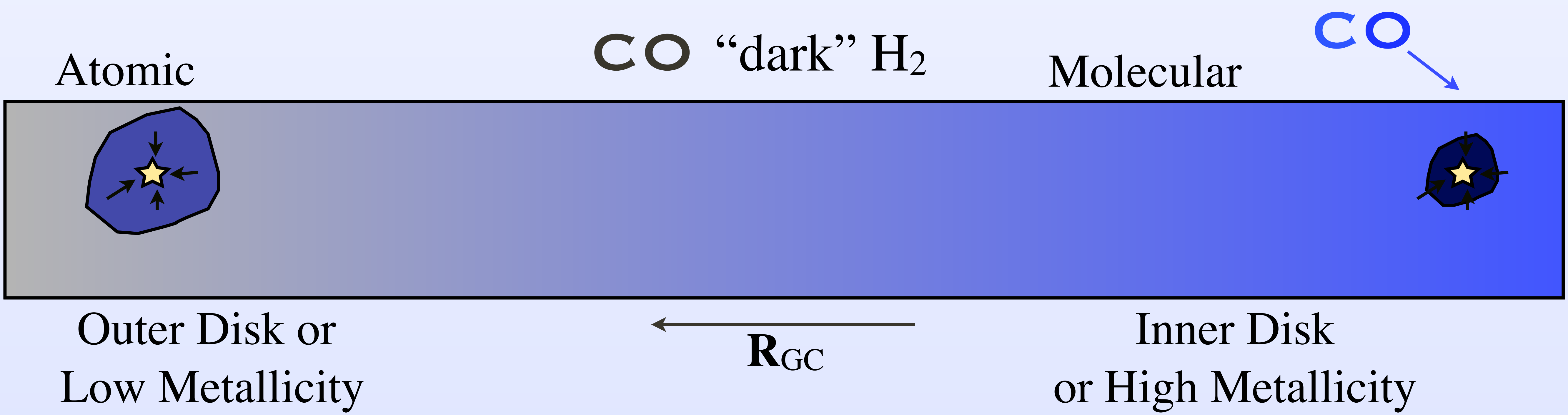

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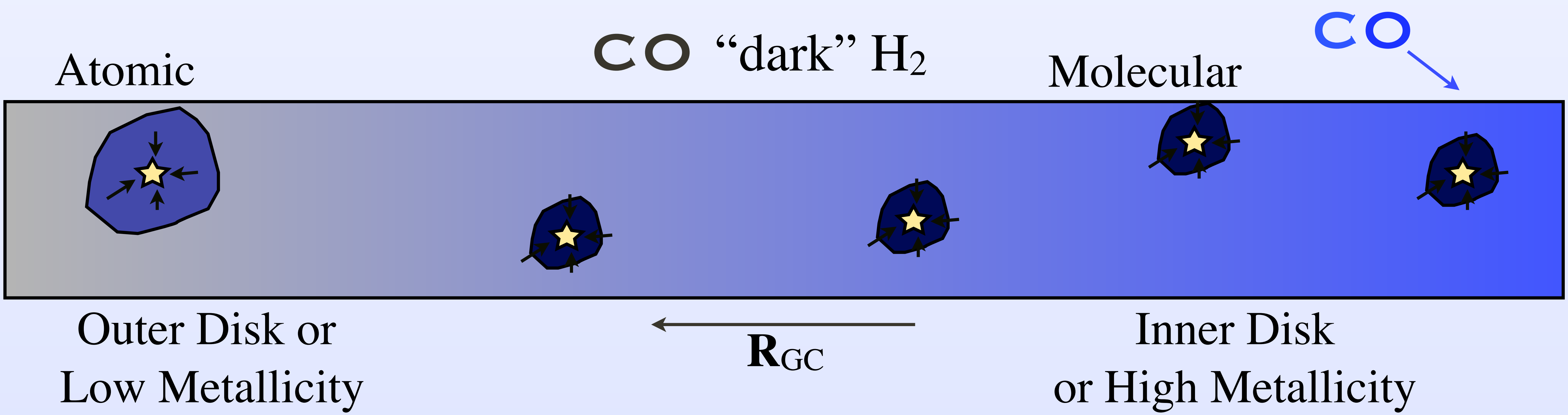

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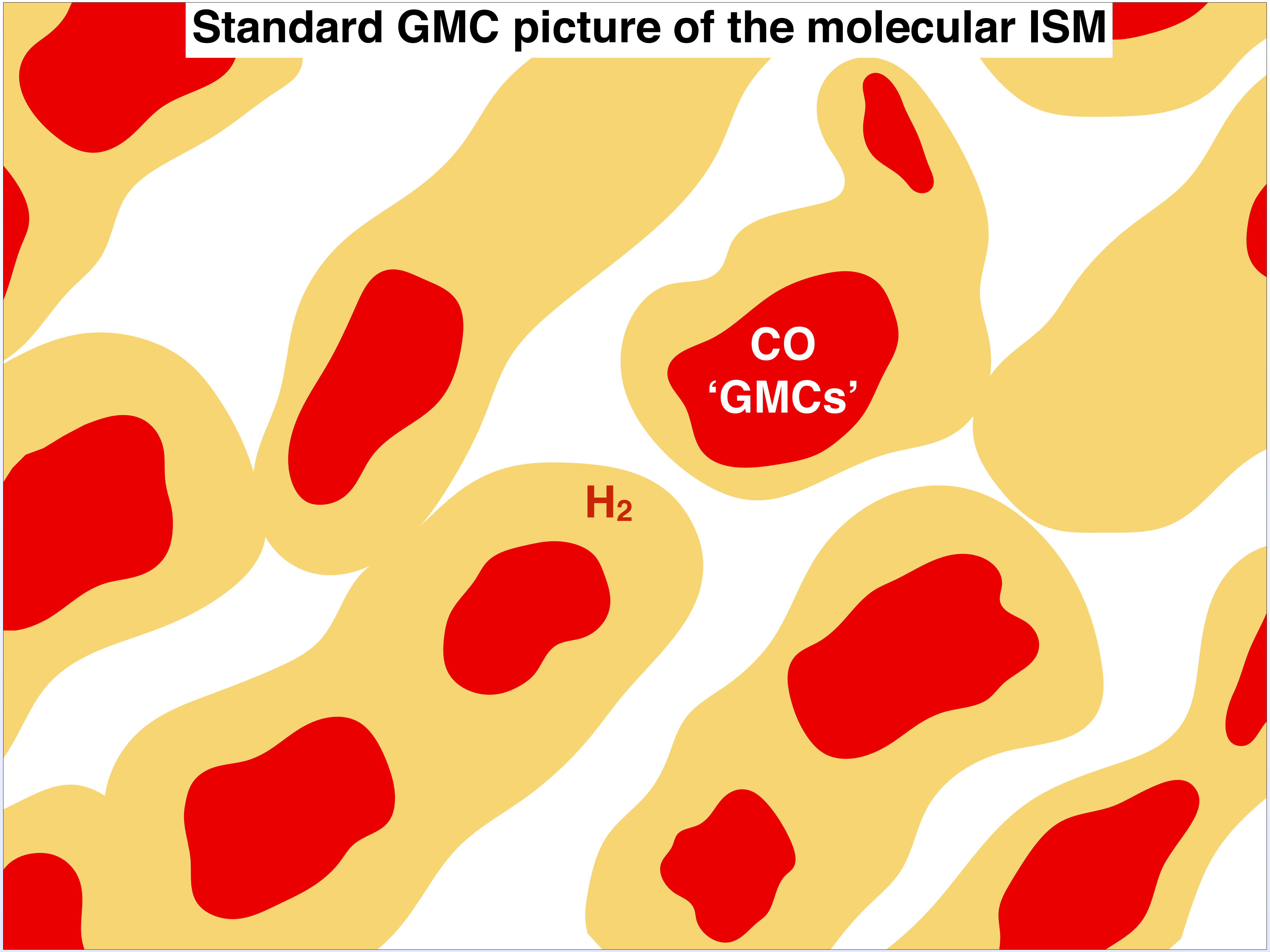
What are “GMCs”?



CO traced objects?

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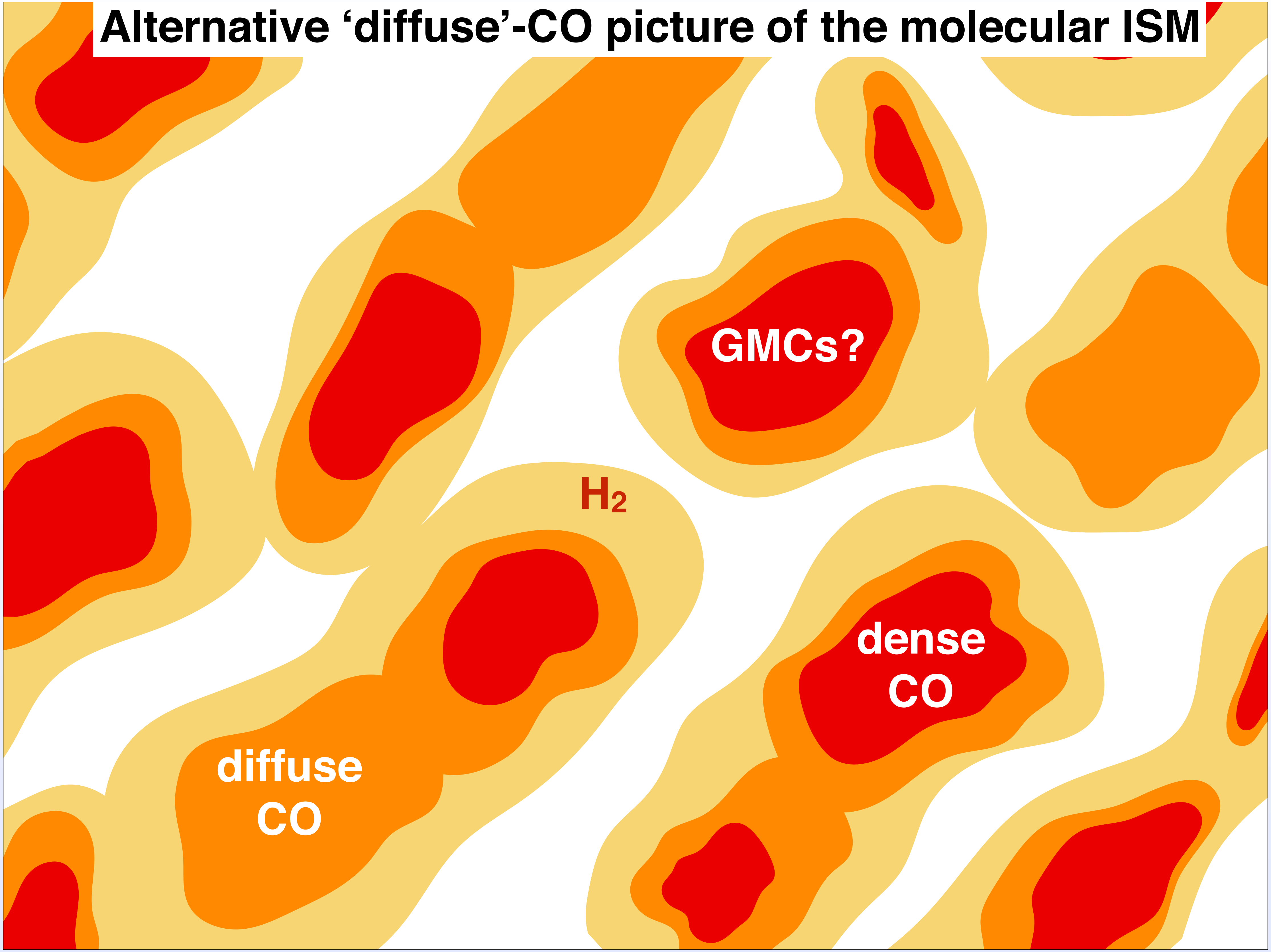

If CO exists elsewhere, are GMCs well defined?

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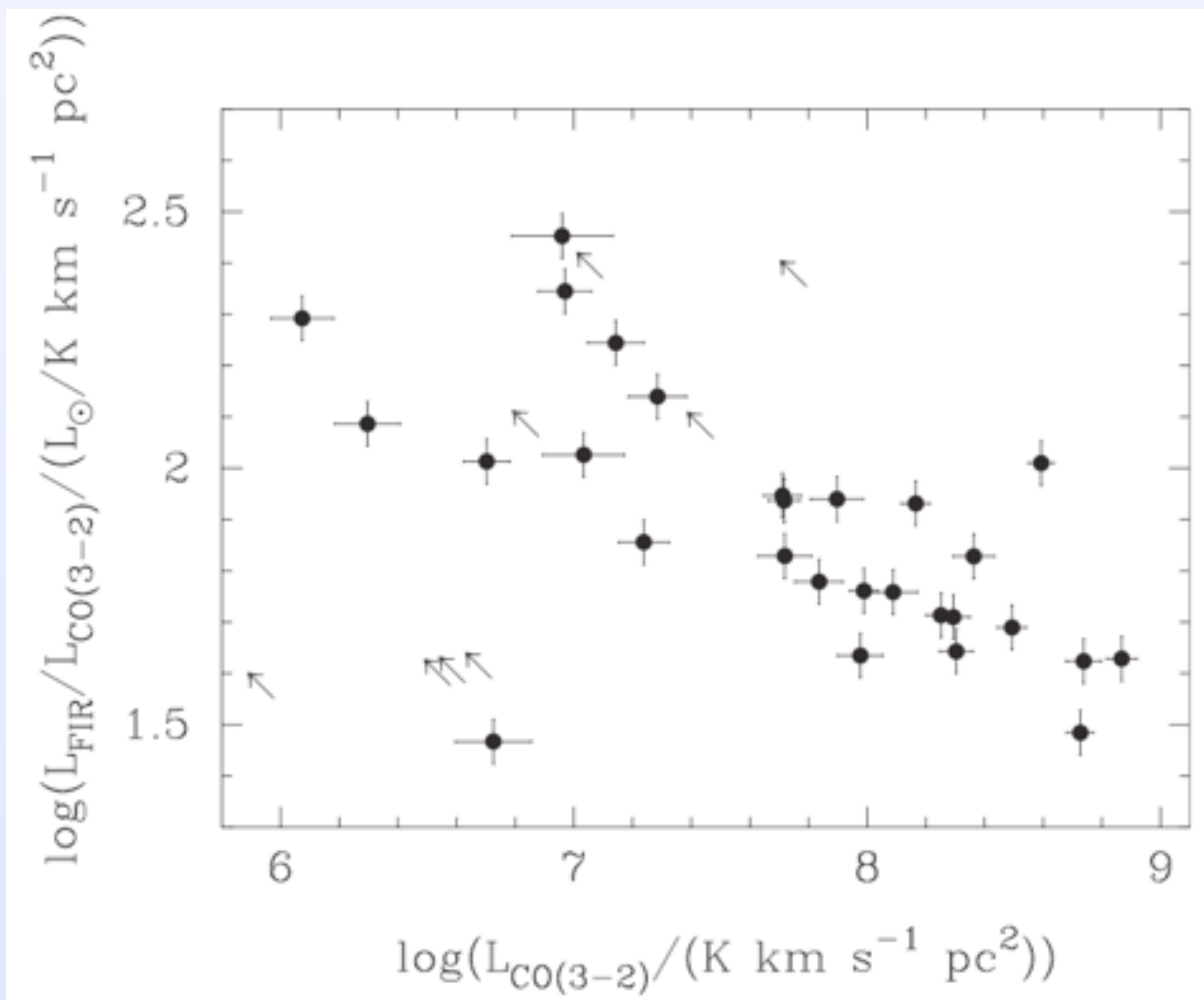
Recent results where $N_{mol} < 1$

- Blanc + ’09: N_{mol} = 0.85 +/- 0.03 in M51.
  - PAWS survey indicates CO is tracing a significant diffuse molecular component (Pety+’13, Hughes+’13)
- Ford + ’13: N_{mol} ≈0.6 in Andromeda.
- From CO (J=3-2) NGLS, inverse correlations between SF efficiency and molecular gas density (Wilson + ’12)

$\propto 1/\tau_{dep}$



(How Much) Diffuse Molecular Gas?

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- Presence of non-star forming molecular gas postulated by Elmegreen (1993). Chemistry matters, including metallicity, UV radiation field, ambient density, etc...

- M51 the most sublinear slope (0.72) in Bigiel + '08 sample: Broad wings in CO suggestive that 50% of emission is from a diffuse molecular component (Pety+ '13).

- From UMSB+GRS survey (Solomon+'87, Jackson + '06), significant fraction (≳20%) of CO luminosity not associated with dense gas (^{13}CO), even considering the distance ambiguity (Roman-Duval et al. In prep).

The L_{IR} - L_{CO} Relationship

Assumption: $L_{IR} \propto L_{CO}^{n}$

In log Space: $\log L_{\rm IR} = A + n \log L_{\rm CO}$

Common Assumption of Fixed Conversion Factors

Slope equivalent to KS index: $\Sigma_{\rm SFR} = a\Sigma_{\rm mol}^{n}$

Dust SEDs

The Observed Flux:

$$S_\nu = N_\mathrm{d} B_\nu(T_\mathrm{d}) \kappa_0 (\nu/\nu_0)^\beta$$

In fitting the SED, there are three free parameters:

Column Density N_d,
Temperature T_d,
and Spectral Index β

L_{IR} from SEDs

Total IR Luminosity:

$$L_{\rm IR} = \int S_\nu d\nu = N_{\rm d} \int B_\nu(T_{\rm d}) \kappa_\nu d\nu$$

Rearranging:

$$\log N_{\rm d} = \log L_{\rm IR} - \log \left(\int B_\nu(T_{\rm d}) \kappa_\nu d\nu \right)$$

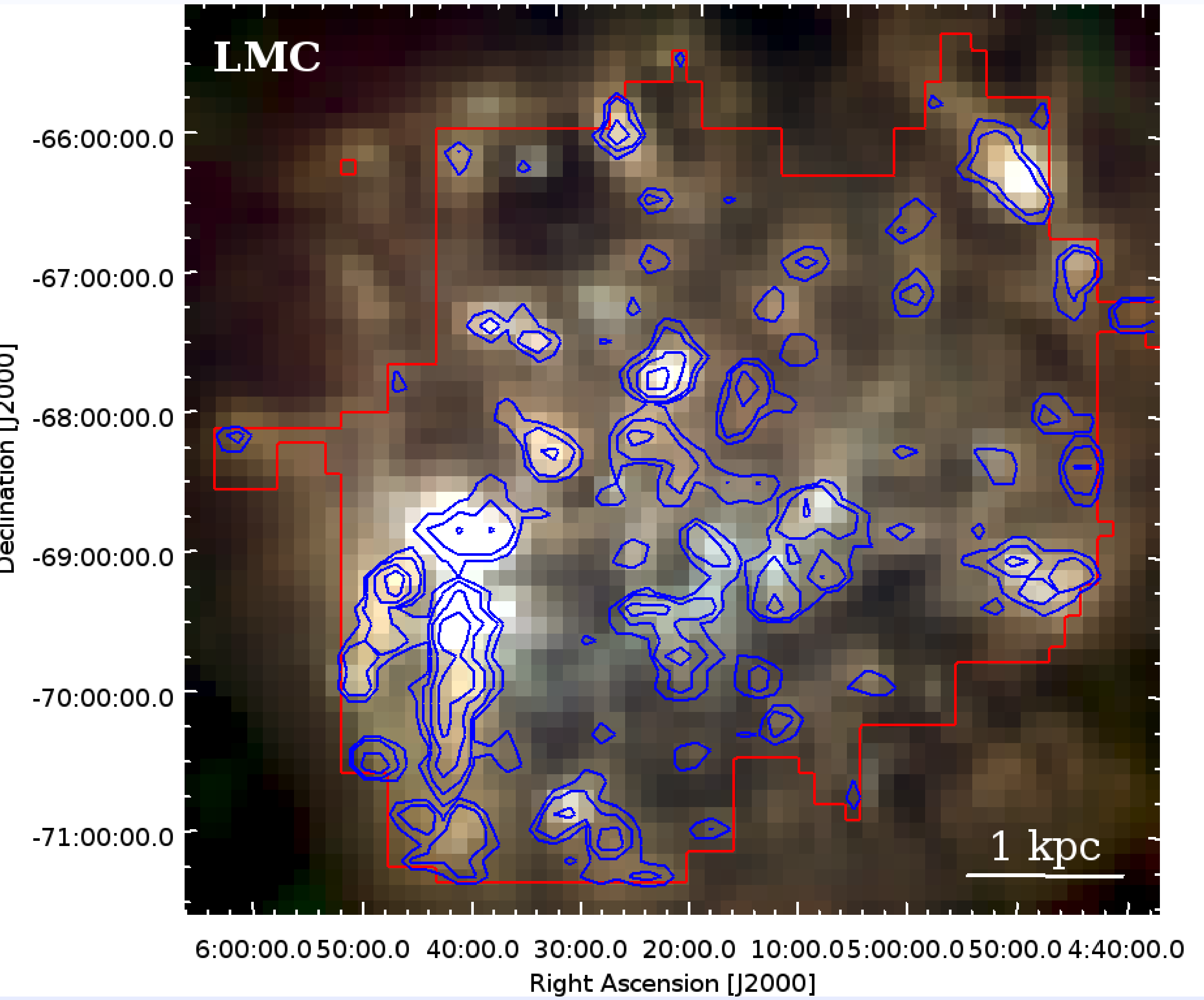
Combined with $L_{ir} \propto L_{CO}$:

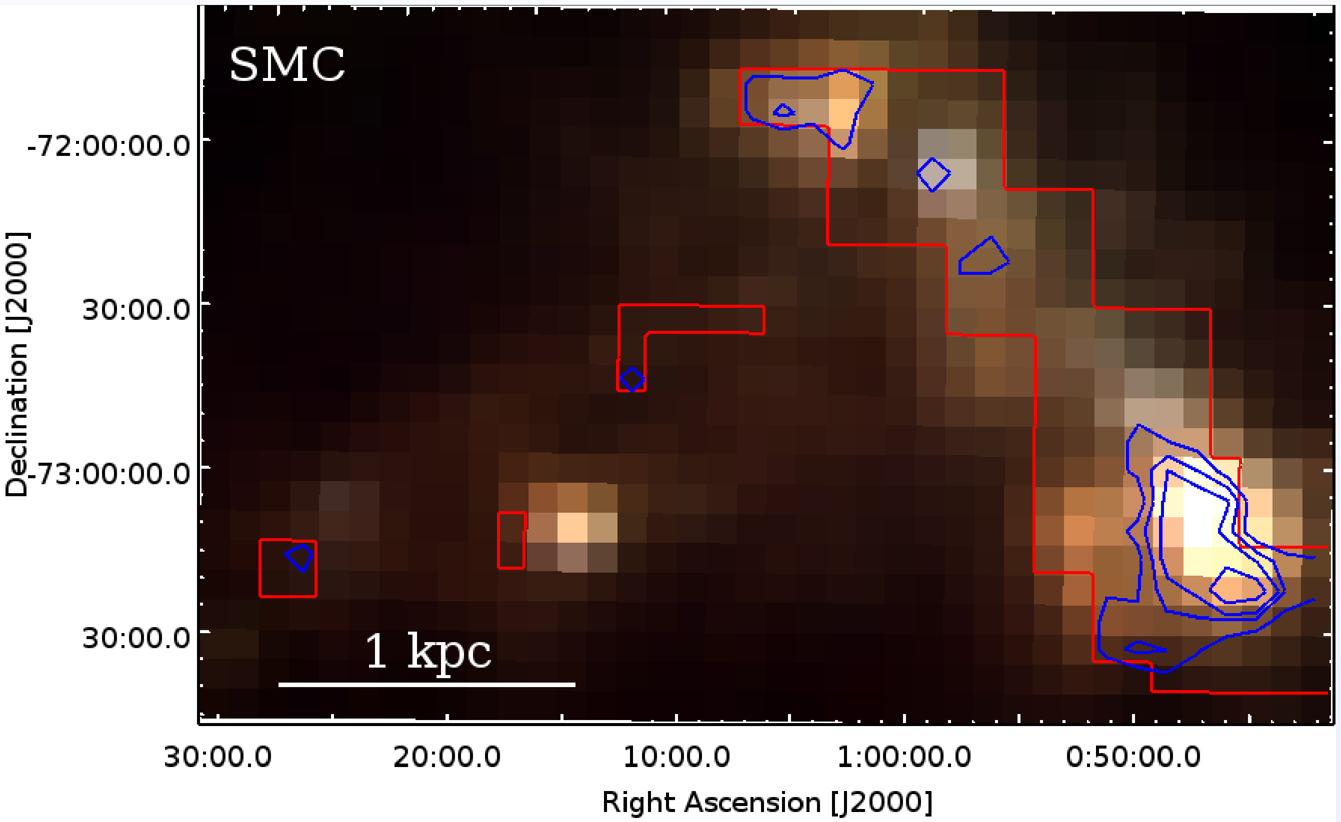
$$\log N_{\rm d} = A + n \log L_{\rm CO} - \log \left(\int B_\nu(T_{\rm d}) \kappa_\nu d\nu \right)$$

⟶ Given $\hat{L}_{CO}$ and $\hat{S}_\nu$, estimate N_d, T_d, β, A & n

Shetty+'15 (arXiv/1509.00639)

Application:Magellanic Clouds





Herschel HERITAGE Survey (Meixner+'10) (see also Roman-Duval+'14, Gordon+'14)

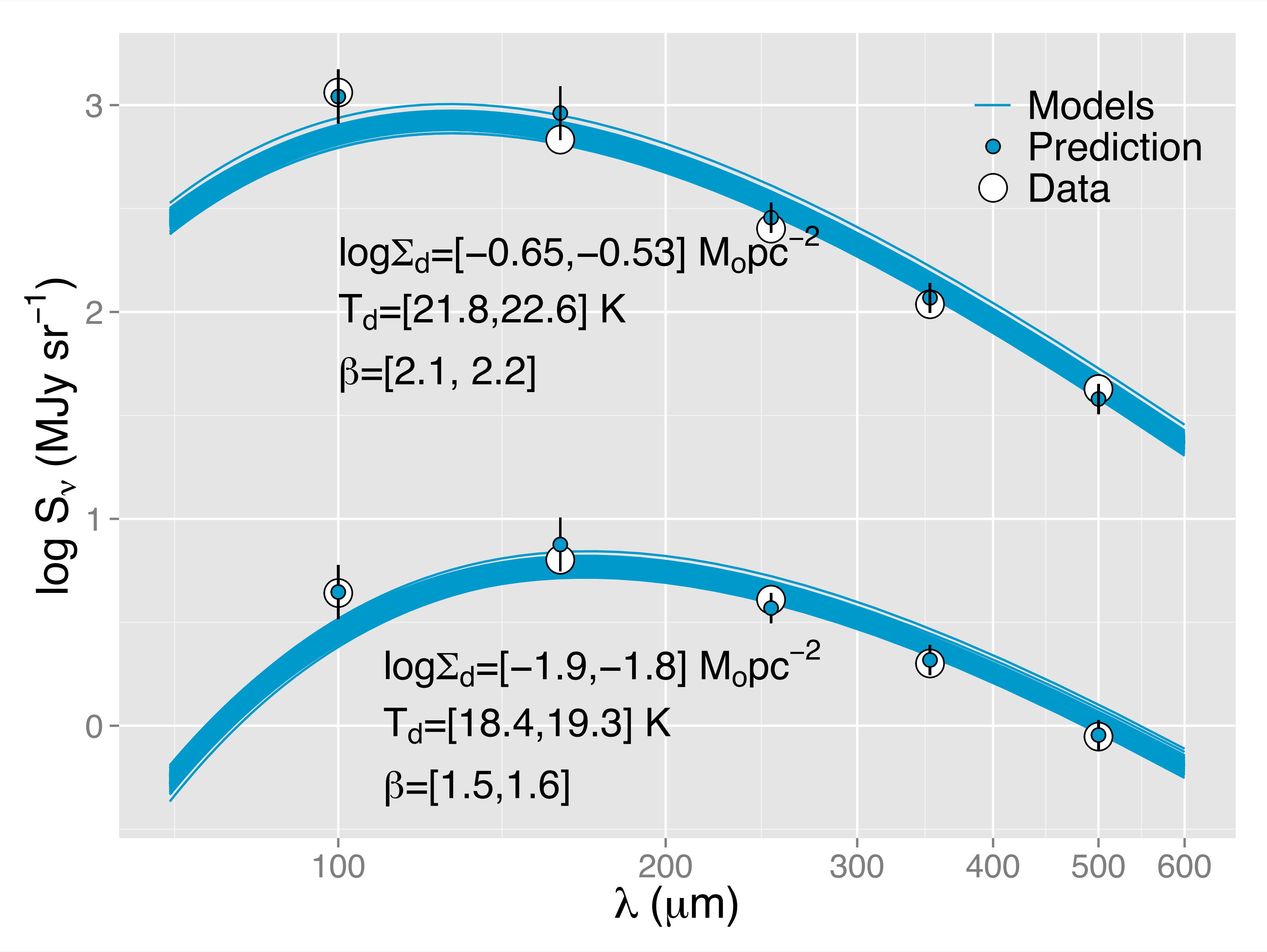
100 pc resolution

CO NANTEN Data (Mizuno+'01)

Shetty+'15 (arXiv/1509.00639)

Results: Magellanic Clouds

Shetty+'15 (arXiv/1509.00639)



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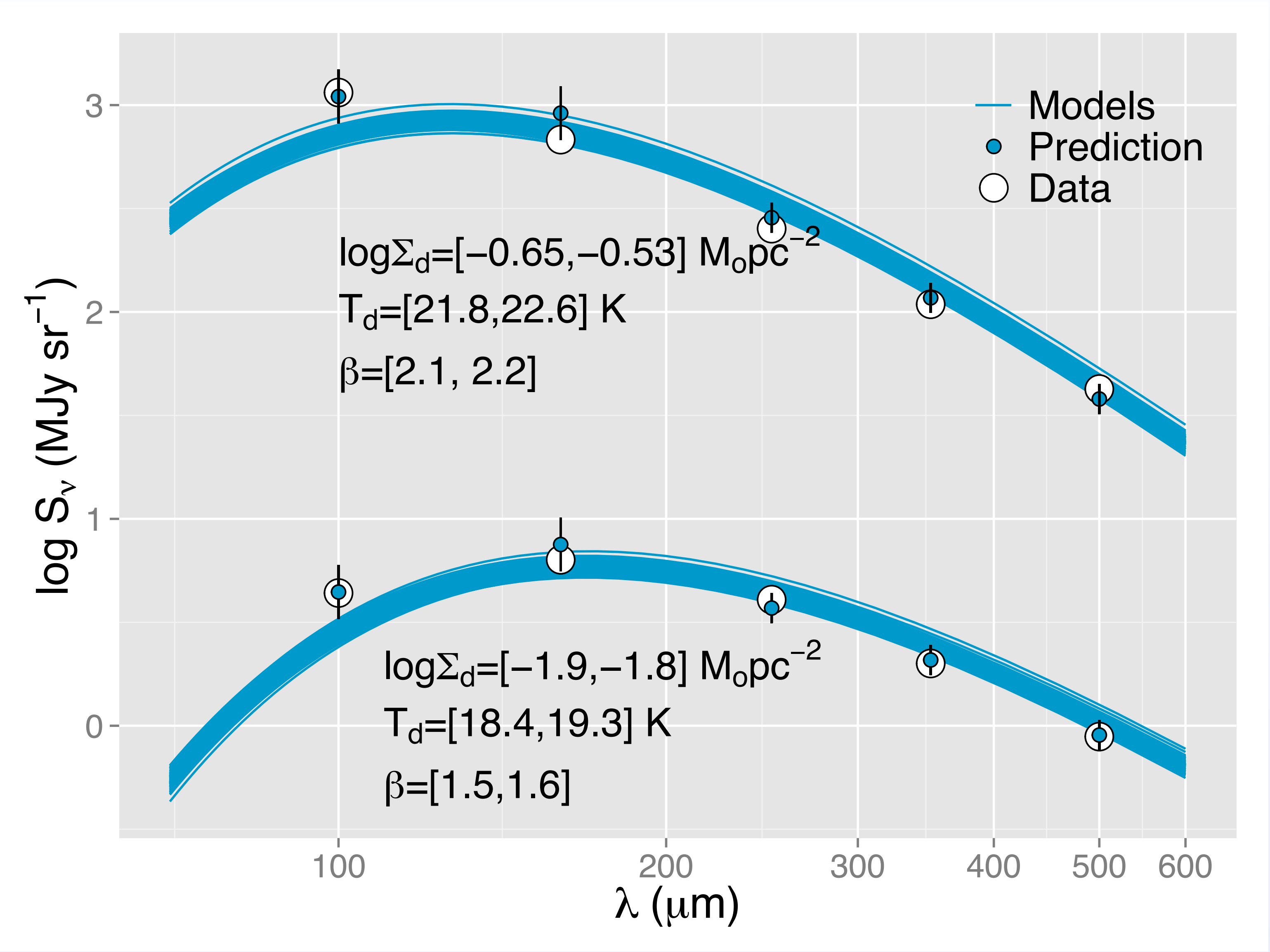

Model successful in predicting fluxes

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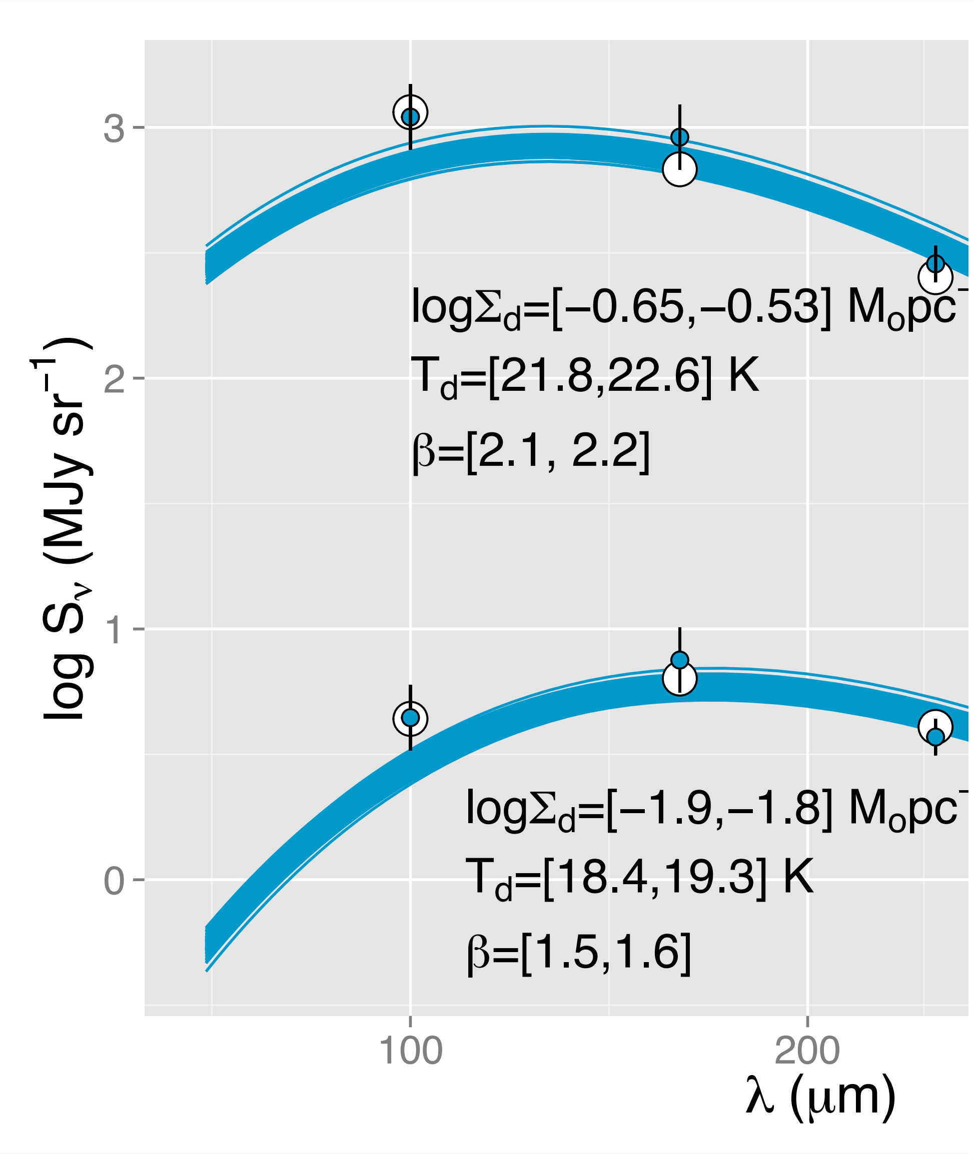

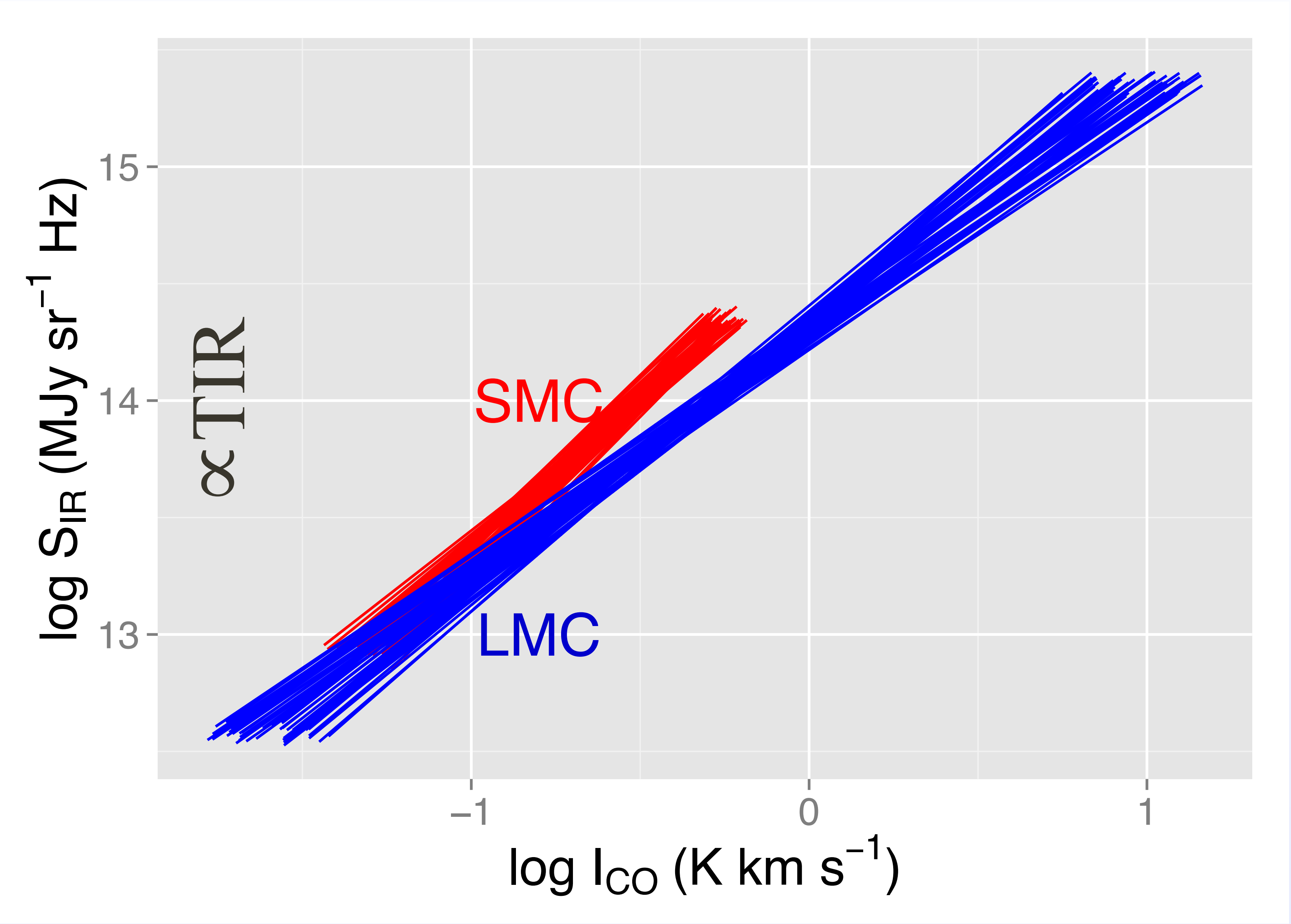

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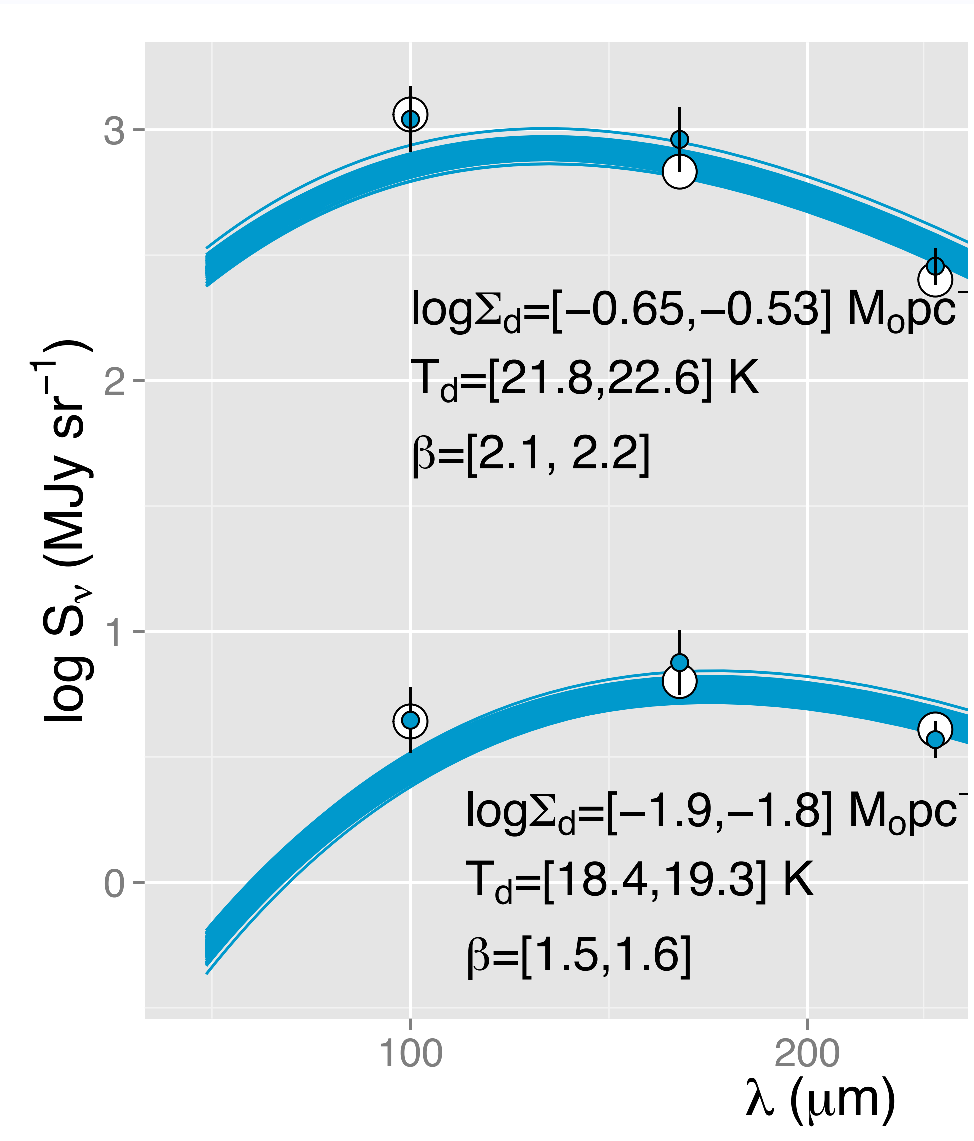

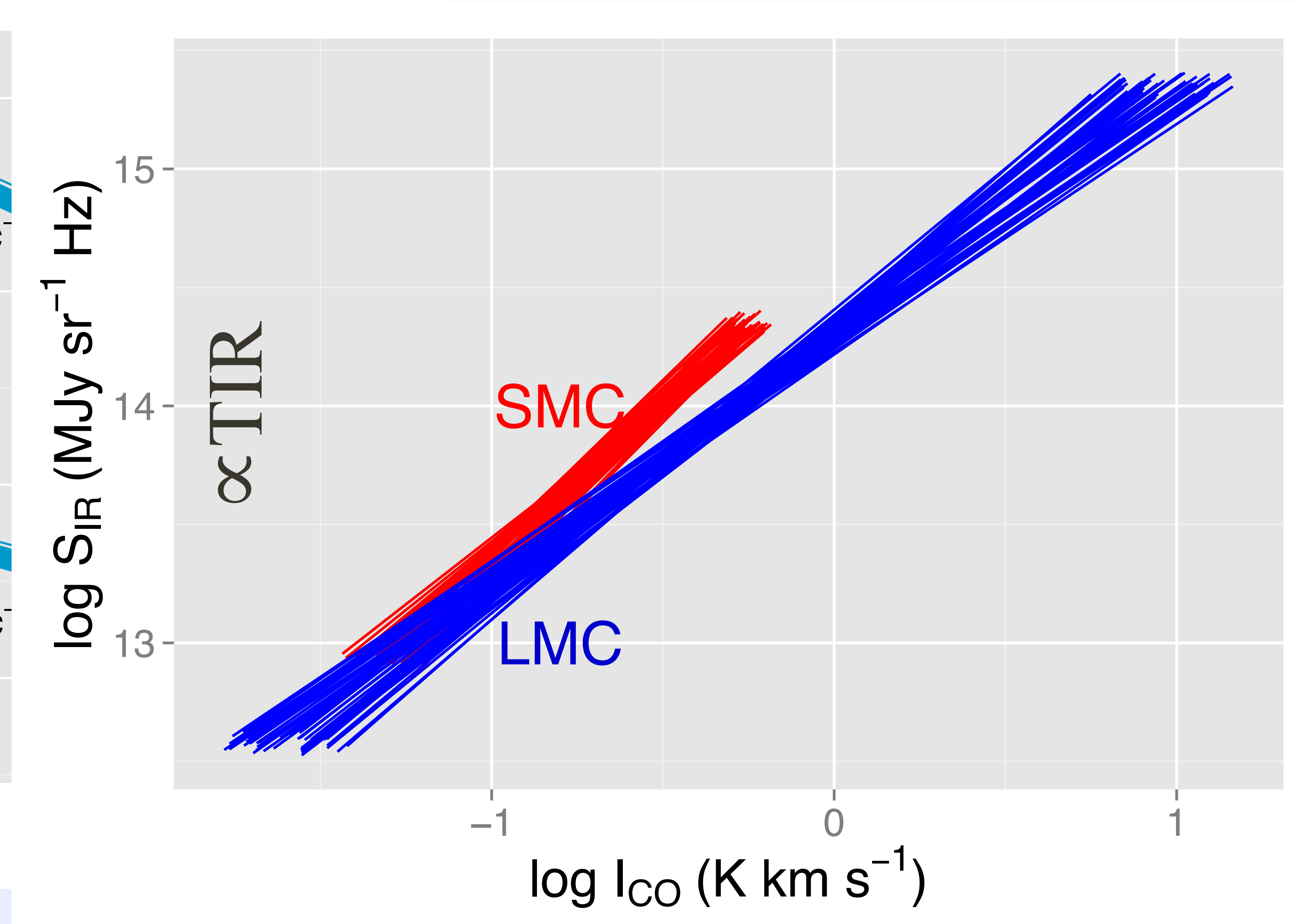

SMC has higher S_{IR} per unit I_{CO}, due to lower SMC metallicity (0.2 $Z_\odot$) compared to LMC (0.5 $Z_\odot$)

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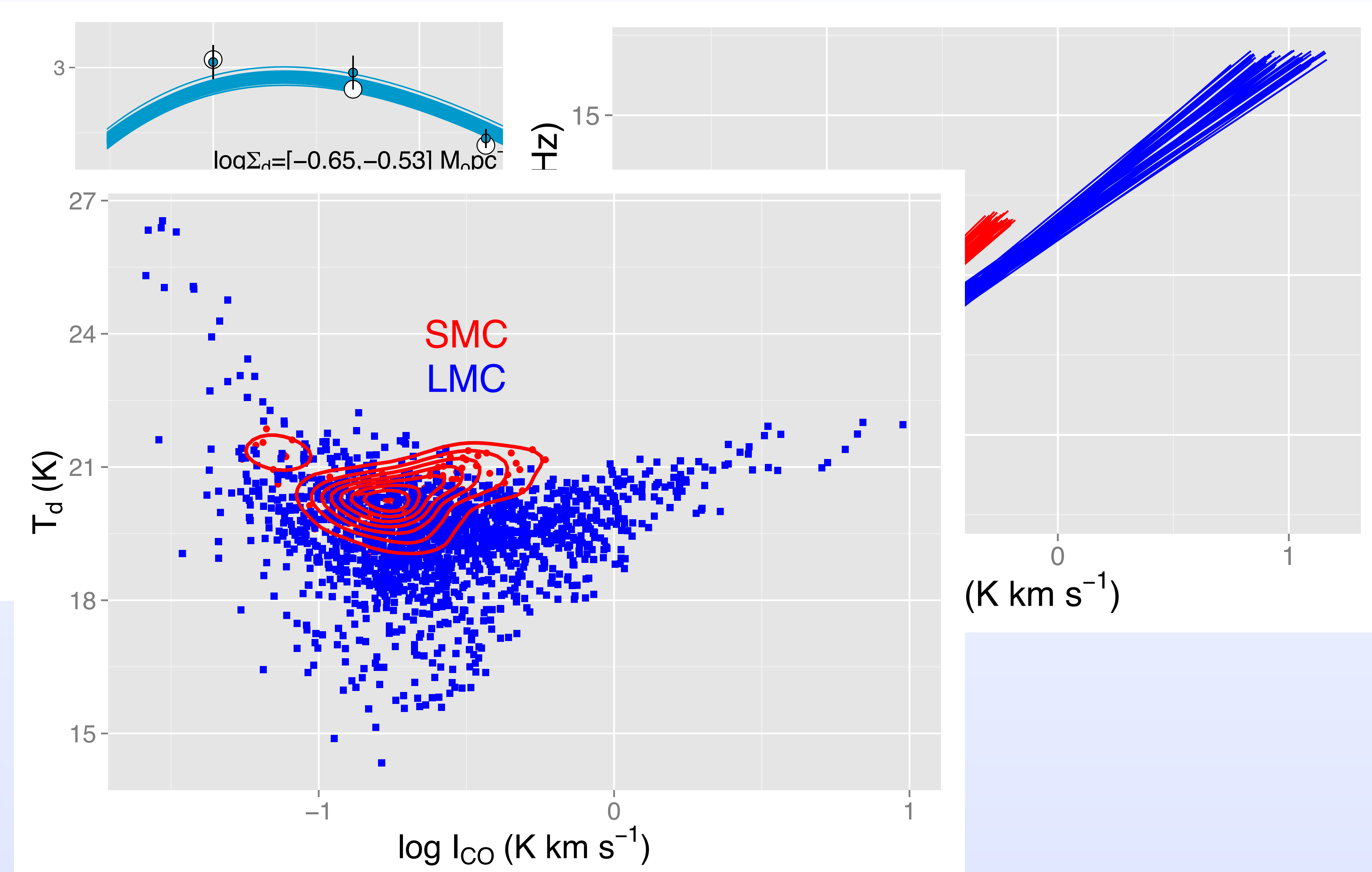

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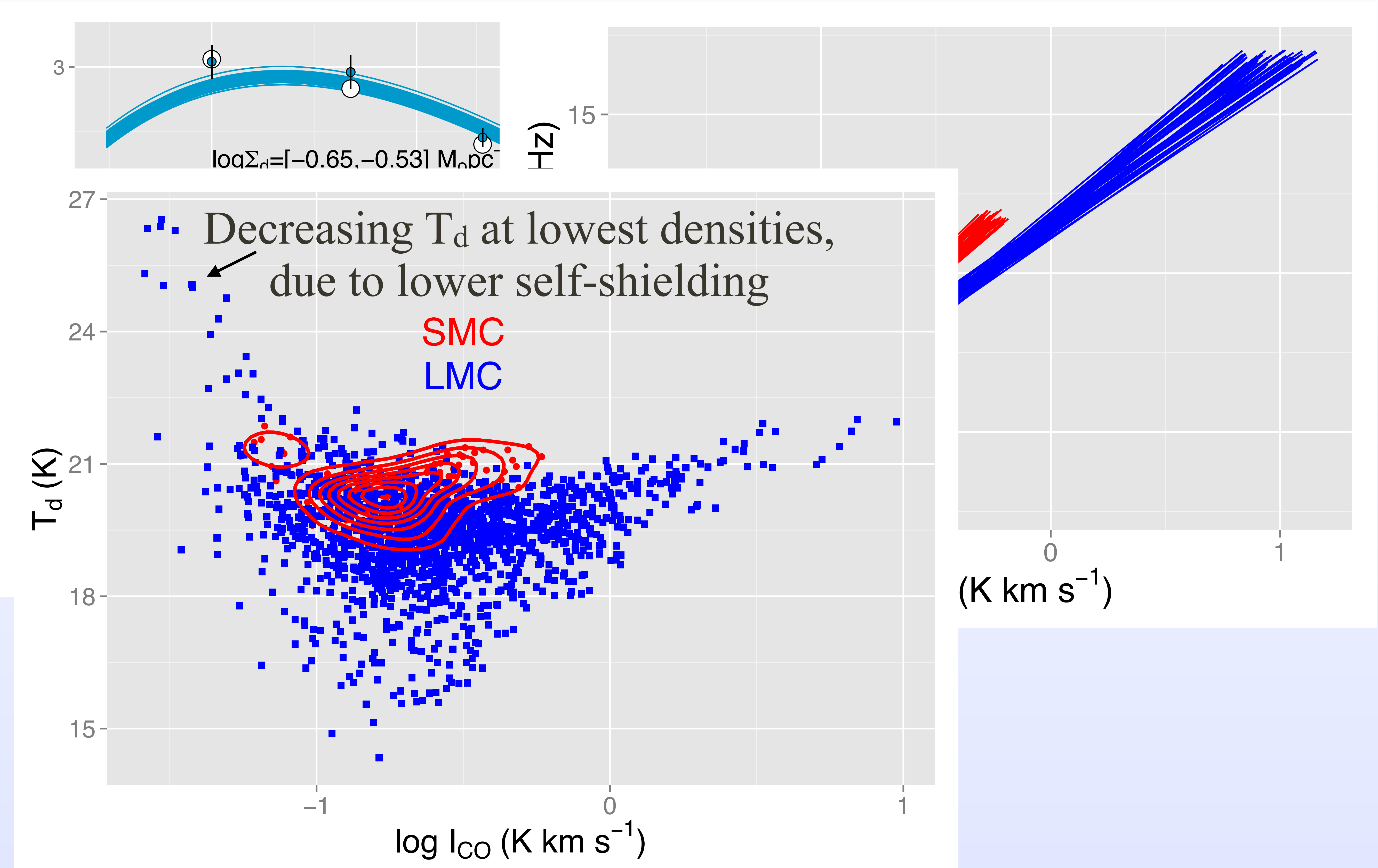

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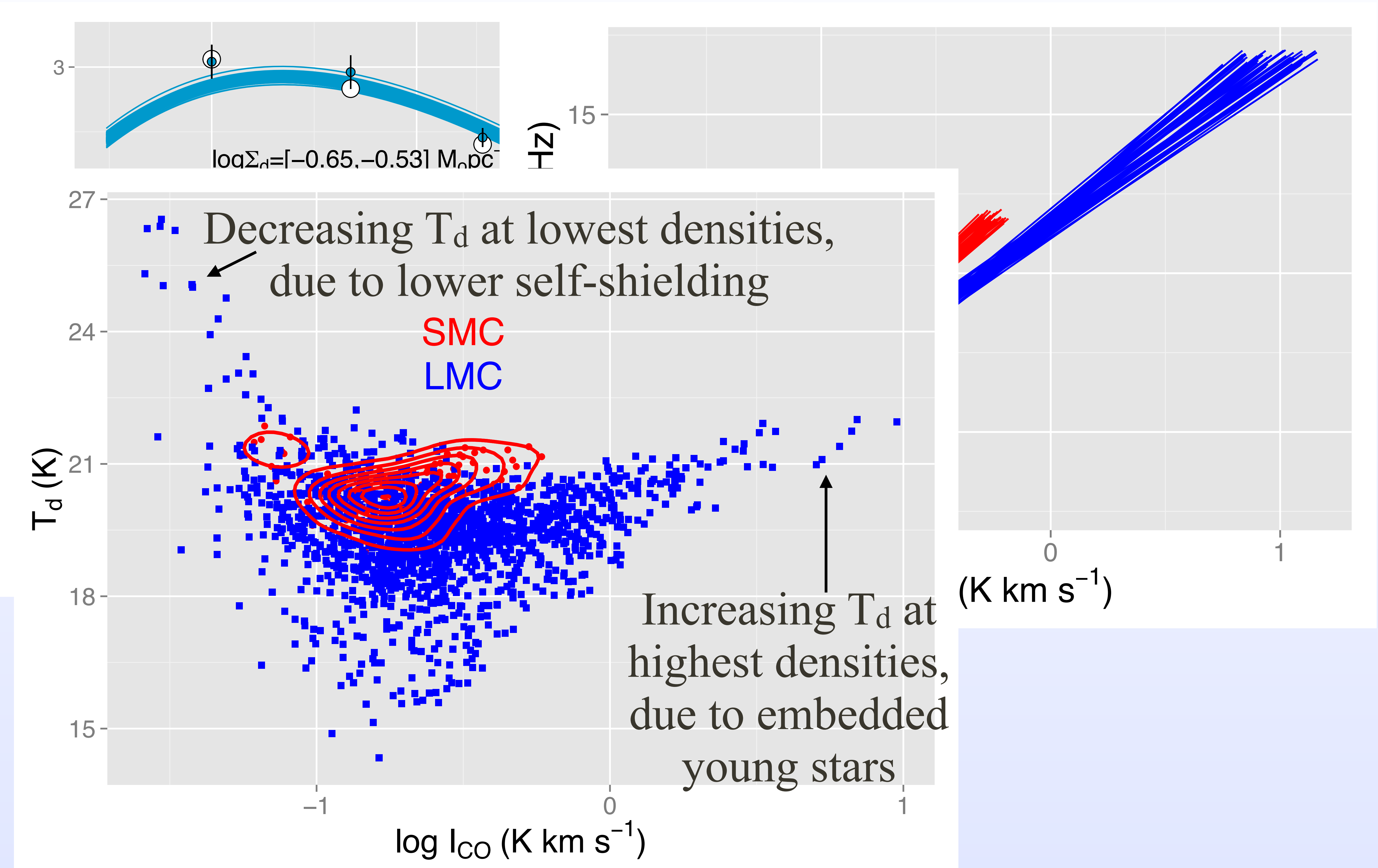

KINGFISH Galaxies: Preliminary Results
(Kennicutt+'11)

Galaxy	n
NGC0337	1.08
NGC0628	1.1
NGC2146	0.87
NGC2841	0.9
NGC2976	1.2
NGC3077	0.7
NGC3184	1.02
NGC3198	0.76
NGC3351	0.99
NGC3521	0.91
NGC3627	0.98
NGC3938	0.85
NGC4254	0.92
NGC4321	0.89
NGC4536	0.86
NGC4559	1.58
NGC4579	0.71
NGC4631	0.71
NGC4725	0.72
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NGC5055	1.08
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Wide Range of Slopes: No "Universal" KS relation or depletion timescale

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13/21 Galaxies show sublinear slopes

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13/21 Galaxies show sublinear slopes

Slope ~ 1 in LMC and SMC.
KS slope metallicity relationship?
…Other Galactic properties?

Summary

- 2 datasets show non-universal KS relationship, and sub-linear slopes for most galaxies
- Implications:
  - τ_{dep} = 2 Gyr not a representative timescale
  - τ_{dep} increases with CO traced surface density
  - sublinear KS slope suggestive of a diffuse CO component
  - What are "GMCs"?
- Magellanic Clouds: increasing T_d towards densest molecular gas due to SF. Nearly linear KS slopes
- KINGFISH: Range of slopes → dependence on metallicity, mass, other ISM properties…?