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What Controls the Amount of Dense Gas

in Molecular Clouds?

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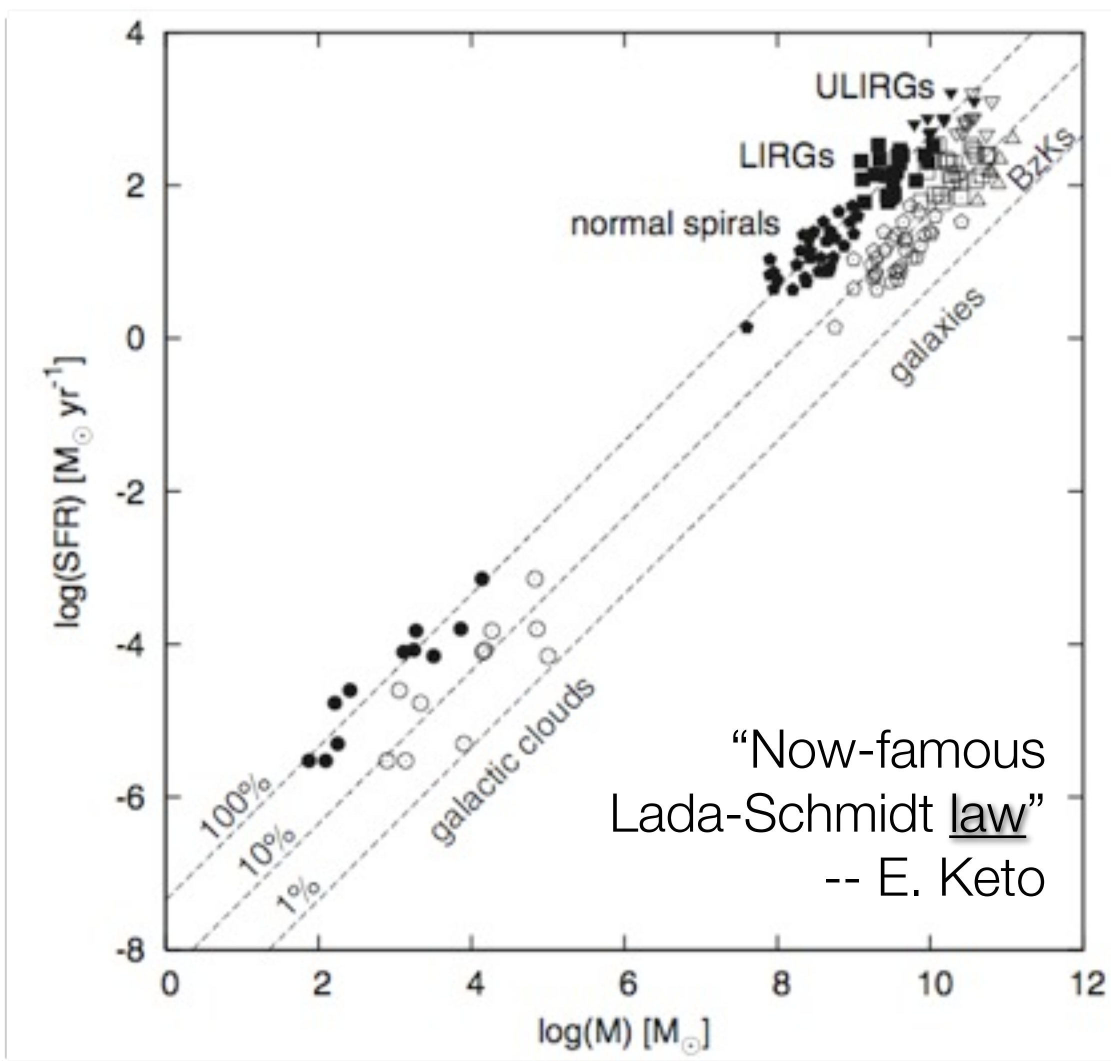
Dense Gas and Star Formation

$SFR \sim (\Sigma_{H2})^{\beta}$ Kennicutt (1998)

$SFR \sim f_{dg}(\Sigma_{gas})^{\beta}$ Lada et al. (2012)

$f_{dg} \sim$ physics of the ISM

Krumholz et al. (2009)
Ostriker et al. (2011)
Dobbs et al.; Tasker et al.; Federrath et al.; Klessen et al.; many people here...
....

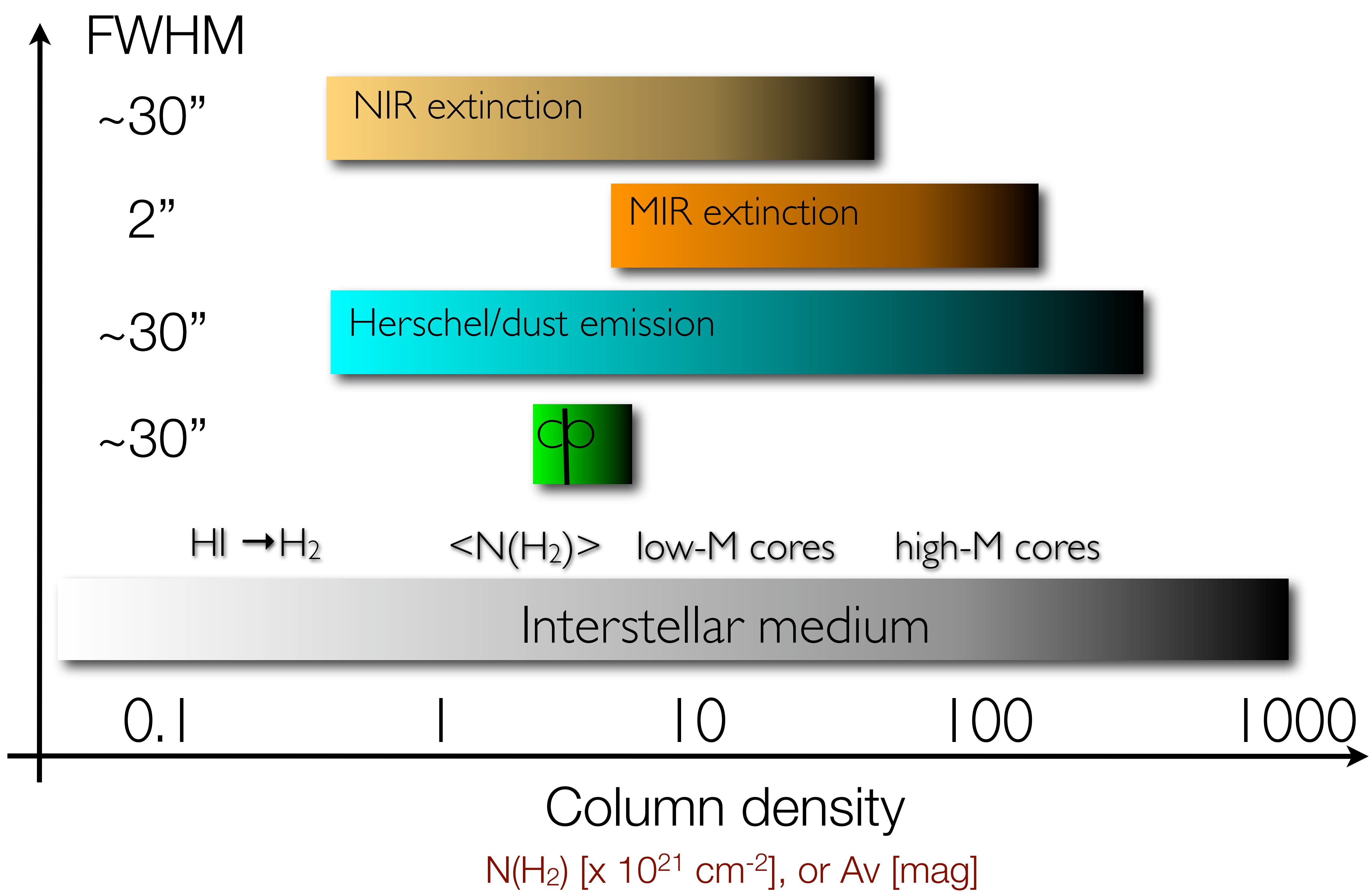


"Now-famous
Lada-Schmidt law"
-- E. Keto

This talk:

1. **Observations:** Quantifying dense gas fractions of MCs with dust extinction.
2. **Theory:** What parameters set how much dense gas molecular clouds have?

1. Observing Density Distribution of the ISM?

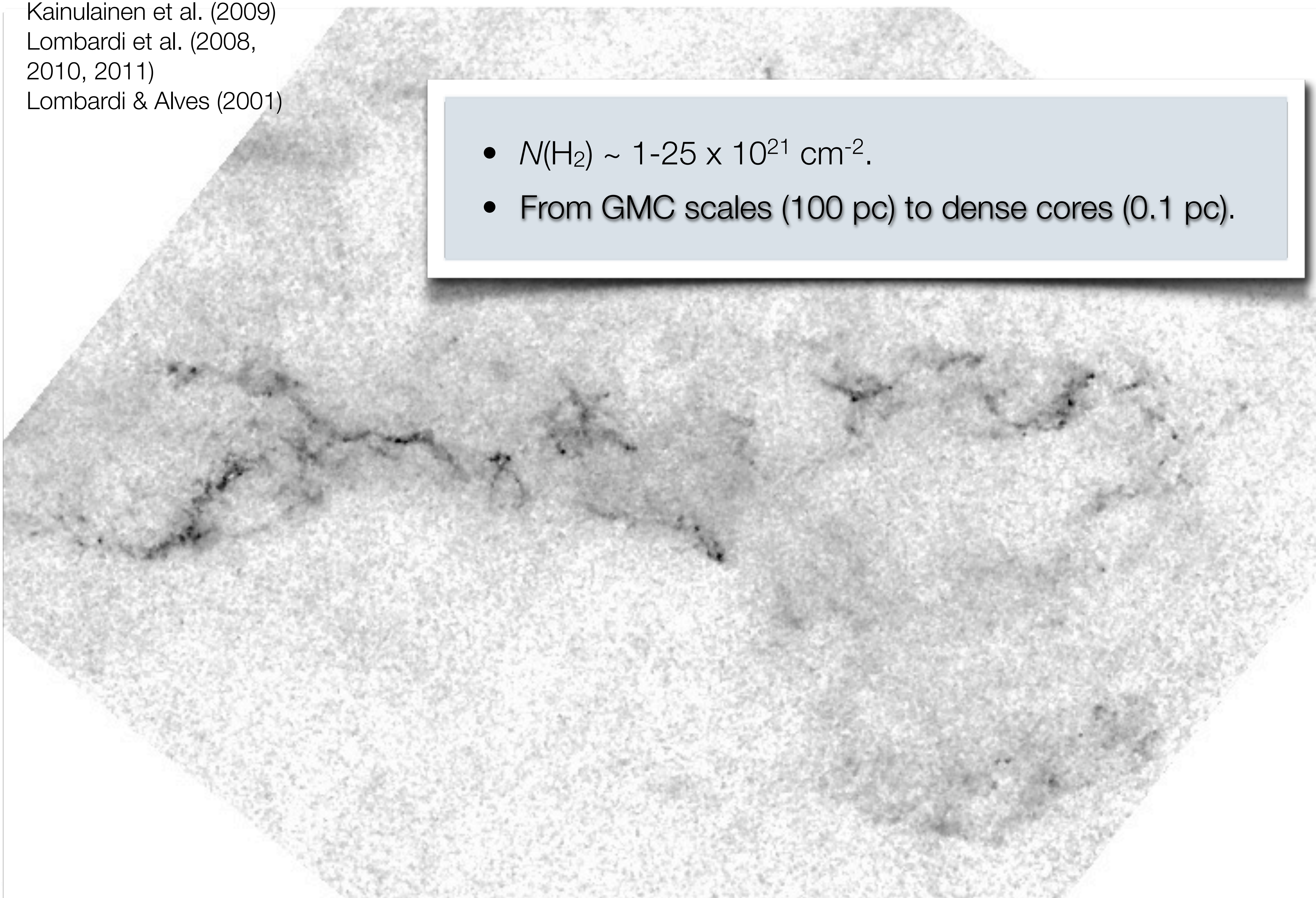


Nearby clouds: NIR dust extinction mapping

cf., talks by C. Lada, M. Lombardi

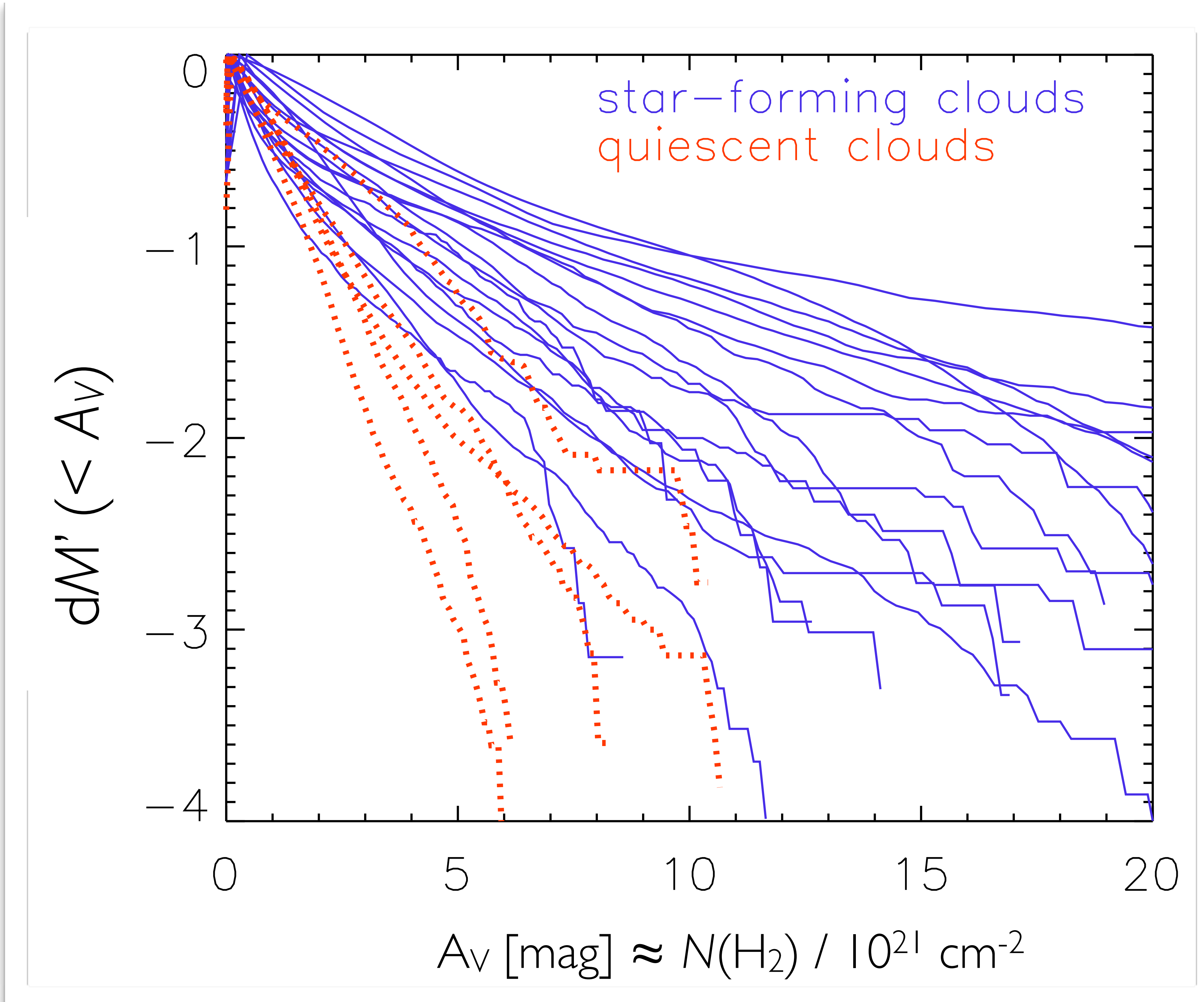
Kainulainen et al. (2009)
Lombardi et al. (2008, 2010, 2011)
Lombardi & Alves (2001)

- $N(H_2)$ ~ 1-25 x 10^{21} cm^{-2}.
- From GMC scales (100 pc) to dense cores (0.1 pc).



Dense Gas in Nearby Molecular Clouds

All molecular clouds within 500 pc distance:

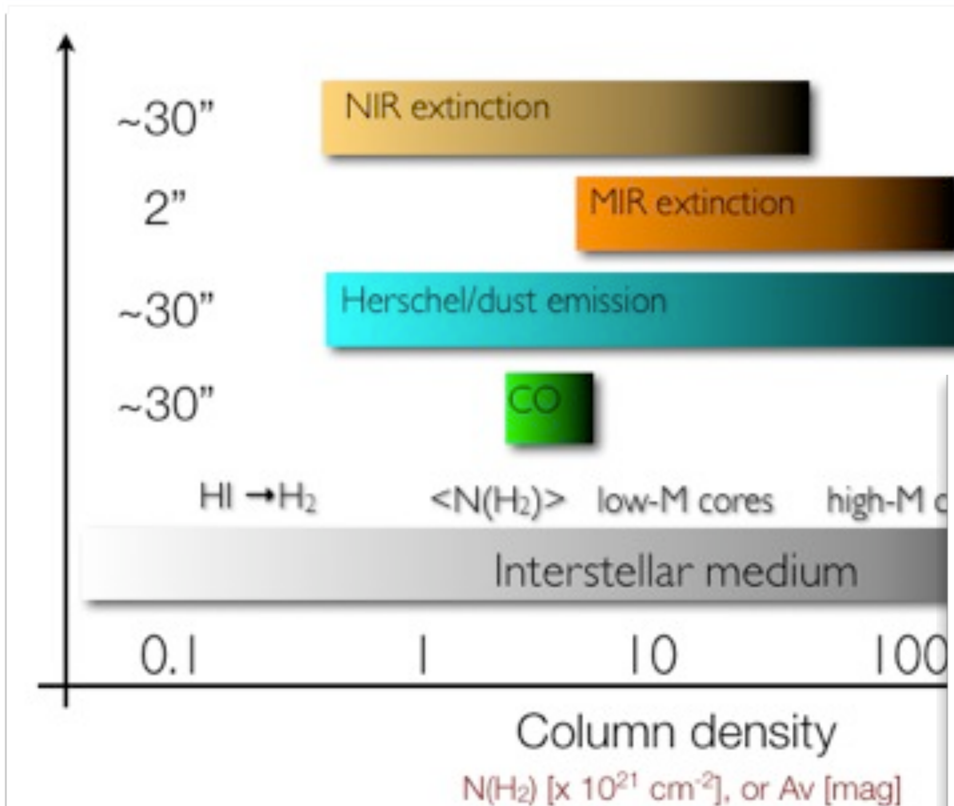


Kainulainen et al. (2009)

low-mass → high-mass

From Solar neighborhood to Galactic environment?

0.05 pc at 3.5 kpc is 3”



Combined NIR+MIR extinction mapping

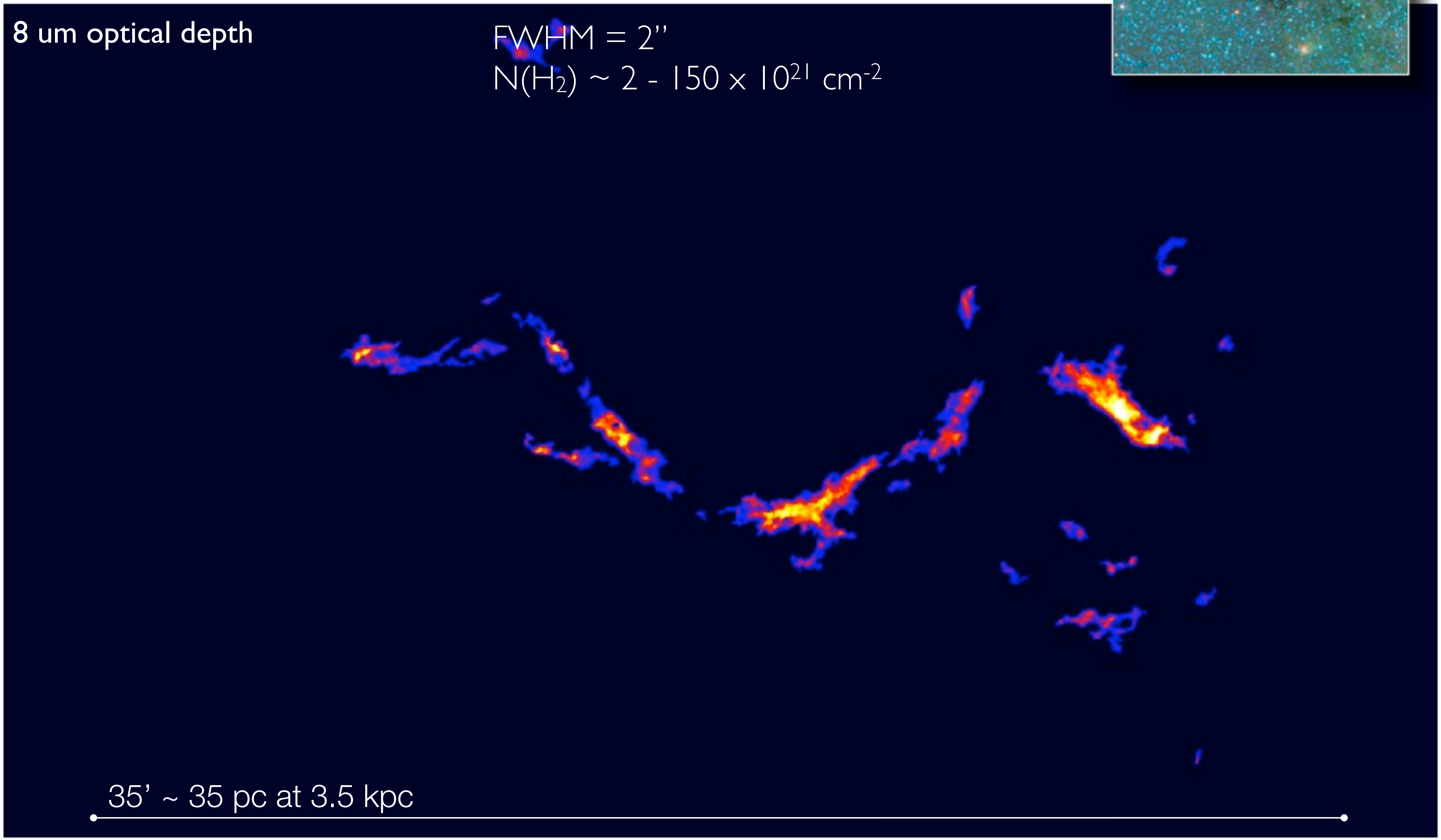
(Kainulainen et al. 2011; Kainulainen & Tan 2013)

- MIR technique suffers from calibration issues (background estimation).
- NIR technique performs well at low columns.
- Dynamic ranges of NIR and MIR overlap.

→ Re-calibration of MIR data with NIR data

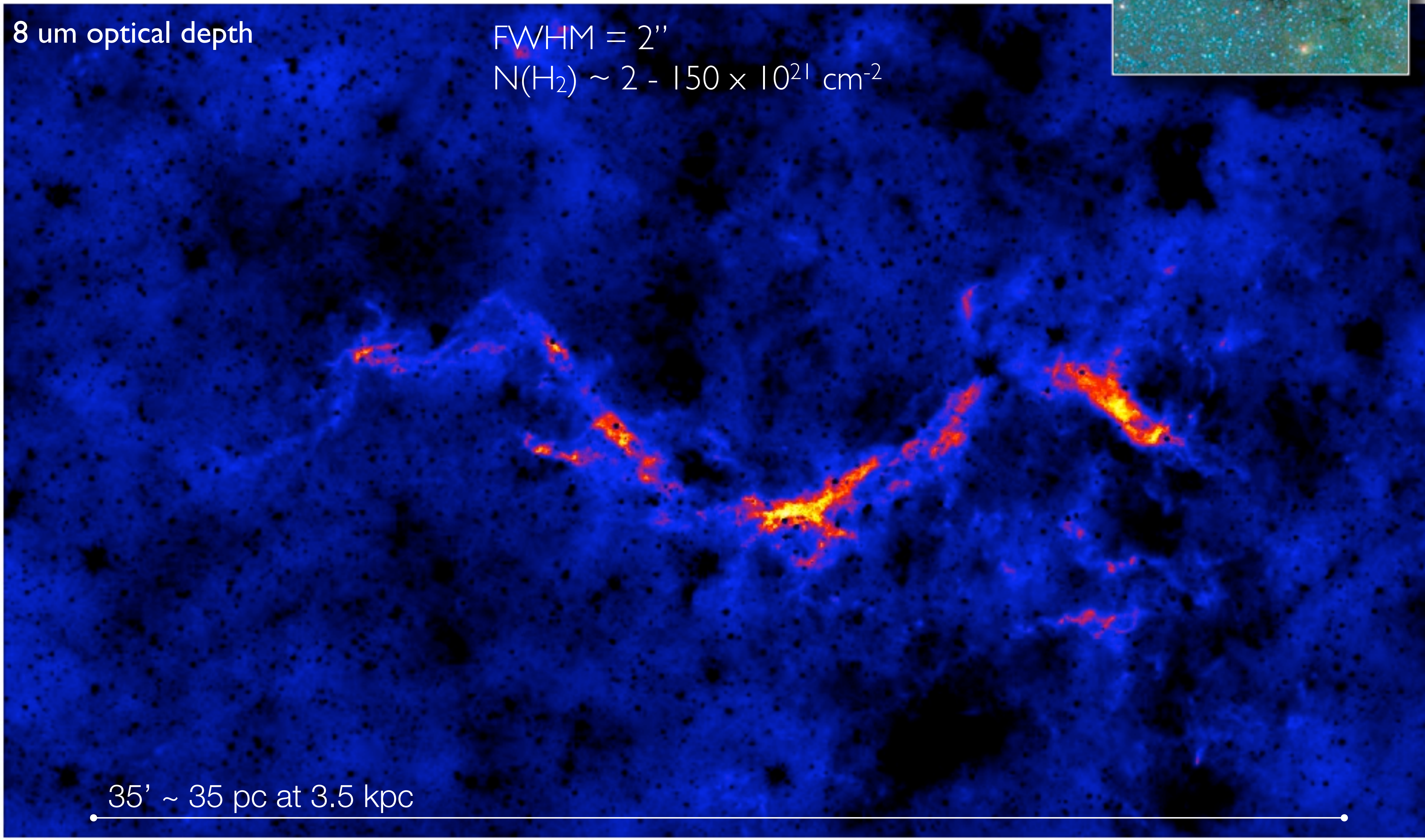
Spitzer/GLIMPSE+MIPSGAL

Example: "The Snake" (IRDC G11.11-0.12)



Peretto & Fuller (2009)/Kainulainen et al. (2011) | Sarah Ragan | Kainulainen et al. (2013)

Example: "The Snake" (IRDC G11.11-0.12)



Peretto & Fuller (2009)/Kainulainen et al. (2011)

Sarah Ragan

Kainulainen et al. (2013)

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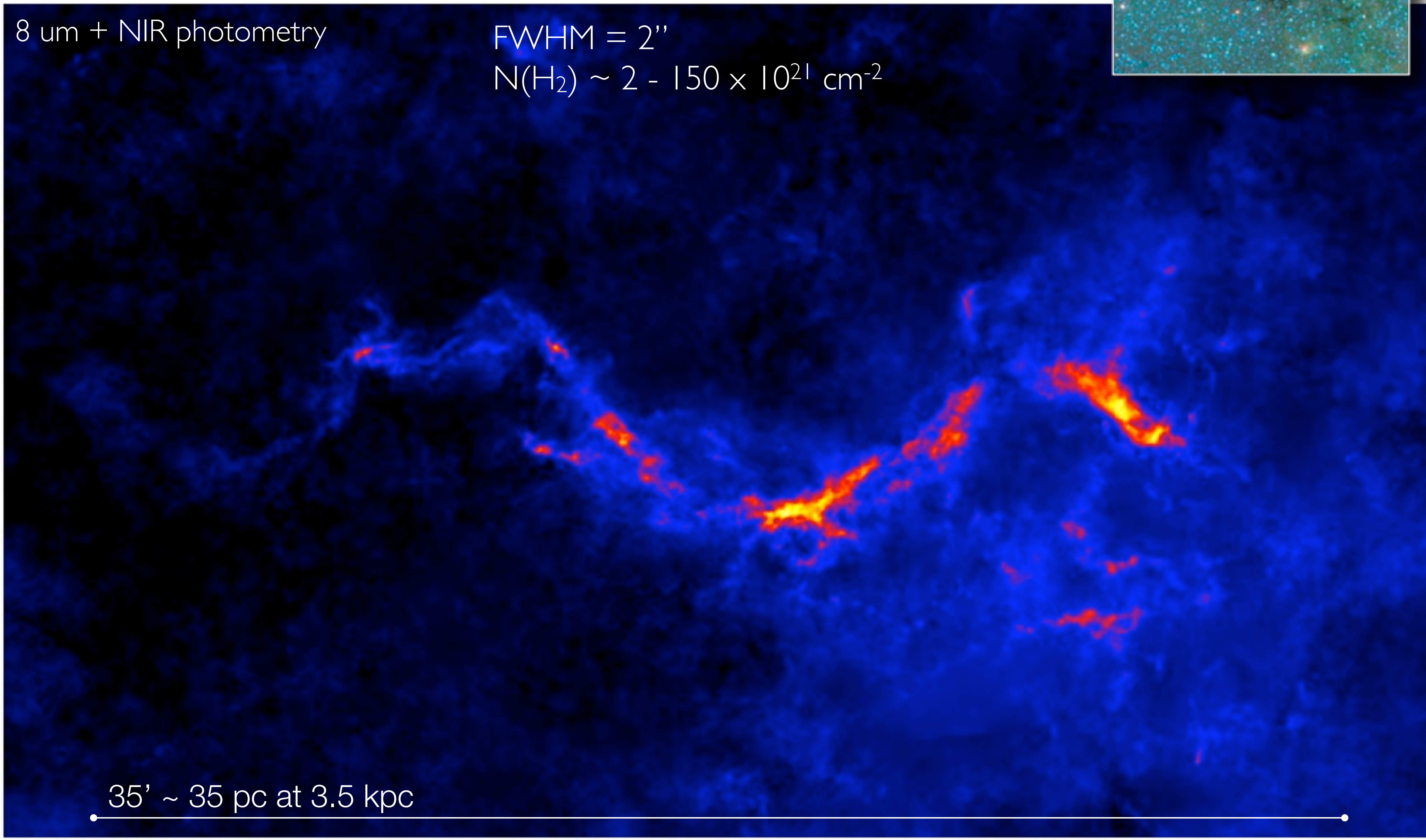

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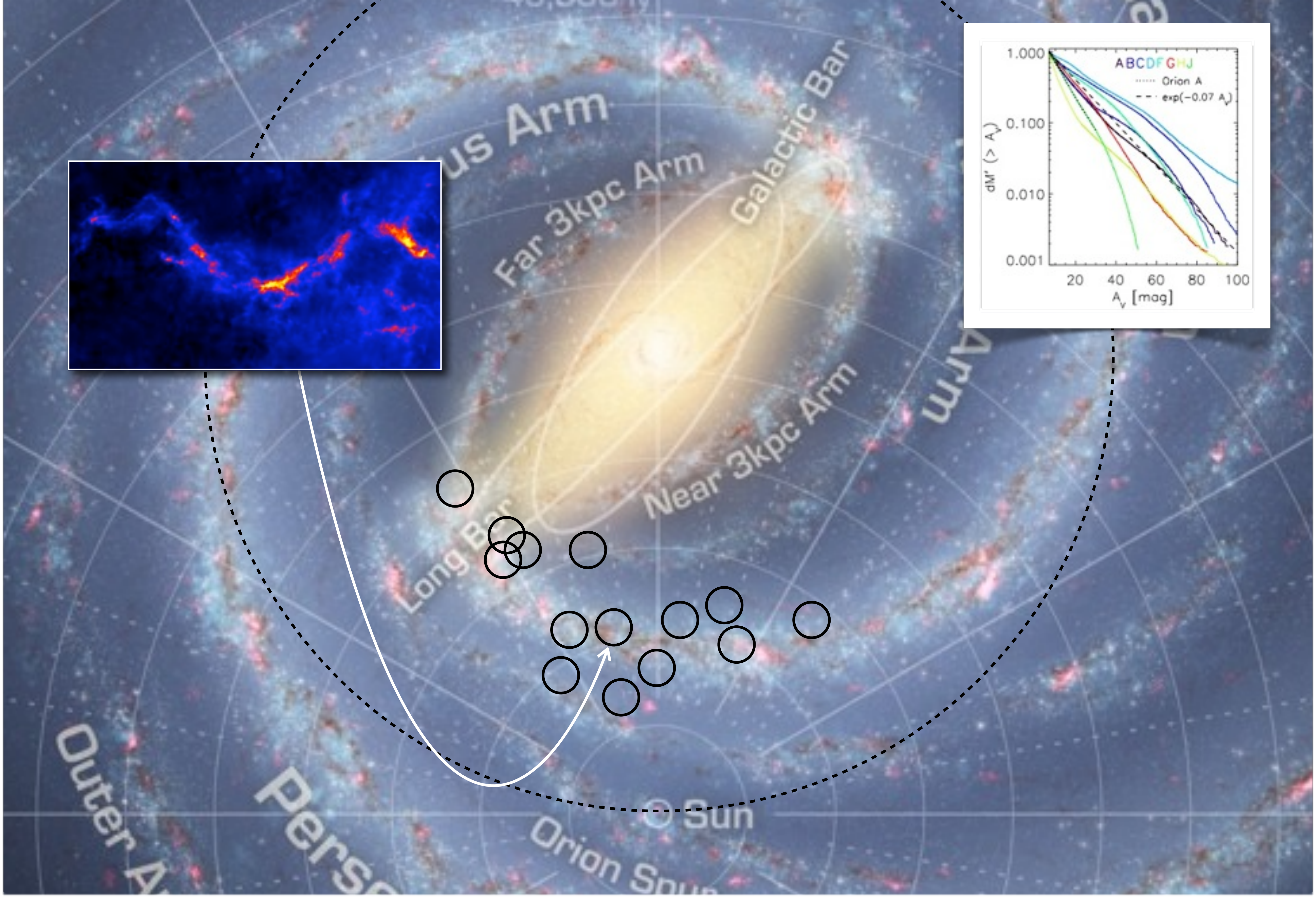
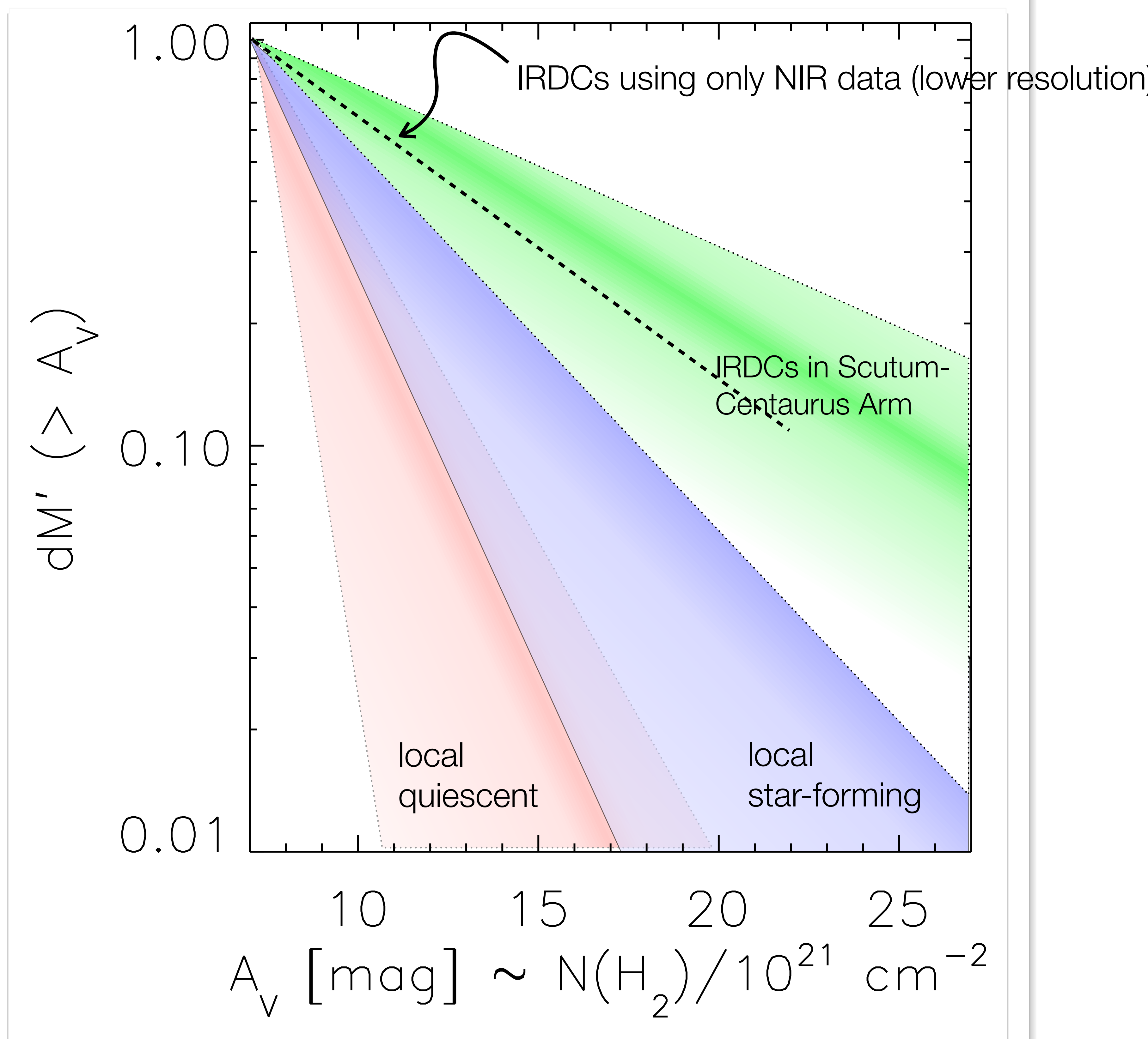
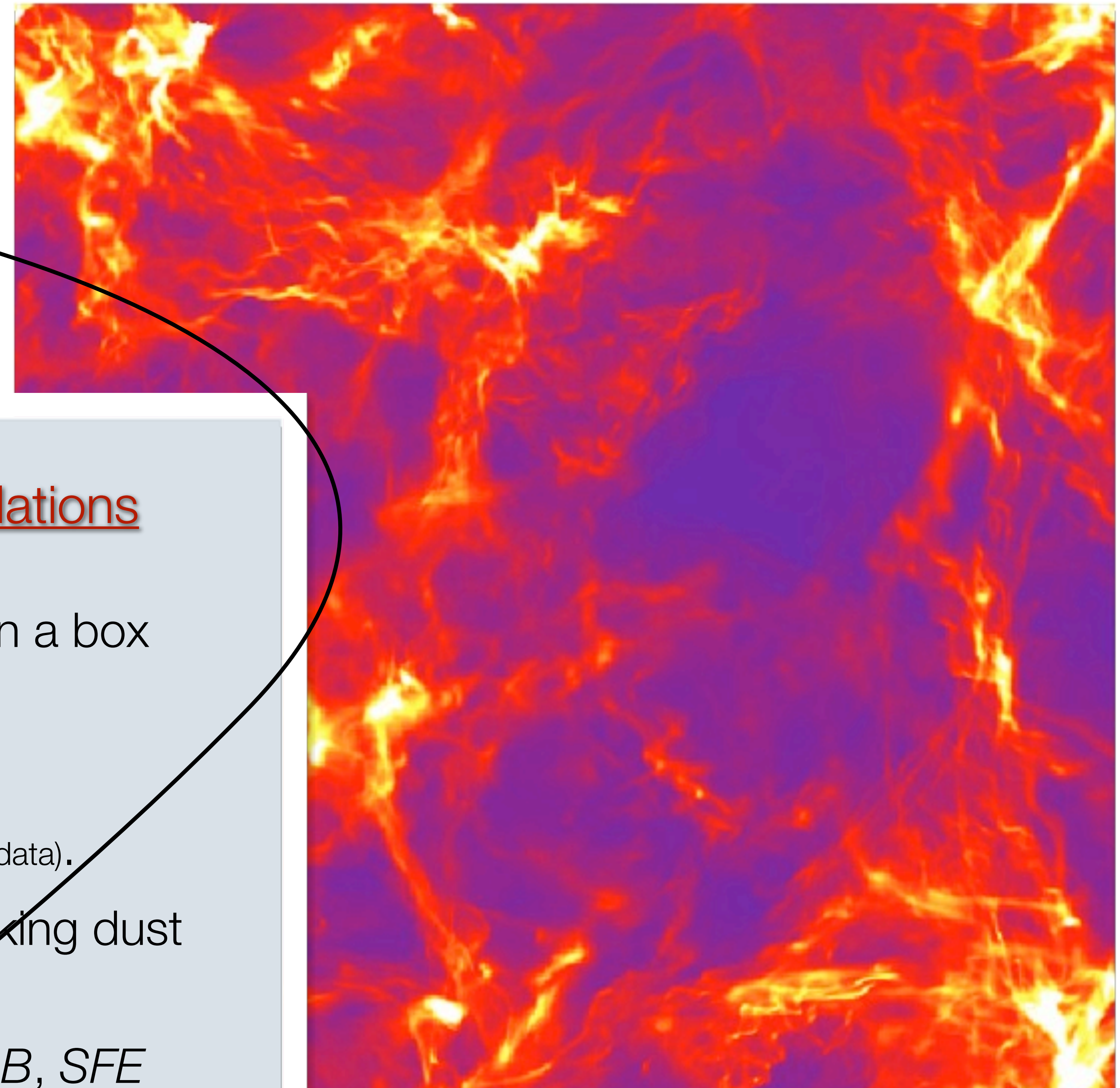

Galactic Bar
Far 3kpc Arm
Near 3kpc Arm
Long Bar
Arm
Sun
Outer
1.000
0.100
0.010
0.001
ABCDFGHJ
Orion A
exp(−0.07 A_V)
dM' (> A_V)
20
40
60
80
100
A_V [mag]



Adapted from: Kainulainen & Tan (2013), Kainulainen et al. (2013), Kainulainen et al. (2011)

2) What affects the amount of dense gas?

Solenoidal forcing: $b = 1/3$
Compressive forcing: $b = 1$



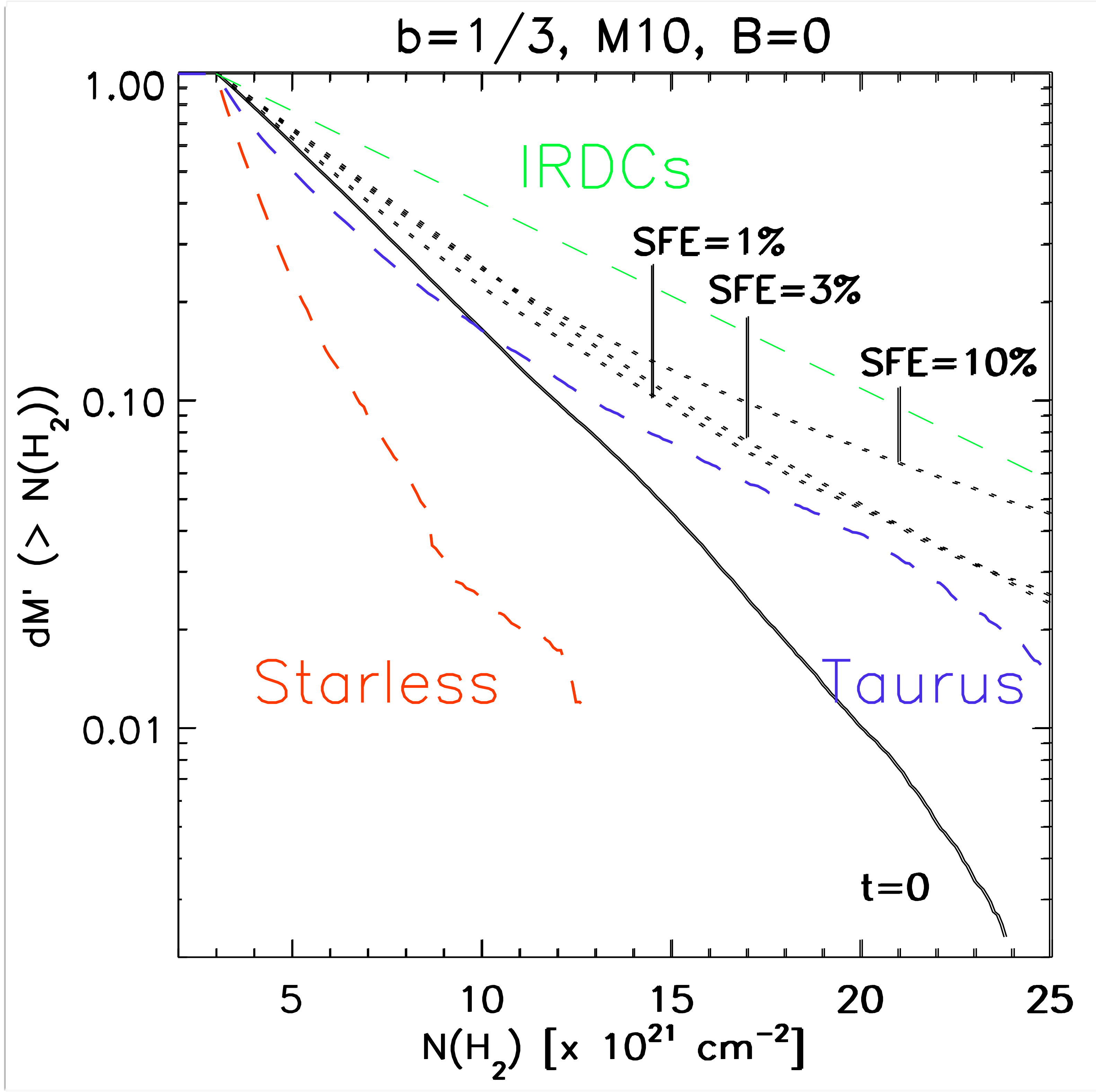
Federrath & Klessen (2012)

Analysis of numerical simulations

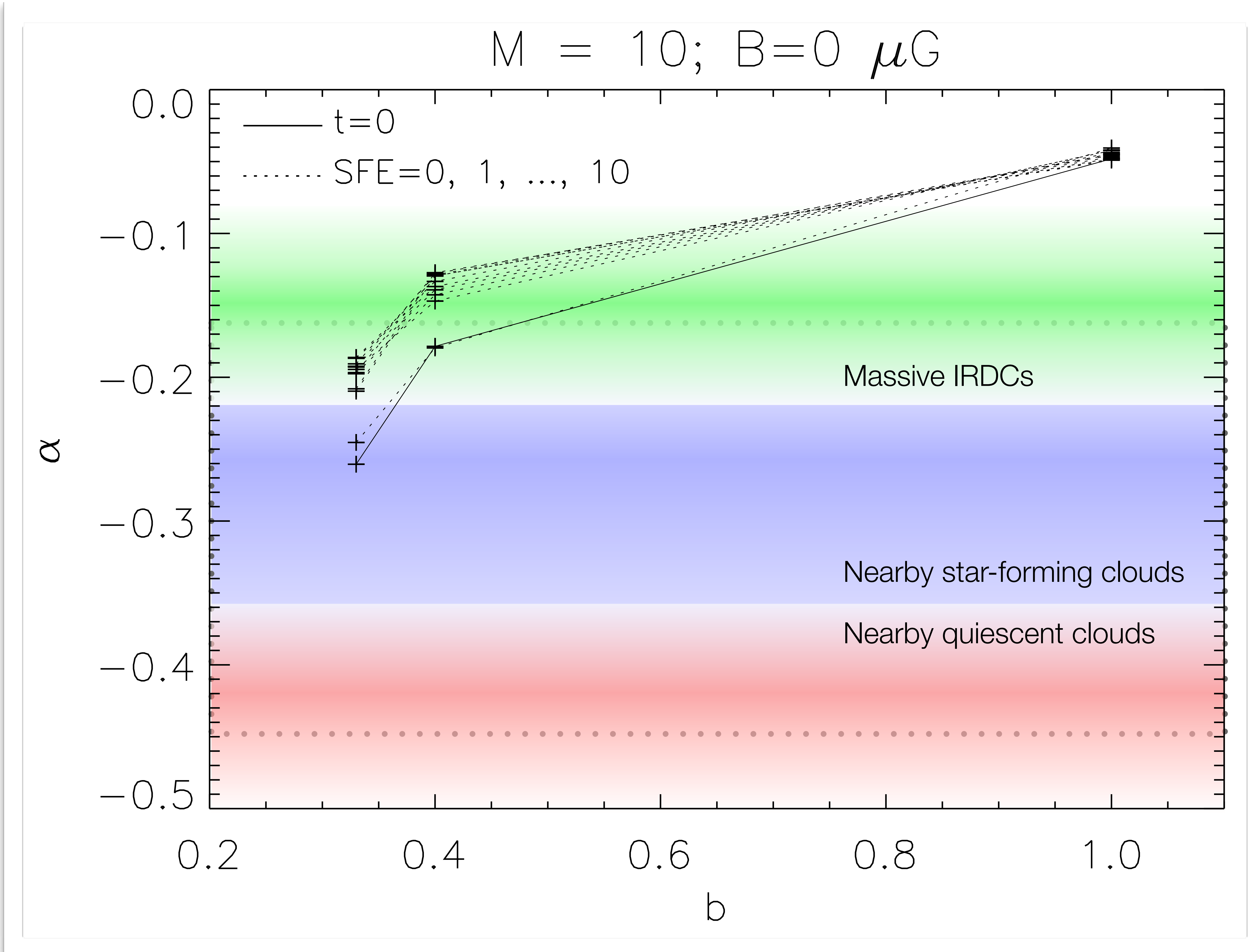
- Isothermal, driven turbulence in a box (Federrath & Klessen 2012).
- Gravity and sink particles.
- $\alpha_{vir} = 1$ (also tested w/ mean-normalized data).
- Simulated observations mimicking dust extinction mapping
- Varying: driving mode (*b*), *Ms*, *B*, *SFE*

→ simulated DGMFs

"Observed" DGMFs from simulations



Kainulainen et al. (2013)



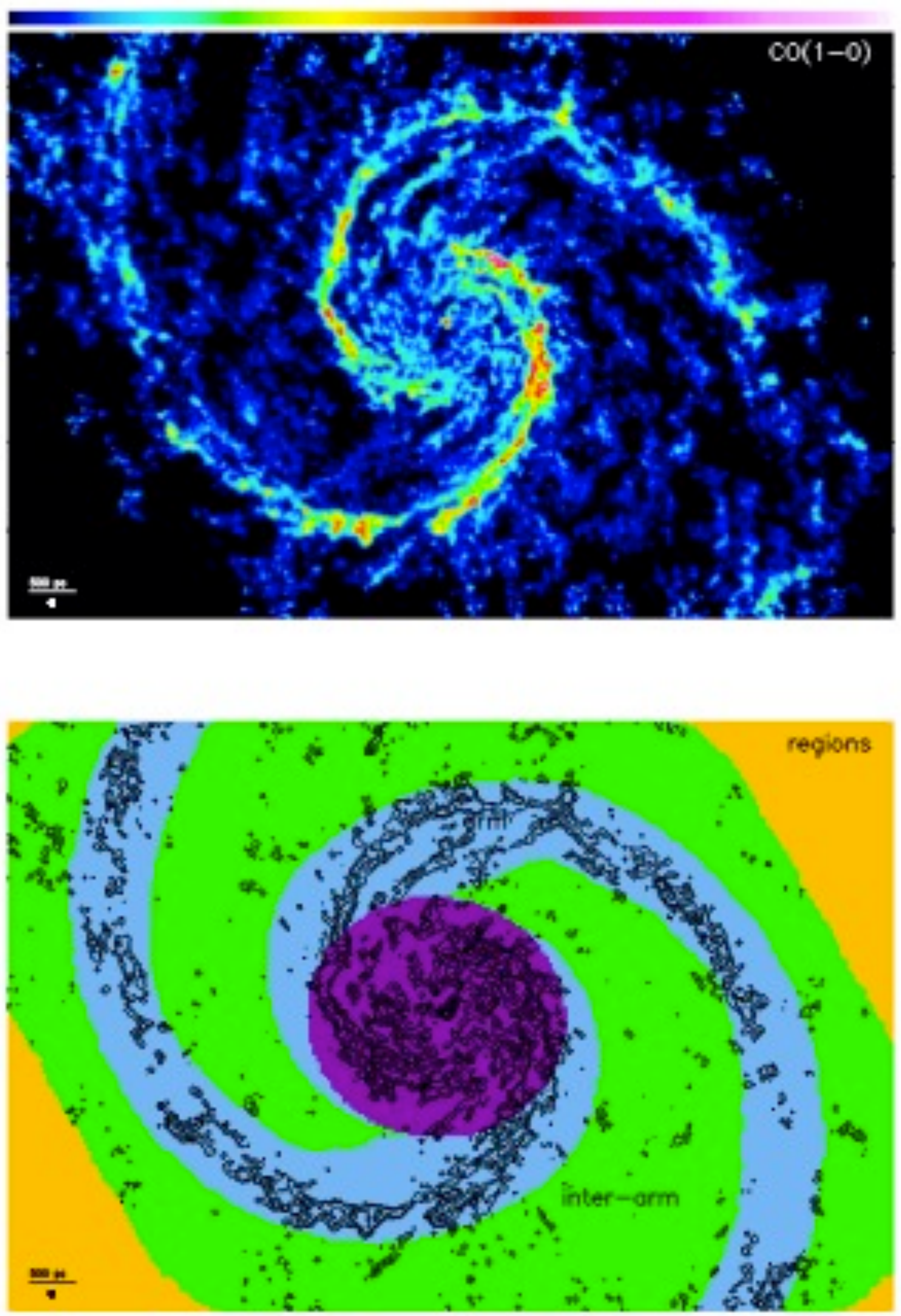
Kainulainen et al. (2013)

From synthetic observations of driven turbulence simulations:

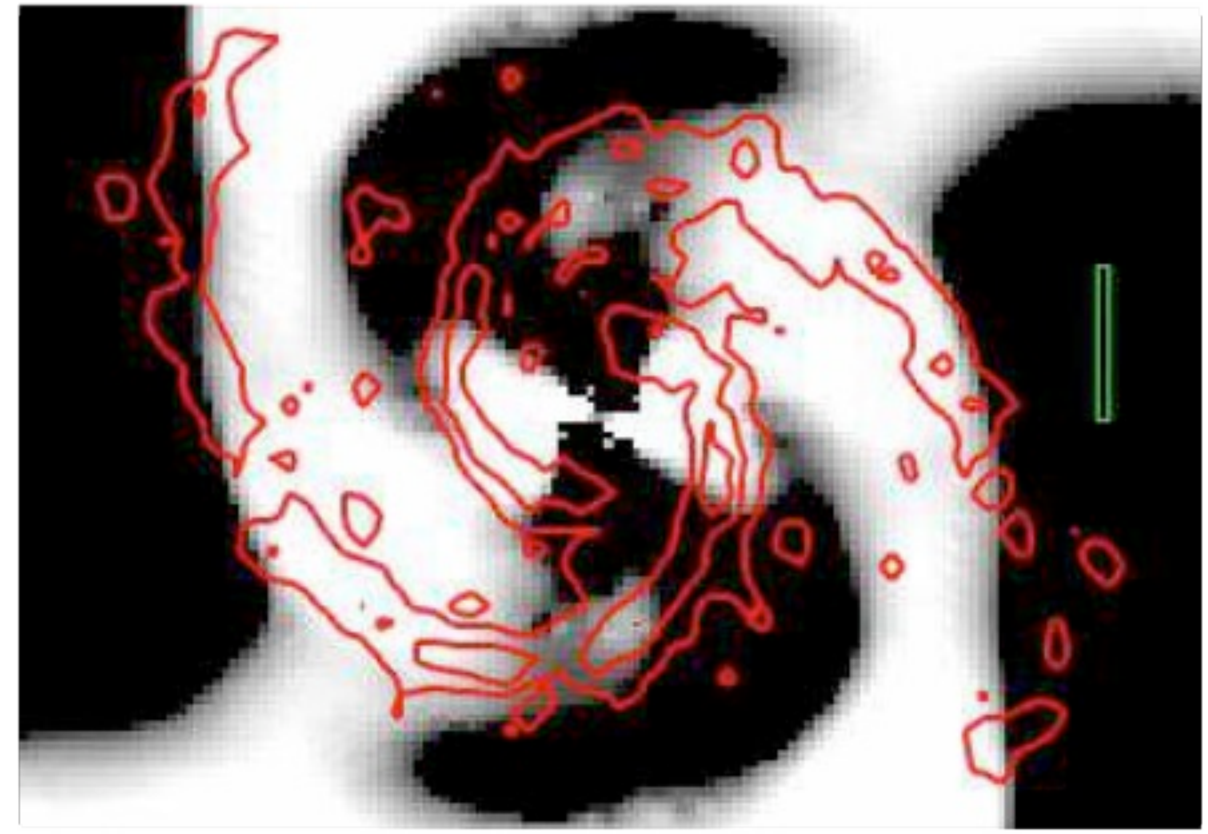
- The observed f_{dg} (DGMF) affected by:
  - Compression (*b*)
  - Evolution (*SFE; Gravity*)
  - Random variations
  - *B* and *Ms*

From comparison to observations:

- Nearby clouds → low compression parameter, *b ~ 1/3.*
  → steep DGMFs of quiescent clouds unexplained.
- Massive IRDCs: High amount of dense gas despite the low SF activity
  → Variations in compression needed.
  → Role of Galactic environment/formation process.



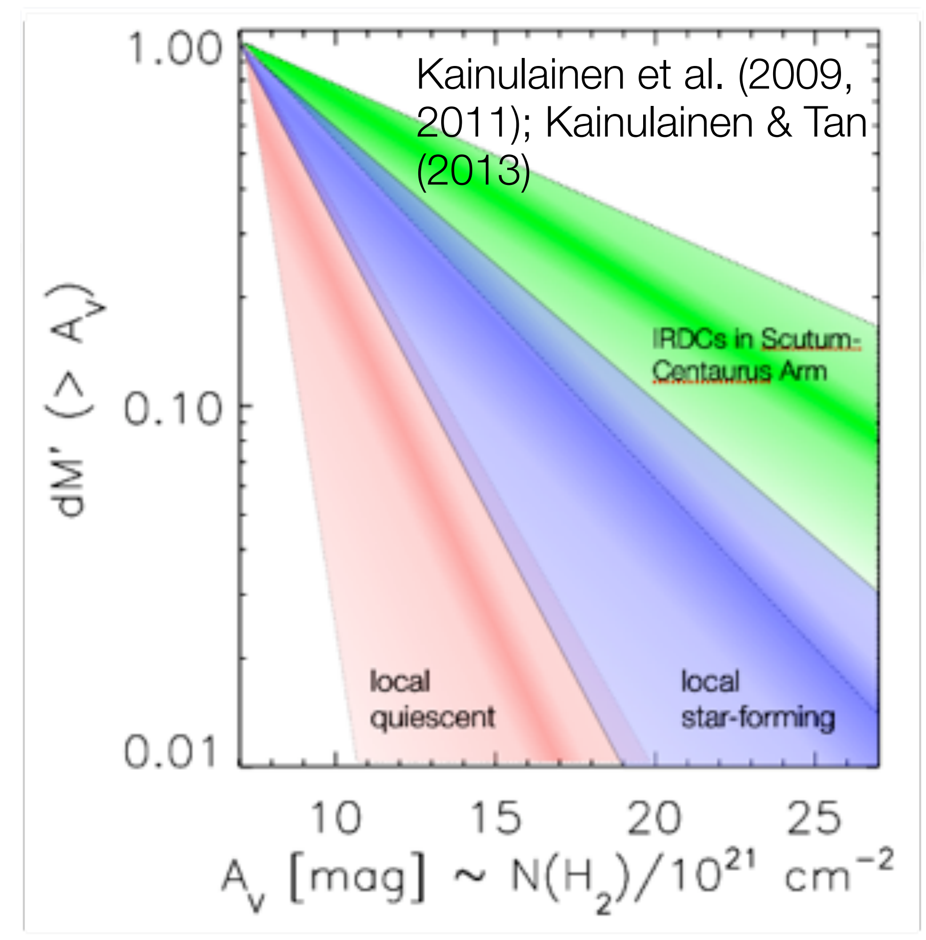
Schinnerer et al. (2013)
Hughes et al. (2013)
Colombo et al. in prep.



Meidt et al. (2013)

- Compare with: Environment-dependence of GMC/PDF properties in M51.
- Galactic environment reflects strongly to $f_{\rm dg}$ (DGMF) of molecular clouds.
- cf.,Bob Benjamin's poster; Hill et al. (2011)

Summary



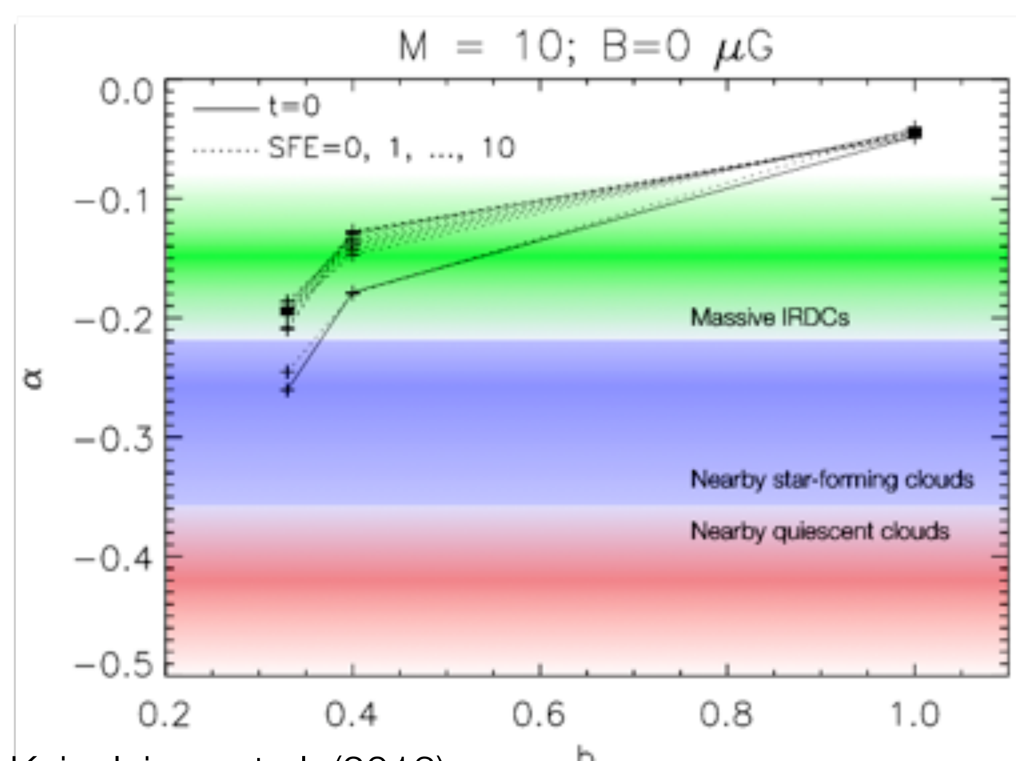
1) Dense gas in molecular clouds -- observations:

- High-resolution (2"), high-fidelity dust extinction mapping technique for IRDCs (Kainulainen & Tan 2013).
- Effects of SFE and environment on f_{dg} (DGMF) (Kainulainen et al. 2009, 2011; Kainulainen & Tan 2013).

2) Dense gas in molecular clouds -- predictions:

(Kainulainen et al. 2013; from iso-*T*, periodic box simulations)

- f_{dg} (DGMF) controlled by the gas compression (over *SFE*, random variations, *B*, *Ms*).
- Variations in compression are needed.
- Control of dense gas (and SF) by the Galaxy-scale (dynamical?) environment (e.g., Hughes et al. 2013, Meidt et al. 2013; Hill et al. 2011).



Kainulainen et al. (2013)