# Tracing the CO-dark gas in (low-metallicity) galaxies

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Dwarfs self-consistent modeling

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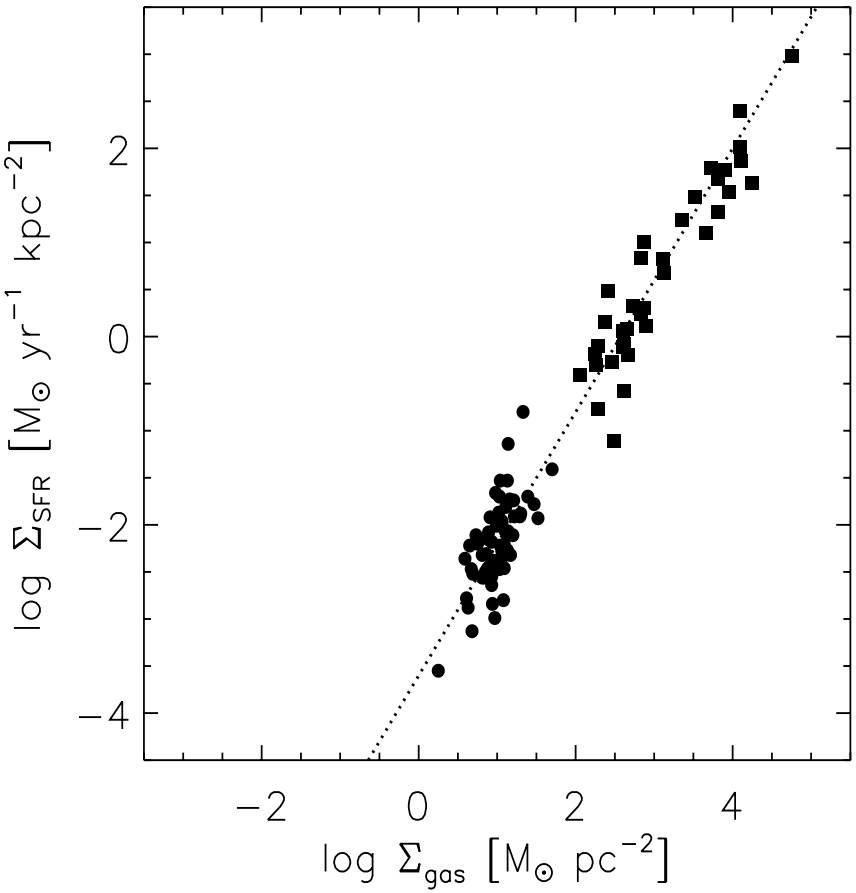
NGC4214

NGC6946

# Motivations: star formation at low metallicity

- Little molecular gas traced by CO

  *(e.g. Tacconi et al. 1987, Taylor et al. 1998, Leroy et al. 2007, Schruba et al. 2012, Elmegreen et al. 2013, Cormier et al. 2014, Hunt et al. 2015, Shi et al. 2015, Amorin et al. 2016)*




*Kennicutt 1998*

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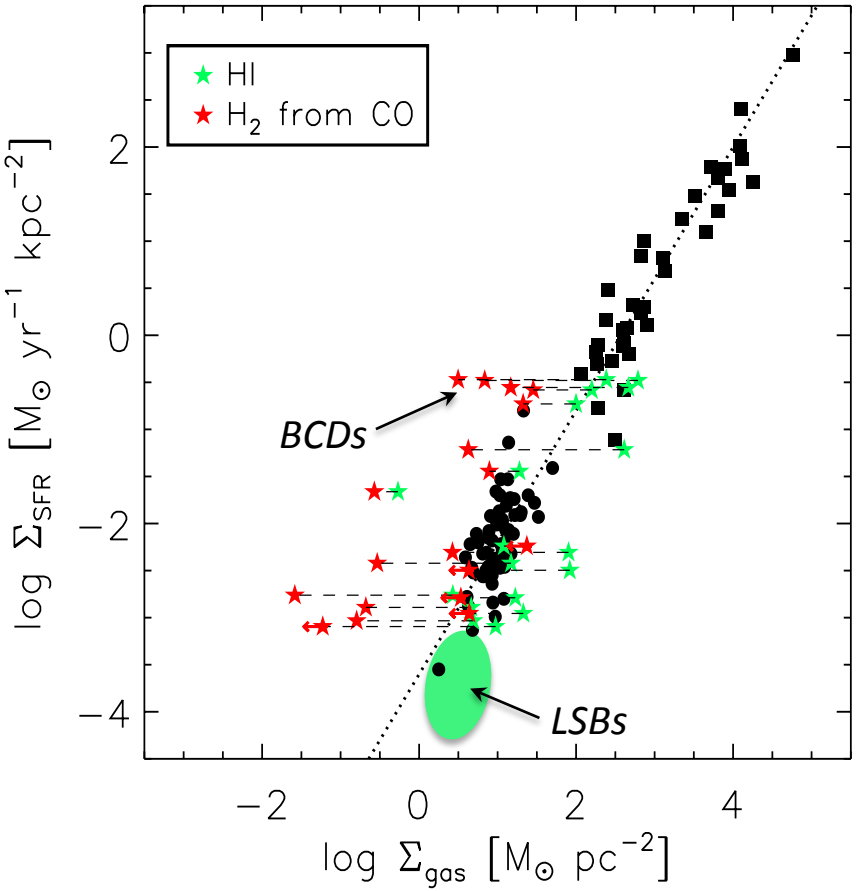
- Low SFE in HI gas but high SFE in $H_2$ gas




⇒ Efficient SF from $H_2$?

⇒ SF in atomic gas?

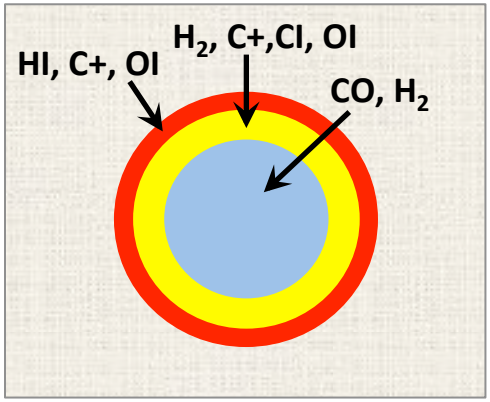
*Glover & Clark 2012*
*Krumholz 2012*

⇒ Time/evolution bias?

⇒ More $H_2$ than seen by CO?

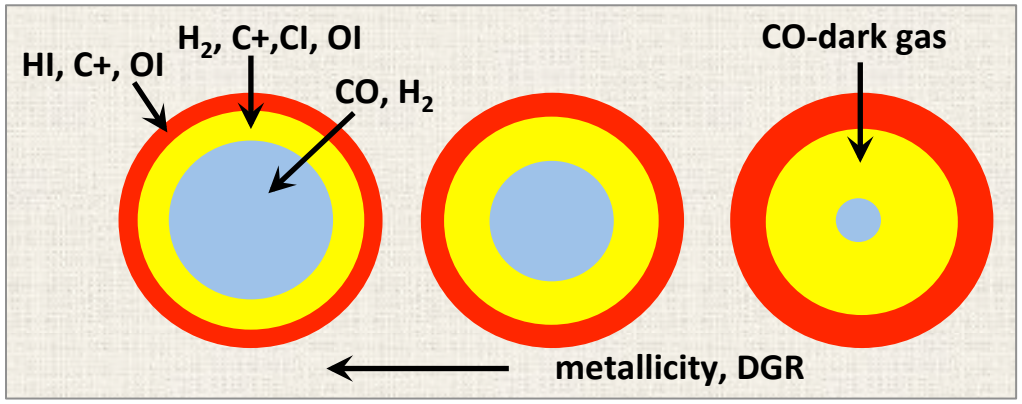
*Wyder et al. 2009*
*Cormier et al. 2014*

# Tracing the CO-dark gas




- Milky Way: 30% of molecular mass is CO-dark
  *(Pineda et al. 2013, GOT C+)*

# Tracing the CO-dark gas




*e.g. Bolatto et al. 2013*

- Milky Way: 30% of molecular mass is CO-dark
  *(Pineda et al. 2013, GOT C+)*

- Local dwarfs (IC10, LMC, SMC, NGC6822):
  10-100 more CO-dark than CO-bright gas mass
  *e.g. Poglitsch et al. 1995, Israel et al. 1997, Madden et al. 1997, Leroy et al. 2011*
  *+ new work on Magellanic Clouds with Herschel and SOFIA*

# [CII]/CO ratio and PDR structure

[CII] is the main observable at low- and high-redshift

- High [CII]/CO ratios observed in star-forming dwarf galaxies

What is this telling us about the molecular cloud/PDR structure?

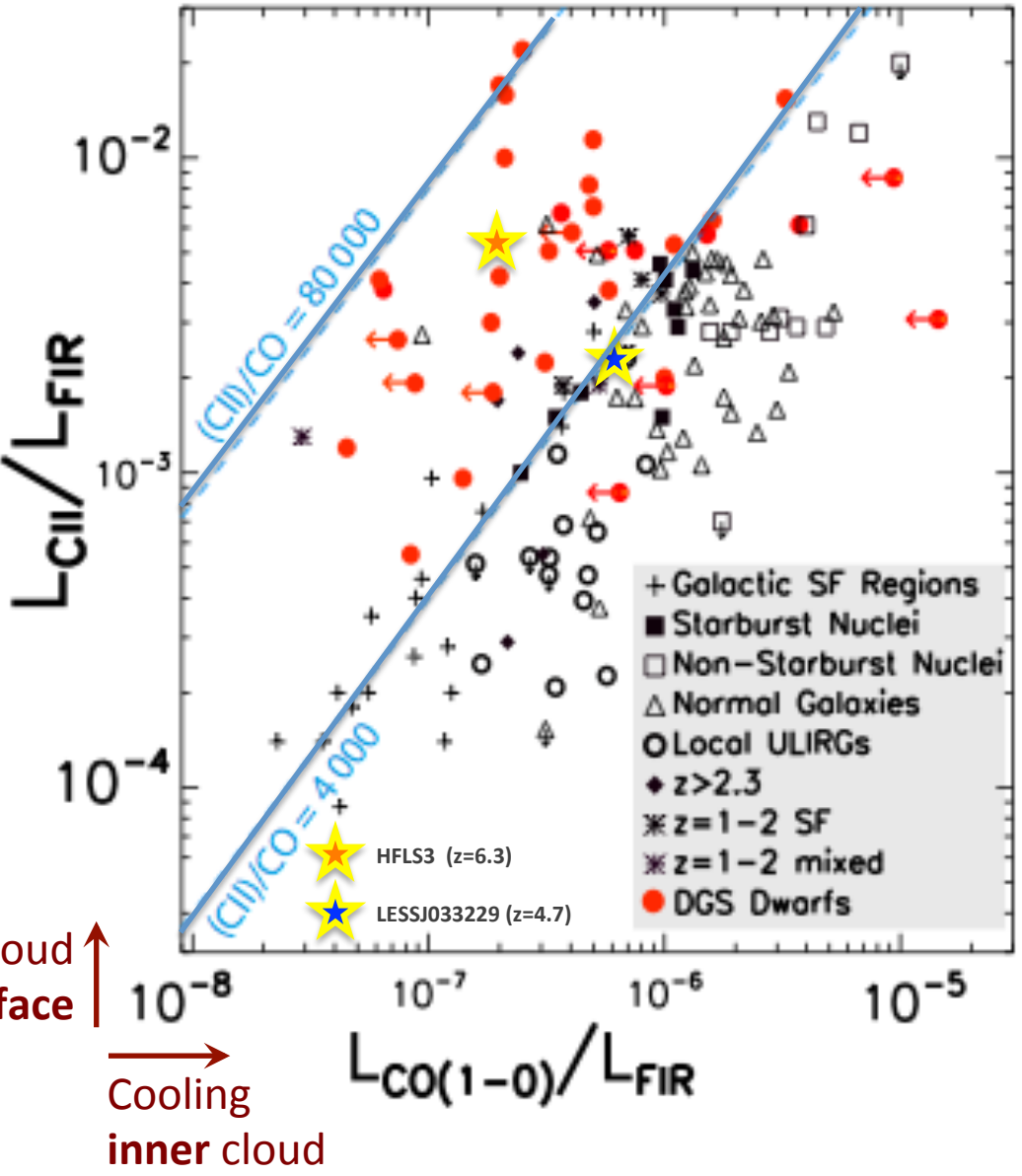
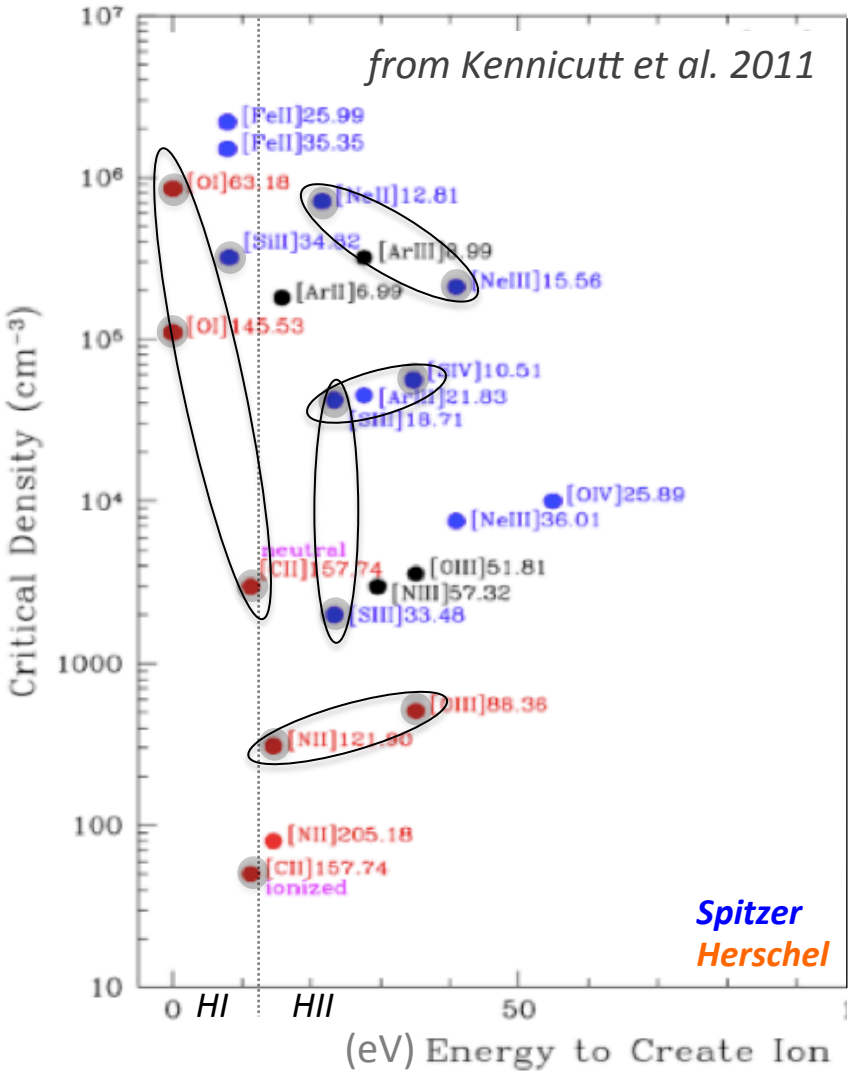



*Figure adapted from:*
*Madden 2000,*
*Stacey et al. 2010*
*Hailey-Dunsheath et al. 2010*

# Tracers of the ISM conditions

Tools: *Herschel, Spitzer* and optical observations
+ Cloudy spectral synthesis models

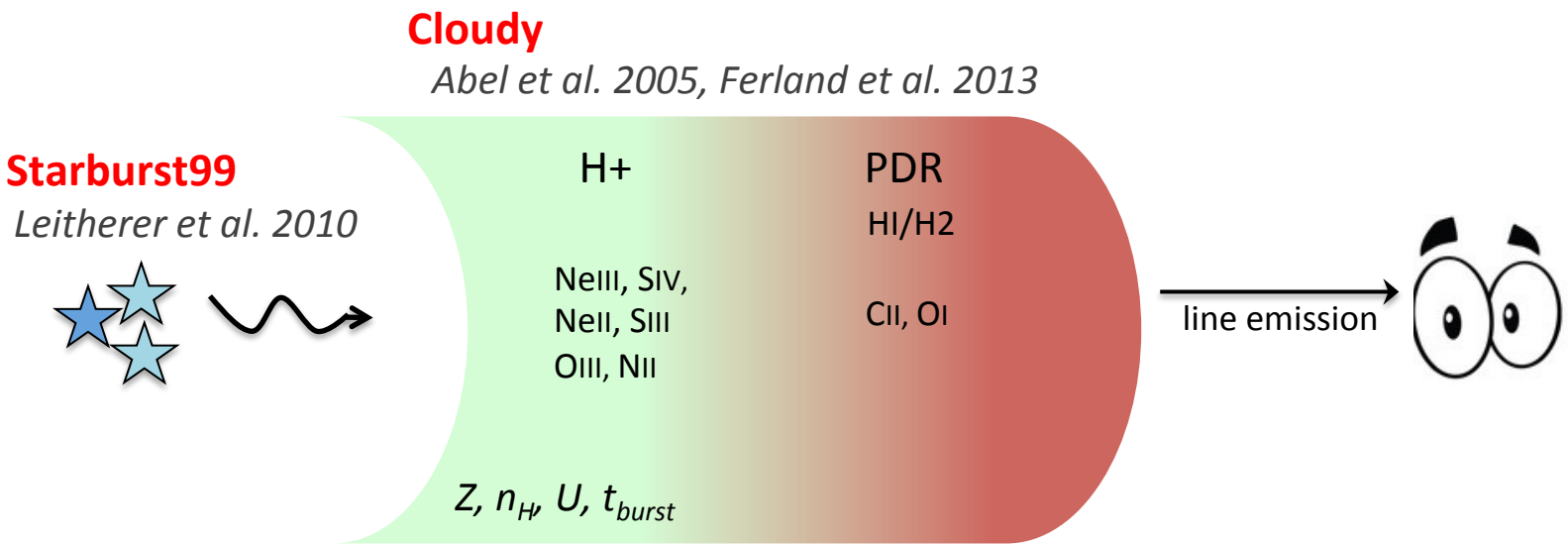



*ISM diagnostics:*

HII
- [SIII]18/33 => electron density
- [NeIII]/[NeII]
- [SIV]/[SIII]18 => radiation field
- [OIII]/[NII]

PDR
- [OI]/[CII]
- [OI]/L(TIR) => temperature, density
- [OI]63/145
- [CII]/CO => $A_V$

# Modeling: *strategy*




Model grid setting:

Instantaneous SF
Abundances varied with Z
**Stopped at $A_V$ = 10 mag**
Pressure equilibrium

Five bins of Z [0.05, 0.1, 0.25, 0.5, 1]
Grids varying: $n_H$ , U, $t_{burst}$

Strategy: *(30 galaxies)*

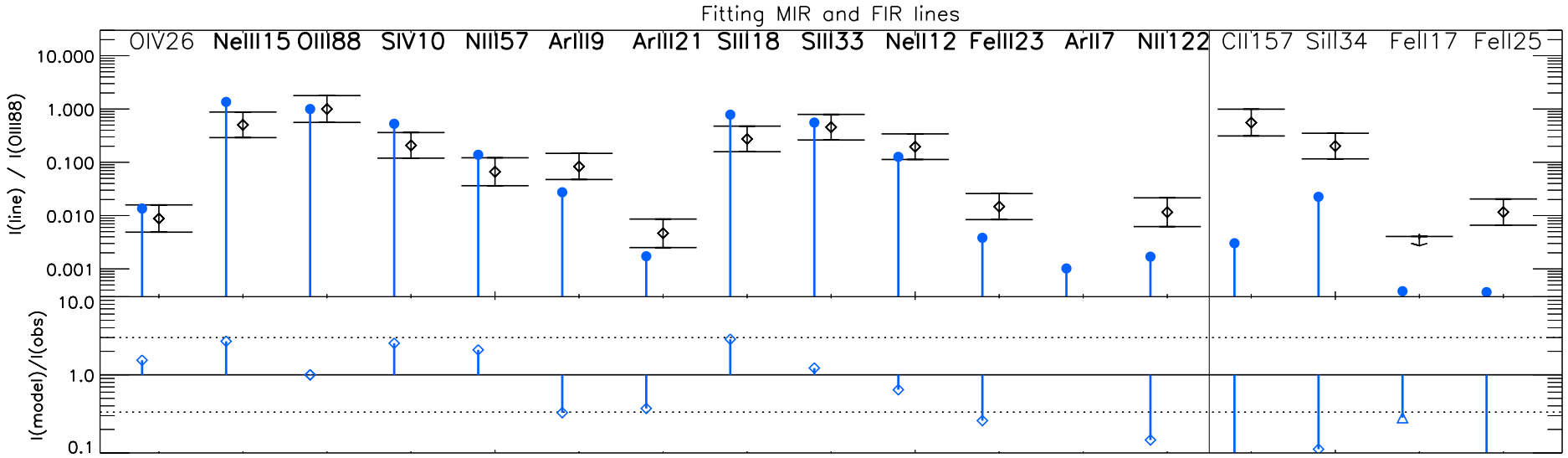
1) Derive best-fitting model for HII region
2) Predict PDR phase

*Cormier et al. 2015*
*Cormier et al. in prep*

# Modeling: *HII region results*

- Haro3

Blue: 1-component




- <u>Results over sample</u>:

  $\log n_H = 2.2$ [0.5; 3.5 $cm^{-3}$]

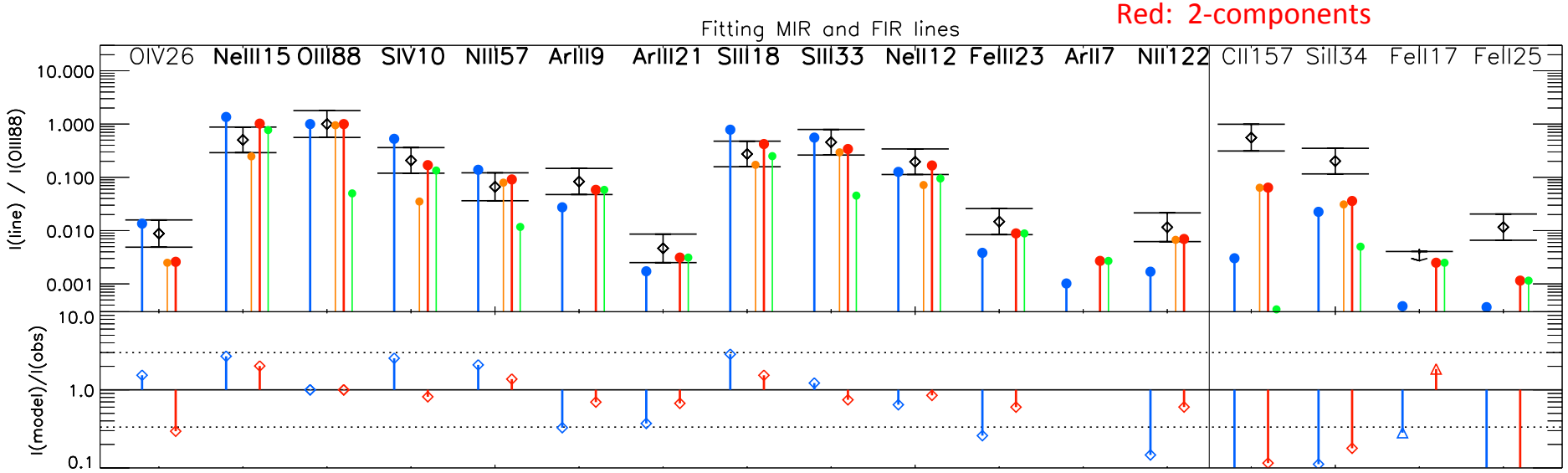
  $\log U = -2$ [-3; -1]

  $t_{burst} = 3$ [1; 4 Myr]

# Modeling: *HII region results*

- Haro3

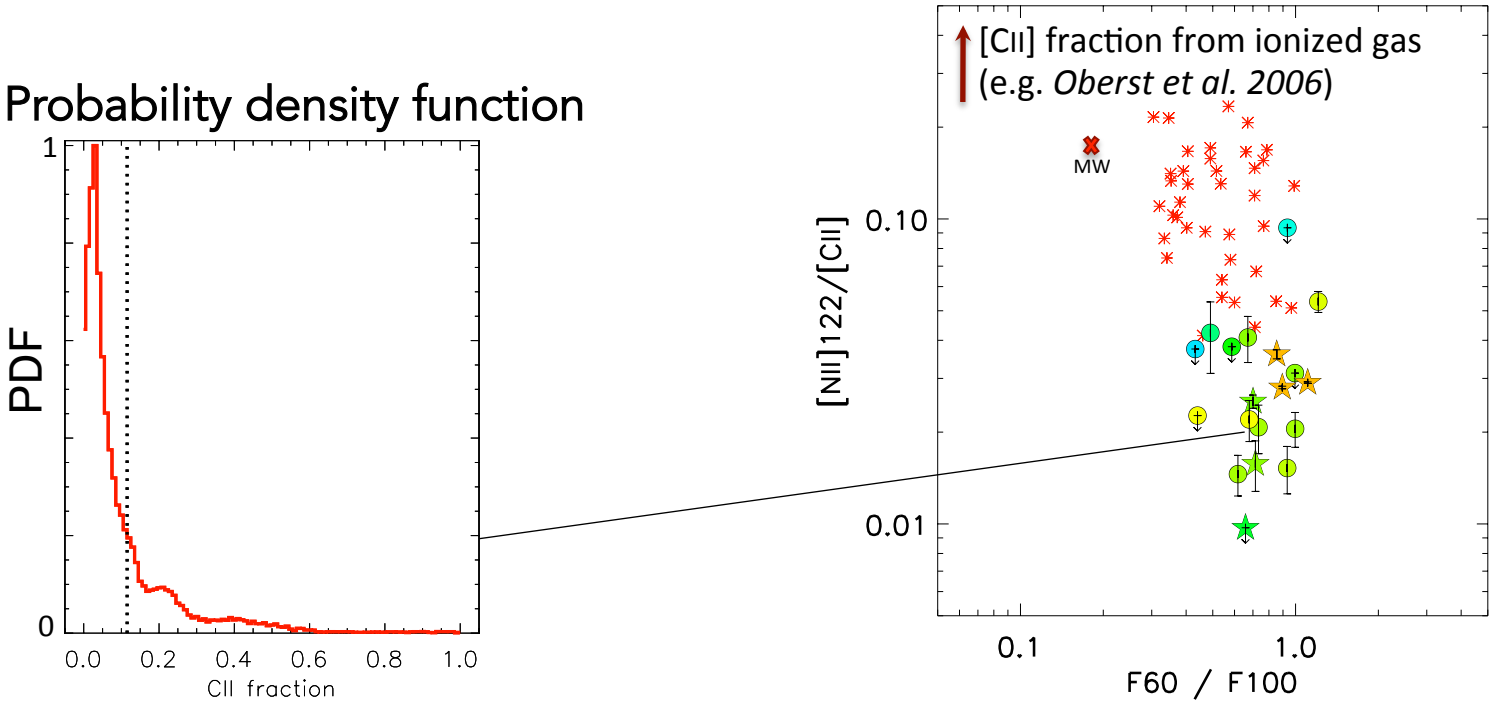
Blue: 1-component
Red: 2-components




- Results over sample:
  log $n_H$ = 2.2 [0.5; 3.5 $cm^{-3}$]
  log U = -2 [-3; -1]
  $t_{burst}$ = 3 [1; 4 Myr]

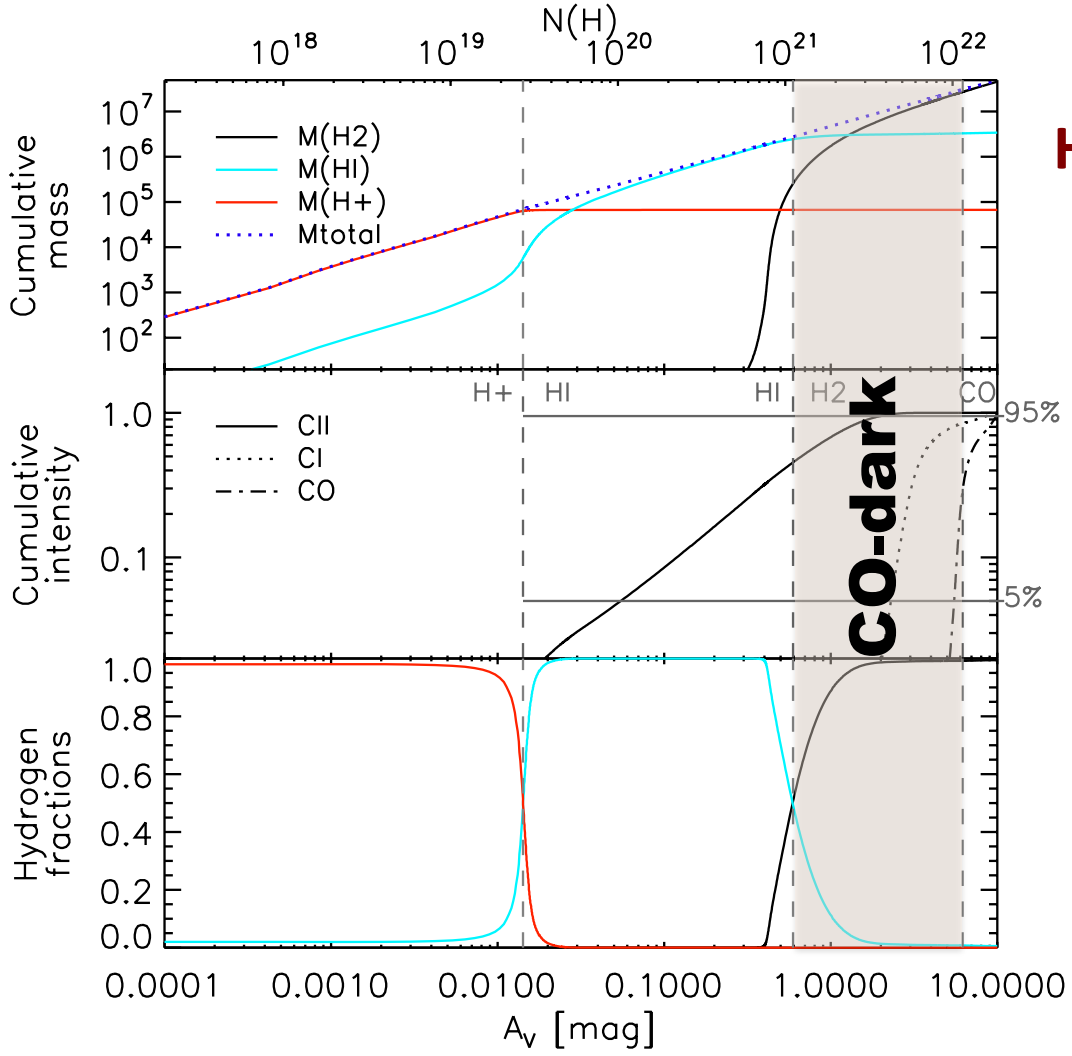
- Second HII component usually lower-$n_H$ and lower-U but less well constrained

# Modeling: *[CII] in the HII region*



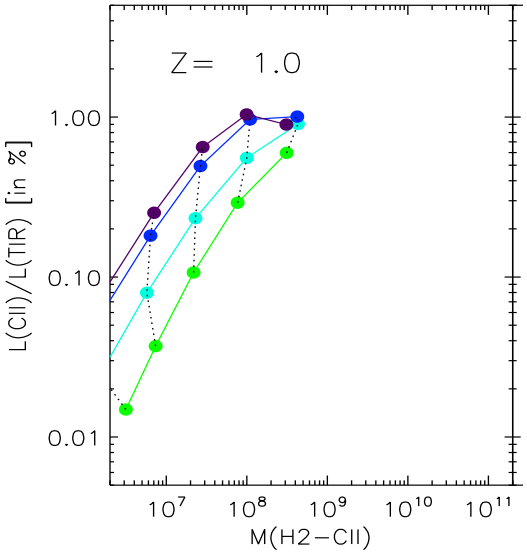

- Small fraction of [CII] from the ionized gas: 10% [0%; 30%] in low-metallicity star-forming galaxies

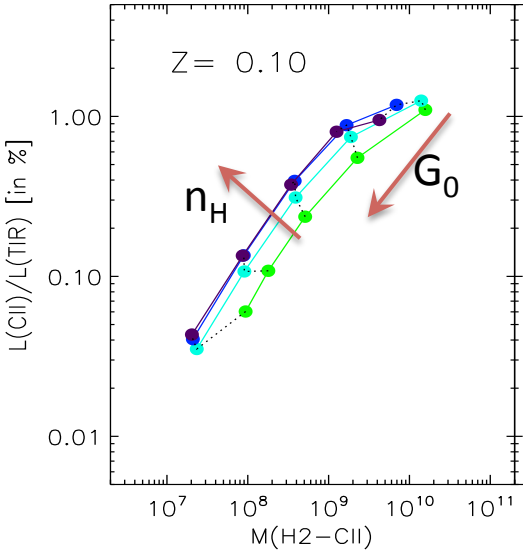
# Modeling: *phase transition*




**How much mass is *seen* by $C^+$ and $C^0$?**

# Modeling: *PDR mass evolution*




- Derived mass more sensitive to $G_0$ than to $n_H$ or Z
  *(see also Wolfire et al. 2010*
  *Bisbas et al. 2015*
  *Sternberg et al. 2015)*

Traceable by CII/TIR

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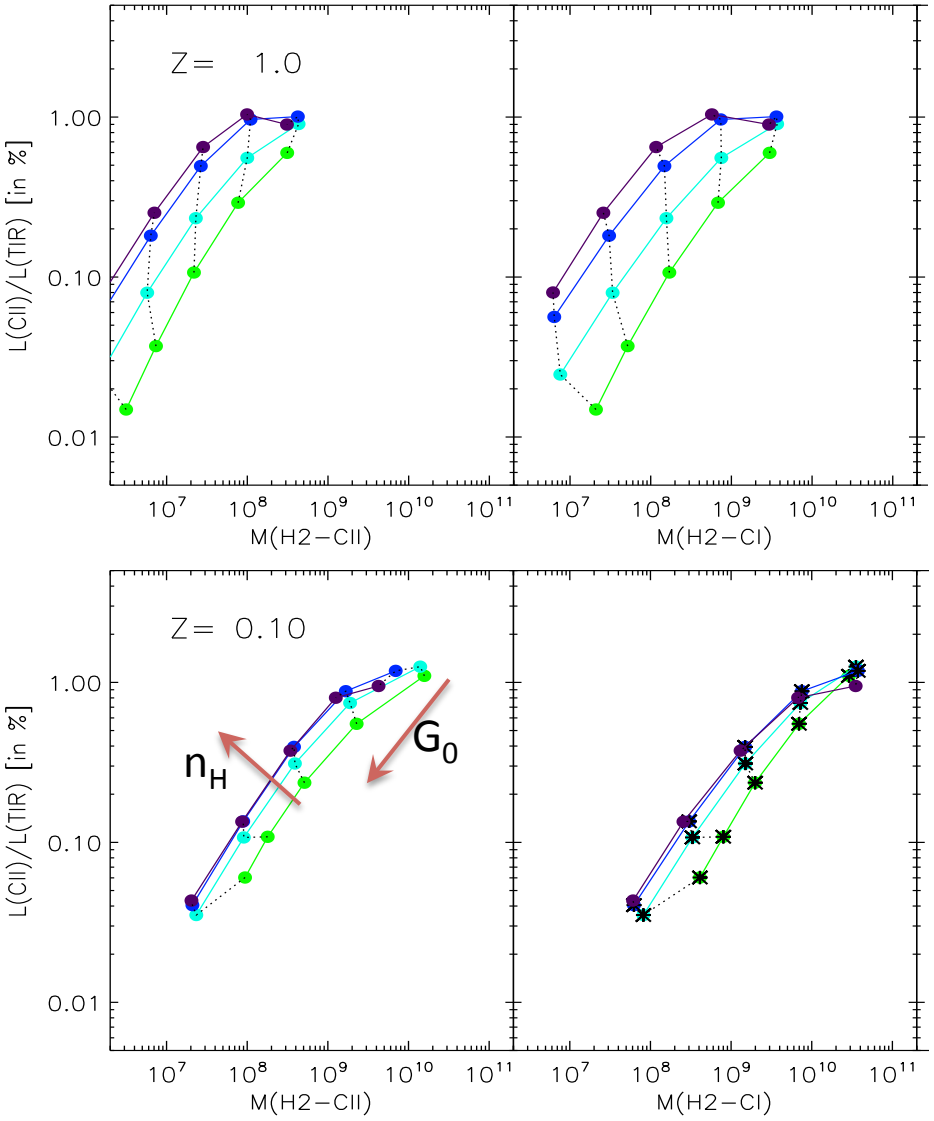


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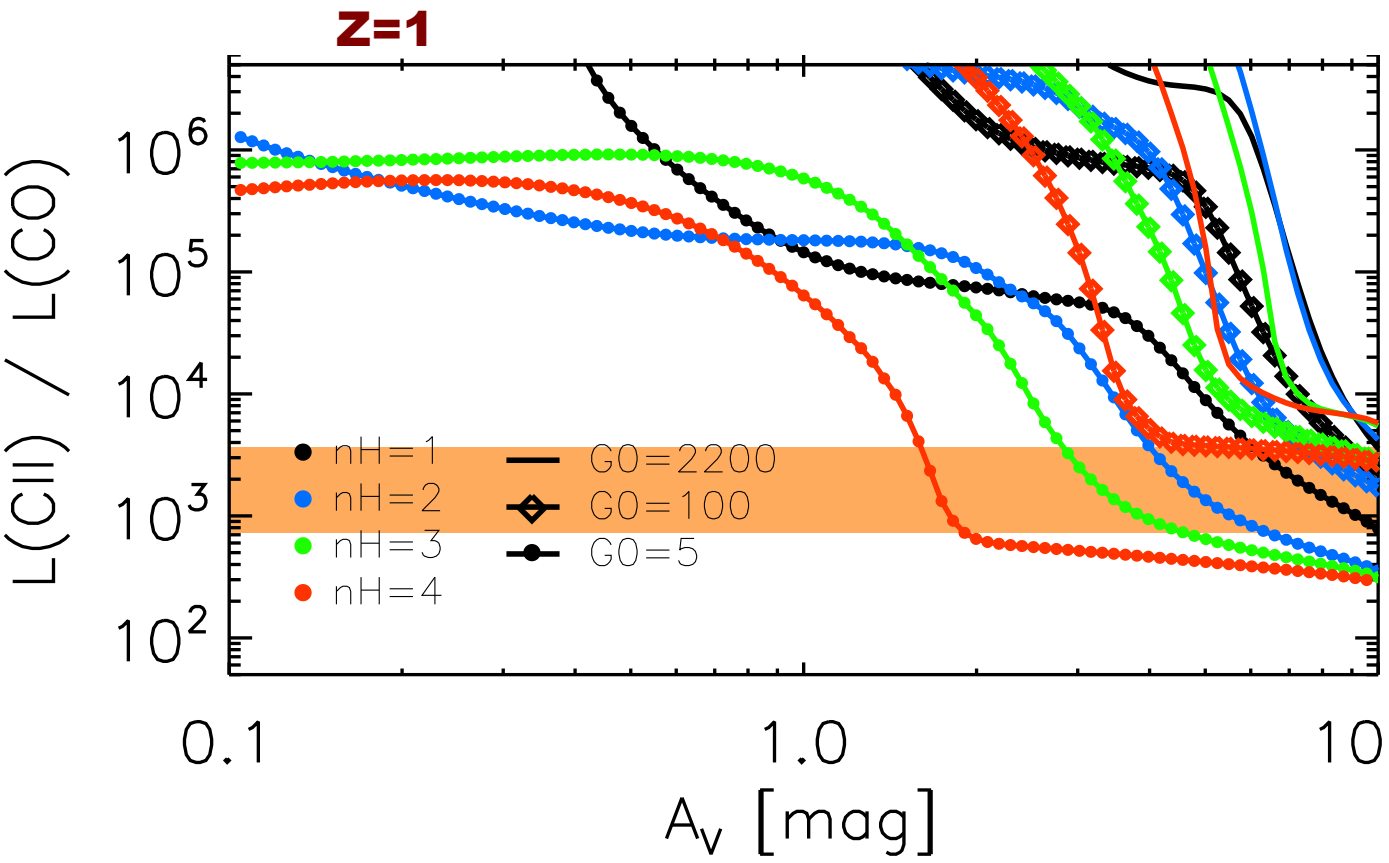
  *Bisbas et al. 2015*
  *Sternberg et al. 2015)*
  Traceable by CII/TIR

- CI *sees* more mass than CII, but… at $A_V$ of 10!

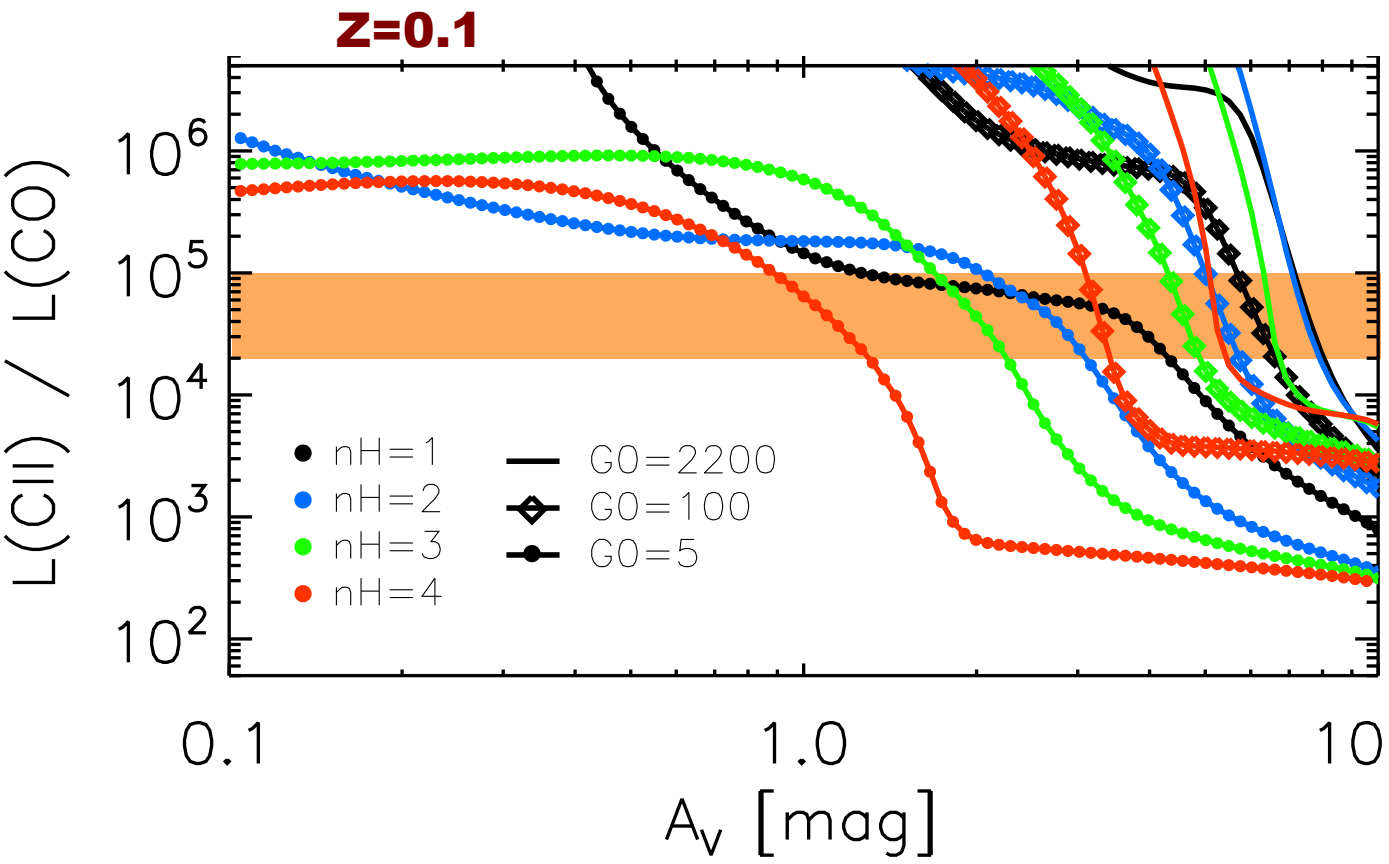
**How does this apply to galaxies?**

# Modeling: *the [CII]/CO ratio determines $A_V$*



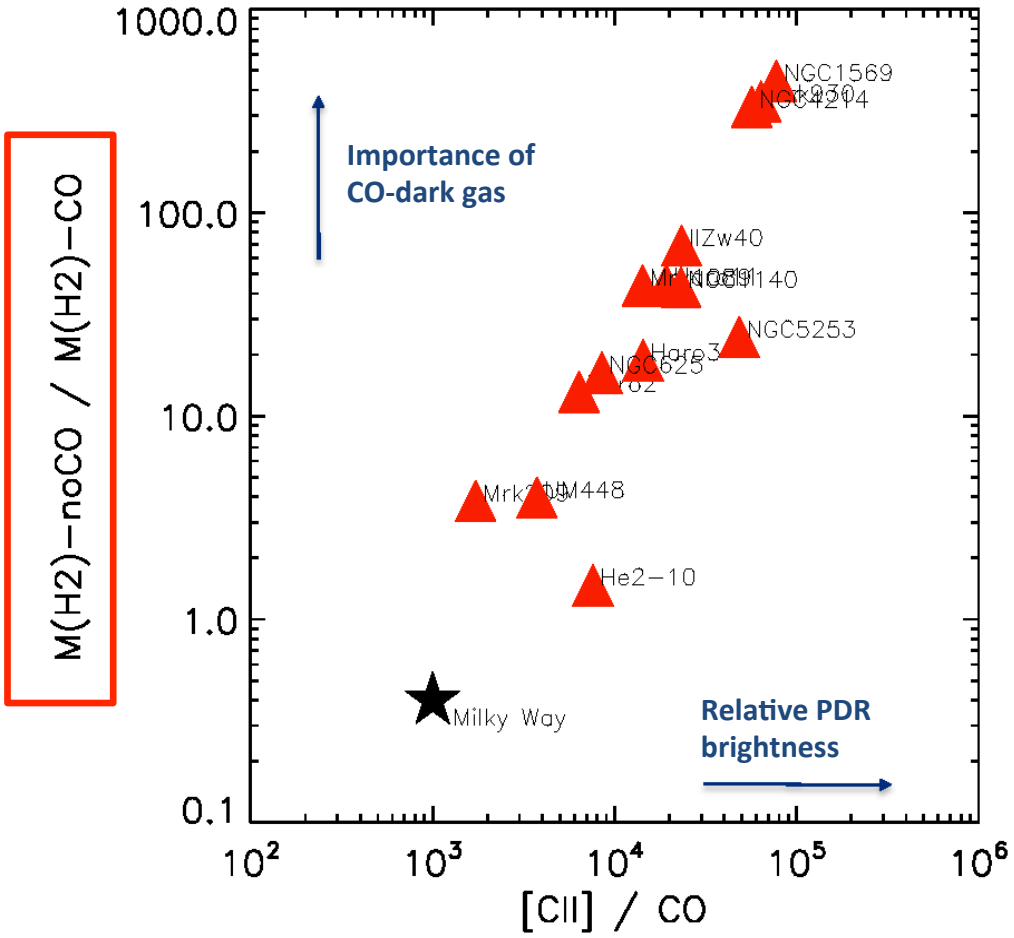

- Most of the CO has formed
  CO-dark gas **does not dominate** the mass budget

# Modeling: *the [CII]/CO ratio determines $A_V$*




- Average depth of the clouds lower CO-dark gas **dominates** the mass budget

# The [CII]/CO ratio as a total mass tracer

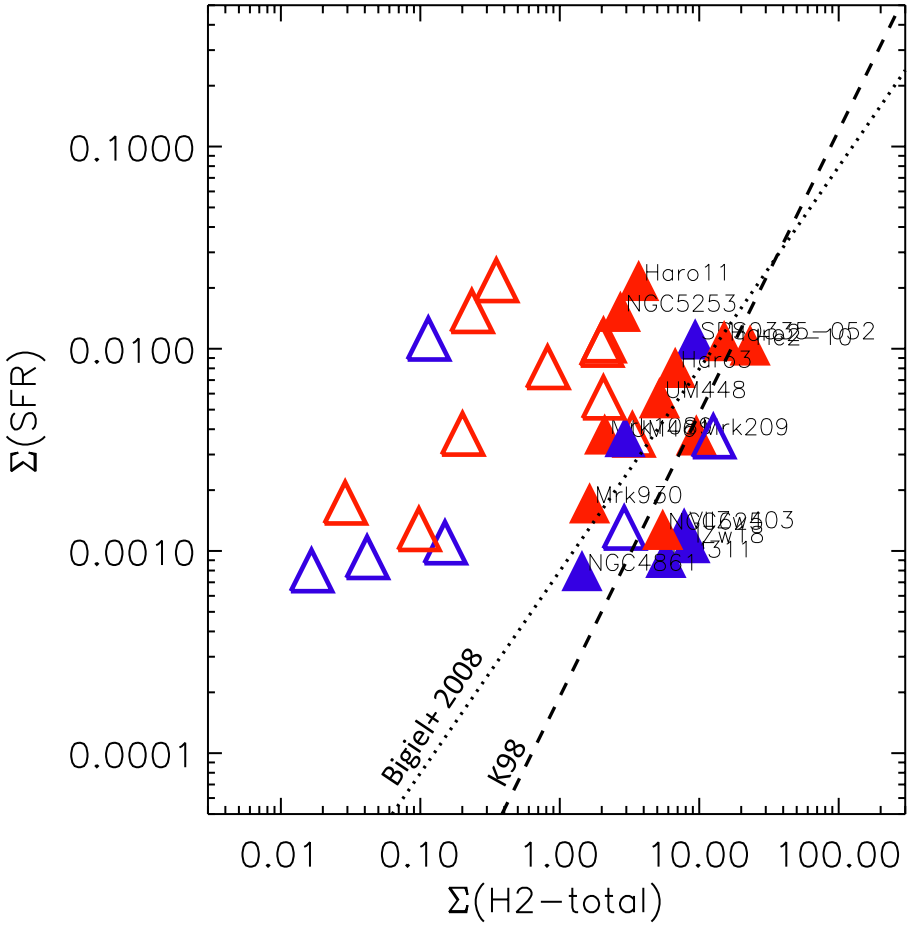



- CO-dark gas **dominates** the mass budget
- [CII]/CO as a new tool

\+ ALMA CO follow-ups for robust calibration

*Madden+ in prep.*

# The Schmidt-Kennicutt relation for dwarfs




Open triangles: $H_2$ from CO
Filled triangles: total $H_2$ (from [CII])
Blue: upper limit in CO
Red: detected in CO

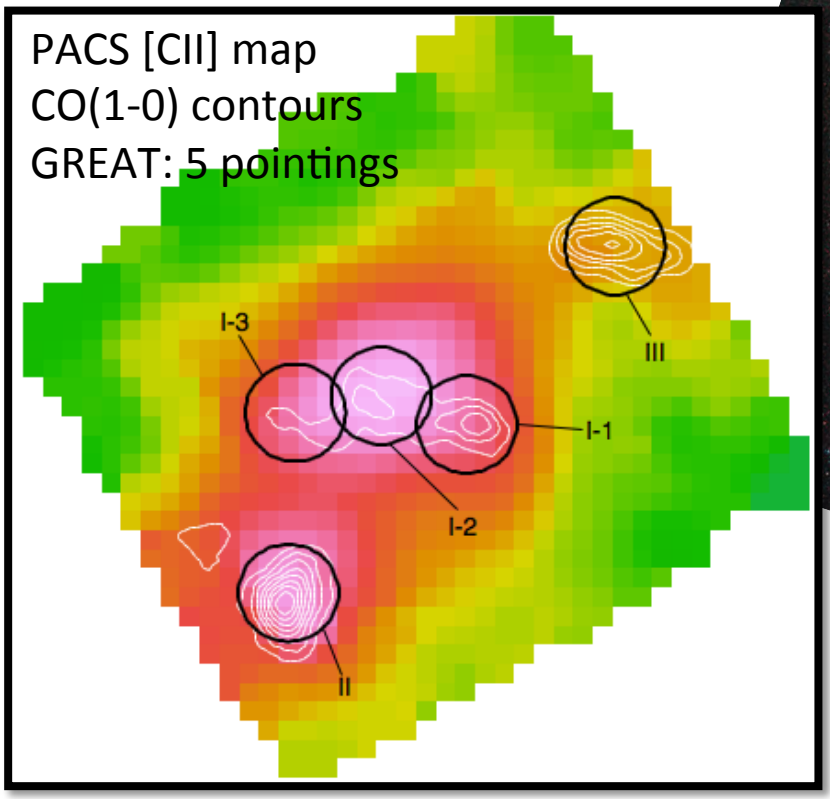
- Offset of dwarf galaxies in Schmidt-Kennicutt relation reduced by CO-dark gas

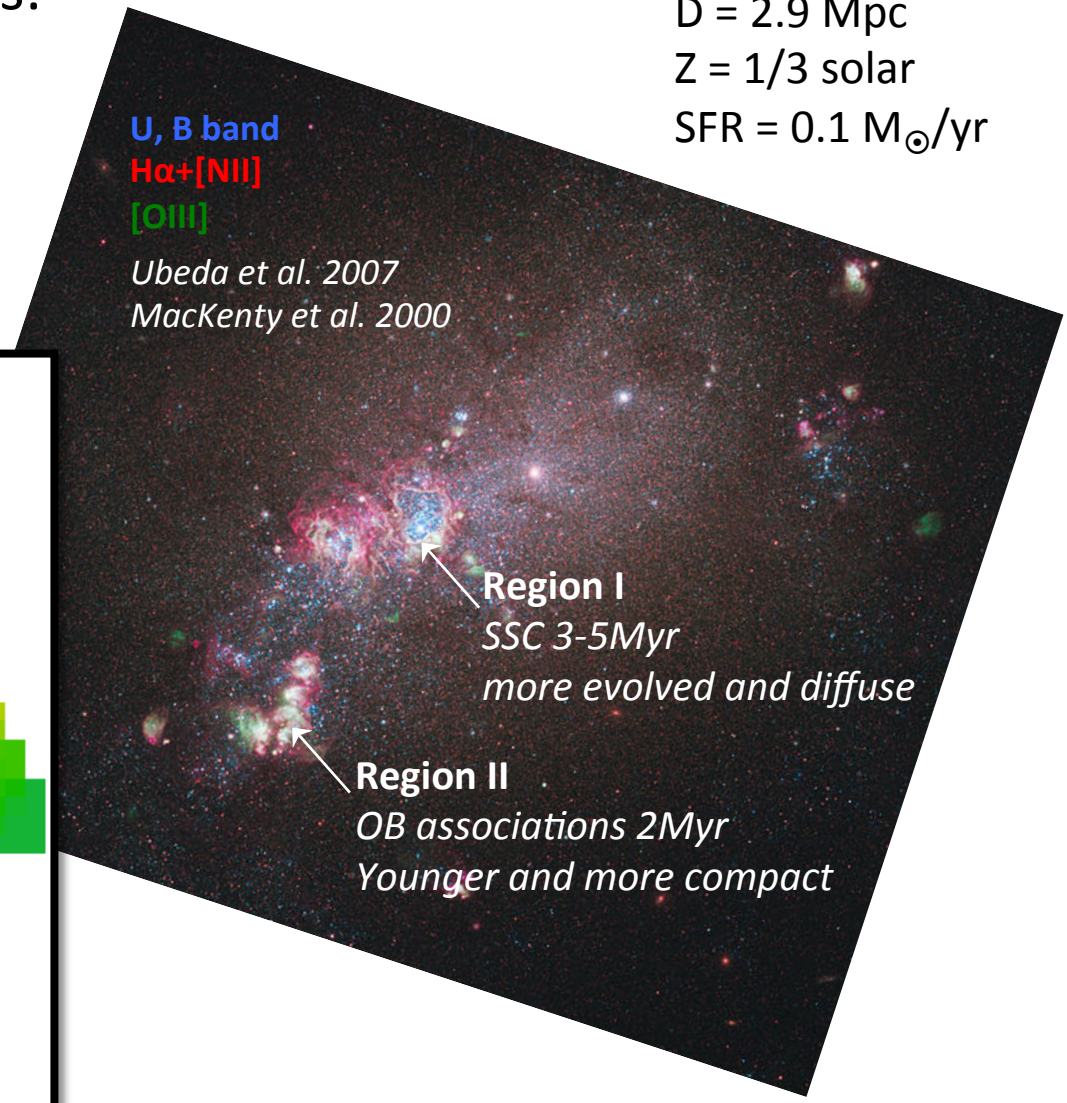
*Madden+ in prep.*

# NGC4214: *close-up view on separate regions*

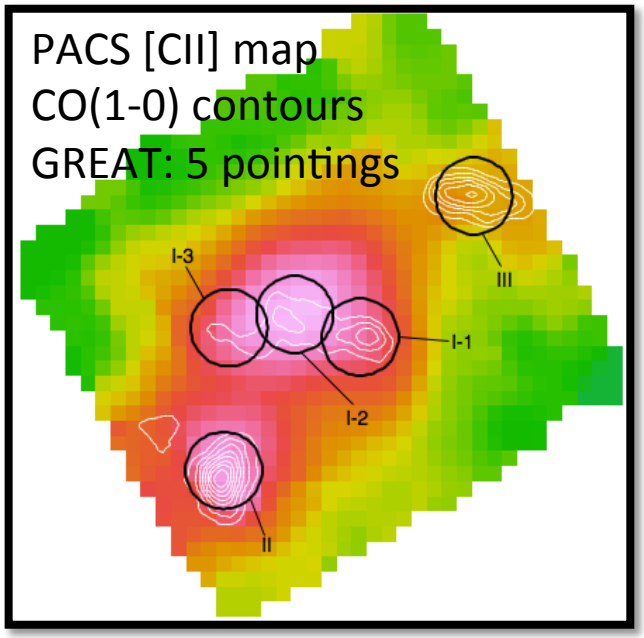
Low-metallicity ISM properties: result of evolution or intrinsically different?

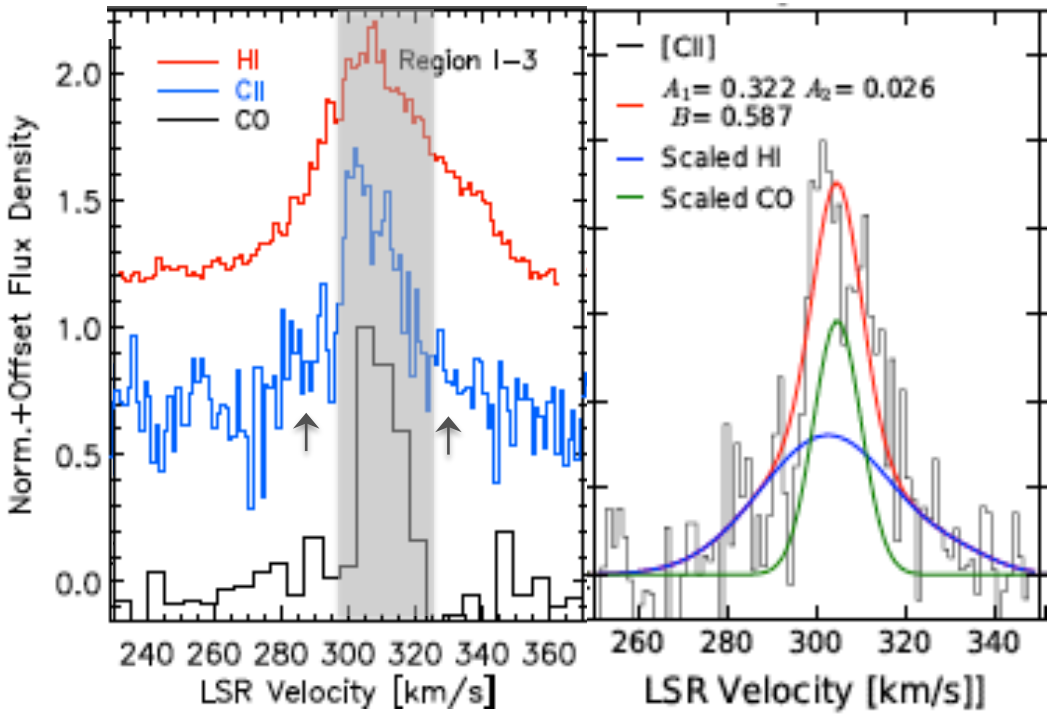
D = 2.9 Mpc
Z = 1/3 solar
SFR = 0.1 $M_{\odot}$/yr



# NGC4214: *C+ associated with the dense phase?*

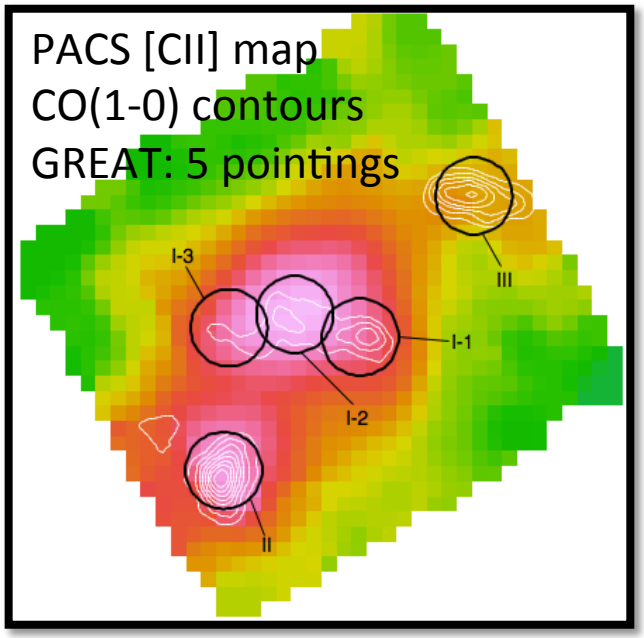


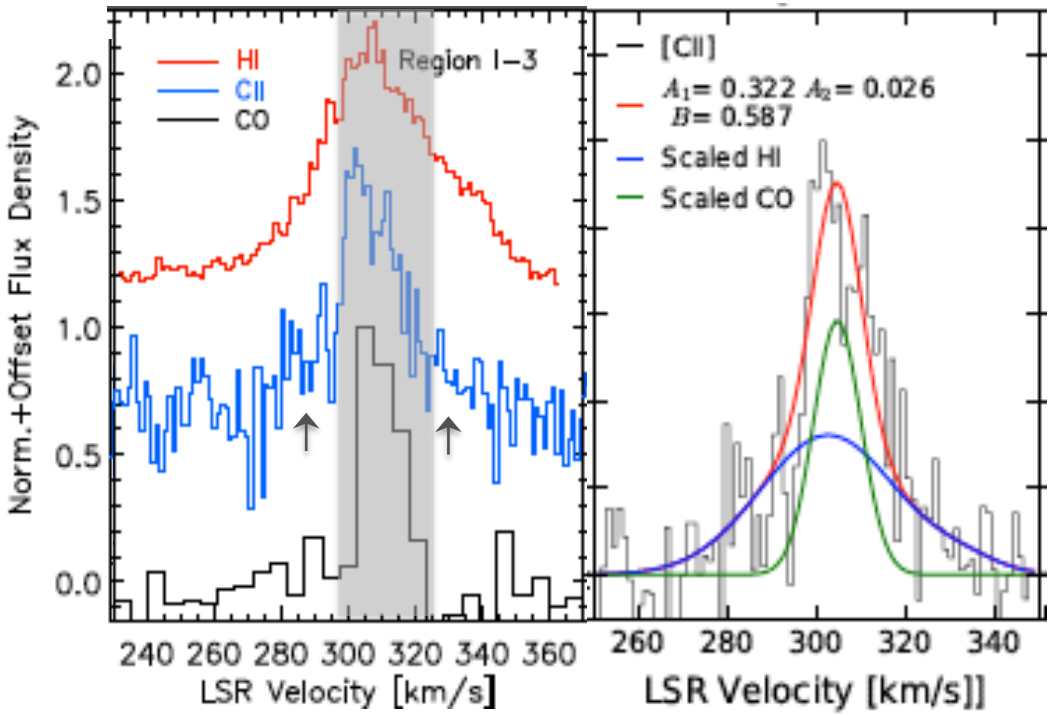




| | Region I | Region II | Region III |
|---|---|---|---|
| I(CII) attributed to CO | 75% | 55% | 20% |

*Fahrion+ subm.*

# NGC4214: *effects of evolution*



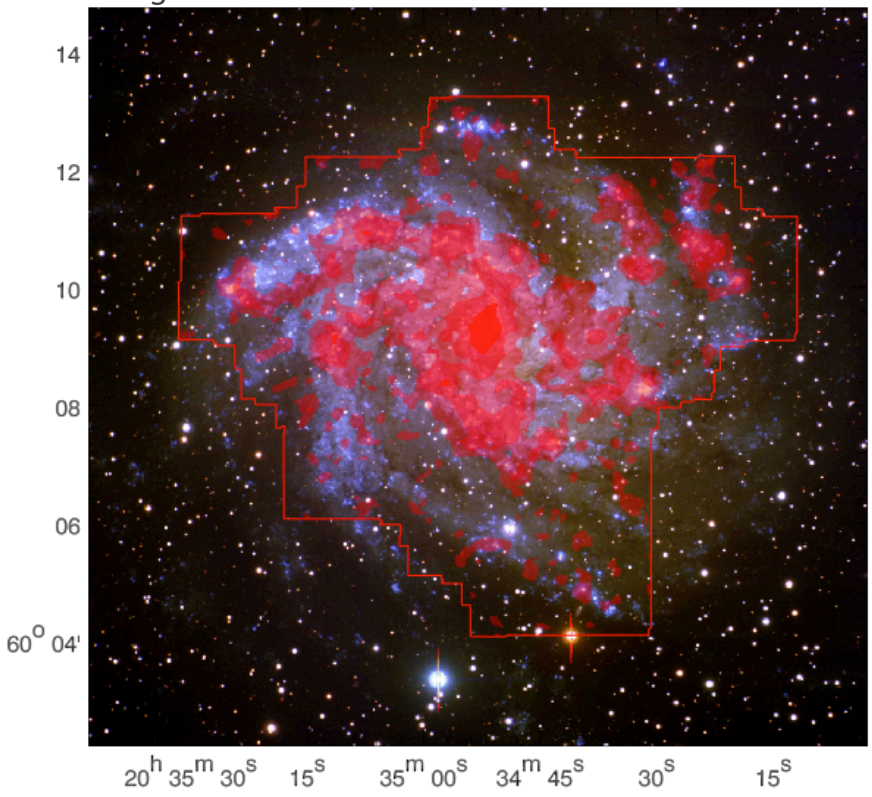

| | Region I | Region II | Region III |
|---|---|---|---|
| I(CII) attributed to CO | 75% | 50% | 20% |
| CO-dark $H_2$ mass | 80% | 65% | <10% |
| Covering factor | 1/3 | 1/2 | |
| D(PDR) | 170pc | 110pc | |

*Fahrion+ subm.*
*Dimaratos+ 2015*

} *Porosity and CO-dark gas linked to evolution*

# NGC6946: *mapping full disks with FIFI-LS*

*Image credit: C. Iserlohe*




- Extend coverage from bright regions to full maps at high resolution with FIFI-LS
- What is the full dynamic range of C+ emission across a disk galaxy?

**PIs: F. Bigiel & A. Krabbe**

D. Cormier, S. Madden, Ch. Fischer, I. de Looze, A. Leroy, J. Stutzki, A. Poglitsch, N. Geis, A. Bryant, A. Bolatto & FIFI-LS Team

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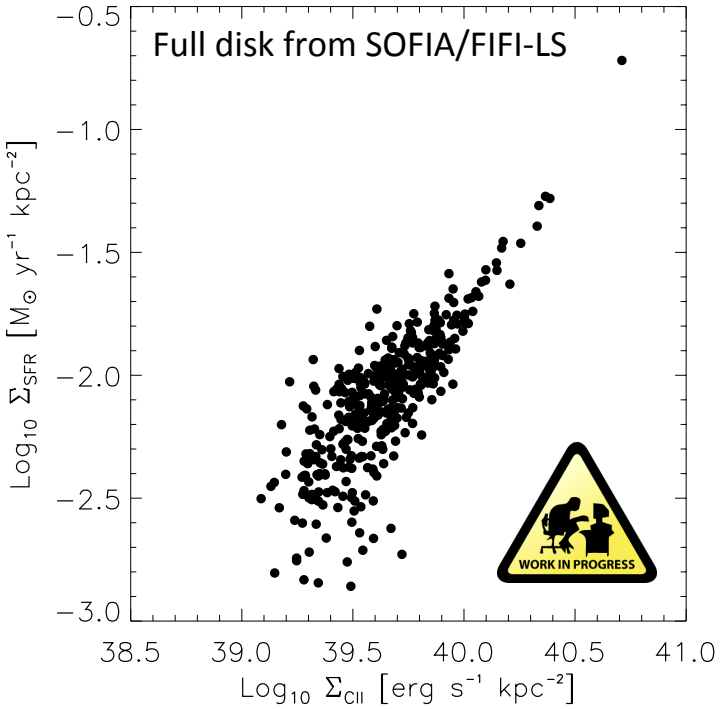
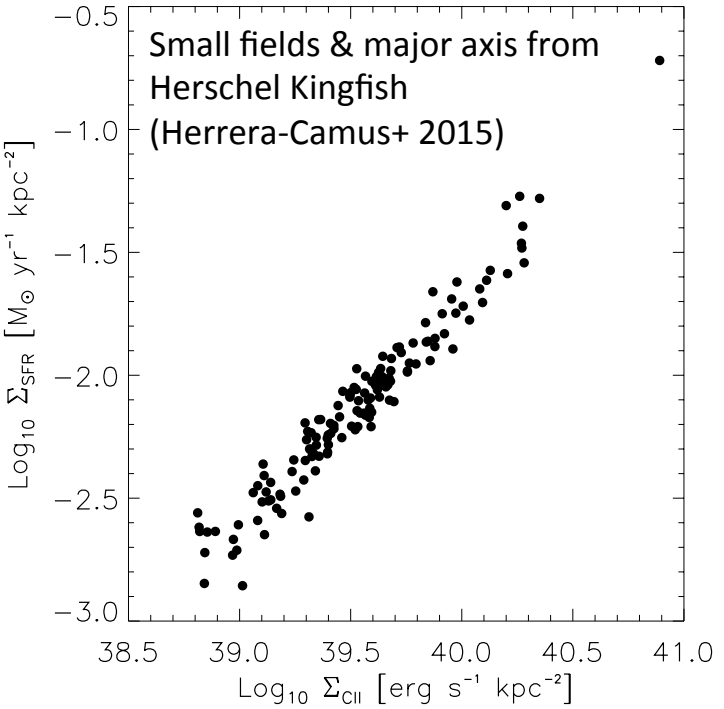
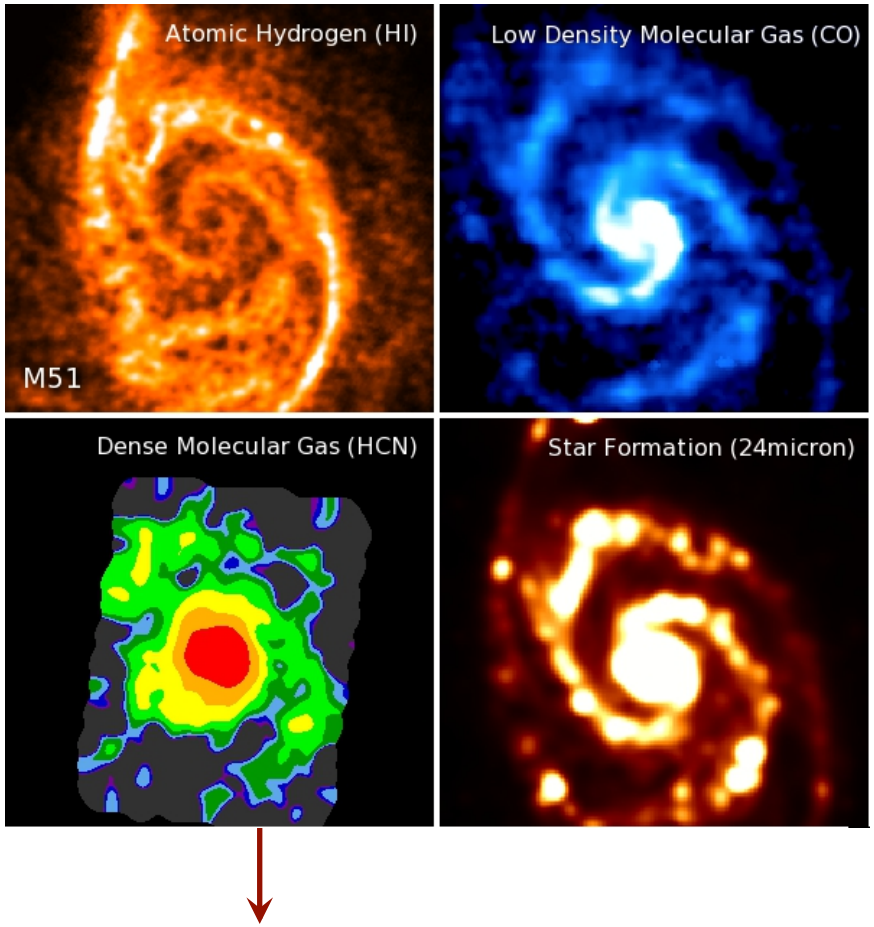



- FIFI-LS map reveals much increased scatter in relation.
- How accurate is CII as a SFR tracer across full disks? Which other local conditions matter?
- Does the scaling change away from bright star-forming regions (inter-arm, outer parts) and how?

# Nearby galaxies: *full physics of star-formation*




- Unique opportunity with FIFI-LS and upGREAT
- Significant progress in ISM studies going from small fields to full galaxy maps at many different wavelengths
- Such maps do not exist at matched, high resolution for any PDR tracer / CII.

Example: EMPIRE survey at IRAM 30m – 500hr
to map high-density molecular gas tracers and probe conditions in the immediately star-forming gas across a sample of disk galaxies.

# Conclusions

- Modeling HII region + PDR in individual galaxies:
  representative physical conditions ($G_0$, $n_H$, $A_V$)

- Mass budget: most of the molecular gas is *not* traced by CO at low metallicity

- No clear metallicity dependence
  but rather on $G_0$ / evolution of regions ($A_V$)

- CO-dark gas can be calibrated with [CII]/CO

- [CII] is a reliable tracer of the PDR in low-metallicity galaxies
  *need SOFIA to disentangle HI/CO contribution*
  *map all regimes within galaxies*