S. Garcia-Burillo

Star formation laws in LIRGs/ULIRGs

We have used the IRAM 30m telescope to observe a sample of 15 LIRGs simultaneously in the 1--0 lines of HCN and HCO^+. With the proposed observations we have significantly improved the statistics of LIRGs where high-quality data are available for these key molecular probes of the dense gas content. These observations complement the survey of LIRGs and ULIRGs made by Gracía-Carpio et al.(2006, 2008) and make possible to build up a final sample of 24 LIRGs with HCN and HCO^+ data. Both the star formation rates (SFR) and the typical sizes of the star forming (SF) regions of the galaxies in our sample are well characterized through available high-resolution imaging at different wavelengths (Alonso-Herrero et al 2006). We analyze the star formation efficiency and the SF law derived for the dense molecular gas as traced by HCN(1--0) and HCO^+(1-0) in 24 LIRGs. Results issued from these observations will be discussed in the context of the currently debated SF laws in galaxies.

STAR FORMATION LAWS IN IR LUMINOUS GALAXIES

Santiago GARCIA-BURILLO

Observatorio Astronómico Nacional (OAN)-Spain

STAR FORMATION LAWS IN IR LUMINOUS GALAXIES

In collaboration with:

Almudena Alonso-Herrero (CAB-CSIC)-Spain

Javier Graciá-Carpio (MPG)-Germany

Miguel Pereira-Santaella (CAB-CSIC)-Spain

Luis Colina (CAB-CSIC)-Spain

Pere Planesas (ALMA)-Chile

Santiago Arribas (CAB-CSIC)-Spain

SF Laws: Scaling Relations

IN THEORY…

$\rho(SFR) \sim \rho_{gas}^{\alpha} \leftrightarrow \Sigma_{SFR} \sim \Sigma_{gas}^{\alpha}$

If $\rho(SFR) \sim \rho / t_{\text{free fall}} \sim \rho_{gas}^{1.5}$

If $\rho(SFR) \sim \rho \times \Omega \sim \rho_{gas}^{1.5}$, in Q~1 disks

Schmidt 1959; Silk 1997; Elmegreen 1997

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Schmidt 1959; Silk 1997; Elmegreen 1997

In practice…

Σ_{SFR} ?: UV, Hα, Pα, FIR, RC...

Σ_{gas} ? : H_2 (CO, HCN), HI, H_2+HI…

scales?: global, resolved, ...

SF Laws: Scaling Relations

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IN PRACTICE...

Σ_{SFR} ?: UV, Hα, Pα, FIR, RC...

Σ_{gas} ? : H_2 (CO, HCN), HI, H_2+HI…

scales?: global, resolved, ...

Star Formation Efficiency

$SFE = SFR/M_{gas}$

Power Laws for SFR

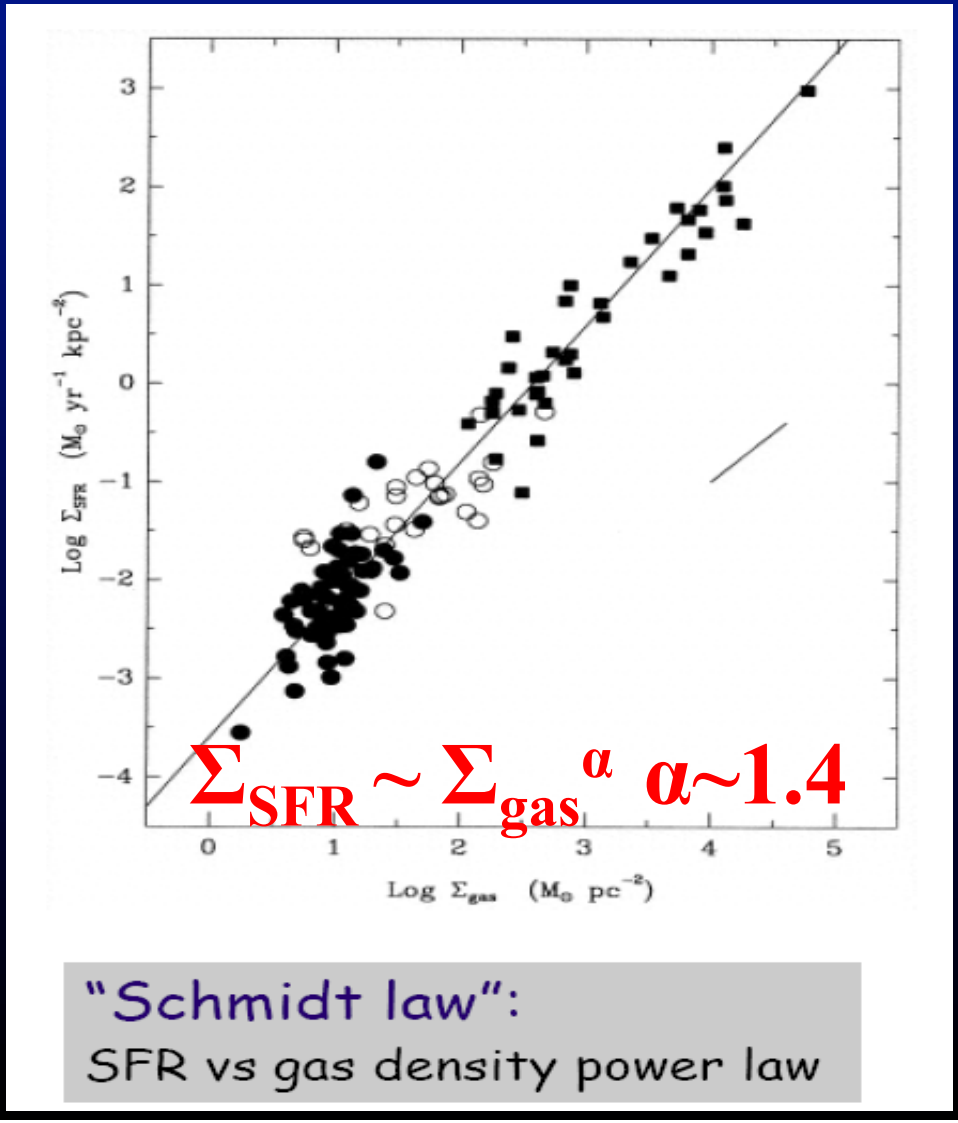
$\Sigma_{SFR} \sim \Sigma_{gas}^{\alpha}$

SF Laws: Scaling Relations

Kennicutt 1998

Gas tracers: HI + CO(→H_2)

Global fit on 100 galaxies dominated by nuclear + extreme starbursts

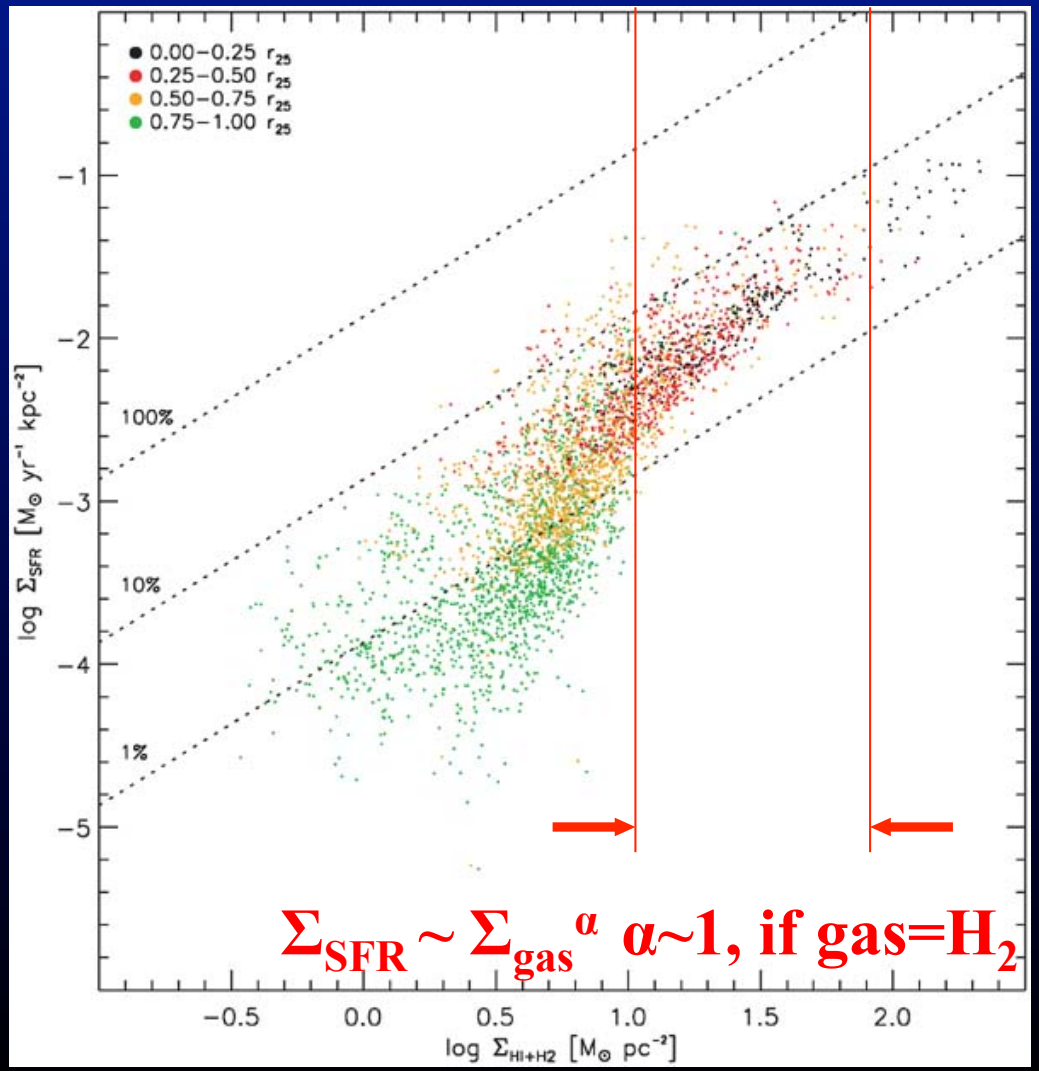


SF Laws: Scaling Relations

Bigiel et al 2008

Gas tracers: HI+CO(→H_2)

Survey of 18 'normal' SF galaxy disks with sub kpc-scale resolution



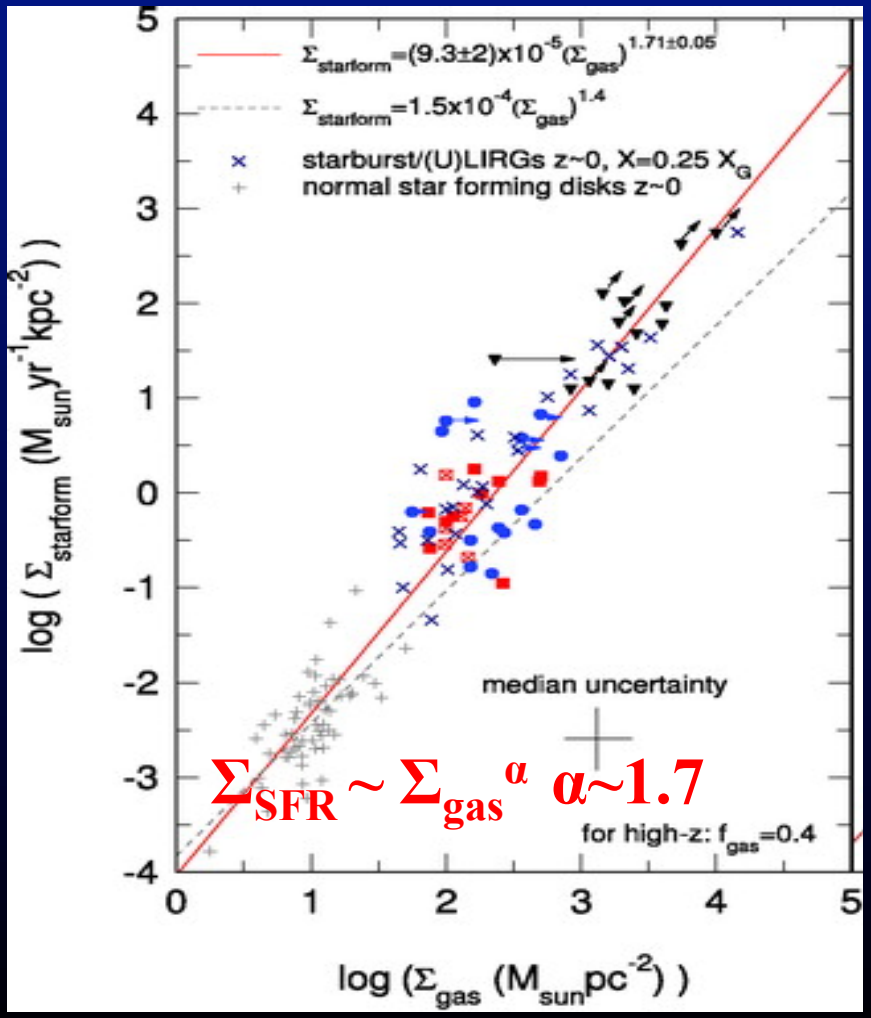
$\Sigma_{SFR} \sim \Sigma_{gas}^{\alpha}$ $\alpha \sim 1$, if gas=H_2

SF Laws: Scaling Relations

Bouché et al 2007

Gas tracers: HI + CO(→H_2)

Global fit on >100 galaxies: addition of SMGs→extreme starbursts



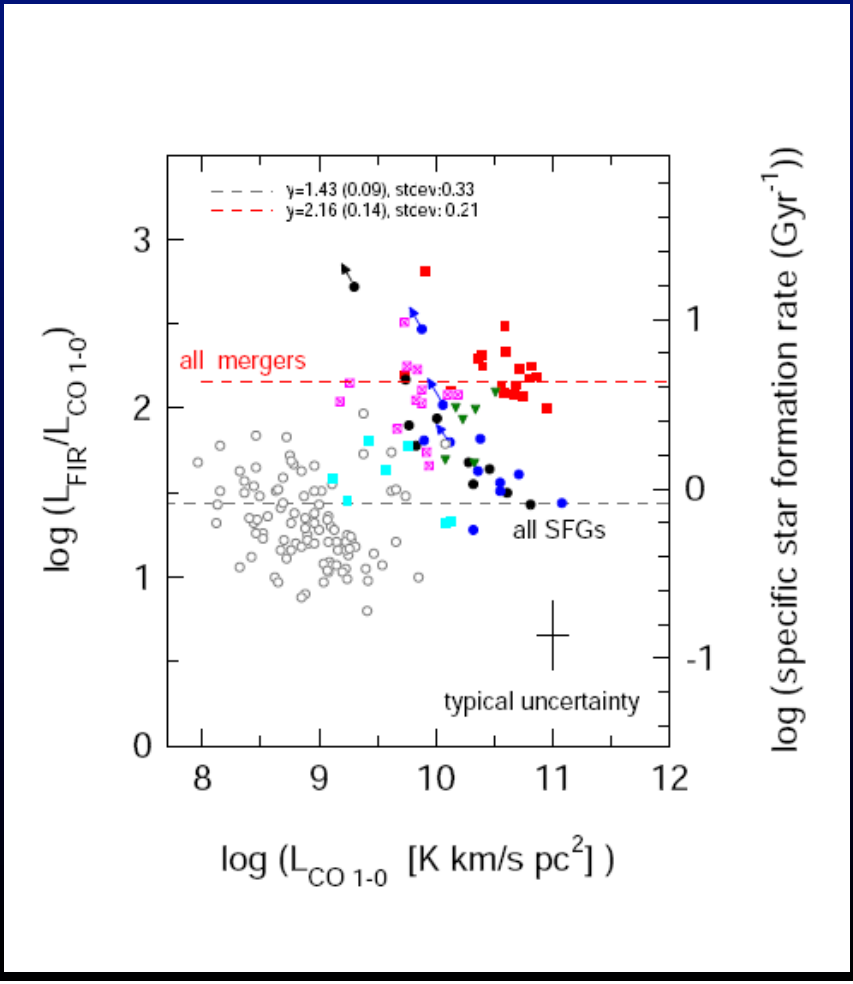
SF Laws: Scaling Relations

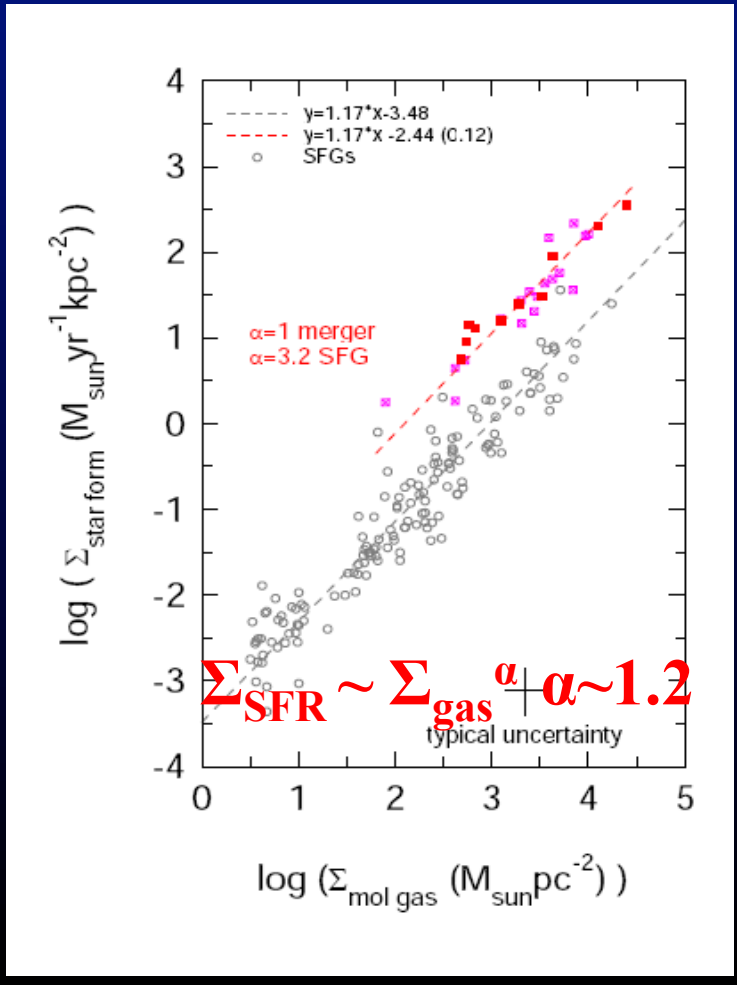
Genzel et al. 2010

A study of SF laws over cosmic time (´normal´ vs ´extreme´ galaxies at all redshifts)

SFE (mergers) ~ (5-6) x SFE (normal), for a given L_{CO}

Σ_{SFR} (mergers) ~ 10 x Σ_{SFR}(normal), for a given Σ_{gas}





SF Laws: 'normal' vs 'extreme' SF

$SFE = SFR/M_{gas}$ $\quad\quad$ $\Sigma_{SFR} \sim \Sigma_{gas}^{\alpha}$

Any difference between 'normal' galaxies and 'extreme SB' if we use HCN as a tracer of Σ_{gas} ?

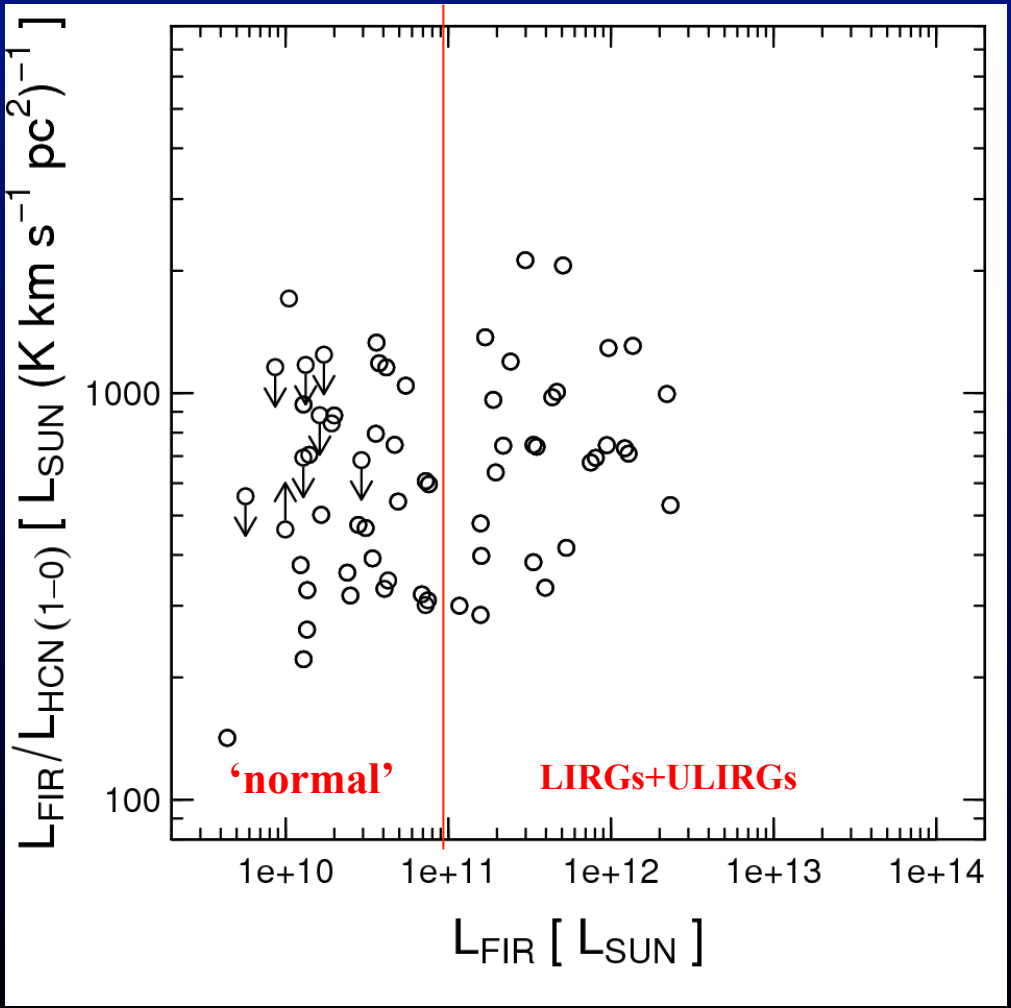
First studies point to no difference: $\Sigma_{SFR} \sim \Sigma_{gas}^{\alpha}$, $\alpha \sim 1$ for ´all´ galaxies

(e.g., Gao & Solomon 2004)

Star Formation Efficiency: SFE_{dense}

Gao & Solomon 2004

$SFE_{dense} = L_{FIR}/L_{HCN} \sim$ **constant** as a function of L_{FIR} : from SFG to ´mergers´

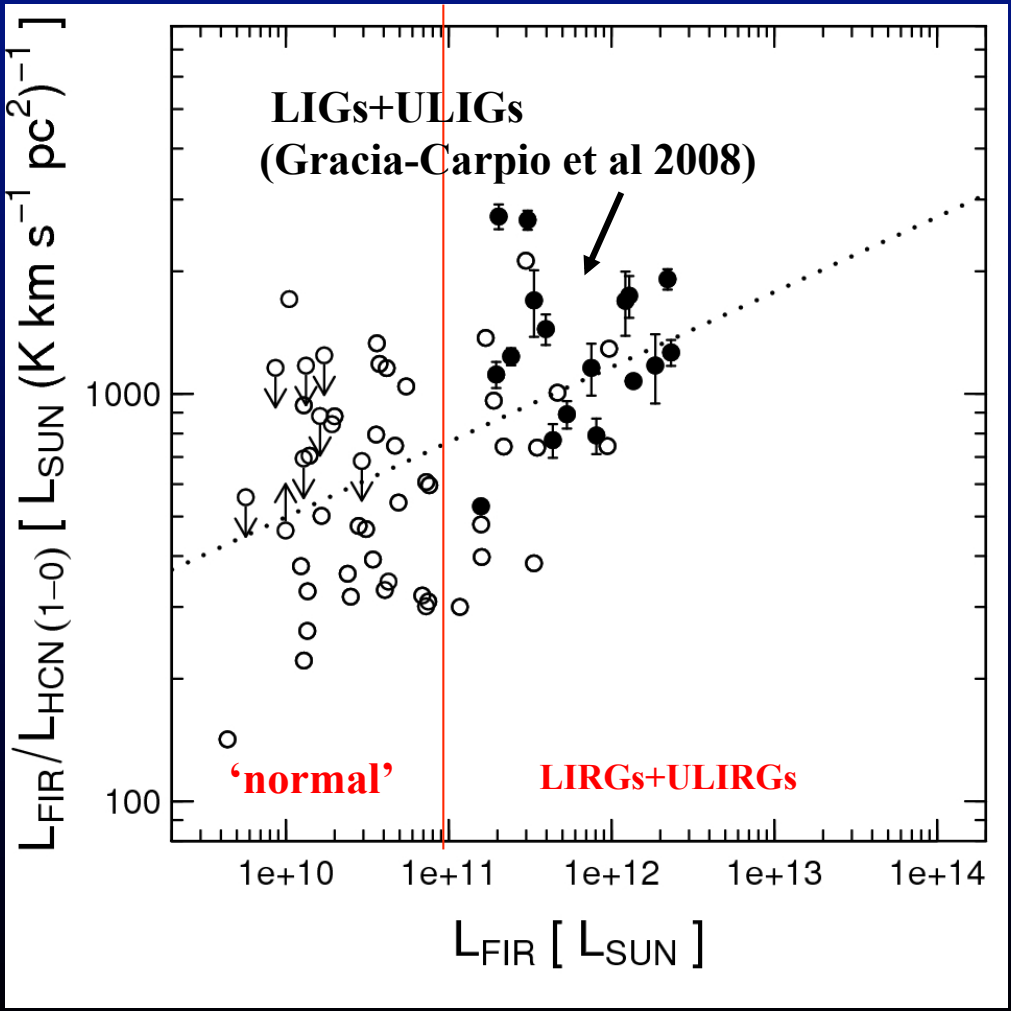


However...

Star Formation Efficiency: SFE_{dense}

Graciá-Carpio et al. 2008

New HCN data suggest higher SFE_{dense} for LIGs and ULIGs



Star Formation Efficiency: SFE_{dense}

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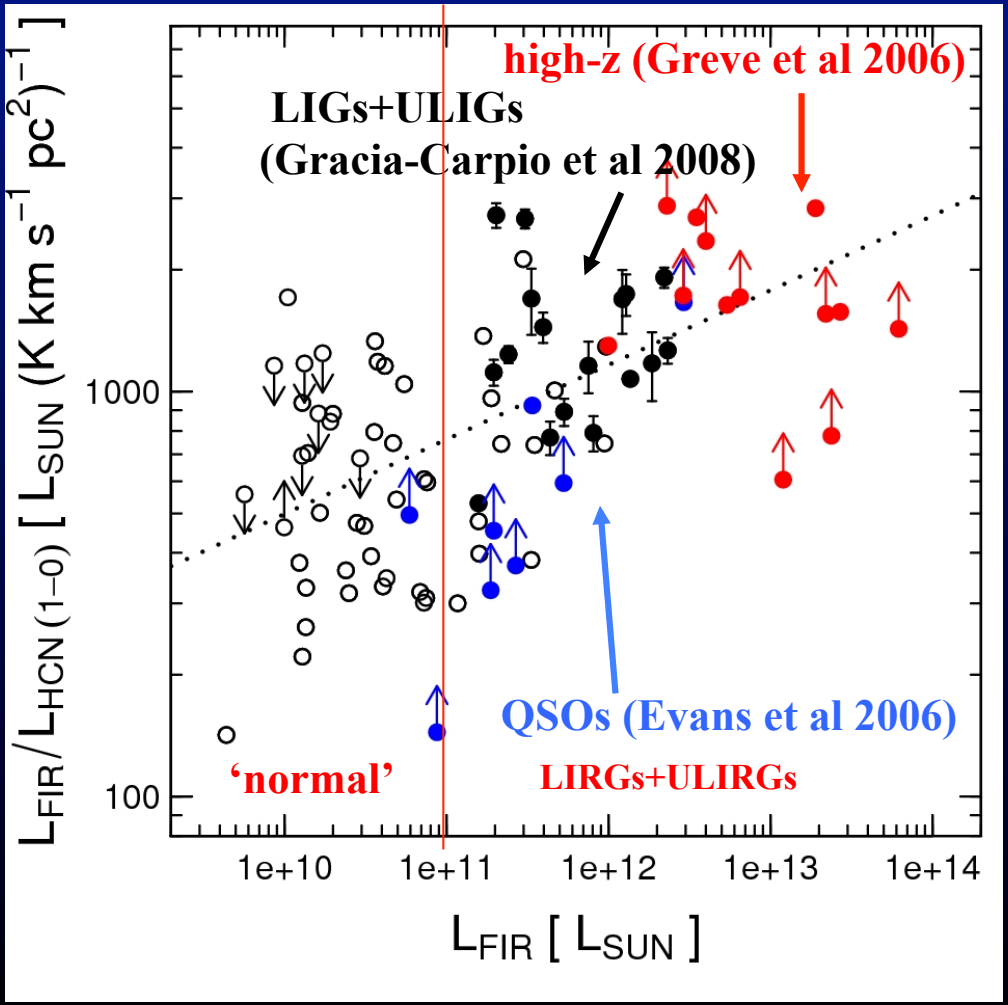
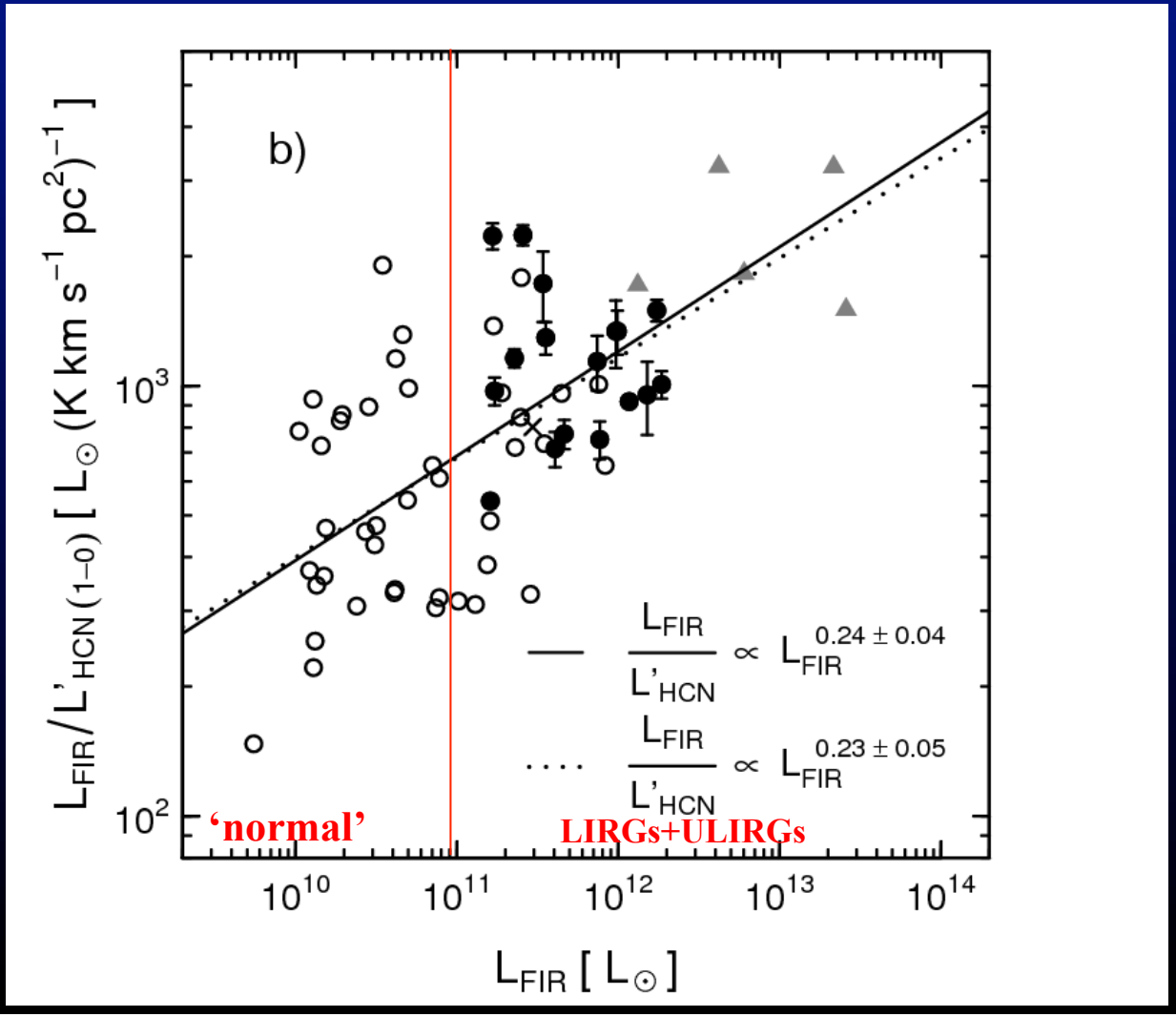


Star Formation Efficiency: SFE_{dense}

Graciá-Carpio et al. 2008

SFE_{dense} (LIGs/ULIGs) ~ 3 x SFE_{dense} ('normal' SFGs)

$L_{FIR} \sim L_{HCN}^{1.23} \Rightarrow L_{FIR}/L_{HCN} \neq$ constant but $\sim L_{FIR}^{n}$, n ~ 0.23



SF Laws in LIRGs: a new sample

García-Burillo et al. 2010, in prep

Need of new HCN data for LIRGs: *'turning' point in SF laws*

SF Laws in LIRGs: a new sample

García-Burillo et al. 2010, in prep

➡ **Need of new HCN data for LIRGs:** ➡ *'turning' point in SF laws*

➡ **HCN / HCO^+ IRAM 30m survey of 19 LIRGs: 9→9+19=28**

LIRGs extracted from 30 galaxy sample of *Alonso-Herrero et al. 2006*

-30 nearby (v<5200km/s) LIRGs, 80% of RBGS sample

-Sizes for dense molecular gas + SF disks < 10" << 30m-beam@88GHz

➡ *'Everything' inside the beam*

-High-resolution imaging in several SF tracers

-HST NICMOS Paα

-CAHA + VLT Hα

-Spitzer/MIPS 24mμ

➡ *Cross-check of SFR values*

➡ *Spatially resolved images of SF: KS laws*

LIRGs: a new sample

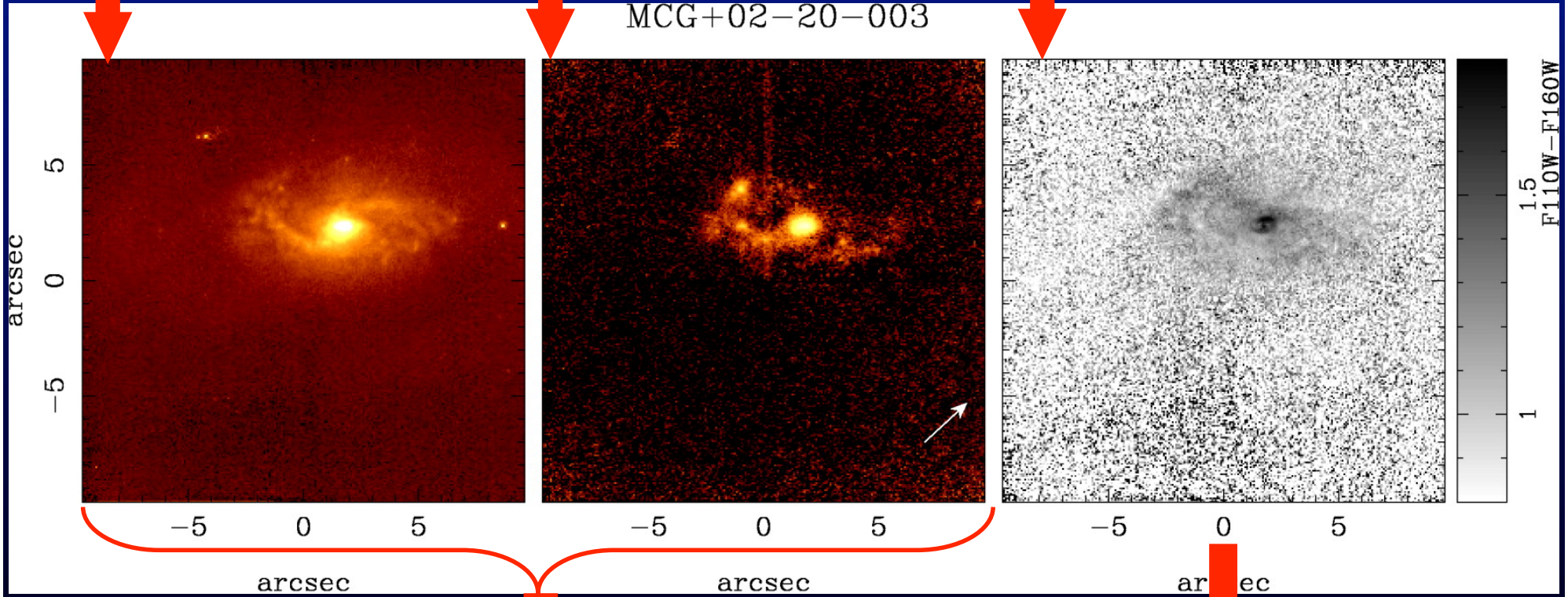
1.1mμ continuum

Paα

m_{F110W}-m_{F160W}

FOV~19”

Alonso-Herrero et al. 2006

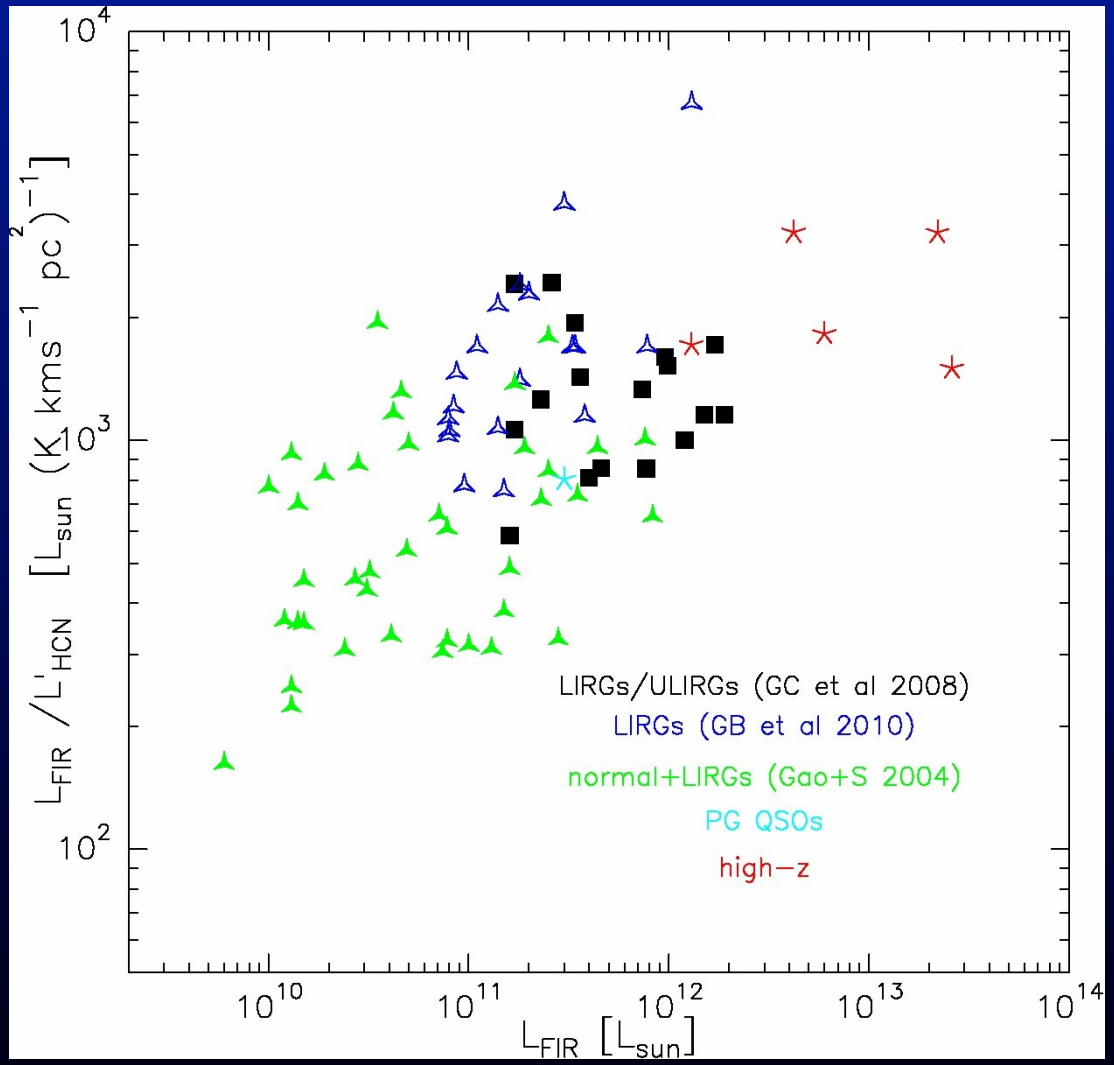


Star Formation

Dusty Disk

Star Formation Efficiency: SFE_{dense}

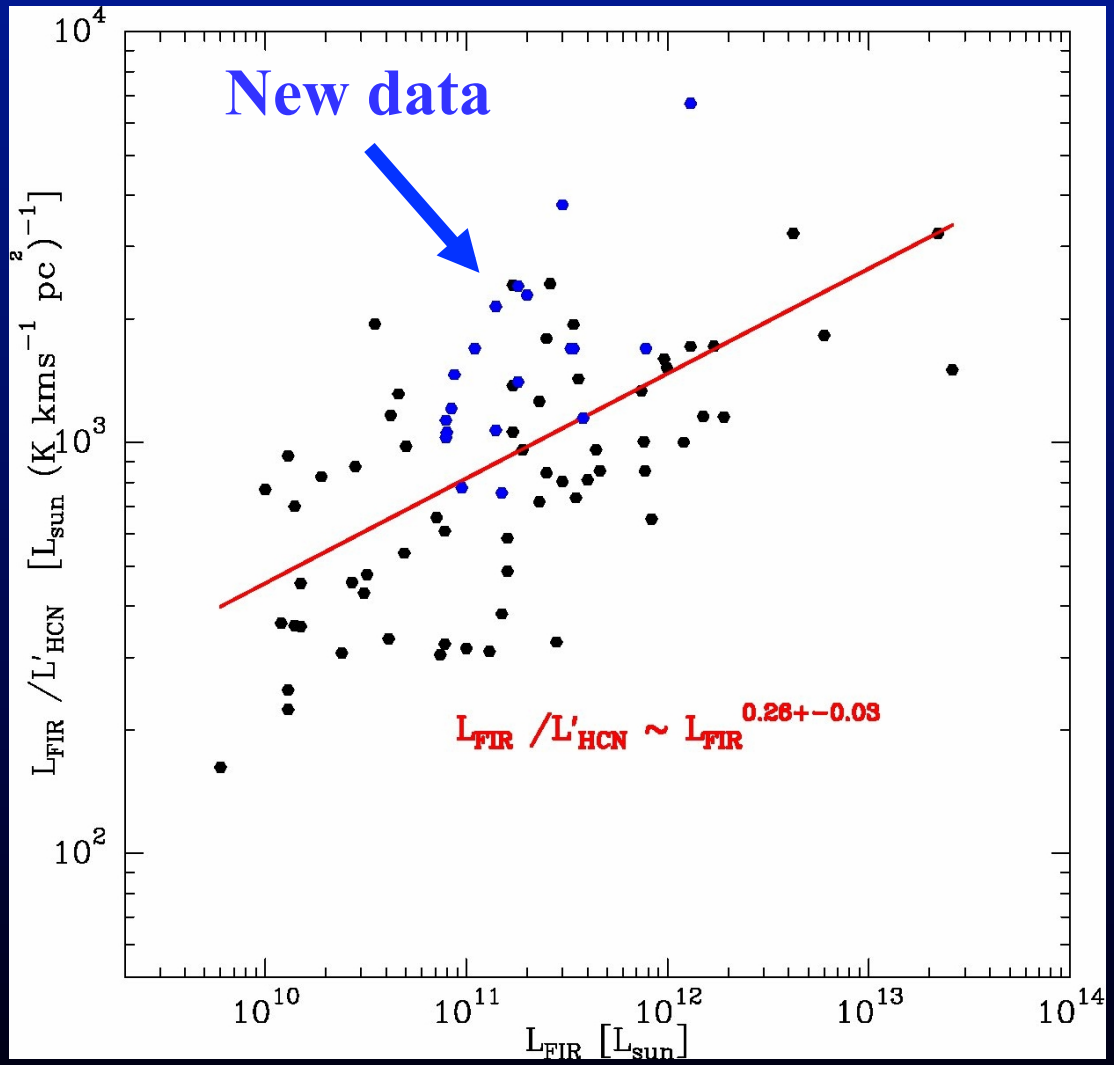
García-Burillo et al. 2010, in prep



New data confirm enhanced SFE_{dense} in LIRGs

Star Formation Efficiency: SFE_{dense}

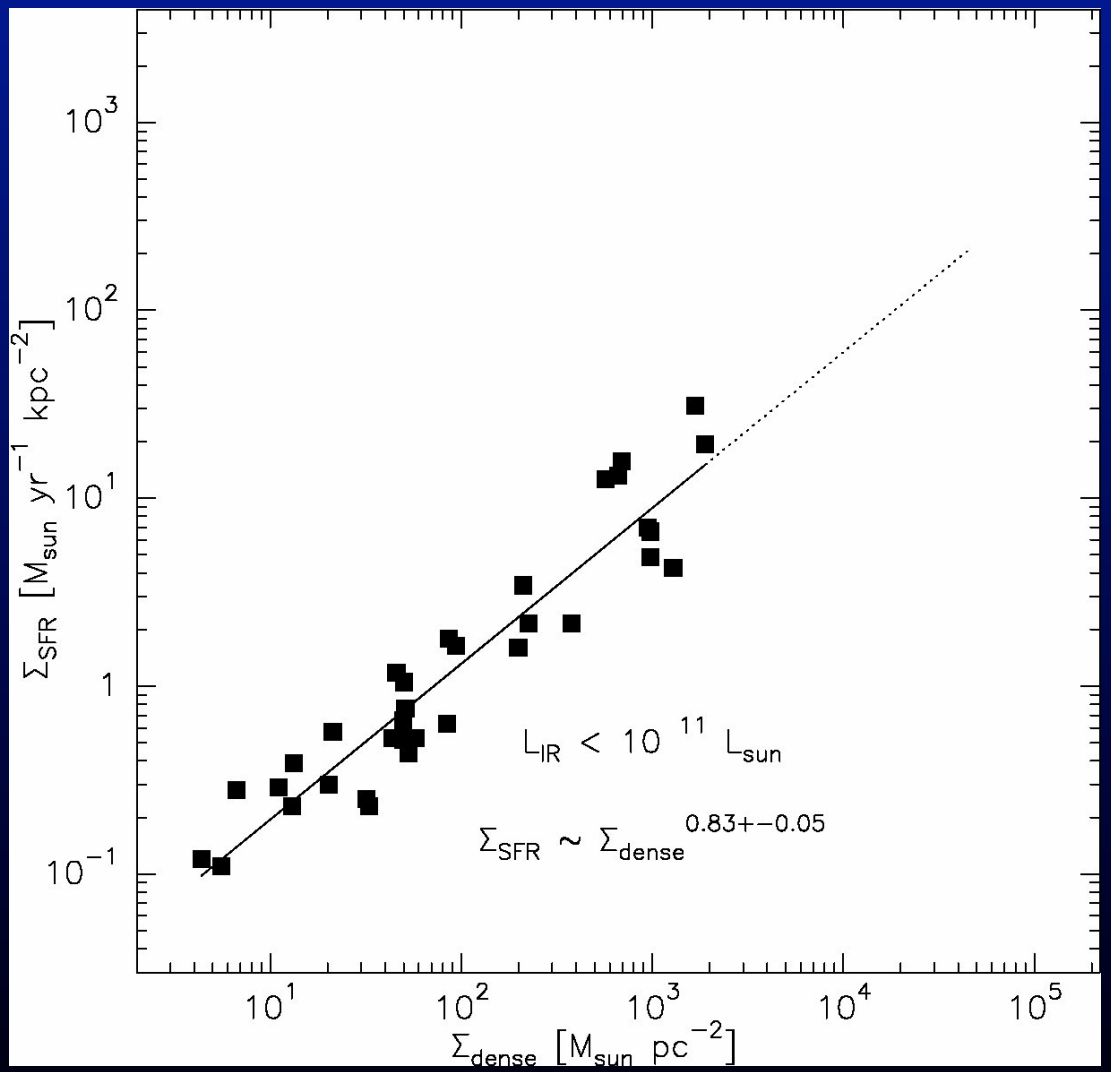
García-Burillo et al. 2010, in prep



$SFE_{dense} = L_{FIR}/L_{HCN} \neq$ constant but $\sim L_{FIR}^{n}$, n ~ 0.25 (+/-0.03)

KS Laws for Dense Gas

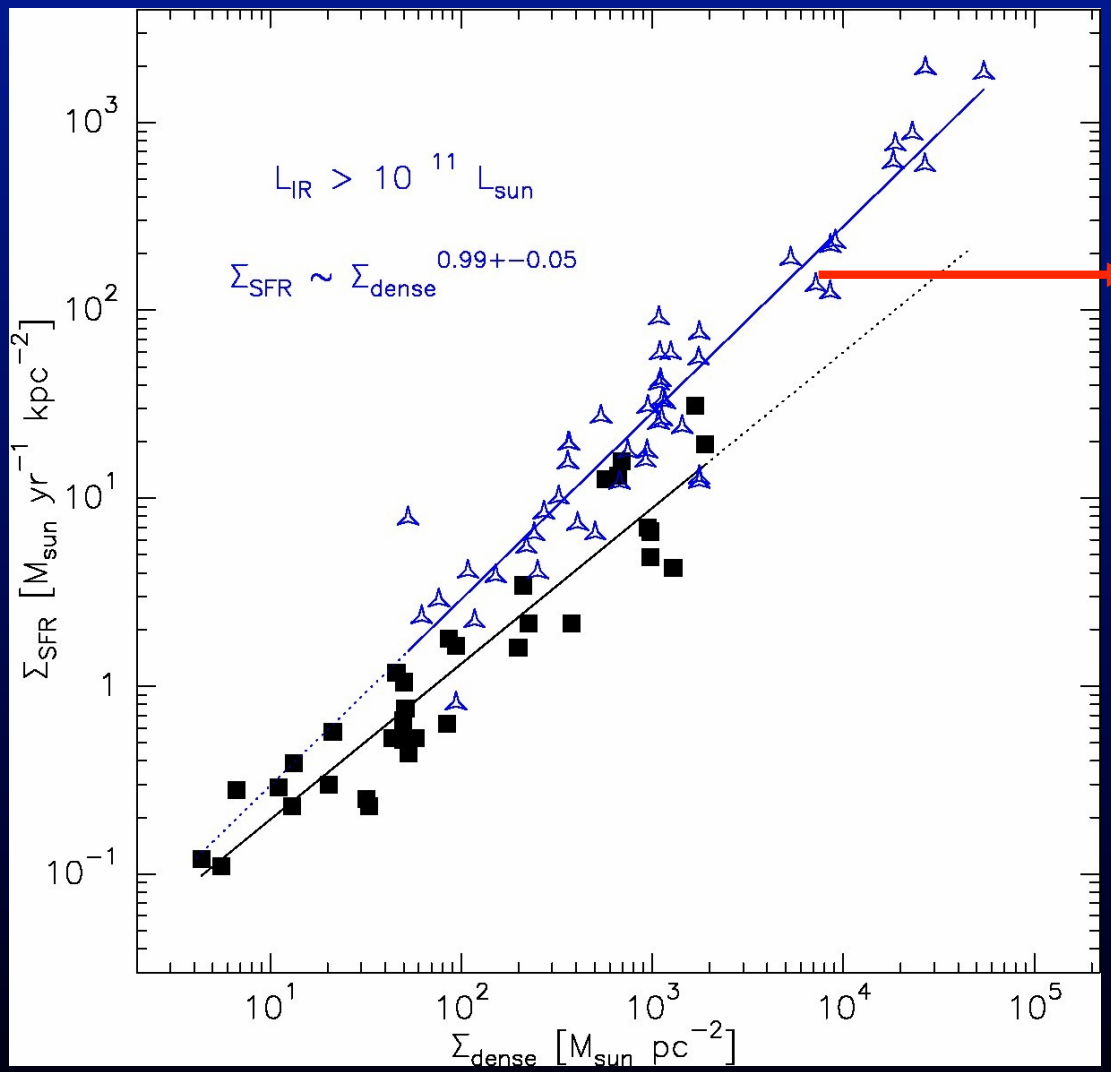
García-Burillo et al. 2010, in prep



$\Sigma_{SFR} \sim \Sigma^{n}_{dense}$, **n~0.8** (+/- 0.05) for **'normal'** galaxies

KS Laws for Dense Gas

García-Burillo et al. 2010, in prep



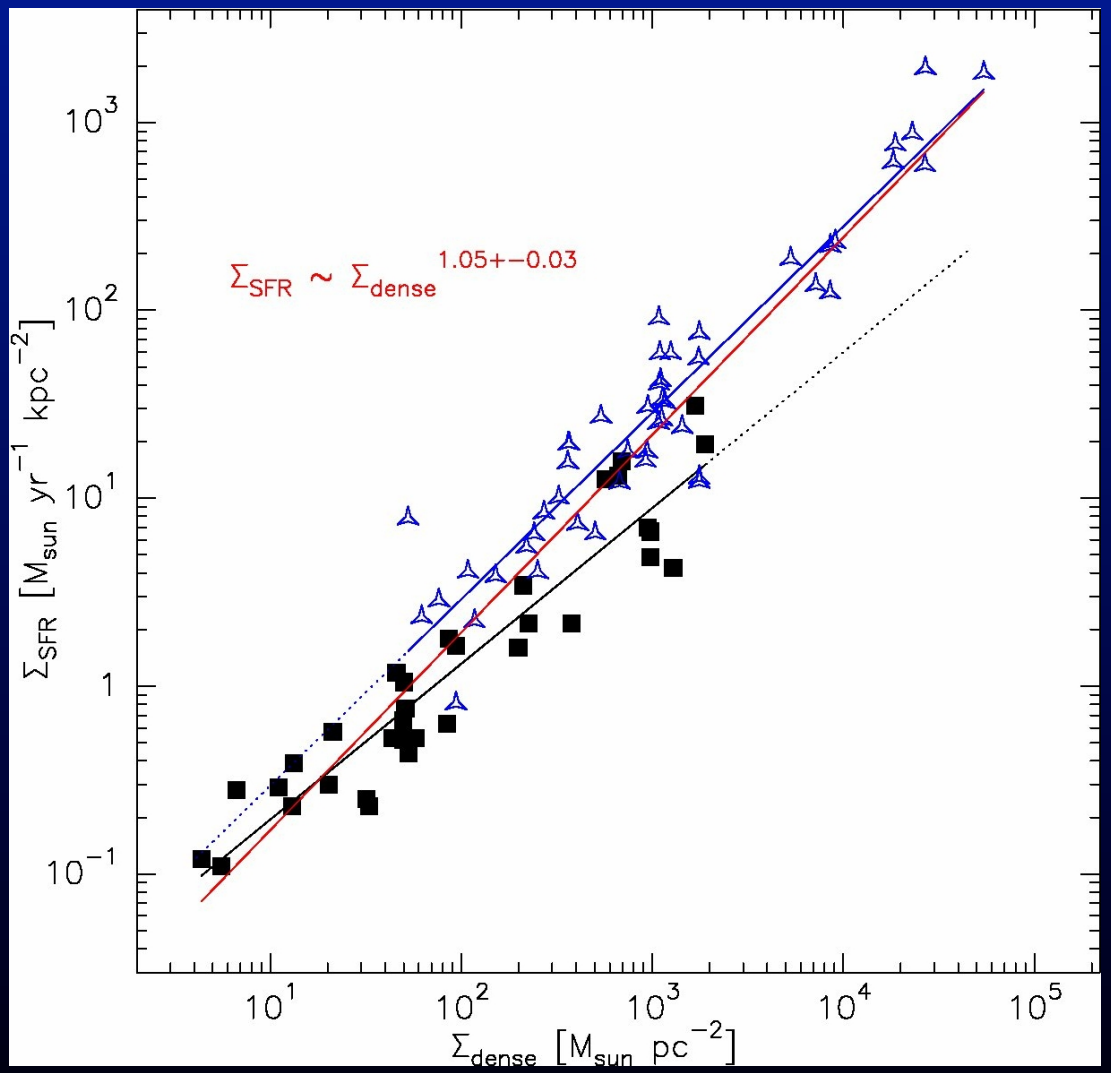
´normal´ vs ´IR luminous´

bimodality?

$\Sigma_{SFR} \sim \Sigma^{n}_{dense}$, n~1.0 (+/- 0.05) for <u>'LIRGs/ULIRGs'</u>

KS Laws for Dense Gas

García-Burillo et al. 2010, in prep



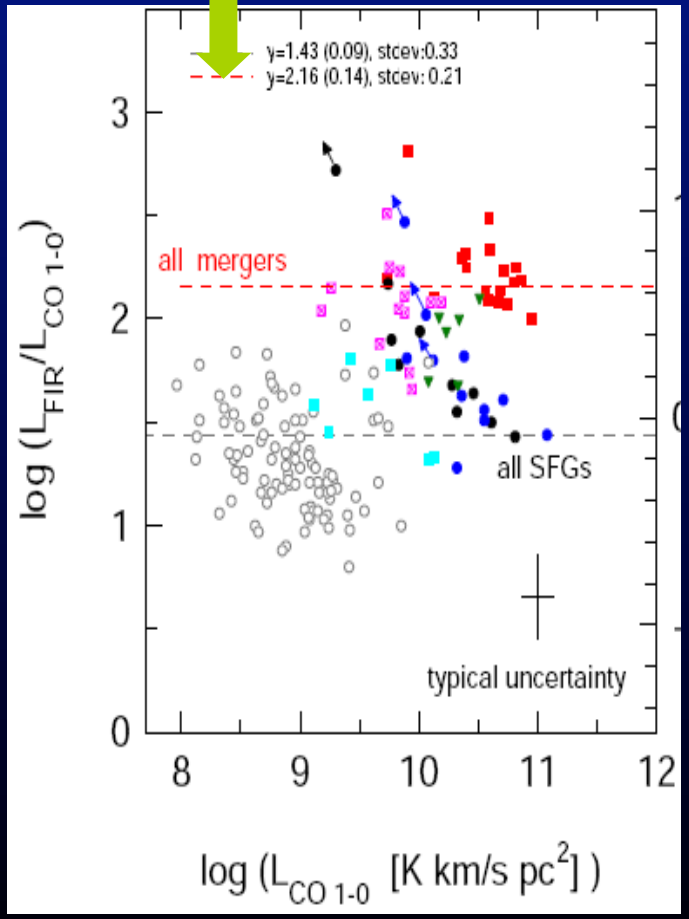
$\Sigma_{SFR} \sim \Sigma^{n}_{dense}$, **n~1.1 (+/- 0.03)** global fit

SF Laws in Galaxies: Bimodality?

´extreme´ SB (mergers) versus ´normal´ SF galaxies

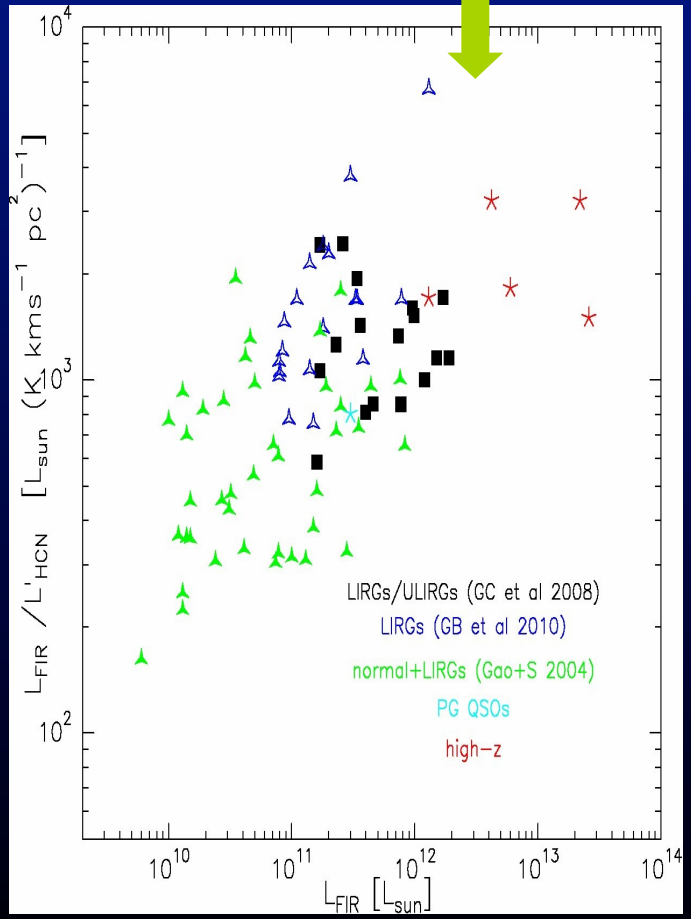
SFE (mergers) ~ (5-6) x SFE (normal)

CO → **(mol. gas)**



Genzel et al. 2010

SFE$_{dense}$ (mergers) ~ 3 x SFE$_{dense}$ (normal)



← **HCN** **(dense mol. gas)**

García-Burillo et al. 2010, in prep

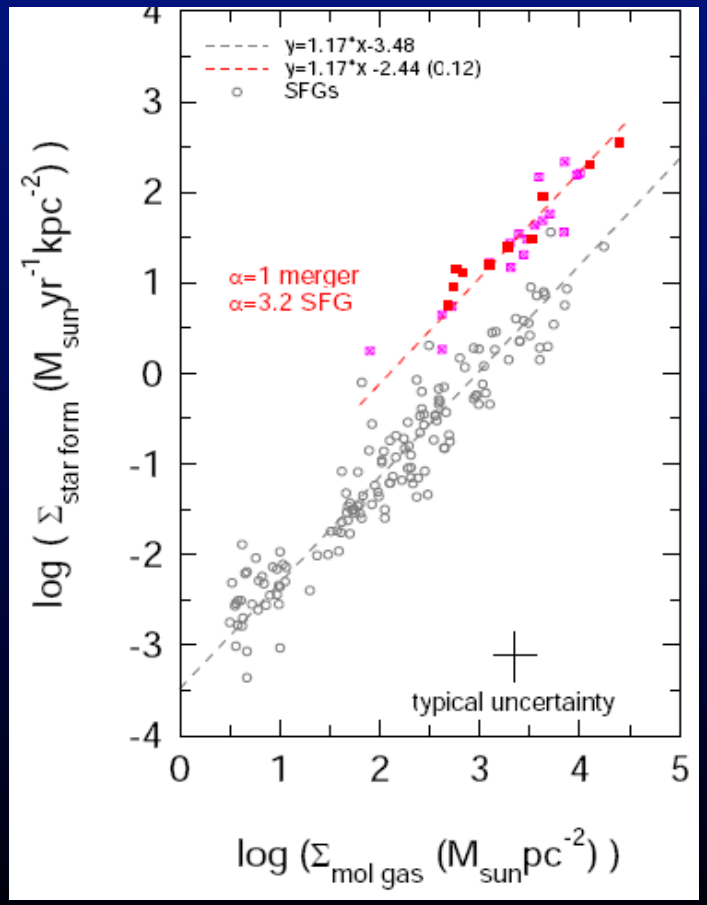
SF Laws in Galaxies: Bimodality?

'extreme' SB (mergers) versus 'normal' SF galaxies

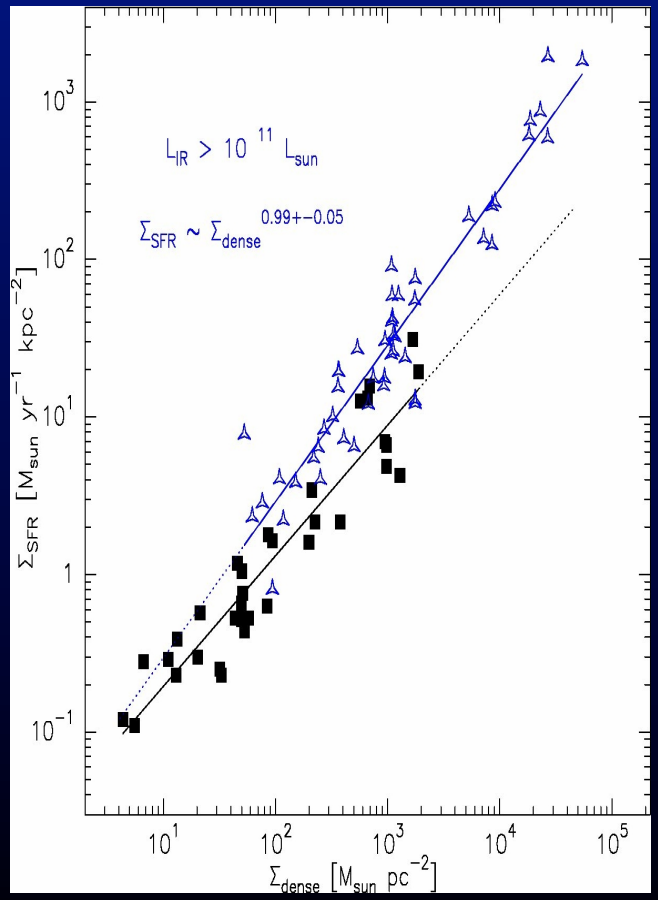
Σ_{SFR} *(mergers) ~ 10 x* Σ_{SFR}*(normal), for a given* Σ_{gas}

Σ_{SFR} *(mergers) ~ 3 x* Σ_{SFR}*(normal), for a given* Σ_{dense}

CO → **(mol. gas)**



Genzel et al. 2010

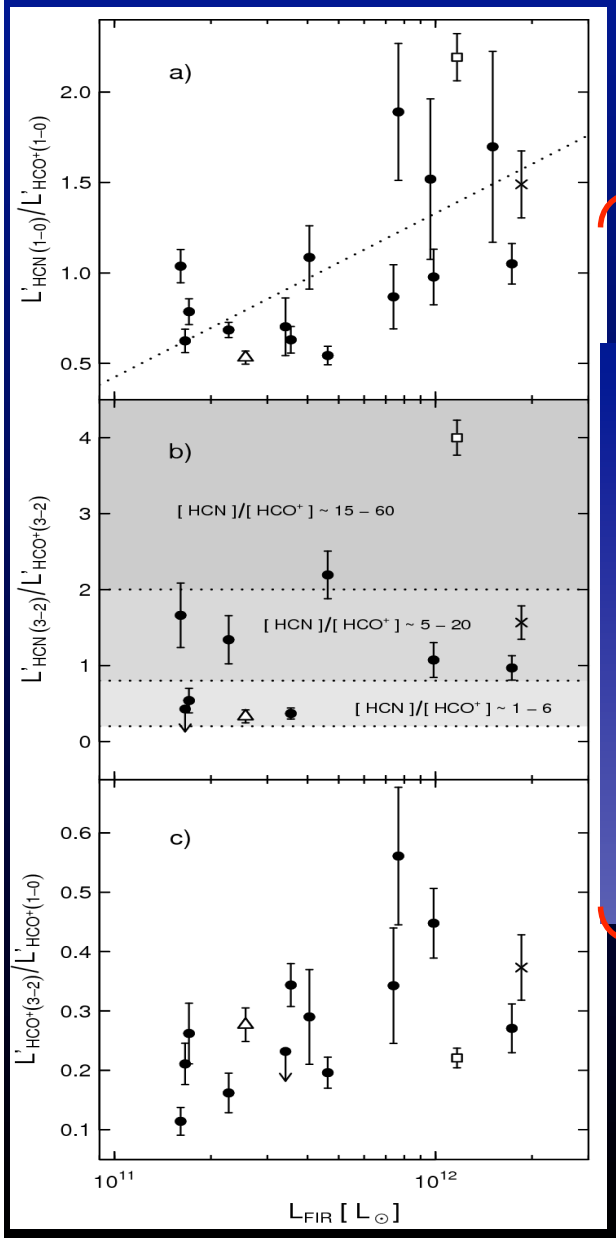


García-Burillo et al. 2010, in prep

← **HCN** **(dense mol. gas)**

Conversion Factors: X_{HCN} and SFE_{dense}

Graciá-Carpio et al. 2008



Extension of HCN + HCO^+ -survey to J=3-2 lines

LVG models

One phase

[HCN]/[HCO^+] > 5-10
in most ULIRGs

HCN 'overabundance'

Two phases

I $n_{H2}=10^5$ cm^{-3}, T=80K, [HCN]/[HCO^+] ~10^3
II $n_{H2}=10^4$ cm^{-3}, T=25K, [HCN]/[HCO^+] ~1

[HCN]/[HCO^+] ~1 for LIRGs and ULIRGs!

HCN 'overabundance' vanishes!

In either case:

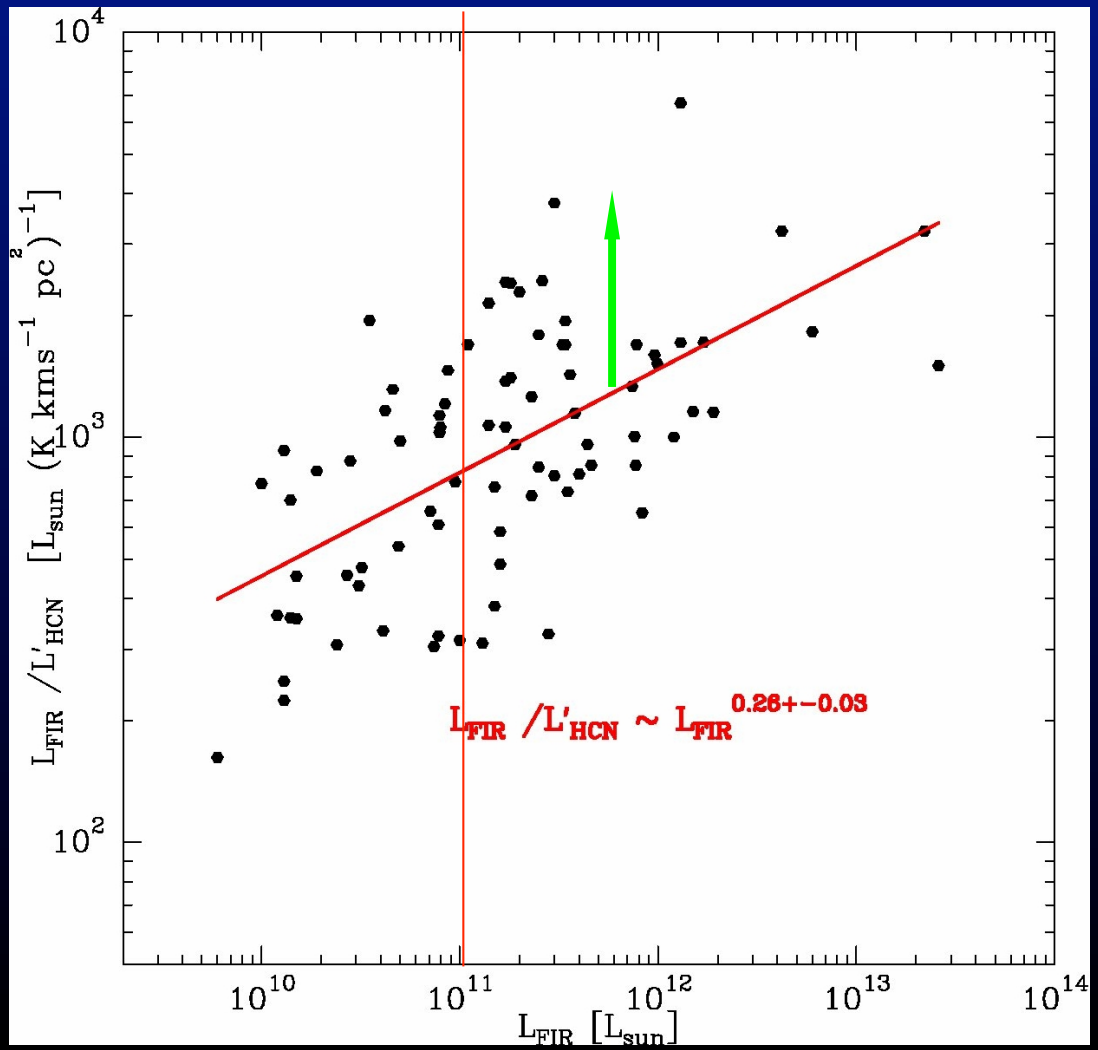
X_{HCN}(LIRGs) ~ 3-5 x X_{HCN}(ULIRGs)

Conversion Factors: X_{HCN} and SFE_{dense}

Graciá-Carpio et al. 2008

X_{HCN}-conversion factor may be 3-5 times lower at high L_{FIR}!!

$SFE_{dense}=SFR/M_{dense}$ **changes** by a factor ~3x(3-5) ~**10** from 'normal' to 'extreme'

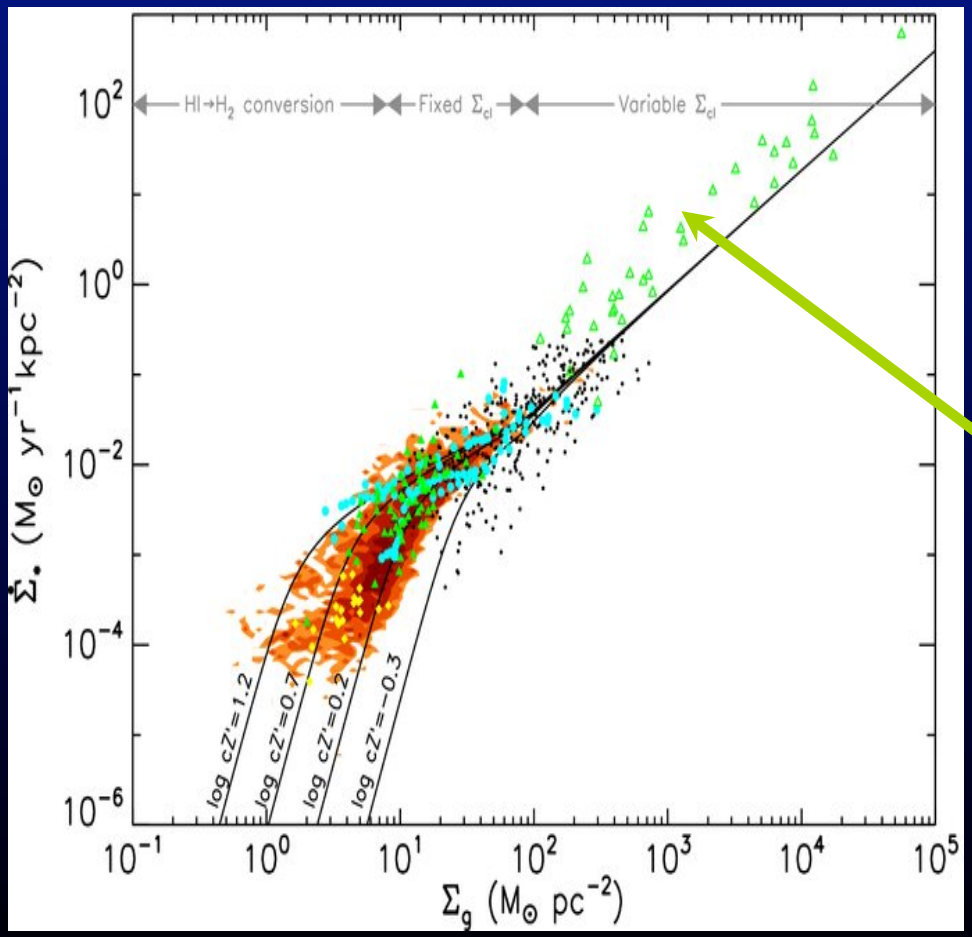


Models *versus* Observations

Krumholtz et al. 2008, 2009

➡ Analytic model for a 'universal' SF law:

- HI/H_2 fraction
- Properties of GMCs
- SFE $= SFR_{ff}/t_{ff}$



Krumholtz et al. 2009

➡ CO-based SF laws *vs* model

Good agreement for 'normal' SFG

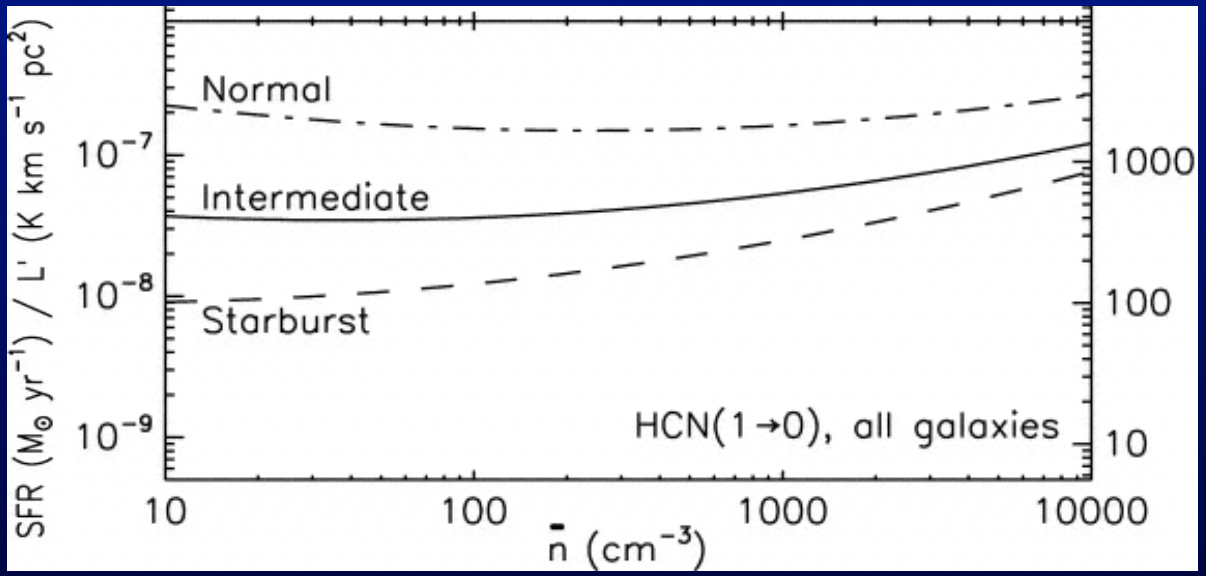
Σ_{SFR} in 'extreme' SB

underpredicted!

Models *versus* Observations

Krumholtz et al. 2007 ; García-Burillo et al. 2010, in prep

➡ ***Models underpredict SFE_{dense} derived from HCN in 'extreme' SBs!***



Krumholtz et al. 2007

➡ Failure of models suggest SF in **'extreme' SBs** (LIRGs/ULIRGs/SMGs) are driven by **large-scale dynamical effects** *(see, e.g., Genzel et al 2010)*

CONCLUSIONS

- **Observational evidence of bimodality in SF laws:**
  ´normal´ SF galaxies (SFG) vs ´extreme´ SB (LIRGs/ULIRGs/SMGs)

- **CO/HCN data suggest SFE and Σ_{SFR} enhanced in ‘extreme’ SB**

- **Models fall short to account for SF laws in ‘extreme’ SB**

CONCLUSIONS

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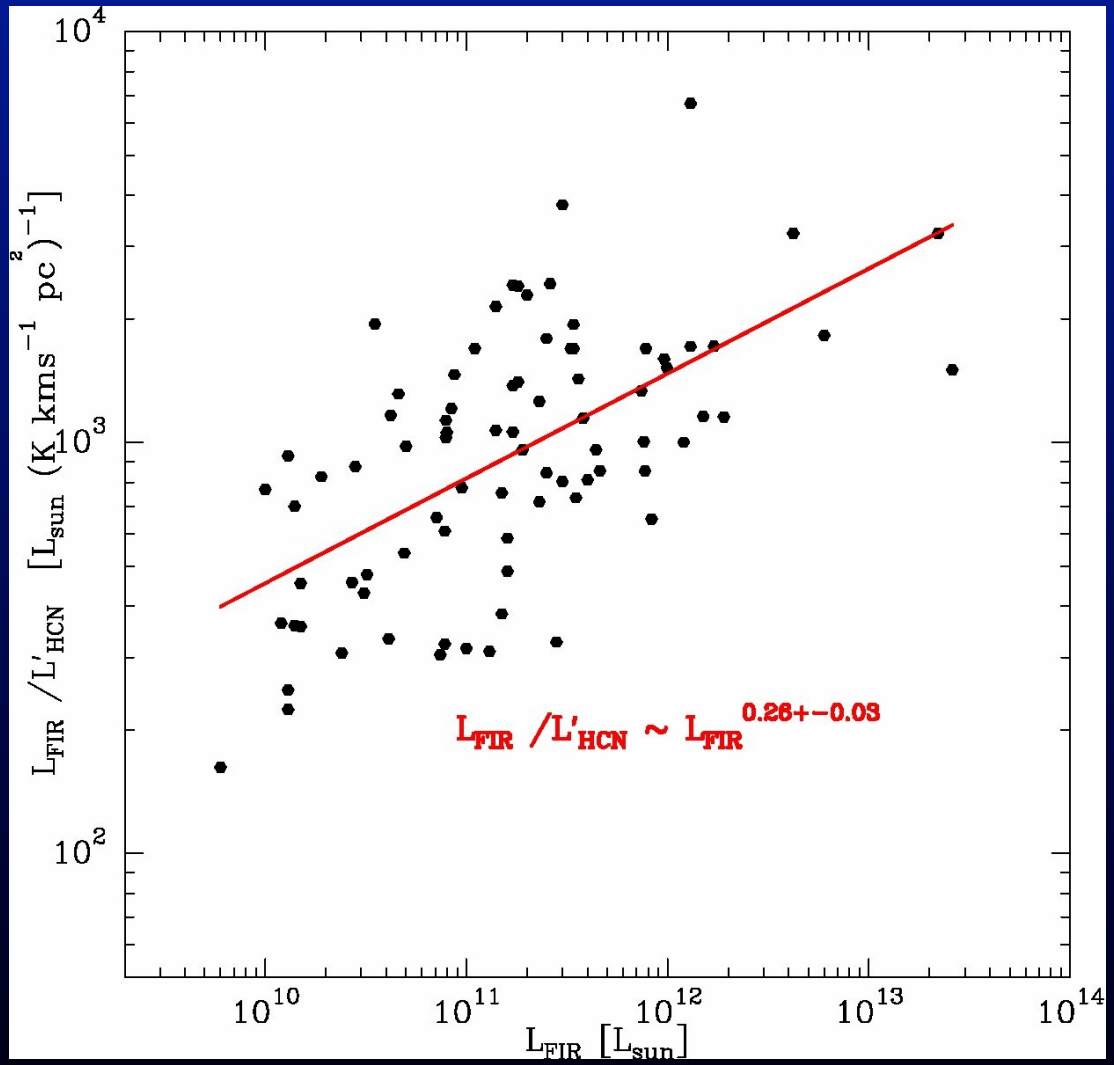
- **Models fall short to account for SF laws in 'extreme' SB**

Future directions…

- *Multiline studies of molecular gas (CO, HCN,…,HCO^+)*
  - *-constrain ($n(H_2)$, T_k) and I->$N(H_2)$ conversion factors*
- *Spatially resolved SF laws at ~100pc scales*
  - *-local normal galaxies*
  - *-local IR luminous galaxies*

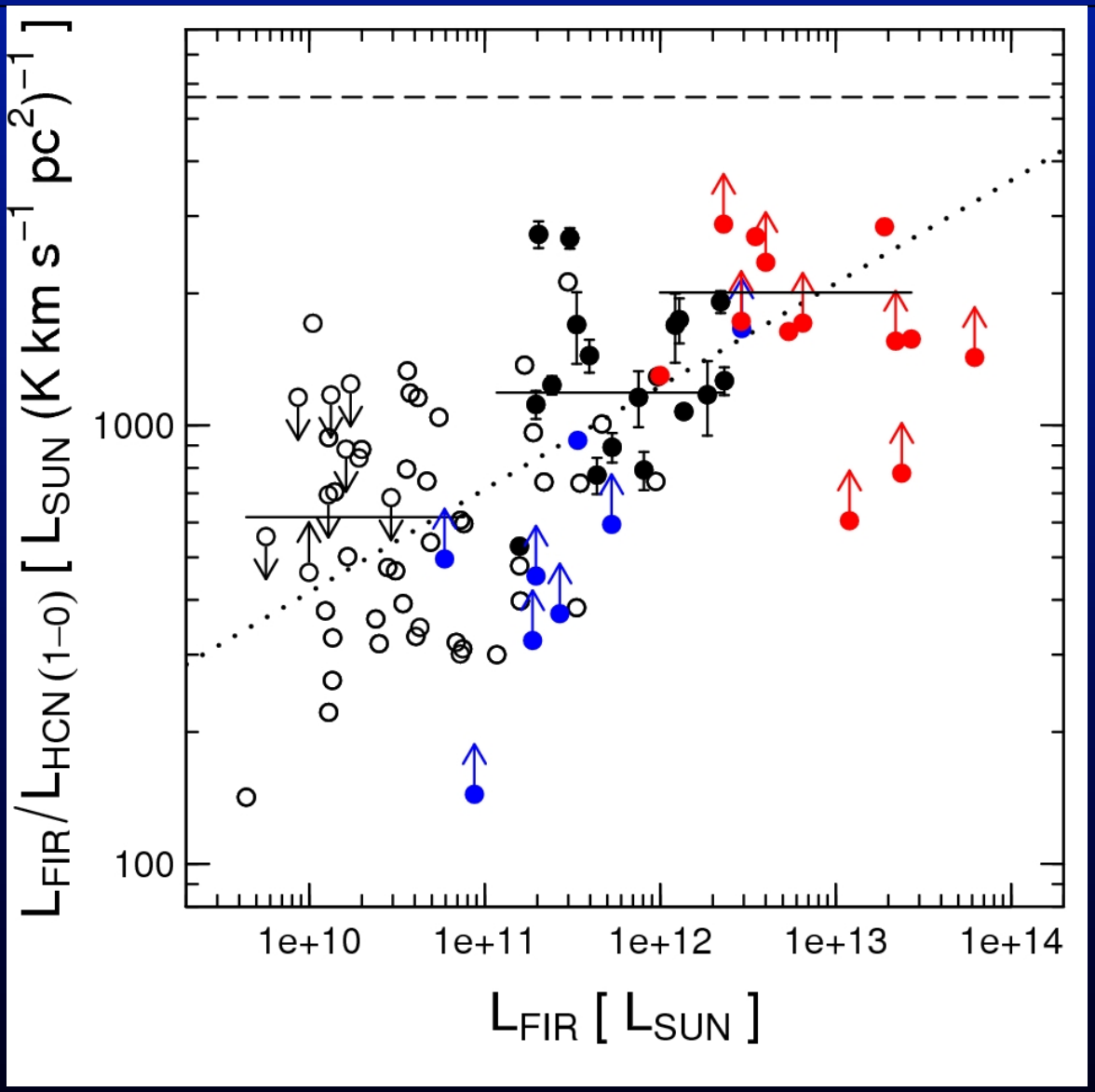
Star Formation Efficiency: SFE_{dense}

García-Burillo et al. 2010, in prep



$SFE_{dense} = L_{FIR}/L_{HCN} \neq$ constant but $\sim L_{FIR}^{n}$, n ~ 0.25 (+/-0.03)

The SFE law: from z=0 to high-z galaxies



A higher SFE in ULIGs/HyLIGS?

or

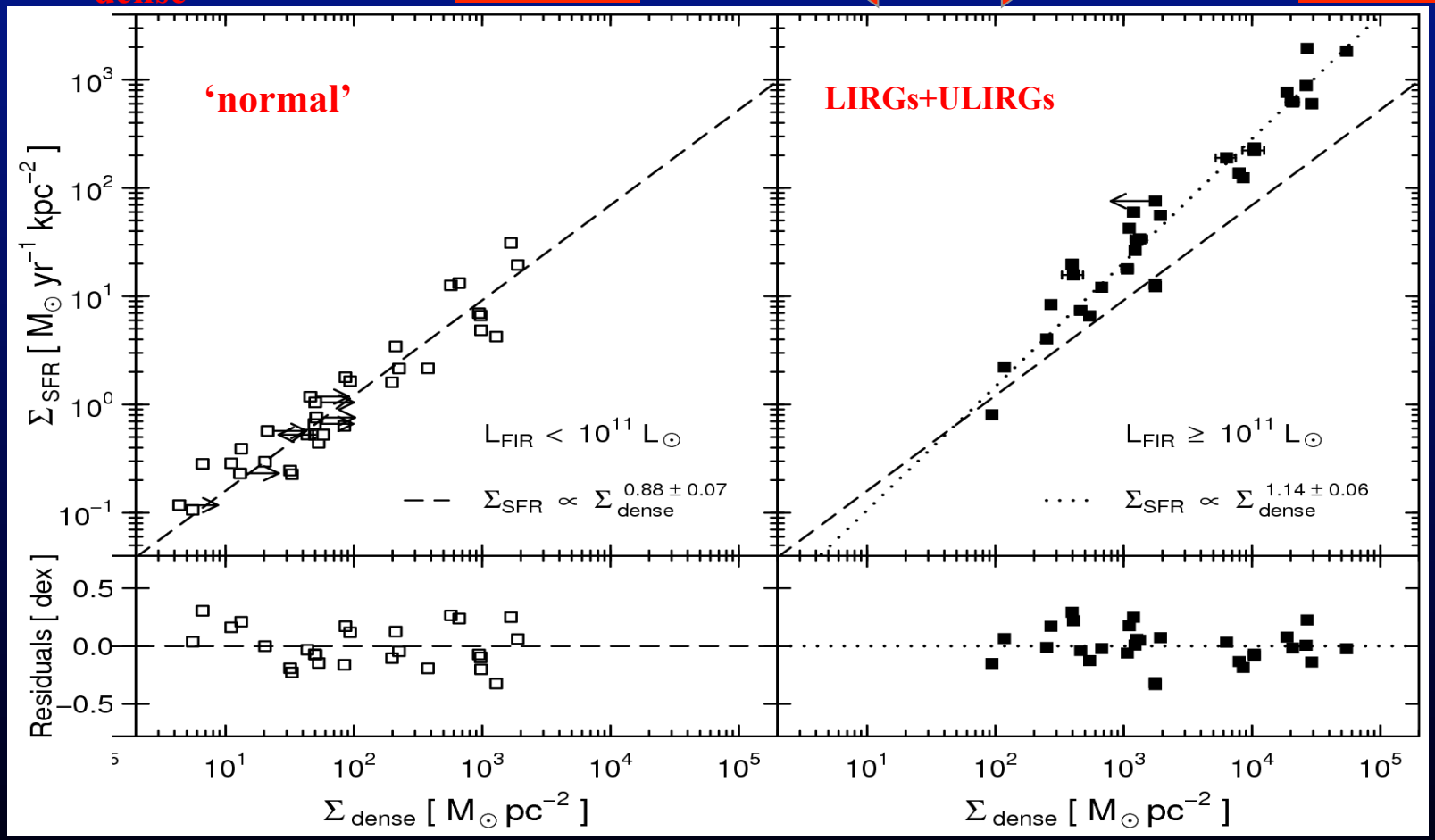
A contribution from embedded AGNs to L_{FIR}?

SF Laws in LIRGs/ULIRGs

Graciá-Carpio et al. 2008

Different SFE_{dense} imply significant turn upward in KS law at high L_{FIR}

$\Sigma_{SFR} \sim \Sigma^{n}_{dense}$, **n~0.9** for **'normal'** galaxies ⟷ **n~1.2** for **LIRGs/ULIRGs**

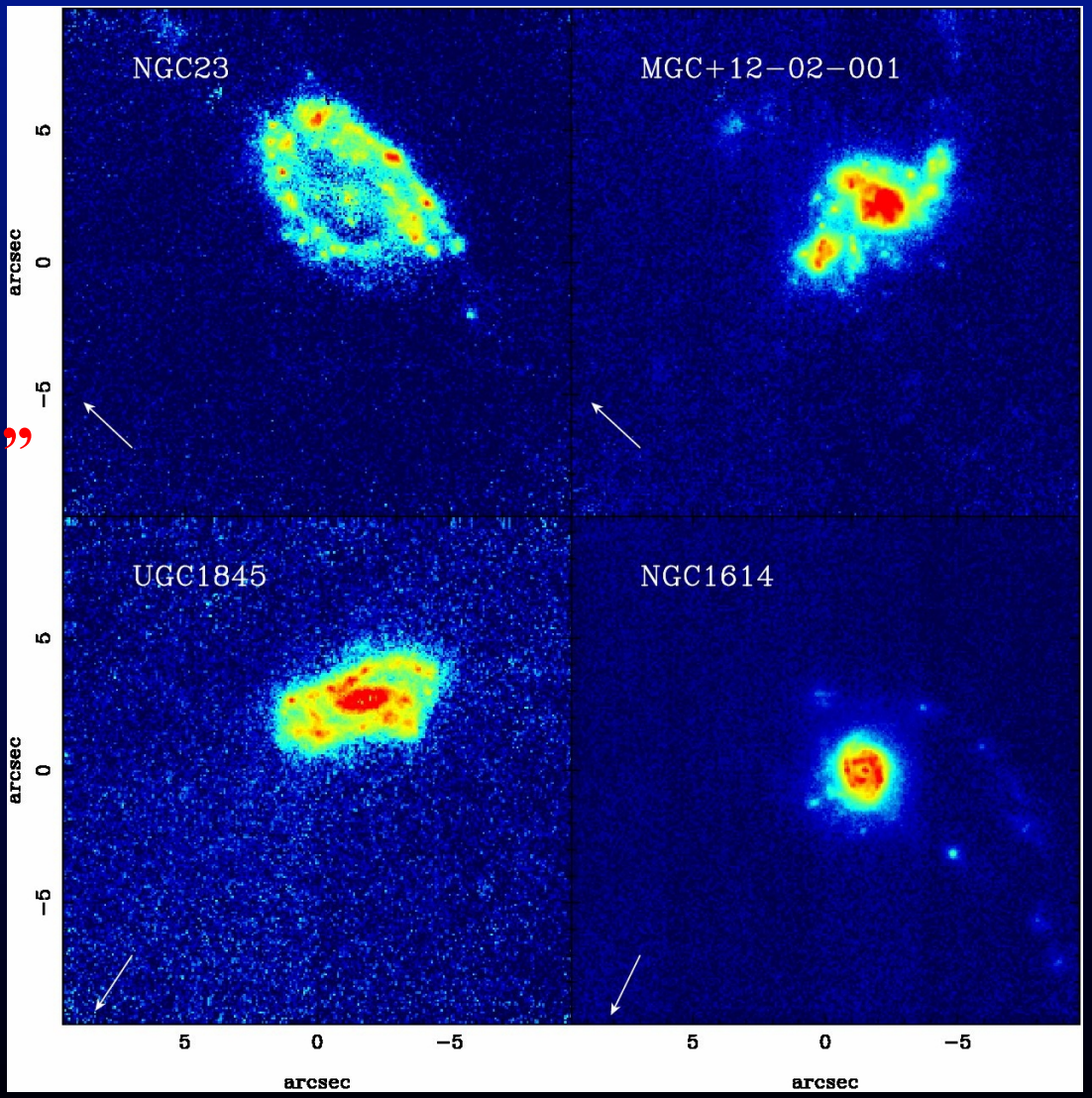


These results confirm predictions of *Krumholz & McKee*´s SF models

LIRGs: a new sample

HST NICMOS Paα images of LIRG sample

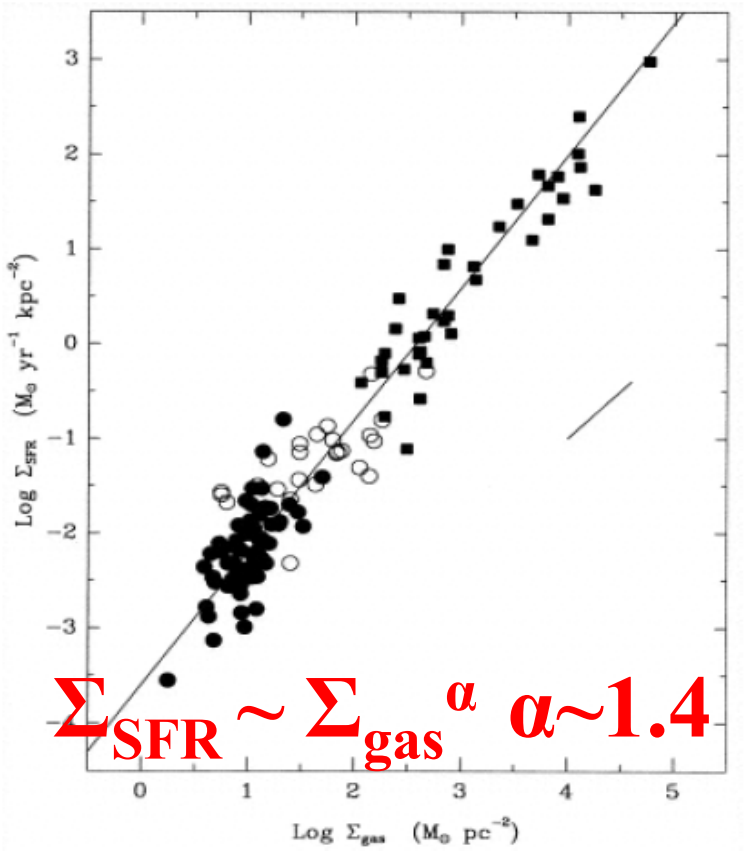
FOV~19”



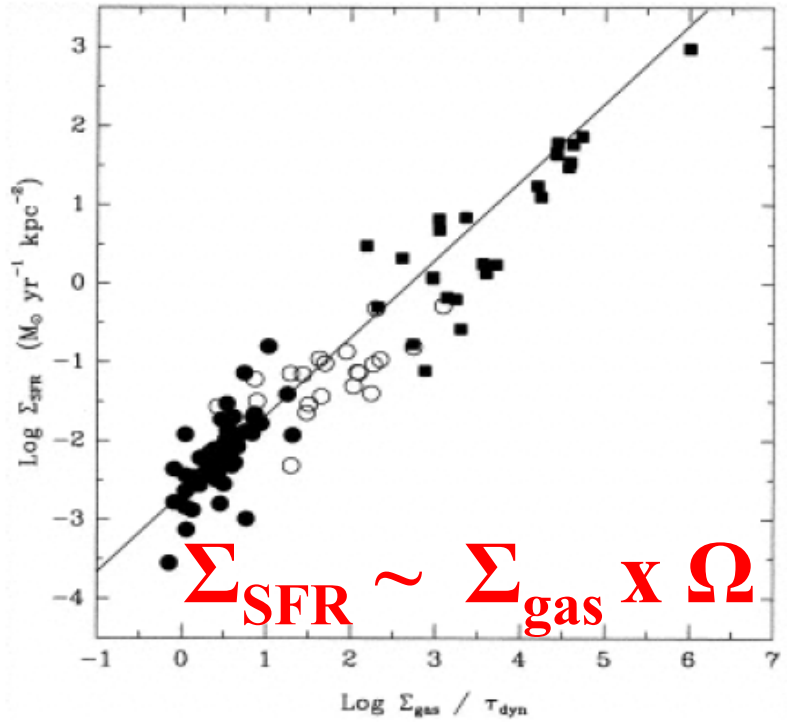
Alonso-Herrero et al. 2006

SF Laws: Scaling Relations

Kennicutt 1998



$\Sigma_{SFR} \sim \Sigma_{gas}^{\alpha}$ $\alpha \sim 1.4$



$\Sigma_{SFR} \sim \Sigma_{gas} \times \Omega$

"Schmidt law":
SFR vs gas density power law

"Silk law":
SFR vs gas density/dynamical time

SF Laws: Scaling Relations

Bouché et al 2007