What drives the [CII]/FIR deficit in dusty, star-forming galaxies?

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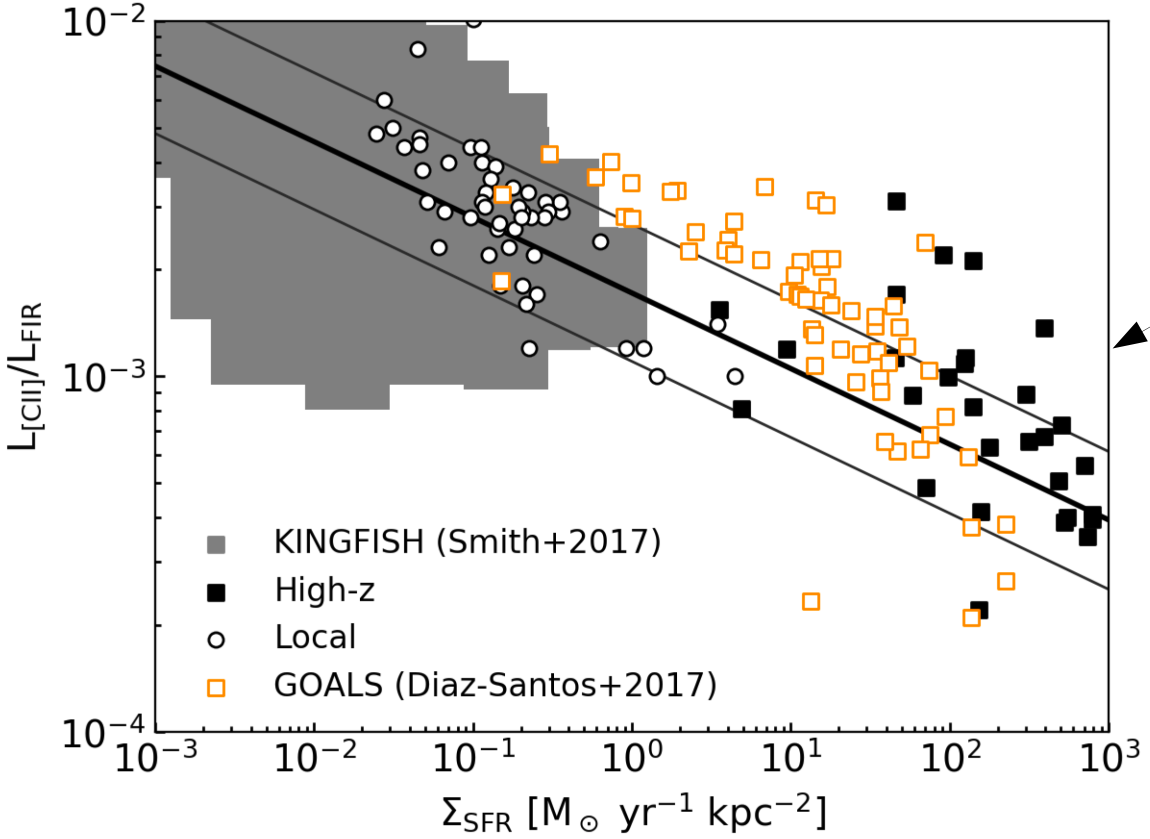
[CII] 158 um – bright, but what does it trace?

[CII] 158 um

- Main cooling line of neutral ISM
- Extremely bright: L_{CII} ~ up to 1% of L_{FIR}
- Workhorse line at z>5: low-J CO difficult to detect due to high T_{CMB}
- (e.g. daCunha+2013)
- difficult to interpret: traces diverse environments: Cold/Warm Neutral medium, HII regions, diffuse ionized gas…

- Local Universe: **[CII] – FIR (SFR) correlation**

[CII]/FIR deficit



Unresolved
Stacey+2010,
Gullberg+2015,
Spilker+2016,
Decarli+2017, …

Smith+2017:
[CII]/FIR~Σ_{SFR}

Smith+2017

Matched-resolution [CII]/CO/FIR study in z~3 DSFGs

- **Aim: compare [CII] to FIR (SFR tracer) and low-J CO (molecular gas tracer)**
- Target: [CII] + FIR, CO (3-2) at z=~2.2, 3.0
- Pre-requisites: redshift in the right range!
  - high-resolution ALMA imaging
  - NIR spectroscopy
- Selected 4 sources from the 99 DSFGs of the ALESS sample (ECDFS, Hodge+2013)
- CO(3-2) in Band 3, [CII] & FIR in Bands 8/9
- Matched-resolution to 0.5”

Matched-resolution [CII]/CO/FIR study in z~3 DSFGs

- **CO(3-2)** observed at 0.7" resolution for all 4 sources → **Calistro-Rivera+2018**
- CO(3-2) vs 870-um continuum stacking: FIR continuum ~3 more compact than CO(3-2) → **evidence for T_{dust} and optical depth**

- **[CII]** observed only for ALESS 49.1 & 57.1 (z~2.94)→ **Rybak+2019**
- On-source time: ~11 min per target
- Resolution: ~0.15" (**~1 kpc @ z=3**), LAS ~ 2.0"

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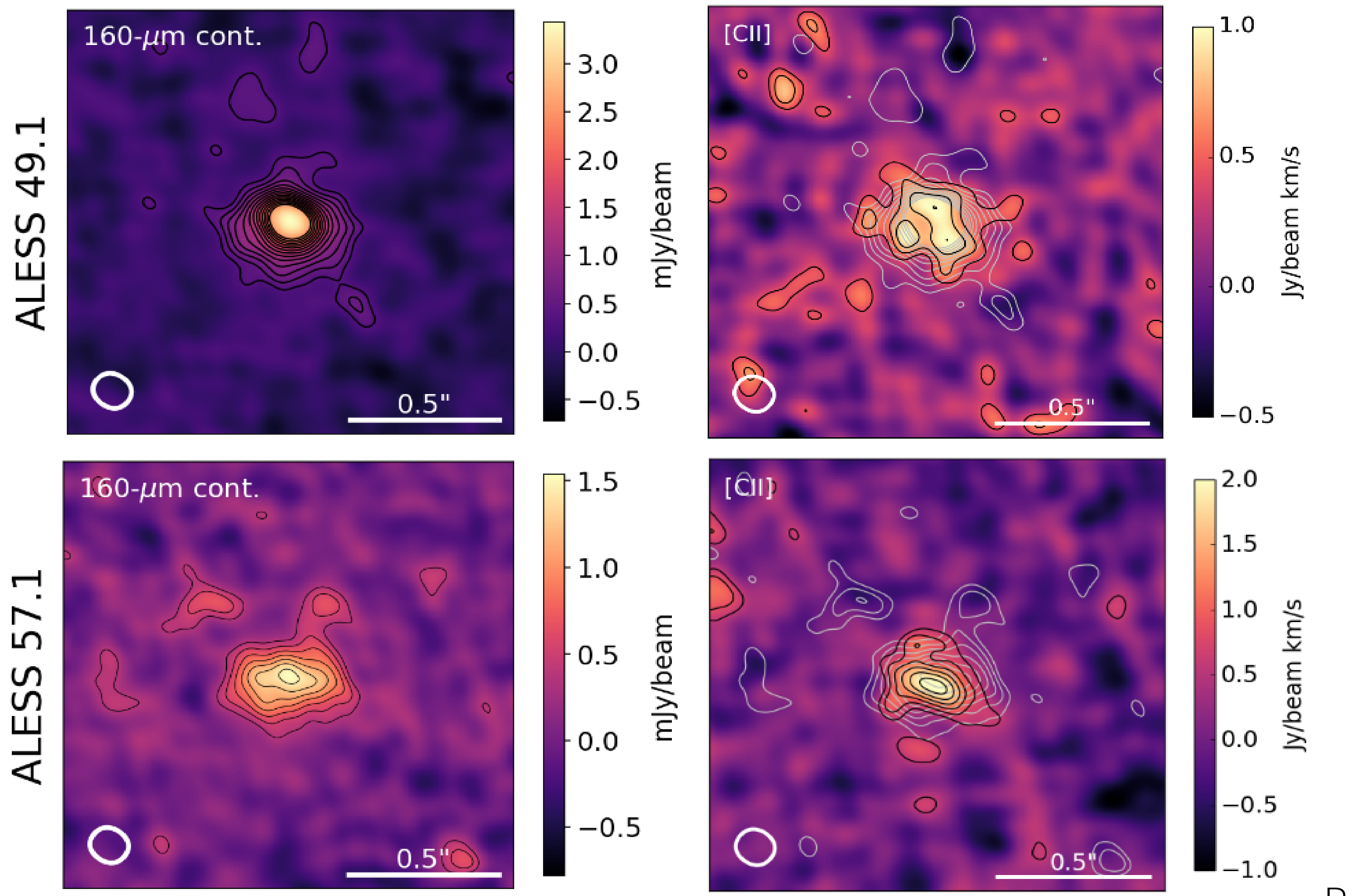
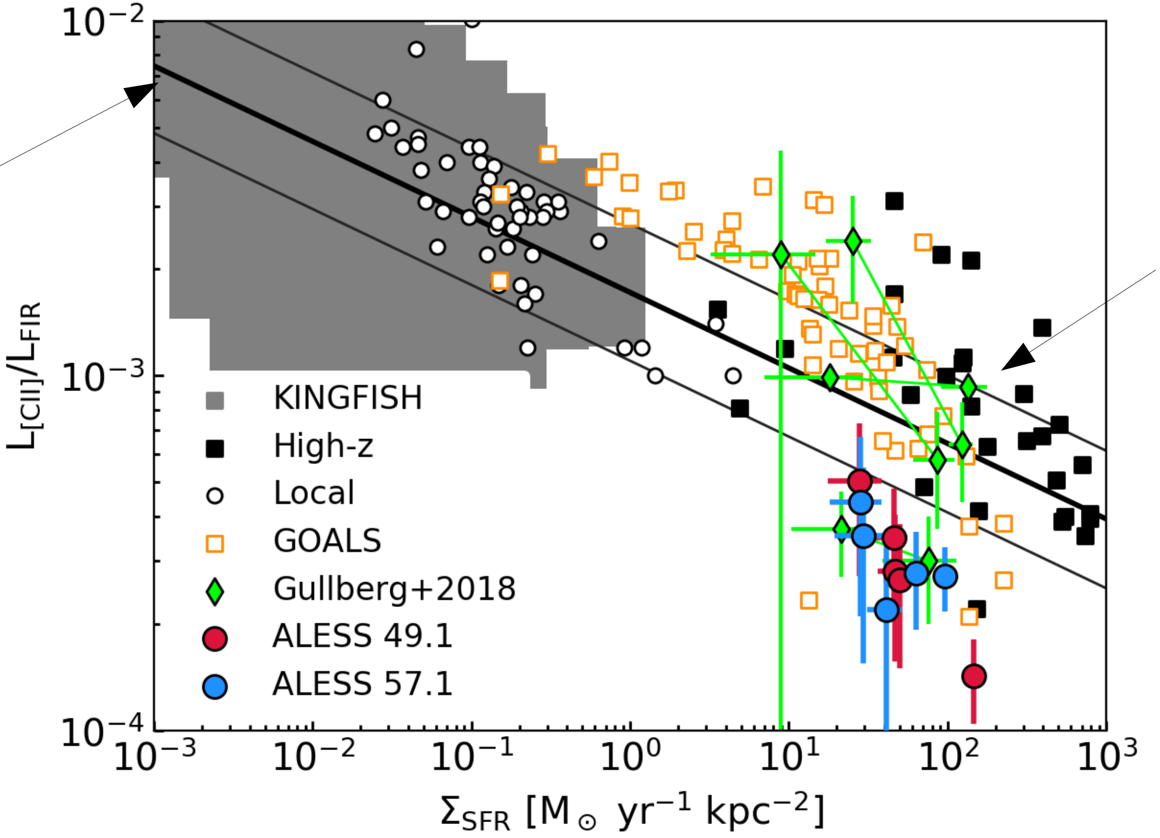
ApJ accepted 6:23 am


ALESS 49.1
160-μm cont.
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
mJy/beam
0.5"
[CII]
1.0
0.5
0.0
−0.5
Jy/beam km/s
0.5"
ALESS 57.1
160-μm cont.
1.5
1.0
0.5
0.0
−0.5
mJy/beam
0.5"
[CII]
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
Jy/beam km/s
0.5"

Rybak+2019

[CII]/FIR deficit on kpc-scales

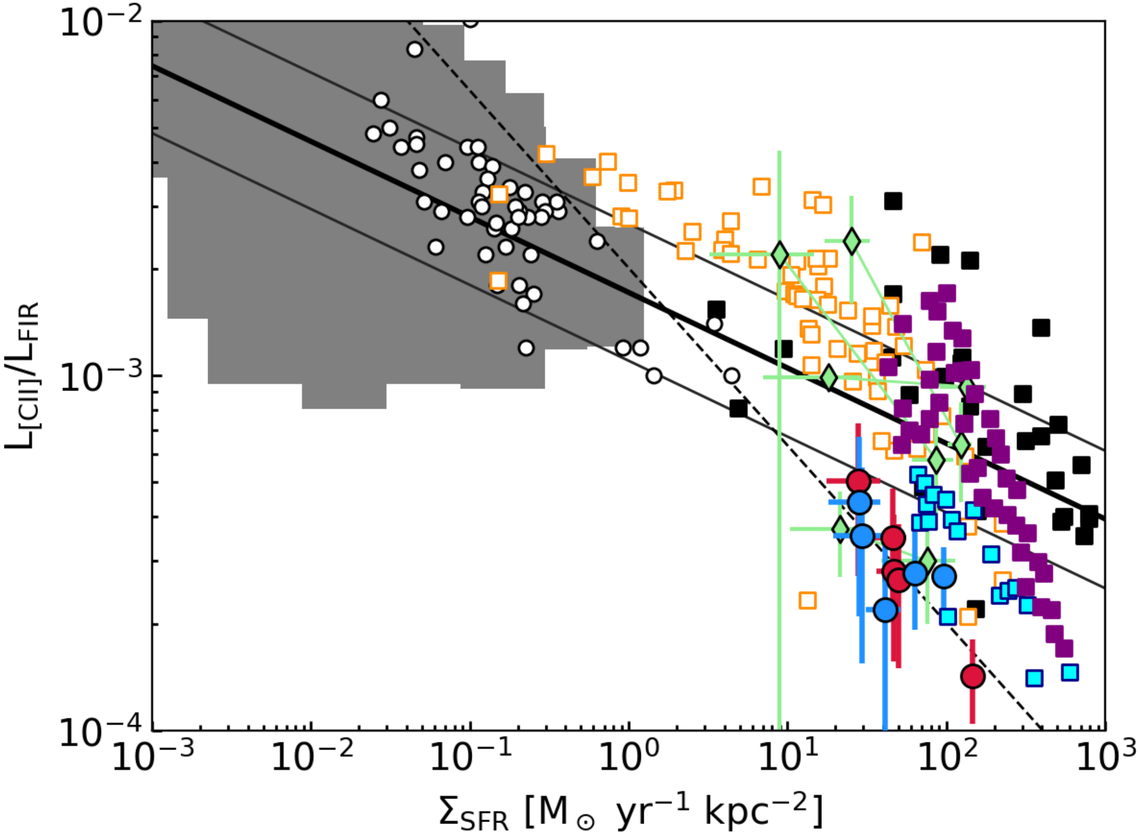
Smith+2017
Empirical trend



Gullberg+2018:
four z~4.5 SMGs
2 annuli per source

Rybak+2019

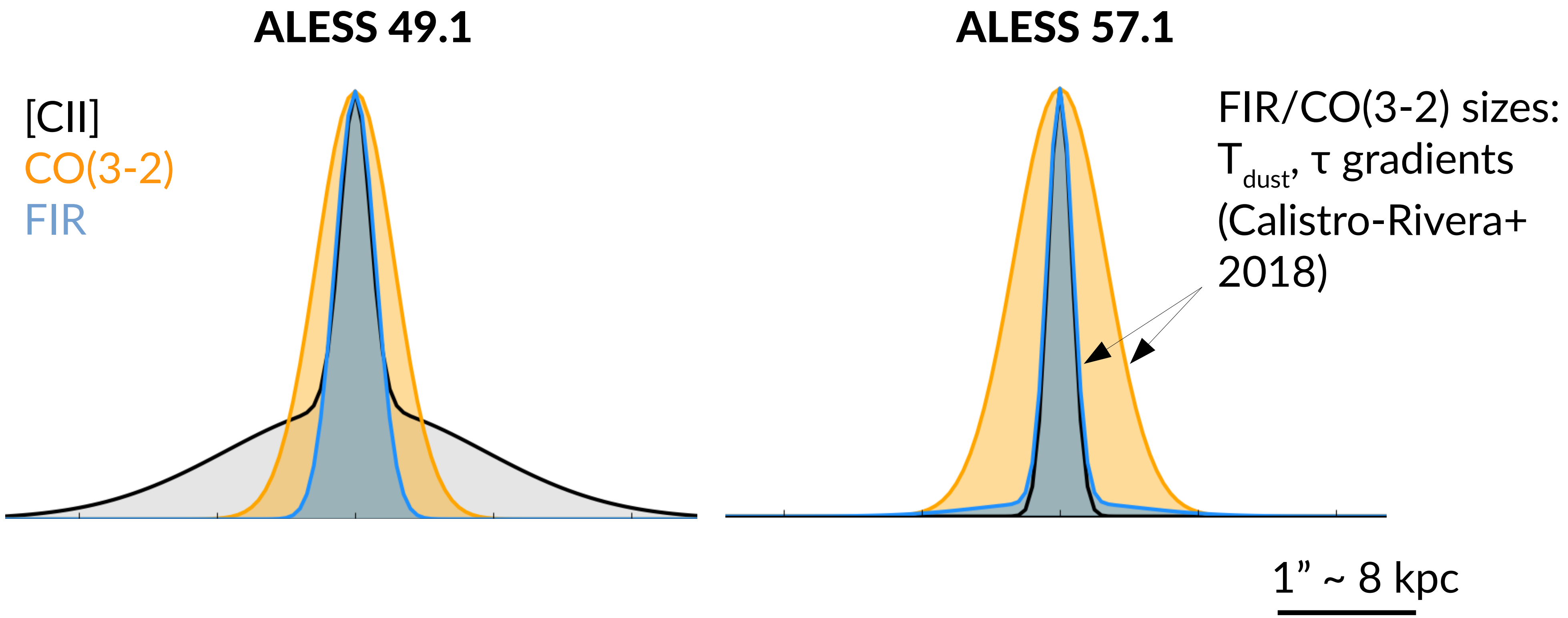
[CII]/FIR deficit on kpc-scales



Litke+2019
z~5.6

Lamarche+2018
z~1.7

Sizes from the uv-plane analysis



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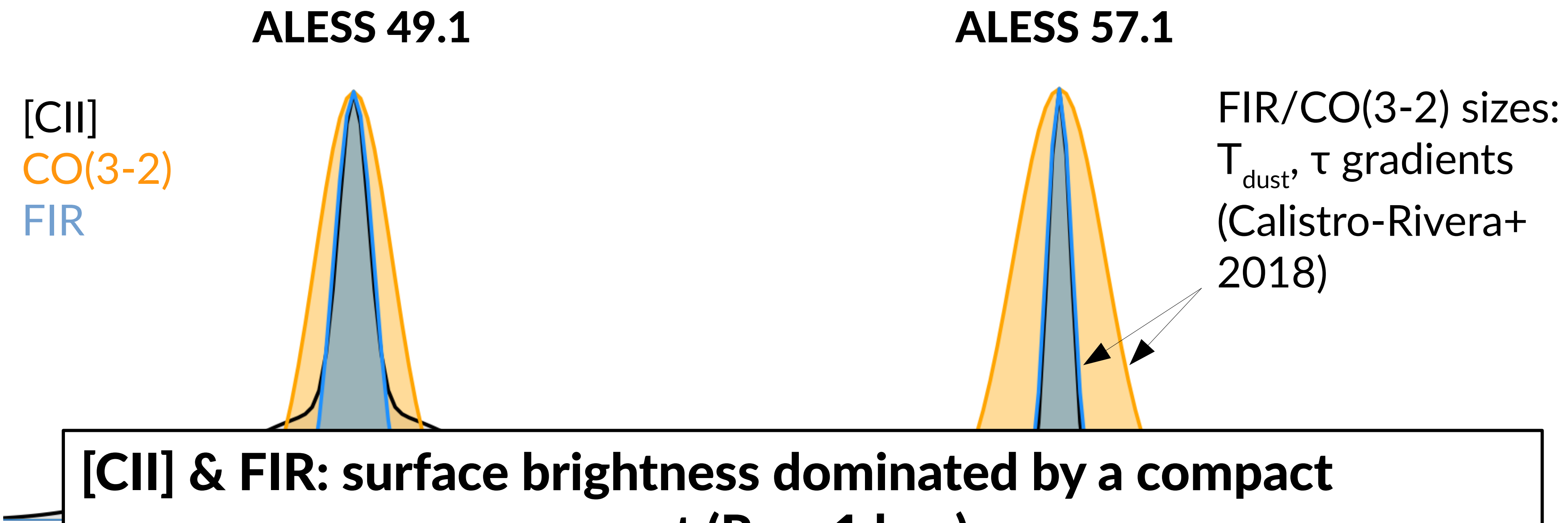


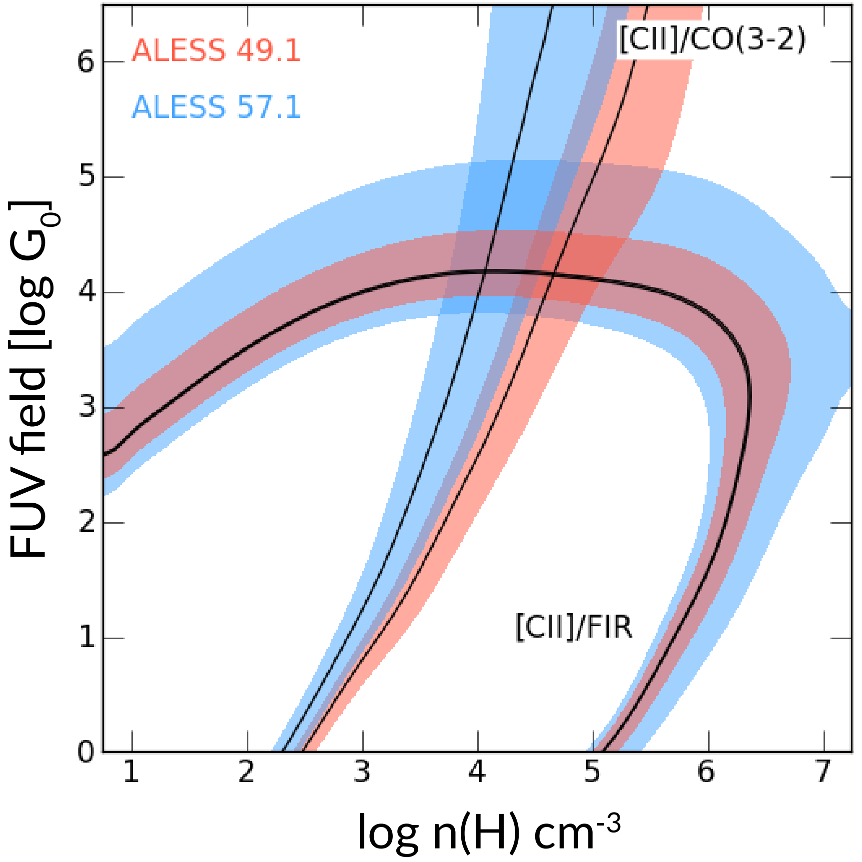
[CII] & FIR: surface brightness dominated by a compact component ($R_{1/2}$~1 kpc).

Extended [CII] emission in ALESS 49.1.

[CII]+CO+FIR → PDR modelling

- PDR Toolbox (Kaufman+2006, Pound&Wolfire 2008)
- considering only R<2 kpc
- [CII] optically thin, 80% contribution from PDRs
-

FUV field ~ 10^4 G_0
n(H) = 10^4-10^5 cm^{-3}
T_{PDR} = 400 – 700 K



Rybak+2019

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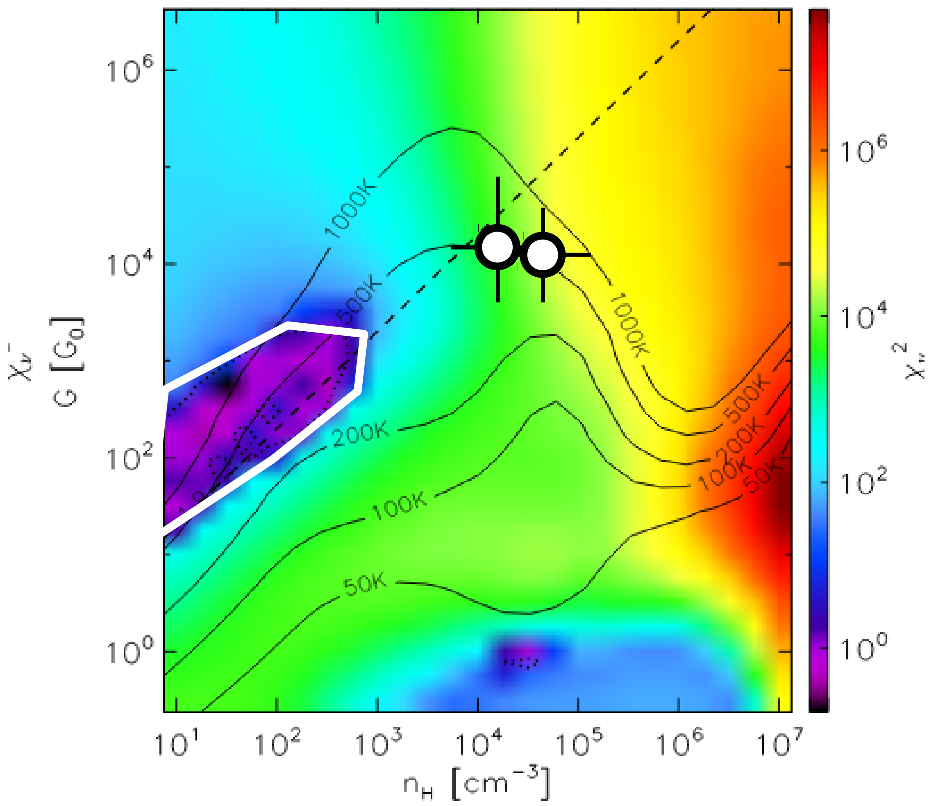
GOALS ULIRGs (Diaz-Santos+2017)



Strong FUV fields: [CII] thermally saturated

- T_{PDR} is >> [CII] transition temperature 91 K
- relative occupancy of the C^+ fine-structure levels saturates (Munoz&Oh 2016); FIR luminosity still increases with T_{dust}

[CII] cooling rate: $$\Lambda_{[\mathrm{CII}]} = 2.3 \times 10^{-6}\, k_\mathrm{B}\, T_{[\mathrm{CII}]} \frac{2}{2 + \exp(T_\mathrm{CII}/T_\mathrm{gas}) \frac{C}{H}}$$

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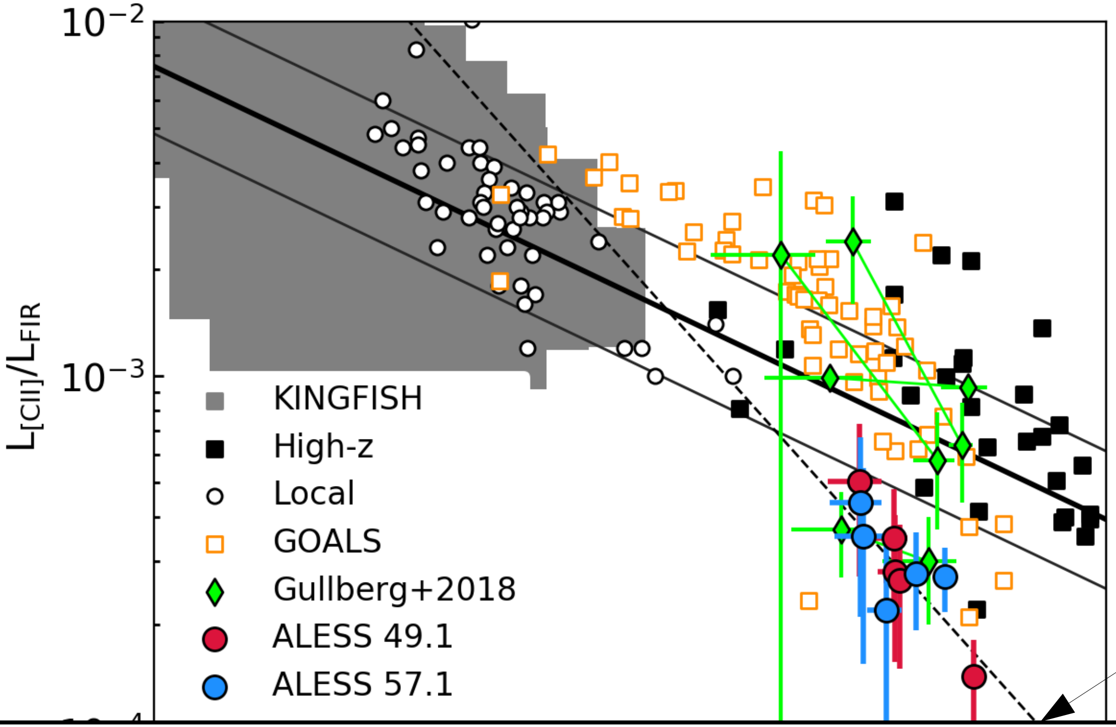
Other potential causes:

- AGN contribution — Negligible on >1 kpc scales
- Grain charging — Yes, but not important
  (e.g., Bakes & Tielens 1994, Malhotra+2001)
- dust-bounded HII regions — FUV fields too strong
  (Abel+2009)

[CII]/FIR deficit on kpc-scales



Munoz&Oh, 2016
[CII] thermal saturation

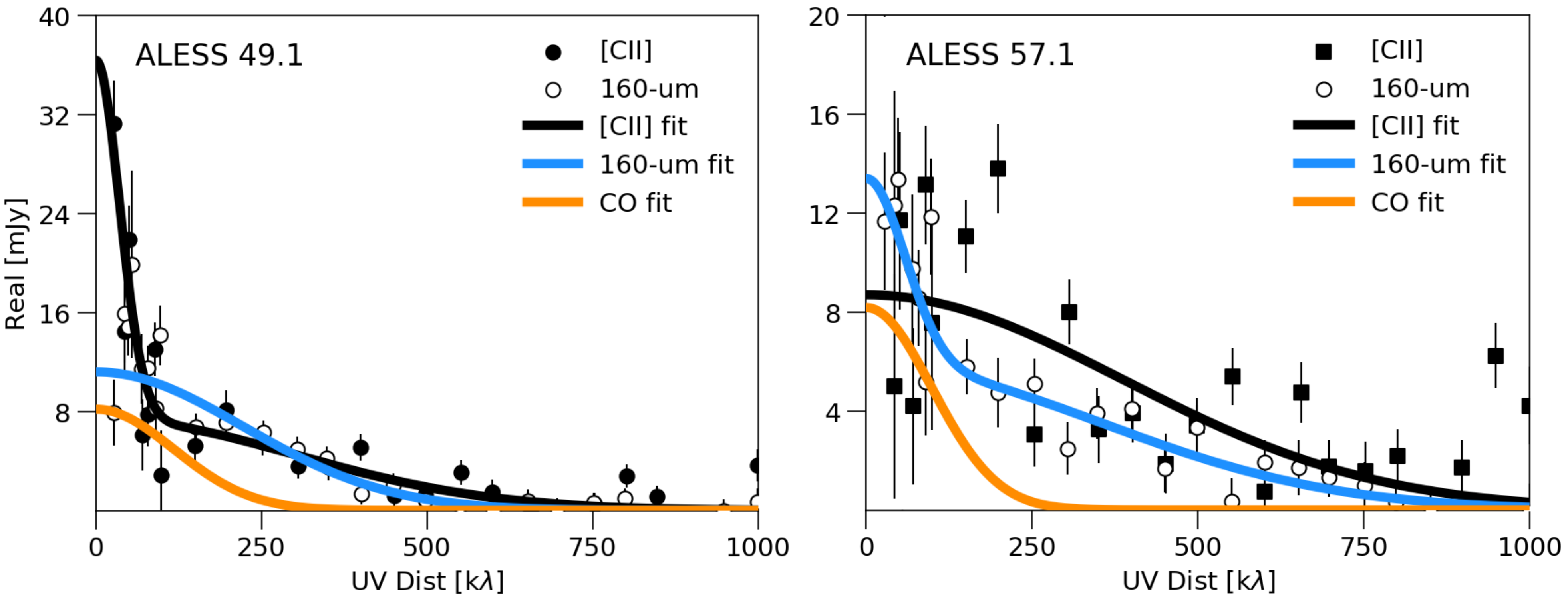
ALESS 49.1 & 57.1 show a pronounced [CII]/FIR deficit
Slope -0.53±0.12 consistent with thermal saturation (-0.5)

Strong FUV fields drive the [CII]/FIR deficit in DSFGs

- DSFGs have a **pronounced [CII]/FIR deficit** (down to 10^{-4}) on ~1 kpc scales (see also Lamarche+2018, Litke+2019)

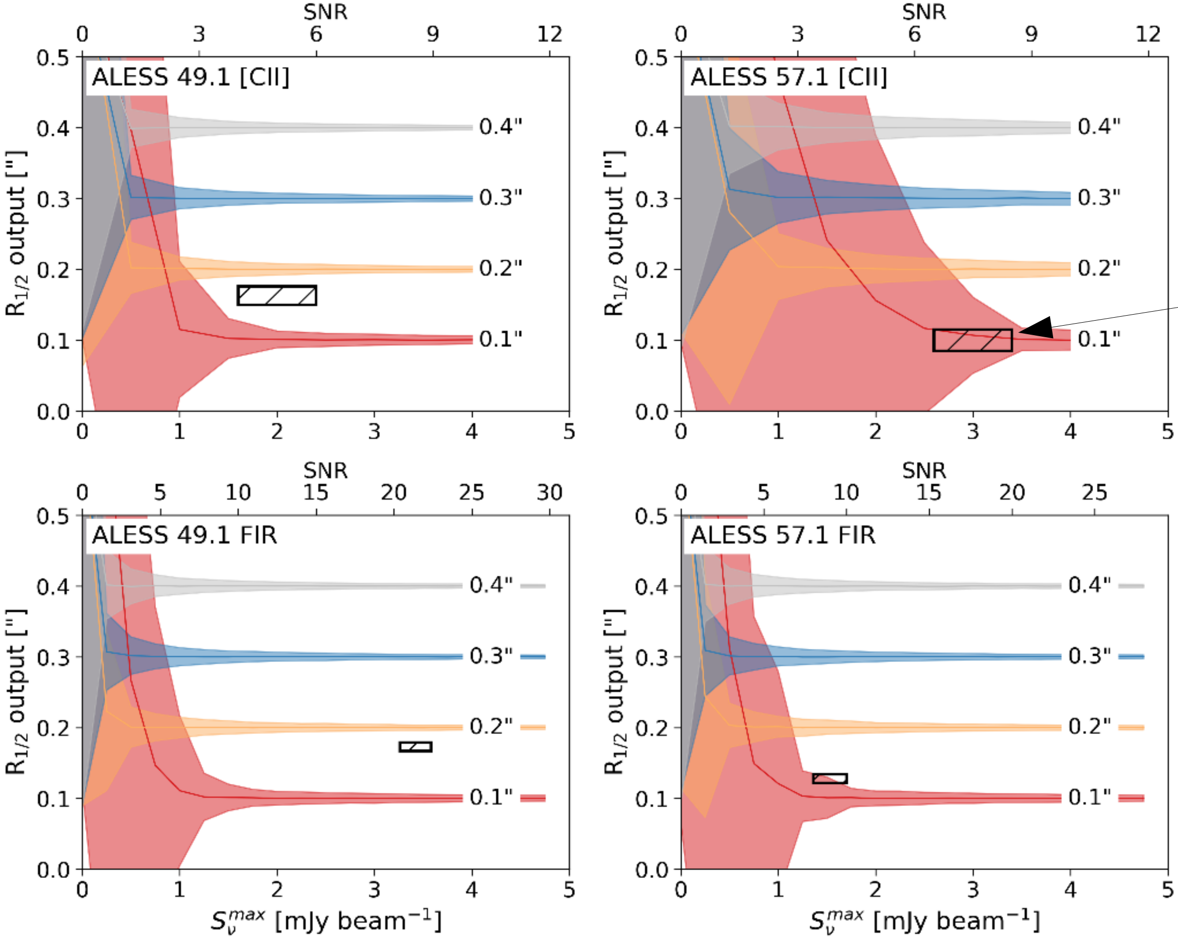
- **[CII]+CO(3-2)+FIR**: PDR modelling indicates strong FUV fields, PDR surface temperature >500 K

- **Thermal saturation of the [CII] line → weak correlation with SFR**


ALESS 49.1
[CII]
160-um
[CII] fit
160-um fit
CO fit
Real [mJy]
40
32
24
16
8
0
250
500
750
1000
UV Dist [kλ]
ALESS 57.1
[CII]
160-um
[CII] fit
160-um fit
CO fit
20
16
12
8
4
0
250
500
750
1000
UV Dist [kλ]

Rybak+2019

Are [CII] and FIR sizes robust? → mock data



1σ confidence interval

Rybak+2019