VALES

The Valparaíso ALMA Line Emission Survey

Tom Hughes / 舒大同

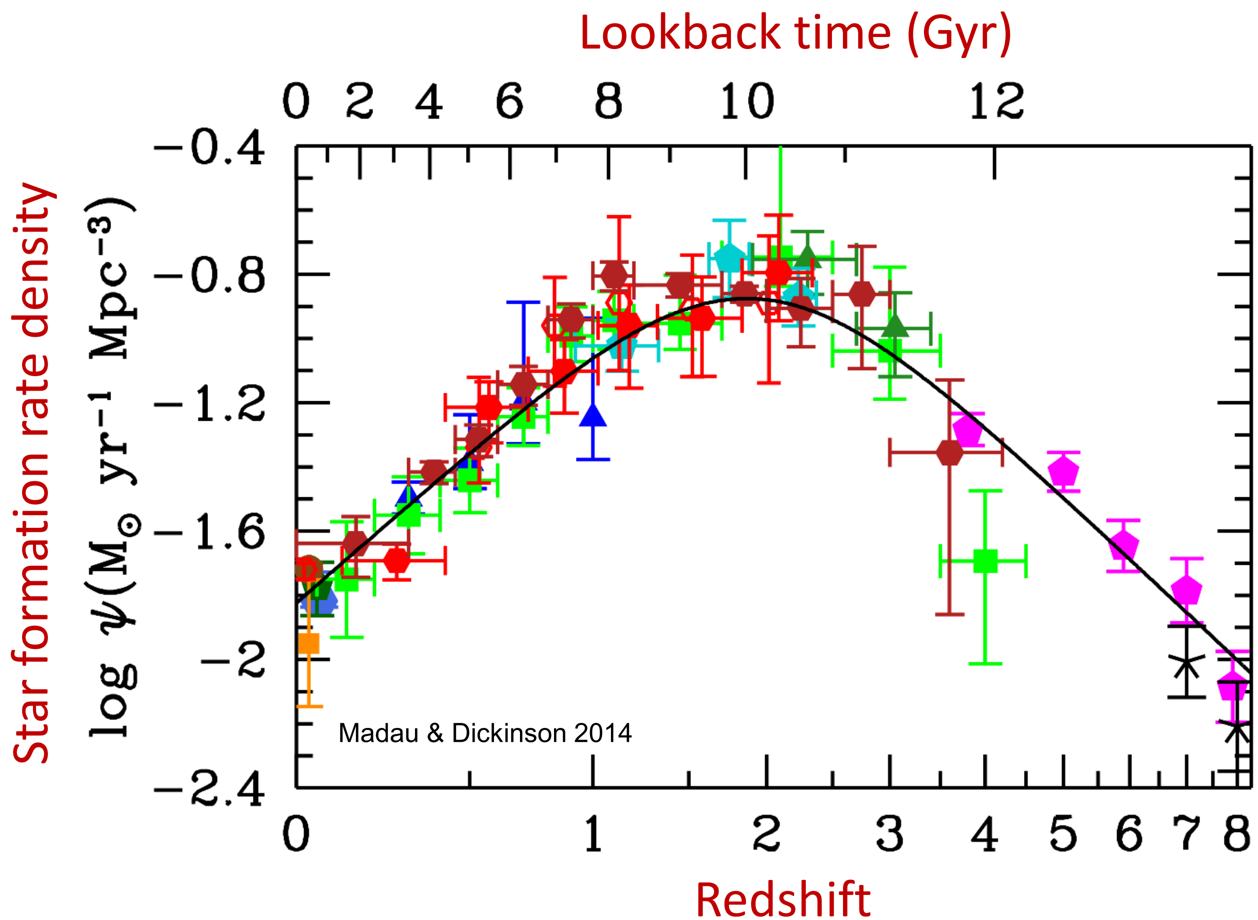
China-Chile Joint Fellow

EAO – Nov 2017

Outline

- The importance of gas and dust in galaxy evolution
- Results from the VALES
- Ongoing projects and future collaborative opportunities

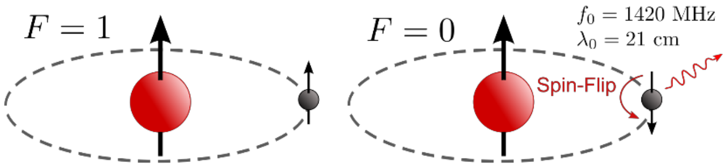
Cosmic star formation



The origin of this behaviour is likely a reflection of the underlying evolution in the physical processes concerning gas in star formation.

Gas tracers

- Neutral H 21 cm hyperfine transition



- Molecular H quadrupole transitions

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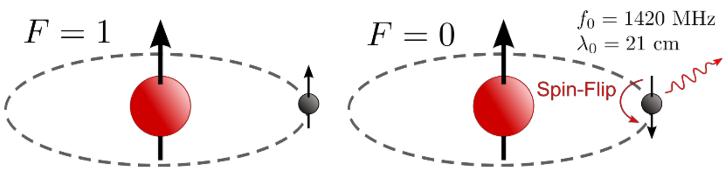
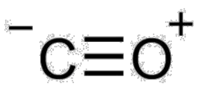


- ~~Molecular H quadrupole transitions~~
  CO rotational transitions



J = 1-0 : λ = 2.6 mm
J = 2-1 : λ = 1.3 mm
J = 3-2 : λ = 0.6 mm

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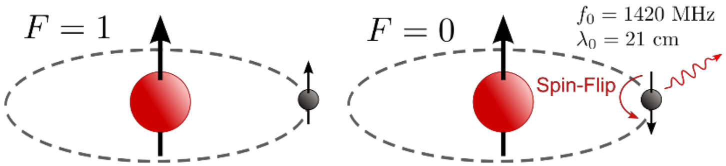


- ~~Molecular H quadrupole transitions~~

CO rotational transitions

$^{-}C \equiv O^{+}$

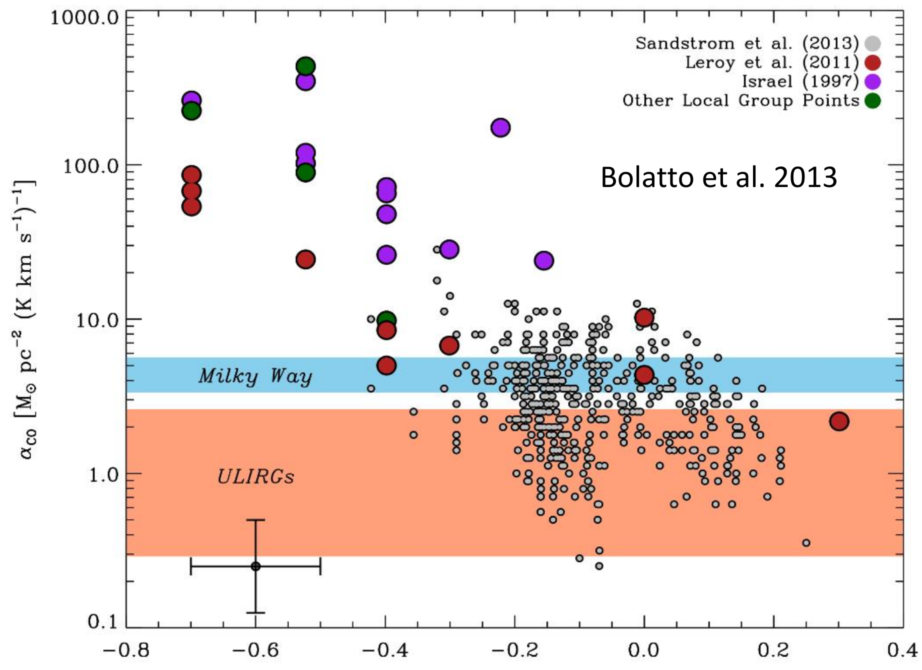
J = 1-0 : λ = 2.6 mm
J = 2-1 : λ = 1.3 mm
J = 3-2 : λ = 0.6 mm

Require the conversion factor between L_{CO} and M_{H_2} :

$$M_{H_2} = \alpha_{CO}\, L_{CO}$$

<u>but</u> there exists a dependency on the galaxy type and metallicity.

CO-to-H_2 factor



Log metallicity

Gas tracers

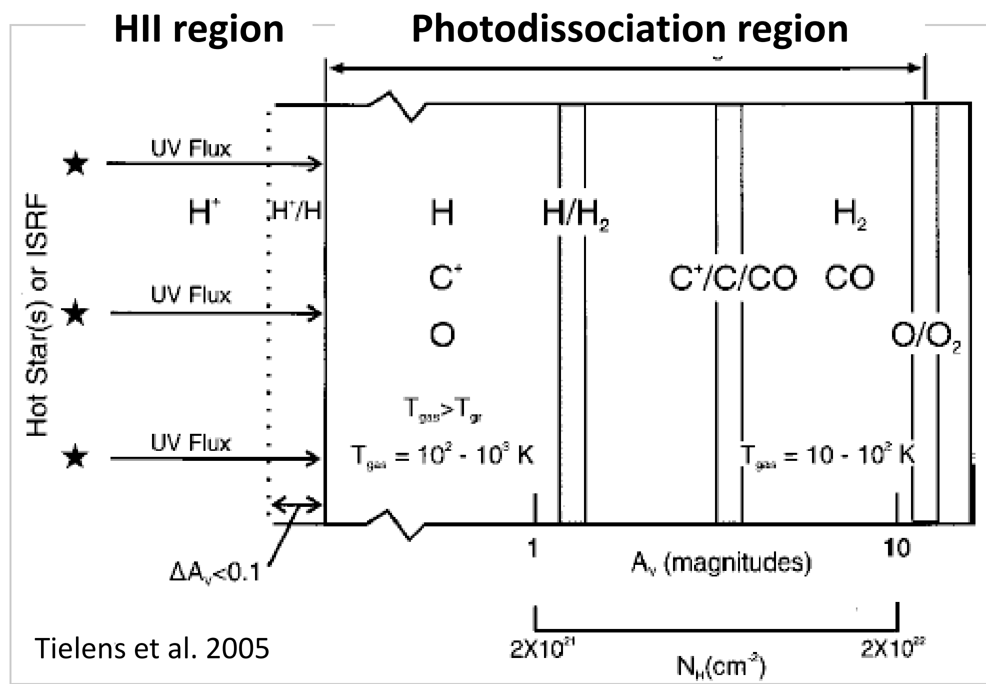
Fine-structure cooling lines

collisionally-excited atoms de-excite through forbidden transitions, emitting photons in FIR

e.g. [C II] 158, [O I] 63 and 145 µm

Powerful diagnostics of gas properties, e.g.:

- ([O I] 63 + [C II] 158) / F_{TIR}
  - probe of photoelectric heating efficiency of FUV radiation field
- [C II] 158 / [O I] 63
  - sensitive to the gas density
- [O I] 145 / [O I] 63
  - probe temperatures T_{gas} ~ 300 K



Tielens et al. 2005

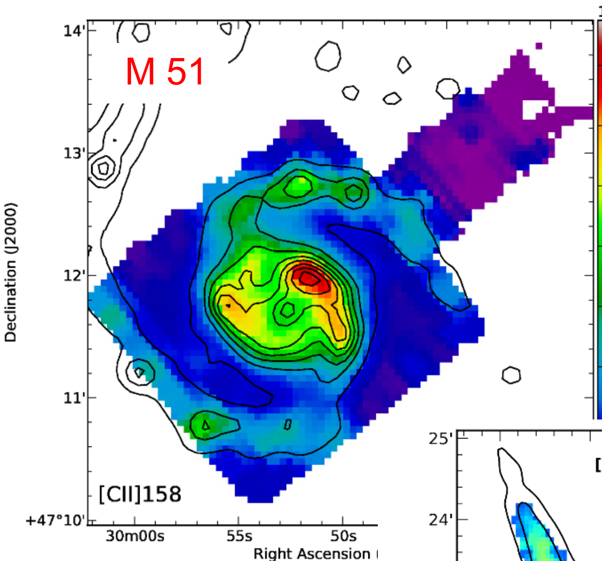
Physical gas properties derived via comparison with PDR models, e.g. Tielens & Hollenbach (1985), characterised by

FUV radiation field strength G_o

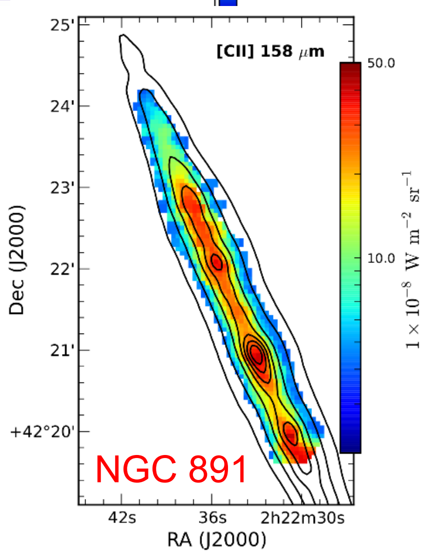
incident on slab of hydrogen density *n* [Kaufman et al. 1999, 2006]

Extragalactic observations

The *Herschel* Very Nearby Galaxies Survey



Parkin et al. 2013



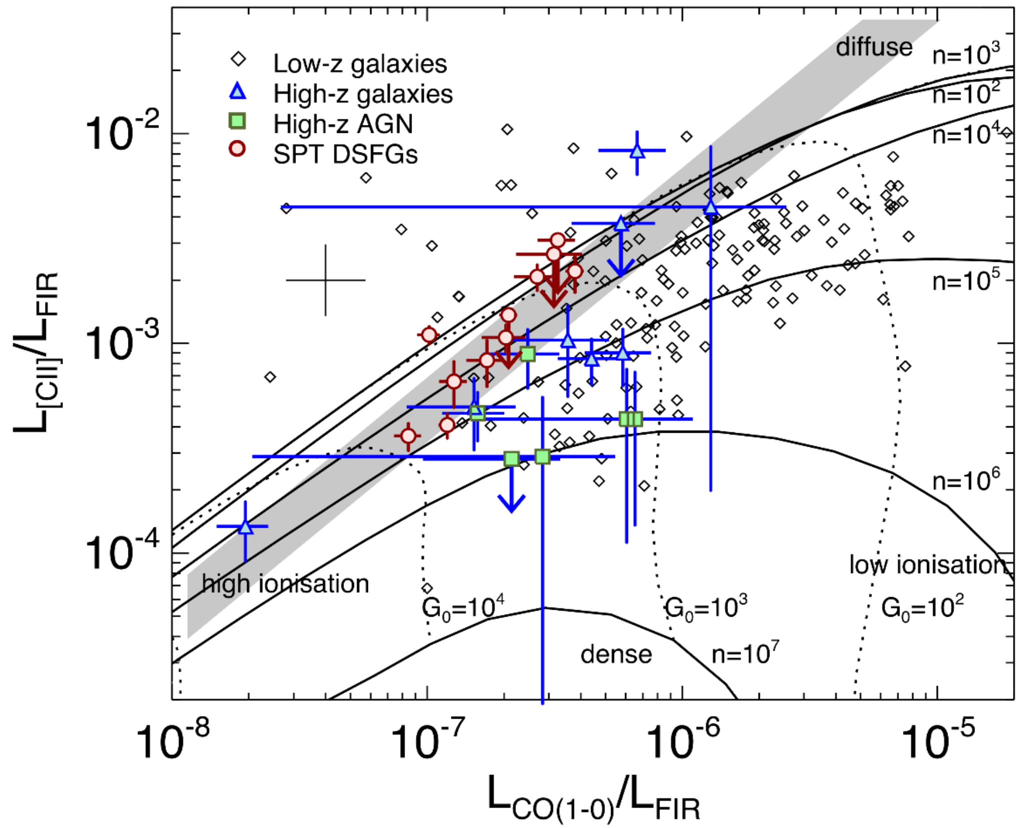
Hughes et al. 2015

Typically:

$2 < \log G_0 < 3$
$3 < \log n < 4$

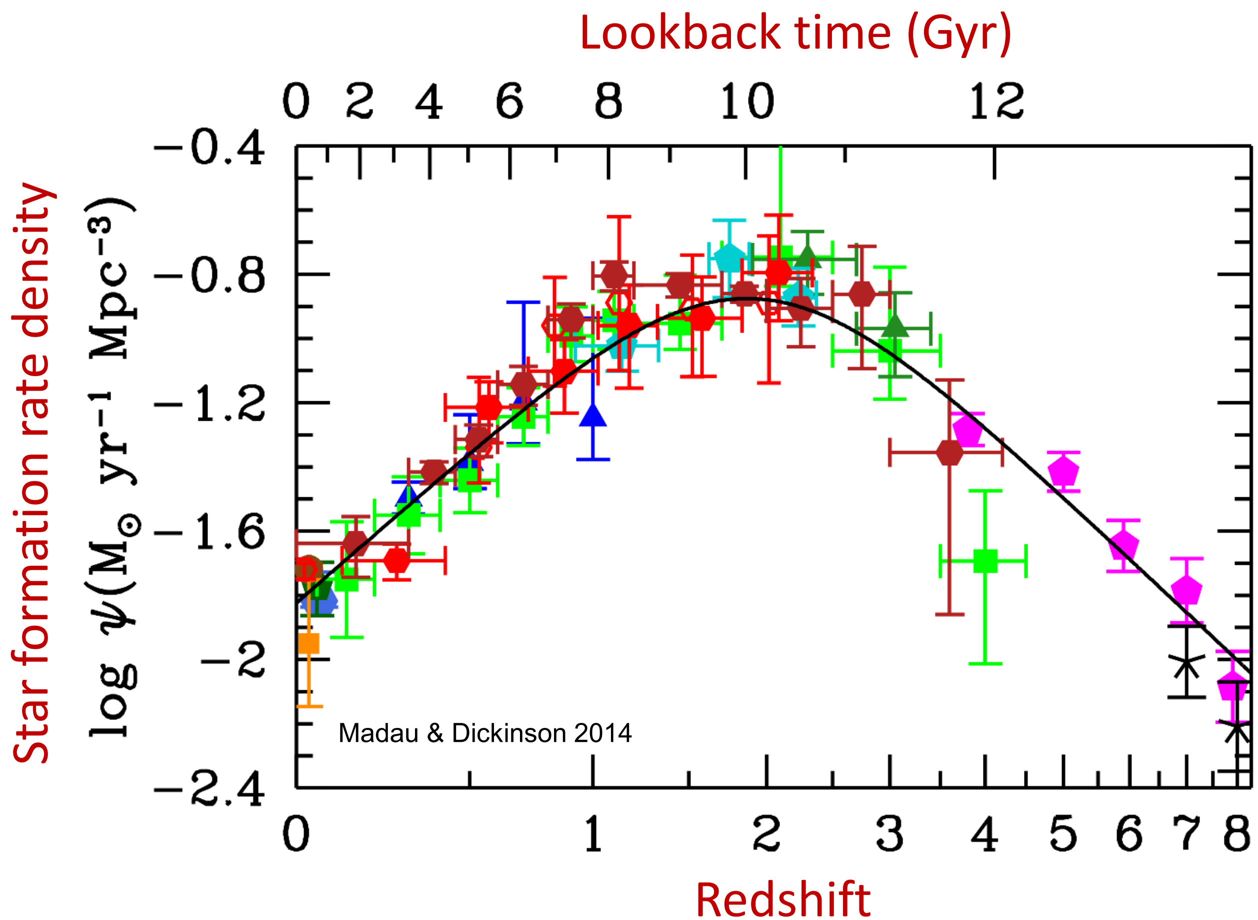
High-z gravitationally-lensed galaxies

Gullberg et al. 2015 and Aravena et al. 2016



(These are just a few examples!)

Cosmic star formation



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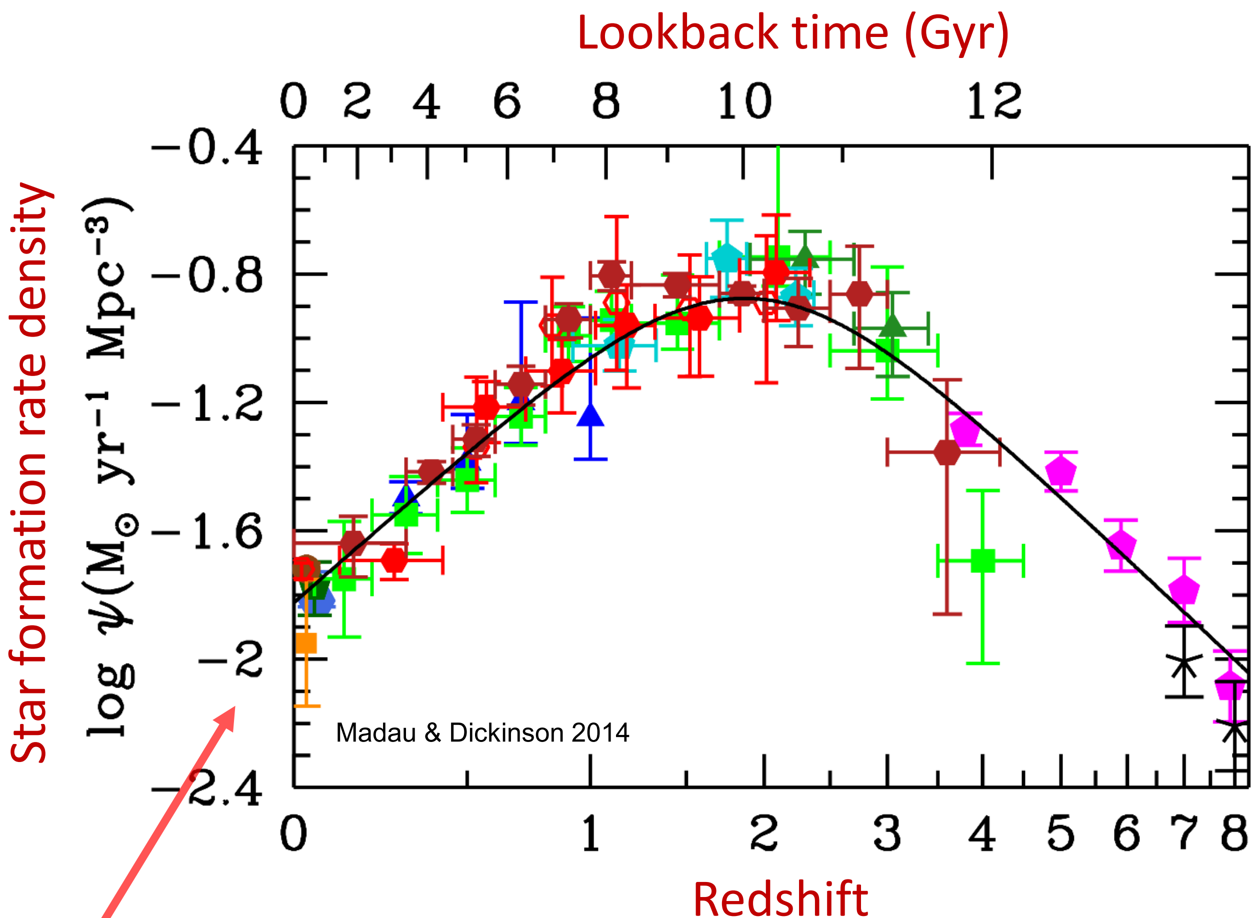

Physical conditions of interstellar gas in nearby galaxies

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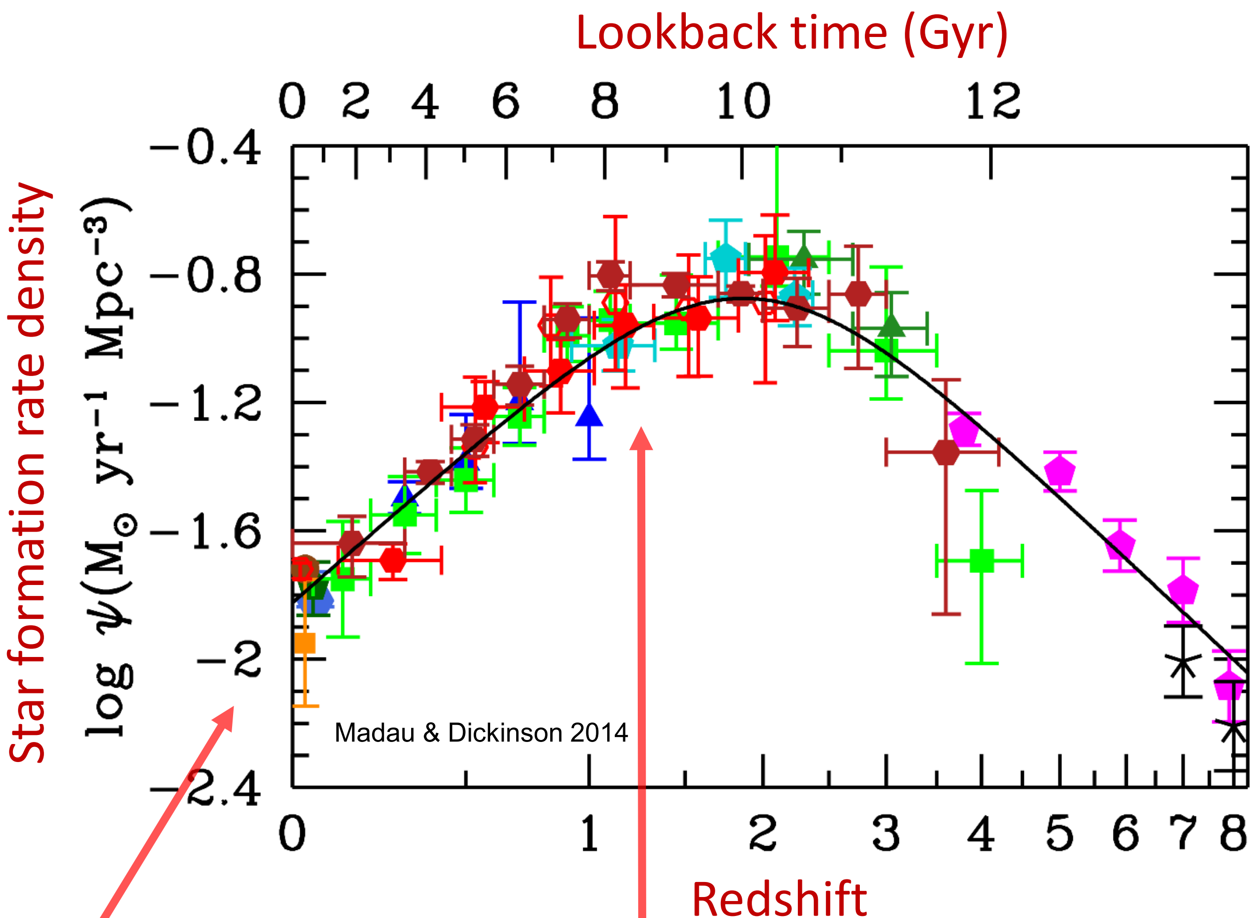
Cosmic star formation



Physical conditions of interstellar gas in nearby galaxies

The transition from normal to starburst galaxies

T ... viou ... of the underlying evolution
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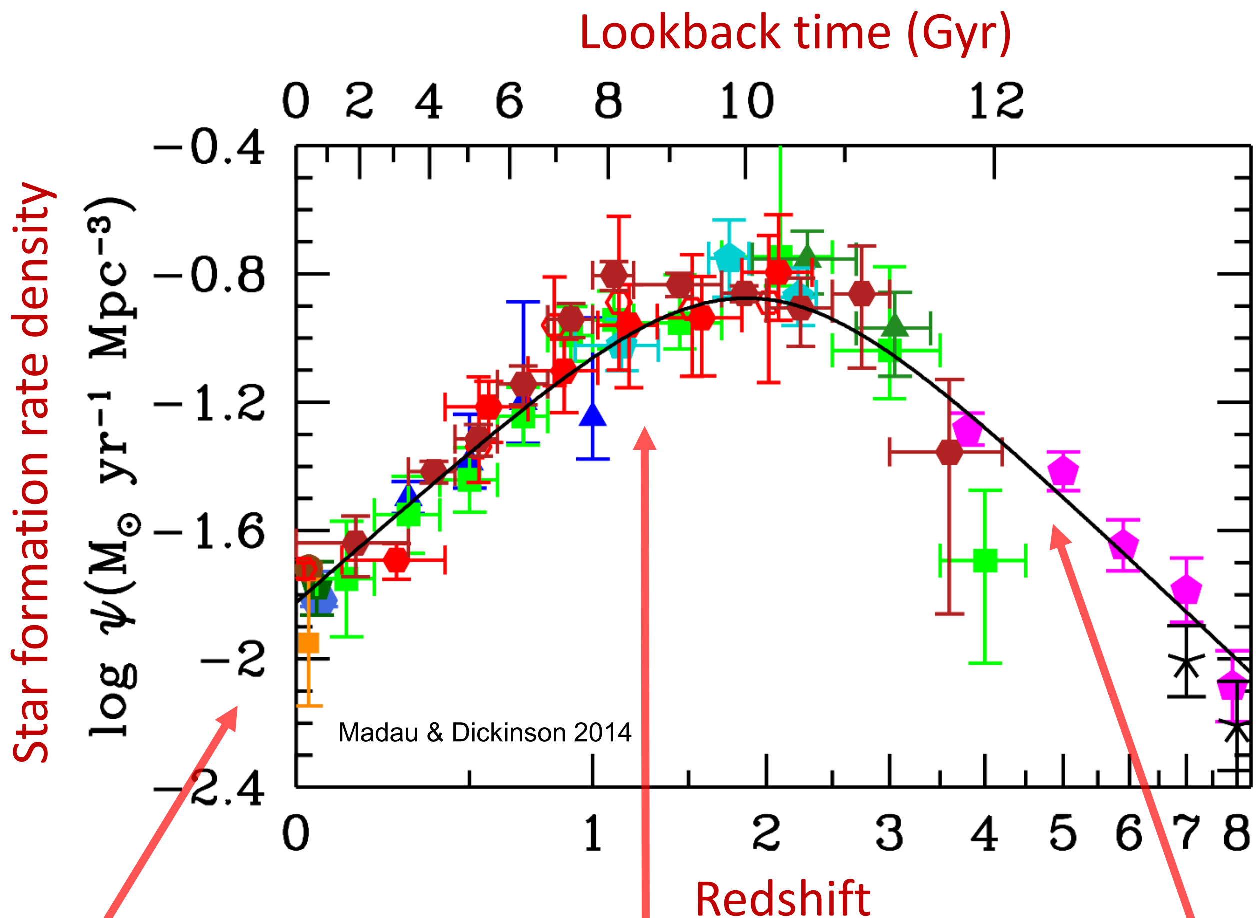
Cosmic star formation



Physical conditions of interstellar gas in nearby galaxies

The transition from normal to starburst galaxies

Estimating gas from dust in higher redshift galaxies

Introducing VALES

The *Valparaíso ALMA Line Emission Survey* (P.I. E. Ibar)

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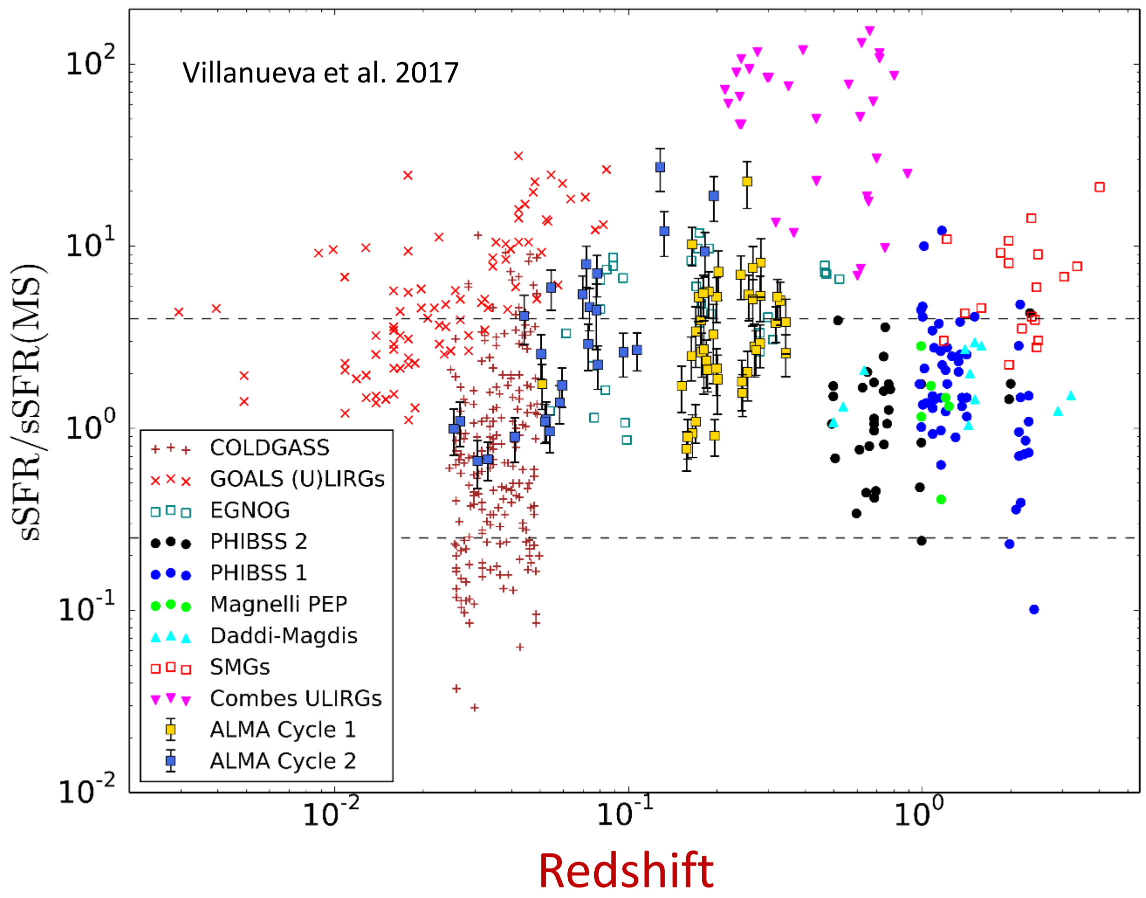

Currently: 67 galaxies from HATLAS observed with ALMA Band 3 targeting CO(1-0).

P.I. of follow-up observing campaign targeting other emission lines with ALMA and other Chilean facilities.

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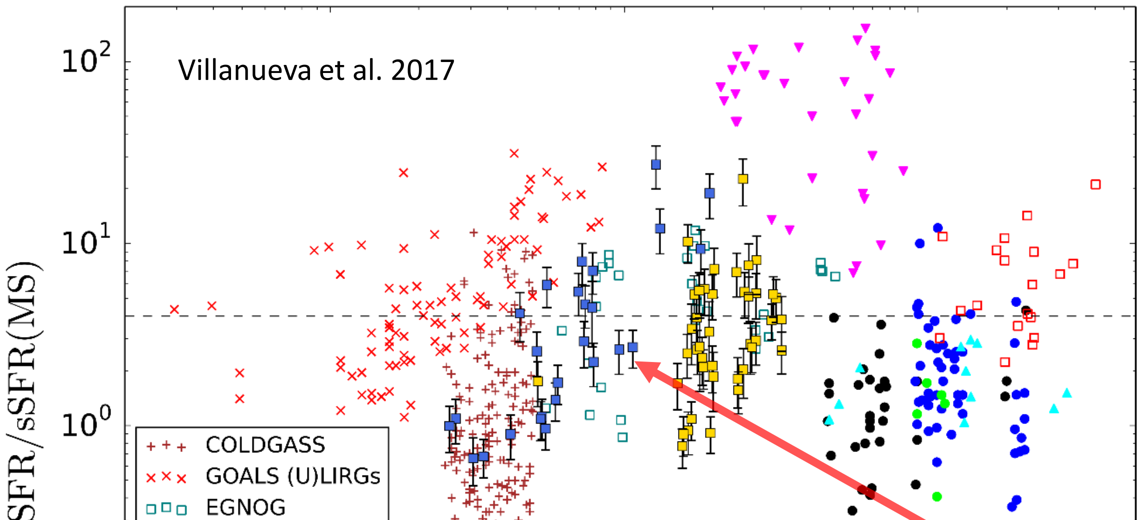

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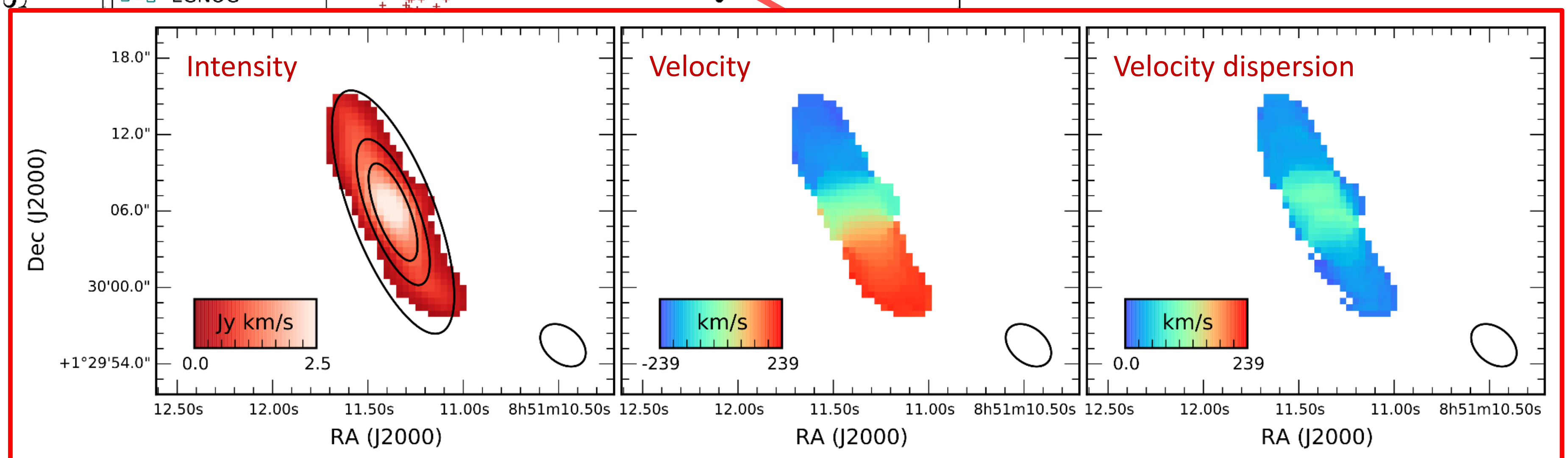

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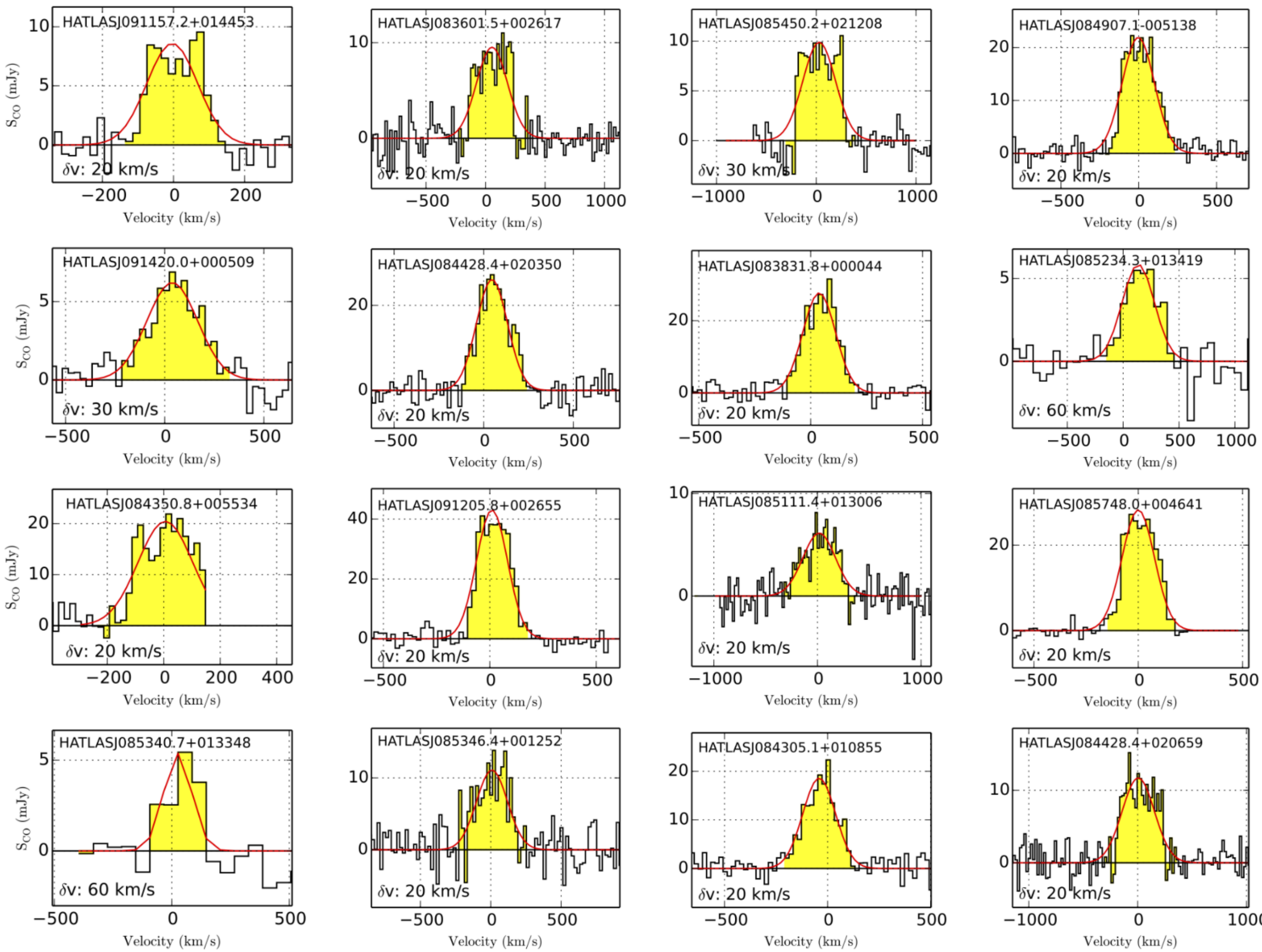
CO(1-0)



Villanueva et al. 2017

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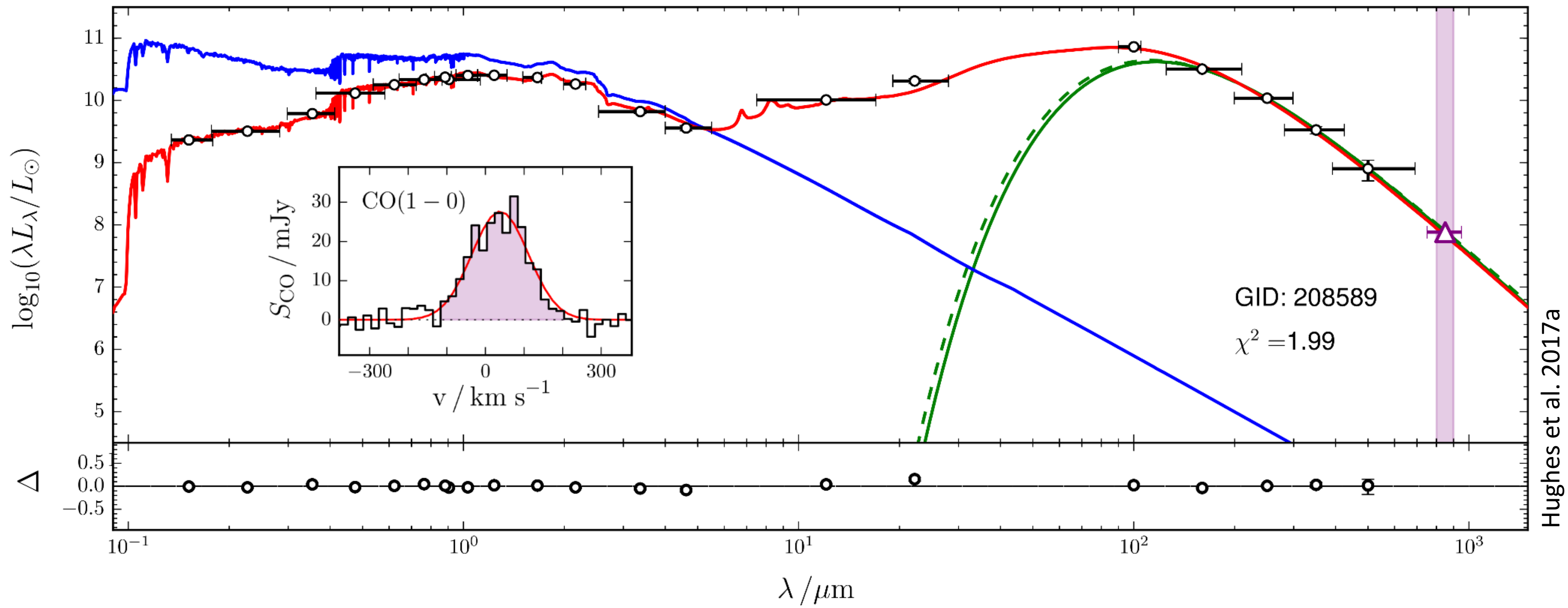
The *Valparaíso ALMA Line Emission Survey* (P.I. E. Ibar)

All galaxies have HATLAS/GAMA photometry sampling UV to FIR/submm SED:



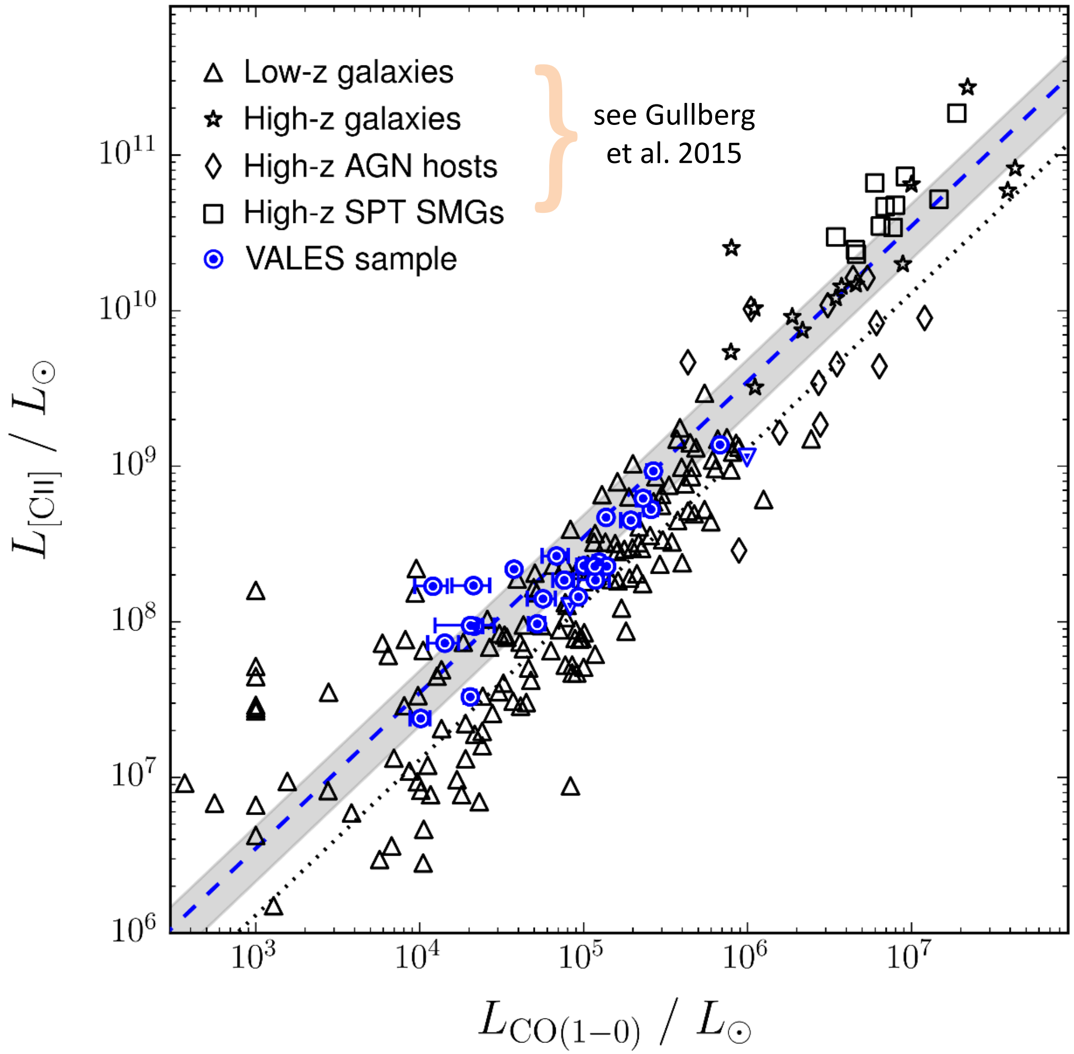
SED fitting with MAGPHYS
(see Driver et al. in prep.)

+

26 galaxies have *Herschel*-PACS [CII] 158 μm spectroscopy
(Ibar et al. 2015)

[ALMA Band 6/7 CO(3-2) line and 850 μm + APEX CO(2-1) + MUSE optical spectroscopy…]

[CII] - CO correlation



Well-studied correlation found for wide range of galaxy types up to $z<6$

(Crawford et al. 1985)

Mean $L_{[CII]}$ / L_{CO} = 3500 consistent with literature

(e.g. Swinbank et al. 2012)

Origin of line emission

Fixing $L_{[CII]}$ / L_{CO}, consider solutions to ratio of source functions:

$$\frac{L_{[\mathrm{C\,II}]}}{L_{\mathrm{CO}(1-0)}} = \left(\frac{\nu_{[\mathrm{C\,II}]}}{\nu_{\mathrm{CO}(1-0)}}\right)^3 \times \left(\frac{\Delta\nu_{[\mathrm{C\,II}]}}{\Delta\nu_{\mathrm{CO}(1-0)}}\right) \times \frac{1-e^{-\tau_{[\mathrm{C\,II}]}}}{1-e^{-\tau_{\mathrm{CO}(1-0)}}} \times \frac{e^{h\nu_{\mathrm{CO}(1-0)}/kT_{\mathrm{ex,CO}(1-0)}}-1}{e^{h\nu_{[\mathrm{C\,II}]}/kT_{\mathrm{ex,[C\,II]}}}-1}$$

- Equal excitation temperatures?

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- ~~Equal excitation temperatures?~~
  - requires equal optical depths at T_{ex} > 50 K for both lines
  - contrary to most literature (Graf et al. 2012, Ossenkopf et al. 2013)

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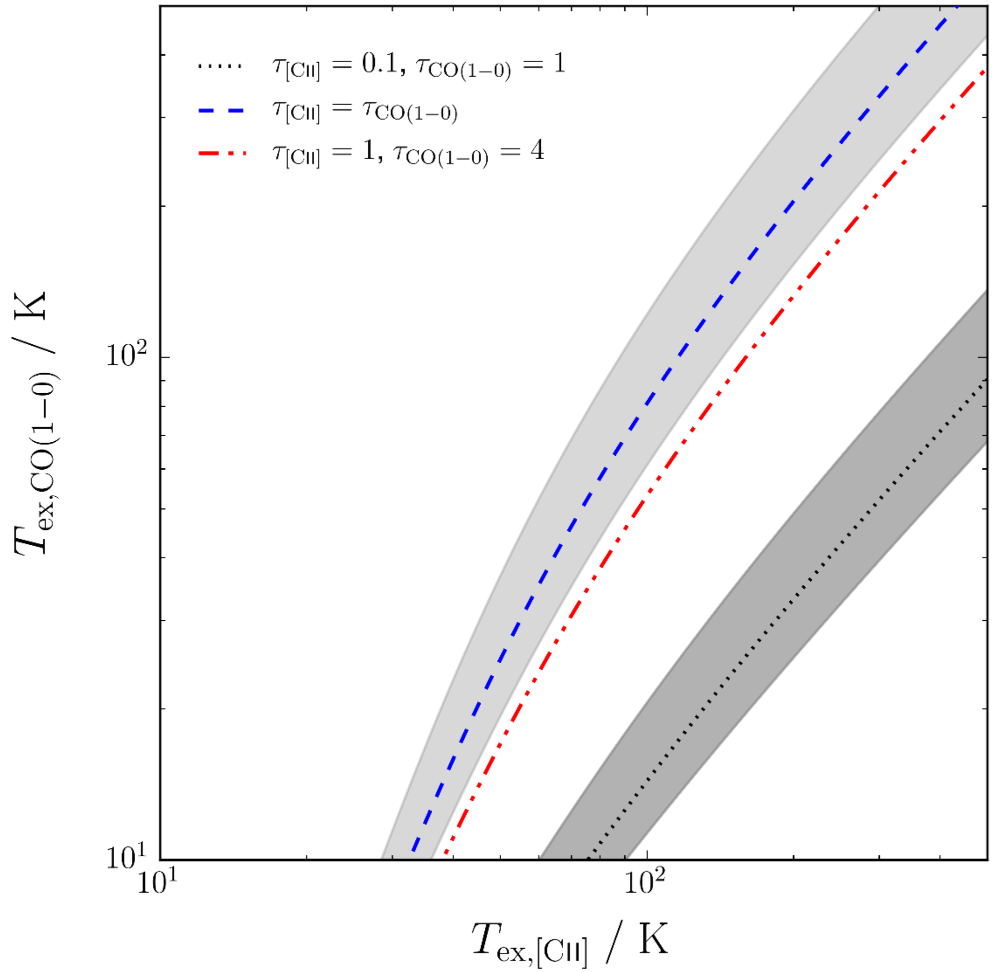
  - fix T_{ex}(CO) to temperature of dust thermalized in molecular clouds…



Hughes et al. 2017a

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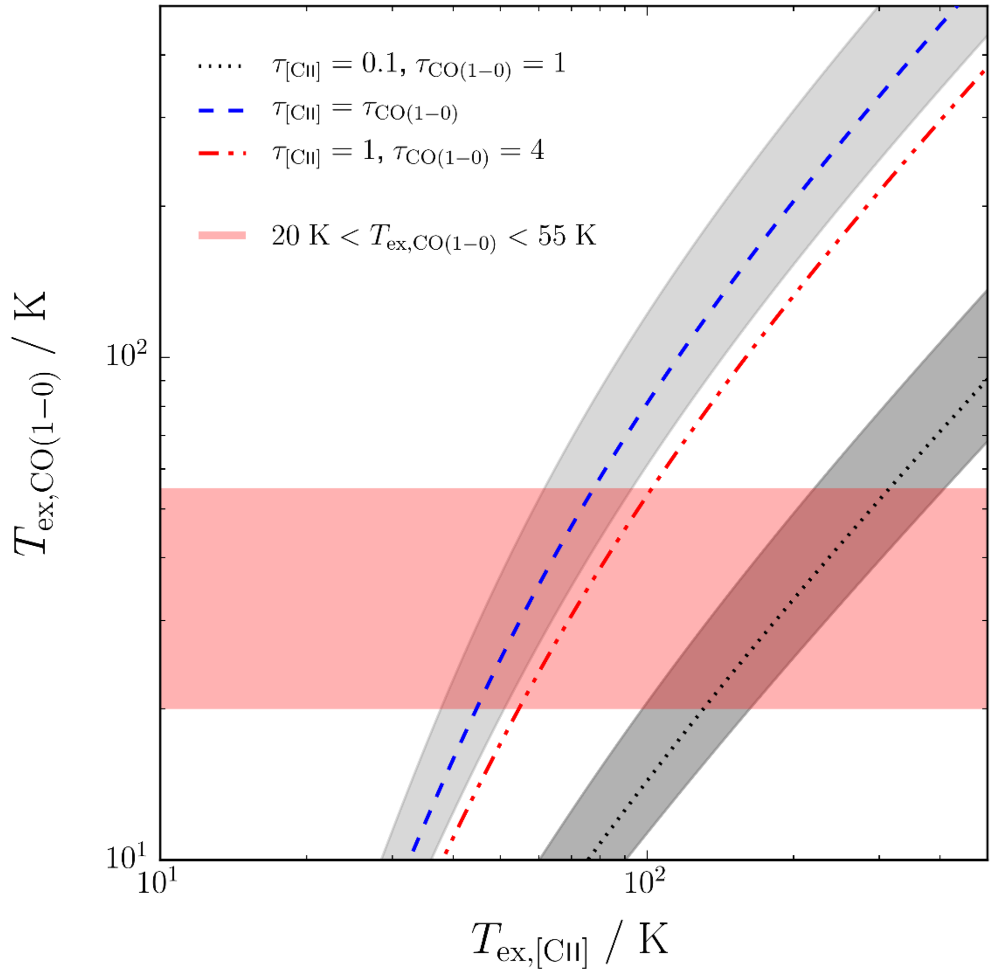
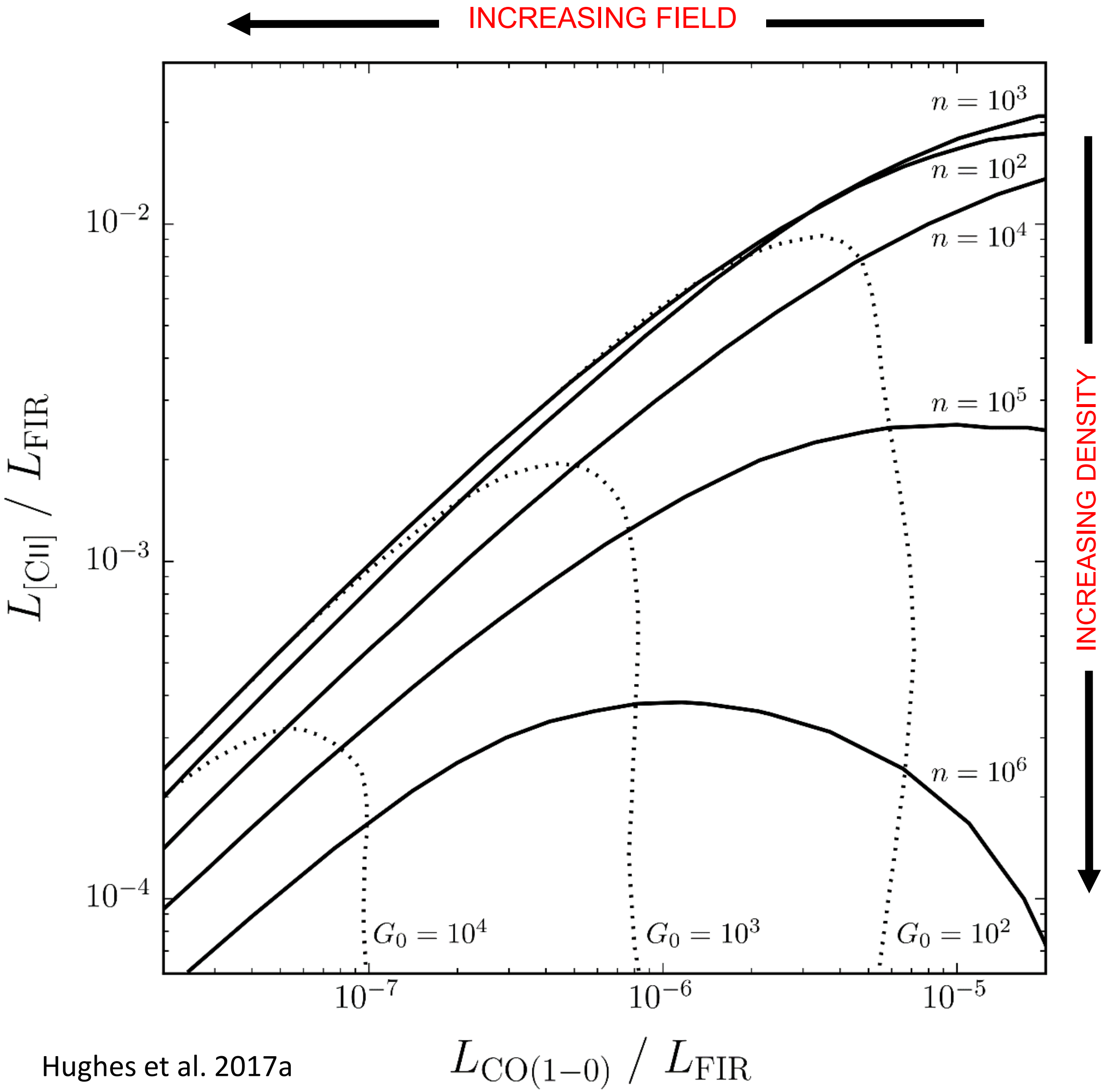


Hughes et al. 2017a

T_{ex}([CII]) > T_{ex}(CO)
Optically thick CO
Optically thin [CII]

PDR modelling



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[CII]-CO diagnositc diagram

(e.g. Hailey-Dunsheath et al. 2010)

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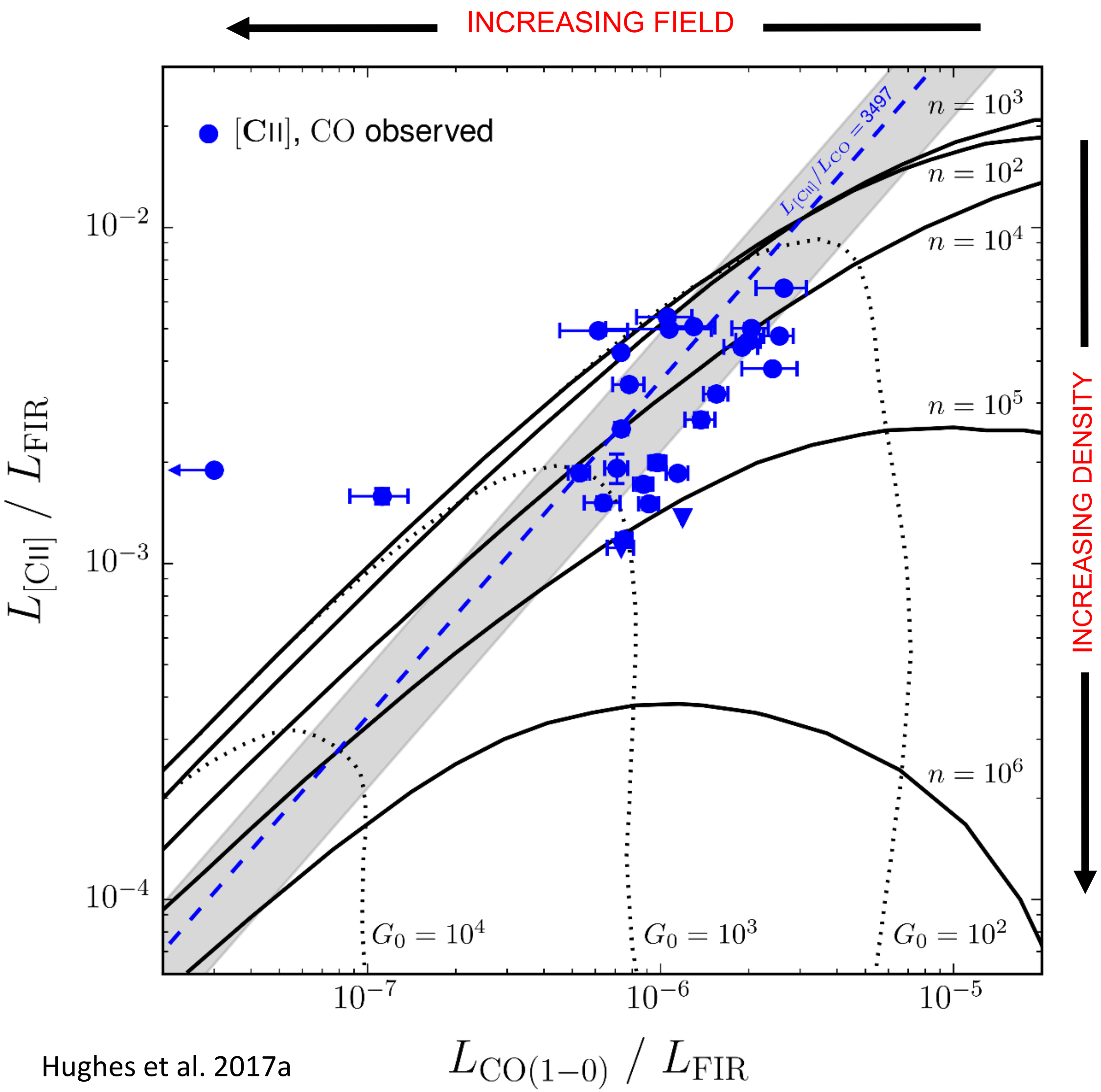

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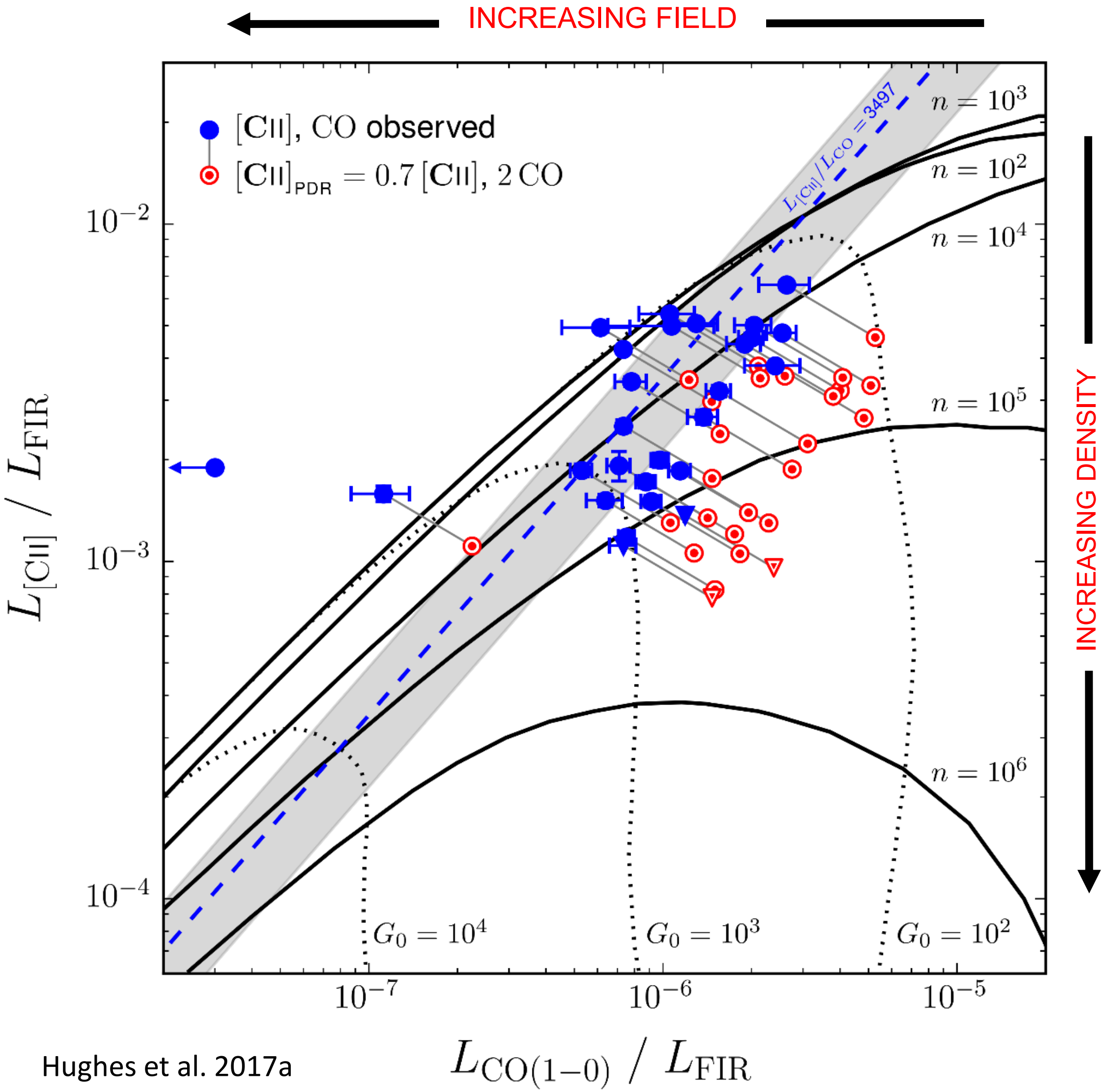

Hughes et al. 2017a

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- Adjustment to [CII]
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  - observations miss ~50% of the optical thick CO
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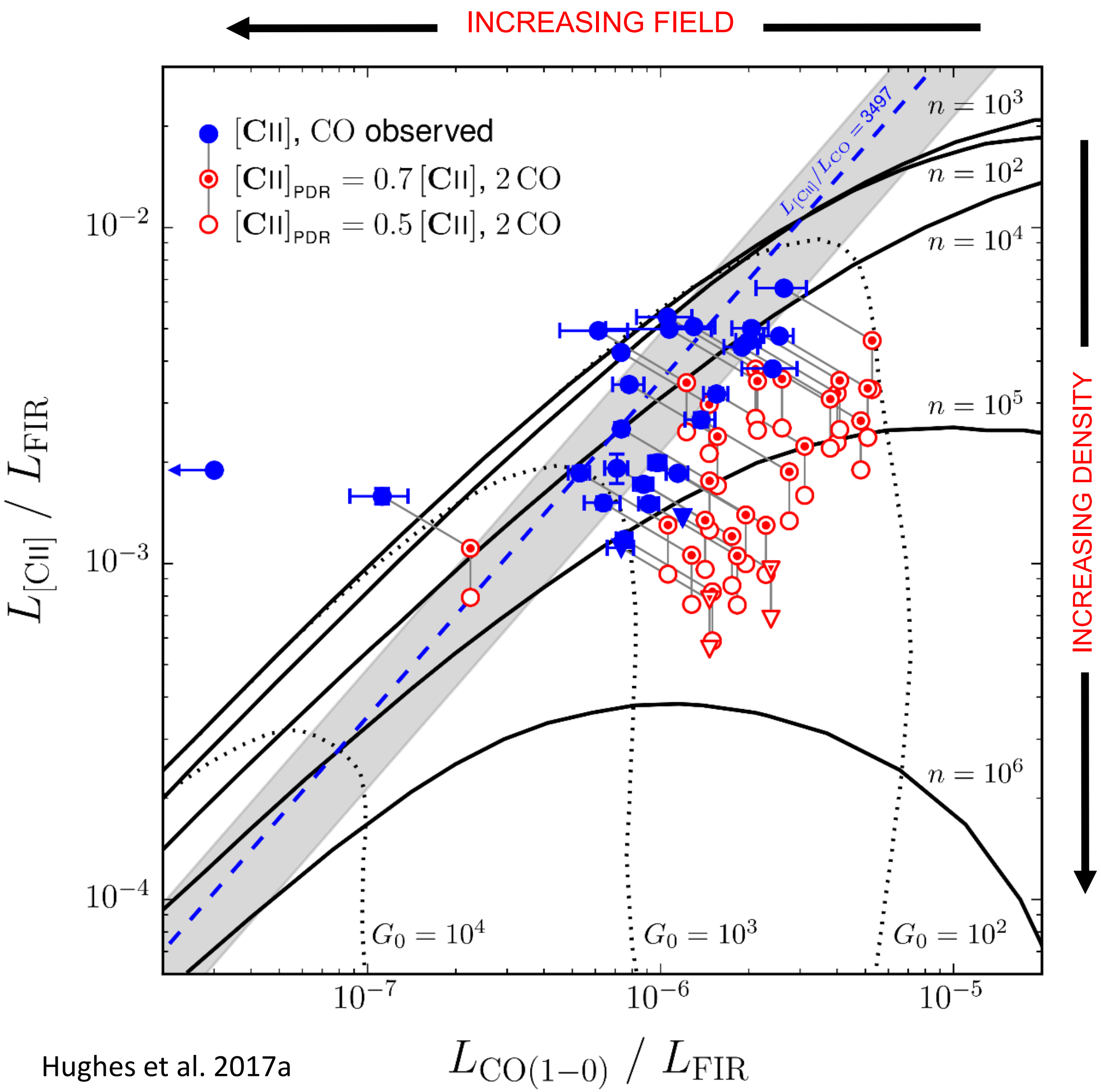

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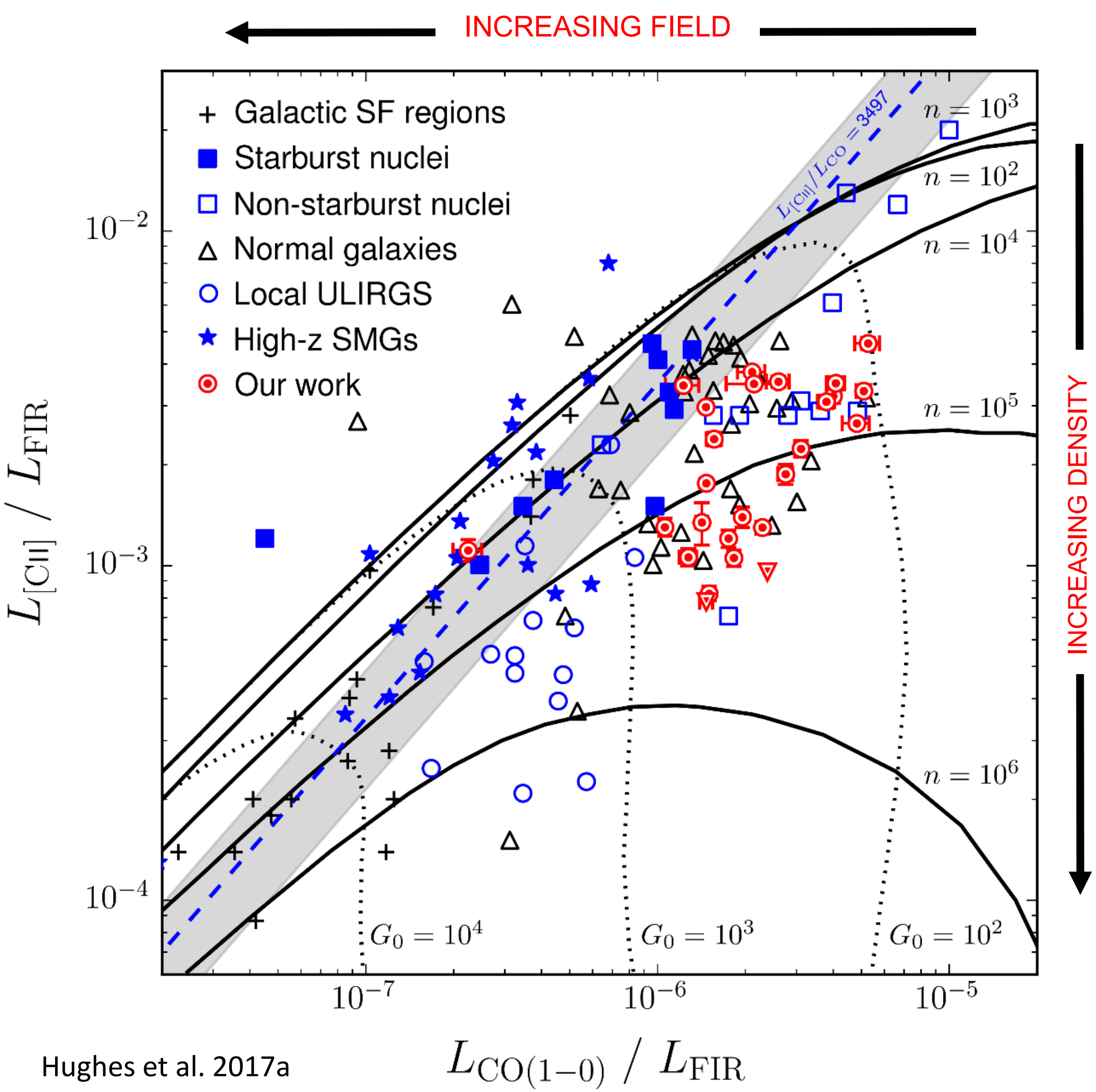

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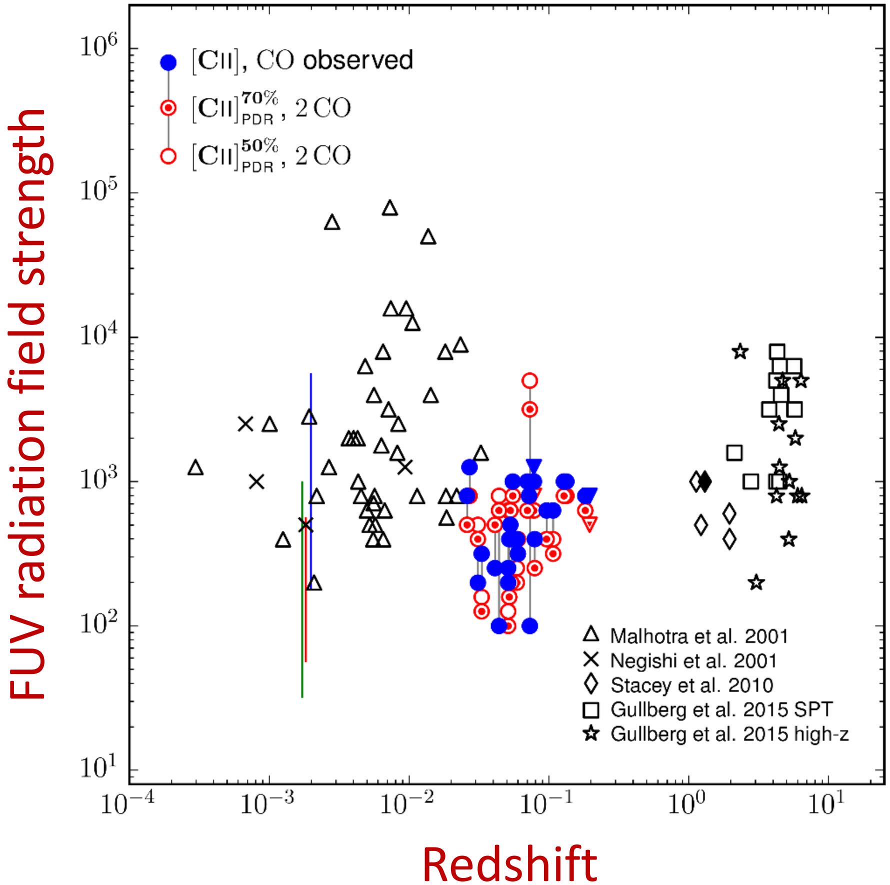
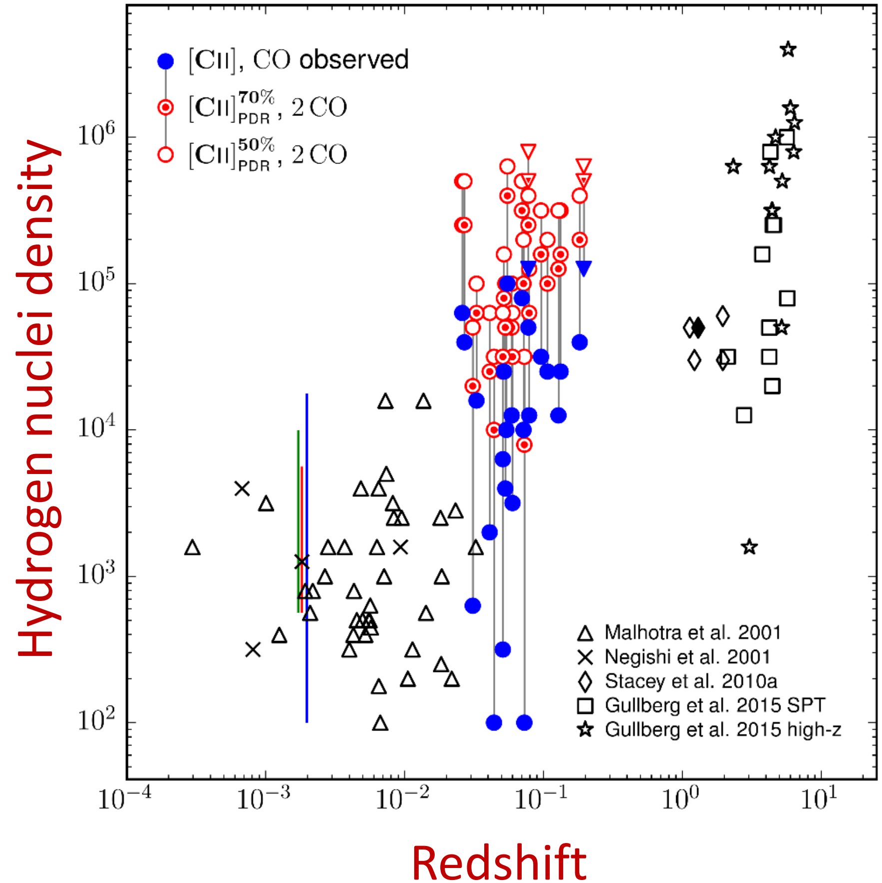
Observations and model parameters indicate normal star formation mode

Redshift evolution?

Compare samples with both [CII] and CO observations…



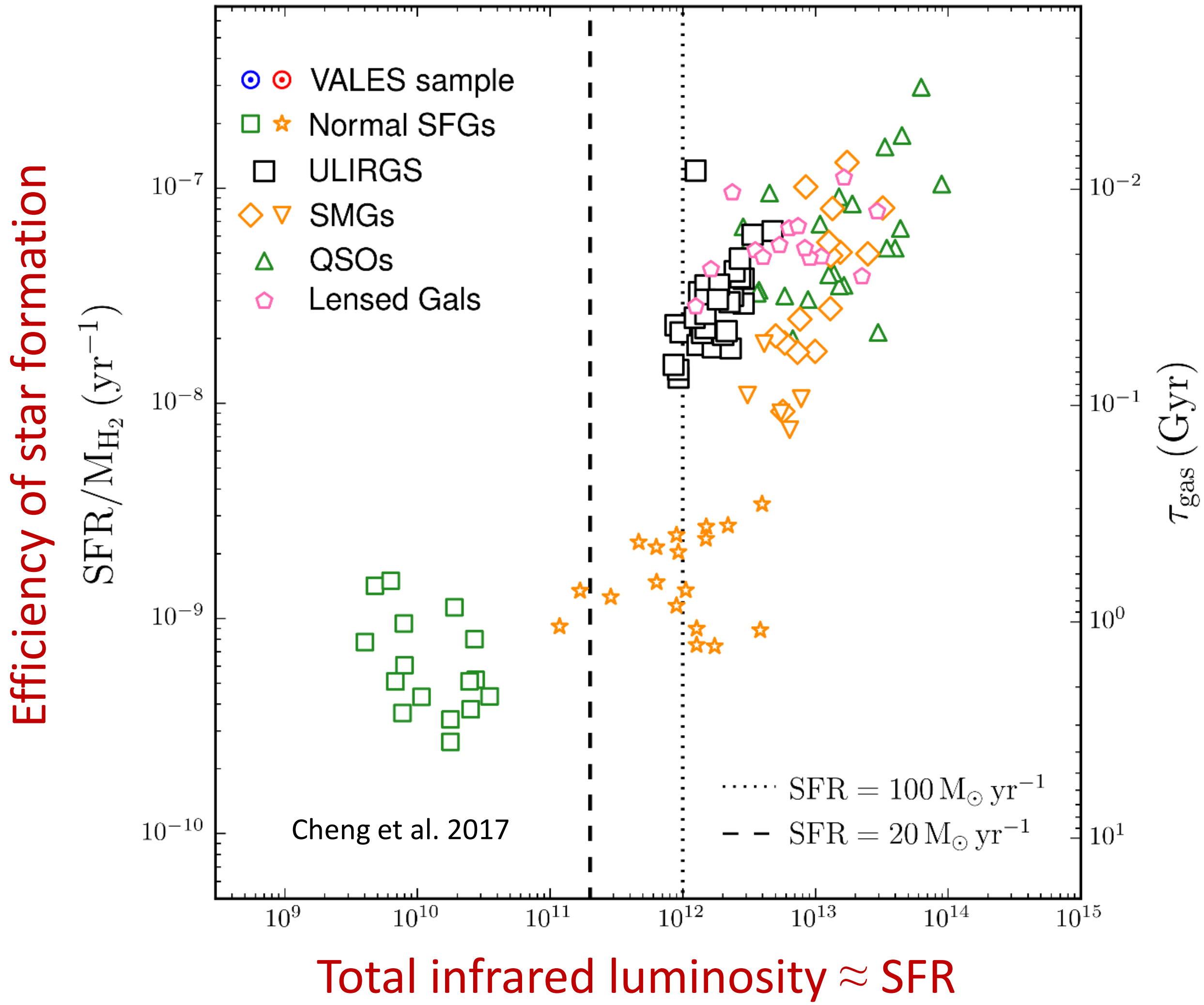


Hughes et al. 2017a

… but <u>beware</u> of biases in sample selection and methodology!

Transition to starbursts

How are normal and starburst modes related?



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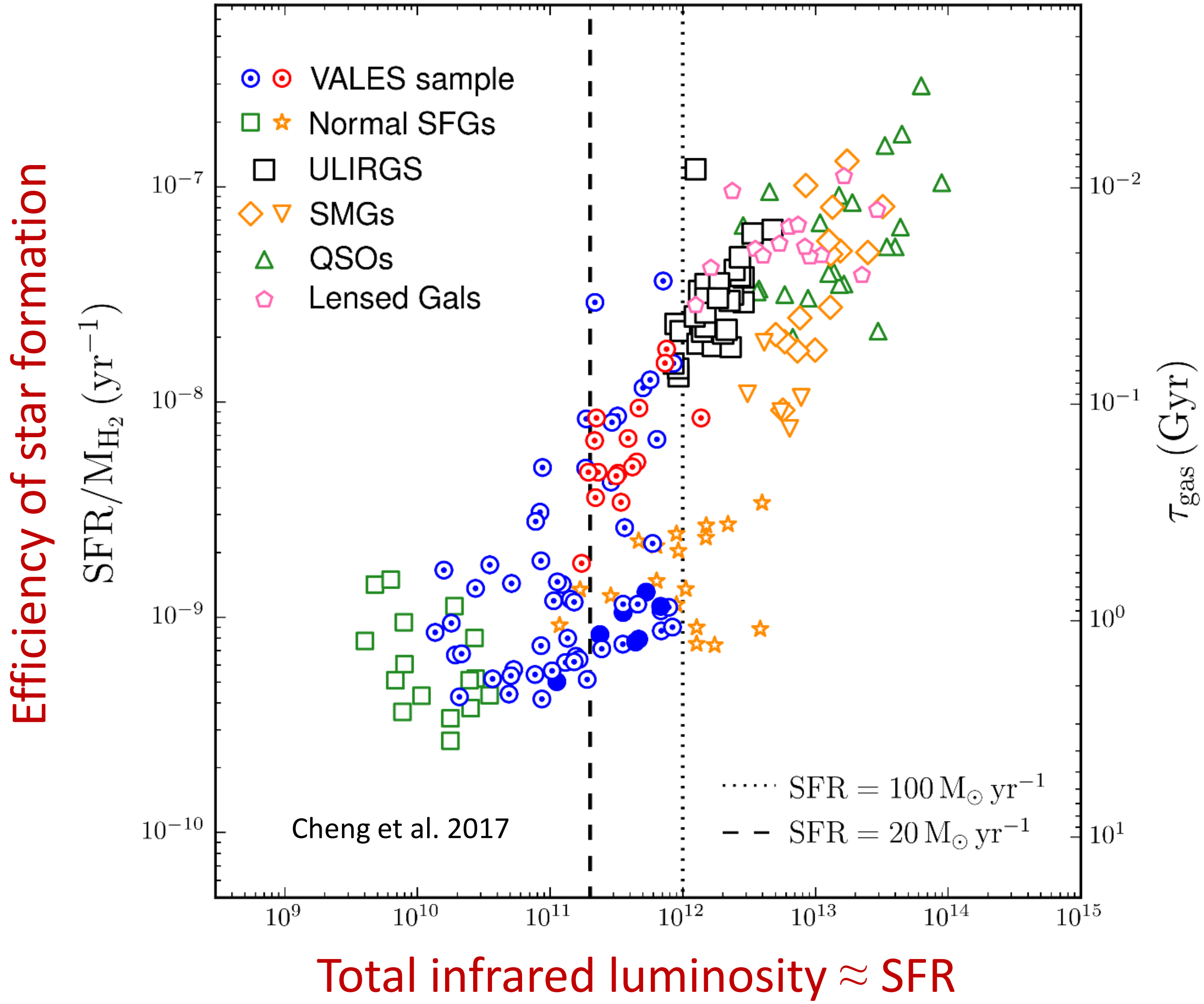

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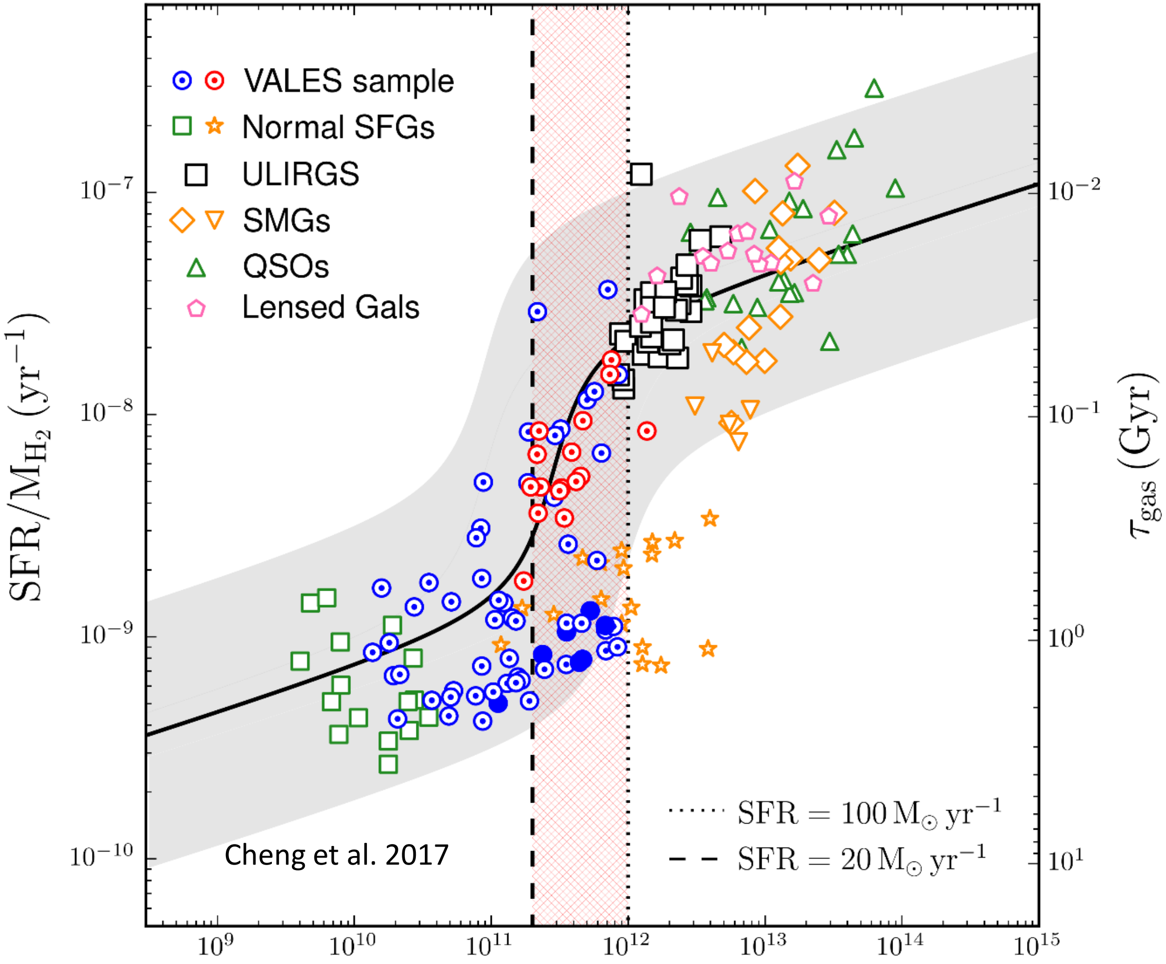
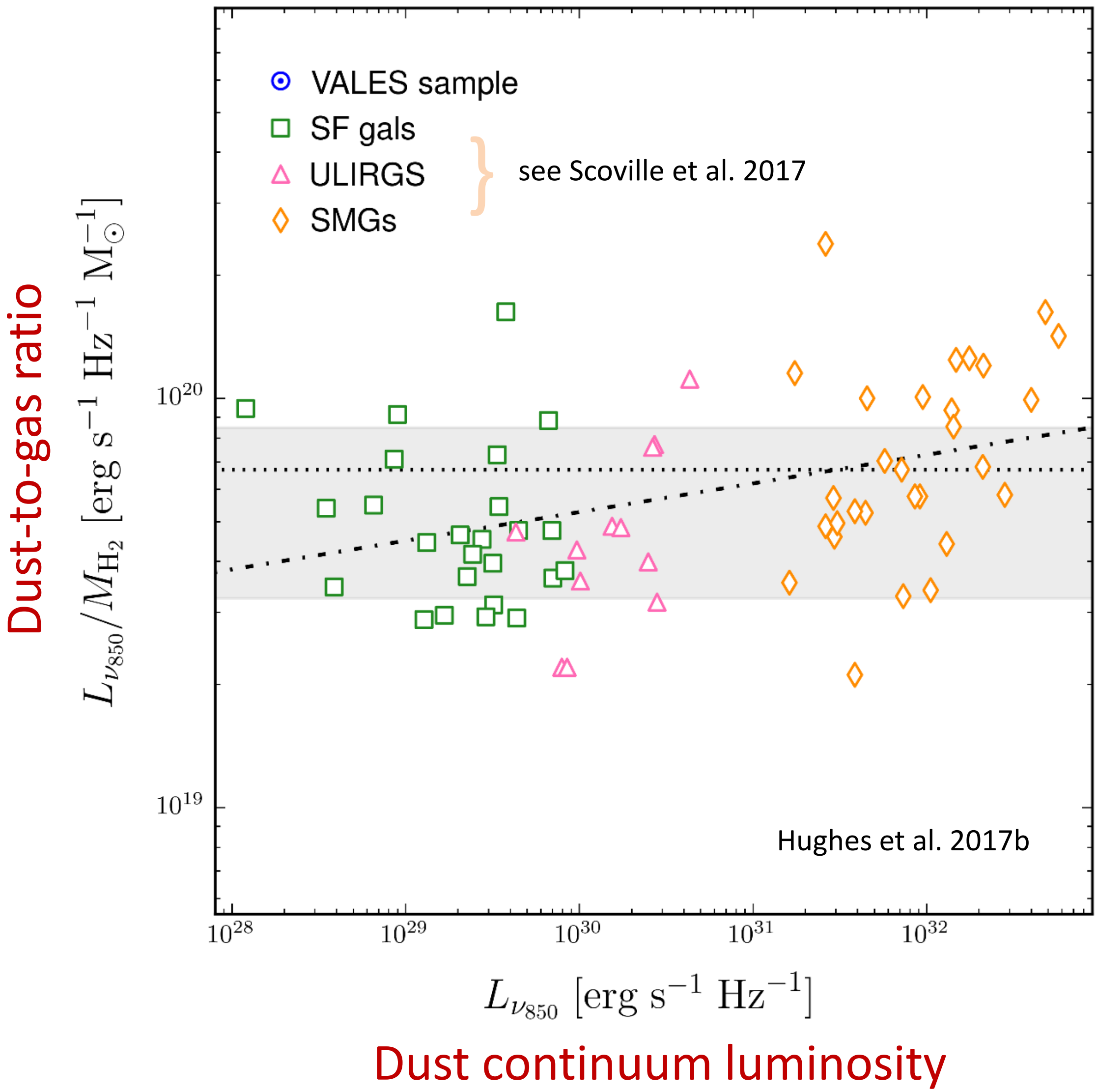
Efficiency of star formation



Total infrared luminosity ≈ SFR

Awarded VLT/MUSE observations will study the ionised gas across the transition.

Dust – gas relation



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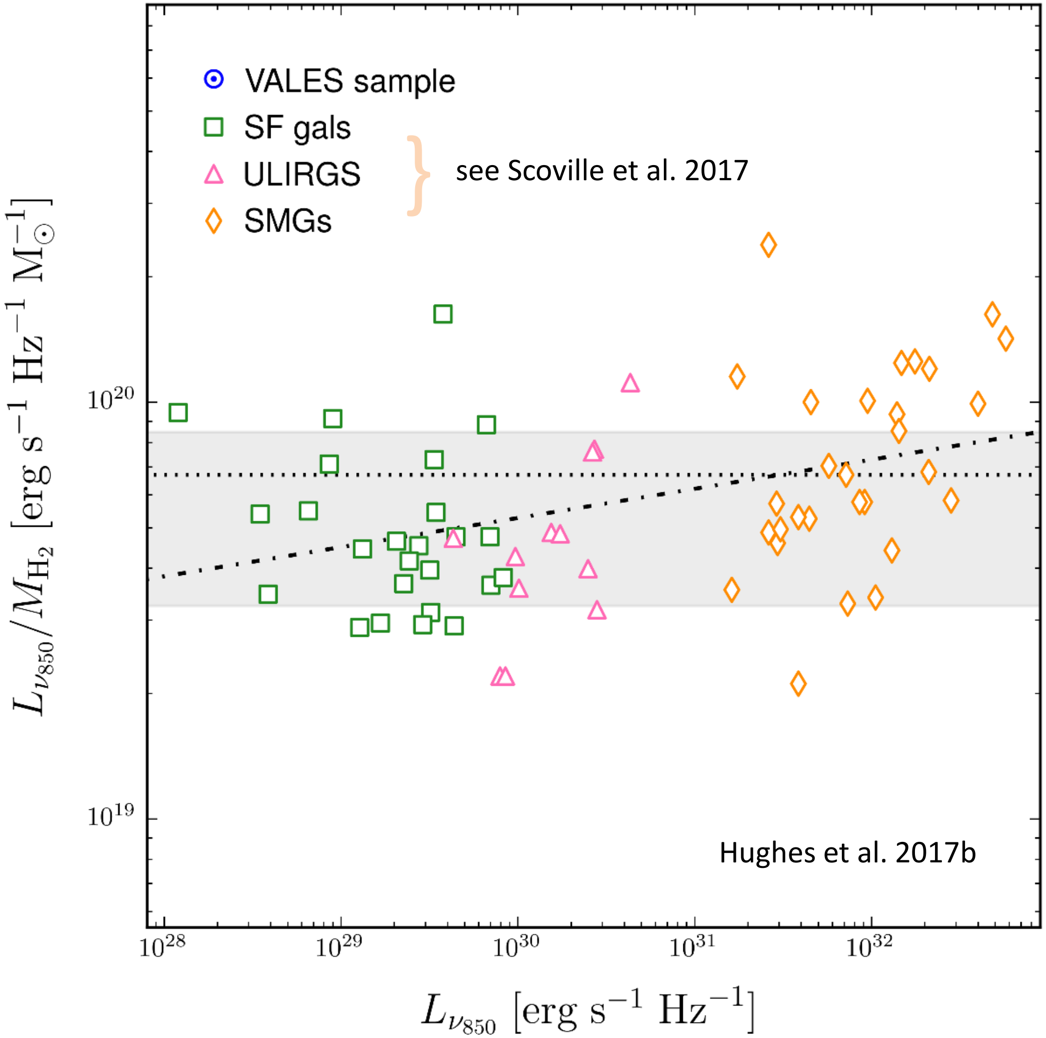
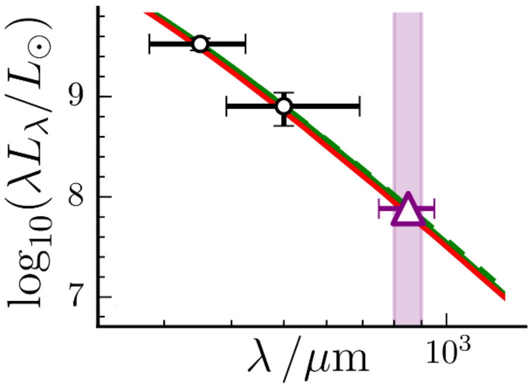


Dust-to-gas ratio

Dust continuum luminosity

Dust continuum luminosity extrapolated from *Herschel* SEDs:



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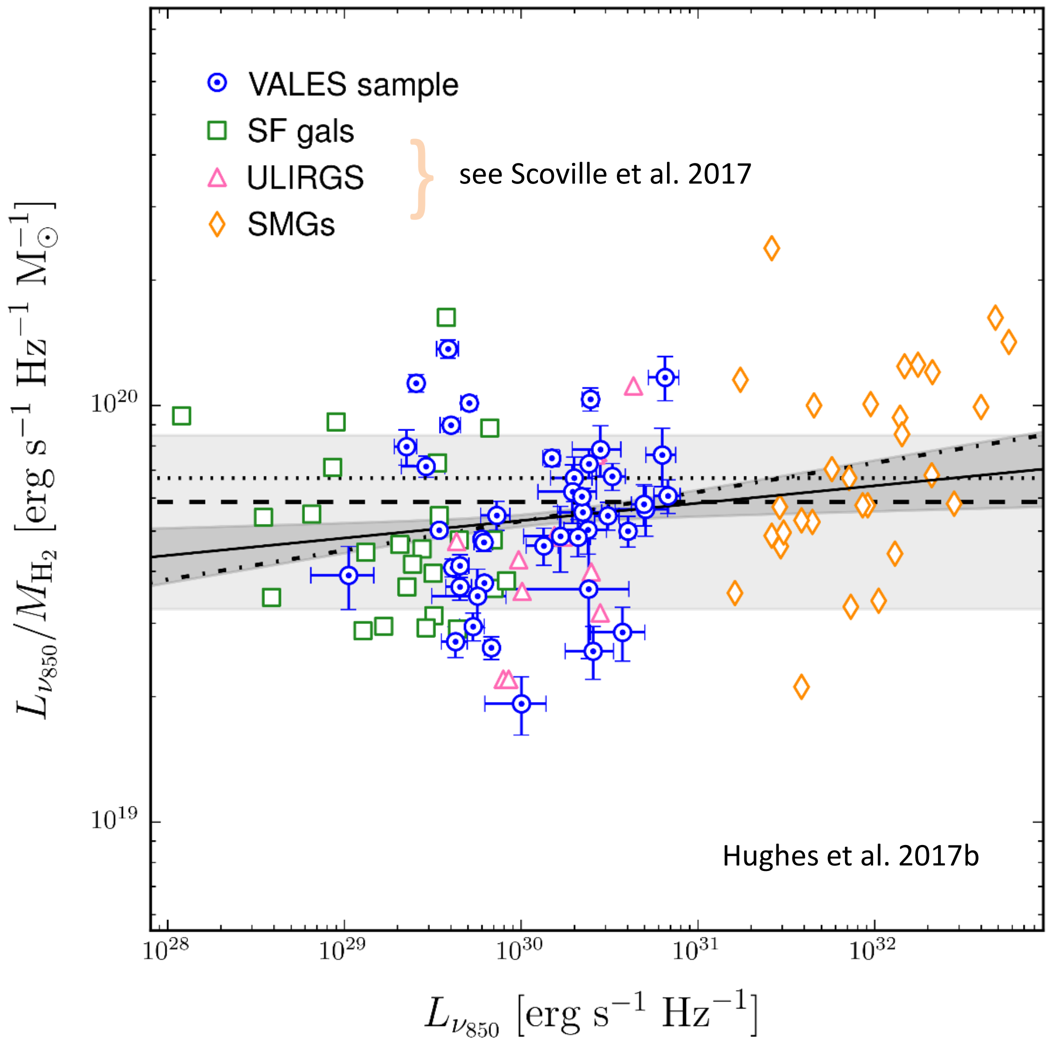

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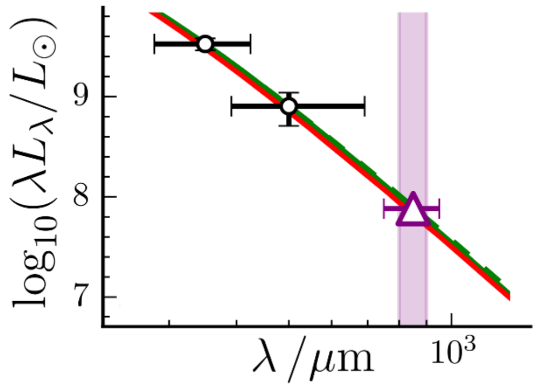


To directly observe the dust-to-gas ratio, awarded:

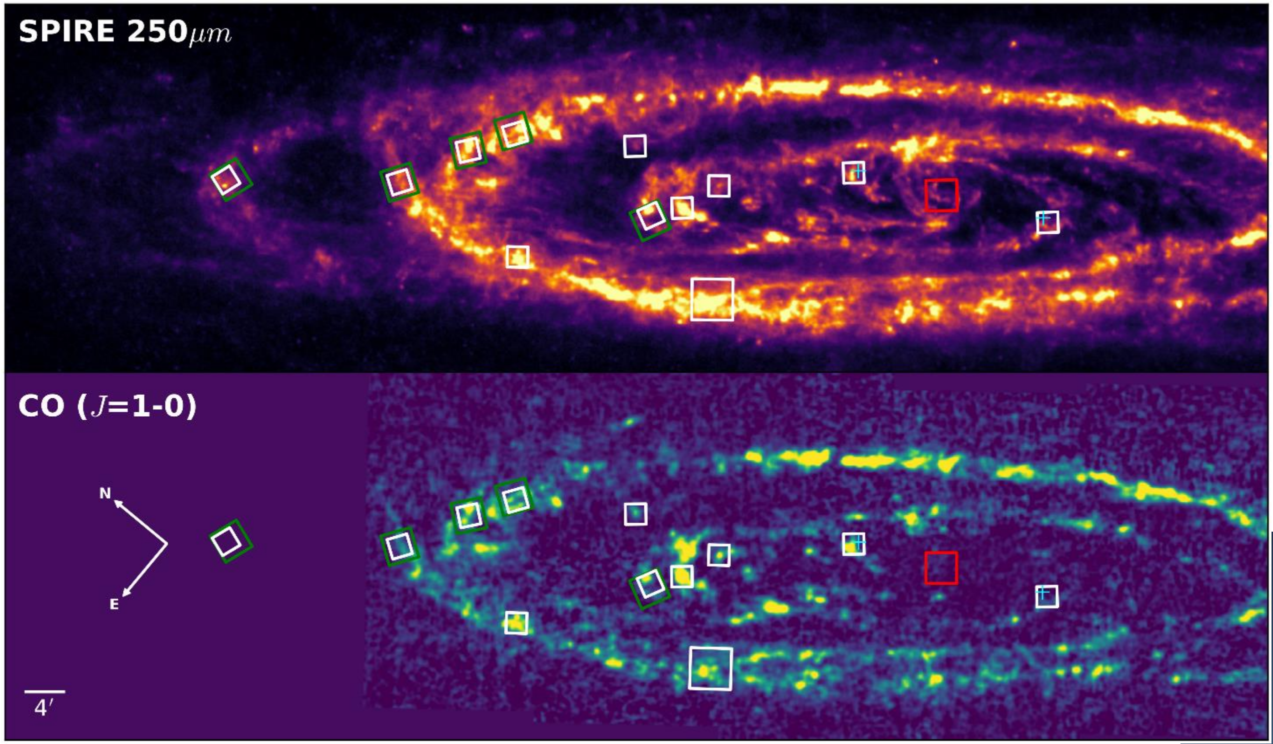
- 11 hrs on ALMA
- 35 hrs on VLT with MUSE
- 22 hrs on APEX

+ other proposals.

Introducing HASHTAG

HARP and SCUBA-2 High-resolution Terahertz Andromeda Galaxy Survey

(P.I.s A. Chung, C. Kemper, Z. Li, M. Smith, T. Takeuchi, C. Wilson)



JCMT Large Program (300 hrs) to map Andromeda at 450 and 850 µm, and CO(3-2) in selected star-forming regions.

Joined the program as a USTC Fellow, will observe at JCMT when program starts in Oct.

Summary

- Understanding the evolution of galaxies in the Universe requires knowledge of the gas content and physical conditions, and how these relate to star formation.

- The derived gas content and physical conditions in VALES are comparable to normal star-forming galaxies in the local Universe.

- An observed increase in gas density with redshift persists regardless of adjustments, but potential biases highlight a systematic study is necessary.

References: **VALES I:** Villanueva et al. 2017, arxiv:1705.09826
VALES II: Hughes et al. 2017a, arxiv:1611.05867
VALES III: Hughes et al. 2017b, arxiv:1702.07350
VALES IV: Cheng et al. 2017, submitted

Acknowledgements

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CAS-CONICYT Joint Postdoctoral Research Fellowship 3rd Call 2017 + CONICYT/ALMA funding Program in Astronomy/PCI Project N:31140020

IMAGE CREDITS:

Stefan Binneweis, www.capella-observatory.com

Large Synoptic Survey Telescope

East Asian Observatory

NASA, ESA, and the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration