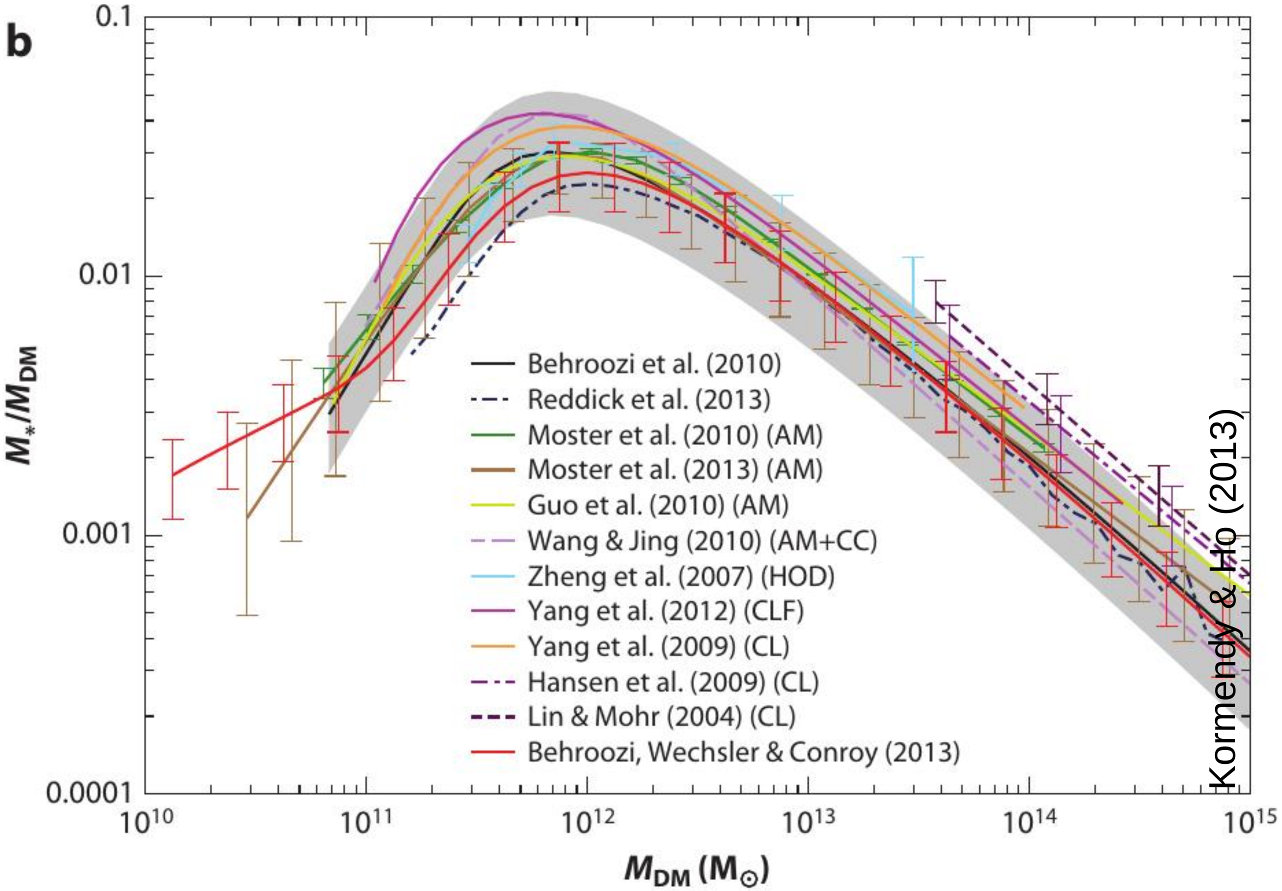
Self-regulated growth of the most vigorously, gravitationally lensed, star-forming galaxies at high redshift

Planck's Dusty GEMS.

Nicole Nesvadba & Raoul Canameras, Institut d' Astrophysique Spatiale (Orsay), A. Beelen, M. Bethermin, F. Boone, R. Chary, H. Dole, E. Le Floc'h, R. Gavazzi, M. Gerin, R. Kneissl, S. Koenig, G. Lagache, M. Limousin, S. Malhotra, L. Montier, M. Negrello, A. Omont, G. Petitpas, D. Scott

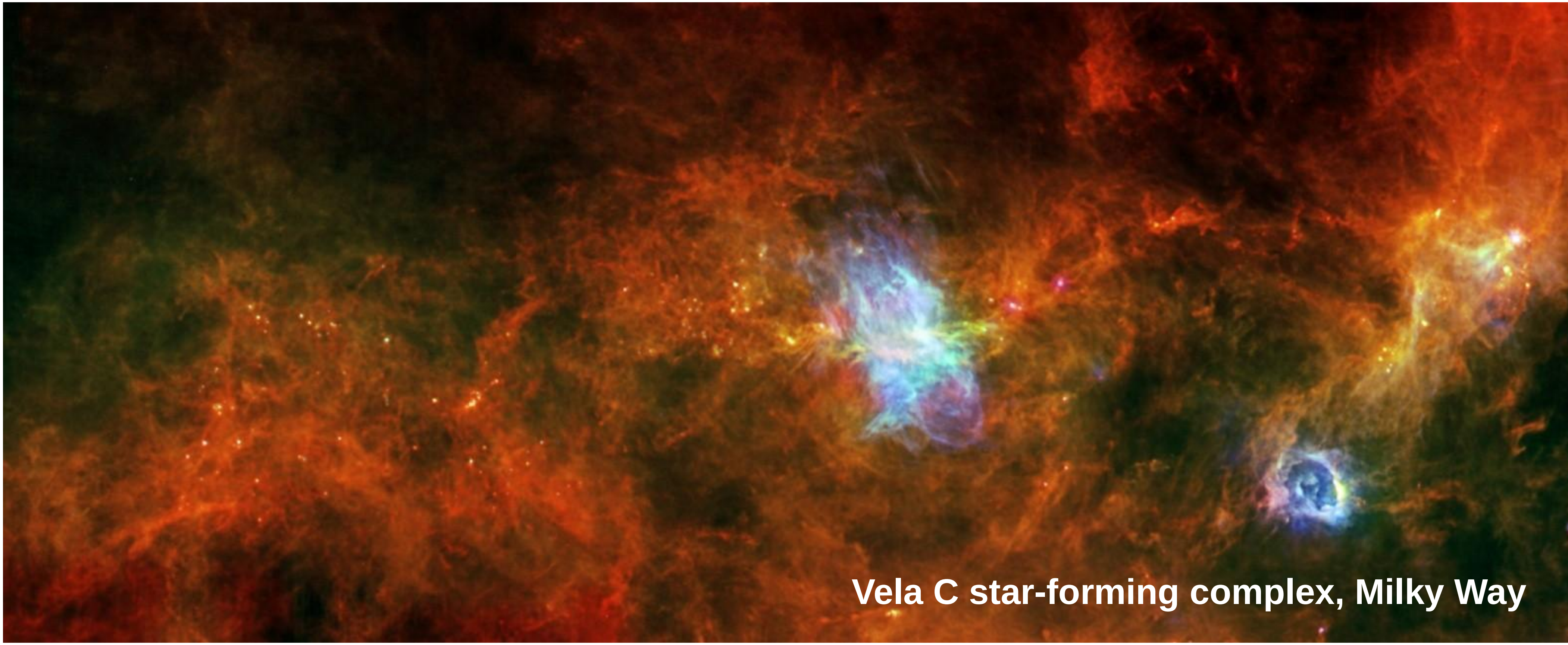
Why don’t galaxies form more stars?



Kormendy & Ho (2013)

Cosmic baryon cooling onto galaxies is ***highly inefficient***: ~20% of cosmic baryon fraction at best (at 10^{12} M_{DM} halo mass), even less in higher and lower mass halos

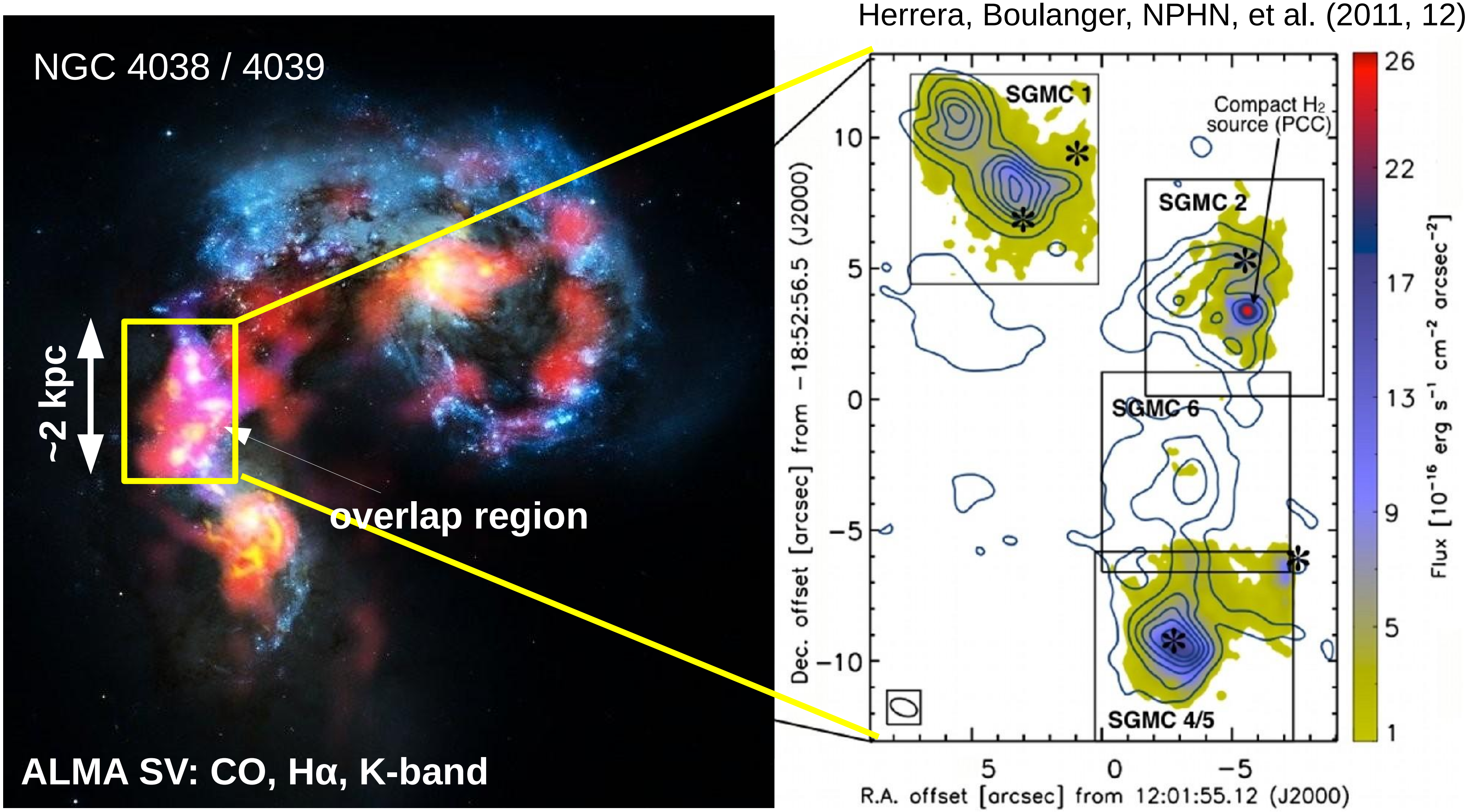
What limits the most intense star formation in the early Universe?



Vela C star-forming complex, Milky Way

Hill et al. (2012)

From global to local regulation of star formation



Herrera, Boulanger, NPHN, et al. (2011, 12)

$$\boldsymbol{\sigma_t\, \Omega / \pi\, G\, \Sigma > 1}$$

Shear dominates stability (Toomre 1964, Romeo et al. 2010, Escala et al. 2013)

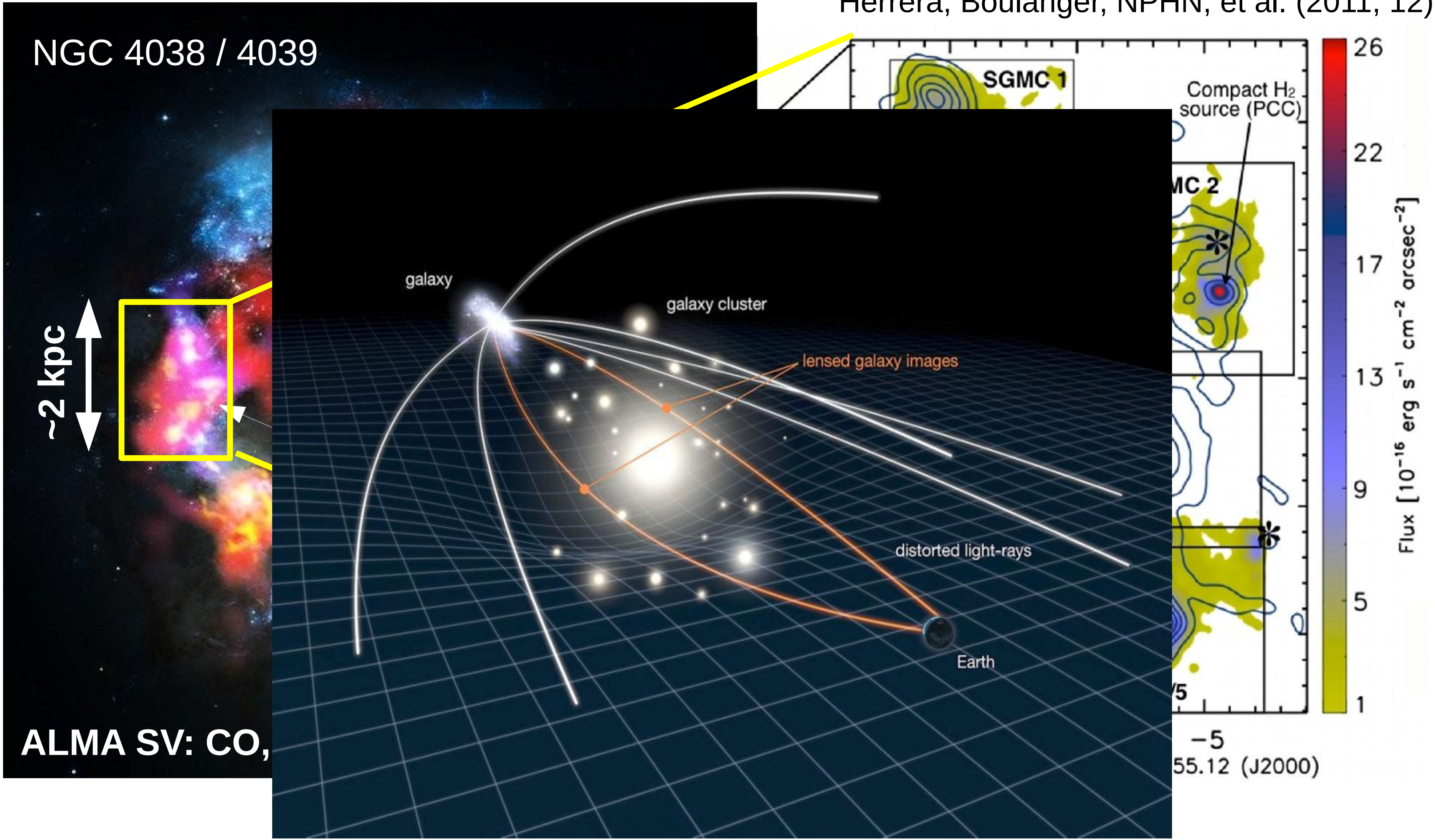
~100 pc → 0.0125” @ z~2

Local internal pressure

(radiation, turbulence, CR)

From global to local regulation of star formation

Herrera, Boulanger, NPHN, et al. (2011, 12)



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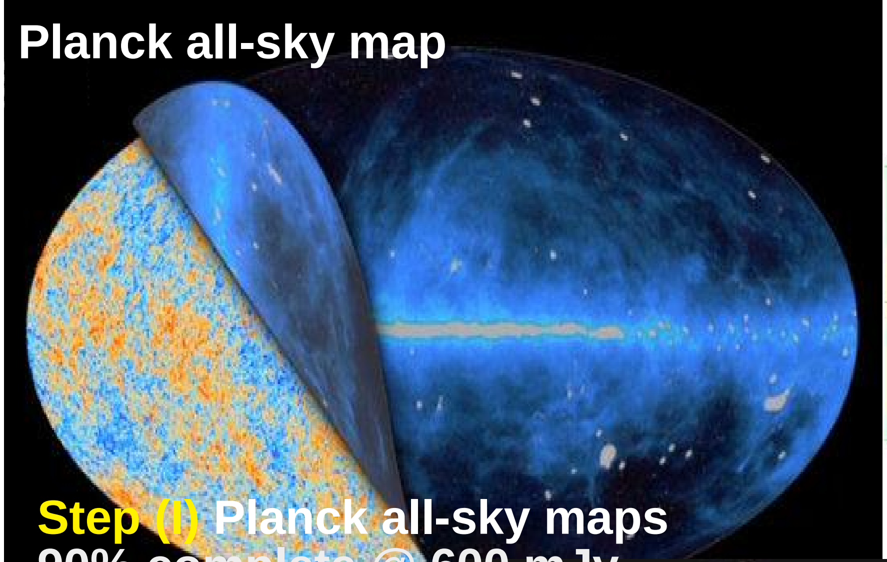
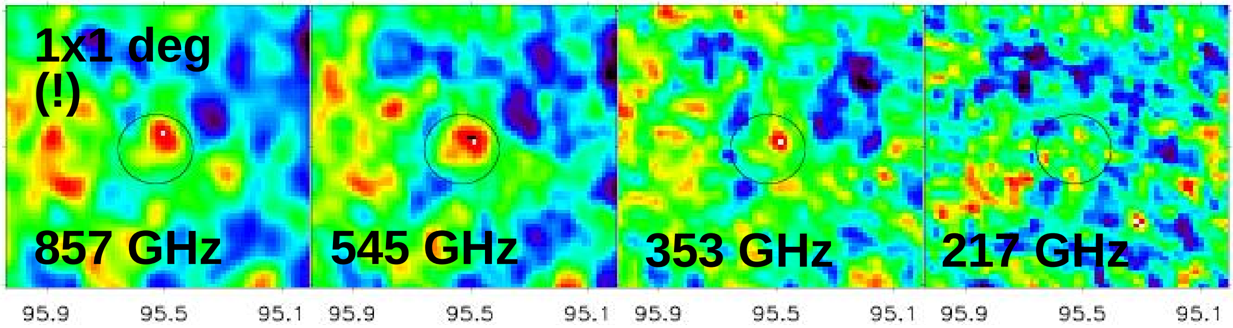
Planck's Dusty GEMS



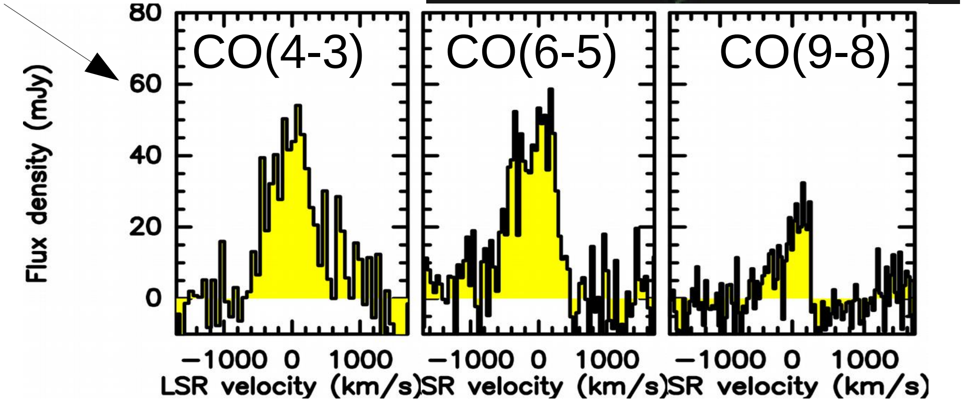
Step (I) **Planck all-sky maps**
90% complete @ 600 mJy
$\sim 5\mathrm{x}10^{13}\ L_{\odot}$ @ z=2



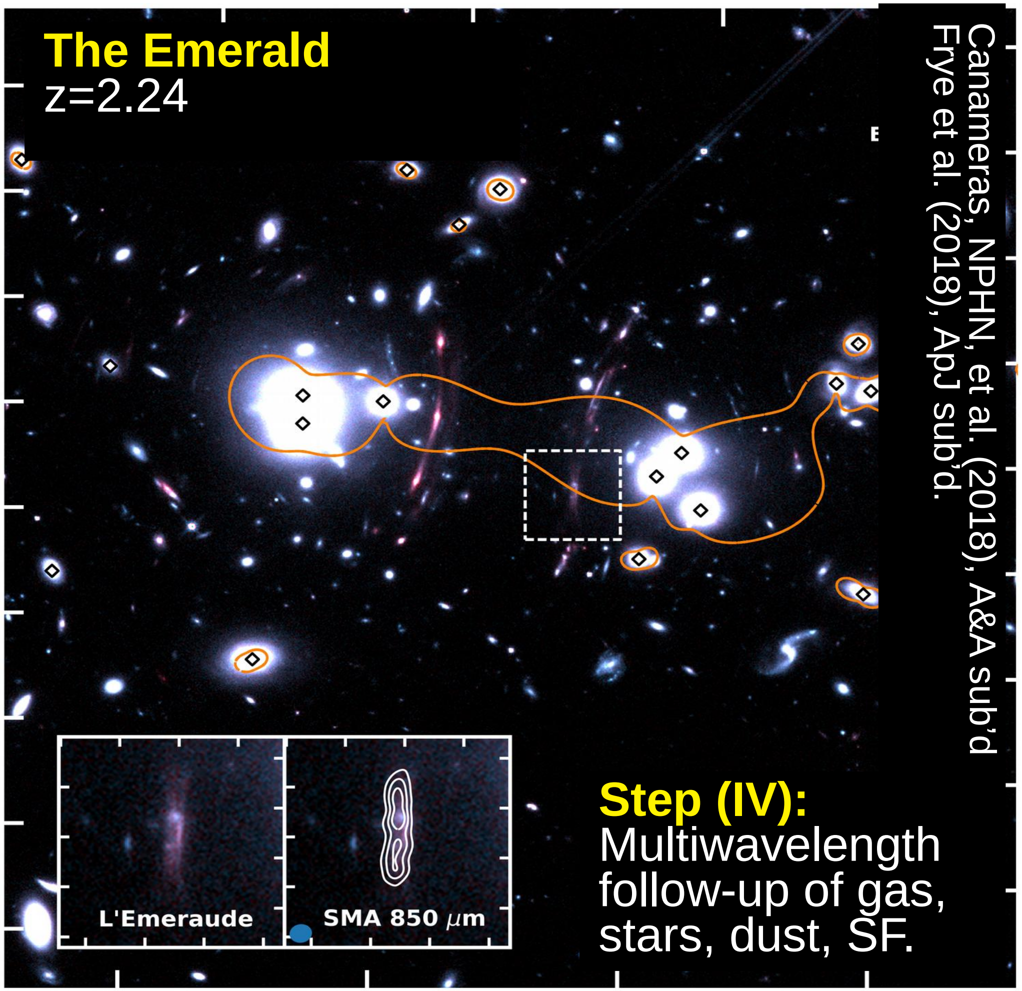
High-z color selection $S_{875GHz}/S_{575\ GHz} > 1.5$, $S_{216\ GHz} < S_{353\ GHz}$

Step (II)
SPIRE follow-up
15" beam size

Step (III)
IRAM blind spectroscopic survey



Redshifts: $z_{spec} = 2.2 – 3.6$



The Emerald
z=2.24

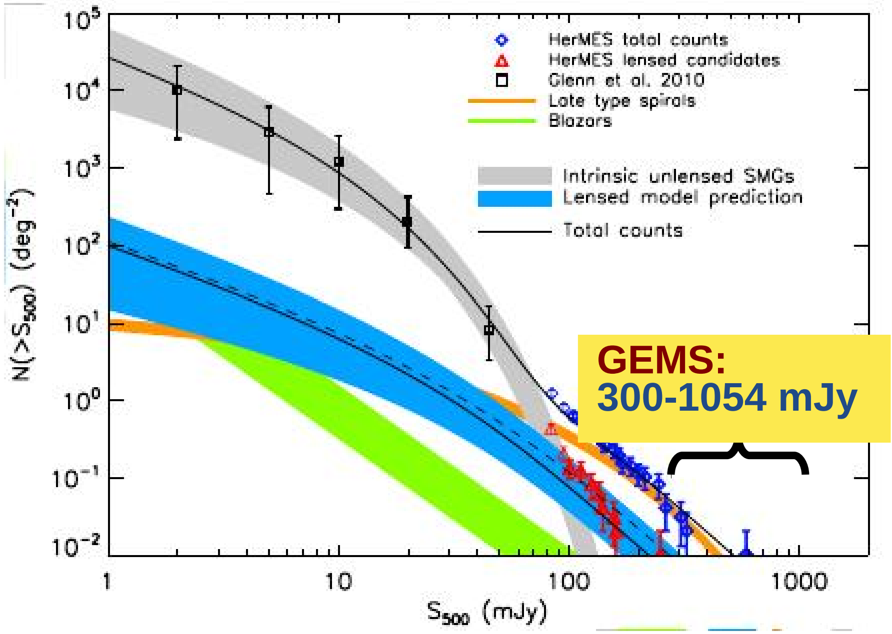
Canameras, NPHN, et al. (2018), A&A sub'd
Frye et al. (2018), ApJ sub'd.

Step (IV):
Multiwavelength follow-up of gas, stars, dust, SF.

Intense starbursts without obvious AGN

Planck Collaboration XXVII (2015), A&A 582, 30
Canameras, NPHN, et al. (2015), A&A 581, 105

Wardlow et al (2013)



GEMS:
300-1054 mJy

Luminous FIR sources

$\mu L_{FIR} = 10^{13\text{-}14} L_\odot$ ($\mu \sim 10\text{-}50$)

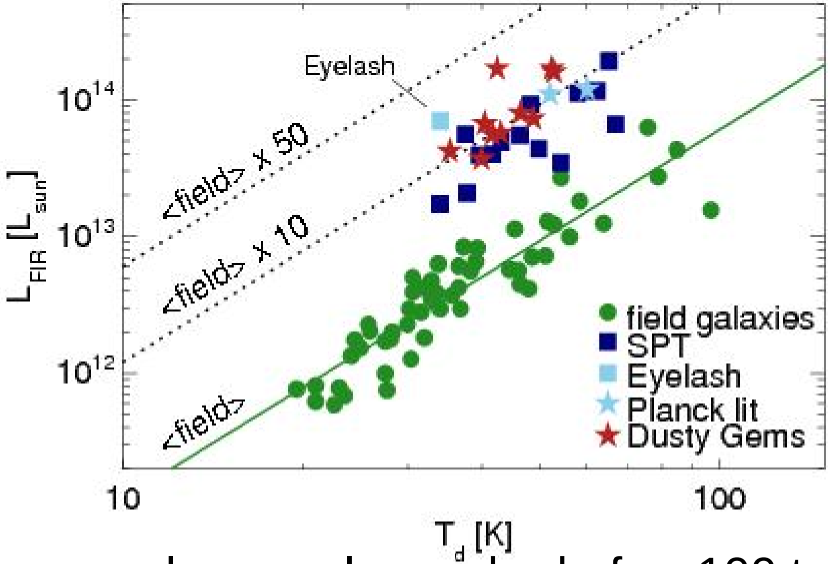
Little evidence for bright AGN

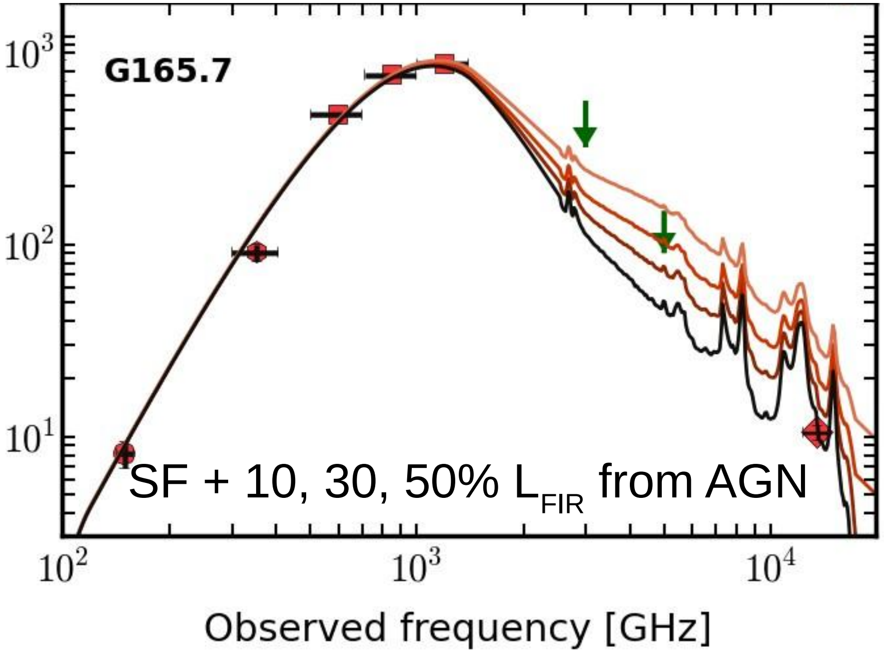
IRAS / WISE / SOFIA photometry
& unconspicuous FIR-radio correlation

Starburst-like dust temperatures

$T_d \sim 30\text{-}50$ K

L'_{CO}/M_{dust} = 40 - 140 → **$\alpha_{CO} \sim 1$ → α_{ULIRG}**





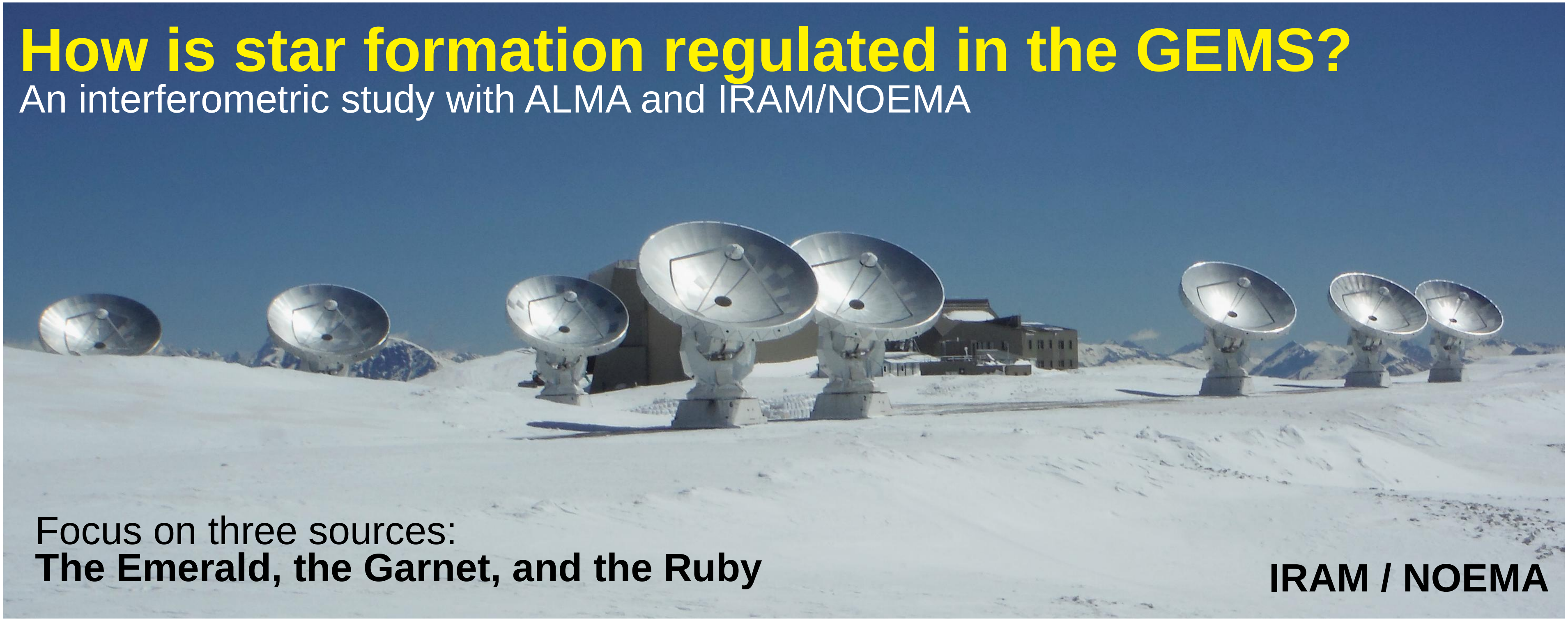
SF + 10, 30, 50% L_{FIR} from AGN

Source-plane scales probed ~few 100 to ~60 pc

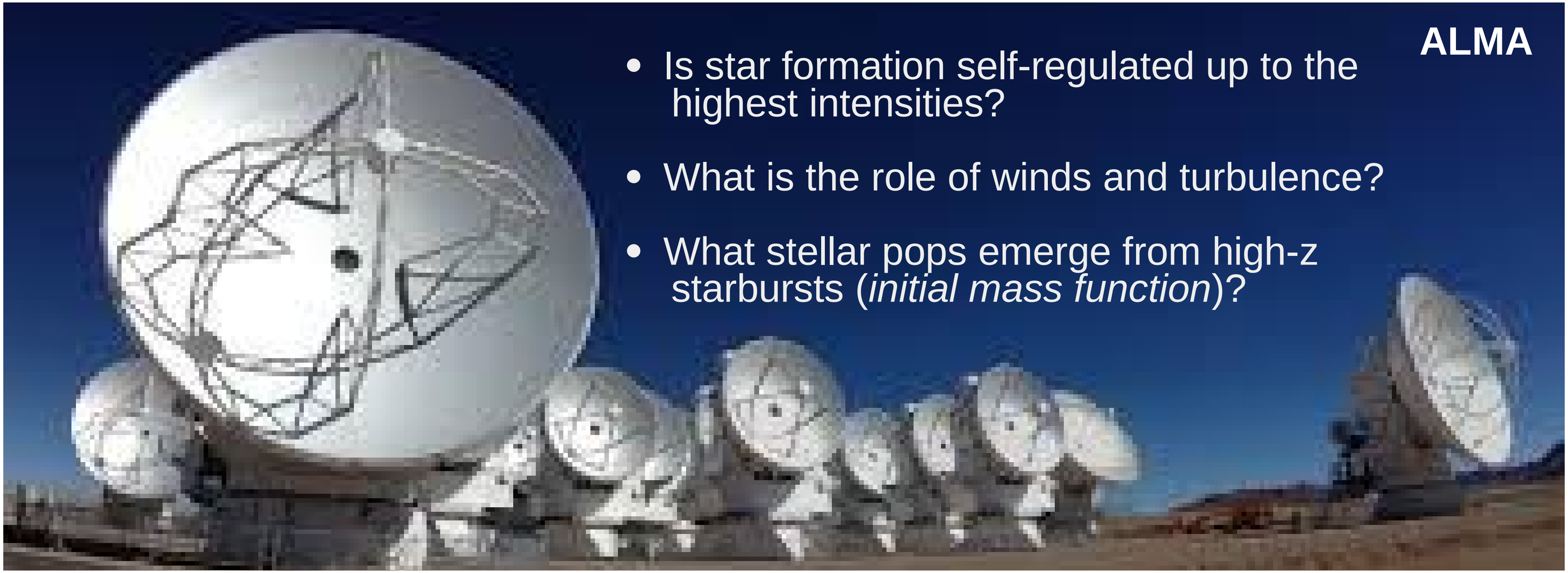
Detailed lens models (HST+lenstool) for all GEMS.

How is star formation regulated in the GEMS?

An interferometric study with ALMA and IRAM/NOEMA



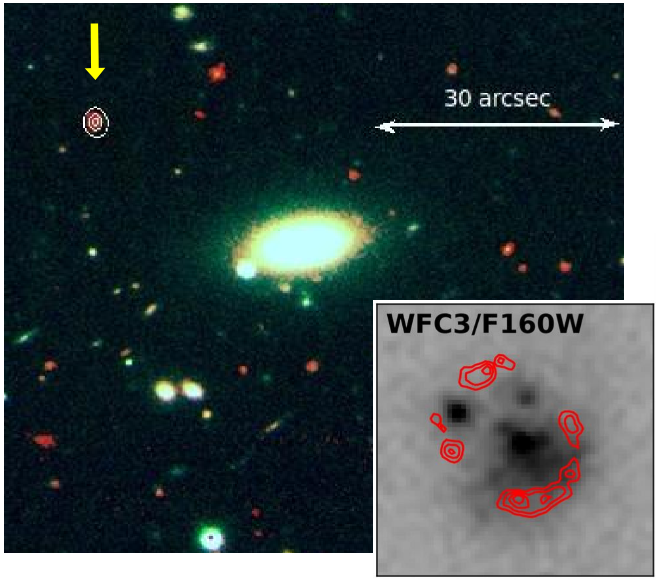
Focus on three sources:
The Emerald, the Garnet, and the Ruby



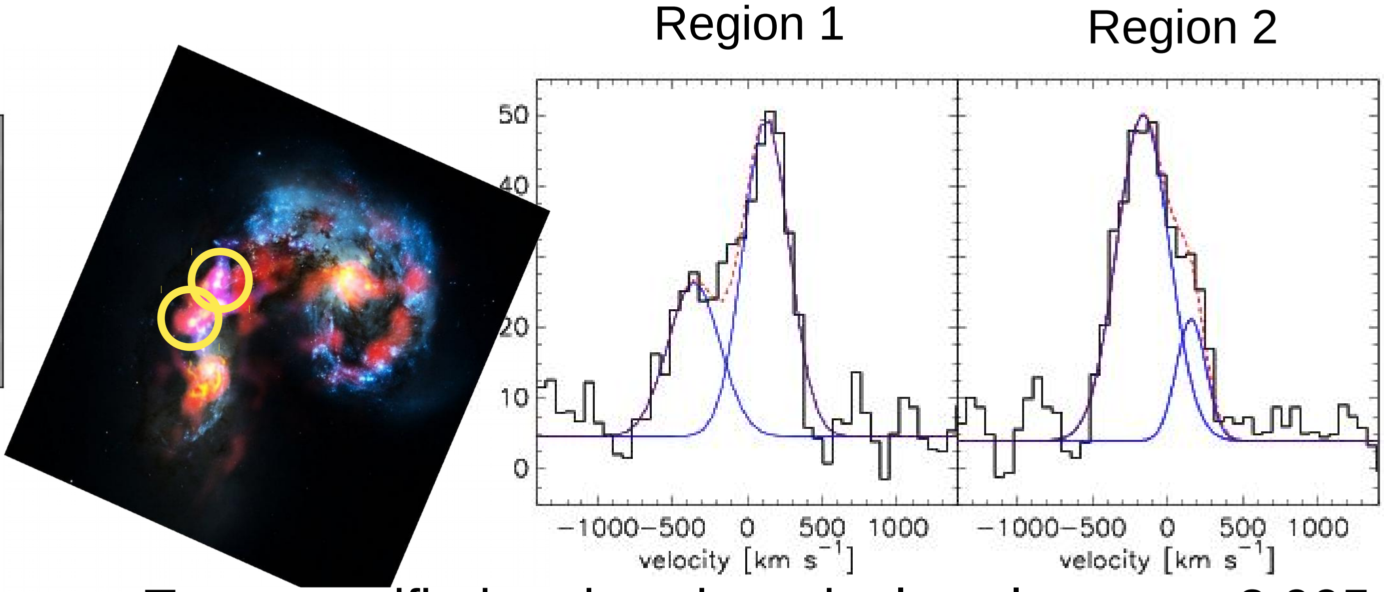
- Is star formation self-regulated up to the highest intensities?
- What is the role of winds and turbulence?
- What stellar pops emerge from high-z starbursts (*initial mass function*)?

The Ruby: The brightest high-z galaxy on the sub-mm sky

Canameras, NPHN, Kneissl et al. (2017a), A&A 604, 117

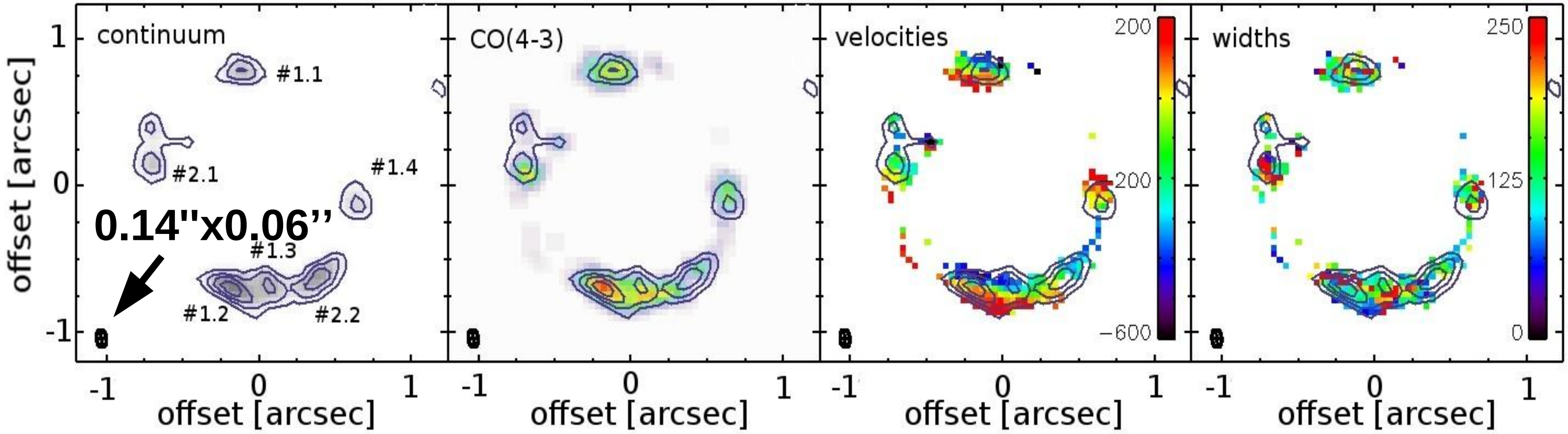


ALMA 13 km baseline, 0.1” beam:
60 – 160 pc source-plane resolution



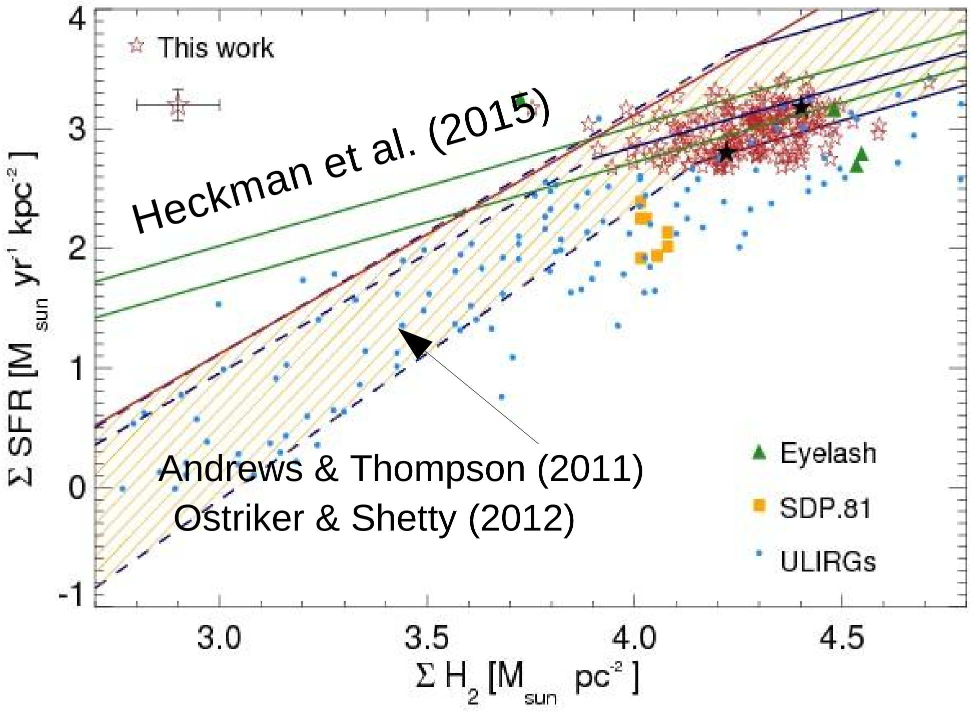
- SFR = 1400 $M_\odot$ yr^{-1}
- Δv ~ 550 km s^{-1}
- σ = 25 – 200 km s^{-1}
- Σ_{dyn} = few 10^{10} $M_\odot$ kpc^{-2}

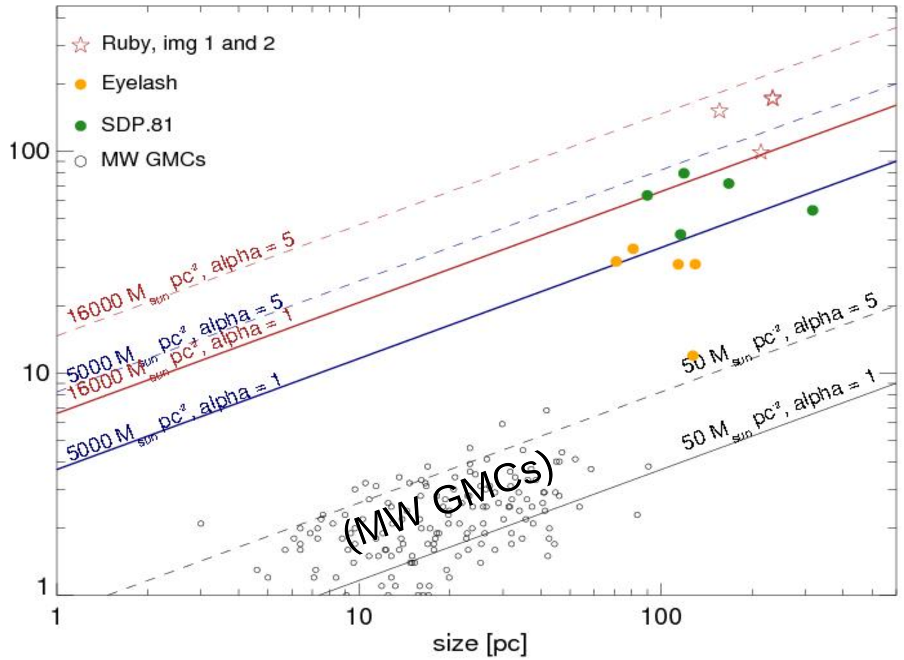
Two magnified regions in a single galaxy at z=3.005
~1 kpc in size each, 0.5 kpc apart


0.14"x0.06’’

A peculiar high-z mode of star formation?

… rather not!





Local SFR (~50-100 pc) similar to model predictions for self-regulated star formation.

Constraints from total energy injection:
Radiation pressure? Kinetic energy from stellar winds and SNe? …. perhaps both ??

$$\boxed{SFR/\ t_{ff} = 1 – 9\ \%\ M_{gas}}$$

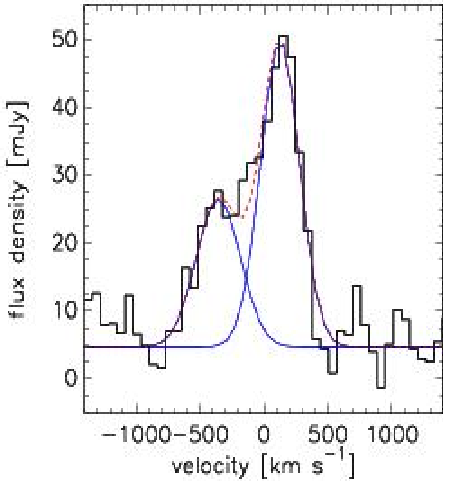
Self-regulation through turbulence?

Virial parameter:

$$5\ \sigma_t^2 / \pi\ G\ R\ \Sigma_{gas}$$

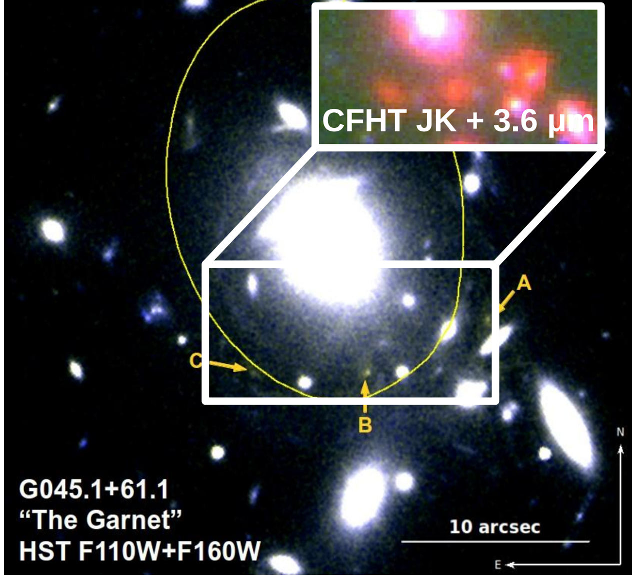
$$E_{turb} = E_{grav}$$

$$\boxed{\alpha = 1 - 5}$$



Canameras, NPHN, Kneissl et al. (2017a), A&A 604, 117

Clouds on the Garnet



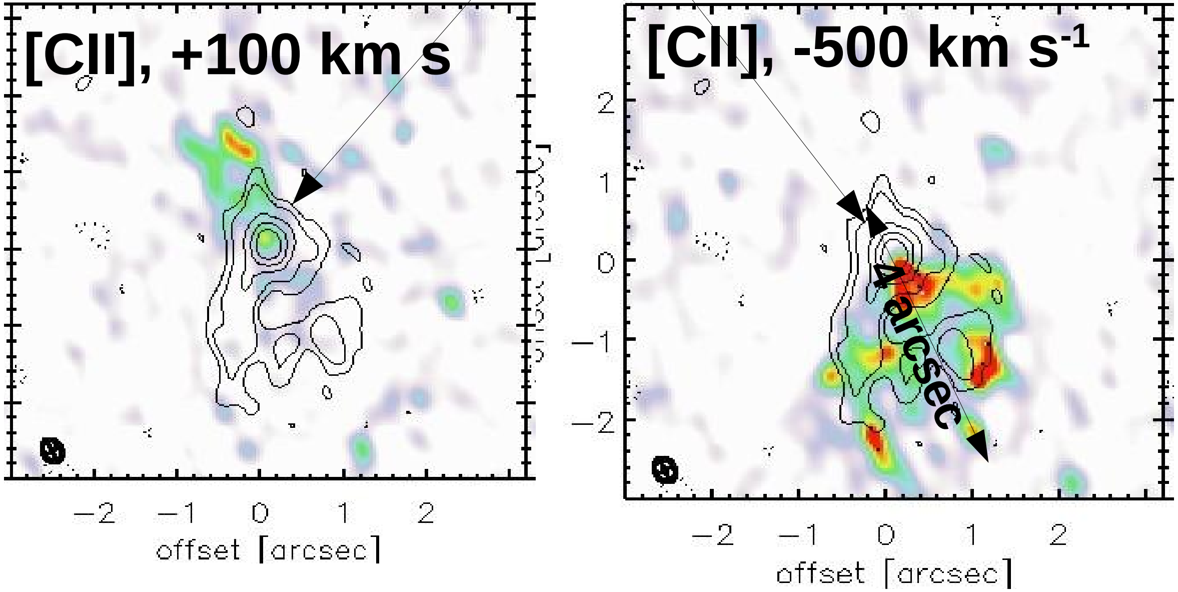
Generally, GEMS show little evidence of molecular outflows, in spite of extreme $\sum_{\mathrm{SFR}}$

The Garnet, *z*=3.4

Clump

SFR ~ 200 $M_\odot$ /yr /kpc^2

[CII] channel maps



ALMA band 9 –
[CII] interferometry, 0.4'' beam

Emission-line gas:

- R ~ 100-200 pc (source plane)
- **FWZI ~ 1000 km s^{-1}**

Momentum input from SF (wind & radiation pressure):

SFR = 400 $M_\odot$ yr^{-1} → 1.9x10^{36} dyn (Heckman et al. 2015)

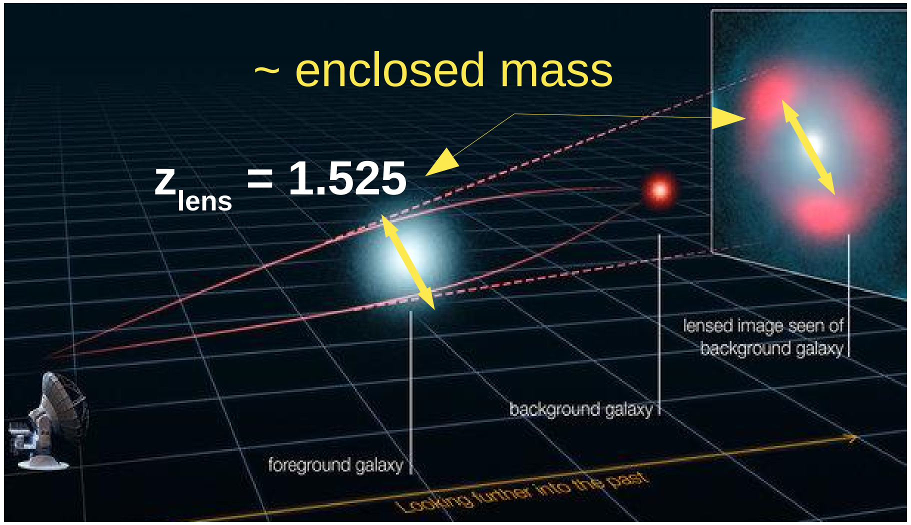
Momentum to unbind the gas: 2 x 10^{36} dyn, **~ need 10x more for outflow**

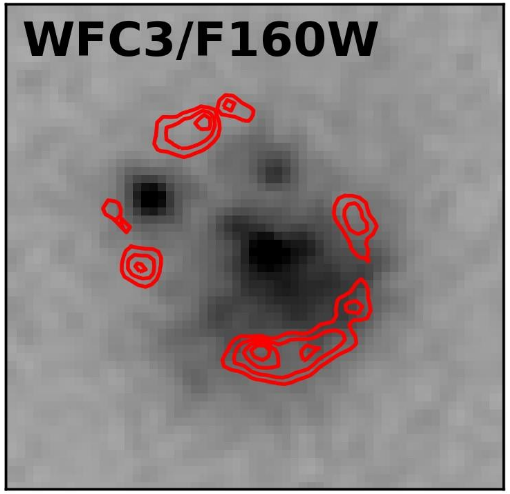
NPHN, Canameras, et al. (2016), A&A 593, L2

Gas escape unlikely. SF regulation?

Probing the outcome of a past starburst …

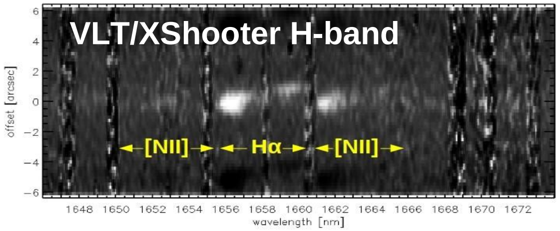
Direct IMF measurement at z=1.5





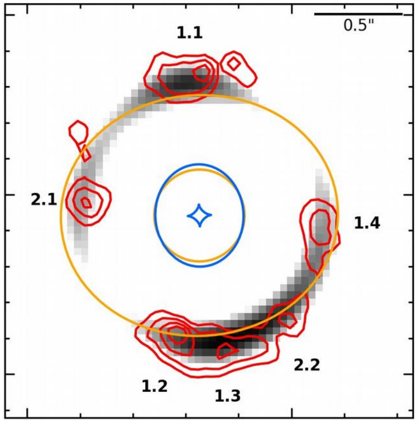
Stellar initial mass function:

- universal,
- top or bottom-heavy?
- Redshift-dependent?

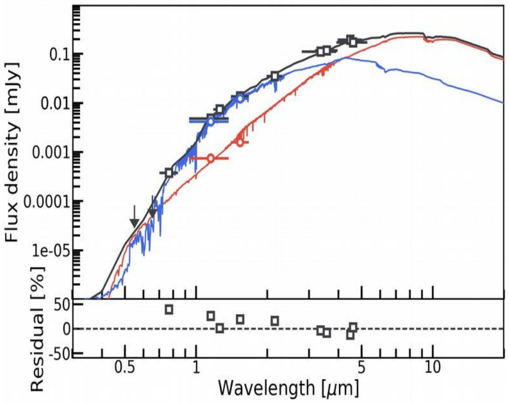


Sub-mm / NIR bands: Very clear separation of foreground and background galaxy

Lensing mass



Stellar mass



Total mass ≤ R=6.7 kpc

M_{lens} =(3.7±0.4)x10^{11} $M_\odot$

(Lenstool)

Chabrier IMF

M= 2.0-2.5 x 10^{11} $M_\odot$

Salpeter IMF

M= 3.4-4.3 x 10^{11} $M_\odot$

“Bottom-heavy” IMF

Chabrier ruled out at 5σ

✘ SAM expectations, challenges cosmic mass assembly history

✔ direct observations out to *z*≈0.8

Canameras, NPHN et al. (2017b), A&A 600, L3

Summary

+ 11 brightest individual high-z galaxies from Planck:
- intense starbursts, strongly lensed, no significant AGN (FIR and radio)

+ Turbulence-regulated star formation at the Eddington limit
- consistent with expectations from analytical models.
- radiation pressure + winds provide enough energy and momentum
- $E_{turb} \sim 1\text{-}5 \times E_{grav}$ + SFE ~ 0.01-0.09

→ ***Universal 'unboundedness', universal star-formation law?***

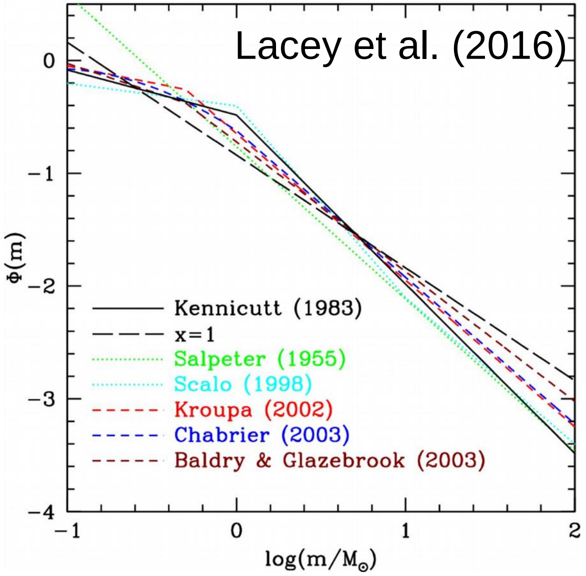
+ Little evidence for 'classical' gas depletion through winds
- little evidence of strong molecular outflows, in spite of extreme gas kinematics

… where outflow components are seen, they are high mass, low velocity

→ they can leave the clumps, but not the galaxy!
→ galactic fountains and cyclical fueling of starburst?
→ short gas depletion times of few Myr → are clumps transitory structures depending on balance between gas accretion and loss?

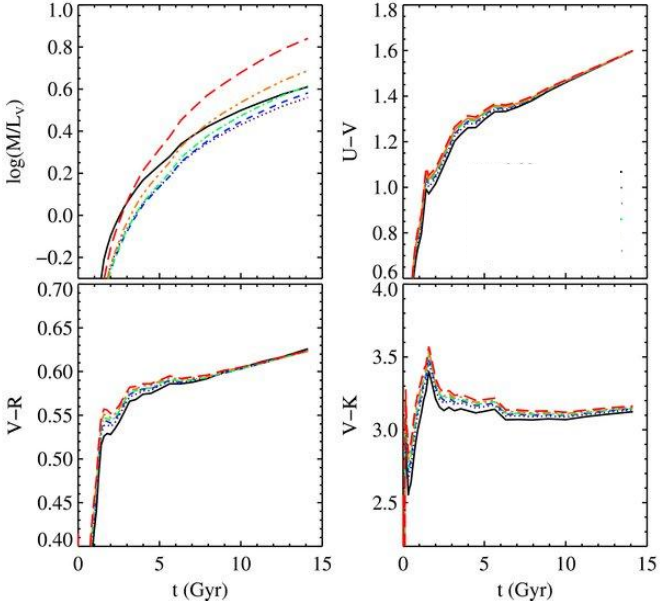
Ruby's lens: Initial mass function at z=1.52

Canameras, NPHN et al. (2017a), A&A 600, L3



Lacey et al. (2016)

Conroy et al. (2009)



Main uncertainty in stellar masses:

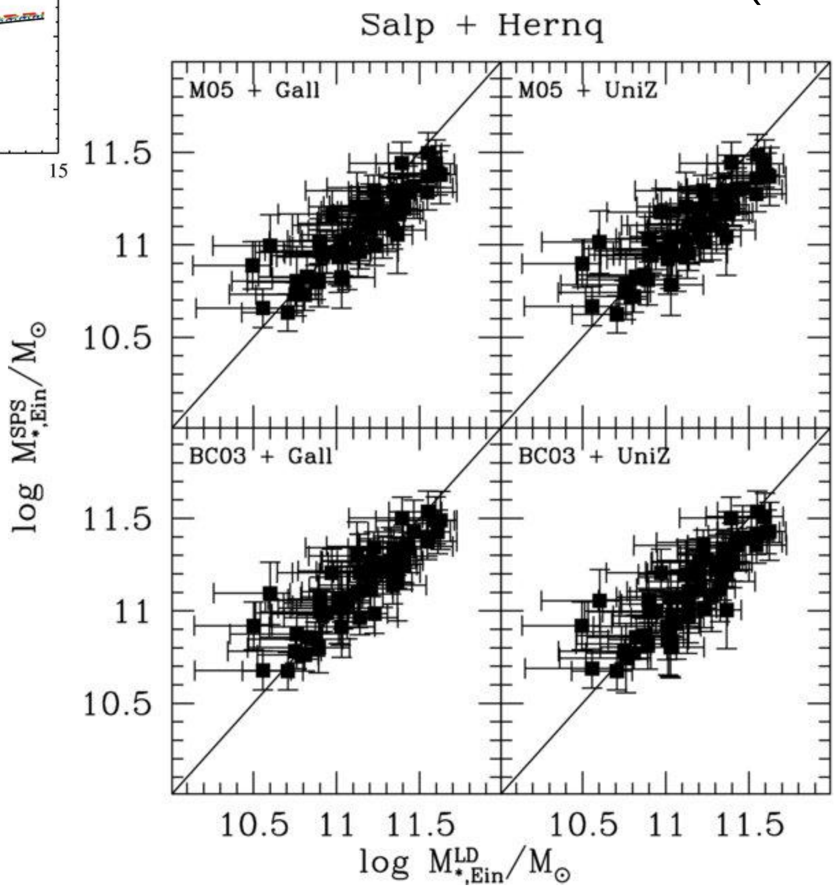
e.g., $M_{\rm stellar,Salpeter} = 1.7 \times M_{\rm stellar,Chab}$

Is the initial mass function

- ***universal?*** (e.g., Bastian et al. 2010)
- ***redshift-dependent?*** (e.g. Weider et al. 2013)
- ***top-heavy?*** (Baugh et al. 200X, Lacey et al. 2016)
- ***bottom-heavy?***
  (e.g., Treu et al. 2010, Barberi et al. 2013)

- ***Set by radiation pressure?***
  (Larsen et al. 2005, Krumholz et al. 2010)
- ***Set by turbulence?***
  (Hopkins et al. 2013, Chabrier et al. 2014)
- ***… ???***

Treu et al. (2010)



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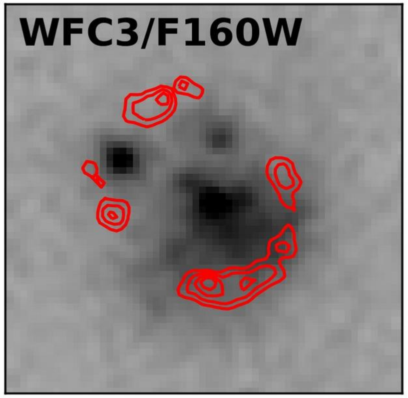
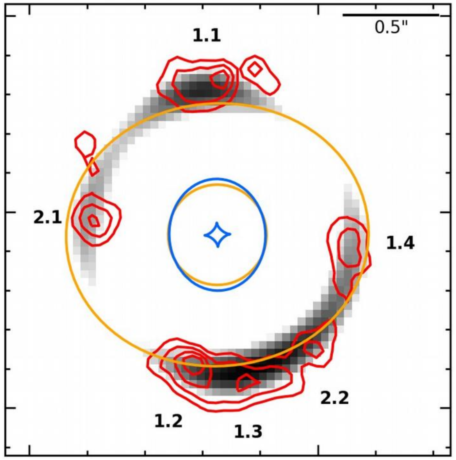
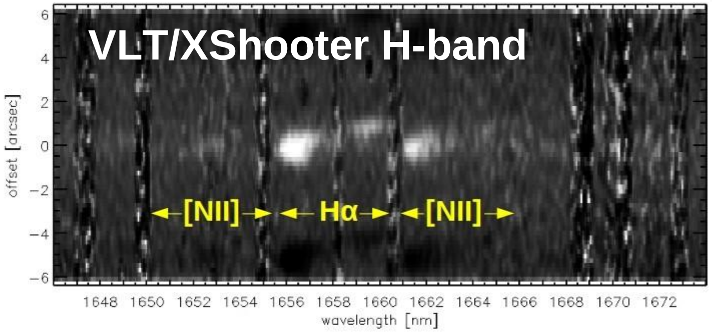
Canameras, NPHN et al. (2017a), A&A 600, L3

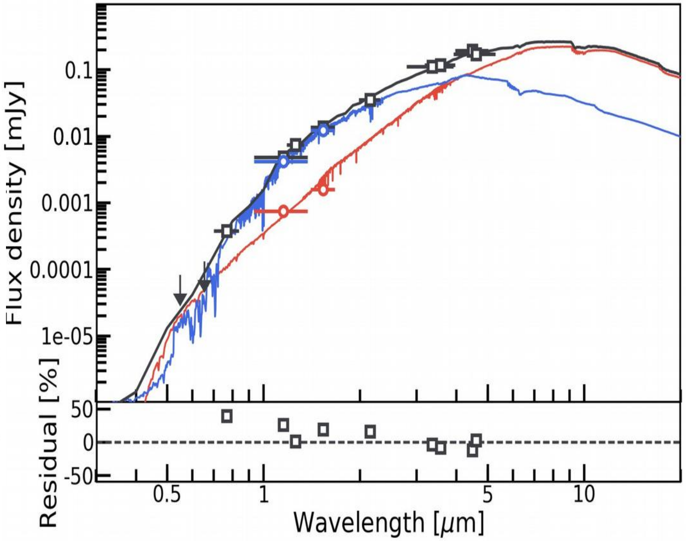


LENSING MASS





STELLAR MASS



$M_{mol} < 10^9\ M_{sun}$

[ALMA dust, IRAM CO]

$M_{DM} < 10^{10}\ M_{sun}$

[Maccio et al. 2011, Genzel et al. 2017]

Chabrier IMF

$M = 2.0\text{-}2.5 \times 10^{11}\ M_{sun}$

Total mass within R=6.7 kpc

$M_{lens} = (3.7 \pm 0.4) \times 10^{11}\ M_{sun}$ ⟷

Salpeter IMF

$M = 3.4\text{-}4.3 \times 10^{11}\ M_{sun}$

“Bottom-heavy” IMF