Powerful quasar-feedback in local and very distant galaxies

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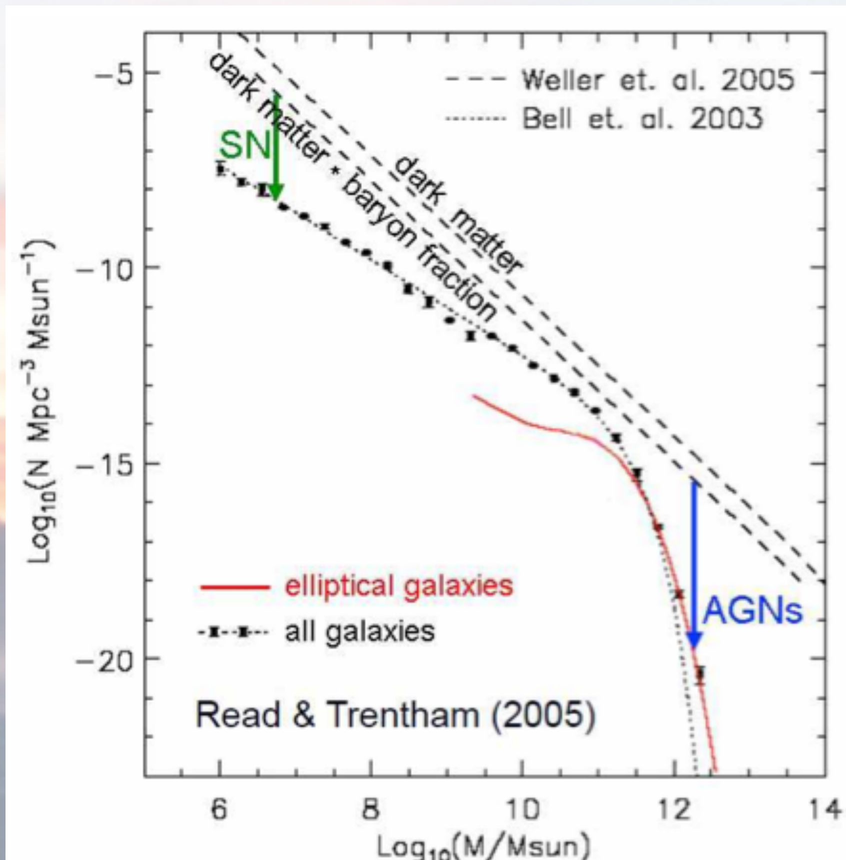
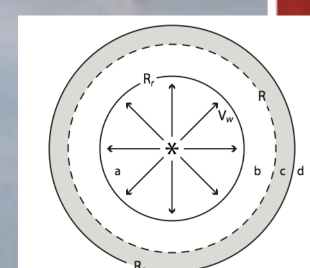
THE NEED FOR NEGATIVE FEEDBACK

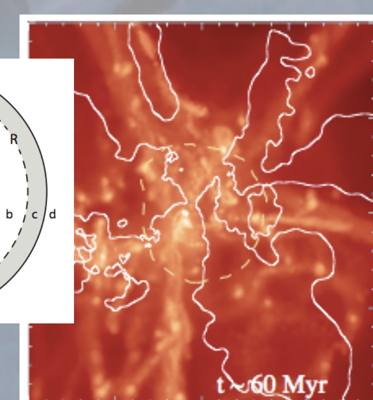
Why are feedback mechanisms invoked to **quench star formation** in galaxies?



[Kormendy & Ho 2013]

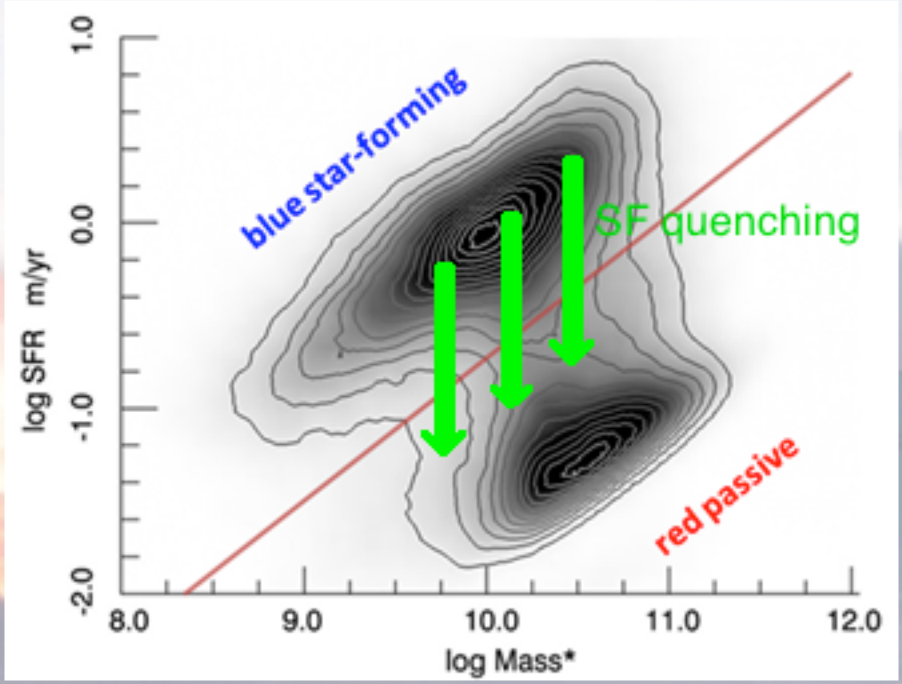
- Deficit of baryons in galaxies, especially at low and high M_*
- What causes this deficit?
  - Negative feedback from **star formation** required to keep SF efficiency low in low-M_* galaxies
  - For more massive galaxies models invoke **AGN feedback**



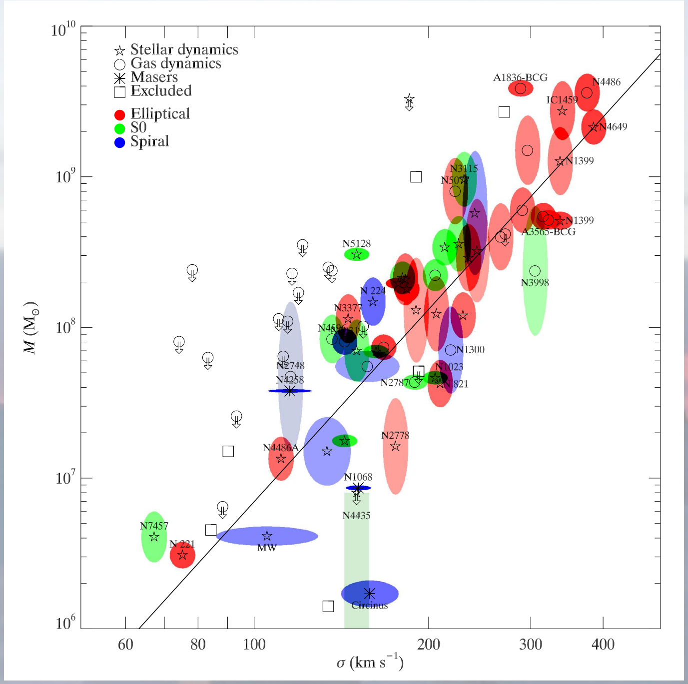


[Costa+14]

QUASAR-MODE NEGATIVE FEEDBACK



[Peng+10]



[Gultekin+09]

"Red-and-dead" properties of local and z ~ 2 massive ellipticals

Coevolution of stellar bulges and SMBH

QSO-mode feedback → Massive quasar-driven outflows

Part I

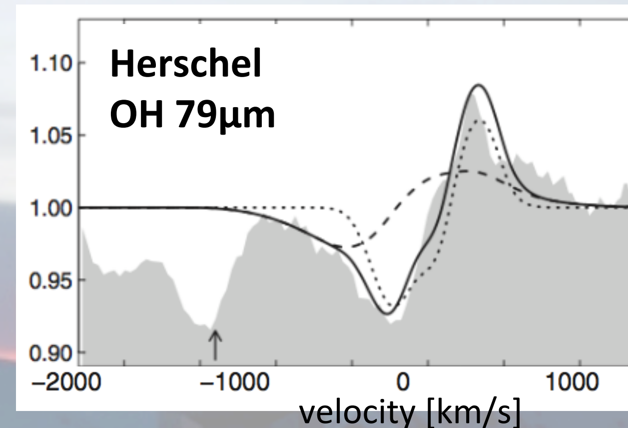
Massive molecular outflows in local (U)LIRGs

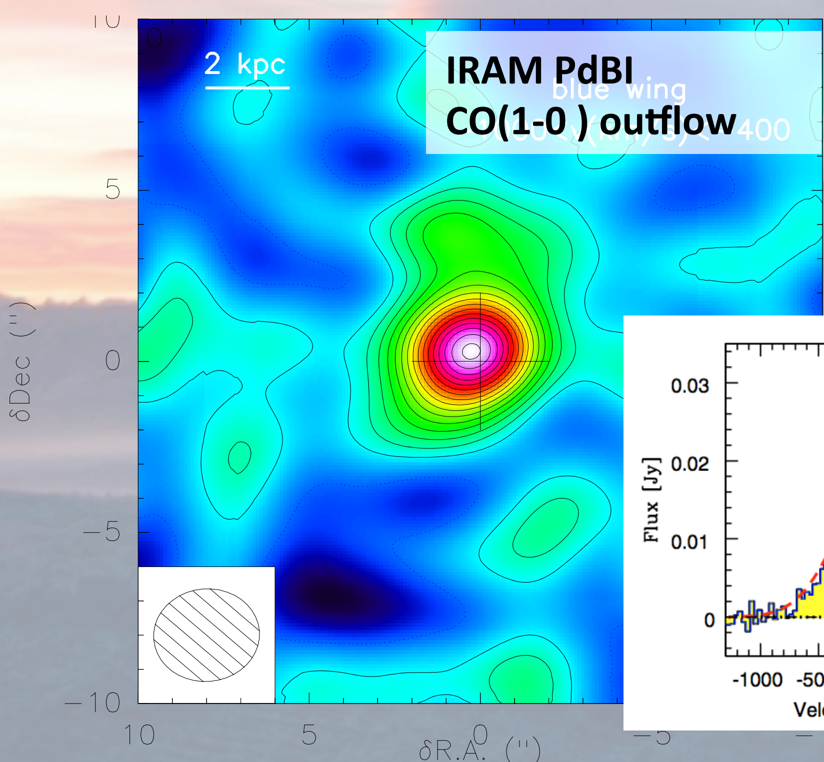
THE PROTOTYPE: MRK 231

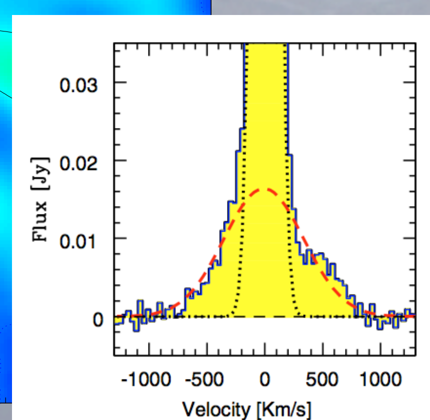
Discovery of a **massive molecular outflow** affecting galaxy on kpc scales

1) **OH and H_2O P-Cygni** profiles indicating molecular gas outflowing at **v ~ 1000 km/s**

[Fischer+10, Sturm+11]







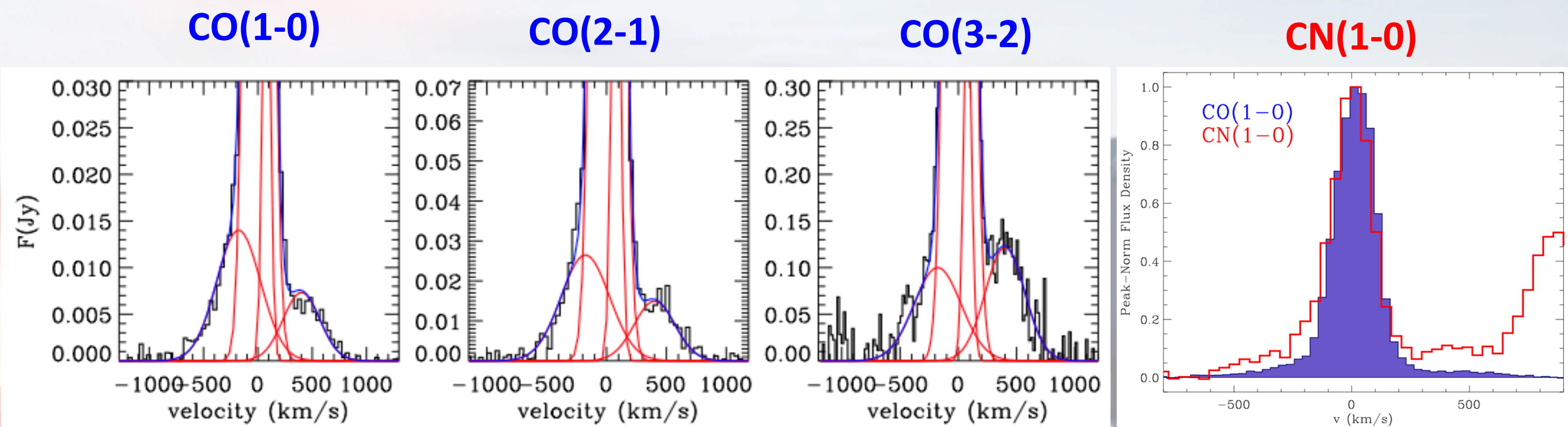
2) Broad wings of CO(1-0) line, allow to map the outflow and measure size:

- Outflow radius **~ 1 kpc**
- Outflow mass-loss rate estimate **$\dot{M}_{out}$~ 1000 $M_\odot$/yr = 5 times SFR** (outflow mass load factor η = 5)

[Feruglio+10, Cicone+12]

THE PROTOTYPE: MRK 231

Outflow detected in **multiple CO** transitions and in **dense** molecular tracers

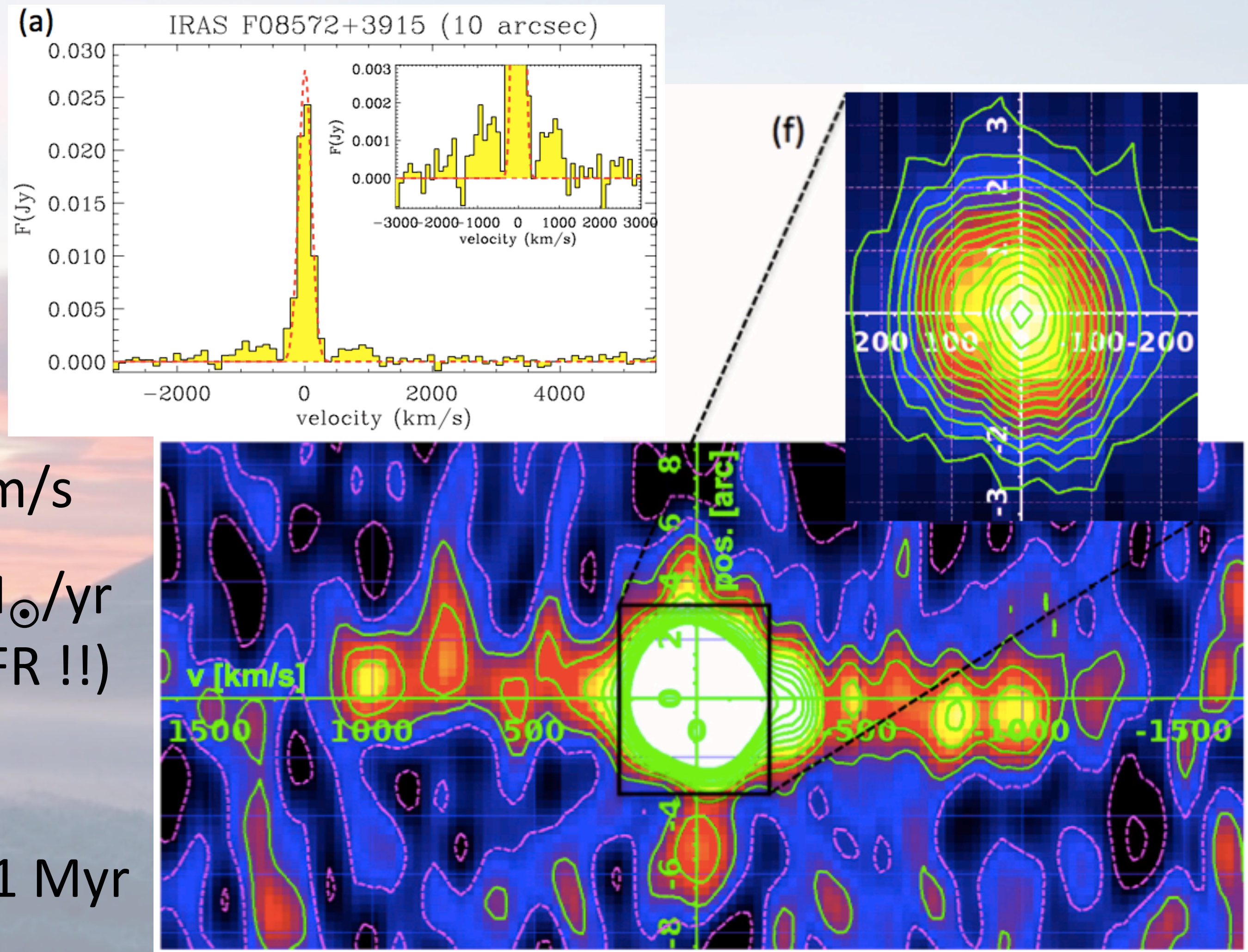


[Cicone+12, Aalto+12, Cicone+, in prep]

Open questions:

- Are CN, HCN enhanced in the outflow because of **shocks**?
- Do CN, HCN really trace **dense cores** ($n \sim 10^5$ cm^{-3}) in outflow?
- If so, how can such dense cores be **accelerated to v~1000 km/s**?
- Does dense gas instead **condense** in the outflow (i.e. positive feedback)?

IRAS F08572+3915



v_{max} ~ 1200 km/s

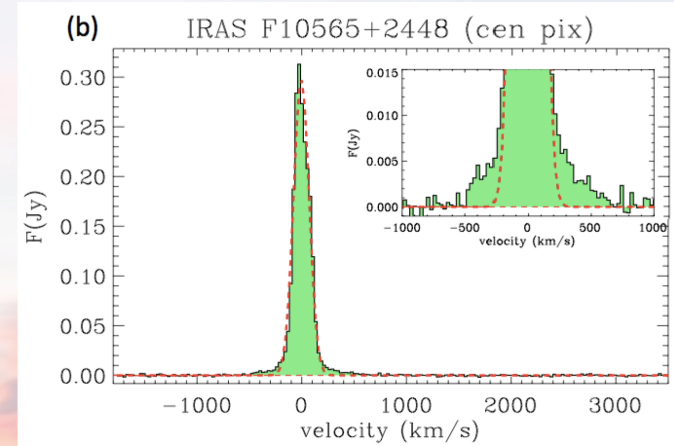
$\dot{M}_{out}$ = 1200 $M_{\odot}$/yr
(= 60 times SFR !!)

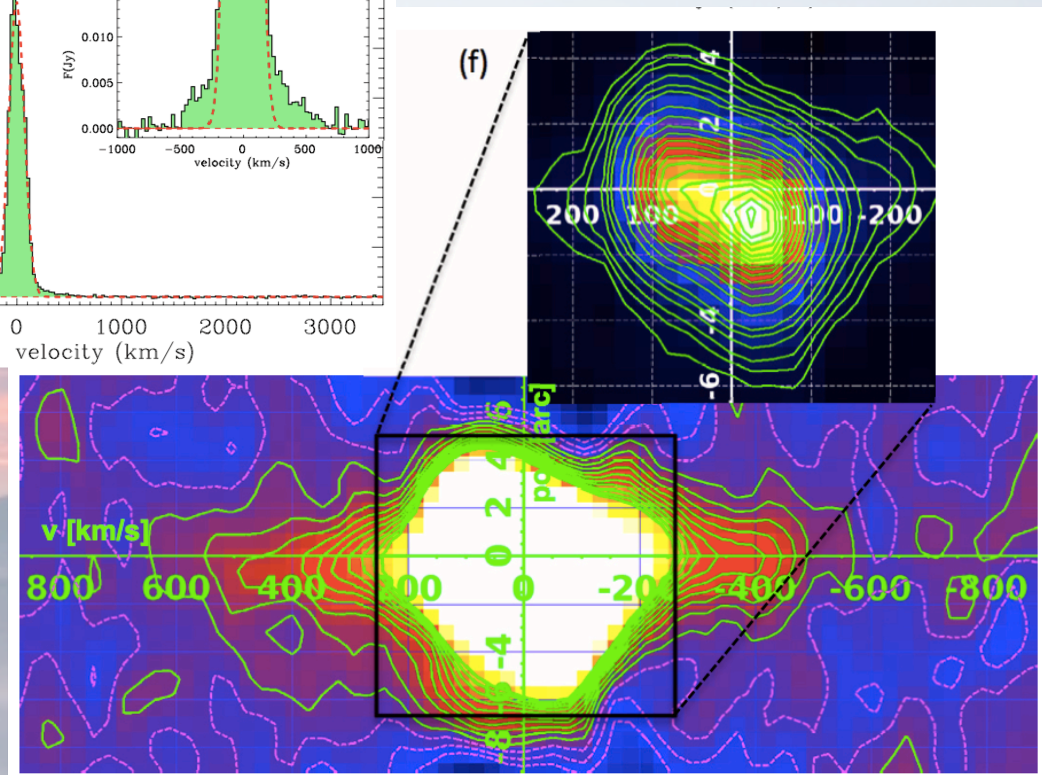
$R_{outflow}$~1 kpc

$t_{depletion}(H_2)$ ~ 1 Myr

IRAM PdBI, CO(1-0) observations, [Cicone+14a]

IRAS F10565+2448





v_{max} ~ 500 km/s

$\dot{M}_{out} = 300\ M_{\odot}$/yr
(= 3 times SFR)

$R_{outflow}$ ~ 1 kpc

$t_{depletion}(H_2)$ ~ 30 Myr

[Cicone+14a]

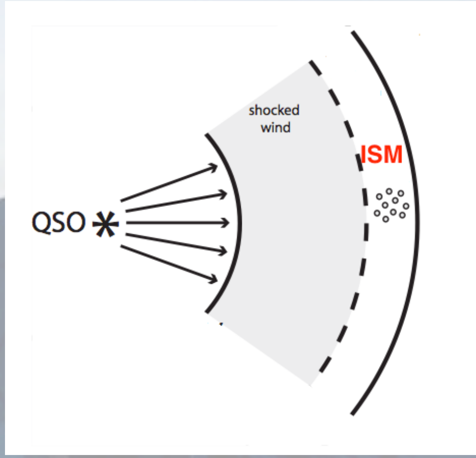
Massive molecular outflows seems **relatively common in (U)LIRGs**

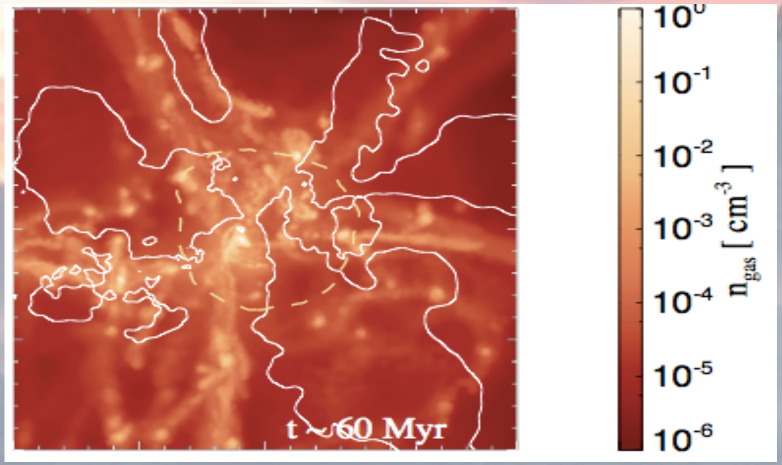
[*some* refs: Cicone+12,14a, Feruglio+10,13, Aalto+12, Alatalo+11, Garcia-Burillo+14 Combes+13, Sturm+11, Veilleux+13, Spoon+13]

A QUICK LOOK AT MODELS..

Blast-wave models...

- Inner ultras-fast (v~0.1c) and highly ionized winds drive strong **shocks into the ISM** that sweep up ISM gas (large-scale outflow) **[Lapi+05, Menci+06, King10, Zubovas+King10, Faucher-Giguere+12]**
- The outflow may be energy- or momentum- driven





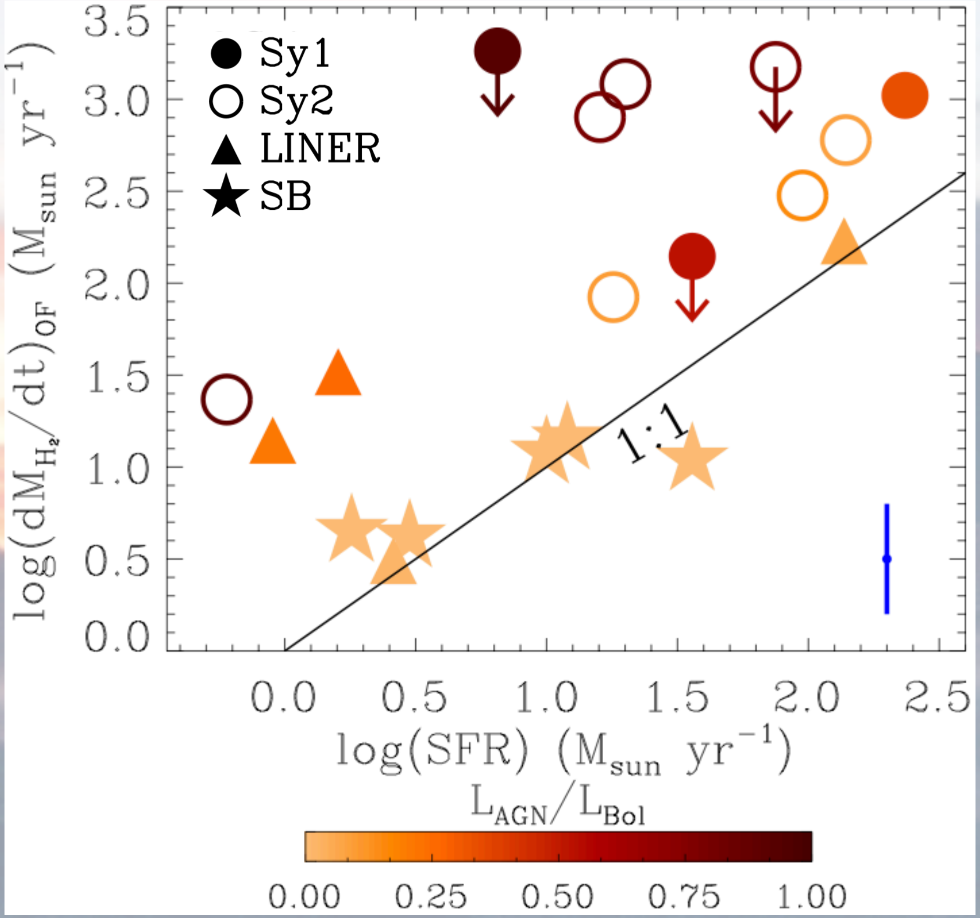
- Cold dense clumps may cool out of the outflow (and eventually form stars?) **[Zubovas+King13,Costa+14]**

.. Or Radiation-pressure on dust

[Hopkins+Elvis10,Fabian12,Roth+12,Thompson+14]

MASSIVE MOLECULAR OUTFLOWS

Outflow mass-loss rate vs SFR

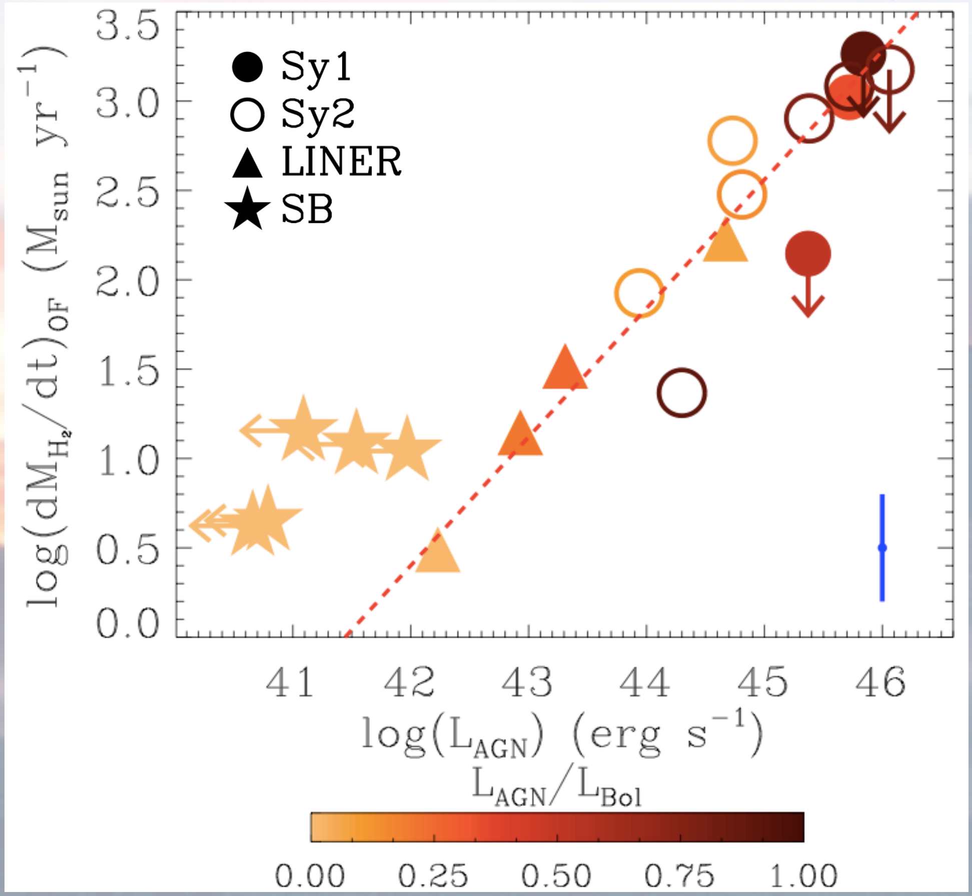


[Cicone+14a]

- Starburst-dominated galaxies: outflow rate and SFR comparable (wind mass loading factor η~1)
- Outflow rates strongly **"boosted"** by the presence of an AGN (outflow boost increases with L_{AGN}/L_{bol} and up to factor of ~100)

MASSIVE MOLECULAR OUTFLOWS

Outflow mass-loss rate vs L_{AGN}

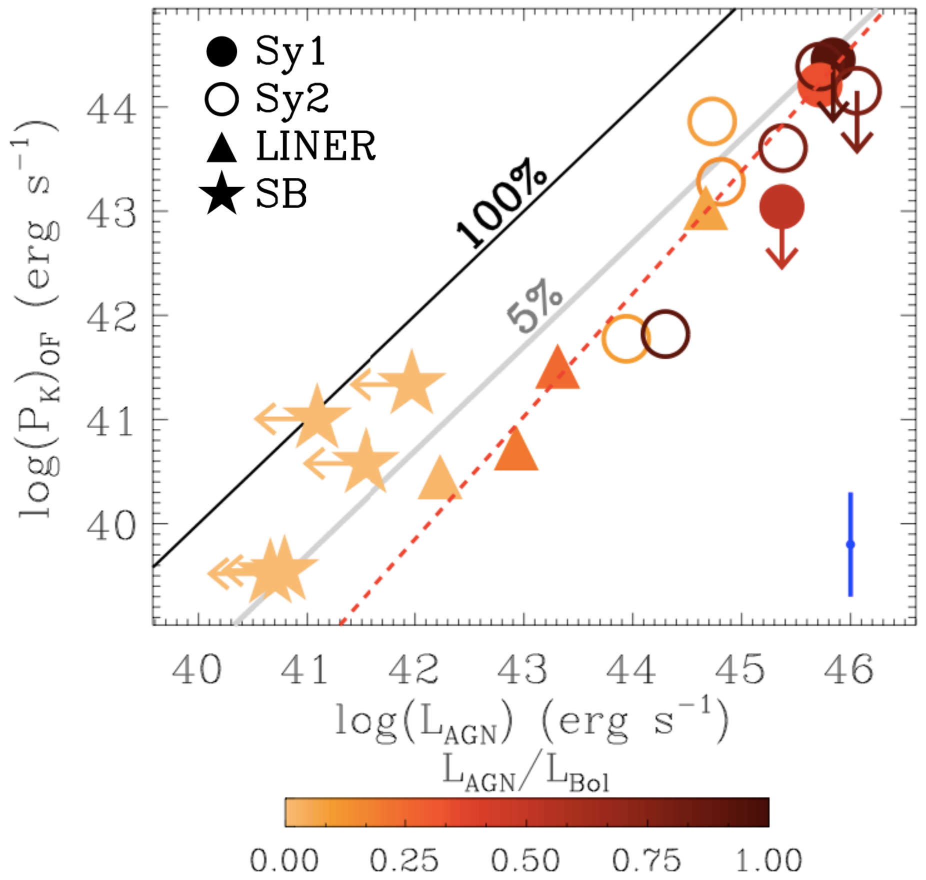


[Cicone+14a]

- AGN luminosity correlates with outflow rate in AGN host galaxies ➔ **AGN-driven outflows**
- Yet possible biases (upper envelope of a broader distribution?)
- "Pure" starbursts are outliers: different feedback mechanism

MASSIVE MOLECULAR OUTFLOWS

Outflow kinetic power vs L_{AGN}

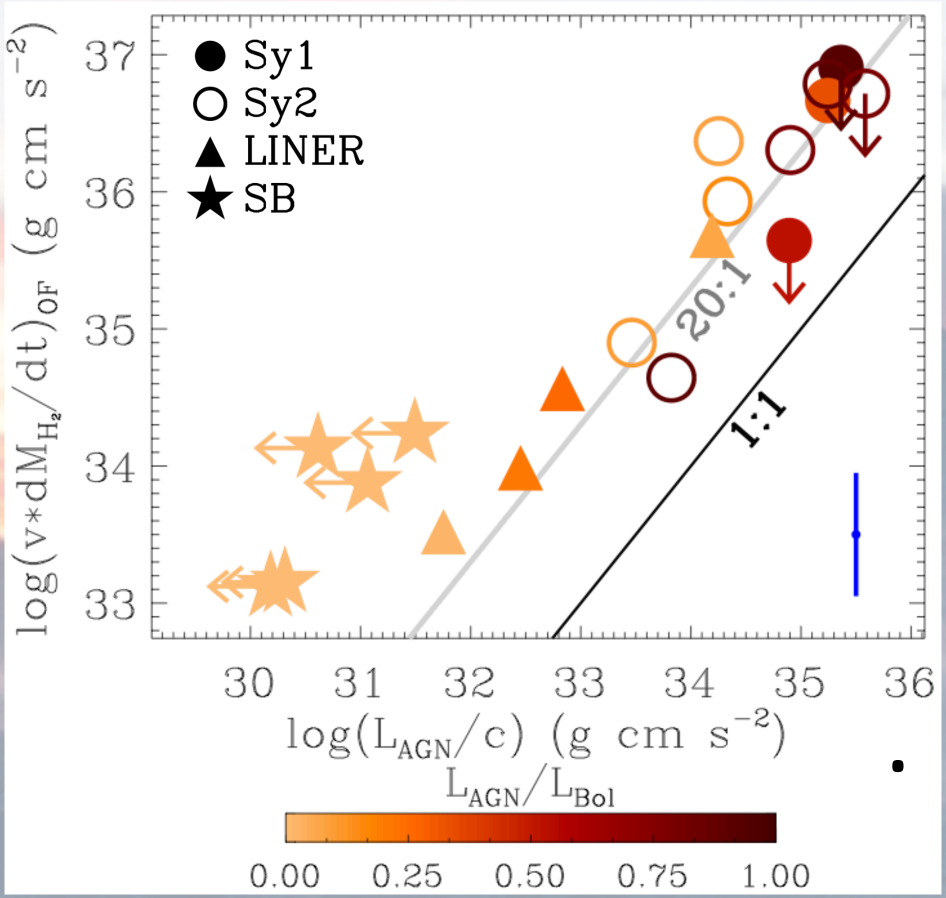


[Cicone+14a]

- Coupling efficiency consistent with models and simulations of AGN feedback (~5%)
- Lower efficiency in LINERs: role of jets?
- "Pure" starburst upper limits are above 5%: additional mechanism (e.g. SNe)

MASSIVE MOLECULAR OUTFLOWS

Outflow momentum rate vs L_{AGN}/c



[Cicone+14a]

- **M_{OUT} v ~ 20 L_{AGN}/c** Momentum boosts of ~20, as predicted by "blast-wave" models (energy-driven scenario)
- Some sources show lower momentum-boosts (~5-10), which are also consistent with outflows driven by radiation-pressure on dust

Part II

Probing cold baryons in the halo of a bright quasar at z>6

Very extended cold gas, star formation and outflows in the halo of a bright quasar at $z > 6$

C. Cicone[1,2], R. Maiolino[1,2], S. Gallerani[3], R. Neri[4], A. Ferrara[3], E. Sturm[5], F. Fiore[6], E. Piconcelli[6], and C. Feruglio[4]

A&A in press (arXiv:1409.4418)

J1148+5251: RECORDS HOLDER AT z=6.4

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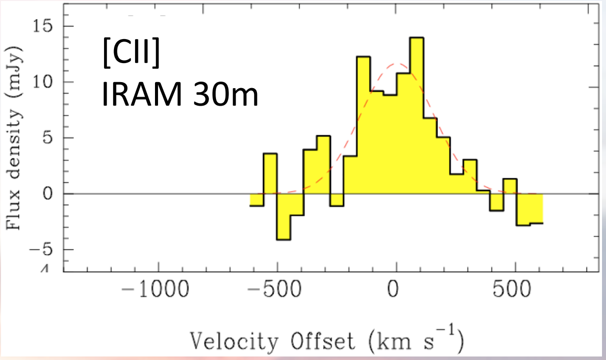
(1) First detection of [CII]158µm at high redshift



[Maiolino+05]

J1148+5251: RECORDS HOLDER AT z=6.4

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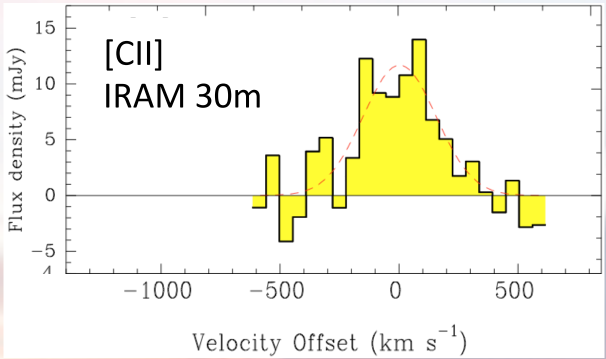


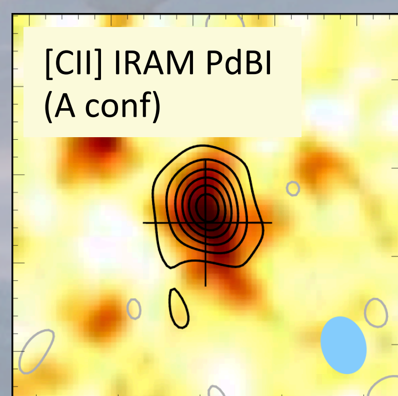
[Maiolino+05]

(2) A ~1.5 kpc size 'hyper starburst'

Σ_{SFR} = 1000 $M_\odot$ yr^{-1} kpc^{-2}

i.e. comparable to nuclei (r <100 pc) of local ULIRGs but on ~kpc scales!

[Walter+03,+04, Reichers+09]



[Walter+09]

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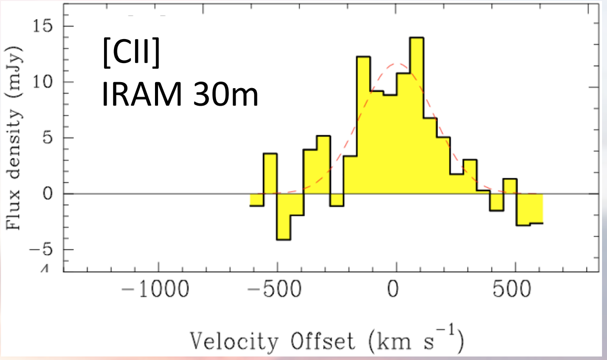

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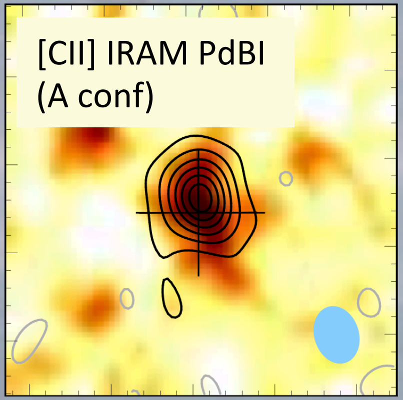
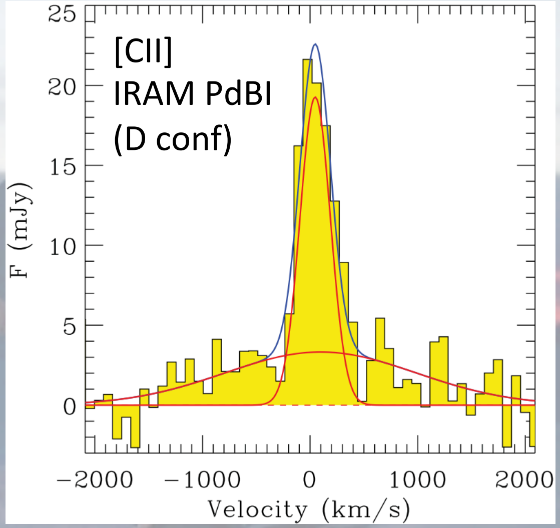


[Walter+09]

(3) First detection of a *massive* quasar-driven outflow at z>6



[Maiolino+12]

v ~ 1300 km s^{-1}
size ~ 16 kpc
$\dot{M}_{OUT}$ > 3500 $M_\odot$ yr^{-1}
Depletion timescale < 10^7 yr

(4) More surprises coming..
[Gallerani+14],
[Cicone+14b, rest of the talk]

NEW OBSERVATIONS OF [CII] IN J1148

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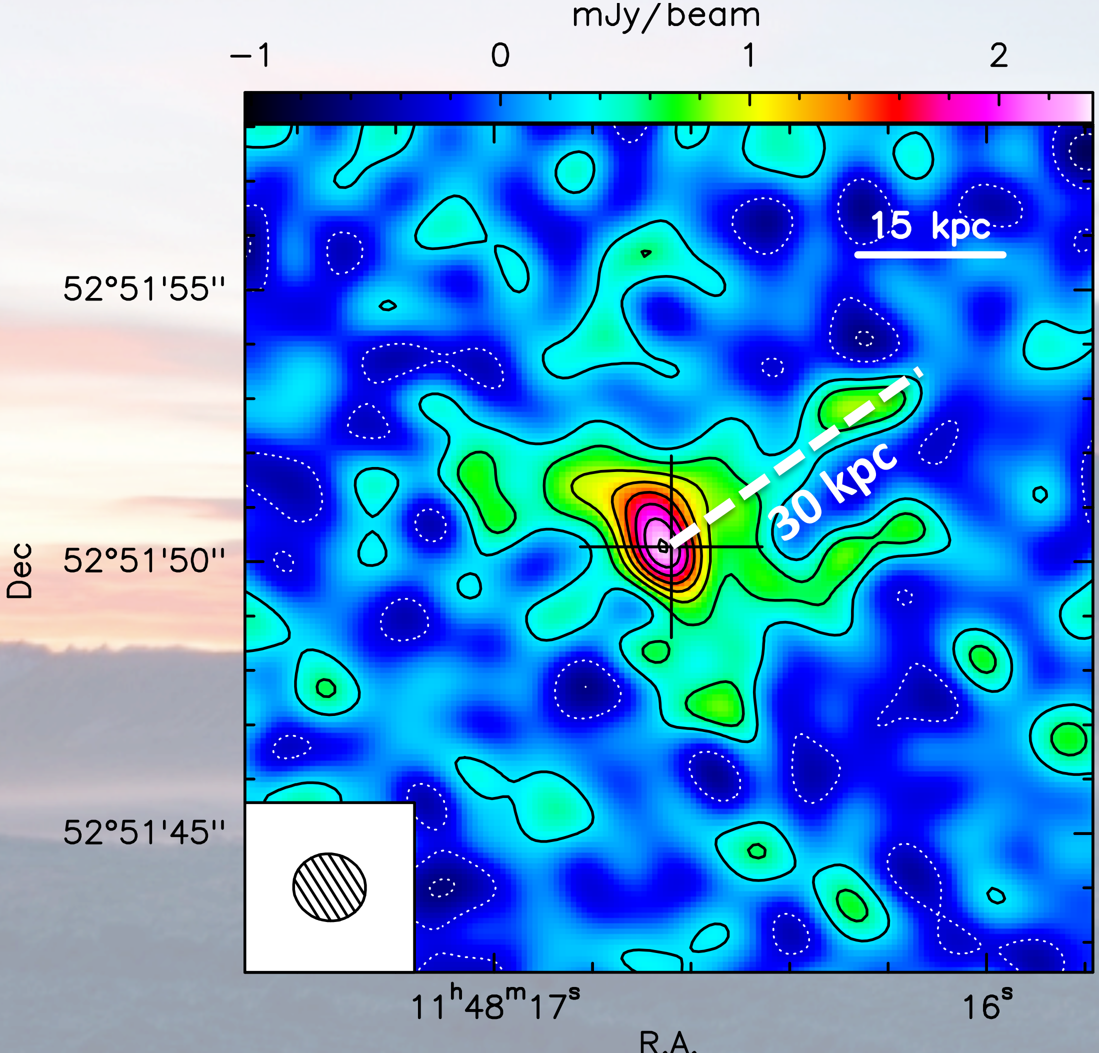
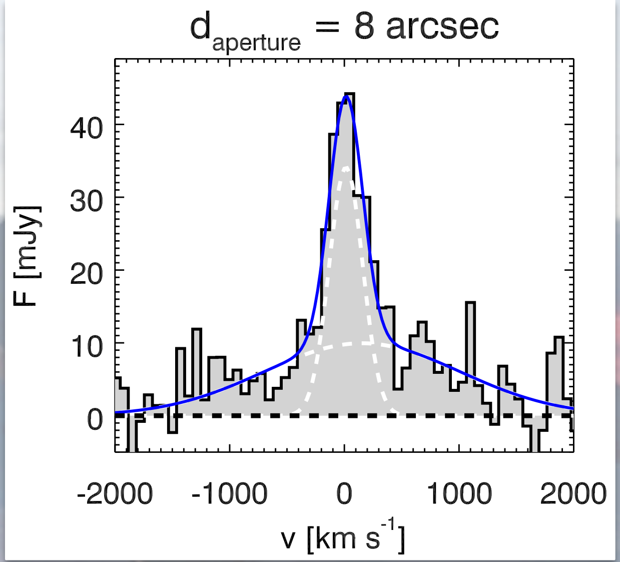
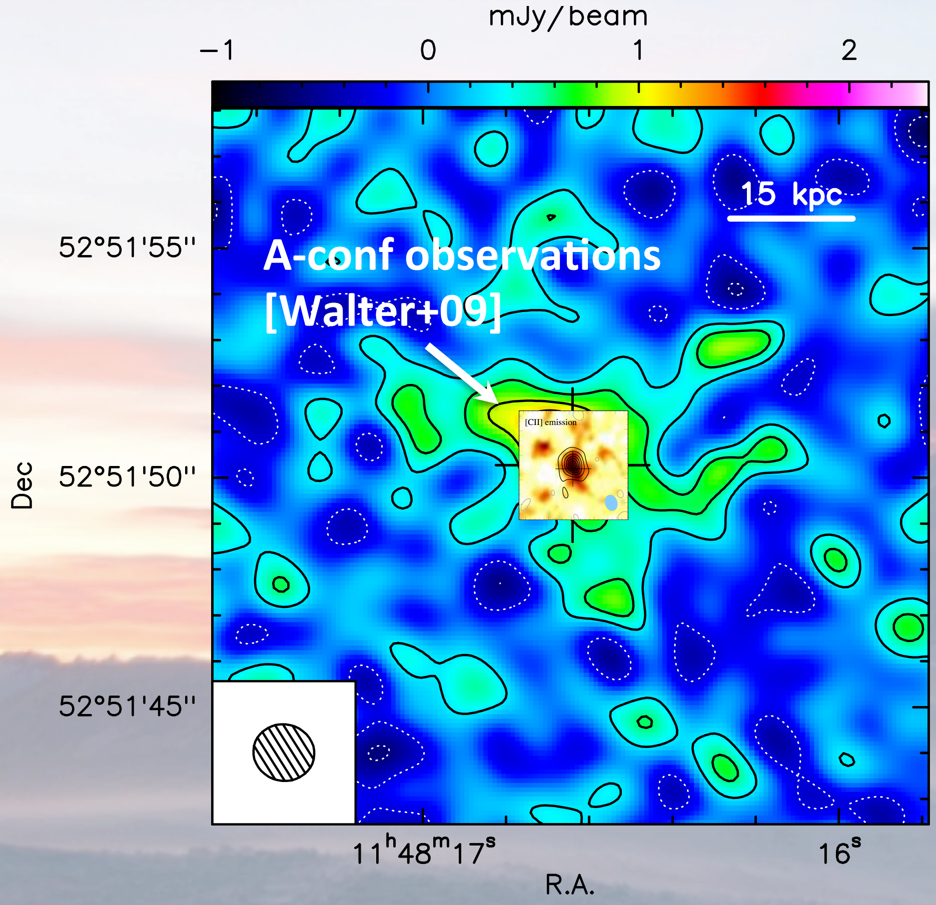




IRAM PdBI follow-up observations in D+C configuration

[Cicone+14b]

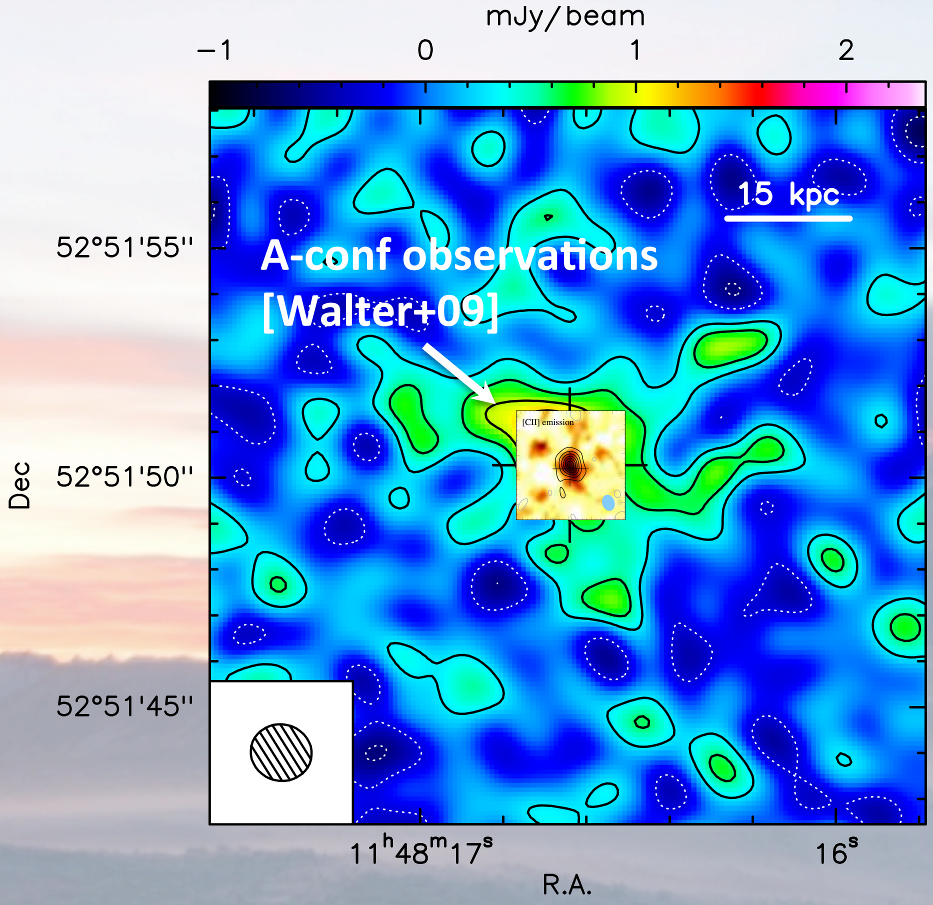
NEW OBSERVATIONS OF [CII] IN J1148



- Very extended [CII] emission, completely resolved-out by previous high-res observations by Walter et al. (2009)

[Cicone+14b]

NEW OBSERVATIONS OF [CII] IN J1148

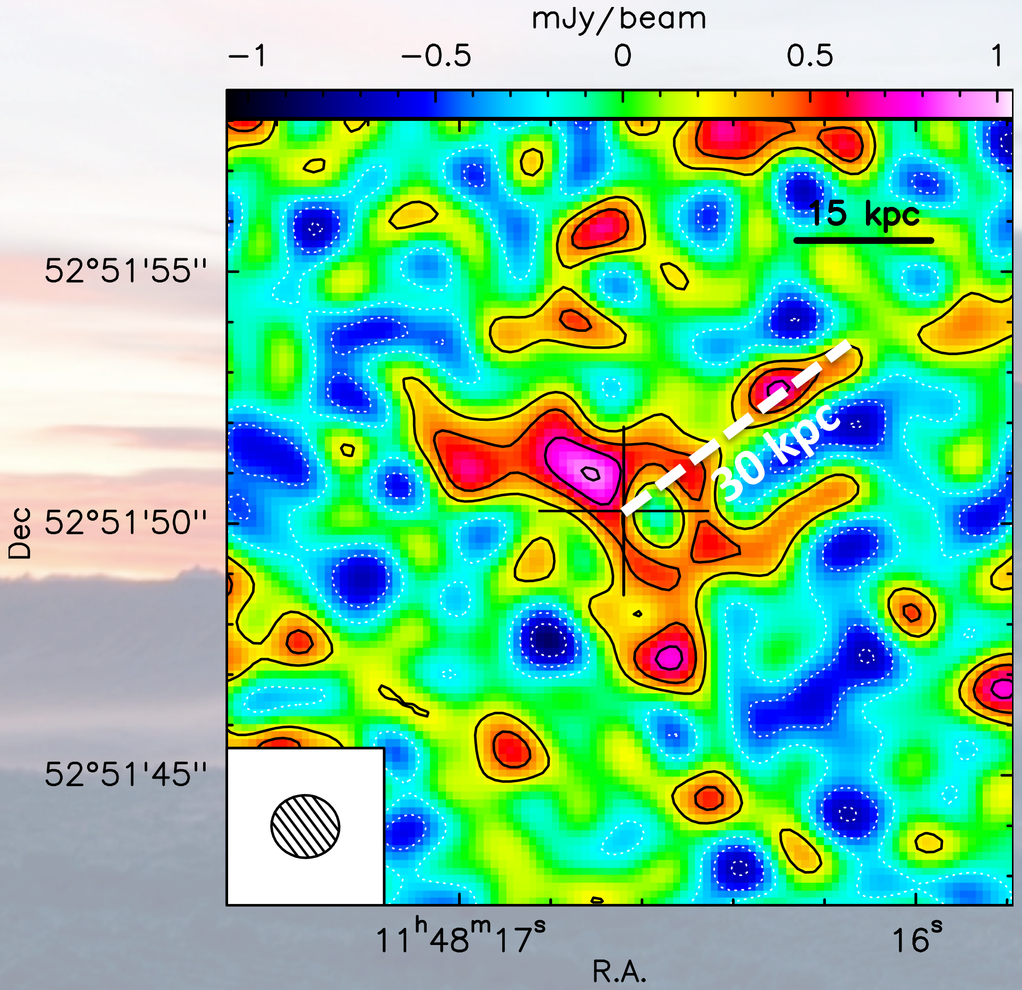


- Very extended [CII] emission, completely resolved-out by previous high-res observations by Walter et al. (2009)
- What does this extended [CII] emission trace? Outflowing and/or quiescent gas?

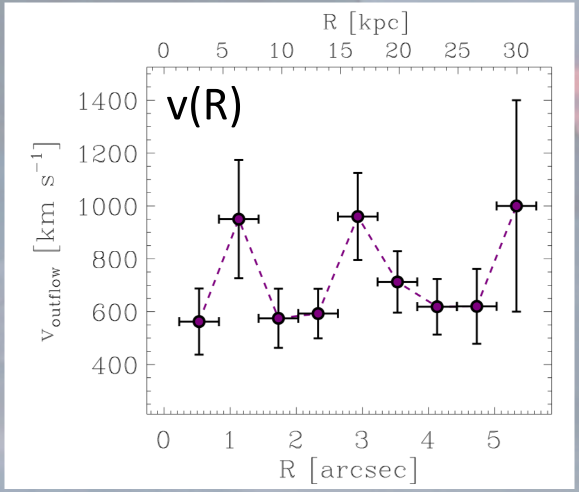
[Cicone+14b]

MAP OF THE HIGH VELOCITY [CII] WINGS

Resolved gigantic [CII] outflow extended up to r ~ 30 kpc !!!



- Complex, "butterfly-like" morphology

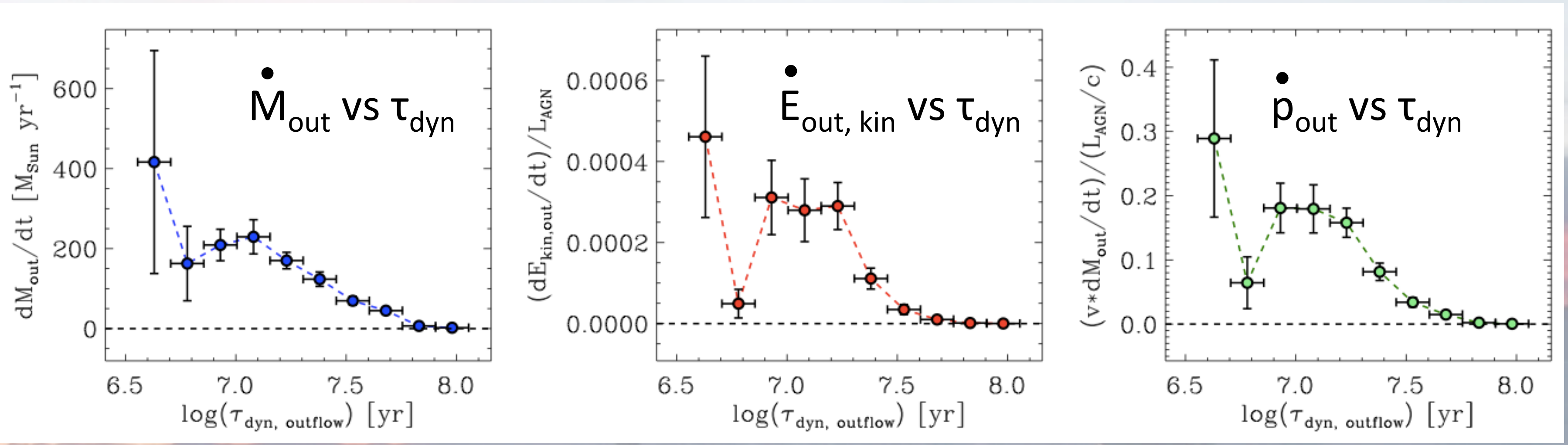


- Velocity ~ constant with R

[Cicone+14b]

RESOLVED OUTFLOW PROPERTIES

Mass-loss rate, kinetic power and momentum rate vs **dynamical time-scale**

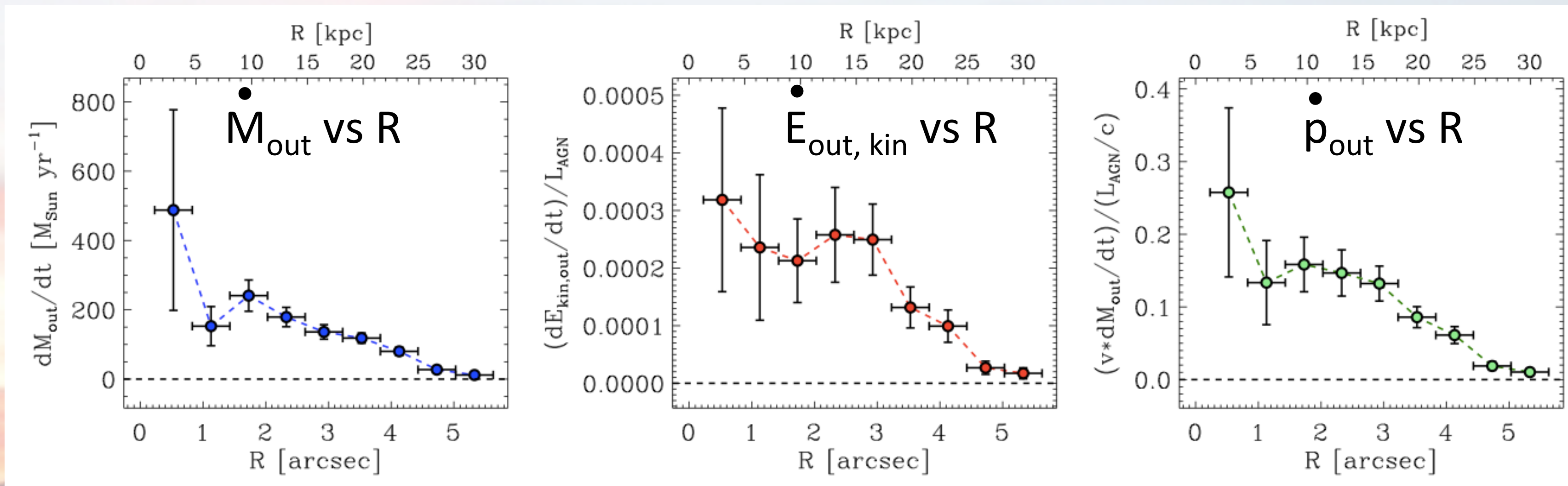


- The outflow may have been in place for as long as ~ 100 Myr
- Ejection of gas has not occurred at a constant rate
- Bulk of the mass, energy and momentum released in the past 20 Myr

[Cicone+14b]

RESOLVED OUTFLOW PROPERTIES

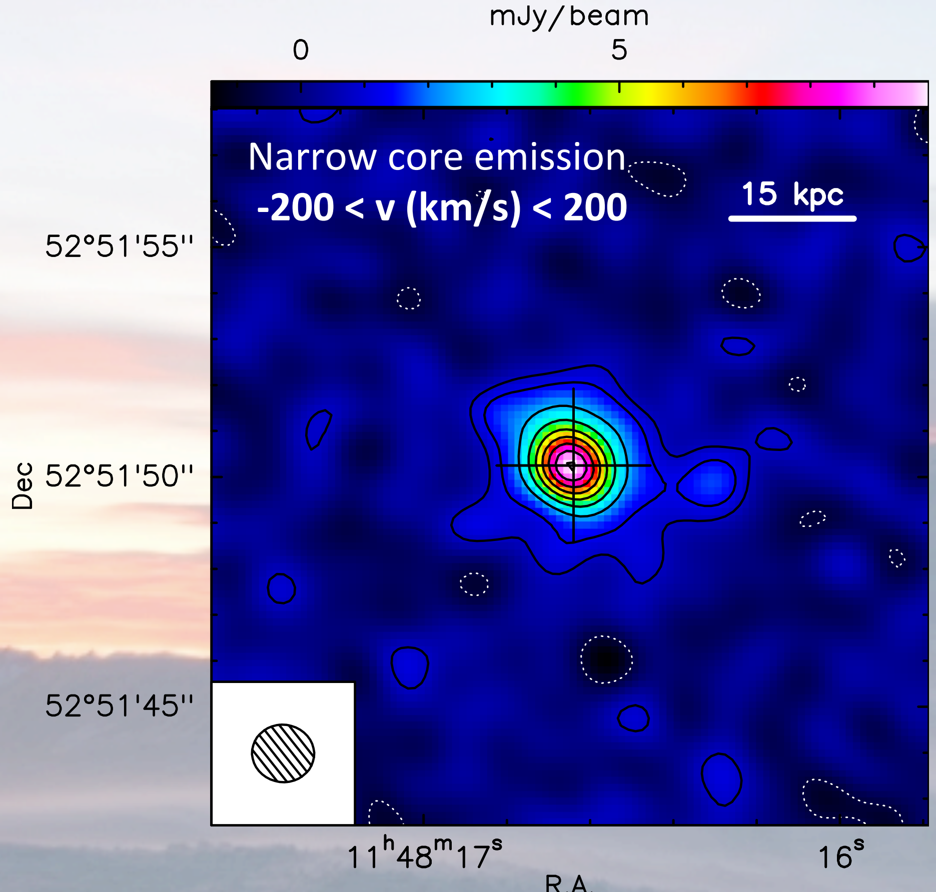
Mass-loss rate, kinetic power and momentum rate vs **radius**

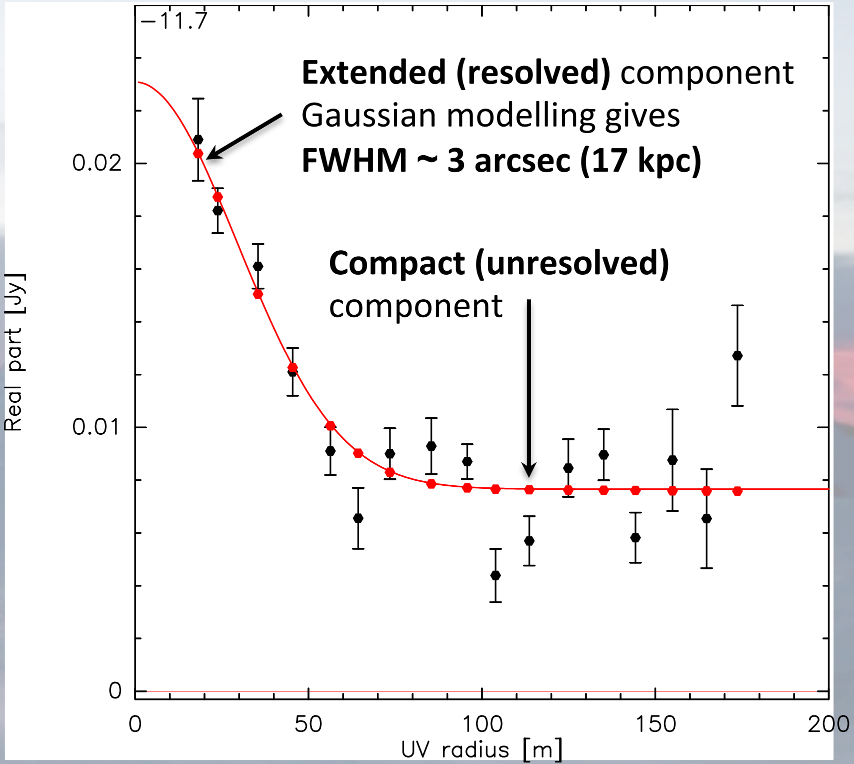


- Overall decreasing trend as a function of R
- These trends are *qualitatively* consistent with recent models of radiation-pressure driven dusty shells (however we cannot exclude “blast wave” models)

[Cicone+14b]

THE [CII] NARROW EMISSION





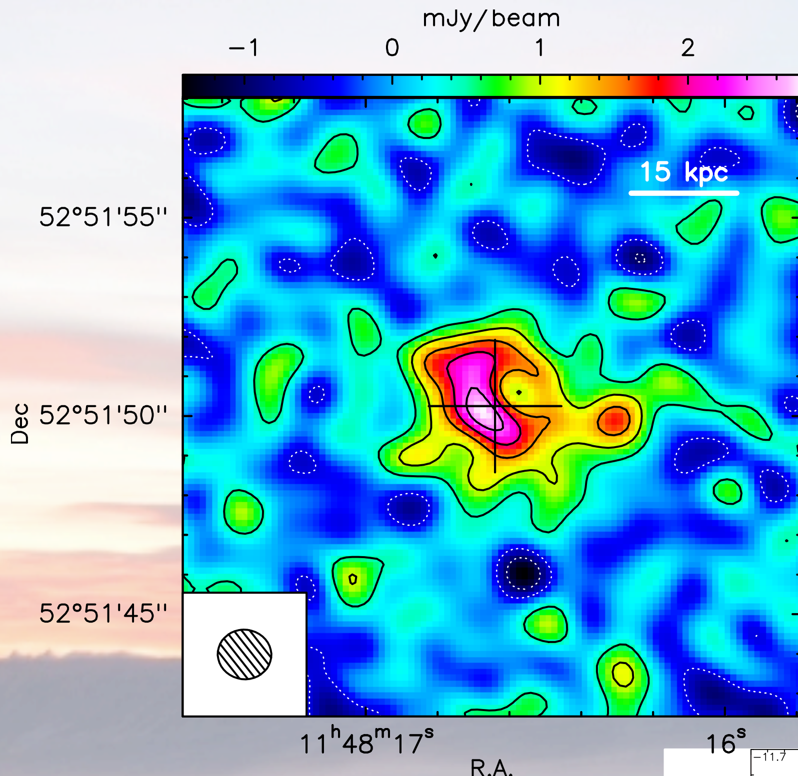
[CII] narrow emission extended on scales > 20 kpc !!!! …

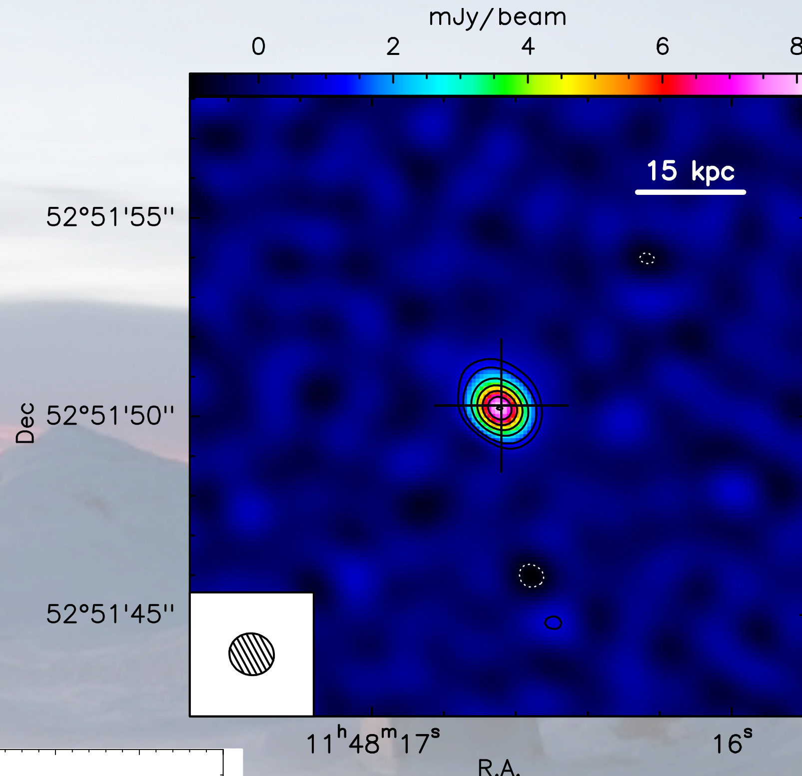
… in a galaxy at z=6.4!!!!

UV-plane modeling: almost 70% of narrow [CII] emission is extended (d~20 kpc)

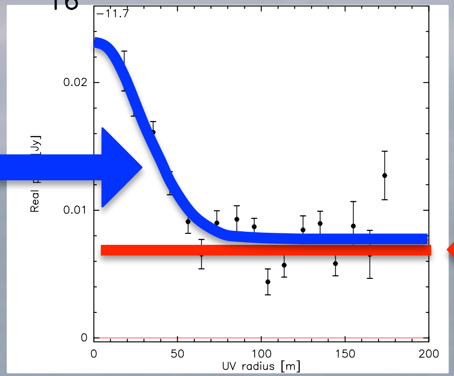
[Cicone+14b]

THE [CII] NARROW EMISSION





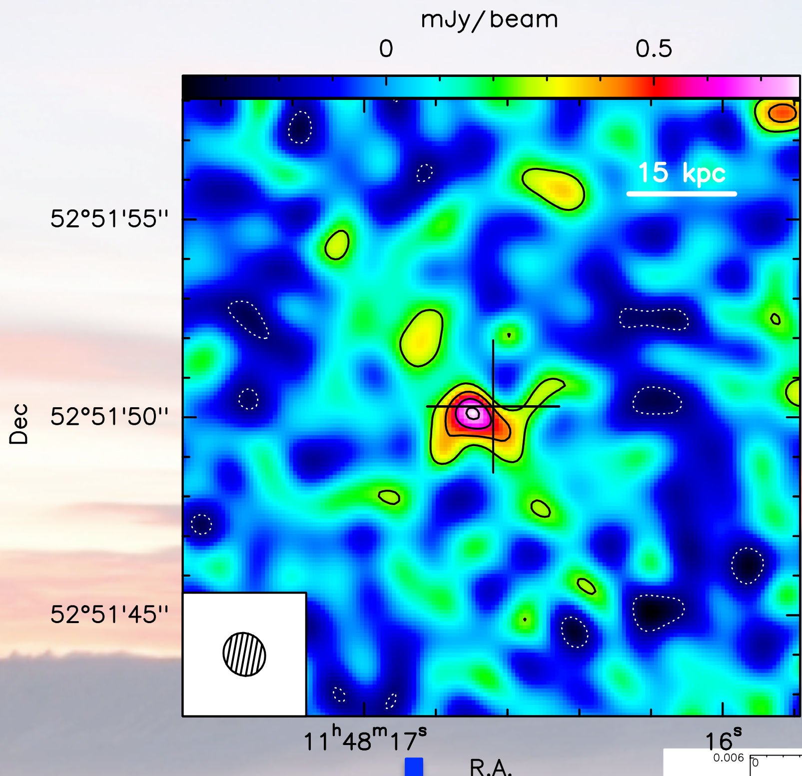
Extended (resolved) component

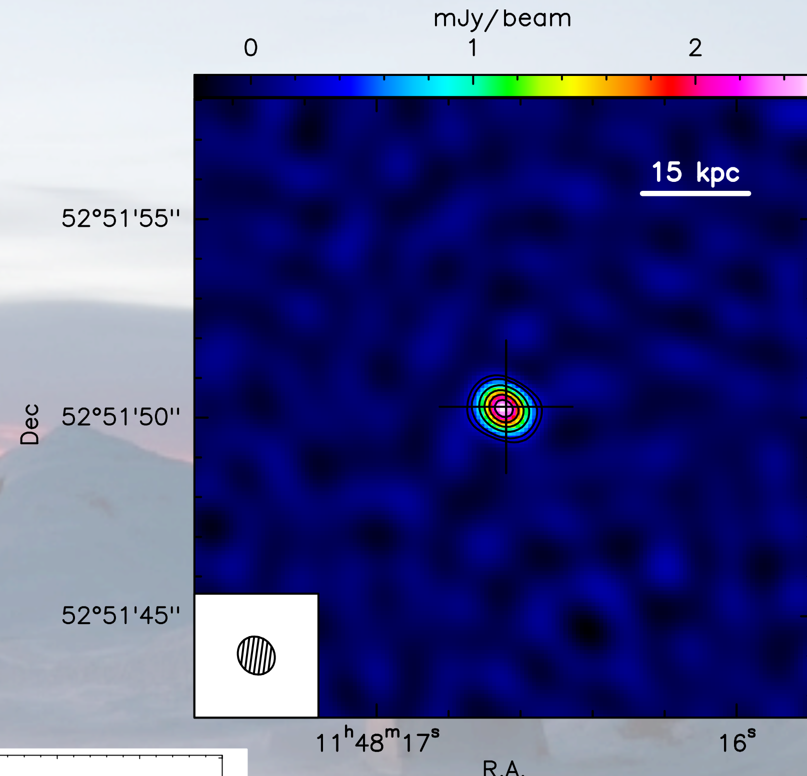


Compact (unresolved) component

[Cicone+14b]

THE FIR EMISSION





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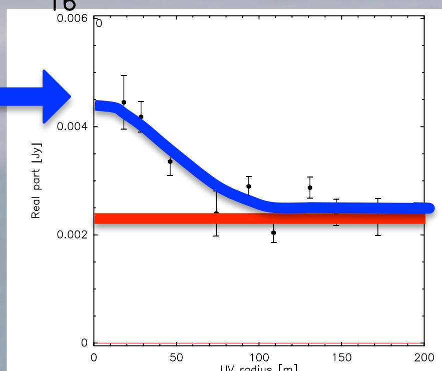
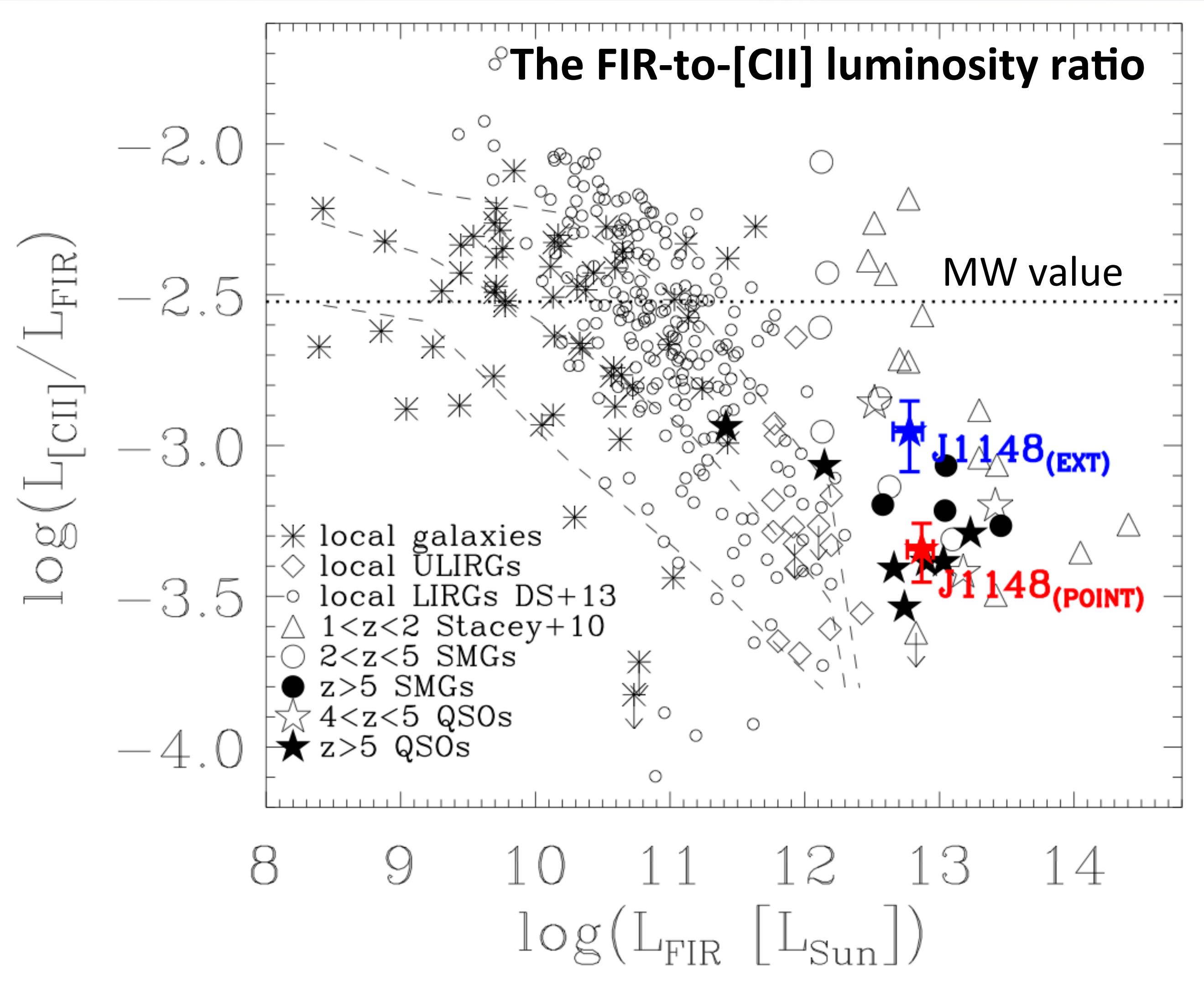


Compact (unresolved) component

[Cicone+14b]

ORIGIN OF THE EXTENDED [CII]



[Cicone+14b]

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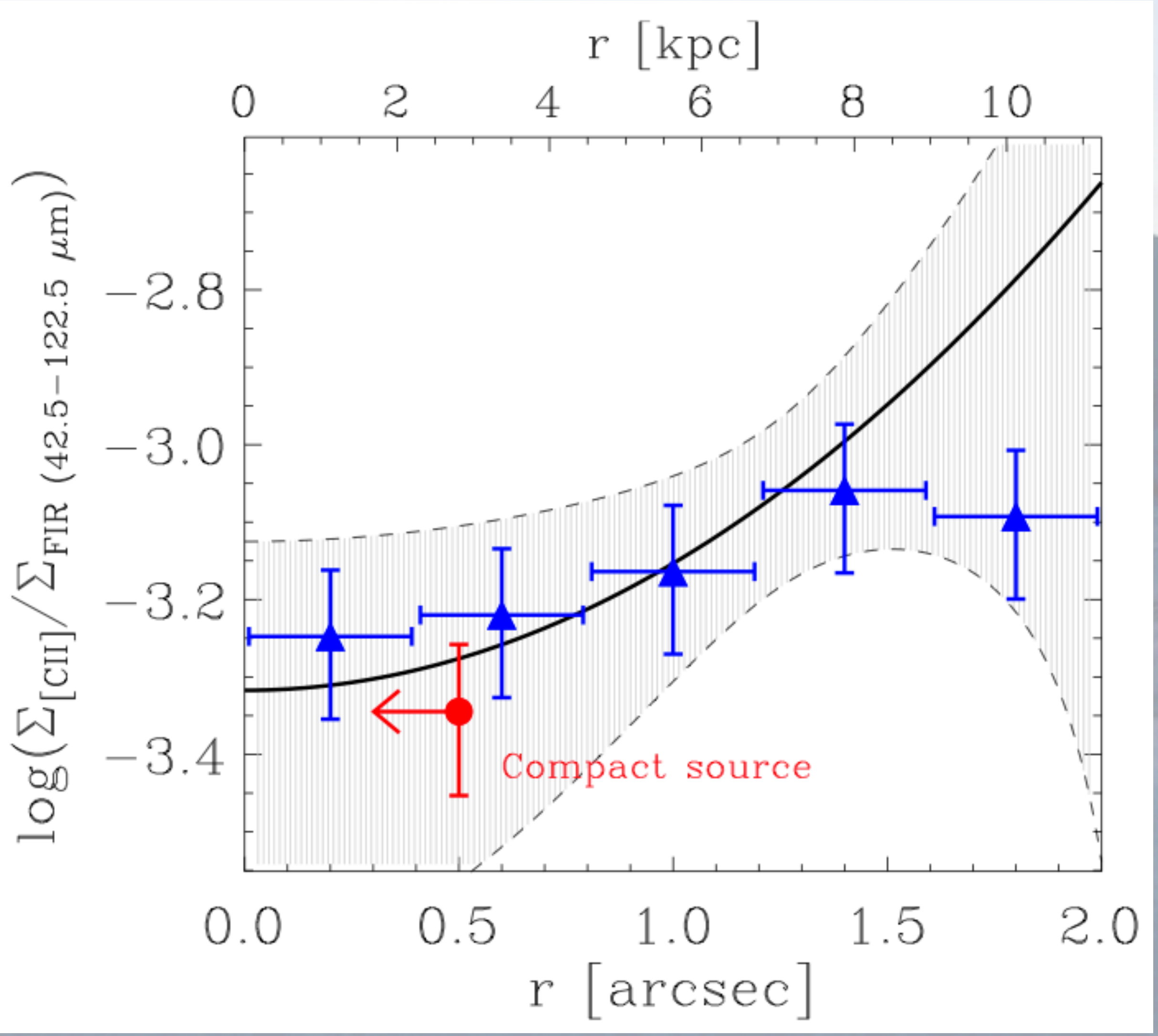


[Cicone+14b]

THE EXTENDED [CII] NARROW EMISSION

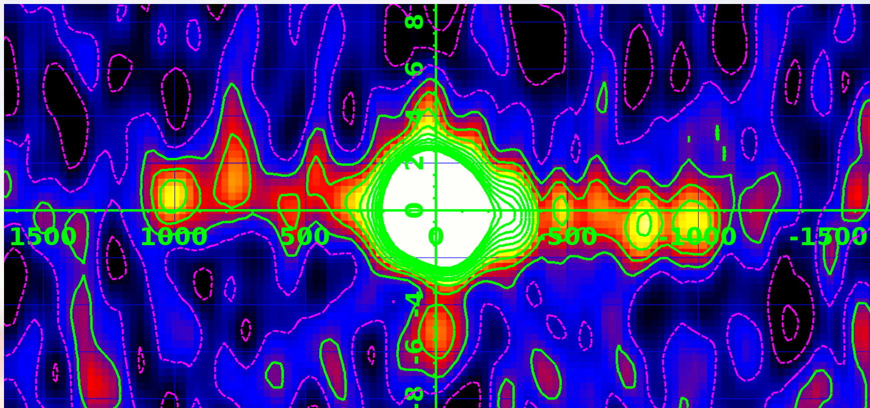
Two possible scenarios to explain this *very* extended narrow [CII] component:

1) PDRs associated with star formation
   on large scales (in a galaxy at z=6.4 !!!)

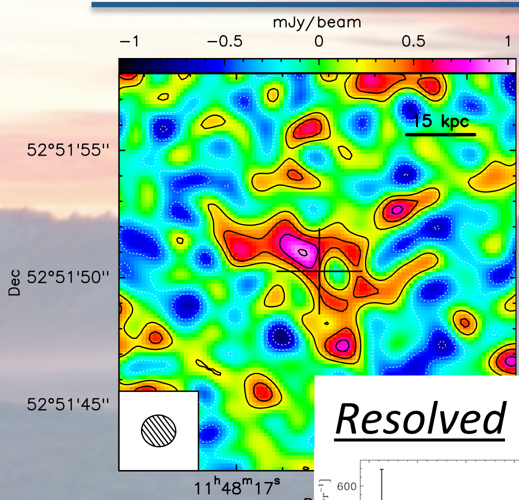
2) Diffuse atomic gas on very large scales excited by the central QSO and/or the nuclear SB, by low level in-situ SF (or by shocks!), tracing large masses (> 10^9 $M_{\odot}$) of cold gas in the halo very little star forming (accreting?)

Not yet a definitive answer. But likely (1) for r < 10 kpc (where we also detect extended FIR continuum emission), and (2) dominating at r > 10 kpc

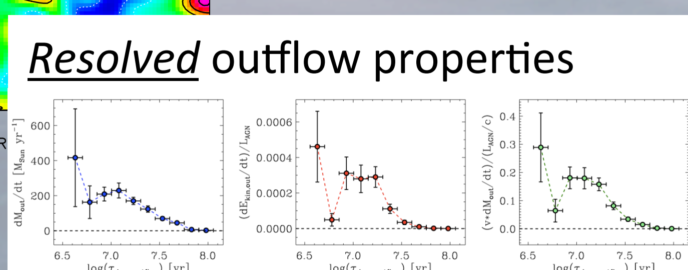
Conclusions

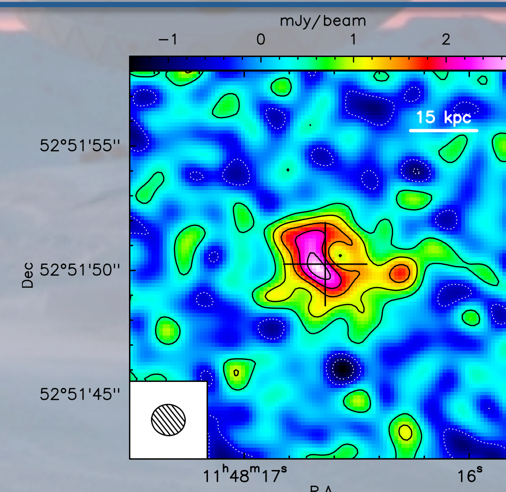


(1) Massive molecular outflows revealed by CO(1-0) (but also OH, HCN, CN, HCO+) observations of (U)LIRGs at z~0



(2) Extremely extended outflow in a QSO-host at z=6.4 revealed by [CII] observations





(3) Extended narrow [CII] tracing cold gas (and star formation?) on scales of r>10 kpc at z=6.4