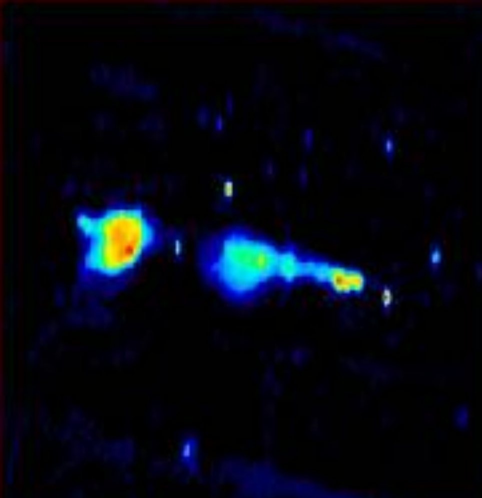
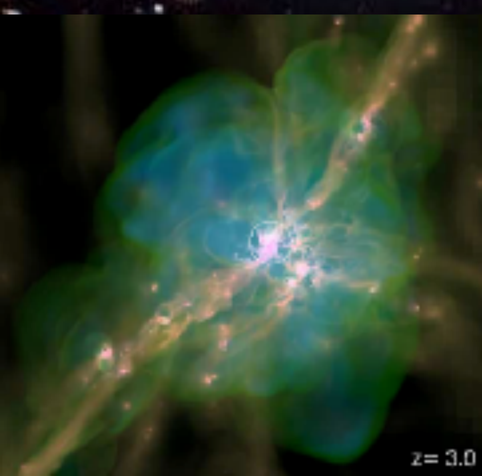
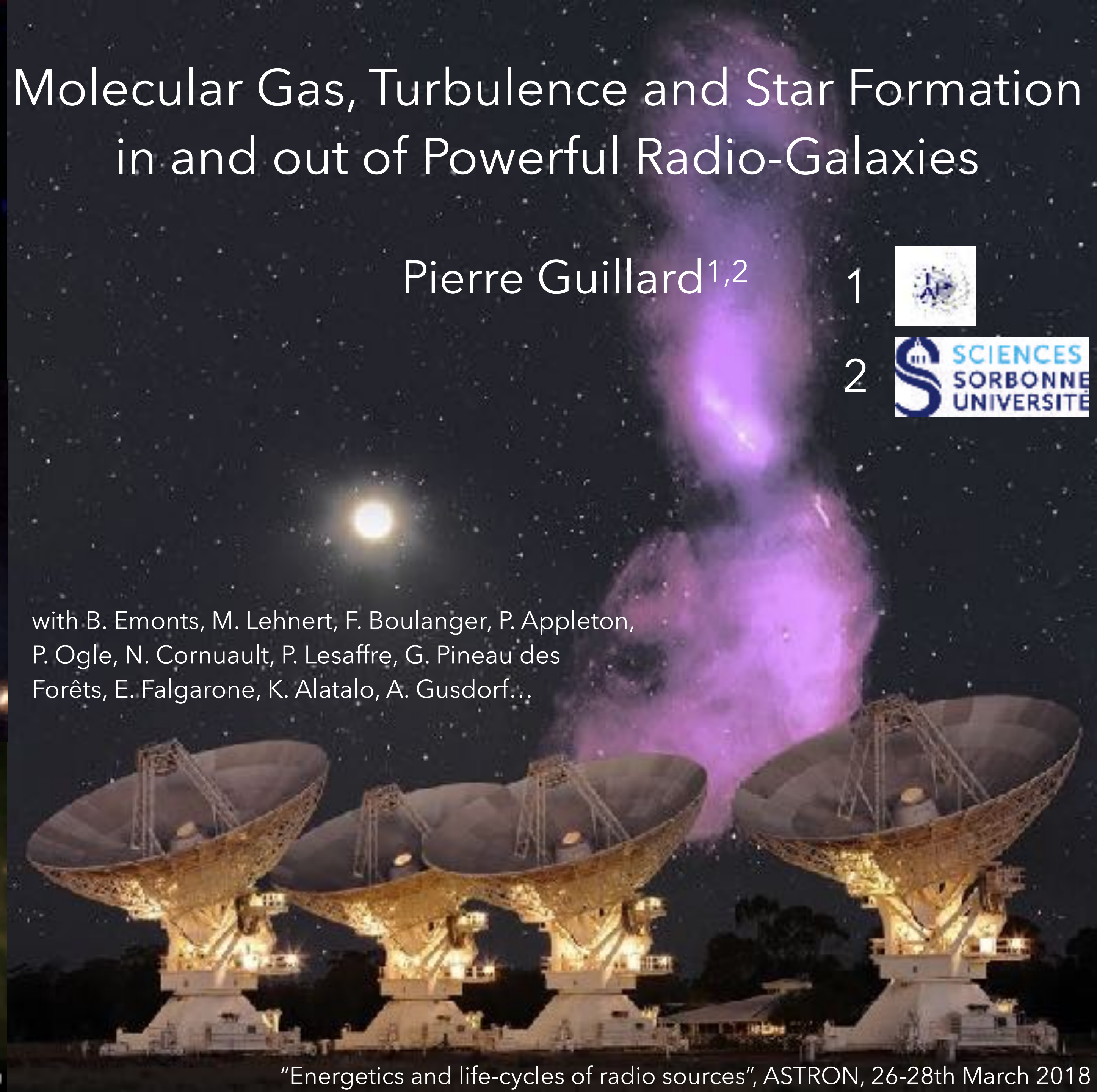






Molecular Gas, Turbulence and Star Formation in and out of Powerful Radio-Galaxies

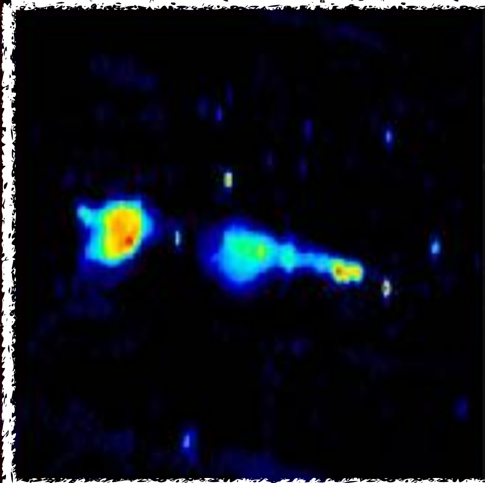
Pierre Guillard[1,2]

1

2 SCIENCES SORBONNE UNIVERSITÉ

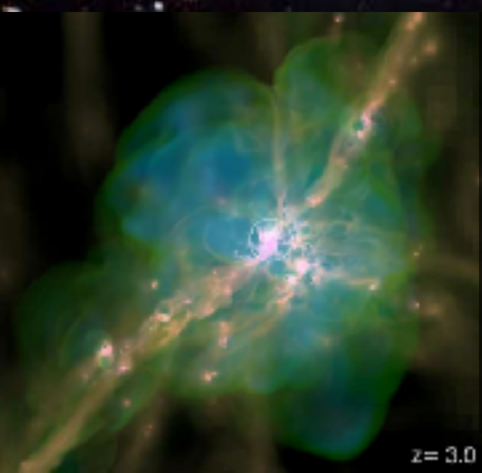
with B. Emonts, M. Lehnert, F. Boulanger, P. Appleton, P. Ogle, N. Cornuault, P. Lesaffre, G. Pineau des Forêts, E. Falgarone, K. Alatalo, A. Gusdorf…

“Energetics and life-cycles of radio sources”, ASTRON, 26-28th March 2018

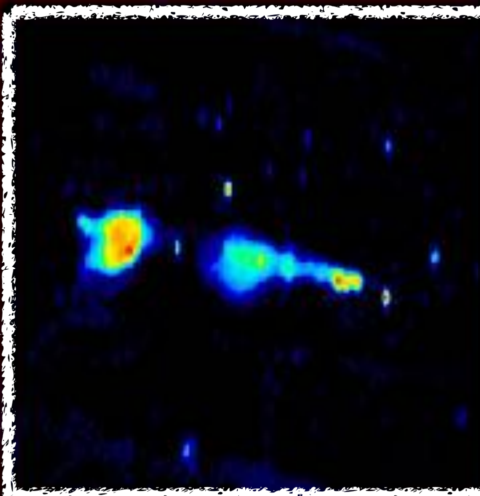


1. Warm molecular gas in RGs

2. Discovery of cold gas in the halo of the Spiderweb RG

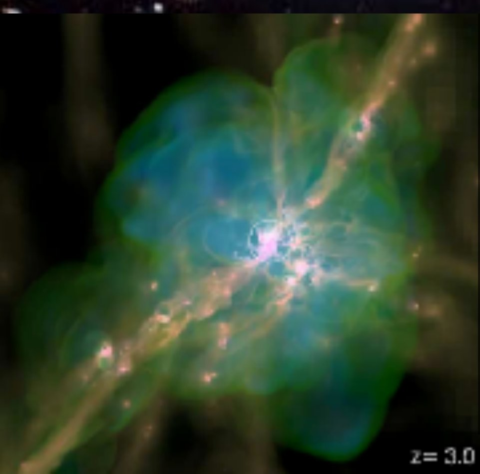


3. *What do we learn about the physics of AGN feedback?*

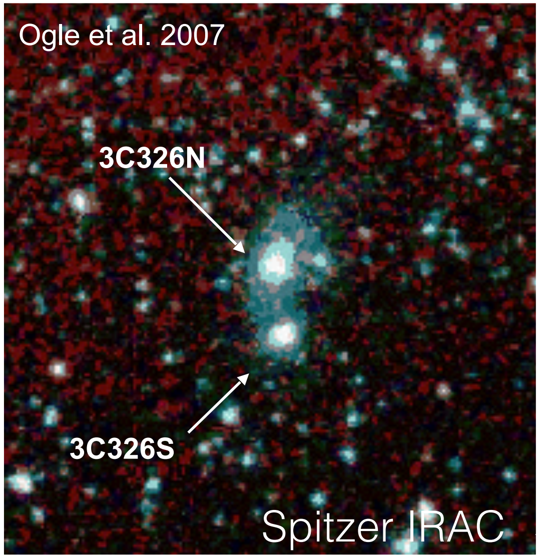


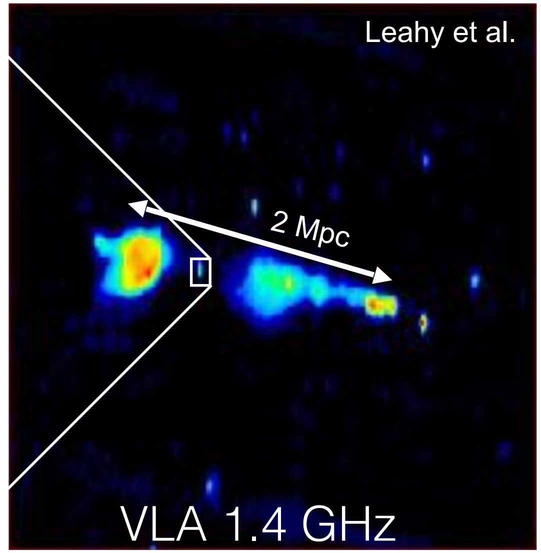
1. Warm molecular gas in RGs
   gas excitation: dissipation of turbulence, shocks, cosmic-rays ionisation

2. Discovery of cold gas in the halo of the Spiderweb RG
   growth of massive cluster ellipticals, fuel for star formation in halos and feedback

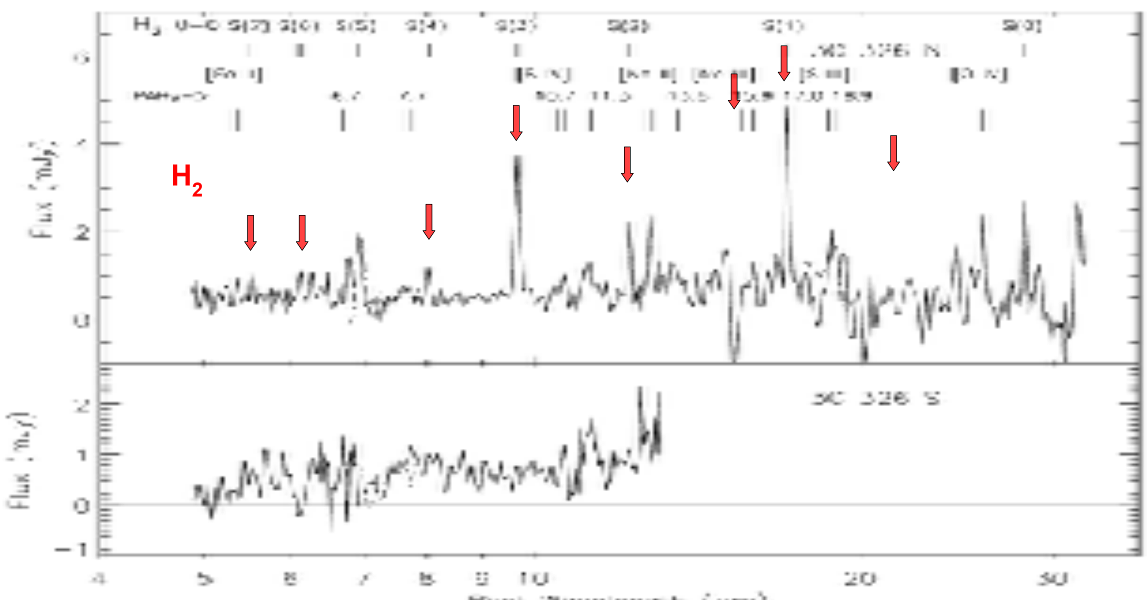


3. *What do we learn about the physics of AGN feedback?*
   where and how is the kinetic and gravitational energies dissipated





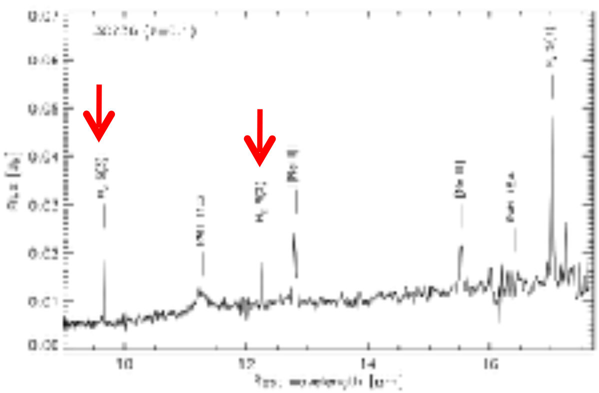
- Pair of galaxies 3C 326N & S at z=0.089
- Both contain nuclear radio sources (Rawlings et al. 1990)



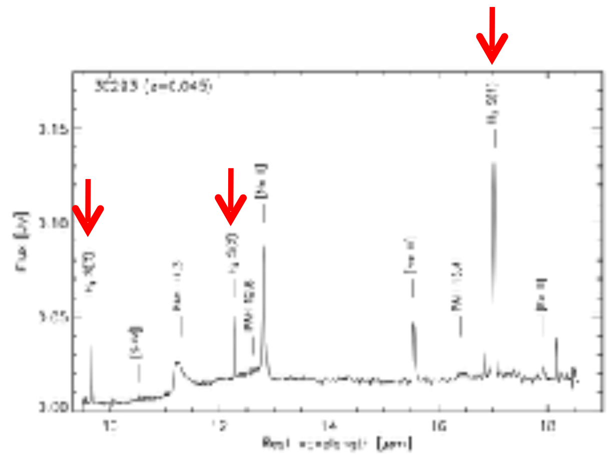
- $L(H_2)=8x10^{41}$ erg/s
- 10^9 $M_\odot$ of warm H_2
- 3kpc turbulent H_2 disk
- SFR < 0.07 $M_\odot$ yr $^{-1}$
- $L(H_2)/L(IR)$ ~ 0.2 !!

Ogle et al. 2007, 2010
Nesvadba et al. 2011a

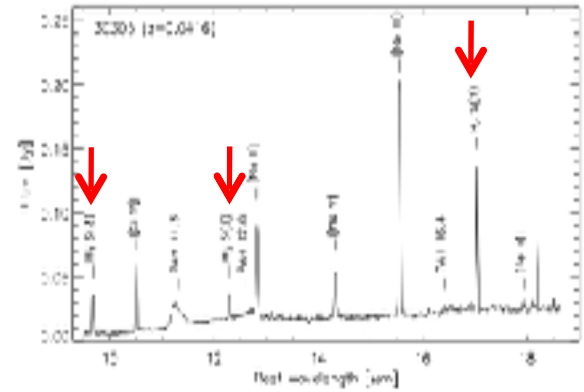
30% of 3CR radio galaxies* have bright, shock-excited rotational H_2 lines



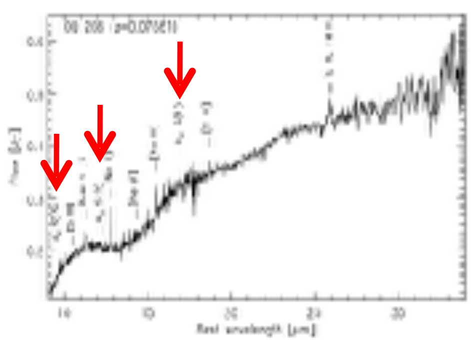
3C 236



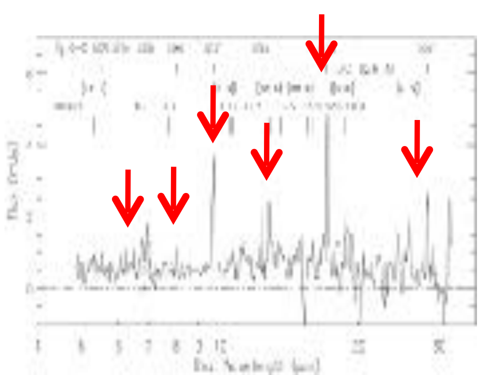
3C 293



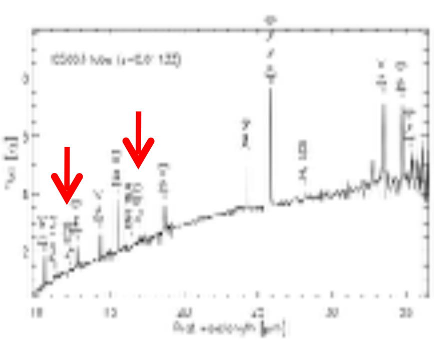
3C 305



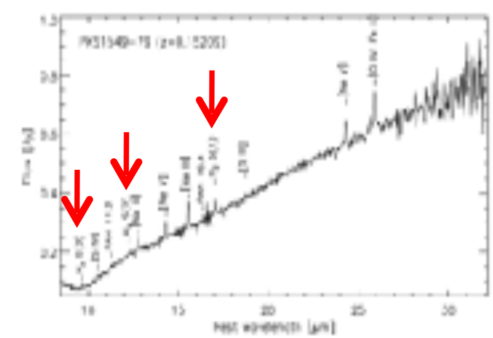
OQ 208



3C 326



IC 5063



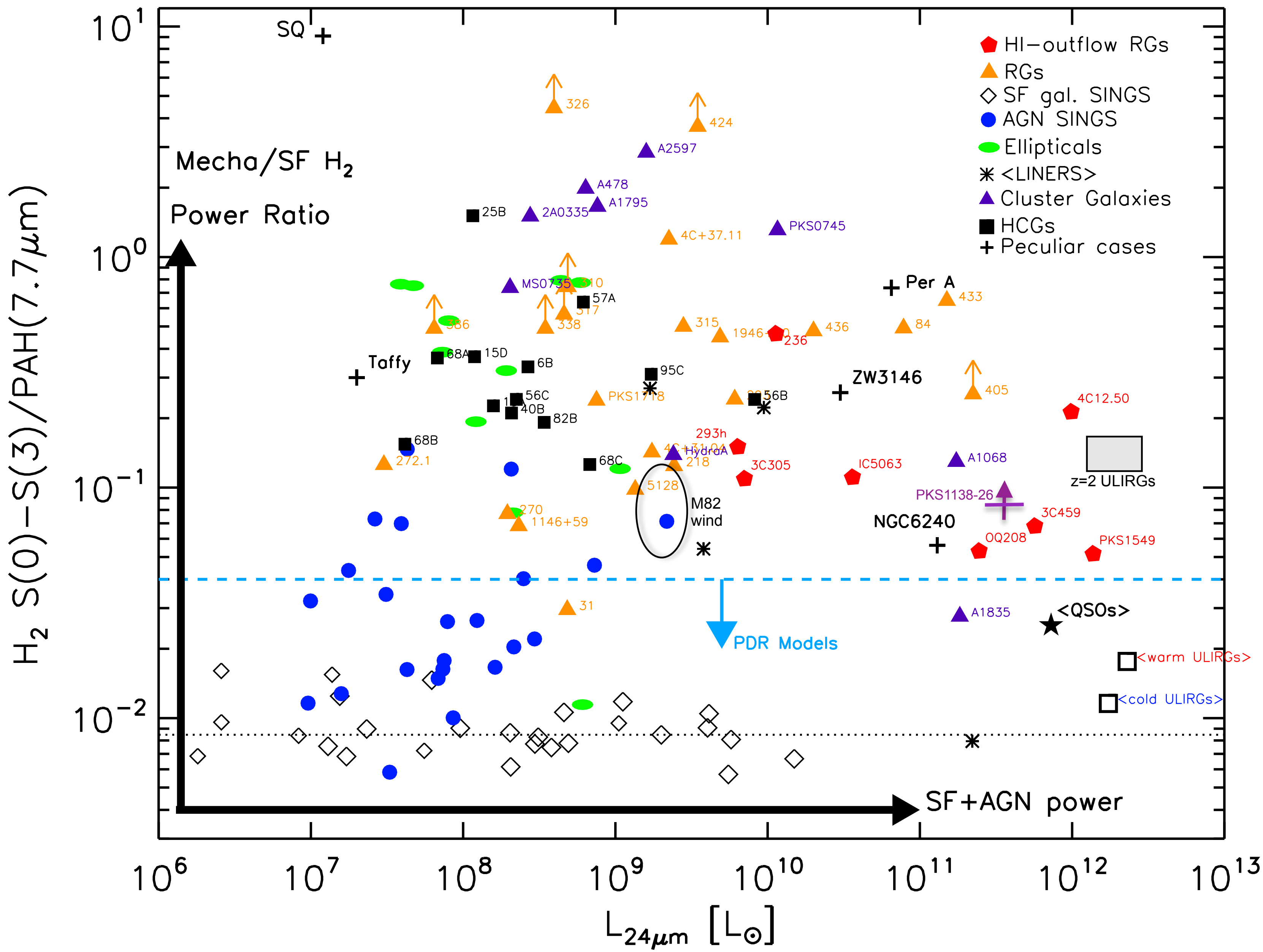
PKS 1549-79

Morganti & Tadhunter sample

Guillard et al., 2012a

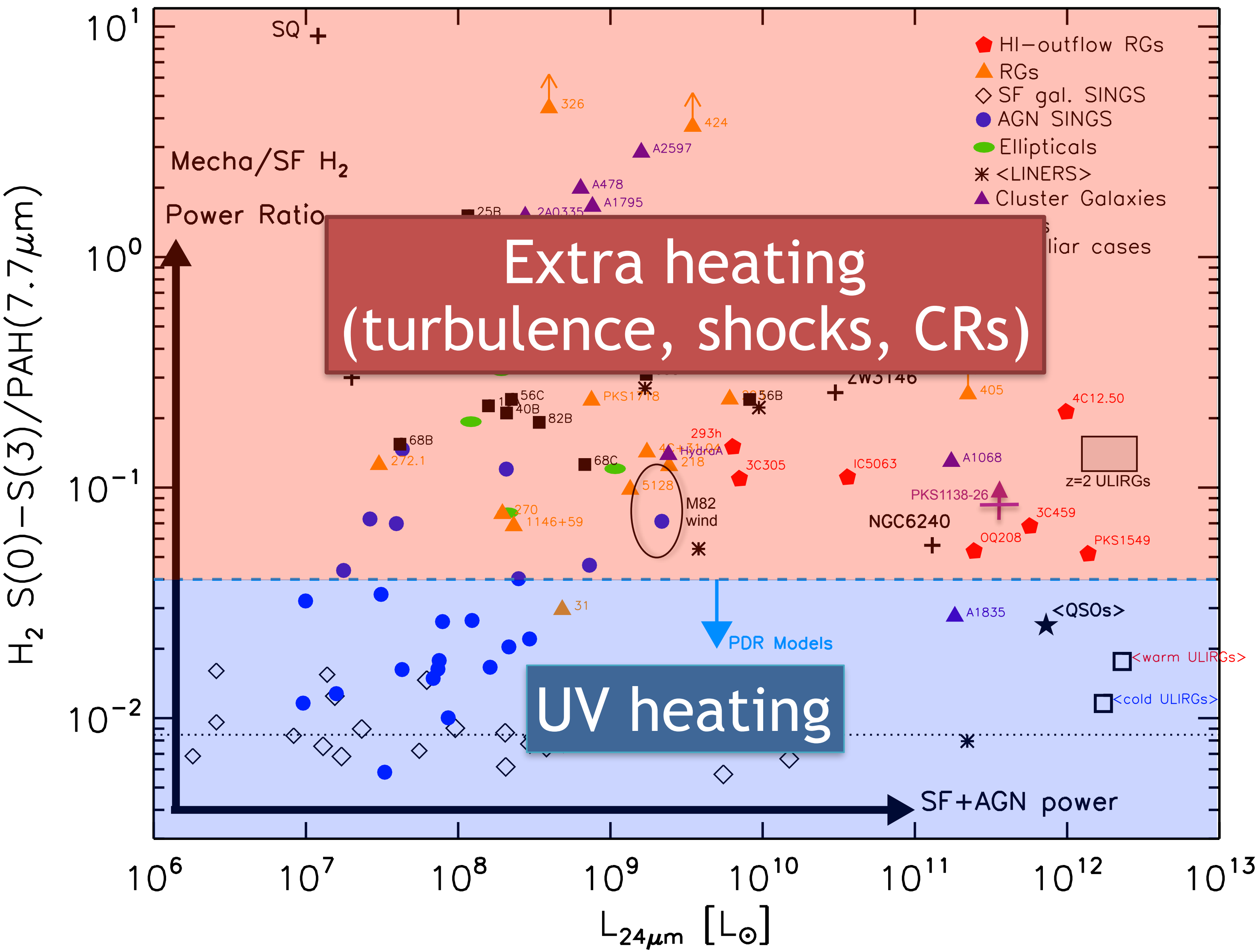
*all RGs with HI outflows!

H_2 line emission in galaxies (Spitzer)



Updated from Guillard et al. 2012a

H_2 line emission in galaxies (Spitzer)

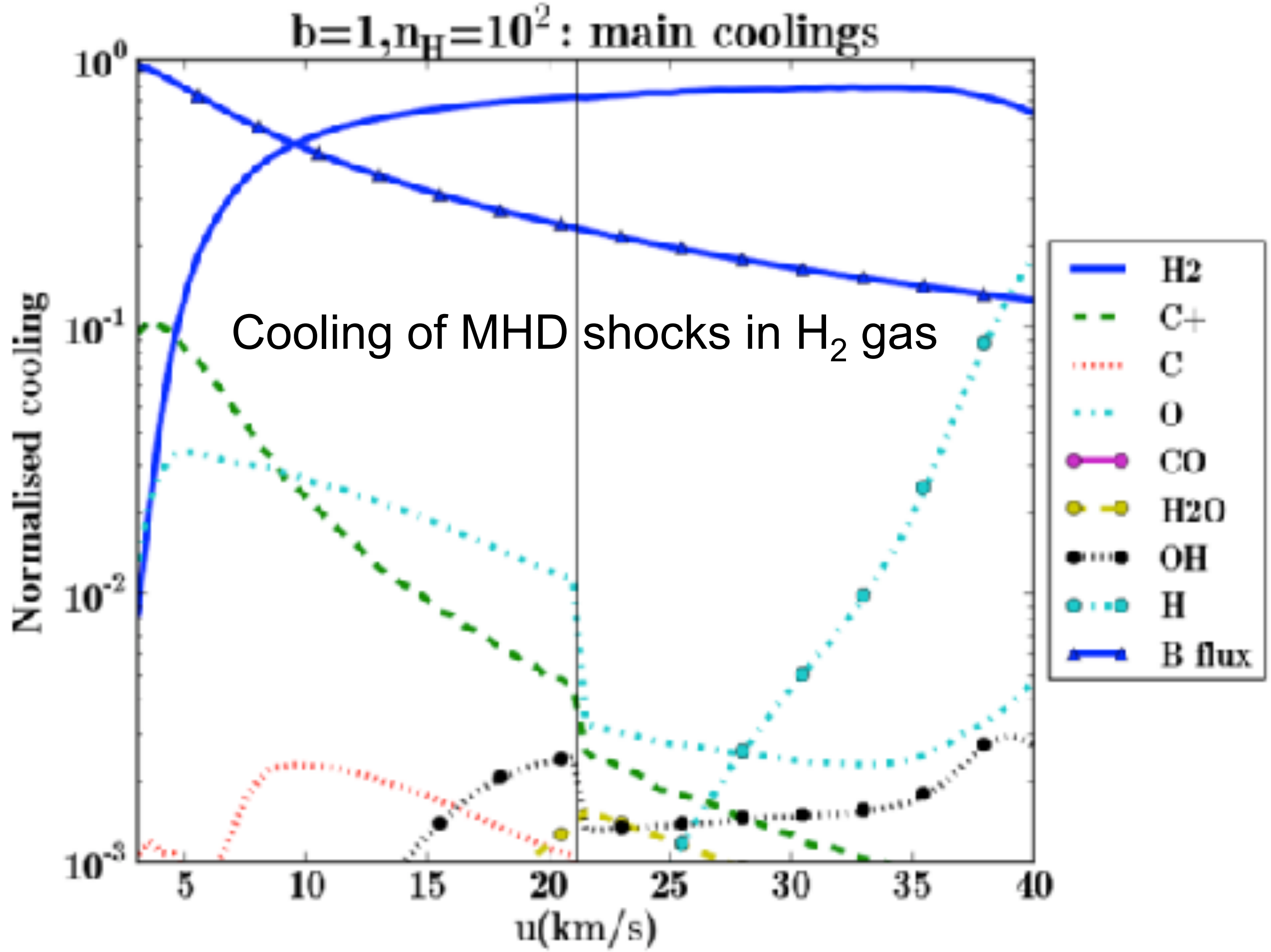


Updated from Guillard et al. 2012a

H_2 emission from shocks

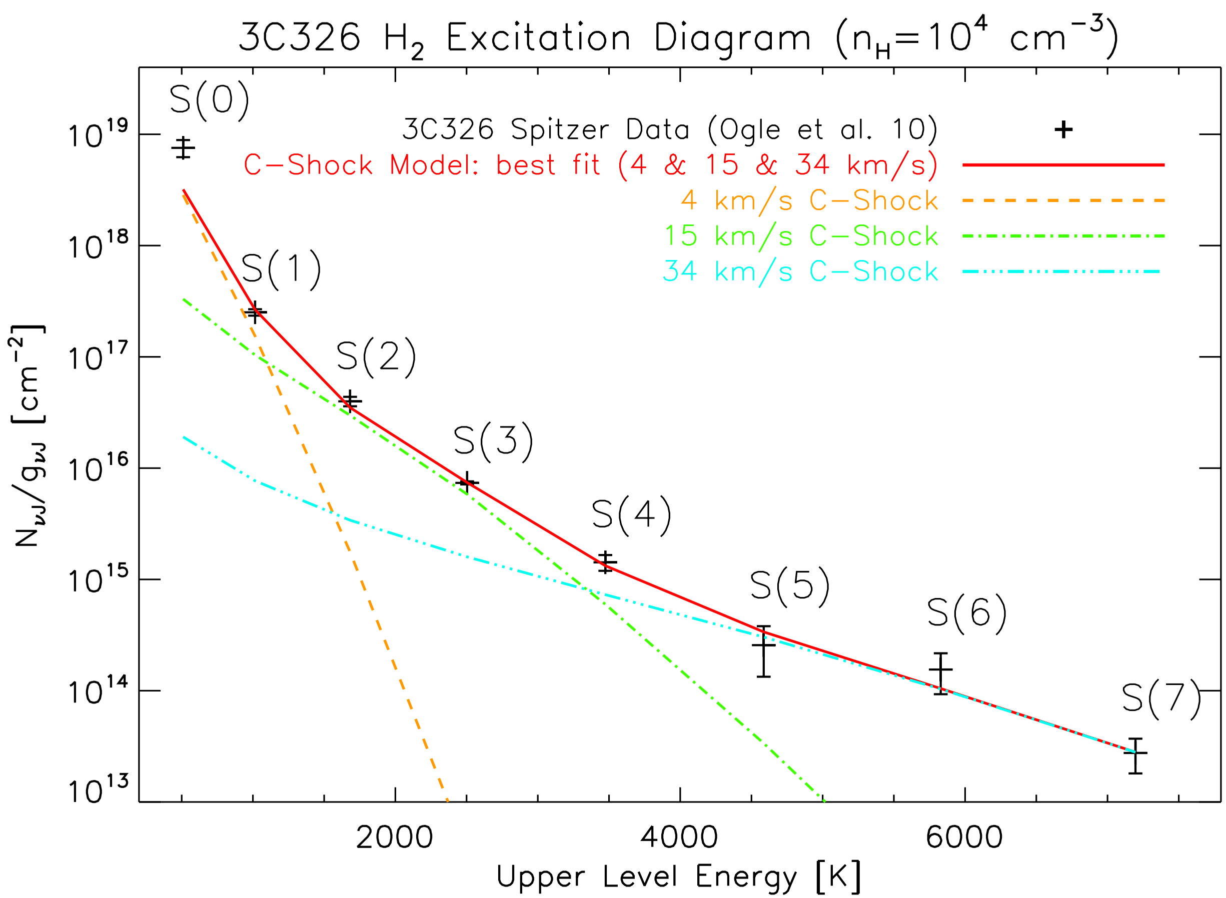
H_2 mid-IR lines are the main cooling lines of shocked molecular for $5 < V_s < 40$ km/s

Shocks trigger the formation of H_2 gas if the gas is initially atomic provided that there is dust (Bergin+2007, Guillard+2009)



1D models of shocks within diffuse irradiated gas (Guillard+09, Lesaffre+13, Flower+15,)

Modelling shock-excited H_2 lines: example of 3C326



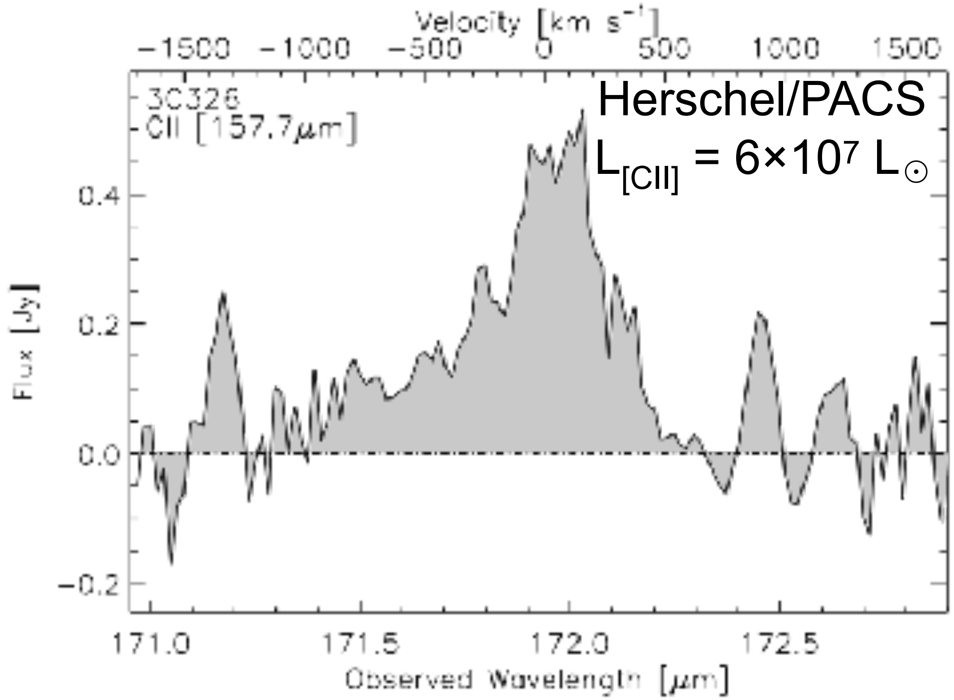
Guillard et al. 2012b, 2015

Table 7.1: MHD shock model parameters, mass flows and cooling times for 3C326 [a].

V_s [b]	Mass Flow	Cooling Times		Gas Masses	
		t_{cool}(150K) [c]	t_{cool}(50K) [c]	(150 K)	(50 K)
[km s^{-1}]	[M$_\odot$ yr^{-1}]	[yr]	[yr]	[M$_\odot$]	[M$_\odot$]
4	70100	19050	24960	1.3×10^9	1.7×10^8
15	5950	3320	4500	2.0×10^7	2.7×10^7
34	730	1000	1350	7.3×10^5	9.8×10^5

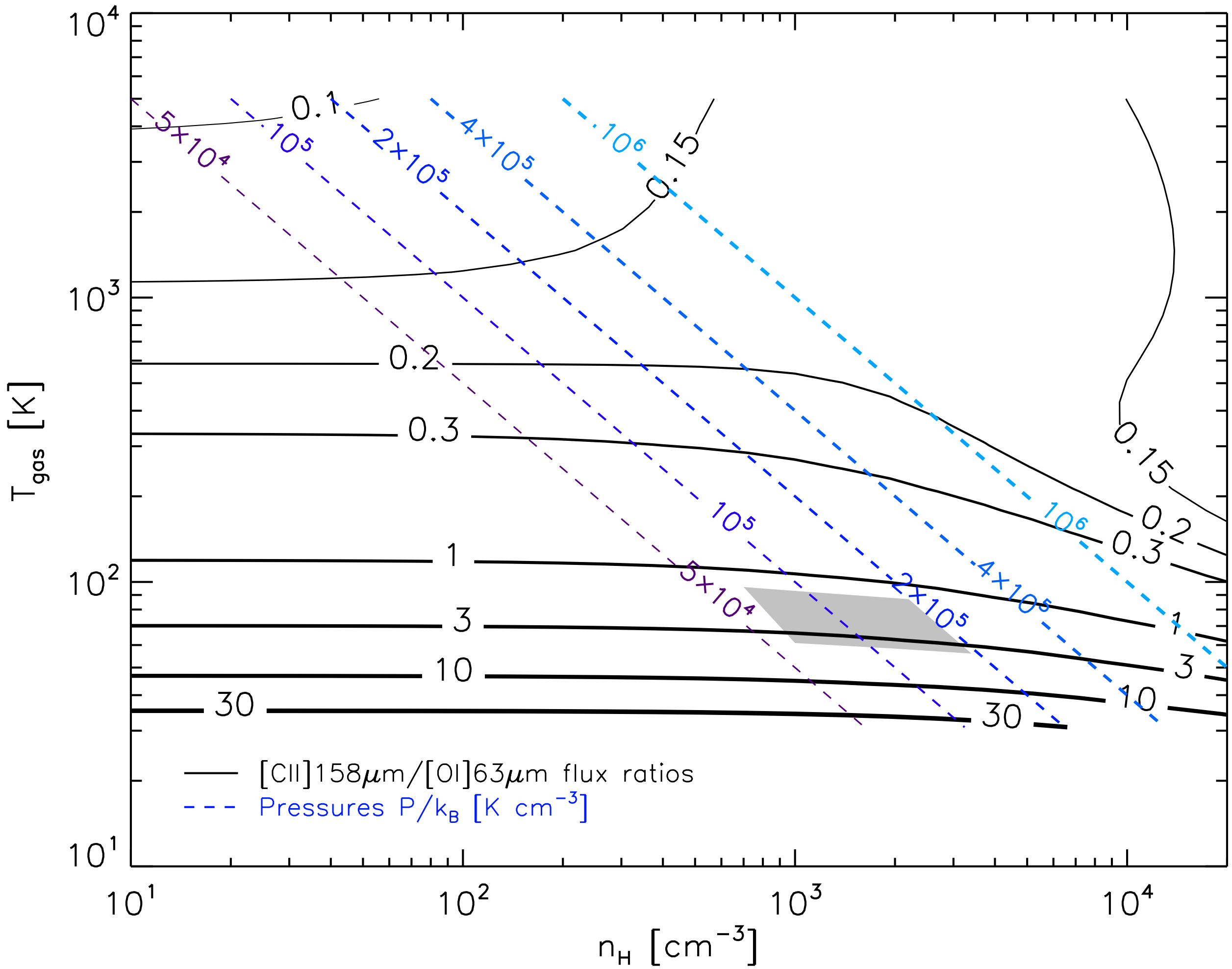
Powerful [CII] line but weak UV and star formation in 3C 326 N

- [CII] twice as strong as the H_2 0-0 S(1) line
- Mass of [CII]-emitting gas: 6×10^8 $M_\odot$ at n_H = 1000 cm^{-3} and T=100 K
- The warm molecular gas is the only gas reservoir that can account for the [CII] emission



Guillard et al. 2015

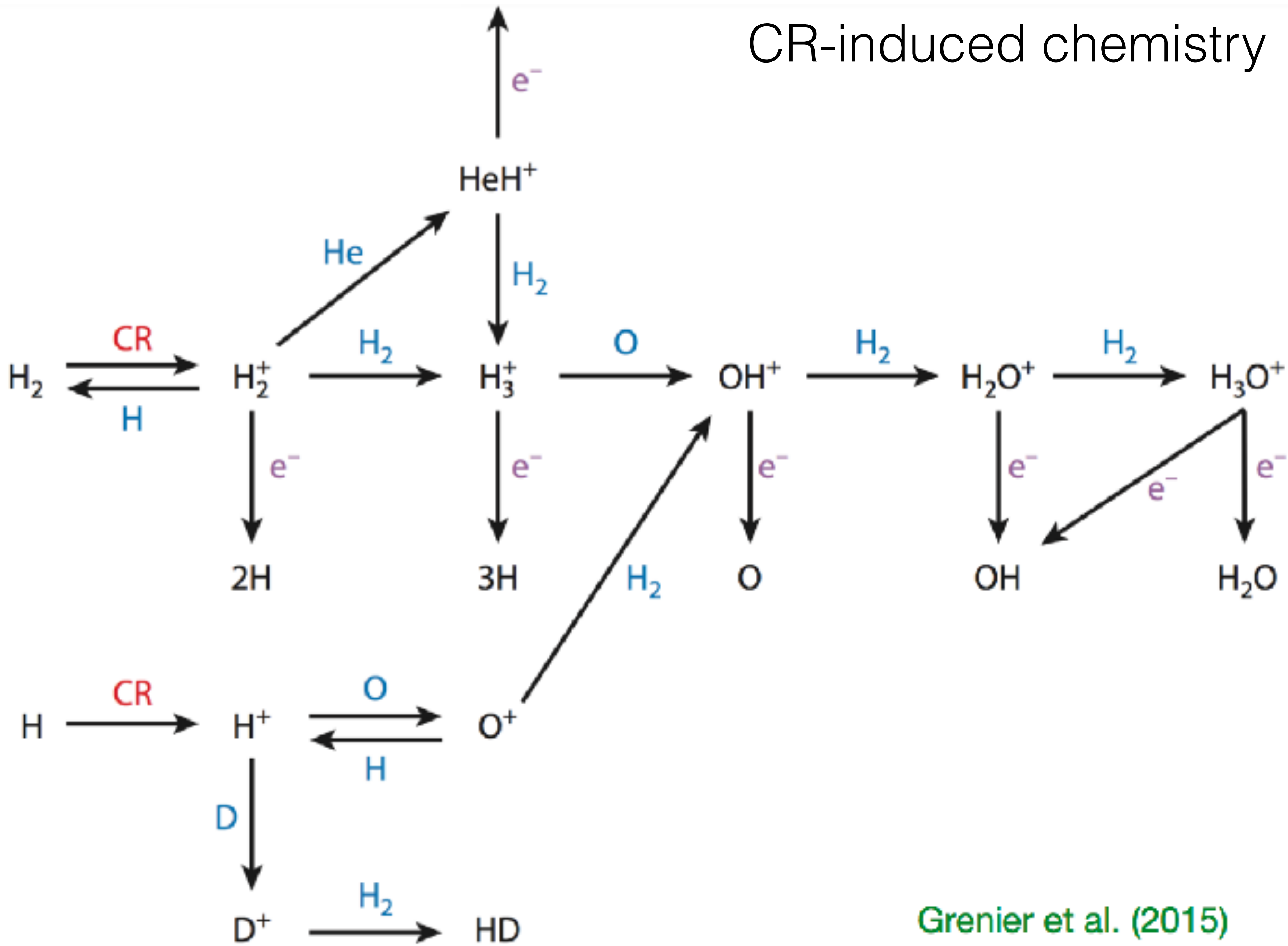
Physical state of the molecular gas in 3C 326N



- Collisional excitation of [CII]158µm and [OI]63µm (solar abundance, 40% of carbon in the gas phase)
- Pressure constrained by [CII]/FIR ratio (dust model)
- temperature constrained by [CII]/[OI] = 2.4±0.6
- No detection of high-J CO lines in the SPIRE spectrum
- Are those physical conditions compatible with CR heating?

Guillard et al. 2015

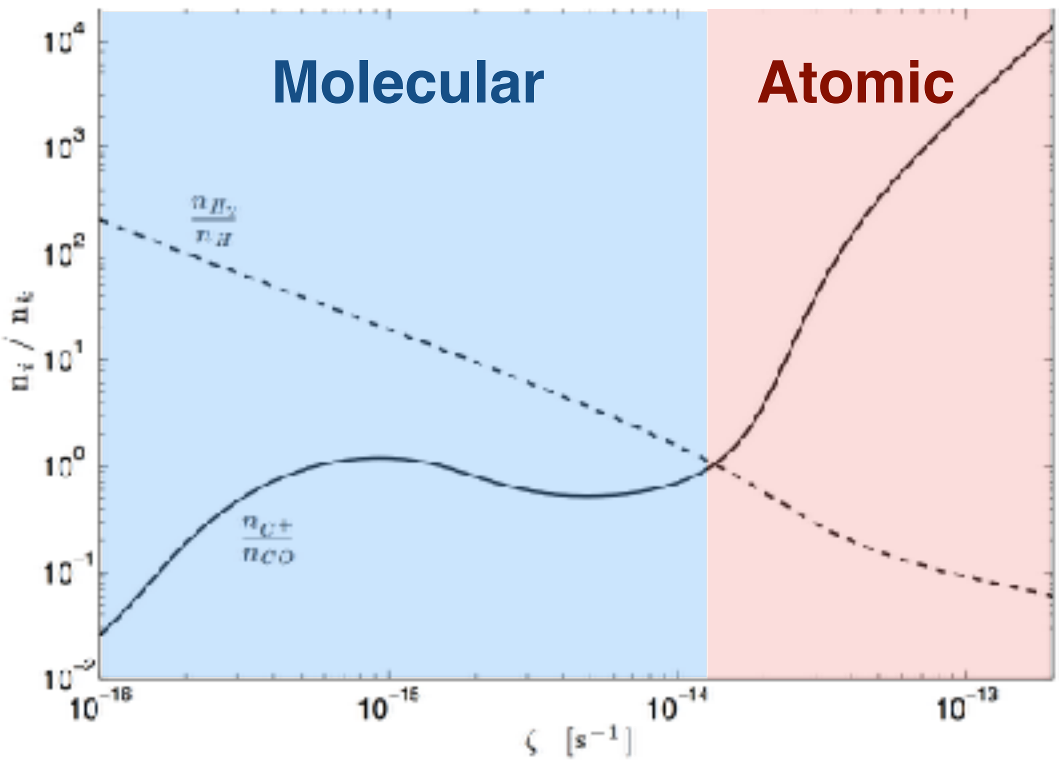
CR-induced chemistry



Grenier et al. (2015)

Can CRs explain the high C^+/CO fractional abundance?

- $\zeta = 2\times10^{-14} s^{-1}$ required to balance the observed [CII]+H_2 cooling rate (line luminosity to mass ratio). This is comparable to the galactic center value (Indriolo et al. 2015)
- CRs dissociate CO molecules (via secondary photons)
- The gas has to be denser than $n_H \approx 3\times10^3$ cm^{-3} to remain molecular
- Weak [CII]/[OI] and high [CII]/FIR impose $7\times10^2 < n_H < 3\times10^3$ cm^{-3}
- Models show that in $n_{H_2} = 10^3$ cm^{-3}, T = 160 K, UV-shielded gas, the gas can be molecular ($1 < n_{H_2}/n_H < 50$) with $n(C^+)/n(CO) \approx 0.8$ for $3 \times 10^{-16} < \zeta < 2 \times 10^{-14}$ s^{-1}.



Mashian et al. 2013

Conclusions

- Very little constrains on CR ionisation rates in AGN
- Large masses of warm molecular gas and high C^+/CO abundances observed in radio-galaxies
- CRs are an important source of gas heating in AGN, affecting kinematics and chemistry
- Complexity and degeneracies of line diagnostics vs. models. Need for hybrid models (e.g. CRs- and Xrays-irradiated shocks — Lehman, Guillard in prep.)

Molecular gas in High-z Radio-Galaxies

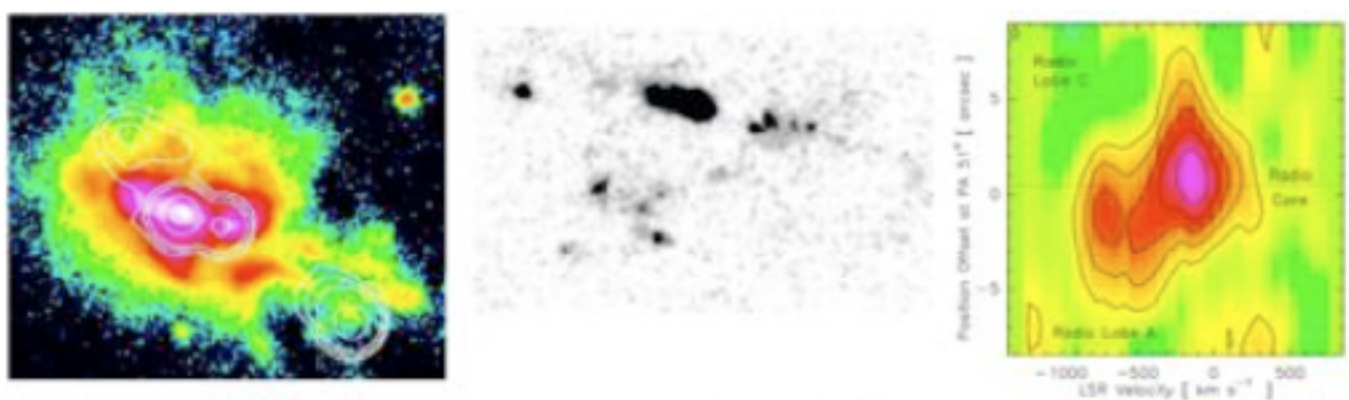
- First (single-dish) surveys failed to detect CO *(Evans+ 1996, van Ojik+ 1997)*
- Since then, CO detected in individual HzRG
  (Miley & De Breuck 2008; also Scoville et al. 1997, Papadopoulos et al. 2000, 2001, Alloin et al. 2000, De Breuck et al. 2003a,b, 2005, Greve et al. 2004, Klamer et al. 2005, Ivison et al. 2008, 2011; Nesvadba et al. 2009; Emonts et al 2011, 2013, 2014)
- CO across tens of kpc (e.g. Papadopoulos et al. 2000)
  CO in giant Lyα halos (Nesvadba 2009)
  CO aligned with radio jets (Klamer et al 2004)

Bias towards high-J CO transitions

+ need for low-surface brightness!

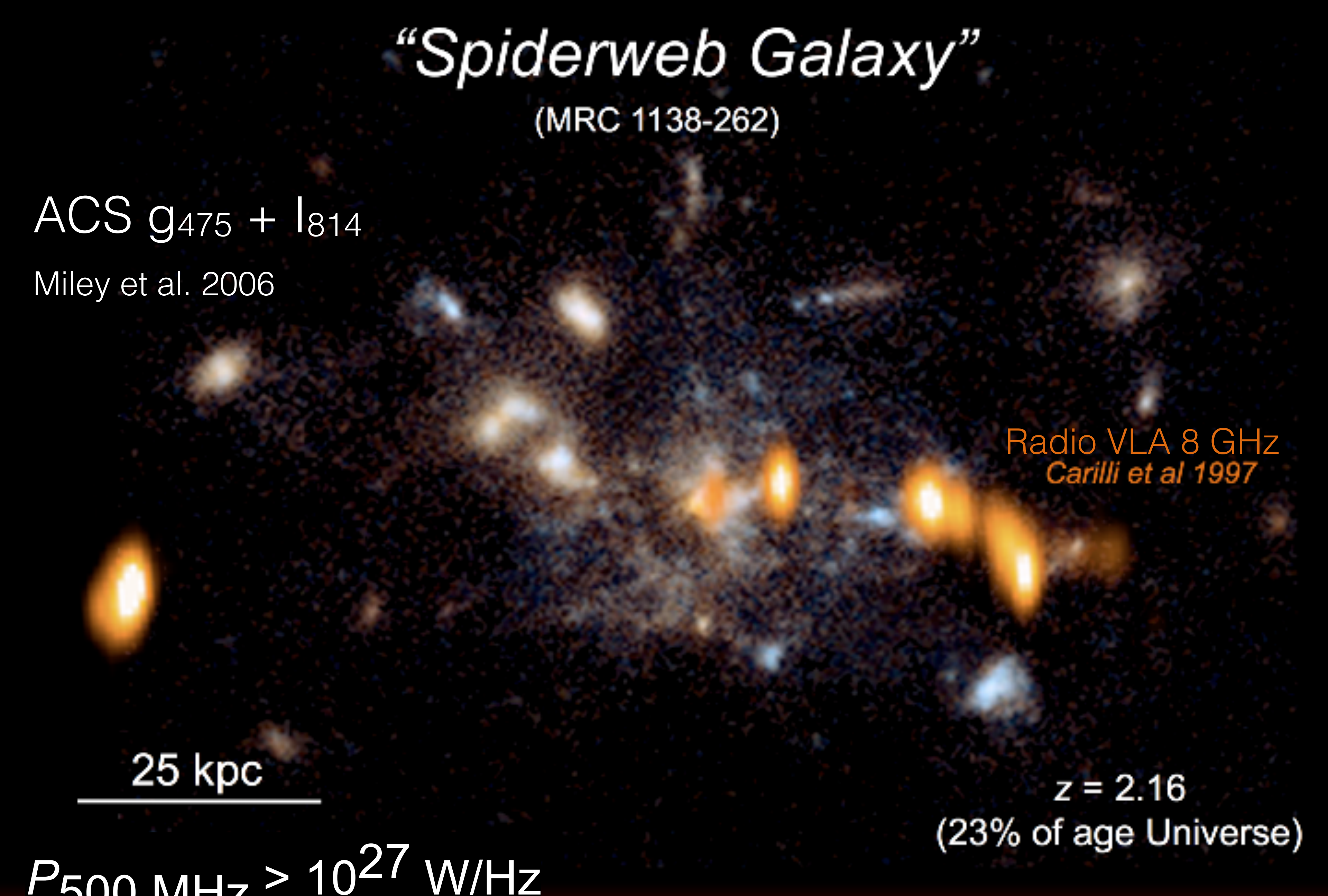
4C41.17 (z = 3.8)

Reuland et al. (2003); Carilli et al (1997)



De Breuck et al. (2005)

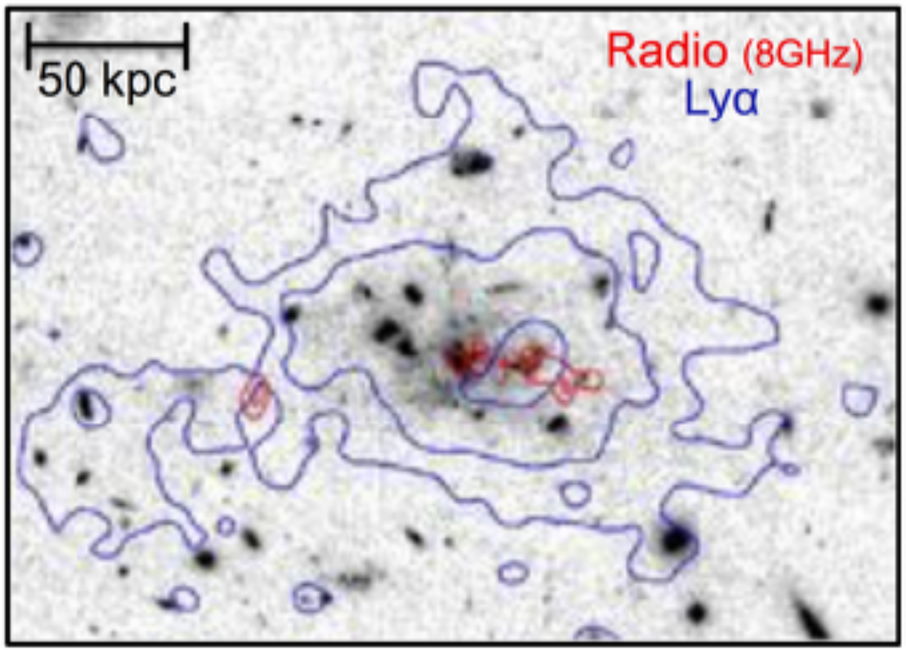
VLA radio on Keck Lya | **HST Image, WFPC2 (7000A)** | **CO(4-3)**



$P_{500\ \mathrm{MHz}} > 10^{27}$ W/Hz

Strong beacons among best studied high-z objects

Extended Halo of ionised gas around a massive high-z radio-galaxy



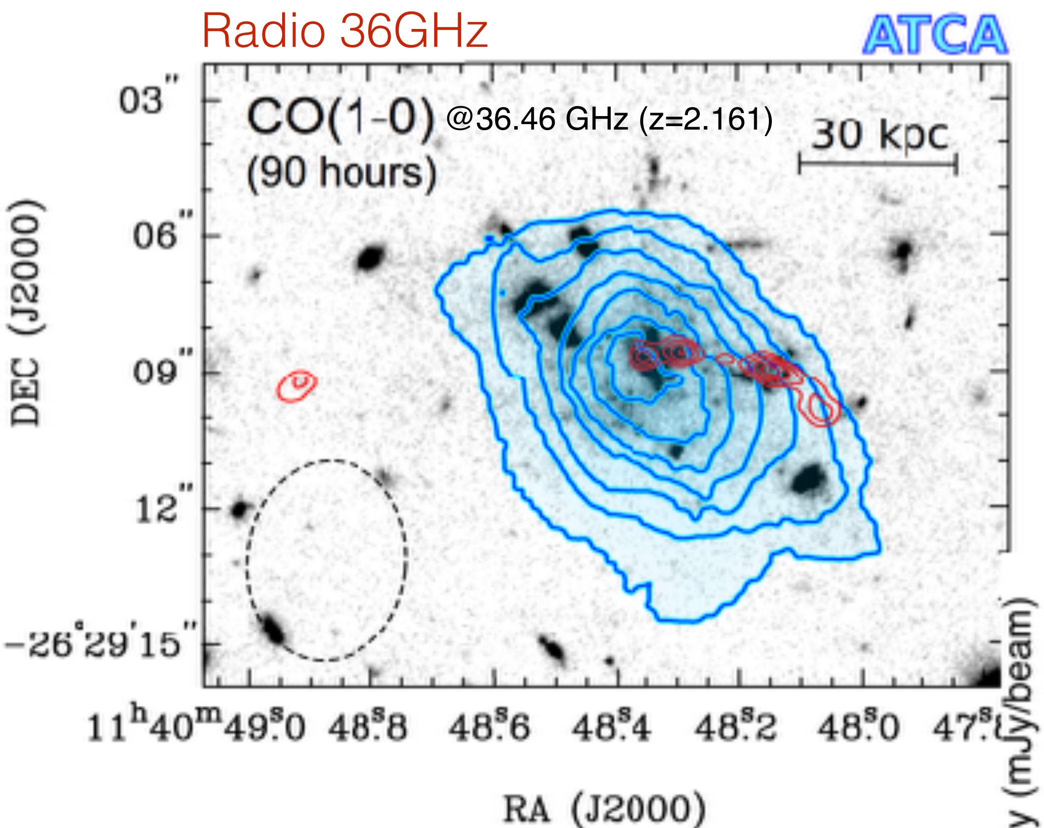
Miley+ (2006)

Spiderweb Galaxy

MRC1138-262 (z=2.2)

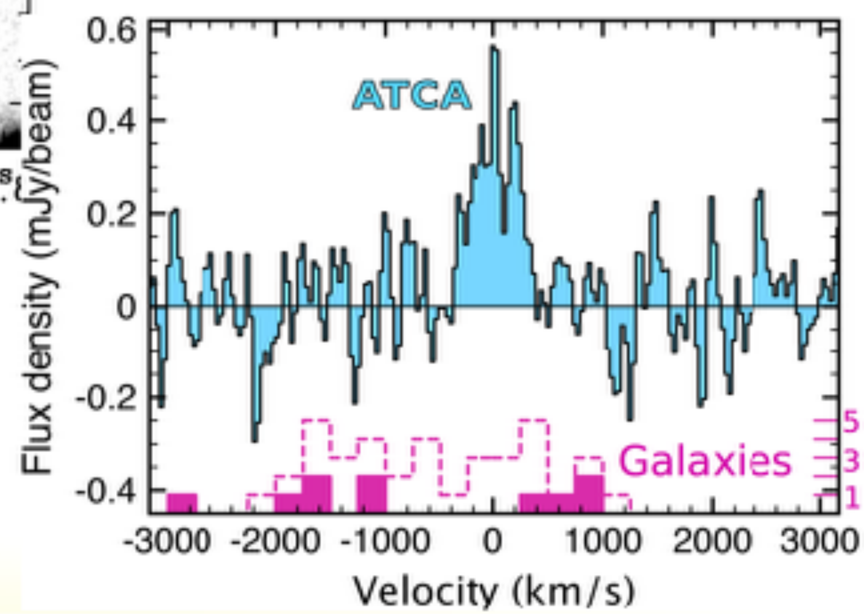
- Giant Lyα halo *(Pentericci+ '97, Miley+ '06)*
- SFR 1400 $M_{\odot}$/yr *(Seymour+ '12, Ogle+ '12)*
- Dust & SF widespread *(Stevens+ '03, Hatch+ '09)*

A Giant Molecular Halo around the z=2 Spiderweb proto-cluster



Spiderweb Galaxy

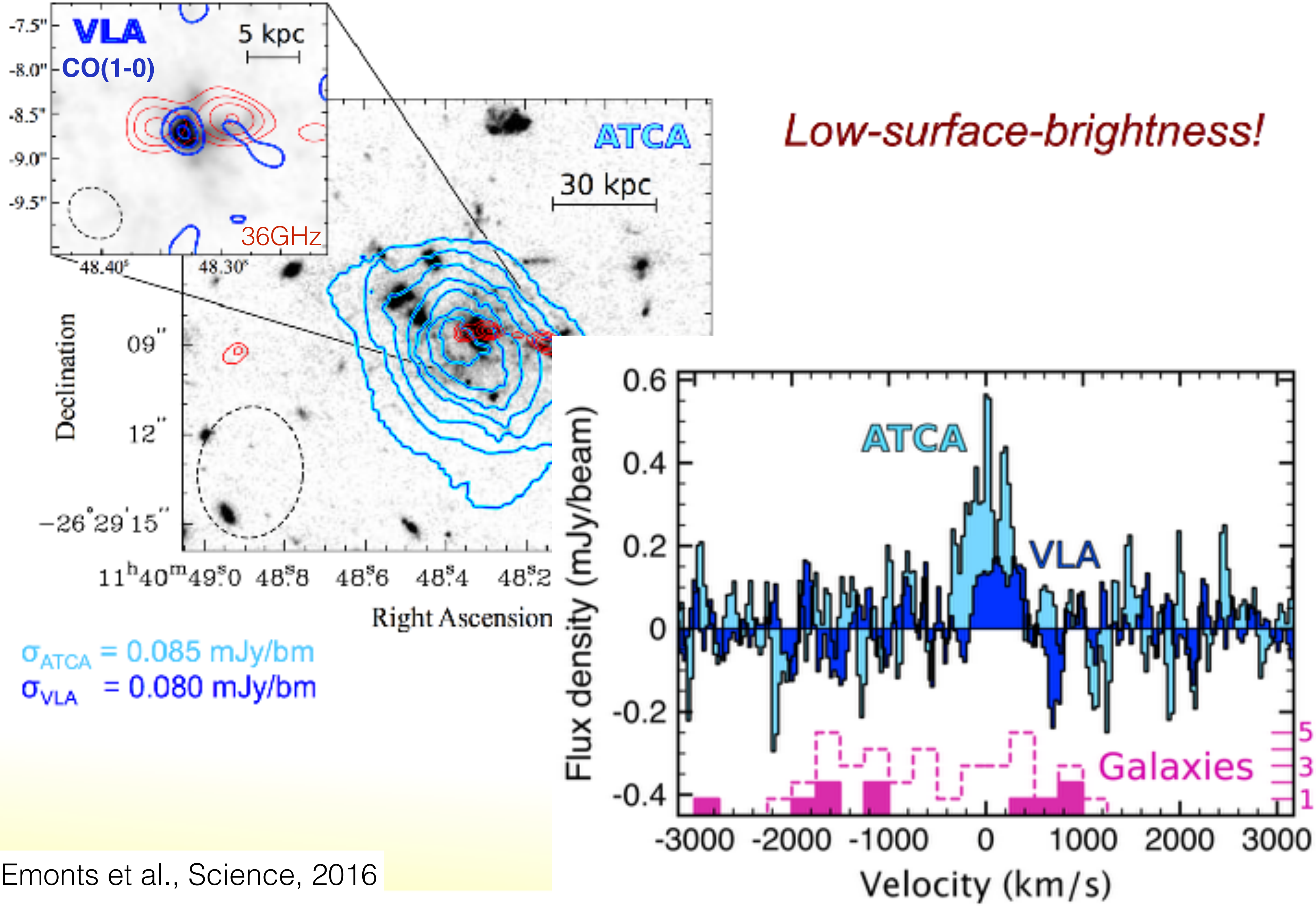
MRC1138-262 (z=2.2)



$L'_{CO} = 5.6 \times 10^{10}$ K km/s pc^2

Emonts et al., Science, 2016

VLA sees only 32% of ATCA flux!

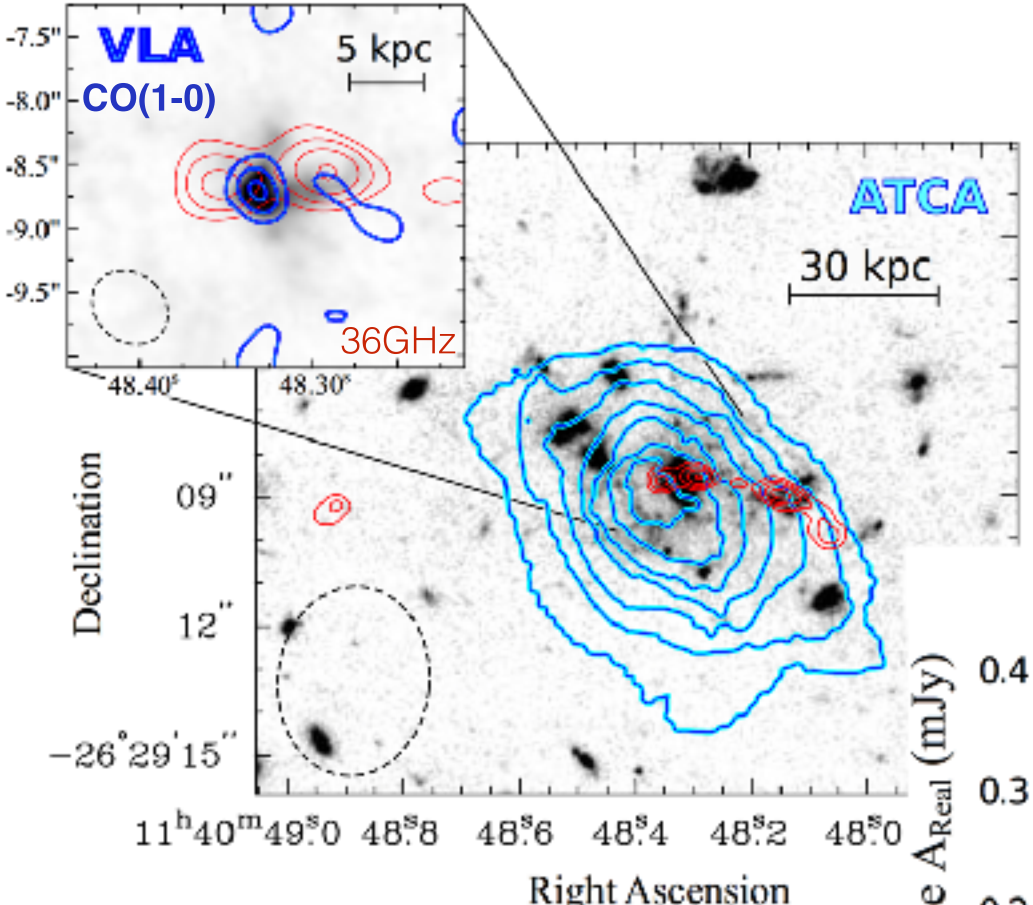


Low-surface-brightness!

σ_{ATCA} = 0.085 mJy/bm
σ_{VLA} = 0.080 mJy/bm

Emonts et al., Science, 2016

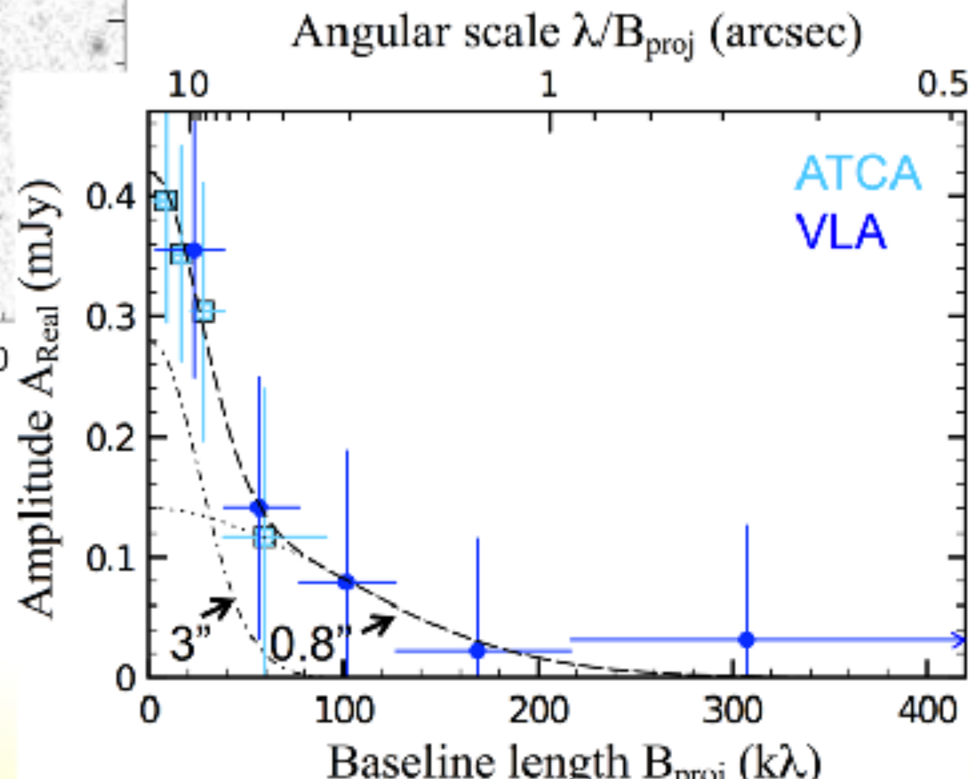
VLA sees only 32% of ATCA flux!



σ_{ATCA} = 0.085 mJy/bm
σ_{VLA} = 0.080 mJy/bm

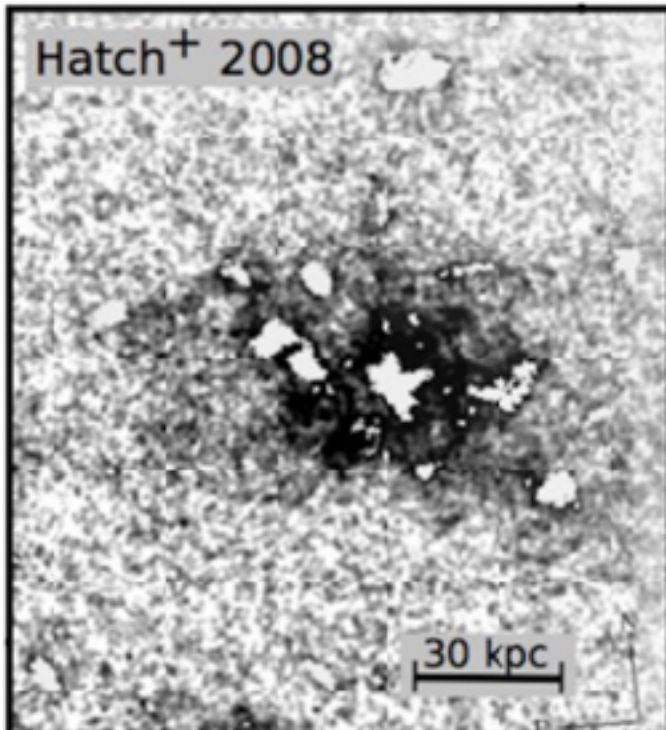
Signal easily resolved out in mm!

For example, at z=2,
1km baselines resolve out:
- CO(1-0) on >14 kpc scales
- CO(4-3) on >4 kpc scales!

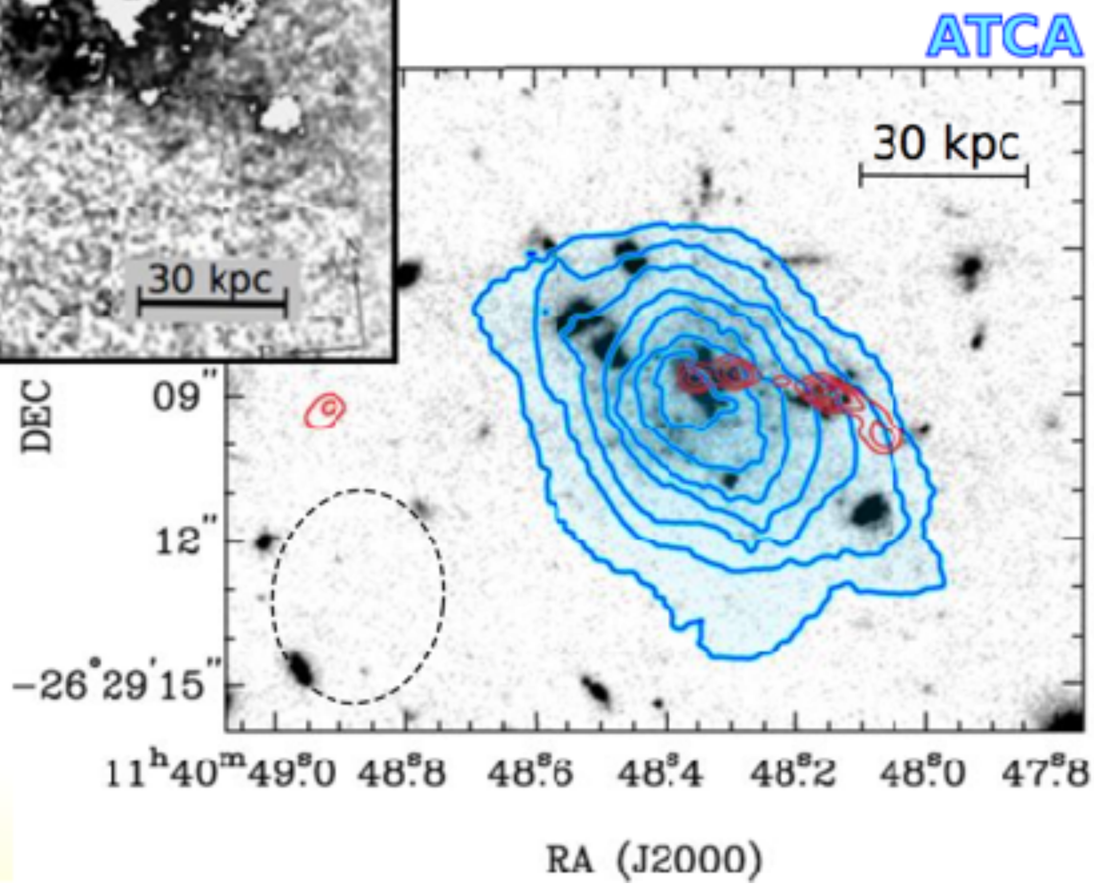


Emonts et al., Science, 2016

In-situ star formation across the IGM!



SFR$_{IGM}$ ~ 142 $M_\odot$/yr

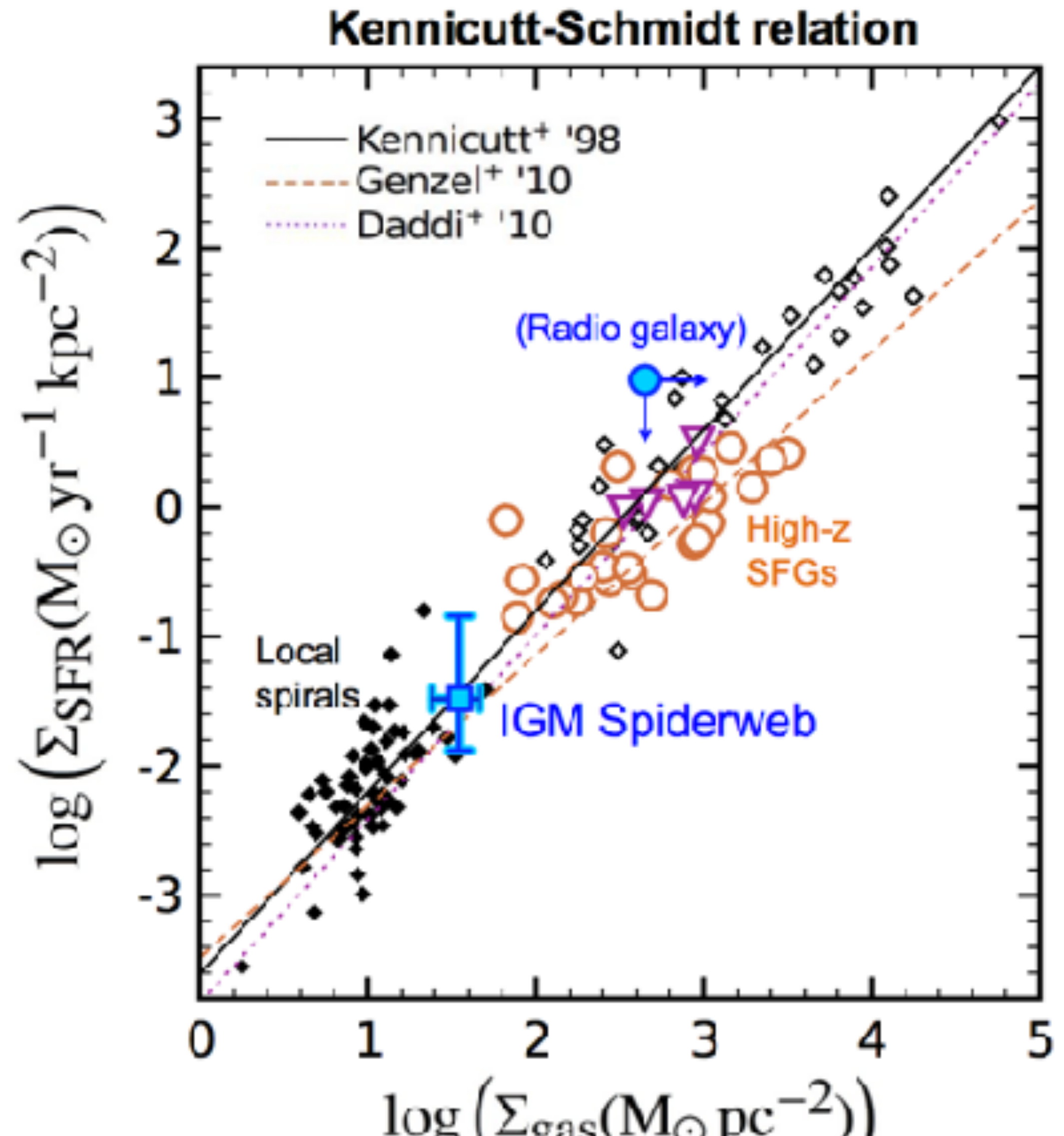


M_{H2}(IGM) =
1.5 x 10^{11} (X_{CO}/4) $M_\odot$

Early assembly of giant cluster elliptical out of enriched IGM

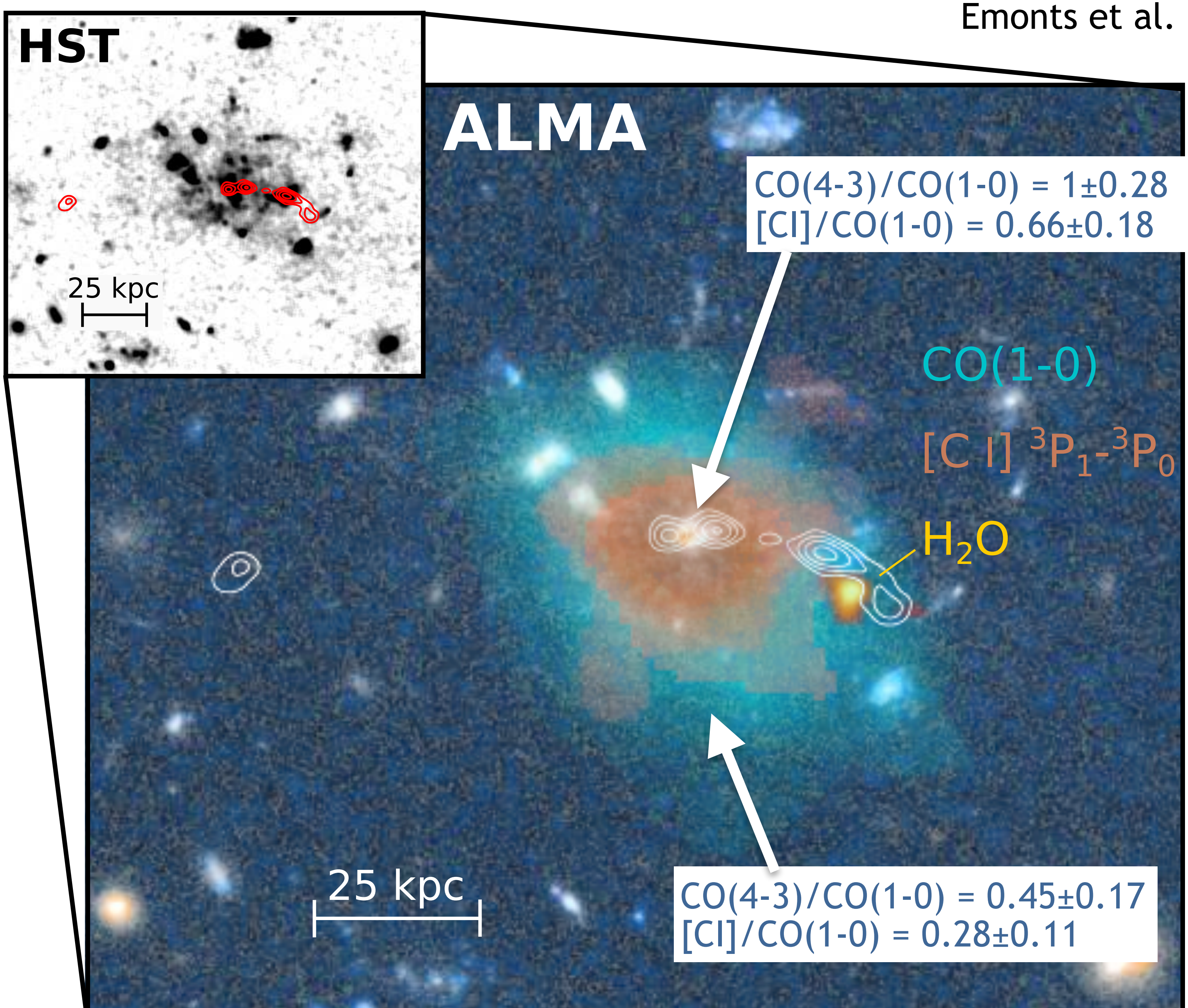
CO(1-0) drives
“in-situ” star formation

Gas depleted by z=1.6
→ stellar halo can age!

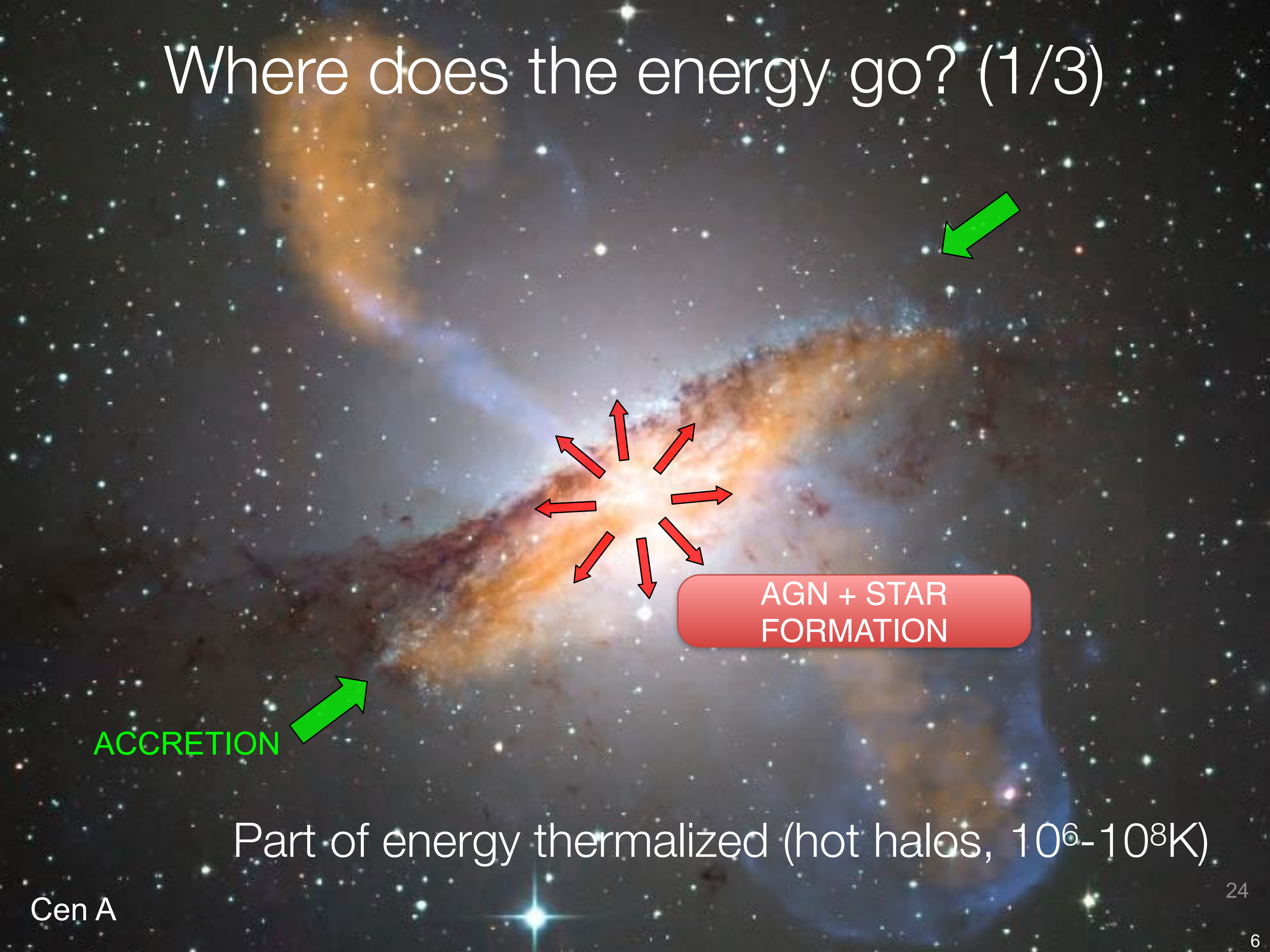


Emonts et al., Science, 2016

Emonts et al. 2018



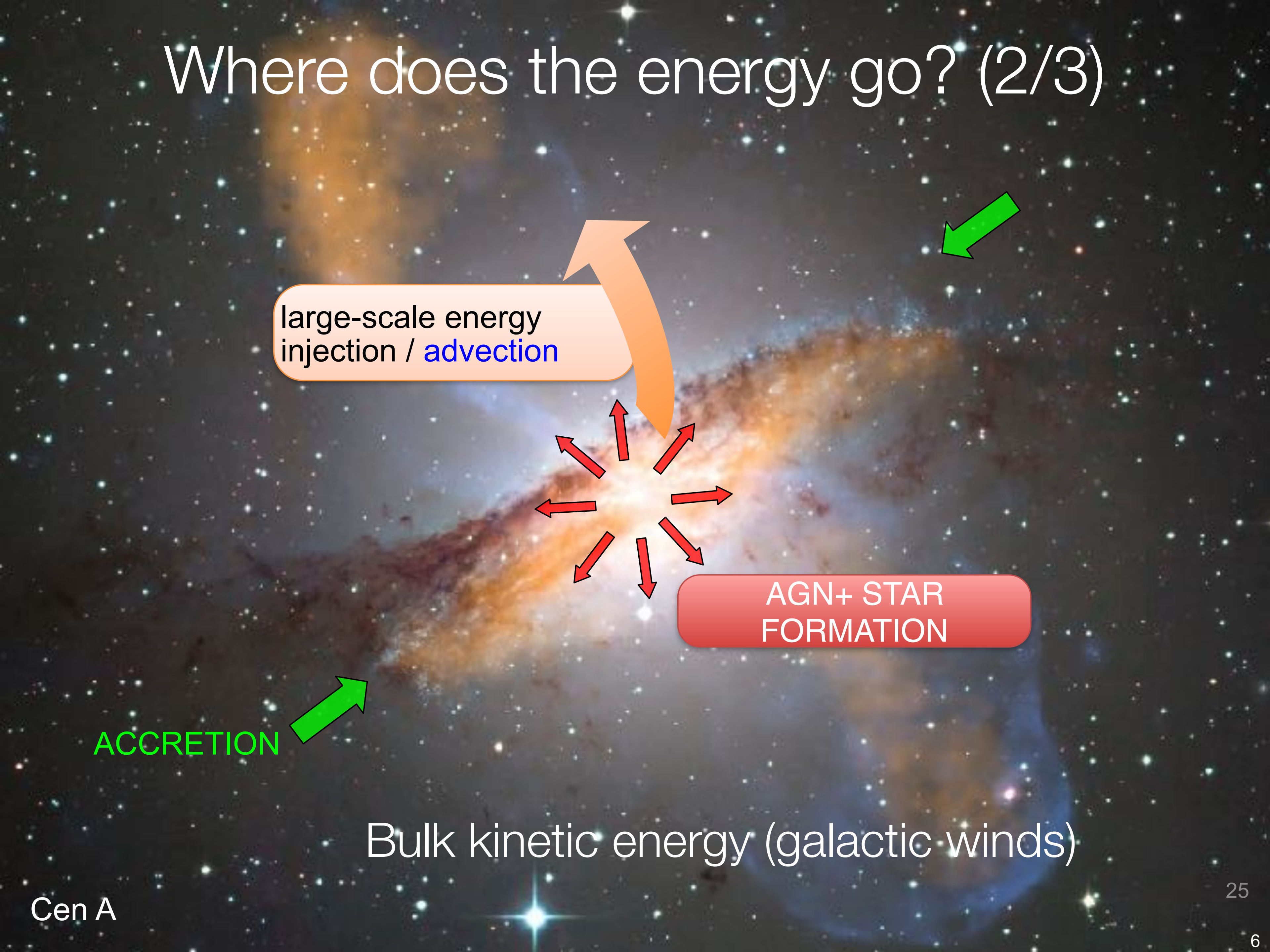
Where does the energy go? (1/3)



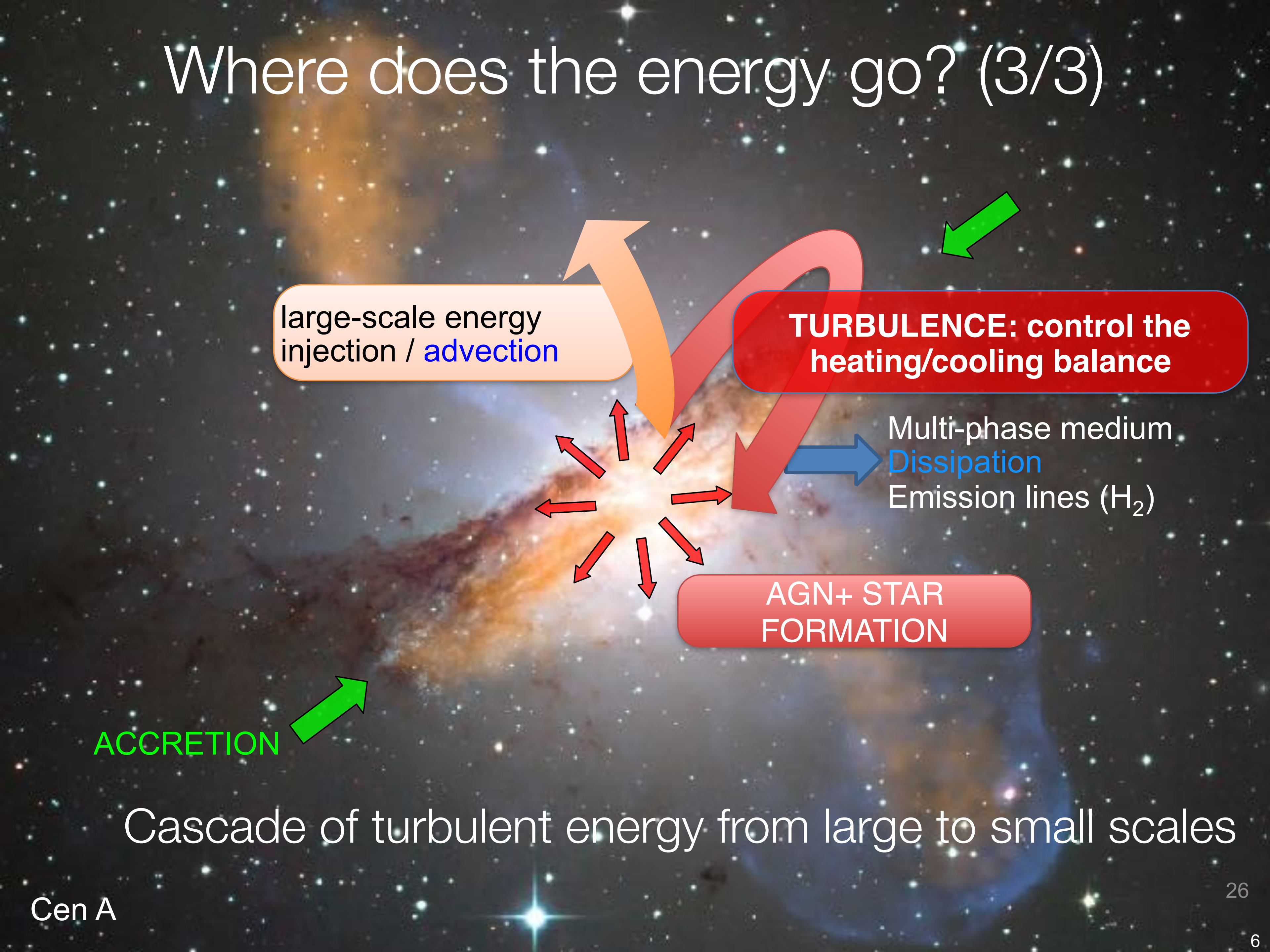
Part of energy thermalized (hot halos, 10^6-10^8K)

Cen A

Where does the energy go? (2/3)



Where does the energy go? (3/3)



Cascade of turbulent energy from large to small scales

Cen A

Lessons learned

From line luminosities and energy balance arguments:

- Molecular cooling rate can be higher than X-ray cooling
- Gas cooling is controlled by the dissipation of turbulent energy
- Turbulent dissipation time >> dynamical time

From kinematics:

- Mechanical energy >> thermal energy
- The gas has to cool dynamically (not only thermally).
- The different gas phases are kinematically coupled

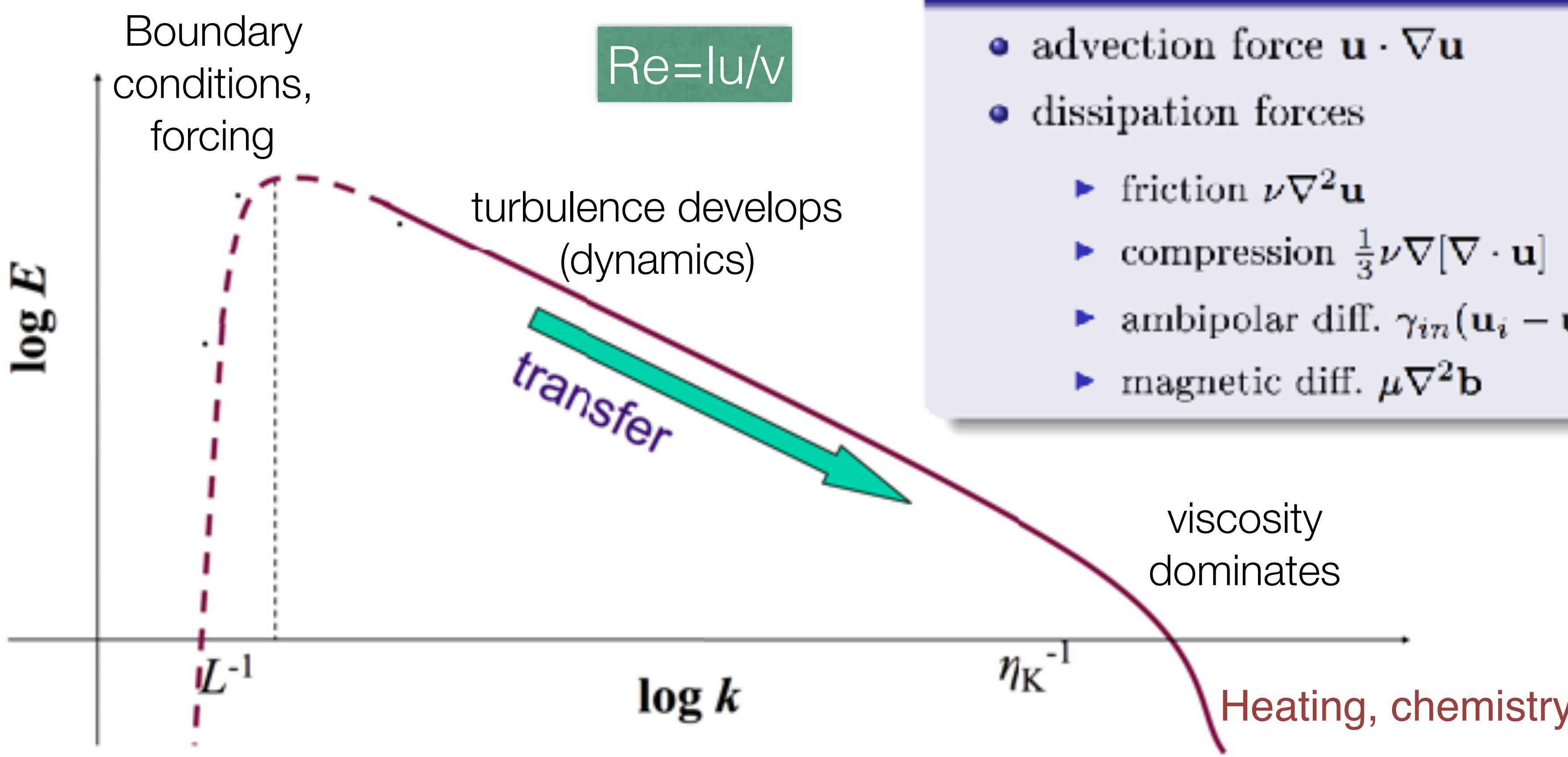
From shock models and simulations:

- Turbulence is supersonic in the dense phase
- Amplitude of turbulence is beyond what is explored in current models/simulations of star formation
- Large dynamical range of spatial scales: ~100 kpc — 0.01pc

Thanks for your time!

http://www.sensitivelight.com/smoke2/

Richardson's turbulent cascade



turbulent cascade

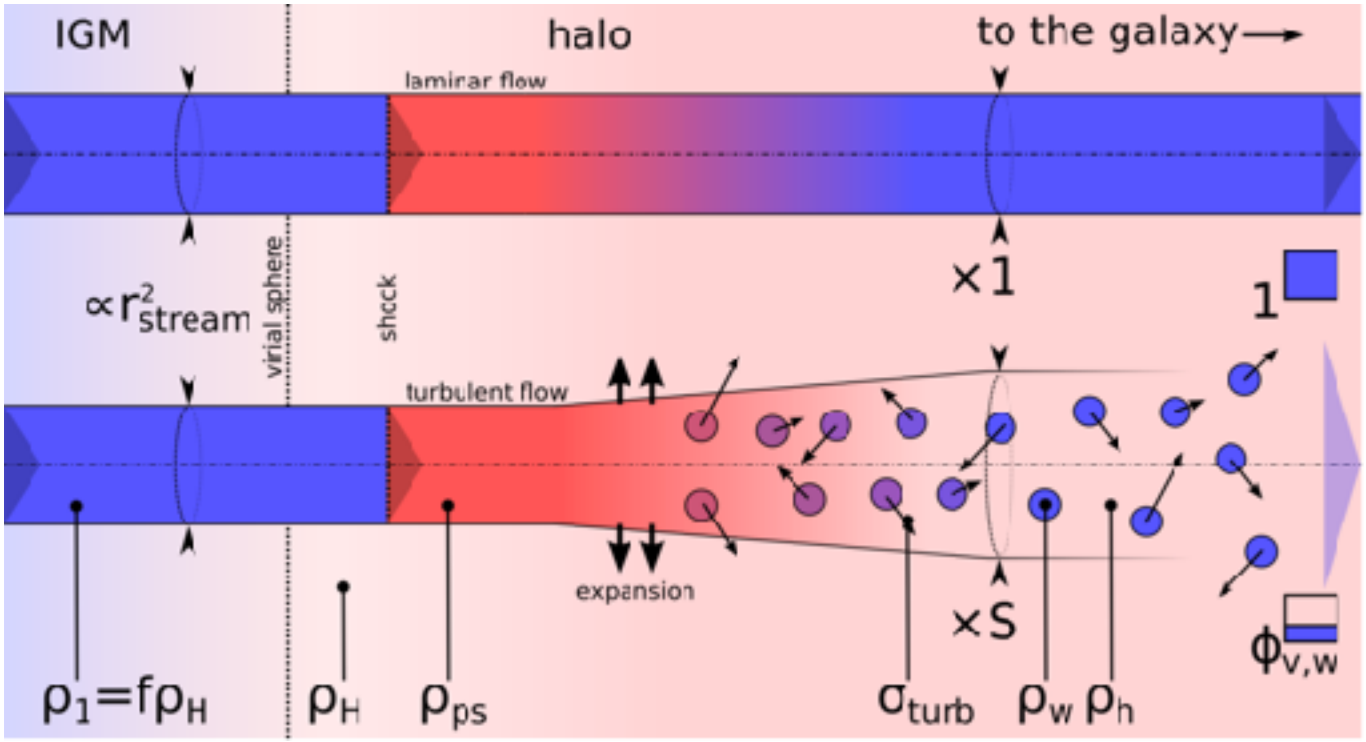
- advection force $\mathbf{u} \cdot \nabla \mathbf{u}$
- dissipation forces
  - friction $\nu \nabla^2 \mathbf{u}$
  - compression $\frac{1}{3} \nu \nabla [\nabla \cdot \mathbf{u}]$
  - ambipolar diff. $\gamma_{in}(\mathbf{u}_i - \mathbf{u}_n)$
  - magnetic diff. $\mu \nabla^2 \mathbf{b}$

energy source & scale
NOT known
(supernovae, winds,
spiral density waves?)

dissipation scale not known

- Friction
- Compression
- Ambipolar + molecular diff.
- Magnetic diff.

Sketch of the model



- Expansion of the post-shock gas and mixing with the ambient hot halo gas
- Density and velocity inhomogeneities may arise through the dynamics of the shock itself (Sutherland et al. 2003; Kornreich & Scalo 2000).
- Inhomogeneities amplified by hydrodynamic and thermal instabilities leading to the formation of warm clouds.
- Part of the kinetic energy of the infalling gas is converted to random motions among and turbulence within the warm clouds (e.g., Hennebelle & Pérault 1999; Kritsuk & Norman 2002).

Cornuault et al. 2016