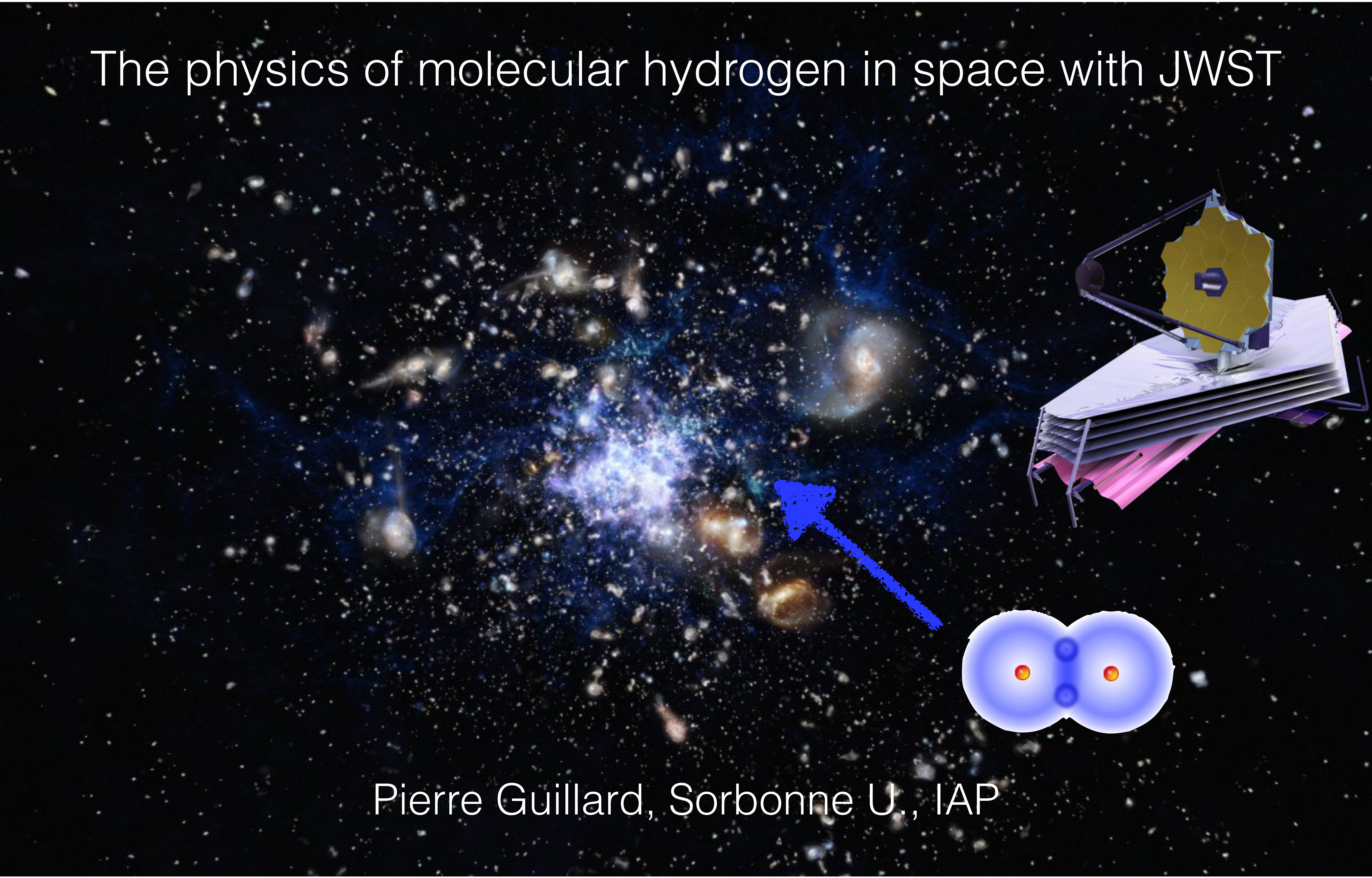
The physics of molecular hydrogen in space with JWST



Pierre Guillard, Sorbonne U., IAP

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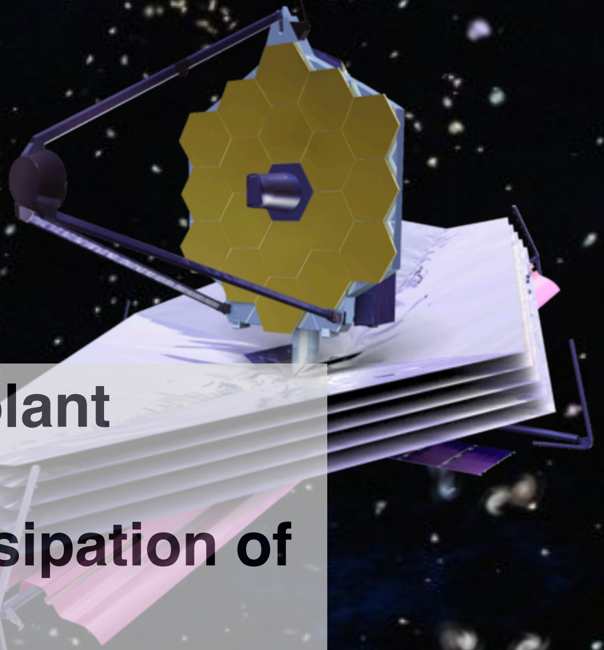
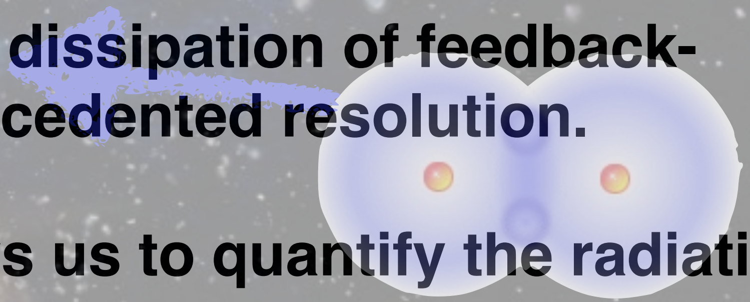
The physics of molecular hydrogen in space with JWST



- Why H_2? A tracer of dissipative processes and efficient gas coolant
- Identification of sources where H_2 unambiguously trace the dissipation of turbulent energy: JWST opens new perspectives
- JWST enables studies of the link between the dissipation of feedback-driven turbulence and H_2 emission with unprecedented resolution.

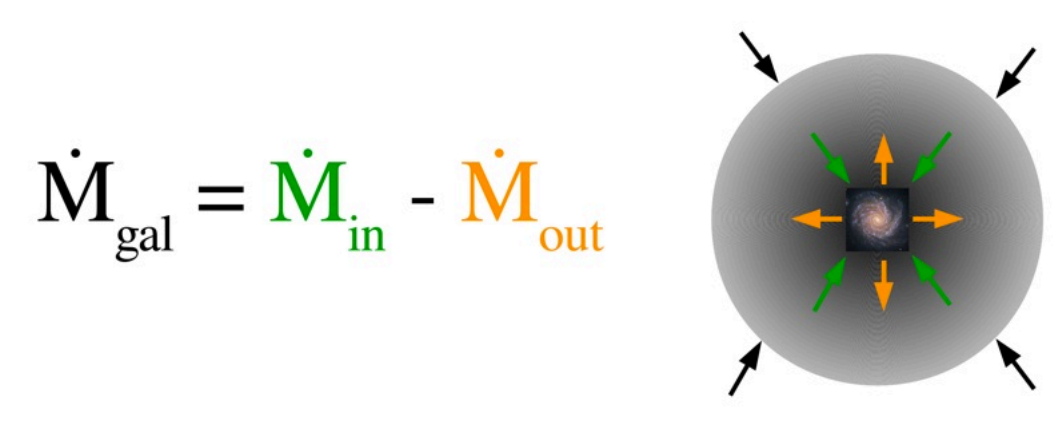


- Modelling of atomic and molecular lines allows us to quantify the radiative and energy budgets of galaxies

Is H_2 emission a reliable tracer of the dissipation of turbulence driven by accretion and feedback?

- During early phases of galaxy formation, the potential energy of gas accreting dominates the energy released by young stars (Elmegreen & Burkert 2010)
- The mechanical energy from gas accretion, merging and feedback has to dissipate for galaxies to grow.
- Part of this energy is stored in a turbulent reservoir, cascades down to small scales, and is dissipated in cold gas (e.g. molecules). Challenging to capture in numerical simulations.
- The turbulent dissipation sets the timescale of the thermodynamic evolution of the gas and is associated with the formation of multiphase ISM

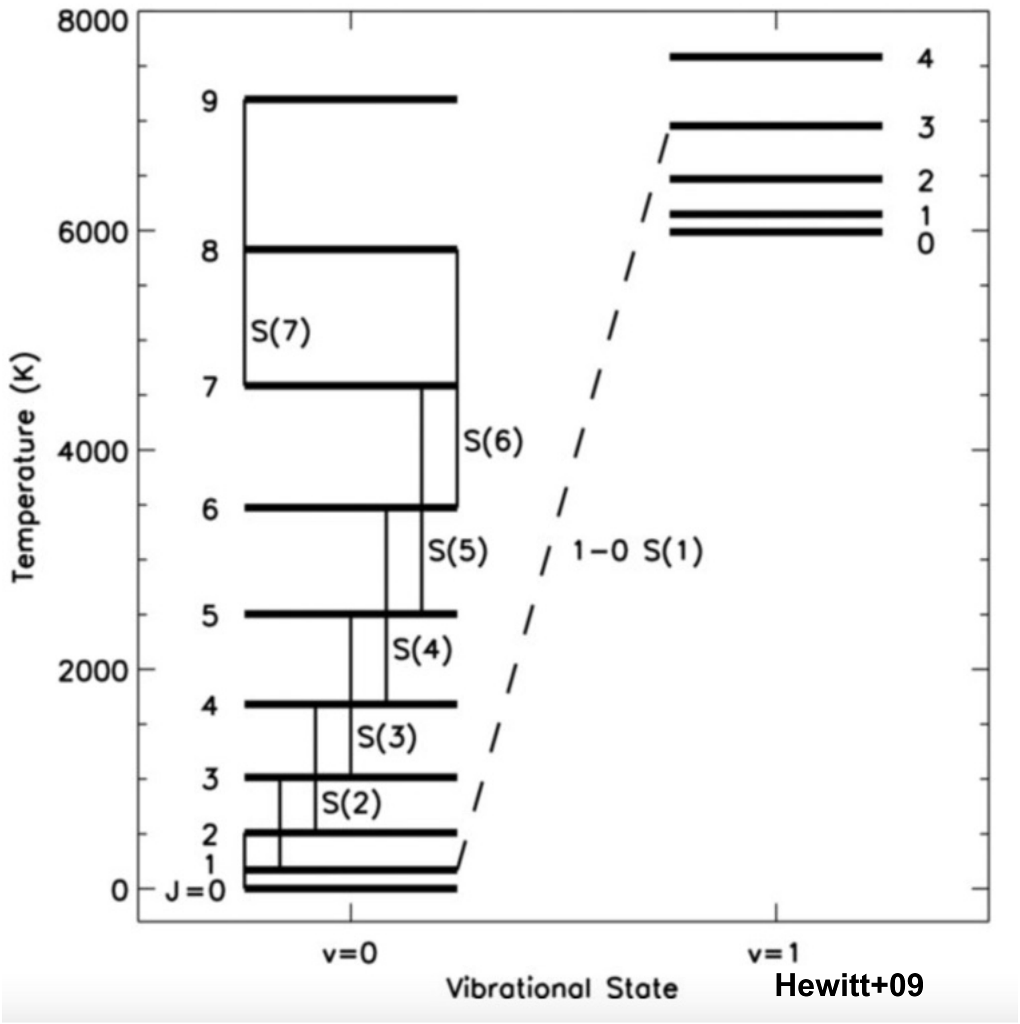
Galaxies grow in time by exchanging matter with their halos



$$\dot{M}_{gal} = \dot{M}_{in} - \dot{M}_{out}$$

H_2 emission: a major coolant, bridging warm to cold phases of the ISM

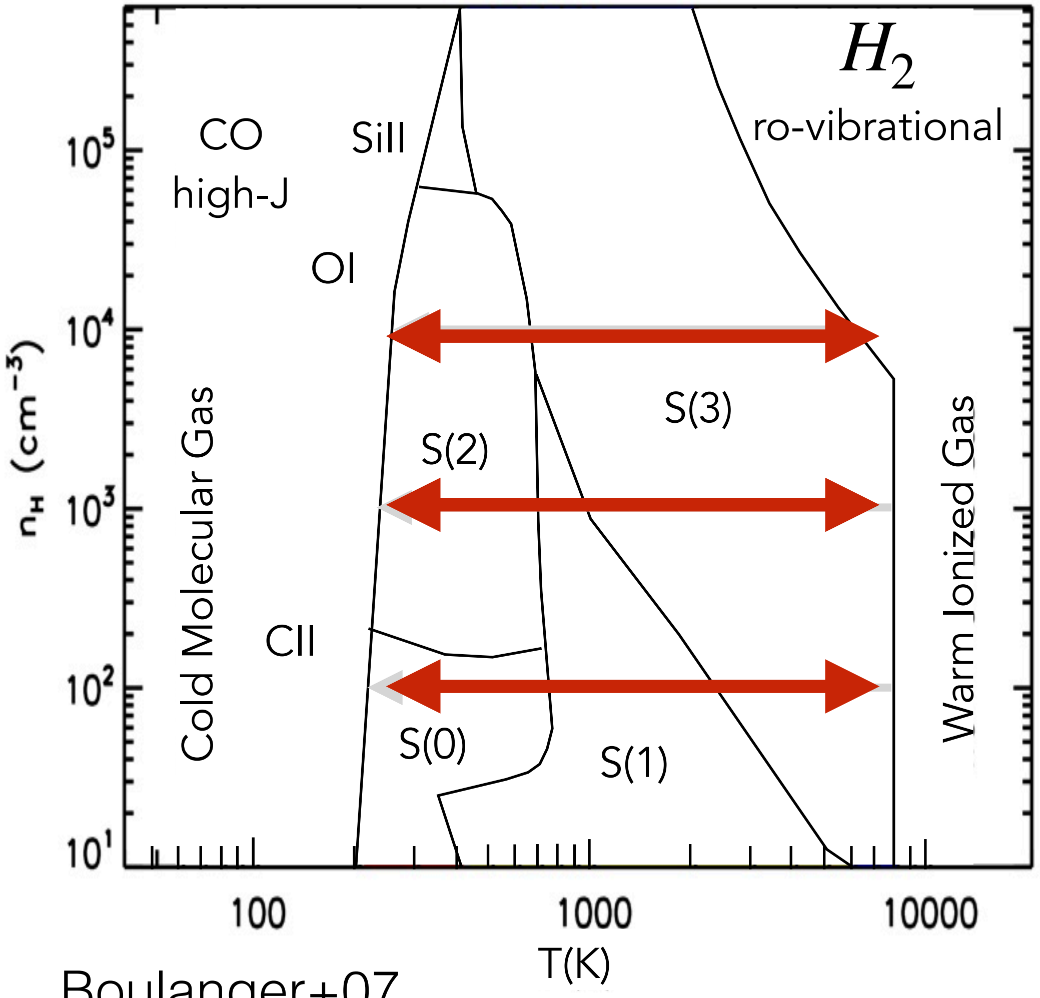
Energy levels (in K), and main transitions observed in the infrared



Hewitt+09

- Formation onto grains and 3-body
- Collisional non-reactive: H, He, and o/p-H2
- Collisional reactive: H, H+, H3+,...
- UV-pumping
- Chemical pumping

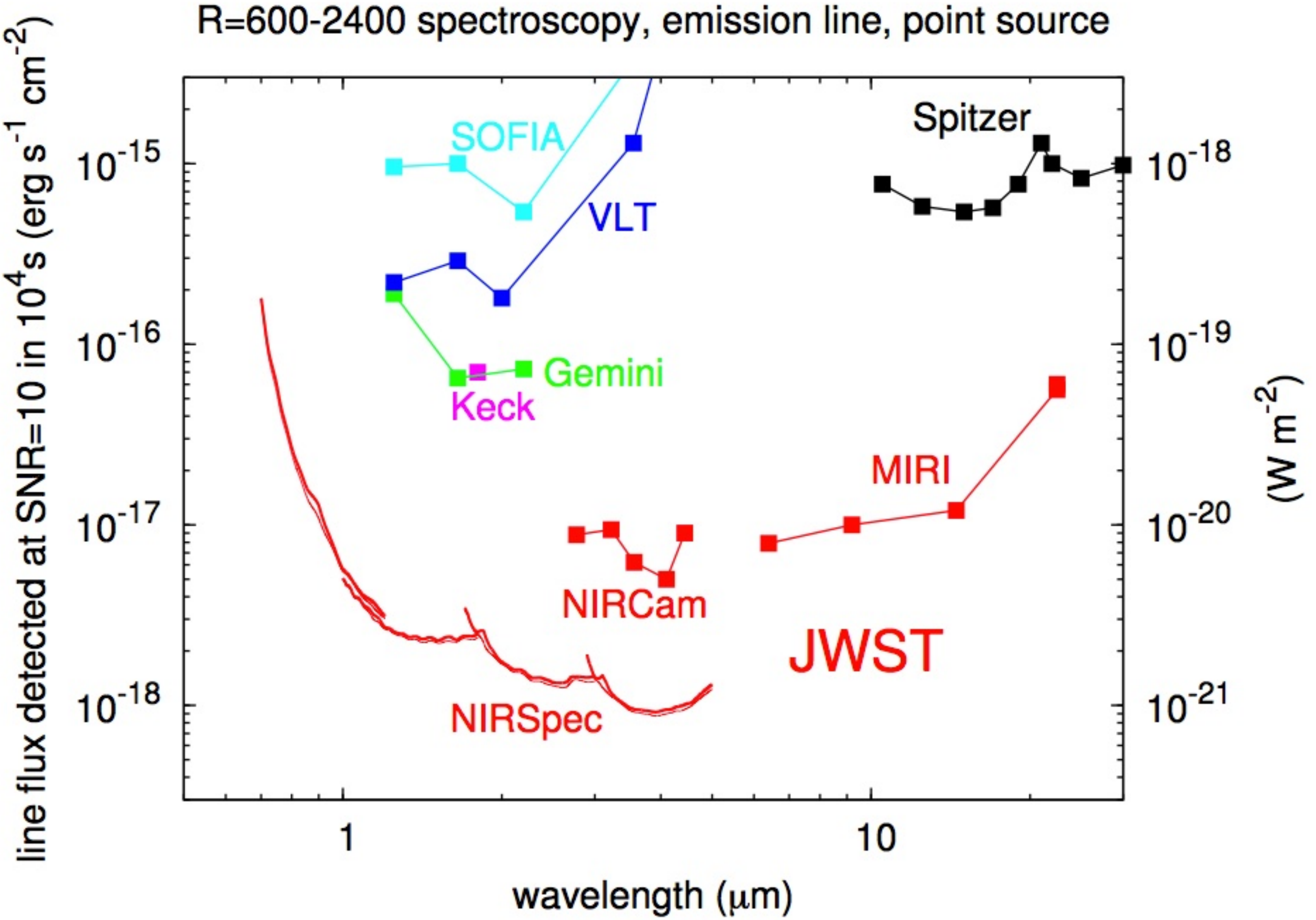
Main cooling lines as a function of density and temperature, assuming isobaric model



Boulanger+07

H_2 lines probe gas heated by dissipation of energy in existing molecular gas and H_2 formed out of warm atomic gas.

JWST: new perspective for H_2 spectroscopy



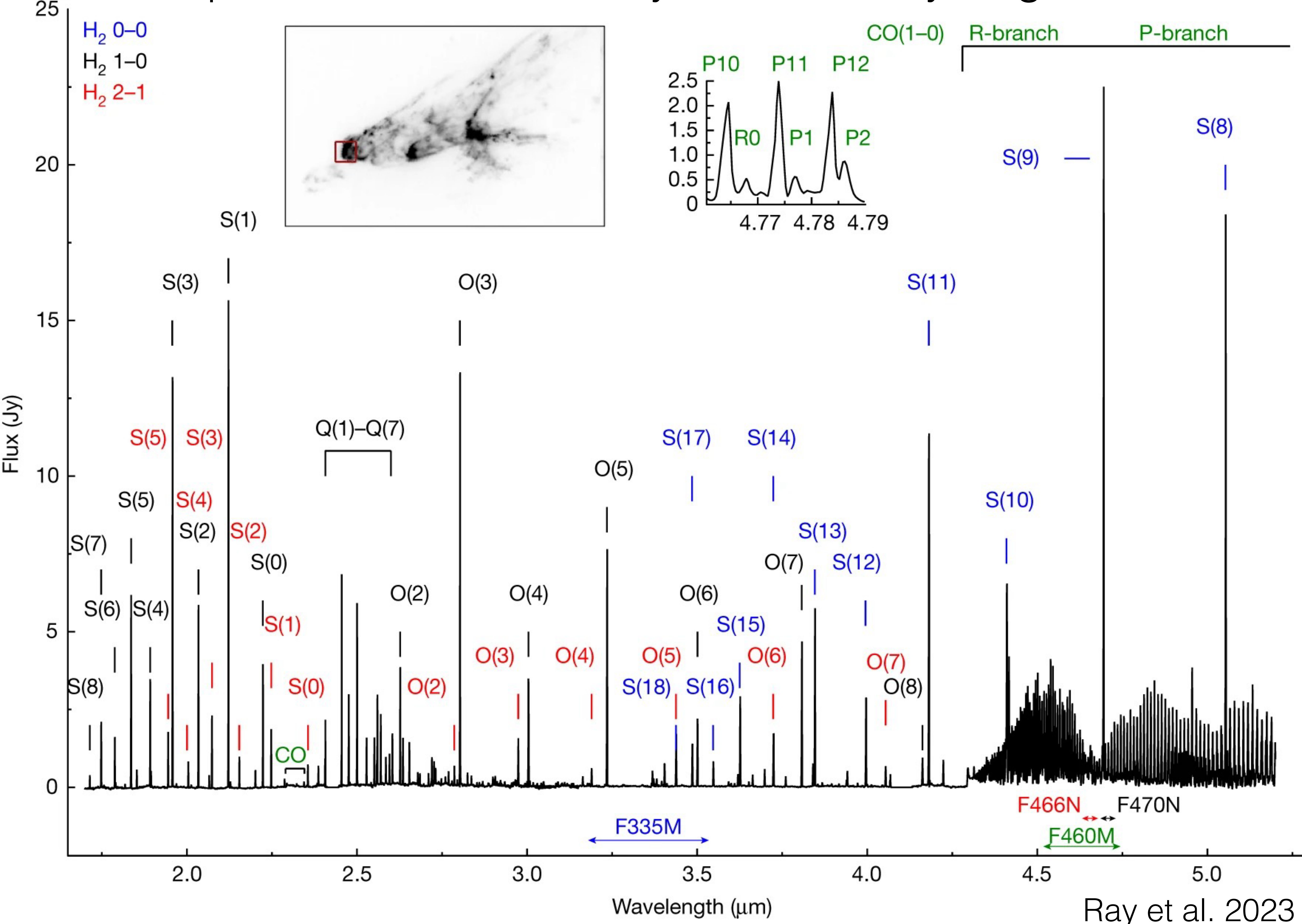
H_2, a tracer of dissipation of kinetic energy: protostellar outflows

- Important phase of star formation:
  up to 80% of the final mass gathered,
  and most of mass dispersed
- Source of radiative and mechanical feedback

Ray et al. 2023

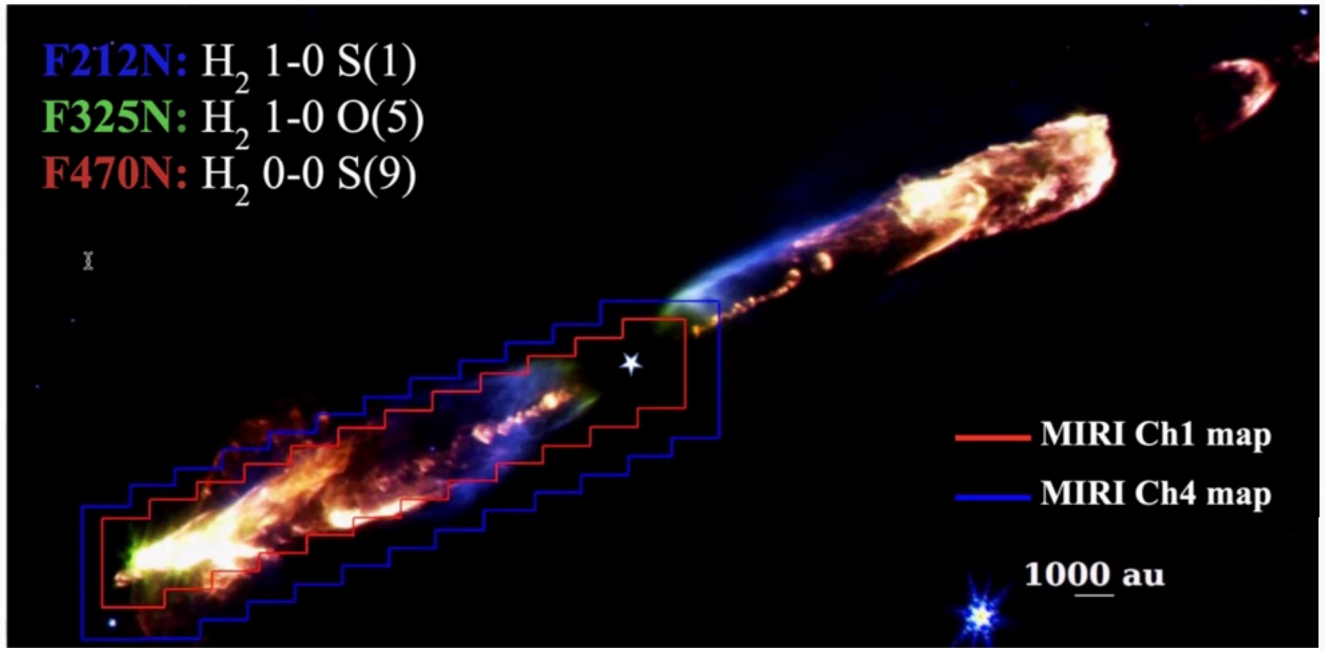
Purple: F162M + F164N, Blue: F210M + F323N, Cyan: F335M, Green: F460M, Orange: F466N, Red: F470N

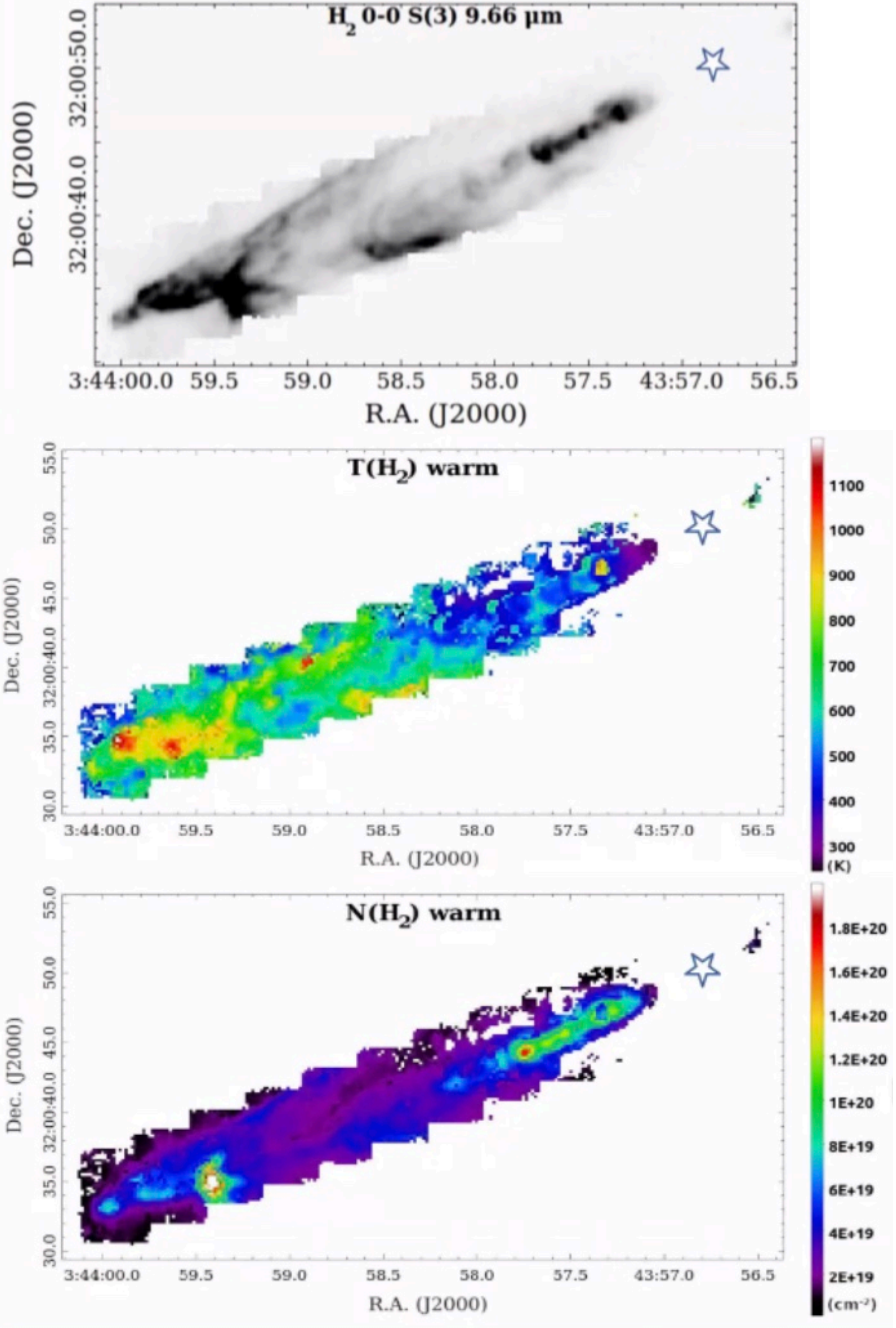
HH 221 spectrum dominated by molecular hydrogen emission



Ray et al. 2023

Physics of the flow





- Jet is mostly molecular, with atomic+ionic core.
- Temperature increases moving away from the source (from jet to bow shocks)
- N(H_2) decreases and density moving away from the source.
- Velocity decreases as jet shocks the ISM, forming terminal bow shocks: stronger shocks in less dense medium away from source.

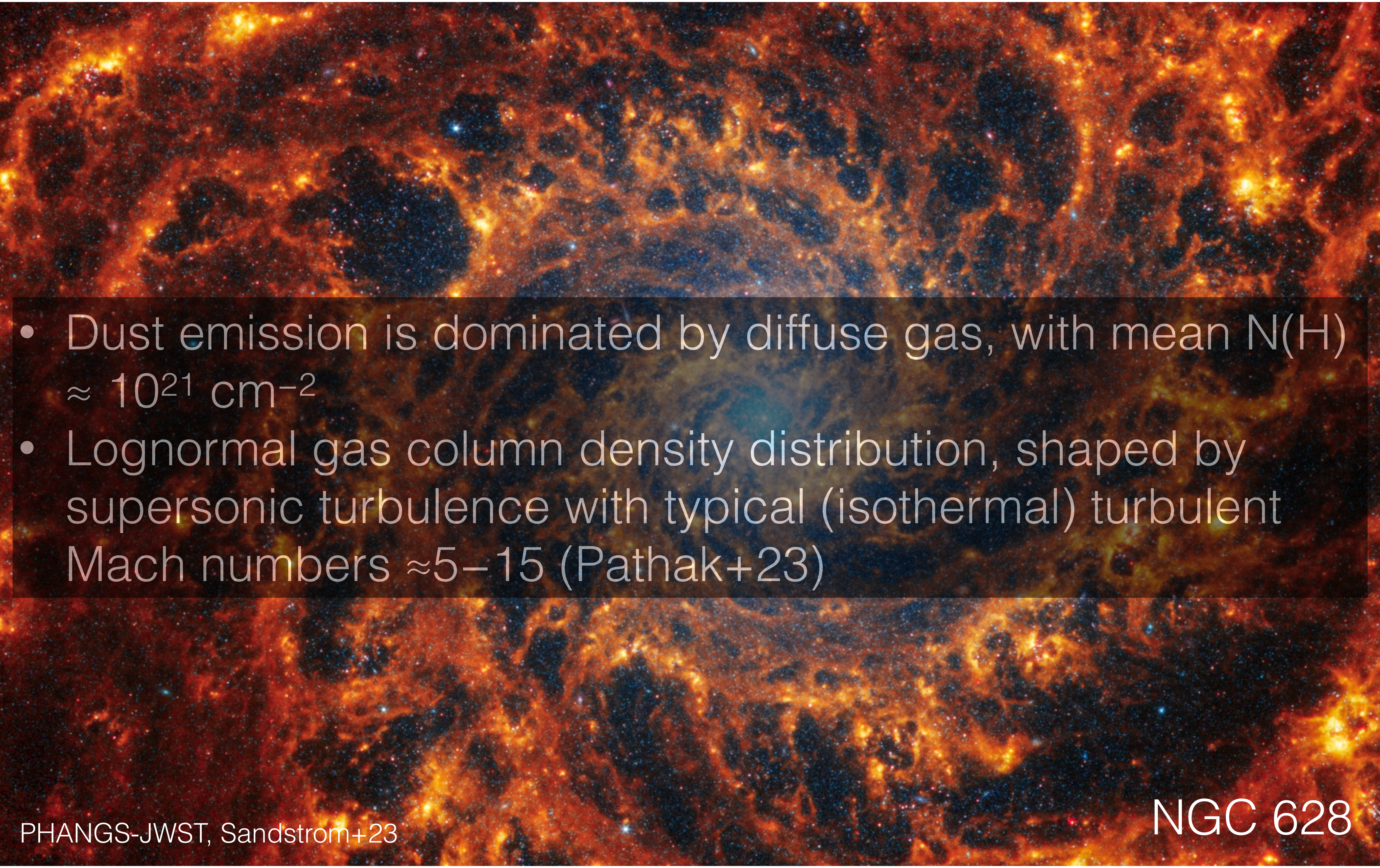
Caratti o Garatti+24

JWST enables to image the structure of the ISM with unprecedented resolution

PHANGS-JWST, Sandstrom+23

2 fundamental questions: how and where is the energy dissipated?

JWST enables to image the structure of the ISM with unprecedented resolution



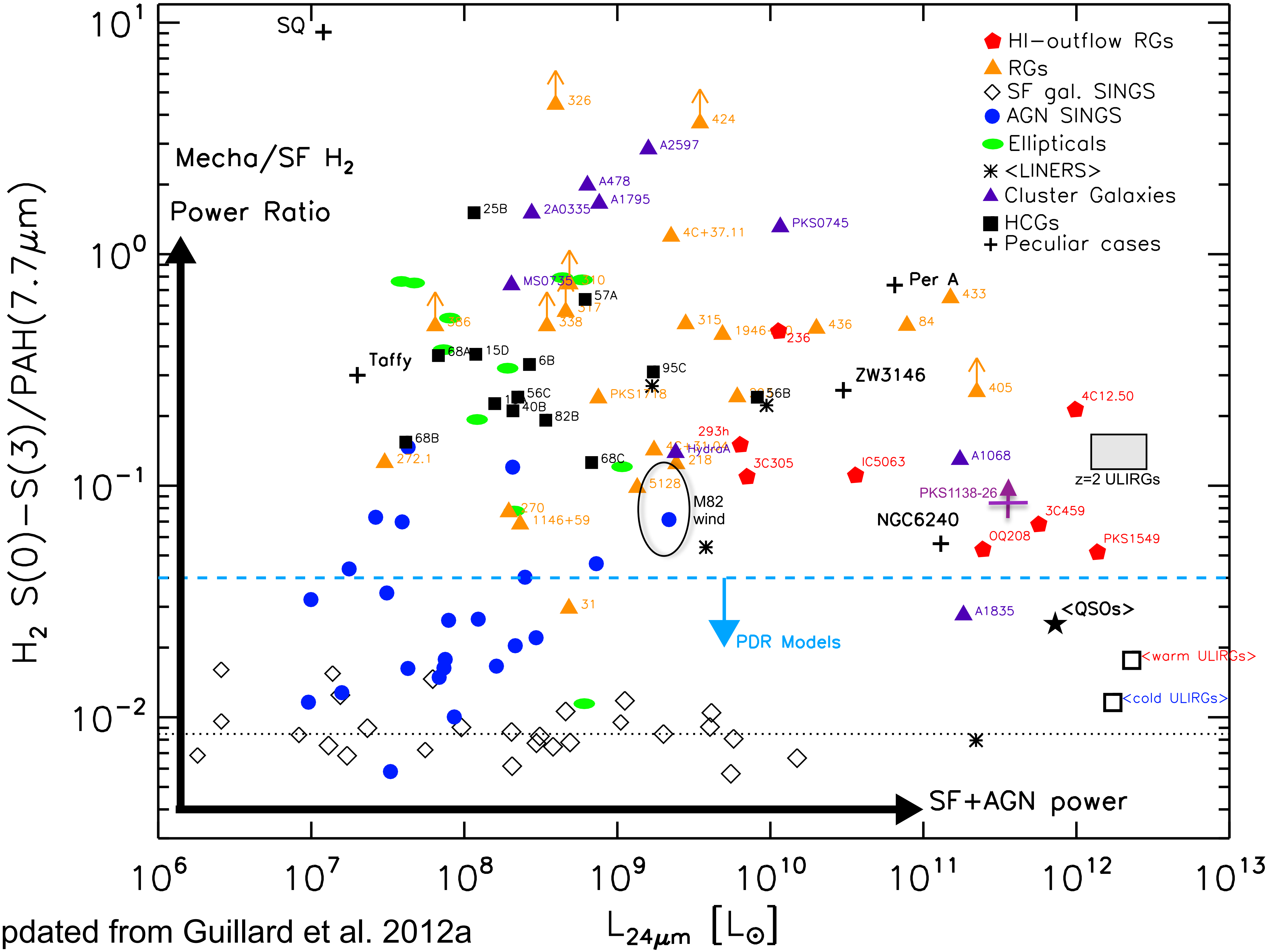
- Dust emission is dominated by diffuse gas, with mean N(H) $\approx 10^{21}$ cm^{-2}
- Lognormal gas column density distribution, shaped by supersonic turbulence with typical (isothermal) turbulent Mach numbers ≈5–15 (Pathak+23)

PHANGS-JWST, Sandstrom+23

NGC 628

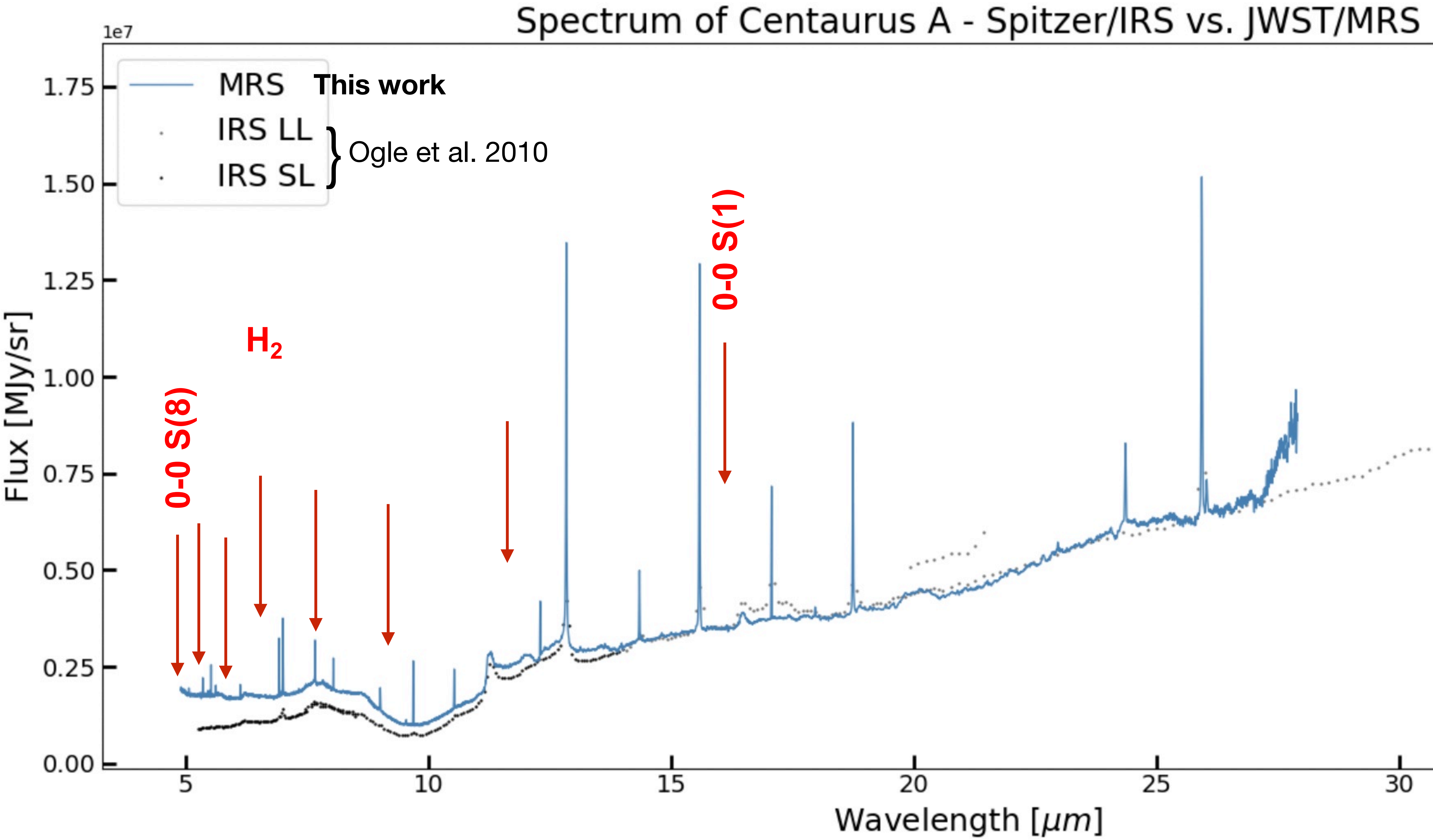
2 fundamental questions: how and where is the energy dissipated?

H_2 line emission in galaxies (Spitzer era)



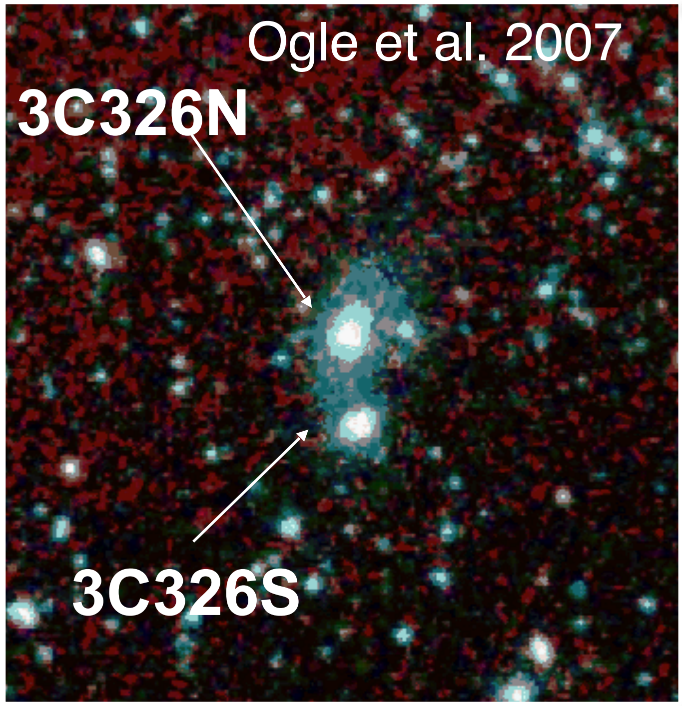
Updated from Guillard et al. 2012a

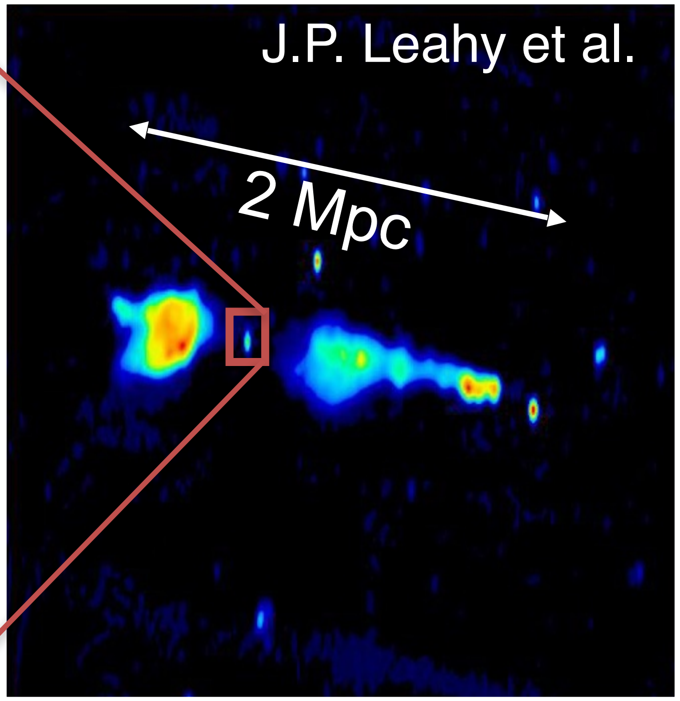
An example of H_2-bright galaxy with JWST MRS



Guillard, Evangelista et al. in prep.

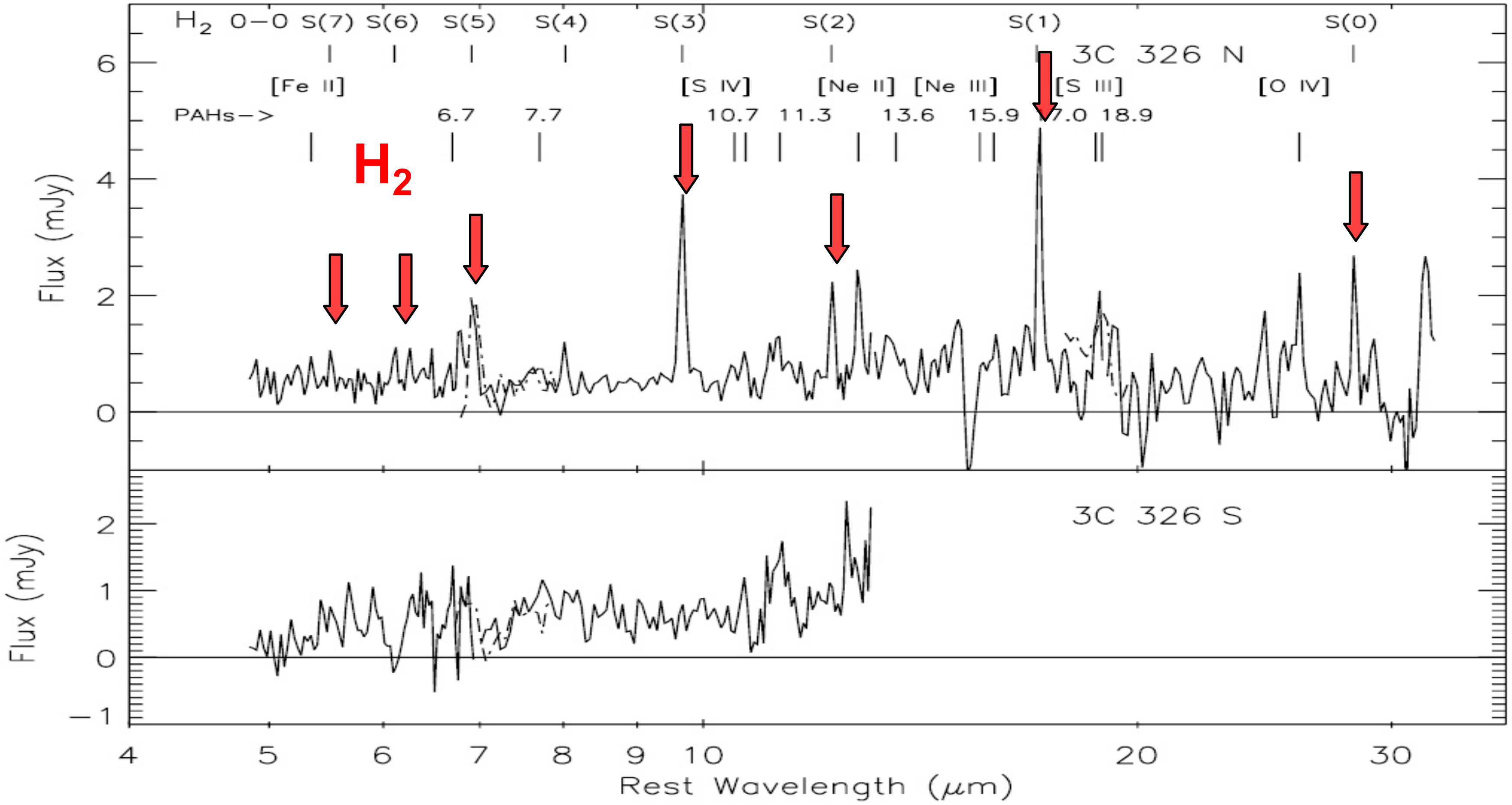
An H_2-rich radio-loud AGN with extremely weak star formation





VLA 1.4 GHz image

- Pair of galaxies 3C 326N & S at z=0.089



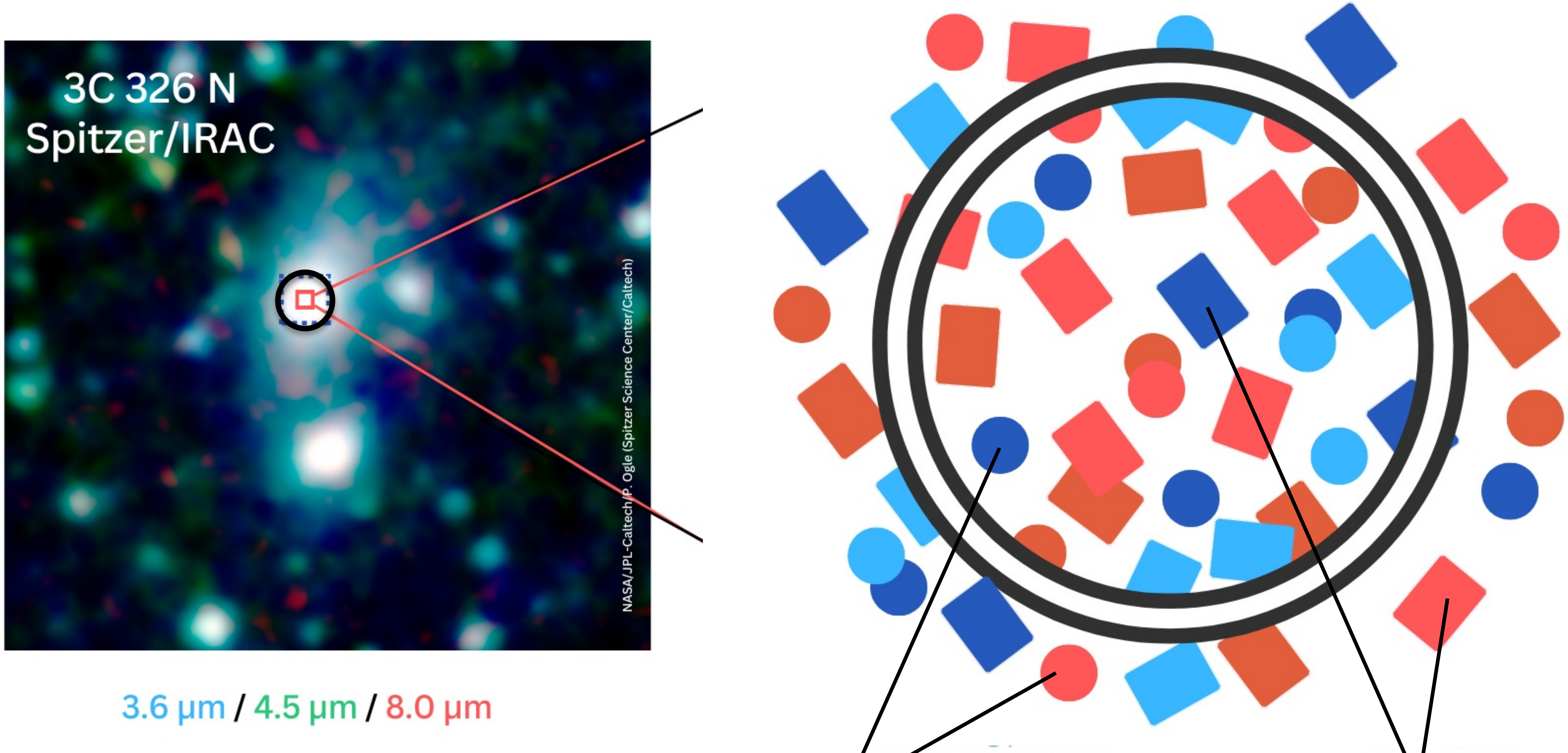
- $L(H_2)=8\times10^{41}$ erg/s
- $10^9\ M_\odot$ of warm H_2
- SFR < $0.07\ M_\odot\ yr^{-1}$
- $L(H_2)/L(IR) \sim 0.2$!!

H_2/PAH flux ratio: diagnostic of kinetic VS UV heating of the gas (Ogle+10, Guillard+12a, 15)

A toy model

To describe line emission from an ensemble of shocks and PDRs

Extension of the approach developed in Lehmann et al. 2022



Blue- and red-shifted shocks

Ω_S

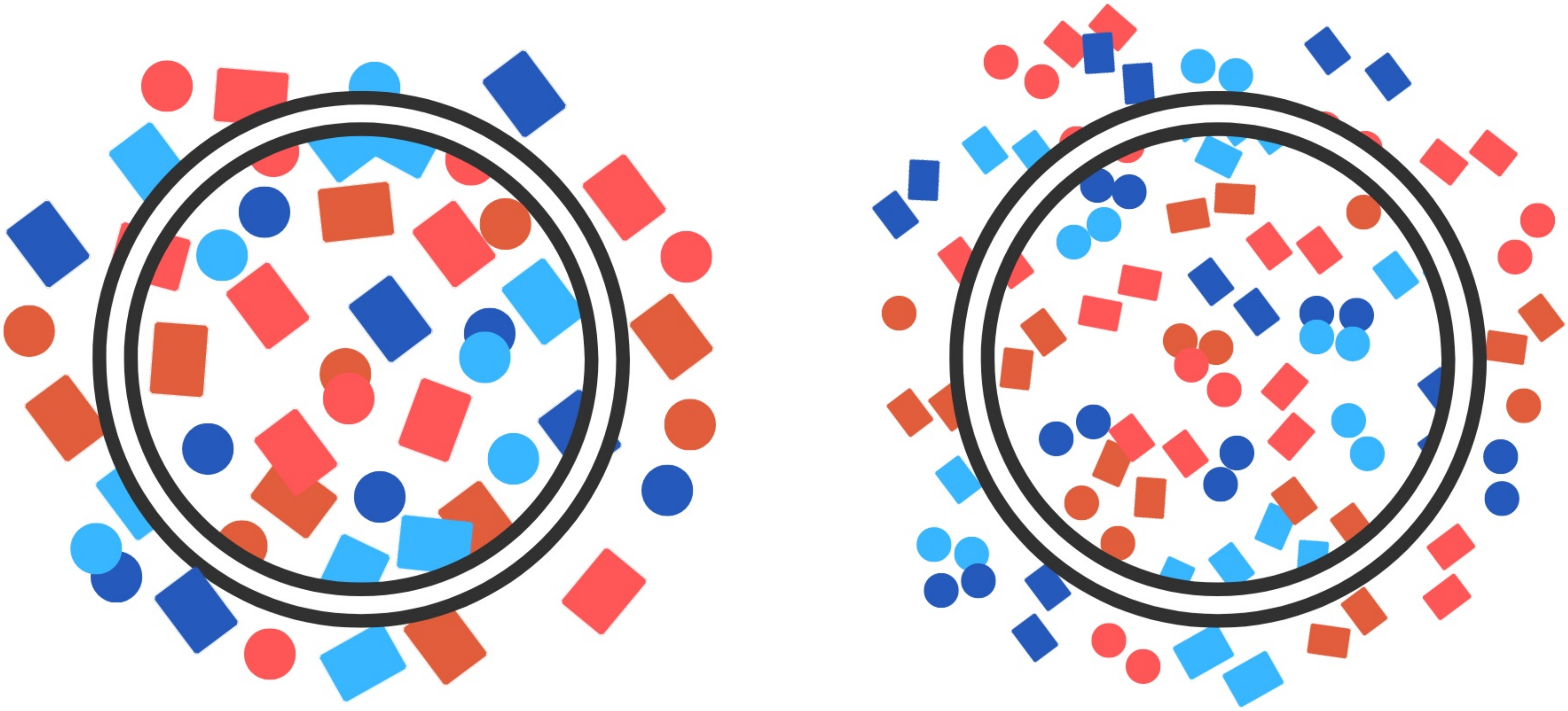
Blue- and red-shifted PDRs

Ω_P

J. Villa-Velez, B. Godard, P. Guillard, G. Pineau des Forêts, A&A 2024

A toy model

To describe line emission from an ensemble of shocks and PDRs



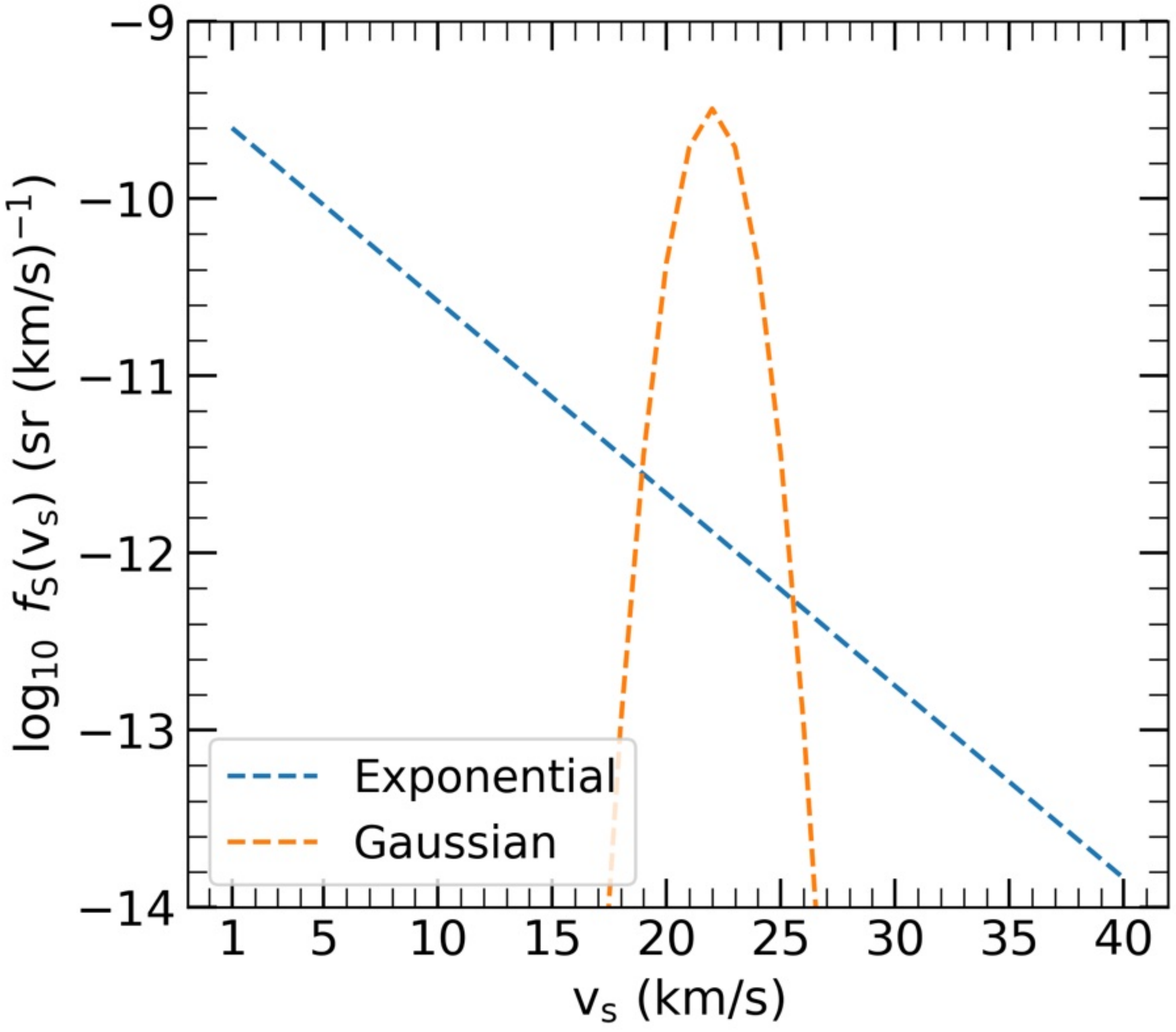
Different ways to pave the observational beam,
but same solid angles Ω_S and Ω_P

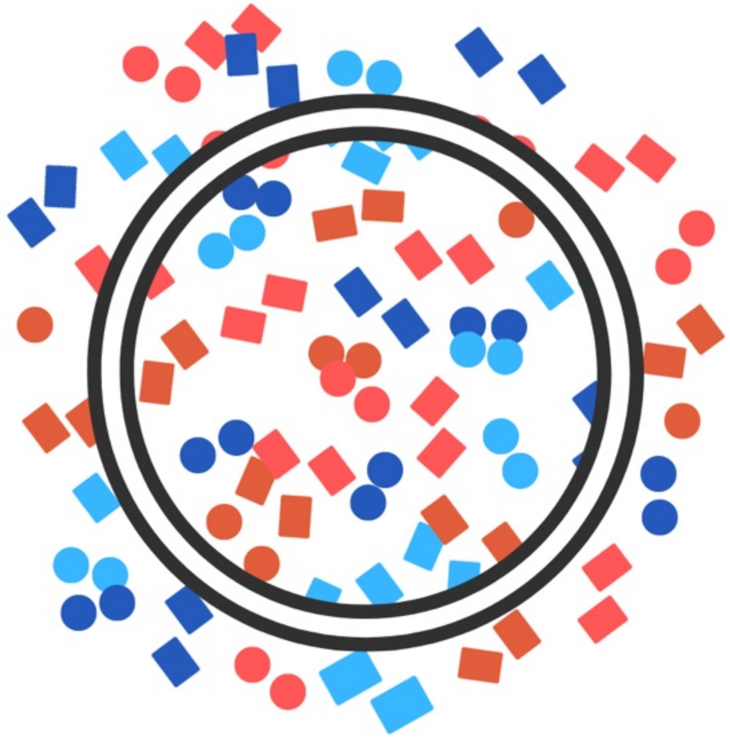
A toy model

To describe line emission from an ensemble of shocks and PDRs

Distributions of shocks (V_S) and PDRs (G_0)

$$f_S(v_s) = d\Omega_S/dv_s$$





IF no spatial overlap or IF line opacities (in any frequency bin) are small:

Shocks PDRs

$$I^{\mathrm{m}}(v_s, G_0) = \frac{1}{\Omega_{\mathrm{obs}}}\left(\int_{v_s} f_S(v_s) I_s(v_s) dv_s + \int_{G_0} f_P(G_0) I_p(G_0) dG_0\right)$$

Energy budgets and fitting the data with grids of PDR and shock models

dissipation rate of mechanical energy:

$$\mathcal{L}_{\mathrm{K}} = \frac{1}{2}\rho_0 \left(\int_{\mathrm{v_s}} f_{\mathrm{S}}(\mathrm{v_s}) \mathrm{v_s^3} d\mathrm{v_s} \right) \mathrm{D_A^2}$$

UV-reprocessed power:

$$\mathcal{L}_{\mathrm{UV}} = 1.92 \times 10^{-3} \ (\mathrm{G_0} + 1.0) \left(\int_{\mathrm{G_0}} f_{\mathrm{P}}(\mathrm{G_0}) d\mathrm{G_0} \right) \mathrm{D_A^2}$$

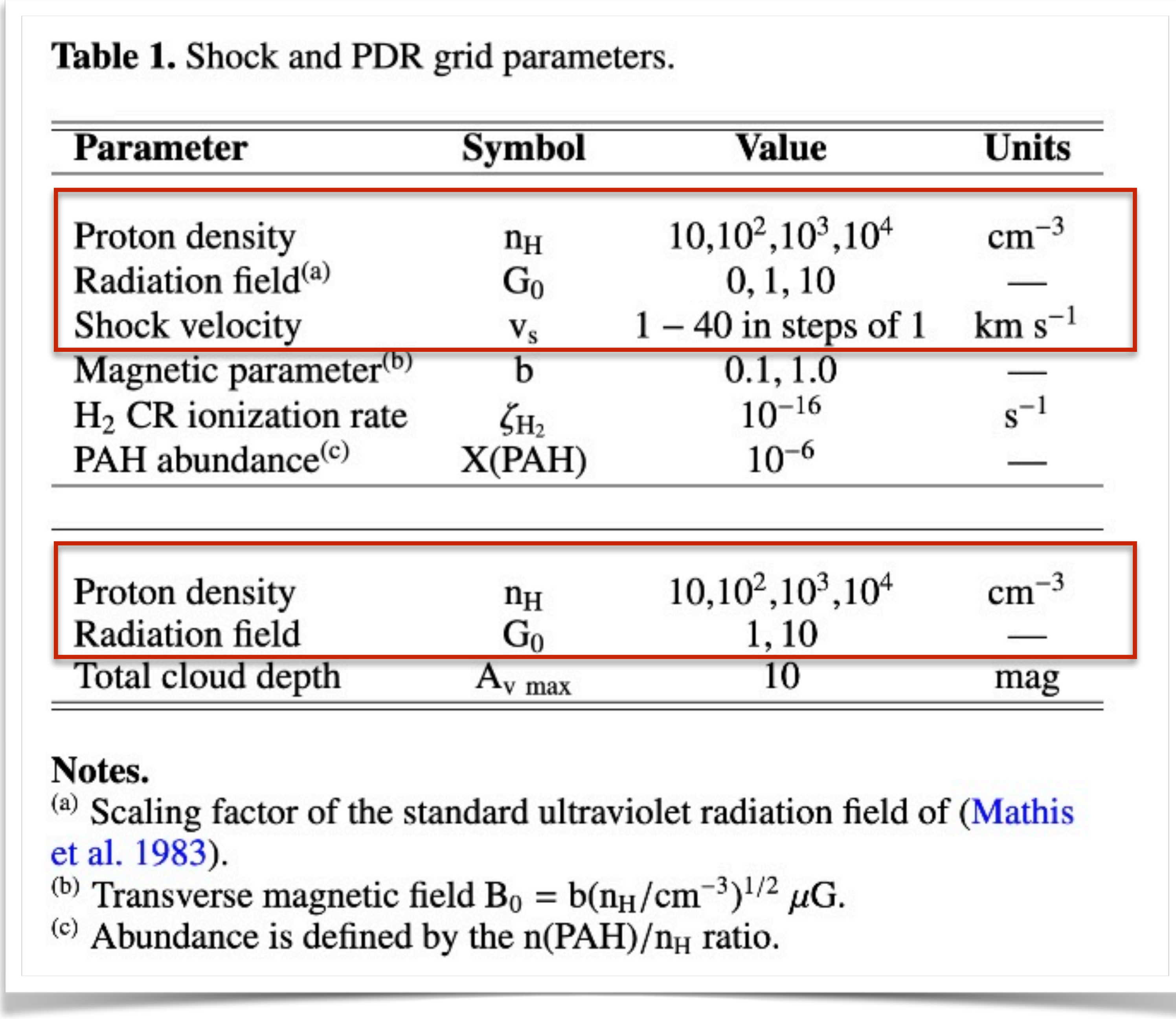


Table 1. Shock and PDR grid parameters.

Parameter	Symbol	Value	Units
Proton density	n_H	$10, 10^2, 10^3, 10^4$	cm^{-3}
Radiation field[(a)]	G_0	0, 1, 10	—
Shock velocity	v_s	1 – 40 in steps of 1	$km\ s^{-1}$
Magnetic parameter[(b)]	b	0.1, 1.0	—
H_2 CR ionization rate	ζ_{H_2}	10^{-16}	s^{-1}
PAH abundance[(c)]	X(PAH)	10^{-6}	—
Proton density	n_H	$10, 10^2, 10^3, 10^4$	cm^{-3}
Radiation field	G_0	1, 10	—
Total cloud depth	$A_{V\ max}$	10	mag

Notes.
[(a)] Scaling factor of the standard ultraviolet radiation field of (Mathis et al. 1983).
[(b)] Transverse magnetic field $B_0 = b(n_H/cm^{-3})^{1/2}\ \mu G$.
[(c)] Abundance is defined by the $n(PAH)/n_H$ ratio.

Fit: minimization of the distance = quadratic sum of differences between the model and observations in log space.

Parameters describing

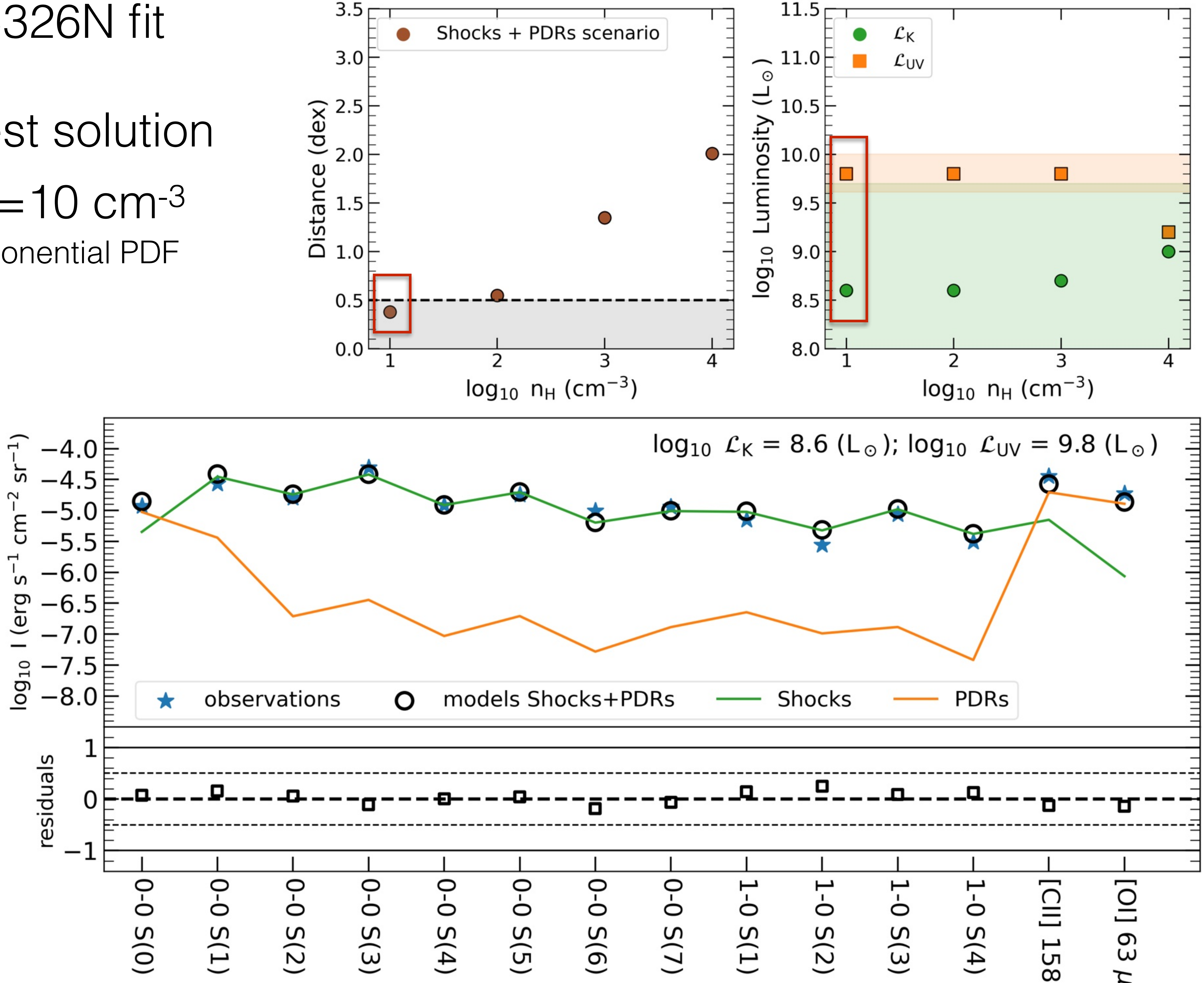
$$f_{\mathrm{S}}(\mathrm{v_s}) = d\Omega_{\mathrm{S}}/d\mathrm{v_s} \quad \text{and} \quad f_{\mathrm{P}}(\mathrm{G_0}) = d\Omega_{\mathrm{P}}/d\mathrm{G_0}$$

3C326N fit

Best solution

n_H=10 cm^{-3}

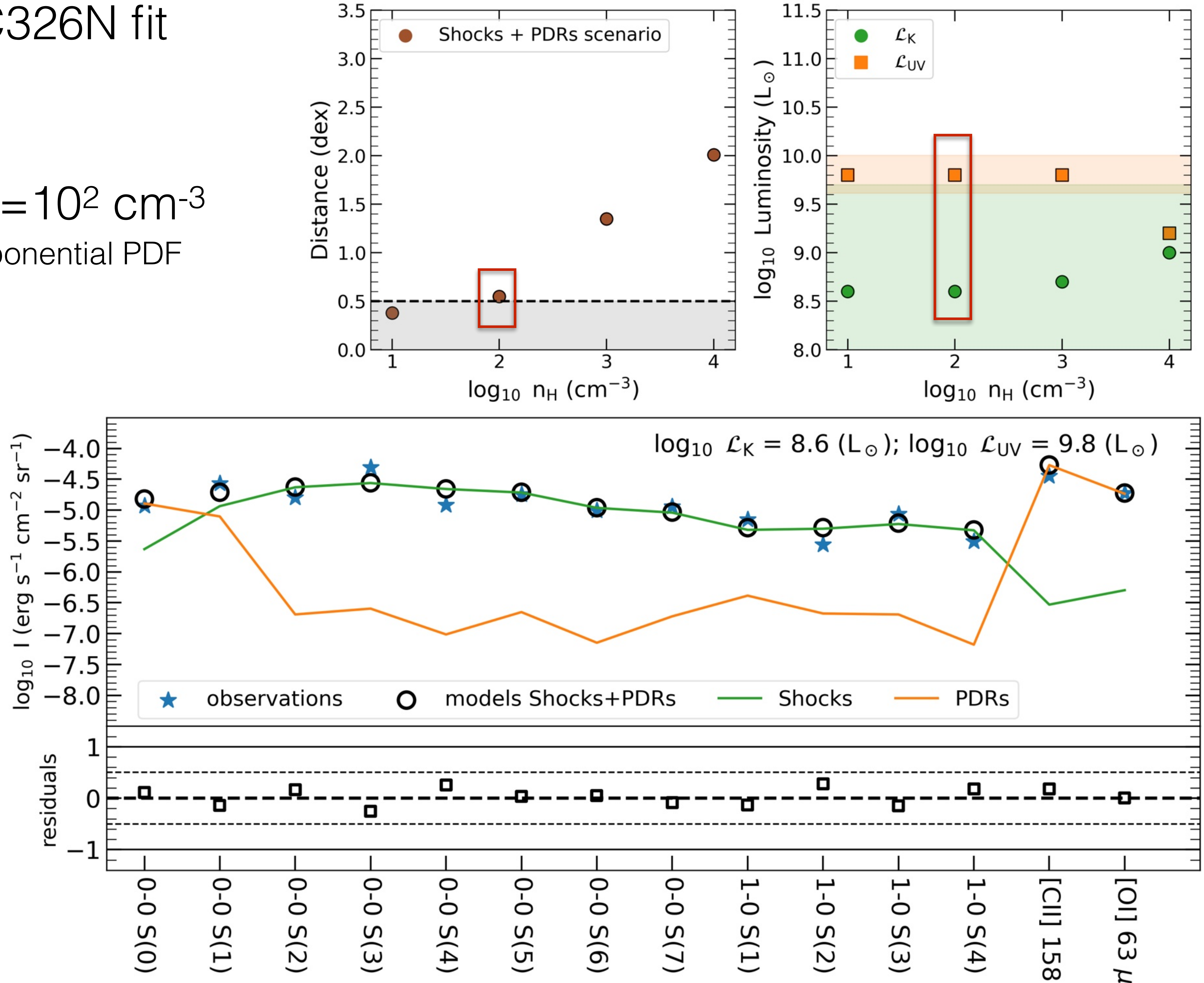
Exponential PDF



3C326N fit

$n_H=10^2$ cm^{-3}

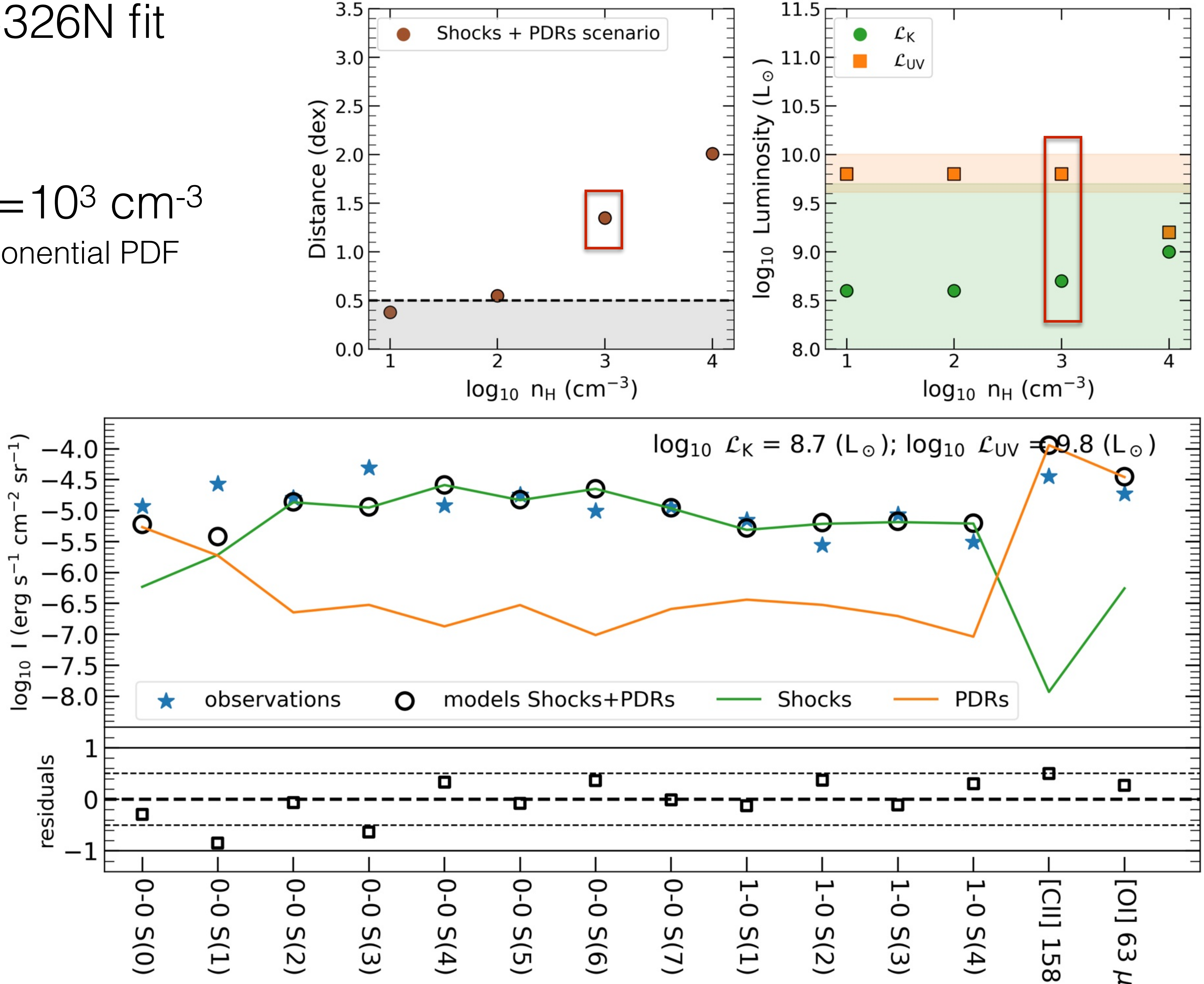
Exponential PDF



3C326N fit

$n_H = 10^3$ cm^{-3}

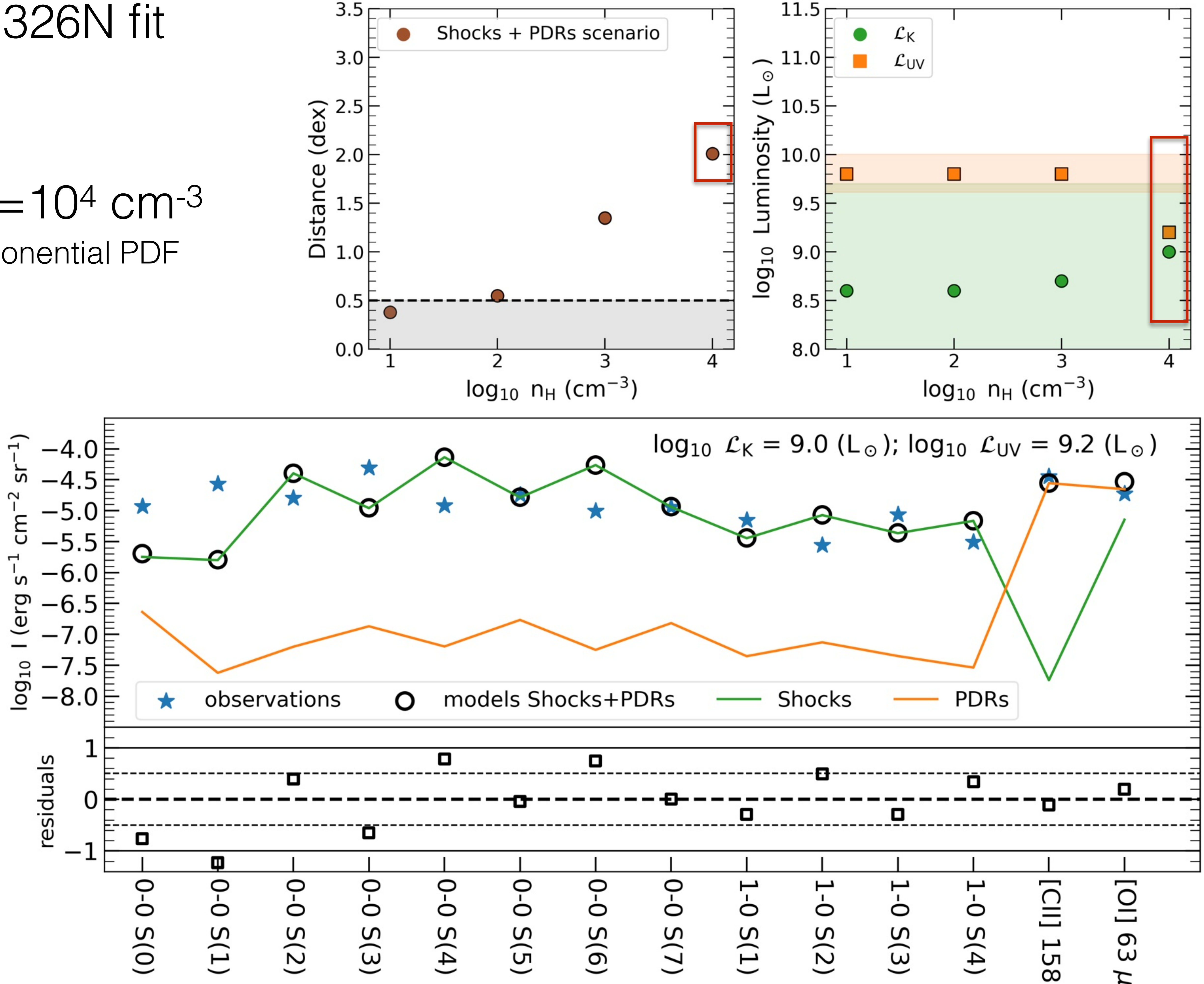
Exponential PDF



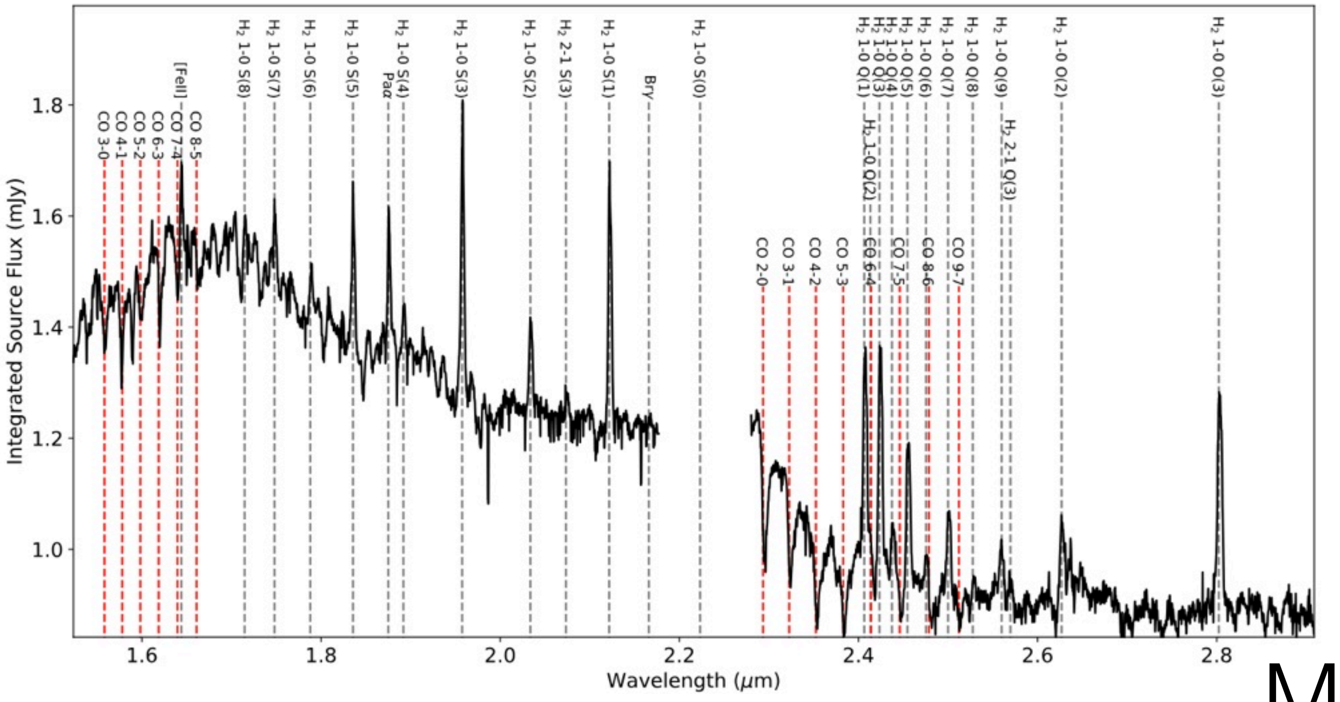
3C326N fit

$n_H = 10^4$ cm^{-3}

Exponential PDF

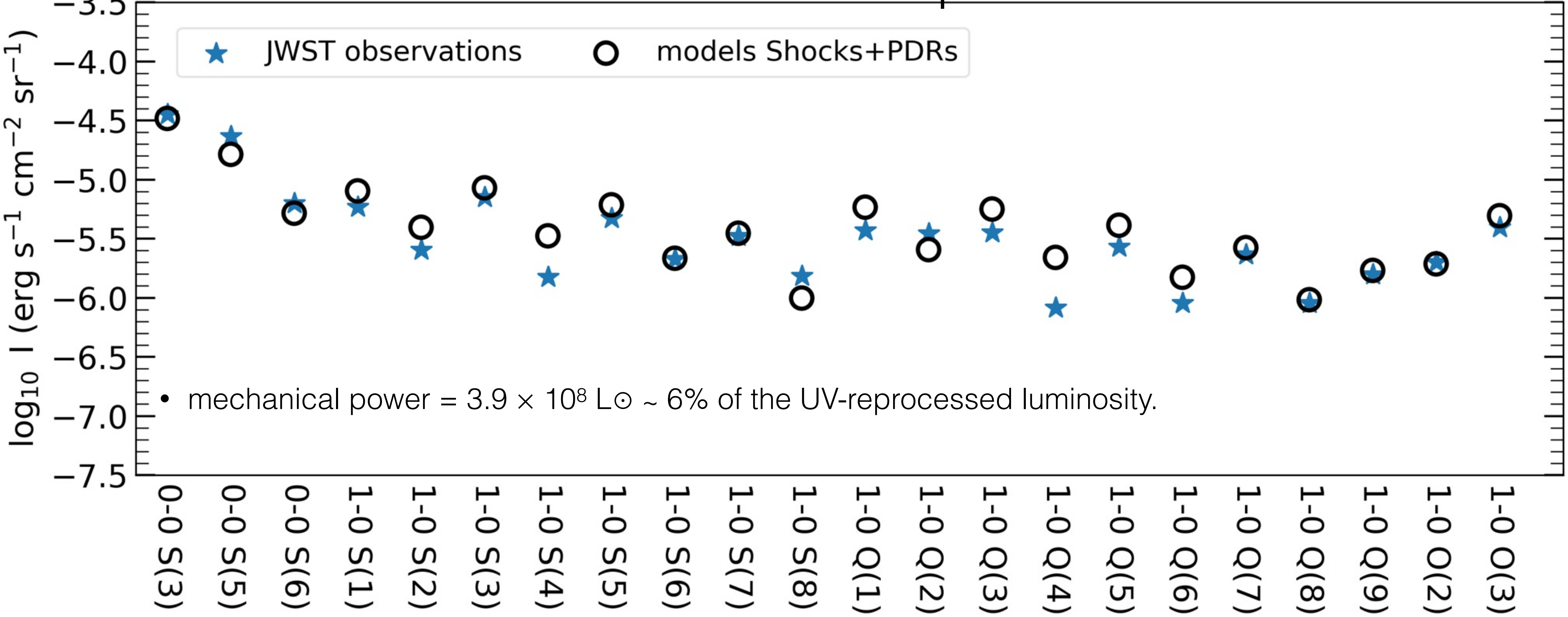


The cherry on the cake



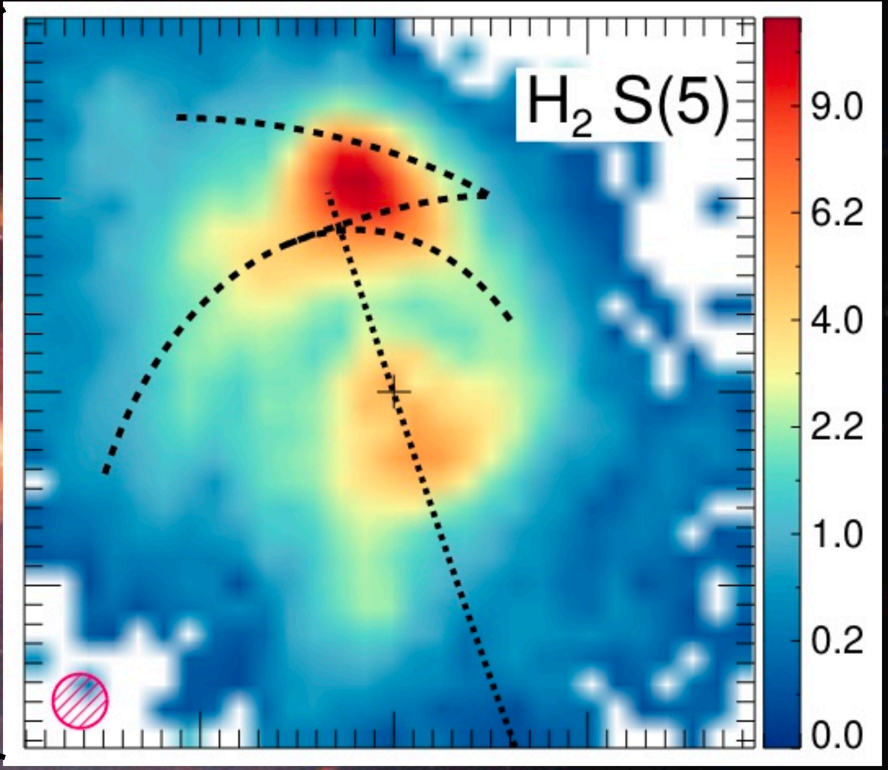
JWST NIRSpec
spectrum of 3C326N
(Leftley+24)

Model prediction vs. JWST obs.

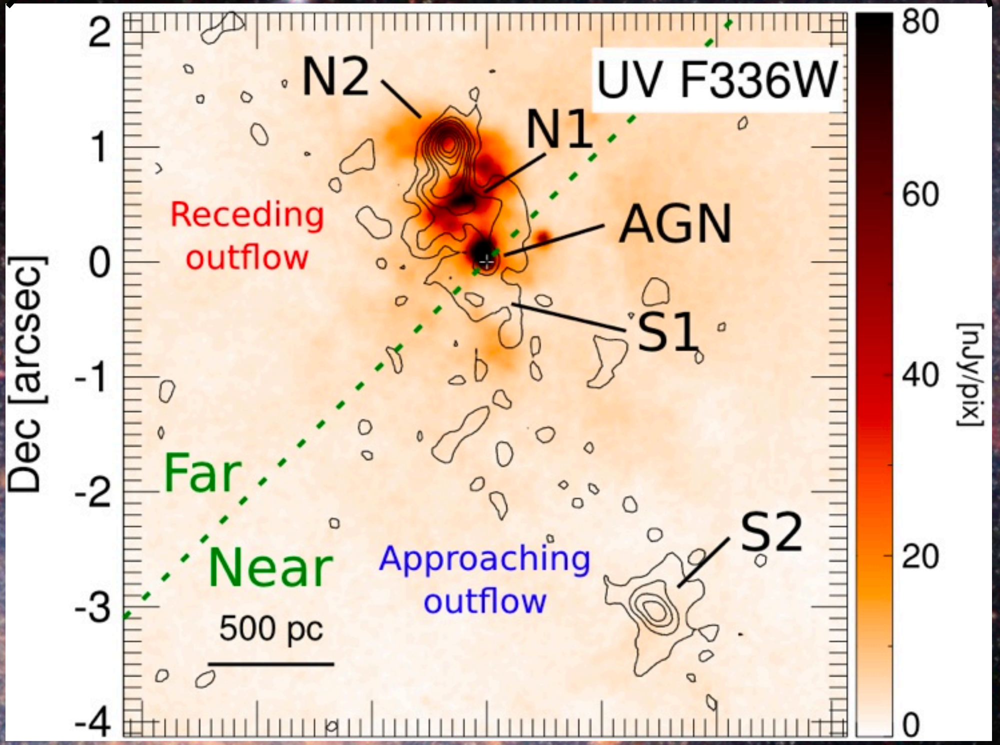


- mechanical power = 3.9 × 10^8 L⊙ ~ 6% of the UV-reprocessed luminosity.

Only 1<% of the AGN-jet kinetic energy remains as mechanical energy in the ISM



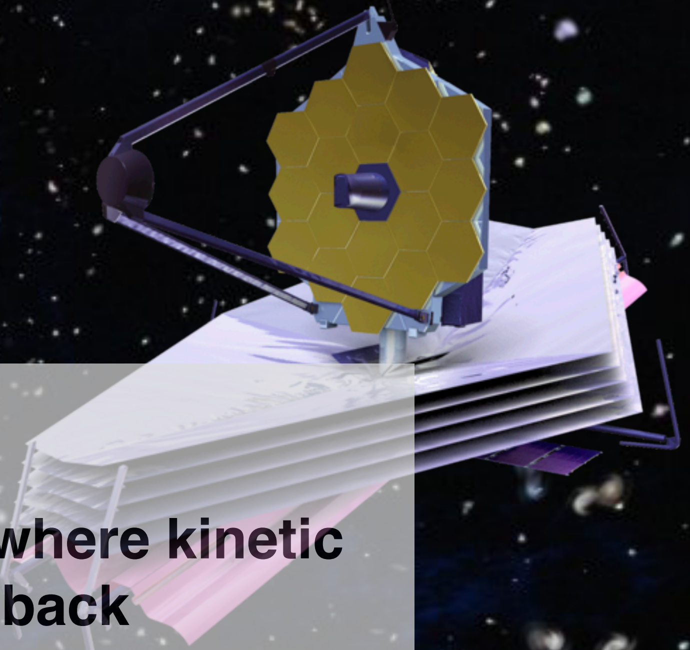
- Increased H_2 flux and dispersion at the intersection between the jet axis and dust lanes in the disk.
- E(H2,w) = (0.4 ± 0.1) × 10^{54} erg.
- Jet kinetic energy = t_{jet} P_{jet} = 10^{56} erg



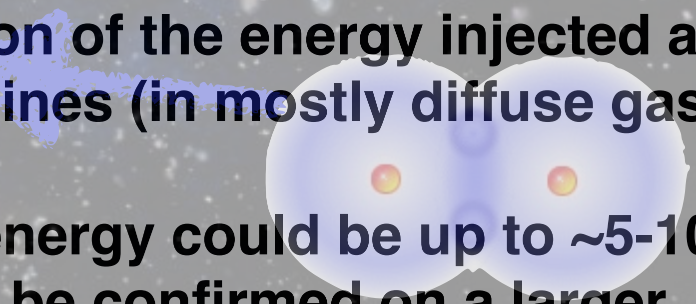
- <1% of the jet energy remains as mechanical energy in ionised and molecular gas.
- This is much lower than the 25–30% of the jet energy that is injected into the ISM according to simulations (Mukherjee et al. 2016).

- Pereira-Santaella+22

The physics of molecular hydrogen in space with JWST



- H_2 is a tracer of dissipative processes and efficient gas coolant
- High spatial and spectral resolution allows us to study how and where kinetic energy is dissipated: constrains for star formation and AGN feedback
- (Challenging) modelling suggest that a small fraction of the energy injected at large scales is dumped and dissipated through H_2 lines (in mostly diffuse gas?)



- Radio galaxies: the total reprocessed mechanical energy could be up to ~5-10% of the total reprocessed UV luminosity. Remains to be confirmed on a larger sample…

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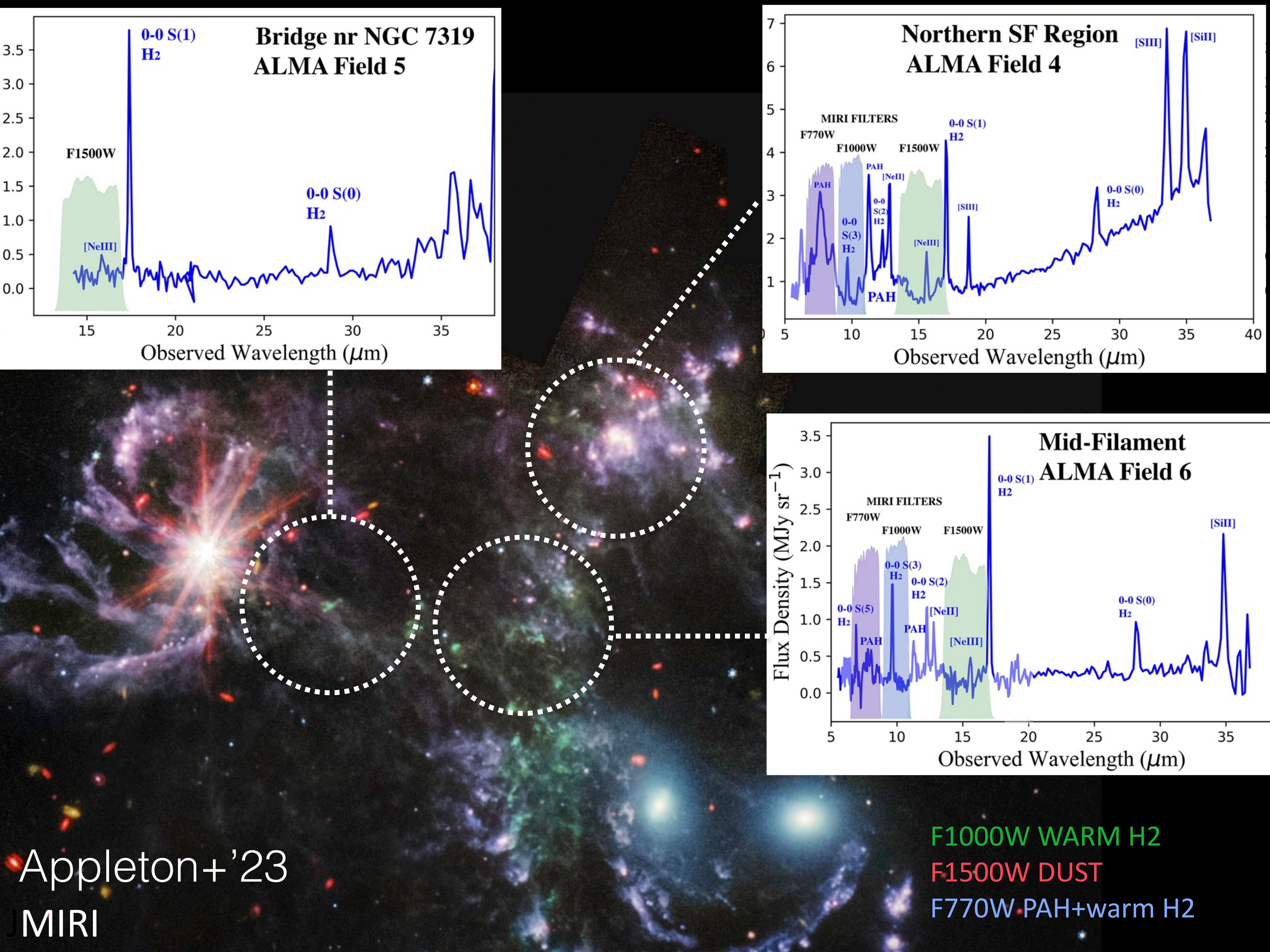
HST

JWST

Spitzer

Appleton, Guillard+2023

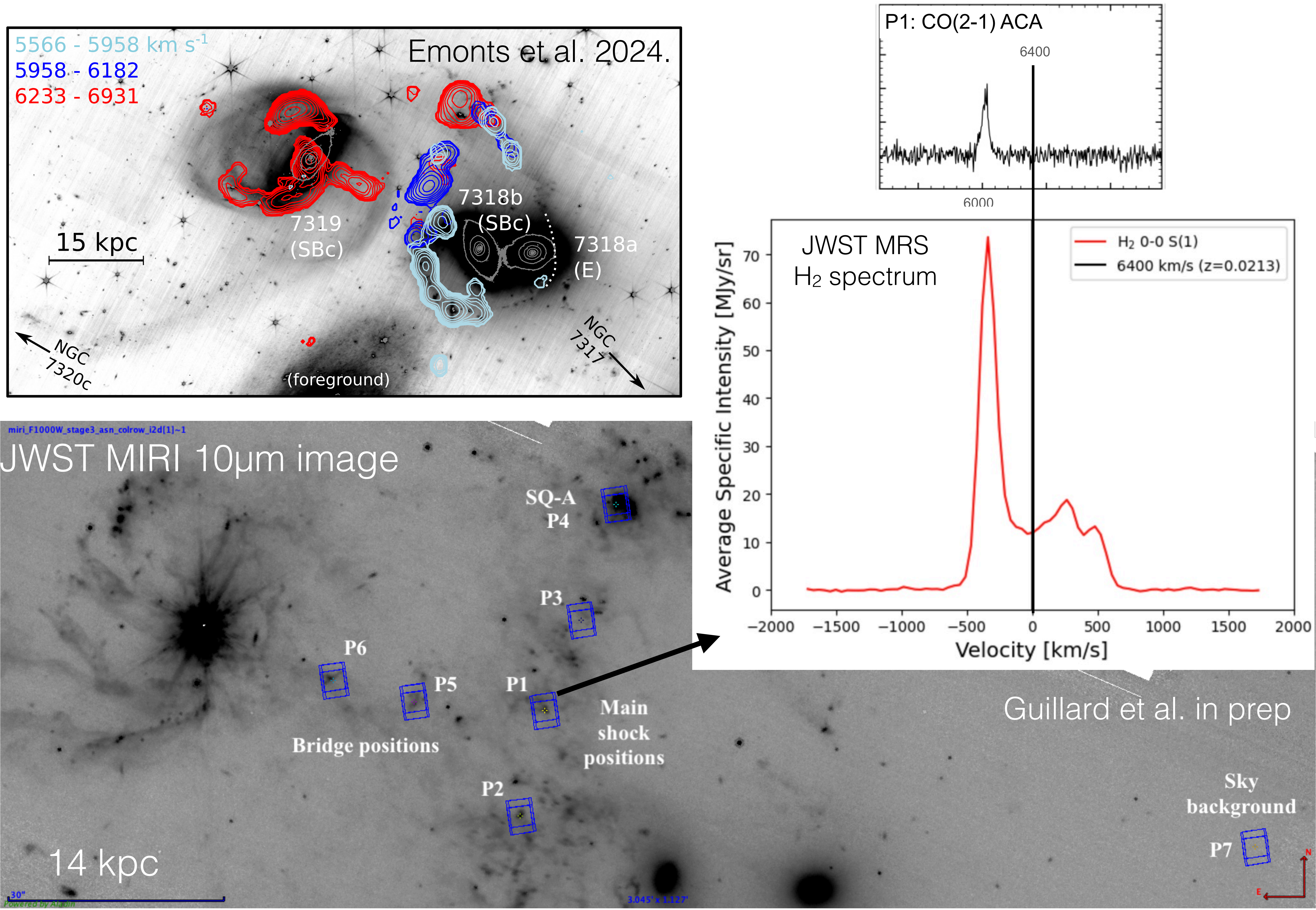
Guillard+09, Cluver+2010



Appleton+’23

MIRI

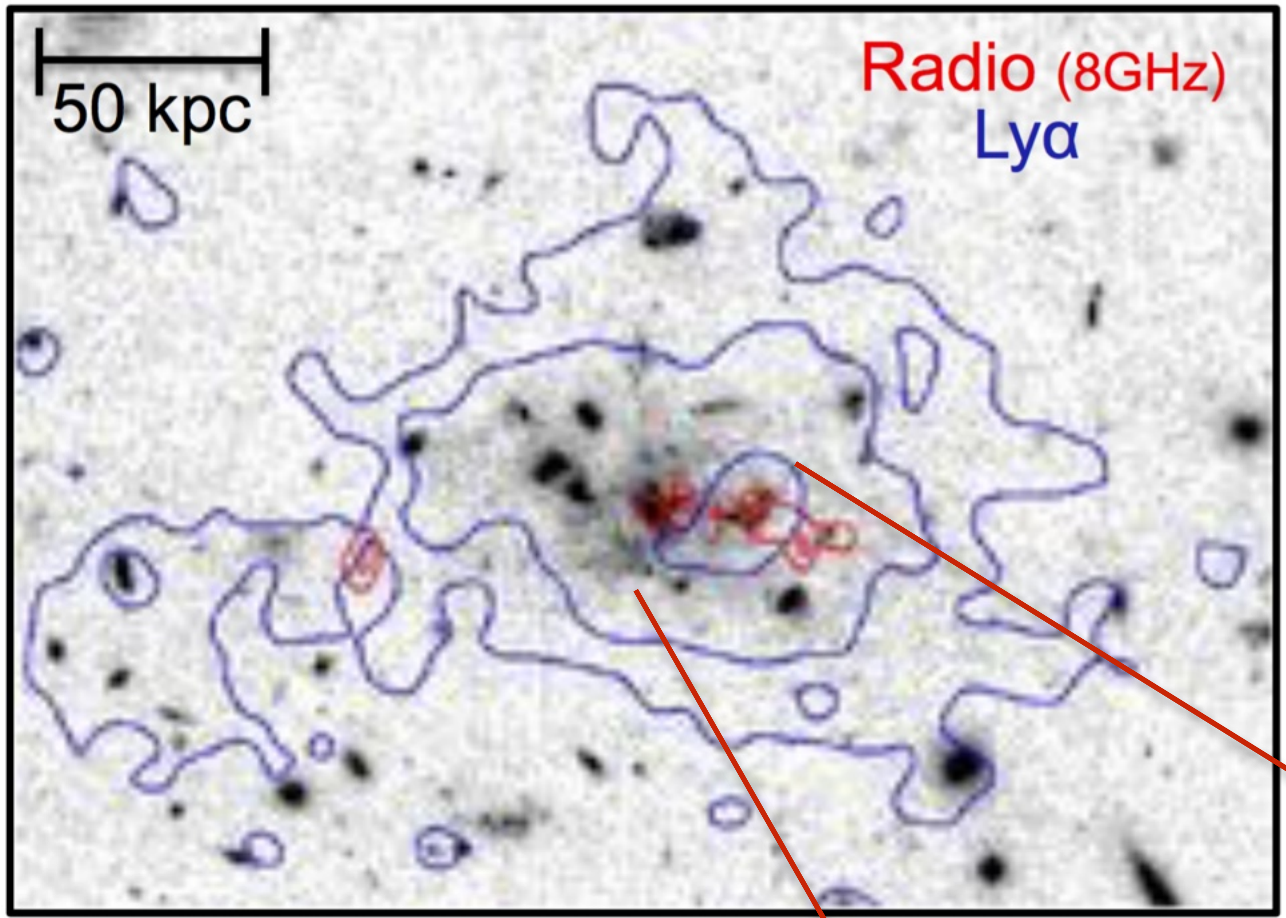
Warm (H_2) and cold (CO) gas have very different kinematics



Emonts et al. 2024.

Guillard et al. in prep

Extended halo of warm gas around a massive high-z radio-galaxy



Miley+ (2006)

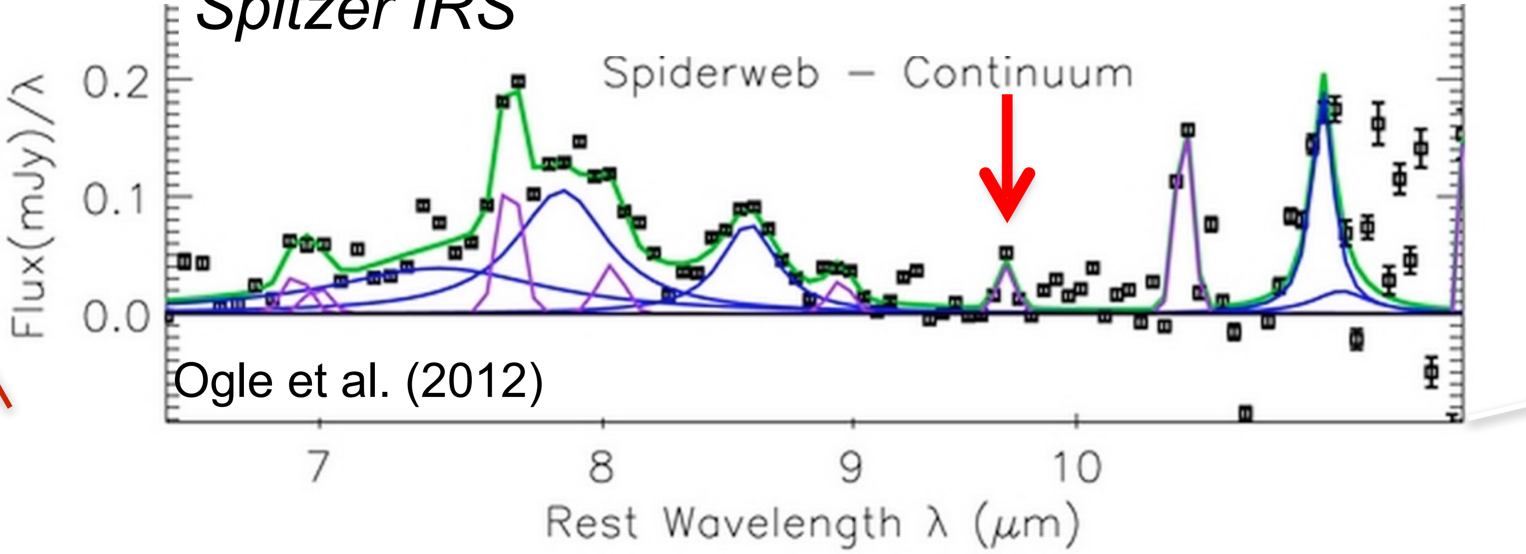
Spiderweb Galaxy

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)*

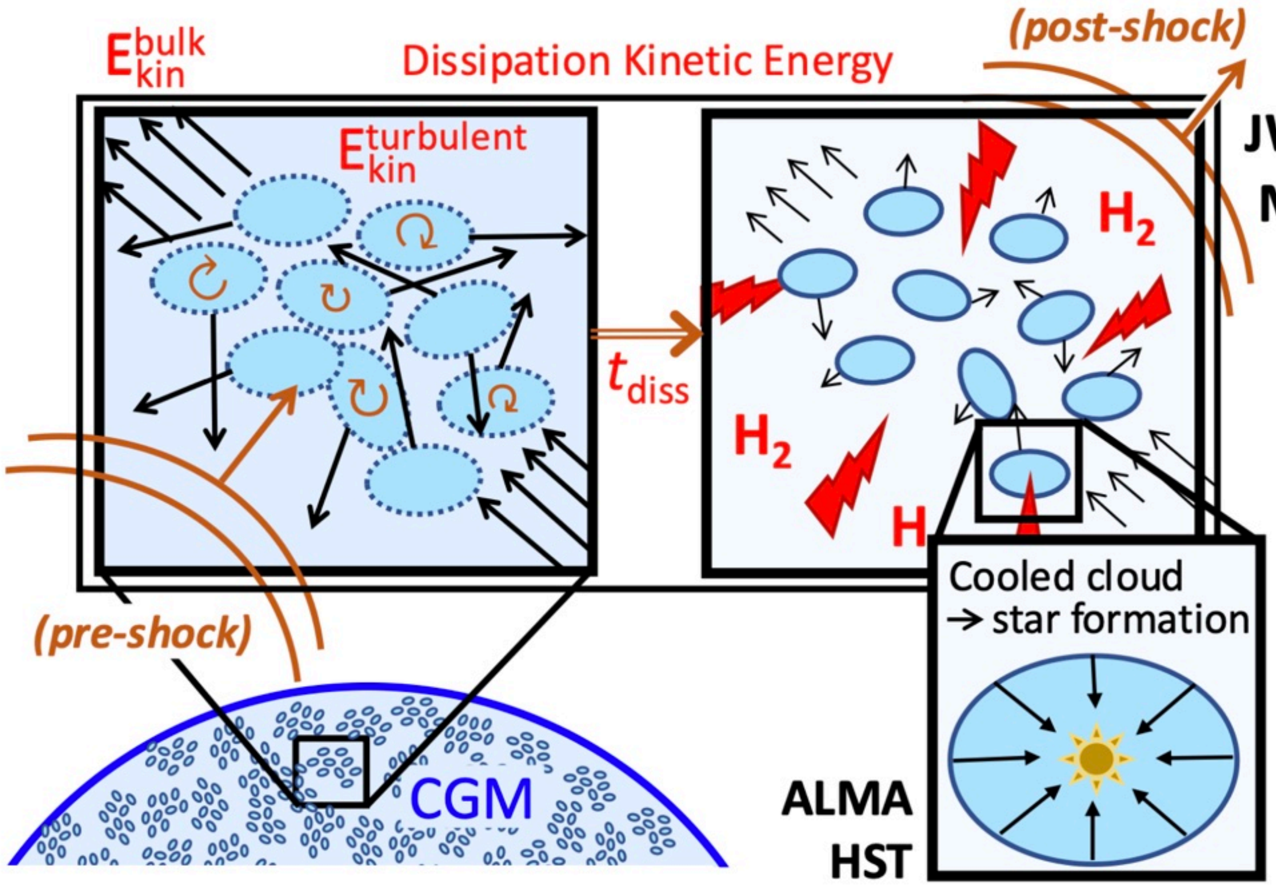
$3.7 \times 10^{10} L_\odot$ in H2 0-0 S(3) line alone!

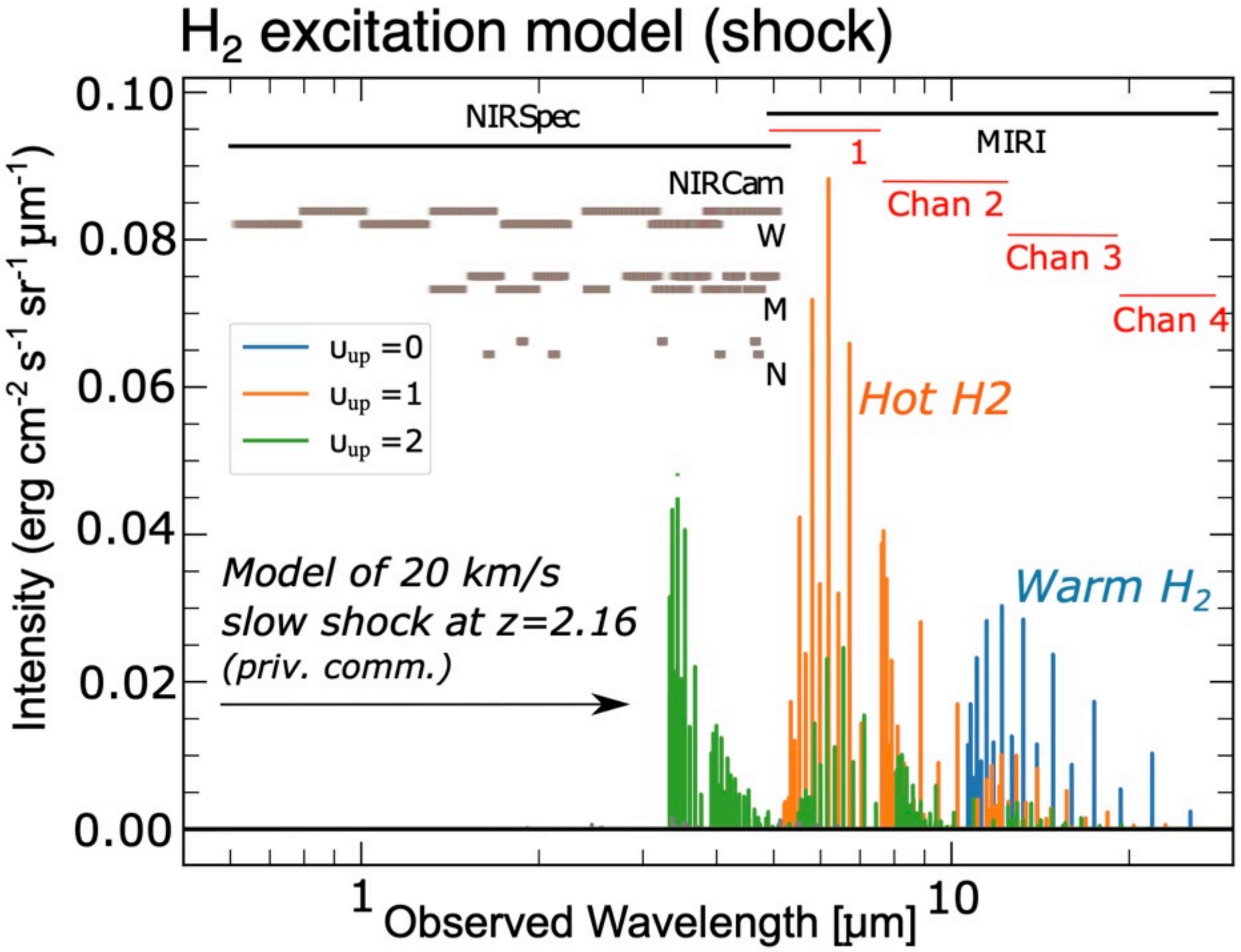
Spitzer IRS



Ogle et al. (2012)

Is H_2 the dominant cooling channel by dissipating mechanical energy from the CGM?




H_2 excitation model (shock)

Model of 20 km/s slow shock at z=2.16 (priv. comm.)

This would provide the missing piece in understanding the in-situ star formation.

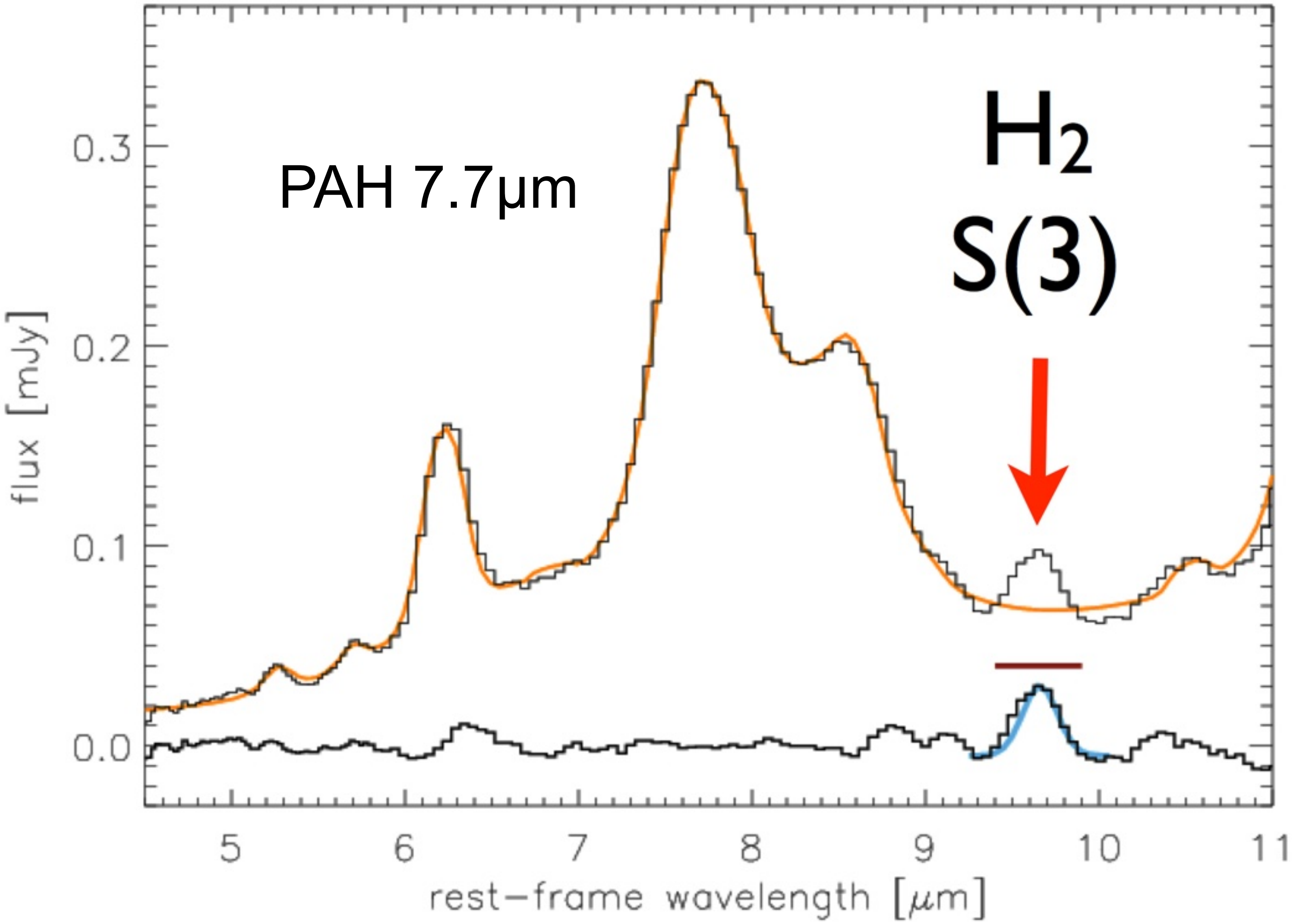
H_2 cooling in high-z starbursts

- 16 Spitzer-selected galaxies at z~2
  IRAC photometry: $\langle M_\star \rangle = 1.5\times10^{11}\ M_\odot$

  Mid-IR spectroscopy: $\langle SFR \rangle \sim 1000\ M_\odot/yr$
  Sub-mm photometry: $M_{gas} \sim 5\times10^{10}\ M_\odot$
  $\Sigma_{gas} \sim 2000\ M_\odot/pc^2$

- $L_{H2}(S(3)) = 1.5\ 10^9\ L_\odot$
- Based on spectra of local H_2 luminous galaxies:
  $L_{H2}(S(0)\text{-}S(5)) \sim 6\ 10^9\ L_\odot$
  $M_{H2}(T>150K) \sim 10^{10}\ M_\odot$: 20% M_{gas}
  $L_{H2}/M_{gas} \sim 0.12\ L_\odot/M_\odot$
  $\equiv 4\ 10^{-25}$ erg/s/H
  ~ 500 times the Milky Way value

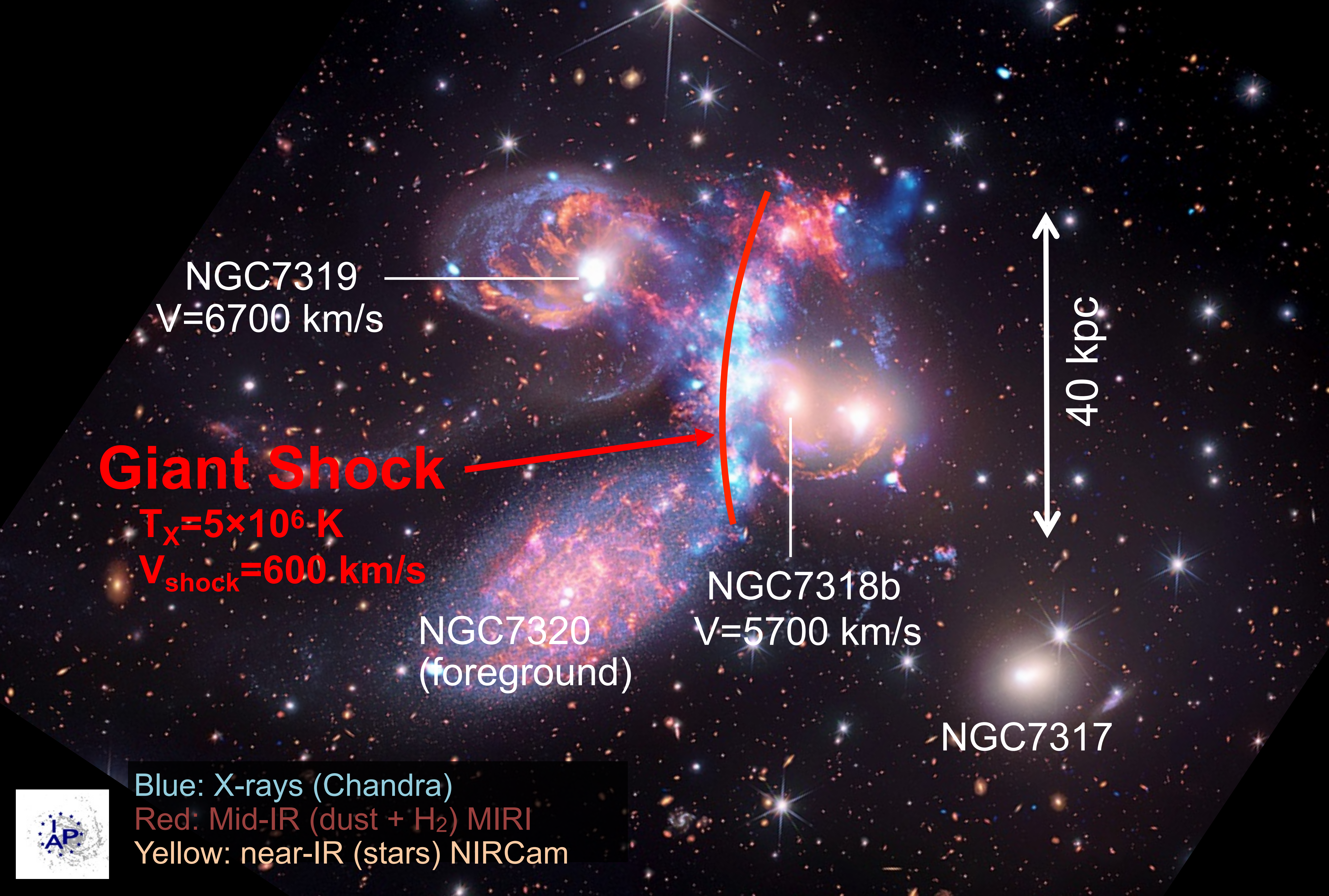
Stacked IRS spectrum (Fiolet+10)



H_2/PAH ratio above what may accounted by UV heating of molecular clouds based on CO, FIR, [CII]λ158μm (Stacey+10)

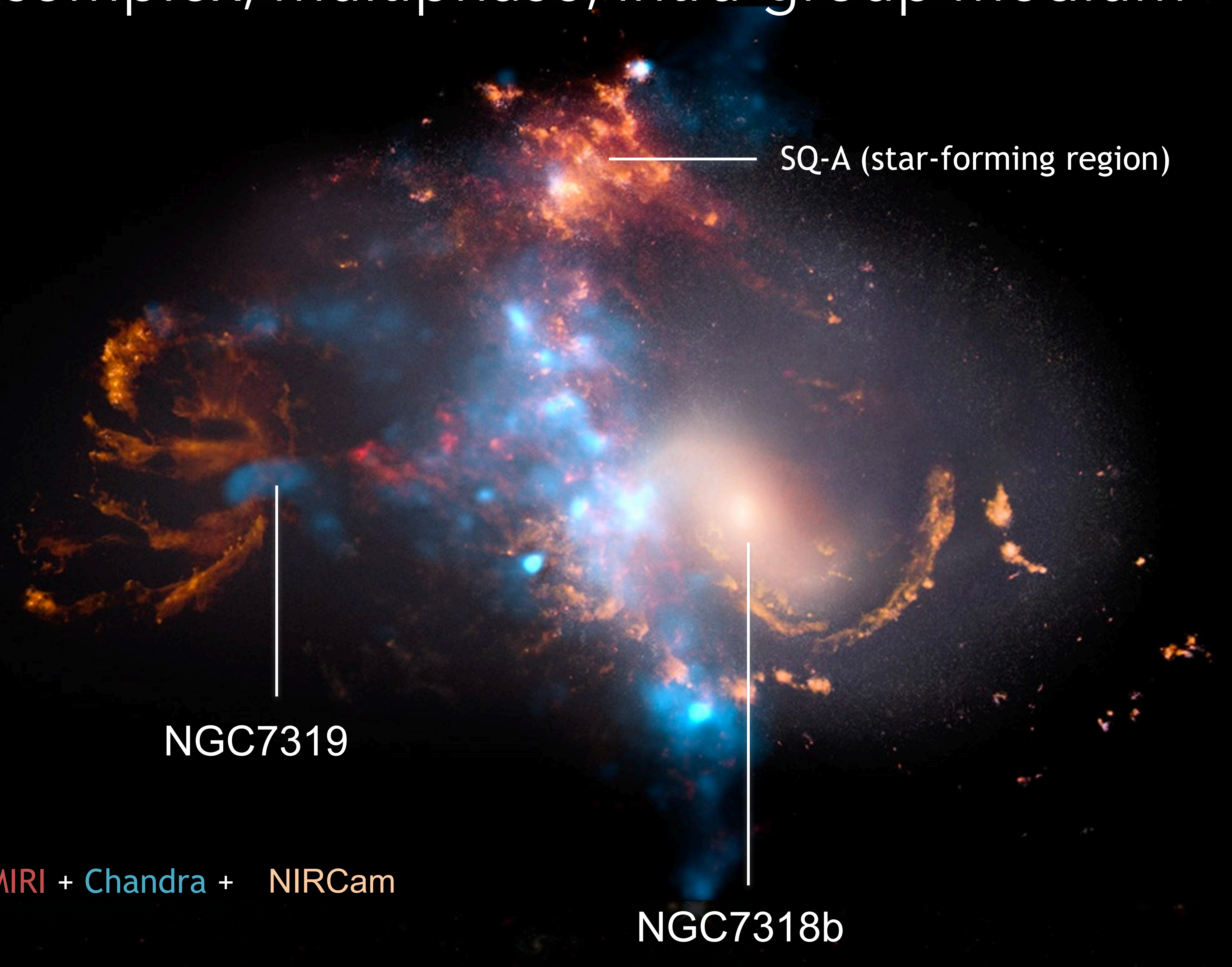
H_2 may be powered by dissipation of turbulence (possible sources: SN, radiation pressure, gas accretion)

A galaxy collision shocking the intra-group medium



Blue: X-rays (Chandra)
Red: Mid-IR (dust + H_2) MIRI
Yellow: near-IR (stars) NIRCam

A complex, multiphase, intra-group medium

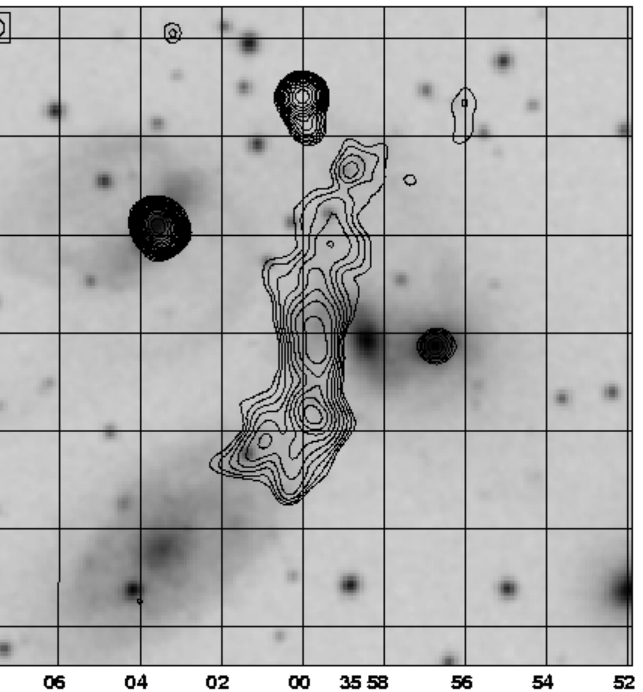


JWST MIRI + Chandra + NIRCam

Stephan's Quintet: a galaxy collision shocking the IGM

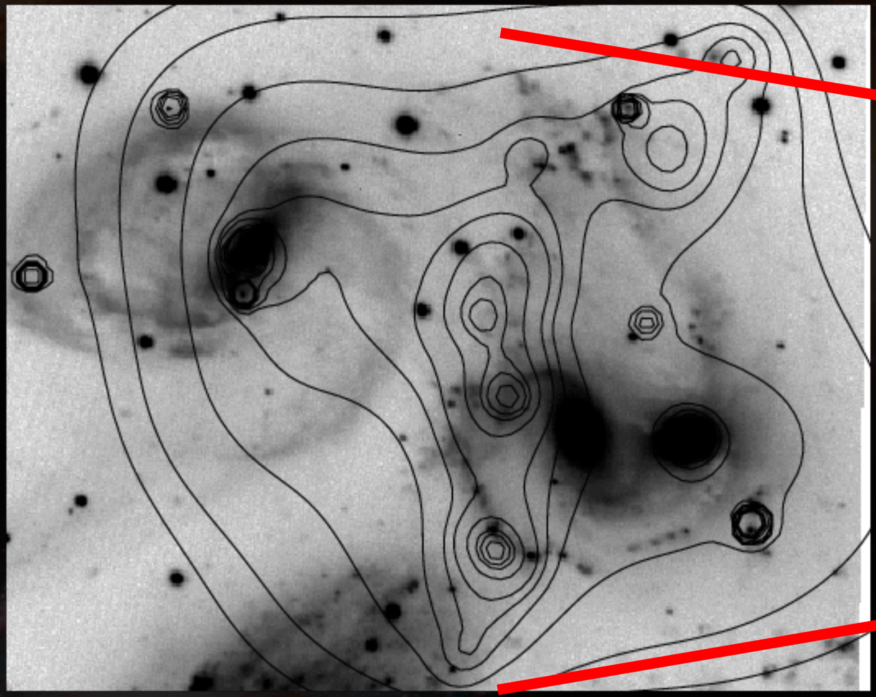
NGC 7318b is crashing into the rest of the group at V ~ 1000 km/s : interloper

VLA Observations (20 cm)



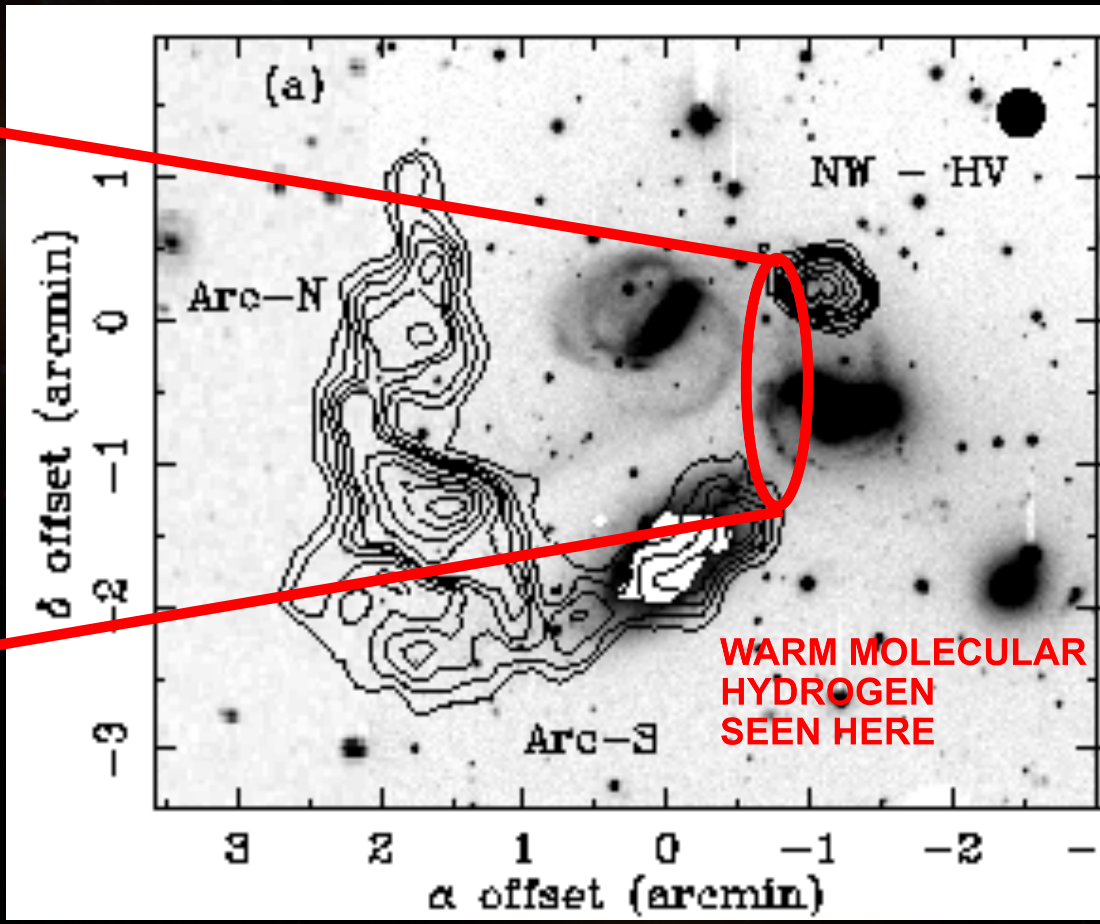
20 cm Radio emission from between galaxies suggested an intergalactic shock (Allen & Hartzuiker 1972)

Hα + Chandra contours



Hot X-ray gas indicating a 600 km/s shock wave (Trinchieri et al. 2003)

VLA Observations (HI line)



WARM MOLECULAR HYDROGEN SEEN HERE

Neutral hydrogen Observations show "gap" in HI where the shock is observed

Isolating the physics of turbulent dissipation “against the dark sky”!

“Pure” H_2 spectrum!

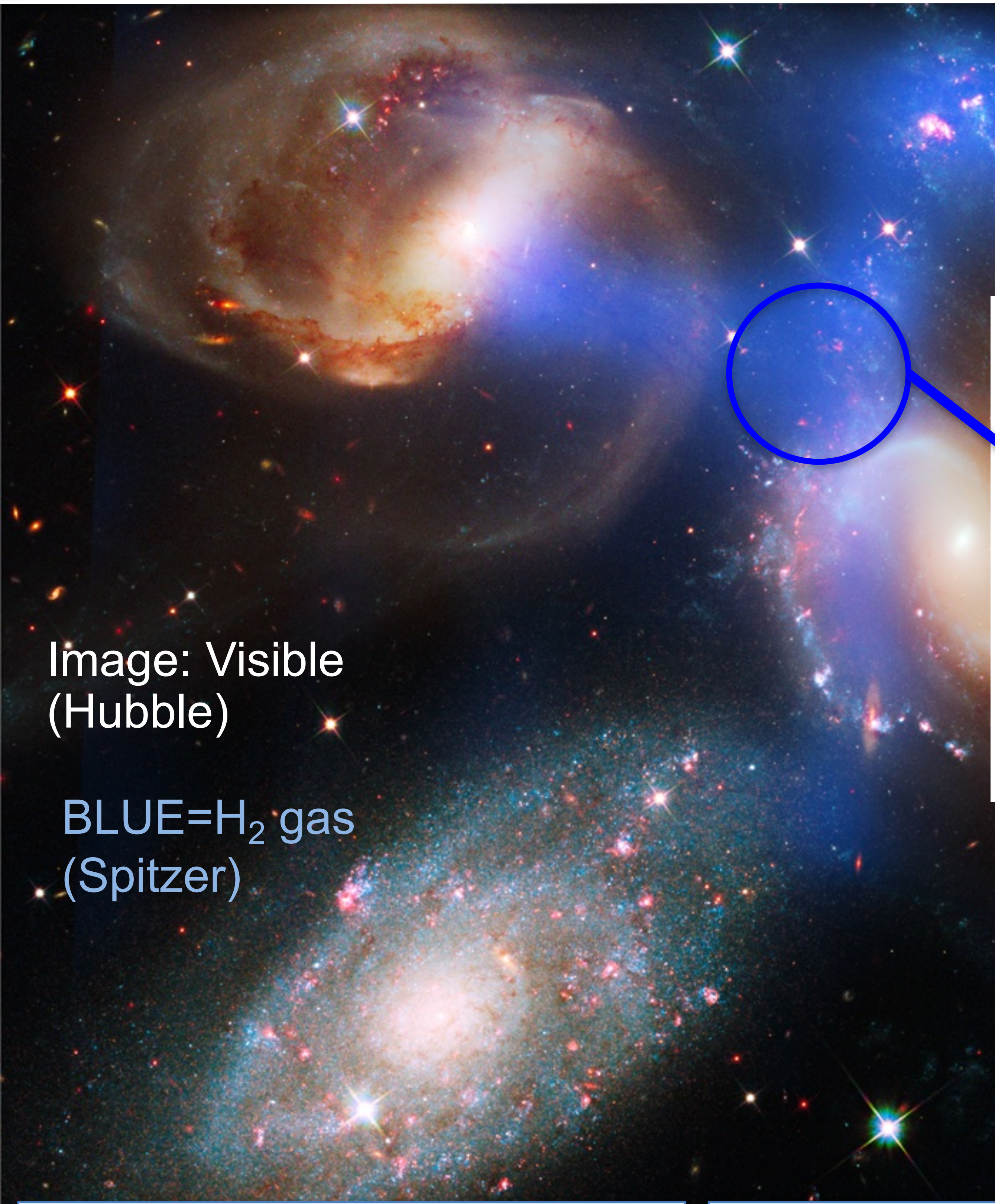
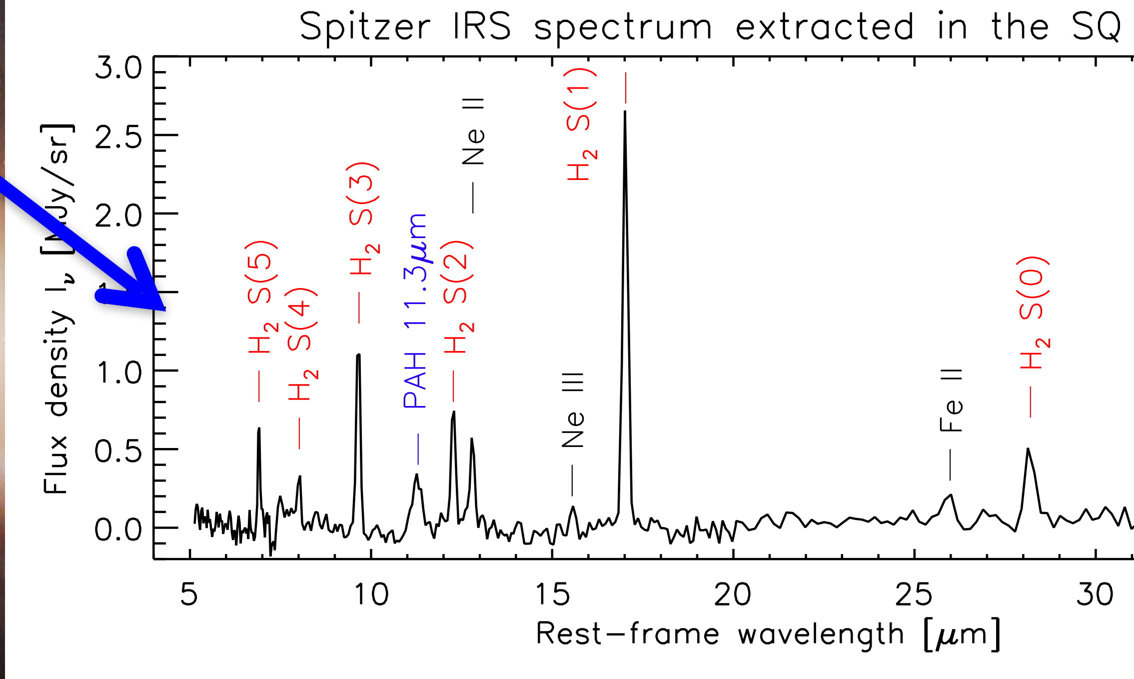


Image: Visible (Hubble)

BLUE=H_2 gas (Spitzer)



$L(H_2) = 3 \times L(\text{X-rays})$

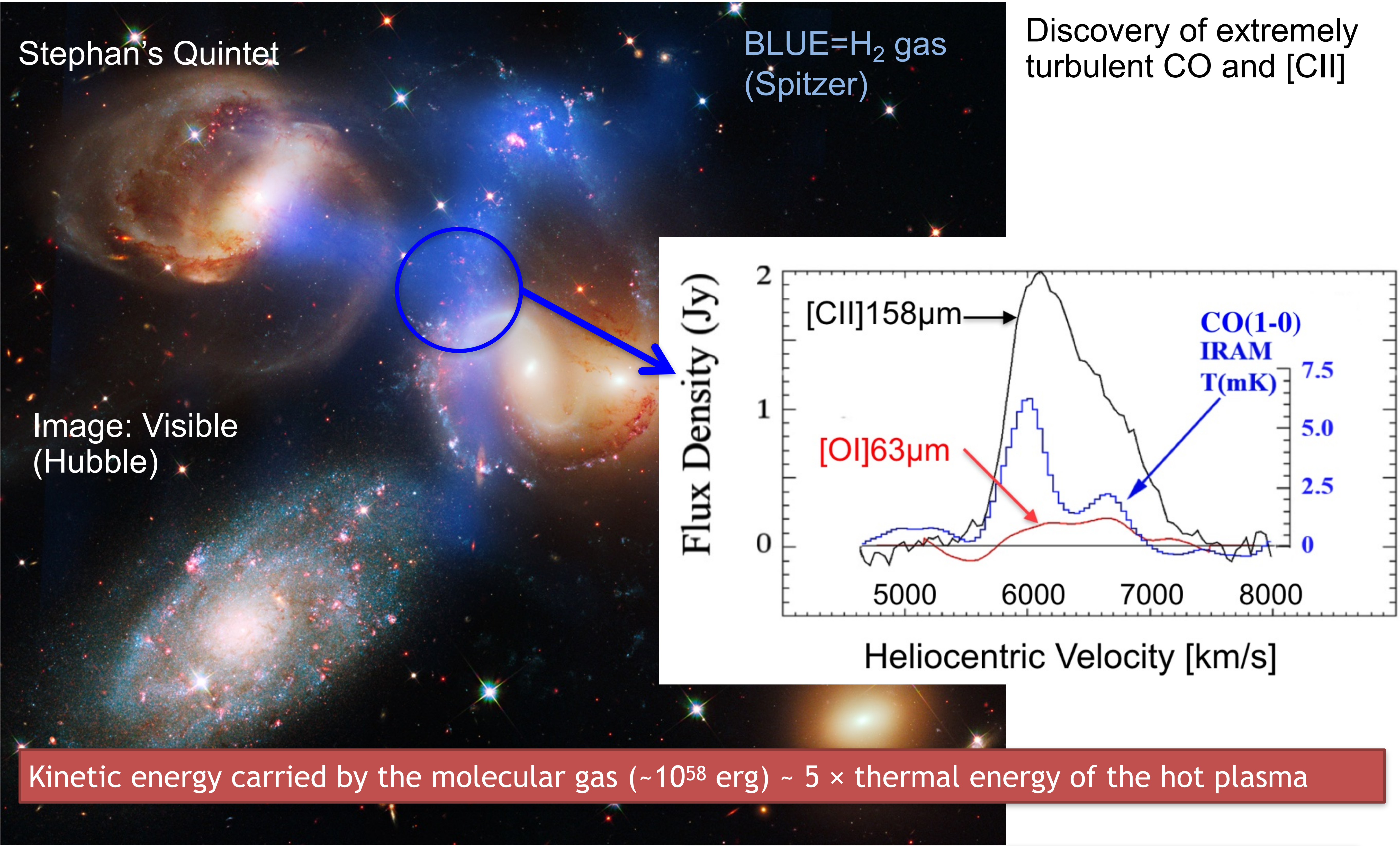
$M(H_2) = 5 \times 10^9\ M_\odot$

$SFR < 0.07\ M_\odot/yr$

Appleton et al. 2006, Guillard et al. 2009; Guillard et al. 2012b; Cluver et al. 2013

The energy of the galaxy collision is not thermalized

Discovery of extremely turbulent CO and [CII]

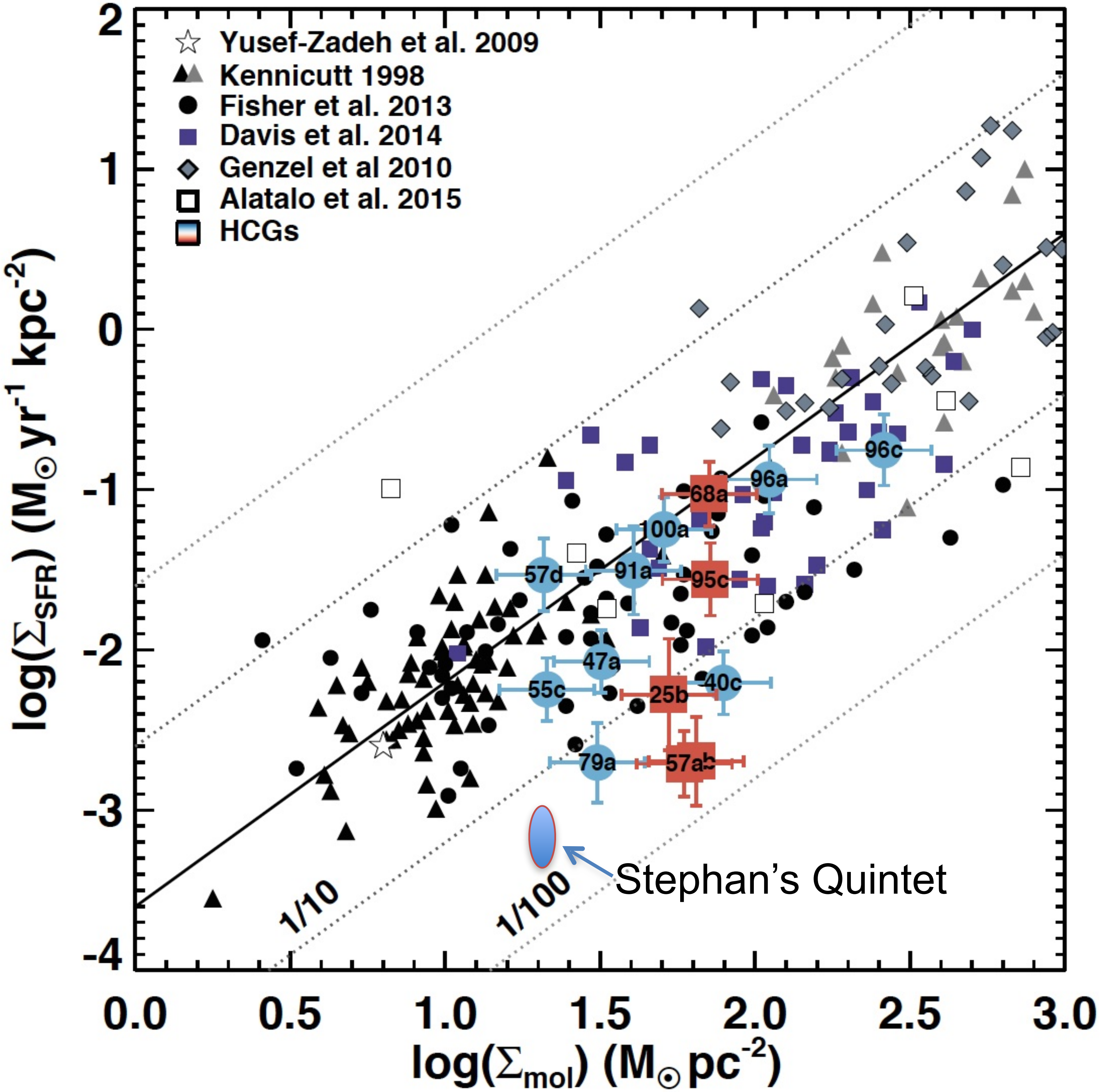


Kinetic energy carried by the molecular gas (~10^{58} erg) ~ 5 × thermal energy of the hot plasma

Guillard et al. 2009; Guillard et al. 2012b
Appleton, Guillard et al. 2013

$t_{diss}=10^8$ yrs >> $t_{dyn}=5\times10^6$ yrs

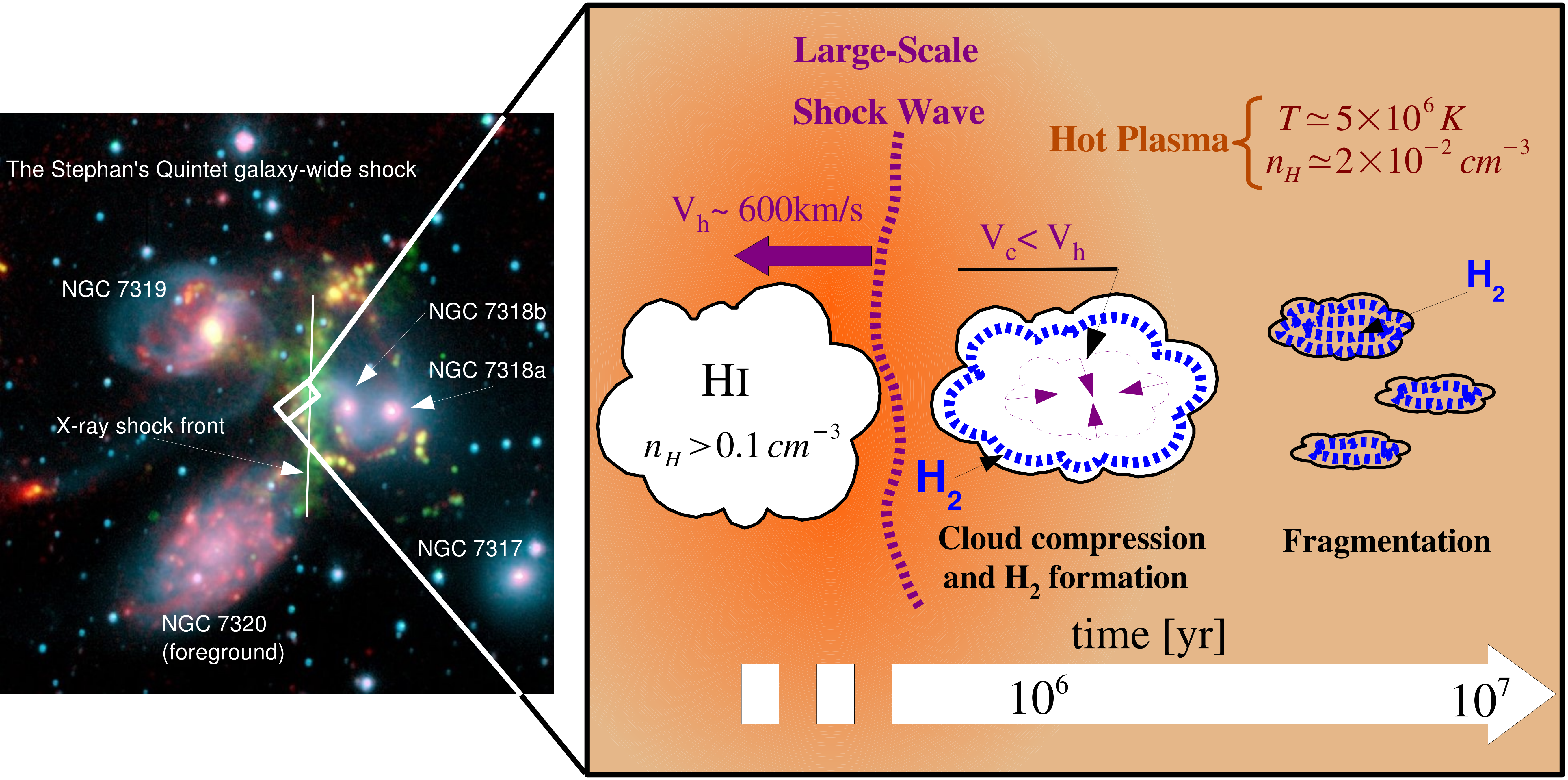
One example amongst other “SF-suppressed” HCGs



Stephan’s Quintet

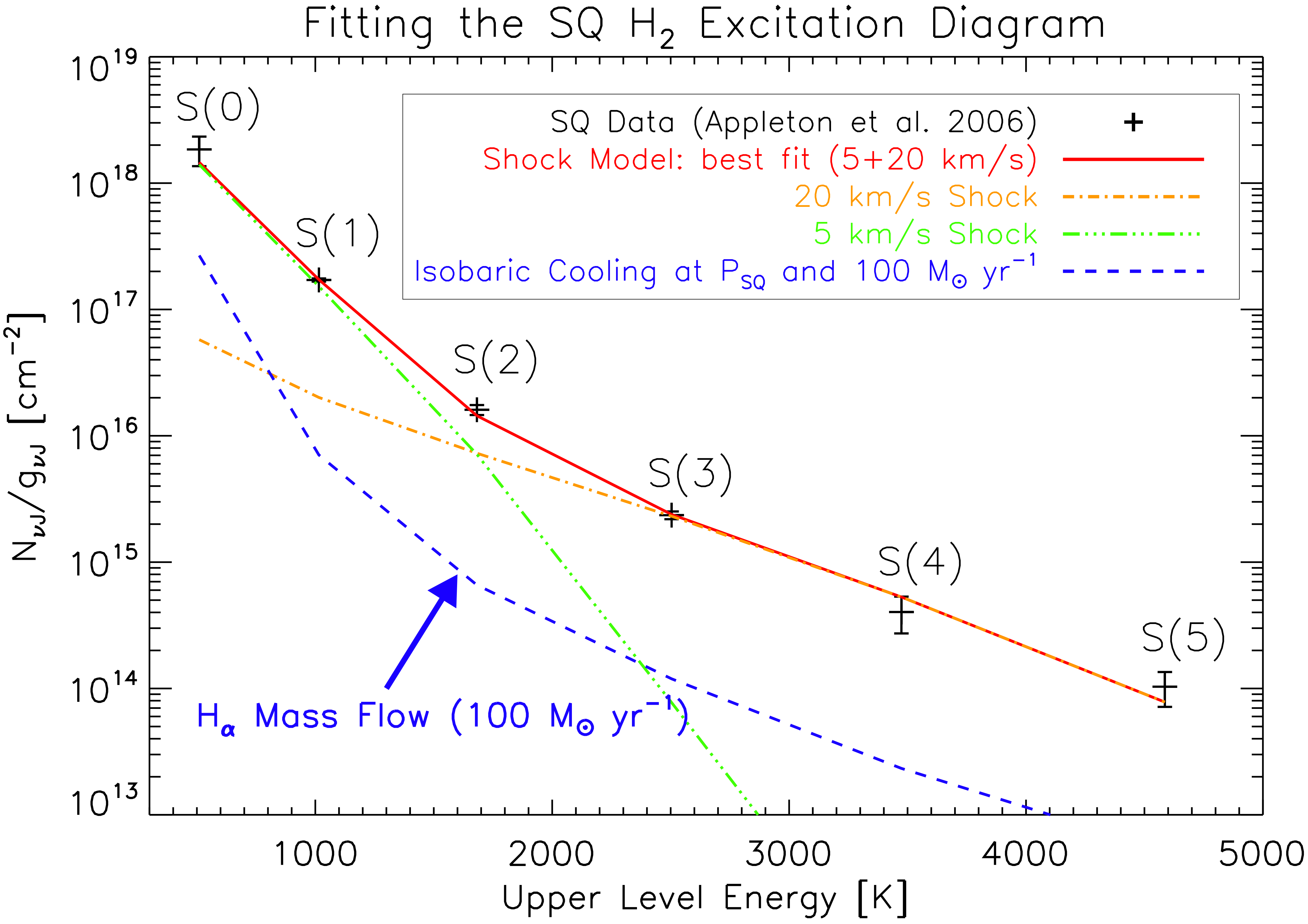
updated from Alatalo et al. 2014
Guillard et al. 2012b, Cluver et al. 2013; Alatalo et al. 2014, 2015c

A scenario for H_2 formation



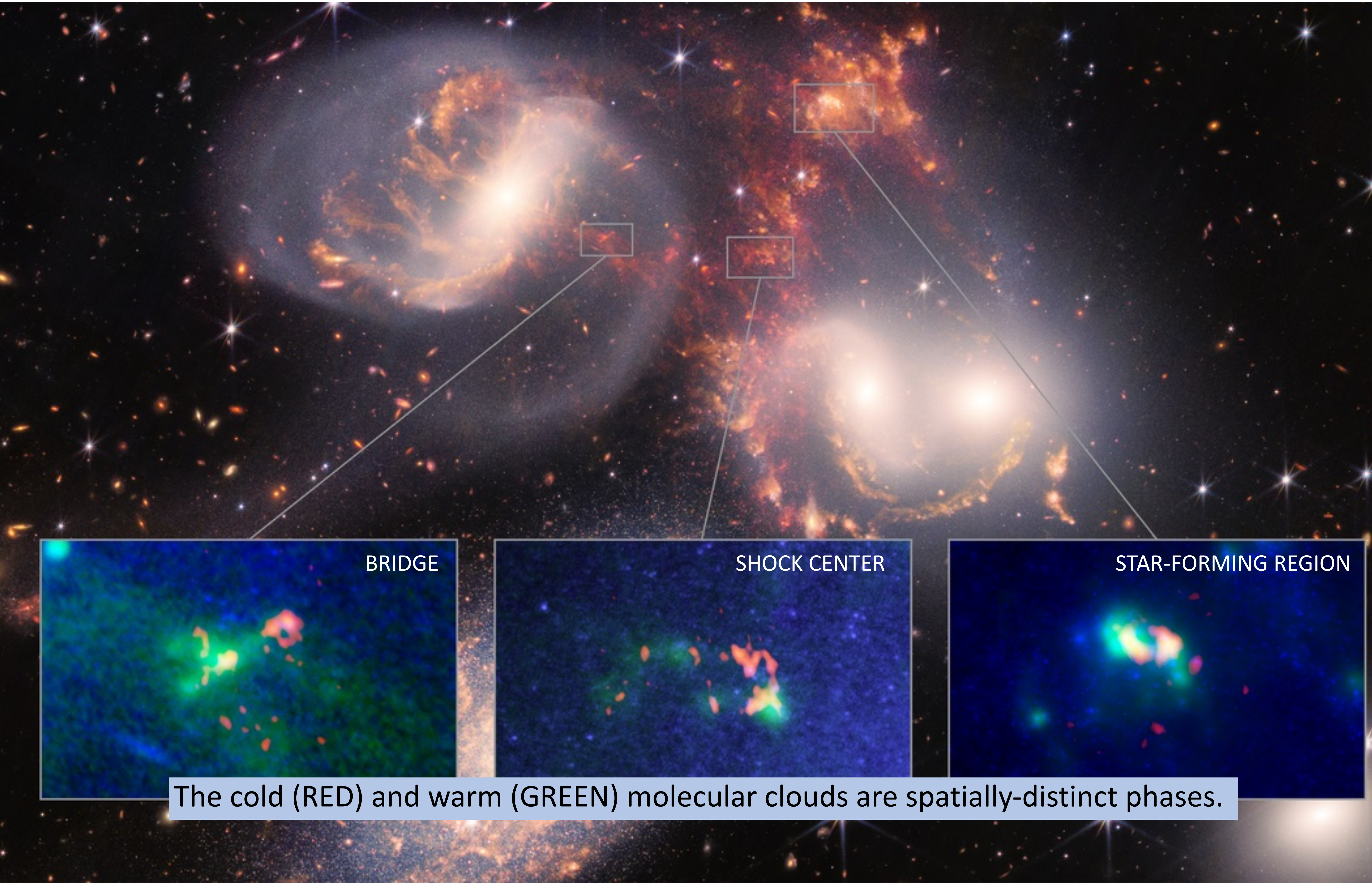
Guillard et al. 2009

Modelling of H_2 suggests that a fraction of the mechanical energy is cascading from large (40 kpc) to small scales (<0.1pc)



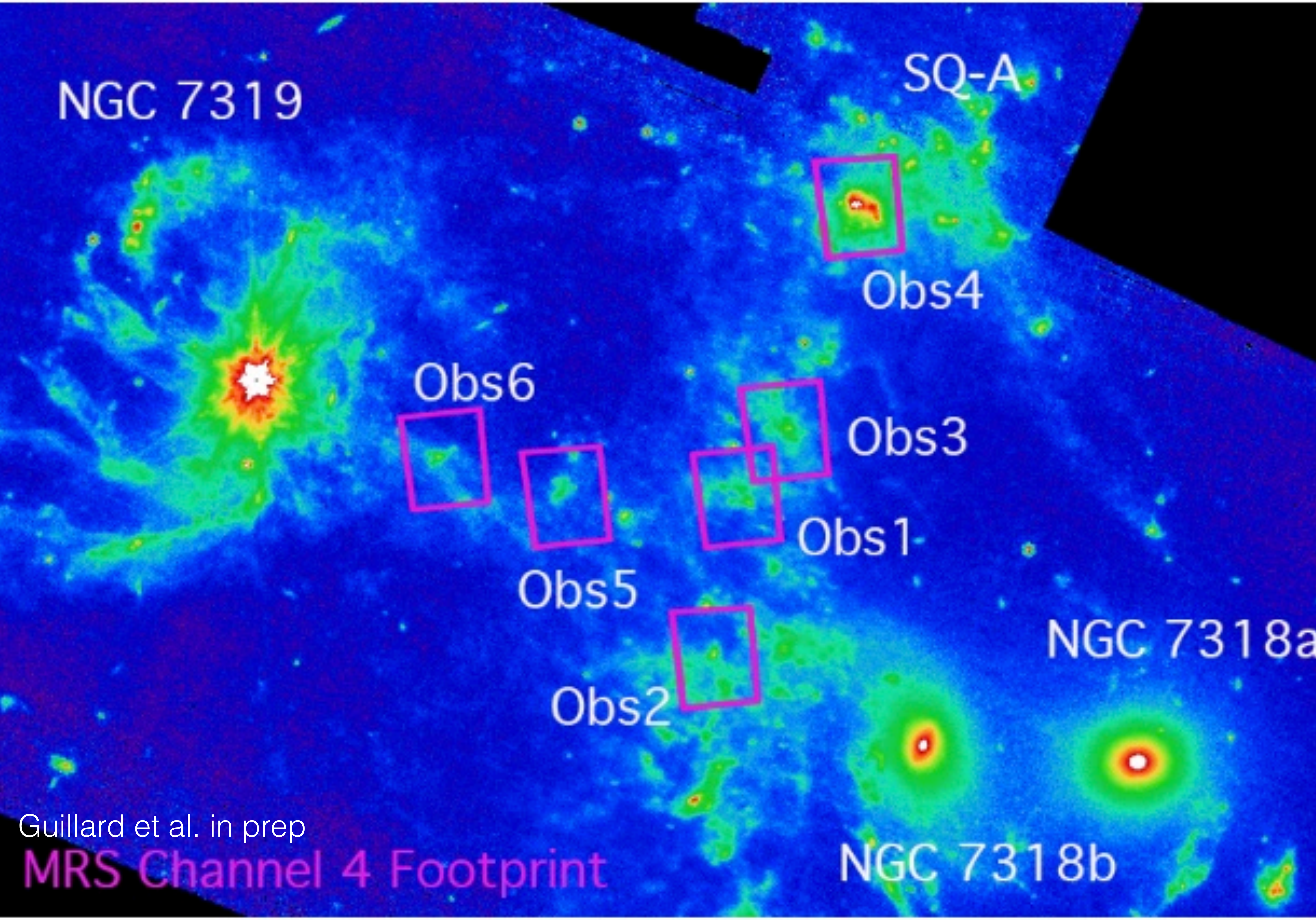
Guillard et al. 2009

Zooming-in on the different phases of the gas: (warm H_2, cold H_2, ionized)



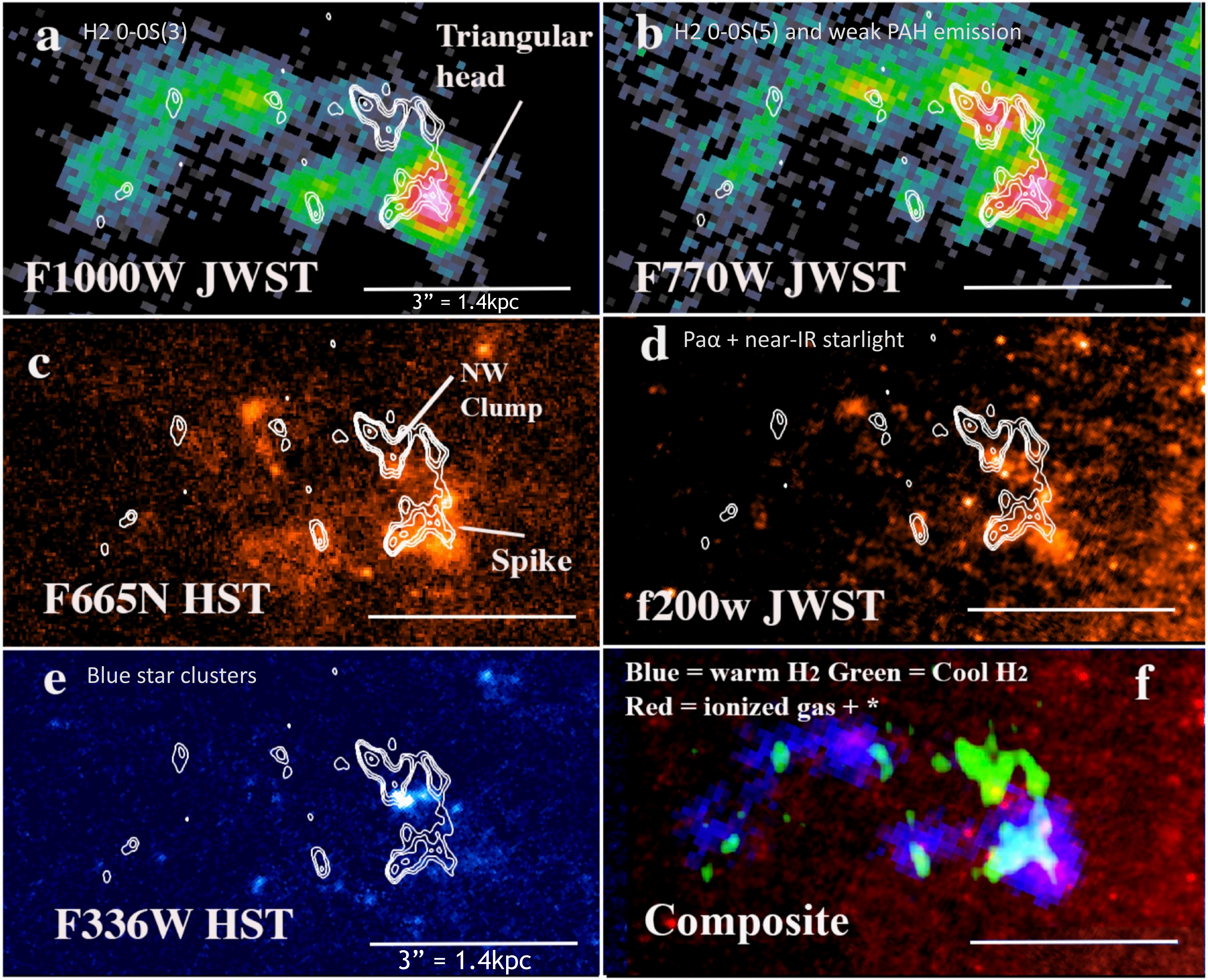
The cold (RED) and warm (GREEN) molecular clouds are spatially-distinct phases.

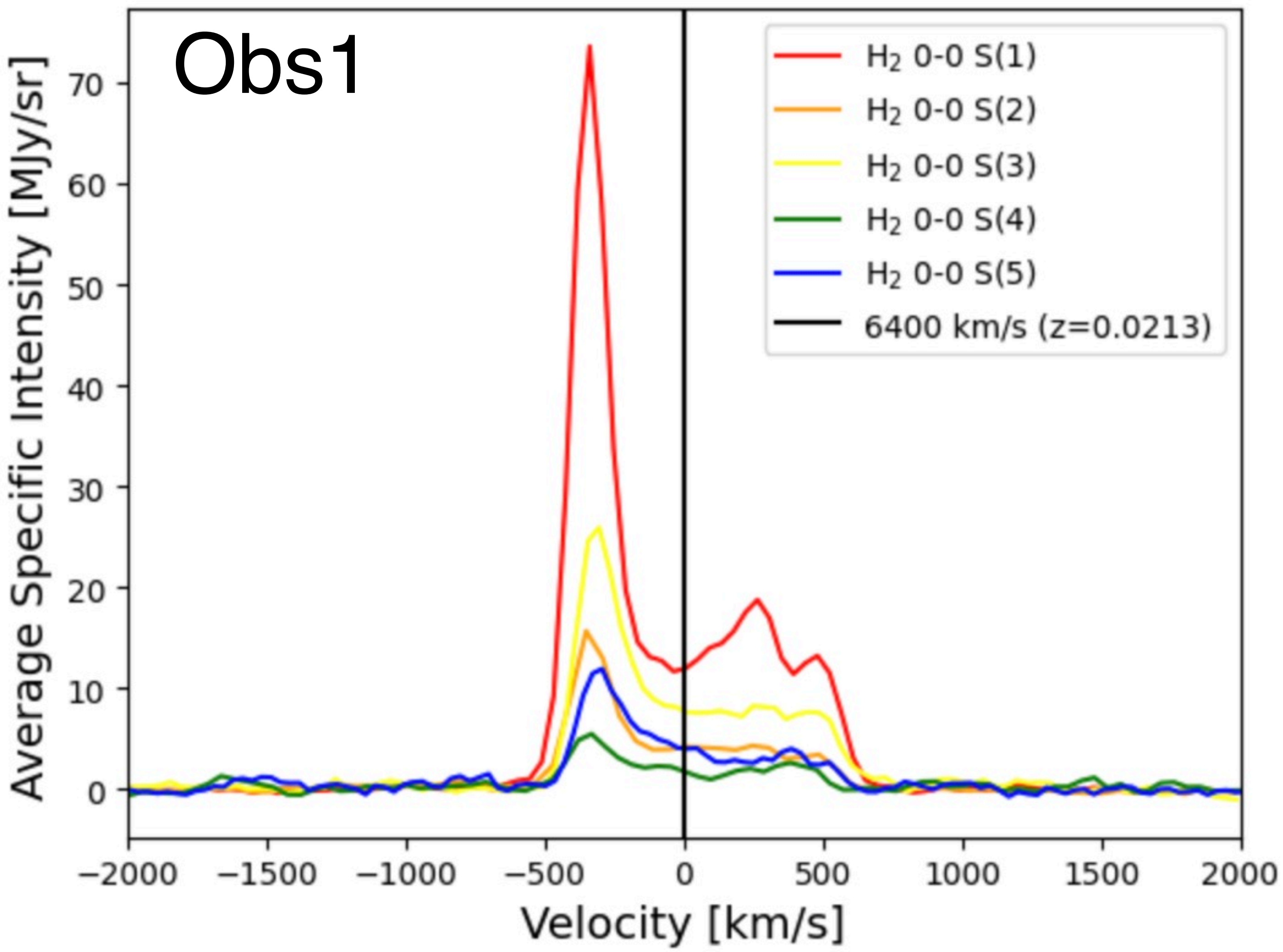
Appleton, Guillard et al. 2023



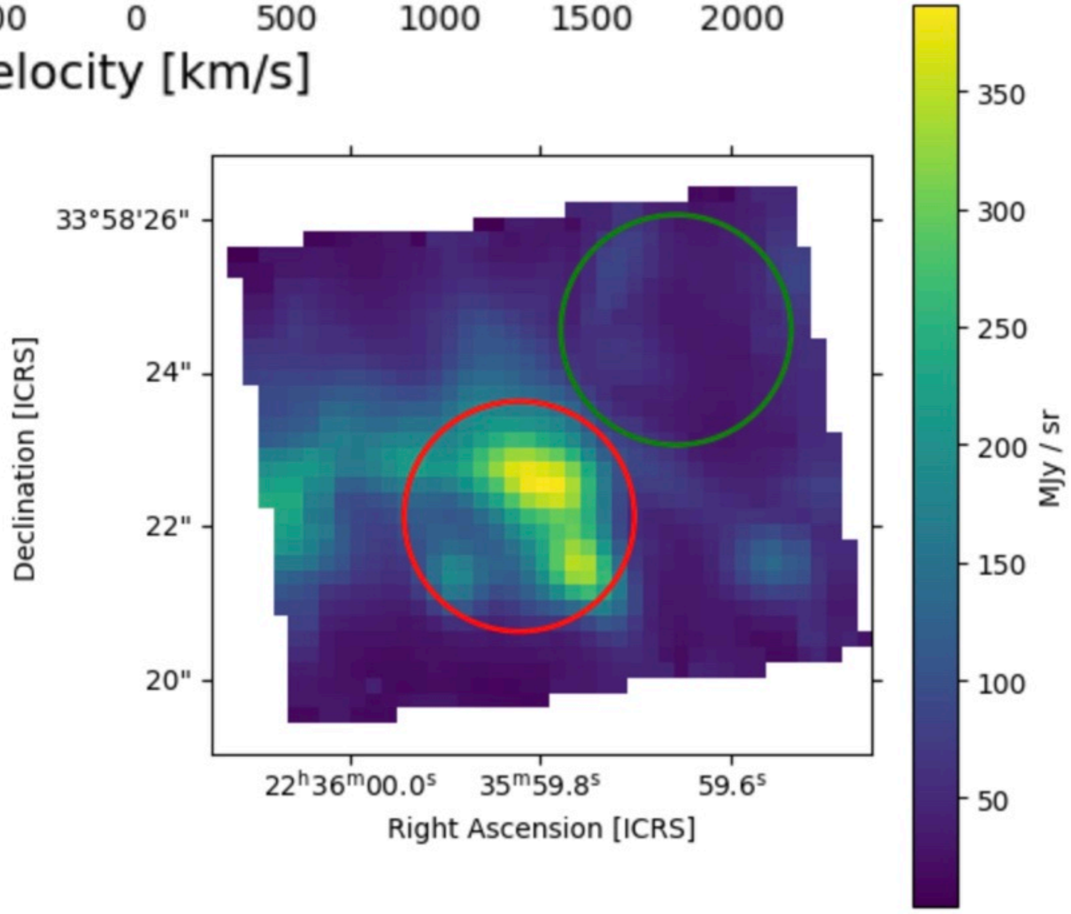
Guillard et al. in prep

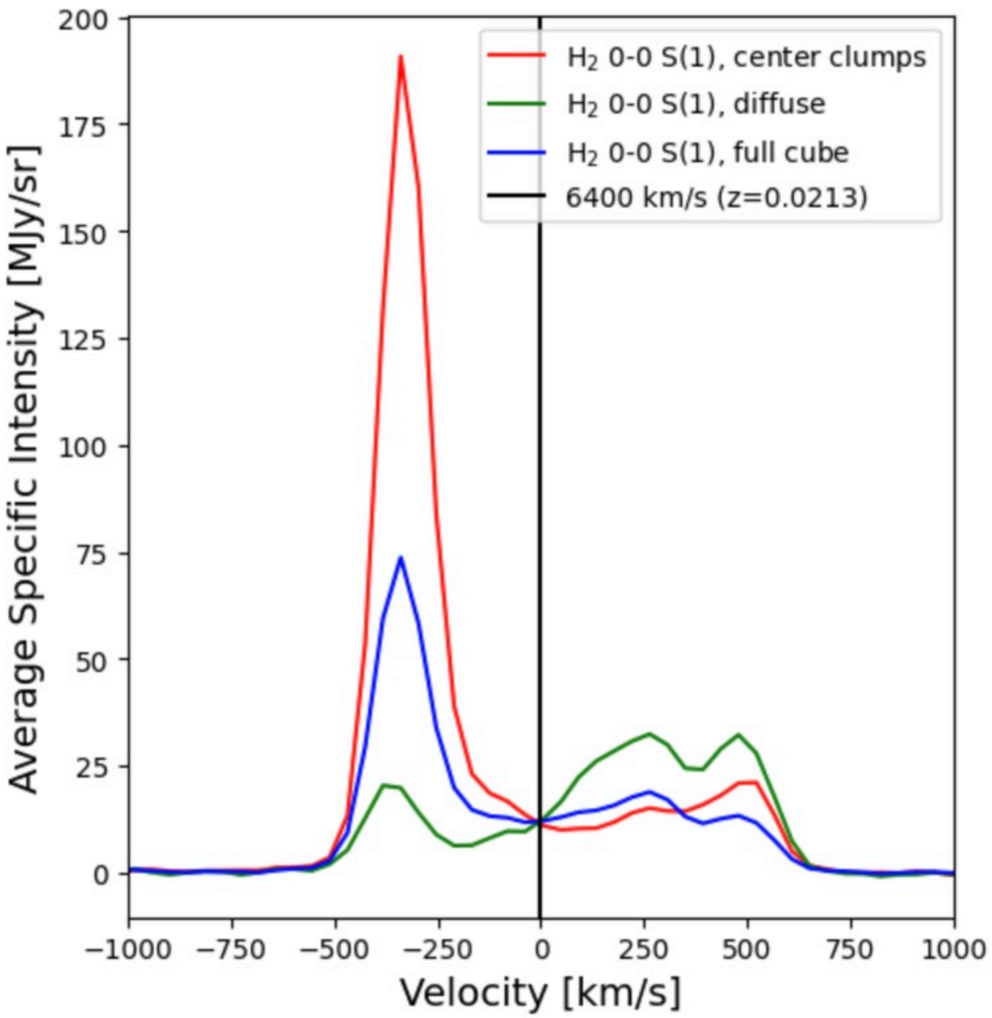
Obs1: shock center





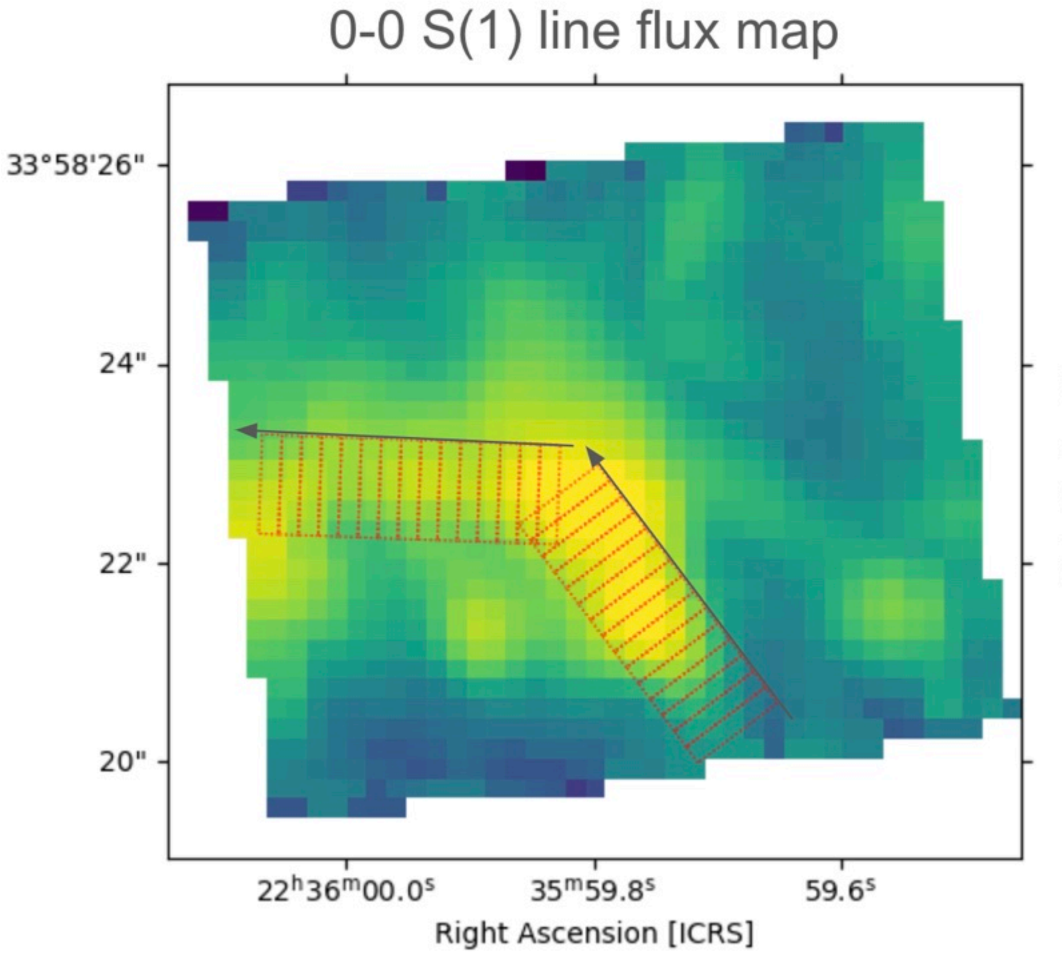
- IGM 6700 km/s gas is more diffuse than gas associated with the intruder (6000 km/s)
- Origin of the high velocity component (6900-7000 km/s) ?

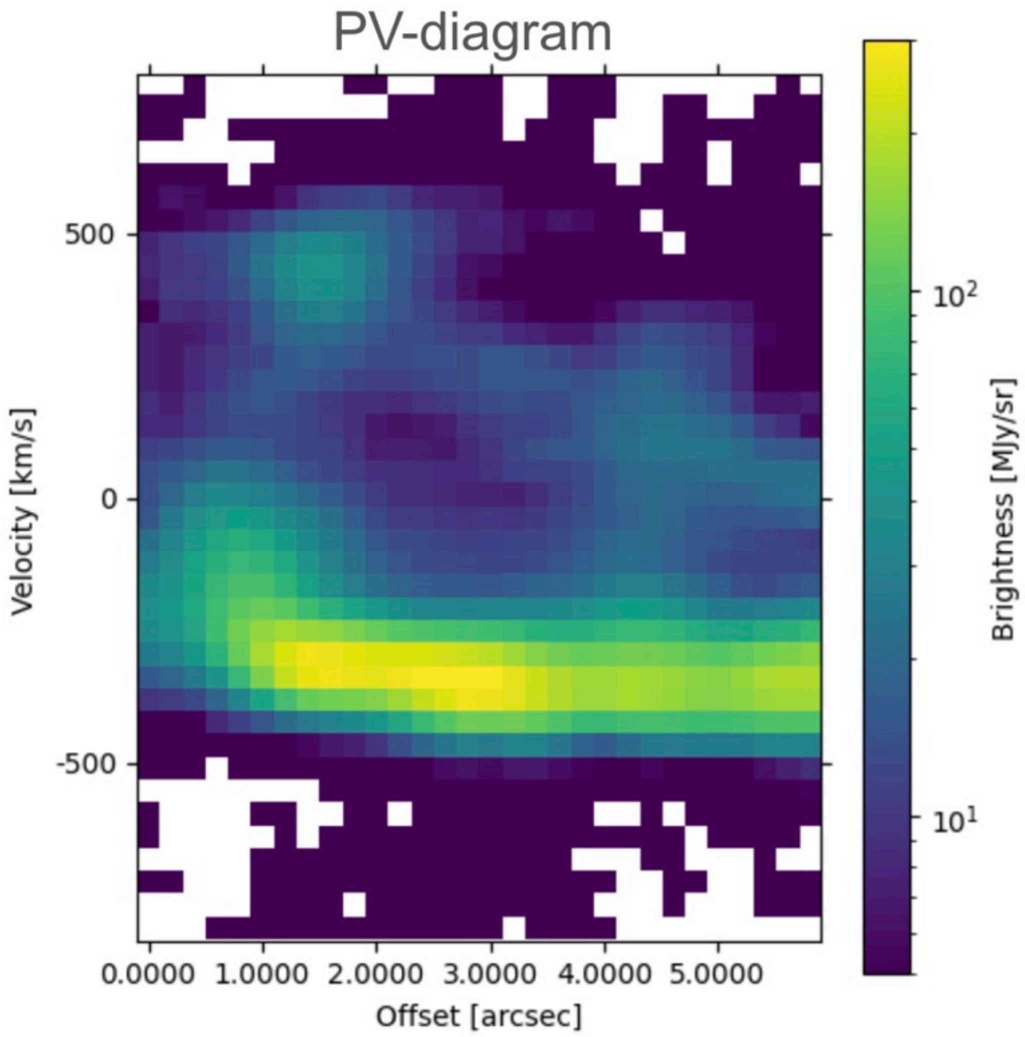


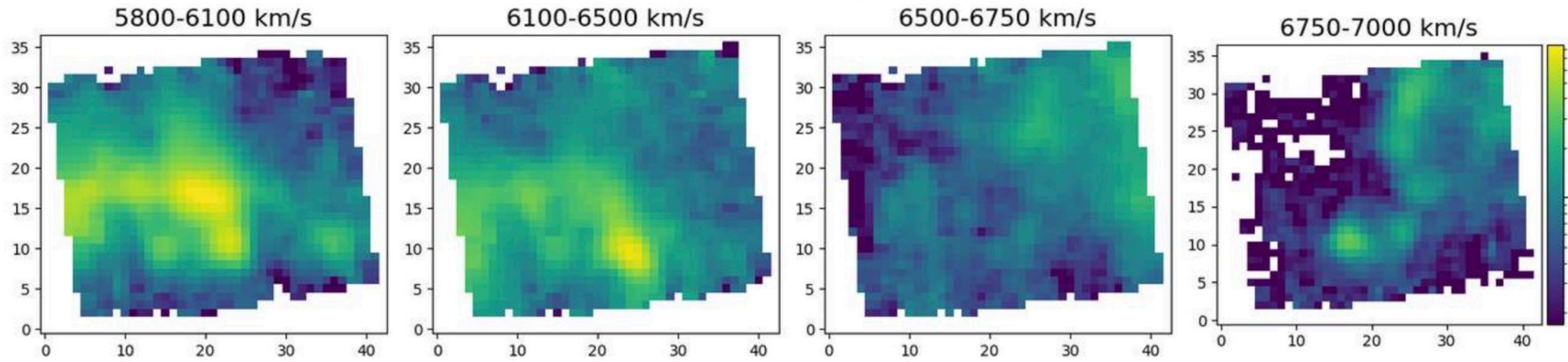


Guillard et al. in prep

Obs1 Detection of very large velocity gradients

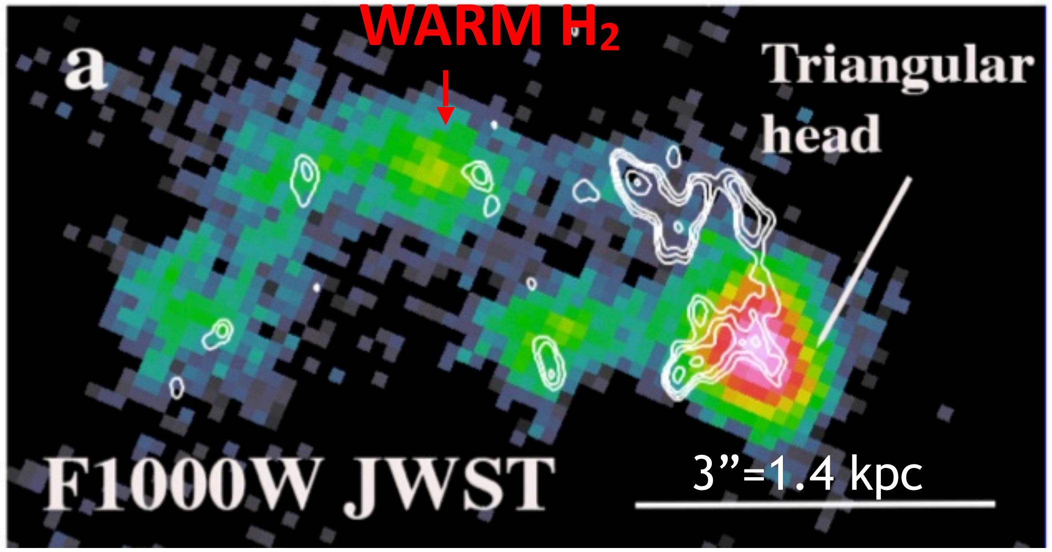

0-0 S(1) line flux map


PV-diagram


5800-6100 km/s
6100-6500 km/s
6500-6750 km/s
6750-7000 km/s

Guillard et al. in prep

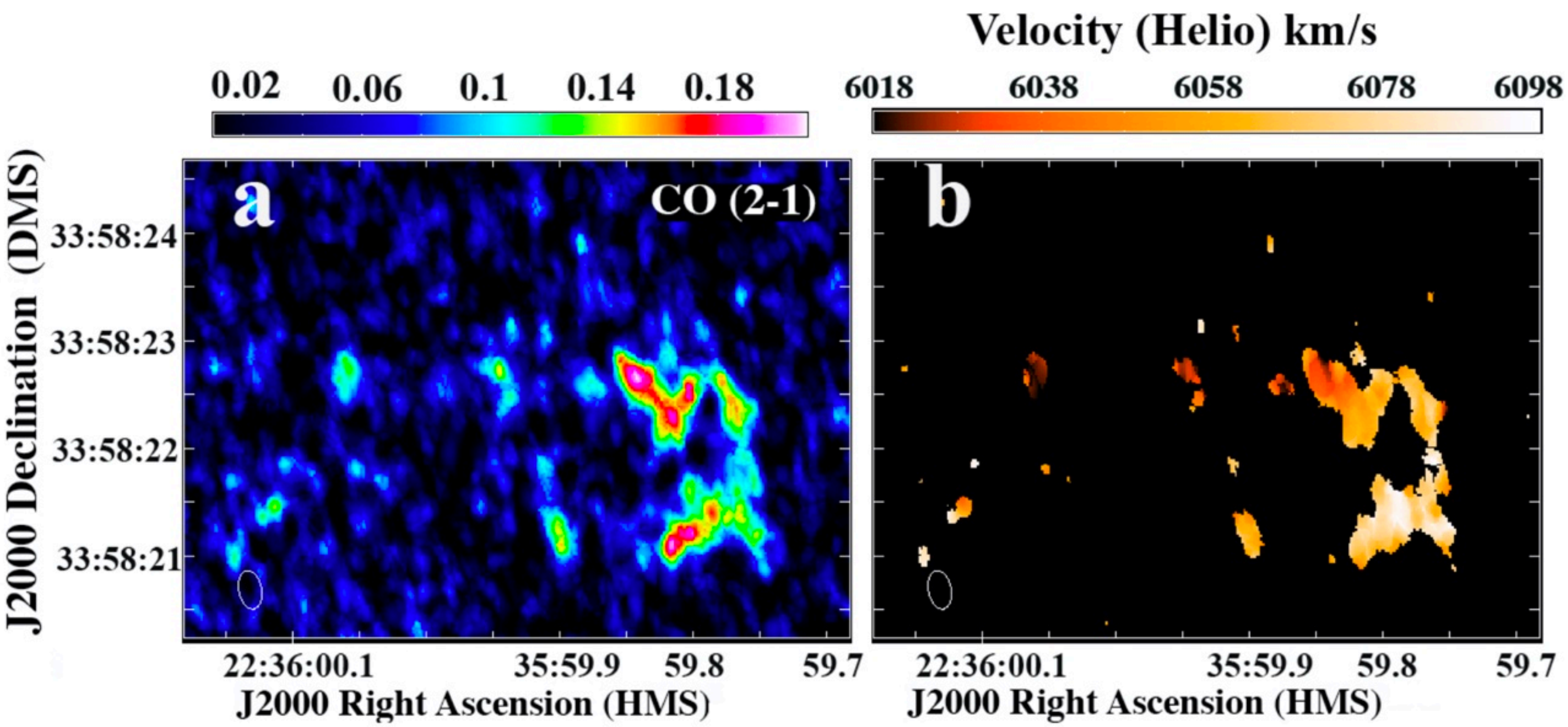
CO (ALMA) For the shock center position



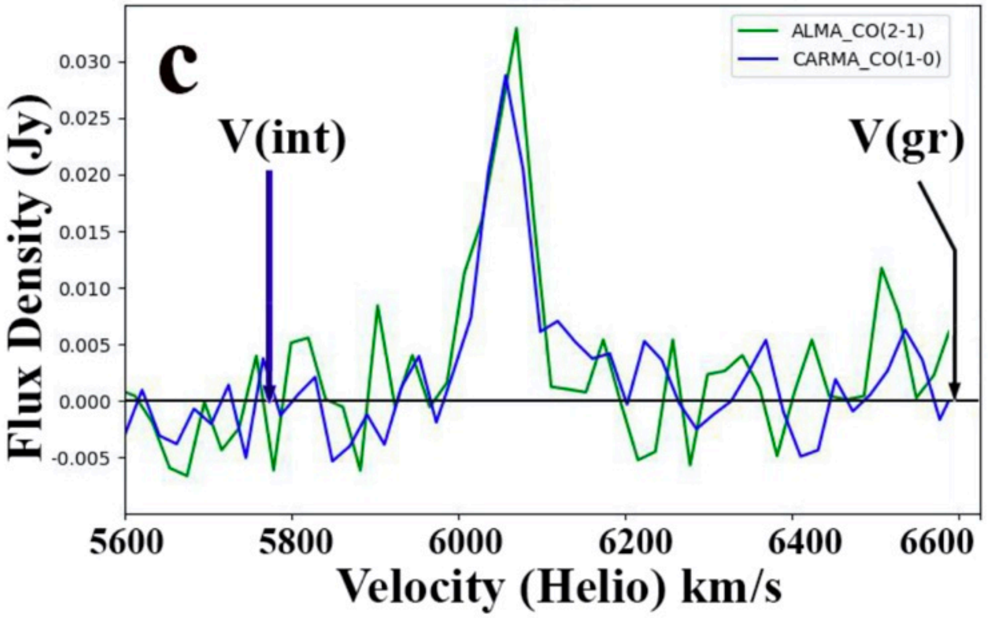
white= COLD H$_2$: CO(1-0) contours

Moment-0

Moment-1



ALMA and CARMA

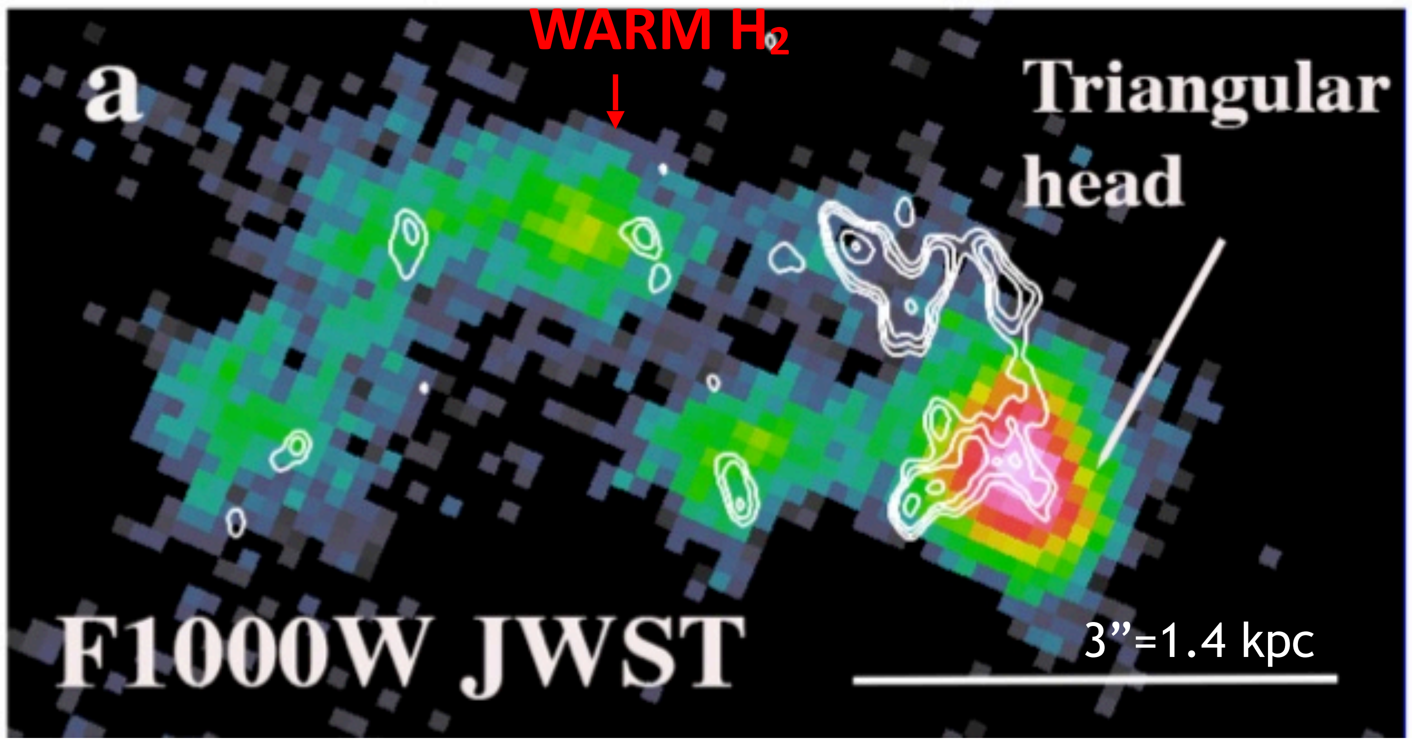


$\Sigma_{gas} = 80\text{-}170\ M_\odot pc^{-2}$

- The cold head and part of the tail contains turbulent motions in the CO gas, up to 100 km/s FWHM for individual clumps.
- The gas appears to stream away from the head over 100 km/s in the cold gas.
- To be in viral equilibrium: $\sigma^2 = (3/5)\pi G R_{cloud} \Sigma_{gas}$ = 8.3km/s, or FWHM~20km/s .

Appleton et al. 2023

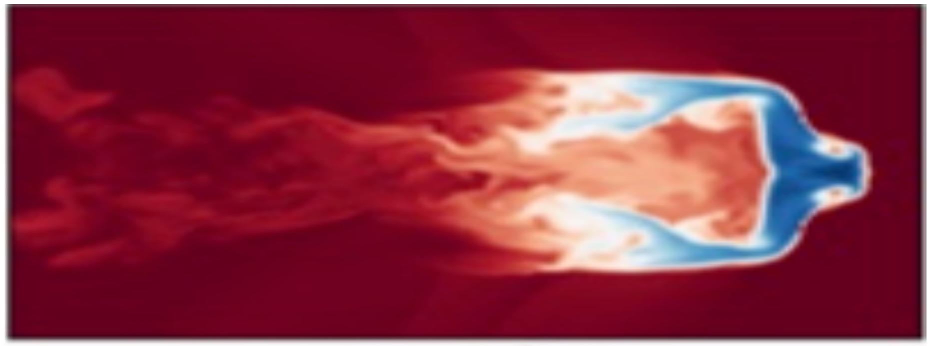
Lets concentrate on the region in the center of the shock



white= COLD H_2: CO(2-1) contours

The **HEAD consists of a dense shell of cold dense H_2** surrounded by warm H_2 and a tail of warm H_2 gas.

A massive cloud is being destroyed ?



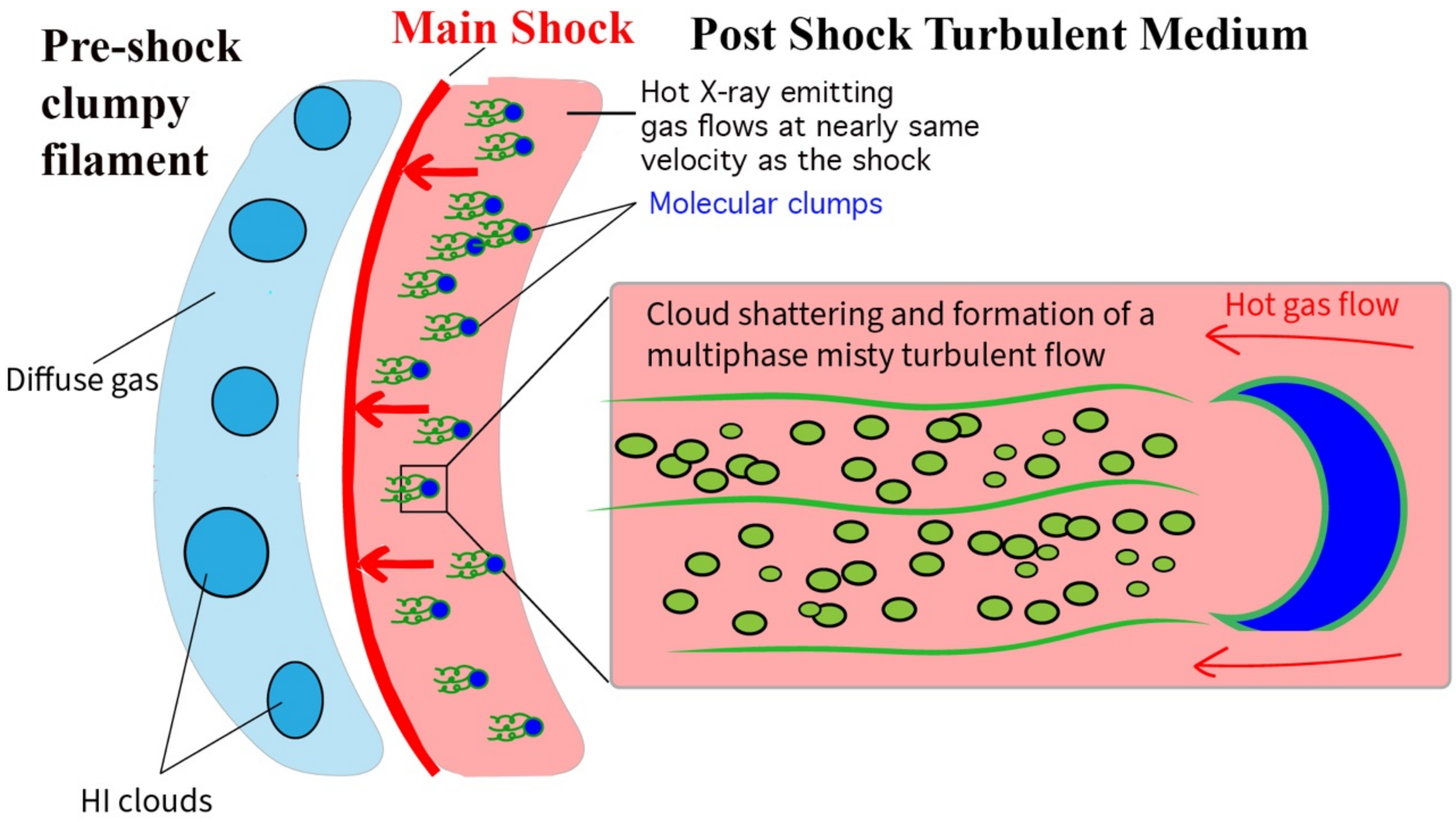
WIND

Structure is reminiscent of what happens when a dense cloud encounters a fast WIND of hot gas

One of a series of models of break-up of massive cloud by fast wind (Farber and Gronke 2022a, Gronke & Oh 2022, Tan & Oh in prep.)

A possible toy model to explain the abundance of warm H_2 in the shock-wave induced by the galaxy collision

Shattering idea (Gronke & Oh 22, Farber and Gronke2022b)



Hot X-ray emitting gas flows at nearly same velocity as the shock

Cloud shattering and formation of a multiphase misty turbulent flow

1) FAST SHOCK WAVE overtake **“clumpy”** tidal filament

2) clumps are compressed into **cold clouds on a crushing timescale** $t_{crush} = L_{cloud} / V_{cloud}$

3) **hot gas** behind the shock flows past **cold clumps** and begin to **shatter the cloud into tiny cloudlets (thermal instability)**

4) the cloudlets initially are shielded from the full impact of the flow

5) They get dragged into the hot flow and start **to mix, warming the gas** (through slow shocks?)

Does shattering and mixing of small clouds within the hot flow explain the formation, survival and emission of H_2?