Title: Unveiling the Multi-phase CGM and ISM in MACS1931-26 with JWST and ALMA

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Subject: Cosmology

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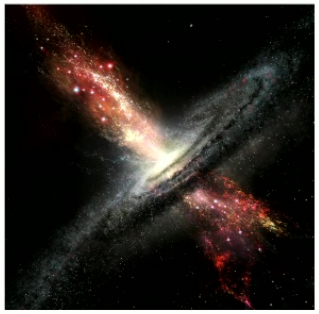
Abstract:

The circumgalactic medium (CGM) serves as the interface between galaxies and their cosmic environment, hosting the baryon cycle across a wide range of temperatures, densities, and energy scales. With its unprecedented sensitivity and spectral coverage, JWST is revolutionizing our view of this cycle by enabling direct detection of warm molecular hydrogen via mid-infrared rotational lines. We present a detailed analysis of the multi-phase molecular gas in the brightest cluster galaxy (BCG) of the cool-core cluster MACS1931-26 (z = 0.35), combining new **JWST/MIRI** and archival **ALMA** observations. This BCG hosts a powerful radio-loud AGN, elevated star formation, and one of the largest known H_2 reservoirs at this redshift. We trace cold molecular gas (10–100 K) using multiple CO and [CI] lines, finding highly excited gas in the ISM, similar to local LIRGs, while the CGM appears much less excited, pointing to distinct excitation sources. Our JWST data reveal warm H_2 (100–1000 K) spatially coincident with the CO-emitting gas and exhibiting comparable kinematics. Intriguingly, the CGM shows a higher H_2 excitation temperature than the ISM, suggesting the presence of more energetic heating mechanisms, including shocks and AGN-driven X-ray emission. This highlights the CGM as a key site of feedback-regulated gas transformation. Moreover, we will discuss our plans to use upcoming JWST Cycle 4 **NIRCam + MIRI** spectroscopy (2–28 μm) to perform comprehensive radiative transfer and shock modeling, aiming to constrain heating sources and baryon cycle in the CGM and ISM. This pilot study lays the groundwork for a broader framework to trace baryon cycling in cool-core BCGs, leveraging the synergy of JWST and cold gas tracers as a transformative tool for CGM studies.

Baryon Cycle

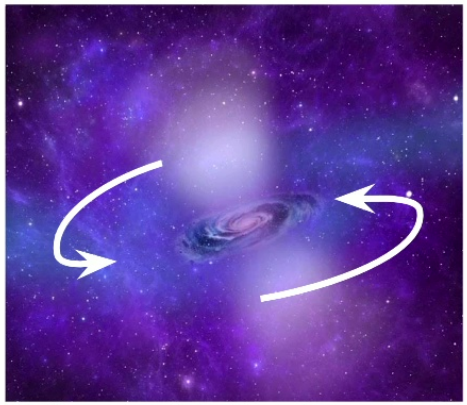
Outflows from the galaxy to the dark matter halo



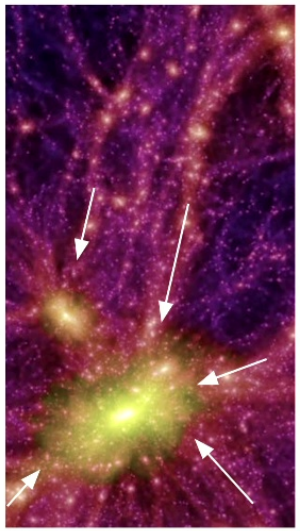
Star formation within the interstellar medium

Cooling

Inflow from the dark matter halo to the interstellar medium

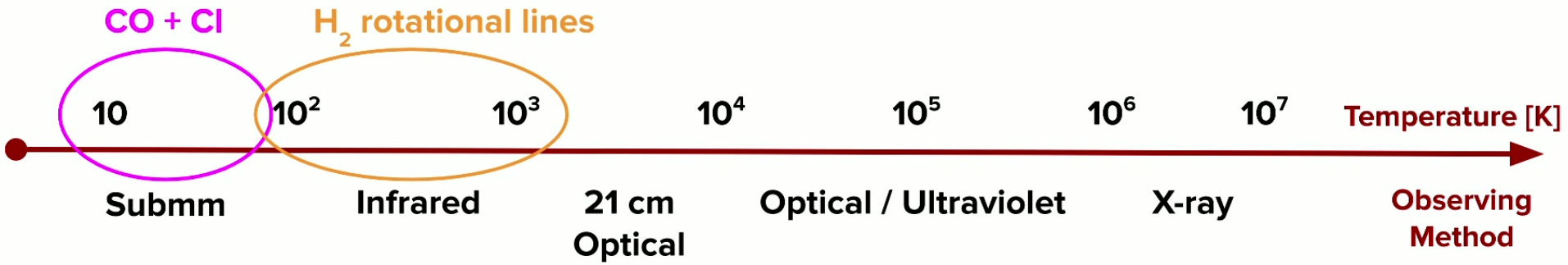


Inflow from cosmic environment to the dark matter halo



Metal-rich gas injection

Baryon Cycle in the Molecular Phase



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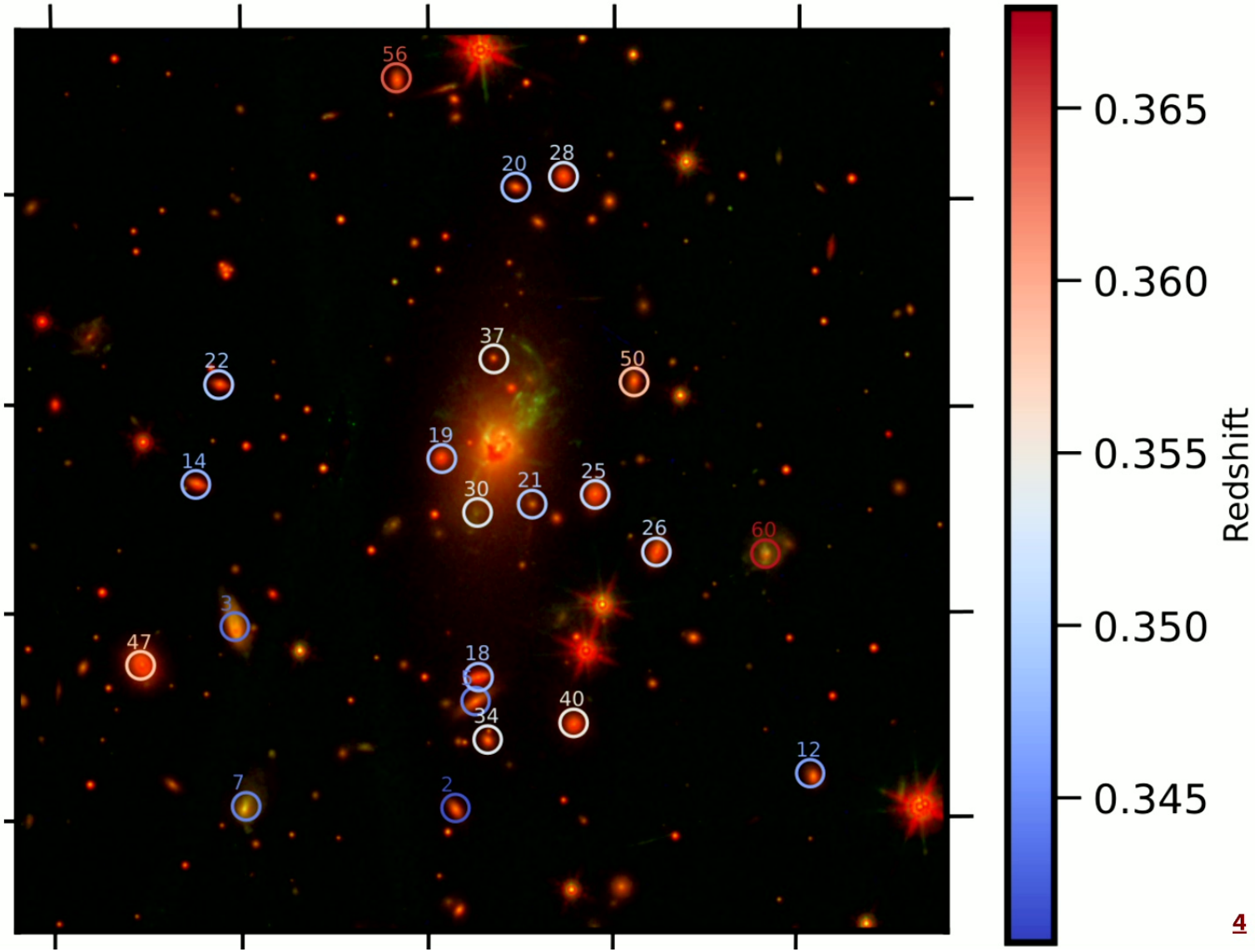
MACS 1931-26



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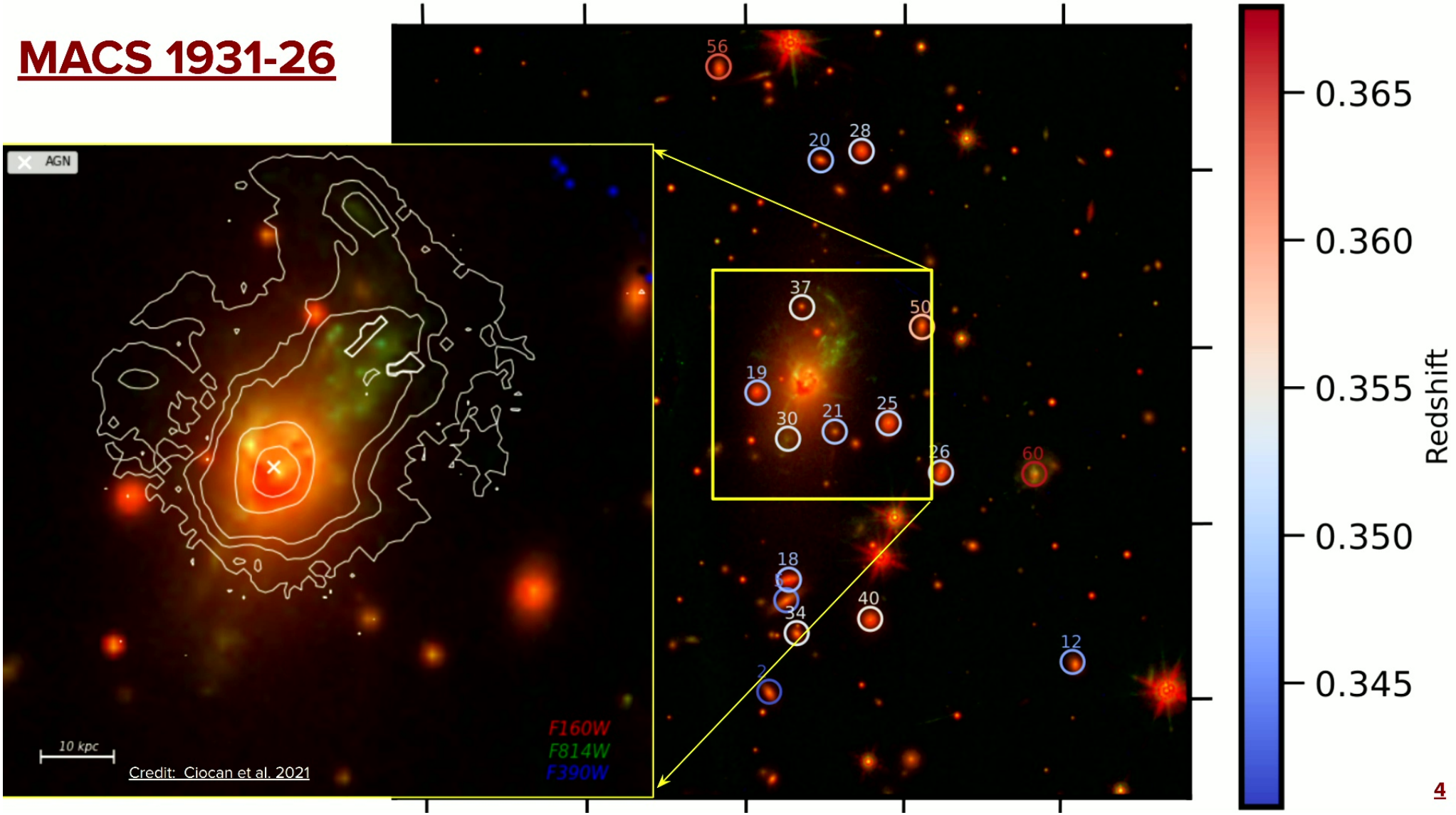
MACS 1931-26



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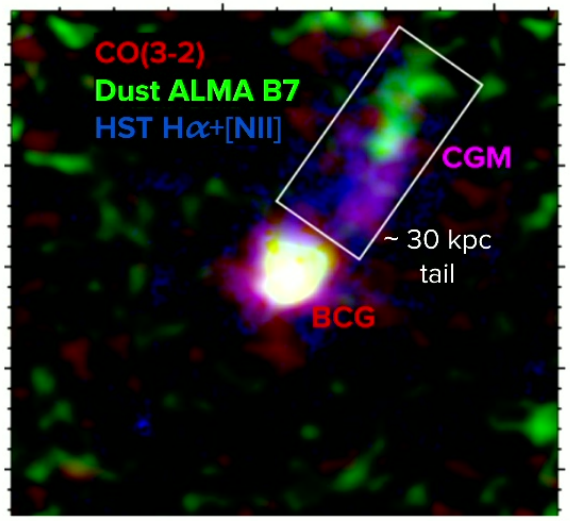
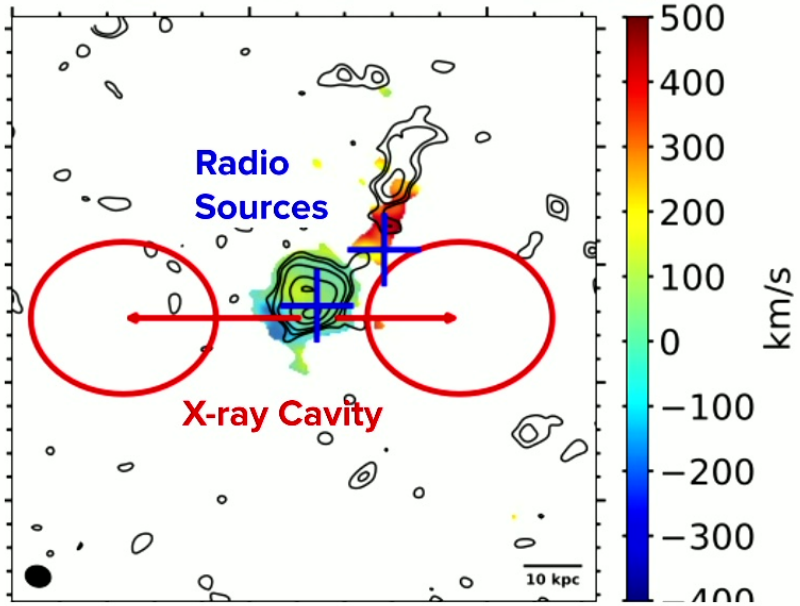
MACS 1931-26

- Cool-core galaxy cluster **MACS 1931-26** at z = 0.35
  - Brightest cluster galaxy (BCG):
    SFR ~ 250 $M_\odot yr^{-1}$, $M_\star$ ~ 5.9 × 10^{11} $M_\odot$
    Radio-loud AGN

- Multiphase gas reservoir nearby

  One of the largest known H_2 reservoirs (2×10^{10} $M_\odot$)





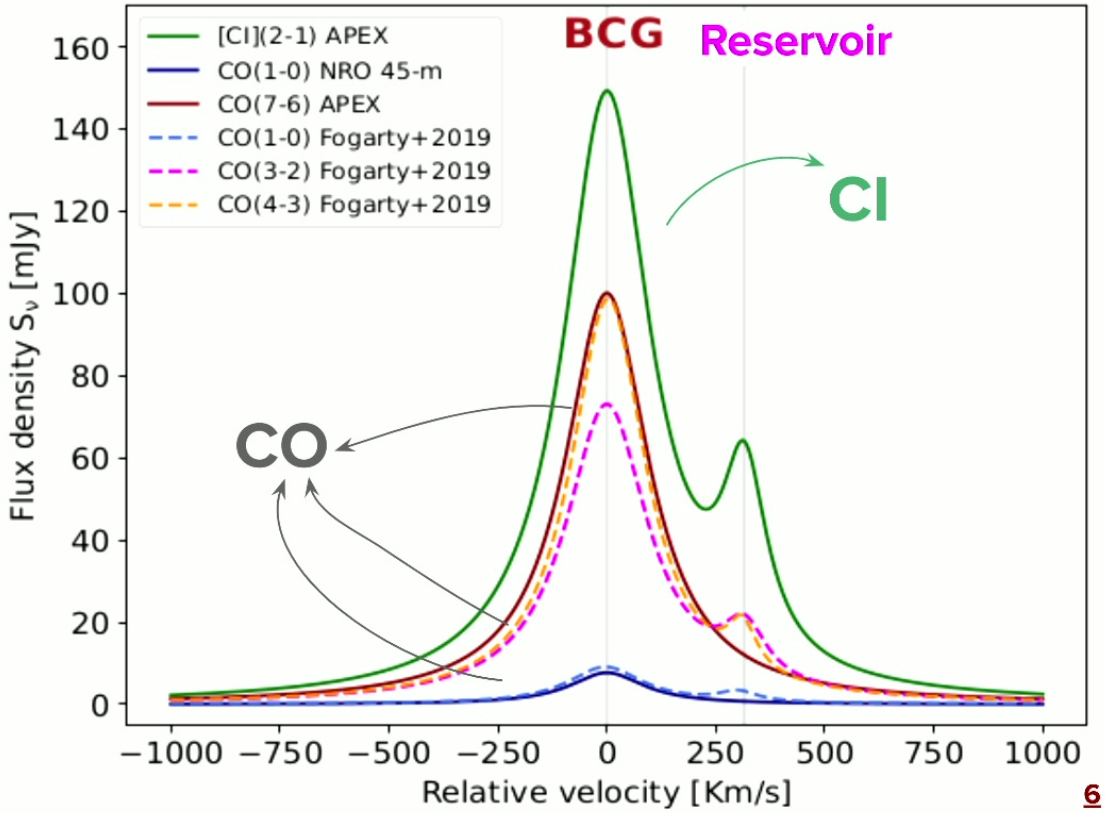
Credit: Fogarty+2019

Cold Molecular Gas : CO + CI in submillimeter

Ghodsi et al. 2024(b)
arXiv:2406.09552

- **Gas reservoir** is redshifted by ~ 300 km/s compared to the **BCG**

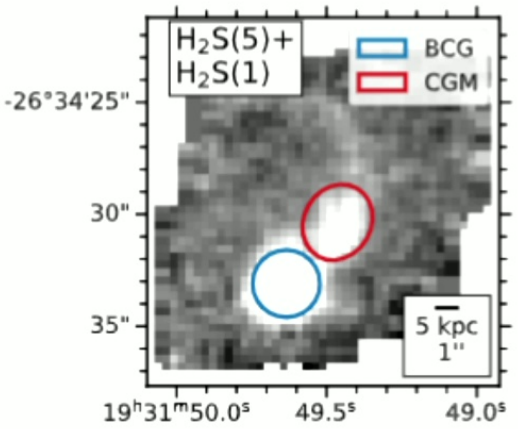
- CI is brighter than CO lines
  ➜ cosmic ray excitation?

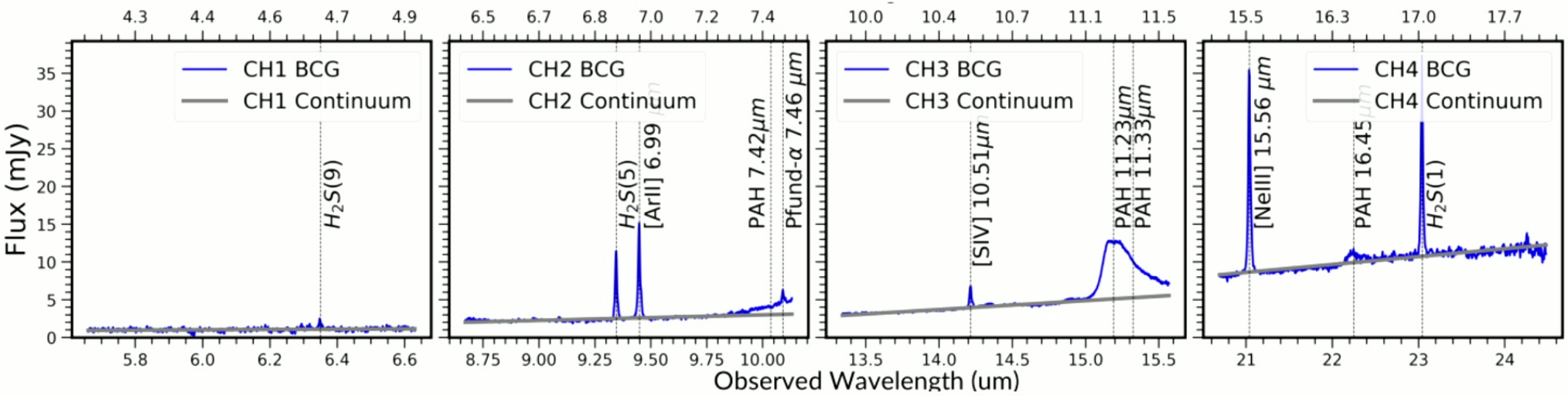


Warm Molecular Gas : H_2 in infrared

- JWST Cycle 2, MIRI/MRS, PI A.Man
- Detecting H_2 rotational lines, ionized lines [Ar II], [S IV], [Ne III], and PAH features

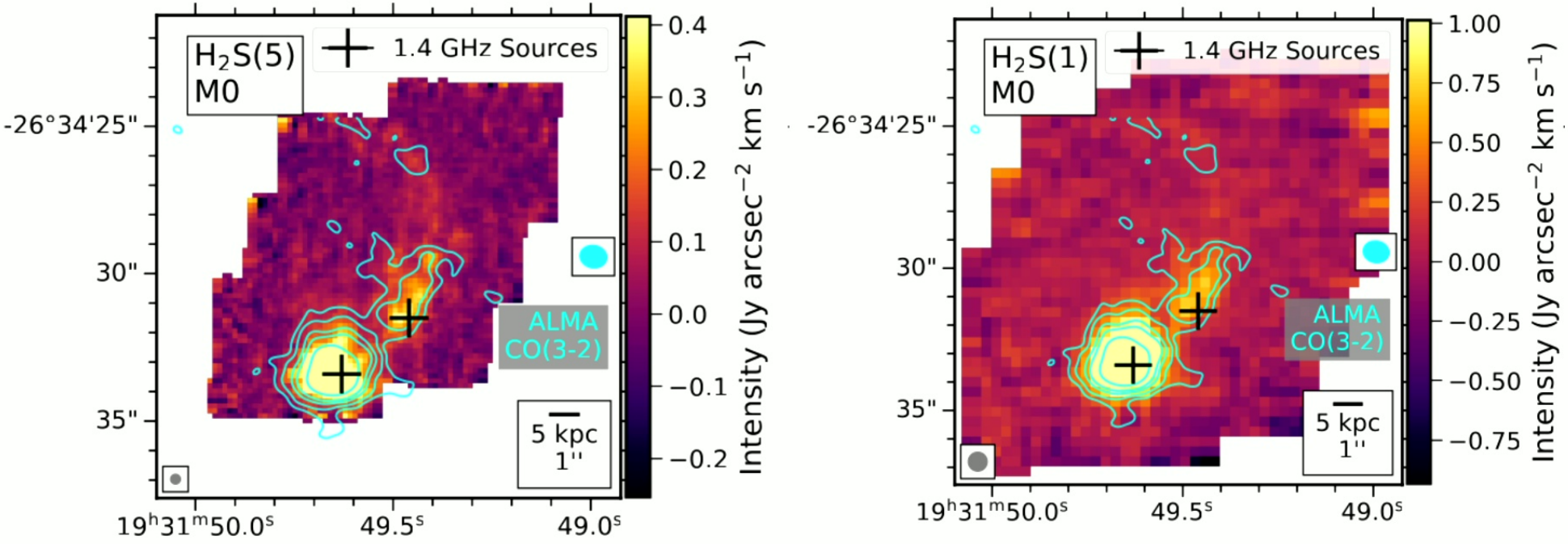
Ghodsi, Man et al. in review
Kuhn, Man et al. in prep





Warm and cold molecular gas are distributed similarly

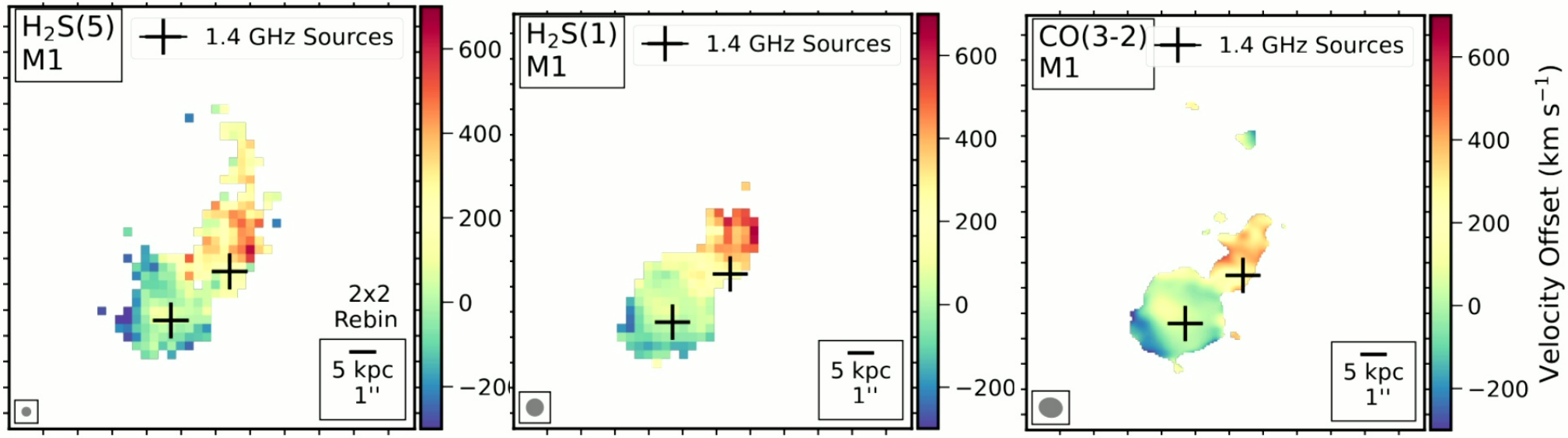
ALMA CO(3-2) contours on JWST emission line intensity maps



Ghodsi, Man et al. in review

Warm and cold molecular gas have similar kinematics

Velocity maps of $H_2S(5)$, $H_2S(1)$, and CO(3-2)



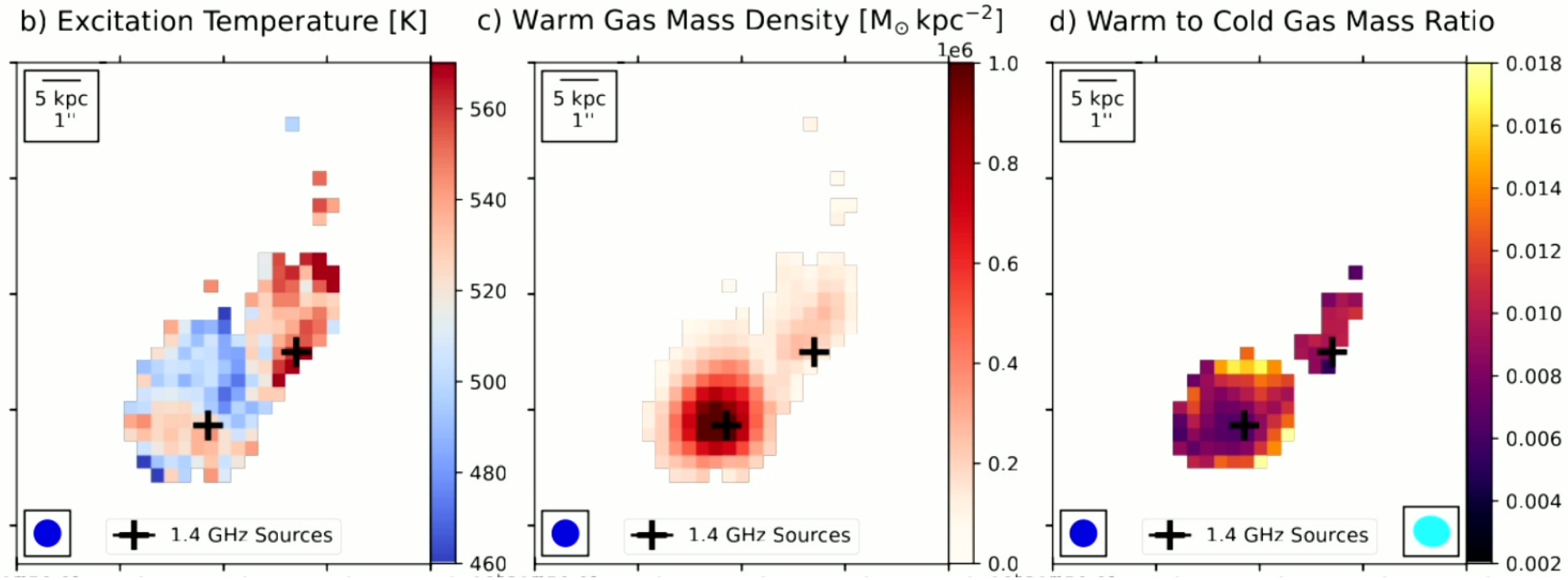
Ghodsi, Man et al. in review

Ghodsi, Man et al. in review

Warm Molecular Gas Excitation

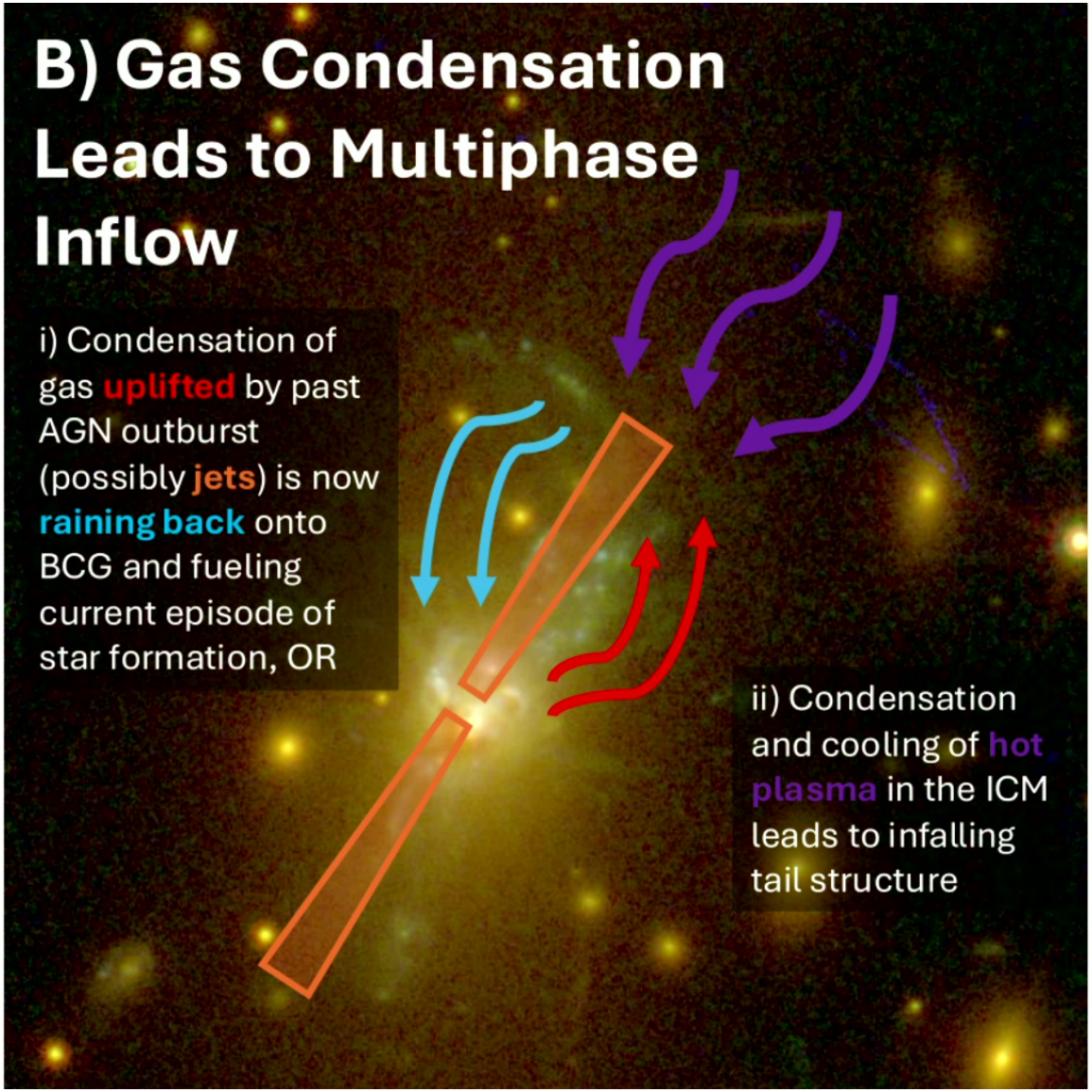
- Excitation temperatures higher in tail (541 K) than the Galaxy (510 K)

- Warm to cold gas mass ratio ~1% in the galaxy ➔ Similar to star-formation excitation



Tail Formation: AGN jets

- Gas reservoir is uplifted by jets?
- Similar spatial distribution and kinematics between hot ionized gas, warm molecular gas, and cold molecular gas are consistent with this scenario.
- Jets are not yet detected.



Credit: Lucas Kuhn

Summary and Future

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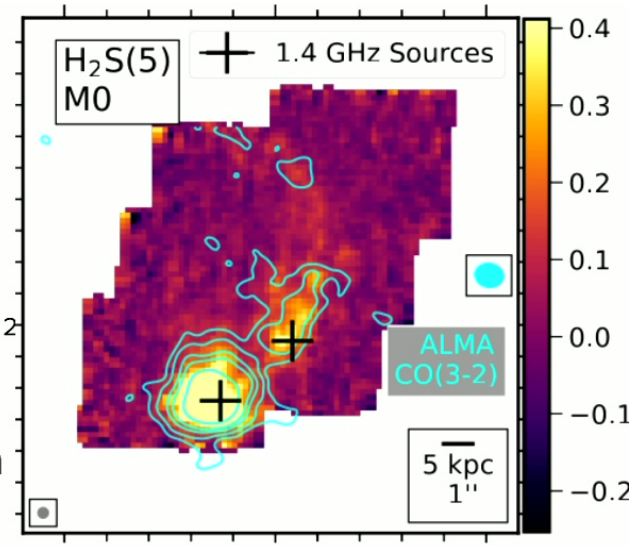
- Multiwavelength observations are important in understanding the baryon cycle in cool core galaxies
- Comparison of JWST and ALMA observations reveal warm and cold H_2 with similar distribution and kinematics
- Molecular gas consists of ~1% warm gas, consistent with UV ionization



- ➢ Coming Cycle 4 JWST data with full MIRI coverage + NIRCam + NIRSpec
  - Detect more H_2 rotational lines ➔ Better modelling of H_2 excitation in the CGM
  - Detect H_2 ro-vibrational lines in NIR ➔ Trace hot molecular gas > 2000 K
  - Detect ionized lines including [NeVI], directly tracing hot shocks and cooling flow
  - Detect PAH features (the MIRI data already show signs of PAH 11.3 μm in the CGM)
- ➢ Shock modelling with the full data set ➔ excitation source
- ➢ Extend the work to a larger sample of cool-core BCGs