First Connection between Cold Gas in Emission and Absorption: CO Emission from a Galaxy-Quasar Pair

Neeleman, M. et al. 2016, ApJL, 820, L39
(http://adsabs.harvard.edu/abs/2016ApJ...820L..39N)

See also;
Rafelski, M. et al. 2016, ApJ, 825, 87
(http://adsabs.harvard.edu/abs/2016ApJ...825...87R)

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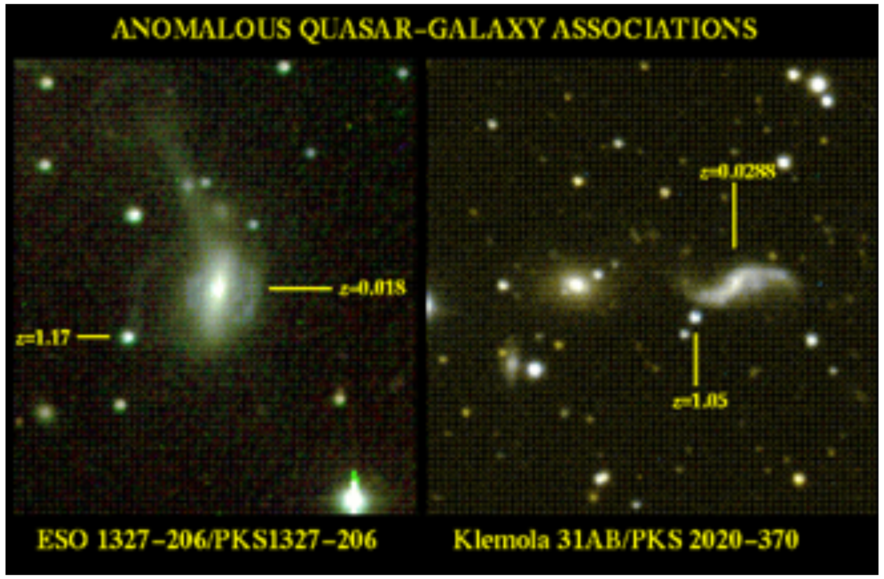
Abstract

We present the first detection of molecular emission from a galaxy selected to be near a projected background quasar using the Atacama Large Millimeter/submillimeter Array (ALMA). The ALMA detection of CO(1−0) emission from the $z = 0.101$ galaxy toward quasar PKS 0439–433 is coincident with its stellar disk and yields a molecular gas mass of $M_{\rm mol} \approx 4.2 \times 10^9\,M_\odot$ (for a Galactic CO-to-H_2 conversion factor), larger than the upper limit on its atomic gas mass. We resolve the CO velocity field, obtaining a rotational velocity of 134 ± 11 km s^{-1} and a resultant dynamical mass of $\geqslant 4 \times 10^{10}\,M_\odot$. Despite its high metallicity and large molecular mass, the $z = 0.101$ galaxy has a low star formation rate, implying a large gas consumption timescale, larger than that typical of late-type galaxies. Most of the molecular gas is hence likely to be in a diffuse extended phase, rather than in dense molecular clouds. By combining the results of emission and absorption studies, we find that the strongest molecular absorption component toward the quasar cannot arise from the molecular disk, but is likely to arise from diffuse gas in the galaxy's circumgalactic medium. Our results emphasize the potential of combining molecular and stellar emission line studies with optical absorption line studies to achieve a more complete picture of the gas within and surrounding high-redshift galaxies.

Introduction

- 銀河形成と銀河進化 — **ガス**が重要な役割を果たす
  - 小さな DM overdensity が成長して銀河のもととなる (ΛCDM model)

    ⇔ **バリオン**が**銀河を形成／成長を促進／星形成の燃料**に
- **吸収線観測** — high-z 銀河での**ガスの性質・環境**を探るツール
  - CGM **(circumgalactic medium)**
    - quasar-galaxy pairs の吸収線観測 — 銀河ごとのCGMを調査
    - 大質量銀河の周囲 100 kpc 以上にわたって広がる
    - 低温／高温の電離ガス
    - 高金属量
  - 観測対象は限定される
- **ALMA観測 — absorption-selected 銀河**の分子輝線観測
  - 可視光輝線では観測できないガス成分

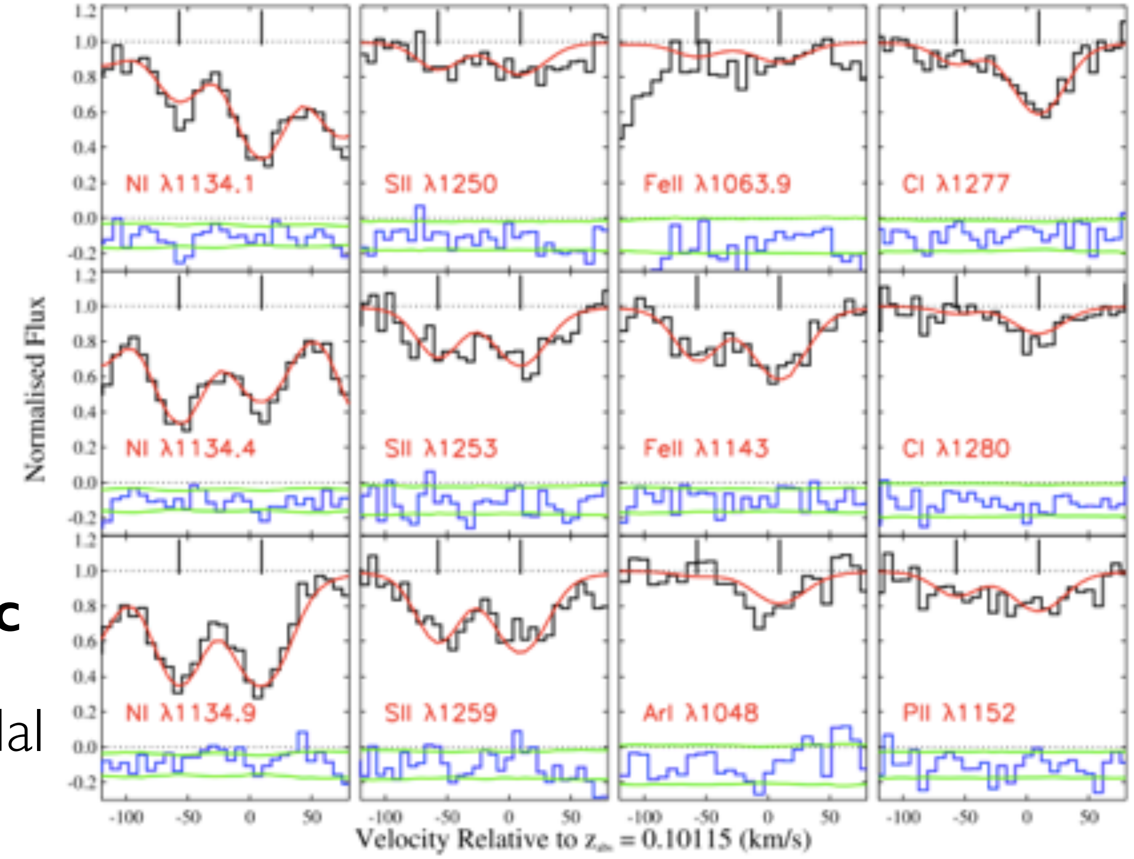


(http://pages.astronomy.ua.edu/keel/galaxies/arp.html)

Target

z = 0.101 absorber **toward PKS 0439-433**

- **渦巻銀河**
- Quasar PKS 0439-433 との **projected distance = 7.3 kpc**
- **2つの速度成分** (z_1 = 0.10094, z_2 = 0.10119) — SII, CaII, NaI
    - **高金属量**：[S/H] = 0.28 ± 0.08
    - $N(H_2) = (4.1 \pm 0.5) \times 10^{16}$ cm^{-2} (← UV H_2 吸収線)
- Lyα 吸収線 → logN(HI) = 19.63 ± 0.08
- **HI 21 cm**
    - **吸収線** — tentative detection (3.3σ) → **T_{rot} ~ 90 K**
    - **輝線** — non-detection → **$M_{atomic} < 3 \times 10^9$ $M_\odot$** (3σ upper limit)
- 可視光輝線分光観測 — Hα, Hβ, [OII]
    - 銀河円盤の **inclination = 58° ± 5°** (← Hβ)
    - **SFR ~ 0.53 $M_\odot$/yr** (← Hα luminosity + Salpeter IMF)
    - **log[$M_*/M_\odot$] = 10.01 ± 0.02, SFR ~ 1.5 $M_\odot$/yr** (← optical photometric SED)



(Dutta et al. 2015)

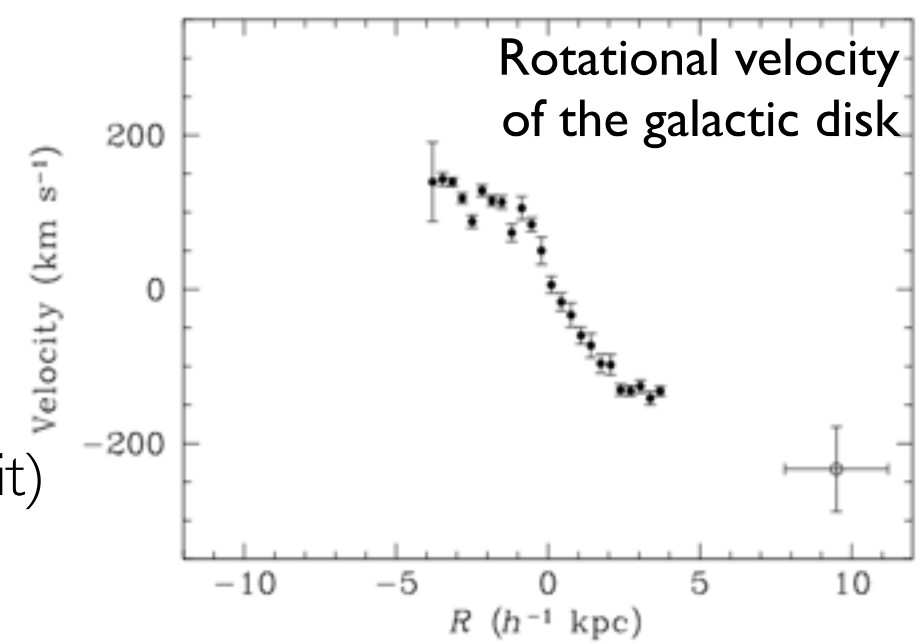


FIG. 5.—Rotational velocity measurements of the DLA galaxy at z = 0.1010 toward PKS 0439−433 vs. galactocentric radius R along the disk (*filled circles*). The velocity measurements presented in the plot have been corrected for the inclination of the stellar disk. The open circle shows the relative motion of the absorber with respect to the systemic velocity of the absorbing galaxy, which has also been deprojected to the stellar disk.

(Chen et al. 2005)

ALMA Observation

- CO(1-0) emission from z = 0.101 galaxy
- ALMA Band 3 **observation** (on 12/25/2014)
  - 1 spw for CO(1-0) @104.7 GHz
  - 3 spw for continuum
  - Compact configuration — **angular resolution ~ 2" (~ 3.7 kpc @z = 0.101)**
- **CASA analysis**
  - **RMS = 61 μJy** for continuum image
  - **20 km/s binning** with briggs weighting (robust factor = 0.5)
  - **self calibration** using the quasar (for phase only / phase & amplitude calibration)
- Final image
  - **synthesized beam size = 4".28 x 1".96** (PA = 73°.85)
  - **RMS = 0.76 mJy/beam** for **20 km/s binning**

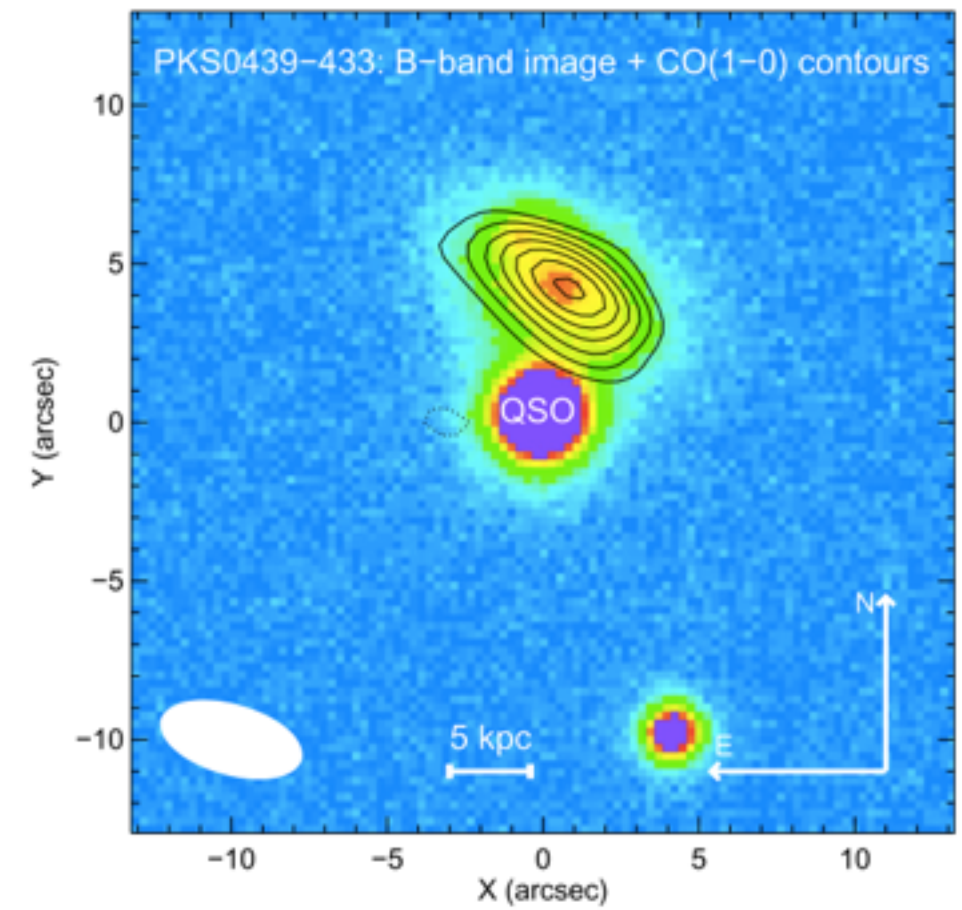
Results

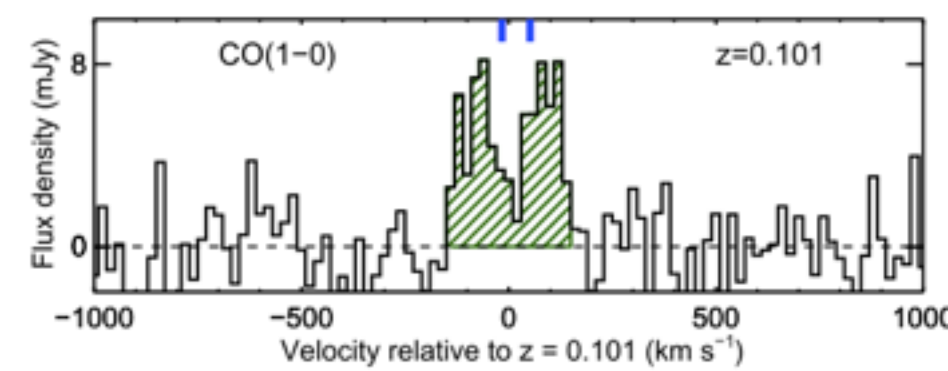
- 12σ detection of CO(1-0) emission line @z = 0.10100
  - absorber / optical emission の位置とよく一致
  - CO(1-0) flux density = 1.46 ± 0.07 Jy km/s
    - L'_{CO} = (7.0 ± 0.3) x 10^8 K km/s pc^2
    - L_{CO} = (3.4 ± 0.2) x 10^4 $L_\odot$
  - 速度構造を空間分解 — 初の速度場マップを取得
    - rotating disk (銀河内のISM) 由来のCO放射

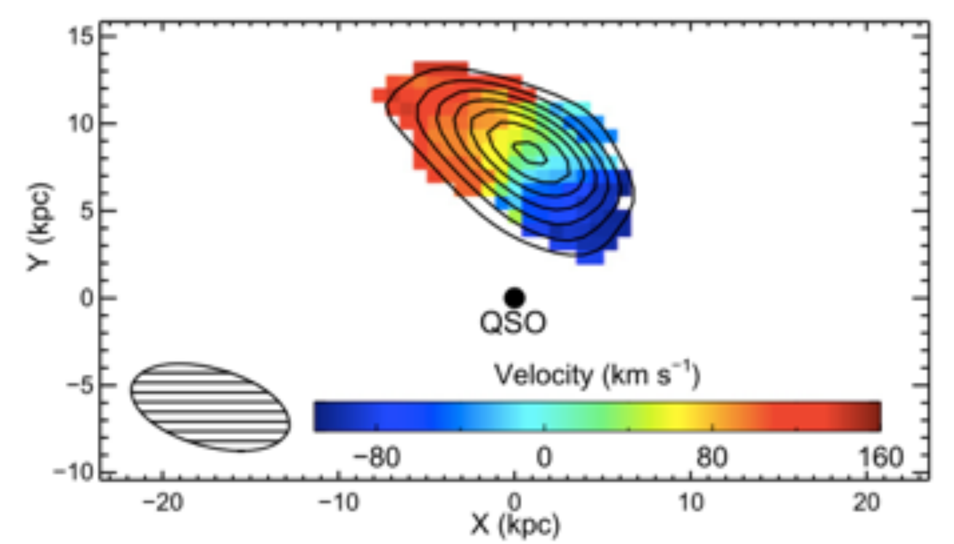
      (← "spider" pattern + "double-horned" spectrum)
- absorption — non-detection
  - integrated line opacity < 0.027 km/s (3σ upper limit)
  - $N(H_2)$ < 6 x 10^{19} cm^{-2}
    - assuming T_{ex} = 10 K

      & X_{CO} = 3 x 10^{-6} (for diffuse/translucent clouds)
    - $N(H_2)$ = 4.1 x 10^{16} cm^{-2} (← UV H_2 吸収線観測)

      と consistent







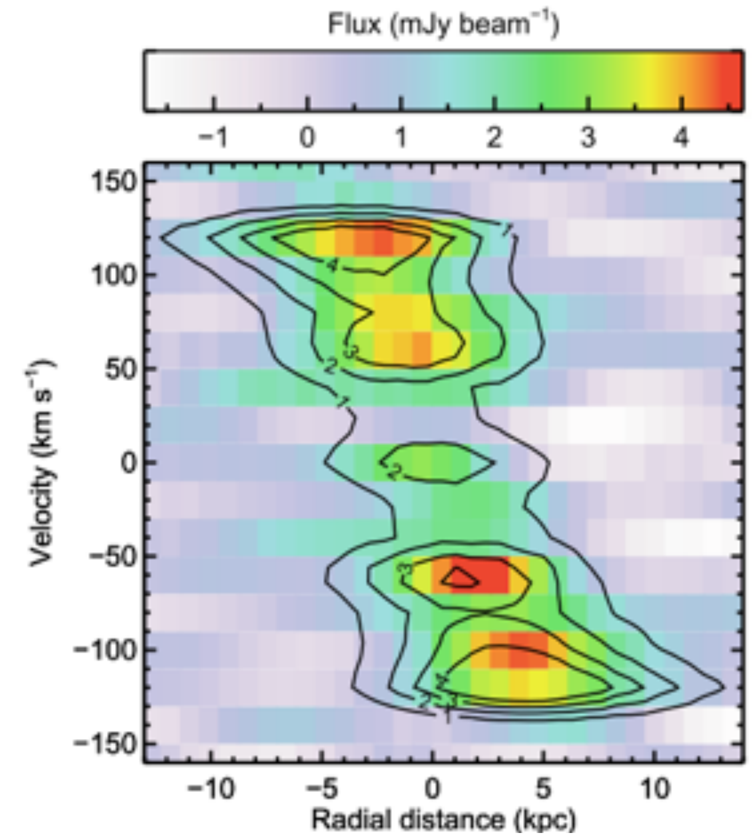
Modeling the CO(1-0) emission

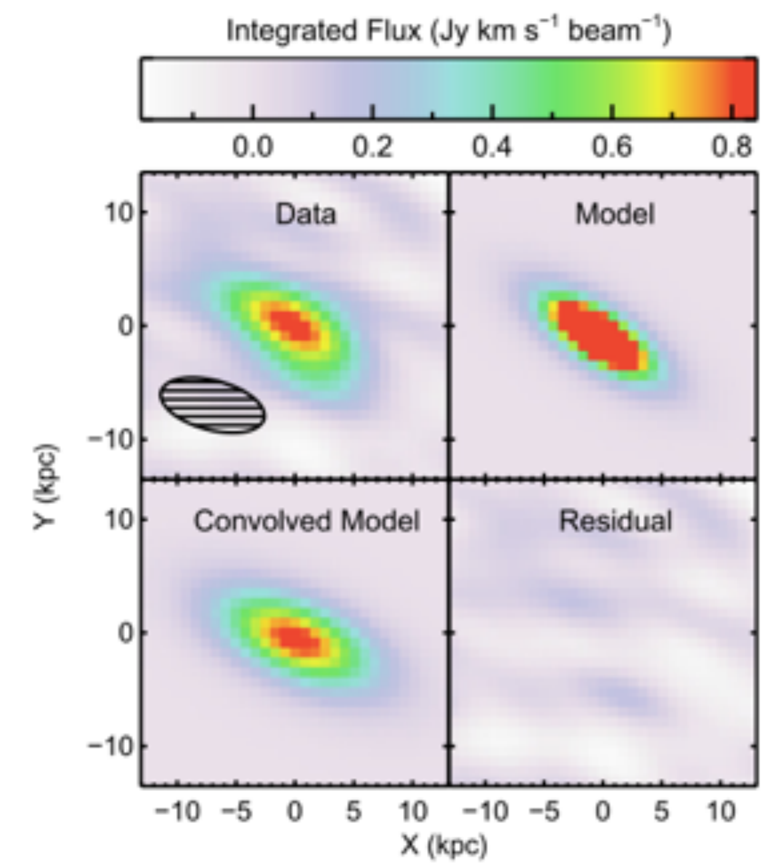
CO(1-0)放射 (@z = 0.101 galaxy) のモデリング

- *$I = I_0 \exp(-R/R_D)$* — **infinitely thin, exponensial disk**
  - I_0 : 中心での強度, R_D : turnover radius
  - **flat rotation** — 分子ガスの回転速度は半径に依らず一定 (v_{max})
  - disk's orientation — inclination と PA から決定
- **ALMA beam との畳み込み**
  - Monte Carlo Markov Chain method + Metropolis-Hastings algorithm
  - モデルの各パラメータの確率分布関数を決定
  - chainの最初の40%は捨てる ("burn-in" phase)
  - 5つの異なる初期条件 + 5つの異なる iteration
- **観測データをよく再現**
  - sub-structure (e.g. warped disk) の兆候はない
    (正確には高分解能観測が必要)
  - **inclination angle = 67^{+6}_{-5}, PA = 56° ± 5°, Vrot = 134^{+8}_{-11} km/s**

    — Hβ 観測結果と consistent

CO(1-0) PV Diagram

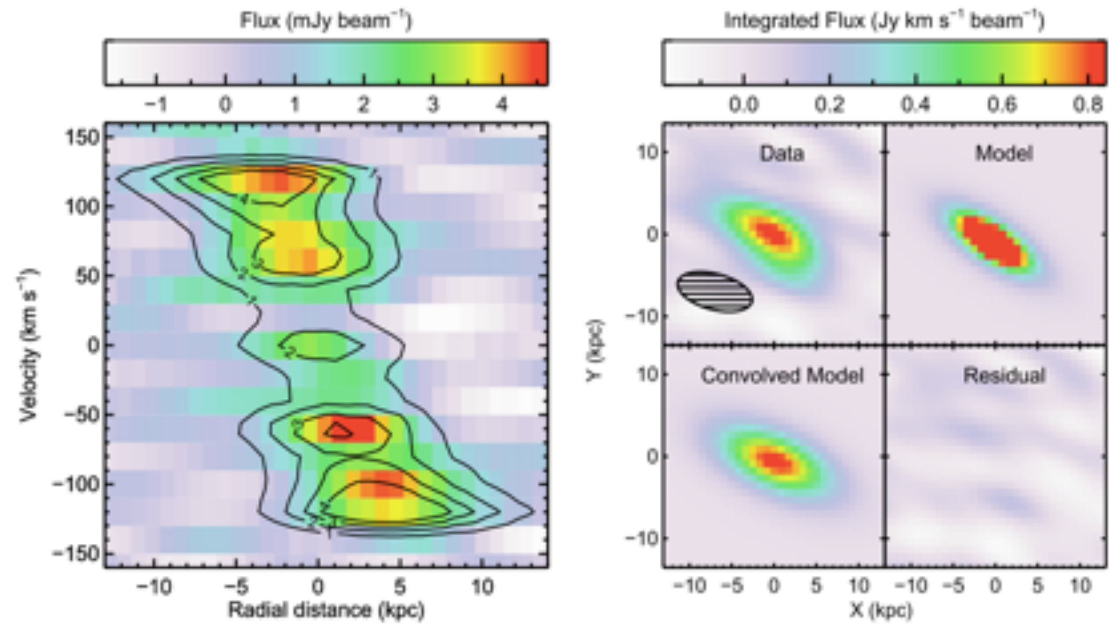




Kinematic Structure of the molecular gas

視線速度場・回転曲線の解析

- **CO(1-0) emission は rotating disk 由来**
  - — absorption も同じ disk から生じているのか？
- **absorption component 1** — disk の速度と一致
- **absorption component 2** (dominant molecular gas)
  - — disk の速度と不一致
  - → CGM由来
    - 輝線で見える **disk 由来ではない**
      1. CGM?
      2. metal-rich outflow?
      3. nearby faint dwarf galaxy?
    - **高金属量** — 1., 2. が有力
    - H_2・NaI 吸収線の光電離モデリング結果 (Dutta et al. 2015) は 1. を示唆



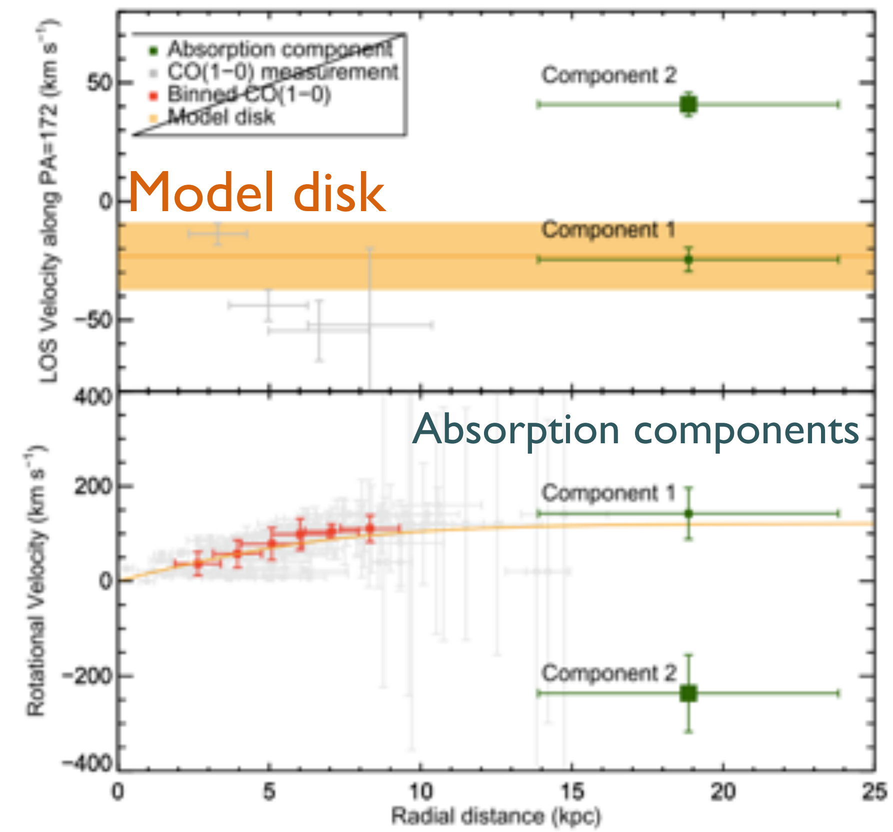


Figure 4. Top: line of sight (LOS) velocity component along PA = 172°. The gray points are measurements of the LOS velocity of the CO emission, whereas the orange shaded region is the LOS velocity along this PA for the best-fit model. The green data points are the two absorption components. Bottom: rotation curve of the molecular disk. The CO(1−0) emission profile (with raw and binned measurements in gray and red, respectively) is well described by a model with constant rotational velocity (orange). Both plots show that the main absorption complex (component 2) is inconsistent with coming from an extended molecular disk.

The Gas and Dynamical Mass of the Galaxy

	z = 0.101 absorber (This work)	Typical late-type galaxies	Assumptions	Notes
Molecular gas mass M_{mol}	$(4.2 \pm 0.2) \times 10^9\ M_\odot$		$\alpha_{CO} = 4.3\ M_\odot$ (K km/s pc^2)$^{-1}$ (Bolatto et al. 2013)	Larger than M_{atomic} ($< 3 \times 10^9\ M_\odot$)
M_{mol}/M_{atomic}	> 1.3	< 1	Similar stellar mass	**Top end** of the distribution of other late-type galaxies
M_{mol}/M_*	~ 0.4	~ 0.1		**Higher ratio**, though within the dispersion
Gas consumption timescale	2.8 Gyr	1.5 Gyr	Similar stellar mass, SFR = 1.5 $M_\odot$/yr (derived from optical photometric SED)	**Larger timescale, Low SFR** — The molecular gas is **dominated by diffuse gas**, rather than by dense GMCs
Dynamical mass $M_{dyn} \sim V^2R/G$	$> 4 \times 10^{10}\ M_\odot$		V = 134 km/s (from the rotation curve), R = 10 kpc	Lower limit for molecular disk (atmoic gas is more extended)

Surface Mass Density of the Molecular Gas

Absorbing molecular components

- **Surface mass density** — 単位面積当りのCO強度(r)から導出
  - assumption = $M_{H2} = \alpha_{CO} L'_{CO}$
  - **exponential disk model と一致せず**
  - **CO(1-0) を放射するガスよりも** diffuse **な成分**をトレース
- **$M_{mol, absorbing} < 10^5 M_{\odot}$**
  - assumptions
    1. covering fraction < 10%
    2. PKS 0439-433 方向の $N(H_2)$ は全ガス分布に由来
    3. 銀河中心から半径 20 kpc 以内のみを考慮
  - 銀河の質量 (~ $10^{9\text{-}10}$ $M_{\odot}$) より十分小さい — ALMAでも遠方では検出不可能
- CGMの存在
  - 大部分の分子ガスは、輻射からシールドされるほど低温・高密度ではない
  - 別の場所で生成され **CGM へと移動** (cf. local high-velocity clouds) or **dust grain で生成**
- 銀河内の**星形成・銀河進化に寄与** (⇔ 全分子ガスのごく一部に過ぎない)
  - 支持する観測事実：母銀河による enrichment / 重力的束縛 / 低温 (星形成の材料となりやすい)

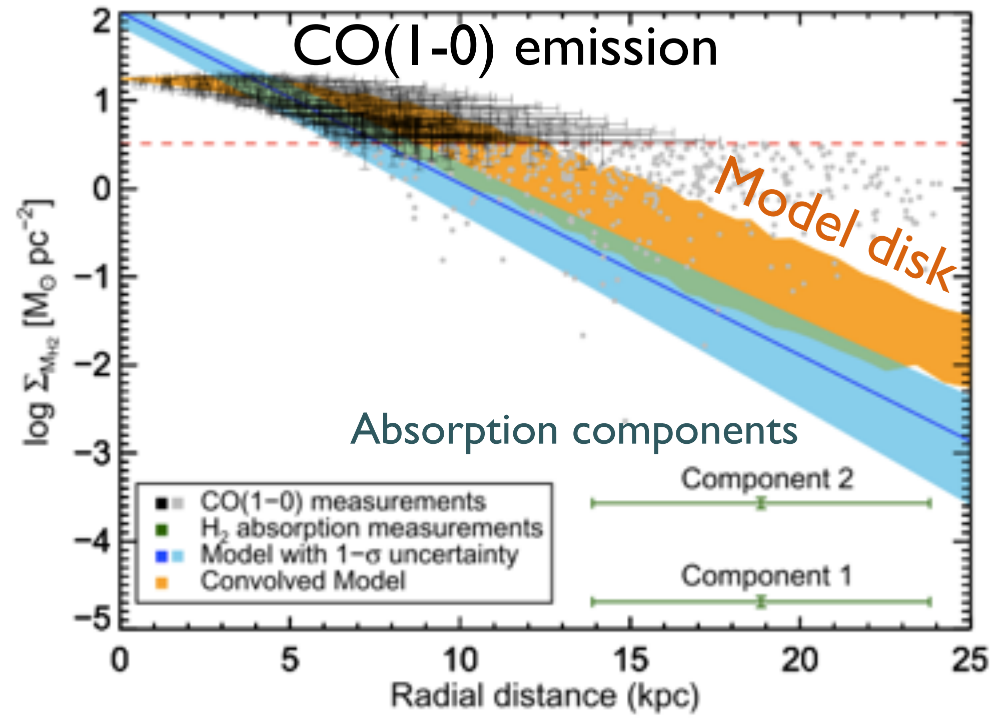


Figure 5. Surface density of molecular hydrogen as a function of radius. The red dashed line indicates the 2σ detection limit of the ALMA data. Integrated CO(1−0) emission features of $\geqslant 2\sigma$ significance are plotted in black with associated error bars, whereas those below this limit are shown in gray. The blue line marks the exponential disk model used for the MCMC analysis. This model is convolved with the ALMA beam (orange region), showing the excellent agreement between the model fit and the data. The surface densities computed from the H_2 absorption lines are plotted at the distance the line of sight crosses the plane of the disk, showing that neither absorption component trace the same molecular phase responsible for the CO(1−0) emission.

Conclusion

We present the first detection of molecular emission from a galaxy selected to be near a projected background quasar using the Atacama Large Millimeter/submillimeter Array (ALMA). The ALMA detection of CO(1−0) emission from the $z = 0.101$ galaxy toward quasar PKS 0439–433 is coincident with its stellar disk and yields a molecular gas mass of $M_{\rm mol} \approx 4.2 \times 10^9\, M_\odot$ (for a Galactic CO-to-H_2 conversion factor), larger than the upper limit on its atomic gas mass. We resolve the CO velocity field, obtaining a rotational velocity of 134 ± 11 km s^{-1} and a resultant dynamical mass of $\geqslant 4 \times 10^{10}\, M_\odot$. Despite its high metallicity and large molecular mass, the $z = 0.101$ galaxy has a low star formation rate, implying a large gas consumption timescale, larger than that typical of late-type galaxies. Most of the molecular gas is hence likely to be in a diffuse extended phase, rather than in dense molecular clouds. By combining the results of emission and absorption studies, we find that the strongest molecular absorption component toward the quasar cannot arise from the molecular disk, but is likely to arise from diffuse gas in the galaxy's circumgalactic medium. Our results emphasize the potential of combining molecular and stellar emission line studies with optical absorption line studies to achieve a more complete picture of the gas within and surrounding high-redshift galaxies.

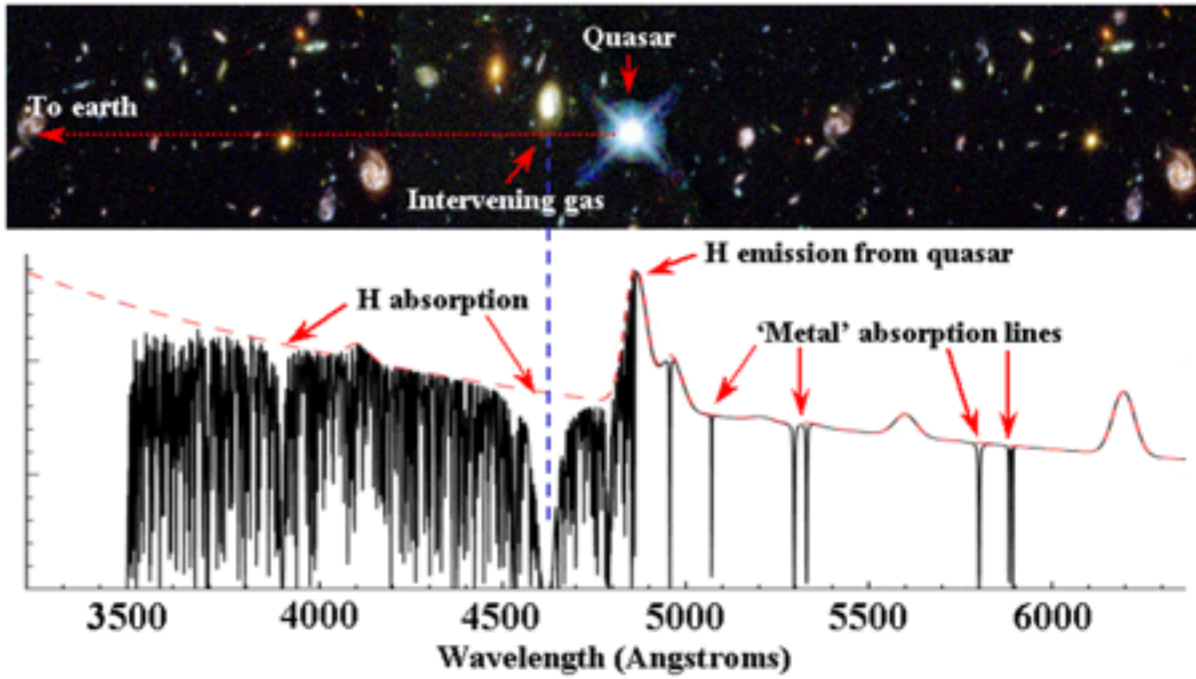
- **クエーサー吸収線で選ばれた銀河**からの**CO分子輝線**放射を ALMA で**初検出**
  - $M_{\rm mol} = (4.2 \pm 0.2) \times 10^9\, M_\odot > M_{\rm atomic}$
  - **gas depletion time が長い** — 大部分の分子ガスは **diffuse phase** (dense GMCs ではない)
- **吸収線・輝線観測の合わせ技 (synergy)**
  - **吸収線でトレースされる分子ガス** — **diffuse CGM 由来** **(銀河円盤由来ではない)**
    - 輝線観測・可視イメージングでは検出不可能
    - 母銀河による **enrichment** を受ける
    - 将来の**星形成の燃料**となる
  - **銀河内外のガスのサイクル**を探る強力な手法

Appendix

Talk "Lighting Up Shadows" by M. Neeleman @ALMA Conference

- Absorption-selected galaxies
  - あらゆる z で **normal galaxy** を効率的に見つけられる
  - Emission-selected では selection bias を受けてしまう
- 2つの DLA (Damped Lyα) で [CII]輝線 @z~4 **を初検出**
  - **DLA 母銀河としては再遠方**
  - **cool disk** からの放射
  - moderate SFR (~ 20 - 80 $M_{\odot}$/yr,) large dust obscuration
  - metal enrichment を受けた、
    広がった原子ガスエンベロープ

Damped Lyα



(http://www.astro.uvic.ca/~trystynb/research.html)