Universiteit Leiden Observatory

Sterrewacht Leiden

Neutral OH+ Outflows in Dusty High Redshift Galaxies

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What are Galaxy Outflows?

Galaxies form from within dark matter halos by accreting gas from the intergalactic medium into their potentials. Over time, this gas cools and collapses to form stars and blackholes which inject energy back into interstellar medium, pushing gas out of the galaxy in the form of outflows.

Are they Important?

- Galaxy outflows are ubiquitously observed in the local universe
- Outflow mass rates can be equivalent or greater than the star formation rate in heavily star forming galaxies
- Our simulations *require* them to
  - Form disks (like the Milky Way)
  - Regulate Star Formation (by heating and removing the gas needed to build them)
  - Shape fundamental galaxy relations such as the stellar mass and mass-metallicity relations (by transporting low angular momentum and metal enriched gas out of the disk)

Simultaneous observations of OH+ and CO(9-8) in a gravitationally lensed dusty galaxy, 1.5-2 Gyr after the big bang

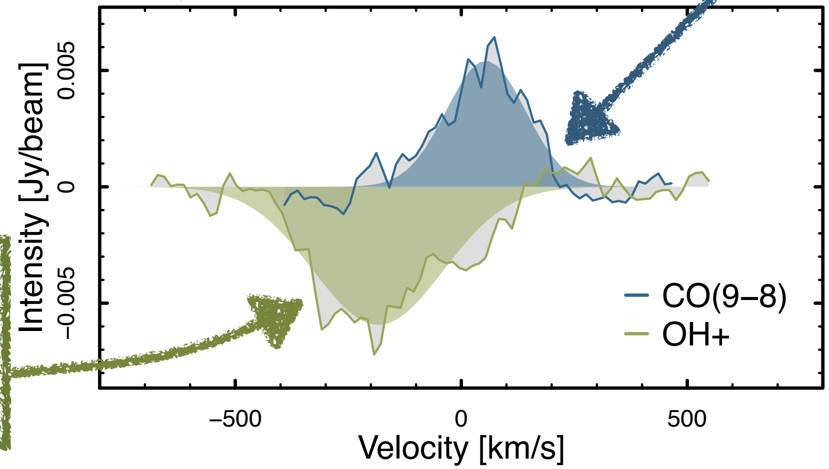
A single ALMA telescope sideband

Star formation at a peak in the universe and therefore where outflows are most impactful. (z=2-4)

CO(9-8) traces warm dense gas in the disk

Magnified signal = Higher spatial resolution + Higher signal to noise

OH+ traces the blue shifted (moving towards us) neutral gas outflow

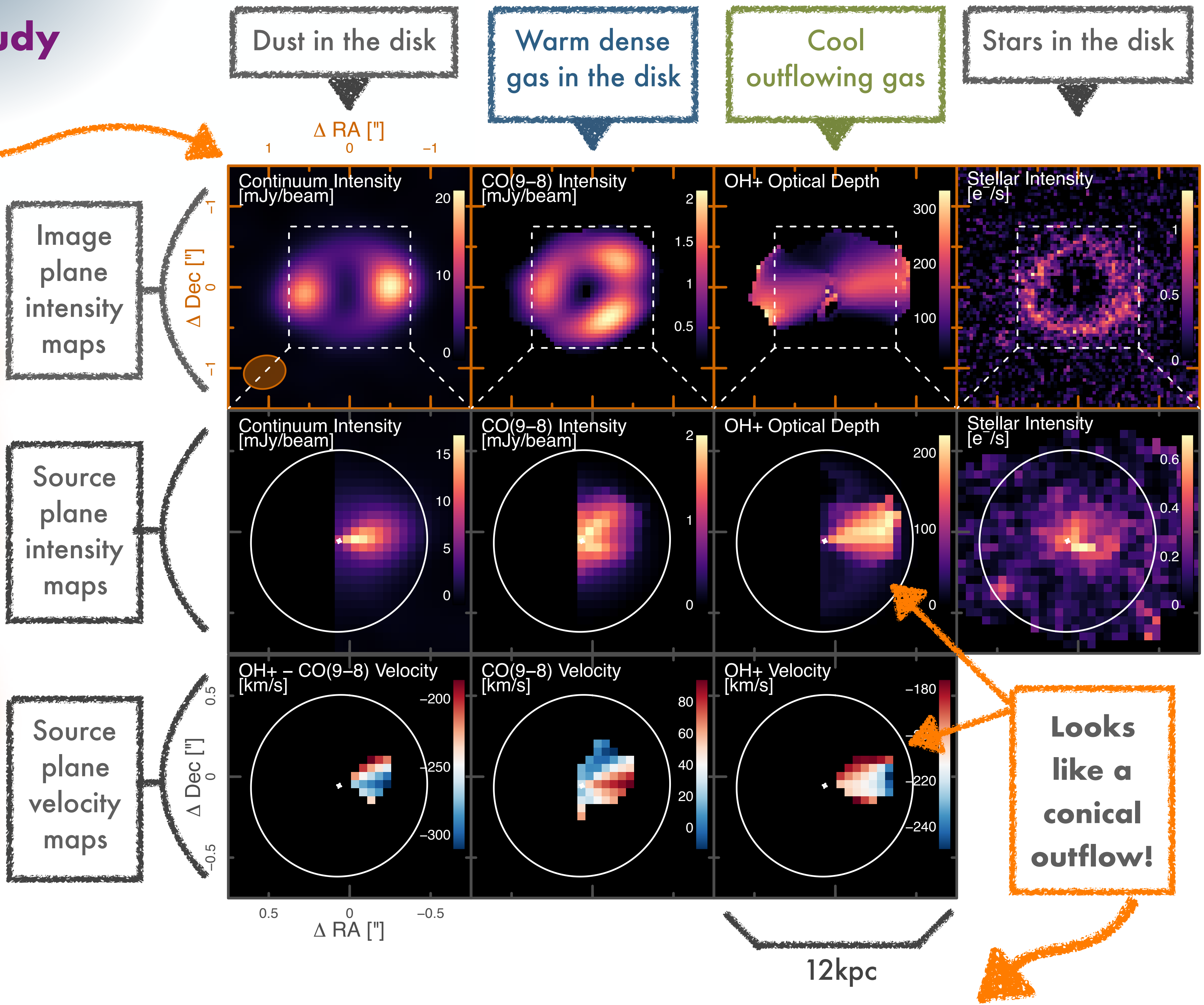


G09v1.4

A case Study

Every pixel in our image has a spectra

We use the lens fitting code *visilens* (Hezaveh et al. 2013, Spilker et al. 2016a) to model the gravitational distortion of G09v1.4 by the foreground galaxy (not shown). Intrinsic intensity and velocity maps are then reconstructed in the source plane using LENSTOOL (Kneib et al. 2011).



What impact is the outflow having on its galaxy?

1st

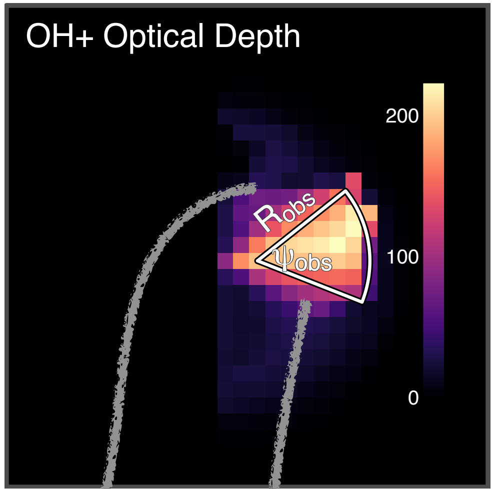
We convert our observed OH+ mass to a total neutral gas mass using the abundance from Bialy et al. 2019, finding $M = 6.7\times10^{9}\ M_{\odot}$. More than 25% of the molecular gas mass in the galaxy.

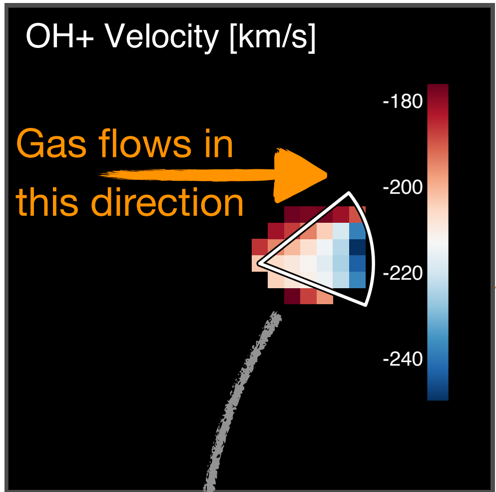
2nd

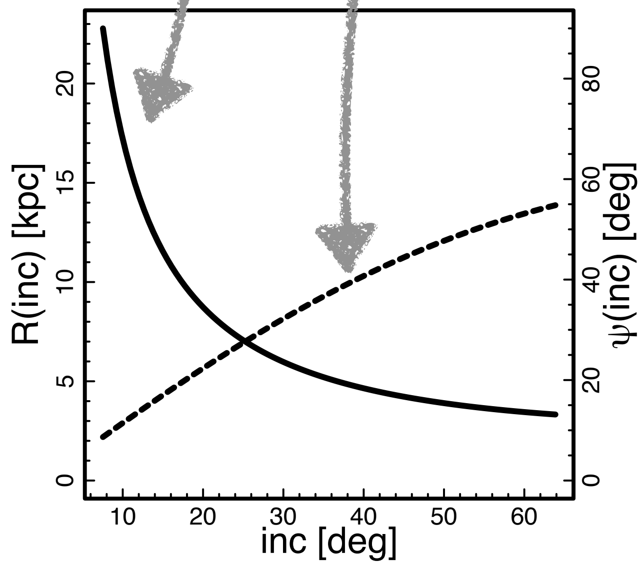
The mass outflow rate (MOFR) tells us how rapidly this mass is ejected from the galaxy

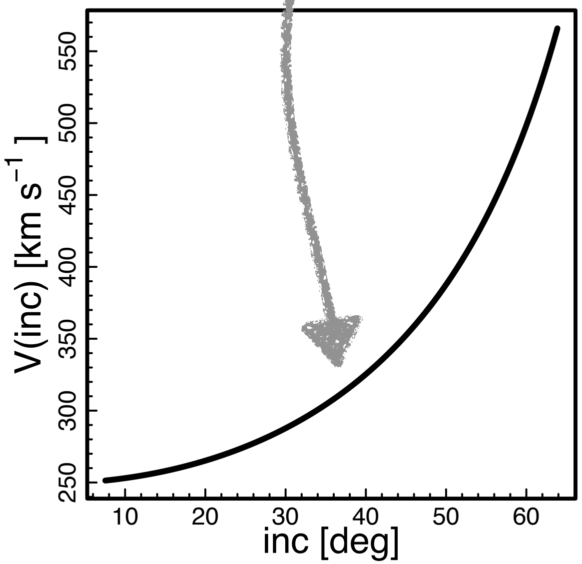
$$\dot{M} = 3\frac{MV}{R}$$

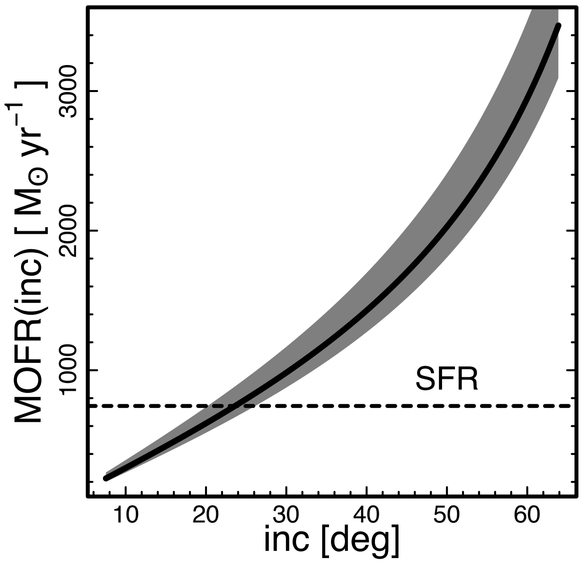
This requires measurements of the velocity V and radius R of the outflow which need to be corrected for the outflow's inclination to our line of sight.
We can't directly measure the inclination so we derive $\dot{M}$ over a range of possible inclinations, finding $\dot{M} = 230 - 3500\ M_{\odot}/yr$
At most inclinations this far exceeds the star formation rate of $740\ M_{\odot}/yr$.



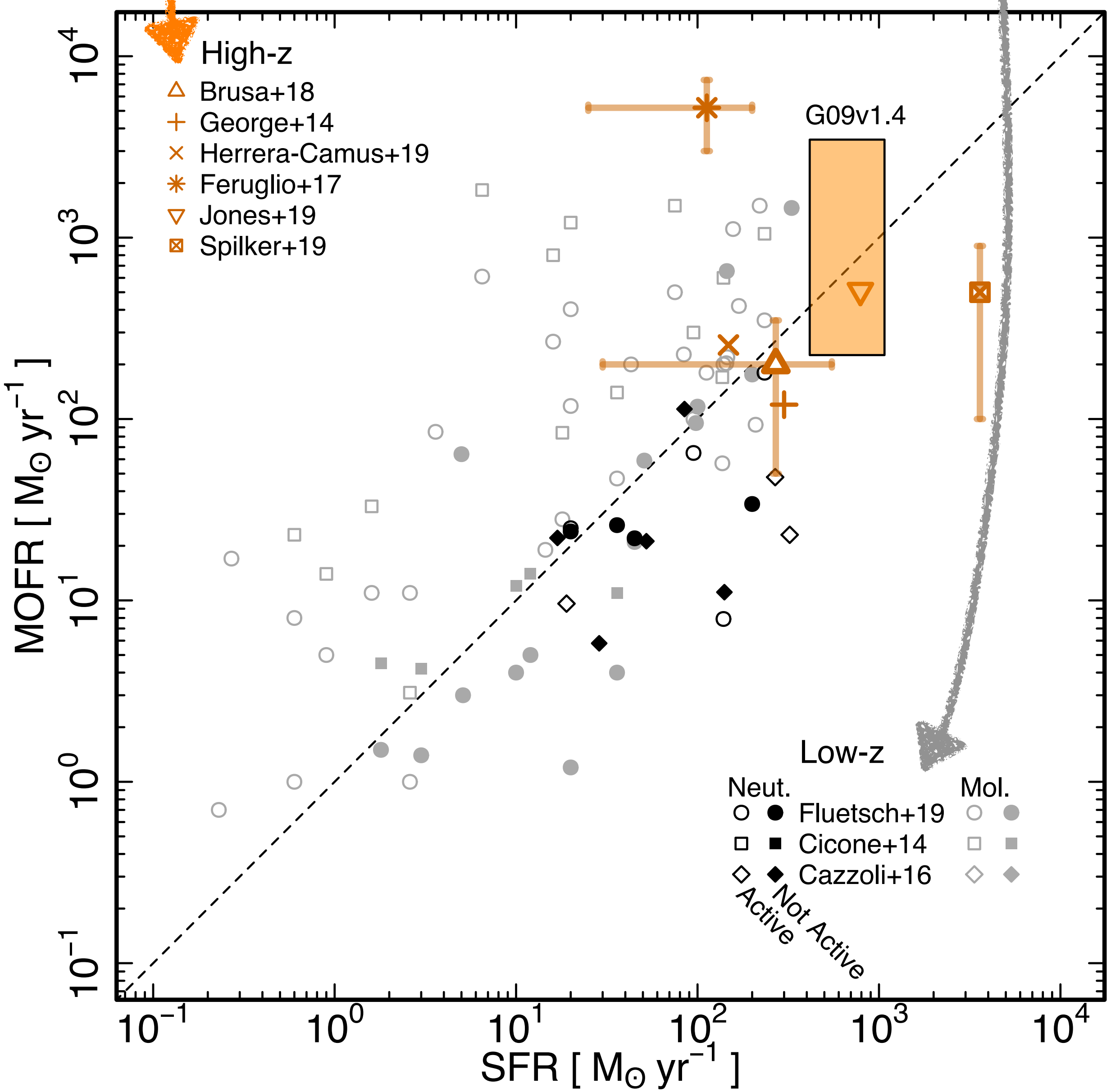








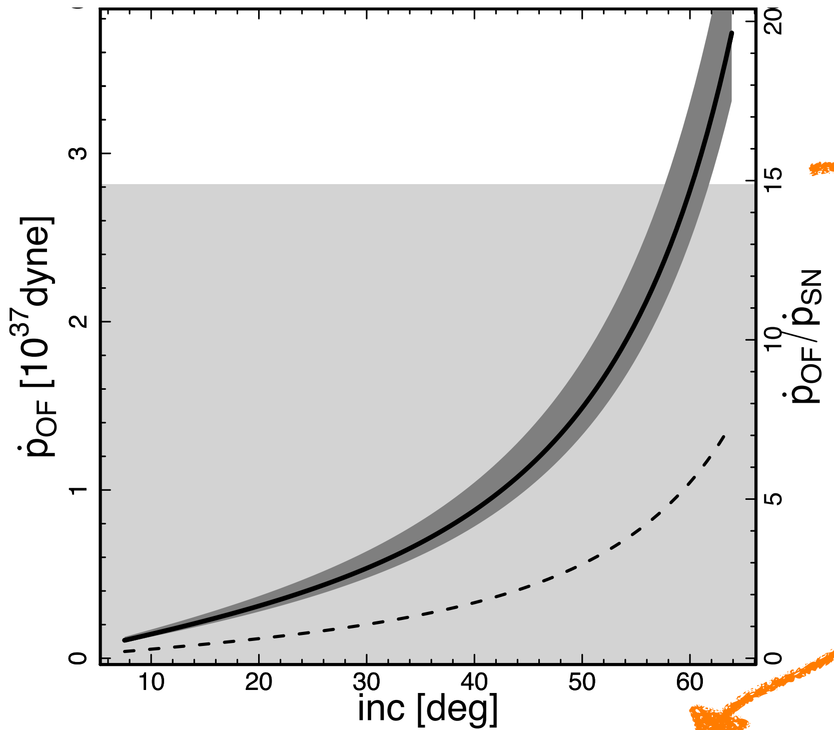
This is one of the biggest cool gas outflows observed at both low (local) and high (early universe) red shift.



If we compare the momentum flux in the outflow..

$$\dot{p}_{OF} = \dot{M}V$$

..with that supplied by super novae $\dot{p}_{SN}$



We find that the expected rate of ~15 super novae per year (derived from the star formation rate) can supply enough momentum to drive the observed outflow at most possible inclinations!