# The evolution of the molecular gas fraction of star-forming galaxies

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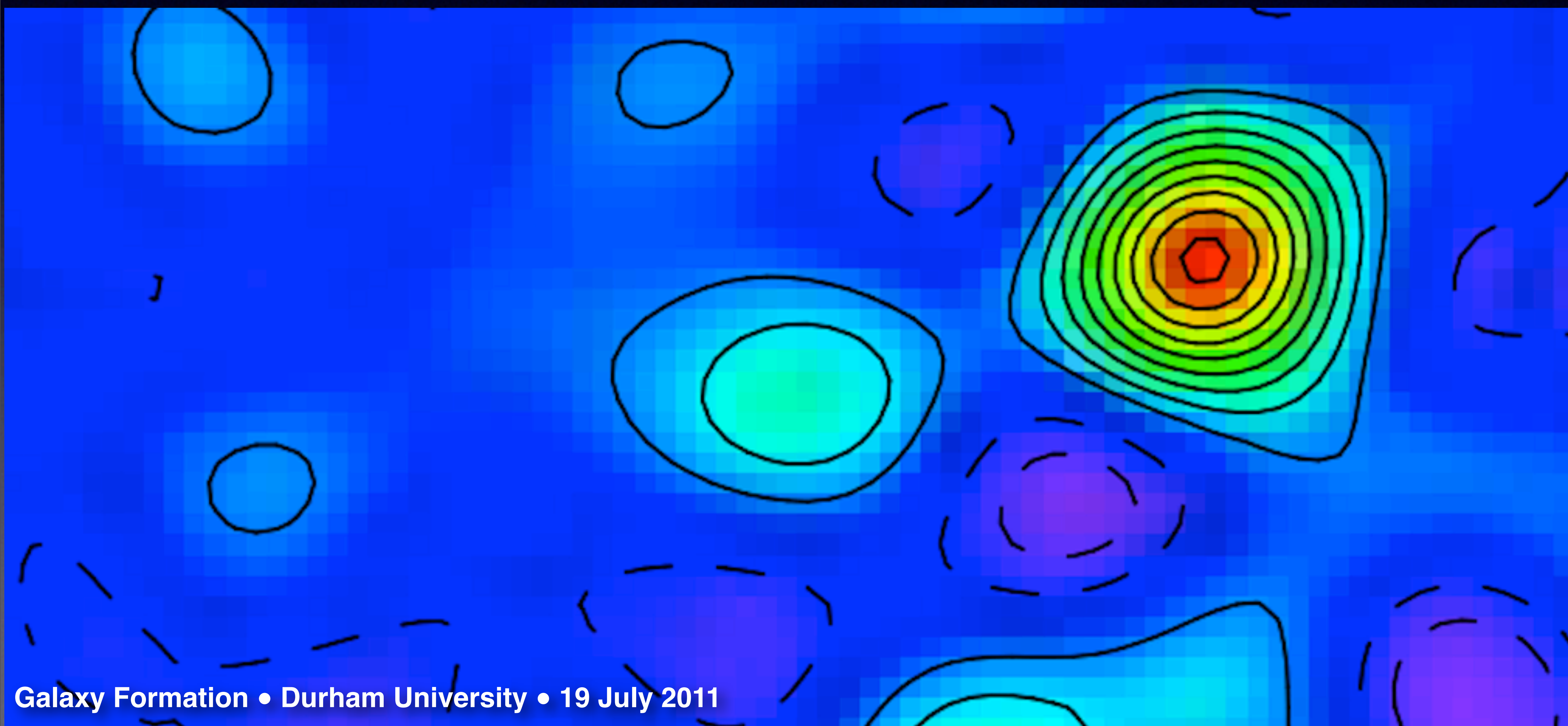
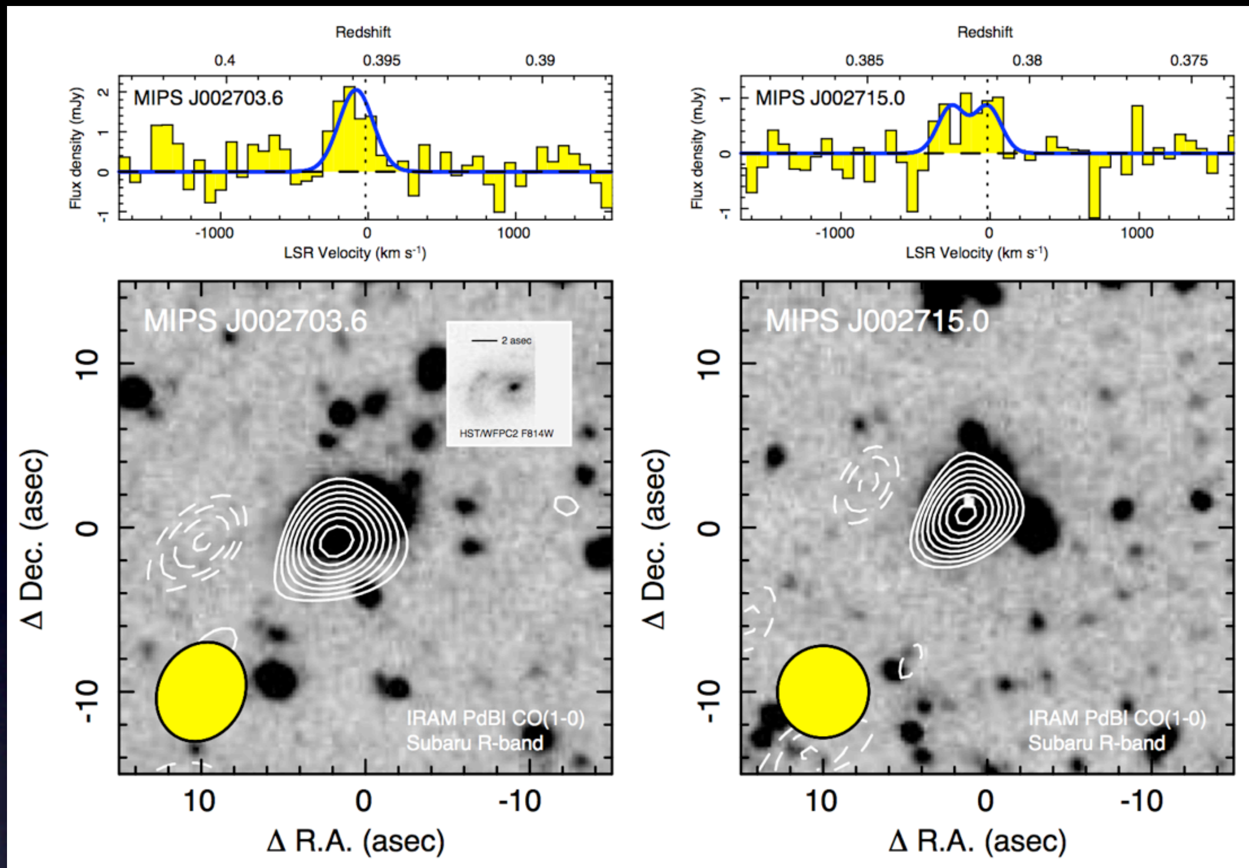


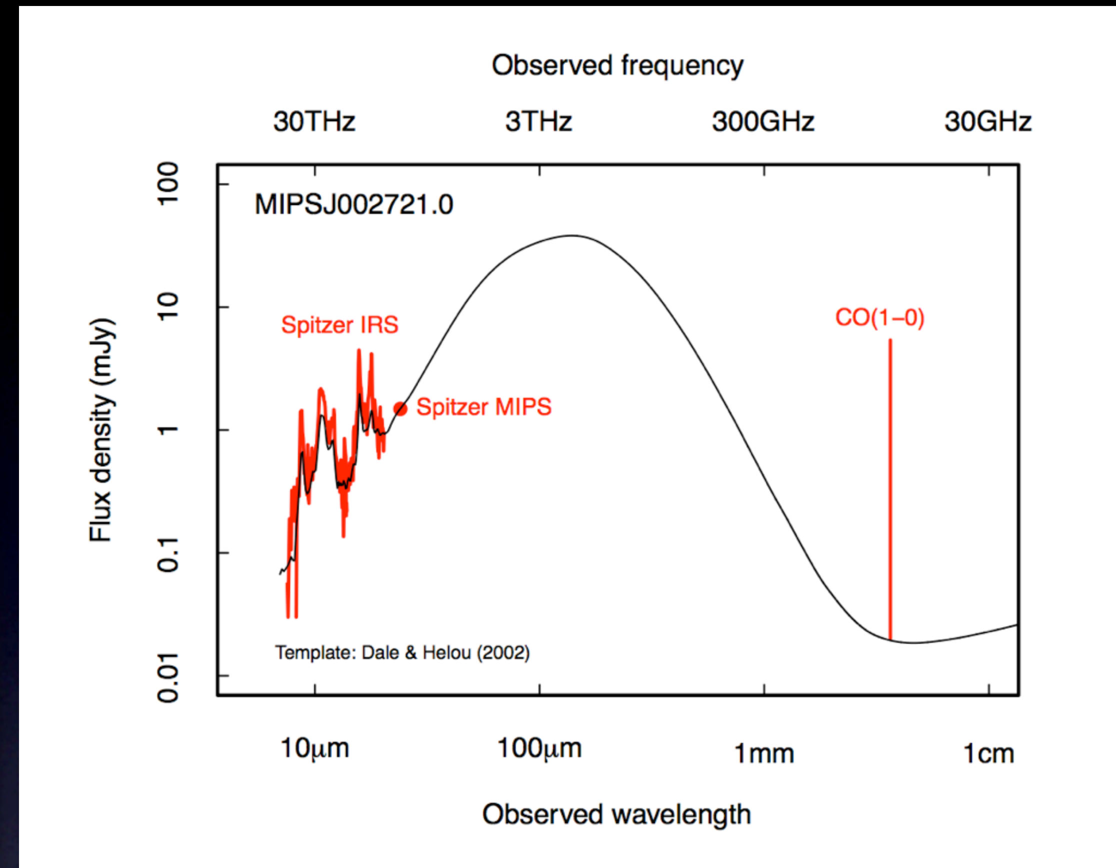
Galaxy Formation • Durham University • 19 July 2011

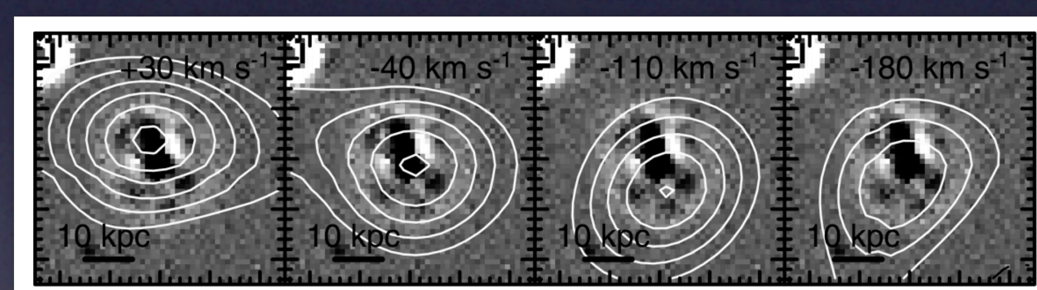
## Cosmic history of molecular gas fraction reflects physics of galaxy formation

- Missing link between observed cosmic evolution of SFR and stellar mass
- Encode wide variety of physics: cooling, feedback, environmental effects, mode of stellar mass assembly: mix makes interpretation challenging
- Progress made in last decade thanks to improved sensitivity in cm/mm interferometers: CO in gas-rich discs at z=1.5-2 (Daddi et al. 2010, Tacconi et al. 2010), very high-*z* [CII]/CO/other detections (De Breuck et al. 2011, Walter et al. 2009, Coppin et al. 2009), now access to CO(1-0) at z>1.5 (Ivison et al. 2011)
- We're always limited to indirect $H_2$ tracers (CO, [CI], etc.)... this introduces range of observational challenges, and we must rely on resolved studies of local systems for interpretation
- Development of ALMA, EVLA, SKA (and pathfinders) will see an explosion of high-z gas studies the next decade(s), pushing to very high-z (Heywood et al. 2011)
- This talk: some initial hints of what will be possible, and prospects for future surveys

# CO(1-0) detections of *z*=0.4 LIRGs




**24um + PAH 7.7um selected LIRGs on the outskirts of Cl0024+16 (z=0.4). SFRs~30-60 $M_{Sun}$/yr**

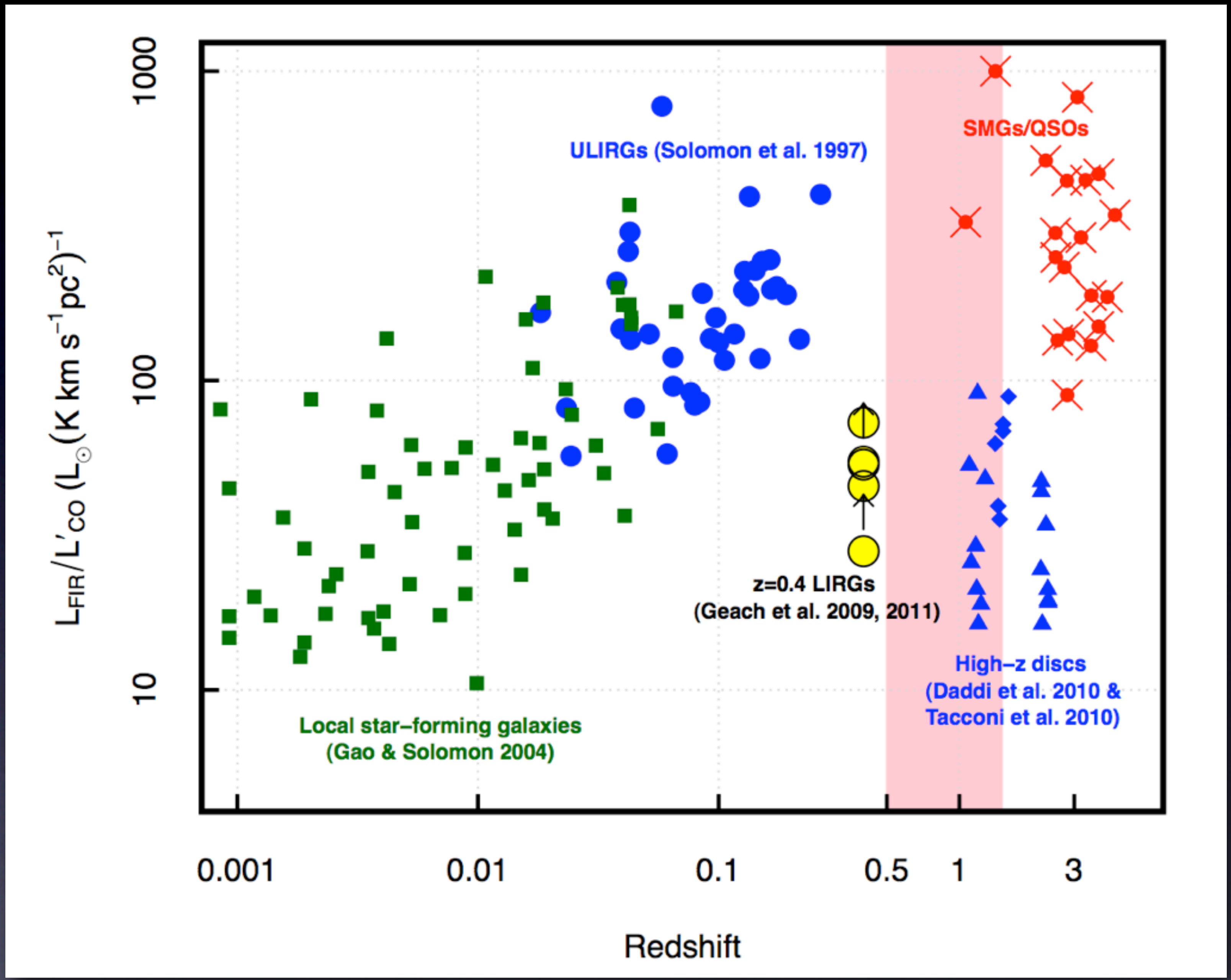
**IRAM PdBI detections at 3mm (8-10hr tracks) yield $L'_{CO(1-0)}$~$10^{10}$ K km/s $pc^2$**

**Linewidths 150-350 km/s (but broad due to disc-like profile)**

**CO(1-0) tracing low-density (700 $cm^3$), low-excitation (30 K) gas over large (10 kpc) discs. No excitation correction required, but still a large uncertainty on $M(H_2)/L_{CO(1-0)}$**

# IR-CO-*z* parameter space

## 0.1 < z < 1.5 poorly explored in terms of sub-ULIRG properties



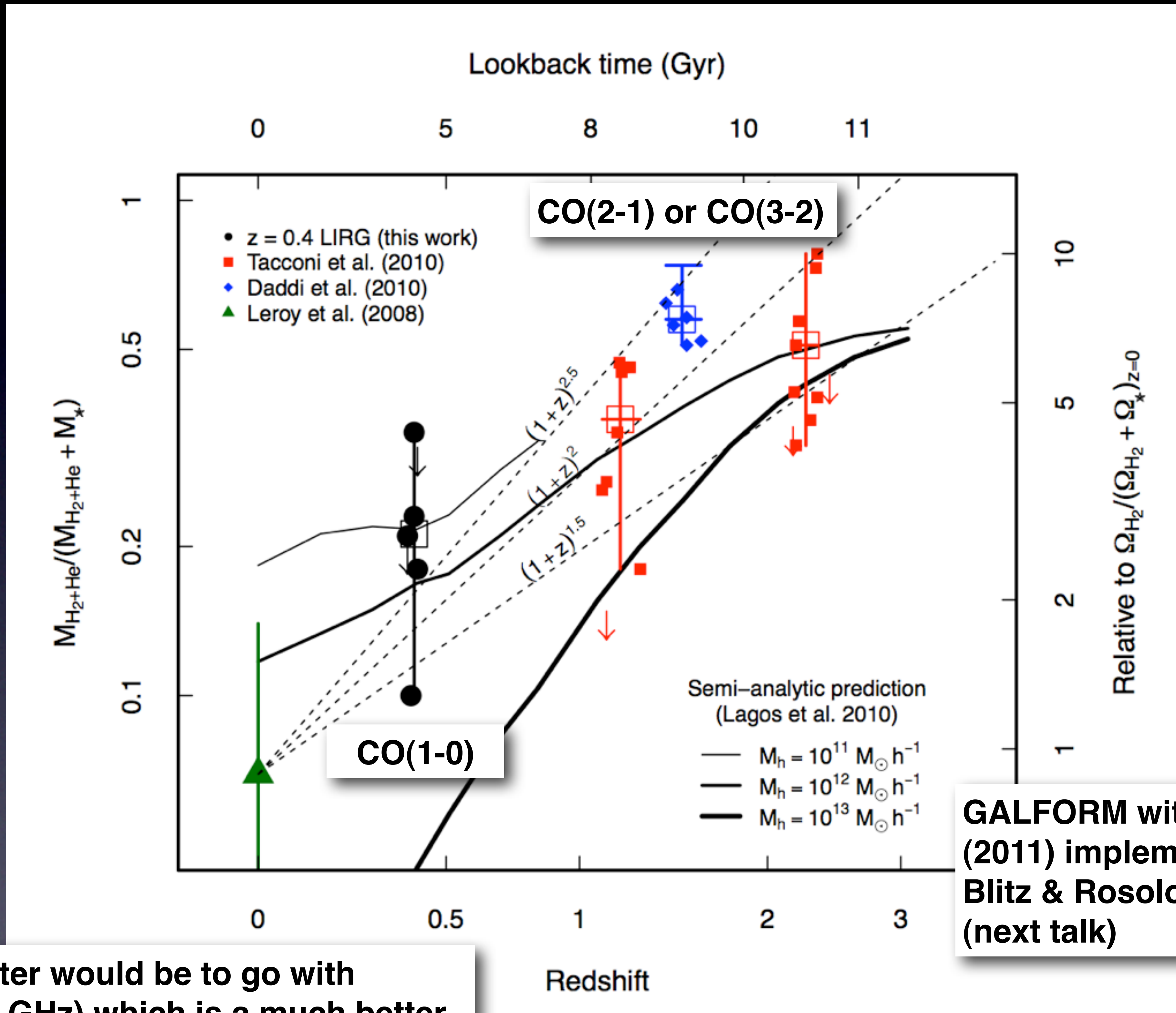

**Bursts & mergers**

**Regular star formation**

**Well-sampled CO SLEDs critical to properly interpret gas mass from single $J_{up}$>1 lines. Need to know what fraction of gas is 'hiding' in different phases: implications for any analysis of evolution**

**High-z CO recently limited to $J_{up}$>1, but now CO (1-0) accessible at z>1.3 with EVLA revealing large (maybe quiescent) reservoirs in SMGs (Ivison et al. 2011)**

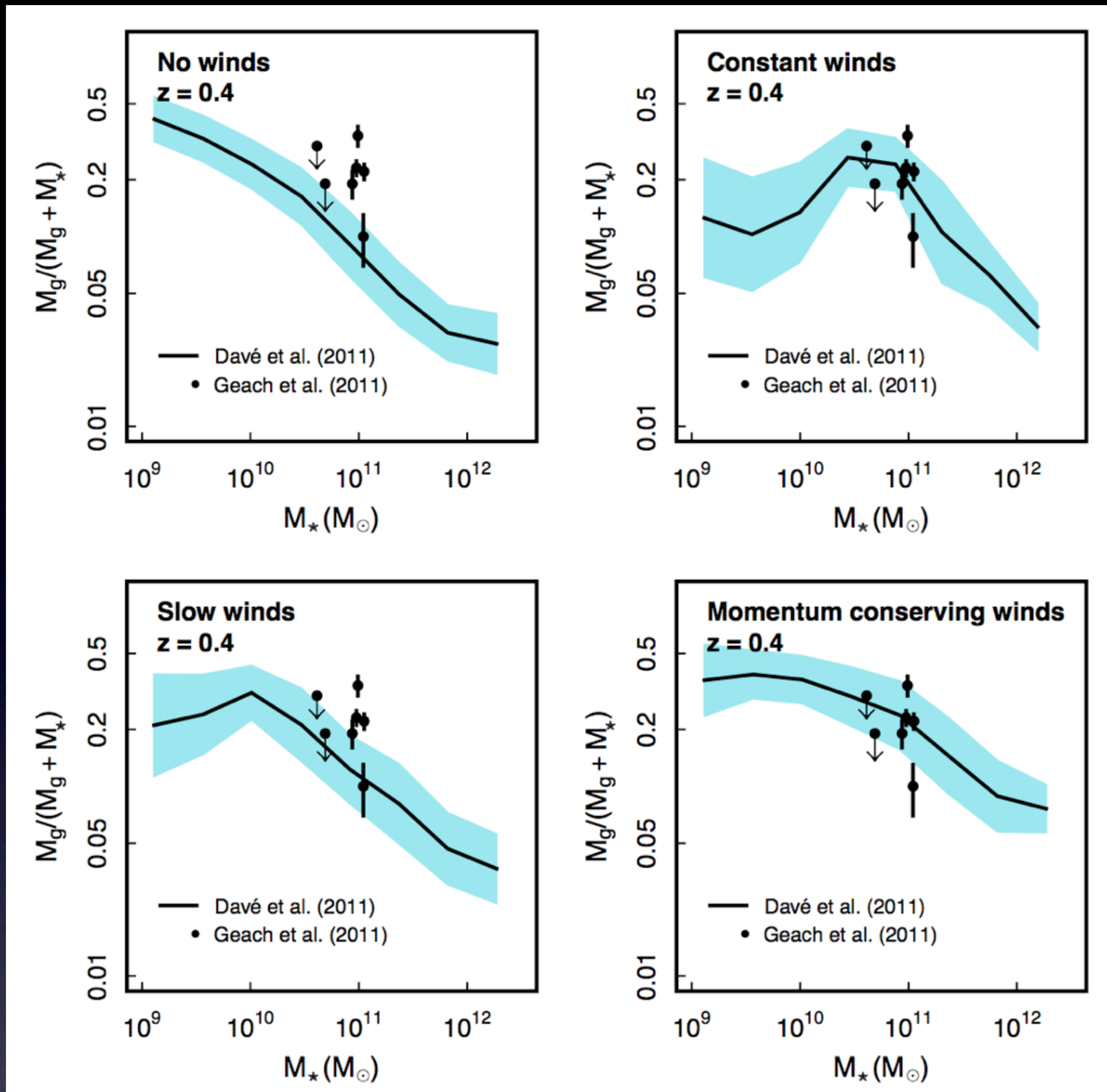
# The evolving molecular gas fraction

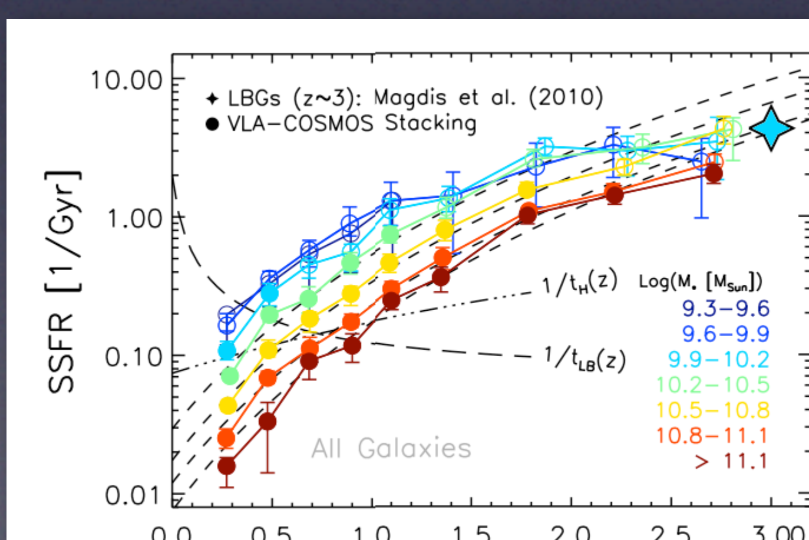



**GALFORM with Lagos et al. (2011) implementation of Blitz & Rosolowsky SF law (next talk)**

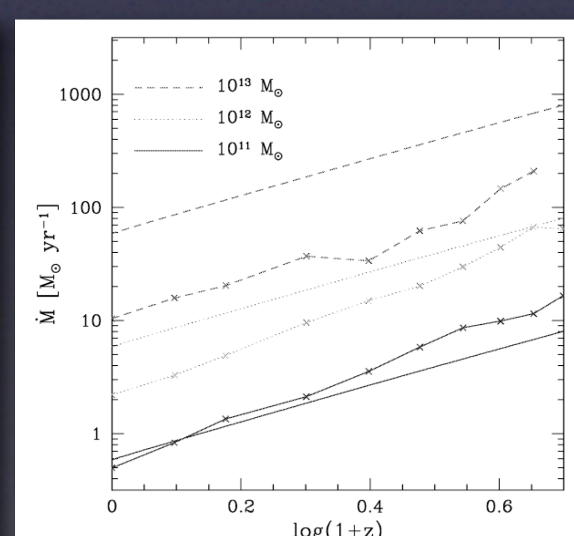
**Aside: much better would be to go with [CI]$^3P_1$-$^3P_0$ (~492 GHz) which is a much better tracer of total gas mass and is accessible over most of 0<*z*<3 with ALMA**

**Geach et al. (2011), ApJ, 730, L19**




Karim et al. (2011)




Kereš et al. (2005)

## Encodes range of evolution physics:

## Decline in cooling rate

- Delivery of fresh gas declining
- Feedback curtailing cooling

## Consumption of gas reservoirs

- SFR declining in galaxies of fixed mass

## Growth of discs

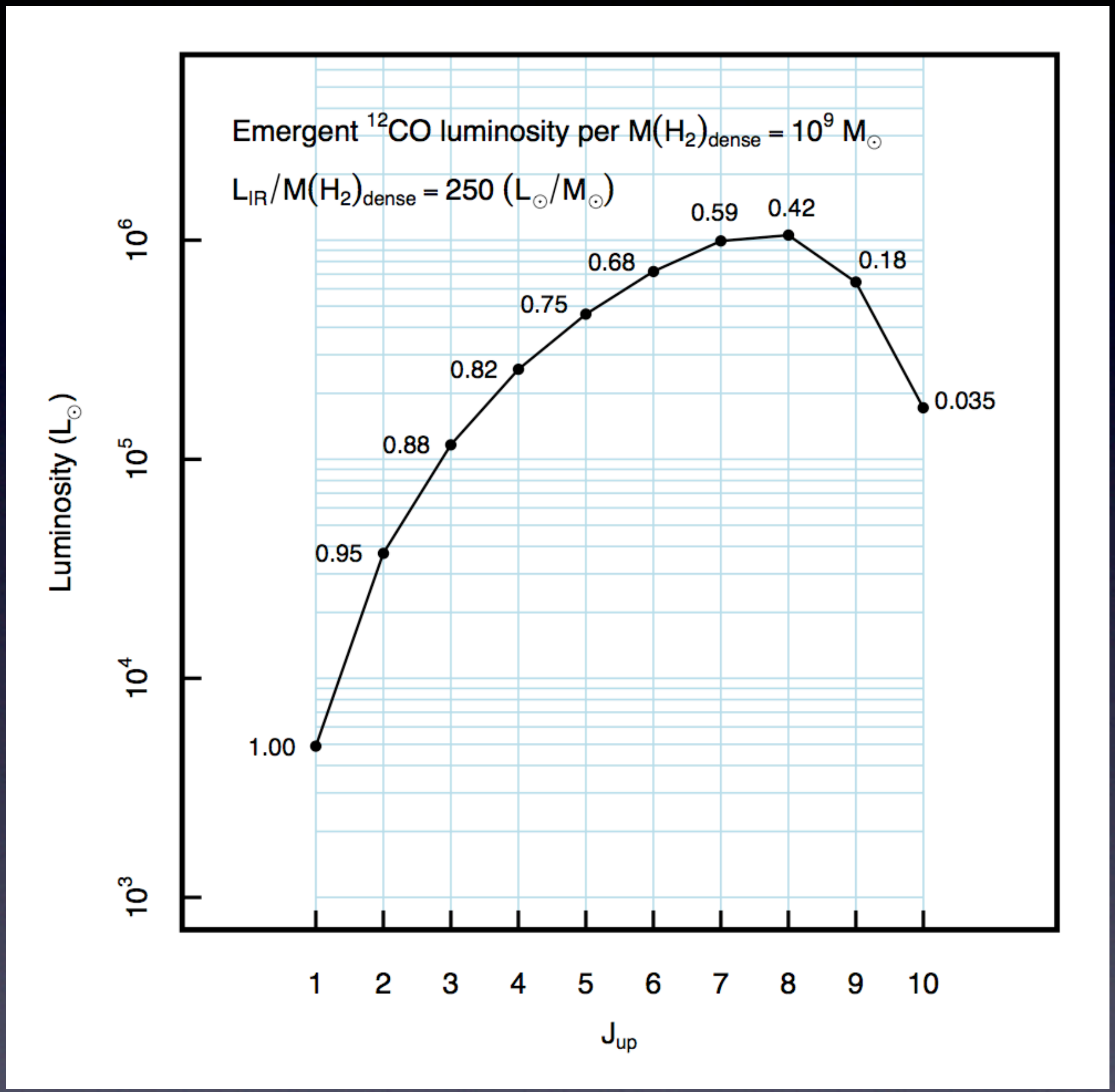
- Reduction in disc hydrostatic pressure and therefore formation of $H_2$. Reflected in HI/$H_2$

## Environmental effects (linked to cooling rate)

- Cluster atmospheres affect cooling/strip gas, central radio feedback exacerbates this
- Galaxies in most massive halos might exhaust their gas reservoirs earlier (e.g. SMGs)
- Build-up of structure drives evolution of $f_{gas}$, with stronger evolution expected for massive halos

Need a systematic survey of gas in SF galaxies

# Minimum CO emission for $L_{IR}$




Geach & Papadopoulos 2011, in prep

**What is minimum CO emission expected for the dense gas phase?**

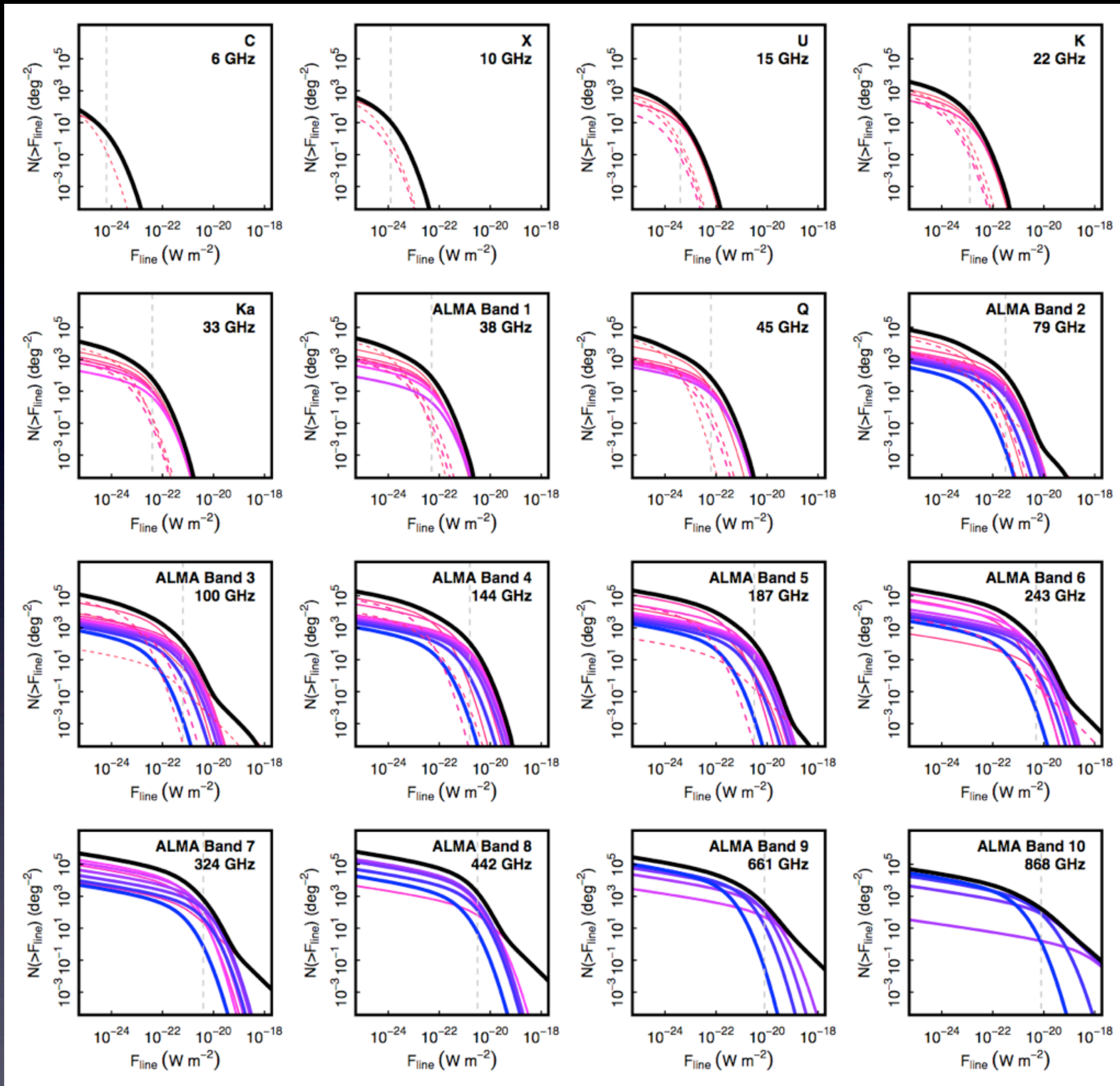
**Local well-sampled HCN SLEDs can be used to predict emergent CO SLED for dense, SF gas phase since $n_{crit}$(HCN)>$n_{crit}$(CO) (see also Combes et al. 1999, Blain et al. 2000)**

**Typical dense SF phase $n(H_2) = 3\times10^4$ cm$^{-3}$, $T_{kin}$ = 40K for HCN SLED - yields CO SLED**

**Normalisation of SLED provided by $L_{IR}$: $L_{IR}/M_{dense}$~250 for star-forming cores**

**Emergent $L_{CO}$ implies envelope for $L_{FIR}/L_{CO}$**

**Can tie this together with predictions for IR luminosity density evolution to predict lower limit to line counts**




Line counts built on IR LF evolution model of Bethermin et al (2011) which well matches IR/sub-mm number counts.

**1 hour integration / 300 km s$^{-1}$ bins:**

| | |
|---|---|
| Band 3 | 265 deg$^{-2}$ |
| Band 4 | 500 deg$^{-2}$ |
| Band 5 | 720 deg$^{-2}$ |
| Band 6 | 1330 deg$^{-2}$ |
| Band 7 | 4100 deg$^{-2}$ |
| Band 8 | 200 deg$^{-2}$ |
| Band 9 | 16 deg$^{-2}$ |
| Band 10 | 10 deg$^{-2}$ |

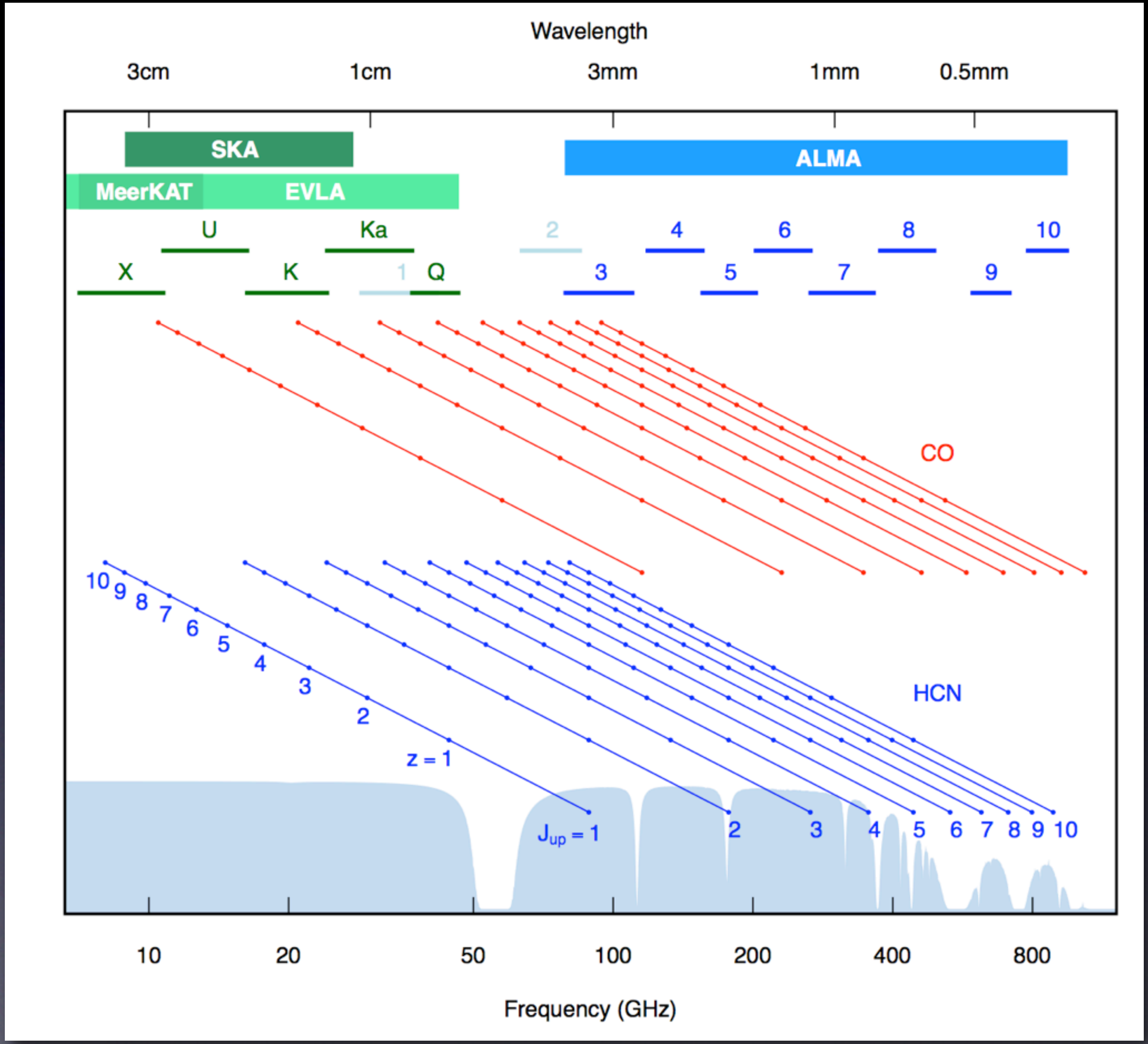
In 4GHz windows

Small FoV kills us for blind surveys.

Solutions:

- target known sources (e.g. sensitive radio survey ASKAP EMU, Norris et al. 2011)
- larger FoV with MeerKAT/SKA could pinpoint low-*J* HCN/CO emitters at z>2 that could be re-targeted with ALMA (e.g. [CI](1-0))

# Discovery space



# Summary

- Starting to fill in the parameter space of CO studies at moderate redshift ($0.1<z<1$): continuing picture of $L_{IR}/L_{CO} < 100$ in 'normal' star-forming discs

- At ~fixed stellar mass molecular gas fraction $M_{gas}/(M_{gas}+M_{star})$ has undergone $(1+z)^{\sim 2}$ since z~2. Reflects the balance of consumption/replenishment/recycling of gas reservoirs

- Piecemeal sample selection clouding the issue. We need to be thinking about systematic gas surveys across cosmic time

- Can we make robust predictions for ALMA, SKA, etc.? Emergent CO SLED sets minimum CO emission for a IR limited sample (in SF systems):

    - Tells us the sensitivity required to detect the dense SF reservoirs

    - Combined with models of evolution of $L_{IR}$ density yields minimum number of line-emitting galaxies in blind survey