Extragalactic Spectral Lines SWG (Made in Sicily...)

<u>Our meeting times this week:</u> *Please join*!

Session 1 (*Tue. 11:00 – 12:30*) – **general kick-off**

- aims, objectives and outcomes from this science area, discuss USE CASE outlines
- potential areas of commensality with other KSP/SWG areas
- technical limitations/opportunities,
- outline role of this SWG and spawn potential KSP collectives

Session 2 (*Tue. 15:00 – 16:30*) – Science area: **nearby galaxies**

- moderate-to-Nearby galaxies, local group etc.
- cover range of science areas (incl. local (ex-gal) maser studies, molecular lines in nearby galaxies, resolved mega-maser astrophysics, RRLs etc.)

Session 3 (*Wed. 11:00 – 12:30*) – Science area: **distant galaxies**

- higher redshift studies
- highly redshifted lines (CO, HCN, H_2O etc.), lensed sources, mega-masers.

Session 4 (*Wed. 15:30 – 17:00*) – **wrap up/toward use cases**

- Overview of science areas, Discussion of use cases, discussion of KSP development and commensality within this SWG and other areas.

Overview

- Processes/objects probed by non-HI spectral lines at the SKA
- Meet the lines
- Line coverage by SKA bands
- Science projects targeting Local Group/low redshift galaxies
- Science projects targeting galaxies at intermediate/high redshift

Non-HI spectral line science @ SKA

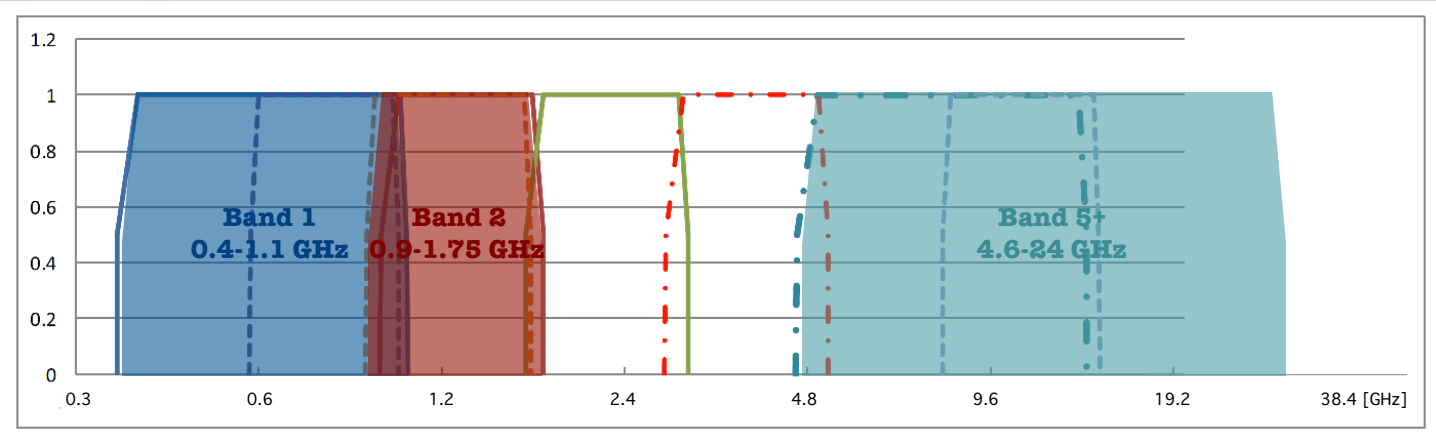
- ISM physics/composition
- Star formation
- Active nuclei (AGN & starbursts)
- Cosmological applications

Lines/line types of interest *(add yours!)*

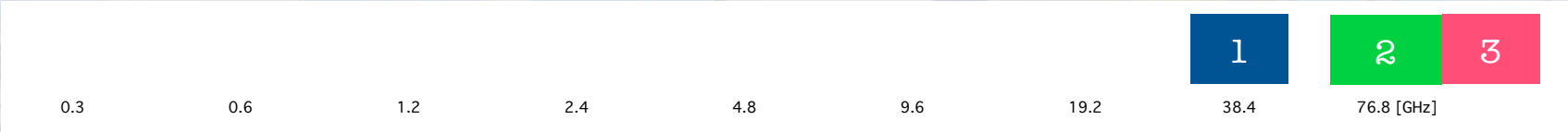
- Masers (hydroxyl; water; methanol; formaldehyde; ...) & mega-masers
- Molecular lines (vibrational & rotational transitions)
- Radio recombination lines (RRLs)
- (HI absorption)

Frequency coverage of main lines

SKA1-MID



ALMA



OH masers

OH * masers formaldehyde maser

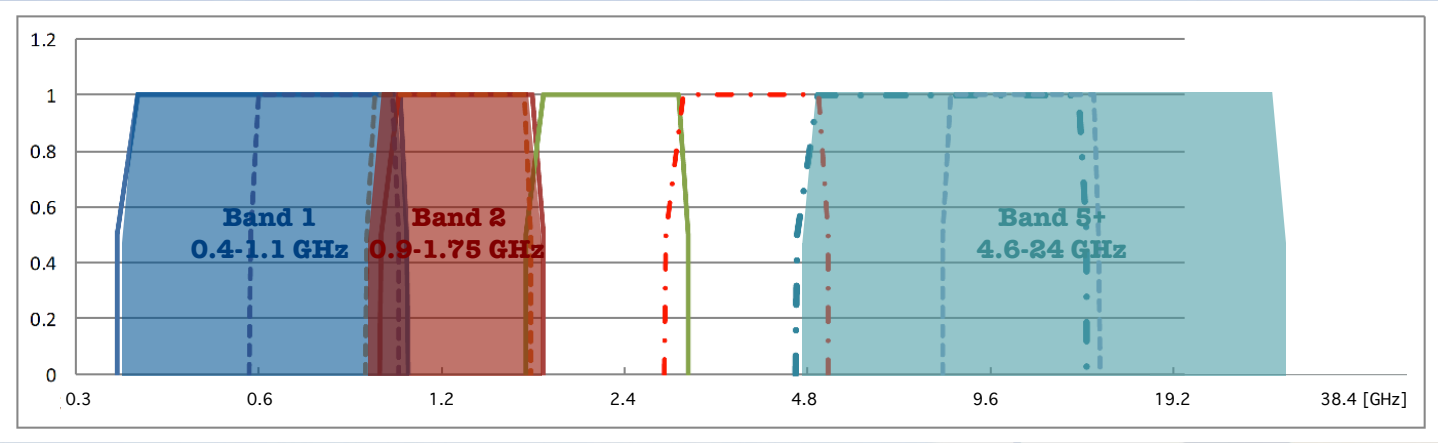
OH * masers methanol maser

methanol * maser

H_2O maser

Frequency coverage of main lines

SKA1-MID



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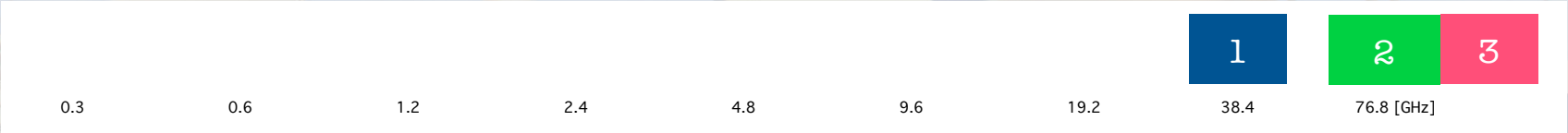
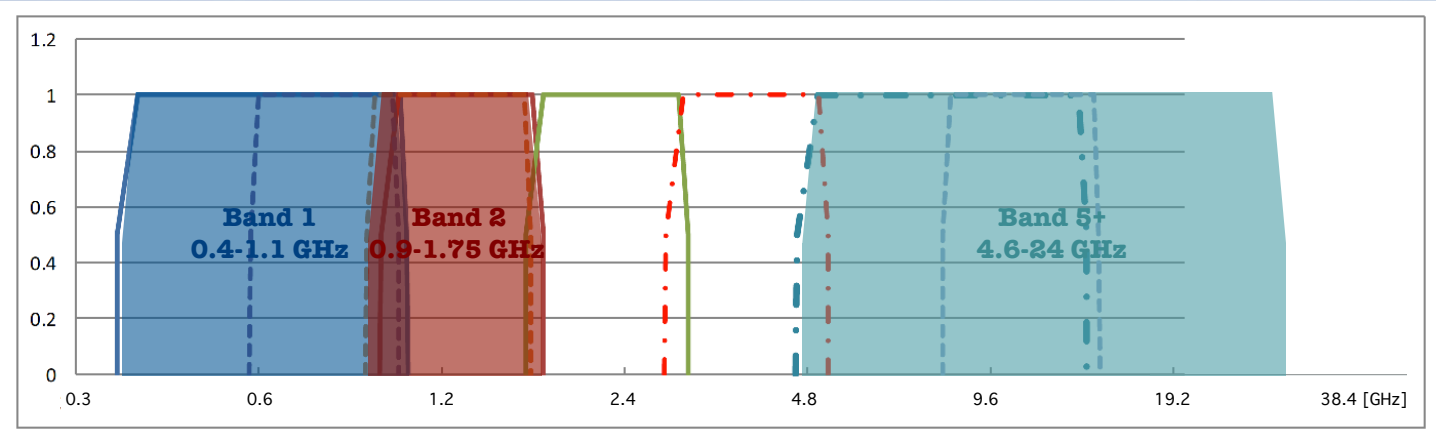


Radio recombination lines

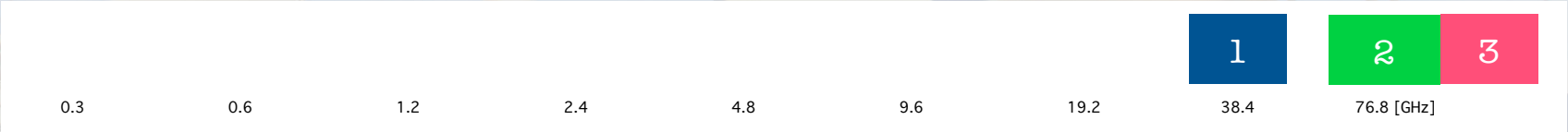
Radio recombination lines

Frequency coverage of main lines

SKA1-MID



ALMA



CS[1-0]
HCN[1-0]
HCO+[1-0]
CO[1-0]
CS[1-0]
HCN[1-0]
HCO+[1-0]
CO[1-0]

redshift

Science applications for nearby galaxies

Radio recombination lines (RRLs)

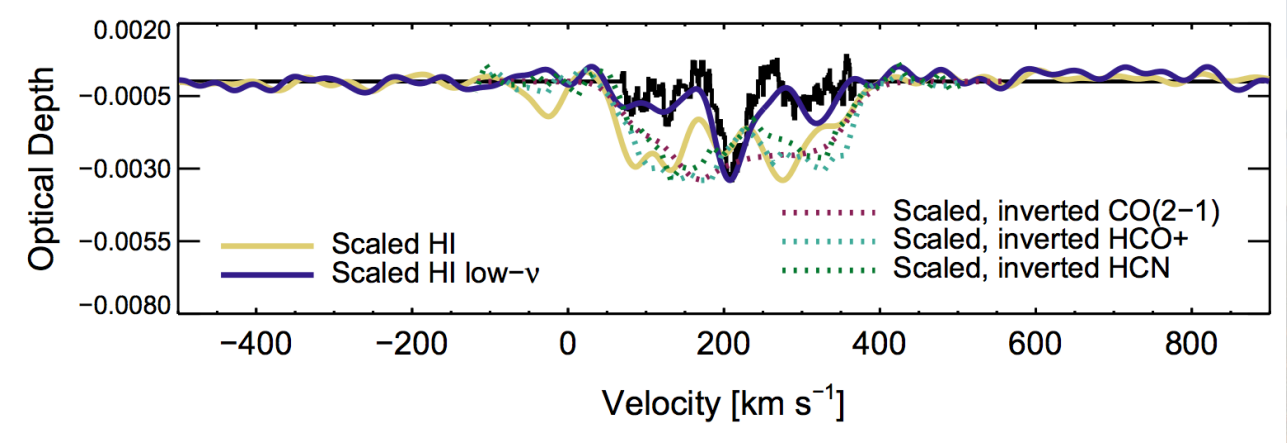
"Discrete" RRLs:

- Generally found at ≥1 GHz (mostly from hydrogen & helium)
- Trace the warm, ionized medium

"Diffuse" RRLs:

- Trace the elusive cold, neutral (atomic – i.e. provide complementary information to molecular emission) medium
- Often (e.g. carbon RRLs) lie in the tuning range of SKA-LOW
- Alternative to using atoms in absorption (e.g. HI)

M82: CRRLs (in absorption) & HI absorption appear to <u>originate from similar region</u> (close to nucleus).



(See also SKA science book chapter by J. Oonk.)

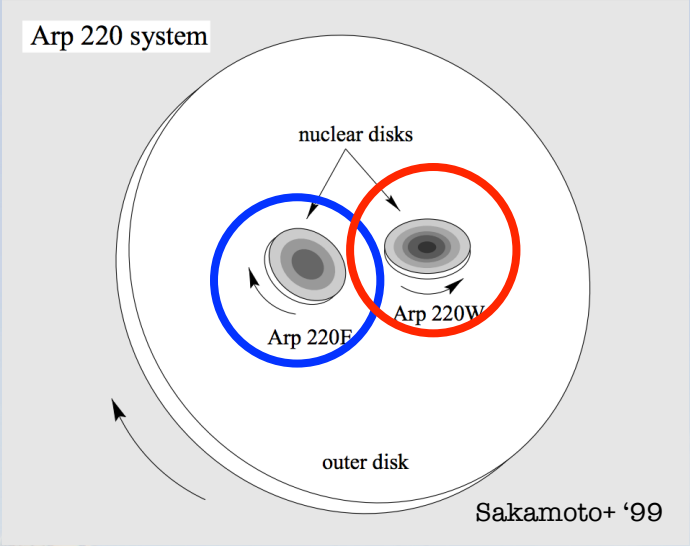
Molecular lines at <10 GHz

Many of these line are recent additions to the molecular line inventory – the SKA will be exploring new territory.

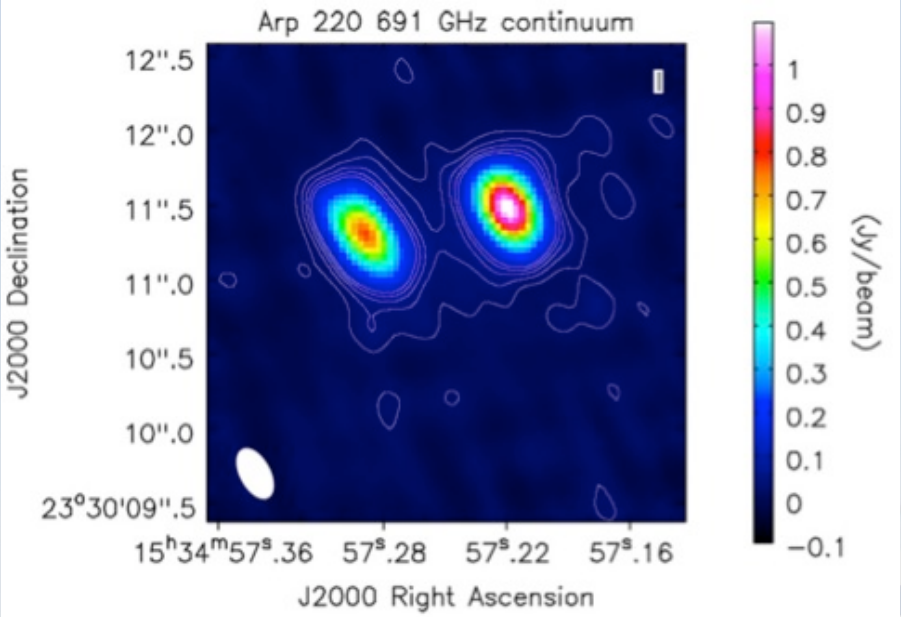
Line	Rest freq (MHz)	SKA-1 MID band
HCN $v_2 = 1, \Delta J = 0, J = 2$	1346.765	2
HCN $v_2 = 1, \Delta J = 0, J = 4$	4488.4718	4
H_2CO	4829	4/5
N_2H+	5009.8278	4/5
H_2CNH $1_{10} - 1_{11}, \Delta F = 0, \pm 1$	5289.813	5
HCO+	6350.908	5
HNC	6484.497	5
CH_3OH $5_1 - 6_0 A^+$	6668.5192	5
HCN $v_2 = 1, \Delta J = 0, J = 5$	6731.9098	5
HCO+	8890.452	5
HCN $v_2 = 1, \Delta J = 0, J = 6$	9423.3338	5
HNC	9724.644	5

Beswick+ '15

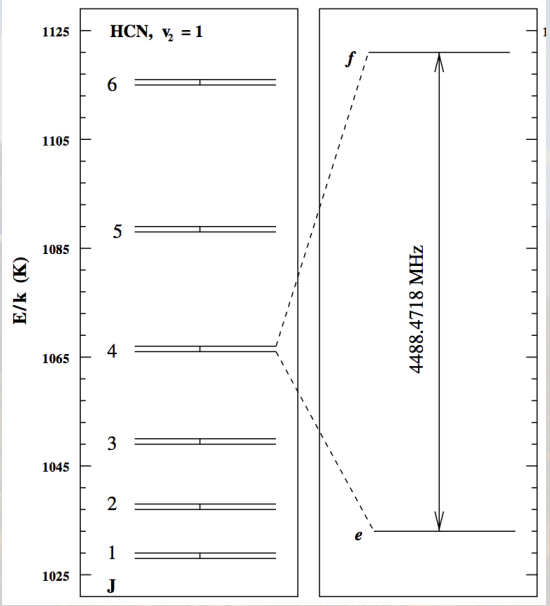
Probing the nuclear environment(s) in Arp 220



ALMA continuum image (Wilson+ '14):



Transitions between HCN vibrational levels with identical J:



Eastern nucleus

- rotational HCN transitions only
- starburst activity only?

Western nucleus

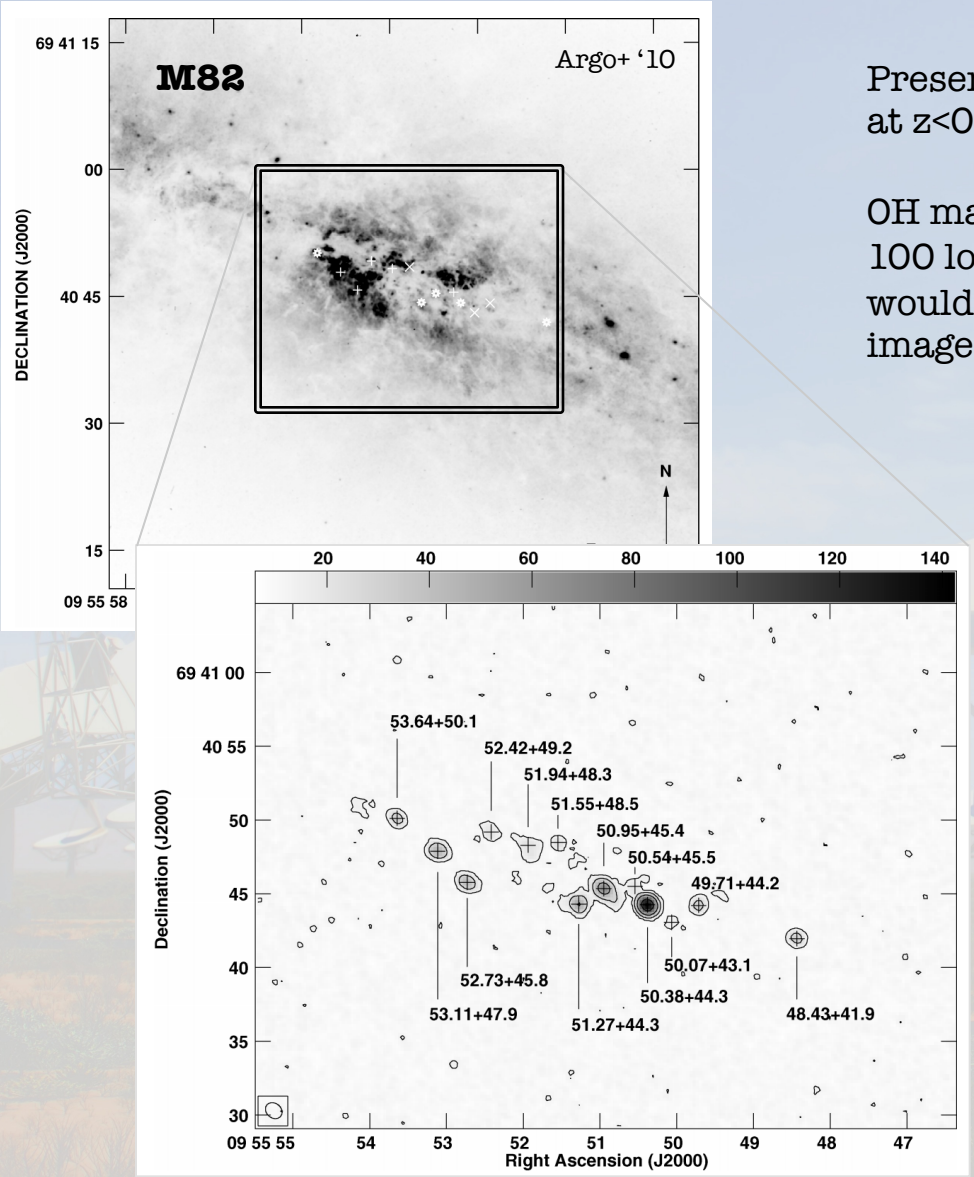
- rotational *and* direct l-type HCN transitions (Salter+ '08; Rickert+ '11)
- evidence for AGN from dust emission

Maser science

- Trace star formation, jet-ISM interactions, maybe molecular outflows
- Probe ISM chemistry
- Local volume and low-z Hubble flow cosmology
- Internal kinematics of galaxies and velocity vectors/positions of nearby galaxies
- Trace bulk motion due to outflows/feedback
- Measure black hole masses
- Magnetic field measurements through Zeeman splitting (up to z=1 with full SKA, see SKA science book chapter by T. Robishaw)
- Quantify number & flux contribution of potential HI-line survey contaminants

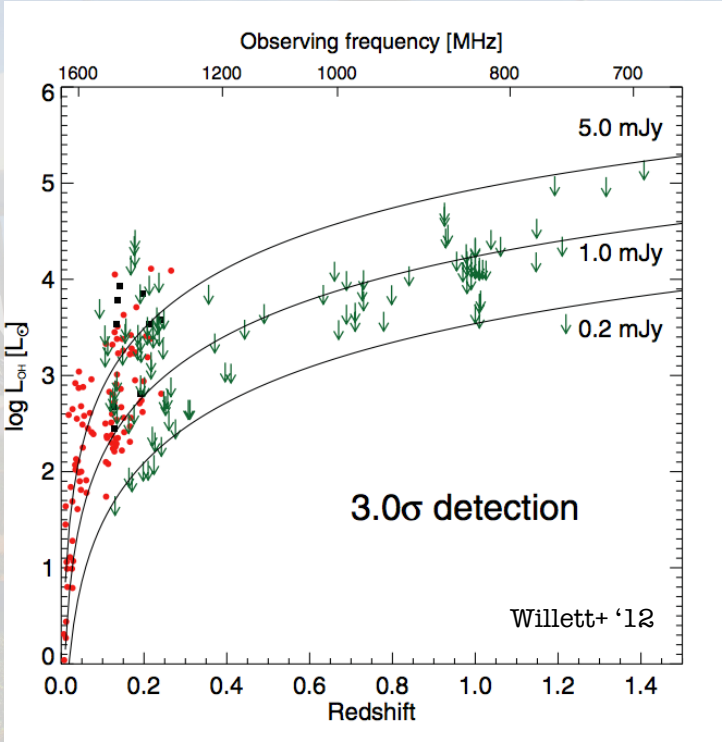
(See also SKA science book chapters by S. Etoka, R. Beswick, M. Thompson, J. Green.)

Maser distribution maps in galaxies



Presently OH maser distribution maps exist only at z<0..05 and for about 10 galaxies (e.g. M82).

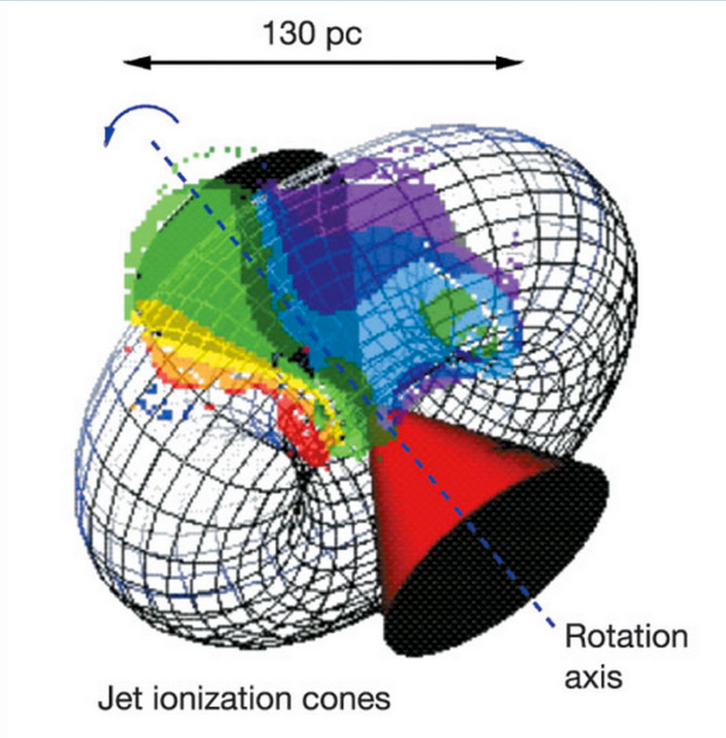
OH maser emission has been detected in about 100 low-z & intermediate-z galaxies; these would be potential targets for resolved maser images with SKA.



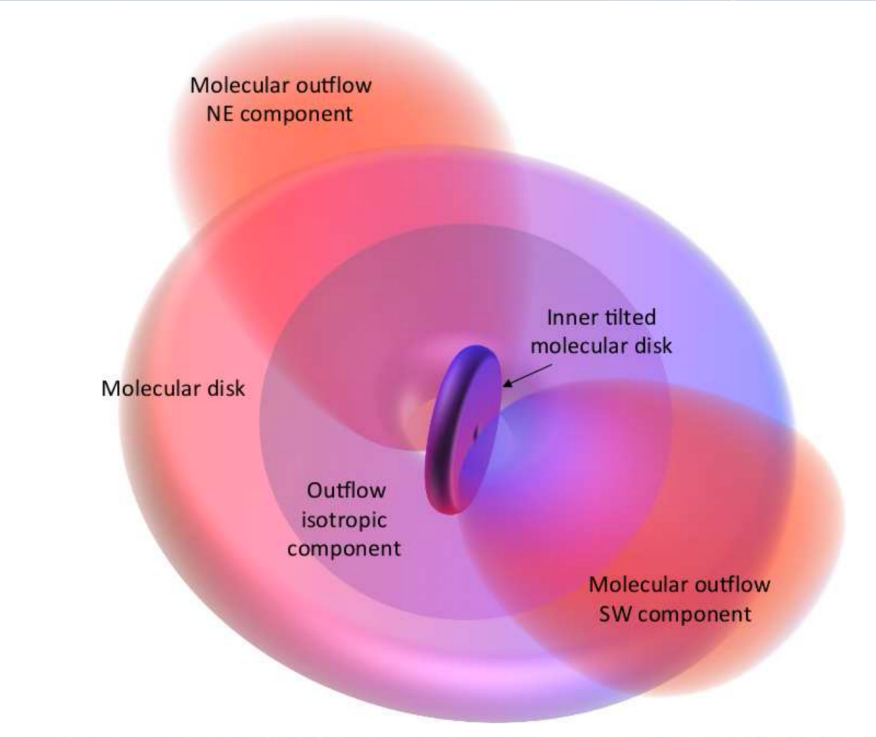
Masers as tracers of outflows and feedback – Mrk 231

OH masers trace the motion of molecules away from central BH on small scales (approx. 200 pc).

CO emission reveals molecular outflows on large scales (500 pc – 1 kpc) that are well-aligned with outflows traced by masers.



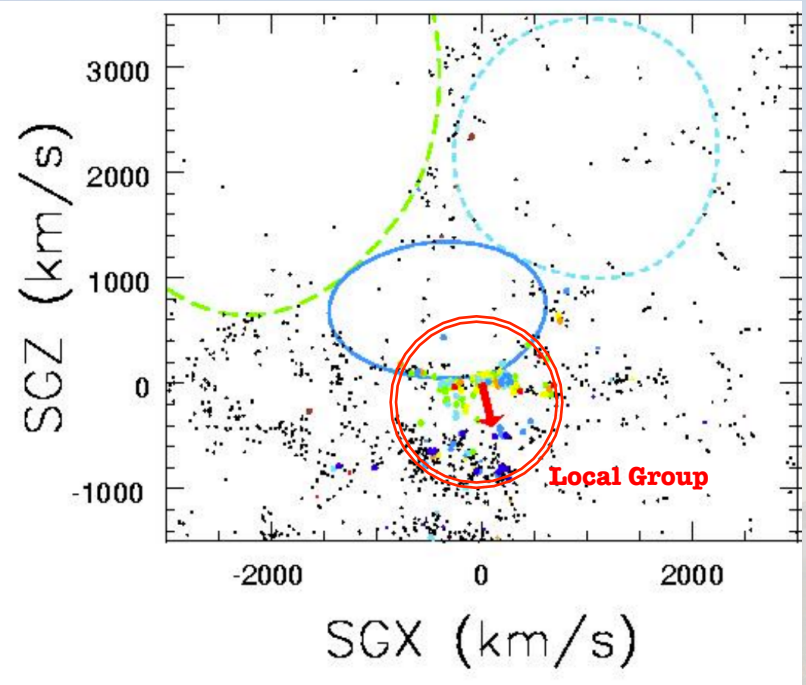
Klöckner+ '03



Feruglio+ '15

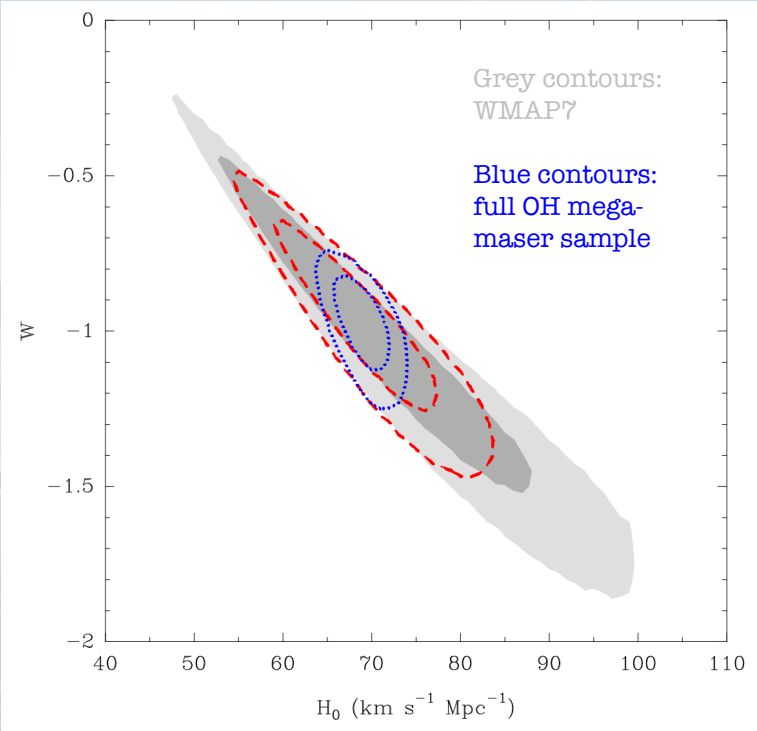
Masers for cosmology

Precision distances and kinematics of Local Group galaxies to determine proper motion of local galaxies w.r.t. LSS.



Tully+ '07

Precision angular diameter distance measurements to galaxies within approx. 50 kpc for alternative estimates of the Hubble parameter.



Reid+ '13; Mega-maser cosmology project

(Requires VLBI; see also SKA science book chapter by J. Green.)

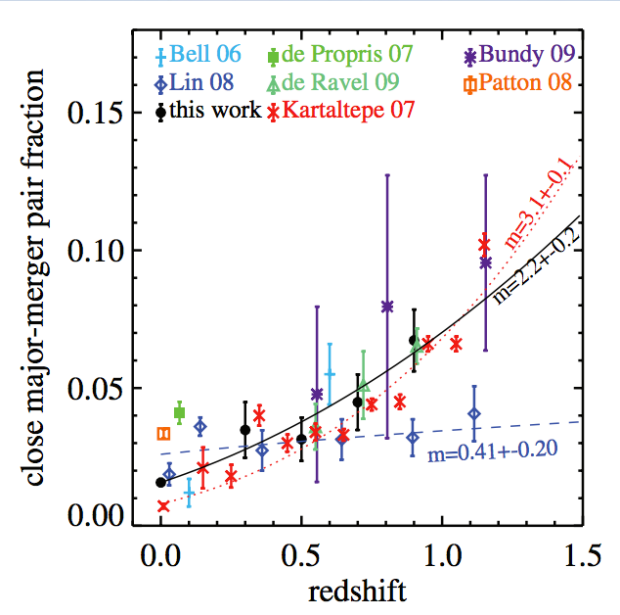
Science applications for distant galaxies

OH & H_2O (Mega-)Masers: applications at high redshift

1) The **evolution of the merger rate** (inferred from galaxy pairs) is highly uncertain/debated

Mergers provide the conditions required for OH mega-maser emission; OH mega-masers can hence be used to trace the merger rate. (Current constraints: m<6 for power law $[1+z]^m$.)

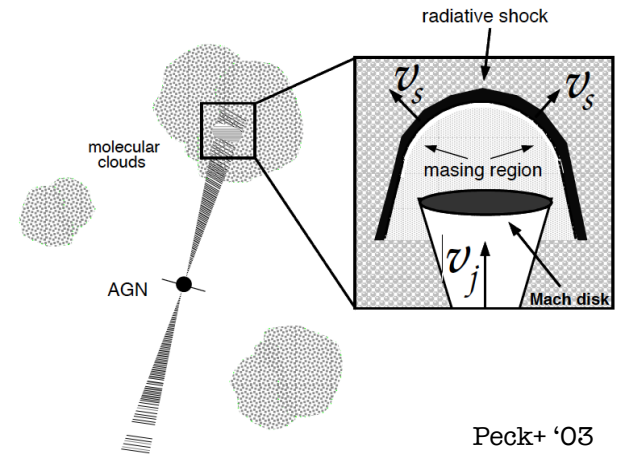
Xu+ '12



band 5+ science

AGN/BH science:

- Testing the AGN unification model for accreting SMBH hosted by gas rich high-redshift galaxies.
- Kinematic measurements of BH masses.



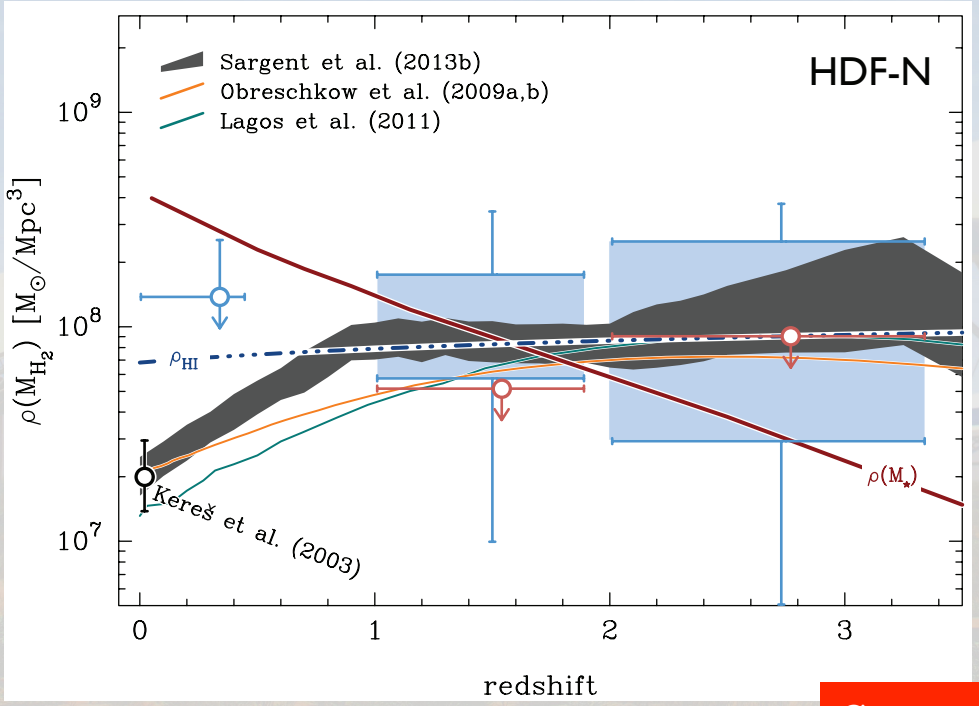
Peck+ '03

Towards a cosmic inventory of star-forming g

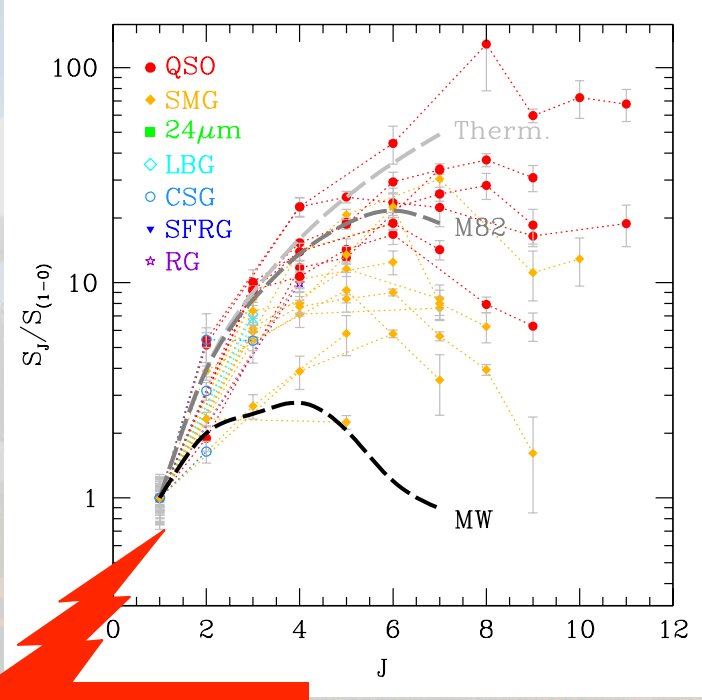
band 5+ science

With blind PdBI, JVLA & ALMA line scan surveys we are beginning to sample CO luminosity function evolution and the "molecular Lilly-Madau plot" ...

... but, we really would like to do this based on the ground-state CO transition which is either not accessible or limited by sensitivity for present observatories.



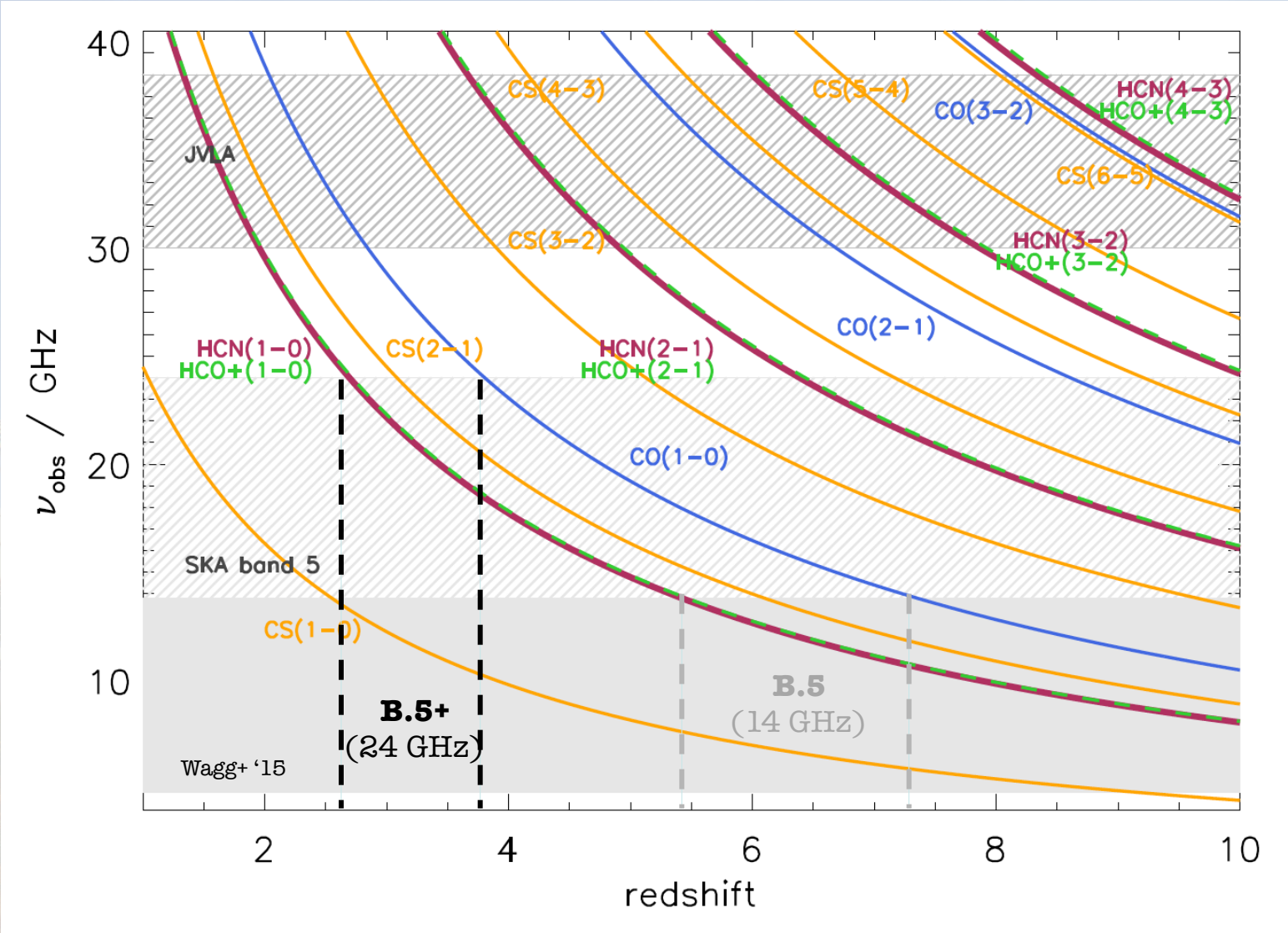
Walter+ '14; Decarli+ '14



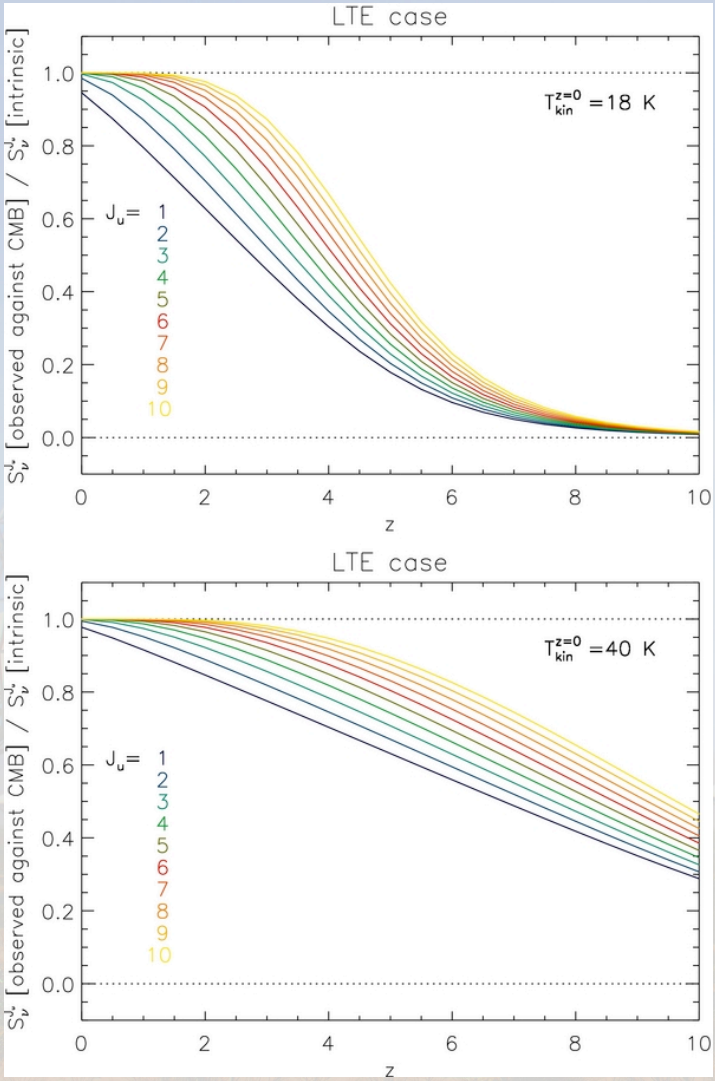
Carilli & Walter '13

Ground-state CO ➽ total molecular gas reservoir

Molecular gas at high z w/ band 5(+): low-J transitions



CO vs. HCN emission from high-z galaxies



da Cunha+ '13

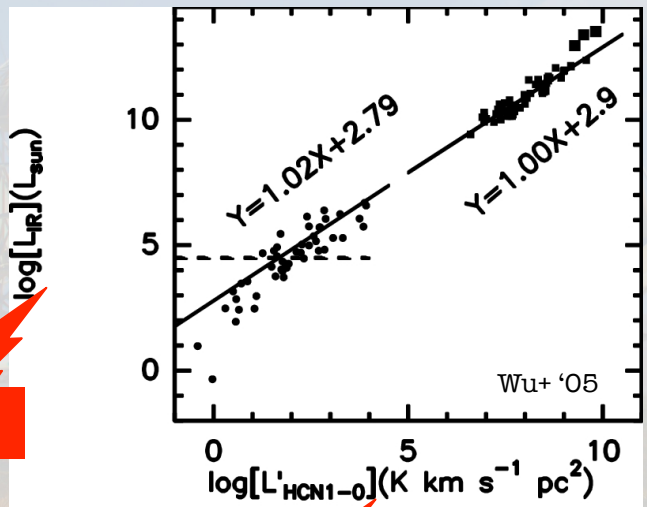
At z>>4 it will likely be very difficult to observe CO against the background of the CMB in "normal" galaxies with low levels of star formation.

(Further difficulty: low-metallicity. Bonus: temperature evolution of ISM as traced by IR dust SEDs.)

The dense, star-forming gas (as traced, e.g., by HCN) has kinetic temperatures around 40-50 K and is less affected by the warming CMB than CO which traces more diffuse gas reservoirs.

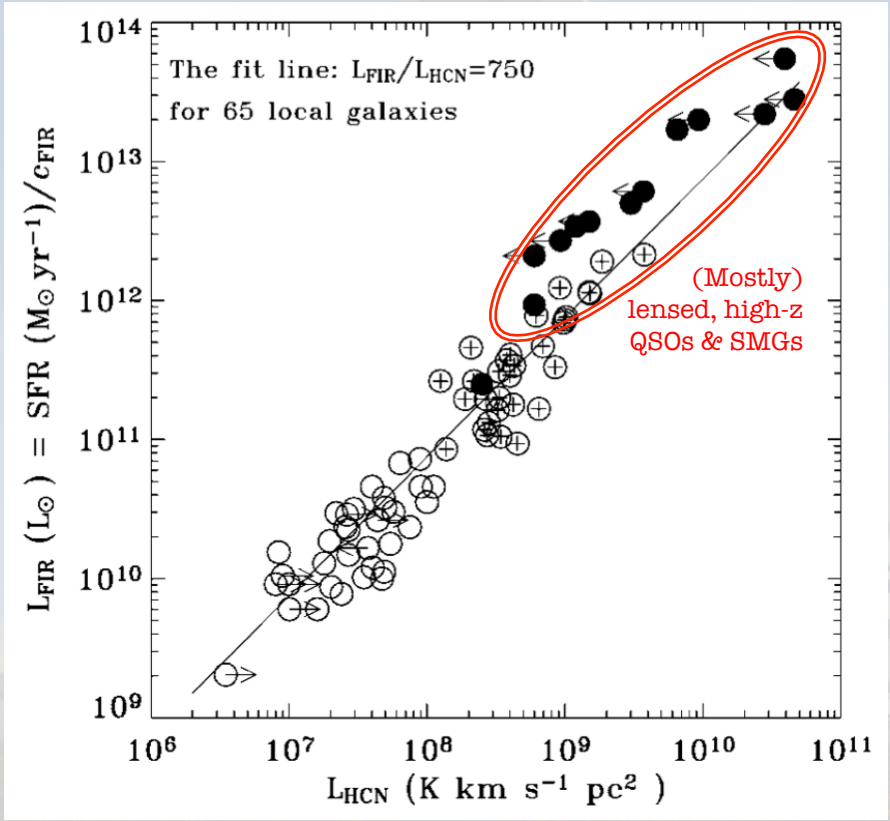
CO vs. HCN emission from high-z galaxies

L_{IR} and L'_{HCN} correlate over 8 orders in magnitude, suggesting <u>a universal star-formation efficiency</u> from Galactic cores to starburst ULIRGs



SFR

dense gas mass

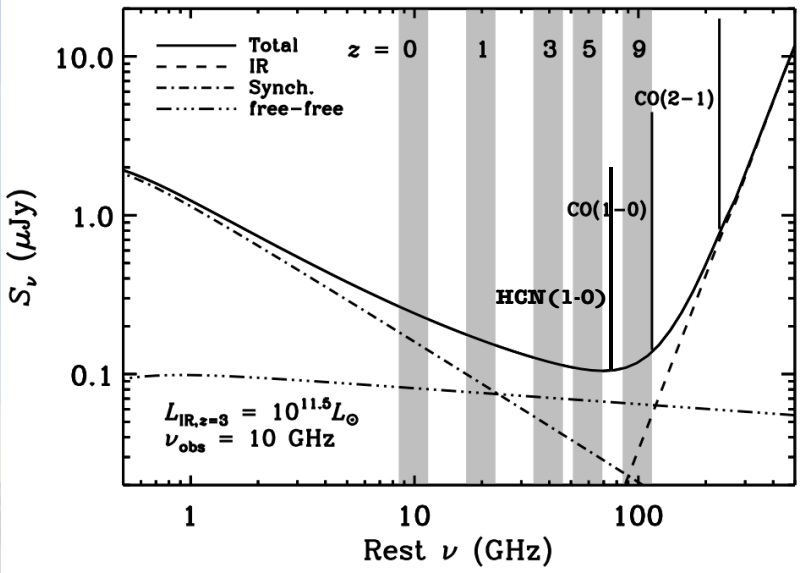


It is <u>very</u> time-consuming to search for HCN in "normal" high-z galaxies which are not amplified by gravitational lensing (a few hours even with ALMA).

SKA band 5(+) – the key to SFE studies at high redshift

Band 5 can directly target ground-state (low-excitation) molecular gas at high redshift!

(At z>6 w/ SKA1, at z>2.5 w/ extension to 24 GHz.)



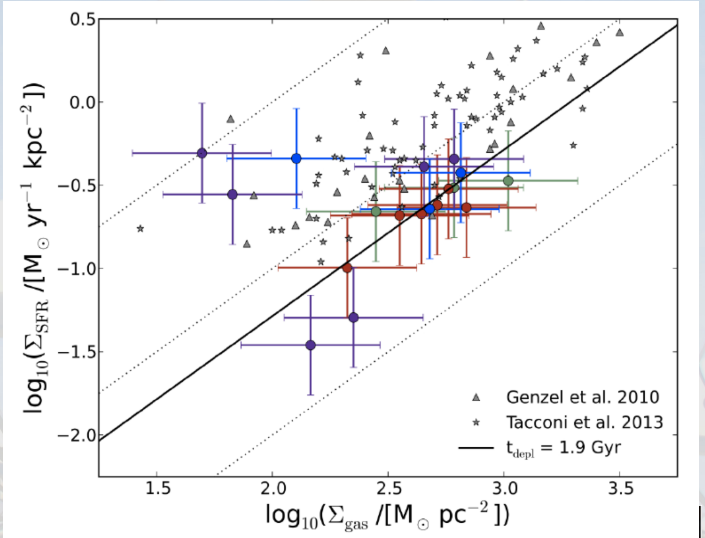
^{12}CO[1-0] ➡ overall molecular gas reservoir

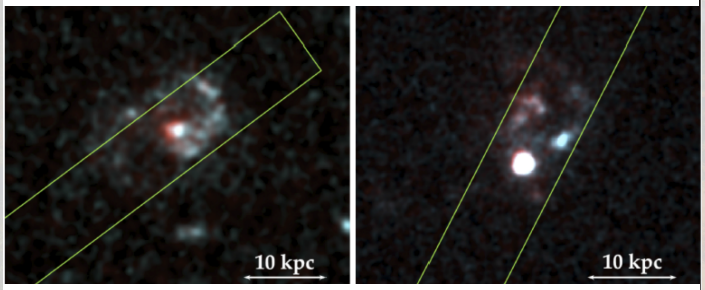
HCN[1-0], HCO+[1-0] ➡ dense, star-forming gas

^{12}CO/^{13}CO ➡ e$^-$ temp. in HII regions, IMF variations

Marginally resolved (8 kpc) Schmidt-Kennicutt relation in z = 1.2 galaxies:

➽ SKA could extend analysis to several 10s of resolution elements





Freundlich+ '13