# A Cosmic History of Molecular Gas (with Intensity Mapping)

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*on behalf of the ngVLA Intensity Mapping Community Study Group:*
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*and with contributions from:*
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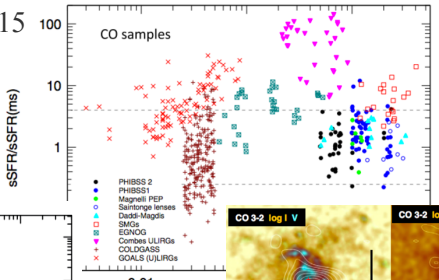
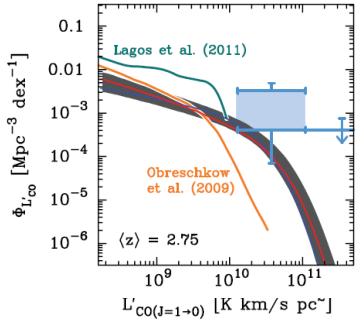
**ngVLA Science Workshop**
**June 28th, 2017**

# *The New Frontier of Molecular Gas*

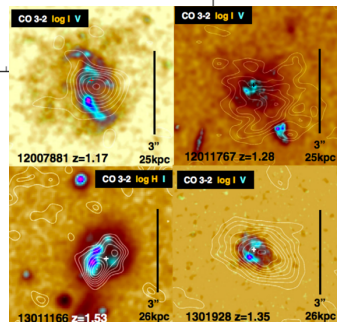
## Current instruments have yielded hundreds of high-redshift CO detections

Genzel et al. 2015

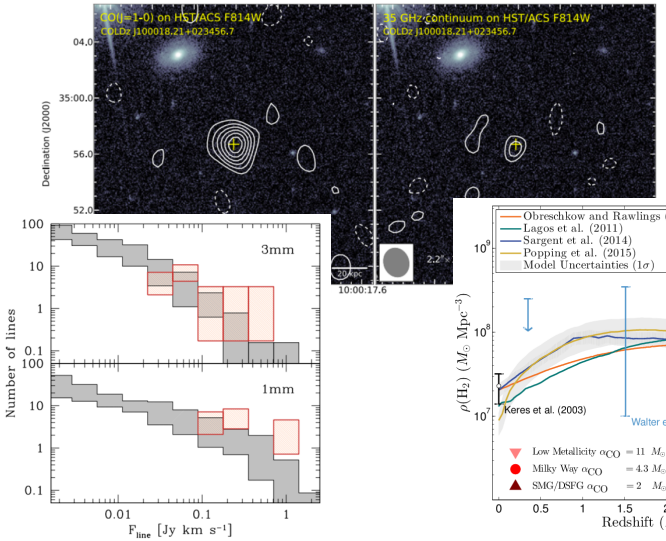



Walter et al. 2014




Tacconi et al. 2013




Walter et al. 2016

Lentati et al. 2015



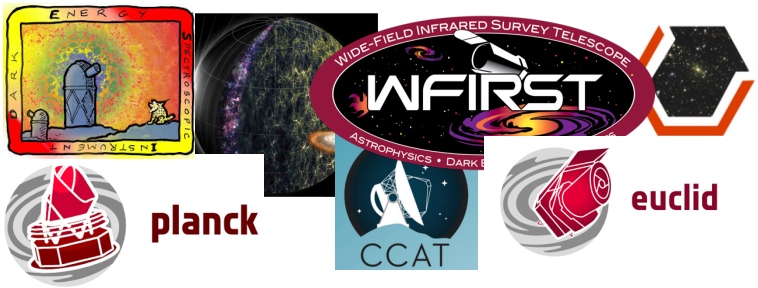

Keating et al. 2016

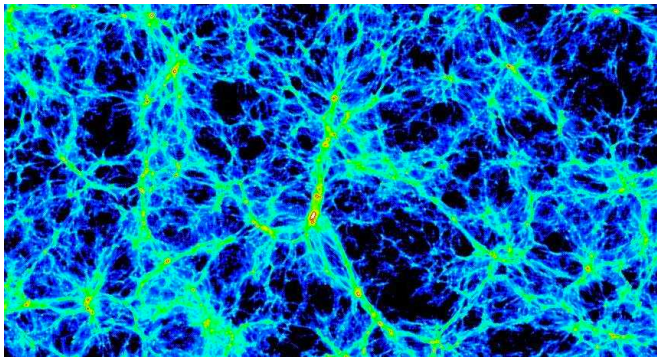
The Next Generation VLA will afford high-resolution studies of *thousands* of galaxies…

**…but could it perform wide-field, wideband surveys to measure emission arising from *millions or billions* of galaxies?**

# *Why Wide-Field?*

**A wealth of full-sky/large-area data:**
Entering an era of large, multi-wavelength full sky surveys (photo + spec)



**Cosmological applications:**
Multiple cosmology-related measurements require $\gg 1\ \mathrm{deg}^2$

**Molecular Gas is incredibly complex:**
CO is dependent on chemistry, feedback, etc.; understanding how its ties to molecular gas requires both detailed studies *and* large, statistical samples

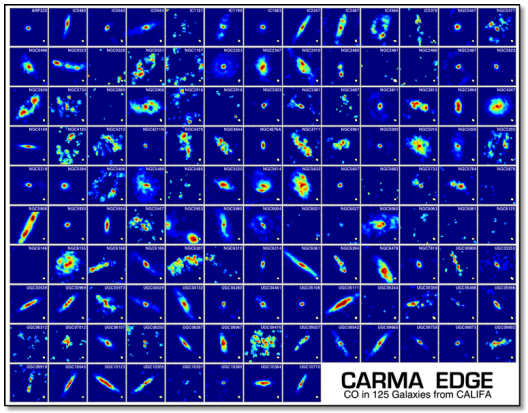
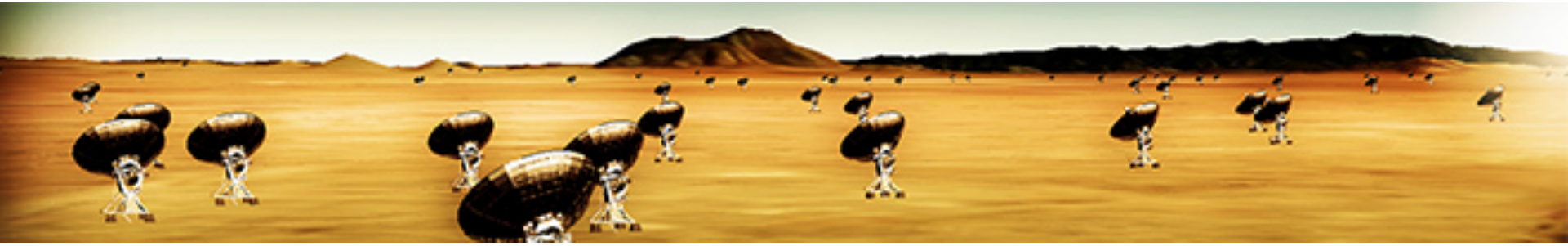


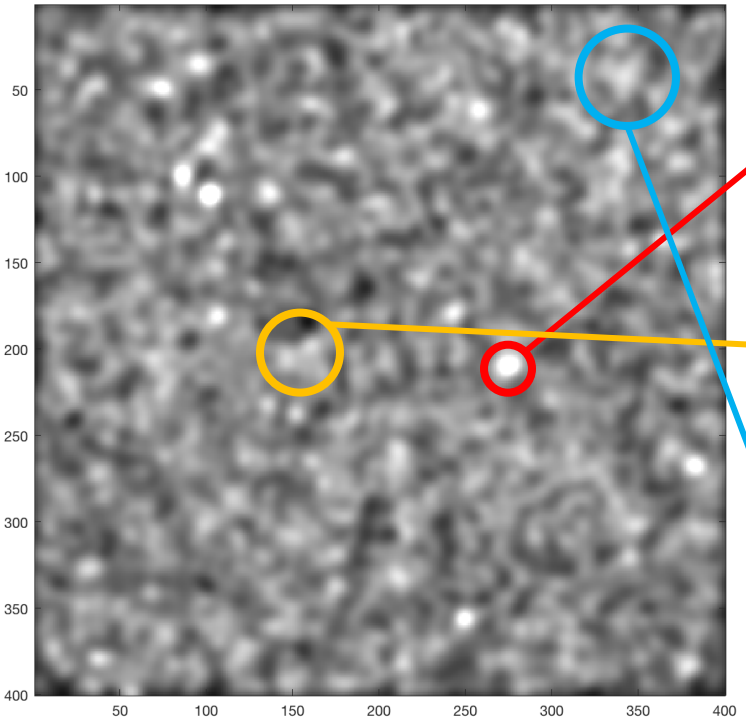

Image Credit: Alberto Bolatto

# *Why ngVLA?*

- **Spectral coverage of 10-115 GHz + wideband correlator**
- **$T_{\mathrm{sys}}/\eta_{\mathrm{eff}}$ + number of detectors**
  - Science case most driven by $N_{\mathrm{det}}$
- **Dense antenna core**
  - *"Galaxies as point sources"*
- **Potential for total power measurements**



# *Extracting Galaxy Emission*



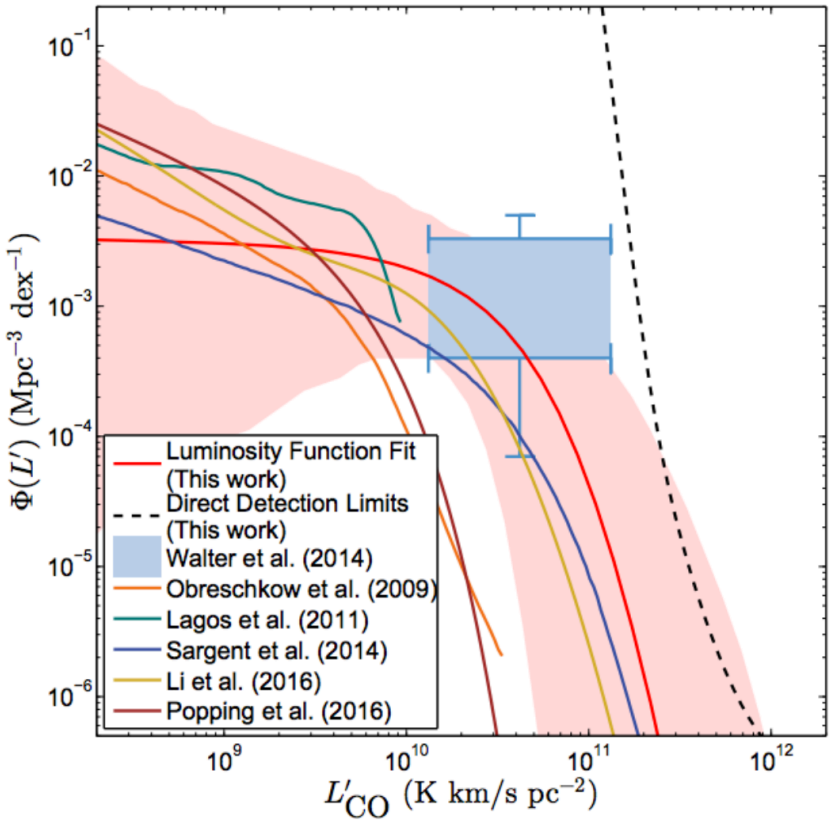

**Direct Detection:** Faint objects can be prohibitively expensive.

**Source Stacking:** Needs ancillary data

**Intensity Mapping:**
Excellent for faint sources, requires strong control of systematics.

# *Extracting Galaxy Emission*

Keating et al., 2016




***Intensity mapping is a tool for better leveraging wider, shallower datasets***

**Intensity Mapping:**
Excellent for faint sources, requires strong control of systematics.

- On smaller scales ($< 1'$), it measures contributions from individual galaxies
- On larger scales ($> 1'$), it probes contributions from the cosmic web

# “Small” Area Experiment


NASA, ESA, G. Illingworth (University of California, Santa Cruz), P. Oesch (University of California, Santa Cruz; Yale University), R. Bouwens and I. Labbé (Leiden University), and the Science Team

## *“What if we take the ngVLA as-is?”*

- 0.1 – 1 sq. deg. field of view, e.g. GOODS-N
- Spectral coverage between 10-50 GHz
- $\theta_{\rm min} > 3$”, no upper limit for $\theta_{\rm max}$
- $R \sim 1000$ (300 km/s channel resolution)

**NEED:**

- *Baseline specification is suitable*
- 120 18-m antennas in a dense core
- 20 GHz instantaneous BW
- 100-1000 hours observing time

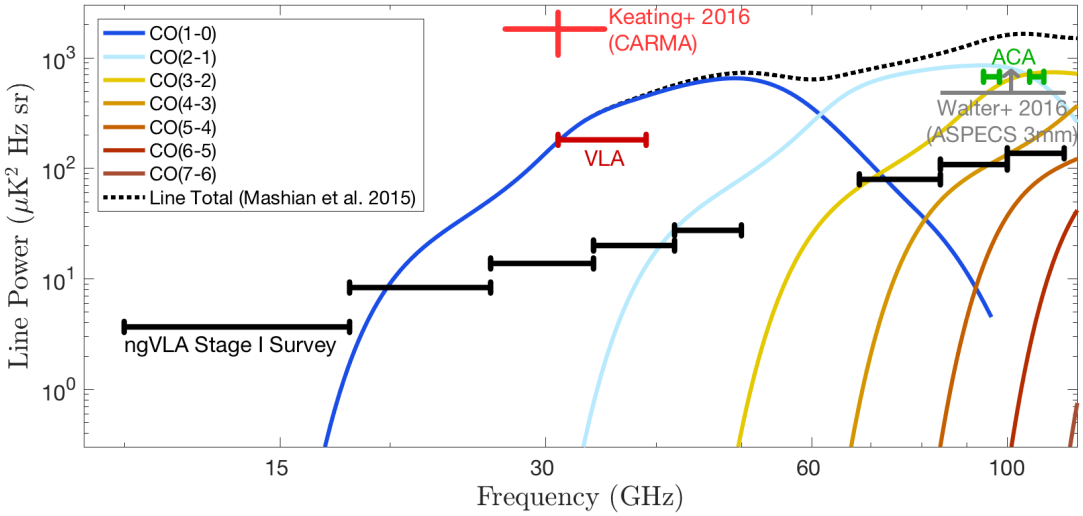
**WANT:**

- Spectral coverage between 10-115 GHz
- Very compact array (e.g., ACA)

# "Small" Area Science

● Direct Detection
● Source Stacking
● Intensity Mapping

*All the science just discussed with direct detection, plus…*

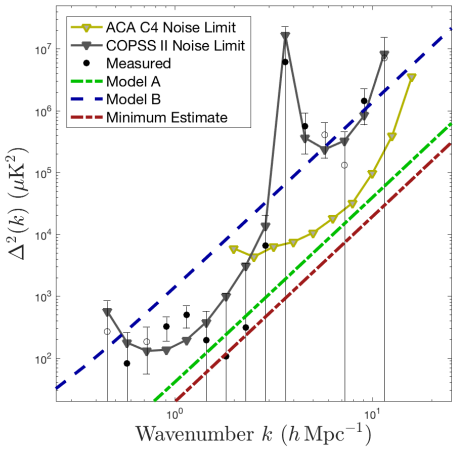



**Bulk CO Emission at $z > 3$** ●

- *"Onset of Molecular Gas" (OMG)*

**CO Line Ratios at $z > 3$** ● ●

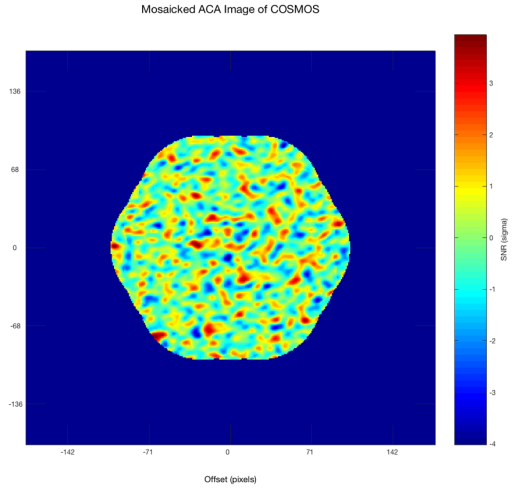
- *Cross-correlation between line species*



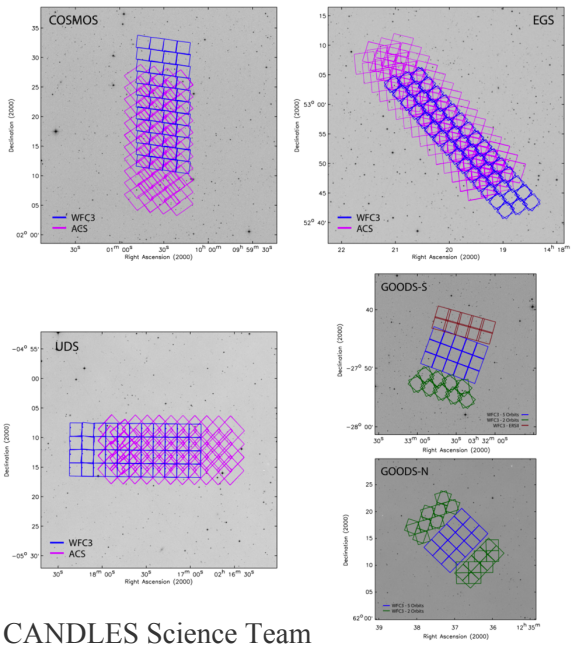

***Pilot survey work with VLA, ACA, and SMA covering ~0.01 sq. deg. presently underway (PI: Keating)***

**VLA (1cm)** **ACA (3mm)** **SMA (1mm)**

*** Pilot instrument construction with COMAP (1cm; PI: Cleary), YTLA (3mm; PI: Bower), TIME (1mm; PI: Bock) also underway*



# Medium Area Experiment




CANDLES Science Team

***"What if we slightly modify the ngVLA?"***

- 10 – 100 sq. deg. sky coverage, e.g. CANDLES-Wide; "Famous Fields Survey"
- Spectral coverage between 10-115 GHz
- $\theta_{\rm min} \geq 3$", $\theta_{\rm max} \sim 1^\circ - 10^\circ$
- $R \sim 3000$ (100 km/s channel resolution)

**NEED:**

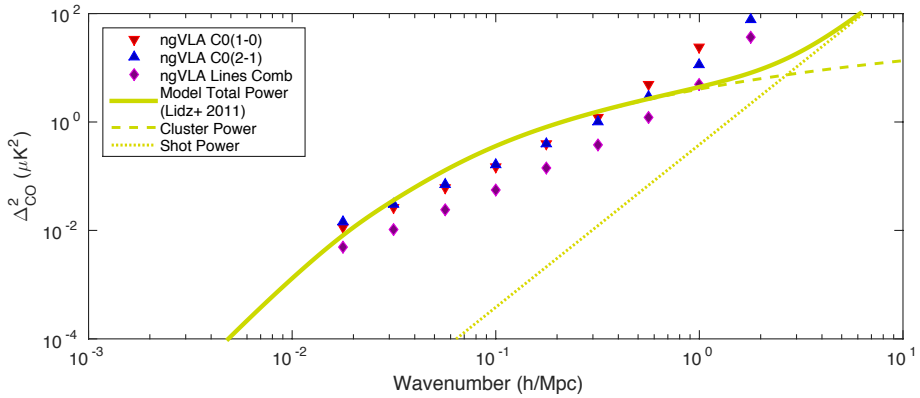
- OTF interferometric capabilities
- 20-40 GHz instantaneous bandwidth
- 1000-3000 hours observing time

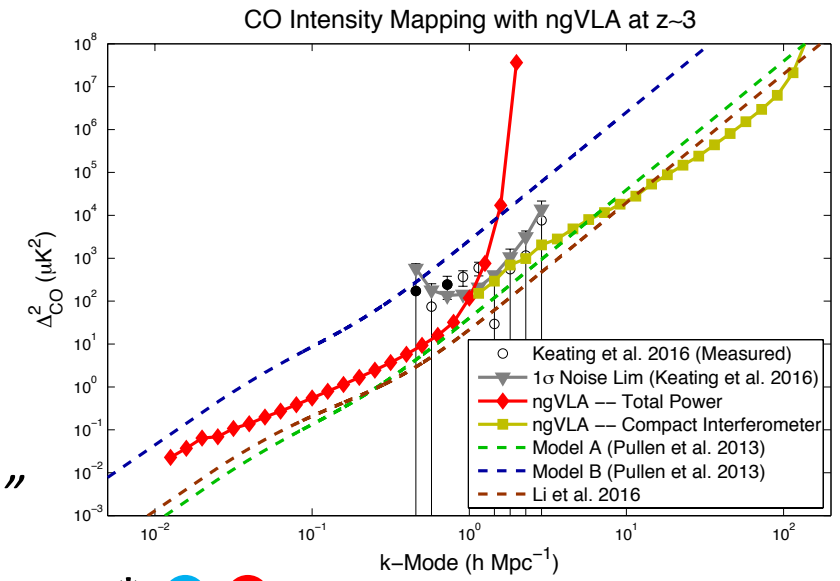
**WANT:**

- Total power measurement capability on a subset of array
  - ***Outfit outrigger stations?***
- Subarray capabilities
- Additional antennas in dense core
- More elements (e.g. heterogeneous array)

# Medium Area Science

● Direct Detection
● Source Stacking
● Intensity Mapping




**CO LF/SLED for $0.2 < z < 10$** ● ● ●

- *"How correlated are CO LFs for different J's"*

**Limited Cross-Correlation with 21-cm Experiments*** ● ●

**Total power required*

**Influence of structure growth on the buildup of molecular gas in galaxies*** ●

**Non-linear growth of structure*** ●

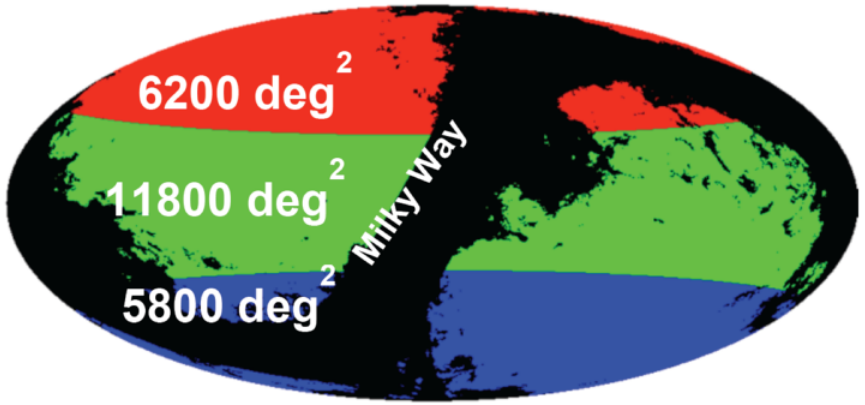
**Tully-Fisher analyses and the "quenching" of molecular gas formation** ● ● ●

**Correlation between optical and radio properties of galaxies** ● ●

- *Free-free emission as a tracer for SFR (versus optical lines; e.g., $H\alpha$, $[OII]$)*
- *SFR versus molecular gas (i.e., integrated Schmidt-Kennicutt)*

# Large Area Experiment

***"What if I could purpose-build the ngVLA for wide-field surveys?"***




DESI Collaboration

- 1,000 – 10,000 sq. deg. sky coverage, e.g., DESI surveys
- Spectral coverage between 10-115 GHz
- $\theta_{\rm min} \sim 1''$, $\theta_{\rm max} \sim 30^{\circ}$.

**NEED:**

- Total power on subset of array
- More elements/detectors on sky
- 40 GHz instantaneous bandwidth
- OTF interferometric capabilities
- Subarray capabilities
- 10,000 hours observing time

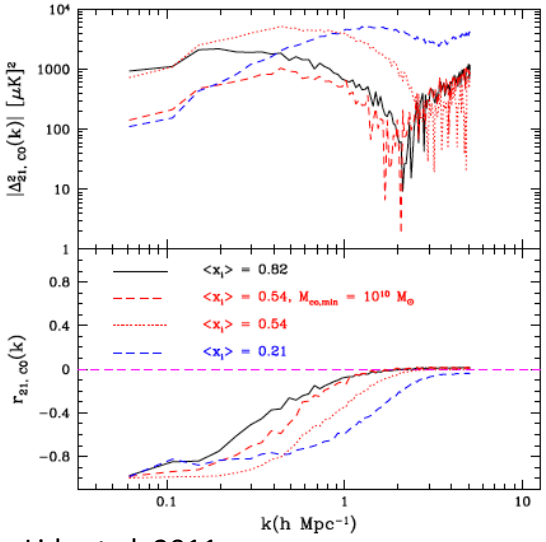
**WANT:**

- **Total power measurement capability across full array**
- Multi-element platforms
- 80 GHz instantaneous bandwidth (i.e., full freq range of the ngVLA)*

***Of course, you can't always get what you want…***

# Large Area Science

● Direct Detection
● Source Stacking
● Intensity Mapping




Lidz et al. 2011

**Full Cross-Correlation with 21-cm Experiments** ● ●

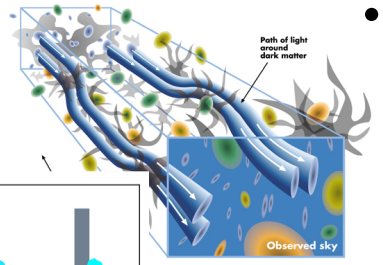
- *Highly dependent on 21-cm experimental landscape*

**[CII] in the Dark Ages of the Universe** ●

- *Dependent on cross-corr w/ strong 21-cm detection*

**Non-Gaussianity** ($f_{NL}$) ● ●

- *Multi-tracer potential*
- *Direct detections correlated against intensity map(?)*




**Weak Lensing** ●

- *Applicable to both spectral line and continuum*

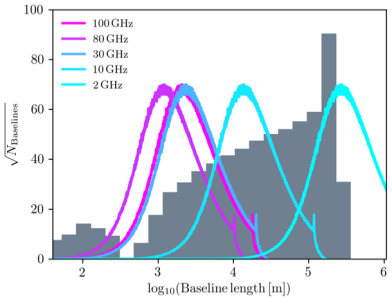



Image Credit: Ian Harrison

**"High Latitude Molecular Gas Census"** ● ● ●

- *Measurements of molecular gas over > 100,000,000 galaxies!*

**NOTICE: PRELIMINARY RESULTS, AREA STILL UNDER STUDY!**

# *Science Forecast and Conclusions*

- ngVLA wide-field surveys would have ***rich*** science potential for both cosmology and (g)astrophysics at high-redshift.
- Total power capabilities (even on a limited number of antennas) could greatly increase the science value of such surveys.

| **Small – 0.01 sr (up to 1,000 hrs)** | **Medium – 0.1 sr (up to 3,000 hrs)** | **Large – 1 sr (up to 10,000 hrs)** |
|---|---|---|
| - Meaningful constraints for CO at $z > 3$<br>- Constraints on CO line ratios at $z > 3$.<br>- *"Is there any CO-rich mol gas during the EoR and Dark Ages?"* | - Constraints on the CO LF from $0.2 \leq z \leq 10$<br>- Growth of structure, and its effect of molecular gas content<br>- Optical-radio (CO and free-free emission) correlation<br>- Cross-corr w/ 21-cm EoR experiments | - Potential cosmology apps: weak lensing, non-Gaussianity, BAO<br>- EoR measurements, cross-correlation with 21-cm experiments<br>- Fully leveraging optical surveys from Euclid, WFIRST, DESI, DES (and other wavelengths…) |

***Special thanks to Chris Carilli, Joseph Lazio, and Eric Murphy for the time spent talking about this science case!***

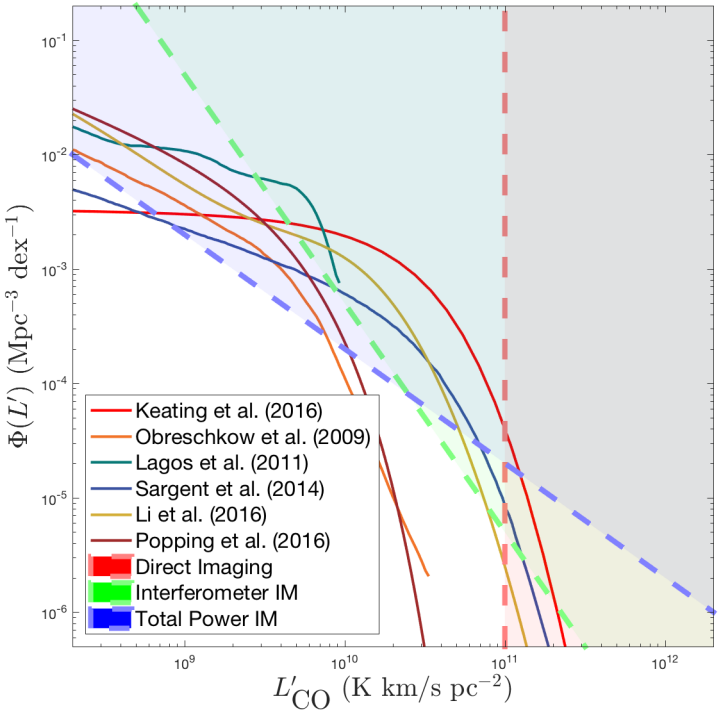
# Supplementary Slides

# The CO Luminosity Function

Luminosity function of the form

$$\Phi_{CO}(L) = \phi^* \left(\frac{L}{L_*}\right)^{\alpha} e^{-L/L_*}\, dL \quad L > L_{min}$$

*Normalization* *Low L slope* *High L Cutoff* *Low L Cutoff*

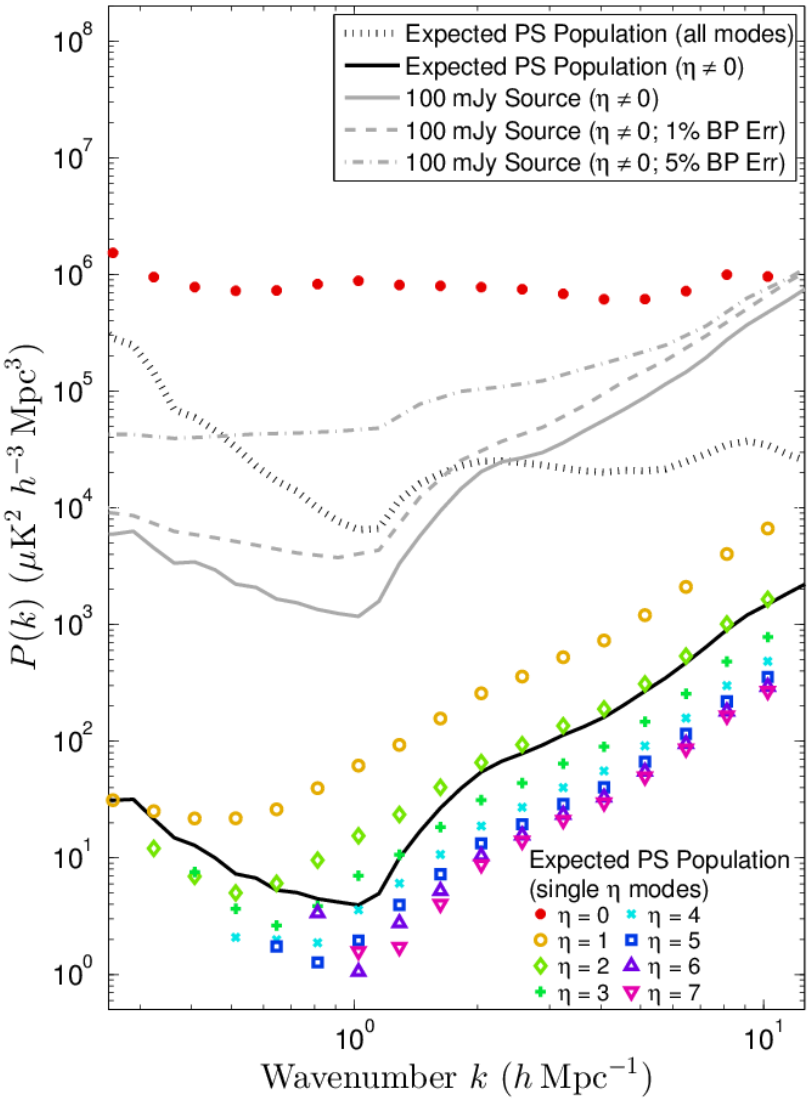


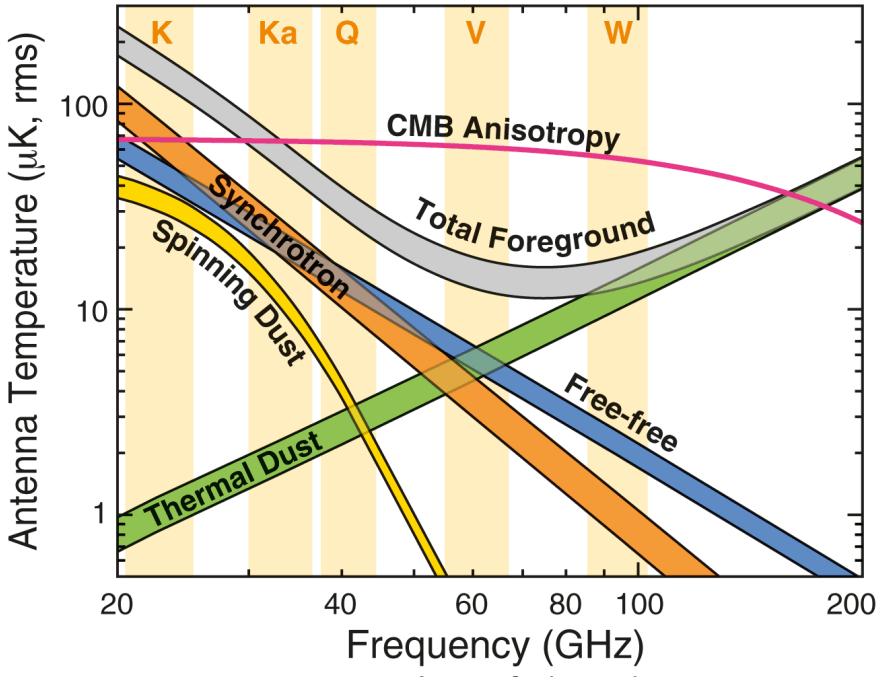

**Cluster Power**: Sensitive to the broad population of galaxies (one molecule, one vote!)

**Shot Power**: Sensitive to "luminous-but-common" systems, i.e., Milky Way-like galaxies.

# Continuum Foregrounds

Keating et al., 2015




WMAP Collaboration

**Dominant foregrounds are likely to be continuum point source and Galactic – interferometer helps with the former, CMB experiments have well-measured the latter**

# General Survey Requirements

**Systematics**:

Measurement is statistical in nature, and requires several things to ensure the fidelity of the measurement, including:

- **Bandpass stability:** < 1% errors per channel
- **Pointing stability:** < 10% FWHM errors
- **Coupling/cross-talk:** > 40-50 dB isolation between elements
  - ***NB: Exact value depends on instrument stability***
- **Primary beam fidelity:** exact requirements are array/survey-specific, but generally want to know beam within 2xFWHM
- **Polarization fidelity:** Survey-specific, 10% fidelity likely acceptable (somewhat looser at higher frequencies)
- **Noise flatness:** Would ideally want $T_{\rm sys}$ consistent to within $\sim 1$ dB over a window of $\Delta\nu/\nu \sim 30$
- **Flux Calibration:** Survey dependent, target is a few % fidelity