Cosmological Galaxy Surveys:
The Molecular Perspective

Atomic &

Steven T. Myers (NRAO)

**National Radio Astronomy Observatory, Socorro, NM*

Why this talk?

- Previous speakers have demonstrated the great promise of galaxy studies this decade
  - galaxies are full of incendiary gas, abrasive dust grains, noxious chemicals, and nuclear waste…
- But, they can also be a force for good
  - COSMOLOGY!!!
- I present sundry assertions and speculations on exploring this final frontier
  - some trailheads, if not a roadmap
  - a possible path forward

Science Goal: Cosmology

- Cosmological Galaxy Surveys
  - identify and count galaxies (traditional survey)
    - Spectra for 10^4 - 10^9 galaxies to $z > 1.5$ in > Gpc volume
  - cosmological parameters
    - "Dark Energy" (DE) via H(z) measurements (BAO &c)
  - growth of structure (counts, galaxy evolution)
  - a large galaxy database for (ga)strophysical studies
  - alternative: "intensity mapping" (angular power spectrum)
    - targeted cosmology experiments
- also Galaxy Continuum Photometry
  - synchrotron / free-free in Milky Way-like galaxies
  - weak lensing studies (DE), AGN surveys

A Game of Questions

- The Themes
  - Cosmic Dawn
  - Physics of the Universe
  - Discovery, Origins, Cosmic Order, Frontiers of Knowledge
- The Questions
  - How do cosmic structures form and evolve?
  - Why is the universe accelerating?
  - What is the fossil record of galaxy assembly and evolution from the first stars to the present?
  - How do baryons cycle in and out of galaxies and what do they do while they are there?

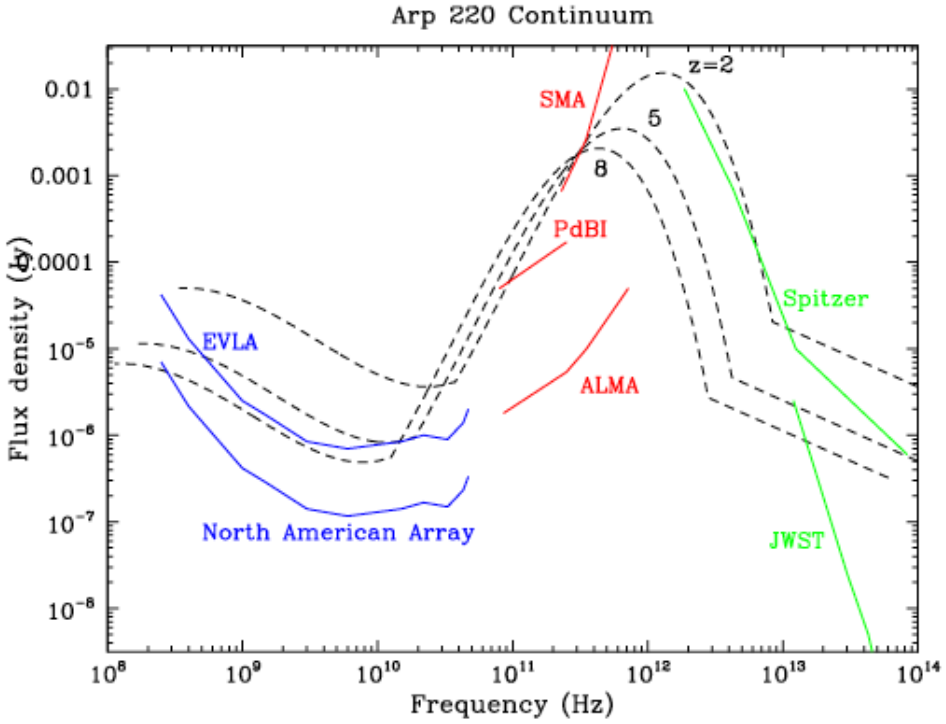
A multi-purpose galaxy survey for all!

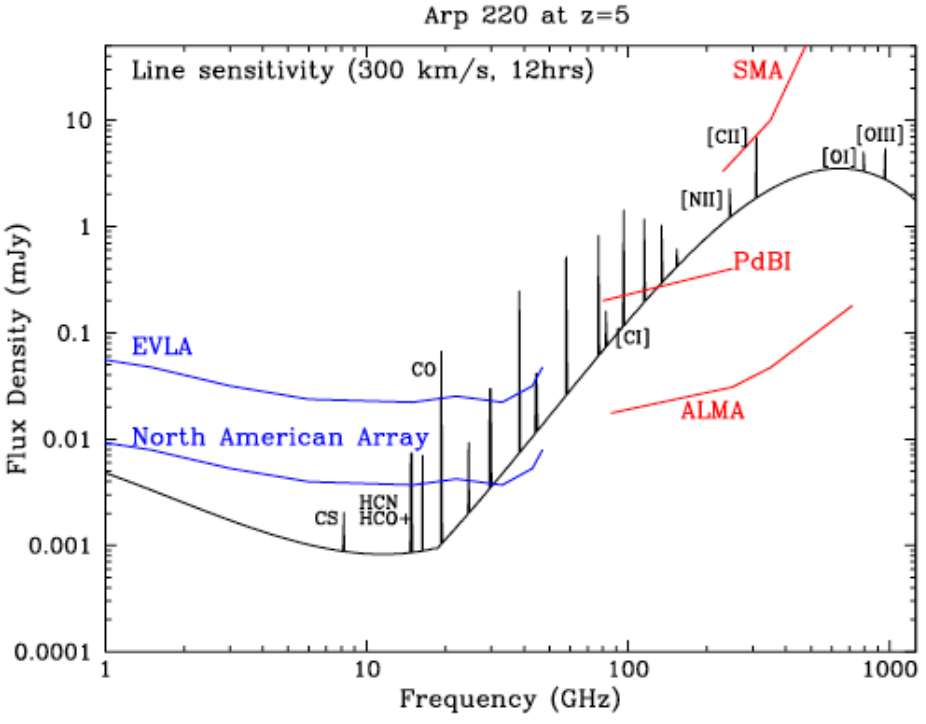
The Probes: Key UFIR Lines

- 1 - Atomic Hydrogen (weak transition)
  - HI line (rest 1.42 GHz, z=1.5 at 568 MHz)
  - single line in “clean” part of spectrum
    - single line redshift determination almost assured
- 2 - Molecular CO (strong transition)
  - CO ladder (1-0 rest 115.27 GHz, z=1.5 at 46.11 GHz)
  - whole J ladder of lines (115,230,345,460…)
    - no ambiguity in redshift if multiple transition seen
  - forested area of spectrum
    - danger: many weaker lines could contribute to correlated signal
- 3 - High-J CO and C+
  - CCAT: Stacey, Glenn talks (possibly the winning approach)

Landscape: Galaxy Spectra

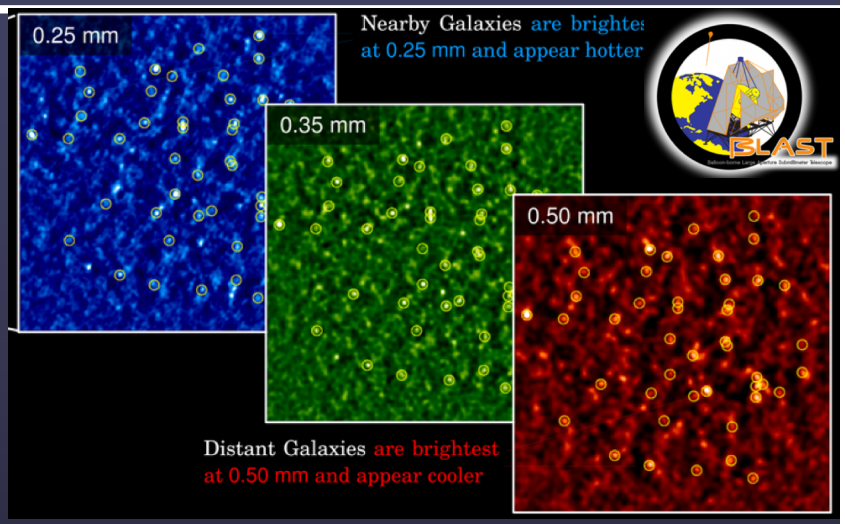
- Lines and continua of star-forming galaxies
  - see Carilli talk





From Myers et al. NAA Astro2010 white paper

Launchpad: High Redshift Galaxies



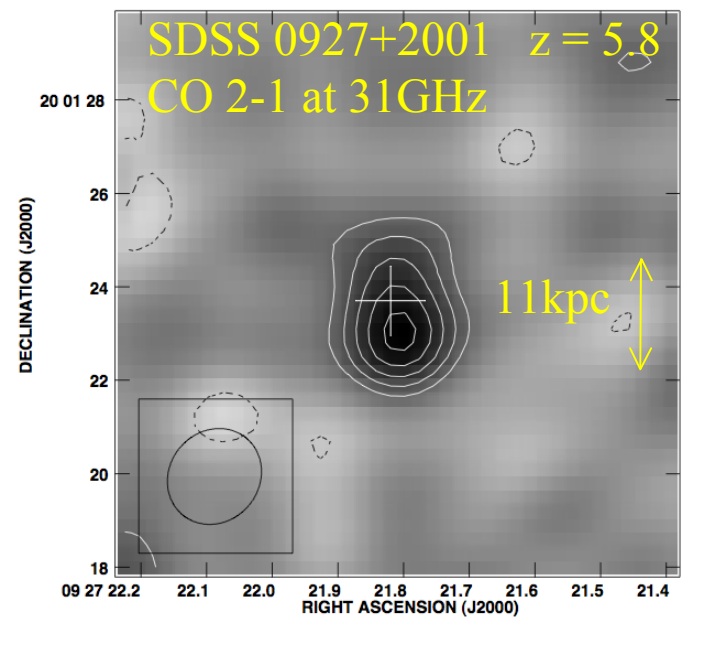
- mm/sub-mm/IR
  - dusty galaxies, ULIRGS,
  - we have the ABCs:
    - ALMA, BLAST, CARMA, CCAT, …
    - and ACT, APEX, …
- sub-m (HI)
  - local universe z<0.2: Arecibo, EVLA, GBT, Parkes, &c
  - GBT correlation with O/IR z=0.8 (Chang et al.)
  - pave the way: need next-gen facilities for high-z
- our departure point: cm
  - redshifted CO lines (EVLA, GBT), continuum

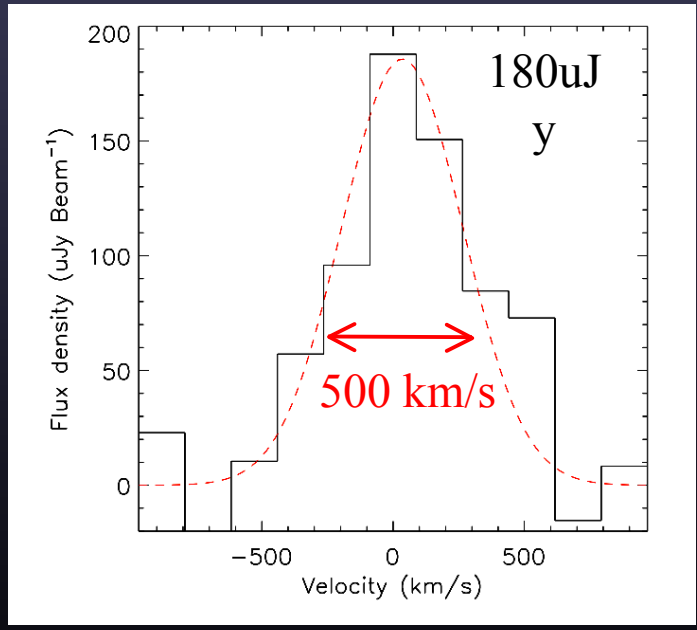
State of the Art: EVLA

- EVLA early science:

Approaching first light: molecular gas in z~6 quasar host galaxies

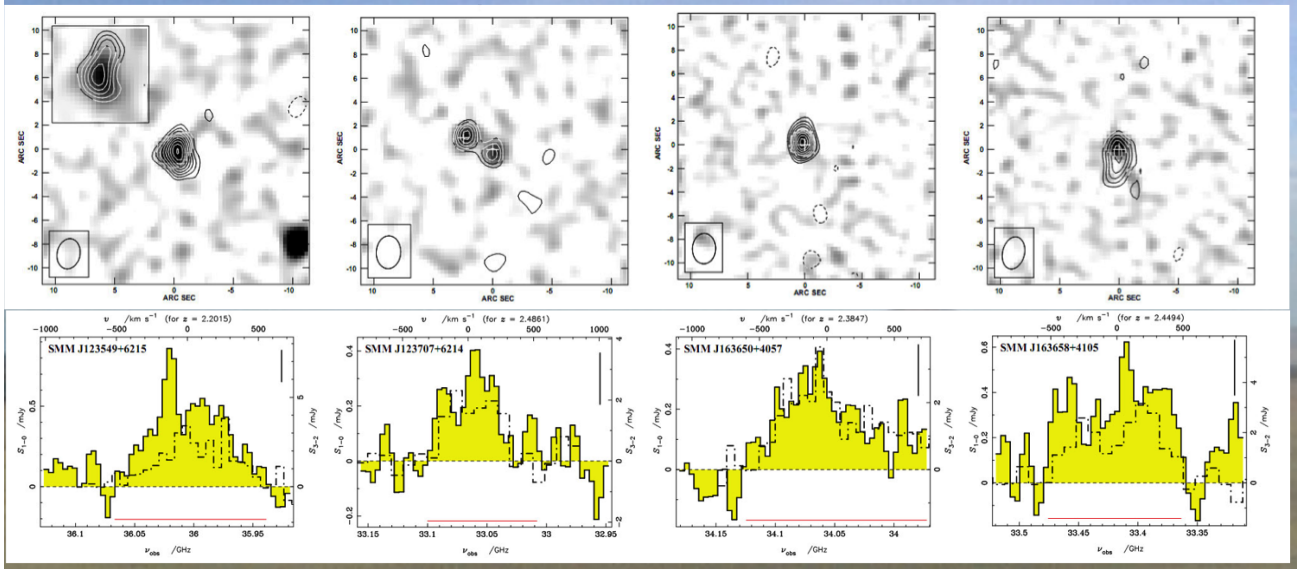
‣ Coeval formation of SMBH and massive galaxies within 1Gyr of Big Bang



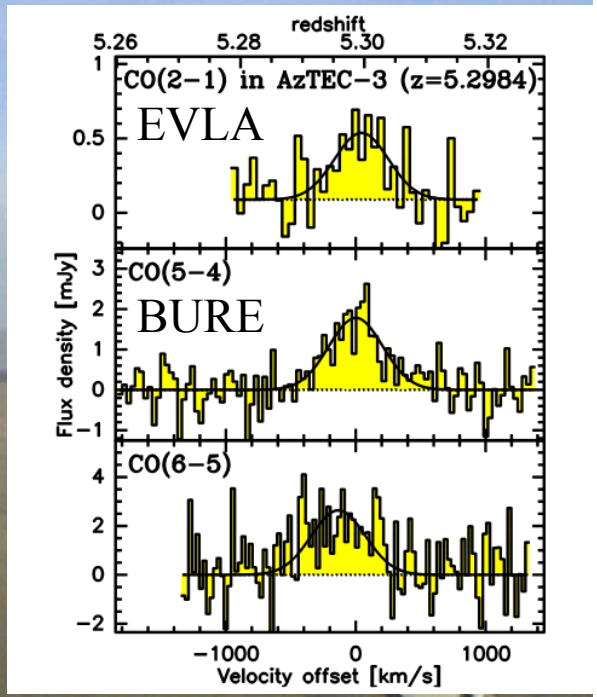


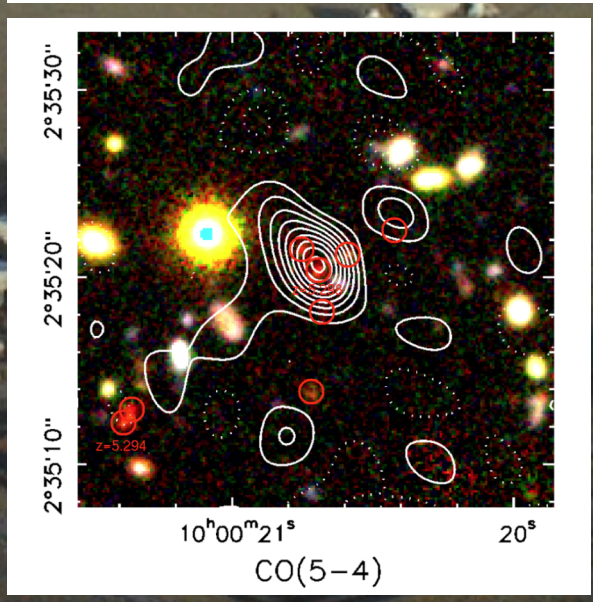
Wang, Wagg et al.

Blue Skies over the EVLA



Extended, low excitation CO in z~2.3 SMG (Ivison ea)





Courtesy C. Carilli

Multitransition CO study of most distance SMG z=5.3 (Riechers, Capak ea)

Cosmology Projections

- Galaxy counts and power spectra
  - **Righi et al. (arXiv:0805.2174)**

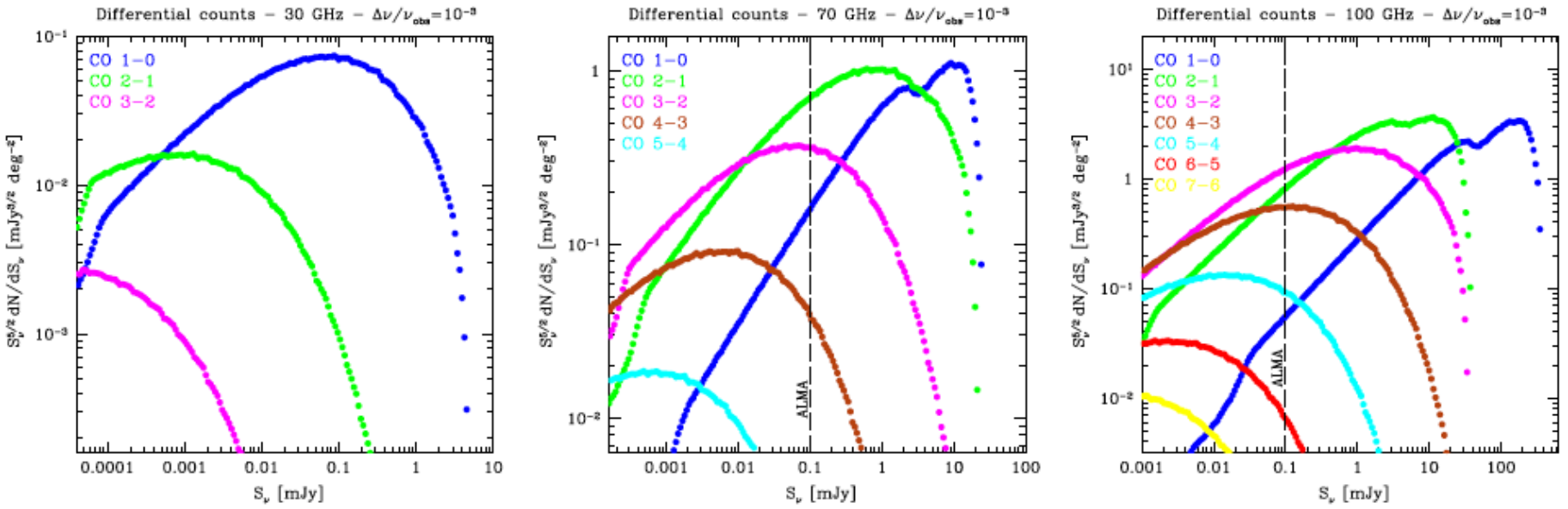


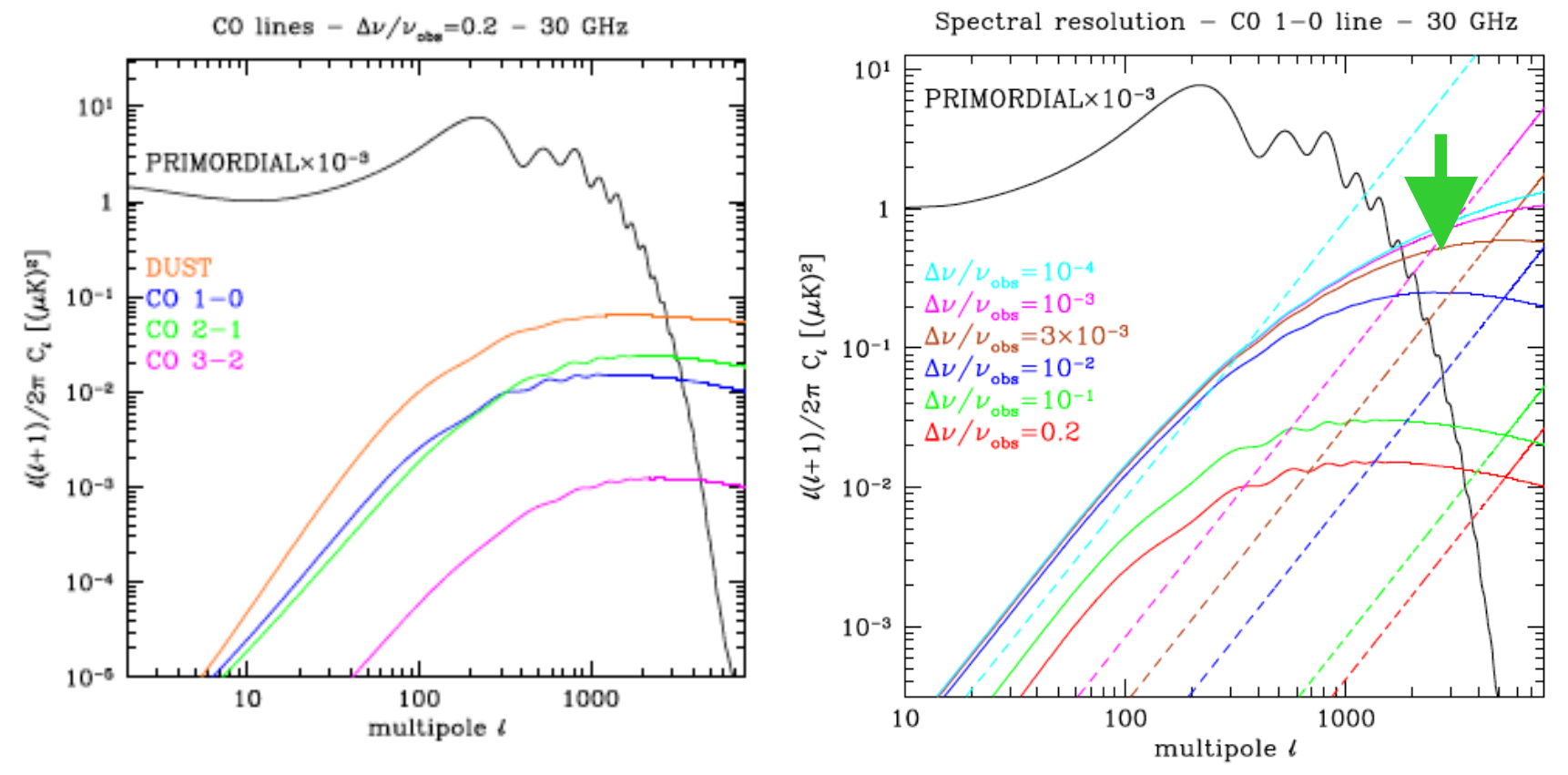
Fig. 3. The predicted differential source counts for the CO lines at 30, 70, and 100 GHz, for a spectral resolution $\Delta\nu/\nu_{\rm obs} = 10^{-3}$. The vertical line is the expected sensitivity of ALMA to the line emission, computed for the same spectral resolution and an integration time of 3 hours.

Cosmology Projections

- Galaxy counts and power spectra
  - **Righi et al. (arXiv:0805.2174)**
  - **Gong et al. (arXiv:1101.2892)**
  - **Carilli (arXiv:1102.0745)**
- Upshot
  - **~10/sq.deg. $\Delta z \sim 10^{-3}$ at 0.1 mJy at 30 GHz B=30MHz**
    - **EVLA ~ 30 min integration**
  - **integrated signals ~1 μK (need Bt~10^{15} for Tsys~30K)**
    - **for 1 GHz BW need Msec integration**
  - **fluctuations 0.1 this level for $\Delta z < 10^{-2}$**
    - **want equivalent of multiple "beams", careful calculations**
  - **cross-correlation with galaxies and HI (e.g. EOR)**

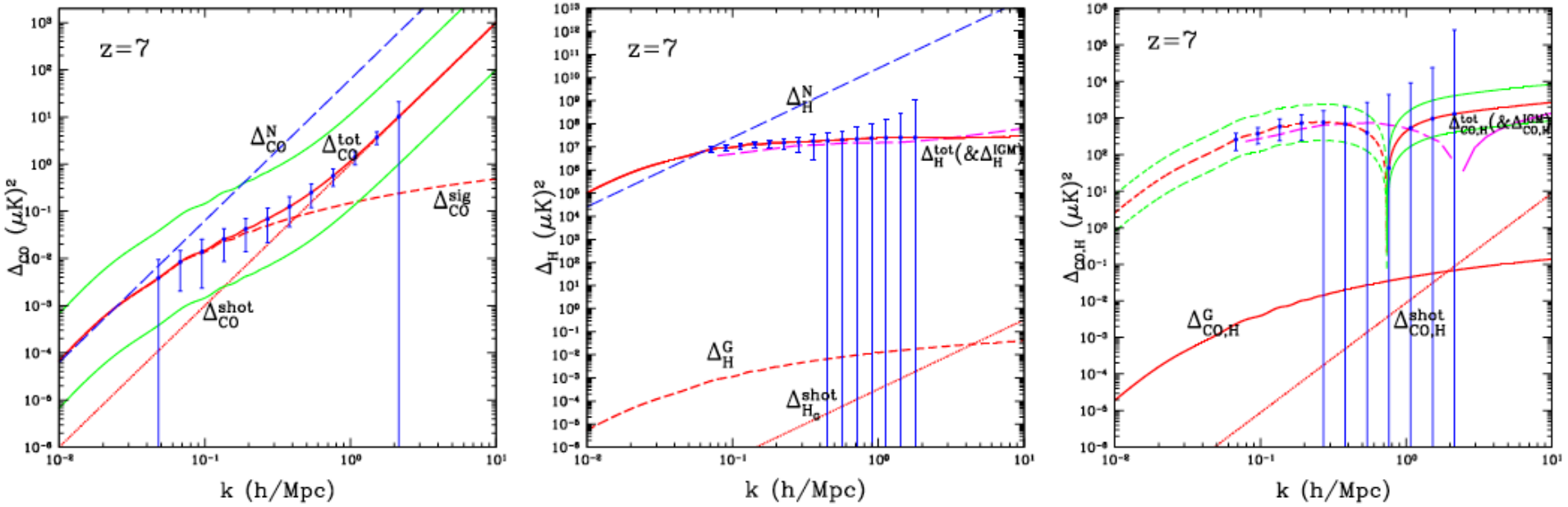
Projections

- Galaxy counts and power spectra
  - **Righi et al. (arXiv:0805.2174)**



Projections

- Galaxy counts and power spectra
  - **Righi et al. (arXiv:0805.2174)**
  - **Gong et al. (arXiv:1101.2892)**



(L) CO power-spectrum (M) HI power-spectrum (R) CO-HI cross-power
CO z=7 @ 14.4 GHz HI z=7 @ 177 MHz

Instrumenting the Science: 2010-2020

- Current facilities, including
  - Expanded Very Large Array EVLA (NM)
  - Arecibo Observatory AO (PR)
  - Green Bank Telescope GBT (WV)
  - ALMA (Chile), ACT, APEX, SPT…
  - CARMA (CA), SMA, …
- Later this decade, including
  - ASKAP (Australia)
  - CCAT (Chile)
  - LMT (Mexico)
  - HERA-II (?)
  - MeerKAT (S.Africa)
- We have a wealth of instruments! Use them.

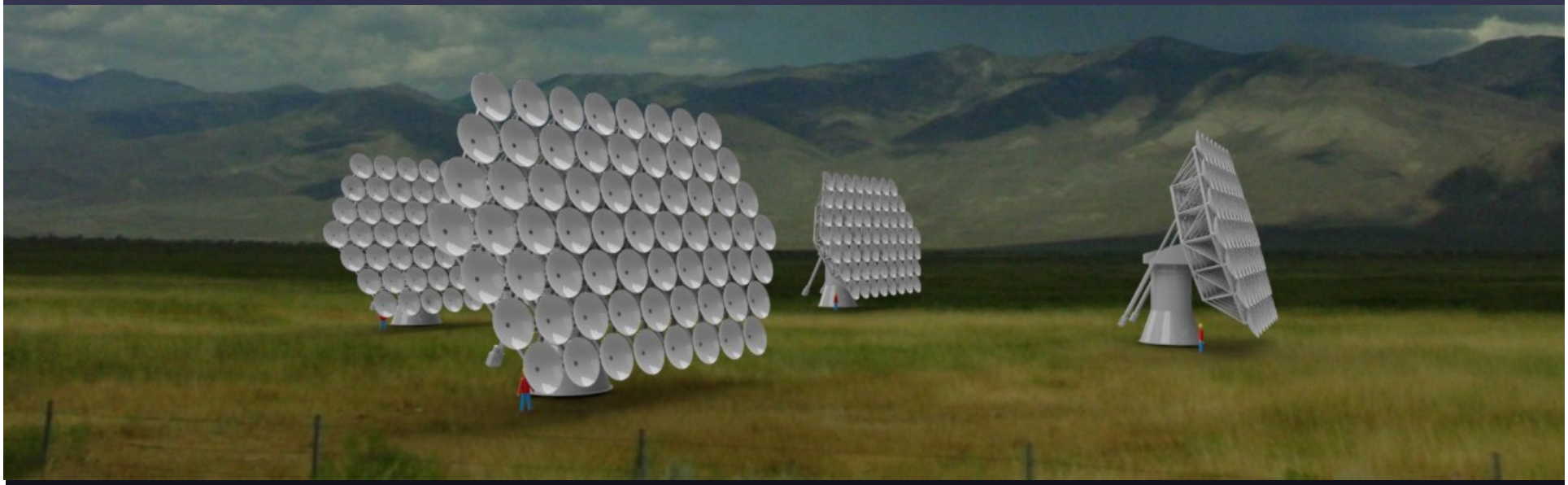
Instrumenting the Science: Innovate!

- Example: DACOTA (Bower et al. poster)

Dense **A**rray for **CO**smology and **T**ransient **A**strophysics

An Array Concept for this Decade

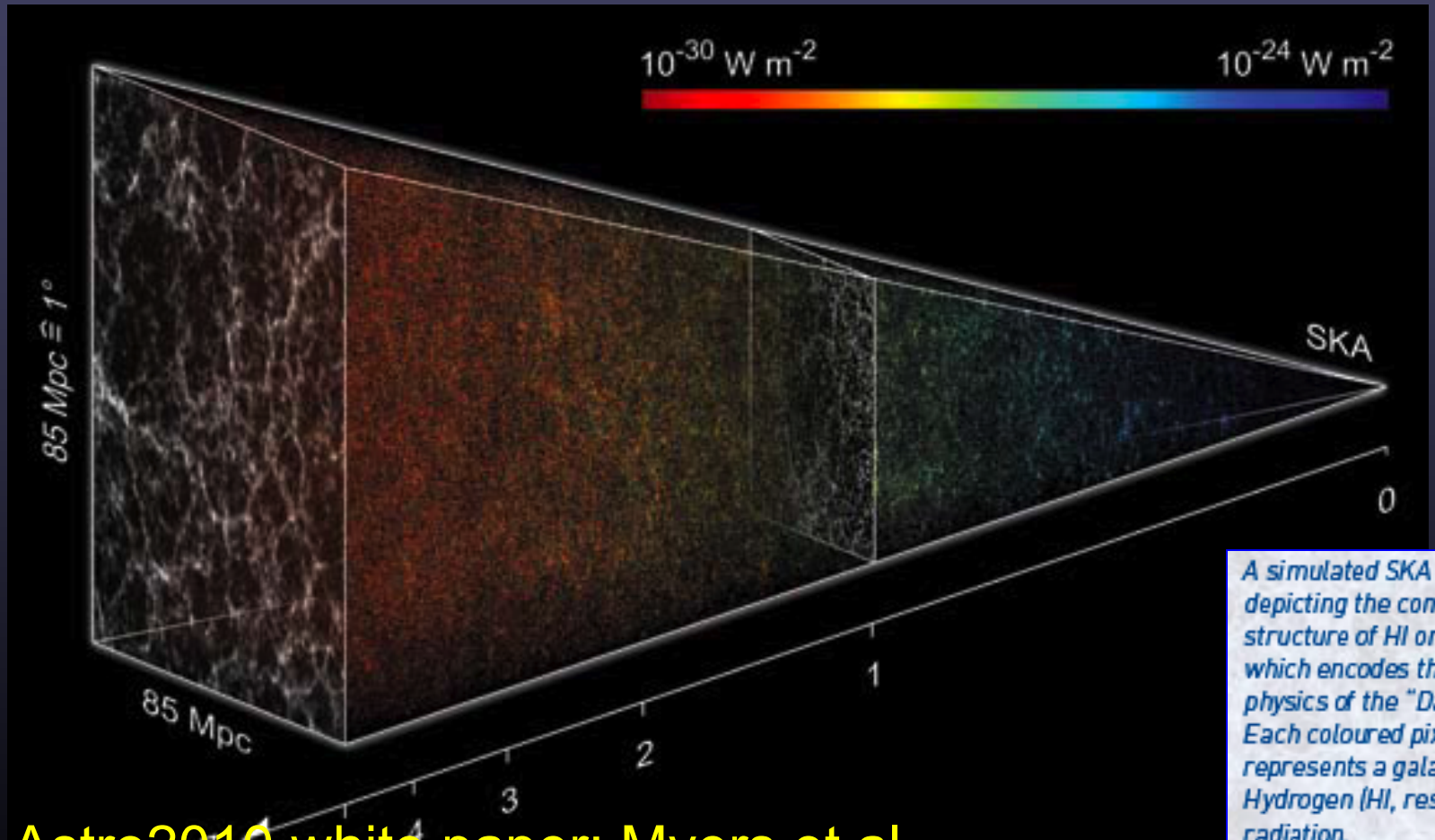
Geoffrey C. Bower, David R. DeBoer, Matt C. Fleming
(UC Berkeley)



- Example: GBT cameras
  - spectroscopic cm surveys, counterpart to LMT and CCAT

Final Fantasy MMXXV: SKA

- Billion Galaxy HI survey to z > 1.5



A simulated SKA observing cone depicting the complex filamentary structure of HI on cosmic scales, which encodes the mysterious physics of the "Dark Universe". Each coloured pixel in the cone represents a galaxy emitting neutral Hydrogen (HI, rest-frame 21-cm) radiation.
(Credit: Danail Obreschkow (Oxford) and the SKADS Sky Simulation team.)

Astro2010 white paper: Myers et al.
arXiv:0903.0615

Instrumenting the Science: 2020+

- Ultimate Radio Cosmology
  - m: HERA-III
  - sub-m: the Square Kilometer Array (SKA)
  - cm: the "North America Array" (NAA)
- Towards a North America Array
  - future evolution of NA facilities (EVLA, GBT, VLBA, &c)
  - collecting area: 10 x EVLA (half on "VLB" baselines?)
  - key science ("SKA High"):
    - astrometry
    - "ALMA science" at high-z and in obscured regions
      - detailed (sub-arcsecond) imaging as well as detection
  - for more info:
    - http://www.nrao.edu/nio/naa/

North America Array: (r)Evolution

- A heterogeneous array network
  - e.g. EVLA + GBT + VLBA (20% there already!)
  - baselines from 10-m to 3000-km not homogeneous!
  - not all parts operate together all the time
- New model for facility program development
  - community must have science ownership (not NRAO)
  - network sites throughout North America : opportunities
    - local university involvement (like old US VLB Network :)
    - can antennas be affordable (commodity, like ATA concept)?
  - the long view : a phased approach
    - need not build all at once, adopt “HERA-like” strategy
    - different parts different timescales (e.g. CO vs. astrometry)

What Next?

- Molecular Galaxy Cosmology
  - needs more science development (decade of discovery)
    - warning: still need to crunch the numbers in detail
    - what is the right approach (cm vs mm/smm)? multiple probes?
- A New Decade of Innovation
  - investigation of more novel concepts (e.g. DACOTA)
  - TDP2: can we make cm-capable elements cheaper?
- Towards a North America Array
  - good words in Astro2010, look to Astro2020 and beyond
  - science ownership: the University community future
    - a chance to evolve and adapt the facility paradigm
  - need community proponents and champions
    - I hope some are in this room!