Radio Cosmology in the era of LSST

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Cosmology

- Cosmological parameters & large-scale structure surveys
- Reionization probes
- Two fun sciences/experiments with radio cosmology

Cosmology post Planck

- Is it still interesting? Do we need even smaller error bars?
- Not end of story - we still don't know the initial conditions, dark matter, and dark energy.
- Need to nail parameters with LSS surveys
  - Dark energy (for wCDM, best probe at $z<2$).
  - Curvature (LSS geometry probes): $d\Omega_k < 10^{-3}$?
  - Sum of neutrino mass (damping of p(k)): $dE < 0.01eV$
  - Non-gaussianity (scale-dependent bias): $df_{nl} < 1$?

Large-scale structure probes

- Besides (next generation) CMB polarization, actions are here.
- CMB: ~2D information, mode # ∝ $(l_{max})^2$
- LSS redshift surveys: 3D information, mode # ∝ $(k_{max})^3$
  - shot noise dominates p(k) at high wavenumber k
    - shot noise ~ 1/n_gal
      - n_gal = 10^{-4} h^3 Mpc^{-3} (SDSS, WiggleZ)
      - n_gal = (3-5) x 10^{-4} h^3 Mpc^{-3} (BOSS, HETDEX, HSC, PFS)
      - n_gal = 10^{-3} h^3 Mpc^{-3} (Euclid, LSST)

What can (low-freq) radio do?

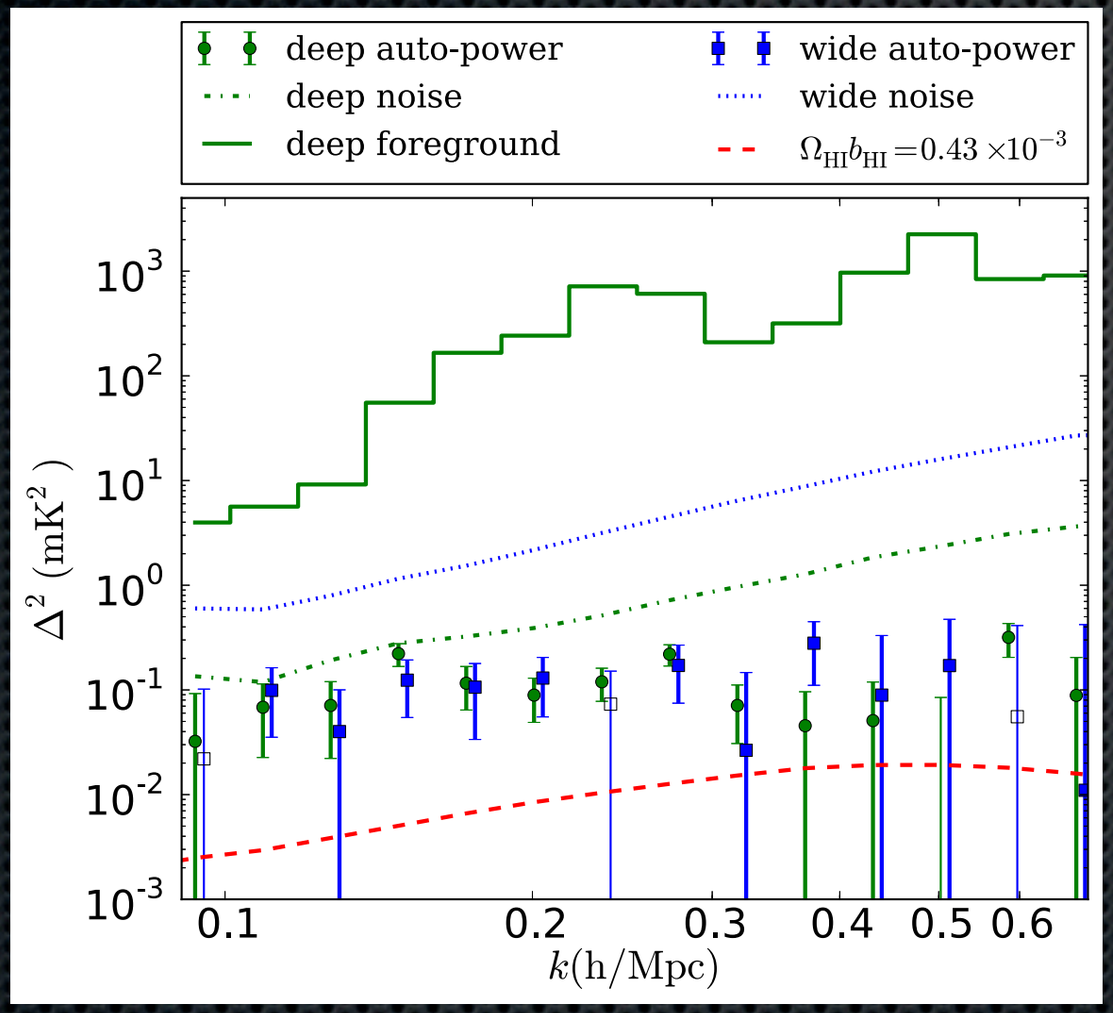
- Emission v.s. absorption (21-cm forest; difficult)
- Continuum emissions (see Matt Jarvis' talk)
  - "thresholded": radio continuum sources (e.g., FIRST, NVSS, EMU, LADUMA surveys. Owen & Morrison 08, Condon+ 12)
  - "non-thresholded": radio background intensity and fluctuations (e.g. ARCADE-2, Fixsen+ 09)
- Line emissions (in particular, HI 21cm)
  - "thresholded": "SKA: billions of HI galaxies at z>1" (e.g., Verheijen+ 10, Fernandez+ 13). MeerkAT and ASKAP surveys. Gas and galaxy evolution.
  - "non-thresholded": 21cm Intensity Mapping (e.g., Chang+ 08, 10, Masui+ 13, Switzer+ 13) for LSS; Reionization probes.

21cm Intensity Mapping

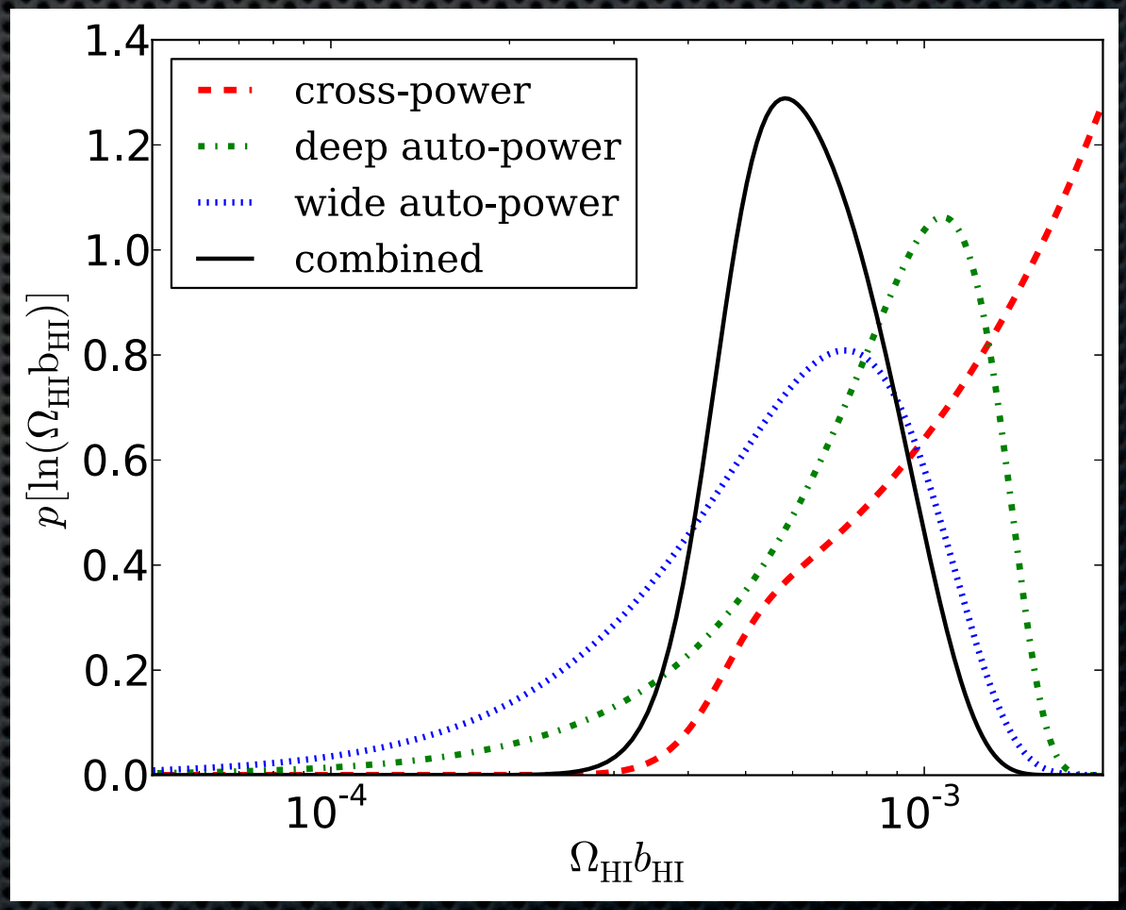
- Measure HI associated with large-scale structure instead of with galaxies (Wyithe & Loeb 08, Chang+08, Seo+10).
- CMB-like, but measure 3D temperature fluctuations.
- Low angular resolution, high spectral/redshift resolution - tangential to photometric redshift surveys.
- Provides a broad redshift window ($0< z < 25$) and offers an economical way for a powerful LSS survey.
- Confusion limited. Observational challenges: Foreground/ signal > 10^3. RFI.
- Initial results are promising (Chang+10, Masui+13, Switzer+13) but needs to be further verified.

21cm Intensity Mapping

- Current limits on 21cm auto power spectrum and measurements on $\Omega_{HI}\, b_{HI}$ at z=0.8 using the GBT.

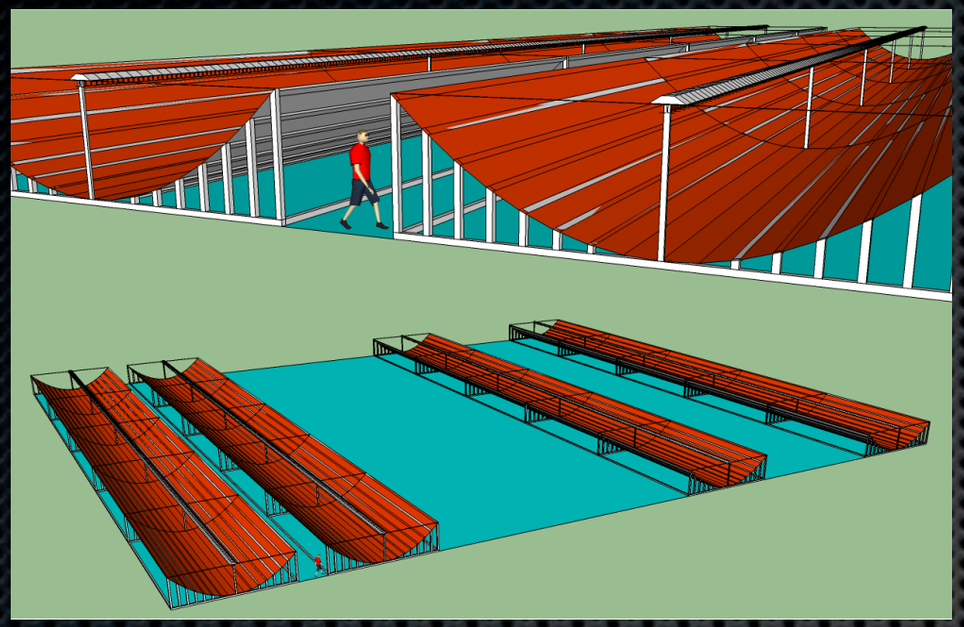


Switzer+ 13, the GBT-HIM team



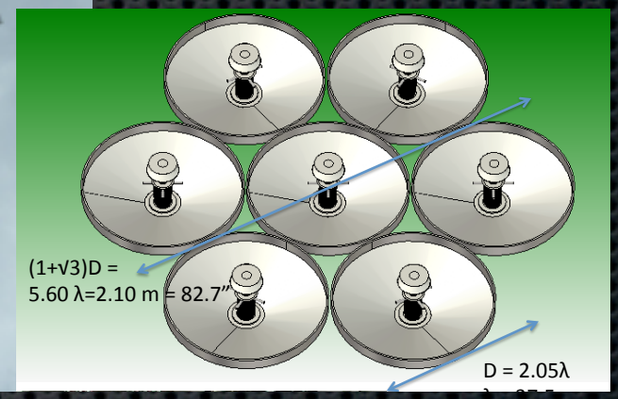
- $\Omega_{HI}\, b_{HI} = [0.62\ ^{+0.23}\ _{-0.15}] \times 10^{-3}$

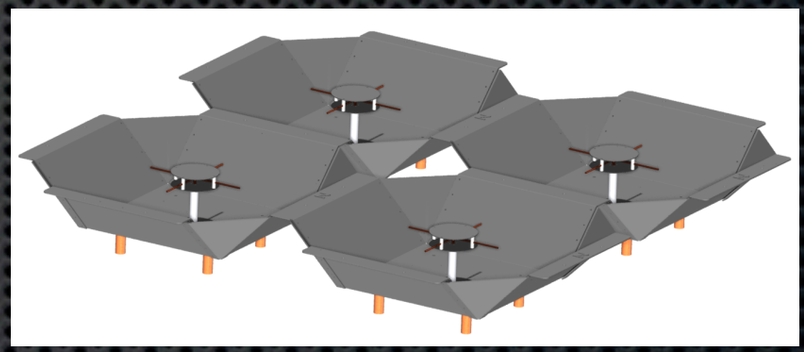
21cm Intensity Mapping current/future telescopes



CHIME/Tian-Lai/CRT/BAORadio

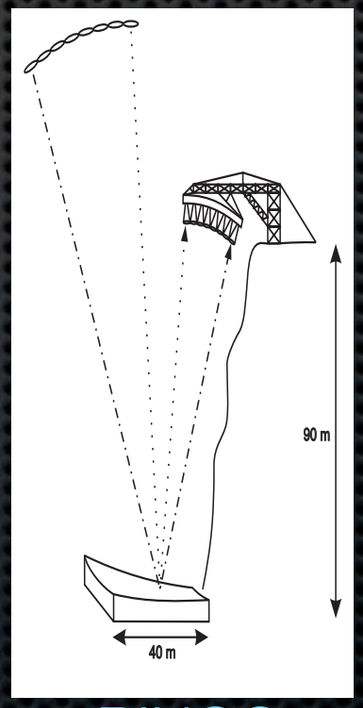
GBT-HIM multi-beam



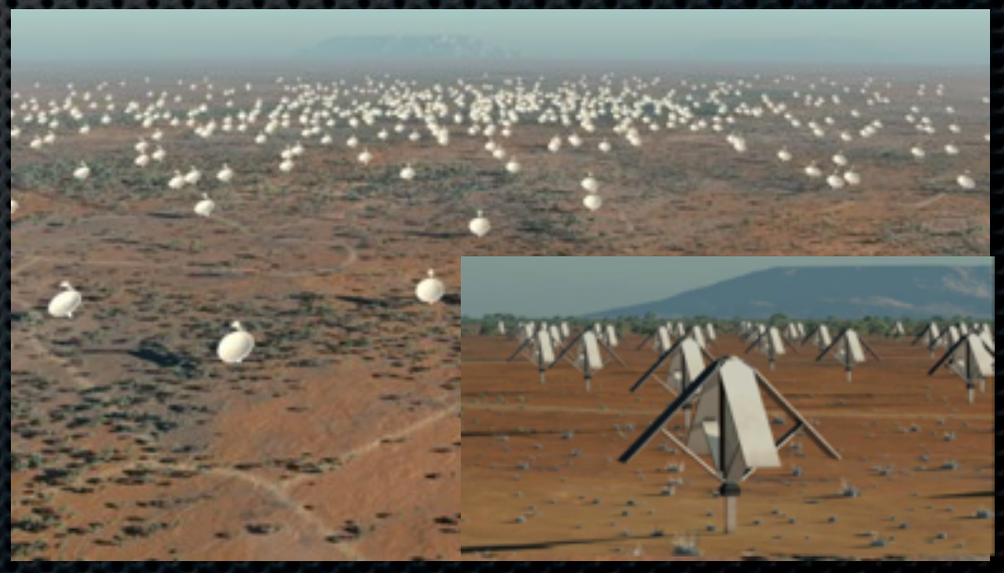


BAOBAB

FFT/OMNISCOPE Telescope



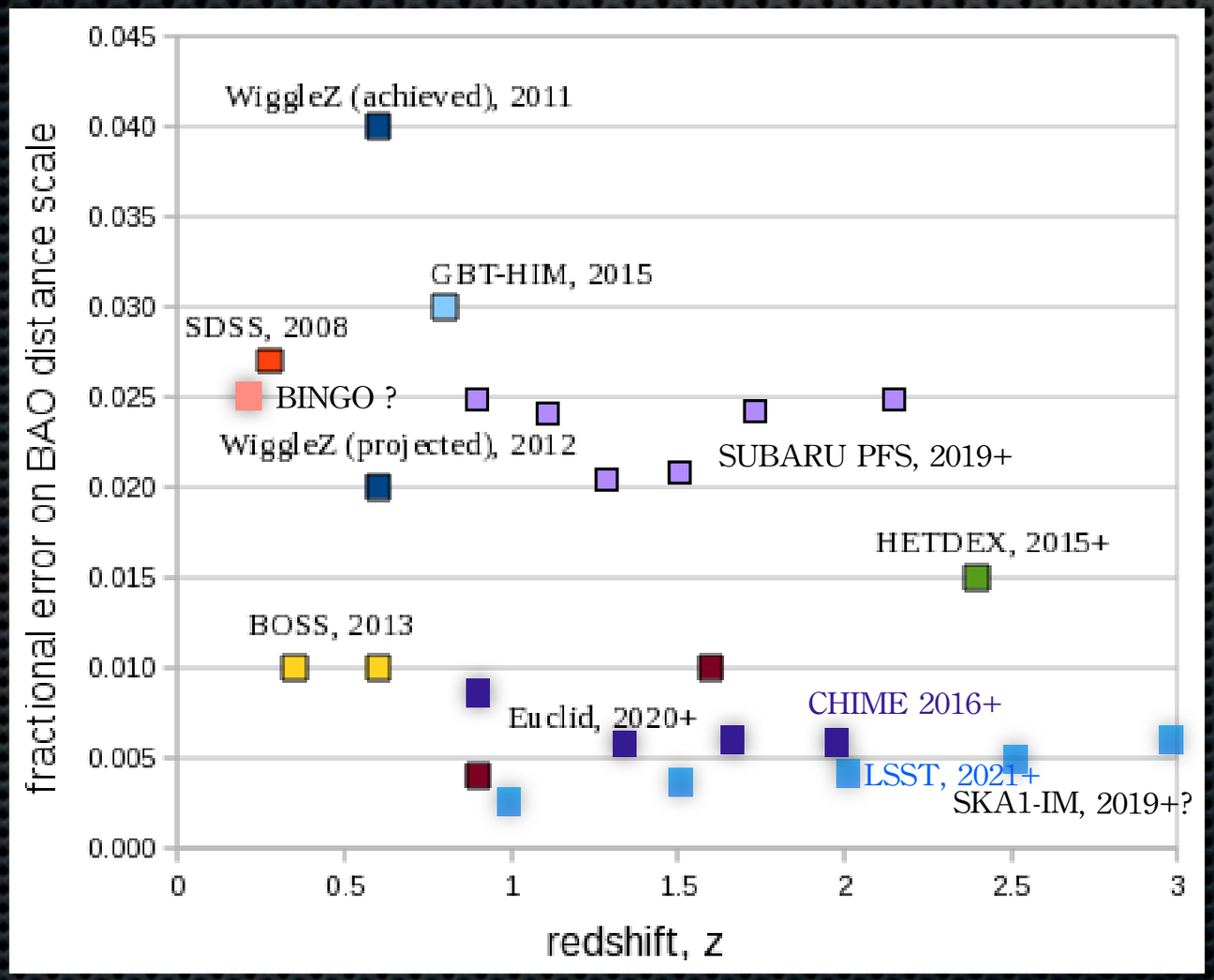
BINGO



SKA-low and SKA-mid Telescope

21cm Intensity Mapping

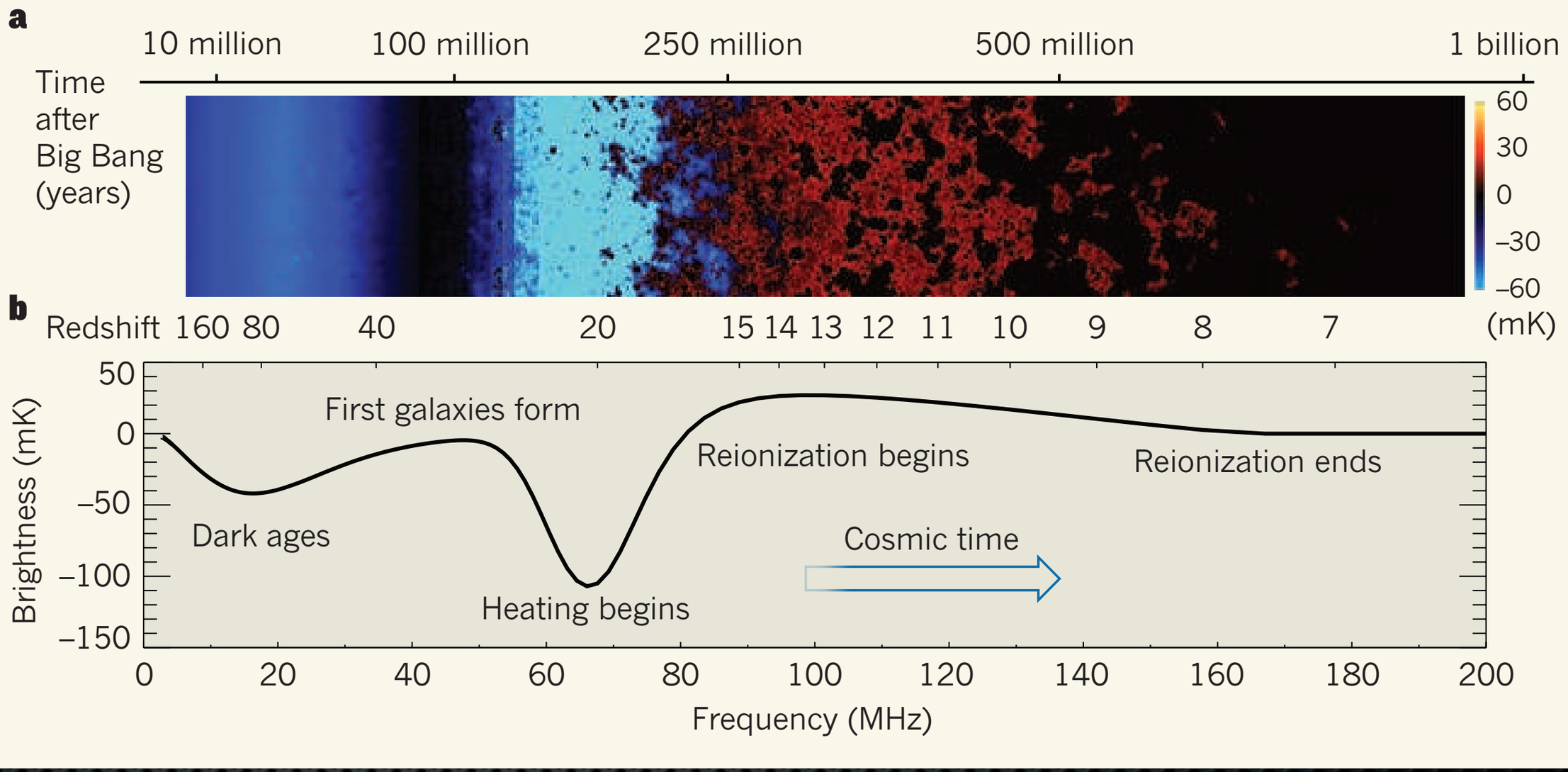
- Forecasts on Baryon Acoustic Oscillation (BAO) distance scale.



Radio-Optical synergy

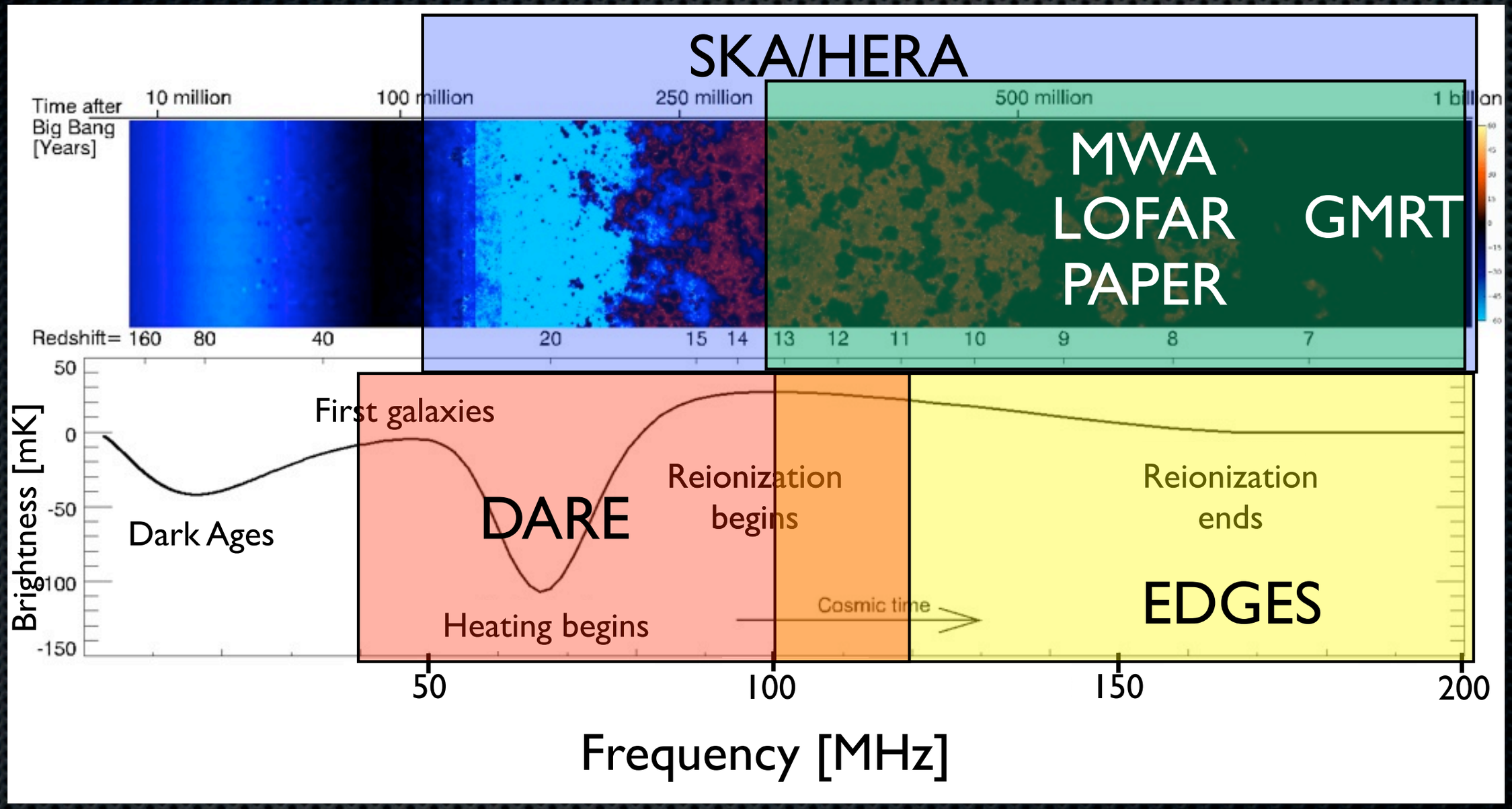
- Cross-correlating radio continuum sources and LSST samples to obtain redshift distribution of radio sources (e.g., Menard+ 13, Sam Lindsay's talk).
  - With dn/dz, besides galaxy-galaxy, galaxy-shear, shear-shear, and cosmic shear measurements (Minh Huynh's talk), one can do magnification lensing using radio continuum sources.
- Cross-correlating galaxy-scale 21cm emissions with LSST sample to help sharpen the photo-z accuracy.
- Cross-correlating 21cm intensity maps with LSST samples (accurate redshift info v.s. accurate angular info) to extract more info? See talk by Albert Stebbins.
- Cross-correlating for BAO and RSD measurements using multi-tracer (McDonald & Seljek 08), eliminating cosmic variance.

Reionization probes



Pritchard & Loeb (2010)

Reionization probes



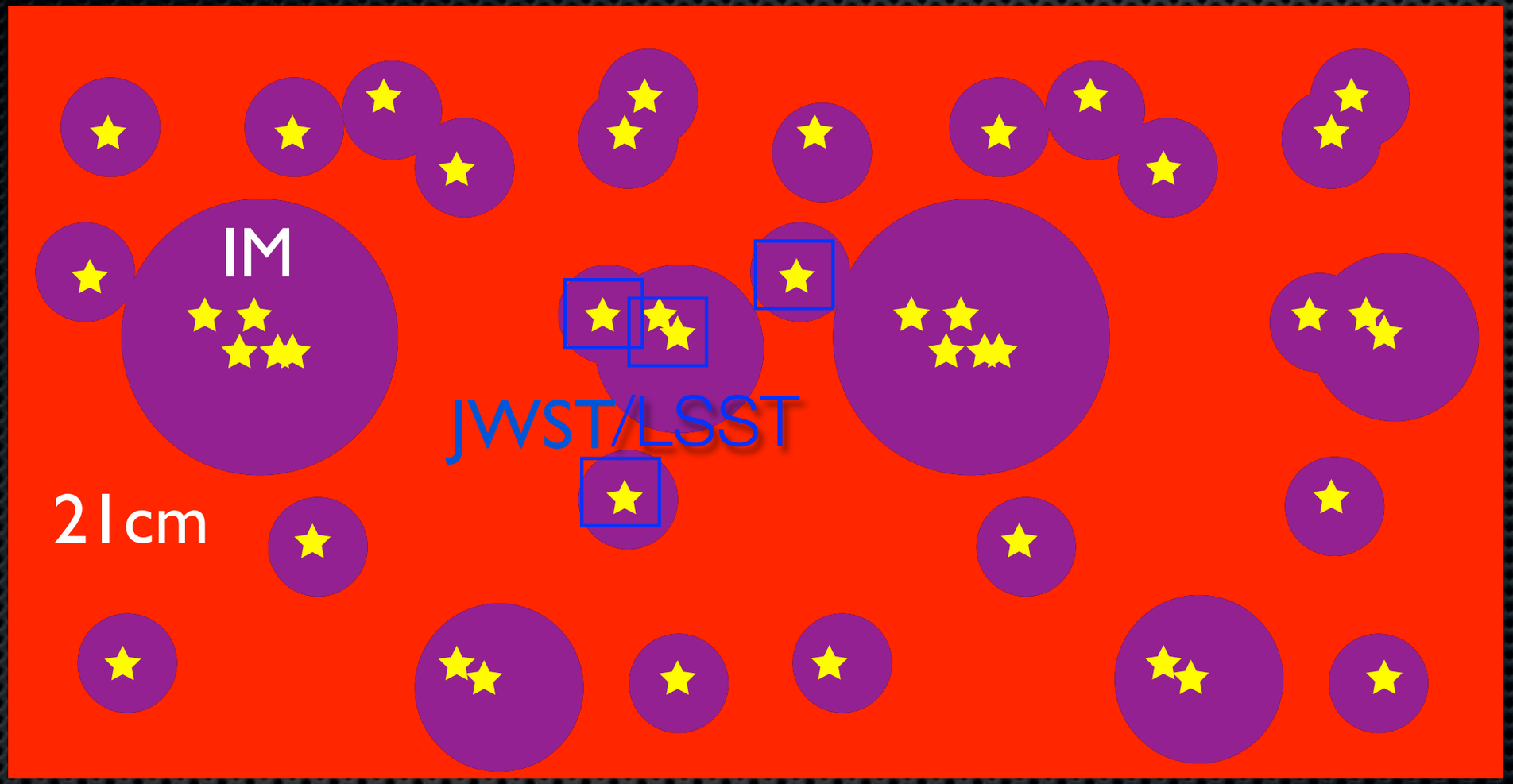
Pritchard & Loeb (2010)

Reionization p(k) current limits

- GMRT: <256 mK at z=8.6
  Paciga, .. Chang+ 13
- PAPER: <52mK at z=7.7
  Parsons+ 13
- MWA: <300mK at z=9.5
  Dillon+ 13

Radio-optical/IR synergy

Pritchard & Loeb 2012

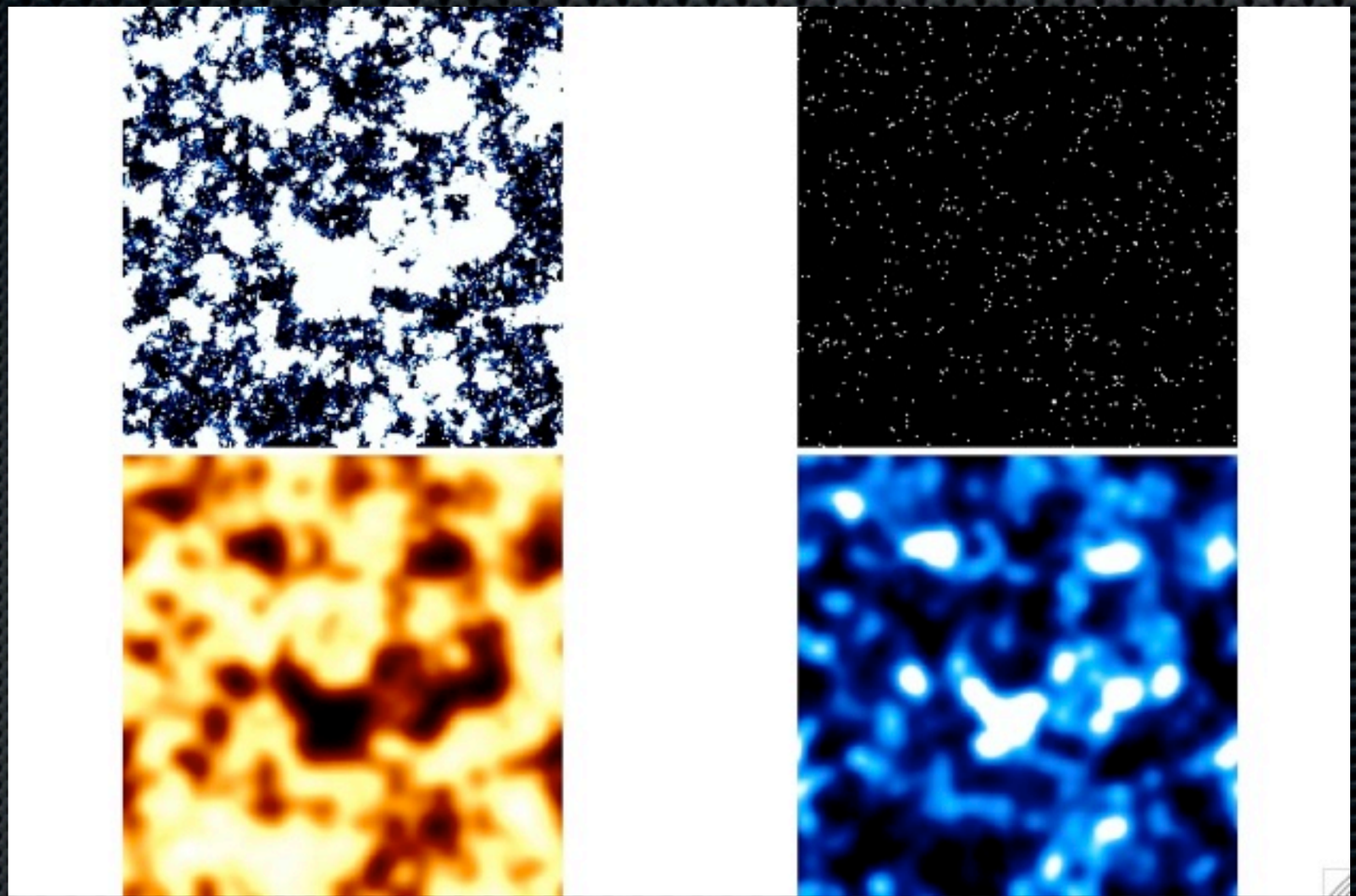


- LSST can find many high-z sources to be followed up by JWST.
  - with dropout techniques
  - with galaxy clusters as lenses
- Luminosity function (z), accounting for ionizing photons.

Radio-optical synergy

Lidz, Furlanetto, Oh, Aguirre, Chang, Dore, Pritchard 2011

Ionization field



galaxy/halo field

HI field

CO field

- HI-Co anti-correlates on large-scales, constraining size evolution of ionized regions at EoR (Lidz et al. 2009)
- CO Intensity Mapping may be a viable way of probing reionization (Gong+10, Carilli 10, Lidz+11)

Other experiments in radio cosmology

- Masers (H_2O maser at 22GHz)
  - Megamaser Cosmology Project for direct Ho measurements (Braatz, Henkel+12, Kuo+12, Reid+12).
- Strong gravitational lenses (ALMA lensing at 345GHz)
  - Sub-mm bright galaxies by Herschel/SPT tend to be strongly lensed (Vieira+ 13, Hezaveh+ 13a).
  - With velocity information, radio lenses are promising tools for halo substructure and small-scale matter power spectrum measurements with ALMA (Hezaveh+ 13b), which can't be done in the optical.

Cosmology

- Cosmological parameters & large-scale structure surveys
  - Intensity Mapping a promising approach for powerful and economical LSS probe
- Reionization probes
  - 21cm fluctuations probe reionization tomography at $6 < z < 20$
  - 21cm global temperature probes IGM evolution at $6 < z < 27$
- Two fun sciences/experiments with radio cosmology