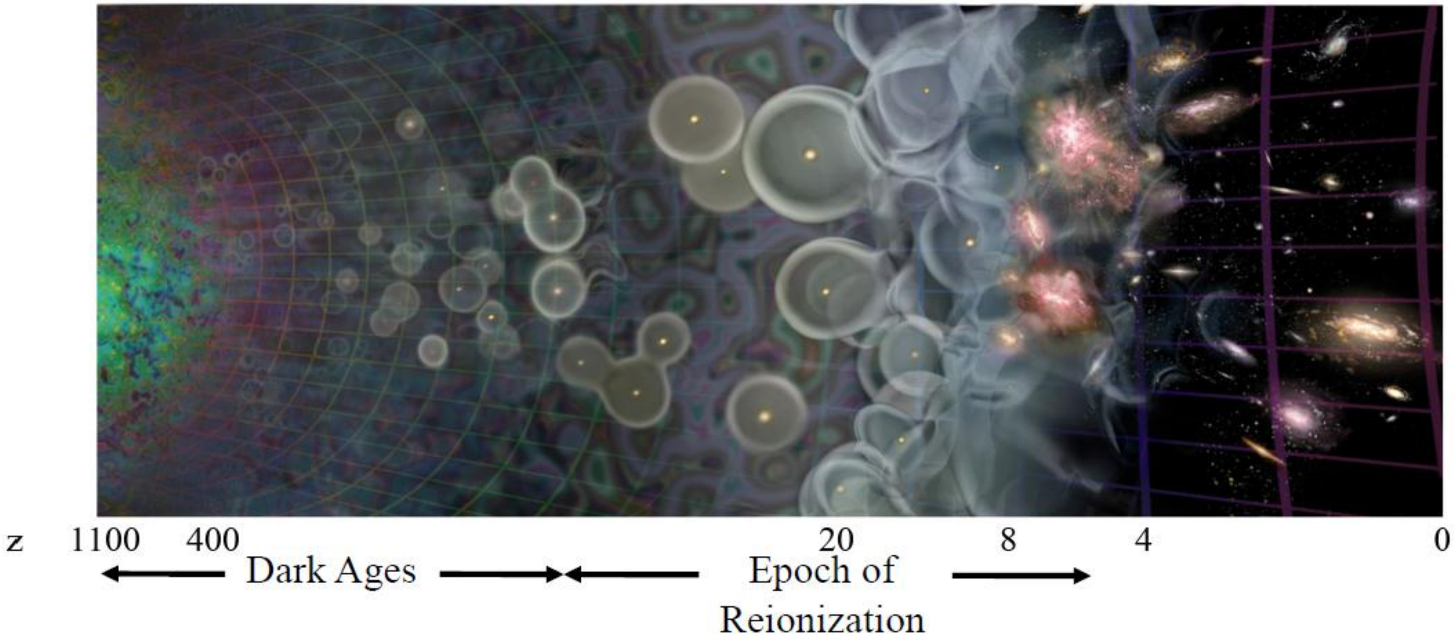
Mapping CO at Reionization: A pathfinder telescope

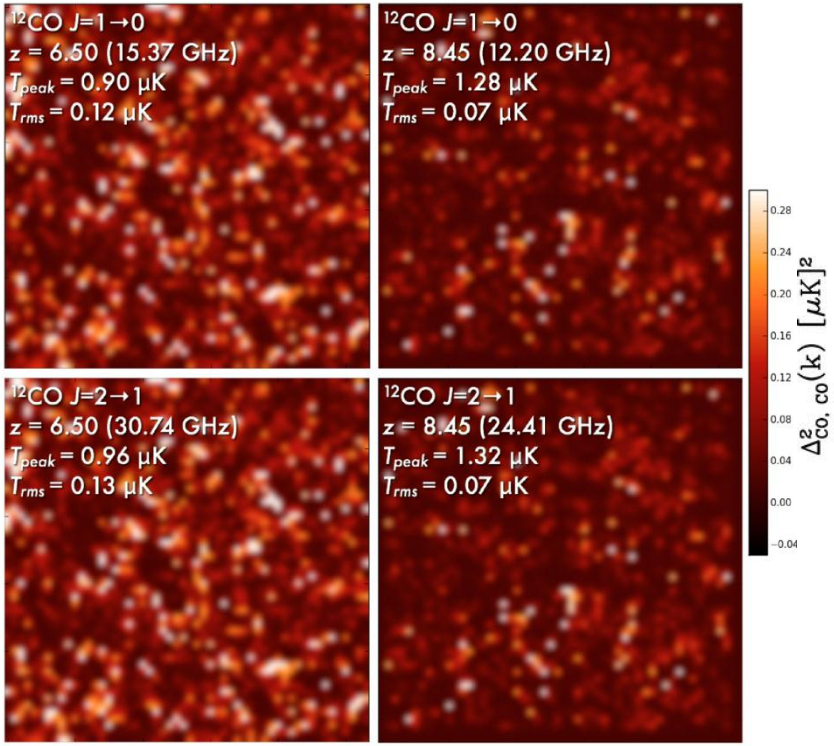
Jamie Leech
Michael Jones
Angela Taylor
Ian Heywood
Garret Cotter
+ Keck Institute of Space Studies (KISS)
Workshop collaborators (Caltech/JPL, Berkeley, Stanford)

Science: Introduction

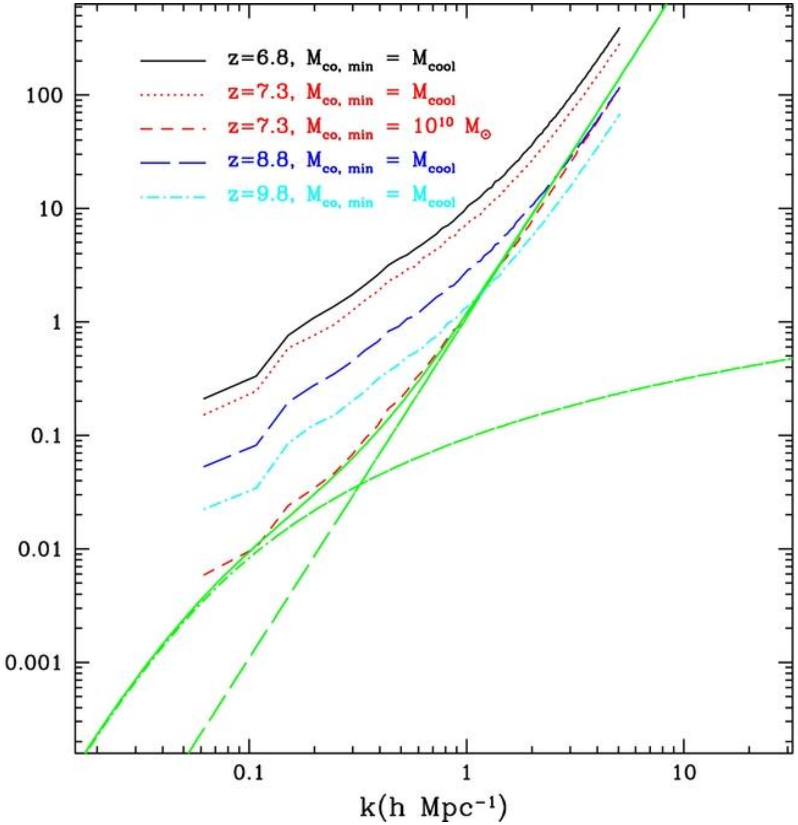


- First stars form out of primordial hydrogen (z = 7-10).
- CO molecules trace H_2 and sites of massive star formation driving the EoR.
- CO dipole moment → line emission (unlike H_2).
- While HI emission better traces total mass, CO emission traces the matter that is forming the first stars .
- Conveniently multiple CO rotational lines (e.g. J=1-0, 2-1, 3-2) will allow unambiguous detection in the presence of foregrounds.
- HI and CO will correlate on larger scales and anti-correlate on smaller scales, showing the extent of the re-ionization "bubbles".

Science: Simulations, expected Power spectrum

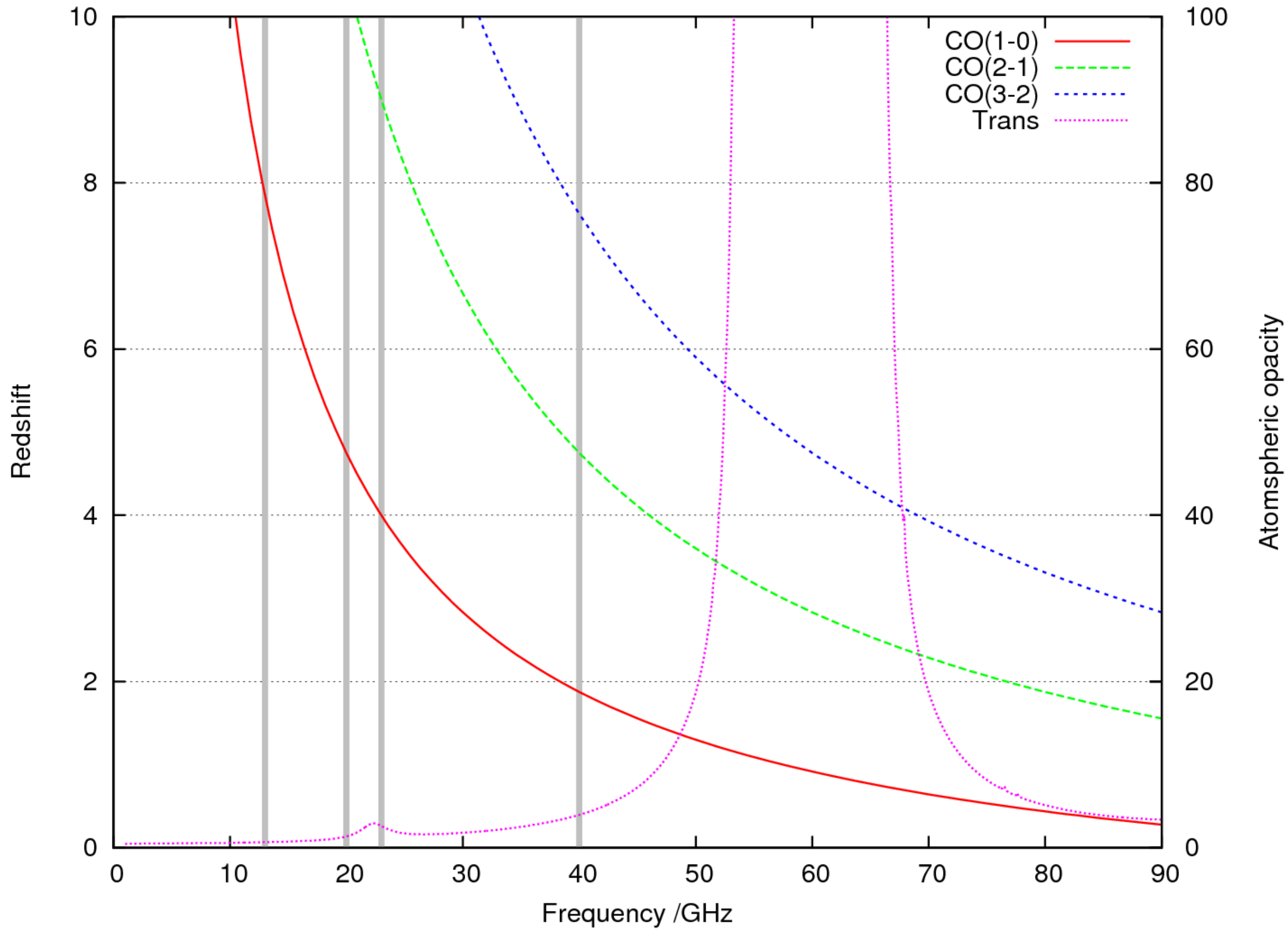


Predicted aggregate CO intensity z = 6.5-8.45, (over 5 sq. degs, resolution 5 arcmin, 1.5 Mpc at z=8), based on S^3-SAX (Heywood et. al. in Prep., Obreschkow et al. 2009)



Auto power spectrum of CO brightness temperature (Lidz et al 2011), for various values for the host halo mass of CO luminous galaxies.

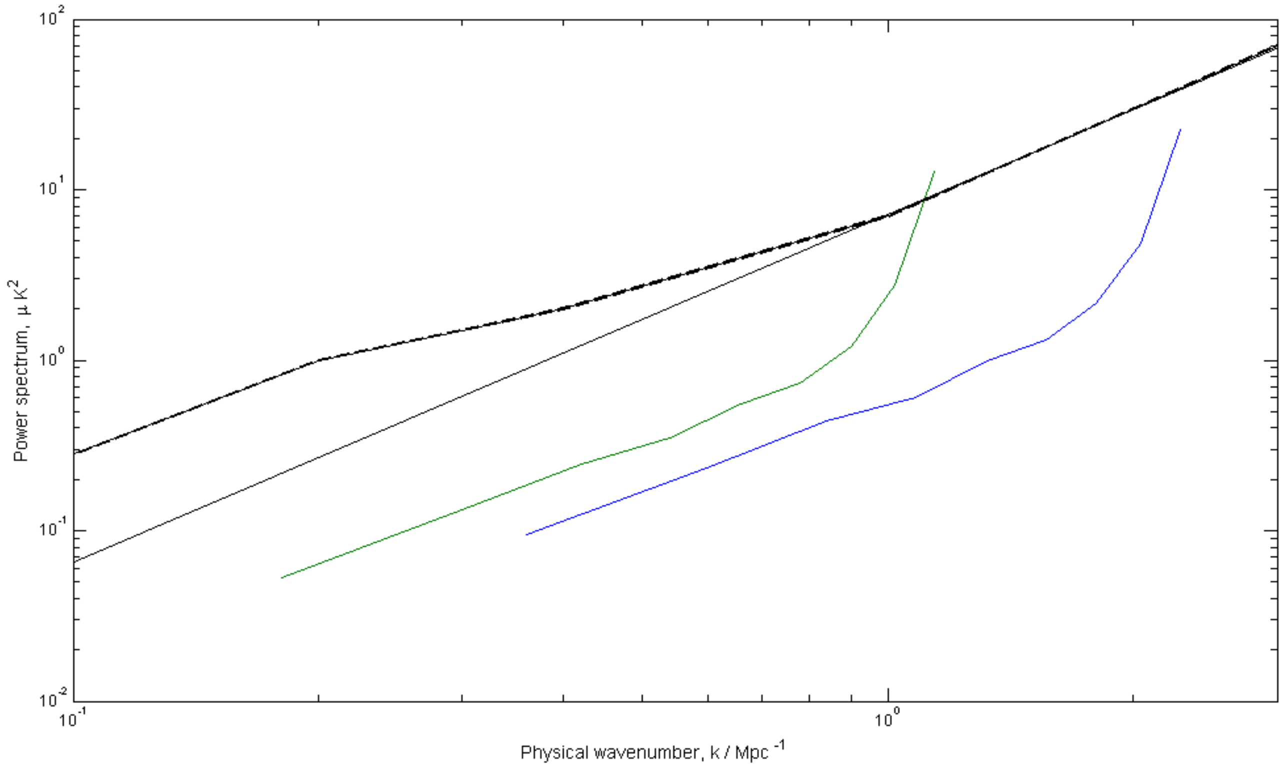
Science: Observability from the ground and space



Atmosphere opaque above ~40 GHz, but

- CO(1-0) ($z>2$) observable in Ku band,
- CO(2-1) ($z>5$) and CO(3-2) ($z>7.5$) observable in Ka band.
- CO(2-1) and CO(3-2) observable from gas at **same redshift** in Ka band – **v. important** when removing foregrounds.

Science: Observability from the ground and space



- **Solid line:** Predicted CO power spectrum z = 7. (Lidz et. al (2011),
  - Model with $M_{CO} = 10^8 M_{sun}$ (largest signal amplitude)
- **Coloured lines:** thermal noise in a 100 MHz freq. bin after 7000 hours, Ku band (green), Ka band (blue) 6-m dishes, 19 feeds.

Specifications for a full survey telescope

- No existing telescope can detect more than a few brightest galaxies. We want full 3-D power spectrum between $z = 3 - 10$
- **1 Mpc** corresponds of **5′** at redshift of EoR, and **~150 MHz** in ν-space.
  - Dish size/baseline of 5-15 m at frequencies of interest (15-40 GHz)
- Full sky maps ~2 years requires:
  - a **single dish telescope ~ 10-20m** with **~1000 elements** in the focal plane
  - or: **a compact interferometer**, with **~30 antennas**, each with 30 horns in the focal plane.
- **Large single dish**
  - more expensive and prone to scan sensitive systematics,
  - simpler backend spectroscopic backend.
- **Interferometer**
  - less prone to atmospheric and amplifier gain fluctuations,
  - large, expensive digital correlator for backend.
- **Frequency resolution** = $\Delta\nu/\nu \sim 10^{-3}$
- **Instantaneous IF bandwidth** ~ 3-10 GHz.
- **Sensitivity** = ~0.1 μK /pixel /month for ~2 years.

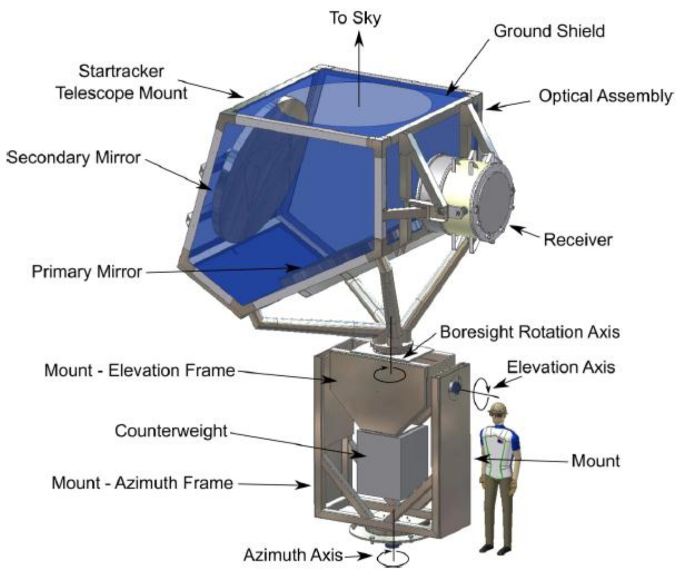
Proposed Pathfinder telescope(s)

- **Pathfinder Telescope ideas:**
  - 19-element focal plane array on a 1.8-m (Clover) telescope, $\nu = 26 – 40$ GHz. ~20 arcmin (~10 Mpc) resolution. Technology prototype for a single element of a much larger (30 element array).
  - 19-element focal plane arrays on two 6-m (C-BASS, OVRO) dishes. Would allow observing in two bands, Ku band ($\nu = 13 – 20$ GHz) and Ka band ($\nu = 26 – 40$).

- **Science Aims for the Pathfinder:**
  - Prove the technology (horns, OMTs, amplifiers, backend) is scalable to the required ~1000 mapping pixels for future full-sky instruments.
  - Map around ~100 square degrees of the sky.
  - Unambiguous detection of two lines e.g. arising from emission at the same redshift (e.g. J=2-1 and J=3-2 at z = ~7.6).

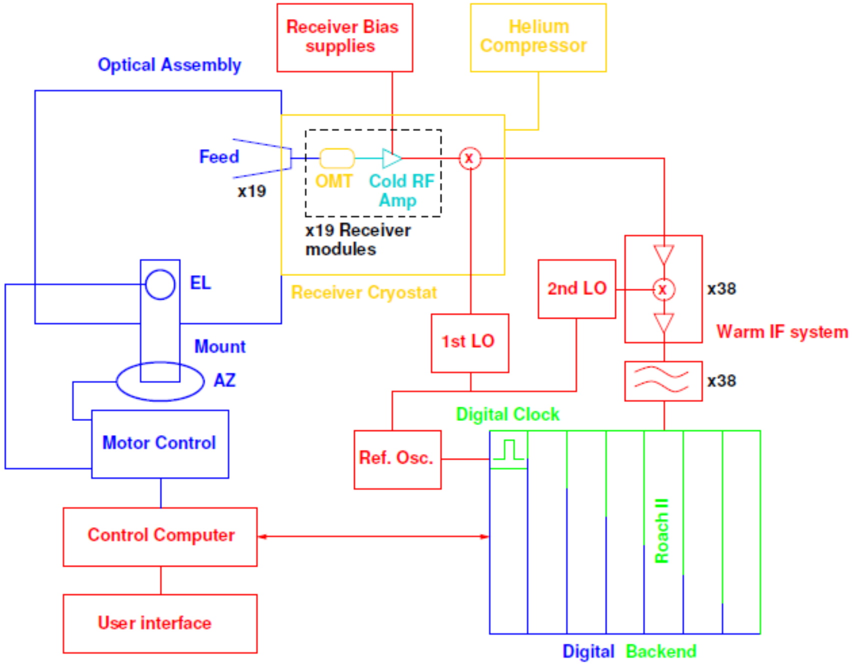
Pathfinder telescope: Dishes and Optics

- Could use an existing compact range antenna (Clover project for 87-230 GHz).
    - optically perfect at the lower frequencies of 26-40 GHz.
- Or: Use 2 6-m ex-NASA Deep Space Network dishes at Owen's Valley. Resolution better matched to ~ 5′ required. Surface good to 40 GHz

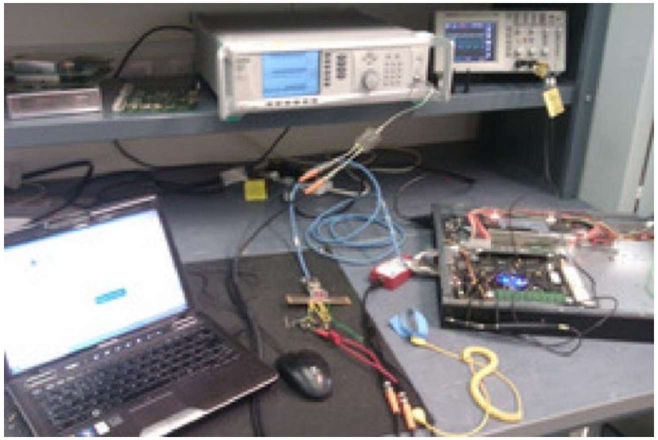


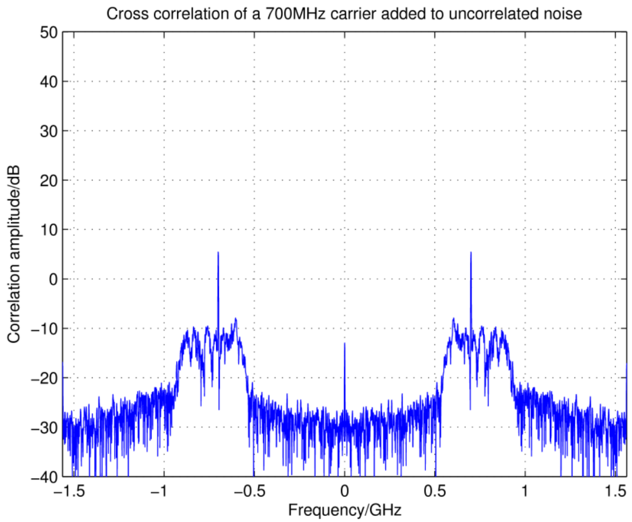
Pathfinder telescope: Feeds, OMTs, RF frontend

- **Feeds:** Large focal plane will accommodate 19 close packed horns in a suitable cryostat. Feed horns could be traditional corrugated horns or smooth-walled horns with multiple flare angle discontinuities, developed at Oxford.
- **OMTs:** Orthogonal polarisations will be captured using planar probe-based OMTs.
- **Low Noise Amplifiers:** Will use 38 commercially purchased, discrete transisitor LNAs (Low Noise Factory. S. Weinreb (Caltech)). Future instruments with 1000+ pixels need development of MMIC based technology (JPL/Caltech).
- **Cryostat:** and other RF components (warm amplifiers, filters) will be constructed at Oxford Astrophysics.



Pathfinder telescope: Digital backend





- **Backend:** Xilinx ROACH-II FPGA board (as used in 2-PAD (SKA), C-BASS South),
  - **Either** using the digital serial inputs as a two level (1 bit) sampler can give ~3 GHz instantaneous IF bandwidth (cheaper) **or:**
  - Dedicated Hittite Microwave Sampler board – 9 GHz of instantaneous IF bandwidth (better).

Conclusion

- **Actively developing required technologies in Oxford.**
- **Actively seeking funding for both pathfinder concepts.**
- **Collaborating with Caltech/JPL (Science, site), Berkeley, Stanford (MMIC LNAs, digitals backends, cryostats).**