Data Analysis for CHIME

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Drift Scan Telescopes

- All intensity mapping experiments have a common set of analysis challenges:

Wide field	at given instant
All sky	as total surveyed area is large
Polarised	analysis to address leakage

- Restrict to drift scan instruments
  - Signal is power from one antenna or correlation betweeb two.
  - Instantaneously signal is a linear combination of the Stokes parameters on the sky.
  - Transit instrument, no moving parts, time variation comes only from Earth rotation, plus noise.

Drift Scan Analysis

- Visibility is the instantaneous correlation $V_{ij} \propto \left\langle F_i F_j^* \right\rangle$. After including noise (n_α) and sky rotation (ϕ)

$$V_{ij}(\phi) = \int \Big[B_{ij}^T(\hat{\boldsymbol{n}};\phi)\, T(\hat{\boldsymbol{n}}) + B_{ij}^Q(\hat{\boldsymbol{n}};\phi)\, Q(\hat{\boldsymbol{n}}) + B_{ij}^U(\hat{\boldsymbol{n}};\phi)\, U(\hat{\boldsymbol{n}}) \Big] d^2\hat{\boldsymbol{n}} + n_{ij}(\phi) \quad (1)$$

  and the transfer function is

$$B_{ij}^X(\hat{\boldsymbol{n}};\phi) = \frac{1}{\Omega_{ij}} A_i^a(\hat{\boldsymbol{n}};\phi) A_j^{b*}(\hat{\boldsymbol{n}};\phi) \mathcal{P}_{ab}^X(\hat{\boldsymbol{n}})\, e^{2\pi i \hat{\boldsymbol{n}}\cdot \boldsymbol{u}_\alpha(\phi)} \,. \quad (2)$$

- Signal is periodic in ϕ — fourier transform. Using spherical transform, and map $Q, U \rightarrow E, B$

$$V_{ij;m} = \sum_l \left[B_{ij;lm}^T a_{lm}^T + B_{ij;lm}^E a_{lm}^E + B_{ij;lm}^B a_{lm}^B \right] + n_{ij;m} \,. \quad (3)$$

m-transform

- Observing process does not mix m-modes on the sky. V_m uncorrelated for stationary noise.
- Write as vector equation *for each* m

$$\boldsymbol{v} = \mathbf{B}\,\boldsymbol{a} + \boldsymbol{n}\,. \tag{4}$$

- Dramatically reduces correlated degrees of freedom. *Huge computational saving*.
- Expresses problem in a language we understand. *Linear signal processing*. (e.g. imaging = inversion)
- Gives an alternative way of analysing interferometers.
  - Naturally treats all wide-field effects.
  - Polarisation is fully treated from the start.

Requirements

- Coping with polarisation leakage will always require knowing the full polarised response of every antenna.
- How do we measure this? *Pulsar holography*
  - Cross correlate every feed with an external antenna tracking a source as it drifts through the beams.
  - Pulsar gating (subtract off from on), removes confusion limitations.
  - Directly measures electric field response at pulsar location.
- Also require high stability of system (> 30 dB). Use *rigidization* to achieve this.
  - Inject a known, common, stable noise source.
  - Cross correlate with each to determine complex gain fluctuations.

Foreground Removal

- Spectral smoothness allows separation of 21cm. Options:
  1. Fit power law to maps
  2. Remove low order polynomials
  3. Measure components and model (Liu and Tegmark)
  4. FastICA (Chapman et al., for EoR)
- Most methods have difficulties:

  Mode mixing of angular and frequency fluctuations by frequency-dependent beams (esp. interferometers) [1, 2]

  Robustness Biasing introduced if foreground model poorly understood (esp. non-gaussianities). [1, 3]

  Statistical Optimality Need to keep track of transformations on statistics, for optimal PS estimation [1, 2]

Signal-to-Noise Eigenmodes

- Construct the covariances of the signal and foregrounds

$$\mathbf{S} = \mathbf{B} \left\langle \boldsymbol{a}_s \boldsymbol{a}_s^\dagger \right\rangle \mathbf{B}^\dagger \,, \qquad \mathbf{F} = \mathbf{B} \left\langle \boldsymbol{a}_f \boldsymbol{a}_f^\dagger \right\rangle \mathbf{B}^\dagger \tag{5}$$

- Jointly diagonalise both matrices (eigenvalue problem)

$$\mathbf{S}\boldsymbol{x} = \lambda \mathbf{F} \boldsymbol{x} \tag{6}$$

  Gives a new, uncorrelated, basis. Eigenvalue λ_i gives ratio of signal to foreground variance for mode i.

- Foreground removal is performed by projecting out modes with low signal-to-foreground ratio.
- Addresses the previous problems
  - Analysis uses all measured data to avoid *mode mixing*.
  - Can be made arbitrarily *robust*, by increasing threshold.
  - Linear transform on data, keeps track of *statistics*

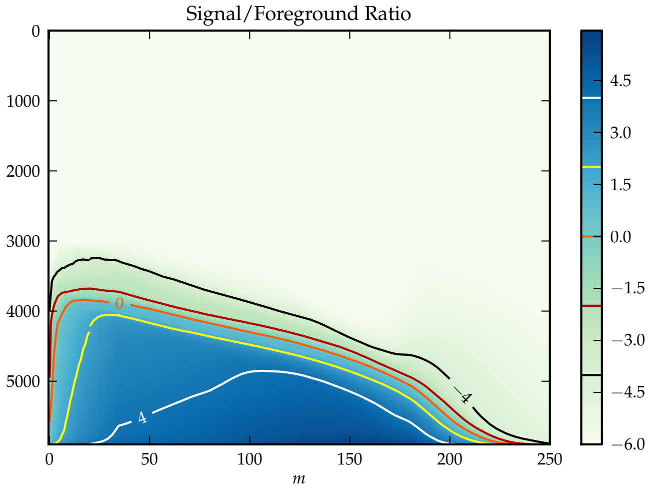
Conclusions

- Instruments like CHIME are a very different class of interferometers, require completely different analysis technique.
- m-mode decomposition reduces entire analysis to linear signal processing, naturally treats effects that are traditionally very difficult: wide-field imaging, polarisation leakage.
- Computational efficiency allows 'optimal' foreground removal and power spectrum estimation.
- Requirements are strict:

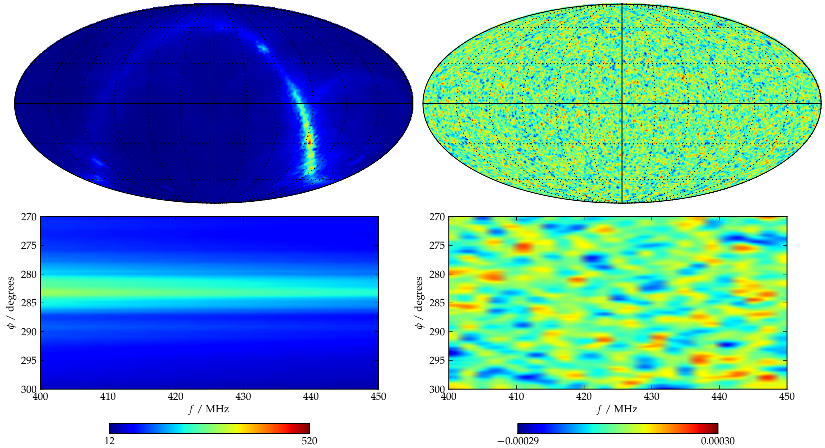
  Time stability by rigidization

  Polarisation response by pulsar holography

Signal/Foreground Spectrum

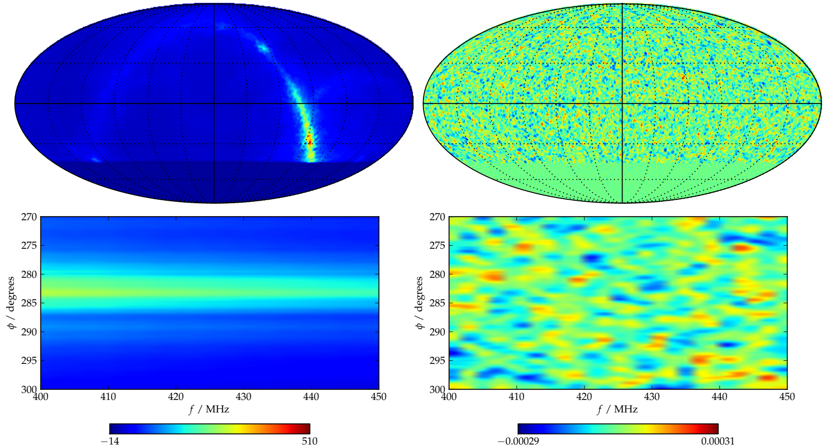


Sky simulation



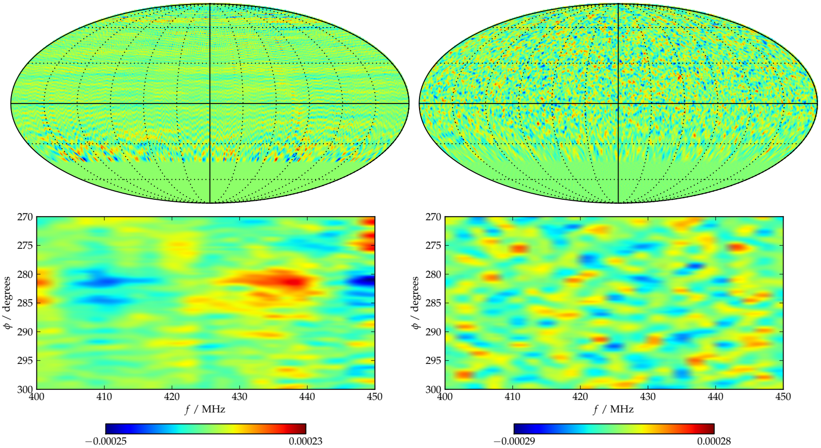
$\sim 10^6 \times$ brighter

Beam Projected



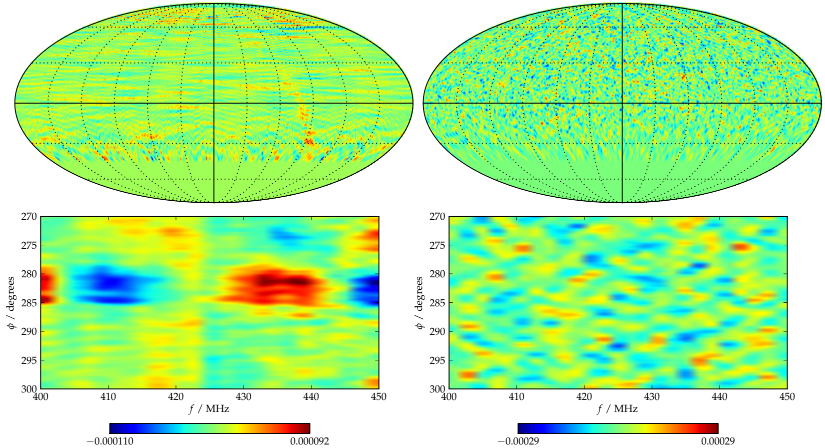
$\sim 10^6 \times$ brighter

S/N > 0.01



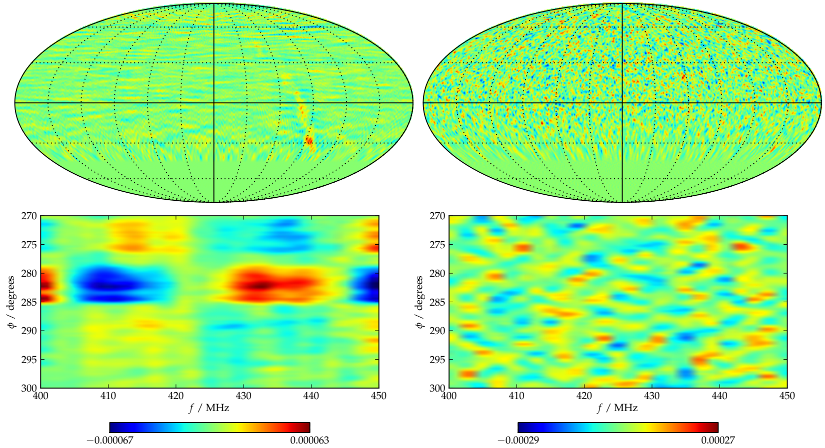
∼ same brightness

S/N > 0.1



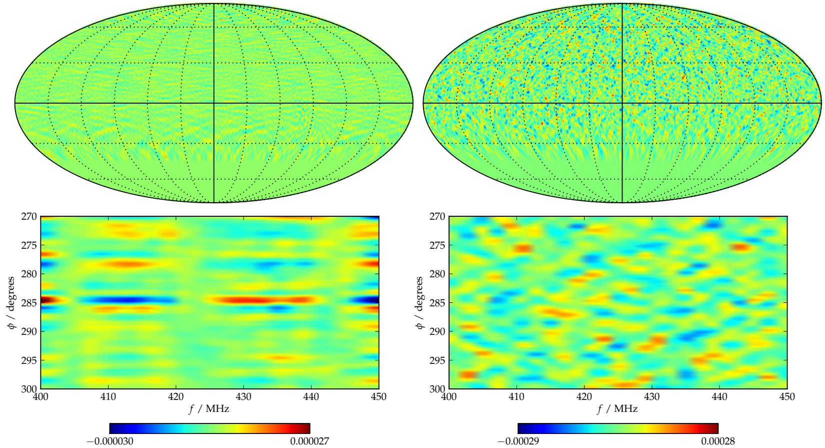
$\sim 3\times$ dimmer

S/N > 1



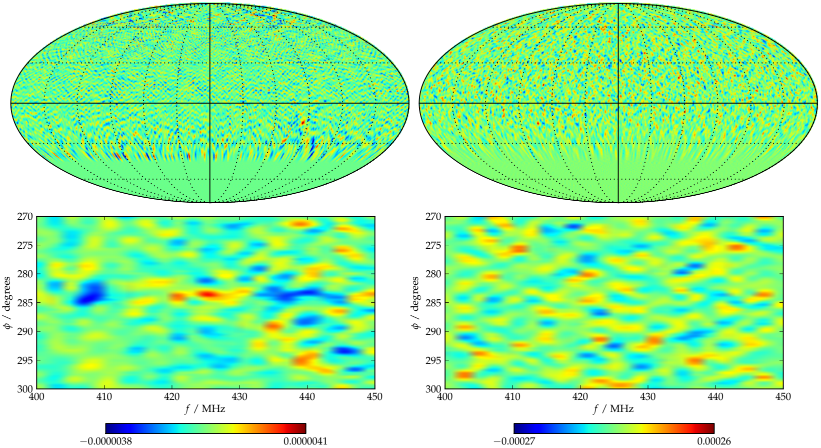
$\sim 5\times$ dimmer

S/N > 10



$\sim 10\times$ dimmer

S/N > 100



$\sim 70\times$ dimmer