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The challenges of HI intensity mapping

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ArXiv:1405.1751, 1409.????

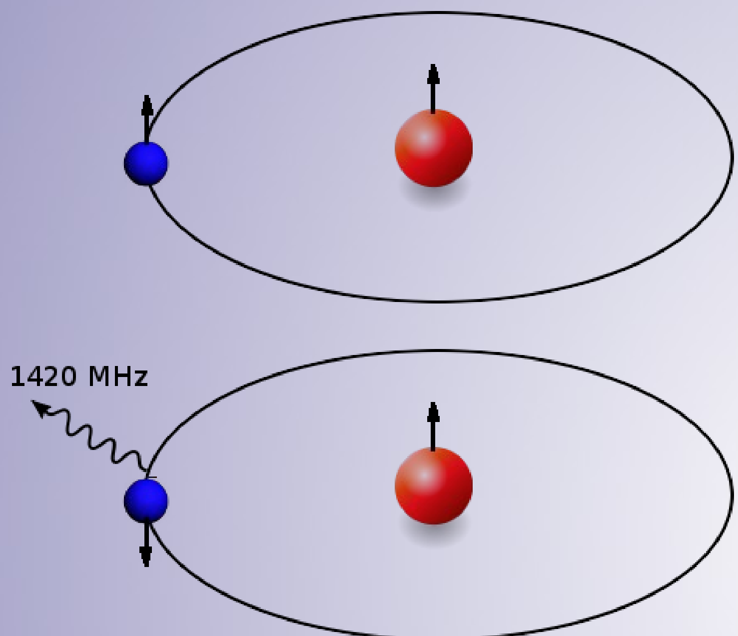
Benasque – 13 August 2014

Oxford Physics

Outline

- **Intensity mapping**
  - The signal
  - Observational techniques
- **Foregrounds**
  - Galactic synchrotron
  - Extragalactic foregrounds
  - Simulations
- **Blind foreground subtraction**
  - Blind cleaning methods: a unified picture
  - Results
  - When does it break down?
- **Summary**

The 21cm signal



- Hyperfine transition
- Strongly forbidden

$$t_{1/2} \simeq A_{01}^{-1} = 1.11\times 10^7\,\mathrm{y}$$

- A 3D tracer of neutral hydrogen

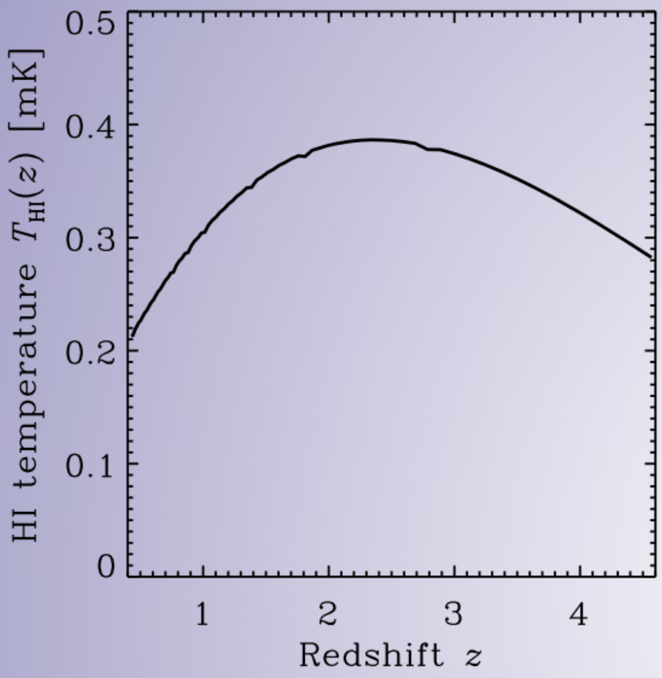
$$\nu = \frac{\nu_{21}}{1+z}$$

$$dL = \frac{3}{4} A_{10} h\nu_{21} n_{\rm HI}\,\phi(\nu)\,d\nu\,dA\,dr$$

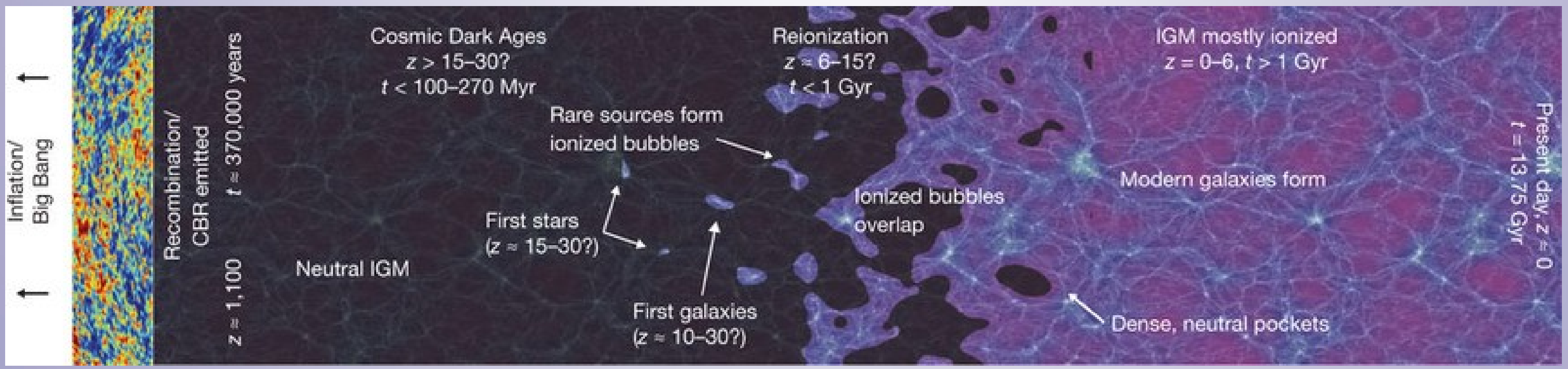
$$T_{21}(z,\hat{\mathbf{n}}) = (0.19055\,\mathrm{K})\,\frac{\Omega_{\rm b}\,h\,(1+z)^2\,x_{\rm HI}(z)}{\sqrt{\Omega_{\rm M}(1+z)^3+\Omega_\Lambda}}\,(1+\delta_{\rm HI})$$

Review: Furlanetto, Oh & Briggs, 2006

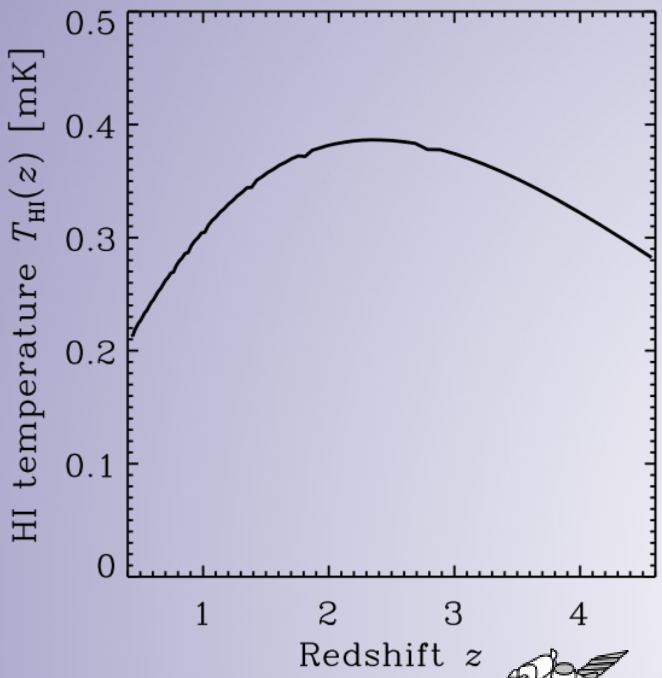
Neutral hydrogen in the Universe



- 21cm is ideal to study the physics of the EoR and the Dark Ages.
- At late times the Universe is ionized. HI inside galaxies (DLAs).



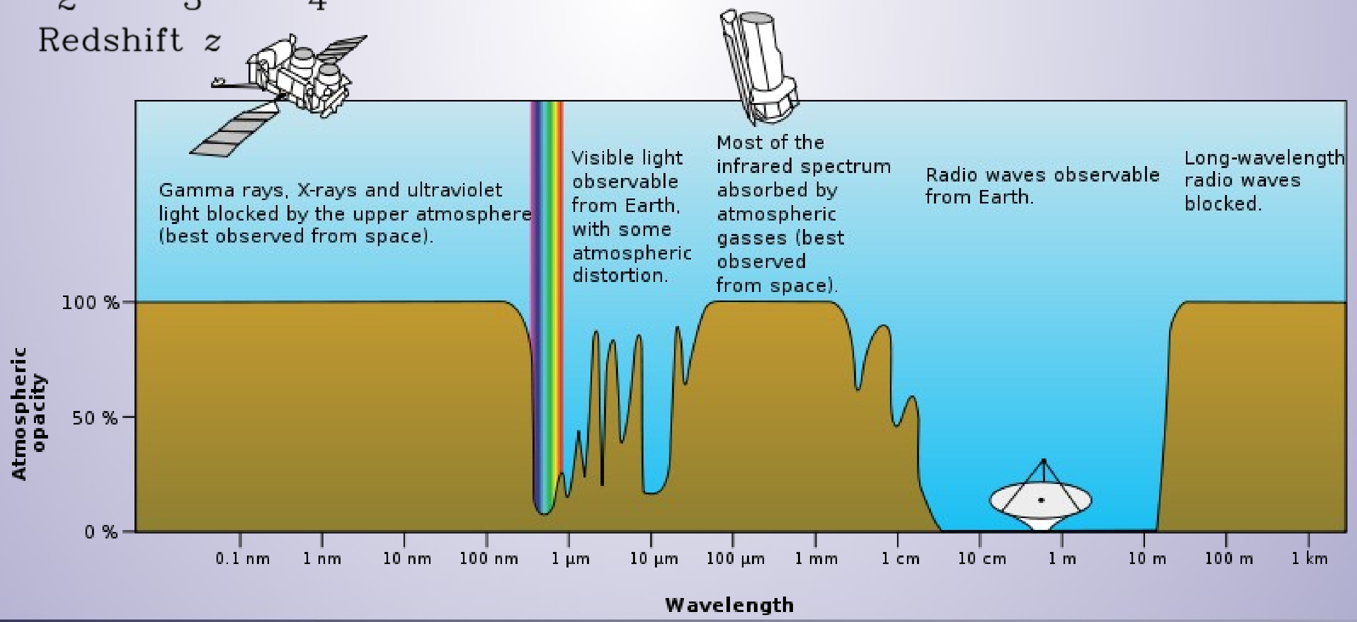
Neutral hydrogen in the Universe



- 21cm is ideal to study the physics of the EoR and the Dark Ages.
- At late times the Universe is ionized. HI inside galaxies (DLAs).

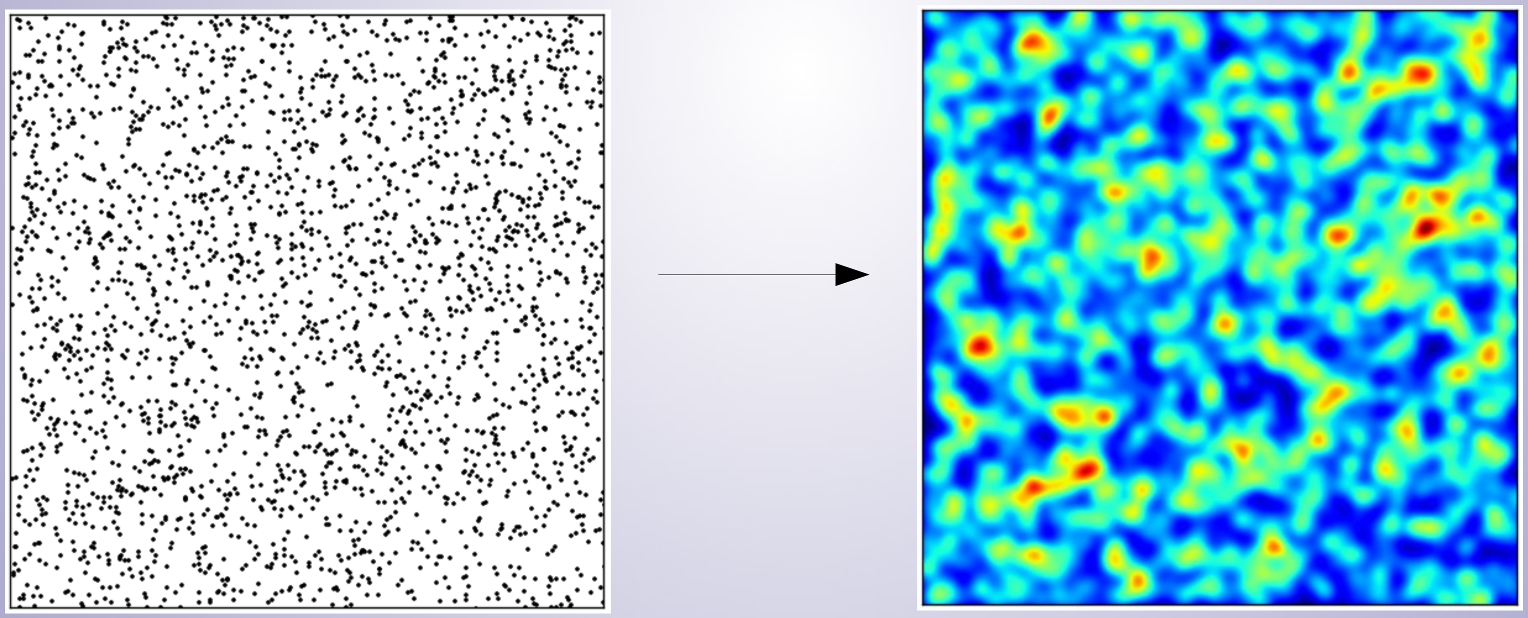
✔ Spectrally isolated
✔ Small obscuration
✔ Signal grows with z

✗ Difficult to observe many individual objects
→ Intensity mapping



Intensity mapping

- Large pixels: joint emission from multiple galaxies instead of resolving them.
- We only care about large scales
- “Cheap” way to observe large volumes



Intensity mapping

- Large pixels: joint emission from multiple galaxies instead of resolving them.
- We only care about large scales
- "Cheap" way to observe large volumes
- Interferometers vs. single dish

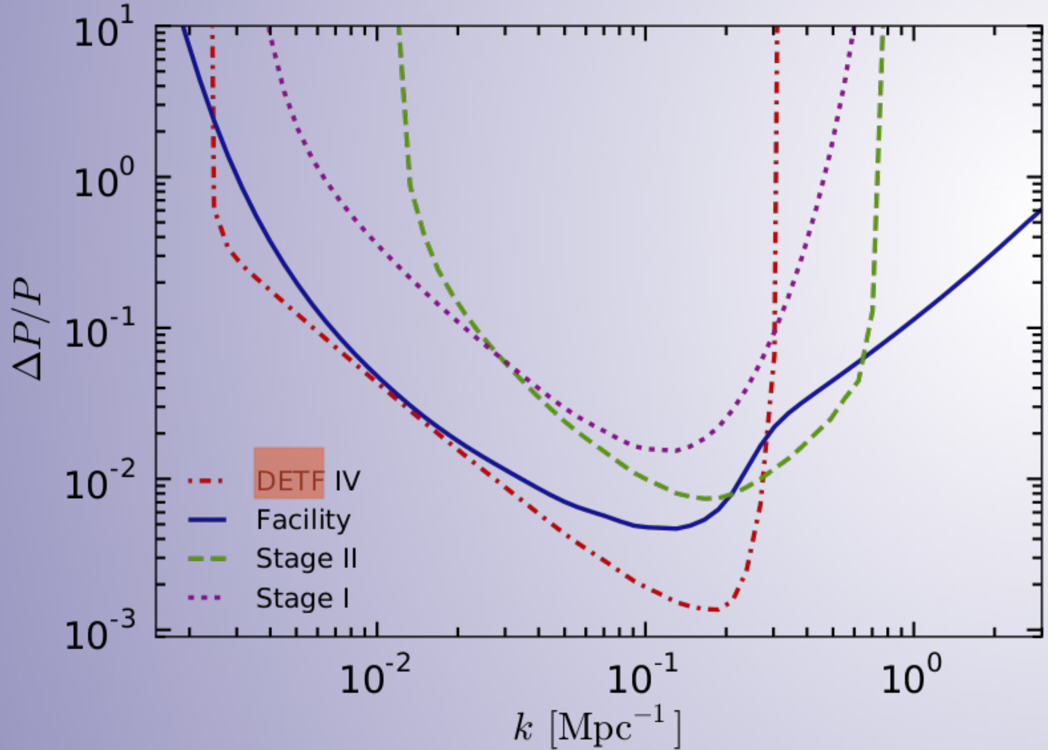
$$\frac{\lambda}{b_{\rm max}} < \Delta\theta < \frac{\lambda}{b_{\rm min}}$$

$$\frac{\lambda}{D_{\rm dish}} < \Delta\theta$$

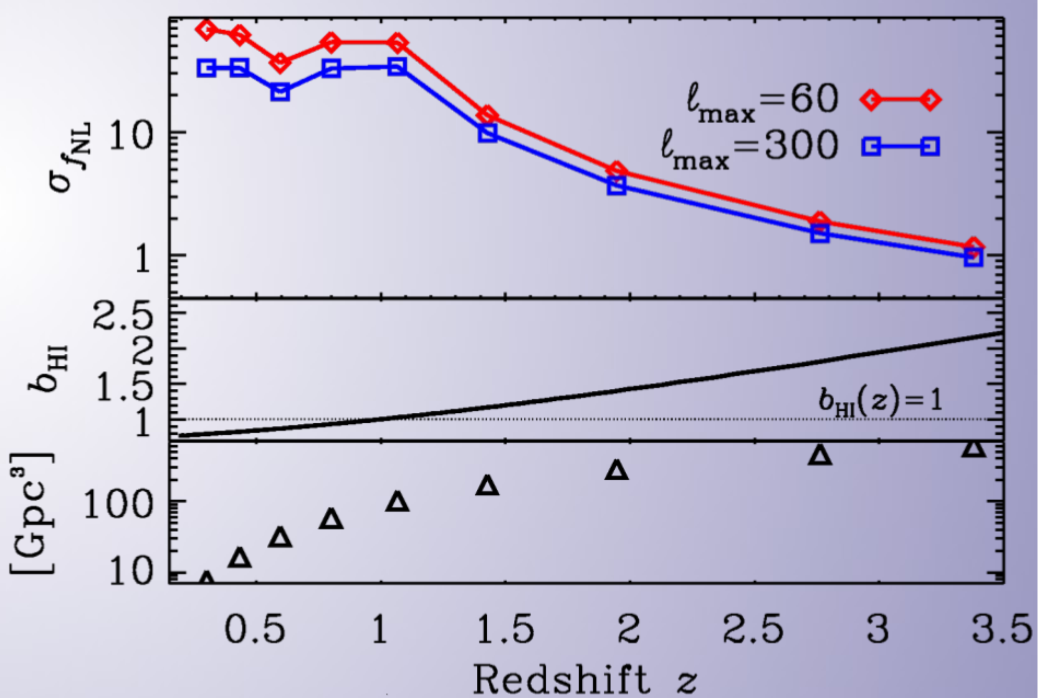
Bull et al. 2014

Intensity mapping

- Forecasts: constraining power competitive with largest redshift surveys.
- Main science goals: BAO,RSD, ultra-large scales



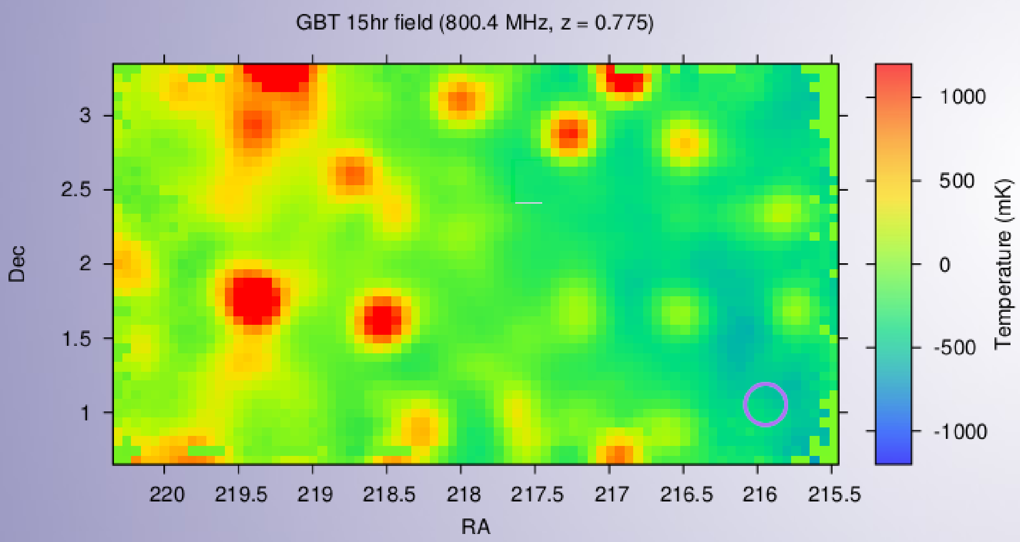
Bull et al. 2014

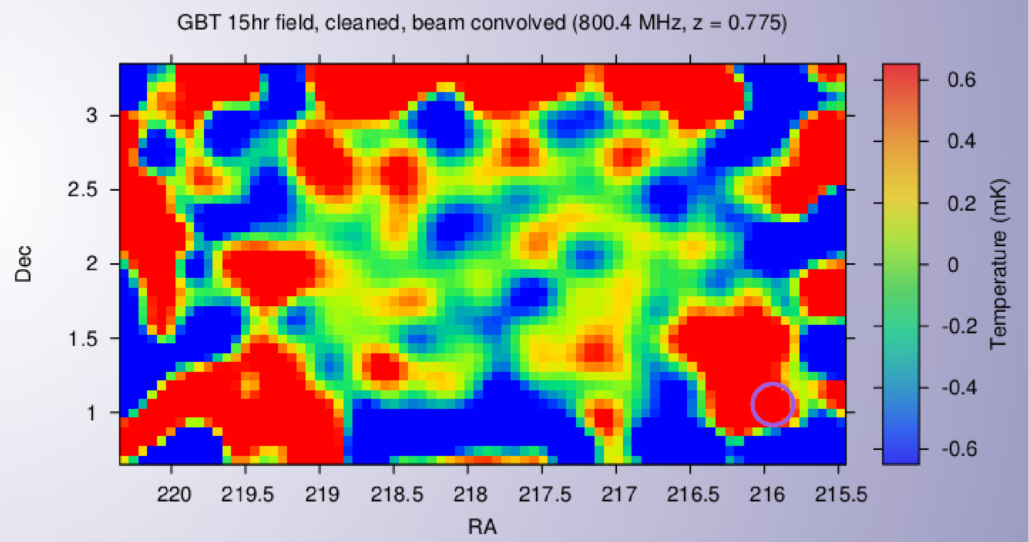


Camera et al. 2013

Intensity mapping

- Forecasts: constraining power competitive with largest redshift surveys.
- Main science goals: BAO,RSD, ultra-large scales
- First measurements have already taken place. Main challenge: foregrounds.





Masui et al. 2013
Switzer et al. 2013

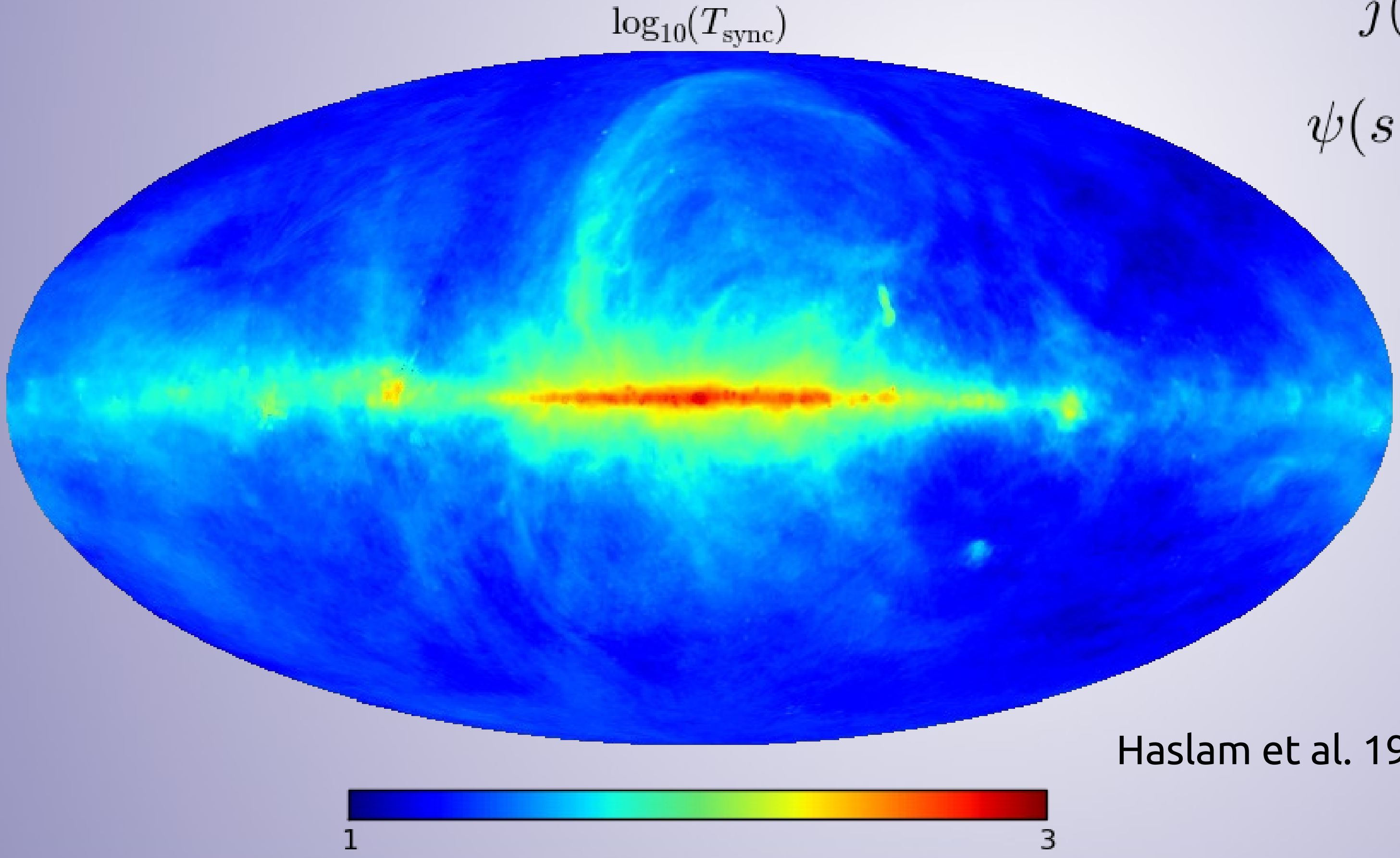
Radio foregrounds

Galactic synchrotron

$$I_P = \int ds\, j(s,\hat{\mathbf{n}},\nu)\, \exp 2i\left[\phi_0 + \psi(s,\hat{\mathbf{n}})/\nu^2\right]$$

$$j(s,\hat{\mathbf{n}},\nu) \propto n_{\rm CR}\, B_\perp\, \nu^\alpha$$

$$\psi(s,\hat{\mathbf{n}}) \propto \int_0^s n_e\, B_\parallel\, ds'$$

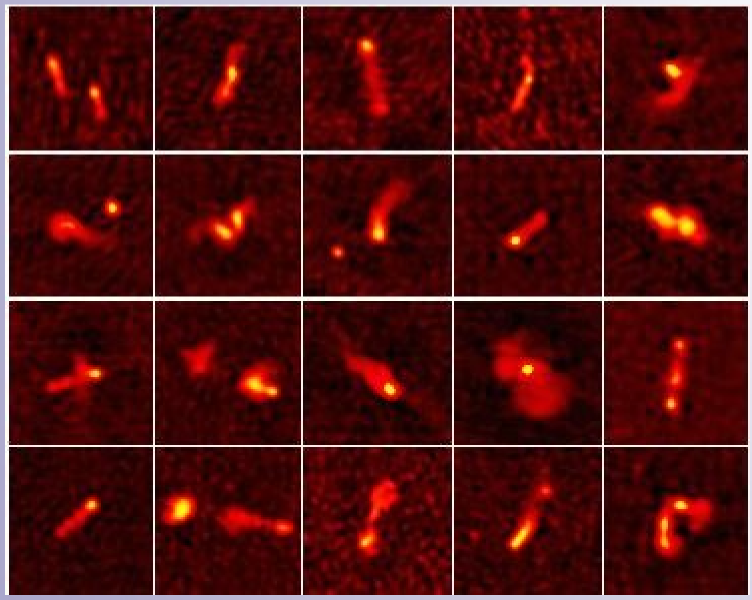


Haslam et al. 1982

Radio foregrounds

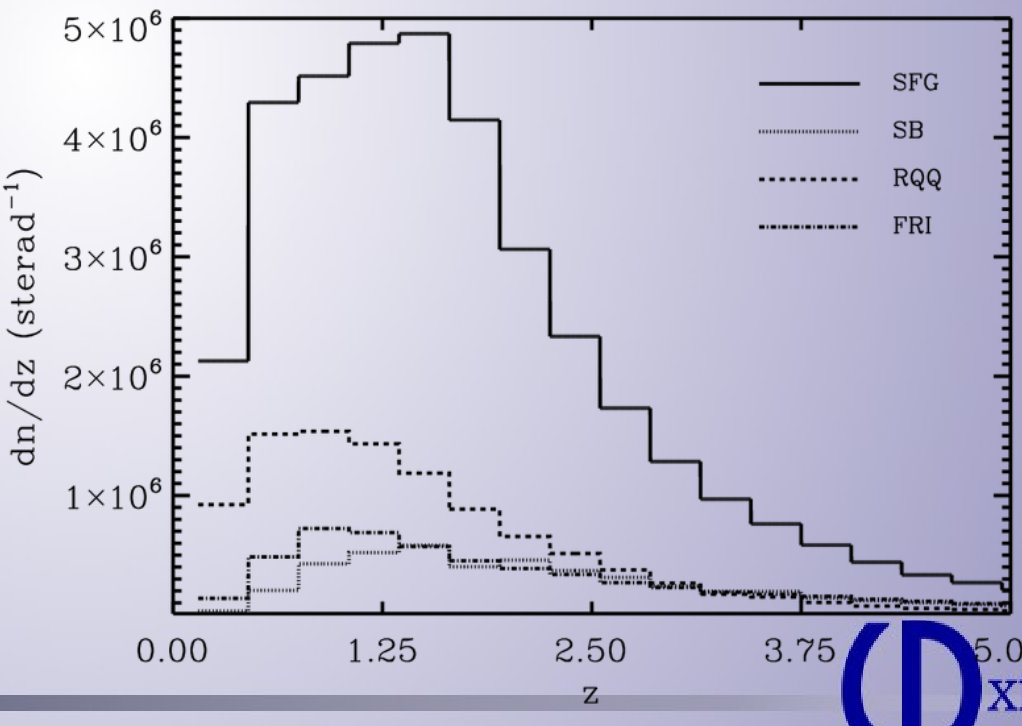
Extragalactic foregrounds

- Point sources: radio galaxies (star-forming galaxies, AGNs...)
- Free-free emission
- For IM may actually be “behind” the signal!
- Extragalactic sources could be potentially correlated with the signal!



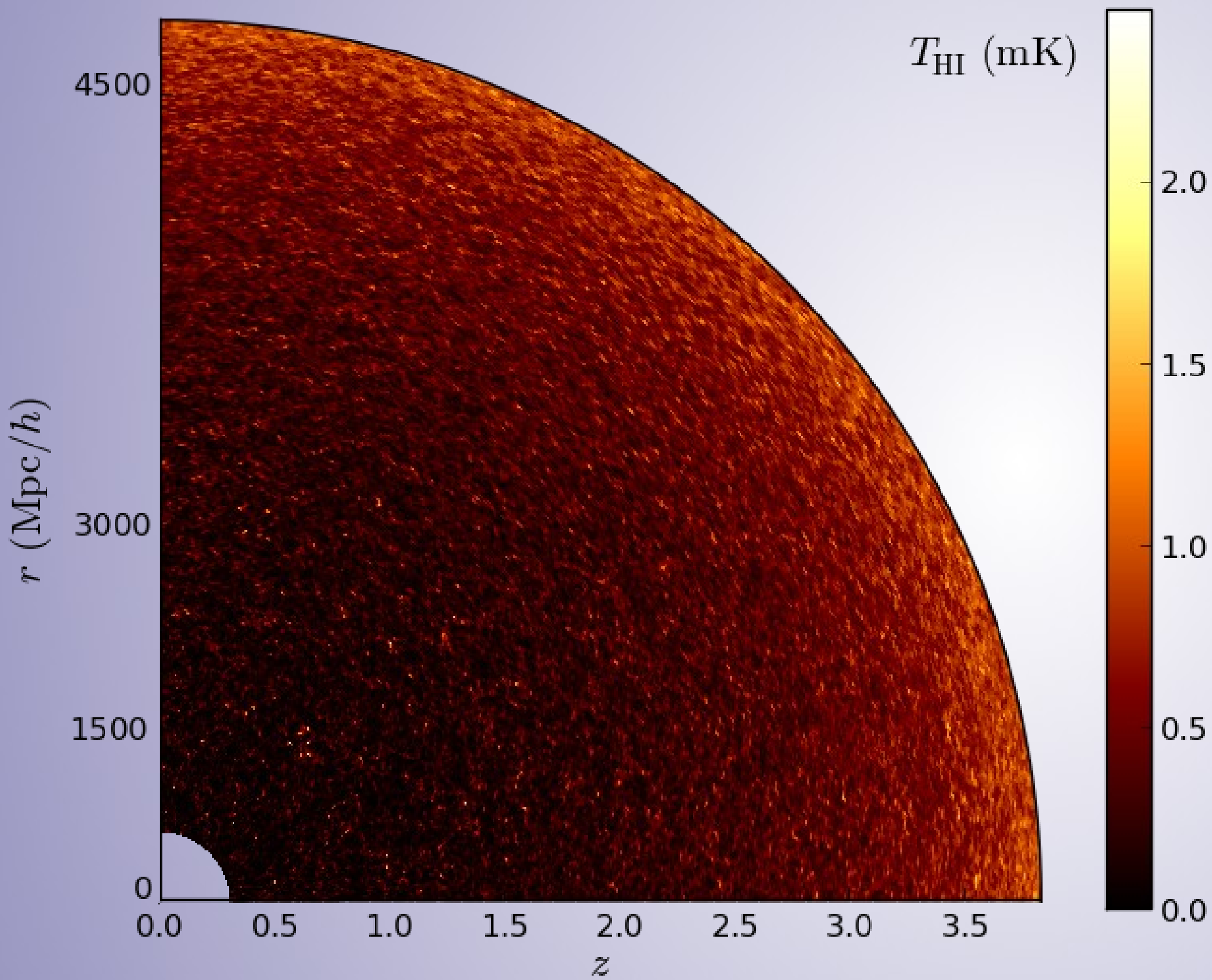
Source: nrao.edu

Ferramacho et al. 2014



Intensity mapping simulations

The cosmological signal



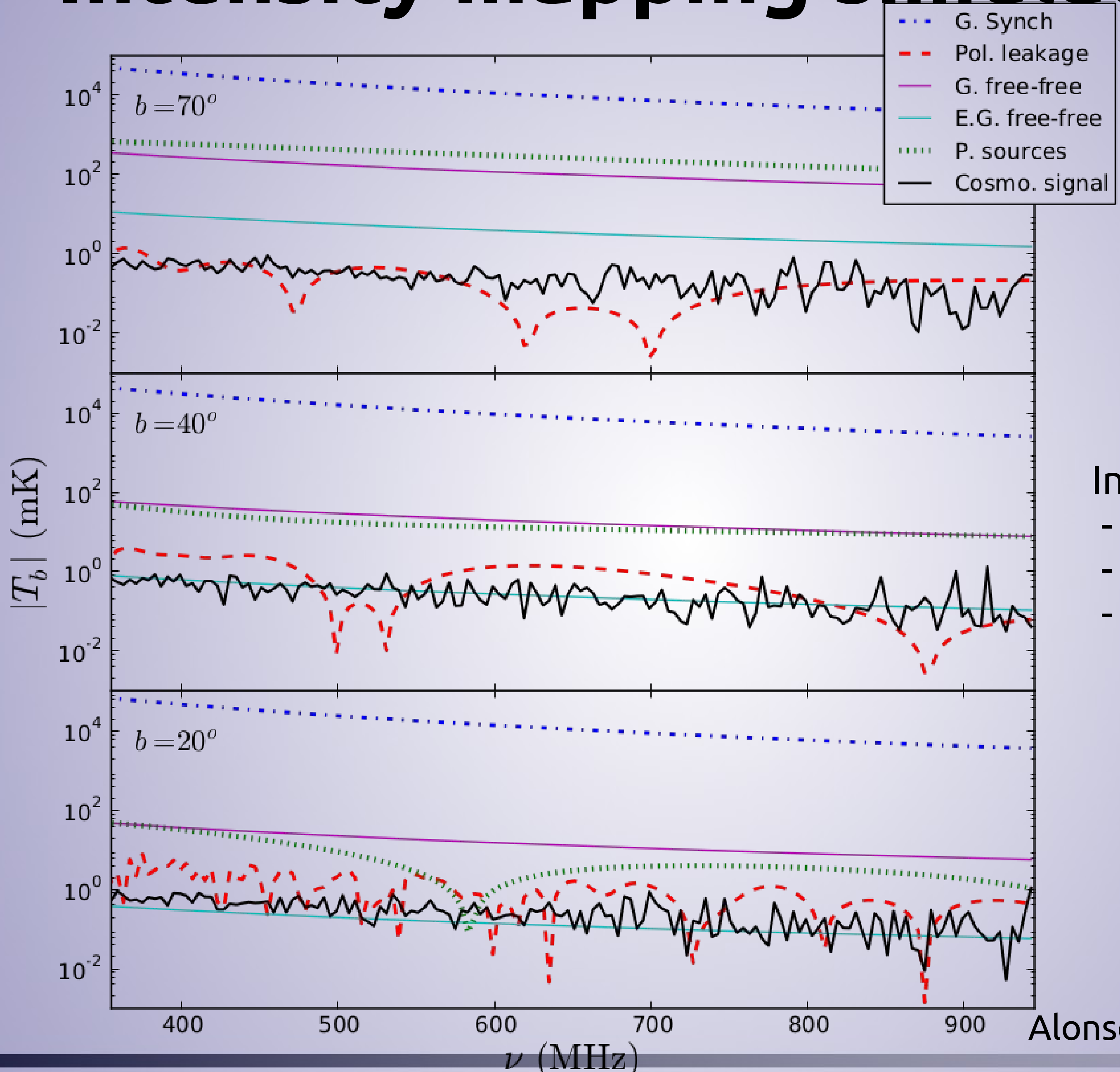
Alonso et al. 2013

(1) Generate lognormal density and radial velocities.

(2) Compute 3D HI mass grid.

(3) Interpolate to pixel maps and implement RSDs.

Intensity mapping simulations



Alonso et al. 2013

Instrumental effects:
- Beam convolution
- Polarization leakage
- Noise

Blind foreground subtraction

- Blind methods: minimize assumptions about foregrounds → foregrounds are ν-smooth

- Blind source equation

$$T(\nu,\theta)=\sum_{k=1}^{N_{\rm fg}} f_k(\nu)\,S_k(\theta)+T_{\rm cosmo}(\nu,\theta)+T_{\rm noise}(\nu,\theta)$$

$$x_i=T(\nu_i,\theta),\quad A_{ik}=f_k(\nu_i)\quad s_k=S_k(\theta)$$

$$\mathbf{x}=\hat{\mathbf{A}}\cdot\mathbf{s}+\mathbf{n},$$

- 3 different methods:
  - **LOS fitting**: choose ad-hoc smooth functions.
    Usually polynomial fitting in log-log space.
  - **PCA**: *uncorrelated* sources maximizing the variance.
    Diagonalize ν-covariance and subtract principal eigenvectors.
  - **ICA**: *independent* sources maximizing the variance.
    Find independent sources by maximizing non-Gaussianity (CLT).
    (See Wolz et al. 2013 for a first application to IM).
    Equivalent to PCA for Gaussian foregrounds.

- Aim: agnostic comparison of all these methods

Blind foreground subtraction

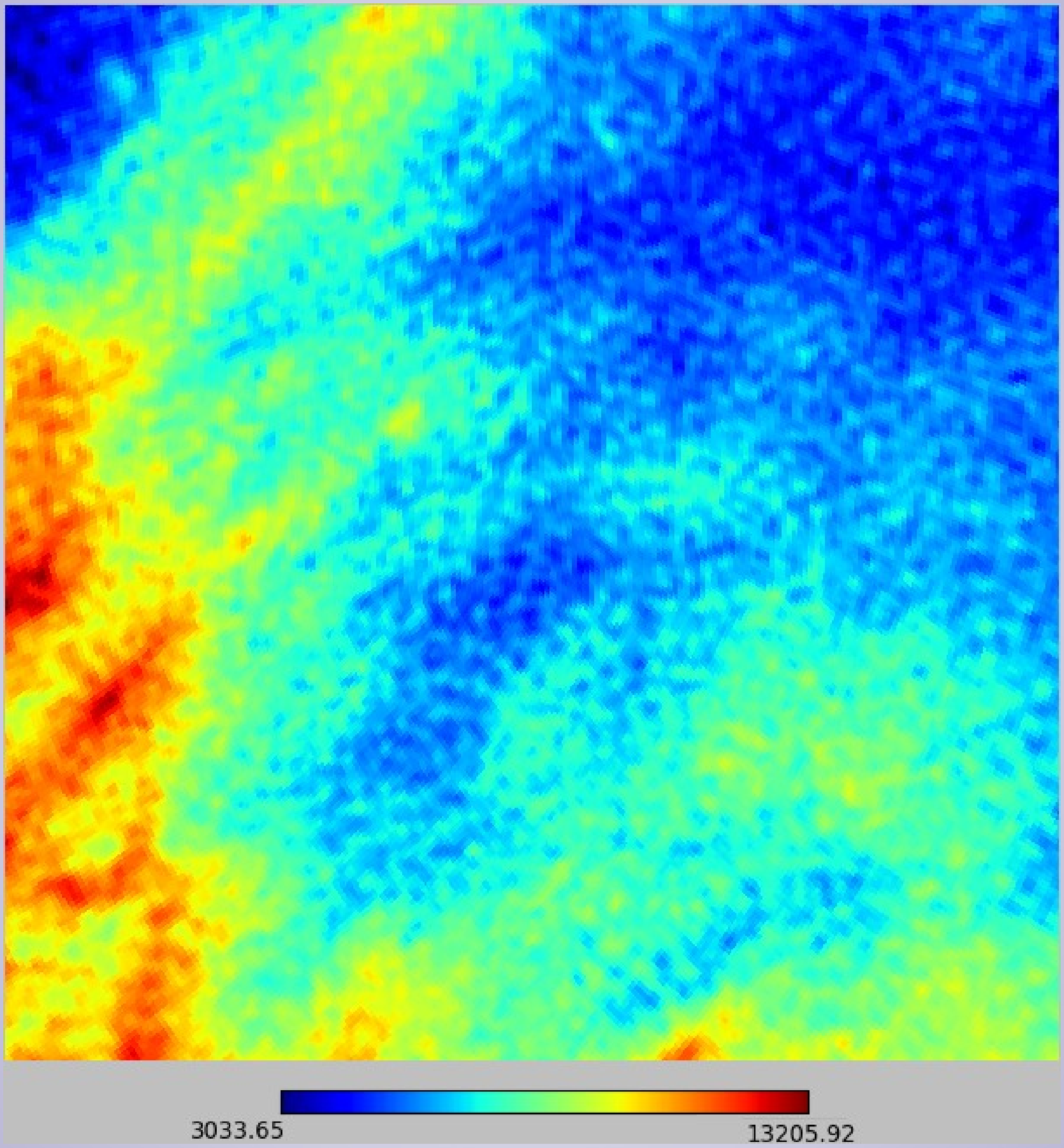
- We define 2 figures-of-merit for foreground subtraction:

$$\eta \equiv \frac{\langle P_{\rm clean} - P_{\rm cosmo} \rangle}{\sigma_P} \qquad\qquad \rho \equiv \frac{\langle P_{\rm res} \rangle}{\sigma_P}$$

- η: bias in the power spectrum. ρ: signal loss.
- Must be evaluated both in the angular and radial power spectra.
- Studied cleaning efficiency by averaging over 100 independent simulations. SKA-mid parameters (D_{dish}=15m, N_{dish}=254, t=10K h, T_{sys}=25K). No polarization leakage.

Blind foreground subtraction

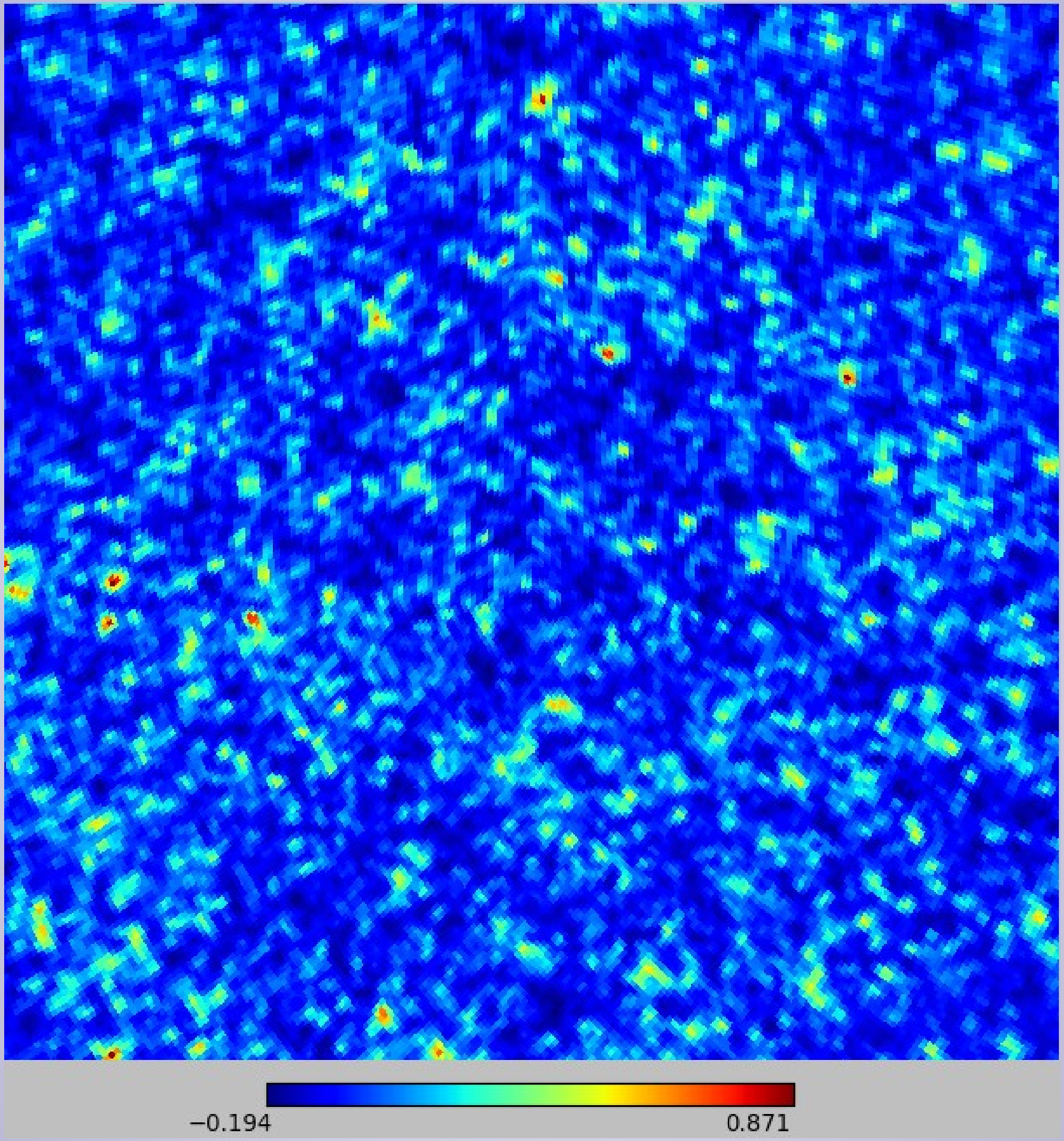
Signal+FG



Oxford Physics

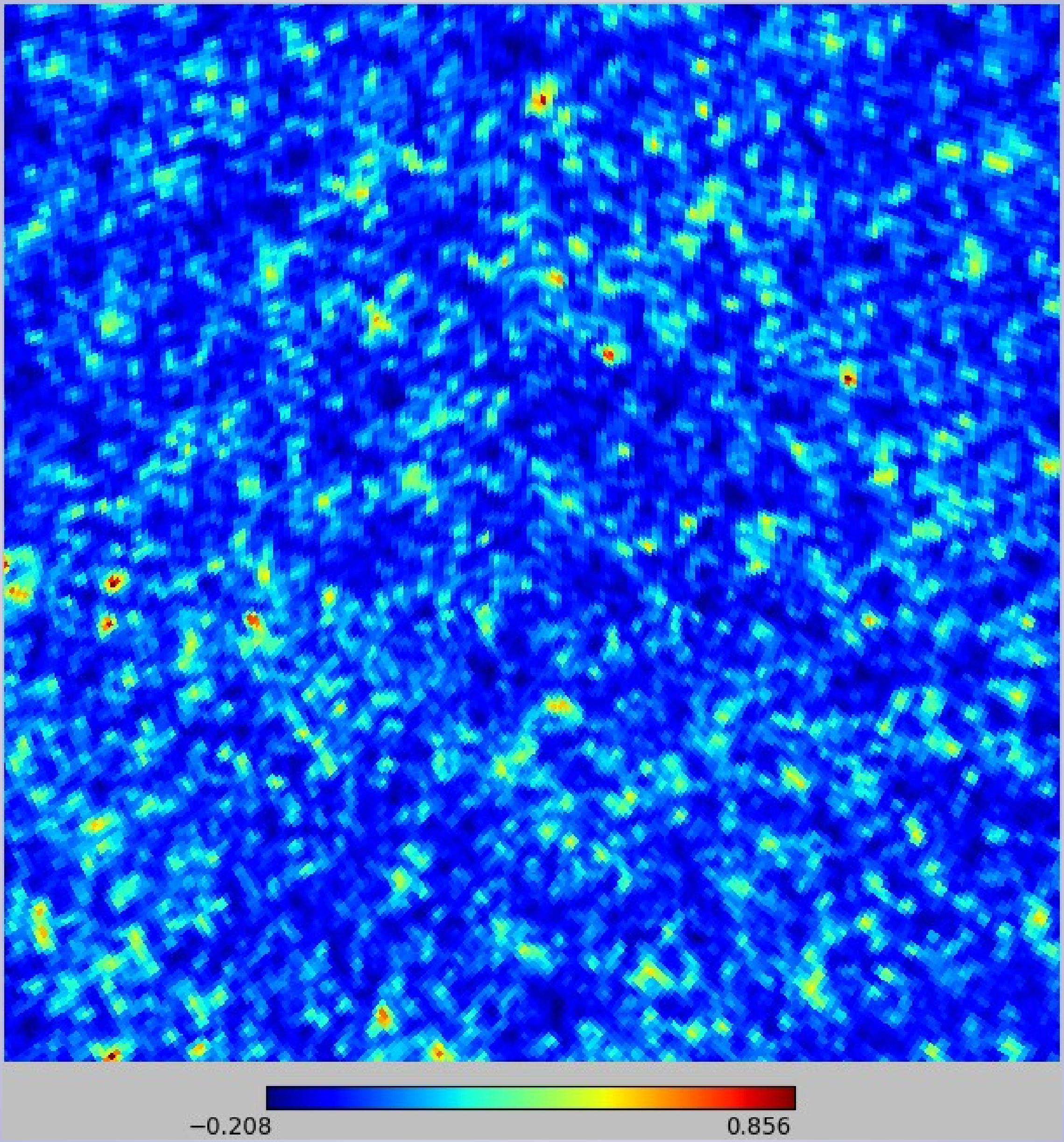
Blind foreground subtraction

Signal only

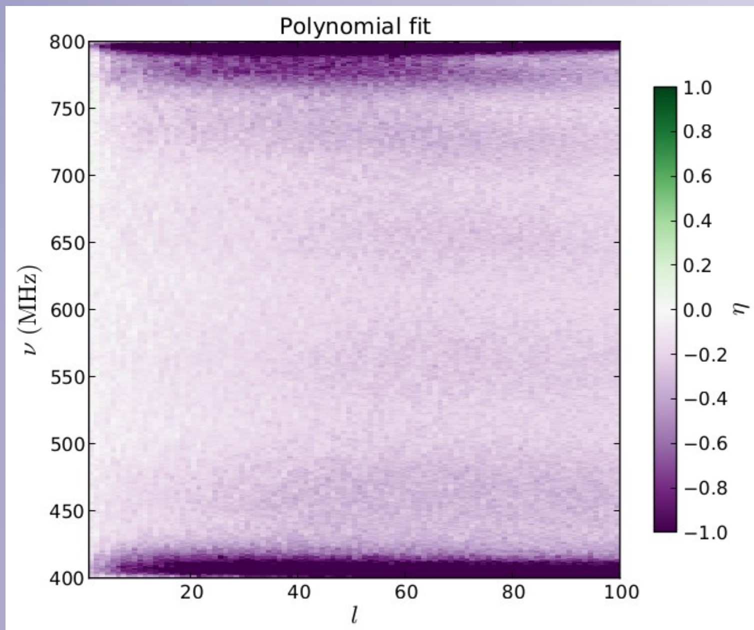


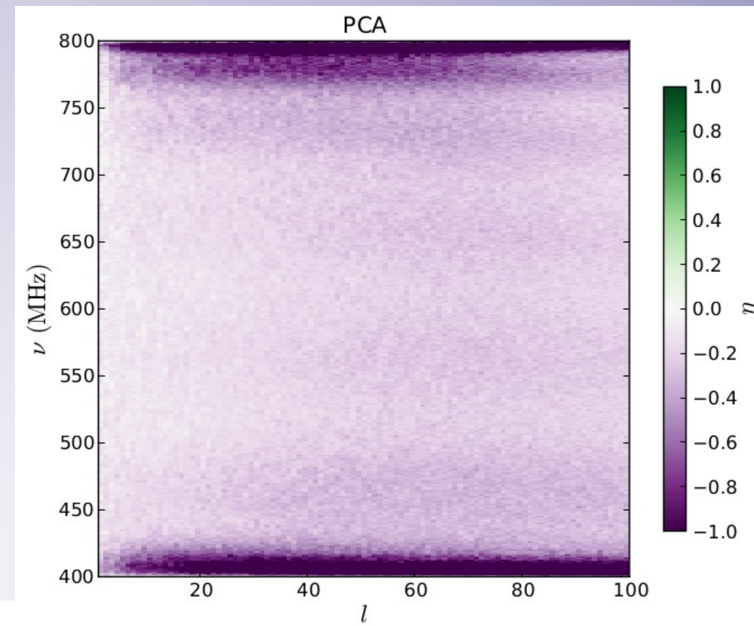
Blind foreground subtraction

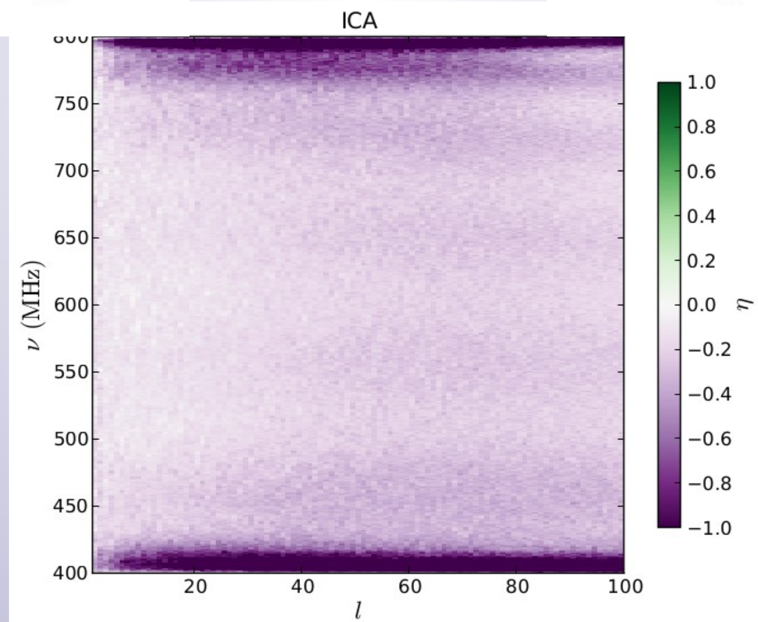
Cleaned map



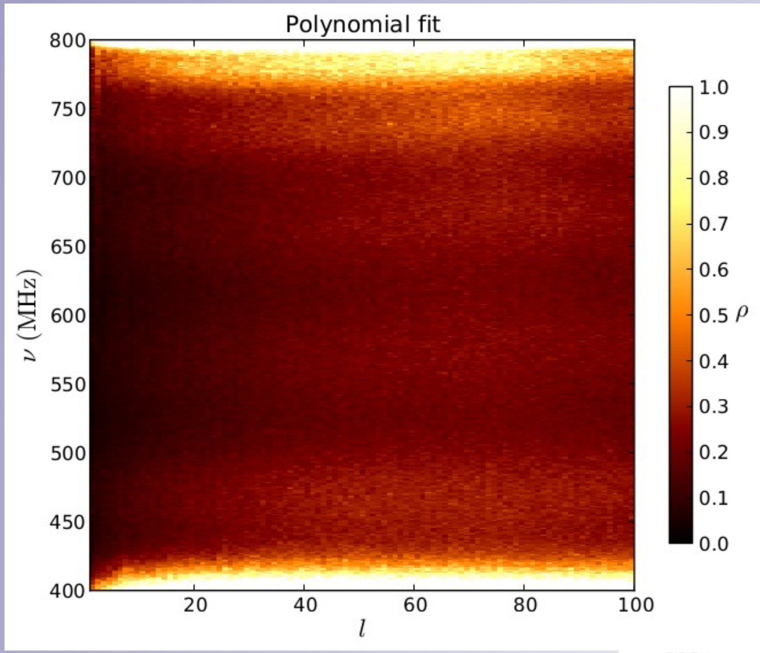
Blind foreground subtraction

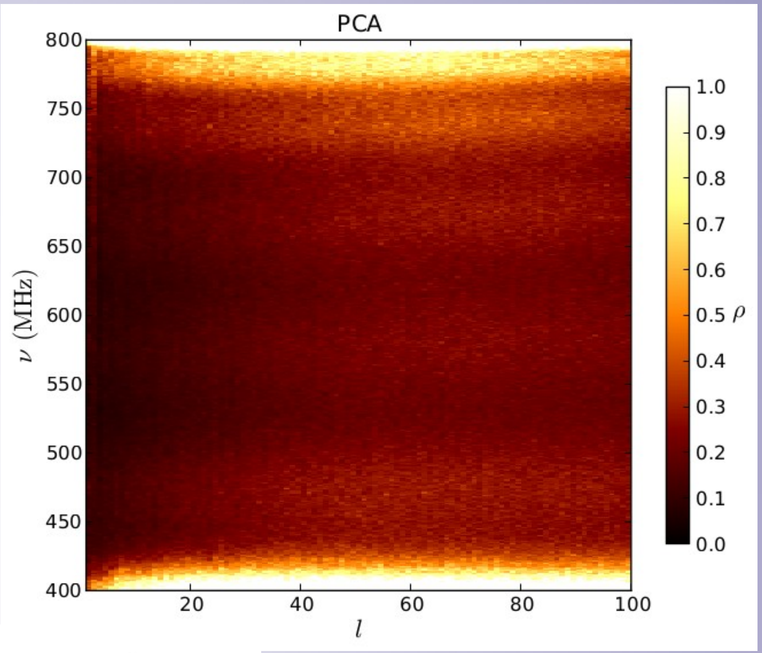


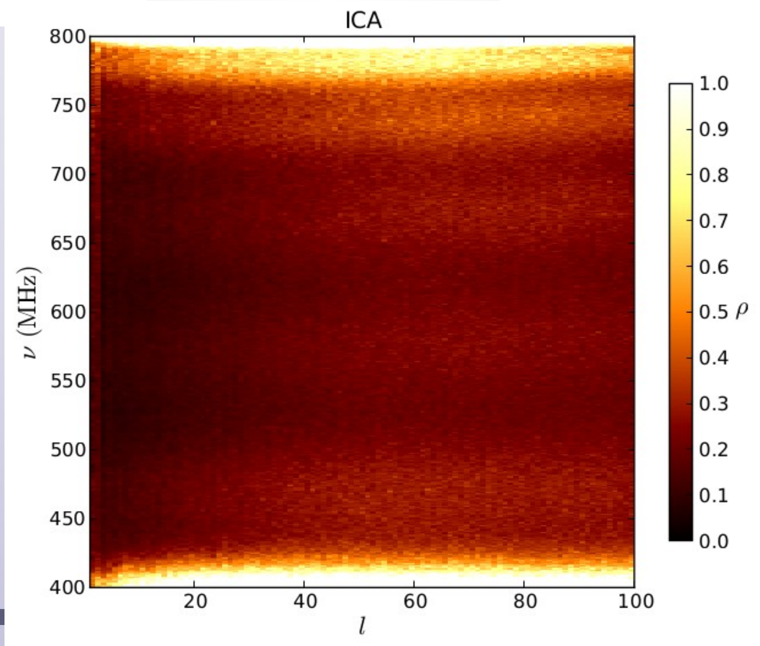




Blind foreground subtraction



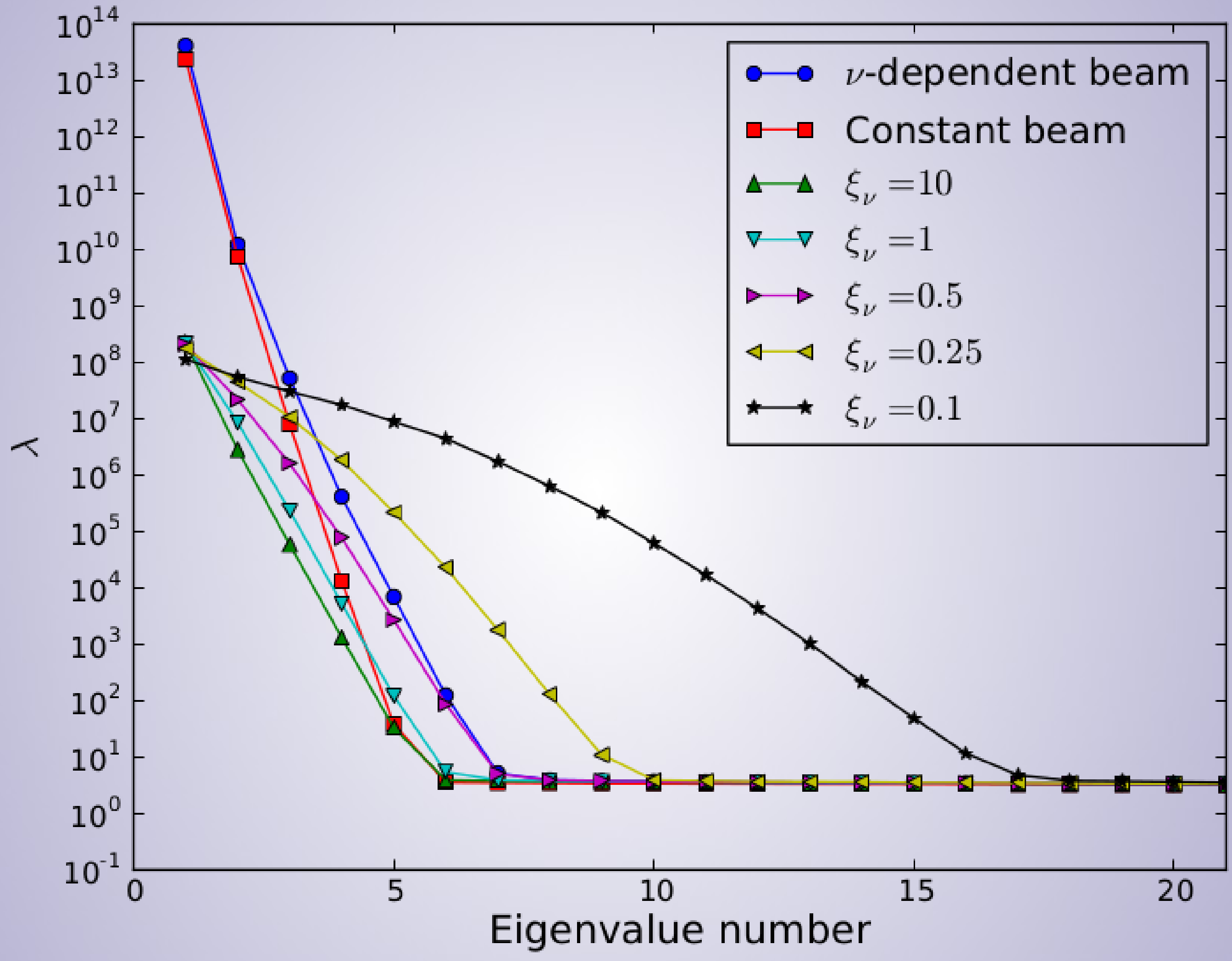




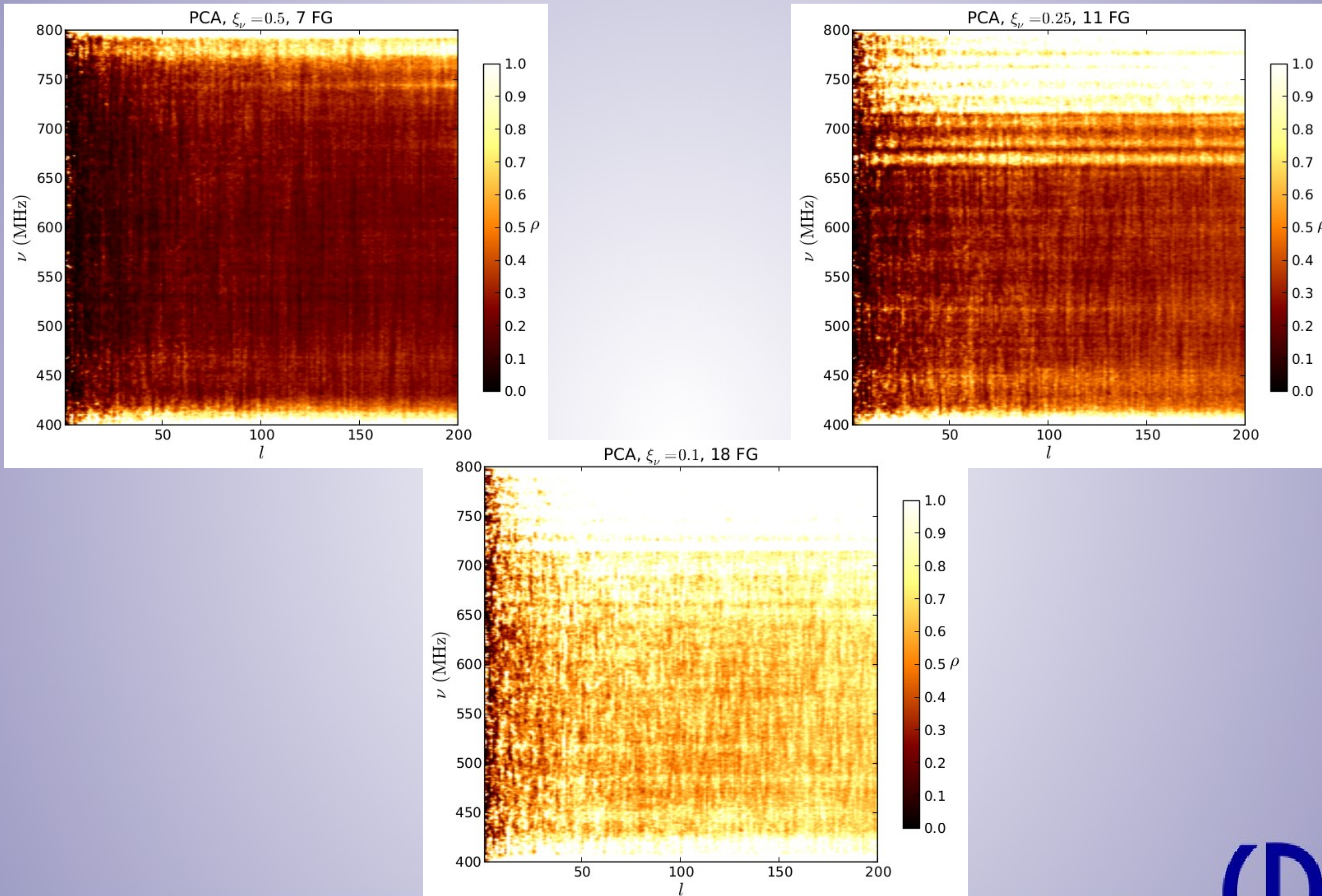
Equivalent results!

Blind foreground subtraction

When does it break down?



Blind foreground subtraction



Conclusions

- Intensity mapping is a potentially powerful cosmological probe.
- Computational challenges: fast simulations to study errors, systematics, model independence...
- Observational challenges: huge (10^5) galactic and extragalactic foregrounds.
- Blind foreground subtraction: simplest but efficient methods.
- Formally equivalent, but also similar in practice.
- Foregrounds must be smooth (and they are).
- Instrumental effects (beam, polarization leakage) may be a lot more important.

Conclusions

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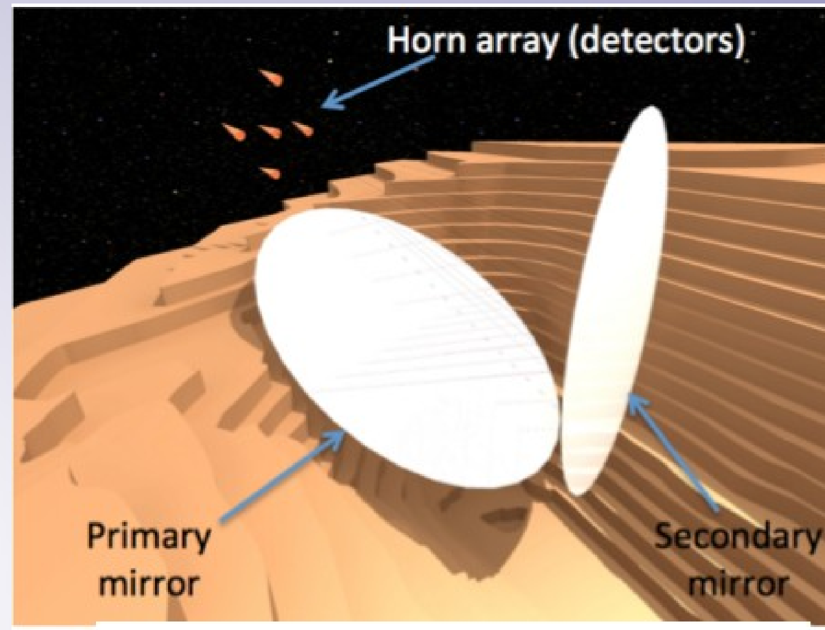
¡Muchas gracias!

Intensity mapping

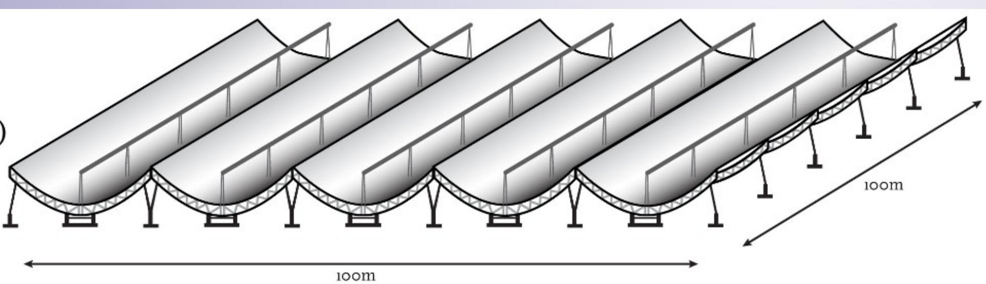
Overview of experiments

– **GBT** (Chang et al.)



BINGO (Battye, et al.1209.1041)

CHIME (Canada)
Tianlai (China)



MeerKAT -> SKA1-Mid

Radio foregrounds

Extragalactic foregrounds

- Point sources: radio galaxies (star-forming galaxies, AGNs...)
- Free-free emission
- For IM may actually be "behind" the signal!
- Extragalactic sources could be potentially correlated with the signal!

Other foregrounds

- Line foregrounds. The only candidates for line confusion are very faint!

IAU list of important spectral lines

Substance	Rest Frequency	Suggested minimum bandwidth
Deuterium (DI)	327.384 MHz	327.0 - 327.7 MHz
Hydrogen (HI)	1420.406 MHz	1370.0 - 1427.0 MHz
Hydroxyl radical (OH)	1612.231 MHz	1606.8 - 1722.2 MHz
Methyladyne (CH)	3335.481 MHz	3324.4 - 3338.8 MHz

Source: craf.eu

Intensity mapping simulations

Foregrounds: extragalactic foregrounds

- Foreground contamination modeled as a Gaussian random field, based on the SCK 05 model.
- The correlation length ξ will determine the efficiency of foreground cleaning.

Foreground	A (mK^2)	β	α	ξ
Galactic synchrotron	700	2.4	2.80	4.0
Point sources	57	1.1	2.07	1.0
Galactic free-free	0.088	3.0	2.15	35
Extragalactic free-free	0.014	1.0	2.10	35

$$C_l(\nu_1, \nu_2) = A\left(\frac{l_{\rm ref}}{l}\right)^{\beta}\left(\frac{\nu_{\rm ref}^2}{\nu_1\,\nu_2}\right)^{\alpha}\exp\left(-\frac{\log^2(\nu_1/\nu_2)}{2\,\xi^2}\right)$$

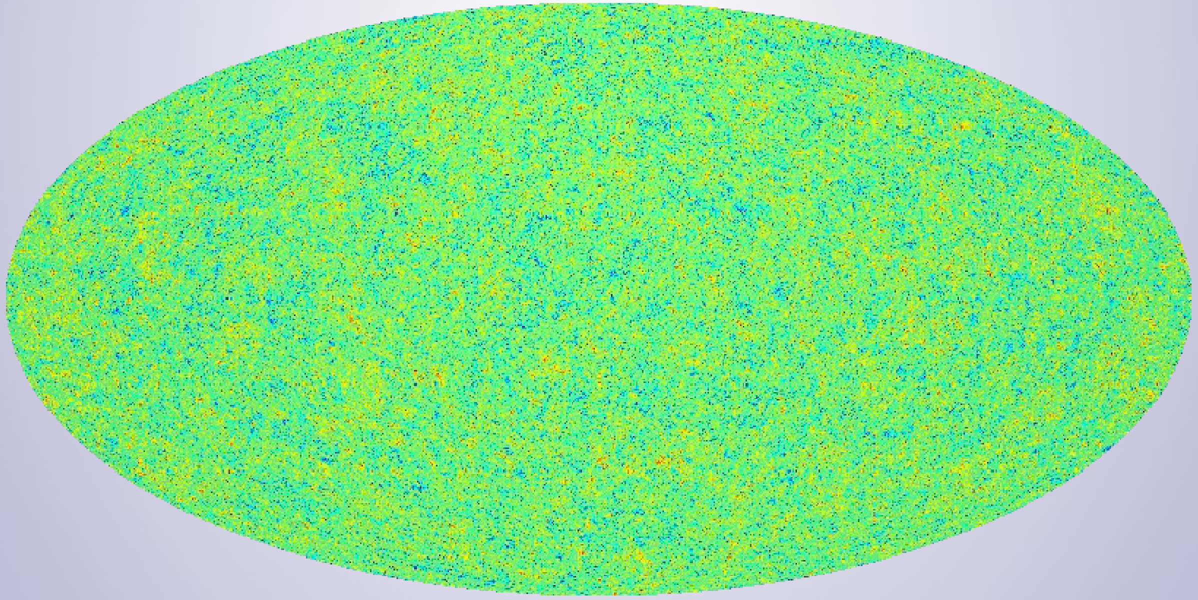
Santos, Cooray, Knox 2005

Alonso et al. 2013

Intensity mapping simulations

Foregrounds: extragalactic foregrounds

- Foreground contamination modeled as a Gaussian random field, based on the SCK 05 model.
- The correlation length ξ will determine the efficiency of foreground cleaning.
- Dominates contamination on small scales.

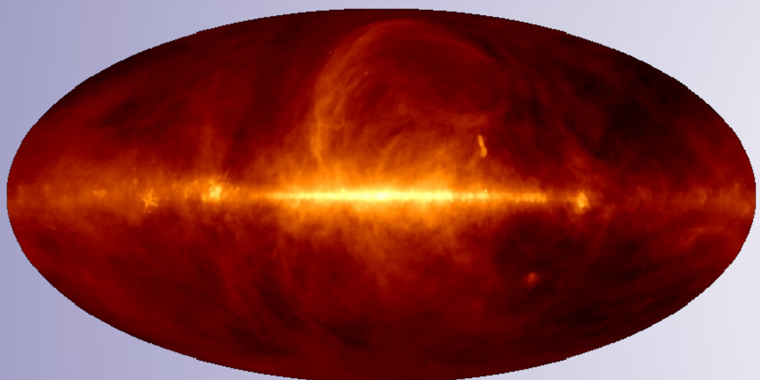


Alonso et al. 2013

Intensity mapping simulations

Foregrounds: synchrotron

Haslam et al. 1982



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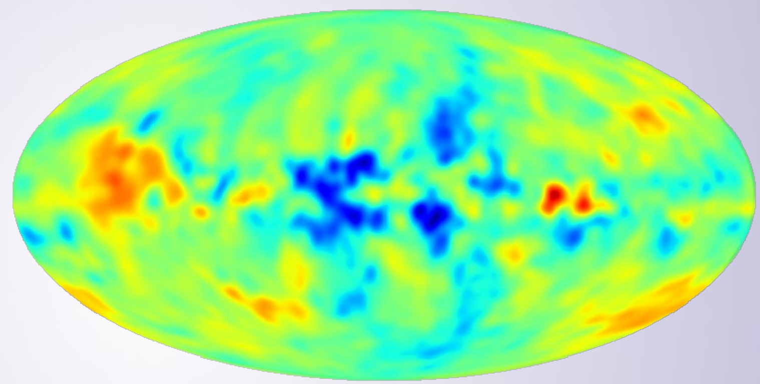
Delabrouille et al. 2013 (PSM)



+ SCK

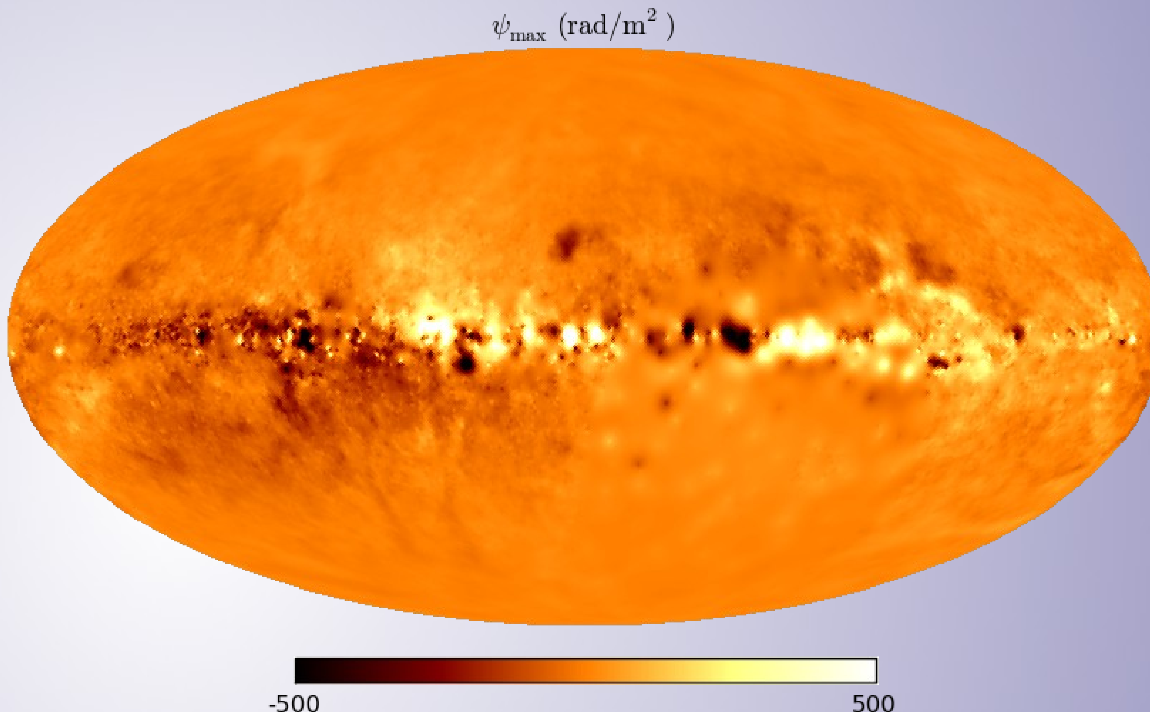
$$T_{\rm sync}(\nu,\hat{\mathbf{n}})=T_{408}(\hat{\mathbf{n}})\left(\frac{\nu_H}{\nu}\right)^{\beta(\hat{\mathbf{n}})}+\Delta T_{\rm SCK}(\nu,\hat{\mathbf{n}})$$

Alonso et al. 2013

Intensity mapping simulations

Foregrounds: polarized synchrotron

- Very few observations of the polarized radio sky.
- Should improve with GMIMS, SKA
- Simplistic models (single Faraday screen)
- Simulations based on models of n_{CR}, n_e, $B_{gal.}$ (Waelkens et al. 2009, HAMMURABI)



Oppermann et al. 2012

$$I_P(\nu, \hat{\mathbf{n}}) = \int d\psi\, k(\psi, \hat{\mathbf{n}}, \nu)\, e^{i\psi x_\nu}$$

Alonso et al. 2013

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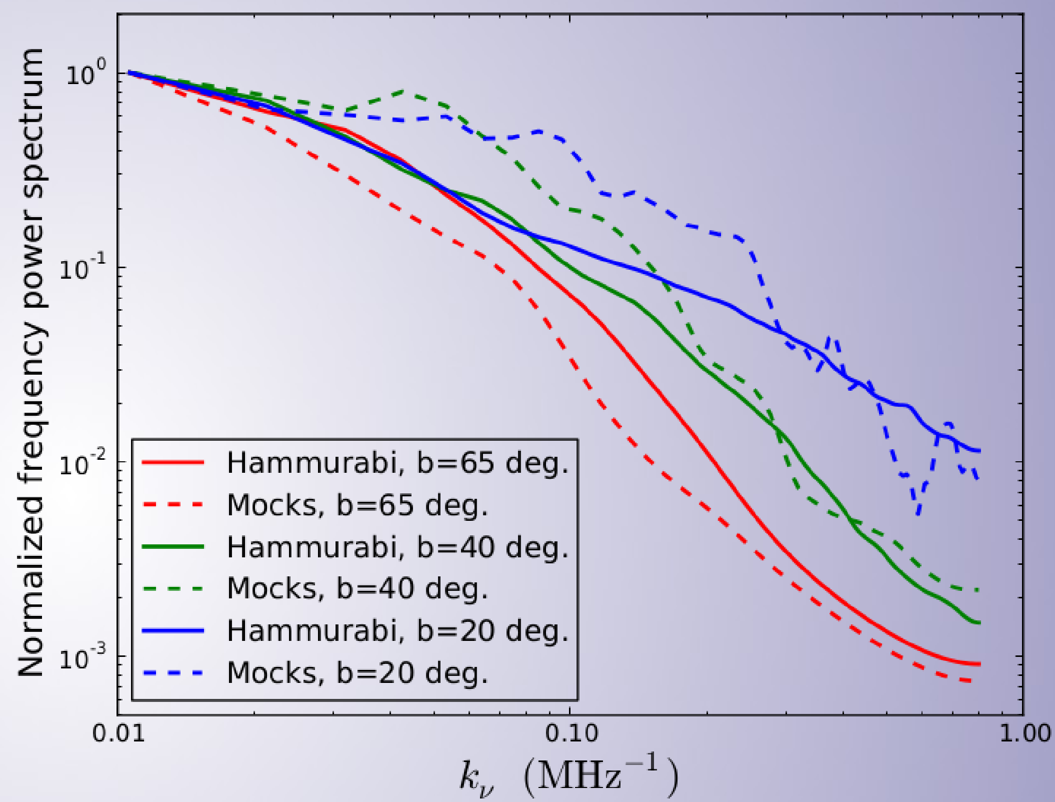

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Alonso et al. 2013

Blind foreground subtraction