# Intensity mapping experiments
## (forecasting)

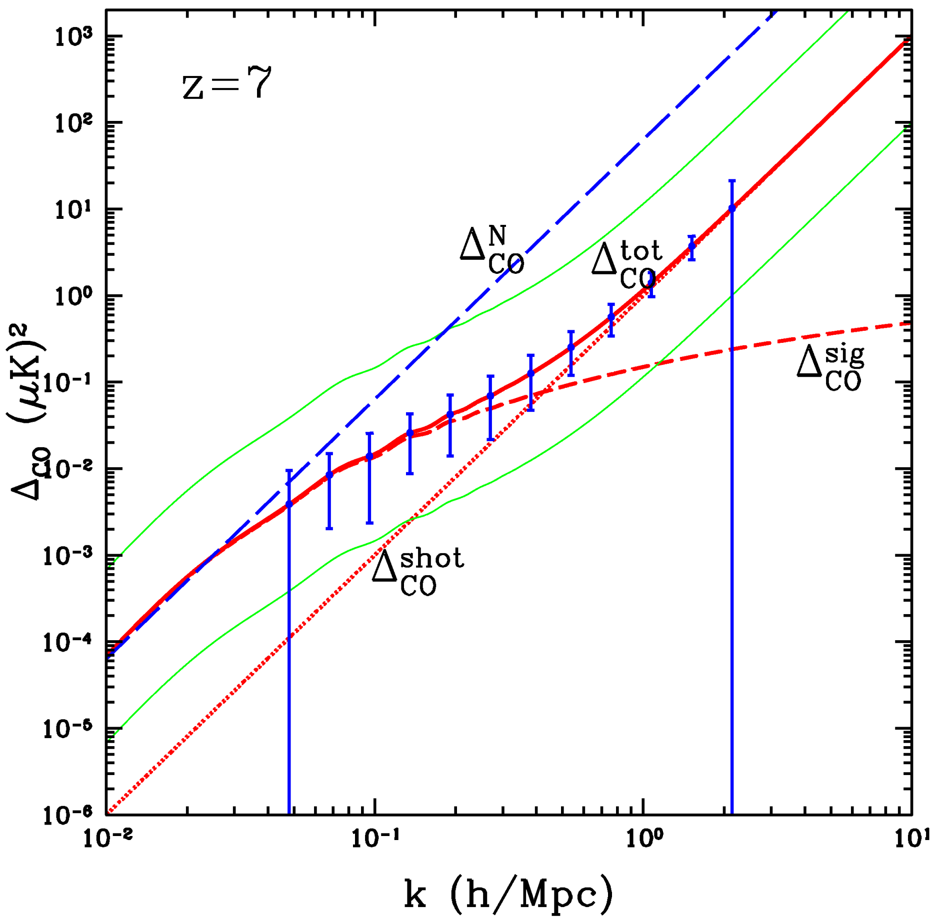
Mário G. Santos (CENTRA - IST)
Oxford, Nov 23, 2012

# EoR - adding other lines…

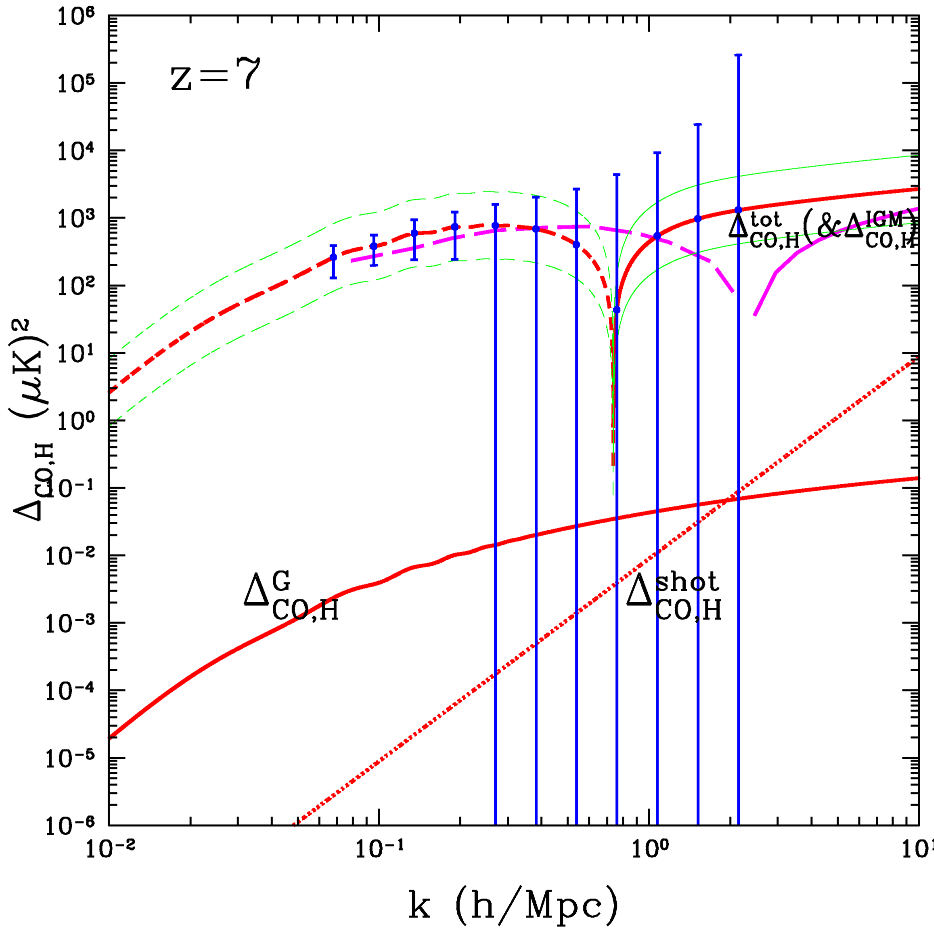
- Complementary picture of the EoR (Galaxies versus IGM)
- Cross-correlation can help to beat 21 cm foregrounds and radio calibration issues!
- Most relevant at $z \lesssim 10$
- Lines:
    - CO
    - CII
    - Lyman-α

# CO lines at z>6

- CO(1–0) ~ 115 GHz – 2.6 mm (< 15 GHz during EoR)




CO(1–0) Power Spectrum



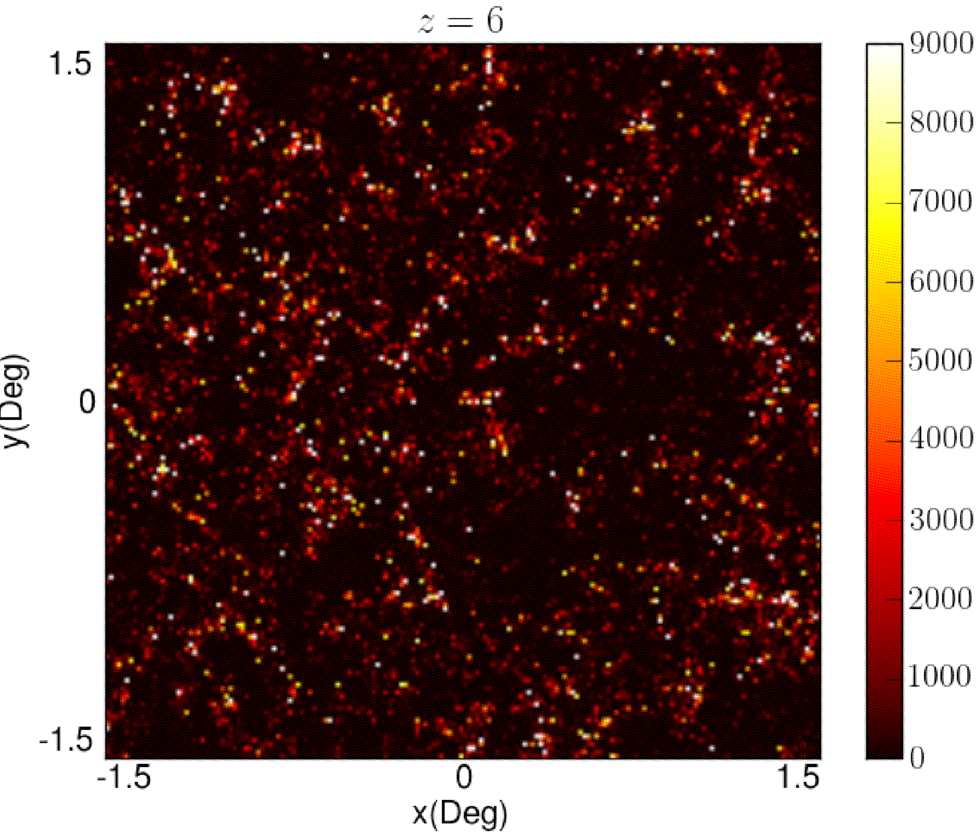

Cross-correlation with LOFAR

Gong et al., ApJL 2011

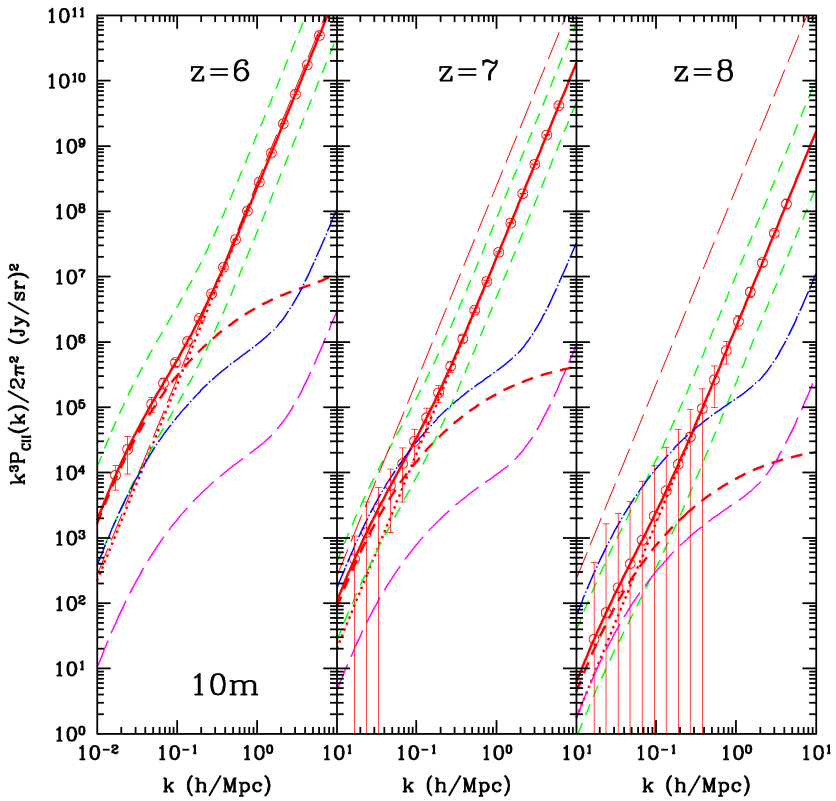
- CO: Interferometer with ~ 70 cm dishes, 380 $m^2$ collecting area, 1 GHz BW, 20 K, FoV ~ 5 $deg^2$

# CII (238 GHz – 1.3 mm at z=7)

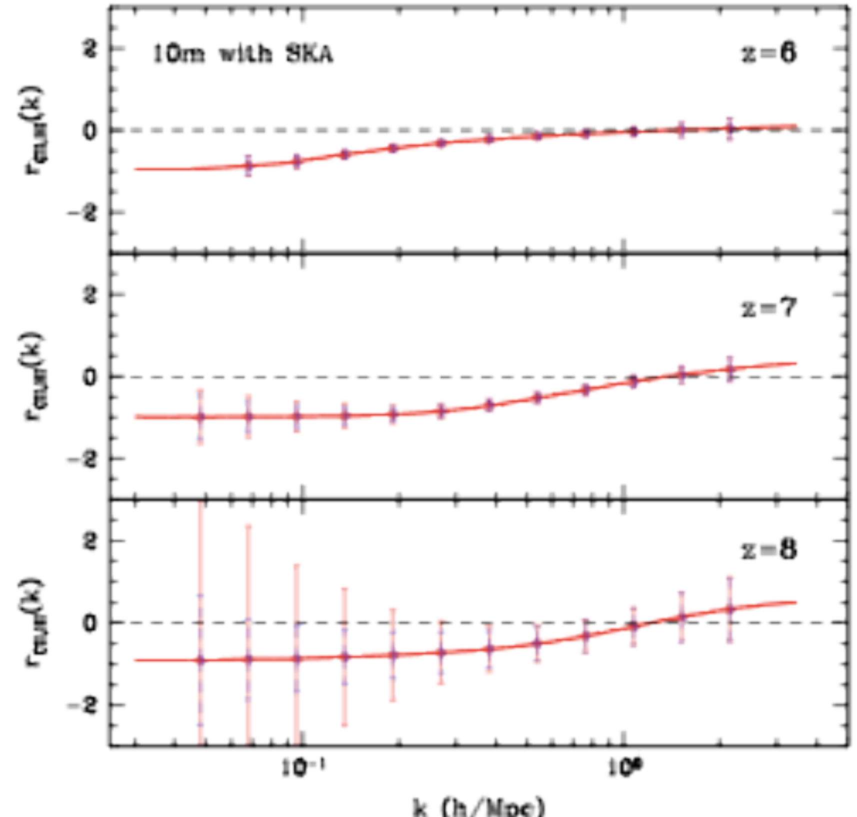
Gong et al., ApJ 2012




CII map




CII Power spectrum

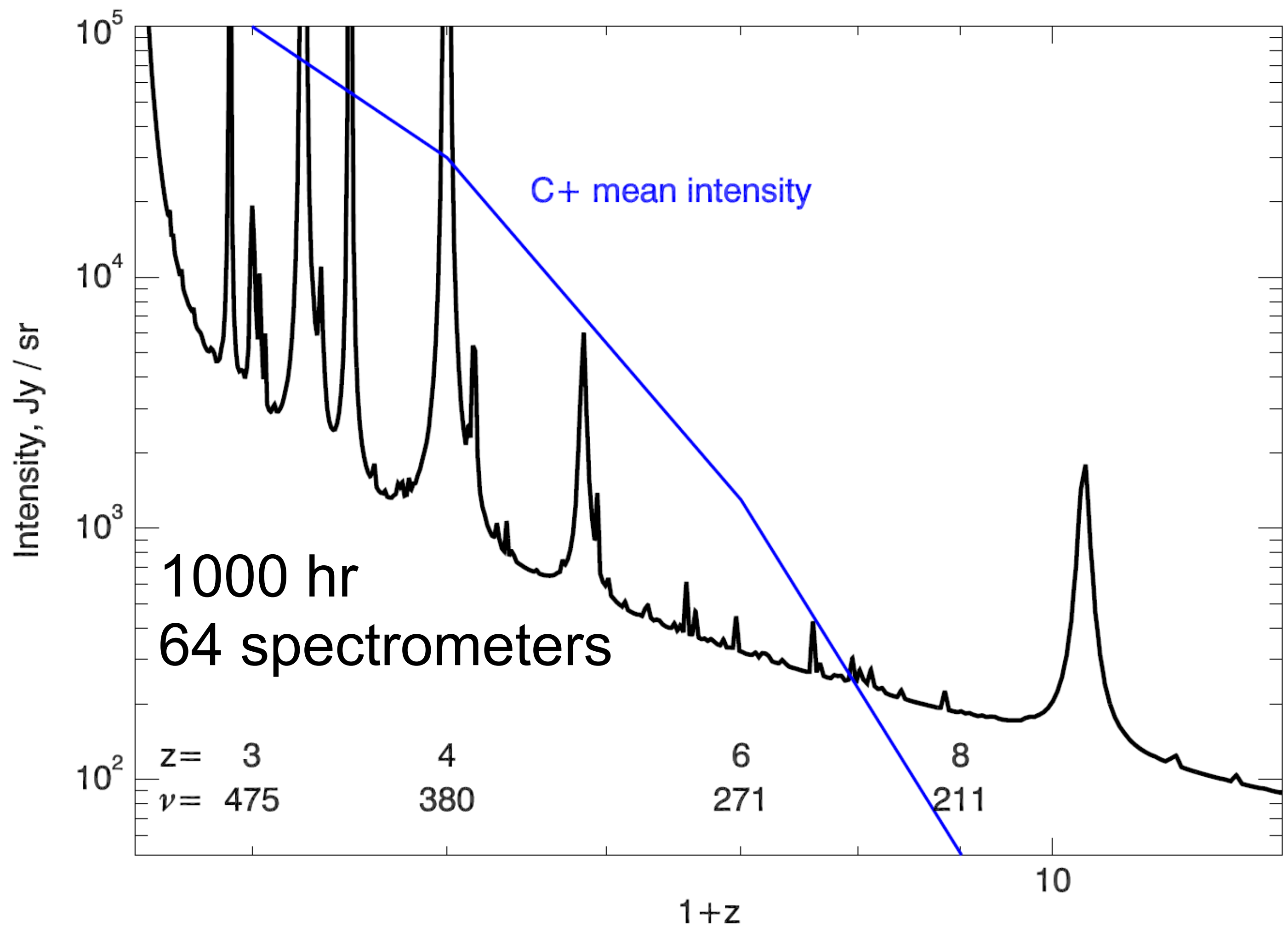



CII/21 cm cross-correlation

- CII galaxies trace the large-scale structure
- Cross-correlation constrains bubble size, number CII galaxies in HII bubbles...
- Experimental setup above: 10m dish; 16 $deg^2$ survey area; 20,000 bolometers

Table 1. Nominal TIME Instrument Parameters

| | | | |
|---|---|---|---|
| Aperture | 3 m | Photon NEP | 6.7 x $10^{-18}$ W/√Hz |
| Beam Size | 1.5 arcmin FWHM | Detector NEP | 5.4 x $10^{-18}$ W/√Hz |
| Survey Area | 16 sq. degrees | Sensitivity per Detector | 2.5 x $10^{6}$ Jy/sr √s |
| Total Observing Time | 4000 h | Frequency Coverage | 185 – 310 GHz |
| Number of Spectrometers | 64 | Frequency Resolution | 0.4 GHz |
| Number of Detectors | 20,000 | Optical Efficiency | 30 %, dual-pol |




TIME team:
Jamie Bock (JPL: PI)
Matt Bradford (JPL)
Asantha Cooray (UCI)
Mike Zemcov (Caltech)
Mario Santos (IST - CENTRA)

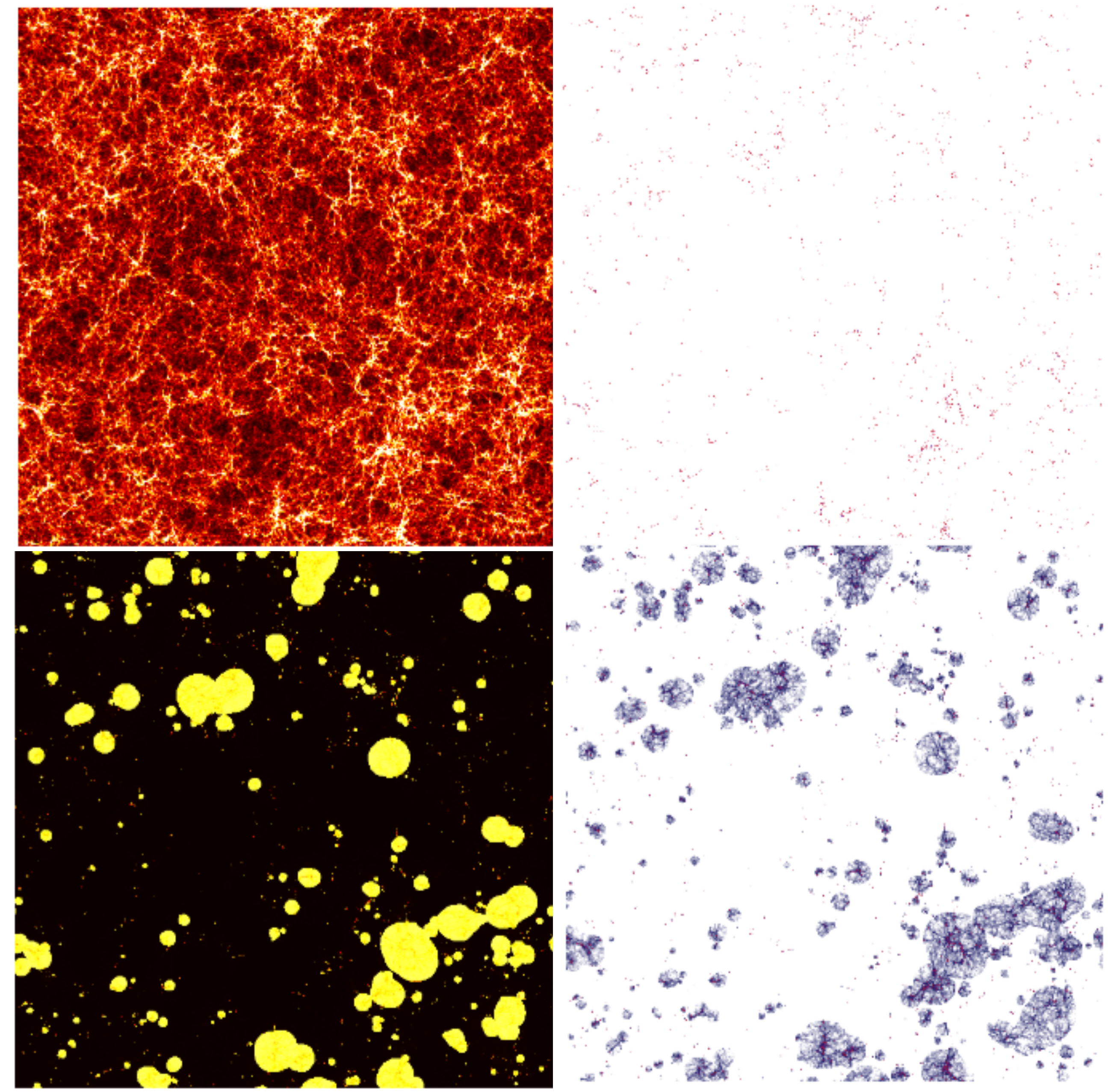
*Proposal stage; ground-based, 3 to 5m aperture.*
*Looking for an existing mm-wave telescope to host an instrument (Beijing Group has expressed interest in Dome-C TerraHertz Telescope)*

# TIME: Tomographic Ionized-Carbon Mapping Experiment

# What about the Lyα line?

M. B. Silva et al. (2012)

- 0.97 μm at z=7 (NIR)
- Emission from galaxies and IGM (recombinations, collisions…)
- $\nu I \sim 2\times10^{-8}$ ergs/s/cm$^2$/sr
- Simulations include full reionization history
- Using Modifications to Simfast21 (Simfast21.org)
- Depends on:
  - UV escape fraction
  - Lyman-alpha Luminosity functions



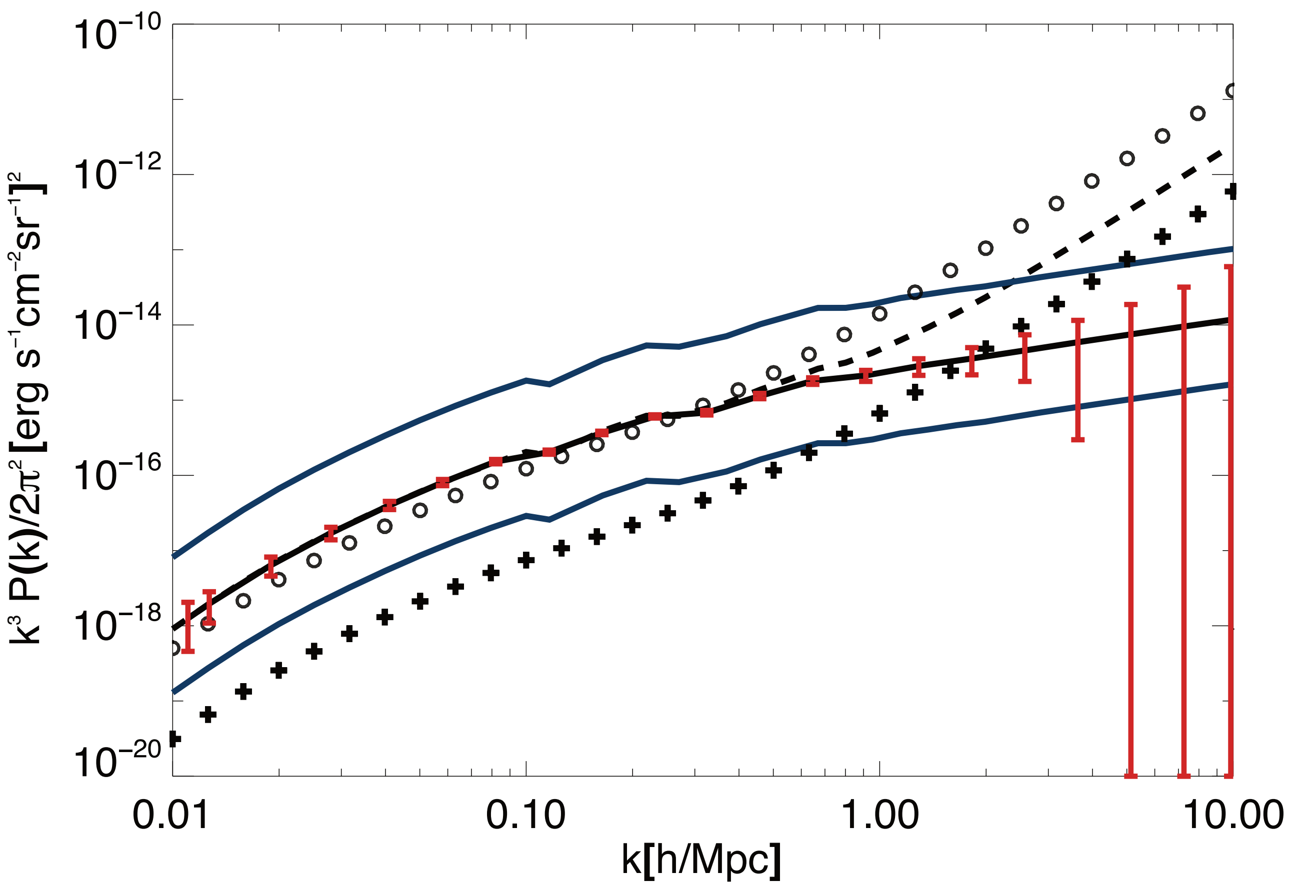
From top left, clockwise: dark matter, dark matter halos, HII bubles, Lyα emission

# Lyα intensity mapping observations

- Need to go to space? (contamination from atmospheric lines)
- Proposal for a low orbit satellite /telescope in preparation

Lyα 3d Power spectrum

z=7



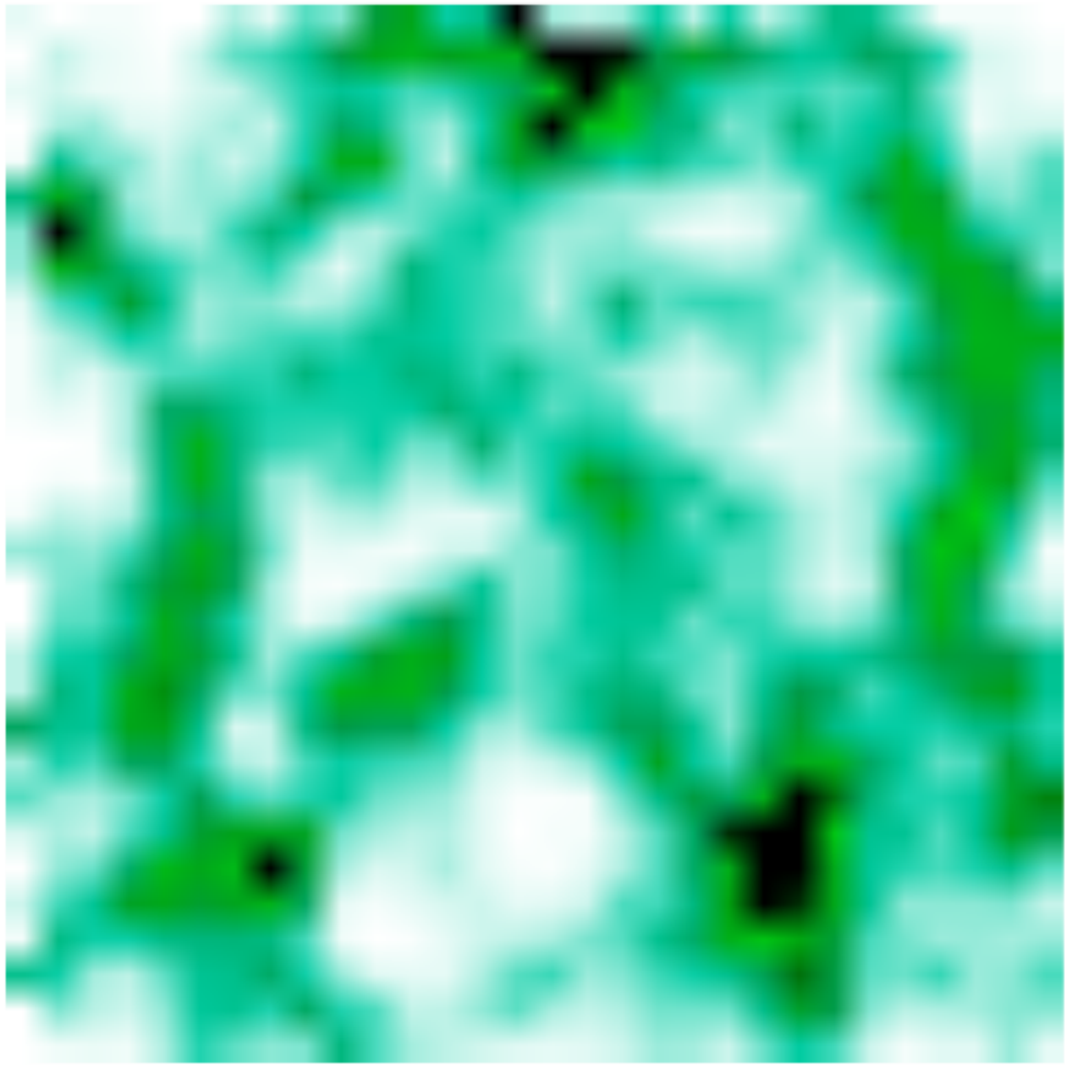

- Experiment:
  - Space-borne (observations ~ 1 μm)
  - 20 cm aperture
  - Spectrometer, R=200
  - 2048x2048 pixel array
  - FoV=45x45 deg2
  - 10'' pixels
  - 20 deg2 survey area

- Solid lines: Lya power spectrum (different models)
- Open circles: Ha contamination (z=0.5)
- Crosses: Ha after masking

*(Silva et al., ApJ 2012)*

# Cosmology with HI Intensity Mapping after Reionization

- Measure integrated flux in each pixel instead of galaxies
- $0<z<2$ – dark energy
- $2<z<6$ – curvature of the Universe
- $0<z<6$ – Primordial non-Gaussianity…
- Cosmology on extremely large scales!



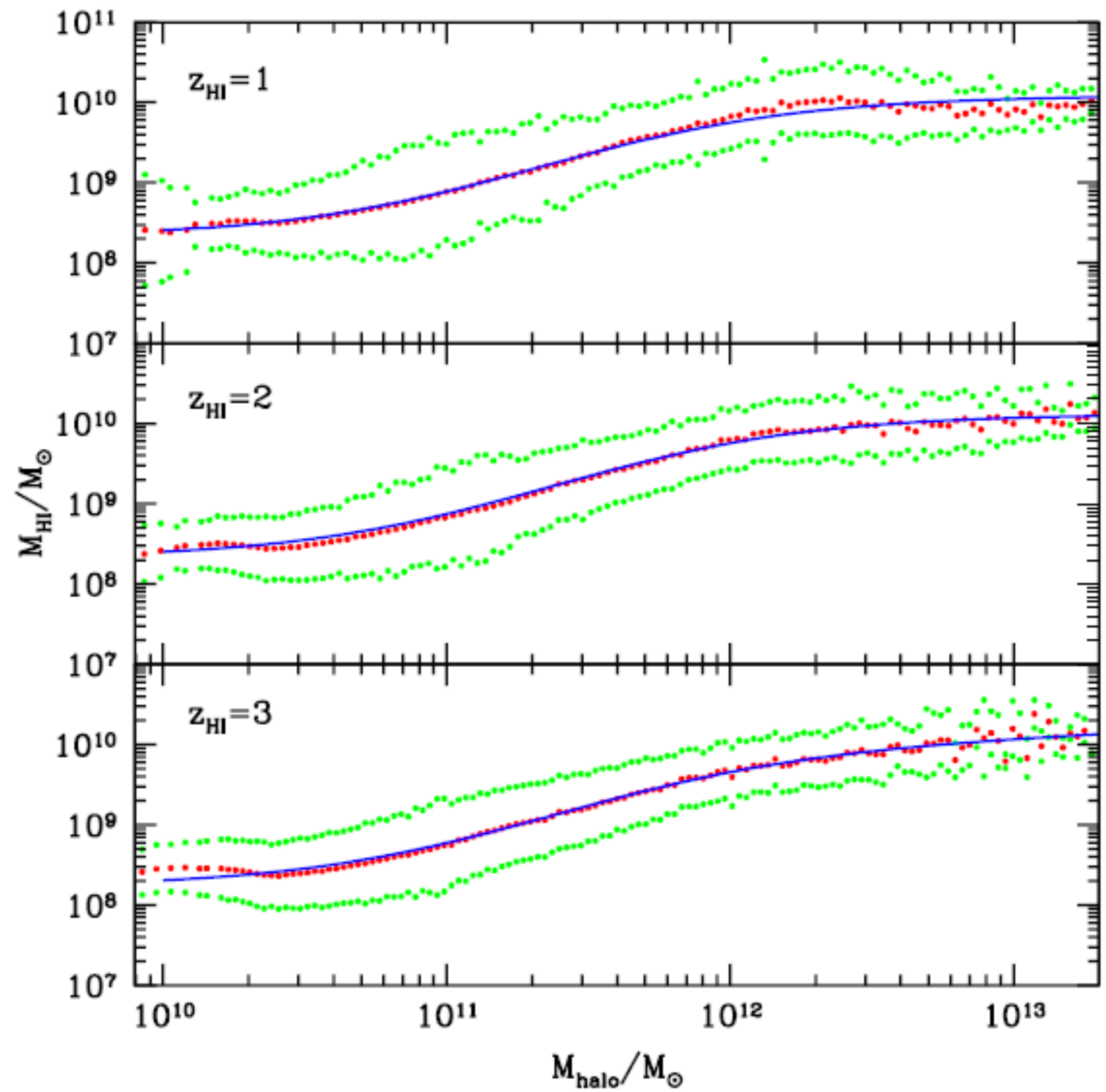
HI intensity map at $z=1.3$

# HI intensity: expected signal

- Assume all HI in galaxies
- Assume: $M_{HI}(M_{halo})$ at z
- Remember: large pixels! (low resolution)
- ~ (888, 1228, 1067) μK at z=(1,2,3)
- $\Omega_{HI} \sim 10^{-3}$
- Consistent with Chang et al. measurements, etc
- Bias ~ 1 at z=1

$$\rho_{\rm HI}(z) = \int_{M_{\rm min}}^{M_{\rm max}} dM \, \frac{dn}{dM} M_{\rm HI}(M)$$

$$\overline{T}_{21}(z) \approx \frac{900\,\mu{\rm K}}{(1+z)} \frac{H(z)}{120.7\,{\rm Km/s/Mpc}} \frac{\Omega_{\rm HI}(z)}{0.004}$$




Using Obreschkow et al., 2010 + Millennium Simulation

Gong et al, ApJL 2012

# HI intensity: Power spectrum

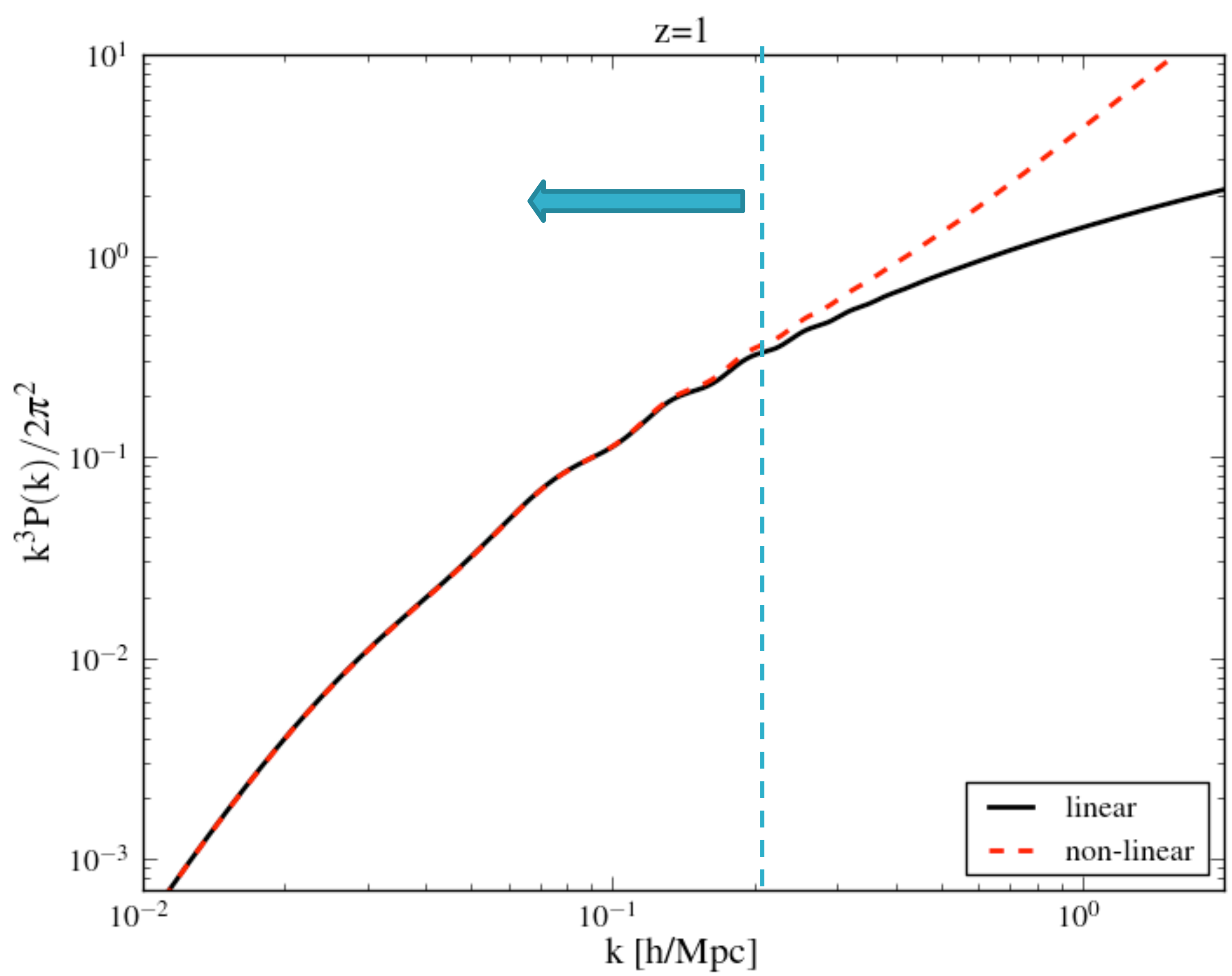
- Flat sky (small patch)
- No cosmic evolution... (BW < 100 MHz)
- Proportional to dark matter
- Linear approximation:

$$\mathrm{P}_{21}(k_{\mathrm{los}}, k_{\mathrm{perp}}) = \left(\overline{T}_{21}(z)\right)^2 \left[b_{\mathrm{HI}} + \left(\frac{k_{\mathrm{los}}}{\sqrt{k_{\mathrm{perp}}^2 + k_{\mathrm{los}}^2}}\right)^2 \frac{1}{H(z)} \frac{\dot{D}(z)}{D(z)}\right]^2 P_\delta(k)$$

Possible k dependence (modulation from ionizing background)

# BAO observations wish list

Dark matter power spectrum




- Scales of interest (z=1):
  - Min. BAO scale ~ 15.7 Mpc/h
  - $k_{max}$ ~ 0.2 h/Mpc
  - Angular resol ~ 22.8 arcmin (D ~ 60m)
  - dz ~ 0.009
  - Freq. resol ~ 3.14 MHz

  - Max. BAO scale ~ 628 Mpc/h
  - $k_{min}$ ~ 0.01 h/Mpc
  - Maximum angular scale ~ 15 deg
  - dz ~ 0.35
  - BW ~ 123 MHz

# Constraints 101: Dish

Instrument noise

$$T_{\rm sys} = T_{\rm inst} + T_{\rm sky}$$

Sky

$$T_{\rm sky} = 60\left(\frac{300\,\rm MHz}{\nu}\right)^{2.55}$$

$$\sigma_N = \frac{T_{\rm sys}}{\sqrt{\delta\nu\, t_{\rm total}}}\sqrt{\frac{S_{\rm area}}{\rm beam}}$$

$$P_N = \sigma_N^2\, V_{\rm pix}$$

pixel volume

$$V_{\rm pix} \propto beam \times \delta\nu$$

Error

$$\Delta P_{21}(k) \propto \frac{P_{21}(k) + P_N}{\sqrt{S_{\rm area} \times {\rm BW}}}\, k^{-3/2}$$

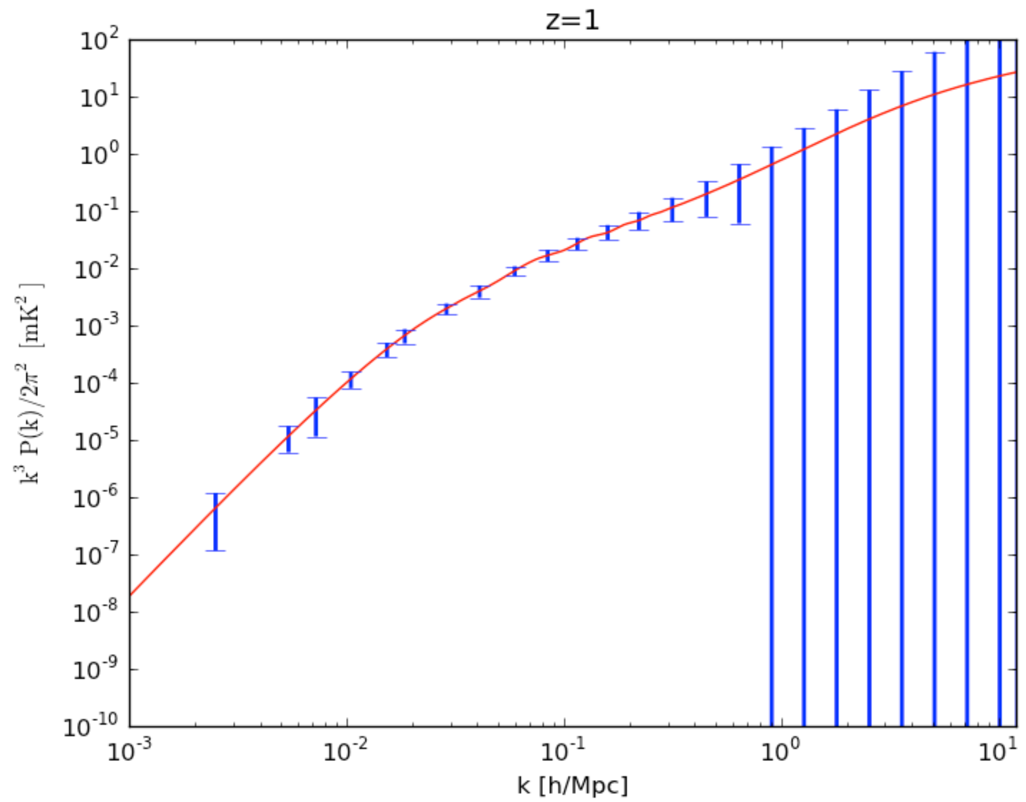
Noise dominated regime

$$\Delta P_{21}(k) \propto \frac{T_{\rm sys}^2}{t_{\rm total}}\sqrt{\frac{S_{\rm area}}{\rm BW}}\, k^{-3/2}$$

Survey area

Bandwidth

- Ready to make forecasts…
- Example:
  - 2m dish (beam ~ 215 deg²)
  - $T_{\rm inst}$ ~ 40 K
  - 1000 deg² survey
  - BW ~ 100 MHz
  - ~ 10,000 hours



# Constraints 101: Interferometers

- Note: we cannot probe scales larger than ~ $\sqrt{\mathrm{FoV}} \sim \lambda / D_e$

- Noise power spectrum for 1 pointing:

$$P_N(k_{\rm los}, k_{\rm perp}) = \left(r^2 \frac{dr}{d\nu}\right) \frac{\lambda^4 T_{\rm sys}^2}{A_e^2} \frac{1}{t_{\rm tot}\, n(k_{\rm perp})} \sim \left(r^2 \frac{dr}{d\nu}\right) \frac{\lambda^2 T_{\rm sys}^2}{A_{\rm tot}^2} \frac{D_{\rm max}^2}{t_{\rm tot}} \sim \left(r^2 \frac{dr}{d\nu}\right) \frac{\rm beam}{f^2} \frac{T_{\rm sys}^2}{t_{\rm tot}}$$

Collecting area for 1 element

baseline density distribution

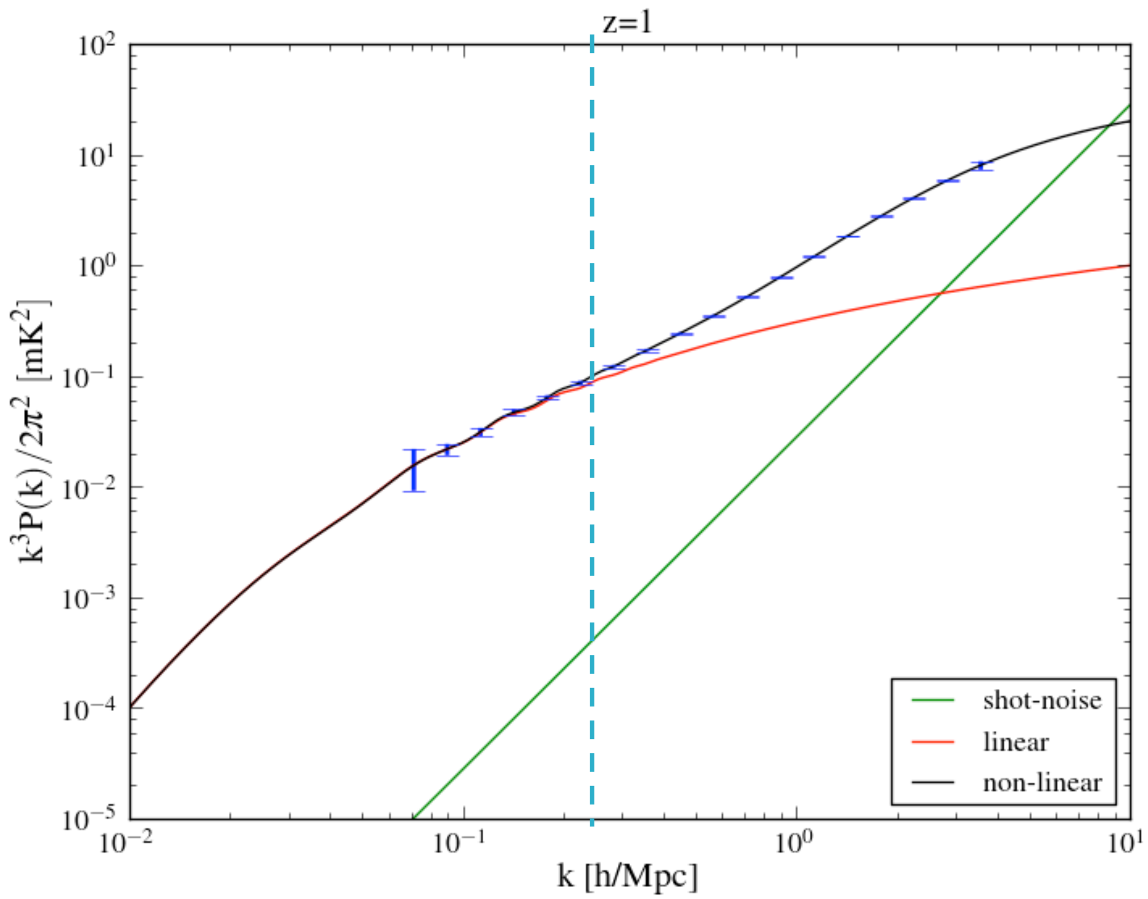
$$f = \frac{A_{\rm tot}}{D_{\rm max}^2} \sim N_e \frac{\rm beam}{\rm FoV}$$

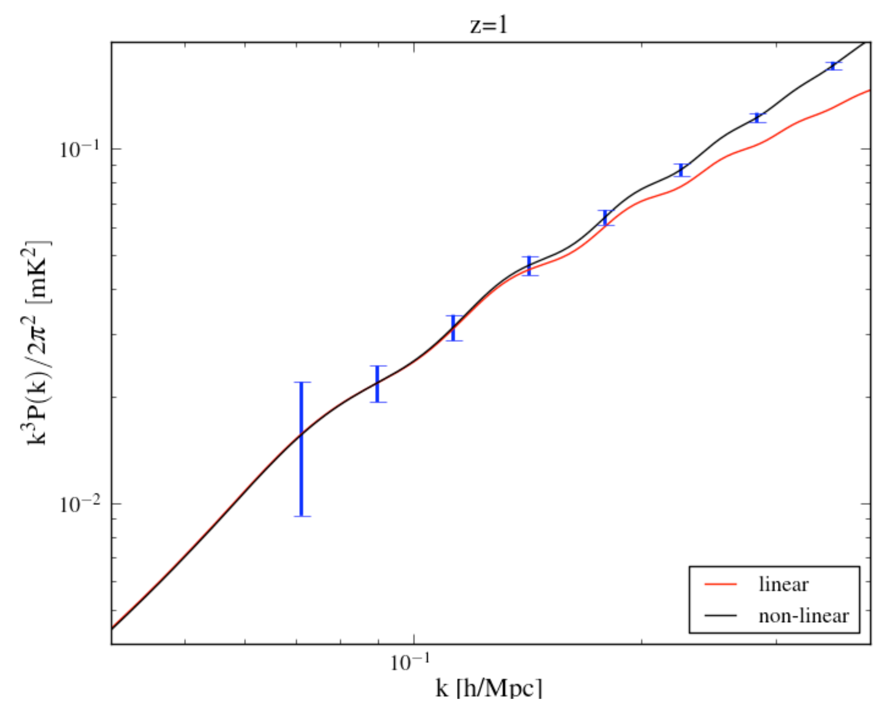
- Take a survey with area $S_{area}=N_p x\mathrm{FoV}$
- Error (noise dominated):

$$\Delta P_{21} \propto \frac{1}{A_{\rm tot}} \frac{1}{f} \frac{T_{\rm sys}^2}{t_{\rm tot}} \sqrt{\frac{N_p}{\mathrm{FoV} \times \mathrm{BW}}}\, k^{-3/2}$$

# EMMA BAO constraints

- Assume:
  - A=2000 $m^2$
  - 14 stations
  - Tsys~45K
  - FoV=78 $deg^2$
  - time=2000 hours
  - Maximum baseline=300m
  - Minimum baseline=10m ?
  - Frequency resolution=0.3 MHz




z=1 – 710.25 MHz

dz ~ 0.2 (0.3 MHz)

Note: with 500 MHz BW can measure 7 bins in one go!

# Medicina – Northern Cross

(info from Kristian Zarb Adami)

- (Using BEST-2)
- Obs. freq: 407 MHz
- Observation time: 2000 hours;  Syst. temp: 86 K
- Collecting area: 964 $m^2$
- Bandwidth: 16 MHz
- FoV: 37.65 $deg^2$
- Angular resolution: 57 arcmin