Pros and Cons of Cosmology with 21cm Background

Kyungjin Ahn
Chosun University

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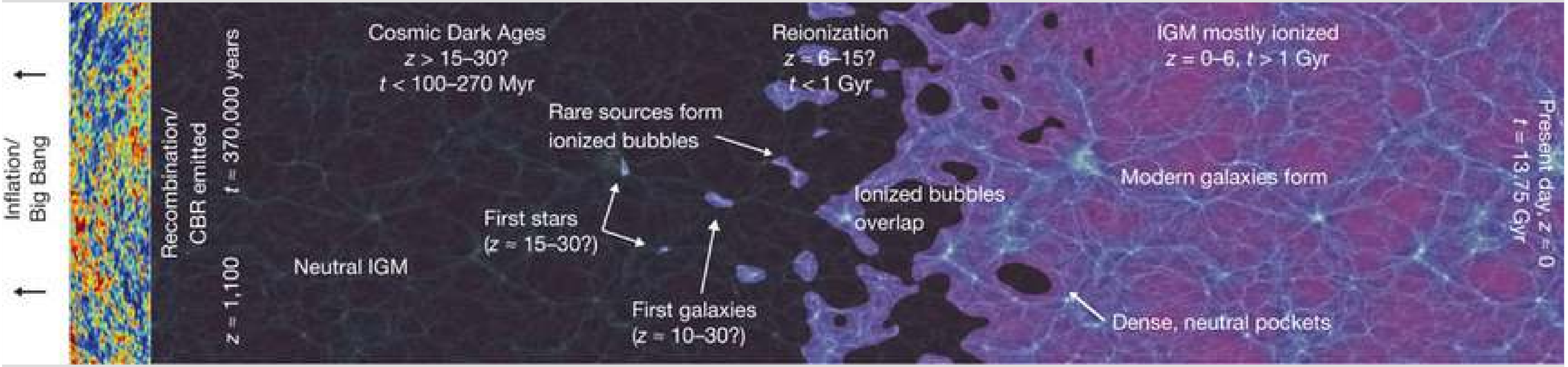
HI intensity mapping

Cosmic History in a Nutshell



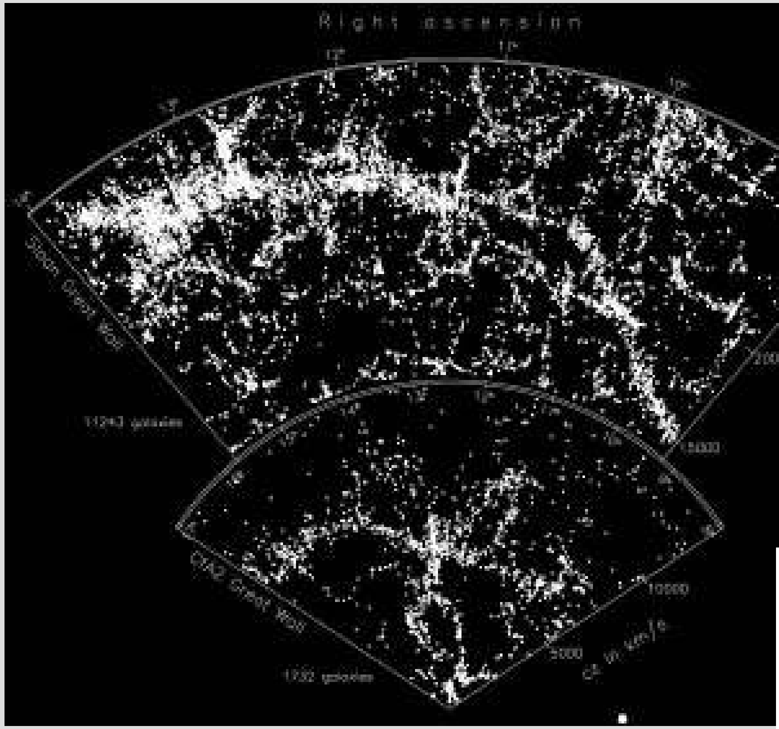
HI intensity mapping

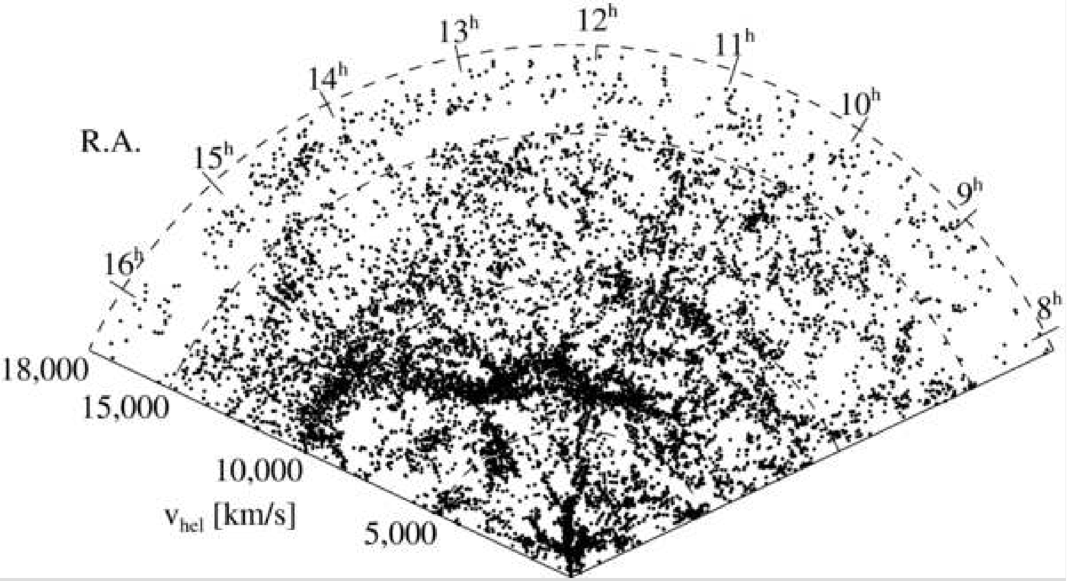
- (Relatively) Low-z: z =~ 1 to ~ 0
  - HI gas attached to galaxies or proto-galaxies (Damped Lyman Alpha, DLAs)
  - Not individual-galaxy detection, but more diffuse background from many galaxies
  - Redshift from measured frequency (up to peculiar velocity)
    - ν=1.42 GHz / (1+z)
  - Relatively closer, but neutral fraction is lower

- High-z: z =~ 40 to ~ 7
  - HI gas in intergalactic medium (IGM)
  - Cosmic Dark Ages: very rare astrophysical sources: cosmological information pristine
  - Epoch of Reionization: cosmological information + astrophysical information
  - Relatively further (very far), but neutral fraction is higher

HI intensity mapping
@ (Relatively) Low-z

Low-z Intensity mapping: ALFALFA survey (z,~0.06)

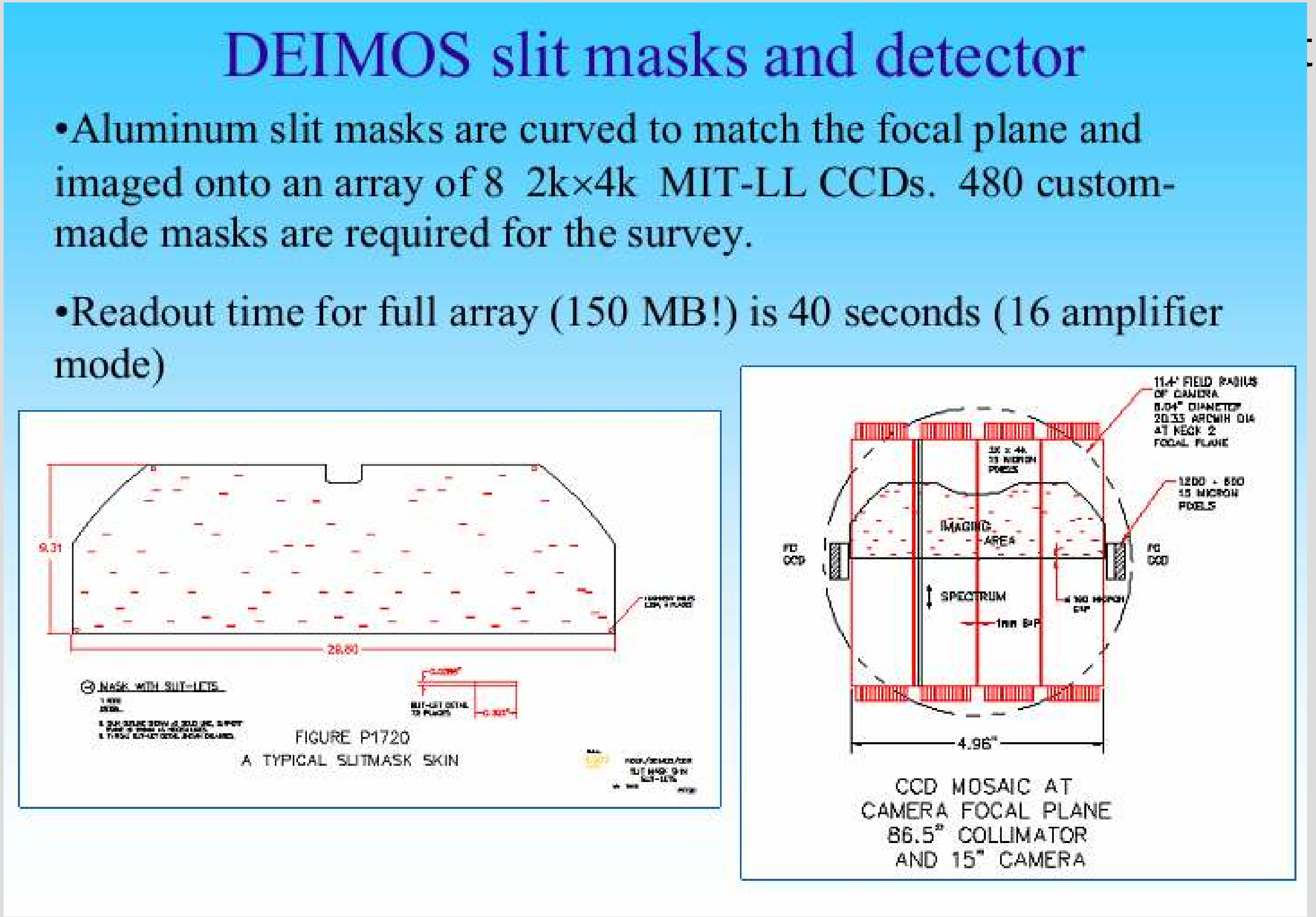




Low-z Intensity mapping: z=0.8 (Chang+ 2010, Nature)

- Still baby step: Constrained neutral hydrogen content at z=0.8 (with uncertainty in HI- galaxy bias)
- galaxy mapping from DEEP2 (Keck+DEIMOS)
- HI mapping with Green Bank Telescope (GBT)
  - 100m diameter
- measured correlation function

Low-z Intensity mapping: z=0.8 (Chang+ 2010, Nature)



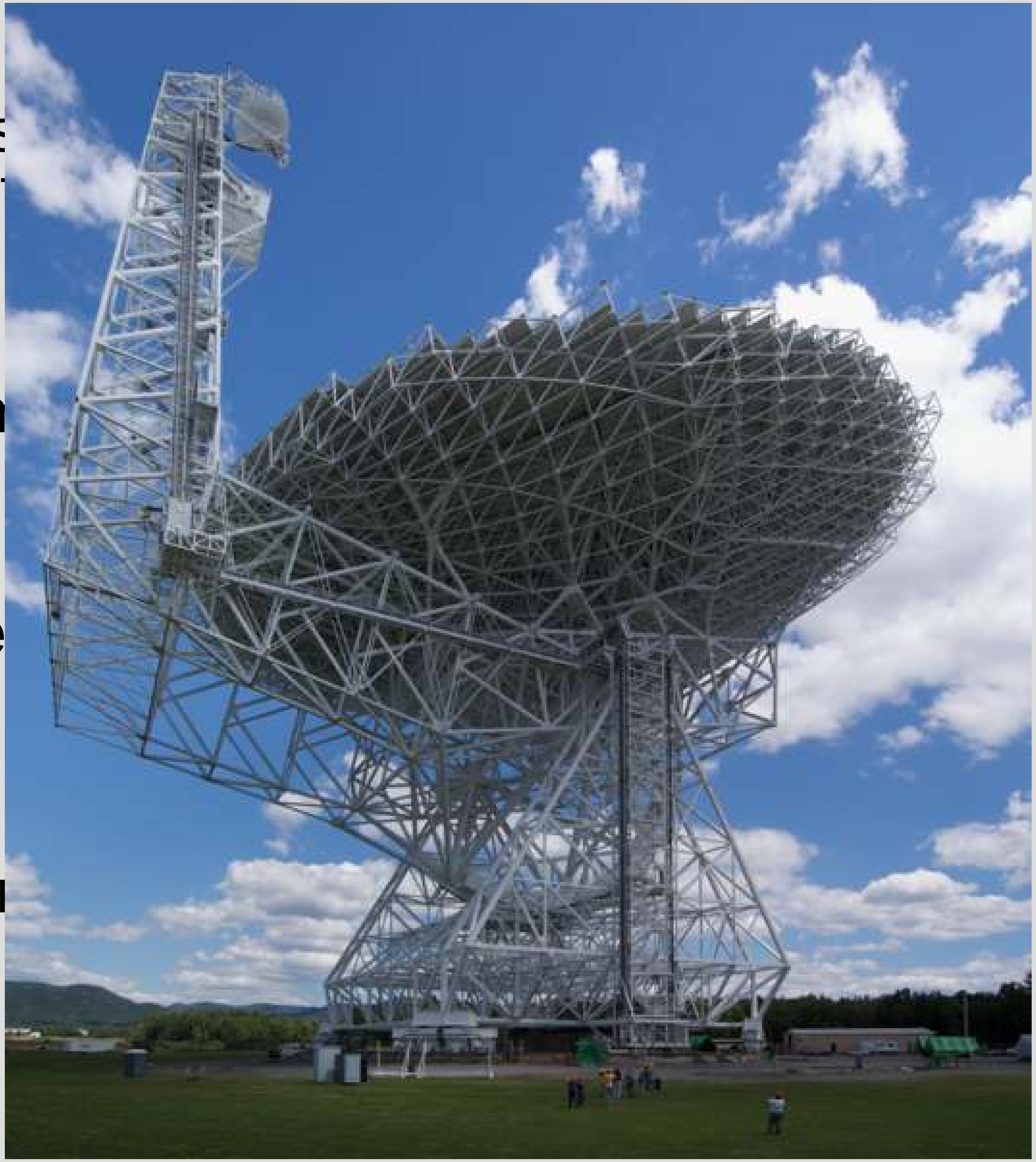
DEIMOS slit masks and detector

- Aluminum slit masks are curved to match the focal plane and imaged onto an array of 8 2k×4k MIT-LL CCDs. 480 custom-made masks are required for the survey.
- Readout time for full array (150 MB!) is 40 seconds (16 amplifier mode)

FIGURE P1720
A TYPICAL SLITMASK SKIN

CCD MOSAIC AT
CAMERA FOCAL PLANE
86.5" COLLIMATOR
AND 15" CAMERA

Low-z Intensity mapping: z=0.8 (Chang+ 2010, Nature)



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  at z=0.8 (with uncer
- galaxy mapping fron
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- **Still baby step: Constrained neutral hydrogen content at z=0.8 (with uncertainty in HI- galaxy bias)**

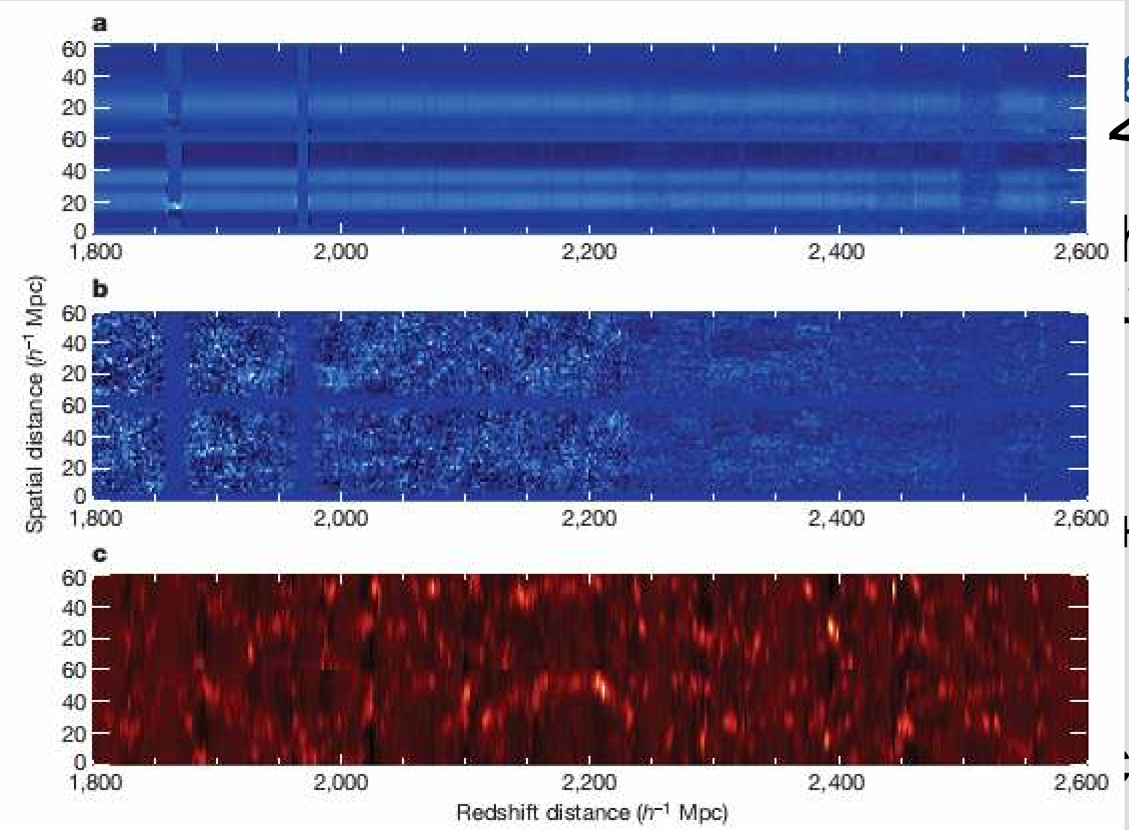
- galaxy mapping from DEEP2 (Keck+DEIMOS) δ_{opt}

- HI mapping with Green Bank Telescope (GBT) δT_b
  - 100m diameter

- **measured correlation function** $\langle \delta T_b(z)\, \delta_{opt}(z+dz) \rangle$

l g+ 2010)

raw (CMB galactic RFI ...)



- hydrogen content
xy bias)

- +DEIMOS)

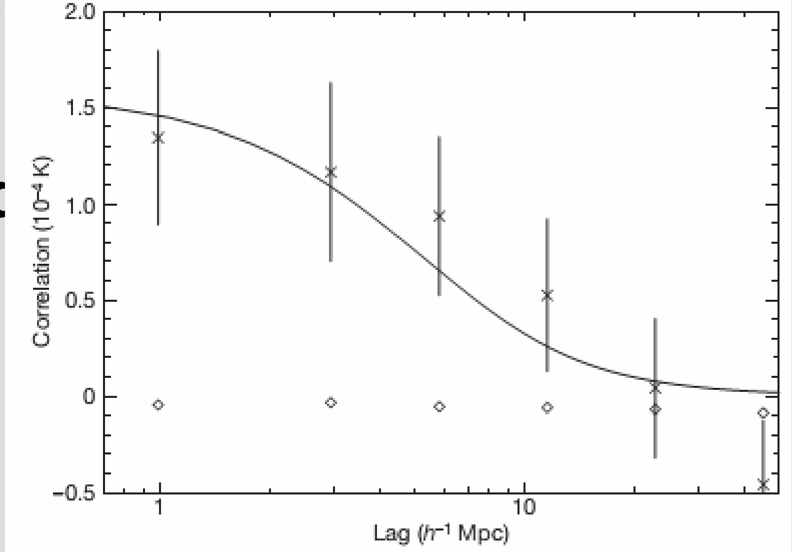
δ_{opt}

- cope (GBT)

δT_b

  - 100m d

- **measured**



$\langle \delta T_b(\vec{x}) \, \delta_{opt}(\vec{x}+\vec{r}) \rangle$

$\vec{r}$ // line of sight

Low-z Intensity mapping: z=0.8 (Chang+ 2010, Nature)

- Constrained $\Omega_{HI}*r*b = (5.5 \pm 1.5)*10^{-4}$
  - $\Omega_{HI}=\rho_{HI}/\rho_{crit,0}$
  - r: stocasticity
  - b: bias (HI to galaxy bias)
  - If b=r=1, a few percent neutral
  - b & r still very uncertain

- Lesson
  - cosmology possible
  - HI and galaxy correlated
  - very dim: aggressive foreground removal
  - no need for individual spectroscopy (diffuse background)
  - galaxy bias + HI bias

Low-z HI intensity mapping: Proposal

- https://science.nrao.edu/science/Decadal%20Survey/rac/cfp
  - 21cm Intensity Mapping (Jeffrey Peterson+)
- Target: Baryonic Acoustic Oscillation (BAO) measure
  - cosmology by ~ 10 Mpc resolution survey
  - BAO: standard ruler of ~150 Mpc → extract dark energy equation of state
  - a few tens – hundres μK rms
  - z~0-1 thru 10000 m^2 telescope
- Peterson building Cylinder Radio Telescope (CRT) at Morocco
- some papers even claiming z up to 5
- HR will be useful

Low-z HI intensity mapping: Proposal

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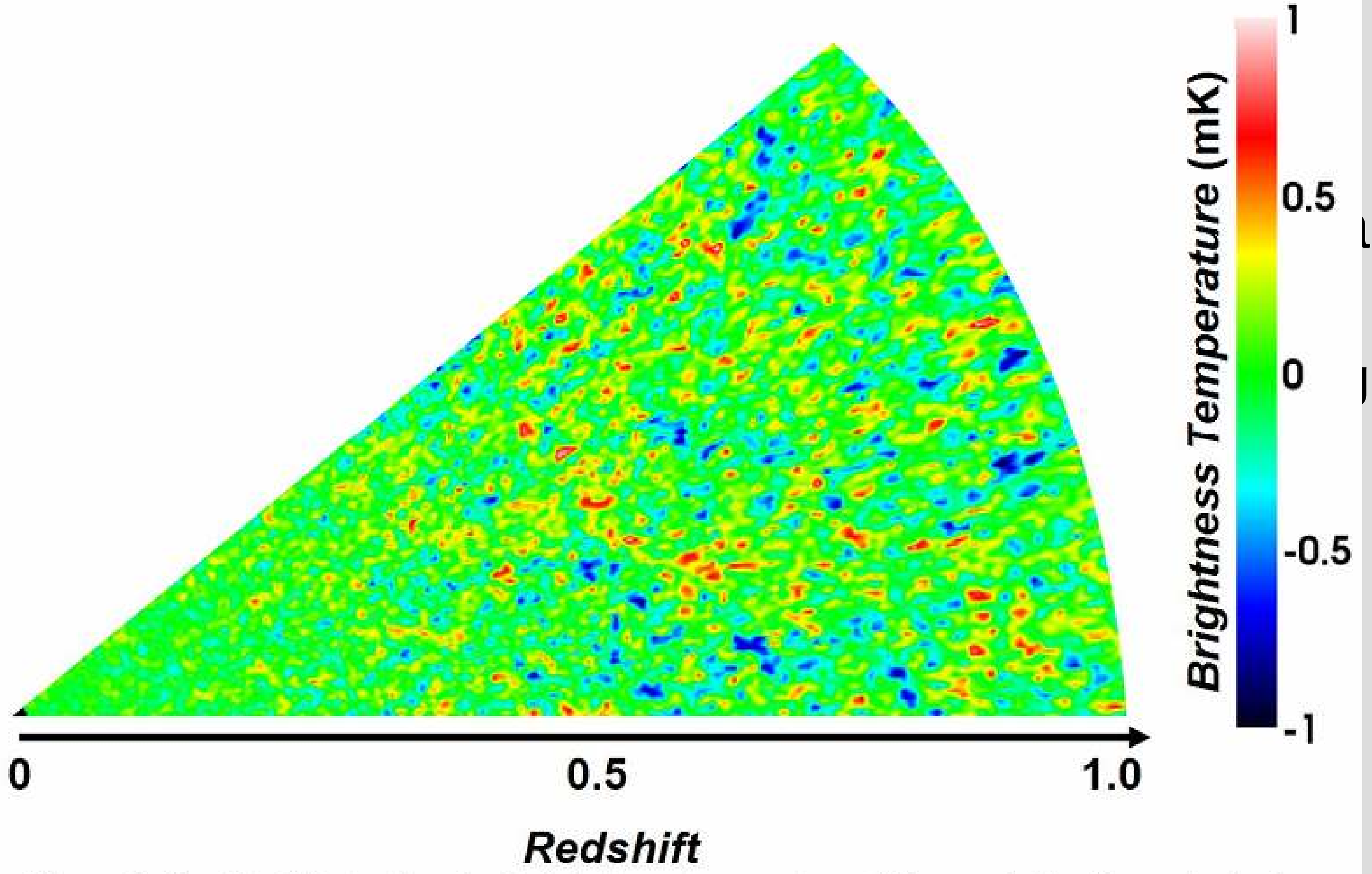

Figure 2: Simulated fluctuations in the brightness temperature of 21cm emission from galaxies in a slice through the universe. The emission is smoothed over 8/h Mpc. The redshift, z, translates to frequency: ν=1.42GHz/(1+z). Red indicates overdensity and blue underdensity.

Low-z HI intensity mapping: Proposal

- https:/
  - 21c
- Targe easure
  - co:
  - BA ergy equ
  - a f
  - z~

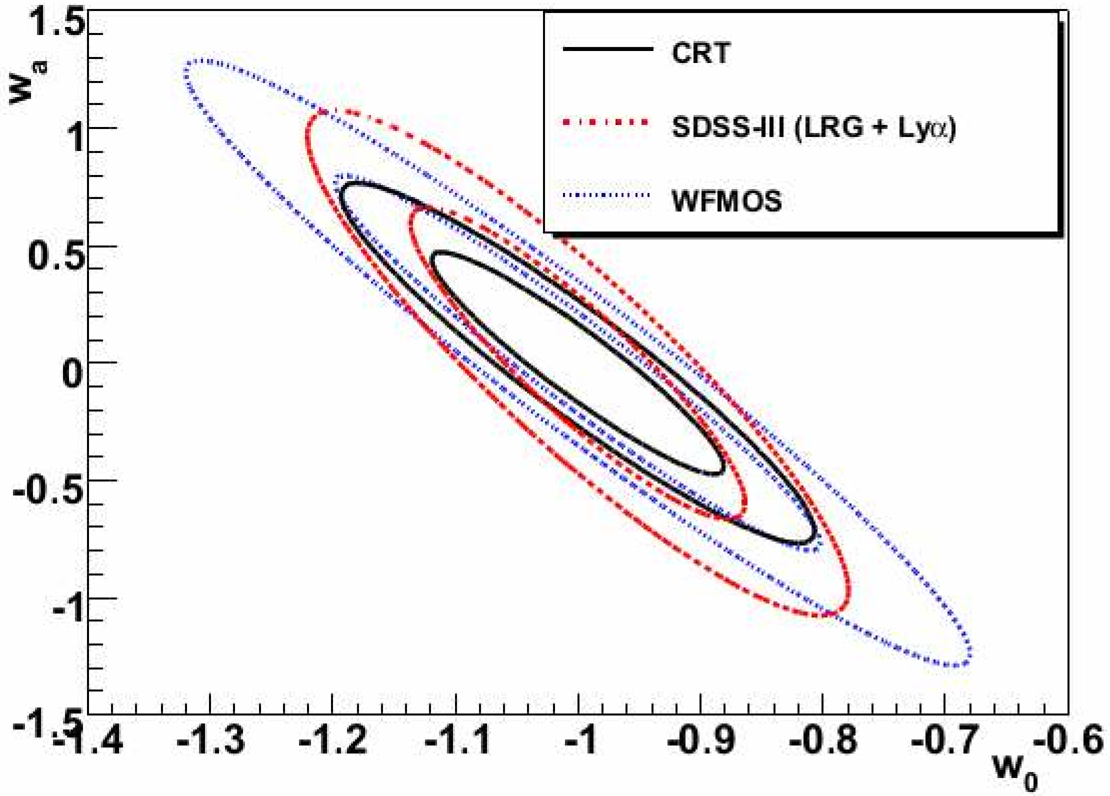

Figure 1. Sensitivity to Dark Energy Models. The plot shows projected error ellipses in the parameter space laid out by the Dark Energy Task Force. $w_0 = p/\rho$ is the dark energy equation of state, and w_a is the first derivative of w. Plotted in black are 1-σ and 2-σ contours for HI Intensity Mapping assuming a Cylinder Radio Telescope of area 10,000 sq meters. Also plotted are contours for the optical BAO experiments SDSS-III after combining the Large Red Galaxy and Lyman-alpha surveys (red) and WFMOS (blue).

HI intensity mapping
@ very high-z

HI intensity mapping

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- **High- z: z =~ 40 to ~ 7**
  - **HI gas in intergalactic medium (IGM)**
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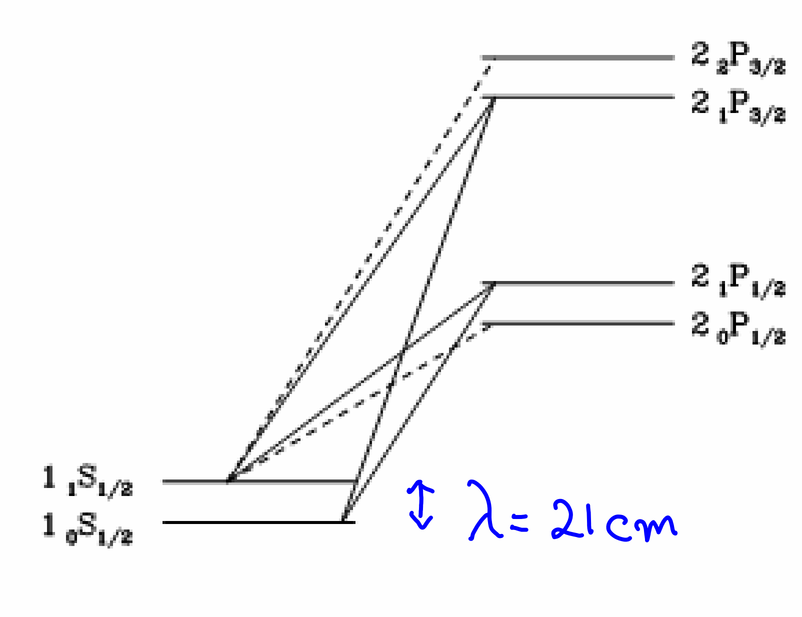
What determines 21cm strength

- CMB
  - 21cm absorption/emission
- collision
  - kinetic 21cm excitation/deexcitation
- Lyα pumping (Wouthysen- Field effect)
  - 1s → 2p → 1s

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$



T_S : spin temperature

T_R : CMB temperature

T_K : gas temperature

T_α : Lyα brightness temperature

$(T_\alpha \approx T_K)$

- signal strength

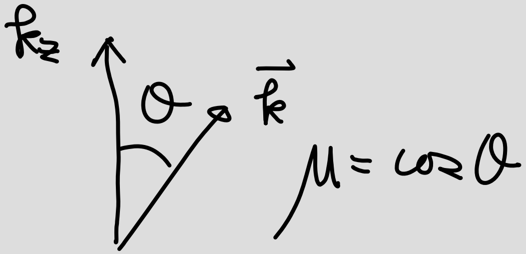
$$\delta T_b = \frac{T_S - T_R}{1+z}(1 - e^{-\tau_\nu})$$

$$\approx \frac{T_S - T_R}{1+z}\tau$$

$\propto n_{HI}$ when $T_S \gg T_R$

Separating Cosmology and Astrophysics (Mao, Shapiro, Mellema, Iliev, Koda, Ahn 2012)

- Cosmology
  - cosmological parameters: May improve on cosmology through CMB



- Astrophysics
  - source emissivity
  - source clustering

- But two physics appear mixed

- Separation possible in the linear regime
  - μ- decomposition scheme

$$P_{\delta T_b} = P_{\mu^0} + \mu^2 P_{\mu^2} + \mu^4 P_{\mu^4}$$

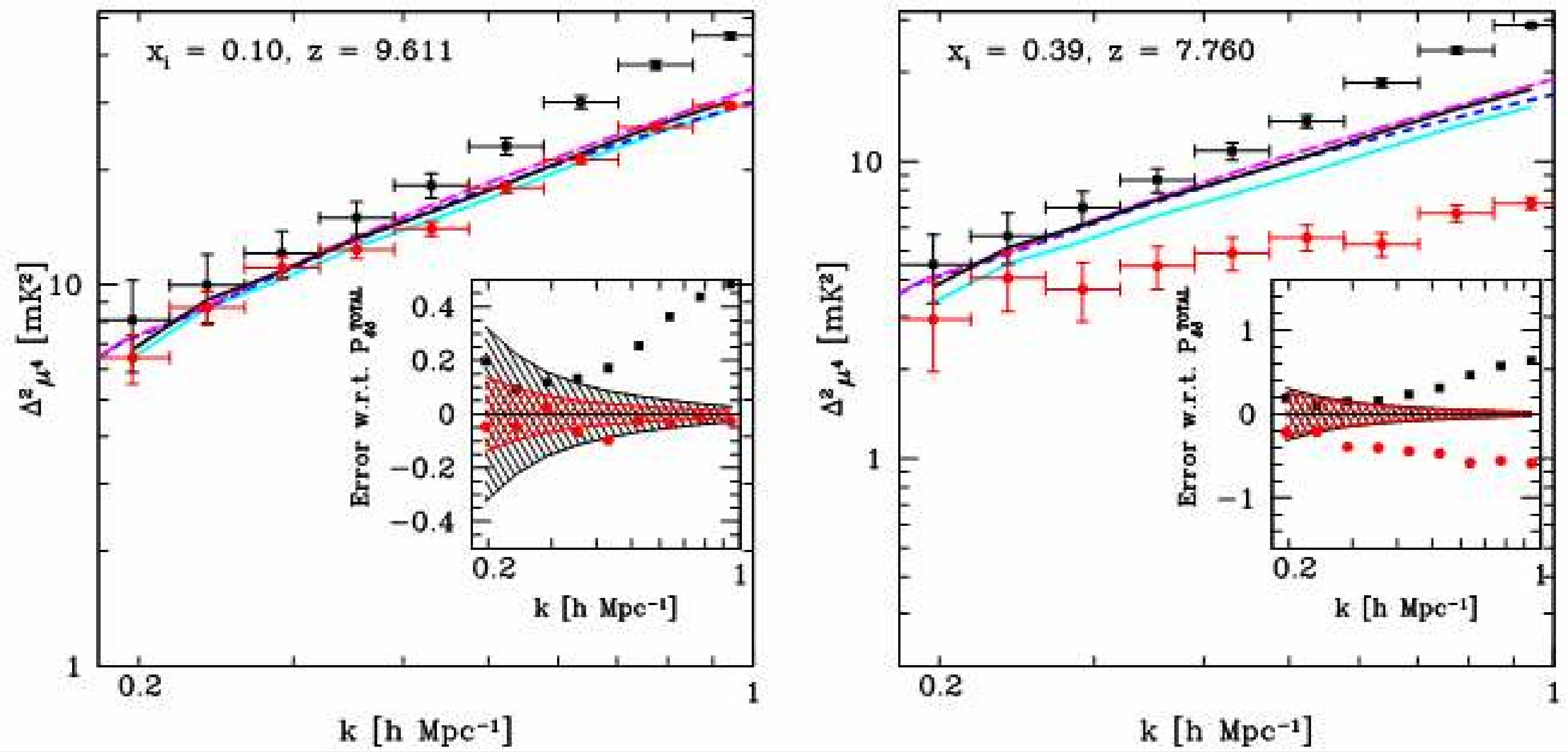
$$\begin{aligned}
P_{\mu^0}(k) &= \left(\widehat{\delta T}_b\bar{\eta}\right)^2\left[P^r_{\delta_{\rho_{\rm HI}},\delta_{\rho_{\rm HI}}}(k) + P^r_{\delta_\eta,\delta_\eta}(k)\right. \\
&\quad \left. +2P^r_{\delta_{\rho_{\rm HI}},\delta_\eta}(k)\right]\,, \\
P_{\mu^2}(k) &= 2\left(\widehat{\delta T}_b\bar{\eta}\right)^2\left[P^r_{\delta_{\rho_{\rm HI}},\delta_{\rho_{\rm H}}}(k) + P^r_{\delta_\eta,\delta_{\rho_{\rm H}}}(k)\right]\,, \\
P_{\mu^4}(k) &= \left(\widehat{\delta T}_b\bar{\eta}\right)^2 P^r_{\delta_{\rho_{\rm H}},\delta_{\rho_{\rm H}}}(k)\,,
\end{aligned}$$

$\longleftarrow$ Astro-physics

$\longleftarrow$ cosmology

Separating Cosmology : Astrophysics (Shapiro, Mao, Iliev, Mellema, Datta, Ahn, Koda 2013)

- works in “linear” regime in
  - matter density fluctuation
  - ionization density fluctuation



Corruption of Cosmology by Lya fluctuation
(speculation from Ahn, Xu, Norman, Alvarez, Wise in prep)

- 21cm from "RarePeak"
  - original simulation by EnZo (Xu, Wise, Norman 2013)
  - ~3.5σ peak @ z=15 with filtering scale~5 Mpc
  - proto galaxy-cluster region
  - jungle of Pop III/Pop II formation
  - now very efficient X-ray sources attached (Xu, Ahn, Norman, Wise in prep)
  - Lyα field calculated
  - X-ray heating calculated
  - δT_b calculated

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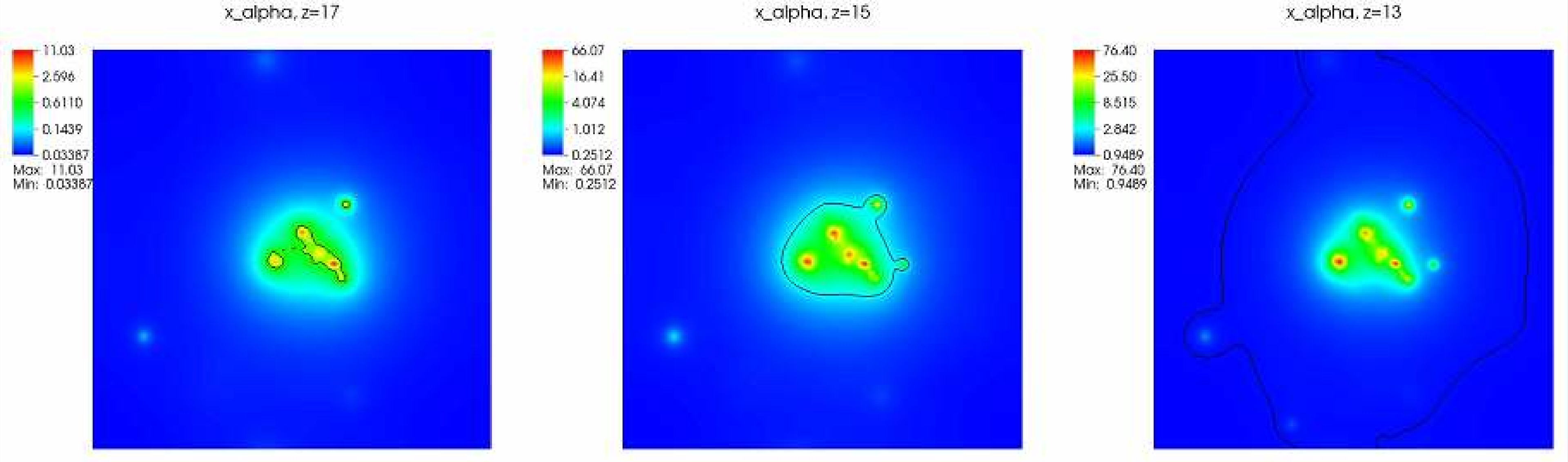

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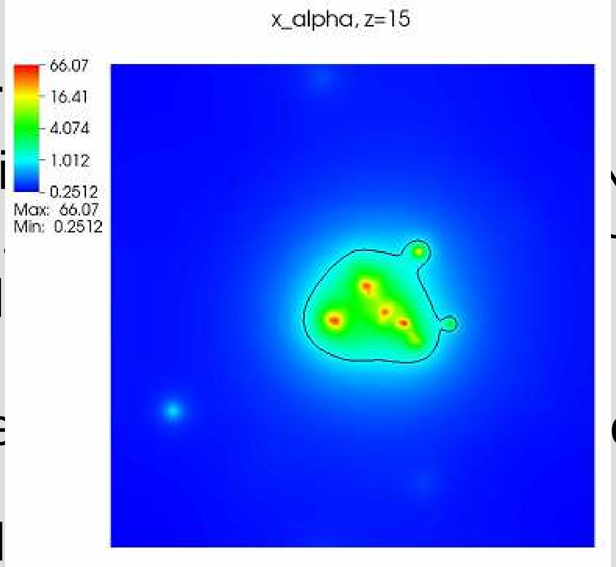

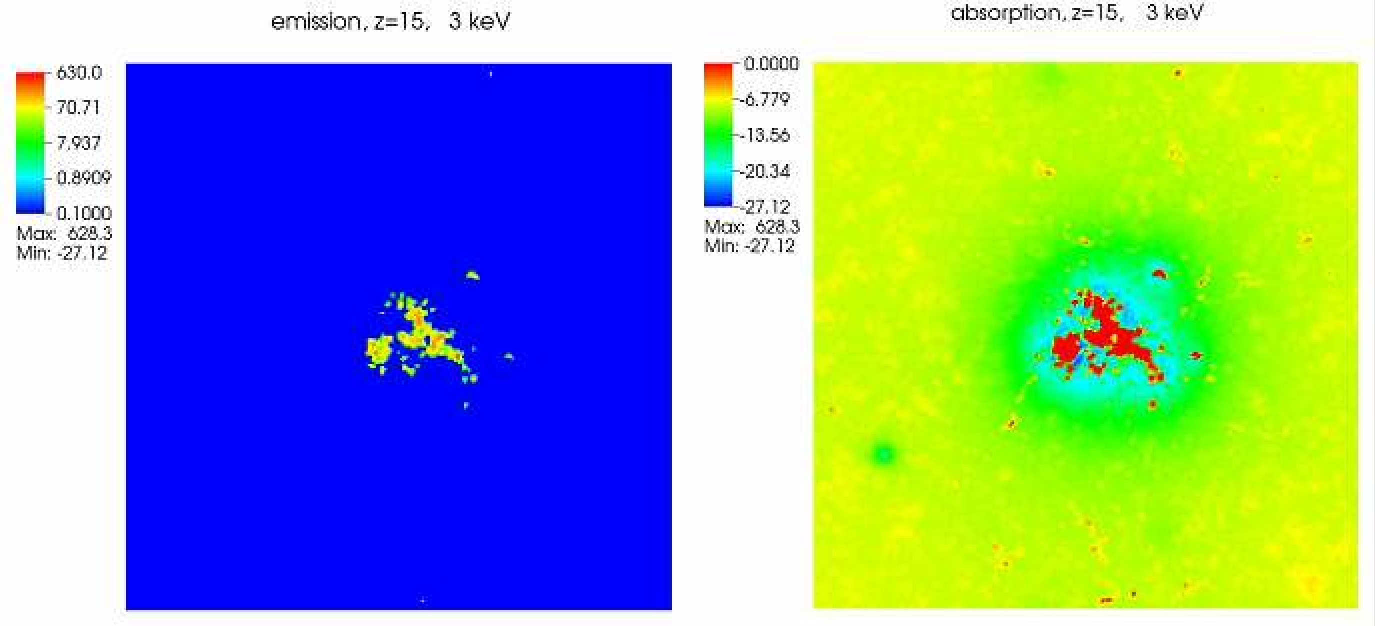

Corruption of Cosmology by Lya fluctuation
(speculation from Ahn, Xu, Norman, Alvarez, Wise in prep)

- Lesson
  - rare peaks can corrupt cosmology by producing large- scale fluctuations in Lyα pumping
  - when reionization peaked, best to study astrophysics thru 21cm
  - very high- z (z~ 25) observation favored for cosmology
    - feasible with Square Kilometre Array (SKA- EoR science white paper)
  - again, foreground removal is difficult (but some contraints coming: Bowman, Rogers 2010 Nature)
  - signal is very dim (~ 30 mK)

Summary

- HI intensity mapping useful for cosmology
- Low-z (z<~ 1) HI mapping a strong contender (c.f. SDSSIII (2008-2014))
  - pros
    - science by low-resolution survey
    - large filled-aperture telescopes existing (GBT, Arecibo)
    - FAST being built
  - cons
    - tougher foreground removal
    - HI-galaxy bias unknown

Summary

- High- z (z>~ 7) HI mapping
  - pros
    - large scale structure more linear → cosmology to higher wavenumber
    - can probe regime not feasible with galaxy survey
    - no galaxy bias!
  - cons
    - foreground removal toughest
    - corruption from high- z astrophysical sources