Future Science Possibilities for the WSRT:

Aperture Synthesis enters the Focal Plane Array Era

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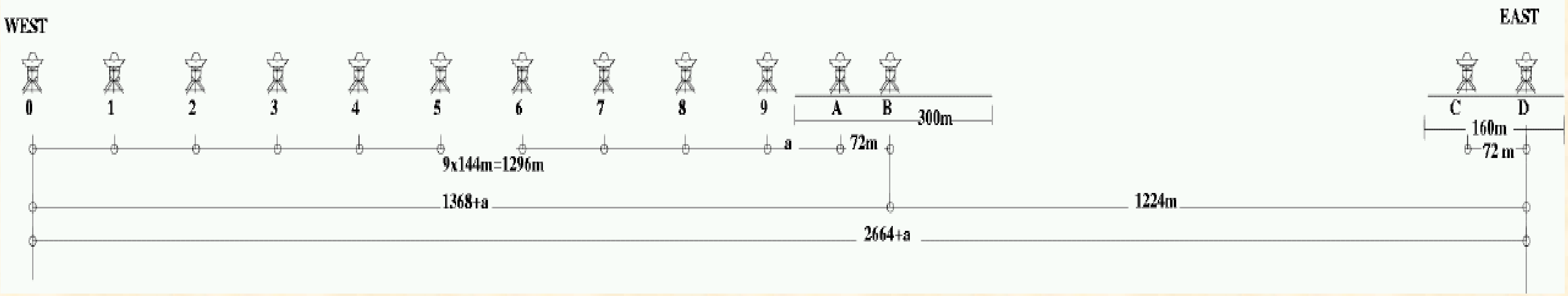
Outline

- background
- Focal Plane Array receivers and back-ends
- new capabilities
  - overview
  - eg. constraining dark energy
  - eg. imaging the low red-shift cosmic web

Background

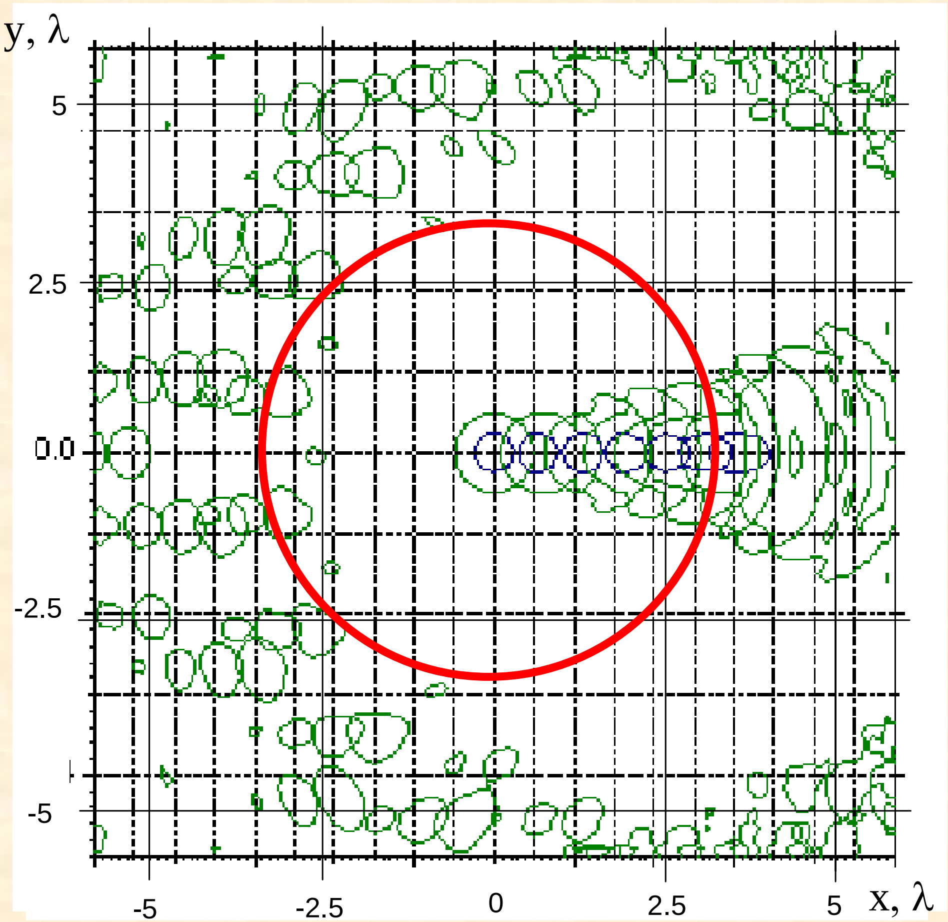


- WSRT collecting area (50% VLA) is competitive at those frequencies where it can be efficiently illuminated and the surface is sufficiently reflective (ν = 150 MHz – 2400 MHz)
- WSRT "market niche" is (red-shifted) HI and (polarimetric-) continuum imaging with high surface brightness sensitivity
- also: tied-array pulsar observing and VLBI participation

Aperture Synthesis enters the Focal Plane Array Era

To what extent can existing telescope's FOV be extended ?

- **simulations for a f/D = 0.35 parabola show good illumination (η > 0.8) possible over a field with diameter of about 10 FWHM if ~ 6.5λ diameter field is fully-sampled (or ~5 FWHM for 3.3 λ)**
- **full sampling requires about λ/3 - λ/4 spacing**
- **=> about 100 elements for 3.3λ circle (0.8 m @ 1200 MHz)**
- **yields ~25 times the FOV with high η in all beams**



1.3 m prime focus circle yields ~10 FWHM @ f/D = 0.35 (WSRT)

Proposed FPA System Parameters

- **Frequency Band: 850 – 1750 MHz (bottom end by TV RFI, top end from OH lines)**
- **Dual Polarization**
- **Instantaneous BW: minimum of 320 MHz (to be competitive with other L-band systems) preferred goal of 1 GHz (ie. entire band)**
- **Tsys < 50 K, η_A > 70%**
- **Freq. resolution: 20 kHz over full BW or finer for smaller BW (corresponds to 4 km/s for the HI line)**
- **Instantaneous FoV: 25 primary beams (formed from the 100 elements of each FPA)**
- **Correlation: 14*14 for each of 25 beams, full polarization**
- **Wide-field application efficiency: 25/4 = 6 x EVLA**

What will become possible?

- Survey programs are **50 times faster, so 7 times deeper** in the same total integration time
- Continuum Sensitivity: < 7 μJy in 12 hours over 13 deg^2

  20 μJy 130 deg^2

  70 μJy 1300 deg^2

  spanning 850 – 1750 MHz => RM synthesis, spectral shape
- **Orphan GRB's**
  - 1 GRB / day in γ-rays, but those are only the beamed ones
  - 10-100 "orphan" GRB's/day
  - radio lifetime of ~ 1 month, peak radio flux ~ 100 μJy
  - weekly imaging of same 130 deg^2 should yield ~ 5 simultaneous orphans above detection limit per epoch

What will become possible?

- **The Scintillating Universe**
  - scintillation on minute to hour scales (like J1819) yield source properties on 10's of flat spectrum AGN per deg^2 at 100 μJy level @μarcsec scales and detailed foreground screen parms.
- **The Magnetic Universe** (confusion limit in Q,U,V perhaps 1 μJy)
  - produce **RM grid** from Galactic pulsars plus background AGN at various distances; with 7 μJy rms (12 hr obs) get detected polarized **source density of ~100 deg^{-2}**
  - ➢ precision mapping of Galactic B field, nearby galaxy B fields, cluster B fields (eg. Perseus) and first chance to detect IGM inter-cluster B filaments

What will become possible for Pulsars?

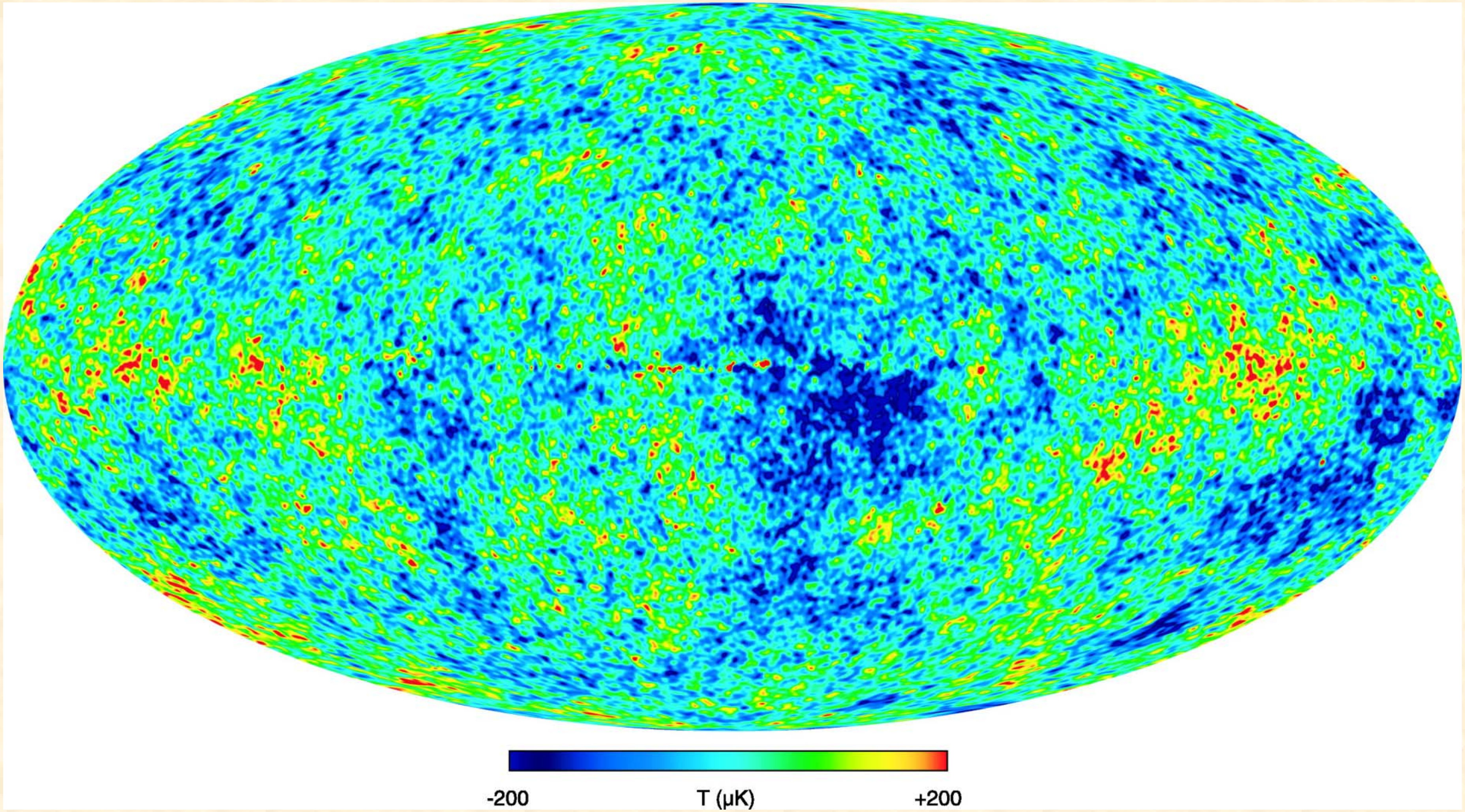
Survey Figure of Merit: M = FoV x $(A/T)^2$ x BW x $\nu^{-3.6}$

	FoV (deg^2)	A/T (m^2/K)	BW (MHz)	M
Parkes 20 cm 13-bm	0.41	107	300	$4.2x10^5$
Parkes 70 cm	0.39	49	32	$7.6x10^5$
Arecibo 20 cm ALFA 7-bm	0.019	1240	300	$2.6x10^6$
WSRT 90 cm 8-grate	4.2	47	10	$5.6x10^6$
WSRT 20 cm FPA-grate	13	196	300	$1.5x10^8$

~70 times the 2005 state-of-the-art at 20 cm !!

Constraining Dark Energy

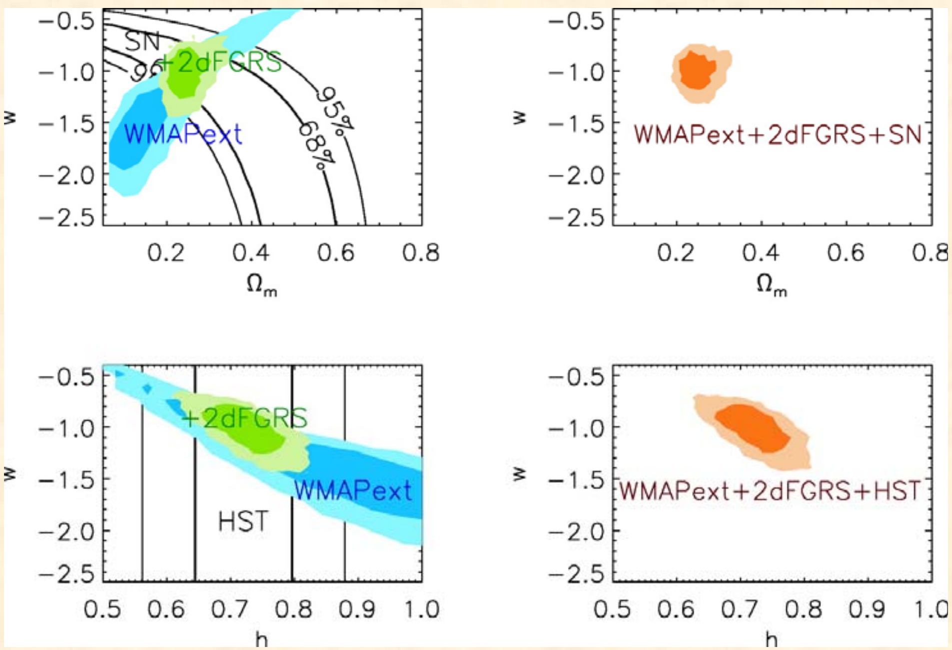
- **WMAP (first-year) image of CMB fluctuations defines current state-of-the-art**

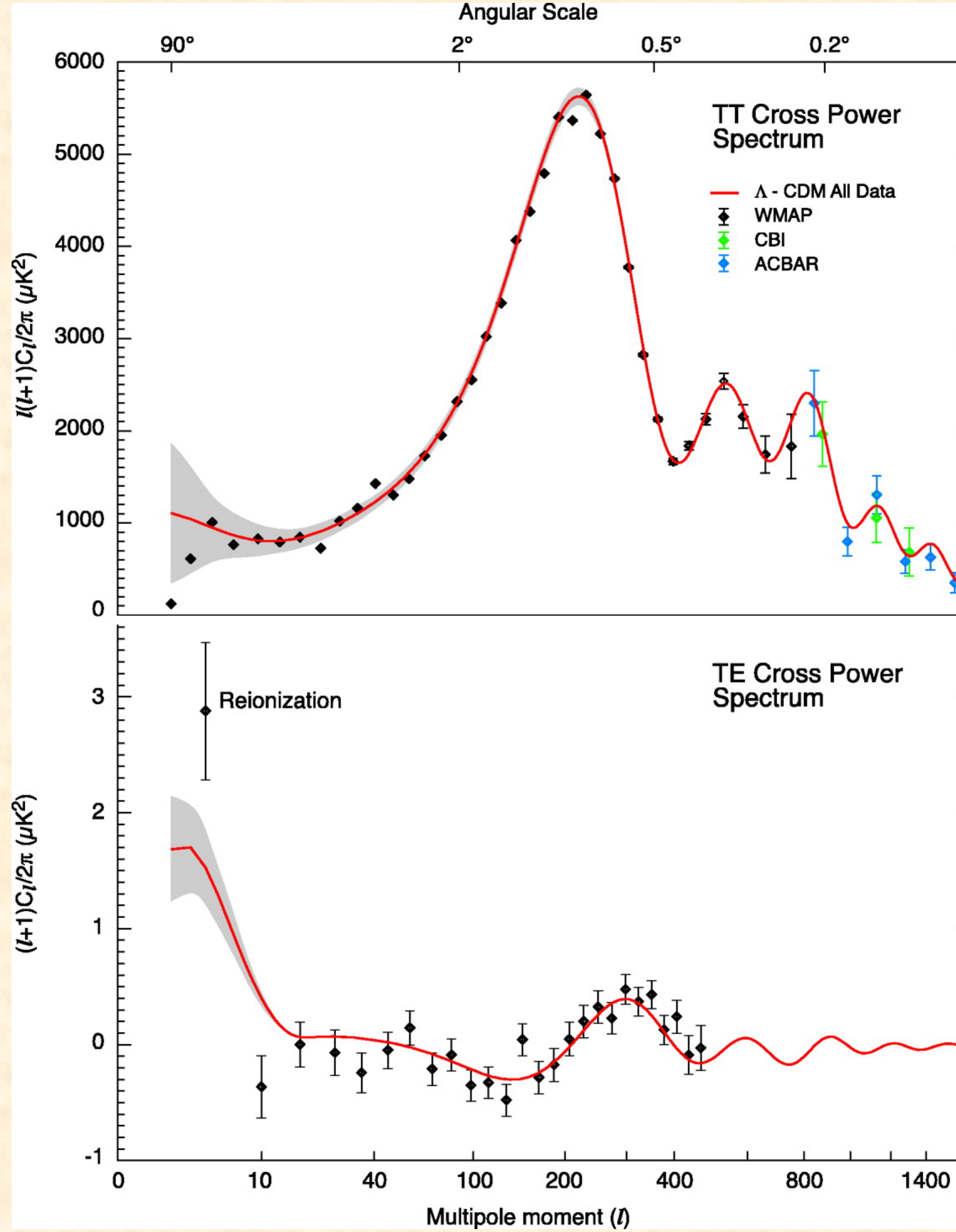


Bennett et al. 2003, ApJS, 148, 1

Constraining Dark Energy

- **CMB data provide excellent constraints on model parms. assuming ΛCDM cosmologies**
- **BUT direct constraints on dark energy ($w=p/\rho$) are weak**



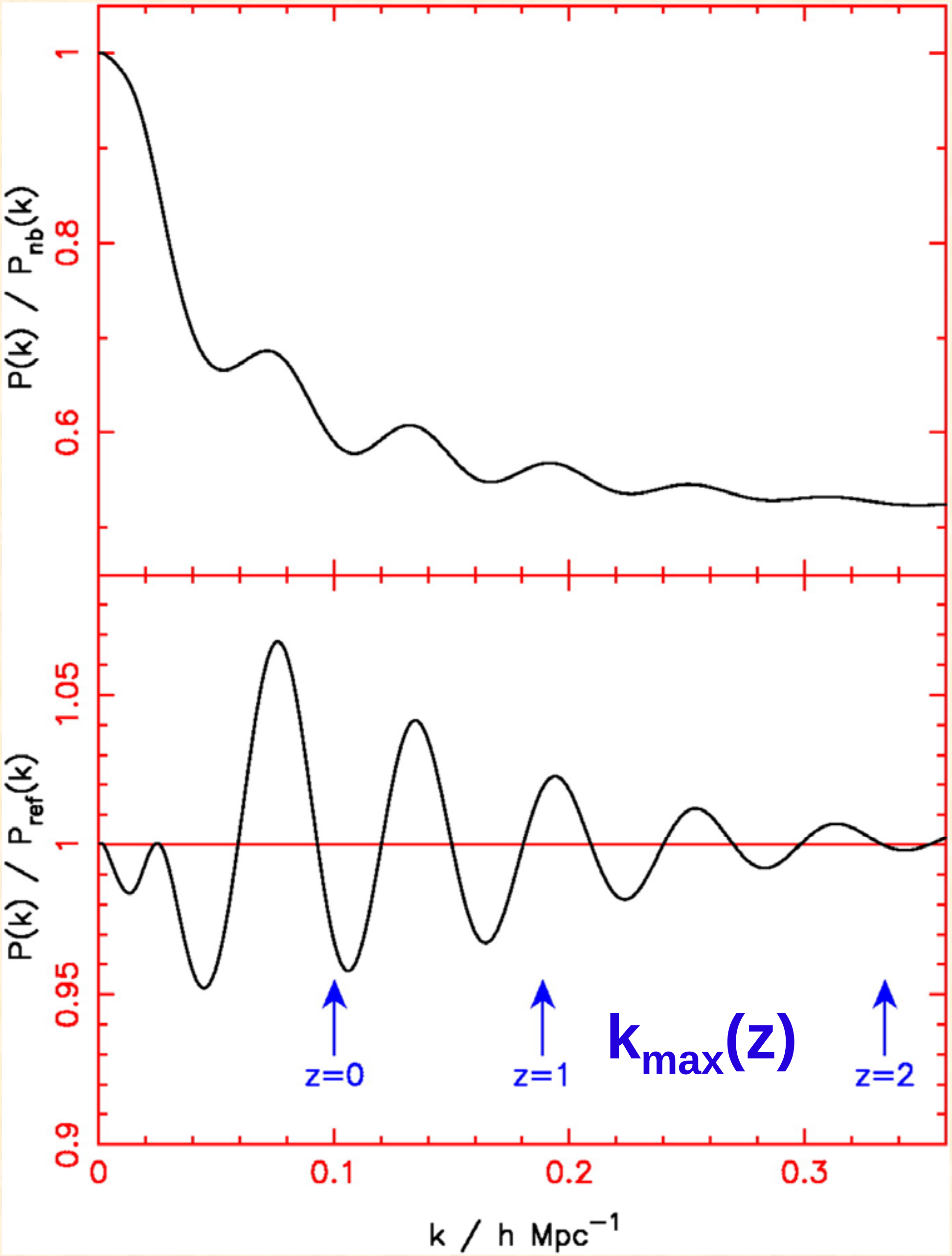


Spergel et al. 2003, ApJS, 148, 175

Bennett et al. 2003, ApJS, 148, 1

Constraining Dark Energy

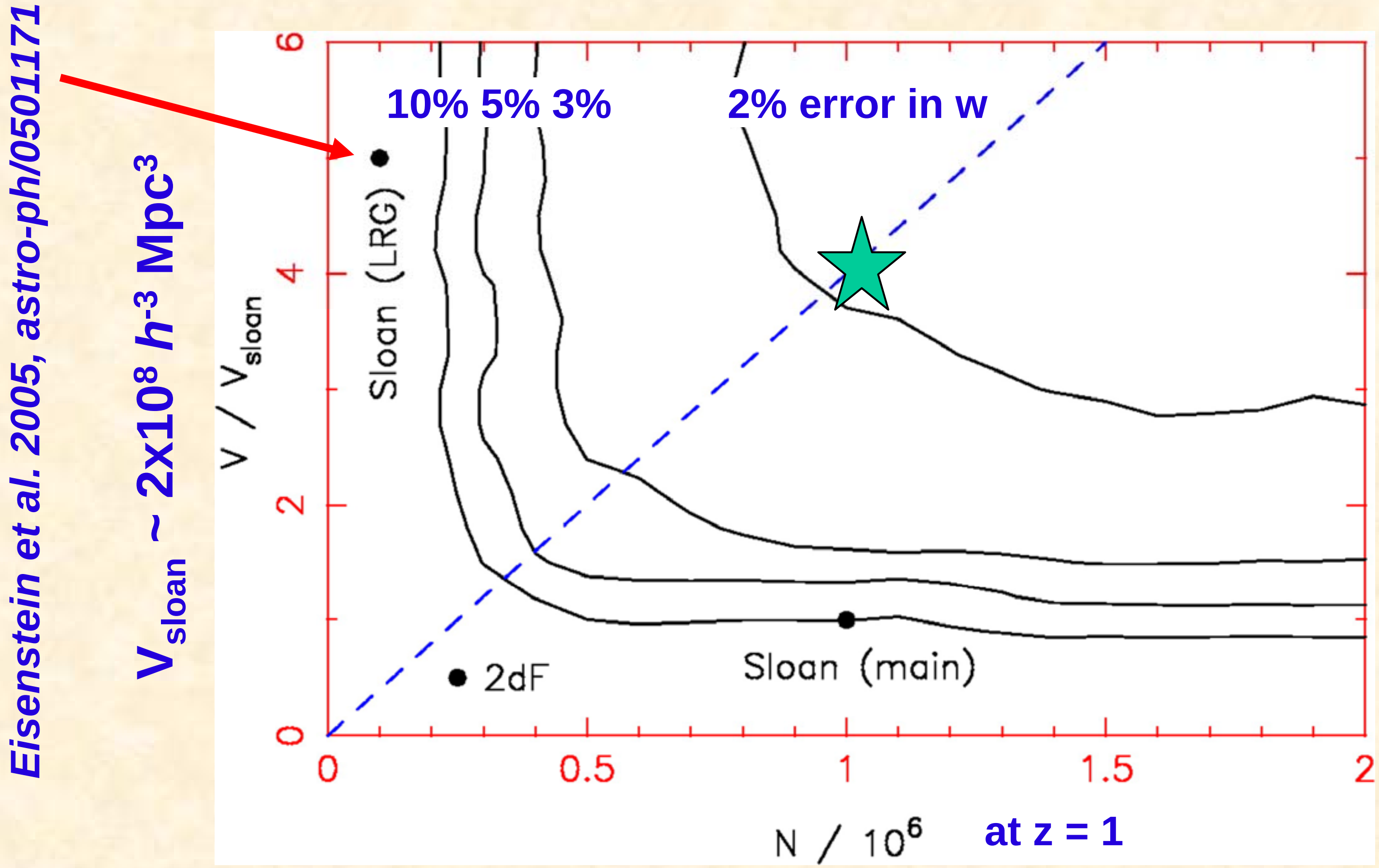
- acoustic oscillations at harmonics of the sound horizon at de-coupling (WMAP: r_s =144+/- 4 Mpc) also leave imprint on the **baryonic** power spectrum
- provides a "**standard cosmological ruler**" to measure change of scale as function of red-shift (Eisenstein et al. 1998, ApJ 504, L57)
- only holds in linear regime, ie. k < k_{max}(z) , z ~ 1 is desirable



Blake & Glazebrook 2003, ApJ, 594, 665

Constraining Dark Energy

- very good prospects for determination of w(z) with galaxy surveys
- optimum strategy is to aim for diagonal in (N,V) measurement space (trade-off of cosmic variance versus shot noise)
- benchmark is SDSS with ~10^6 galaxies over ~10^4 deg^2 at z < 0.2
- goal is ~10^6, z~1 galaxies over ~300 deg^2 => V/V_{sloan} ~ 4

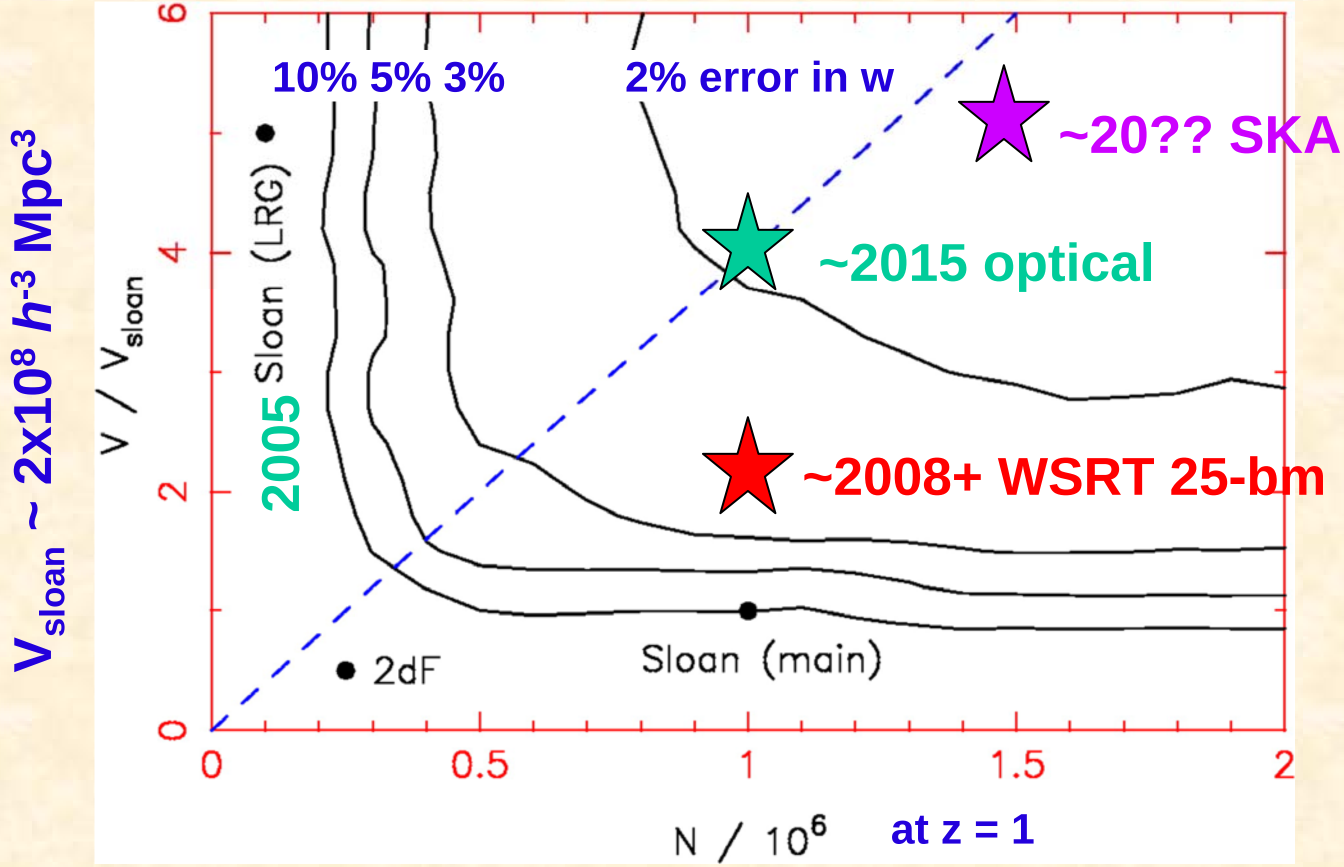


Blake & Glazebrook 2003, ApJ, 594, 665, plus adaptations

Constraining Dark Energy

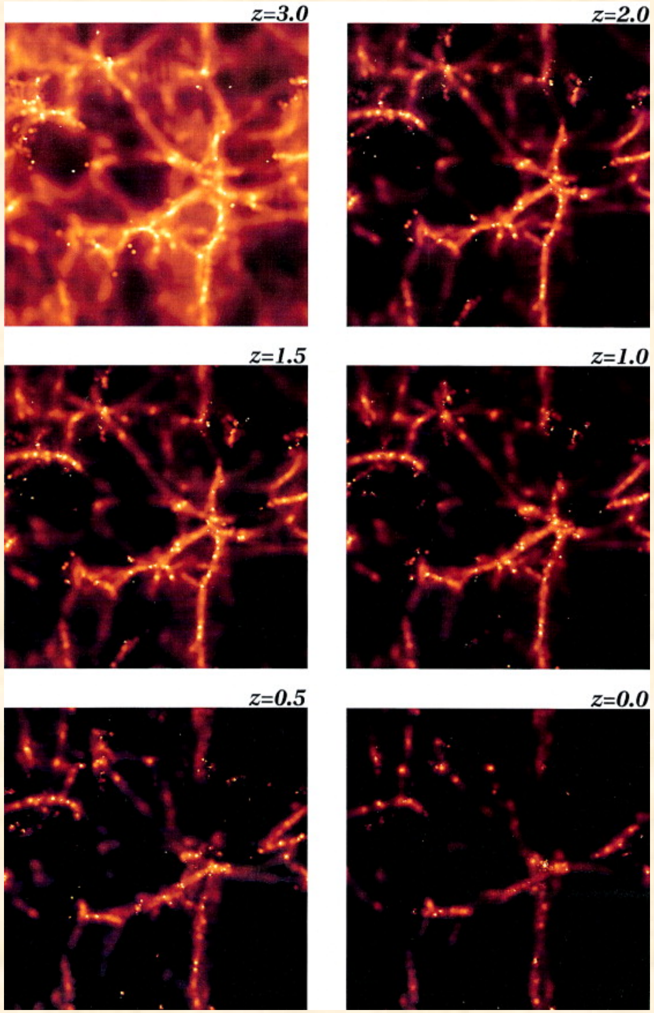
What will be possible ?

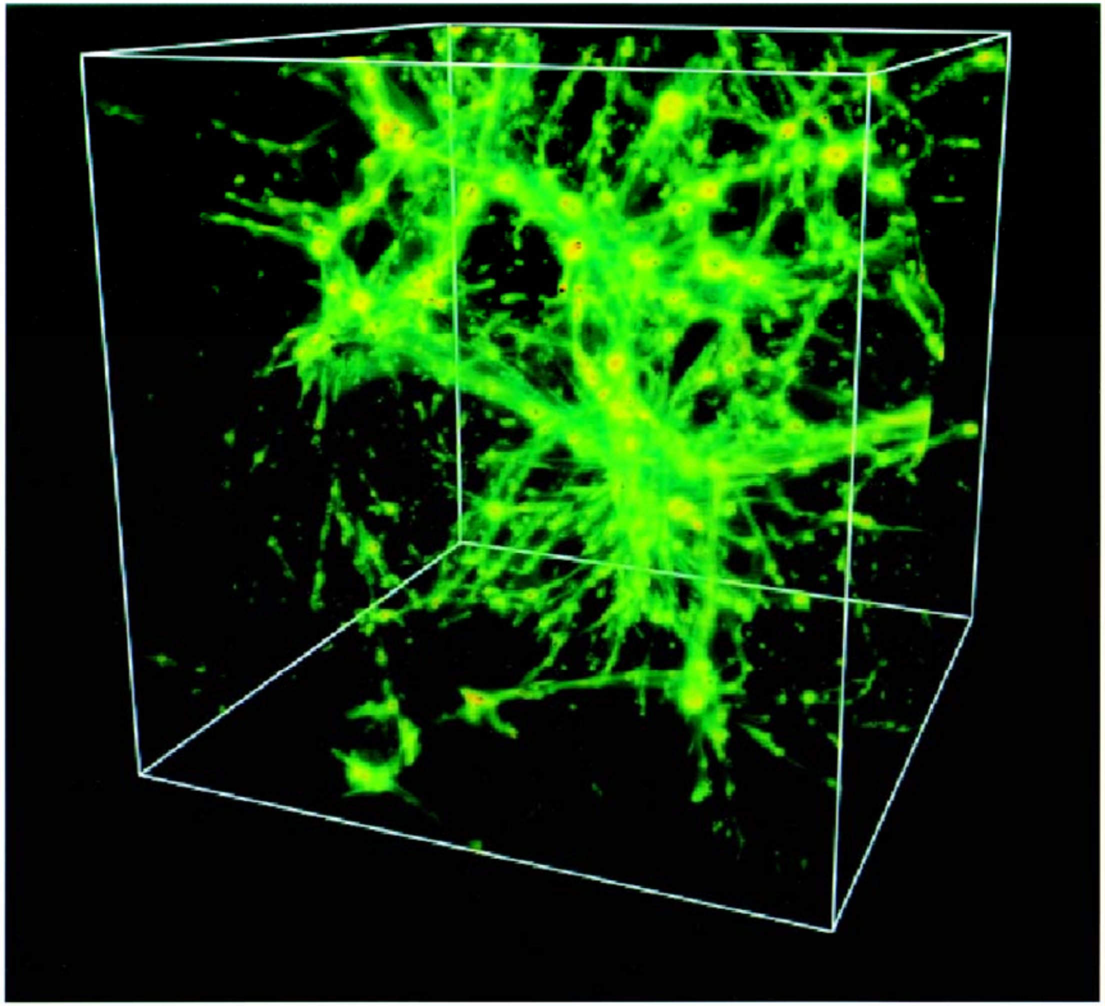
- (2008+) WSRT 25-beam FPA (13 deg^2 FOV)
  - could get ~10^6 galaxy in $2x10^4$ deg^2 at z < 0.25 in 3 year survey
- (20??) SKA (100x current sensitivity, 1 deg^2 FOV)
  - could get ~$1.5x10^6$ galaxy in 400 deg^2 at z < 1.5 in 50 day survey
- (2010-2020) dedicated optical 8m class with multi-object spectrograph



Blake & Glazebrook 2003, ApJ, 594, 665, plus adaptations

Imaging the low-z Cosmic Web

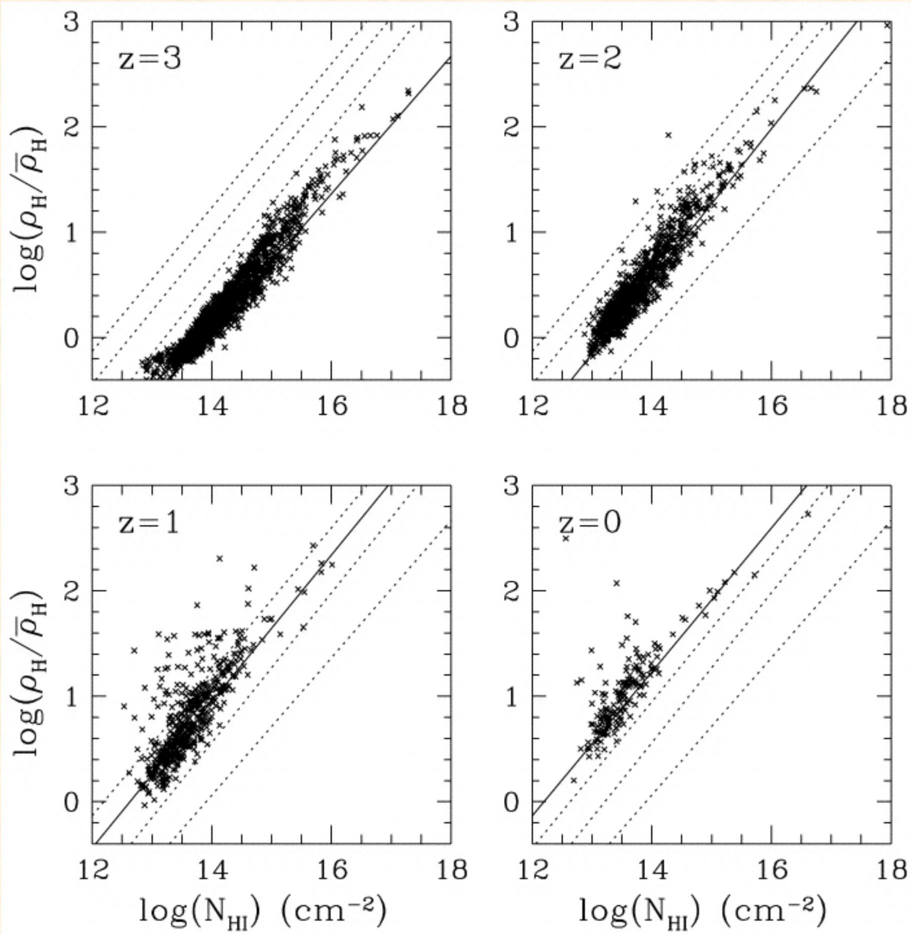


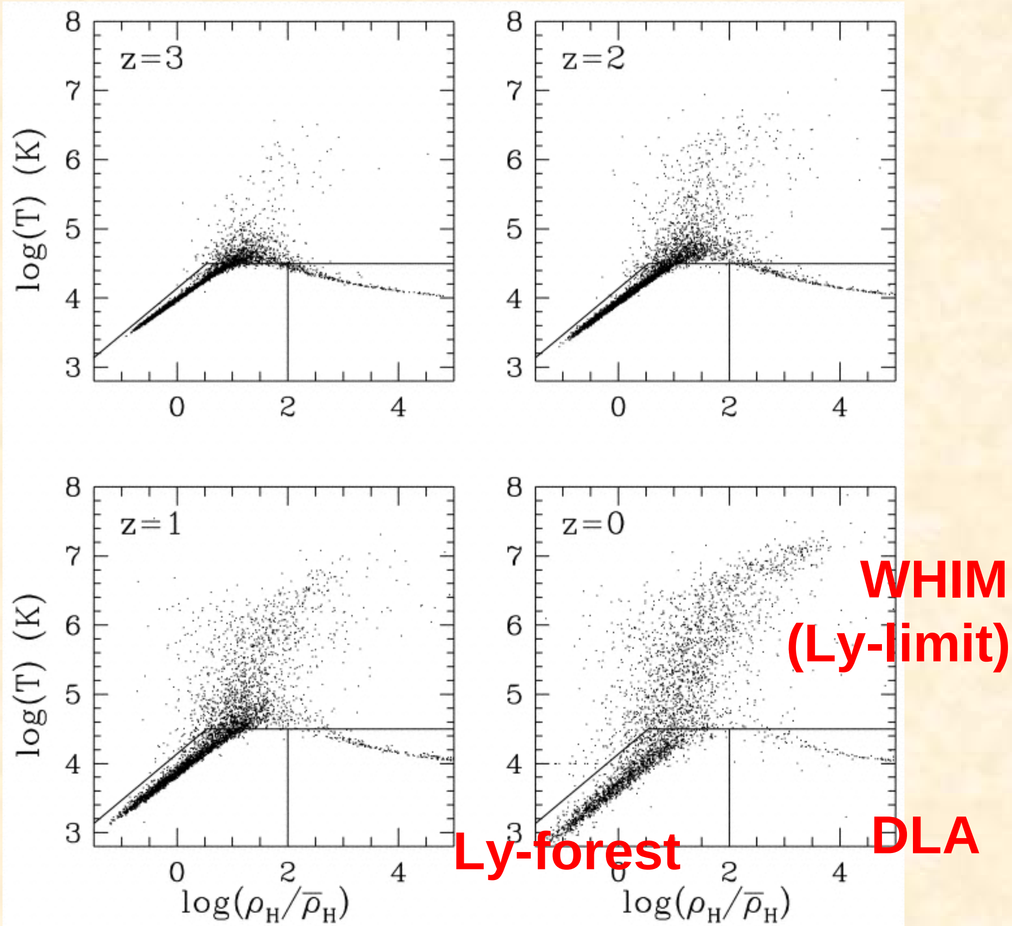


Dave et al. 1999, ApJ 511, 521, 2001, ApJ 552, 473

- **high res. num. sim. predict cosmic web of filaments between galaxies**
- **apparent correspondence with QSO absorbers**

Imaging the low-z Cosmic Web





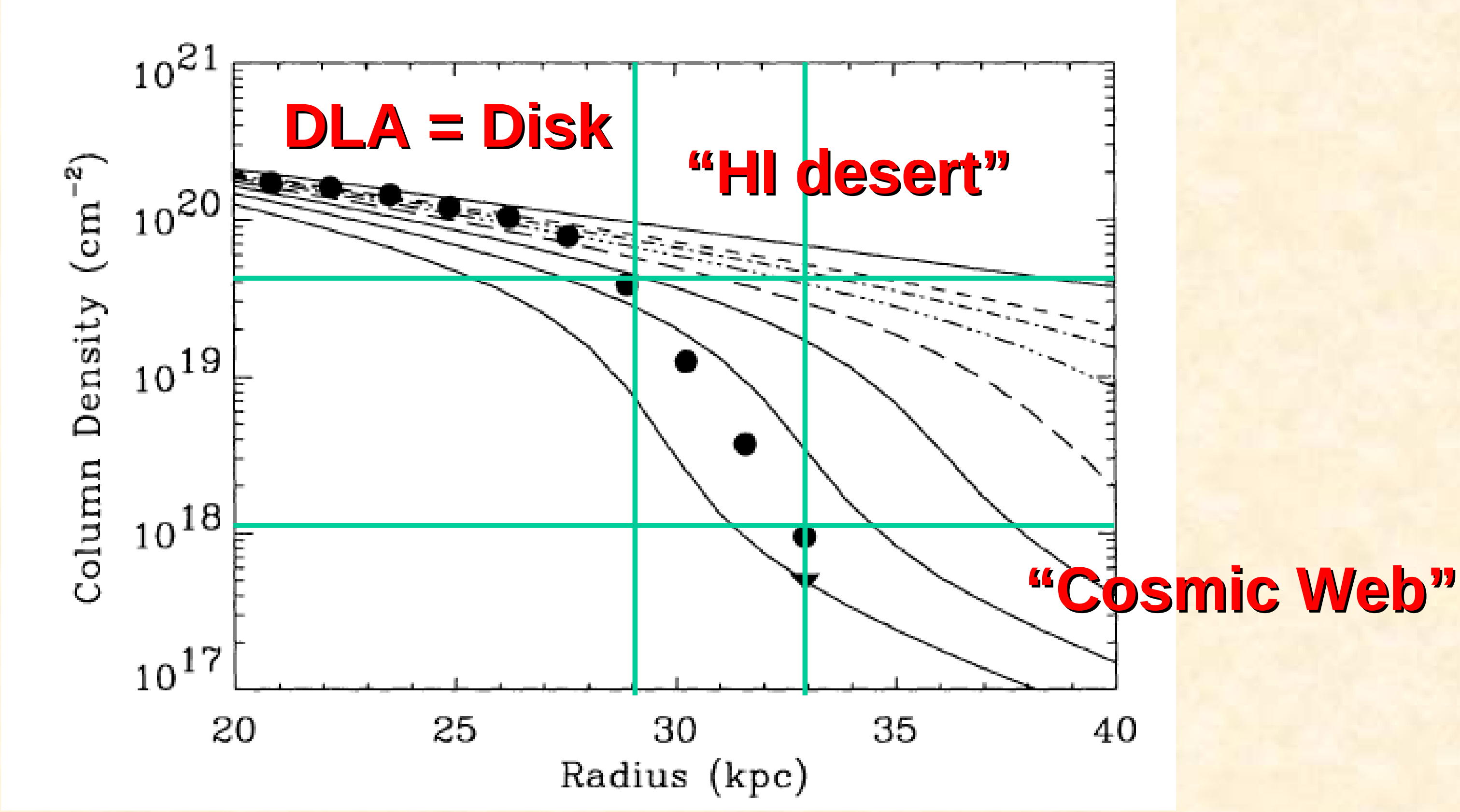
Dave et al. 1999, ApJ 511, 521

- strong (density-dependent) evolution with cosmic epoch
- collapse of over-dense regions yields greater proportion of WHIM (z=0)

Imaging the low-z Cosmic Web

- **~30% baryons in galaxies** (@ z = 0)
  - association with QSO absorbers with $N_{HI} = 10^{18} – 10^{22}$ cm^{-2}
- **~30% baryons in warm-hot inter-galactic medium (WHIM)**
  - condensed, shock-heated phase: $T \sim 10^5 – 10^7$ K
  - association with QSO absorbers with $N_{HI} = 10^{14} – 10^{18}$ cm^{-2}
  - ties in with evidence from FUSE OVI absorption (Sembach et al. 2003) for Galactic corona, R > 70 kpc, n ~10^{-4}-10^{-5} cm^{-3}
- **~30% baryons in diffuse inter-galactic medium**
  - diffuse, photo-ionized phase: $T \sim 10^4$ K
  - association with QSO absorbers with $N_{HI} = 10^{12} – 10^{14}$ cm^{-2}
- **decreasing (micro- not macro-) neutral fraction with N_{HI}**
  - ~1% at $N_{HI} = 10^{17}$ cm^{-2}, < 0.1% at $N_{HI} = 10^{13}$ cm^{-2}
- **role of "cold-mode" versus "hot-mode" accretion ???**
  - Binney (2004, MNRAS 347, 421) Keres et al. (2004, astro-ph/0407095)

Imaging the low-z Cosmic Web

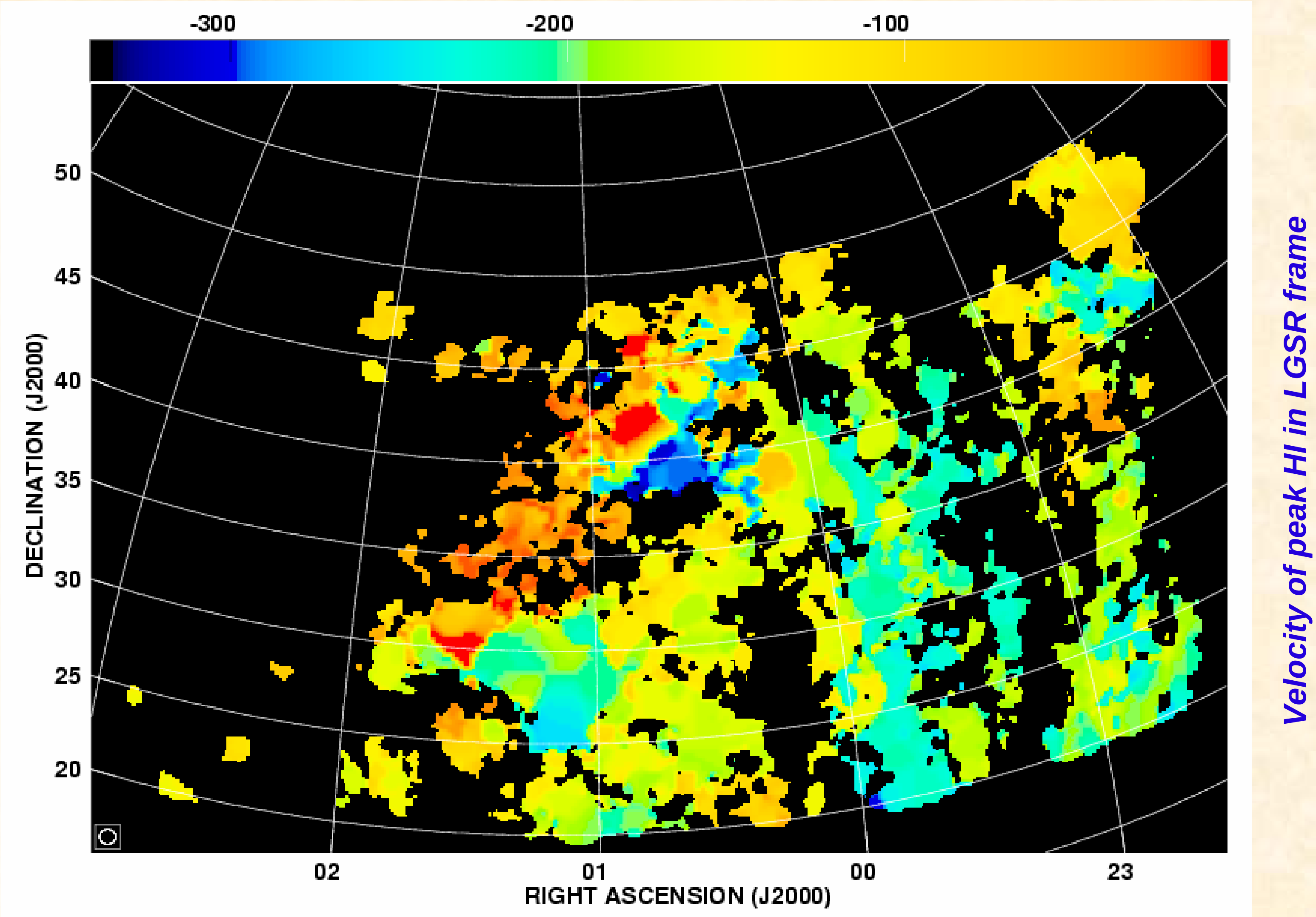


eg. Dove & Shull 1994, ApJ 423, 196

- **ionization by intergalactic UV leads to exponential decline in neutral fraction: ~100 % to ~3 % from log(N_{HI}) ~ 19.5 to ~ 18**
- **"HI desert" is major observational challenge !!**
- **slow decline of neutral fraction below log(N_{HI}) ~ 18 !!**

Imaging the low-z Cosmic Web

Braun & Thilker 2004, A&A, 417, 421

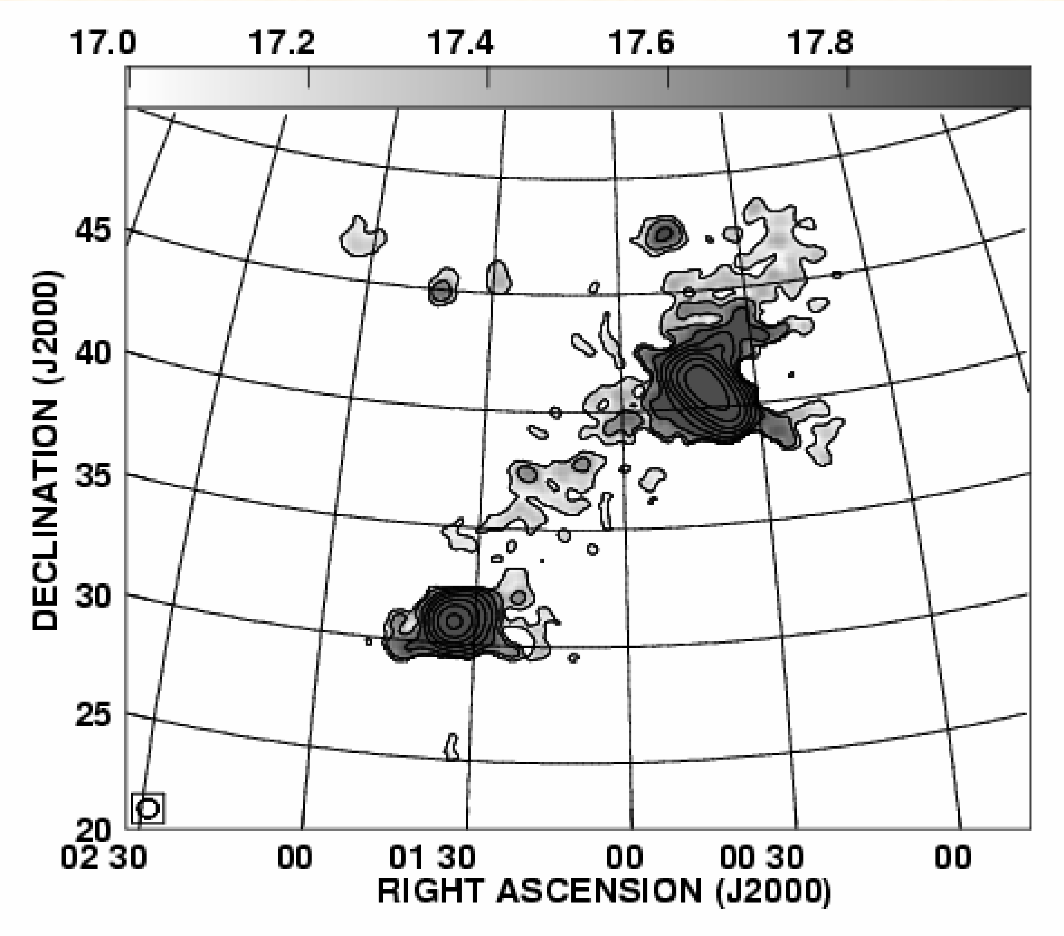


- **M31/M33 filament near systemic velocity, $N_{HI} \sim 4 \times 10^{17} cm^{-2}$ (peak)**

Imaging the low-z Cosmic Web

The M31 – M33 filament

- connects V_{SYS} of M31 and M33
- continues in anti-M33 direction (300 kpc total extent)
- filamentary structure within 30 kpc
- connects to **ongoing fueling of both M31 and M33**



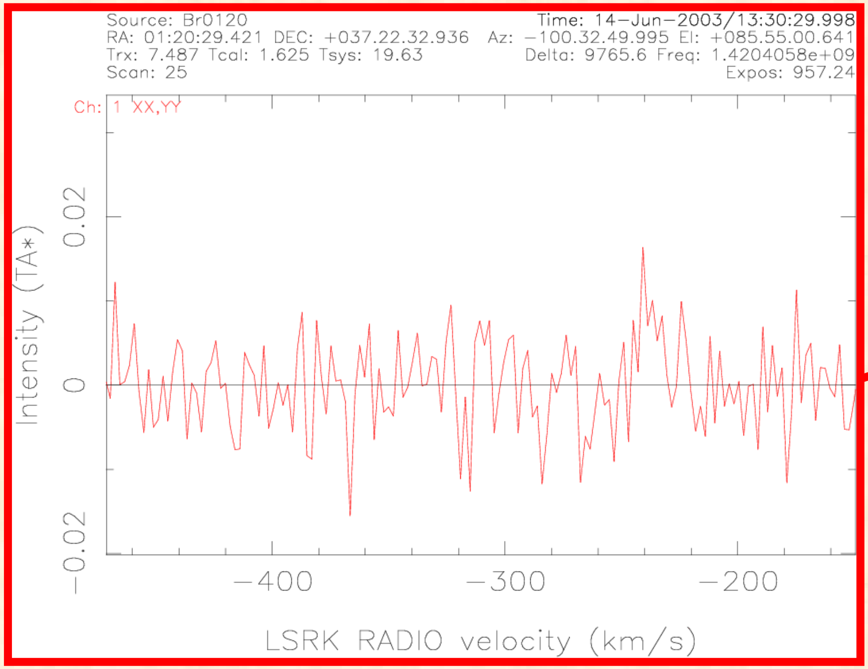
Braun & Thilker 2004, A&A, 417, 421

wide-field WSRT data

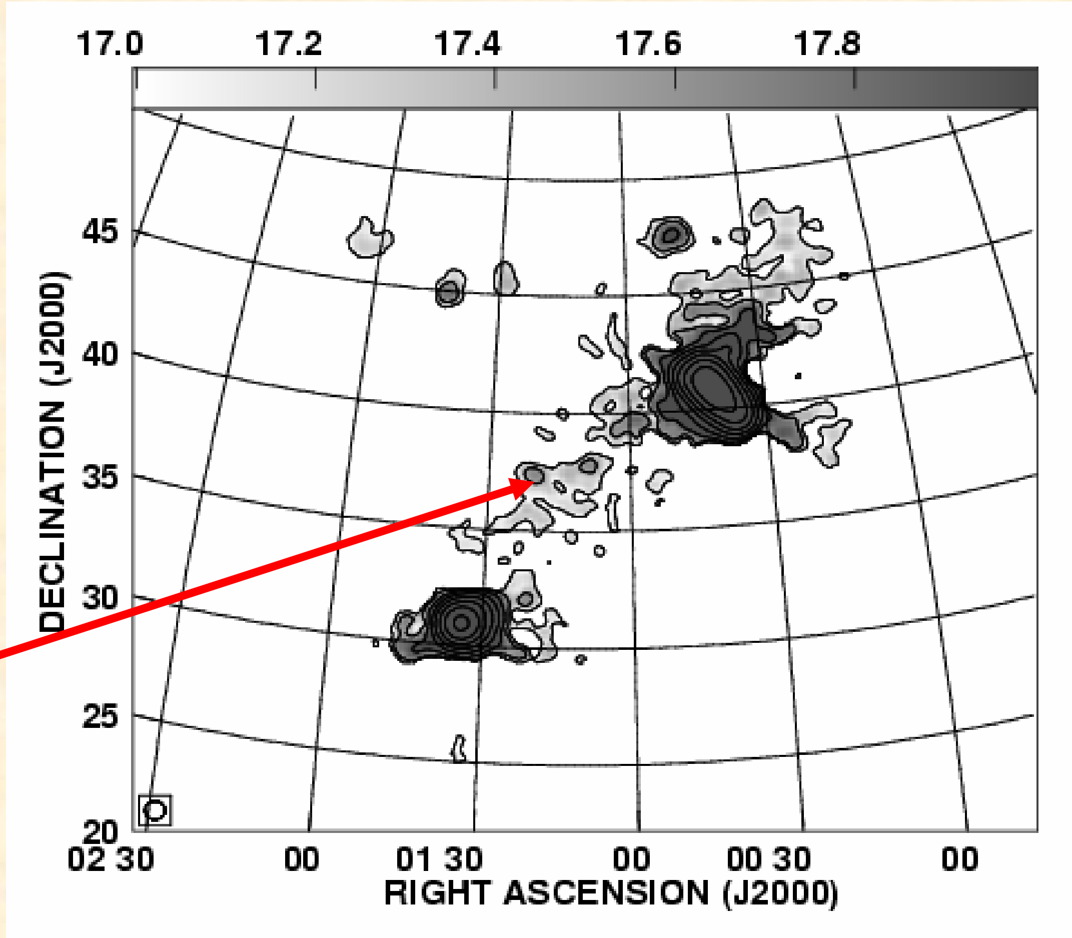
Imaging the low-z Cosmic Web

The M31 – M33 filament

- extremely diffuse in bridge region (same low N_{HI} in GBT and WSRT TP beams)



GBT confirmation (30 min ON/OFF)



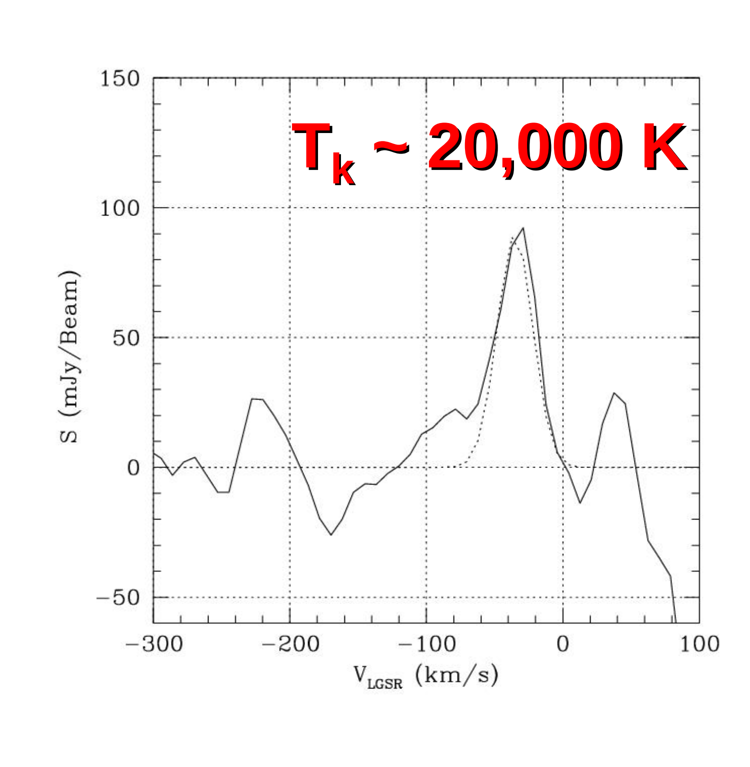
wide-field WSRT data

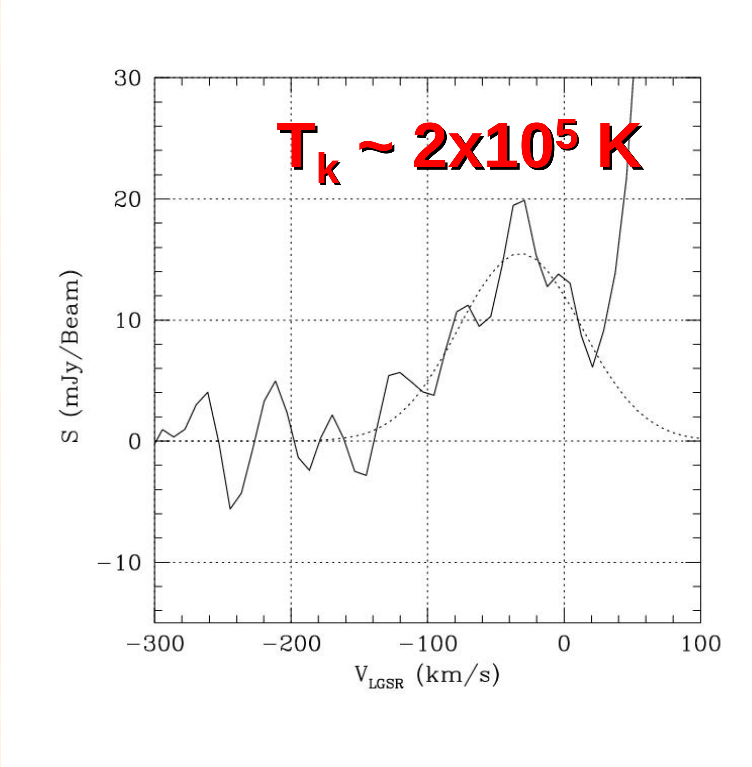
Braun & Thilker 2004, A&A, 417, 421

➢ **the first detection of the "cosmic web"/ WHIM in HI emission**

Imaging the low-z Cosmic Web

The M31 – M33 filament

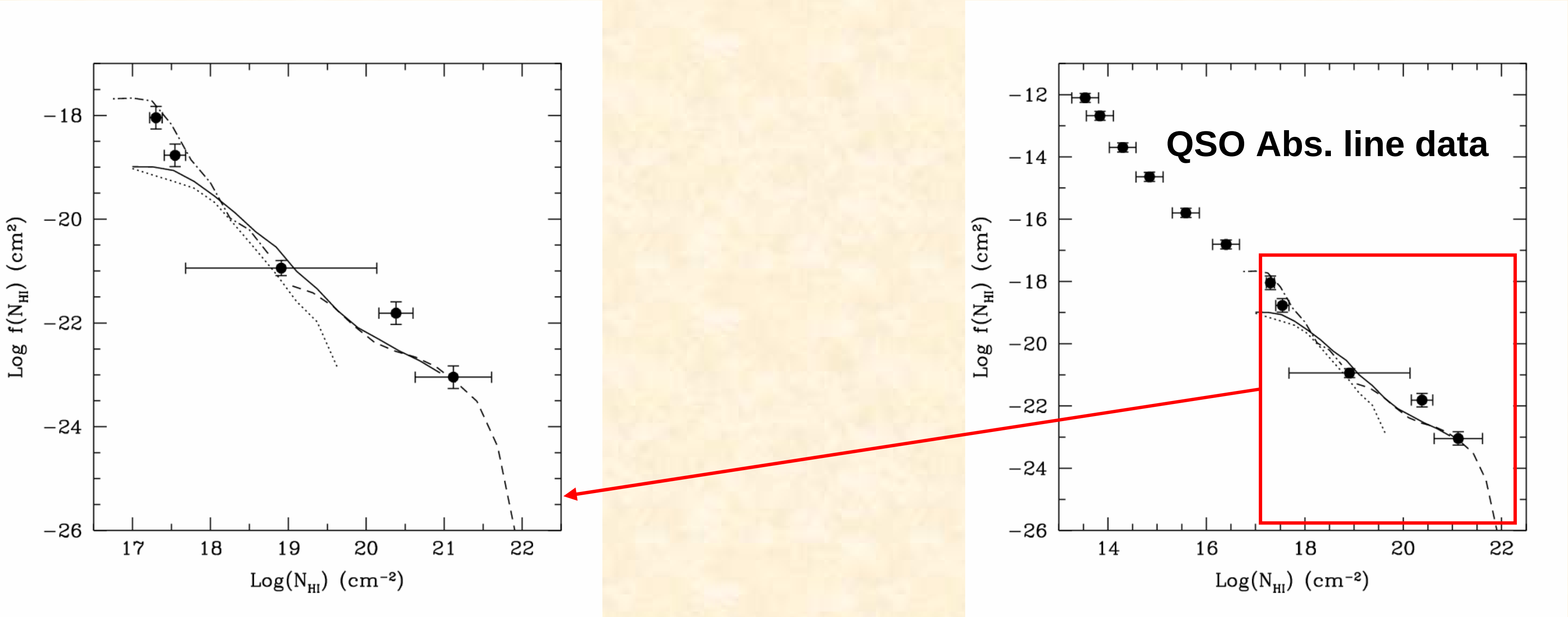




- clump spectrum, σ ~ 13 km/s => T_k ~ 20,000 K
- average spectrum over 4x3 deg, σ ~ 45 km/s
  - velocity field sub-structure yields σ < 20 km/s
  - looks like T_k ~ 2x10^5 K (possibly hot-mode accretion)
  - ➢ condensations in the WHIM

Imaging the low-z Cosmic Web

Cosmic Web and QSO absorption lines *Braun & Thilker 2004, A&A, 417, 421*



- composite N_{HI} distribution from WSRT mosaic, GBT, wide-field WSRT
- normalization from HIPASS BGC (Zwaan et al. 2003, AJ, 125, 2842)

➢ **good agreement with QSO absorption line data**

➢ **confirmation of 30-fold increase in covering factor 10^{19} – 10^{17} cm^{-2}**

➢ **the first image of a Lyman Limit absorption System**

Imaging the low-z Cosmic Web

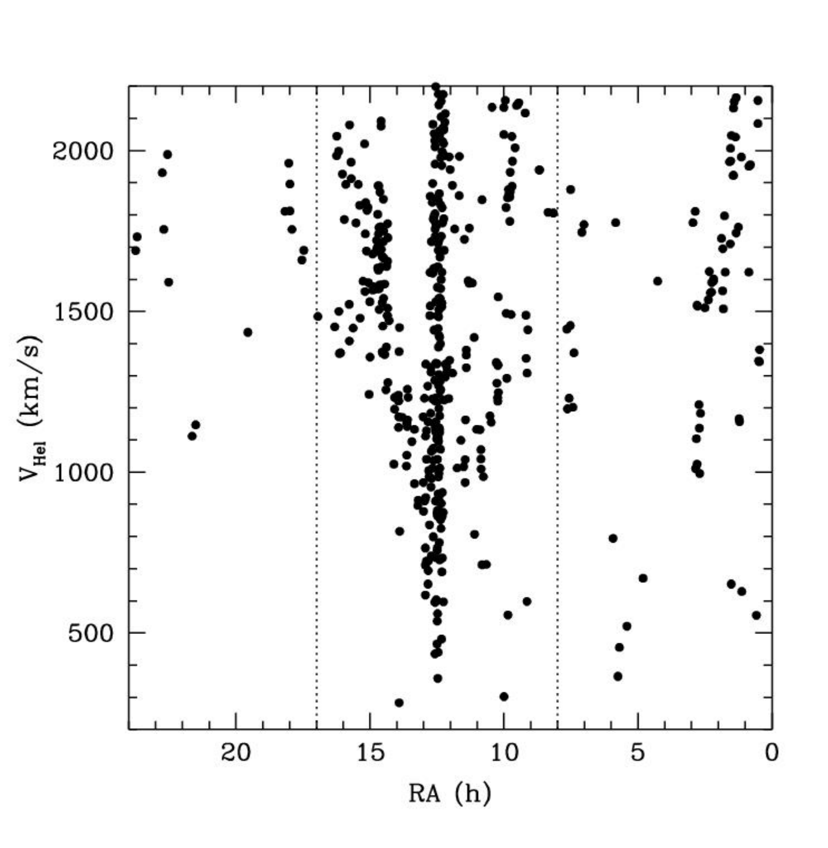
How can we go beyond the Local Group?

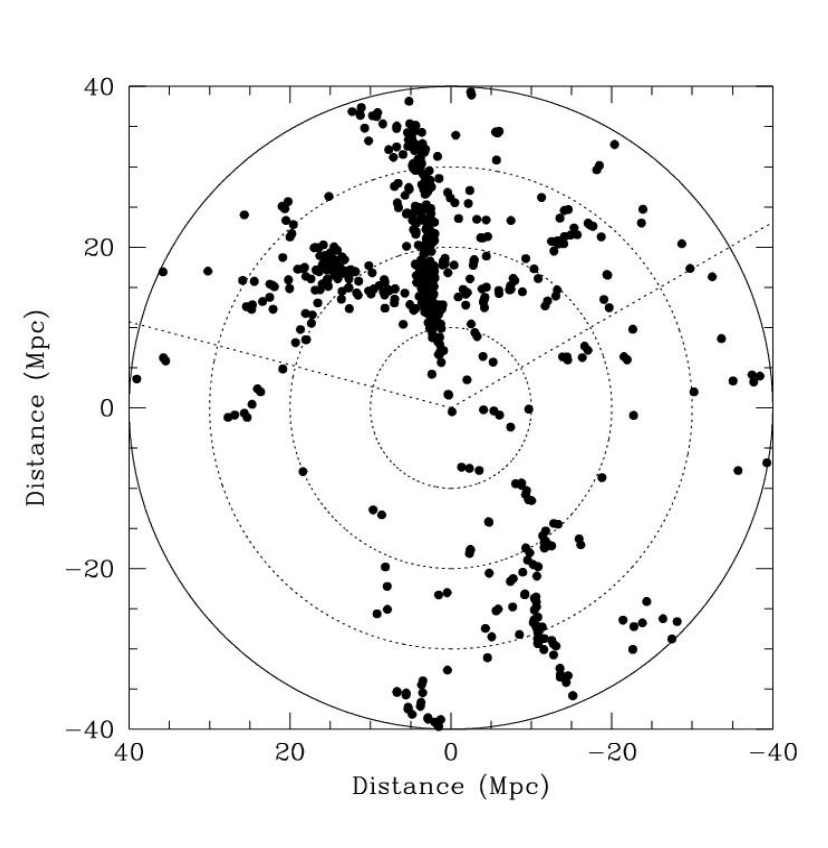
- **require: $\Delta N_{HI} < 10^{18}$ cm^{-2} over ΔV=20 km/s , Dθ < 20 kpc**

First Glimpse

- **(2005 – 2006) WSRT semi-shadowed mode survey of the super-galactic plane filament (α = 8 – 17 h, δ = 0 – +10^o)**
  - **simulate filled aperture by observing at extreme HA's for δ=0 to +10^O: grating array (12x144 m) becomes filled- aperture (25x300 m) with spectral baseline quality of interferometer(!) and beam of 3 x 35 arcmin**
  - **achieve $\Delta N_{HI} \sim 2 \times 10^{17}$ cm^{-2} over ΔV = 20 km/s**

Imaging the low-z Cosmic Web





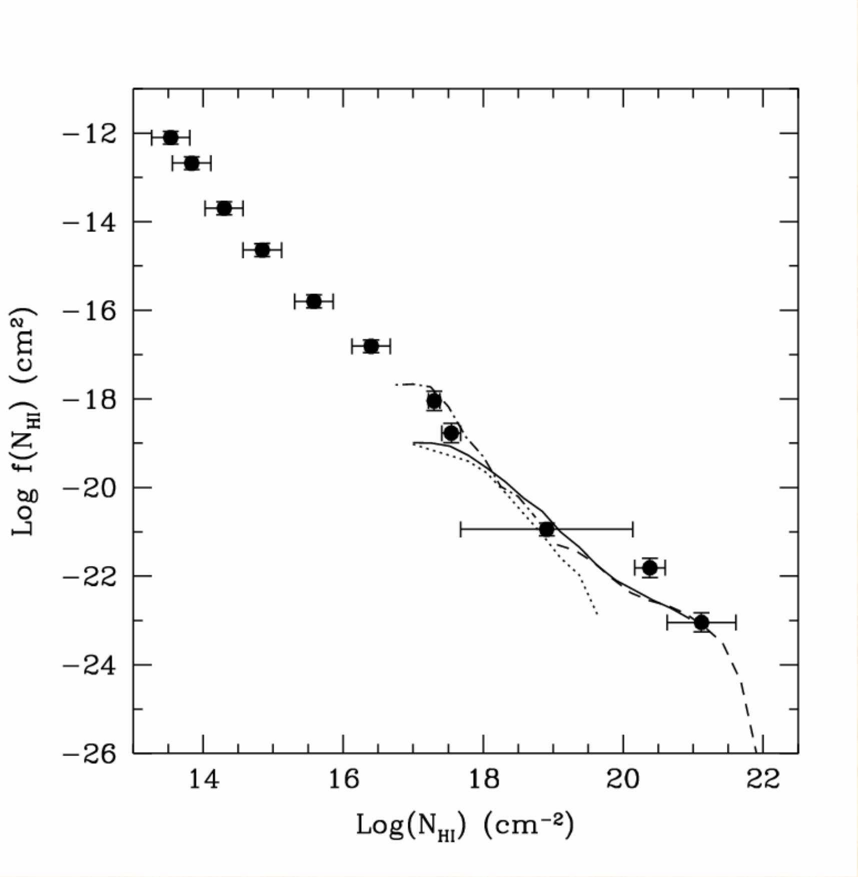
- probe extended environments of > 340 galaxies within 40 Mpc with a **22,000 pointing** mosaic
- survey (~1000 hr) begun in December 2004, now **45% complete**

Imaging the low-z Cosmic Web

How can we go beyond the Local Group?

The Next Generation

- (2008+) WSRT 25-beam FPA
  - will approach $\Delta N_{HI} \sim 10^{16}$ cm^{-2} over ΔV=20 km/s
  - the next order of magnitude in surface covering factor
  - background source density will allow (optical/UV/X-ray) absorption obs. of metallicity and ionization state



➢ baryonic mass measurements and enrichment history