BAO from Integrated Neutral Gas Observations

HI Intensity Mapping
using a novel single-dish radio telescope

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with inputs from

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The University of Manchester

FAPESP

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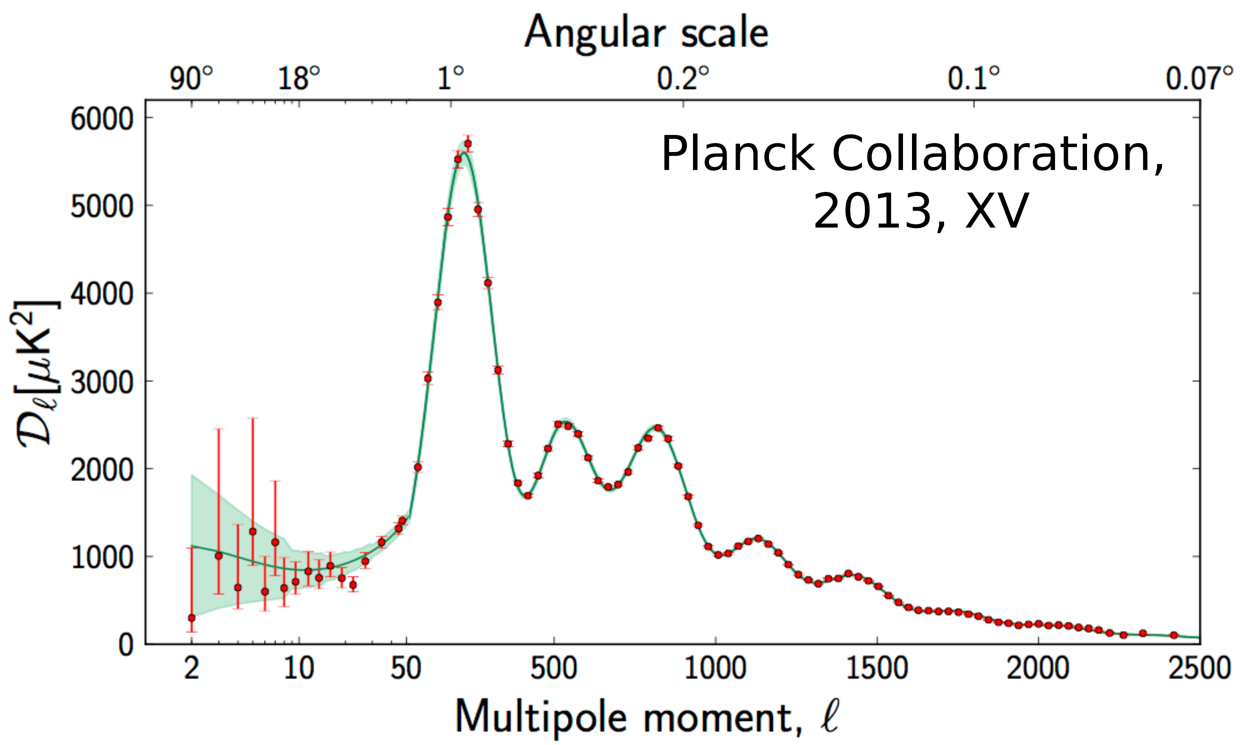
Plan of the talk

- Introducing BAOs and Intensity Mapping
- Introducing BINGO
- Why BINGO is competitive scientifically
- Challenges & how to address them
- Additional science possibilities
- Conclusions and project status

Introducing BAOs and Intensity Mapping

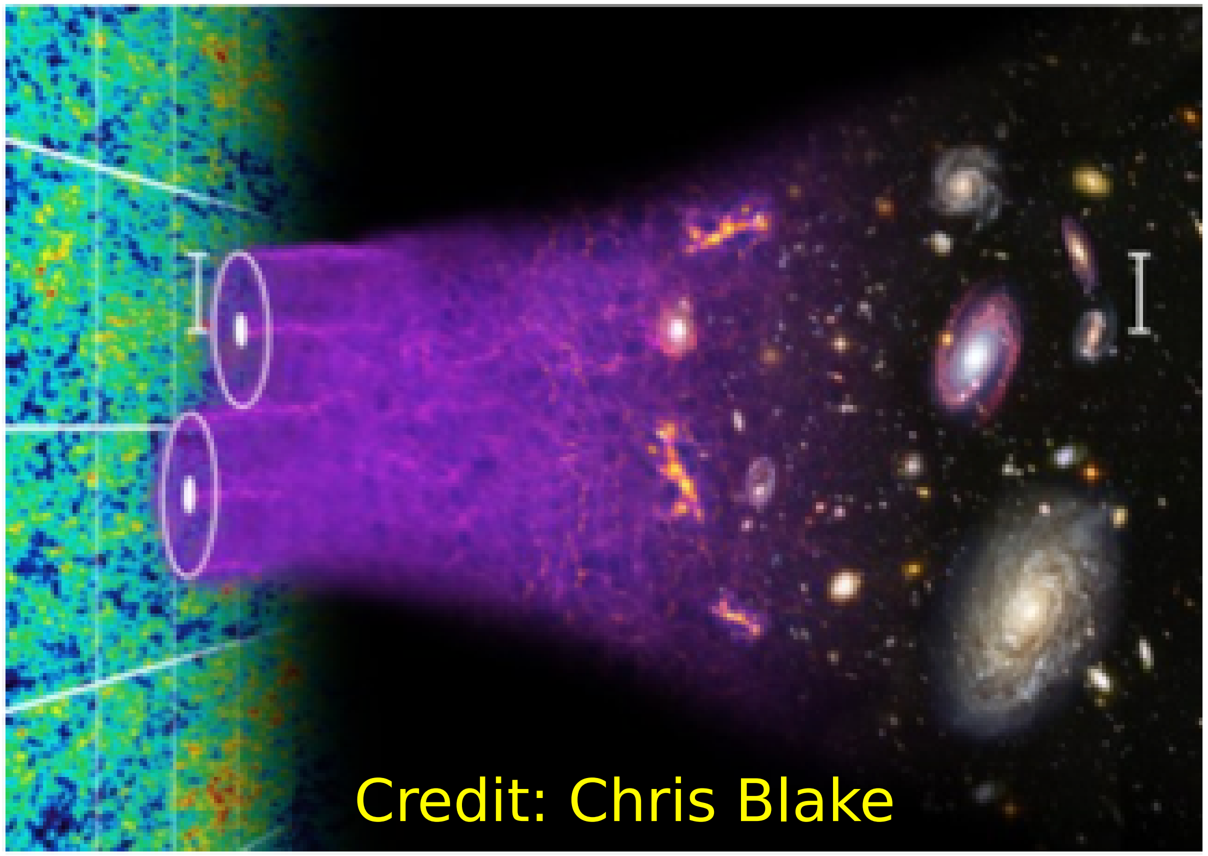
Baryon Acoustic Oscillations (BAOs)

- Acoustic waves imprinted on CMB 380,000 years after Big Bang
  - Acoustic scale set by distance light travelled at that time
  - Scale known to 0.2% precision from CMB power spectrum (147.4±0.3 Mpc)



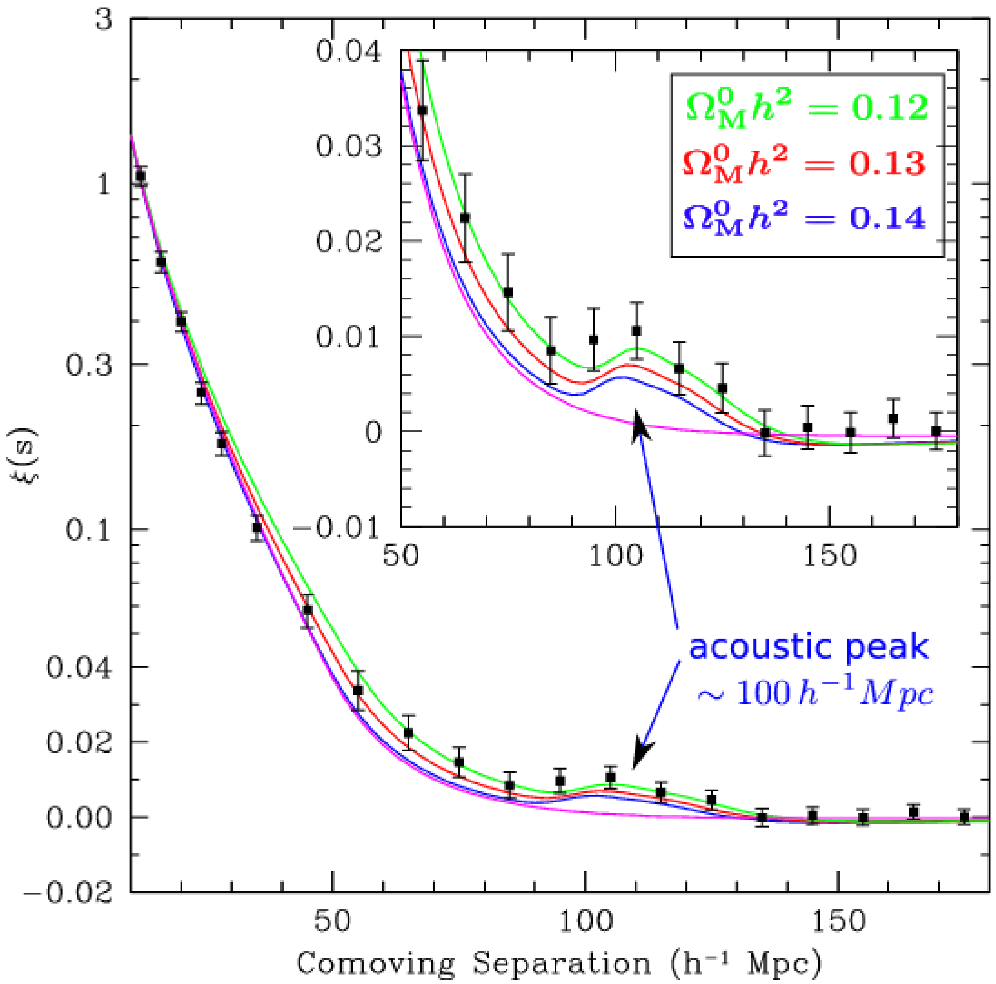
- Simulations clearly show that this preferred scale is imprinted on all matter in the Universe at the level of ~5%

- **BAOs are a "standard ruler" to measure expansion history of the Universe**
  - **Constrain cosmological models and dark energy**

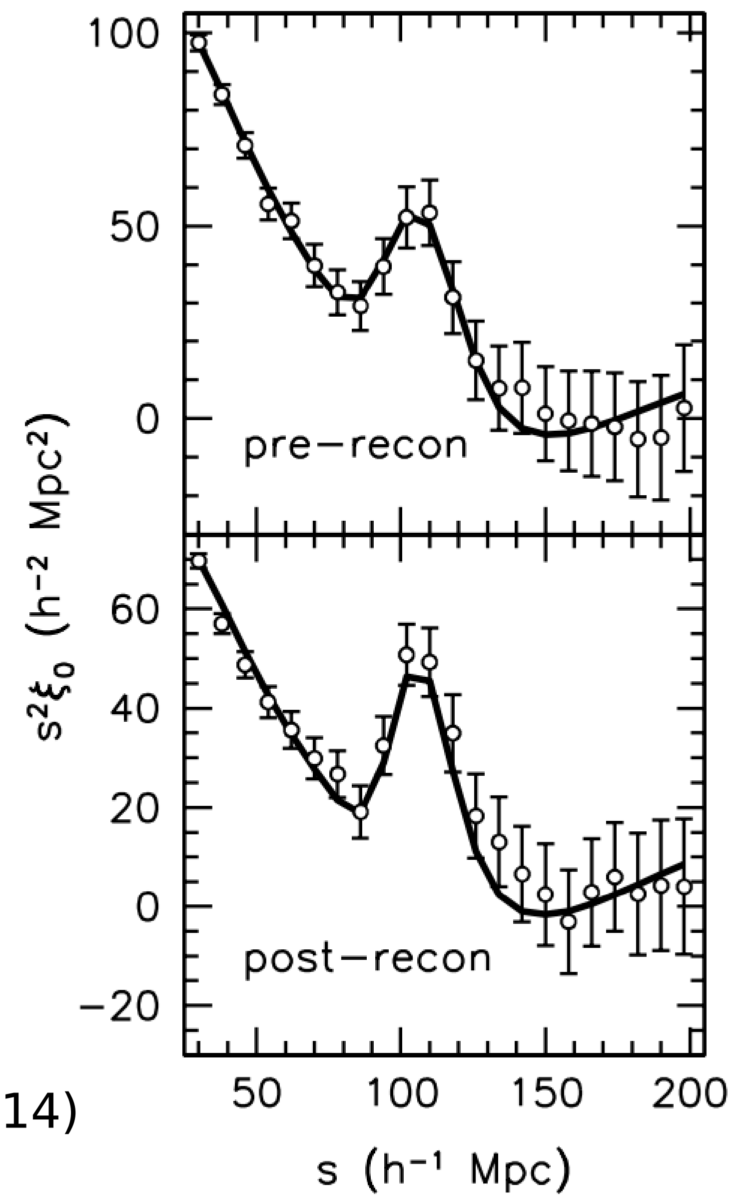


BAOs at optical wavelengths

- First BAO detection (Eisenstein 2005)
  - ~47000 galaxies correlation function
- Massive improvements over last few years with large spectroscopy surveys
  - 2dF, 6dF, WiggleZ, BOSS (SDSS-III)….
- Future surveys: DES, DESI, Euclid….



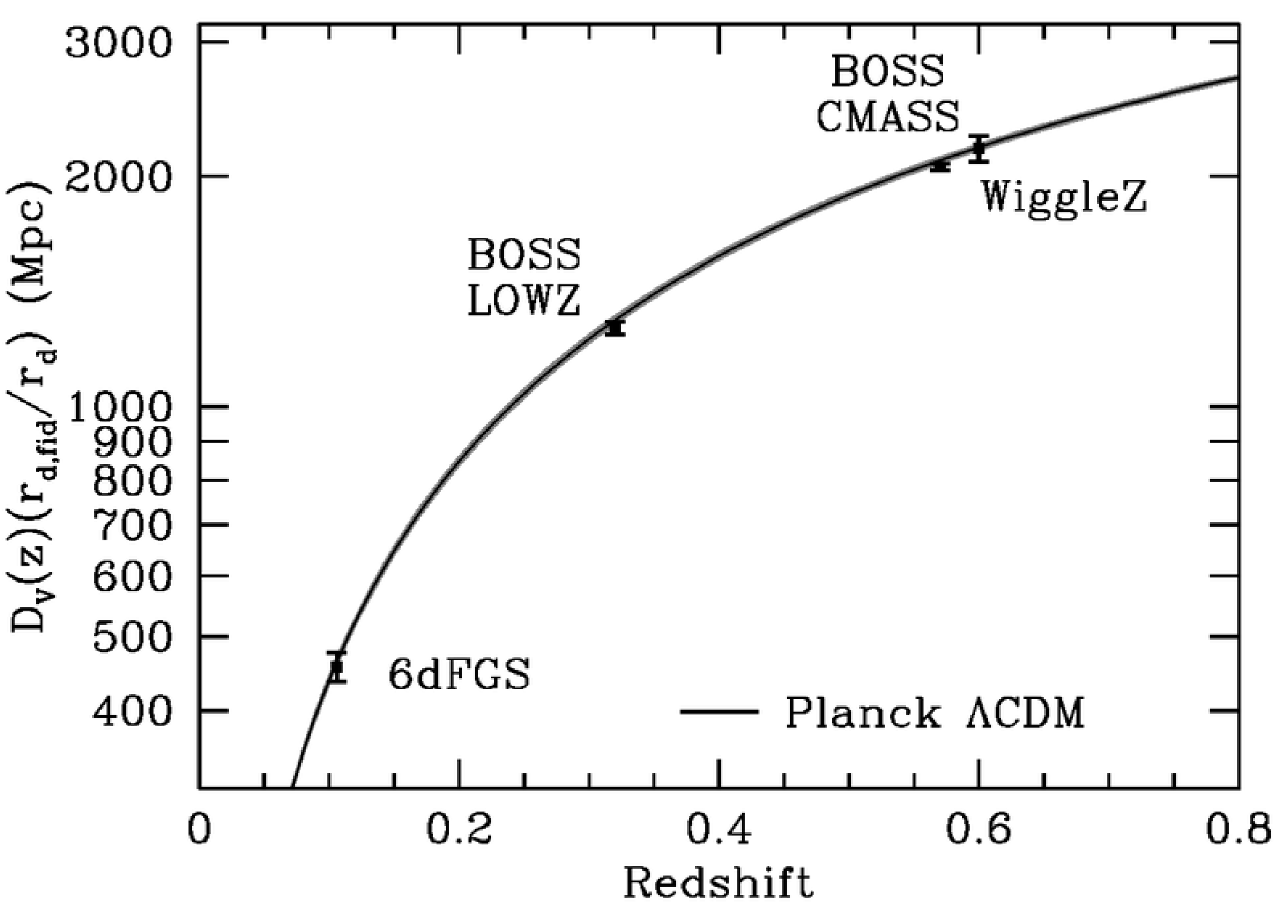
Eisenstein et al. (2005)

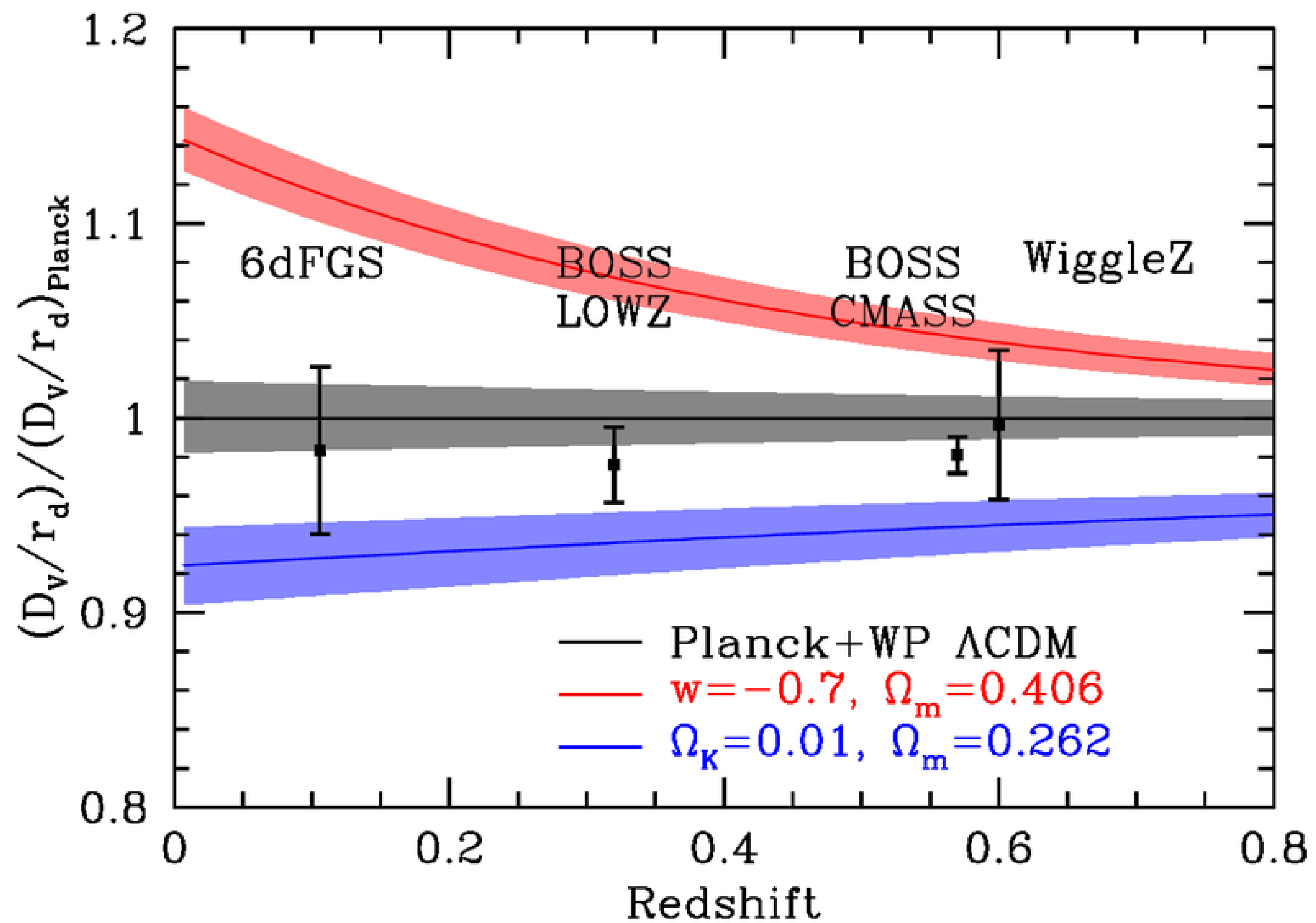


Anderson et al. (2014)

BAO Hubble diagram

- Relative volume-averaged distance vs redshift
- Test expansion rate models of the Universe
- **Requires precise measurements over a range of redshifts**

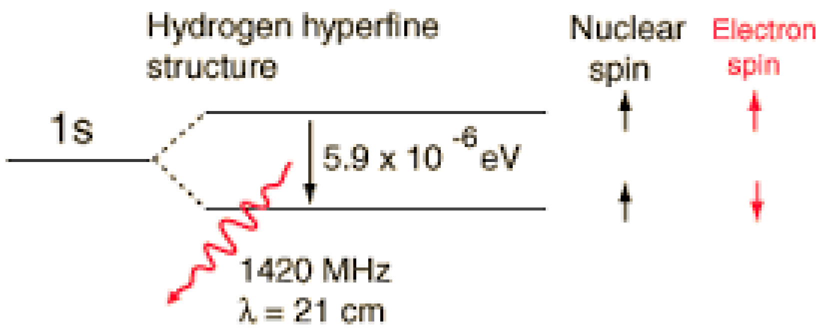


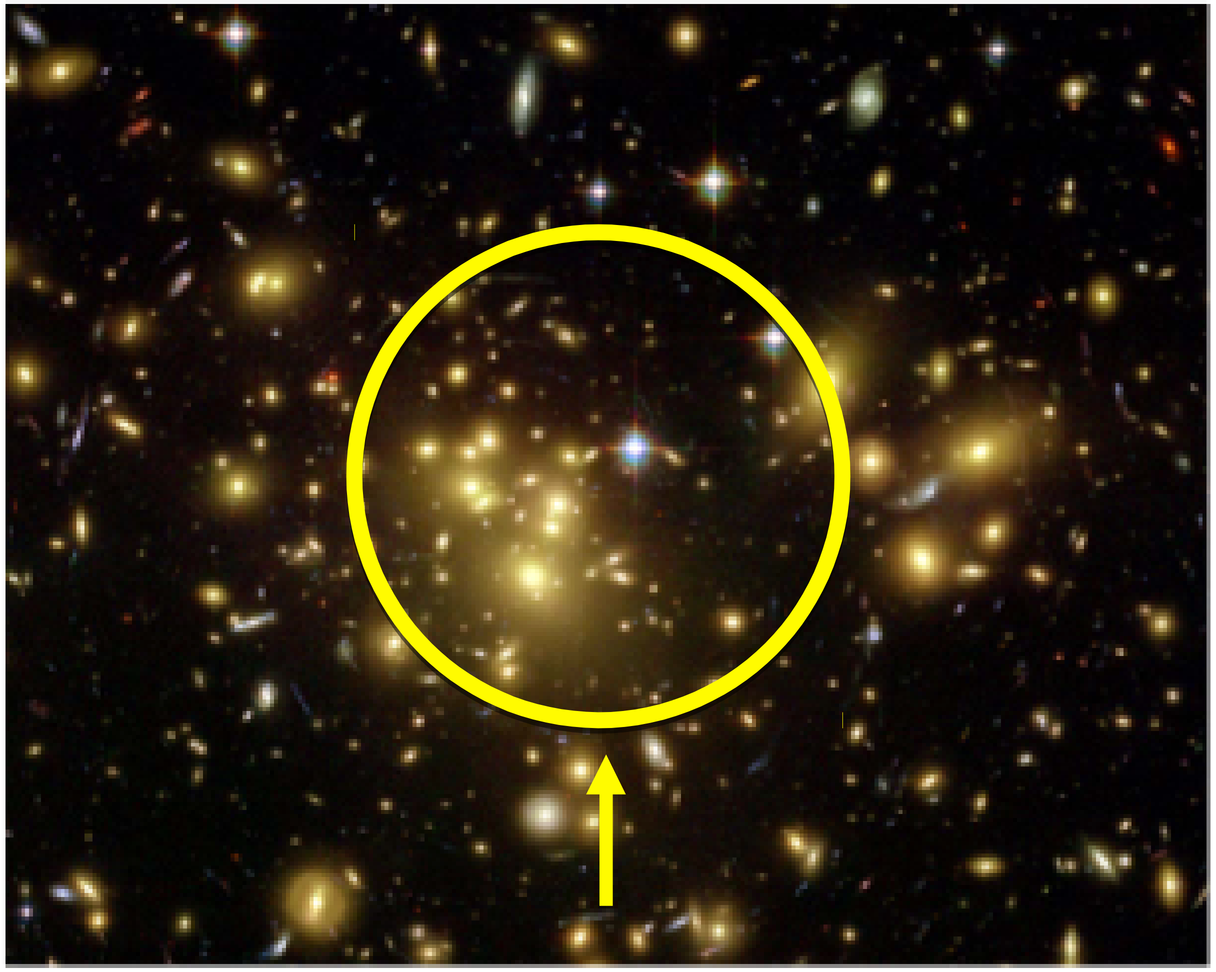


BOSS papers (e.g. Anderson et al. 2014)

(HI) Intensity Mapping in a nut-shell

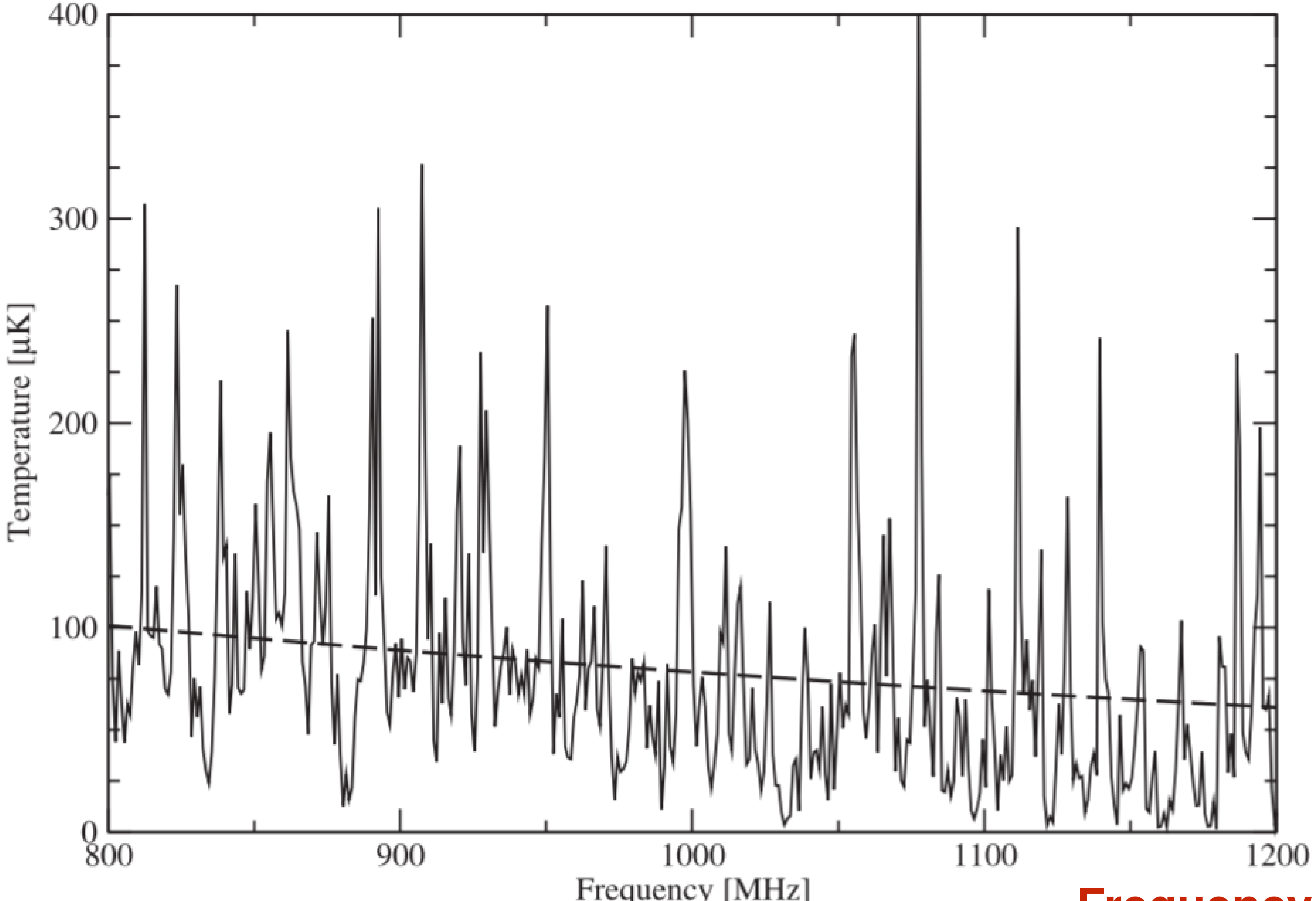
- Efficient alternative to measuring $>10^6$ galaxies individually (Peterson 2006)
  - e.g. BOSS, WiggleZ, Euclid, SKA...
- Use emission line to map *fluctuations*
  - HI, CO, CII...
  - Power spectrum as a function of frequency (redshift)
- Use relatively large beam on the sky (small telescope)
- Redshift directly given by frequency
- No absorption along line-of-sight
- HI is a good tracer of mass on large scales (not strongly biased)





Large beam on the sky (~1 deg) contains large number of galaxies

Typical expected frequency spectrum



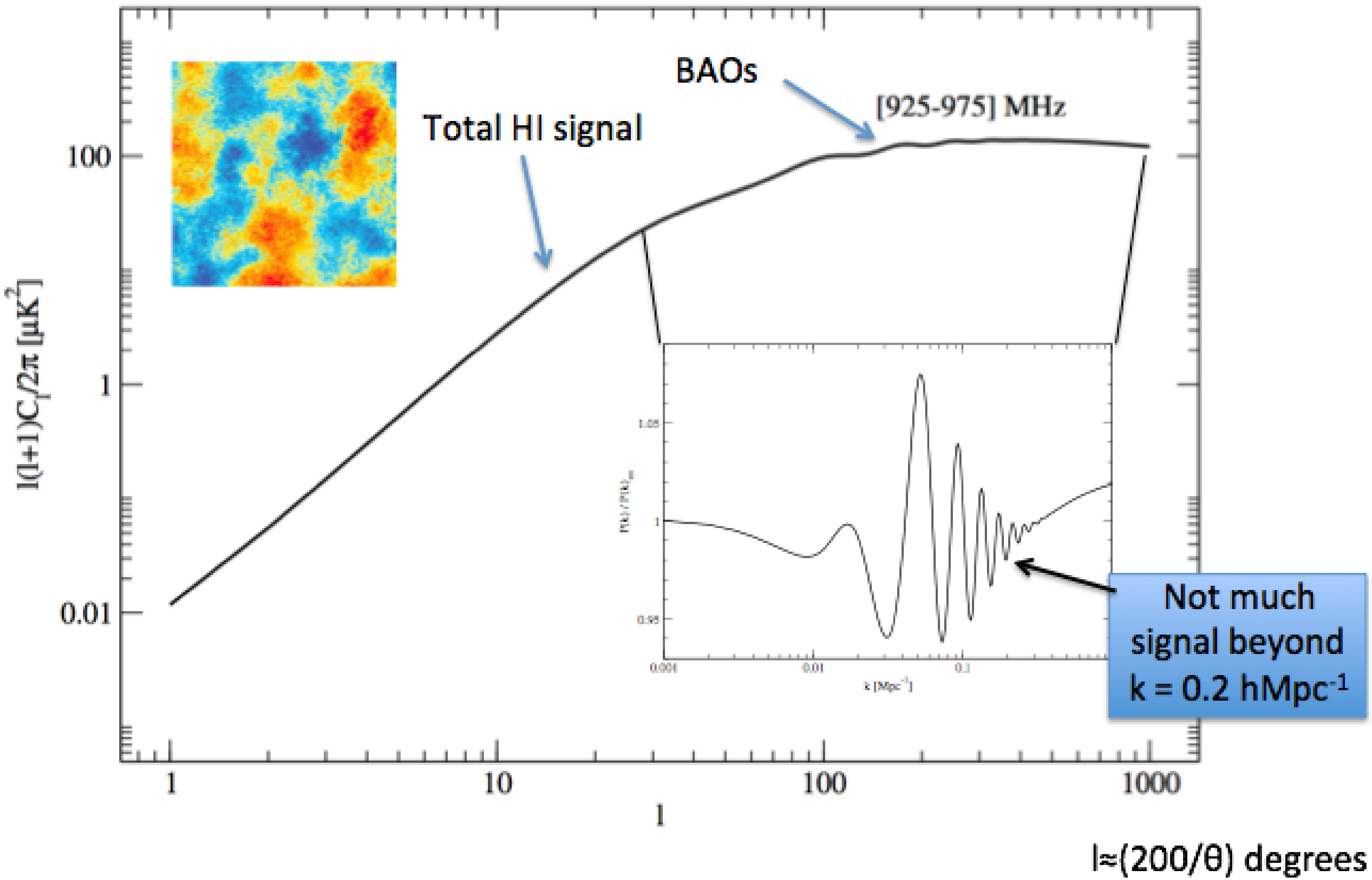
Frequency ~ 1/redshift

(a) $\Delta f = 1\,\mathrm{MHz}, \theta_{\mathrm{FWHM}} = 60\,\mathrm{arcmin}$

Battye et al. (2013)

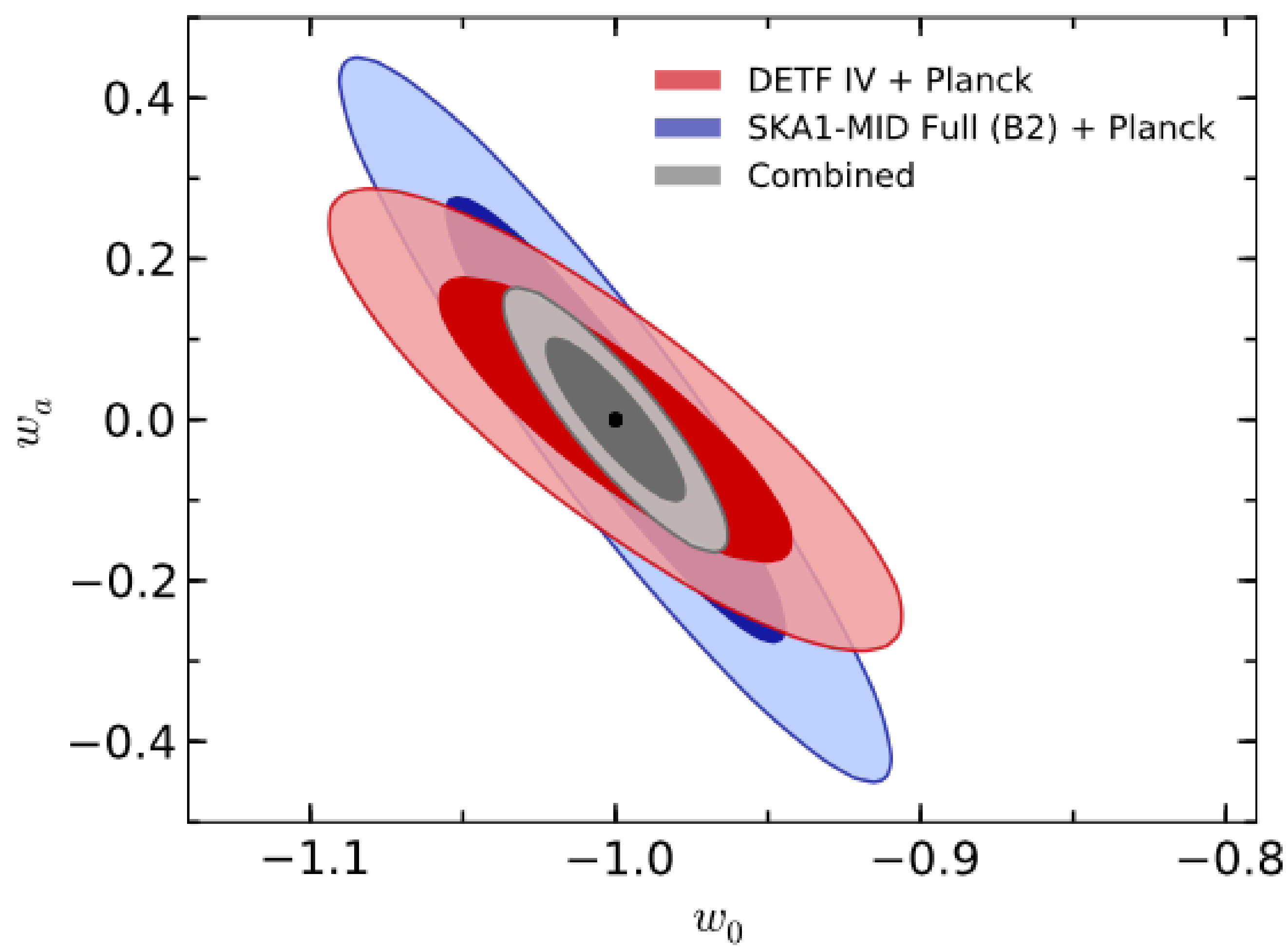
The HI (21cm) power spectrum

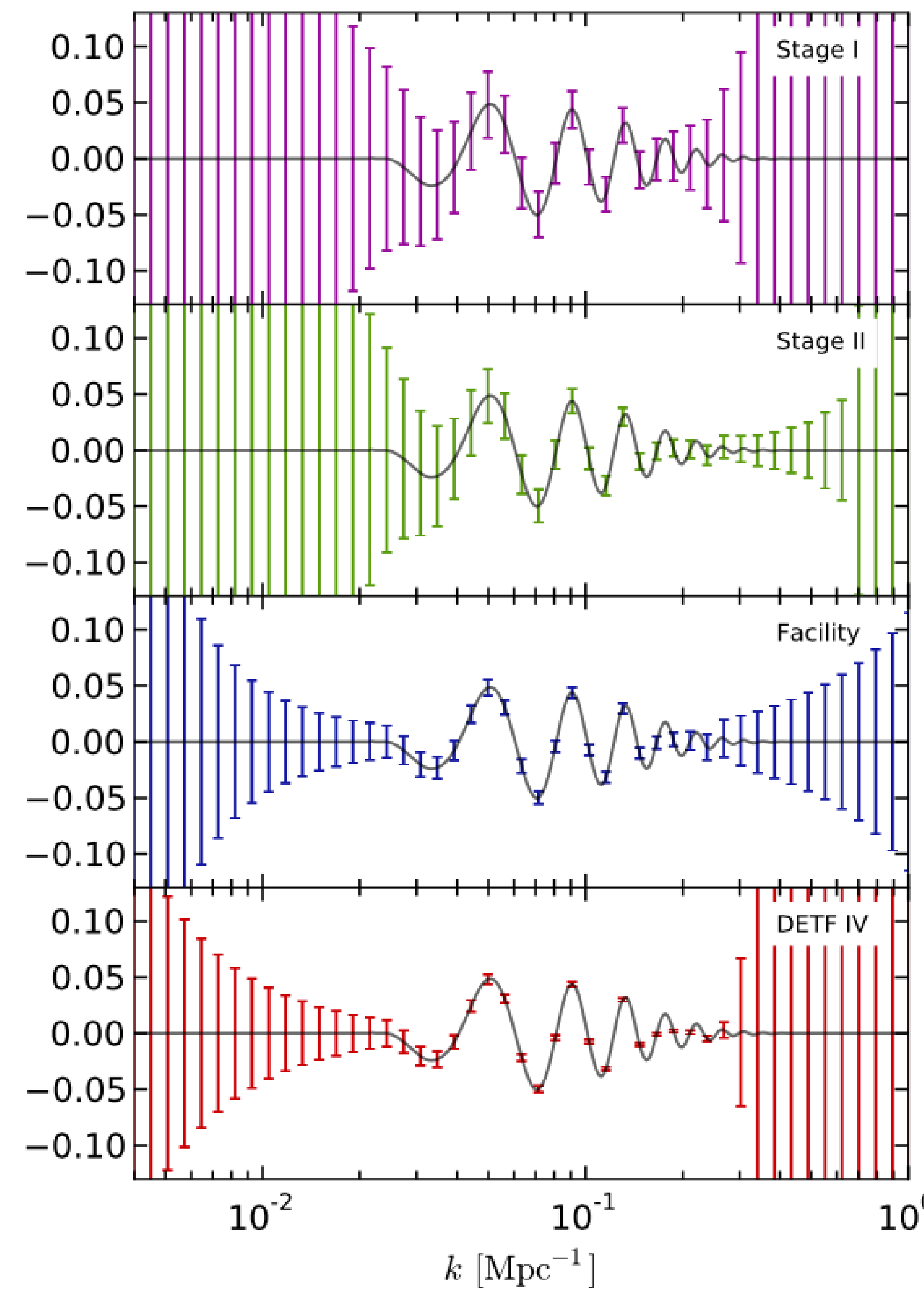
Cosmological HI signal is weak! (≈100 μK rms) and on degree scales



SKA

- SKA-MID
  - Phase 1: ~200 15m dishes in South Africa acting as an interferometer!
- Baselines too long to be useful for BAOs via intensity mapping
- Bull et al. (2014) showed that in single-dish (“autocorrelation”) mode, it could be hugely sensitive!
  - More powerful than Euclid!



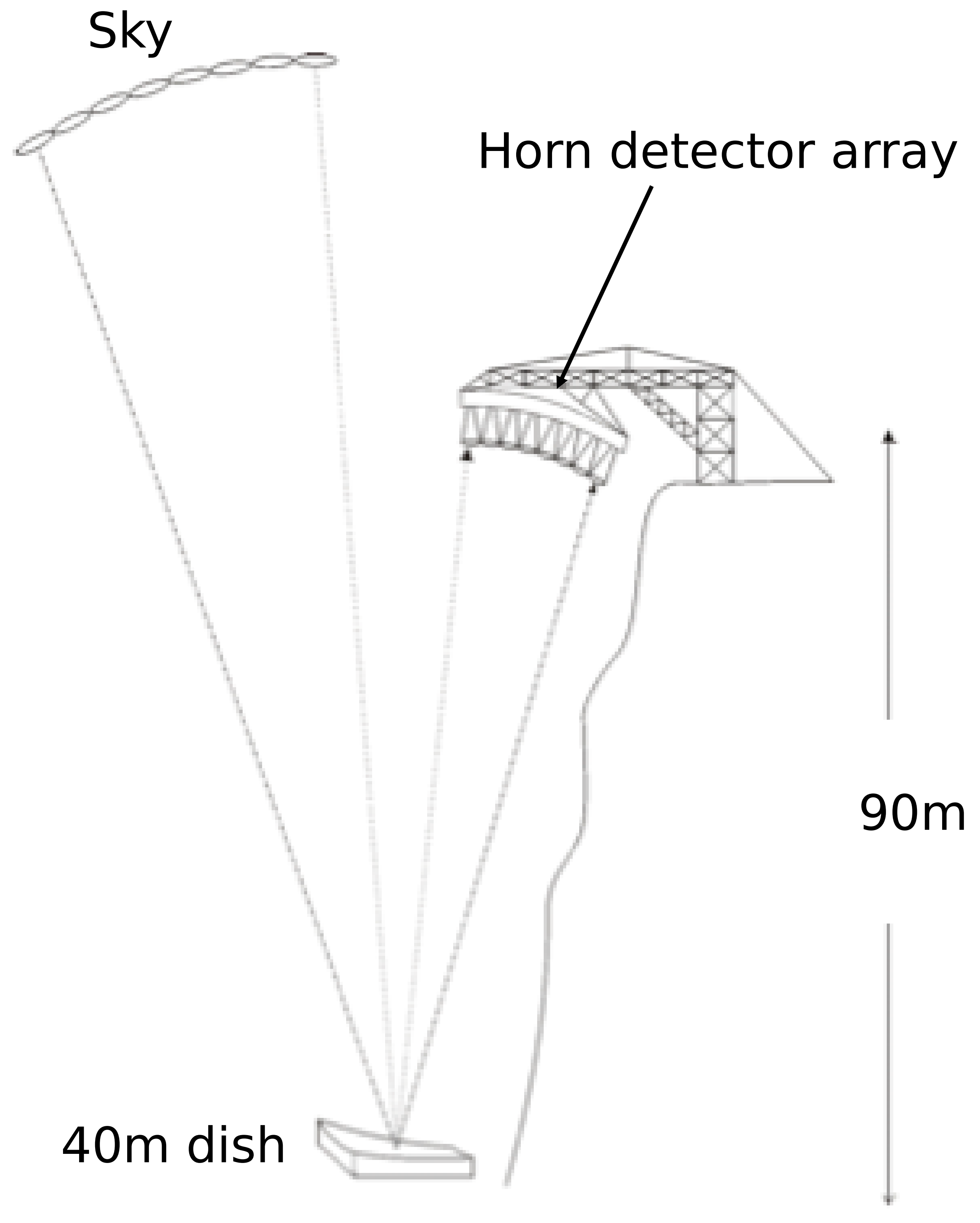


Introducing BINGO

BINGO concept

Guiding principle : simplicity!

- **A pathfinder for SKA**
- **Key specifications:**
  - Dish diameter : 40 m
  - Resolution: ~2/3 deg
  - Frequency range : 960 - 1260 MHz **(z=0.12-0.48)**
  - Number of feeds: 50 (dual pol)
  - Field-of-view: ~15 deg, at (-5) -20 dec
  - **No cryogenic cooling** : Tsys ~ 50K
  - Digital correlation receiver
  - Channel width << 50 MHz ($\Delta z<0.05$)
  - **Majority of receiver components "off-the-shelf"**
  - **Transit telescope (no moving parts): observe declination strip with drift scans**
  - 2 years observing (~1 year on source)



Battye, Browne, Dickinson, Heron, Maffei, Pourtsidou, 2013, MNRAS, 434, 1239 [arXiv:1209.0343]

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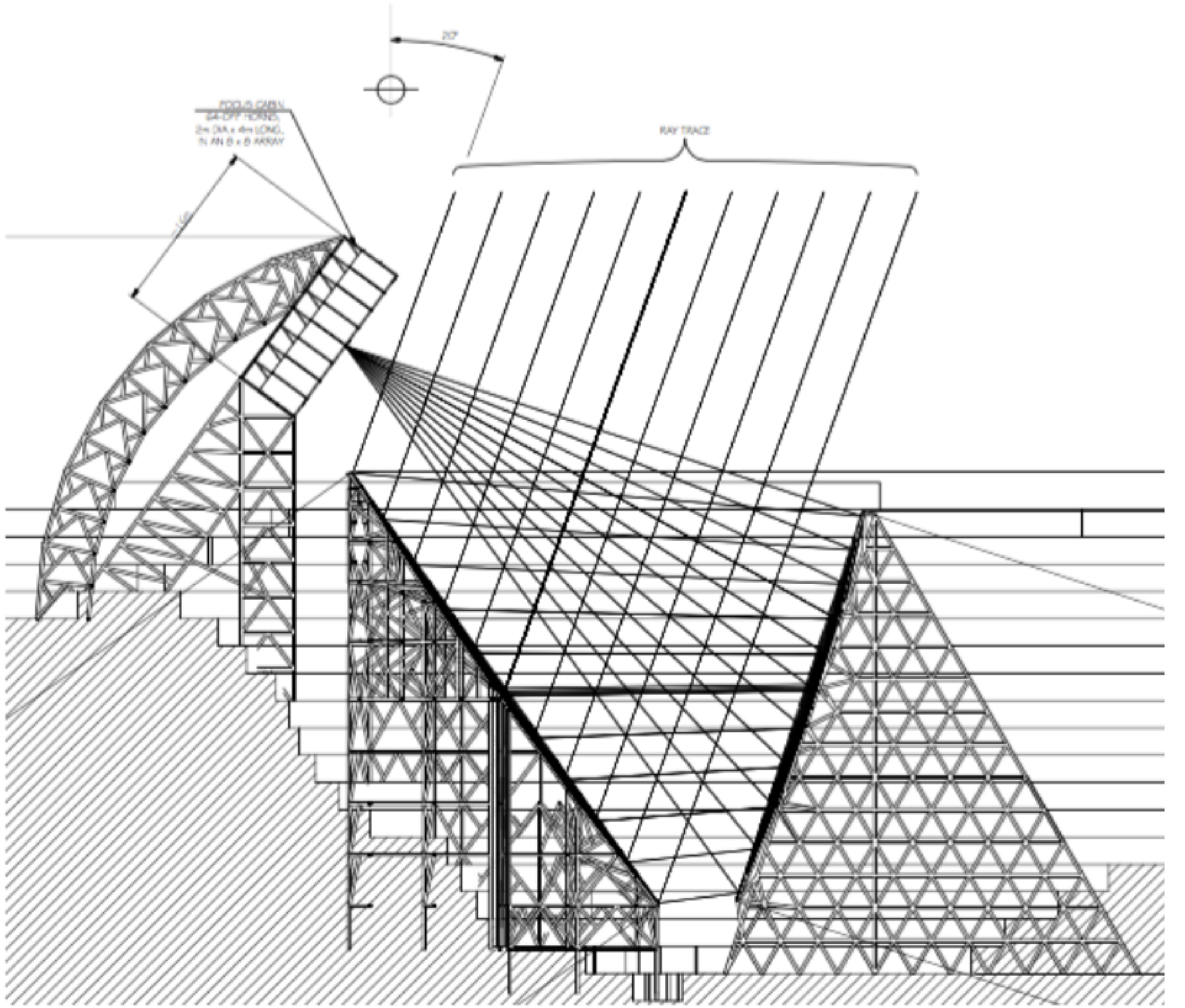
Crossed-Dragone configuration



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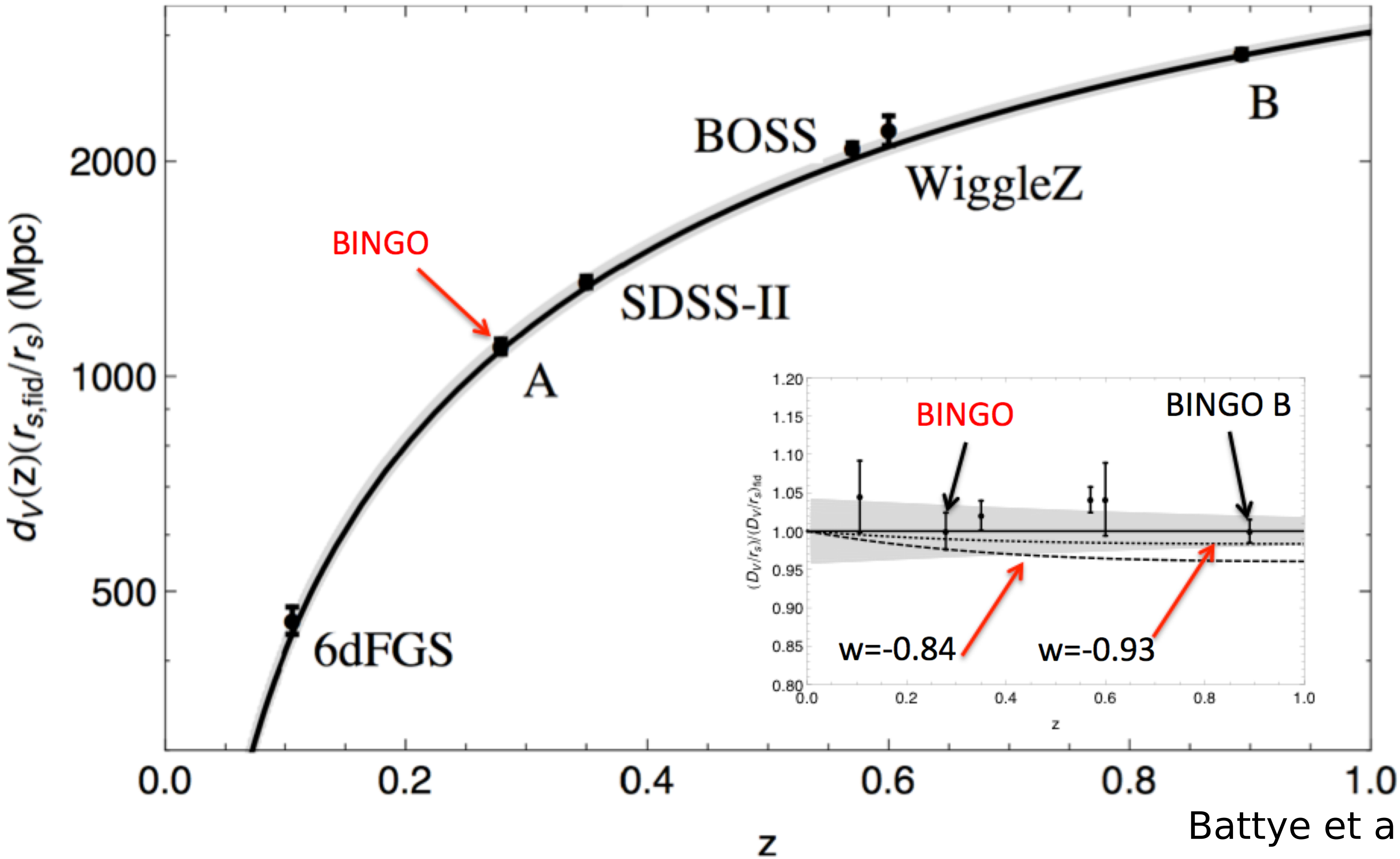
BINGO players

- **U. Sao Paolo, Brazil**
  - Elcio Abdalla (P.I.), Raul Abramo, Mike Peel (FAPESP Fellow, ex-Manchester), Andreia Pereira de Souza (engineer), Benjamim Galvão (engineer, industry liaison), Marcos Lima
- **INPE, Brazil**
  - Alex Wuensche, Thryso Villela, Renato Branco (engineer)
- **U. de la Republica, Montevideo; Ministry of Communications, Uruguay**
  - Gonzalo Tancredi, Manuel Calas, Emilio Falco, Ana Mosquera
- **JBCA, Manchester, UK**
  - Richard Battye, Ian Browne, Tianyue Chen, Peter Dewdney (SKAO), Richard Davis, Clive Dickinson, Keith Grainge, Stuart Harper, Lucas Olivari, Mathieu Remazeilles, Sambit Roychowdhury, Peter Wilkinson
- **ETH, Zurich, Switzerland**
  - Alex Refregier, Adam Amara, Christian Monstein
- **UCL, London, UK**
  - Filipe Abdalla
- **IAS, Paris, France**
  - Bruno Maffei (ex-Manchester)
- **U. Cardiff, UK**
  - Giampaolo Pisano
- **UKZN, South Africa**
  - Yin-Zhe Ma (ex-Manchester)
- **U. Portsmouth, UK**
  - Alkistis Portsidou (ex-Manchester)

Why BINGO is competitive scientifically

BINGO on BAO Hubble diagram



Battye et al. (2013)

- Additional points on BAO Hubble diagram competitive with current surveys
- Consistency check with different technique and systematics
- Proof-of-concept/pathfinder for SKA autocorrelation

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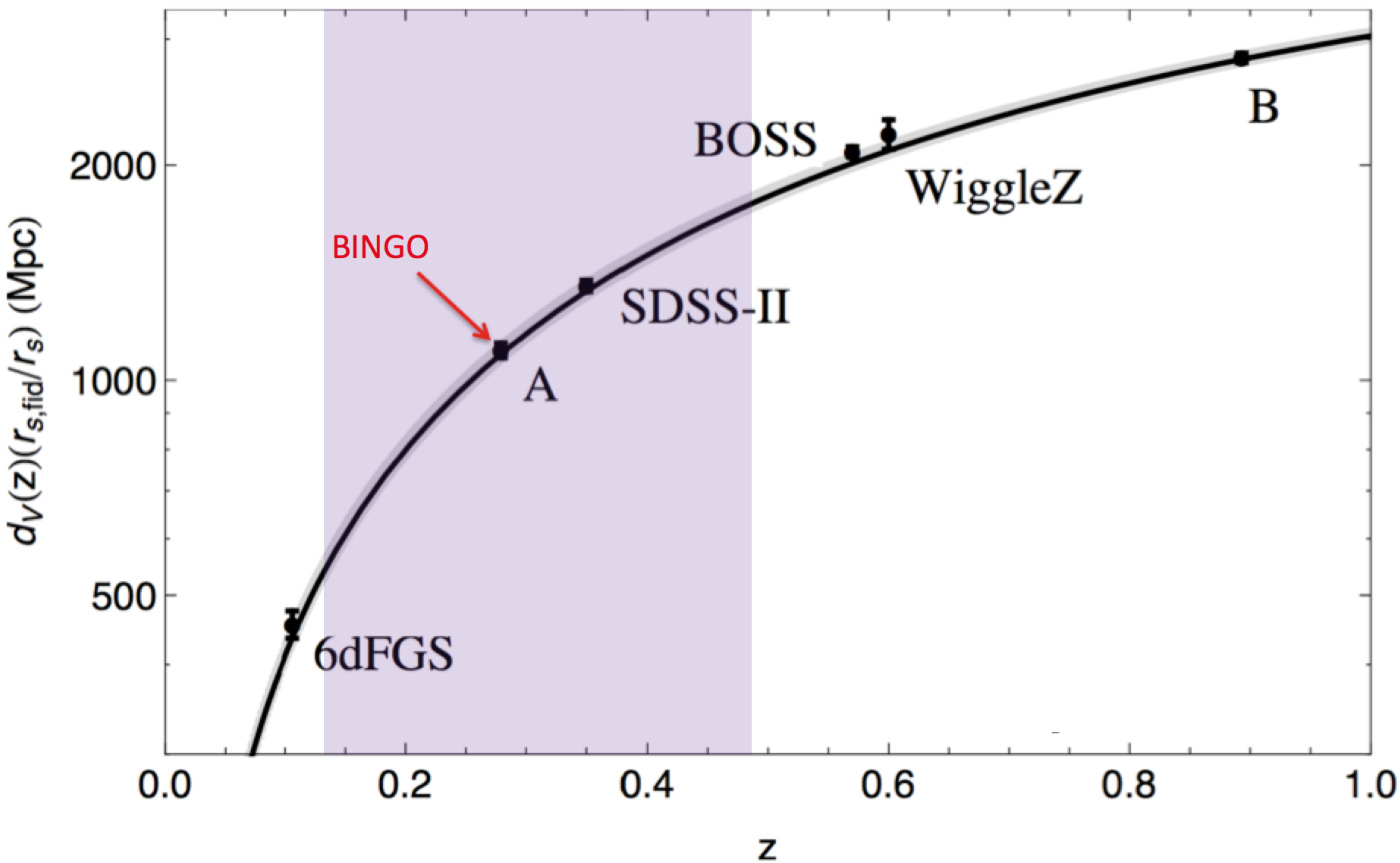

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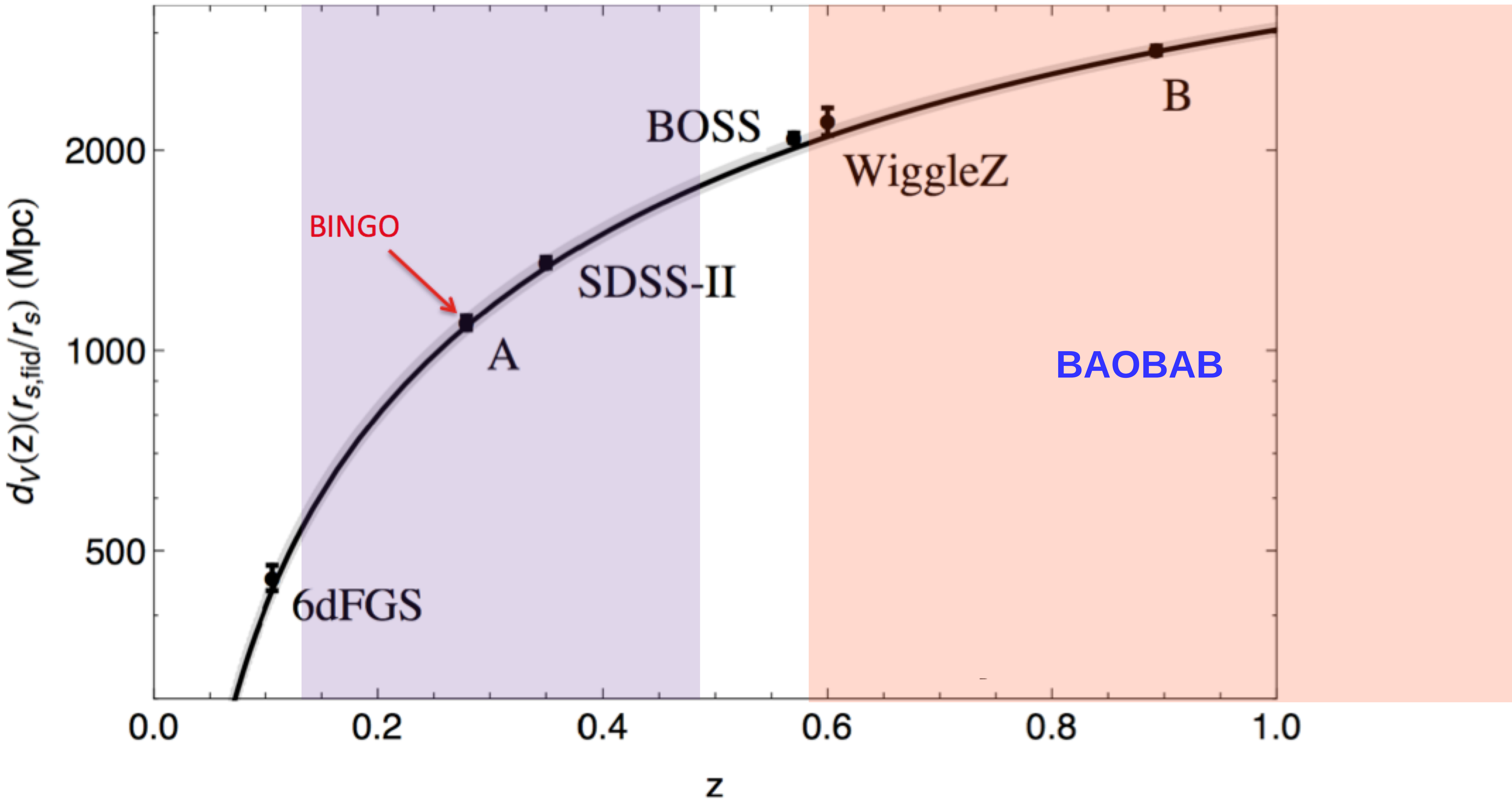
Compared to other HI IM projects



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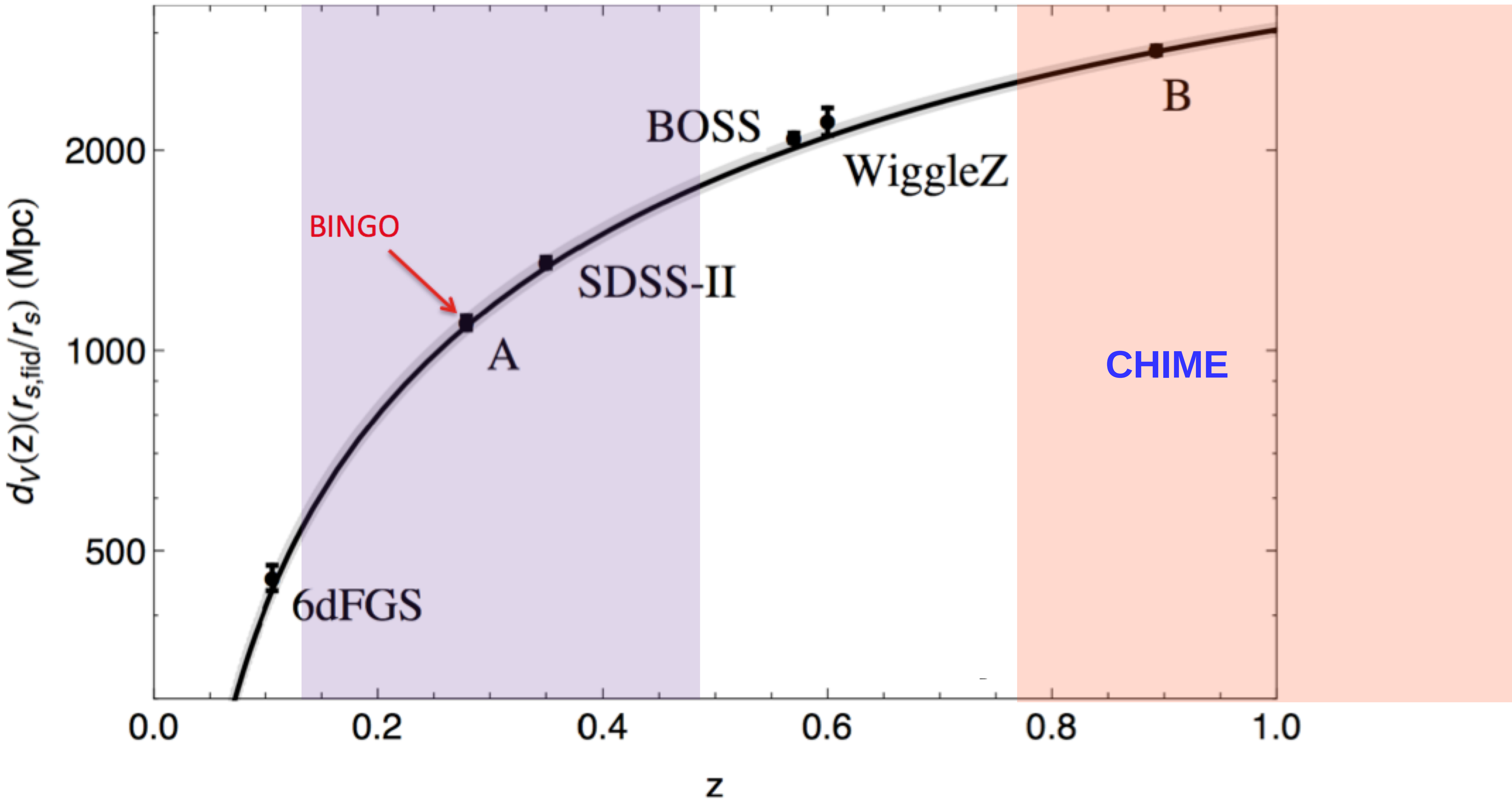

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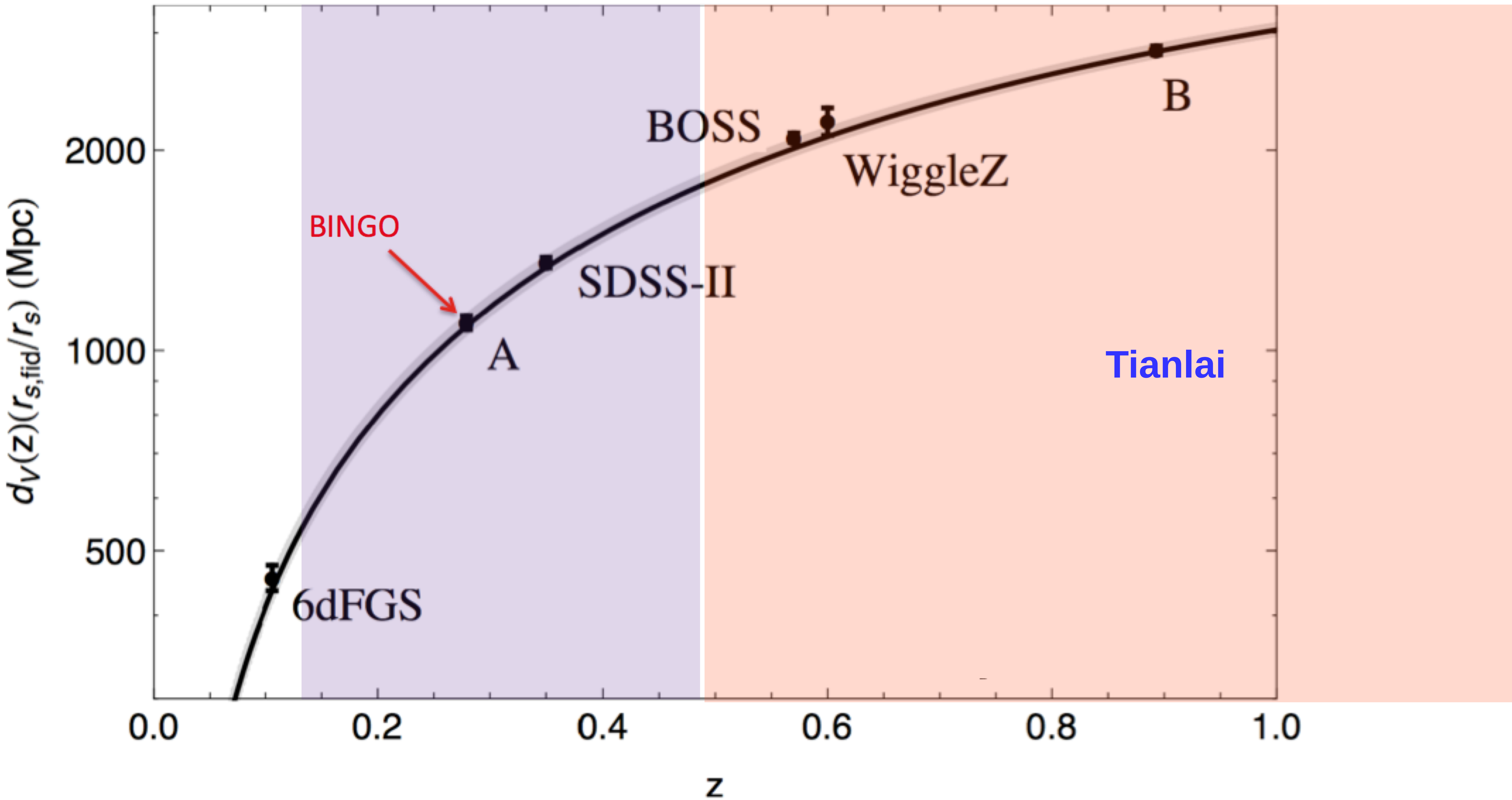

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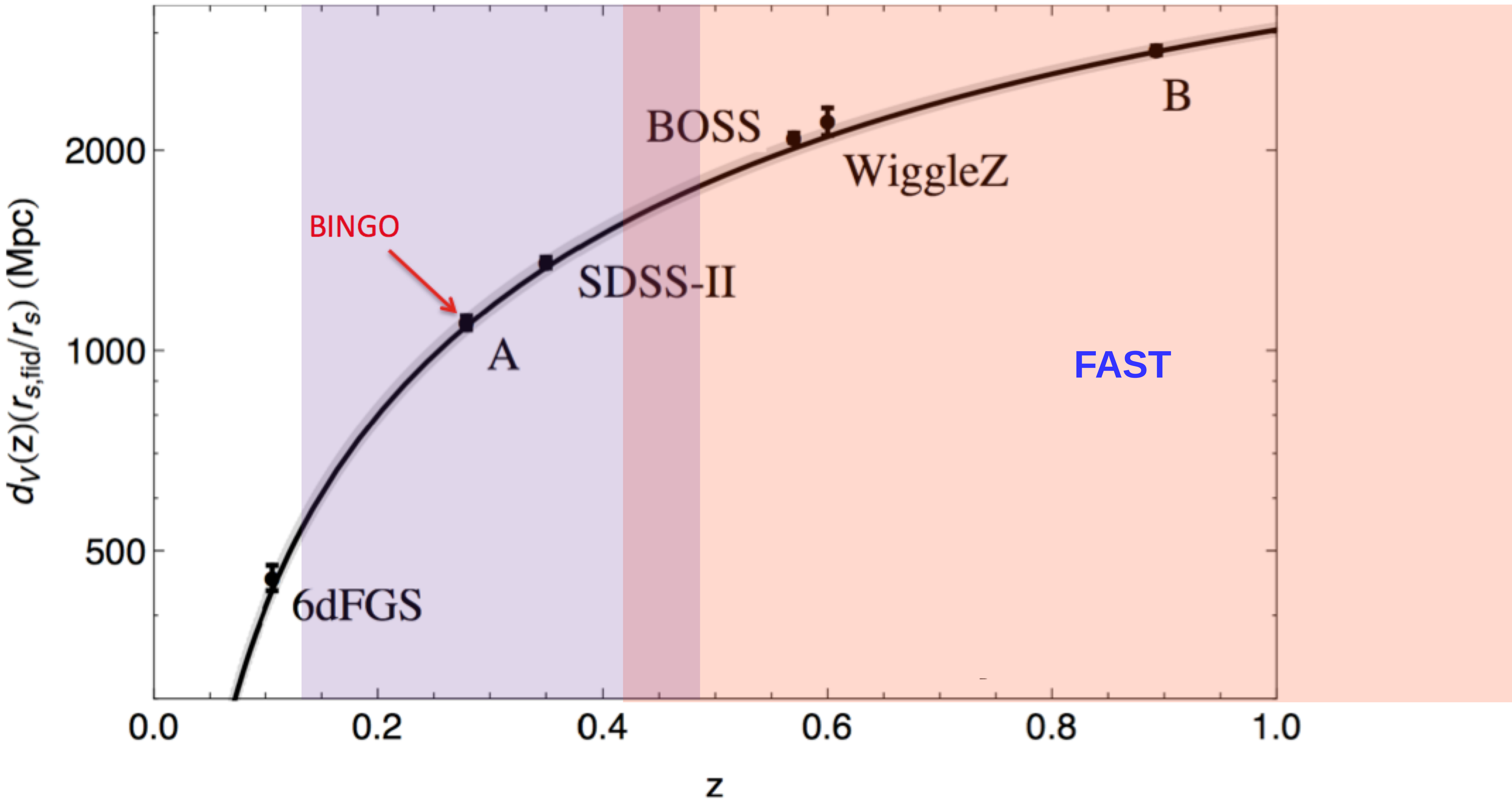

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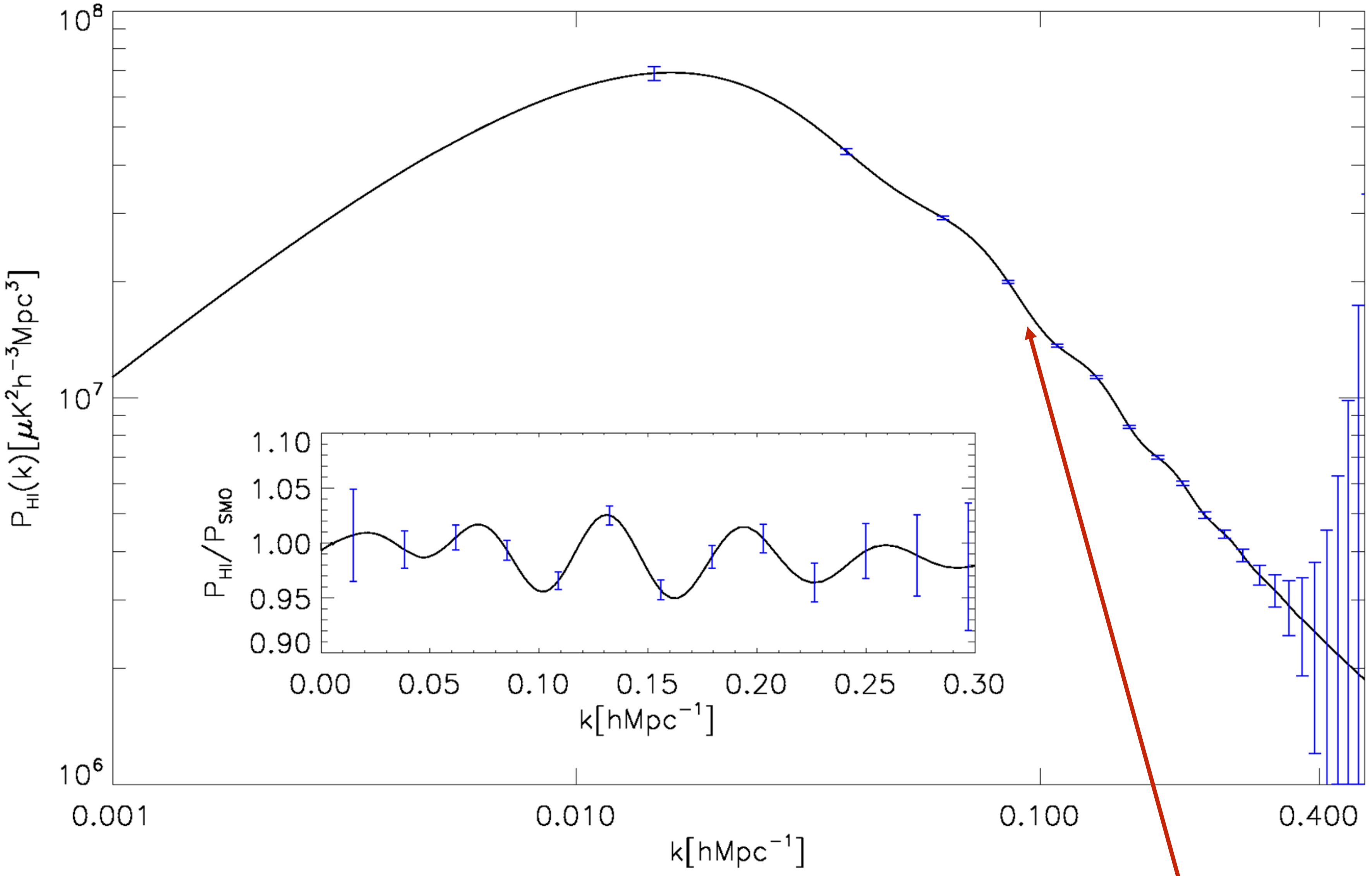
BINGO sensitivity

1 year on-sky (2 years in practice)



- Ultra deep HI maps over ~5000 sq. deg.
  - ~100 μK sensitivity
- Detection of BAOs at ~5-7σ
  - Measurement of acoustic scale to $\delta k_A/k_A \sim 0.024$
  - Constrain dark energy $\delta w/w \sim 0.16$

Much more cosmological information from the HI power spectrum itself (Olivari et al., in prep.)

Challenges & how to address them

It is not going to be easy!

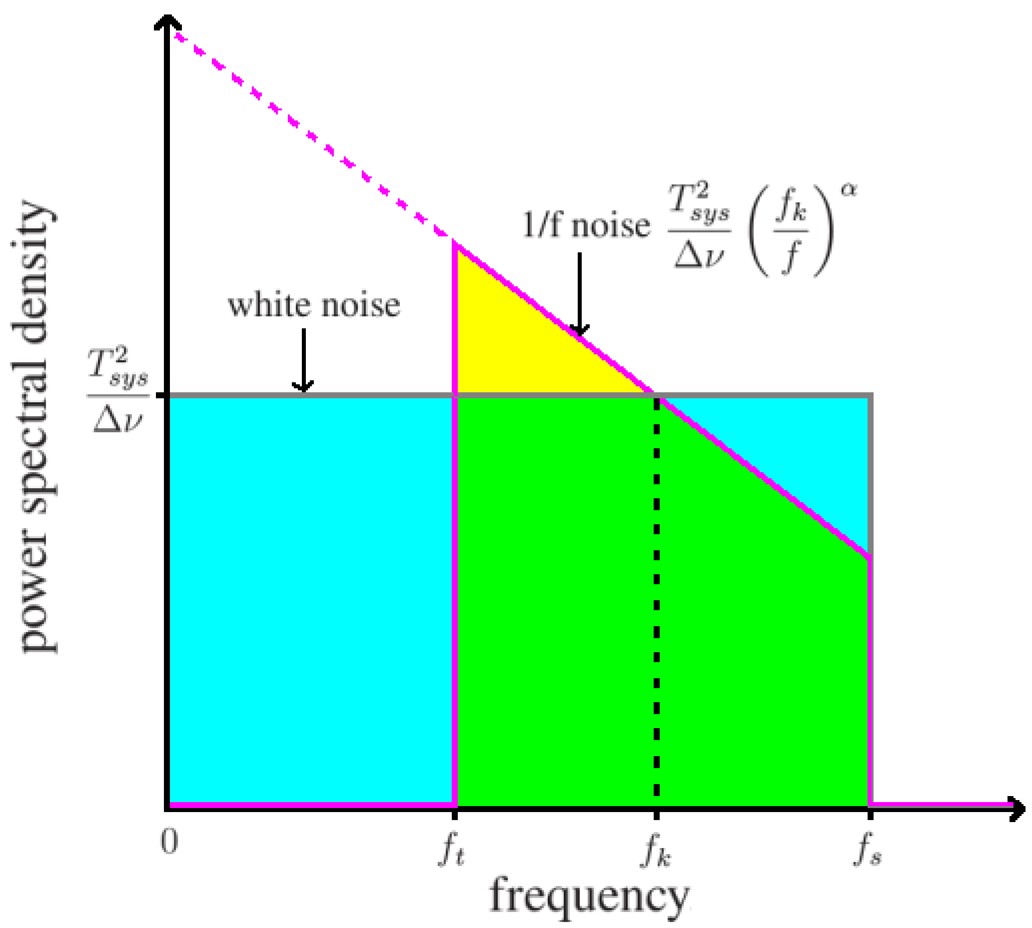
- Large telescope!
- Novel horn fabrication to reduce weight and cost
- 1/f noise (pink noise – correlated over various timescales)
- Radio Frequency Interference (RFI): satellites, mobiles, aeroplanes, ...
- Bright foreground emissions – 10^5 times stronger!
  - Diffuse Galactic radio emission
  - Extragalactic sources
- Calibration and stability → in time and frequency
- Sidelobe pick-up
- Atmospheric fluctuations
- ....

Custom built to keep instrumental effects under control from design stage itself

Quantify effect of other sources of error by designing an end-to-end pipeline

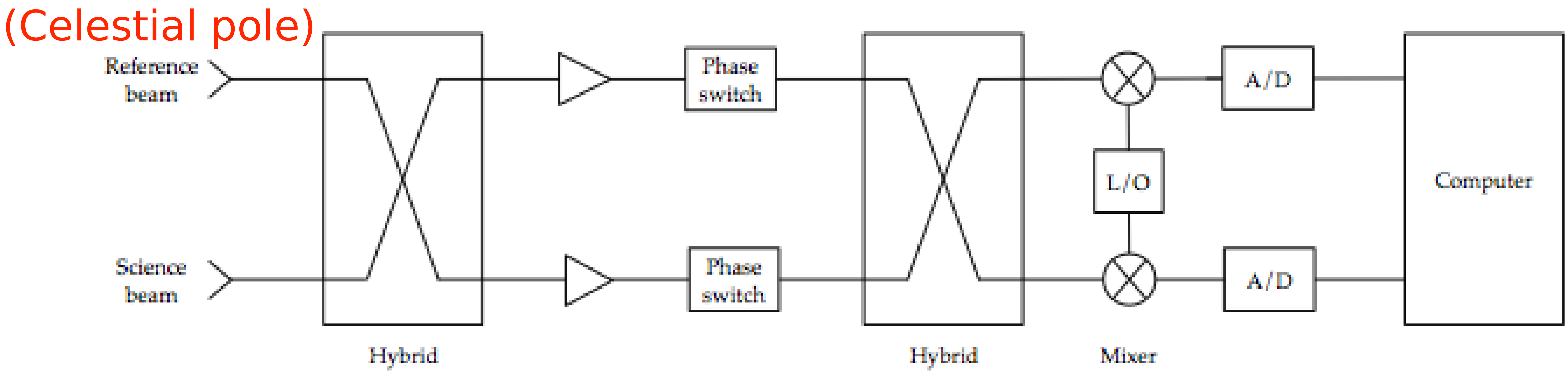
Improve methods for doing component separation, etc.

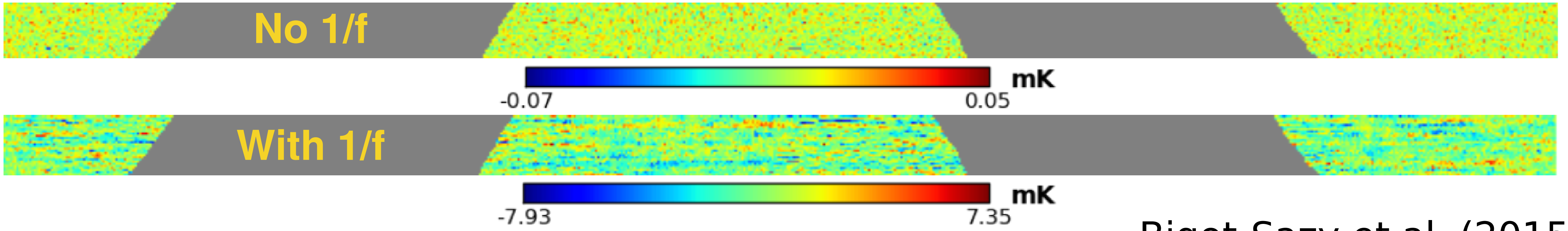
Tackling 1/f noise



- 1/f knee frequency of typical receivers ~1 Hz
  - Produces long time-scale fluctuations of total-power (1/f noise)
  - larger noise level, stripes in the map…

Correlation receiver





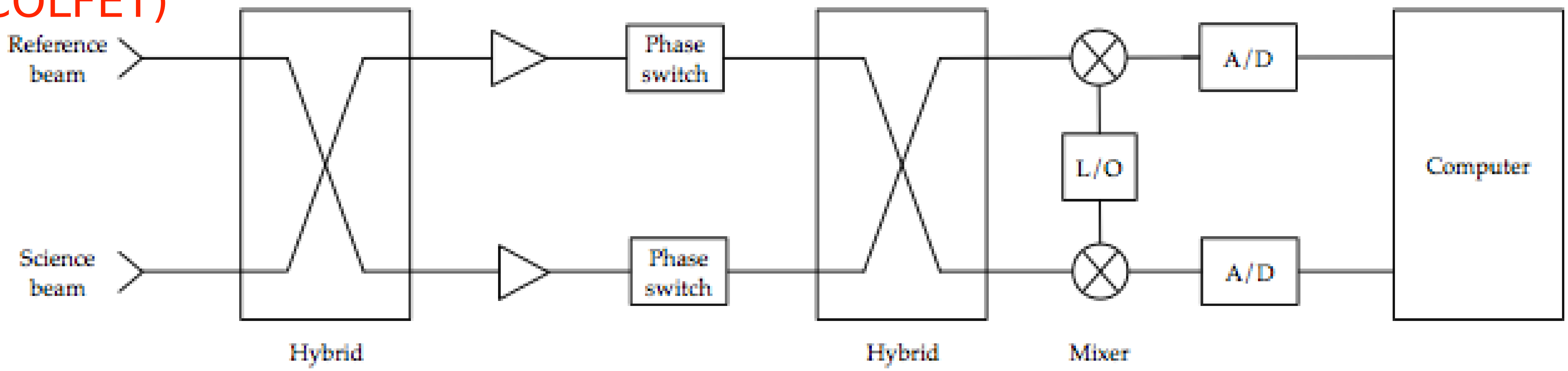
Bigot-Sazy et al. (2015)

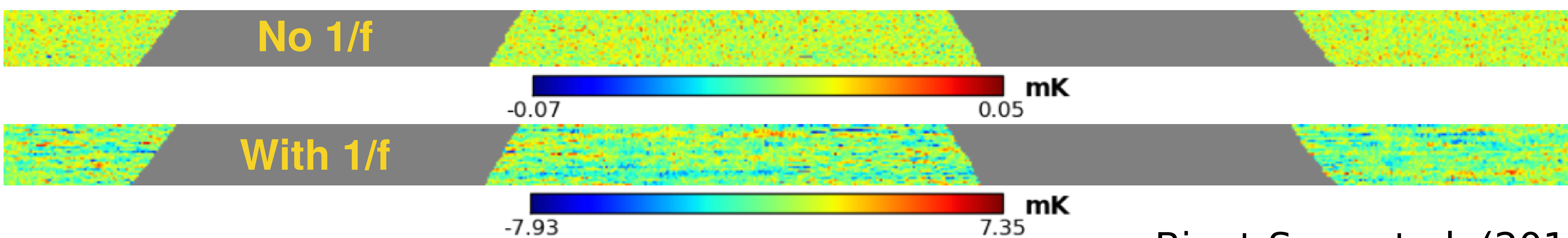
- 1/f knee frequency of typical receivers ~1 Hz
  - Produces long time-scale fluctuations of total-power (1/f noise)
  - larger noise level, stripes in the map…
- Perfect pseudo-correlation (e.g. WMAP/Planck) can remove 1/f noise
- Use (South) Celestial Pole as reference

Battye et al. (2013)

Correlation receiver

(COLFET)





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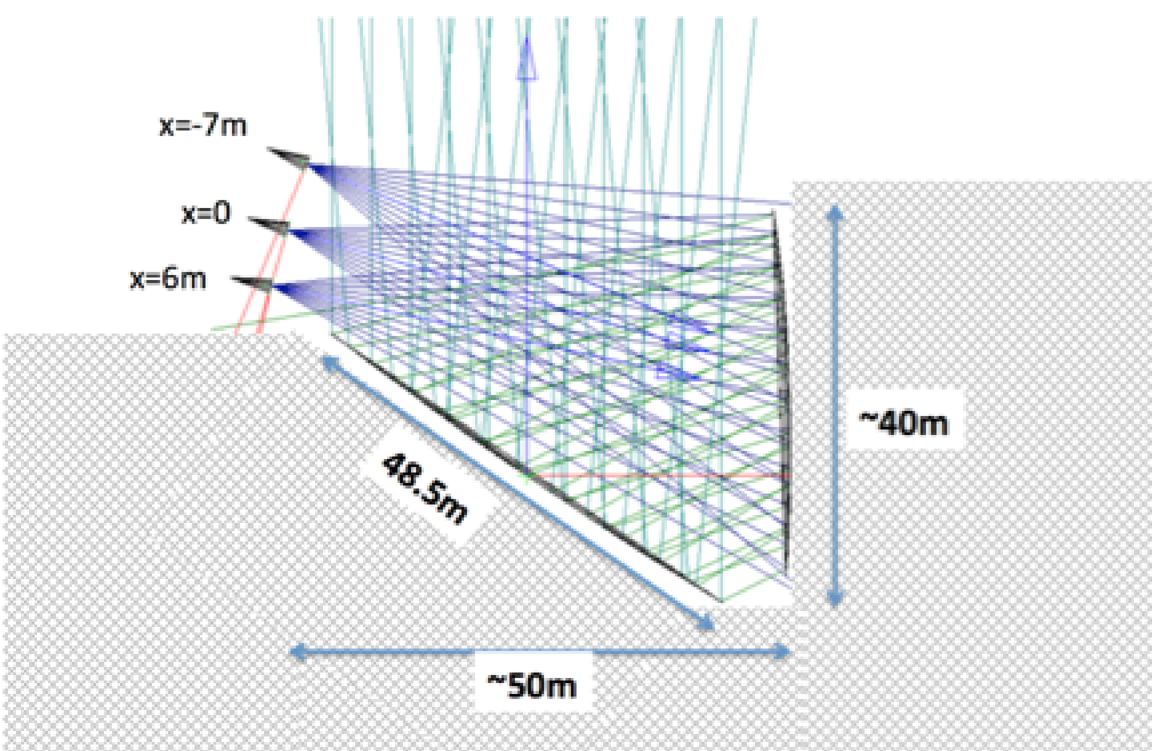
  - Produces long time-scale fluctuations of total-power (1/f noise)
  - larger noise level, stripes in the map…
- Perfect pseudo-correlation (e.g. WMAP/Planck) can remove 1/f noise
- Use an ‘active’ cold noise source, COLFET as reference

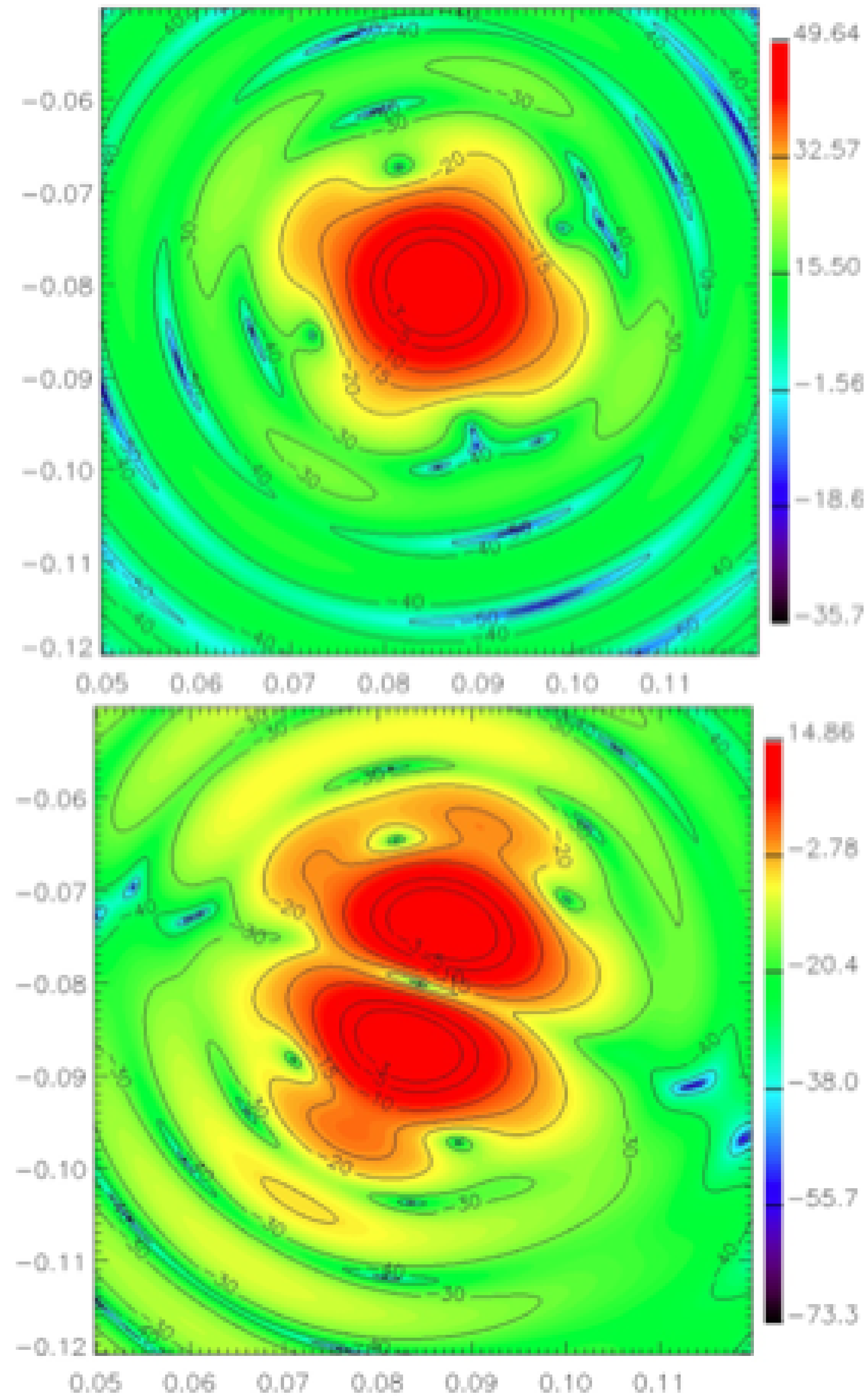
(Frater & Williams, 1981)

BINGO beams

Pixel Position	Forward Gain	Ellipticity	Peak X-Pol	FWHM
	dB		dB	arcmin
Centre	49.8	10^{-3}	-40	38
Edge	49.6	0.07	-35	39

- Careful optical design (Bruno Maffei)
- Beam must be well-known with minimal sideline and X-pol response
- New 2-dish compact antenna range design gives even better performance
  - Horn aperture diameter ~ 1.7m
  - Focal plane size to cover 10x10 deg ~ 14 x 14 m



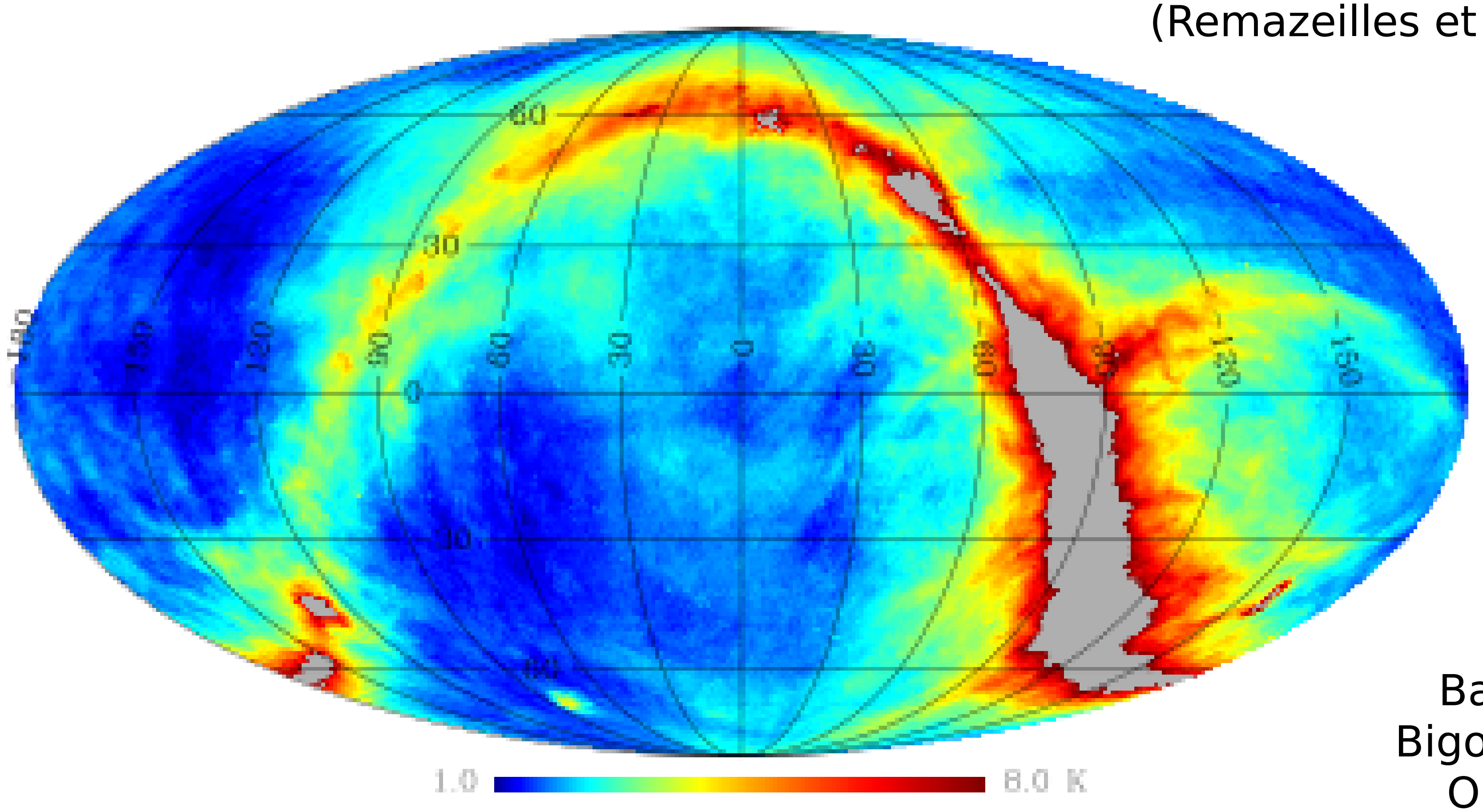


Battye et al. (2013)

Foreground contamination

- **Diffuse Galactic continuum** radiation - synchrotron and free-free radiation
- Spectrum expected to be smooth (should allow for it to be subtracted)
- Mean ~5K at 1 GHz
- Fluctuations on degree scales **~70mK**
- Note: HI signal ~ 0.1 mK !

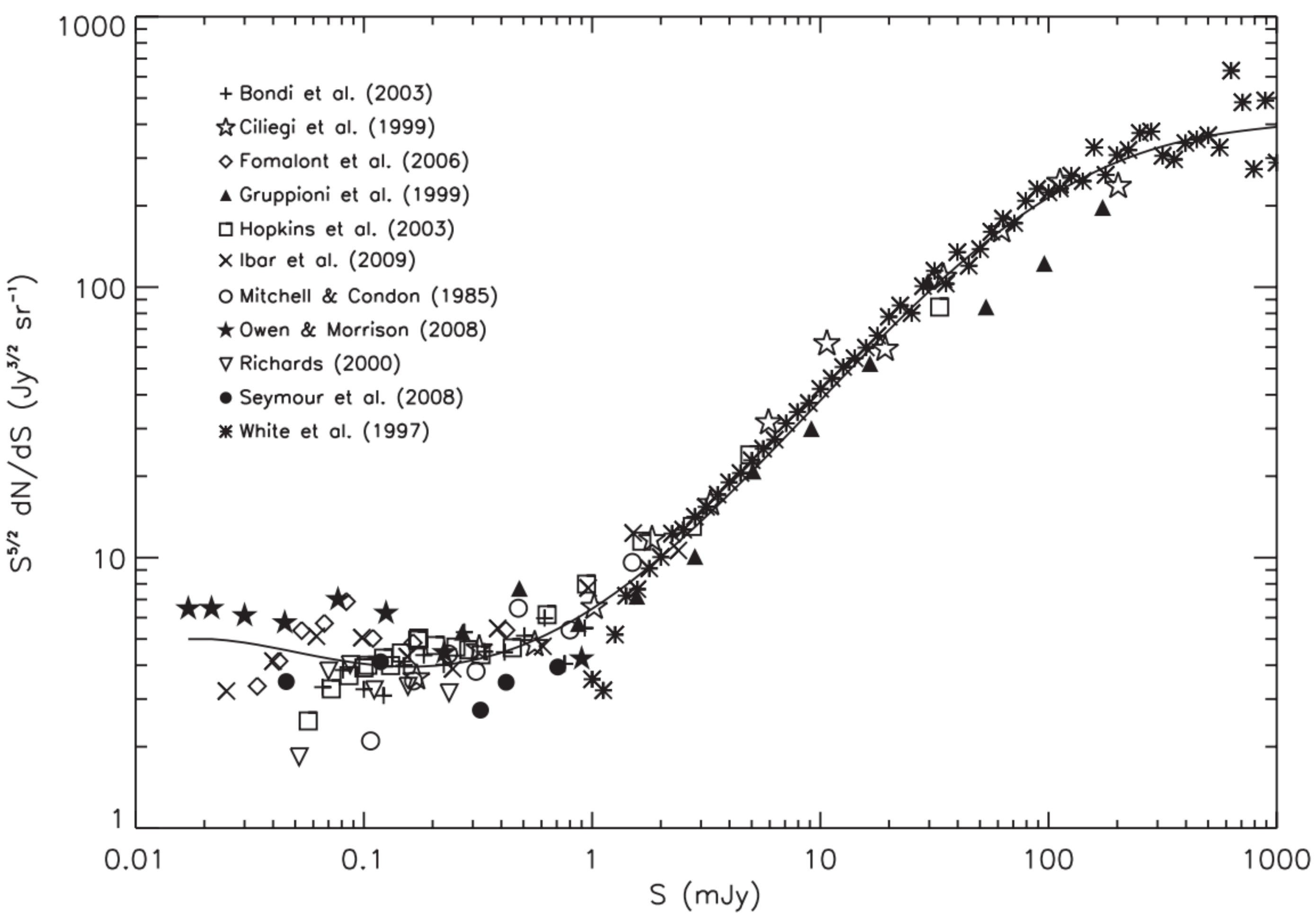
Improved 408 MHz Haslam map now available (Remazeilles et al. 2015)



Battye et al. (2013); Bigot-Sazy et al. (2015); Olivari et al. (2016)

Foreground contamination

- **Extragalactic point sources**
- 1.4 GHz source counts well known above ~1 mJy
- Not well known below this
- **ΔT~6 mK** from Poisson part
- Clustered sources at lower flux density may dominate on ~1 deg scales
  - NVSS: $w_l \sim 0.0048\, l^{-1.2}$
  - **ΔT~48 mK**



$$C_\ell^{\text{Poisson}} = \left(\frac{dB}{dT}\right)^{-2} \int_0^{S_{\text{cut}}} S^2 \frac{dN}{dS} dS$$

$$C_\ell^{\text{clustered}} = w_\ell \left(\frac{dB}{dT}\right)^{-2} \left(\int_0^{S_{\text{cut}}} S \frac{dN}{dS} dS\right)^2$$

Battye et al. (2013)

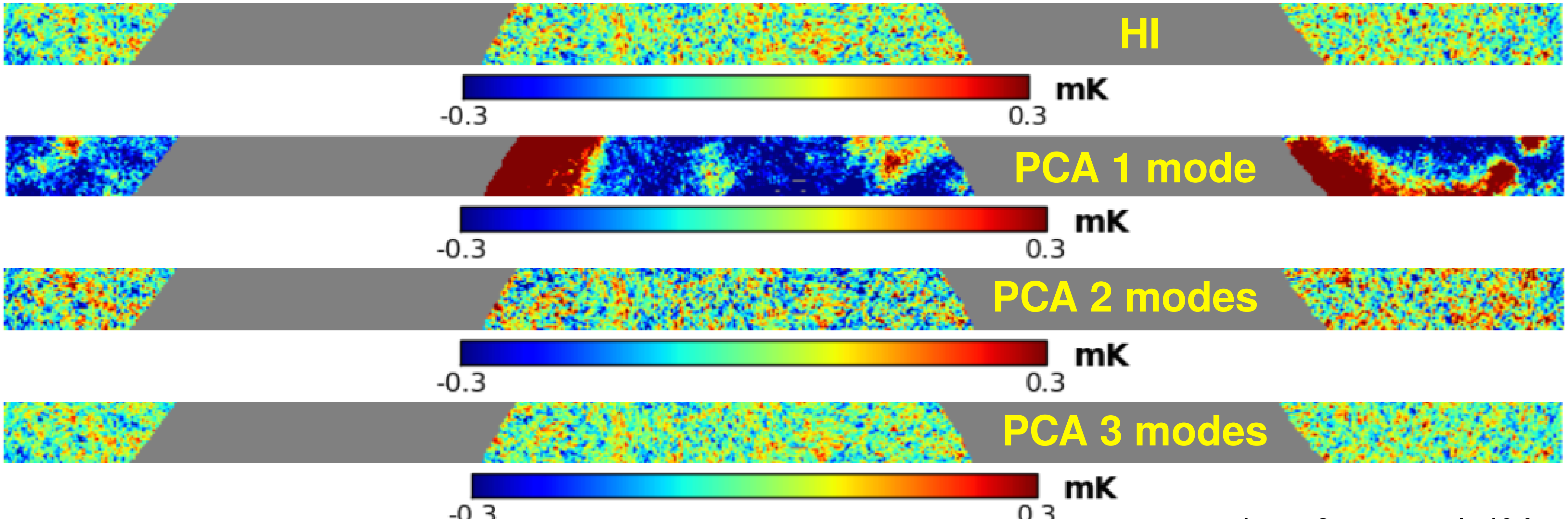
Foreground contamination

Foreground	$\bar{T}$ (mK)	δT (mK)	Notes
Synchrotron	1700	67	Power-law spectrum with $\beta \approx -2.7$.
Free–free	5.0	0.25	Power-law spectrum with $\beta \approx -2.1$.
Radio sources (Poisson)	–	5.5	Assuming removal of sources at $S > 10$ mJy.
Radio sources (clustered)	–	9.1	Assuming removal of sources at $S > 10$ mJy.
Extragalactic sources (total)	205	10.6	Combination of Poisson and clustered radio sources.
CMB	2726	0.07	Blackbody spectrum, ($\beta = 0$).
Thermal dust	–	$\sim 2 \times 10^{-6}$	Model of Finkbeiner, Davis & Schlegel (1999).
Spinning dust	–	$\sim 2 \times 10^{-3}$	Davies et al. (2006) and CNM model of Draine & Lazarian (1998).
RRL	0.05	3×10^{-3}	Hydrogen RRLs with $\Delta n = 1$.
Total foregrounds	$\sim$4600	$\sim$67	Total contribution assuming that the components are uncorrelated.
H I	$\sim$0.1	$\sim$0.1	Cosmological H I signal we are intending to detect.

Battye et al. (2013)

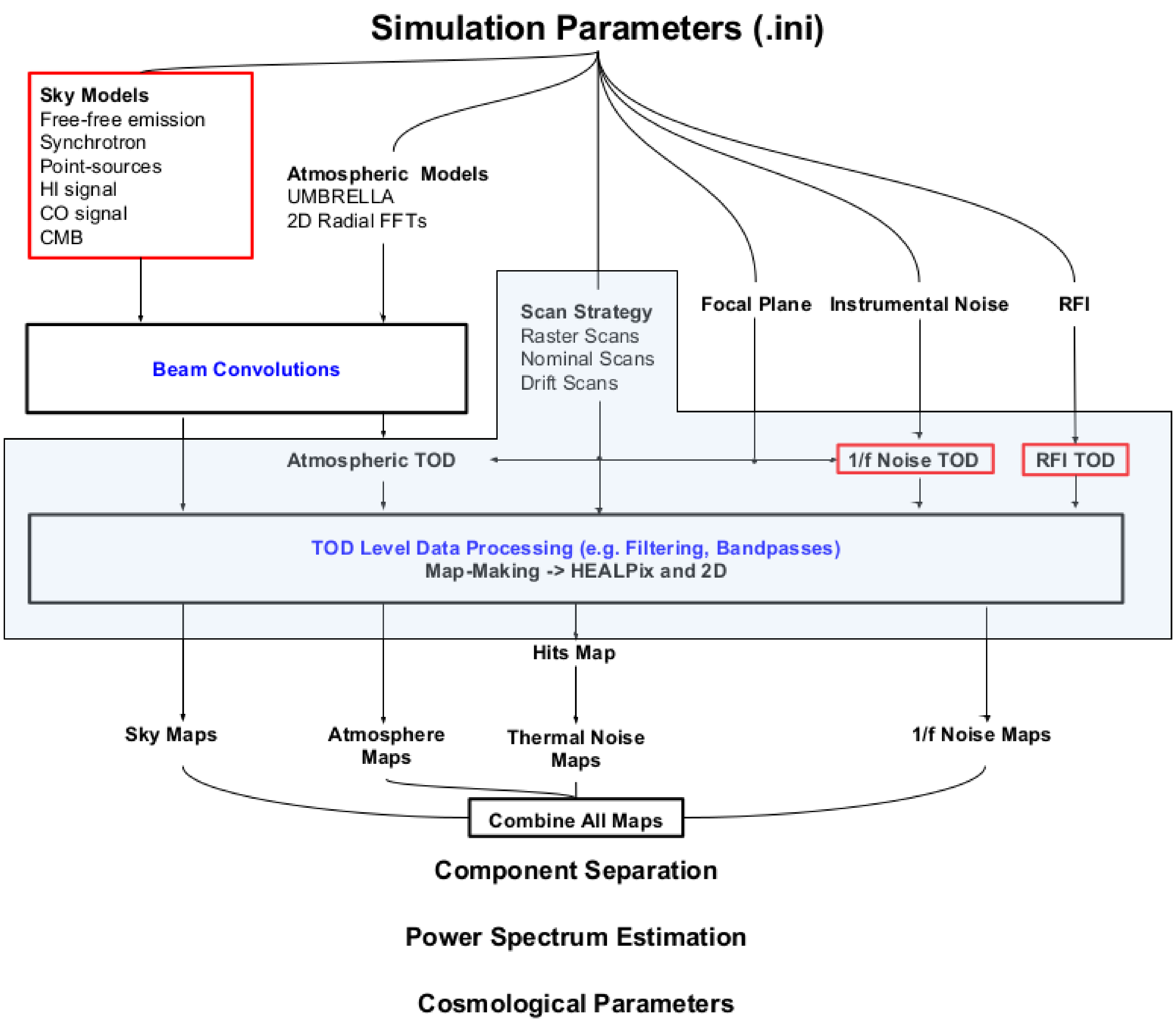
Component separation

- Dominant foregrounds are expected to be **spectrally very smooth**
- **HI signal fluctuates in frequency allowing for it to be extracted**
- Simple PCA can do a remarkable job by removing the first few eigenmodes of the frequency-frequency covariance matrix
  - BUT assumes calibration is *perfect*!
- ***Generalized Needlet internal Linear Combination* (GNILC): New method which uses frequency and spatial information → developed by Olivari et al., (2016)**



Bigot-Sazy et al. (2015)

Intensity Mapping Pipeline

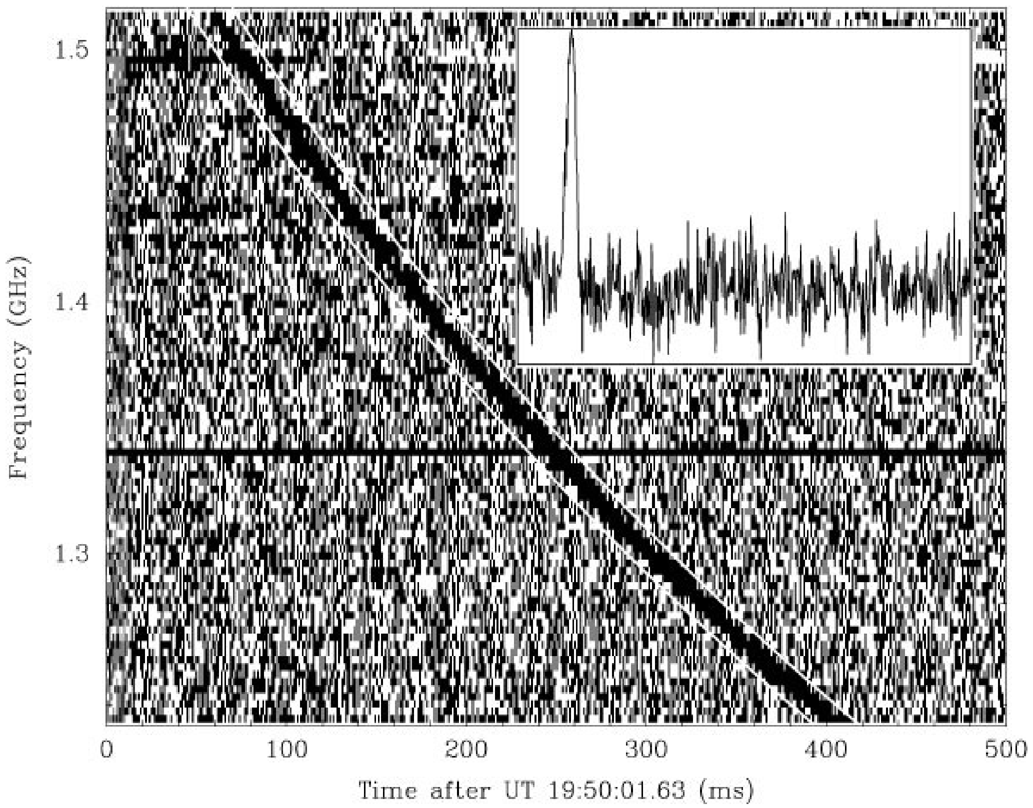


Additional science possibilities

Additional science with BINGO

- **1. BAOs and HI spectrum contain additional information**
  - Matter density, RSD, anisotropic BAOs, curvature, neutrino masses, non-Gaussianity, growth of structure…
  - Life history of hydrogen (Ω_{HI}, bias, T_{spin})
  - Cross-correlation with other LSS tracers (ISW, weak lensing…)

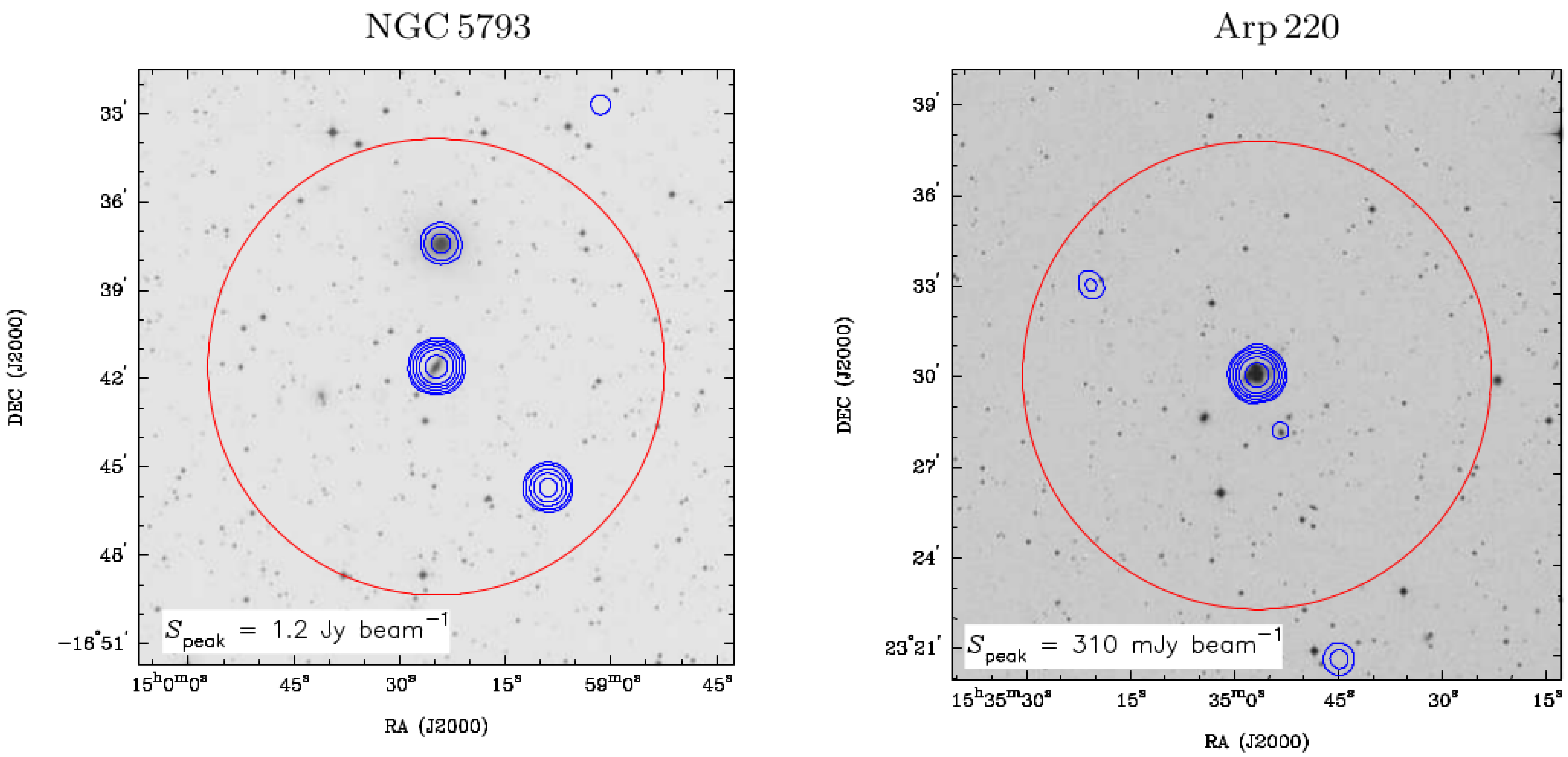
- **2. Fast Radio Bursts (FRBs/"Lorimer" bursts)**
  - New transient sources (~20 known)
  - Very bright but only last a few milliseconds!
  - First one localized recently (Chatterjee+ 2017)
  - BINGO is an ideal survey instrument (~1 detection/week estimated)
  - BINGO phase-3 : add outriggers to do accurate astrometry



Lorimer et al. (2007)

Additional science with BINGO

- **3. Associated HI absorption in selected continuum sources**
  - Allison et al. 2014 → from 4 **compact AGNs** and **nuclear starbursts** using shallow HIPASS survey with 15.5 arcmin beam
  - The HI cloud (~100 pc) covers the region having majority of the emission



  - BINGO: **sensitive** coverage of a large part of sky **upto higher z** → many such potential sources which would have otherwise been flagged
  - Any detection will be followed up by targeted interferometric observations

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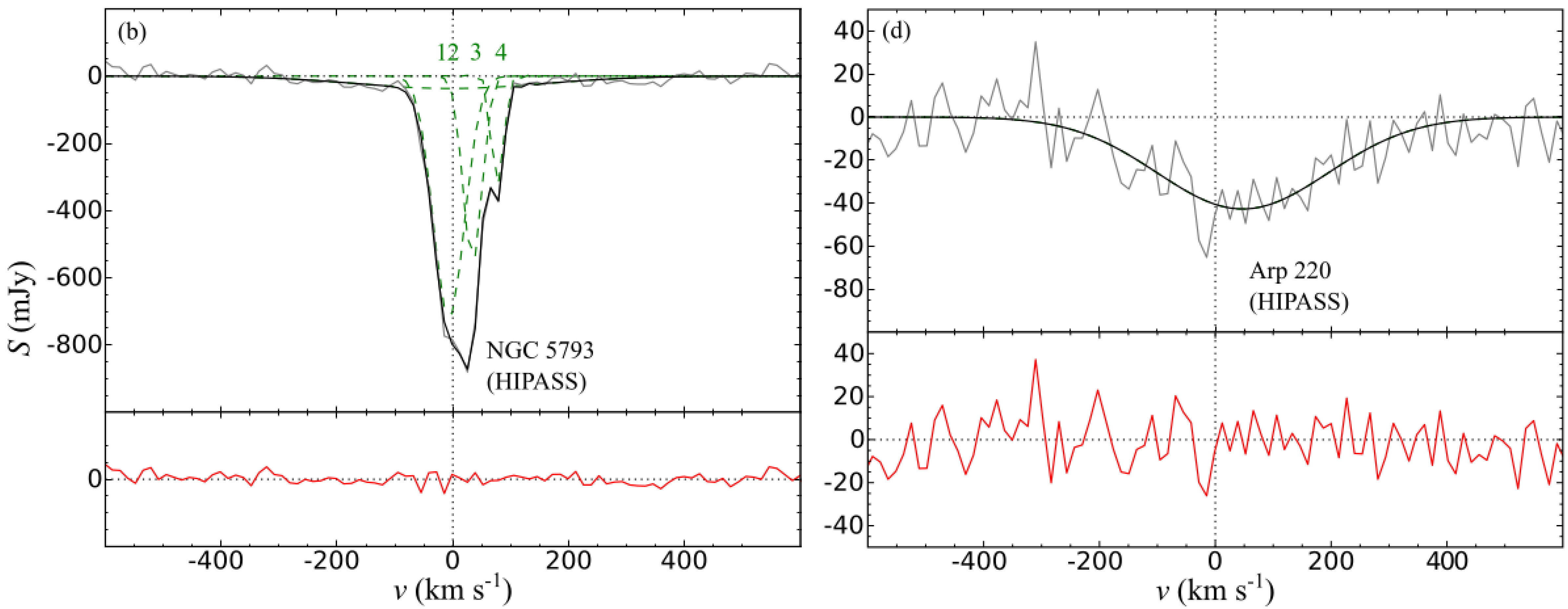

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Conclusions and project status

- **BINGO is a novel experiment to make an ultra-deep redshifted HI survey at z-0.1-0.5**
  - Much cheaper than large optical surveys (hardware ~$3M)
  - Complementary to optical galaxies/surveys
  - Test of HI intensity mapping technique
  - Pathfinder for SKA and future intensity mapping experiments
  - More data points on the BAO Hubble diagram → constrain cosmology
  - Deep large-area spectral radio survey will have many other benefits → suggestions regarding potential additional (HI) science very welcome!
- **We are basically ready to go!**
  - Good collaboration with wide range of expertise
  - Basic design ready
  - Hardware components and software techniques being tested
  - Good site identified with local support

- **Funding from FAPESP (Brazil) approved for ~$3M**
  - One year long Phase I started in December 2016