EoR/Cosmic Dawn SWG
Feedback on SKA1-Low Array Configuration

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CAASTRO ALL-SKY ASTROPHYSICS

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The University of Western Australia

Outline

SKA1 EoR/Cosmic Dawn program:

- Power spectrum z = 5.5 – 27
- Tomography (image cubes) z = 5.5 – 20

Proposed configurations:

- "Fixed" station size (BD-RBS)
- "Physical" substation/station/superstation (V4A)
- "Virtual" substation/ "physical" station/superstation (V4D)

Hybrid arrays:

- Benefits of forming baselines between different-sized stations

Suggested array design:

- Core: "sea-of-elements" *flexibility* to form *virtual substations*
- Core: maximal correlator capacity to *correlate full core sensitivity*
- Long baselines: *individual* stations (80-90% core sensitivity)

Summary and recommendations

- *Flexibility* is key for maximising science
- Correlator capacity can be pushed to optimise observational strategy
- Different observational setups are optimal for different experiments

Ionospheric analysis + EoR/CD analysis suggests an array with:

- maximal core sensitivity (80-90%)
- no long-baseline superstations (stations-only adequate for ionosphere)
- flexibility for forming custom virtual/physical substations (“sea of elements”*)
- V4A/BD hybrid with capacity to correlate full core

* Balance sensitivity loss due to packing problem with flexibility of “sea”

EoR/CD suite of experiments – stations (BD)

Power Spectrum

Shallow 2 beams

10,000 sq. deg = 4 sr; b>30 degrees; BW = 50-250 MHz
10 hours/field; drift scan; Δt = 5-10s; Δν = 5 kHz (averaged to 40-100kHz)
2,500 hours

Medium 2 beams

1,000 sq. deg; **b>20** degrees; **BW = 50-350 MHz**
100 hours/field; pointed; Δt = 5-10s; Δν = 5 kHz (40-100kHz)
2,500 hours

Deep

100 sq. deg; b>30 degrees; BW = 50-250 MHz
1000 hours/field; pointed; Δt = 5-10s; Δν = 5 kHz (40-100kHz) **2,500 hours**

Tomography

HI absorption

HI Forest: absorption line; targetted toward high-z continuum AGN
1000 hours**; Δν = 1 kHz; **50-350 MHz**

EoR/CD suite of experiments – substations (core: 1764 correlatable entities) – *reduce overall observing time*

Power Spectrum

Shallow
1 beam

10,000 sq. deg = 4 sr; b>30 degrees; BW = 50-250 MHz
40 hours/field; drift scan; Δt = 5-10s; Δν = 5 kHz (averaged to 40-100kHz)
2,000 hours

Medium
1 beams

1,000 sq. deg; **b>20** degrees; **BW = 50-350 MHz**
400 hours/field; pointed; Δt = 5-10s; Δν = 5 kHz (40-100kHz)
2,000 hours

Deep

100 sq. deg; b>30 degrees; BW = 50-250 MHz
4000 hours/field; pointed; Δt = 5-10s; Δν = 5 kHz (40-100kHz) **2,000 hours**

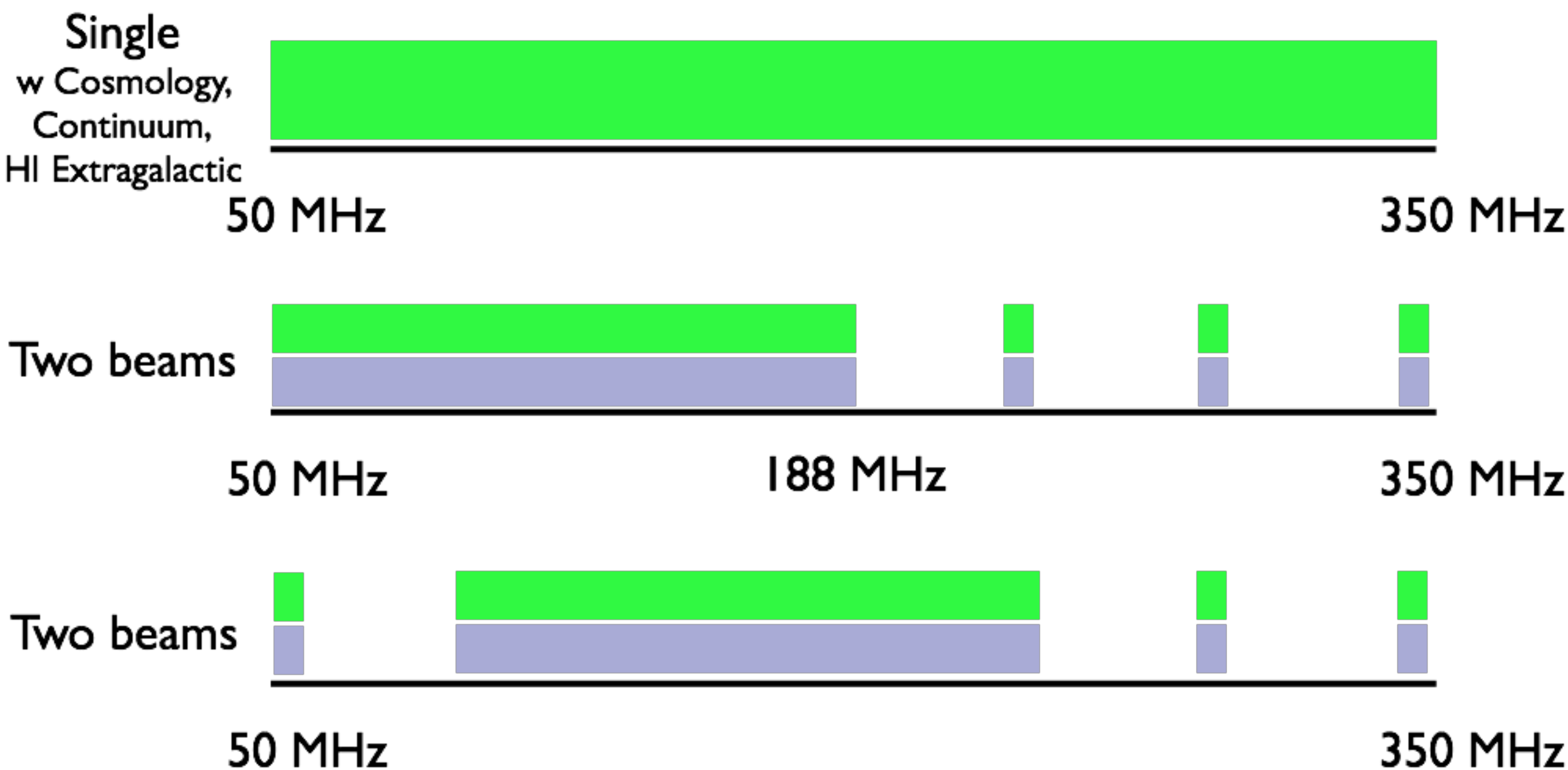
Tomography

HI absorption

HI Forest: absorption line; targetted toward high-z continuum AGN
4000 hours**; Δν = 1 kHz; **50-350 MHz**

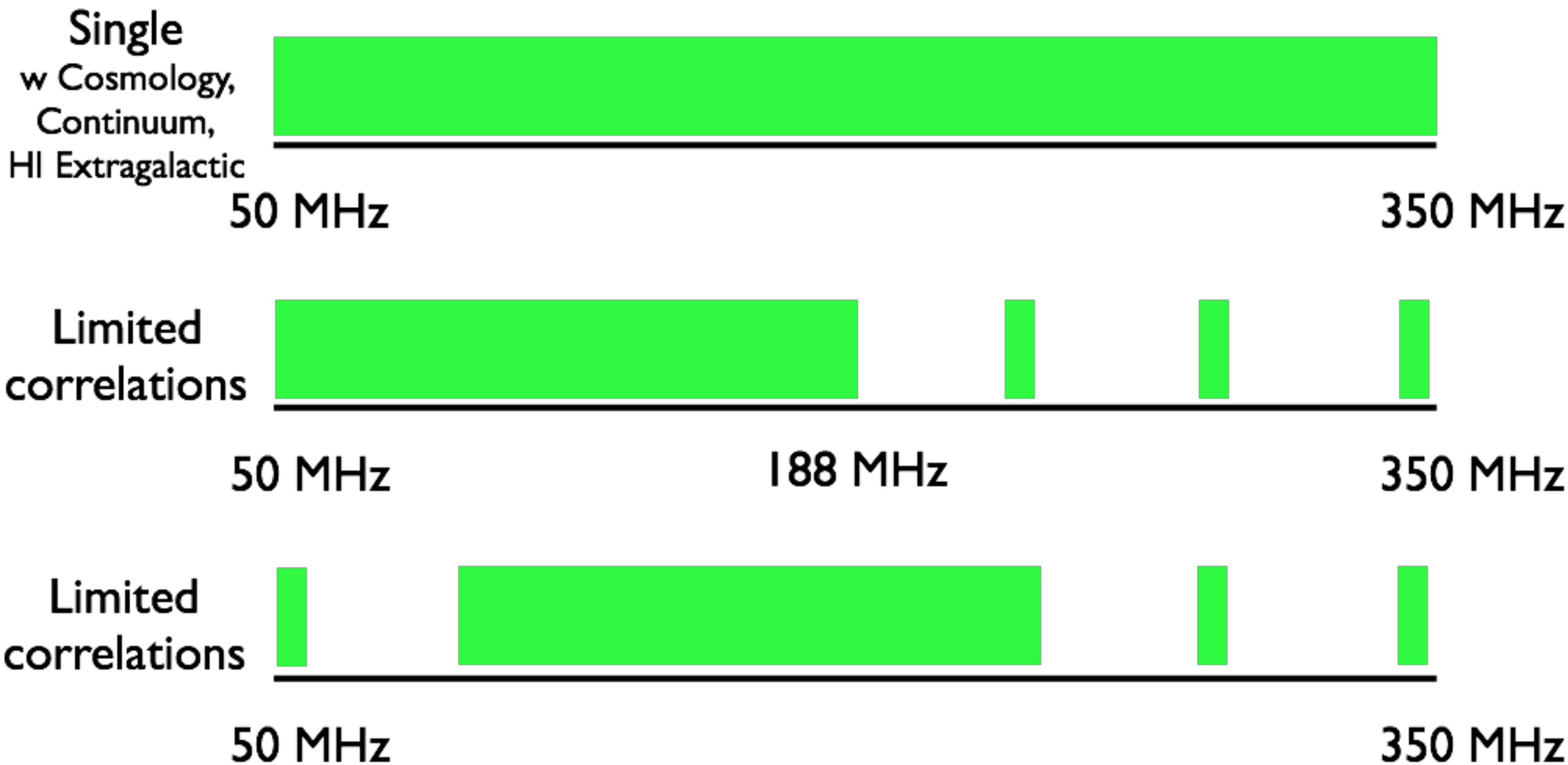
EoR/CD frequency coverage - Stockholm

Flexibility in assigning correlator



EoR/CD frequency coverage - flexible

Flexibility in assigning correlator



Reducing bandwidth can offset reduction in sensitivity for substations if correlator capacity is limited

Summary of results – power spectrum

See Andrei's talk for deeper analysis and EoR *physics* implications

- Sample variance significantly reduced with availability of substations ($r \approx 10$m) at a large range of redshifts, compared with BD-RBS
- Sample variance limited for $z \leq 18$ at small k
- Thermal noise limited for $z \geq 18$ at small k (Cosmic Dawn)
- Thermal noise limited at large k for all redshifts

- Sample variance unchanged for physical versus virtual substations (V4A/V4D)
- Thermal noise worse for virtual substations: packing problem
- For Cosmic Dawn, microflowers better than virtual substations (V4A optimal; V4D good; BD-RBS sub-optimal)

ASSUMES CORRELATION OF FULL CORE SUBSTATIONS

Summary of results – tomography

- Thermal noise independent of station size, *for same collecting area, filling factor and spatial scale*
- Smaller stations = larger FOV → useful for matching to bubble sizes at low redshift
- $z > 9$, $r_{bubble} \approx 1$ Mpc (comoving) ≈ 20 arcsec (30m FOV = 4 deg.)
- $z \approx 6$, $r_{bubble} \approx 100$ Mpc (comoving) ≈ 1 degree (30m FOV = 2.5 deg.)
- BD-RBS okay across most redshifts, but too small at z=5-6
- V4A optimal for full sensitivity: use stations for z>9, use substations for z<7
- V4D okay, but loss of sensitivity (packing problem) impacts noise floor → not likely a problem at low z where sensitivity is good
- (V4A optimal; V4D very good; BD-RBS sub-optimal)

ASSUMES CORRELATION OF FULL CORE SUBSTATIONS

Power spectrum – noise considerations

- Sample variance determined by number of measurements of a given mode in the observation volume: bigger FOV = less sample variance
- Sample variance scales as: $\Delta^2 \propto D$
- Thermal noise scales as:

$$\Delta^2 \propto D$$

  - Therefore, for *constant collecting area* and core size

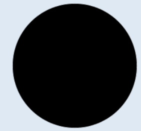
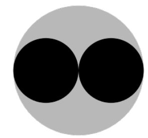
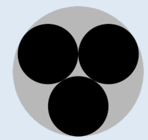
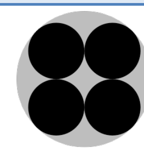
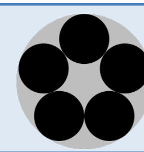
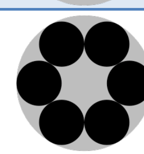
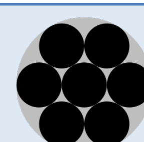
$$\Delta^2 \propto \sqrt{A_{eff}}$$

  - *Smaller stations are better for sample variance and thermal noise, assuming no loss in sensitivity*

Power spectrum – packing problem

- V4A allows full sensitivity to be retained for substations. V4D suffers from the "packing problem": fitting small circles optimally into a larger circle

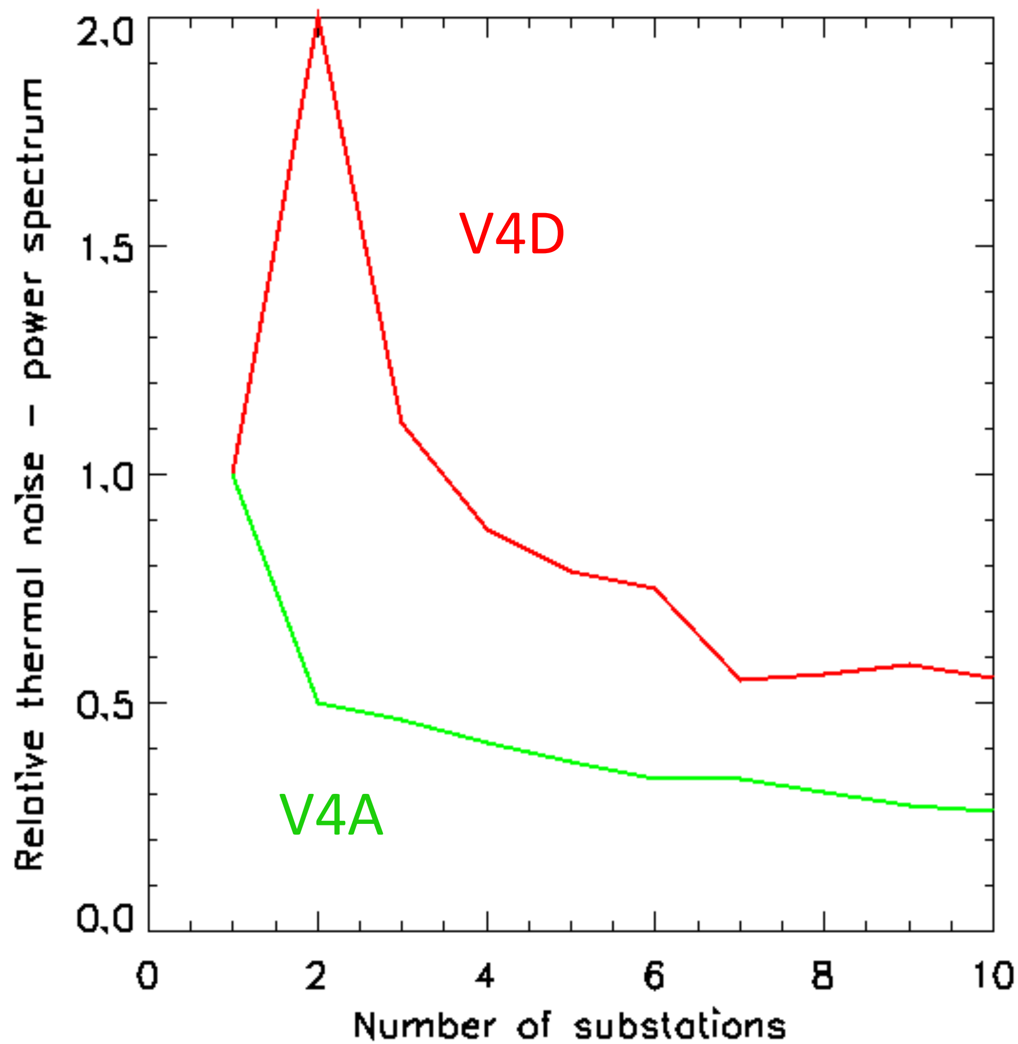
Power spectrum – packing problem

# circles	Radius (cf unity)	Density	Optimal configuration	Δ^2 (V4A)	Δ^2 (V4D)
1	1	1		1	1
2	0.5	0.5		0.5	2
3	0.46	0.65		0.46	1.11
4	0.41	0.69		0.41	0.88
5	0.37	0.69		0.37	0.79
6	0.33	0.67		0.33	0.55
7	0.33	0.78		0.33	0.56

Power spectrum – packing problem

Thermal noise relative to a full station:
V4A
V4D

-> Factor of ~2 worse performance for V4D **with full core sensitivity**



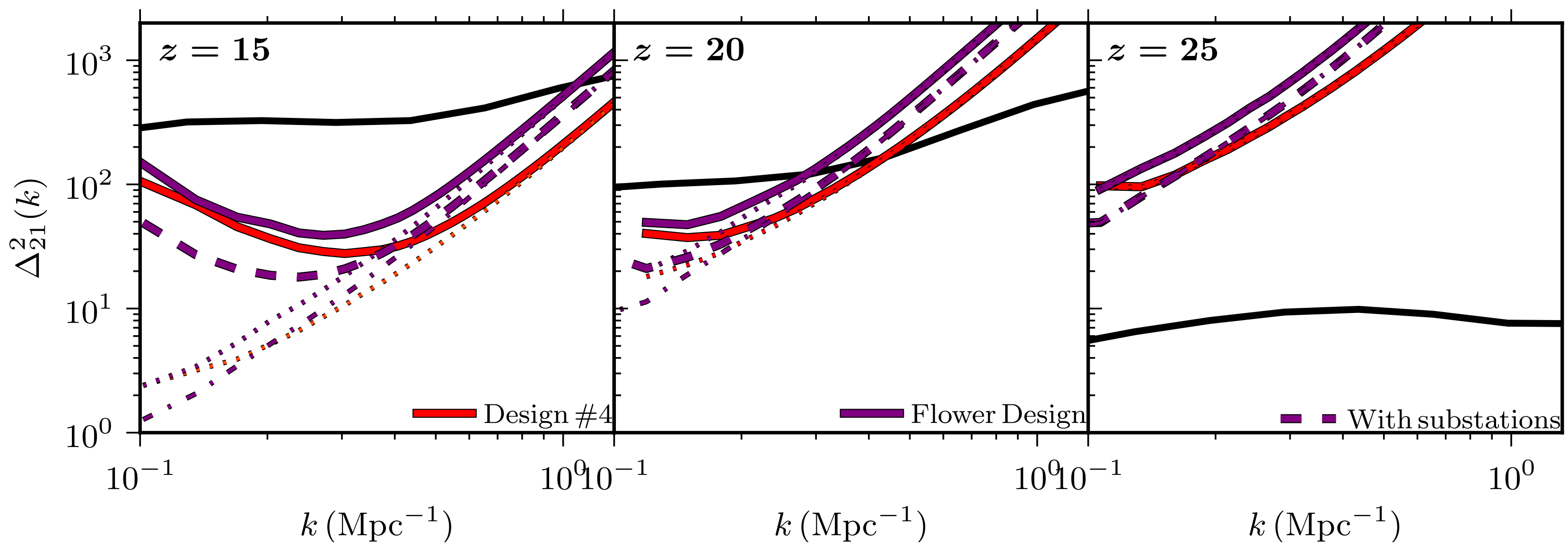
Correlation versus sample variance balance

- If we choose to beamform stations with R<27m, how many can we beamform? What are the correlator limitations?

  6 substations per station:

Design name	Configuration	Core **substations**	Sensitivity retained
Flower design (V4D)	49 core + 36 outer superstations	No substations; 27m stations	100%
Substations (V4A)	49 core + 0 outer superstations	49x6x6 = 1764	100%
"Design A"	14.2 core + 0 outer superstations	512	29%
"Design B"	8.2 core + 36 outer superstations	296	17%

Power spectrum – sensitivity – "high" z



Sensitivity curves courtesy of Brad Greig

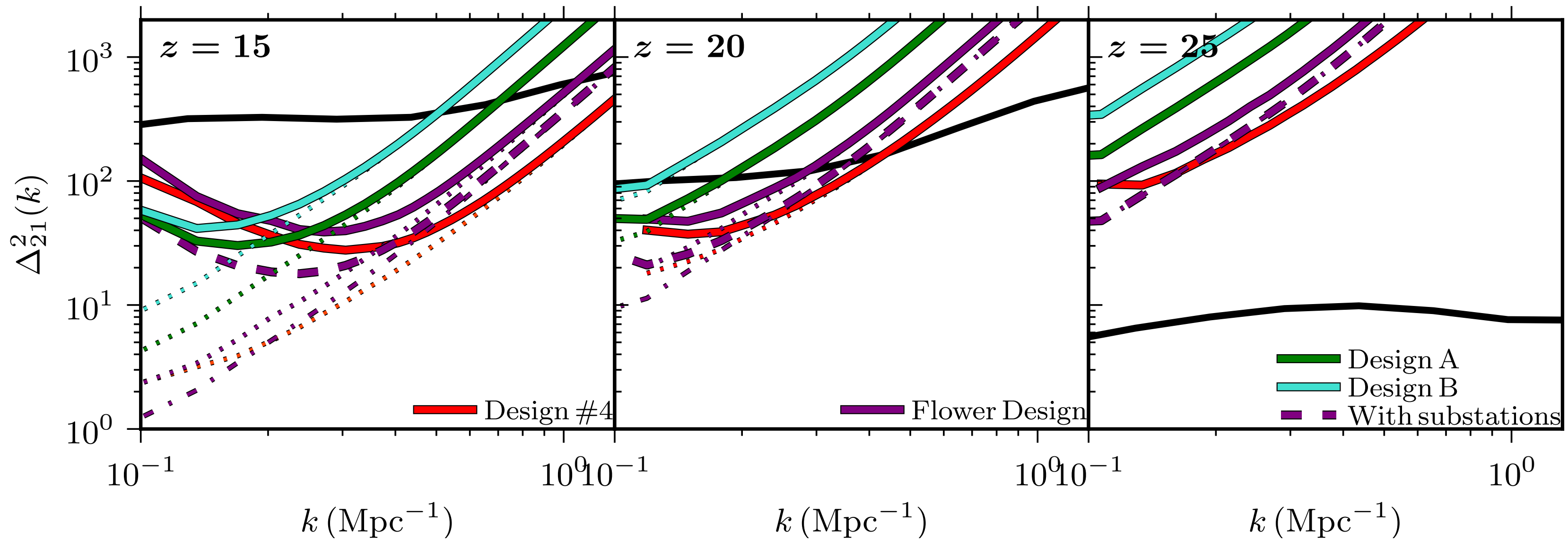
****See Andrei's talk for deeper analysis****

ASSUMPTIONS: Full correlation of core stations or substations

Sample variance reduced for substations for z < 20

Thermal noise slightly reduced (when full sensitivity retained)

Power spectrum – sensitivity – "high" z



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ASSUMPTIONS: Correlation of 512 core substations (reduced sensitivity – DESIGN A)
Correlation of 296 core substations + 36*6 outer (DESIGN B)

Sample variance reduced for substations

Thermal noise reduced

Power spectrum – conclusions

Array	Comment	Ranking
BD - RBS	Physical 30m stations with no substation capability sub-optimal for sample variance reduction	3/3
V4A	Full sensitivity with substations**	1/3 - Best
V4D	Reduced sensitivity *with substations***	2/3

** **Assumes full correlation of core substations. See Andrei's talk for breakeven**

→ **Can recover loss of sensitivity by reducing BW and increasing #correlations**

Tomography – noise considerations

- Confusion noise not an issue for a spectral line experiment. Purely FOV and thermal noise

- Thermal noise (brightness temperature sensitivity) scales as collecting area, filling factor for the same spatial scale
  - -> station size not dominant for noise level
- FOV determined by station size: smaller stations = larger FOV
  - When might we need a larger FOV? Do not want to match FOV to bubble size → primary beams not uniform. Want to be well-sampled within main lobe. Short baselines are relevant.

- V4D with substations worse sensitivity than V4A (packing problem)

Tomography – FOV

Frequency	30m stations FOV	10m substations FOV	Redshift, z	Bubble size
50 MHz	11°	34°	27.4	20”
100 MHz	5.7°	17°	13.2	20”
150 MHz	3.8°	11°	8.5	30”
200 MHz	**2.9°**	8.6°	6.1	**0.5° - 1°**
220 MHz	**2.6°**	7.8°	5.5	**2° - 3°**

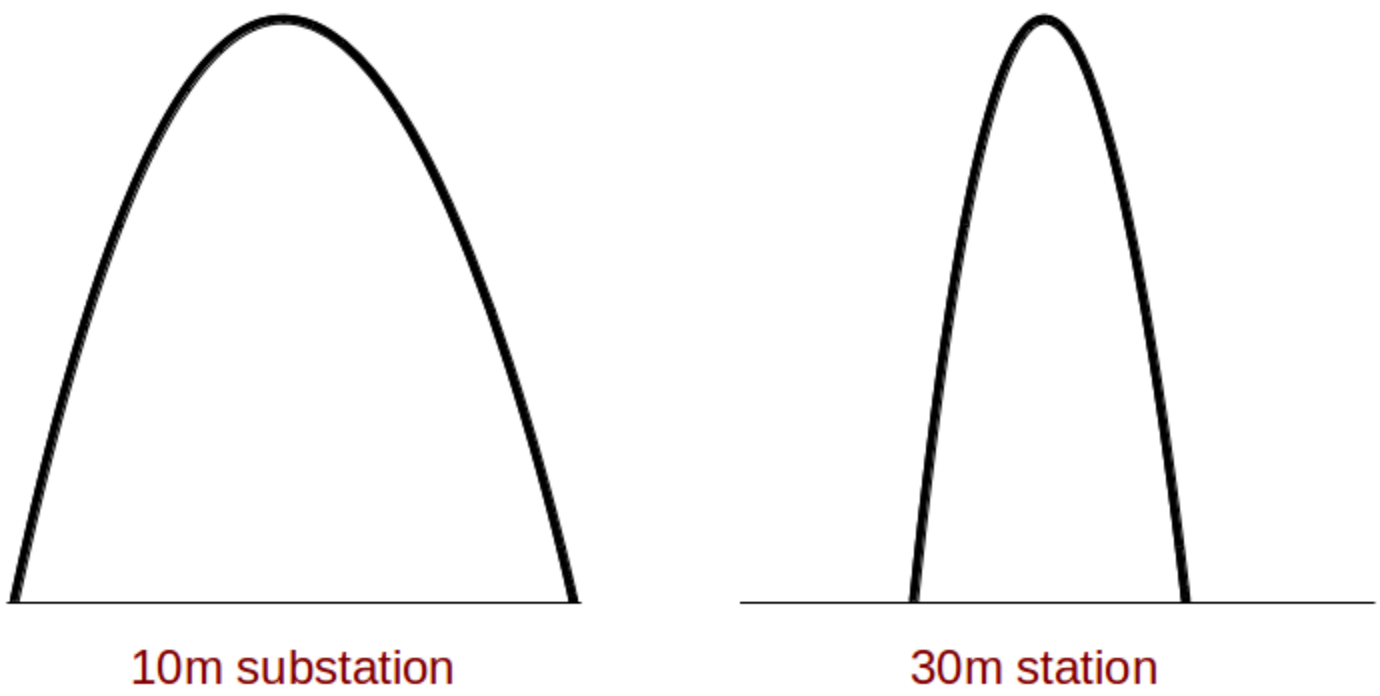
Low redshift bubbles potentially constrained by station primary beam for 30m stations

Tomography – conclusions

Array	Comment	Ranking
BD - RBS	Physical 30m stations with no substation capability sub-optimal for low z imaging	3/3
V4A	Full sensitivity with substations for FOV	1/3 - Best
V4D	Reduced sensitivity with substations potentially limiting accessible z	2/3

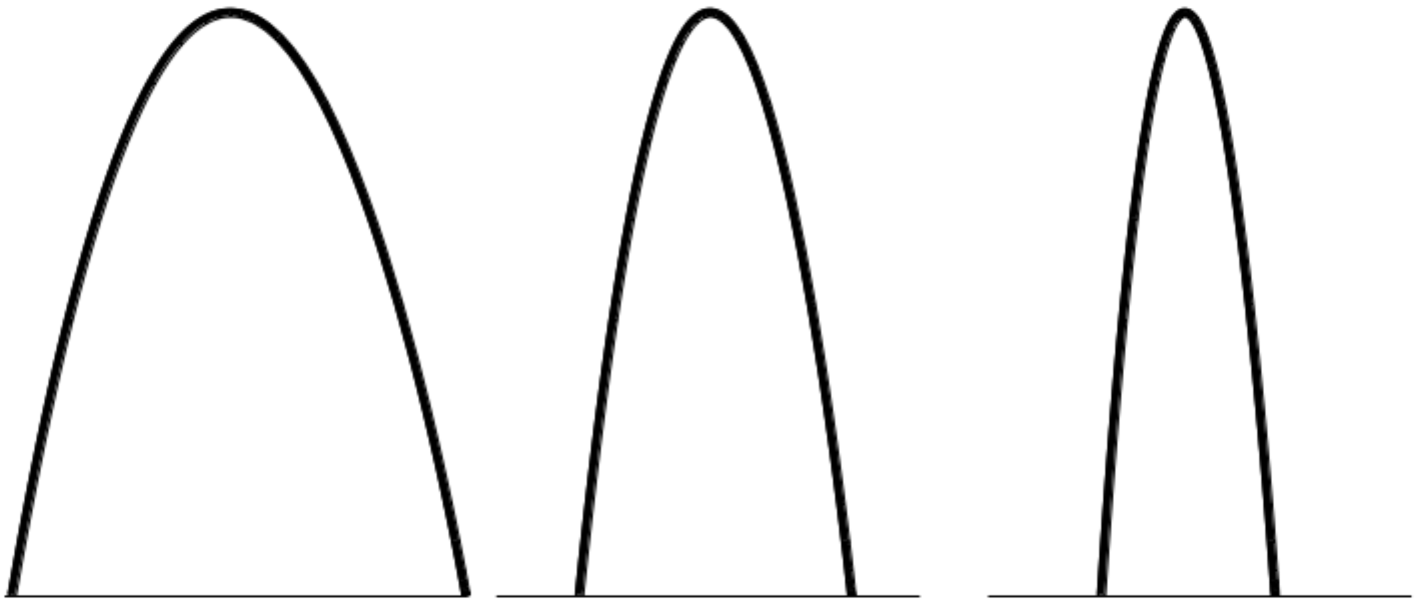
Hybrid station sizes – illumination patterns

Station illumination patterns: D(θ)



Hybrid station sizes – primary beam

Primary beam shapes: $B(\theta) = D_1(\theta).D_2(\theta)$

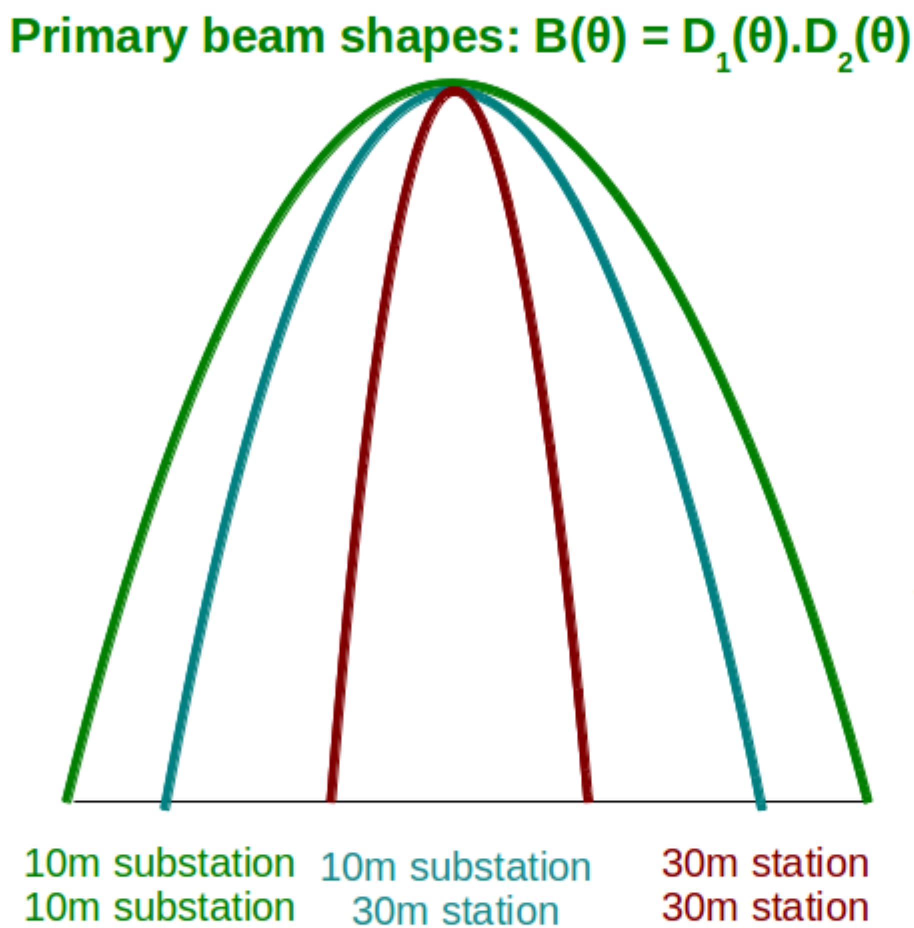


10m substation
10m substation

10m substation
30m station

30m station
30m station

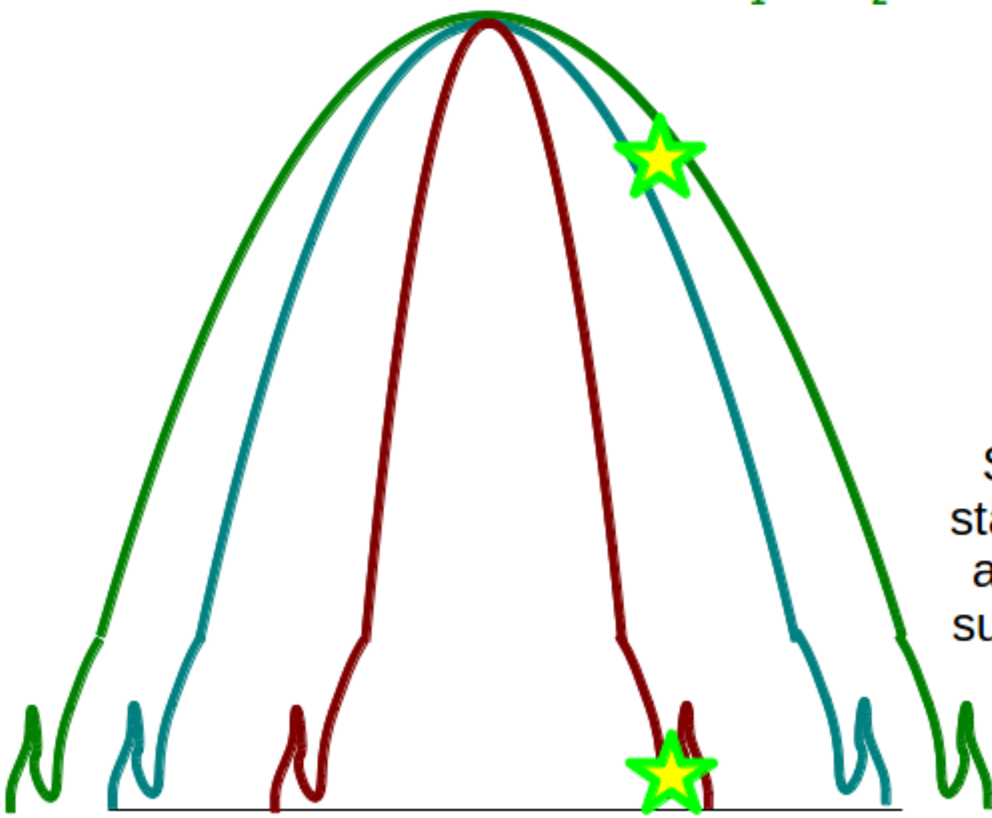
Hybrid station sizes – attenuated sources



Sources in sidelobe of station-station images in main lobe of substation-substation images → calibration with same ionosphere, instrument conditions

Hybrid station sizes – sources in nulls

Primary beam shapes: $B(\theta) = D_1(\theta).D_2(\theta)$



10m substation
10m substation

10m substation
30m station

30m station
30m station

Sources in nulls of station-station beams are well-sampled in substation-substation beams

Hybrid station sizes – very useful

- Availability of multiple station sizes for cross-correlation allows a degree of **flexibility** that is useful for **calibration and science**
- **Calibration**: sidelobe sources characterised with same ionosphere, RFI, environmental conditions
- **EoR/CD science**: foreground model measured with large FOV. Science with smaller FOV. Short baselines constrain diffuse structure.

CONCLUSIONS

- Availability of multiple station sizes for cross-correlation allows a degree of **flexibility** that is useful for **calibration and science**
- **Calibration**: sidelobe sources characterised with same ionosphere, RFI, environmental conditions
- **Ionosphere:** adequate calibration with fewer stations outside core
- **EoR/CD science**: foreground model measured with large FOV. Science with smaller FOV. Short baselines constrain diffuse structure.

OVERALL RECOMMENDATIONS:

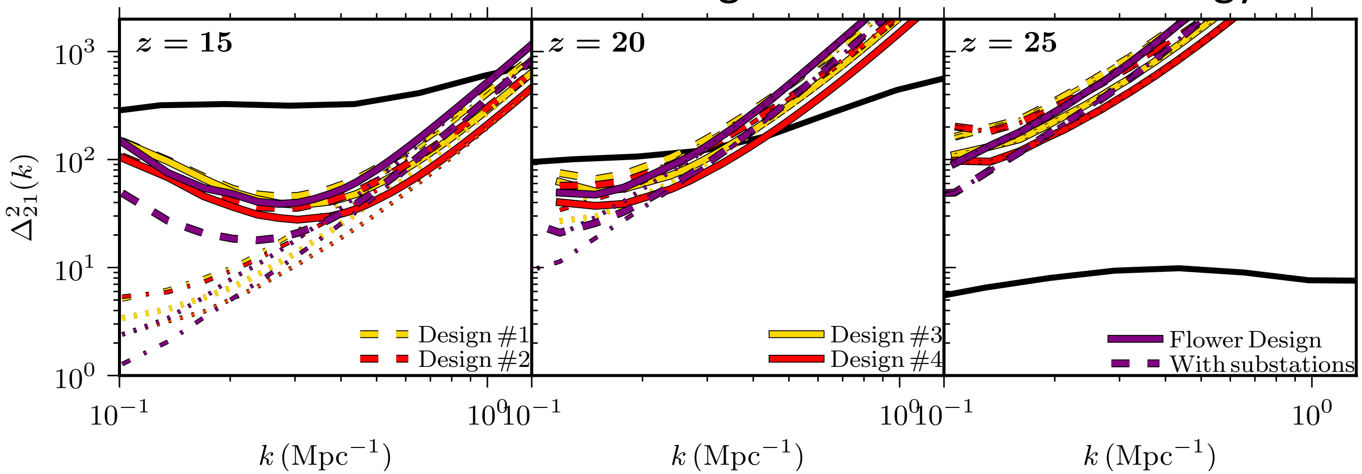
- Flexibility is key for maximising science
- Correlator capacity can be pushed to optimise observational strategy
- Different observational setups are optimal for different experiments

Supporting material: power spectra

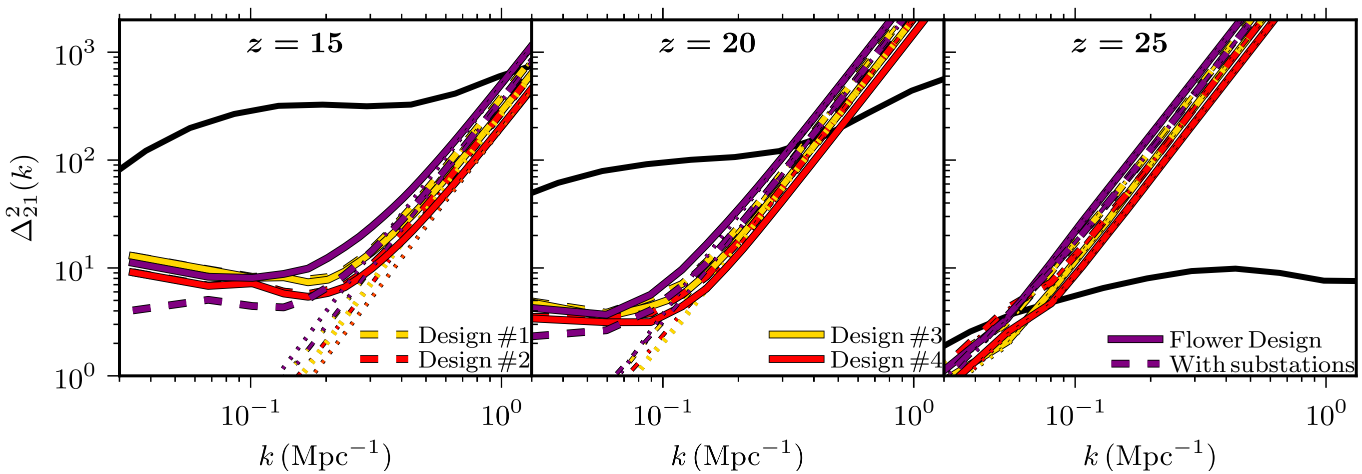
Sensitivity curves courtesy of Brad Greig

Power spectrum – sensitivity – "high" z

Faint galaxies contribute to Reionisation + "foreground avoidance" strategy



Faint galaxies contribute to Reionisation + "foreground subtraction" strategy



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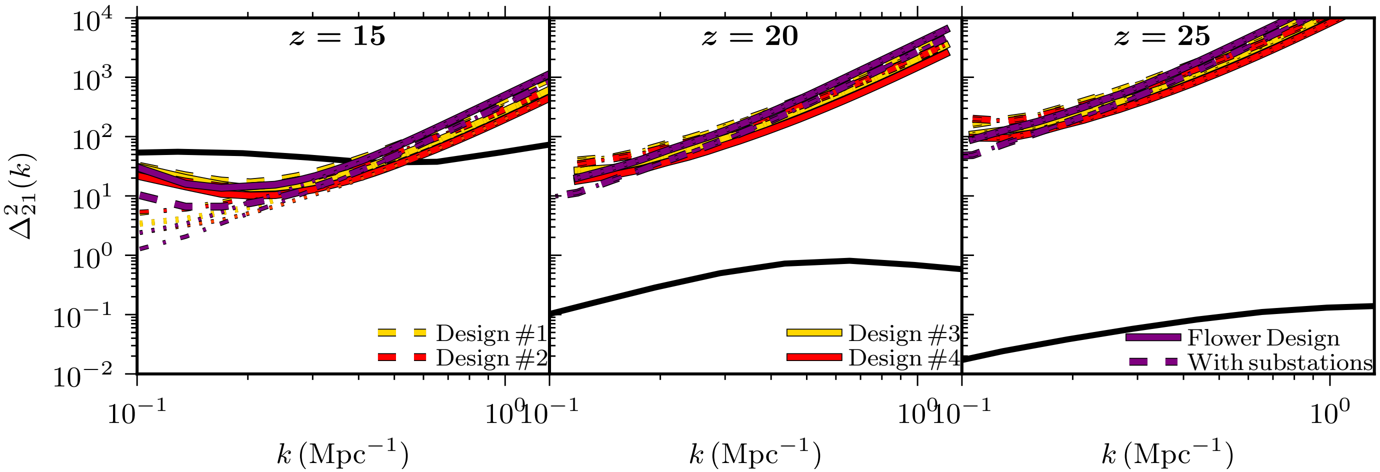
Power spectrum – sensitivity – “high” z

Bright galaxies contribute to Reionisation + “foreground avoidance” strategy



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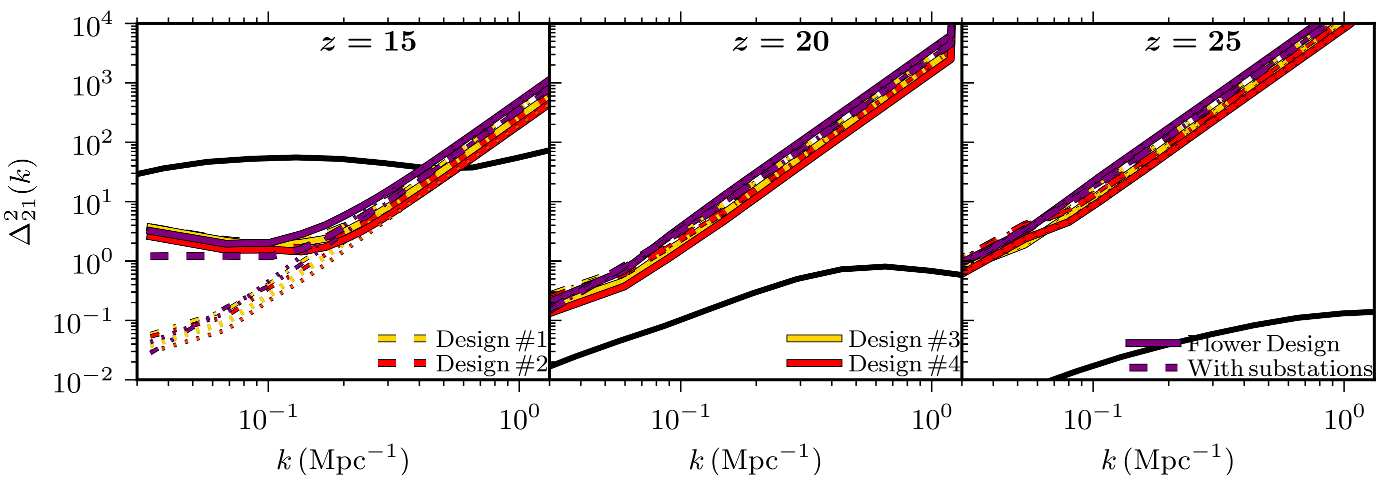

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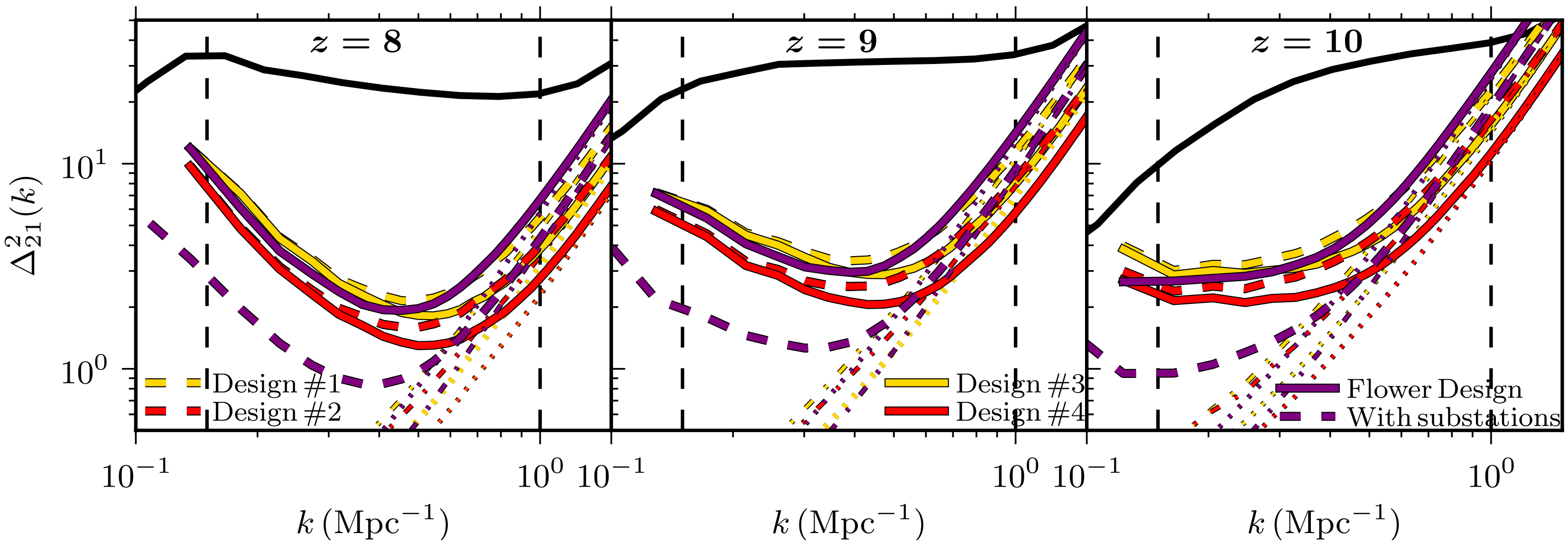
Power spectrum – sensitivity – "low" z



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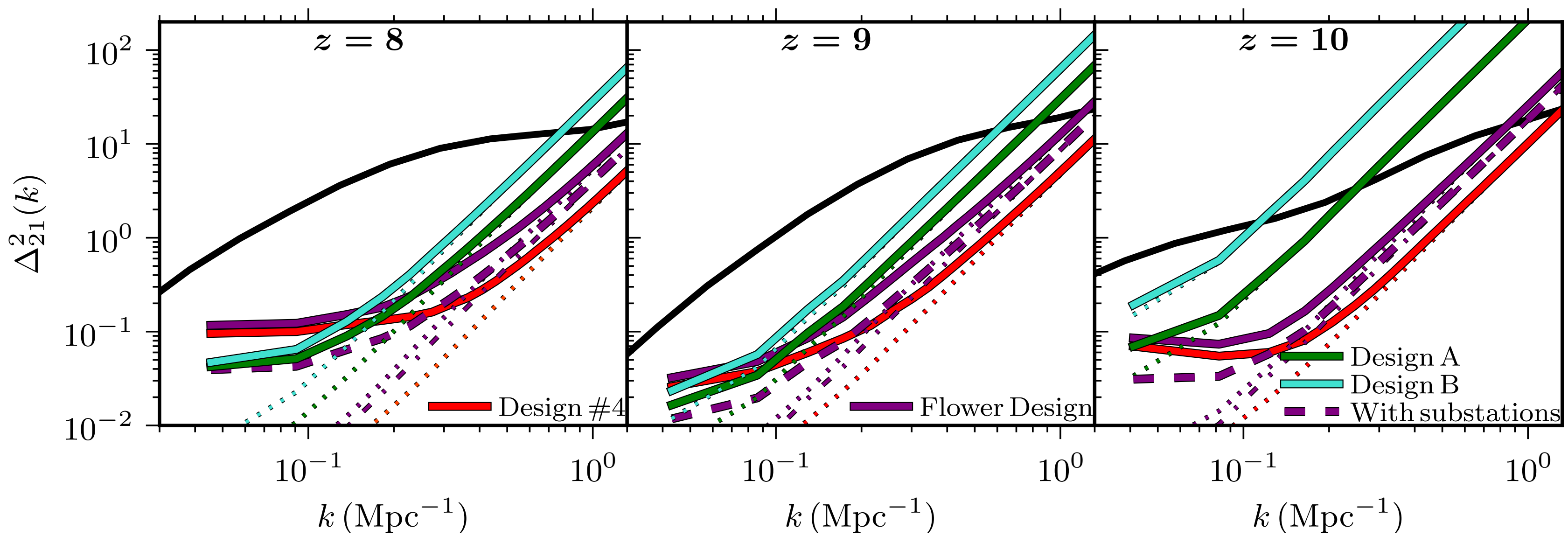
****See Andrei's talk for deeper analysis****

ASSUMPTIONS: Full correlation of core stations or substations

Sample variance reduced when beamforming substations

Thermal noise slightly reduced (when full sensitivity retained)

Power spectrum – sensitivity – "low" z



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