Mapping the Observable Universe with 21cm

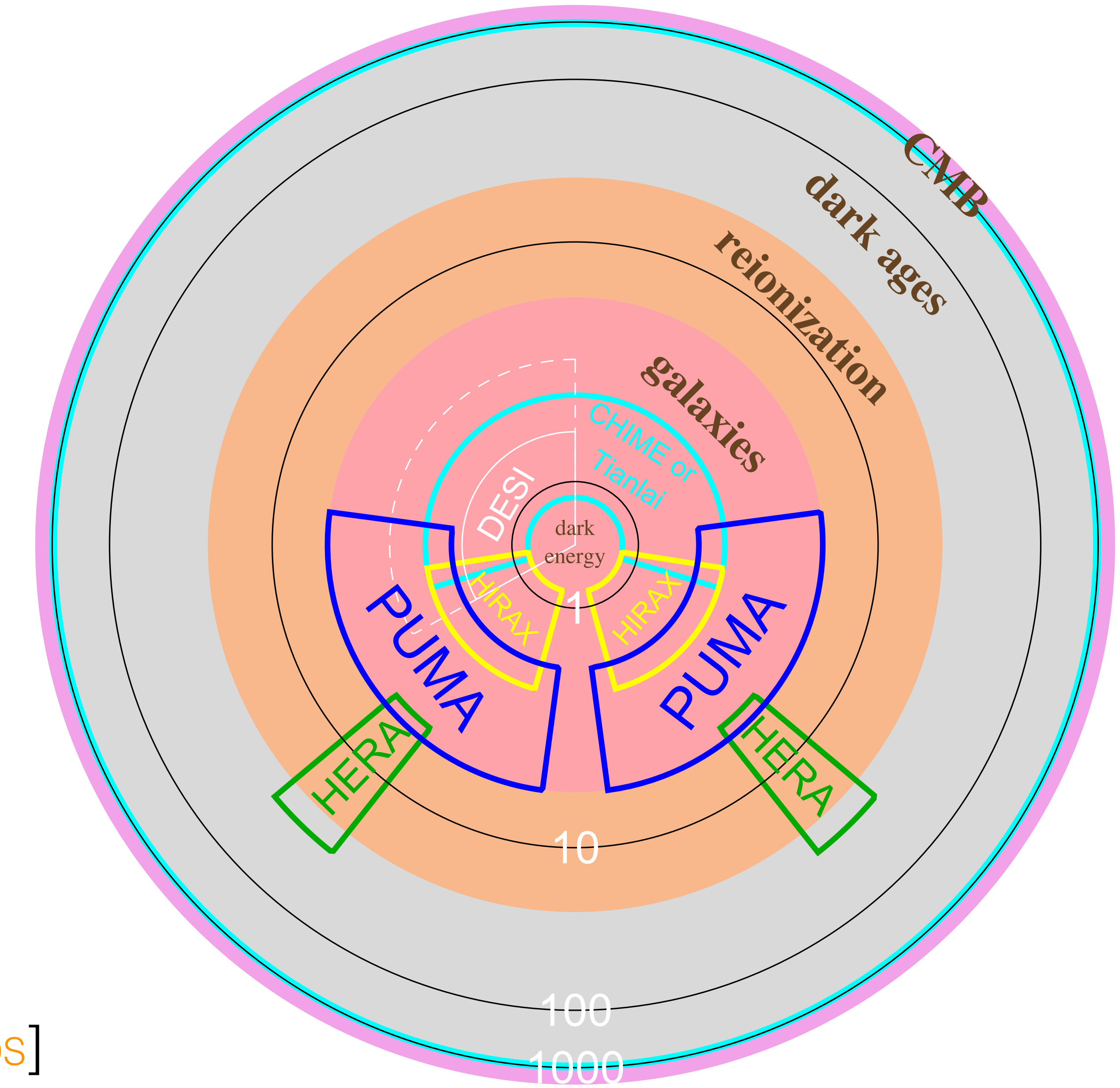
Albert Stebbins
Fermilab

CoSyNe - Institut d'Astrophysique de Paris
2019-12-11

Cosmic Cartography

area ∝ volume

- parameter accuracy ~ $n_{mode}^{-1/2}$
- n_{mode} ~ volume



2D: CMB [SPT/ACT/S4]

large area galaxy imaging/spectroscopy

2D: single band imaging [APM]

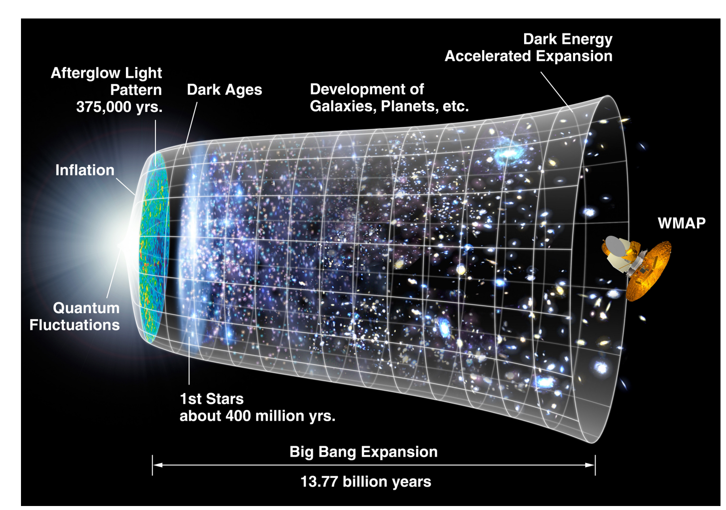
2D+: + multi-band photo-z's [DES/LSST]

3D-: + lo-res spectroscopy [PAU/JPAS/SphereX/MKIDS]

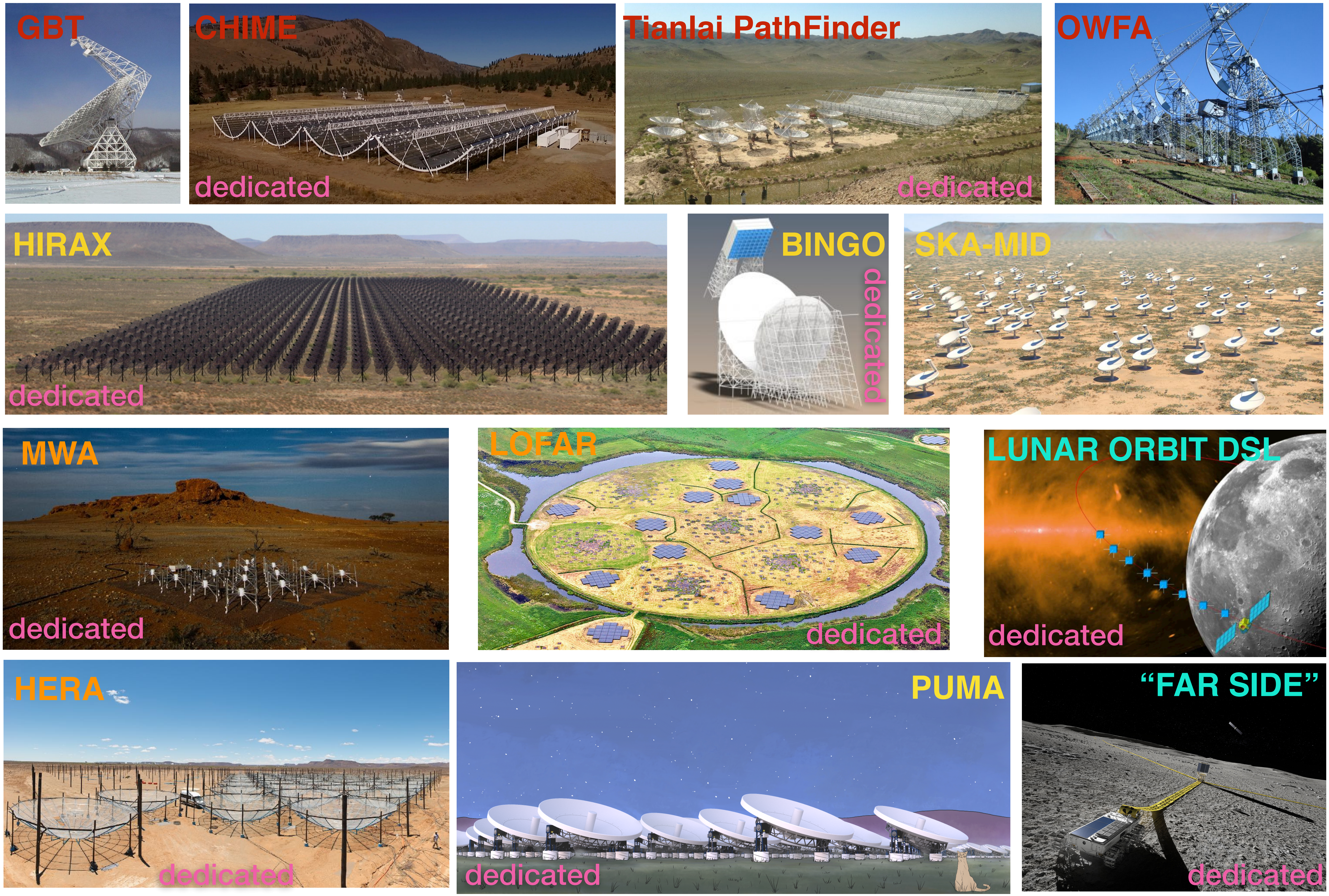
3D: + hi-res spectroscopy [APM/SDSS/DESI/4MOST/Euclid/WFIRST]

intensity imaging of galaxies/LSS

3D: + hi-res HydrogenIntensityMapping [CHIME/Tianlai/HIRAX/BINGO/SKA/PUMA]

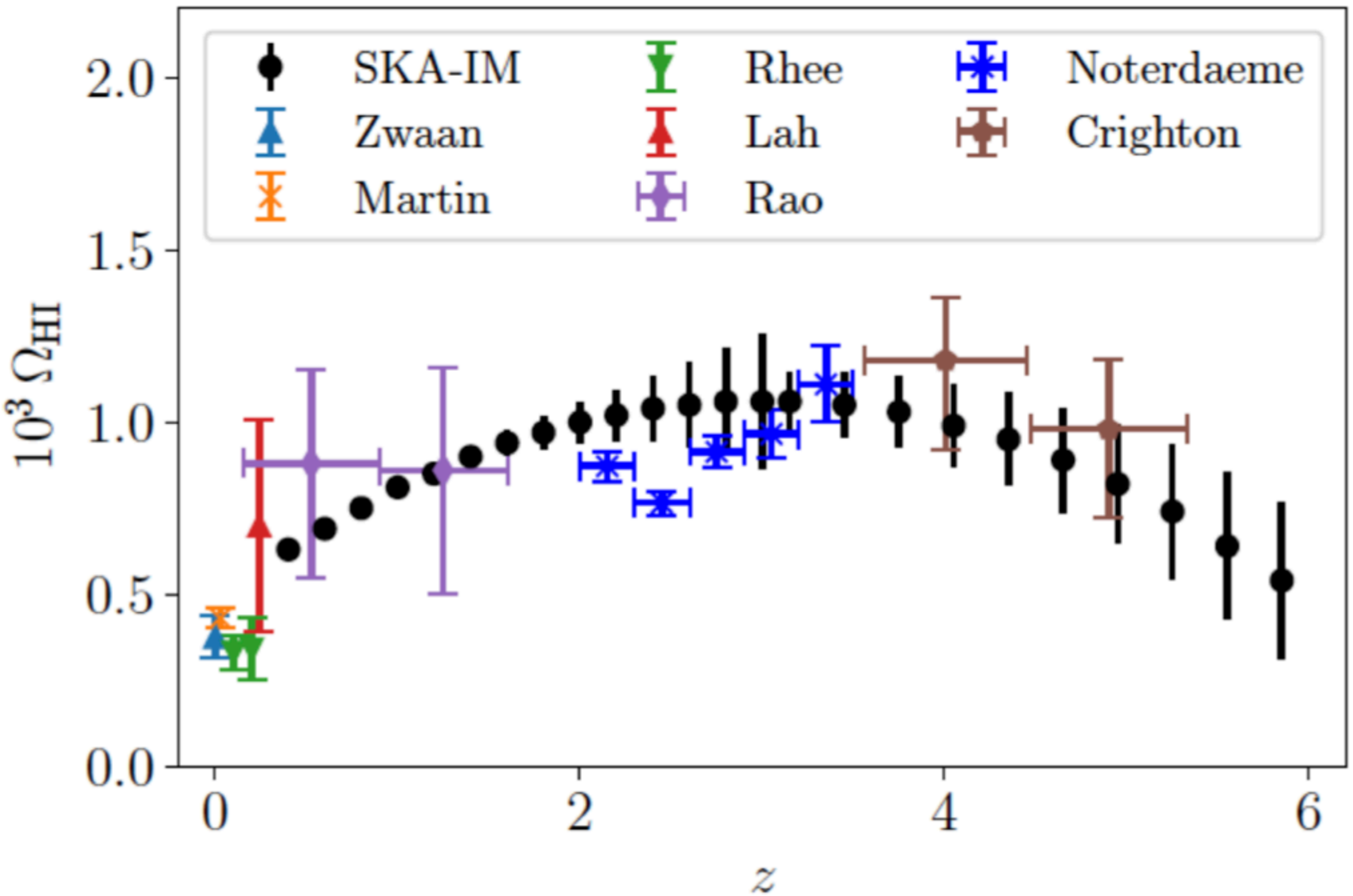


Hydrogen Intensity Mapping (HIM): experiments

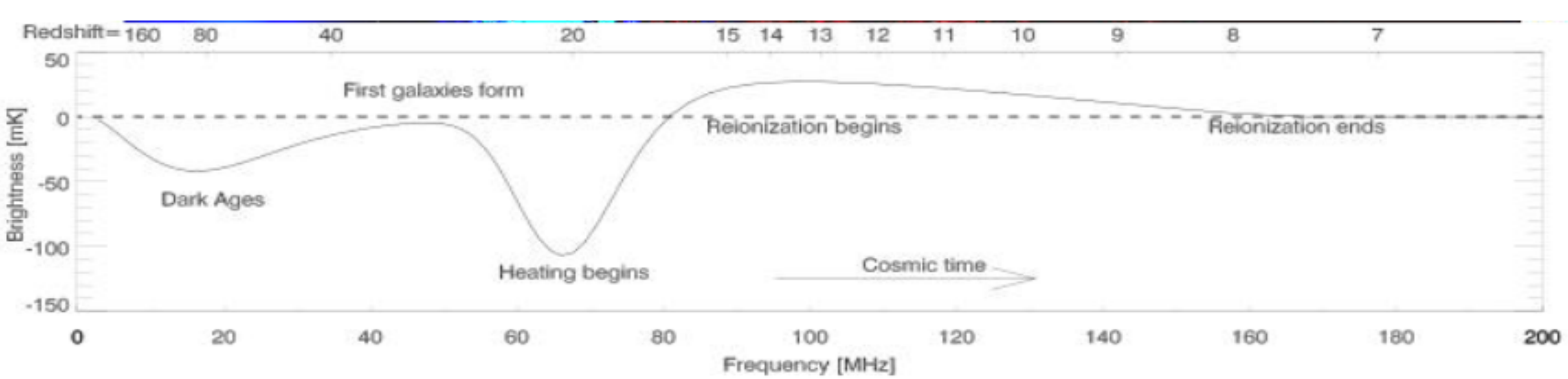


Hydrogen Intensity Mapping: neutral hydrogen (HI)

$$I_\nu = \frac{2}{\lambda^2} k\, T_{\rm RJ} \qquad \bar{T}_{\rm HI} = \Omega_{\rm HI}[z] \frac{9}{128\pi} \frac{\hbar\, c^3 A_{1,0}\, H_0}{G\, m_{\rm H}\, \nu_{21}\, k} \frac{H_0\,(1+z)^2}{H[z]} = 4.72\,{\rm mK}\, \frac{\Omega_{\rm HI}[z]}{10^{-3}} \frac{H_0\,(1+z)^2}{H[z]}$$



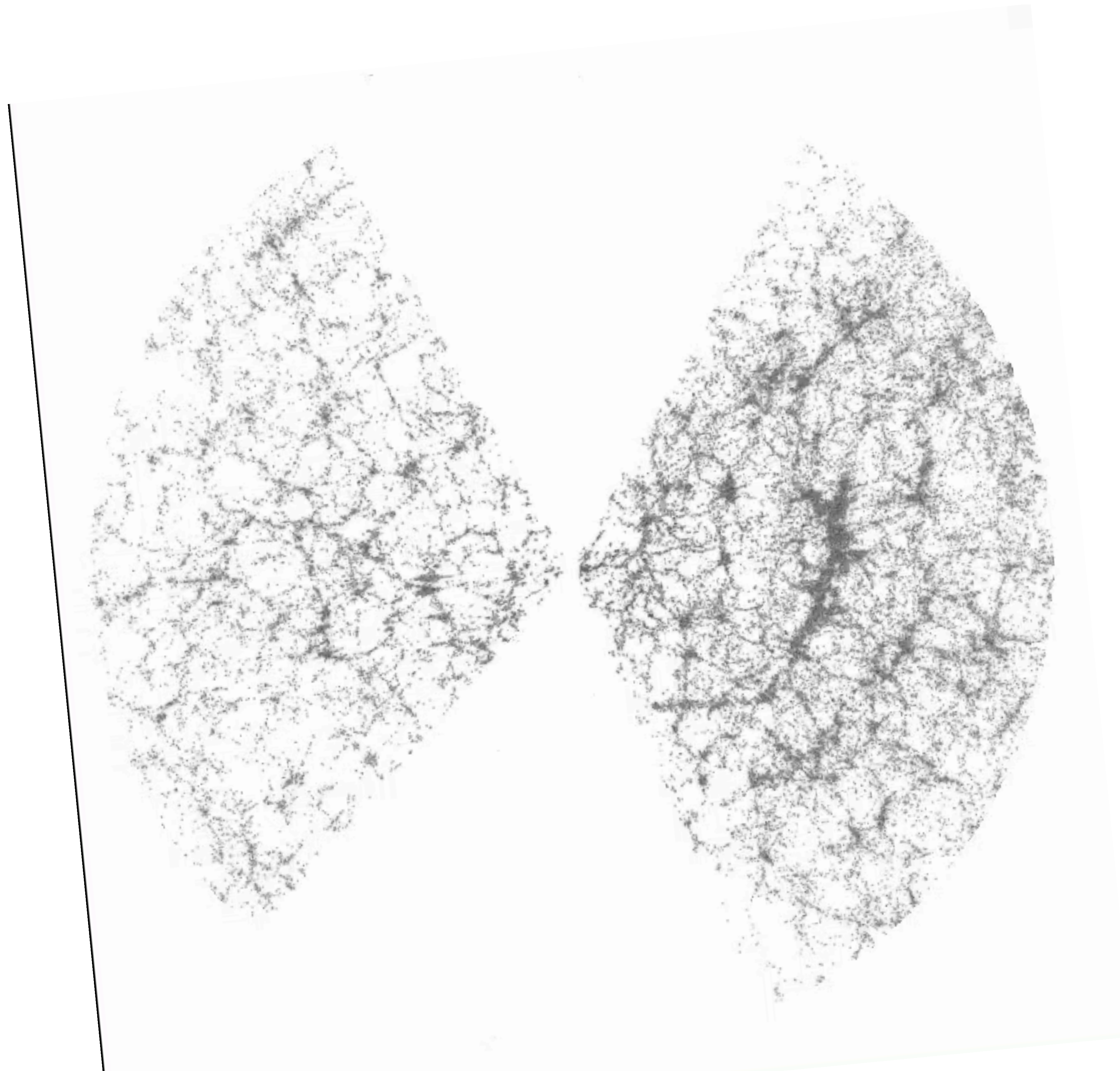
Epoch of Galaxies



EoR / Dark Ages

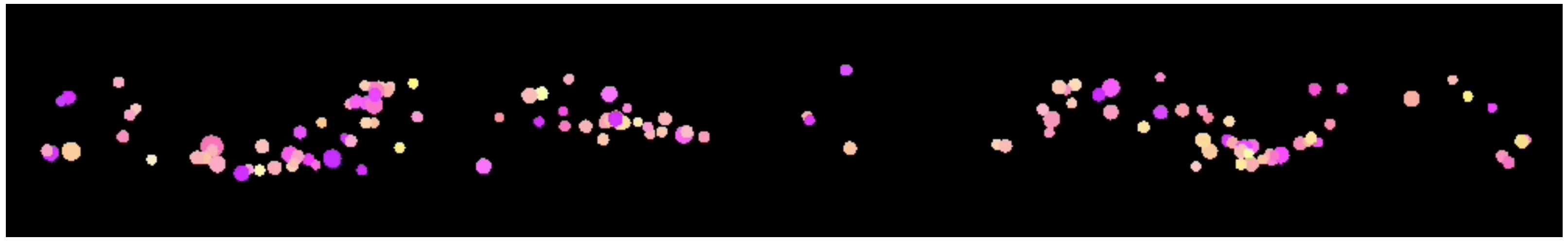
Intensity Mapping: technique

- **intensity mapping concept**: determine distribution of galaxies w/o resolving any of them by measuring the $I_\nu[\alpha,\delta]$.
- can only get galactic redshift this way only in parts of the EM spectrum where a single special lines "dominates" so there is no "confusion" about $z[\nu]$.
- or by correlation redshifts *e.g.* w/21cm
- radio broad spectrum "foregrounds" will be brighter than 21cm line emission from galaxies - however this emission is very smooth spectrum and galactic 21cm lines should dominate other "wiggles: in the spectrum.
- Intensity mapping proposed for
  - HI (21cm 1.4GHz) $(0 \lesssim z \lesssim 100)$
  - CO (14, 29 GHz) $(z \gtrsim 6)$
  - CII (237 GHz) $(6 \lesssim z \lesssim 8)$
  - Ly-α (1.2μm) $(2 \lesssim z \lesssim 12)$



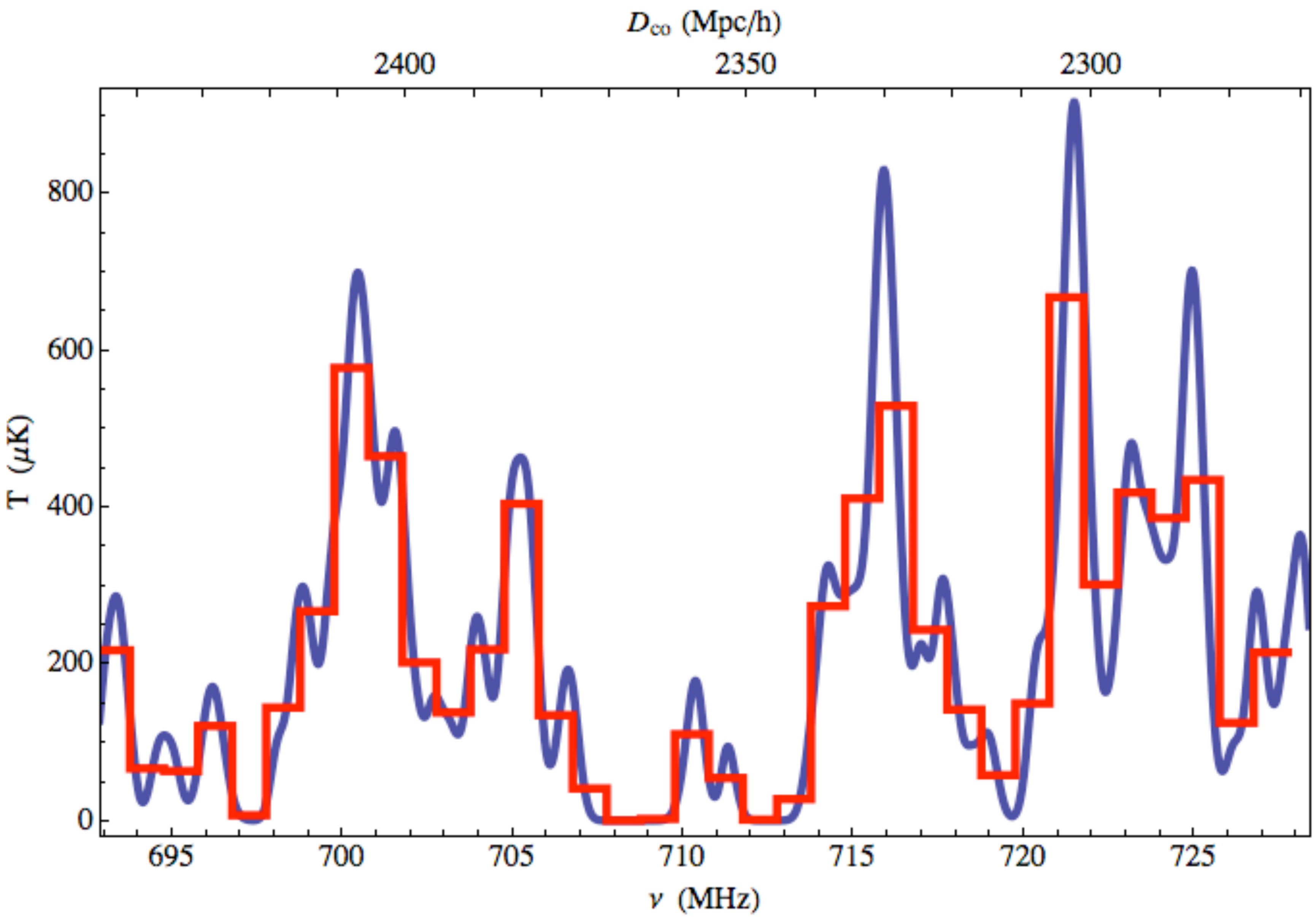
"Expensive" to resolve individual galaxies

Hydrogen Intensity Mapping: Redshift Clump Detection



DEEP2

Davis ++ 2004++



see Wang ++ 2006

21cm brightness

δν=1 MHz

δθ=10’

Tully-Fisher

$M_{HI} \propto L_B$

no ellipticals

!ellipticals believed to contain a lot of HI!

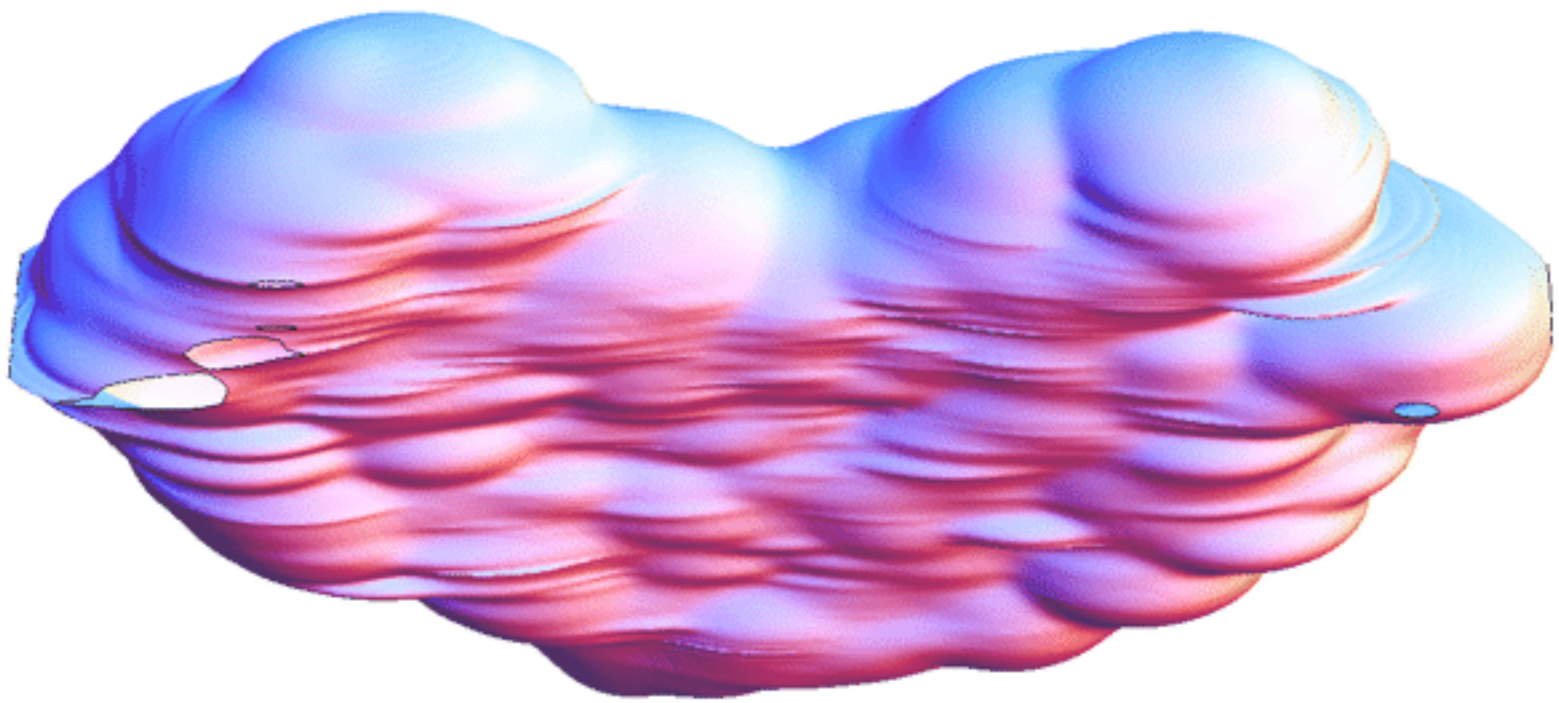
One can <u>nearly</u> resolve galaxy structures in redshift space.

non-Gaussian features in maps

Hydrogen Intensity Mapping: 3D Maps

21cm iso-T_{RJ} contours of slice of Alfalfa HI redshift survey
includes galaxy line-widths / velocity dispersions
translated to z=1 smoothed: δv=100kHz δθ=10’

stack of pancakes



T_{RJ} = 1μK

- S/N ≳1 requires $\delta T_{\rm b} \gtrapprox 100\,\mu K$

$$\delta R_{\rm co} = (1+z)^2 \frac{c}{H[z]} \frac{\delta\nu}{\nu_{21}}$$
$$= 2.9\,{\rm Mpc} \left((1+z)^2 \frac{H_0}{H[z]}\right) \frac{\delta\nu}{\rm MHz}$$

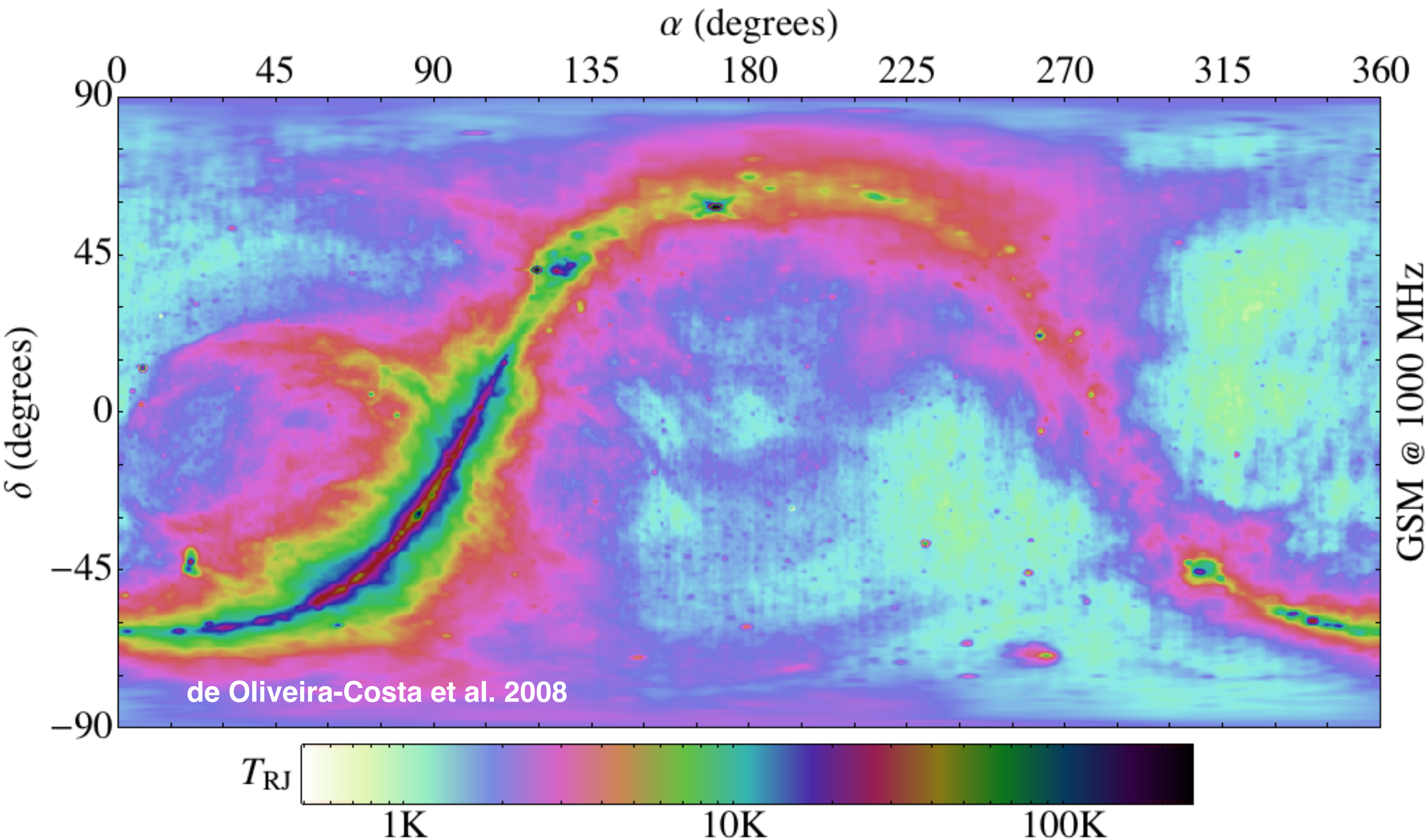
- HIM easily obtains high spectral (redshift) resolution

$$\delta\theta \sim \frac{\lambda}{b_{\rm max}} = 10' \frac{72\,{\rm m}}{b_{\rm max}} (1+z)$$

- angular resolution more difficult

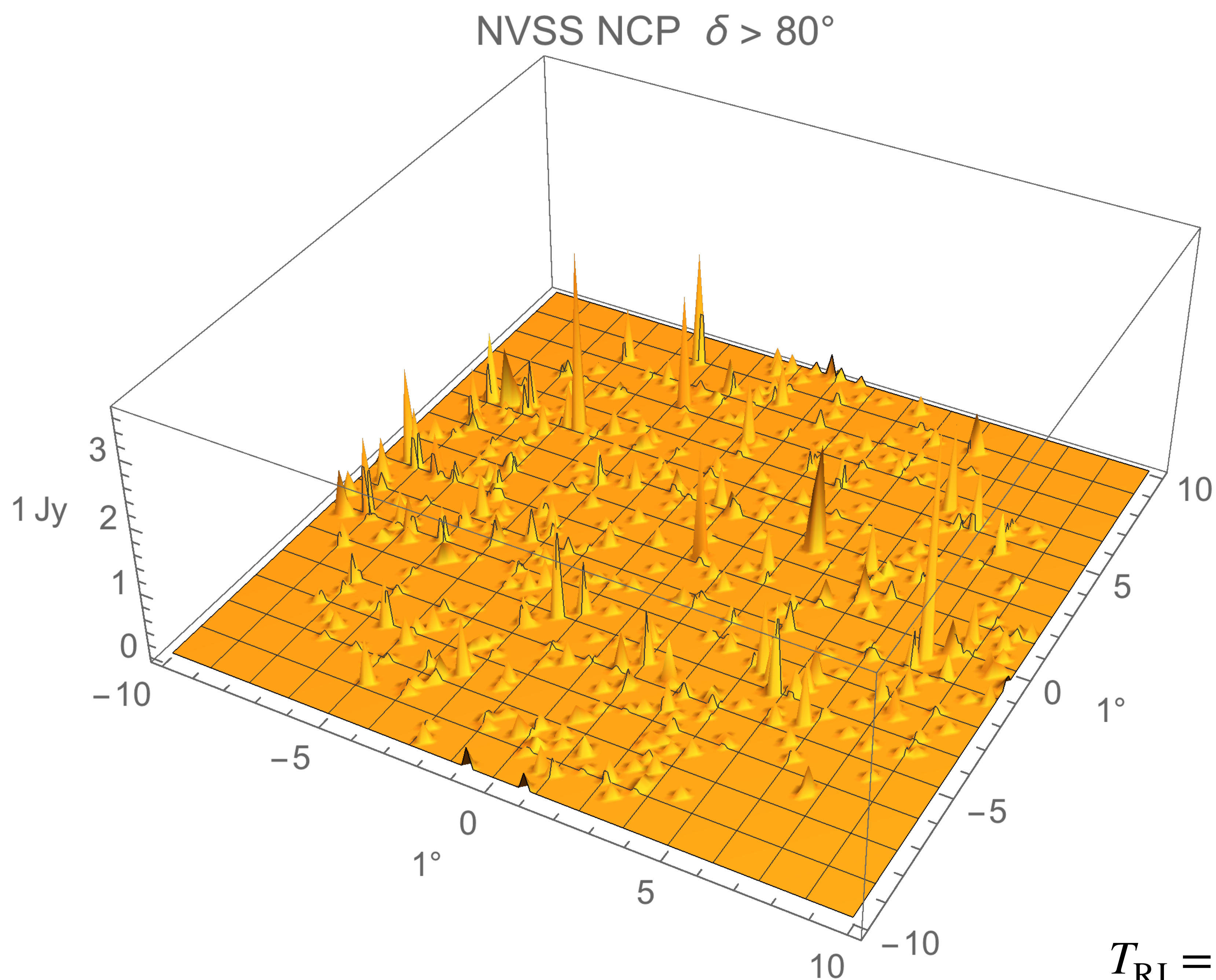
$$\delta R_{\rm co}^{\perp} = \delta\theta \int_0^z \frac{c\,dz}{H[z]} = 10\,{\rm Mpc}\, \frac{\delta\theta}{10'} \int_0^z dz\, \frac{H_0}{H[z]}$$

Hydrogen Intensity Mapping: Galactic Foregrounds



versus ~3⁺K! **prediction:** this will be worked out by 2020

Hydrogen Intensity Mapping: ExtraGalactic Foregrounds



Not feasible to mask, subtract or otherwise remove every extragalactic radio sources!

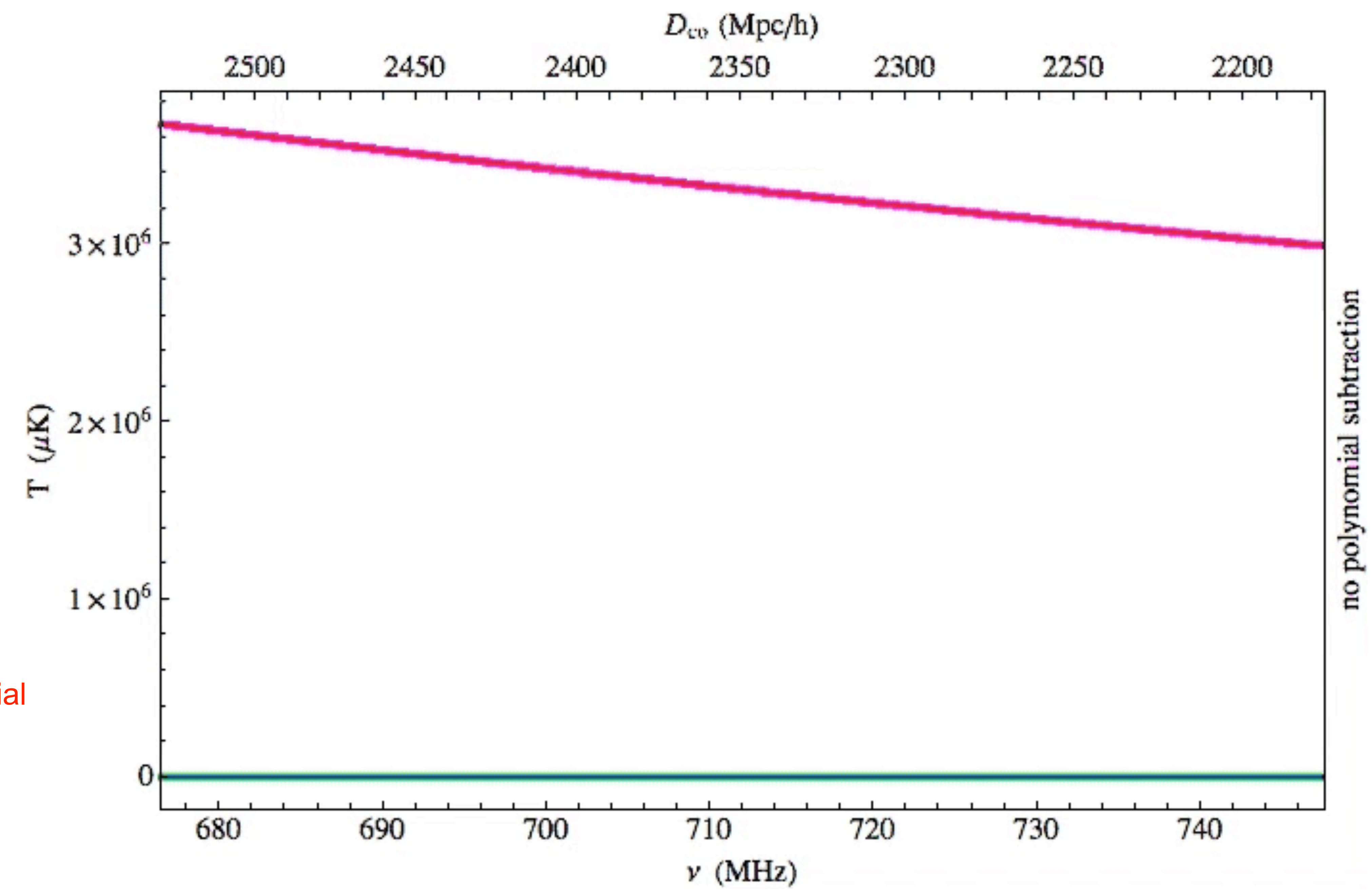
Must find “generic” method of source removal in order to unmask 21cm signal.

$$T_{\mathrm{RJ}} = \frac{\lambda^2}{2k\,\Omega_{\mathrm{p}}}\,f_\nu$$

$$= 1.9\,\mathrm{K}\,(1+z)^2\,\frac{f_{\frac{\nu_{21}}{1+z}}}{\mathrm{Jy}}$$

Hydrogen Intensity Mapping: Foreground Filtering

see also **Wang ++ 2006**



21 cm signal

21cm-polynomial

21 cm+synch-polynomial

residual

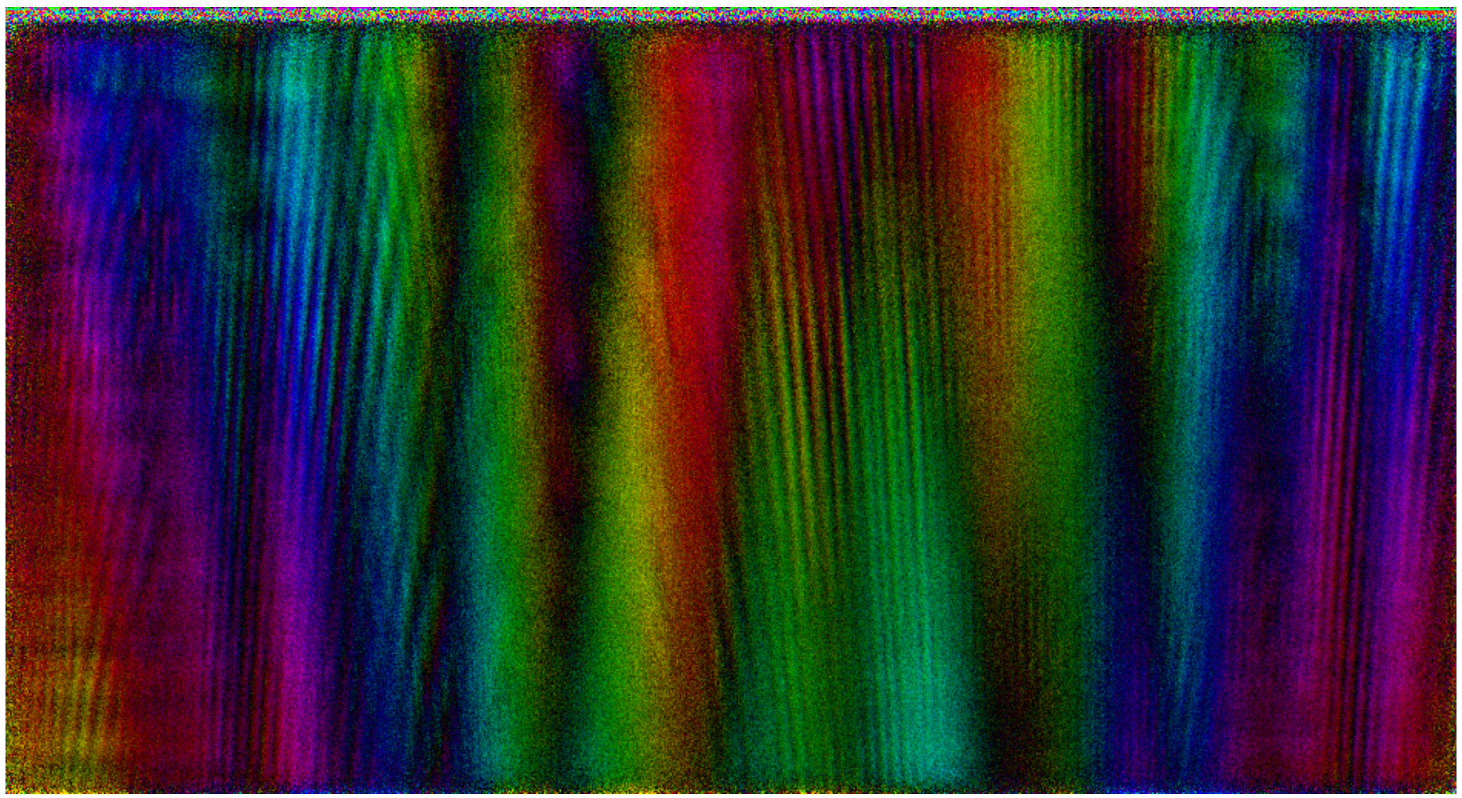
Δθ=10’

Model: Maximally Curved Synchrotron + DEEP2 galaxies

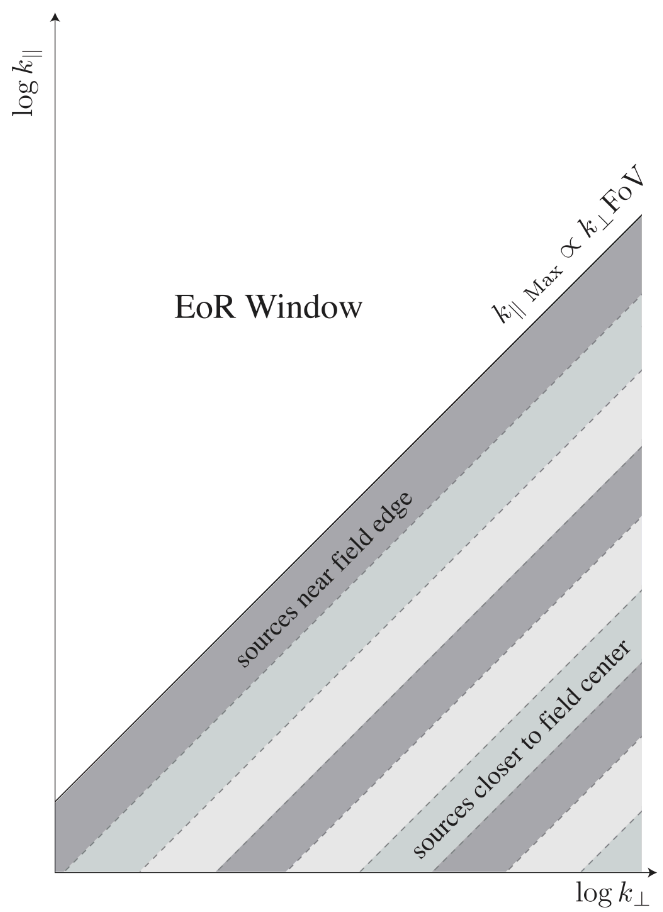
Hydrogen Intensity Mapping: The Wedge

In radio astronomy beams are always *chromatic*

- beam patterns on sky vary with frequency.
- this mixes angular variation which can be very non-smooth with frequency variation which might be smooth (*mode mixing*)
- lo-pass filtering in frequency will first reveal spatial variations



(complex) interferogram or visibility



Hydrogen Intensity Mapping: Non Smooth Foregrounds

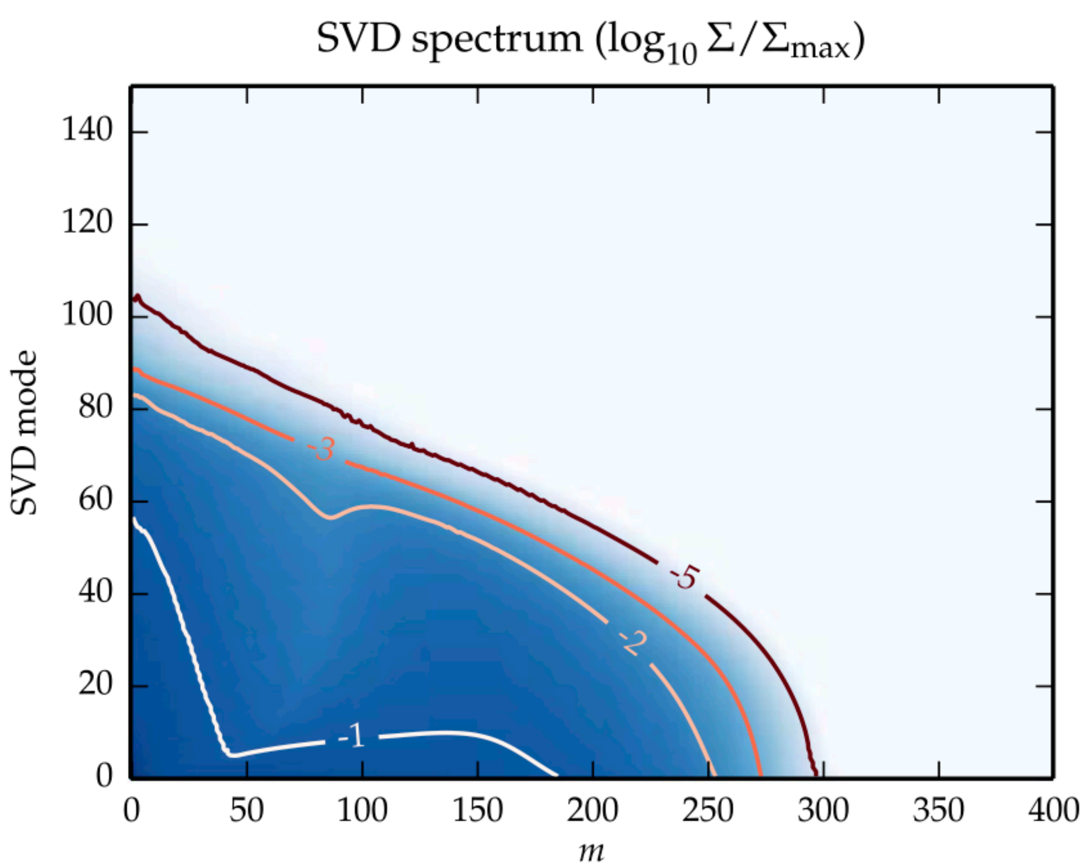
- RFI (human made Radio Frequency Interference) often line like.
  - it is not the obvious RFI that is the problem - other low level RFI will persist in data.
  - intermittent RFI will not repeat with sidereal day - astrophysical sources will

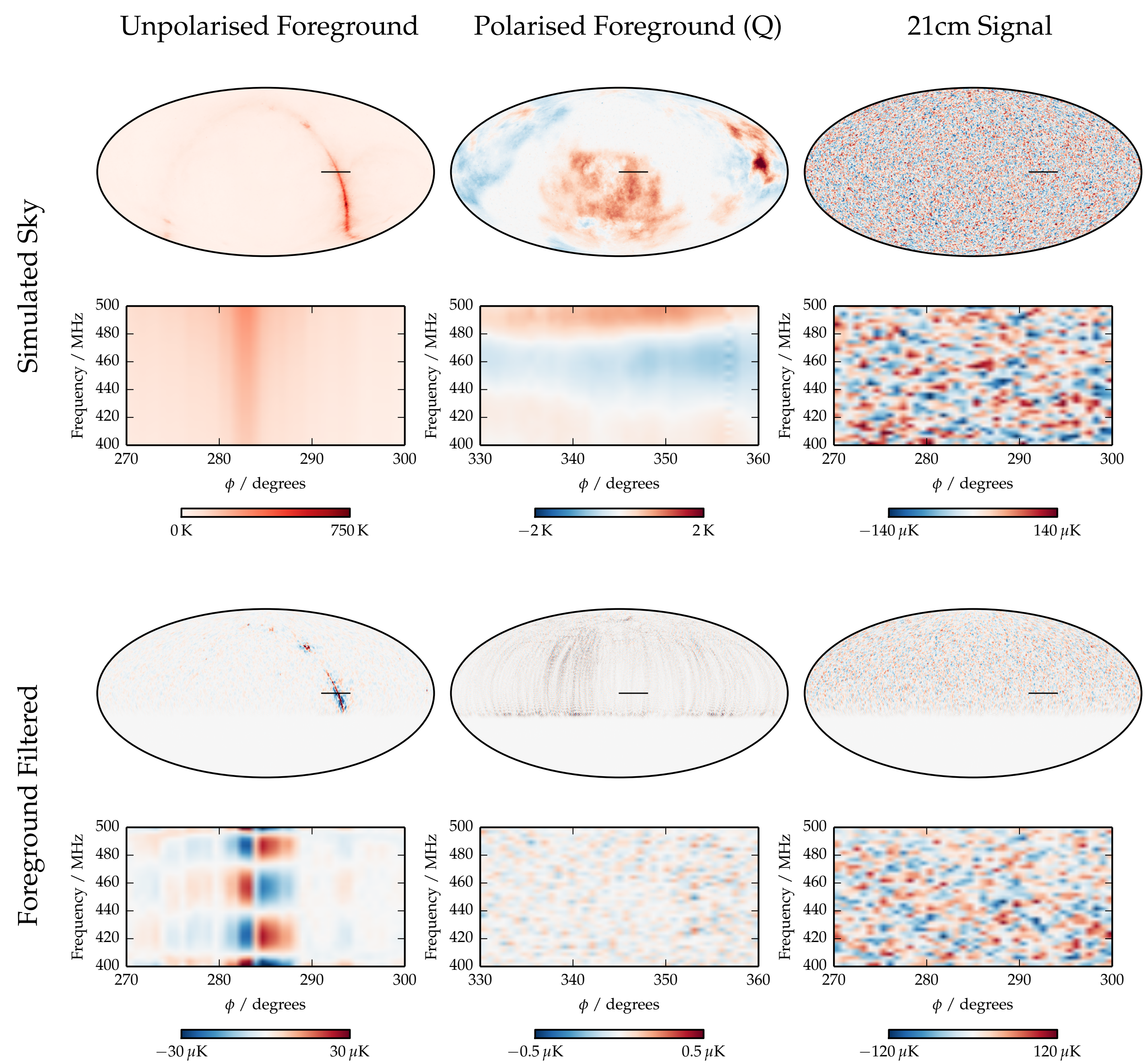
- Self absorbed synchrotron may be more non-smooth
  - GPS (Gigahertz Peaked Sources) may be example of this.

- Faraday rotated linearly-polarized source will oscillate with frequency in each linear polarization but not intensity.
  - Some leakage of polarization into intensity is inevitable for off axis sources.
  - proper map-making can reduce polarization leakage

Hydrogen Intensity Mapping: Foreground Filtering

m-mode
21cm / foreground
Karhunen-Loève decomposition



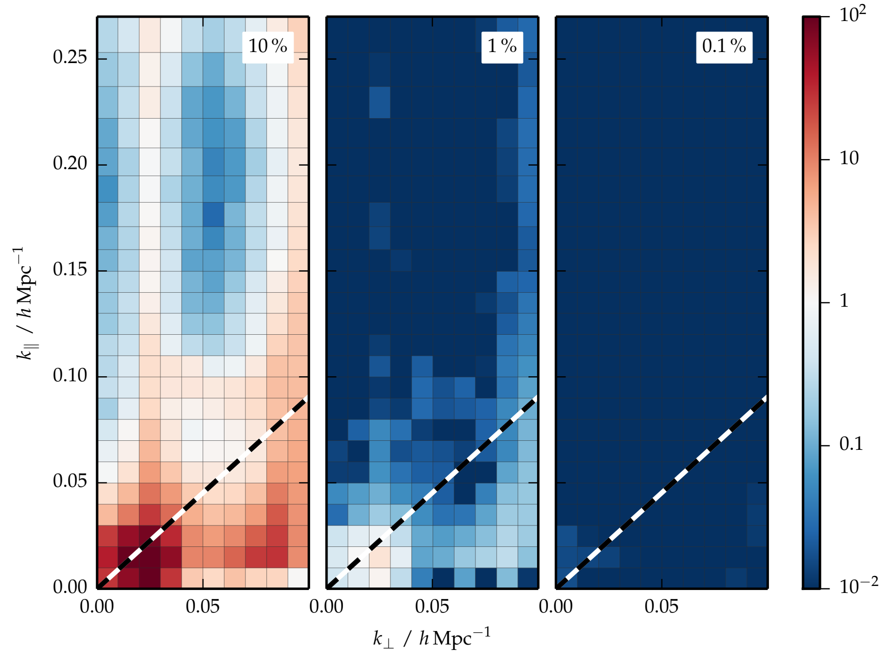


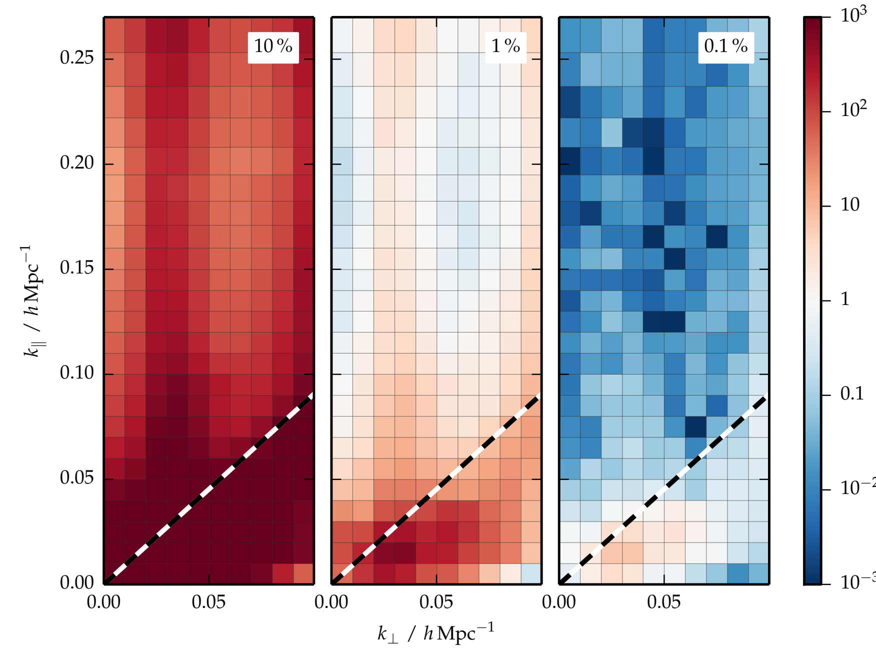
Shaw++ 2014

Hydrogen Intensity Mapping: Beam Calibration

foreground leakage

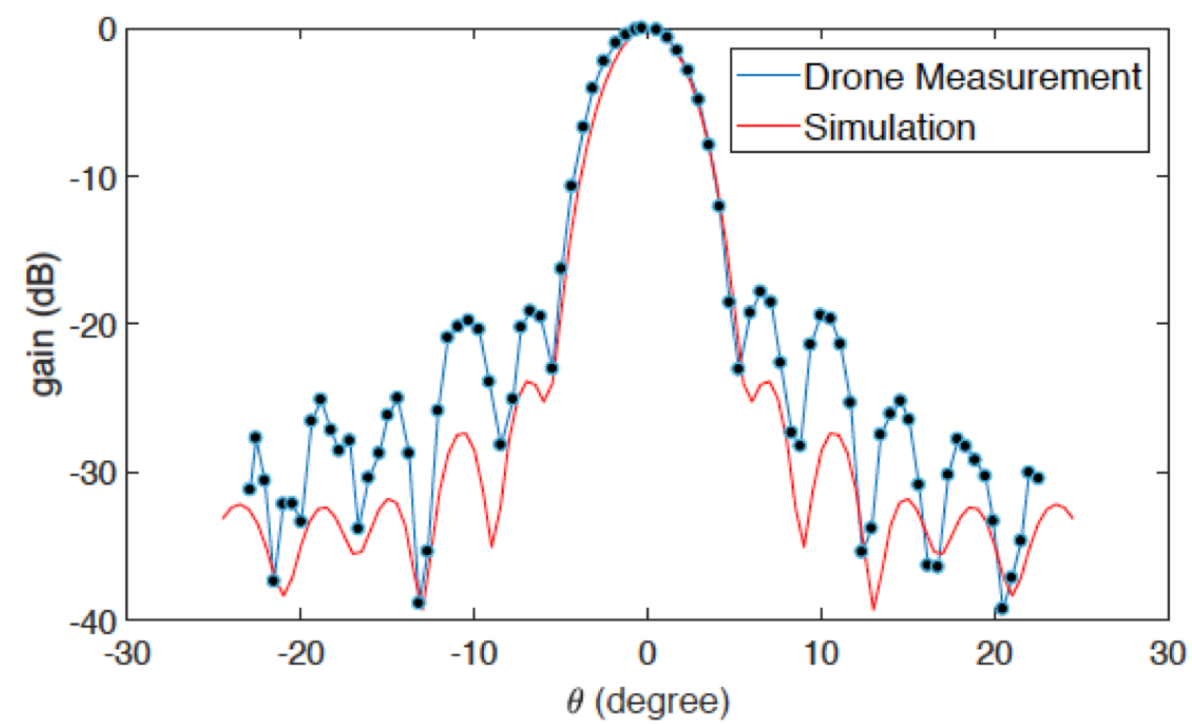
gain errors





beam errors

Shaw++ 2014

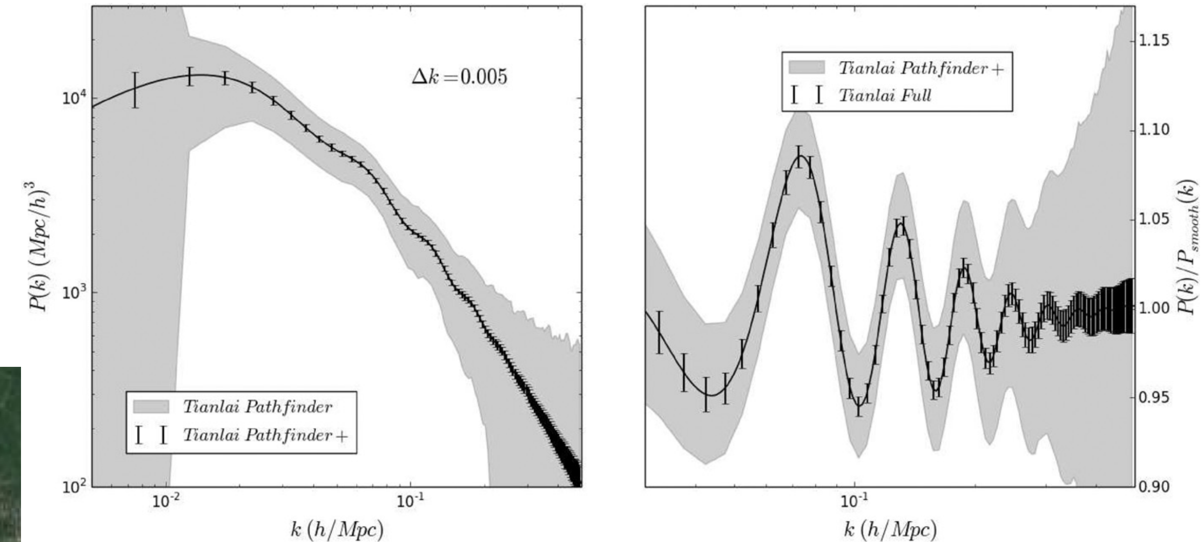


The Tianlai Project

Tianlai Pathfinder

Hydrogen Intensity Mapping: The Tianlai Project

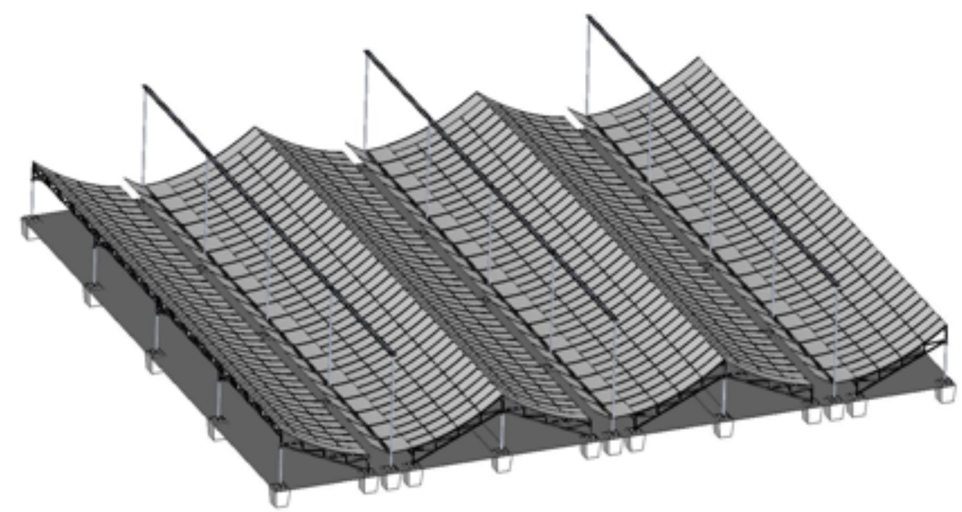
Tianlai ~ "*Heavenly Sound*"

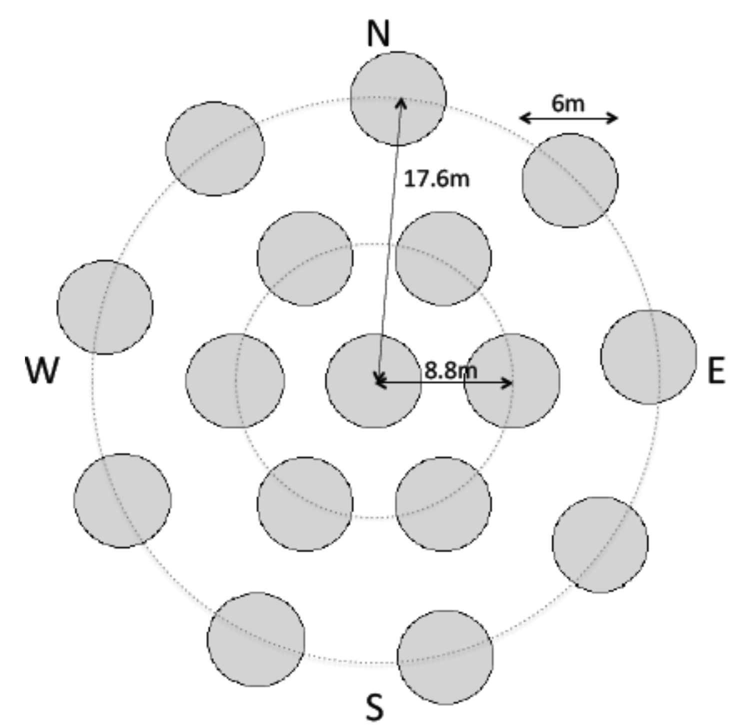


Hydrogen Intensity Mapping: The Tianlai Pathfinder

Pathfinders to demonstrate basic principle and encounter all issues rapidly

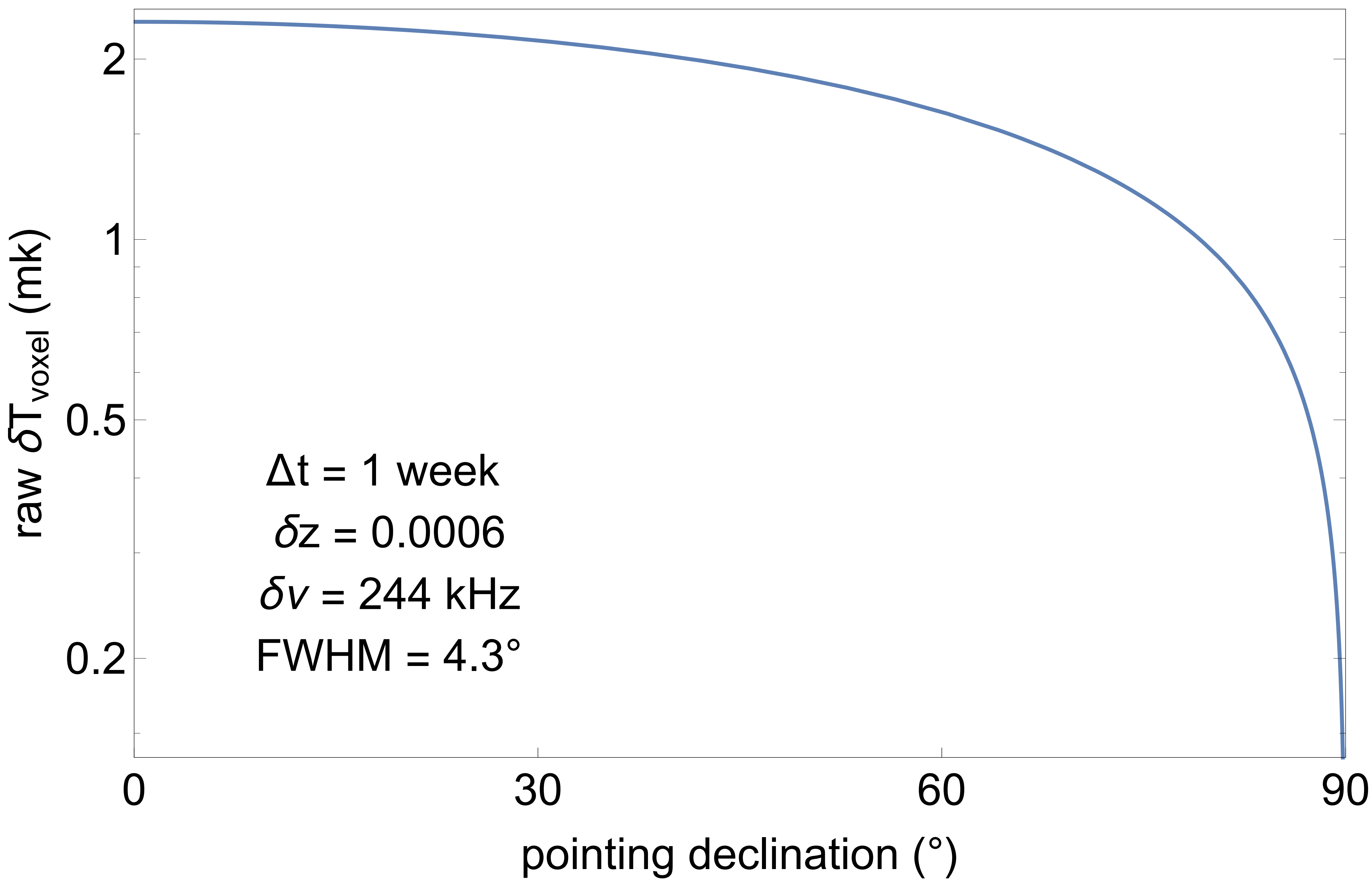
- **Band** 685-810MHz ($0.77<z<1.3$)
  512 frequency channels
  ($\Delta\nu$=125MHz $\delta\nu$=244kHz δz=0.0002)
  tunable in 600-1420MHz ($0<z<1.5$)
- **Cylinder Array** 3 x 15m x 40m cylinders
  96 dual polarization feeds
  4 sec sampling
- **Dish Array** 16 x 6m dishes
  16 dual polarization feeds
  1 sec sampling
- **Pathfinder+ Cylinder Array**
  216 dual polarization feeds
  4 sec sampling
- **Proposed Full Cylinder Array** 8 x 15m x 120m
  2048 dual polarization feeds
  400-1420MHz





HIM: Tianlai Dish Polarscope

BY POINTING DISH ARRAY TOWARD POLE WILL INTEGRATE DOWN TO LOW MAP NOISE TEMPERATURE VERY RAPIDLY SINCE ONE IS ALWAYS POINTING AT SAME SPOT ON SKY.



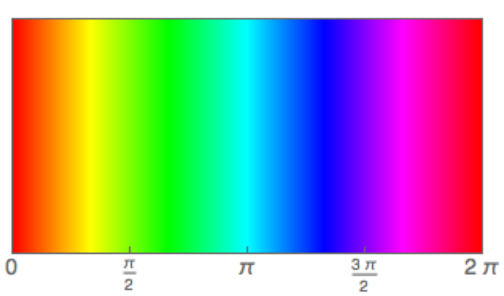
HIM: Tianlai Visibility: 10 Days

example of one “good” visibility V_{3x31}.
this is raw correlator data

11 sidereal days top to bottom
2018-01-02 02:44:15 to 2018-01-11 20:44:12

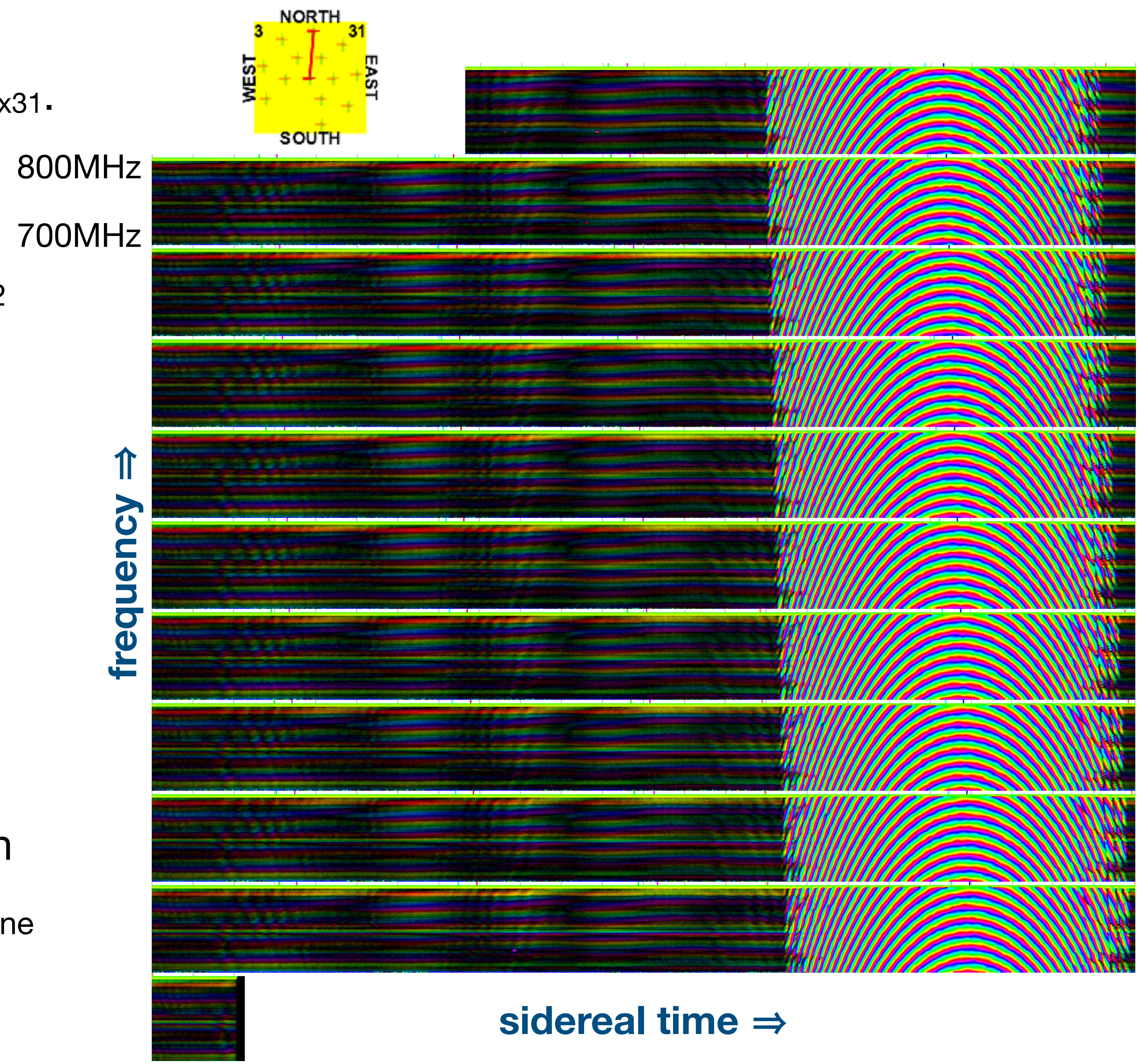
brightness gives $|V_{3x31}|$

color gives complex phase



bright swath of fringes from Sun
fringes vary because Earth rotates
bow occurs when Sun passes “above” baseline direction
Sun dominant source even 110° off axis

dimmer fringes still visible at night



(complex) interferogram or visibility

HIM: Tianlai Visibility: 10 Nights

nighttime only view of V_{3x31}
nighttime mean subtracted for each frequency
image intensified to show nighttime fringes

visibilities repeat with sidereal day period
signal from the sky

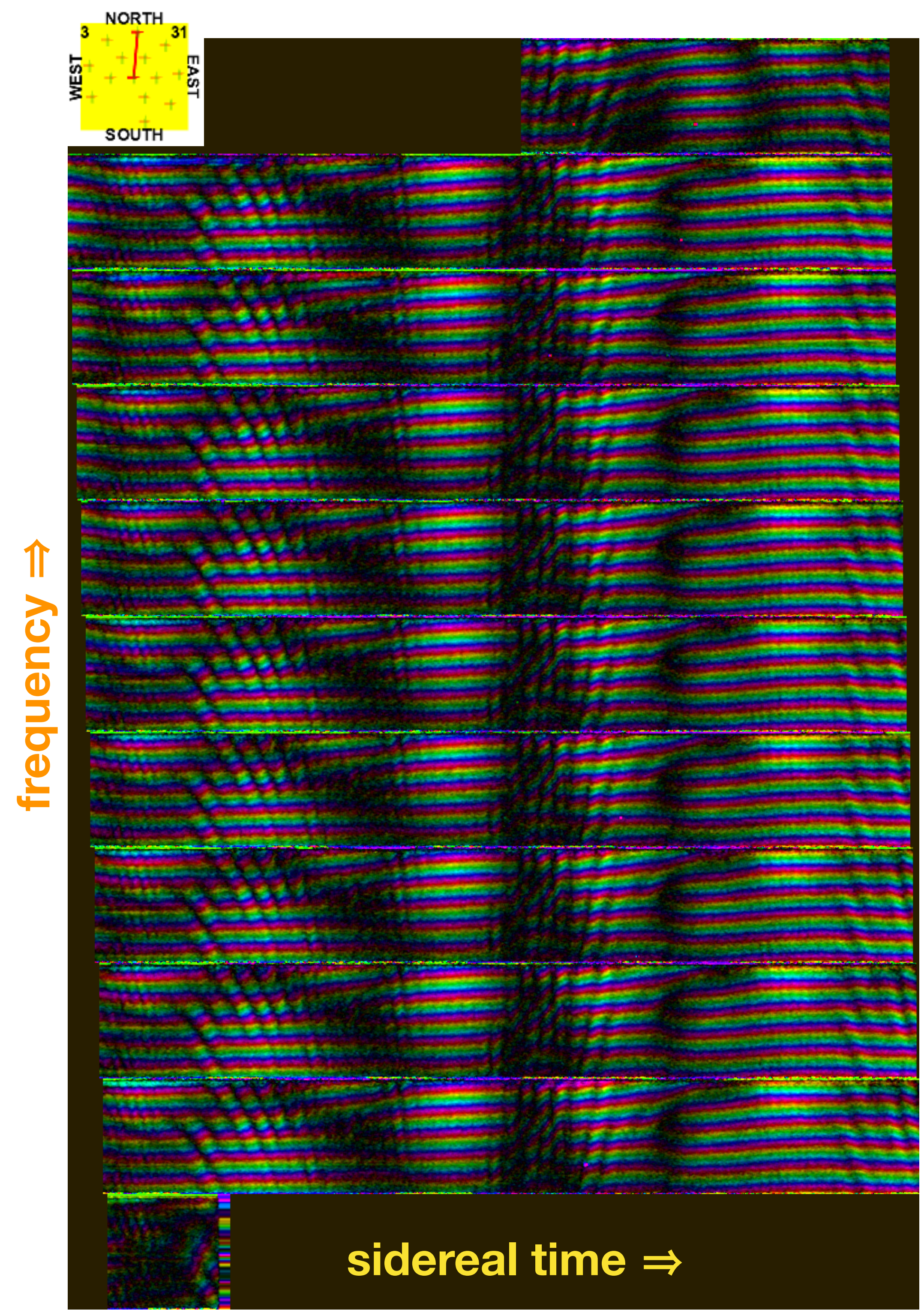
fringe pattern more complicated than bow
indicating multiple bright sources in 2° beam
centered on North Celestial Pole

bright and dark patches
constructive/destructive interference between sources

good S/N in 1min x1MHz pixels

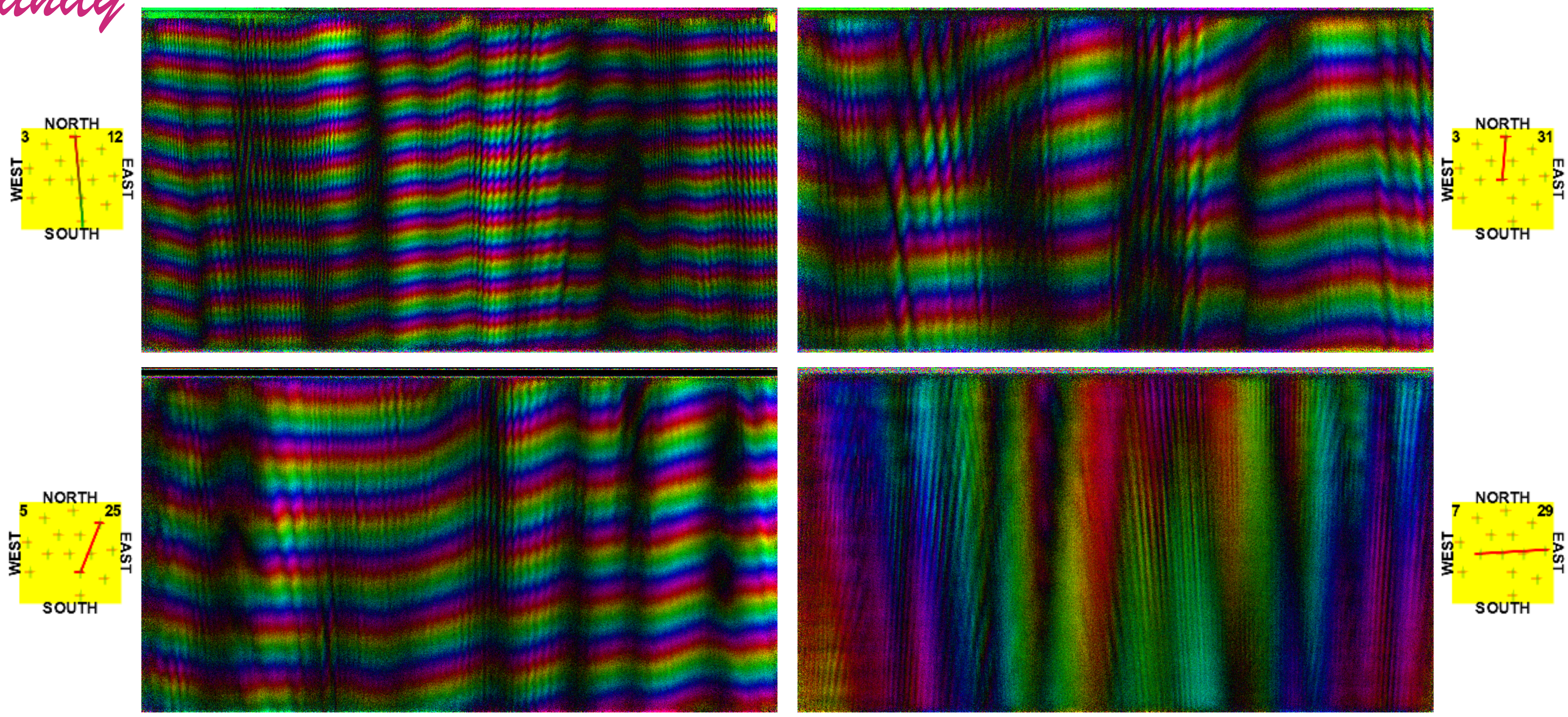
rapid frequency fringe rate
N-S baseline: large ν-dependent phase difference

variable temporal fringe rate
caused by Earth rotation - sources at different declinations



HIM: Tianlai Visibility: Night Median Averaging

ribbon candy



have good measure of visibilities from foreground sources

Hydrogen Intensity Mapping: Power Law Decomposition

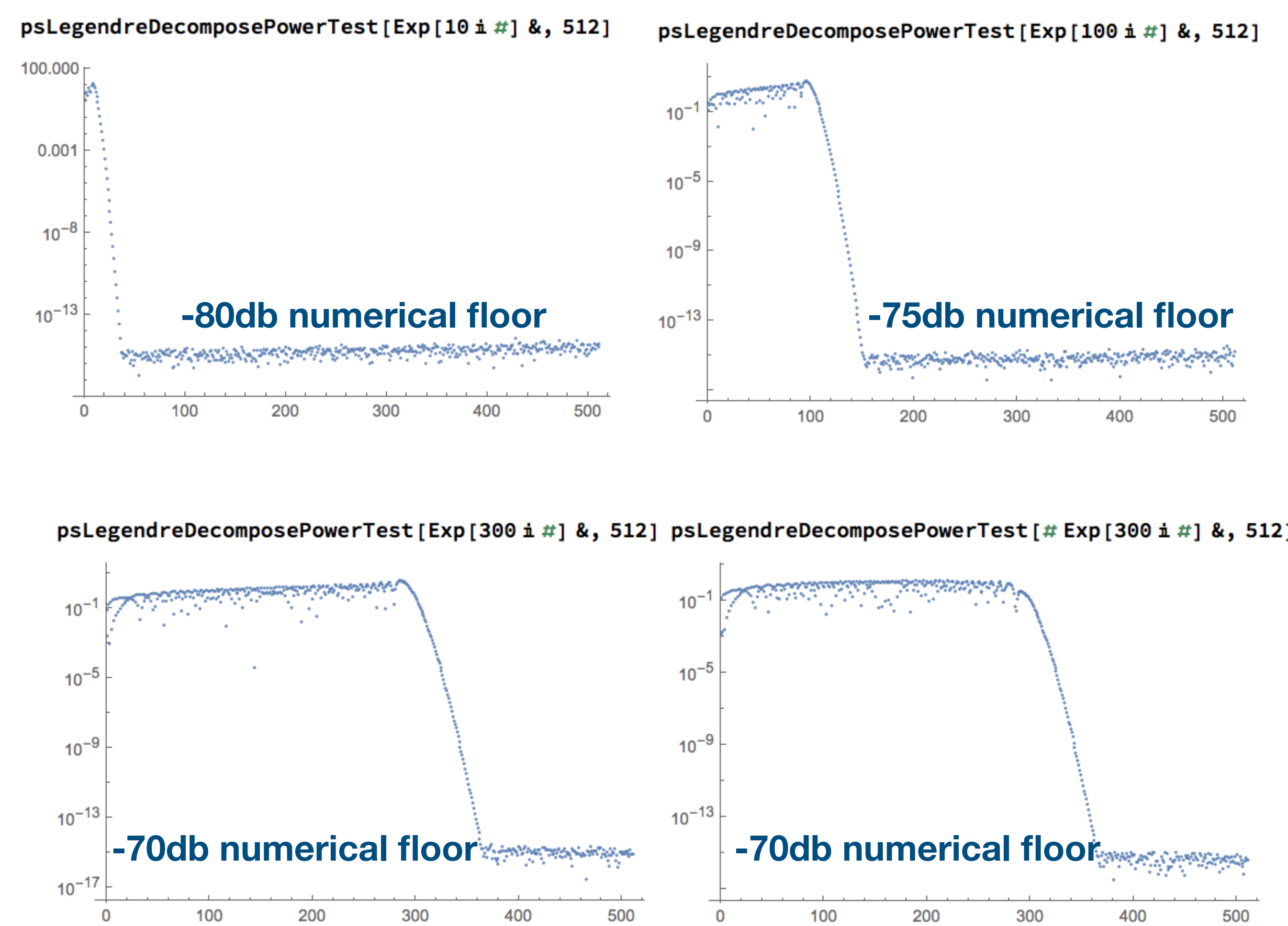
Numerical Tests on Sinusoids+

One can expand a visibility covering a given band into Legendre polynomials (or any other polynomial expansion)

$$V[\nu] = \sum_{n=0}^{N} a_n P_n\left[\frac{2(\nu - \nu_{\rm mid})}{\nu_{\rm max} - \nu_{\rm min}}\right]$$

the larger *n* is the less smooth the frequency dependence. A *carefully designed discrete analog* of this works better than a discrete Fourier transform. The integer index *n* is an analog of $k_{||}$. For small bandwidth

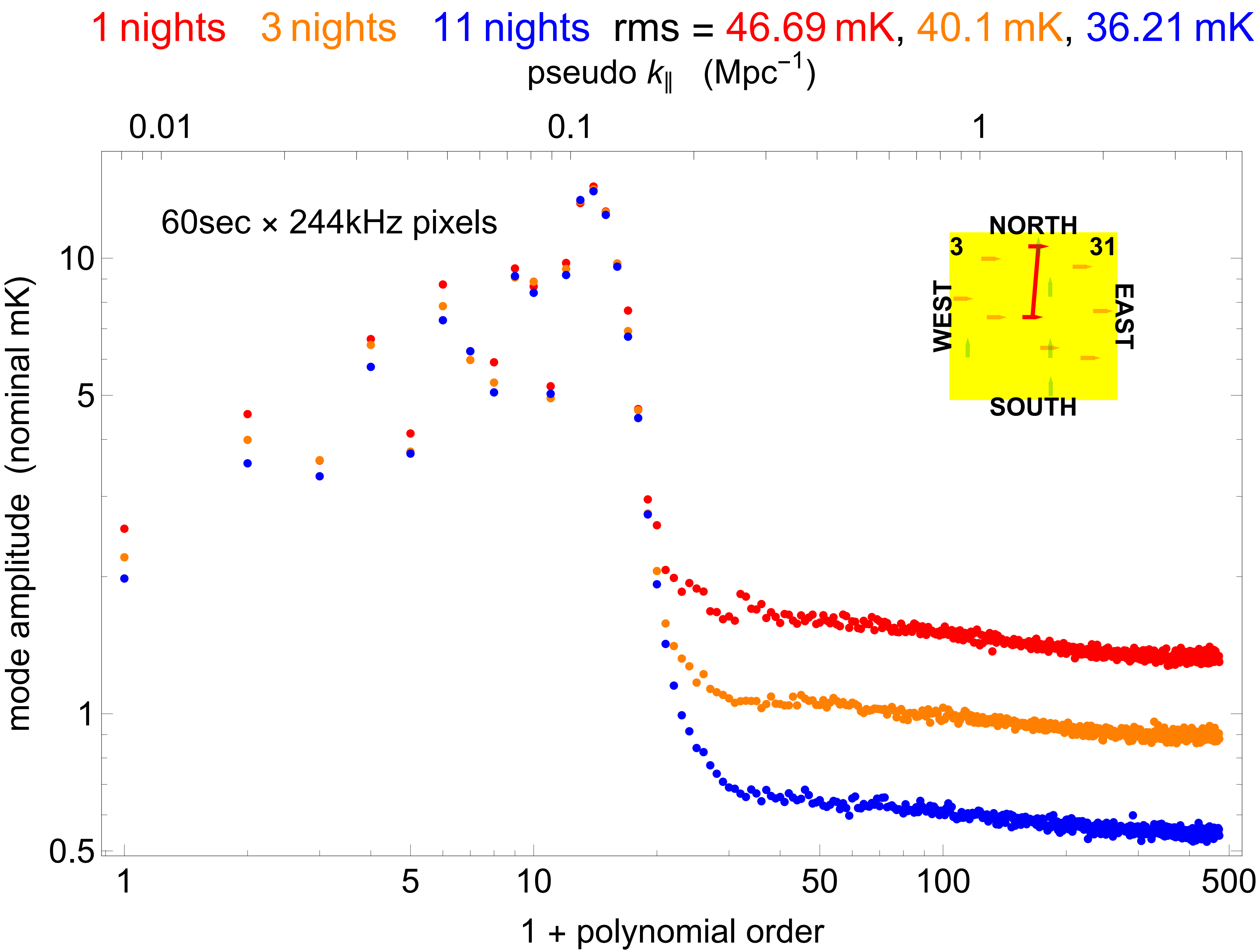
$$k_{||} \approx \frac{2\pi}{\Delta R_{\rm co}}(n+1)$$



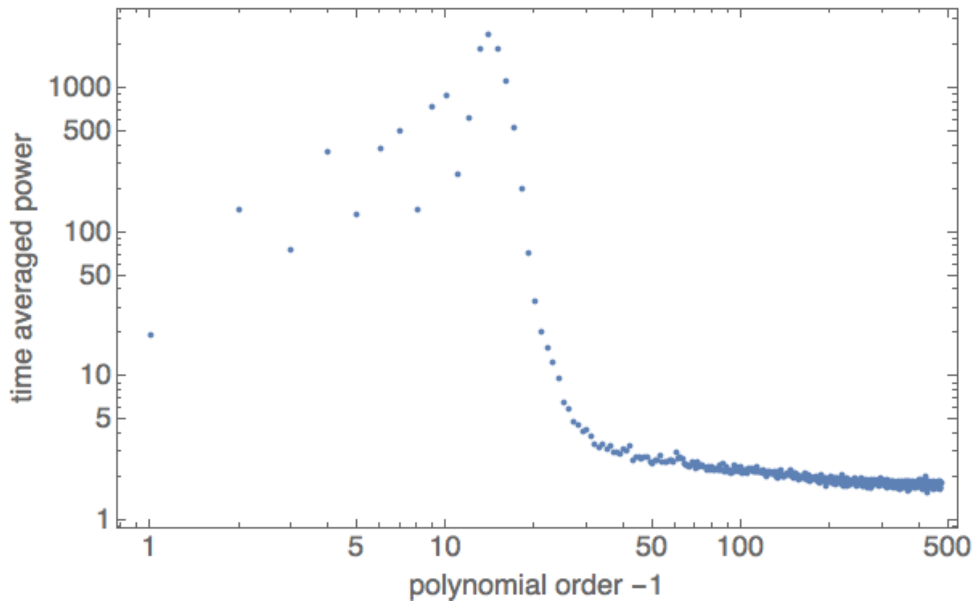
much spill-back, rapid fall-off, little spill-forward

HIM: Tianlai Visibility: Foreground Separation

Are Good Tianlai Visibilities Smooth Spectrum?

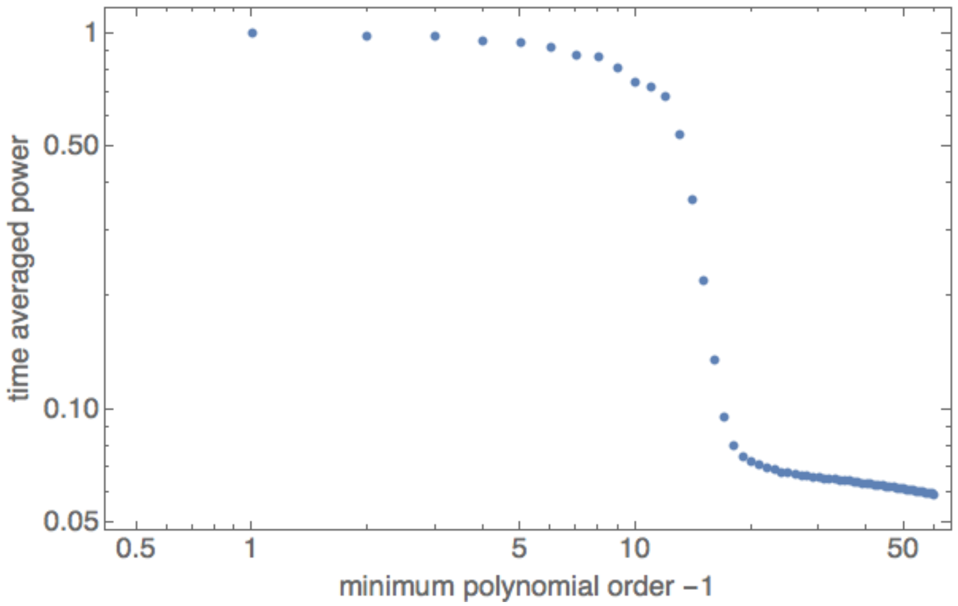


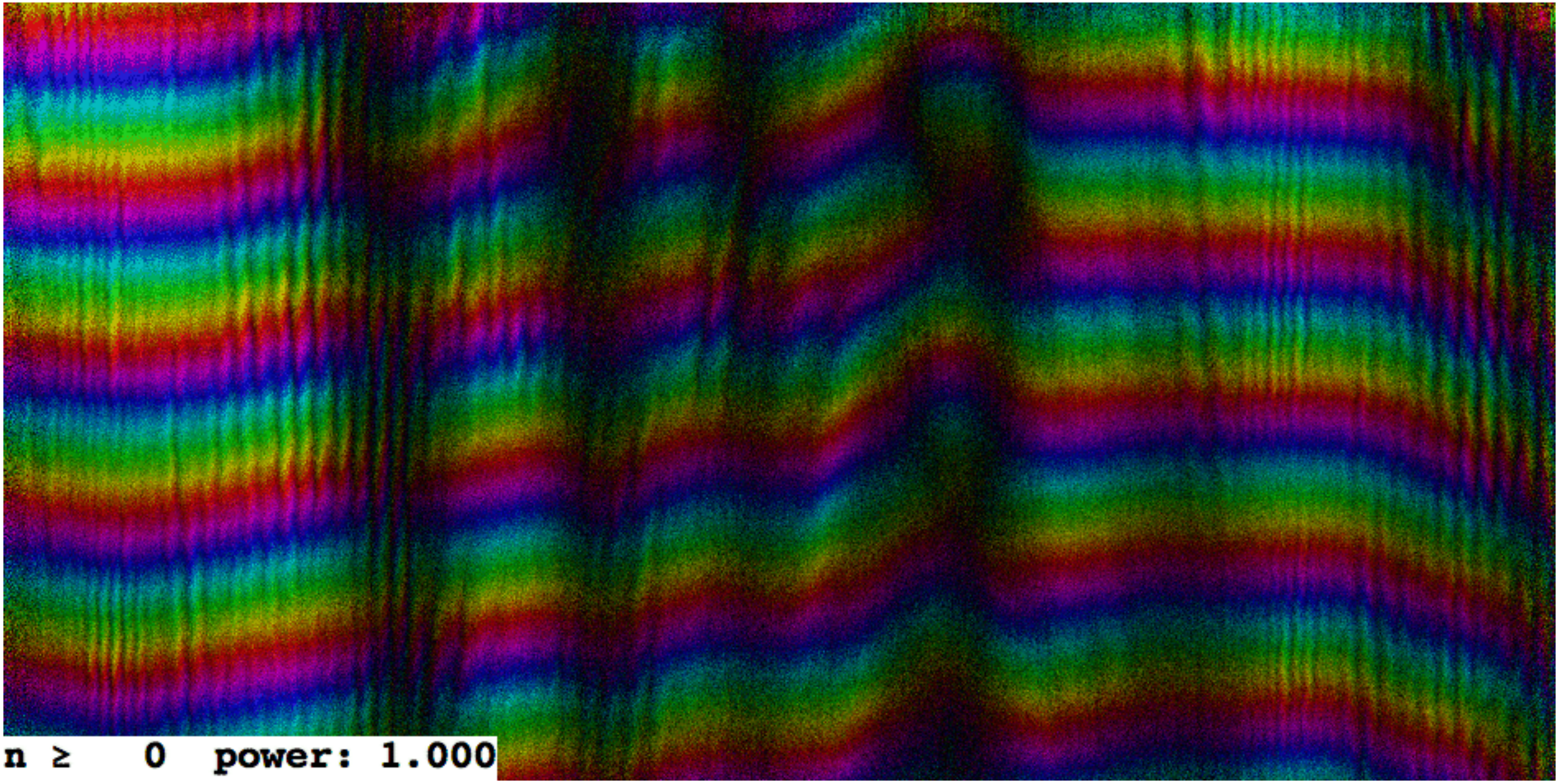
HIM: Tianlai Visibility: Foreground Subtraction



10 night median averaged visibility discrete polynomial subtraction.

residuals n>60!



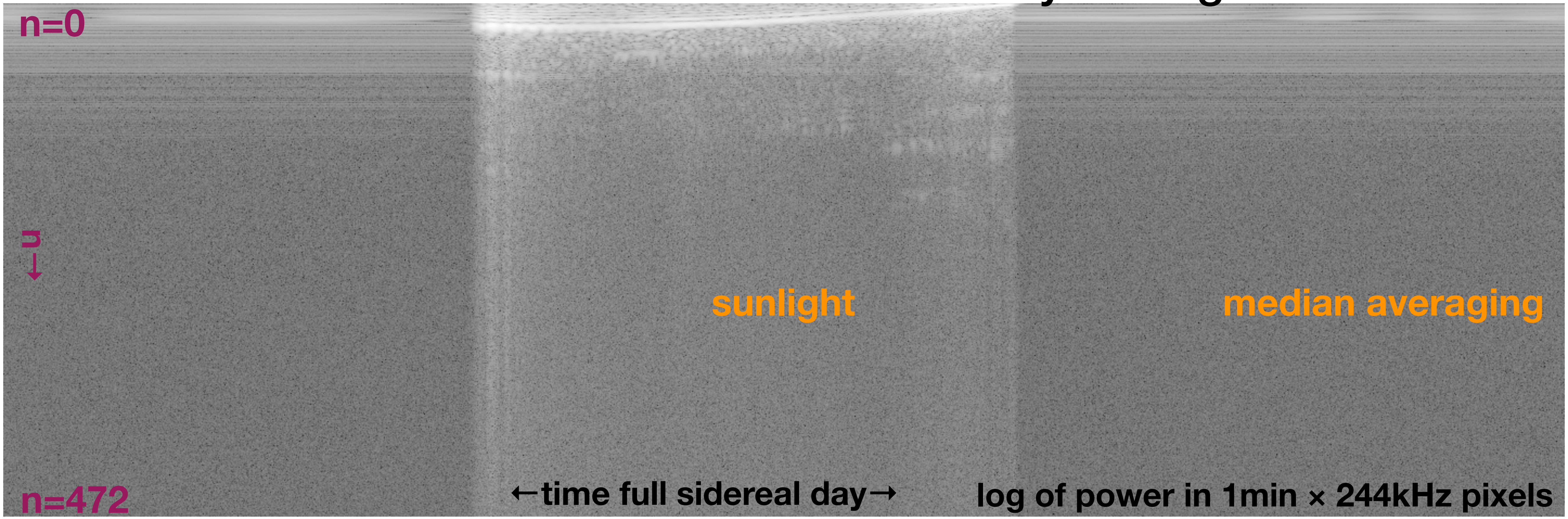


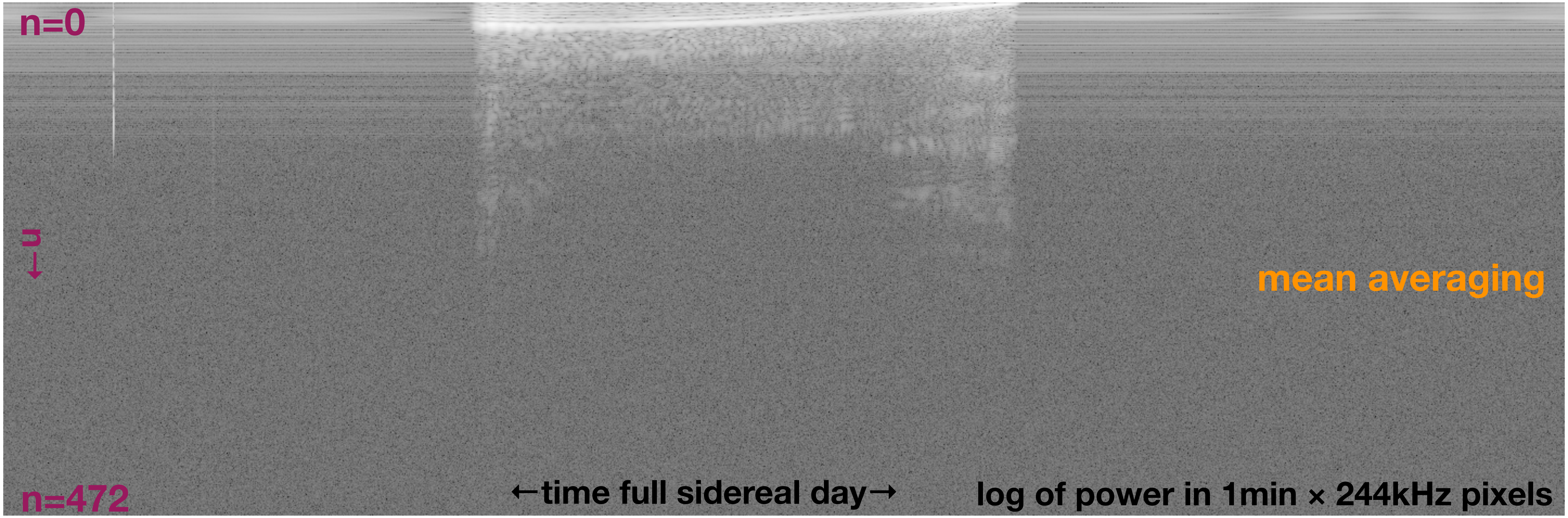
HIM: Tianlai Visibility: Foreground Separation

Power Distribution 03x31

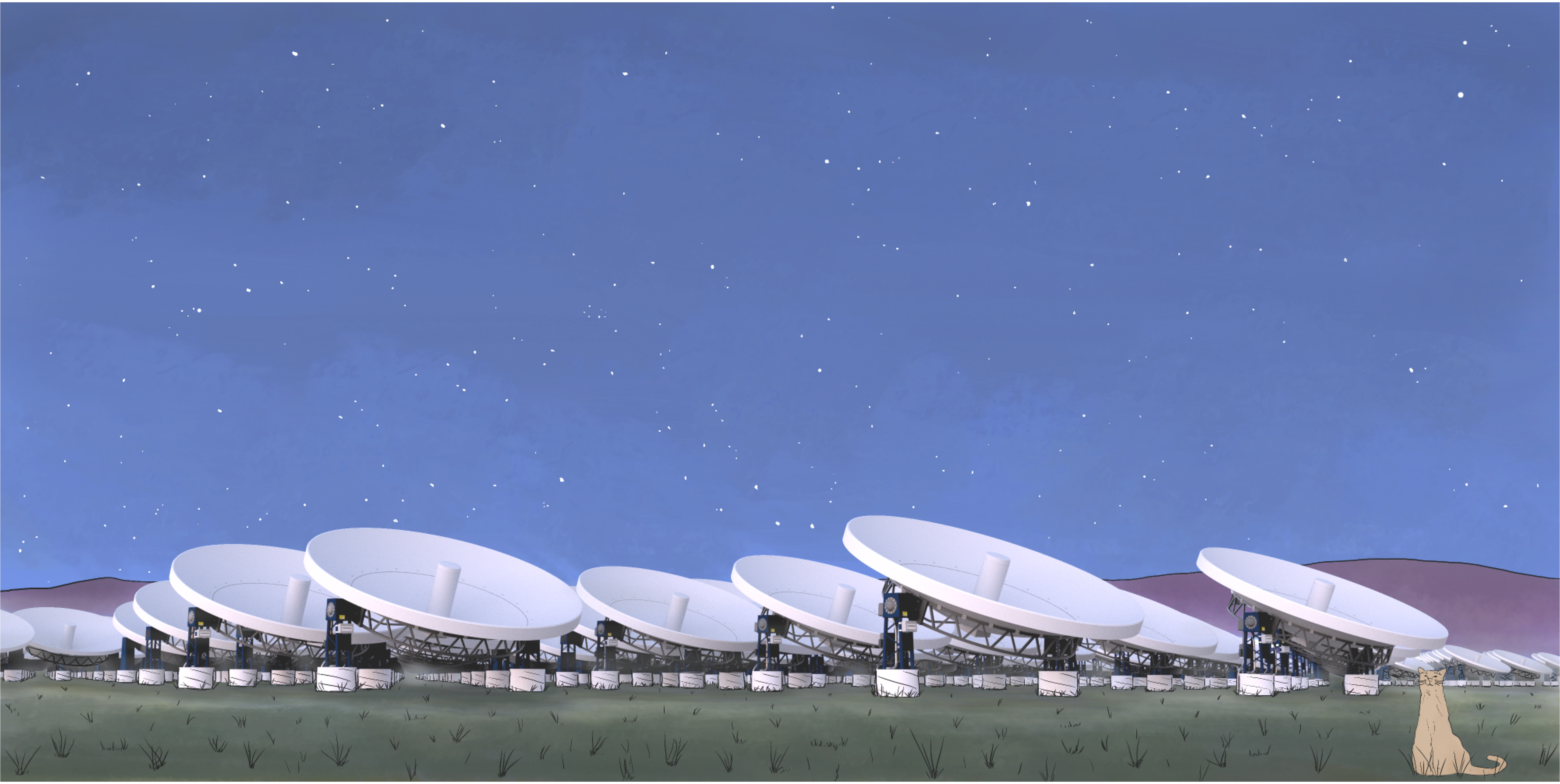
HIM: Tianlai Visibility: Sun Contamination

Power Distribution 09x22   10 day average





PUMA



Packed Ultrawideband Mapping Array formerly known as "Stage II"

PUMA

2 < z < 6 (200-500 MHz)

bandwidth smaller than CHIME/HIRAX

256 x 256 array 6m dishes

64 x HIRAX

dual polarization feeds

close packed

~ 1.5 km^2

(very different design than SKA)

highly redundant baseline

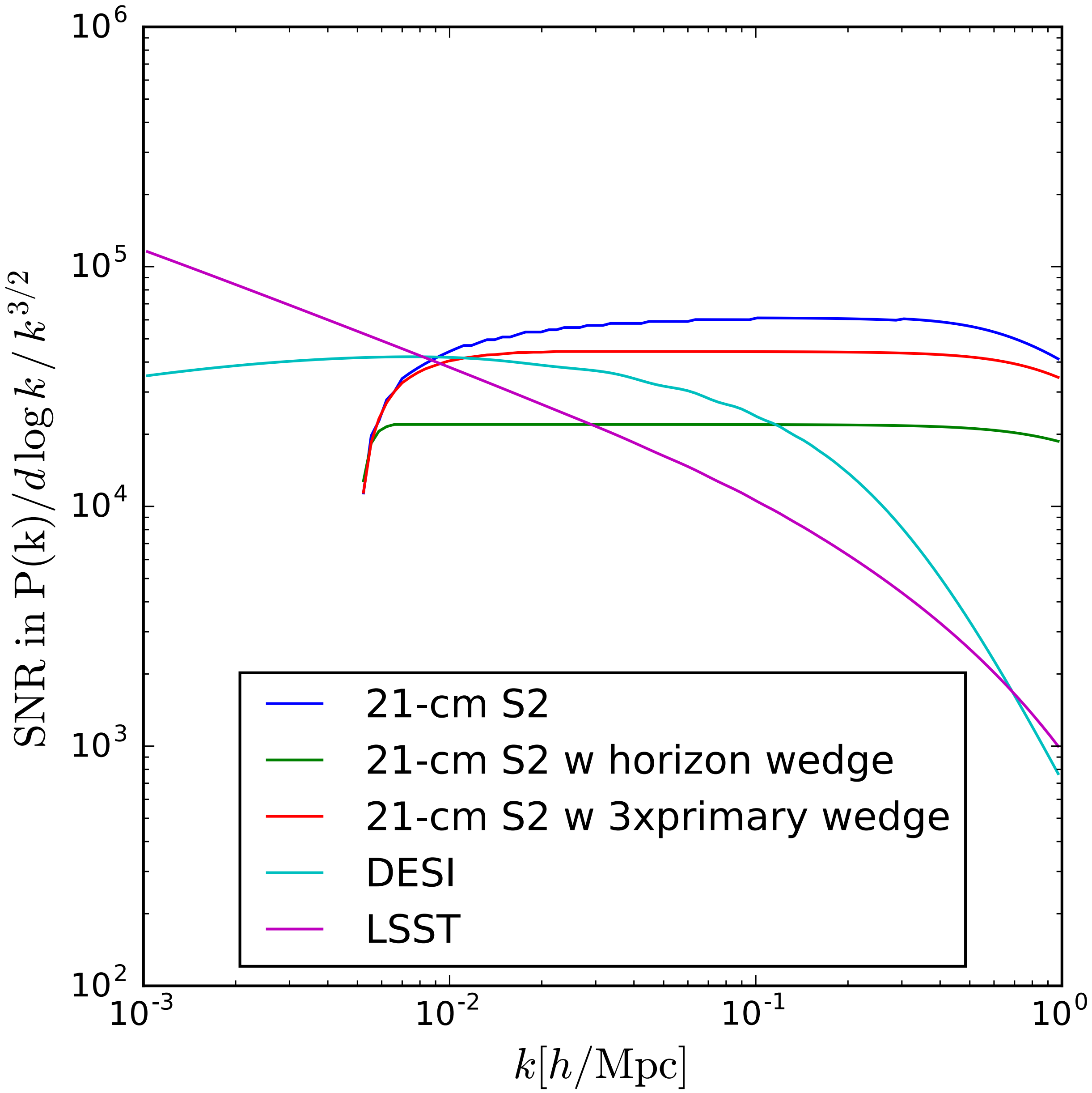
correlator

FFT (n log n) or direct summation ($n^{3/2}$)

learn from HIRAX

radial resolution ~3kHZ

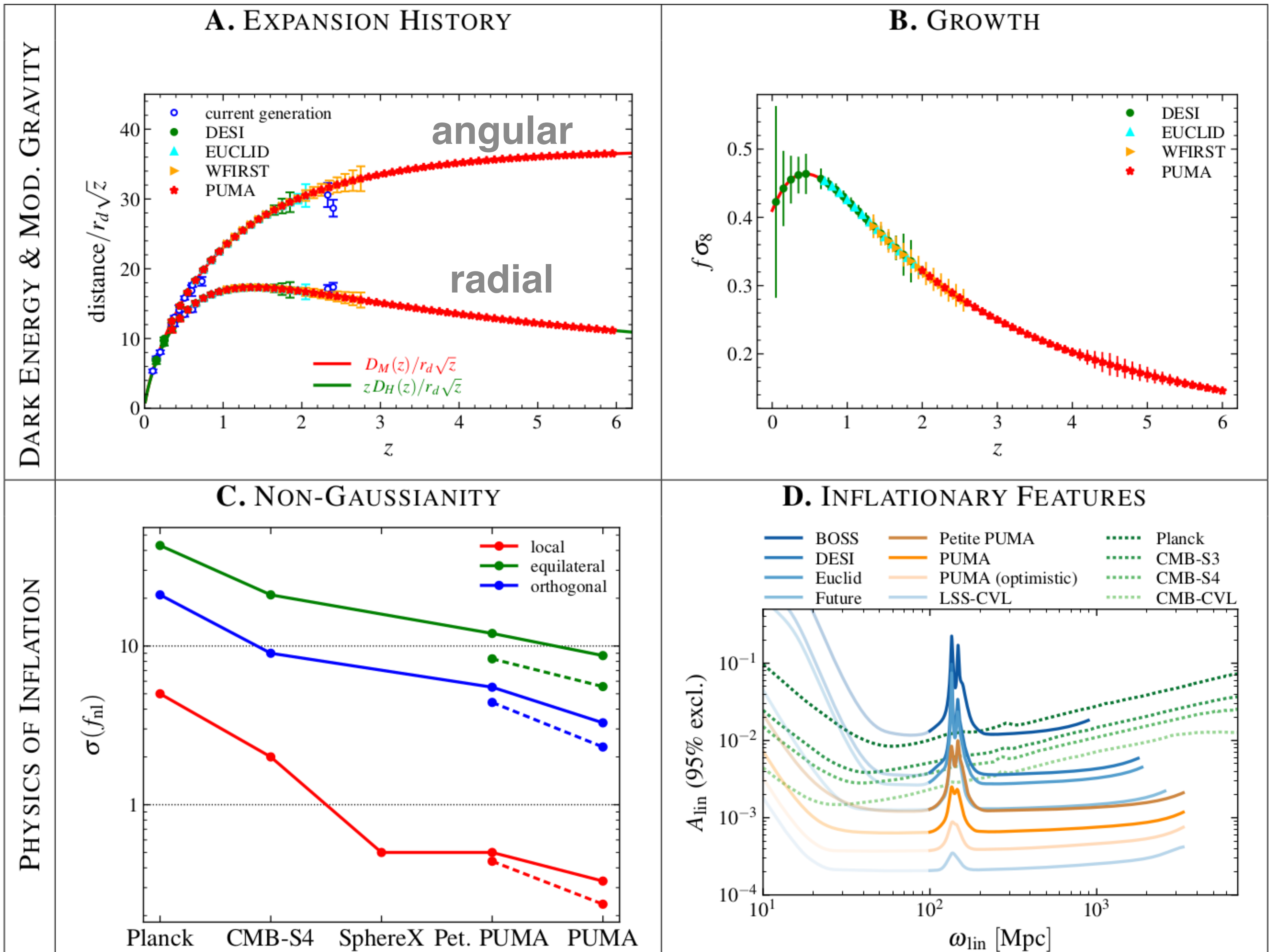
~ HIRAX



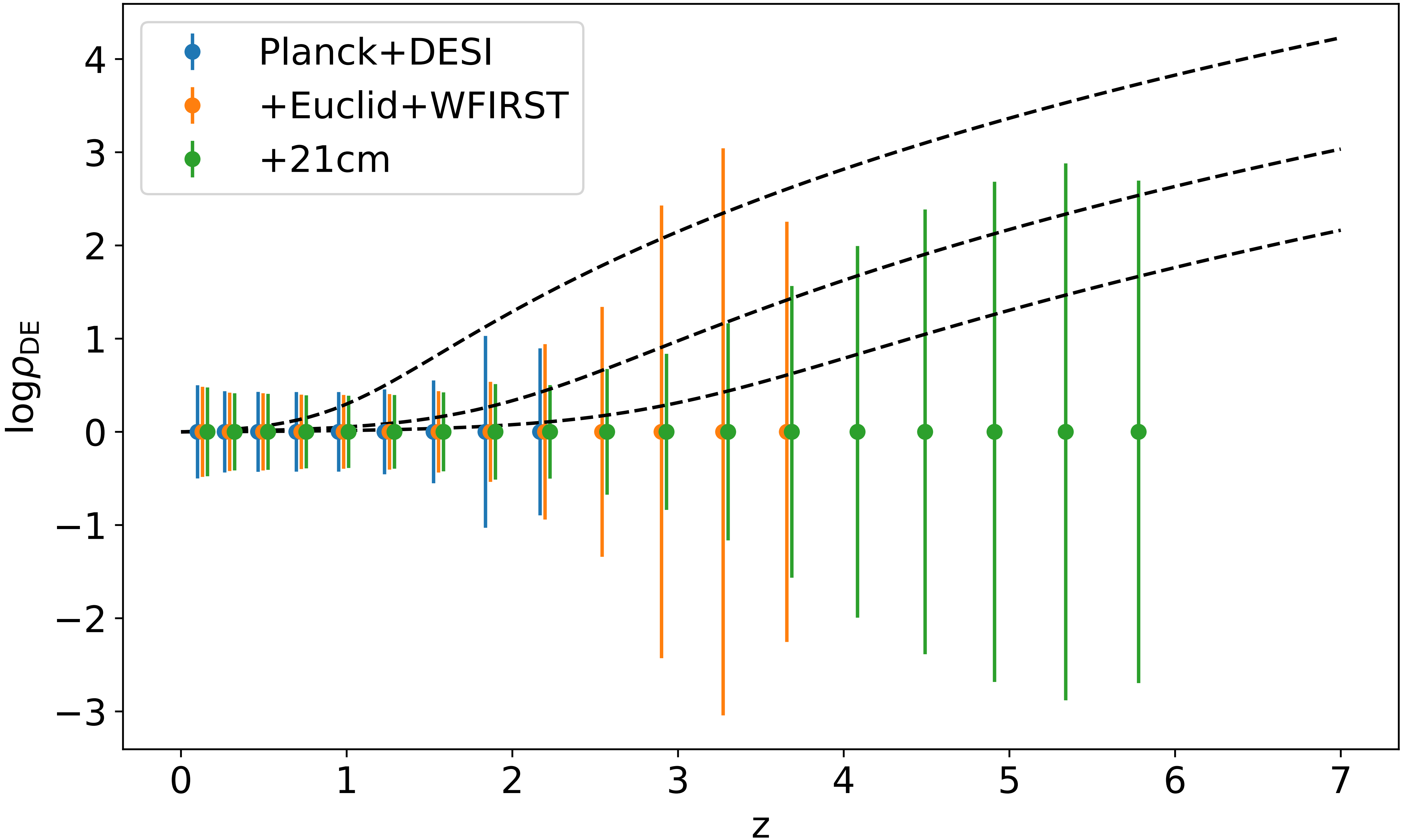
Total S/N in the power spectrum
DESI limited by the number density of sources
LSST by the precision of photometric redshifts.
21cm-S2 looses sensitivity at low-k due to foreground contamination but **has most volume and most accurate sampling**.

DOE21 "Cosmic Visions Dark Energy: 21-cm Roadmap" Slosar & co.

Projected Cosmological Constraints



Dark Energy Density



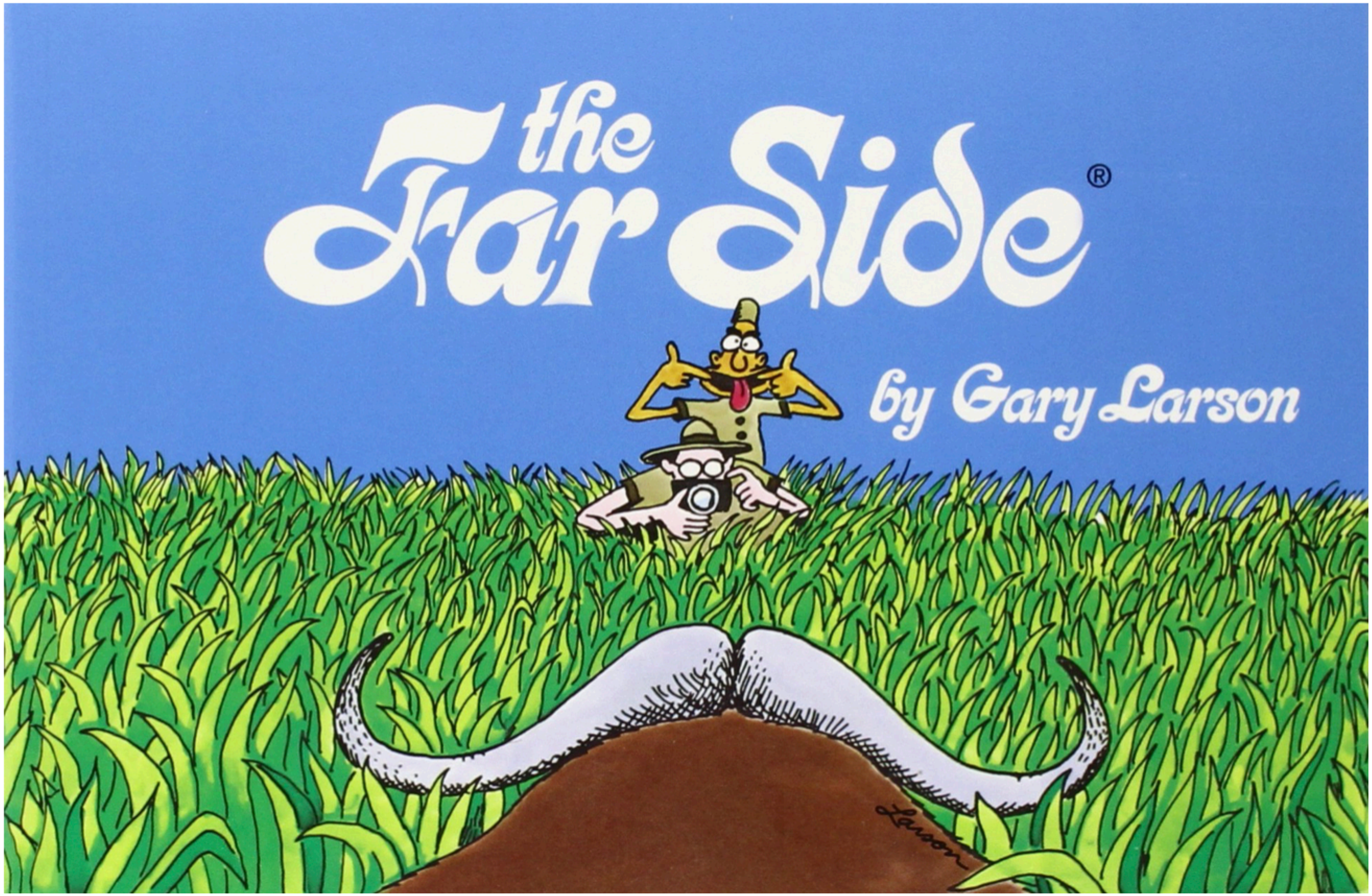
DOE21 "Cosmic Visions Dark Energy: 21-cm Roadmap" Slosar & co.

DOE21: 21cm Roadmap

	generation 1 post reionization 0 < z < 2	generation 2 post reionization 2 < z < 6	generation 3 dark ages 30 < z < 150	context
2018-2020	data taking construction 1st results	community building		LSST/DESI ongoing stage 1 first results decadal survey submission
2020-2025	stage 1 results continuation?	R&D based on stage 1 simulations firm up science case		LSST/DESI/Stage 1 P5 submission Decadal Survey results P5 results SKA online
2025-2030		optimize design collaboration forming CD0/CD1		LSST/DESI ending SKA results
2030-2035		construction start of data taking	feasibility study preliminary design	?
2035-2040		data taking analysis	construction start of data taking	?
2040-2045			data taking analysis	?

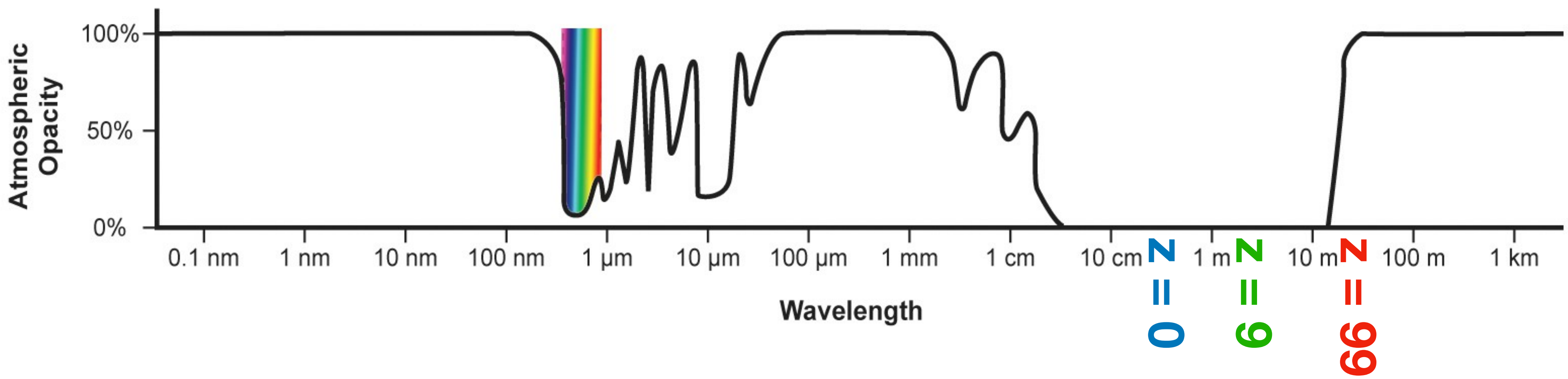
DOE21 “Cosmic Visions Dark Energy: 21-cm Roadmap” Slosar & co.

Space Based 21cm Cosmology

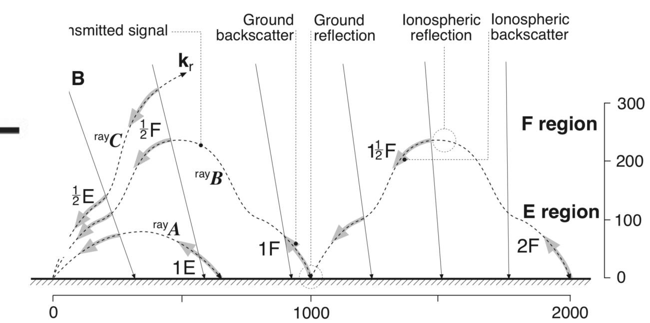


Why the Far Side? (of the Moon)

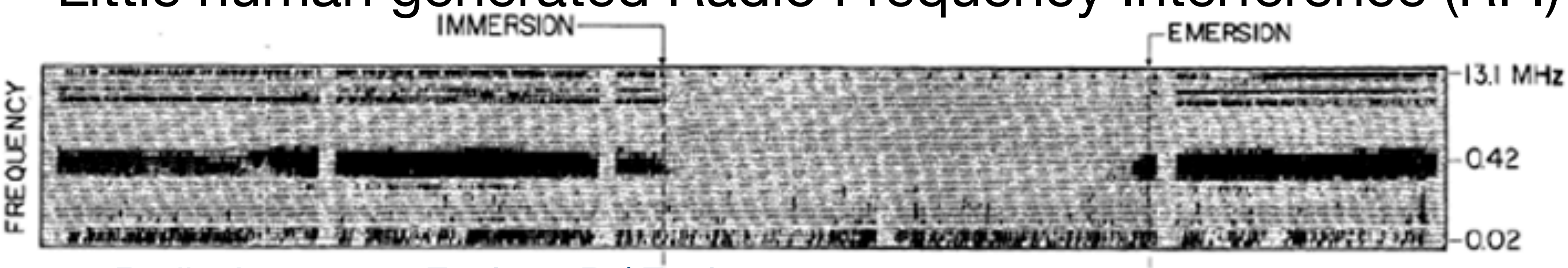
- No ionosphere (atmosphere or magnetic fields)

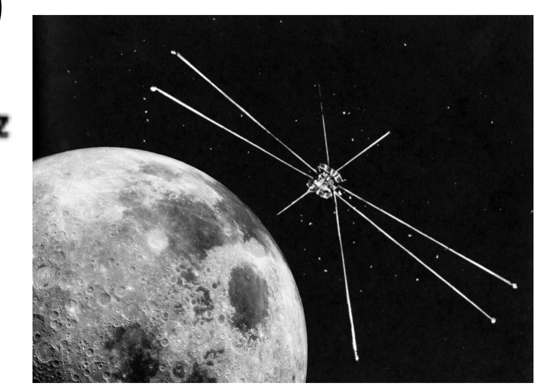


  - ν ≲ 30MHz EM waves don't propagate in straight lines



- Little human generated Radio Frequency Interference (RFI)





1973: Radio Astronomy Explorer B / Explorer 49

2018: Longjiang satellites (interferometer)

2018: Chang'e 4 lander (2018)

Discovering the Sky at the Longest Wavelength (DSL)

Dark Ages Radio Explorer (DARE)

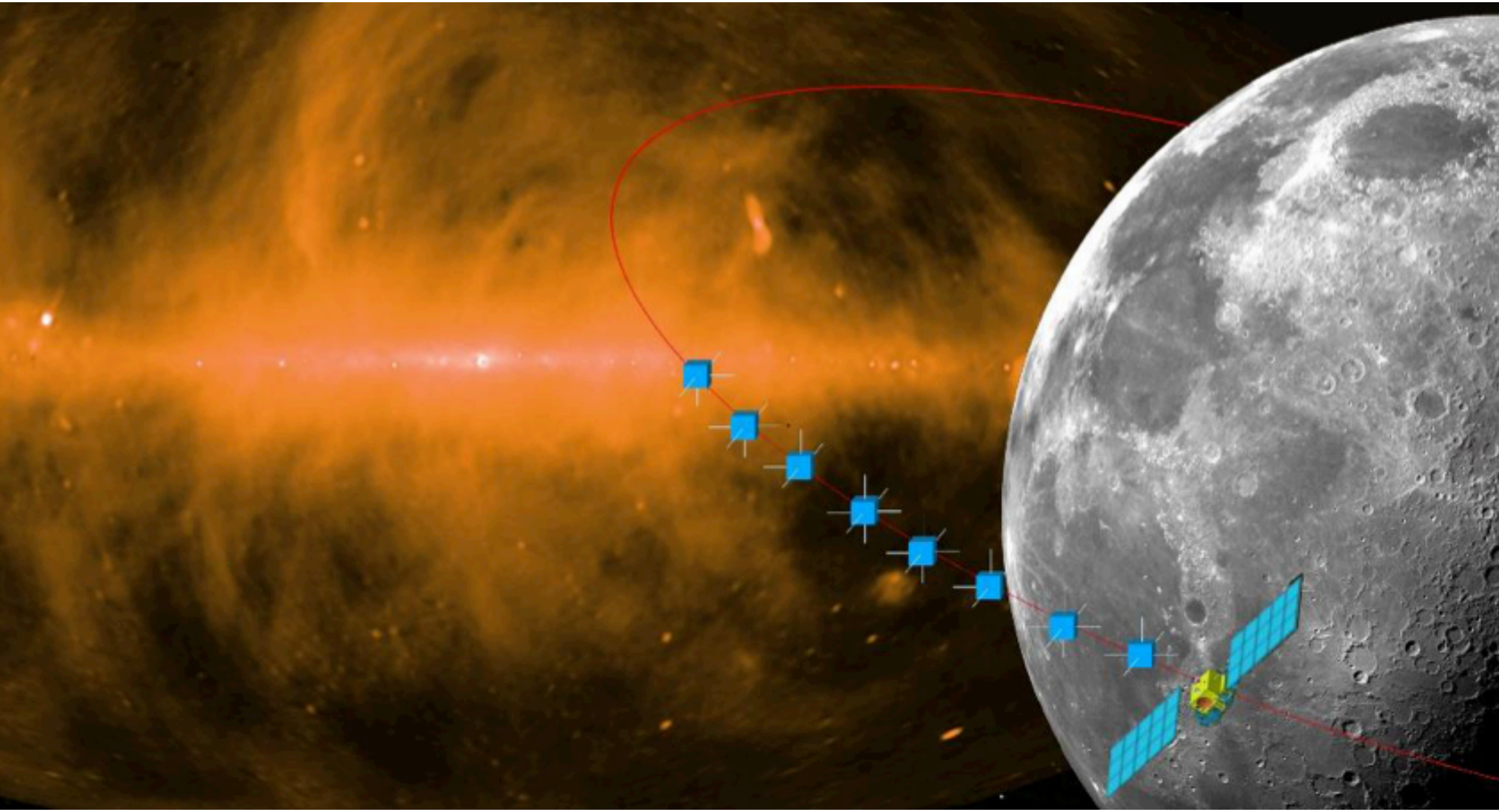
Dark Ages Polarimeter PathfindER (DAPPER)

Probing ReionizATion of the Universe using Signal from Hydrogen (PRATUSH)

Jester Falcke (2009)

Chen Burns Koopmans et al. (2019)

Lunar Orbit DSL



Discovering the Sky at the Longest wavelengths

PI: Xuelei Chen

DSL Technology and Challenges

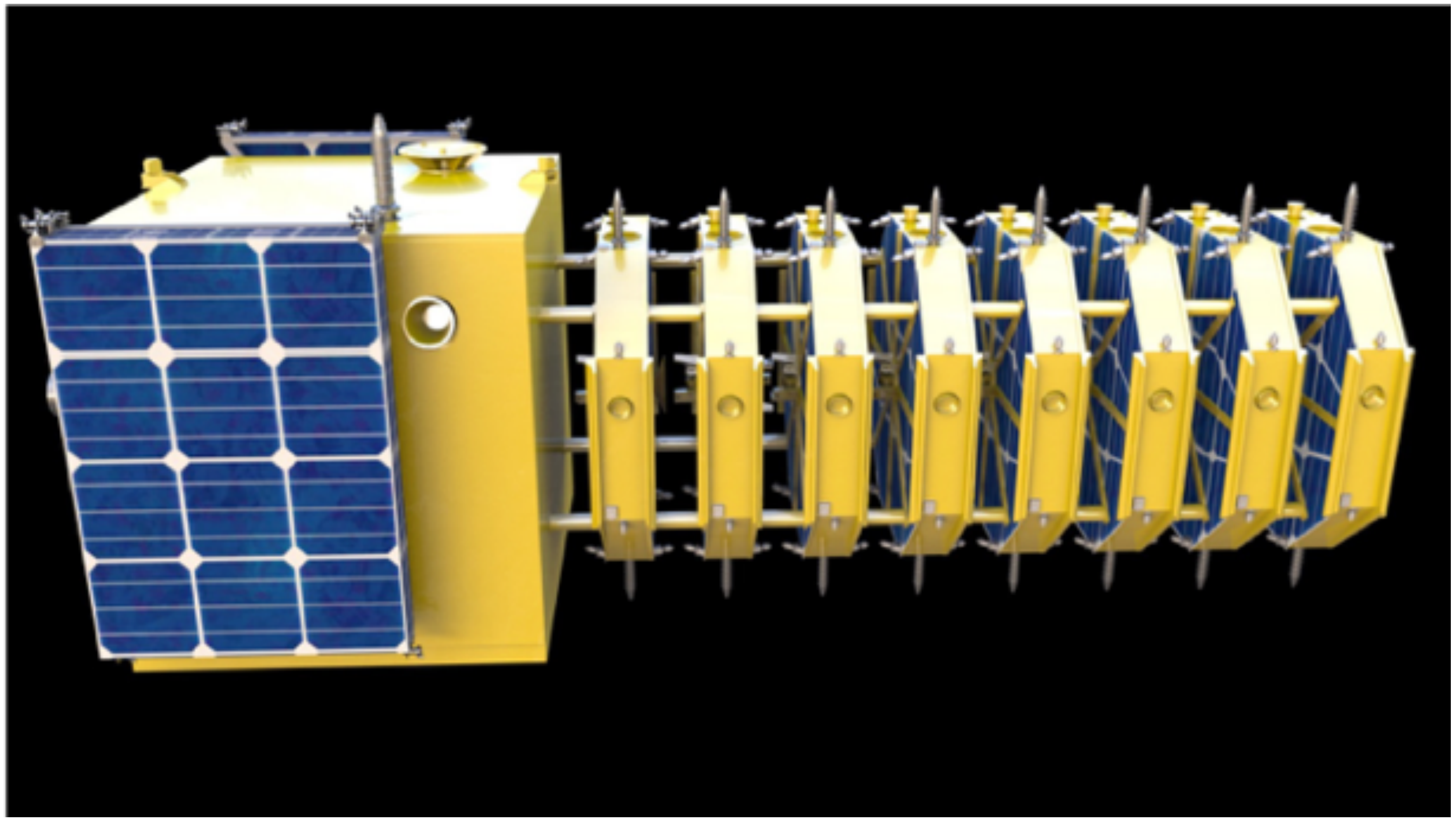
① **Satellite Formation Fly in lunar orbit with large variation on scales**

② **Precision Measurement of Relative Positions and synchronization**

③ **High precision calibration of phase and amplitude**

④ **Imaging algorithm with large field of view, 3D baseline distribution, and time-dependent blockage**

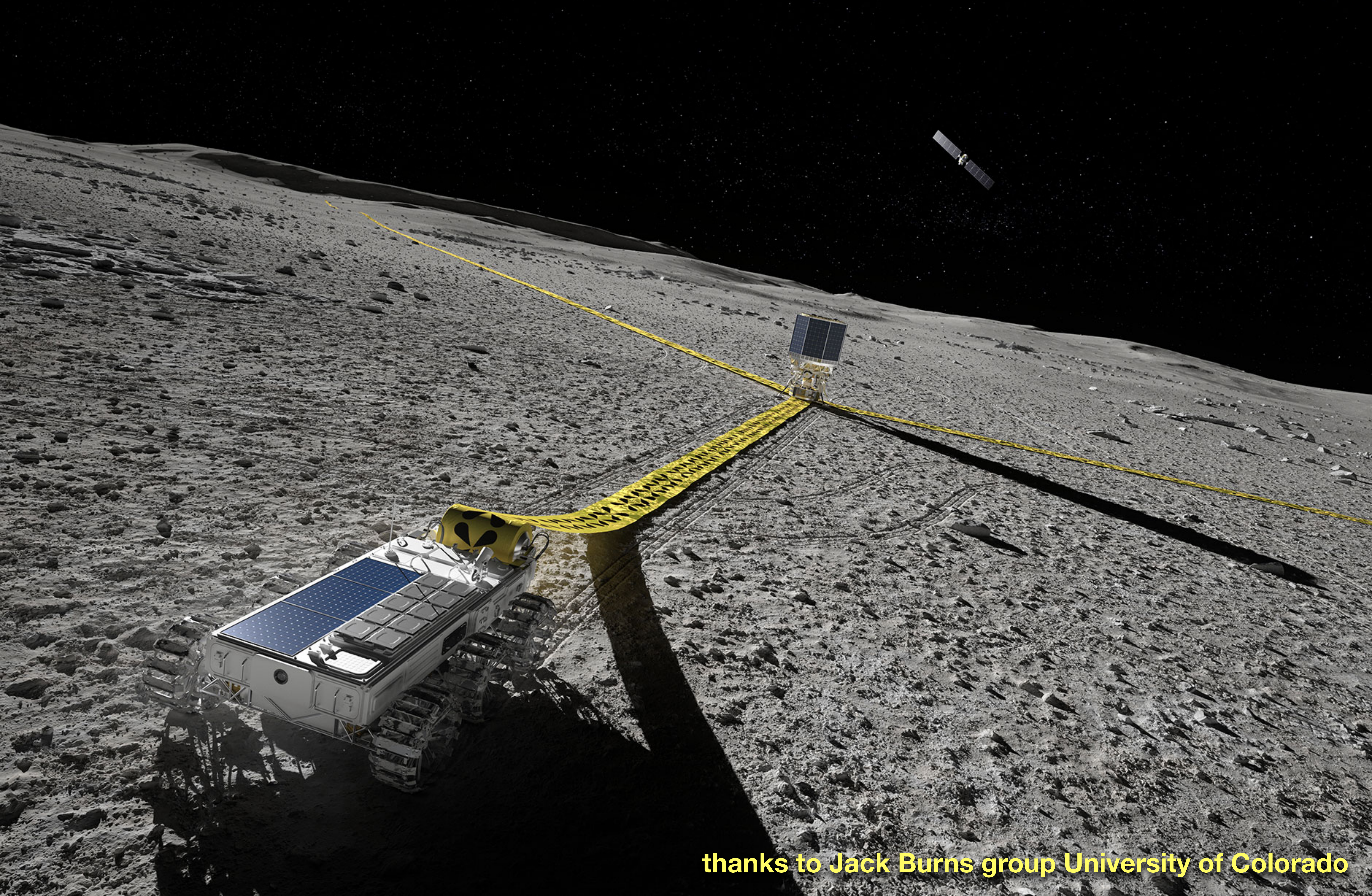
⑤ **Electromagnetic interference (EMI) suppression and removal**



DSL Parameters

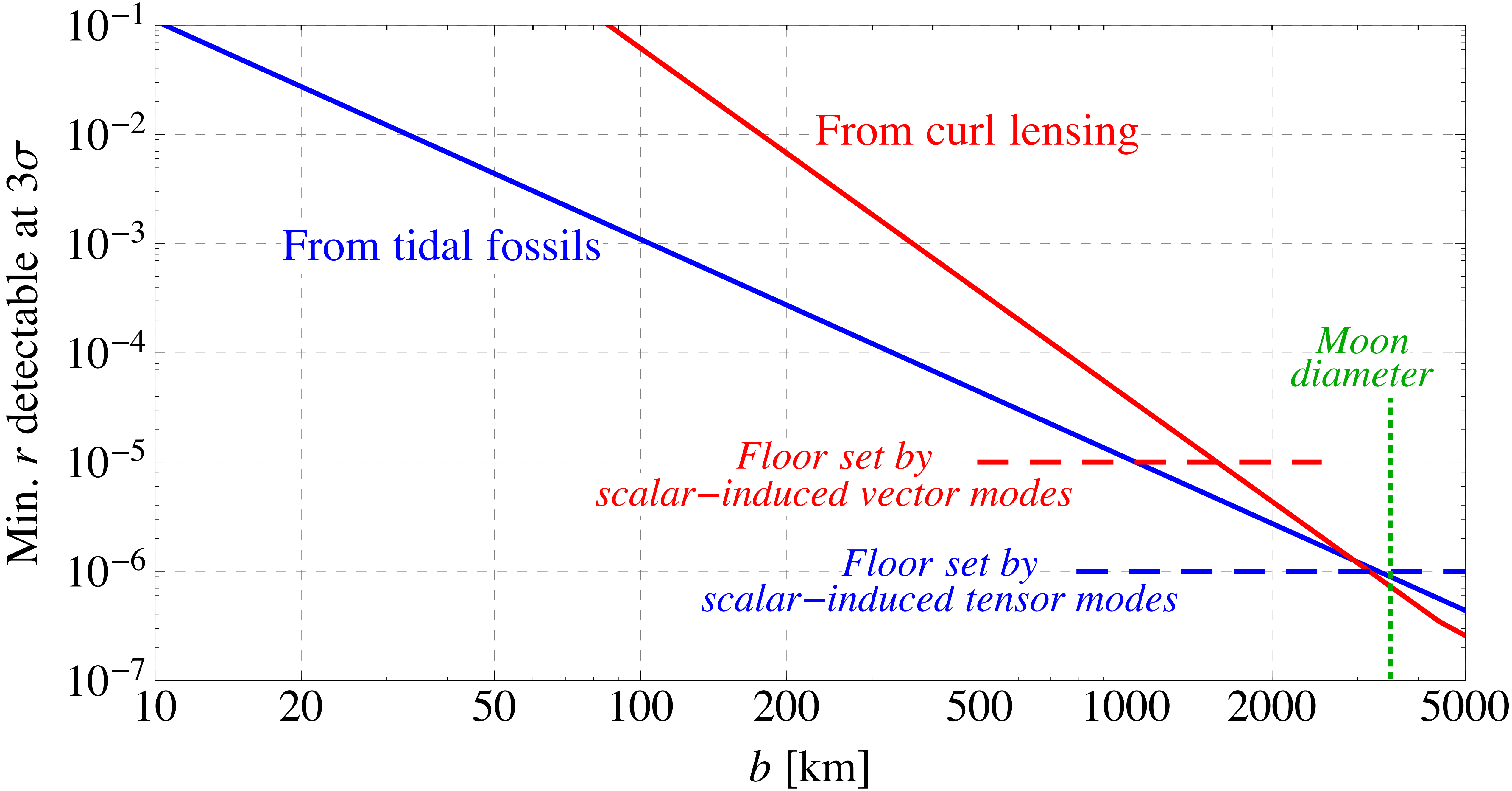
System	Parameter
Number of Satellites	1 mother + 5~8 daughters
Orbit	300km lunar cirlcular orbit, about 30^0 inclination
Baselines	0.1~100km
Sensitivity	<0.1K@30MHz（1 year integration,1MHz BW)
angular resolution	<0.2 degree@1MHz，0.012 degree@30MHz
Individual	
Polarization	3 linear polarization
Frequency	1MHz~30MHz（interferometry incl. spectrum) 30MHz~120MHz（global spectrum)
Baseline prescision in each direction (1σ)	< 1m
Synchronization	<3.3ns
Inter-satellite data communication	>20Mbps each daughter satellite

the Dark Side



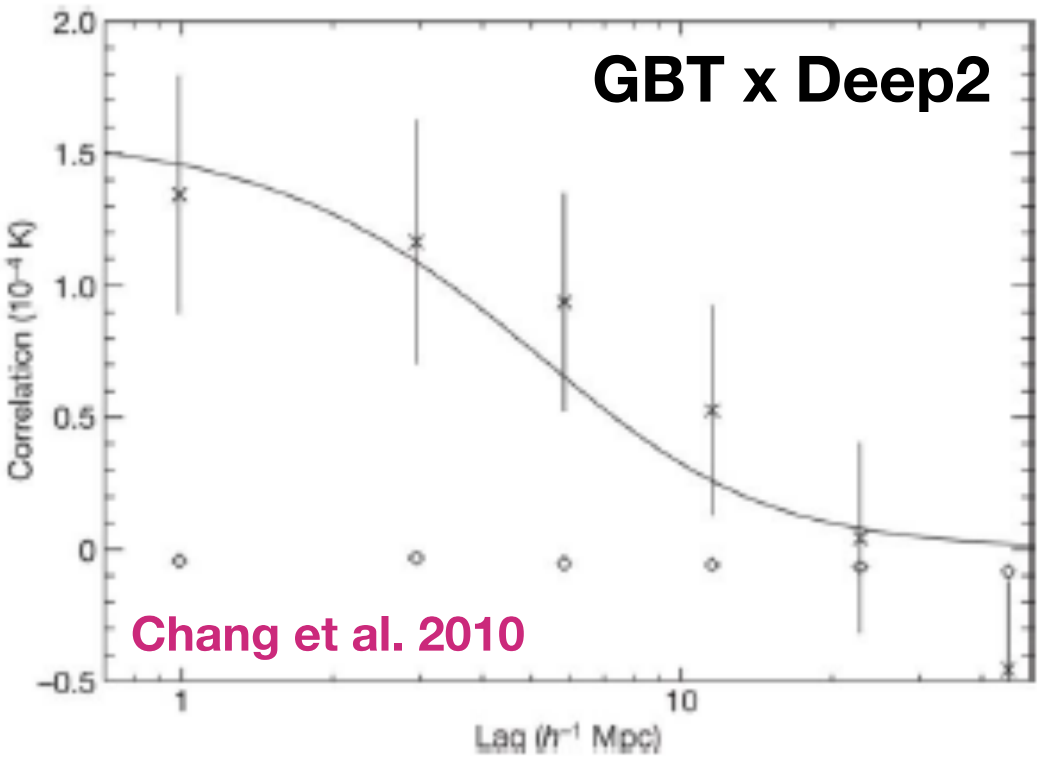
thanks to Jack Burns group University of Colorado

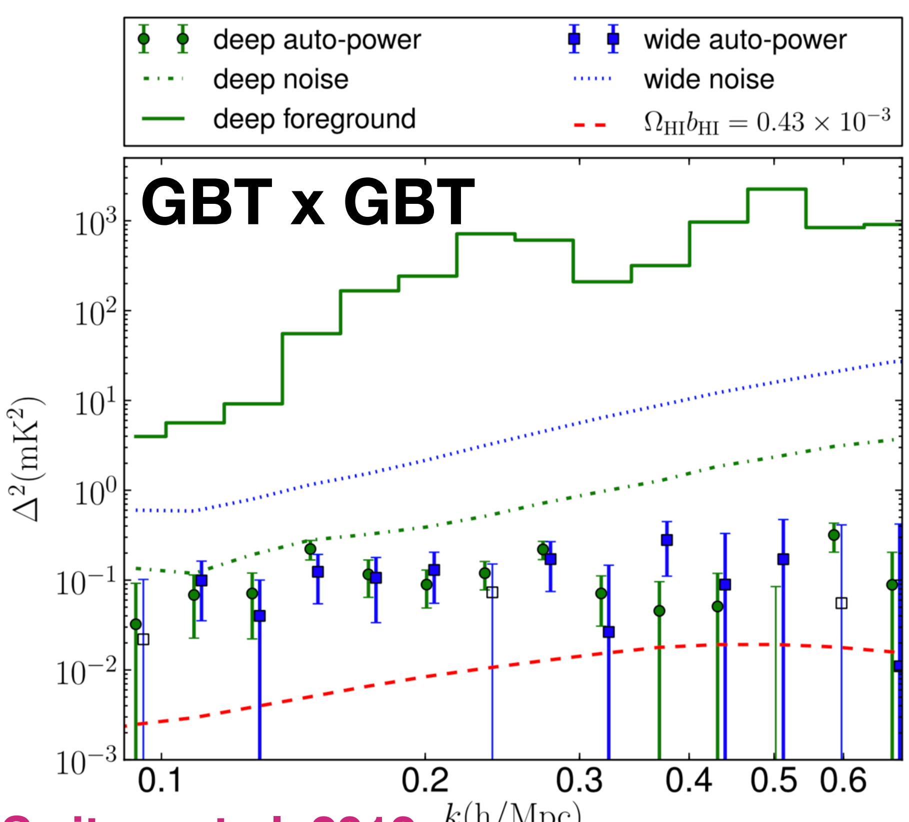
Primordial Gravity Waves from The Dark Side



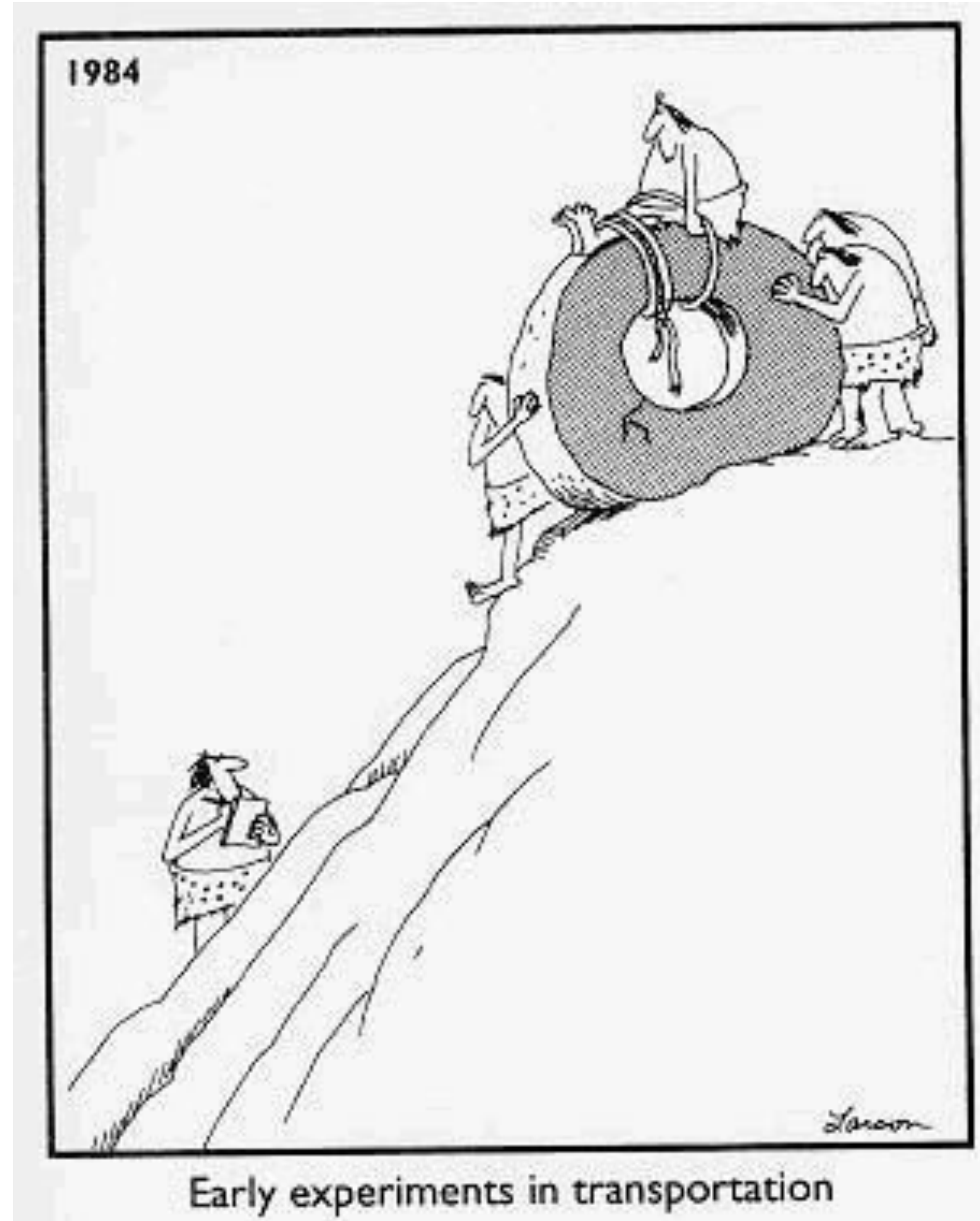
DOE21 "Cosmic Visions Dark Energy: 21-cm Roadmap" Slosar & co.

Where’s the HI?





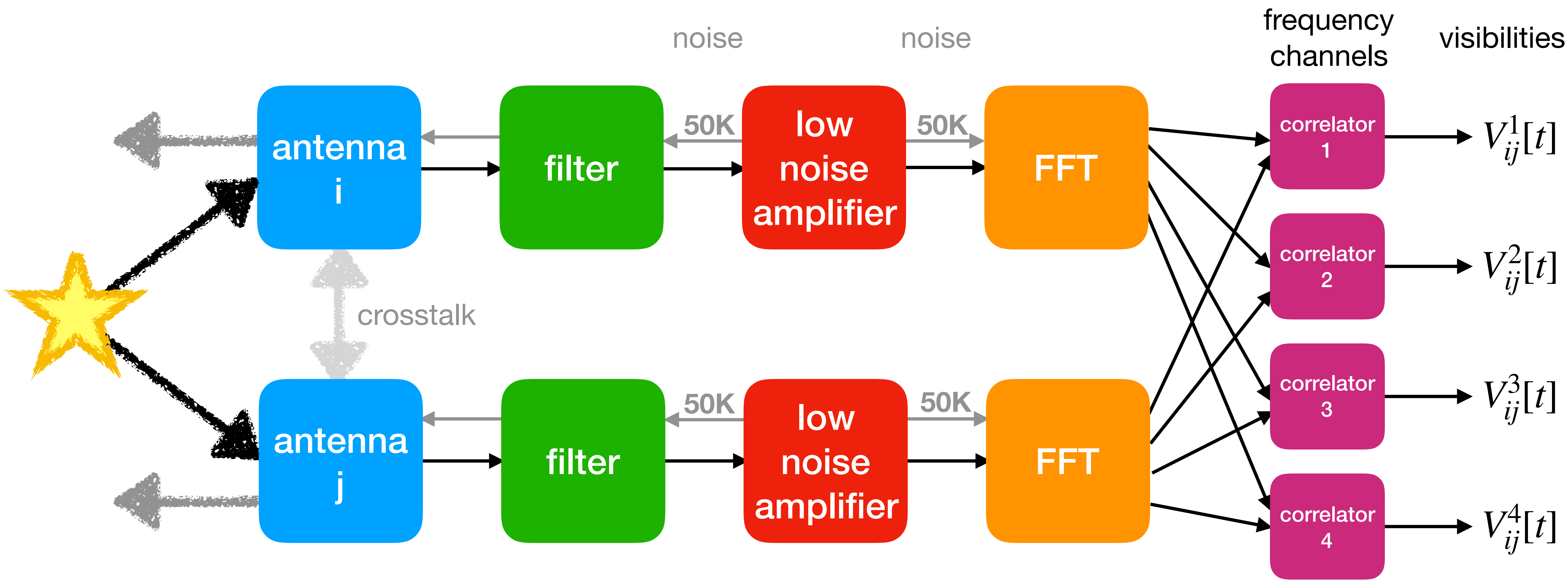
Switzer et al. 2013



see also
Masui et al. 2013
Anderson et al 2017

expect new 21cm detections soon (hopefully)

Hydrogen Intensity Mapping: Visibilities



- $n\,(n+1)\,/\,2$ visibilities $\quad n$ = # of antennae ~10^2-10^3
- number of frequency channels ~10^3
- visibilities computed every $\delta t=1/\delta\nu$ ~ μsec
- visibilities averages over Δt ~ sec
- time ordered data produced ~10^0-10^2 PByte/year
- final 3D HI maps < 1 TByte

Hydrogen Intensity Mapping: Smooth Spectrum Foregrounds

e.g. optically thin ultra-relativistic synchrotron emission

$$I_\nu[\overrightarrow{\theta}] = \frac{3}{4\pi^2}\frac{e^3}{m_e c^2}\int d\ell \int d^2\hat{\overrightarrow{\beta}}\int_0^\infty d\gamma\, \frac{d^3 n_e}{d^2\hat{\overrightarrow{\beta}}\, d\gamma}[\ell, \hat{\overrightarrow{\beta}}, \gamma]\,\frac{\nu}{\nu_c}\,F[\frac{\nu}{\nu_c}]\,\frac{\delta[\psi-\delta]}{Cos[\psi]} \qquad \nu_c = \gamma^2\,\frac{3eB}{4\pi\, m_e\, c}$$

$$F[y] = y\int_{-\infty}^{\infty} dX\,(1+X^2)^2\left(K_{2/3}\left[\frac{1}{2}\,y\,(1+X^2)^{\frac{3}{2}})\right]^2 + \frac{X^2}{1+X^2}\,K_{1/3}\left[\frac{1}{2}\,y\,(1+X^2)^{\frac{3}{2}})\right]^2\right)$$

F[*y*] is an extremely smooth function.

Fourier transform fall off as k^{-4}.

No matter what the electron distribution is I_ν will be a smooth function of ν.

Mono-energetic electrons / fixed B produces most non-smooth spectrum

this is alway the example we will use.

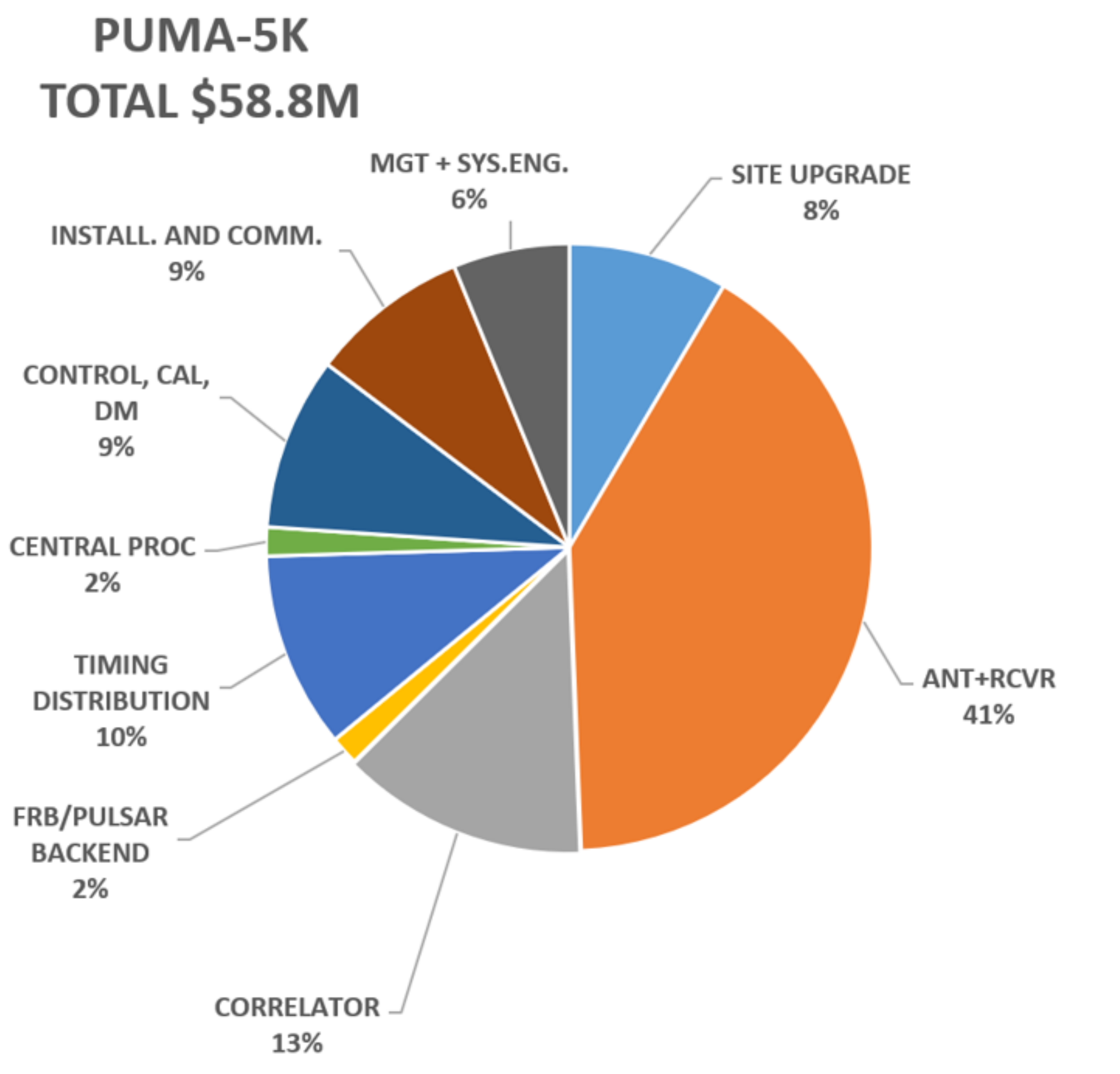
In contrast 21cm line emission can be arbitrarily non-smooth

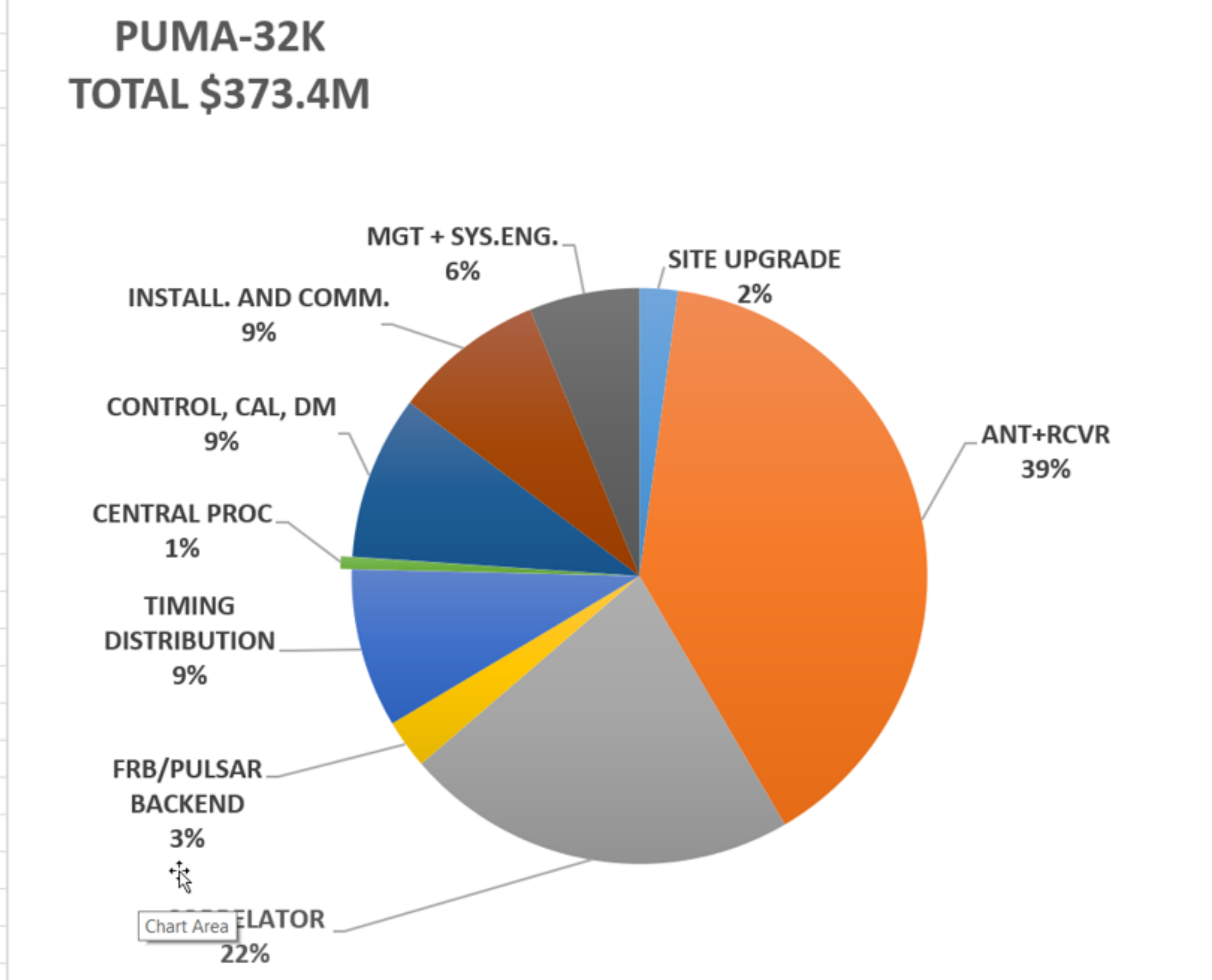
Lo-pass filtering in frequency should reveal 21cm emission

HIM: Transit Telescopes and m-Mode Analysis

- Due to *extreme* sensitivity to telescope beam pattern it is best not to move the telescope array during observation.
    - Moving optical elements wrt each other changes beam pattern.
    - so one does not “point” the telescope.
    - Earth rotation will scan the sky
    - this is a **transit telescope**
- If a transit telescope is “stable”
    - time weighted visibility $e^{-i\,m\,\varphi}\,V_{ij}[t]$ where $\boldsymbol{\varphi}=2\,\pi\,t_{sidereal}/day_{sidereal}$ will only be sensitive to $e^{i\,m\,\boldsymbol{\alpha}}$ component of illumination where $\boldsymbol{\alpha}$ is right ascension (RA) in radians.
    - **there is no uncertainty in RA dependence of “synthetic” beam pattern!**
    - however one must determine declination (dec) dependence.
    - (non varying) astronomical sources provide a constant (RA,dec) illumination
    - non-astronomical sources in Solar System, RFI (human generated Radio Frequency Interference) do not.
- Sidereal time $t_{sidereal}$= Mod[t+(longitude/360°)), $day_{sidereal}$] angle or time: xxx° or $xx^h yy^m zz^s$

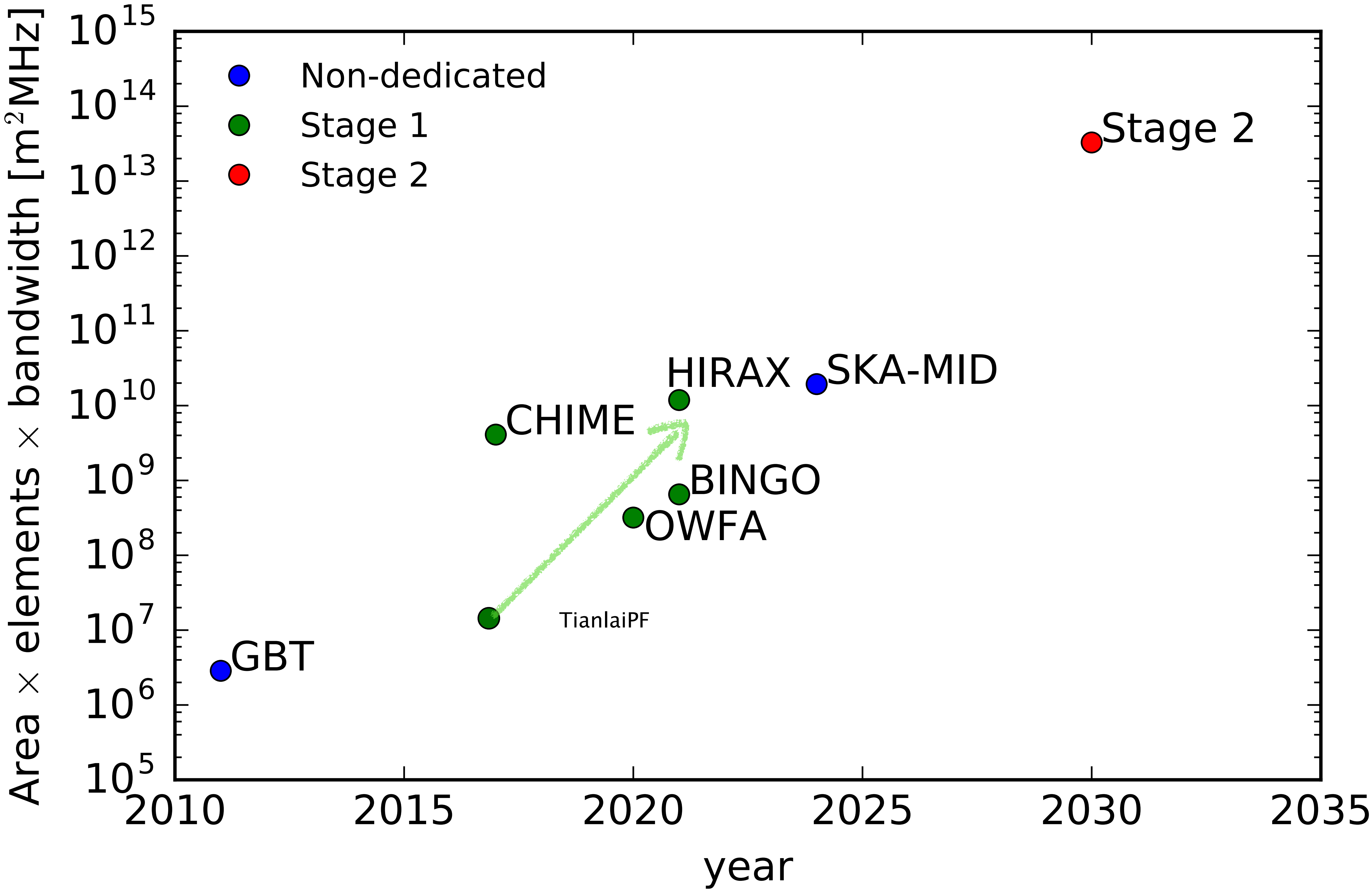
Cost



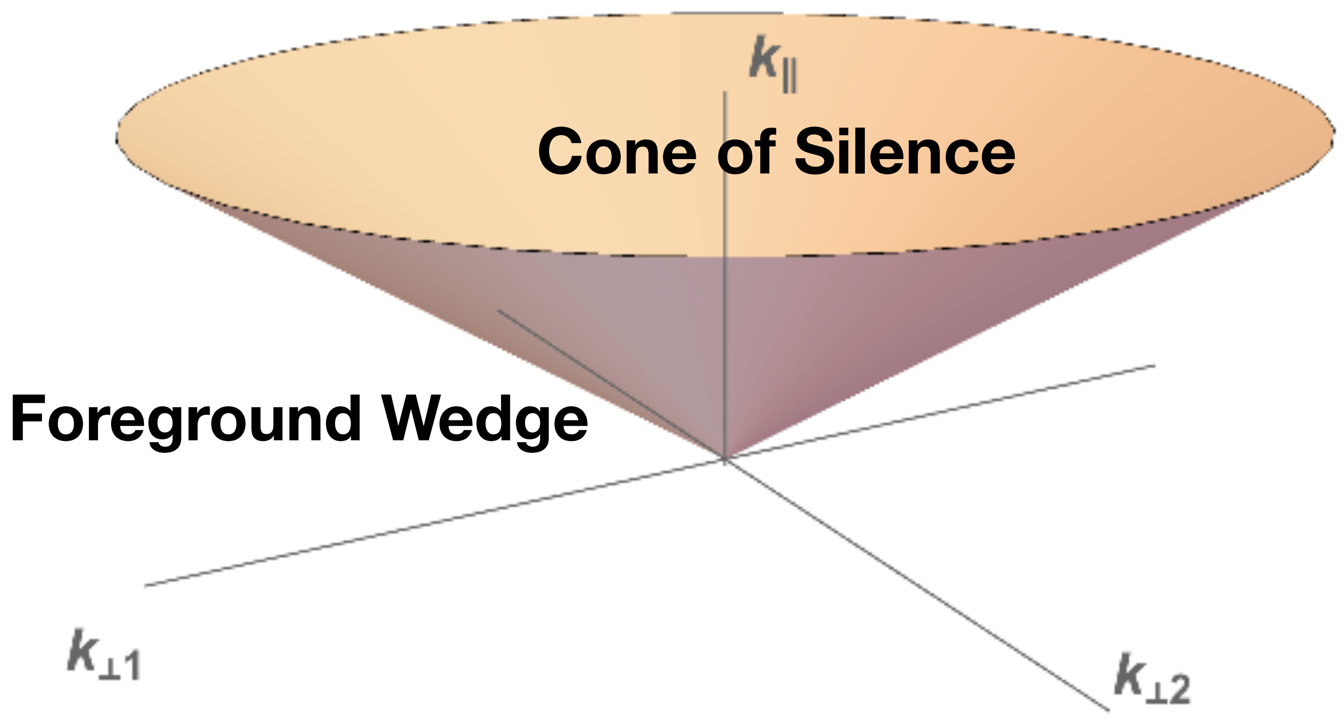


DOE21 "Cosmic Visions Dark Energy: 21-cm Roadmap" Slosar & co.

Hydrogen Intensity Mapping (HIM): experiments



Hydrogen Intensity Mapping: hi-$k_{||}$ analysis



Due to chromaticity of beams non-smooth angular structure of sources will leak into frequency structure (mode mixing) filling the **foreground wedge**. Ideally the **cone of silence**, the complement of the wedge, is not contaminated by smooth spectrum sources, however there is no well defined boundary so one must determine the leakage of smooth spectrum sources into all parts of k-space.

Discover the Hilbert subspace of the "space of beams" with little contamination.

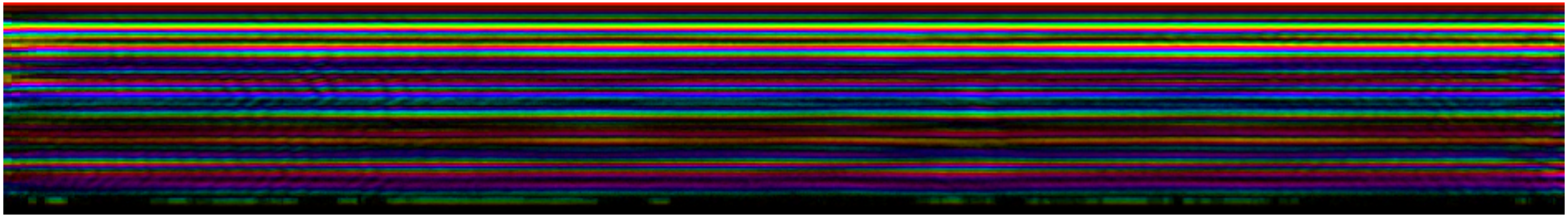
To search for non-smooth spectrum emission one might *initially* look as far away from the foreground wedge as possible, *e.g.* large $k_{||}$ for individual visibilities.

This requires no knowledge of the beam, only that $|k_{||}| \gg |\mathbf{k}_{\perp}|$.

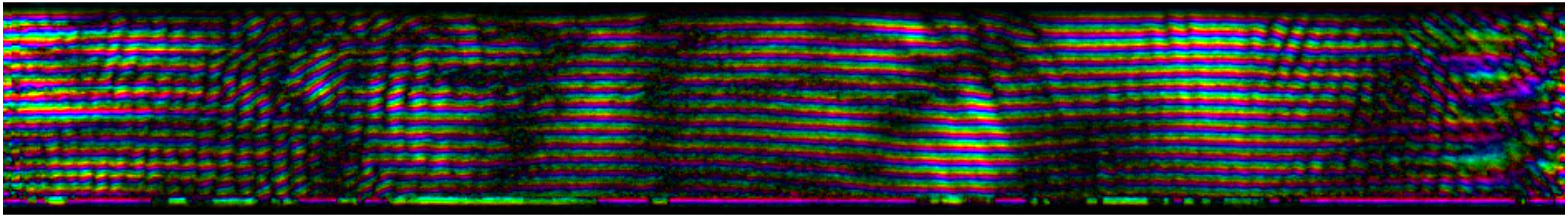
At present 21cm intensity mapping experiments suffer from non-detection of 21cm emission. *"Finding it" should be a high priority*. We can do so by looking for non-smooth spectrum emission away from the wedge.

HIM: Tianlai Visibility: Nighttime Mean Subtraction

without subtraction



with subtraction



? Correlated noise / “cross talk” ?

Hydrogen Intensity Mapping: The Tianlai Site