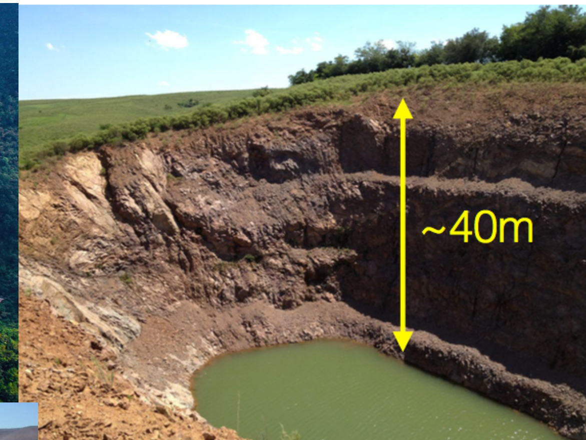
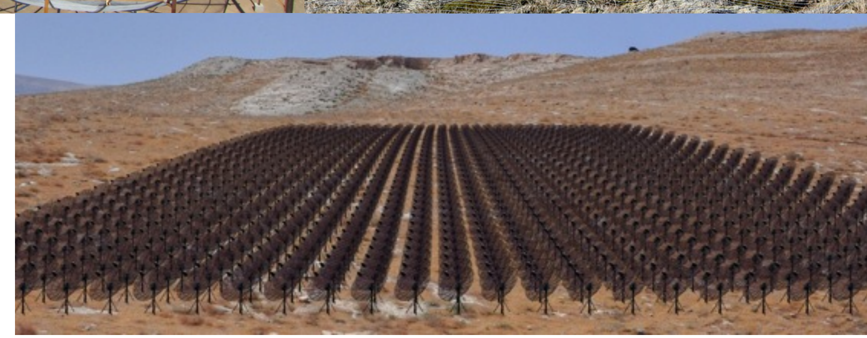
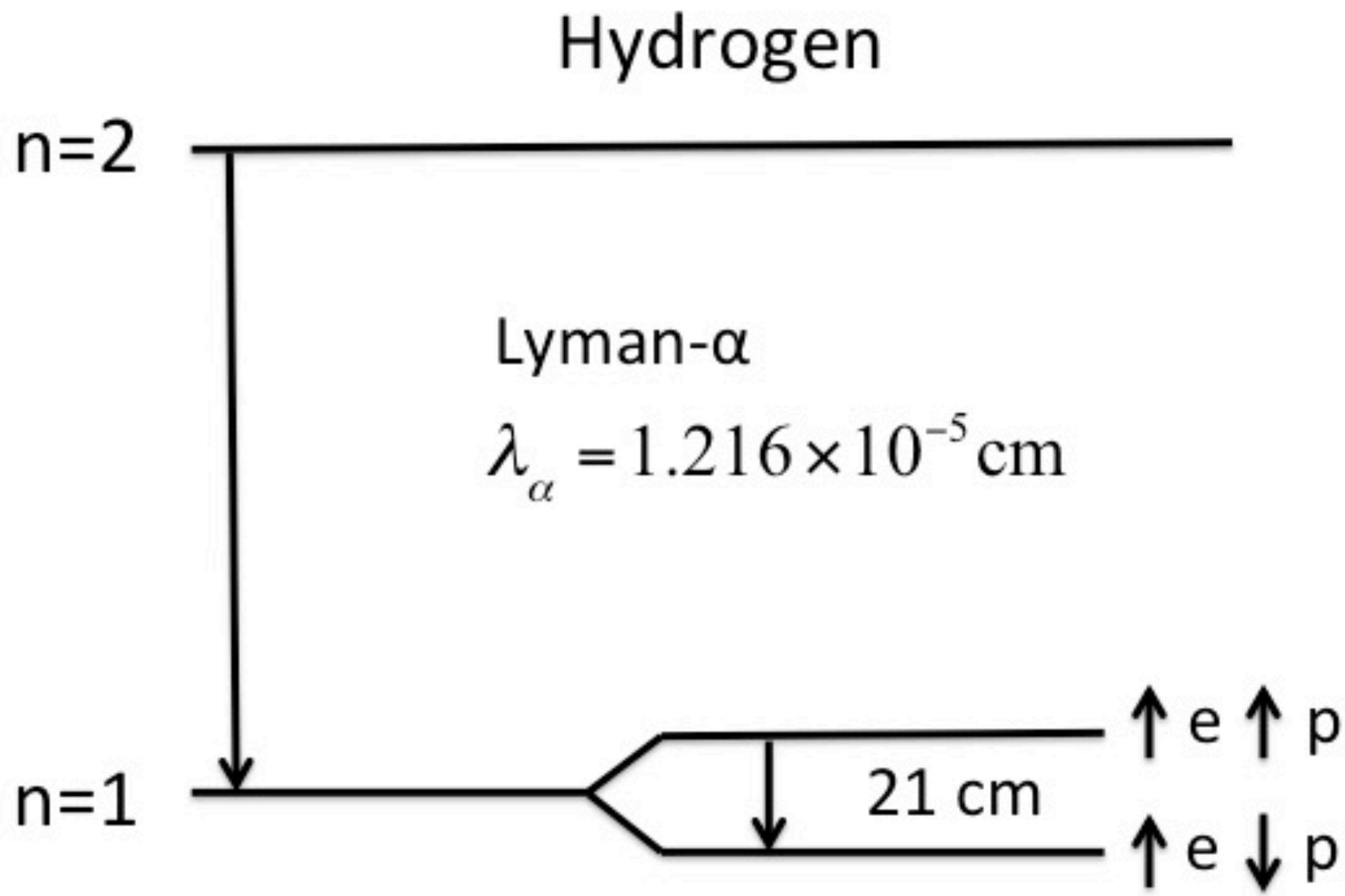
21-cm cosmology

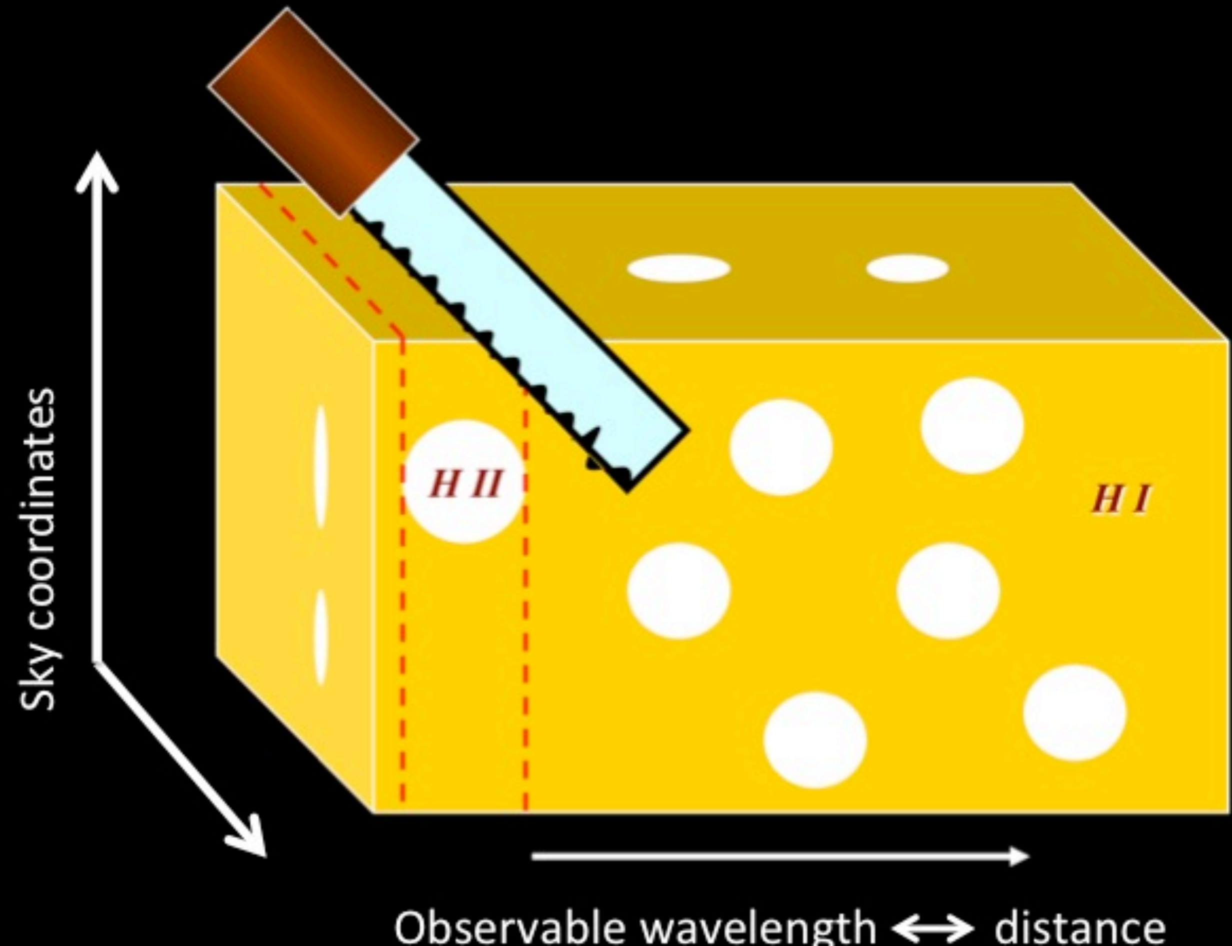




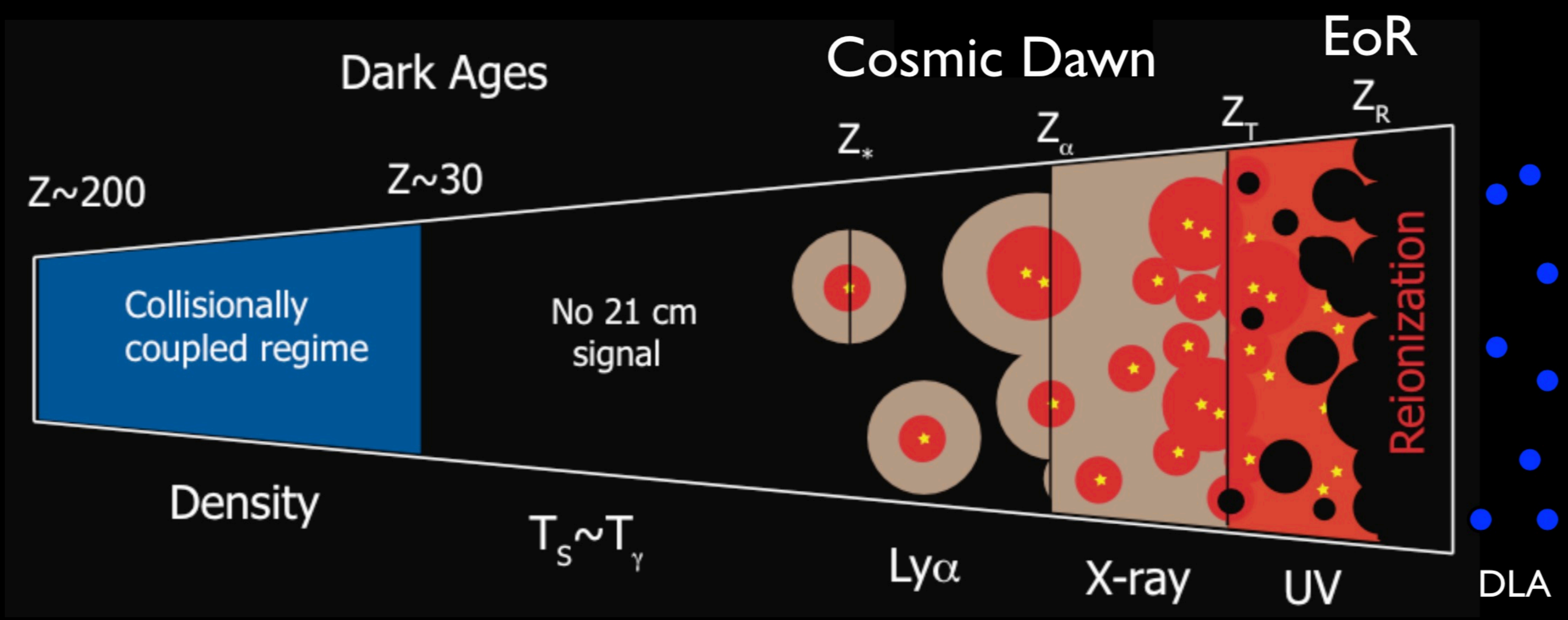
Yin-Zhe Ma
University of KwaZulu-Natal

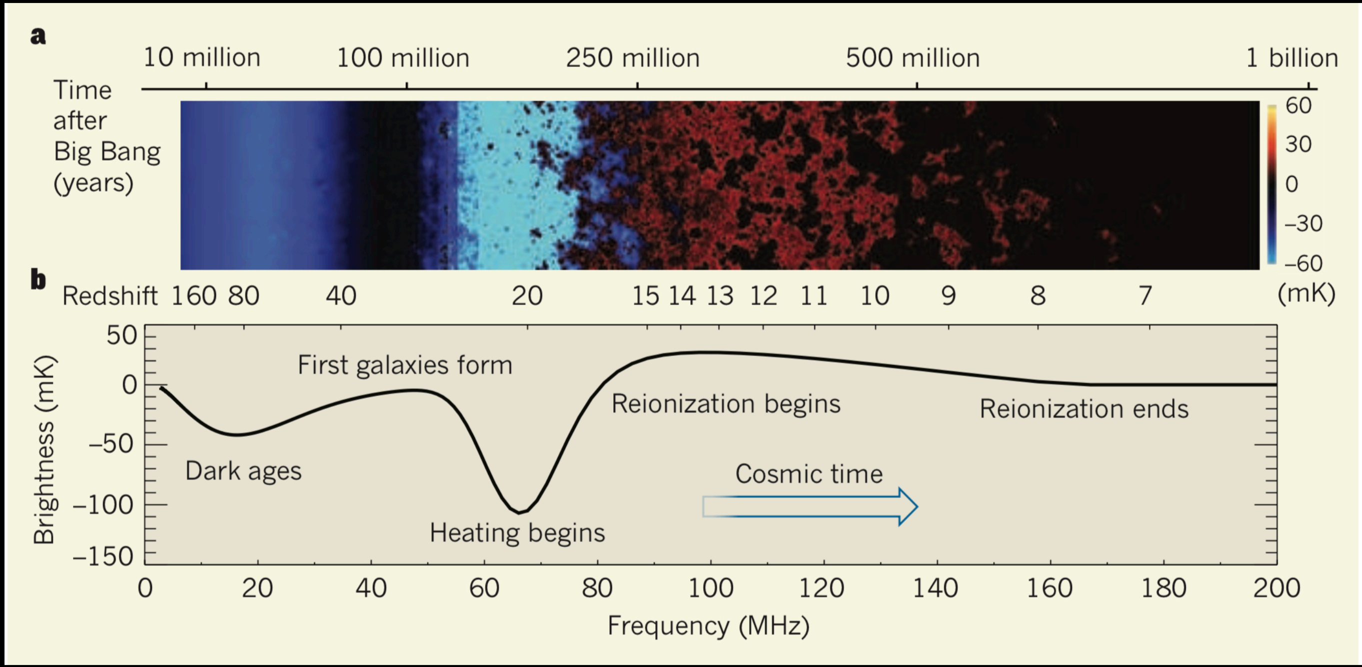
- General forecasts for BINGO, FAST and SKA:
- Xiaodong Xu, Yin-Zhe Ma, Amanda Weltman, 2018, Physical Review D (Impact factor: 4.506), 97, 083504, Constraining the interaction between dark sectors with future HI intensity mapping observations
- M.-A. Bigot-Sazy, Y.-Z. Ma, R. A. Battye, I. W. A. Browne, T. Chen, C. Dickinson, S. Harper, B. Maffei, L. C. Olivari, P. N. Wilkinson, 2016, Astronomical Society of the Pacific Conference Series, 502, 41–48 (8 pages), HI Intensity Mapping with FAST
- L. C. Olivari, C. Dickinson, R. A. Battye, Y.-Z. Ma, A. A. Costa, M. Remazeilles and S. Harper, 2018, Monthly Notices of the Royal Astronomical Society (Impact factor: 4.952), 473, 4242– 4256, Cosmological parameter forecasts for H I intensity mapping experiments using the angular power spectrum
- Yi-Chao Li, Yin-Zhe Ma, 2017, Physical Review D (Impact factor: 4.506) 96, 063525 Constraints on Primordial non-Gaussianity from Future HI Intensity Mapping Experiments
- Specific forecasts for SKA:
- Stuart Harper, Clive Dickinson, Richard Battye, Sambit Roychowdhury, Ian Browne, Yin-Zhe Ma, Lucas Olivari, Tianyue Chen, 2018, MNRAS, 478, 2416, "Impact of Simulated 1/f Noise for HI Intensity Mapping Experiments"
- Santos et al., 1709.06099
- Specific forecasts for BINGO:
- Marie-anne Bigot-Sazy, Clive Dickinson, Richard A. Battye, Ian Browne, Yin-Zhe Ma, Bruno Maffei, Fabio Noviello, Mathieu Remazeilles, Peter Wilkinson, 2015, Monthly Notice of Royal Astronomical Society (Impact factor: 4.952), 454, 3240 (14 pages)
  Simulations for single-dish intensity mapping experiments
- Battye et al., 1610.06826


Hydrogen
n=2
Lyman-α
$\lambda_\alpha = 1.216 \times 10^{-5}$ cm
n=1
21 cm
↑e ↑p
↑e ↓p

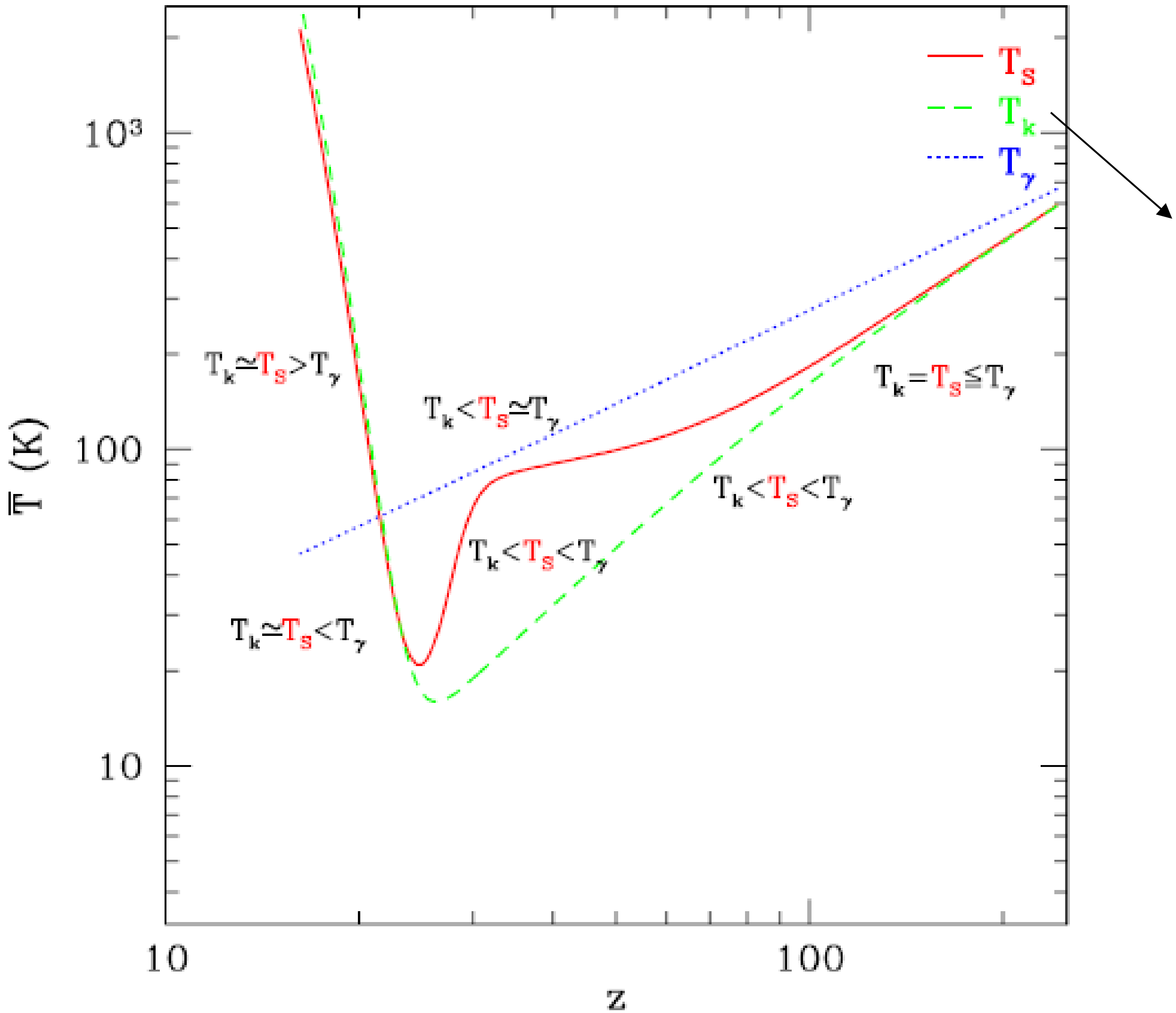


$$\lambda = 21(1+z)\ \text{cm}$$


Dark Ages
Cosmic Dawn
EoR
Z~200
Z~30
Z_*
Z_α
Z_T
Z_R
Collisionally coupled regime
No 21 cm signal
Reionization
Density
$T_S \sim T_\gamma$
Lyα
X-ray
UV
DLA


a
10 million
100 million
250 million
500 million
1 billion
Time after Big Bang (years)
60
30
0
–30
–60
(mK)
b
Redshift 160 80 40 20 15 14 13 12 11 10 9 8 7
Brightness (mK)
50
0
–50
–100
–150
First galaxies form
Reionization begins
Reionization ends
Dark ages
Heating begins
Cosmic time
0 20 40 60 80 100 120 140 160 180 200
Frequency (MHz)

The spin temperature is an interpolation between CMB temperature and gas temperature



Gas: adiabatic cooling

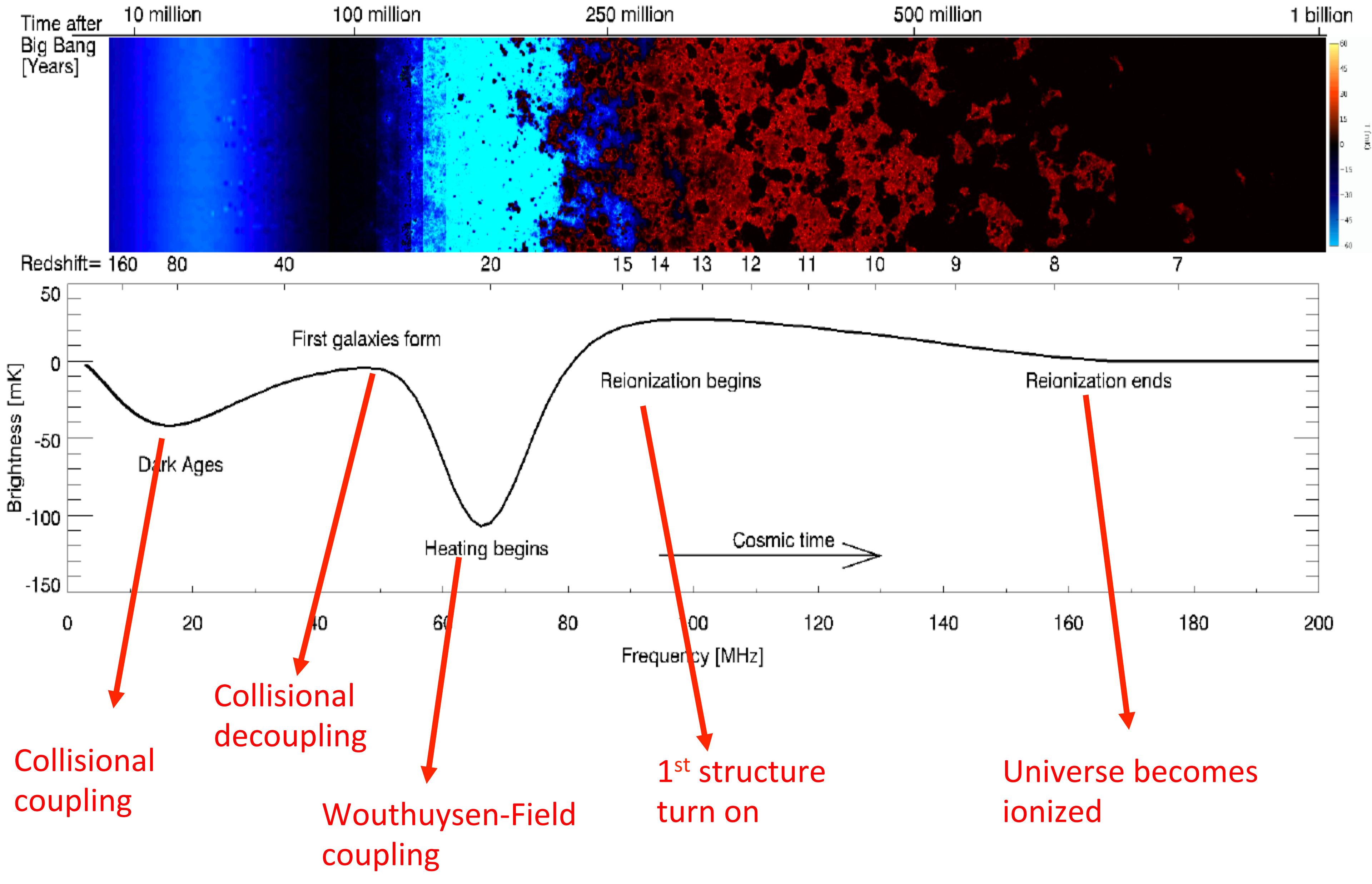
Cosmological 21cm signal

Astrophysics, Cosmology

$$\delta T_b(\nu) \approx 27 x_{HI}(1+\delta_{nl})\left(\frac{H}{dv_r/dr + H}\right)\left(1-\frac{T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\frac{0.15}{\Omega_M h^2}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right)\mathrm{mK}$$

Fraction of neutral hydrogen, gas density, los velocity gradient, spin temperature

Very rich physics, the trick is to effectively modeling the whole process (21cmFast)



Time after Big Bang [Years]
10 million
100 million
250 million
500 million
1 billion
Redshift= 160
80
40
20
15
14
13
12
11
10
9
8
7
Brightness [mK]
50
0
-50
-100
-150
First galaxies form
Dark Ages
Heating begins
Reionization begins
Reionization ends
Cosmic time
Frequency [MHz]
0
20
40
60
80
100
120
140
160
180
200
Collisional coupling
Collisional decoupling
Wouthuysen-Field coupling
1st structure turn on
Universe becomes ionized

- Dark energy equation of the state
- Epoch of reionization
- Cosmological parameters
- Cross-correlation with other optical surveys
- Structure formation
- Missing baryon problems
- HI bias

- 21-cm cosmology
- Challenges
- Machine learning aspects
- Cross-correlation with cosmic fields

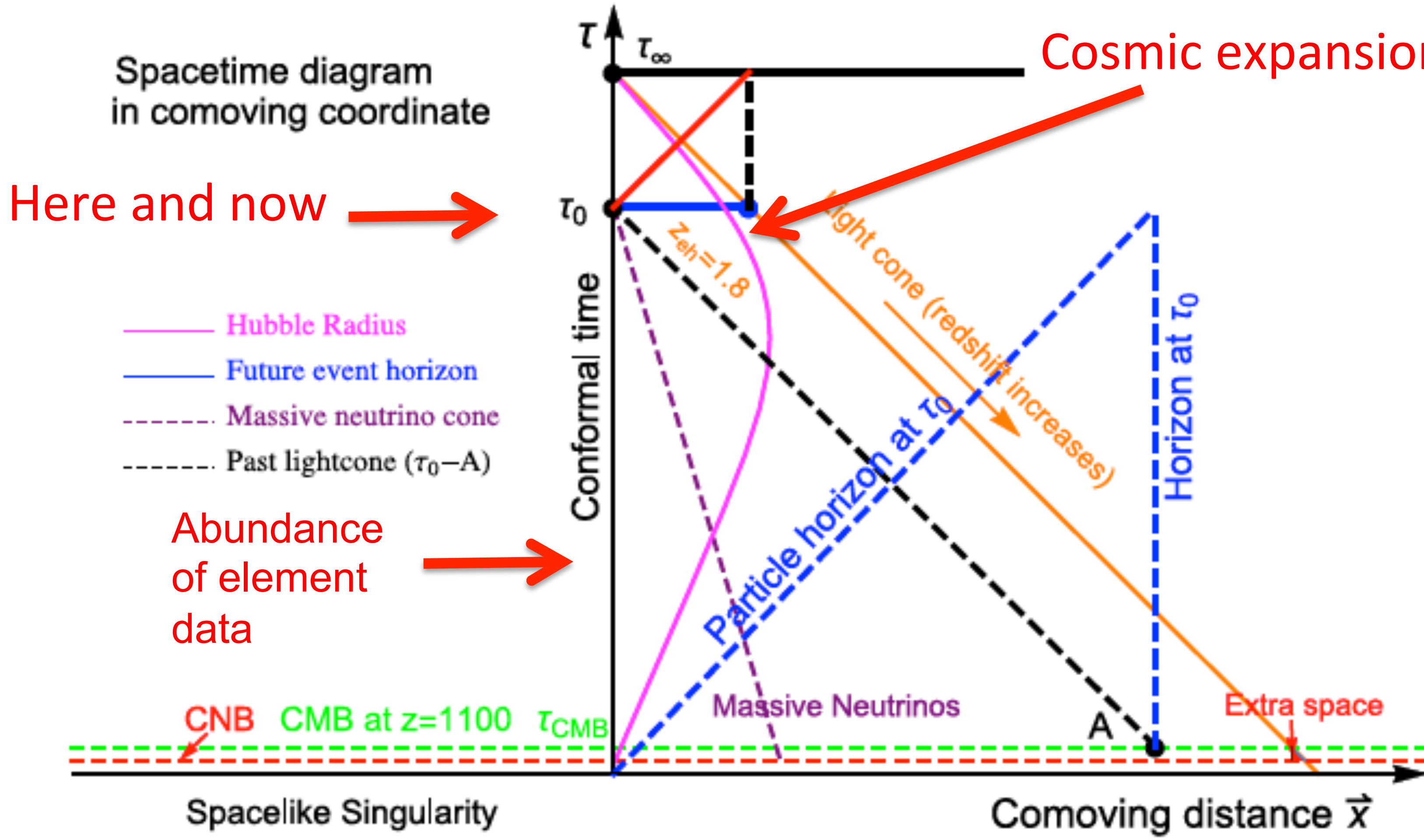
- 21-cm cosmology
- Challenges
- Machine learning aspects
- Cross-correlation with cosmic fields

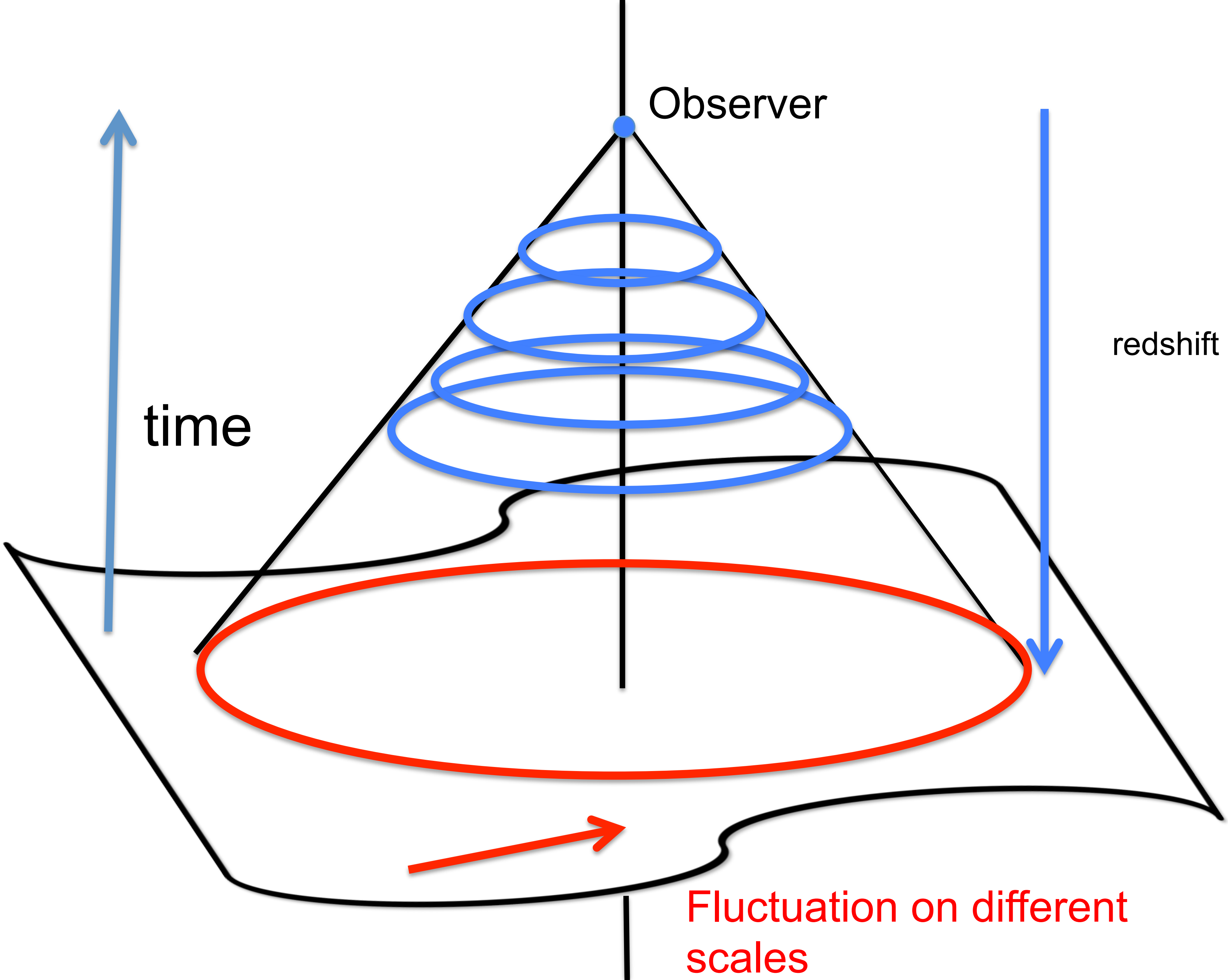
99 per cent of the Cosmology is to measure: (information ascending)

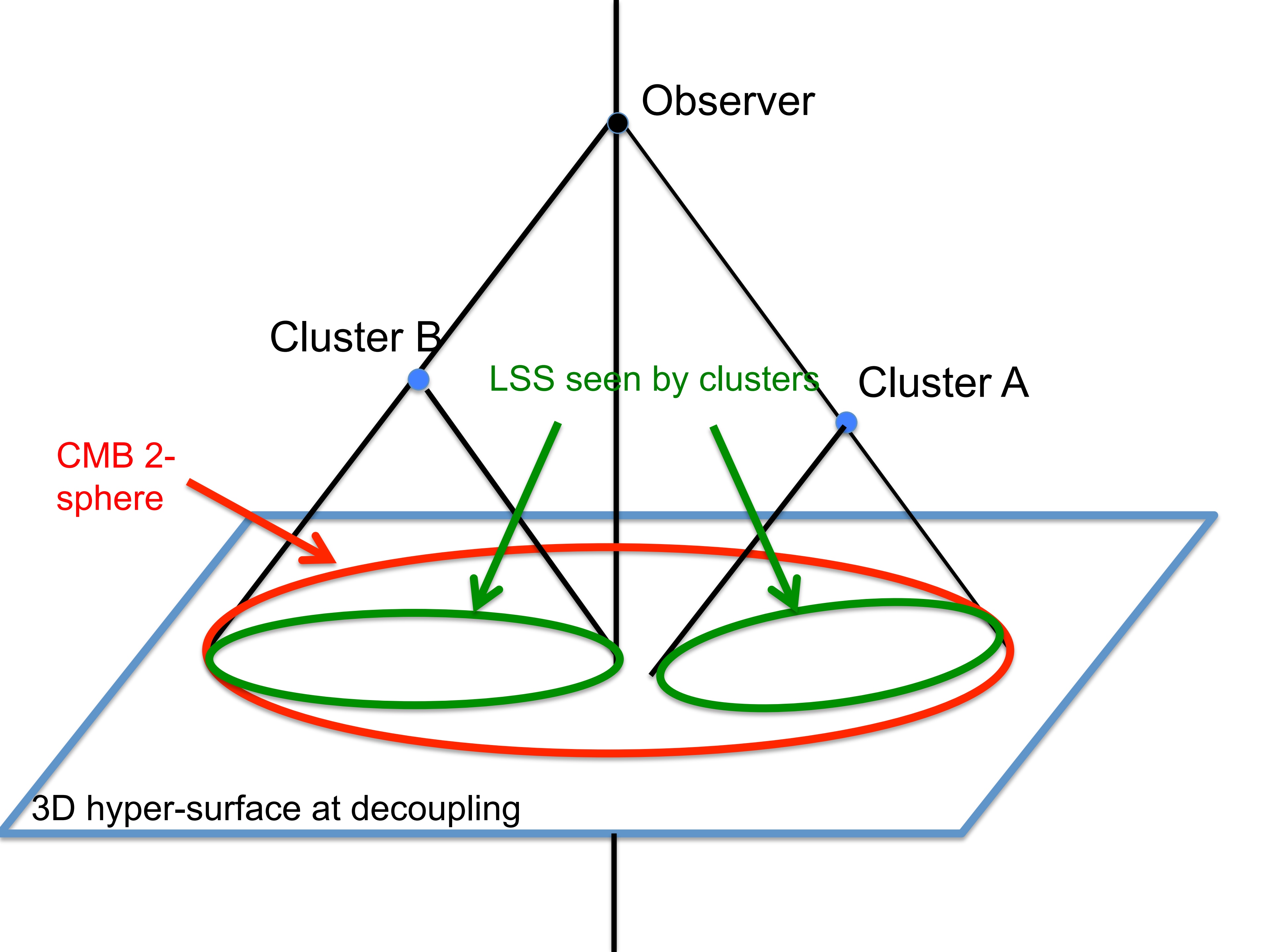
(1)Abundance of the light elements

(2)Cosmic Expansion

(3)Growth of perturbations




Observer
time
redshift
Fluctuation on different scales

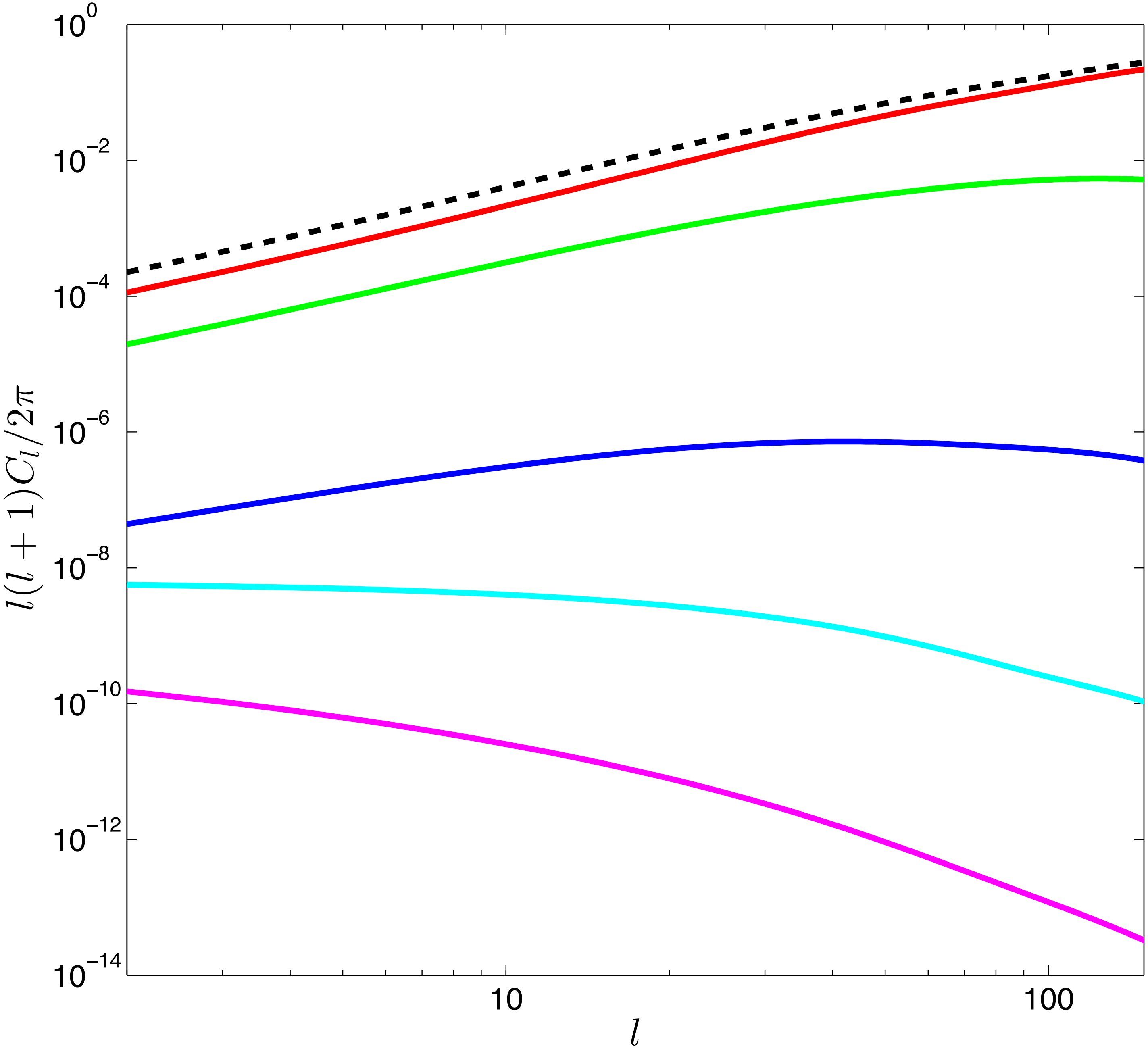

Observer
Cluster B
LSS seen by clusters
Cluster A
CMB 2-
sphere
3D hyper-surface at decoupling

$$
\begin{aligned}
\Delta_{T_{\rm b},\ell}(\mathbf{k},z) &= \Delta^{(1)}_{T_{\rm b},\ell}(\mathbf{k},z)+\Delta^{(2)}_{T_{\rm b},\ell}(\mathbf{k},z)+\Delta^{(3)}_{T_{\rm b},\ell}(\mathbf{k},z)+\Delta^{(4)}_{T_{\rm b},\ell}(\mathbf{k},z)+\Delta^{(5)}_{T_{\rm b},\ell}(\mathbf{k},z) \\
&= \left(\tilde{\delta}_n+\frac{1}{\mathcal{H}}\dot{\tilde{\phi}}+\tilde{\psi}\right) j_\ell(k\chi)+\frac{1}{\mathcal{H}}\tilde{v}(\mathbf{k}) k j''_\ell(k\chi) \\
&- \left(\frac{1}{\mathcal{H}}\frac{\mathrm{d}\ln(a^3\bar{n}_{\rm HI})}{\mathrm{d}\eta}-\frac{\dot{\mathcal{H}}}{\mathcal{H}^2}-2\right)\times\left[\tilde{\psi} j_\ell(k\chi)+\tilde{v}(\mathbf{k}) j'_\ell(k\chi)+\int_0^\chi(\dot{\tilde{\phi}}+\dot{\tilde{\psi}}) j_\ell(k\chi')\mathrm{d}\chi'\right]
\end{aligned}
$$

$$
\Delta^W_{T_b,l}(\mathbf{k})=\int_0^\infty \mathrm{d}z W(z)\Delta_{T_b,l}(\mathbf{k},z)
$$

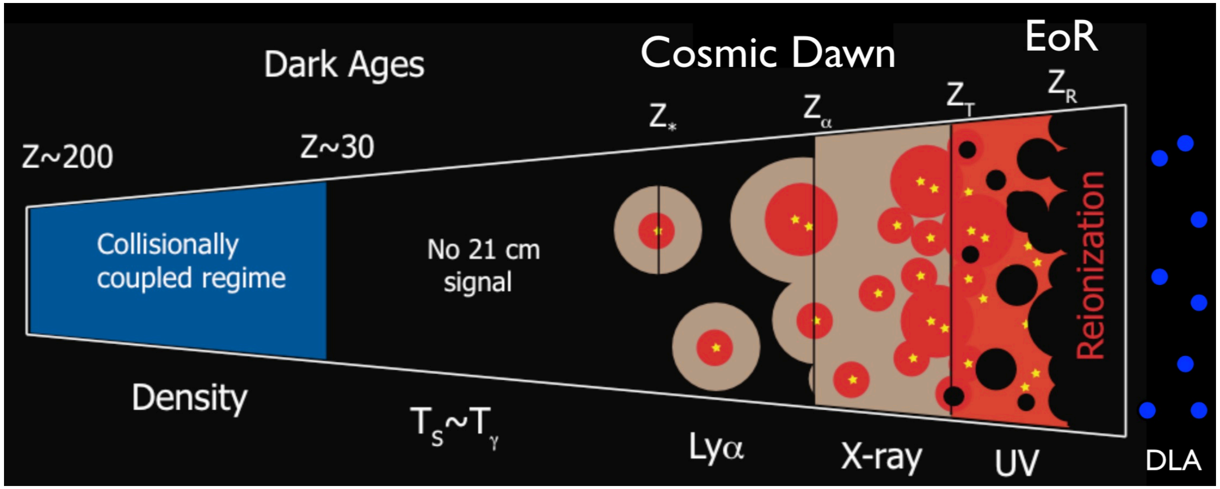
$$
\grave{\Delta}^{\acute{W}}_{T_b,l}(k)\equiv\Delta^W_{T_b,l}(\mathbf{k})/\mathcal{R}(\mathbf{k})
$$

$$
C_l^{WW'}=4\pi\int \mathrm{d}\ln k\,\mathcal{P}_{\mathcal{R}}(k)\Delta^W_{T_b,l}(k)\Delta^{W'}_{T_b,l}(k)
$$



10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
$l(l+1)C_l/2\pi$
10
100
l

- 21-cm cosmology
- Challenges
- (1) featureless power spectrum
- (2) very high foreground
- (3) Various systematics
- Machine learning aspects
- Cross-correlation with cosmic fields



Dark Ages
Cosmic Dawn
EoR
Z~200
Z~30
Z_*
Z_α
Z_T
Z_R
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No 21 cm signal
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$T_S \sim T_\gamma$
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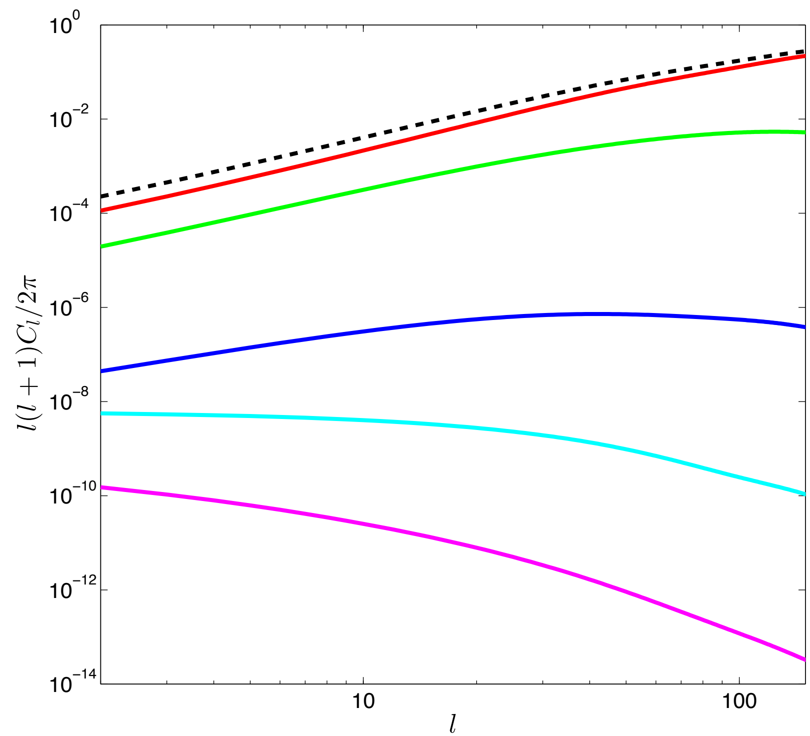
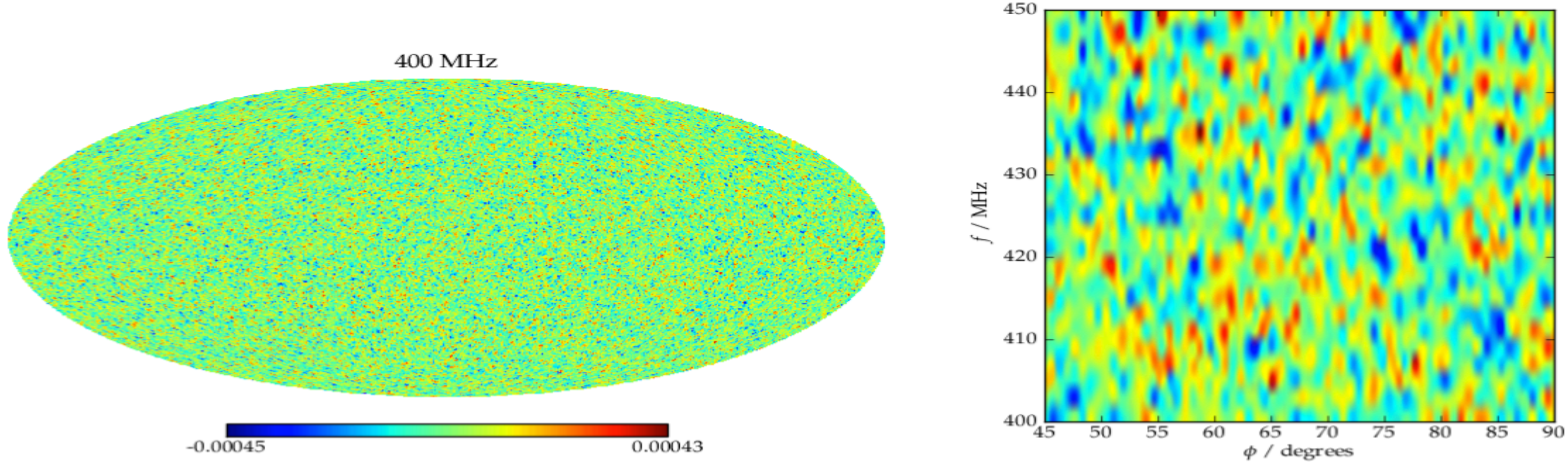
UV
DLA



10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
$l(l+1)C_l/2\pi$
10
100
l

Hydrogen intensity signal

Amplitude 1 mK, lots of spectral structure



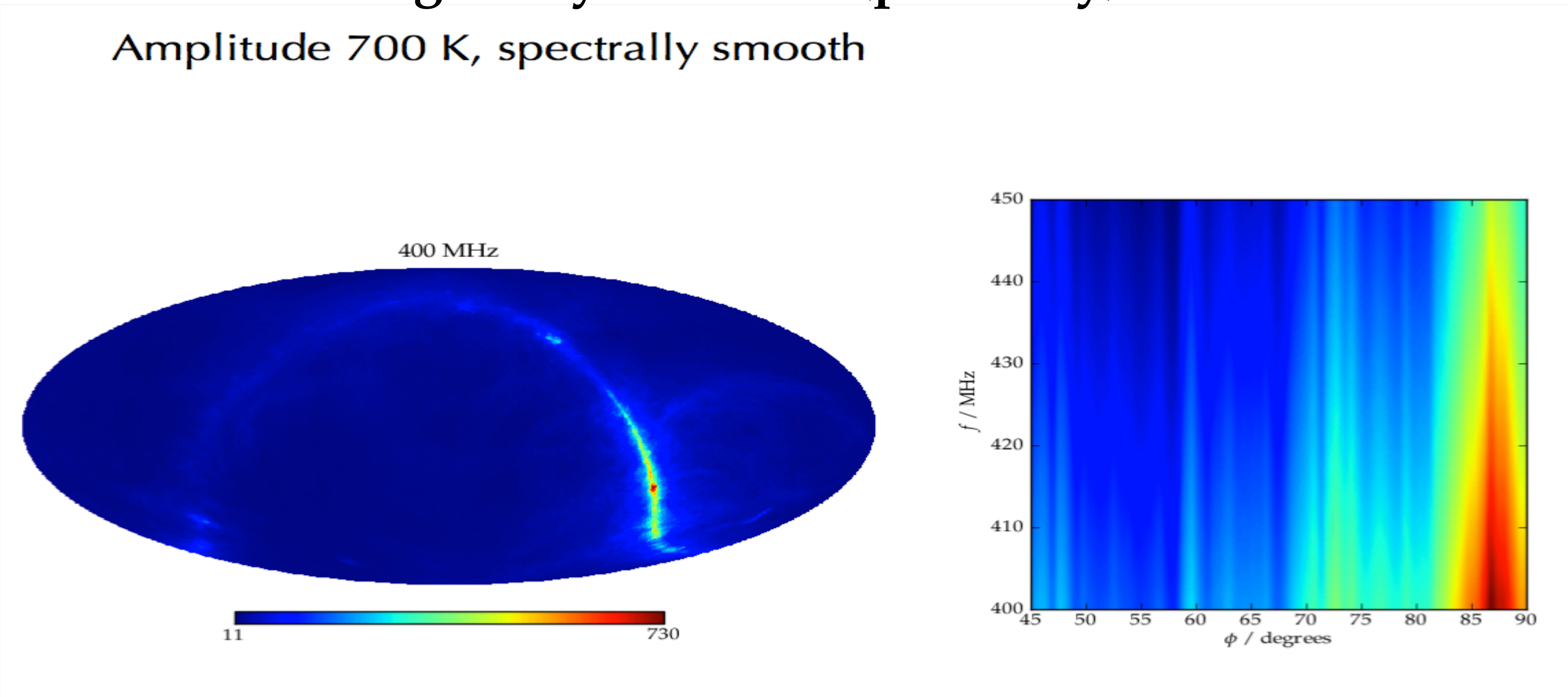
Simulated 21 cm signal, tracer of ρ$HI(\theta,;z)$: $\Delta T \sim 1$ mK

left - over full sky at 400 MHz,

right - over 50 MHz at 1 declination

Main goal is to measure BAO structure in *PHI(k)*, less concerned about amplitude of *PHI(k)*.

The “other” signal: synchrotron (primarily)



Modeled Galaxy signal, ΔT ~ 700 K!
left - over full sky at 400 MHz,
right - over 50 MHz at 1 declination - spectrally smooth

Noise:

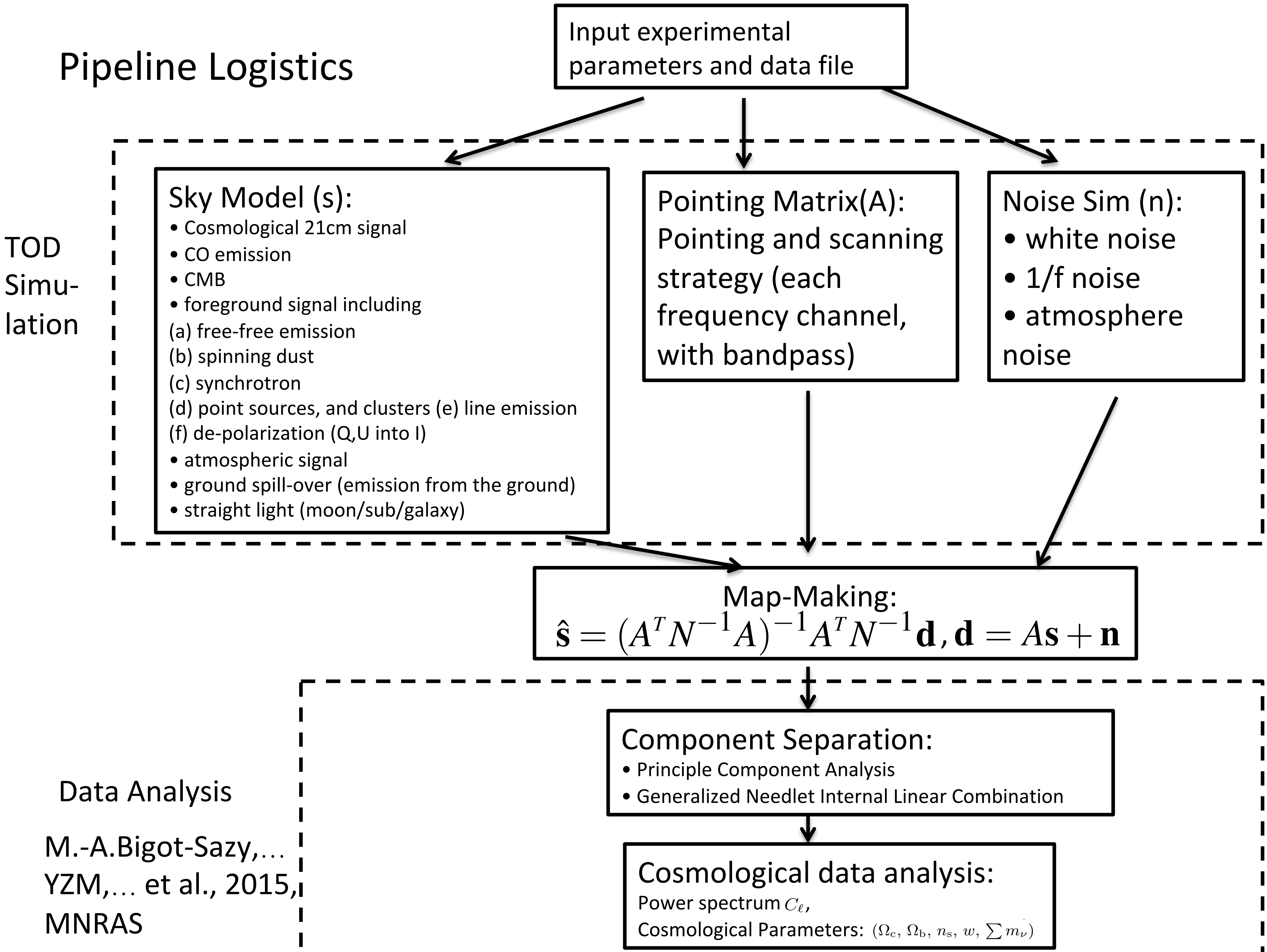
1. uncorrelated noise white noise
2. correlated noise in time and frequency 1/f noise
3. Atmospheric noise

Systematic effect:

1. sidelobes: near, intermediate, far (mode mixing)
2. band-pass calibration
3. Ground spilled over
4. Cross polarization
5. beam ellipticity ....

Without those details, radio cosmology is an unrealistic dream.

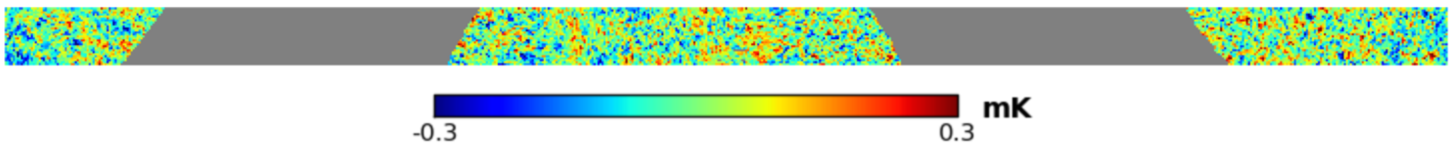
Pipeline Logistics



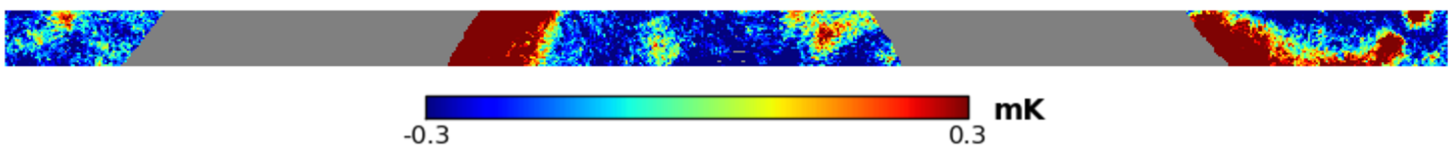
Component separation: PCA

$$C_{ij} = \frac{1}{N_p} SS^T = \frac{1}{N_p} \sum_{p=1}^{N_p} T(\nu_i, \hat{n}_p) T(\nu_j, \hat{n}_p) \qquad R_{jk} = \frac{C_{jk}}{C_{jj}^{1/2} C_{kk}^{1/2}}$$

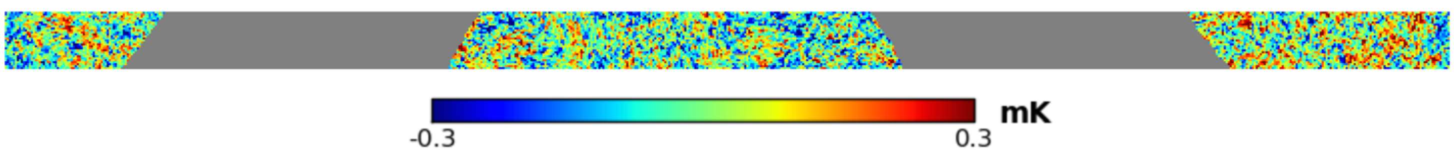
$$P^T R P = \Lambda \equiv \mathrm{diag}\{\lambda_1, \ldots, \lambda_{N_f}\} \qquad \phi = P_c^T S \qquad S_c = P_c \phi \qquad S_{\mathrm{HI}} = S - S_c$$



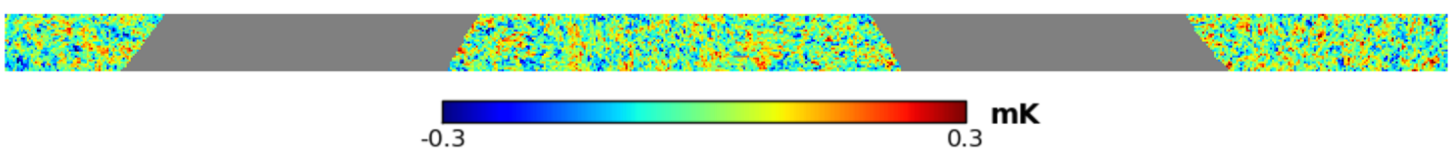
(a) Input HI signal



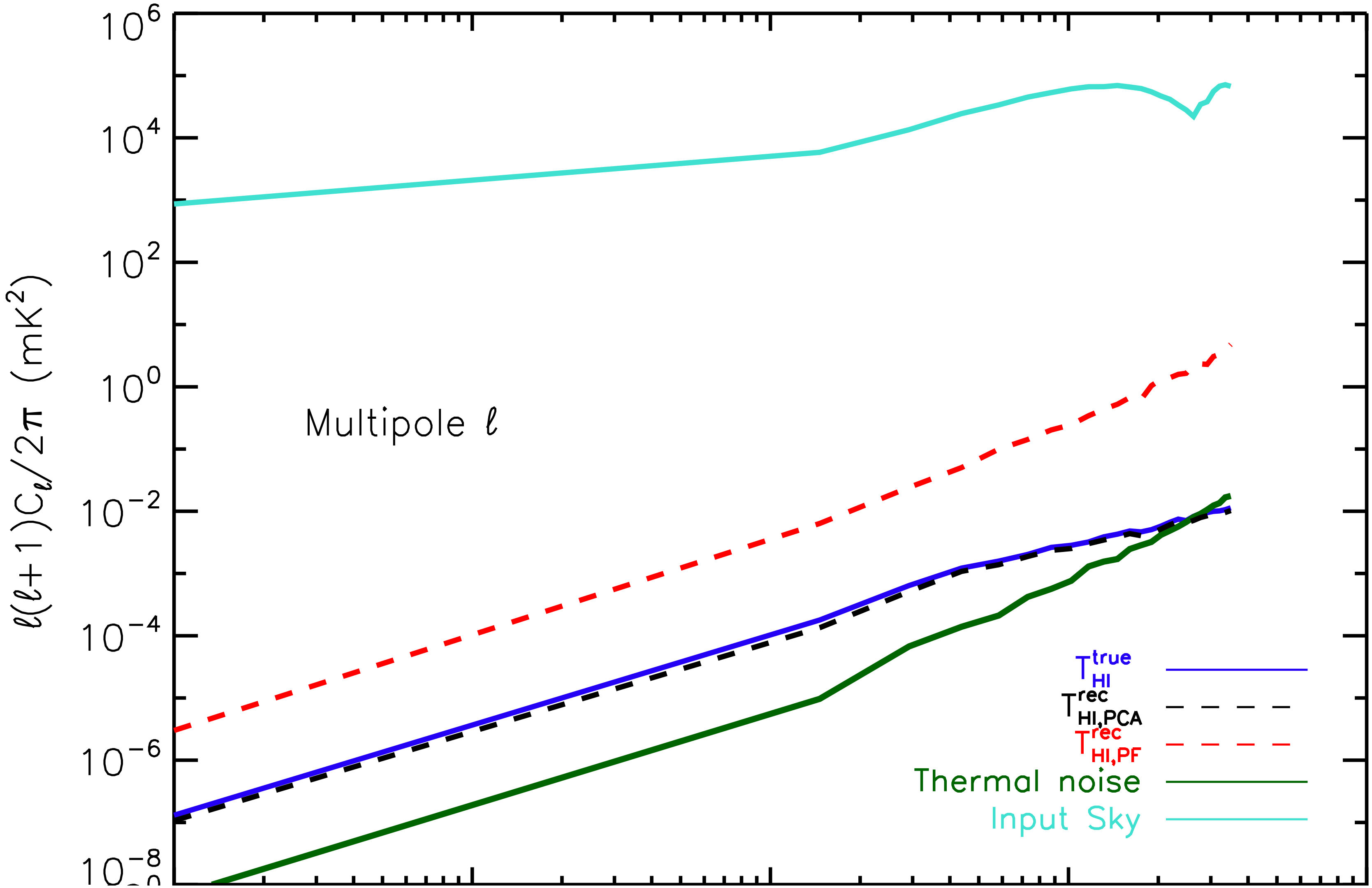
(b) PCA 1 mode removed



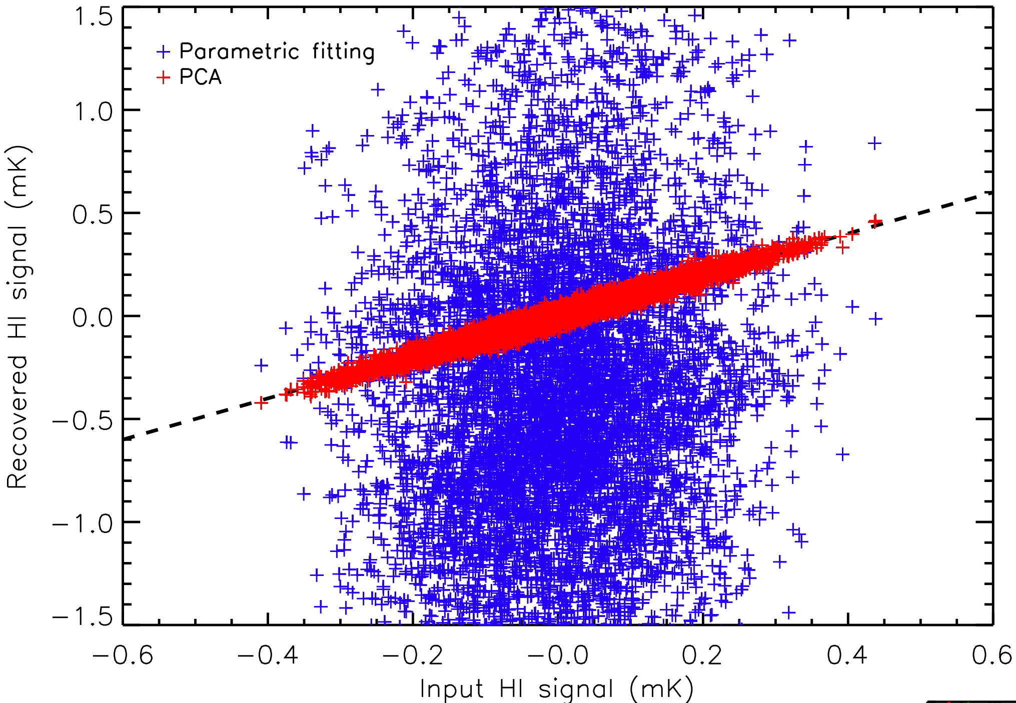
(c) PCA 3 modes removed



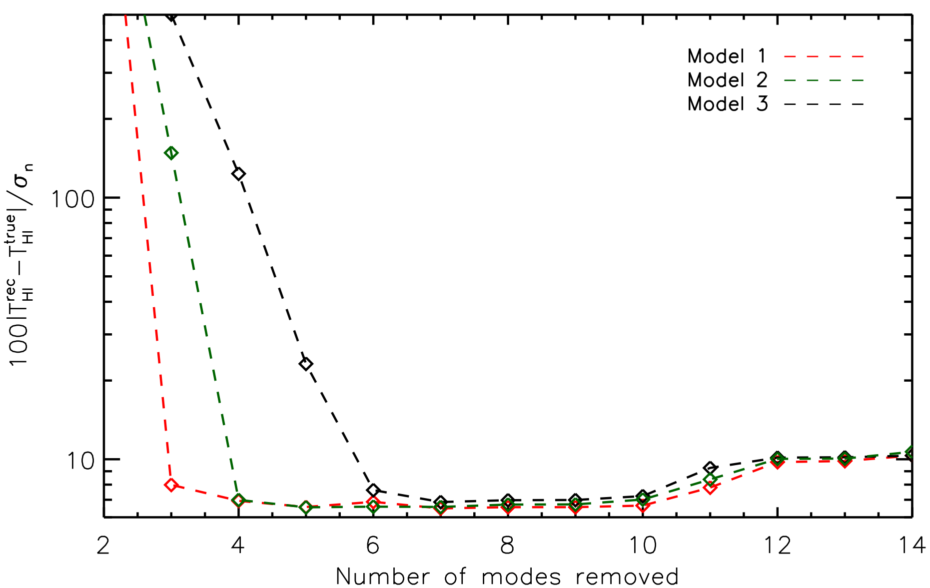
(d) PCA 7 modes removed



10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
$\ell(\ell+1)C_\ell/2\pi$ (mK^2)
Multipole ℓ
T_{HI}^{true}
$T_{HI,PCA}^{rec}$
$T_{HI,PF}^{rec}$
Thermal noise
Input Sky



Parametric fitting
PCA
Recovered HI signal (mK)
Input HI signal (mK)
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−0.6
−0.4
−0.2
−0.0
0.2
0.4
0.6



Model 1
Model 2
Model 3
$100|T_{HI}^{rec}-T_{HI}^{true}|/\sigma_n$
100
10
2
4
6
8
10
12
14
Number of modes removed

1/f noise:

Correlated fluctuation in time

Fluctuations across spectrum, i.e. spectroscopic noise

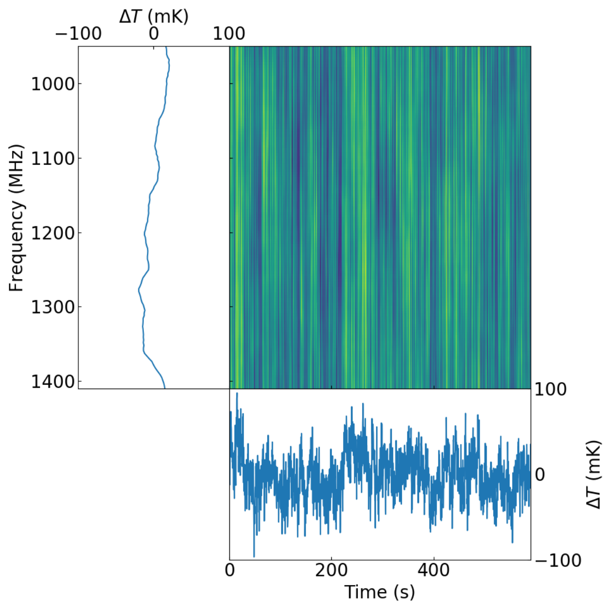
$$\mathrm{PSD}(f,\omega) = \frac{T_{\mathrm{sys}}^2}{\delta\nu}\left[1 + C(\beta, N_\nu)\left(\frac{f_k}{f}\right)^{\alpha}\left(\frac{1}{\omega\Delta\nu}\right)^{\frac{1-\beta}{\beta}}\right]$$

ω is the inverse spectroscopic frequency wavenumber

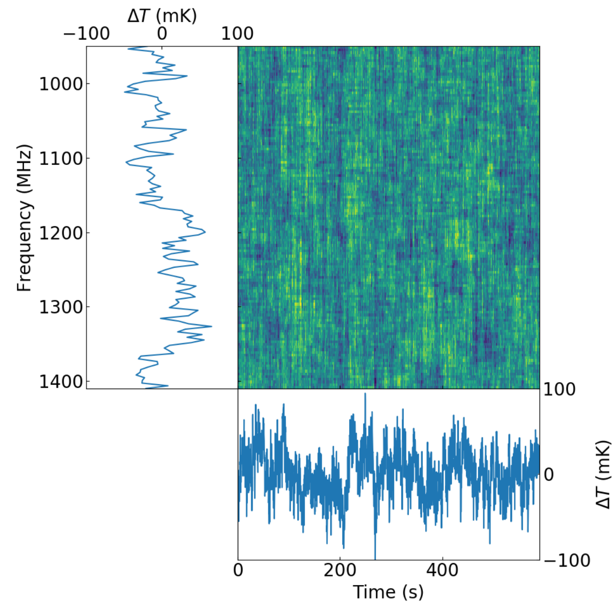
SKA forecast:

S. Harper, …, YZM, … 2018, MNRAS

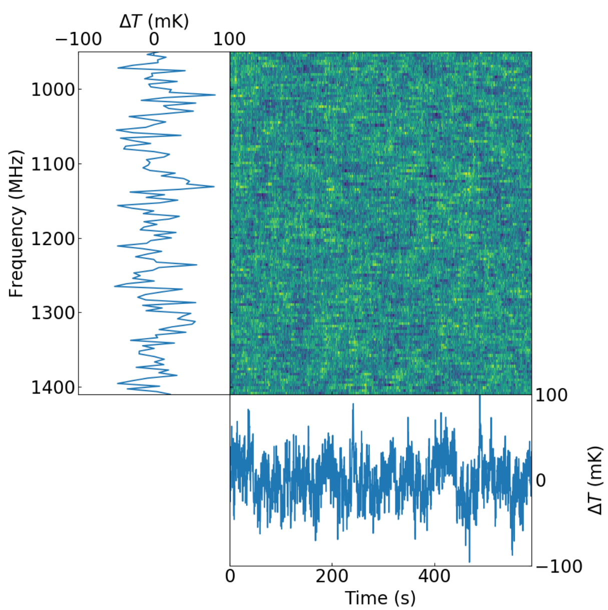
Description	Parameter	Value
Dish Diameter	D_{dish}	15 m[a]
No. Dishes	N_{dish}	200
Receiver + CMB	$T_{\mathrm{CMB}} + T_{\mathrm{rx}}$	20 K[b]
No. Polarimeters	N_{pol}	2
No. Channels	N_ν	23
Bandwidth	$\Delta\nu$	$950 < \nu < 1410$ MHz
Channel width	$\delta\nu$	20 MHz
Sample Rate	f_{sr}	4 Hz
Integration Time	T_{obs}	30 days
Elevation	E	55 deg
Slew Speed	$\mathrm{v_t}$	$0.5 < \mathrm{v_t} < 2.0\,\mathrm{deg\,s^{-1}}$



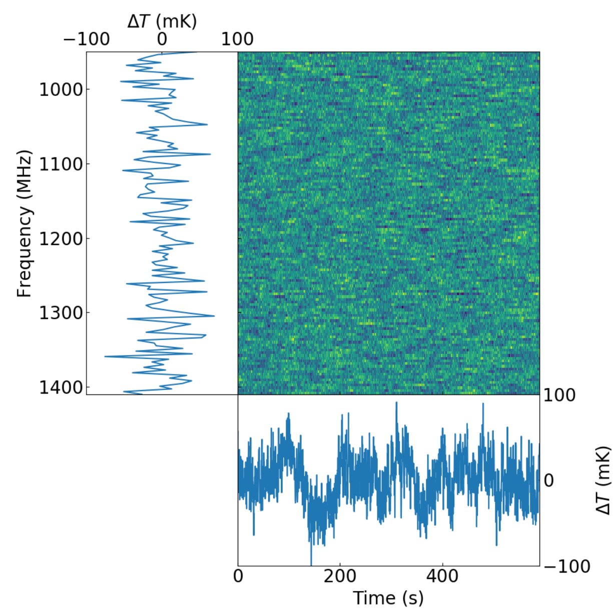
(a) $\beta = 0.25$, $\alpha = 1$, $f_k = 1$ Hz



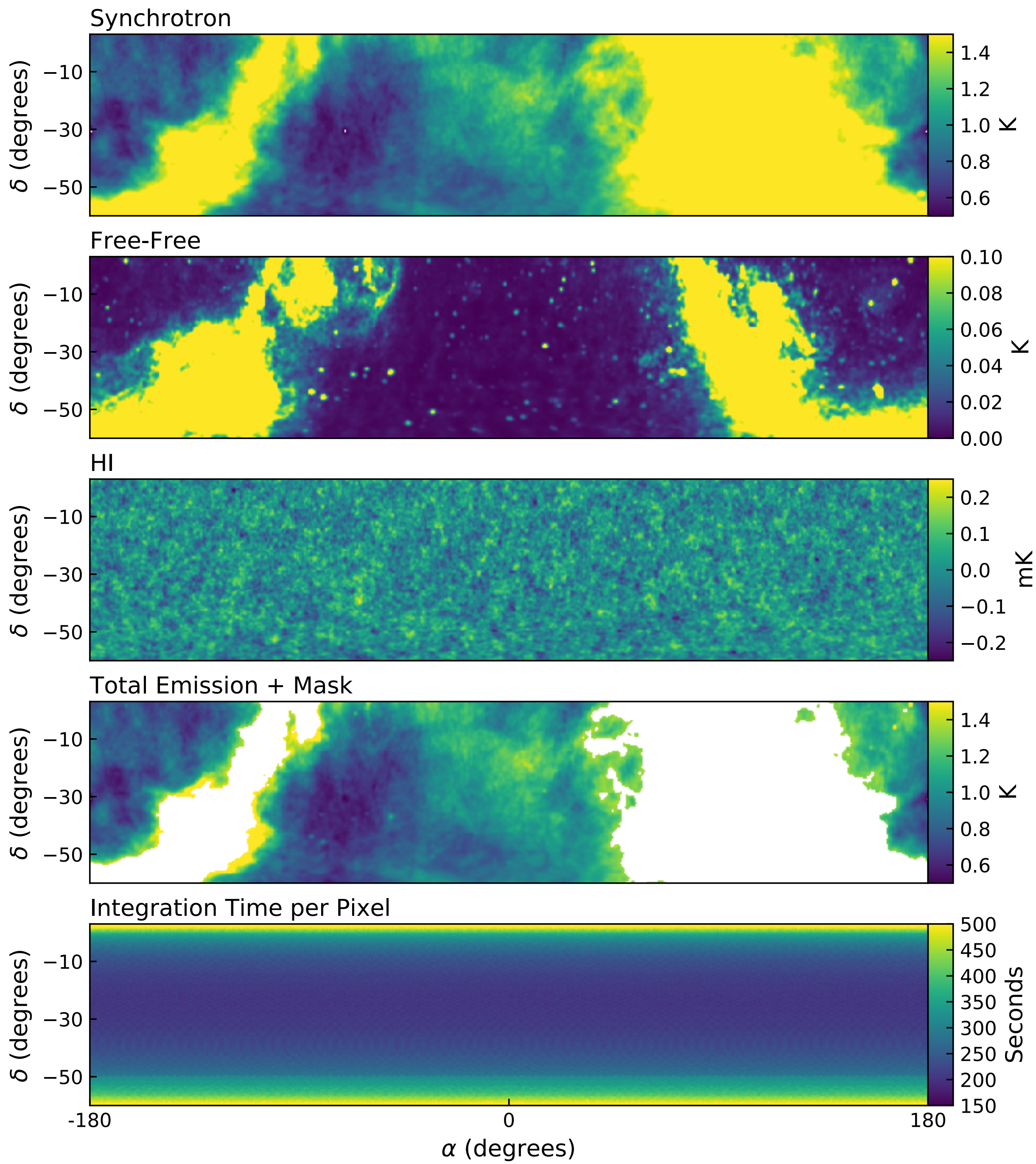
(b) $\beta = 0.5$, $\alpha = 1$, $f_k = 1$ Hz



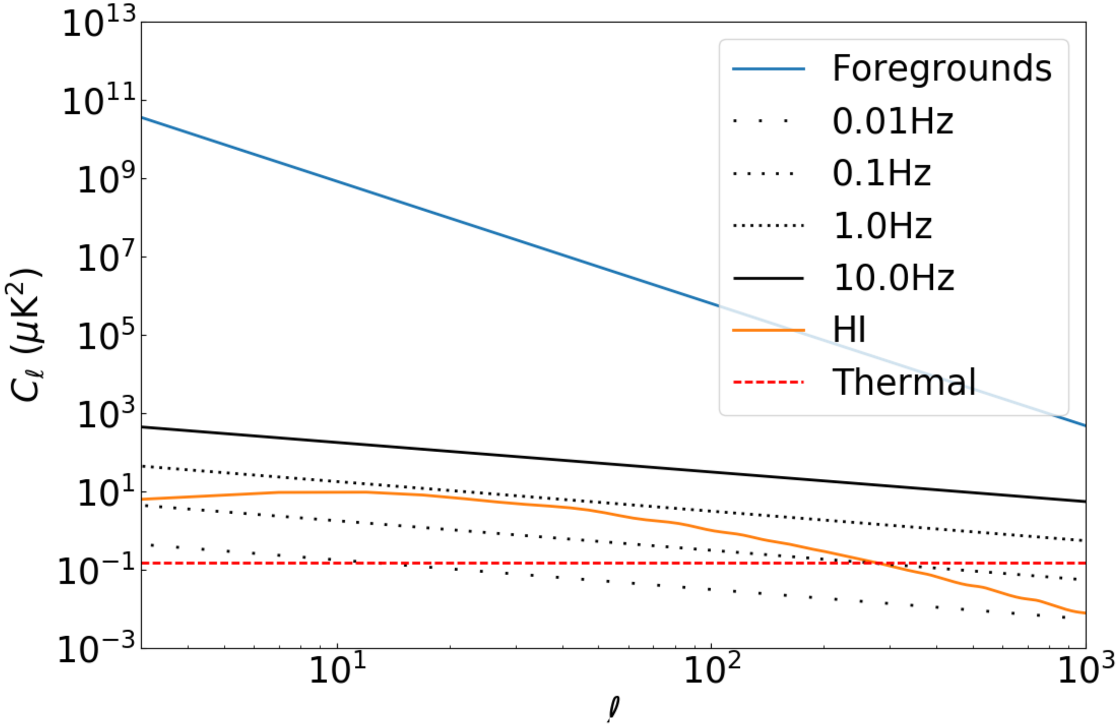
(c) $\beta = 0.75$, $\alpha = 1$, $f_k = 1$ Hz



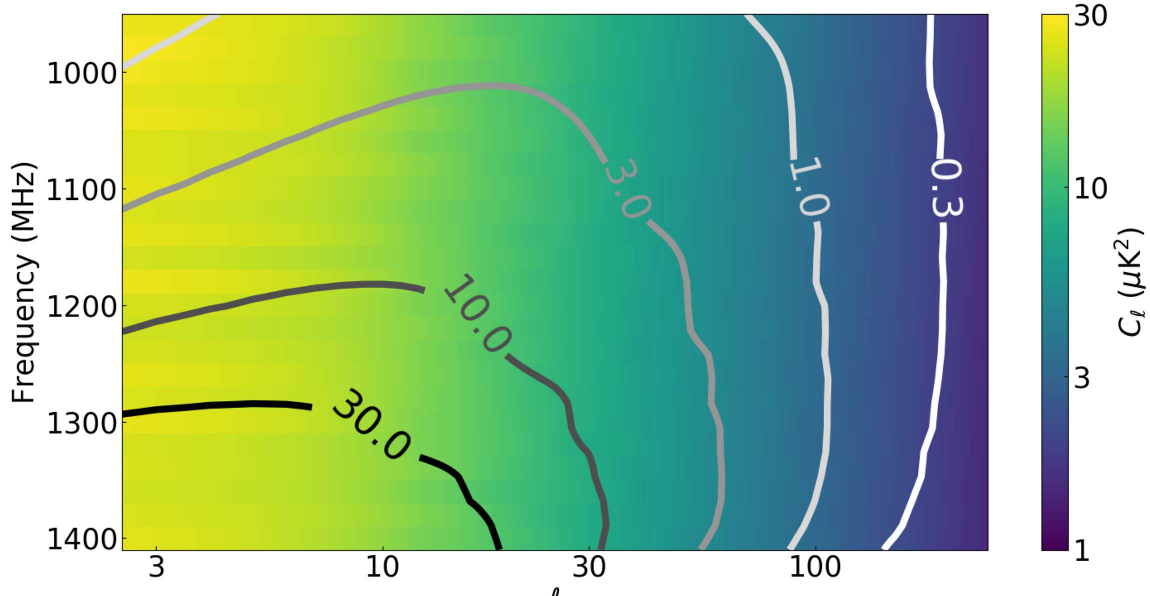
(d) $\beta = 1.0$, $\alpha = 1$, $f_k = 1$ Hz



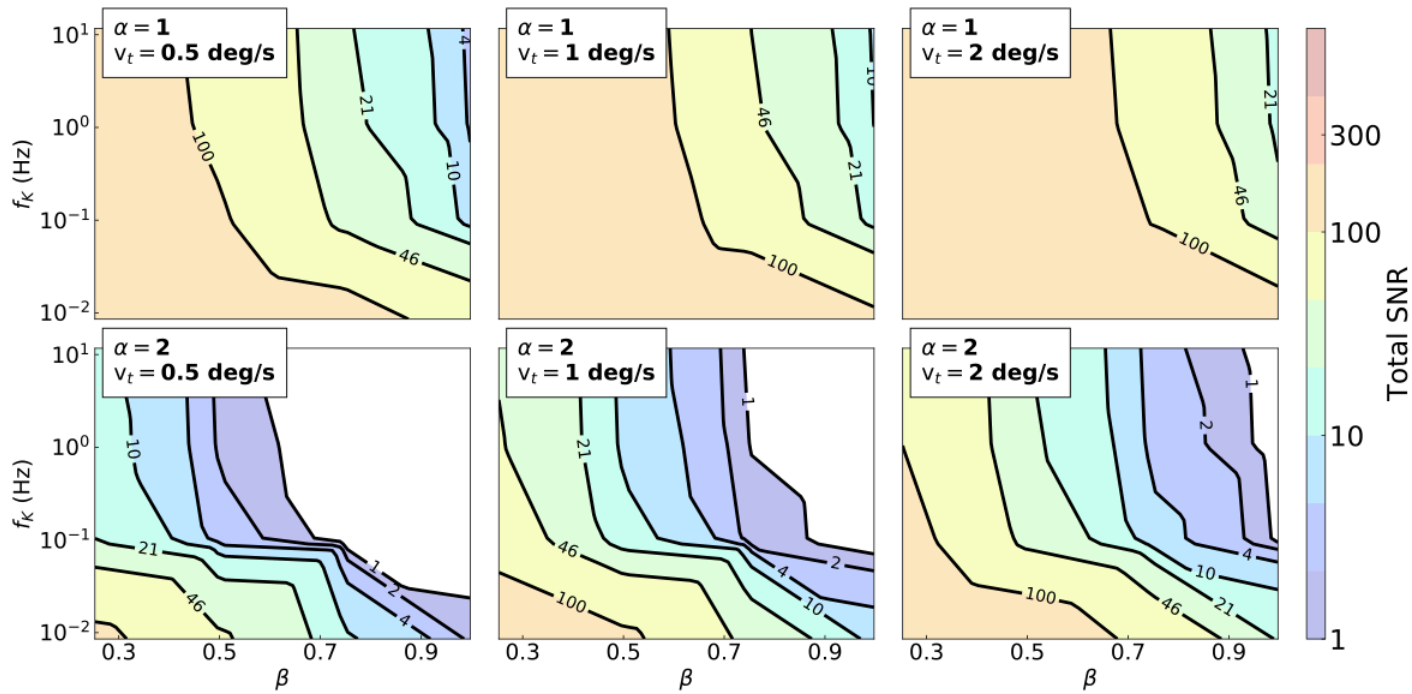
Synchrotron
Free-Free
HI
Total Emission + Mask
Integration Time per Pixel
δ (degrees)
−10
−30
−50
1.4
1.2
1.0
0.8
0.6
K
0.10
0.08
0.06
0.04
0.02
0.00
0.2
0.1
0.0
−0.1
−0.2
mK
500
450
400
350
300
250
200
150
Seconds
-180
0
180
α (degrees)



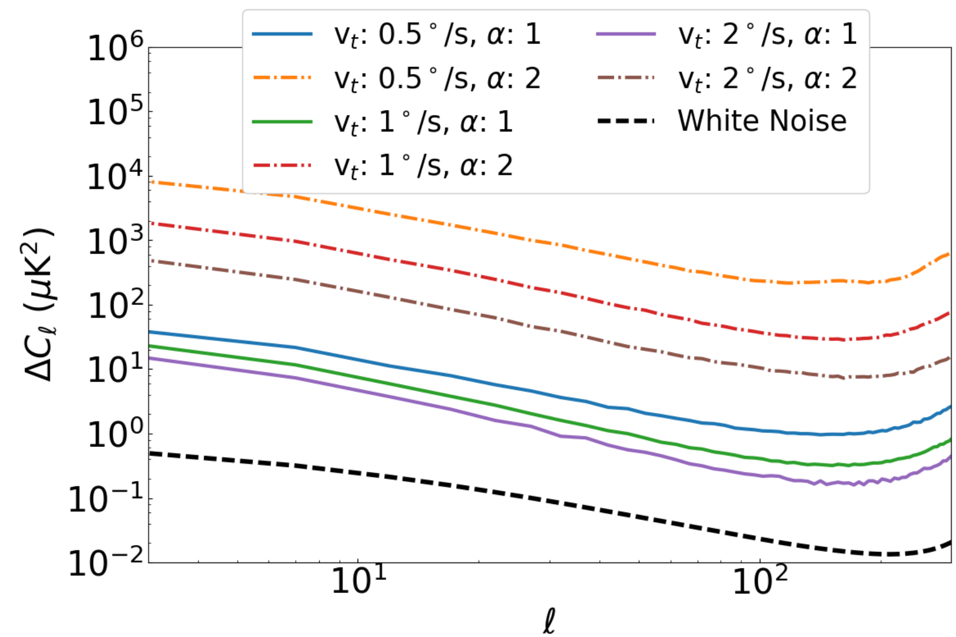
Foregrounds
0.01Hz
0.1Hz
1.0Hz
10.0Hz
HI
Thermal
C_ℓ (μK^2)
ℓ
10^{13}
10^{11}
10^{9}
10^{7}
10^{5}
10^{3}
10^{1}
10^{-1}
10^{-3}
10^{1}
10^{2}
10^{3}



Frequency (MHz)
1000
1100
1200
1300
1400
3
10
30
100
ℓ
30.0
10.0
3.0
1.0
0.3
C_ℓ (μK^2)
30
10
3
1

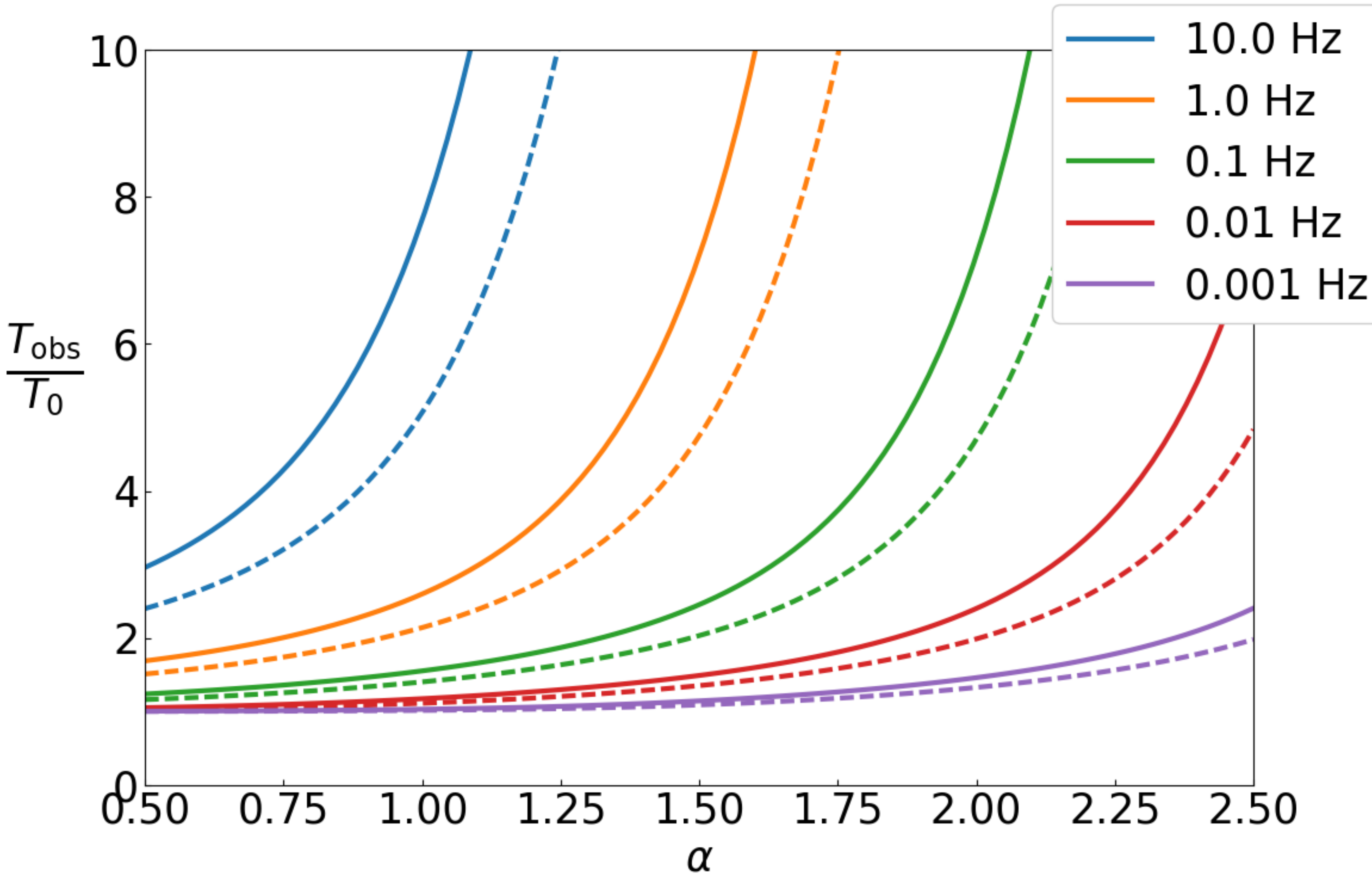


α = 1
v_t = 0.5 deg/s
α = 1
v_t = 1 deg/s
α = 1
v_t = 2 deg/s
α = 2
v_t = 0.5 deg/s
α = 2
v_t = 1 deg/s
α = 2
v_t = 2 deg/s
f_K (Hz)
β
Total SNR



v_t: 0.5 °/s, α: 1
v_t: 0.5 °/s, α: 2
v_t: 1 °/s, α: 1
v_t: 1 °/s, α: 2
v_t: 2 °/s, α: 1
v_t: 2 °/s, α: 2
White Noise
ΔC_ℓ (μK²)
ℓ

$$T_{\rm obs} = T_0 \frac{\rm SNR_w}{\rm SNR}$$



Hydrogen Epoch of Reionzation Array (HERA)

- Radio Telescope dedicated to observing large scale structures prior and during the epoch of reionization.
- Full **HERA-350** will be comprised of 14 meter parabolic dish of 320 forming a Hexagonal core and 30 outriggers, observing at **50MHz-250MHz**, located SKA site, Karoor, South Africa.
- Currently, HERA consist of 47 antennas observing at 100MHz-200MHz.
- On the left is HERA-19. [https://reionization.org/]

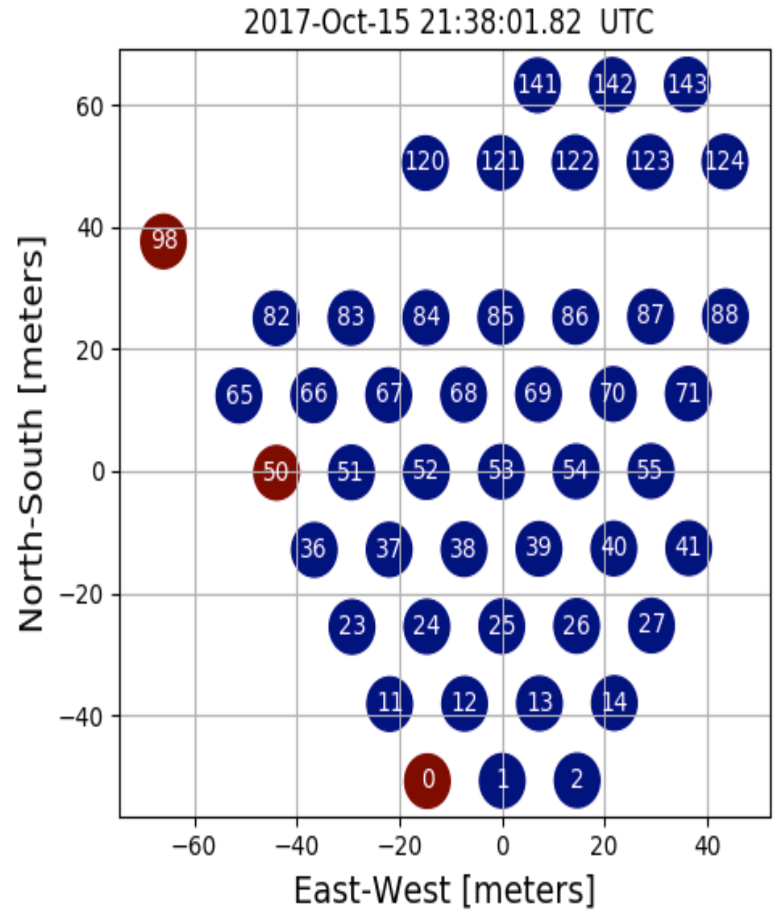
Quasi-Redundant Calibration of HERA-47 : Internal Data Release 1 (IDR1; JD 2458042)

Measurement Equation

$$C_{ij} = g_i^* g_j s_{ij} + n_{ij}$$

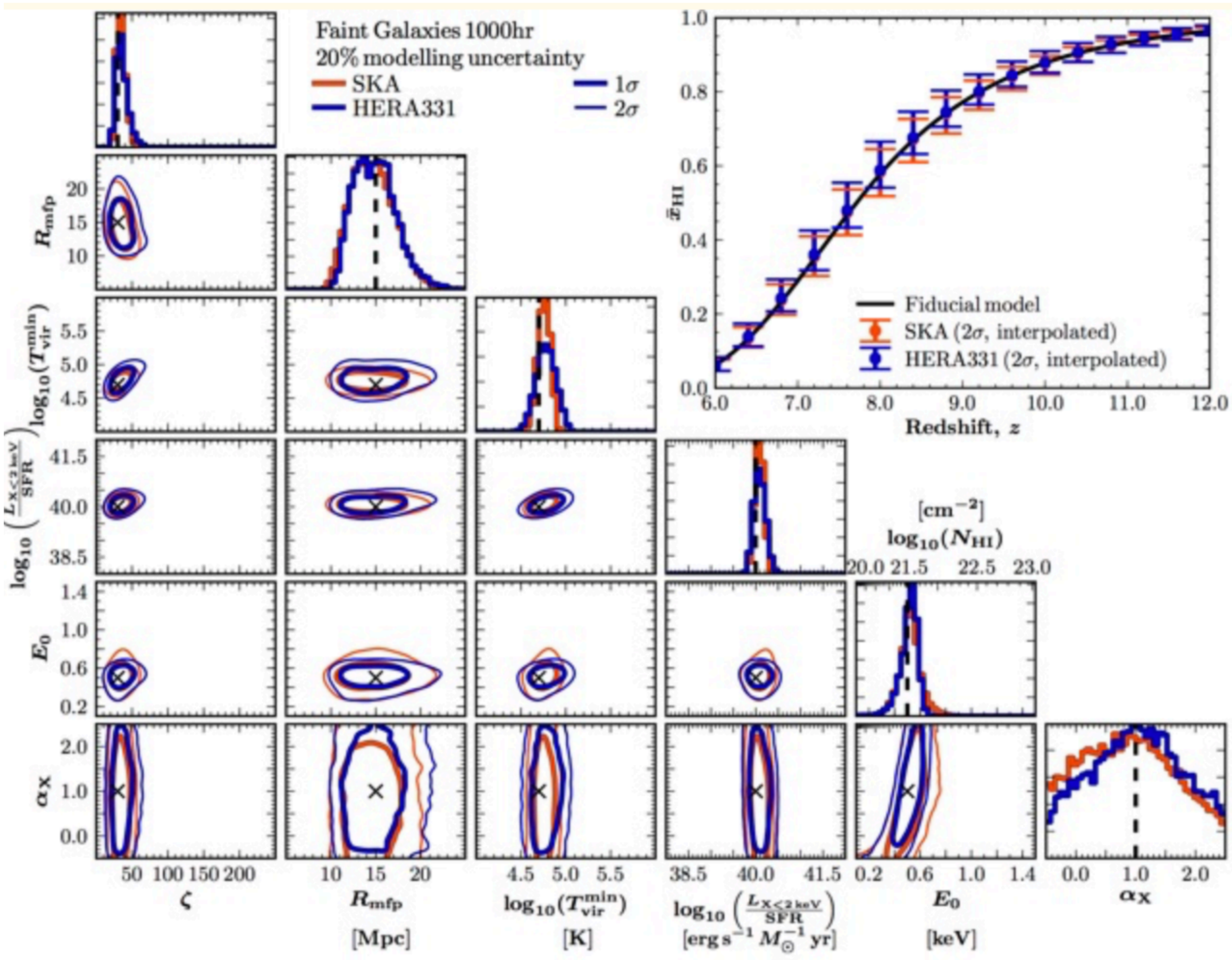
We calibrate HERA-47 using **redundant baseline scheme**, which assume that identical baseline see same sky signal s_{ij} .

Unfortunately, in real life, variations due antenna primary beams and antenna location misplacement, the perfect redundant configuration breaks. This can be resolved by computation of the **expected sky covariance** between baselines with a redundant set**.** This allows the inclusion of the **instrument model** and **bright sources** with known positions. This calibration scheme is called **correlation calibration**



Machine learning aspects

- Characterize the 21-cm tomography field (theory)
- Calibrate the interferometer (technology)



zeta - *the ionizing efficiency of high-z galaxies*

R_{mfp} - *the max horizon for ionizing photons, set by recombining systems*

T_{vir} - *the minimum halo virial temperature hosting star-forming galaxies*

L_X / SFR - *the <2keV X-ray luminosity (per unit star formation) of high-z galaxies*

N_{HI} *(or E_0) - the HI column density (or corresponding photon energy) of host galaxies, responsible for absorbing X-rays*

alpha_x - *the X-ray spectral energy index of high-z galaxies*

People in UKZN groups

- Cheng Cheng (Joint postdoc at Tsinghua U/Beijing): Machine learning in 21-cm tomography
- Devin Crichton (postdoc): HIRAX, instrumentation
- We-Ming Dai (postdoc): single-dish intensity mapping, interferometry, reconstruction of reionisation history
- Matt Hilton (faculty): galaxy clusters, LSST
- Yi-Chao Li (former postdoc, now UWC): experimental characterization of MeerKAT
- Yin-Zhe Ma (faculty): 21-cm cosmology, theory and observations
- Kavilan Moodley (faculty): 21-cm cosmology, weak lensing
- Mthokozisi Mdlalose: Quasi-redundant baseline calibration
- Denis Tramonte (postdoc): HI stacking from Parkes and GBT
- Anthony Walters (postdoc): Fast radio Burst
- Elimboto Yohana (PhD Stu.): single-dish intensity mapping pipeline, FAST

2016 BRICS Pilot call:

		Brazil	Russia			India	China		South Africa
	Thematic areas	CNPq	FASIE	MON	RFBR	DST	MOST	NSFC	NRF
a	Prevention and monitoring of natural disasters	V	V	V	V	V	V		V
b	Water resources and pollution treatment	V	V	V	V	V		V	V
c	Geospatial technology and its applications	V	V	V	V	V	V		V
d	New and renewable energy, and energy efficiency	V	V	V	V	V	V		V
e	Astronomy		V	V	V	V		V	V
f	Biotechnology and biomedicine including human health and neuroscience	V	V	V	V	V		V	V

BRICS submitted proposal: (3—5 years project)

21-cm cosmology and large-scale structure of the Universe

Combination: 4,5,6,15 of the proposed project

South Africa:

Name	Organization, Division	Title	Degree	Speciality
Yin-Zhe Ma	Astronomy and Cosmology Research Unit, University of KwaZulu-Natal	Dr.	PhD	Cosmology, Computational Astrophysics
Romeel Dave	Department of Astronomy, University of Western Cape	Prof.	PhD	Galaxy formation, Cosmology
Mario Santos	Department of Astronomy, University of Western Cape	Prof.	PhD	Radio astronomy, cosmology
Kavilan Moodley	Astronomy and Cosmology Research Unit, University of KwaZulu-Natal	Prof.	PhD	Theoretical and observatoinal cosmology
Jonathan Sievers	Astronomy and Cosmology Research Unit, University of KwaZulu-Natal	Prof.	PhD	Radio astronomy, cosmology
Aroonkumar Beesham	University of Zululand	Prof.	PhD	Theoretical Cosmology

China:

Name	Organization, Division	Title	Degree	Speciality
Xuelei Chen	National Astronomical Observatory, Chinese Academy of Sciences	Prof.	PhD	Radio astronomoy, cosmology
Yan Gong	National Astronomical Observatory, Chinese Academy of Sciences	Prof.	PhD	Cosmology, optical astronomy
Yi Mao	Department of Physics, Tsinghua University	Assoc. Prof.	PhD	Epoch of reionization, cosmology, computational astrophysics
Yi-dong Xu	National Astronomical Observatory, Chinese Academy of Sciences	Assoc. Prof.	PhD	Epoch of reionization, cosmology, computational astrophysics

India:

Name	Organization, Division	Title	Degree	Speciality
Tirthankar Roy Choudhury	National Centre for Radio Astrophysics, Tata Institute for Fundamental Research	Prof.	PhD	Theoretical cosmology, Intergalactic medium, Epoch of reionization
Neeraj Gupta	Inter-University Centre for Astronomy and Astrophysics (IUCAA), Pune University Campus	Prof.	PhD	Observational cosmology, Low-frequency observations, Neutral hydrogen, High-z absorption systems
Kanan K. Datta	Presidency University	Prof.	PhD	Epoch of reionization, HI intensity mapping
Tapomoy Guha Sarkar	Birla Institute of Technology and Science Pilani	Prof.	PhD	Theoretical cosmology, HI intensity mapping

Russia:

Name	Organization, Division	Title	Degree	Speciality
Alexandre Ivanchik	Department of Theoretical Astrophysics, Ioffe Physical-Technical Institute	Prof.	PhD	Cosmology
Sergei Balashev	Department of Theoretical Astrophysics, Ioffe Physical-Technical Institute	Dr.	PhD	Cosmology
Dmitry Varshalovich	Department of Theoretical Astrophysics, Ioffe Physical-Technical Institute	Prof., Academician of RAS	PhD	Cosmology
Viacheslav Klimenko	Department of Theoretical Astrophysics, Ioffe Physical-Technical Institute	Dr.	PhD	Cosmology

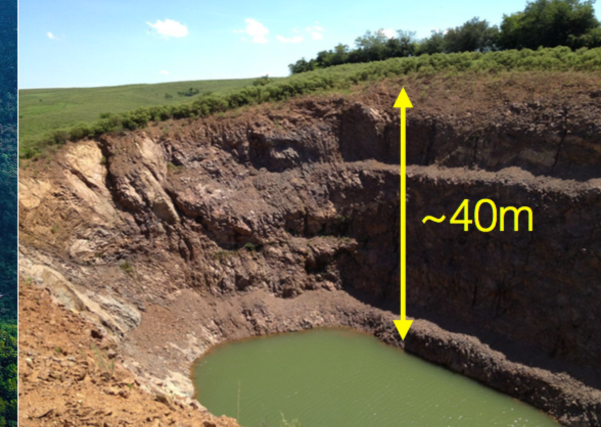
Brazil: (newly added)

Name	Organization, Division	Title	Degree	Speciality
Elicio Abdalla	University of Sao Paulo, Institute of Physics	Prof.	PhD	Cosmology
Carlos Alexander Wuensche Michael Peel	INPE, Sao Jose de campus INPE, Sao Jose de campus	Dr. Dr.	PhD PhD	Radio Astronomy Radio Astronomy

Plan of work:

- Building new models of Epoch of Reionization, and investigating evolution of HI over cosmic time
- Cross-correlation of 21-cm with other cosmic fields
- Subtraction of foreground for 21-cm signal.
- Calibration of telescope systematics

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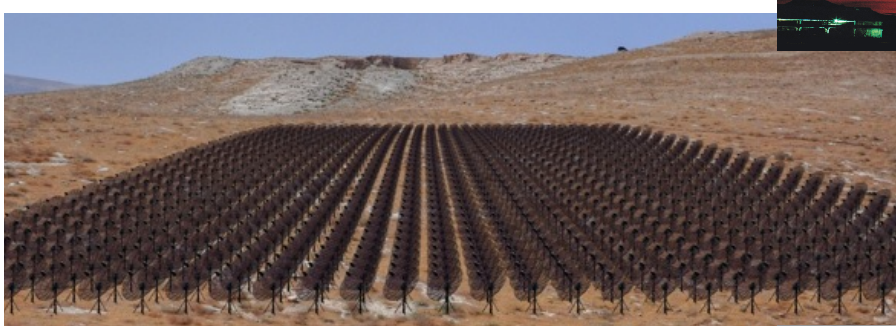

Results: 2016 pilot call

Thank you for the time and effort you took to participate in the BRICS Multilateral Joint Science and Technology Research call.

Funding applications for this instrument were extremely competitive with many high quality proposals. The adjudication process was intense and only proposals that achieved a high ranking according to the designated assessment scorecard were supported. Due to the high number of applications, competitiveness of the programme, alignment with BRICS objectives and budgetary constraints, not all deserving applications were selected for funding.

Review panel comments:

- This is an excellent and innovative project with significant potential for exploitation or commercialisation.
- There is a clear plan for student exchange and their names have been provided. However, there is no other source of funding.

Based on the above remarks, the local panel recommended that this proposal be funded. However, the proposal was not recommended for funding by the Joint Technical Committee (JTC). A very limited number of applications were recommended. The JTC makes a final decision on proposals to be funded.

Please note:

- Cooperation projects with the potential to be sustained beyond the funding period will be favourably considered.
- Only joint proposals that involve at **least three or more** partners from the BRICS countries will be considered for funding.

But each country evaluates its own proposal. The problem can arise from here.

	Country A	Country B	Country C	Country D
Project 1	1	1	4	N/A
Project 2	3	3	2	N/A
Project 3	4	4	1	N/A
Project 4	2	2	2	Evaluated

Please could you tell me which project should be funded?

Since the project is a joint project, it should be required to submit one joint proposal with all partner countries' contribution, and being evaluation at one unique, joint committee.