CROSS-CORRELATION USING THE POST REIONIZATION HI 21 CM OBSERVATIONS

TAPOMOY GUHA SARKAR
Centre for Theoretical Studies
Indian Institute of Technology, Kharagpur.

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The Post Reionization HI:

Two astrophysical systems of interest :

Lyman-α Forest:

Optically Thin Ly-α absorbers N(HI) < 10^{17} cm in a primarily ionized IGM .
UV background ionizing rate $\rightleftarrows$ Recombination rate at local gas density maintains ionizing fraction.

DLA Systems:

Dense, self shielded, Neutral. N(HI) > 10^{19} cm^{-2}
with $\tau \rightarrow 1$, in the damping wings.
Line width independent of the gas velocity structure.
~ 80% of the HI at $z < 4$ is contained in DLAs.

If HI is assumed to trace the underlying dark matter distribution with a possible linear bias ‘b’, we can write the fluctuation in the brightness temperature of the 21cm radiation in Fourier space as (Bharadwaj Ali 2005)

$$\delta T(\hat{\mathbf{n}}, z) = \bar{T}\bar{x}_{\mathrm{HI}} \int \frac{d^3\mathbf{k}}{(2\pi)^3}\, e^{i\mathbf{k}.\hat{\mathbf{n}}r}[b + f\mu^2]\Delta(\mathbf{k}) \,.$$

$$\bar{T}(z) = 4.0\mathrm{mK}(1+\mathrm{z})^2 \left(\frac{\Omega_{\mathrm{b0}}}{0.02}\right)\left(\frac{0.7}{\mathrm{h}}\right)\left(\frac{\mathrm{H_0}}{\mathrm{H(z)}}\right)$$

The Post reionization HI can be studied using 21 cm intensity maps using upcoming Radio Telescope

(**Bharadwaj & Ali 2005 Furlanetto etal 2006**)

Foregrounds are 10^5 times larger than the Signal !!

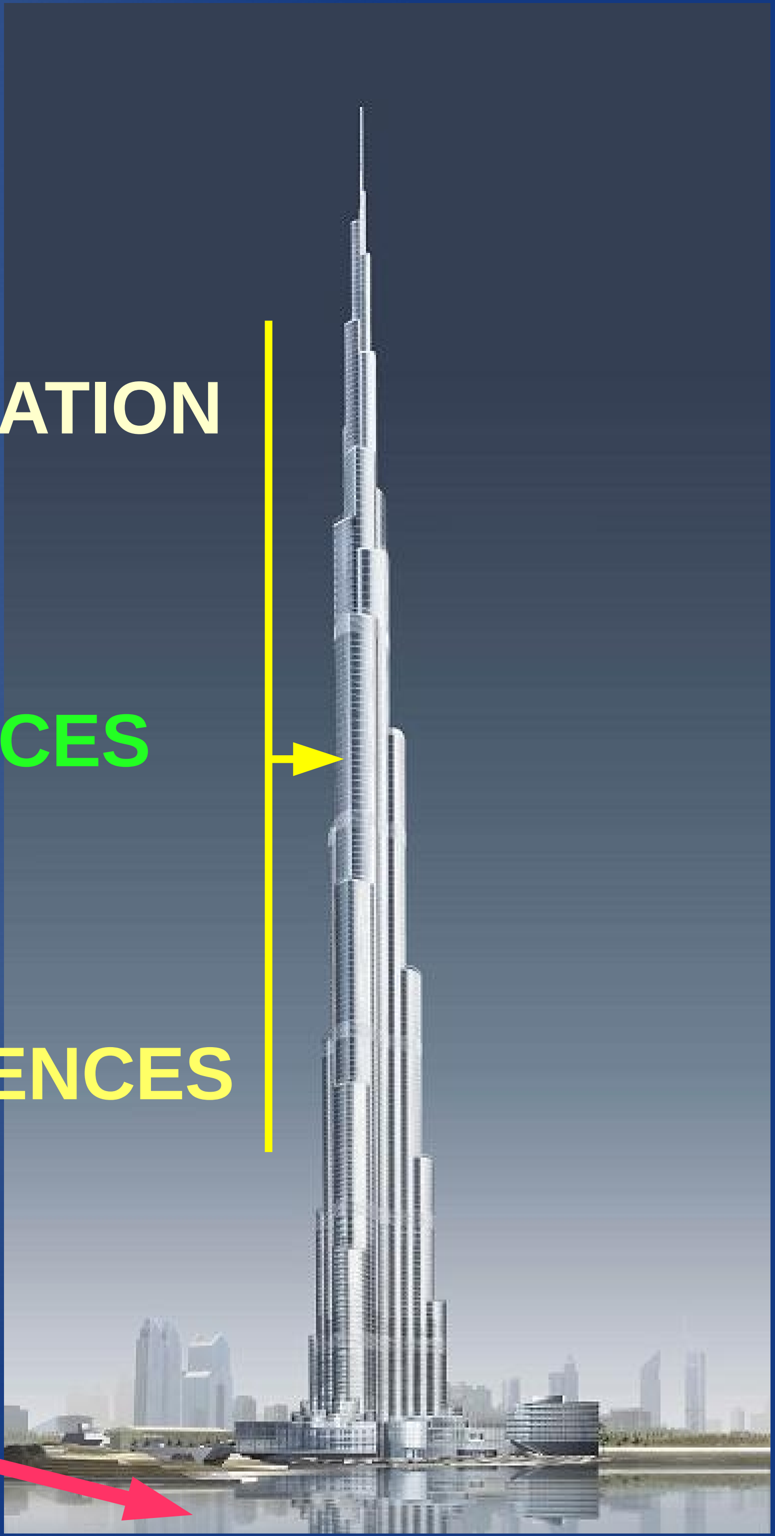
GALACTIC SYNCHOTRON RADIATION

FREE FREE EMISSION

EXTRA GALACTIC POINT SOURCES

CALIBRATION ERRORS

RADIO FREQUENCY INTERFERENCES



S I G N A L

Cross-correlation is one possible way of bypassing the Foreground issue

$$\boxed{A = s_A + F_A}$$

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FOREGROUND and OTHER SYSTEMATICS

SIGNAL

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FOREGROUND and OTHER SYSTEMATICS

SIGNAL

$$\boxed{B = s_B + F_B}$$

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$$\boxed{A = s_A + F_A}$$

FOREGROUND and OTHER SYSTEMATICS

SIGNAL

$$\boxed{B = s_B + F_B}$$

$$\text{If } \langle F_A F_B \rangle = 0 \text{ then } \langle A\, B \rangle = \langle S_A\, S_B \rangle$$

21-cm signal in Cross Correlation

The 21-cm maps can be cross- correlated with other cosmological maps which have a direct or indirect dependence on the underlying LSS.(Afshordi et. al 2003, Cooray et. al 2007)

* **Independent probe of LSS**

* **Instrumental systematics and foregrounds do not affect the signal largely.**

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We have considered 21-cm cross-correlation with CMBR ISW effect and CMBR Weak lensing

We have seen that the Cross -correlation with ISW is not detectable as the signal is cosmic variance dominated.

With weak lensing the signal is detectable under ideal experimental conditions

(Guha Sakar T, Datta , K., et. al. 2008. & Guha Sarkar 2009)

Lyman – α Forest and HI 21-cm Cross-correlation

HI from the same z can be seen through
Redshifted 21 cm line EMISSION or through
ABSORBTION features in Quasar spectra
(Lyman-α forest)

The signals have different origins –
The Lyman-α forest originate from small HI fluctuations in the primarily ionized IGM. 21 cm radiation from these regions is negligible.

The 21 cm radiation originates primarily from the self shielded and dense DLA systems which contain most of the neutral gas.

On large scales however they both trace the underlying Dark Matter distribution and hence expected to be correlated

Writing the Ly- α optical depth as

$$\tau(\hat{\mathbf{n}}, z) = \bar{\tau}(z) + \delta\tau(\hat{\mathbf{n}}, z)$$

With

$$\bar{\tau}(z) = 1.83 \times 10^4 \left(\frac{0.7}{h}\right)\left(\frac{\Omega_b h^2}{0.02}\right)\sqrt{\frac{0.3}{\Omega_{m0}}} x_{HI}(1+z)^{3/2}$$

&

$$\delta\tau(\hat{\mathbf{n}}, z) = \bar{\tau} \int \frac{d^3\mathbf{k}}{(2\pi)^3} e^{i\mathbf{k}.\hat{\mathbf{n}}r}[b_\tau + f\mu^2]\Delta(\mathbf{k})\,.$$

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Effect of Peculiar Velocity Redshift Space Distortion

Similarly for 21-cm Observations we have

$$\delta T(\hat{\mathbf{n}}, z) = \bar{T}\bar{x}_{\rm HI} \int \frac{d^3\mathbf{k}}{(2\pi)^3}\, e^{i\mathbf{k}.\hat{\mathbf{n}}r}[b + f\mu^2]\Delta(\mathbf{k})\,.$$

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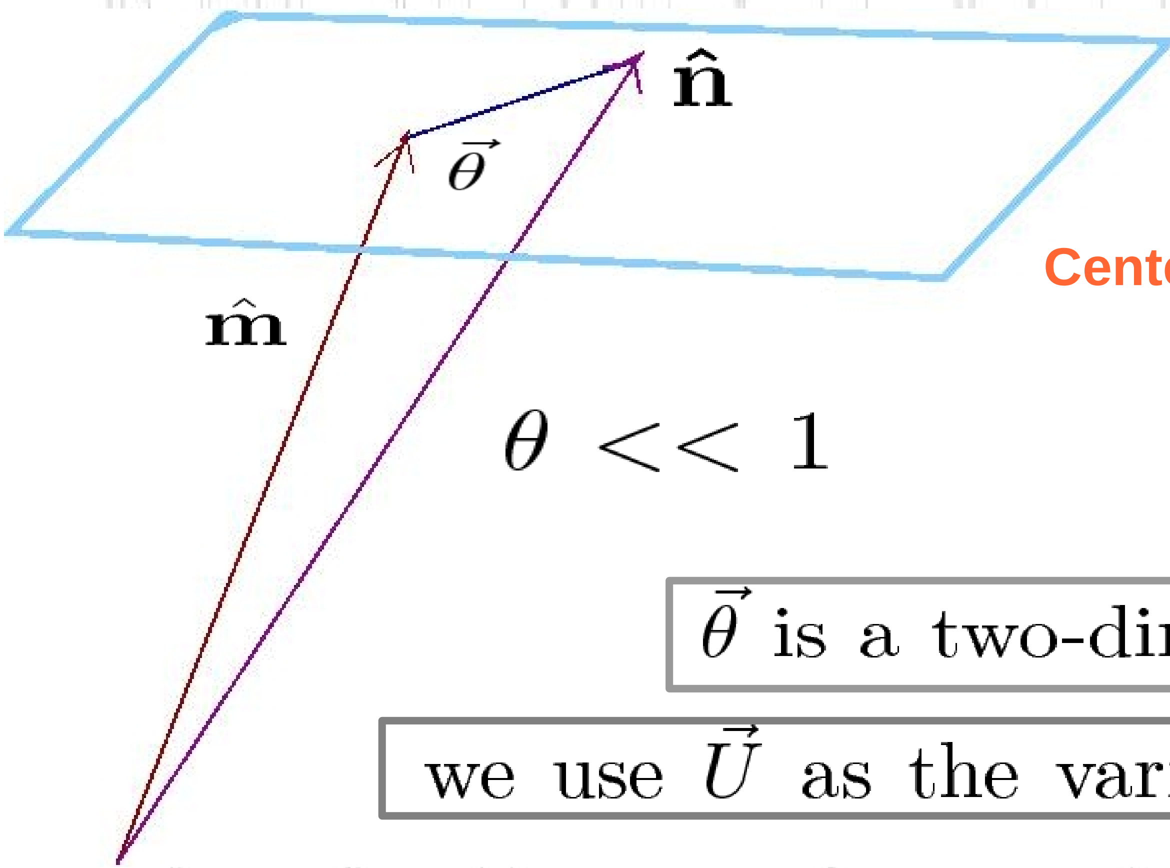
For Small field of View .. Flat Sky Approximation:



$$\theta << 1$$

Center of FOV

$$\hat{\mathbf{n}} = \hat{\mathbf{m}} + \vec{\theta},$$

$\vec{\theta}$ is a two-dimensional $(2D)$ vector

we use $\vec{U}$ as the variable conjugate to $\vec{\theta}$.

Fourier Basis instead of Full Spherical Harmonics on the sky

Angular Power Spectrum

$$P_a(\vec{U}, \Delta z) = \frac{1}{\pi r^2} \int_0^\infty dk_\parallel \ \cos(k_\parallel \Delta r) \ F_a(\mu) P(k) \, .$$

Matter PS

$a = T$ → HI power spectrum

$a = \tau$ → Lyman α optical depth PS

$a = c$ → Cross-correlation PS

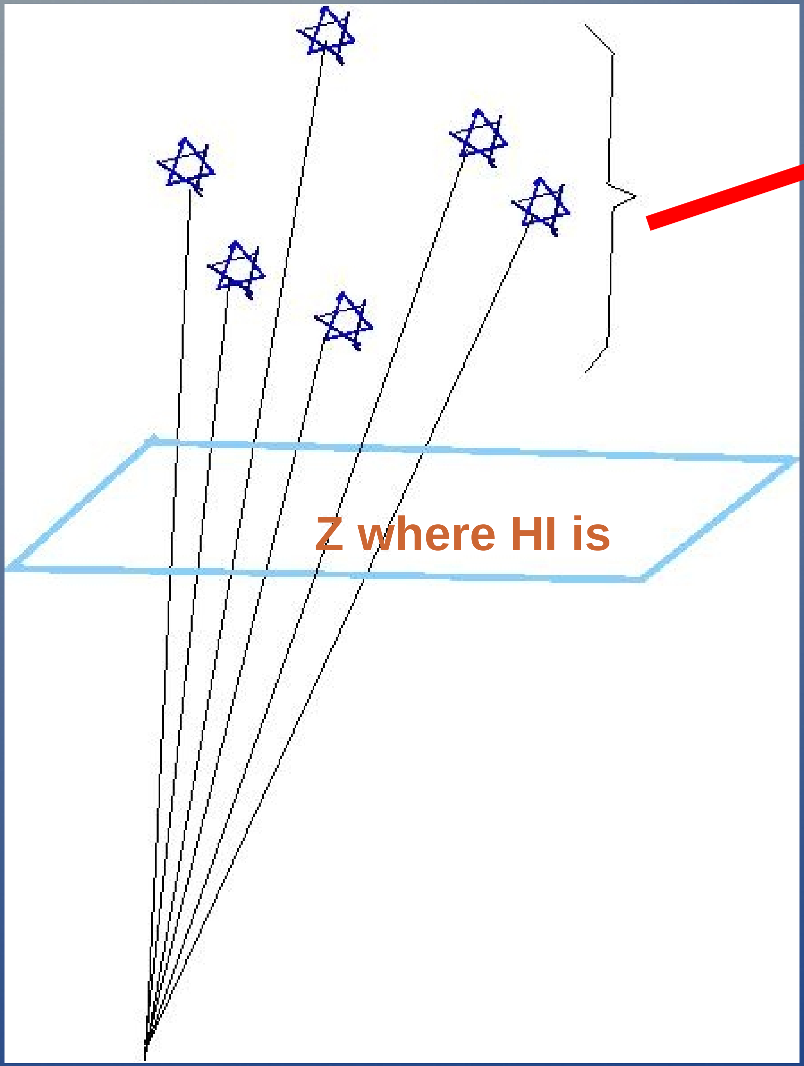
$$k = \sqrt{k_\parallel^2 + (\frac{2\pi U}{r})^2} \text{ and } \mu = k_\parallel / k.$$

$$A(\mu) = T\bar{x}_{HI}[b + f\mu^2]$$

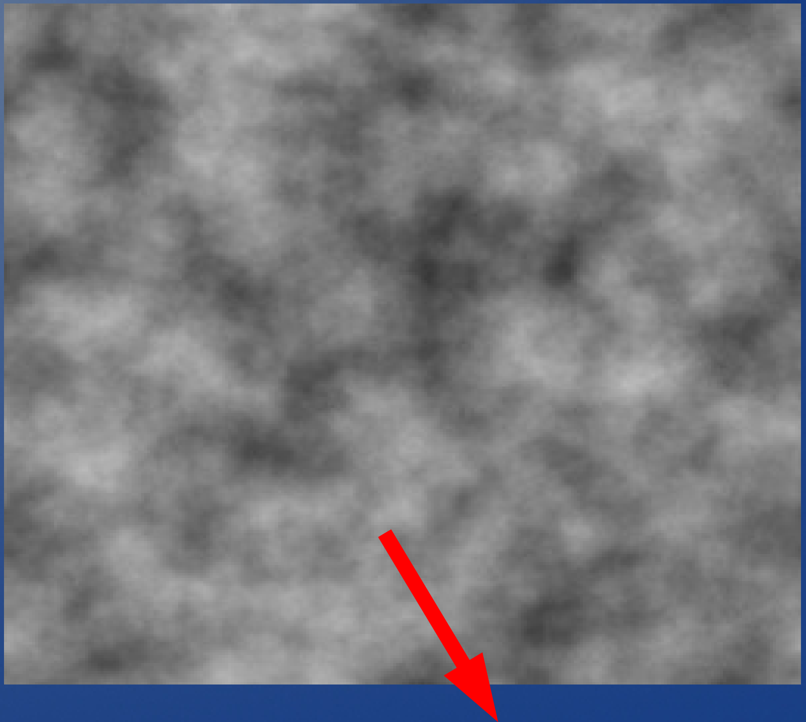
$$B(\mu) = \bar{\tau}[b_\tau + f\mu^2]$$

$$F_a(\mu) = A^2(\mu), \ B^2(\mu), \text{ and } A(\mu) \ B(\mu) \text{ for } a = \tau, T \text{ ,c}$$

Optical Depth is measured for discrete Bright Quasars



Bright Quasars whose optical depth is measured



Single FOV observation

Continuous Field τ

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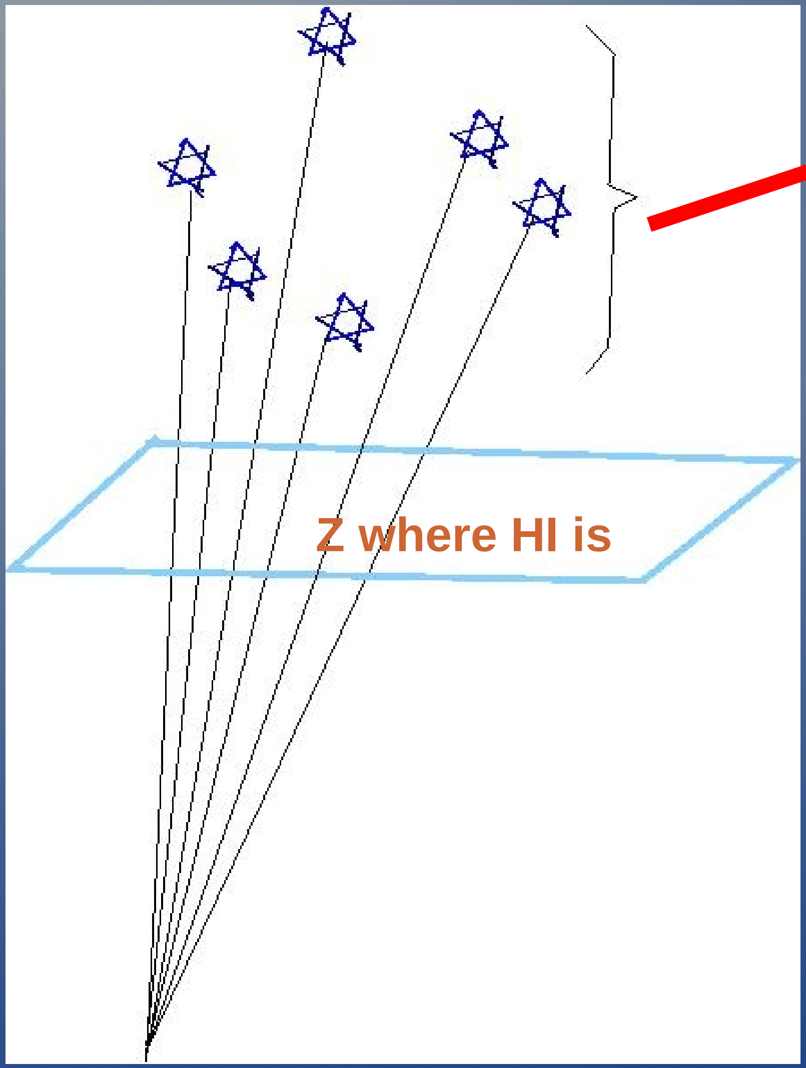

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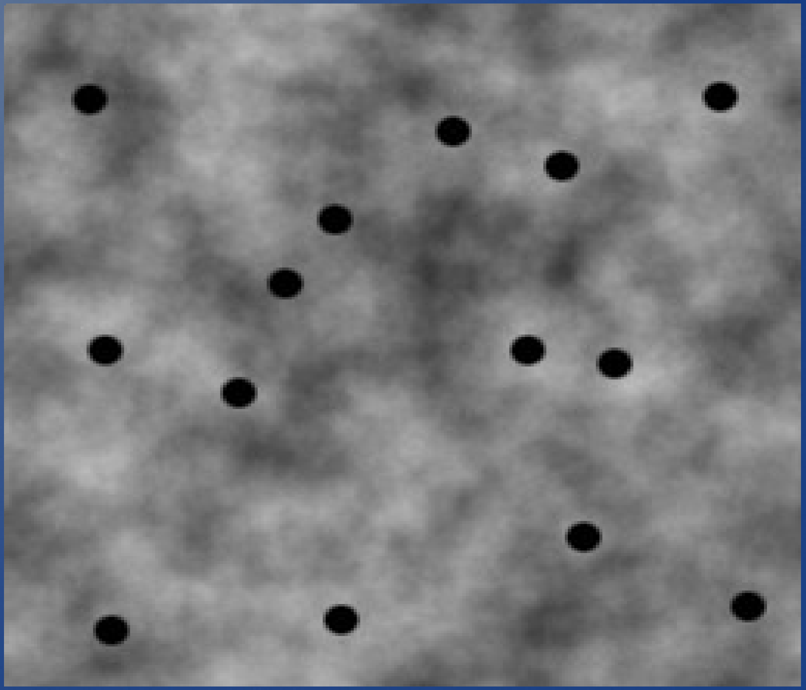
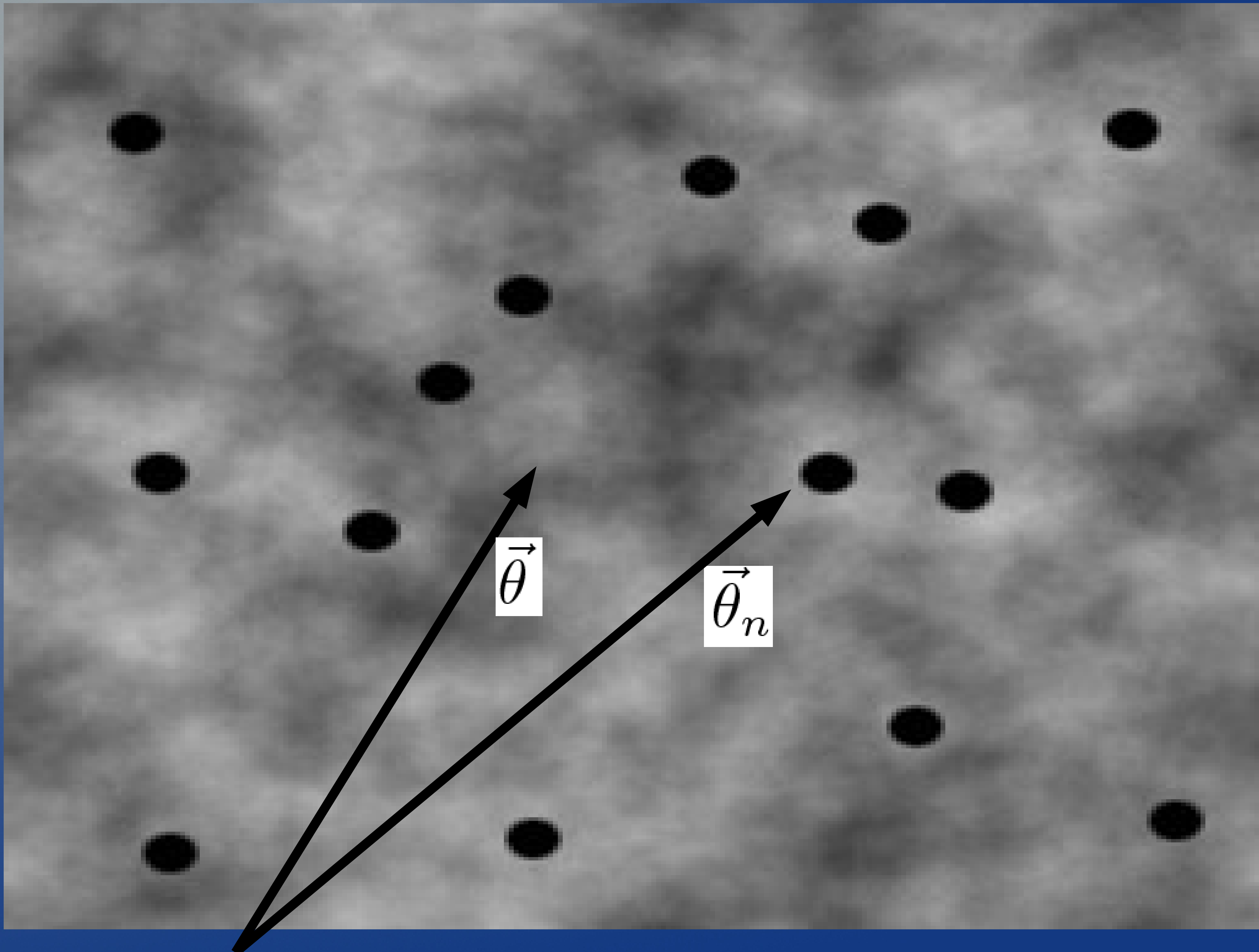
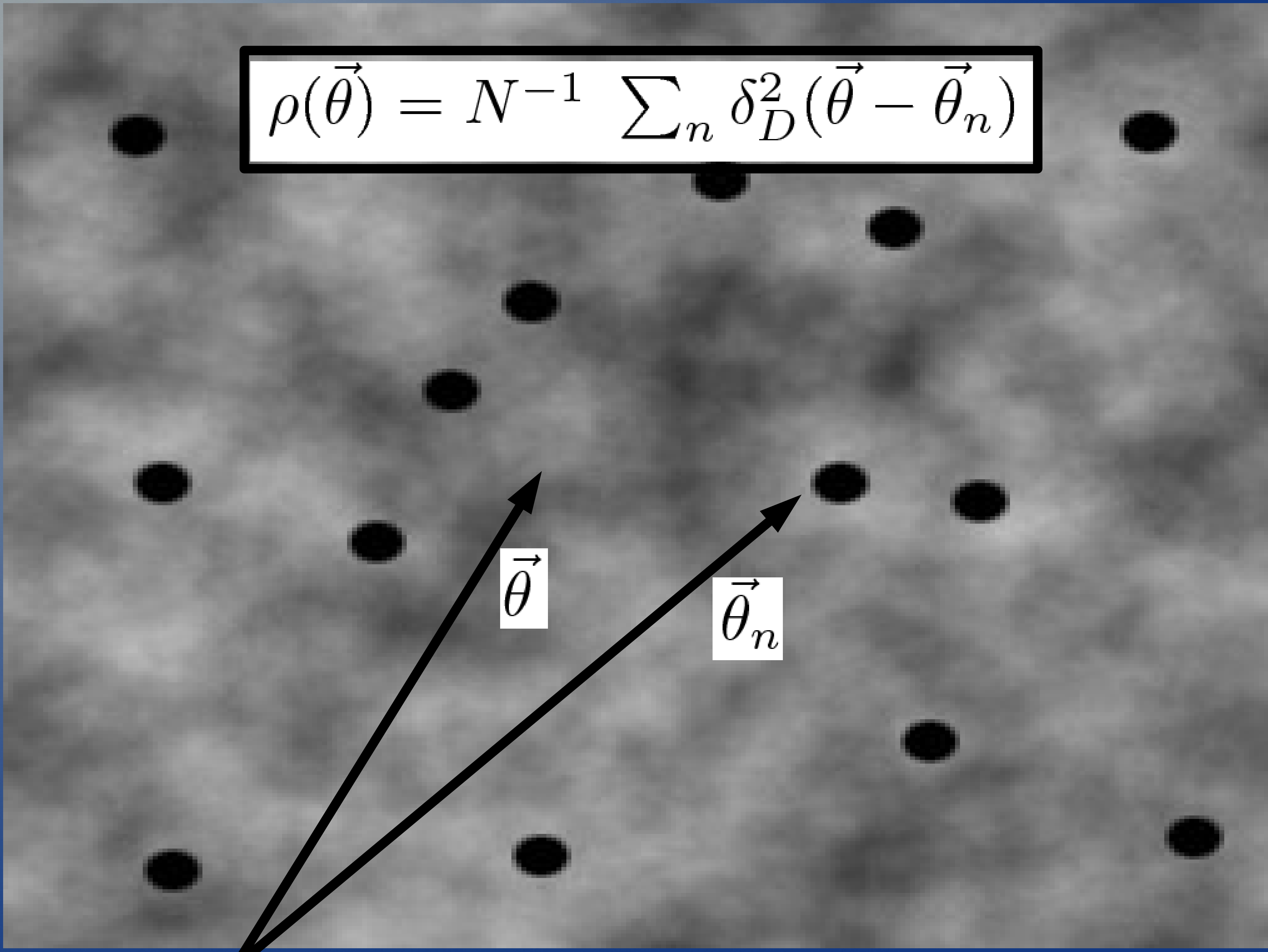


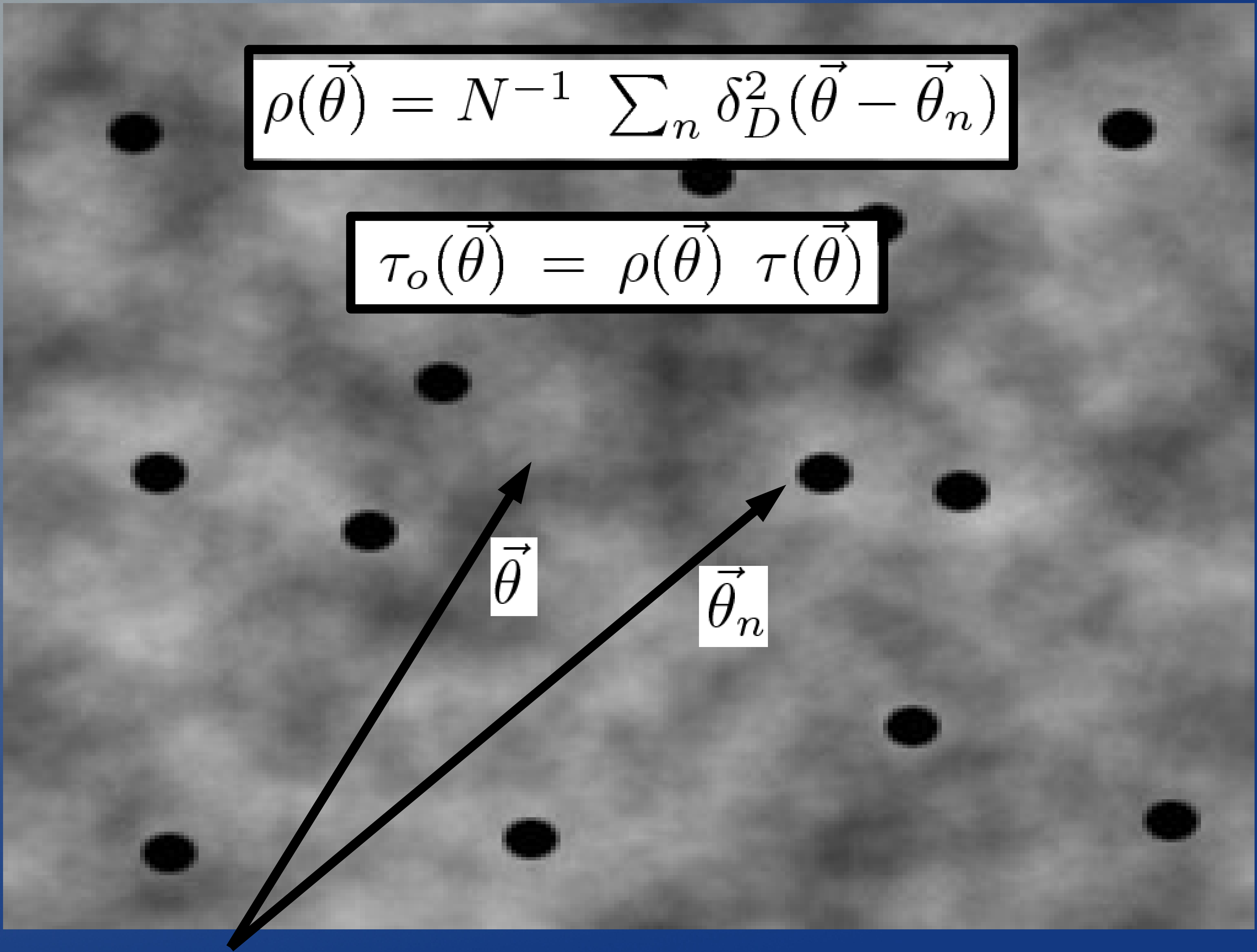
Single FOV observation

Continuous Field τ sampled
At discrete points


$\vec{\theta}$
$\vec{\theta}_n$

$$\rho(\vec{\theta}) = N^{-1} \sum_n \delta_D^2(\vec{\theta} - \vec{\theta}_n)$$





$\rho(\vec{\theta}) = N^{-1} \sum_n \delta_D^2(\vec{\theta} - \vec{\theta}_n)$
$\tau_o(\vec{\theta}) = \rho(\vec{\theta})\ \tau(\vec{\theta})$
$\vec{\theta}$
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In Fourier Space

$$\tilde{\tau}_o(\vec{U}, z) = \mathbf{FT}\ [\rho(\vec{\theta})] \otimes \mathbf{FT}\ [\tau(\vec{\theta})]$$

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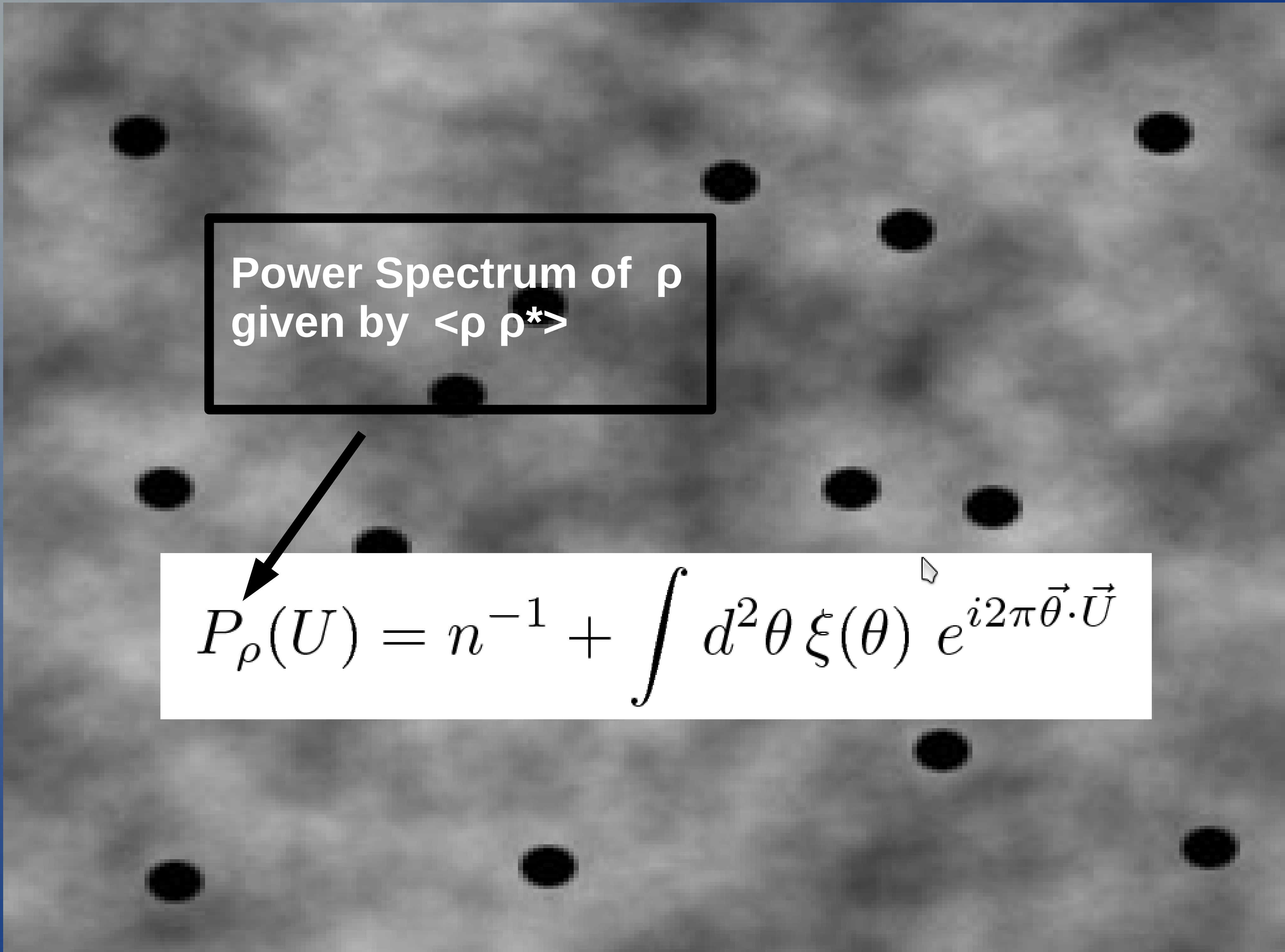
In Fourier Space

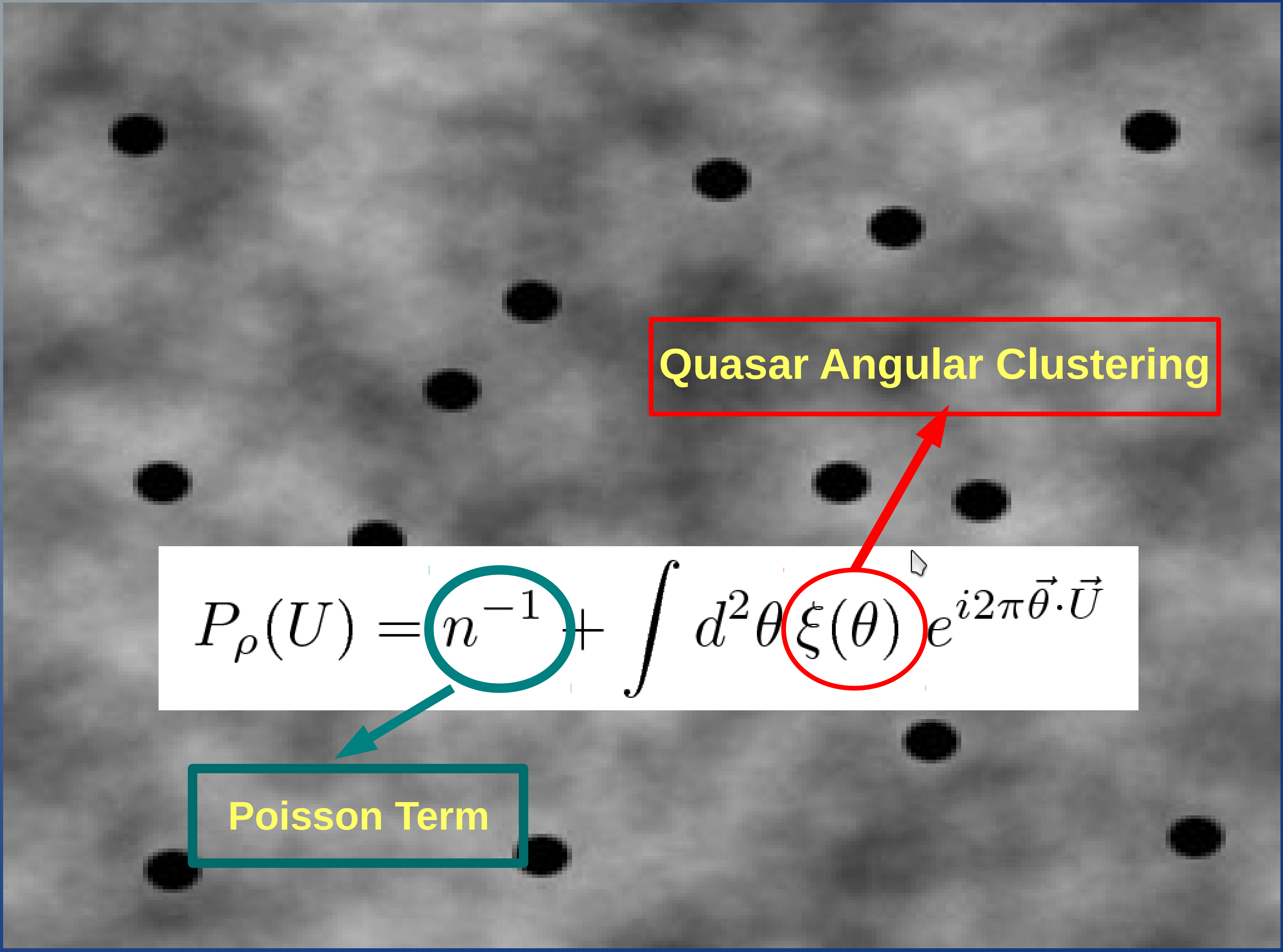
$$\tilde{\tau}_o(\vec{U}, z) = \textbf{FT} \; [\rho(\vec{\theta})] \otimes \textbf{FT} \; [\tau(\vec{\theta})]$$

$$N^{-1} \sum e^{i \vec{U} \vec{\theta}_n}$$



Power Spectrum of ρ given by <ρ ρ*>

$$P_\rho(U) = n^{-1} + \int d^2\theta\, \xi(\theta)\, e^{i2\pi\vec{\theta}\cdot\vec{U}}$$



$$P_\rho(U) = n^{-1} + \int d^2\theta\, \xi(\theta)\, e^{i2\pi \vec{\theta}\cdot\vec{U}}$$

Quasar Angular Clustering

Poisson Term

The Cross-correlation Estimator:

$$\hat{E}(\vec{U}, \Delta z) = \frac{1}{2}\left[\tilde{\tau}_o(\vec{U}, z)\ \delta\tilde{T}^*(\vec{U}, z + \Delta z)\right] + \frac{1}{2}\left[\tilde{\tau}_o^*(\vec{U}, z)\ \delta\tilde{T}(\vec{U}, z + \Delta z)\right].$$

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$$\langle\hat{E}(\vec{U},\Delta z)\rangle=P_c(\vec{U},\Delta z)$$

Assuming that the distribution of Quasars is uncorrelated with either T or τ.

The Cross-correlation Estimator:

$$\hat{E}(\vec{U}, \Delta z) = \frac{1}{2}\left[\tilde{\tau}_o(\vec{U}, z)\ \delta\tilde{T}^*(\vec{U}, z + \Delta z)\right] + \frac{1}{2}\left[\tilde{\tau}_o^*(\vec{U}, z)\ \delta\tilde{T}(\vec{U}, z + \Delta z)\right].$$

$$\langle \hat{E}(\vec{U}, \Delta z) \rangle = P_c(\vec{U}, \Delta z)$$

Unbiased Estimator

$$\hat{E} = (AB^* + A^*B)/2,$$

$$\langle \hat{E}^2 \rangle = \frac{1}{2} \left[3 |\langle AB^* \rangle|^2 + \langle AA^* \rangle \langle BB^* \rangle \right]$$

Discrete Quasar sampling affects the Variance of the Estimator

$$\boxed{\langle \hat{E}^2 \rangle - \langle \hat{E} \rangle^2 = P_c^2 + (P_T + N_T)\ [P_\rho \otimes (P_\tau + N_\tau)]}$$

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System Noise power spectra

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$$\boxed{\sigma^2 \quad = \quad [\langle \hat{E}^2 \rangle - \langle \hat{E} \rangle^2]/N_E\,.}$$

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$$\sigma^2 \quad = \quad [\langle \hat{E}^2 \rangle - \langle \hat{E} \rangle^2]/N_E\,.$$

$$N_E = (2\ell + 1)\,\Delta\ell\,(B/\Delta\nu)\,f\,N_F$$

Detectability is dictated by :

SYSTEM NOISE IN INDIVIDUAL AUTO CORRELATIONS

QUASAR ANGULAR DENSITY

For 21 cm observation the system noise depends on a variety of
Array parameter

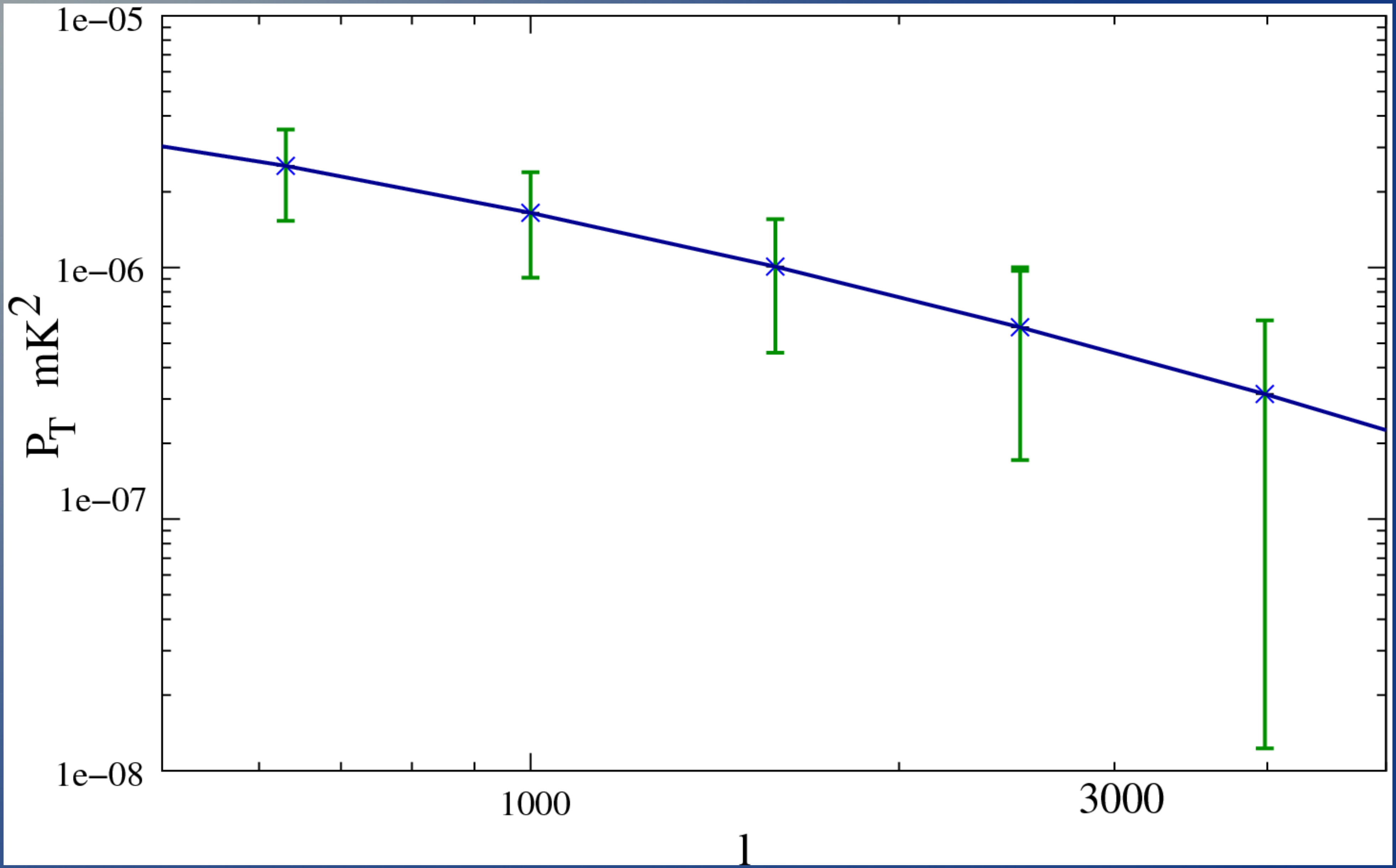
N ~ 1/T T is integration time

$N \sim 1/N_A^{\,2}$ N_A is the number of antennae

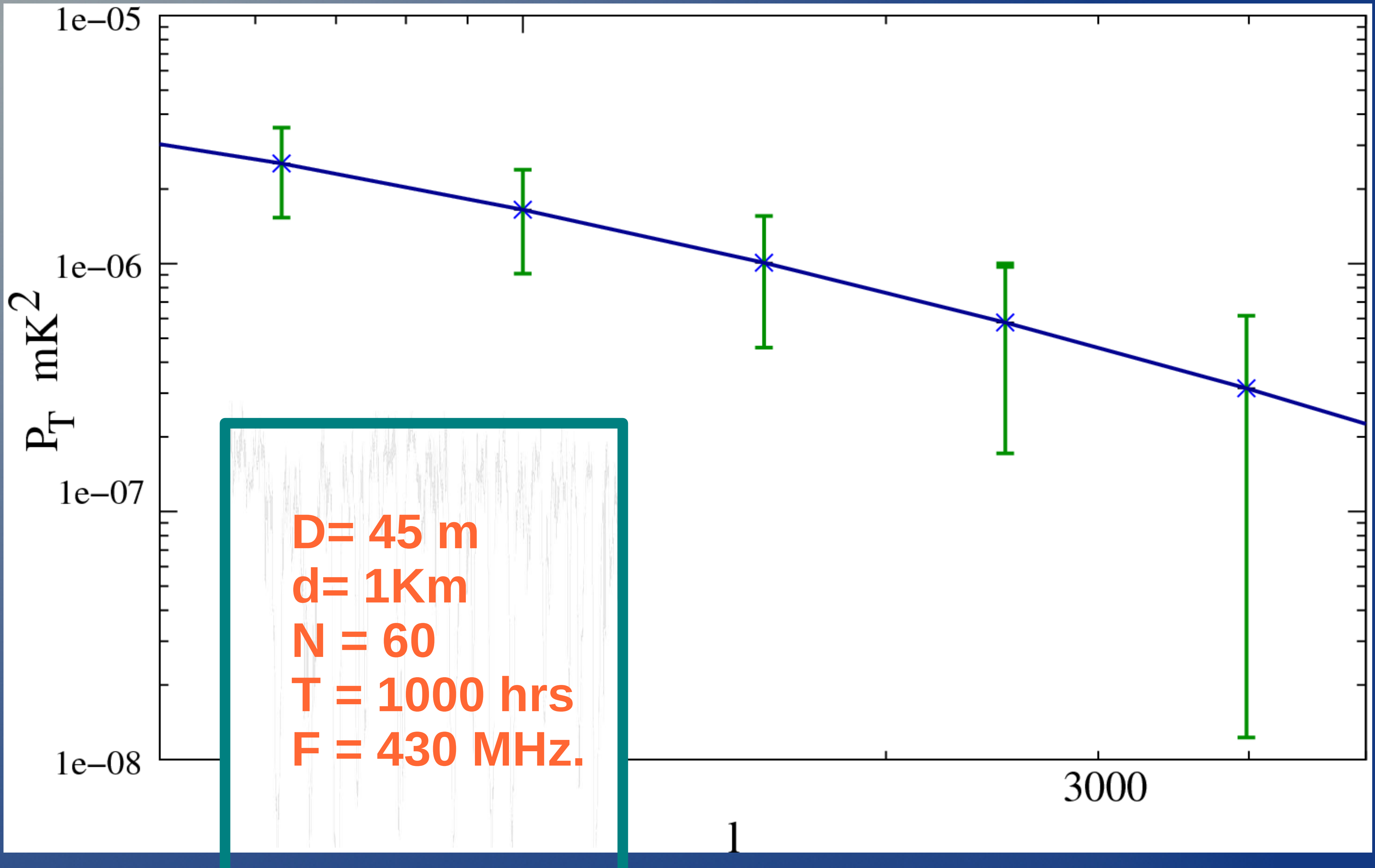
Larger Field of View also increases sensitivity ..

For Lyman alpha optical depth measurement we have assumed
A 3 σ measurement.

Dense sampling will also sensitively affect the noise.



HI Power spectrum for z = 2.2 with 3σ error bars with 1000 hrs EGMRT Observation



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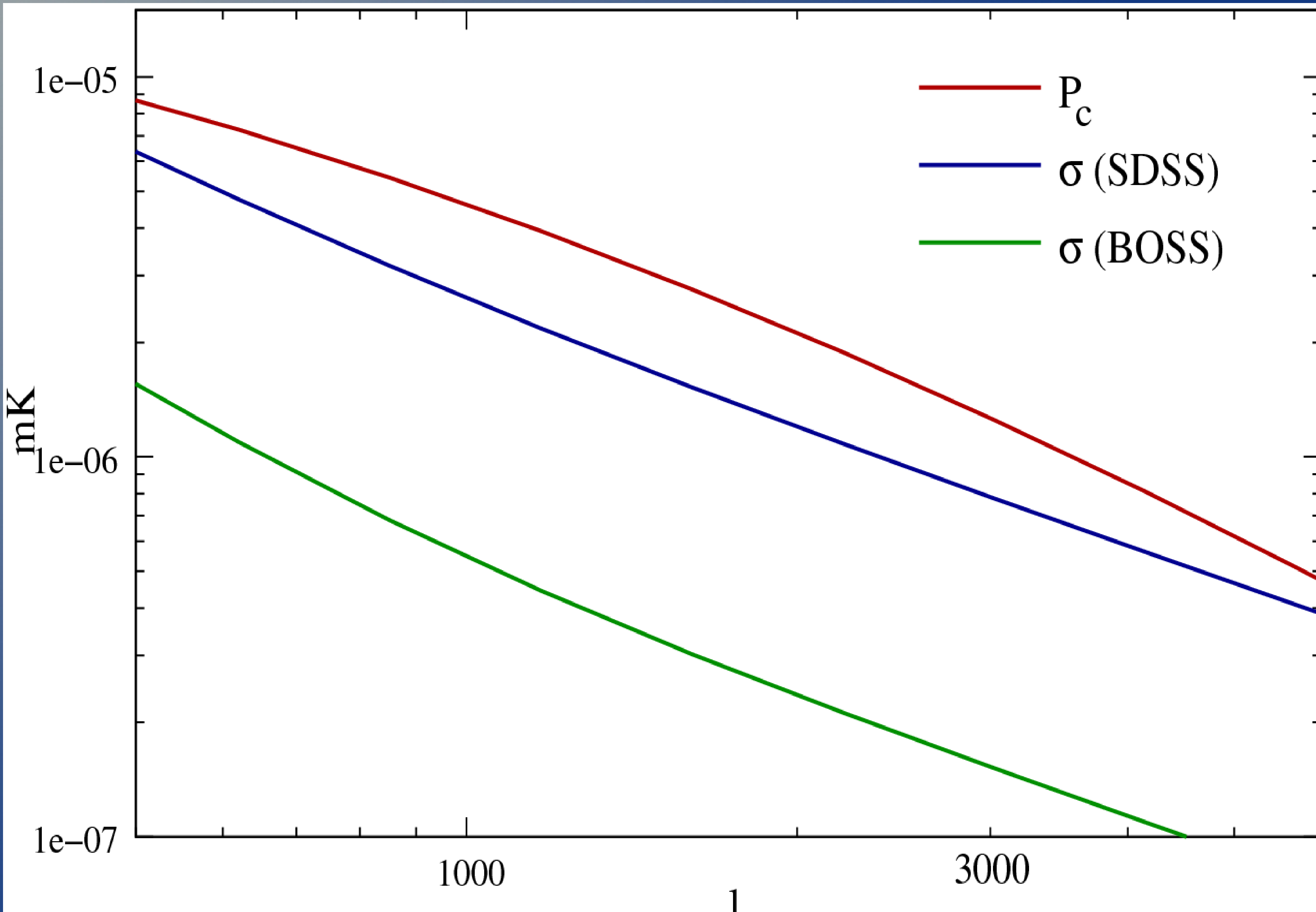
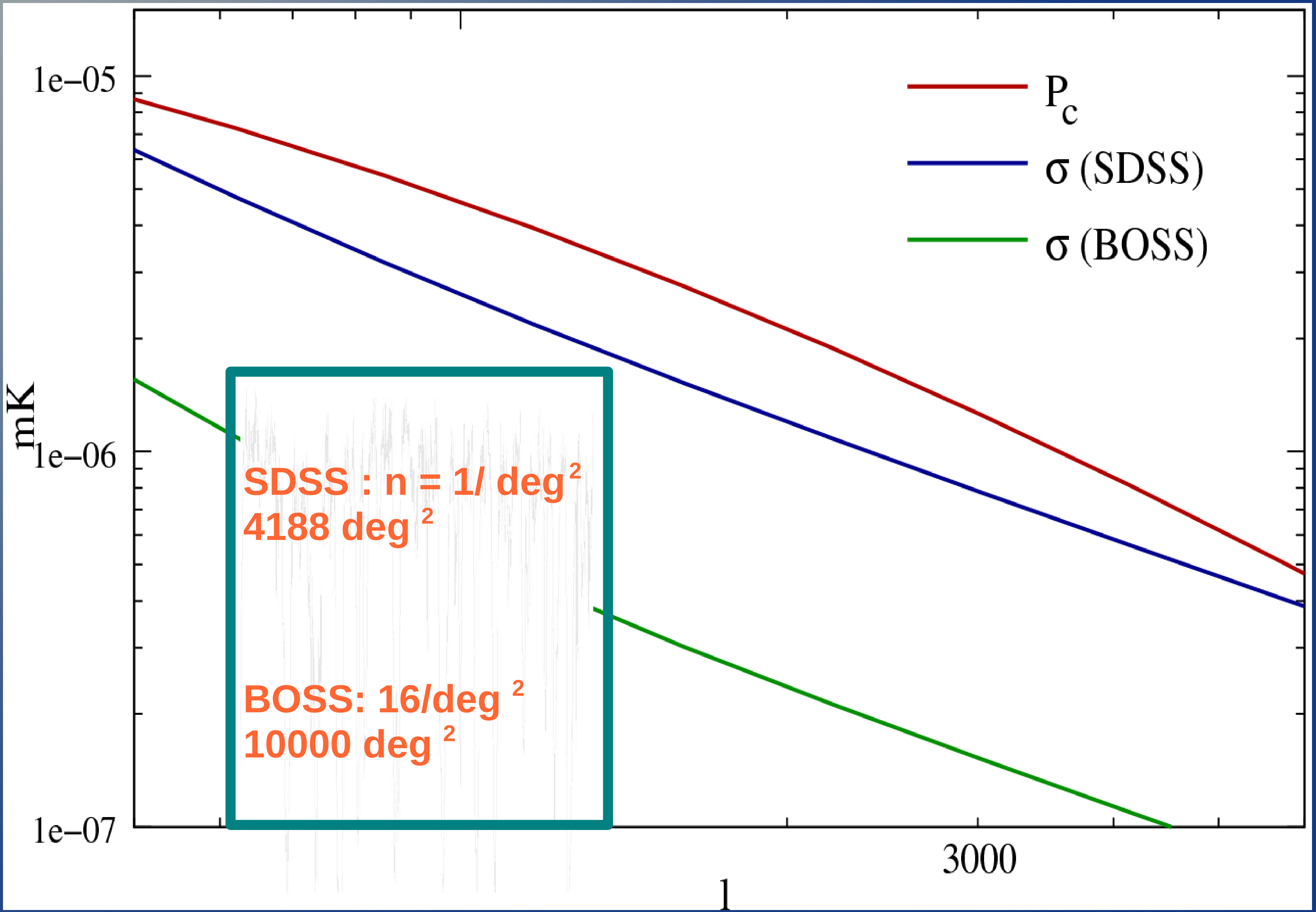
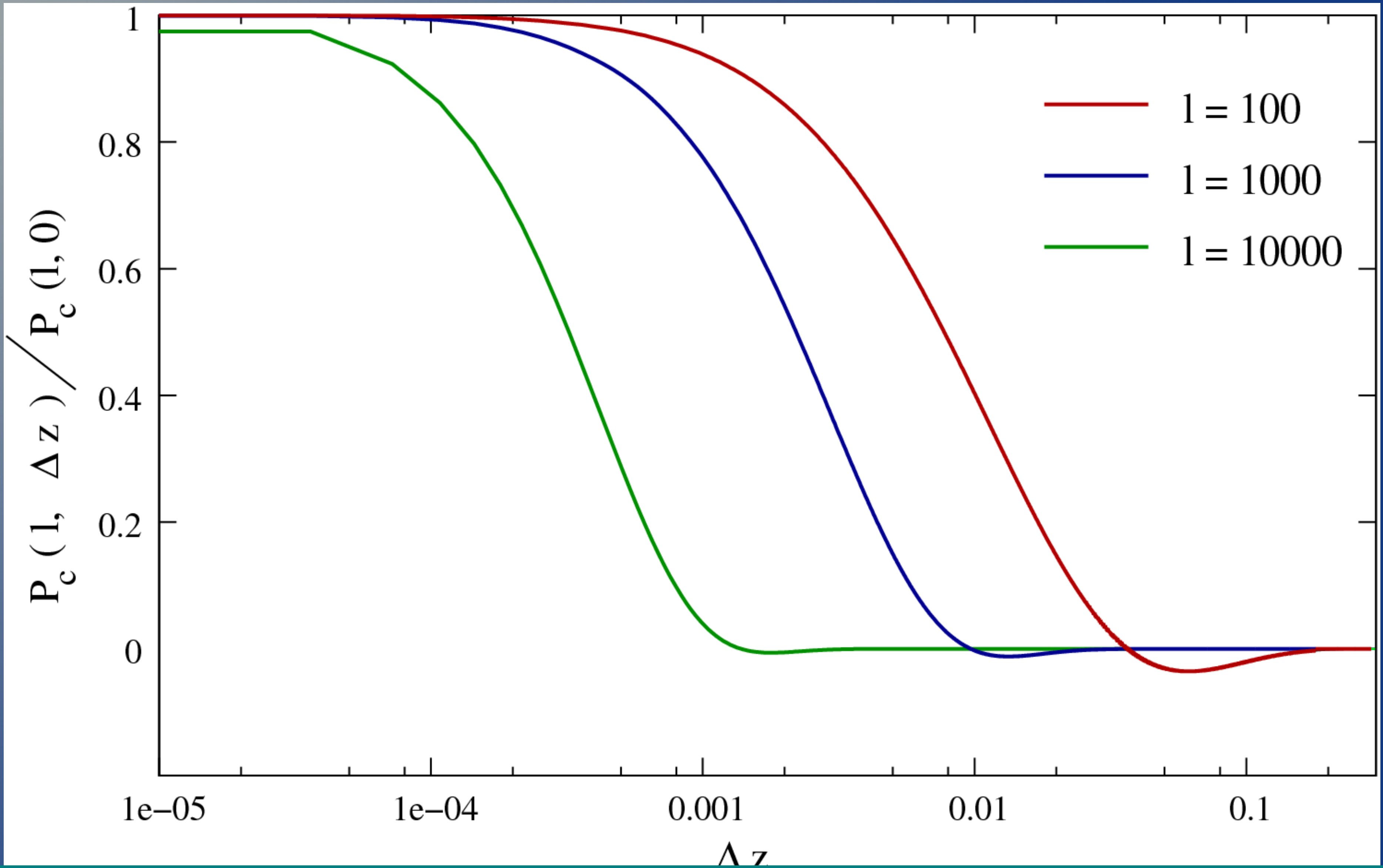


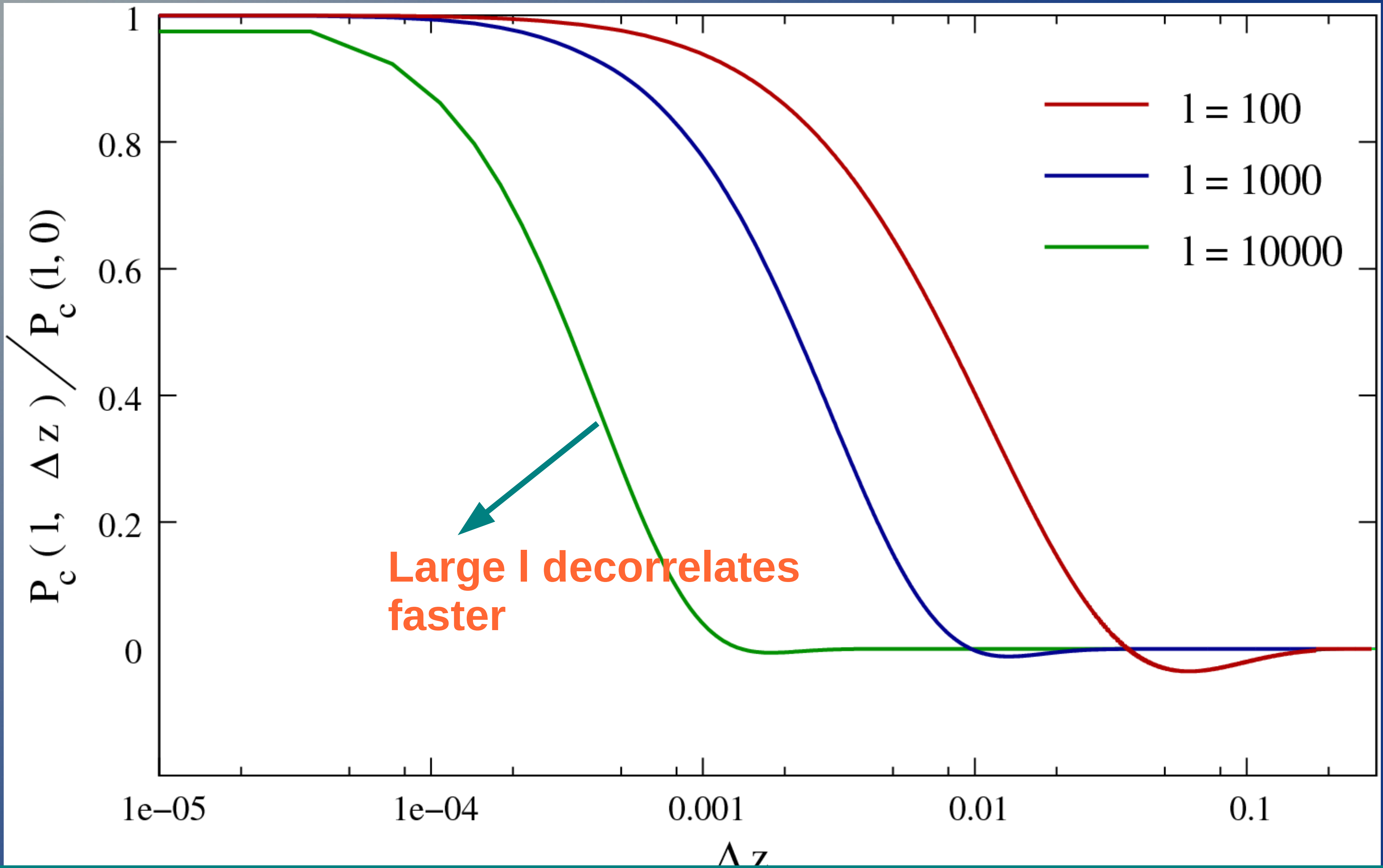
1e−05
1e−06
1e−07
mK
1000
3000
l
Pc
σ (SDSS)
σ (BOSS)



1e−05
1e−06
1e−07
mK
3000
l
P_c
σ (SDSS)
σ (BOSS)
SDSS : n = 1/ deg ^{2}
4188 deg ^{2}
BOSS: 16/deg ^{2}
10000 deg ^{2}



Decorrelation of the signal with increasing Δz for a few representative l values.



Decorrelation of the signal with increasing Δ z for a few representative *l* values.

SUMMARY :

Cross-correlation provides an independent cosmological probe with the same astrophysical/cosmological informations as the Individual auto correlation.

The effect of Foregrounds and other systematics is much less severe.

Cross-correlation of 21-cm observations with ISW is cosmic variance limited

Cross correlation with weak lensing is not cosmic variance limited and summing up multipoles will allow a detection in IDEAL experimental situation.

The Ly alpha and 21 cm correlation is however detectable at a level of precision greater than that for the individual auto correlations.

Collaborators

Somnath Bharadwaj

Tirthankar Roy Choudhury

Kanan Datta

Prasun Dutta

THANKS