

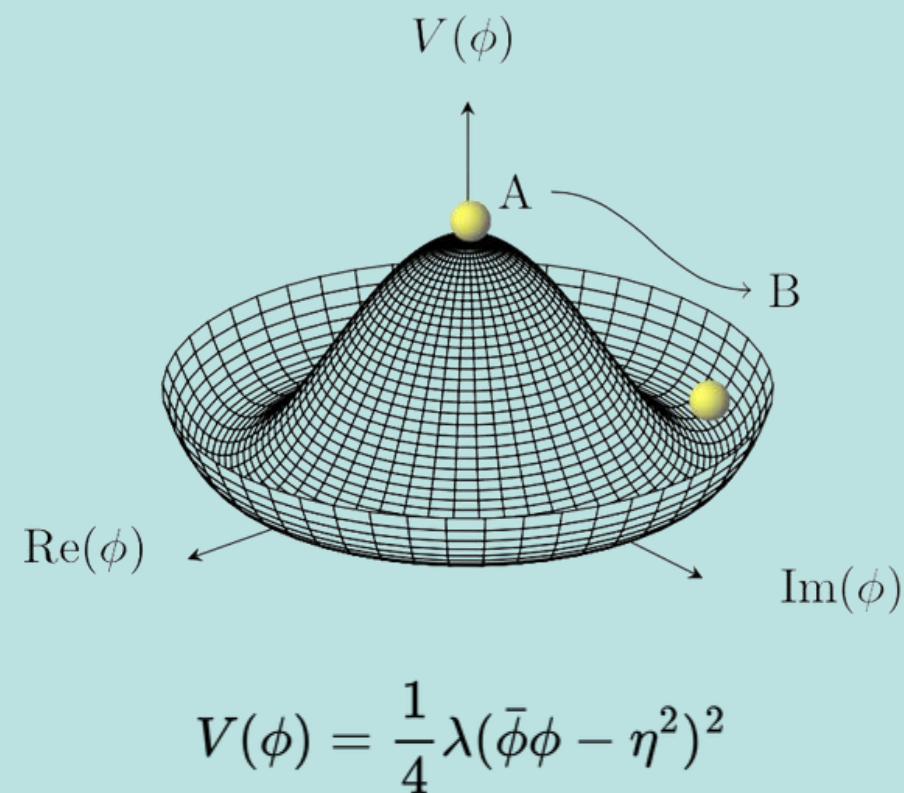
COSMIC STRINGS AND HOW TO FIND THEM?

IN THE CONTEXT OF HI 21CM COSMOLOGY

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PRELUDE: SPONTANEOUS SYMMETRY BREAKING



Unbroken
Symmetry

$$\langle 0 | \phi_A | 0 \rangle = 0$$

$$\langle \phi_A \rangle \rightarrow e^{i\alpha} \langle \phi_A \rangle$$

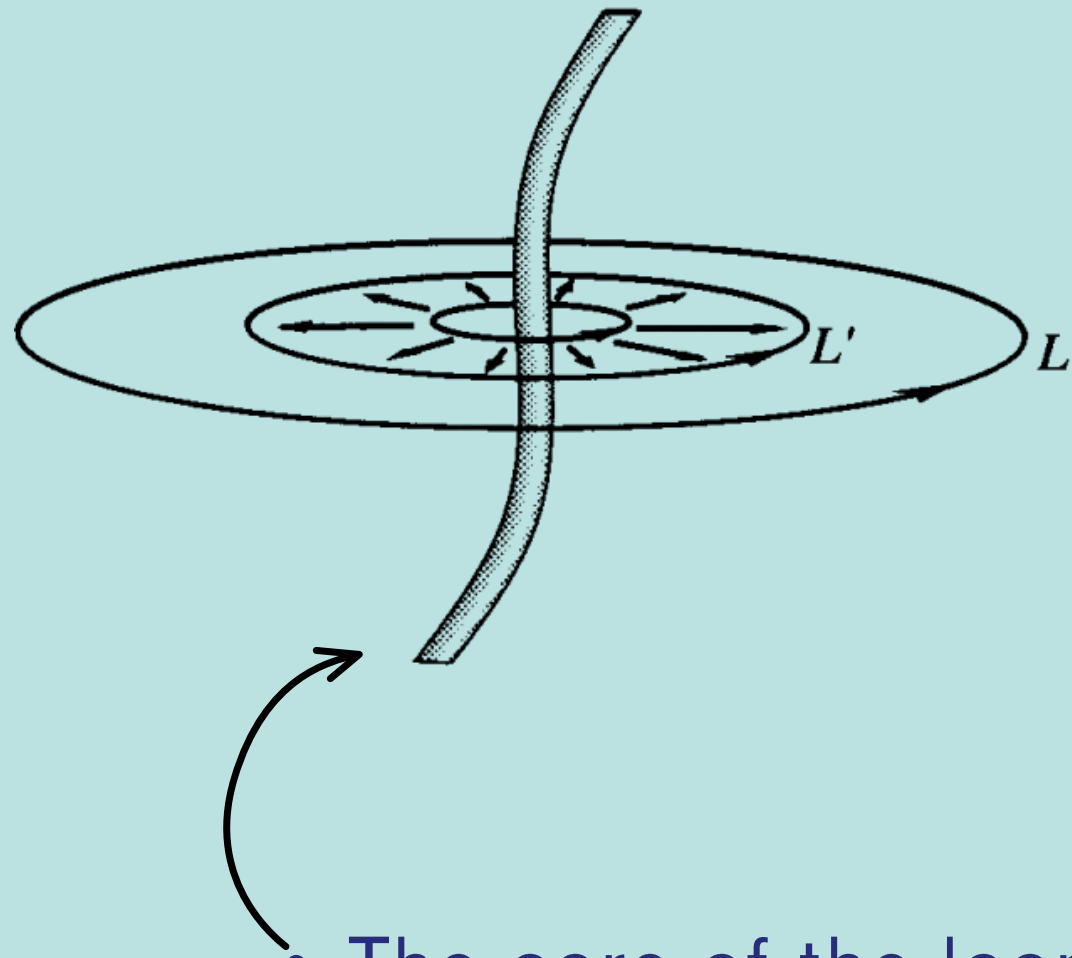
Broken
Symmetry

$$\langle 0 | \phi_B | 0 \rangle = \eta e^{i\theta}$$

$$\langle \phi_B \rangle \rightarrow e^{i(\alpha)} \langle \phi_B \rangle = \eta e^{i(\alpha+\theta)}$$

- As hot the universe cooled, we anticipate the temperature-dependent potential's minima evolved from $\Phi = 0$ to a degenerate circle

- Different (causally disconnected) regions of space can have different vacuum angles



- Non-trivial loops in the vacua phase can form, enclosing smaller loops within

- The core of the loop assumes the unbroken symmetry state with non-zero energy density, forming a **COSMIC STRING**

WHAT ARE COSMIC STRINGS?

- 1-Dimensional **Topological Defects**, formed during the early universe phase transitions
- They are predicted by some Grand Unified Theories(GUTs), where symmetry can produce a non-simply connected vacuum manifold.
- String theory can also produce cosmological string-like objects, known as cosmic superstrings

SOME PROPERTIES OF STRINGS

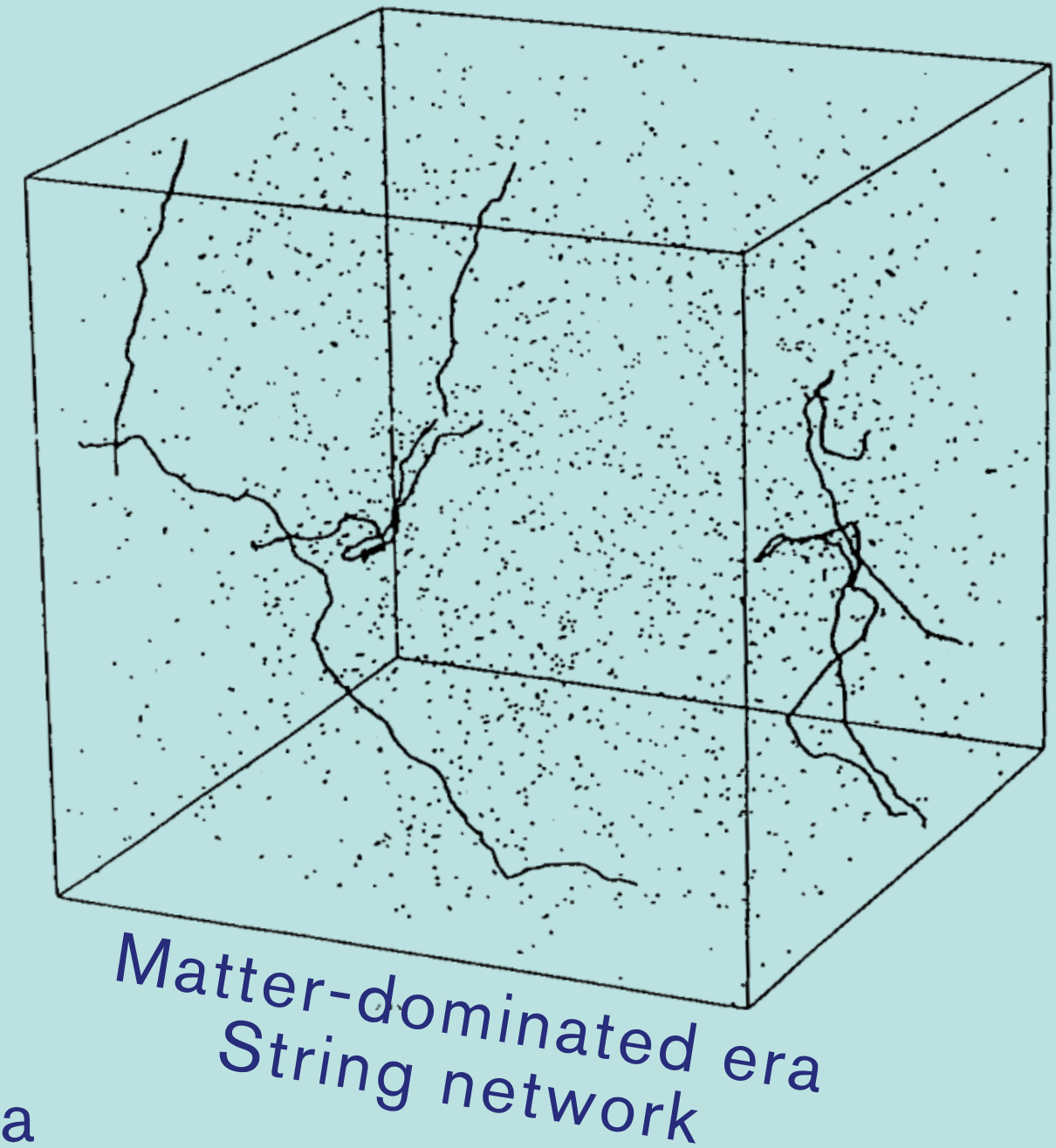
- Their linear mass density goes as,

$$\mu \sim \eta^2$$

For, $\eta \sim 10^{16} \text{ GeV}$

$$\mu \sim 10^{22} \text{ g cm}^{-1}$$

- From Lorentz invariance of the energy-momentum tensor, the tension is equal to the mass density
- String interactions coupled with expansion achieve a scaling solution



IN THE WAKE OF A COSMIC STRING

- From the metric of a cosmic string, we find the space around the string is conical with a deficit angle of:

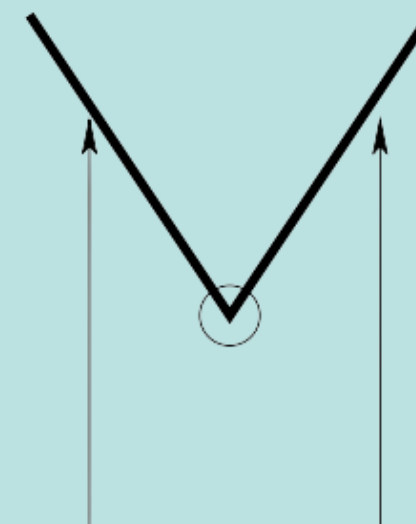
$$\alpha = 8\pi G\mu$$

- For a string traveling with velocity v_s , matter streaming by the string receives a velocity kick

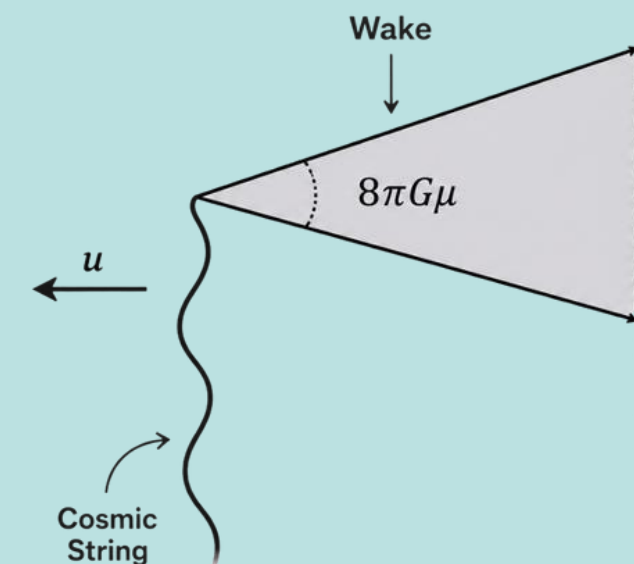
$$\delta v = 4\pi G\mu v_s \gamma_s$$

- This leads to formation of a wedge with twice the background density

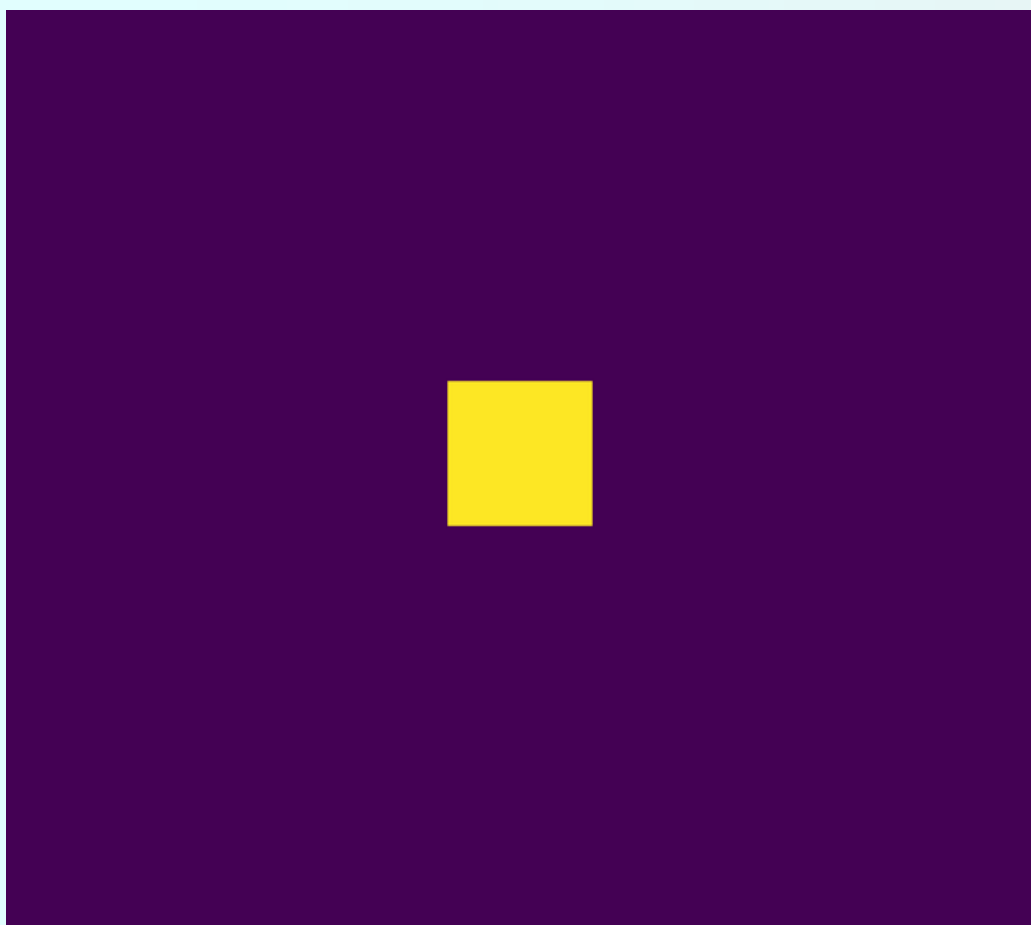
Top view



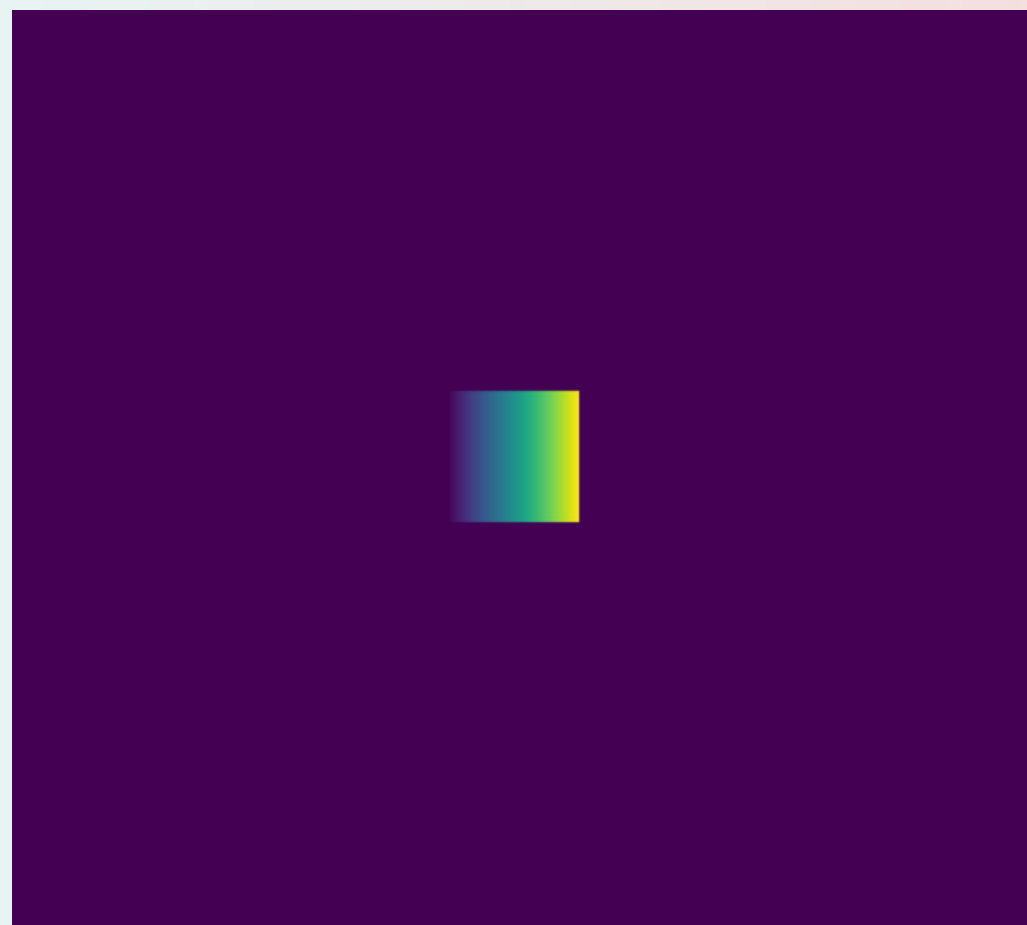
Side view



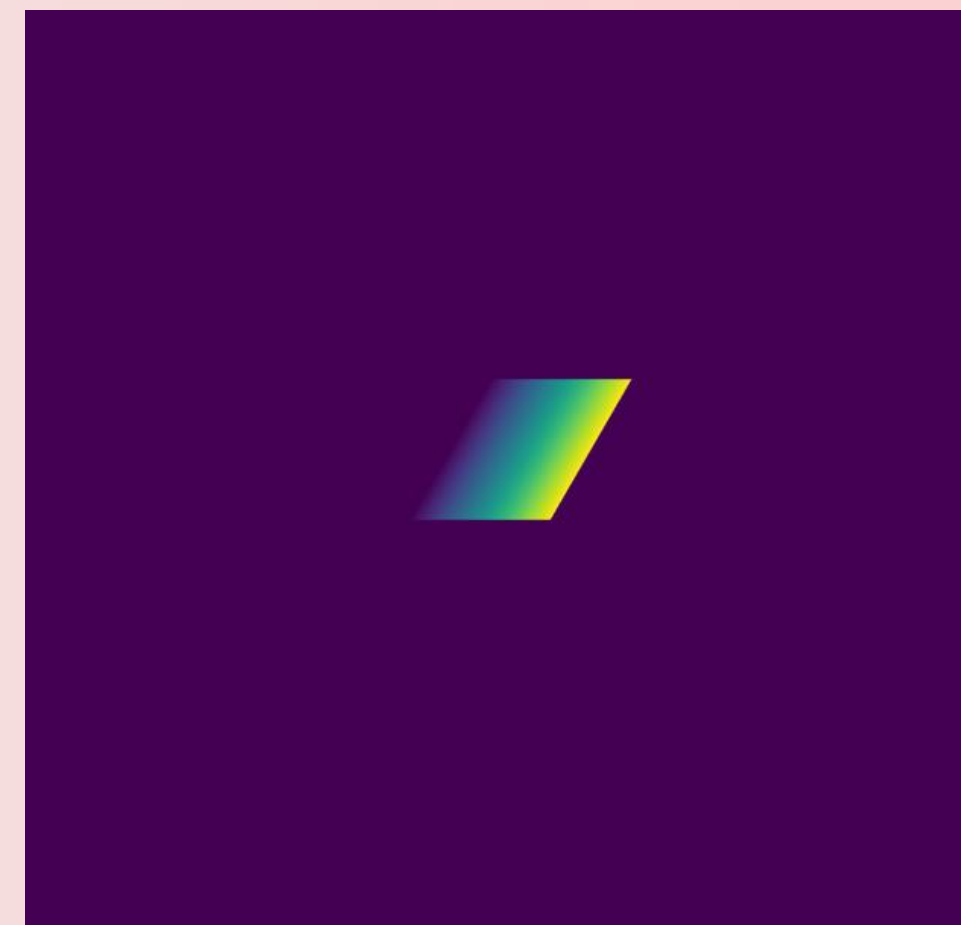
WAKE IN IMAGE SPACE



Ideal Square shape

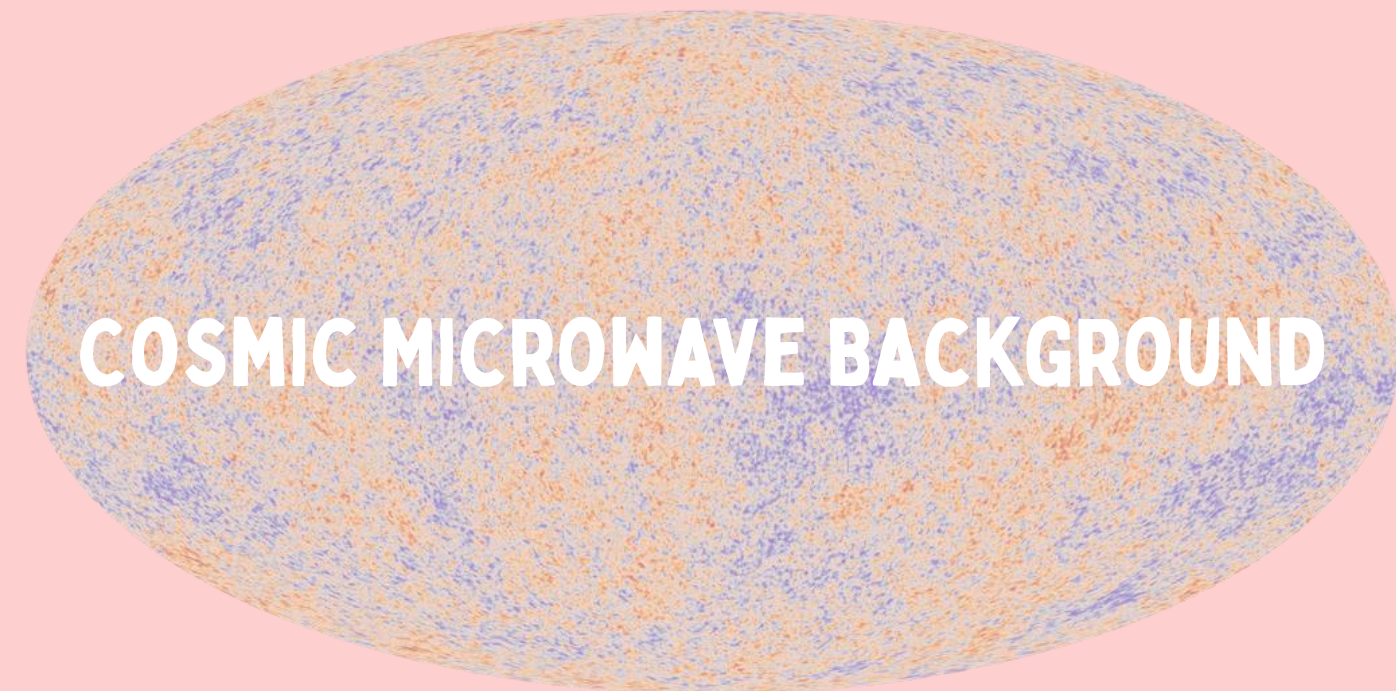


Gradient Brightness

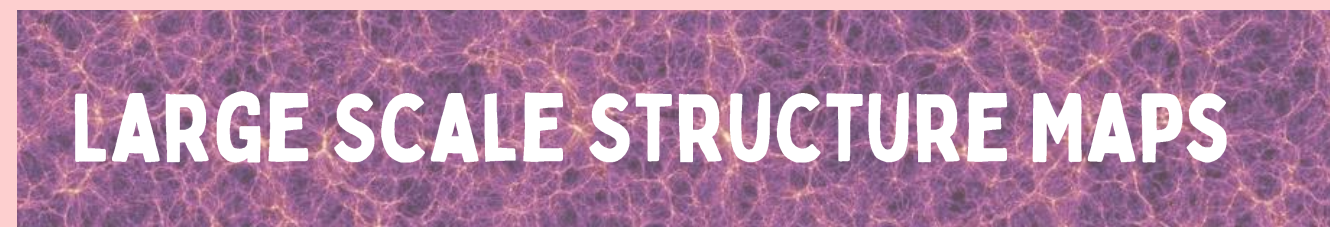


Slanted Projected Area

HOW CAN WE DETECT COSMIC STRINGS?



- Line discontinuities in CMB anisotropies
- Rectangular regions with excess polarization



- Thin planar enhanced densities

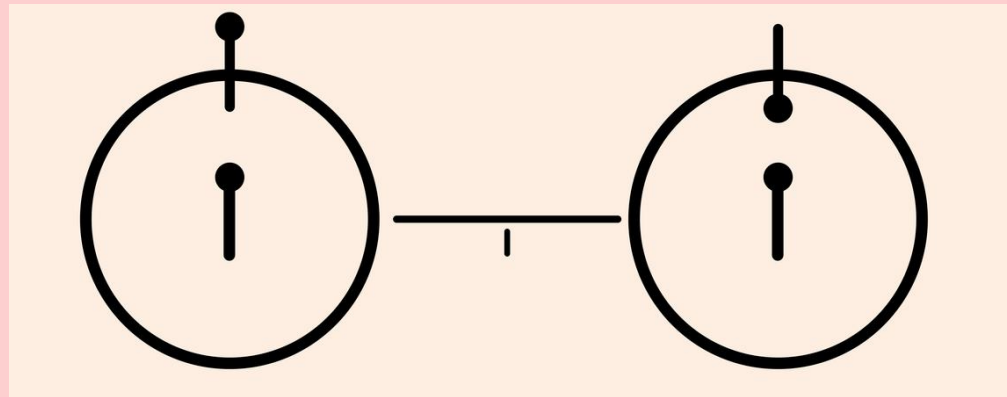


- Wedge Shaped enhanced patch

INTERLUDE: 21 CM COSMOLOGY

- Hydrogen's 1s ground state has two possible hyperfine states decided by spins:

Parallel & Anti-parallel



- The transition of states emits/absorbs 21cm radiation; the characteristic time of this transition is 10^7 years!
- Spin-flip emissions are the only probe to the Cosmic Dark ages, mapping cosmic history from Recombination till Reionization

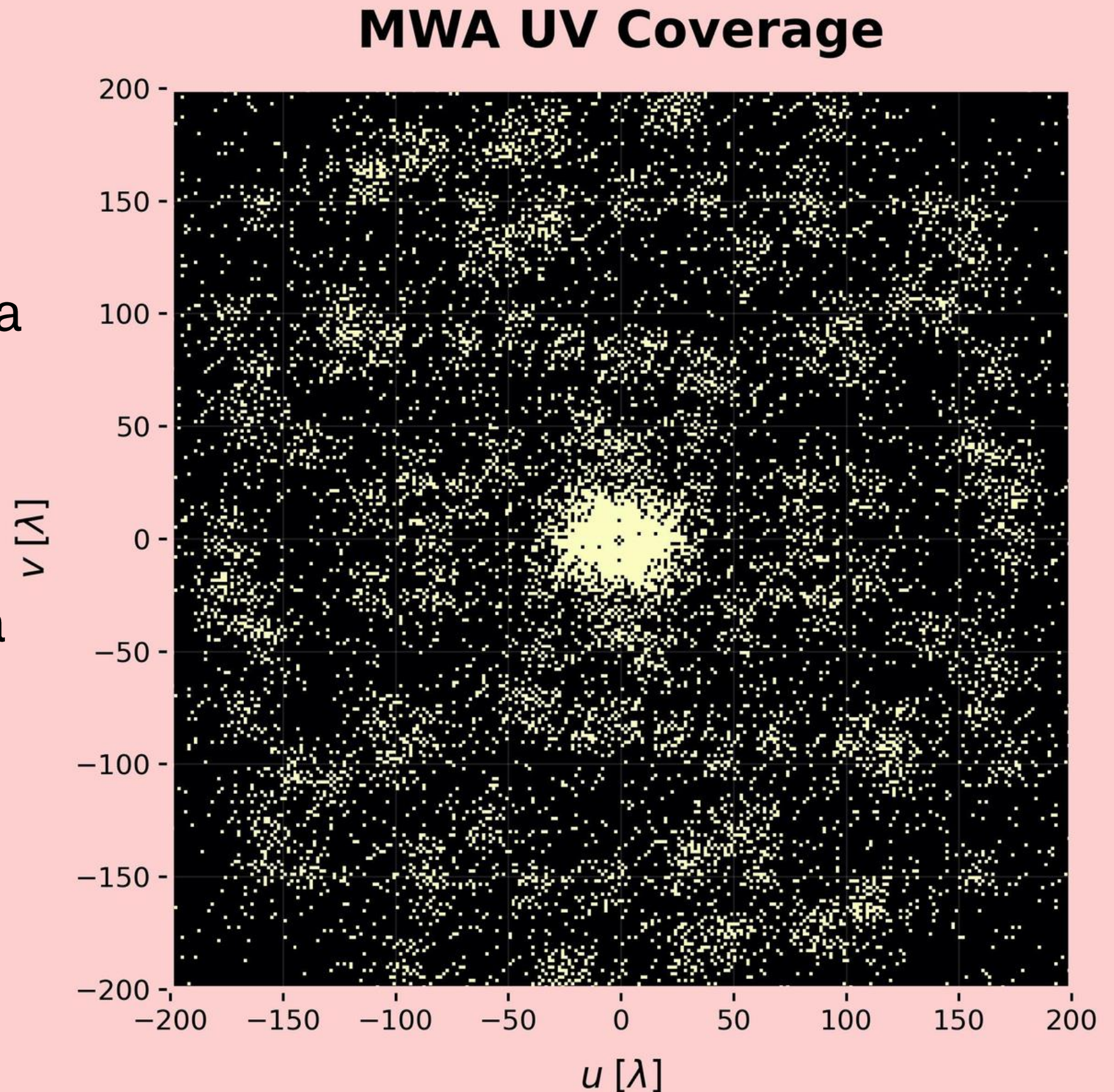
INTERLUDE 2: RADIO INTERFEROMETRY

- Angular resolution $\sim \frac{\lambda}{D}$ To achieve arcmin resolution at redshifted 21 cm wavelengths, we would require diameter $\sim$ Kms
- Possible by spreading out antennas, each pair of antennas observes one Fourier mode of sky brightness
- Creating baselines that sample both long and short Fourier modes are critical for complete observation; the rotation of the Earth helps
- Astrophysical foregrounds and instrumental noise, need to be well-modelled and subtracted

MURCHISON WIDEFIELD ARRAY (MWA)

- Instrument in Western Australia
- Precursor to SKA
- Each point in the UV plane is a baseline for n antennas

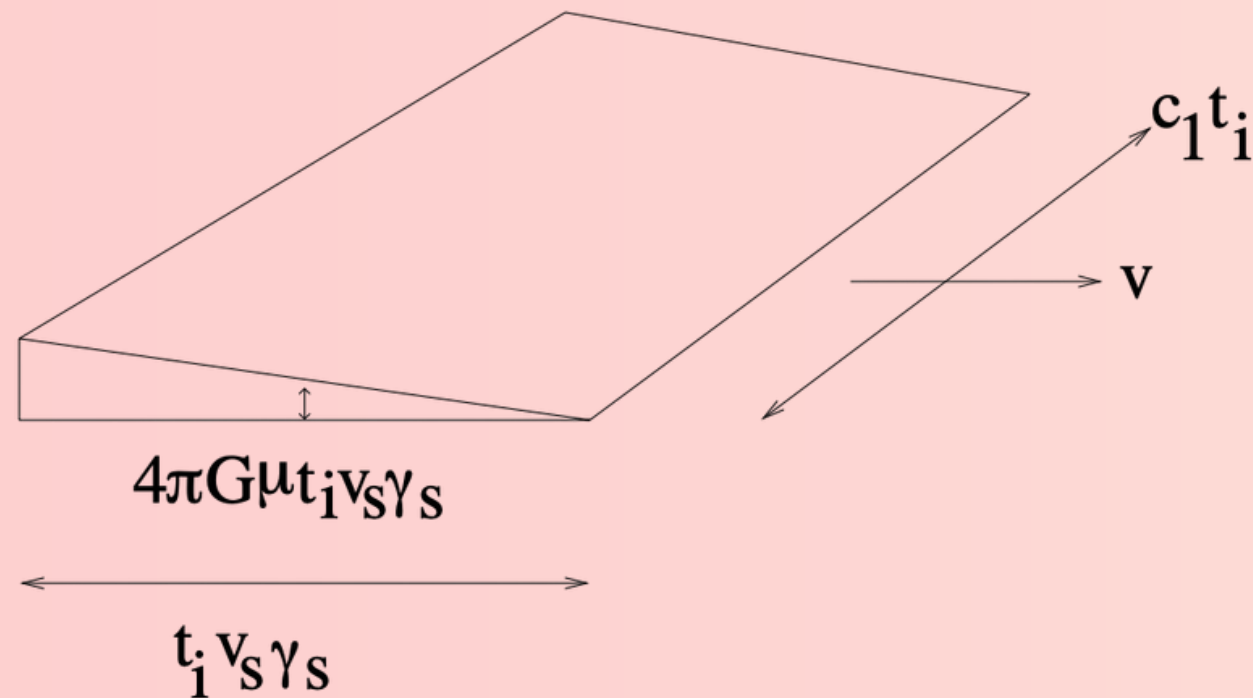
$$N_b = \frac{n \times (n - 1)}{2}$$



COSMIC STRING WAKES IN 21 CM

- The wedge-shaped cosmic string wakes, either emits or absorbs 21 cm

$$T_b(\nu) = T_S(1 - e^{-\tau_\nu}) + T_\gamma(\nu)e^{-\tau_\nu}$$



- We observe the contrast of 21 cm radiation from HI clouds and that of CMB photons

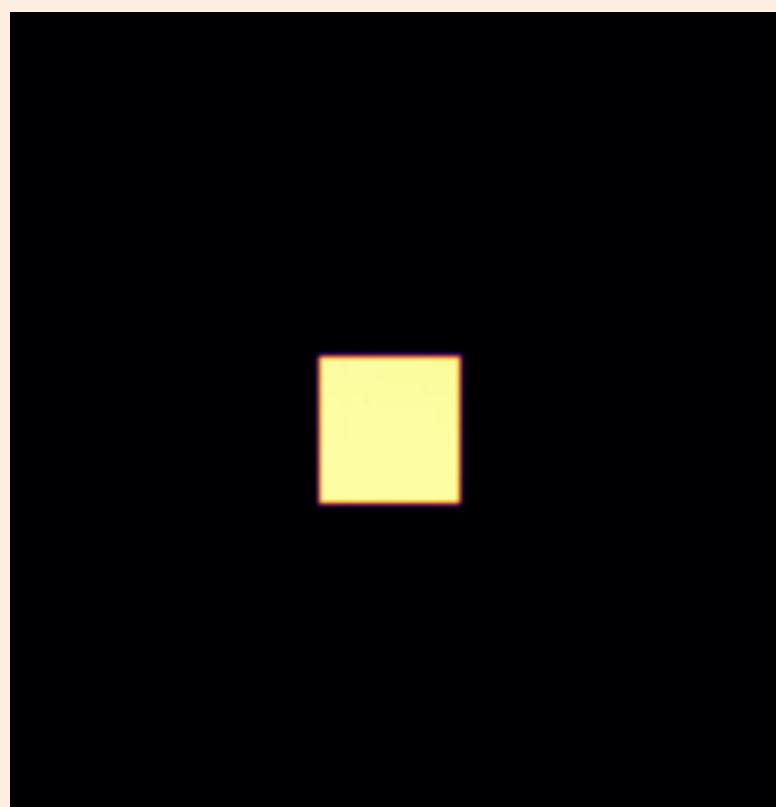
$$\delta T_b(\nu) = \frac{T_b(\nu) - T_\gamma(\nu)}{1 + z}$$

$$T_K \simeq [20 \text{ K}] (G\mu \cdot 10^6)^2 (\gamma_s v_s)^2 \frac{2z_i + 1}{z + 1}$$

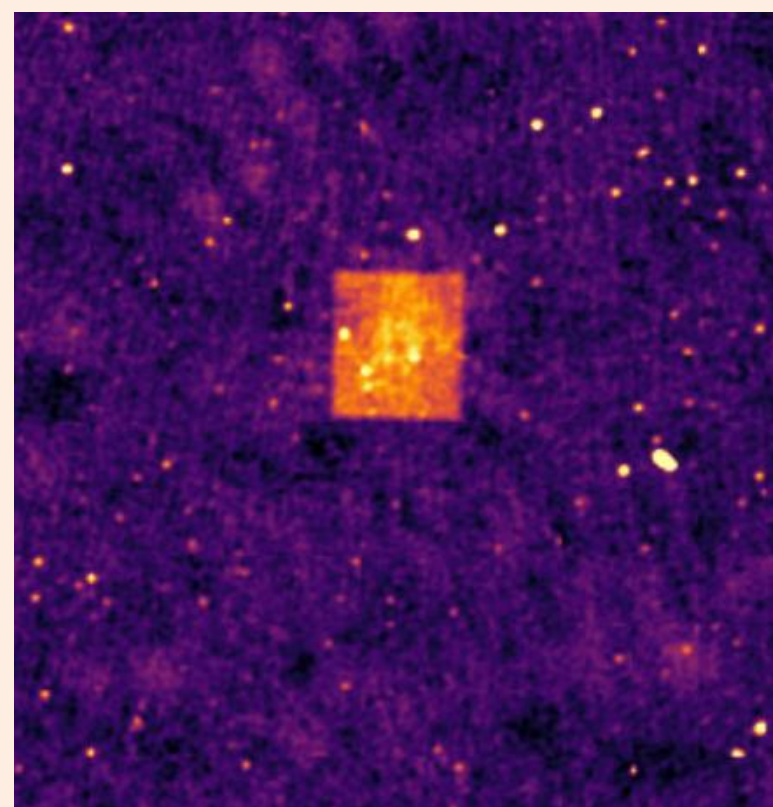
$$\delta T_b(z) = [17 \text{ mK}] \frac{x_c}{1 + x_c} \left(1 - \frac{T_\gamma}{T_K/g} \right) \frac{n_{\text{HI}}^{\text{wake}}}{n_{\text{HI}}^{\text{bg}}} \frac{(1 + z)^{1/2}}{2 \sin^2 \theta}$$

IN SEARCH OF WAKES

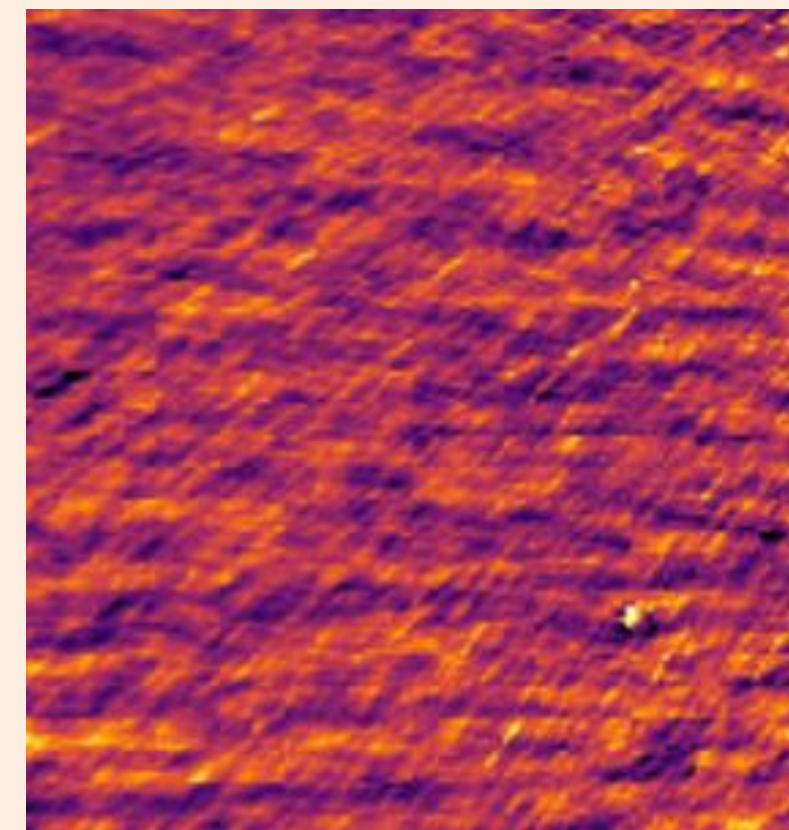
- Wakes are the dominant source of non-linear fluctuations in redshifts larger than that of reionization
- They have distinct geometry, looking at image space:



→
Foregrounds

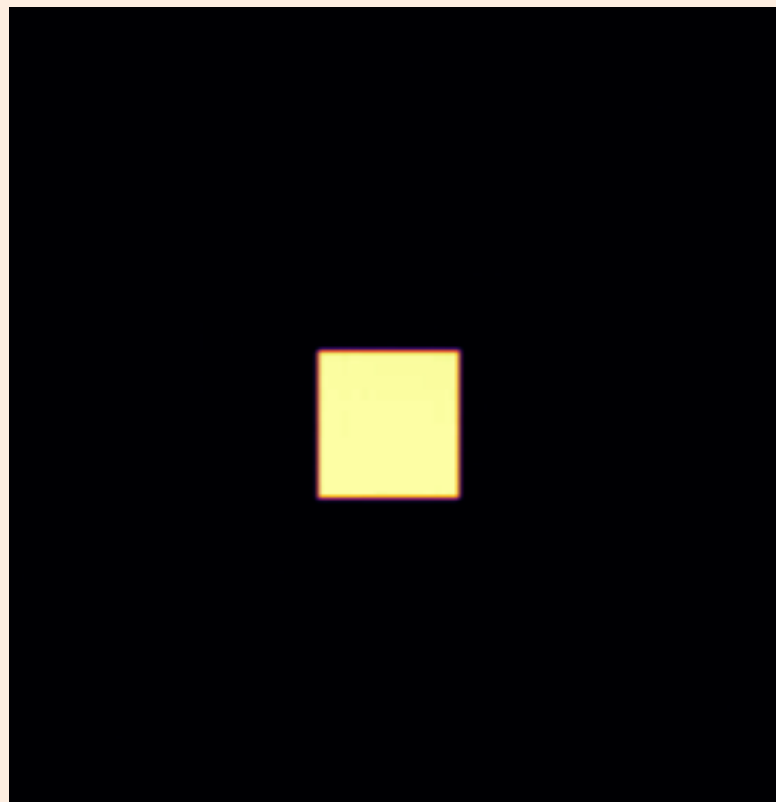


→
Realistic
Flux

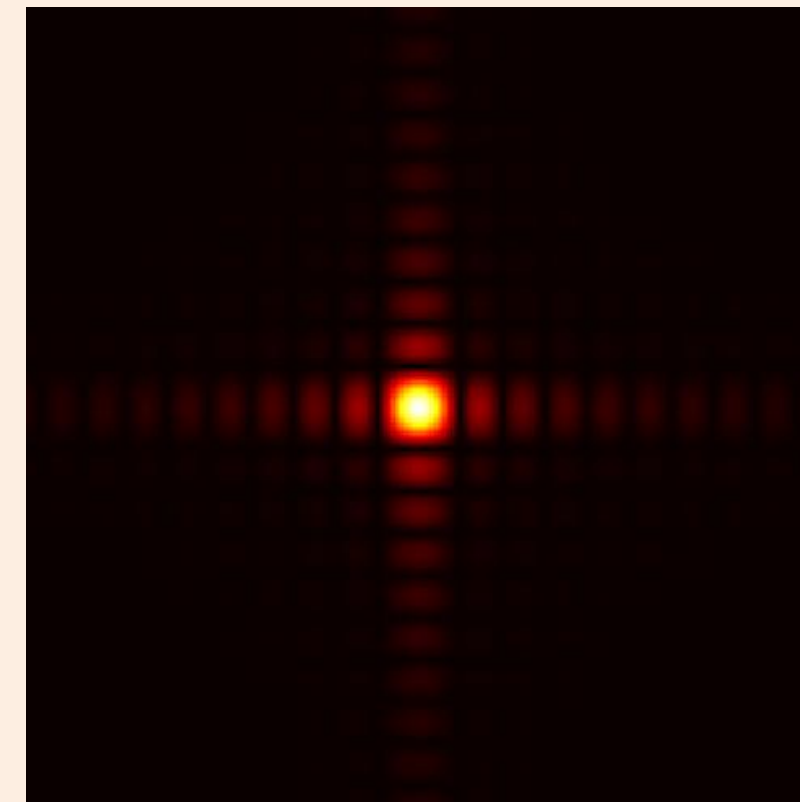


FOURIER SPACE

- The distinct quadrilateral geometry of the wake translates to a unique ridge-like pattern in fourier space

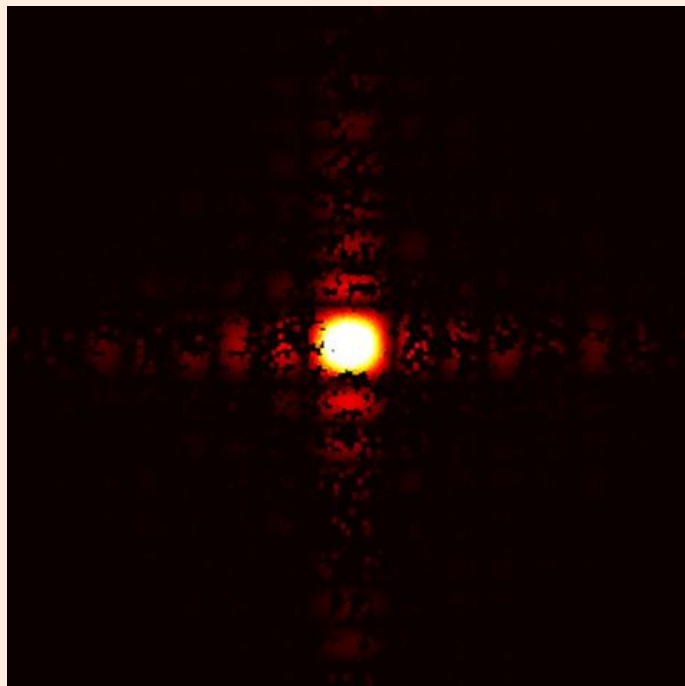


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Computing
Fourier transform

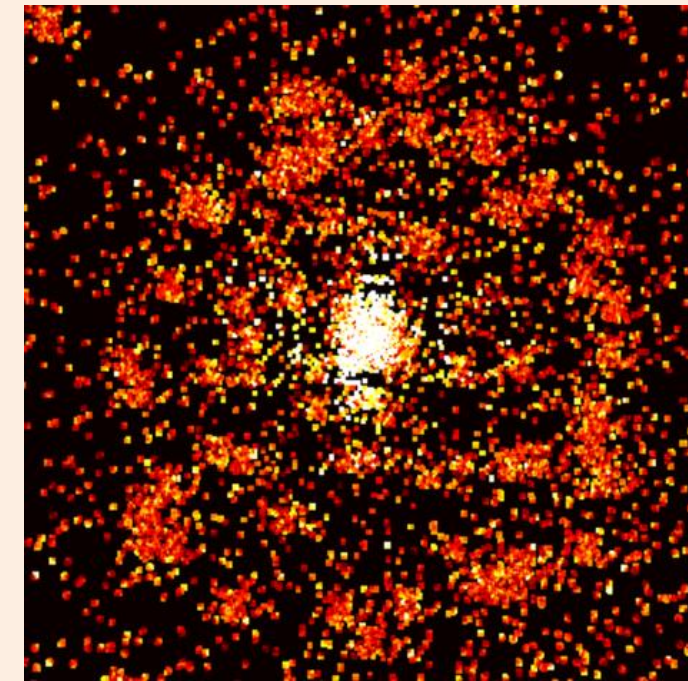


SIMULATING THE WAKES

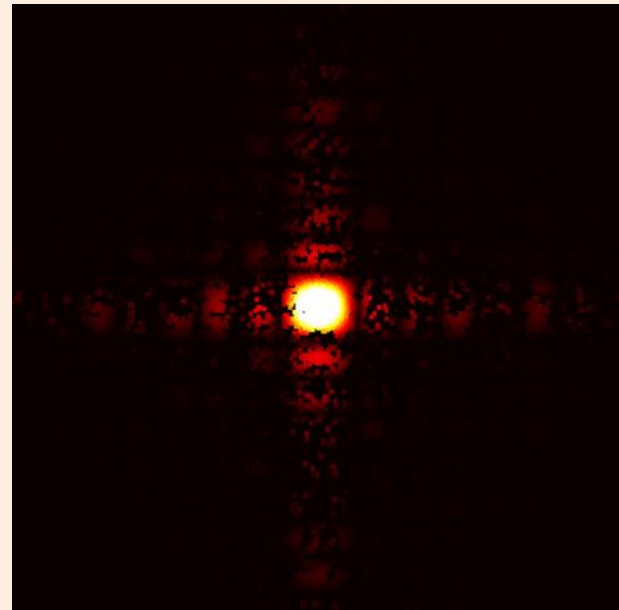
- Woden simulates the MWA visibilities by forward modelling the instrument response
- Along with the source signal, we can introduce foregrounds and instrumental effects such as thermal and gain noise



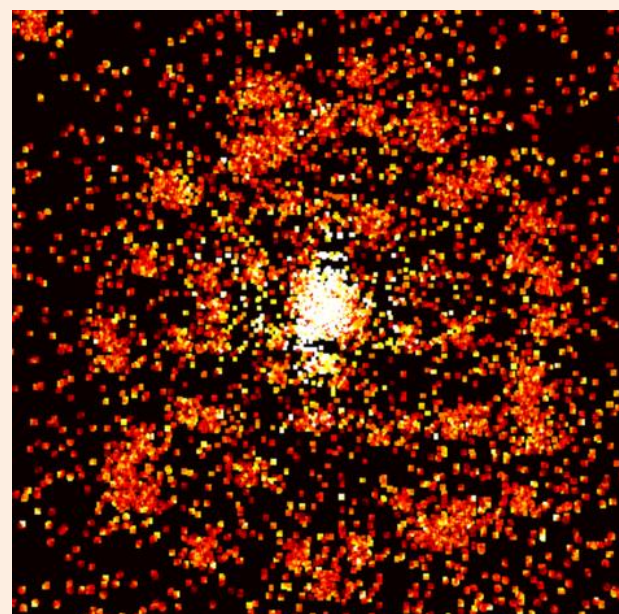
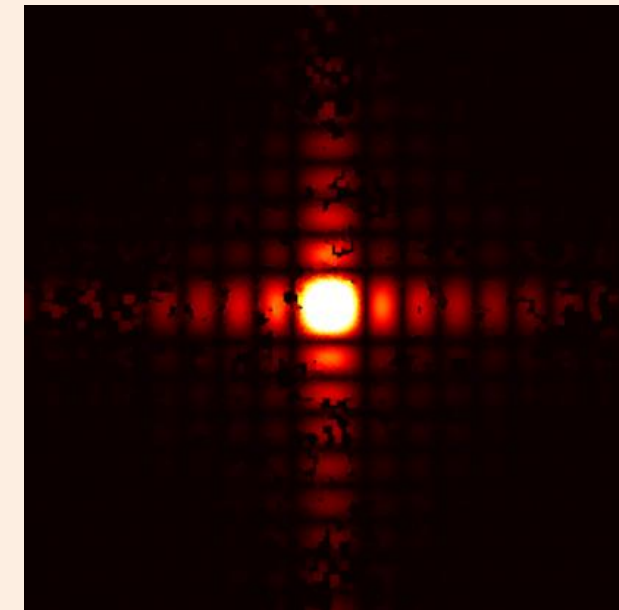
→
Foregrounds in
EoR0 field



FIRSTLY, AN UPGRADE...



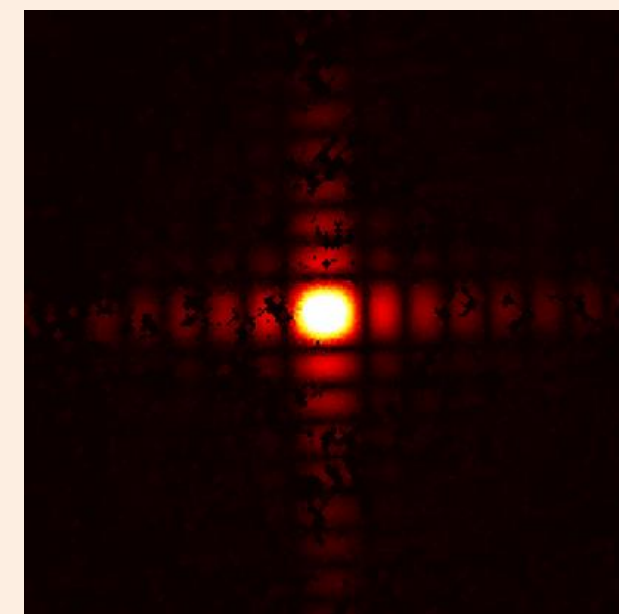
128 tiles to
256 tiles



Foreground subtracted



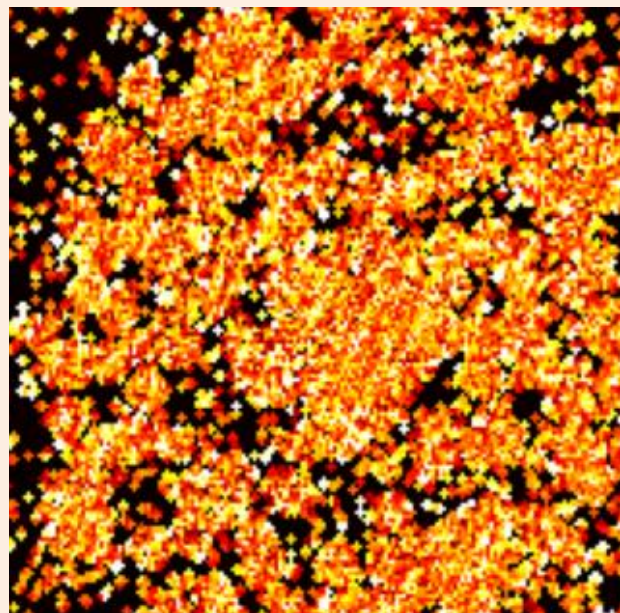
Realistic
Flux



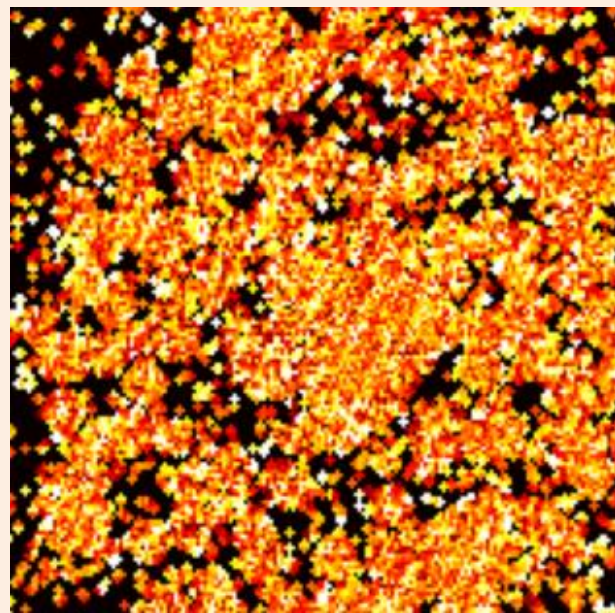
BUT WHAT'S THE DIFFERENCE?

- For a wake at a fixed redshift of emission, the frequency width is very narrow
- This kHz width is encompassed by a single fine frequency channel of MWA
- As the frequency responses for consecutive channels are near identical, we can exploit this to subtract noise

With wake



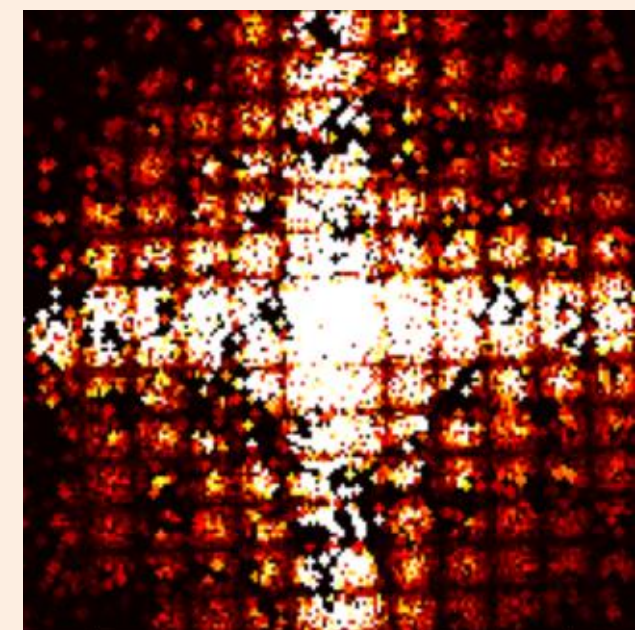
No wake



-

=

Residual



3-POINT FUNCTION

- To statistically exploit the ridge-like pattern, we can compute the triple correlation function of the form

$$\langle T(\mathbf{k}_1)T(\mathbf{k}_2)T(\mathbf{k}_3) \rangle = \int d^2\mathbf{k}_1 d^2\mathbf{k}_2 d^2\mathbf{k}_3 T(\mathbf{k}_1)T(\mathbf{k}_2)T(\mathbf{k}_3)$$

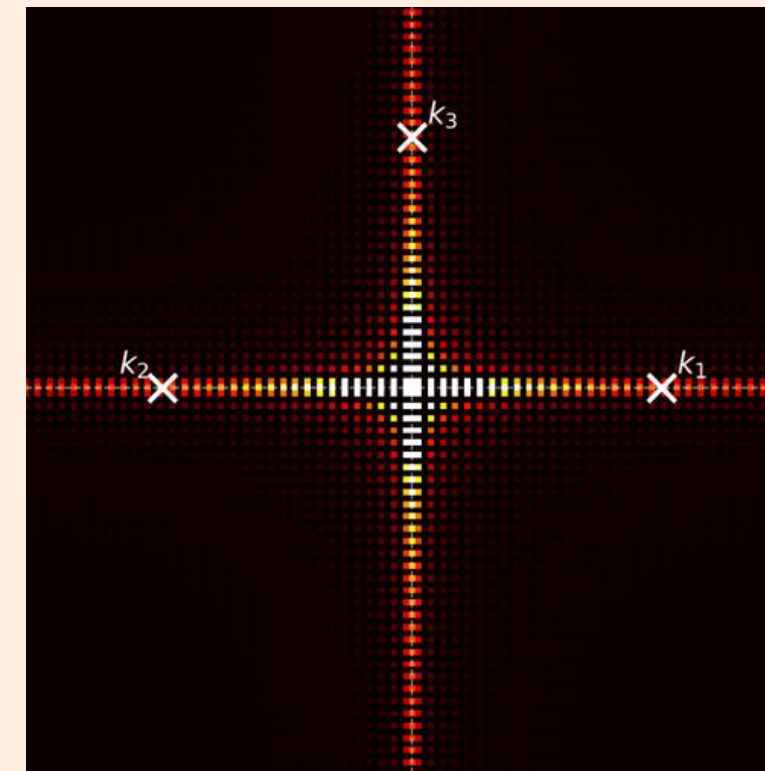
where, $\mathbf{k} = (u, v)$

- This function is tuned, for wakes by selecting,

$$\mathbf{k}_1 \approx -\mathbf{k}_2$$

$$|\mathbf{k}_1| \approx |\mathbf{k}_3|$$

$$\mathbf{k}_1 \cdot \mathbf{k}_3 \approx 0$$



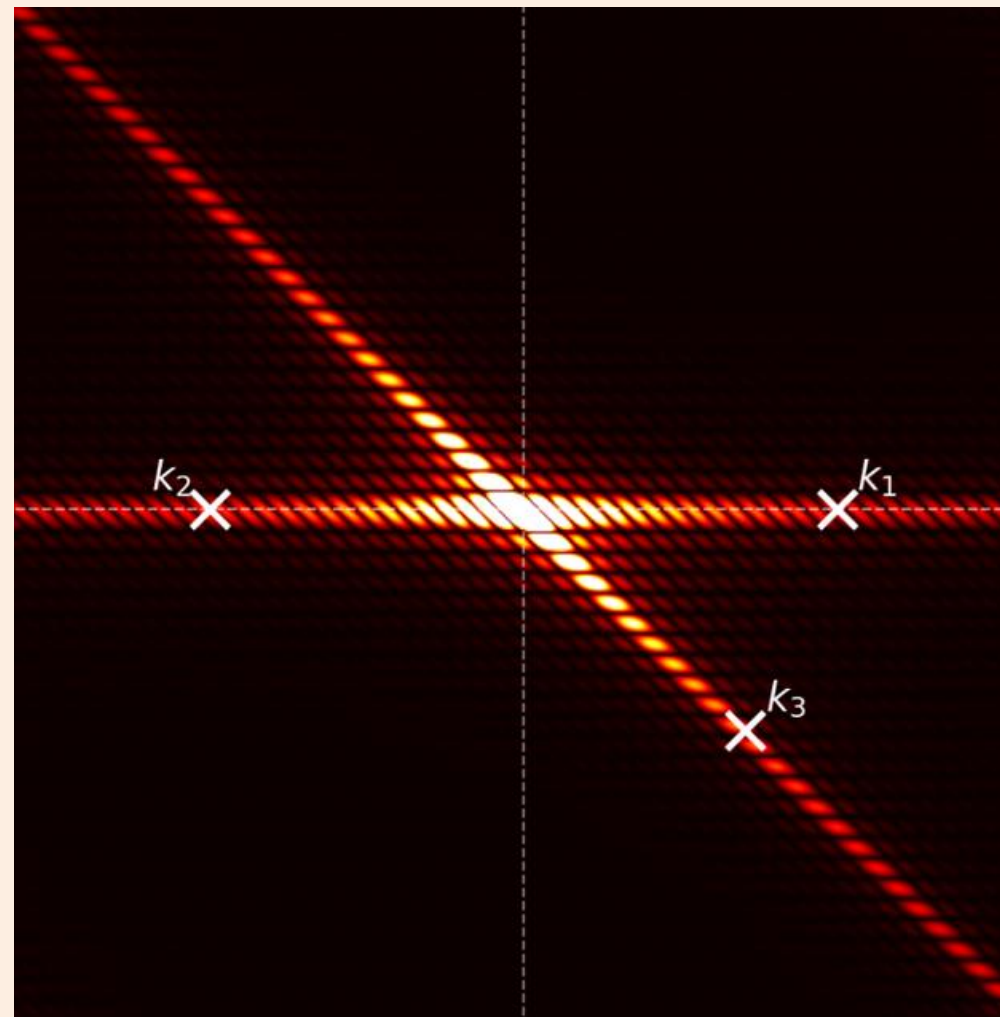
FURTHER TUNING,

- For a parallelogram shaped wake signal we select,

$$\mathbf{k}_1 \cdot \mathbf{k}_3 \approx |\mathbf{k}_1| |\mathbf{k}_2| \sin \alpha$$

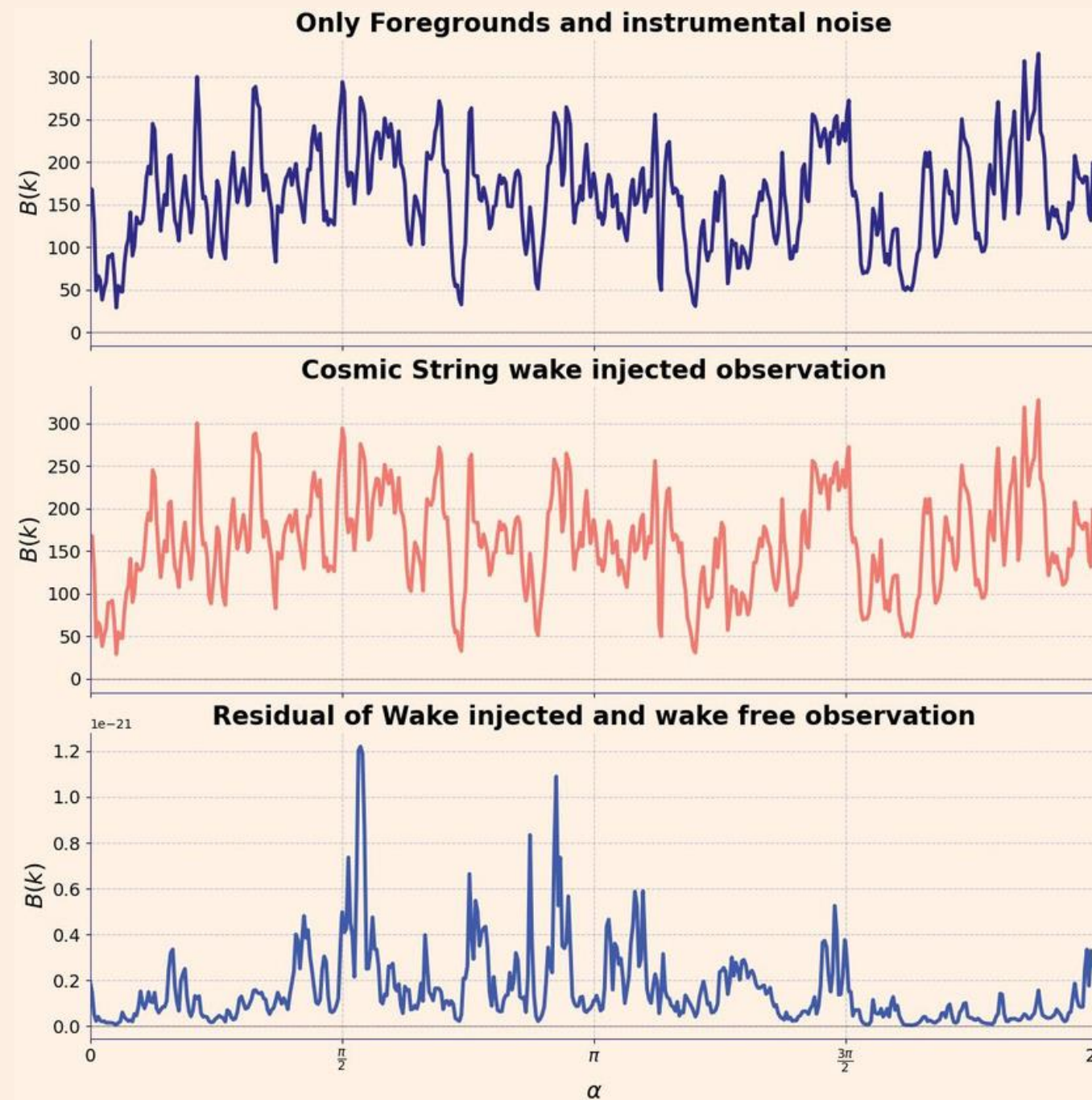
So to compute 3-point function,

- Vary $|\mathbf{k}|$
- Rotate $\mathbf{k}_1, \mathbf{k}_2$ and $\mathbf{k}_3$



DECONSTRUCTING THE 3-POINT FUNCTION

- We can keep $\mathbf{k}_1$ and $\mathbf{k}_2$ fixed, and vary α



Where $F(\alpha)$ is defined as the 3-point function integrated over k , and a function of α

From the residual, the aliasing and UV holes contribute considerably

STEPS TO FISHER:

- Fisher information quantifies an observable's ability to constrain a parameter Θ

$$\mathcal{I}_{m,n} = \frac{\partial \boldsymbol{\mu}^T}{\partial \theta_m} \Sigma^{-1} \frac{\partial \boldsymbol{\mu}}{\partial \theta_n}$$

Where $\frac{\partial \boldsymbol{\mu}}{\partial \theta_m}$ is defined as the score

- If we assume the covariance matrix is identity, or different alpha values are independent, we get the Gram matrix for the score

PARAMETERS AND THEIR RELATIONS

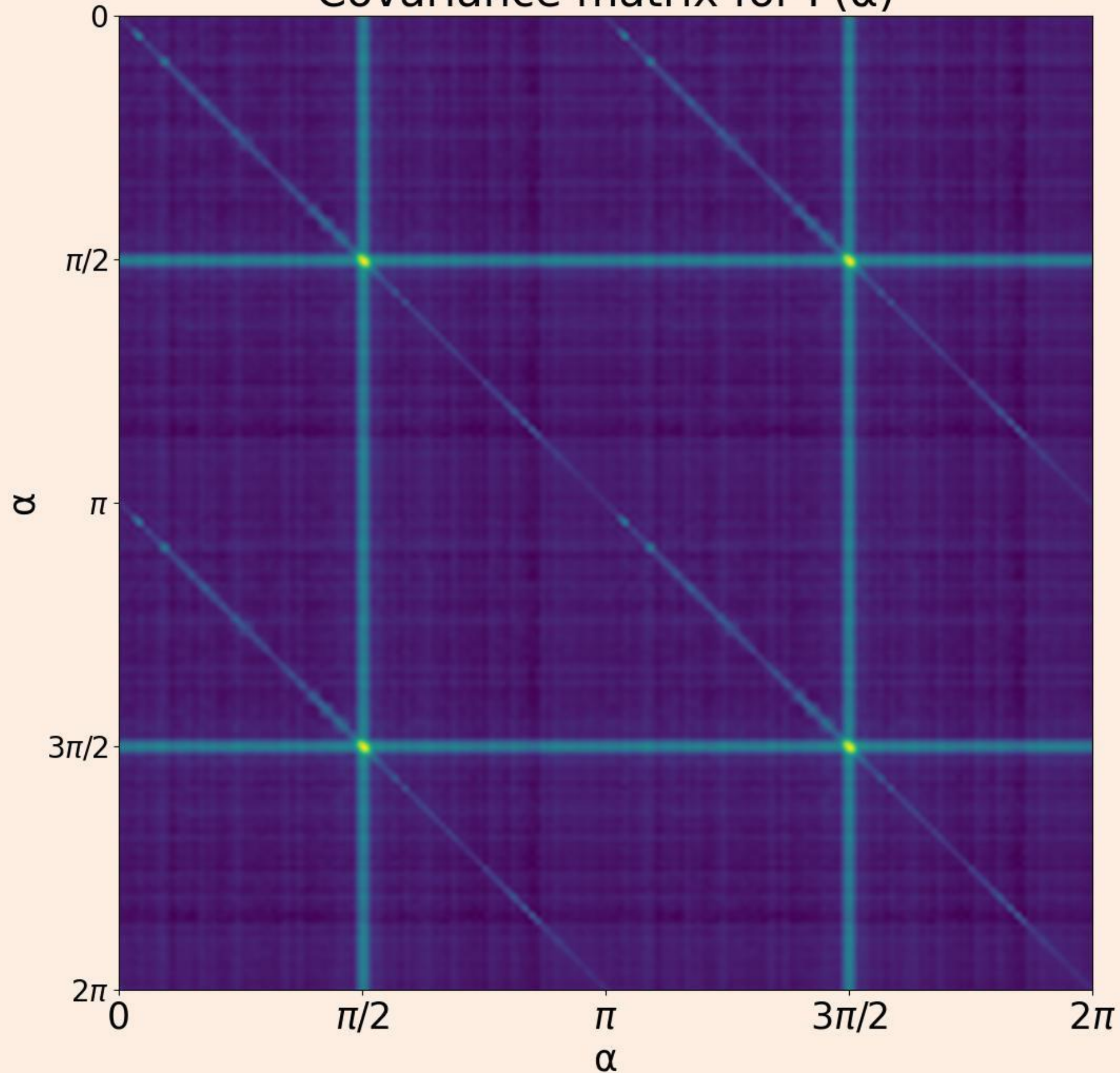
Parameters:

- String tension ($G\mu$)
- String velocity factor ($v_s \gamma_s$)
- Redshift of formation
- Thermal noise
- Foreground removal
- Instrumental gain

Relations:

- String tension is well constrained if the velocity factor is fixed, else degenerate
- Redshift of formation informs the observable and is well constrained
- Thermal noise and foreground removal are slightly correlated with wake parameters
- Instrumental gain does not inform the observable

Covariance matrix for $F(\alpha)$



The alpha values are
periodically correlated

But this will need a lot of
simulations!

POSTLUDE: THE WAY AHEAD

- I will apply 3-point function analysis to 256 tile observations from next observing cycle of MWA
- New choice of statistics: simulation-based inference for parameter constraining with an autoencoder neural network
- SKA will have a comprehensive UV coverage

ENCORE: SUMMARY

- Cosmic strings are 1D topological defects, whose wakes are overdense envelopes with distinct signatures in 21 cm maps
- Wakes have unique geometry in Fourier space, along with a narrow frequency width, which can be exploited to model/subtract noise
- 3-point function is sensitive to wake parameters, but the wake identification is not apparent
- Further investigation of periodic noise and UV-coverage holes must be done
- A new statistic might prove better; one such attempt can be to use a simulation-based inference approach with an autoencoder