

COSMIC STRINGS AND HOW TO FIND THEM?

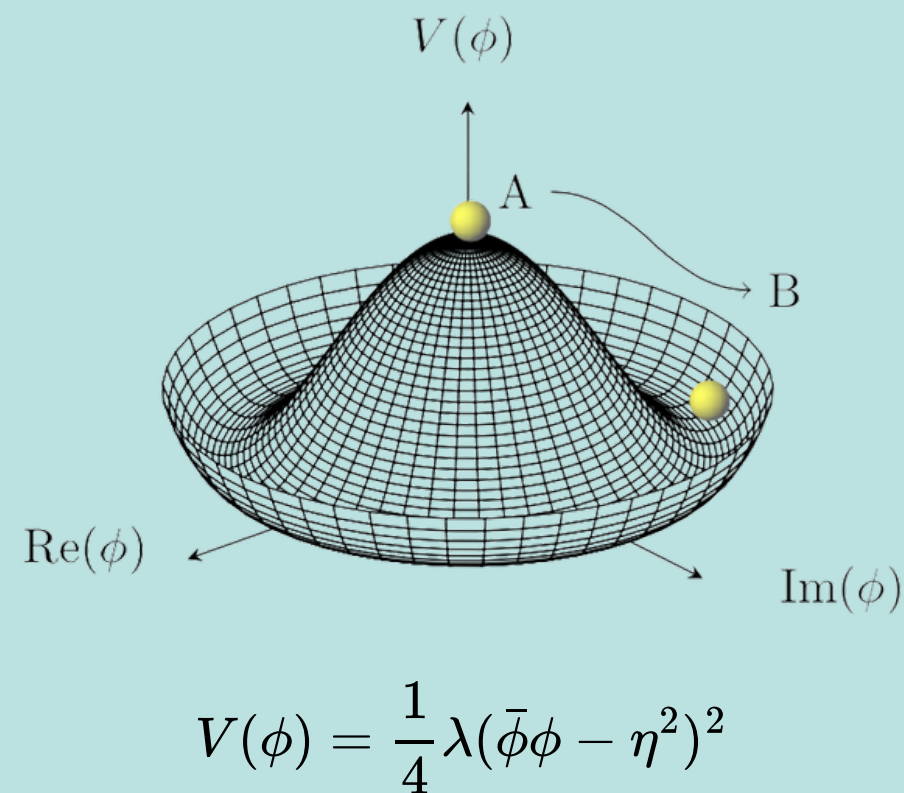
IN THE CONTEXT OF HI 21CM COSMOLOGY

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PRELUDE: SPONTANEOUS SYMMETRY BREAKING



Unbroken Symmetry

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

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

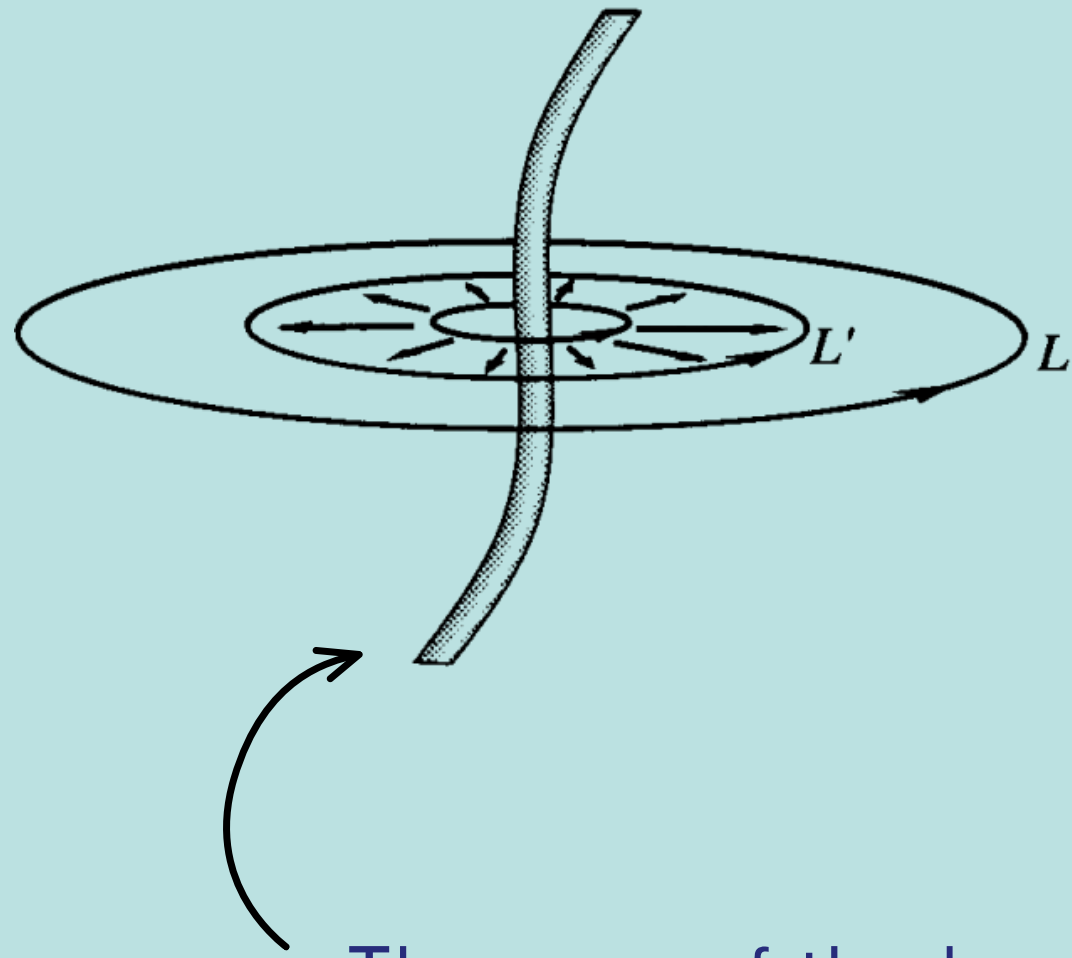
Broken Symmetry

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

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

- 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

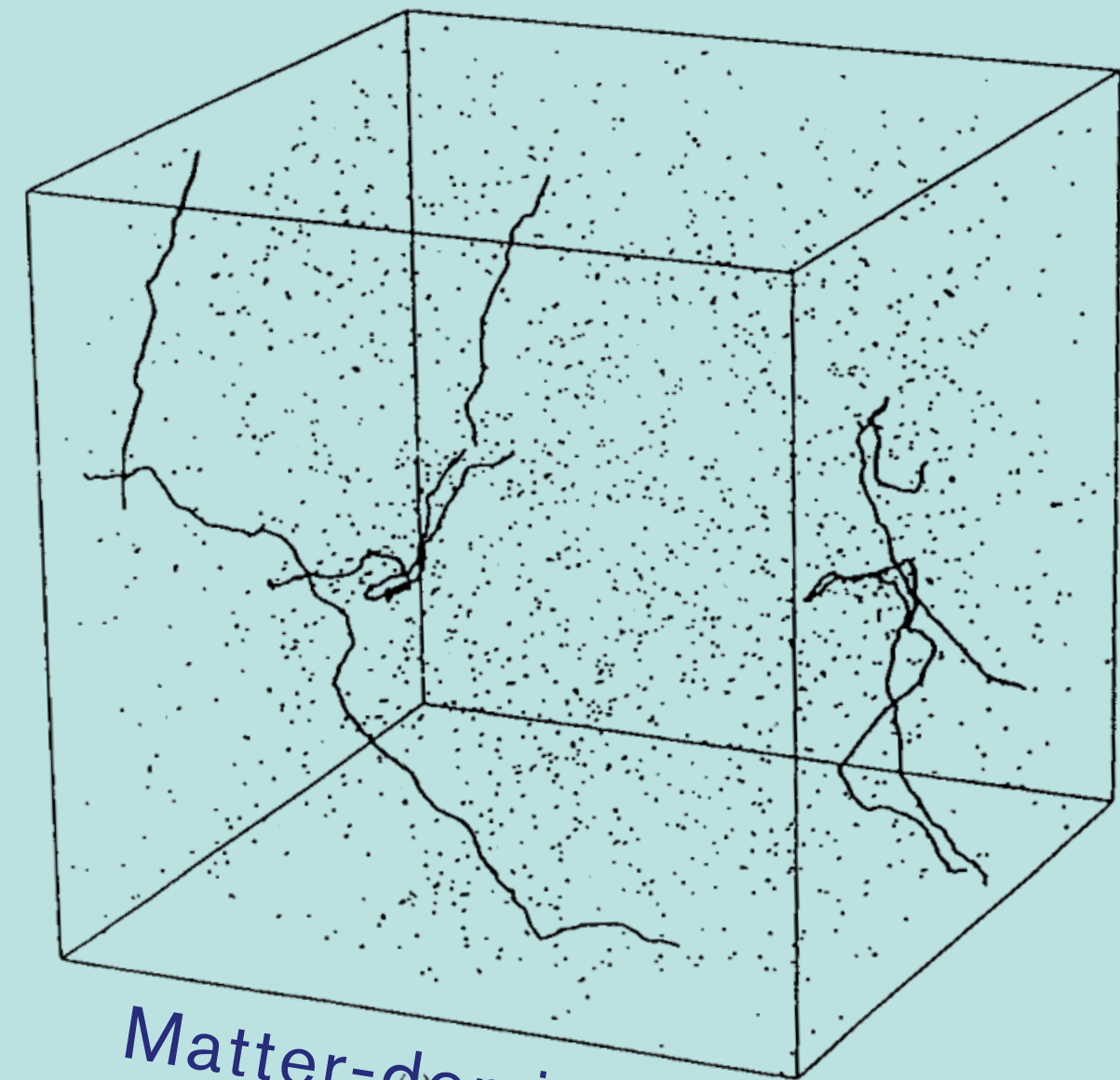
- Their linear mass density goes as,

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

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



*Matter-dominated era
String network*

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:

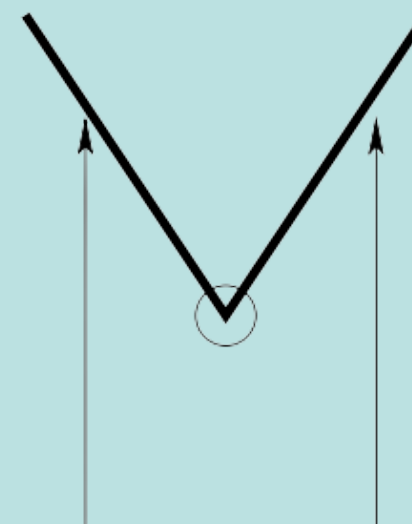
$$\alpha = 8\pi G\mu$$

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

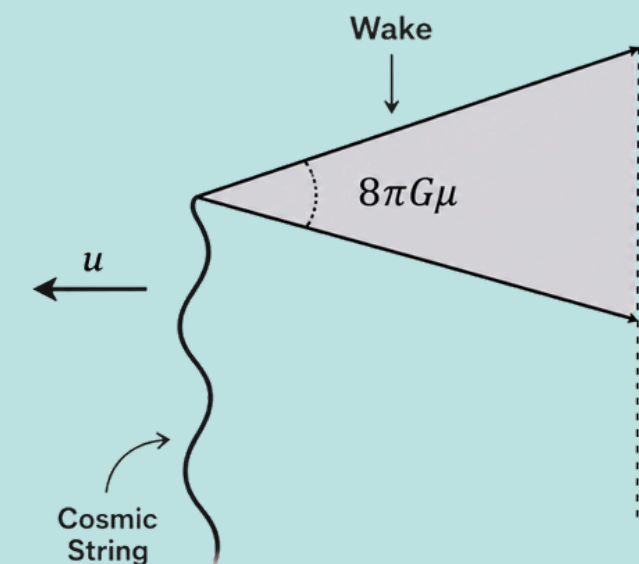
$$\delta v = 4\pi G\mu v_s \gamma_s$$

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

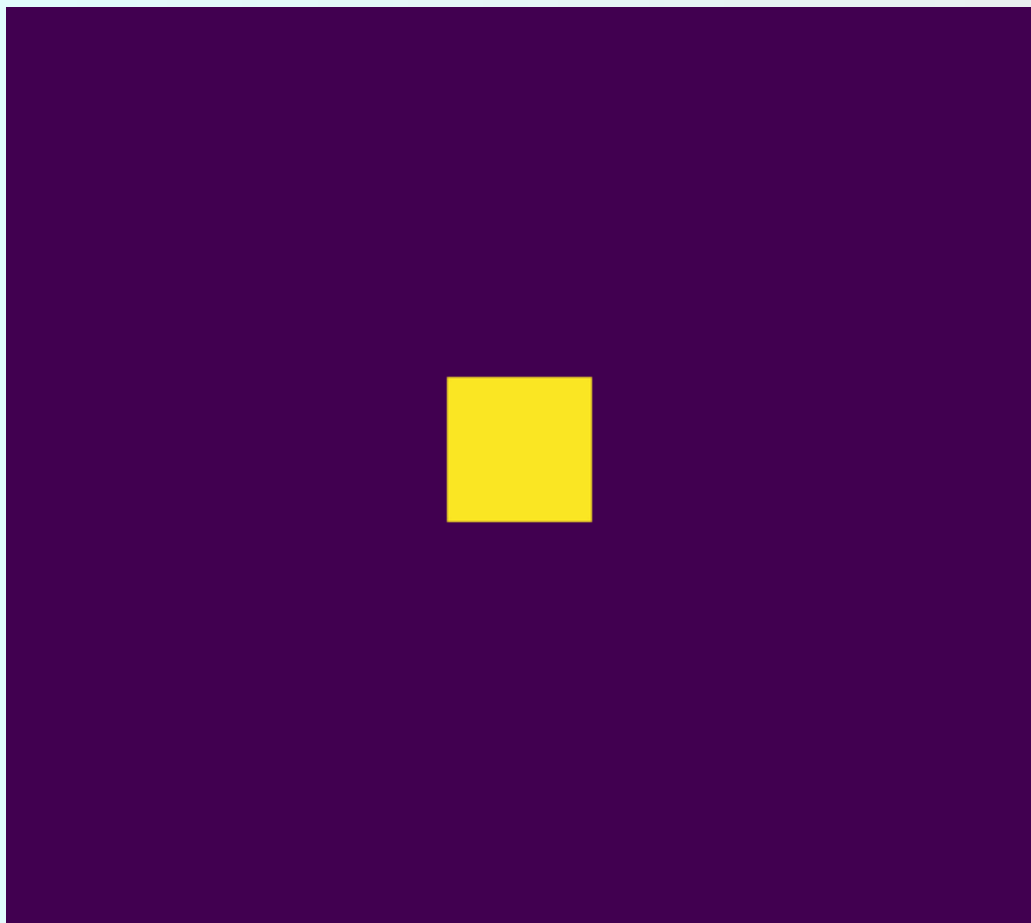
Top view



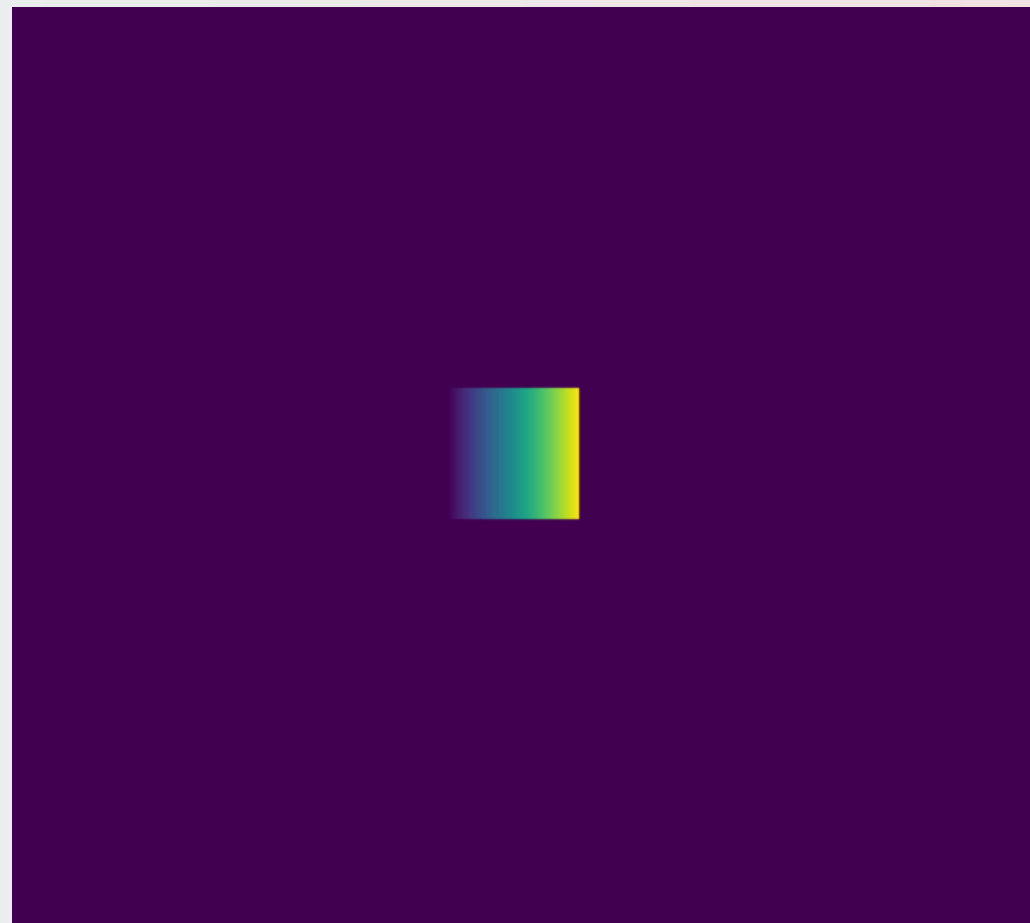
Side view



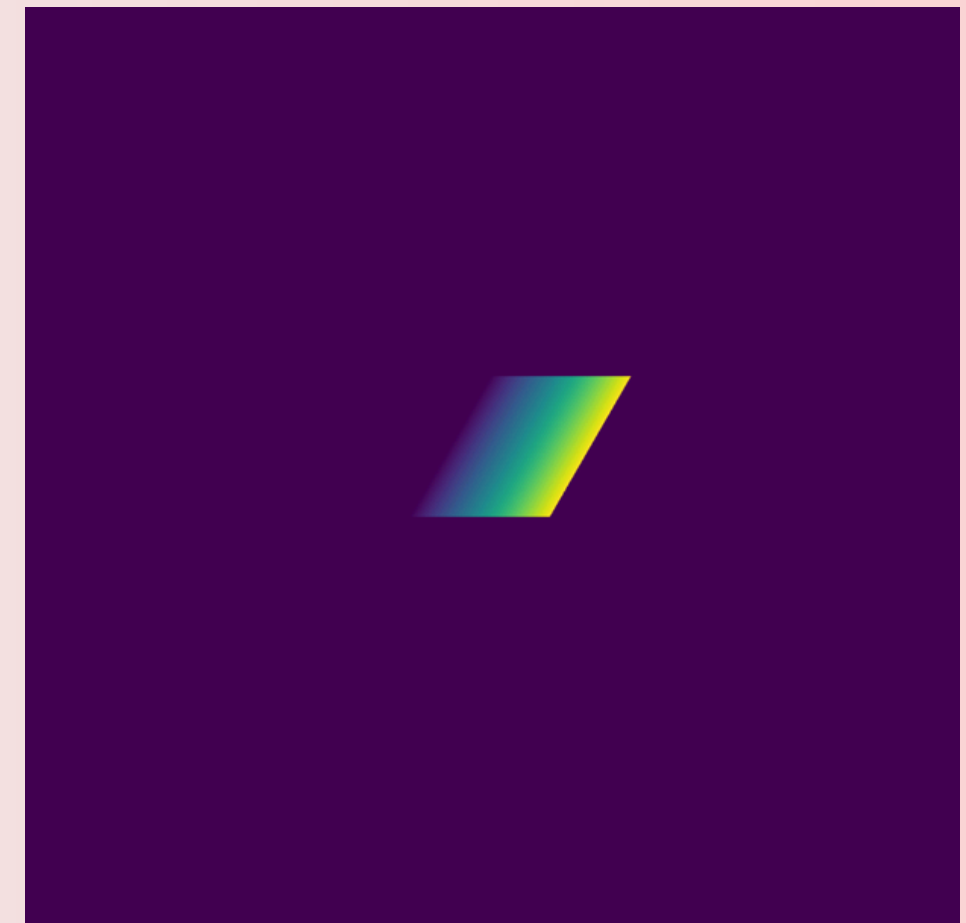
WAKE IN IMAGE SPACE



Ideal Square shape

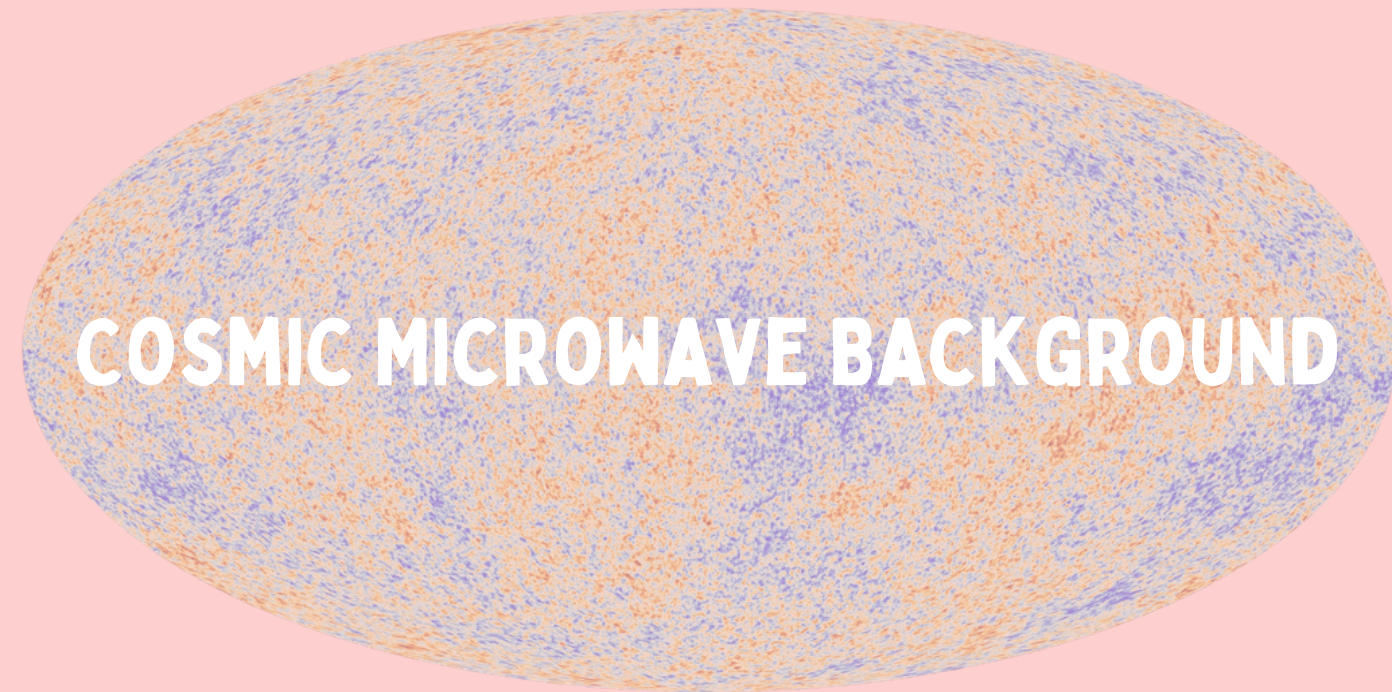


Gradient Brightness

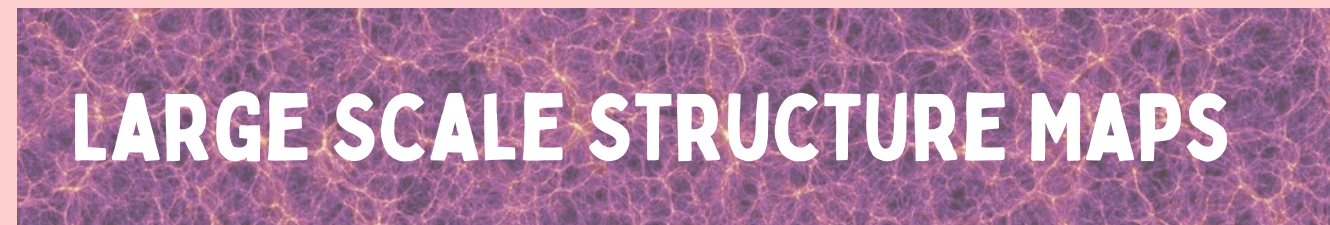


Slanted Projected Area

HOW CAN WE DETECT COSMIC STRINGS?



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



- Thin planar enhanced densities

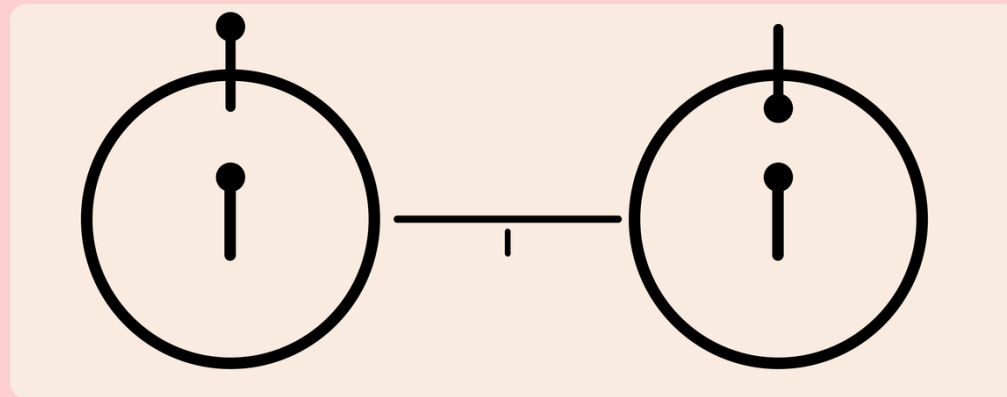


- Wedge Shaped enhanced patch

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

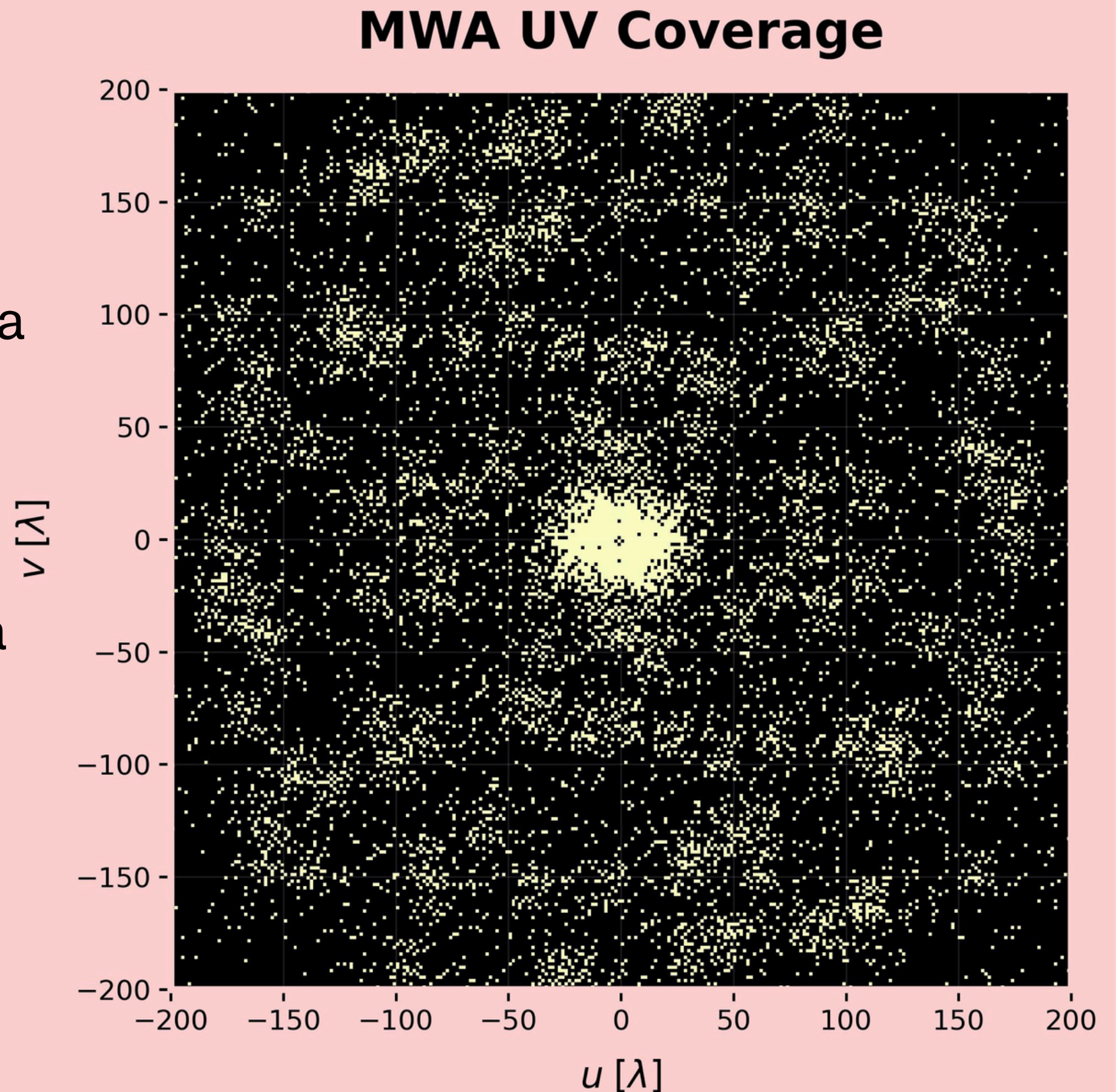
INTERLUDE 2: RADIO INTERFEROMETRY

- 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

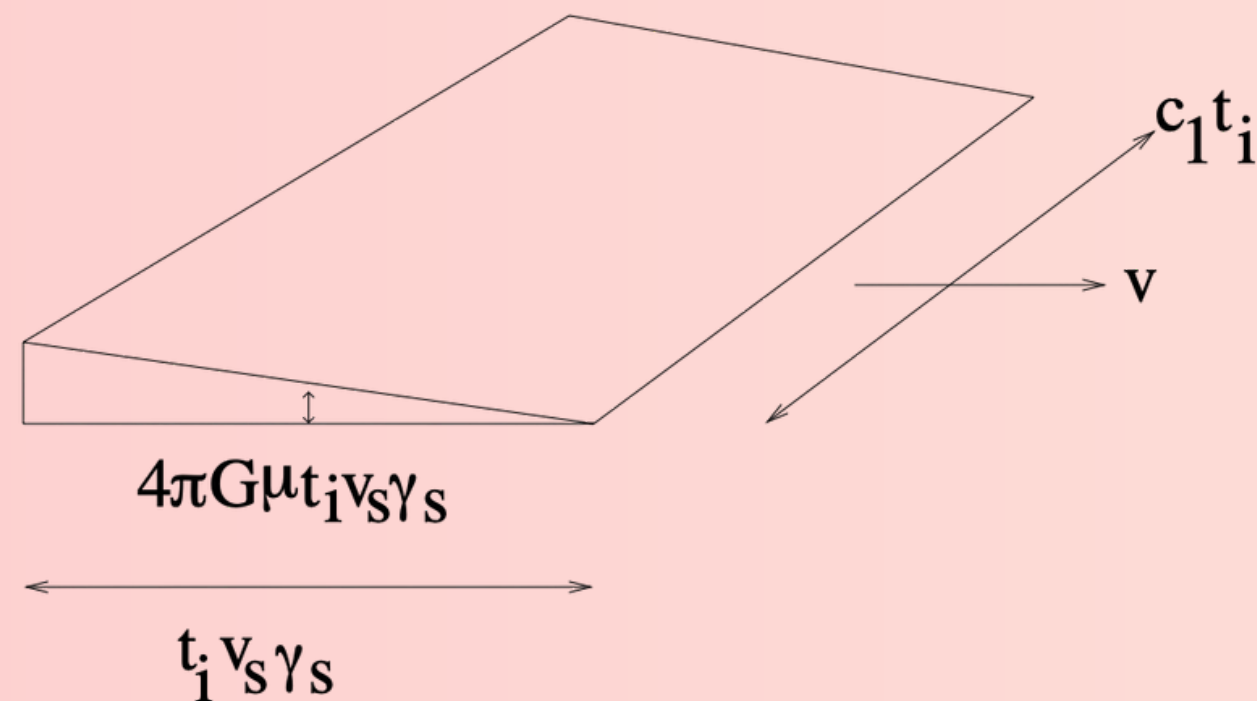
$$N_b = \frac{n \times (n - 1)}{2}$$



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

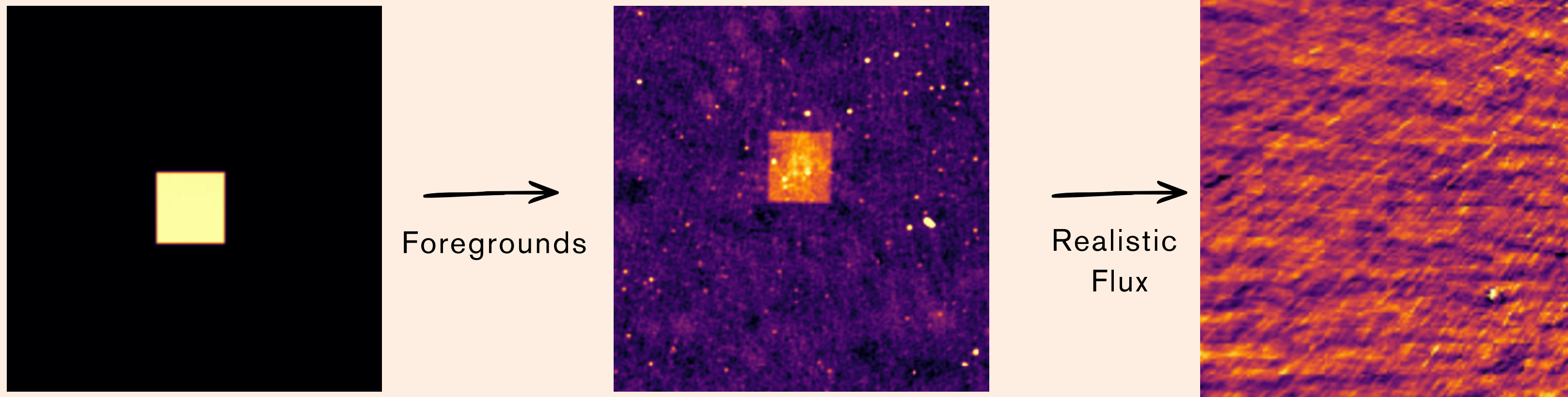
$$\delta T_b(\nu) = \frac{T_b(\nu) - T_\gamma(\nu)}{1 + z}$$

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

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

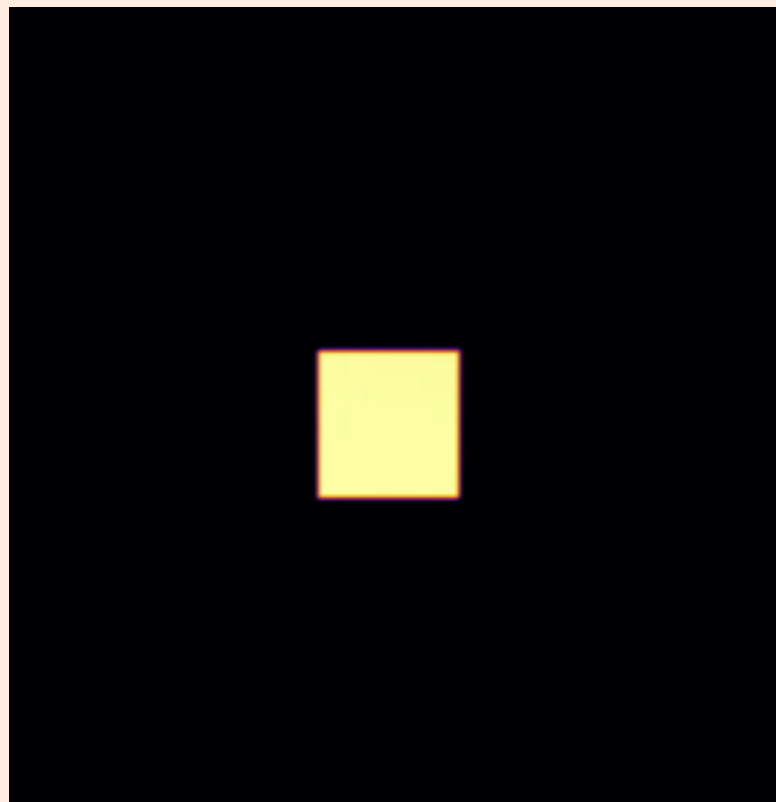
IN SEARCH OF WAKES

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

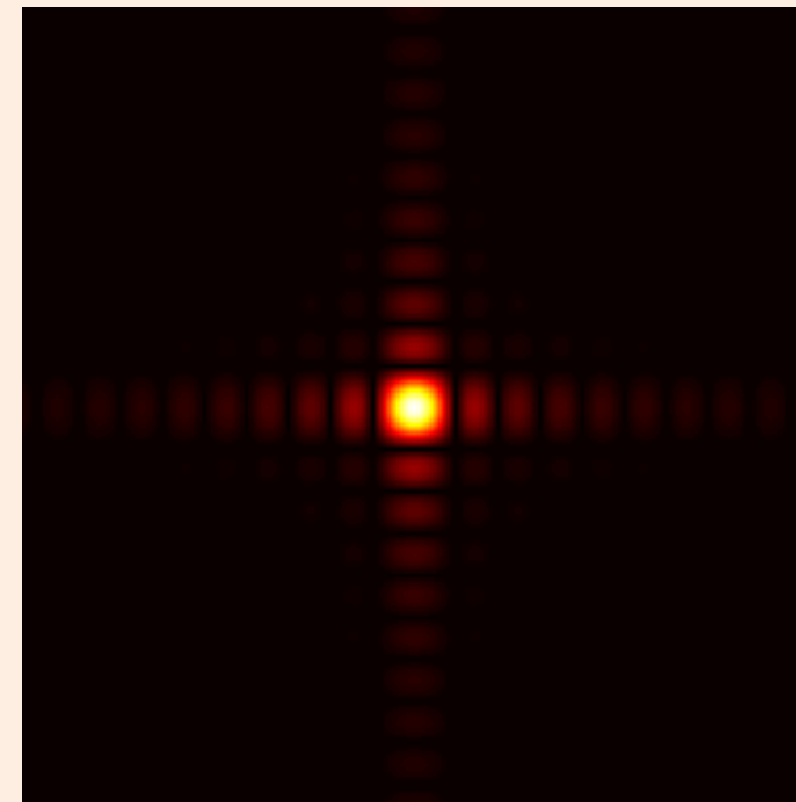


FOURIER SPACE

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

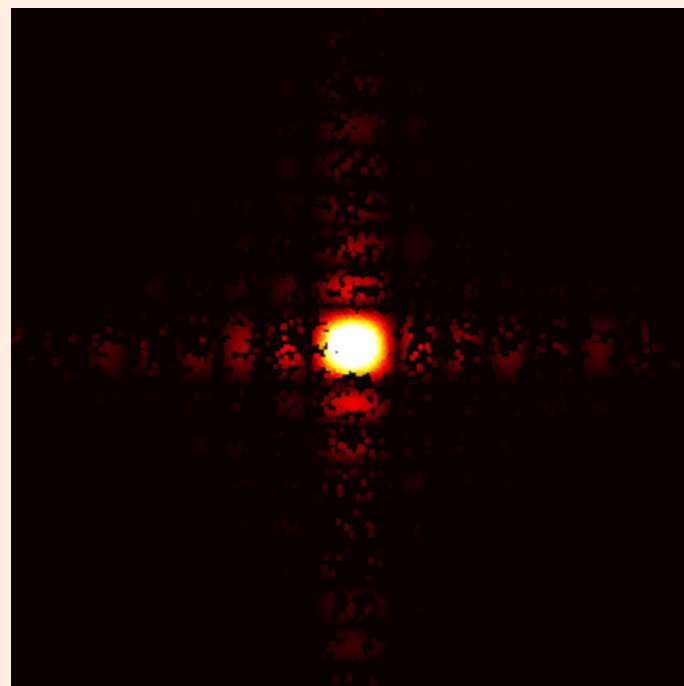


→
Computing
Fourier transform

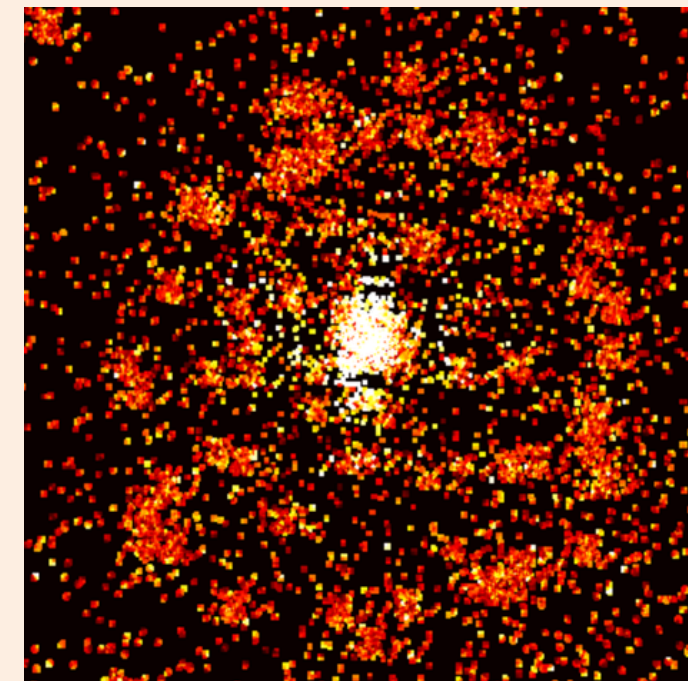


SIMULATING THE WAKES

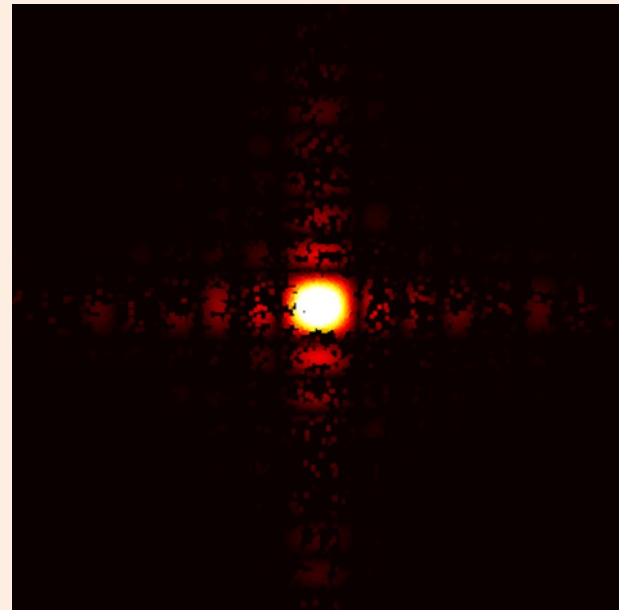
- Woden simulates the MWA visibilities by forward modelling the instrument response
- Along with the source signal, we can introduce foregrounds and instrumental effects such as thermal and gain noise



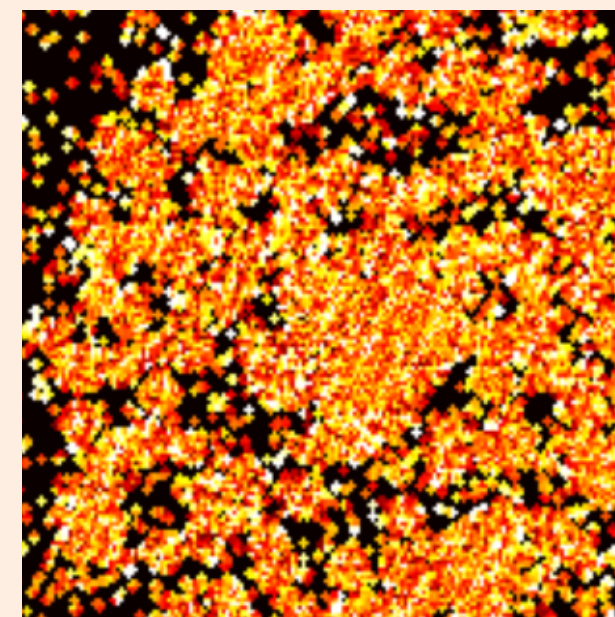
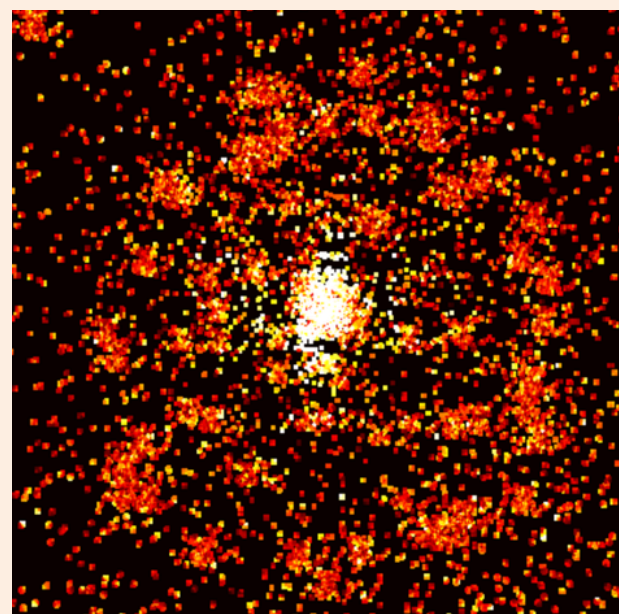
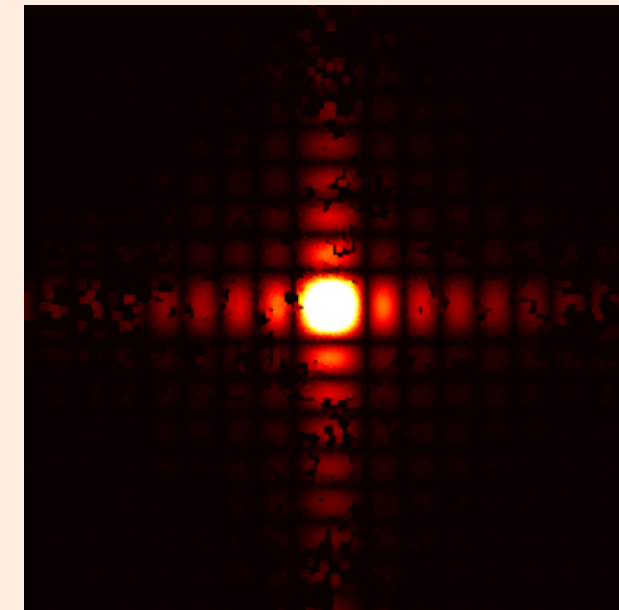
Foregrounds in
EoR0 field



FIRSTLY, AN UPGRADE...



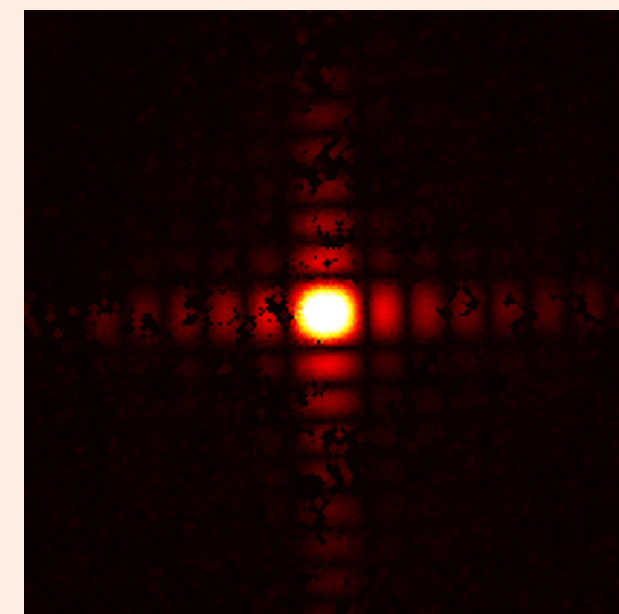
128 tiles to
256 tiles



Foreground subtracted



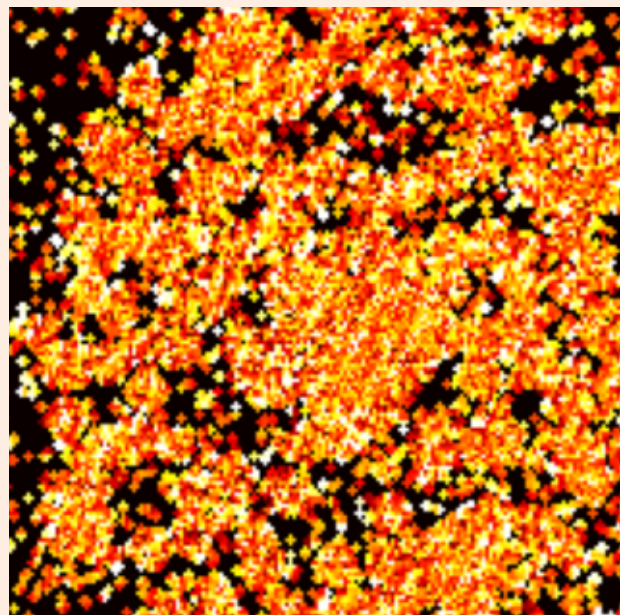
Realistic Flux



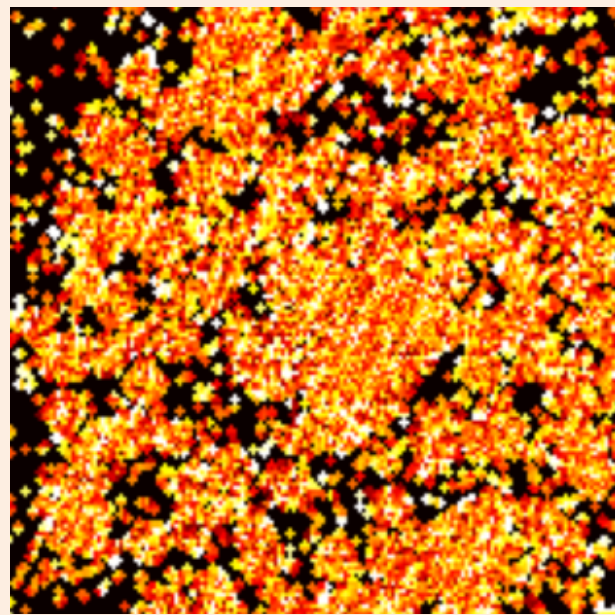
BUT WHAT'S THE DIFFERENCE?

- 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



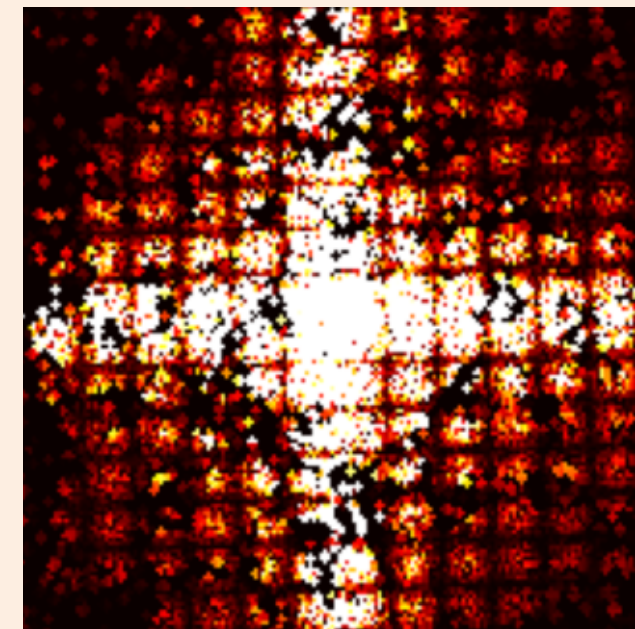
No wake



-

=

Residual



3-POINT FUNCTION

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

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

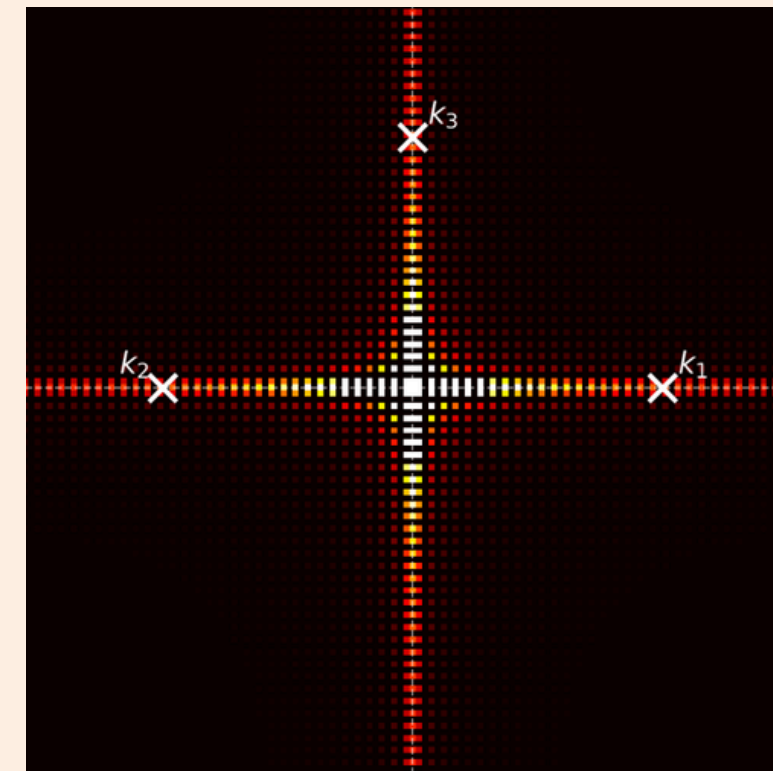
where, $\mathbf{k} = (u, v)$

- This function is tuned, for wakes by selecting,

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

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

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



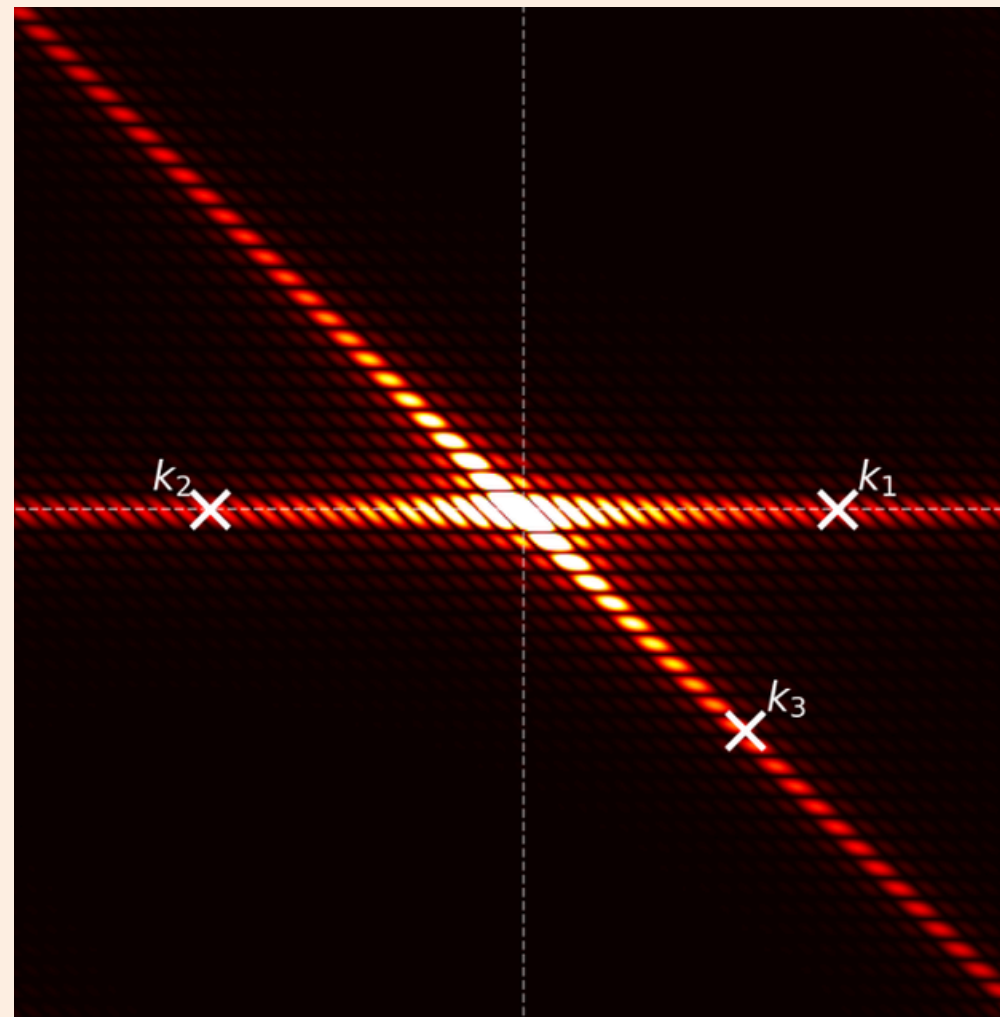
FURTHER TUNING,

- For a parallelogram shaped wake signal we select,

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

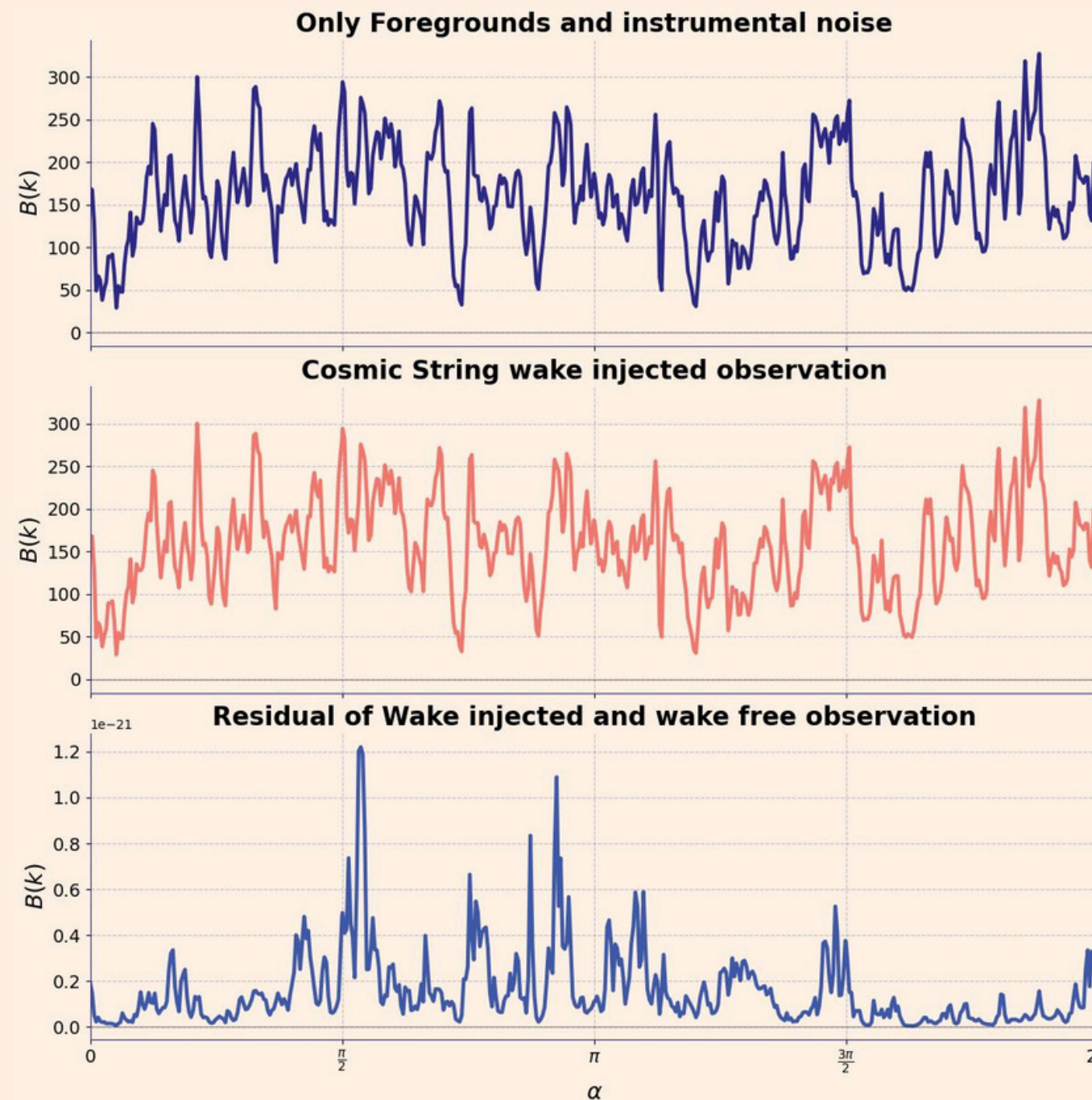
So to compute 3-point function,

- 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

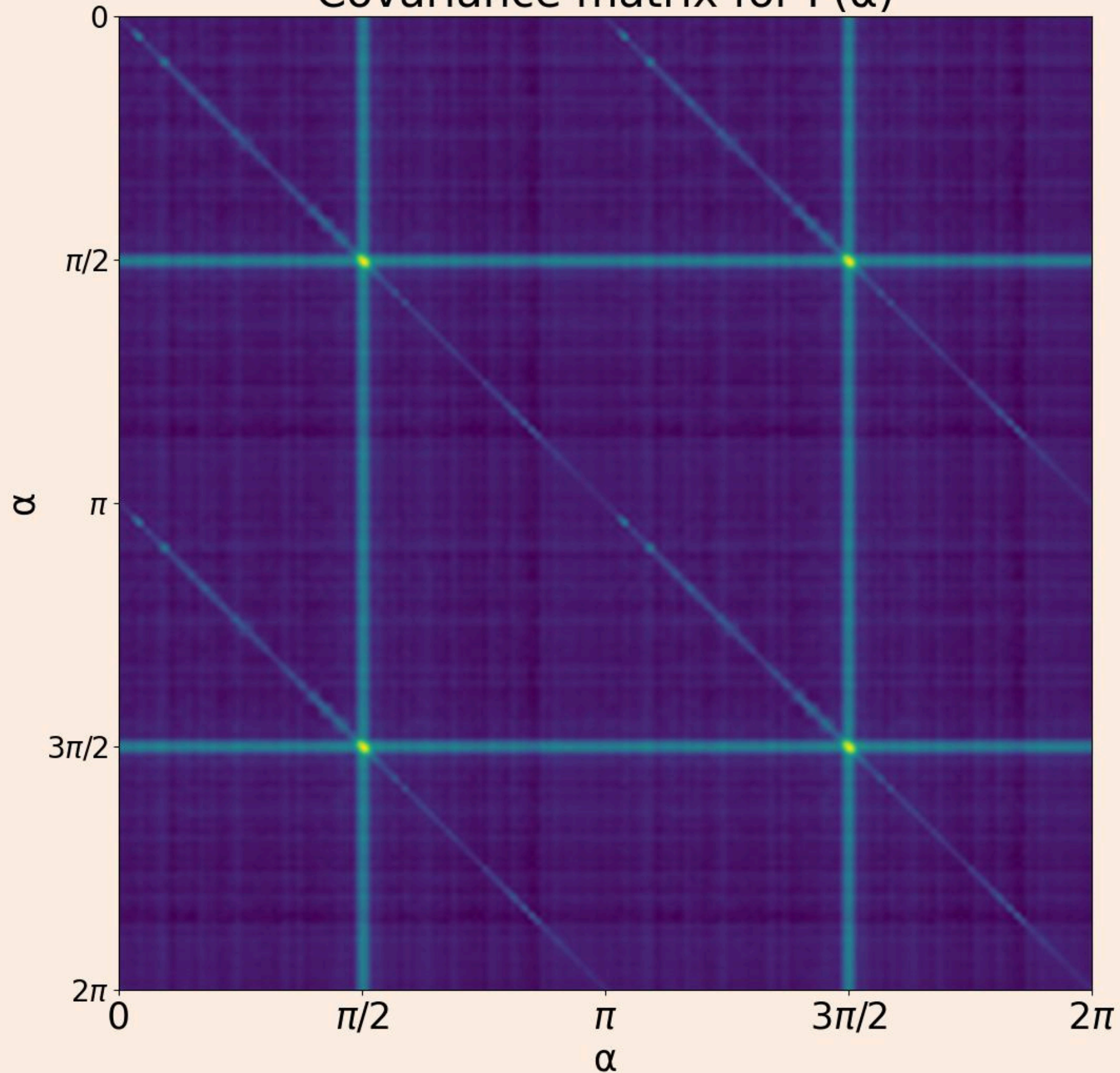
Parameters:

- 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