Ionospheric corruptions of the high-redshift 21-cm signal

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Kapteyn Astronomical Institute

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Dr. Maaijke Mevius (ASTRON)

Motivation

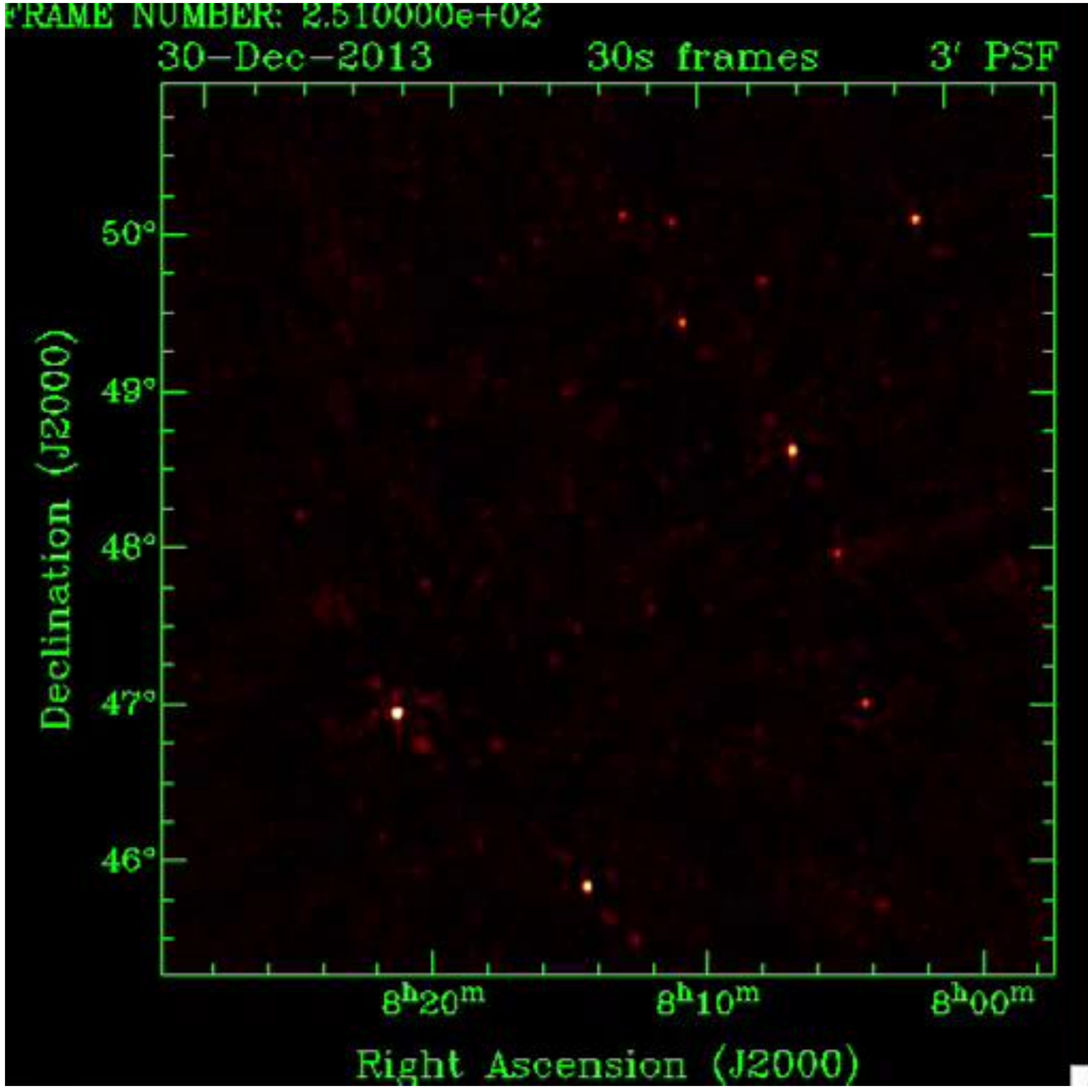

Image credit: Ger de Bruyn
(very bad ionospheric conditions)

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Motivation

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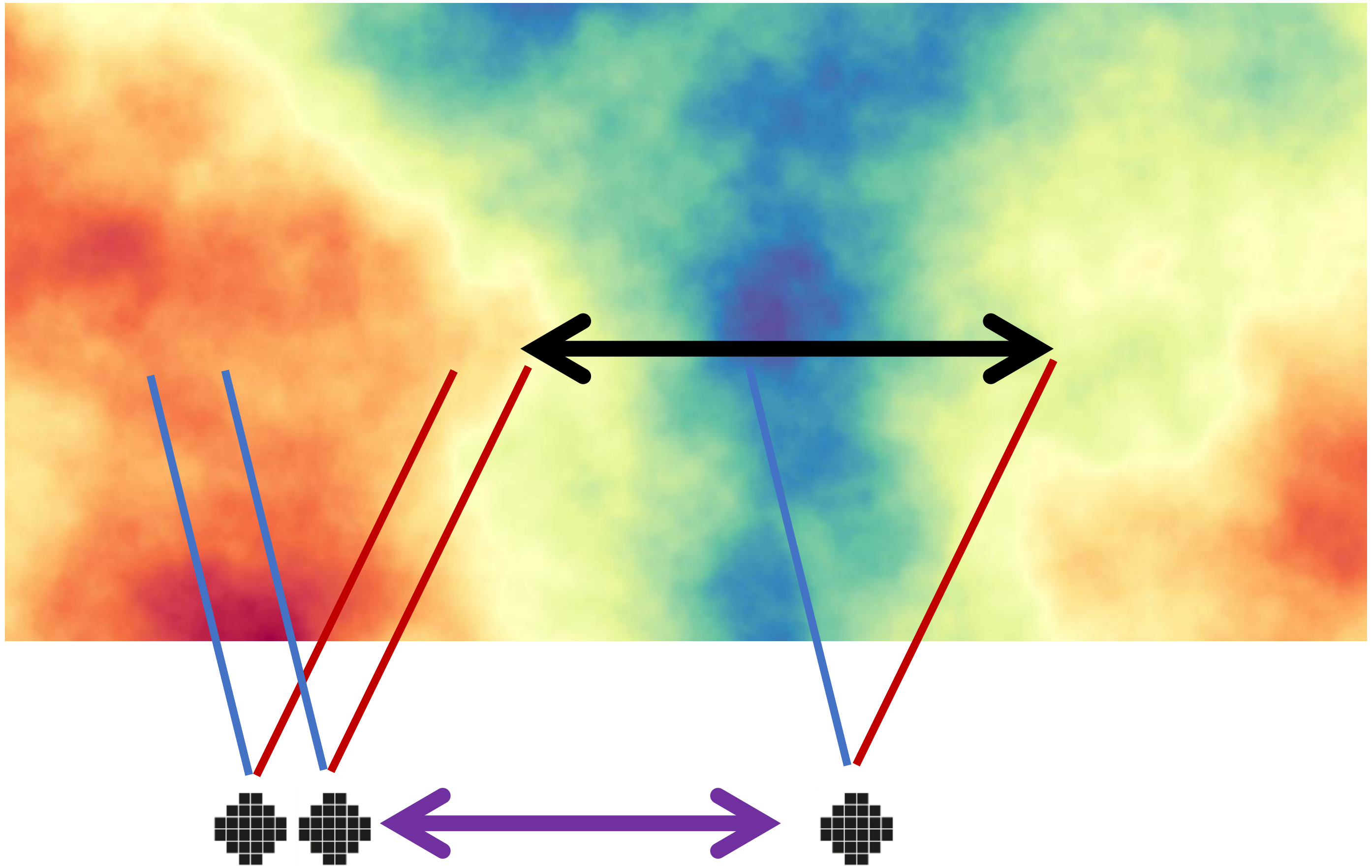
LOFAR EoR and the Ionosphere

Ionospheric scales & LOFAR



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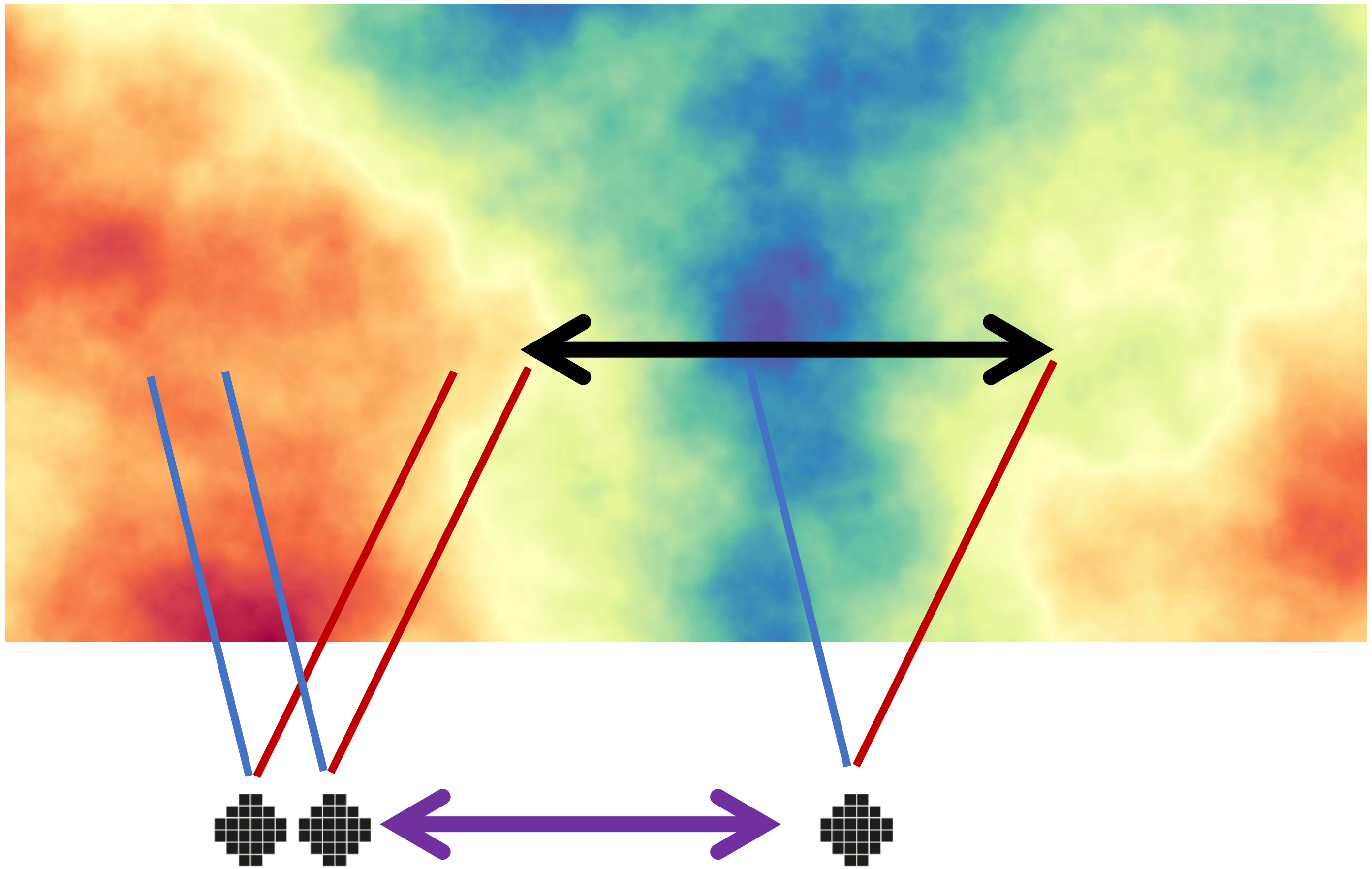
Ionospheric scales & LOFAR



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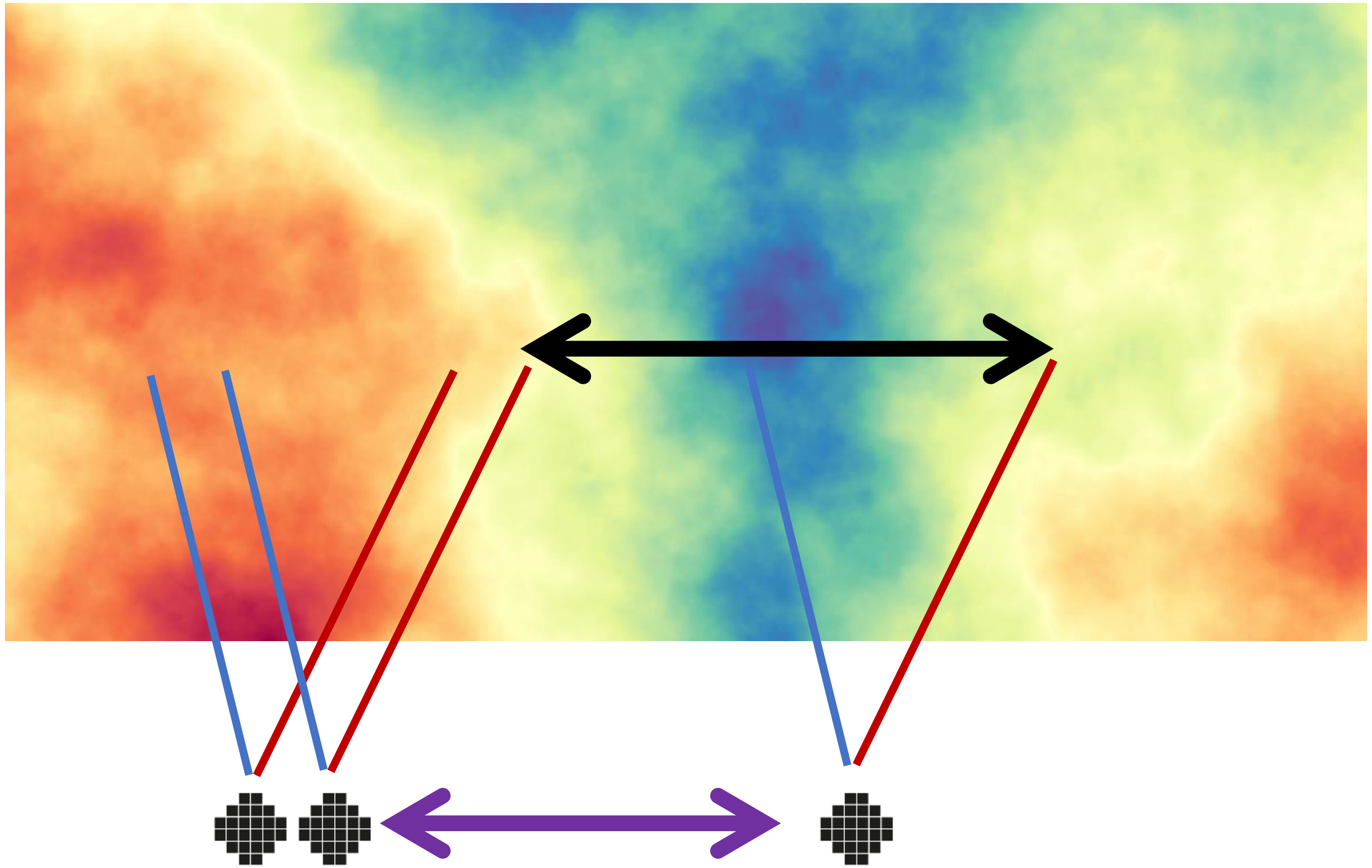
Ionospheric scales & LOFAR



Longer baseline

Larger scale

Larger phase variation

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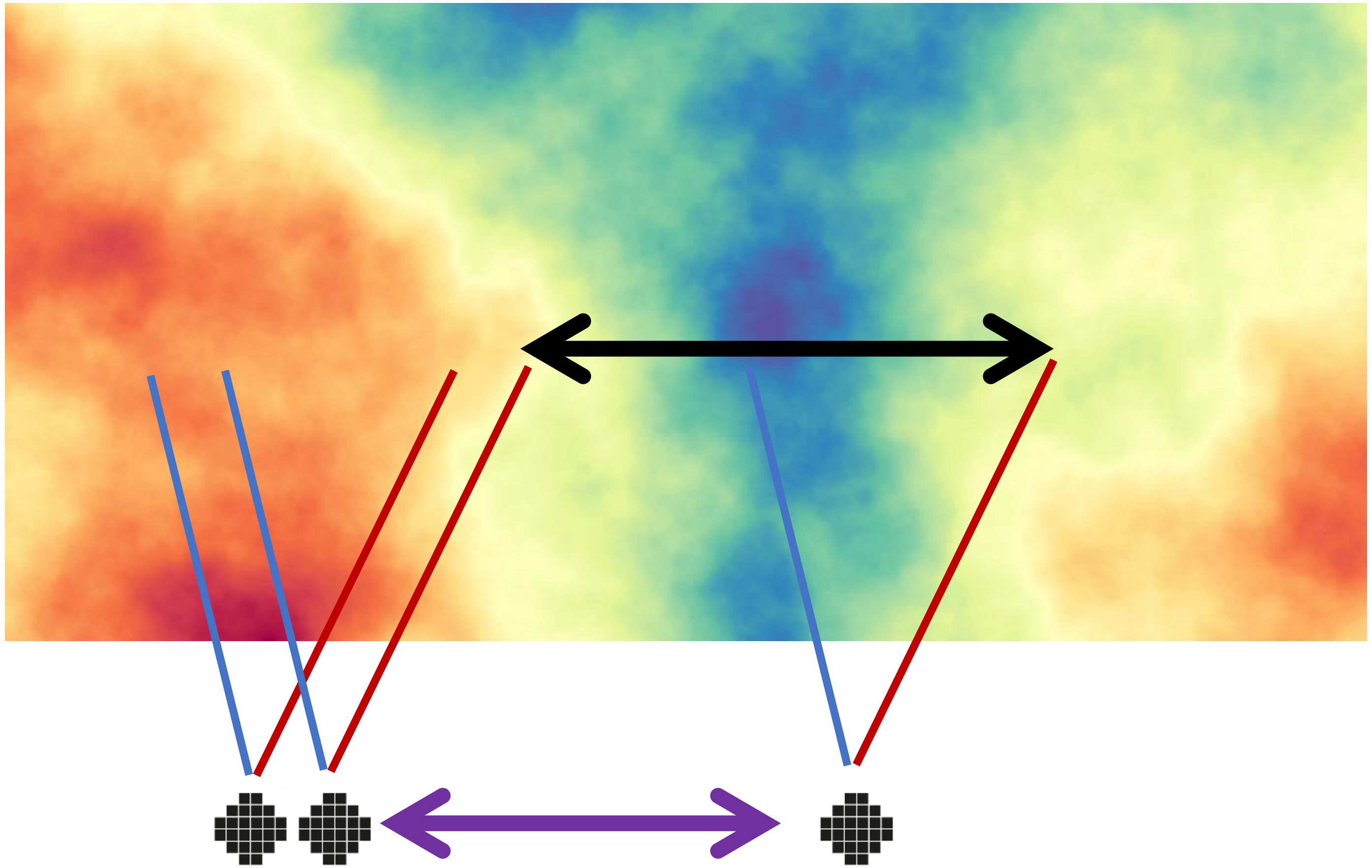
Ionospheric scales & LOFAR



Longer baseline

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Longer time correlation

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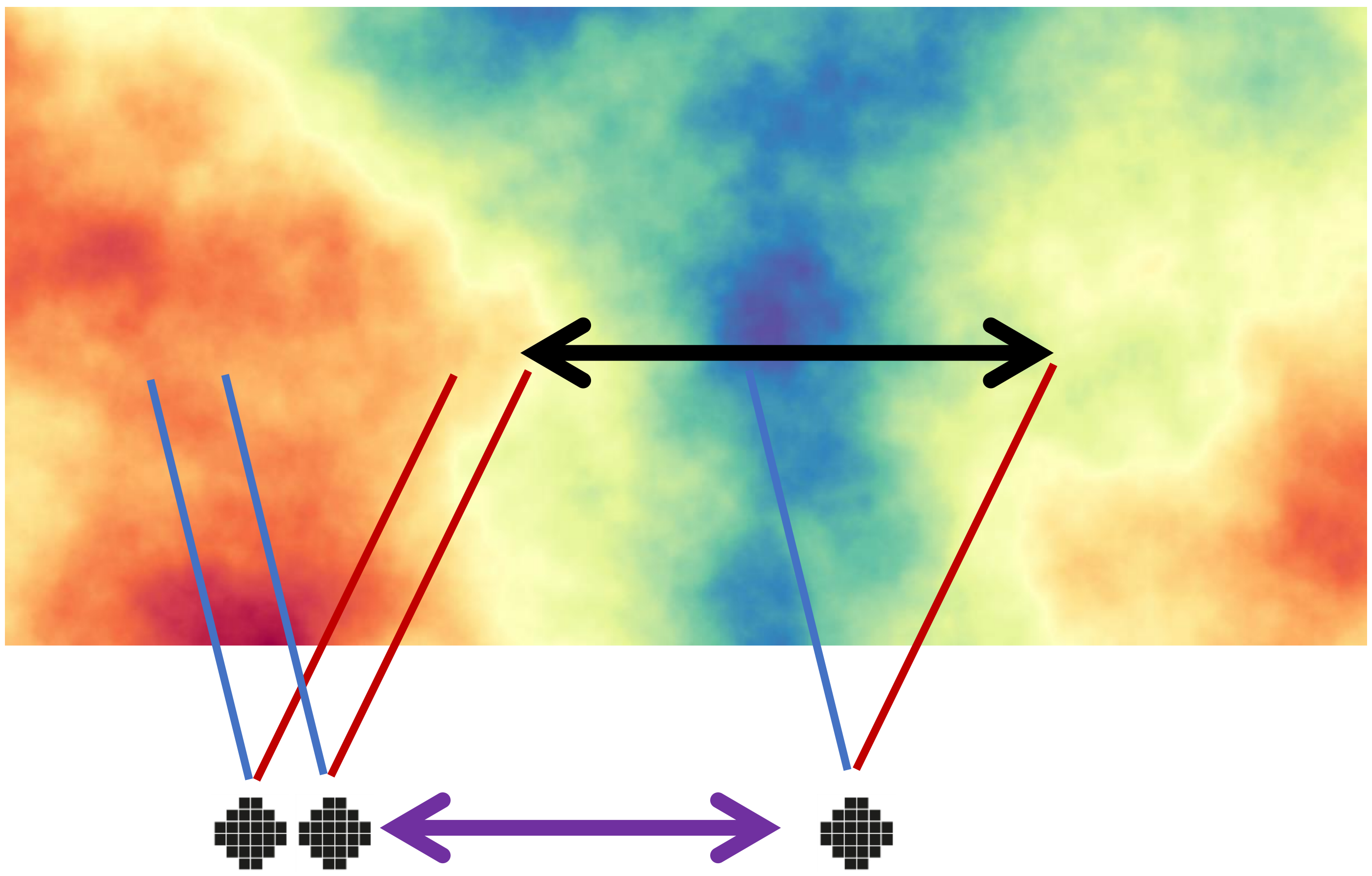
Ionospheric scales & LOFAR



- Longer baseline
- Larger scale
- Larger phase variation
- Longer time correlation
- Easier to calibrate on bright point sources

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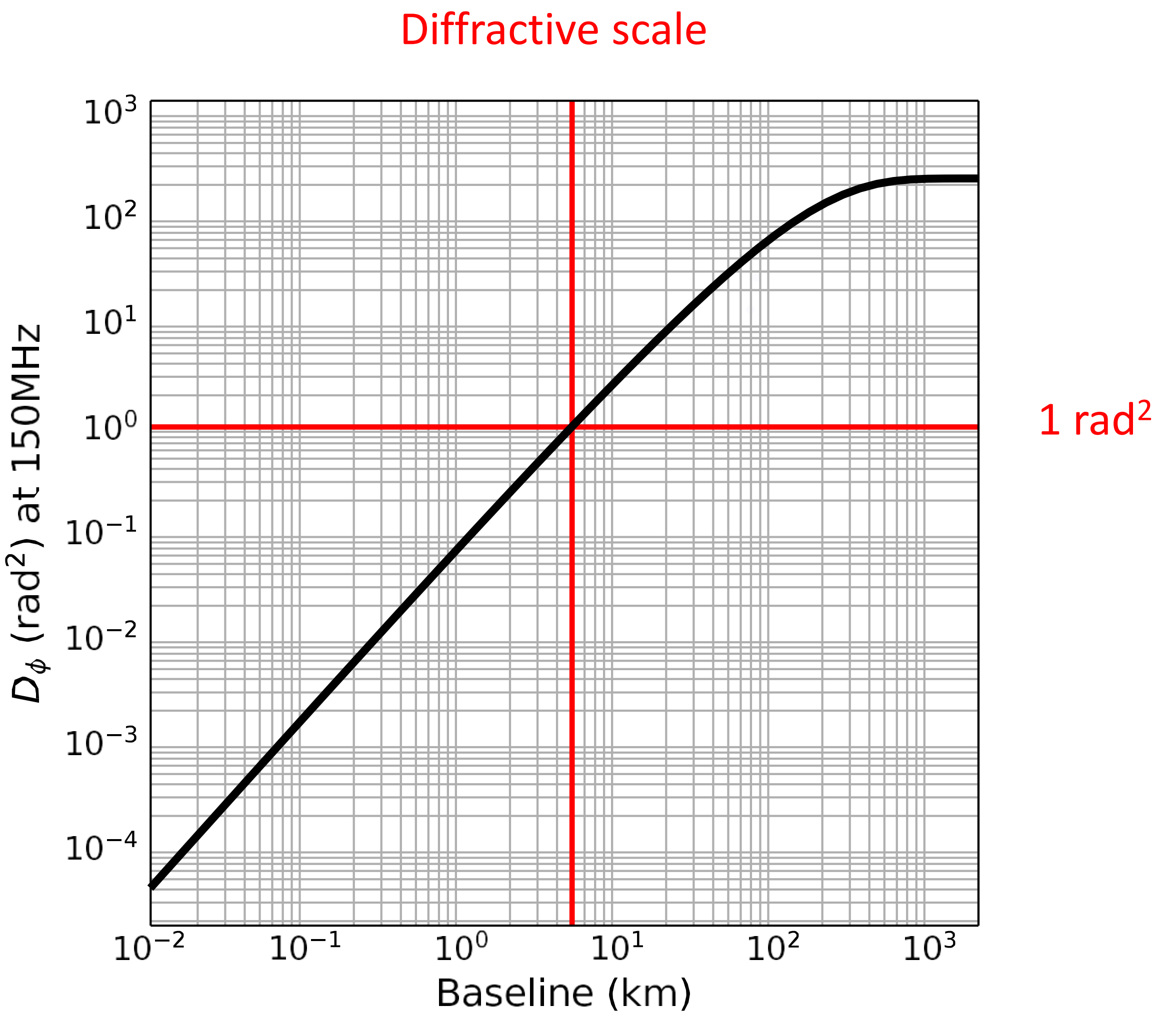
Ionosphere & LOFAR EoR



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Easier to calibrate on bright point sources

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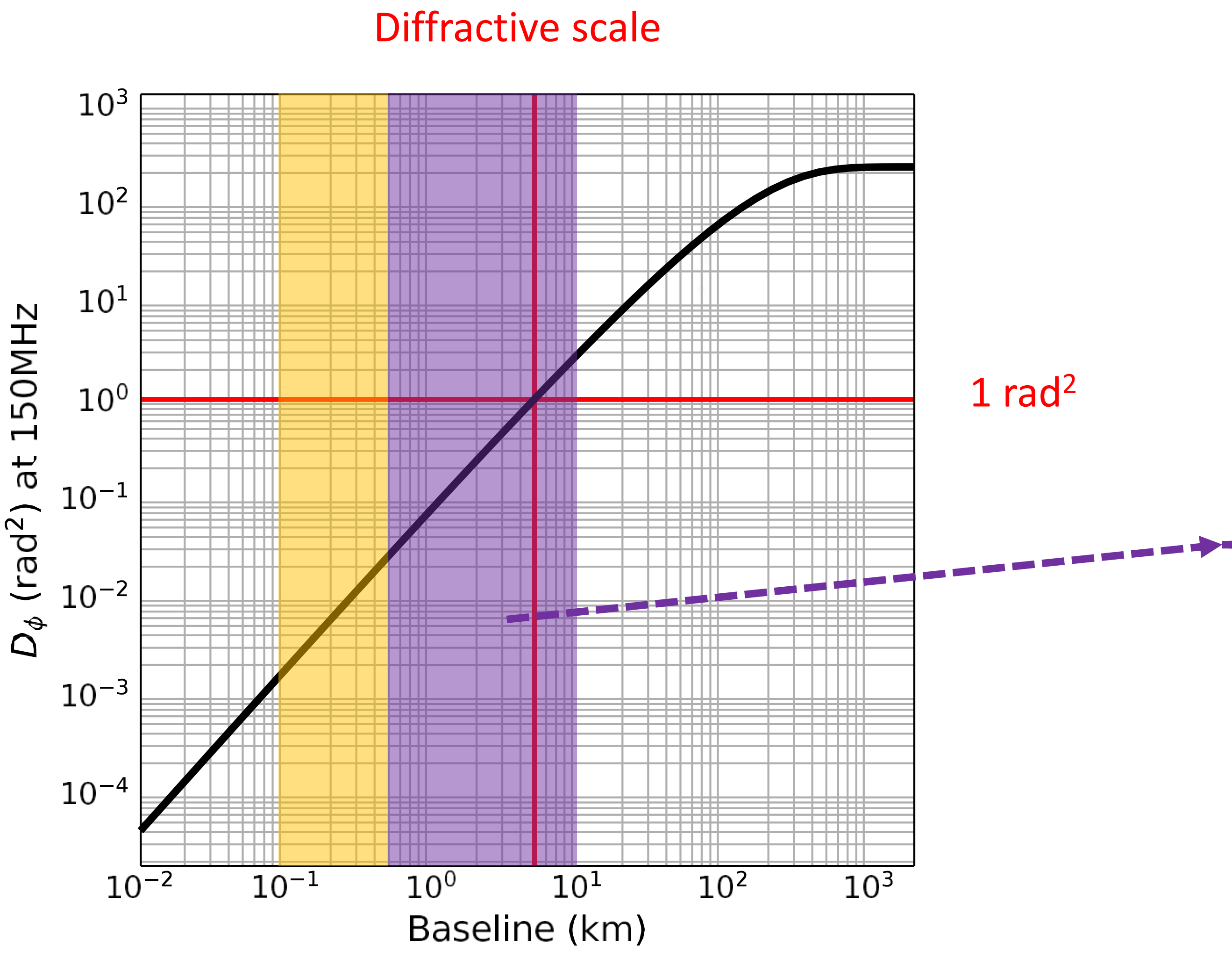
Ionosphere & LOFAR EoR



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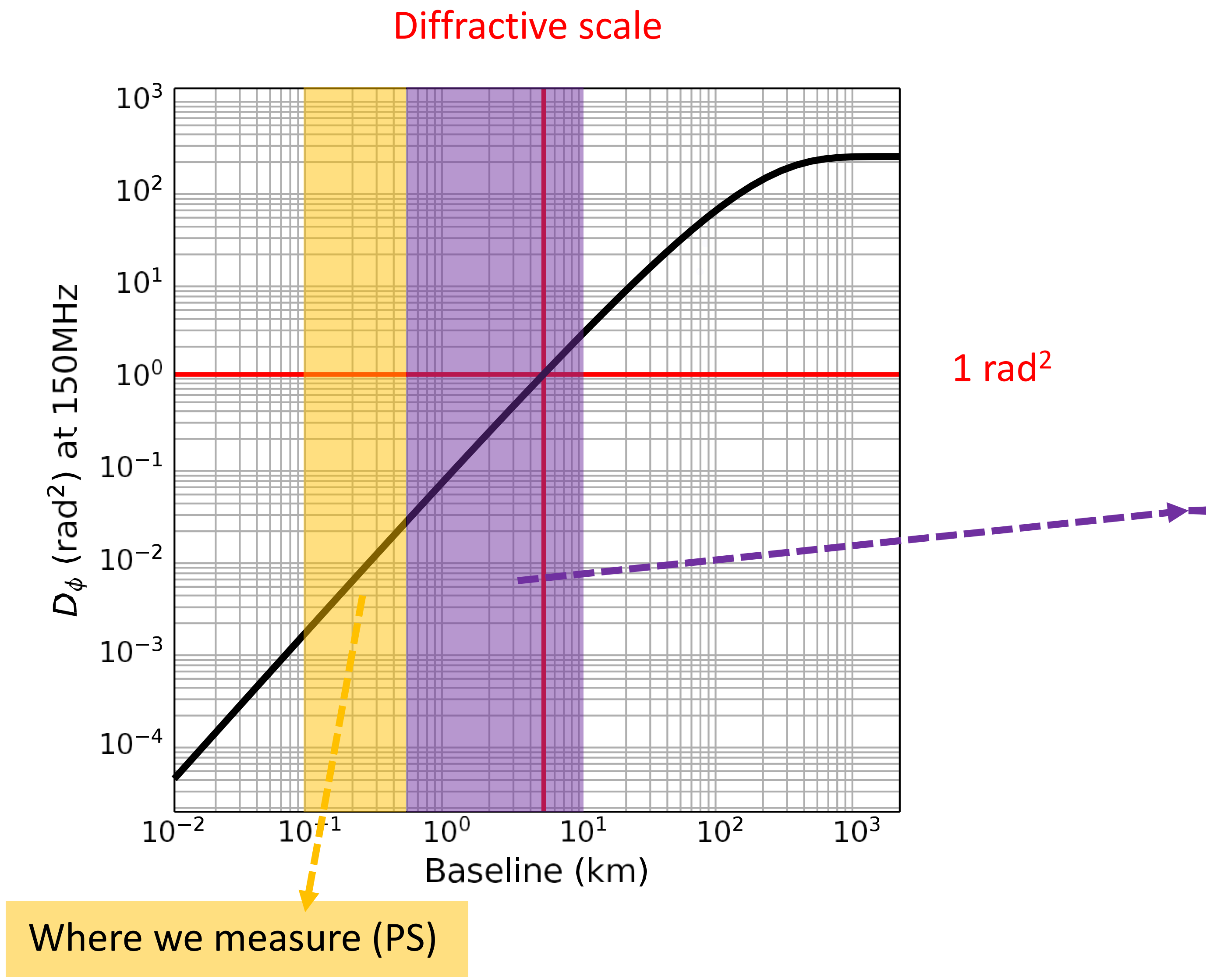
Ionosphere & LOFAR EoR



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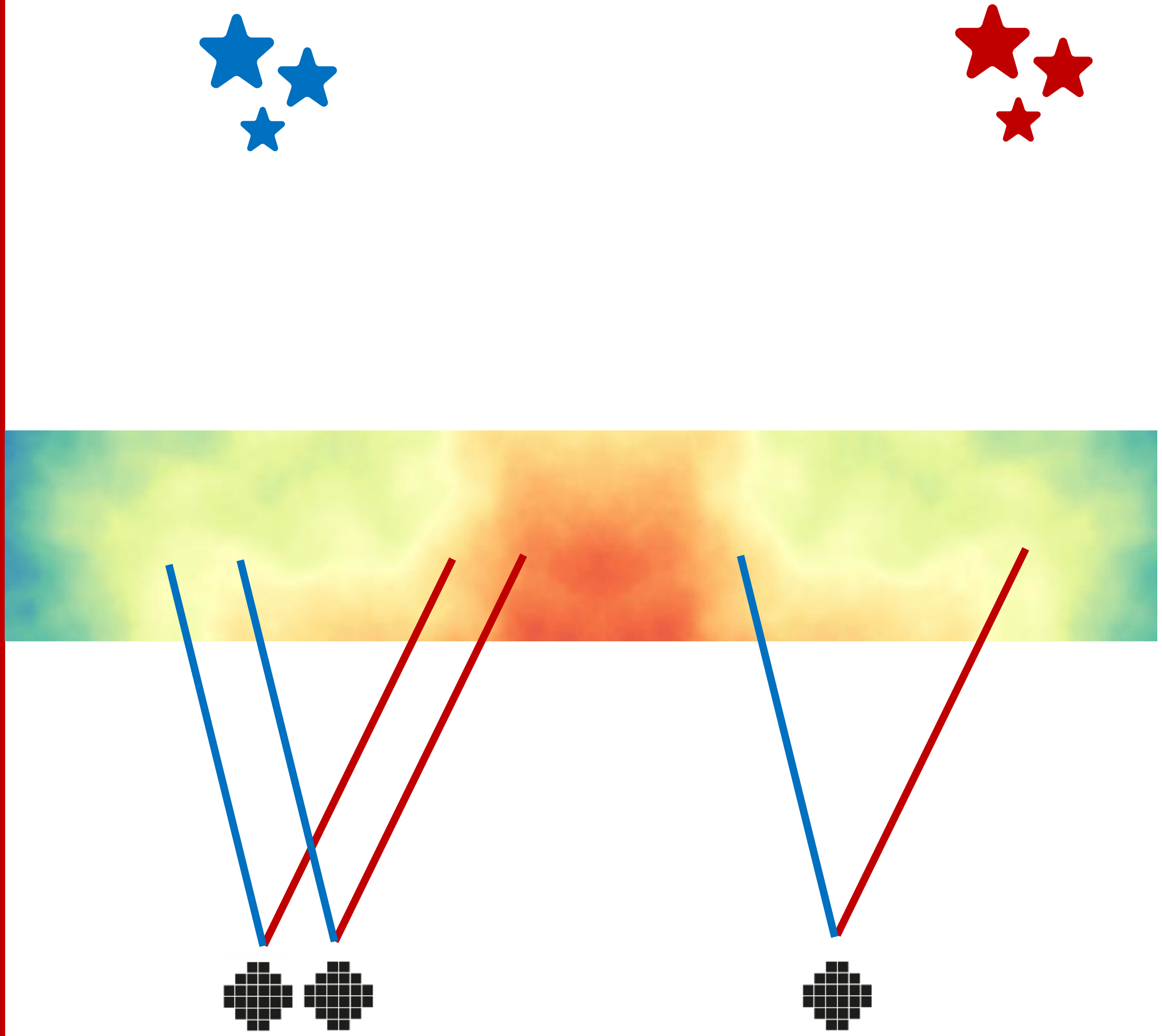
Easier to calibrate on bright point sources

The Simulation

Simulation



LoSiTo (Edler, 2021)

- Integrates with DP3

→Same model for simulation and calibration

Simulate dispersive delays, model only turbulence

Model of ~ 700 sources (NCP field)
+ Cas A

Pipeline

- Simulate foregrounds with ionosphere + thermal noise

Simulation

- Direction Independent Calibration (DP3)

All baselines (50 – 5000 λ)

- Direction Dependent Calibration + Foreground subtraction (DP3)

→ Long baselines (250 – 5000 λ)

→ Short baselines (50 – 250 λ)

- UV-space flagging + Residual foreground removal (ML-GPR)

Short baselines (50 – 250 λ)

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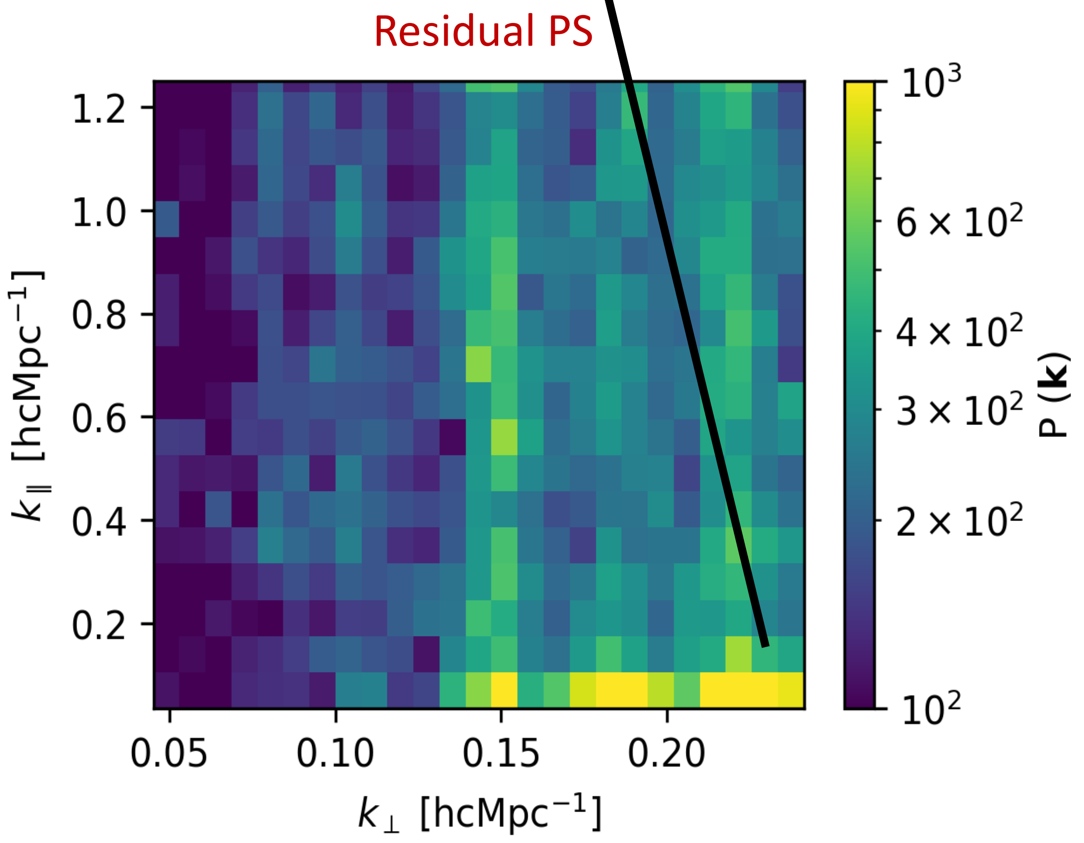
Results

Power Spectrum

- Simulate foregrounds with ionosphere + thermal noise
- Calibration (DI)
- Foreground subtraction (DD)
- Residual foreground removal (ML-GPR)

Yellow = foreground residuals



Before foreground subtraction: residuals ‘simulated’ using model visibilities

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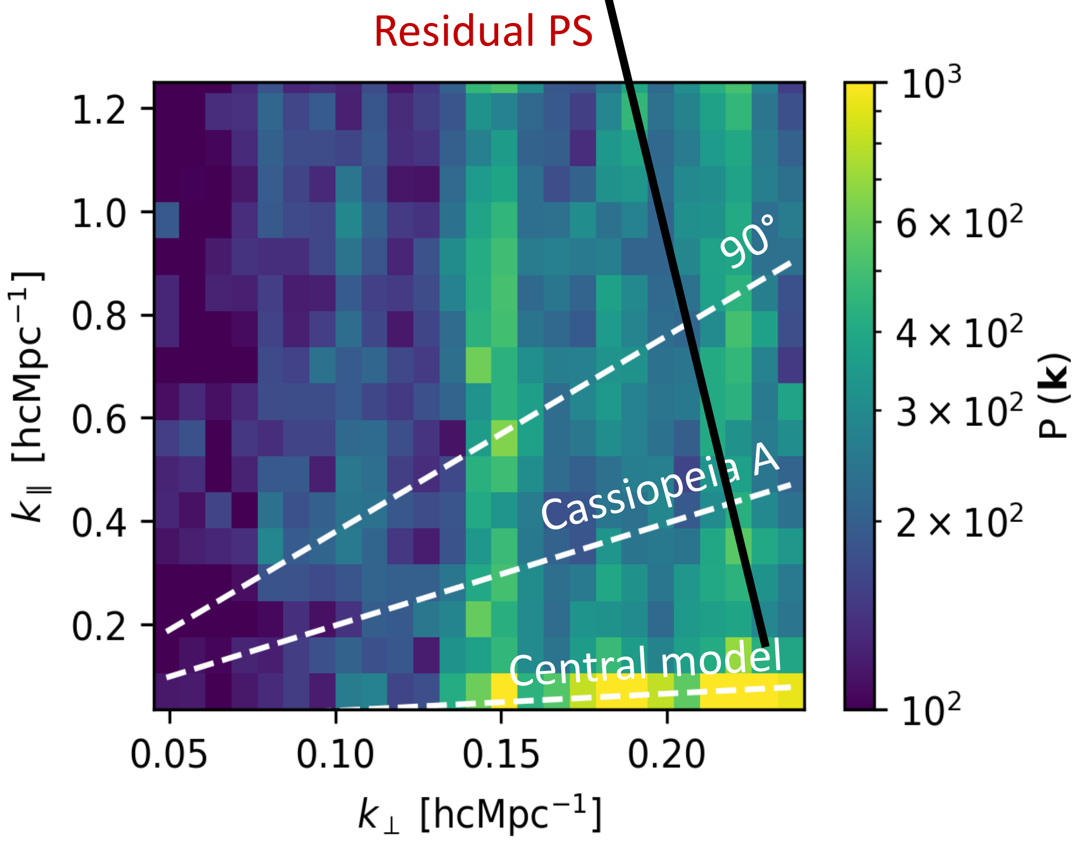
Power Spectrum

- Simulate foregrounds with ionosphere + thermal noise
- Calibration (DI)
- Foreground subtraction (DD)
- Residual foreground removal (ML-GPR)

Yellow = foreground residuals



Before foreground subtraction: residuals 'simulated' using model visibilities

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Power Spectrum

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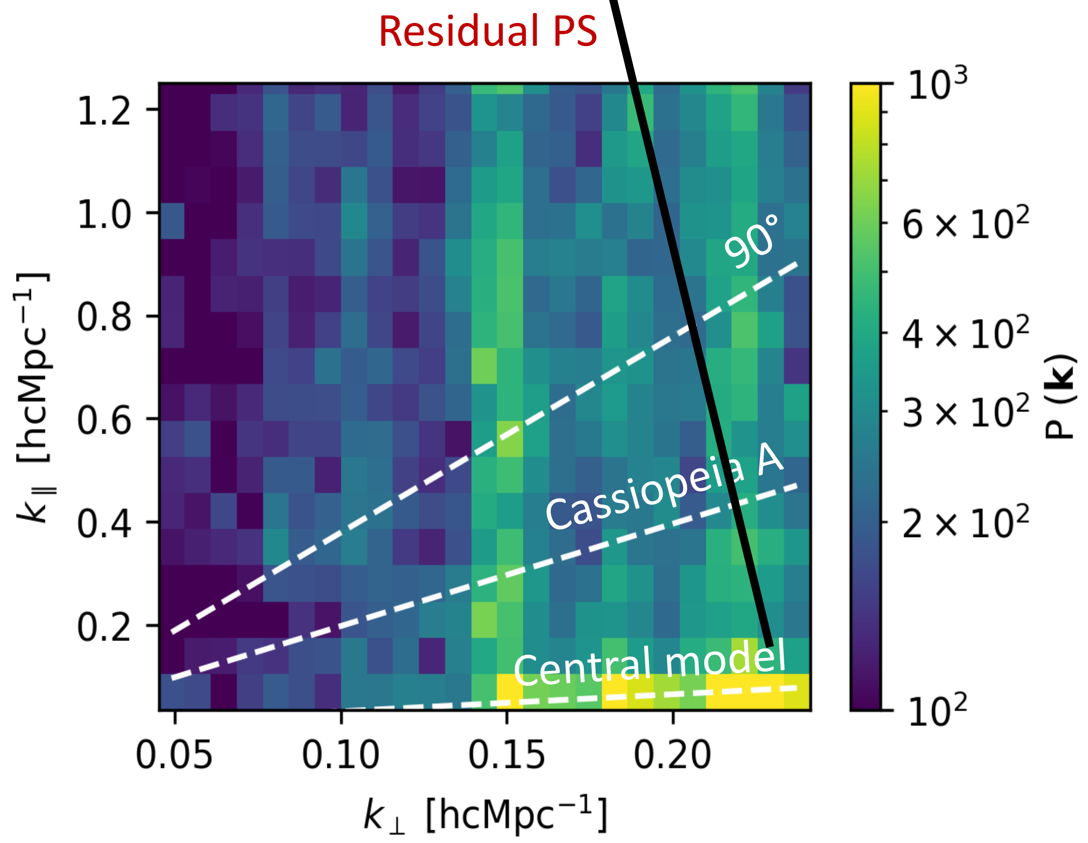

Before foreground subtraction: residuals 'simulated' using model visibilities

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Power Spectrum

- Simulate foregrounds with ionosphere + thermal noise
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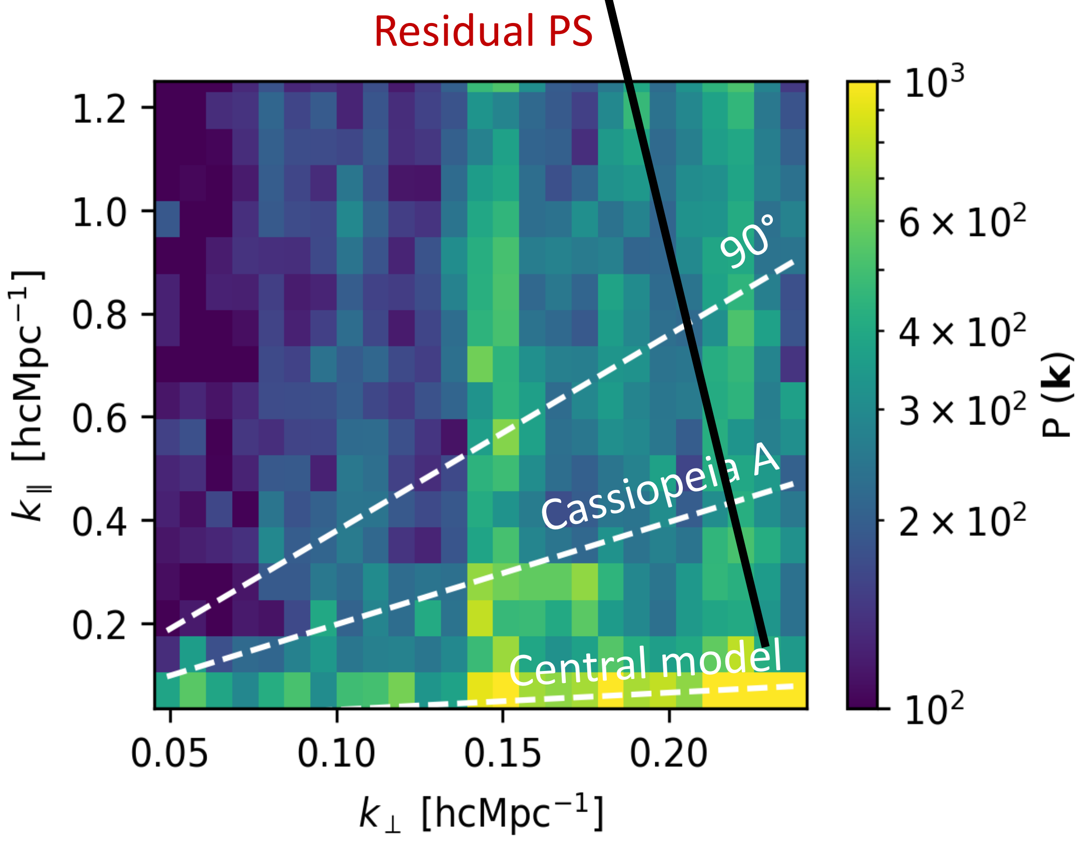

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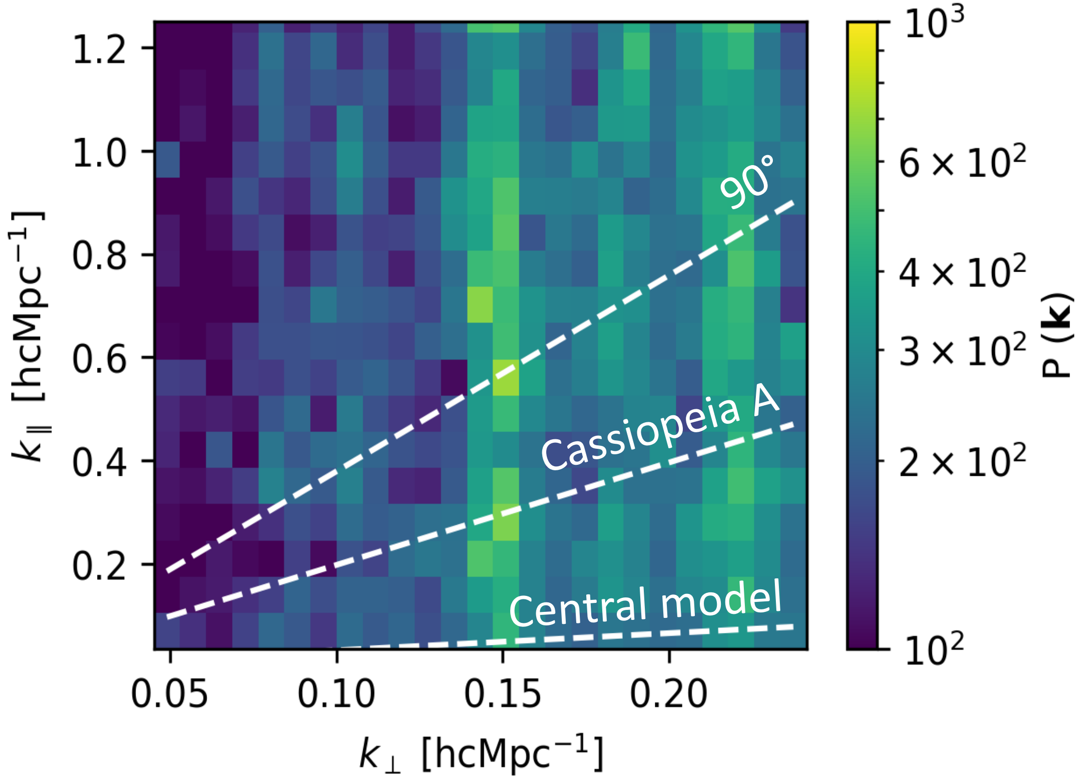
Final Power Spectrum

- Simulate foregrounds with ionosphere + thermal noise
- Calibration (DI)
- Foreground subtraction (DD)
- Residual foreground removal (ML-GPR)

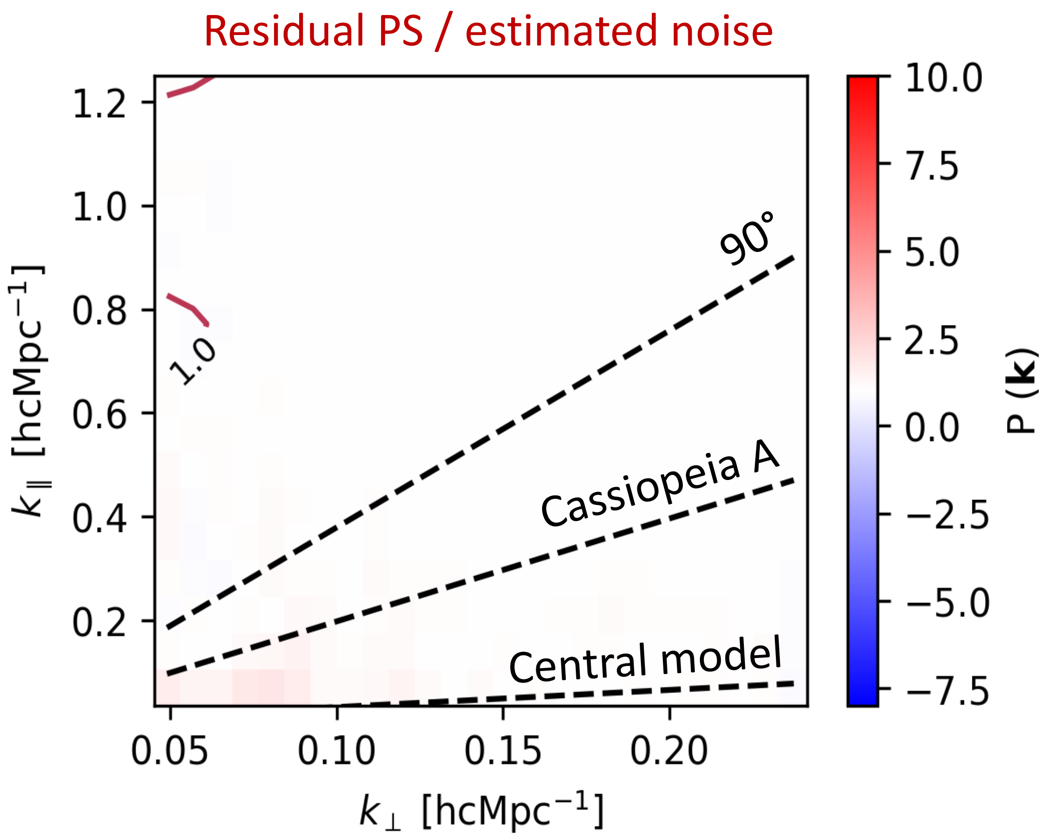
Residual PS



Foreground residuals gone

Power Spectrum

- Simulate foregrounds with ionosphere + thermal noise
- Calibration (DI)
- Foreground subtraction (DD)
- Residual foreground removal (ML-GPR)



Foreground residuals gone

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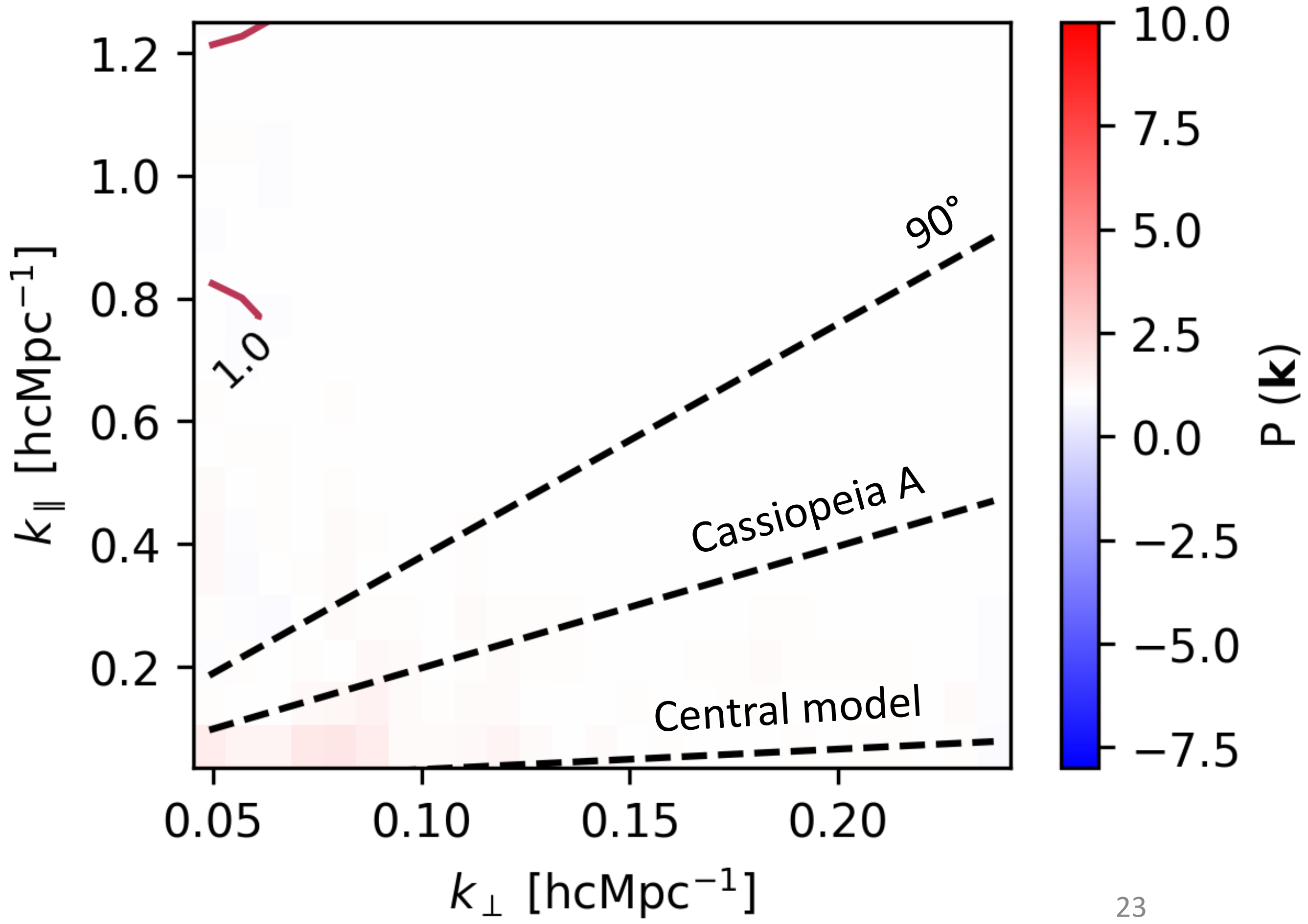
Final Power Spectrum

Foregrounds removed completely

Flag Cas A

Default ML-GPR

Residual PS / estimated noise

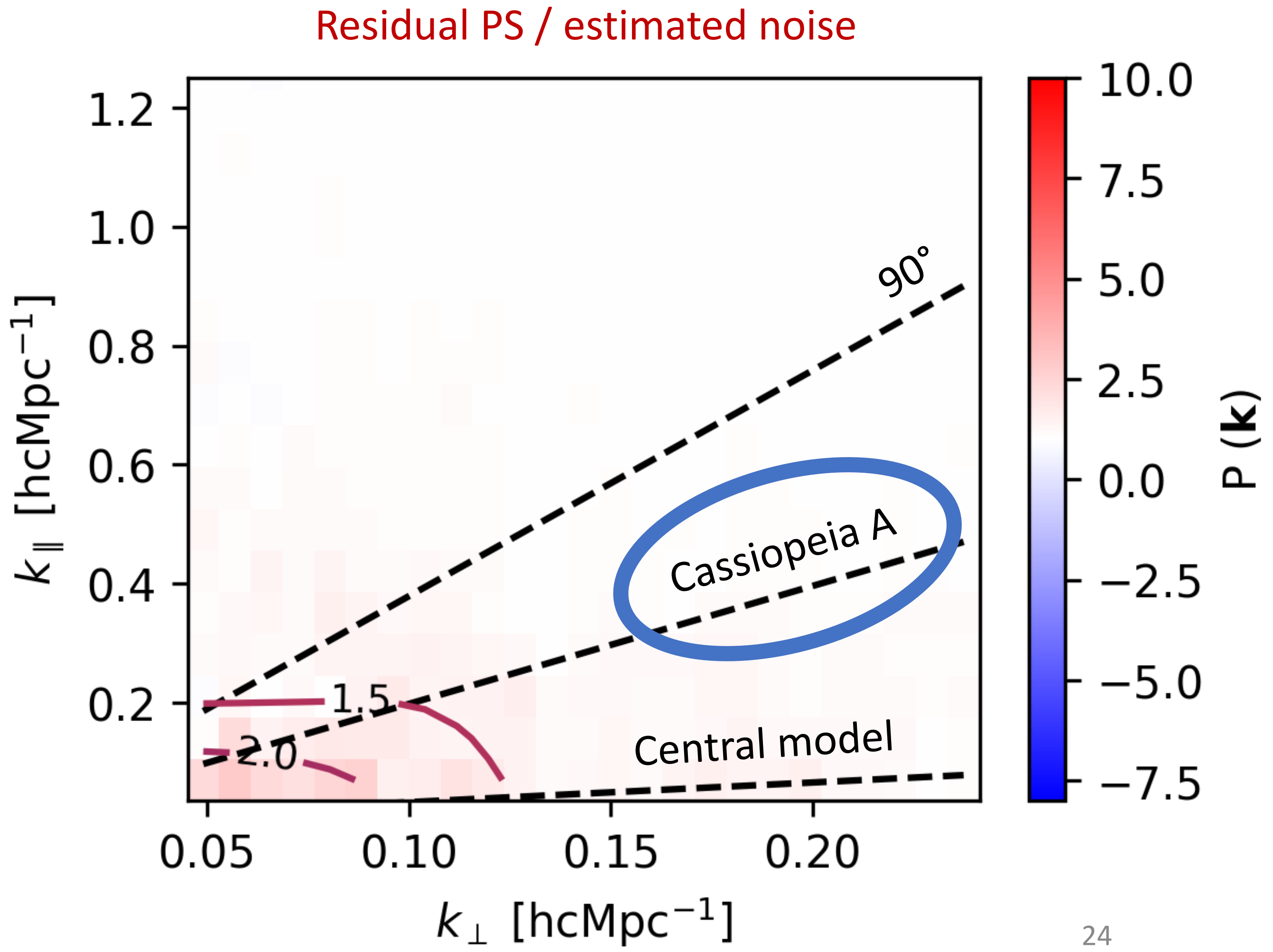


No Additional Flagging

Feature at low k-modes starts to appear

Flag Cas A

Default ML-GPR



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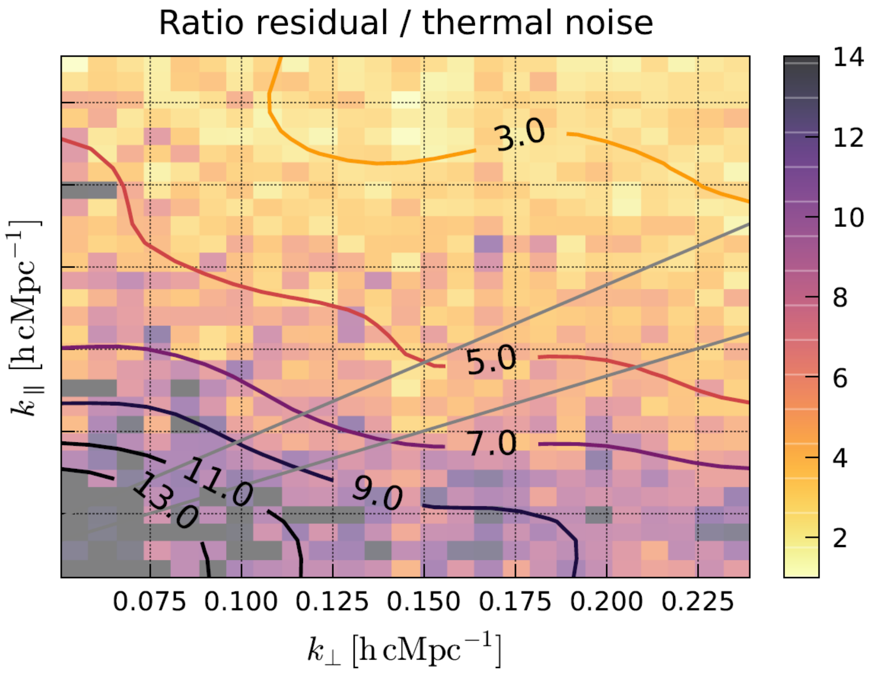
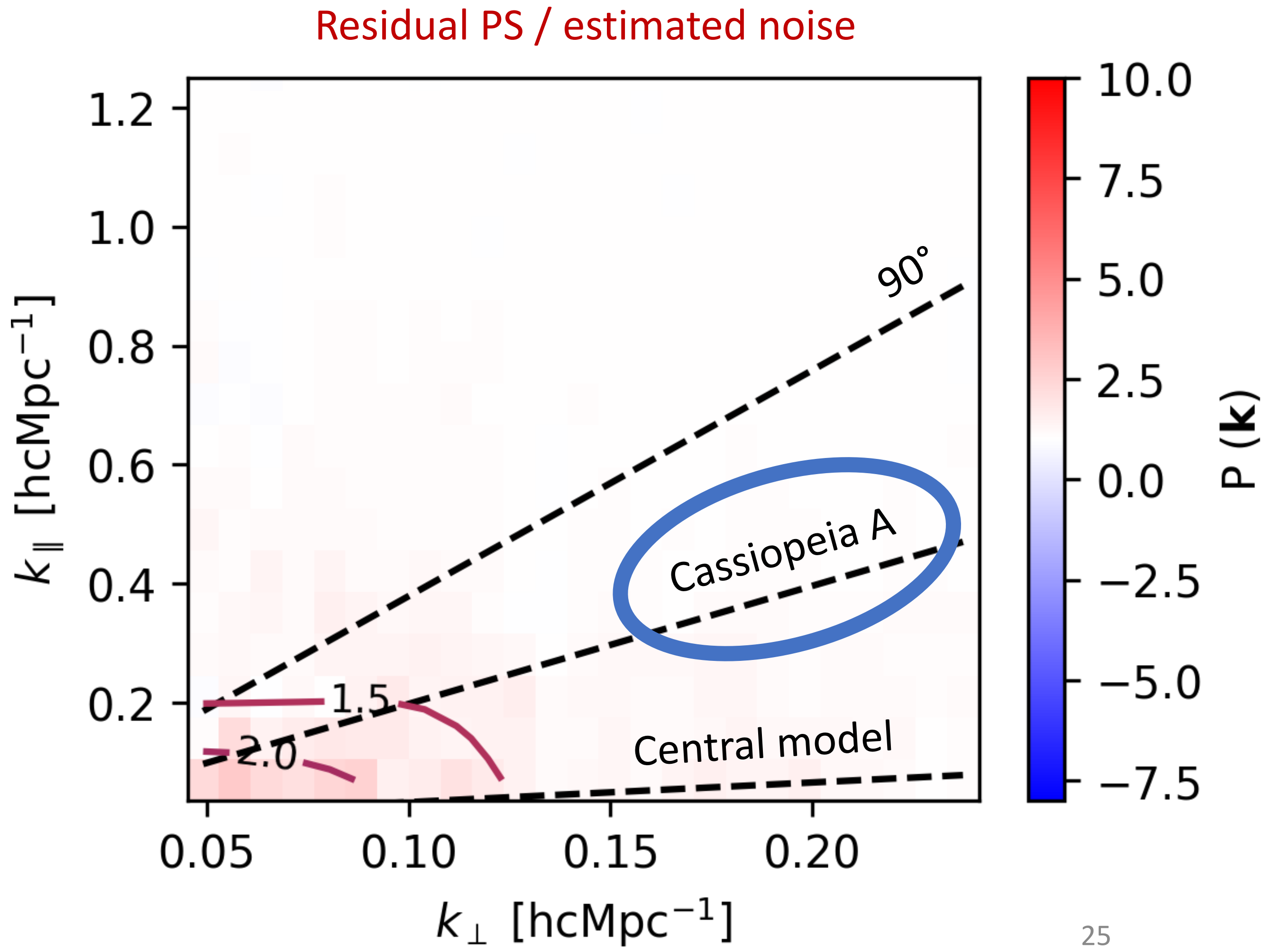
No Additional Flagging

Feature at low k-modes starts to appear



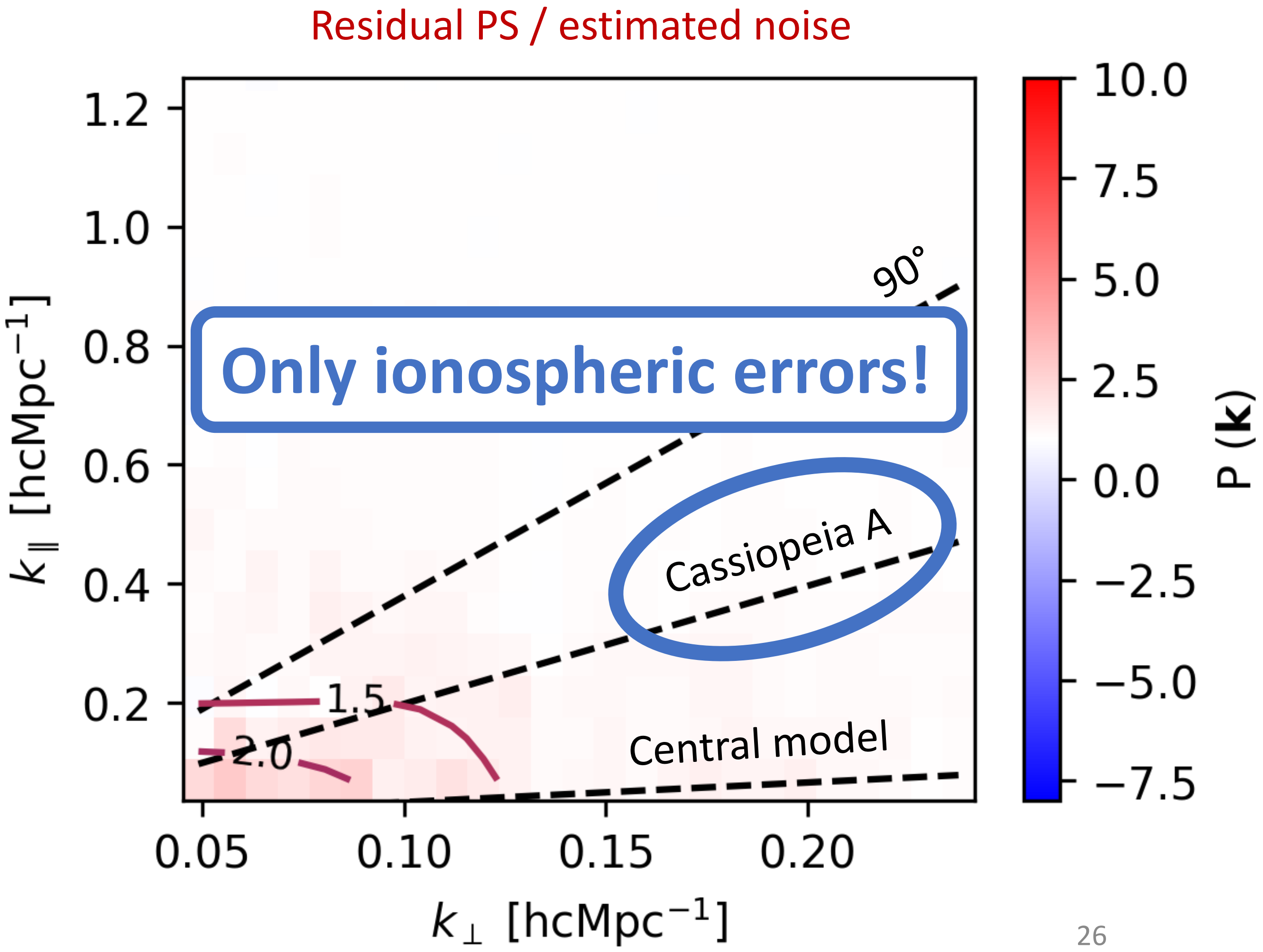


No Additional Flagging

Feature at low k-modes starts to appear

Flag Cas A

Default ML-GPR



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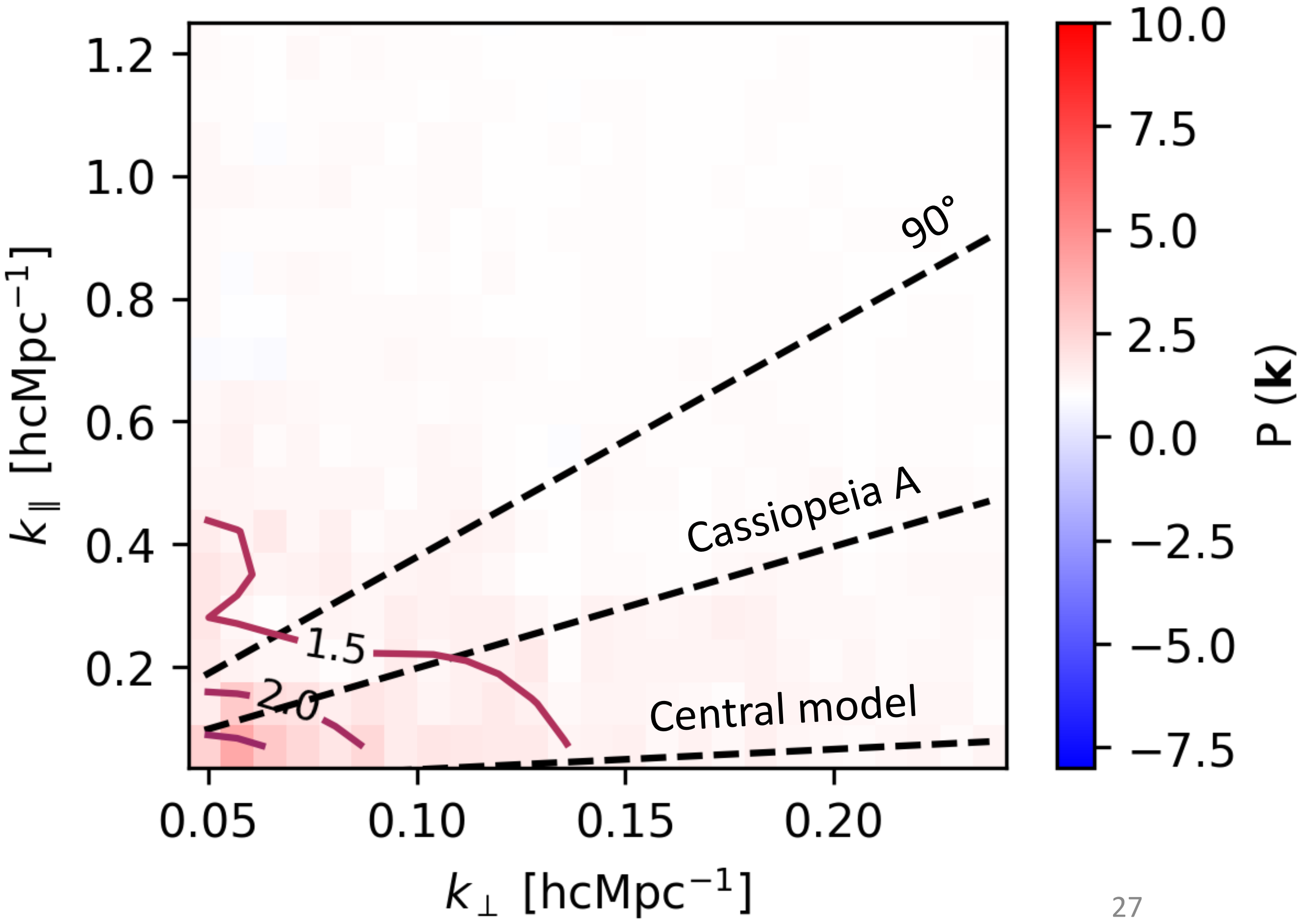
Fewer GPR Components

Stronger feature at low k-modes

Flag Cas A

Simpler ML-GPR

Residual PS / estimated noise



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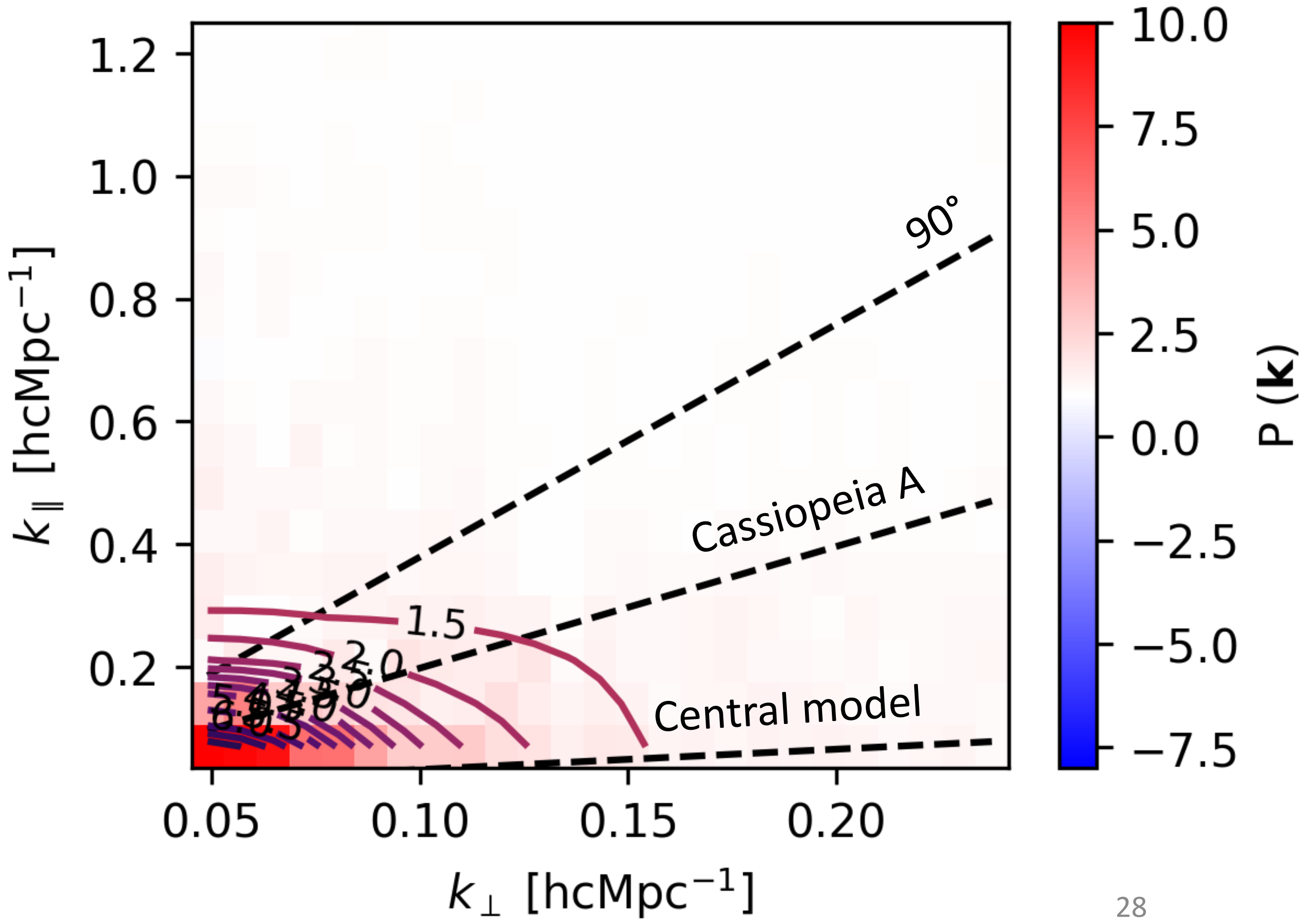
Worse Ionosphere

Feature at low k-modes at same level as in observations

Flag Cas A

Simpler ML-GPR

Residual PS / estimated noise



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Conclusions

Conclusions

- Ionospheric effects **alone can** likely be completely removed in LOFAR EoR data…
- But in the presence of ionospheric errors, removing **off-axis sources** is ineffective, even in an ideal case
- Must optimize configuration of (ML) GPR to remove ionospheric errors
  - Watch out for signal suppression
- Ionospheric errors may **exacerbate other errors** not discussed in this talk

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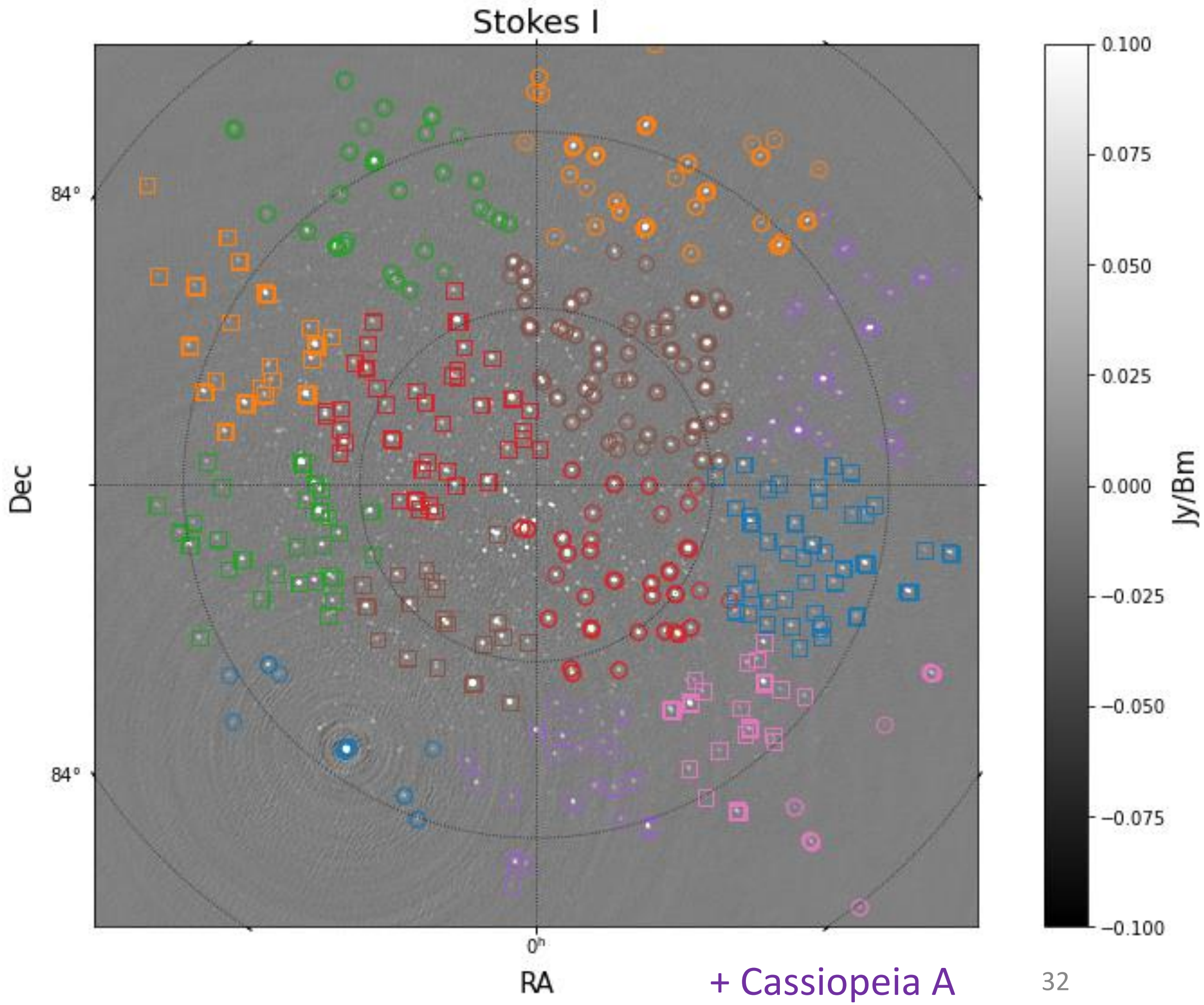
Supplements

Model

Parameter	Value
Telescope	LOFAR HBA
Pointing	NCP
Model	684 sources + Cassiopeia, 15 directions
Observation time	12 hr
Bandwidth	134.1 - 146.7 MHz (redshiftbin 2)
Temporal resolution	2 s
Spectral resolution	195 kHz (1 chan / SB)



+ Cassiopeia A

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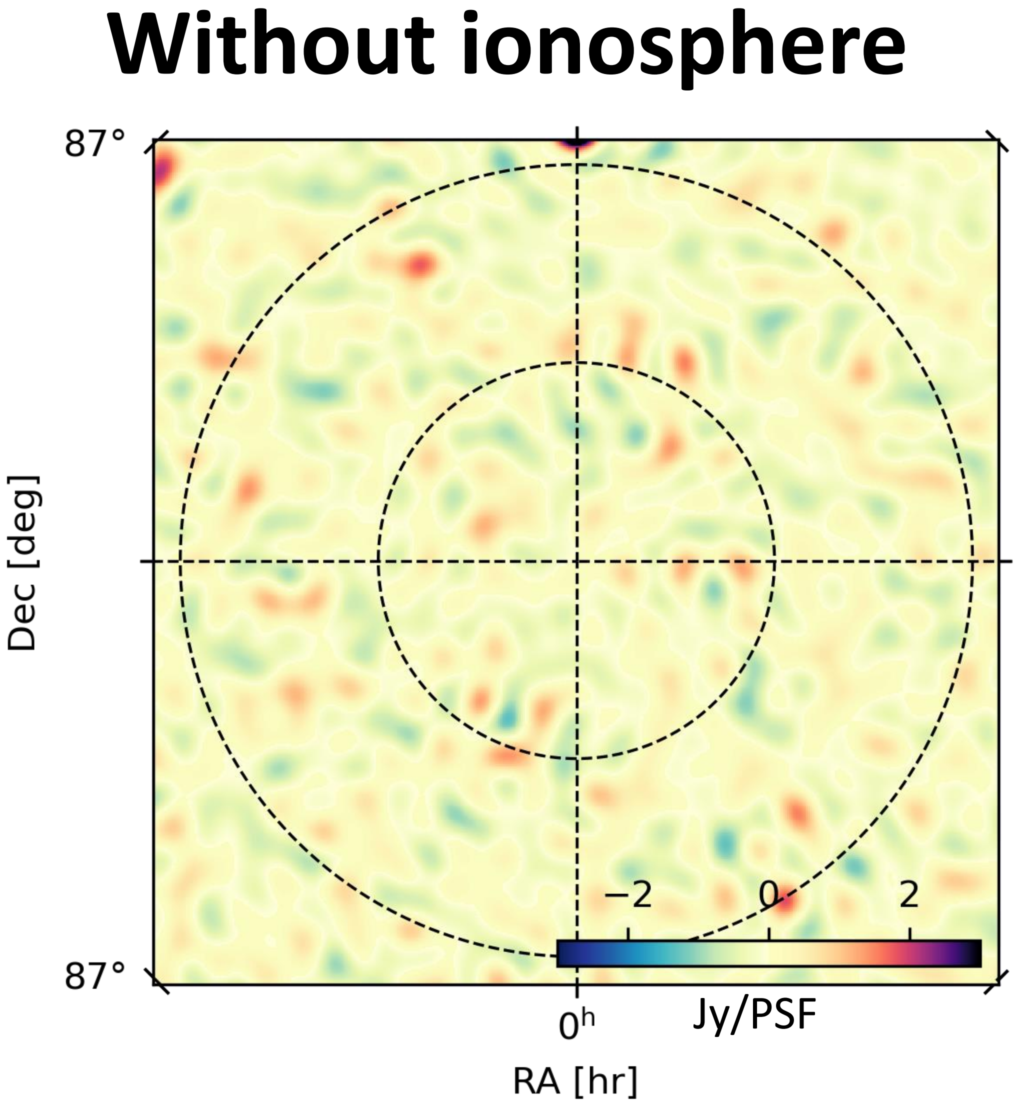
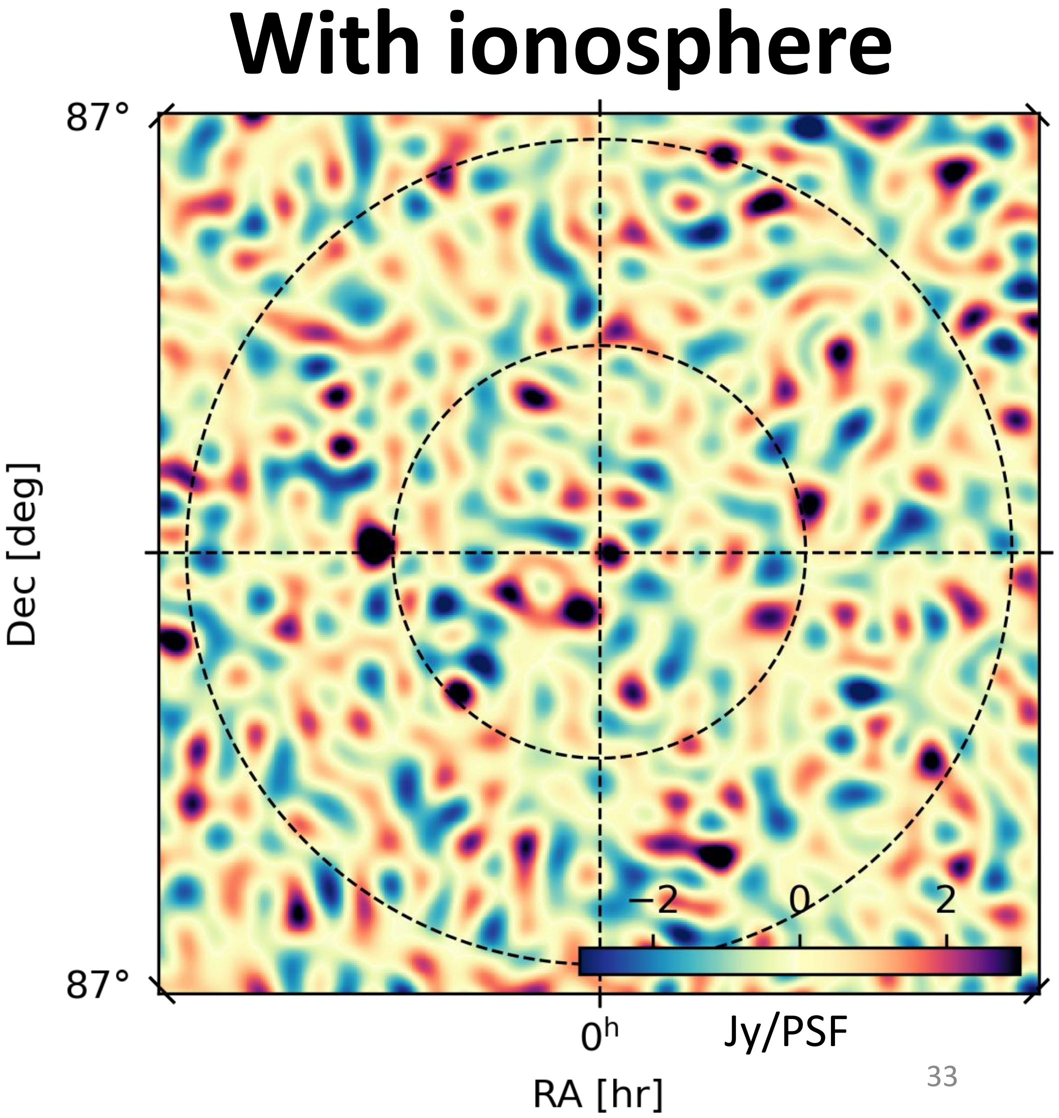
Residual image (after source removal)





GPR components

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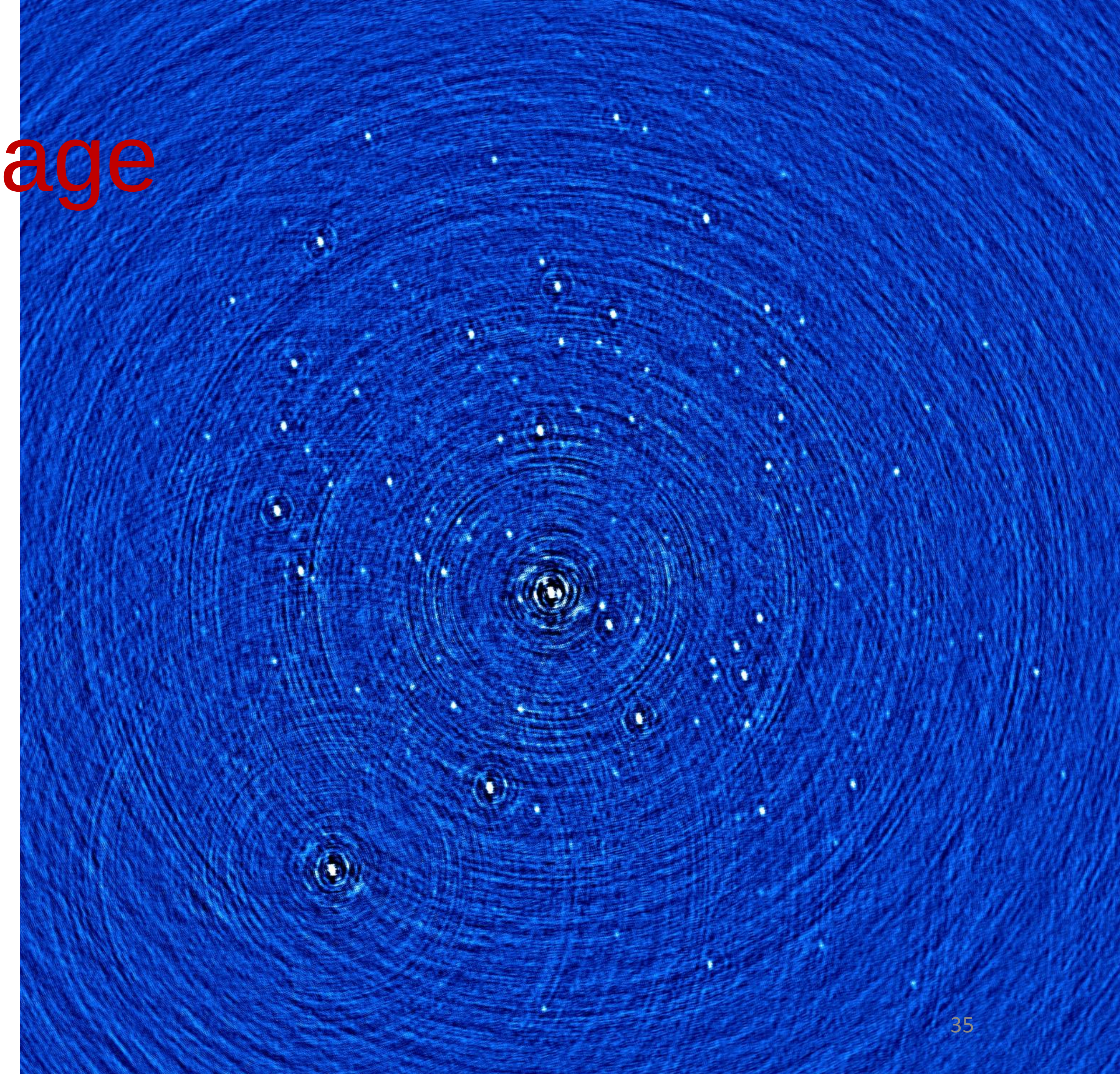
Example Image



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Post GPR

Foregrounds removed completely

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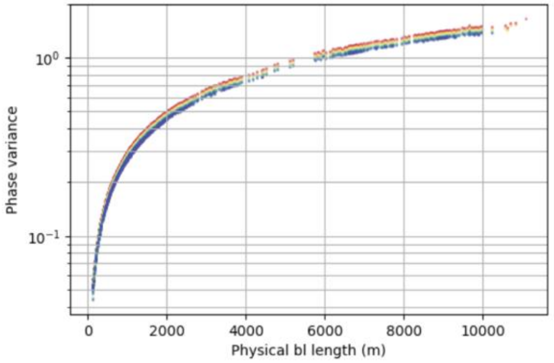
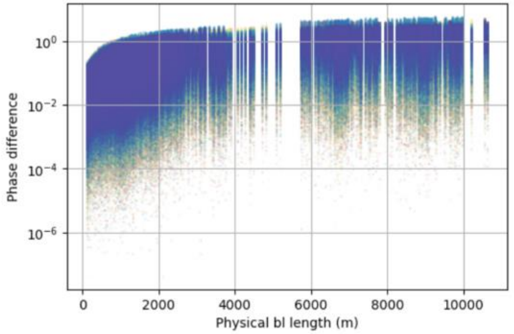
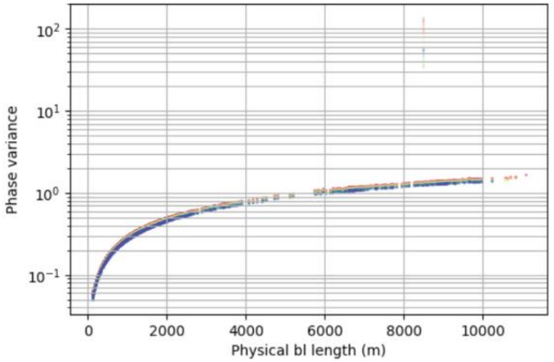
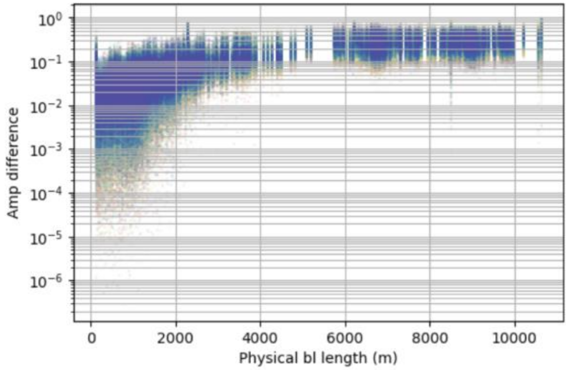
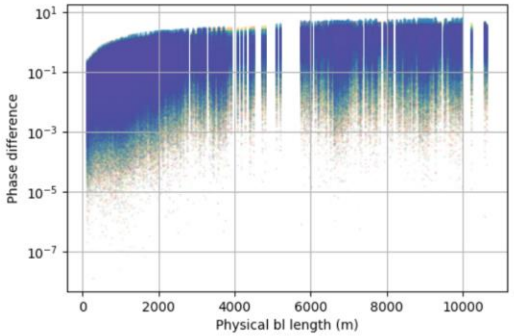
Variance/error transfer plots

What	Variance	Amp	Phase
Just TEC		Not applicable (TEC doesn't have an amplitude effect)	
TEC - DI gain bright source			

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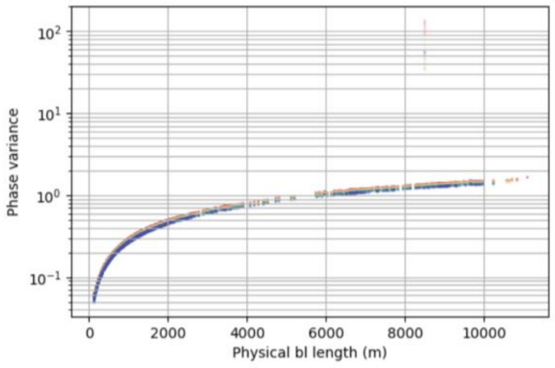
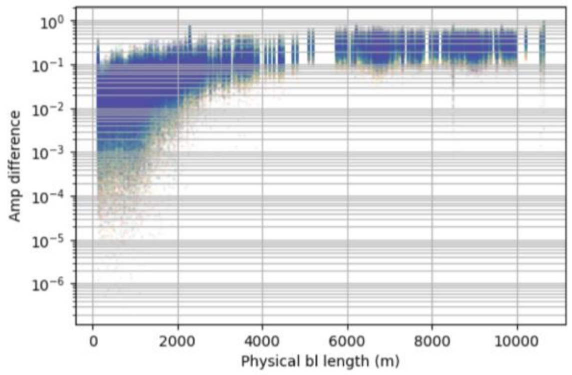
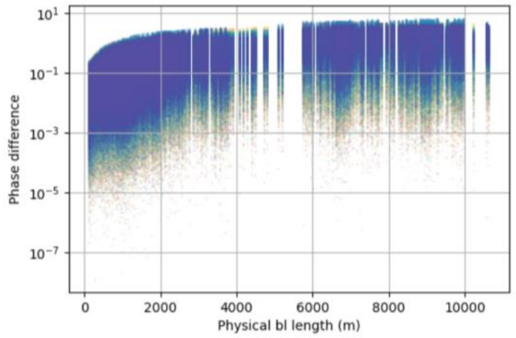
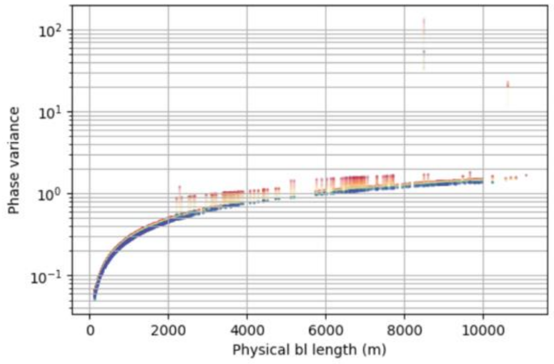
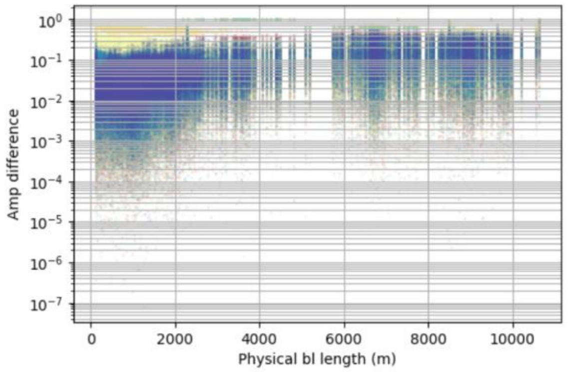
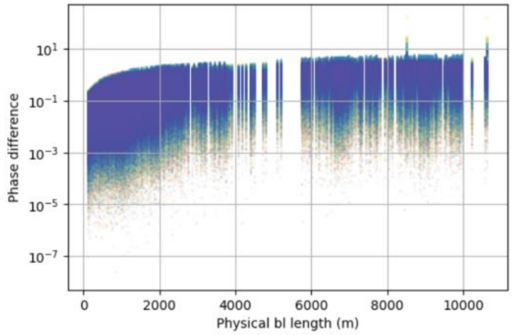
Variance/error transfer plots

What	Variance	Amp	Phase
TEC - DI gain bright source			
TEC - full gain bright source			

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