HI stacking with MeerKLASS

Challenges, Results and Prospects for SKAO x Euclid

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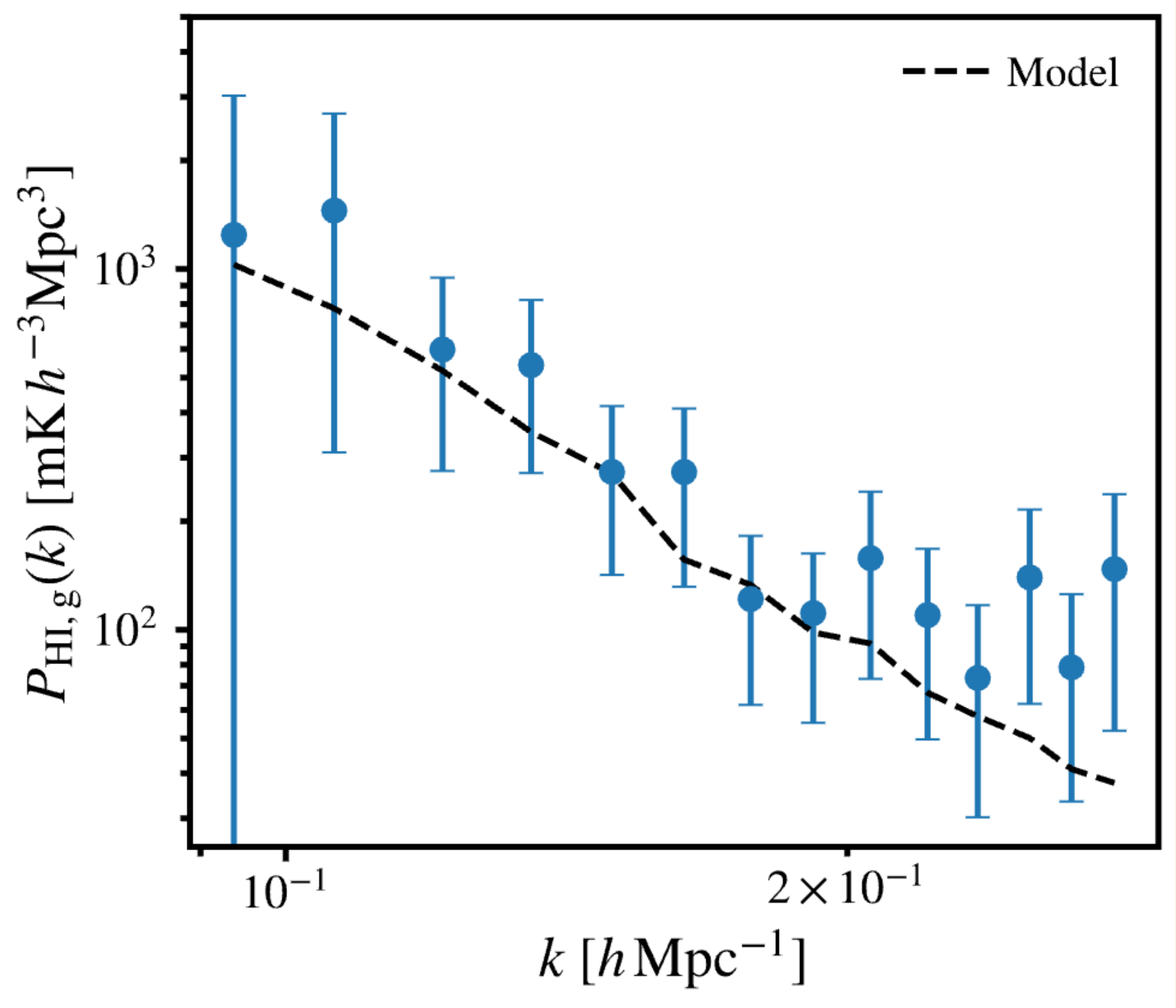
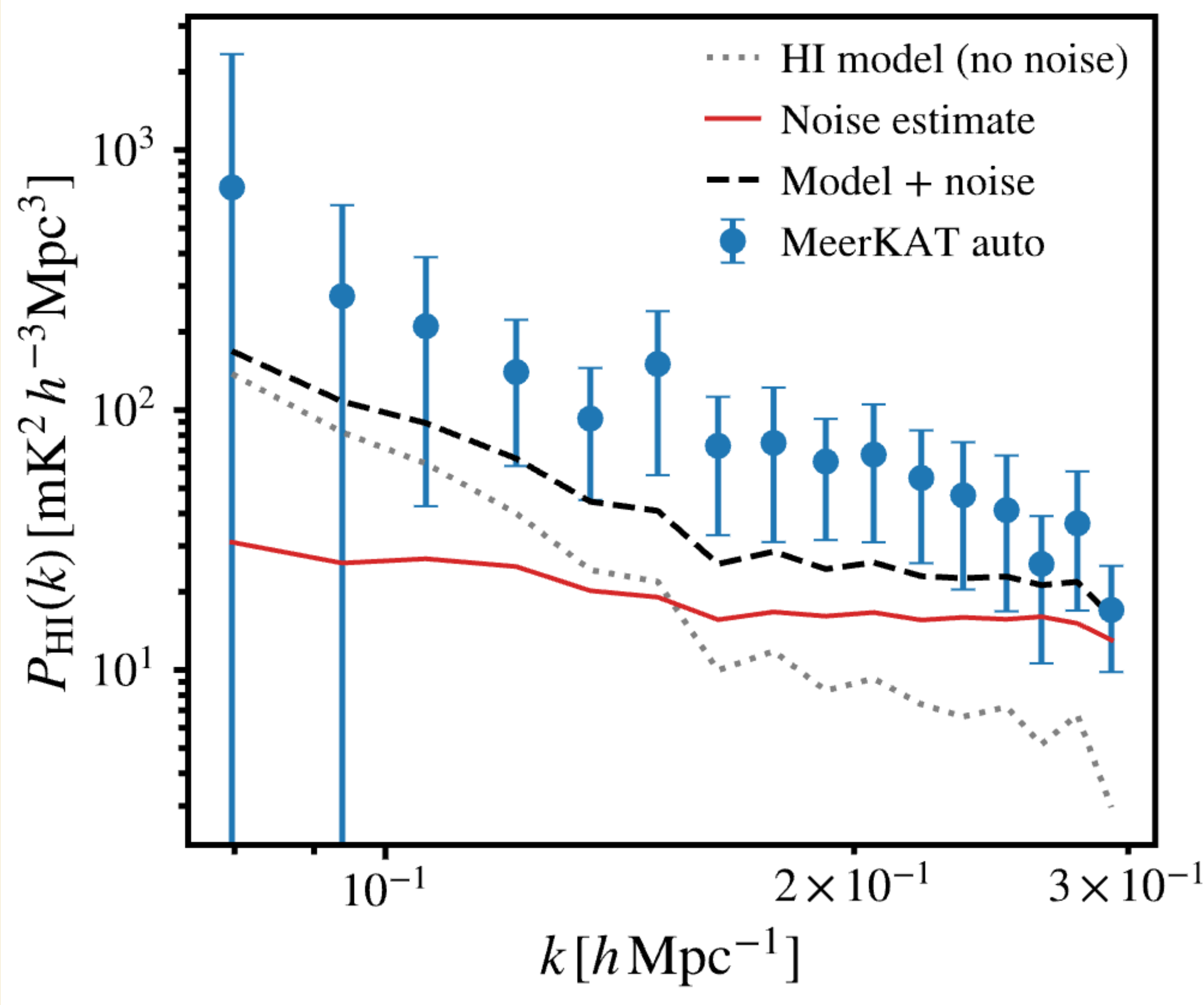
07/11/2024

The MeerKLASS L-band deep-field survey

The MeerKLASS collbartion, 2407.21626

- The deepest single-dish HI intensity mapping survey
- Measurements of cross-correlation power spectrum with GAMA spectroscopic galaxies
- Getting closer to signal-dominated regime
- Auto-correlation detection around the corner

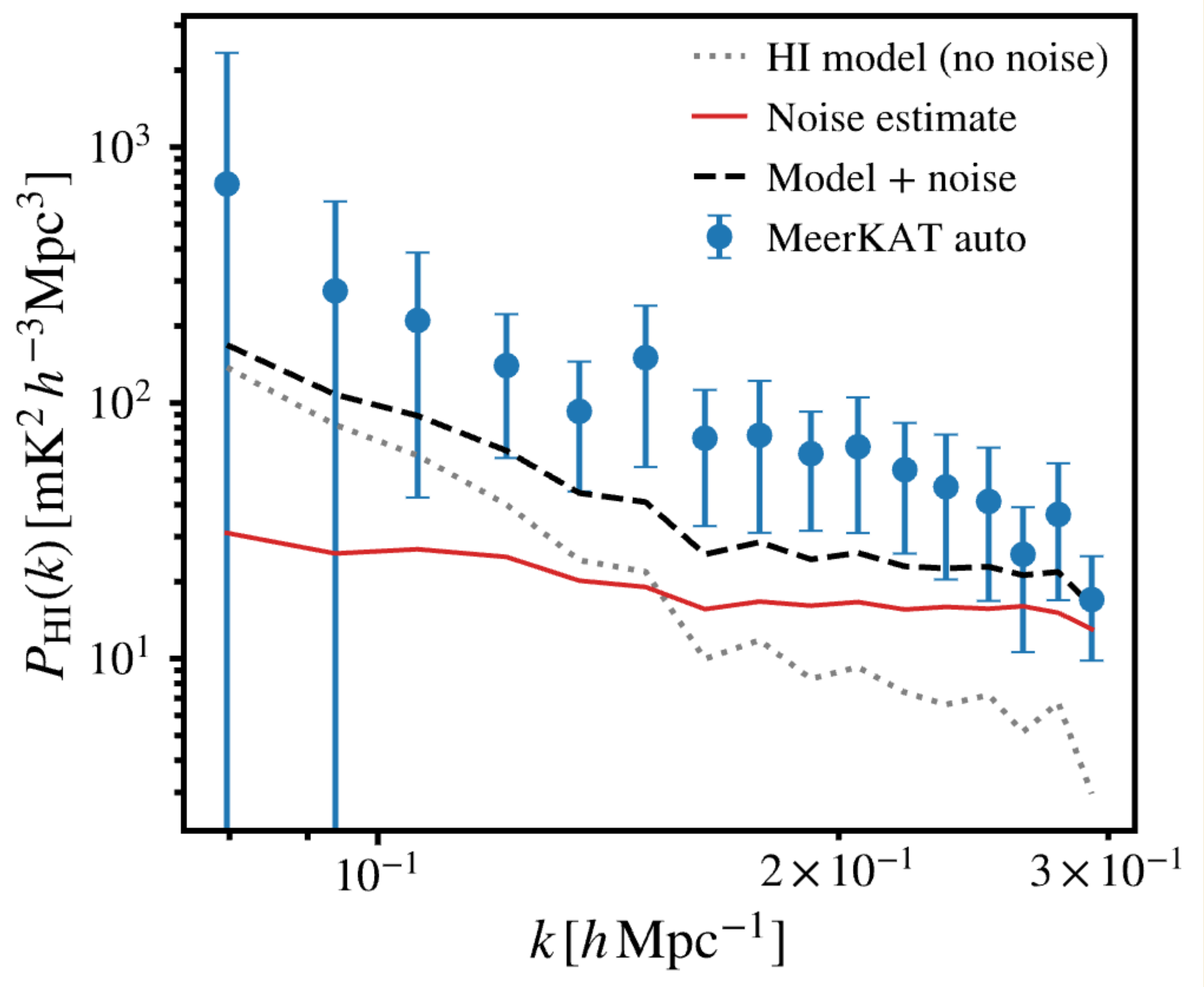




The final push

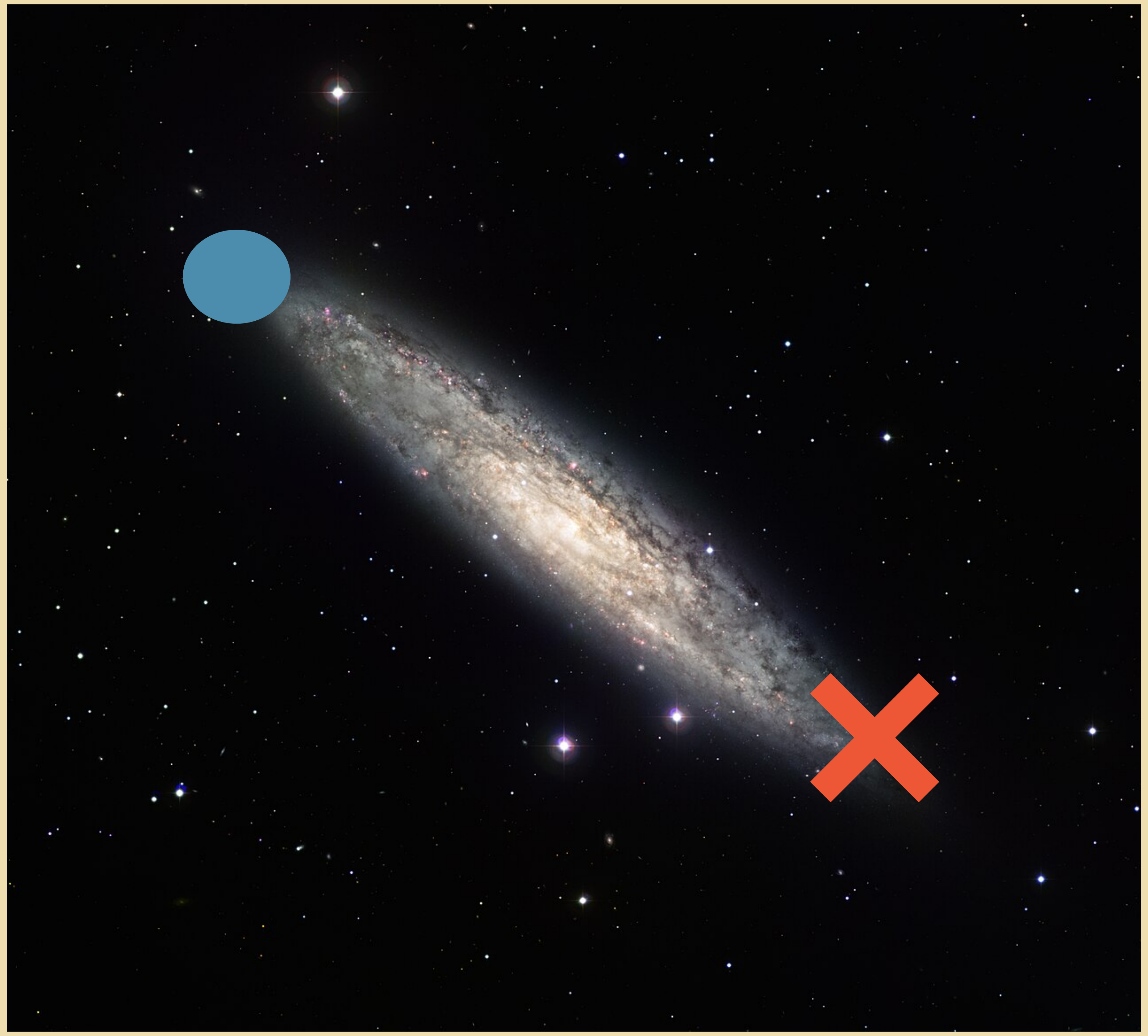
- Various data analysis techniques are being used to bring the data down to the model line.
- Nevertheless, we need alternative summary statistics that:
- Can be used as diagnostics to minimise systematics
- Can be used as complimentary probe to maximise scientific output

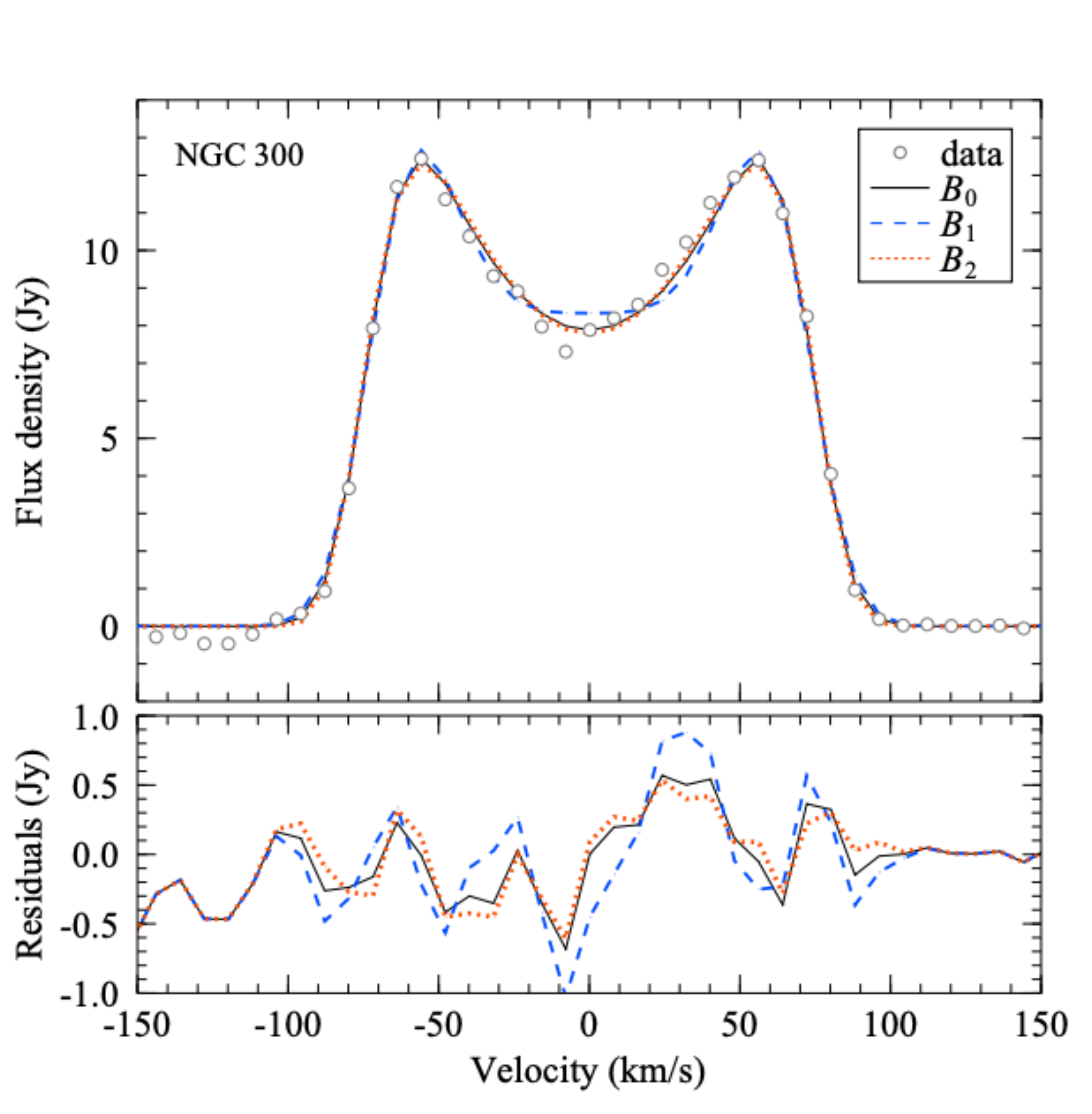
The MeerKLASS collaboration, 2407.21626



The emission line profile of HI galaxy

Westmeier et al., 1311.5308

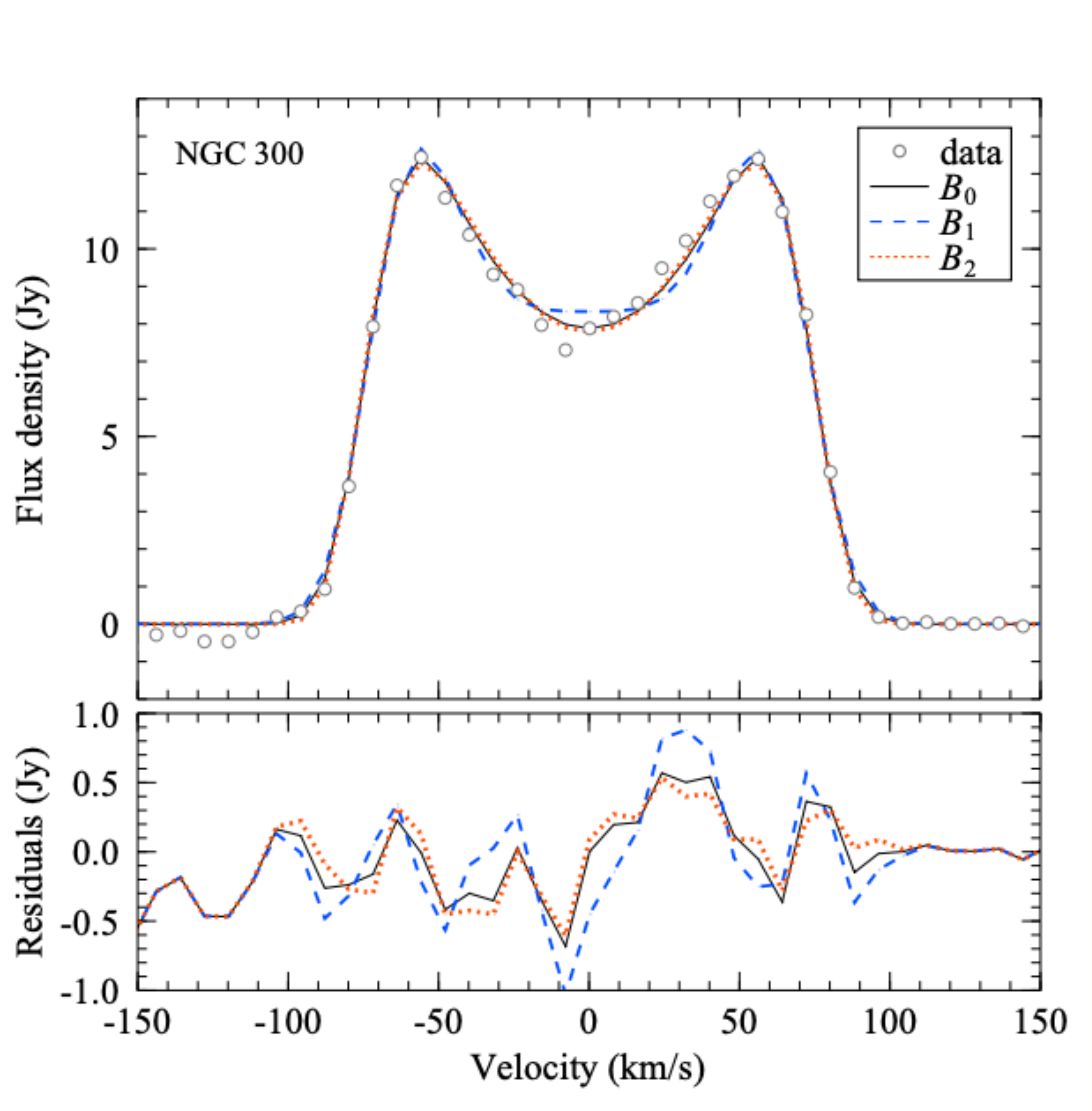




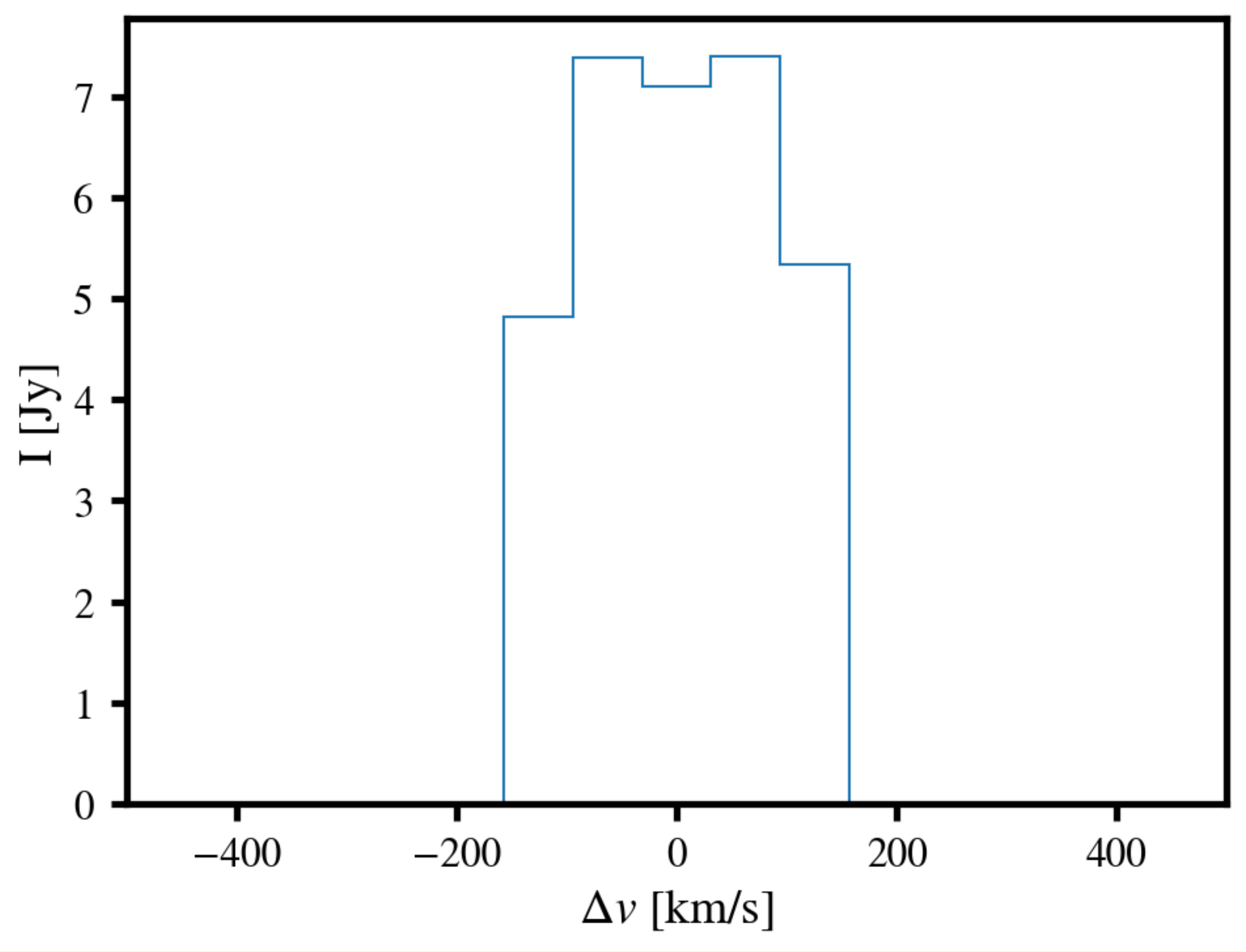
The emission line profile of HI galaxy

- In 4k mode, the MeerKAT L-band receiver has a velocity resolution of ~50km/s at z~0 (~65km/s at z~0.4).

Westmeier et al., 1311.5308



* Illustrative



An ideal stacking for single dish IM

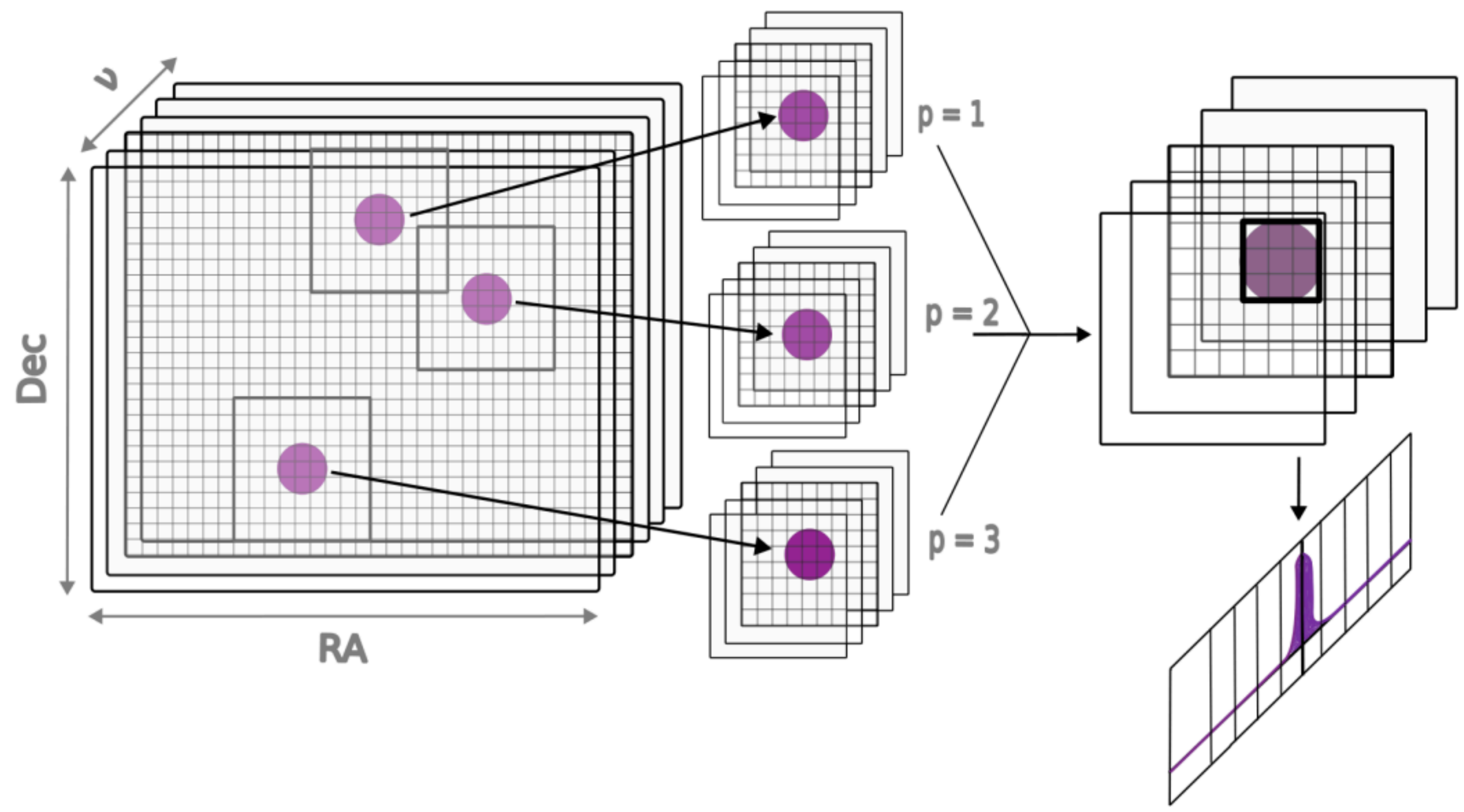
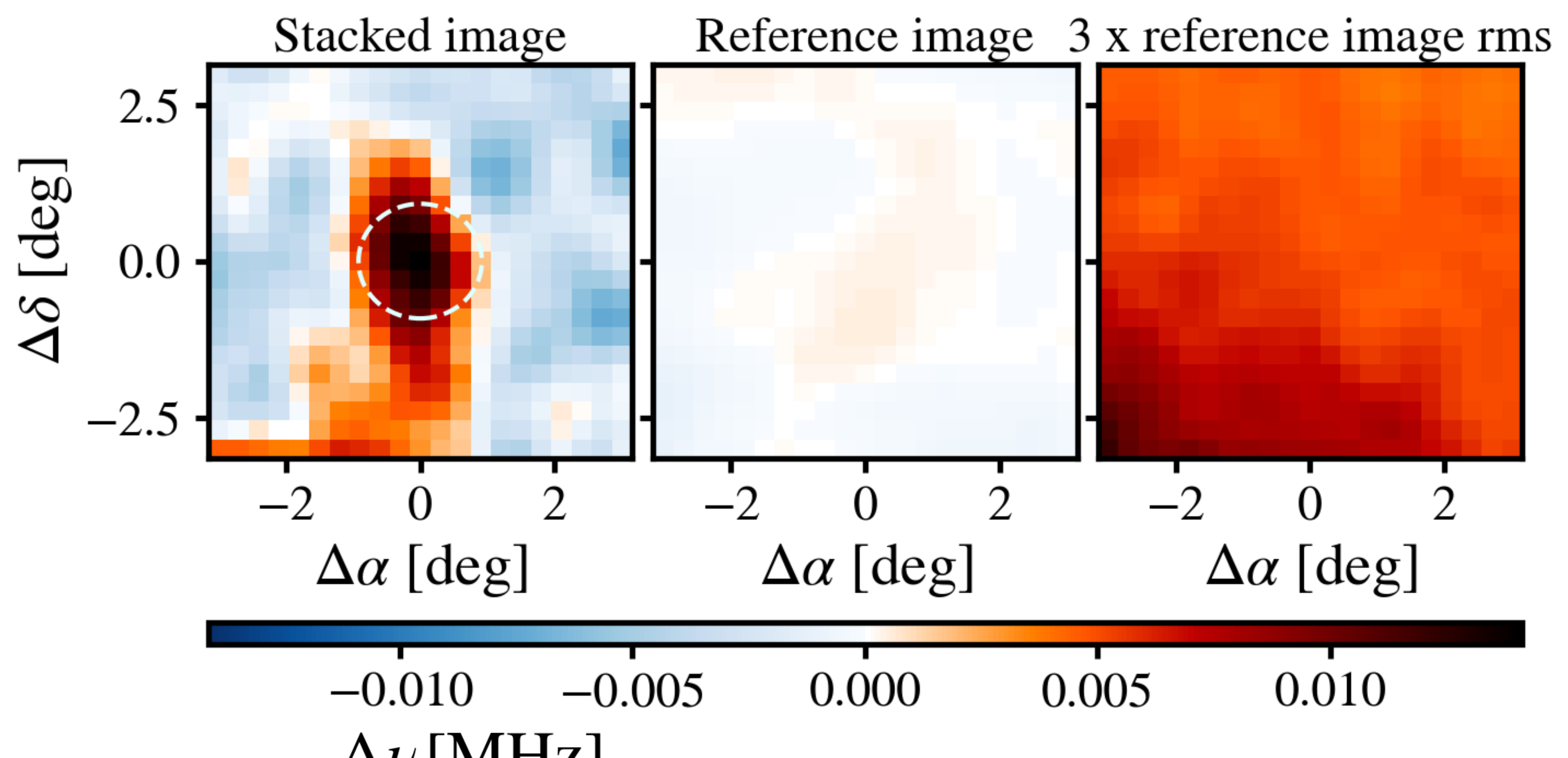


Figure 3. A diagram displaying the methodology used for this stacking analysis. From the full three-dimensional COMAP data cube (left), smaller 3-D cubelets are cut out centered on the position of each eBOSS object (center). These cubelets are then averaged into a single 3-D stack (top right), which is used to determine the average COMAP spectrum of the eBOSS objects (bottom right).

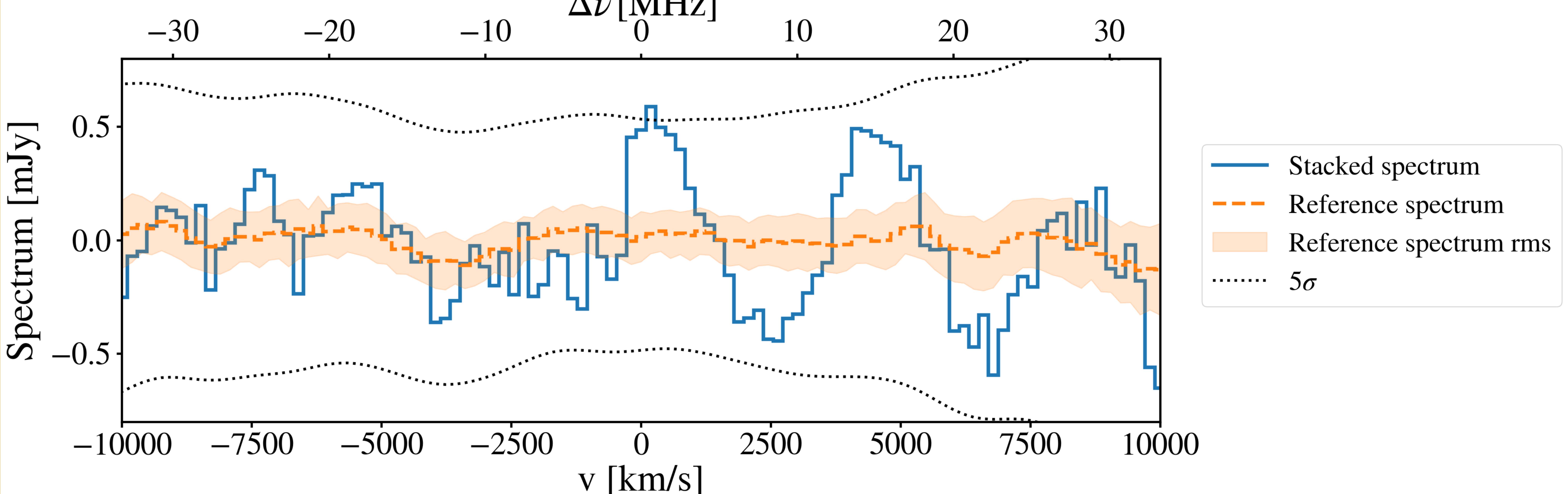
COMAP, 2304.09832

The reality

~ 8 sigma



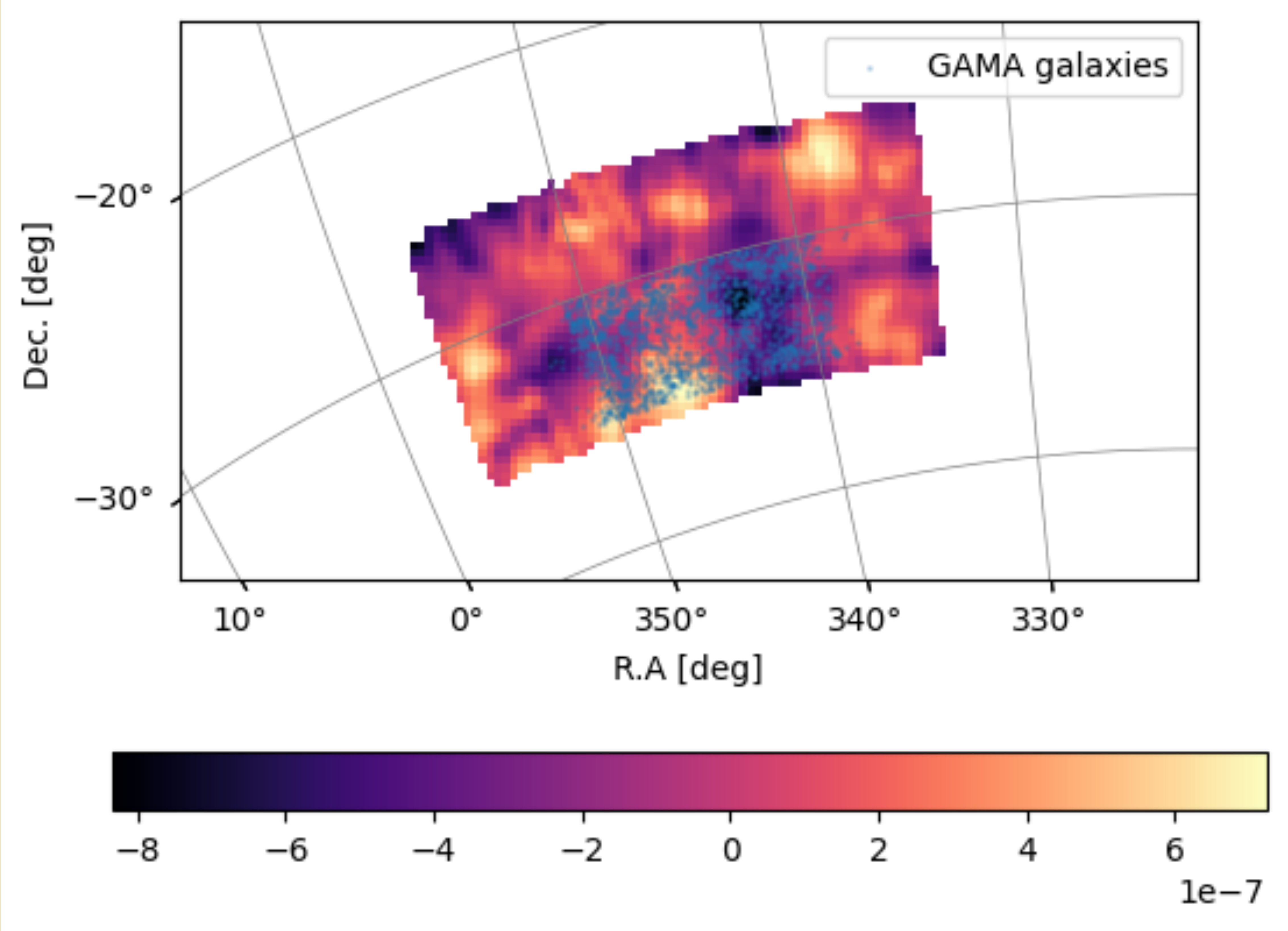
~ 6 sigma



The MeerKLASS collbartion,
2407.21626

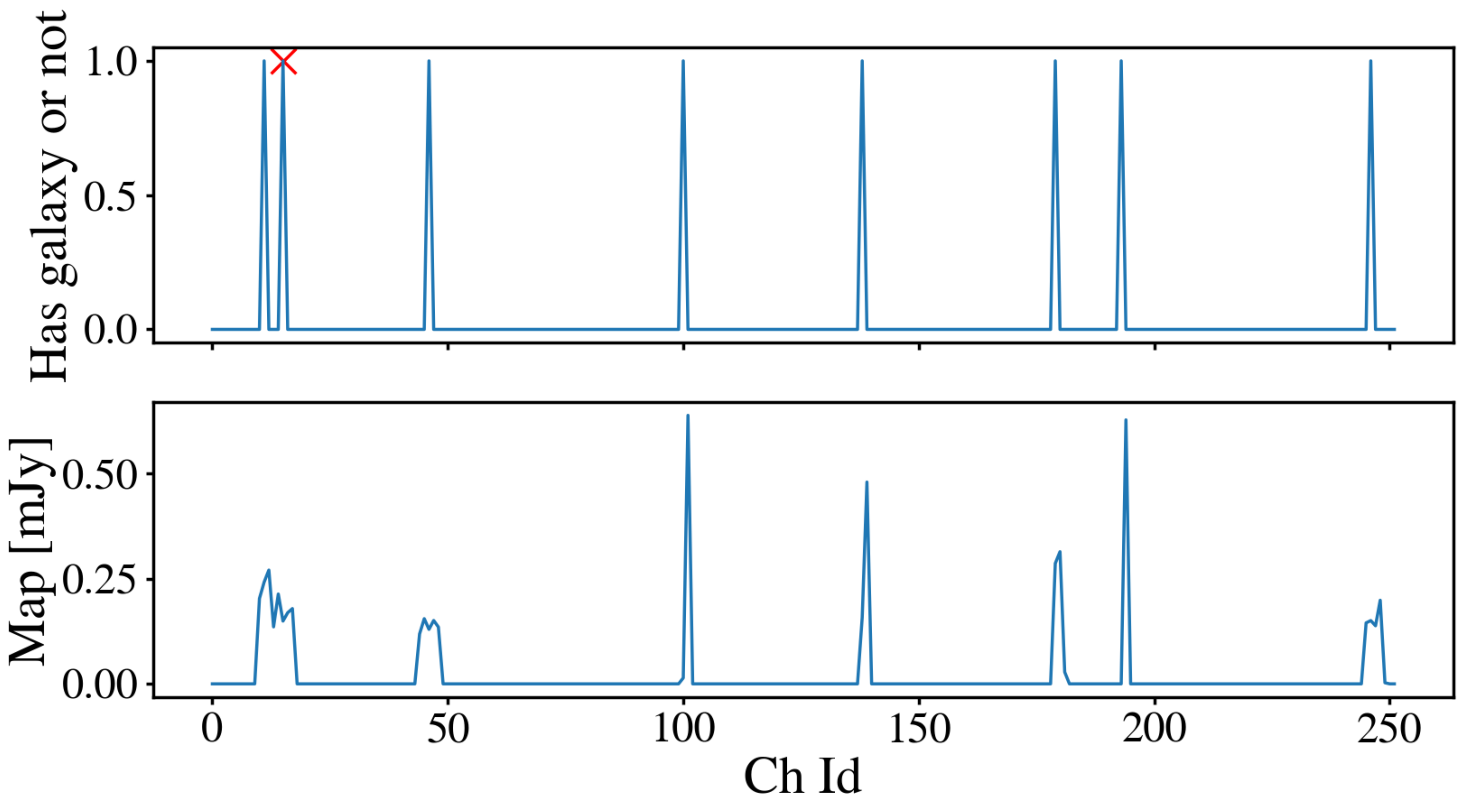
Problem 1: Too many galaxies, too few pixels

- In our data (L-band deep-field x GAMA galaxies), the area covered is only ~60 sqdeg with 2269 galaxies, resulting in ~40 galaxies per sqdeg. The MeerKAT beam is ~1 deg and our scanning strategy produces maps with 0.3 deg size pixel.



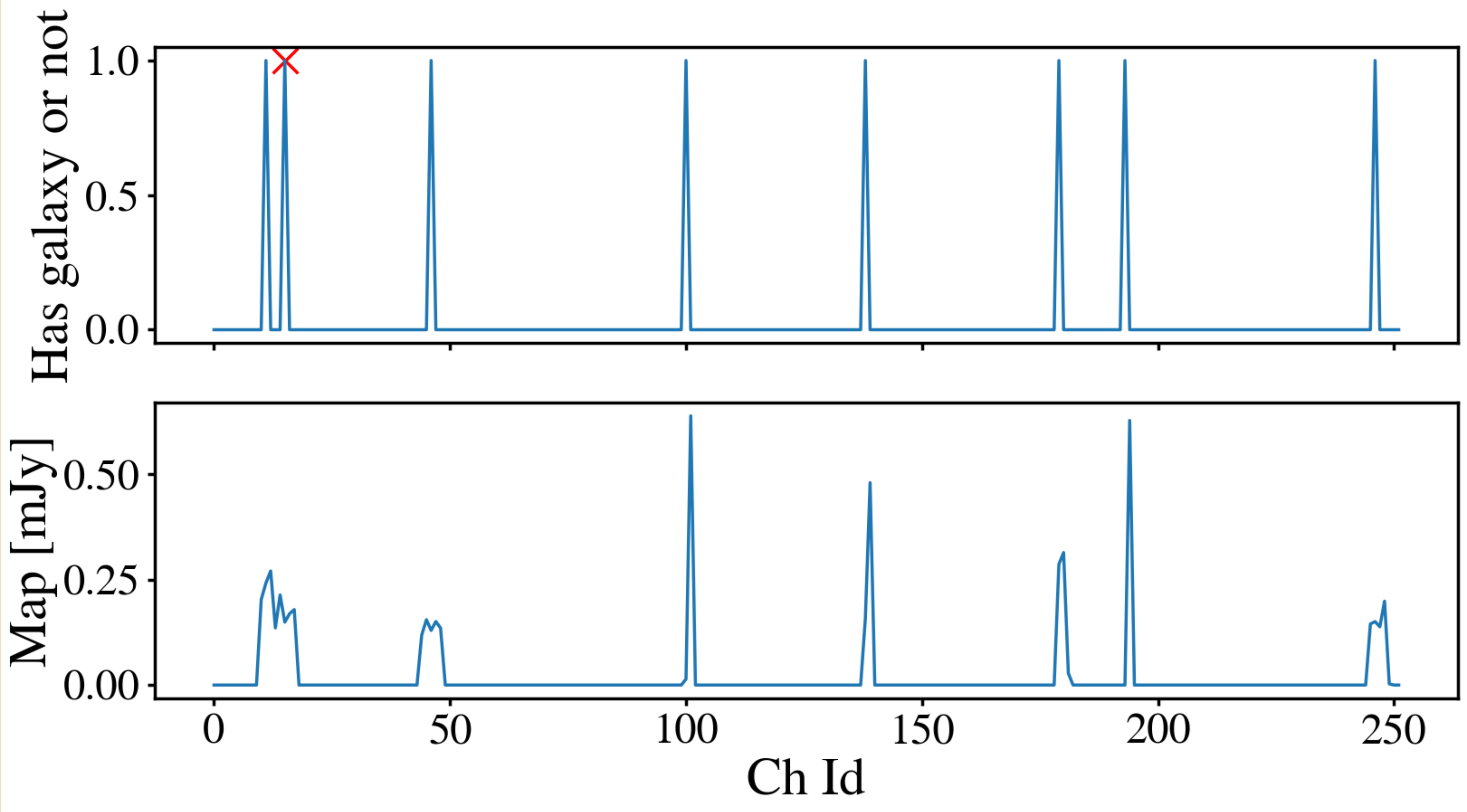
Problem 1: Too many galaxies, too few pixels

- Even without considering the beam, along the line-of-sight of a map pixel there are multiple galaxies.

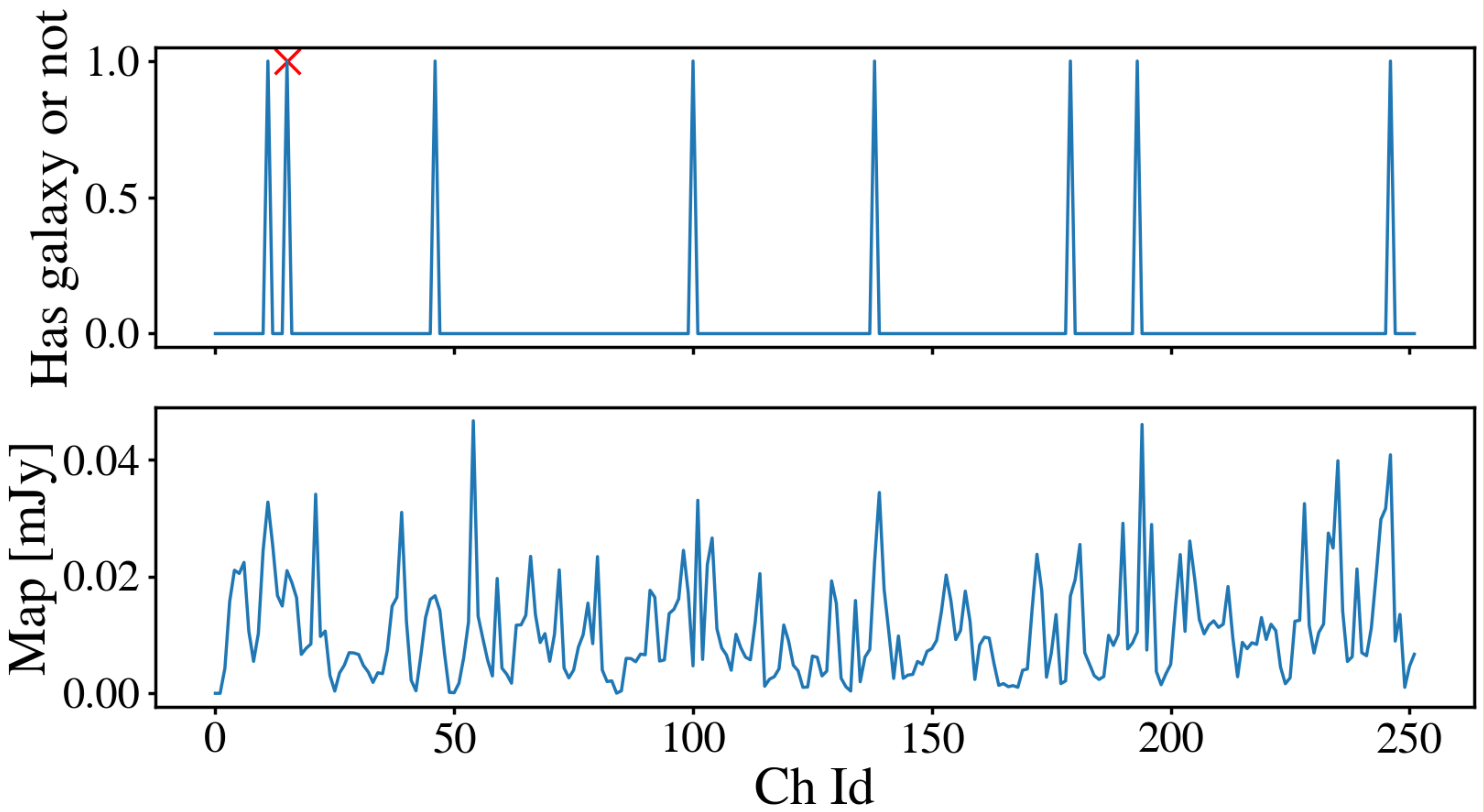


Problem 2: Scattering by the beam

- Including the 1deg beam then further creates double counting in angular space:



With Beam



Problem 2: Scattering by the beam

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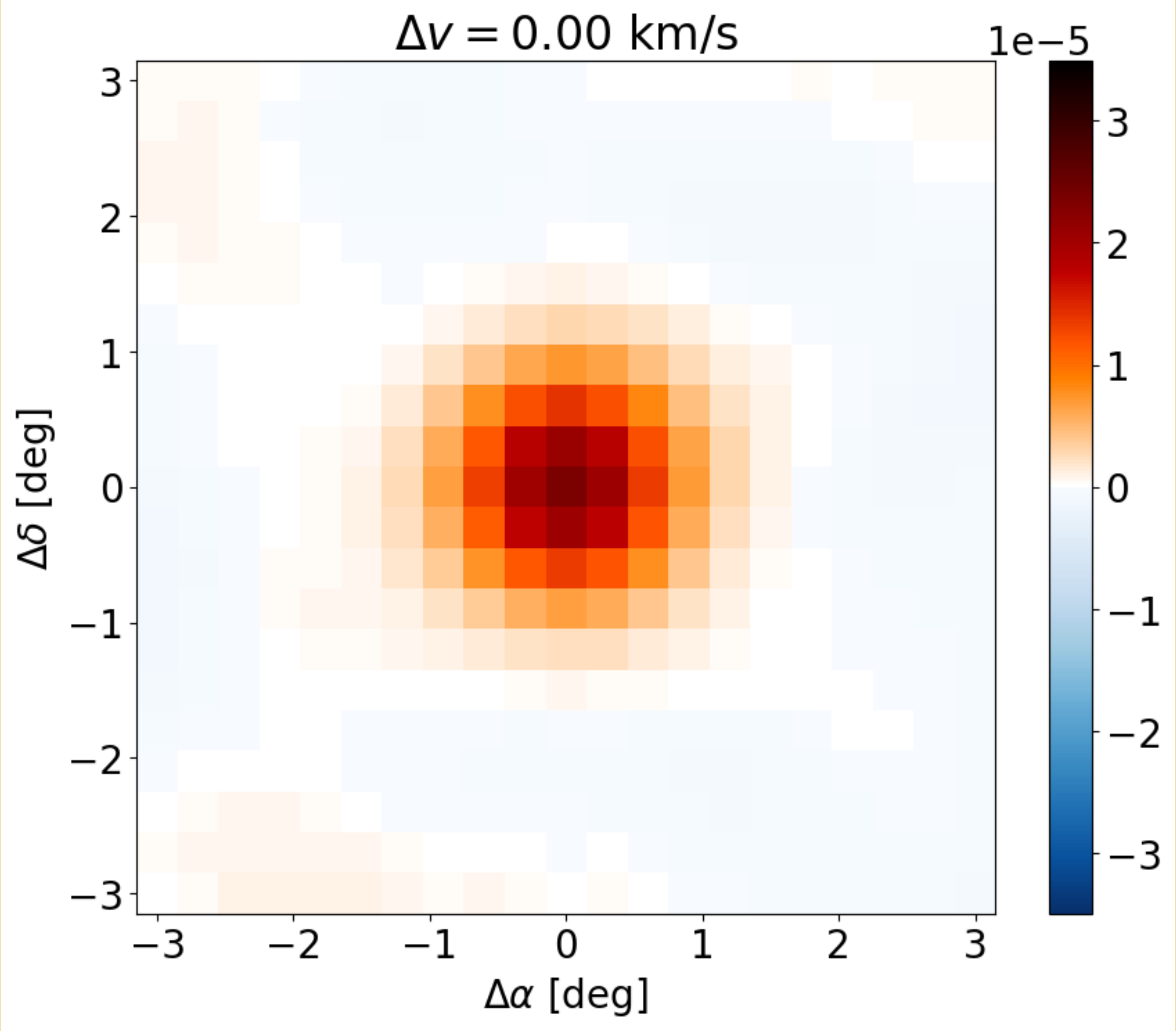
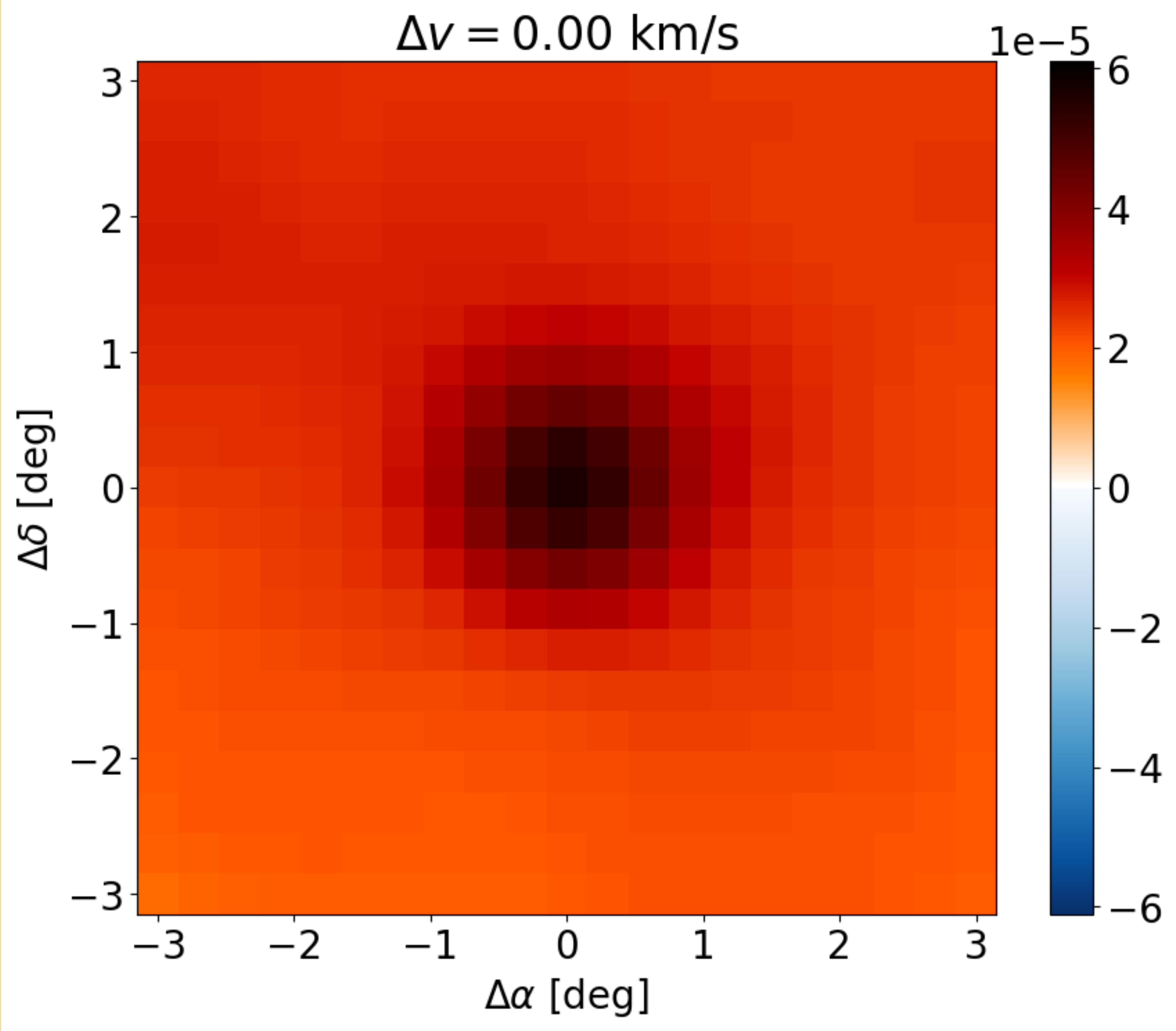
Ideal



With double counting



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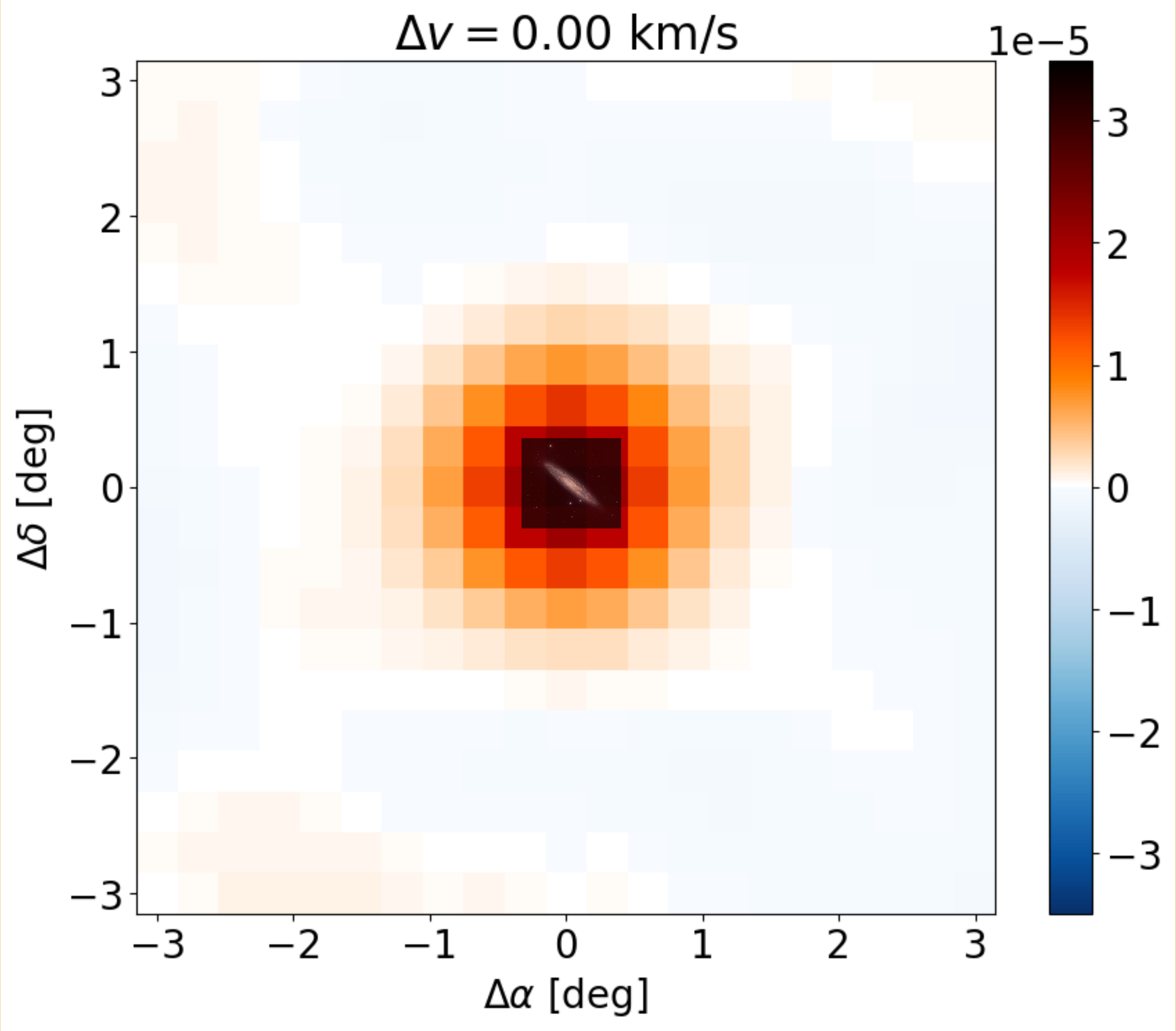
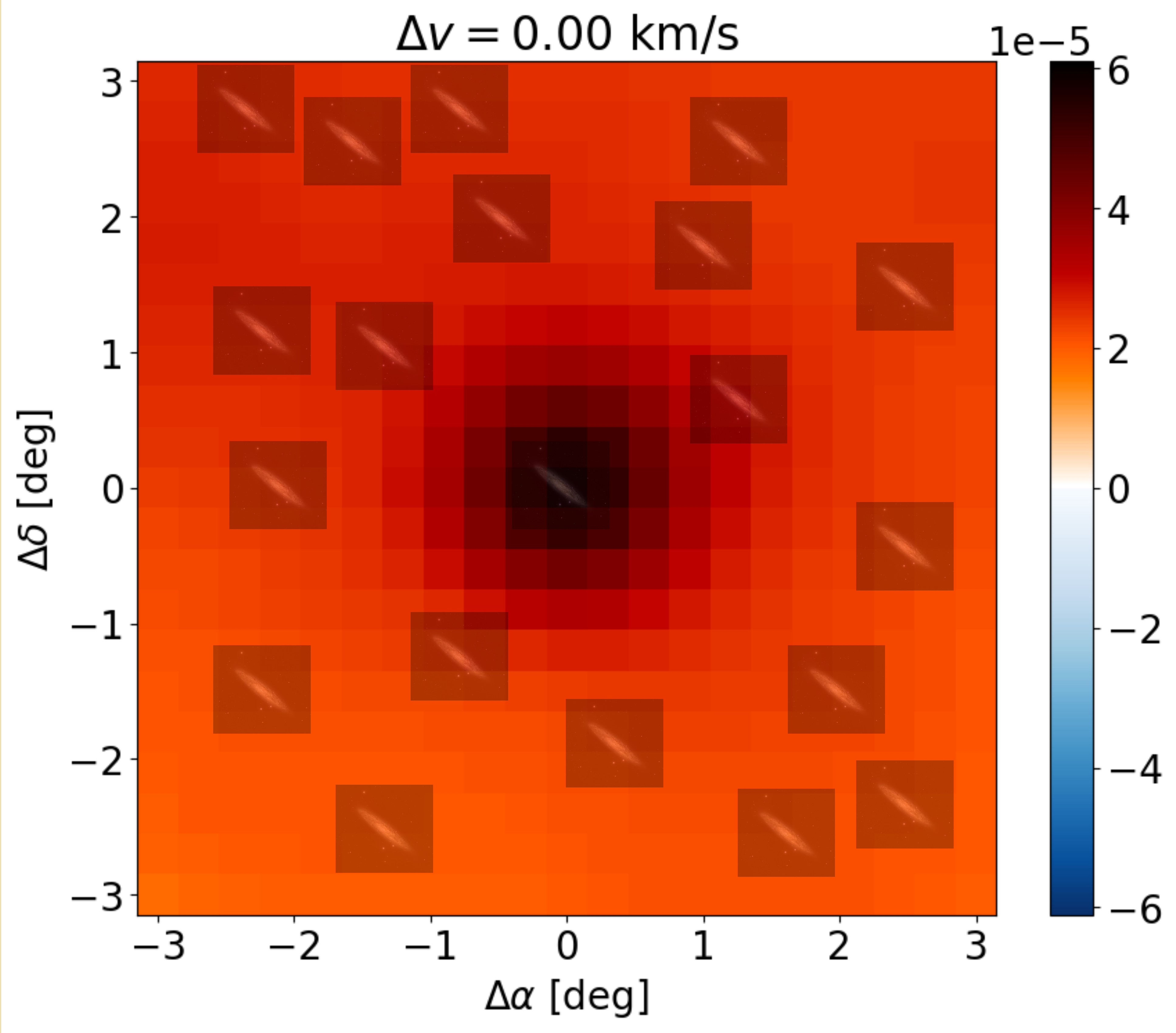
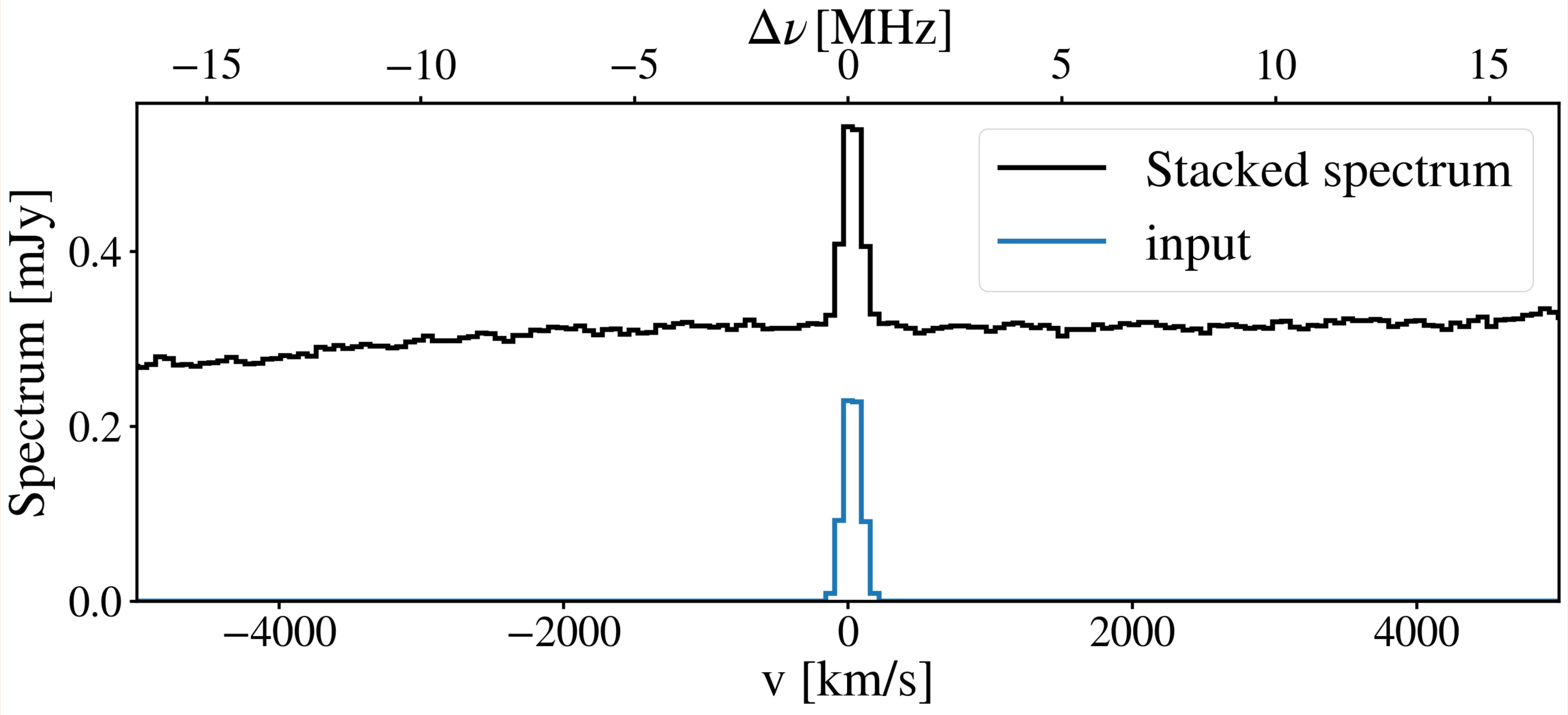


With double counting



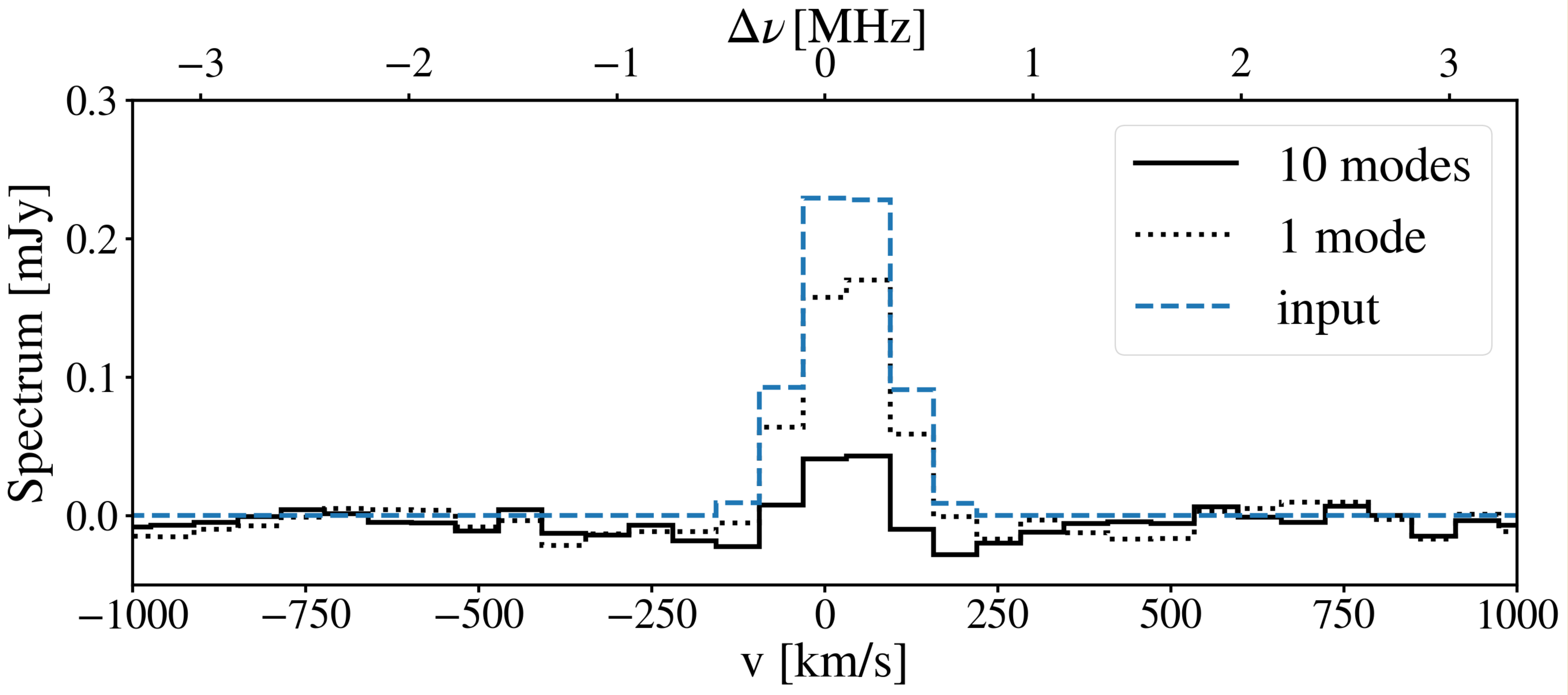
Problem 2: Scattering by the beam

- The double-counting of galaxies effectively creates a plateau:



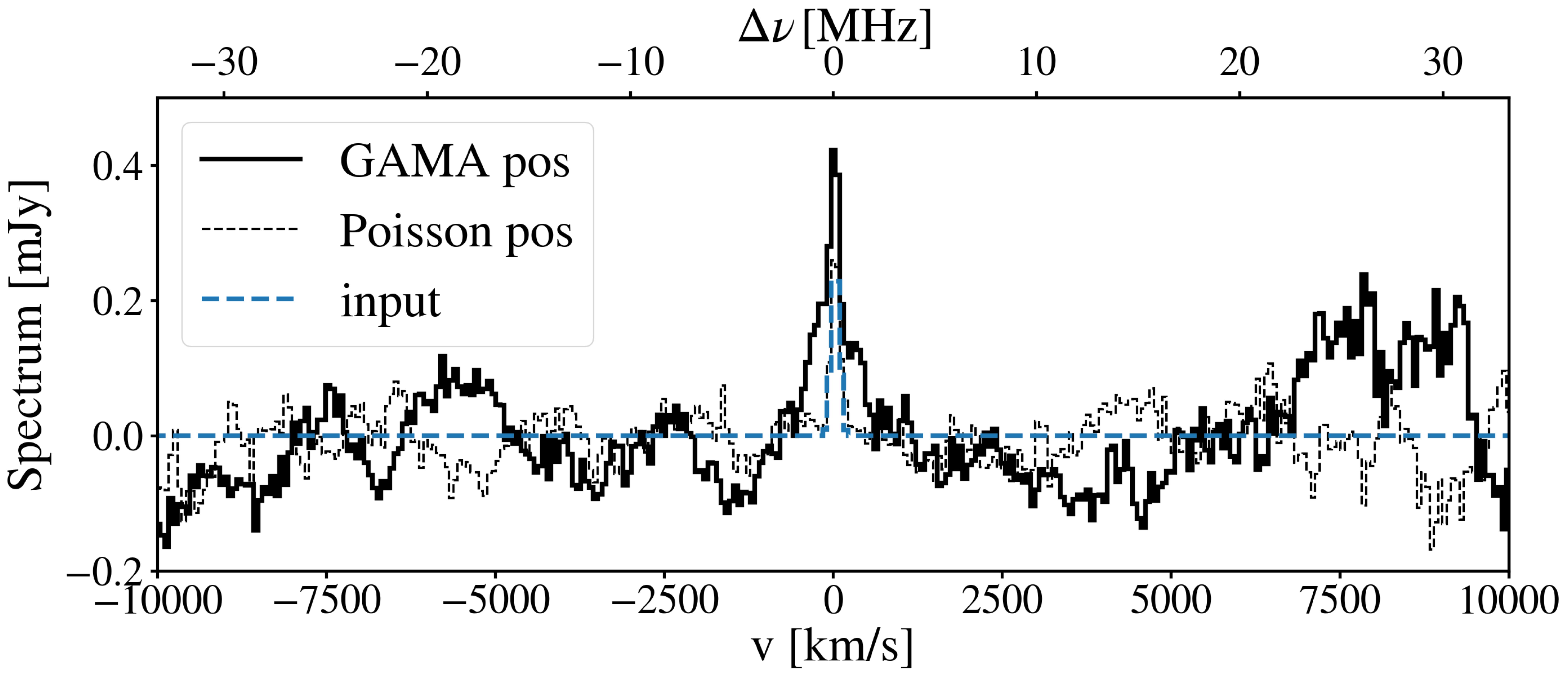
Solution: good ol' PCA

- PCA removes the plateau at the expenses of signal loss and effects from residual systematics



Problem 3: Clustering amplification of signal

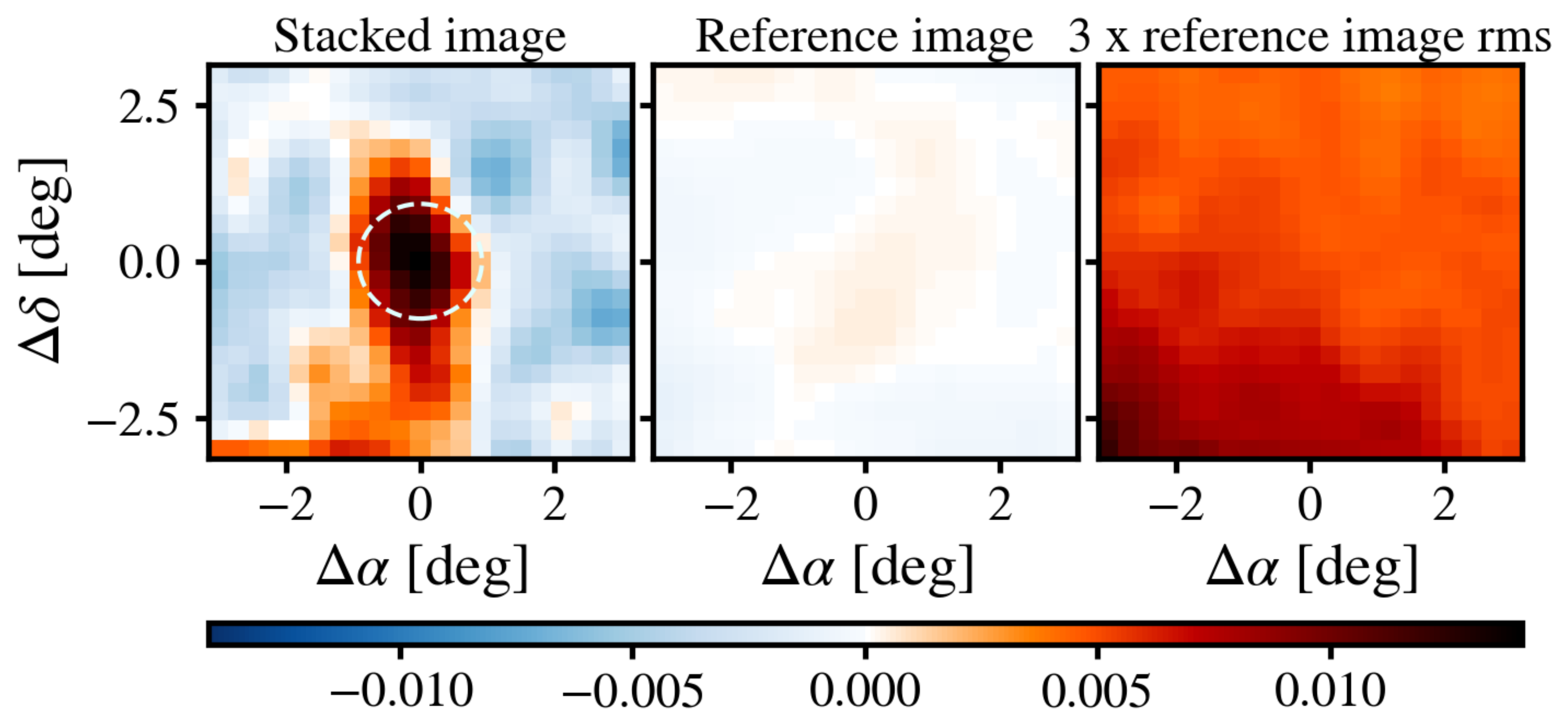
- Including the ~1deg beam corresponds to ~15Mpc scale. The stacked signal includes a clustering component.
- Requires forward modelling of the signal.

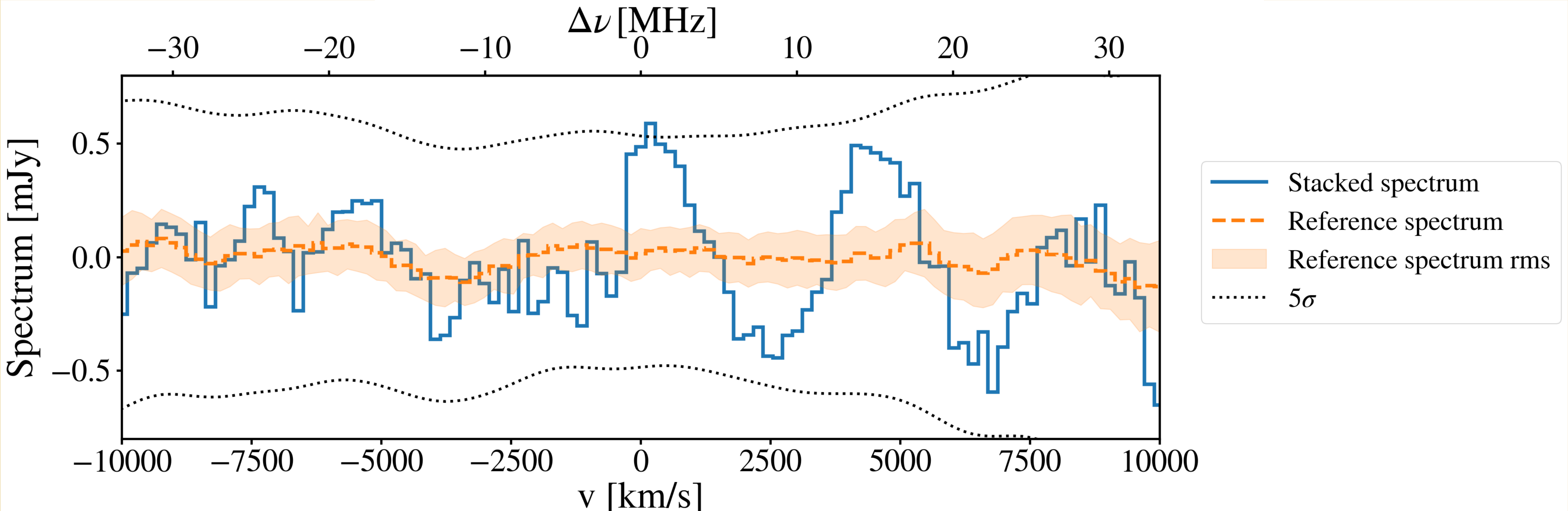


Problem 4: real map has residual systematics

~ 8 sigma

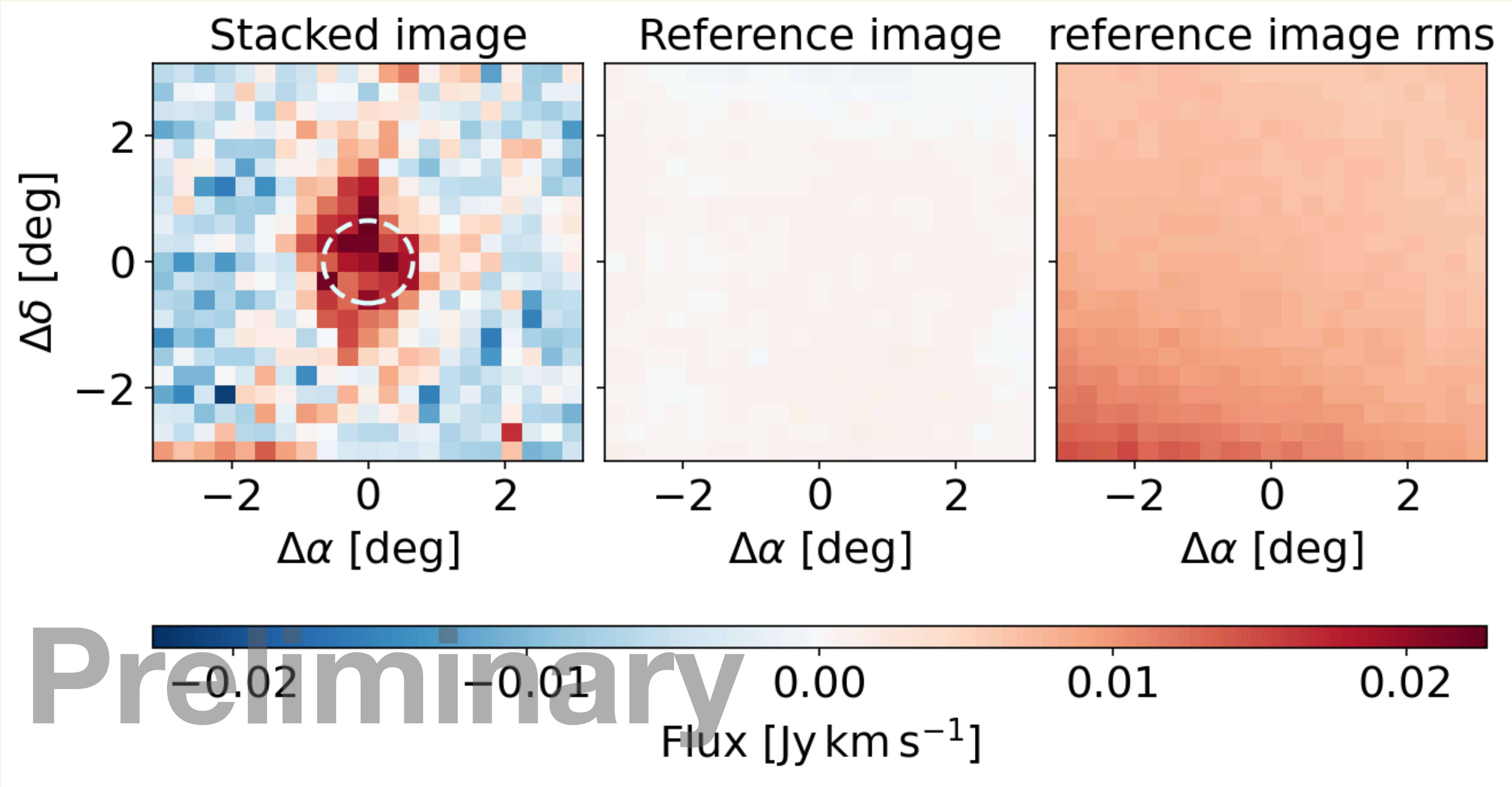
~ 6 sigma



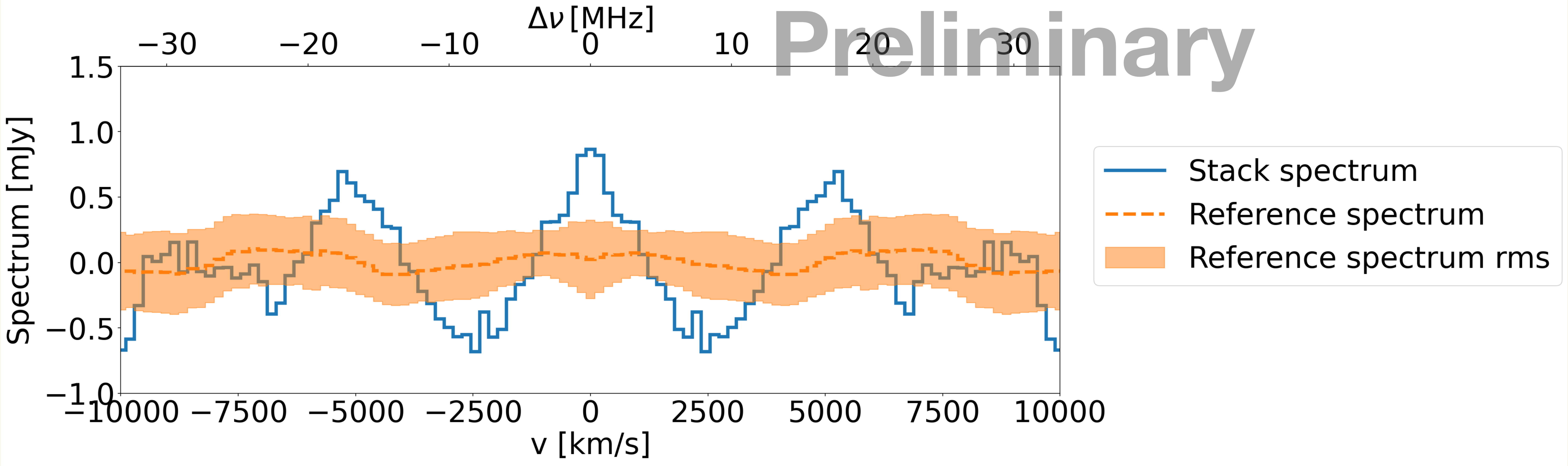


The MeerKLASS collbartion,
2407.21626

Problem 4: real map has residual systematics



Z. Chen,
The MeerKLASS collbartion, in prep

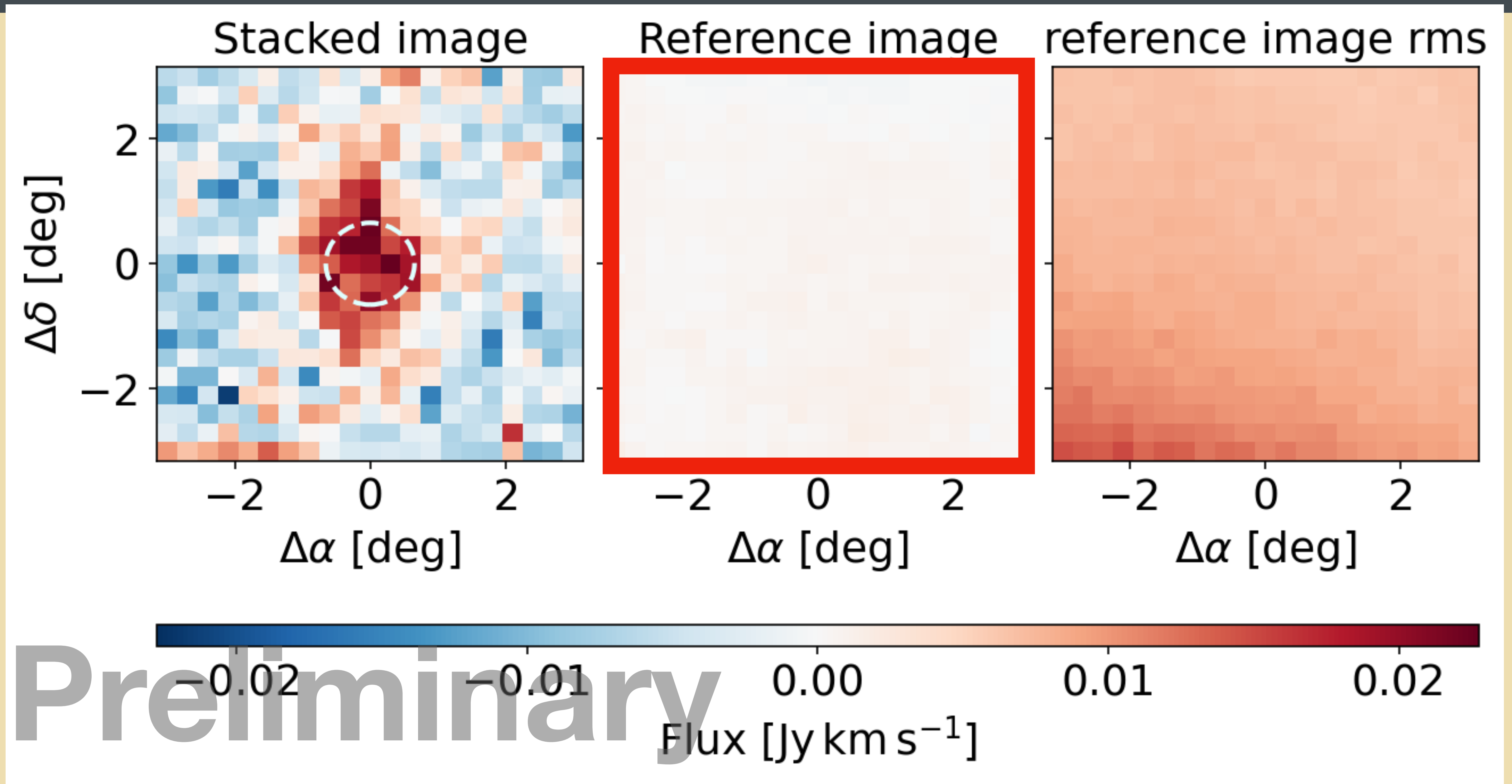


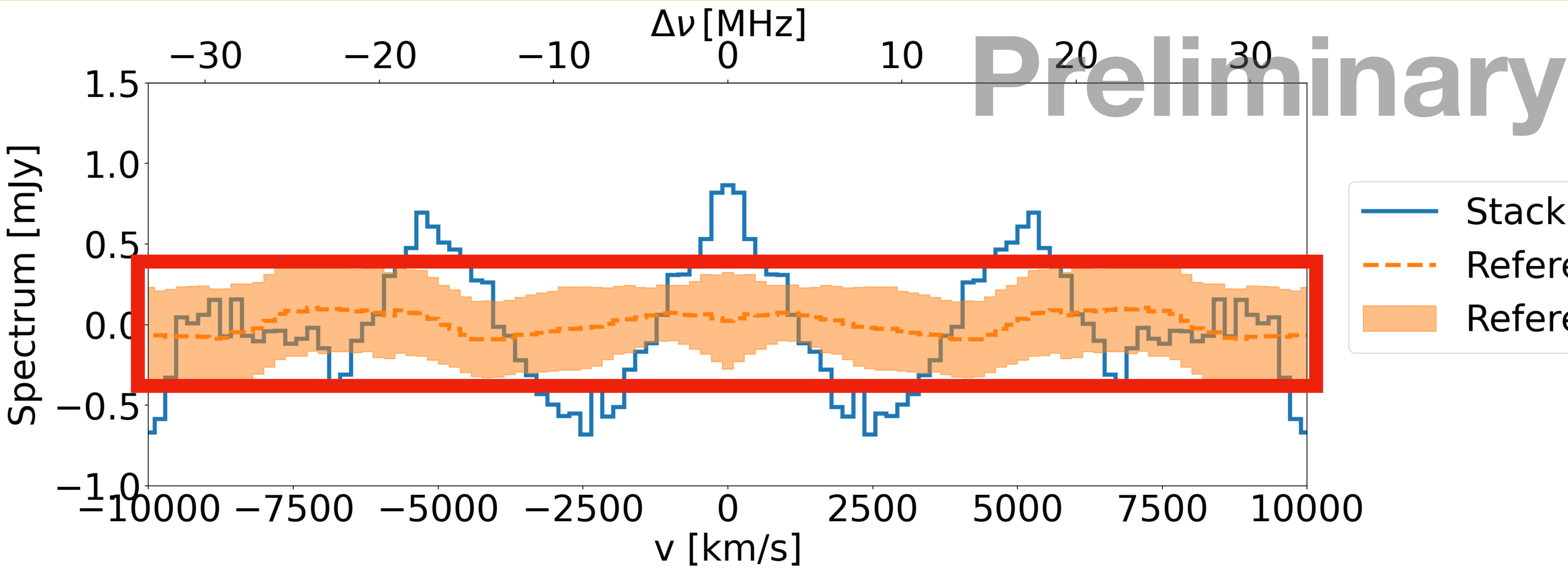
Understanding the systematics

	21cm IM	GC/WL
Additive Systematics	RFI, residual foregrounds …	Interloper …
Multiplicative systematics	Calibration errors …	Source confusion …
Convolutional systematics	Beam chromaticity …	PSF …

Hunting down the source of systematics

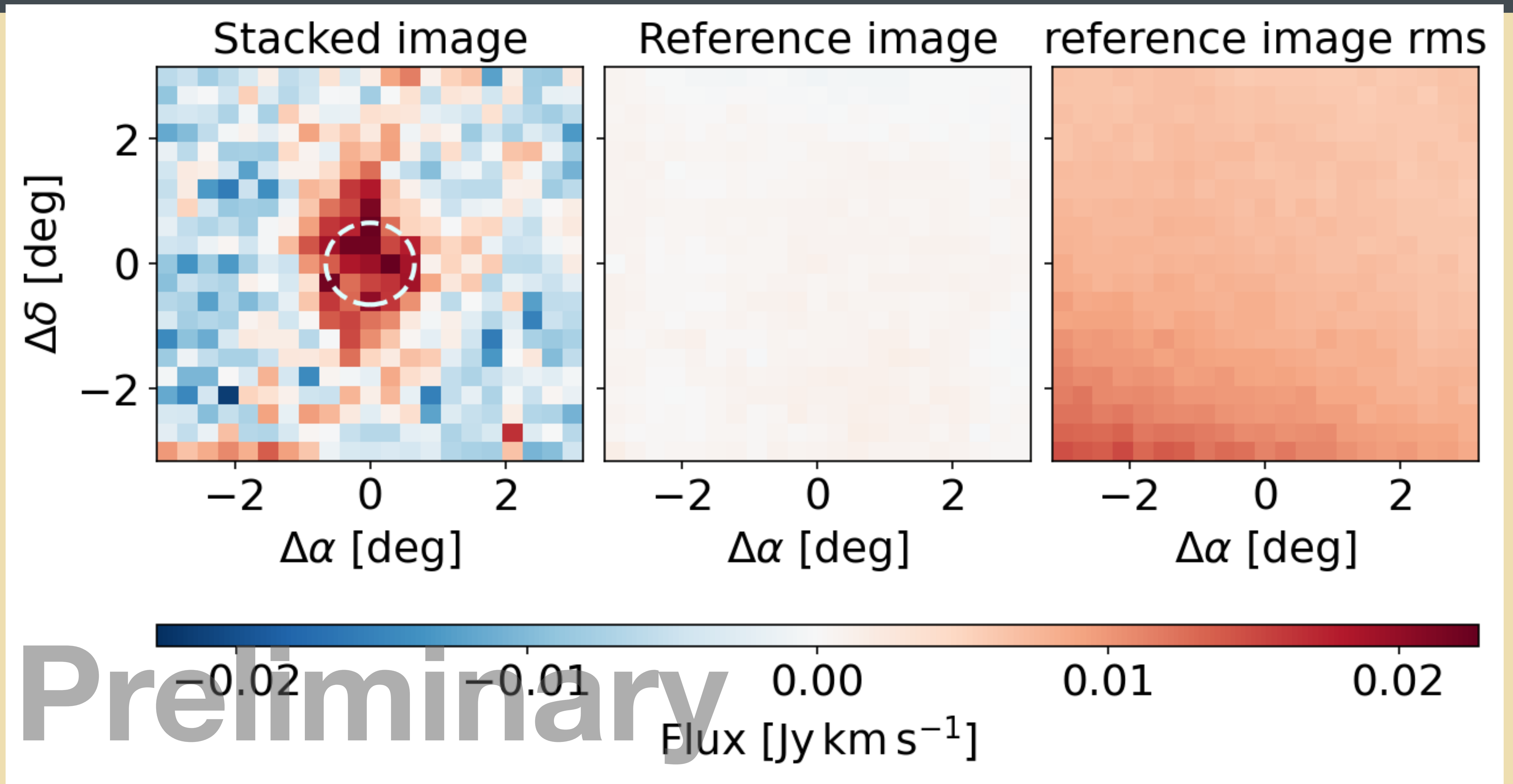
- The reference image and spectrum are calculated by randomly shuffling galaxy positions
- Consistent with zero
- The contamination is not an additional component of the map, but distortion of the HI signal.

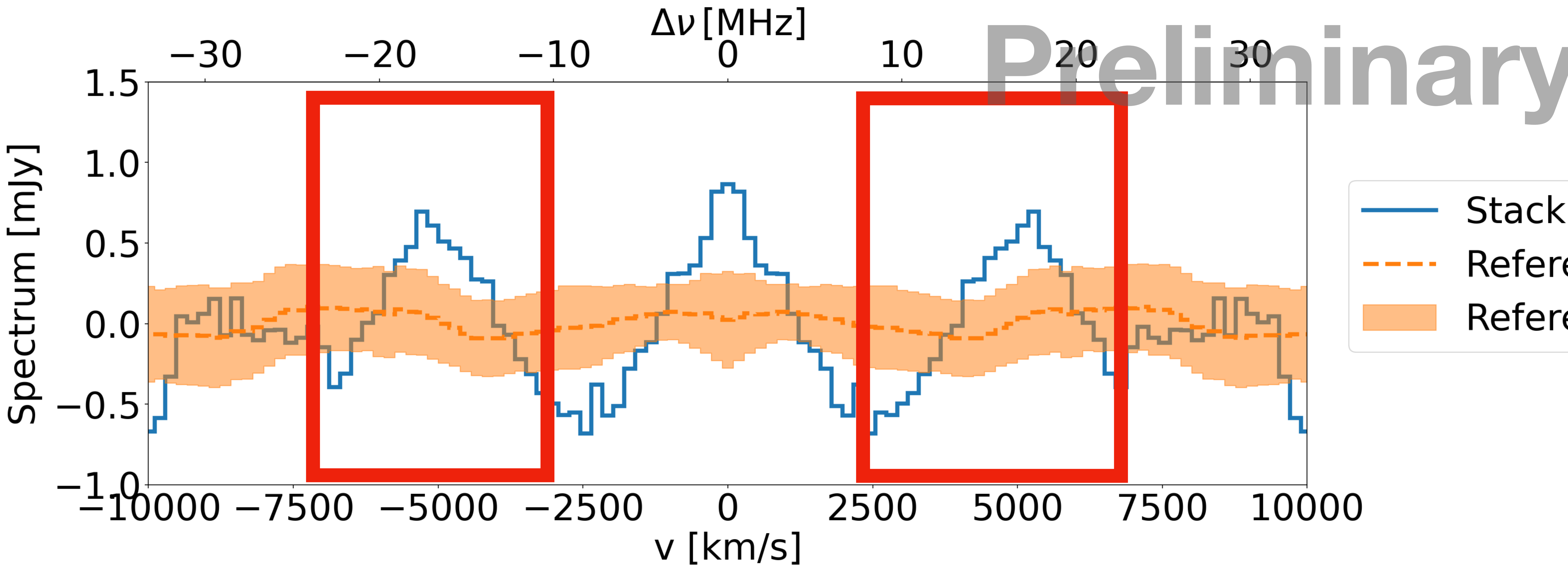




Hunting down the source of systematics

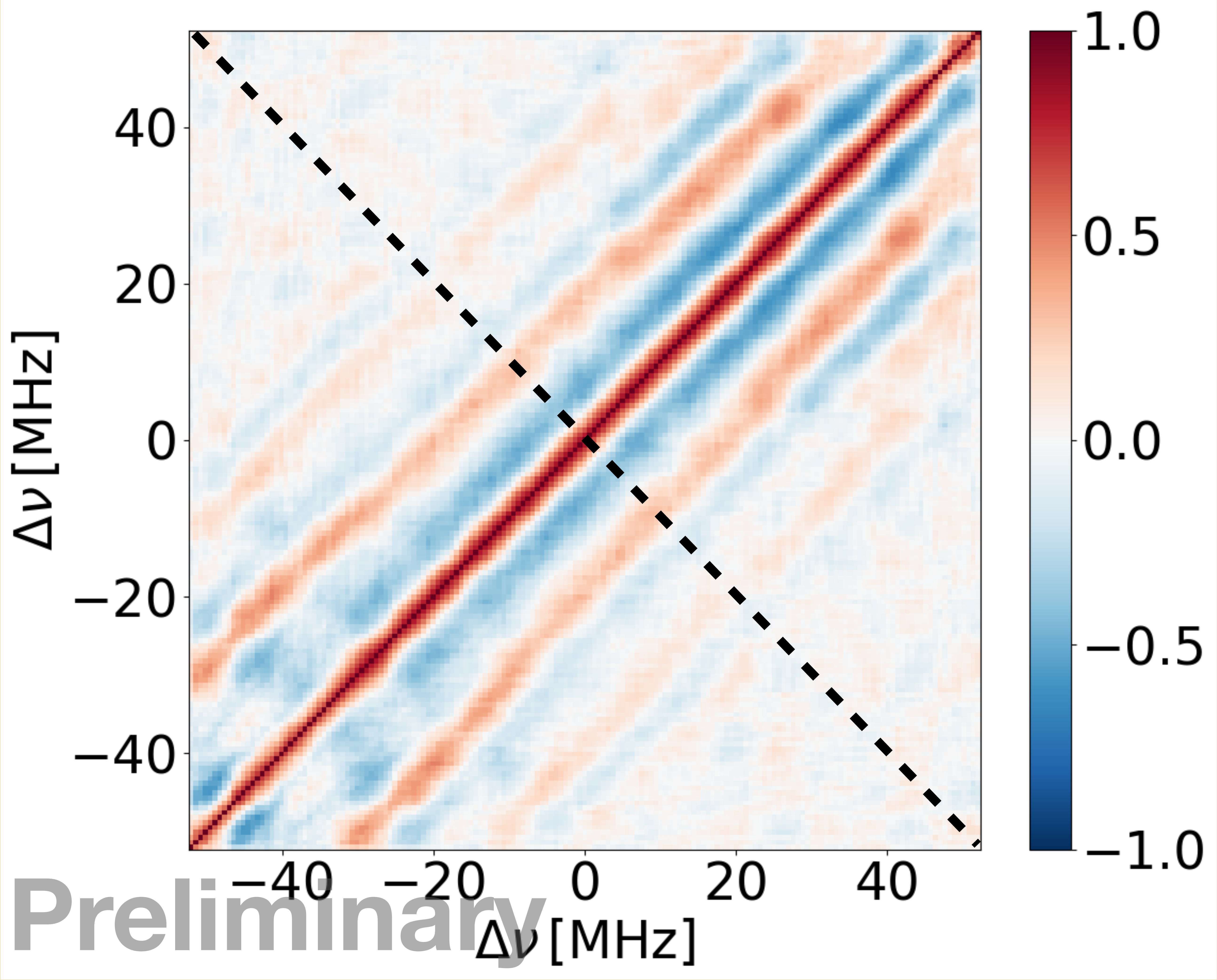
- There is an oscillating structure in frequency and no visible structure in angular space.
- Multiplicative or convolutional effects along the frequencies?





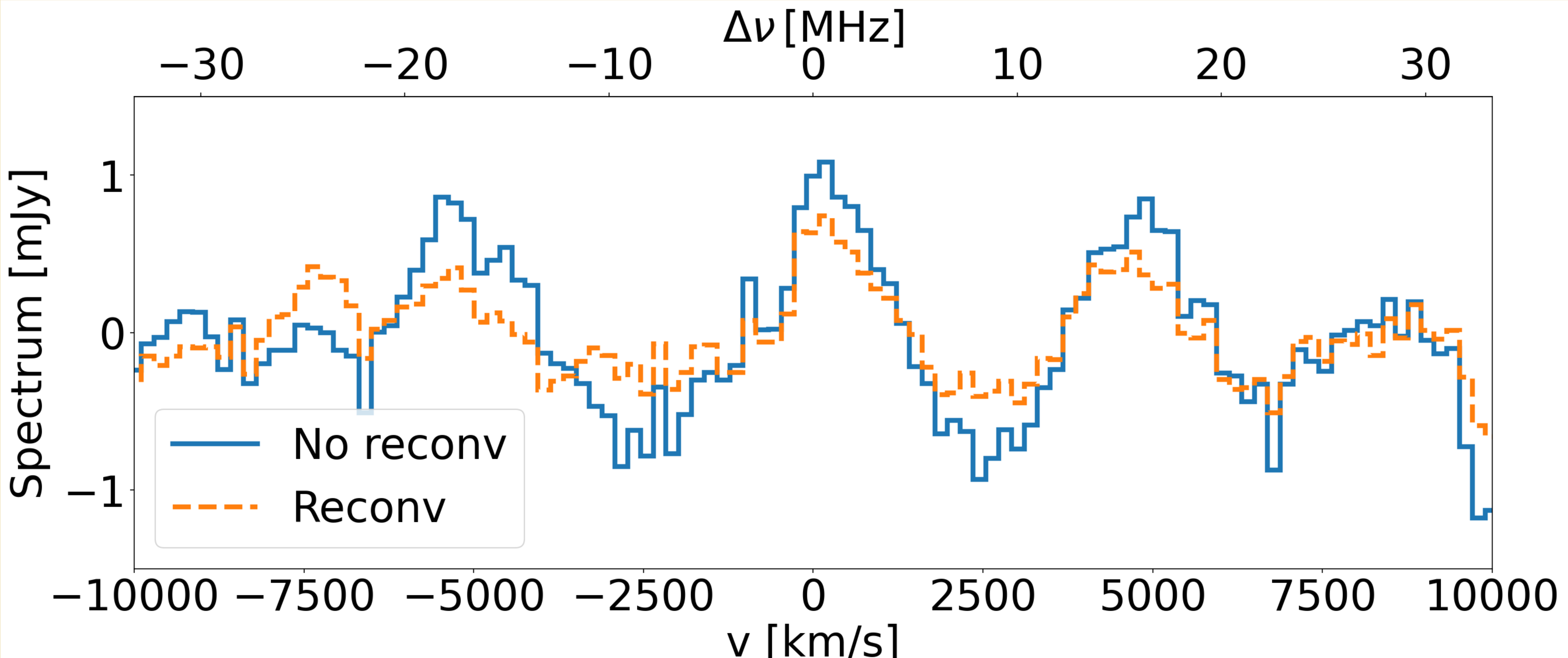
Hunting down the source of systematics

- Using the random shuffling, we can also calculate the covariance of the reference spectrum.
- The correlation matrix shows the oscillation as well
- Suggests that the systematic effect convolves with the signal



Hunting down the source of systematics

- In the L-band deep-field analysis, the maps at each frequency are reconvolved by a common Gaussian beam to a lower resolution.
- If the reconvolution is skipped, the oscillating structure is more visible and at a constant interval.
- The systematics is likely related to the chromaticity of the instrument



Hunting down the source of systematics

- The MeerKAT beam is known to have a rippling structure
- The period of the ripples is ~20MHz, matching the frequency scales of the systematics
- Known to cause effects in foreground cleaning for intensity mapping

Asad et al., 1904.07155

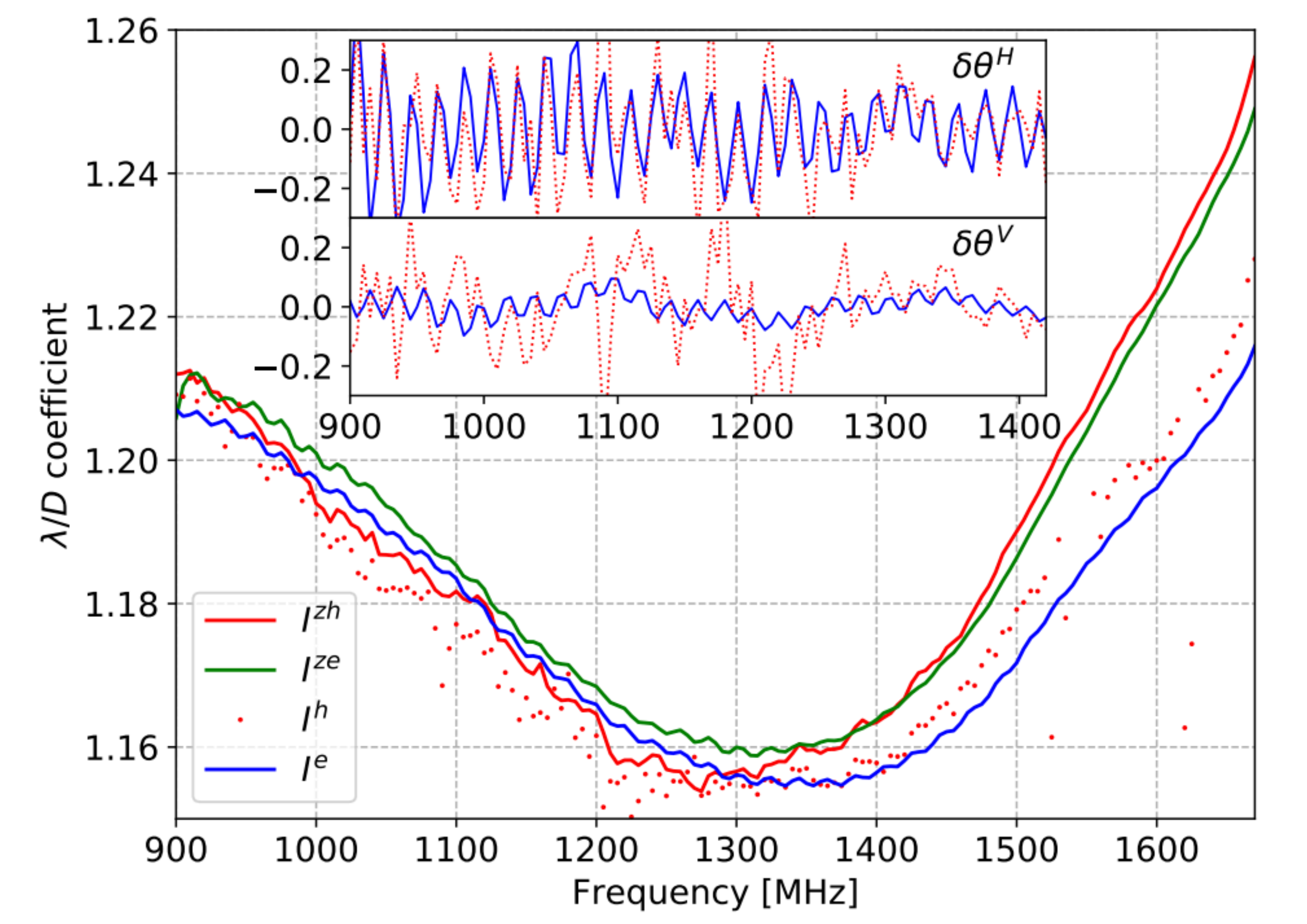
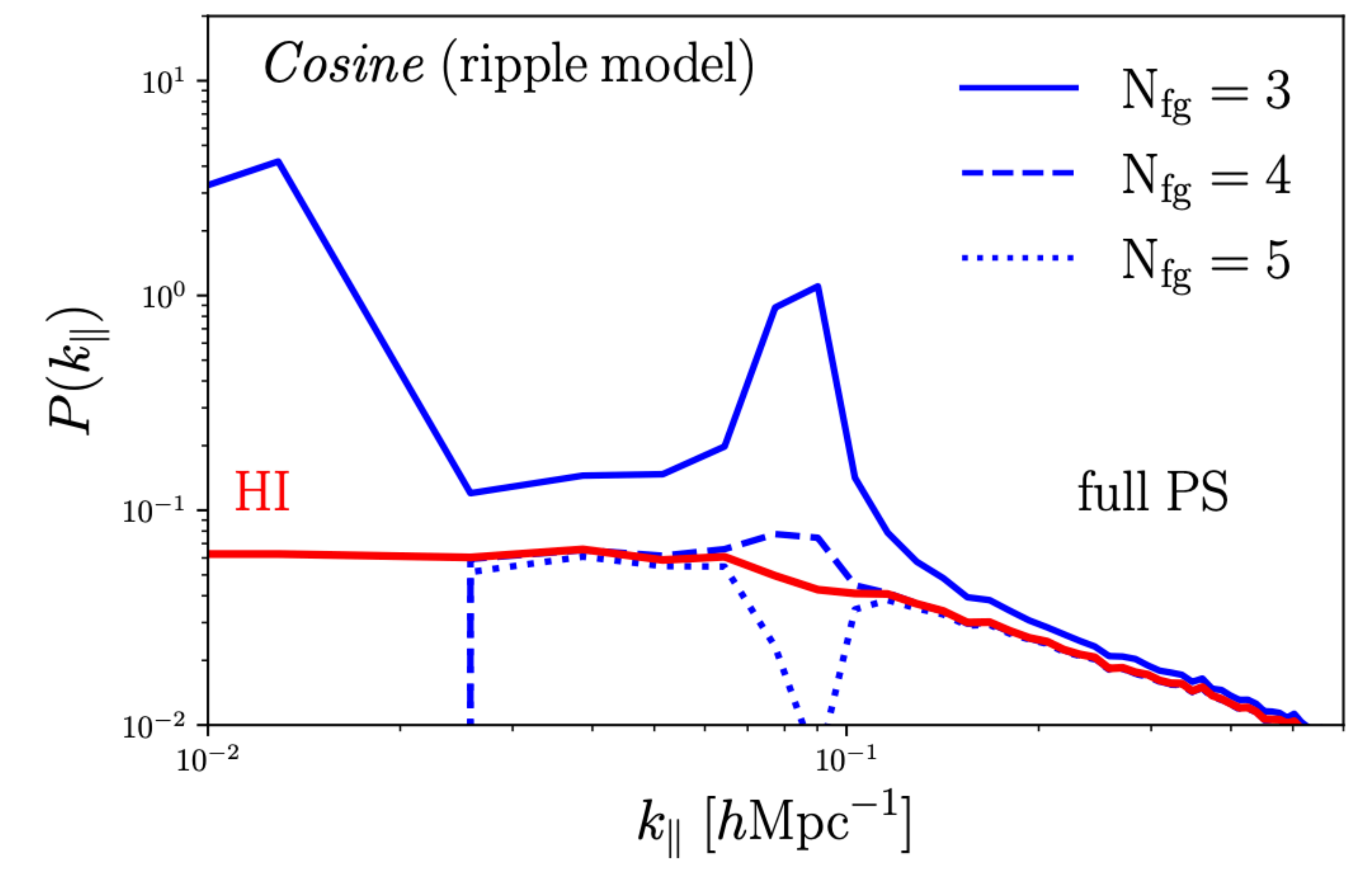


Figure 16. Coefficients of the theoretical beamwidth (λ/D) as a function of frequency for the given AH (red dots) and EM (blue) datasets, and the Zernike-based models created from the AH (red

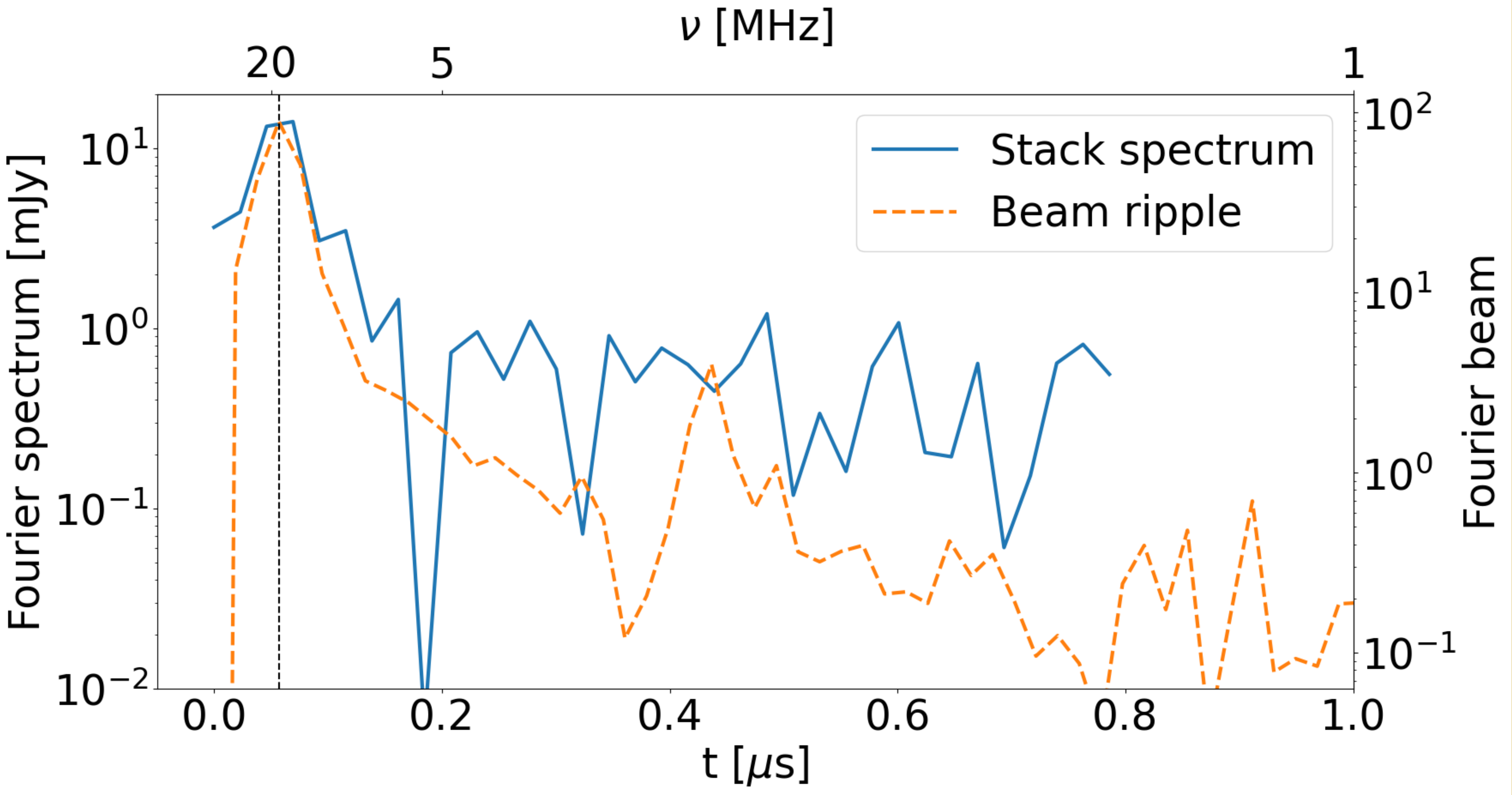
Matshawule et al., 2011.10815

Spinelli et al., 2107.10814



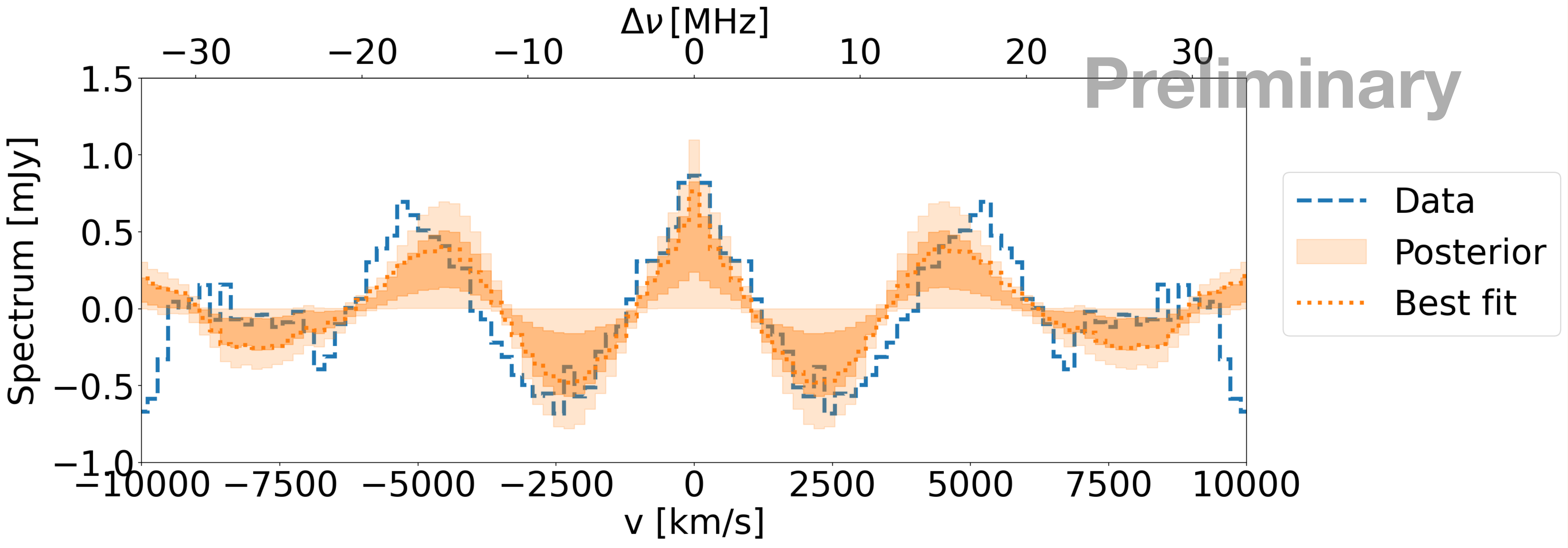
Hunting down the source of systematics

- The Fourier transform of the beam ripple and the Fourier transform of the stacked spectrum match in their peak position
- The systematics in the stacked signal has the same characteristic frequency scale as the beam ripple



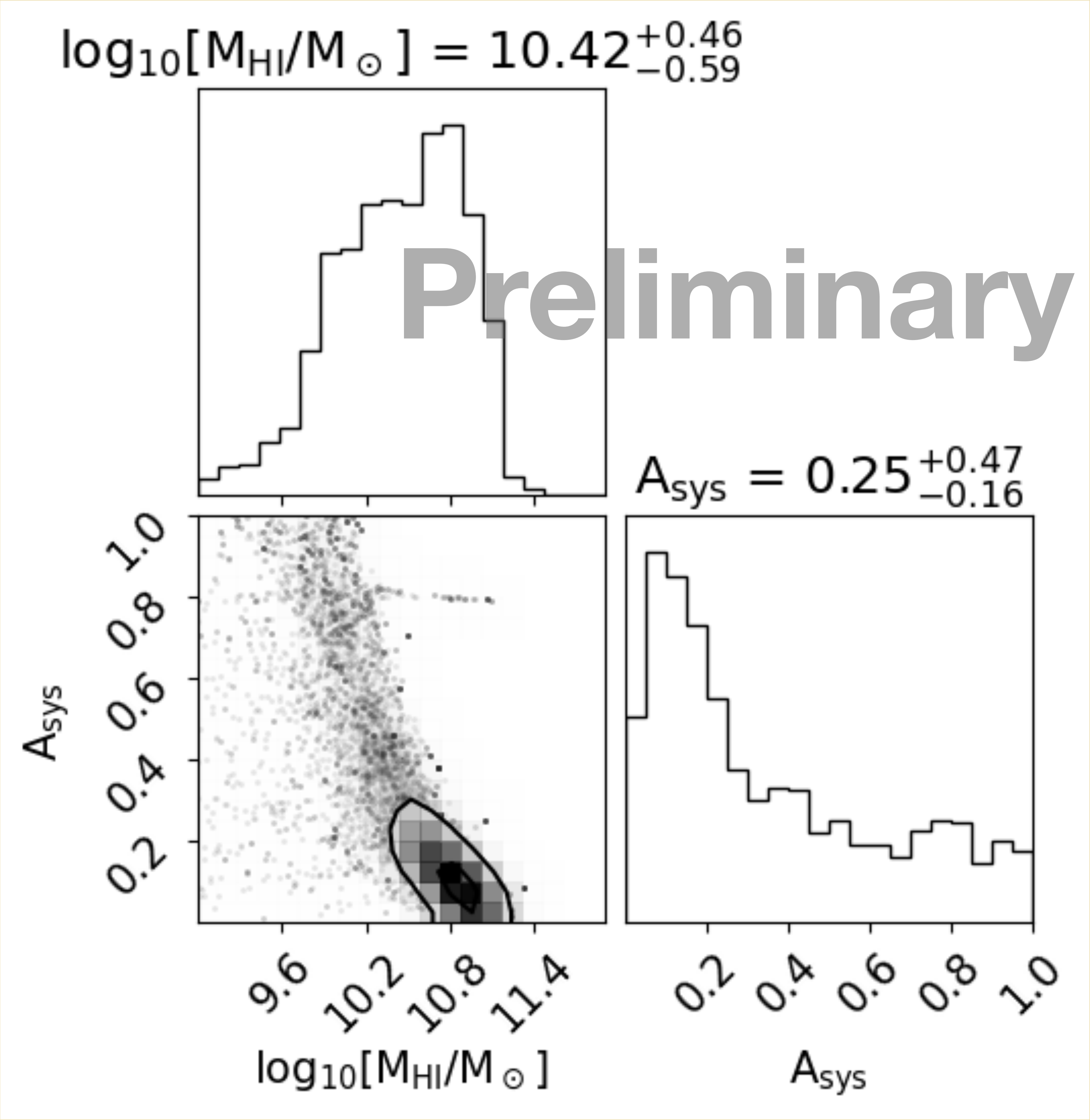
Constraining the systematics

- Simple two-parameter model: amplitude of oscillation and average HI mass of galaxies.
- Fitting suggests a small mismatch of frequency.



Constraining the systematics

- The amplitude of the systematics much larger than the measured beam ripple (A>4% at 95% confidence level).
- Strong degeneracy between the systematics and HI.
- Tentative constraints of HI.
- However, it is likely overestimated due to the incomplete galaxy catalogue and biased due to degeneracy.



Outlook

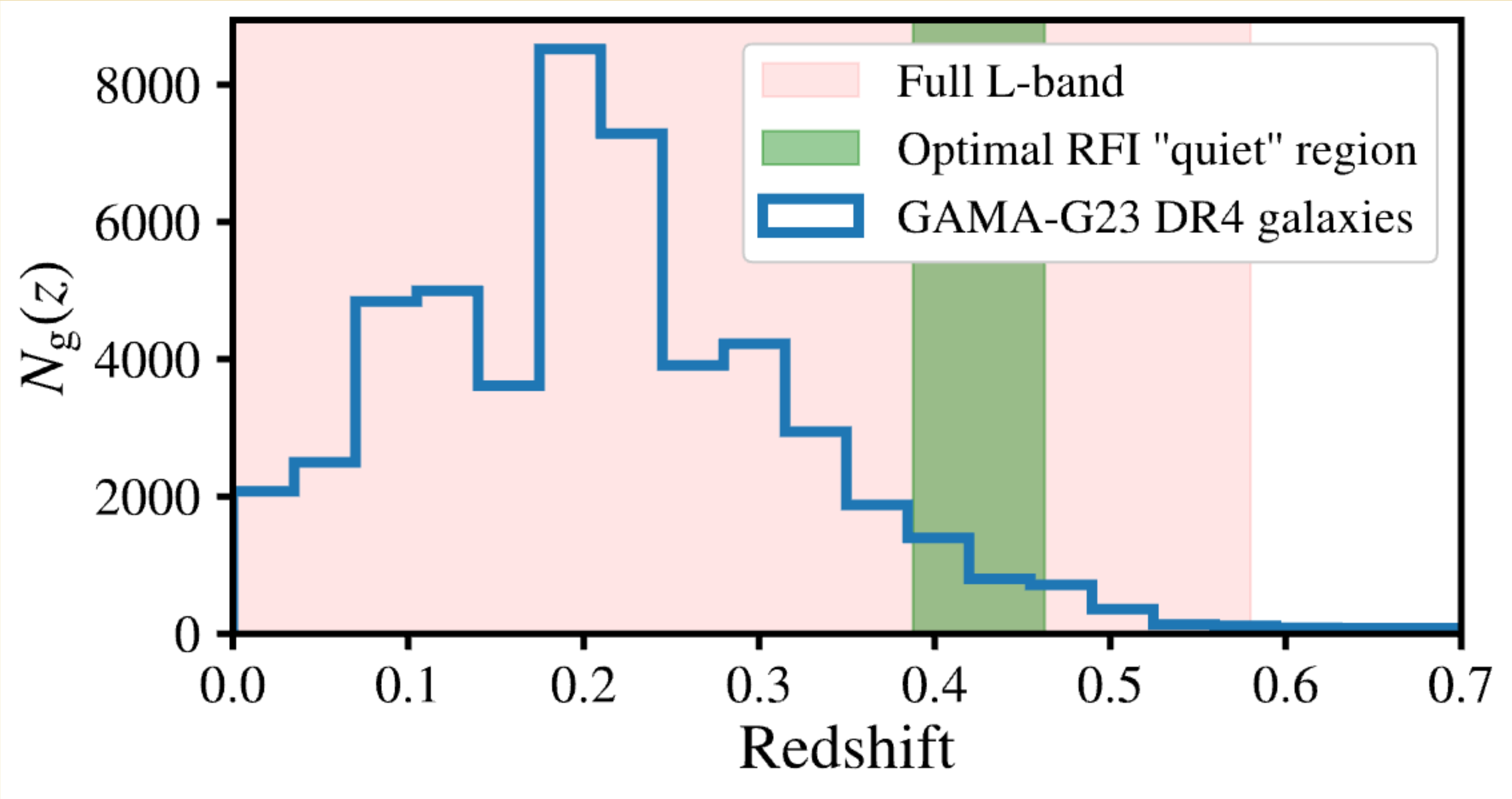
- We can parameterise the beam ripples and incorporate in our forward modelling of the stacked signal
- The stacking measurements can be used to simultaneously marginalise over the HI model and the systematics.
- The fitting results suggest that the systematics is still significant and stands in the way of constraining HI.
- Future MeerKAT UHF and SKAO will fix a few key issues: data quality, overlap with galaxy surveys, signal-to-noise…

SKAO x Euclid: spec-z

- The cleanest frequency range (UHF) sits around z~0.5-1.5. Good overlap with Euclid spec-z
- Power spectrum cross-correlation
- Stacking

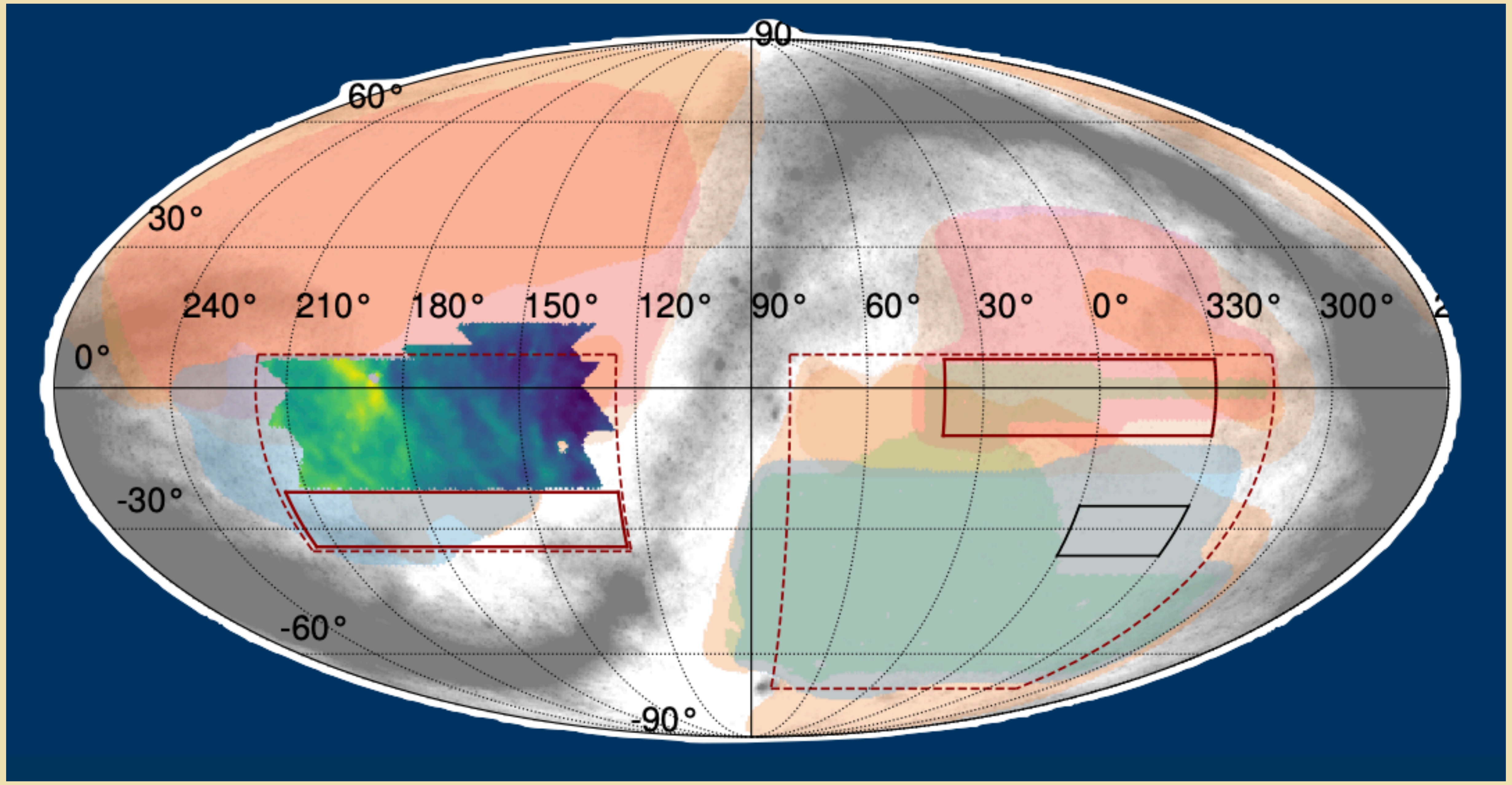
SKAO x Euclid: photo-z

- The current L-band measurement is constrained by the narrow redshift bin.
- Selecting galaxies within the z-range using photo-z will completely decorrelate the signals.



SKAO x Euclid: photo-z

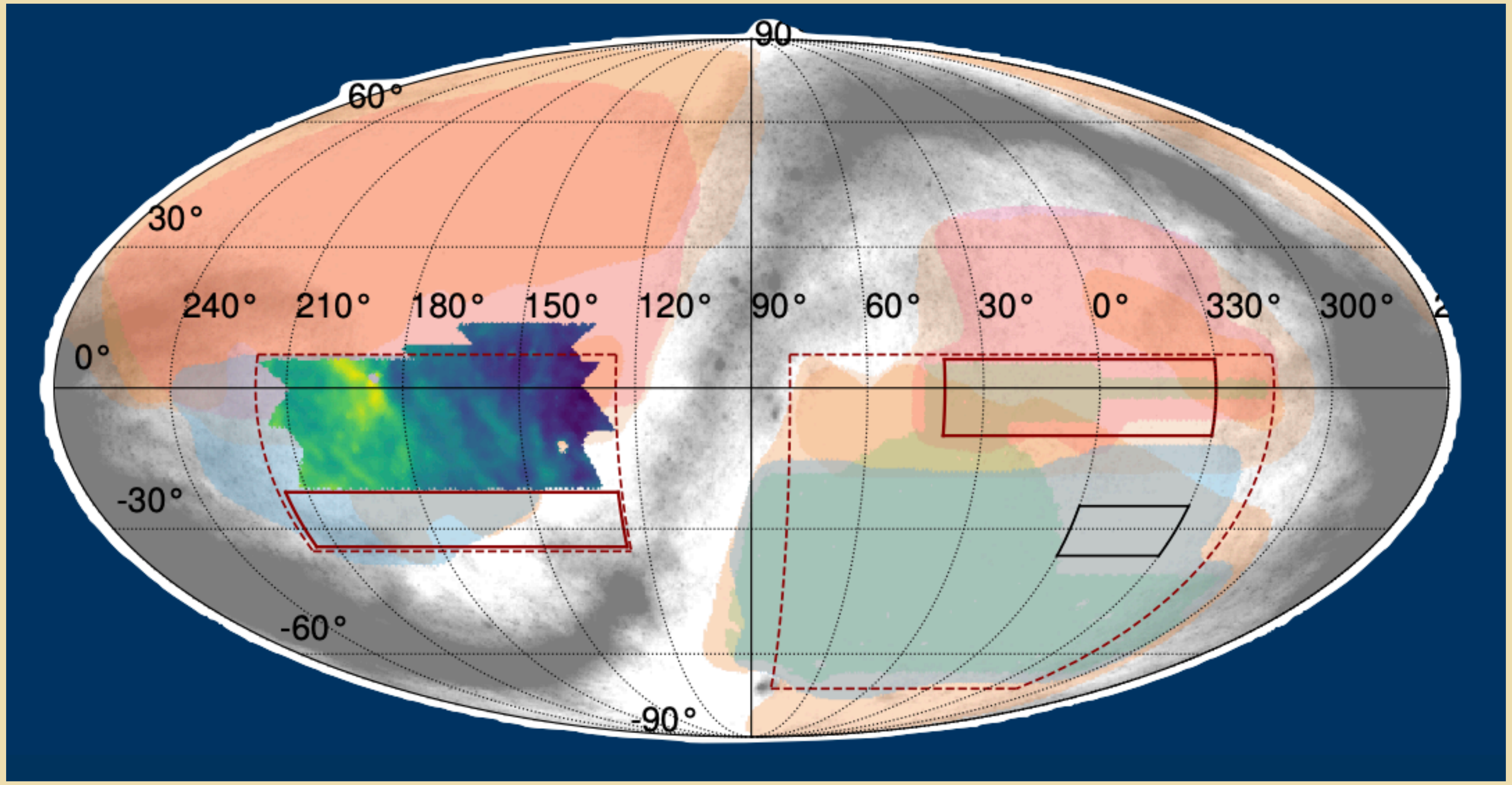
- The MeerKAT UHF survey and future SKA-Mid will cover a wide redshift range.
- 21cm x photo-z will become tangible.
- Need quantification of photo-z errors and 21cm survey specifications
- P(k) first, ultimately C(l) and clustering redshift



Work led by Jiakang “Jack” Han, with ZC, Stefano Camera and Alkistis Pourtsidou

SKAO x Euclid: photo-z

- Lots of open questions:
- Modelling of redshift error kernel beyond Gaussian
- Effects of catastrophic outliers
- Optimal estimator using posteriors instead of mean



Work led by Jiakang “Jack” Han, with ZC, Stefano Camera and Alkistis Pourtsidou

SKAO x Euclid: photo-z

- Bayesian stacking:
- Weights of the stacked cubelets are Bayesianised.
- Can be applied to photo-z galaxies for stacking

Measuring the H I mass function below the detection threshold

Hengxing Pan[1,2,3]★, Matt J. Jarvis[3,4], James R. Allison[3], Ian Heywood[3,5,6], Mario G. Santos[4,6], Natasha Maddox[7], Bradley S. Frank[6,8,9], Xi Kang[1]

Pan et al., 1907.10404

Probing the cosmic web in Lyα emission over large scales: an Intensity Mapping forecast for DECaLS/BASS and DESI

Pablo Renard[1],★ Daniele Spinoso[1], Zechang Sun[1], Hu Zou[2], Paulo Montero-Camacho[3], and Zheng Cai[1]
[1]*Department of Astronomy, Tsinghua University, Beijing 100084, China*
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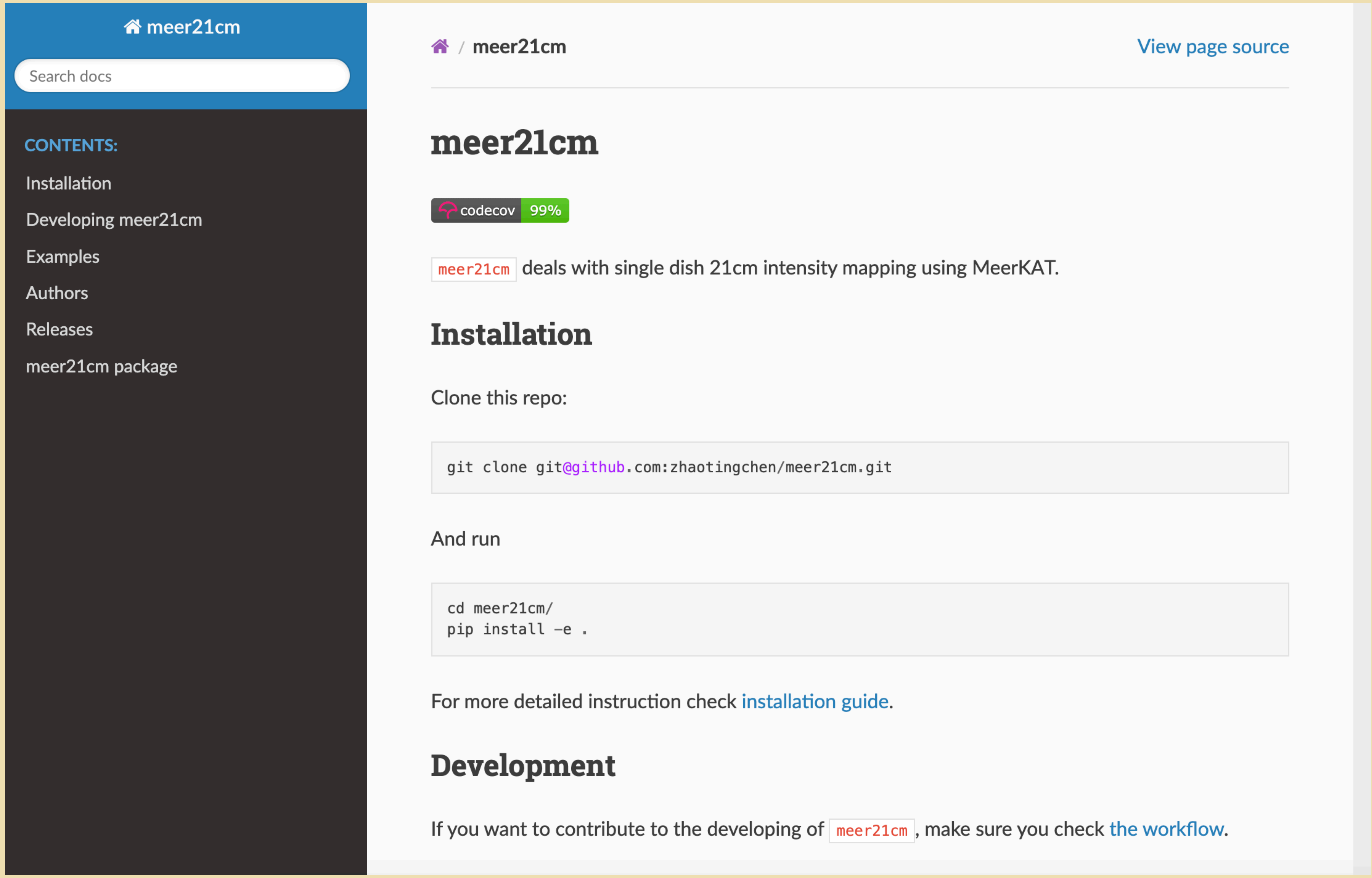
Renard et al., 2406.18775

Conclusion

- Spectral line stacking using single dish IM survey of MeerKAT/SKA-Mid faces a series of challenges before HI science can be extracted
- The scale of measurements, as well as mixing of systematic and signal, requires forward modelling of the observed spectrum
- Stacking is a very powerful tool for validating detection, analysing systematics, and can be used to simultaneously constrain HI signal and observational systematics
- In the future, MeerKAT and SKA-Mid can be used to measure quantities such as HI density and scaling relations through stacking.

Ad: the meer21cm package

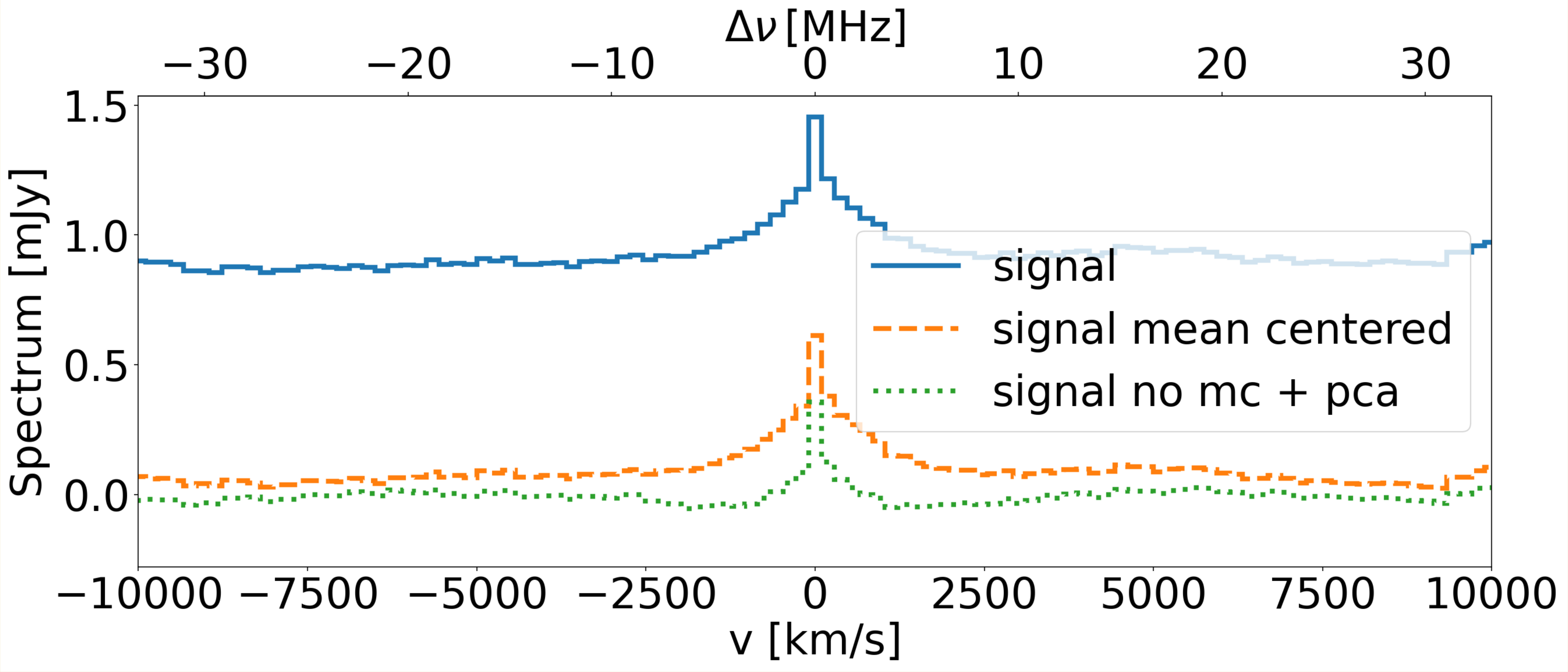
- Used in this work for performing stacking analysis and forward modelling.
- Also working on integrating power spectrum pipeline
  Cunnington & Wolz, 2312.07289
- Fully modulated, easy to use, thoroughly tested and will be documented
- Will be public soon(ish)



Thanks!

Backup: Why PCA removes plateau

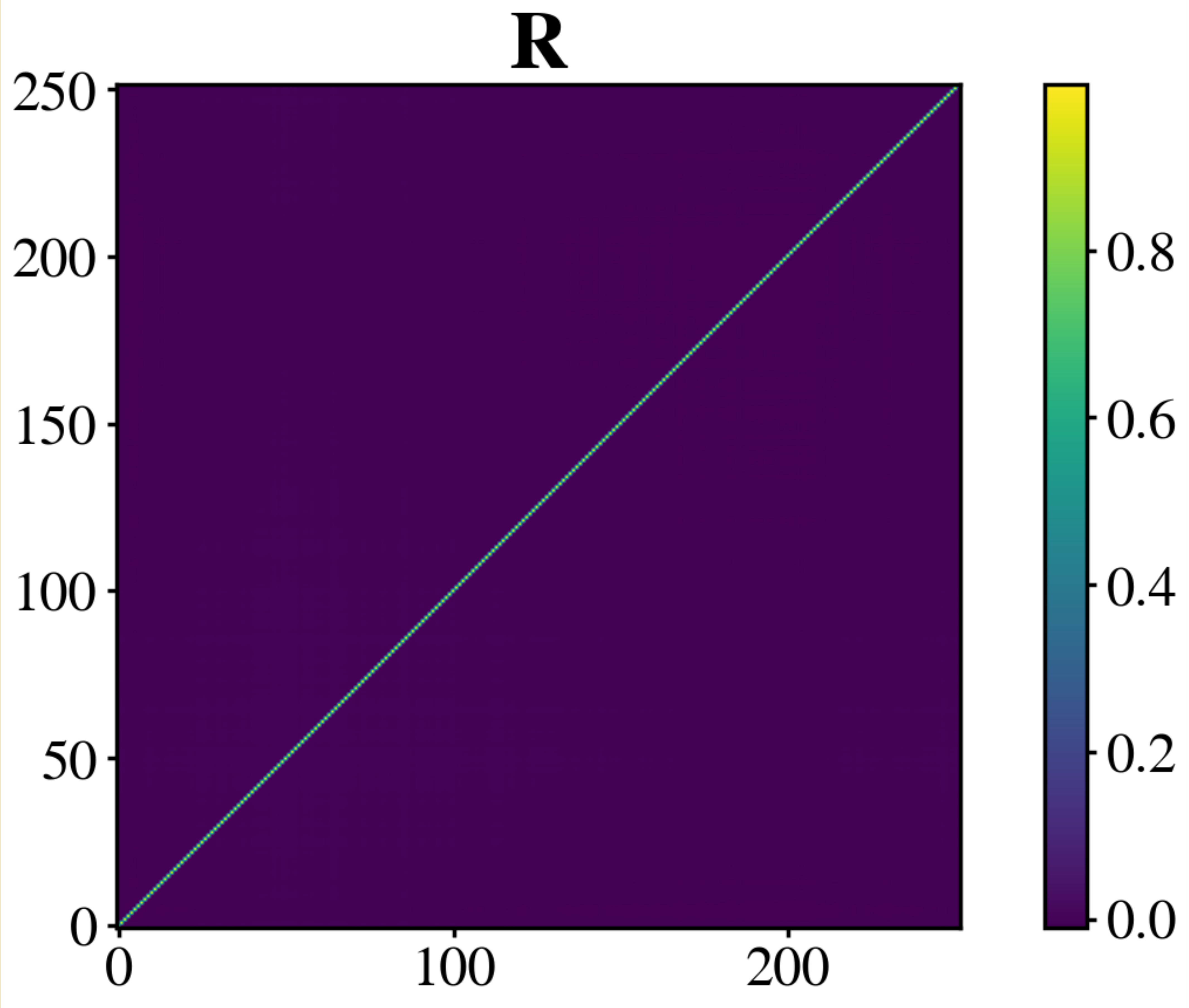
- It is naturally to then conclude that PCA removes the mean so the plateau is gone. But actually even without mean centering:

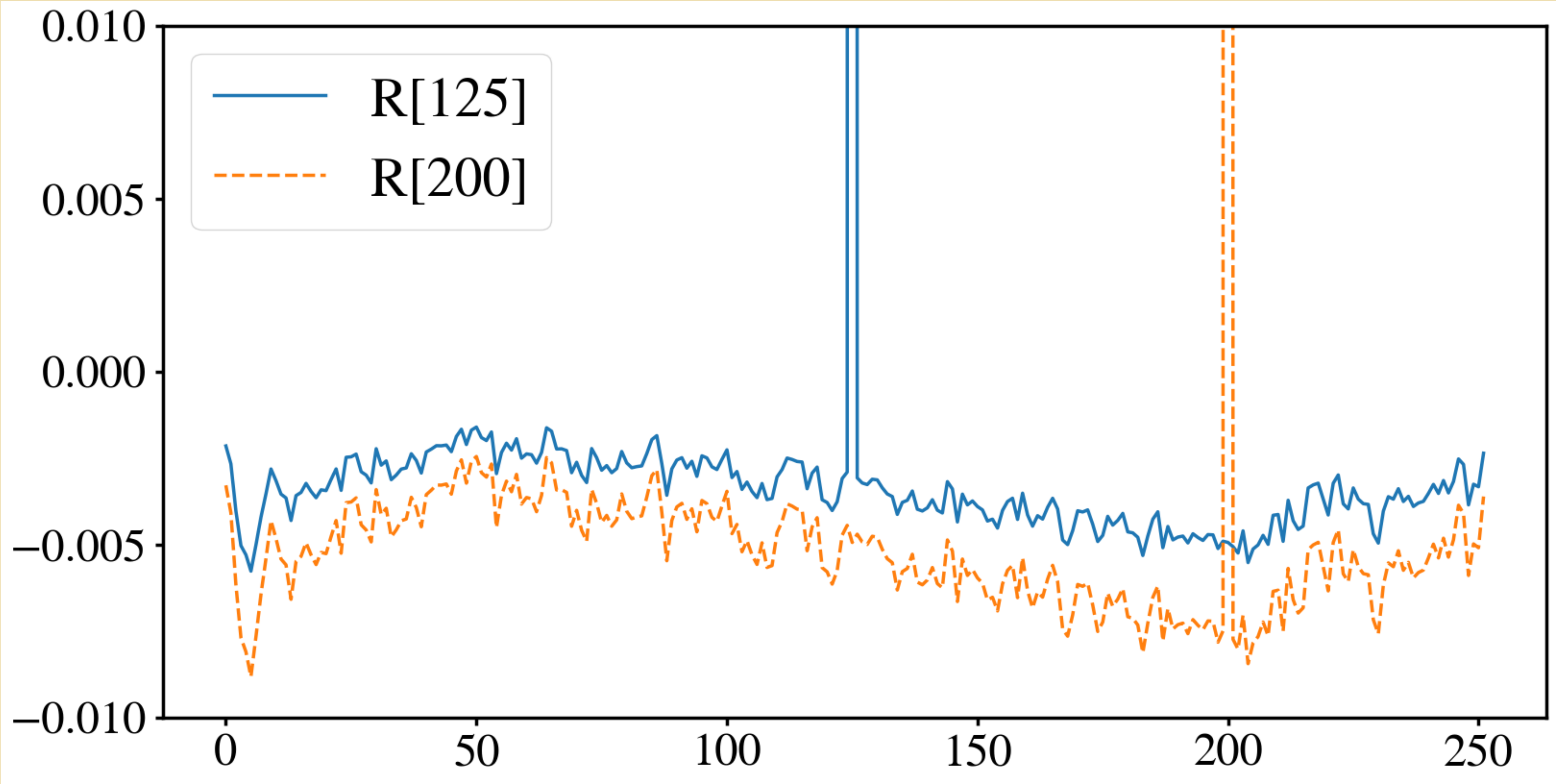


Backup: Why PCA removes plateau

- What PCA does is that it preserves the peak, but also scatters the peak amplitude into negative values across the frequencies:

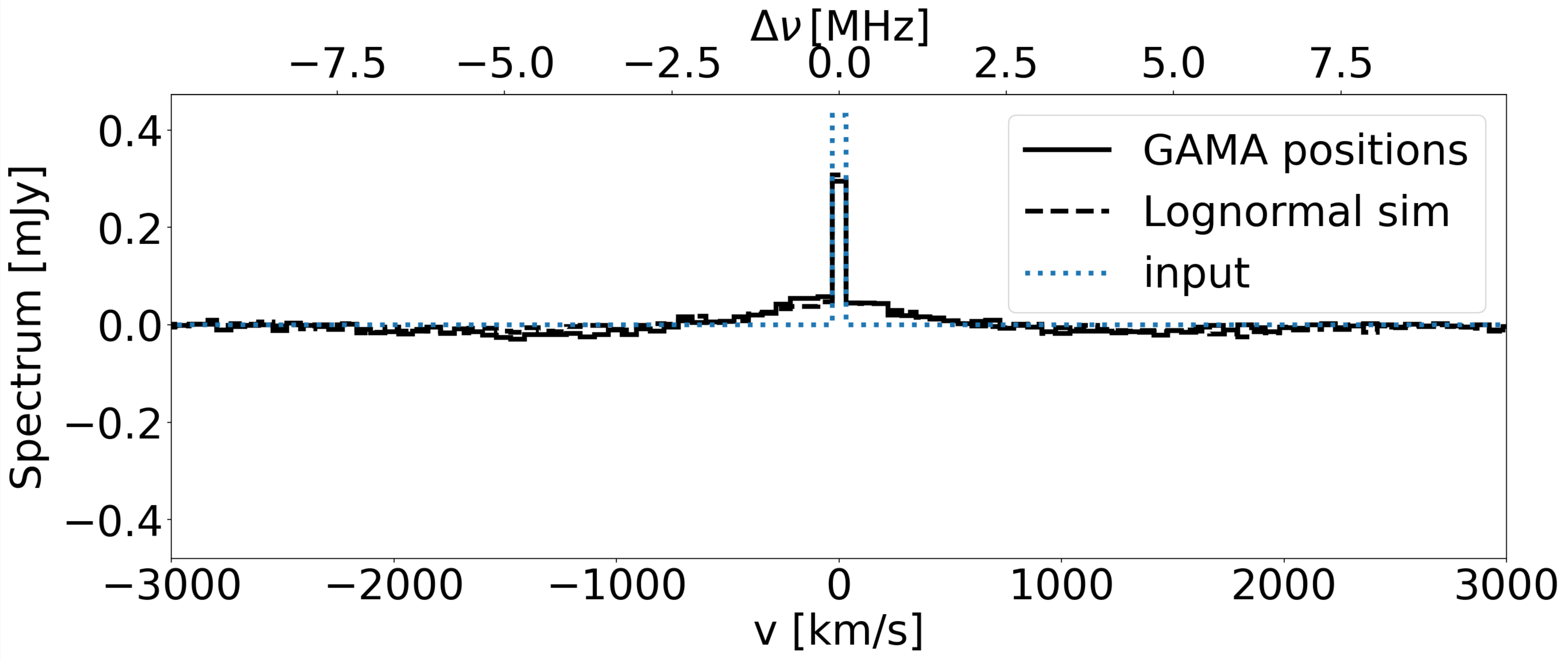
$$\vec{r} = \mathbf{R}\vec{m} = (\mathbf{I} - \mathbf{A}\mathbf{A}^{\mathrm{T}})\vec{m}$$





Backup: matching the clustering amplitude

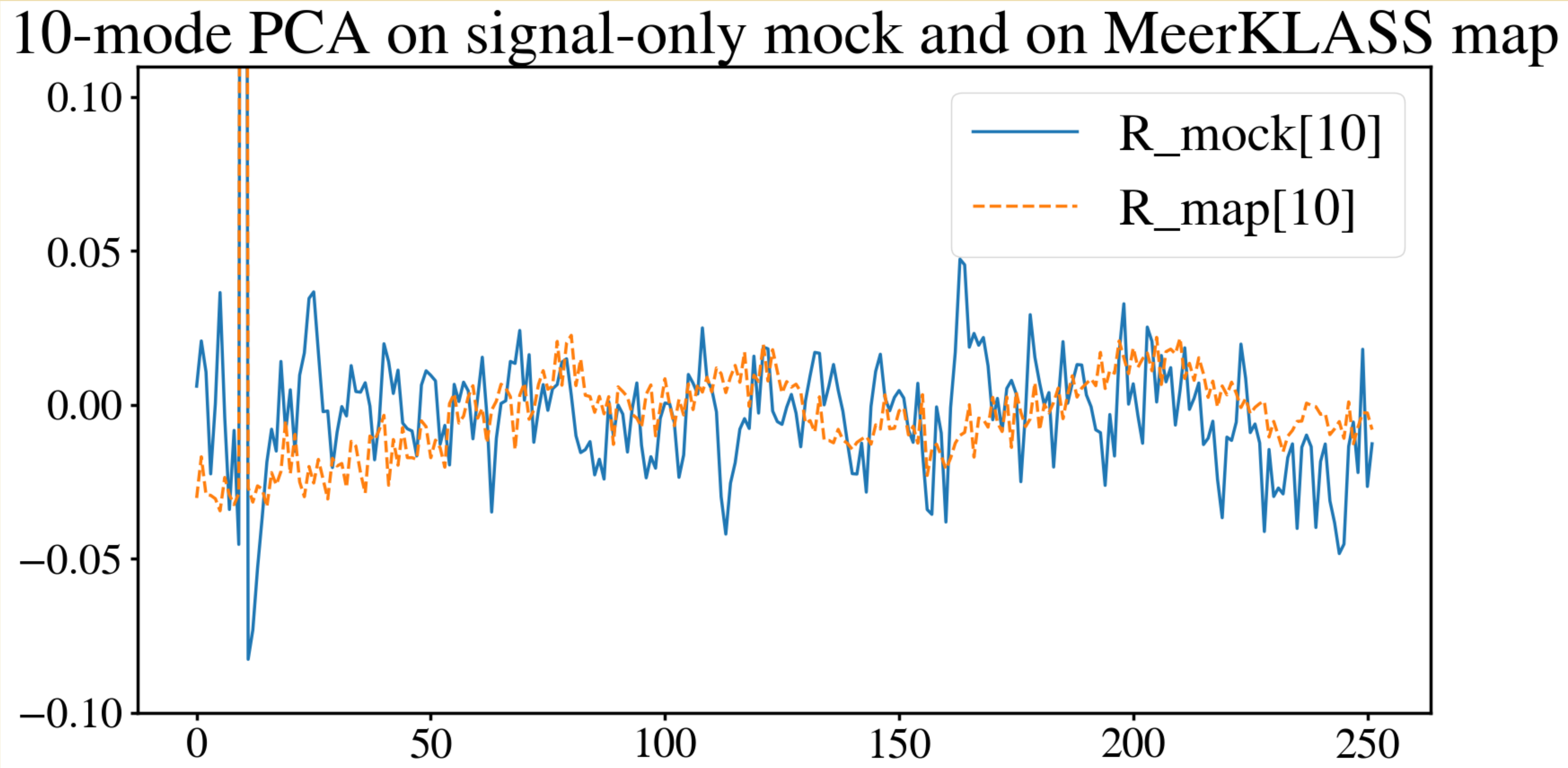
- Simulations using lognormal galaxy mock positions and actual GAMA galaxy positions match quite well.



Backup: correlation comes from PCA

- The thermal noise in the map is not correlated originally.
- The correlation also comes from the fact that PCA matrix is applied to the data
- The oscillation structure is visible in the PCA matrix.

$$\vec{r} = \mathbf{R}\vec{m} = (\mathbf{I} - \mathbf{A}\mathbf{A}^{\mathrm{T}})\vec{m}$$



Backup: parameter fitting

- Need careful treatment of priors for modelling the systematics