Validating 21 cm cosmology analysis pipelines: lessons learned and future outlooks

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Cosmology in the Alps 2024

HERA

National Research Foundation

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South African Radio Astronomy Observatory

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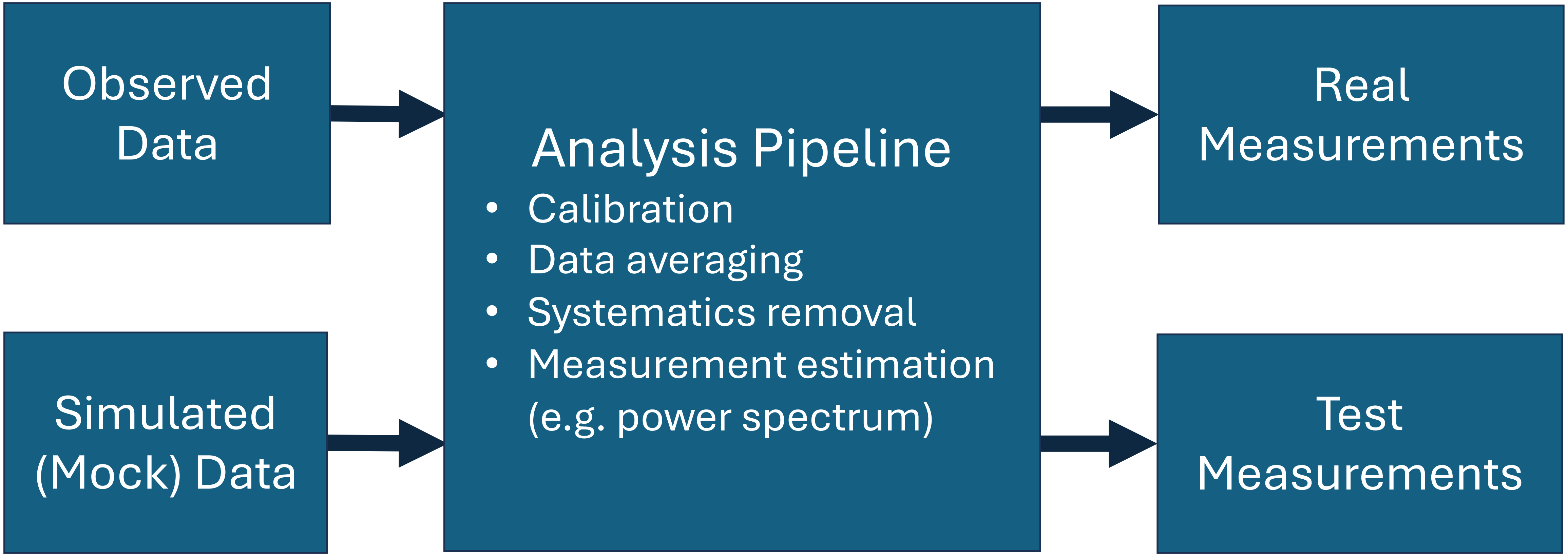
Centre for Radio Cosmology

What is pipeline validation?

Testing of the analysis pipeline with mock data for unknown systematics and signal loss



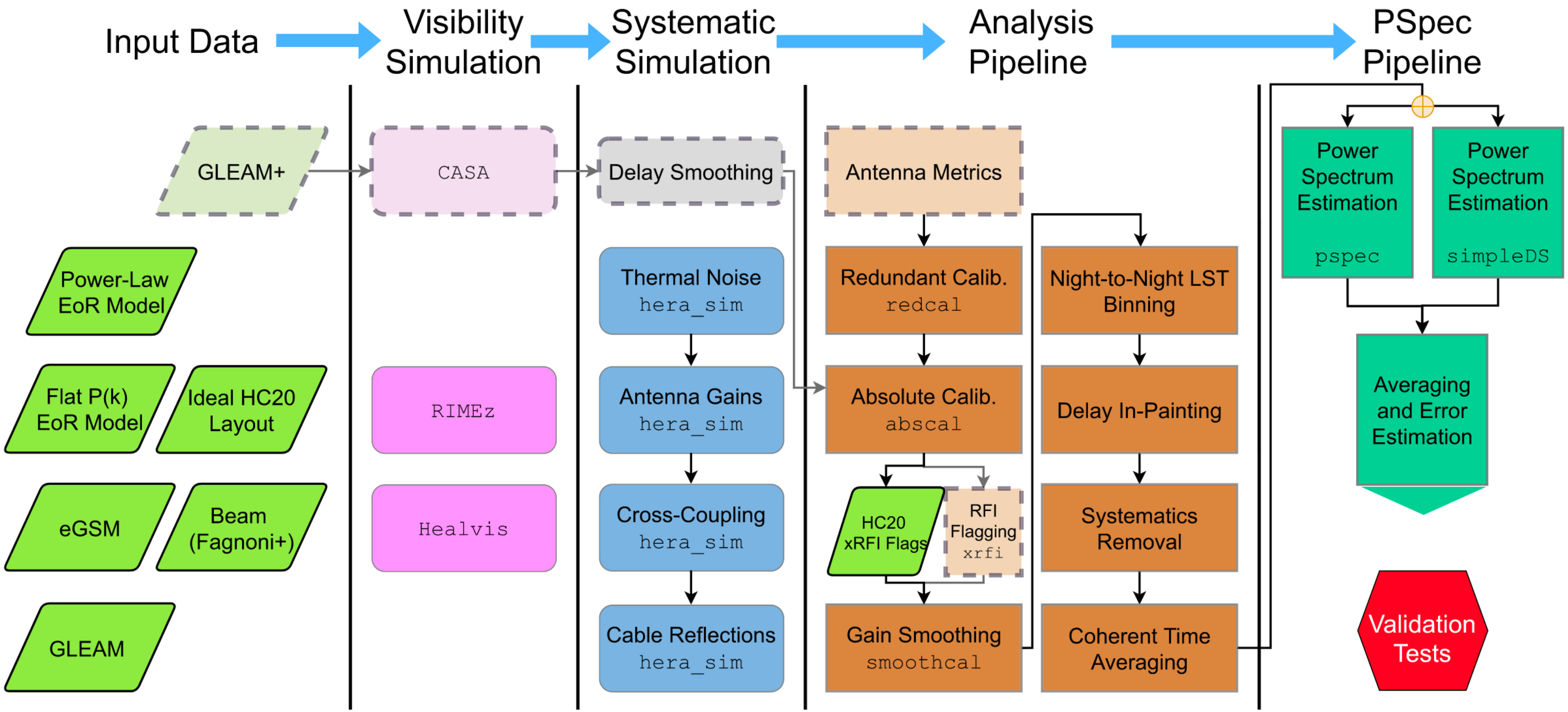
Why should we validate the pipeline?

- History of revising power spectrum limits due to (previously) unknown biases from complex and novel analysis techniques
  - Liu & Shaw 2020 provides a good overview of these analysis issues
- Past revisions:
  - GMRT – Paciga et al. 2011 as amended by Paciga et al. 2013
  - PAPER (precursor of HERA) – Ali et al. 2015 as amended by Kolopanis et al. 2019 and Cheng et al. 2018
  - BICEP2 CMB B-mode polarization fault detection

Validation in Literature

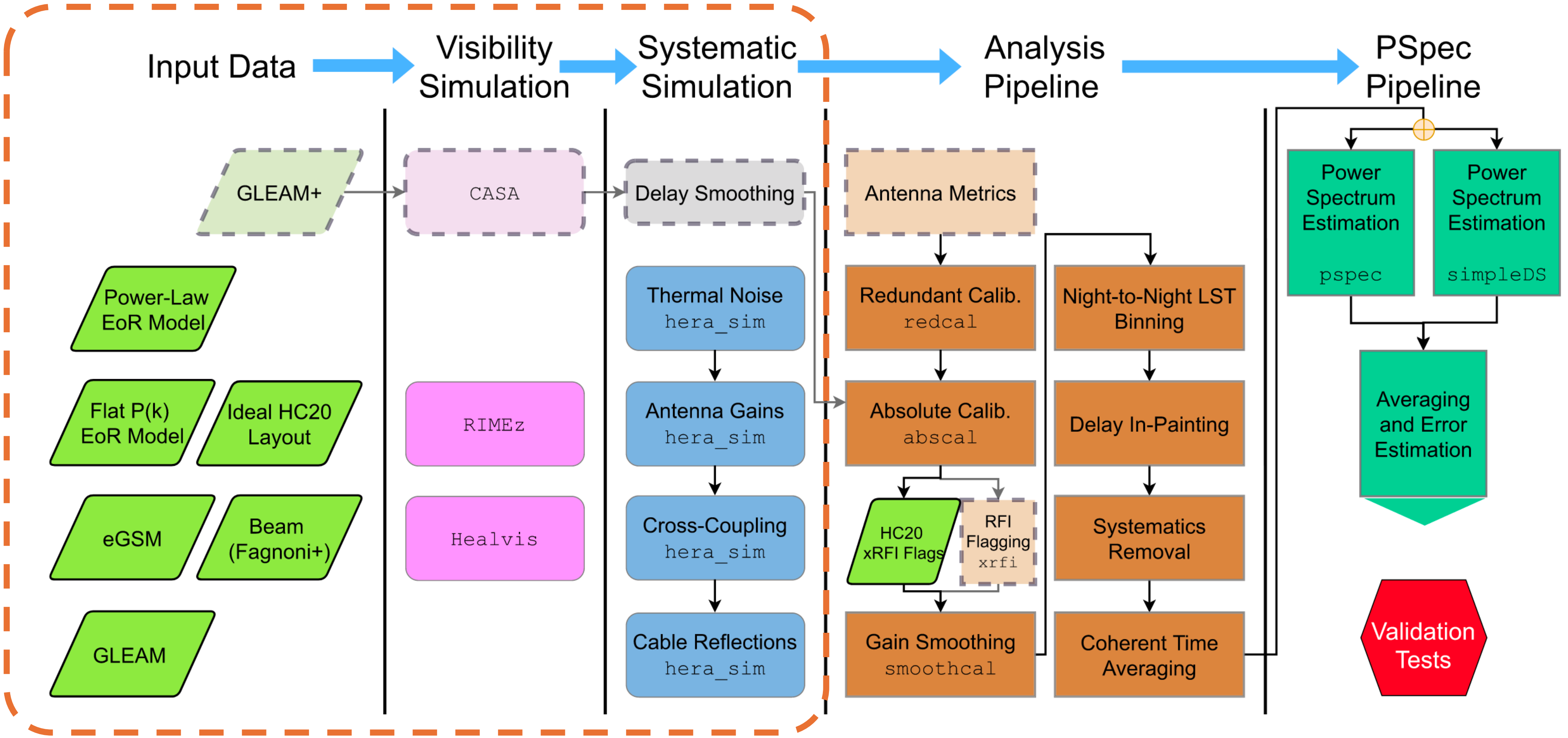
Validation in Literature: HERA

- Full forward modelling approach (Aguirre et al. 2022)



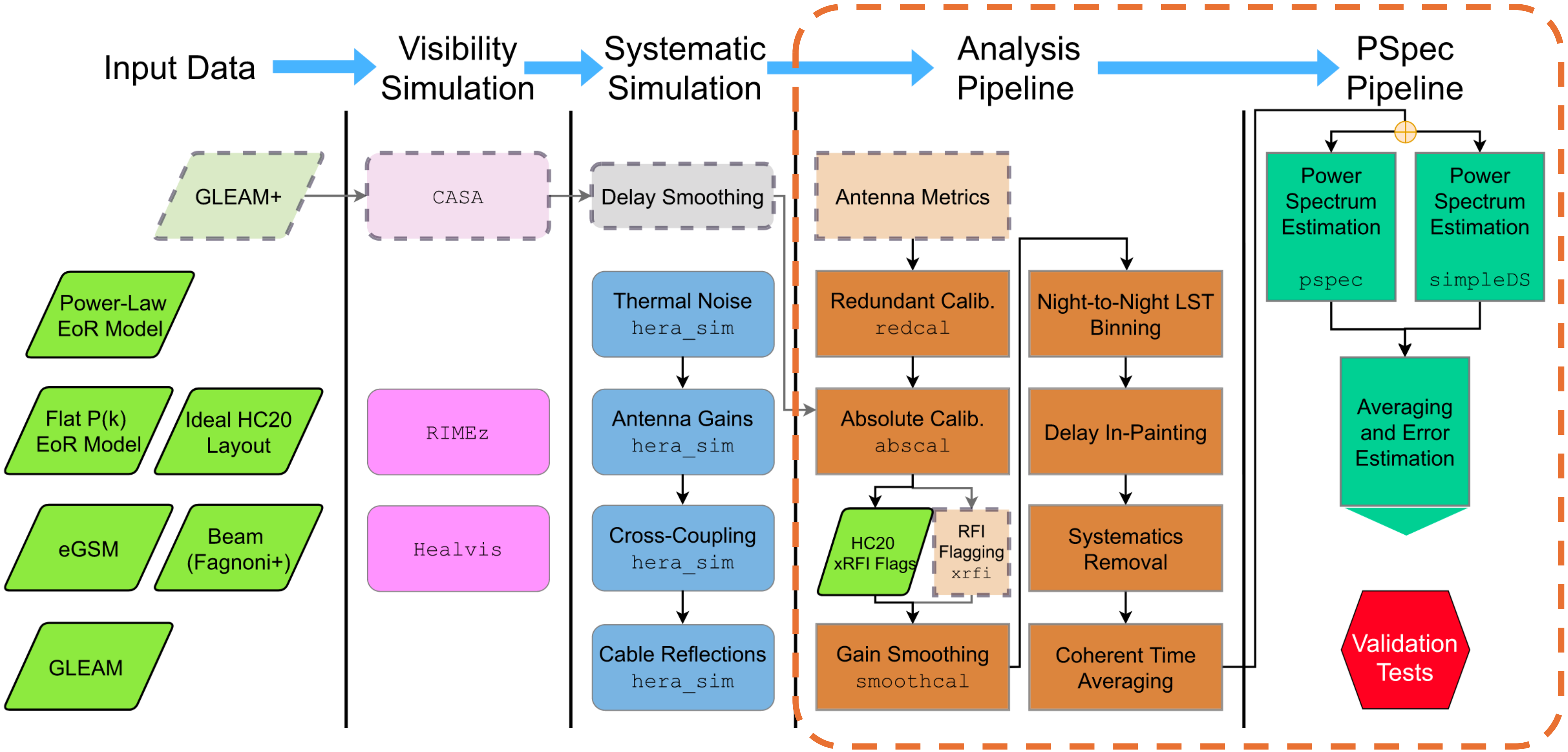
Validation in Literature: HERA

- Simulate mock data with different sky and systematic components



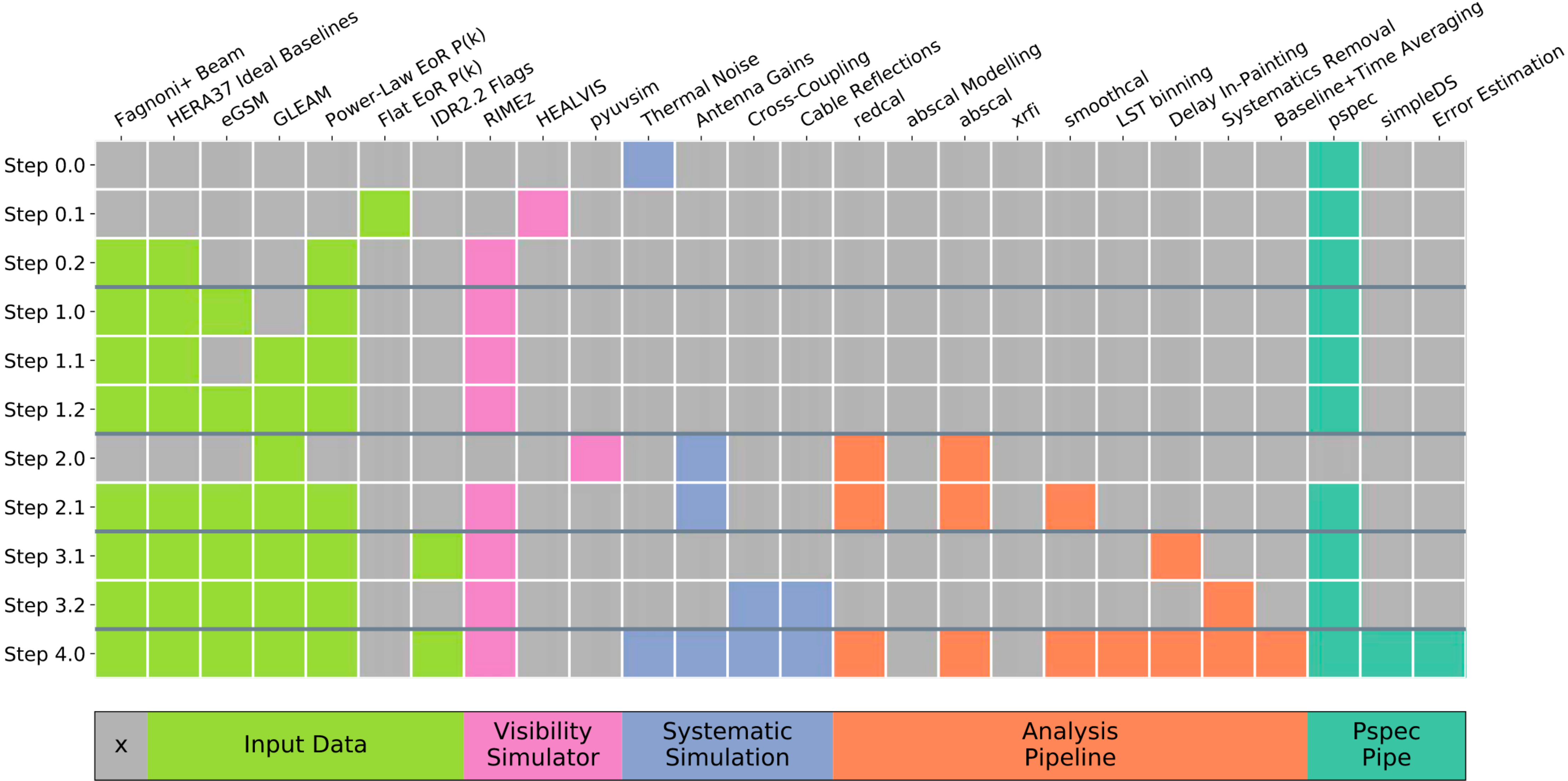
Validation in Literature: HERA

- Test different parts of the pipeline through a series of “validation tests”



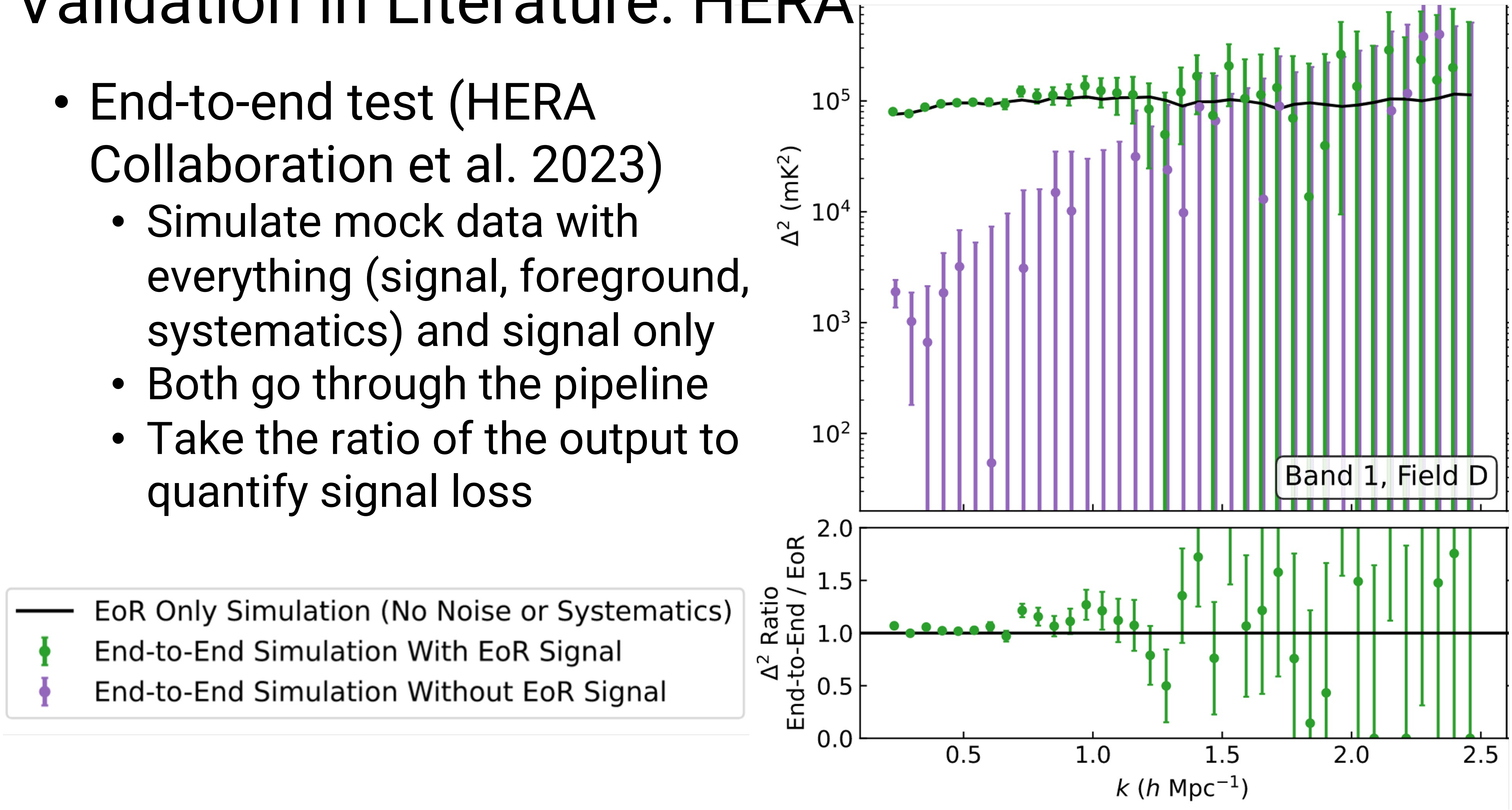
Validation in Literature: HERA

- Gradually building up the complexity of the validation tests



Validation in Literature: HERA

- End-to-end test (HERA Collaboration et al. 2023)
  - Simulate mock data with everything (signal, foreground, systematics) and signal only
  - Both go through the pipeline
  - Take the ratio of the output to quantify signal loss



Validation in Literature: LOFAR & NenuFAR

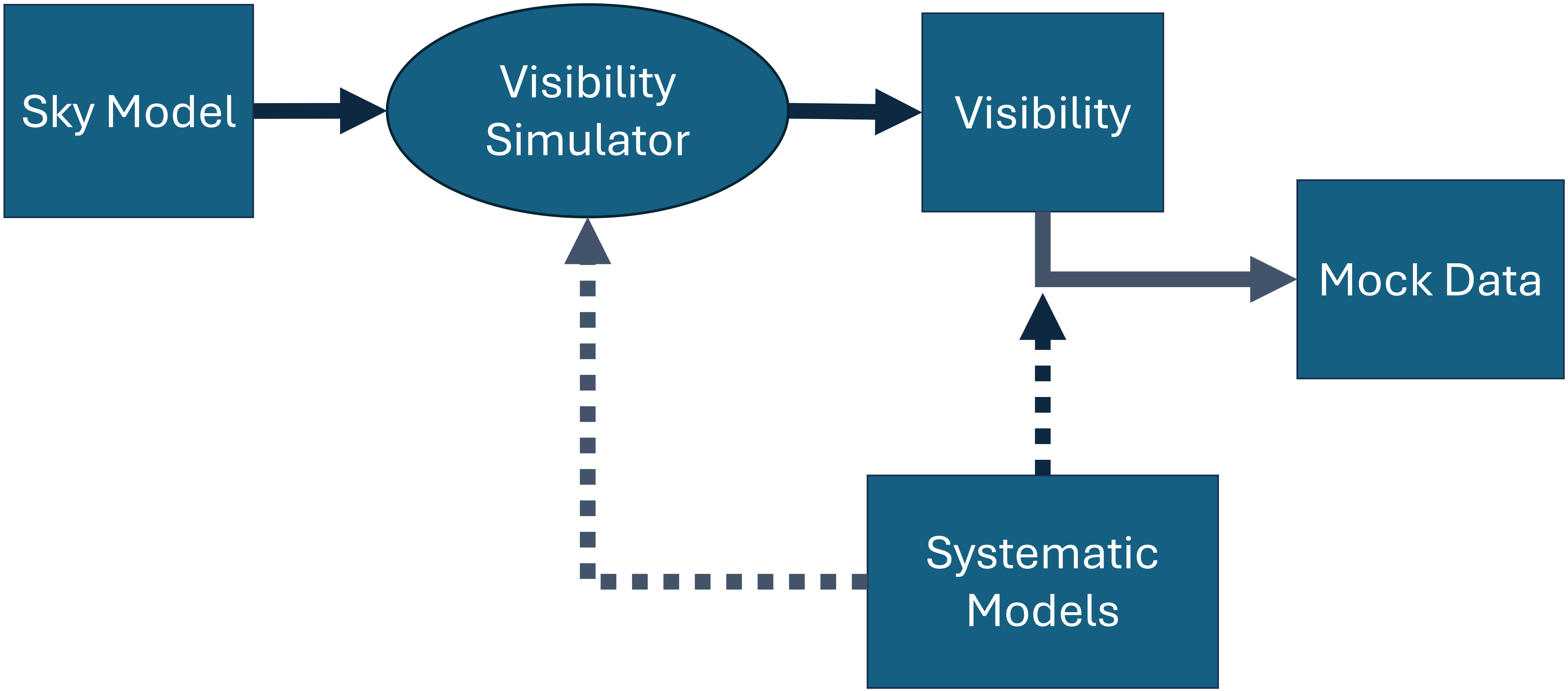
- Signal injection test (Mertens et al. 2018, 2020, Munshi et al. 2024)
  - Inject detectable simulated EoR signal to data (at the level in-between noise and foreground)
  - Signal injected data goes through the pipeline
  - Subtract the output with those from data without injected signal to obtain the residual
  - Form PS from the residual and the injected signal
  - Their ratio determine the signal loss
- Calibration test – Mevius et al. 2022
- GPR foreground removal test – Gan et al. 2023
- Also used similarly in MeerKLASS (Cunnington et al. 2023)

Validation in Literature: MWA

- Multifaceted approach, motivated by 3+ different pipelines used in the analysis
- Cross-validation with other pipelines (Beardsley et al. 2016, Barry et al. 2019b, Li et al.2019, Trott et al 2020)
- End-to-end test through signal-only and signal + foreground simulations to determine signal loss through the FHD+ εppsilon pipeline (Barry et al. 2019a,b Li et al 2019)
- Signal-only simulation from a large EoR lightcone showing no signal loss in the CHIPS pipeline (Trott et al. 2020)

Simulating Mock 21 cm Data

Simulating Mock 21 cm Data



Visibility Simulator

- Evaluate the Radio Interferometric Measurement Equation (RIME)
  - Original formulation: Hamaker et al (1996), Sault et al (1996), Hamaker & Bregman (1996), Hamaker (2000), Hamaker (2006)
  - Revision: Smirnov (2011a, b, c, d), Price & Smirnov (2015)

Sky brightness in the direction $\boldsymbol{\sigma}$

Visibility from baseline pq

$$\mathrm{V}_{pq} = \int_{4\pi} \boldsymbol{J}_p(\boldsymbol{\sigma})\mathrm{B}(\boldsymbol{\sigma})\boldsymbol{J}_q^H(\boldsymbol{\sigma})\, d\Omega$$

Integral over the full sky solid angle

Jones terms for antenna p and q

Visibility Simulator

- On a computer, we must **choose a discrete basis to turn the RIME integral into a sum**
  - The sum may be done in the real, Fourier, or spherical harmonic domains
- Examples of discrete basis
  - Point-source or pixelized: Model sky components as an ensemble of unresolved point sources
  - Spherical harmonic (Shaw et al. 2014): Model sky components as a linear combination of spherical harmonic modes (m modes)
  - Other bases include Gaussian blob and wavelets

Visibility Simulator: Dedicated

Purposely developed software for visibility simulation

Simulator	Basis	Language	Affiliation	Latest Release	Maintained	GitHub Repository
`pyuvsim`	Point source	Python	RASG	2023-0719	Yes	RadioAstronomySoftwareGroup/pyuvsim
`matvis`	Point source	Python, CUDA	HERA	2023-11-30	Yes	HERA-Team/matvis
`WODEN`	Point source, shapelet	C, CUDA, Python	MWA, Curtin	2023-10-25	Yes	JLBLine/WODEN
`OSKAR`	Point source, Gaussian	C, C++, Python	SKA	2022-05-26	Yes	OxfordSKA/OSKAR
`driftscan`	Spherical harmonic	Python, Cython, C++	CHIME, CHORD, HIRAX	2022-10-01	Yes	radiocosmology/driftscan
`healvis`	Point source (HEALPix)	Python	RASG	2019-04-04	Deprecated	rasg-affiliates/healvis
`PRISim`	Point source	Python2	N. Thyagarajan	2020-06-13	Assume No	nithyanandan/PRISim

* As of 2024-03-19

Visibility Simulator: General Purpose

Analysis software with simulation capability, primarily through the building of a sky model for calibration

Simulator	Basis	Language	Affiliation	Latest Release	Maintained	GitHub Repository
FHD	Point source (uv plane)	IDL	U of Washington	2021 (Last update 2024-02)	Yes	EoRImaging/FHD
pyFHD	Point source (uv plane)	Python	N. Barry & ADACS	No stable release yet	Yes	ADACS-Australia/PyFHD
CASA	Point source	Python, Fortran	VLA/ALMA	3 weeks ago	Yes	casangi
WSClean	?	C	A. Offringa, ASTRON	5 months ago	Yes	aroffringa/wsclean/
SAGECal	Point, gaussian, shapelet	C/C++, CUDA	ASTRON, NL eScience Center	2023-07-31	Yes	nlesc-dirac/sagecal
maqtres	?		Rhodes U	2022-2023	Maybe	ratt-ru/meqtrees

* As of 2024-03-19

Making visibility simulator faster for HERA

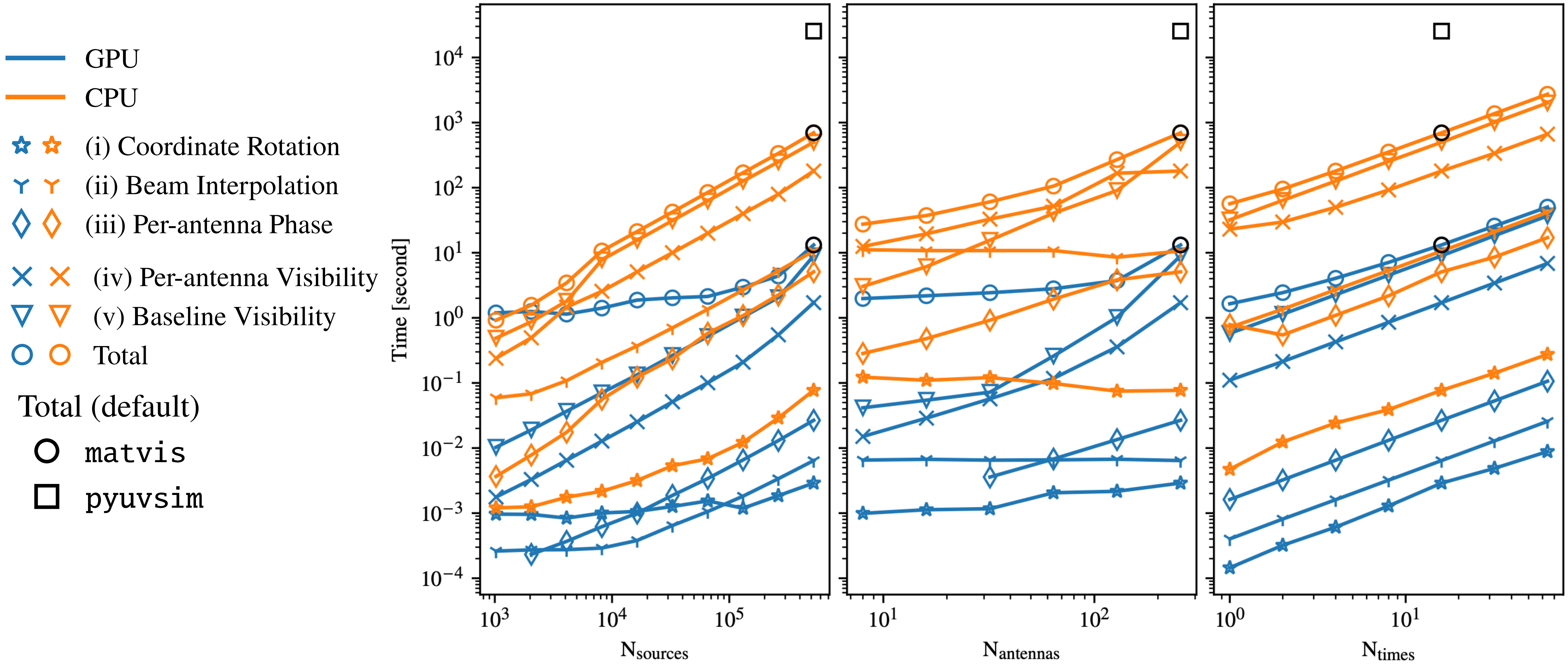
- We want to simulate multiple sky components over real observational parameters
- If using `pyuvsim`, the wall time is ≈3M CPU hours per sky component
- How can we do this faster?

HERA Validation Simulation Parameters	
Baselines	61075
Time steps	17280
Frequency channels	1536
Polarizations	4
Point sources	300,000+
Diffuse/EoR model pixels	786,432

`matvis`: Matrix-based RIME Algorithm

- Calculate **per-antenna** “voltages”
- Form per-baseline visibilities from an outer product of per-antenna voltages
- More number of calculations but can be efficiently performed by modern linear algebra routines and implementable on a GPU
- Further trade some accuracy for speed by opting for trigonometric-based coordinate transformation (with correction) in placed of `astropy`
- See Kittiwisit et al. (submitted to RASTI), arXiv:2312.09763

`matvis`: Speed Improvement



10^1—10^3 faster than `pyuvsim` although still computationally expensive, ≈20,000 GPU hours per sky component for full HERA

`matvis`: (Current) Limitations

- Only support drift-scan simulation
- Only support unpolarized sky although fully support polarized beam
- Sky models must have no negative values
- All baselines (in the provide array configuration) must be simulated at once

Sky Models

- Determine the realism of the simulations
- We do not have complete information in EoR/CD frequencies

Sky Models: Point Source

- Radio source catalogs in EoR frequencies
  - VLA NVSS (Primarily northern Sky)
  - LOFAR LoTSS (Shimwell et al. 2022)
  - MWA GLEAM and GLEAM-X (Hurley-Walker et al 2017, 2022)
  - GMRT SCG (Riseley et al. 2016), TGSS (Intema et al. 2017)
- EoR specific catalogs and models
  - LOFAR NCP (Yatawatta et al. 2013)
  - MWA LoBES (Lynch et al. 2021)
- Already in point-source basis!
- But none covers the full sky, and each survey has different depth.
- Mock catalog based on source count distribution (e.g. Franzen et al 2019) can offer a good alternative for validation (though not for calibration)

Sky Models: A-Team Sources

- Very bright and persistent radio sources with “A” name ending
- Some have extended structures and can be partially resolved at long baseline, needing multi-point or shapelet models
- Shapelet models has been developed for Fornax A (Line et al 2020) and NCP sources (Yatawatta et al 2013) although not publicly available.

Source	RA	Dec	$S_{200\,\mathrm{MHz}}$/Jy	α
3C 444	22 14 26	−17 01 36	60	−0.96
Centaurus A	13 25 28	−43 01 09	1370	−0.50
Hydra A	09 18 06	−12 05 44	280	−0.96
Pictor A	05 19 50	−45 46 44	390	−0.99
Hercules A	16 51 08	+04 59 33	377	−1.07
Virgo A	12 30 49	+12 23 28	861	−0.86
Crab	05 34 32	+22 00 52	1340	−0.22
Cygnus A	19 59 28	+40 44 02	7920	−0.78
Cassiopeia A	23 23 28	+58 48 42	11900	−0.41

Table 2 from Hurley-Walker et al 2017

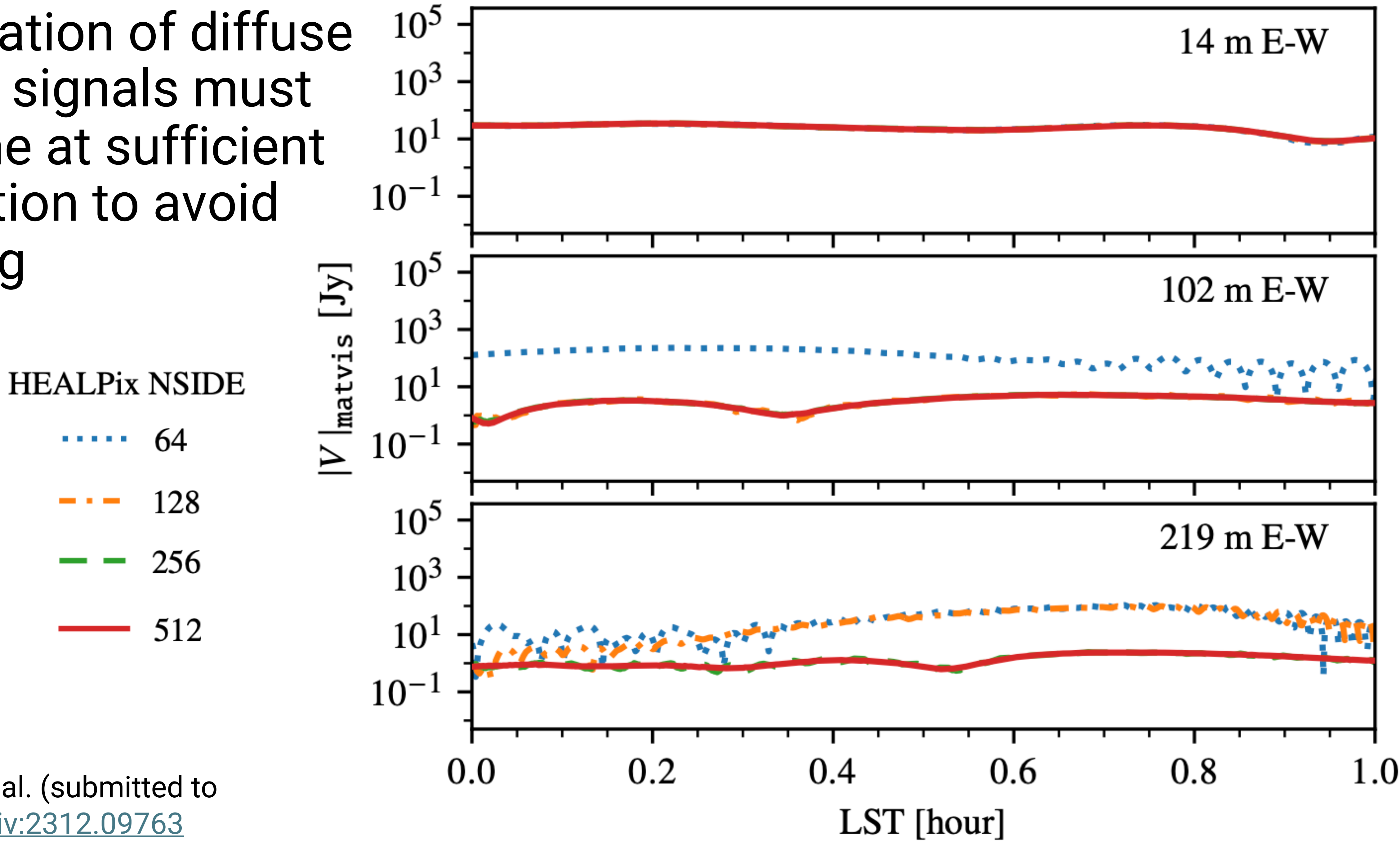
Sky Models: Diffuse Emission

- Must be pixelized (e.g. on a HEALPix grid) for simulators that use point-source basis
- Haslam 408 MHz from 1982(!) is still the most complete diffuse sky model that we have
- The reprocessed Haslam (Remazeilles et al. 2014) is known to have double counting issue
- PCA-based models are widely used: GSM (Oliveira-Costa et. al. 2008), pygsm, pygdsm, pysm3
  - Okay for validation
  - But make sure you know which data it is based on
  - Not really suitable for calibration. We need polarized maps for high-precision calibration (see e.g. Byrne et al 2022)

Sky Models: EoR model

- Hydrodynamic model is too small in volume and too computationally expensive for mock data simulation
- Semi-analytic model, e.g. 21cmFAST, can now produce a much larger simulation volume but not yet full-sky volume.
    - comoving cubes must be tiled into coeval maps via e.g. `cosmotile`
- Analytic model is nice for validation because we can generate the full-sky volume, and know exactly what we put in
- Must also be pixelized for simulators that use point-source approximation

Pixelization of diffuse or EoR signals must be done at sufficient resolution to avoid aliasing

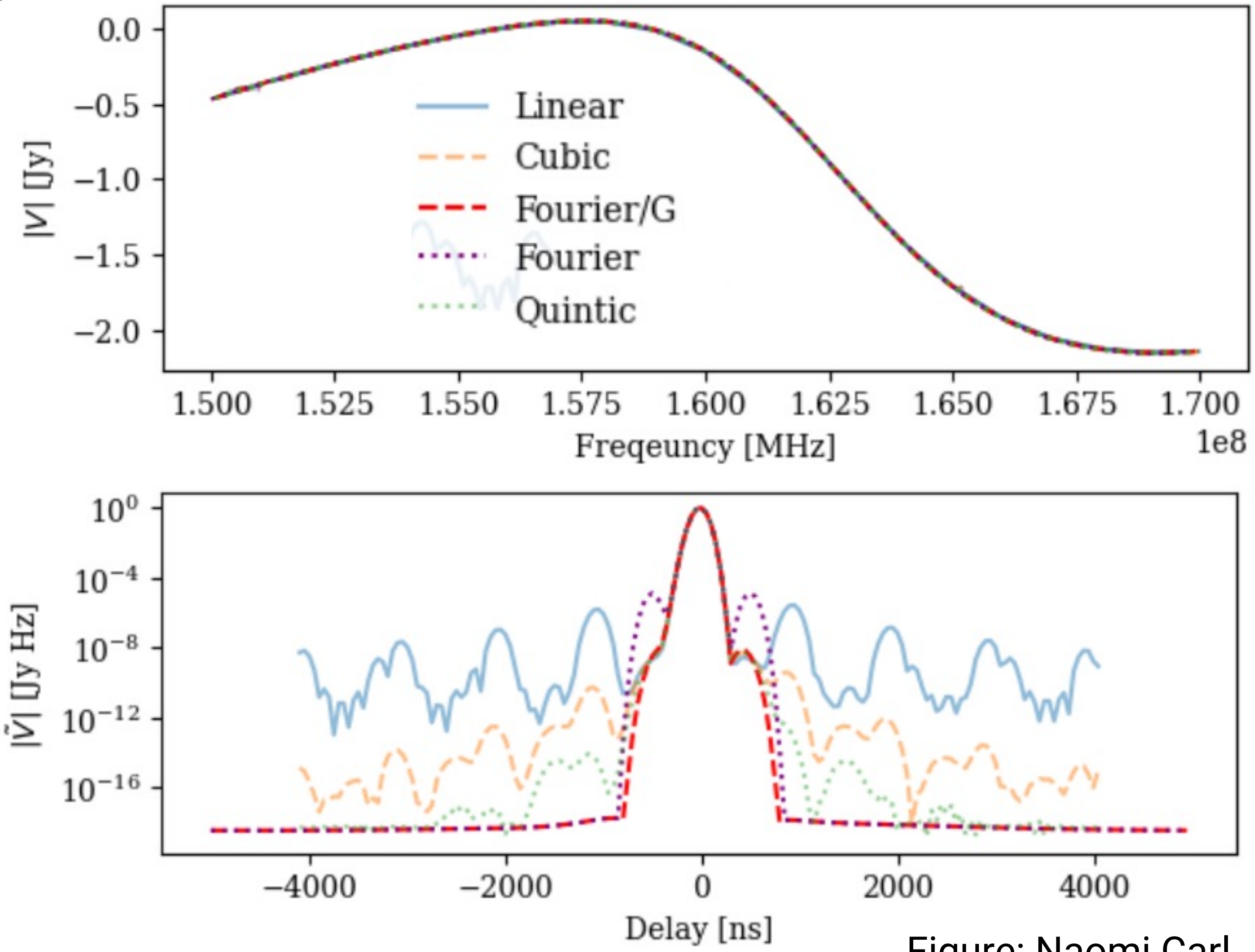


Kittiwisit et al. (submitted to RASTI), arXiv:2312.09763

Primary Beam Model

- Usually derived from computational electromagnetic (CEM) simulation, e.g. for HERA (Fagnoni et al. 2021), LOFAR (van Haarlem 2013), and MWA (Sokolowski et al. 2017)
- A few container packages for beam models has been developed: `everybeam` and `pyuvdata`
- Fitting an analytic model to the CEM beam is tricky but would make the simulation a lot faster (see Wilensky et al., submitted to MNRAS, arXiv:2403.13769)
- Evaluating a CEM-simulated beam at source positions requires interpolation

A higher-order spline interpolation is neccesary to ensure spectral smoothness



See (public) [HERA Memo #126] by Naomi Carl and Steven Murray

Figure: Naomi Carl

Quick Notes on Systematic Simulation

- `hera_sim`: a systematic simulator tools developed by the HERA validation team is publicly available.
  - It provides bandpass, mutual coupling, cable reflections, thermal noise, simple RFI, and mock visibility simulation tools, as well as a wrapper around more realistic visibility simulators.
- Paper(s) describing lessons learned from HERA validation process is in prep.

Outlooks for Validating Future Experiments

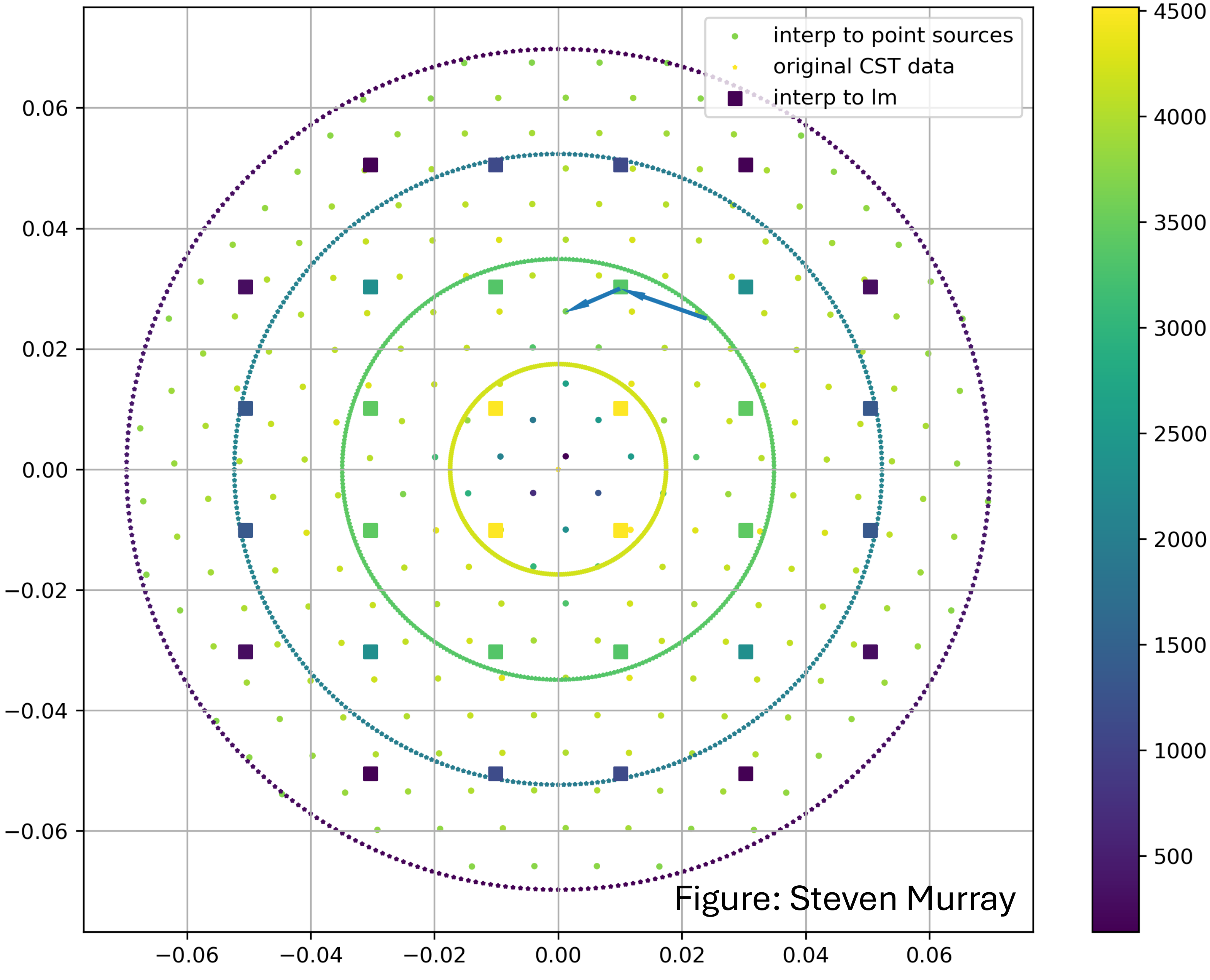
- Lots of already available tools, but we need more documentation, testing, integration and validation of them
- Existing sky and systematic models are okay, but several improvements can still be made
  - GSM can be improved if we have more data (and someone to do the work)
  - Polarized components – Little information
  - Adopting lightcone-based EoR model
- Cross—collaboration efforts would be ideal!

Summary

- Validation of the 21 cm cosmology analysis pipeline is crucial for credibility of our measurements
- Many sky and systematic models, and visibility simulators, have been developed although levels of documentation and testing can vary significantly
- Realism of the mock data simulation primarily depends on the sky models, but we lack the complete sky information in BAO/EoR/CD frequencies
- Making mock data is computationally expensive and has many non-trivial details (e.g. beam interpolation, aliasing from sky pixelization)
- Papers describing these details, and collaboration on modelling and software development, will be extremely useful for the community.

Photo: Dara Storer

- Because a beam usually has a pole at the zenith, interpolation should be done on an azimuth–altitude grid, not rectangular (l, m)
- See Wilensky et al, in prep.



`matvis` calculates per-baseline visibilities from an outer product of per-antenna visibilities

Hamaker's RIME on a point-source basis (e.g. pyuvsim)

$$V_{ij}^{pq}(\nu,t) = \sum_n \boldsymbol{A}_i^p(\boldsymbol{\theta}_n(t)) \cdot \boldsymbol{A}_j^{q*}(\boldsymbol{\theta}_n(t)) \times \mathbf{C}_{pq}^{(n)}(\nu)\, \exp\left(-2\pi \mathrm{i} \nu \tau_{ij}^{(n)}\right)$$

$$\tau_{ij}^{(n)} = \boldsymbol{X}_{\mathrm{hrz}}^{(n)}(t) \cdot \boldsymbol{b}_{ij}/c$$

matvis RIME (GPU implementable)

$$v_{ip}^{nk}(\nu,t) = \boldsymbol{A}_{ip}^{nk}(\nu,t)\sqrt{\mathbf{C}_{pp}^{(n)}(\nu)} \times \exp\left(-2\pi \mathrm{i}\nu\, \boldsymbol{X}_{\mathrm{hrz}}^{(n)}(t) \cdot \boldsymbol{x}_i/c\right)$$

$$V_{ij}^{pq} = \sum_{k,n} v_{ip}^{nk}\left(v_{jq}^{nk}\right)^{\dagger}$$

Trading some accuracies for speed