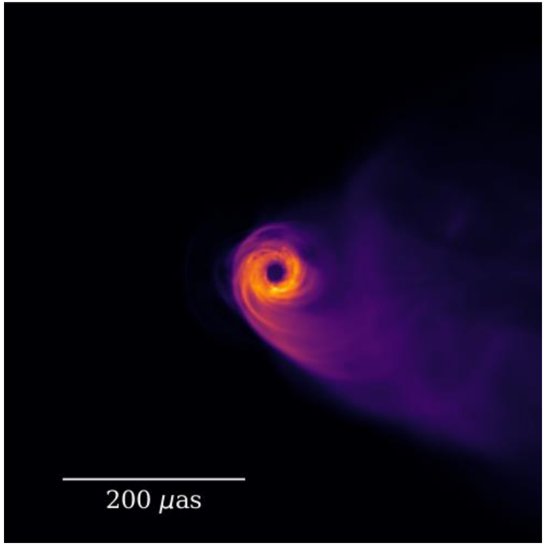
Multifrequency imaging for the ngEHT

Andrew Chael
NHFP Fellow, Princeton University
Broadening Horizons Workshop,
08/23/22

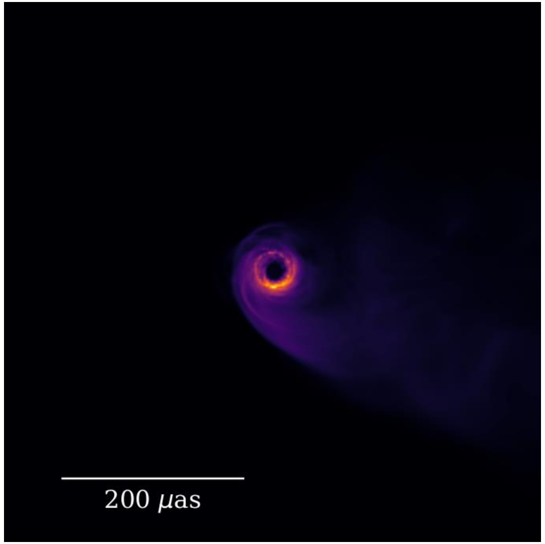
https://github.com/achael/eht-imaging
https://pypi.org/project/ehtim/

NASA Hubble Fellowship Program

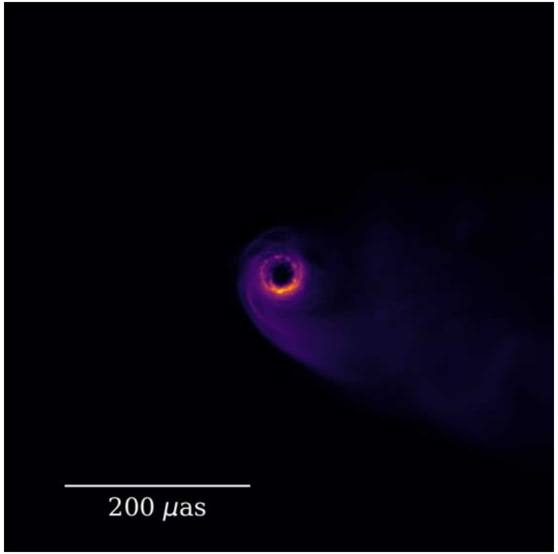
Multifrequency ngEHT Science: M87 jet



86 GHz



230 GHz

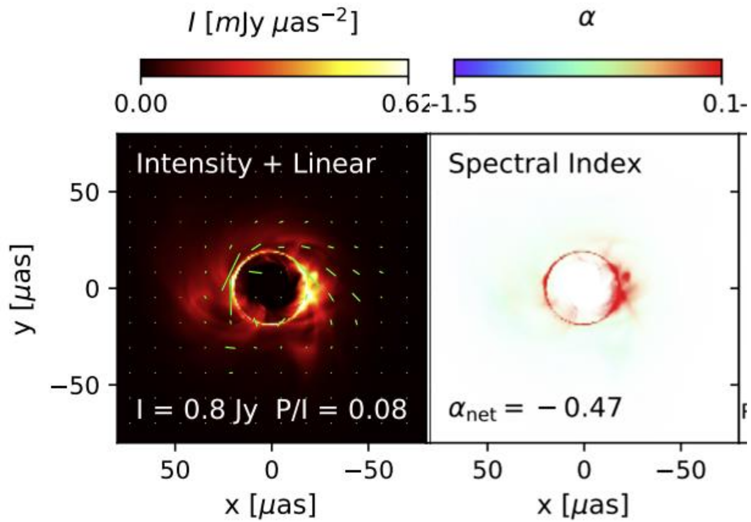


345 GHz

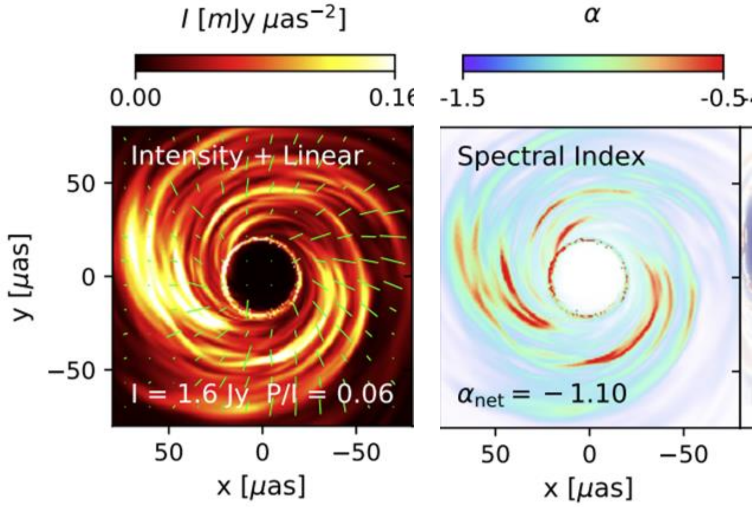
Multifrequency ngEHT images **can constrain plasma properties in the accretion disk & extended jet**

Multifrequency ngEHT Science: Accretion State

MAD model



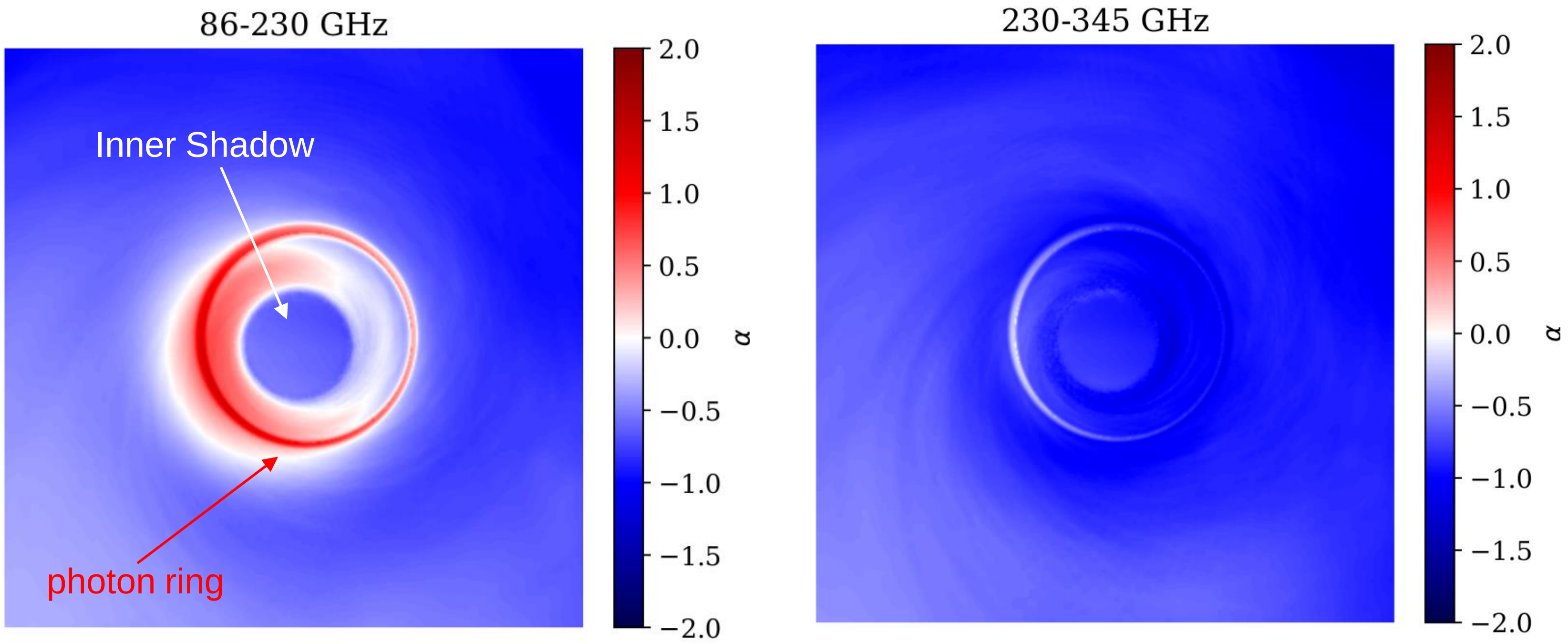
SANE model



Ricarte+ 2021 showed in the EHT GRMHD Library,
MAD models often have distinct spectral index structure from SANE models across the EHT 230 GHz band

Ricarte+ 2021

Multifrequency science: near-horizon features



Multifrequency ngEHT images **can constrain gravitational features** close to the black hole
The accretion disk terminating at the horizon has a different spectral index than jet material in front of the BH

Multifrequency imaging difficulties

- In principle, we can extract a spectral index from images reconstructed separately at different frequencies.

- This approach has several difficulties:
  - **Image registration**: EHT data has no absolute phase information; aligning separately reconstructed images introduces uncertainty
  - **Different uv coverage**: Images reconstructed at different frequencies have features/artifacts at different resolutions
  - **No regularization**: Reconstructing images separately does not allow us to incorporate prior information on the spectral index behavior
  - **Excessive degrees of freedom**: In regions where spectral index changes slowly, we only need 2 degrees of freedom to completely describe the multifrequency image, but we may have more datasets

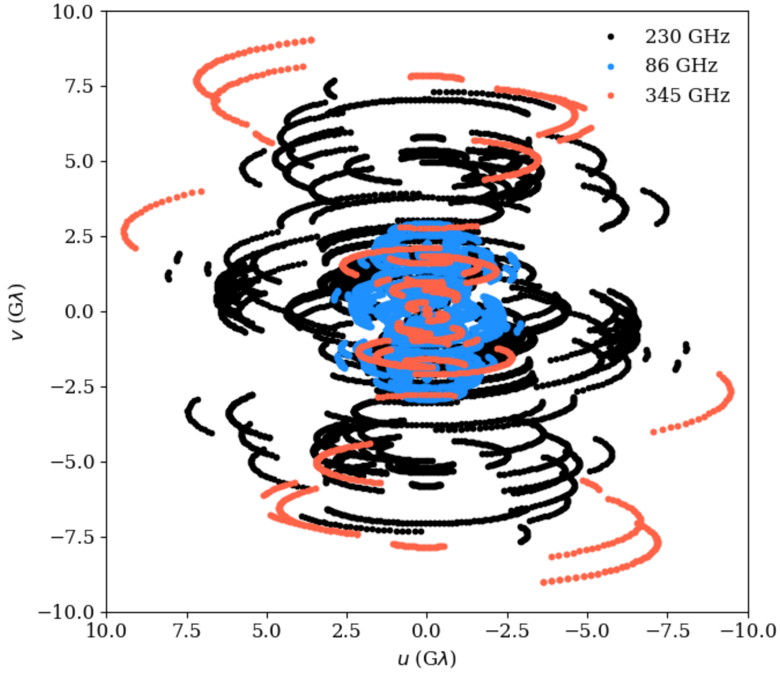
Propagating information between frequencies

- Imaging data at different frequencies together (with regularizing constraints) allows structural information to be shared across different reconstructions.

- Many new and short baselines will increase **dynamic range** of ngEHT

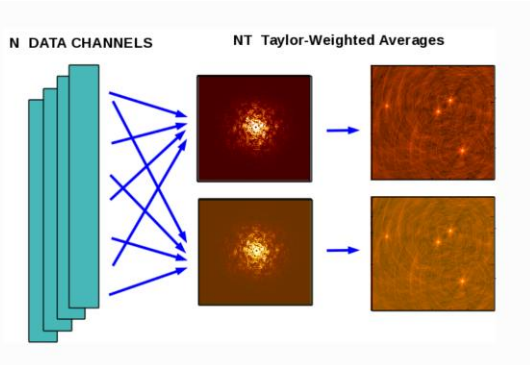
- 86 GHz can help constrain large-scale structure.

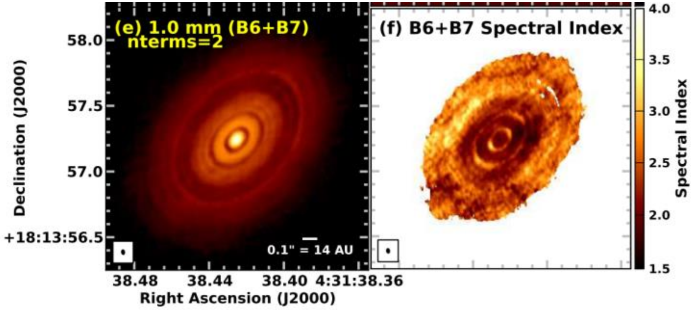
- 345 GHz will increase **resolution**



Multifrequency imaging software: CASA tclean

- Makes CLEAN images of Taylor series expansion of the image in log-frequency space
- Multiple channels can inform limited number of spectral terms (2 for reference frequency image and spectral index)
- Still fundamentally CLEAN:
  - models image as collection of point sources
  - requires phase-calibrated data

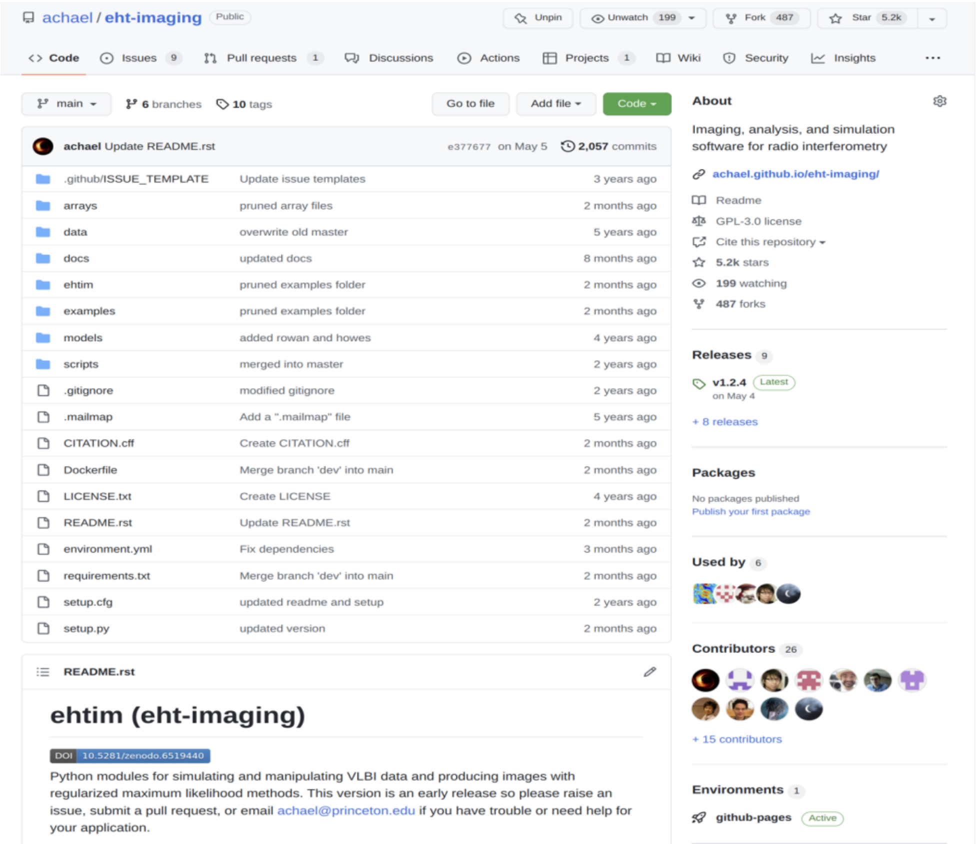




Rau & Cornwell 2011
ALMA Partnership+ 2015
image credit: casadocs.readthedocs.io

Multifrequency imaging software: eht-imaging

- Environment for plotting, analysis, generating synthetic data, calibration, and **imaging** of interferometric data with regularized maximum likelihood (RML)
- Built for EHT data and used in all EHT published images to date
- Widely applicable to other interferometric data sets!



Chael+2016,18

Regularized Maximum Likelihood Imaging (RML)

- Forward-models image from the source plane and attempts to find the best fit to the data, subject to **regularizing constraints**

- Minimizes the **objective function:**

$$J(\mathbf{I}) = \underbrace{-\sum \kappa_D \log \mathcal{L}(\mathbf{d}|\mathbf{I})}_{\text{data terms}} \underbrace{-\sum \lambda_R S_R(\mathbf{I})}_{\text{regularizers}}$$

- Can work directly on **robust data products:** direct fitting to closure phases and closure amplitudes

- **Flexible framework:** easy to experiment with different image models, likelihood, and regularizer terms

Effects of Regularization

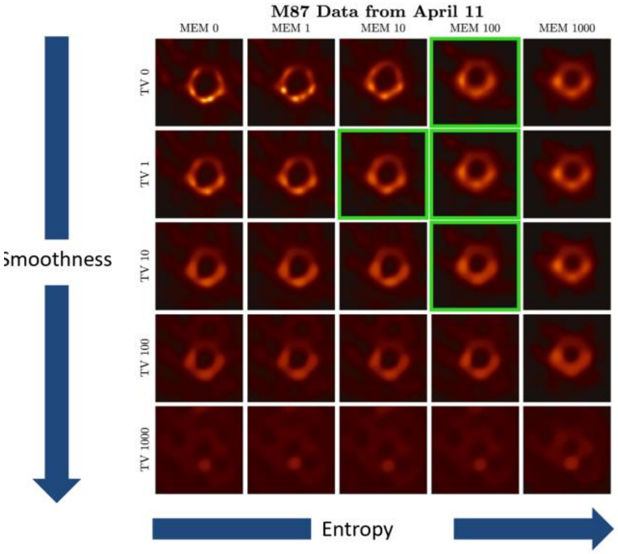


Image Credit: EHT Collaboration 2019 (Paper IV)

Multifrequency synthesis in `eht-imaging`

- **Solve directly for the spectral index map** (and higher order terms) simultaneously with the reference frequency image
- **Fit to data sets at multiple frequencies simultaneously**
- Apply regularizers to the reference frequency image and the spectral terms
- **Propagates structural information across frequencies**
- Automatically registers different frequency images against each other
- Straightforward extension of existing RML methods

Image model:

$$\mathbf{I}_i = \exp\left[\mathbf{y}_0 + \alpha x_i + \beta x_i^2\right]$$

$$x_i = \log\left[\nu_i/\nu_0\right], \quad \mathbf{y}_i = \log\left[\mathbf{I}_i\right],$$

Objective function:

$$J(\mathbf{I}_0, \alpha, \beta) = \sum_{\text{data terms}} \sum_{\nu_i} -\kappa_D \log \mathcal{L}(\mathbf{d}_i|\mathbf{I}_i) + \sum_{\text{regularizers}} -\lambda_I S_I(\mathbf{I}_0) - \lambda_\alpha S_\alpha(\alpha) - \lambda_\beta S_\beta(\beta)$$

Likelihood (amplitudes, closure phases, closure amplitudes)

Regularizers (on image and spectral terms)

Multifrequency synthesis in eht-imaging:example

```
imgr  = eh.imager.Imager([obs86,obs230,obs345], prior, prior, zbl,
                         data_term={'amp':1, 'cphase':1},
                         reg_term={'l1':.1, 'tv':.1, 'tv_alpha':1.e-3},
                         mf_which_solve=(1,1,0),
                         maxit=100, ttype='nfft')
imgr.make_image_I(mf=True,show_updates=False)
```

Spectral Index Regularizers

L2 norm: Prefers a fiducial value of the spectral index in the absence of data

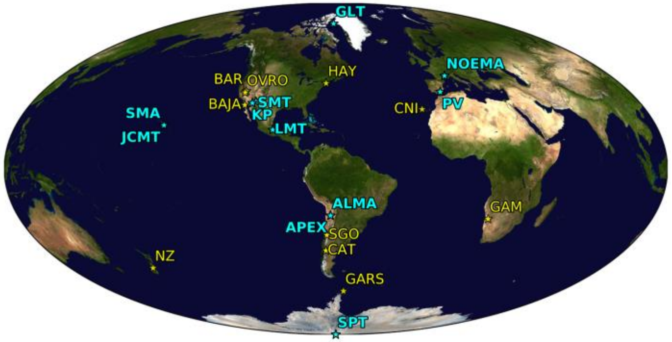
$$S_{\ell_2}(\alpha) = -\frac{1}{N}\sum_{l,m}(\alpha_{lm} - \alpha_0)^2$$

Total variation: Prefers smooth spectral index maps (supreses high frequency structure)

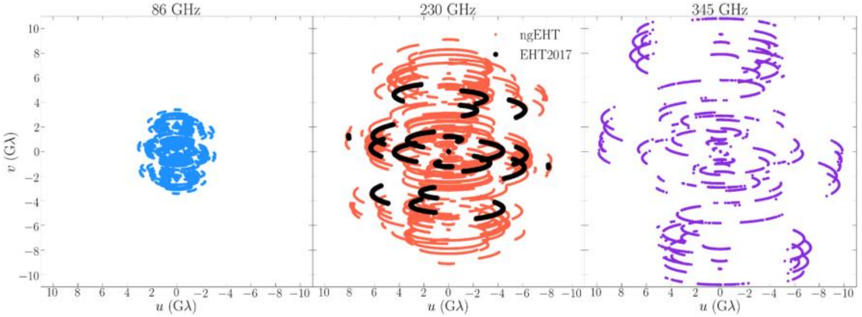
$$S_{\mathrm{TV}}(\alpha) = -\frac{\Theta_{\mathrm{beam}}}{N\Delta\theta}\sum_{l,m}\left[\left(\alpha_{l+1,m} - \alpha_{l,m}\right)^2 + \left(\alpha_{l,m+1} - \alpha_{l,m}\right)^2\right]^{1/2}$$

ngEHT multifrequency imaging simulations

- Data generated using the EHT+ngEHTa reference array
- Data generated at 86, 230, 345 GHz and at 1.3 mm sub-bands (213,215,227,229 GHz) for a variety of source models
- Data generated with full weather, sensitivity, and gain calibration modeling (Paine+ 2019, Raymond+ 2021):
  - 345 GHz coverage and sensitivity is significantly degraded by weather
  - No absolute visibility phase information
- Image reconstructions used identical procedures for imaging with/without mf synthesis
  - same likelihoods, regularizers, self-calibration strategy, etc

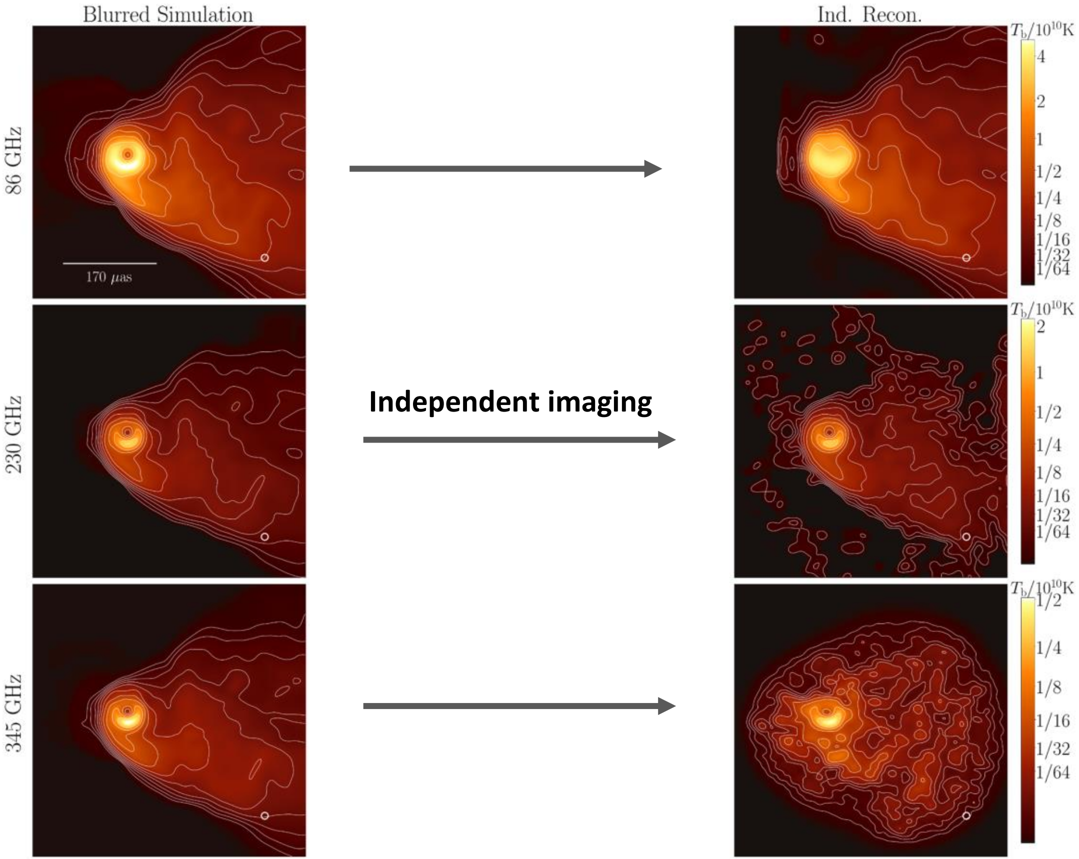


EHT+ngEHTa Reference Array
(Raymond+ 2021, Issaoun,Pesce,Roelofs+ in prep)



Chael+ 2022 in prep

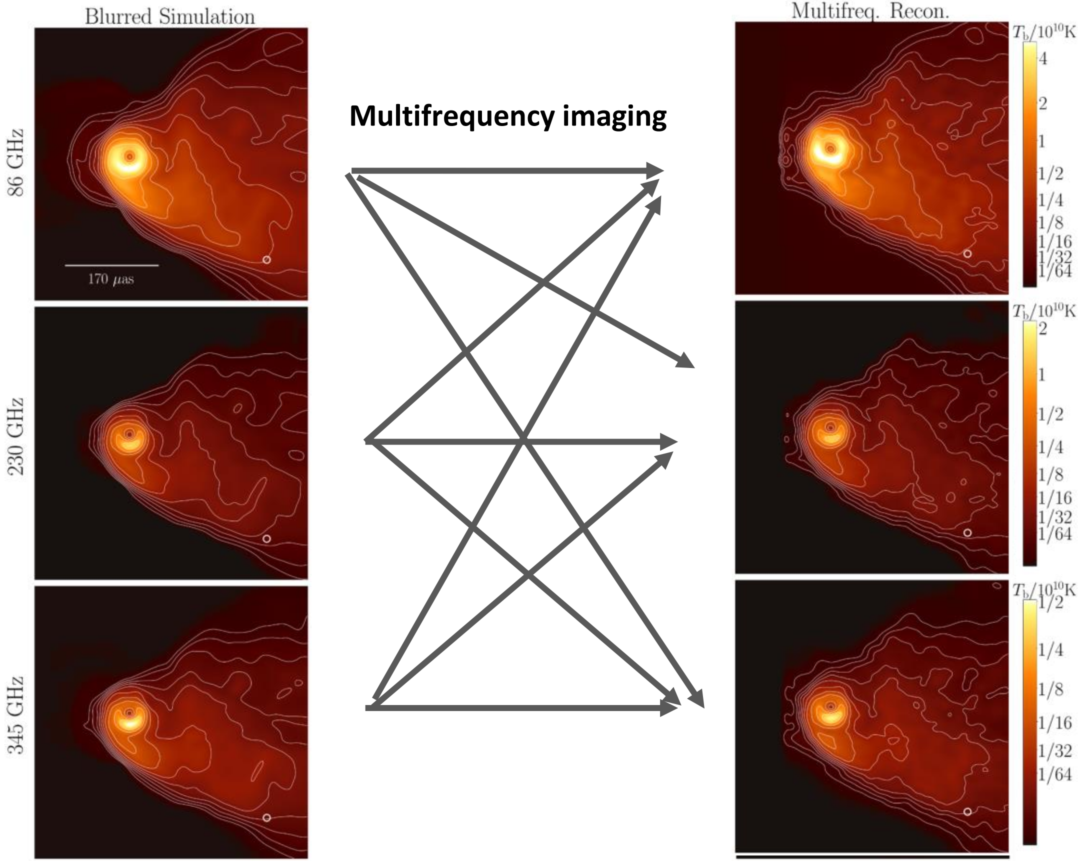
M87 Jet model (Chael+ 2019)



345 GHz sensitivity very poor - little recovery of extended structure!

Chael+ 2022 in prep

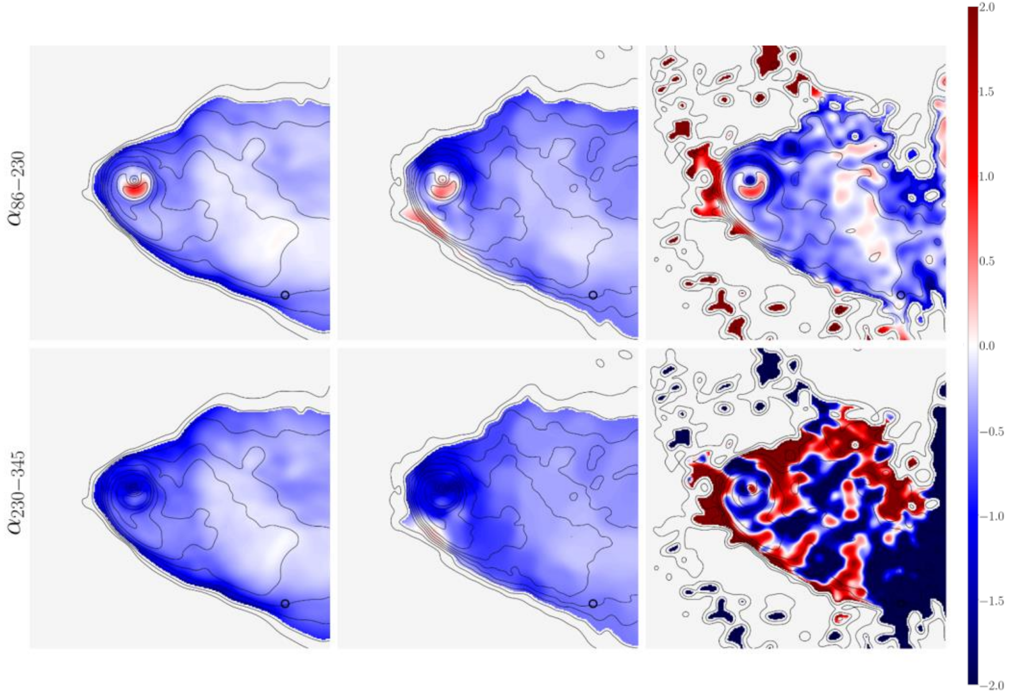
M87 Jet model (Chael+ 2019)



Propagating information across bands enhances resolution and dynamic range of all three reconstructions

Chael+ 2022 in prep

M87 Jet model (Chael+ 2019): Spectral Index

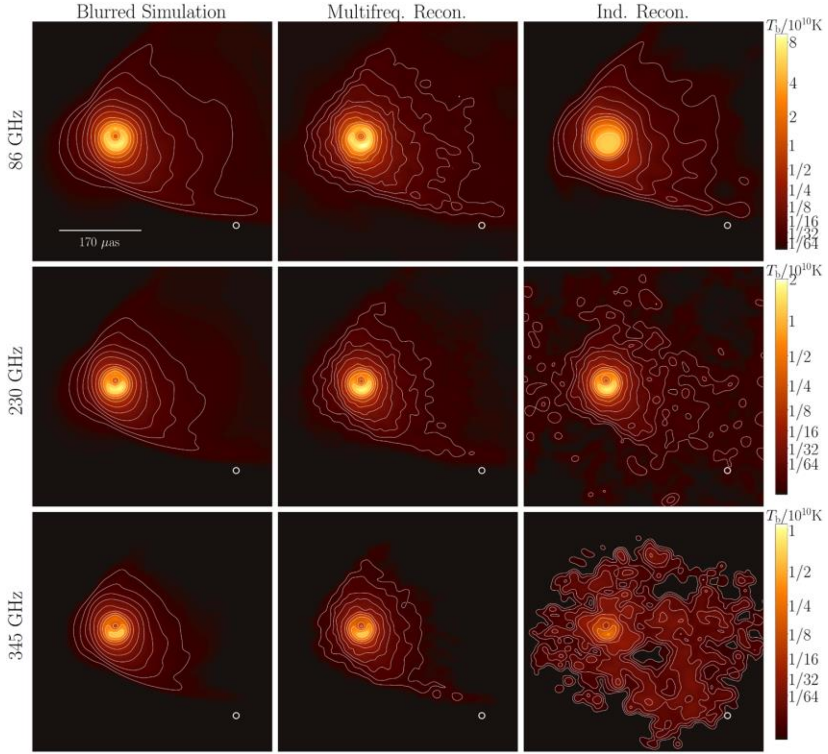


- Independent imaging some correct features of spectral index between 86-230, but with significant artifacts
  - Does not recover any correct details of 230-345 spectral index
- Multifrequency imaging performs better at recovering spectral index between both pairs of frequencies
  - Still some artifacts

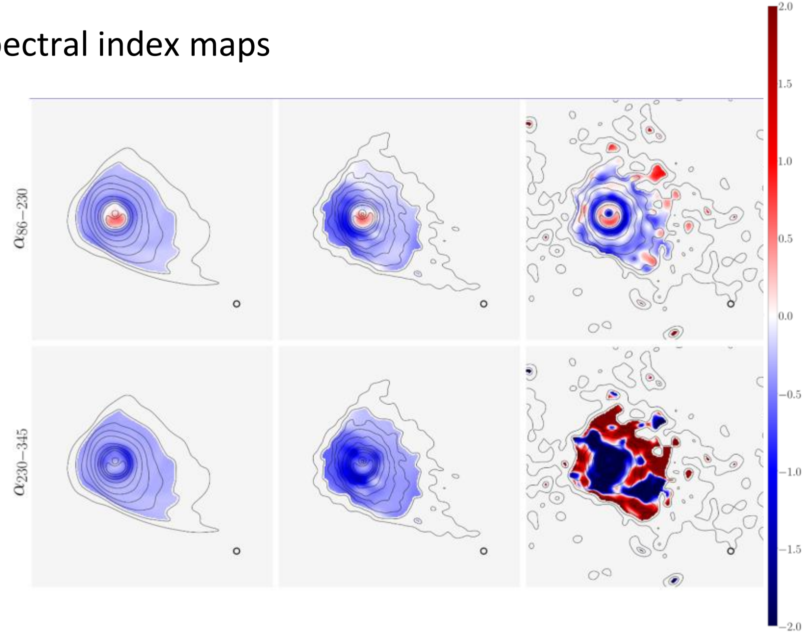
Chael+ 2022 in prep

M87 Jet model (Fromm+ 2021)

Images



Spectral index maps

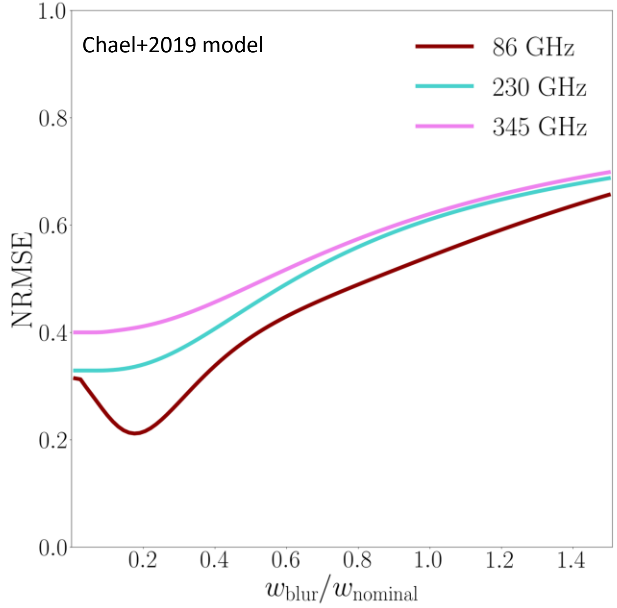


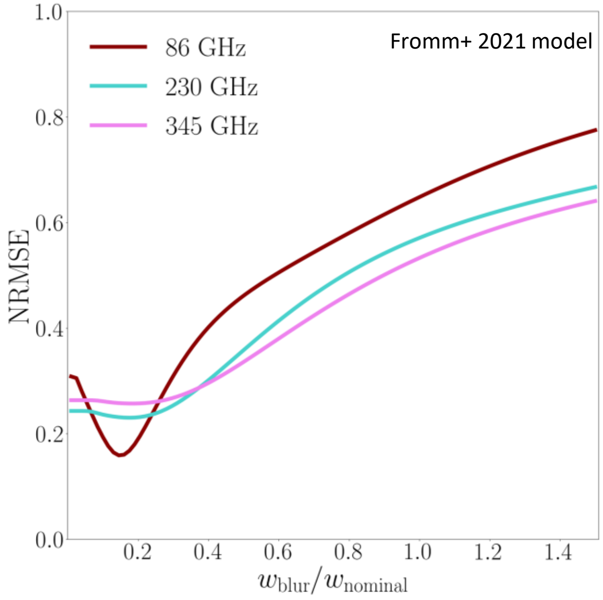
`eht-imaging` multifrequency synthesis also performs well on simulated ngEHT observations of this lower-brightness M87 jet

Chael+ 2022 in prep

Superresolution

Reconstruction error compared to ground truth





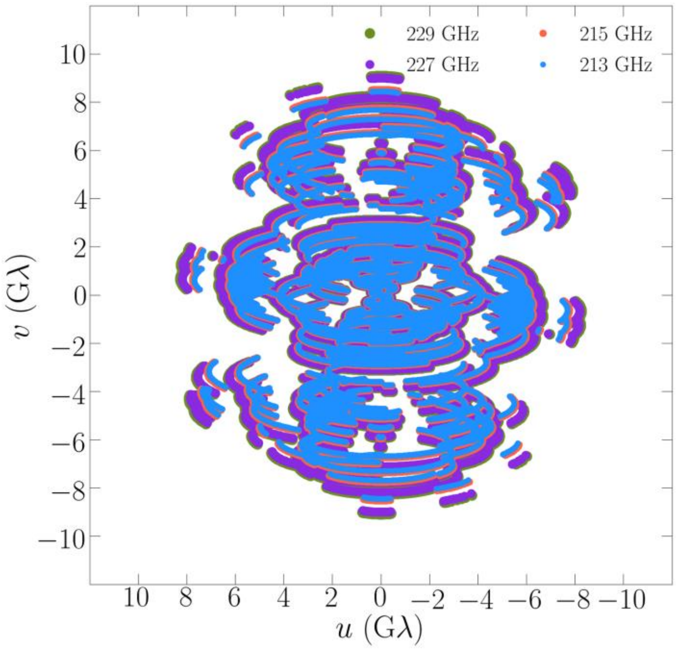
fraction of nominal beam

Multifrequency imaging from 86-345 GHz allows for superresolution at 86 GHz on order of ~20% of nominal resolution

Chael+ 2022 in prep

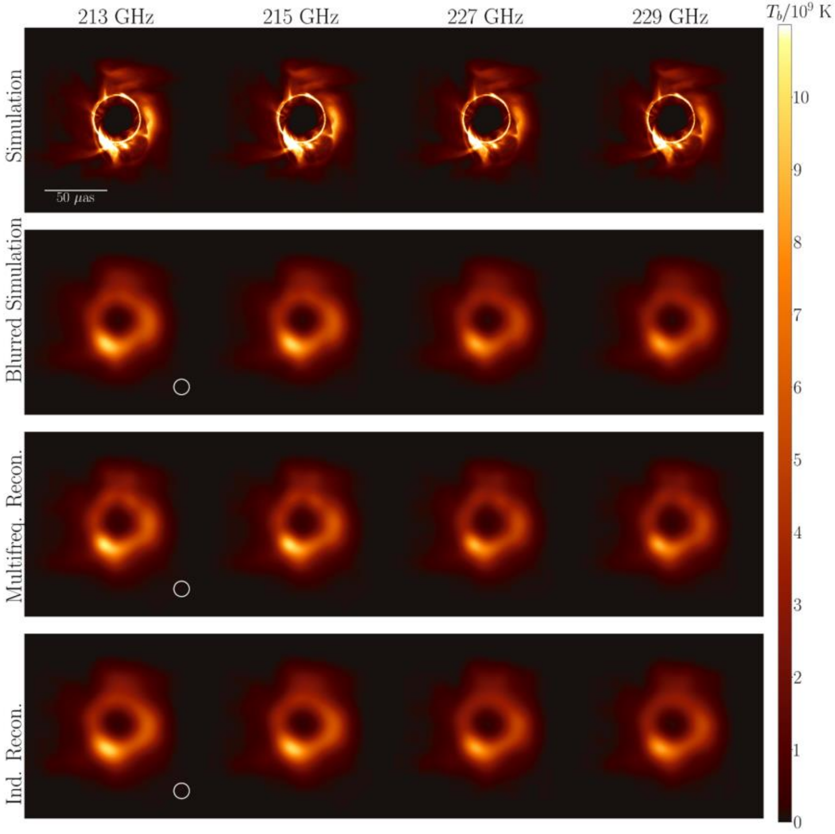
Imaging over a narrower frequency range

- Over the ngEHT bands around 1.3 mm, we can accurately approximate the image without spectral curvature.
- Image 213, 215, 227, 229 GHz bands together & recover the spectral index map.
  - Short $\Delta\nu$ lever arm makes this very difficult with independent image reconstructions
- Use simulated images from Ricarte+2021



Imaging over a narrower frequency range

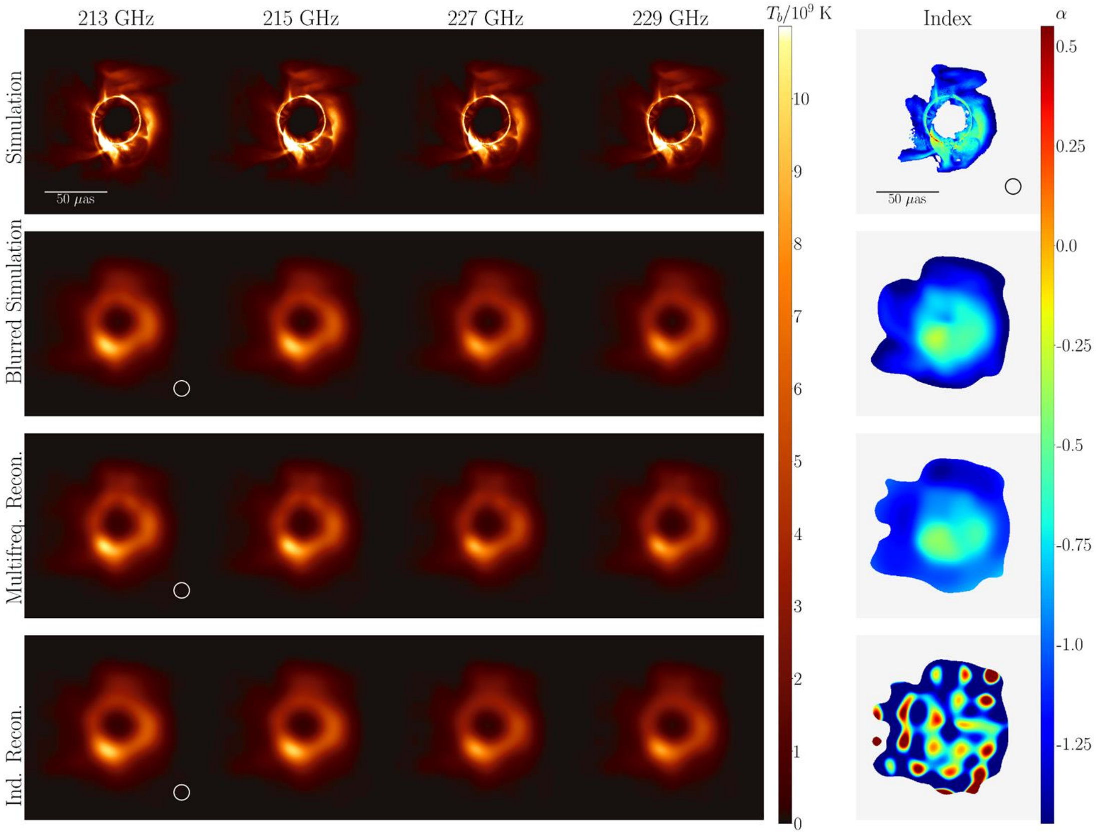
Multifrequency and independent imaging results look nearly indistinguishable by eye



Chael+ 2022 in prep

Imaging over a narrower frequency range

Multifrequency and independent imaging results look nearly indistinguishable by eye

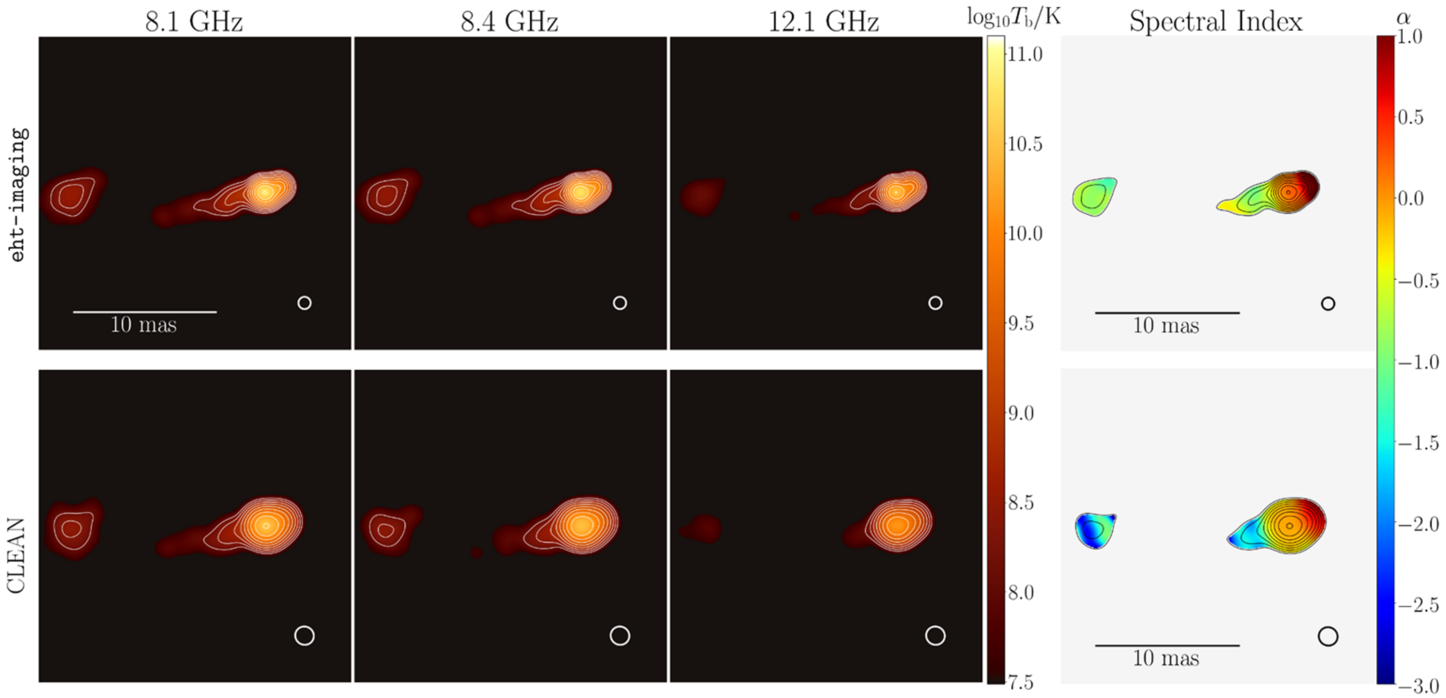


Multifrequency imaging recovers the spectral index map accurately, but independent imaging is limited by small differences in the image brightness between successive bands

Chael+ 2022 in prep

Real data: VLBA MOJAVE observations

0212+73

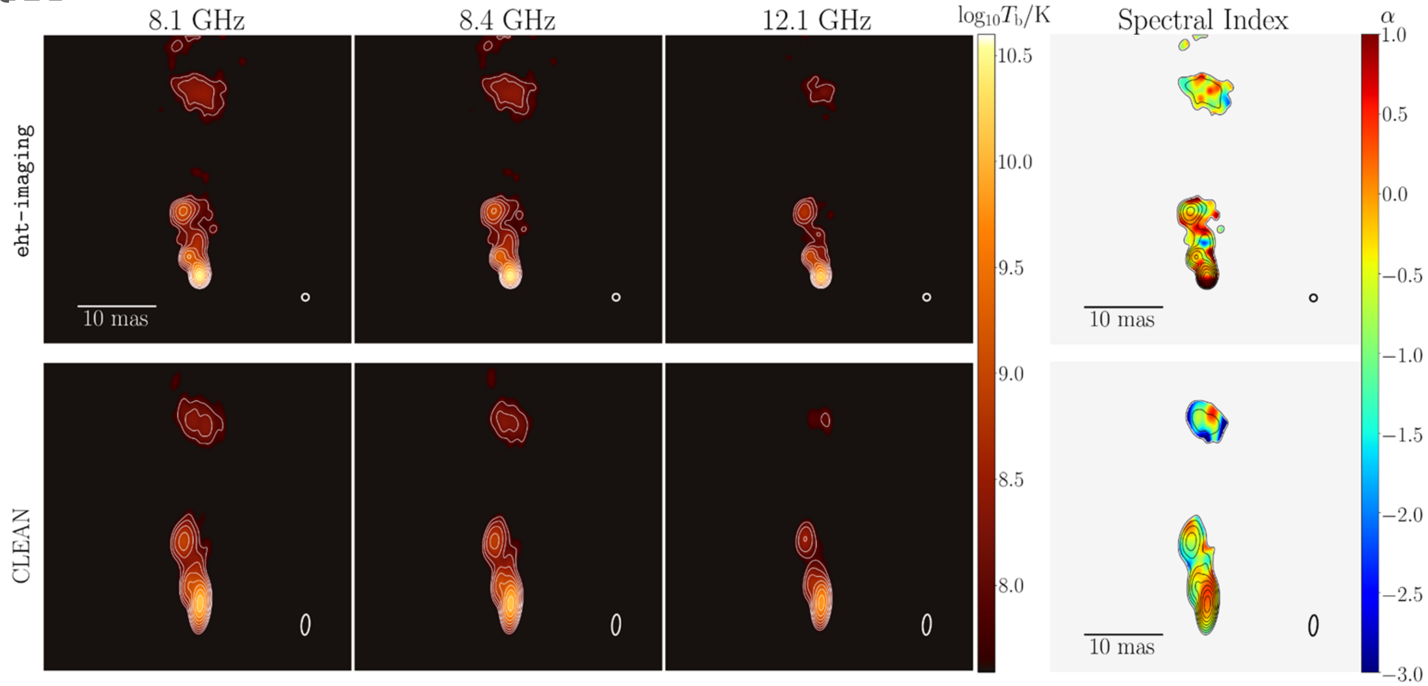


Chael+ 2022 in prep

Hovatta+2014, Lister+ 2018

Real data: VLBA MOJAVE observations

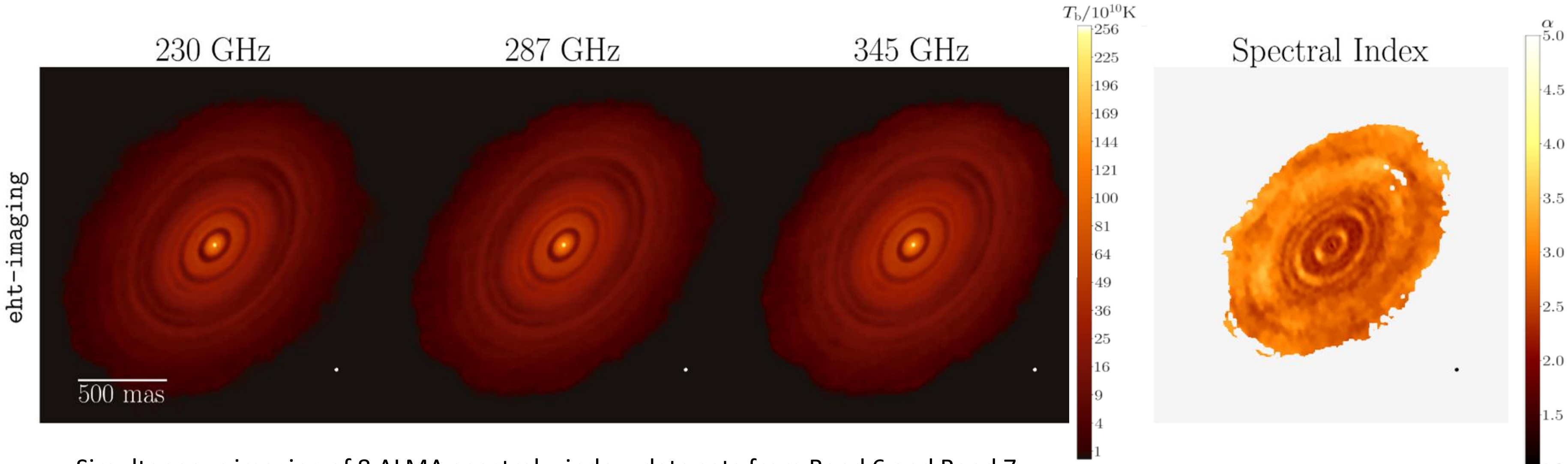
NRAO 530



Chael+ 2022 in prep

Hovatta+2014, Lister+ 2018

Real data: ALMA HL Tau observations



Simultaneous imaging of 8 ALMA spectral window data sets from Band 6 and Band 7

ALMA Partnership+ 2015

Chael+ 2022 in prep

Next Steps

- Paper in progress - ideas and questions welcome!
- Application to more real data sets
  - EHT 2017 + GMVA at 86 GHz?
- Comparison of ngEHT simulated imaging results with realistic application of frequency phase transfer.
- Rotation measure synthesis!

Summary

- Multifrequency data will be a key part of ngEHT science and has great potential!
- RML multifrequency synthesis is implemented in eht-imaging and ready for application on EHT and ngEHT datasets
- RML multifrequency synthesis enhances the accuracy of recovered spectral index maps as well as the resolution and dynamic range of single-frequency images.
- You can play with the method now in eht-imaging, ideas/contributions welcome!
    - This (and other) methods for multifrequency analysis will be a topic in the static imaging subgroup