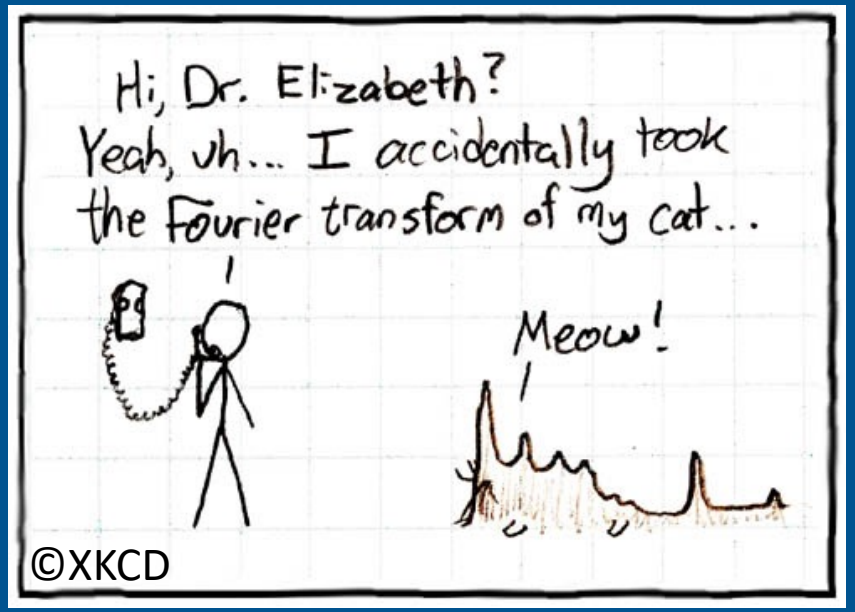
Very Long Baseline Interferometry



Ilse van Bemmel

(JIVE)

Your tutors

- Suma Murthy
- Gabor Orosz
- Zsolt Paragi
- Myself

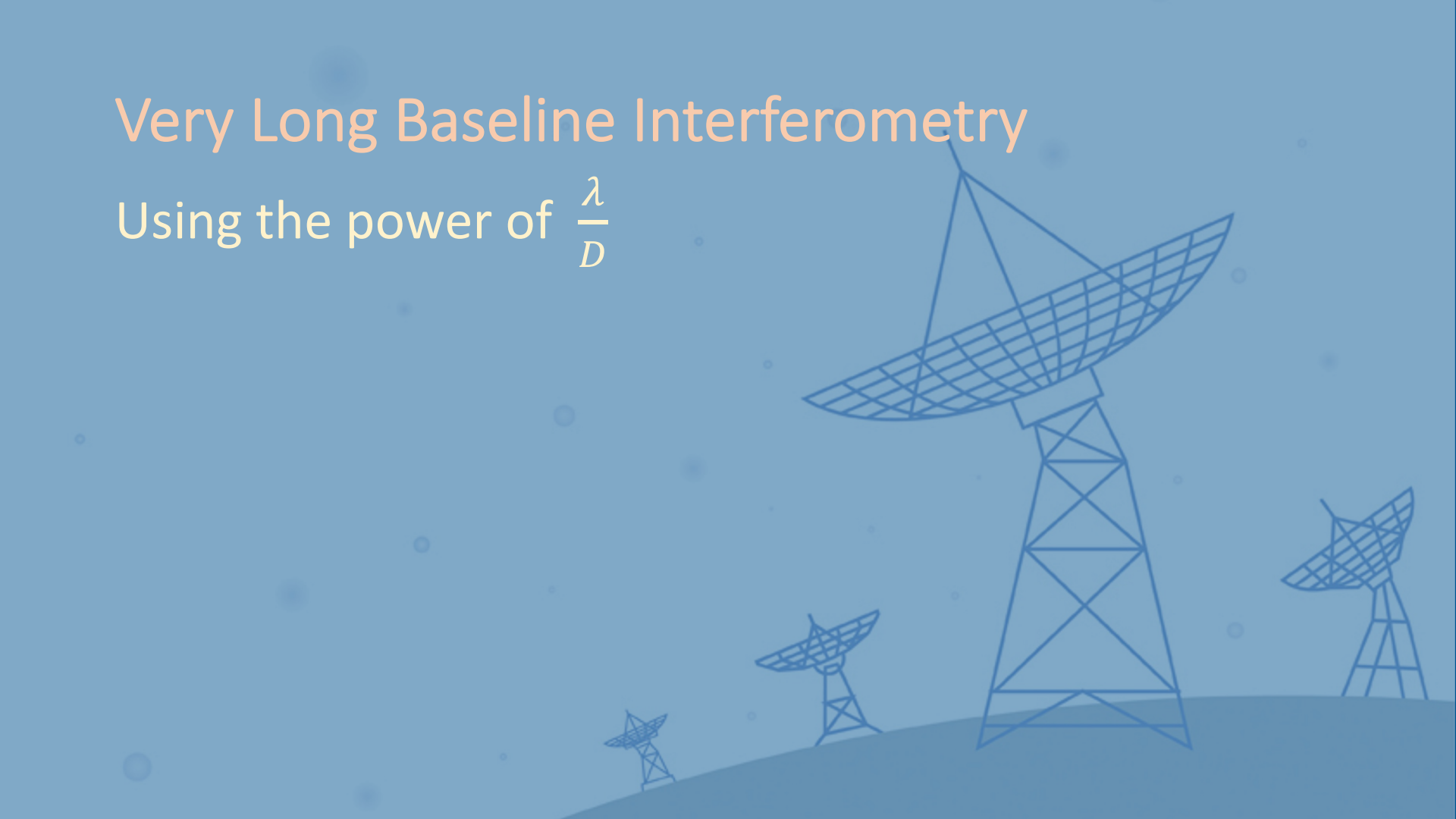
Overview of VLBI lectures

- Three sessions today:
  1. VLBI technology
  2. VLBI science and calibration
  3. Demo/tutorial: living on the fringe

- Advanced sessions tomorrow:
  1. Calibration: from archive to dirty image (Suma & Ilse)
  2. Imaging with Difmap (Gabor & Zsolt)

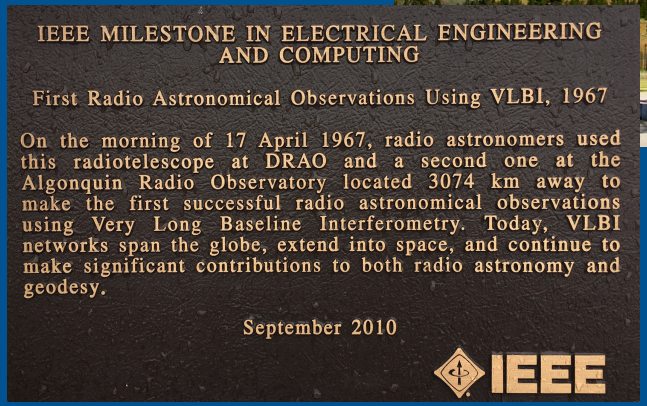
Very Long Baseline Interferometry

Using the power of $\frac{\lambda}{D}$



History

- Almost 55 years old
  - Canada to US
  - Transatlantic: US to Onsala
- First VLBI networks late 1970's
  - European VLBI Network ~1980
- JIVE established ~30 years ago



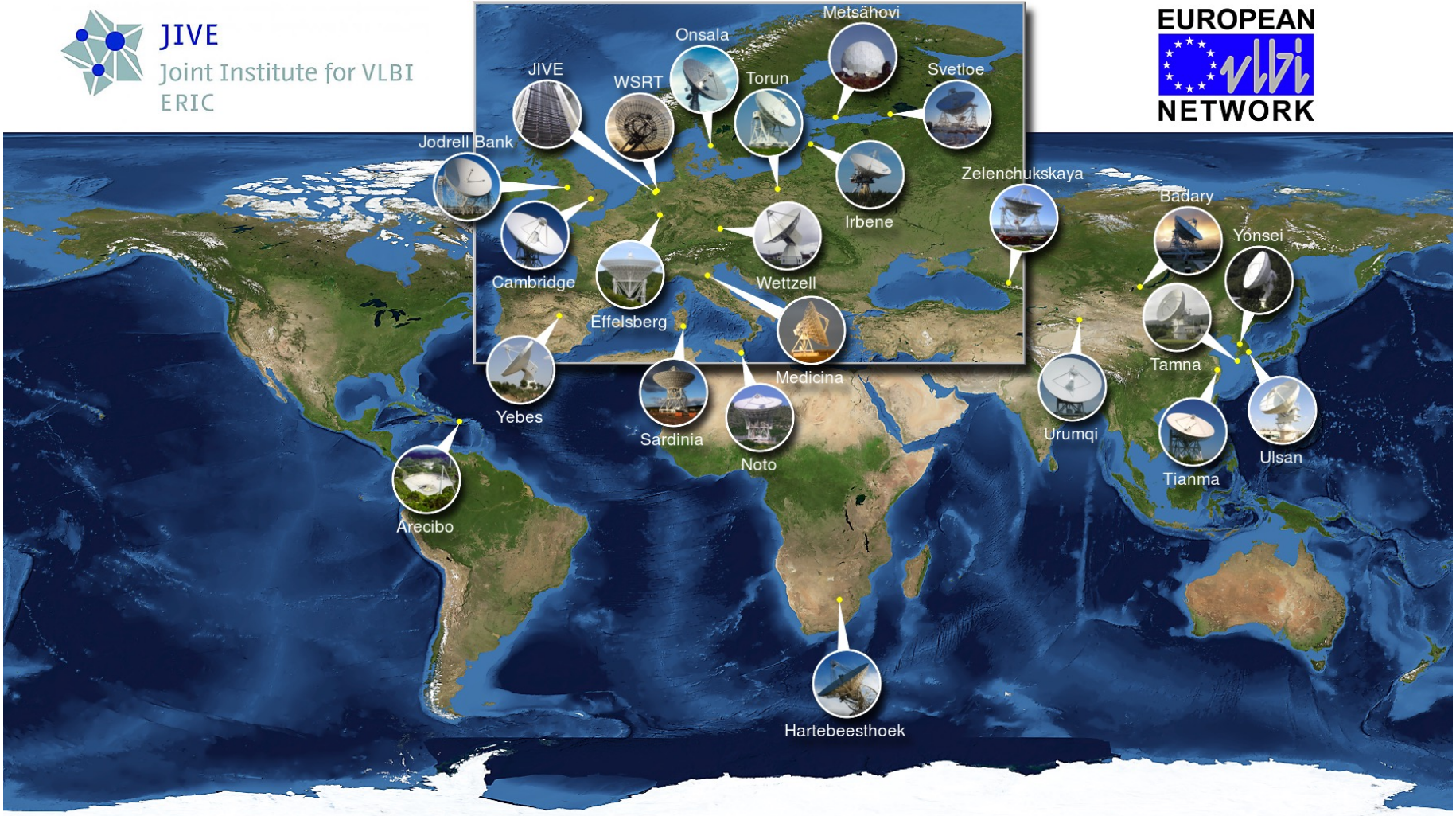
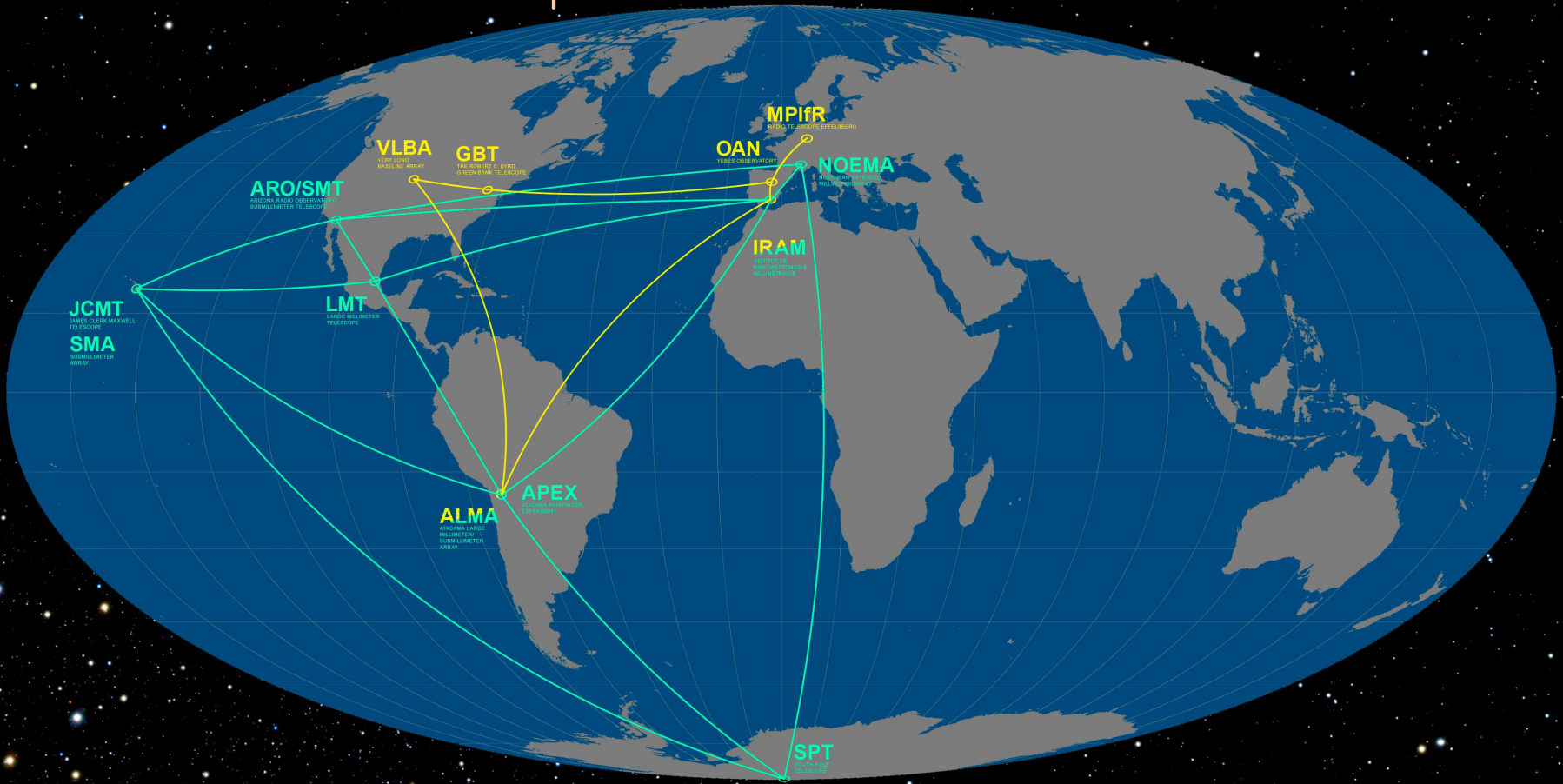


Image by Paul Boven (boven@jive.eu). Satellite image: Blue Marble Next Generation, courtesy of Nasa Visible Earth (visibleearth.nasa.gov).

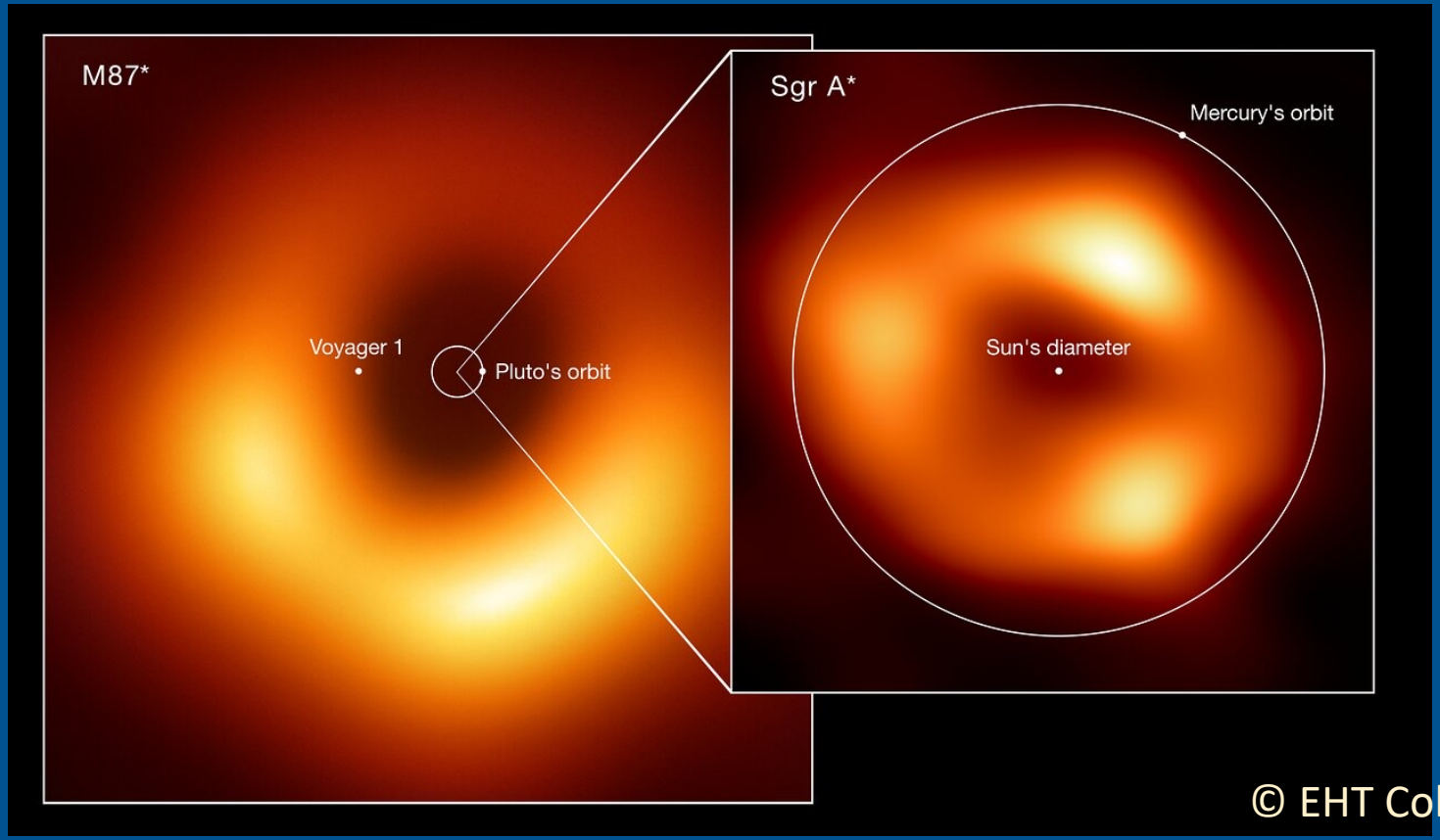
Event Horizon Telescope



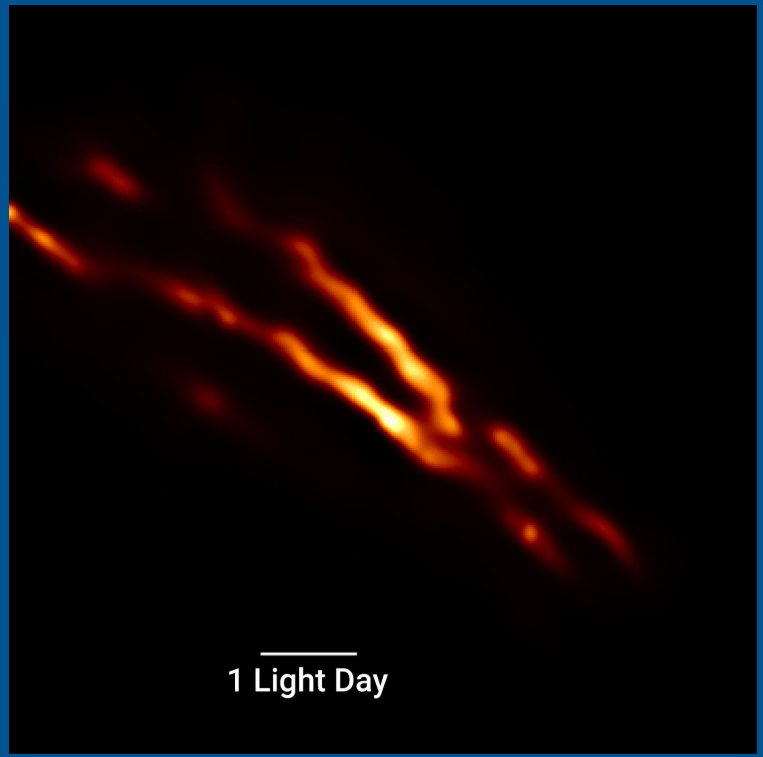
Science cases

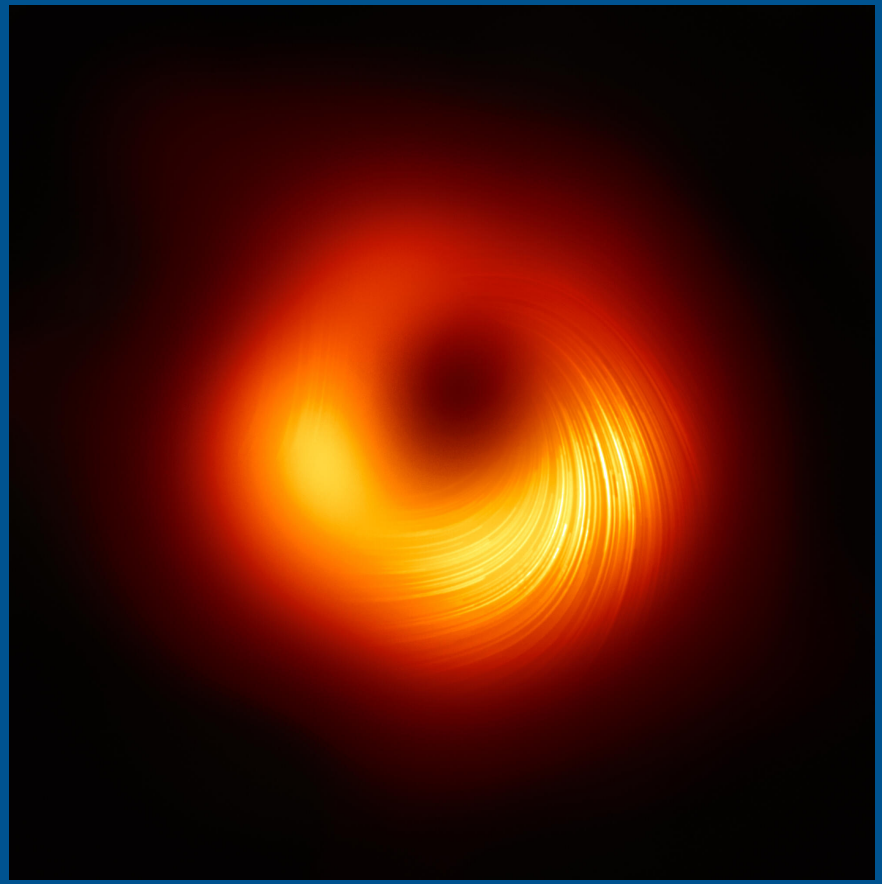
Compact and bright objects

Science highlights

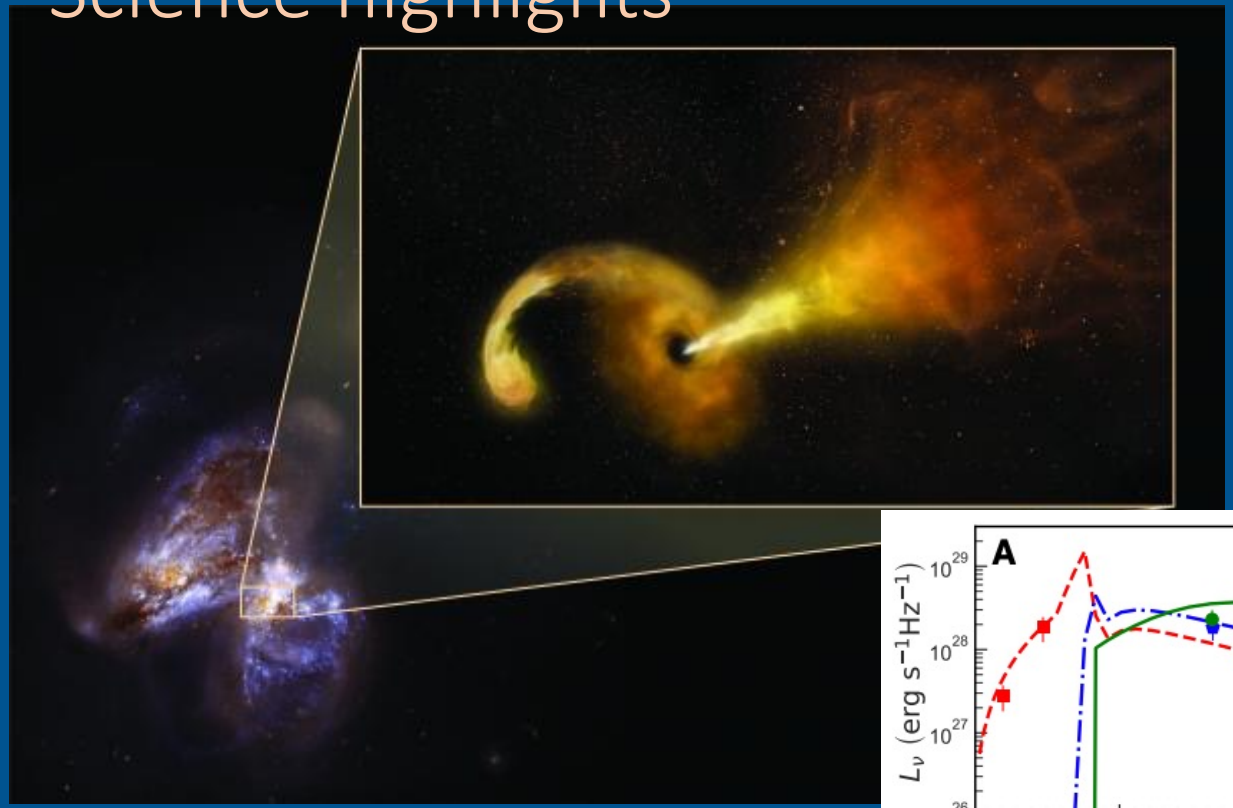


Science highlights

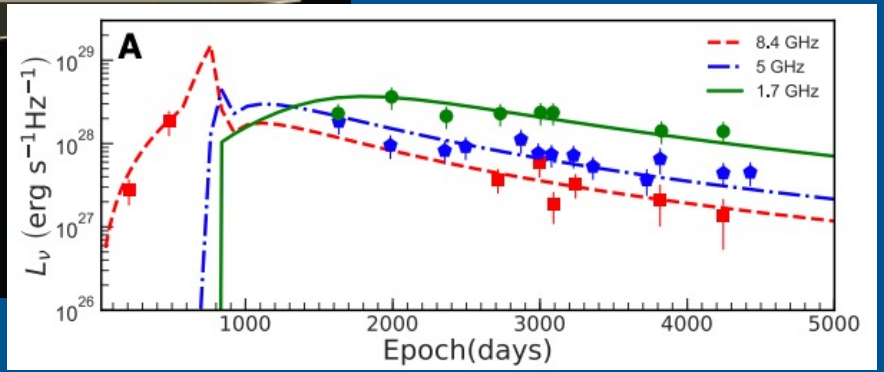




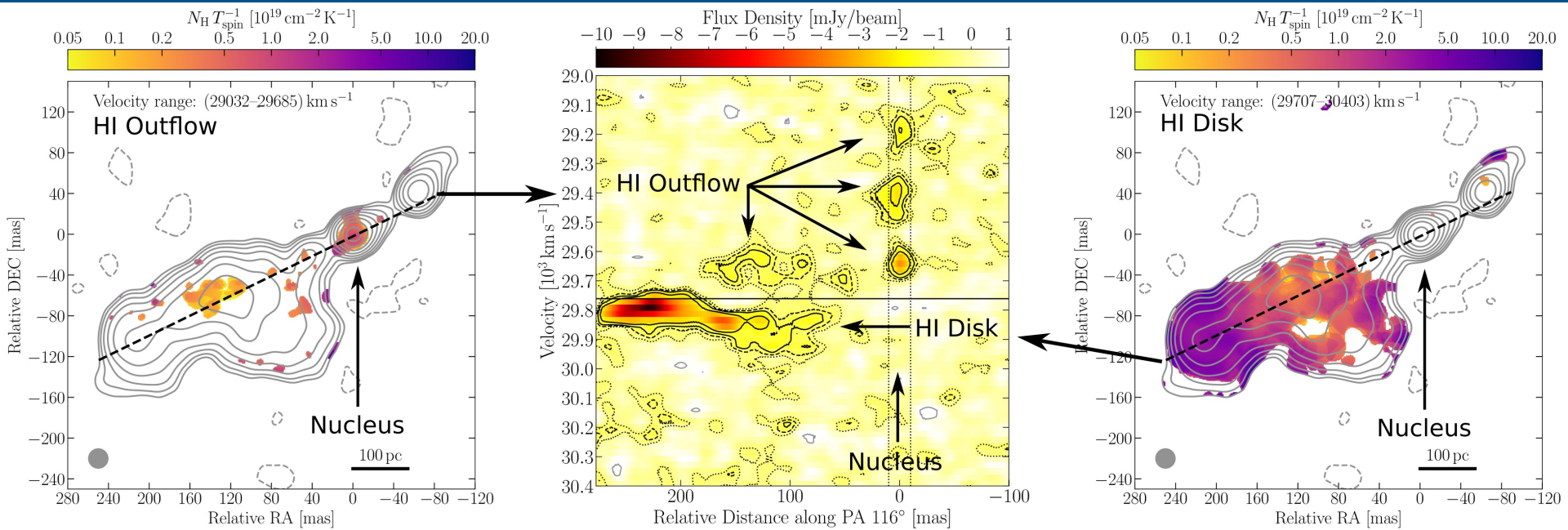
Science highlights



Mattila+ 2018

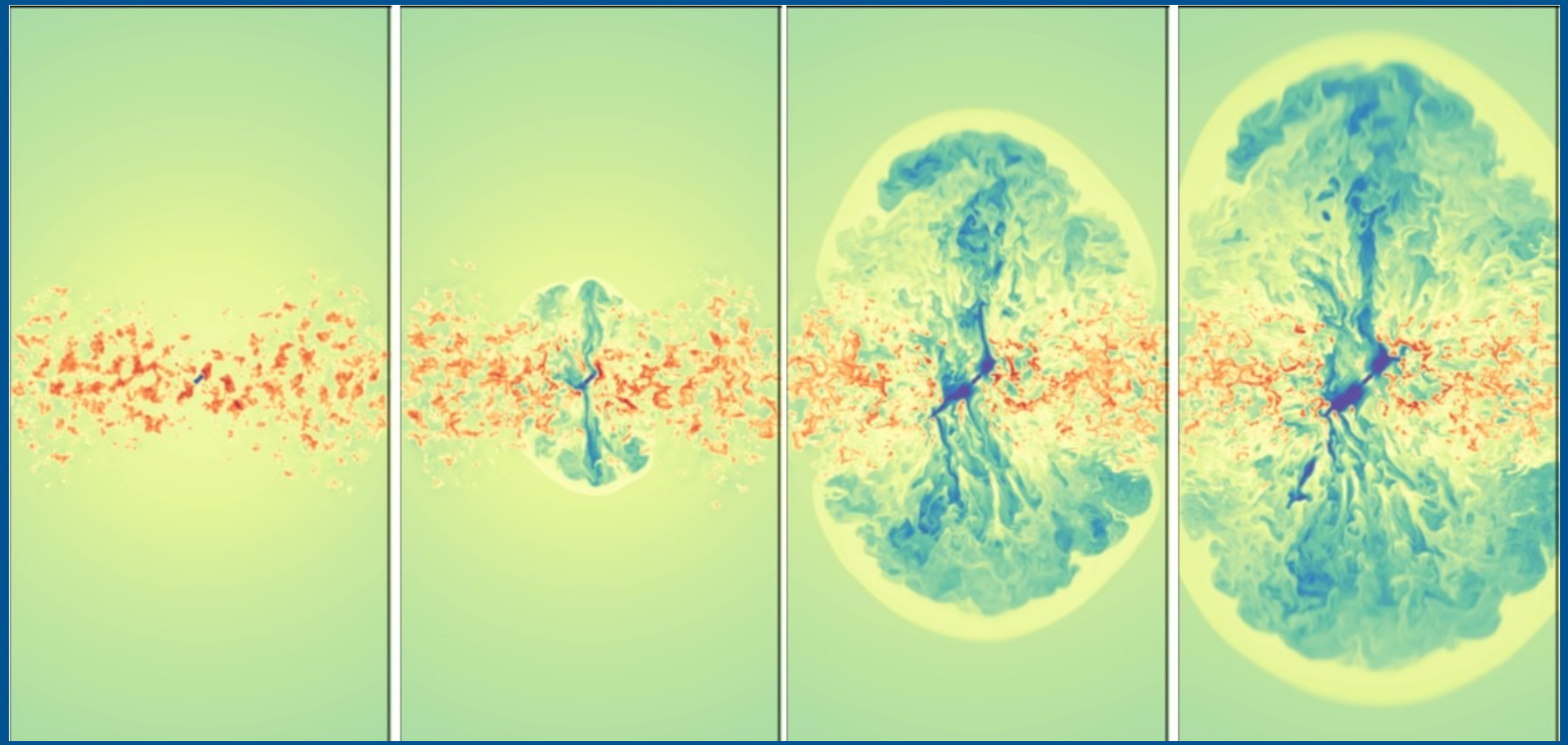


Science highlights



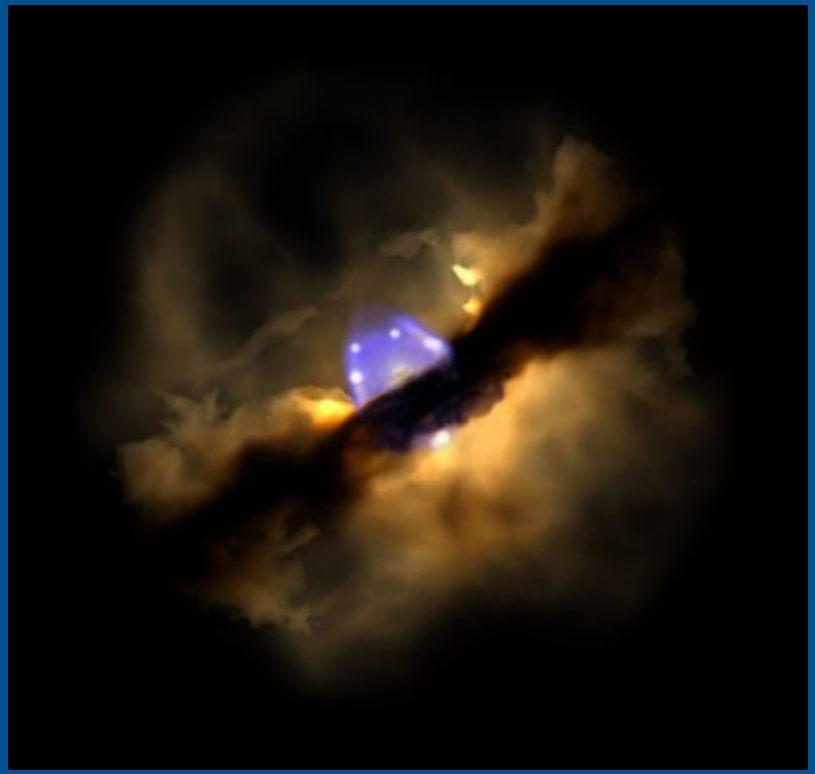
Schulz+ 2018, Morganti+ 2018

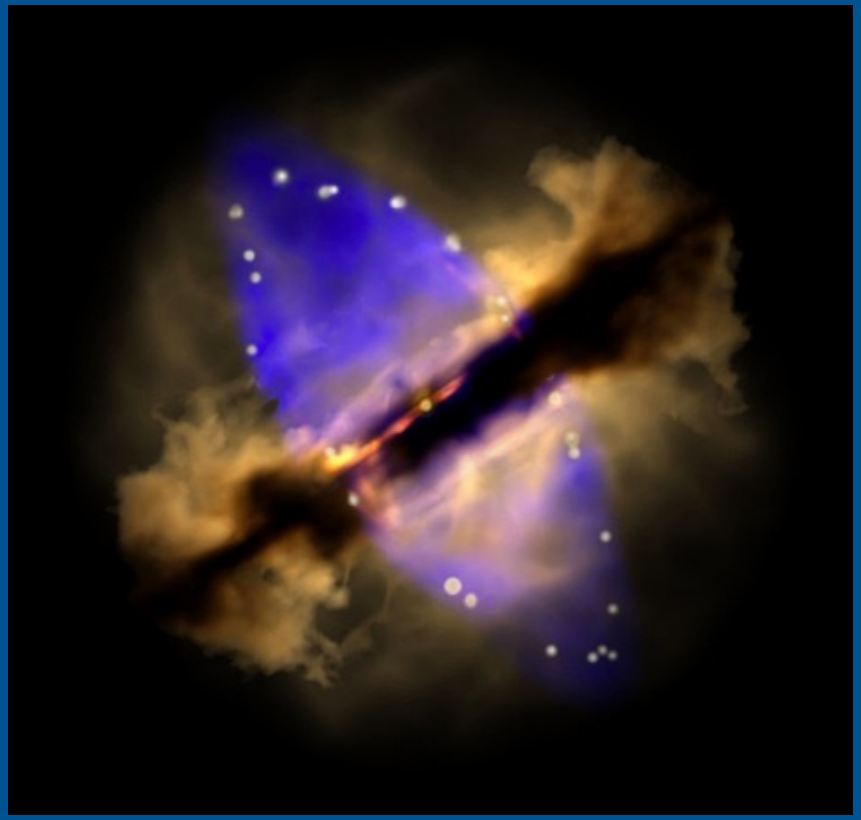
Science highlights



Murthy+ 2022

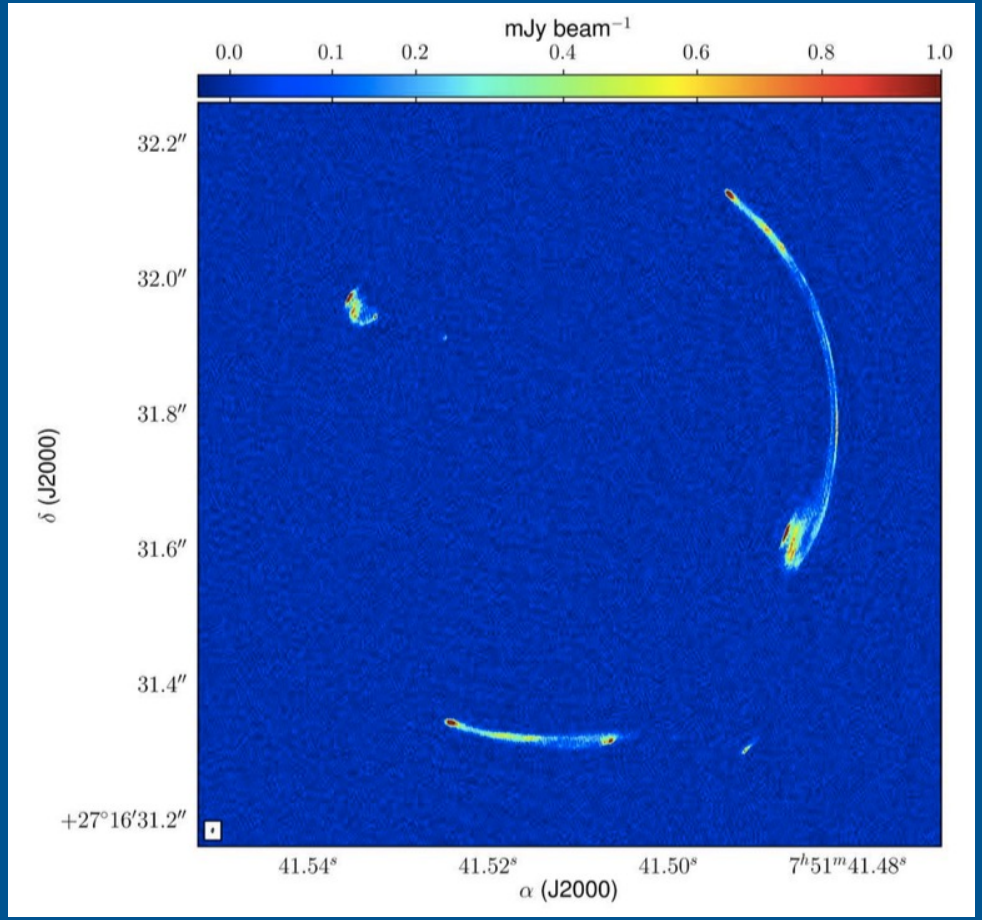
Science highlights





Carrasco-González+ 2015

Science highlights

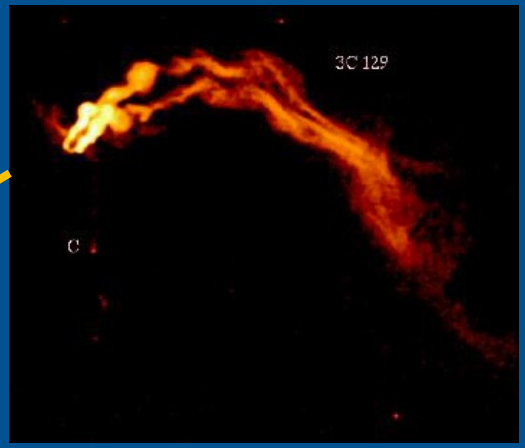


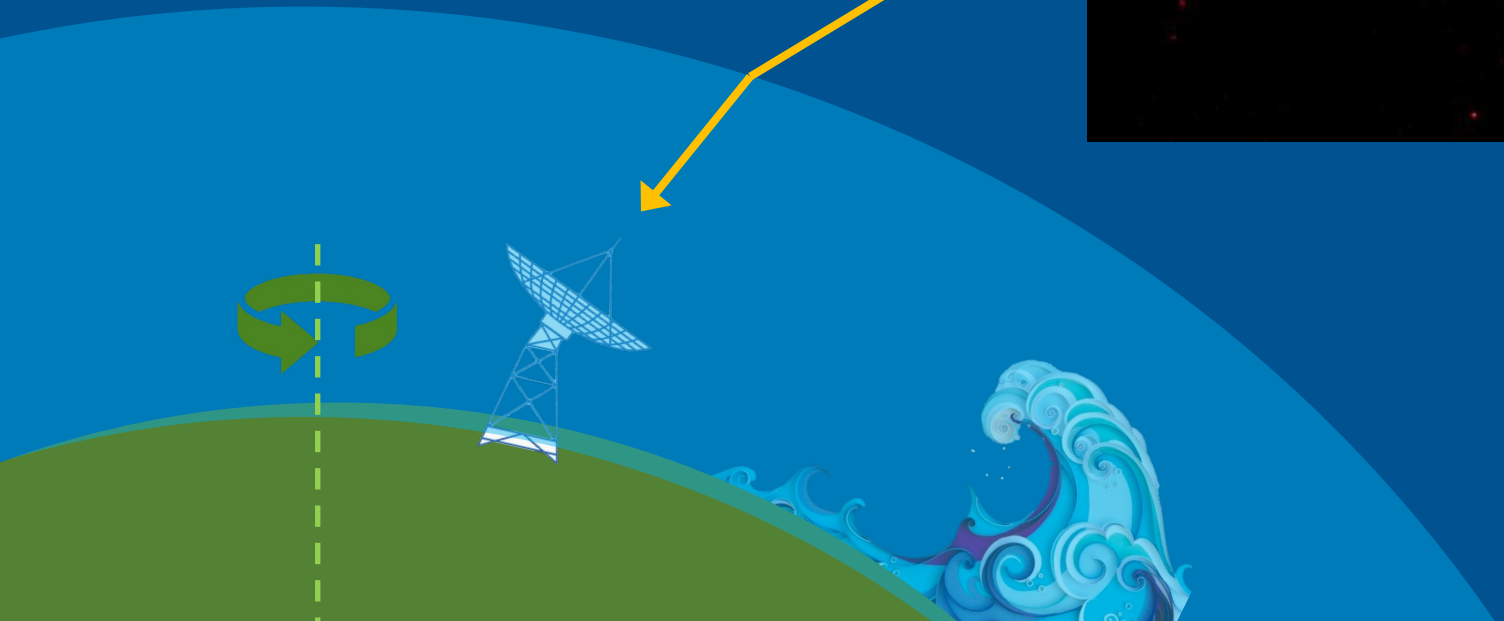
Spingola+ 2018

VLBI specifics

Data acquisition

Correlator model





Inspection

Parallactic angle & mount type

Polarization

- Circular polarization back-end
- Linear polarization back-end

Calibration

Amplitude

- System temperature (Tsys)
- Gain curve

Residual phase errors after correlation

- Clock
- Earth model and telescope positions
- Atmosphere

CASA calibration framework

Based on the Measurement Equation (Hamaker+ ,1996; Smirnov 2011)

$$V_{pq} = 2\langle \boldsymbol{J}_p(\boldsymbol{e}_p\boldsymbol{e}_q^H)\boldsymbol{J}_q^H \rangle = \boldsymbol{J_p B J_q^H}$$

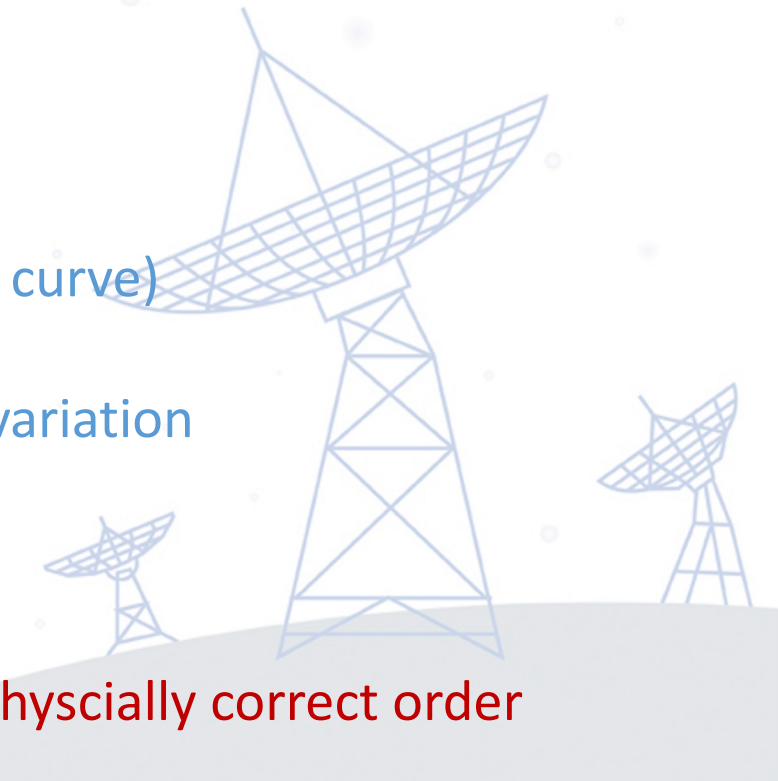
- $\boldsymbol{B}$ **is the brightness distribution on sky**
- $\boldsymbol{B} = \begin{pmatrix} \boldsymbol{I+Q} & \boldsymbol{U+iV} \\ \boldsymbol{U-iV} & \boldsymbol{I-Q} \end{pmatrix}$

The Jones matrices

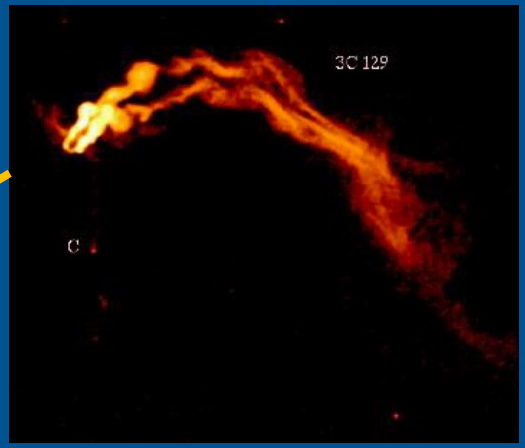
Calibration: determine J_p for all antennas p

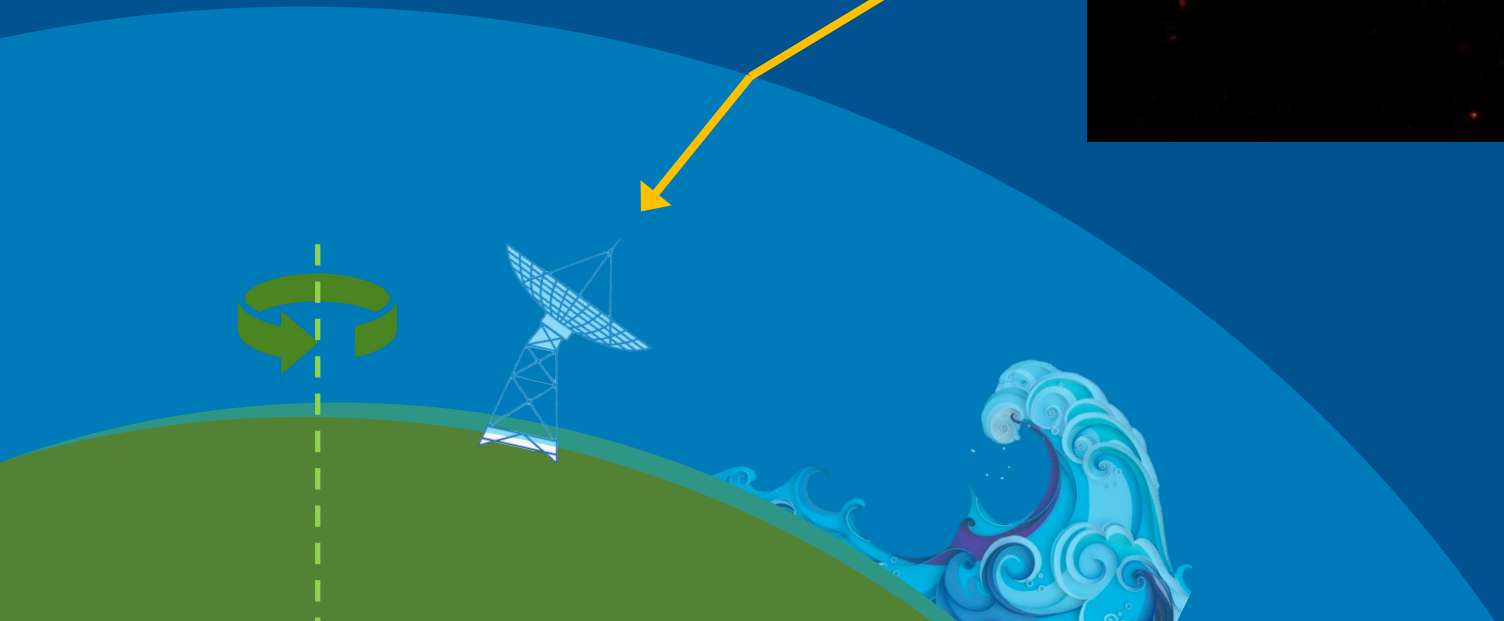
- K_p: delay
- B_p : bandpass
- G_p : electronic gain response
- D_p : instrumental polarization (leakage)
- E_p : telescope based effects (e.g. Tsys, gain curve)
- P_p : parallactic angle
- T_p : tropospheric opacity and path-length variation
- F_p : Faraday rotation
- *(Z_p, beam)*

CASA handles this always in the same and physcially correct order

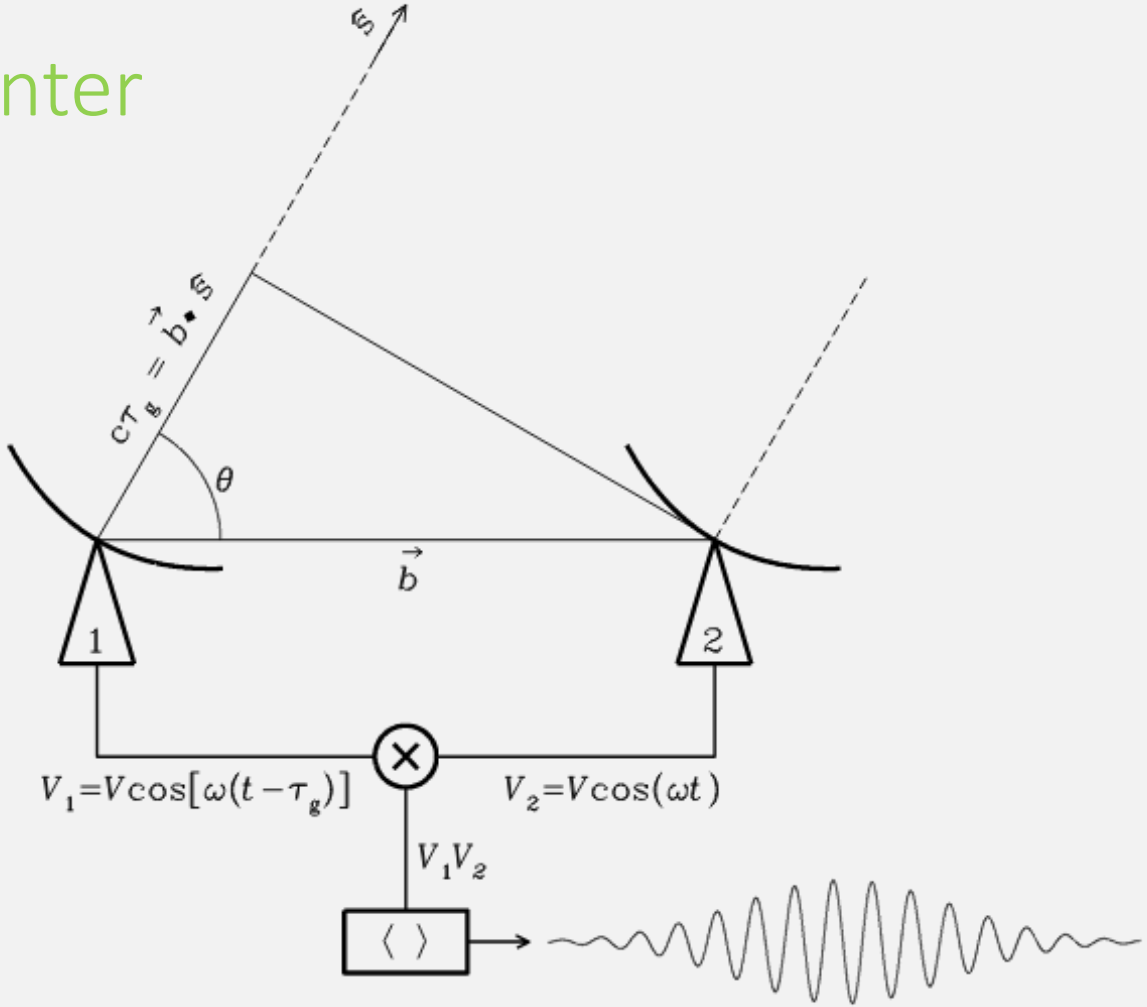


Correlator model

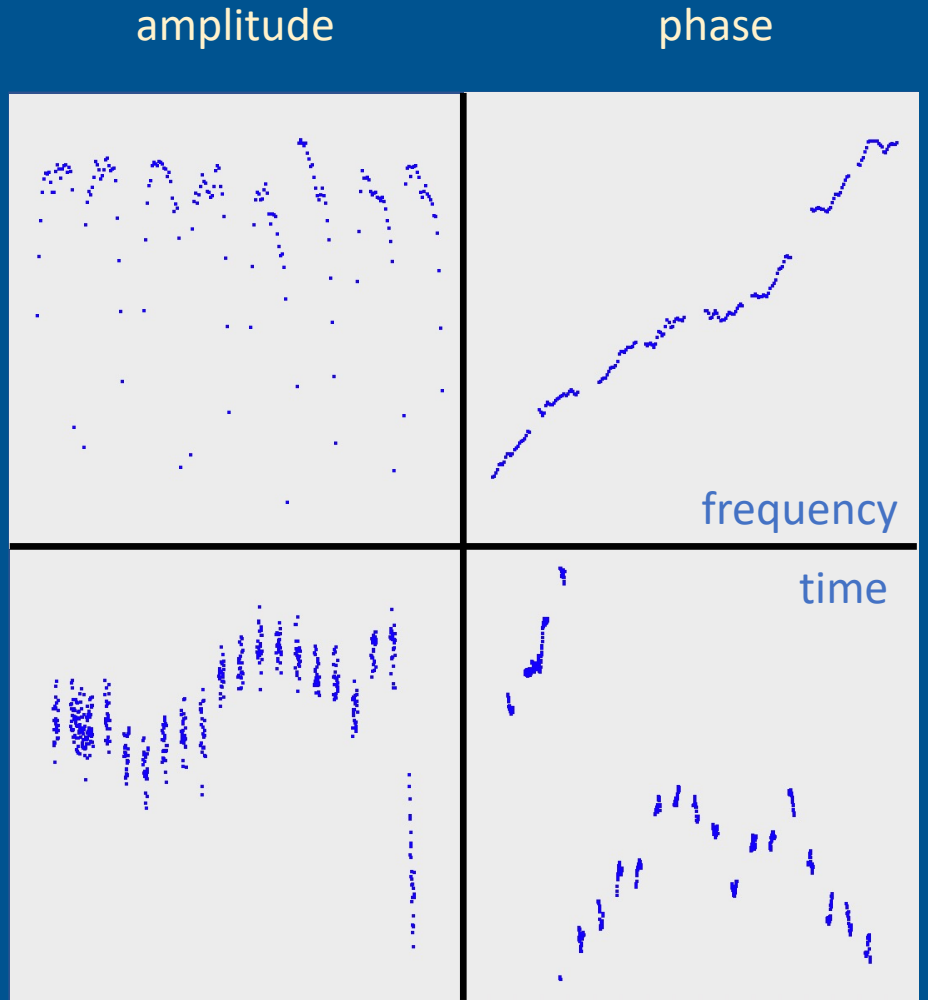




Phase center

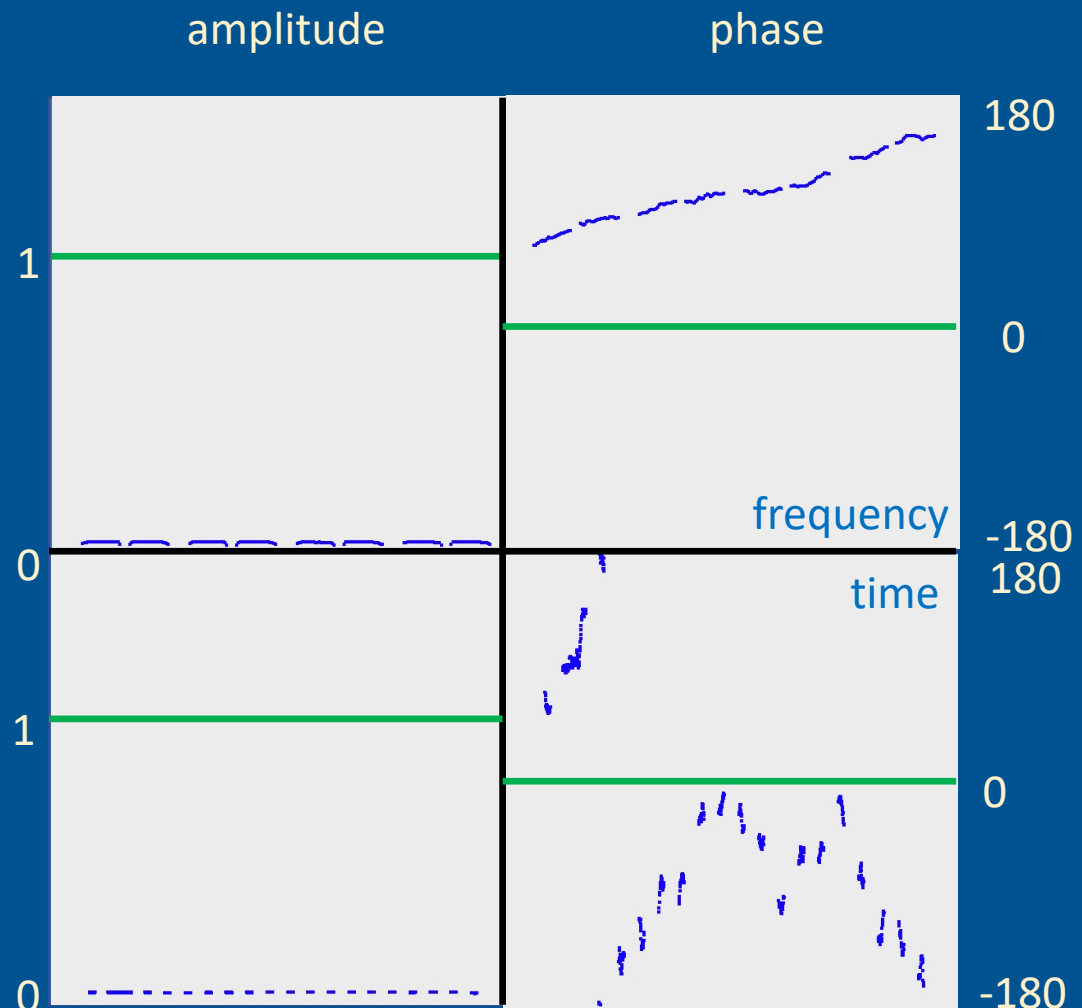


Calibration



One baseline,
one polarization

Calibration



System temperature

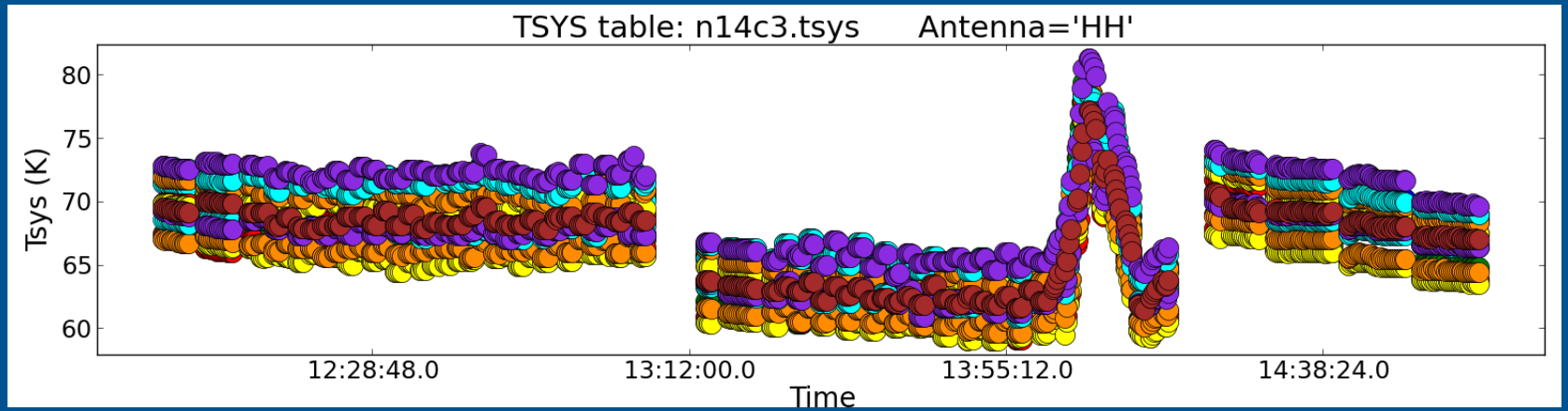
Convert correlator units to flux scale:

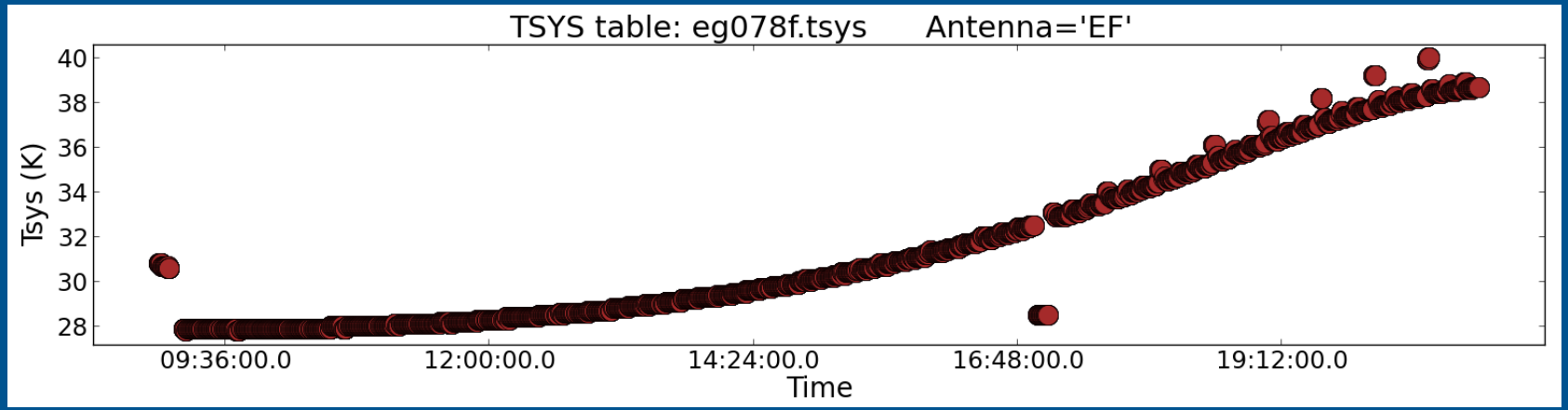
System Equivalent Flux Density

$$\mathrm{SEFD}\ [\mathrm{Jy}] = \frac{2k_B T_{\mathrm{sys}}[K]}{\eta_{\mathrm{A}}\, A_{\mathrm{eff}}}$$

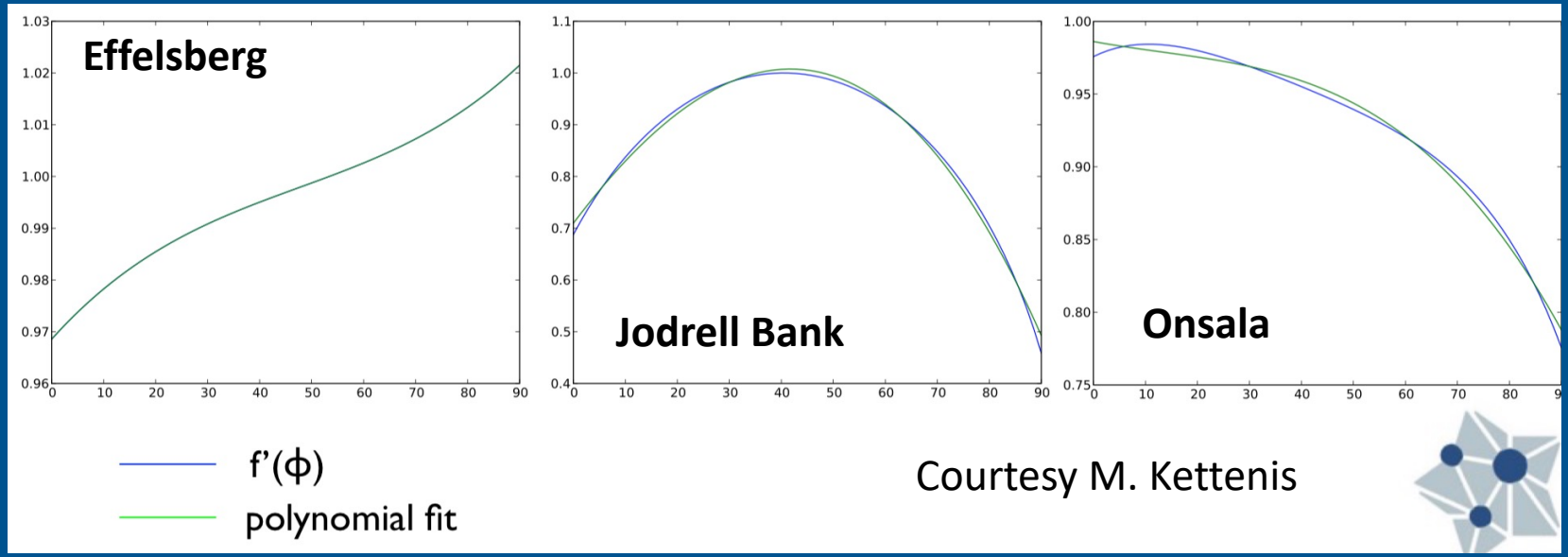
η_{A} : efficiency

A_{eff}: effective antenna area


TSYS table: n14c3.tsys Antenna='HH'
Tsys (K)
80
75
70
65
60
12:28:48.0
13:12:00.0
13:55:12.0
14:38:24.0
Time


TSYS table: eg078f.tsys Antenna='EF'
Tsys (K)
40
38
36
34
32
30
28
09:36:00.0
12:00:00.0
14:24:00.0
16:48:00.0
19:12:00.0
Time

Gain curves


Gain
Effelsberg
Jodrell Bank
Onsala
f'(ϕ)
polynomial fit
Courtesy M. Kettenis

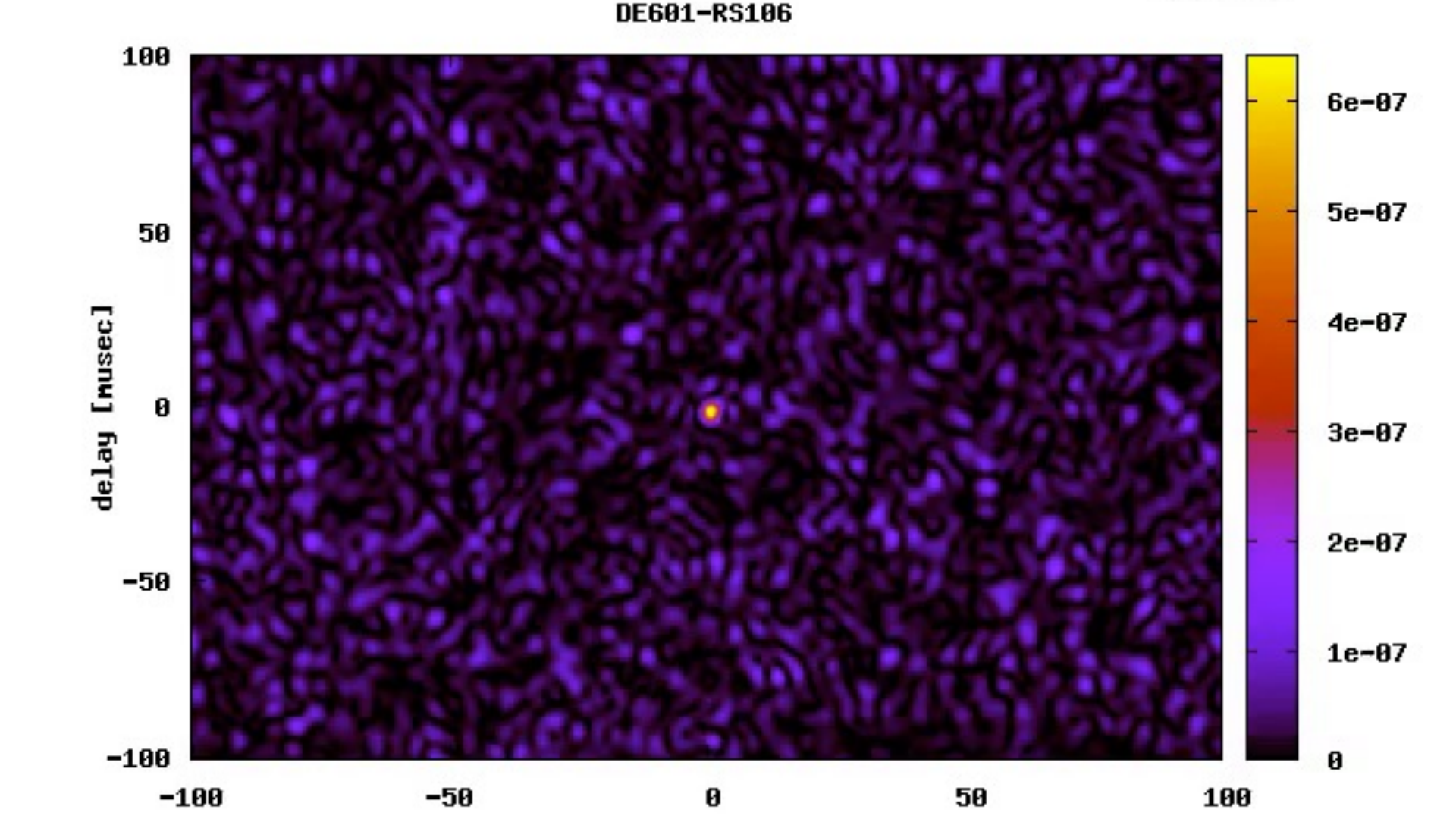
Calibration

- Amplitude: Tsys and gain curve

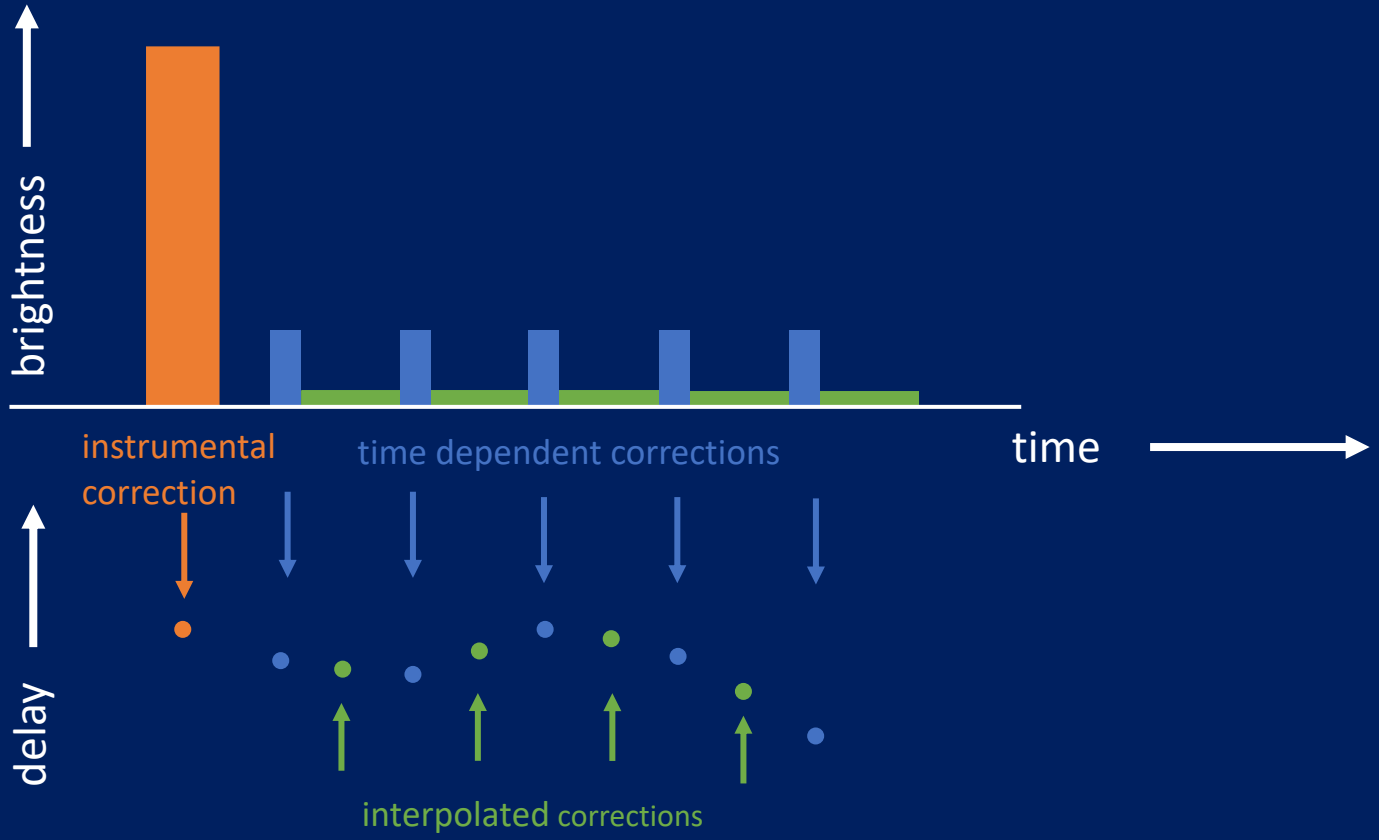
- Phase
- Delay
- Rate

$$\phi_{t,\nu} \approx \phi_0 + \frac{\partial \phi}{\partial \nu} \Delta\nu + \frac{\partial \phi}{\partial t} \Delta t$$

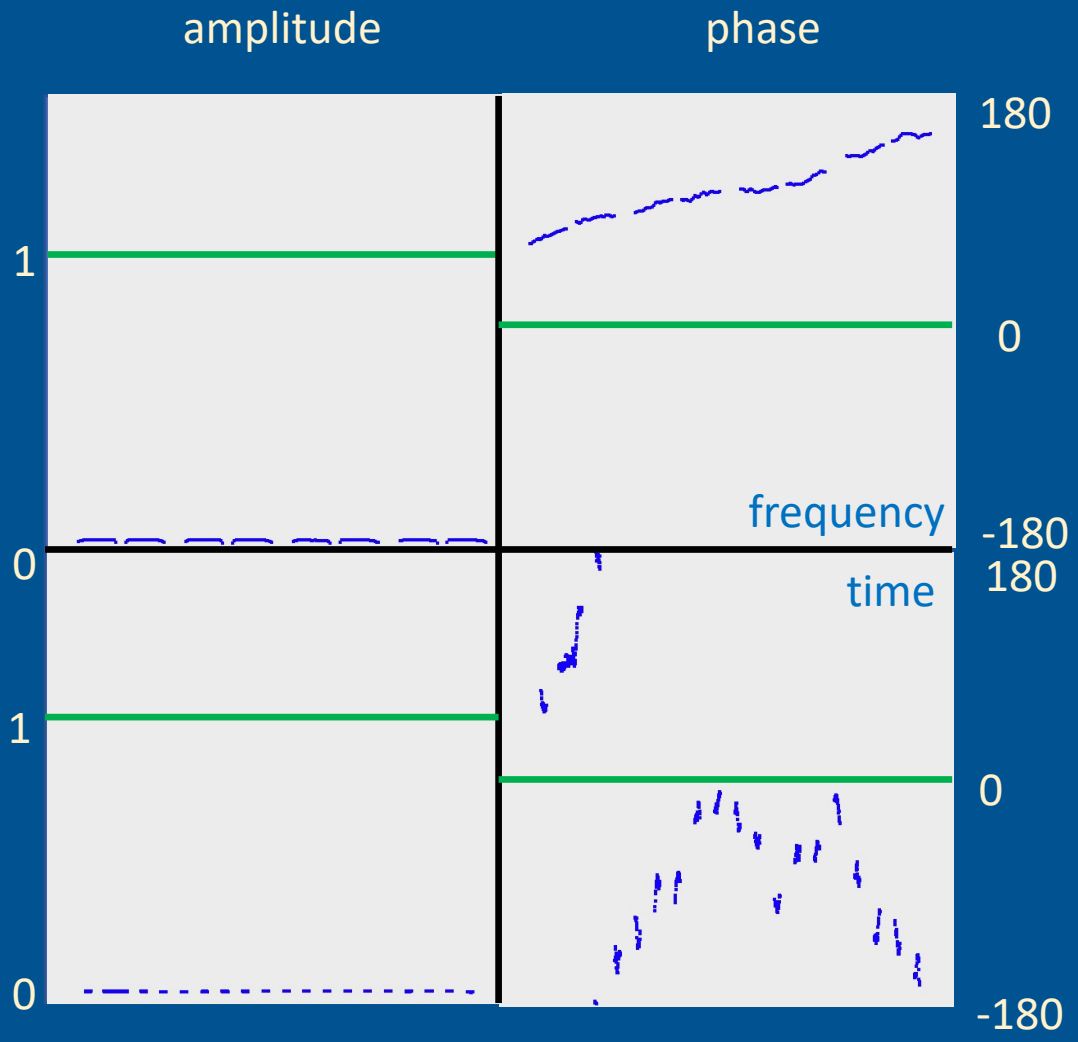
- Higher order terms: dispersive delay, acceleration


DE601-RS106
delay [musec]
100
50
0
-50
-100
-100
-50
0
50
100
6e-07
5e-07
4e-07
3e-07
2e-07
1e-07
0

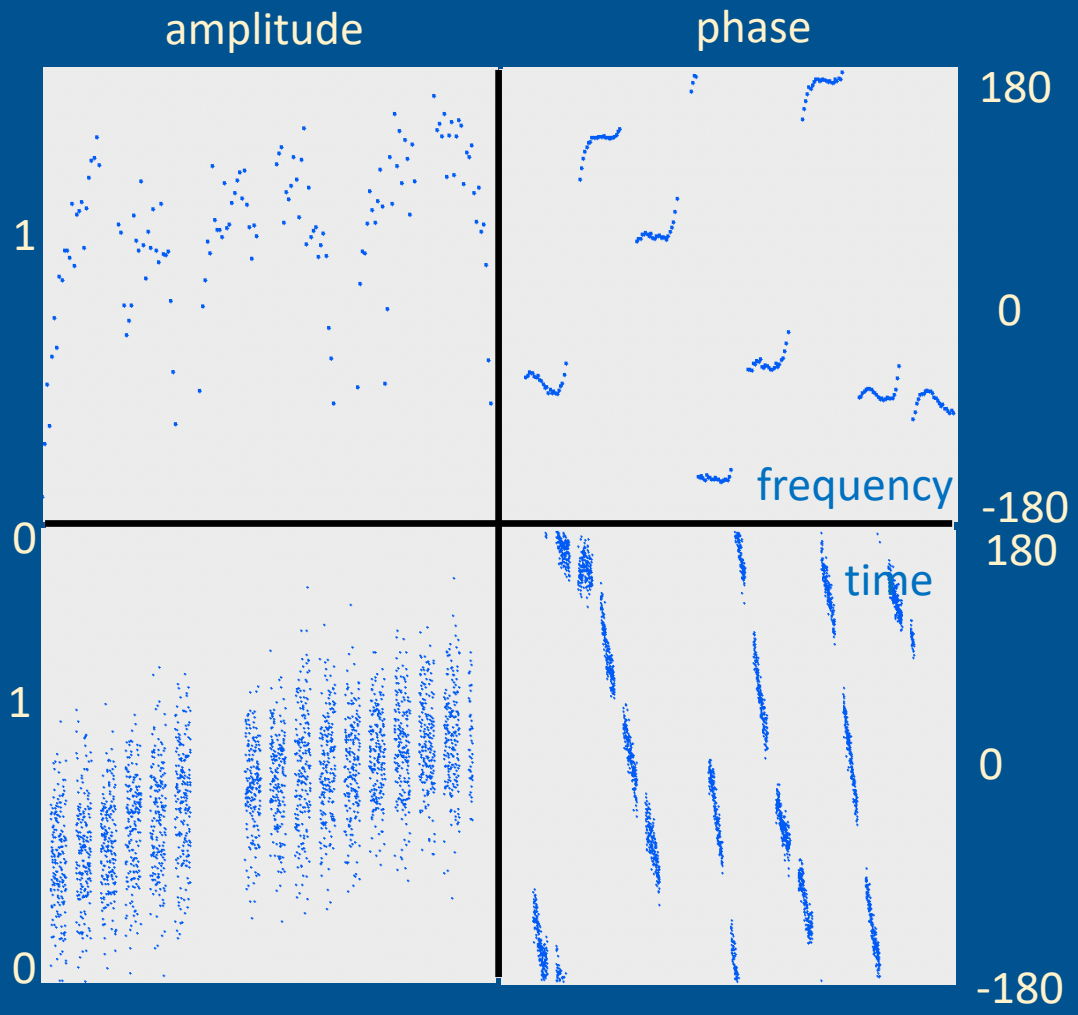
Phase referencing



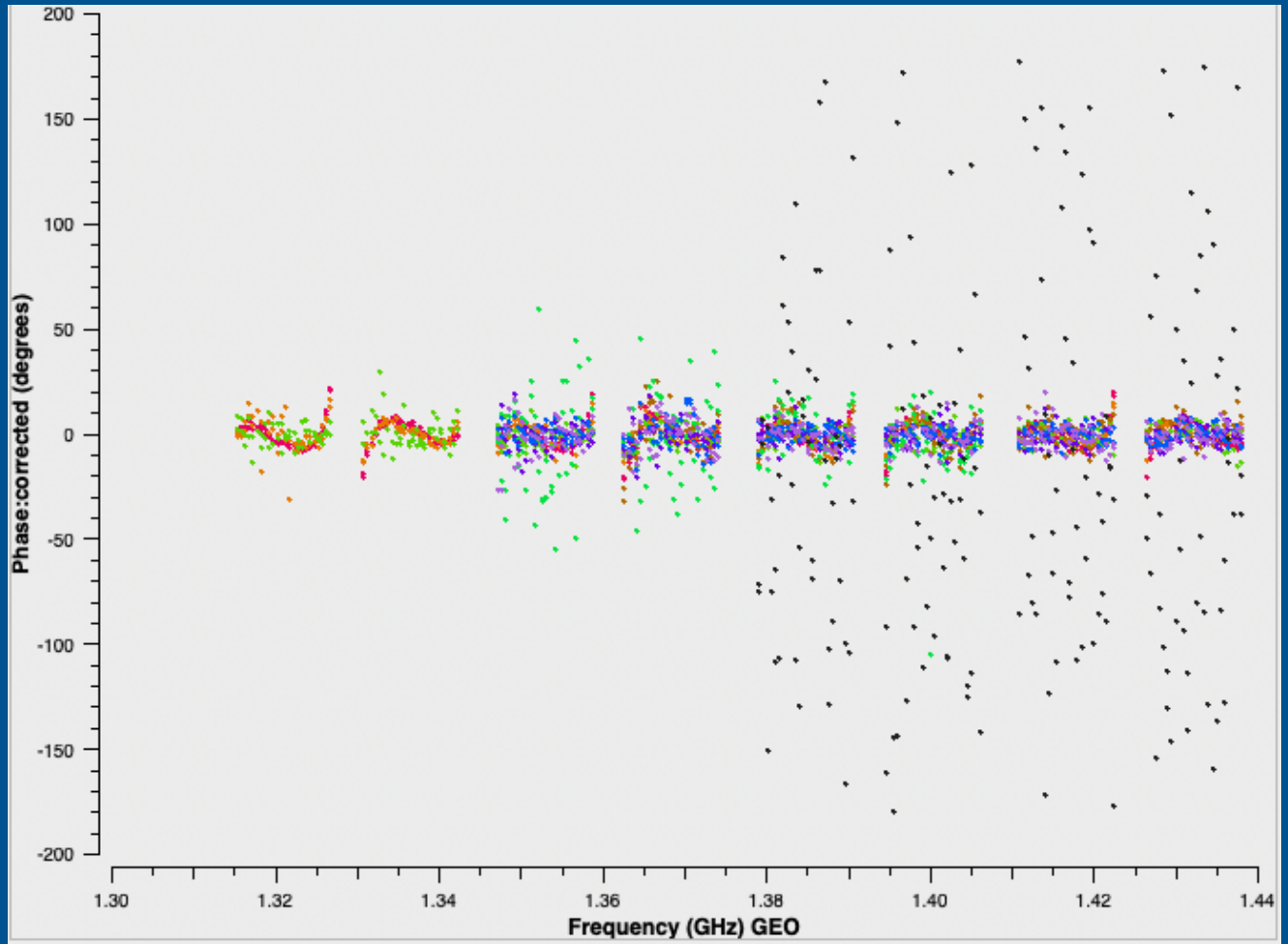
Fringe fit



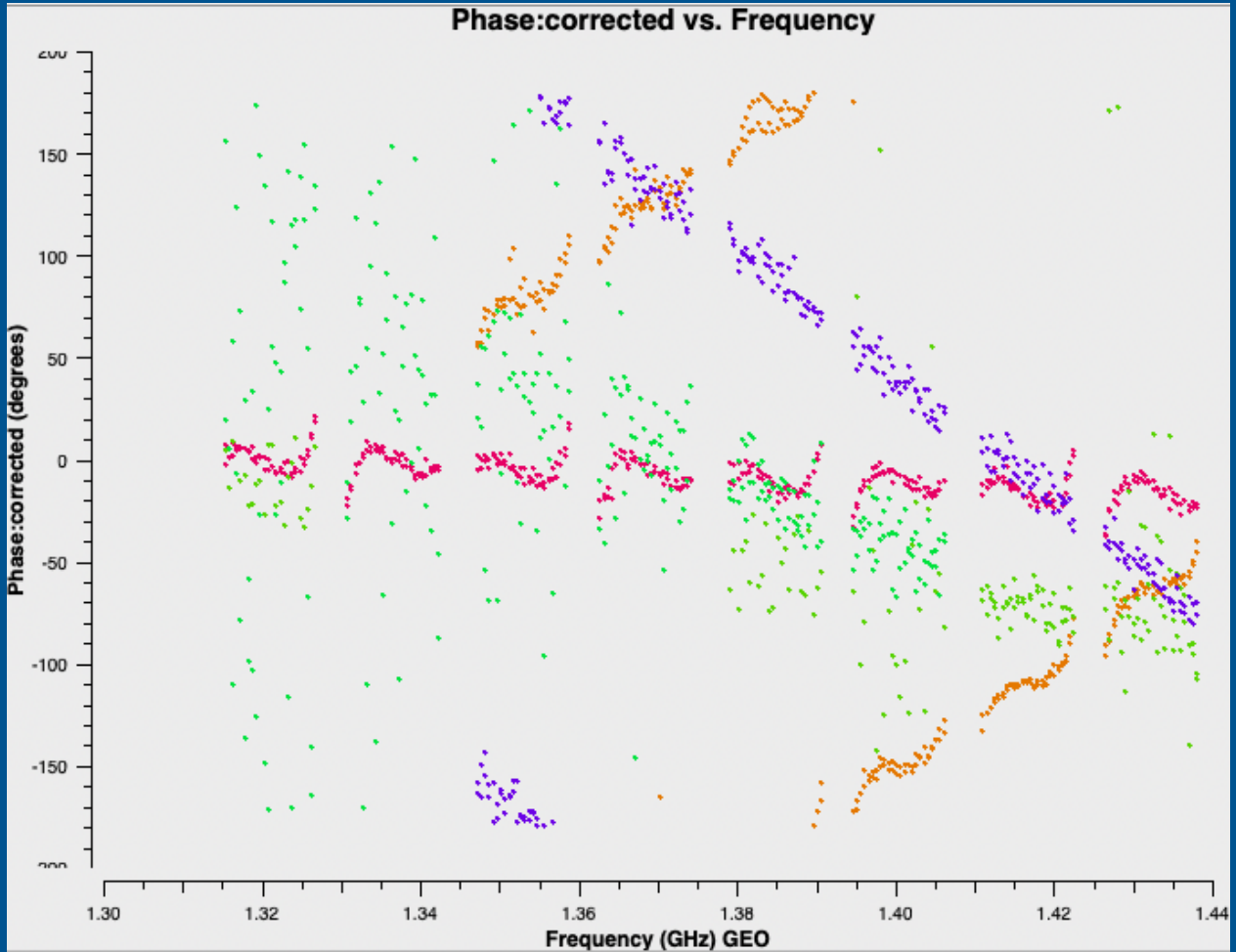
Fringe fit



Fringe fit


Phase:corrected (degrees)
200
150
100
50
0
-50
-100
-150
-200
1.30
1.32
1.34
1.36
1.38
1.40
1.42
1.44
Frequency (GHz) GEO

Fringe fit


Phase:corrected vs. Frequency
Phase:corrected (degrees)
150
100
50
0
-50
-100
-150
1.30
1.32
1.34
1.36
1.38
1.40
1.42
Frequency (GHz) GEO

Left to do

- Bandpass calibration
- Imaging
- Self-calibration

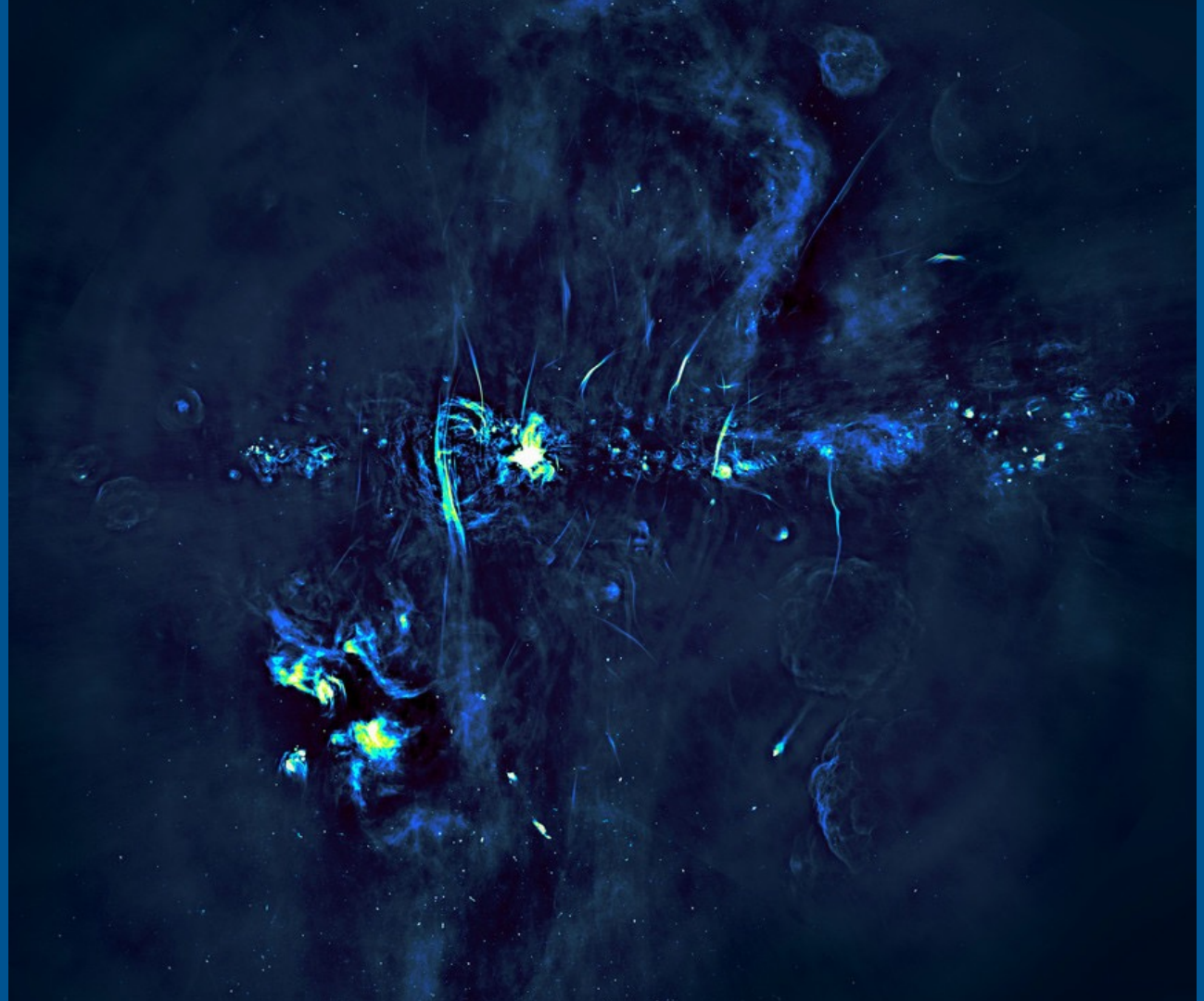
Workings of the EVN

JIVE supports the operations of the EVN:

- Archive
- Proposal handling
- Observation planning
- Correlation and data quality
- Assistance with advanced calibration

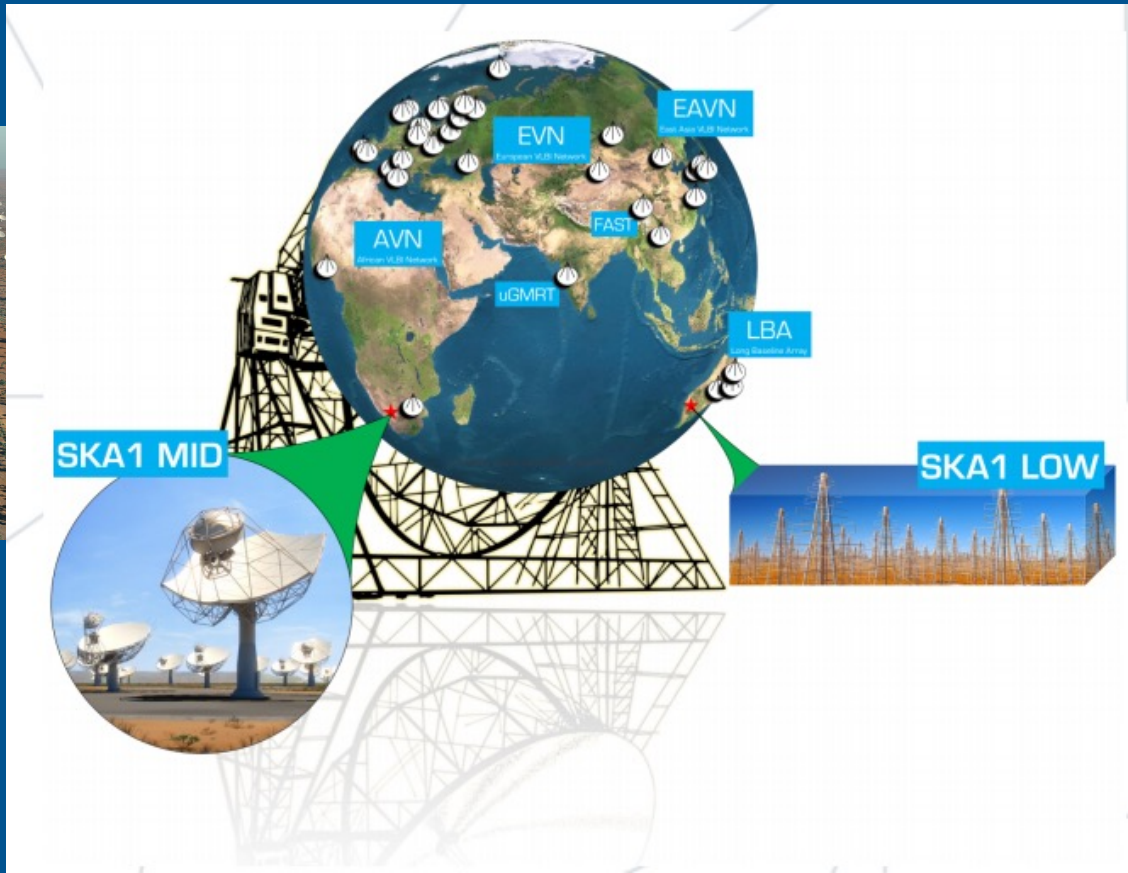
Software development

- CASA now ready for VLBI
- Pipeline development:
  - ALMA
  - VLA
  - EHT
  - rPicard (and others)
  - EVN
  - VLBA



Heywood+ 2019
MeerKAT telescope

Square Kilometre Array



Next: try for yourself