Spectral Line Analysis

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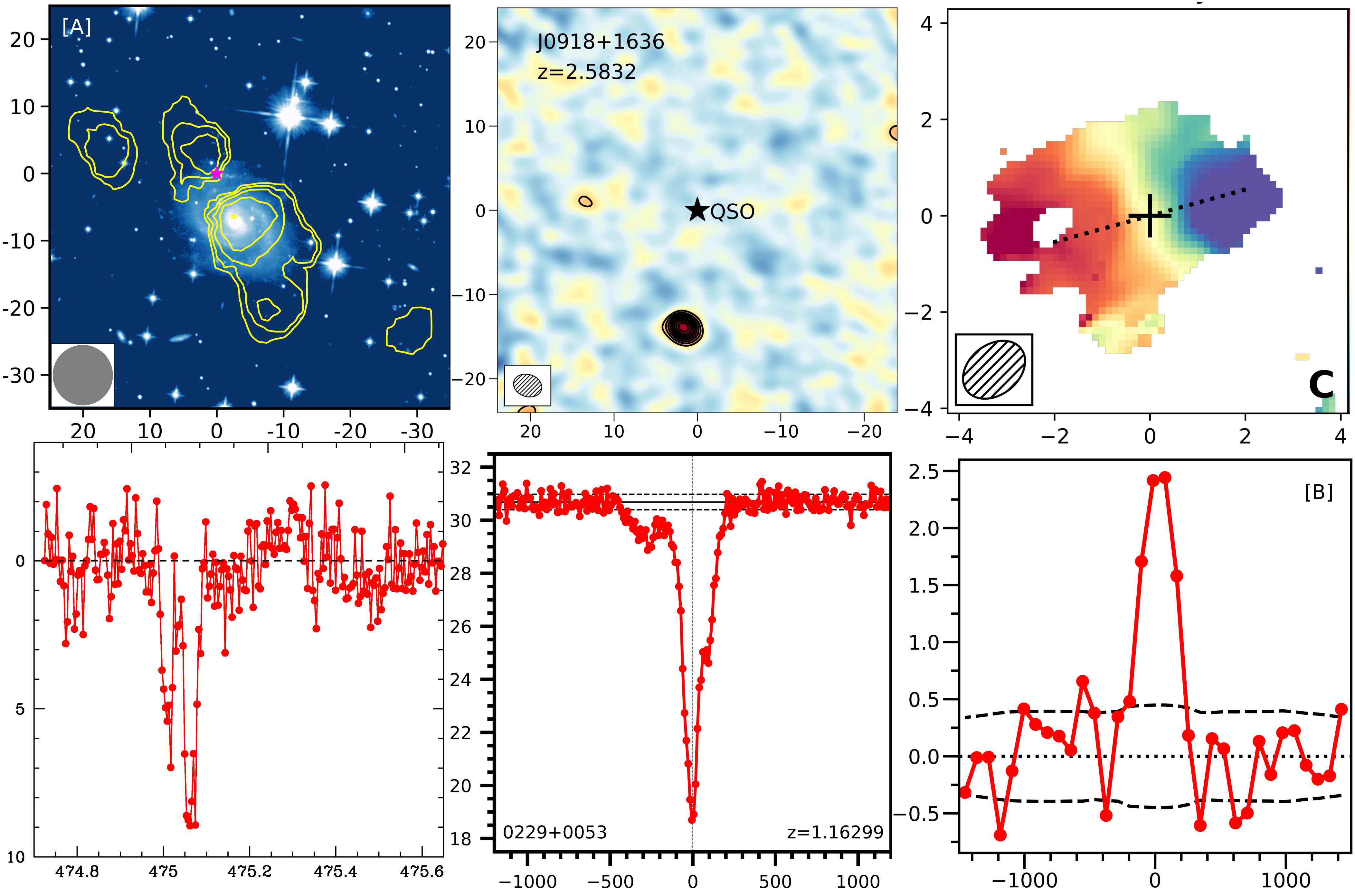
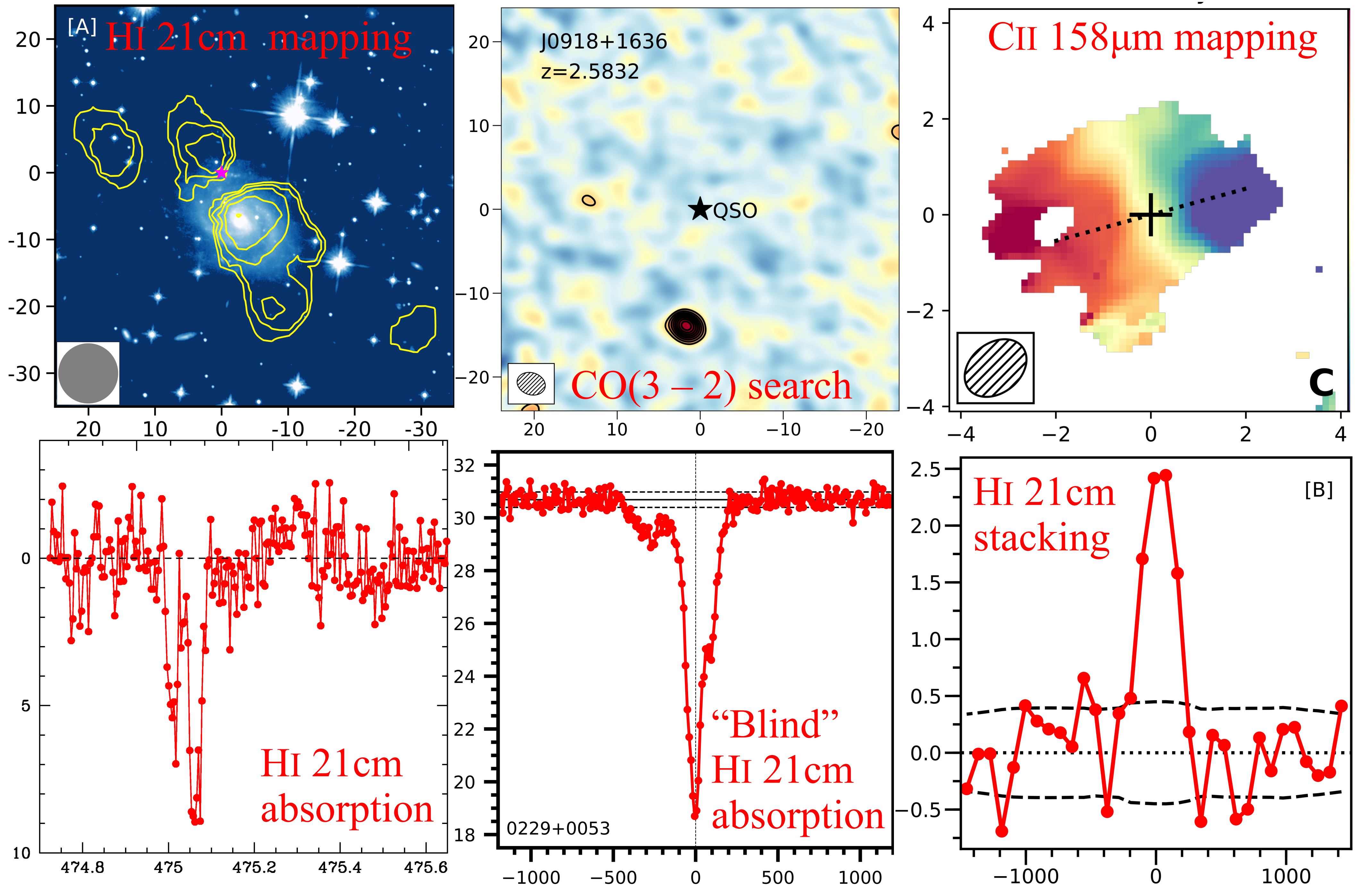


WIDE RANGE OF SCIENCE

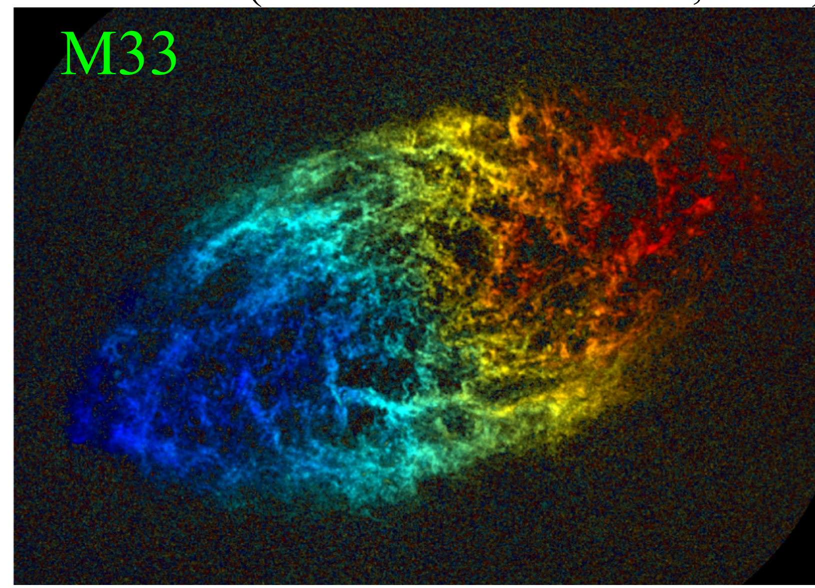
(NK 2014; Neeleman et al. 2020; NK et al. 2020; Chowdhury et al. 2020, 2022; Kaur et al. 2022)



Why Should You Care?

- Quantum mechanical transitions in gas at a specific frequency
  ⇨ Narrowband emission or absorption features.

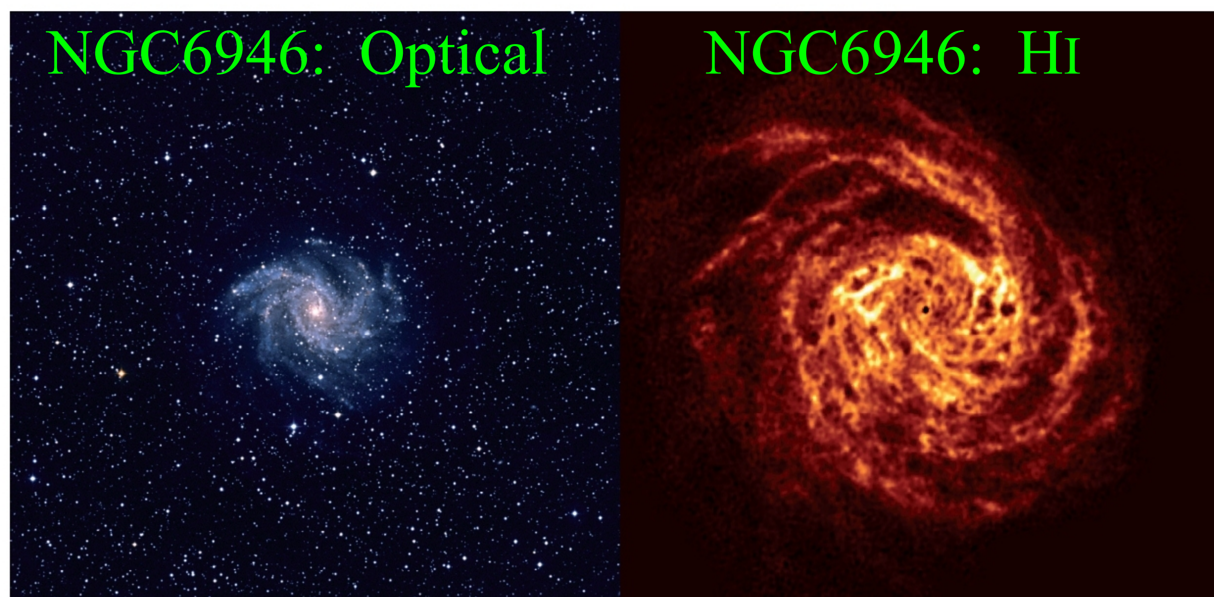
(Braun & Thilker 2004, AAS)



- Doppler shift ⇨ Gas kinematics!

- Critical lines (HI 21cm, CII 158 μm, CO) in the radio band ⇨ 3-D spectral cubes!

- ISM physics and chemistry: Gas density, temperature, surface density, mass, size; magnetic field strength, …



(Boomsma et al. 2008, A&A)

Spectral Line Issues

- Compact or extended line emission region?
- Angular resolution for mapping studies?
- Spectral resolution to resolve the line? Total frequency coverage?
- How bright is the target source? High spectral dynamic range? Additional bandpass calibration?
- Radio Frequency Interference (RFI)? Important to check beforehand. RFI "flagging" essential for detection of weak spectral lines.
- Typically, strong continuum emission: Need to image, deconvolve, and remove the continuum *before* searching for the weaker line emission.
- Every interferometer today always observes in spectral-line mode!!!

Spectral Line Analysis: Approach

- “Flagging” of dead antennas, RFI, bad data.
- Calibrate the interferometer’s response: Antenna-based gains, bandpass.
- Apply calibration to multi-channel data set.
- Combine “off-line” channels into a “channel-0” data set.
- Imaging and self-calibration + Additional flagging ⇨ Continuum image.

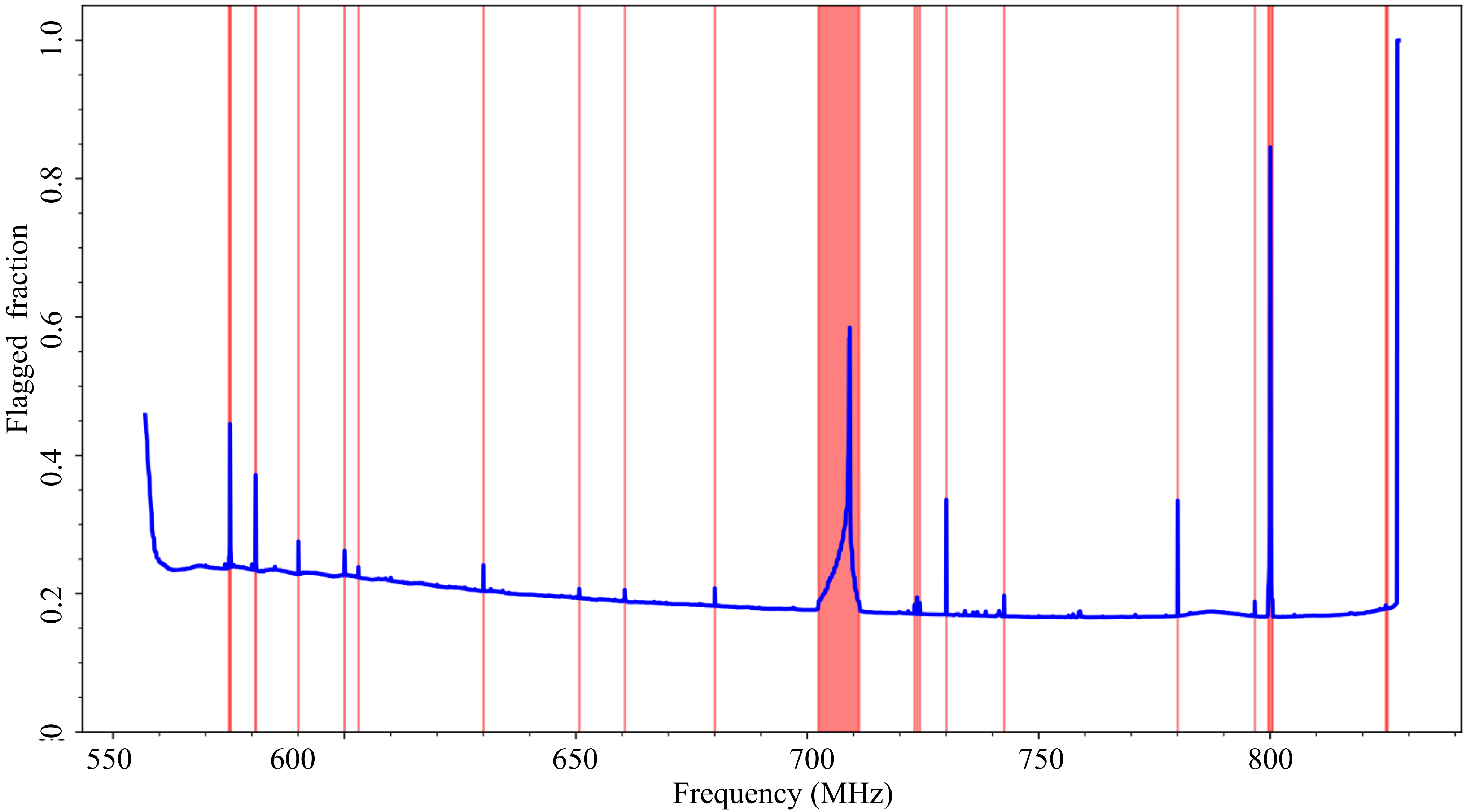
- Apply antenna-based gains from self-calibration to multi-channel data set.
- Subtract the continuum from the multi-channel data set.
- Final flagging on the multi-channel data set.
- Make a spectral cube, at the desired velocity and angular resolution.

The Antenna-Based Gains

- Select a *single good channel* to solve for the antenna-based gains.

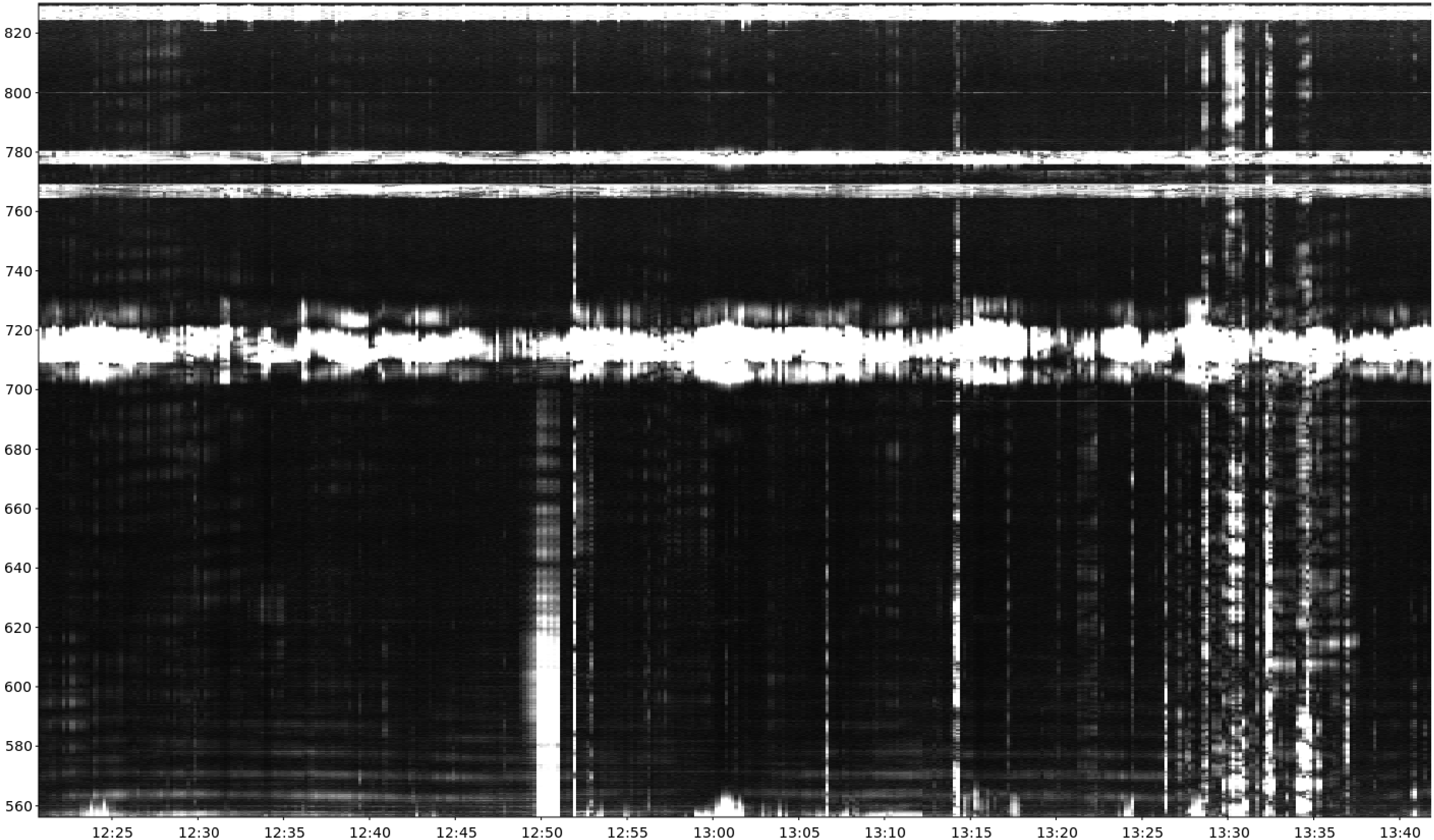
- Good channel: Little RFI and in a sensitive part of the band.

RFI, RFI, RFI



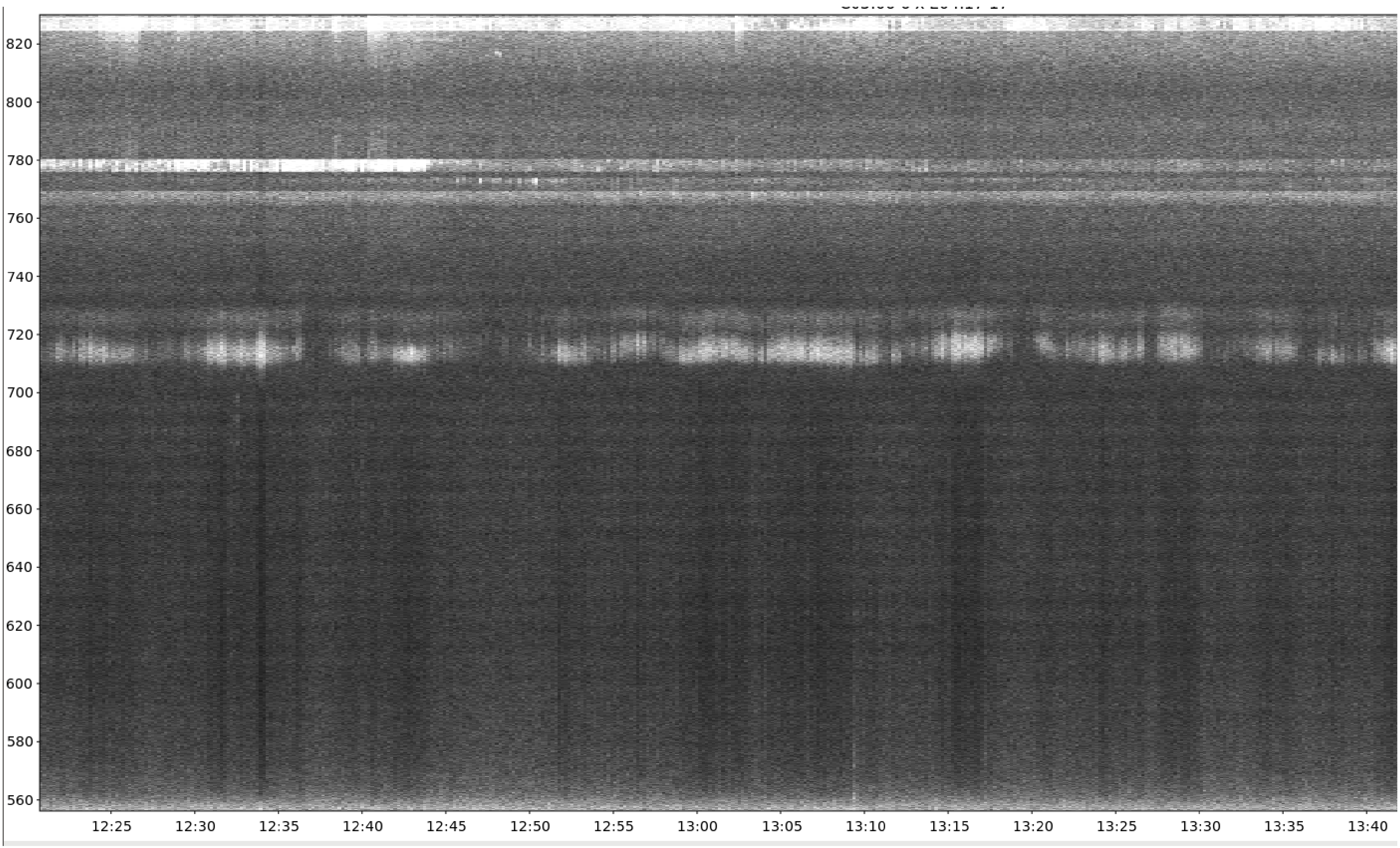
(Courtesy: Aditya Chowdhury)

RFI, RFI, RFI



(Courtesy: Balpreet Kaur)

RFI, RFI, RFI



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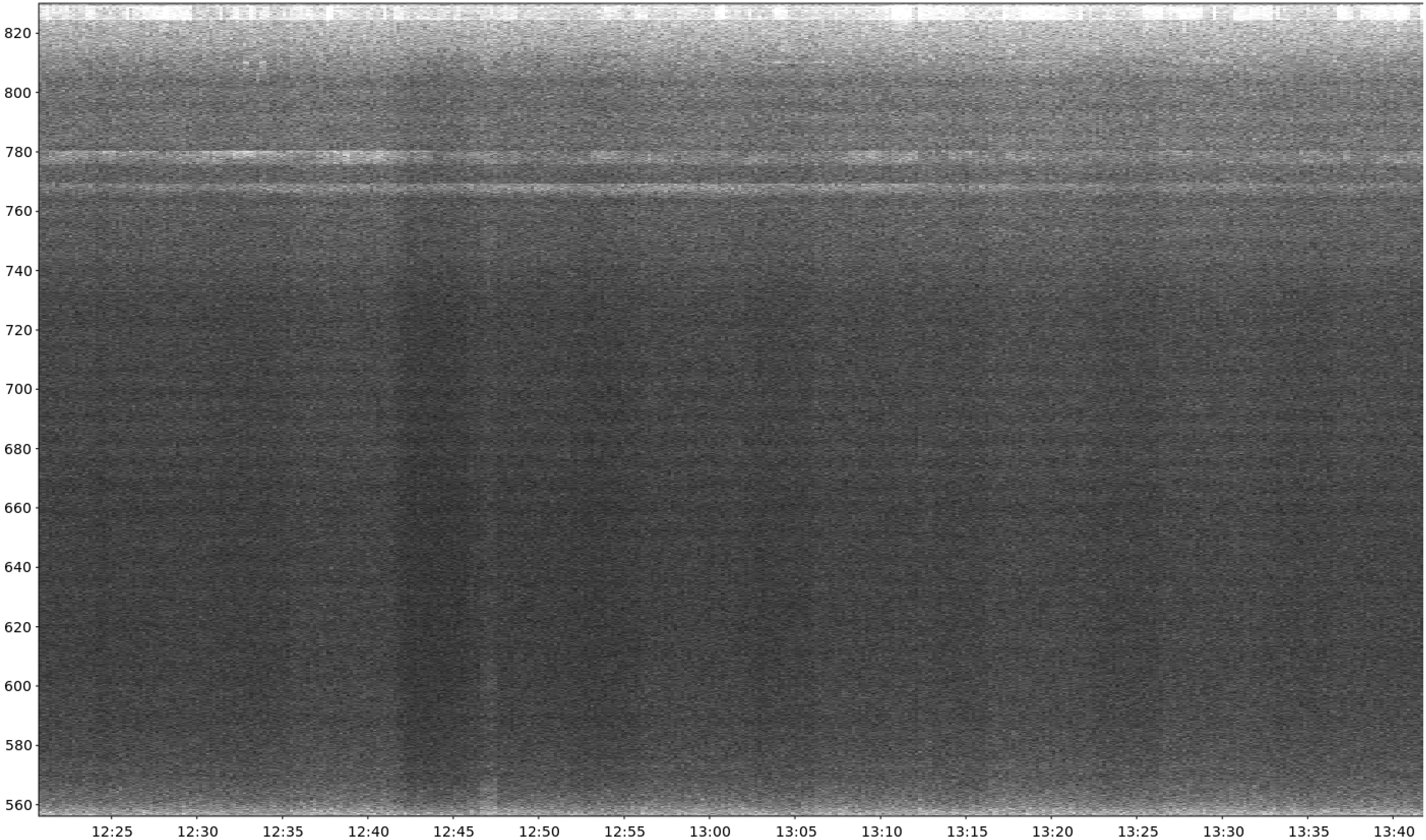
RFI, RFI, RFI



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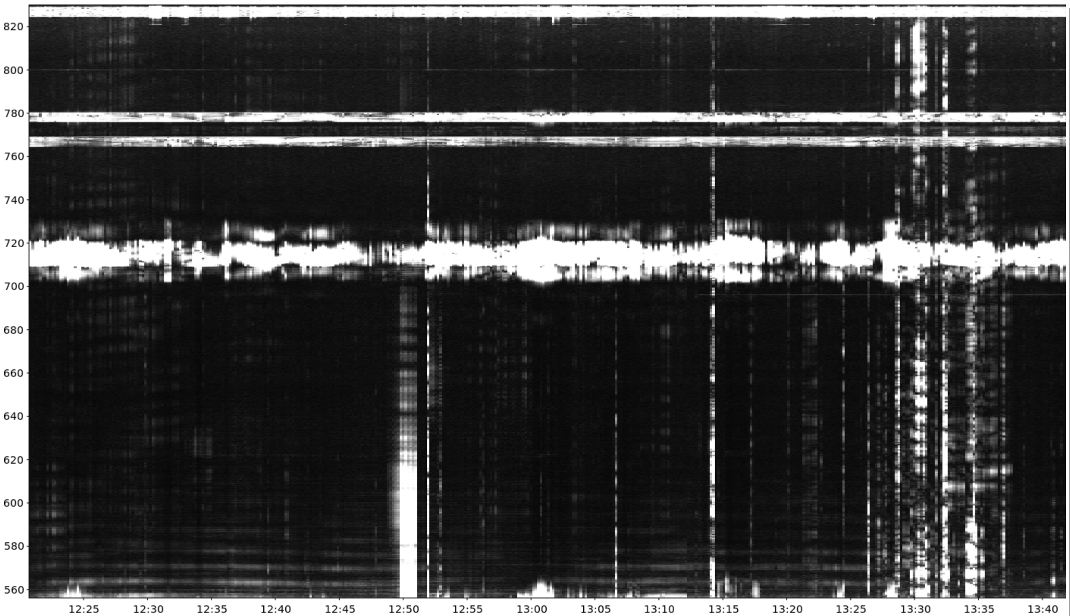
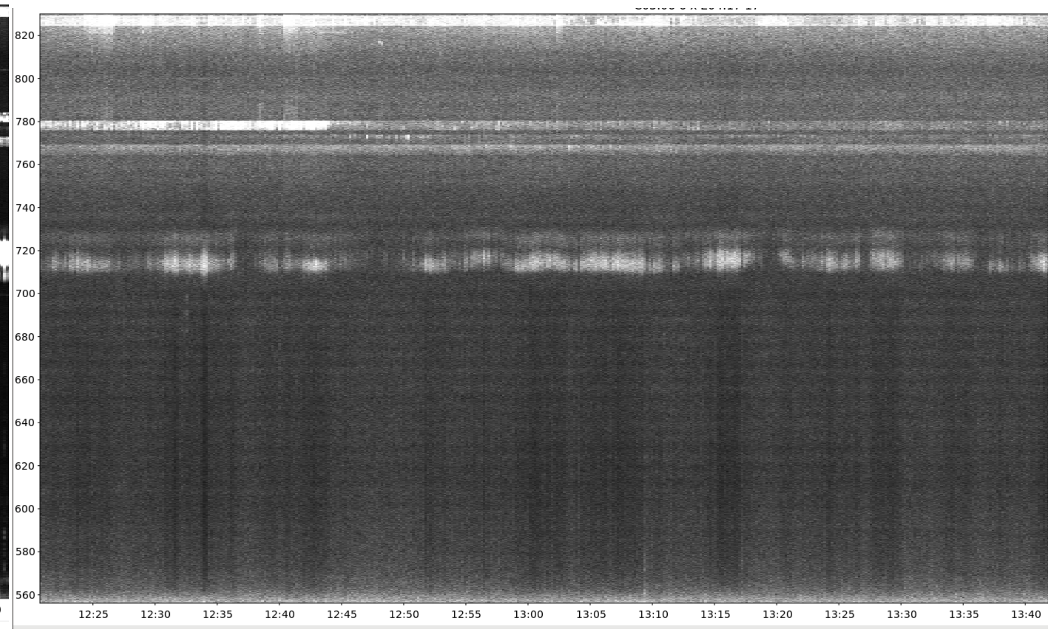
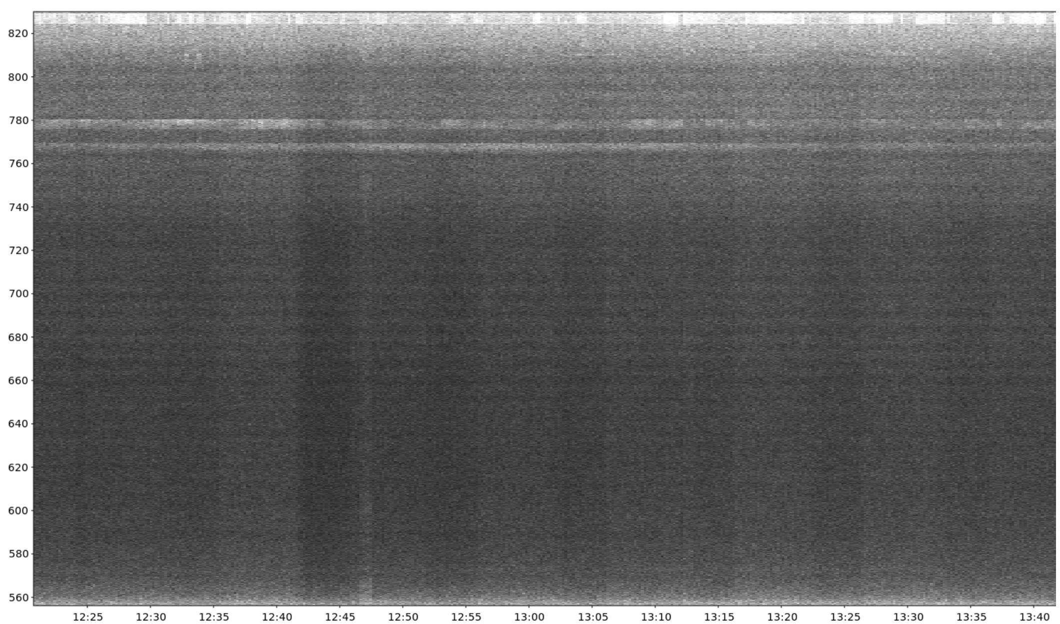
RFI, RFI, RFI

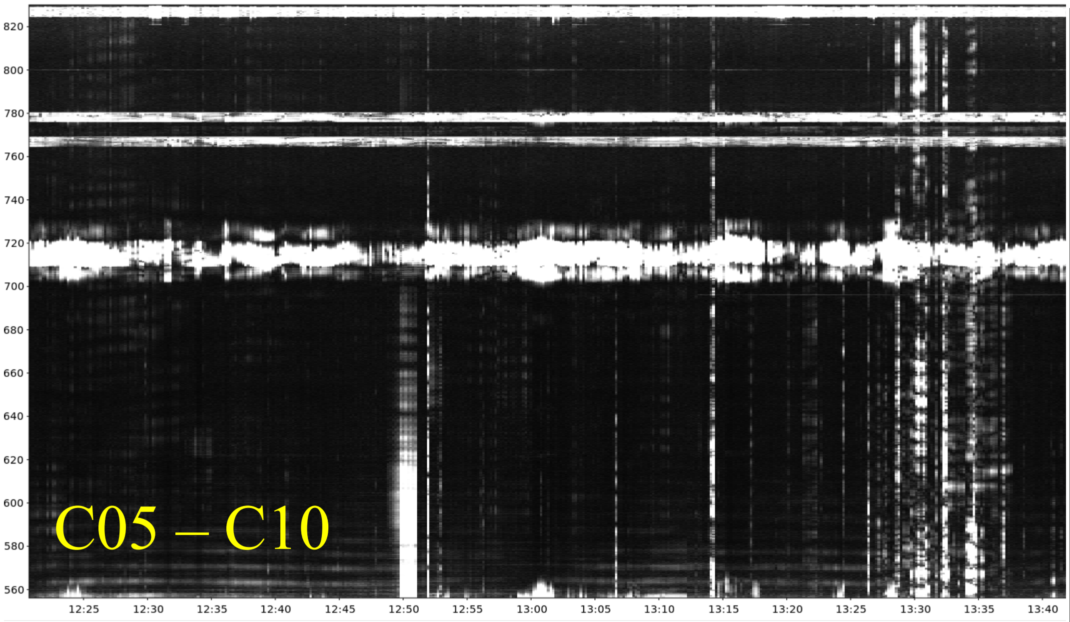


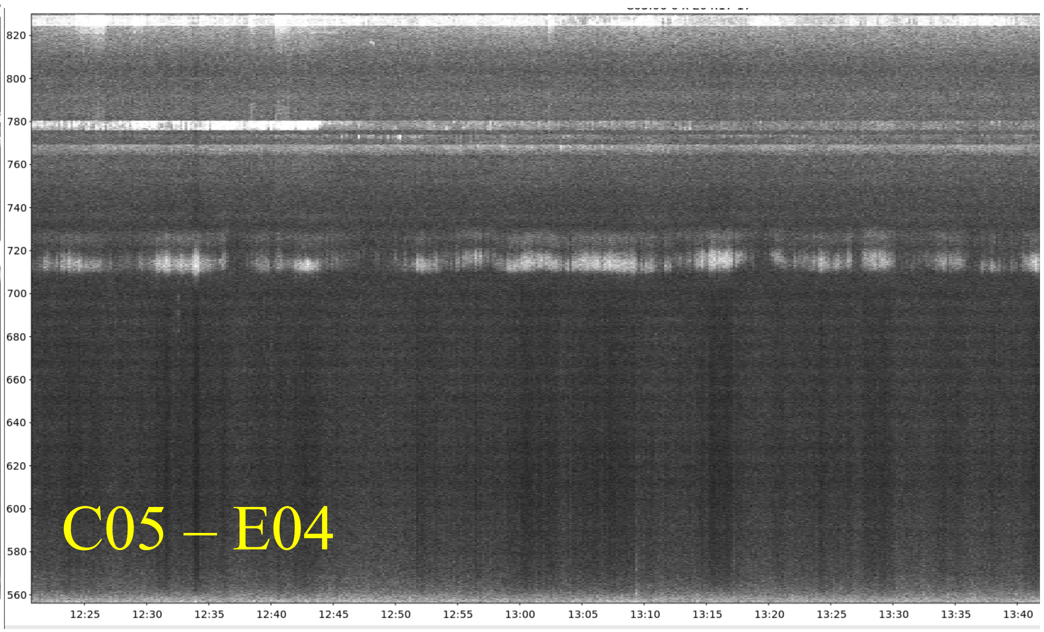


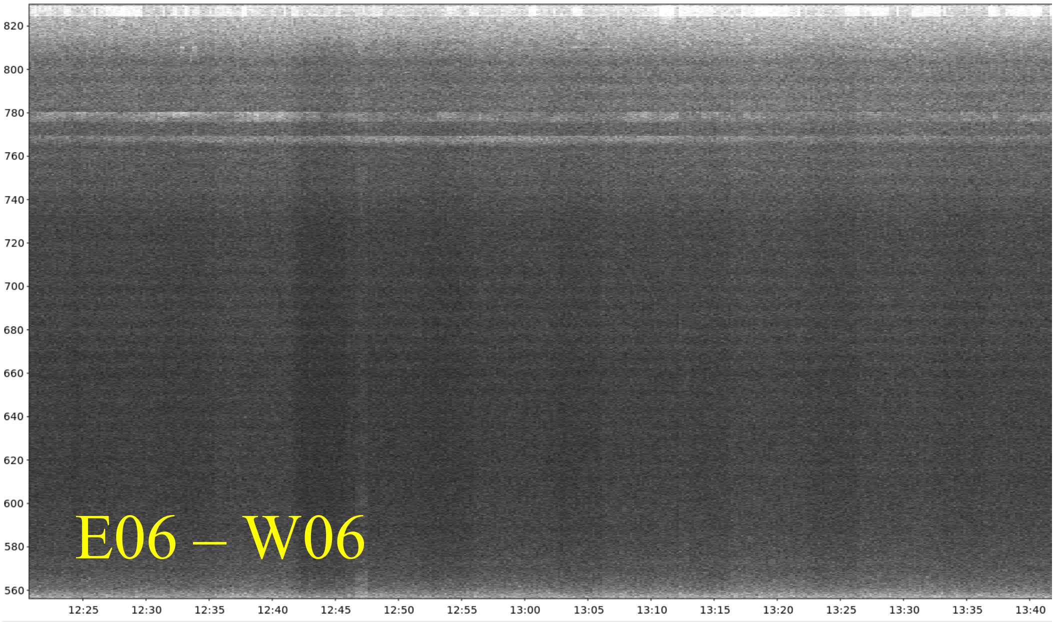


(Courtesy: Balpreet Kaur)

RFI, RFI, RFI







(Courtesy: Balpreet Kaur)

- Use *long baselines* to determine antenna-based gains, bandpasses!

THE ANTENNA-BASED GAINS

- Select a *single good channel* to solve for the antenna-based gains.
- Good channel: Little RFI and in a sensitive part of the band.
- Exclude short baselines (<~ 1.5 km) while solving for gains ⇨ Less RFI!
- Inspect the single-channel data on the calibrators: Flag dead antennas, dead time ranges, scintillation times, time-variable RFI, …
- Check any UV range limits on the calibrators, in the VLA database.
- Solve for the gains (S/N >= 5): Check for any failures in the solutions.
- Apply gains to calibrators and plot calibrated data: Flag outliers.
- Rinse and repeat.

THE ANTENNA-BASED BANDPASSES

- If possible, use the phase calibrator as a bandpass calibrator.
- Apply the antenna-based gains to all bandpass calibrators.
- Exclude short baselines (<~ 1.5 km) while solving for the bandpasses.
- Inspect the calibrated multi-channel data on the calibrators: Use automated tools (e.g. aoflagger, global clipping) to remove bad RFI.
  (Offringa et al. 2012, A&A)
- Solve for the bandpasses, normalizing the bandpasses at the gain channel. Check for any failures in the solutions.
- Plot the bandpass shapes: Do the curves look smooth?
- Apply bandpasses to calibrators and plot calibrated data. Flag outliers.
- Rinse and repeat.

Imaging and Self-Calibration

- Apply calibration to the multi-channel data set. Split out the target.
- Automated algorithms (e.g. aoflagger, rflag, …) to remove very bad data.
- Average line-free channels to produce a "channel-0" data set. Retain enough resolution to avoid bandwidth smearing.
- Wide-field imaging critical at low frequencies: Out to at least first null. If using a large bandwidth, then multi-frequency synthesis.
- Clean to >~10-sigma in first imaging cycle, to get a reliable model. Deeper on later imaging rounds, after self-calibration.
- Few rounds of imaging + phase-only self-calibration. Only positive Clean components in the model.
- Amplitude-and-phase self-calibration: Normalization of the gains critical.
- Subtract out model from calibrated visibilities, flag on residuals, repeat.

Final Preparations

- Apply antenna-based gains from self-calibration to multi-channel data set.
- Add the model continuum image to the calibrated multi-channel data set.
- Subtract the continuum from the calibrated multi-channel data set.
- Final automated flagging on the multi-channel residual data set.
- No “Doppler tracking” at GMRT or JVLA: Topocentric reference frame. Must correct to either the barycentric frame or the LSR frame.

The Spectral Cube

- Choice of weighting (natural, robust, uniform, …) based on science goals.
  Natural weighting for point sources and detection experiments,
  Robust weighting for mapping studies.

- Choice of angular resolution based on science goals (e.g. mapping, point spectroscopy, …).

- Cube velocity resolution based on the line width, to resolve the line.

- High spatial and velocity resolution needed for kinematics.
  High sensitivity needed to see faint features, and for reliable Clean'ing.

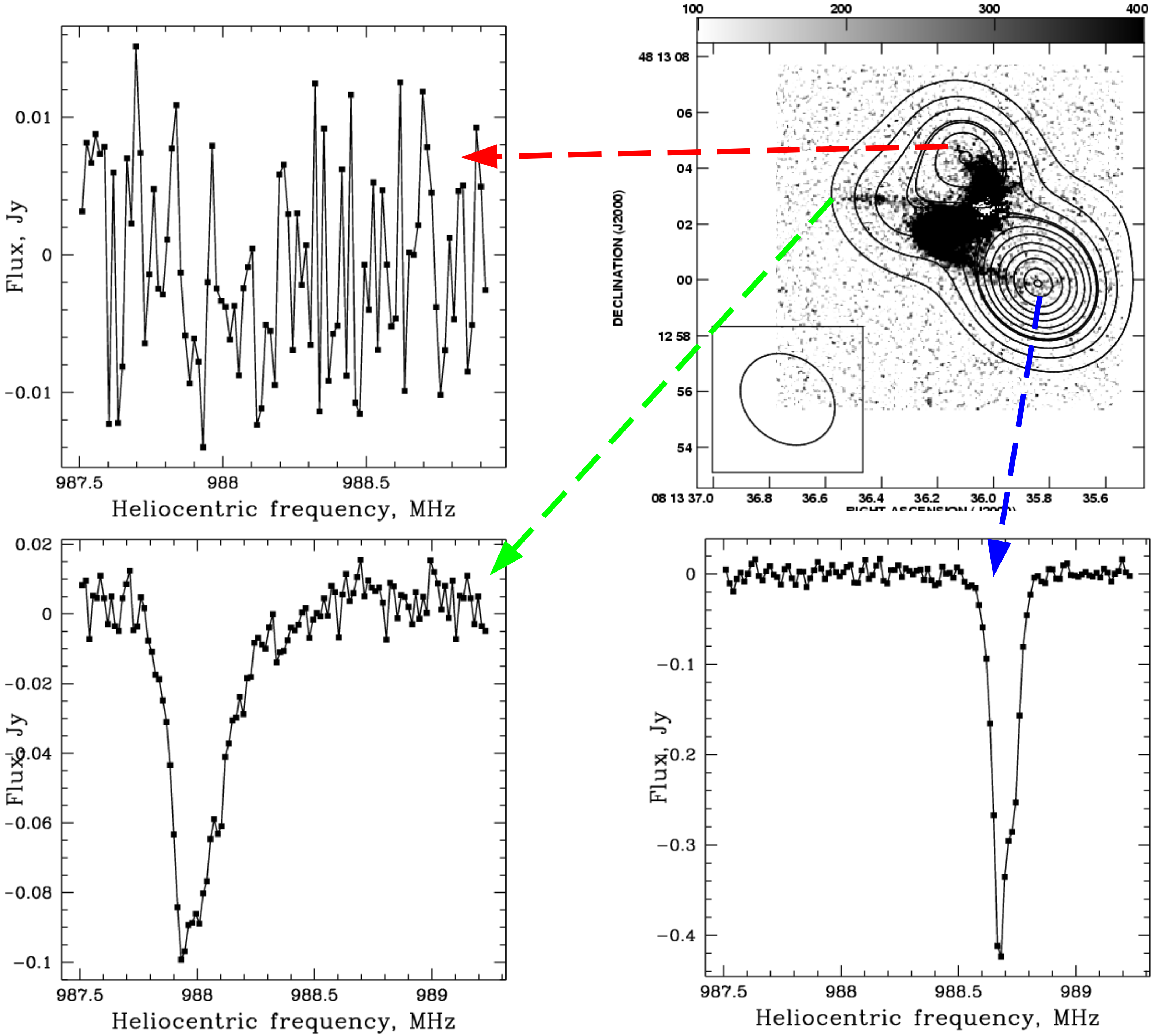
- For spatially-extended spectral features, *must* deconvolve the feature.
  Deep Clean'ing essential, to same depth in all channels.
  Ideally, same synthesized beam in all channels.

- Result: A 3-D spectral cube, with RA, Dec, and velocity/frequency.

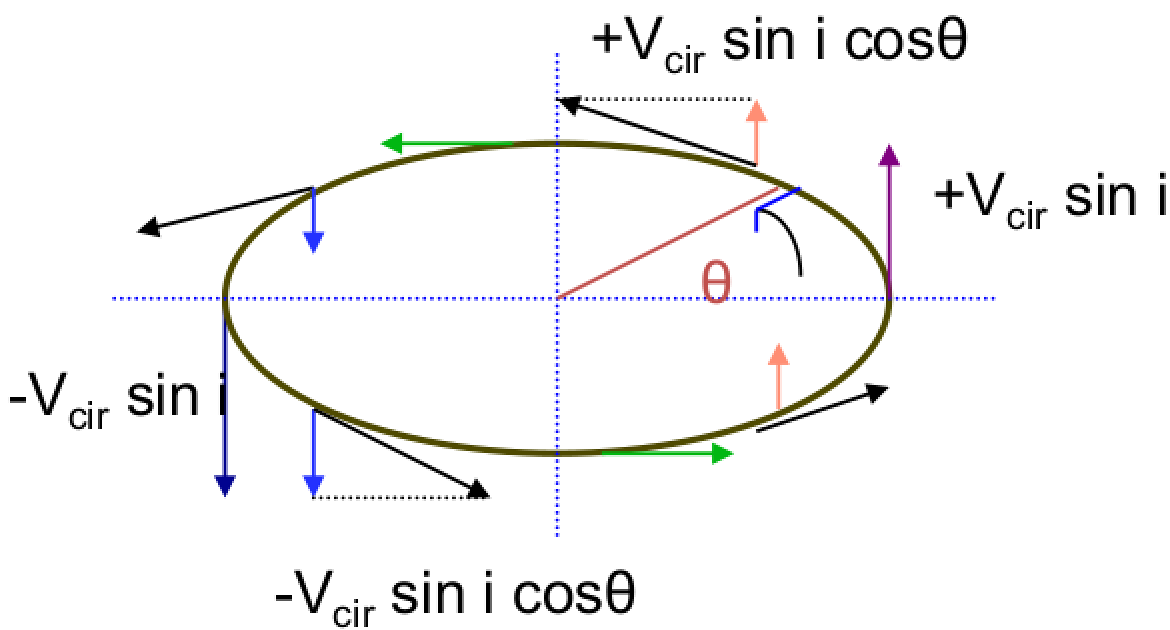
Analysing Cubes

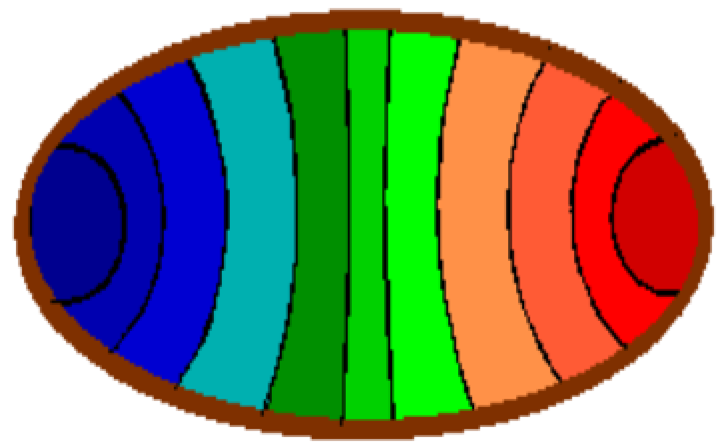
- 3-D visualization software: DS9, kvis, CASA, 3DSlicer, SlicerAstro, …
- Source-finding: DUCHAMP, SoFiA, …
  (Whiting 2012, MNRAS; Serra et al. 2015, MNRAS)
- Model-fitting: 3D-Barolo, Tirific, …
  (Jozsa et al. 2012, ASCL; di Teodoro & Fraternali 2015, ASCL)
- Line profiles: 1-D cut through the cube along the velocity axis.
- Channel maps: 2-D planes showing images at different velocities.
- Moment images: Velocity integrals, as a function of spatial position.

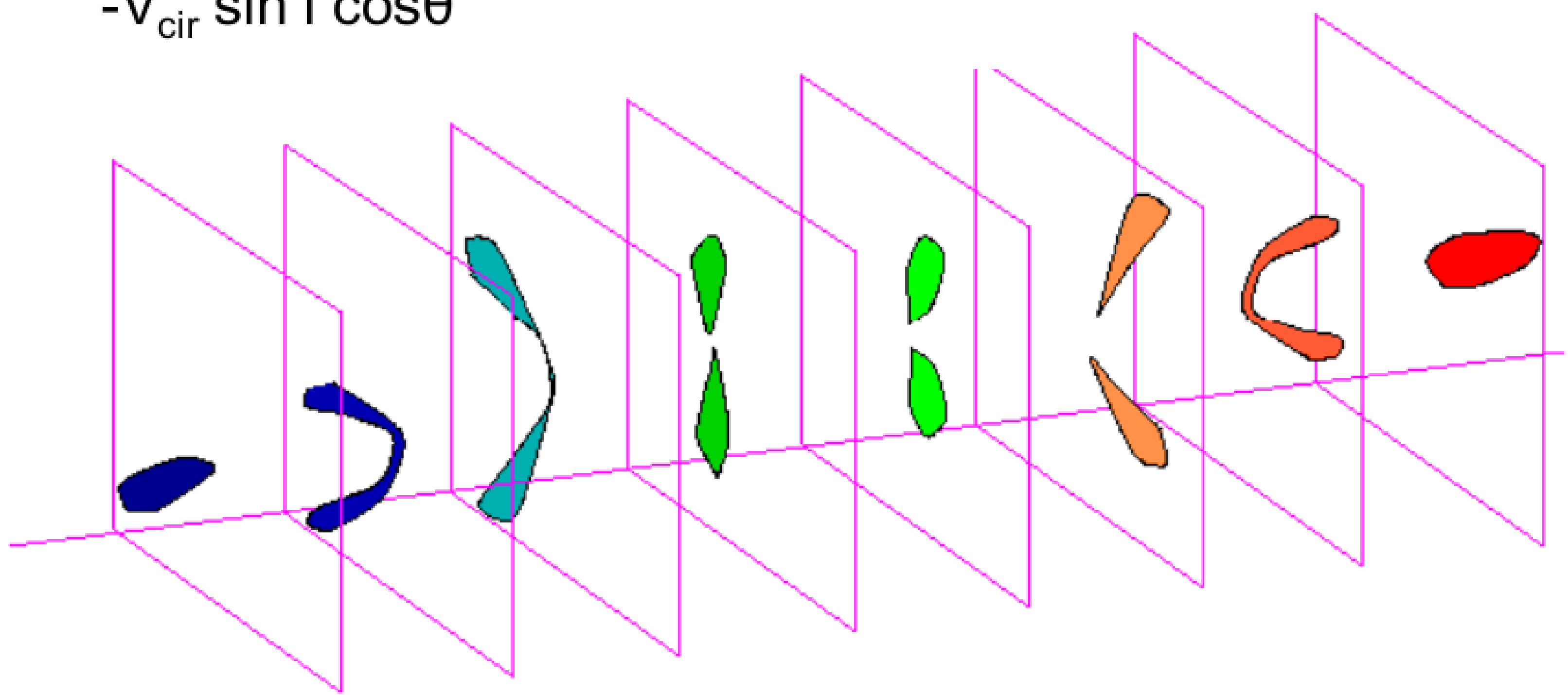
LINE PROFILES



2-D Channel Maps



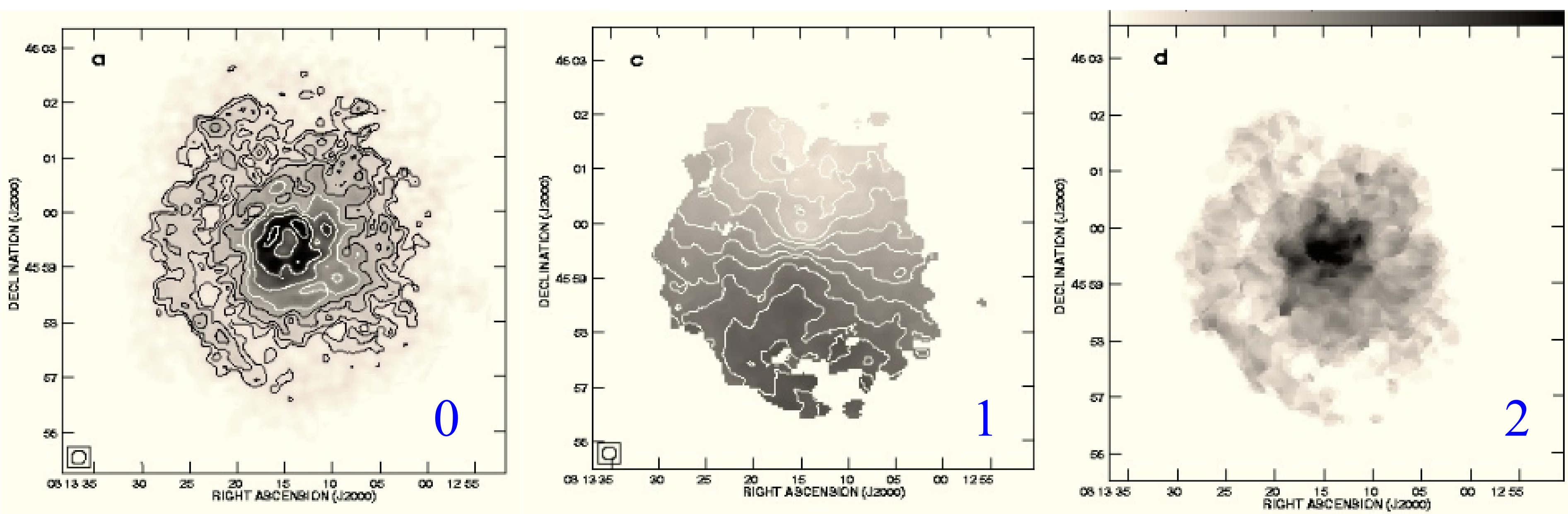




(Pihlstrom 2016, NRAO Workshop)

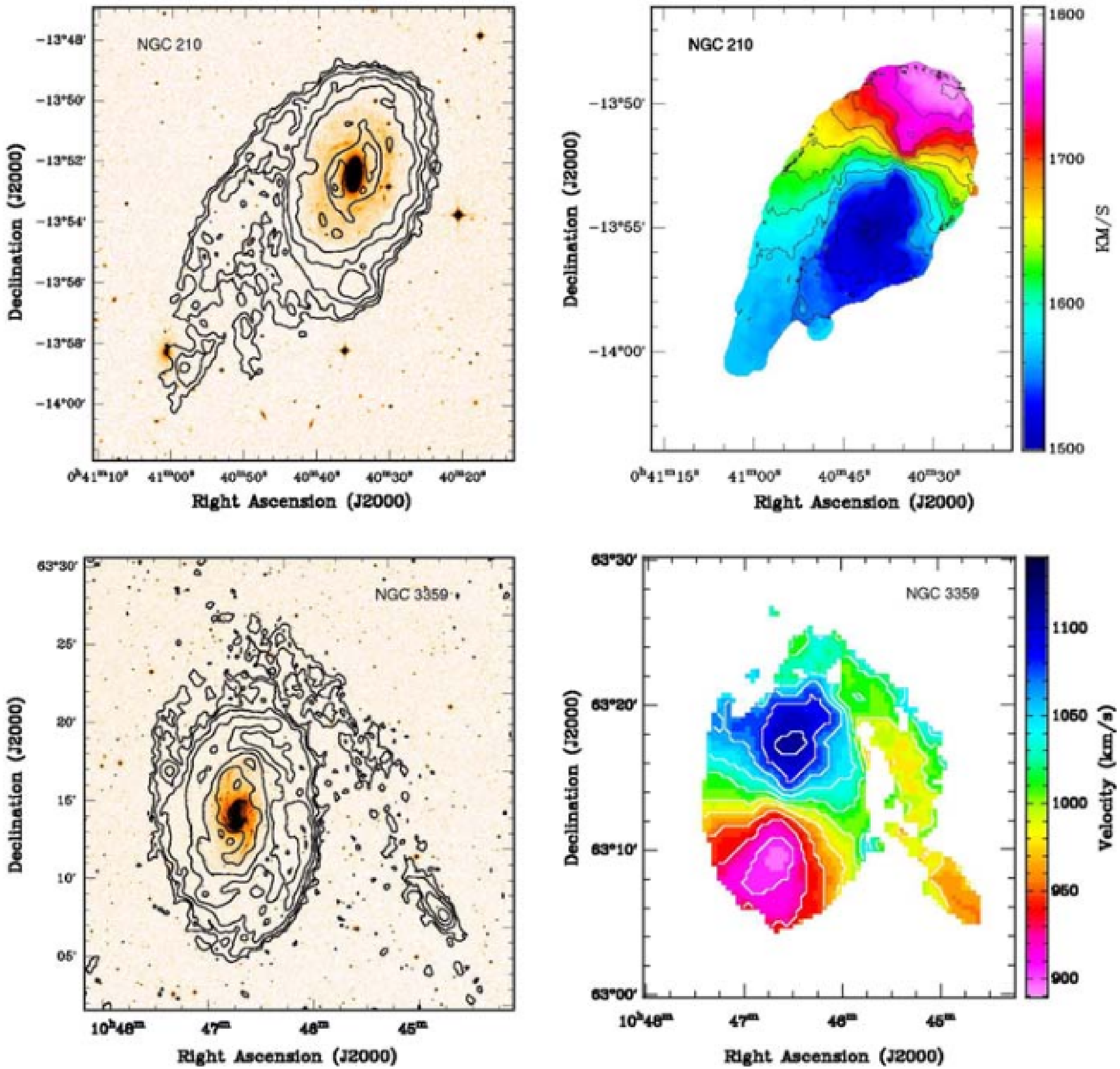
MOMENT IMAGES

- Moment – 0: Velocity-integrated flux density = $\int S_V \, dV$
- Moment – 1: Intensity-weighted velocity $\langle V \rangle = [\int S_V . v \, dv / \int S_V \, dv]$
- Moment – 2: Intensity-weighted dispersion $= \int S_V . (v - \langle V \rangle)^2 \, dv / \int S_V \, dv]$
- Interpretation complicated due to thresholding, to reduce noise effects.



(Pihlstrom 2018, NRAO Workshop)

Moment Images



(Sancisi et al. 2008, A&ARv)