Spectral line interferometry

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HI and optical image of M101

Me

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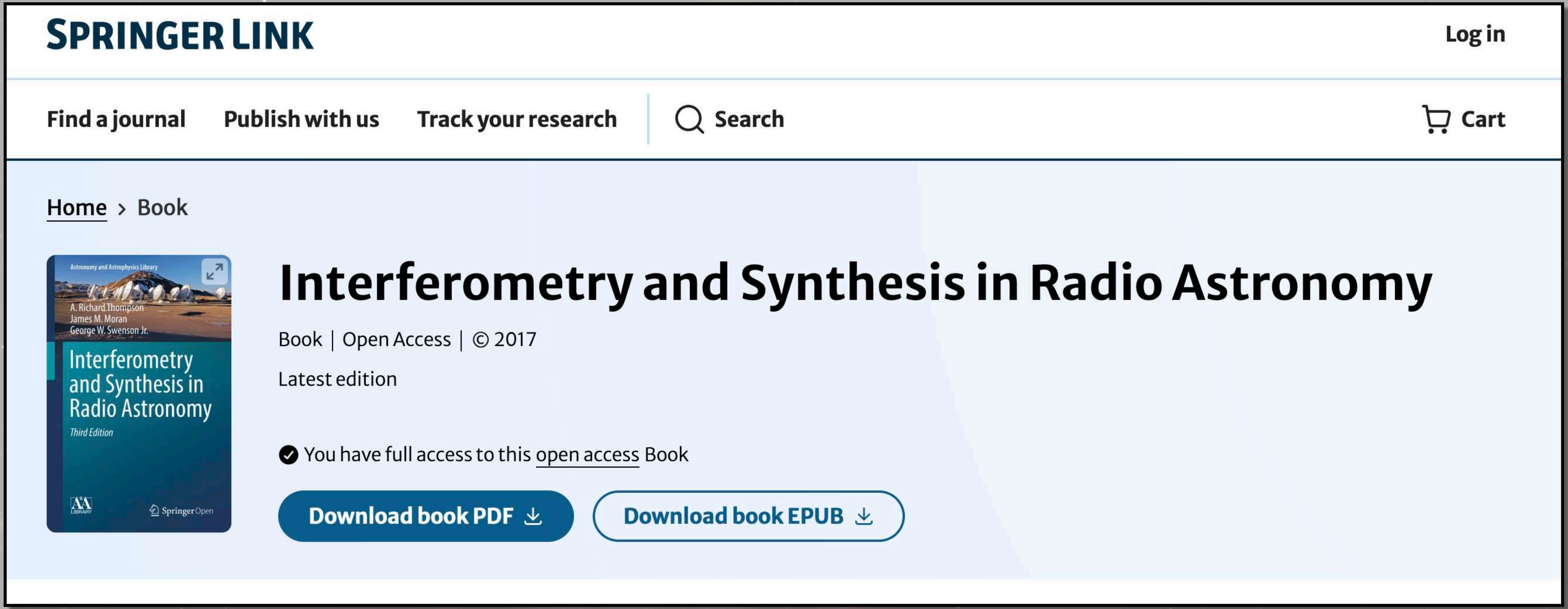
- ‘Retired’ Senior Astronomer at Netherlands Institute for Radio Astronomy (Astron), Dwingeloo
- Honorary professor at Kapteyn Institute at University of Groningen

- Main interests:
  - structure & evolution of galaxies
  - impact of AGN on galaxy evolution

  mainly doing radio interferometry of HI & molecules

  - calibration and analysis of radio observations



Book: Thompson, Moran & Swenson is open access!!
Is a standard reference

Topics

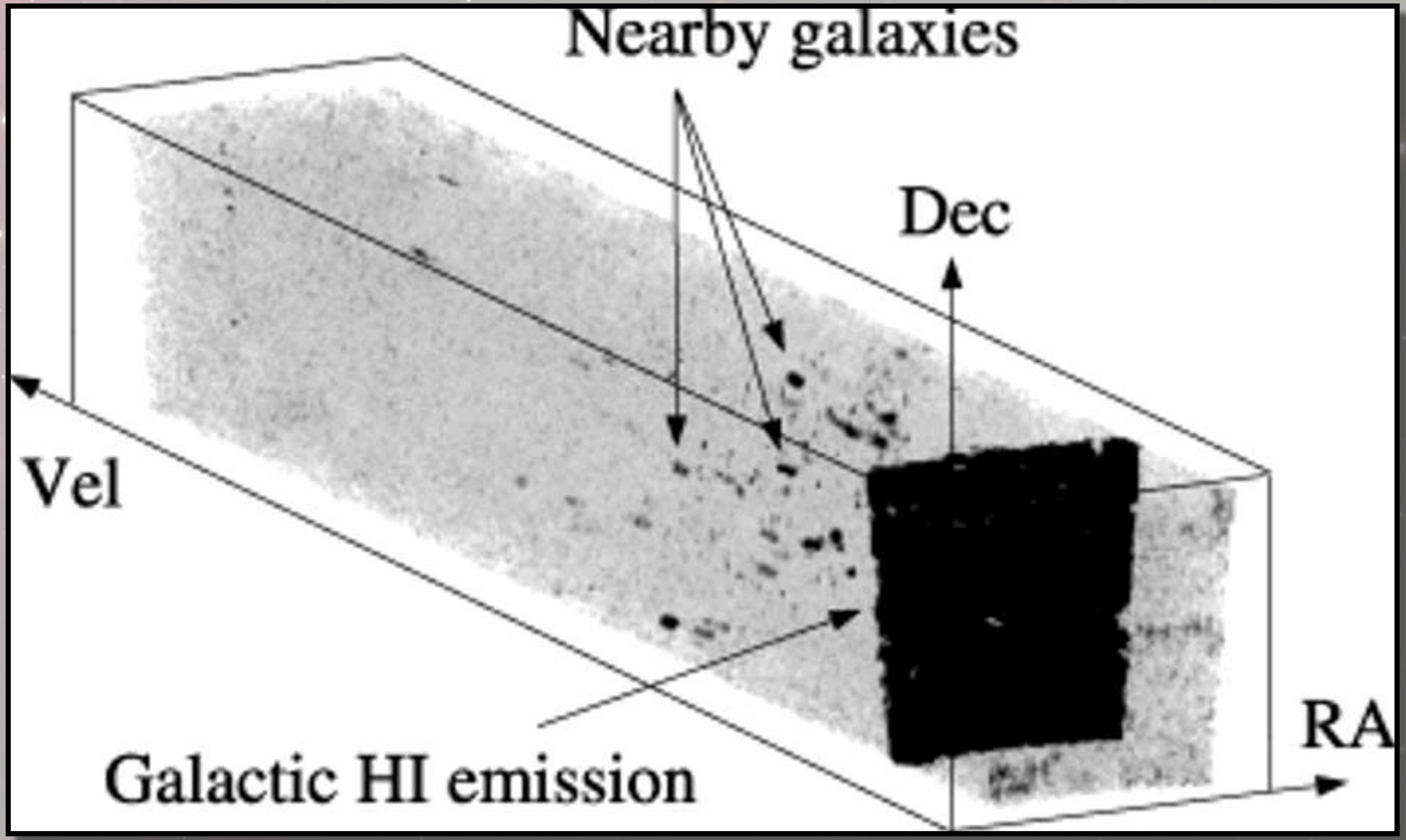
- How to do spectral line interferometry
  - spectral line correlator
  - calibration
  - continuum subtraction
  - analysis
- Future telescopes and topics

What is spectral line interferometry?

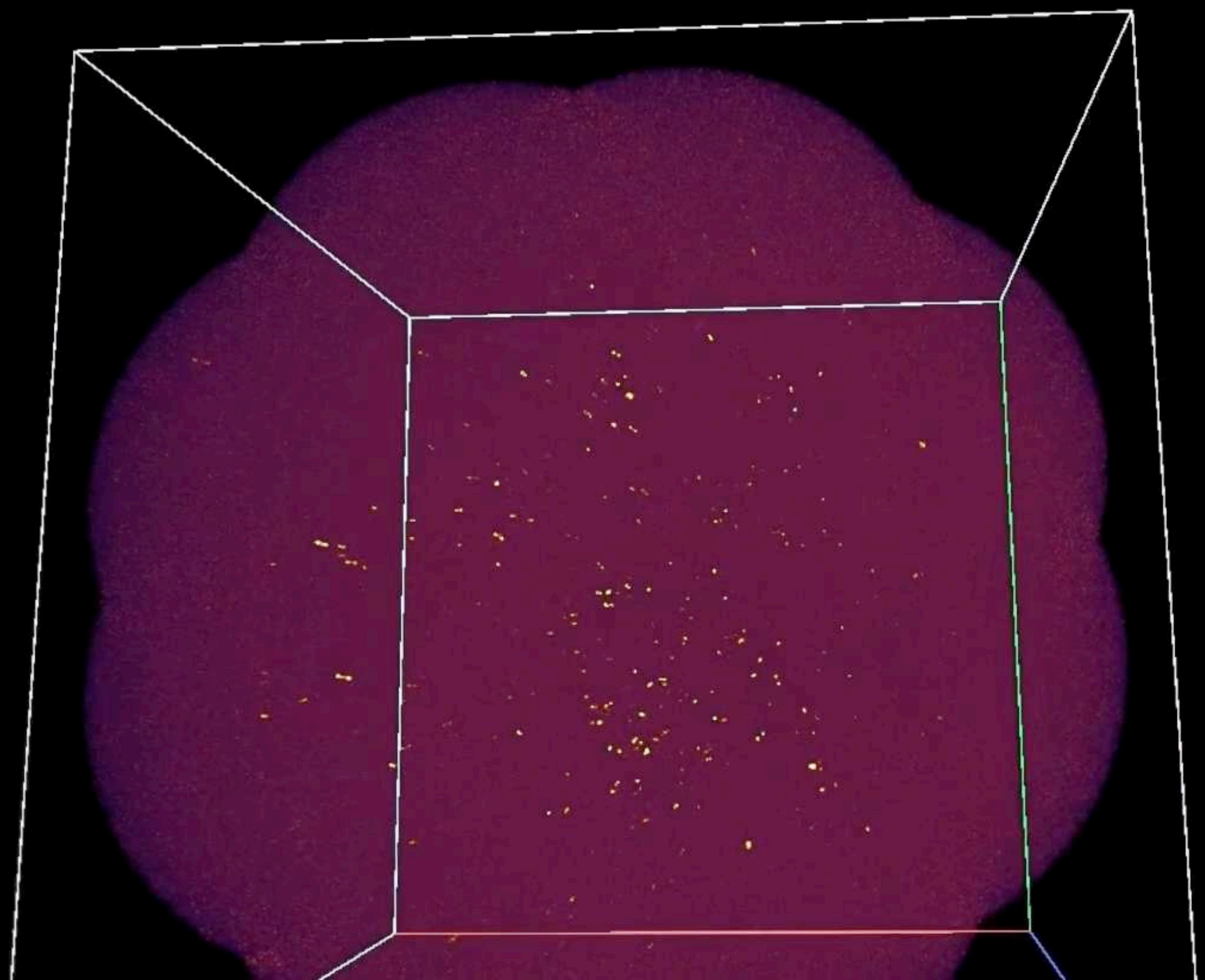
We observe the sky in such a way that we make a large number of images of the same piece of sky, each image at a slightly different frequency.
We get the radio spectrum at every position in the field of view (integral field spectroscopy)

→ a 3D- dataset, also known as a data cube

This maps the kinematics of the objects,
and more...



HI data cube with many galaxies detected



courtesy Marc Verheijen

What do we observe?

There are several radiation mechanisms that radiate in the radio domain

- Atomic hydrogen (H I): low density cold ISM (100 – 5000 K)
- Molecules: cold ISM (10 – few 100 K)
- (Mega)Masers
- Recombination lines: ionised ISM (~10,000 K)

Wide range of astronomy: physics of ISM, star formation, galaxy structure and evolution, AGN, …

From within our Galaxy, to objects at the highest redshifts; at low and at very high spatial resolution

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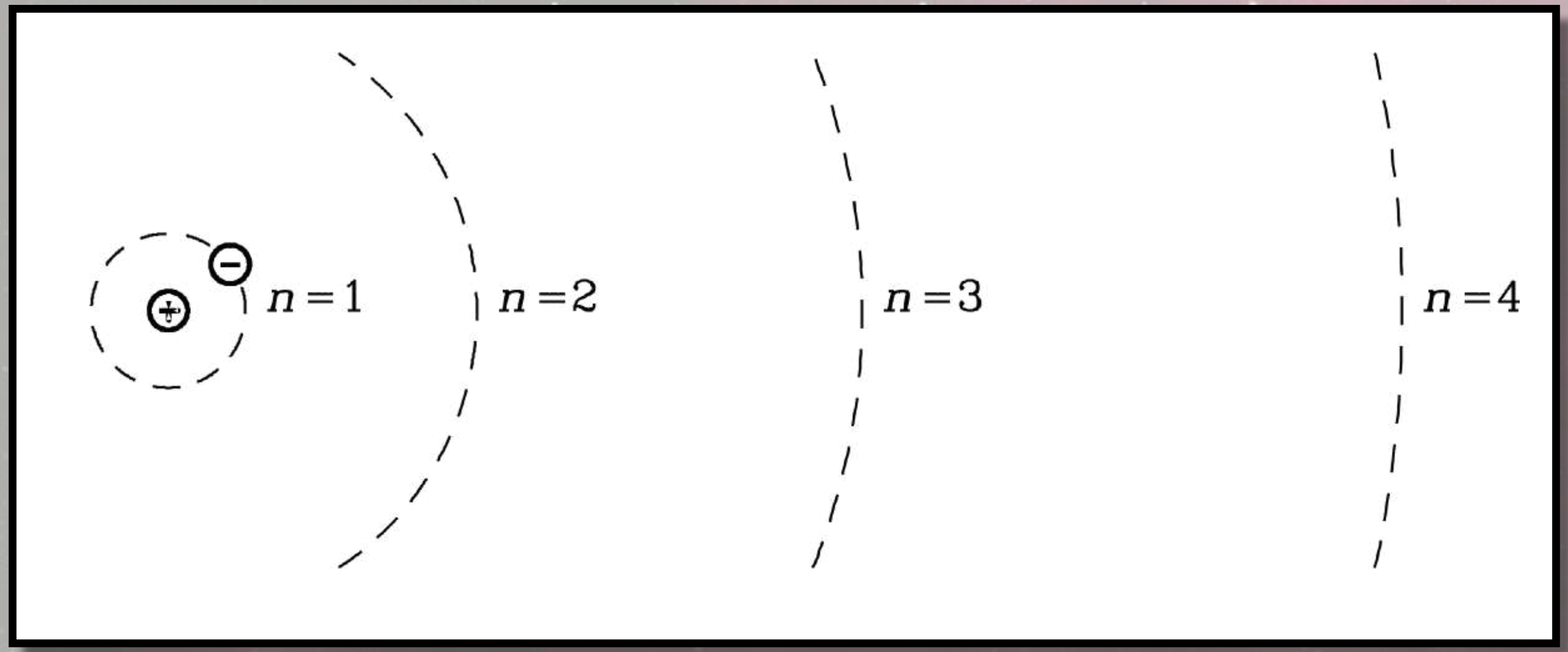
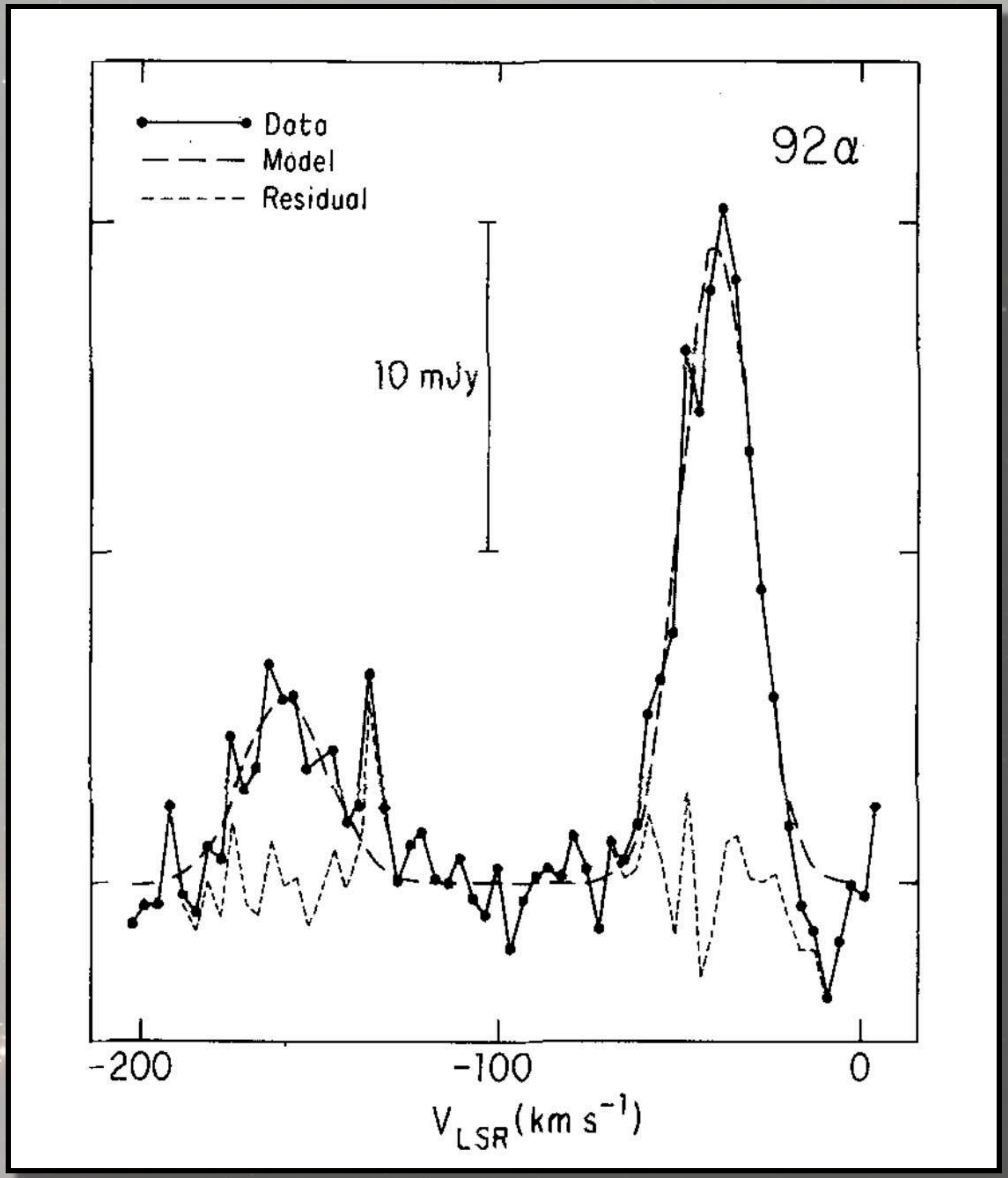
Radio recombination lines



downward transition between *n* to *n*−1 (or *n*−2,...) when *n* is large e.g.. H92α, H166β. Also He, C, ..

Occurs in the ionised ISM. very useful for studying HII regions and the like. Properties vary with quantum number *n*, can occur in emission for some *n* and in absorption for other *n*.

Very good diagnostic of density and temperature



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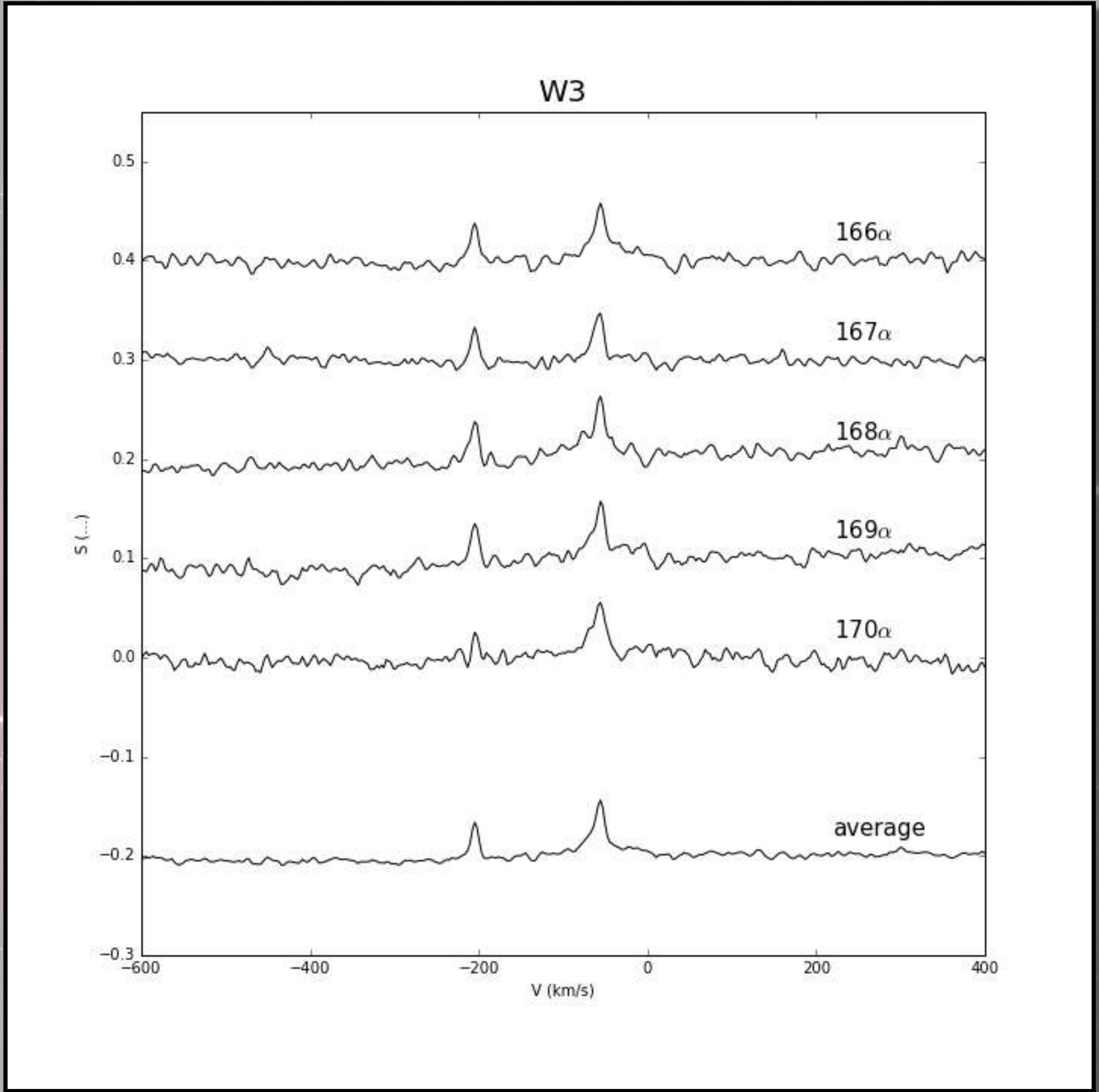
Recombination lines occur at regular intervals.
Can observe several lines at the same time
e.g. 1424.7, 1399.4, 1374.6, 1350.4, 1326.8 MHz

can stack them

properties vary with quantum number n,
can occur in emission for some n
and in absorption for other n

very good diagnostic of density
and temperature

and kinematics



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Spectroscopy in the radio domain has many very interesting applications

We have find a way make a data cube,

i.e. to split the observing band in many narrow channels

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Spectroscopy is not the only reason why we have to split the observing band in narrow channels

- The unit of length of an interferometer is wavelength
  - effectively, the size of the interferometer changes with frequency
  - this gives strong chromatic aberration
  - when averaging over broad bands, chromatic aberration leads to problems
- This means that for any broad-band work (i.e. $\Delta\nu/\nu > 0.1$), you have to split the total band in sub-bands. Also ‘continuum correlator’ has to work in spectral line work
- Modern radio telescopes strive for very large bandwidths.
  E.g. MeerKat in continuum mode has 4096 channels to cover 856 - 1712 MHz (32768 in line mode)

- Also need narrow channels to limit impact of RFI

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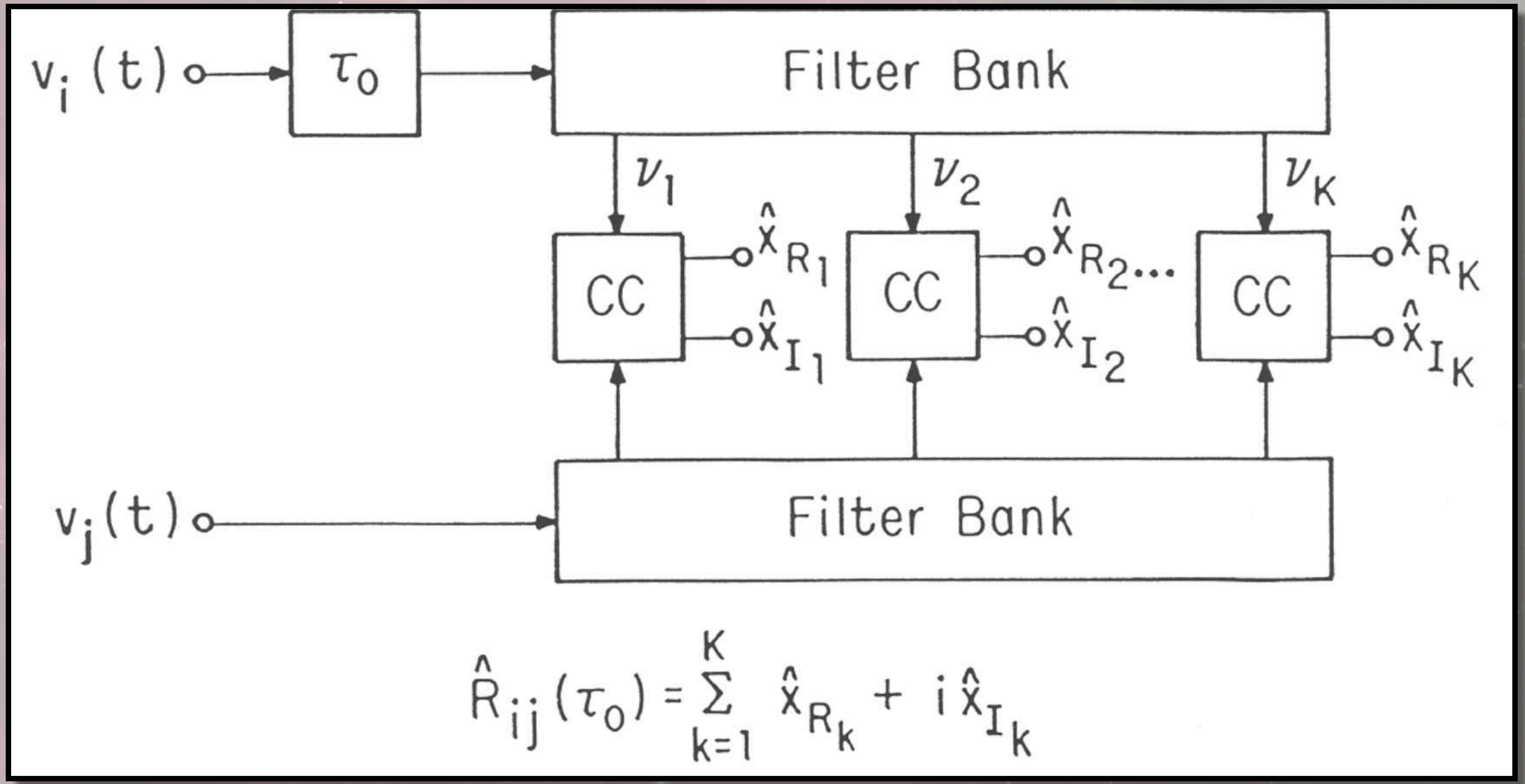
- Correlator makes visibilities by multiplying signals from two antennas.
- Old solution: split antenna signals in many bands by filters (hardware!), correlate each sub-band separately → many correlators in parallel. This gives the visibilities for each sub-band and one can make an image for each sub-band. Each channel has its correlator.



Not practical when number of channels and number of antennas is large

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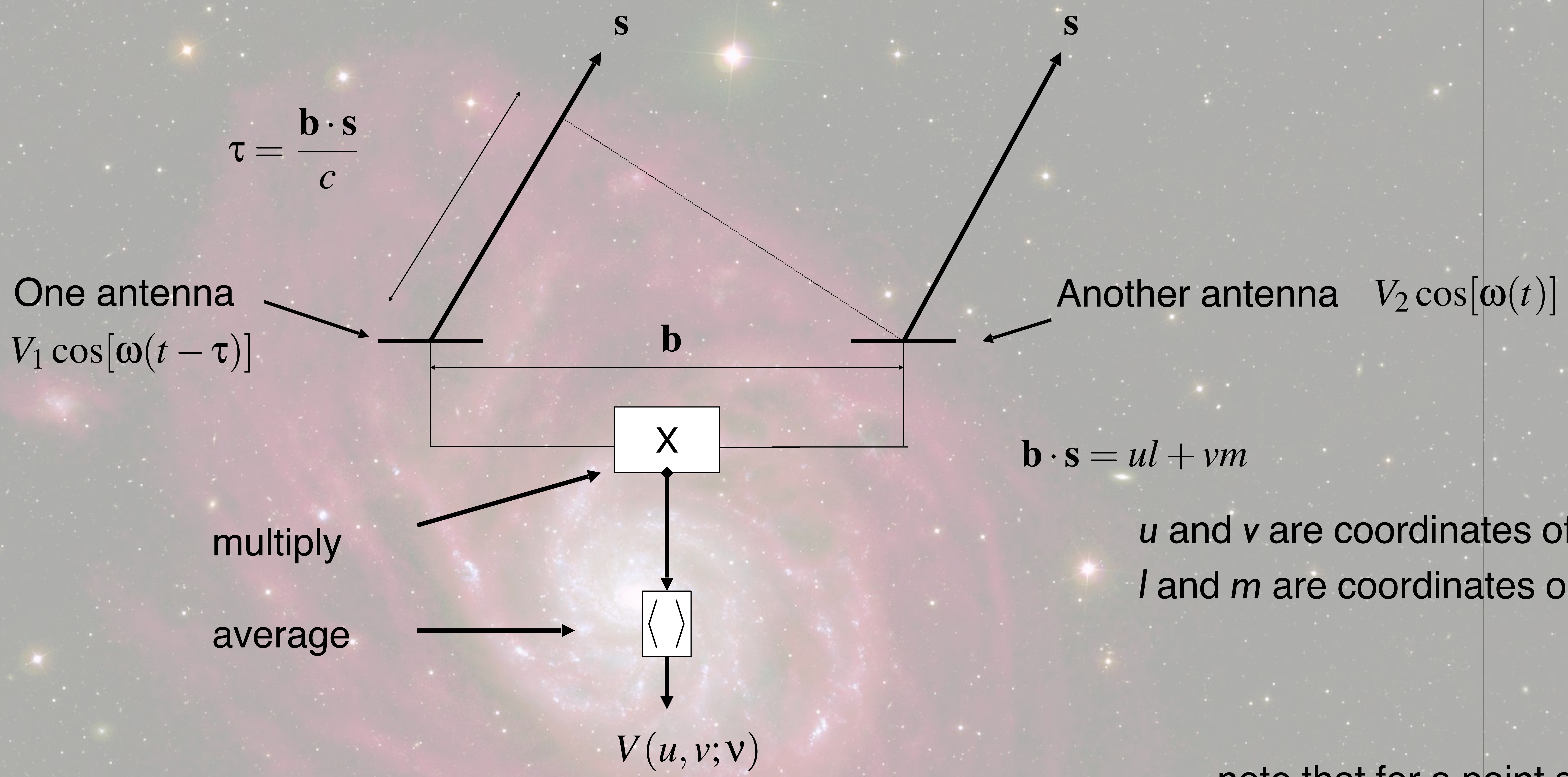

$$\mathbf{b} \cdot \mathbf{s} = ul + vm$$

u and *v* are coordinates of the baseline

l and *m* are coordinates on the sky

$$V(u, v; \nu) = \iint I(l, m; \nu) e^{-2\pi i(ul+vm)}\, dl dm$$

$$I(l.m; \nu) = \iint V(u, v; \nu) e^{2\pi i(ul+vm)} du dv$$

note that for a point source this is

$$V(u, v; \nu) = I(l_o, m_o; \nu) e^{-2\pi i(ul_o+vm_o)}$$

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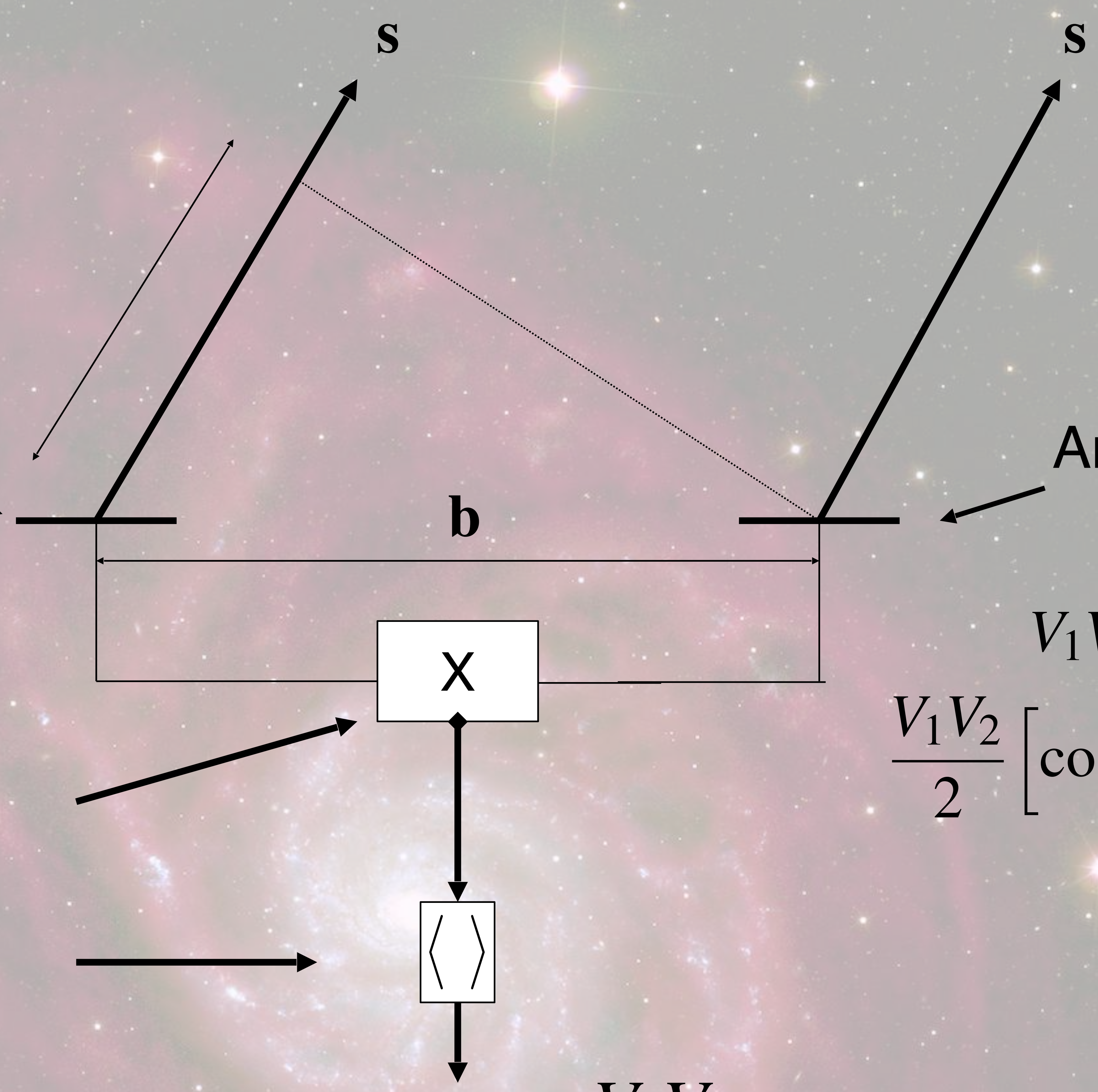
Consider radiation from a single monochromatic point source in direction $\mathbf{s}$

$$\tau = \frac{\mathbf{b} \cdot \mathbf{s}}{c}$$



One antenna
$V_1 \cos[\omega(t - \tau)]$

Another antenna $V_2 \cos[\omega(t)]$

multiply

average

$$V_1 V_2 \cos[\omega(t-\tau)] \cos[\omega(t)] =$$

$$\frac{V_1 V_2}{2}\left[\cos[\omega(\tau)] + \cos[2\omega t - \omega(\tau)]\right]$$

$$R_c = \frac{V_1 V_2}{2} \cos[\omega\tau] = I(\mathbf{s}, \nu) \cos[2\pi\nu \mathbf{b} \cdot (\mathbf{s})/c]$$

$$\omega = 2\pi\nu$$

the real part of the visibility

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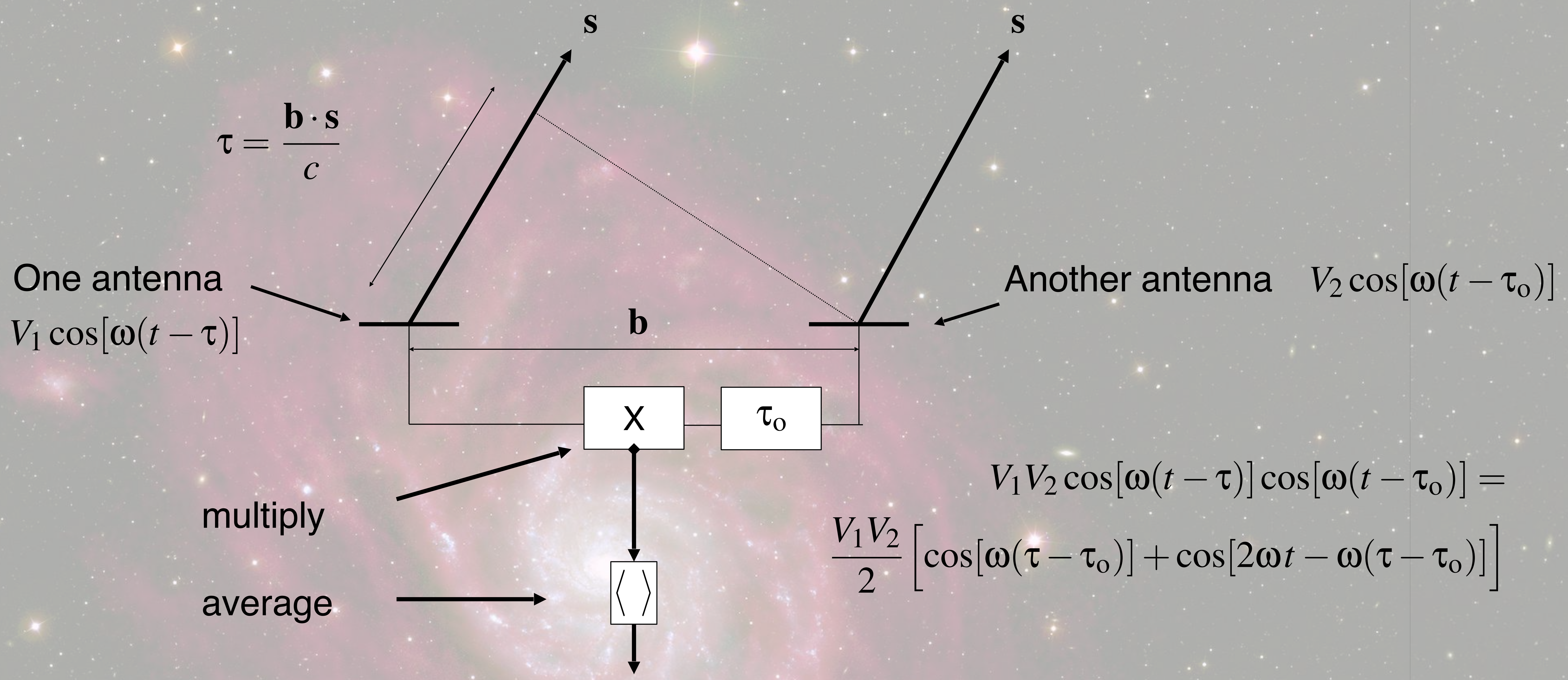
insert a series of time delays τ_o in signal path of one of the antennas



$$V_1 V_2 \cos[\omega(t-\tau)] \cos[\omega(t-\tau_o)] =$$

$$\frac{V_1 V_2}{2} \left[\cos[\omega(\tau-\tau_o)] + \cos[2\omega t - \omega(\tau-\tau_o)] \right]$$

$$R_c = \frac{V_1 V_2}{2} \cos[\omega(\tau-\tau_o)]$$

Now I have a function of time

correlator gives $R_c = I(\mathbf{s},\nu)\cos[\omega(\tau-\tau_o)]$

in a similar way, we can obtain $R_s = I(\mathbf{s},\nu)\sin[\omega(\tau-\tau_o)]$

we can combine this to make the visibility
(remember this is a point source)

$$R(\tau_o) = R_c - iR_s = I(\mathbf{s},\nu)e^{-i\omega(\tau-\tau_o)}$$
$$= I(\mathbf{s},\nu)e^{-2\pi i\nu\mathbf{b}\cdot\mathbf{s}/c}e^{2\pi i\nu\tau_o}$$

This is the true visibility modulated by $e^{2\pi i\nu\tau_o}$

$R(\tau_o)$ is called the *lag spectrum*

Integrating this over the observed band:

$$R(\tau_o) = \int I(\mathbf{s},\nu)e^{-2\pi i\nu\mathbf{b}\cdot\mathbf{s}/c}\, e^{2\pi i\nu\tau_o}\, d\nu$$

This is a Fourier Transform!!!

$R(\tau_o)$ is the ν FT of $I(\mathbf{s},\nu)e^{-2\pi i\nu\mathbf{b}\cdot\mathbf{s}/c}$ the visibility as function of frequency

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$R(\tau)$ is the ν FT of $I(\mathbf{s},\nu)e^{-2\pi i\nu \mathbf{b}\cdot\mathbf{s}/c}$

Thus inverse Fourier transforming $R(\tau)$ wrt τ gives you

$$\int R(\tau)e^{2\pi i\tau\nu}d\tau = I(\mathbf{s},\nu)e^{-2\pi i\nu \mathbf{b}\cdot\mathbf{s}/c}$$ i.e. the visibility as function of frequency

The above is for a point source. Correlator is a linear system $f(a+b) = f(a) + f(b)$

$$\int R(\tau)e^{2\pi i\tau\nu}d\tau = \int R_1(\tau)e^{2\pi i\tau\nu}d\tau + \int R_2(\tau)e^{2\pi i\tau\nu}d\tau = I(\mathbf{s_1},\nu)e^{-2\pi i\nu \mathbf{b}\cdot\mathbf{s_1}/c} + I(\mathbf{s_2},\nu)e^{-2\pi i\nu \mathbf{b}\cdot\mathbf{s_2}/c}$$

So I can integrate over the sky

$$\int R(\tau)e^{2\pi i\tau\nu}d\tau = \iint I(\mathbf{s},\nu)e^{-2\pi i\nu \mathbf{b}\cdot\mathbf{s}/c}d\Omega = \iint I(l,m;\nu)e^{-2\pi i(ul+vm)}dldm = V(u,v;\nu)$$

i.e. I get the visibility as function of frequency. $I(l,m;\nu) = \iint V(u,v;\nu)e^{2\pi i(ul+vm)}\,dudv$

And with this I can make images as function of frequency

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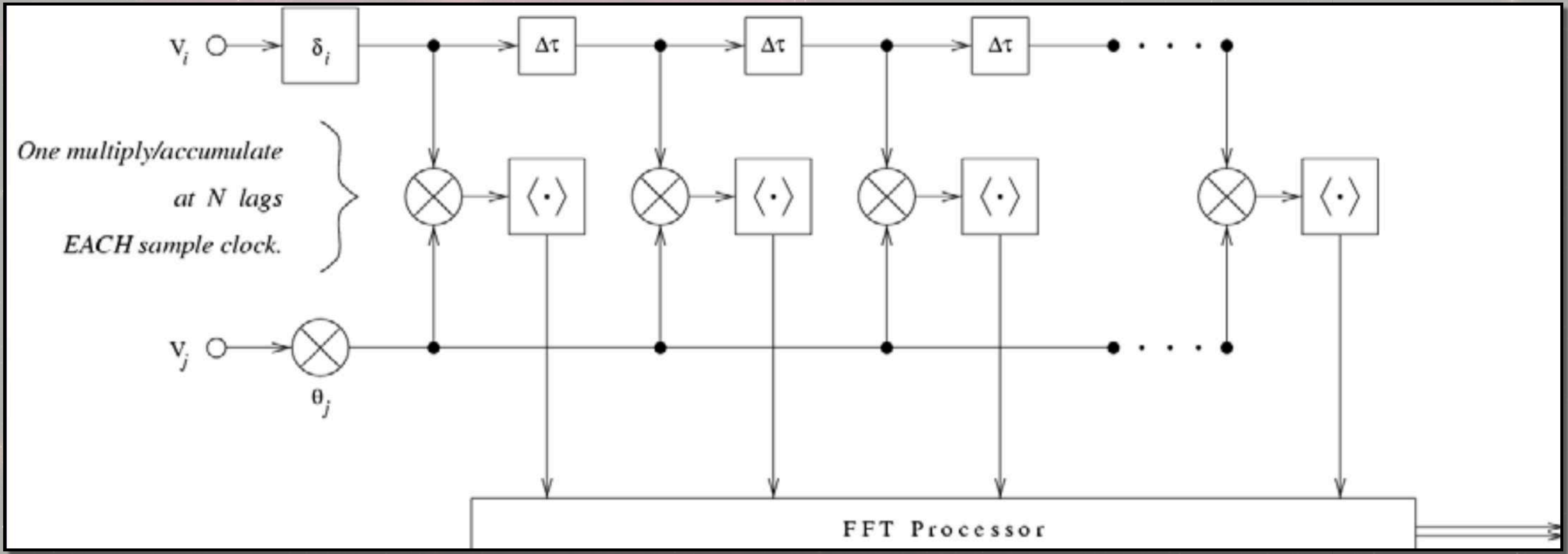
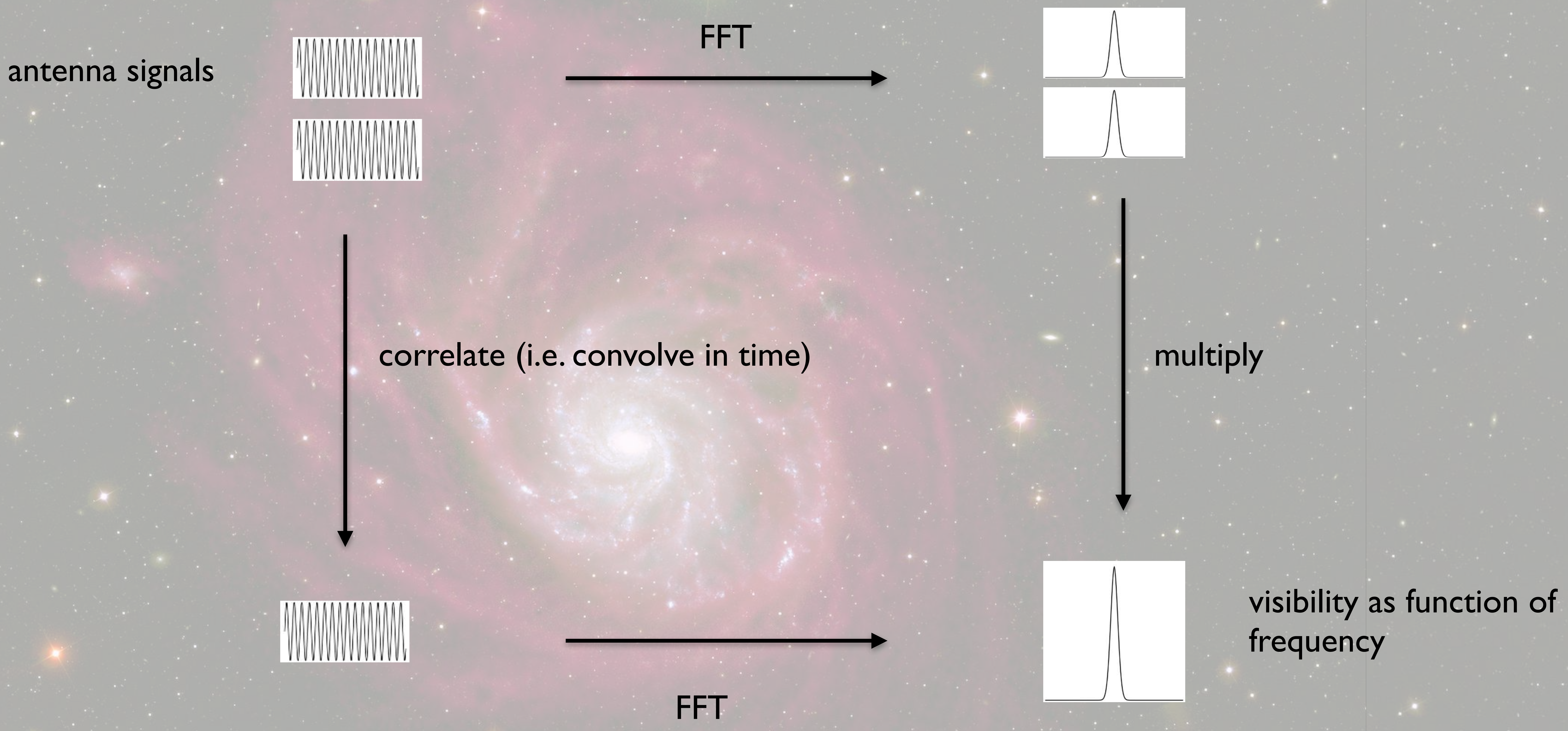
There are two ways of doing this.

XF correlator: correlate first, then FFT

Shift signal in time and correlate each time step to make $R(\tau)$ and then do the FT



Alternative: exploit the convolution theorem: $\mathrm{FT}(f \star g) = \mathrm{FT}(f) \cdot \mathrm{FT}(g)$



Fourier transform signals from antennas and then multiply

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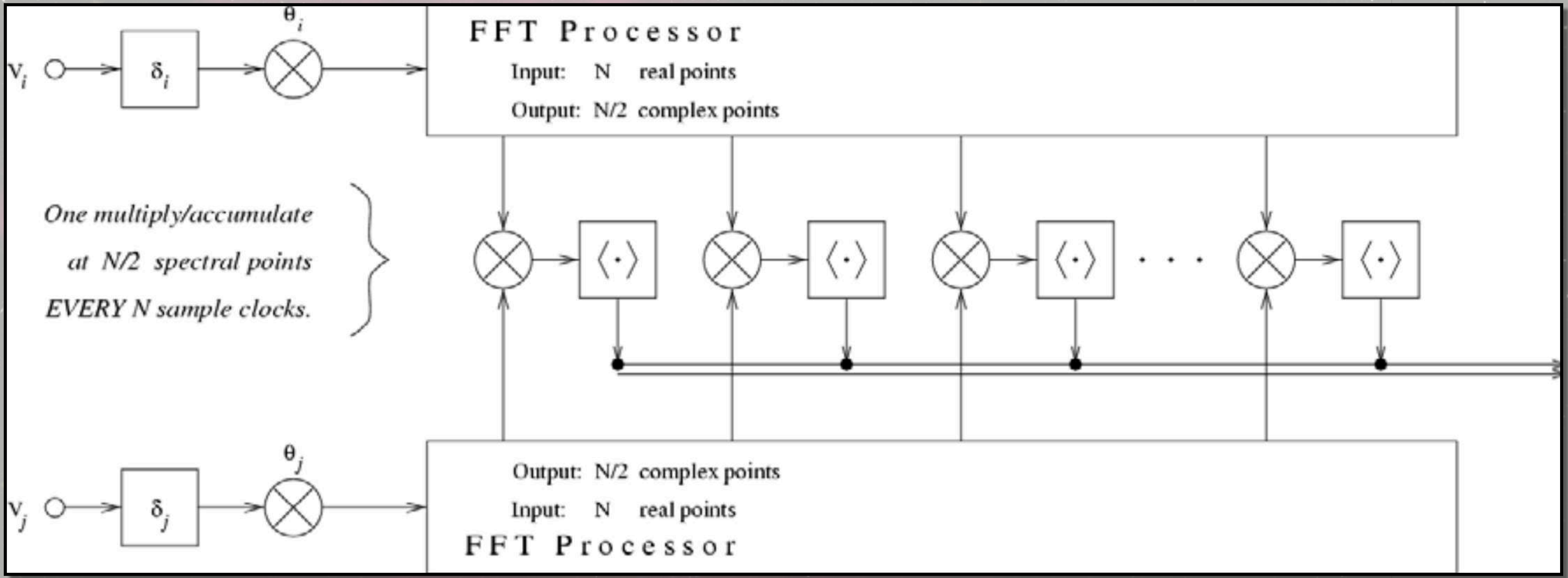
Alternative: do FFT first and then multiply signals (FX correlator)



Modern correlators are of this type

Spectral calibration

Standard calibration equation: $V_{ij}^{\text{true}}(\nu,t) = g_{ij}(\nu,t)\cdot V_{ij}^{\text{obs}}(\nu,t)$

The observed visibilities are multiplied by a correction factor, correcting for changes in instrument and atmosphere (ionosphere)

1st standard assumption: corrections are antenna based, not baseline based

$$g_{ij}(\nu,t) = g_i(\nu,t)g_j^*(\nu,t)$$

This makes the calibration more tractable (apart from being physically motivated… design).

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Spectral line work requires extra calibration

2nd standard assumption: the frequency calibration is time independent and the time-variable changes are frequency independent:

$$g_i(\nu, t) = a_i(t) \cdot b_i(\nu)$$

a_i is referred to as the *gain* of antenna i
b_i is called the *bandpass* of antenna i

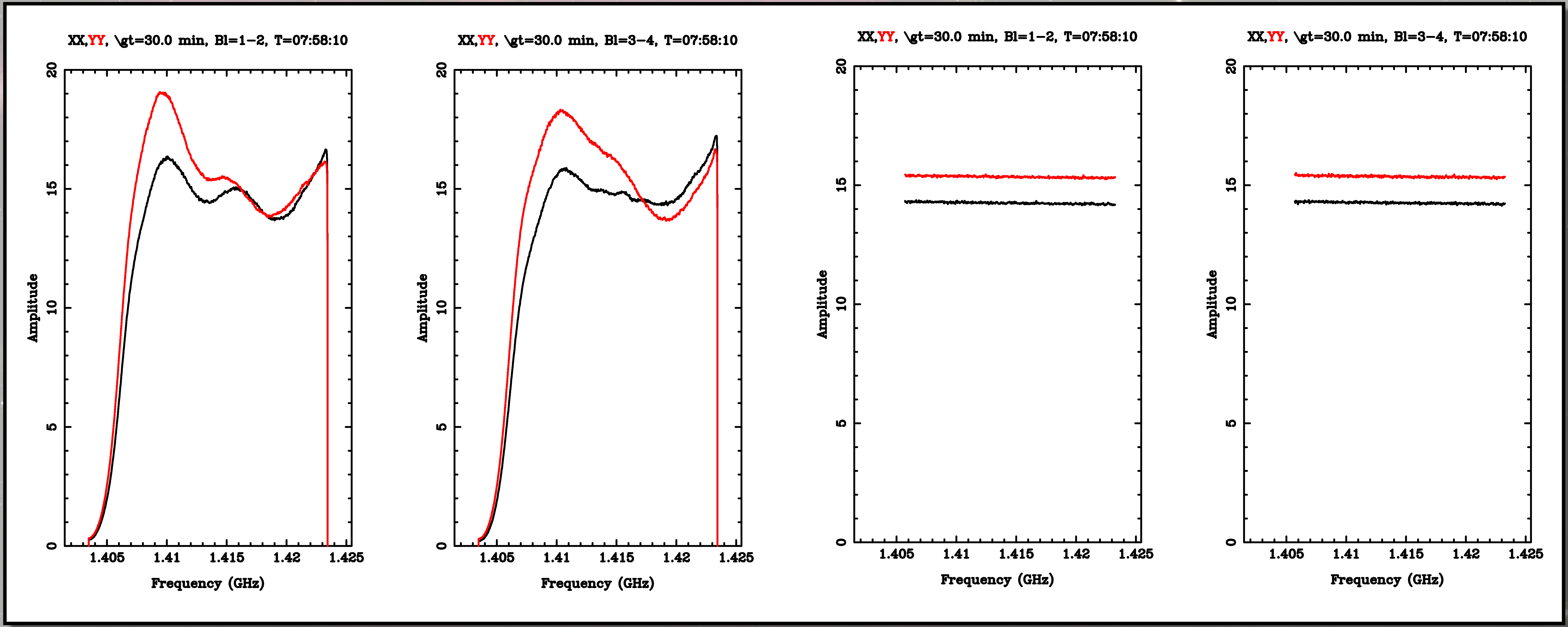
The a_i are found by regularly observing a nearby calibration source during the main observation, or by *selfcal* on the observation itself.
The b_i are found by observing strong calibrator before and/or after main observation.

One great advantage is that in deriving the a_i, the data can be averaged over frequency, greatly increasing the S/N of the calibration (> factor 30)

Bandpass calibration

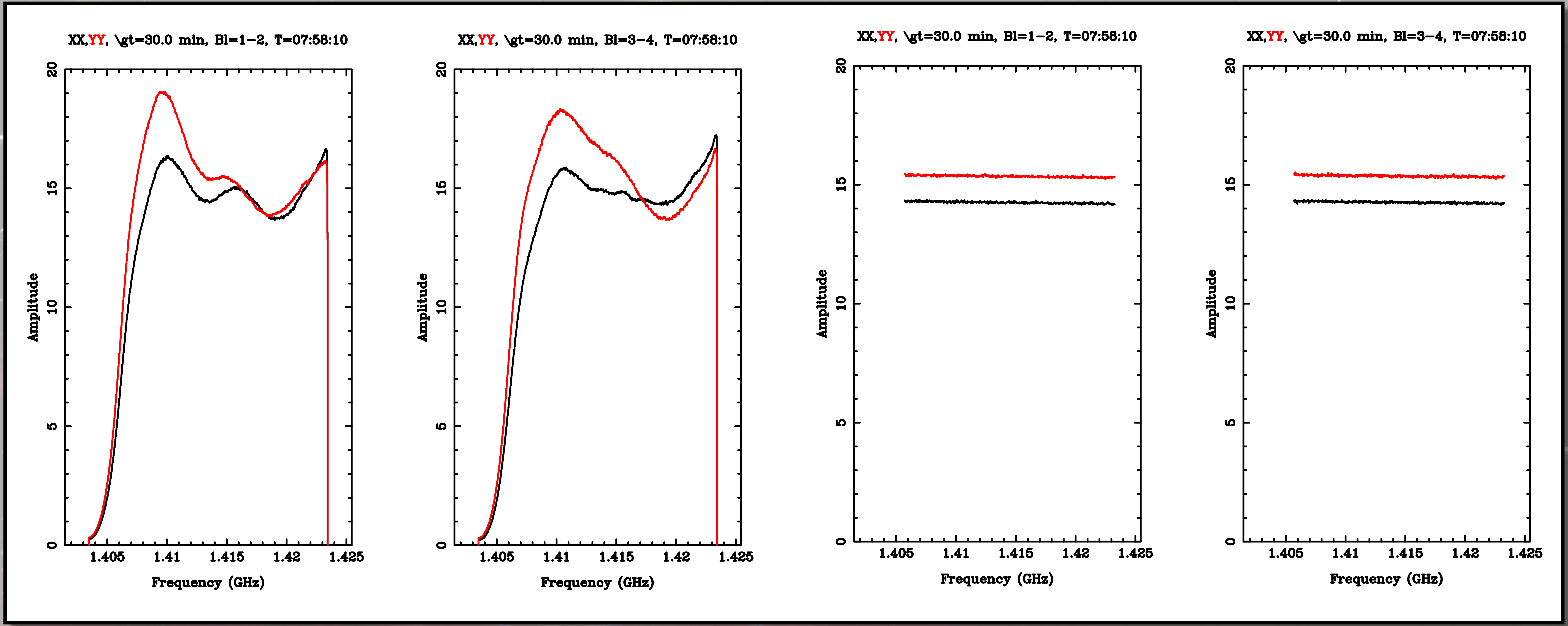
Idea is very simple: observe a very strong source (not necessarily a point source, but it helps a lot) and apply $V_{ij,\mathrm{true}}(\nu,t) = a_i(t)a_j^*(t)\cdot b_i(\nu)b_j^*(\nu)\cdot V_{ij,\mathrm{obs}}$ to solve for the a_i and the b_i .

Shape of bandpass is mainly due to filters.



visibility spectra before calibration after calibration

Note that calibrator (3C286) is polarised and has a non-zero spectral index…



bandpasses can be ugly, but this is not reflected in noise.
(almost) all noise occurs before filters, so the noise is also attenuated!

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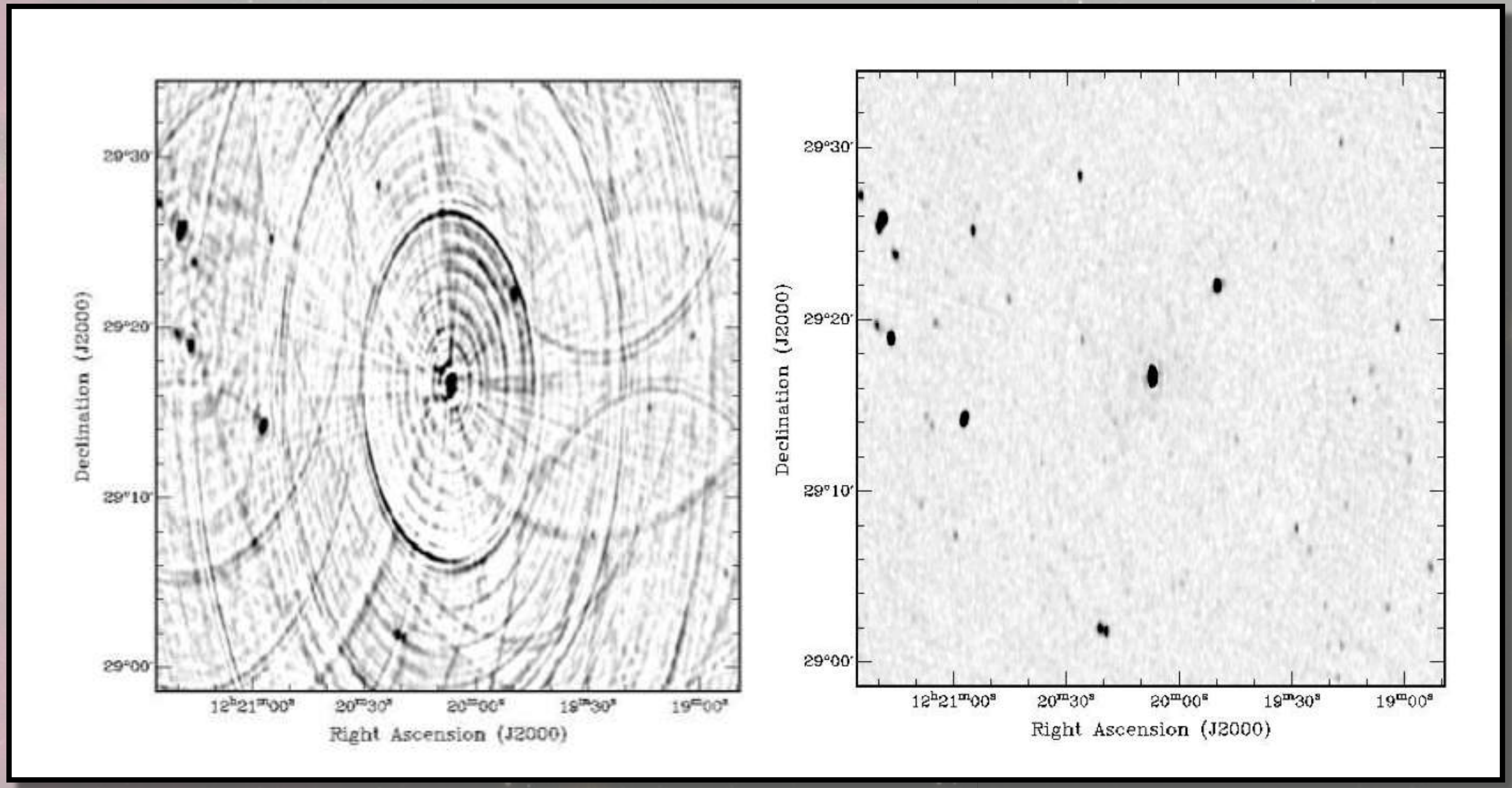
A few more words on $g_i(\nu,t) = a_i(t) \cdot b_i(\nu)$

Important consequence of this assumption is that errors due to imperfect calibration of the a_i are *frequency independent*!!

If there is a strong continuum source in the image that shows all kinds of distortions due to imperfect calibration, the image is said to be dynamic range limited (as opposed to noise limited). But these distortions are frequency independent!!!

If I subtract the continuum from the data in the proper way (see later), I subtract the source *and its errors* and the image becomes noise limited, even if the original images were dynamic range limited

I general (but not always…) the line emission is (much) fainter than the continuum emission. So the dynamic range requirements for line work are (much) less strong. Line images are usually limited by noise, not by calibration artefacts



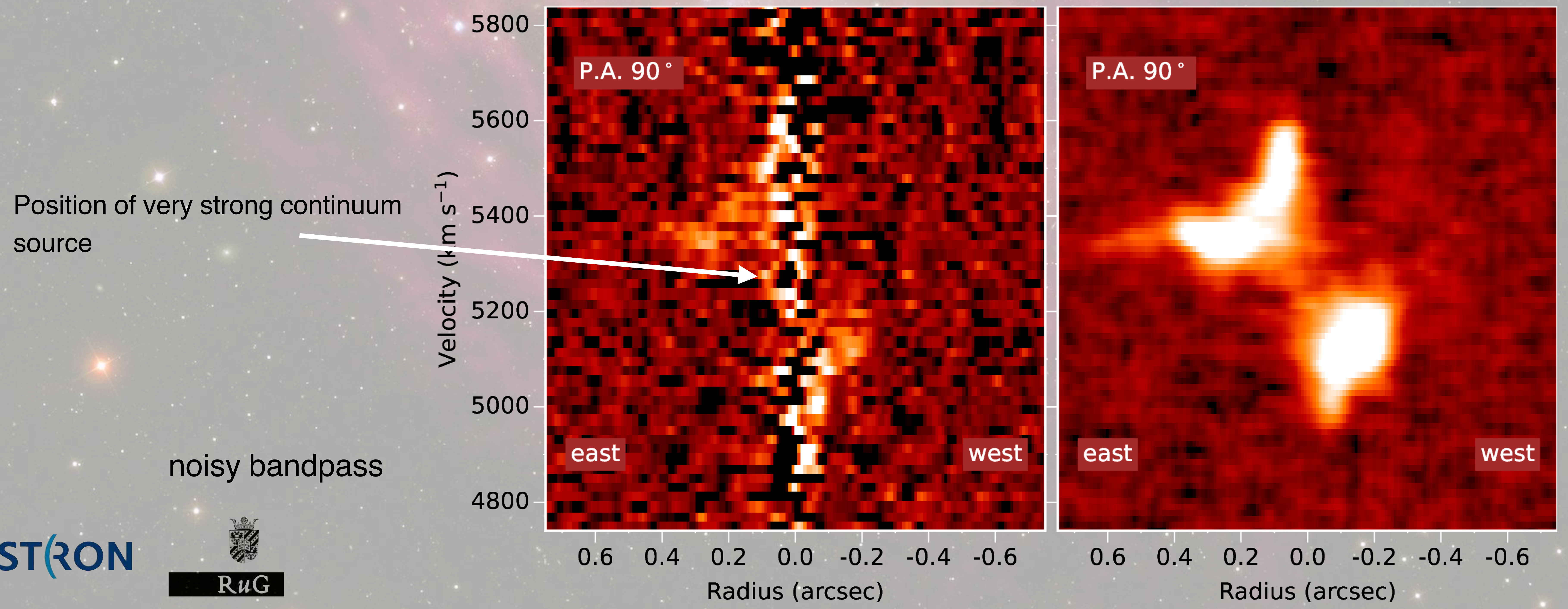
bad a_i good a_i

For very very strong continuum sources, there are complications...
If the target source is stronger than the calibrator (typically 10's of Jy),
the S/N in the calibrator is lower than of the target and the noise in the bandpass becomes important.

$$V_{ij,\mathrm{true}}(\nu,t) = a_i(t)a_j^*(t)\cdot b_i(\nu)b_j^*(\nu)\cdot V_{ij,\mathrm{obs}}$$

$b(\nu) = b_{\mathrm{true}}(\nu)\cdot(1+\varepsilon)$ gives errors of $O(\varepsilon V)$ *that vary with frequency*

if $V_{ij,\mathrm{obs}}$ is very large, $O(\varepsilon V)$ will dominate over thermal noise



noisy bandpass

good bandpass

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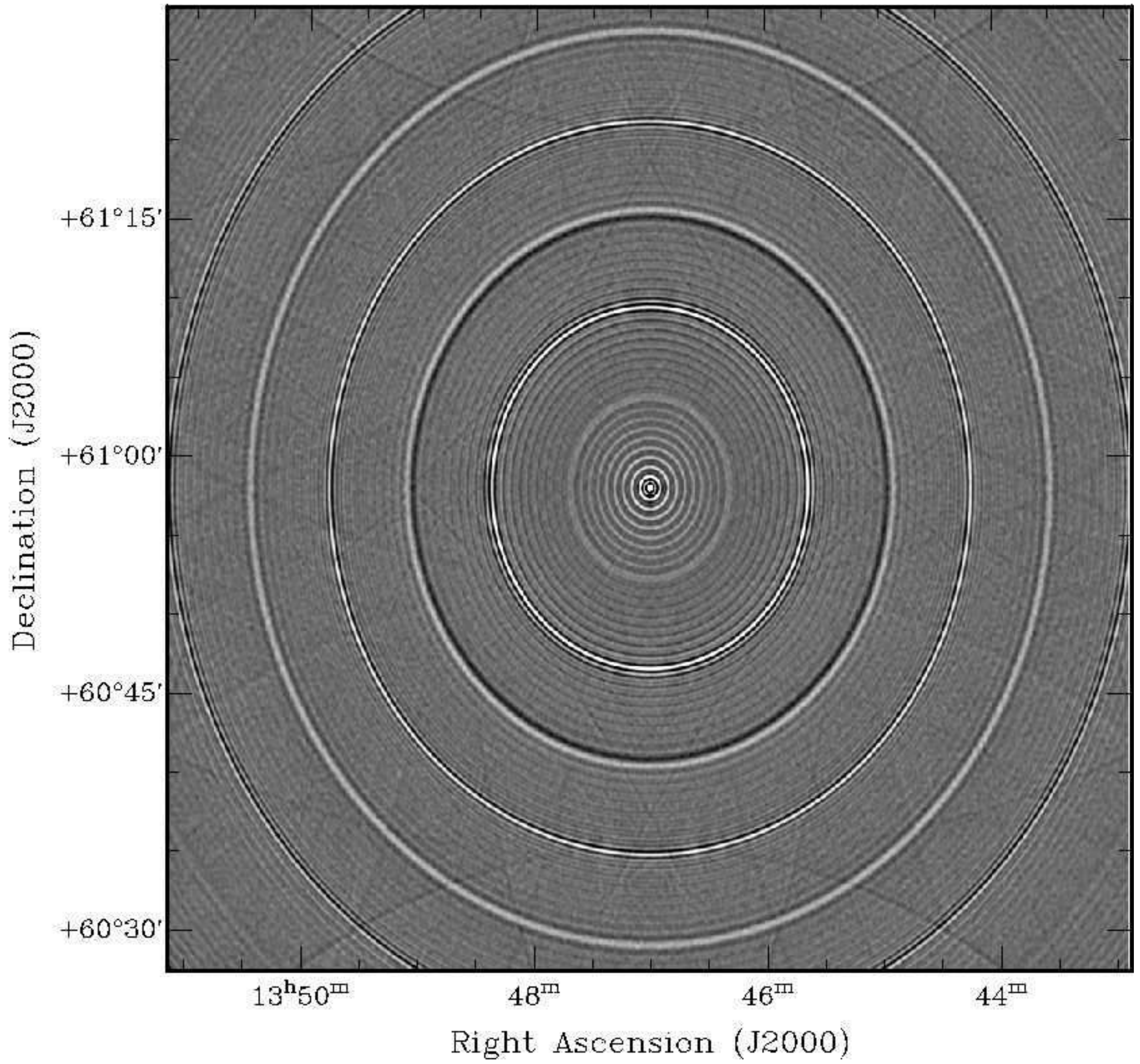
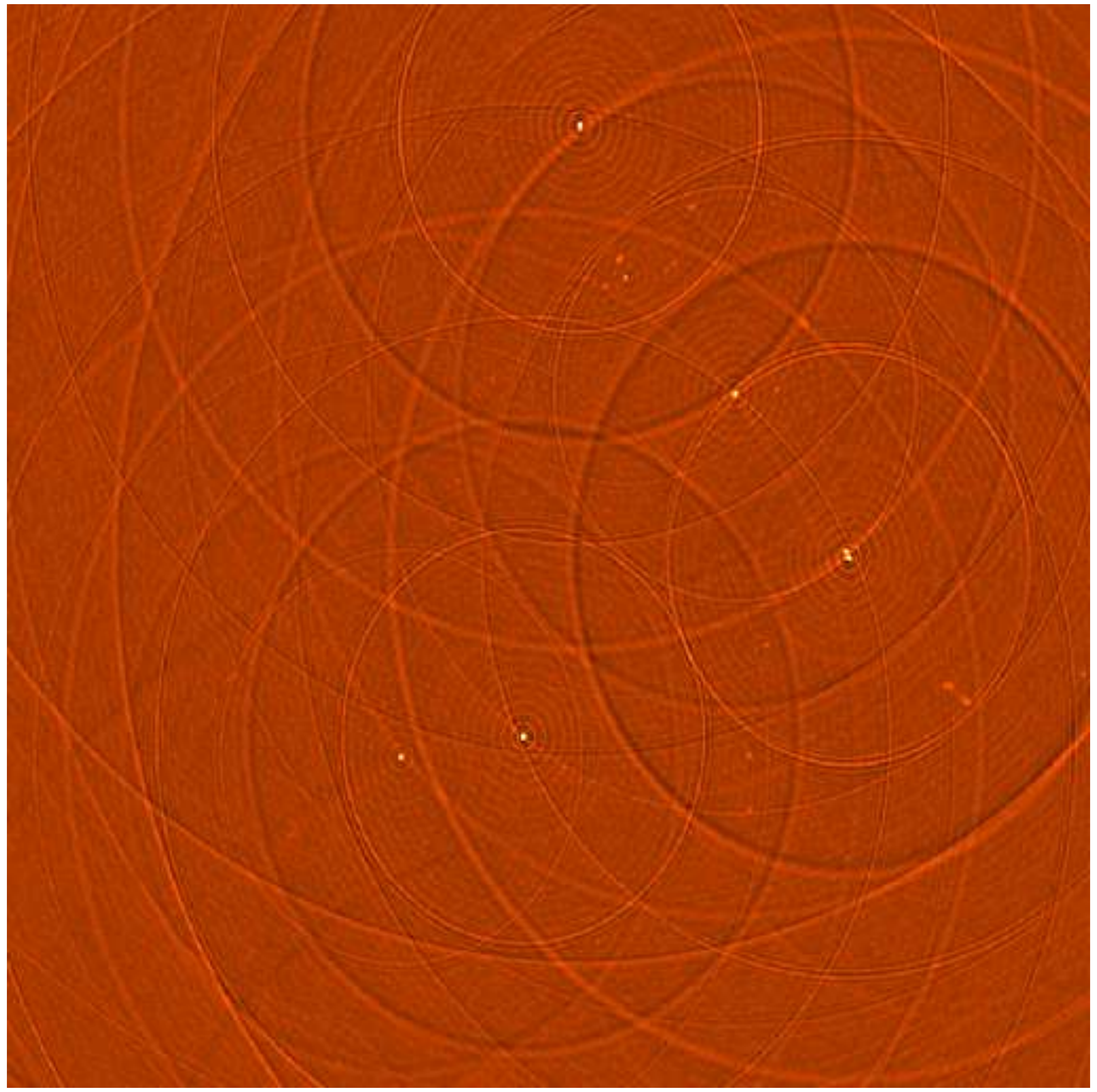
Interferometers are lousy telescopes!!!



PSF



Dirty image

Because our telescope has many large holes, the PSF has many features (sidelobes) that extend over the entire sky!!!

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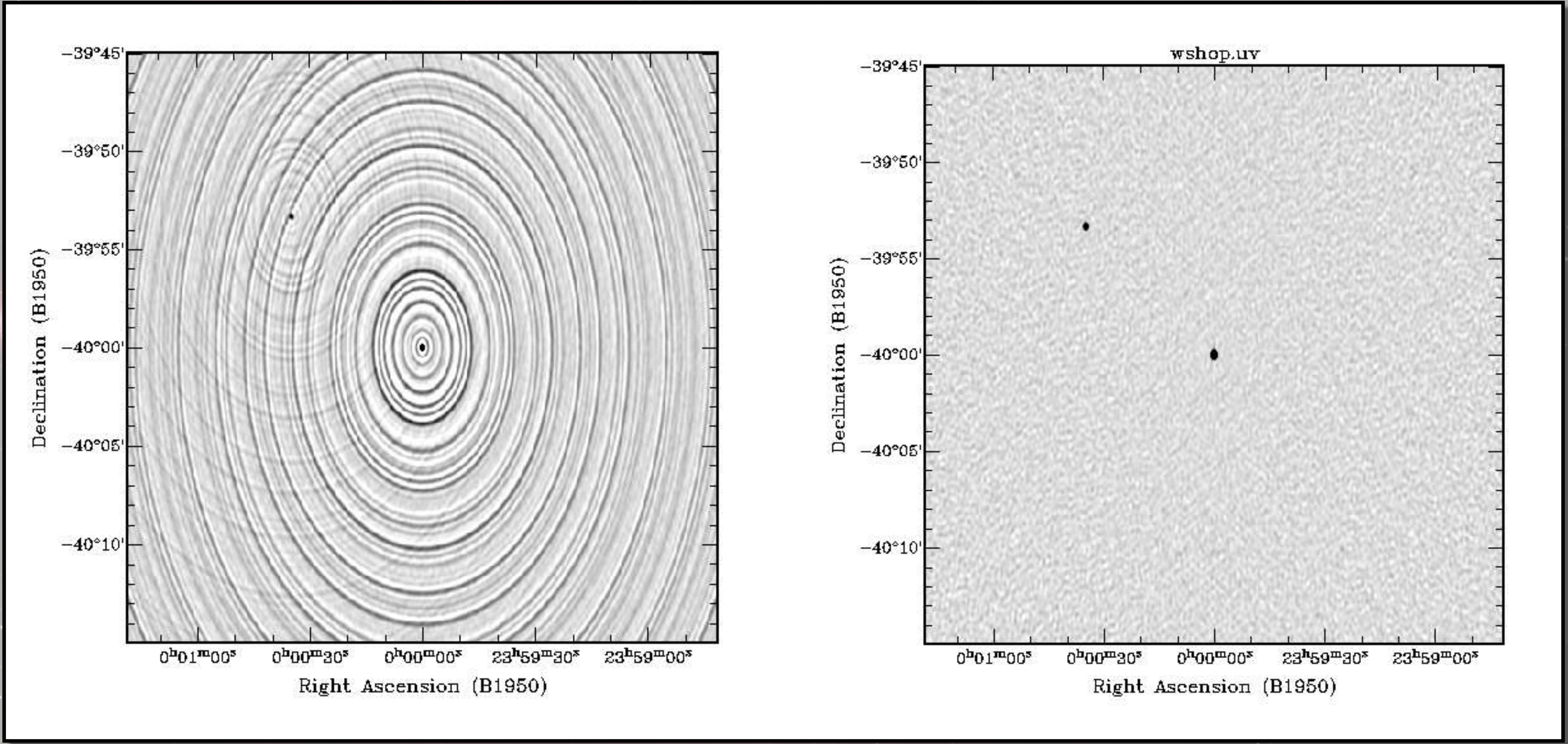
This dirty PSF can be corrected for



Dirty map

Clean map

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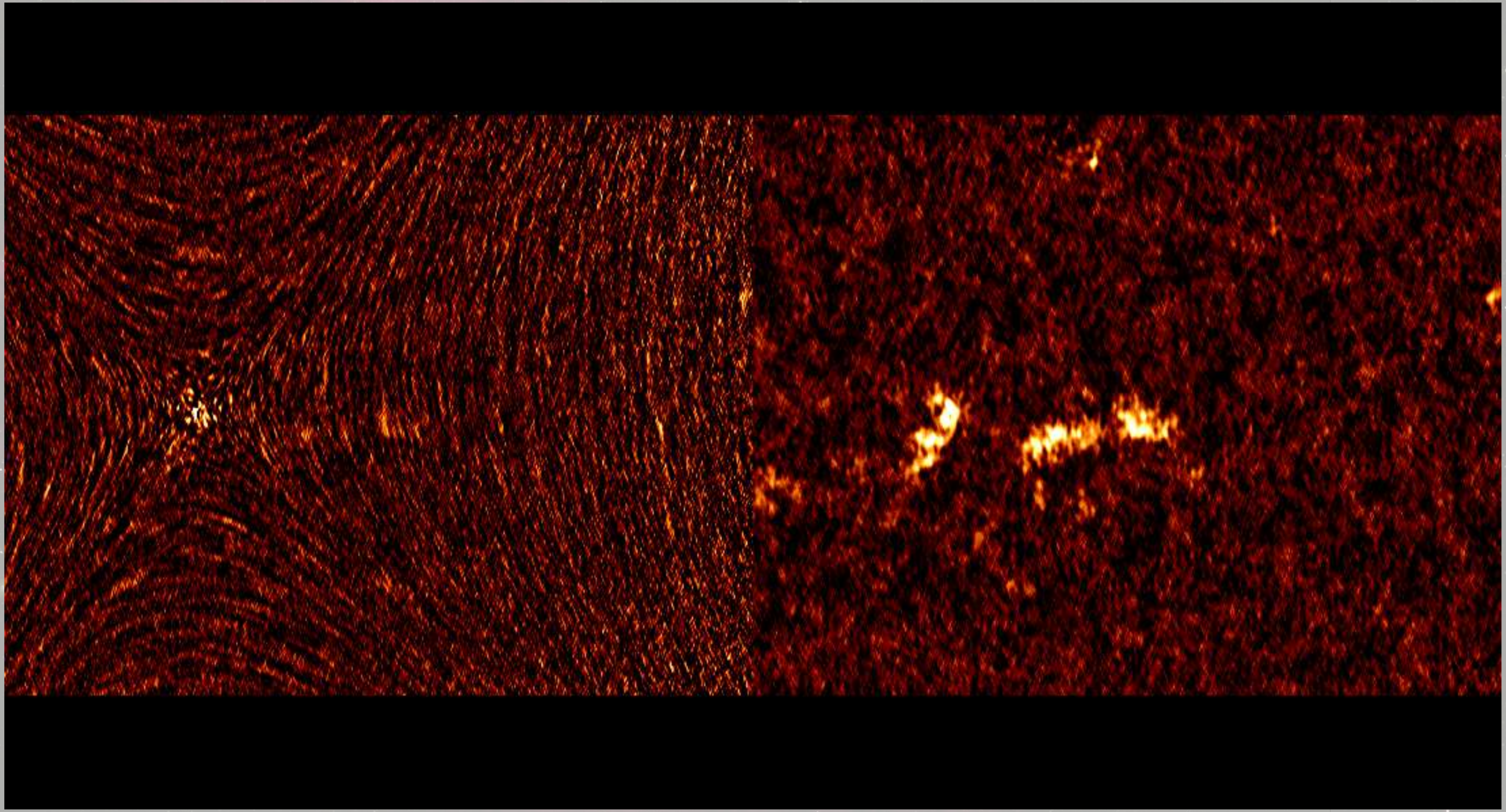
Because PSF covers entire image, so do the errors of the bandpass, even after removal of the continuum



noisy bandpass good bandpass

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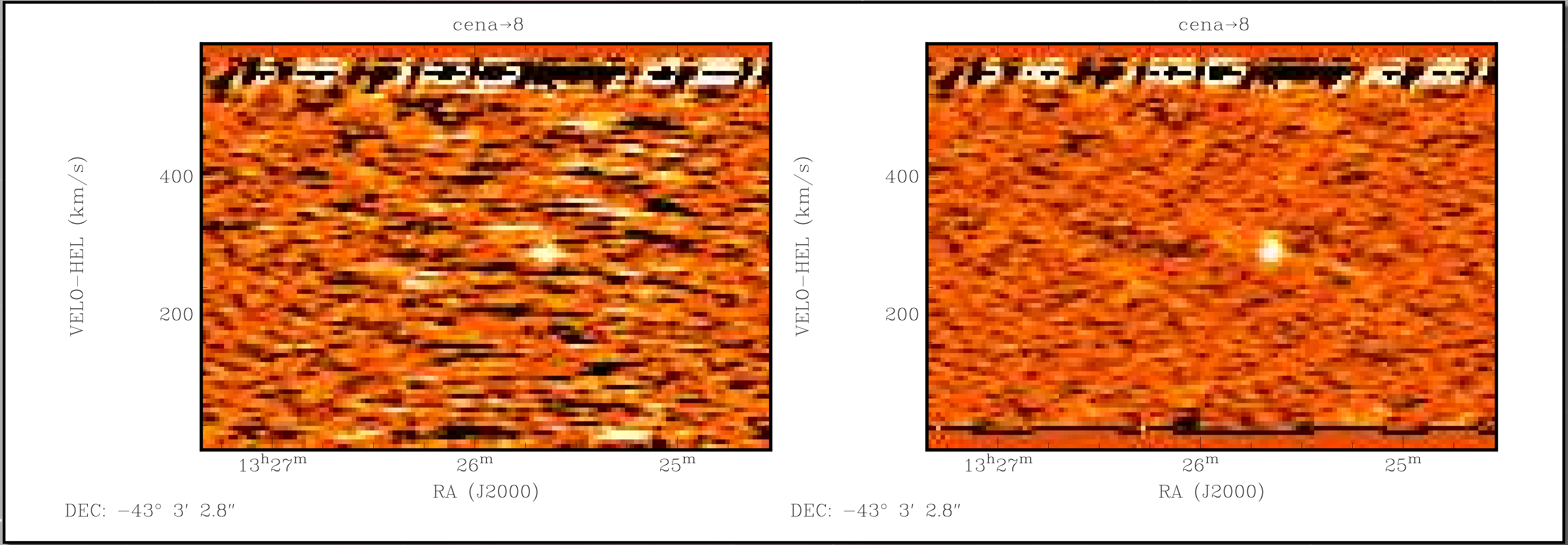
Trick : smooth the bandpass in frequency before applying



noisy bandpass

smoothed bandpass

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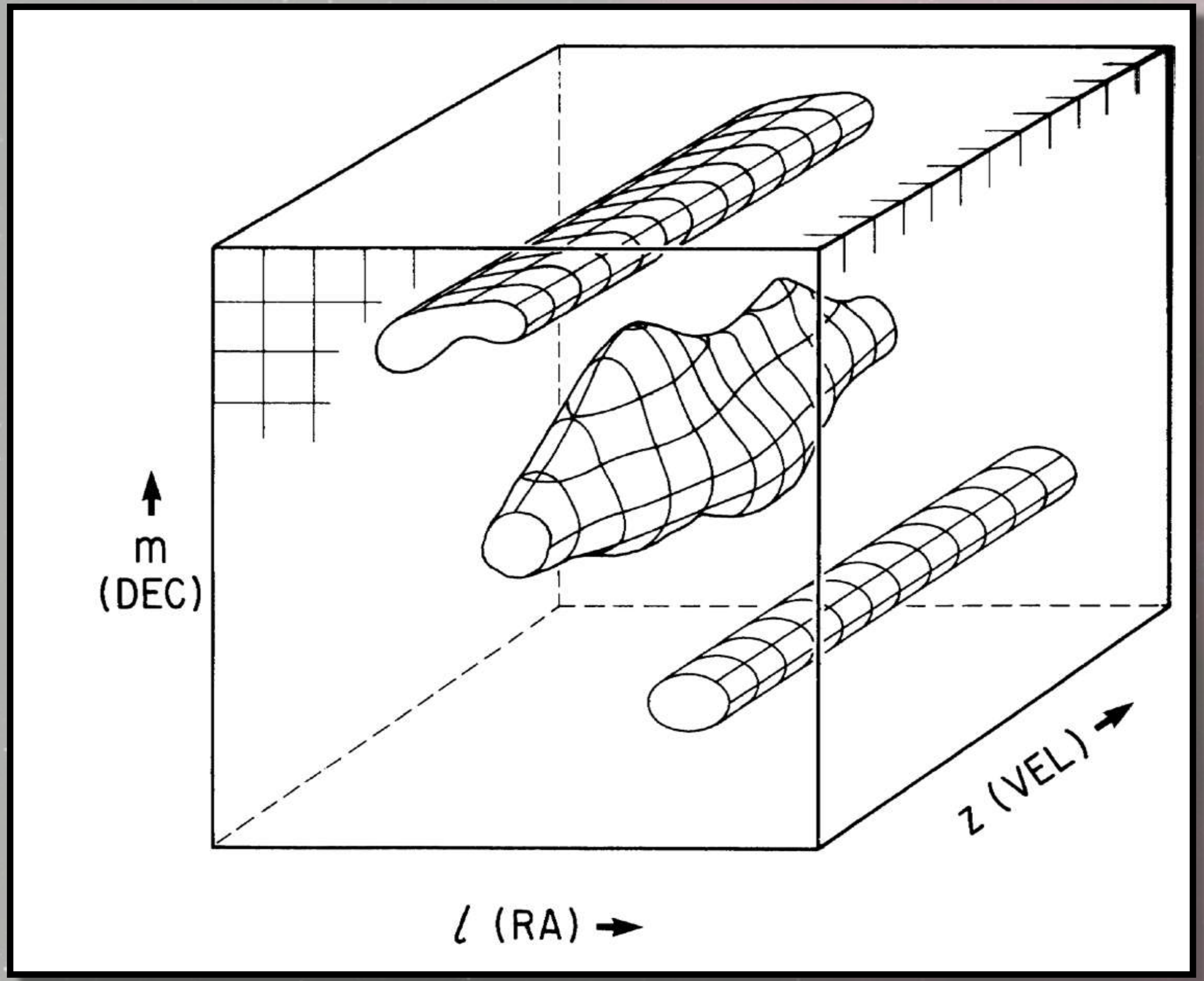
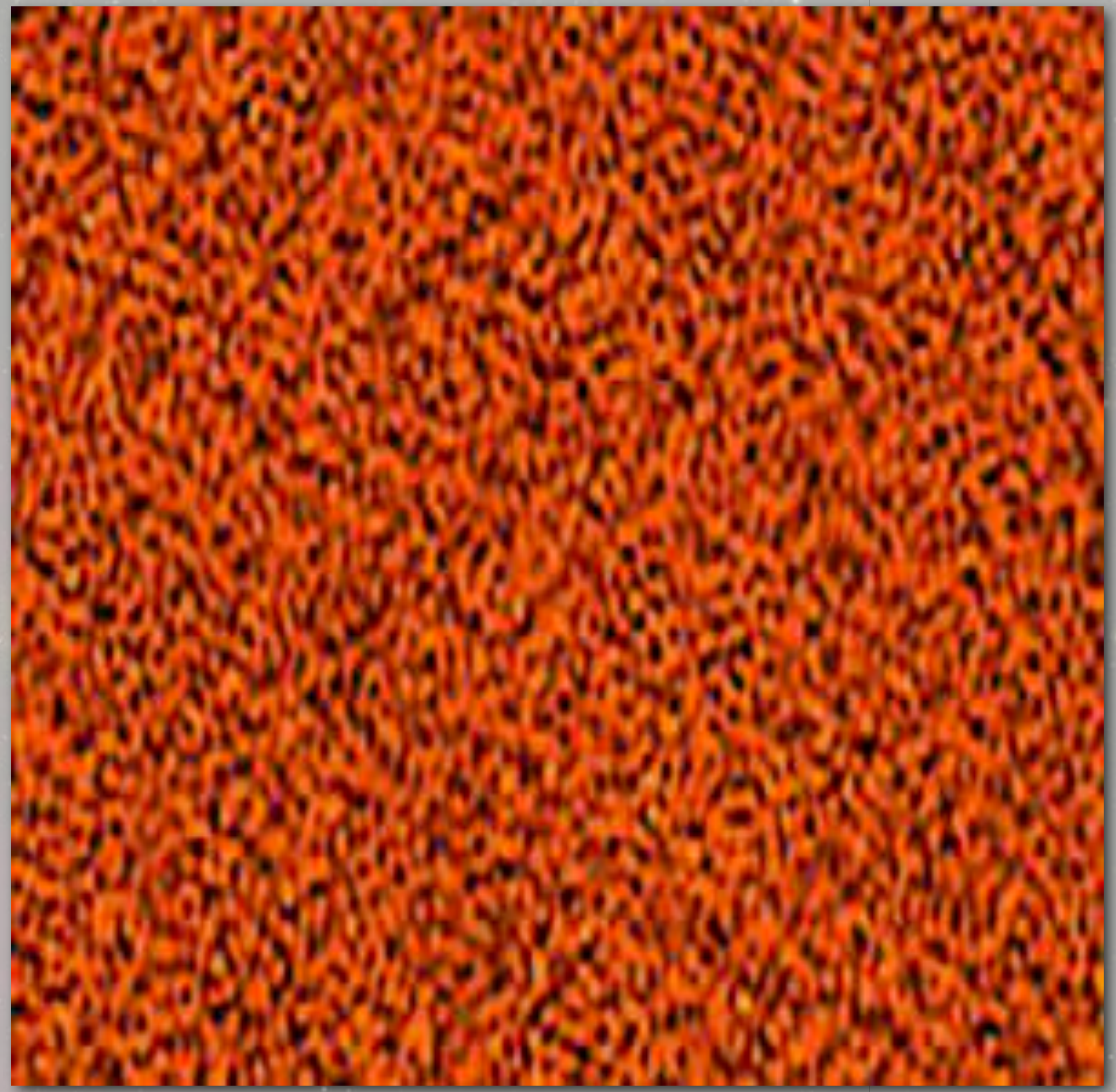
Data cubes

- Frequency received depends on velocity of emitter
- Radio telescopes are integral field spectrographs
- By mapping frequency, you map motions of the gas





HI observation of NGC 4414.
Each image is a narrow-band radio image of the sky,
loop is through frequency

Rotation of galaxy shifts
frequency where gas is detected

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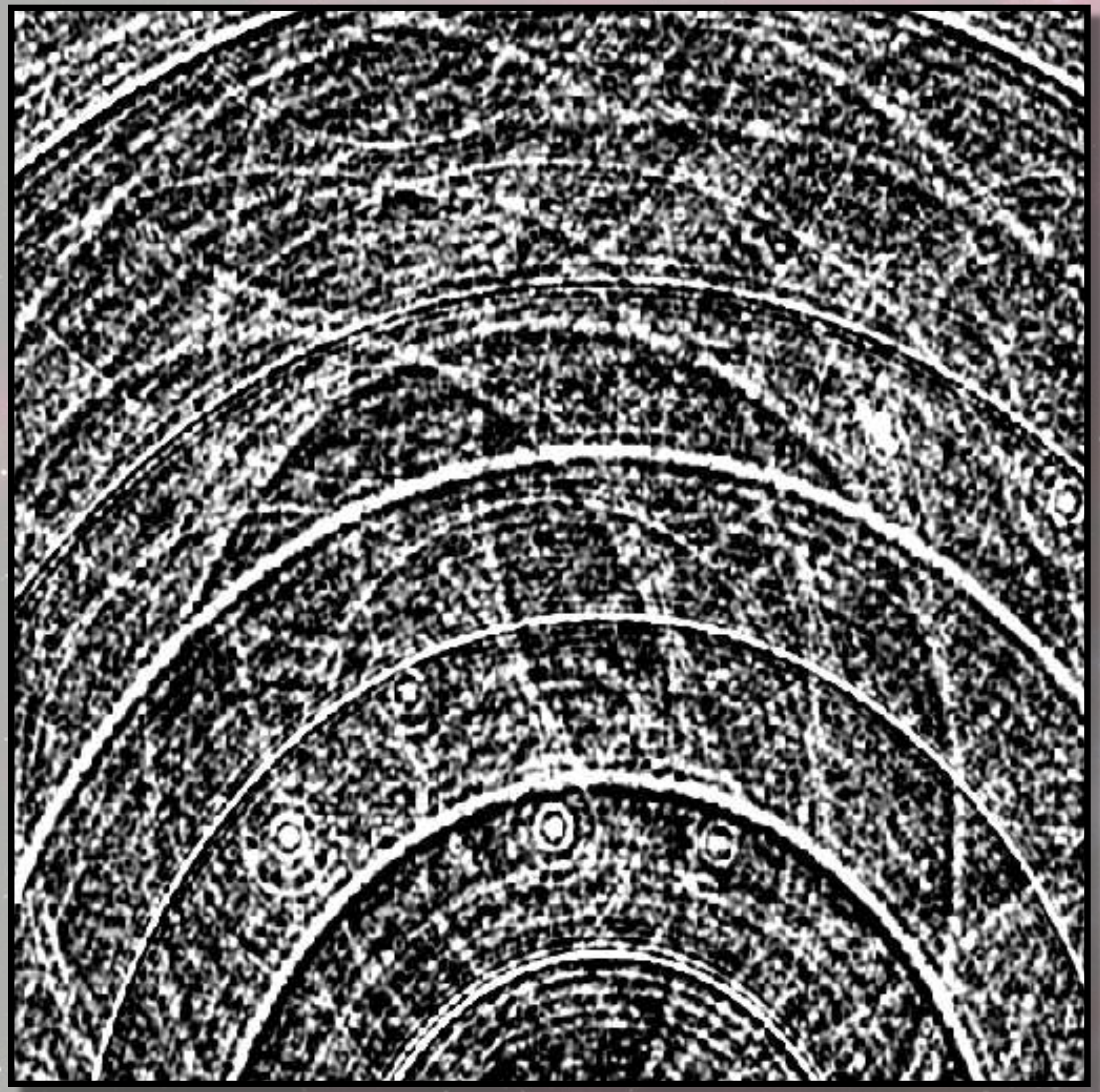
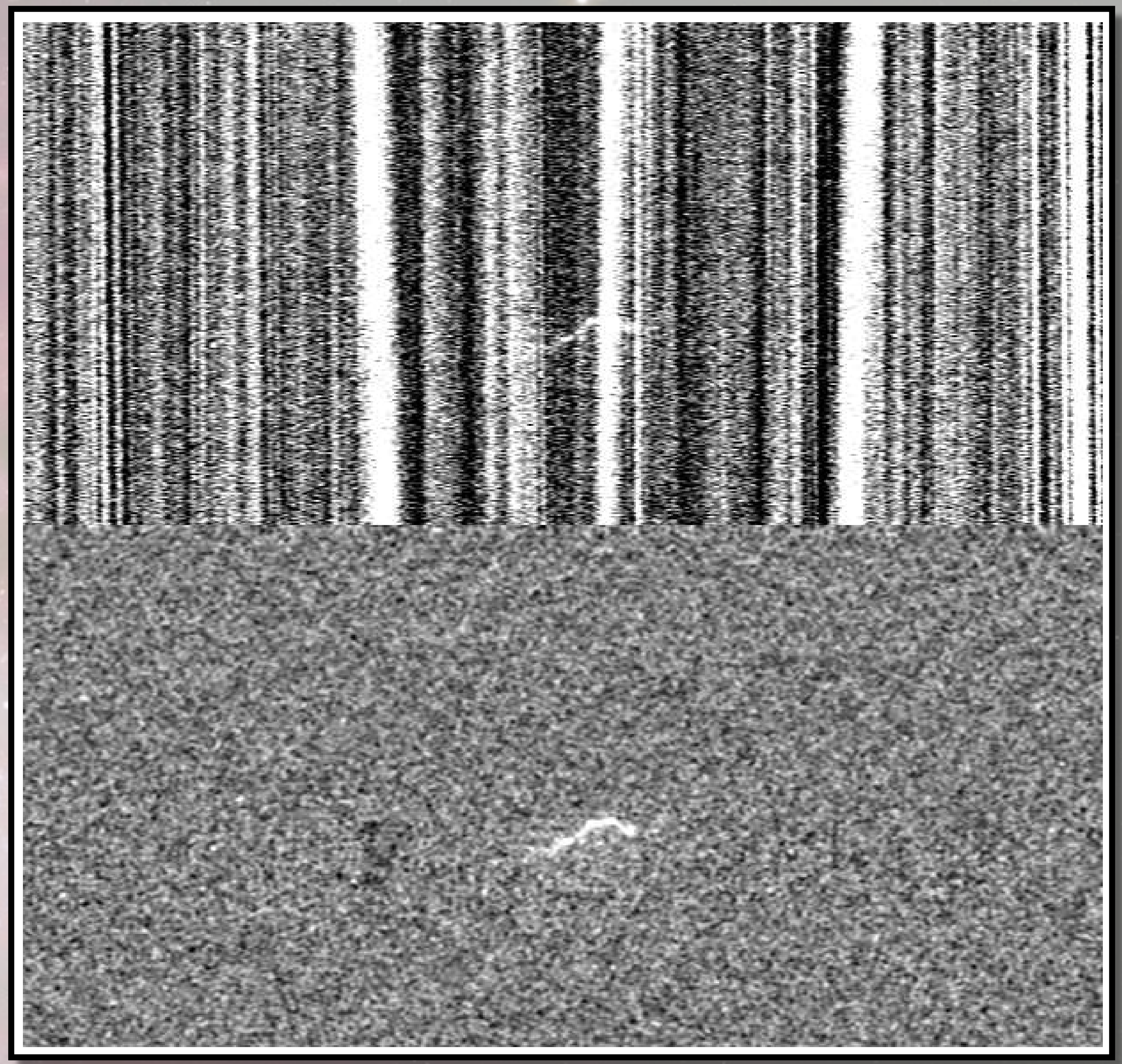
Each channel has continuum and line emission, and the dirty beam of both
To be able to do the analysis of the line emission, we have to remove the continuum

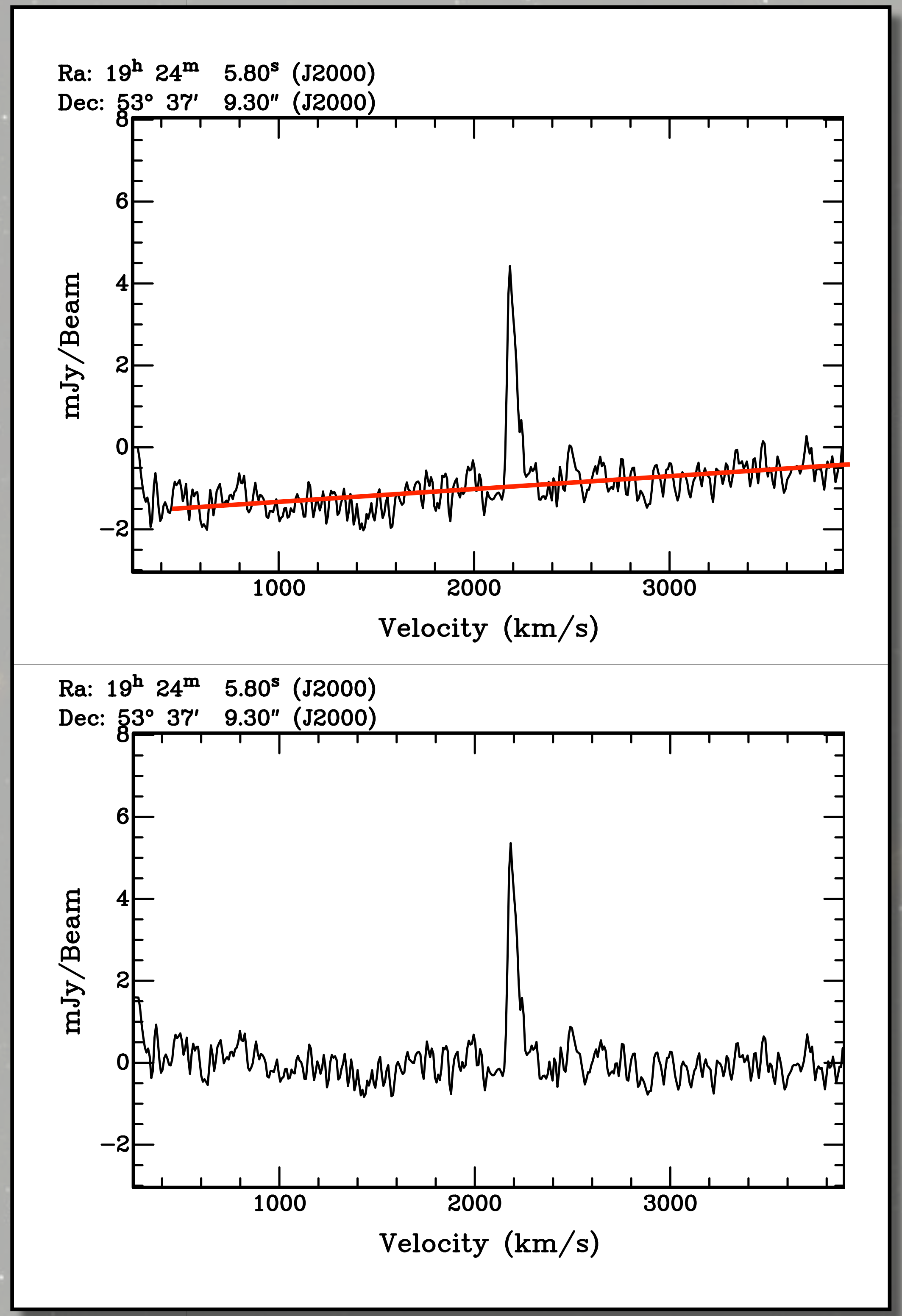
Slice showing line and continuum



movie of channels.
continuum + line.
dirty images



Same slice with continuum removed



Use line-free channels to fit continuum level

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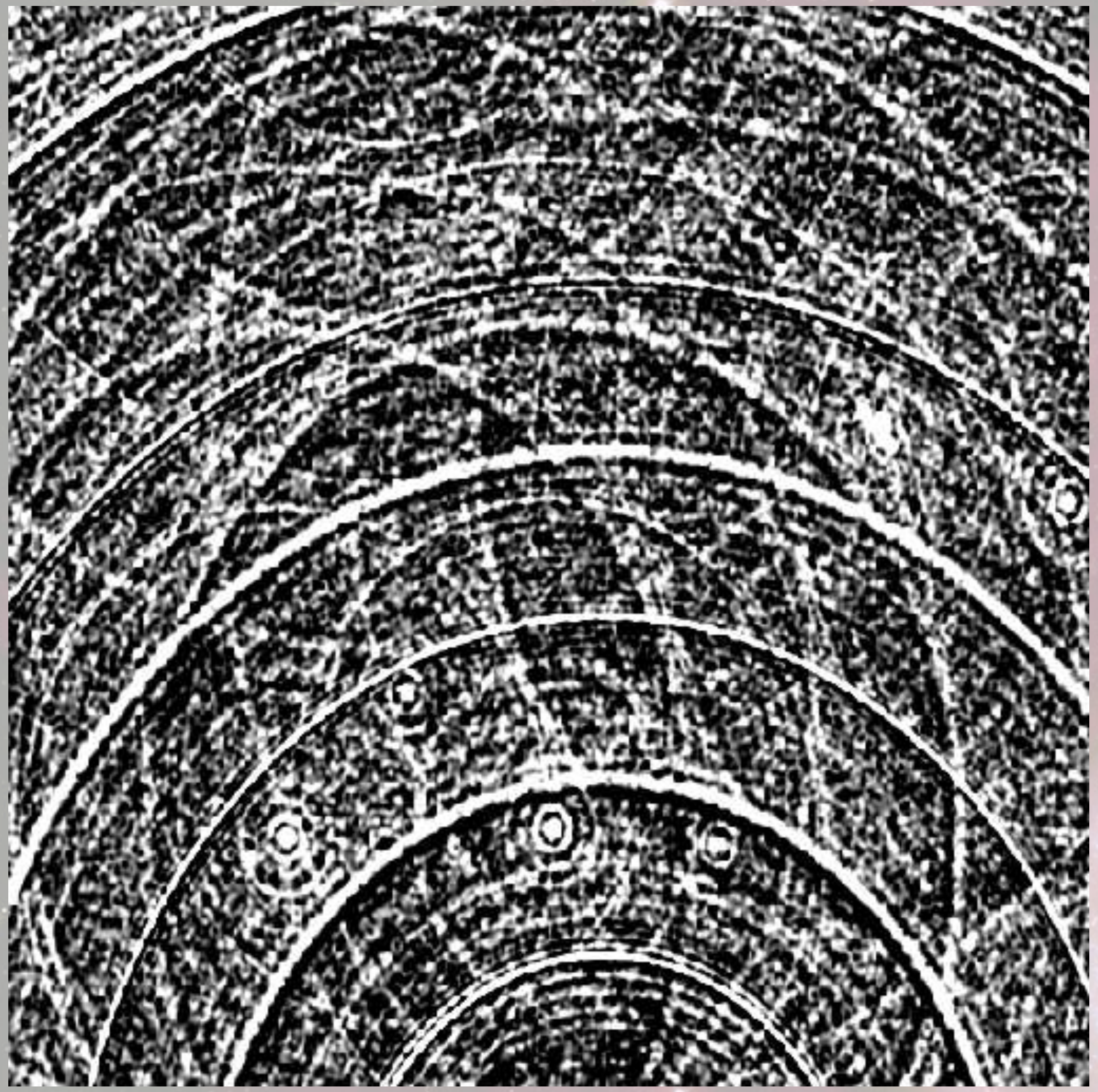
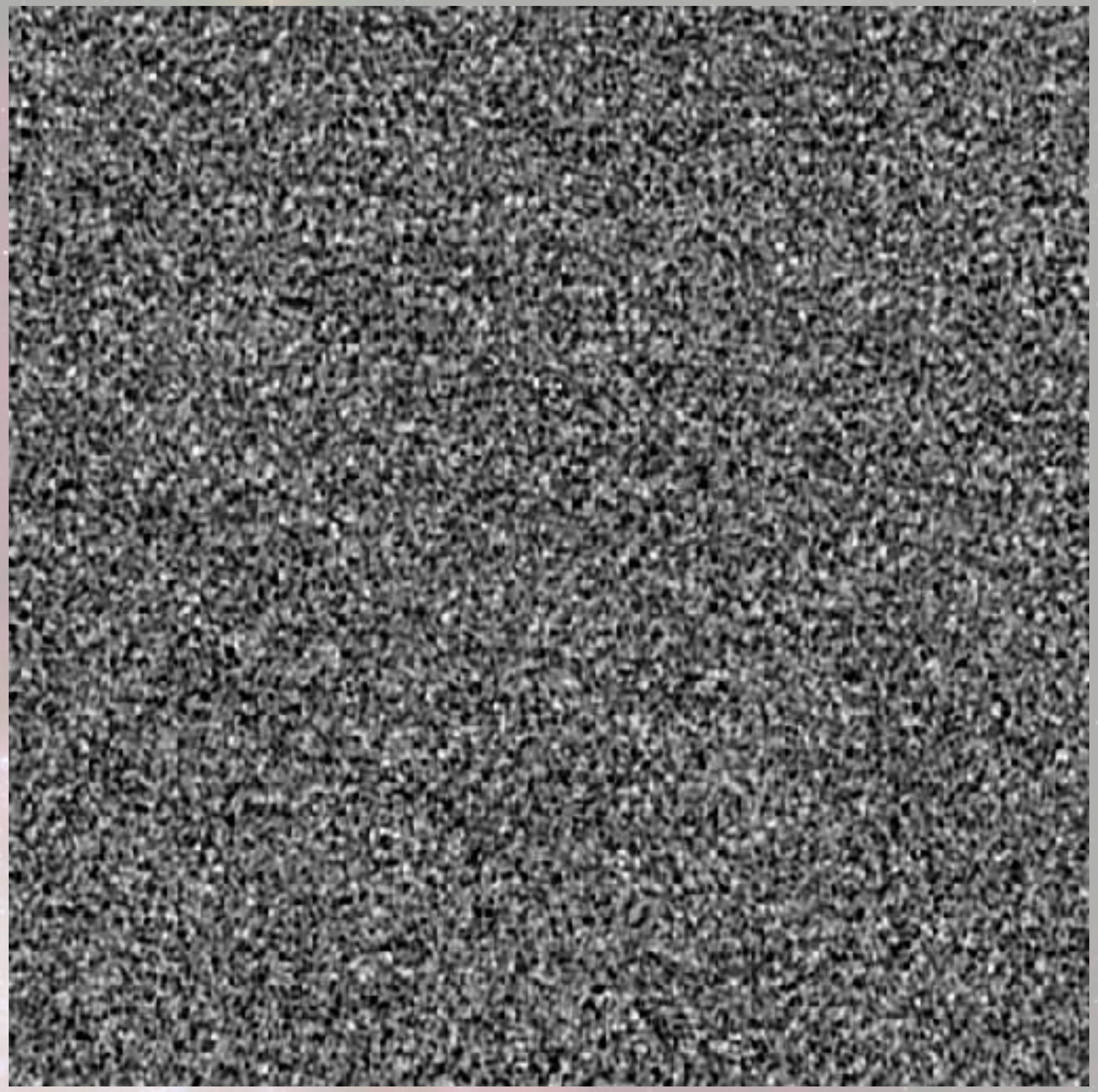
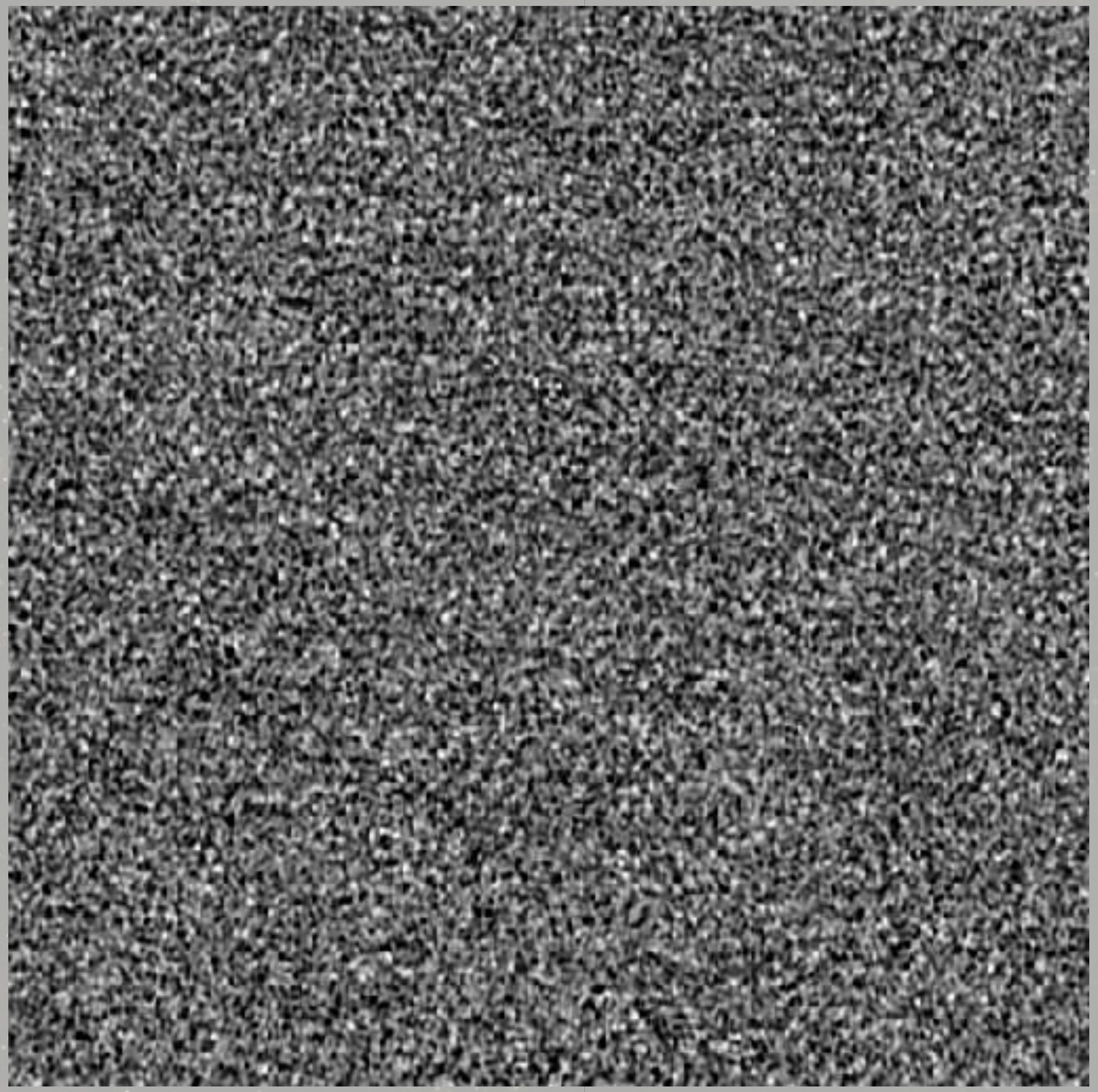


Dirty, with continuum



Dirty, continuum removed



Final cleaned cube

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Continuum subtraction

- uvmodel: make model of sky (e.g. by cleaning continuum image), transform model to uv domain and subtract
  - ✓ works over wide bands
  - – does not handle calibration errors
- uvlin: fit polymonial to spectra in uv domain
  - ✓ insensitive to errors in time-dependent calibration
  - – only works over limited bandwidth
- imlin: fit polynomial in image domain
  - ✓ insensitive to errors in time-dependent calibration
  - – only works over limited bandwidth

standard way: combination of uvmodel and imlin.
Selfcal gives model of continuum sky, it's for free so why not use it????
But is never perfect, so clean up residuals with imlin

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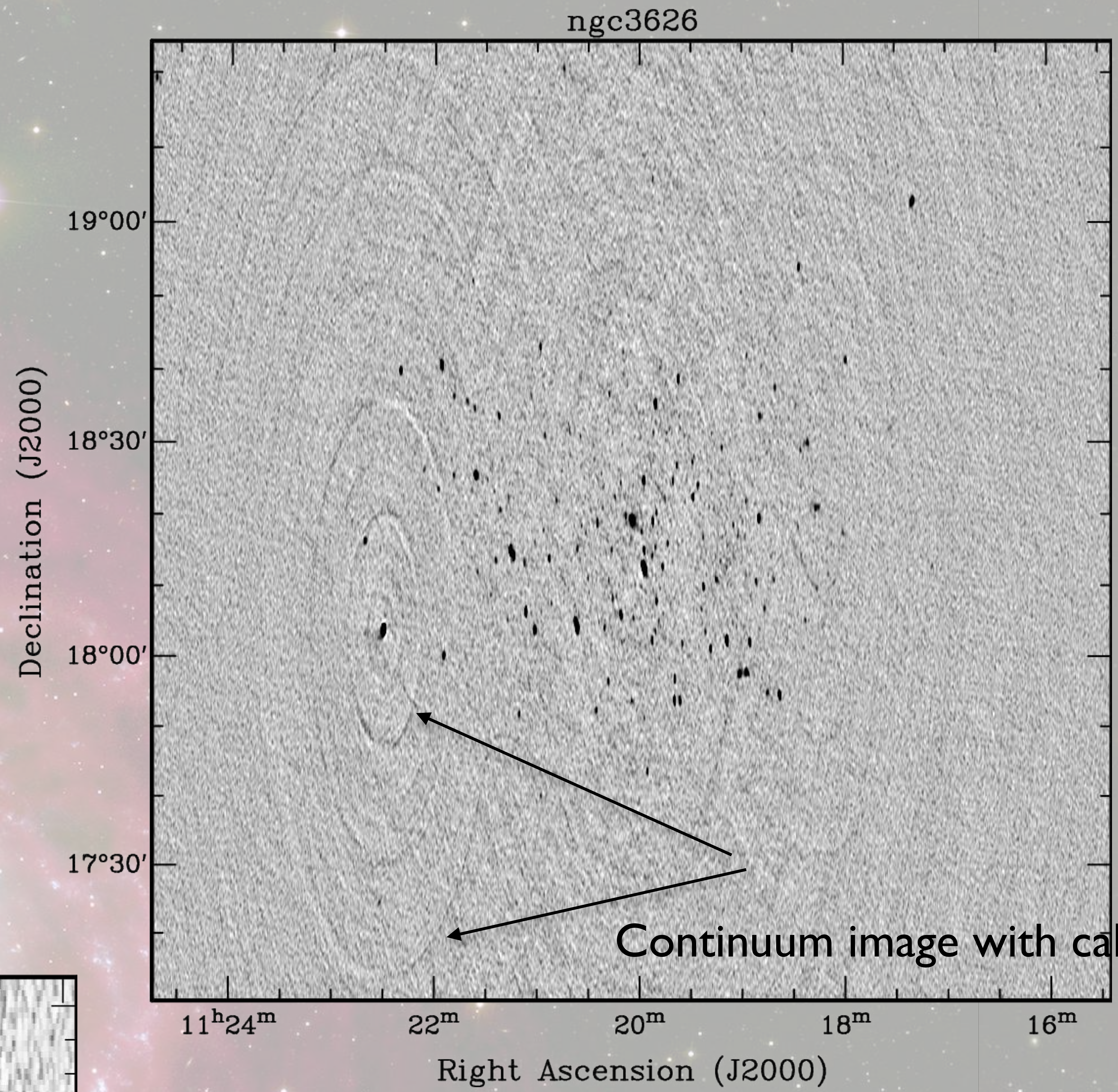
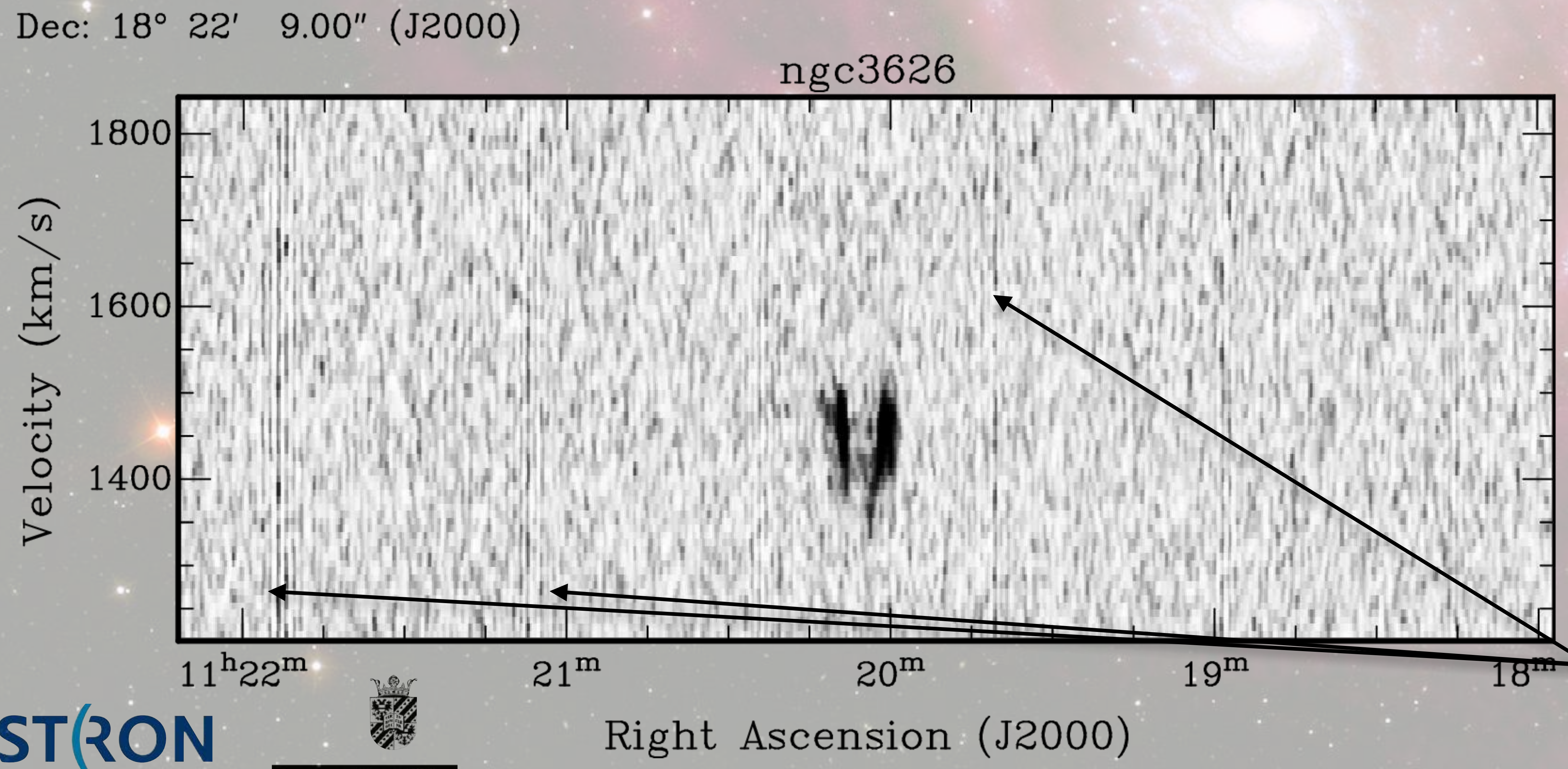
The limitations of uvmodel

Transforming the selfcal model to uv domain can only apply the calibrations we know and only includes the sources in the model.

So if there are calibration errors left, those errors will not be subtracted.

Same for faint sources that are not in the selfcal model





Often direction-dependent errors play a role

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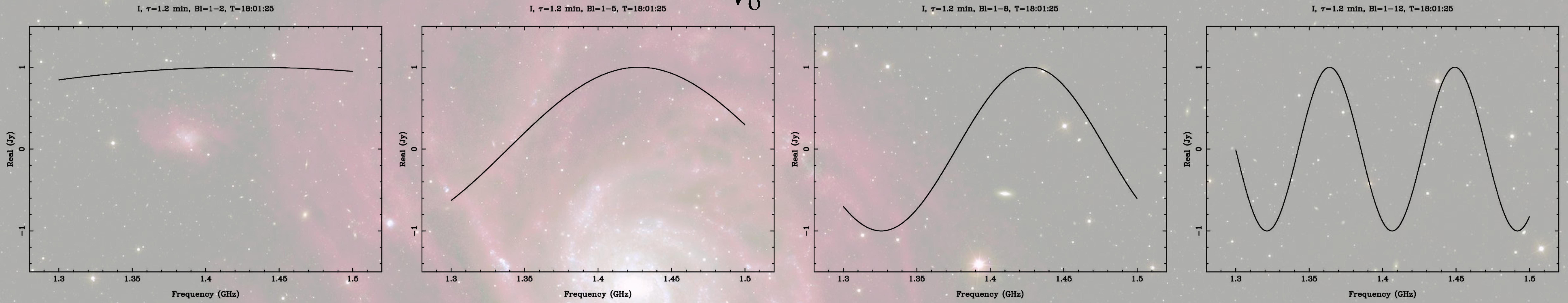
The limitations of uvlin

Visibility of point source at position l is sinusoidal function of frequency $V(u,v;\nu) = e^{-2\pi l (u_0 \frac{\nu}{\nu_0})}$

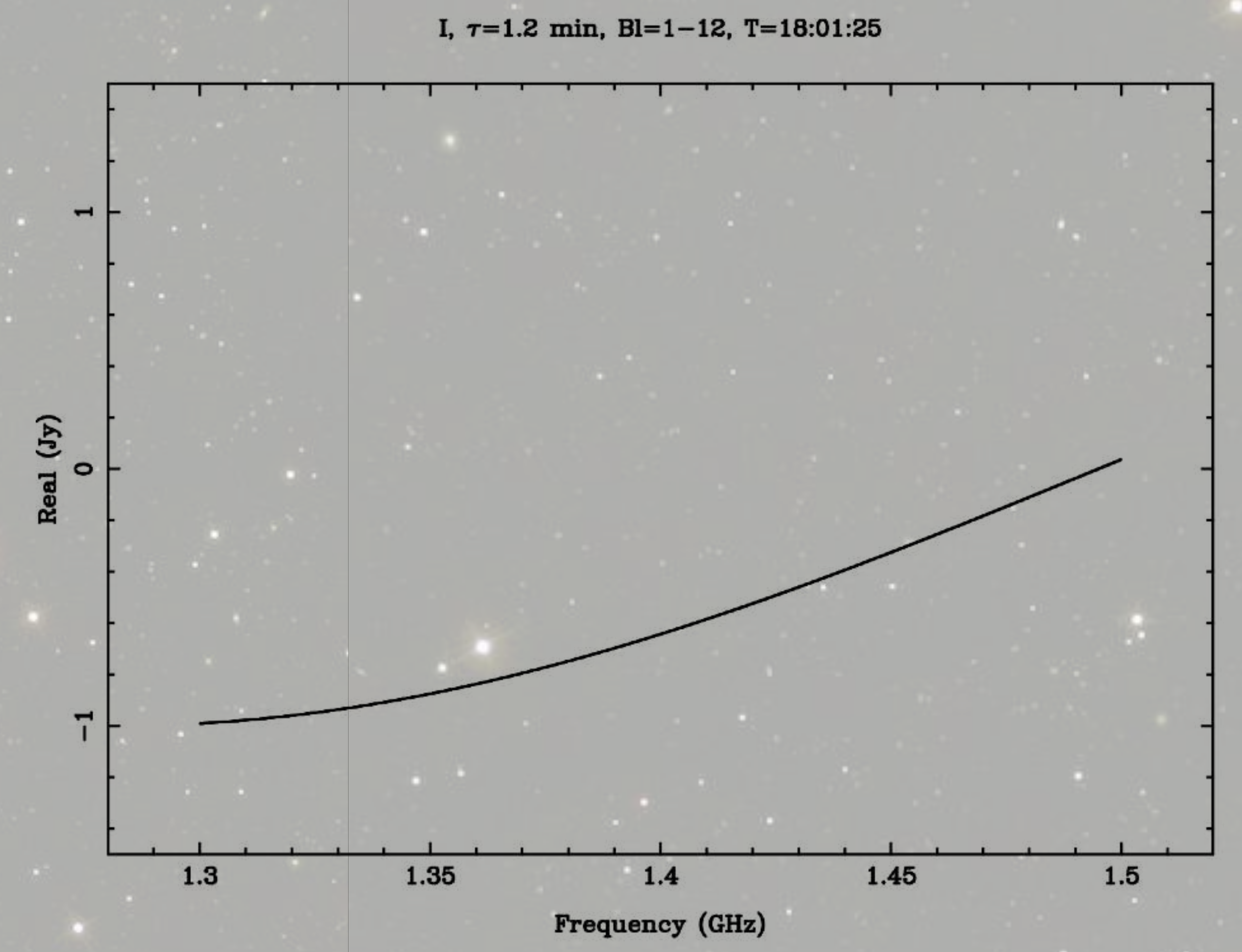
because u scales with frequency: $u = u_0 \frac{\nu}{\nu_0}$



baseline length increases →

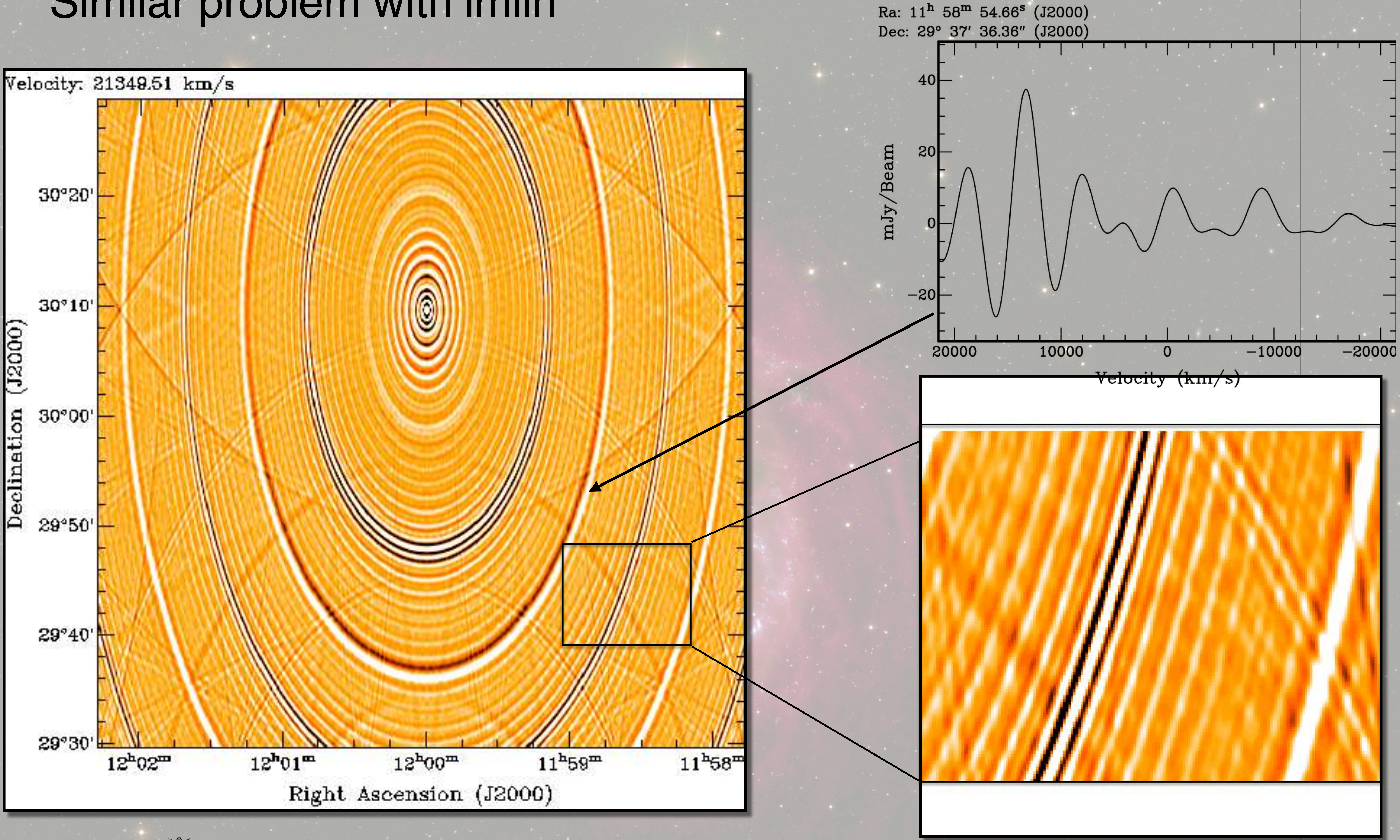
real part of visibility of off-axis source as function of frequency for different baseline lengths

Frequency range over which this can be approximated with polynomial is limited. Depends on bandwidth and location of the source. Only works over limited field of view.



closer to field centre

Similar problem with imlin

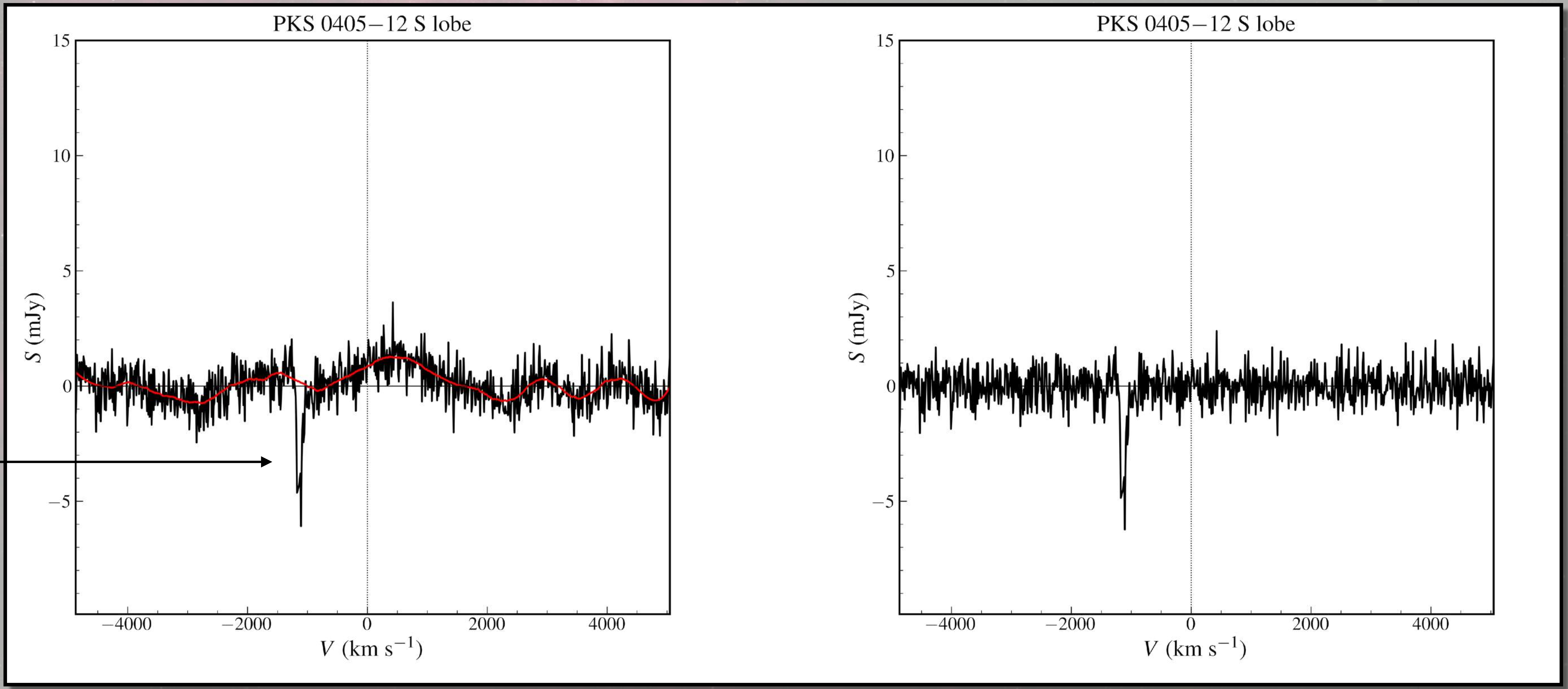


Size of rings changes because wavelength changes

Over wide bands and/or wide field of view, we need something else. Polynomials have a fixed scale. There is not a single scale in the bumps. Use functions/tools that can adapt to local features in spectrum.

- cubic splines
- Savitzky-Golay filter: for every channel, fit a polynomial of a certain degree over a certain range of channels. Can be written as a convolution.

Mask where there is line emission



MeerKat spectrum of 5 Jy source after uvmodel. Better than 0.1%, but still residuals left

After subtracting SG filtered spectrum, better than 0.01%

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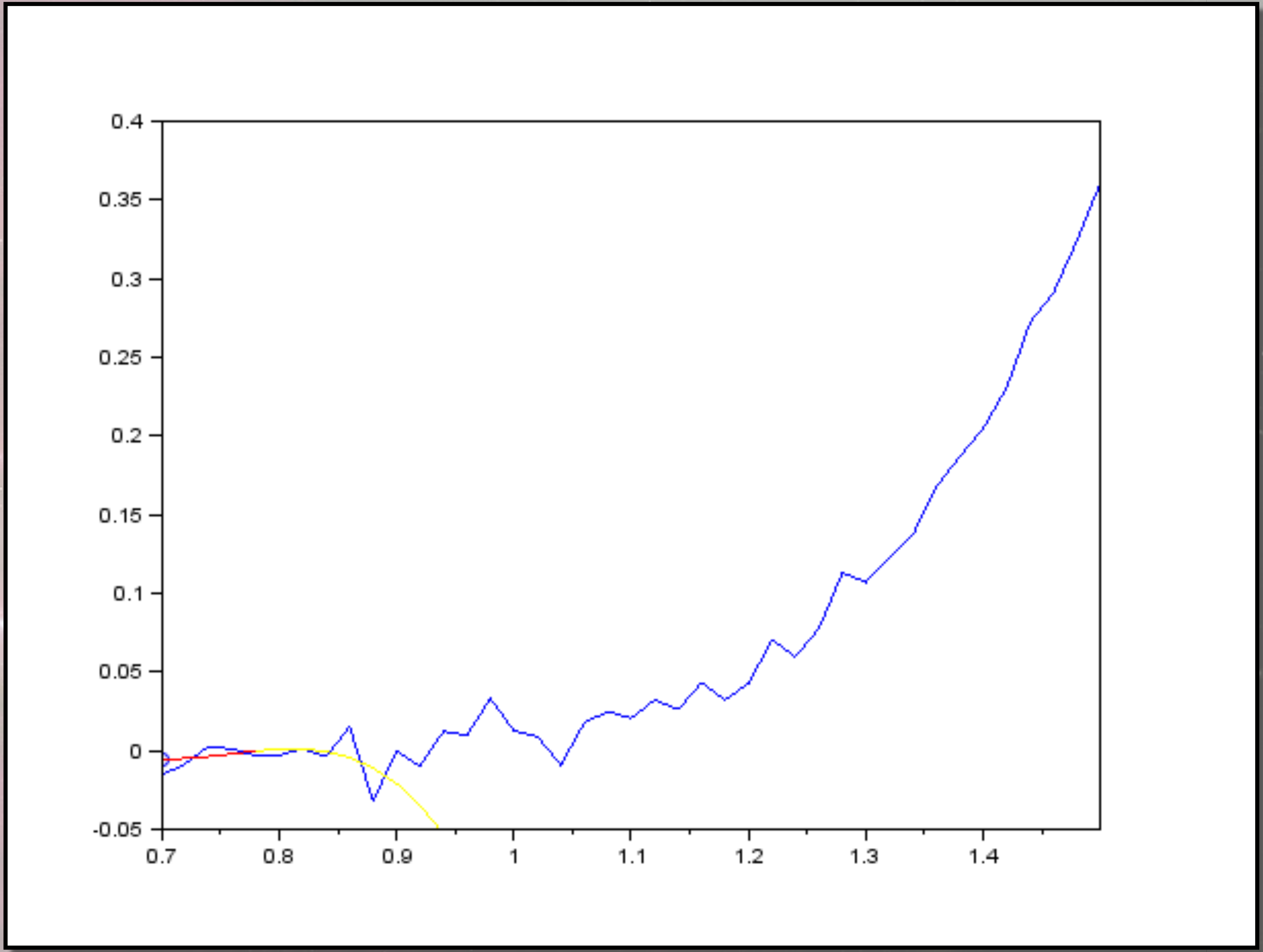
- Savitzky-Golay filter in action, 3rd degree polynomial fitted to 9 points.
- sometimes you have to play a bit with degree and number of points

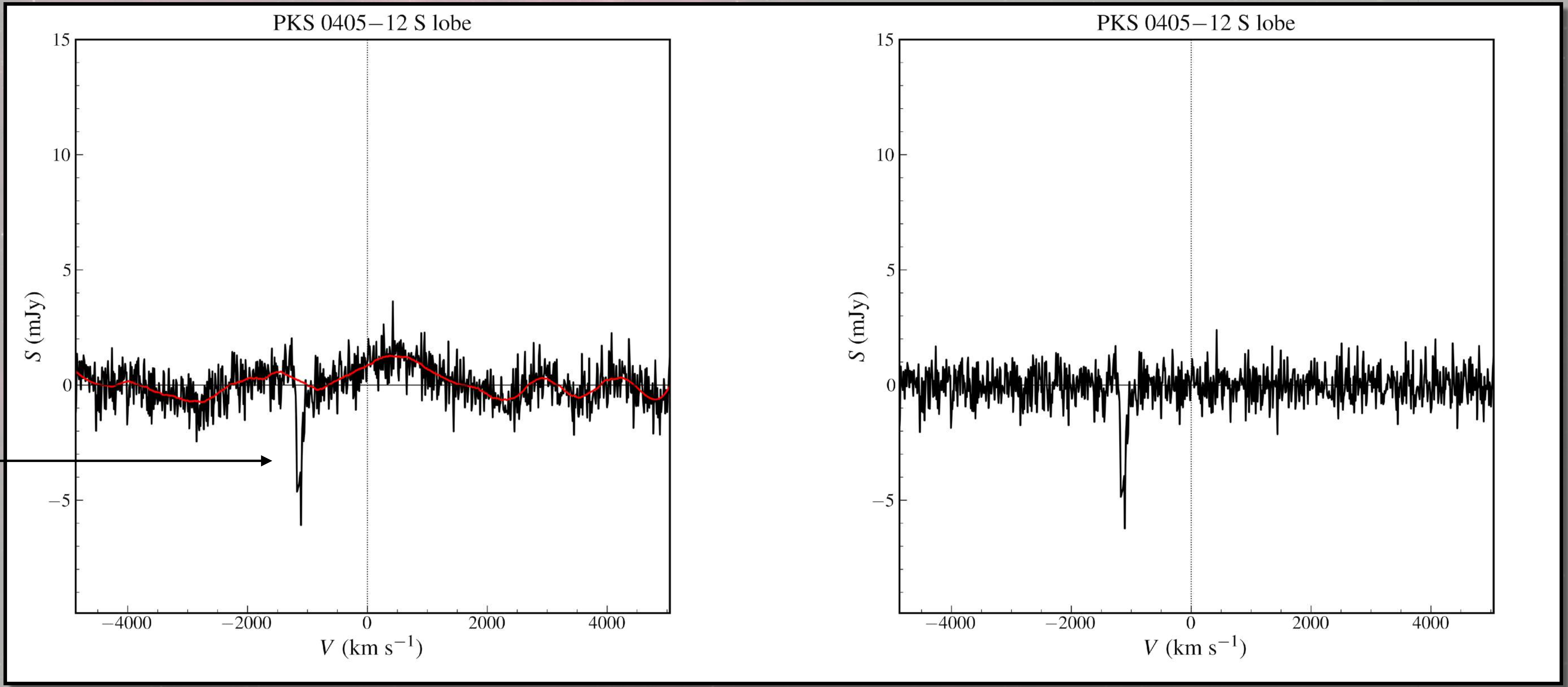


source: Wikipedia

Over wide bands and/or wide field of view, we need something else. Polynomials have a fixed scale. There is not a single scale in the bumps. Use functions/tools that can adapt to local features in spectrum.

- cubic splines
- Savitzky-Golay filter: for every channel, fit a polynomial of a certain degree over a certain range of channels. Can be written as a convolution.

Mask where there is line emission



MeerKat spectrum of 5 Jy source after uvmodel. Better than 0.1%, but still residuals left

After subtracting SG filtered spectrum, better than 0.01%

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Spectral line interferometry part II

Tom Oosterloo

Netherlands Institute for Radio Astronomy (ASTRON), Dwingeloo

Kapteyn Institute, university of Groningen

HI and optical image of M101

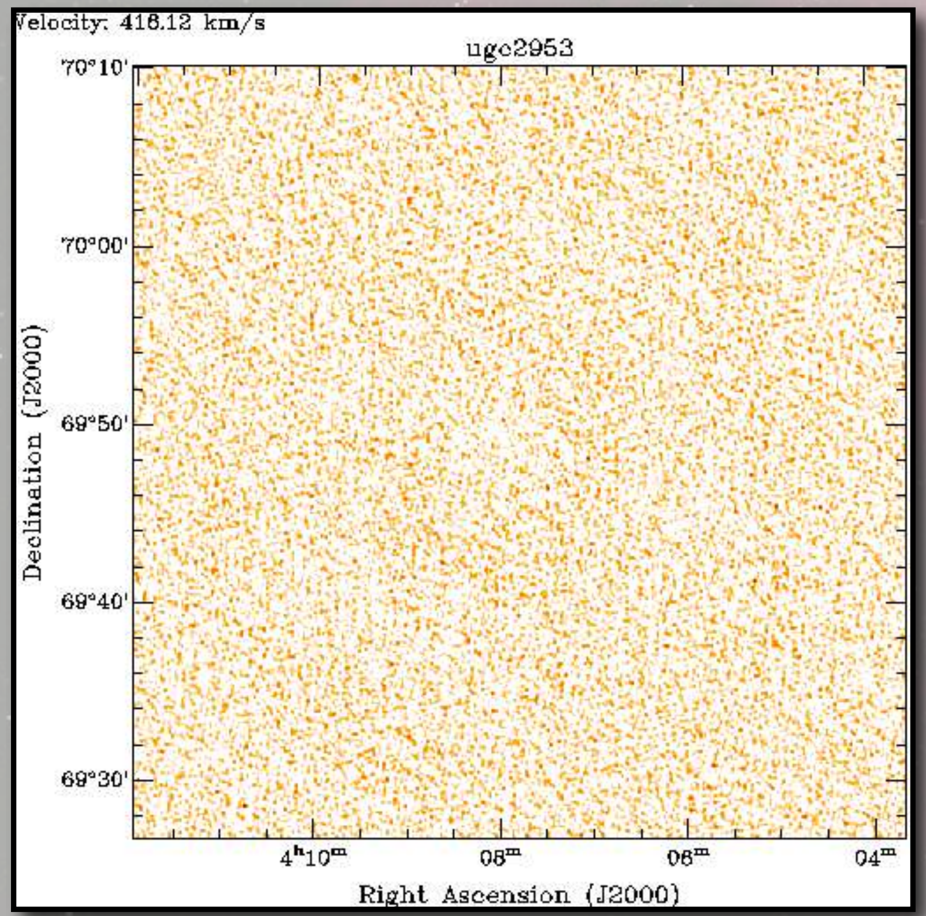
Data analysis

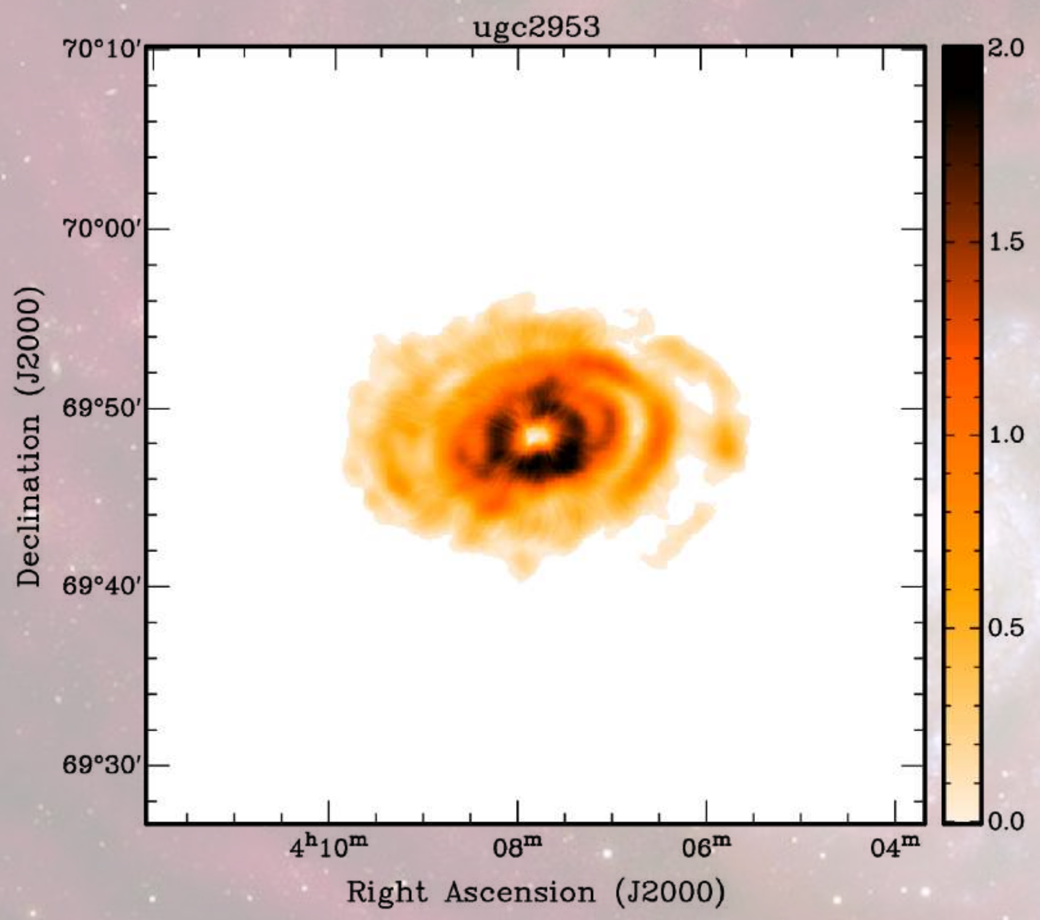
Data analysis

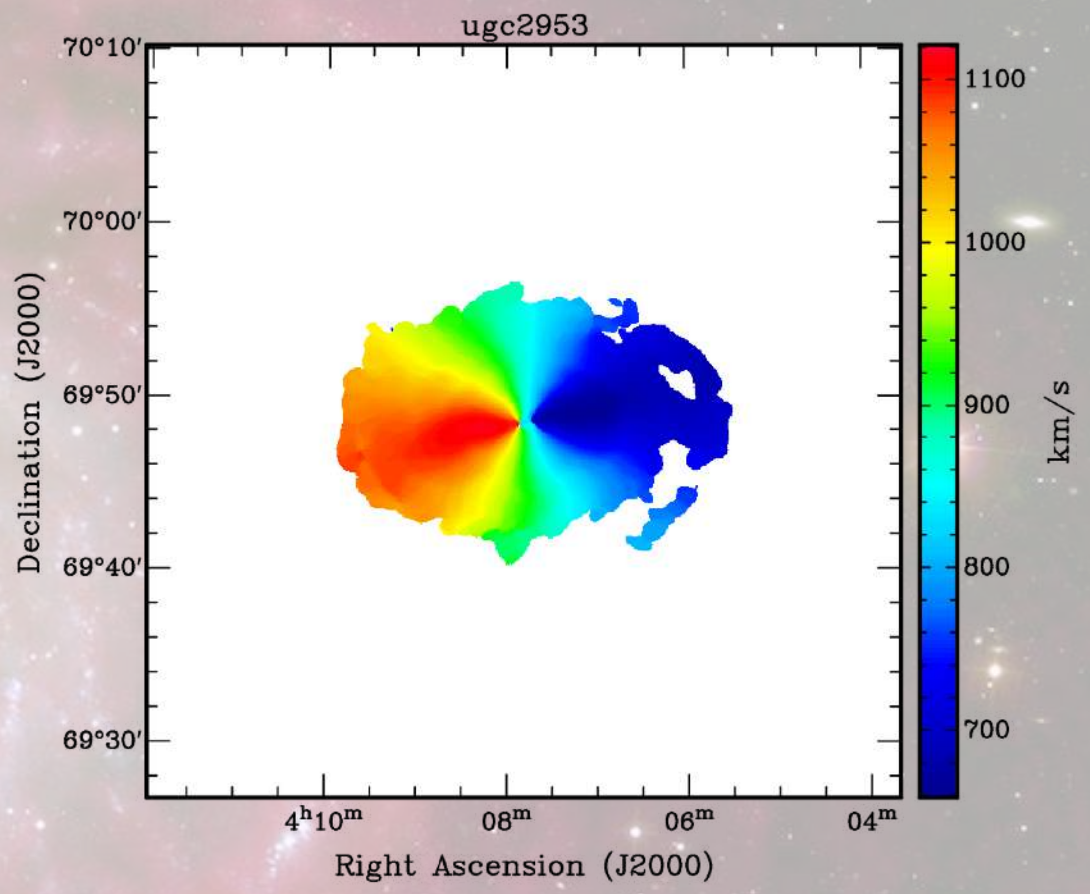
For every position we have a spectrum from which we can measure the total flux and a velocity.

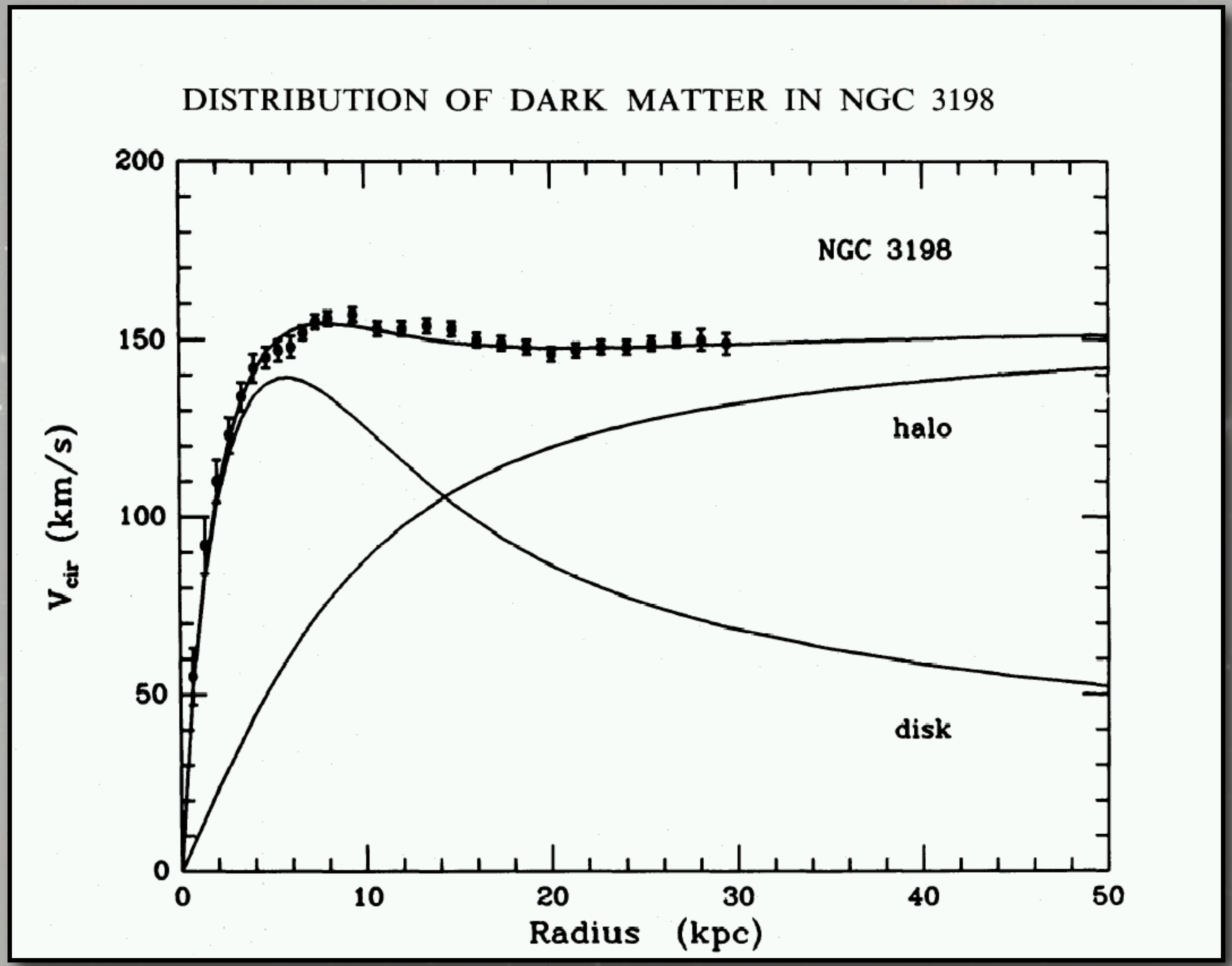
Can map the brightness distribution and kinematics of our object.

Model the kinematics in terms of mass models: dark matter









Kor Begeman

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RuG

Parametrise the intensity and kinematics and make maps of those.

Moment analysis

For every position calculate from the spectrum:

- Total HI flux

$$I = \int S(v)\, dv$$

- Intensity weighted velocity at a given position

$$\langle V \rangle = \frac{\int S(v)\, v\, dv}{\int S(v)\, dv}$$

- Velocity dispersion

$$\langle V^2 \rangle^{1/2} = \sqrt{\frac{\int S(v)(v - \langle V \rangle)^2\, dv}{\int S(v)\, dv}}$$

Alternative: fit Gaussians (but profile shape is not always Gaussian)

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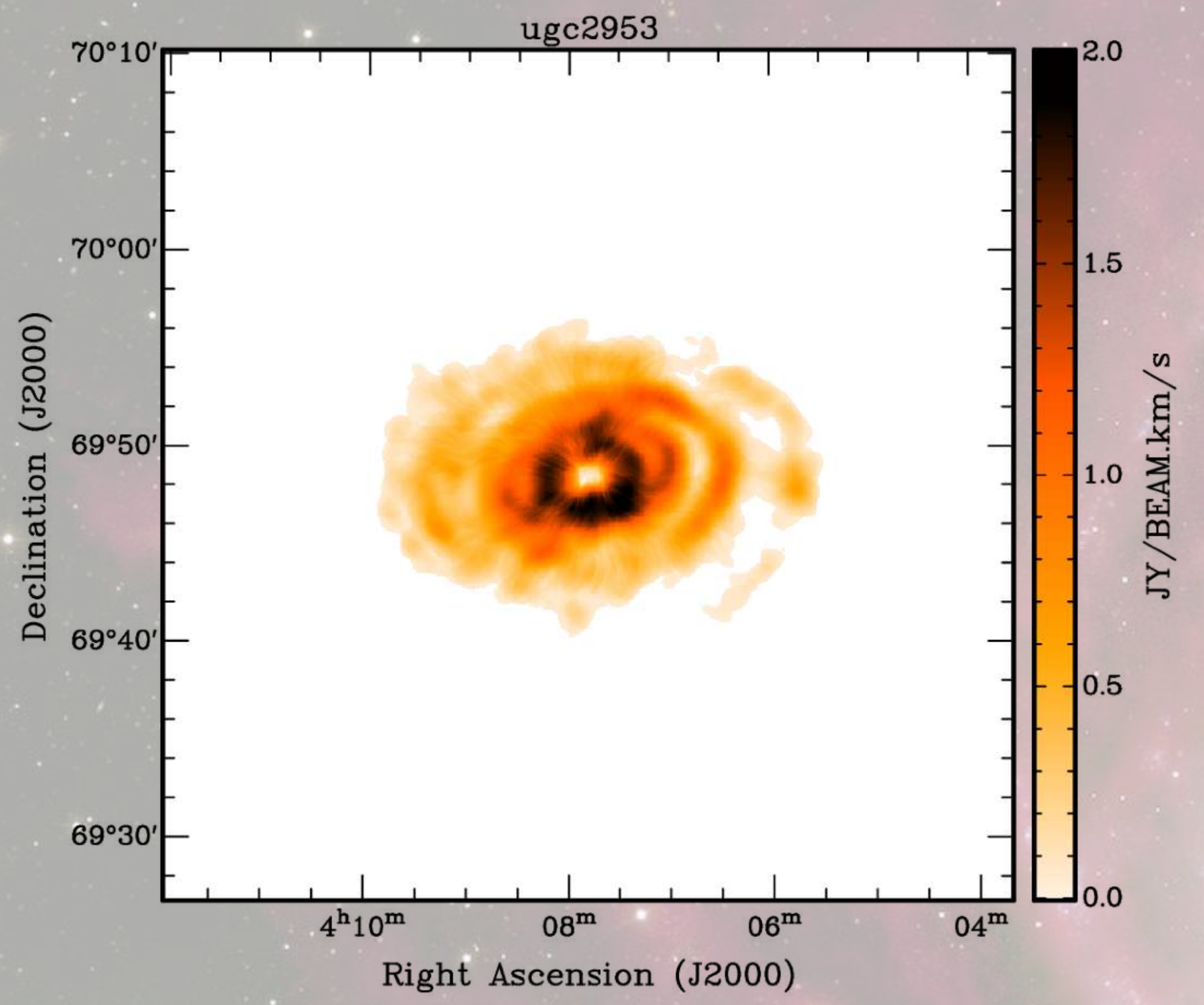
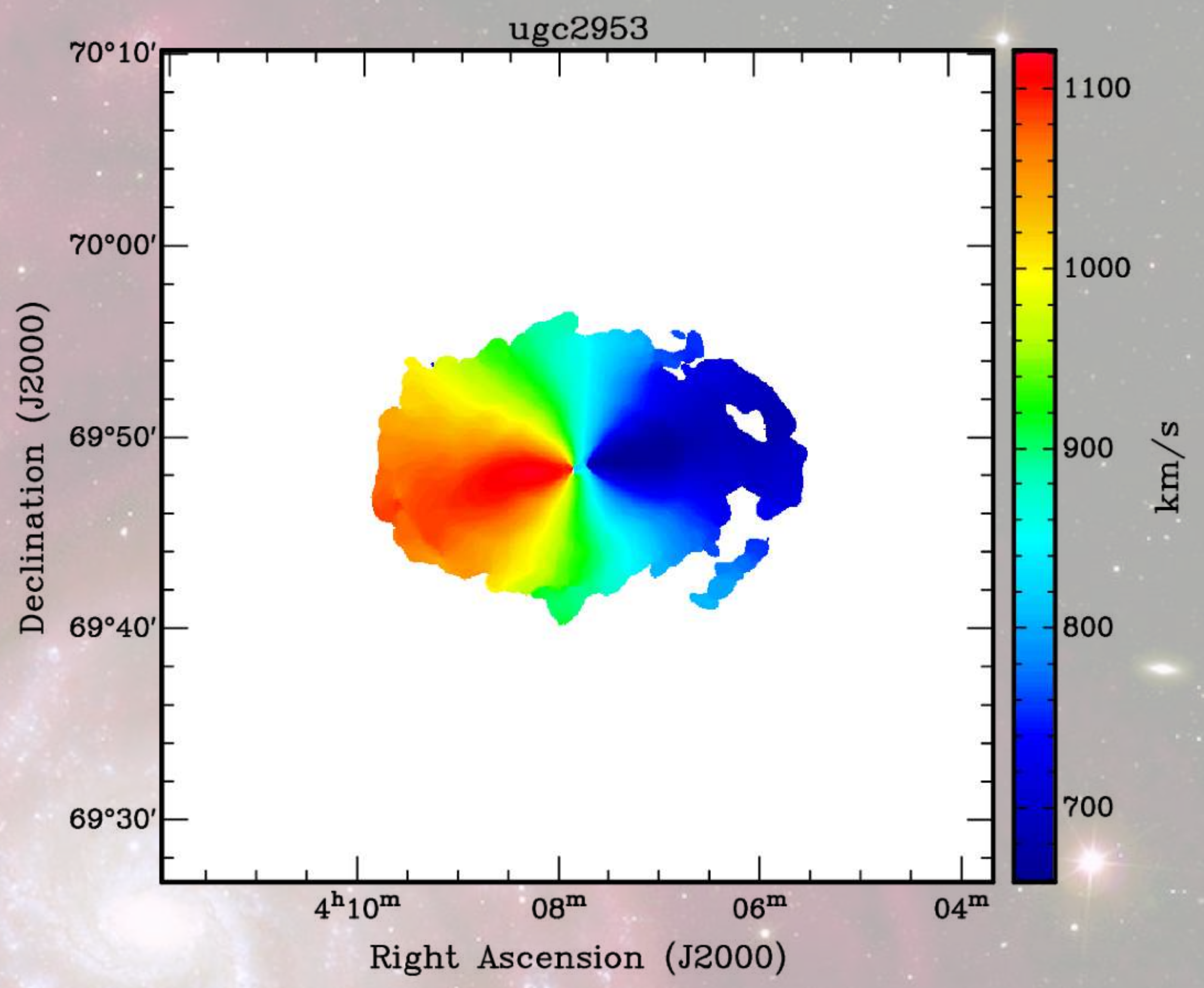
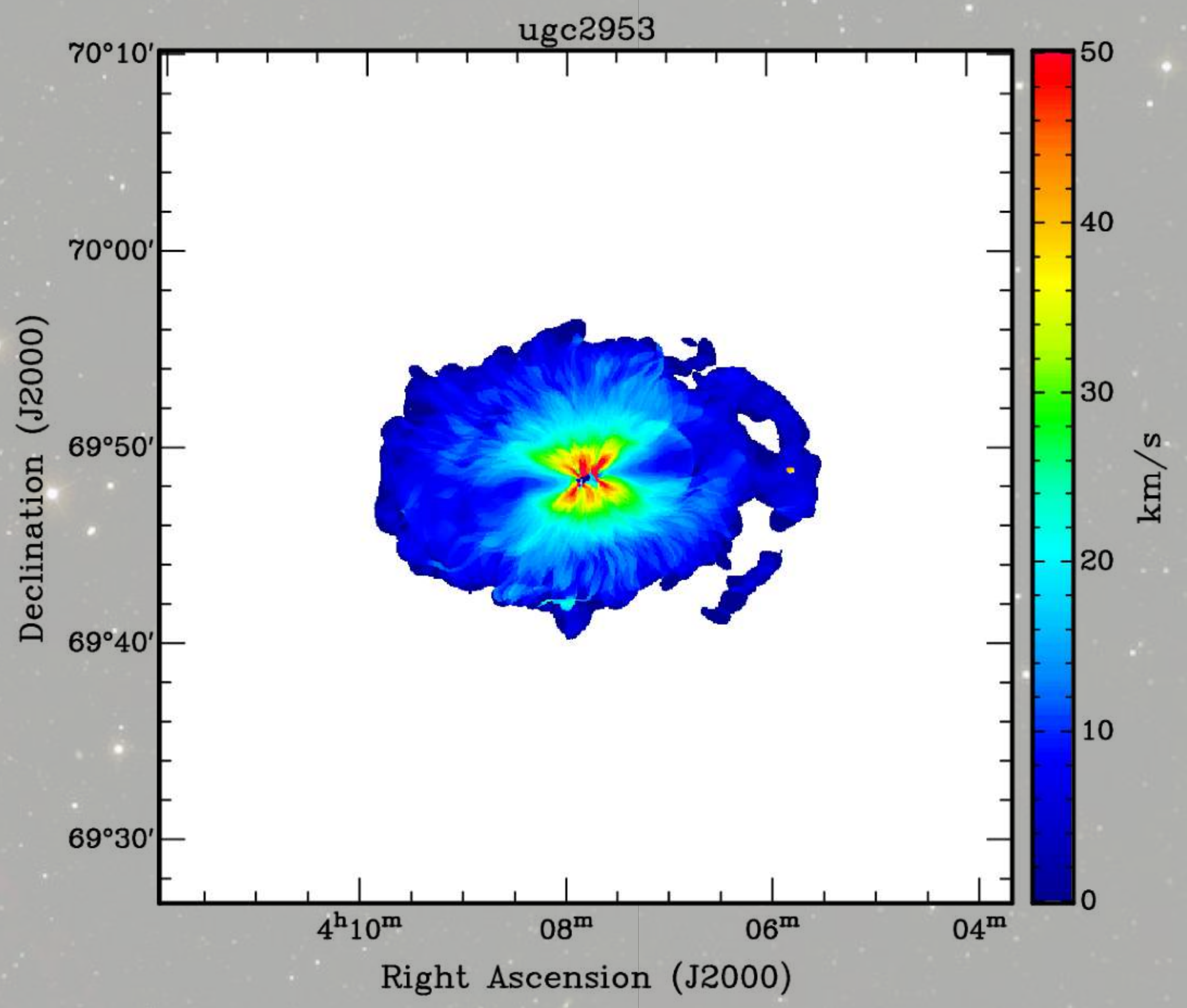
Result of the moment analysis



Total intensity



Velocity field



Dispersion map

With these maps, we can further study the distribution and kinematics of the HI

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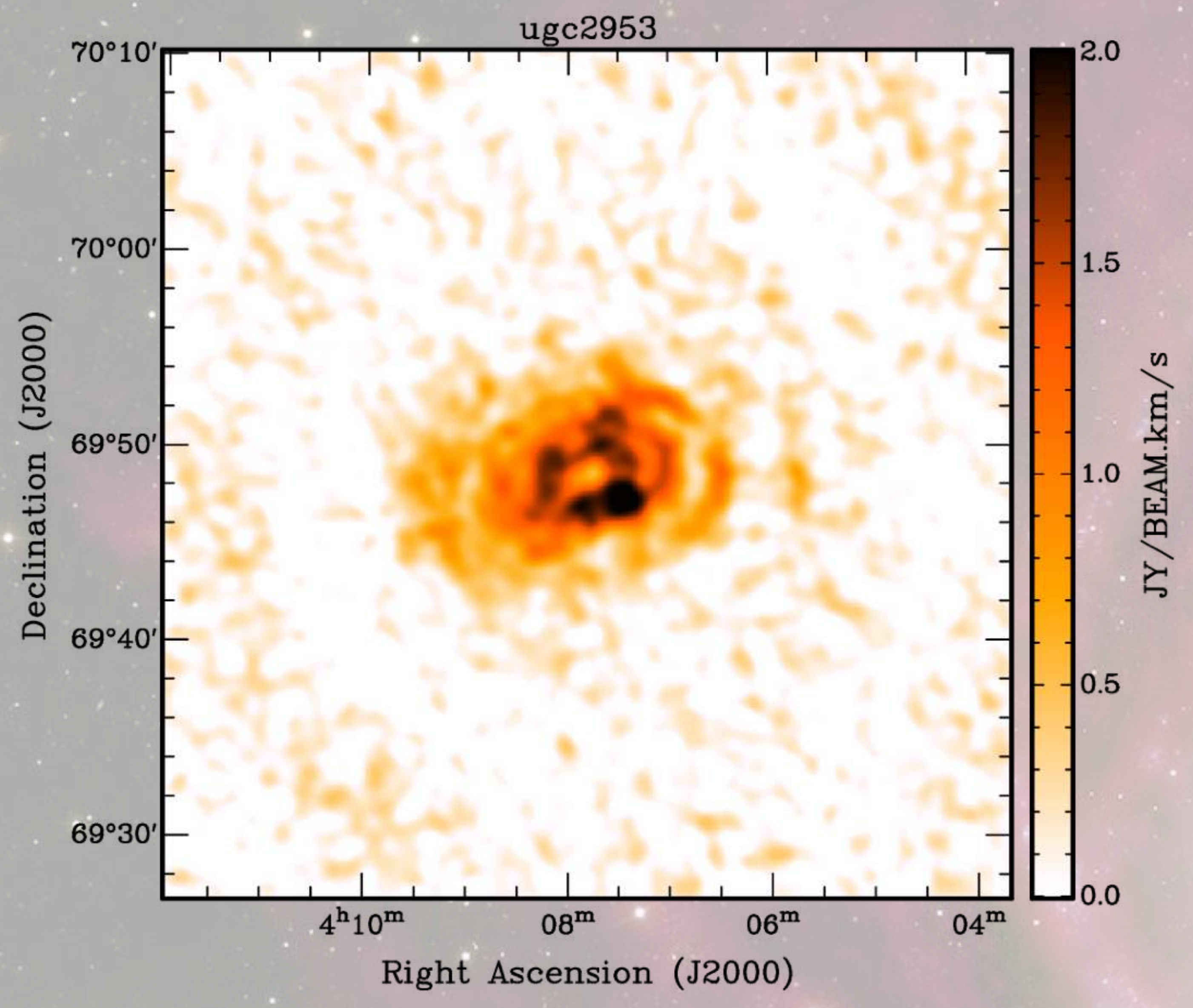
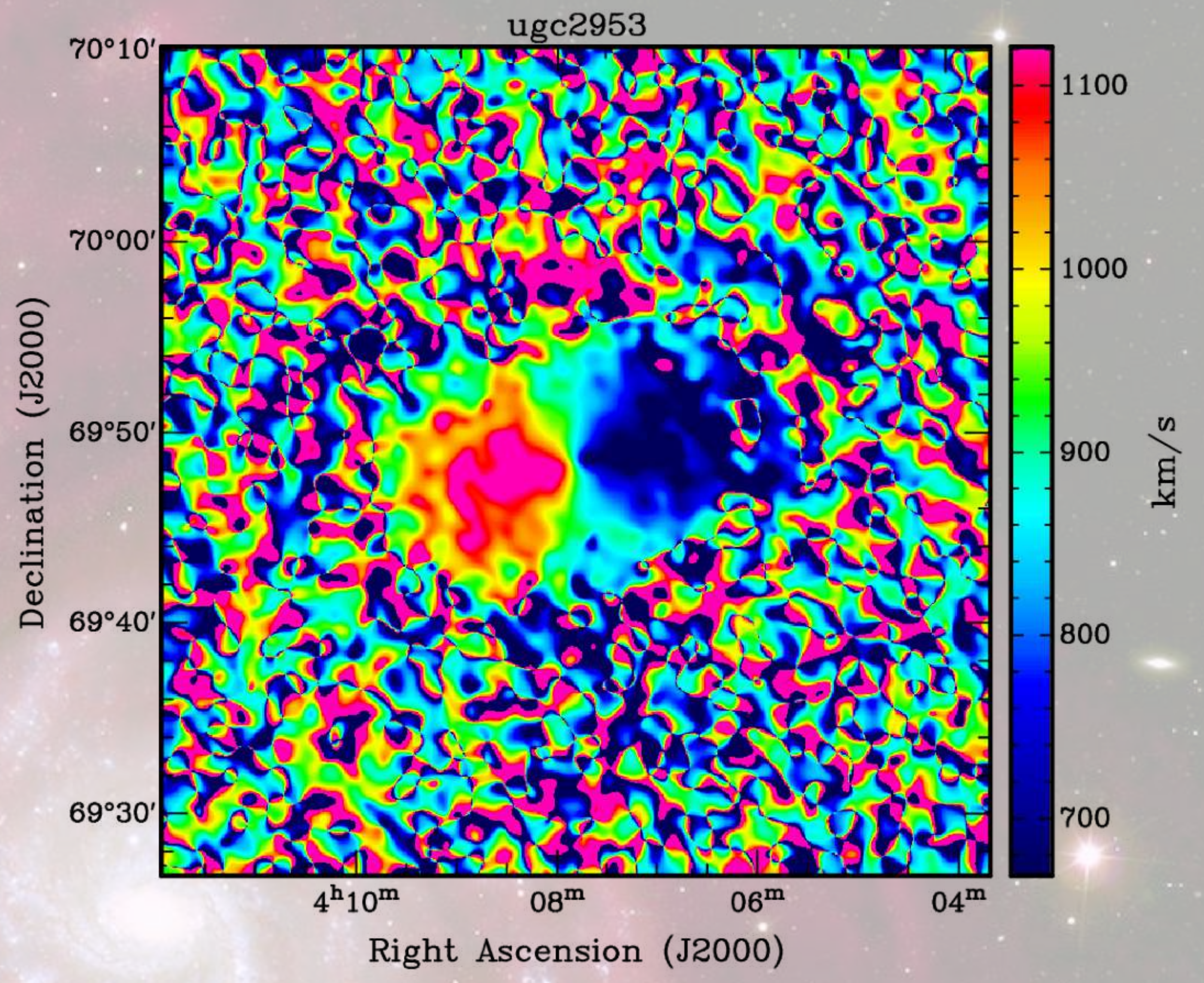
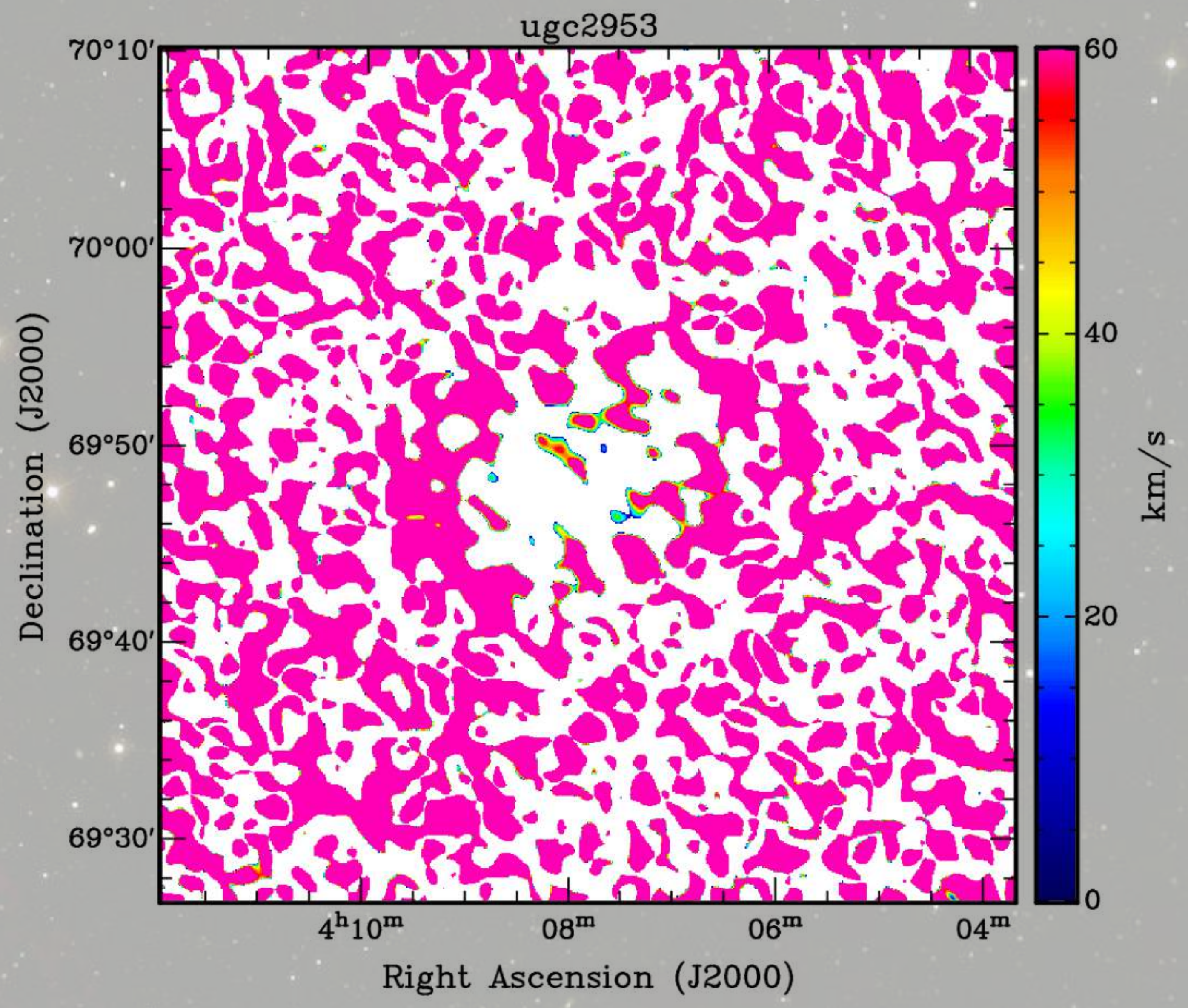
Before we get these nice maps, we have to take care of the noise, otherwise we would get this



Total intensity



Velocity field



Dispersion map

Why?

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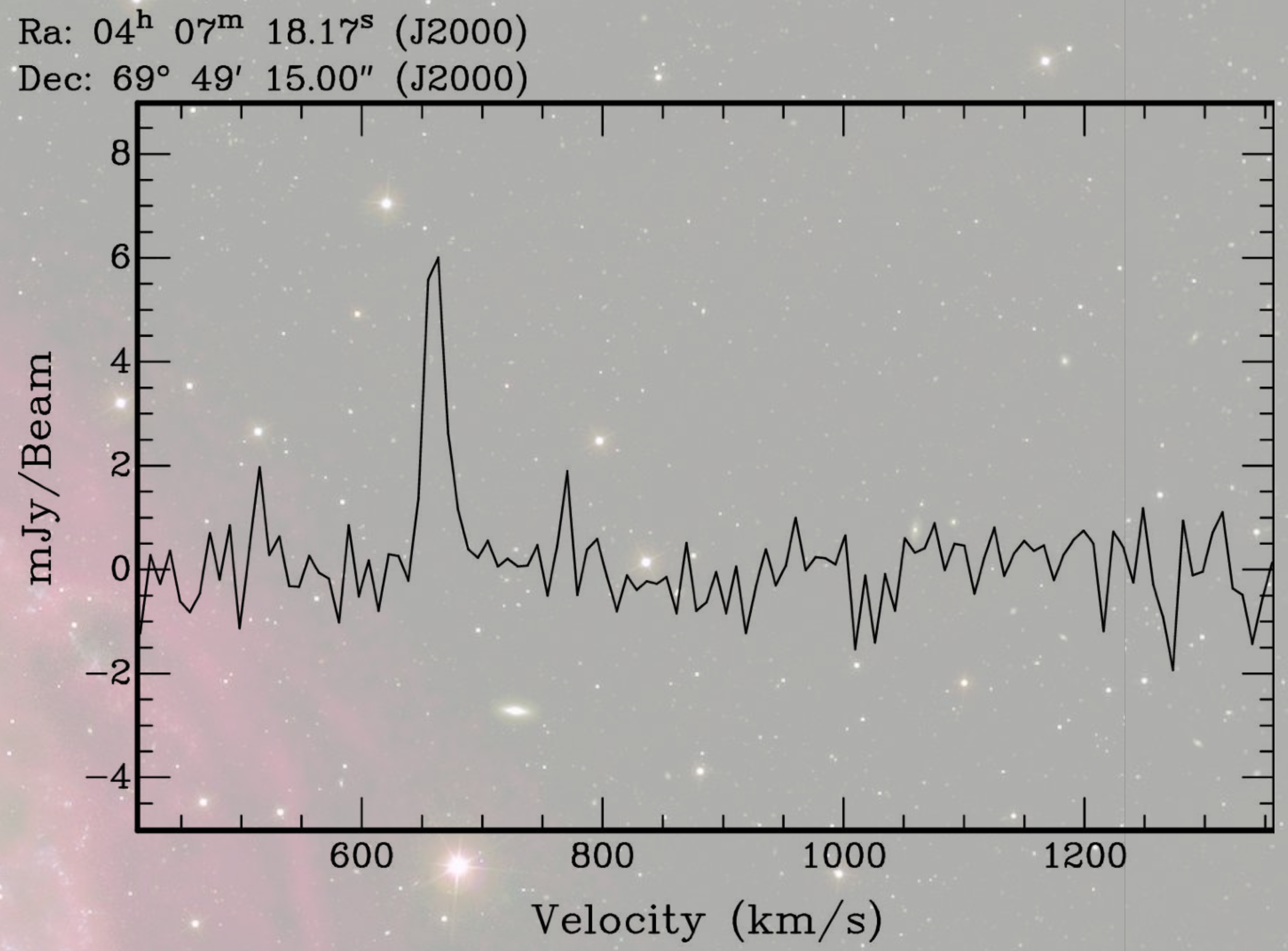
The spectral line only occupies a small part of the full spectrum.

If we integrate the full spectrum, we also add the noise where there is no emission.

Reduces signal-to-noise

Is even worse for higher-order moments



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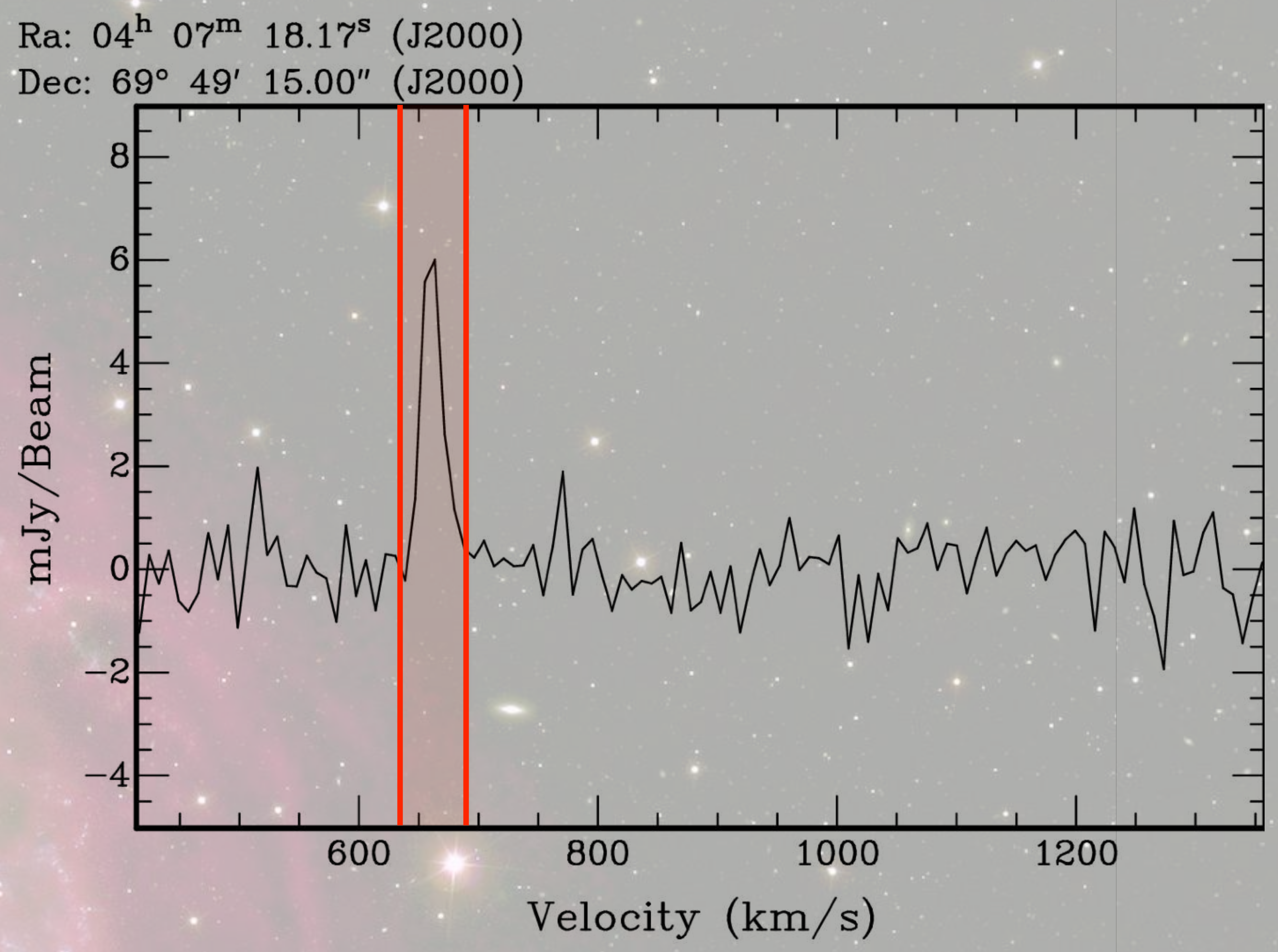

Solution: windowing,
i.e. only integrate over the channels
that contain emission

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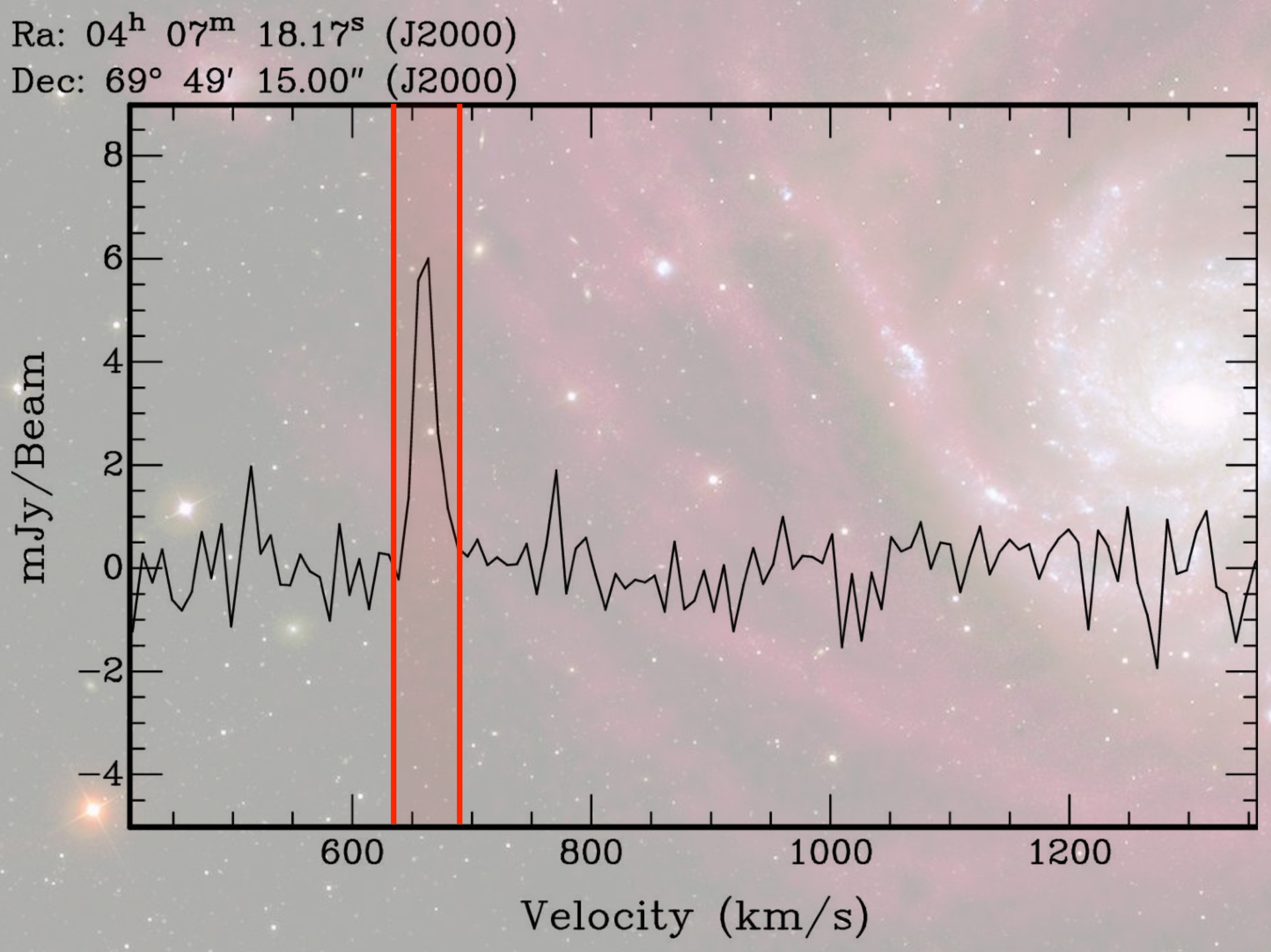
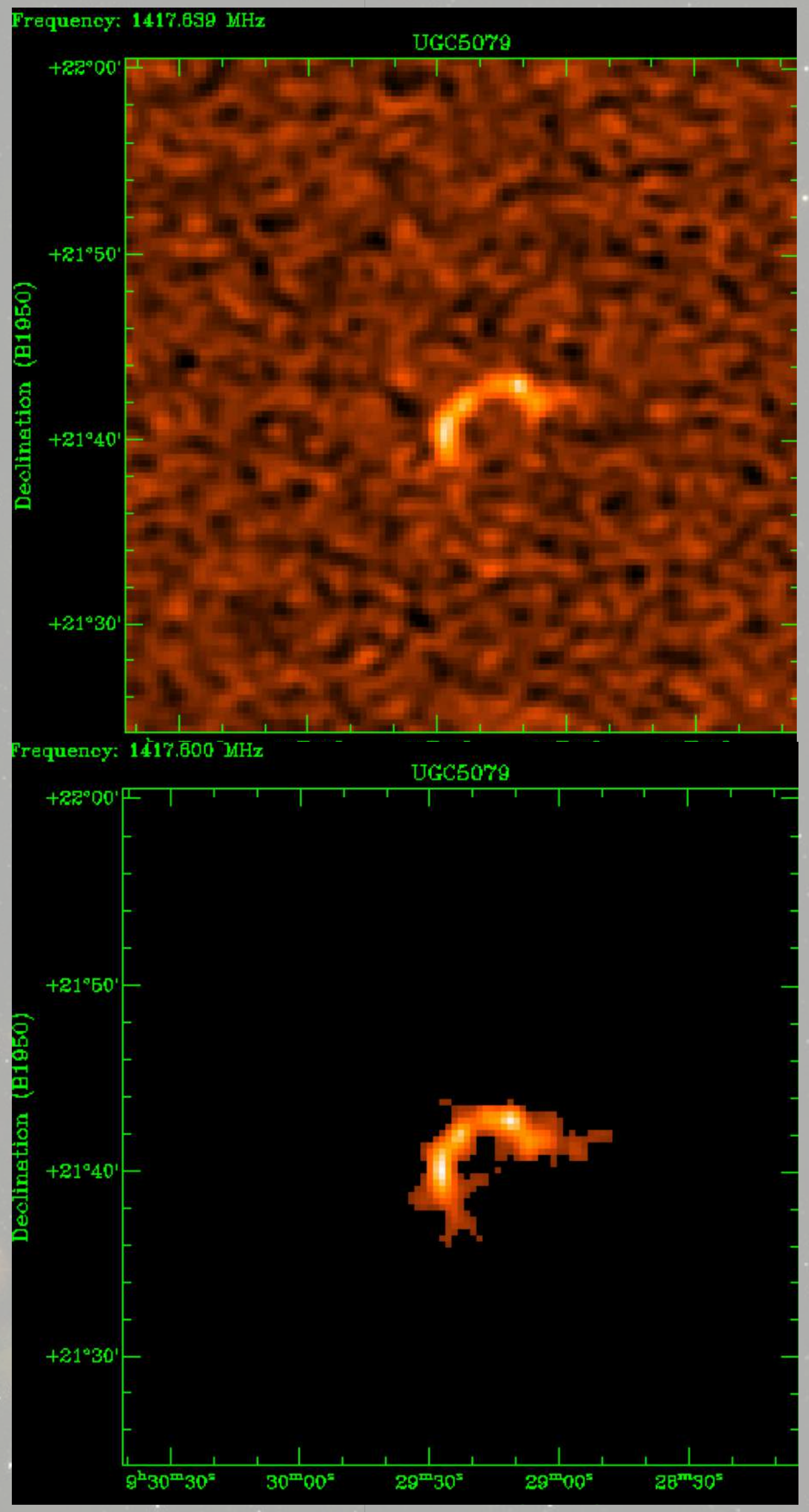
Mask the data cube by blanking the noise

- For each position, use only those channels that have signal, and do moment analysis on masked cube instead of on the original cube



original channel



masked channel

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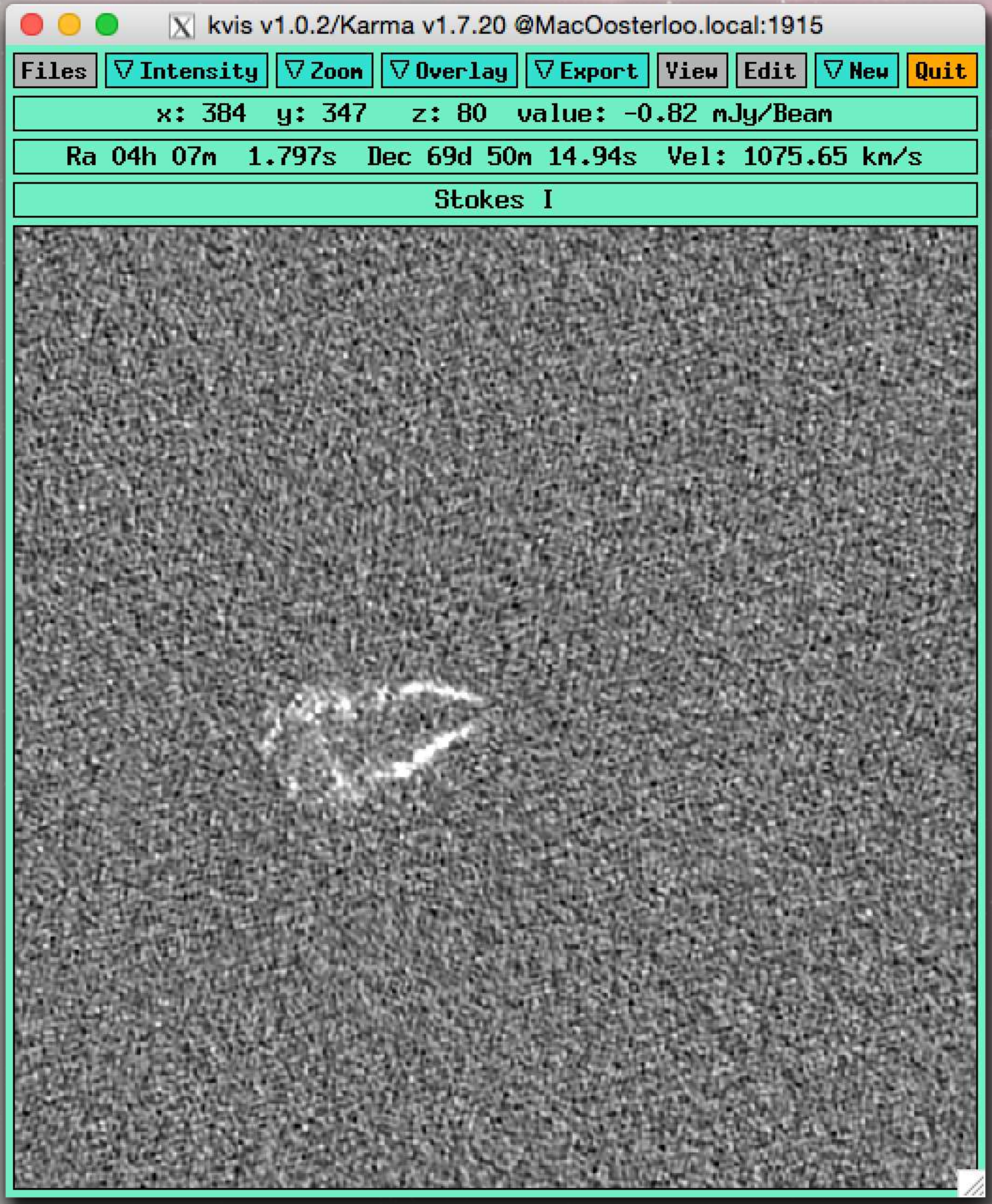
By spatially smoothing the data, the S/N of extended emission increases

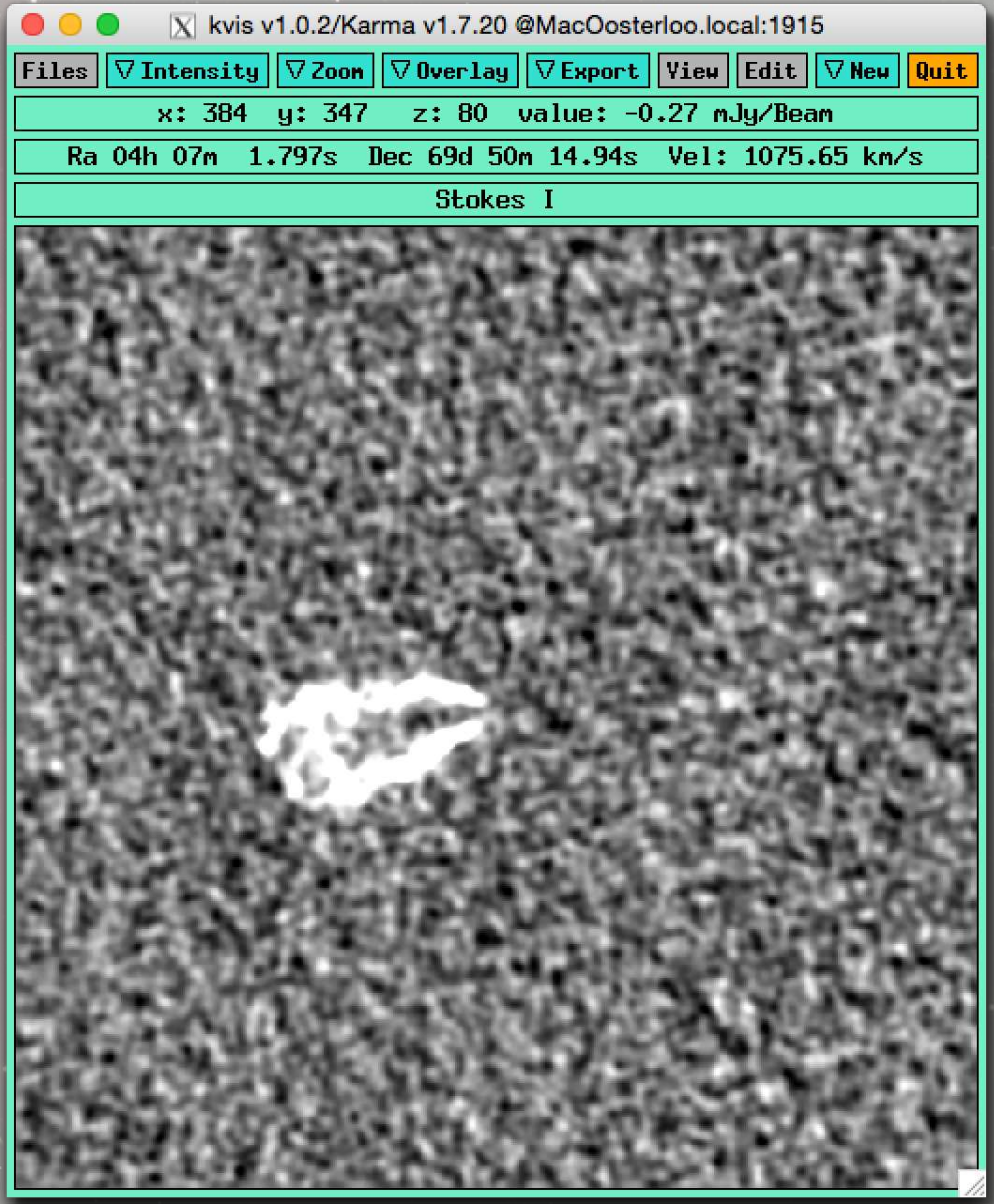
Units of the image are Jy/beam, so if if make the beam larger two things happen:

1. the noise increases(!!)
2. the flux of an extended source increases (because the beam is larger so more Jy/beam)

For an extended source, point 2 wins from point 1; For a point source 1 wins from 2....

15 arcsec





smoothed to 30 arcsec

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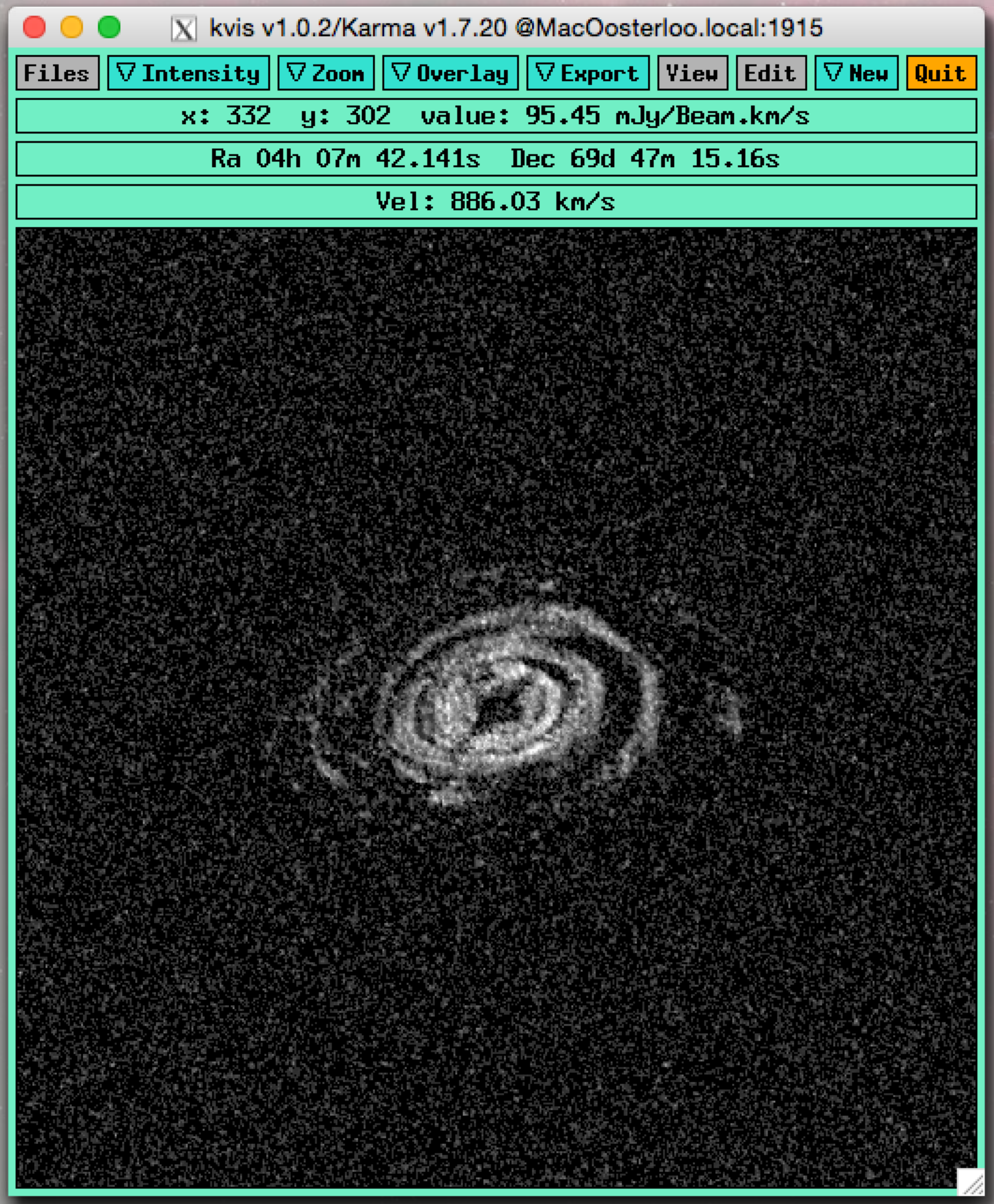
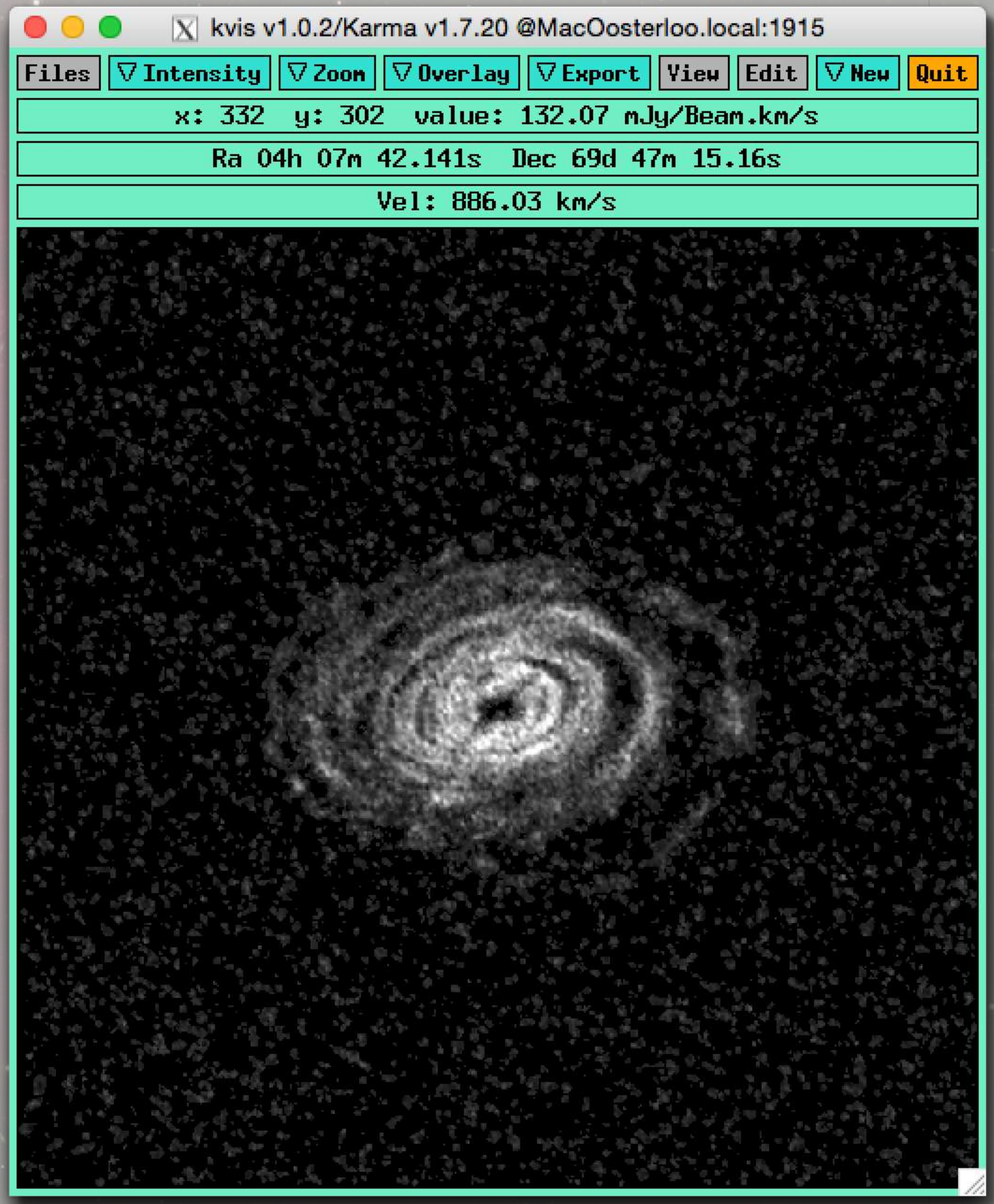
Simple strategy for masking the line emission is to smooth the data to lower resolution, make a mask based on that smoothed data cube (e.g. clip at 3 sigma) and apply this mask to the full-resolution cube.

Total HI by masking full-resolution cube at 3 sigma of full-resolution cube





Total HI by masking full-resolution cube at 3 sigma of smoothed cube

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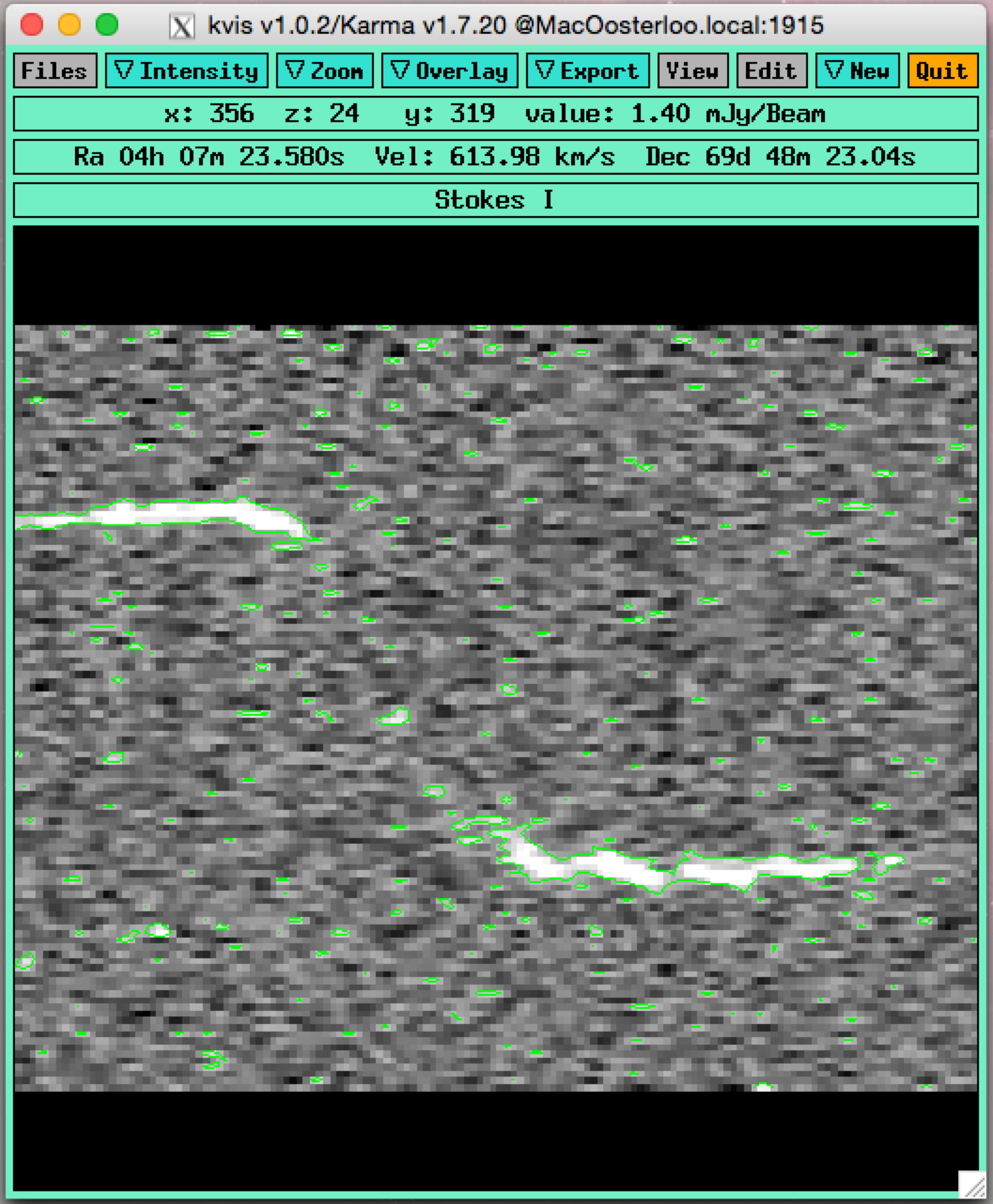
Also smooth in velocity. Masking is a 3-D problem, not a set of 2-D problems

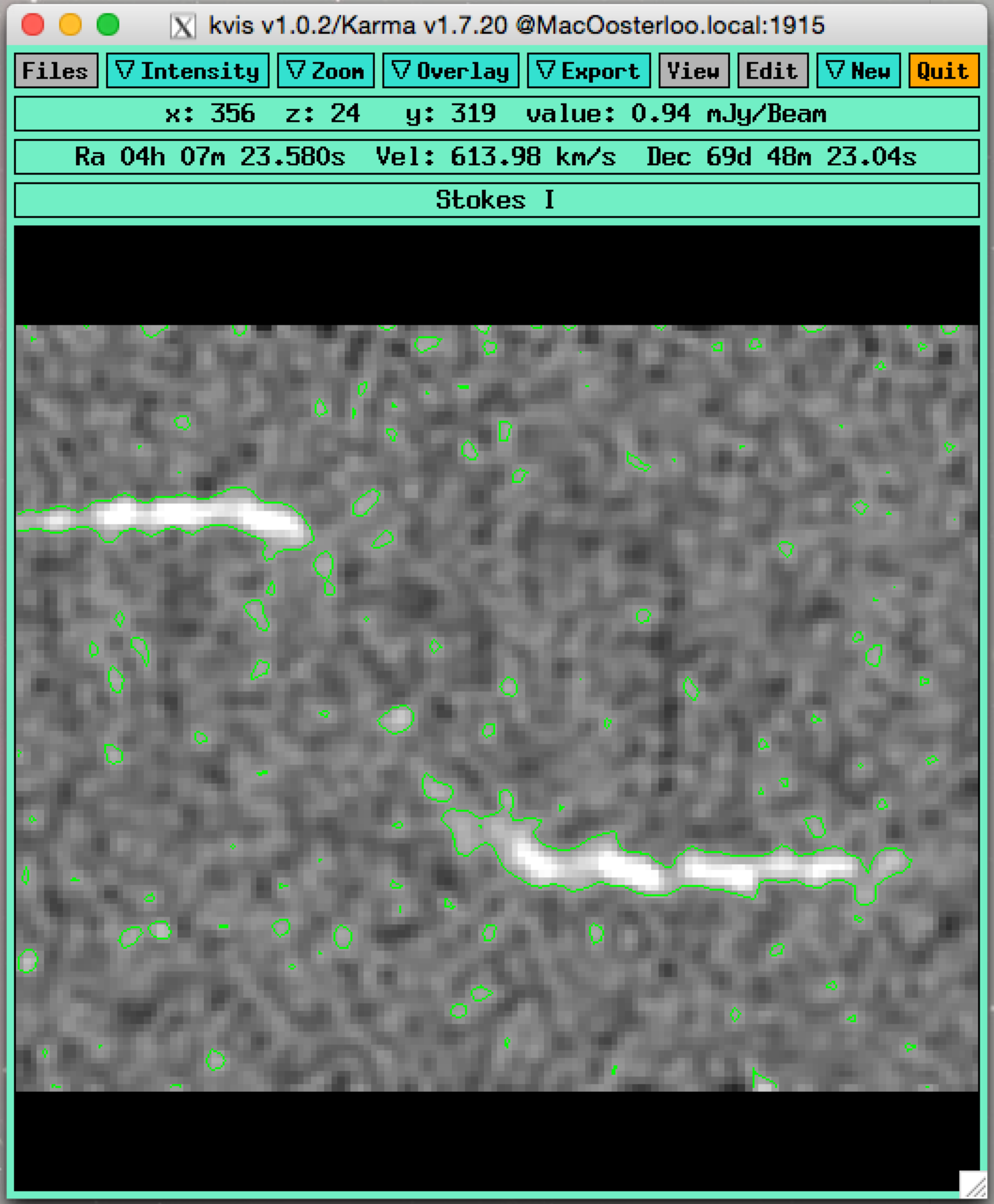
By smoothing in velocity the noise decreases!!!

Because 1 Jy = 10^{-26} W m^{-2} Hz^{-1}, not per channel

full velocity resolution



smoothed to lower velocity resolution



Contours are at 2 sigma of the respective cubes.

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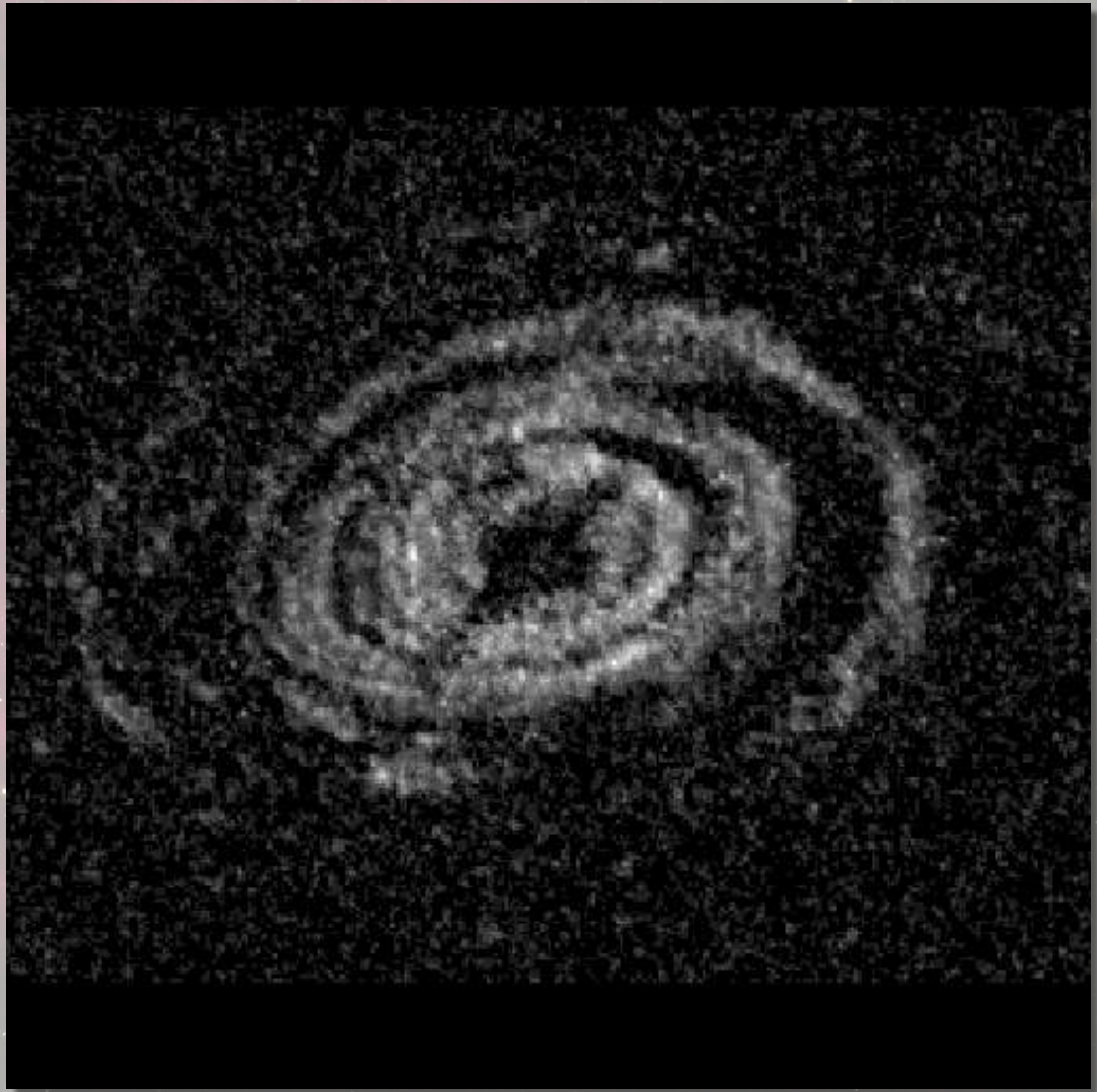
Created mask by clipping full-resolution cube at 3 sigma (1.8 mJy/beam) and by clipping full-resolution cube smoothed in velocity (1.0 mJy/beam).

last one has more signal and fewer noise blobs



How much should I smooth the data?

In principle you should smooth to the scale of the emission you want to detect.
But there is emission at many different scales, ranging from small blobs to large, smooth extended clouds.

Same in velocity: emission with narrow lines vs emission with broad profiles.

Dilemma: by smoothing, I increase the S/N of extended emission, but I decrease the S/N of a point source, so if I smooth too much, I lose S/N!!!

Conclusion: there is not a single, optimum scale

So you have to smooth to many different scales (spatially, but also in velocity), make a mask at each resolution and combine the masks

This is what SoFia does!!!!
Much less work than doing by hand, quite good results
(but sometimes needs tuning of the parameters)

SoFiA
Source Finding Application

Serra+ 2015
Westmeier+ 2021

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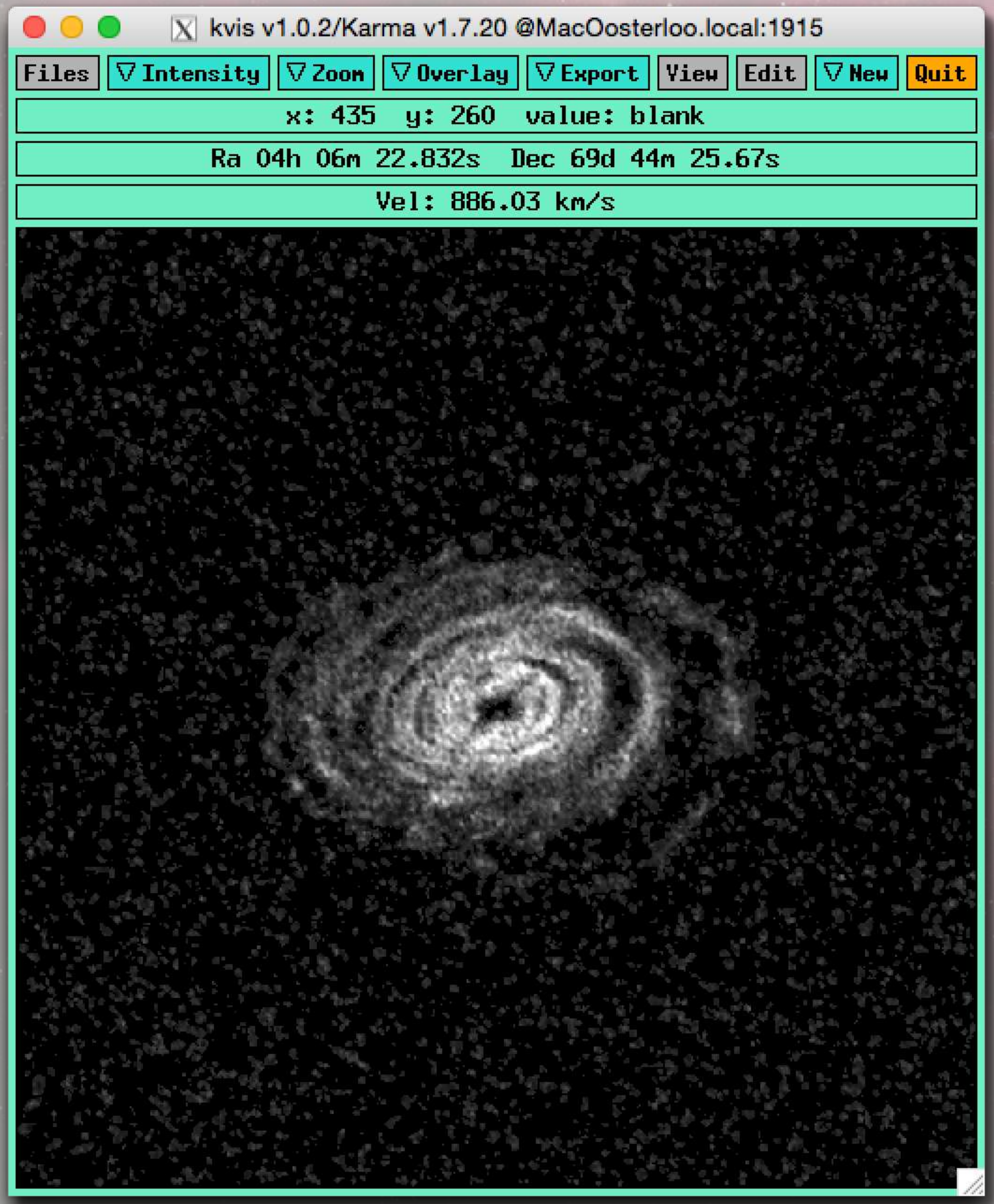
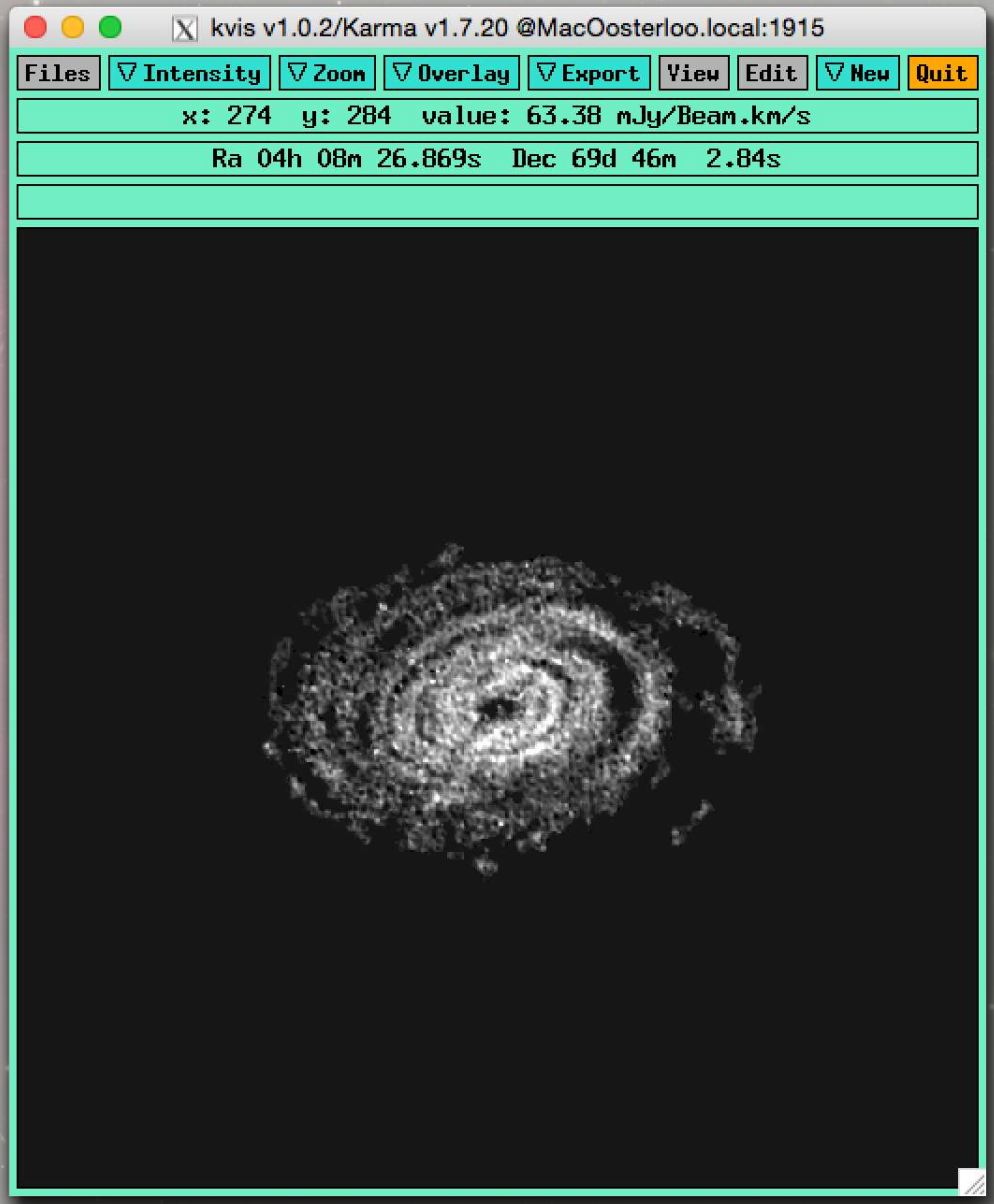
By hand, single scale smoothing



SoFiA using several spatial and velocity scales

Note that noise specks have gone

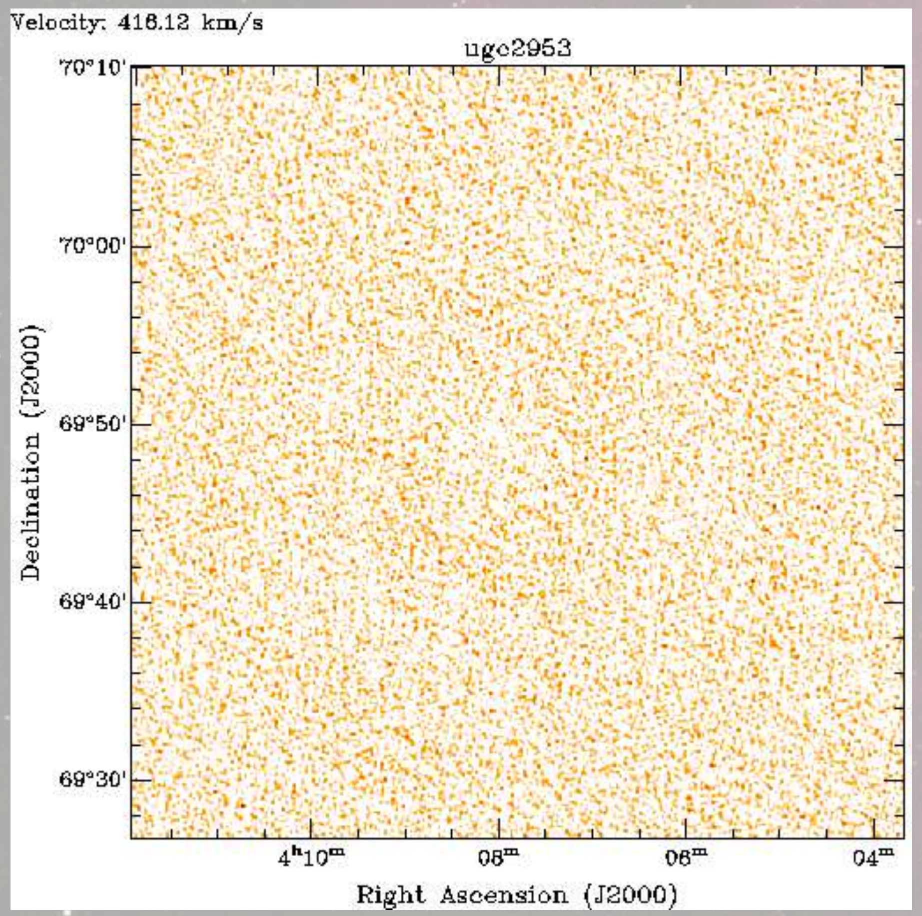


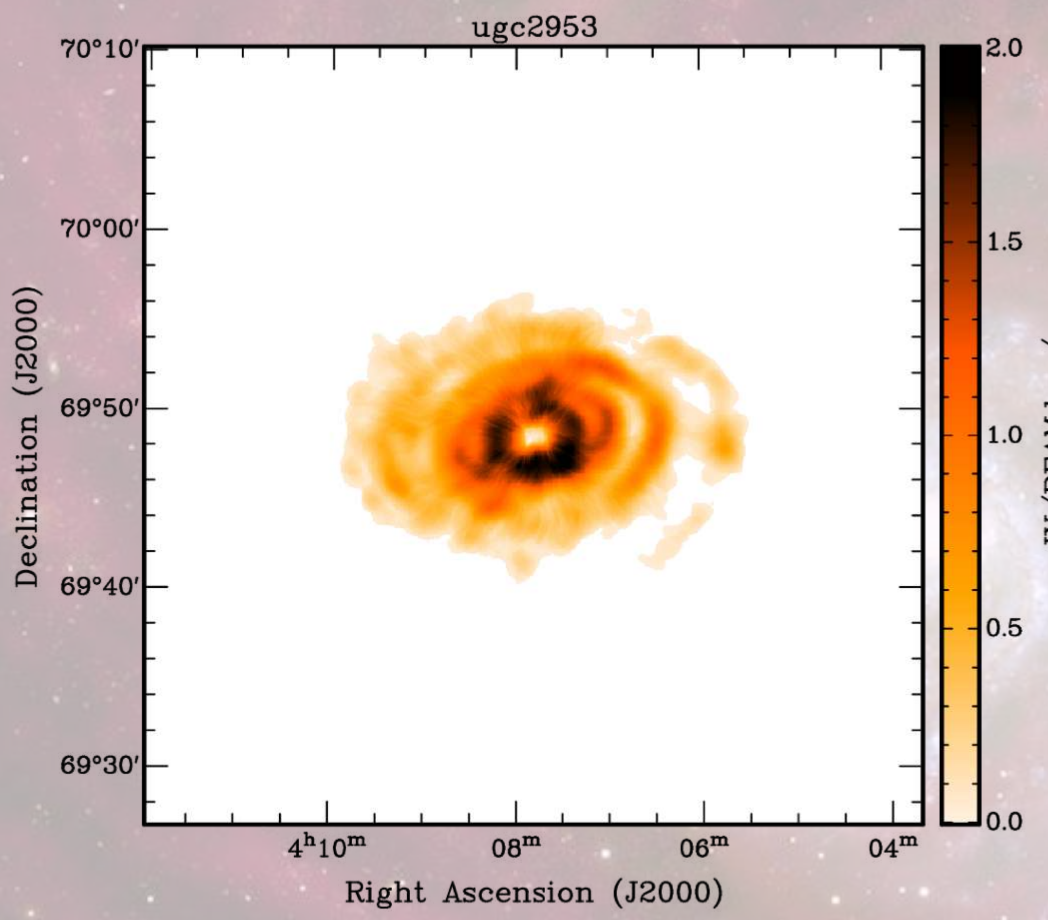
kinematical analysis

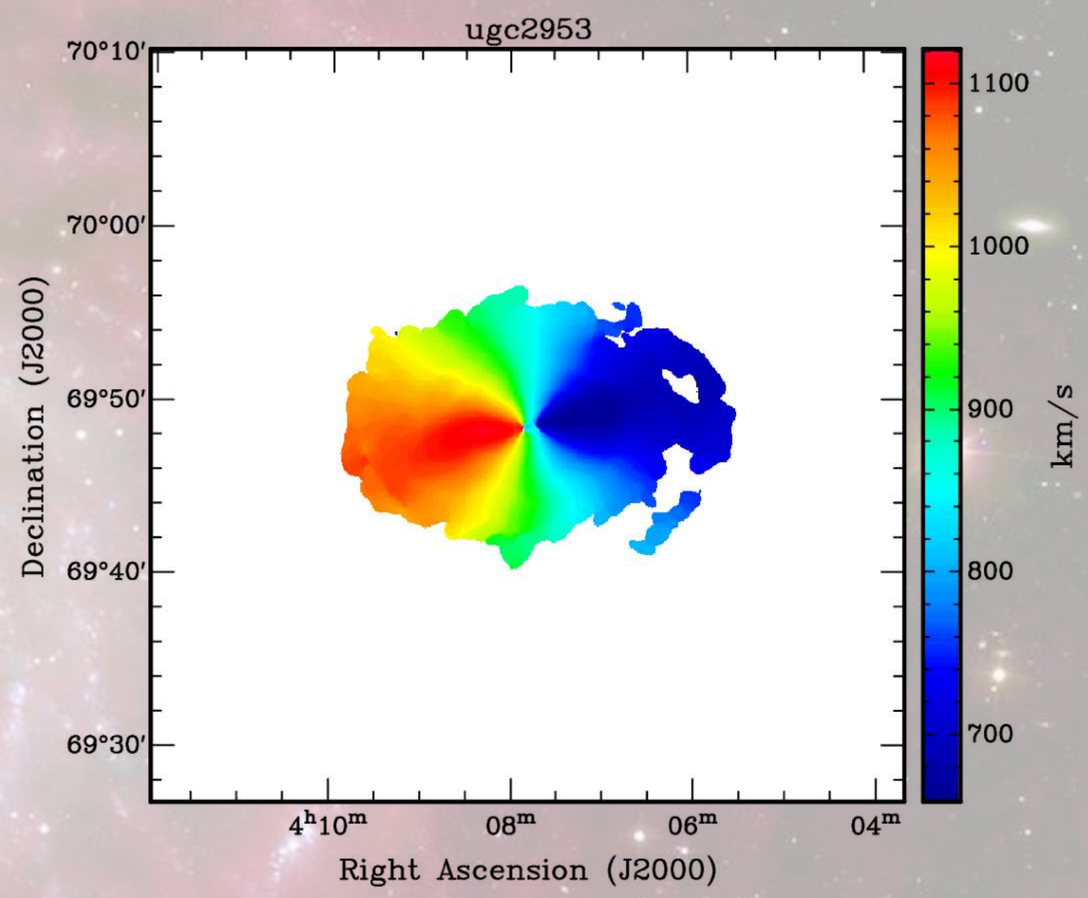
For every position we have a spectrum from which we can measure the total flux and a velocity.

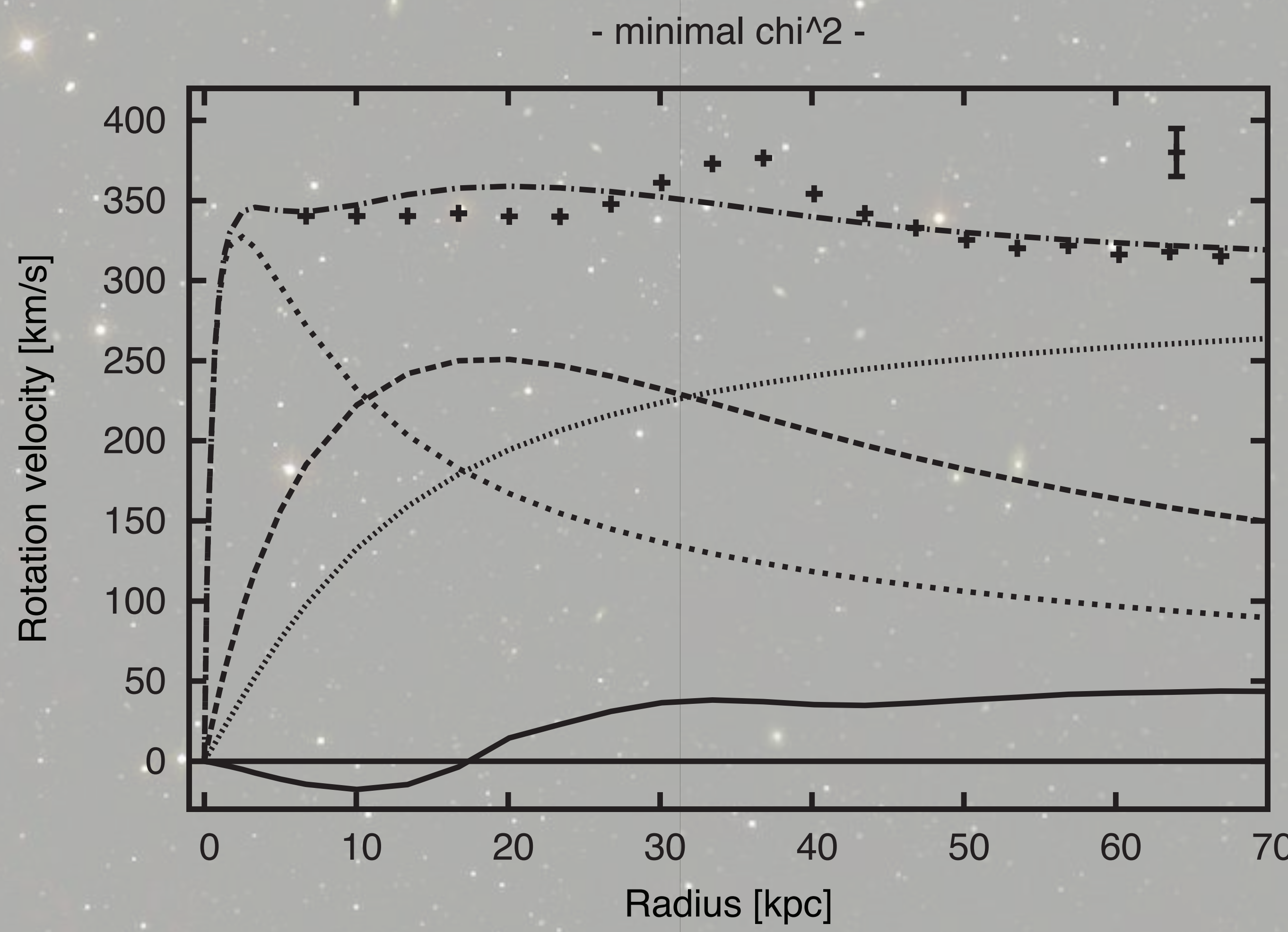
Can map the brightness distribution and kinematics of our object.

Model the kinematics in terms of mass models of all components (bulge, disk, HI disk, dark matter halo)



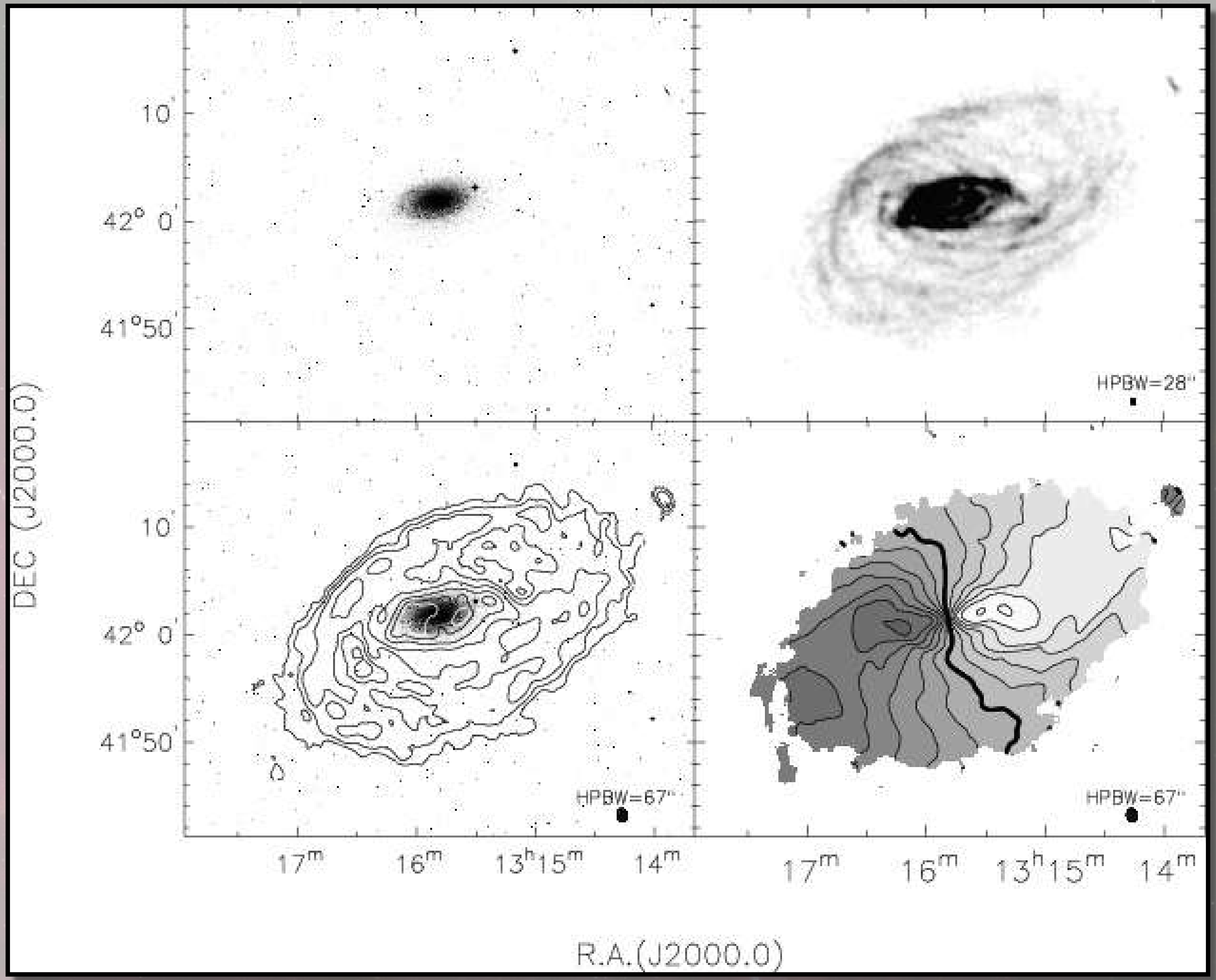


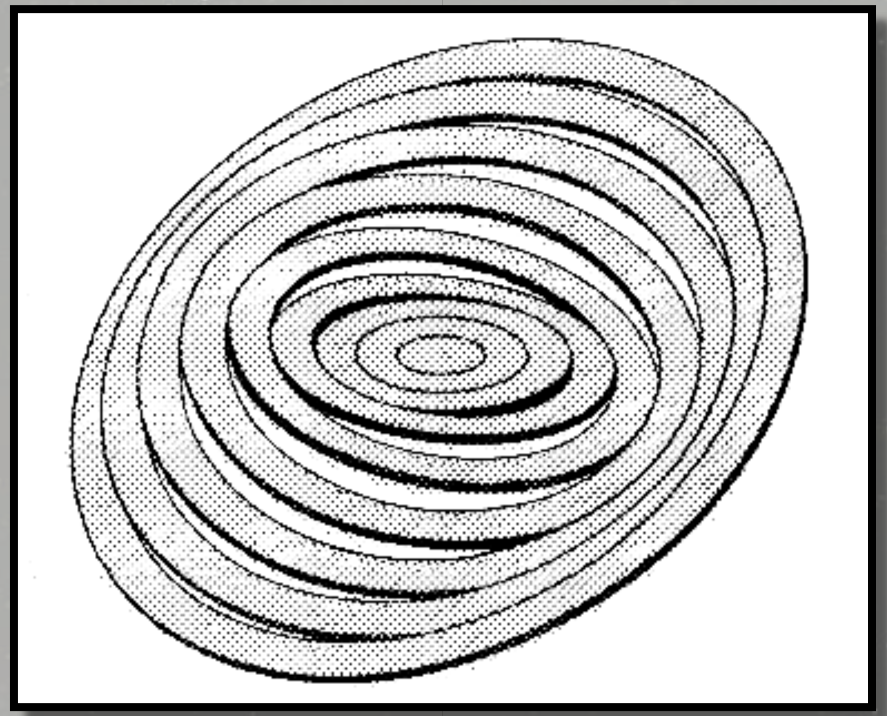




Struve+ 2010

Data cube gives complete mapping of kinematics



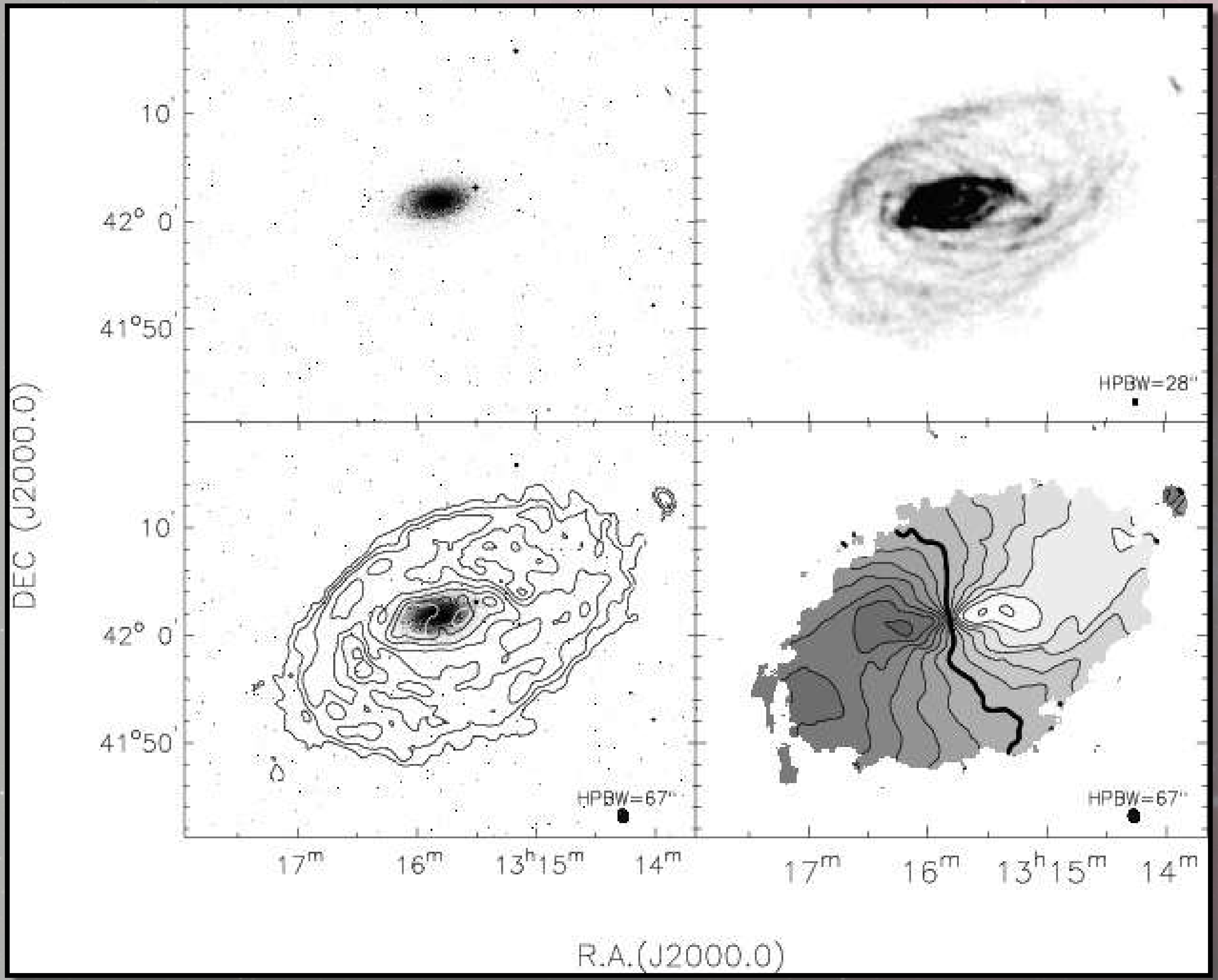


$$V_{\rm los} = V_{\rm sys} + V_{\rm rot}(r)\sin i(r)\,\cos\theta(r) + V_{\rm rad}(r)\sin i(r)\,\sin\theta(r)$$

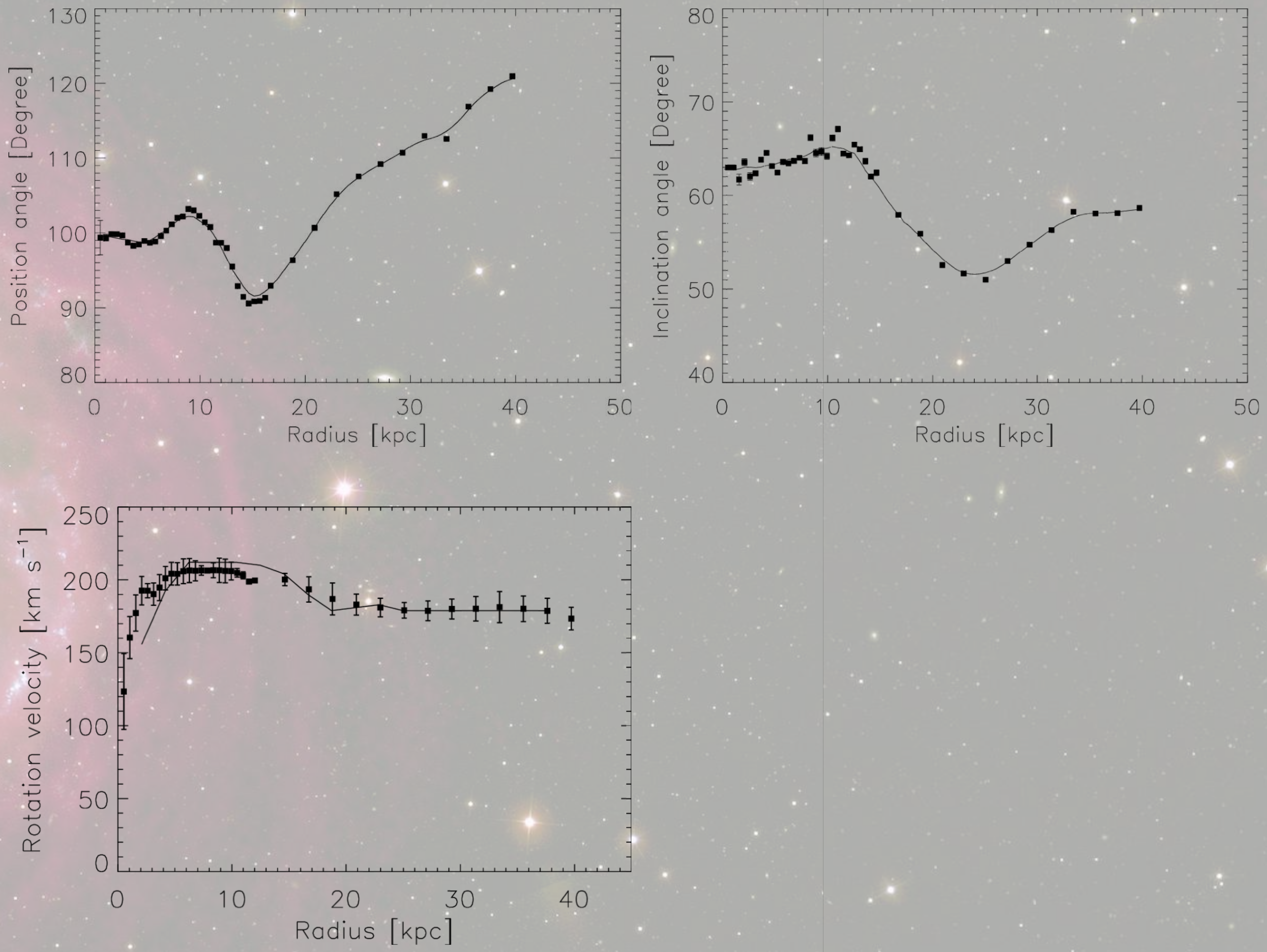
Model the galaxy as a set of tilted rings, each ring with its own rotation- and radial velocity, and inclination and position angle.

“Old’ approach: model the 2D velocity field

Result of modelling the velocity field



Here the model is accurate because the galaxy is well resolved



NGC 5055; Barbieri+ 2005

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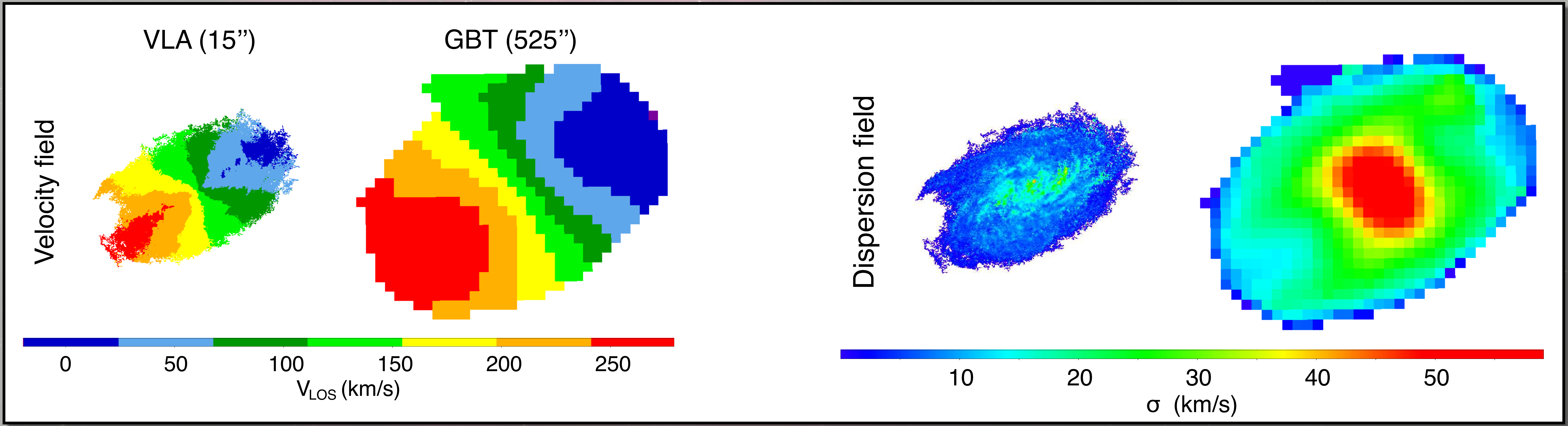
Problem: beam smearing

if the velocity gradients are large on the scale of the resolution of the data, these gradients get smeared out and this affects the fit



Solution: model the data cube in 3D: make model cube of the galaxy at high resolution and smooth it to the resolution of the data cube. e.g. ^{3D}Barolo, Tirific,...

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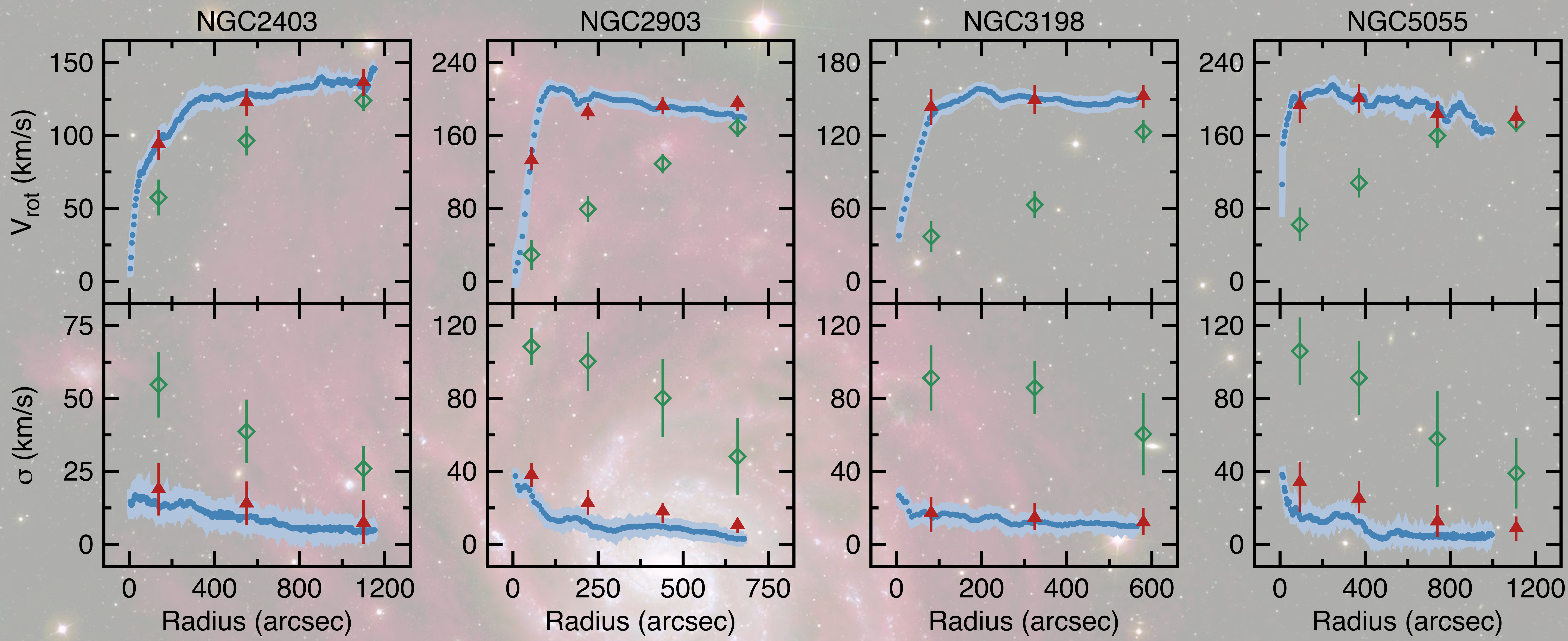
Modelling the data cube instead of the velocity field solves the problem of beam smearing



di Teodoro & Fraternali 2015

blue: true rotation curve

green: model 2-D low-resolution velocity field

red: ^{3D}Barolo on low-resolution cube

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Future HI instruments

(and the impact of RFI)

- Nearby Universe
- Distant Universe; emission and absorption studies ($z > 0.25$)
- Intermediate redshifts ($0.1 < z < 0.25$)

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ALMA millimetre array

at 5000 m in the Andes,
has given spectacular results
and will continue to do so

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ASKAP

（Australia）

- 36 12-m dishes
- 700-1800 MHz

Very large field of view: 30 deg^2

12-m dish has FoV of 1 deg^2

Very good RFI environment

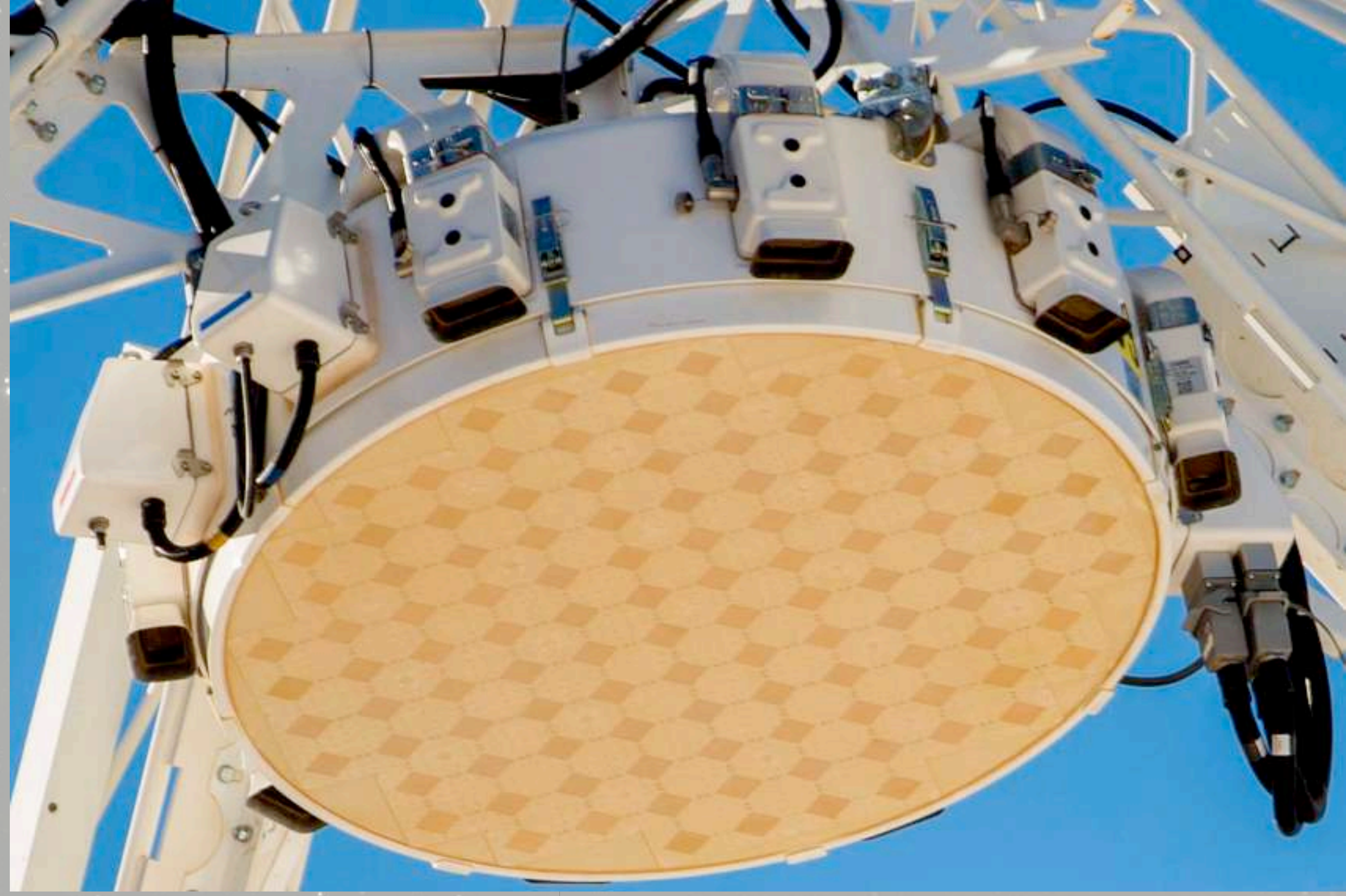
Survey telescope

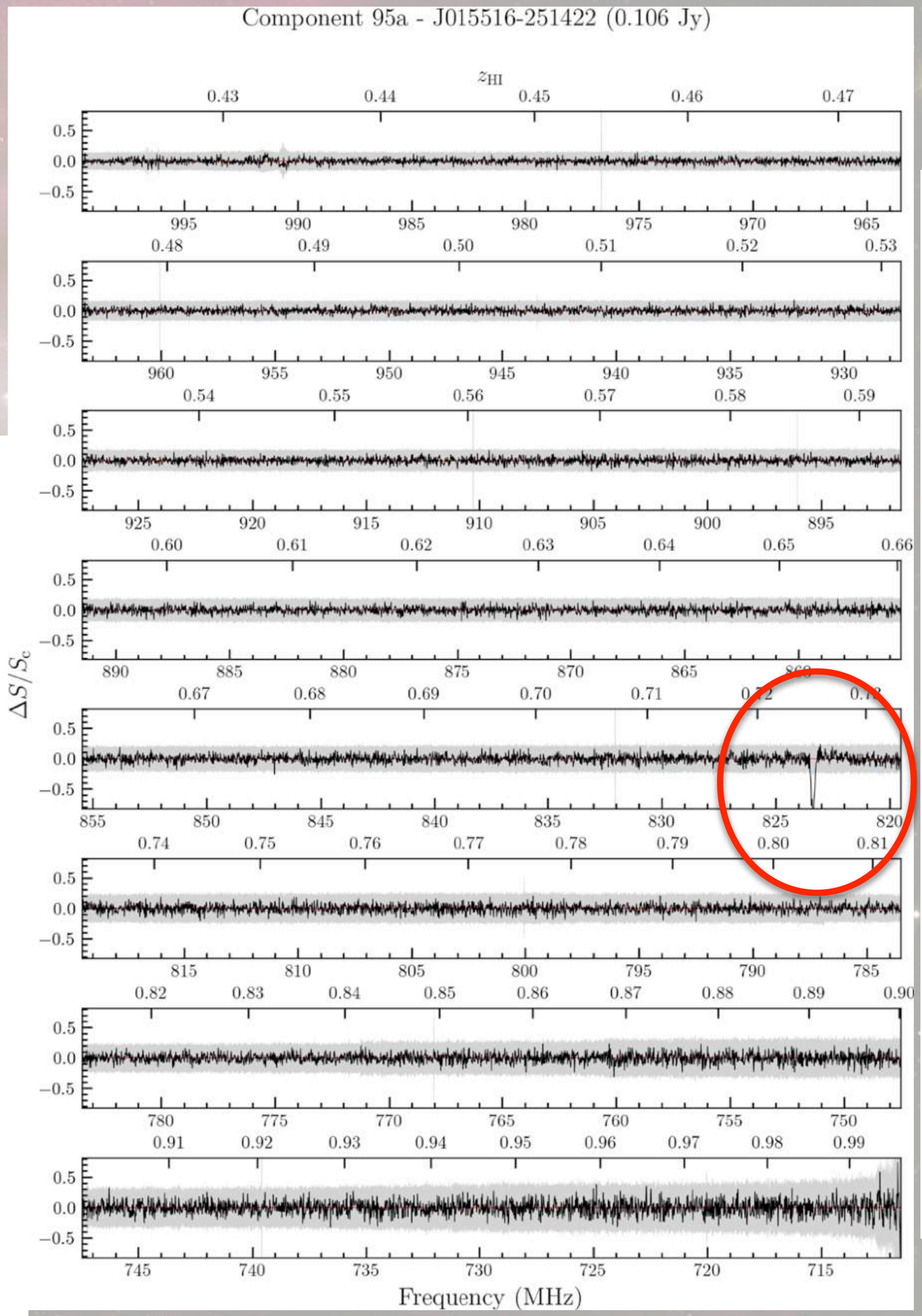
ASTRON RuG

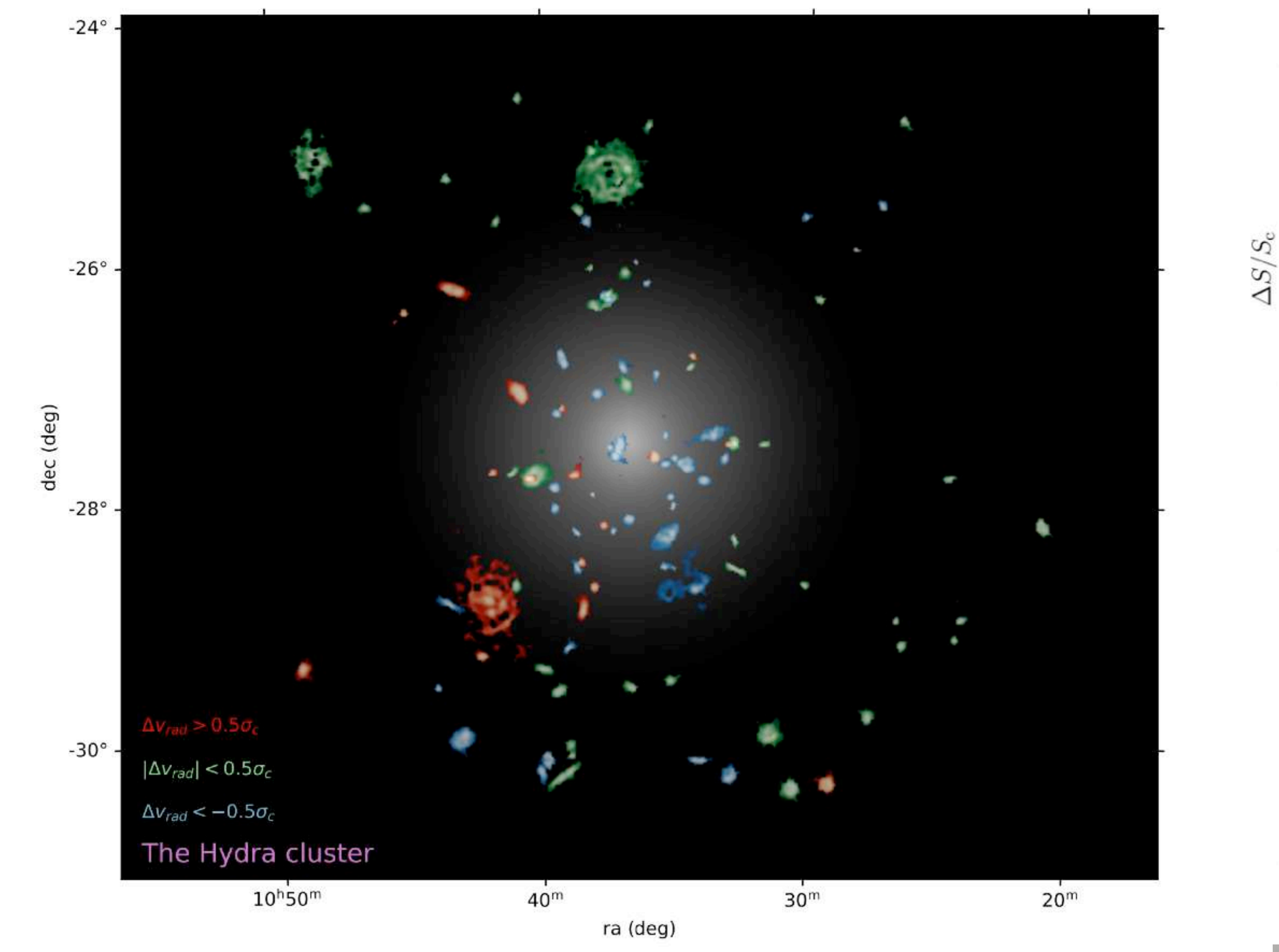
Large FoV created by phased-array feed

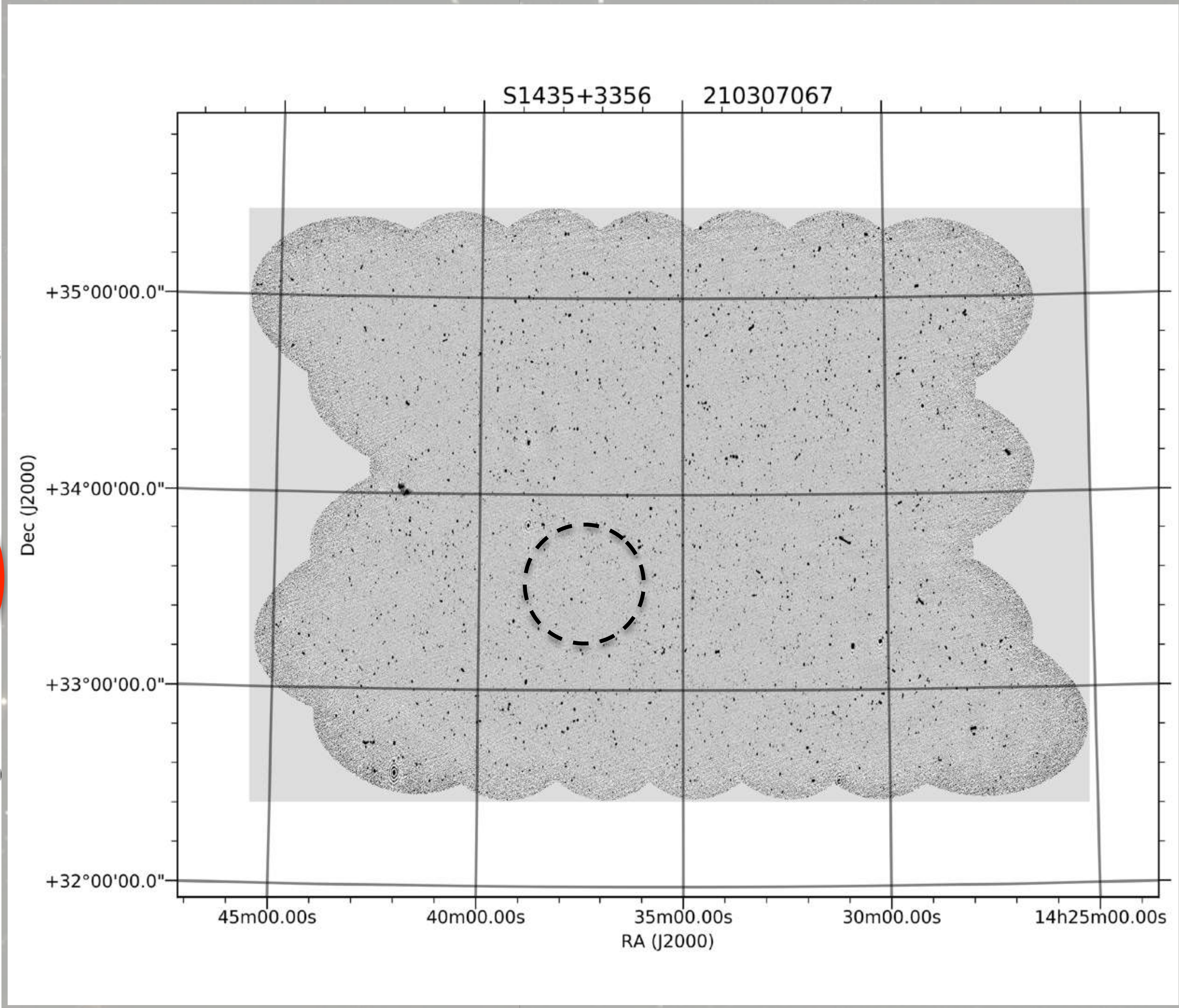
Instead of a single detector, a large array of detectors which is used to create 36 beams on the sky.
Effectively 36 telescopes in parallel.

All-sky HI survey z < 0.1 (Wallaby)
All-sky absorption survey z < 1 (Flash)
Very deep field (Dingo)









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MeerKat
(South Africa)

- 64 13.5-m dishes
- 0.58 – 1.015 GHz
- 0.9 - 1.67 GHz
- 1.75 - 3.5 GHz

Currently the best telescope in this frequency range, in terms of sensitivity and image quality

Relatively low resolution

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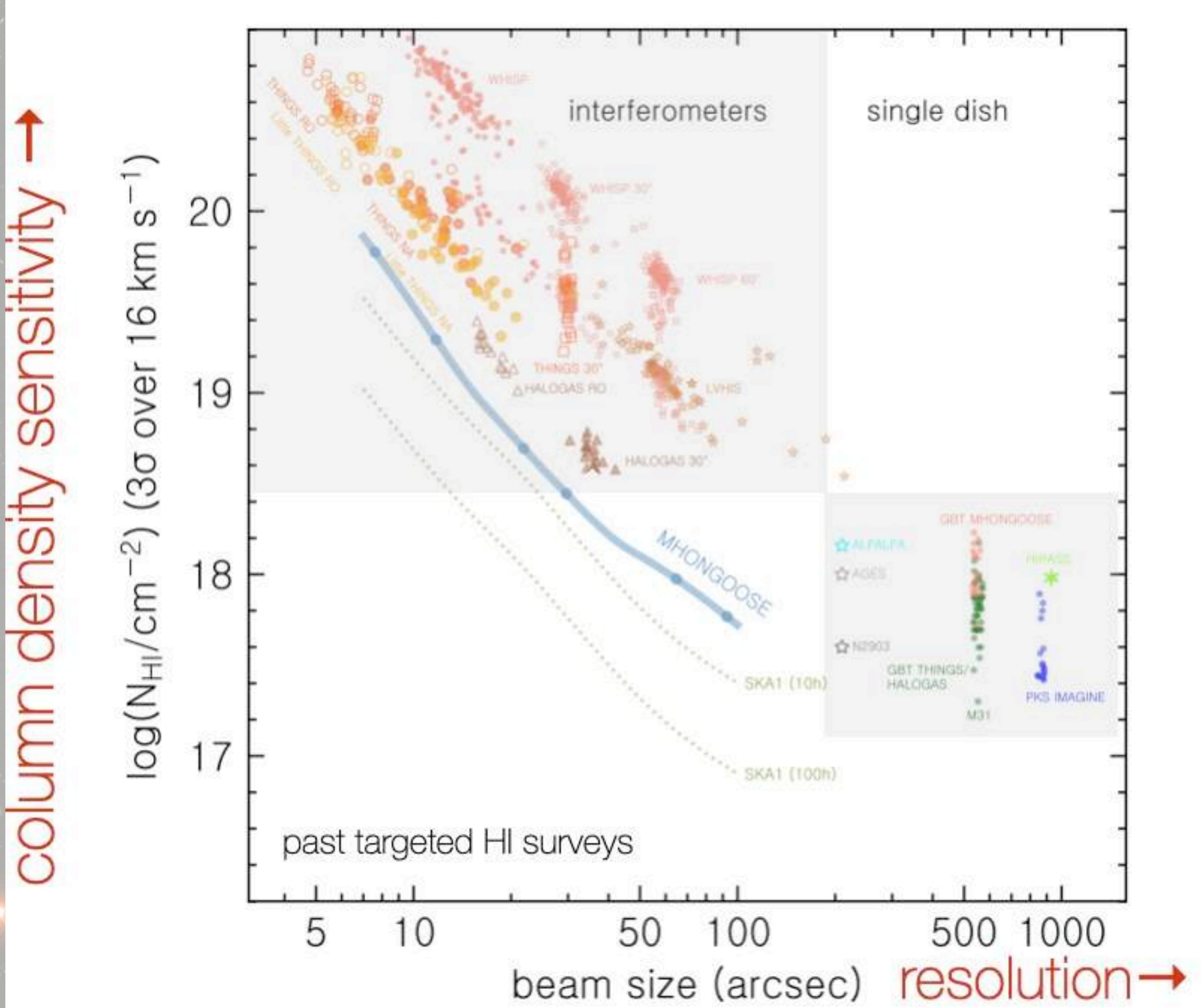
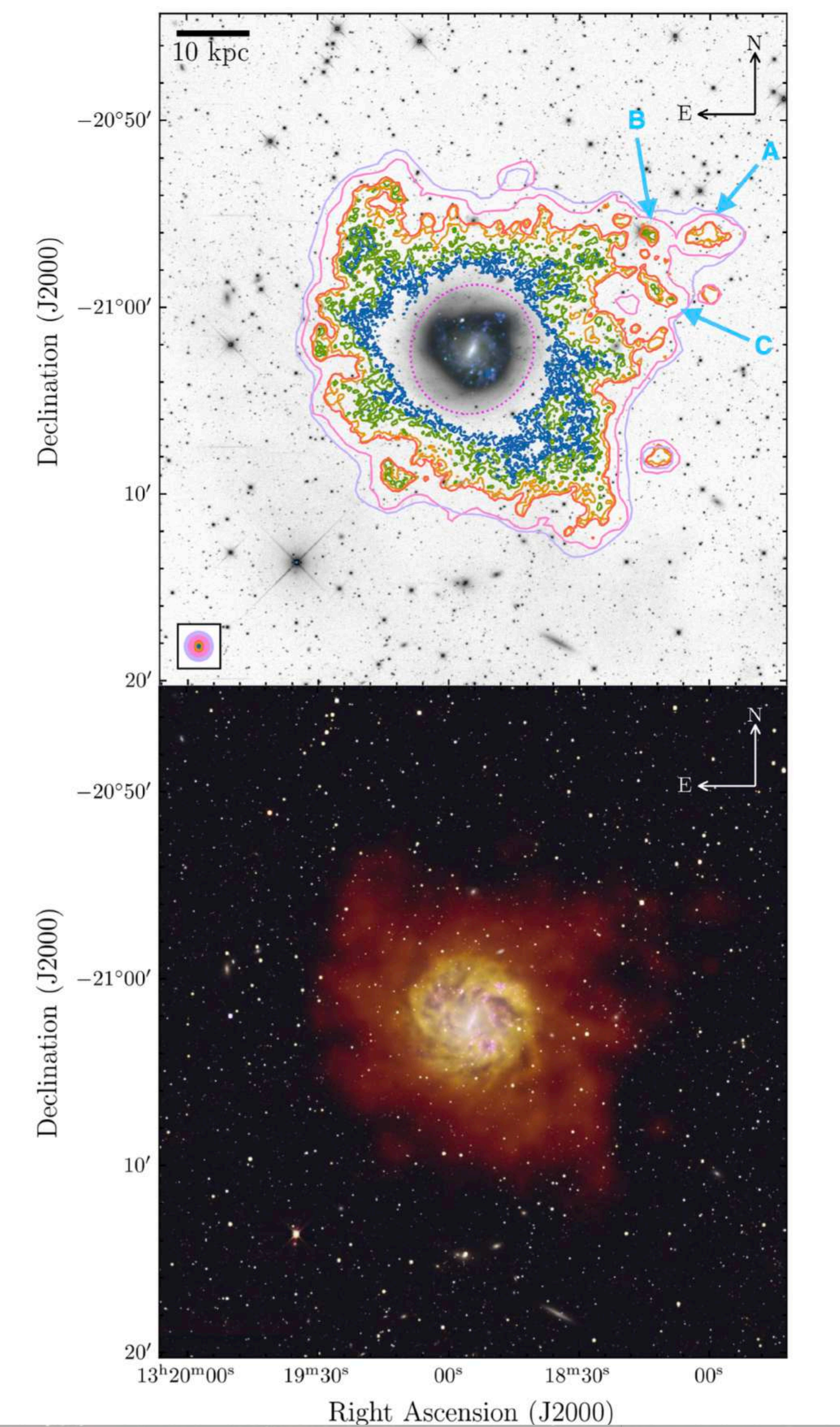
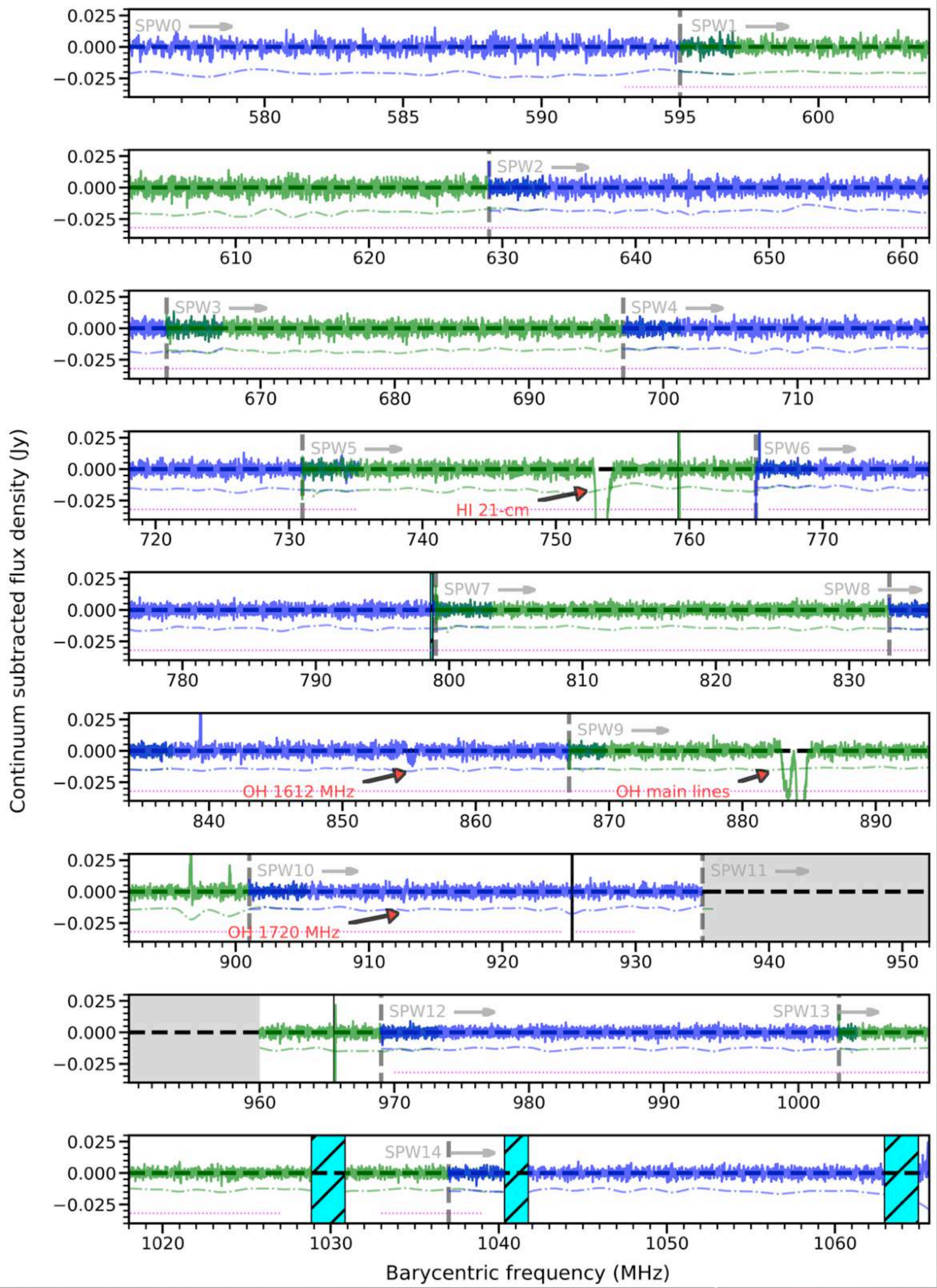
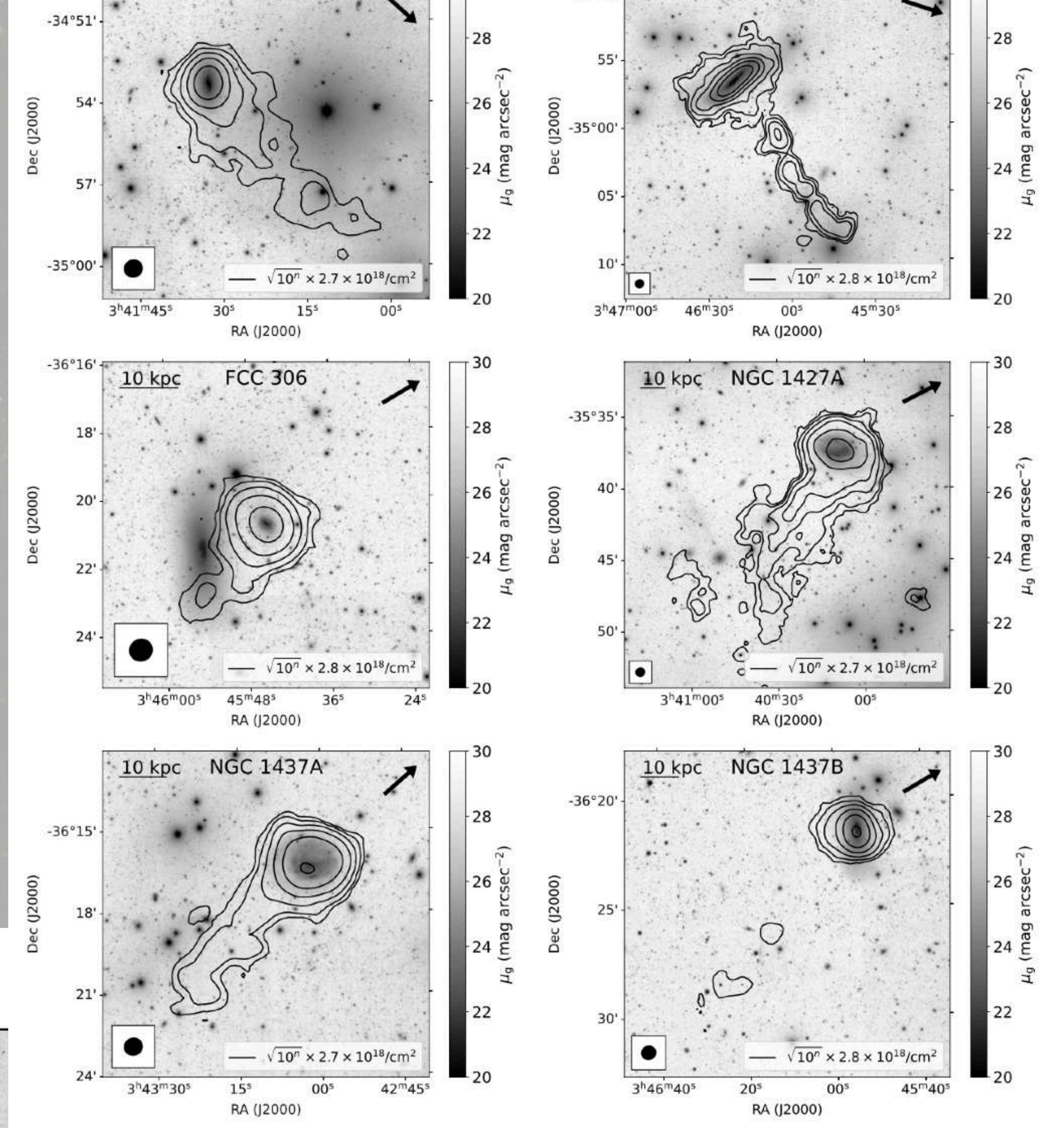
Excellent surface brightness sensitivity

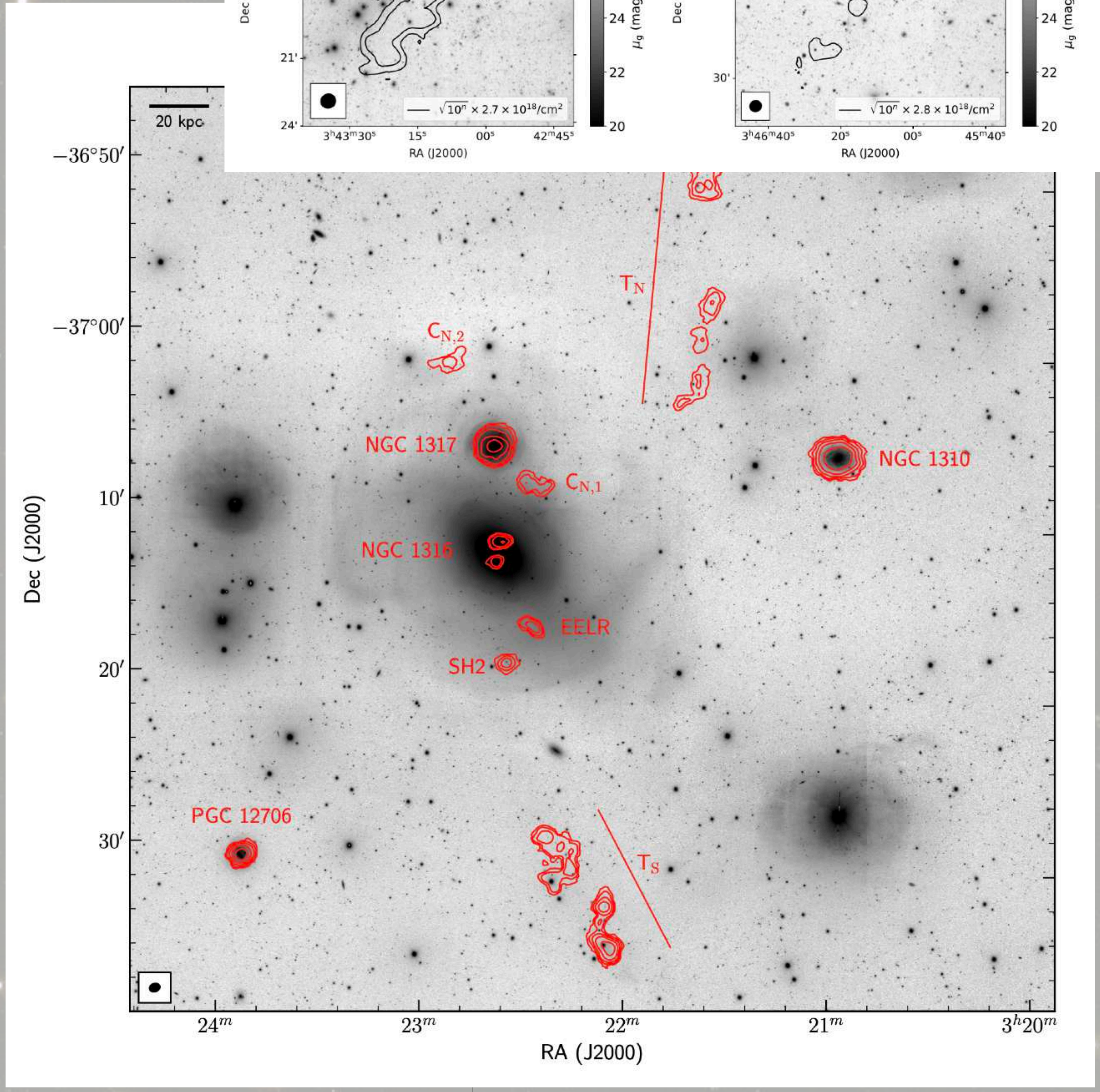




- very deep observations of small sample of galaxies – Mhongoose
- HI survey of Fornax cluster
- very deep field up to z = 1.4 – Laduma
- commensal with continuum survey, moderate depth, 20 deg² – MighteeHI
- absorption survey z < 1.4 – Mals







Square Kilometre Array

(South Africa & Australia)

- low-frequency array (Lofar like but bigger, but lower resolution) 50 — 350 MHz
- ‘expansion’ of MeerKat (~200 dishes) 350 — 15000 MHz

starts observing in 2030

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DSA2000

2000 ‘cheap’ dishes
in the USA

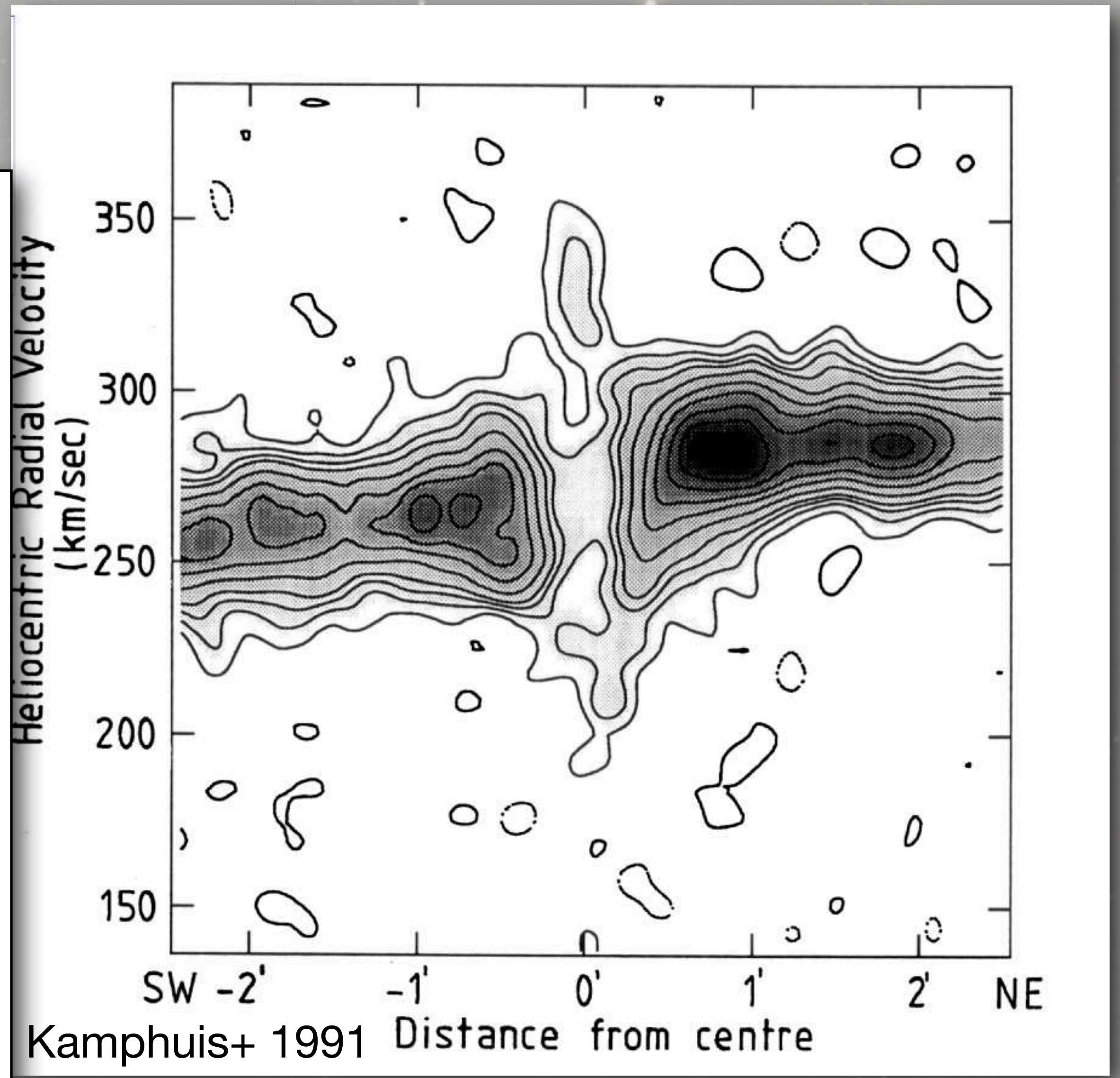
Will survey the entire sky in HI at ‘high’ resolution and sensitivity

Atomic Hydrogen (HI)

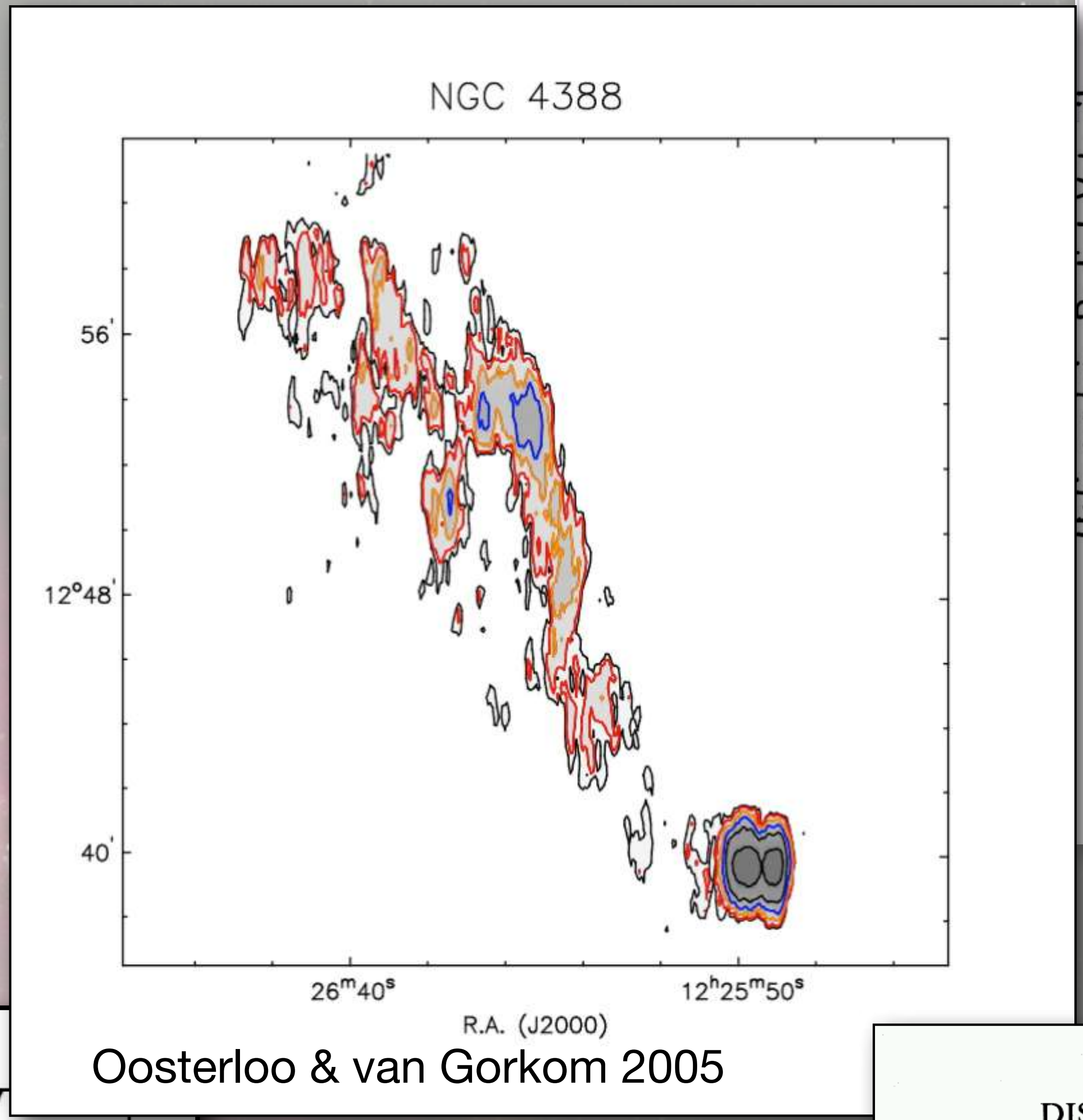
Important part of (radio) astronomy

- physics of the ISM, star formation, gas cycle in galaxies
- structure, kinematics and evolution of galaxies; dark matter
- scaling relations; TFR
- AGN feedback
- Environment
- Milky Way

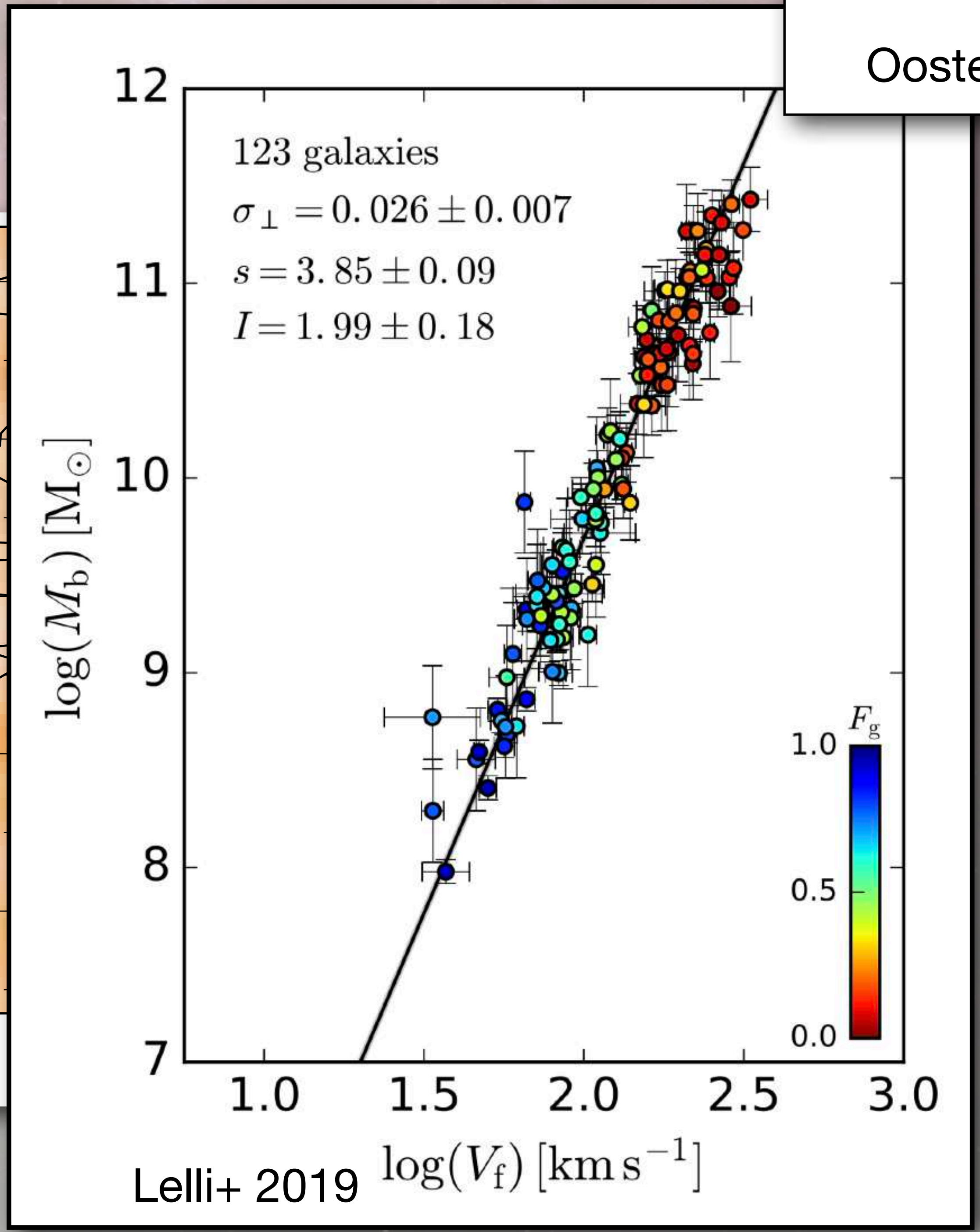
'New' telescopes will allow to make significant progress



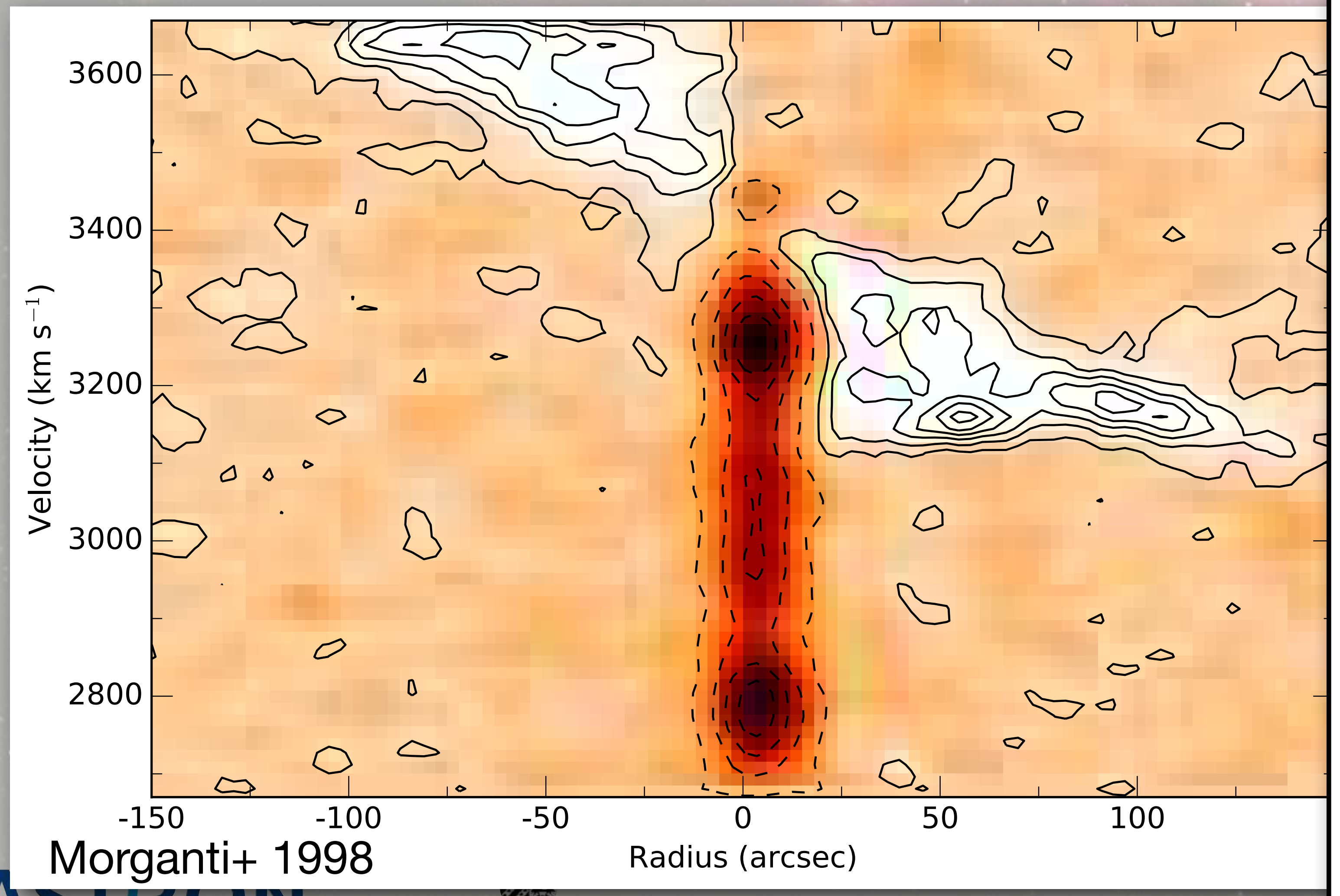
Kamphuis+ 1991



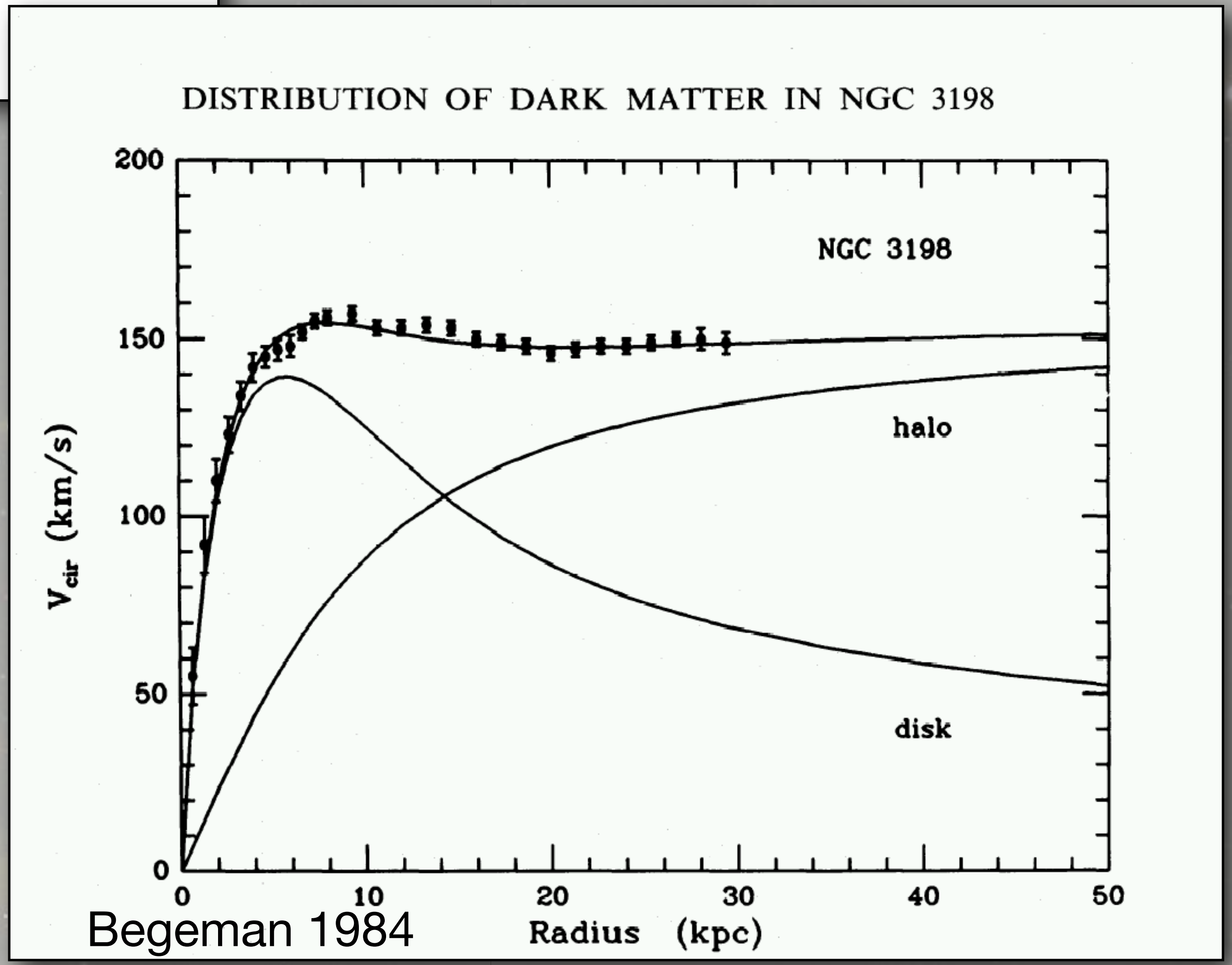
Oosterloo & van Gorkom 2005



Lelli+ 2019



Morganti+ 1998



Begeman 1984

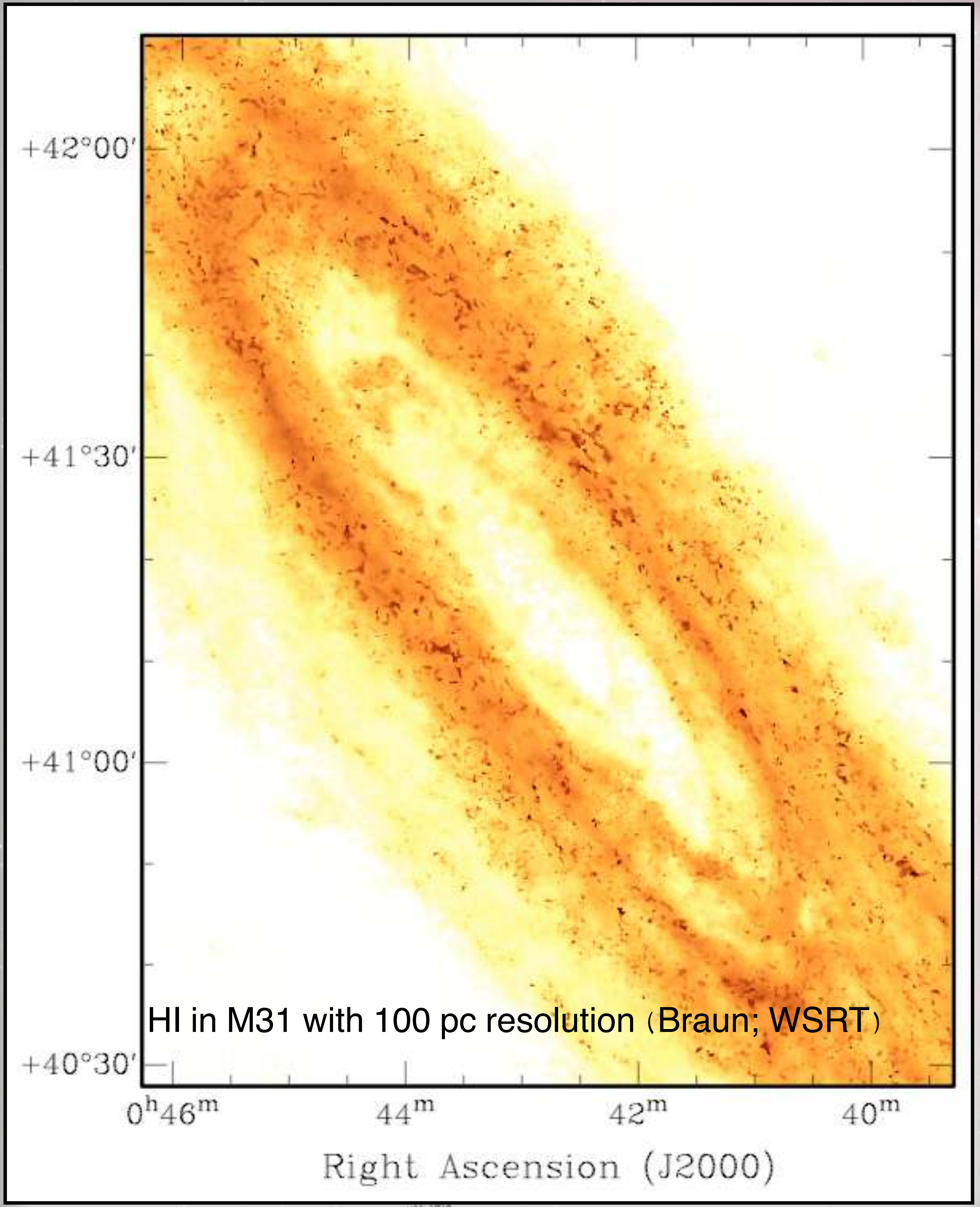
Nearby Universe

The HI surface brightness of the HI disk is the same in all galaxies
→ more collecting area means higher resolution —
Key for answering many questions

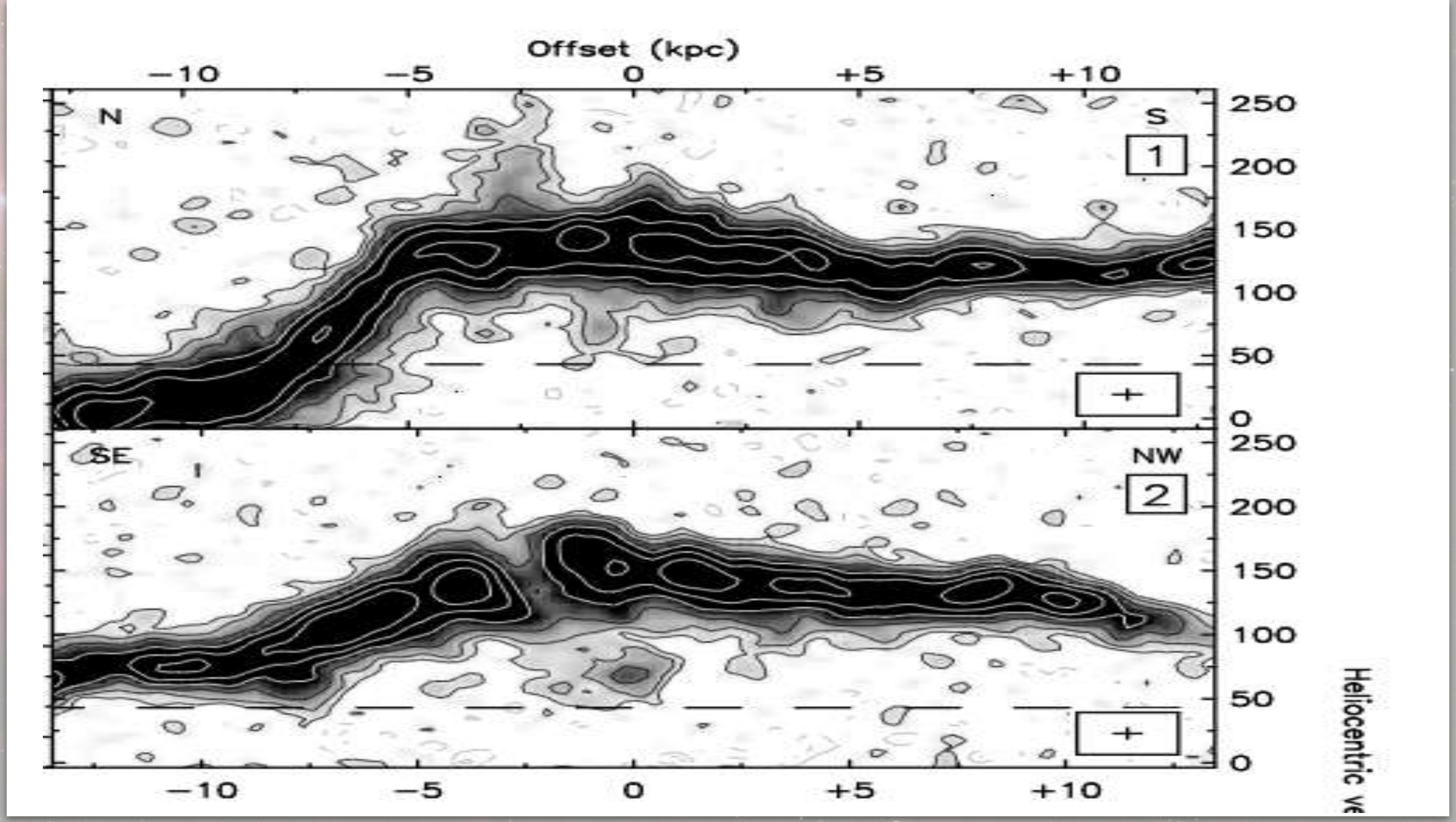
$$\sigma_{HI} \propto \theta^{-2}$$

High-spatial resolution studies of the ISM in a large number of galaxies on scales down to 100 pc
Role of H I in star formation processes; kinematics
Gas cycle in galaxies; Feedback
Significant improvement over current work (THINGS, MHONGOOSE,...)

Combine with tracers from other wavebands (like PHANGS; ALMA, MUSE, JWST,..)



HI in M31 with 100 pc resolution (Braun; WSRT)



Stellar feedback effects on H I disk & halo

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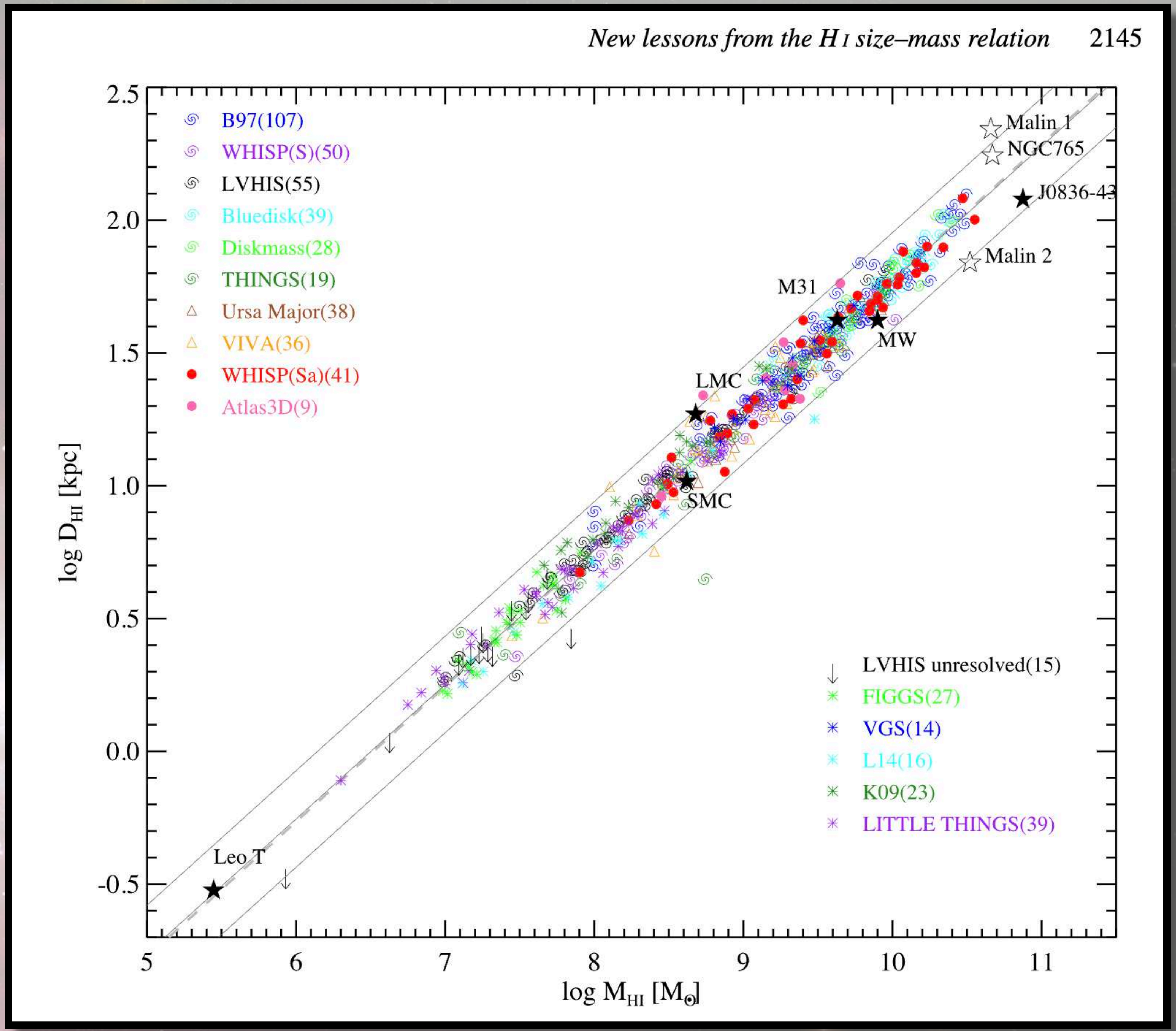
HI diameter of a galaxy correlates well with total HI mass

and has slope 2 $M_{\rm HI} \propto D_{\rm HI}^2$

→ $\langle N_{\rm HI} \rangle$ the same for every galaxy



Wang+ 2016

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Nearby Universe

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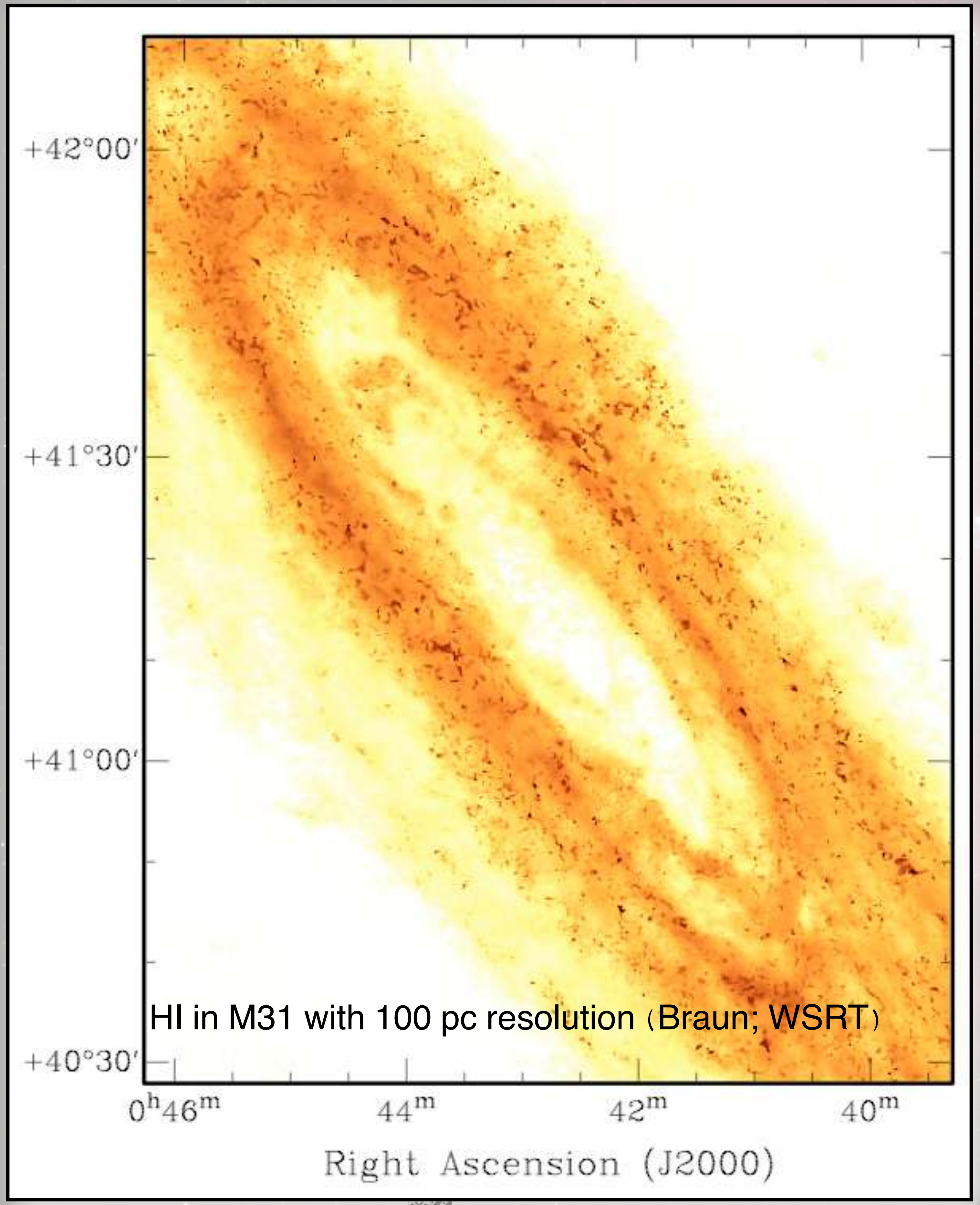
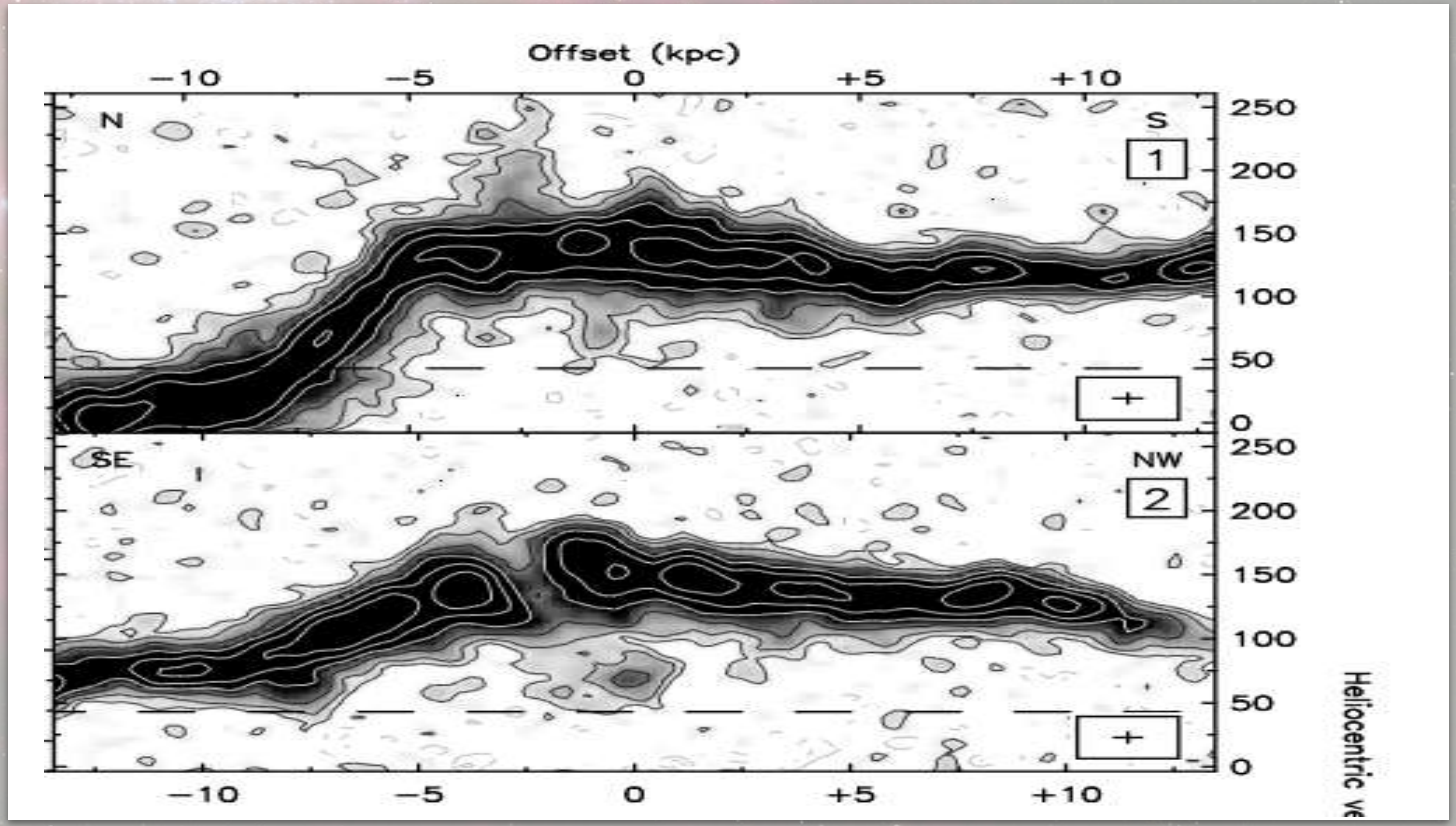
Role of H I in star formation processes; kinematics
Gas cycle in galaxies; Feedback
Significant improvement over current work (THINGS, MHONGOOSE,...)

Combine with tracers from other wavebands (like PHANGS; ALMA, MUSE, JWST,..)



HI in M31 with 100 pc resolution (Braun; WSRT)



Stellar feedback effects on H I disk & halo

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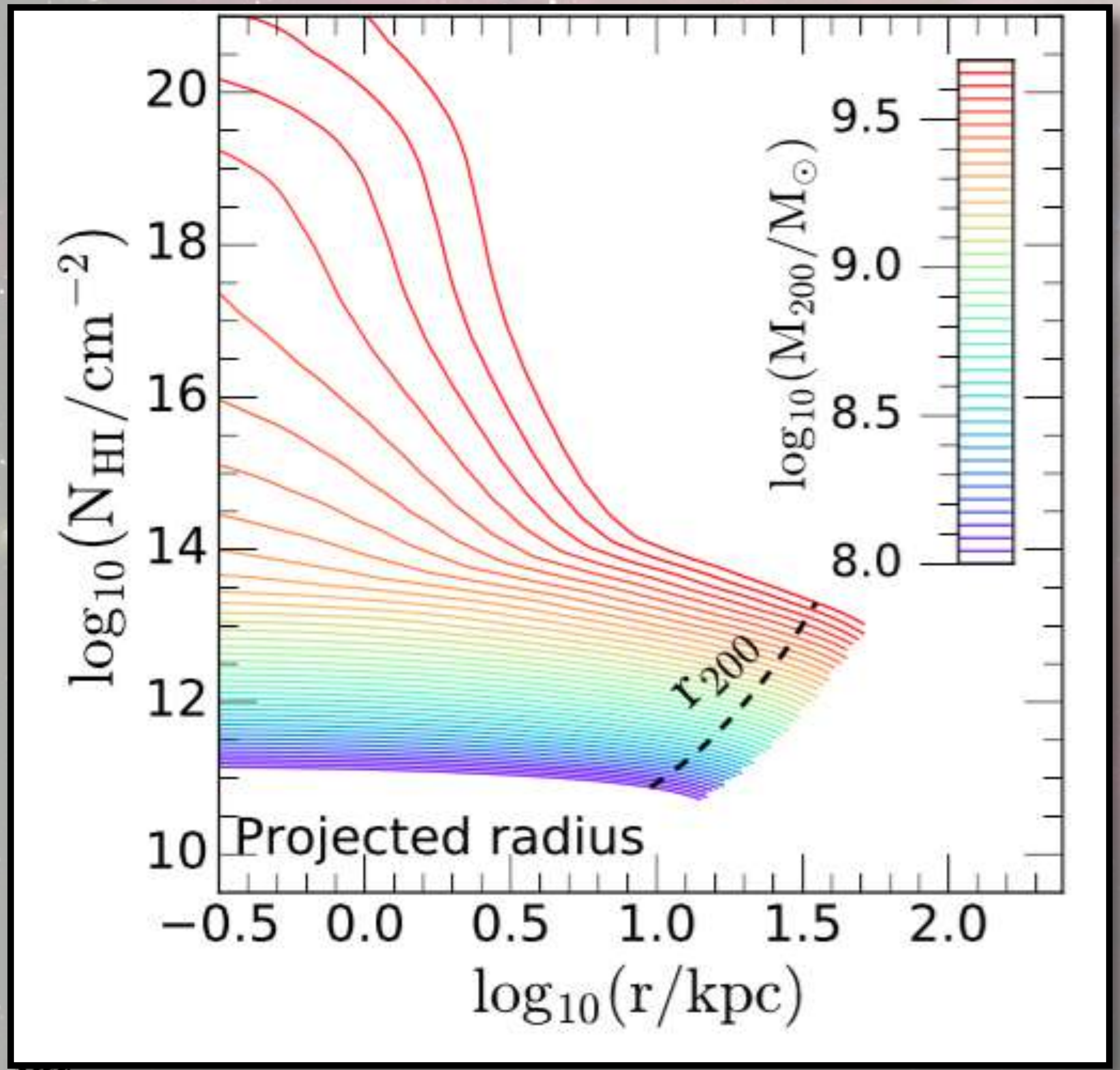
Nearby Universe

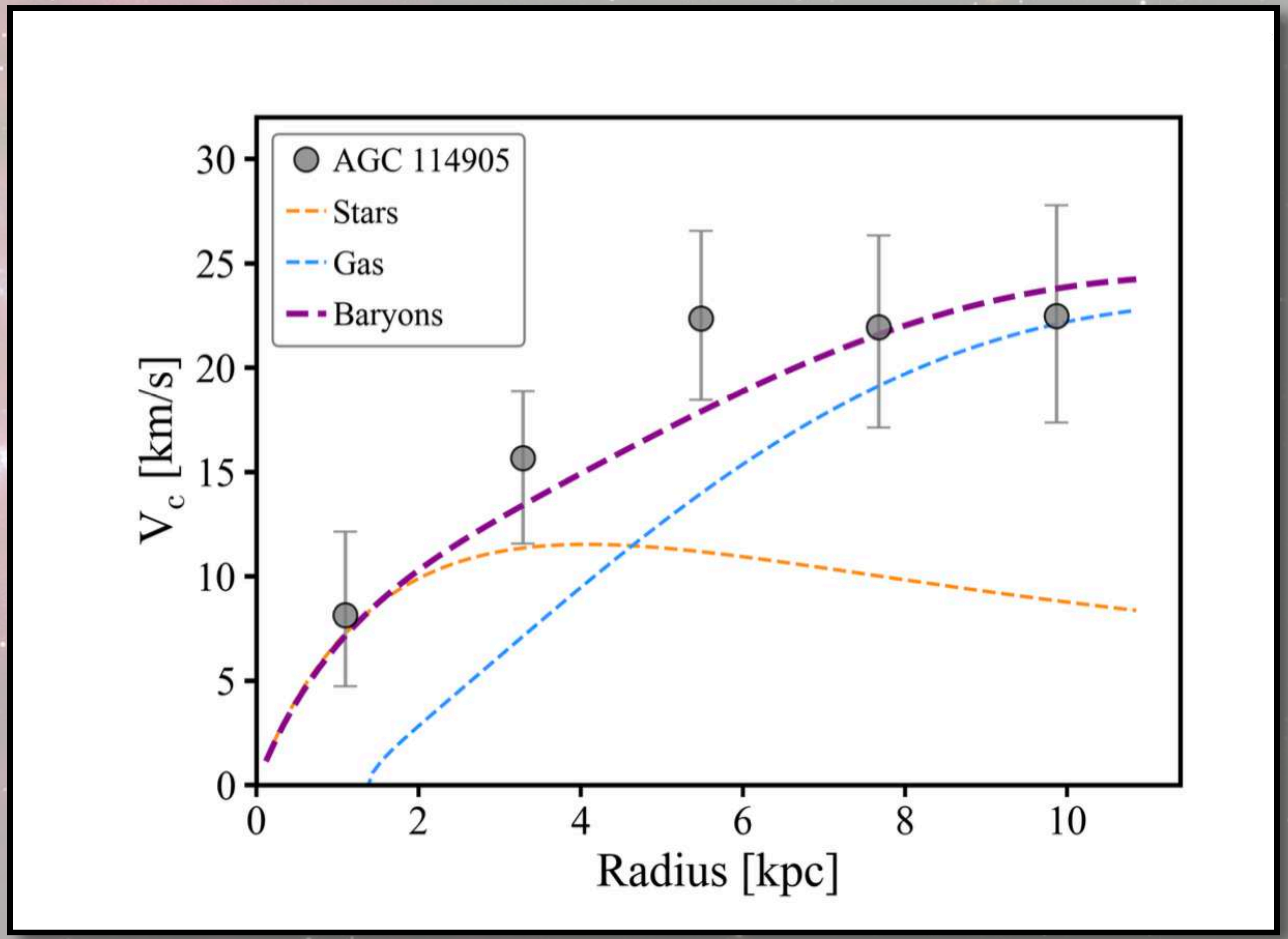
Higher spatial resolution is also needed for kinematics

Studies on dark matter are still interesting for small and faint galaxies

Do dark-matter-free galaxies exist?
- places strong constraints on galaxy formation models
- candidates are ‘distant’, so high resolution needed (< 5 arcsec)

The smallest H I galaxies; require good column density sensitivity
- how small is the smallest H I galaxy?
  - depends on details of galaxy formation & evolution
- may have steep DM profiles, depending on the nature of dark matter





Mancera Piña+ 2020

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[redacted]z-Llambay+ 2017

Nearby Universe

Galaxy - IGM interface
where does the gas come form?

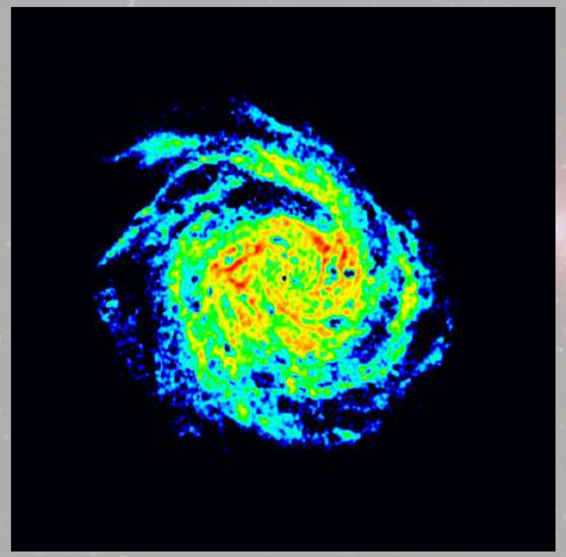
Simulations predict galaxies should be surrounded by low column density gas;
Needed to maintain gas reservoirs and star formation.
To detect this, you need the right sensitivity *at the right resolution*

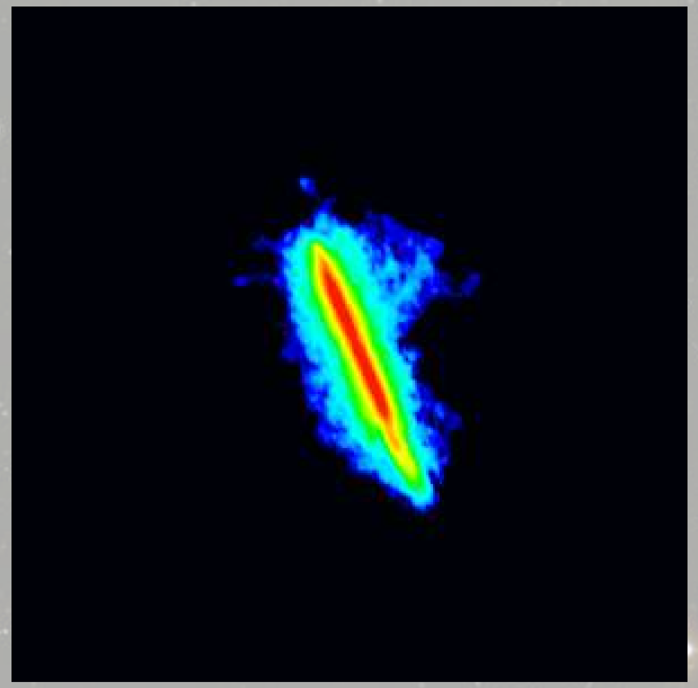
Current state:

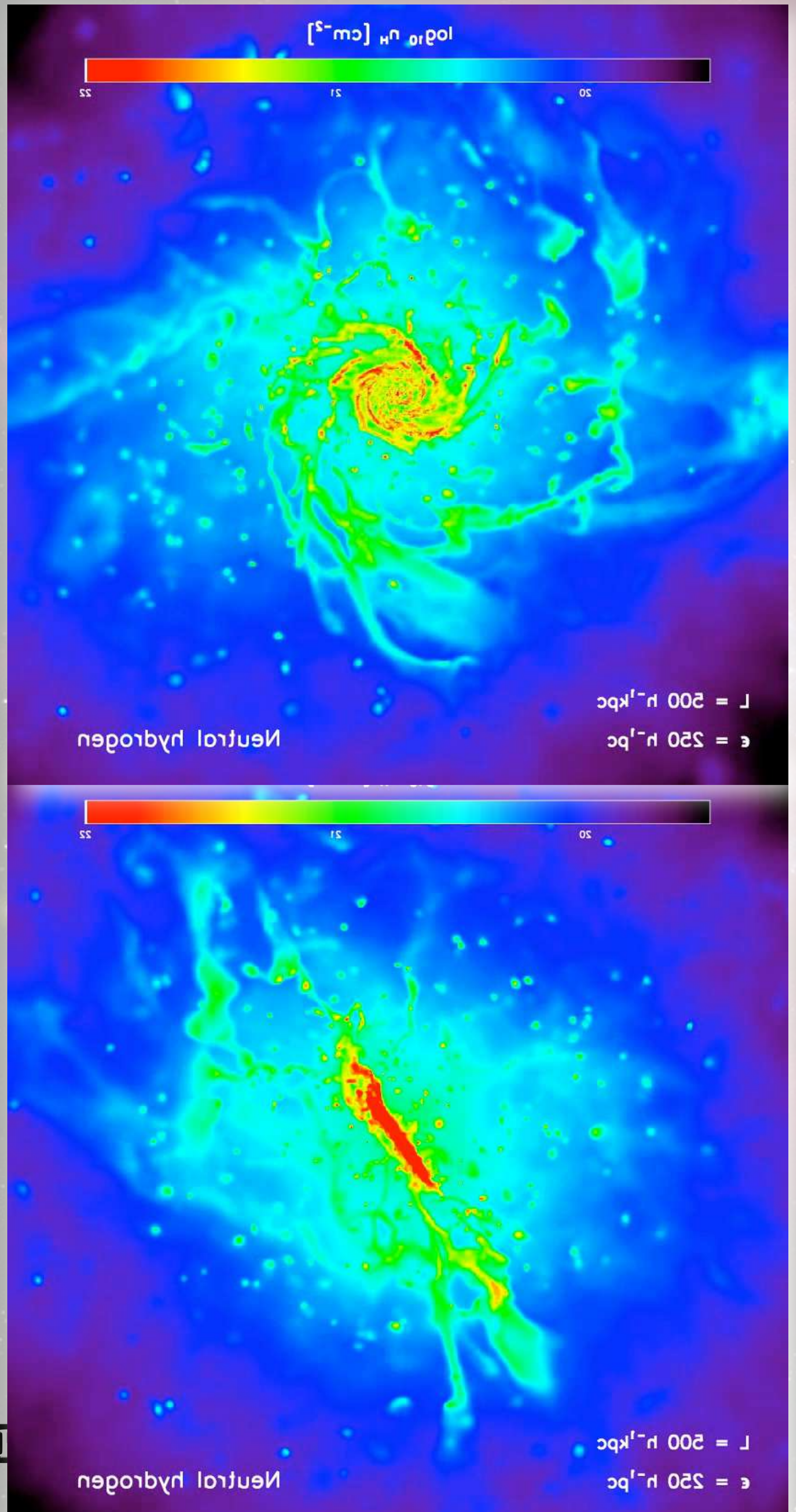
MHONGOOSE: ~5×10^{17} – 10^{18} cm^{-2} at resolution of a few kpc (MeerKAT)

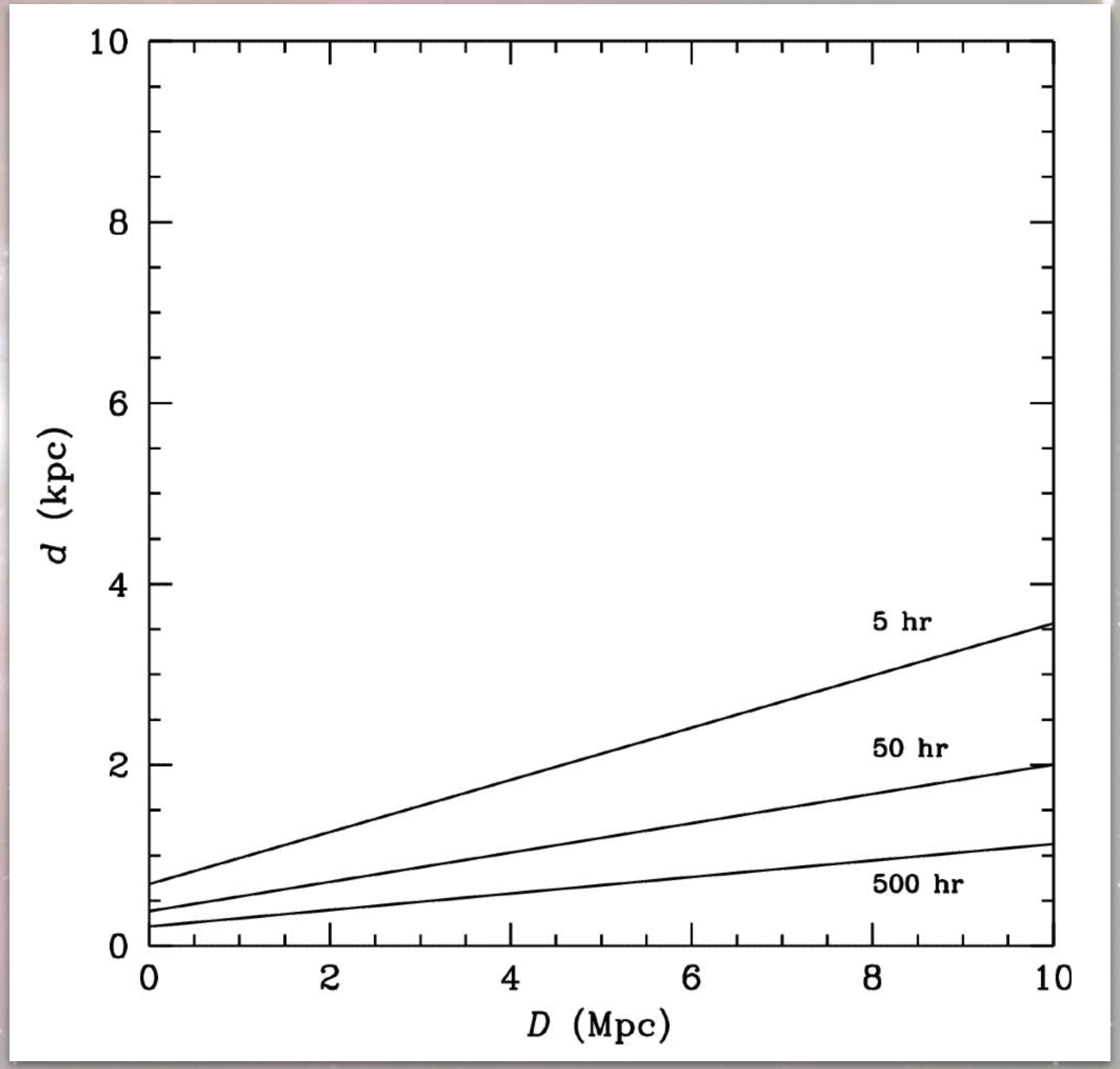
not seeing very much of the extended, low density HI!!!

It looks like we have to go deeper or to higher resolution (or both)

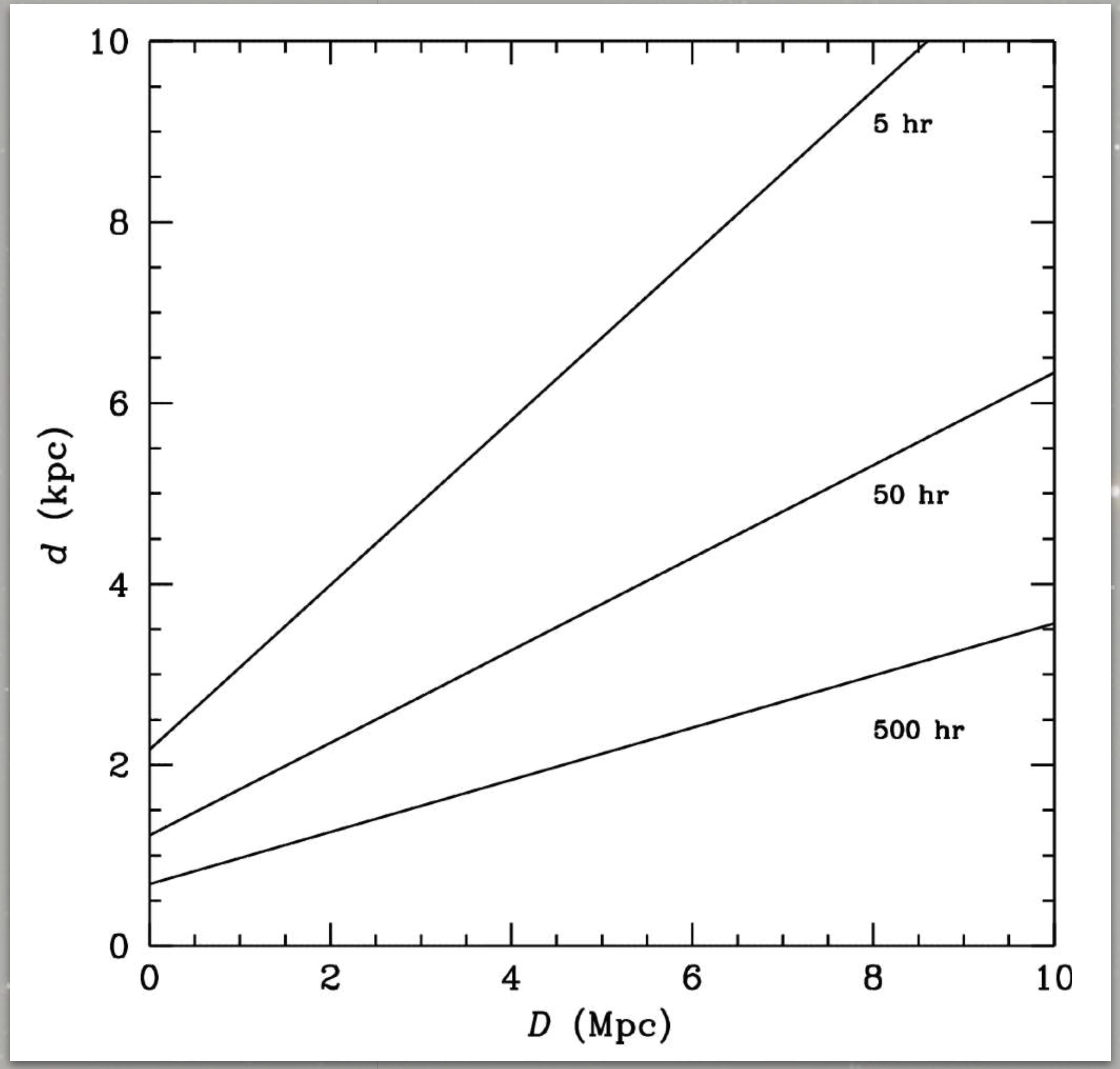








Physical resolution for detecting 10^{18} cm^{-2}



Physical resolution for detecting 10^{17} cm^{-2}

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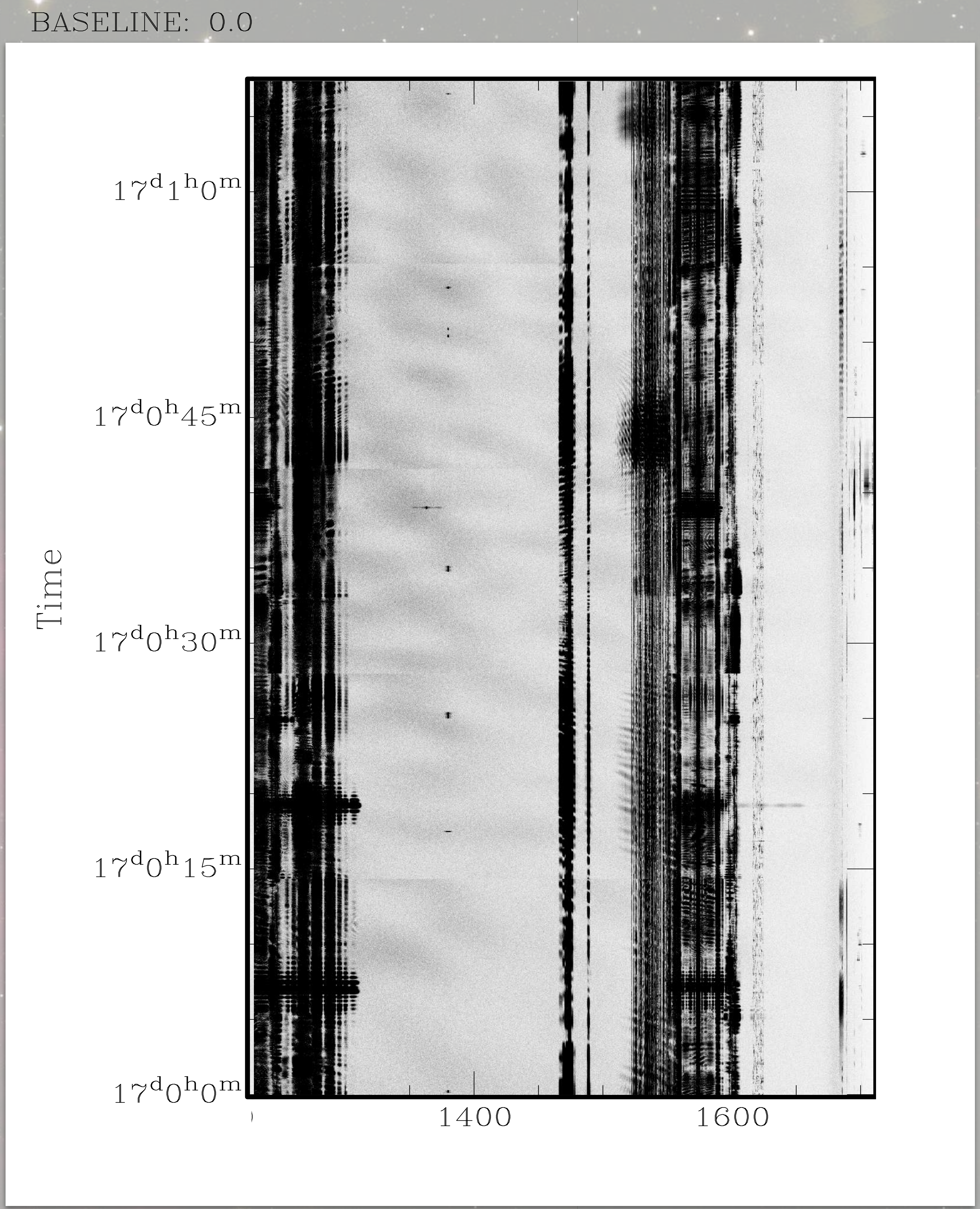
Nearby Universe

No impact of RFI for galaxies D < 60 Mpc (z = 0.015)

because the 1400 – 1427 MHz band is protected by international law

Observing band is relatively clean down to ~1310 MHz (z ~ 0.09)
if you are at the right location



Waterfall plot MeerKAT

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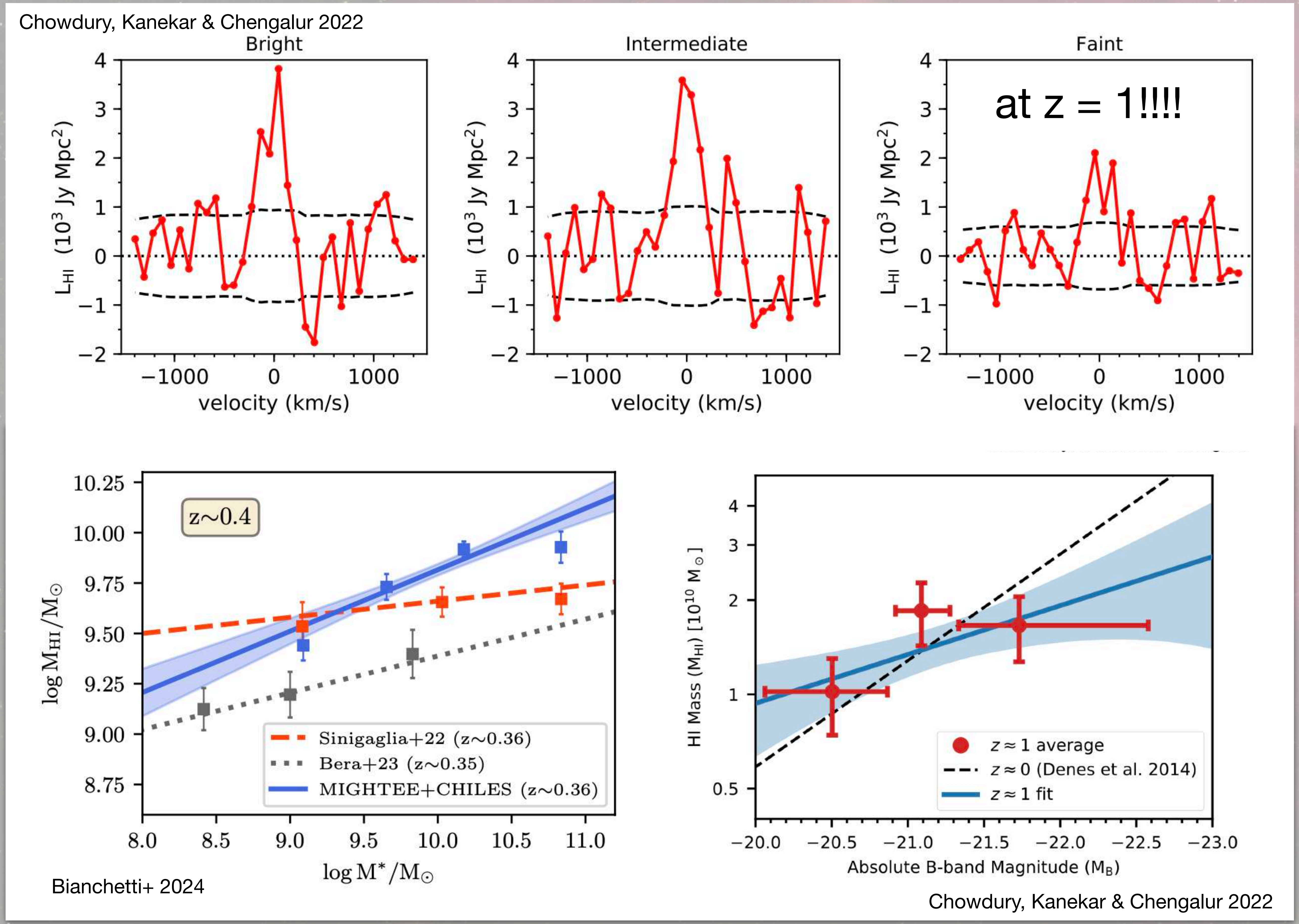
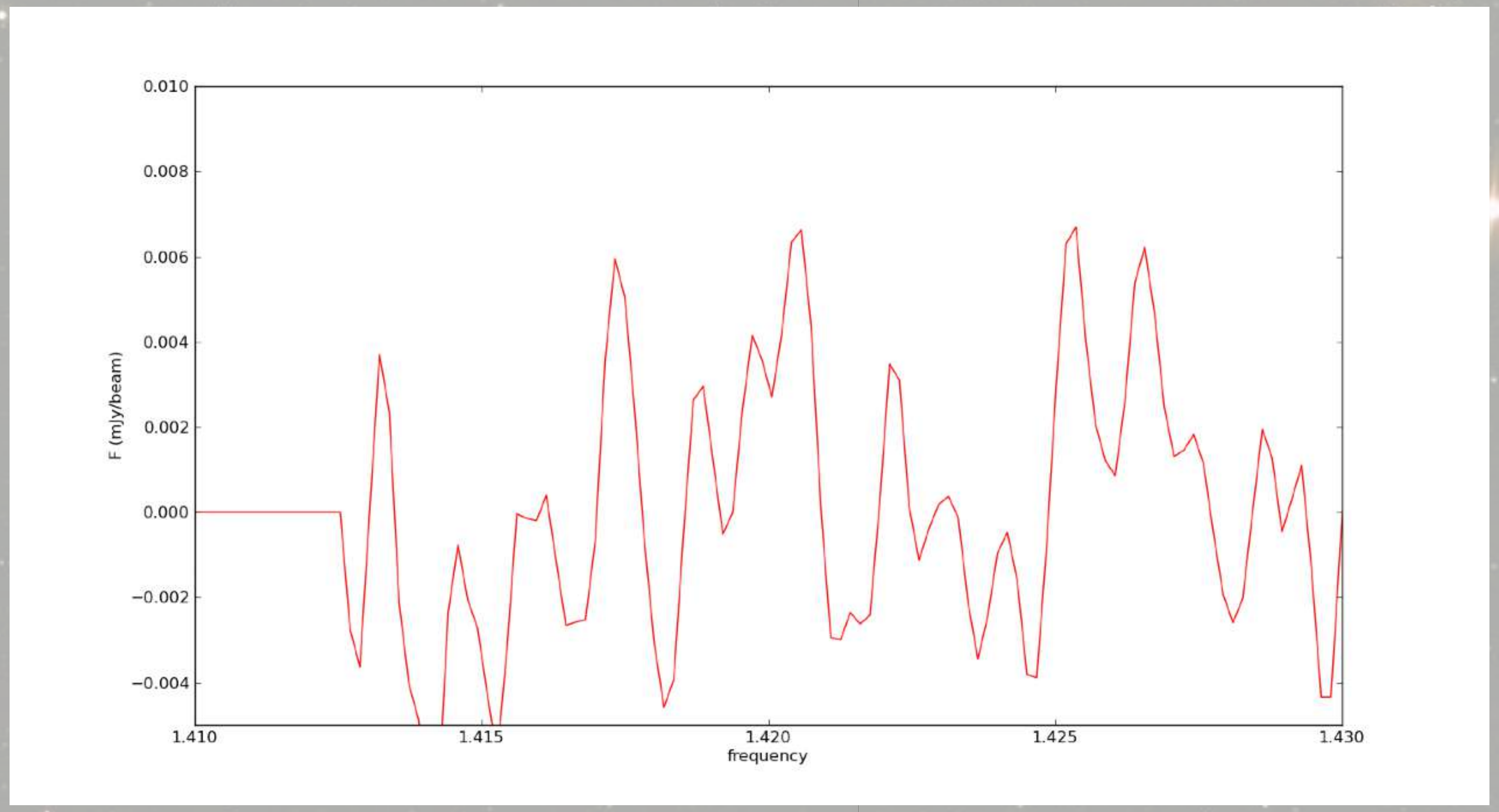
Distant Universe ($z > 0.25$, $t > 3$ Gyr)

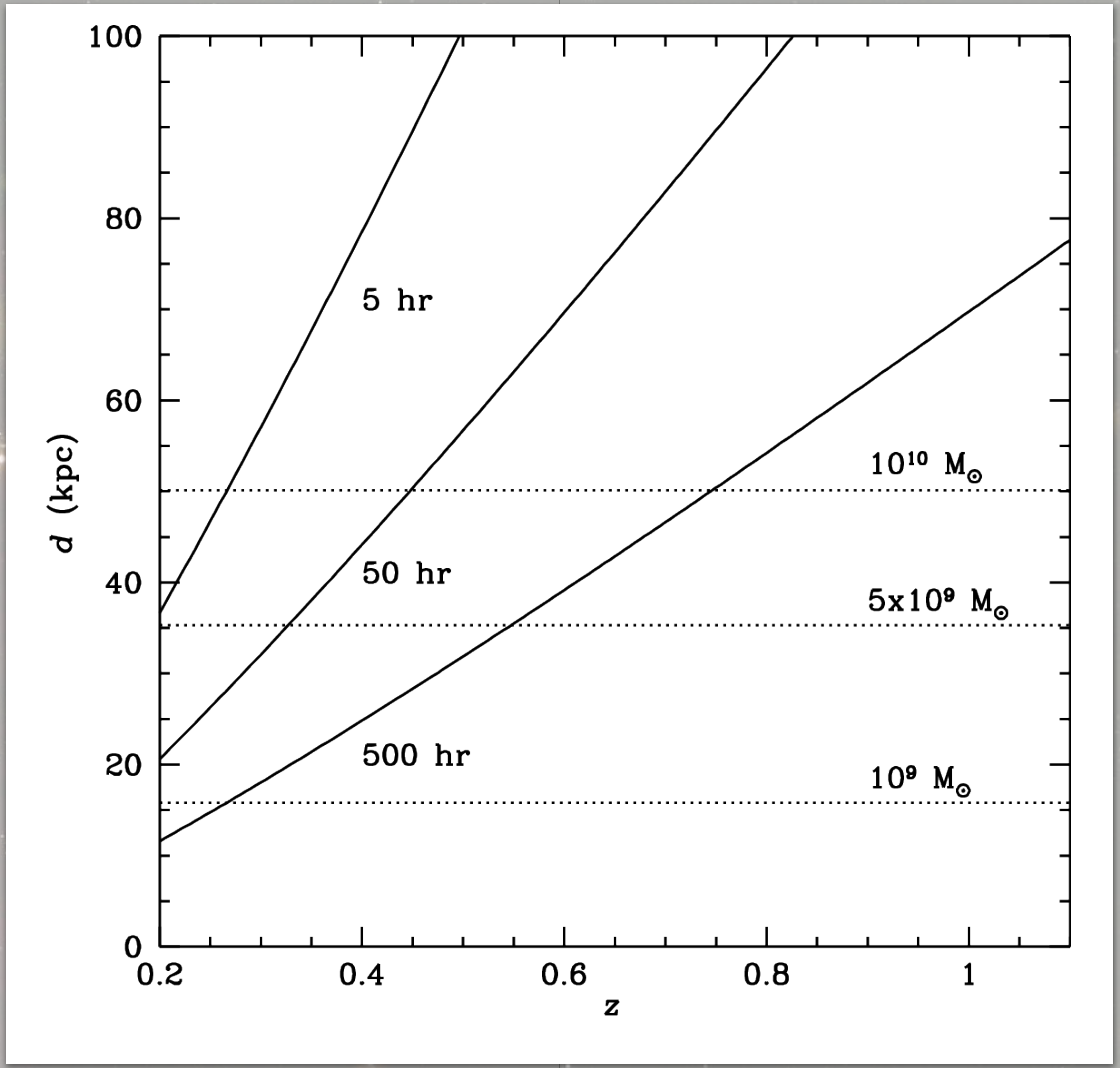
requires (very) deep integrations for resolving/detecting galaxies
much of the science is about the evolution of H I properties and scaling relations of global properties
(many detections will be unresolved)

stacking





Physical resolution for detecting 10^{20} cm^{-2}

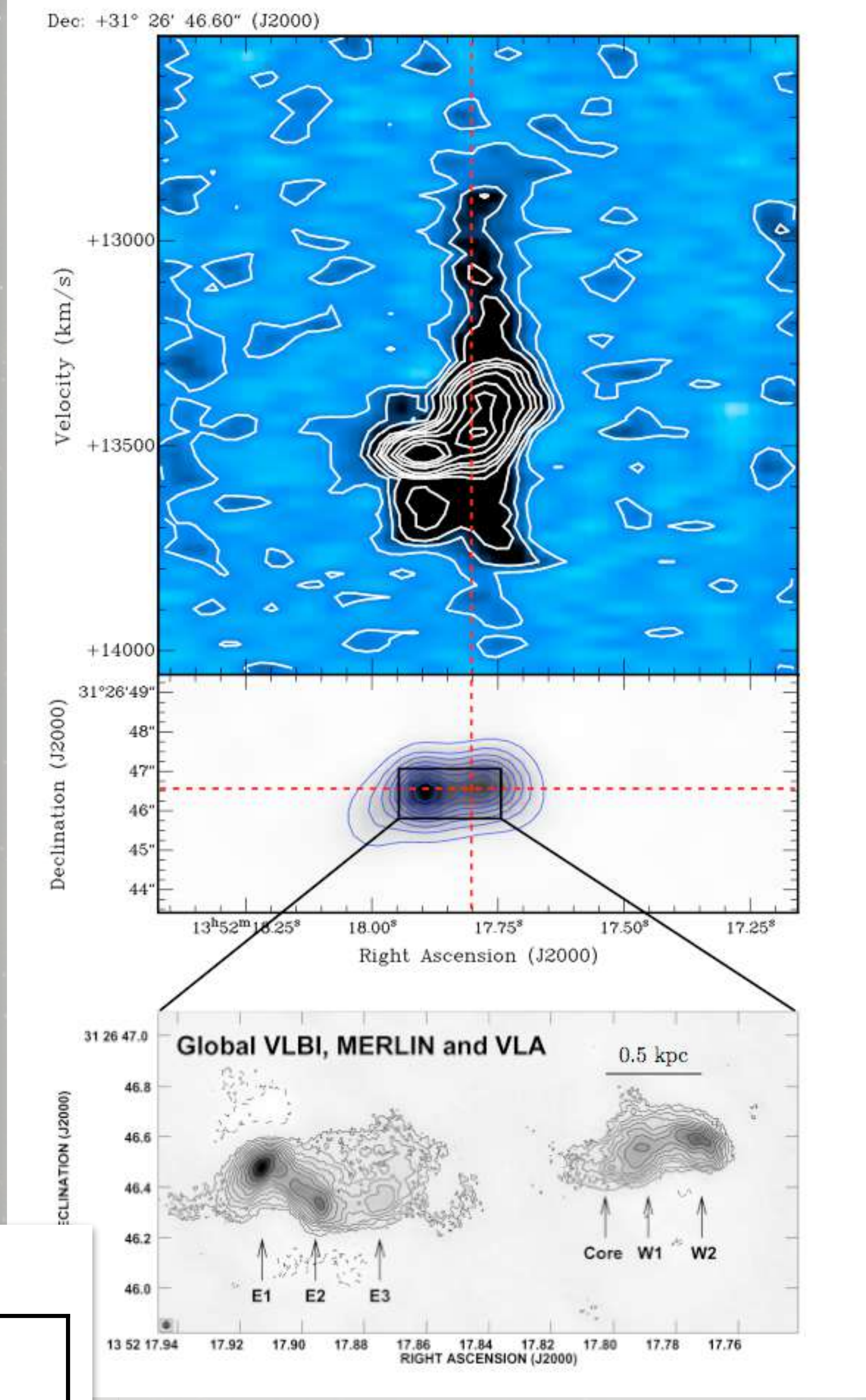


Distant Universe ($z > 0.25$, $t > 3$ Gyr)

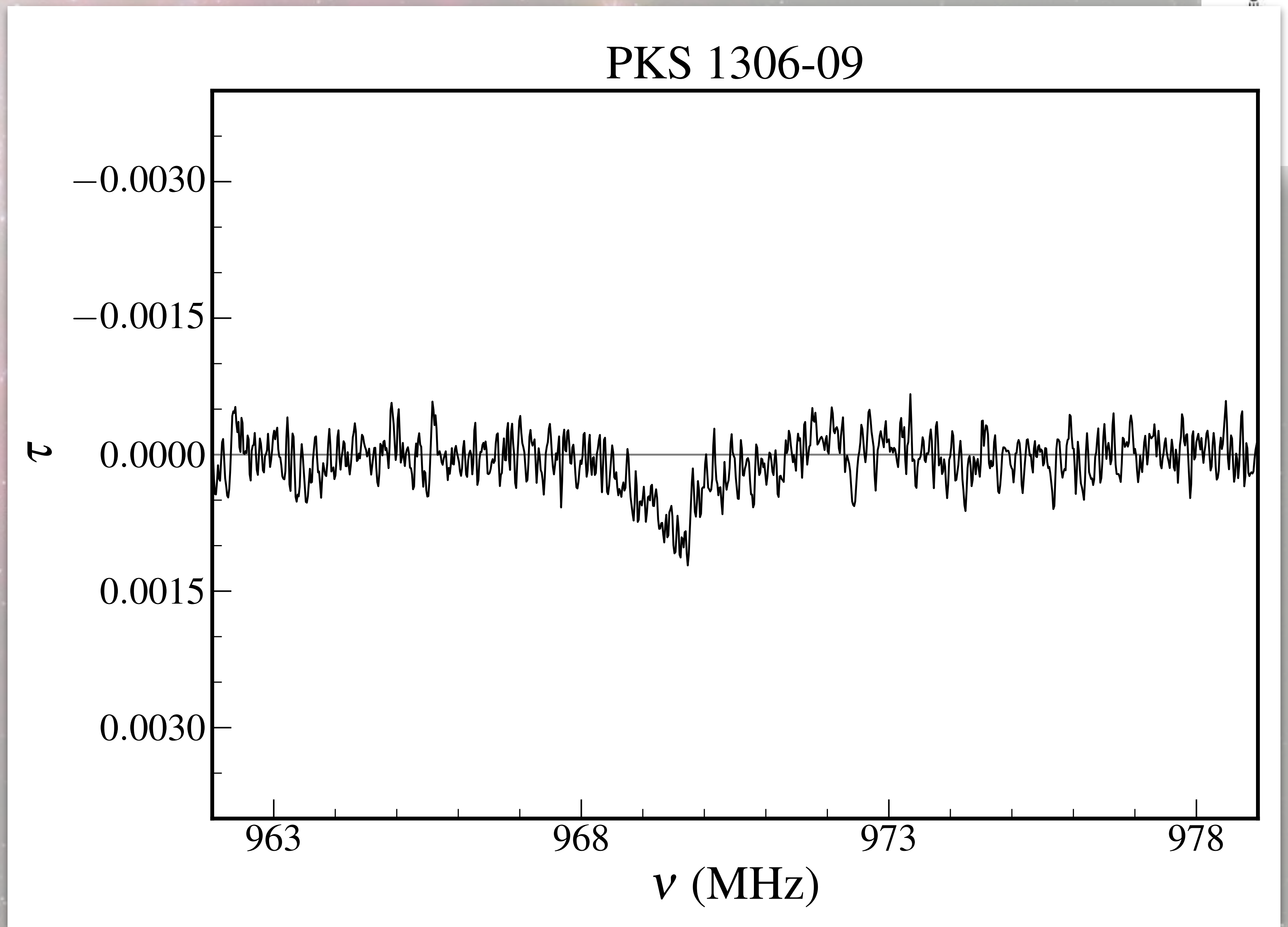
Unique view of the cold circum-nuclear environment of AGN.
Important for understanding AGN physics and AGN feedback.
Out to very high redshift and with very high resolution (VLBI)

Current state:
- z < 0.25 : 30% detection rate!! ($S > 30$ mJy)
- Situation for z > 0.25 unclear. Indications that detection rate drops
  - but could be due to selection effects (distant sources are more powerful)

Progress possible by:
- go deeper
- higher spatial resolution
  - locate where the outflow is occurring
  - much larger volume over which sources are resolved
- explore z > 0.25
  - ASKAP & MeerKat are limited by spatial resolution, SKA will be better



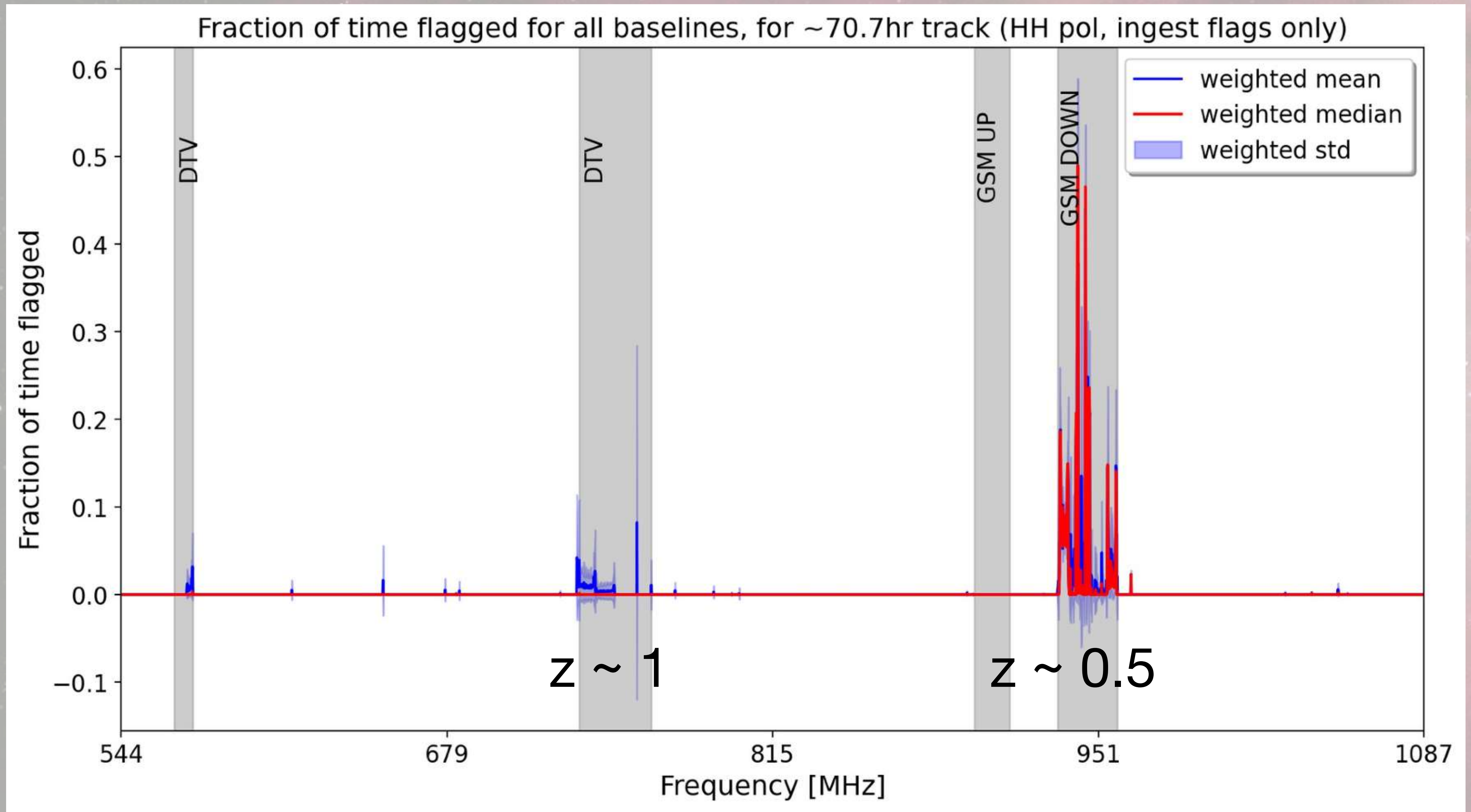
Mahony+ 2014



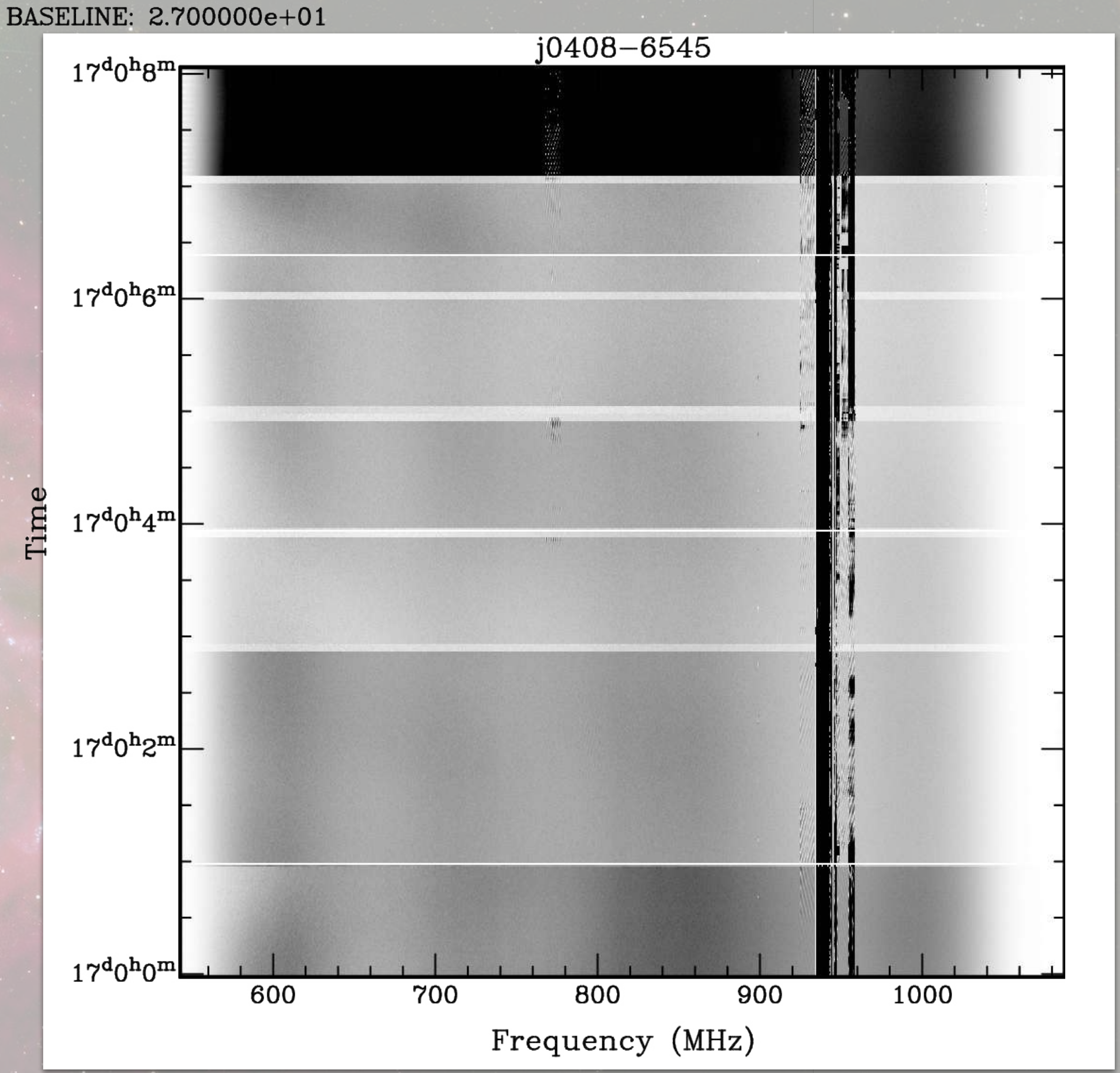
Faint detection at z = 0.46
(MeerKAT; Morganti+ 2024)

Distant Universe ($z > 0.25$, $t > 3$ Gyr)

Band is relatively clean



MeerKAT flagging statistics UHF band



Waterfall plot of recent MeerKat observation

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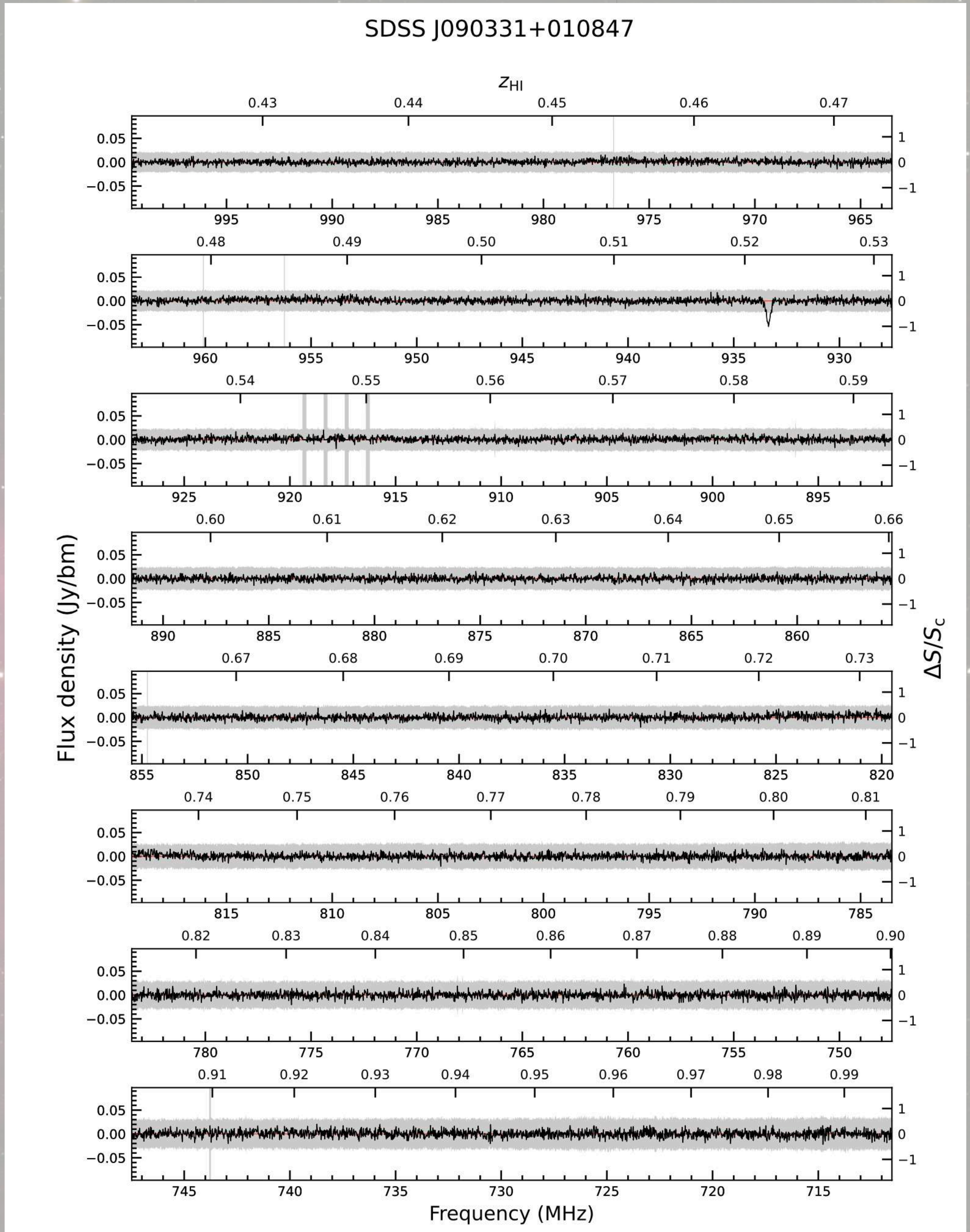
Distant Universe ($z > 0.25$, $t > 3$ Gyr)

At ASKAP very little RFI between 700 - 1000 MHz



FLASH spectrum
Su+ 2022

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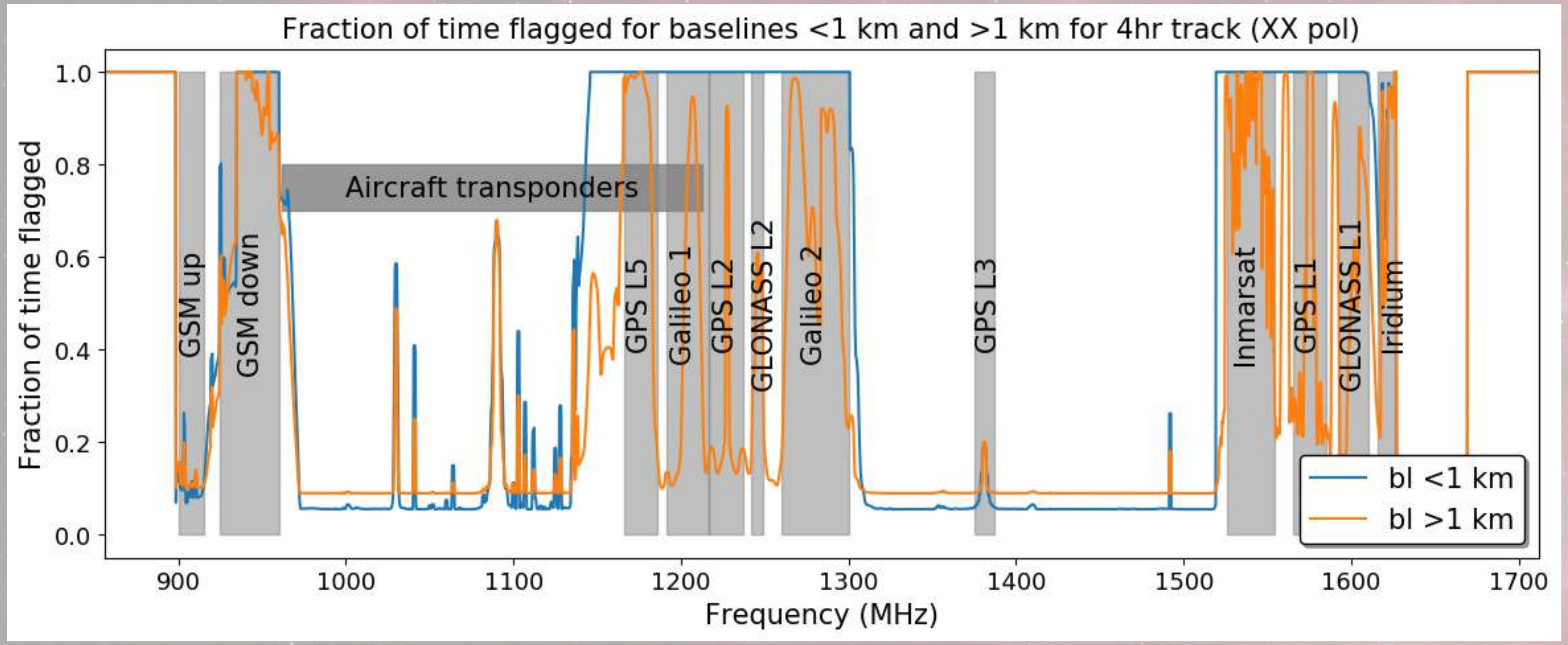
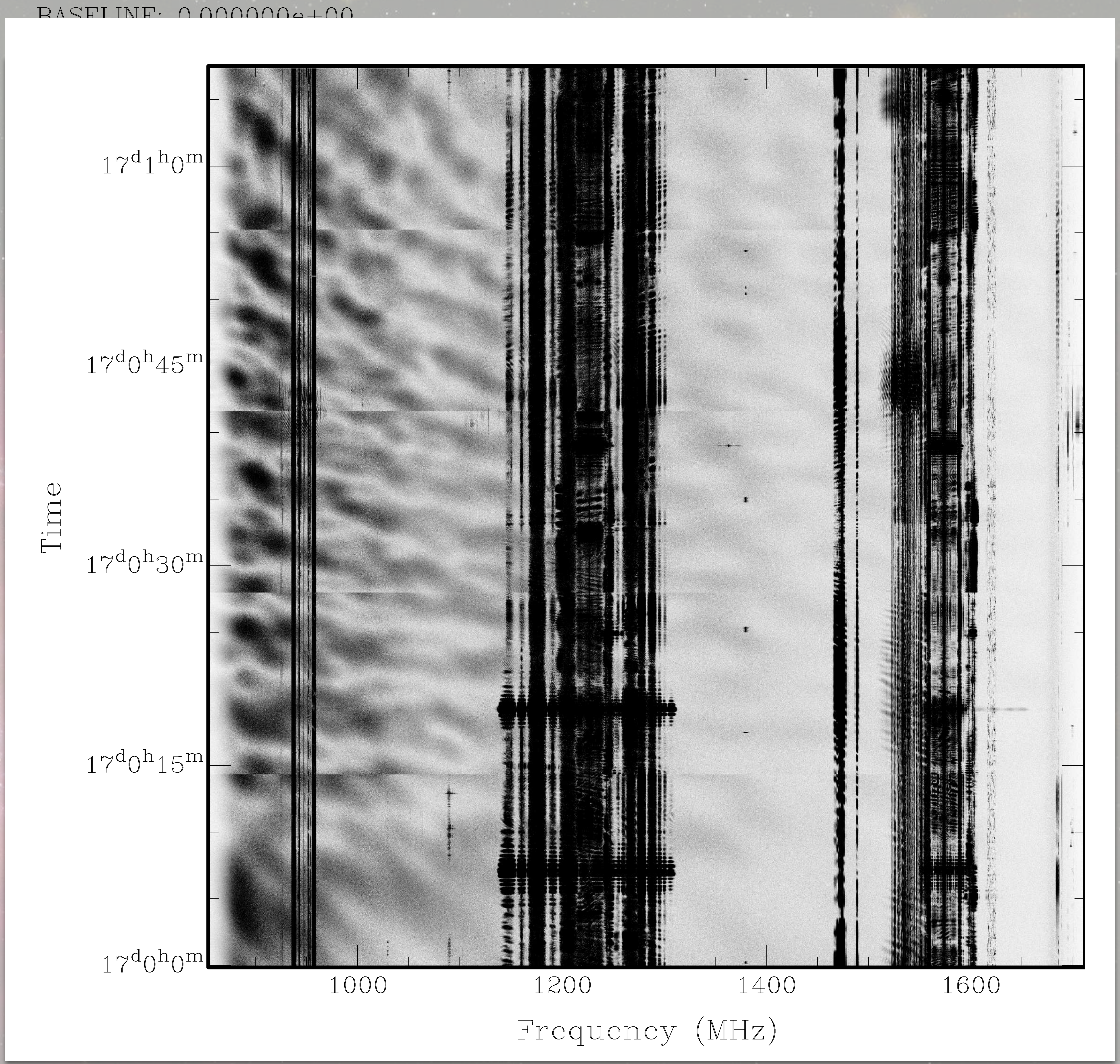
Intermediate redshift (0.1 < z < 0.25)

RFI is a major problem

Kills much of the the science



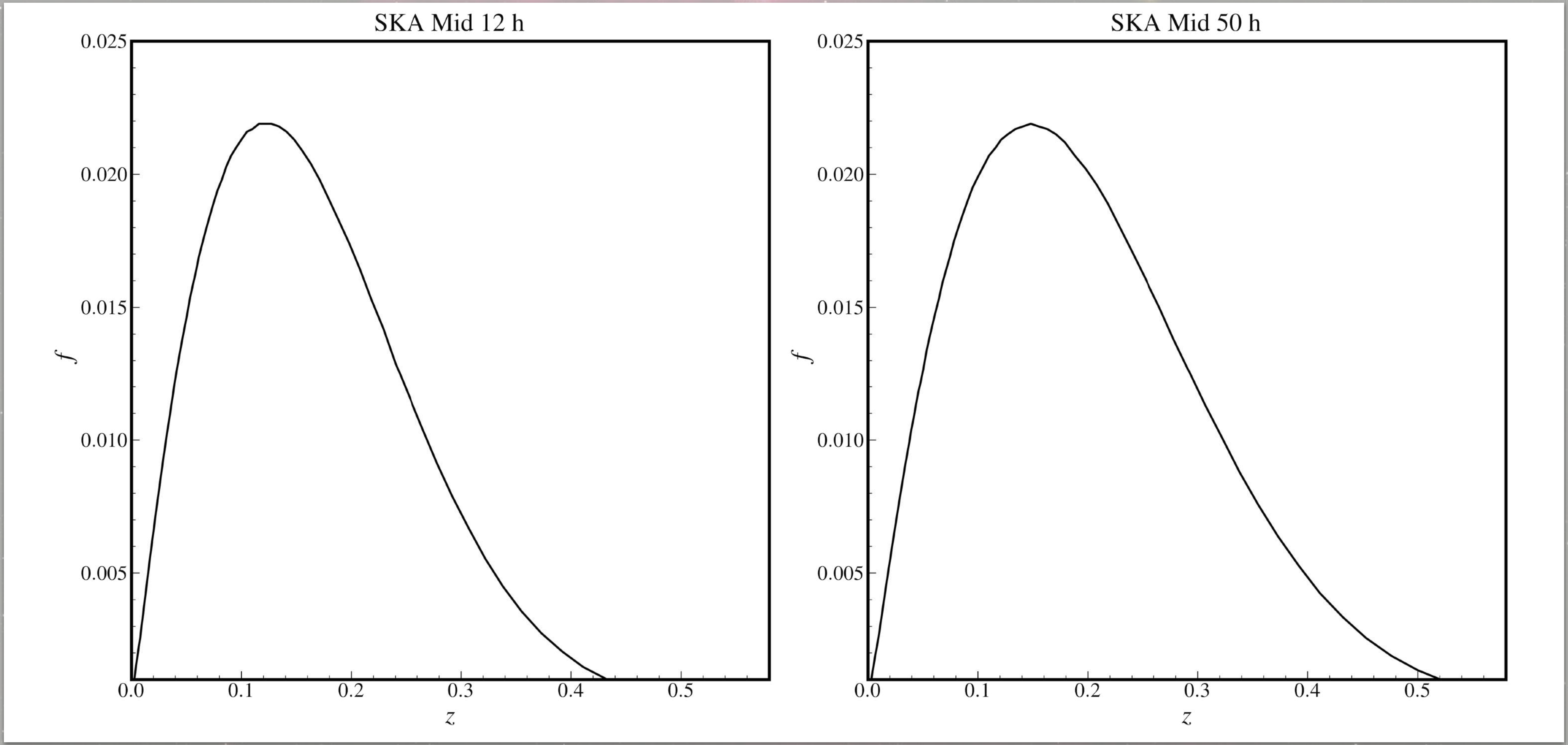
MeerKAT flagging statistics L band



Waterfall plot MeerKAT L band

Intermediate redshift (0.1 < z < 0.25)

Every radio telescope has a natural redshift range for H I emission studies:
the redshift range of detections for a 'normal' observation (i.e. up to 50 hr)



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redshift distribution of HI detections

Intermediate redshift (0.1 < z < 0.25)

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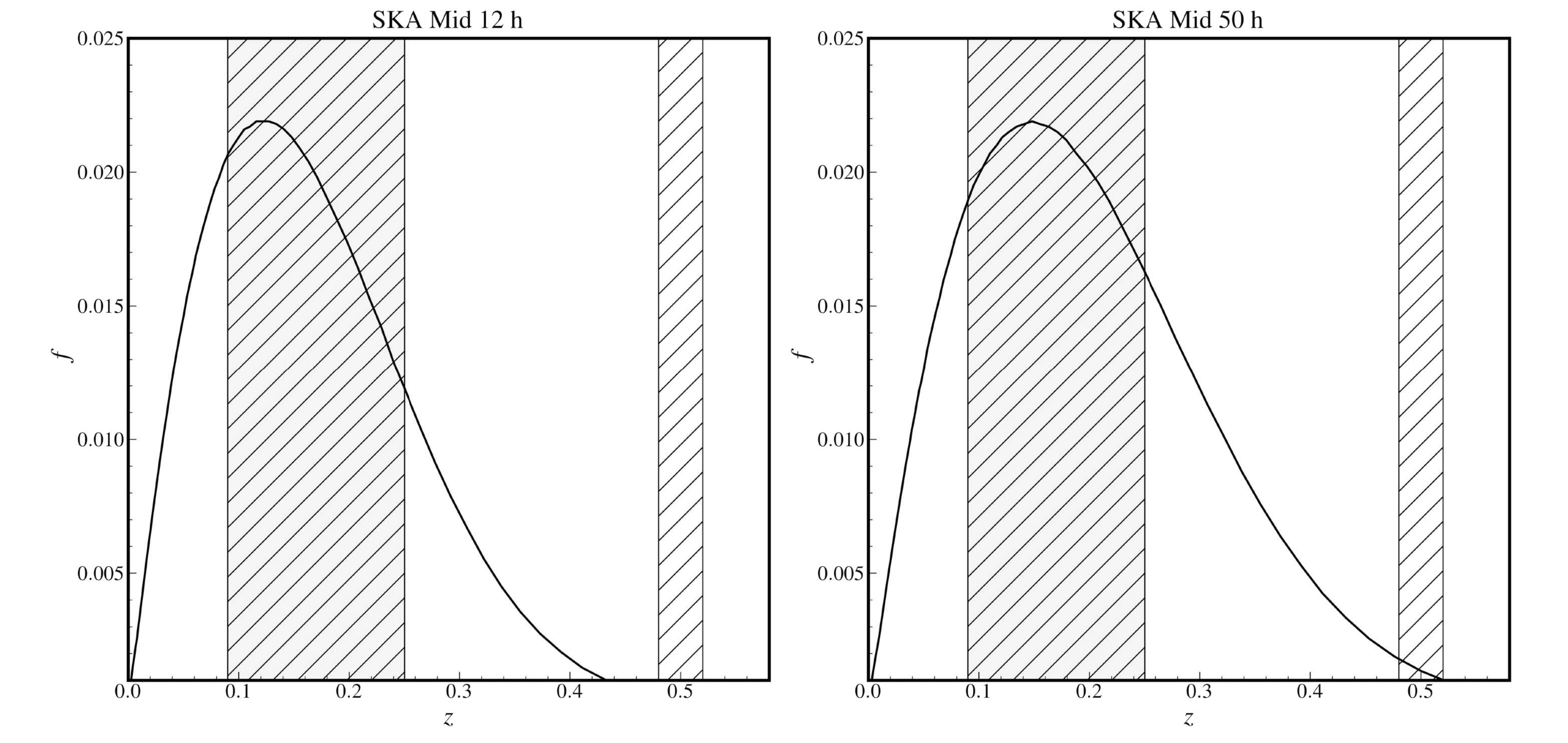
GNSS RFI exactly covers the peak of the redshift distribution of potential H I detections



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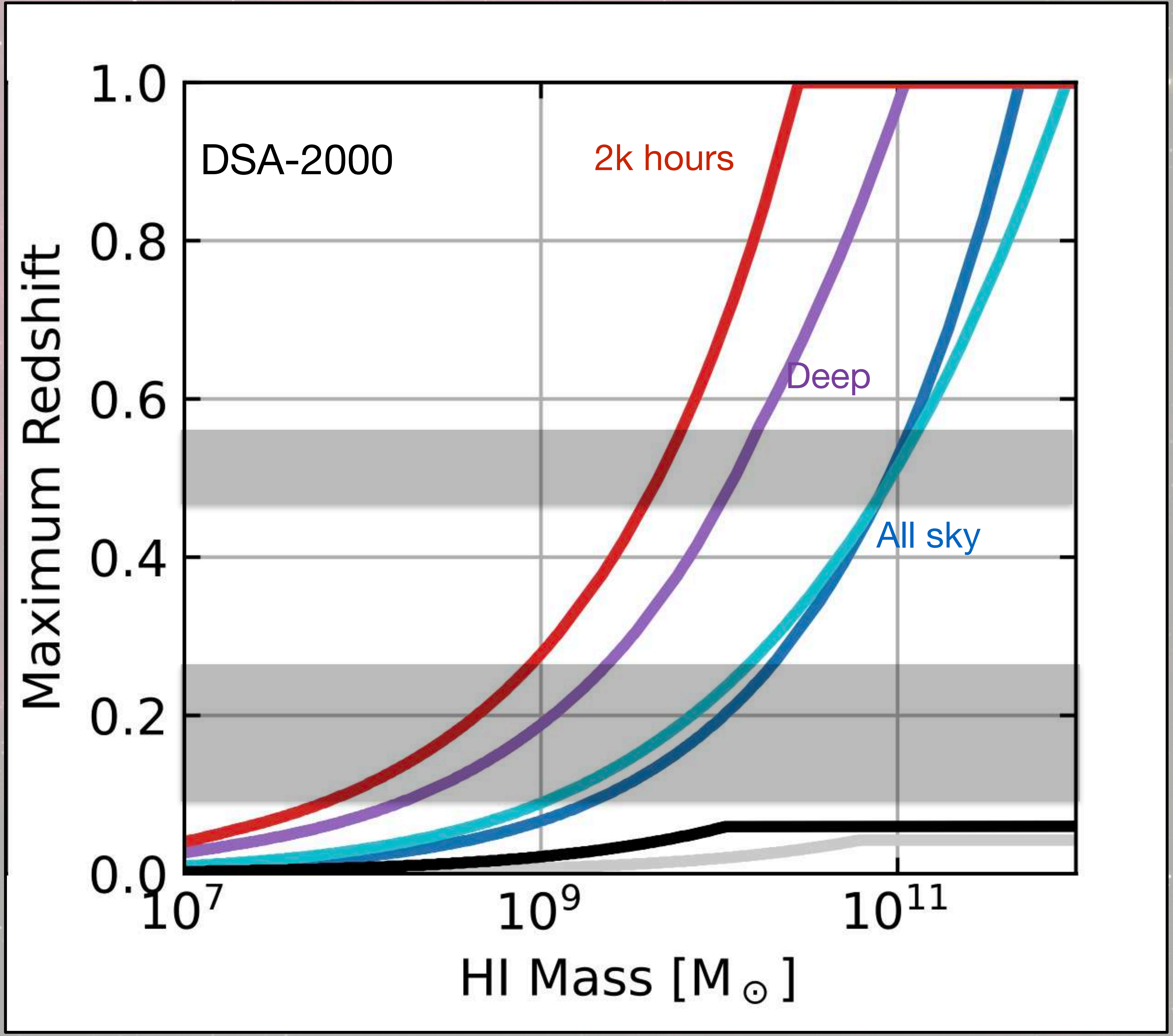

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