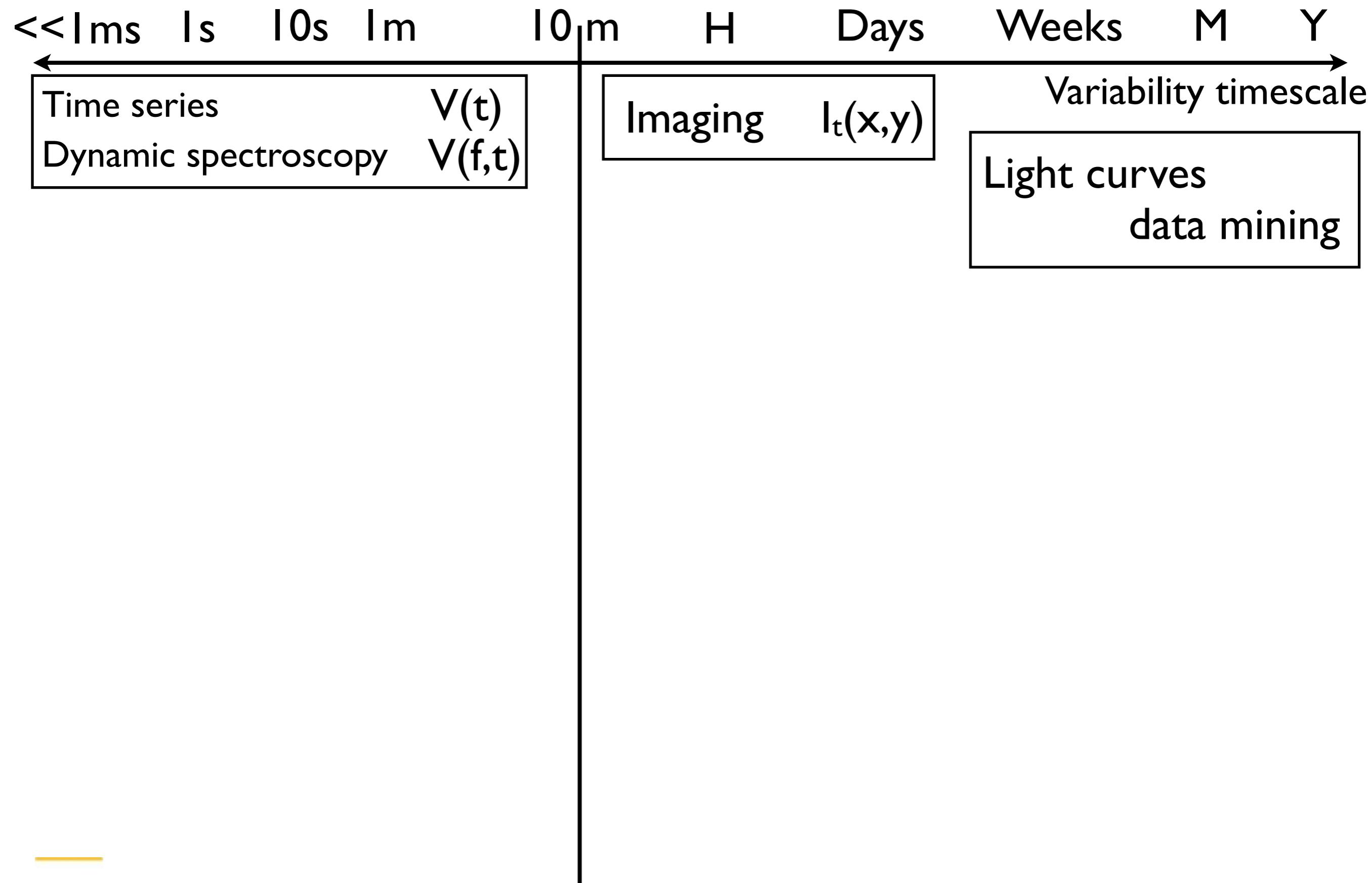

Détection et observation de sources transitoires en radioastronomie basses fréquences

Julien Girard

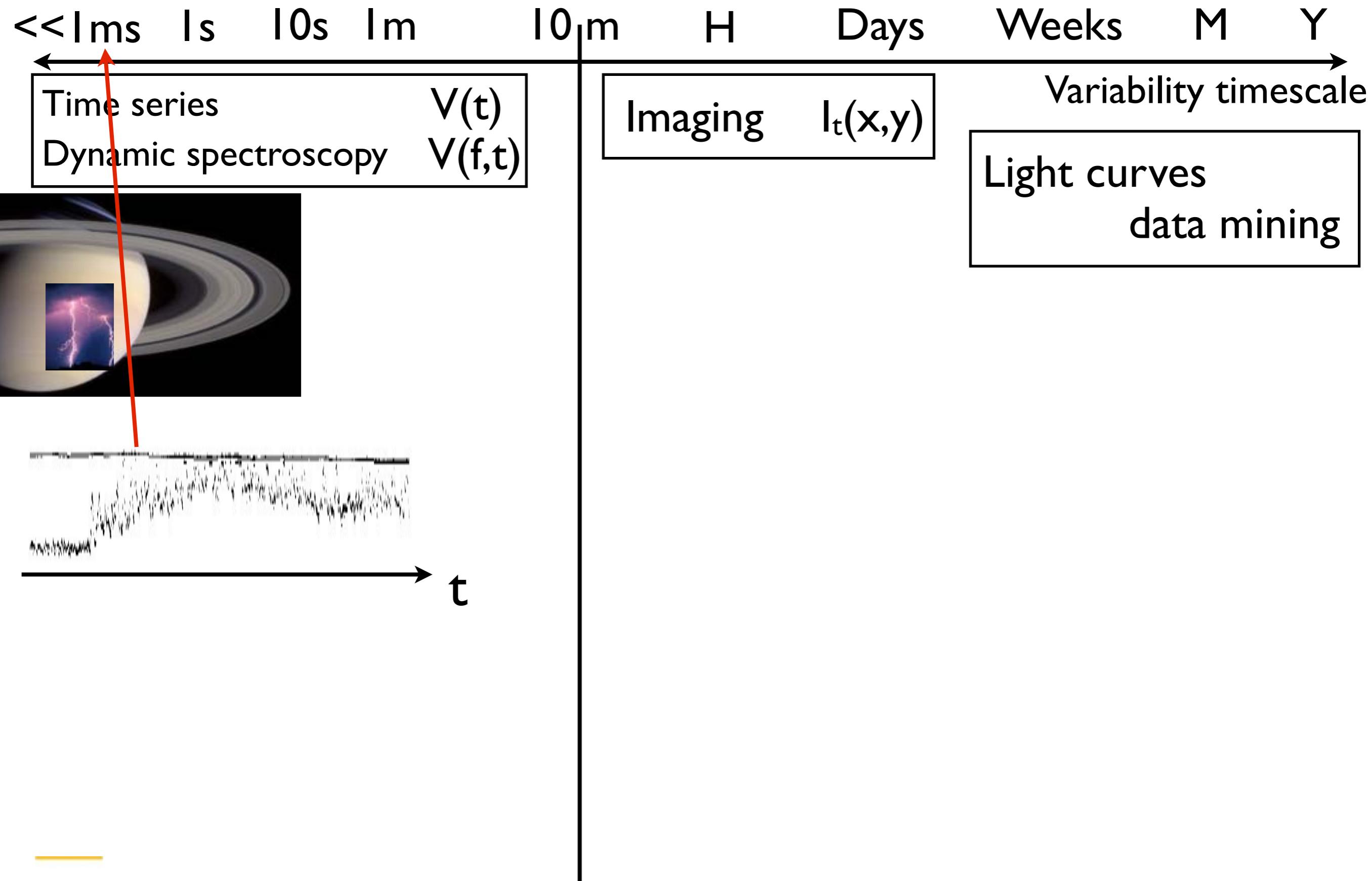
J.-L. Starck, H. Garsden, S. Corbel, C. Tasse, A. Woiselle

CEA Saclay
Service d'astrophysique
équipe Cosmostat

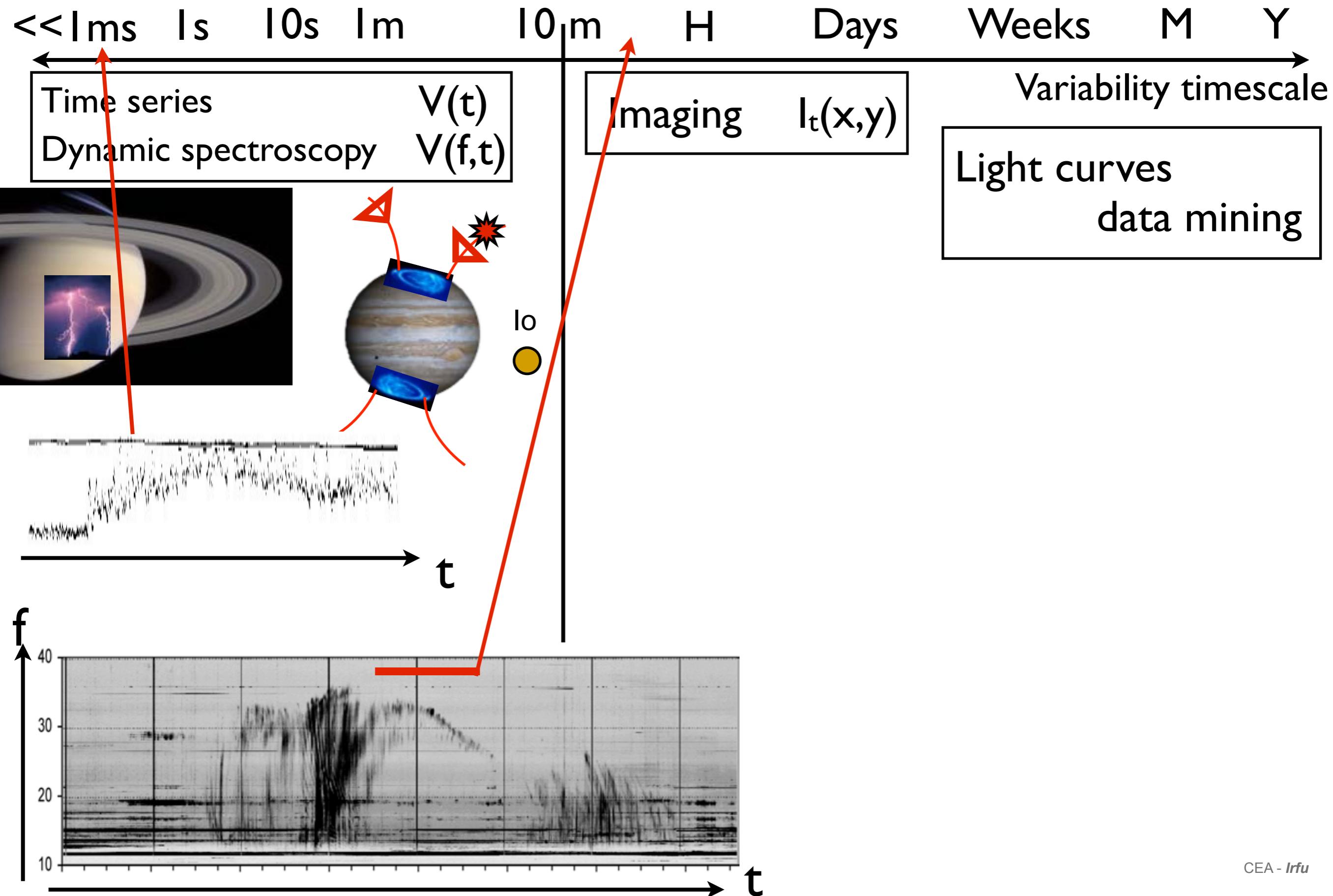
Different kind of transient radio detection in the time domain



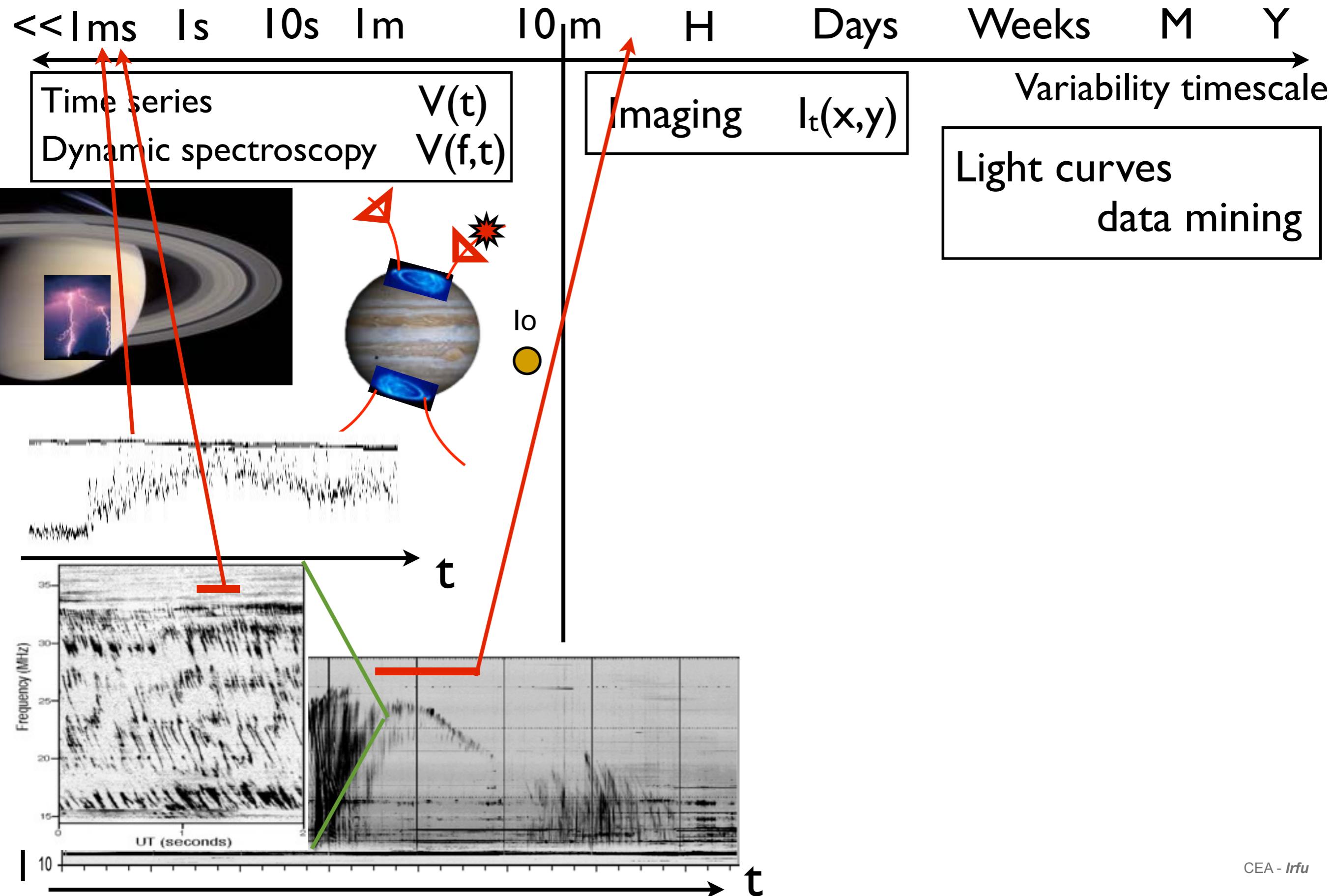
Different kind of transient radio detection in the time domain



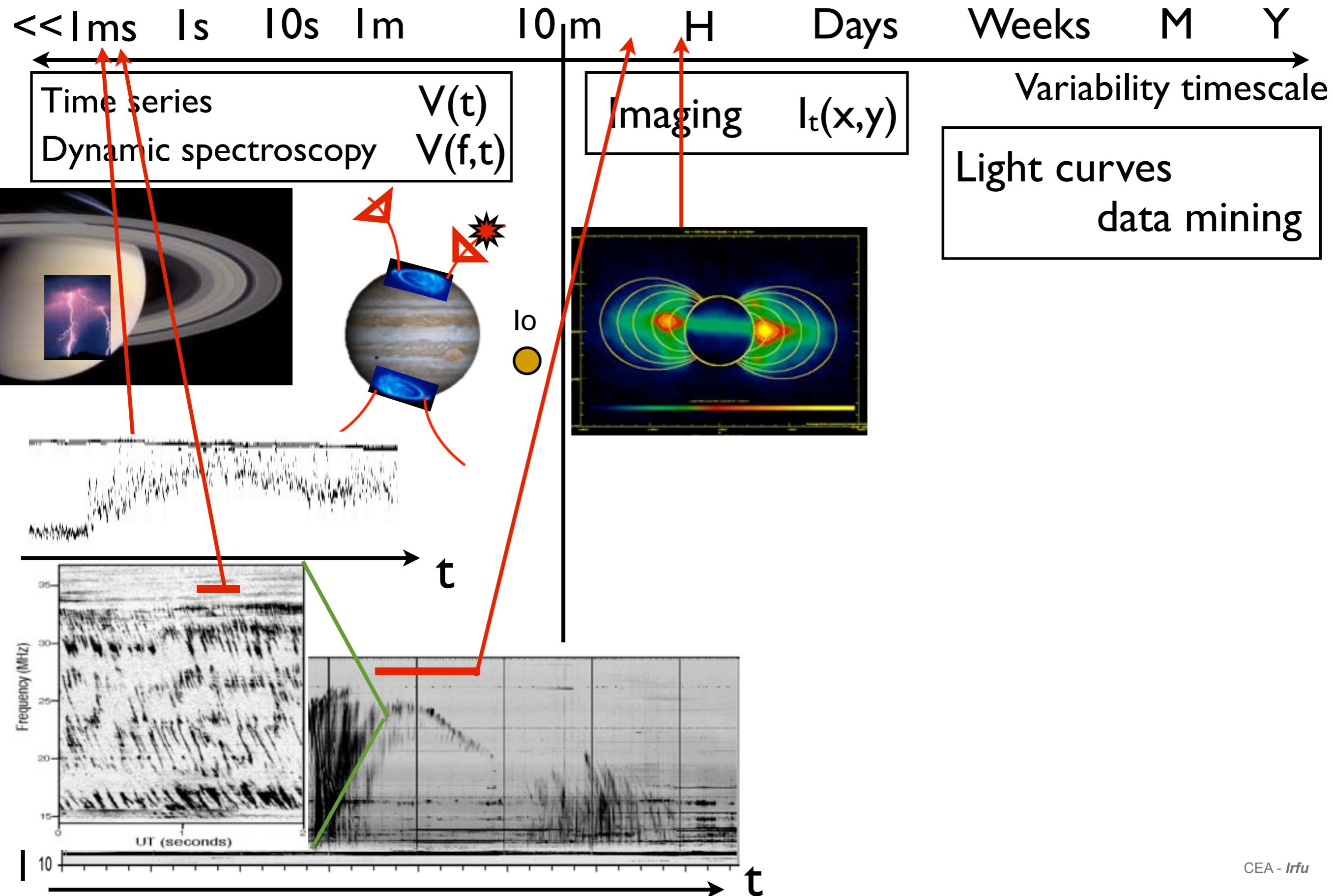
Different kind of transient radio detection in the time domain



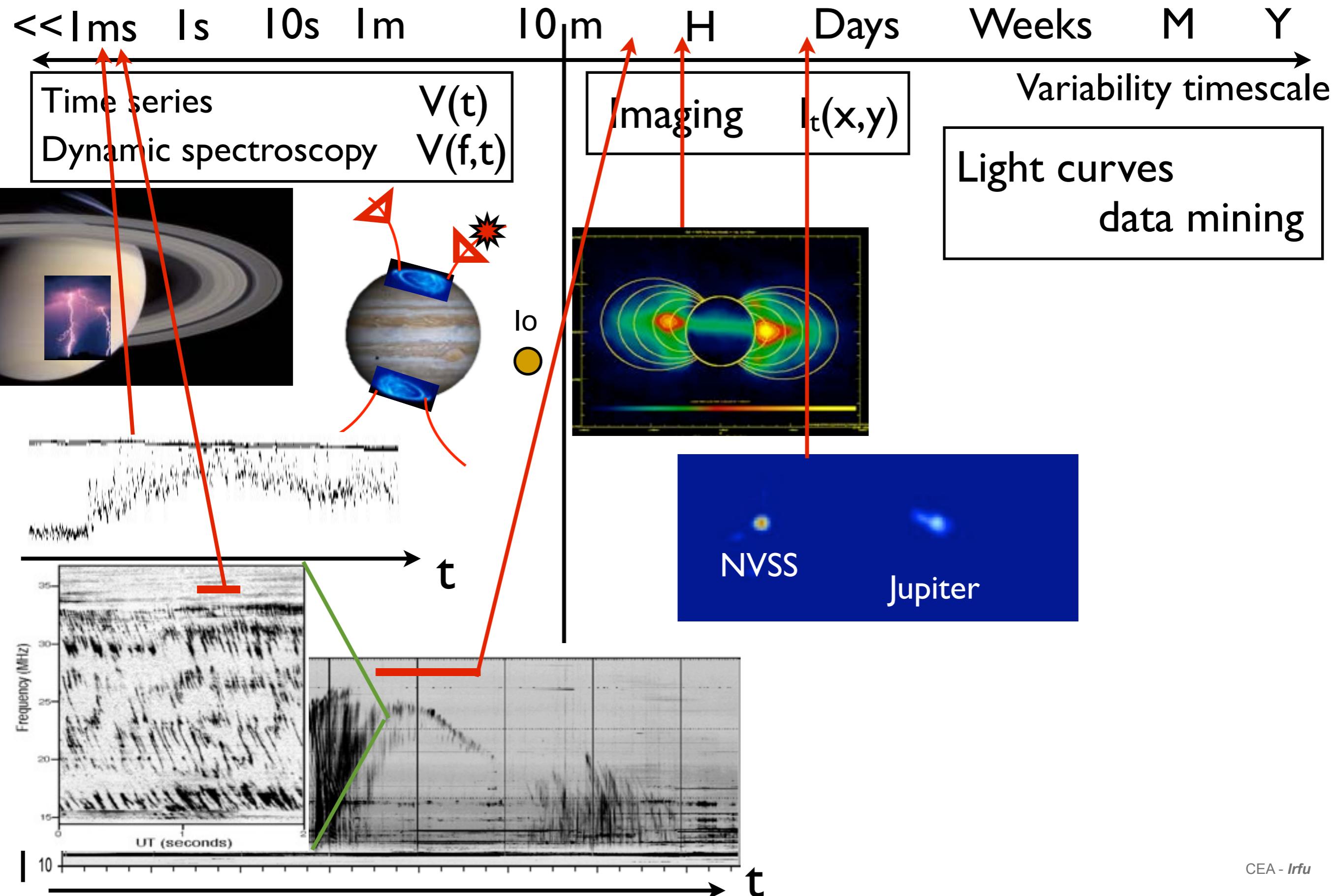
Different kind of transient radio detection in the time domain



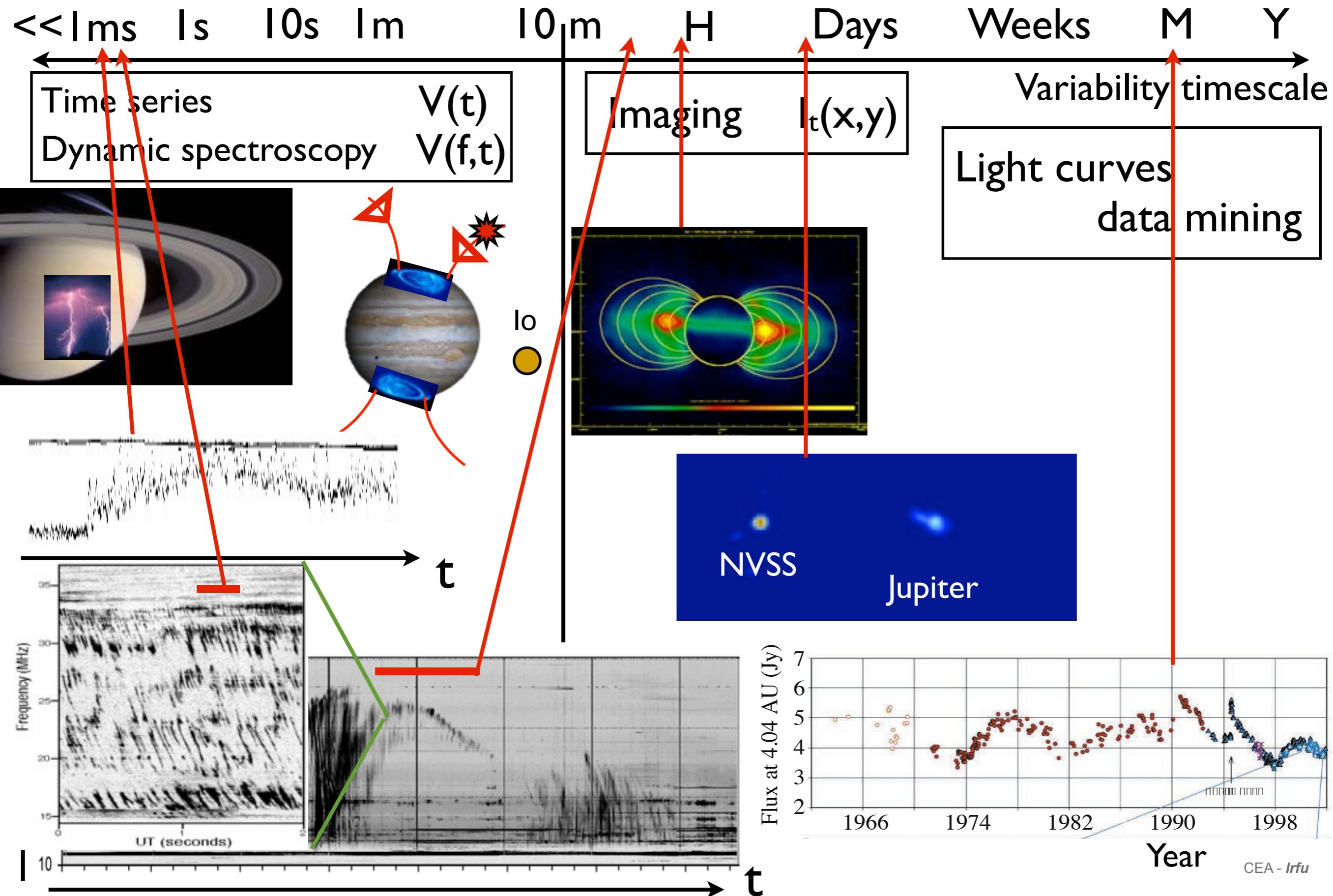
Different kind of transient radio detection in the time domain



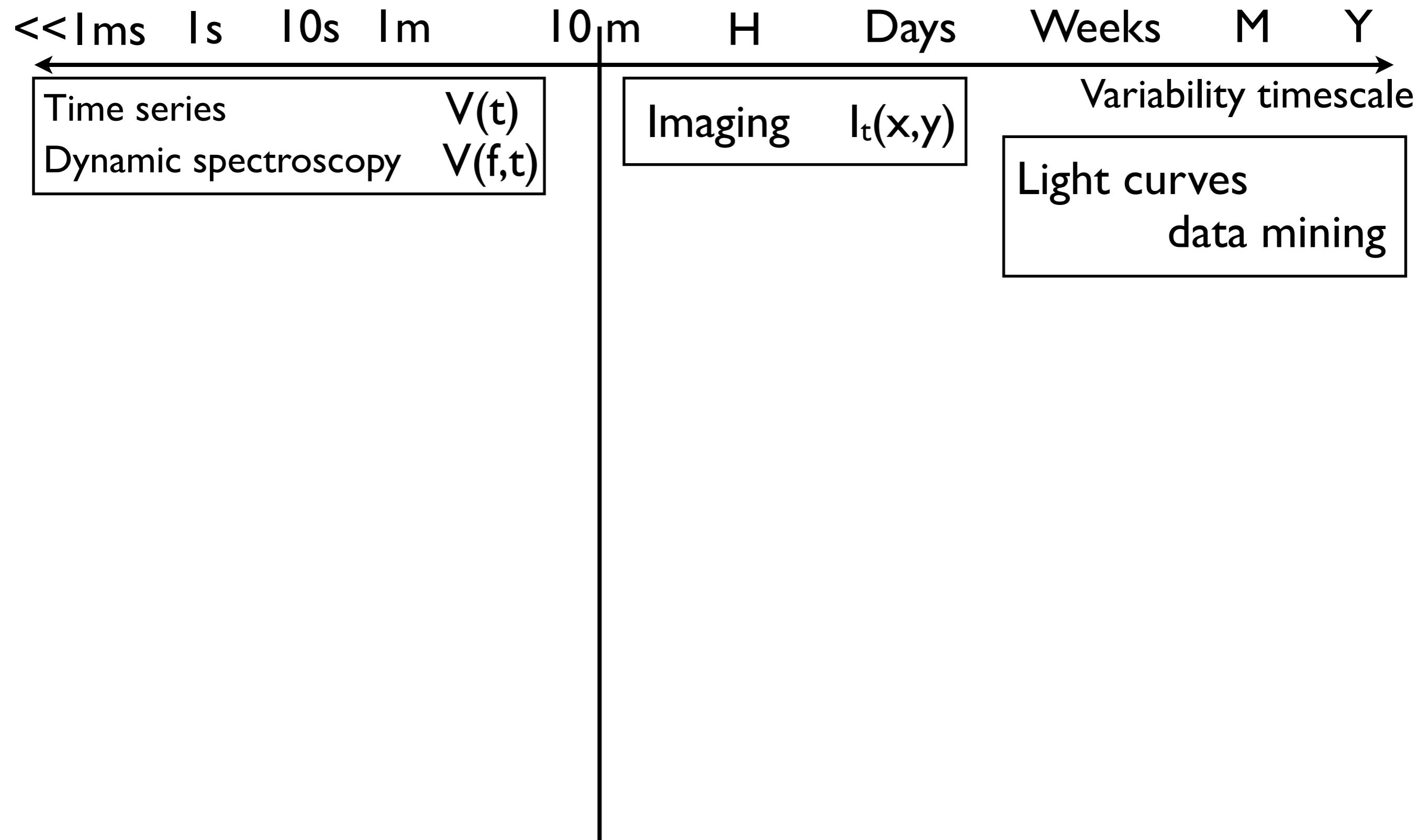
Different kind of transient radio detection in the time domain



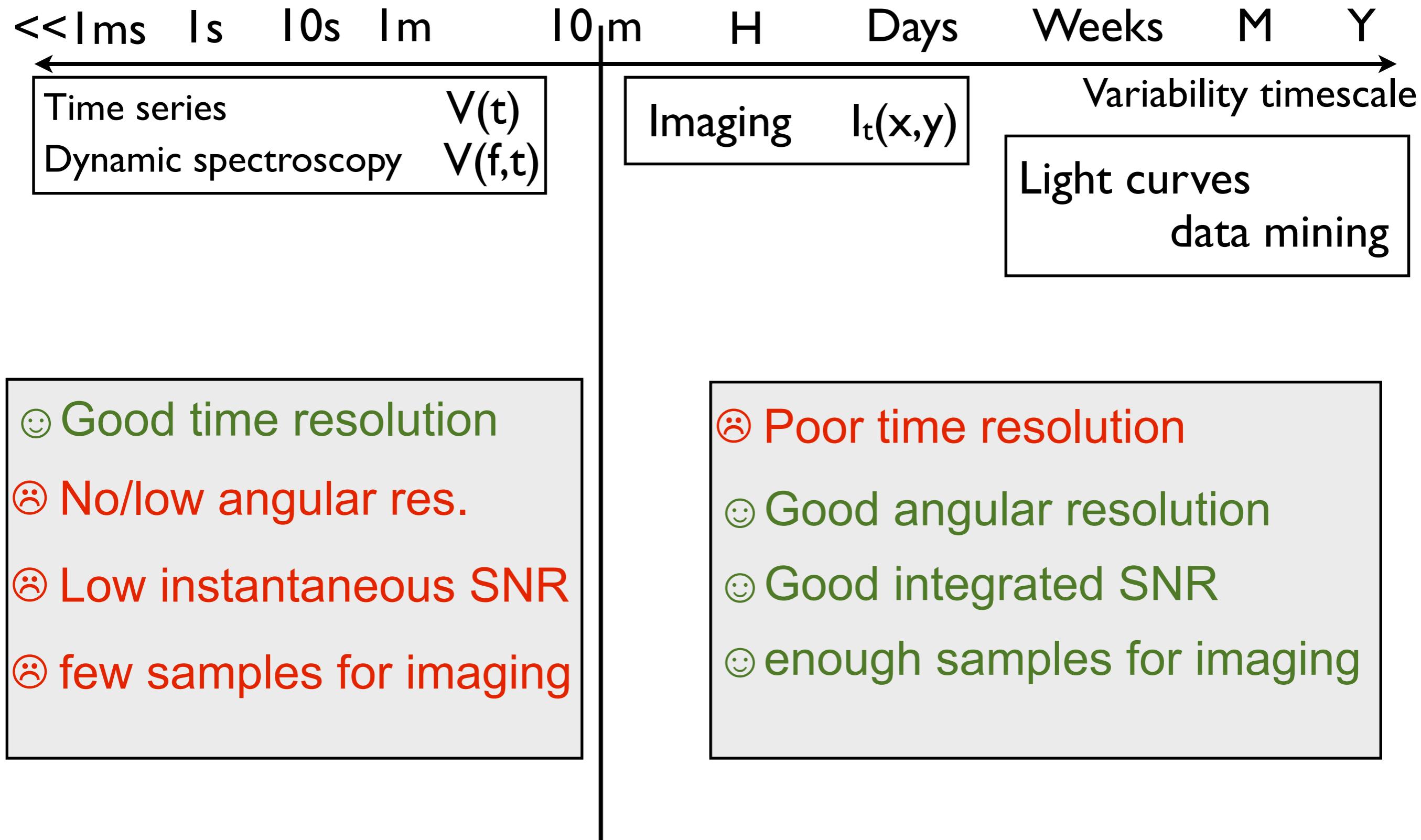
Different kind of transient radio detection in the time domain



Different kind of transient radio detection in the time domain

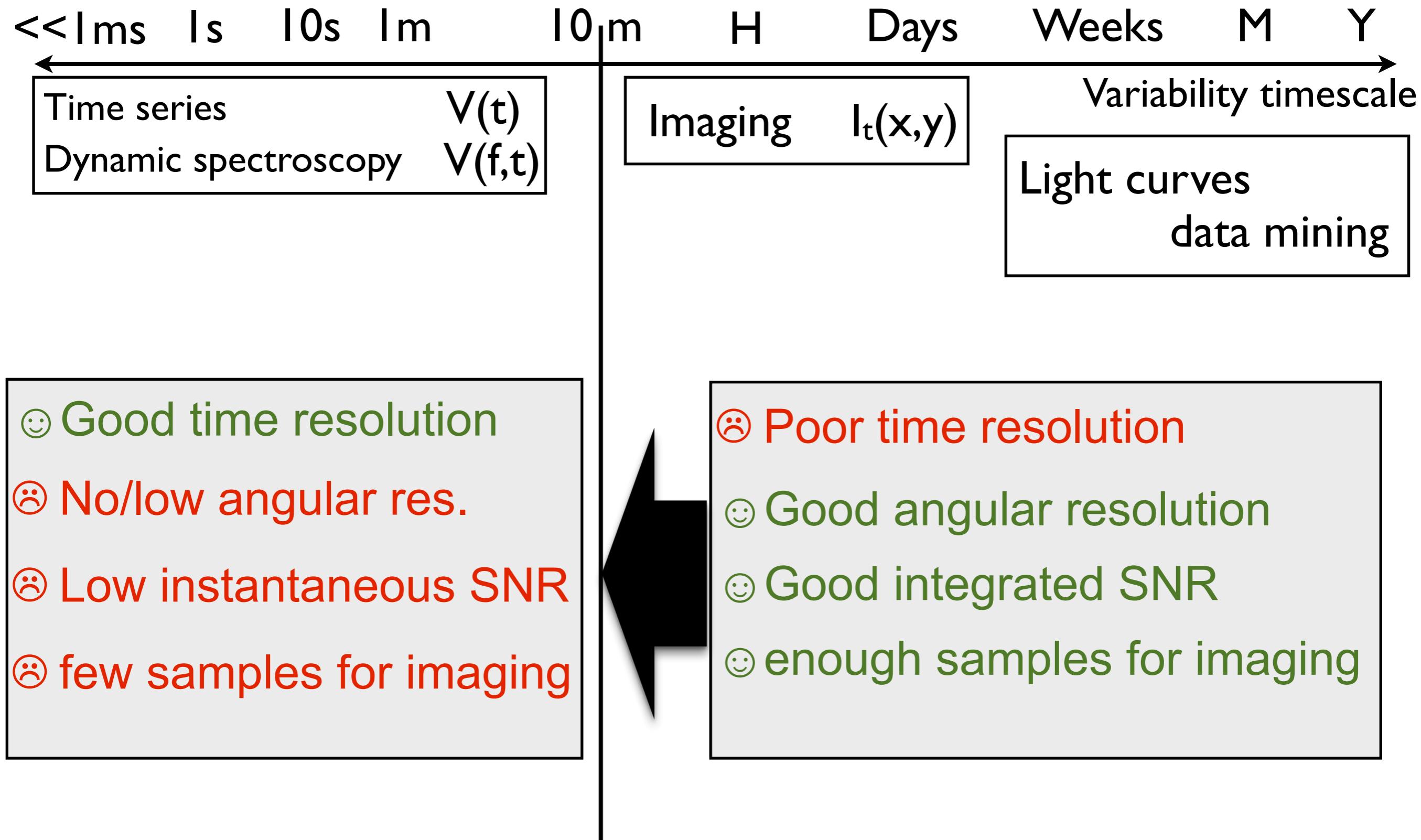


Different kind of transient radio detection in the time domain



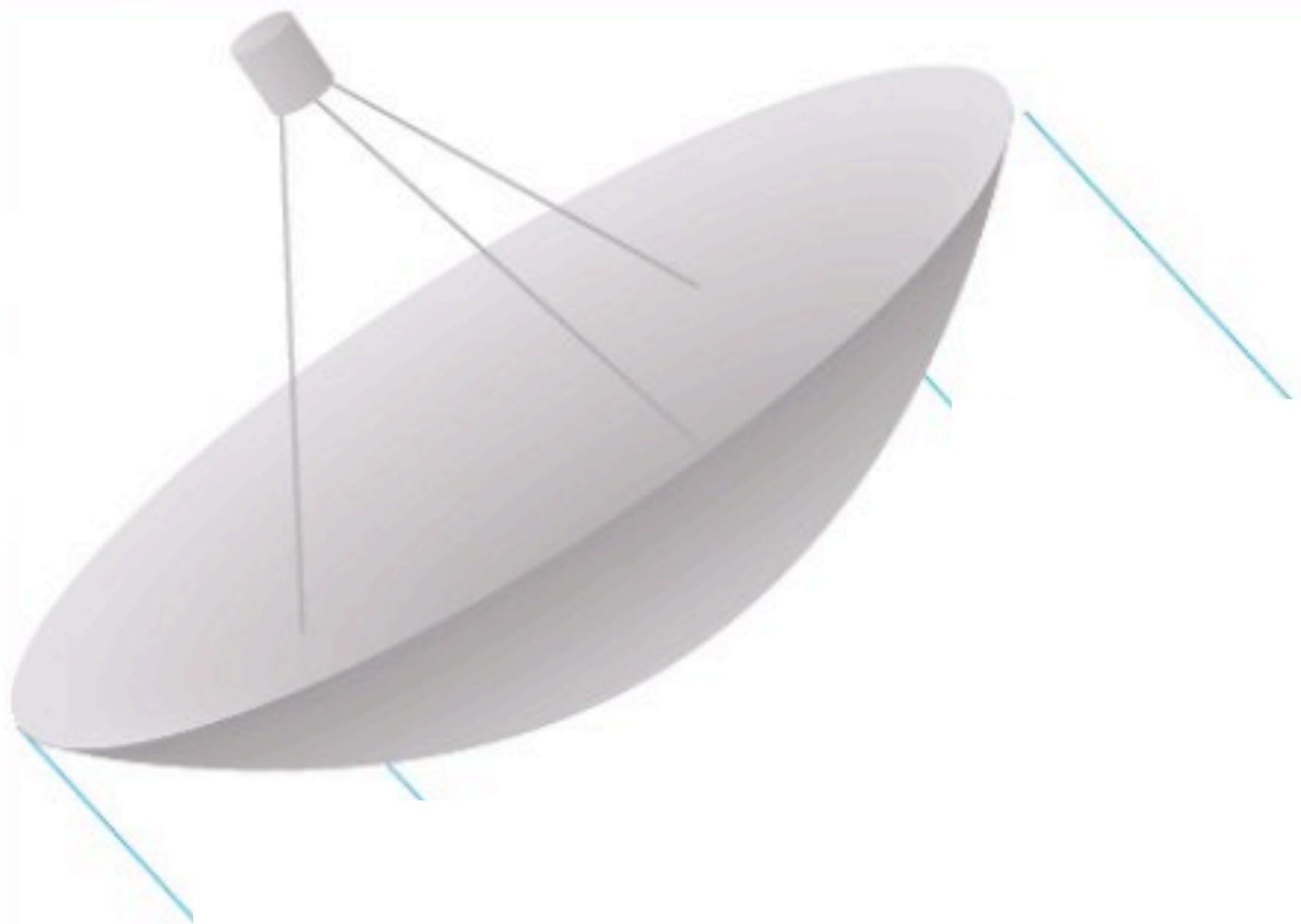
+ others problems (instrument stability, ionosphere...)

Different kind of transient radio detection in the time domain

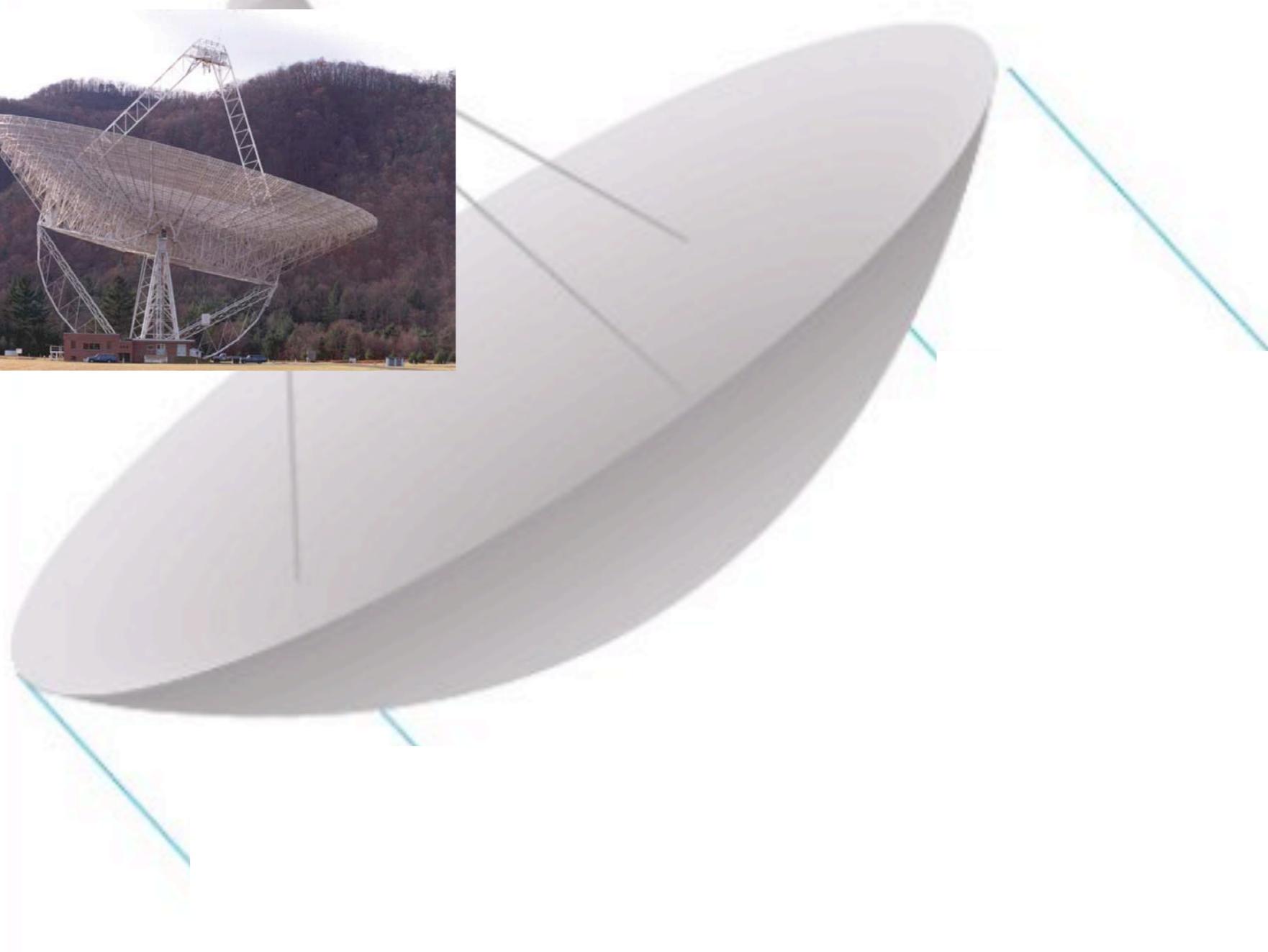


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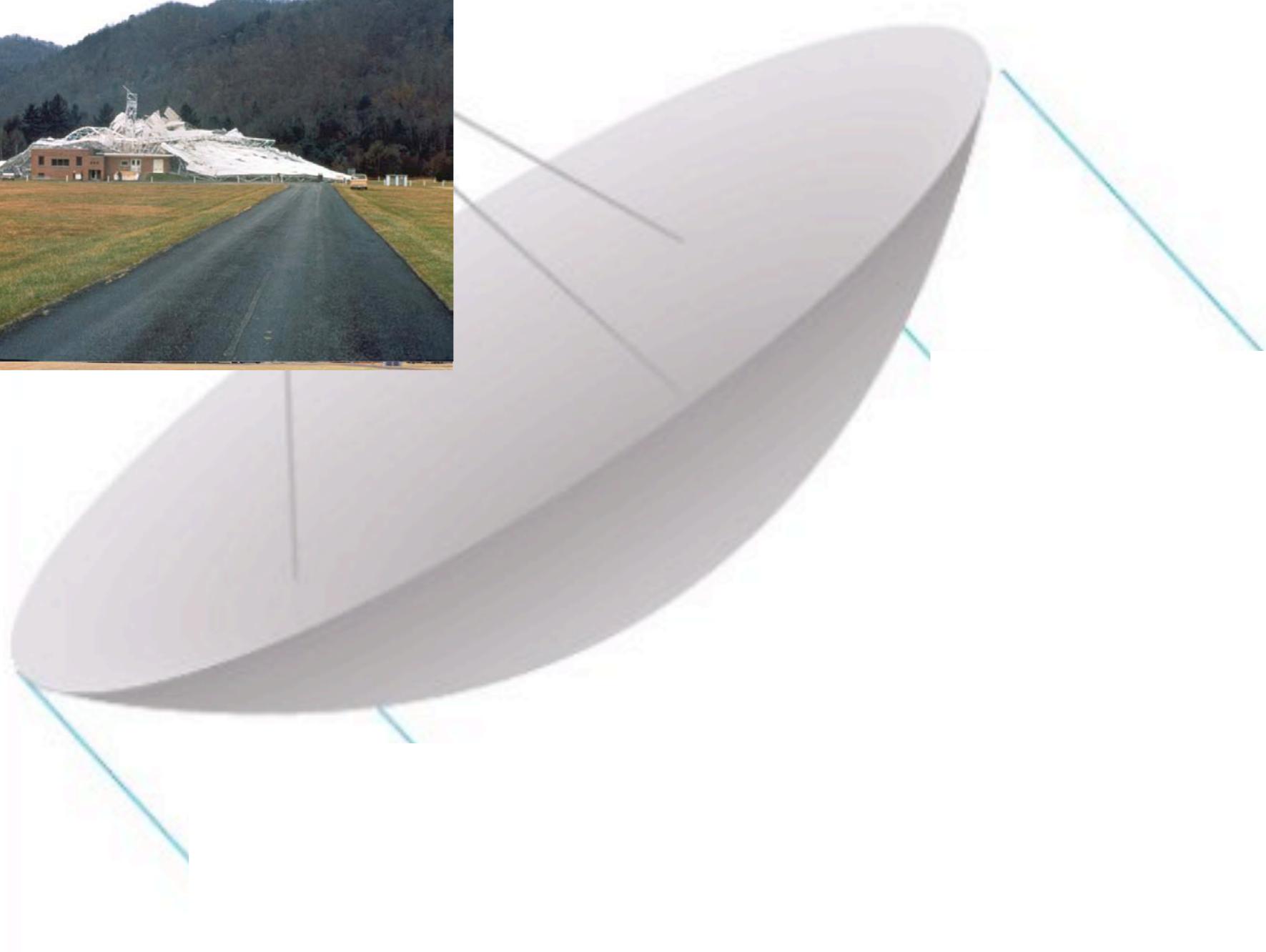
Antenna arrays



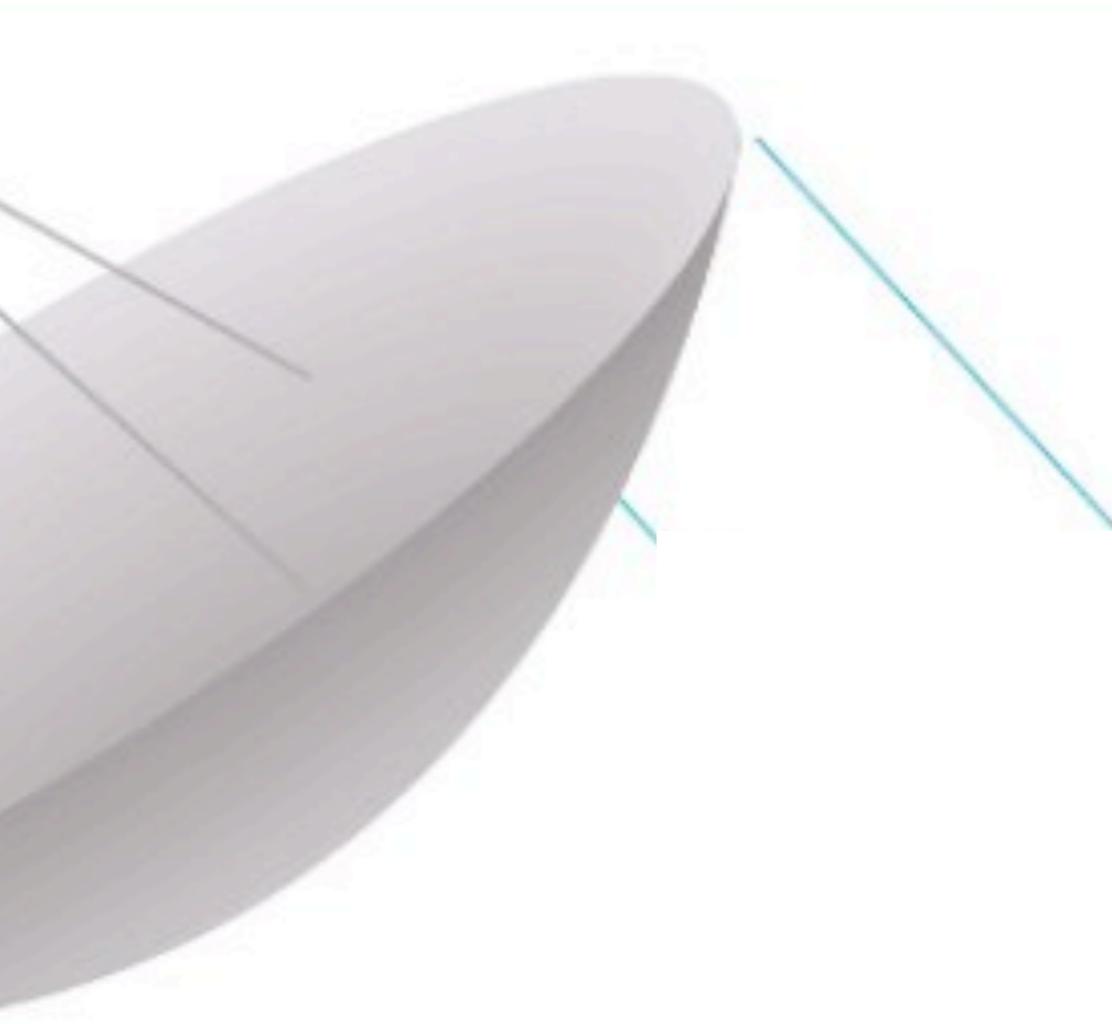
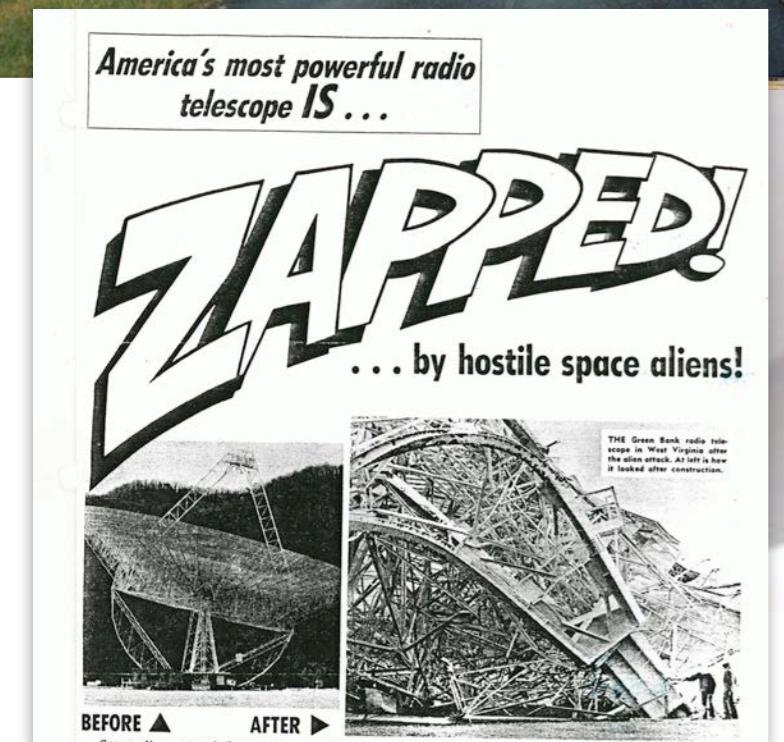
Antenna arrays



Antenna arrays

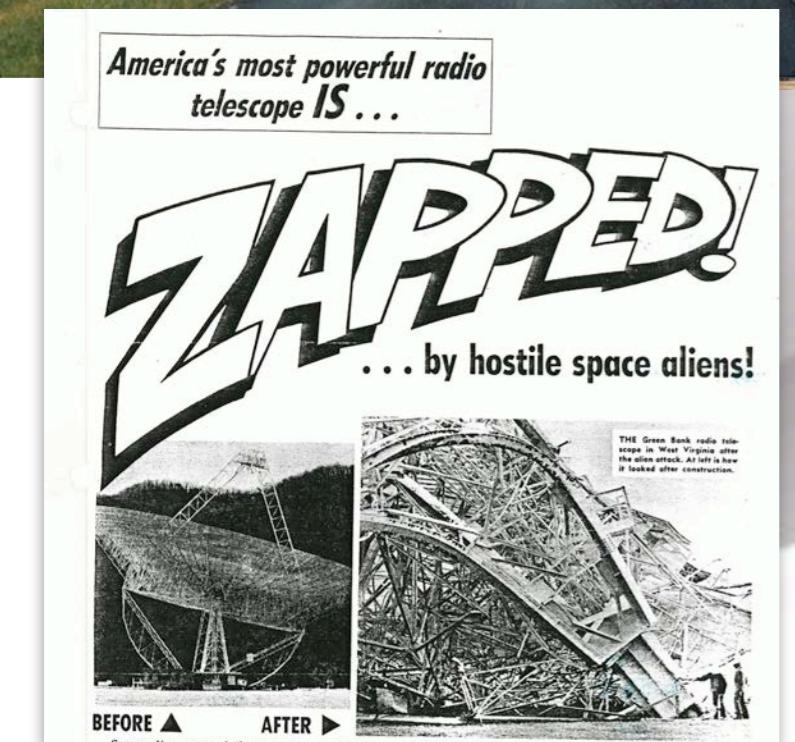


Antenna arrays



Antenna arrays

Arecibo



Antenna arrays

Arecibo



B_{12}

$$\delta\theta \propto \frac{\lambda}{B_{12}}$$

VLA

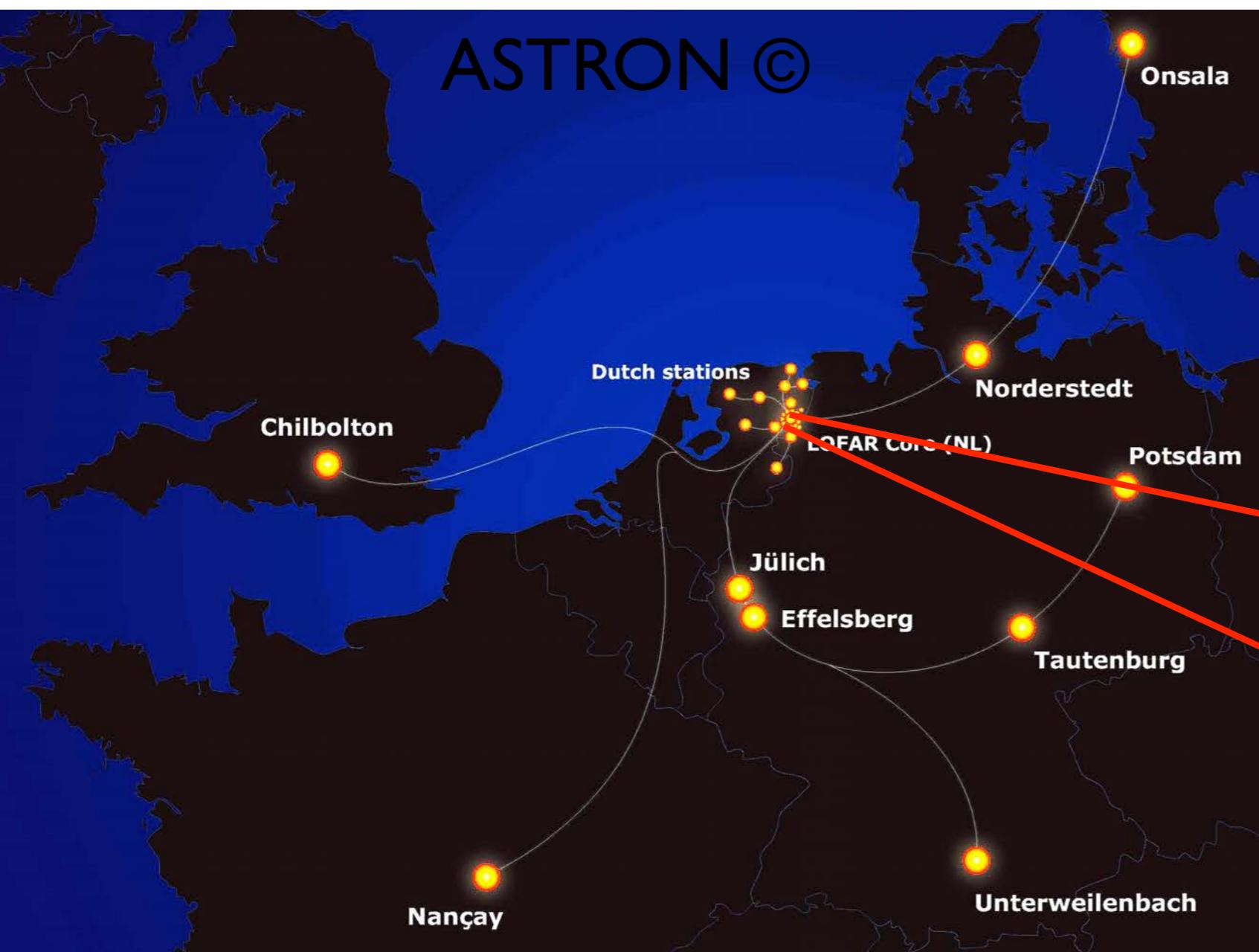


ex: GMRT

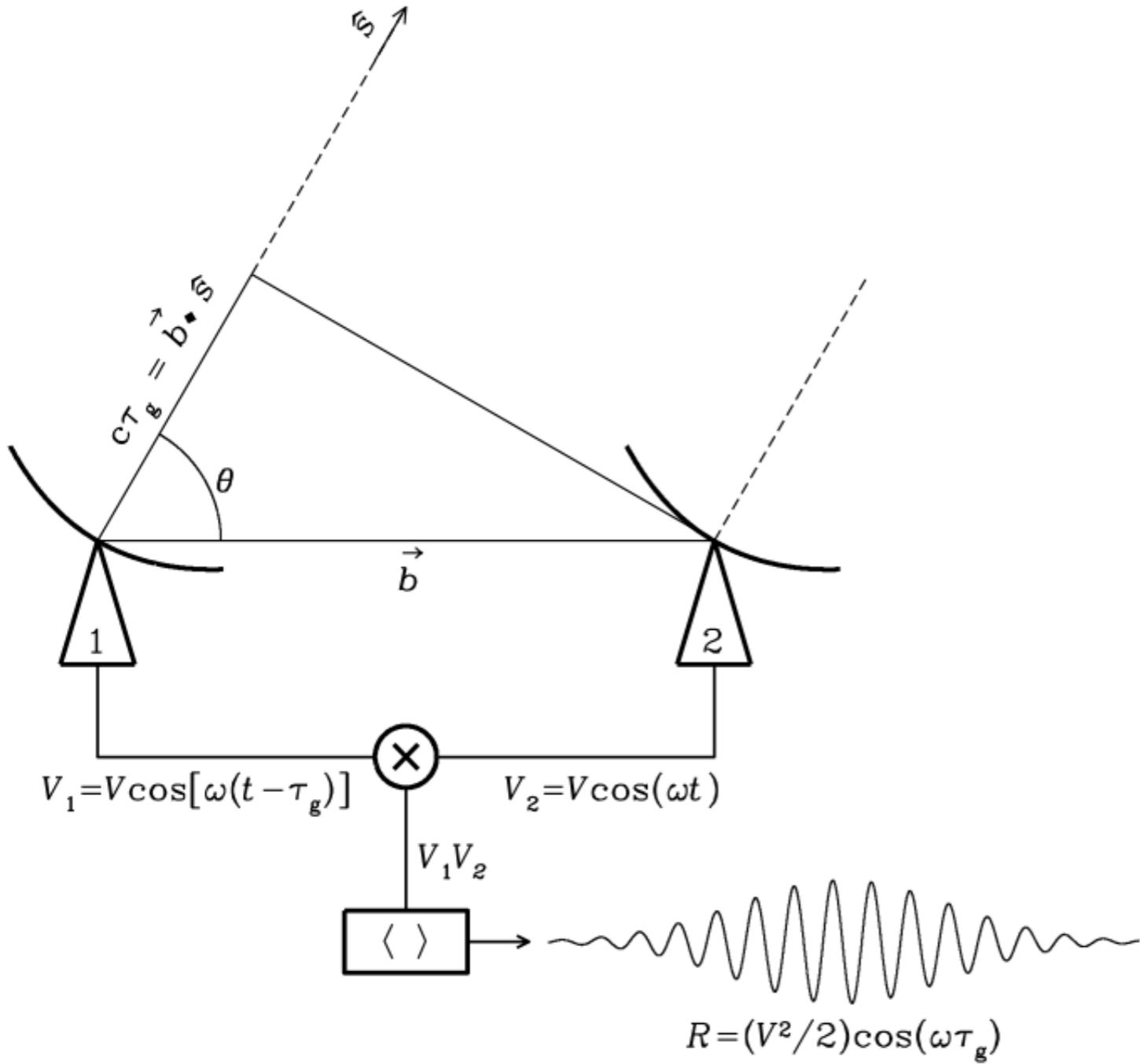


LOFAR: the LOw Frequency ARray

- Giant digital & multi-purpose radio telescope distributed across Europe
- Radio interferometer composed of ~48 phased arrays (stations)
- Working bands: LBA 30-80 MHz & HBA 120-240 MHz
- Improved angular (arcsec), temporal (μ s), spectral (kHz) resolutions
- High sensitivity (~mJy) $1 \text{ Jy} = 10^{-26} \text{ W.m}^{-2}.\text{Hz}^{-1}$



Interferometry I



I baseline b (t, v) + I direction s
=

I spatial frequency of the sky brightness

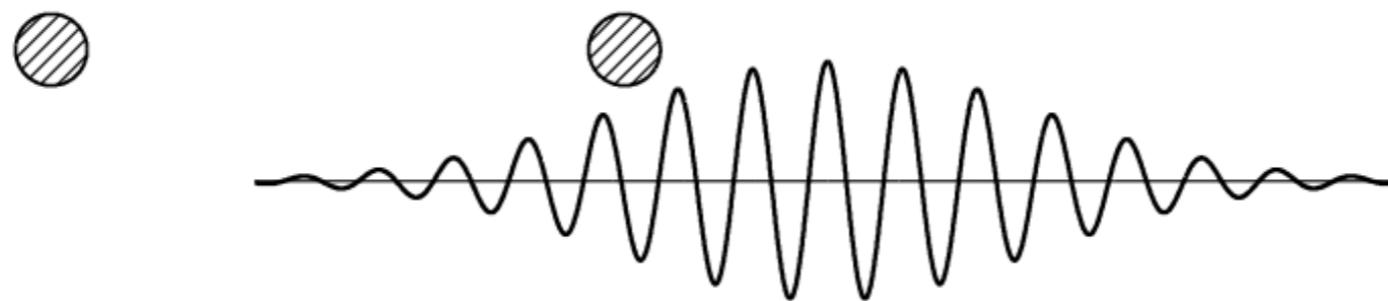
through the measurement of the
fringe contrast
or **fringe « visibility »**

$$V_\nu = \int I_\nu(\hat{s}) \exp(-i2\pi \vec{b} \cdot \hat{s}/\lambda) d\Omega$$

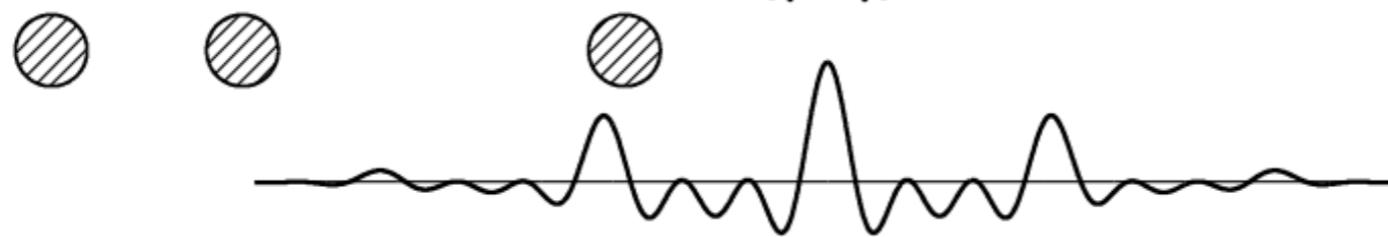
complex visibility V_ν

Interferometry II

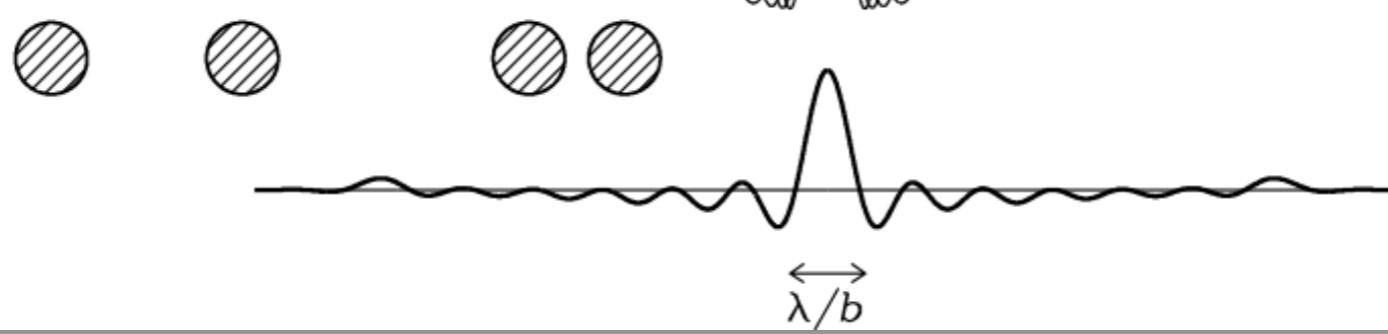
N_{ant} = 2



N_{ant} = 3



N_{ant} = 4



$$\lambda/b$$

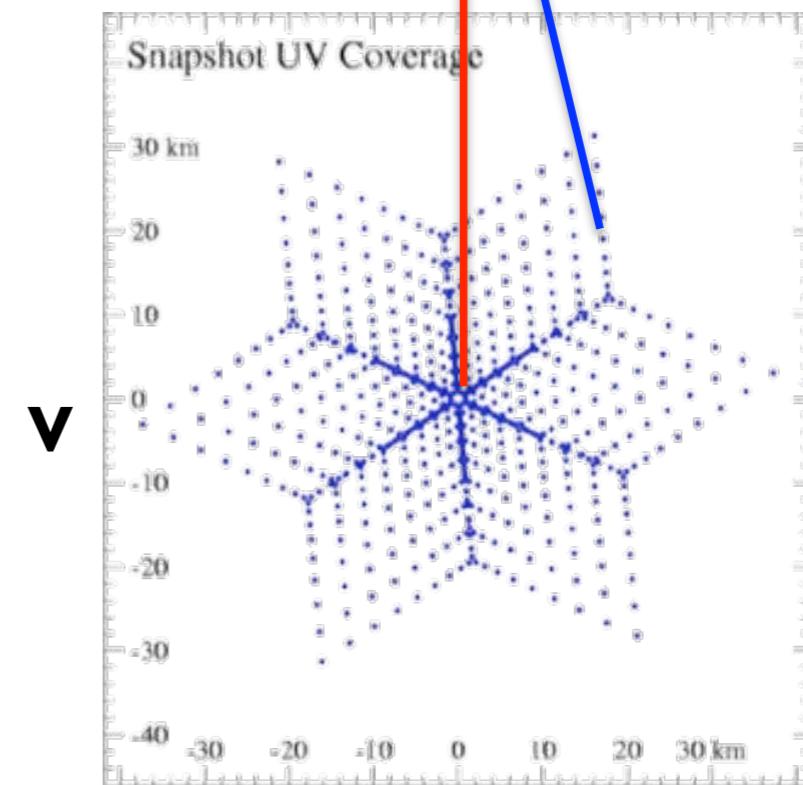
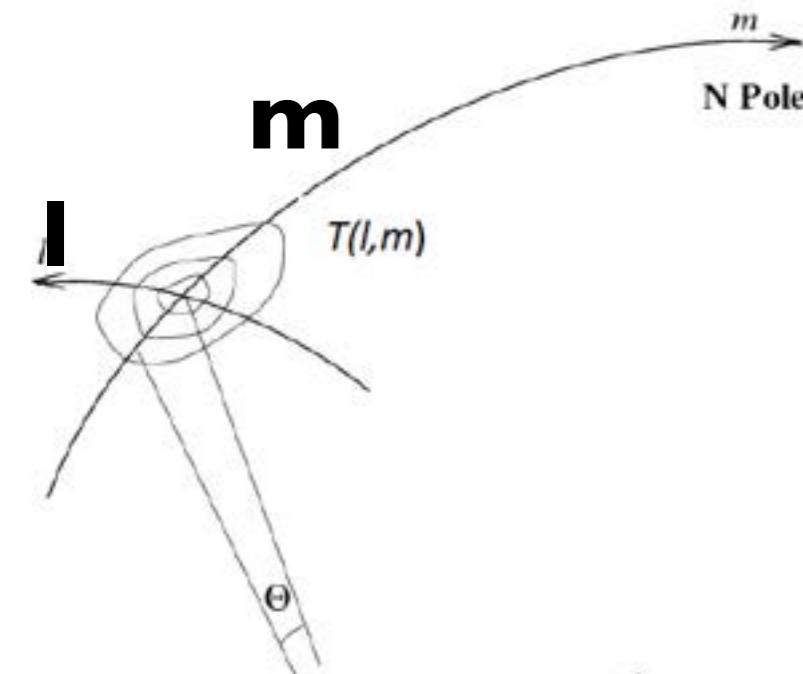
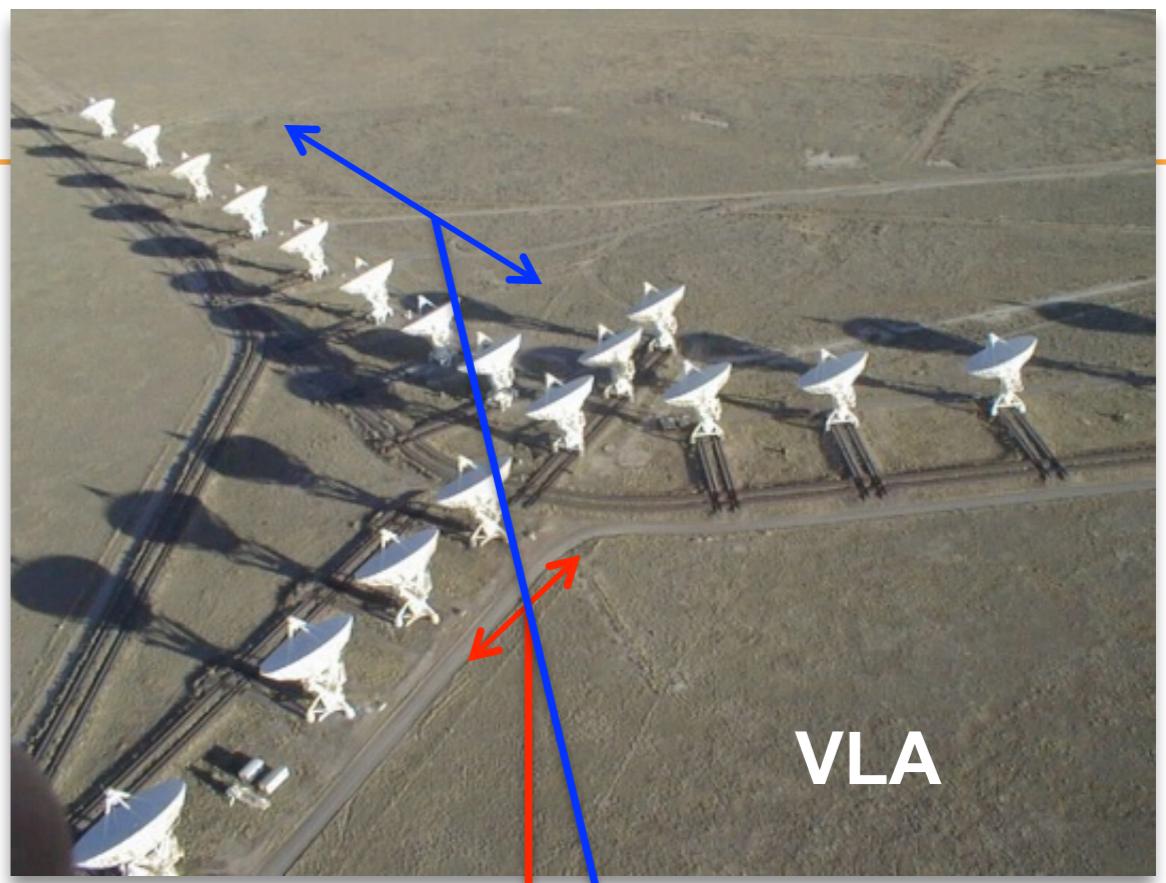
PSF of the interferometer

Interferometry III

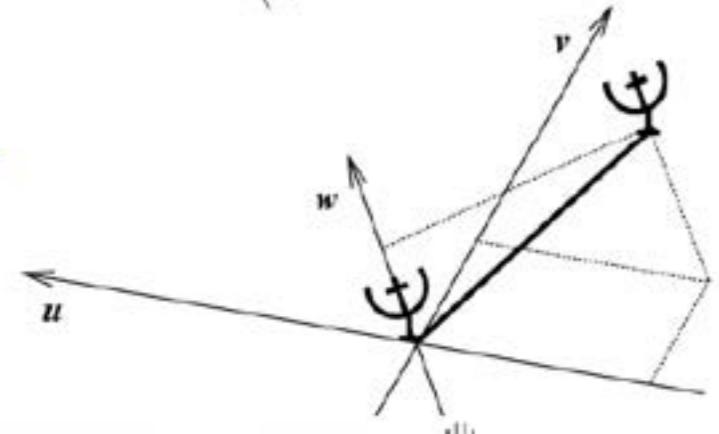
N antennas/telescopes

$\frac{N(N - 1)}{2}$ independent baselines

1 projected baseline
= 1 sample in the Fourier « u,v » plane



(u, v)
plane
sampling



$$V(u, v) = \int \int T(l, m) e^{-i2\pi(ul+vm)} dl dm$$

Inversion 1/2

$$V(u, v) \xrightarrow{\mathcal{F}} T(l, m)$$

- sample Fourier domain at discrete points $S(u, v) = \sum_{k=1}^M \delta(u - u_k, v - v_k)$
- Fourier transform sampled visibility function $V(u, v)S(u, v) \xrightarrow{\mathcal{F}} T^D(l, m)$
- apply the convolution theorem $T(l, m) * s(l, m) = T^D(l, m)$

where the Fourier transform of the sampling pattern $s(l, m) \xrightarrow{\mathcal{F}} S(u, v)$ is the “point spread function”

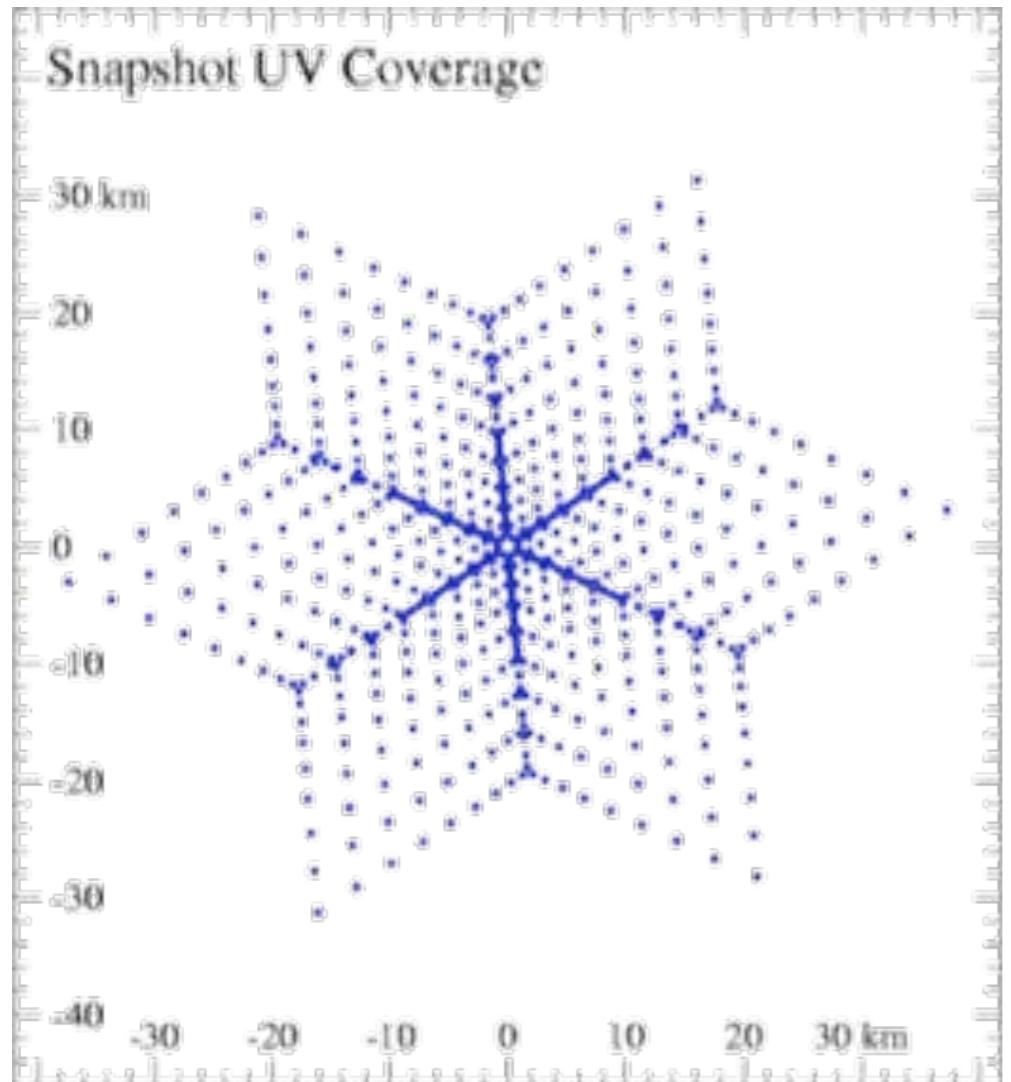
the Fourier transform of the sampled visibilities yields the true sky brightness convolved with the point spread function

radio jargon: the “dirty image” is the true image convolved with the “dirty beam”

Inversion 2/2

Fourier domain

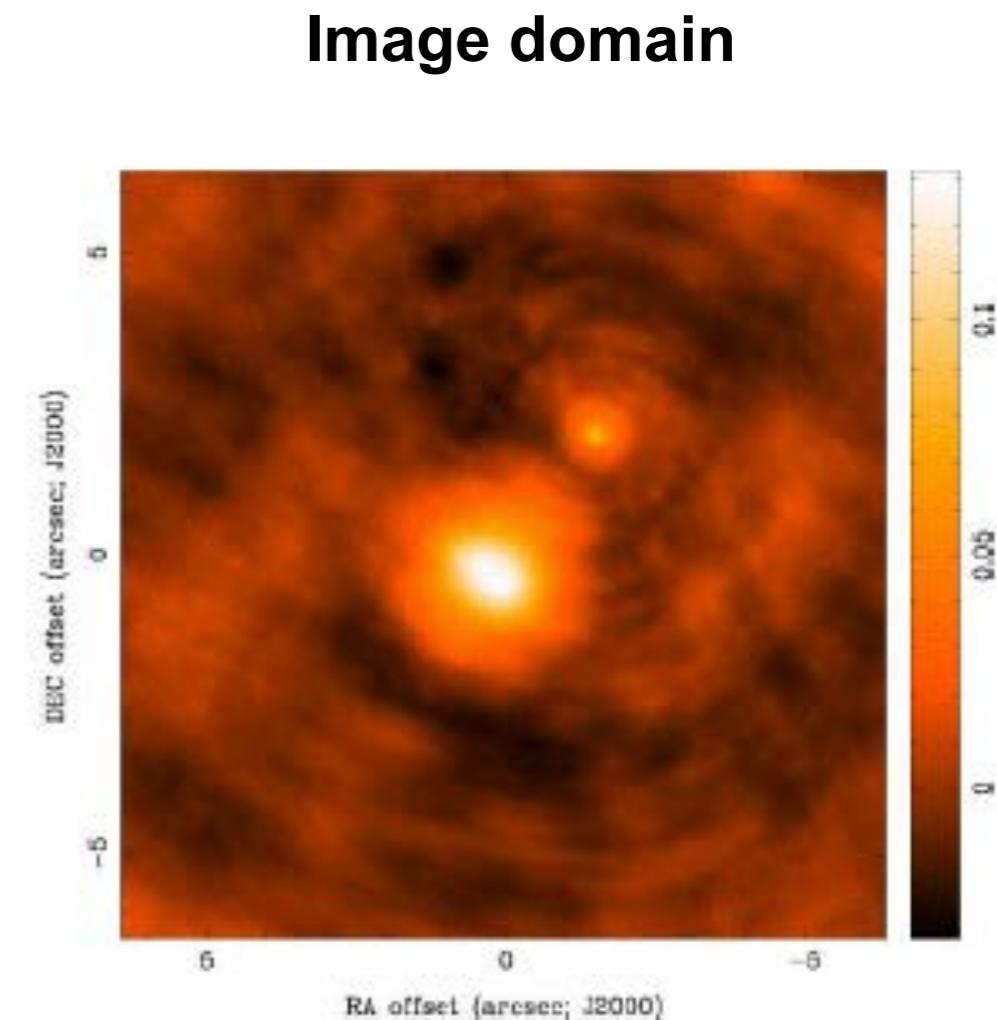
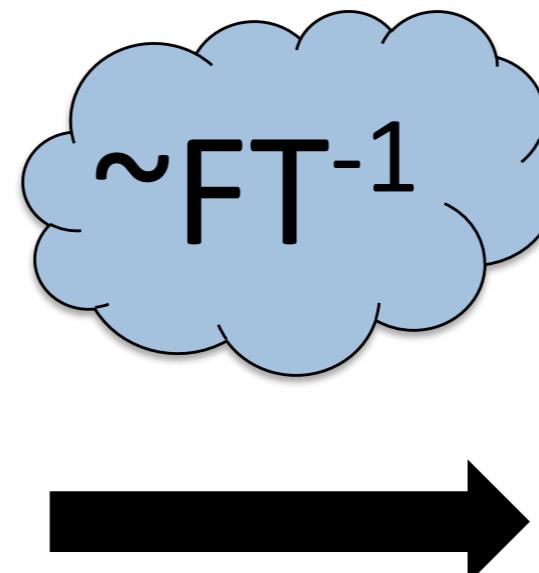
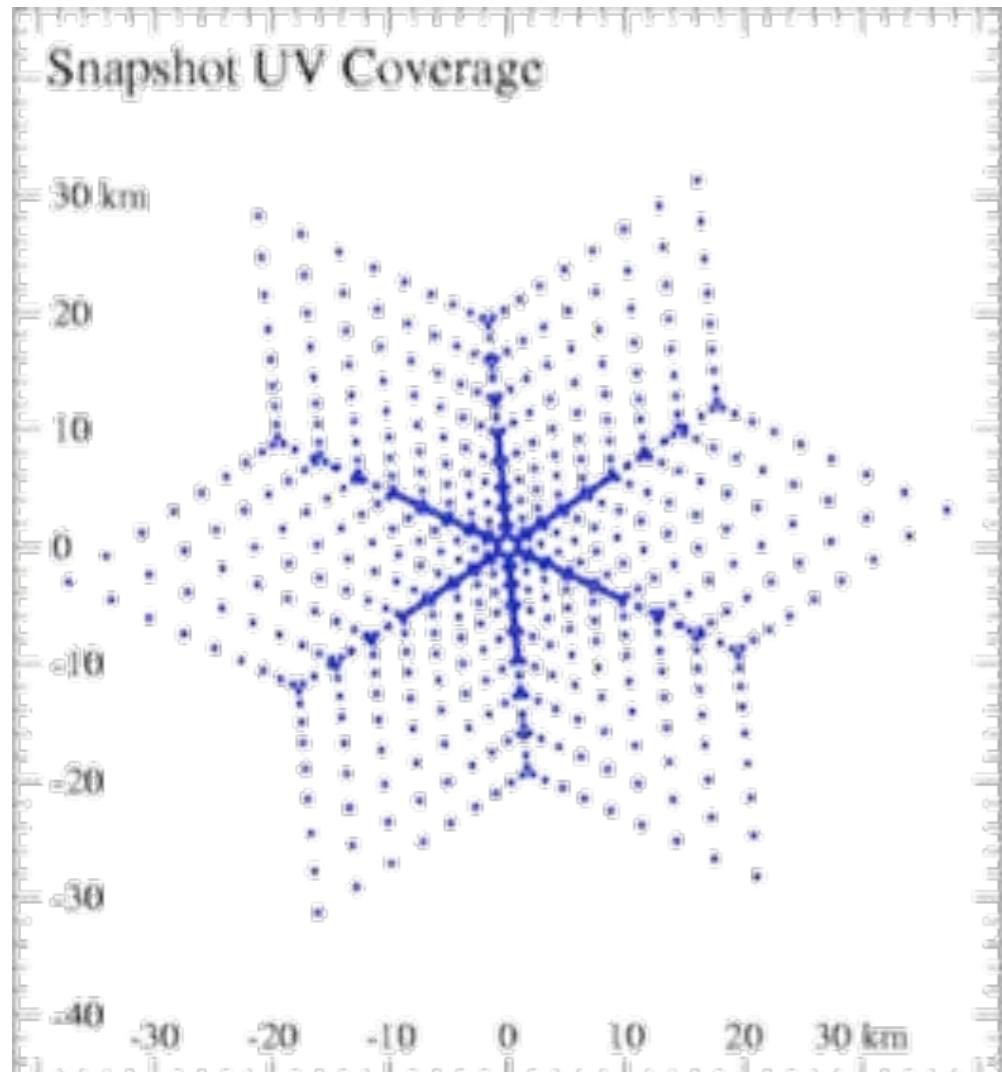
Snapshot (u,v) coverage



discontinuous sampling of the (Fourier) (u,v) plane

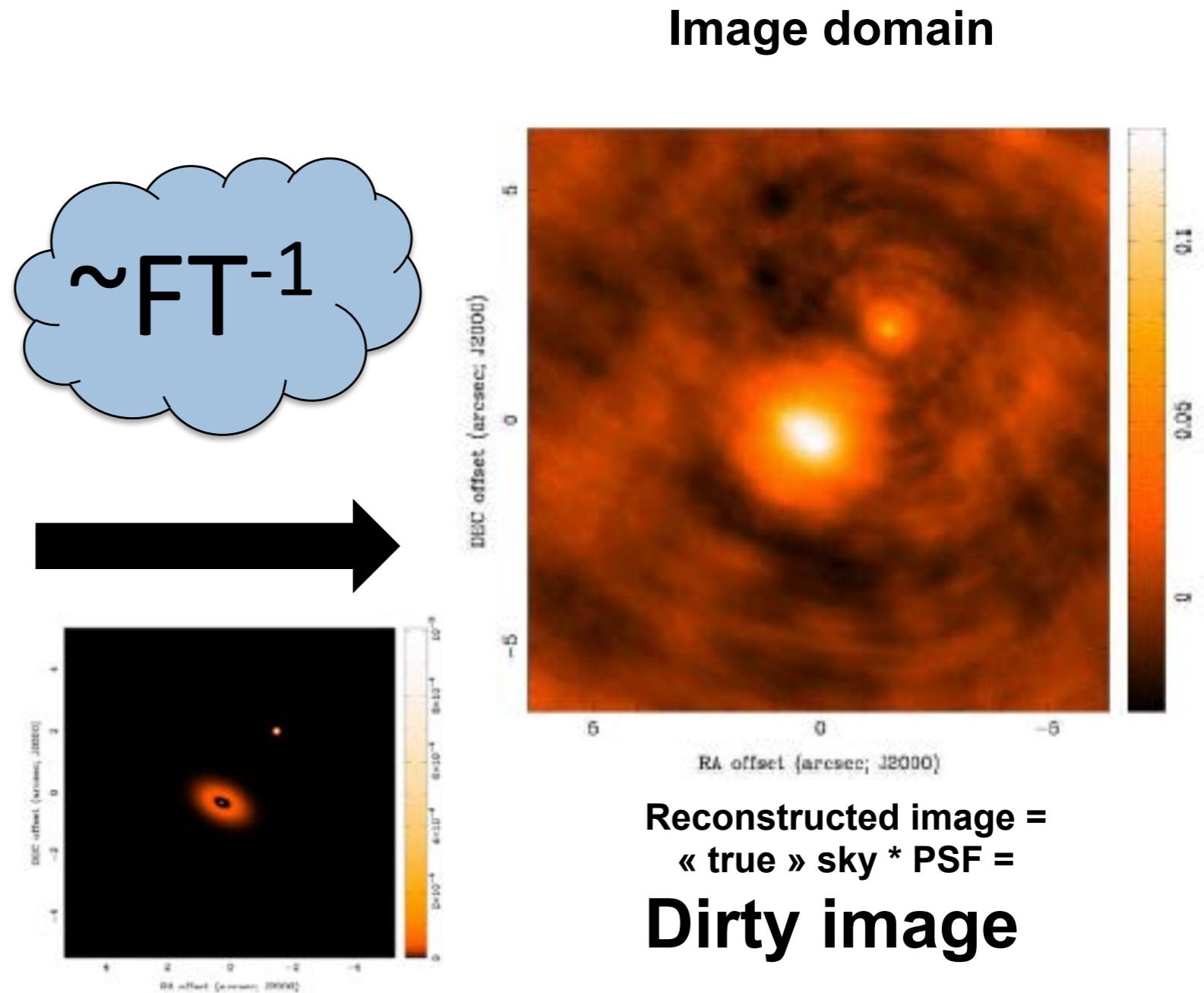
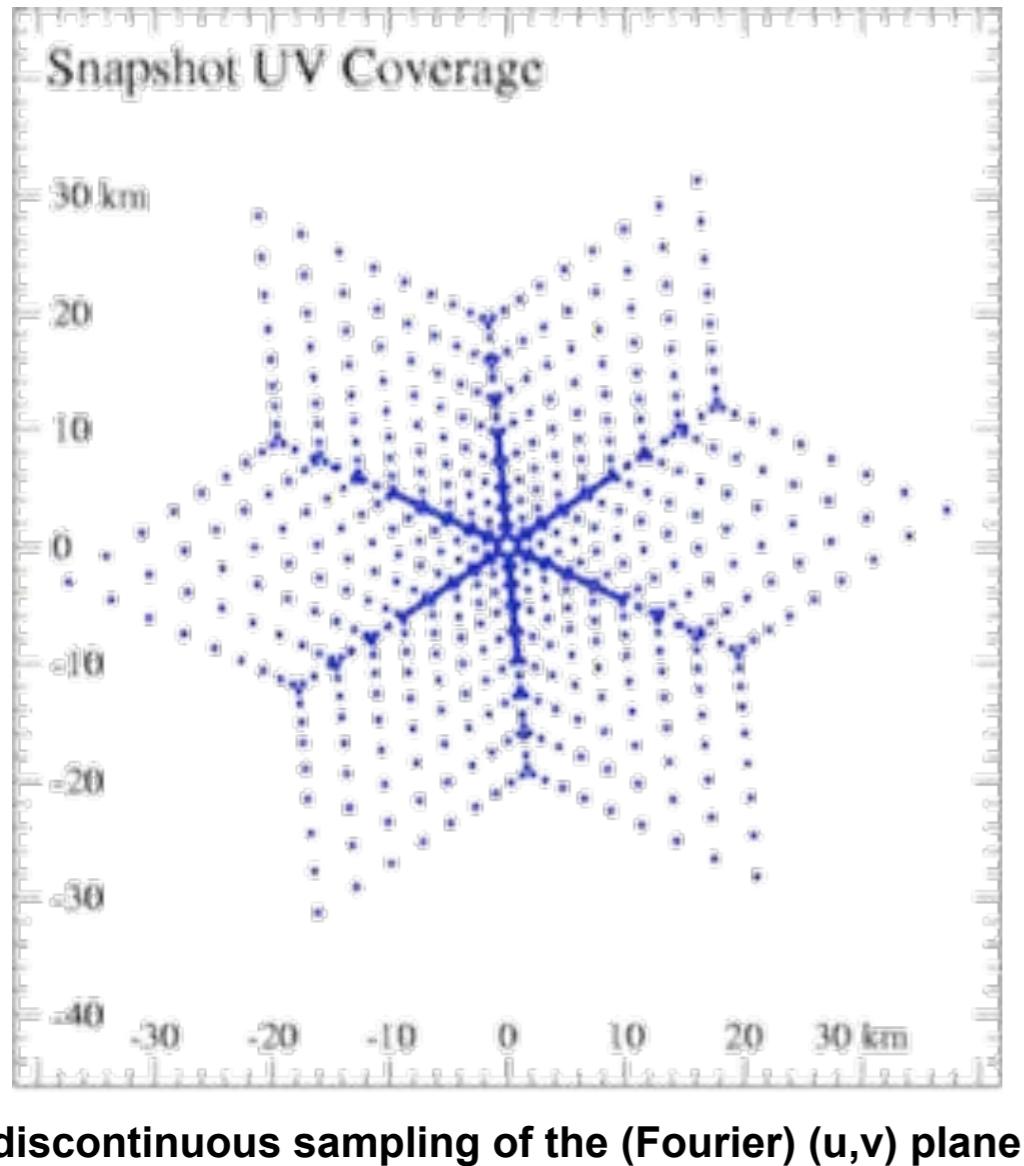
Inversion 2/2

Fourier domain Snapshot (u,v) coverage



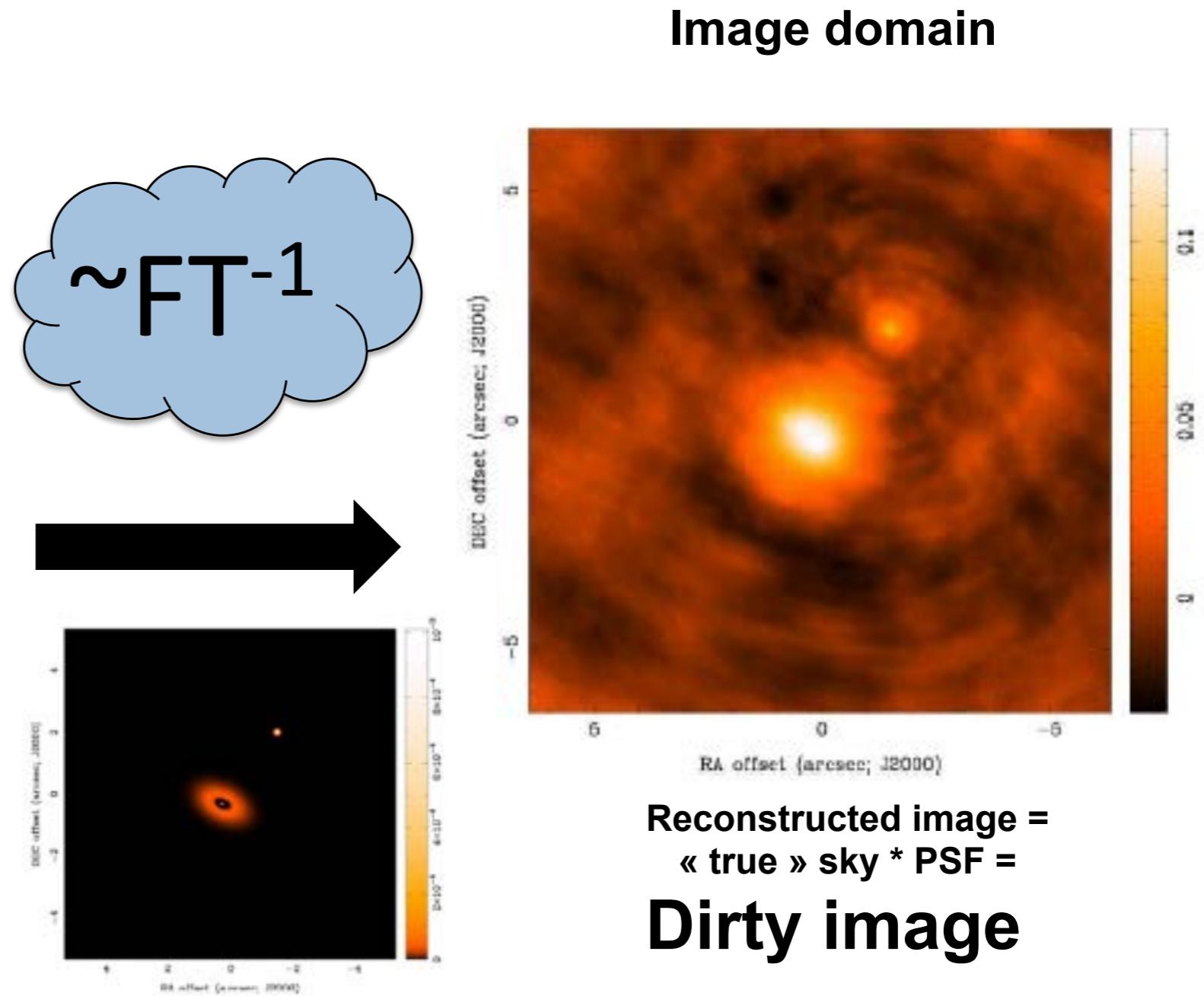
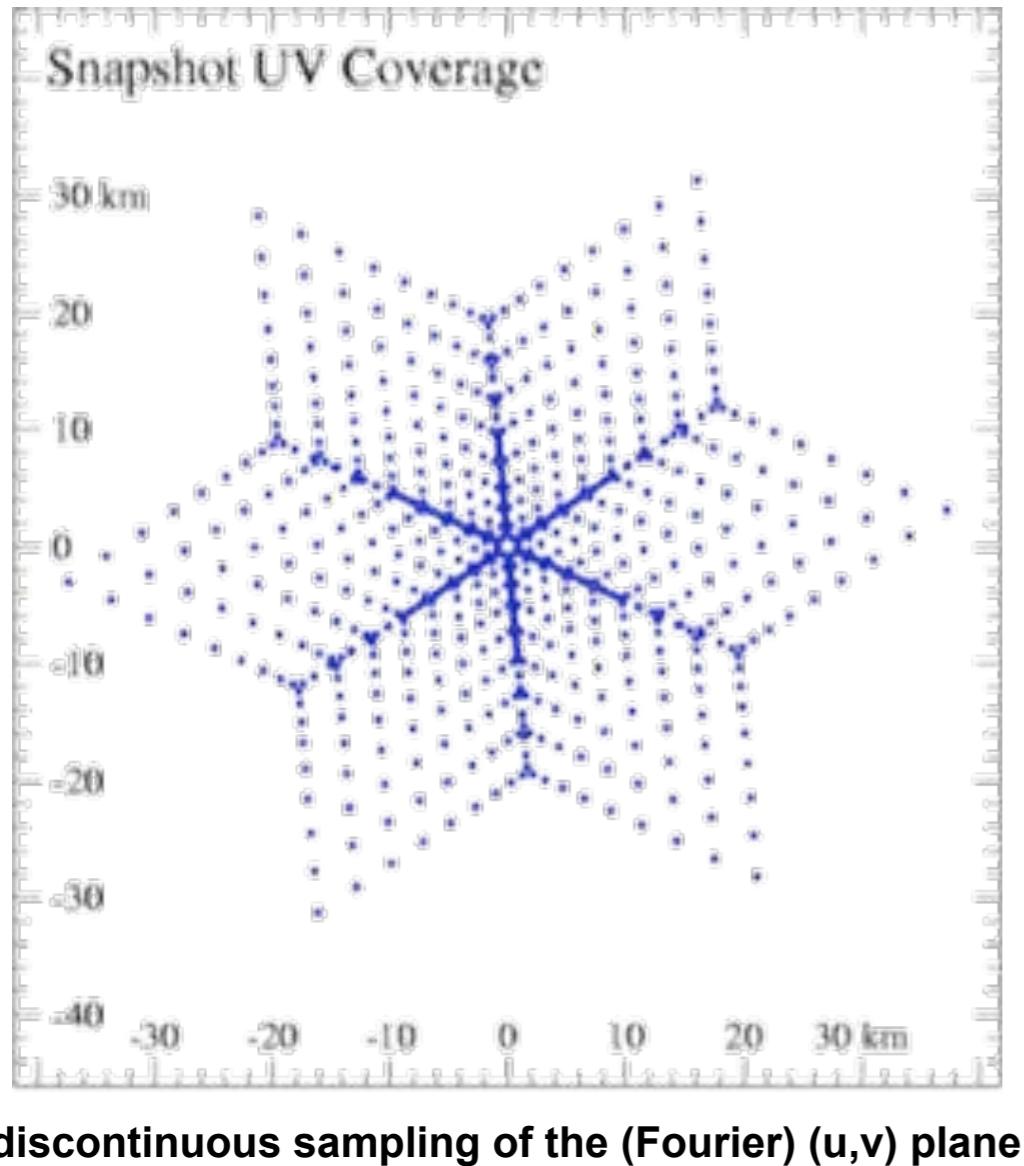
Inversion 2/2

Fourier domain Snapshot (u,v) coverage



Inversion 2/2

Fourier domain Snapshot (u,v) coverage



Usually:

- Poor Fourier sampling
- Not a true FT relation
- Simplifying hypotheses don't hold

insufficient samples, redundancy
non-coplanar interferometer
small field approximation

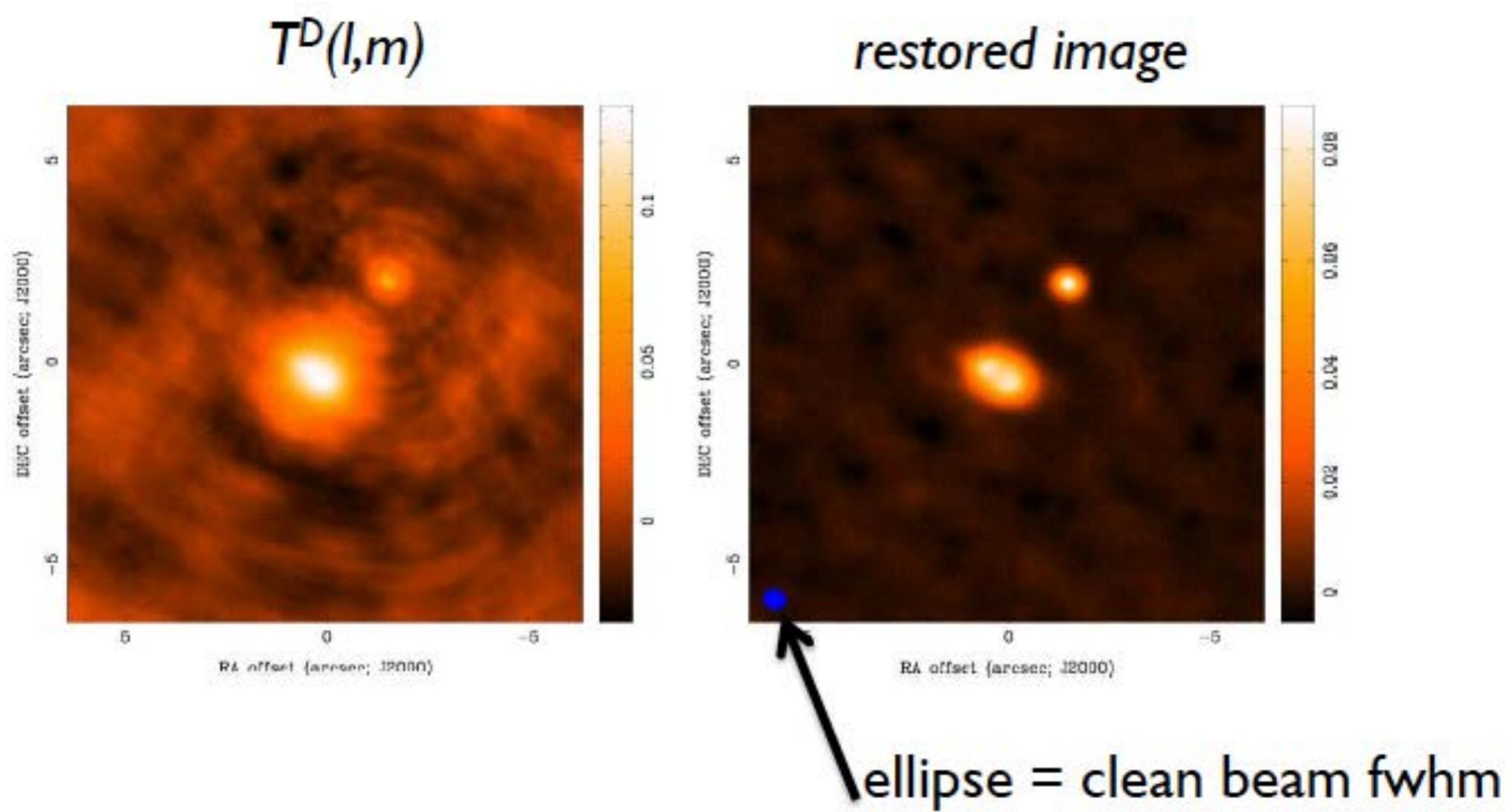
}

difficult inversion problem

+ all other Direction Dependent Effects (DDE) (Beam pattern, ionosphere...)

Animation ionosphère

CLEAN: the classical deconvolution method

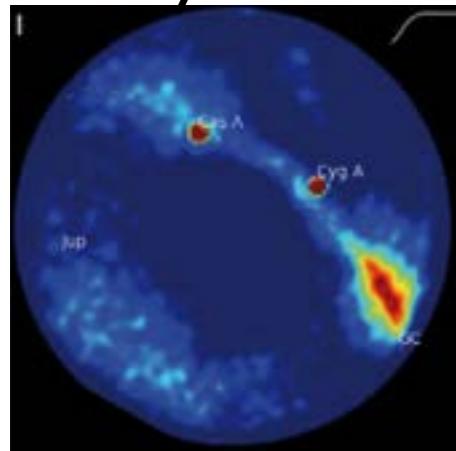


Stolen from D. Wilner presentation at NRAO 14th synthesis imaging workshop, Socorro

Some ground-based instruments fitted for transient detections

In the Image plane

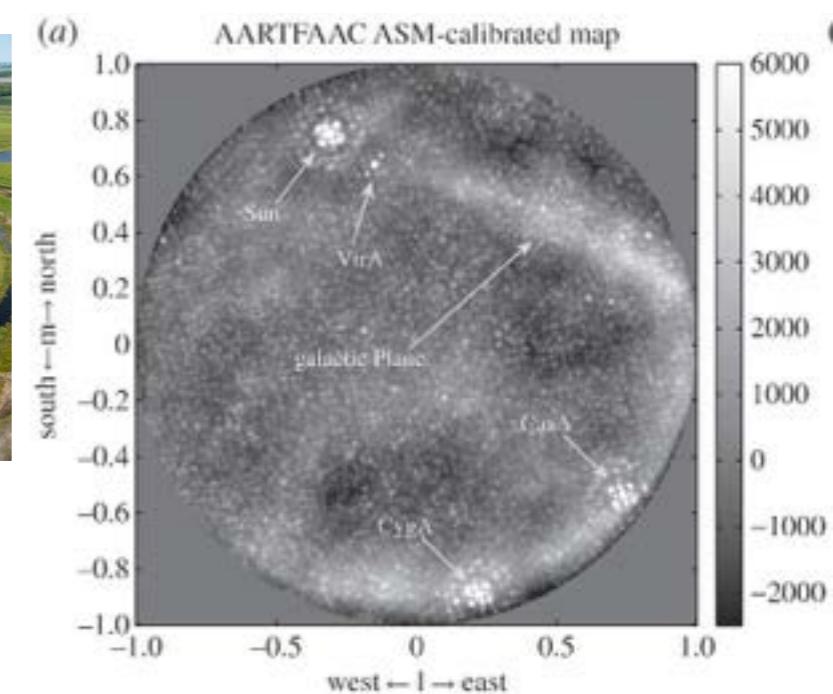
- all-sky monitors (AARTFAAC, LWA)



LWA [Hartman, 2011]



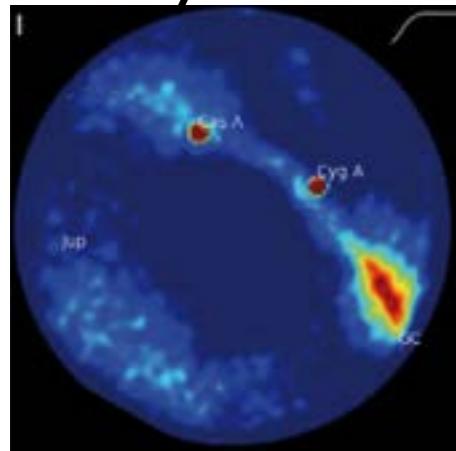
[Prasad, Wijnholds, 2013]



Some ground-based instruments fitted for transient detections

In the Image plane

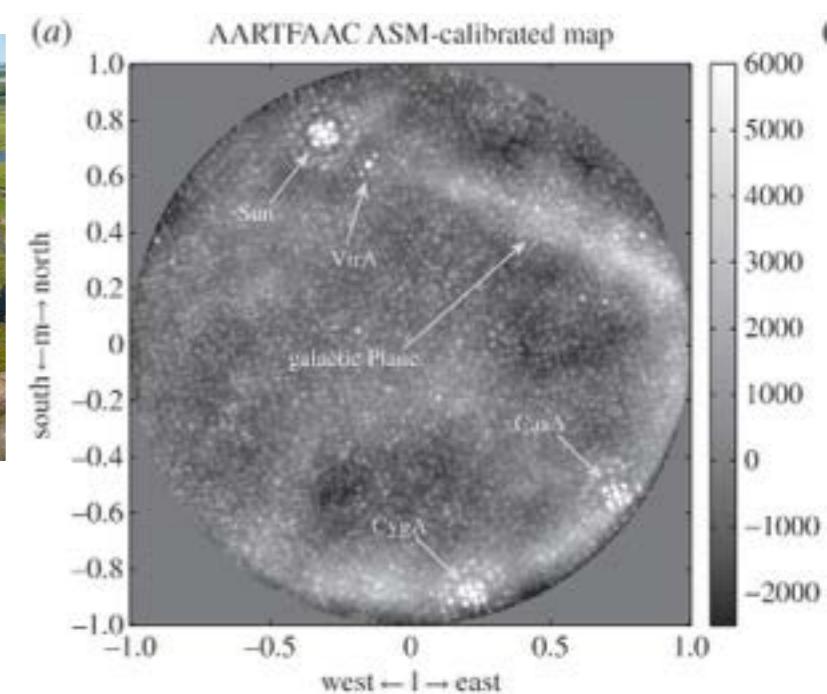
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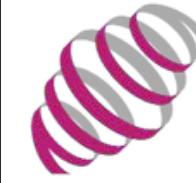
LWA [Hartman, 2011]



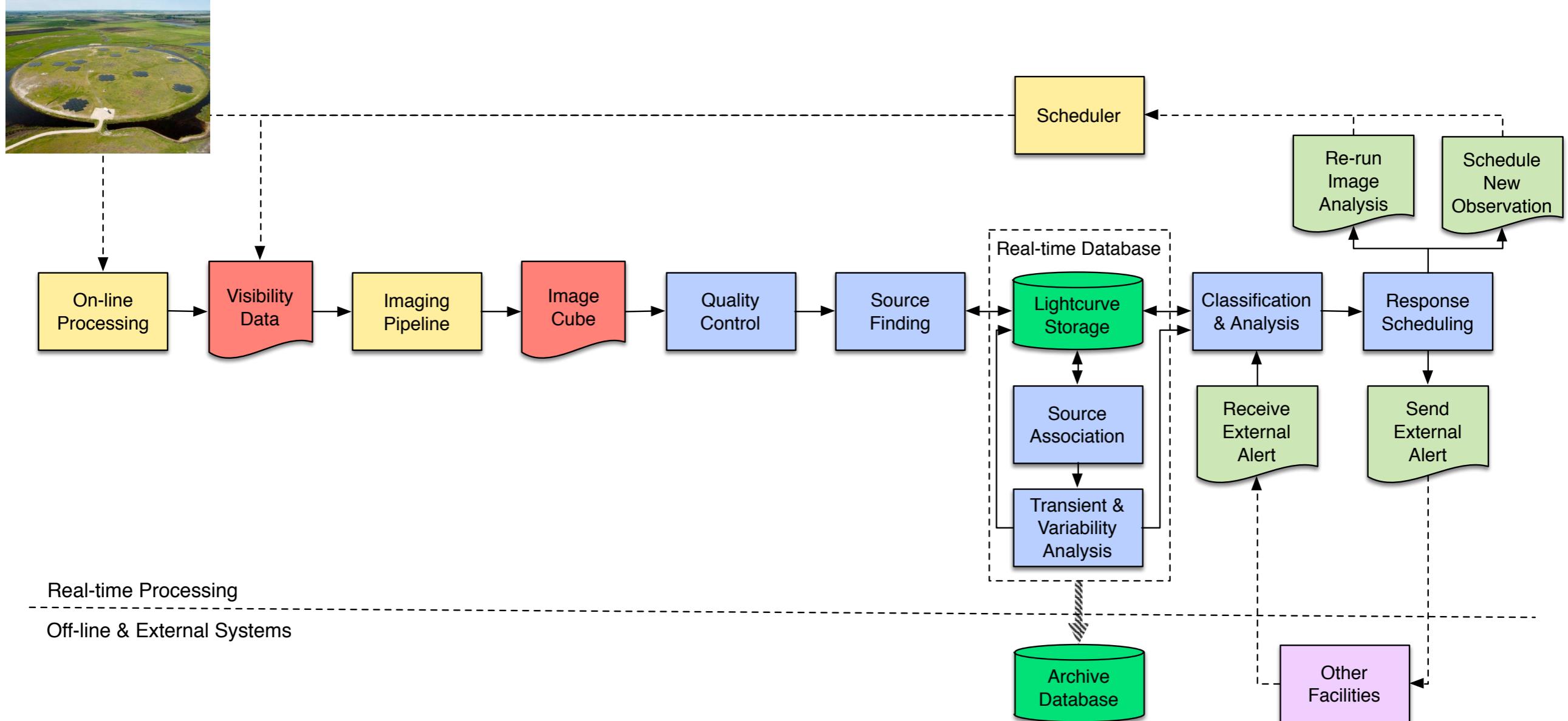
[Prasad, Wijnholds, 2013]



- all interferometers + transient detection pipeline



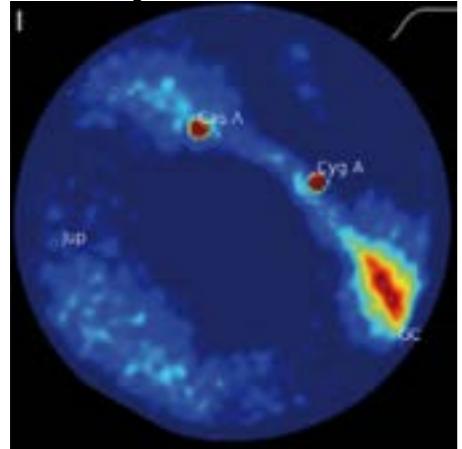
The LOFAR Transients Pipeline



Some ground-based instruments fitted for transient detections

In the Image plane

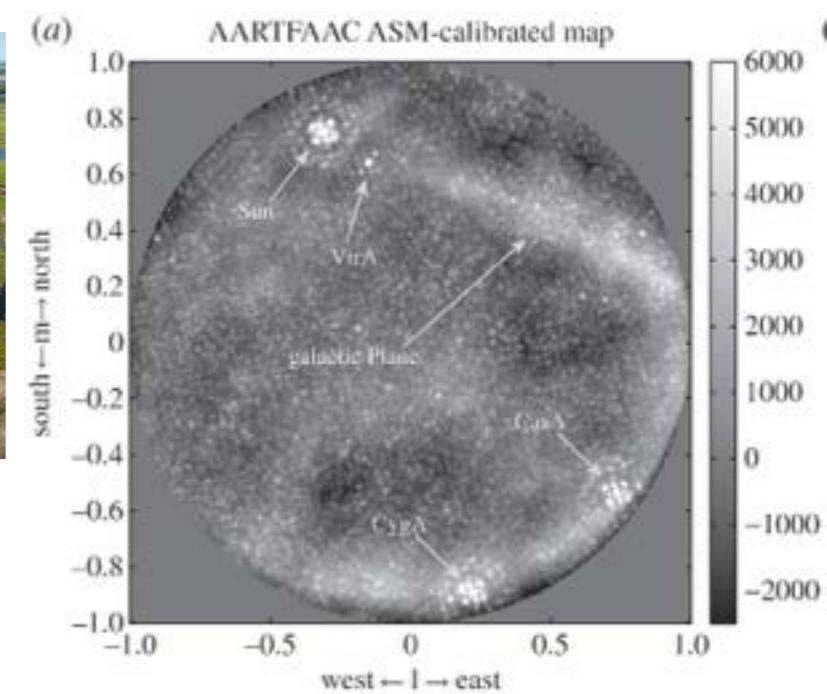
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LWA [Hartman, 2011]



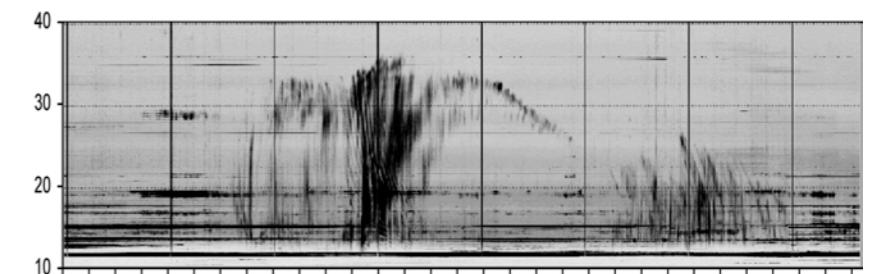
[Prasad, Wijnholds, 2013]



- all interferometers + transient detection pipeline

In the time/frequency domain

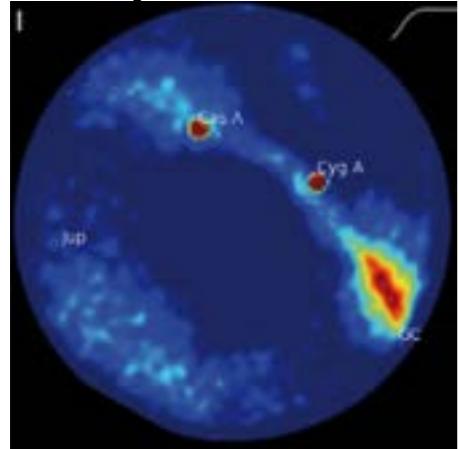
- Nançay Decameter Array, LOFAR, GMRT...
- CODALEMA (CR)...
cf. *Cosmic Ray session*
- Fripons (Meteors)
cf. *Meteors session*



Some ground-based instruments fitted for transient detections

In the Image plane

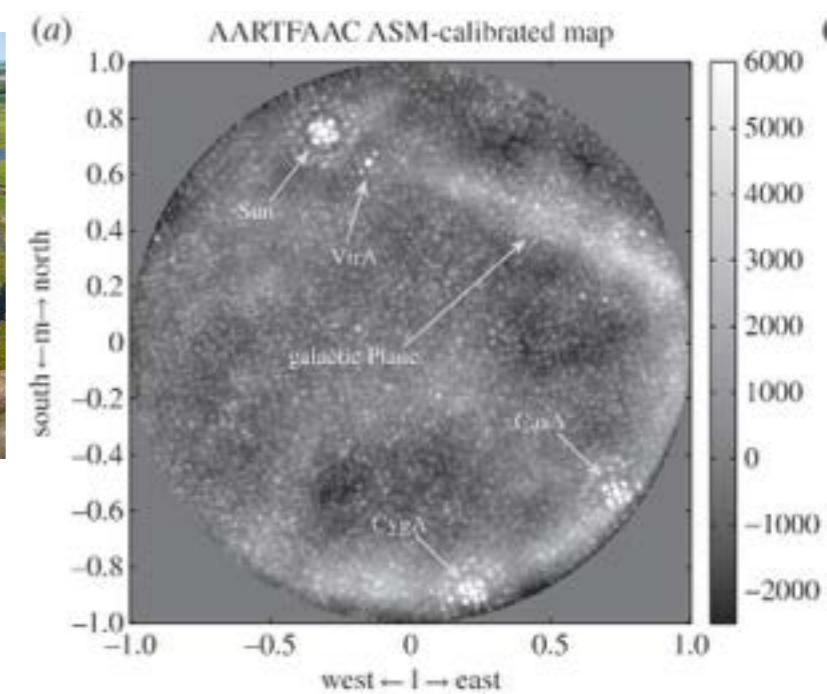
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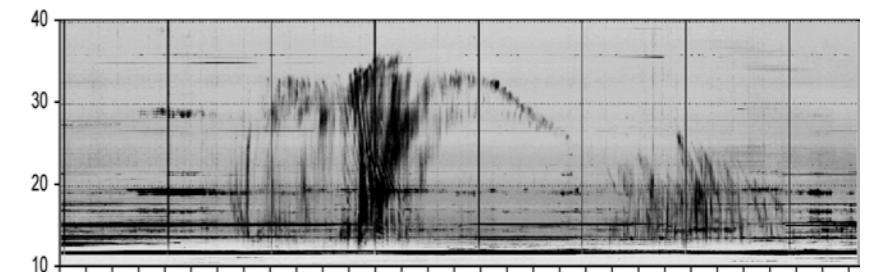
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In the time/frequency domain

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- Fripons (Meteors) cf. *Meteors session*



In the visibility plane

Potentially all interferometers... (but requires very good sky modeling)

[Trott et al., 2011]

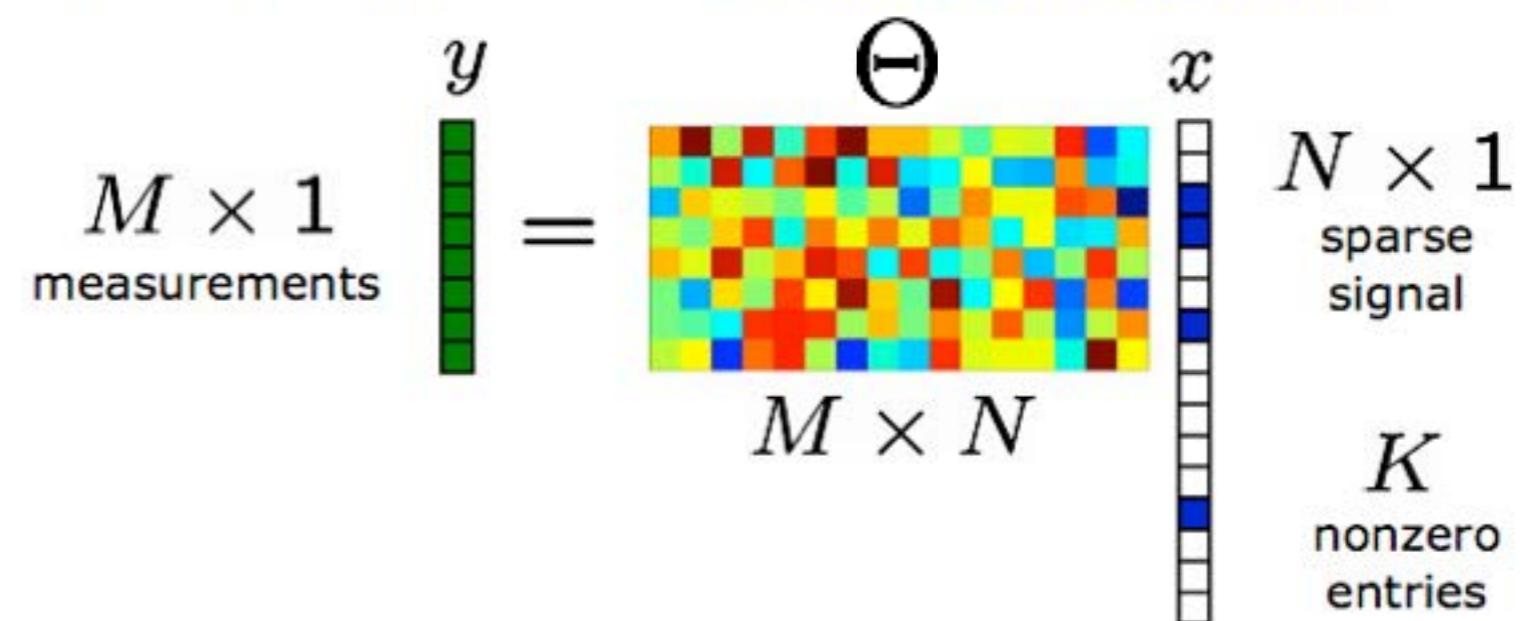
Compressed Sensing

- * E. Candès and T. Tao, “Near Optimal Signal Recovery From Random Projections: Universal Encoding Strategies?”, IEEE Trans. on Information Theory, 52, pp 5406–5425, 2006.
* D. Donoho, “Compressed Sensing”, IEEE Trans. on Information Theory, 52(4), pp. 1289–1306, April 2006.
* E. Candès, J. Romberg and T. Tao, “Robust Uncertainty Principles: Exact Signal Reconstruction from Highly Incomplete Frequency Information”, IEEE Trans. on Information Theory, 52(2) pp. 489 – 509, Feb. 2006.

A non linear sampling theorem

“Signals with exactly K components different from zero can be recovered perfectly from $\sim K \log N$ incoherent measurements”

$$y = \Theta x$$



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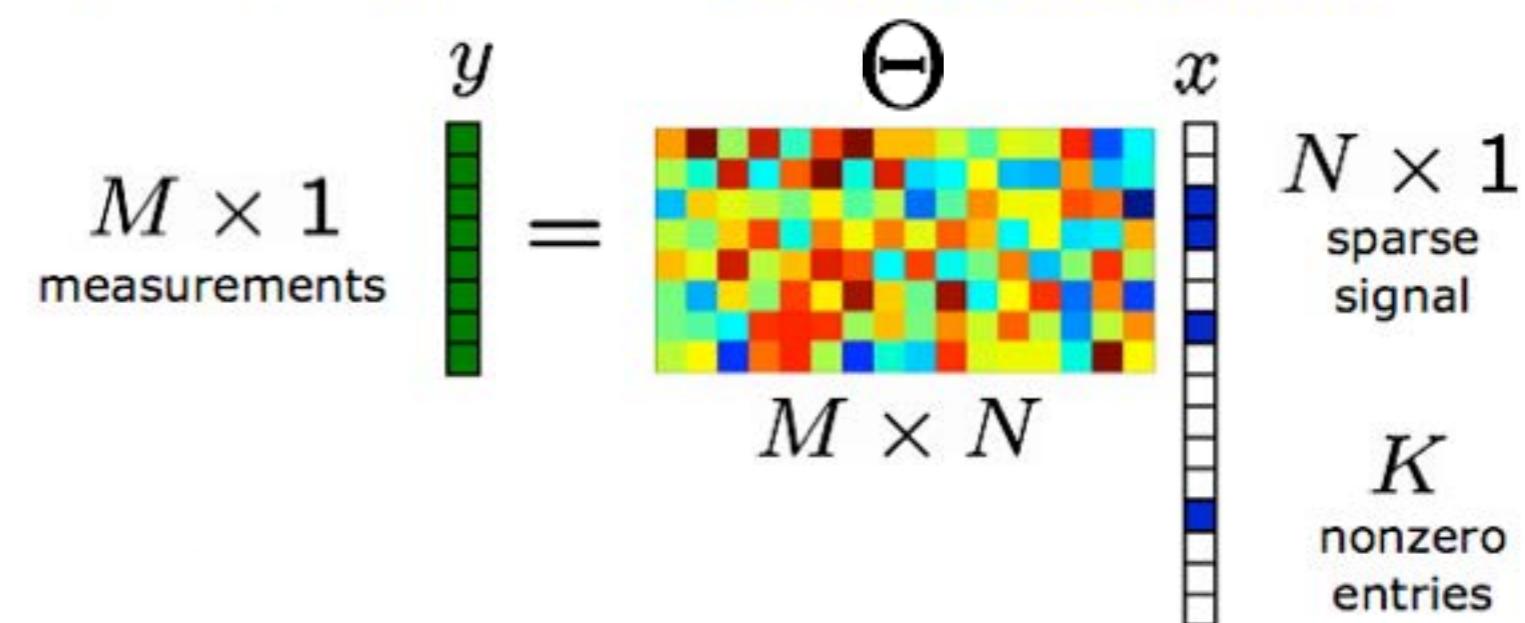
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Assumption on the signal x : - Underdetermined system
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$\} K < M \ll N$



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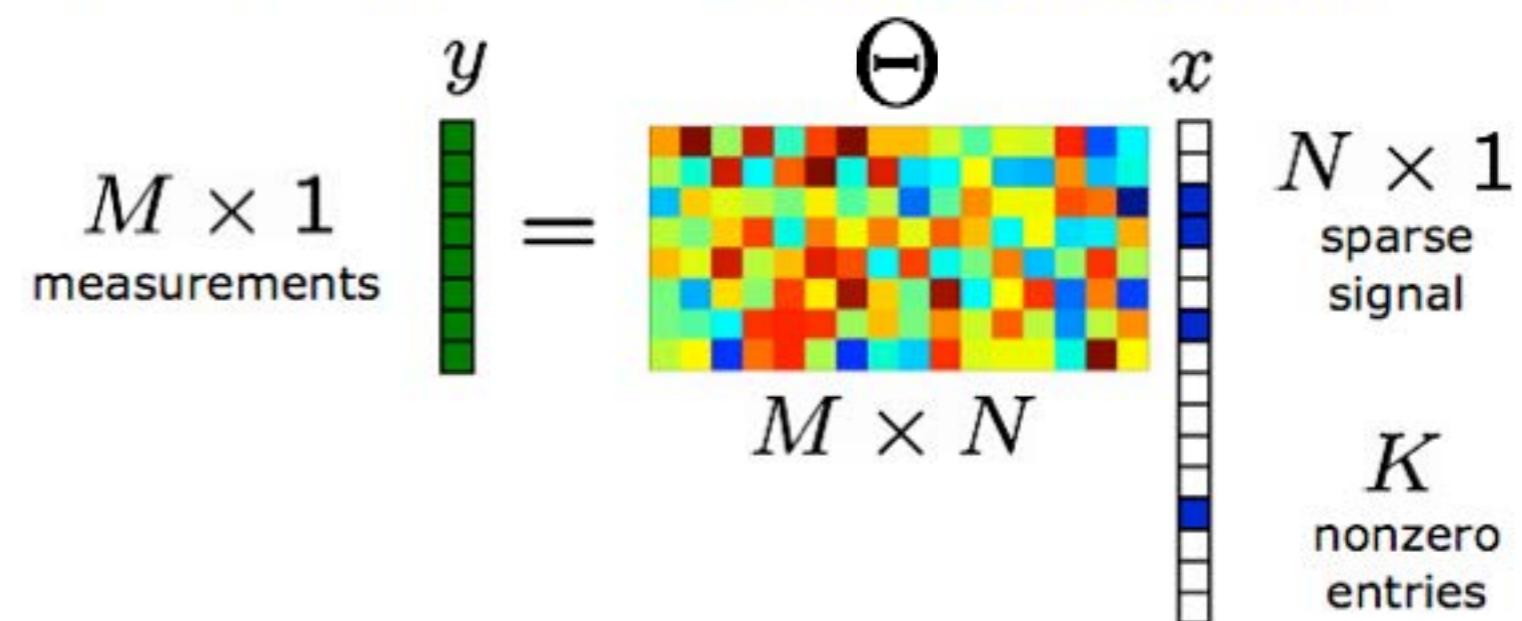
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- Incoherence (Θ random)

$\} K < M \ll N$

Reconstruction based on non-linear algorithms

$$\min_x \|x\|_1 \text{ s.t. } y = \Theta x$$

Radio interferometry & Compressed Sensing

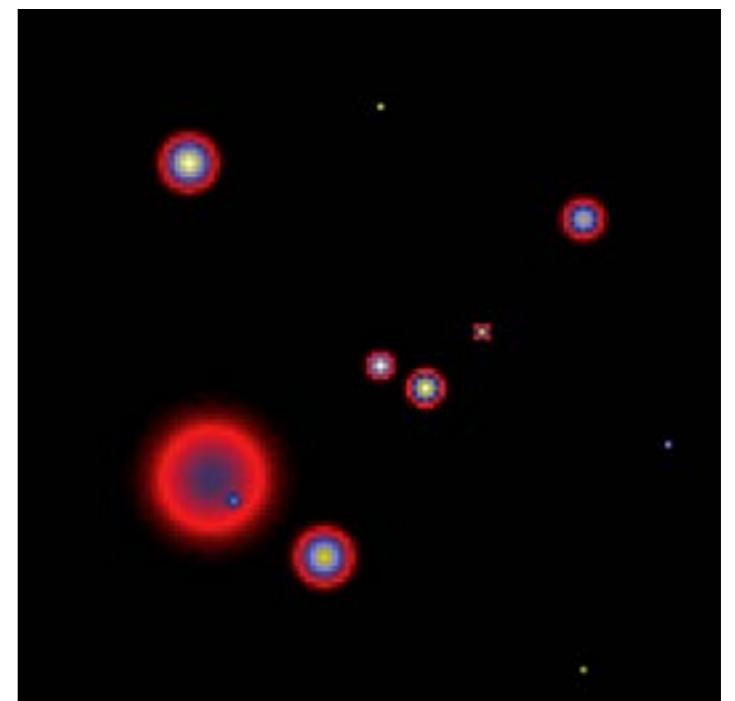


y



=

Visibilities



Sky

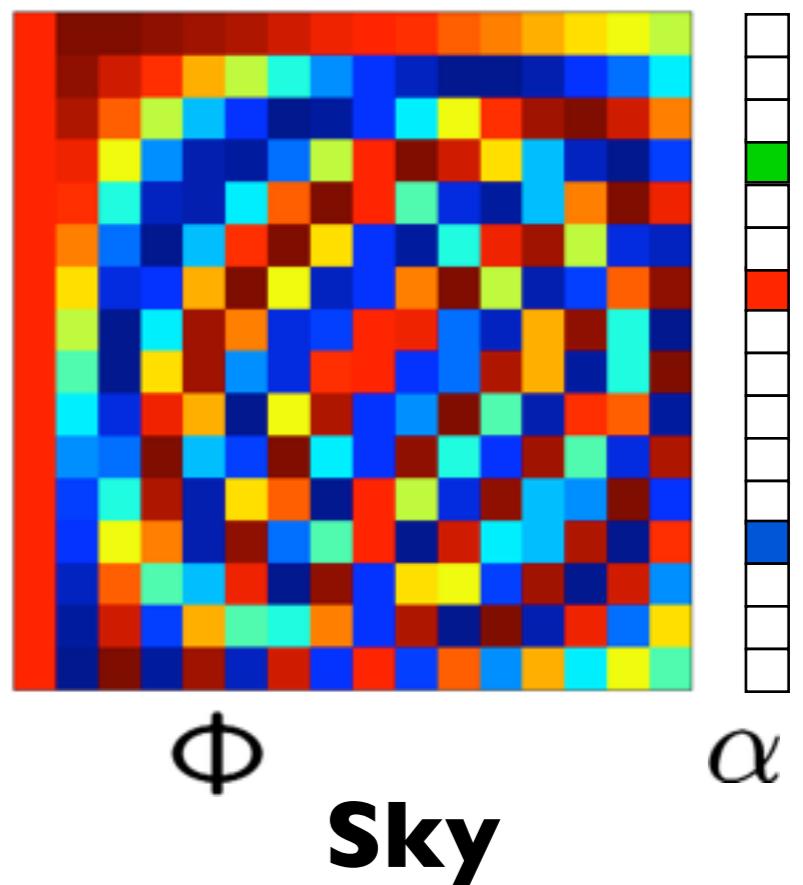
X

[McEwen et al, 2011; Wenger et al, 2010; Wiaux et al, 2009; Cornwell et al, 2009; Suskimo, 2009; Feng et al, 2011; Garsden, Starck and Corbel, 2013]

Radio interferometry & Compressed Sensing



$$y = \text{Visibilities}$$

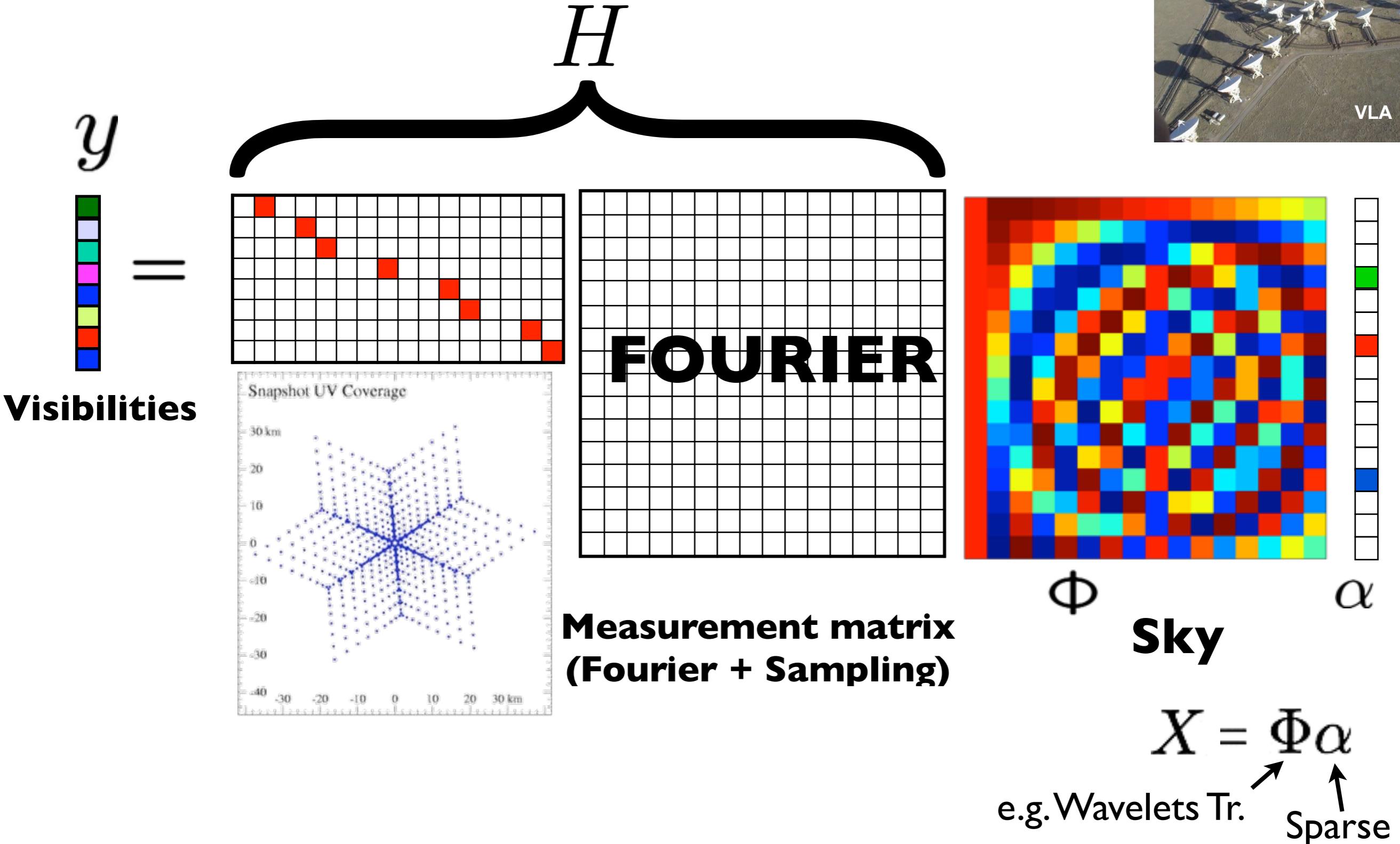


$$X = \Phi\alpha$$

e.g. Wavelets Tr. Sparse

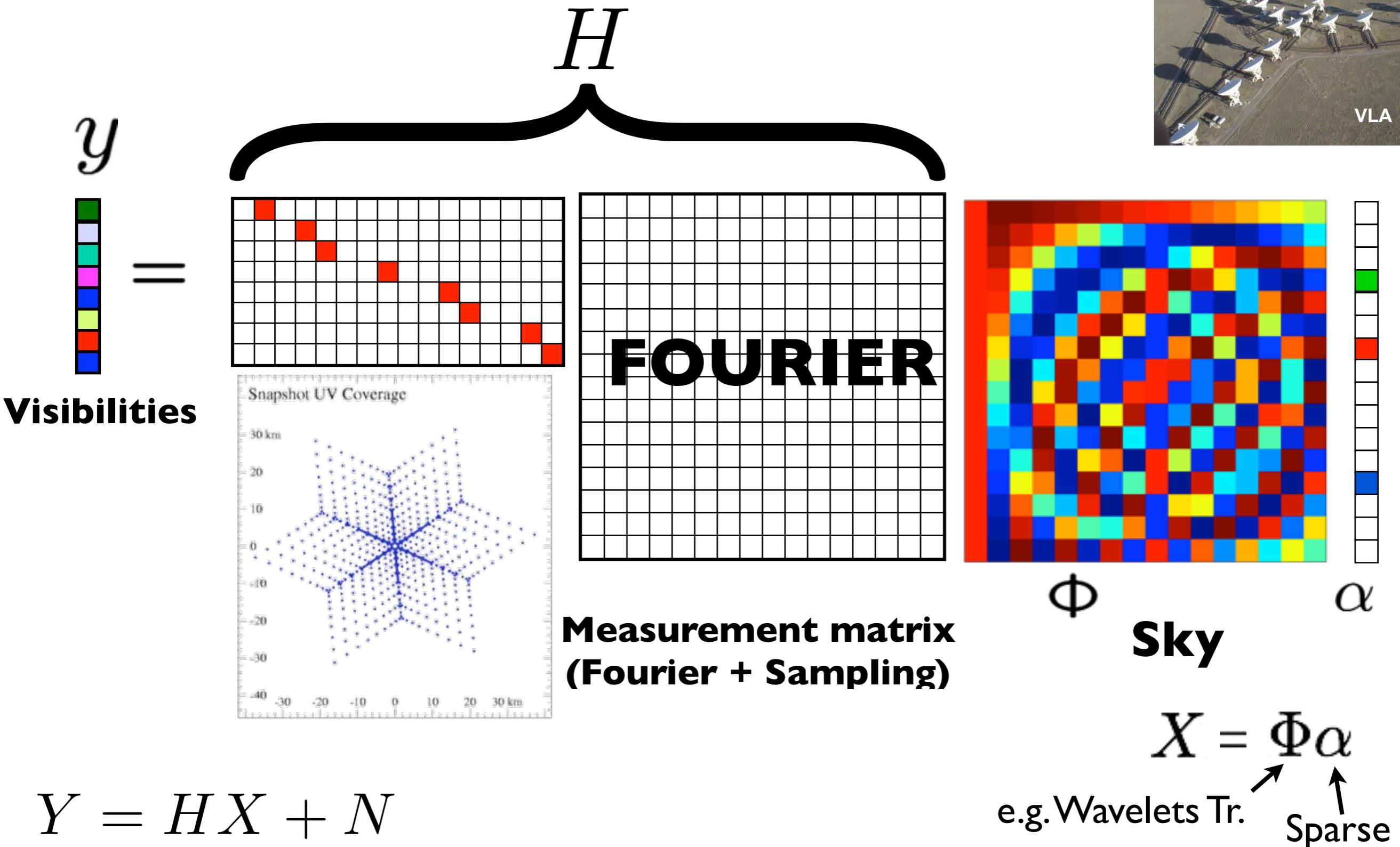
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Radio interferometry & Compressed Sensing



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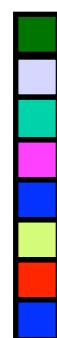
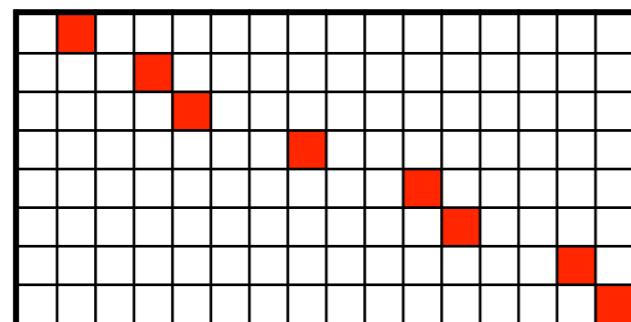
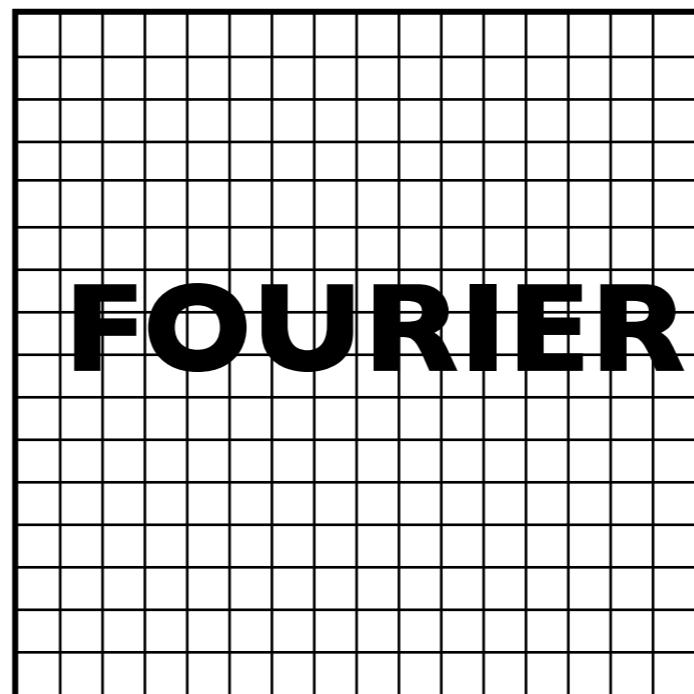
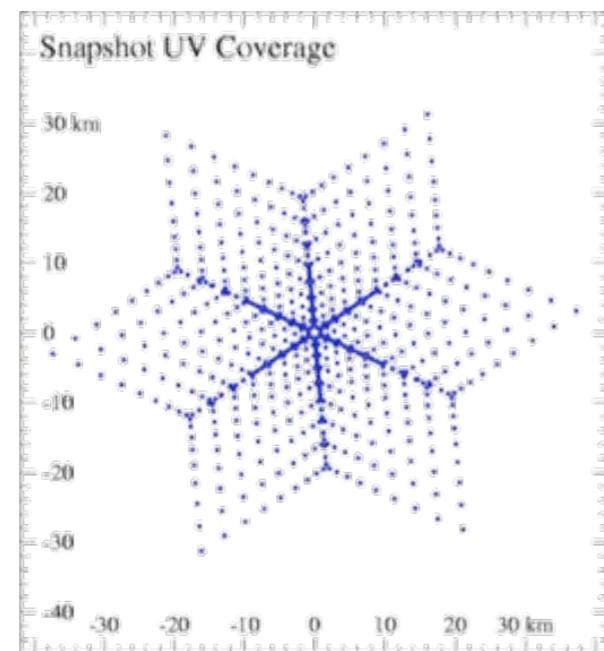
Radio interferometry & Compressed Sensing



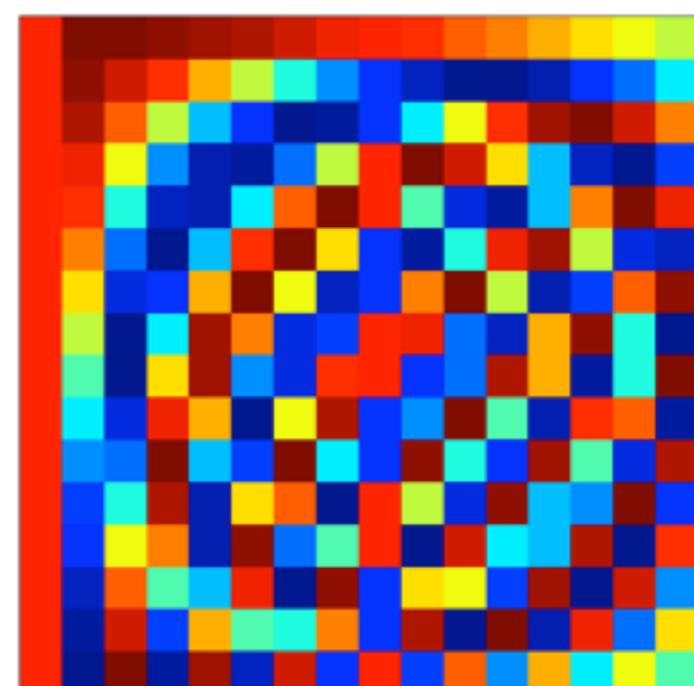
$$Y = HX + N$$

[McEwen et al, 2011; Wenger et al, 2010; Wiaux et al, 2009; Cornwell et al, 2009; Suskimo, 2009; Feng et al, 2011; Garsden, Starck and Corbel, 2013]

Radio interferometry & Compressed Sensing


 y

 $=$

 H
Visibilities


**Measurement matrix
(Fourier + Sampling)**


 Φ
Sky

 α

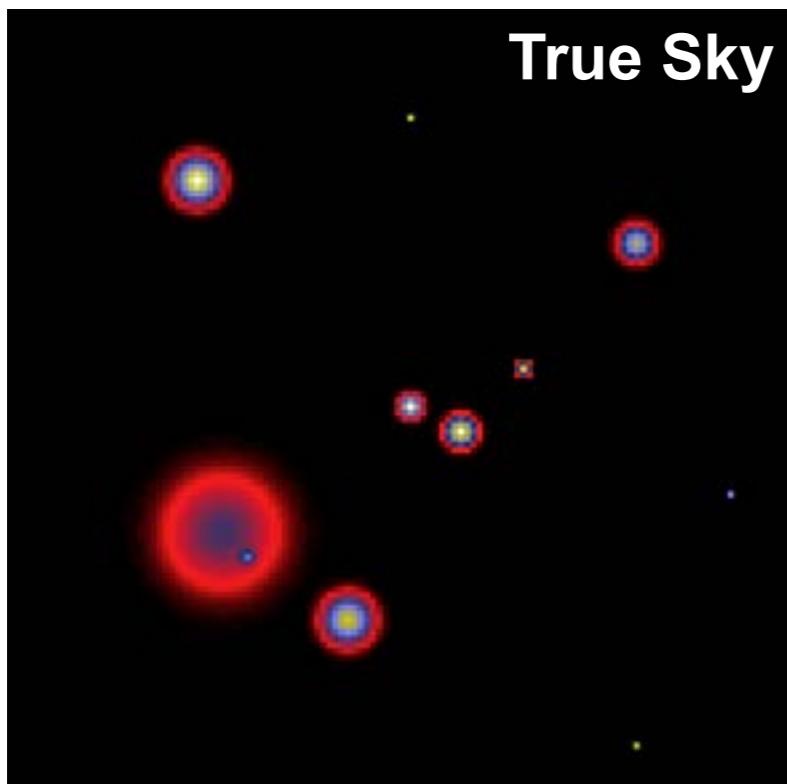
$$Y = HX + N$$

$$\min_{\alpha} \|\alpha\|_p^p \quad \text{subject to} \quad \|Y - H\Phi\alpha\|^2 \leq \epsilon$$

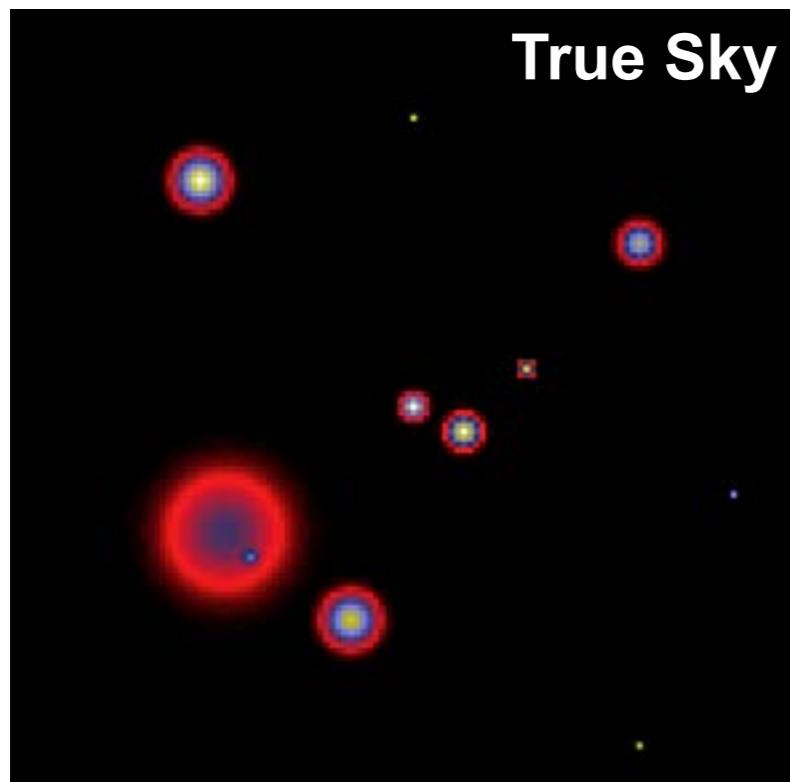
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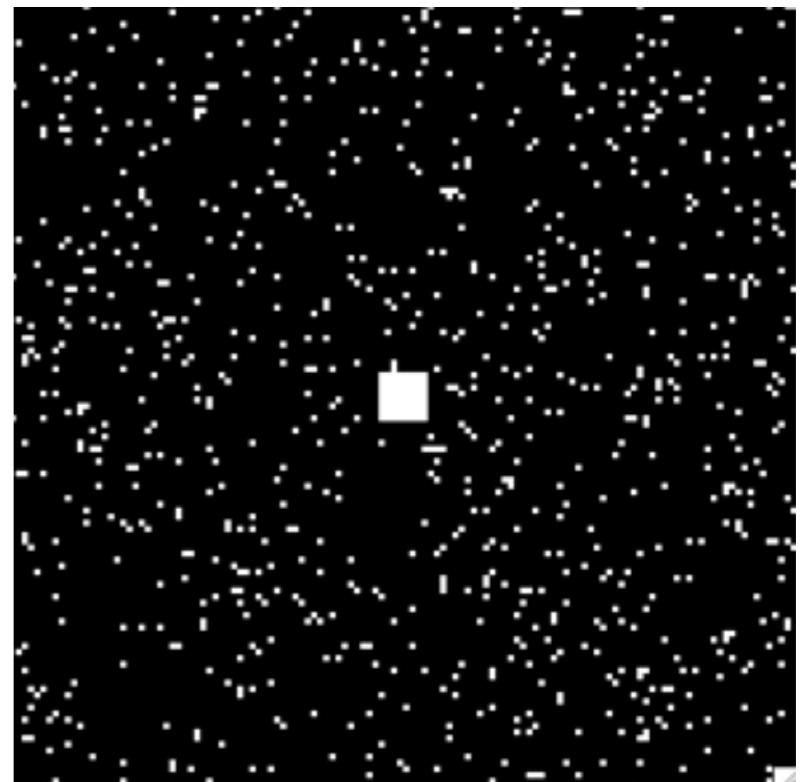
Sparse recovery example



Sparse recovery example

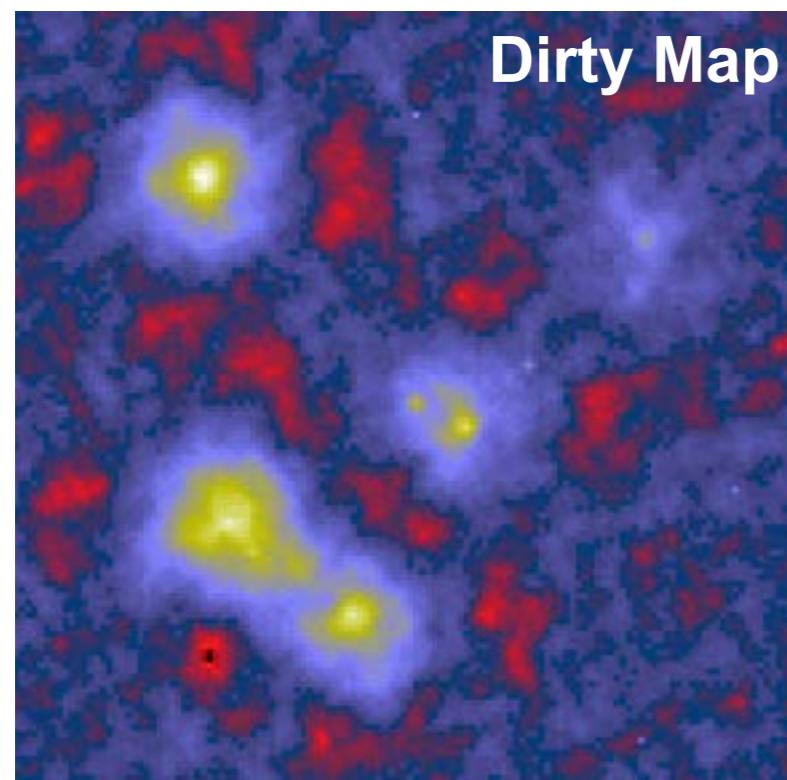
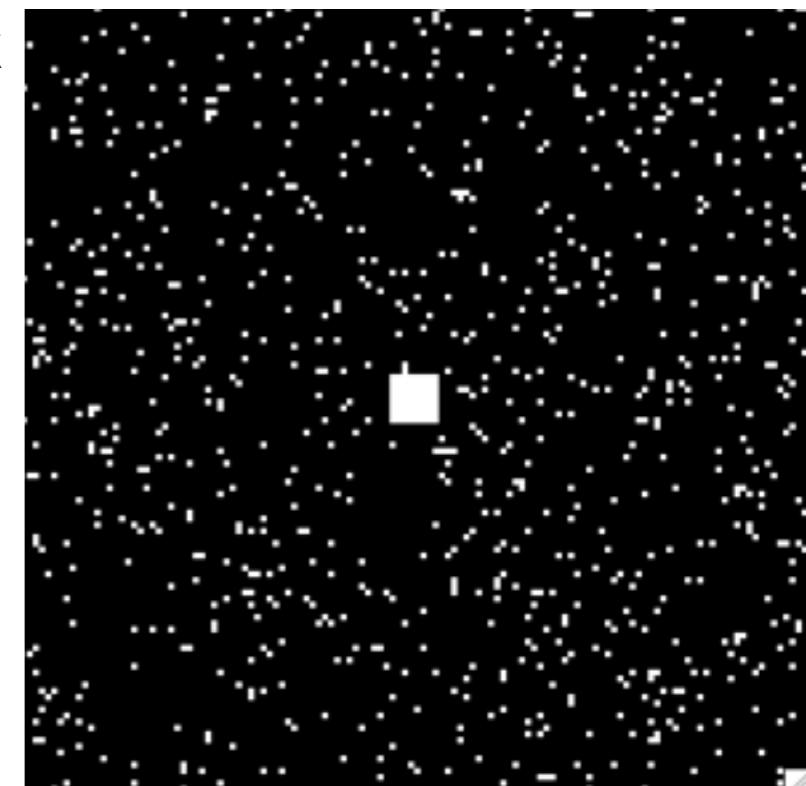
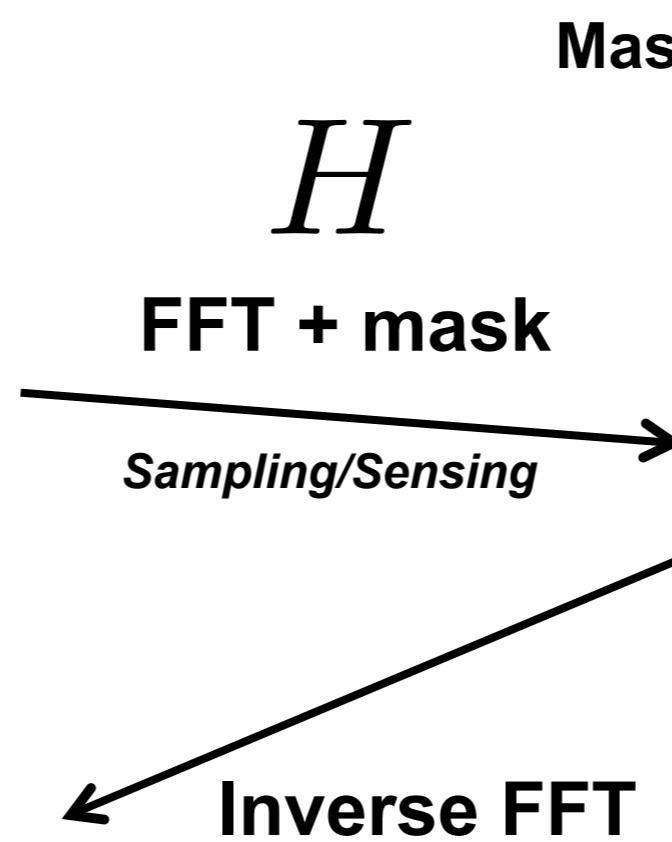
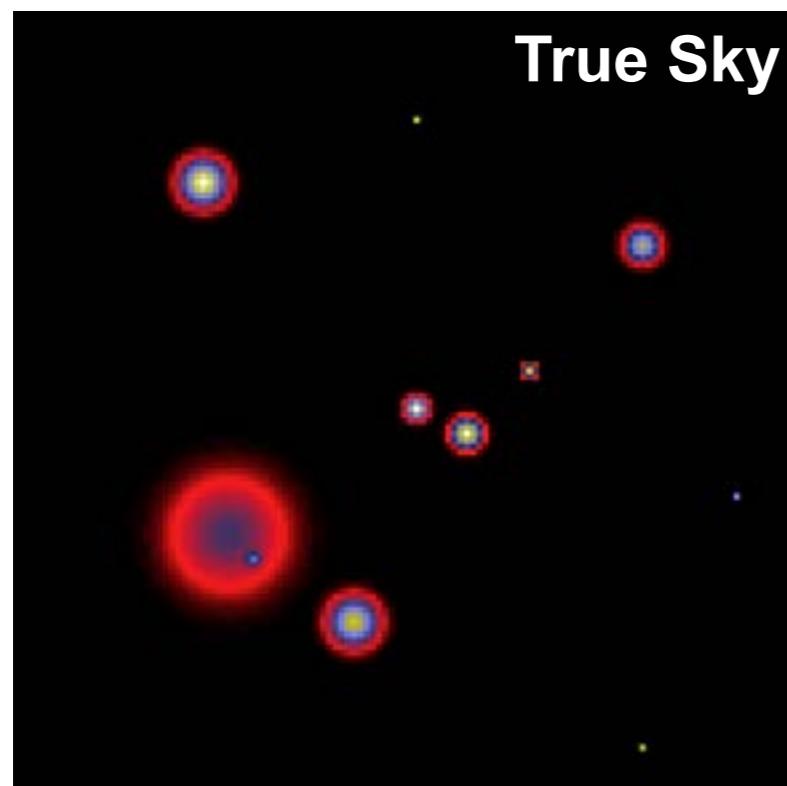


Mask

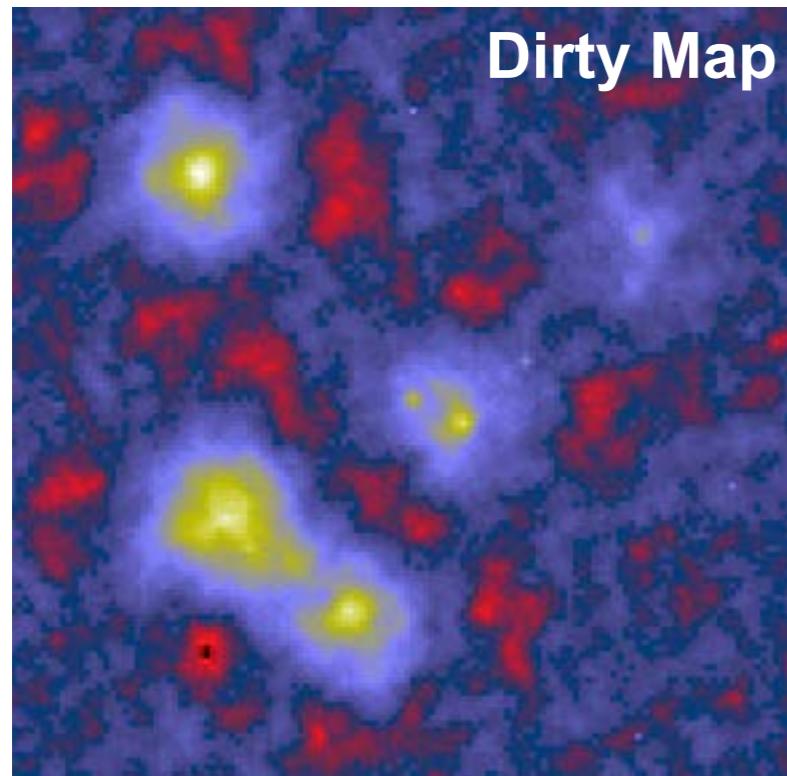
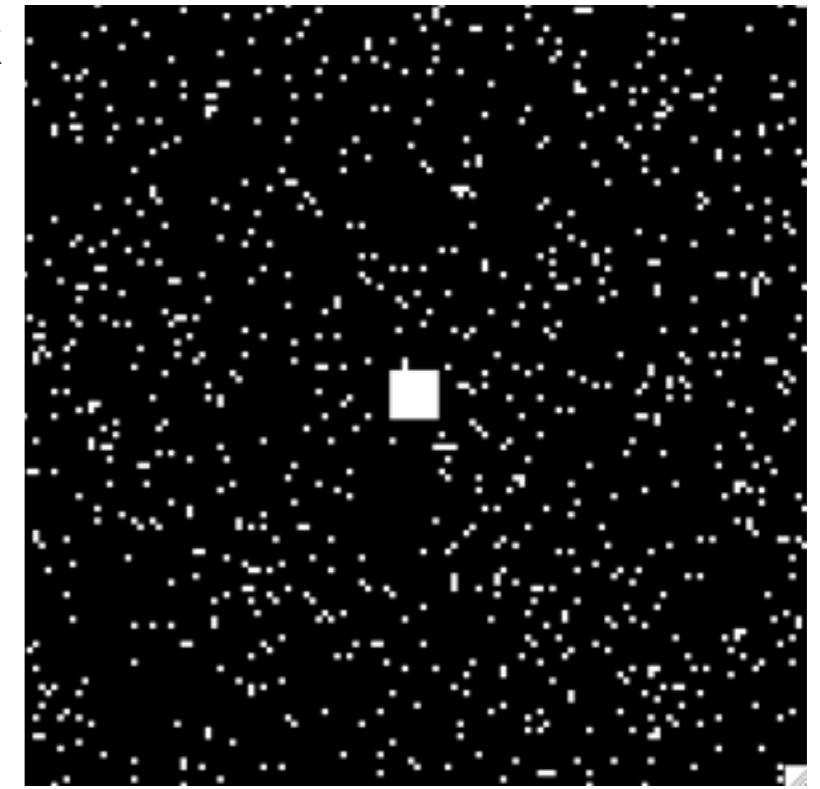
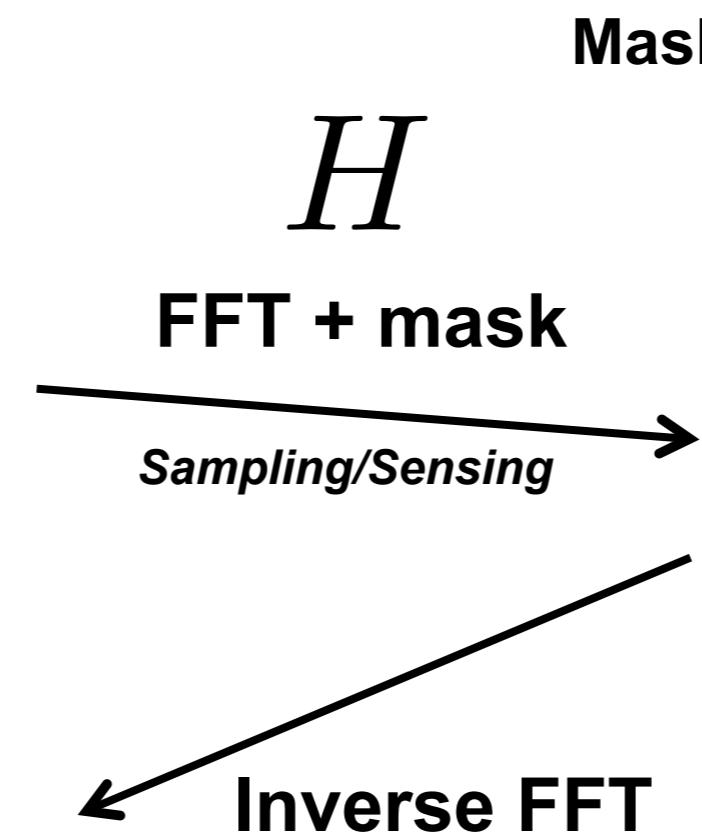
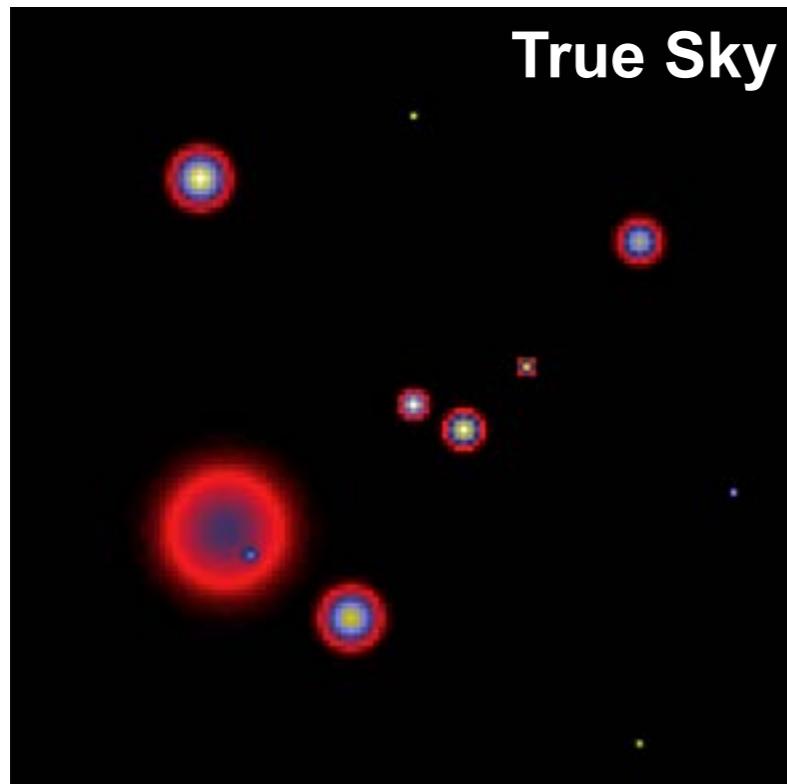


H
FFT + mask
Sampling/Sensing →

Sparse recovery example



Sparse recovery example

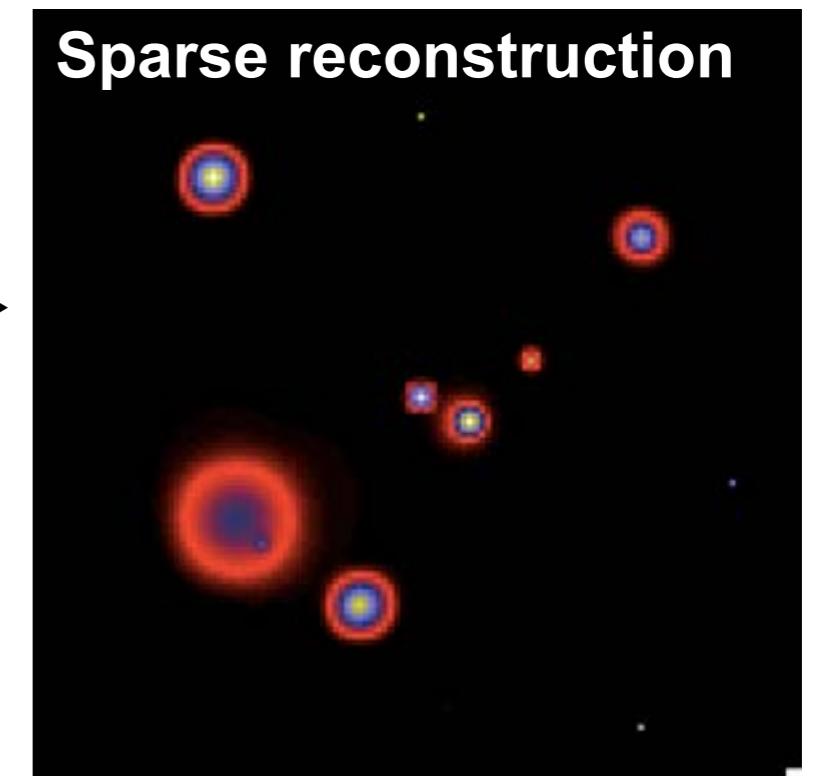


→

**Sparse Recovery
(FISTA)**

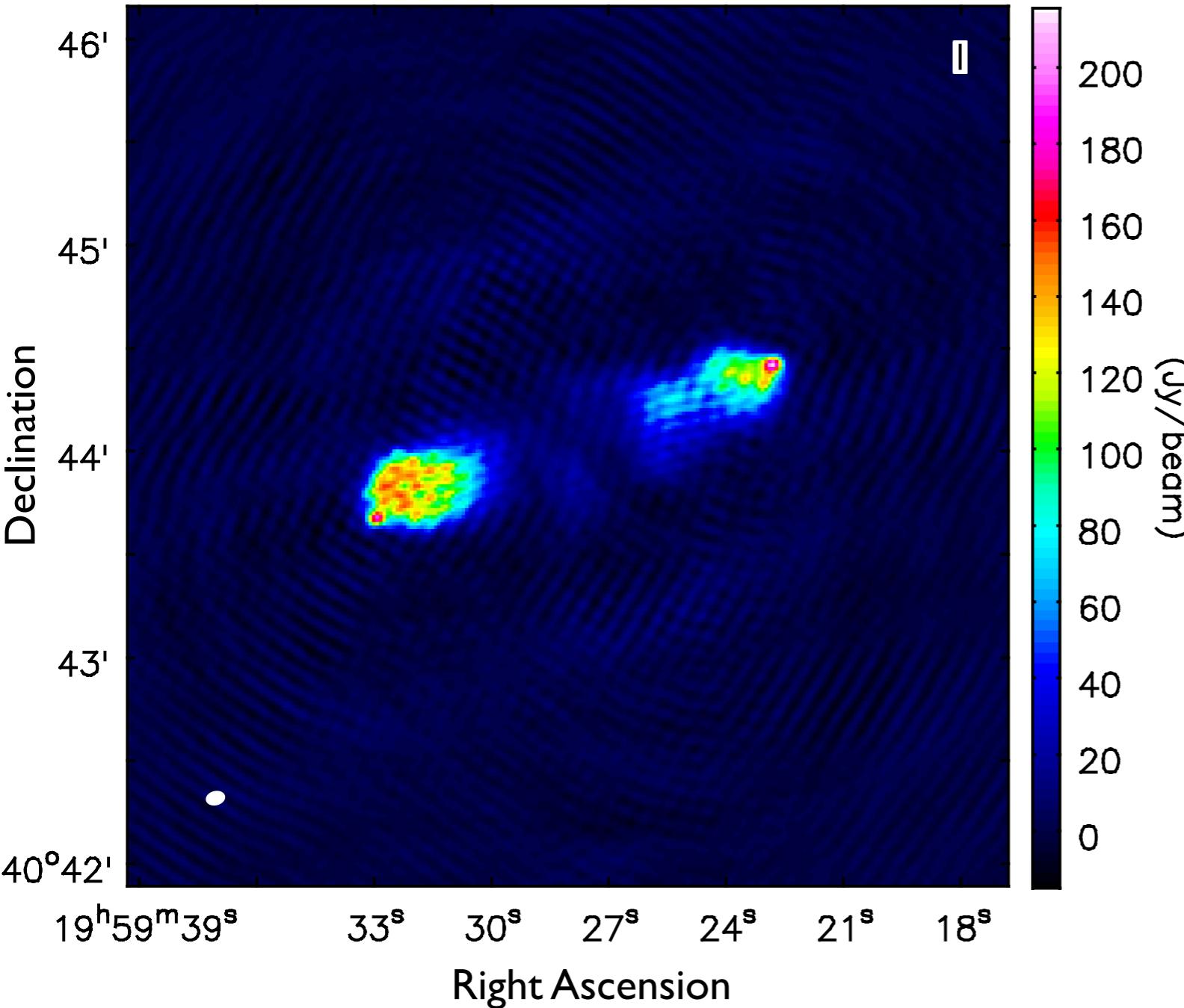
Fast Iterative
Shrinkage-Thresholding
Algorithm

[Beck & Teboulle, 2009]



Cygnus A

CLEAN



Restored image

Total Flux density = 9393 Jy

Residual std-dev = 2,65 Jy/beam

$F = 151 \text{ MHz} - \Delta F = 195 \text{ kHz}$

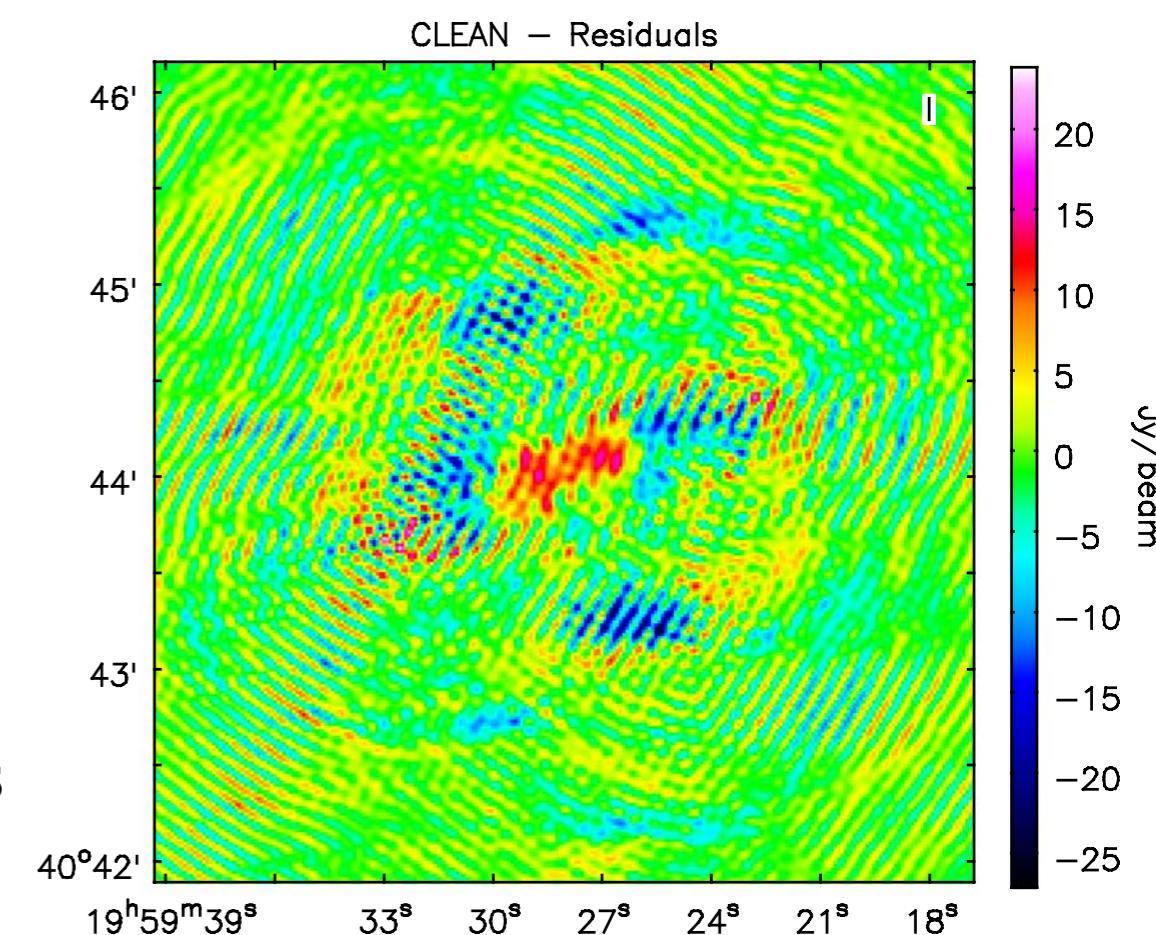
$\Delta T = 6 \text{ Hr}$

36 LOFAR Stations

(dataset courtesy of John McKean)

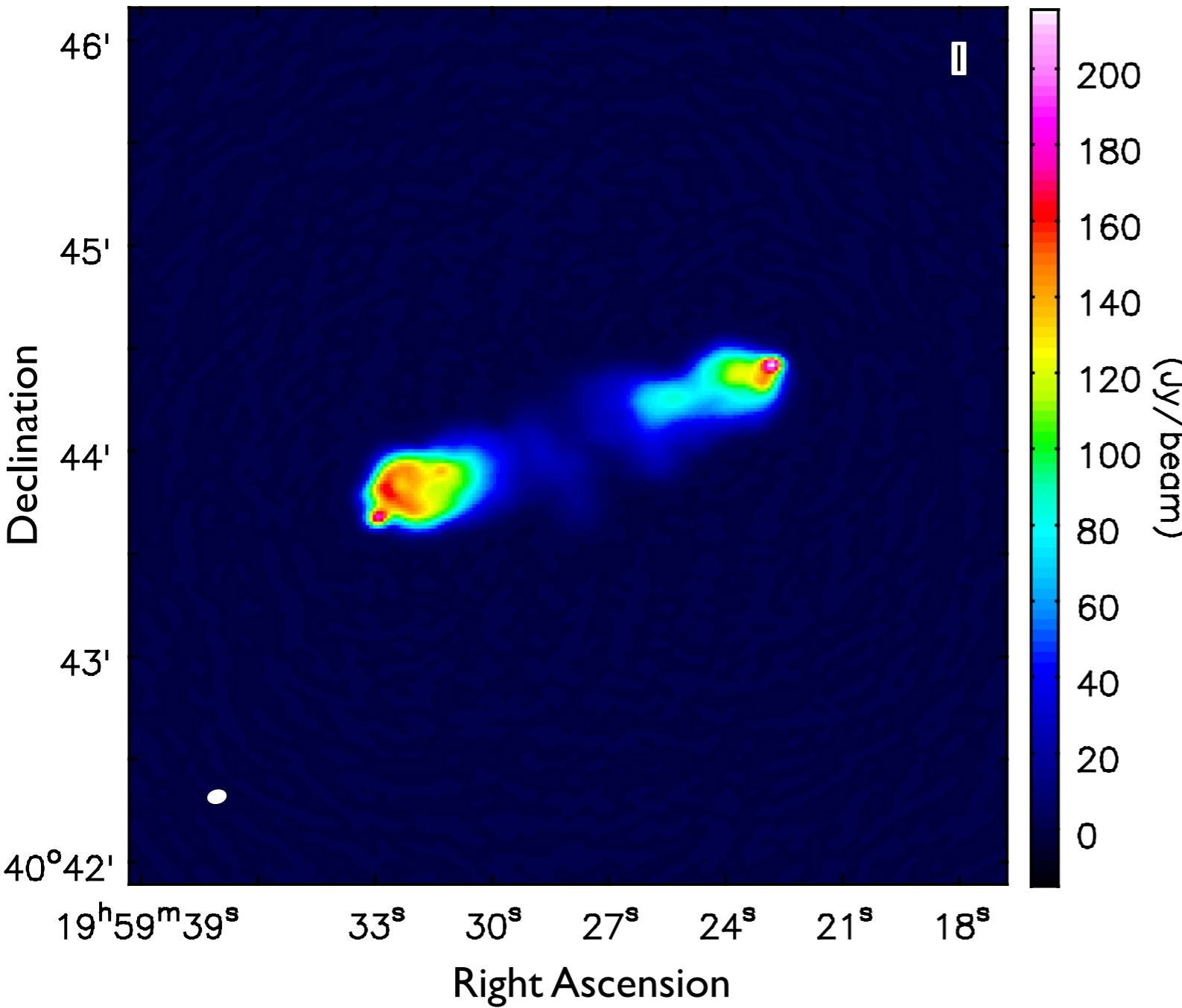
CLEAN

- Pixel = 1" size = 512×512
- Threshold = 0.5 mJy
- Weighting = super uniform



Cygnus A

Multi-Scale CLEAN



F = 151 MHz - $\Delta F = 195$ kHz

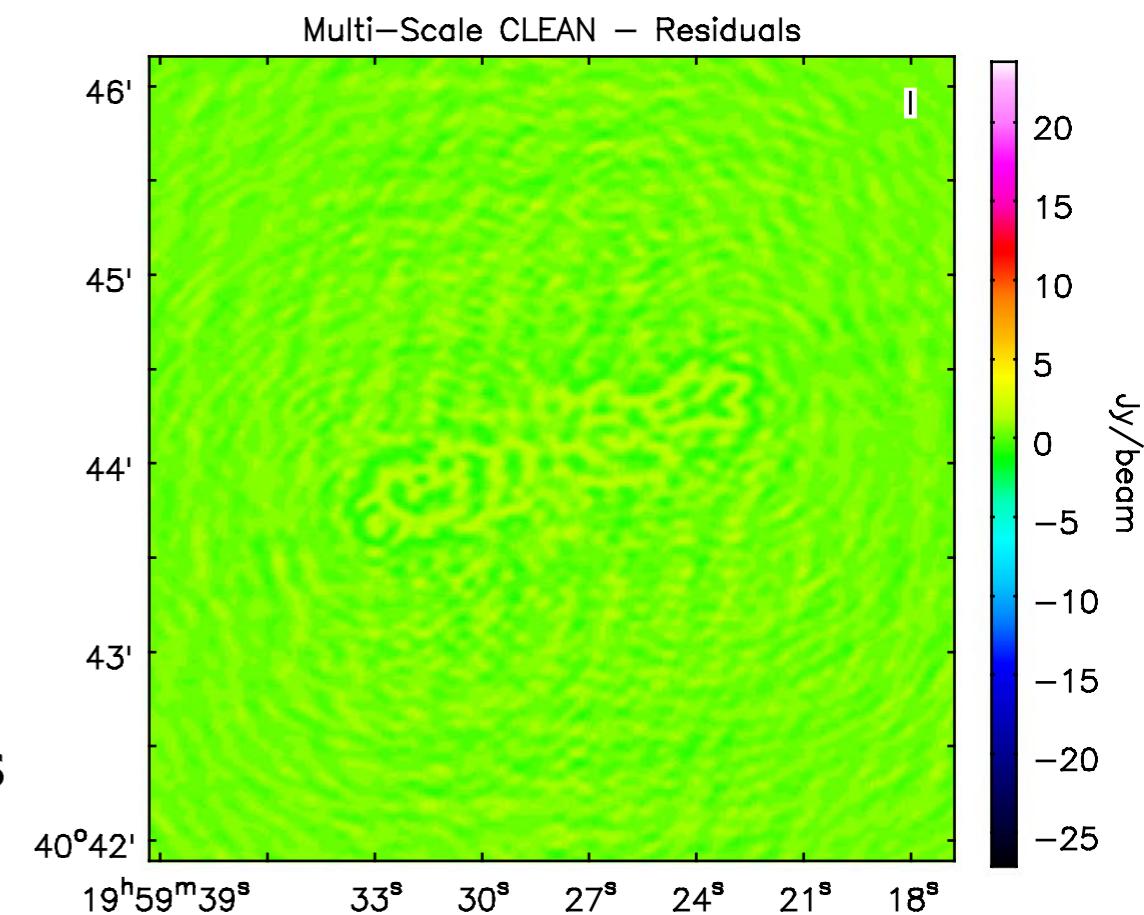
$\Delta T = 6$ Hr

36 LOFAR Stations

(dataset courtesy of John McKean)

Multi-Scale CLEAN

- Pixel = 1" size = 512 x 512
- Threshold = 0.5 mJy
- Weighting = super uniform
- Scales = [0, 5, 10, 15, 20] pixels



Cygnus A

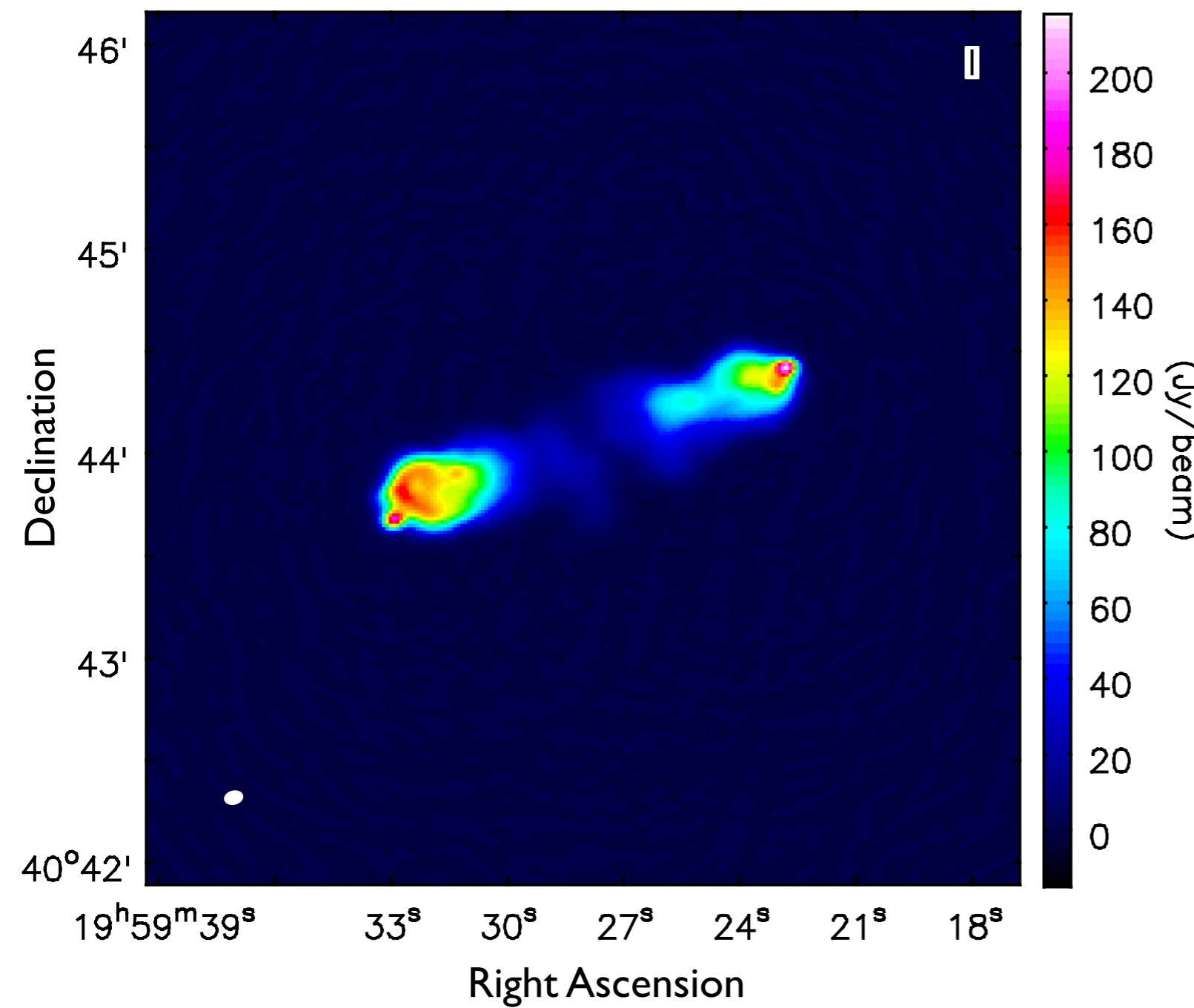
Multi-Scale CLEAN

$F = 151 \text{ MHz} - \Delta F = 195 \text{ kHz}$

$\Delta T = 6 \text{ Hr}$

36 LOFAR Stations

(dataset courtesy of John McKean)

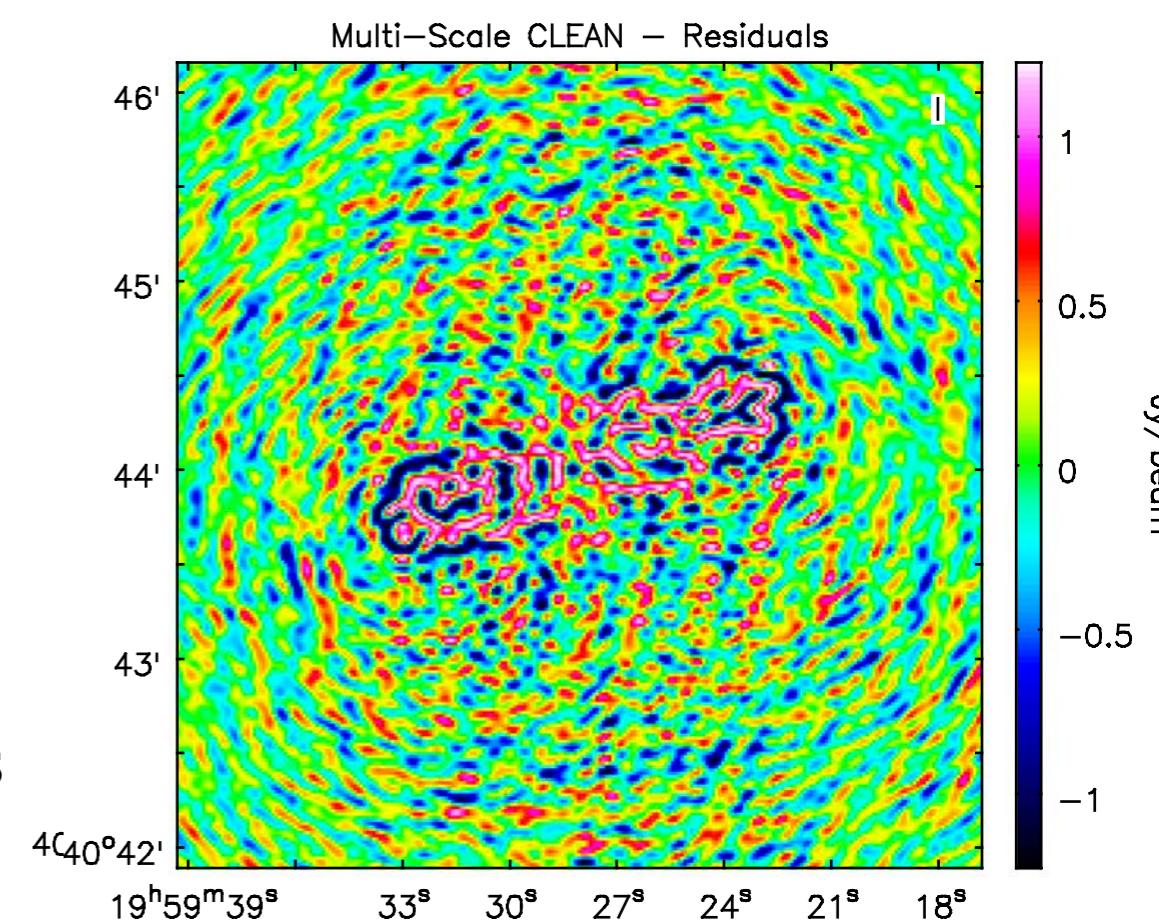


Restored image

Total Flux density = 10553 Jy

Residuals

Residual std-dev = 0,26 Jy/beam

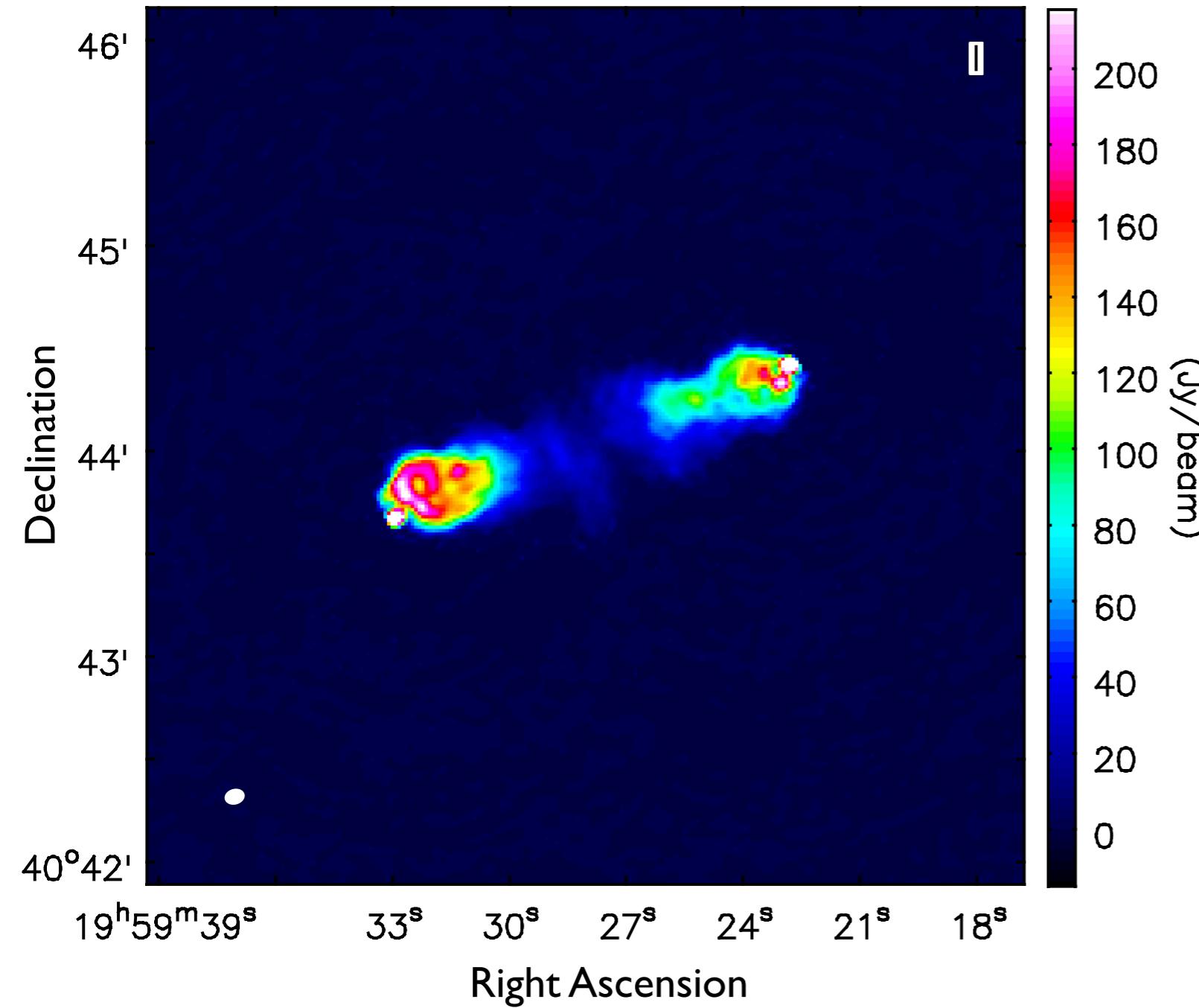


Multi-Scale CLEAN

- Pixel = 1'' size = 512 × 512
- Threshold = 0.5 mJy
- Weighting = super uniform
- Scales = [0, 5, 10, 15, 20] pixels

Cygnus A

Sparse Reconstruction



Restored image

Total Flux density = 10506 Jy

Residual std-dev = 0,05 Jy/beam

$F = 151 \text{ MHz} - \Delta F = 195 \text{ kHz}$

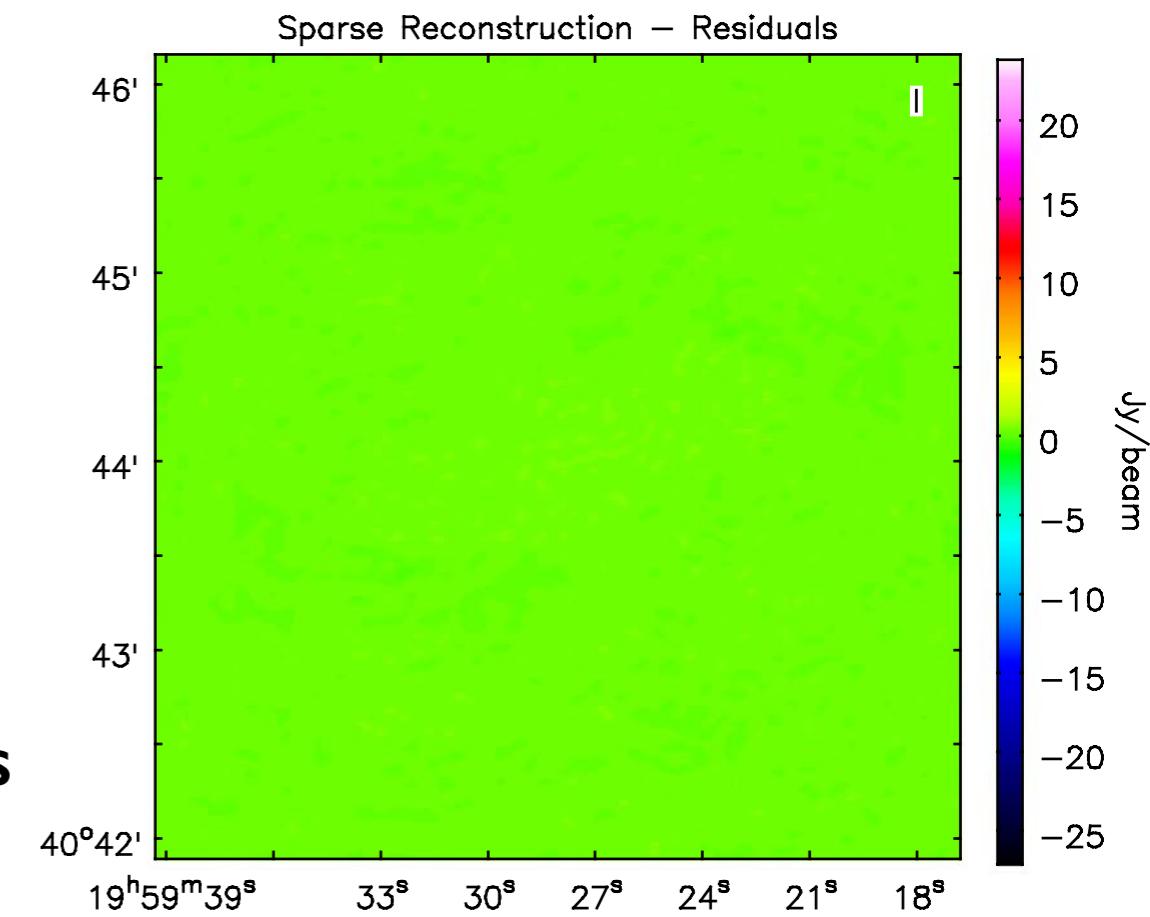
$\Delta T = 6 \text{ Hr}$

36 LOFAR Stations

(dataset courtesy of John McKean)

Sparse Reconstruction

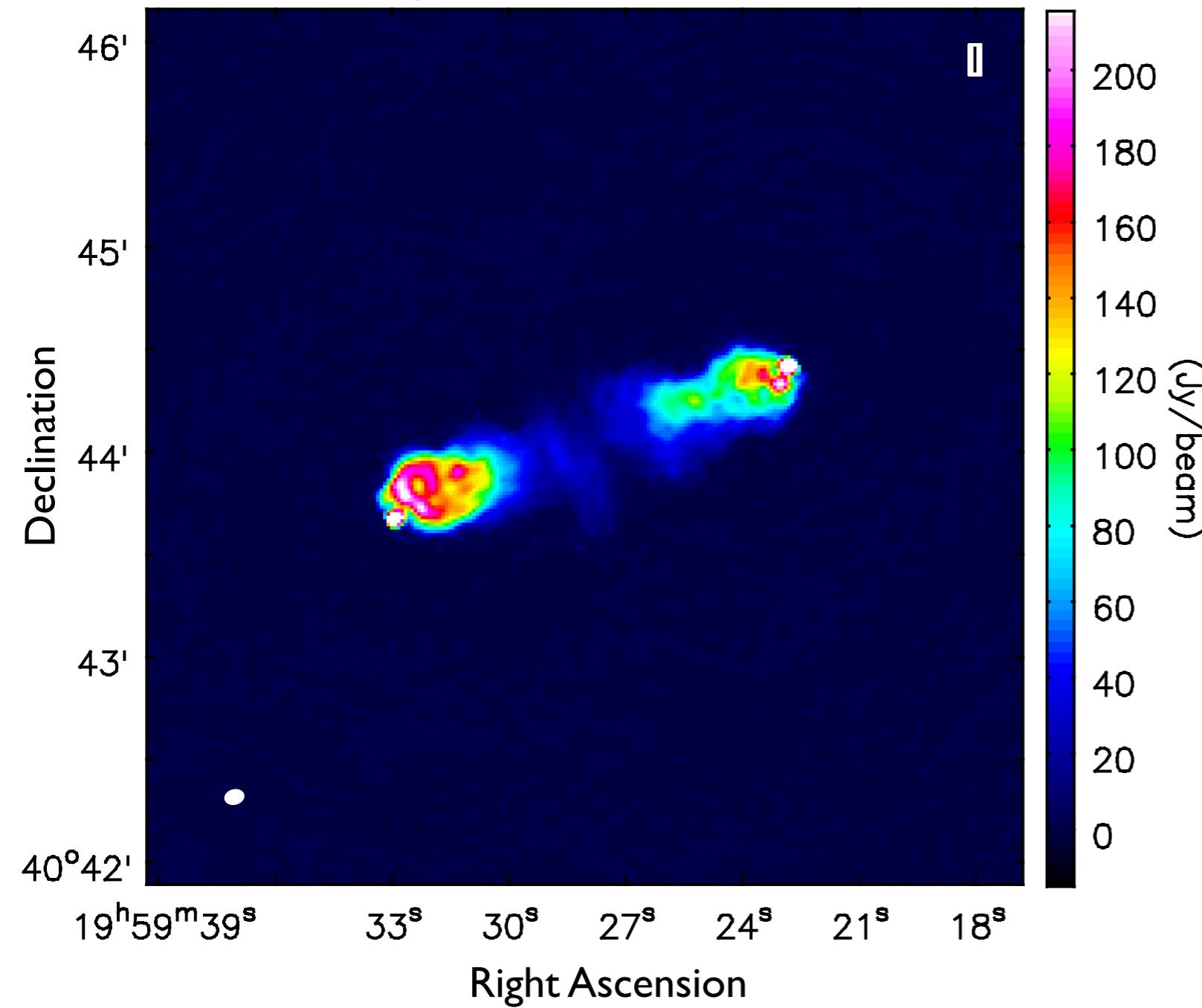
- Pixel = 1" size = 512×512
- Threshold = 0.5 mJy
- Weighting = super uniform
- Scales = 7 wavelets scales
- Minimization algorithm: FISTA
Fast Iterative Shrinkage-Thresholding Algorithm



Residuals

Cygnus A

Sparse Reconstruction



Restored image

Total Flux density = 10506 Jy

Residuals

Residual std-dev = 0,05 Jy/beam

$F = 151 \text{ MHz} - \Delta F = 195 \text{ kHz}$

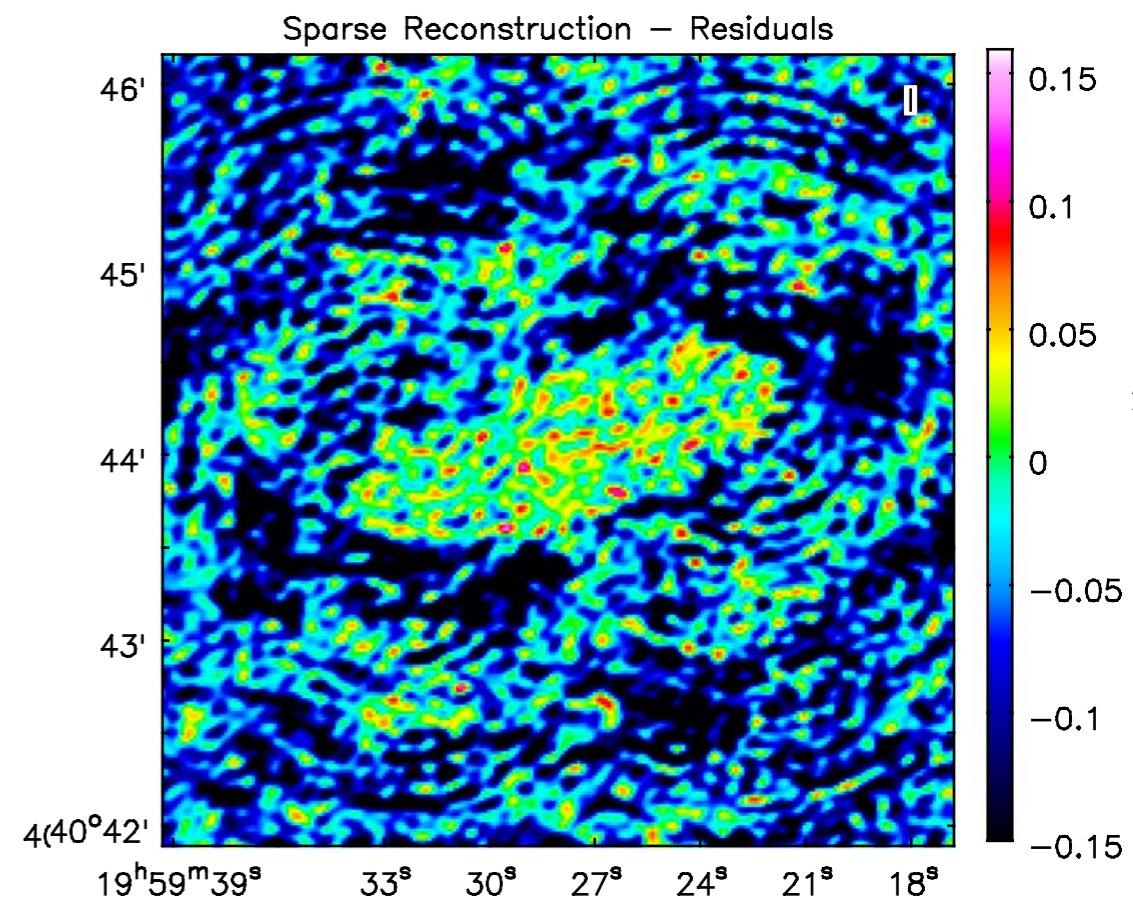
$\Delta T = 6 \text{ Hr}$

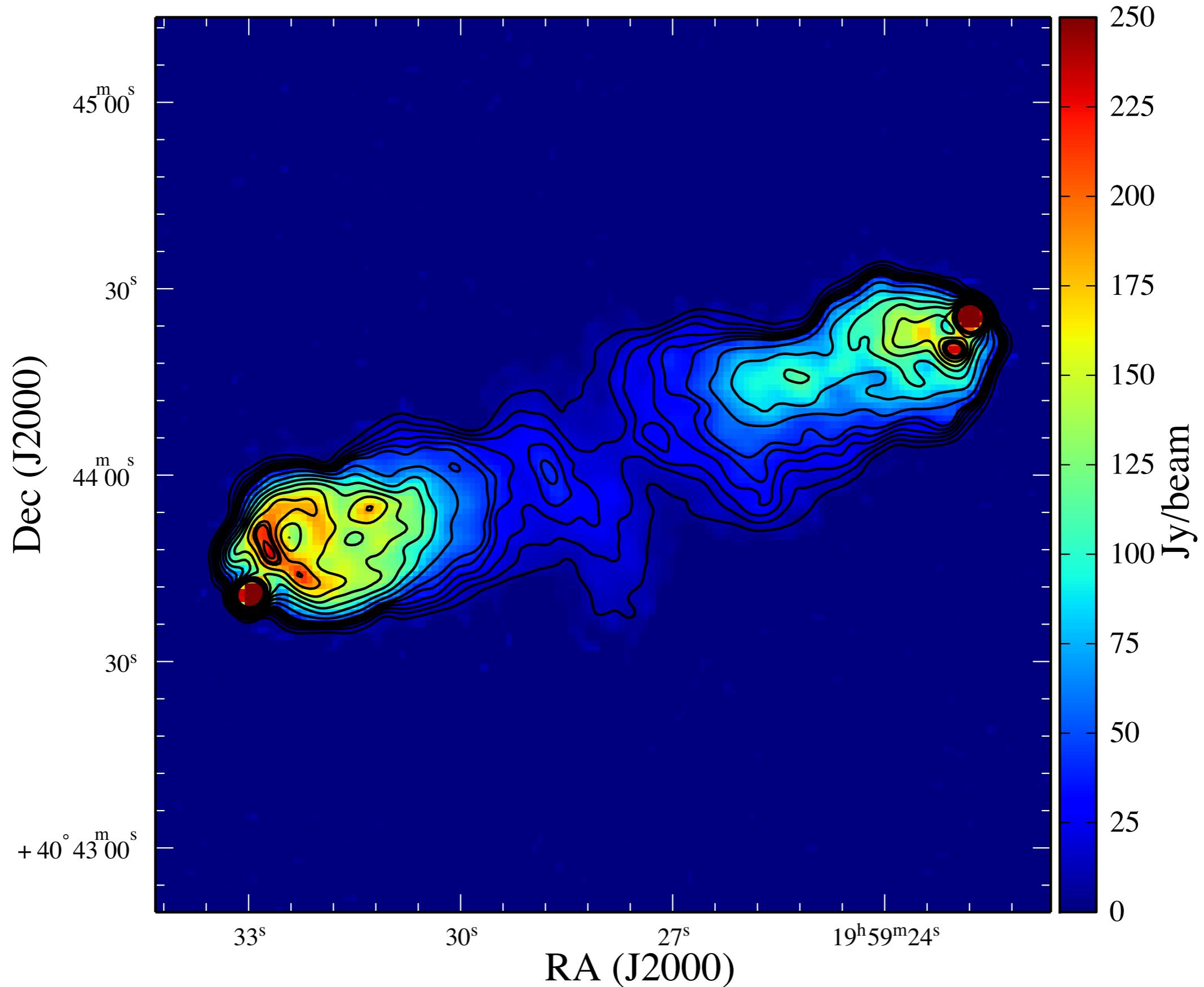
36 LOFAR Stations

(dataset courtesy of John McKean)

Sparse Reconstruction

- Pixel = 1" size = 512×512
- Threshold = 0.5 mJy
- Weighting = super uniform
- Scales = 7 wavelets scales
- Minimization algorithm: FISTA
Fast Iterative Shrinkage-Thresholding Algorithm





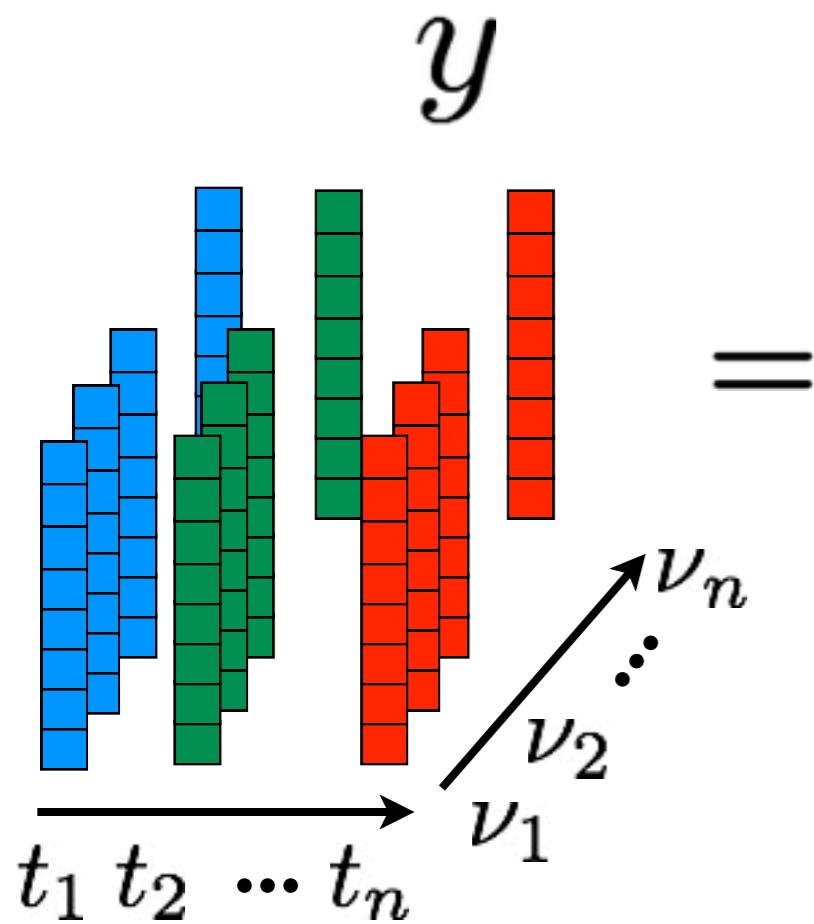
Colorscale: reconstructed 512x512 image of Cygnus A at 151 MHz (with resolution 2.8" and a pixel size of 1"). Contours levels are [1,2,3,4,5,6,9,13,17,21,25,30,35,37,40] Jy/Beam from a 327.5 MHz Cyg A VLA image (Project AK570) at 2.5" angular resolution and a pixel size of 0.5". Most of the recovered features in the CS image correspond to real structures observed at higher frequencies.

Multi-channel Sparse reconstruction



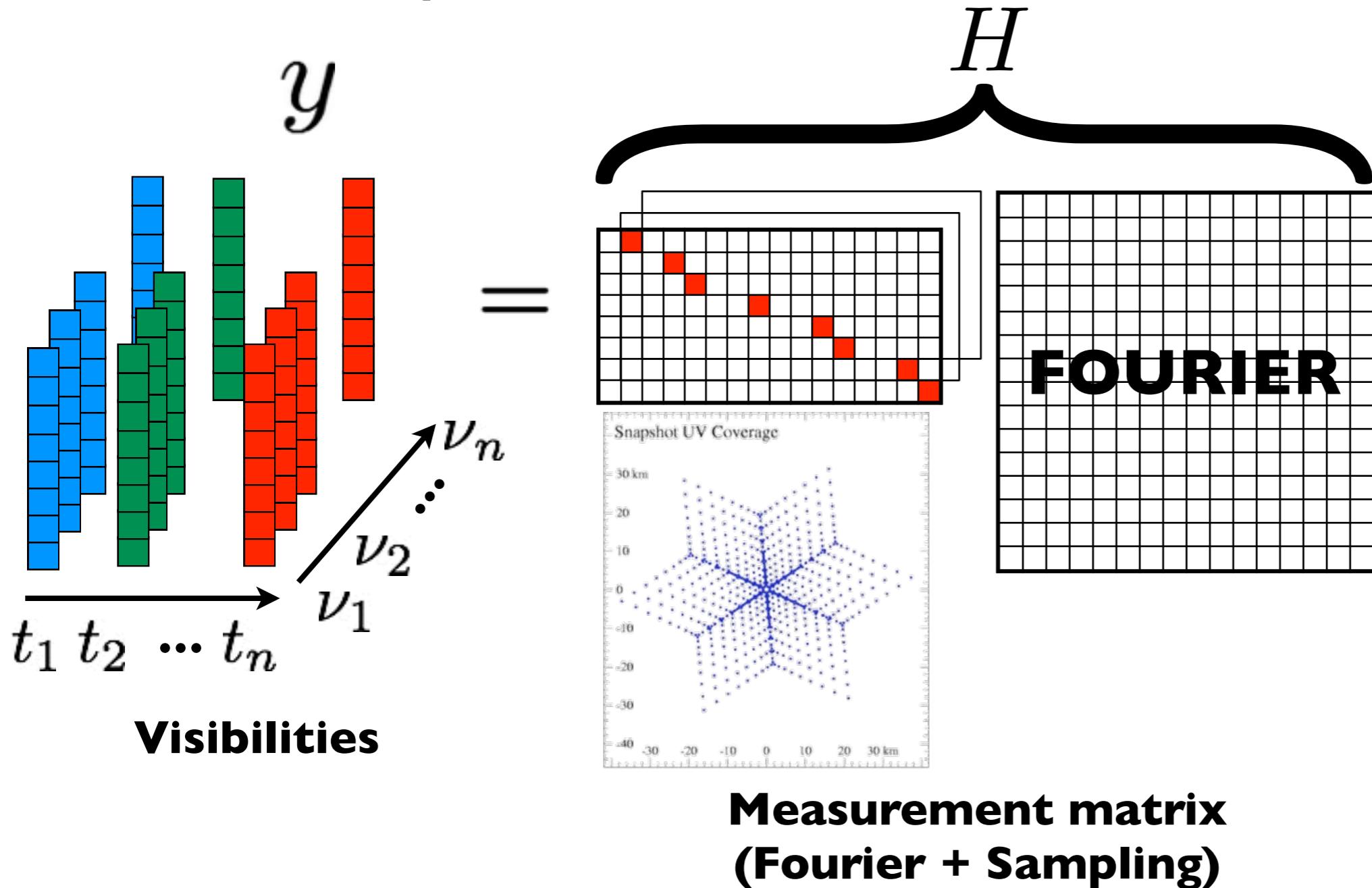
==

Multi-channel Sparse reconstruction

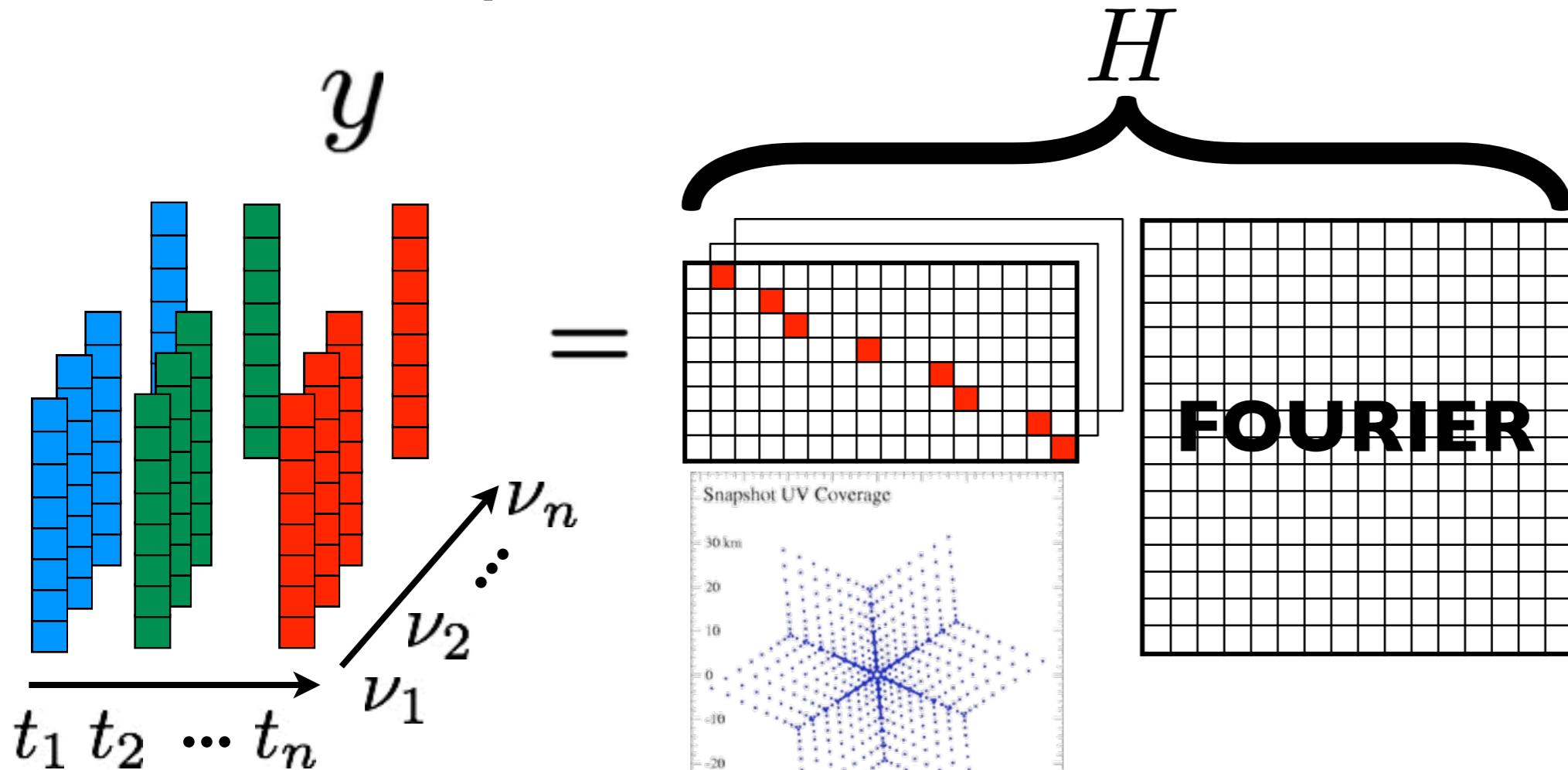


VLA

Multi-channel Sparse reconstruction



Multi-channel Sparse reconstruction



Visibilities

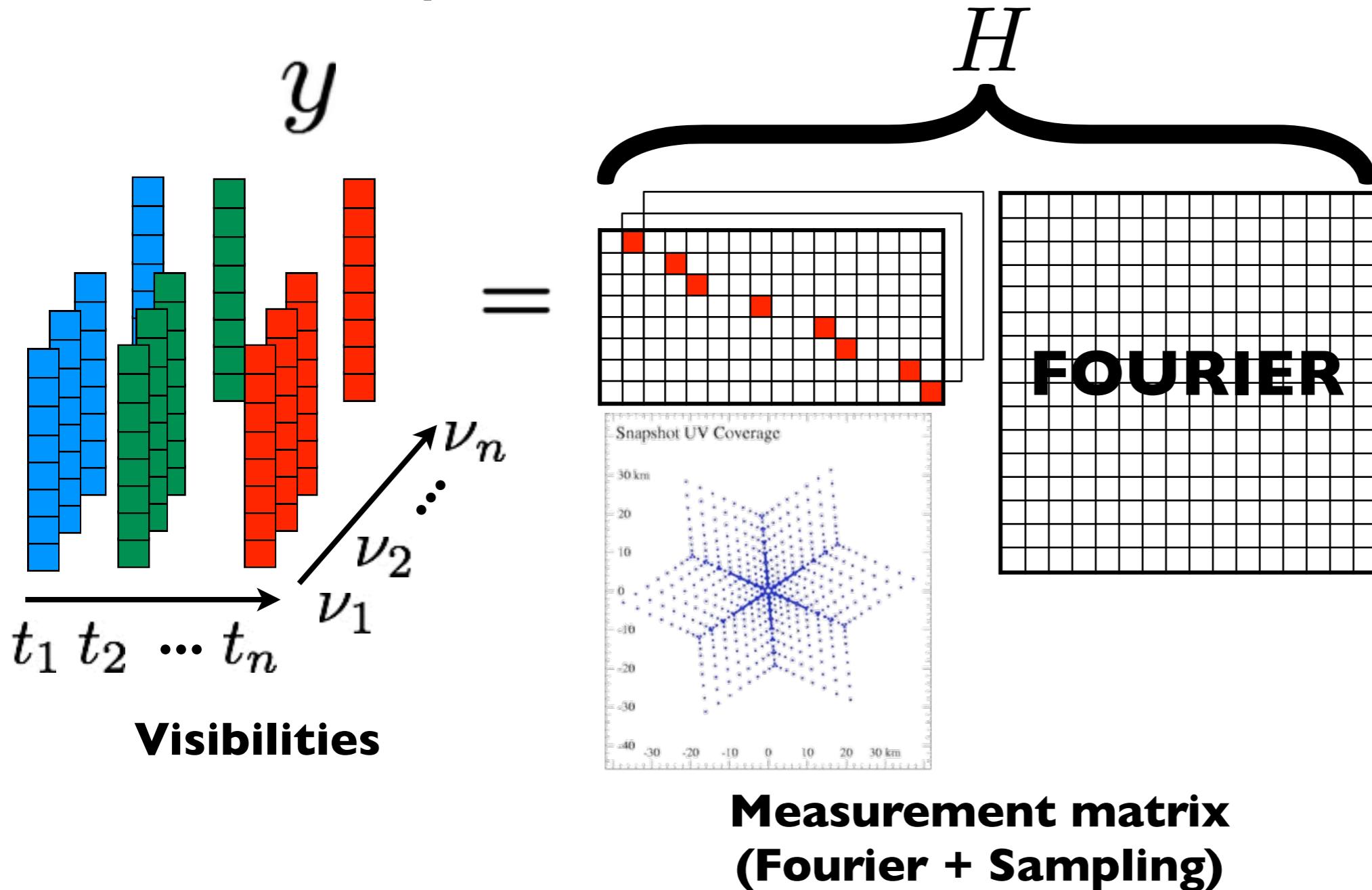
**Measurement matrix
(Fourier + Sampling)**

Snapshot imaging:

- Snapshot = Bad (u,v) coverage = bad PSF \rightarrow deconvolution problem
- Noise: limited by noise in a single timeshot



Multi-channel Sparse reconstruction



VLA

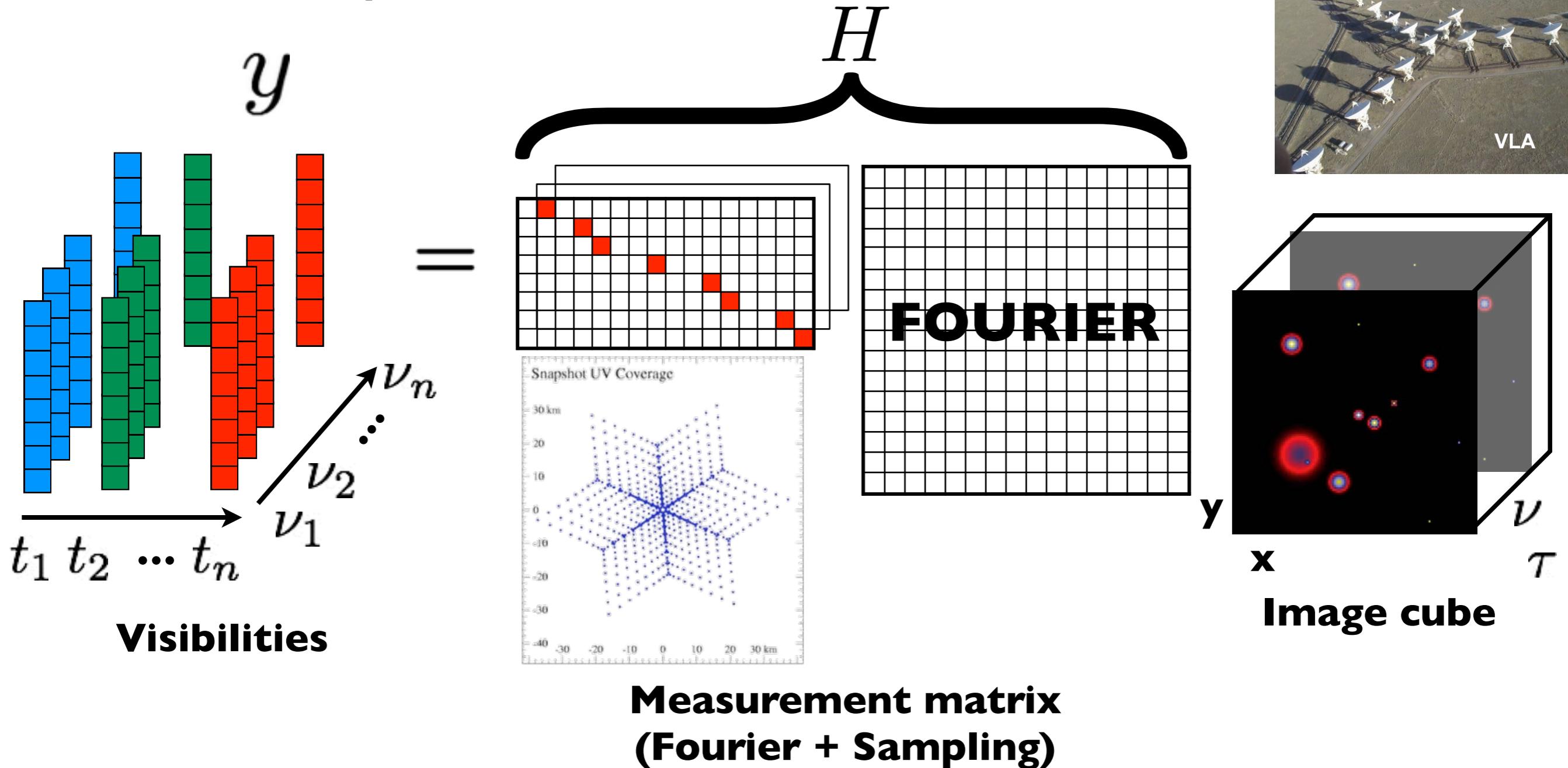
Snapshot imaging:

- Snapshot = Bad (u,v) coverage = bad PSF \rightarrow deconvolution problem
- Noise: limited by noise in a single timeshot

Solution?

- Project the signal in a dictionary where temporal signals are sparse
- Peal all extragalactic non-variable radio sources
- Performing 3D FFTs of the visibilities (as in T-awimager, Tasse et al.)

Multi-channel Sparse reconstruction



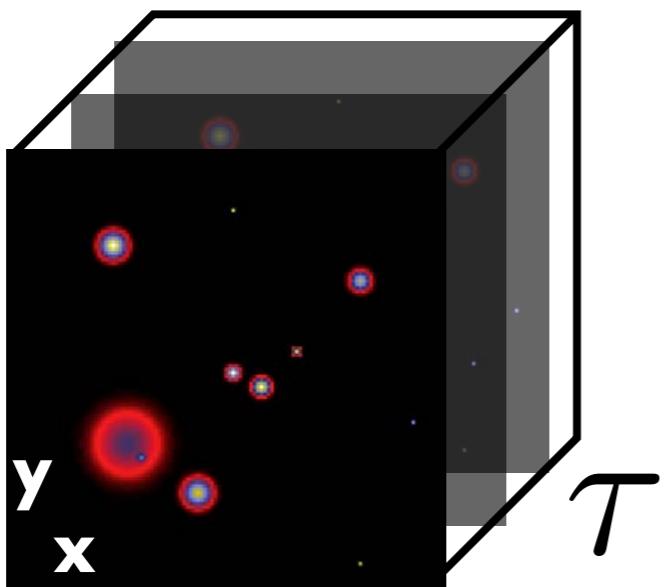
Snapshot imaging:

- Snapshot = Bad (u,v) coverage = bad PSF \rightarrow deconvolution problem
- Noise: limited by noise in a single timeshot

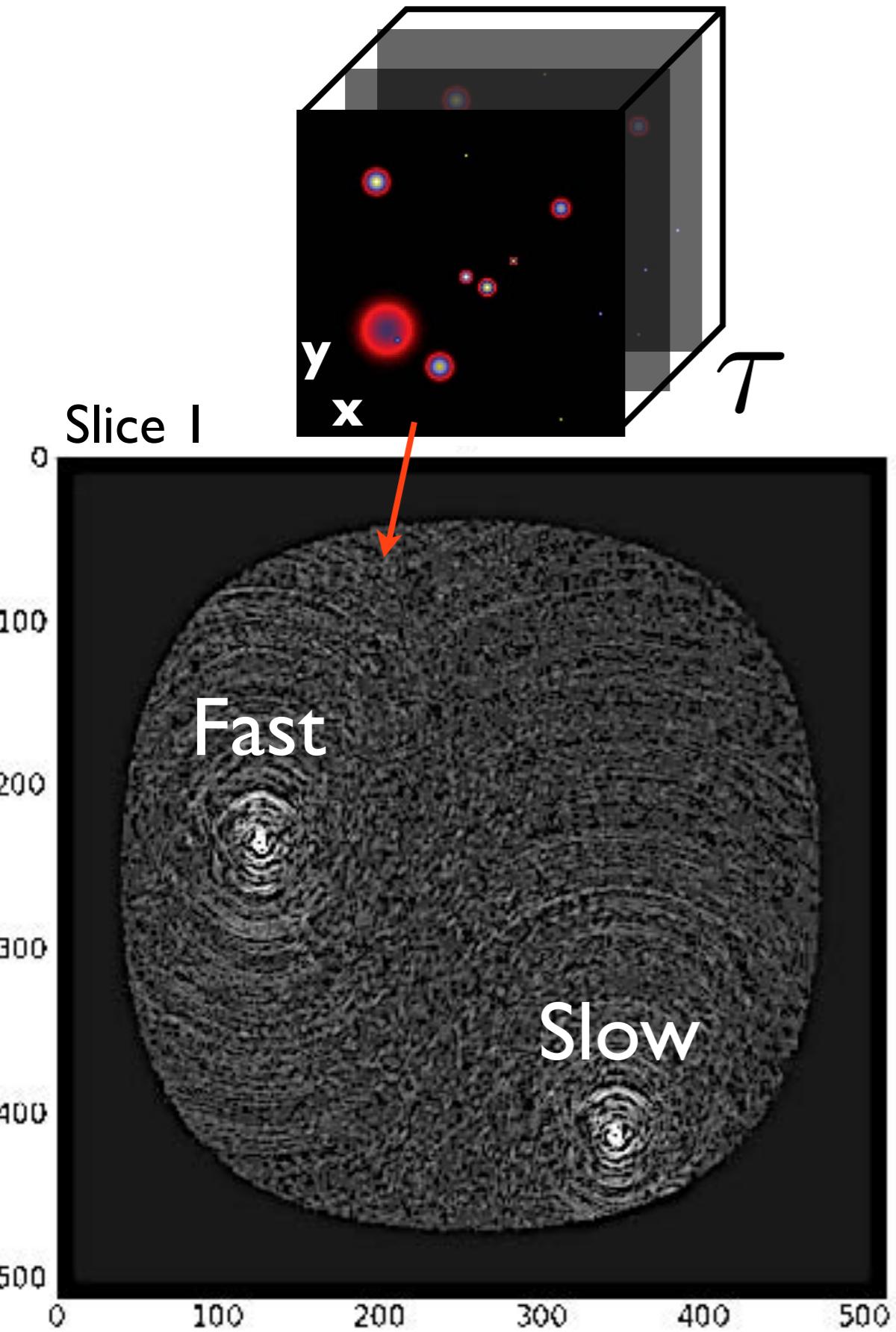
Solution?

- Project the signal in a dictionary where temporal signals are sparse
- Peal all extragalactic non-variable radio sources
- Performing 3D FFTs of the visibilities (as in T-awimager, Tasse et al.)

Multi-channel Sparse reconstruction

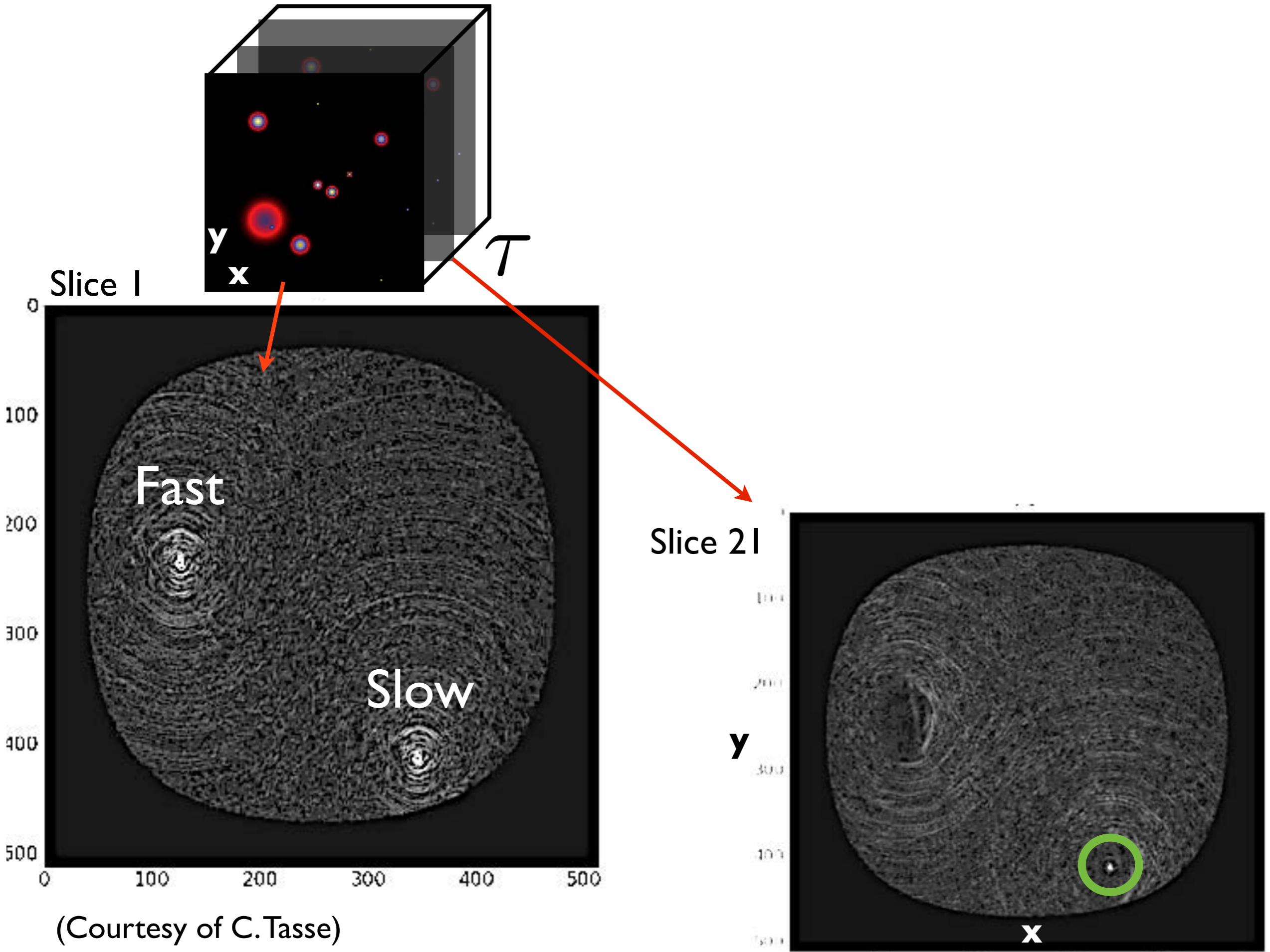


Multi-channel Sparse reconstruction



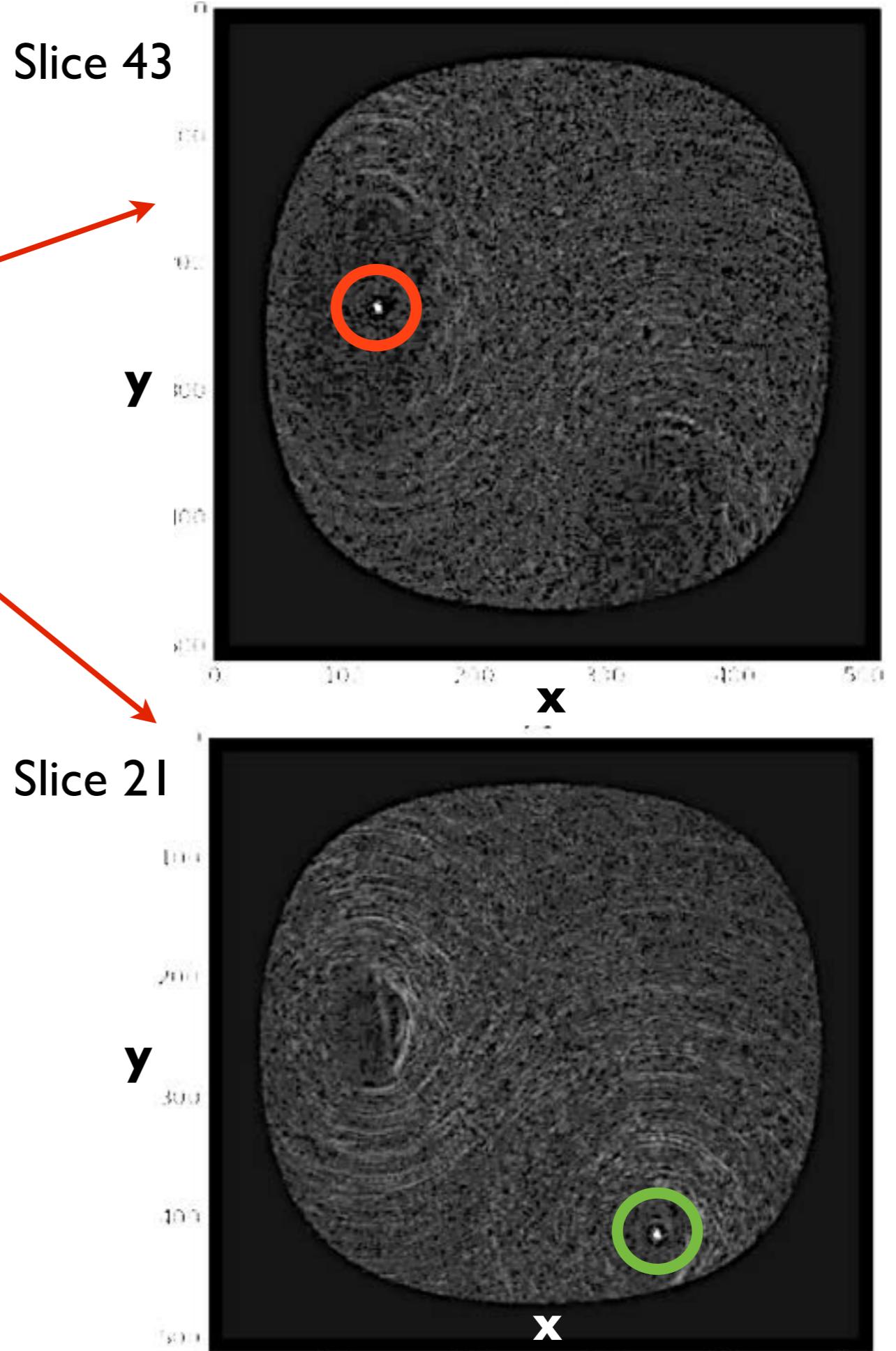
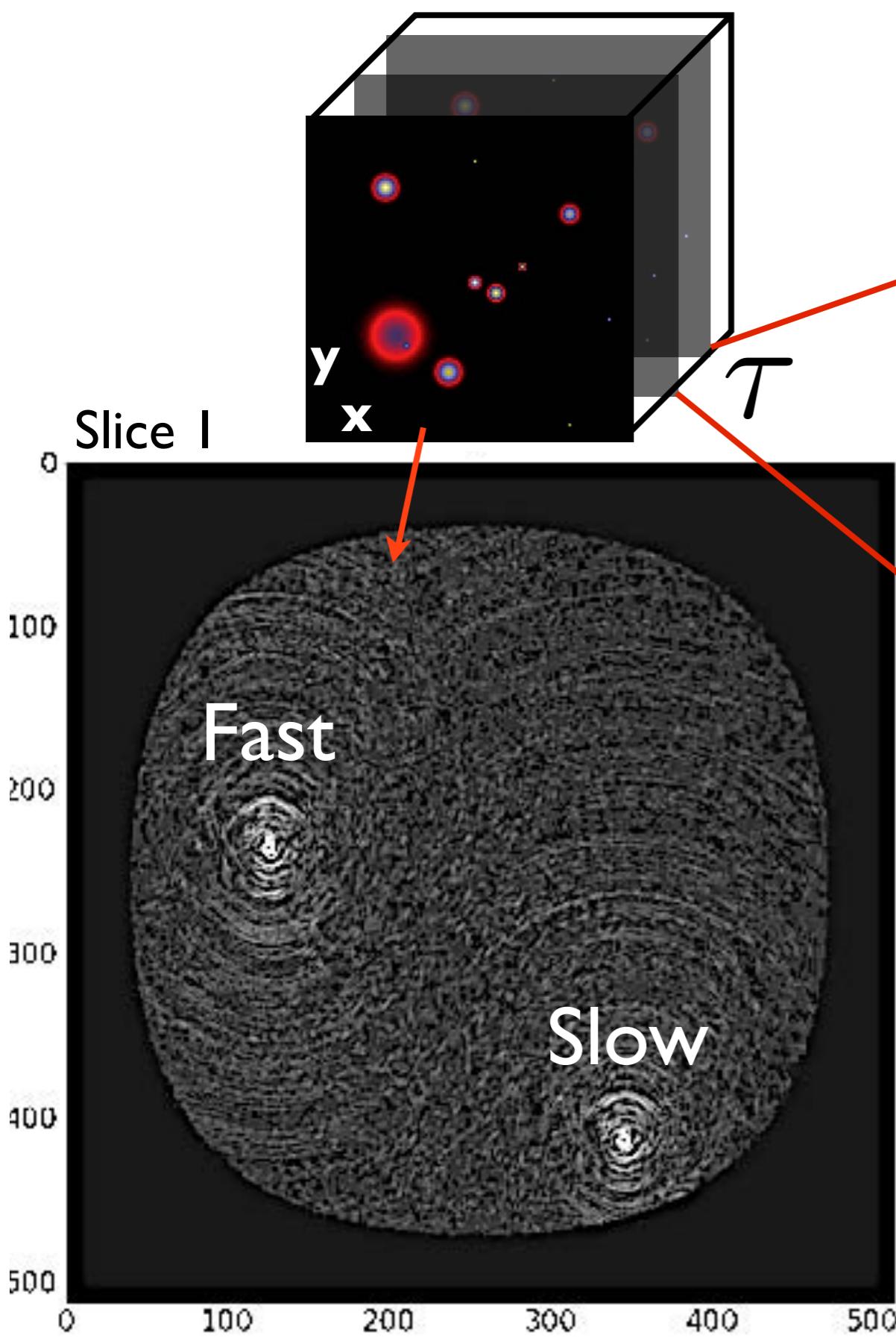
(Courtesy of C.Tasse)

Multi-channel Sparse reconstruction



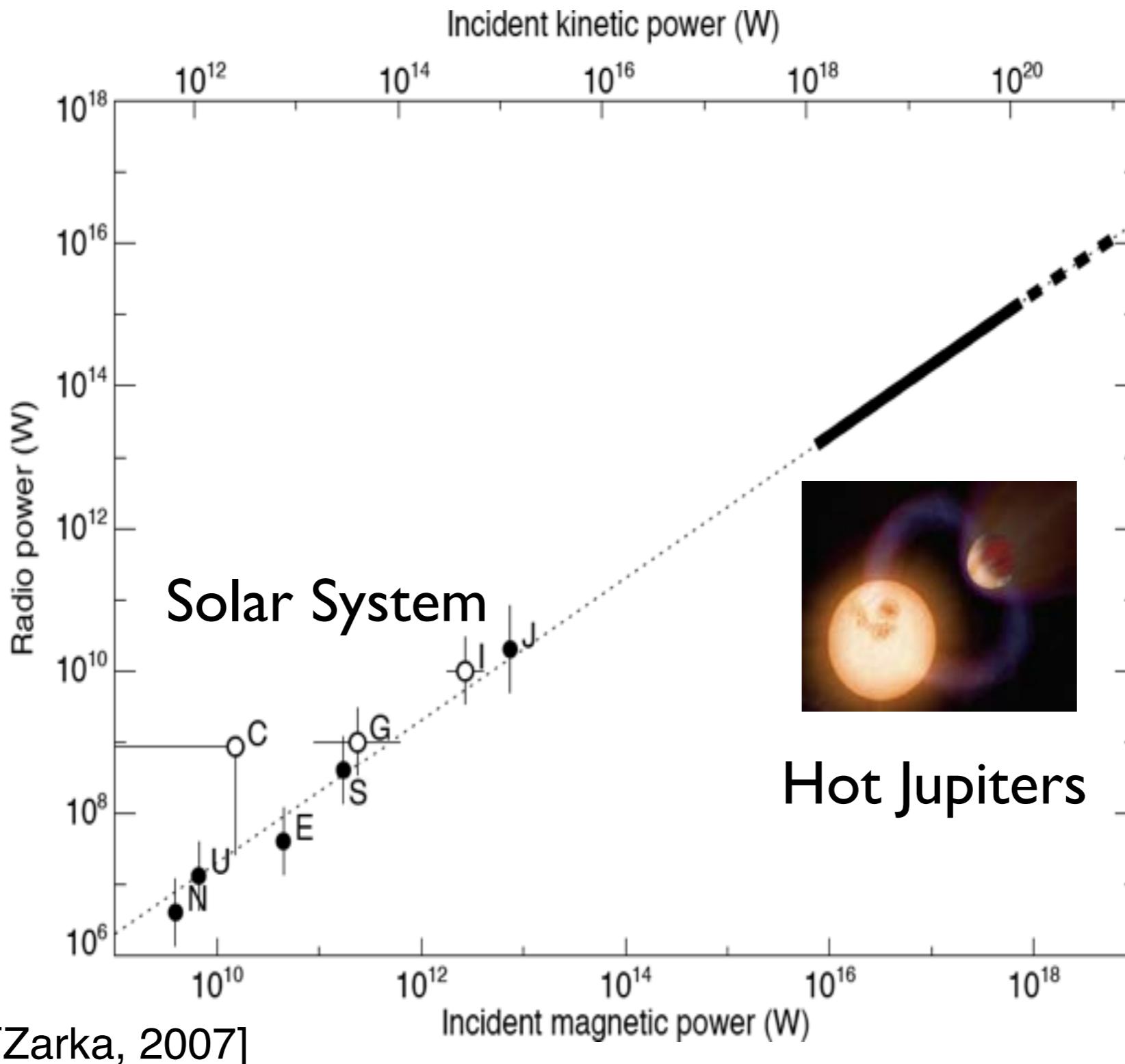
(Courtesy of C. Tasse)

Multi-channel Sparse reconstruction



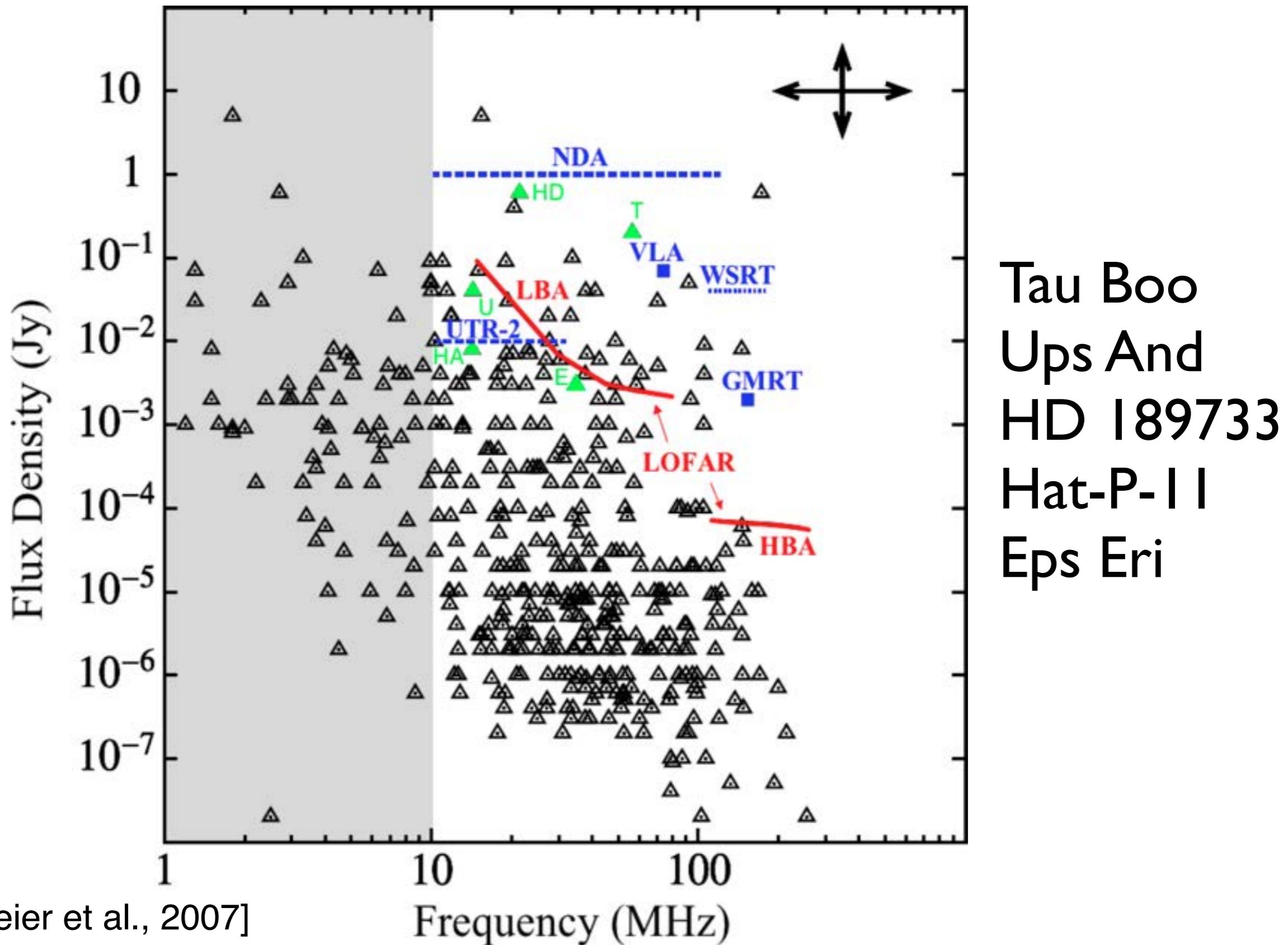
Detection of exoplanetary radio emissions

- principle: detect Jupiter-like emissions
- In radio: Contrast ratio Jupiter/Sun ~ 1
but strong radio background -> Need stronger Jupiters



Detection of exoplanetary radio emissions

- Candidates were observed in beamform & interferometer mode
- No detection yet...



ISOTROPIC UNDECIMATED WAVELET TRANSFORM

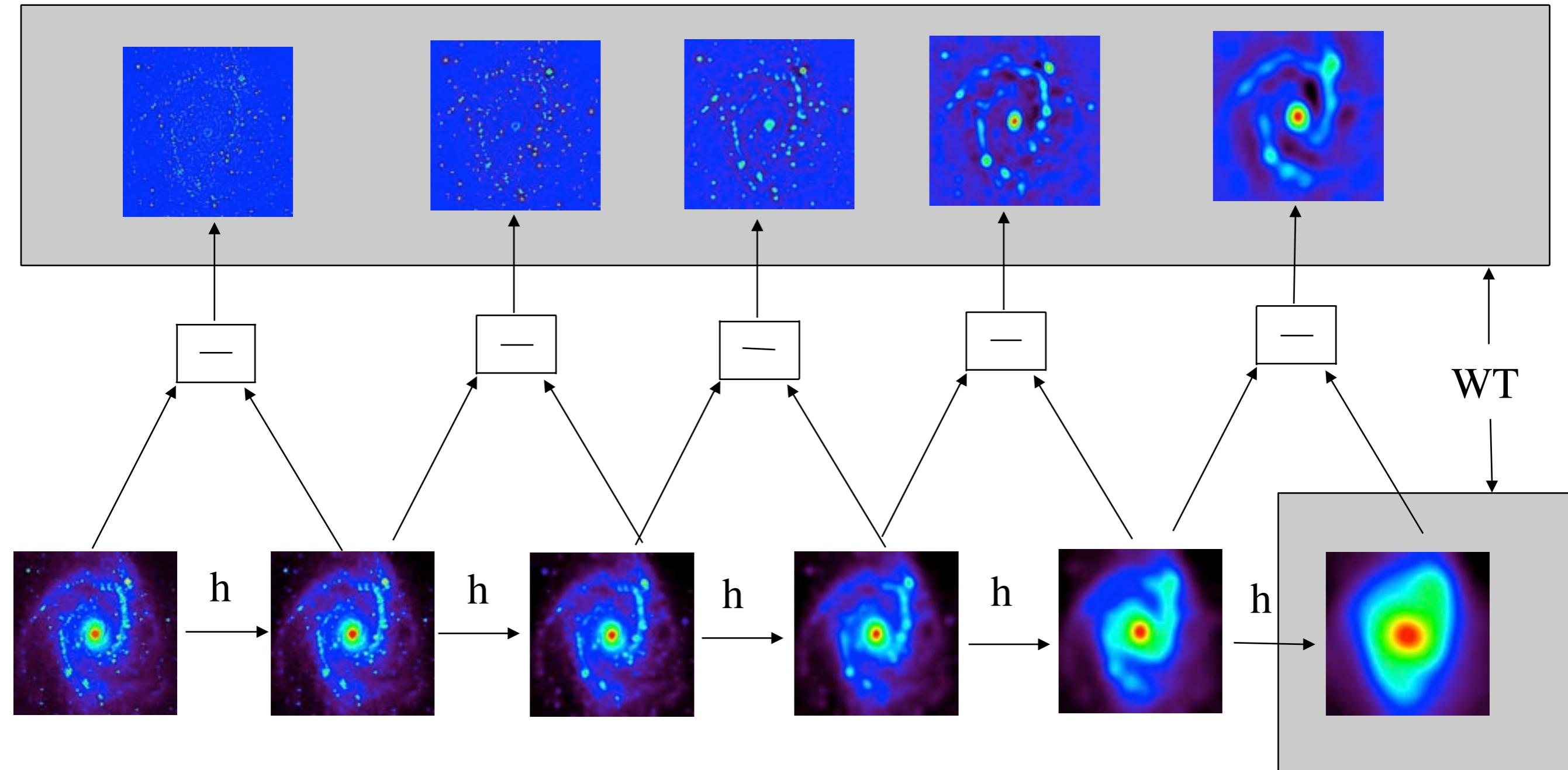
Scale 1

Scale 2

Scale 3

Scale 4

Scale 5



The STARLET Transform

Isotropic Undecimated Wavelet Transform (a trous algorithm)

$$\varphi = B_3 - \text{spline}, \quad \frac{1}{2}\psi\left(\frac{x}{2}\right) = \frac{1}{2}\varphi\left(\frac{x}{2}\right) - \varphi(x)$$

$$h = [1, 4, 6, 4, 1]/16, \quad g = \delta \cdot h, \quad \tilde{h} = \tilde{g} = \delta$$

$$I(k, l) = c_{J, k, l} + \sum_{j=1}^J w_{j, k, l}$$

