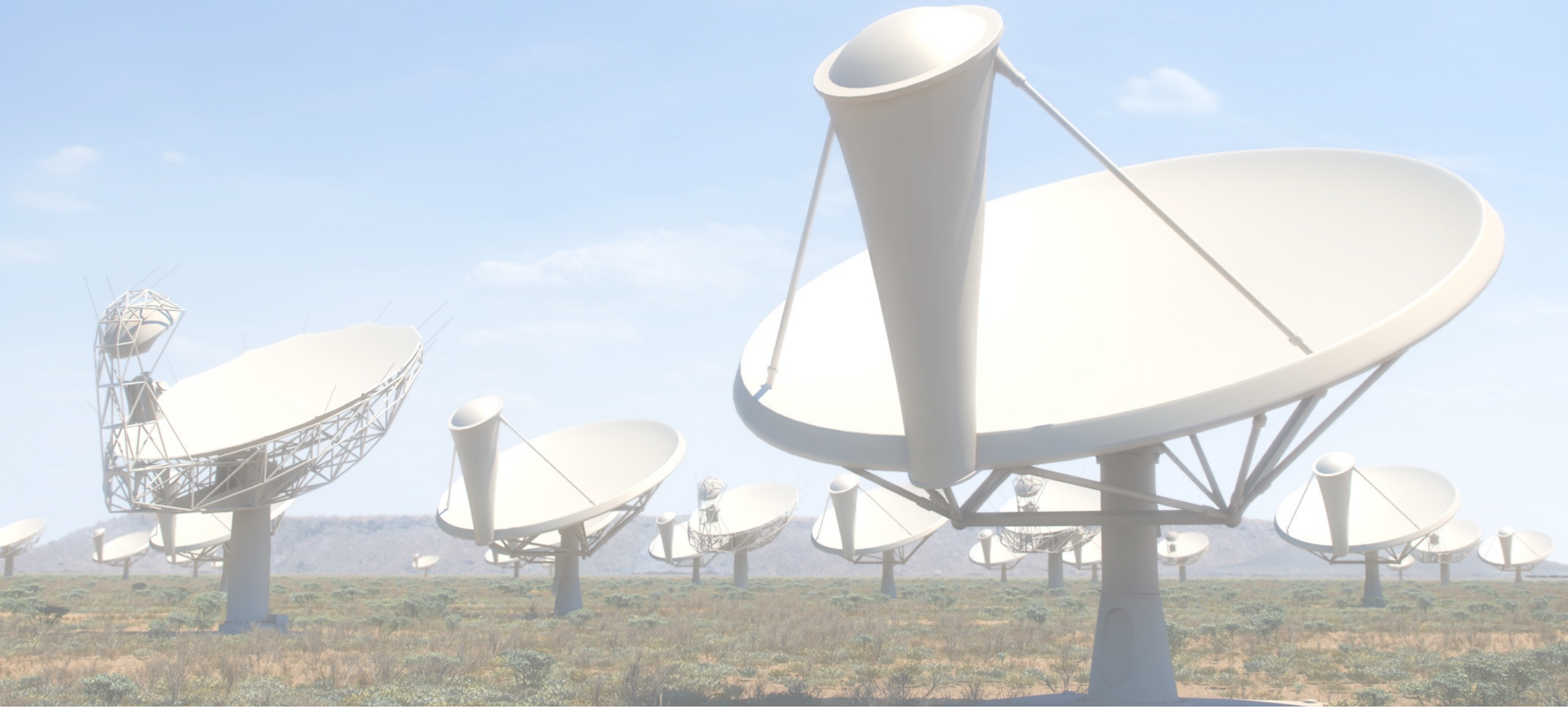


Compressed sensing and radio interferometers to detect transients

Julien Girard

AIM/IRFU/CEA-Saclay
Université Paris Diderot

Microquasars workshop

Outline

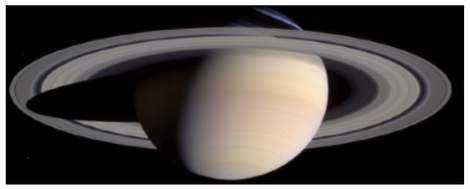
New instrumentation, new problems
(and new solutions !)

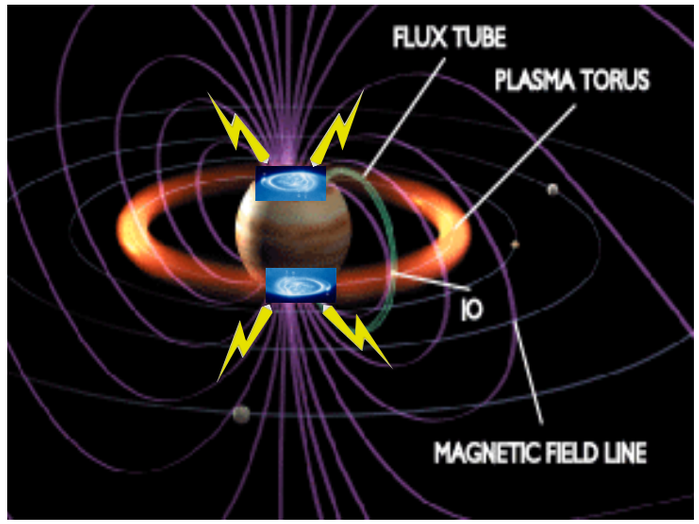
Sparsity and deconvolution

Application to transient imaging

Conclusions

Universality of transients in radio





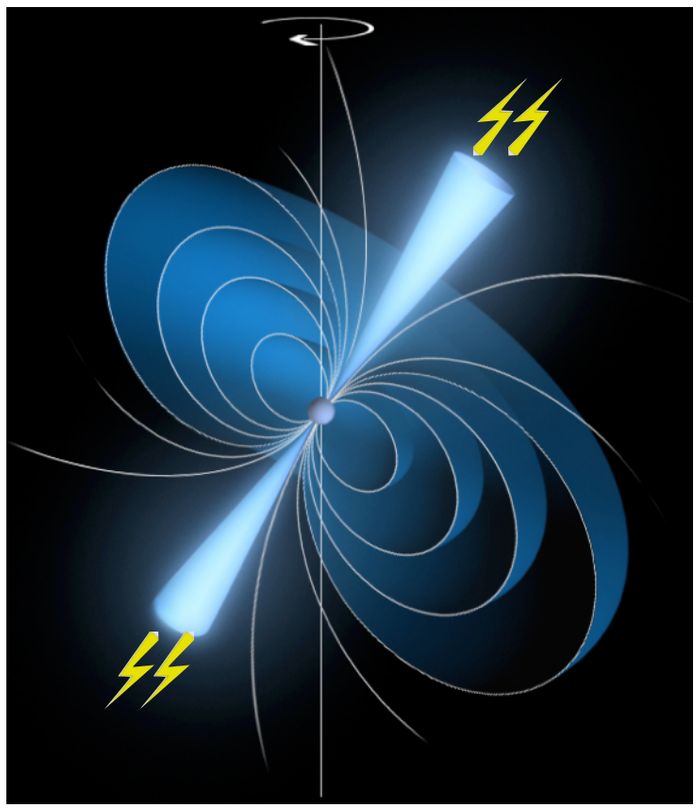
Radio signatures

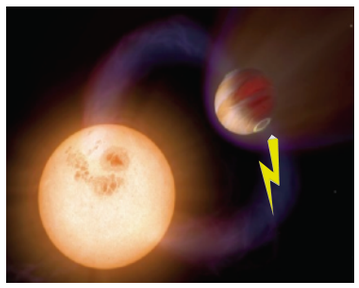
- mark the presence of magnetic fields
- have a rich spectral and temporal features
- associated to catastrophic events

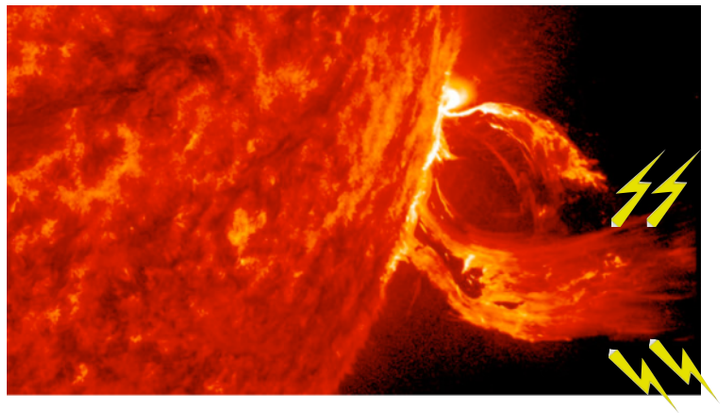
at all scales in energy, distances, durations…

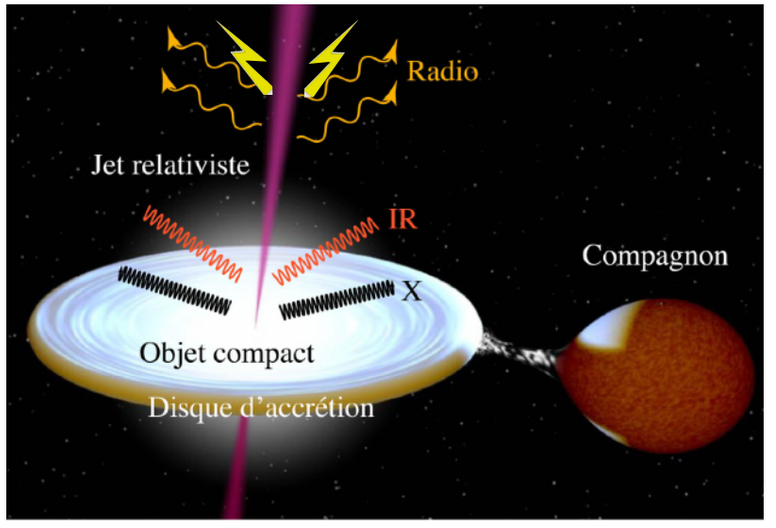
<< 1ms 1s 10s 1m 10m 1h 1d 1 w 1 mo

t

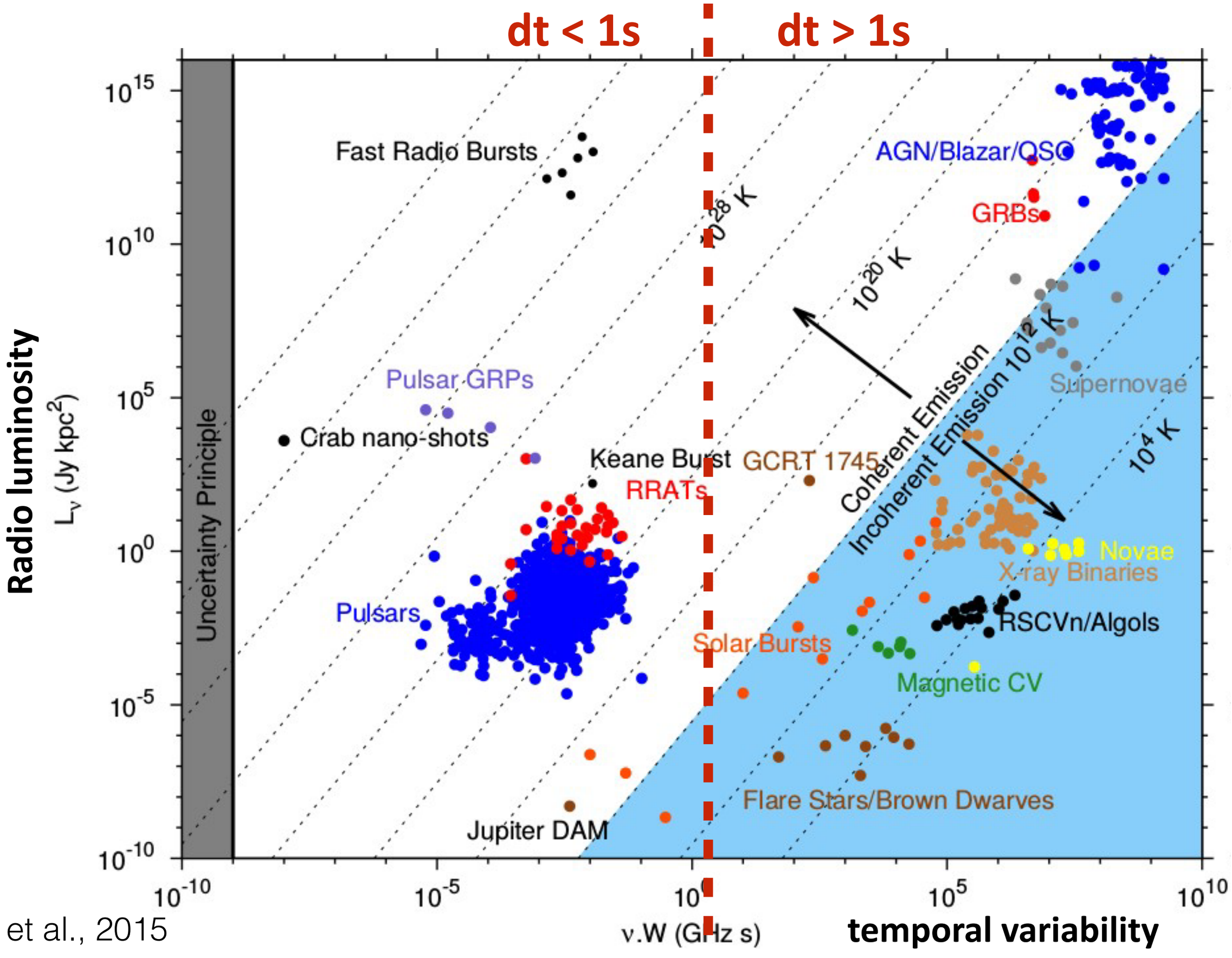






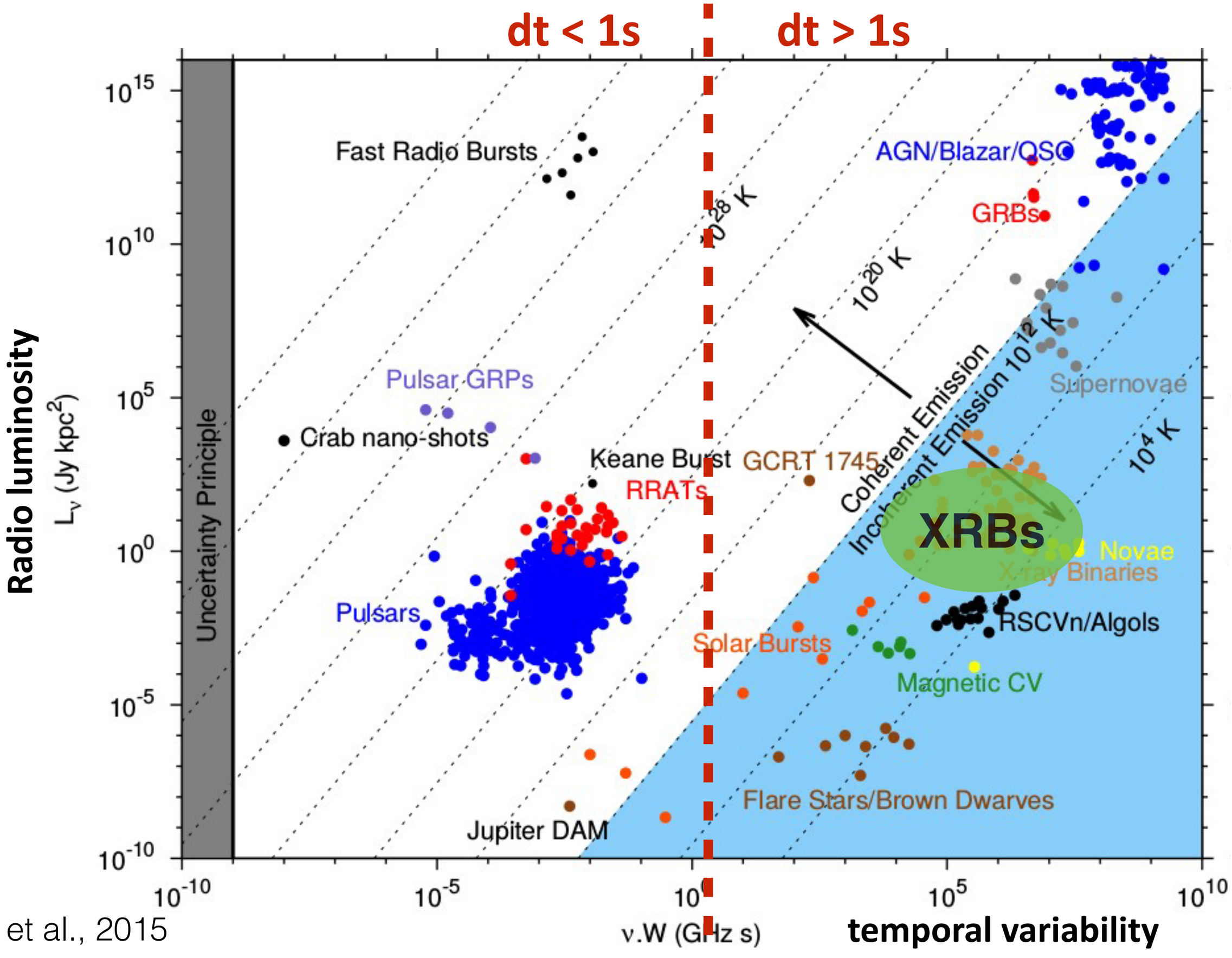


Universality of transients in radio



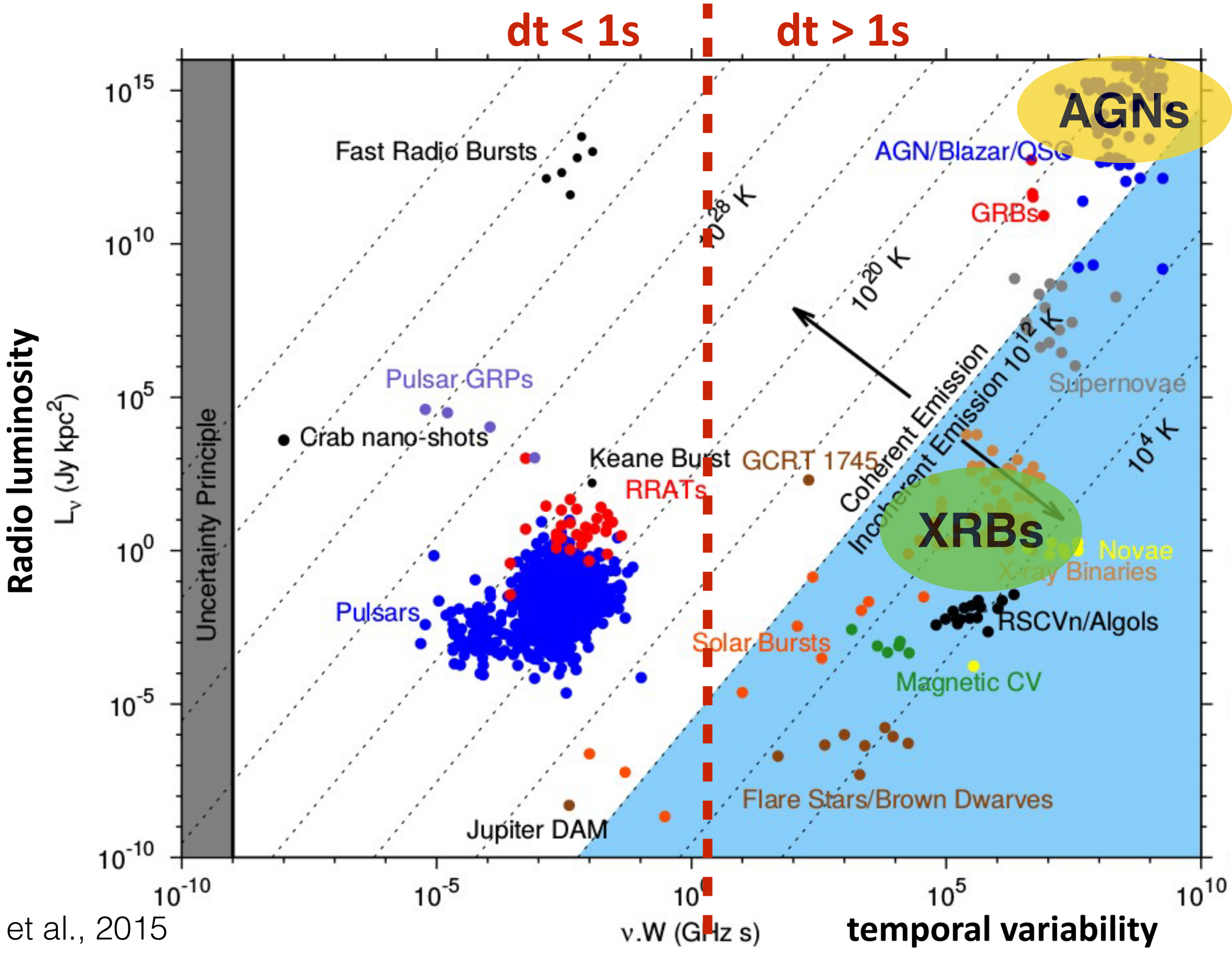
Pietka et al., 2015

Universality of transients in radio



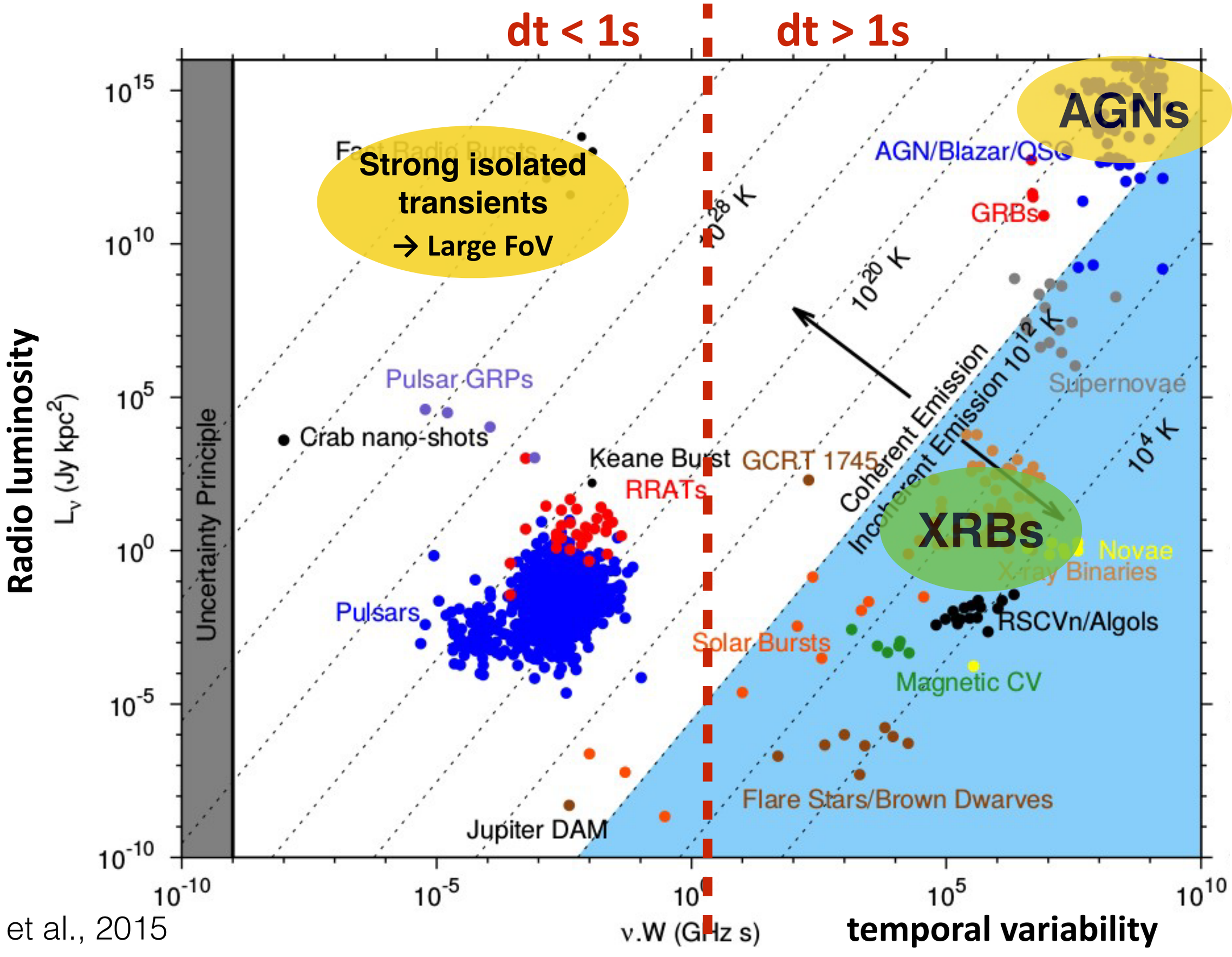
Pietka et al., 2015

Universality of transients in radio



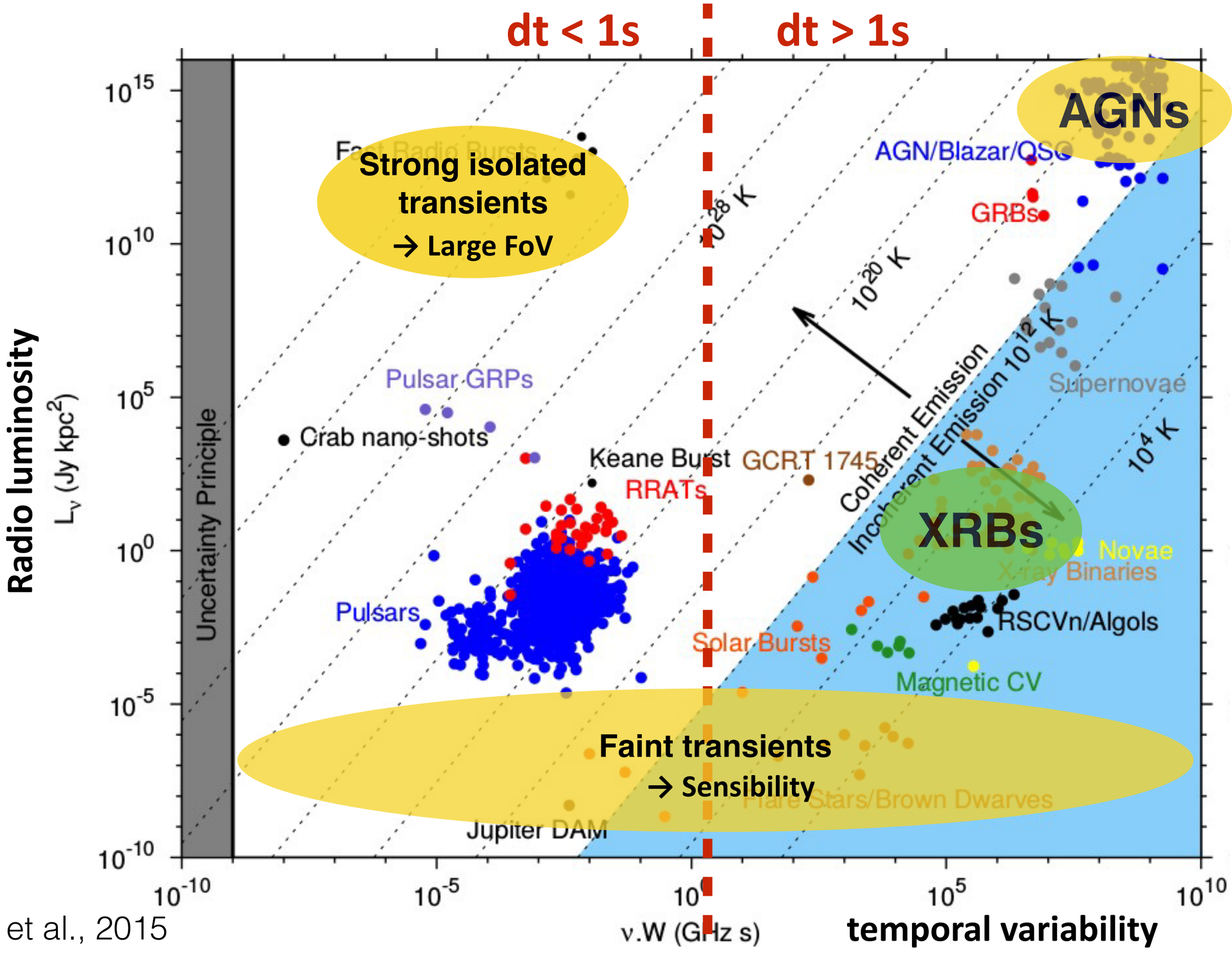
Pietka et al., 2015

Universality of transients in radio



Pietka et al., 2015

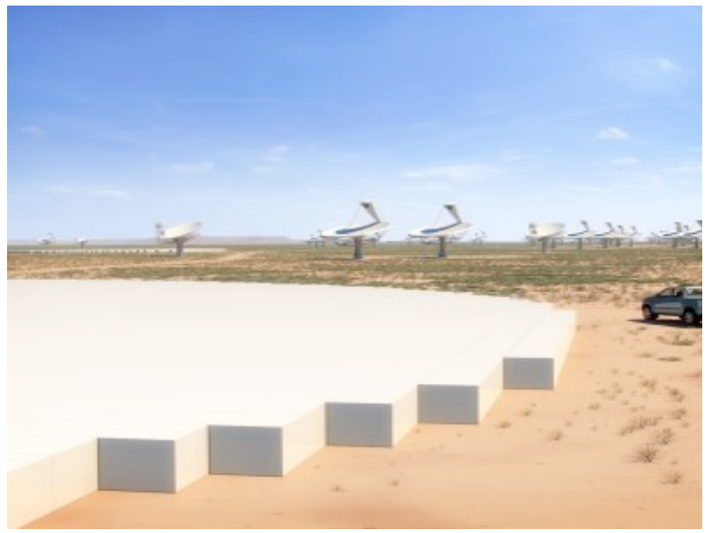
Universality of transients in radio



Pietka et al., 2015

Continental-scale instruments

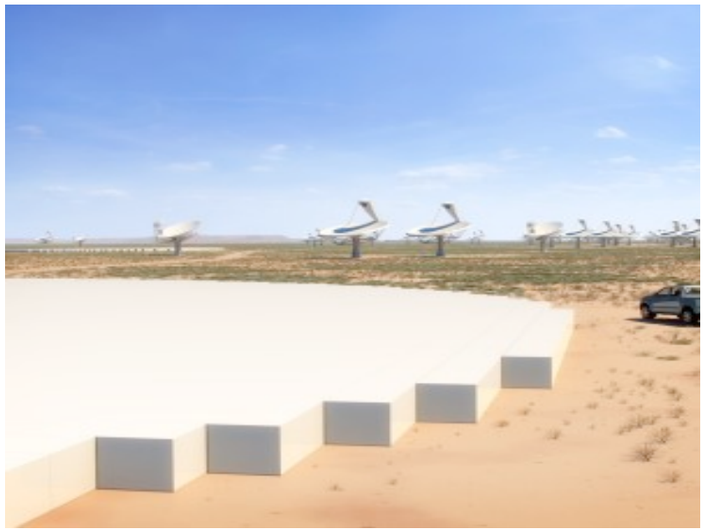
(see Stephane's review)



- Full polarimetric measurement
- Large field of views *10s°*
- High sensitivity *μJy*
- High time resolution *ns*
  - spectral resolution *< kHz*
  - angular resolution *< arcsec*

Continental-scale instruments

(see Stephane's review)



- Full polarimetric measurement

- Large field of views *10s°*
- High sensitivity *μJy*
- High time resolution *ns*
  - spectral resolution *< kHz*
  - angular resolution *< arcsec*

} **Logistical complexity**
} **Increased data rates**
} **Data proc complexity**
} **Instrumental effects**

SKA1 LOW - the SKA's low-frequency instrument

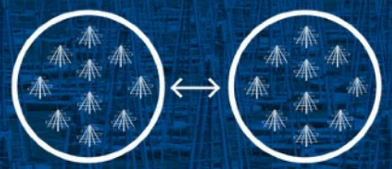
The Square Kilometre Array (SKA) will be the world's largest radio telescope, revolutionising our understanding of the Universe. The SKA will be built in two phases - SKA1 and SKA2 - starting in 2018, with SKA1 representing a fraction of the full SKA. SKA1 will include two instruments - SKA1 MID and SKA1 LOW - observing the Universe at different frequencies.

Location: Australia

Frequency range:
50 MHz to **350 MHz**

~130,000
antennas spread between **500 stations**

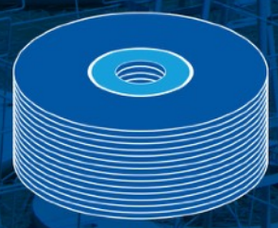
Total collecting area:
0.4km²



Maximum distance between stations:
65km

SKA1 LOW

Total raw data output:
157 terabytes per second
4.9 zettabytes per year



Enough to fill up
35,000 DVDs
every second

5x
the estimated global internet traffic in 2015
(source: Cisco)

Compared to LOFAR Netherlands, the current best similar instrument in the world

25% better resolution
8x more sensitive
135x the survey speed

SKA1 MID - the SKA's mid-frequency instrument

The Square Kilometre Array (SKA) will be the world's largest radio telescope, revolutionising our understanding of the Universe. The SKA will be built in two phases - SKA1 and SKA2 - starting in 2018, with SKA1 representing a fraction of the full SKA. SKA1 will include two instruments - SKA1 MID and SKA1 LOW - observing the Universe at different frequencies.

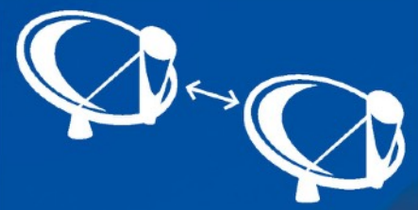
Location: South Africa

Frequency range:
350 MHz to **14 GHz**

~200 dishes
(including 64 MeerKAT dishes)

Total collecting area:
33,000m²

or **126 tennis courts**



Maximum distance between dishes:
150km

SKA1 MID

Total raw data output:
2 terabytes per second
62 exabytes per year

Enough to fill
340,000
average laptops with content **every day**

Compared to the JVLA, the current best similar instrument in the world:

4x the resolution
5x more sensitive
60x the survey speed

Motivations

Astronomers ideally want the whole sky

at 0.001 nsec x 0.001 Hz

x 0.000000001" resolution

everywhere & all the time

Motivations

Astronomers ideally want the whole sky at 0.001 nsec x 0.001 Hz
x 0.000000001" resolution
everywhere & all the time

→ necessary compromises

but permanent search for improved **facilities** and **methods**

1) take the best of the instrument (SNR)

2) while reducing the amount of data with minimal loss

Motivations

Astronomers ideally want the whole sky at 0.001 nsec x 0.001 Hz
x 0.000000001" resolution
everywhere & all the time

→ necessary compromises

but permanent search for improved **facilities** and **methods**

1) take the best of the instrument (SNR)

2) while reducing the amount of data with minimal loss

Impact on transient search

Slow transients	***Fast transients***
Store long term light curves / reduced data to allow revisiting the data (e.g. FRBs…)	Trade-off between SNR and time smearing of transient events (e.g. LOFAR TraP)

Good spectral coverage

Motivations

Astronomers ideally want the whole sky at 0.001 nsec x 0.001 Hz
x 0.000000001" resolution
everywhere & all the time

→ necessary compromises

but permanent search for improved **facilities** and **methods**

1) take the best of the instrument (SNR)

2) while reducing the amount of data with minimal loss

Impact on transient search

Slow transients

Store long term light curves / reduced data
to allow revisiting the data
(e.g. FRBs…)

Fast transients

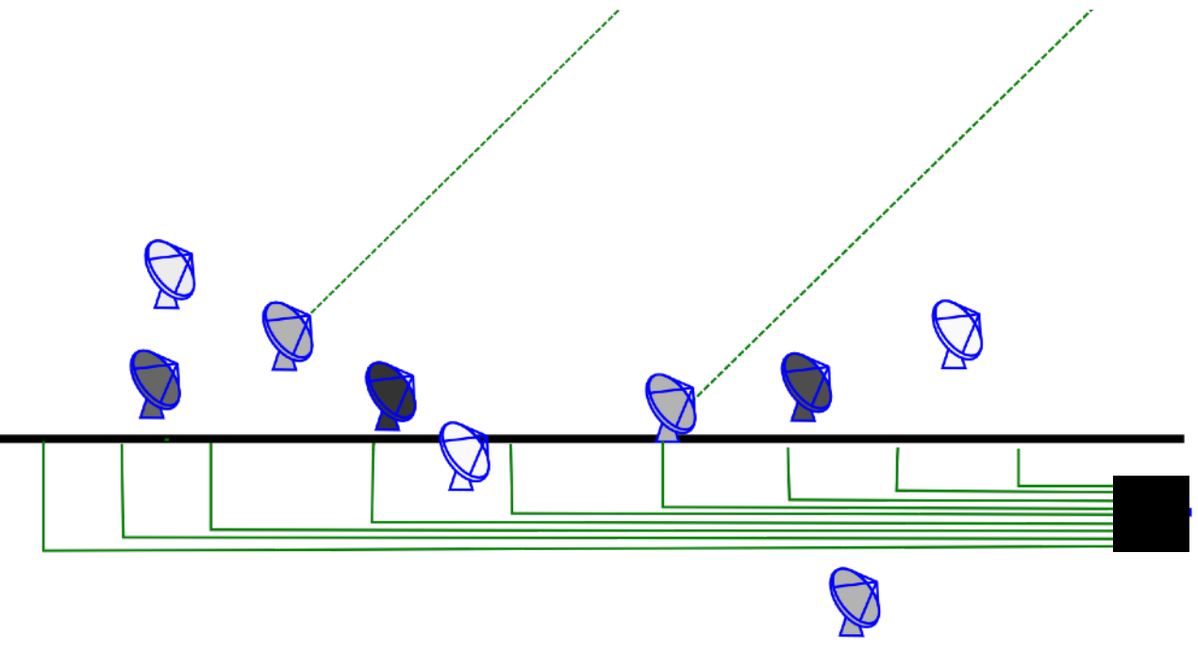
Trade-off between SNR and time
smearing of transient events
(e.g. LOFAR TraP)

Good spectral coverage

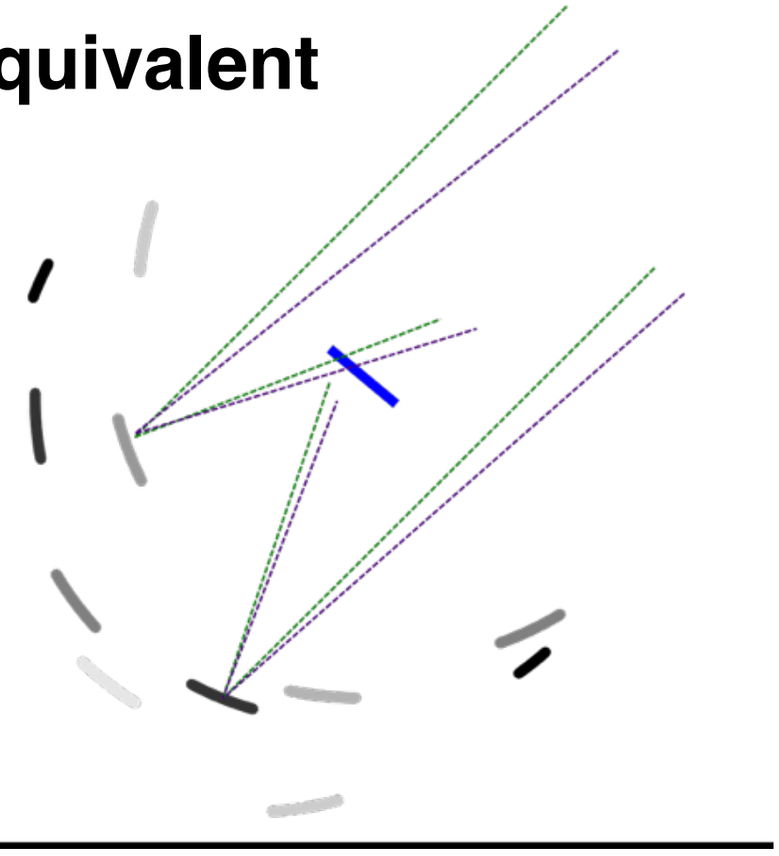
Most transient emissions are not resolved in radio so
… Why should I care?…

Uncalibrated instrument

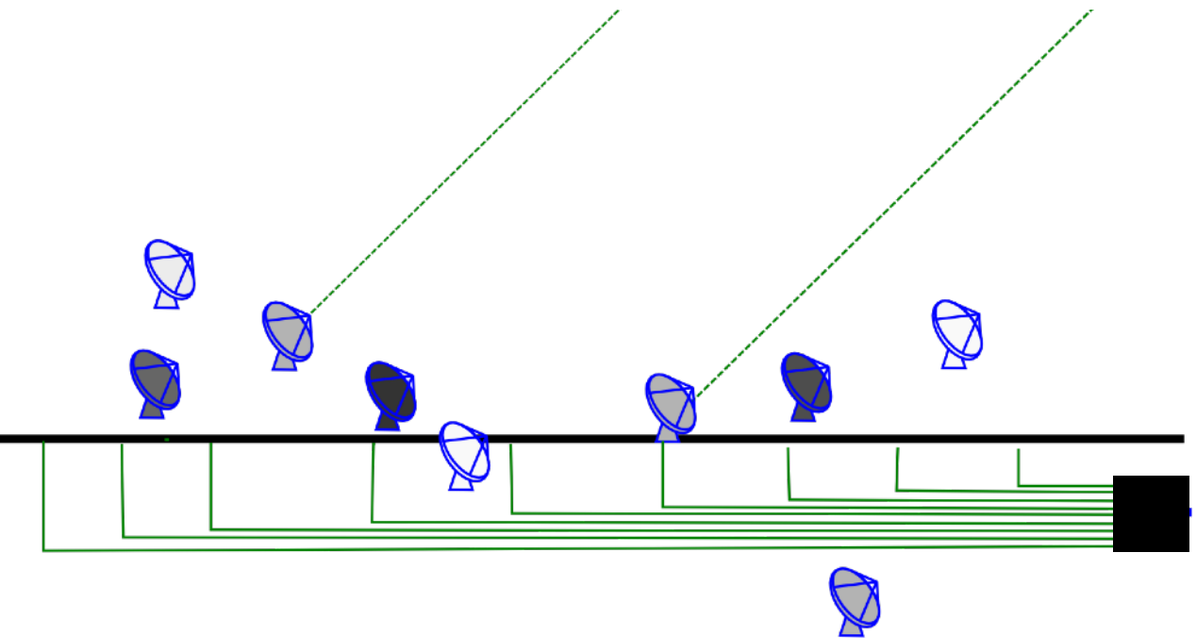
Uncalibrated instrument



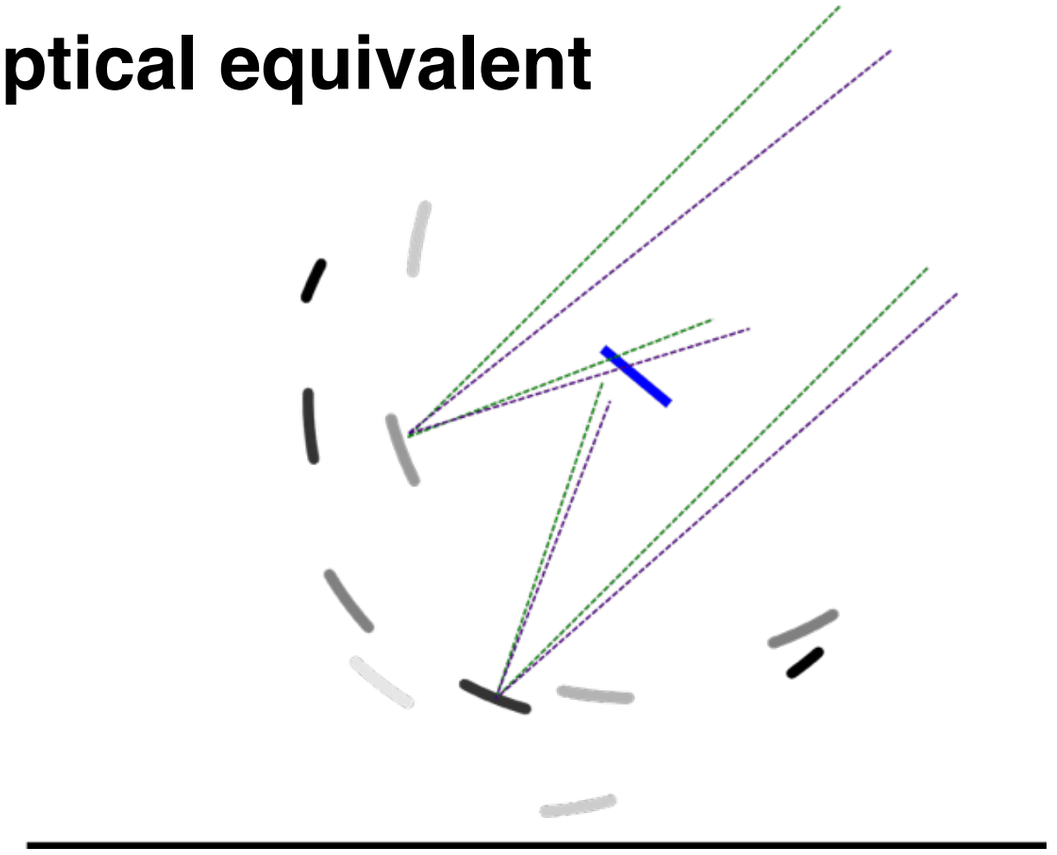
Optical equivalent



Uncalibrated instrument



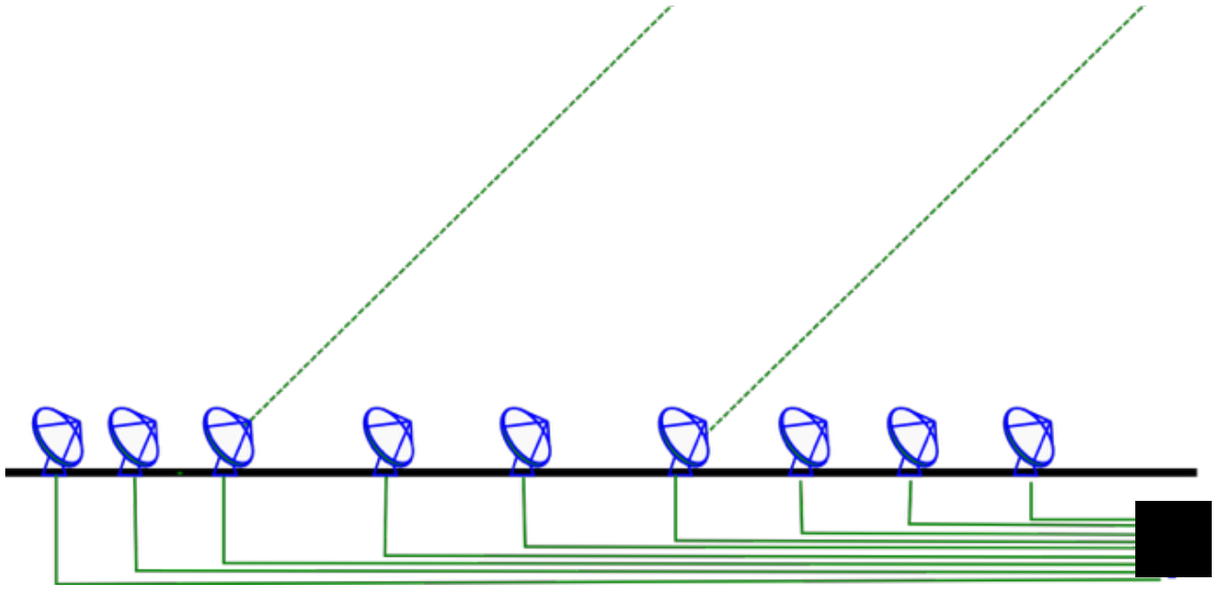
Optical equivalent

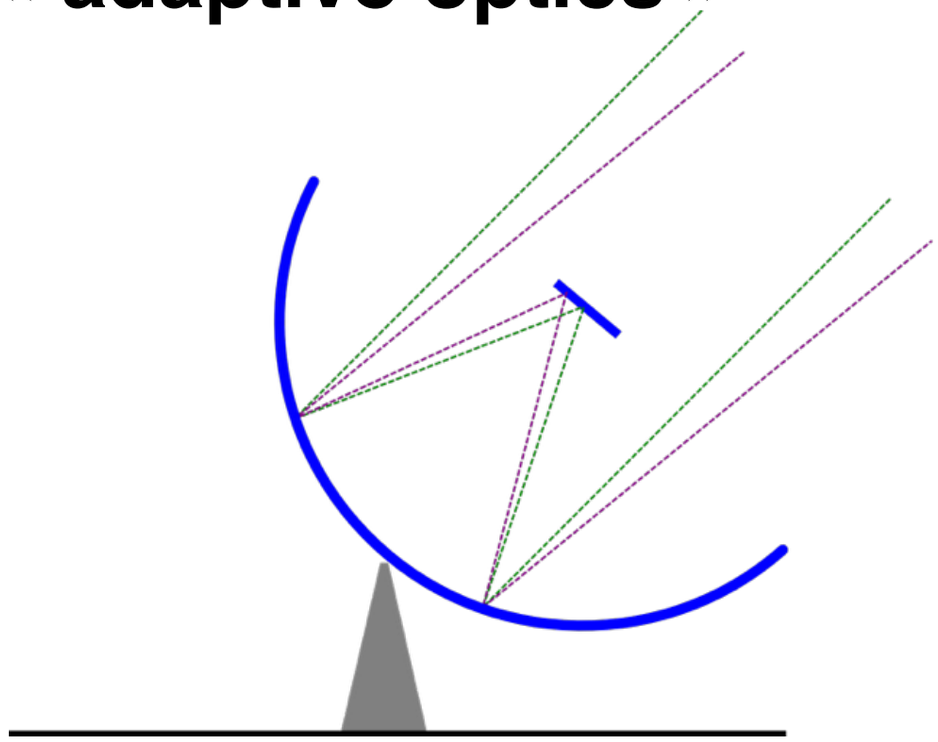


Calibration of a radio interferometer

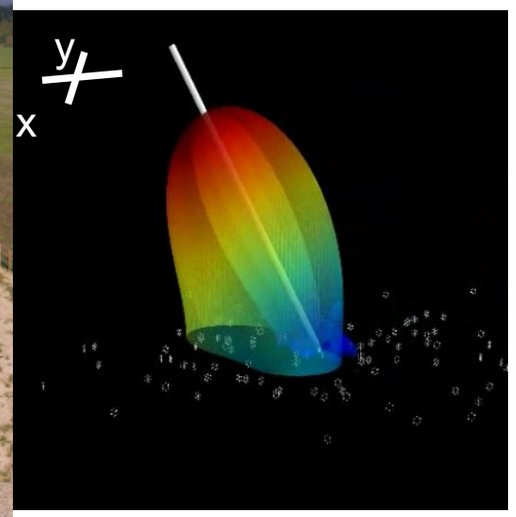
=

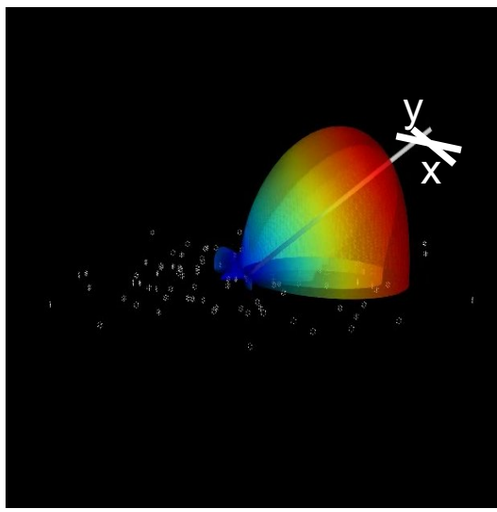
Post-processing « adaptive optics »





Some direction-dependent effects



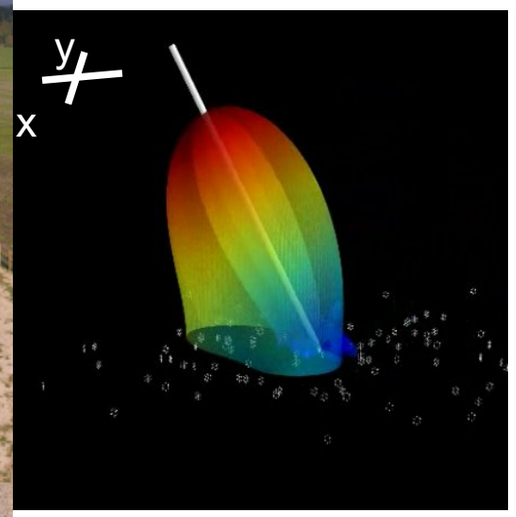


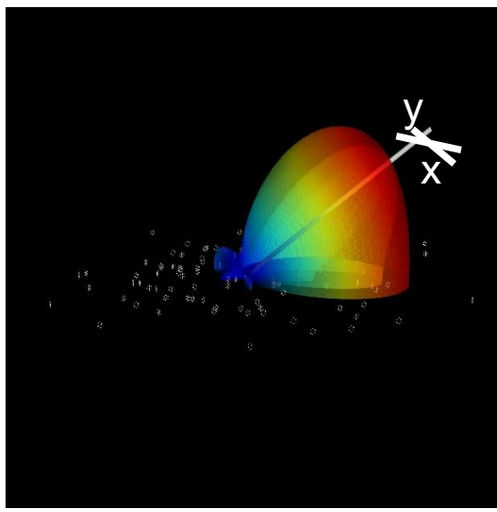
Direction 1 affects gain polarization

Direction 2

Antenna beam

Some direction-dependent effects



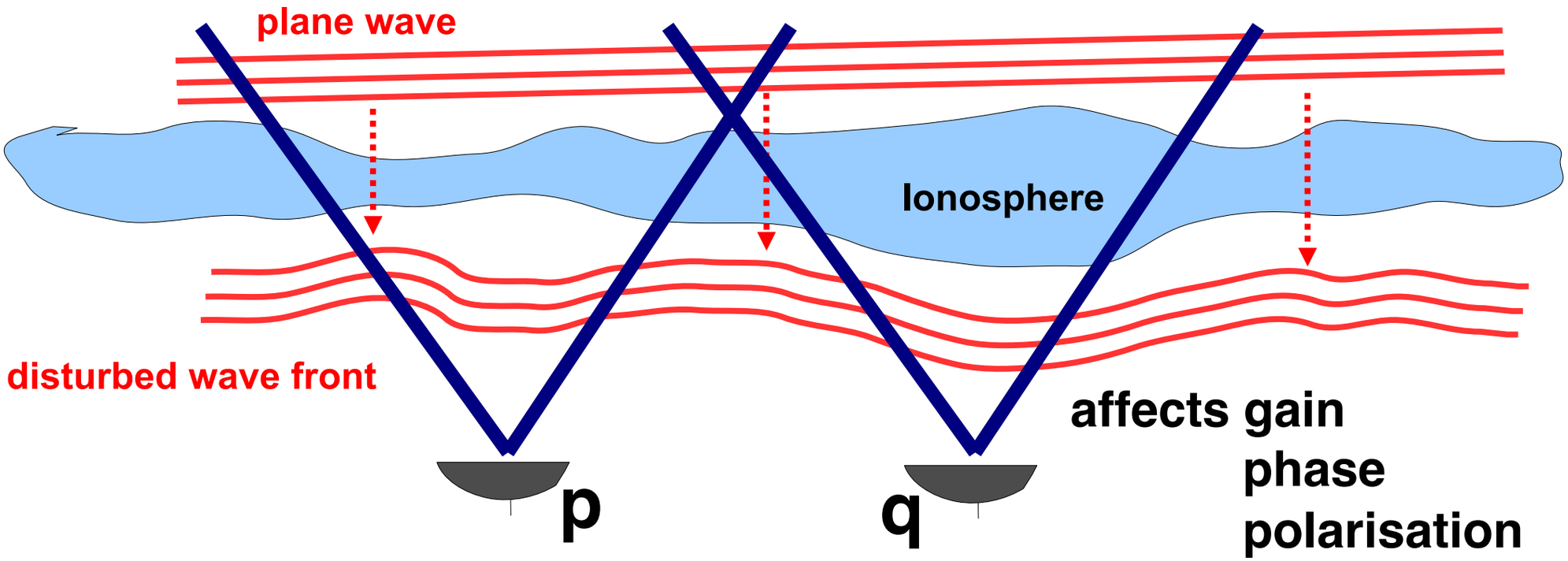


Direction 1 affects gain polarization

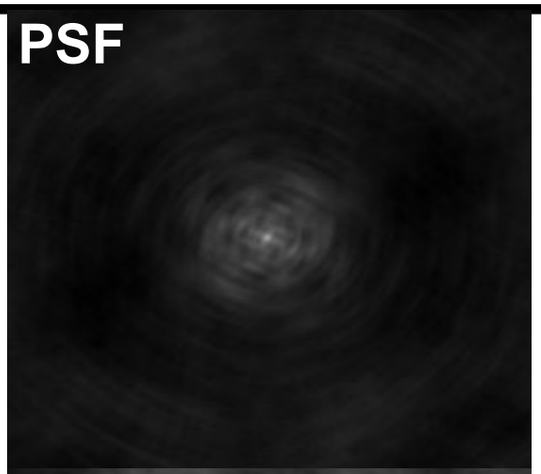
Direction 2

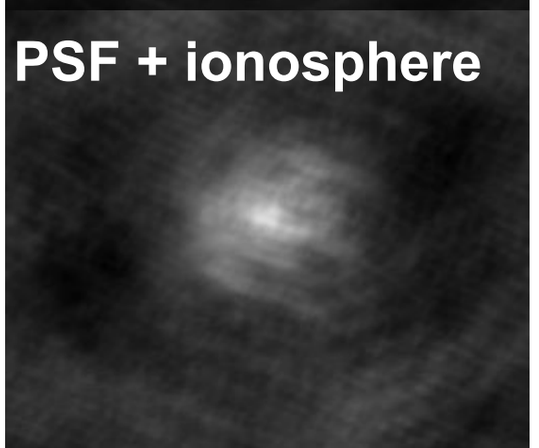
Antenna beam

Ionospheric/Atmospheric disturbance



affects gain
phase
polarisation



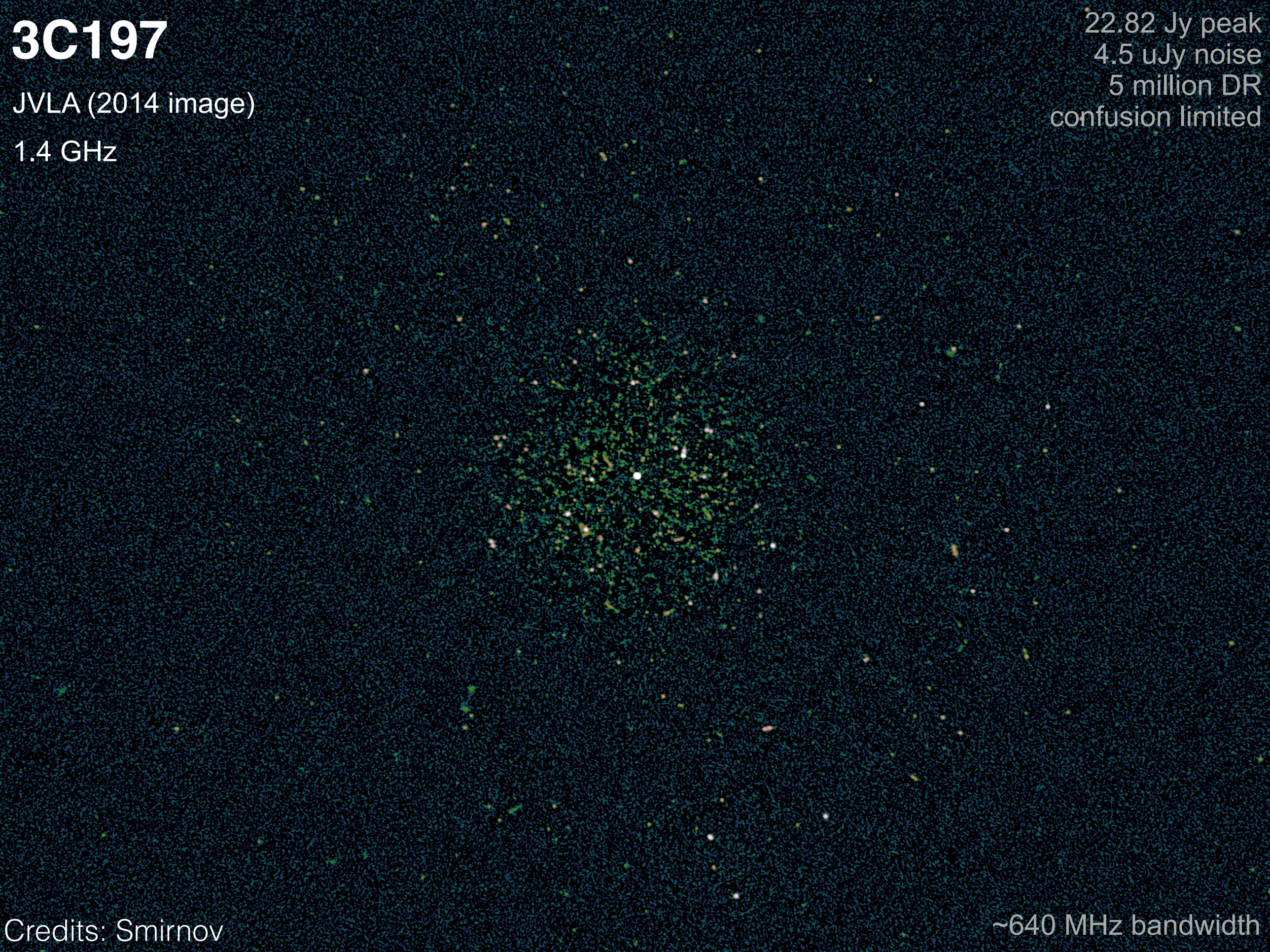


3C197

JVLA (2014 image)

1.4 GHz

22.82 Jy peak
4.5 uJy noise
5 million DR
confusion limited



Credits: Smirnov

~640 MHz bandwidth

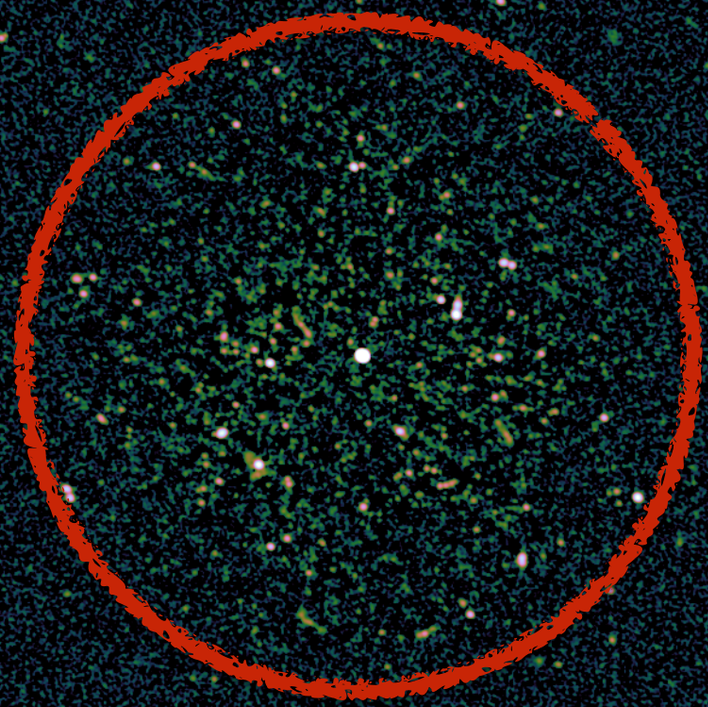
3C197

JVLA (2014 image)

1.4 GHz

Antenna beam

22.82 Jy peak
4.5 uJy noise
5 million DR
confusion limited



Credits: Smirnov

~640 MHz bandwidth

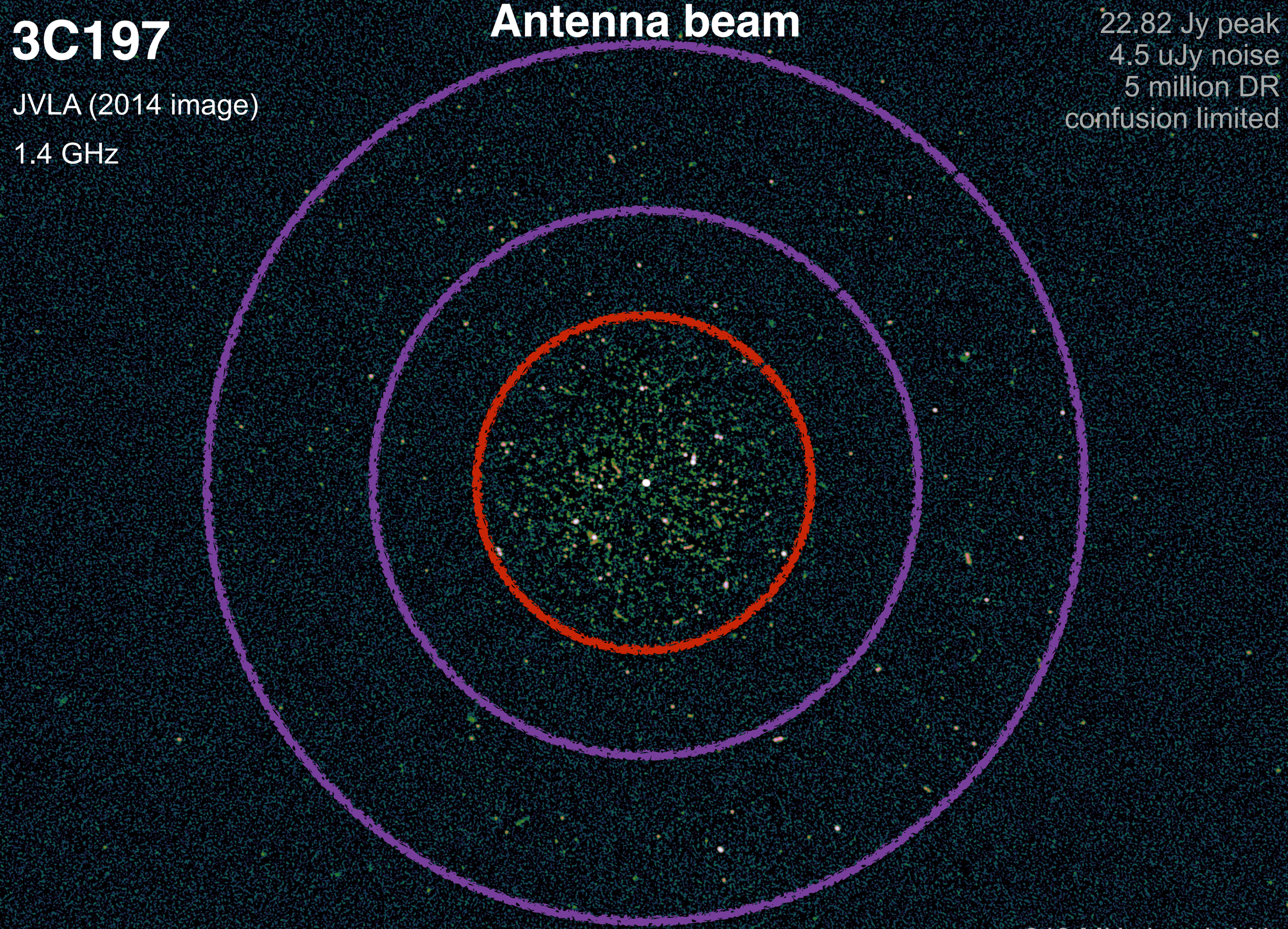
3C197

JVLA (2014 image)

1.4 GHz

Antenna beam

22.82 Jy peak
4.5 uJy noise
5 million DR
confusion limited



Credits: Smirnov

~640 MHz bandwidth

3C197

JVLA (2014 image)

1.4 GHz

Antenna beam

22.82 Jy peak
4.5 uJy noise
5 million DR
confusion limited

~640 MHz bandwidth

3C197

JVLA (2014 image)

1.4 GHz

Antenna beam

22.82 Jy peak
4.5 uJy noise
5 million DR
confusion limited

~640 MHz bandwidth

3C197

JVLA (2014 image)

1.4 GHz

Antenna beam

22.82 Jy peak
4.5 uJy noise
5 million DR
confusion limited

ov

Iheanetu, Girard et al., in prep

~640 MHz bandwidth

3C197

Validity region of
standard calibration

Credits: Tasse & Smirnov

3C197

Validity region of standard calibration

Credits: Tasse & Smirnov

Credits: Tasse & Smirnov

Credits: Tasse & Smirnov

Improper calibration and deconvolution

1) Increases local and global noise

2) Fake variables sources

3) Fake detection of new sources

Hopefully, solutions exists : The RIME(Smirnov 2011)
DDFacet (Tasse et al. 2017?)

Credits: Tasse & Smirnov

Outline

New instrumentation, new problems
(and new solutions !)

Sparsity and deconvolution

Application to transient imaging

Conclusions

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 recent sampling theorem

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

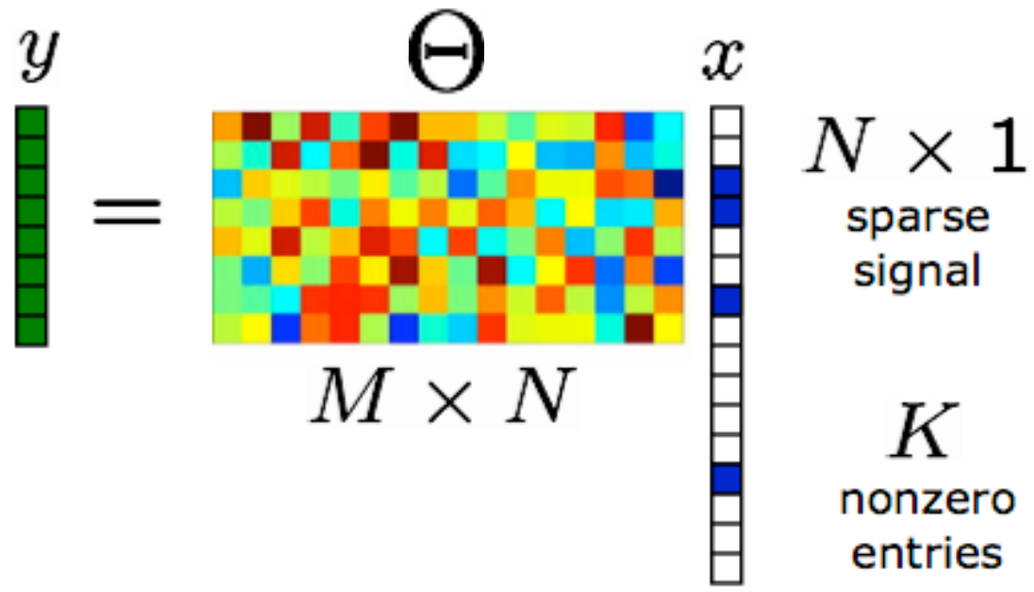
Compressed Sensing

* 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 recent sampling theorem

"Signals with exactly K components different from zero can be recovered perfectly from ~K log N incoherent measurements"

$$y = \Theta x$$



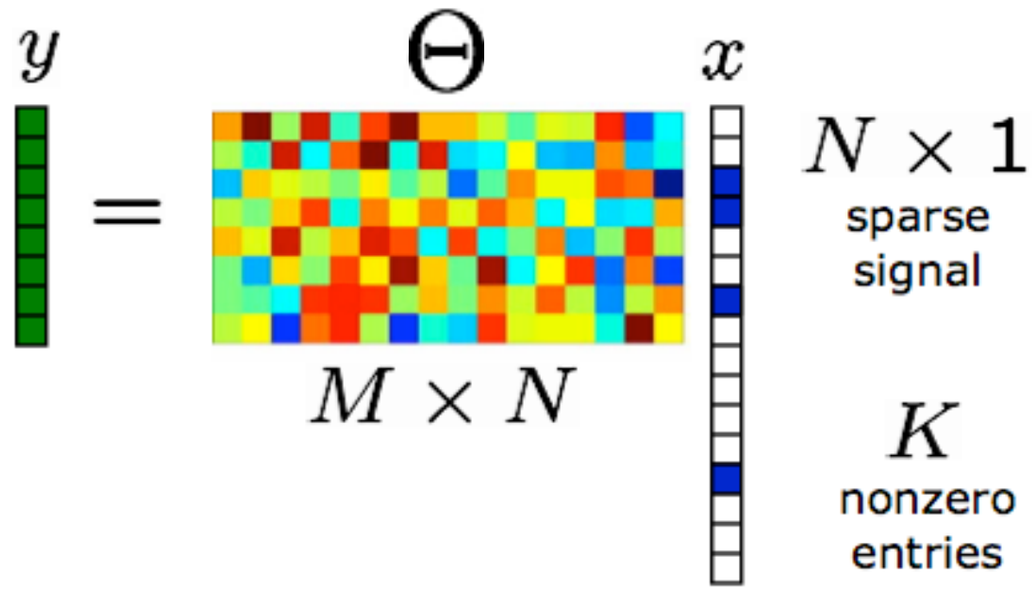
Compressed Sensing

* 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 recent sampling theorem

"Signals with exactly K components different from zero can be recovered perfectly from ~K log N incoherent measurements"

$$y = \Theta x$$



Assumption on the signal x:

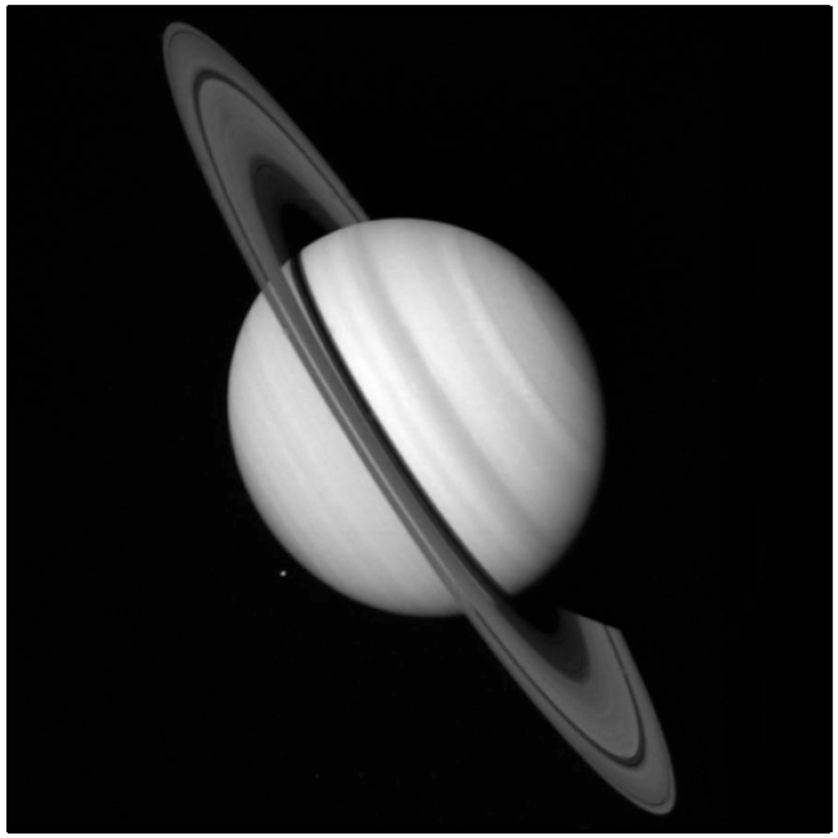
- **Underdetermined system**
- **Sparsity** of x
- **Incoherence** (Θ random)

$$K < M \ll N$$

Reconstruction based on non-linear algorithms

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

Representation of a signal

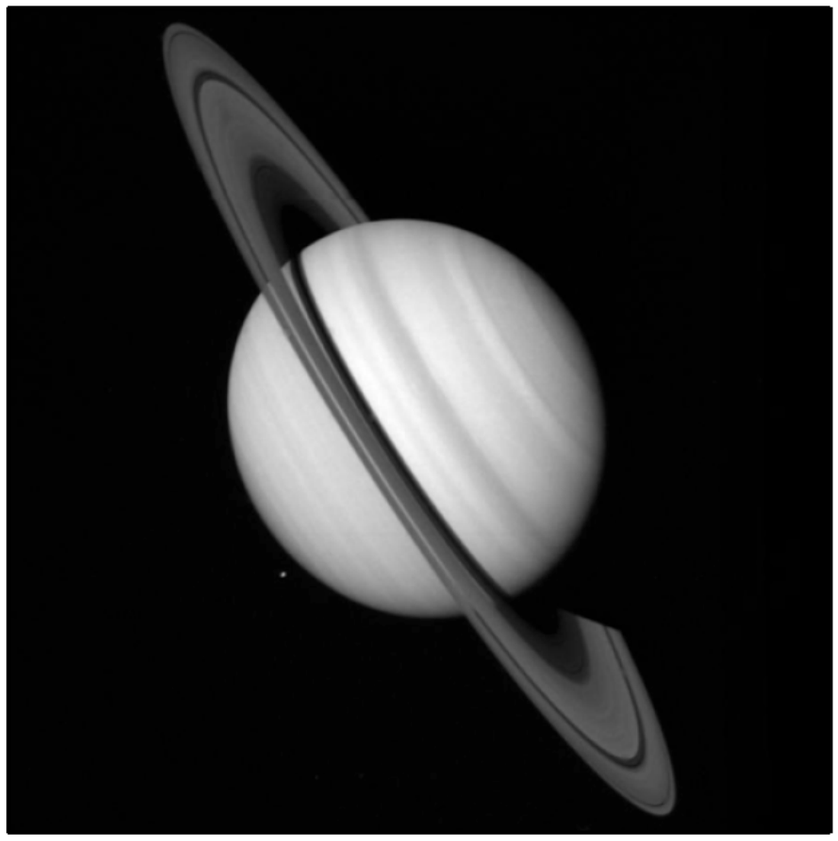


Original image

Direct space

5% of the highest coeff

Representation of a signal



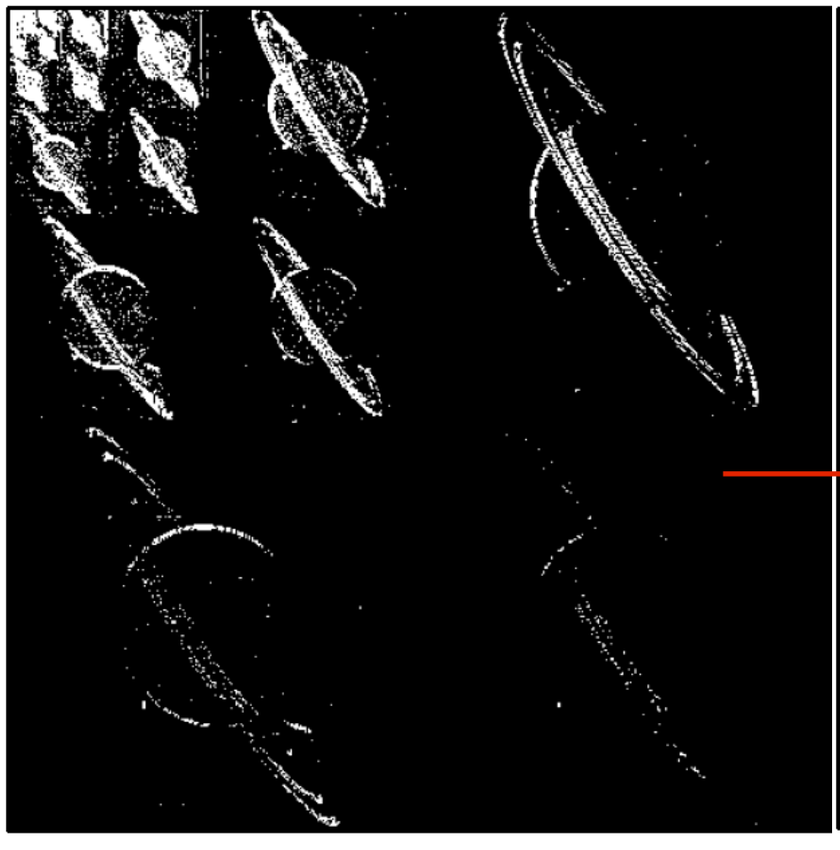
Original image

Direct space

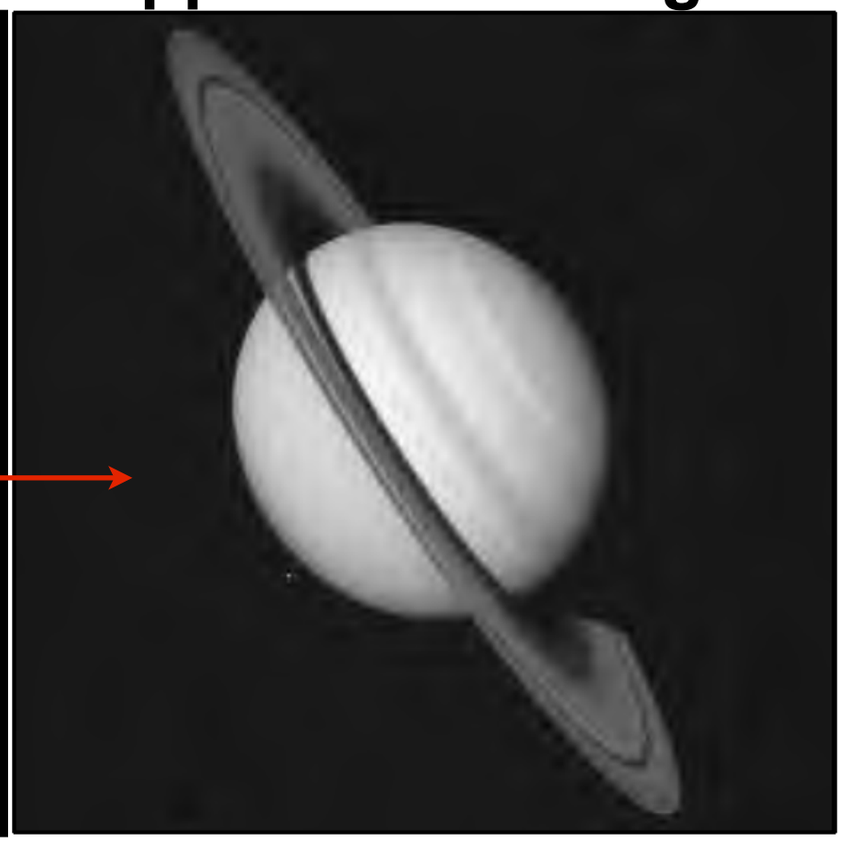
5% of the highest coeff

Wavelet space

0,5% of the highest coeff



Approximate image



Sparsity

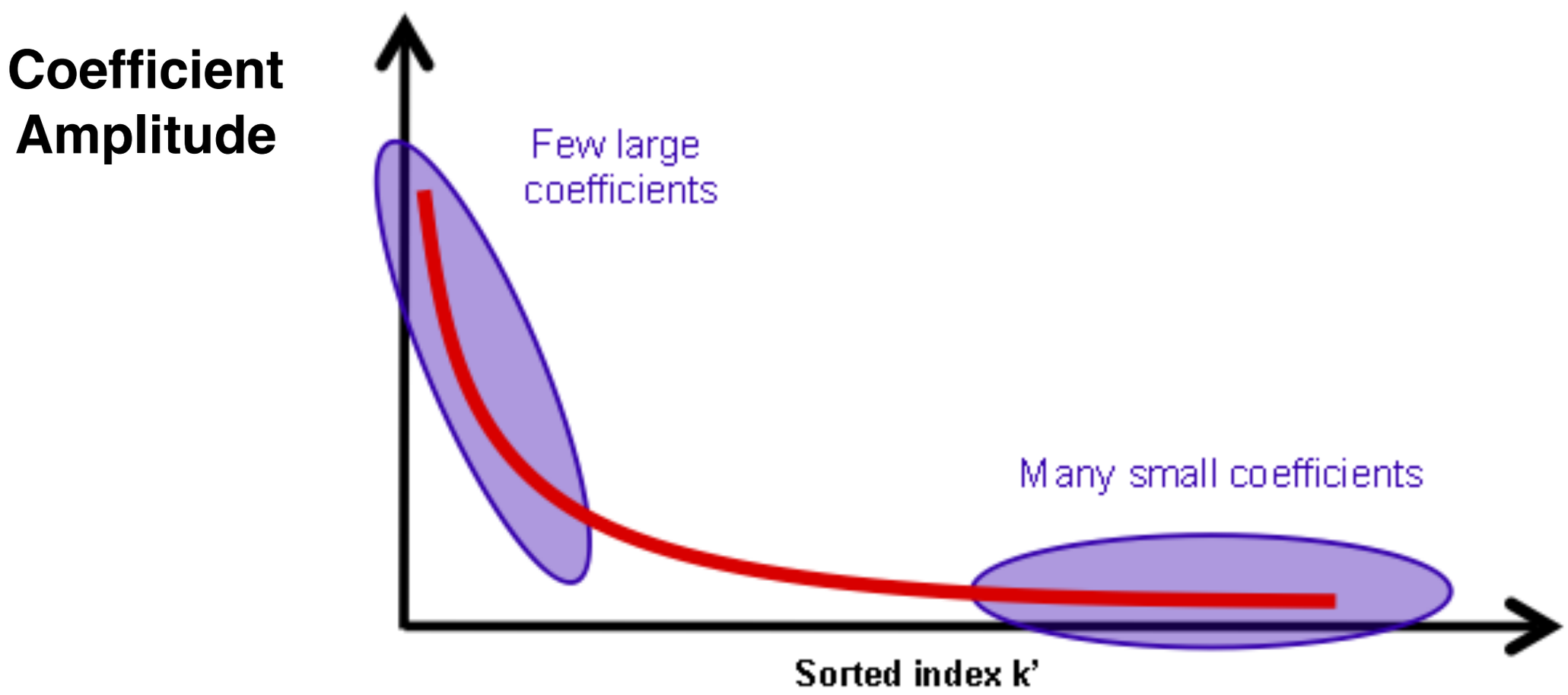
Sparse signal = represented by a small number of coefficients in a « good » dictionary

Dictionary $\Phi = \{\phi_1, \ldots, \phi_K\}$

Atom

What makes a good dictionary ?

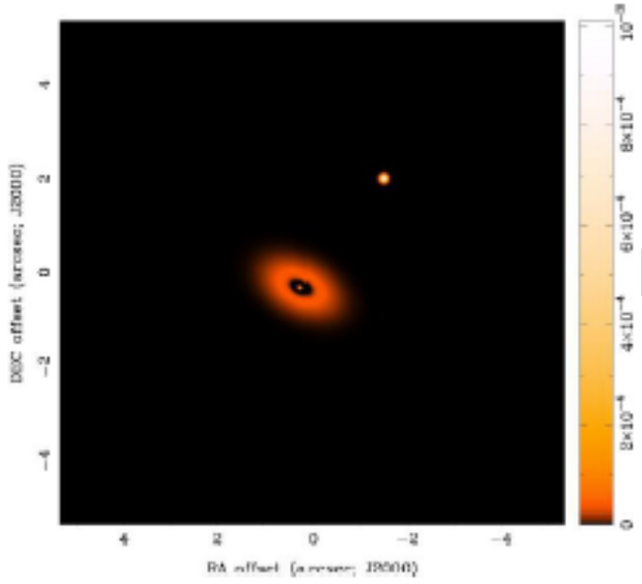
- Fast computation
- Signal analysis through the statistical properties of the coefficients
- **Sparsity of coefficients**



Aperture imaging and deconvolution

Interferometry

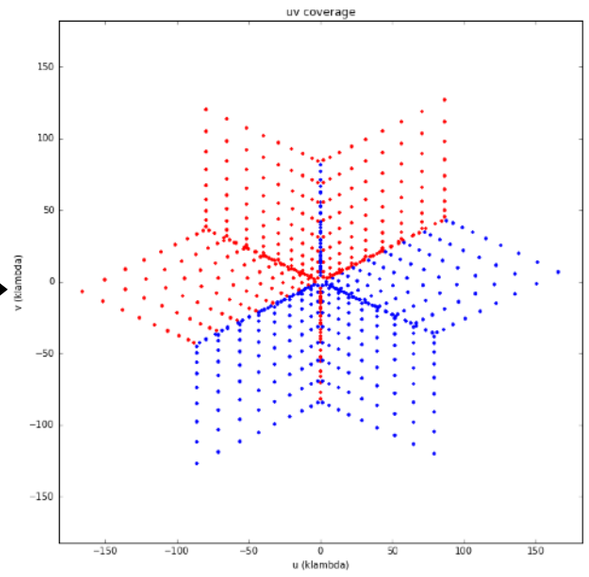
Imaging from a sparse set of Fourier samples



True sky

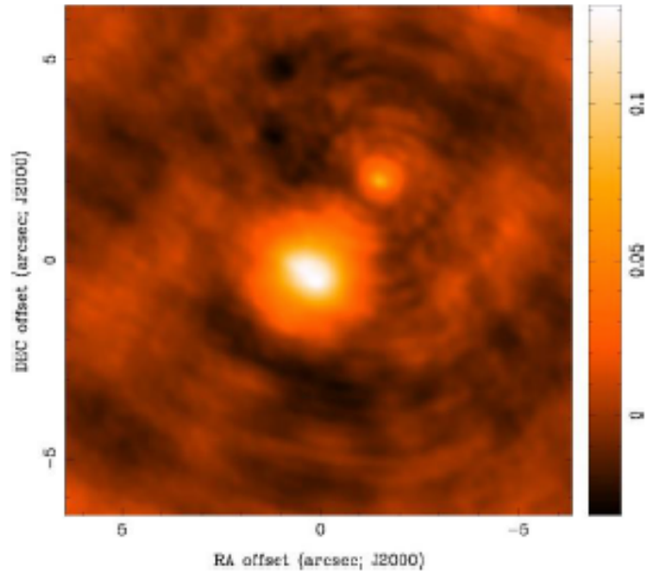
$\mathcal{F}$

$\times$



Sampling of the Fourier Plane

$\mathcal{F}^{-1}$

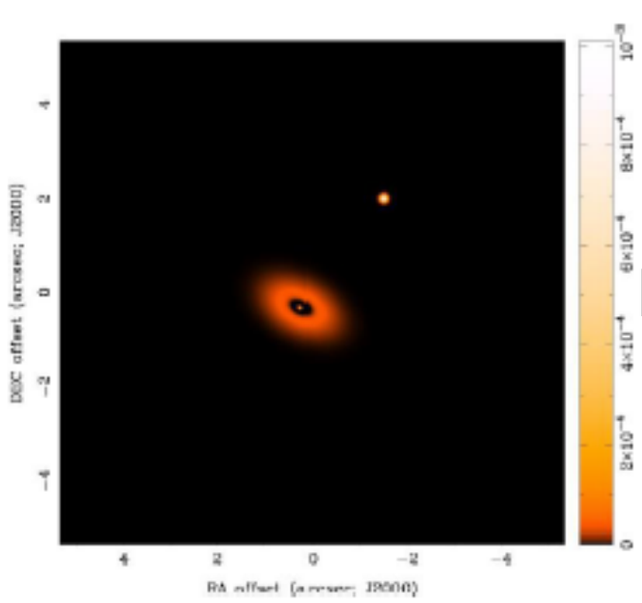


Observed sky

Aperture imaging and deconvolution

Interferometry

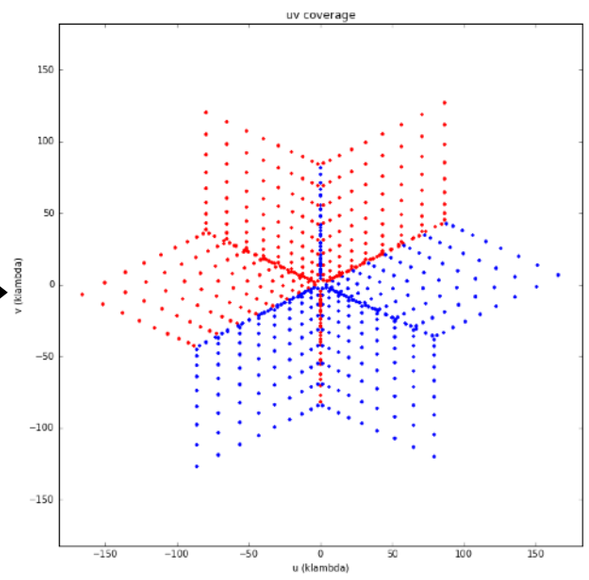
Imaging from a sparse set of Fourier samples



True sky

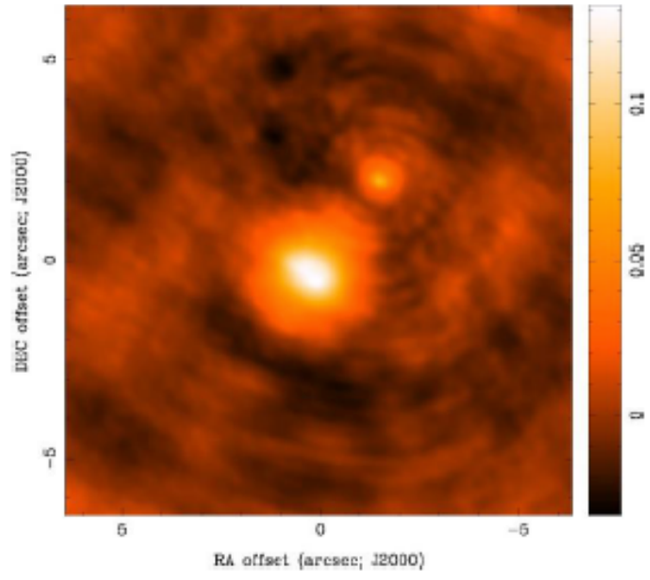
$\mathcal{F}$

$\times$



Sampling of the Fourier Plane

$\mathcal{F}^{-1}$



Observed sky

Inverse problem

$$Y = HX + N$$

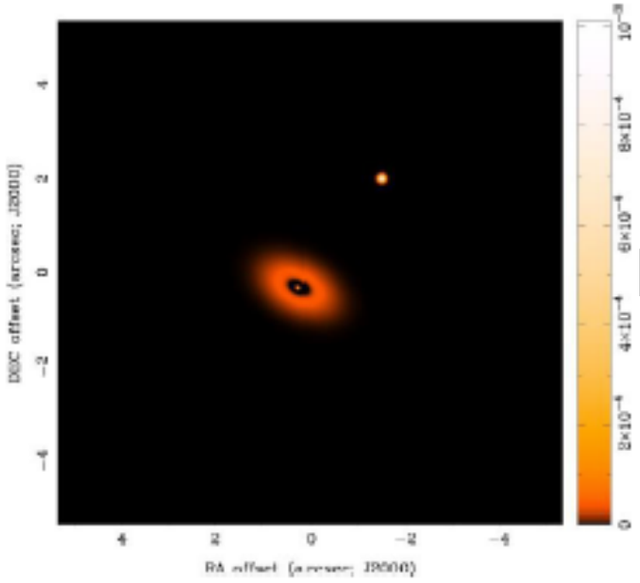
Fourier samples — Instrumental response — True sky — Noise

$\longrightarrow$ CLEAN (1974)

Aperture imaging and deconvolution

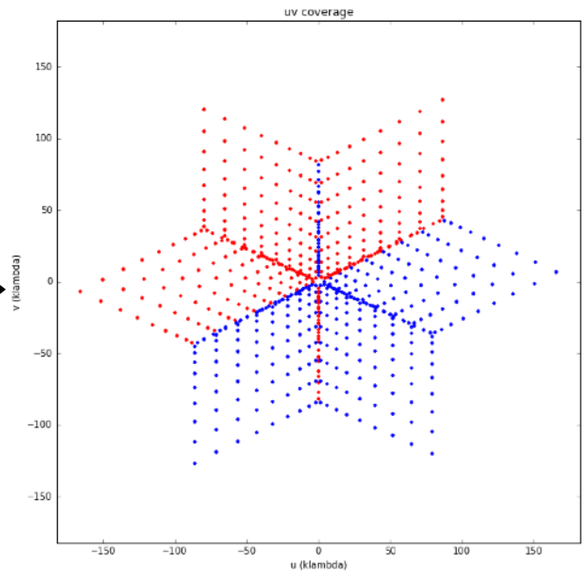
Interferometry

Imaging from a sparse set of Fourier samples



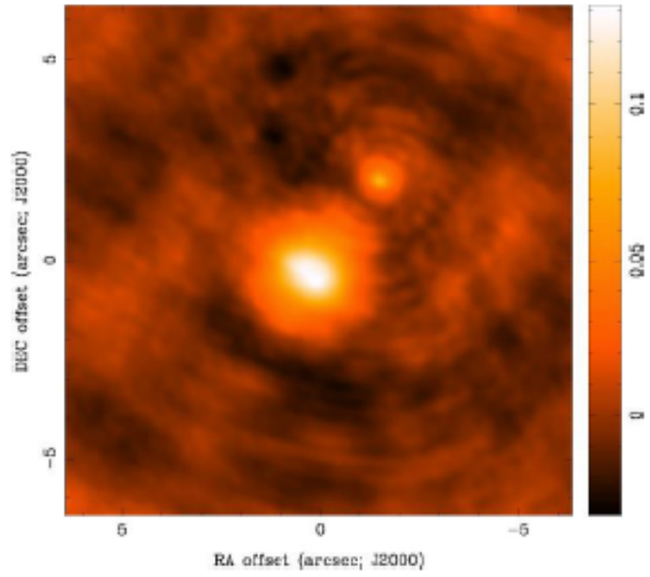
True sky

$\mathcal{F}$



Sampling of the Fourier Plane

$\mathcal{F}^{-1}$



Observed sky

Inverse problem

$$Y = HX + N$$

Fourier samples — Instrumental response — True sky — Noise

→ CLEAN (1974)

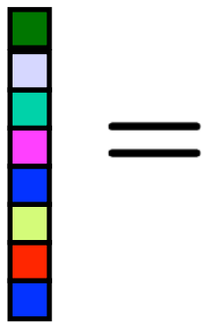
Combining the mathematical framework of **Compressed Sensing** and **sparsity**

$$P : \min_{\alpha} \; ||Y - H\Phi\alpha||_2^2 + \lambda||\alpha||_1 \qquad ||\alpha||_1 = \sum_i |\alpha_i|$$

Data term — Sparsity constraint

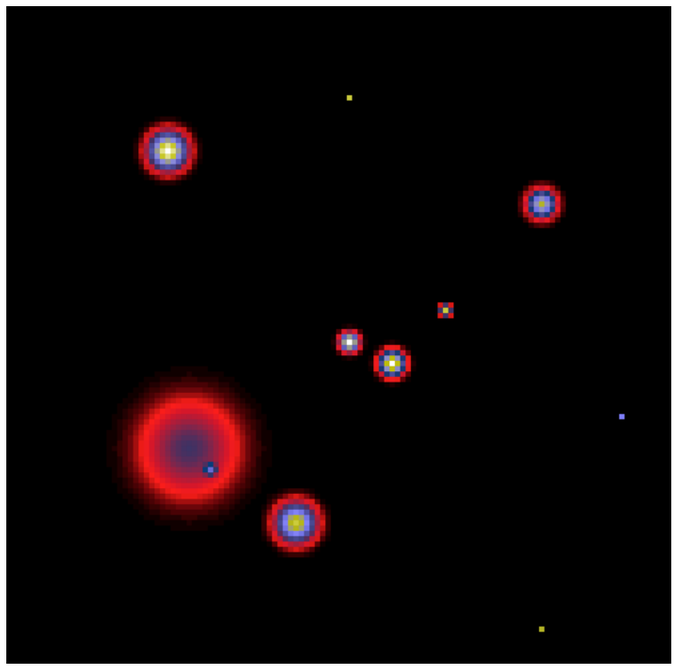
Radio interferometry & Compressed Sensing

$$y$$



$$=$$

Visibilities

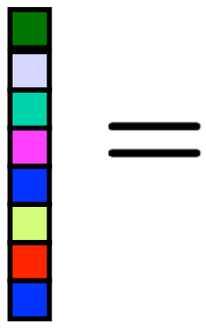


Sky

$$X$$

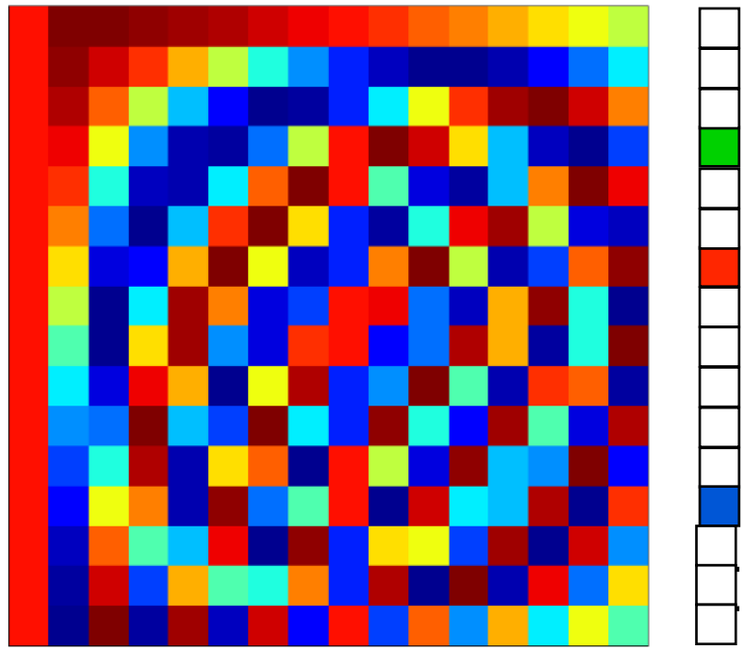
Radio interferometry & Compressed Sensing

$$y$$



$$=$$

Visibilities



$$\Phi \qquad \alpha$$

Sky

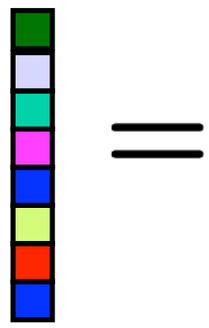
$$X = \Phi\alpha$$

e.g. Wavelets Tr.

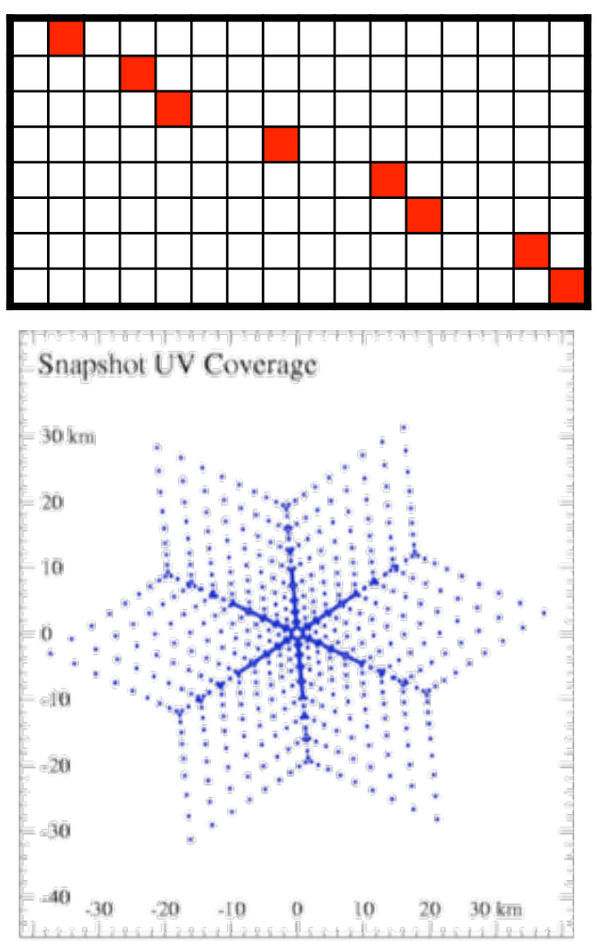
Sparse

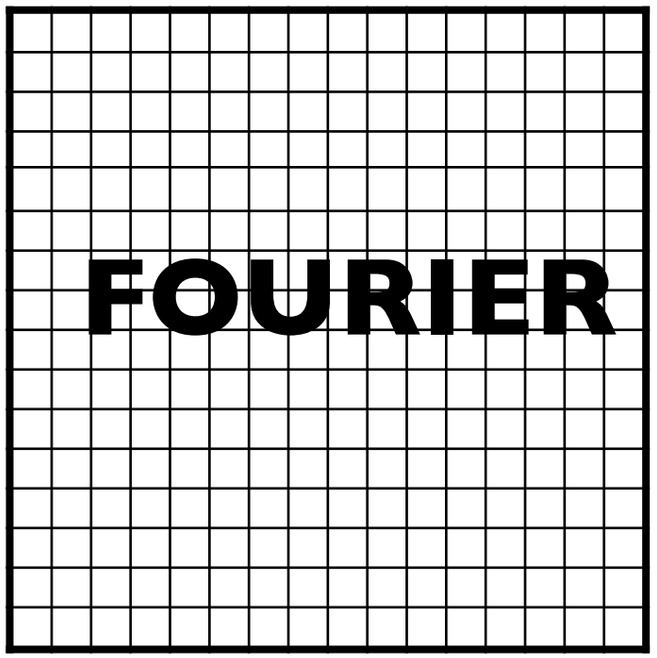
Radio interferometry & Compressed Sensing

$$y = H$$

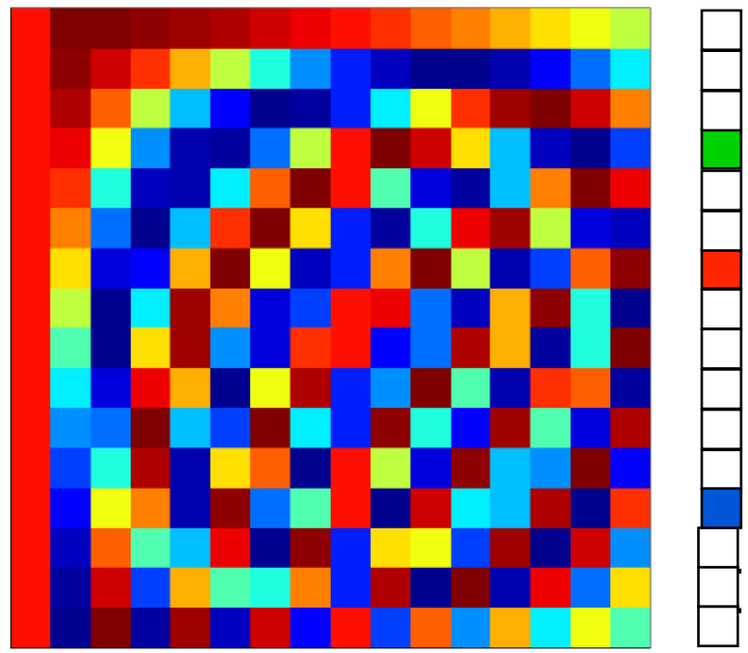


Visibilities





Measurement matrix (Fourier + Sampling)



Φ α

Sky

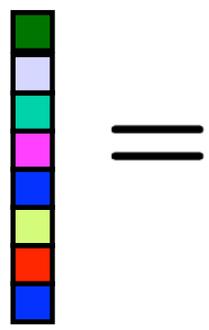
$$X = \Phi\alpha$$

e.g. Wavelets Tr.

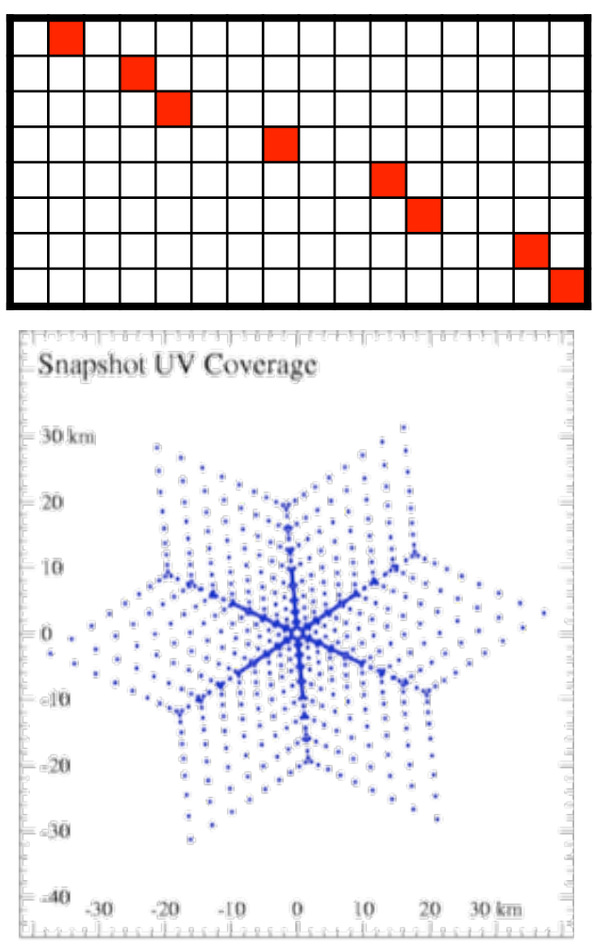
Sparse

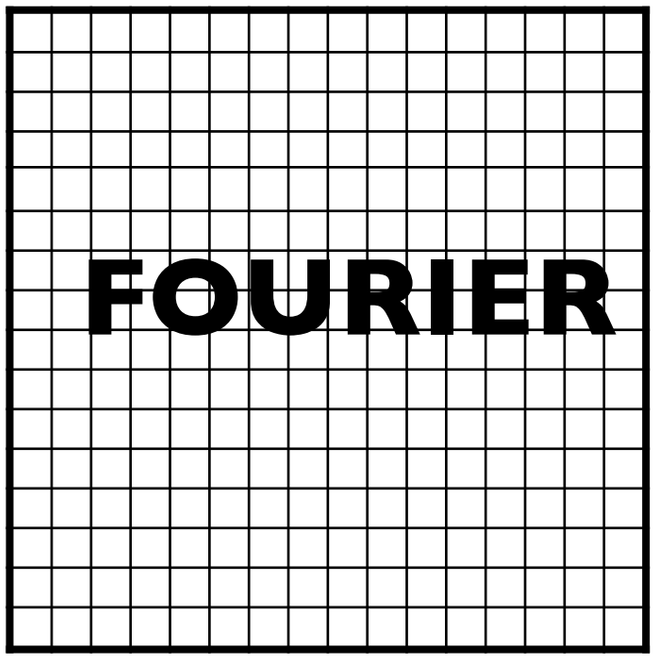
Radio interferometry & Compressed Sensing

$$y = H$$

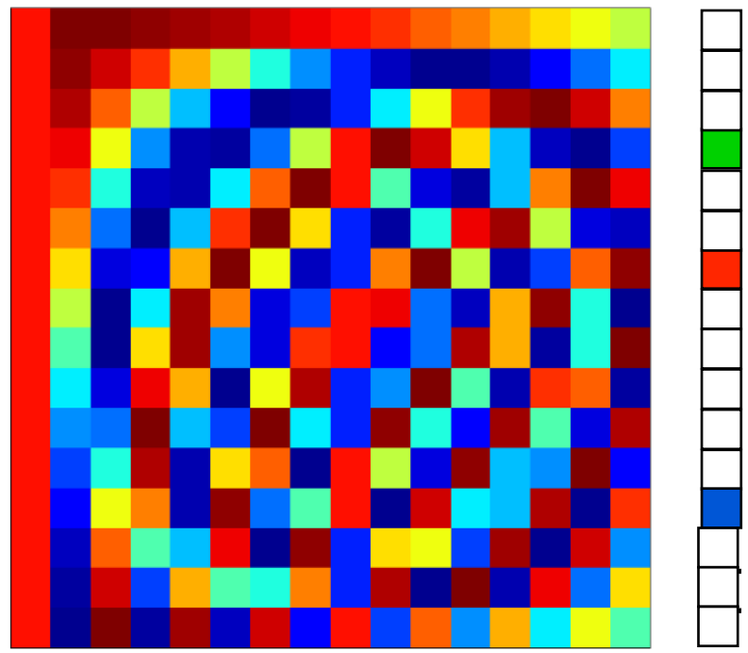


Visibilities





Measurement matrix (Fourier + Sampling)



Φ α

Sky

$$Y = HX + N$$

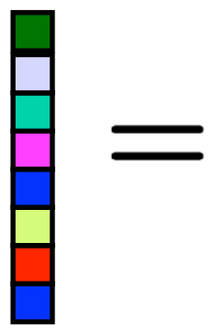
$$X = \Phi\alpha$$

e.g. Wavelets Tr.

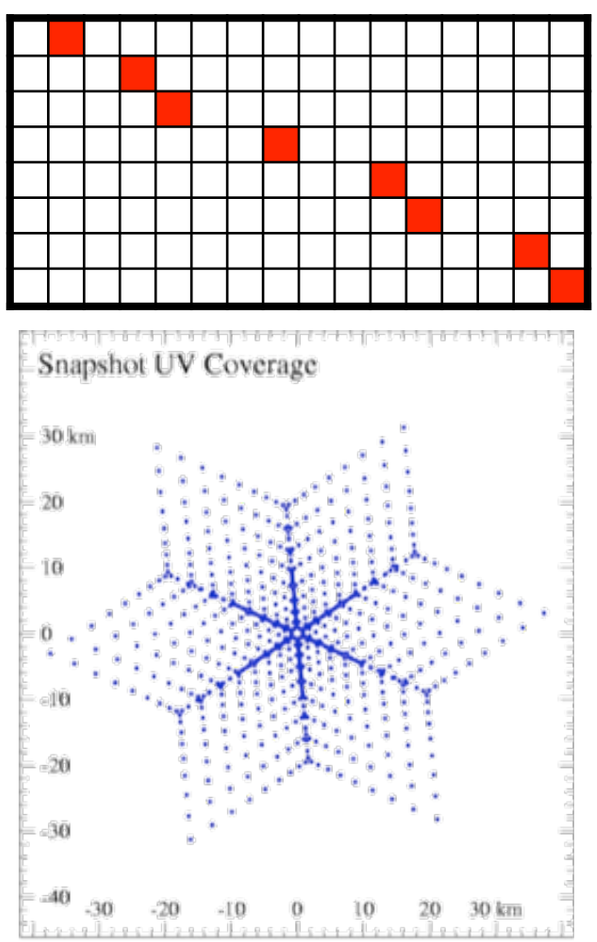
Sparse

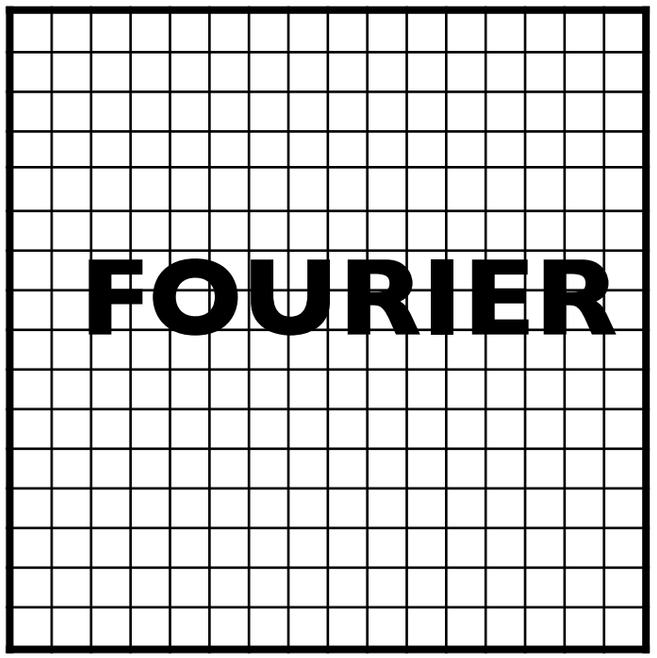
Radio interferometry & Compressed Sensing

$$y = H$$

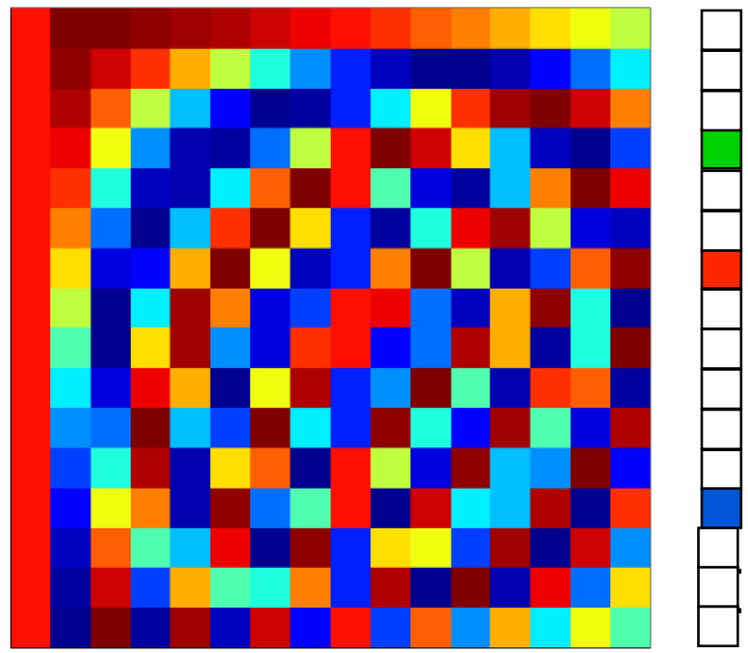


Visibilities





Measurement matrix (Fourier + Sampling)



Φ α

Sky

$$X = \Phi\alpha$$

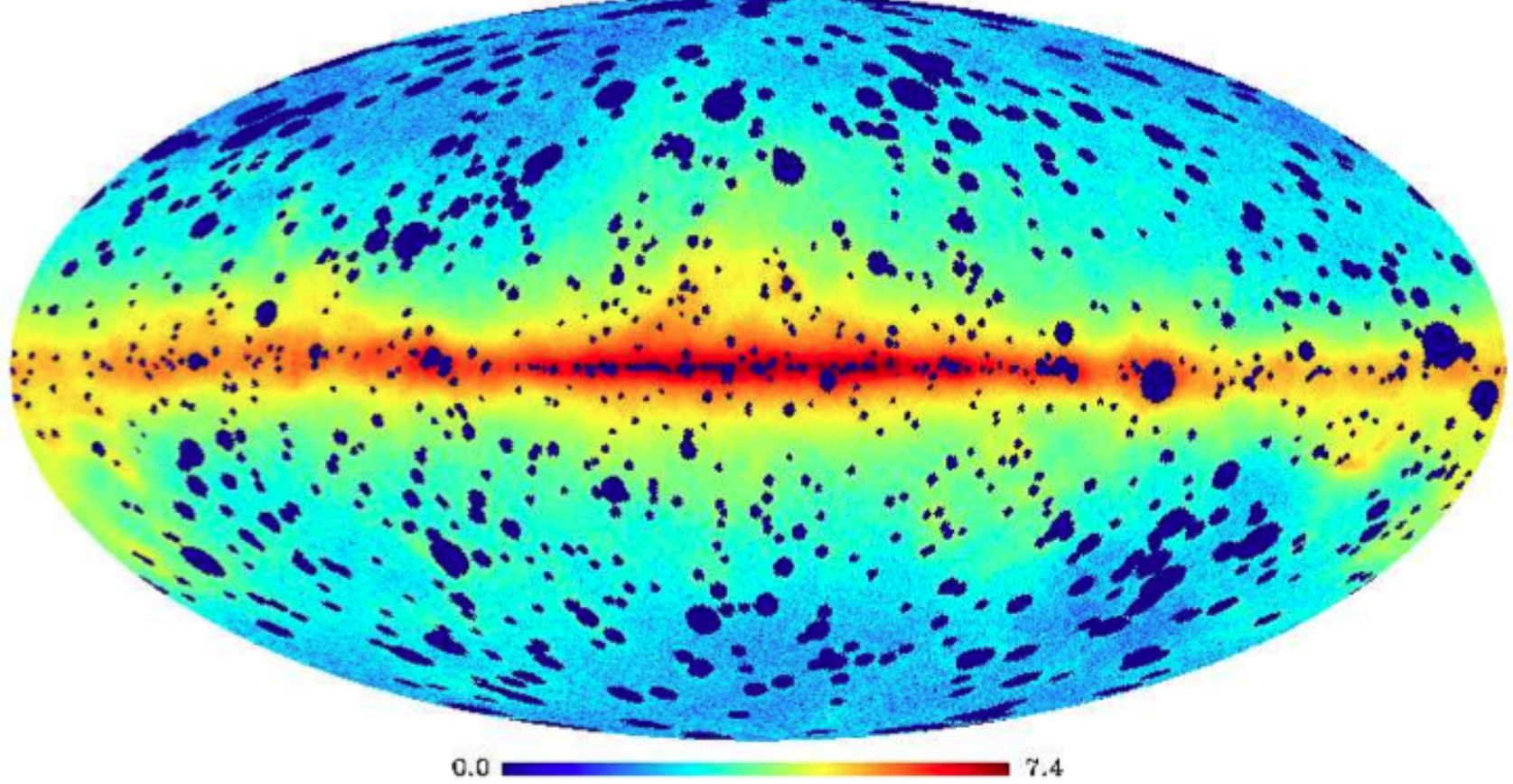
e.g. Wavelets Tr. — Sparse

$$Y = HX + N$$

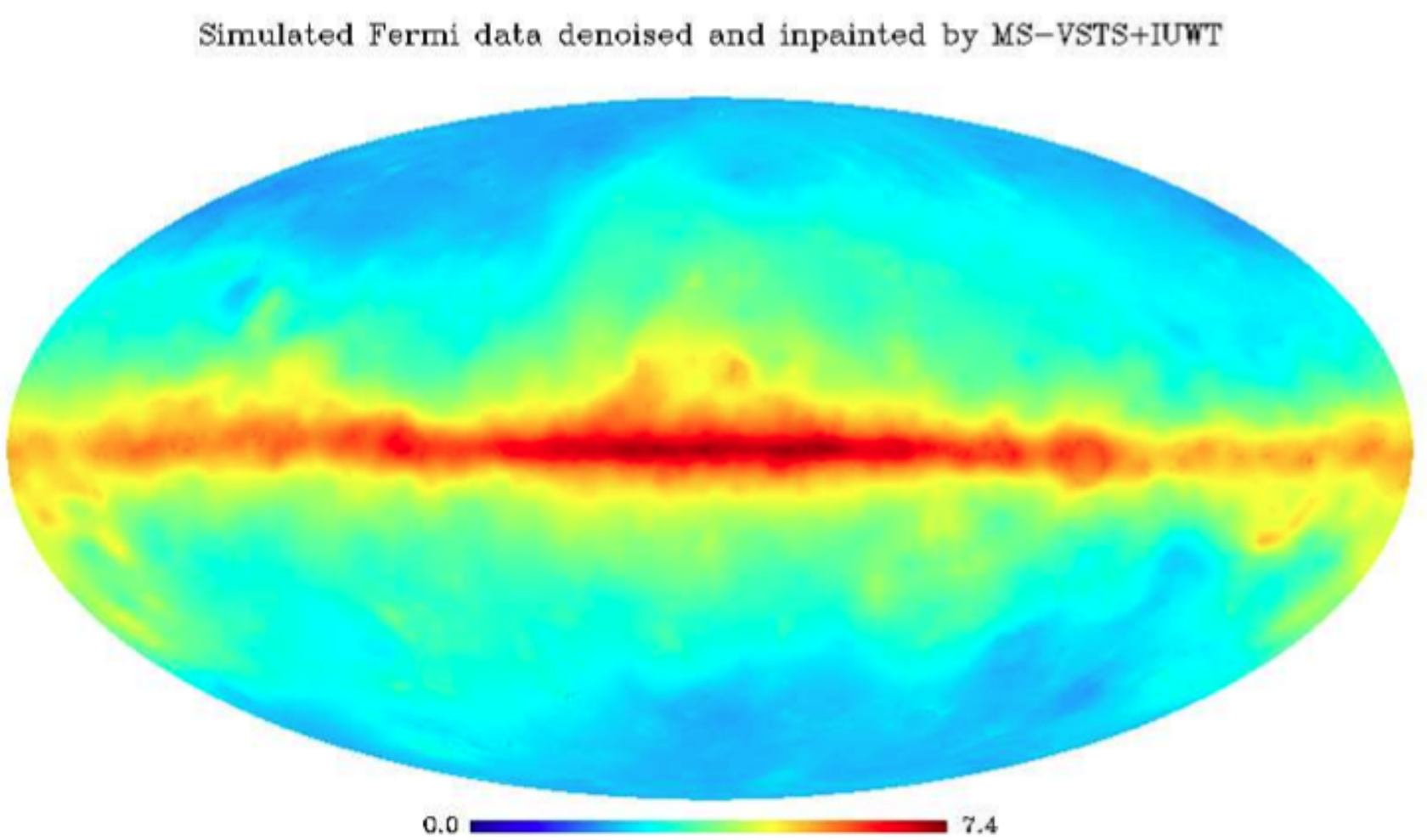
$$\min_{\alpha} \|\alpha\|_p^p \quad \text{subject to} \quad \|Y - H\Phi\alpha\|^2 \leq \epsilon$$

$$\min_{\alpha} \|V - \mathbf{A}\mathbf{\Phi}\alpha\|_2^2 + \sum_j \lambda_j |\alpha_j|.$$

Applications: In-painting

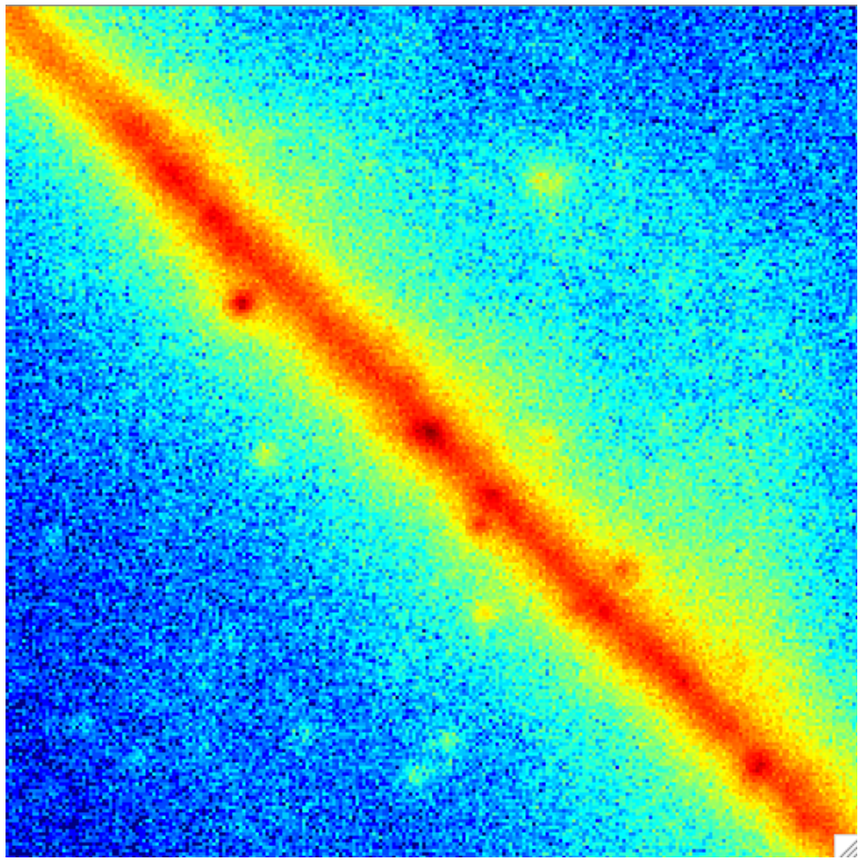


Simulated Fermi data

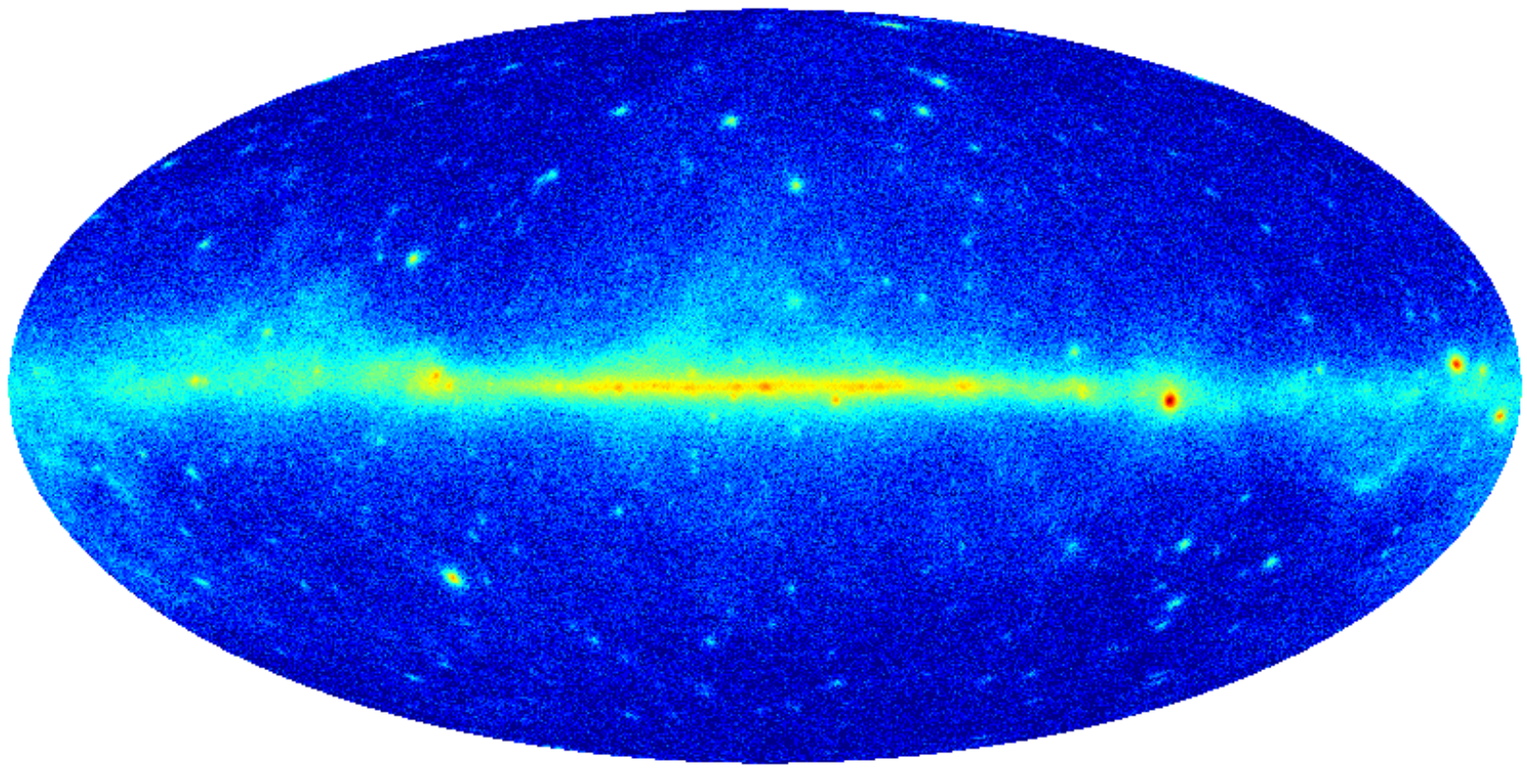


Credits: AIM/LCS

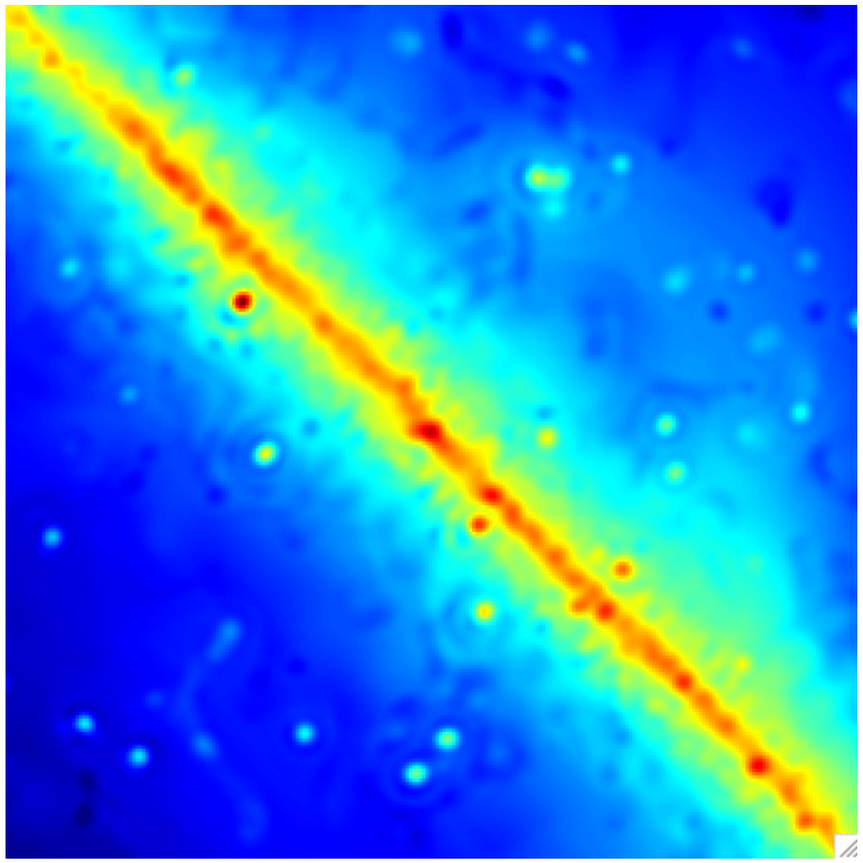
Applications: Denoising / Deconvolution

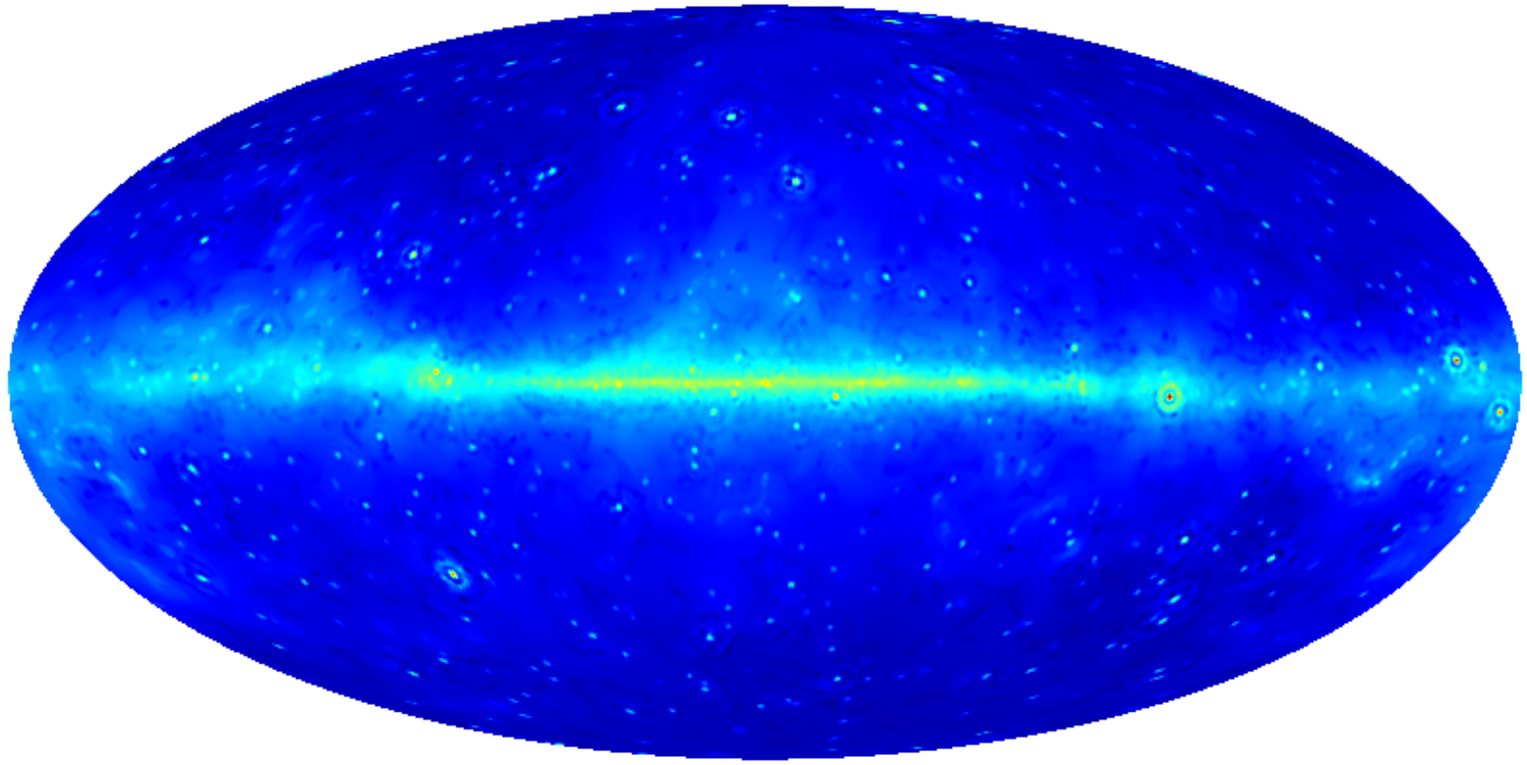


Simulated Fermi Poisson Data – Energy band = 360 MeV – 589 MeV



Simulated Fermi Deconvolved Data – Energy band = 360 MeV – 589 MeV

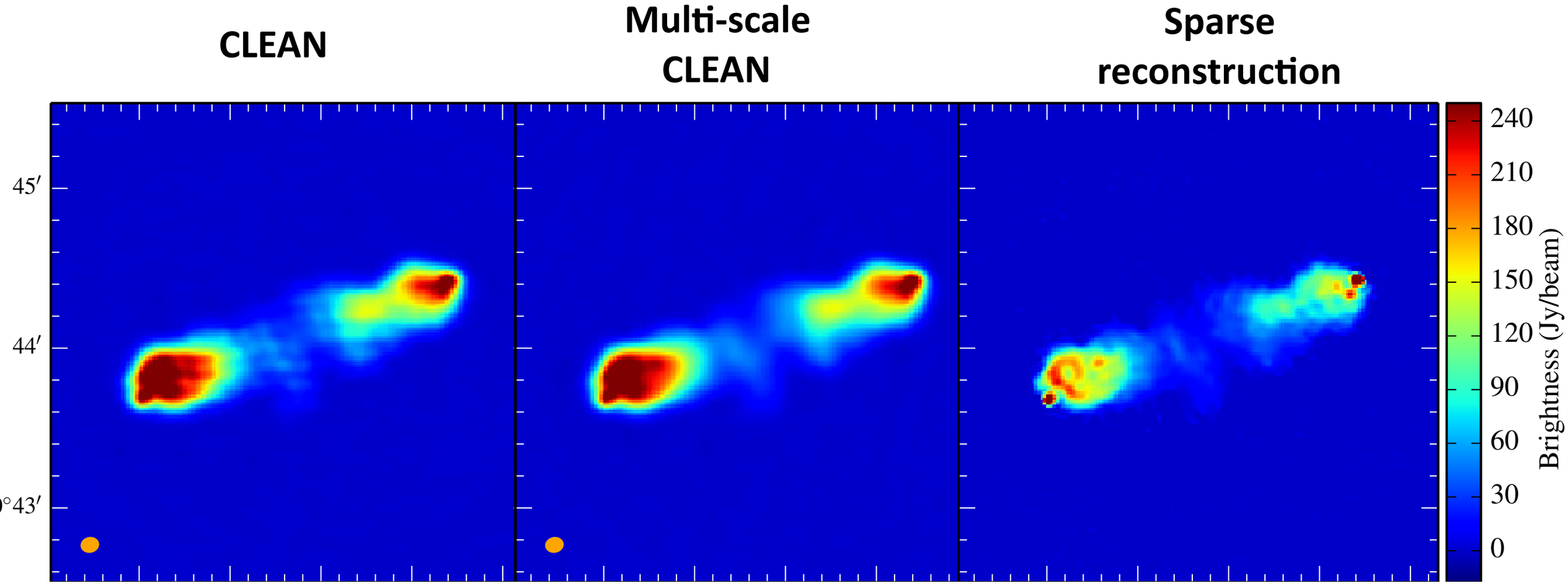




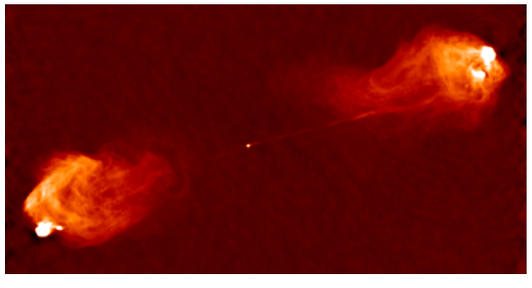
Credits: AIM/LCS

Sparse reconstruction

LOFAR (150 MHz) Cygnus A image reconstruction



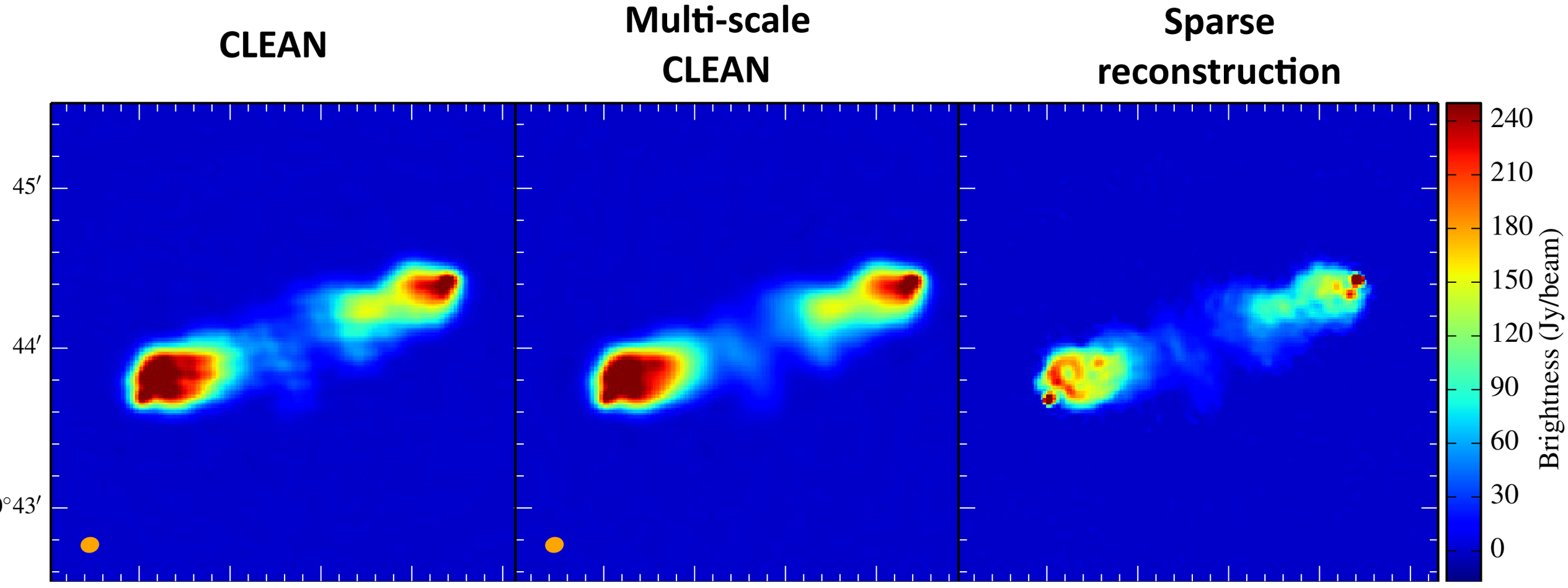
Factor of 4 improvement in angular resolution



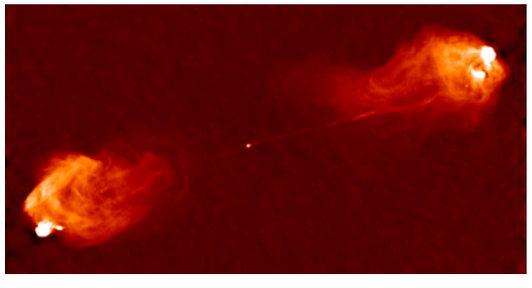
Garsden, Girard, Starck et al., A&A, 2015 & Girard et al., JINST, 2015

Sparse reconstruction

LOFAR (150 MHz) Cygnus A image reconstruction



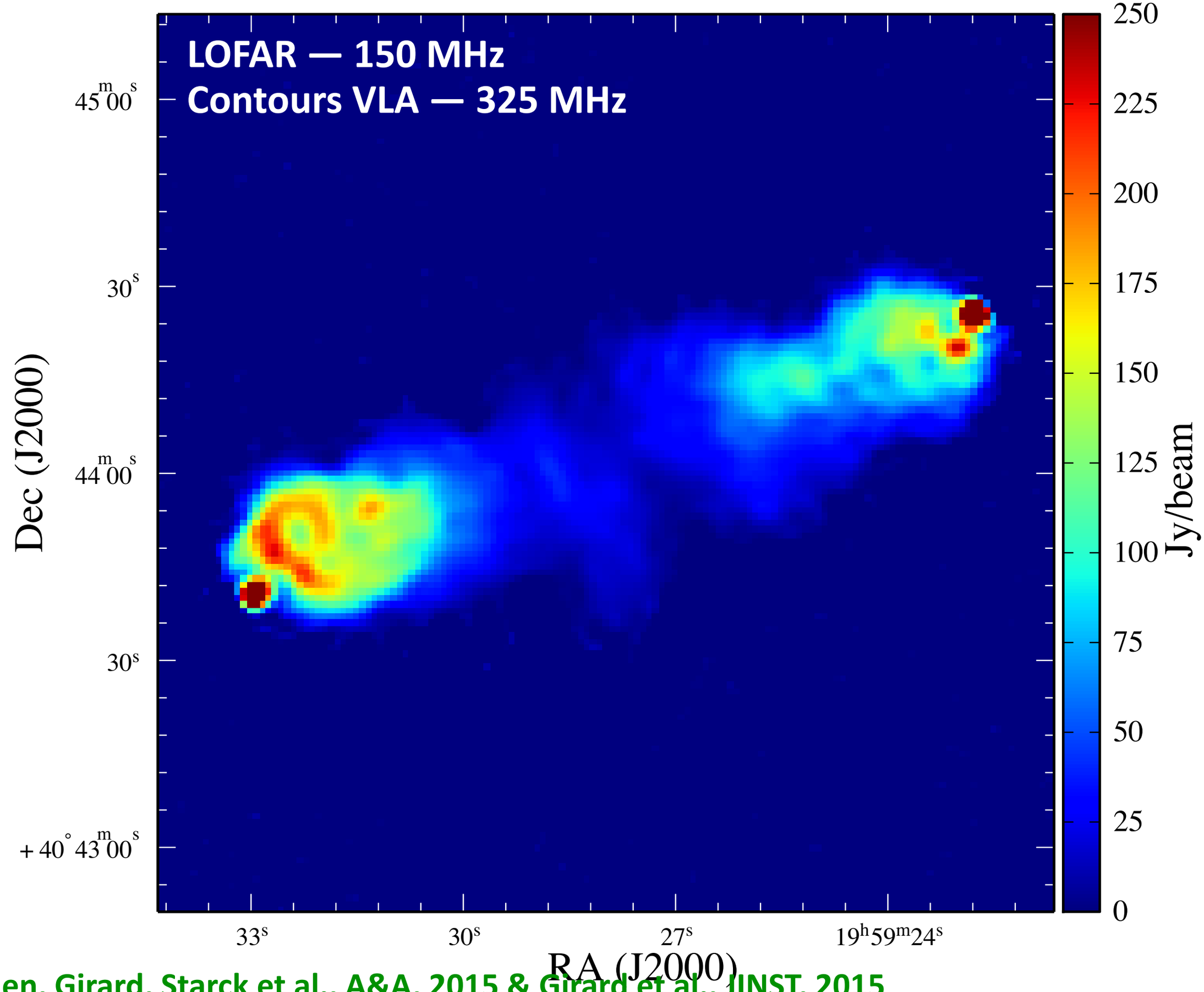
Factor of 4 improvement in angular resolution



but are the reconstructed structures real ?

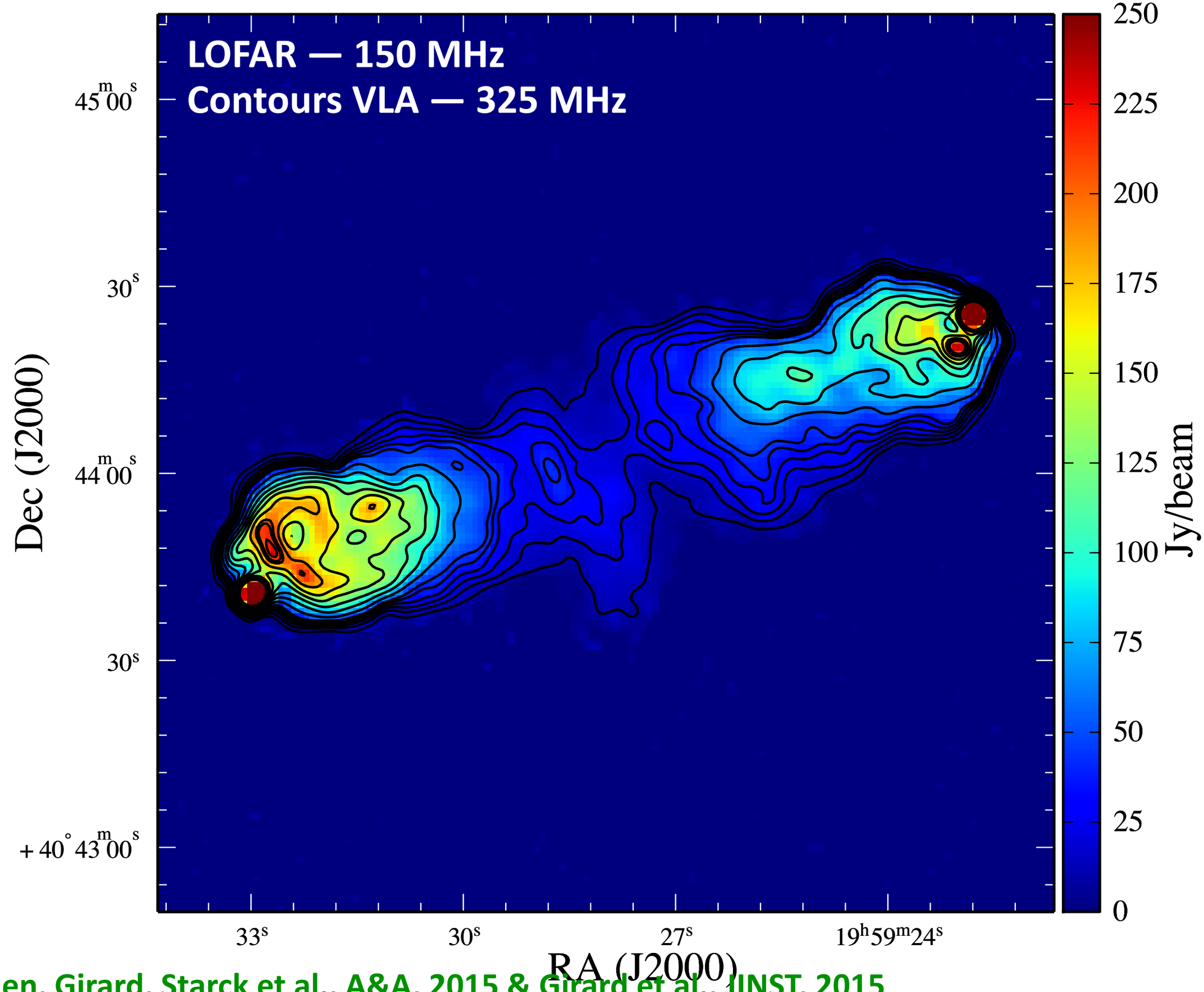
Garsden, Girard, Starck et al., A&A, 2015 & Girard et al., JINST, 2015

Sparse reconstruction



Garsden, Girard, Starck et al., A&A, 2015 & Girard et al., JINST, 2015

Sparse reconstruction



Garsden, Girard, Starck et al., A&A, 2015 & Girard et al., JINST, 2015

Other « Compressed Sensing » / Convex optimization / Sparse imagers on the market (non exhaustive)

« Signal processing world »

« Radio interferometry world »

- **Iterative Soft-Thresholding** → **Li et al., (2011c)**, **Wenger et al. (2010,2013)**, **Hardy (2013)**, **Garsden, Girard (2015)**

  Beck & Teboulle (2009)

- **OMP (Orthogonal Matching Pursuit)** → **Fannjiang (2013)**, **Van belle (MS thesis 2016**, **+ CLEAN (MP) …**, **R. Armstrong (in prep)**

  Davis et al. (2007)

- **Douglas-Rachford splitting** → **Wiaux et al. (2009b)**, **McEwen & Wiaux (2011)**, **Carrillo et al. (2012)**

  Combettes & Pesquet (2007)

- **SDMM/ADMM** → **in Carrillo et al. (2013)**

  Simultaneous-Direction Method of Multipliers
  Alternating

  Afonso et al., Setzer et al. Attouch & Soueycatt, 2009

  Combettes & Pesquet (2011)

- **SARA/PURIFY** Carrillo et al., 2015

- **MORESANE** Dabbech et al. 2015

- **Point-RESOLVE** Junklewitz, 2013

- **SASIR** Garsden et al. 2015, Girard et al. 2015 Girard, Jiang et al., in rev.

Outline

New instrumentation, new problems
(and new solutions !)

Sparsity and deconvolution

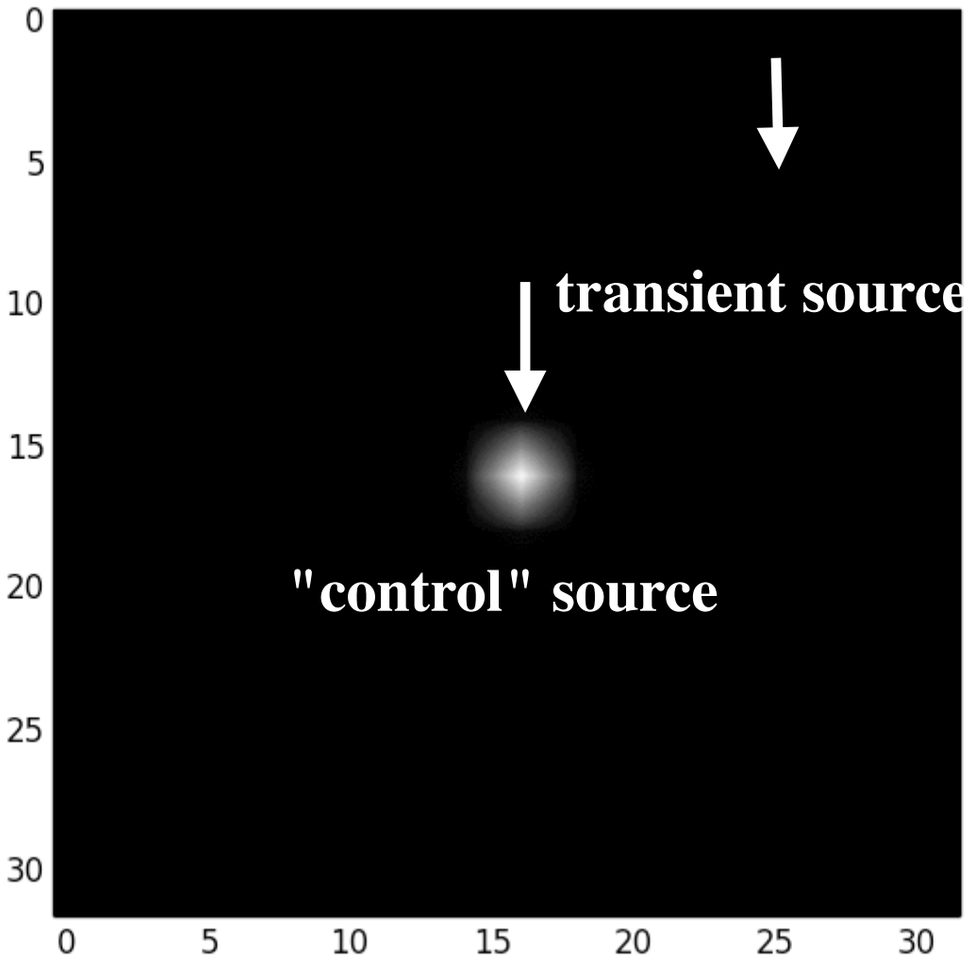
Application to transient imaging

Conclusions

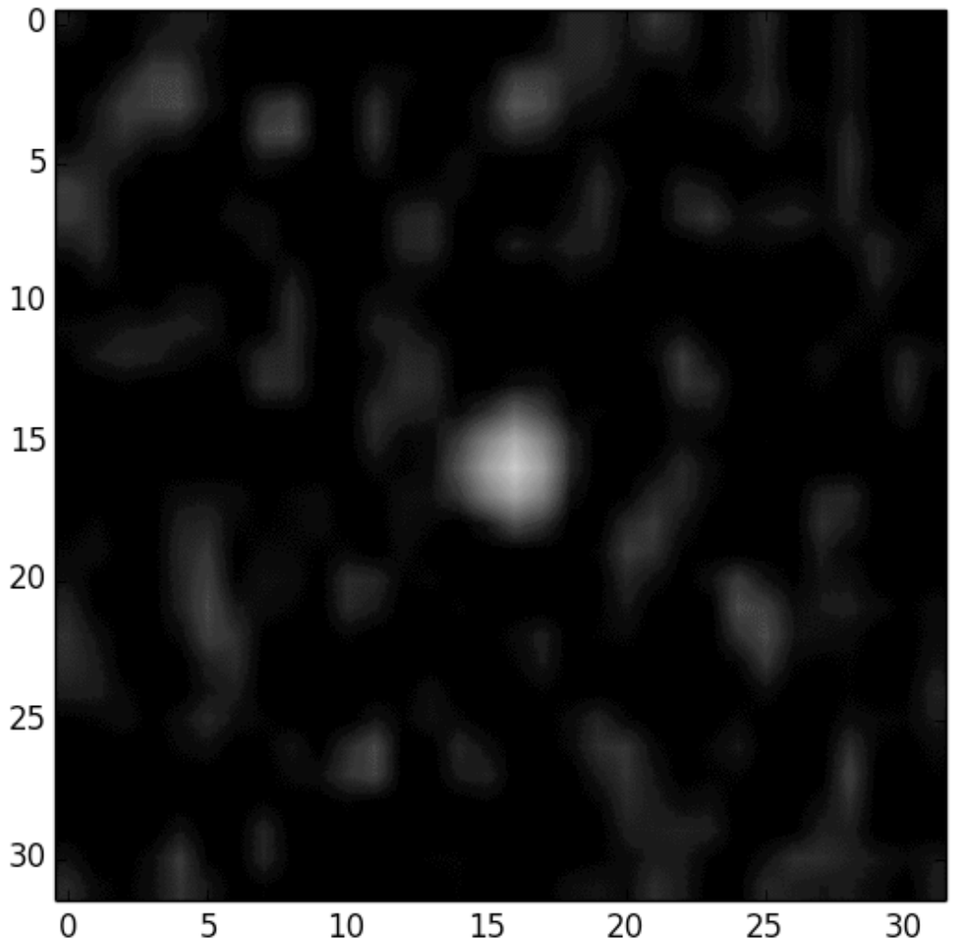
Application to transient imaging

2D+time

Sky model



Dirty map



- **"control" steady source**

- **transient gaussian source**

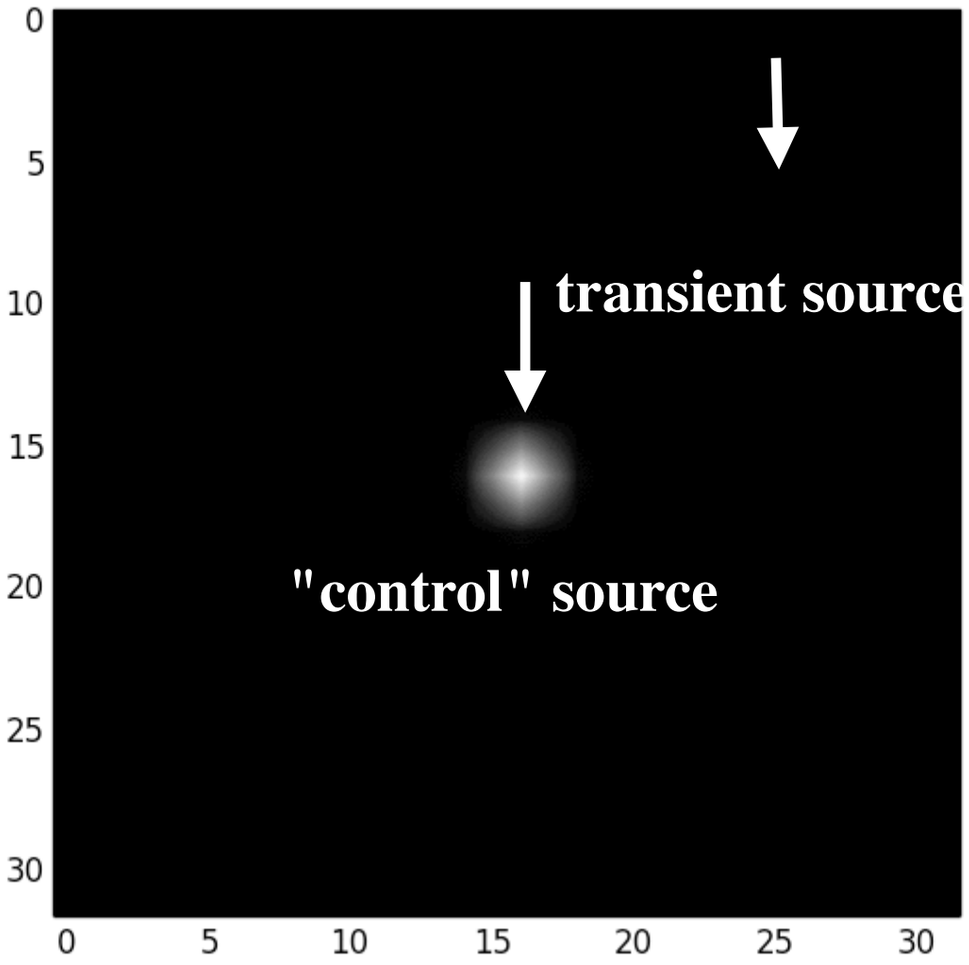
A new source appeared but side lobes as well !

Need a time-agile deconvolution algorithm

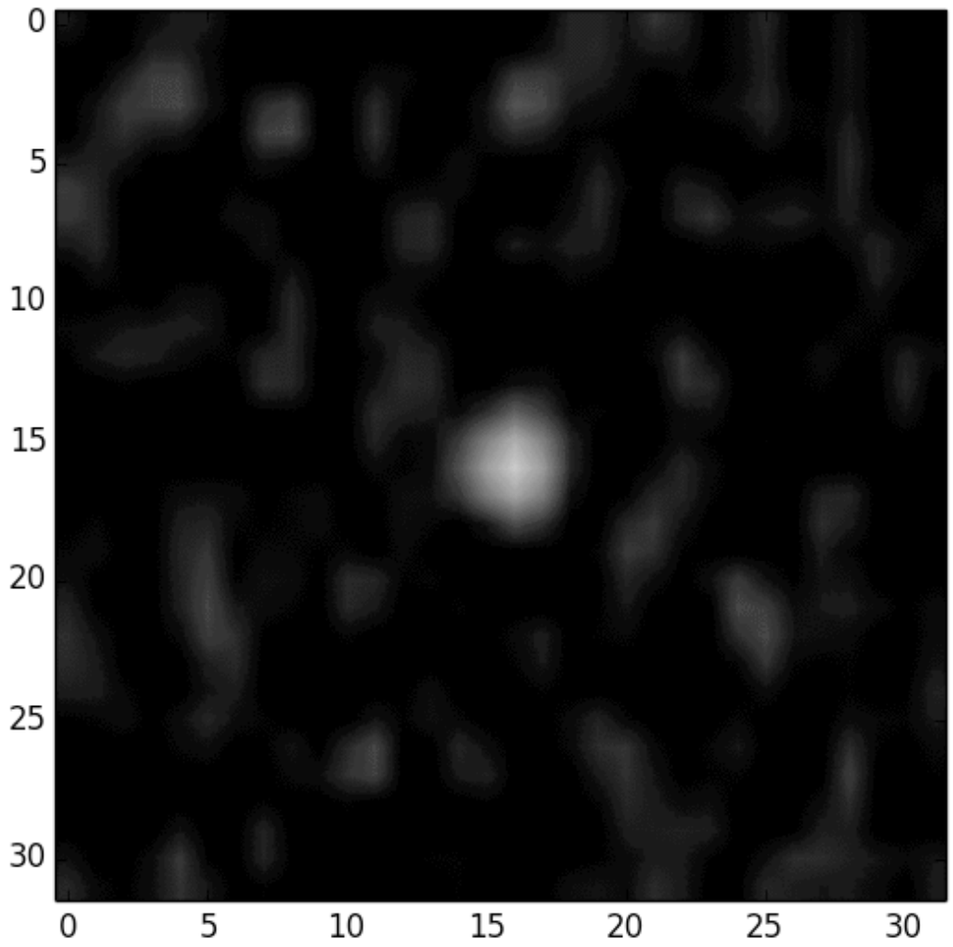
Application to transient imaging

2D+time

Sky model



Dirty map



- **"control" steady source**

- **transient gaussian source**

A new source appeared but side lobes as well !

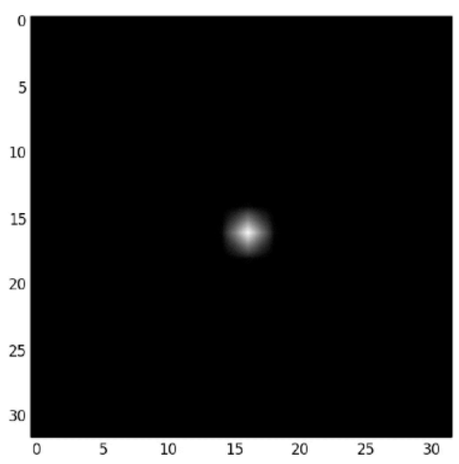
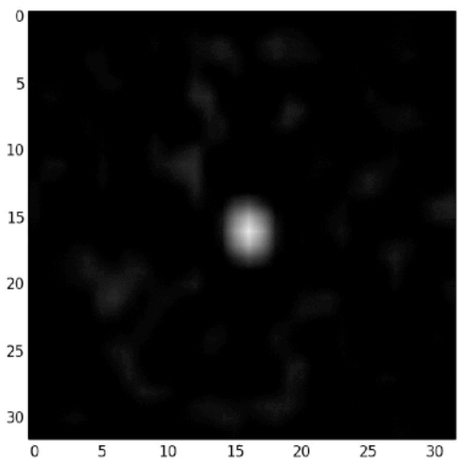
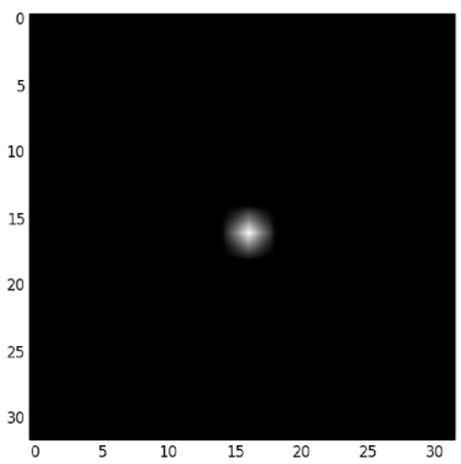
Need a time-agile deconvolution algorithm

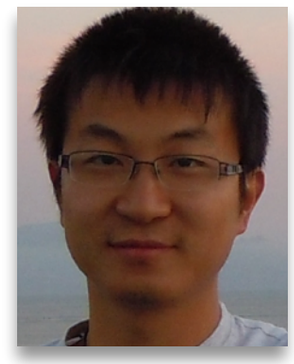
Application to transient imaging

2D+time

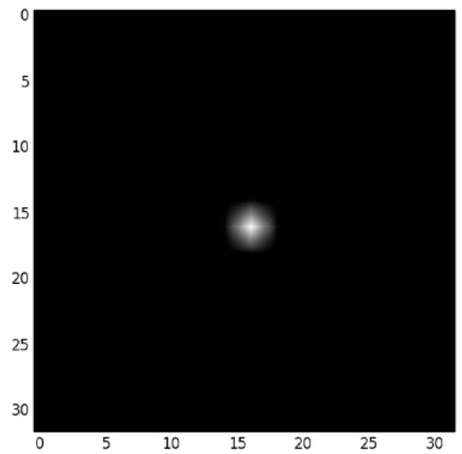
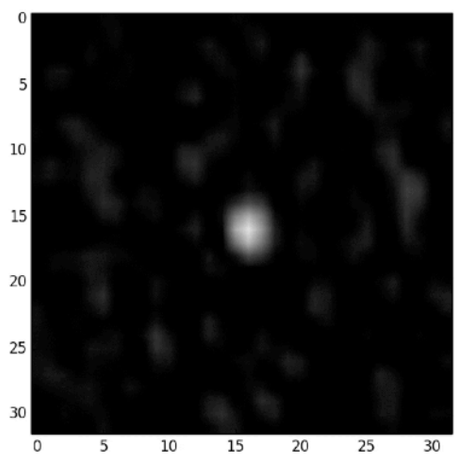
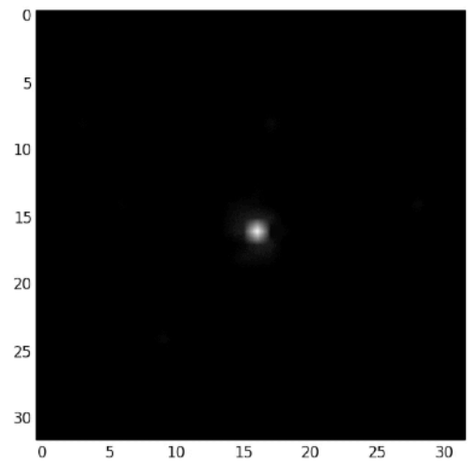
Sky model | Dirty map | Reconstruction

σ=0.5

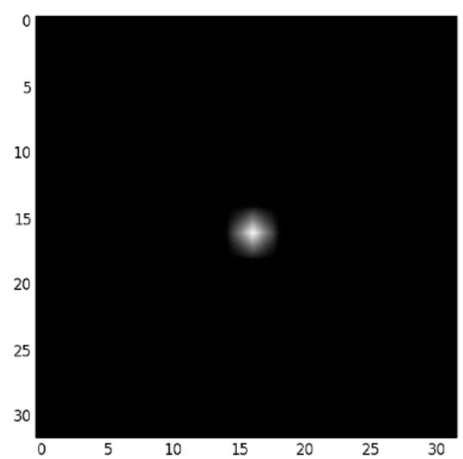
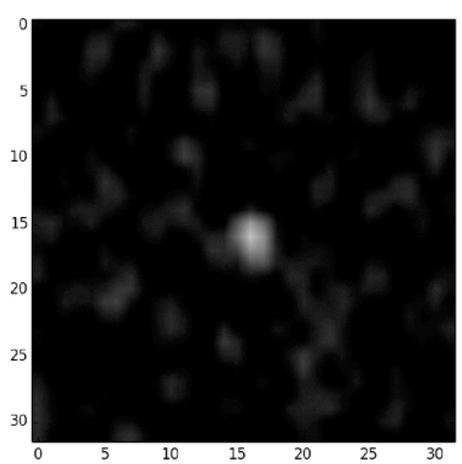
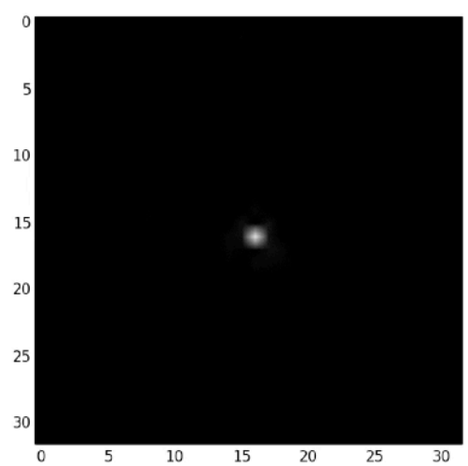






σ =1.0

σ =1.5

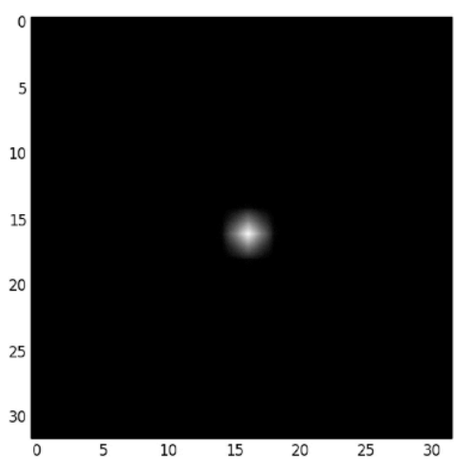
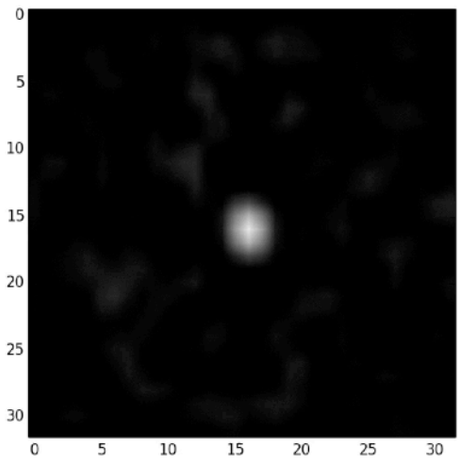
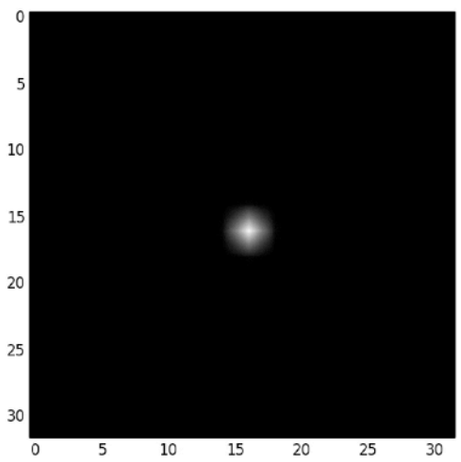
Girard et al, Sparse spatio-temporal imaging of radio transients, in revision

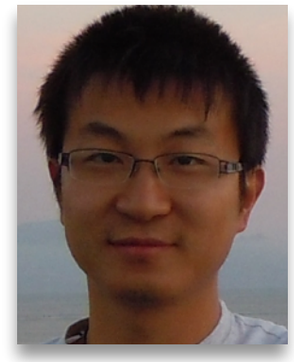
Application to transient imaging

2D+time

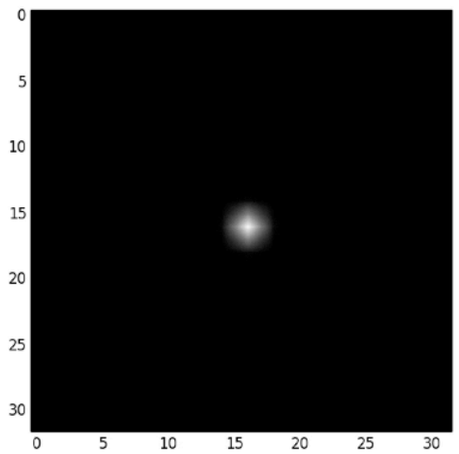
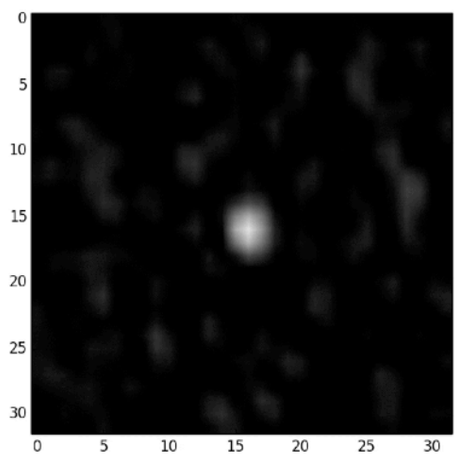
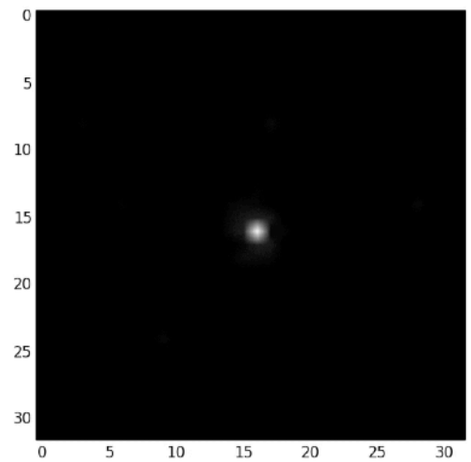
Sky model | Dirty map | Reconstruction

σ=0.5

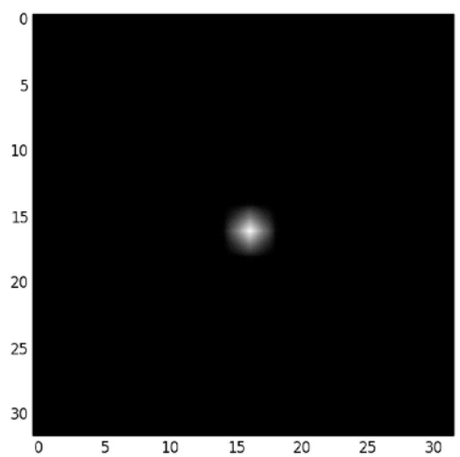
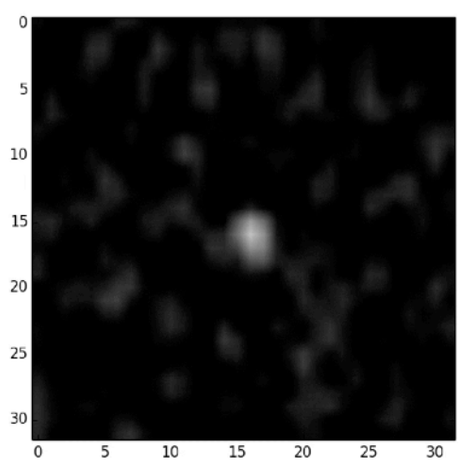
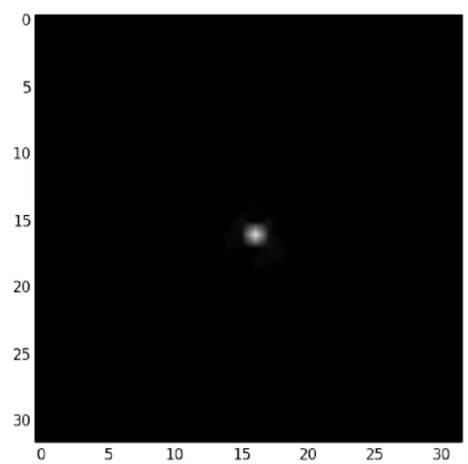






σ =1.0

σ =1.5

Girard et al, Sparse spatio-temporal imaging of radio transients, in revision

Numerical experiments on simulated data

Detection robustness towards **- noise level** σ *detection problem*

- time integration N_t *dilution problem*

➙ **Probing the parameter space** σ [0. - 2.0] arb. units

N_t [2 - 250] time frame

Spanning over a 2-hour radio simulation

Numerical experiments on simulated data

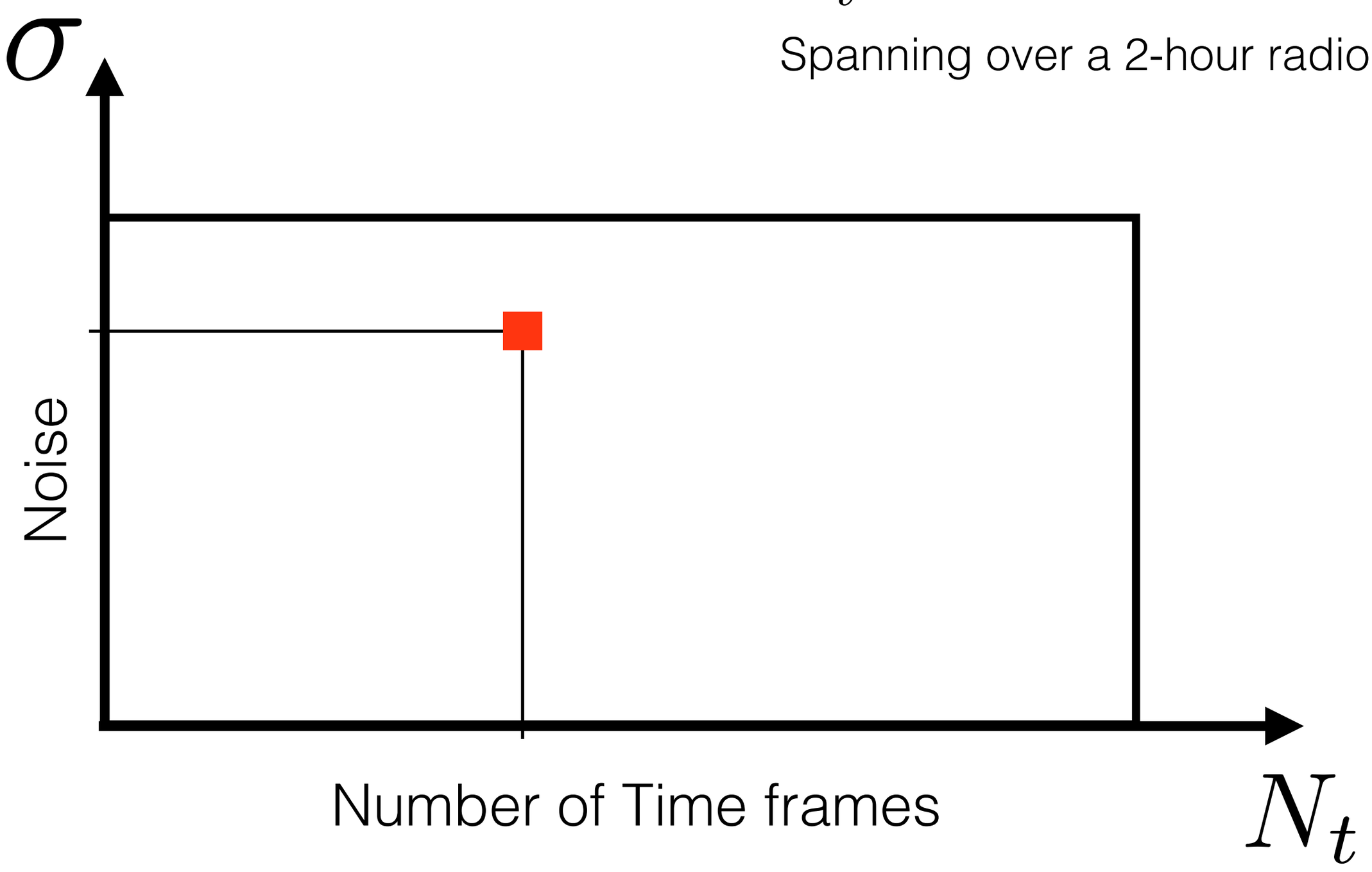
Detection robustness towards **- noise level** σ *detection problem*

- time integration N_t *dilution problem*

→ Probing the parameter space σ **[0. - 2.0] arb. units**

N_t **[2 - 250] time frame**

Spanning over a 2-hour radio simulation



Numerical experiments on simulated data

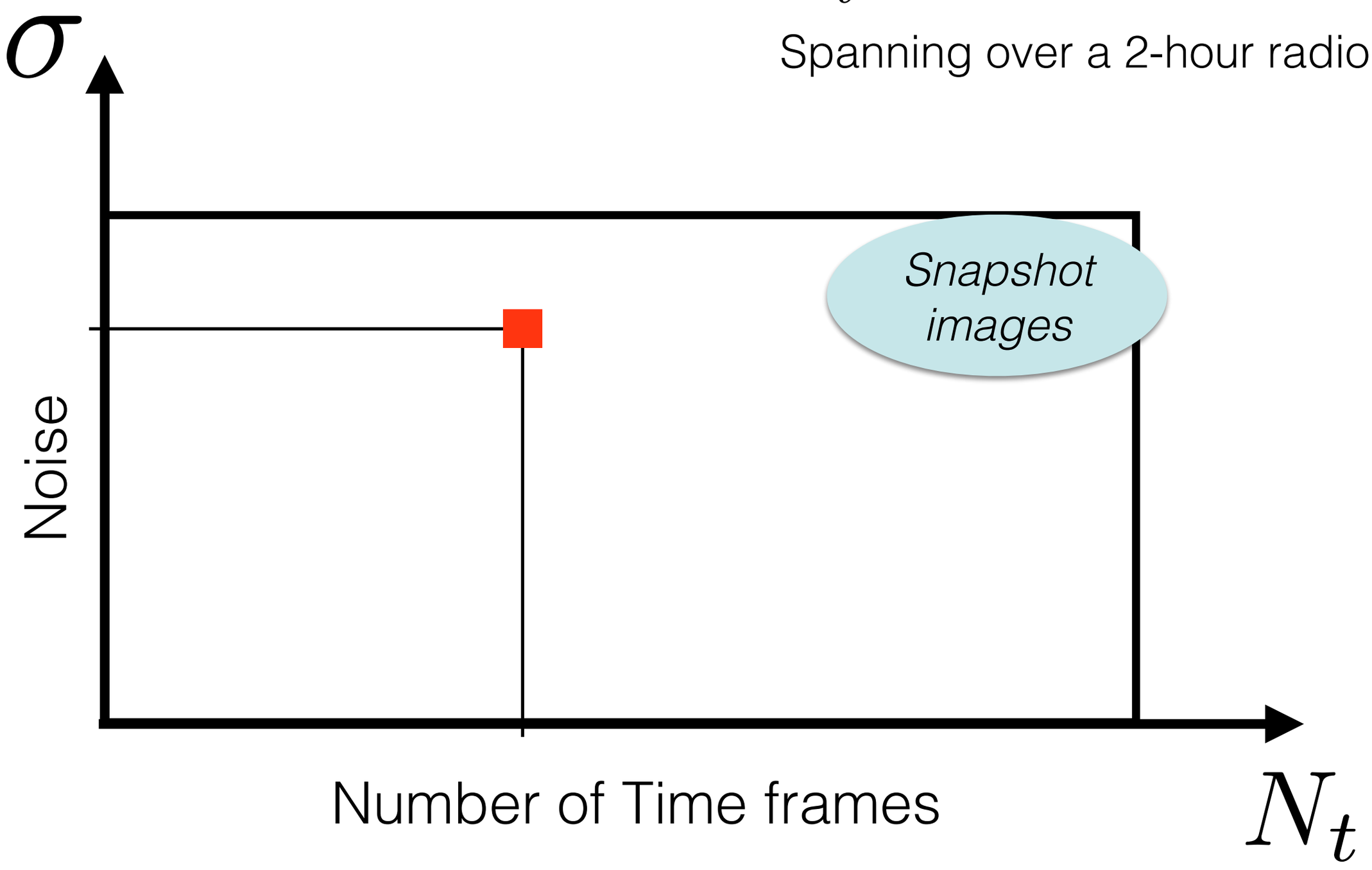
Detection robustness towards **- noise level** σ *detection problem*

- time integration N_t *dilution problem*

→ Probing the parameter space σ **[0. - 2.0] arb. units**

N_t **[2 - 250] time frame**

Spanning over a 2-hour radio simulation



Numerical experiments on simulated data

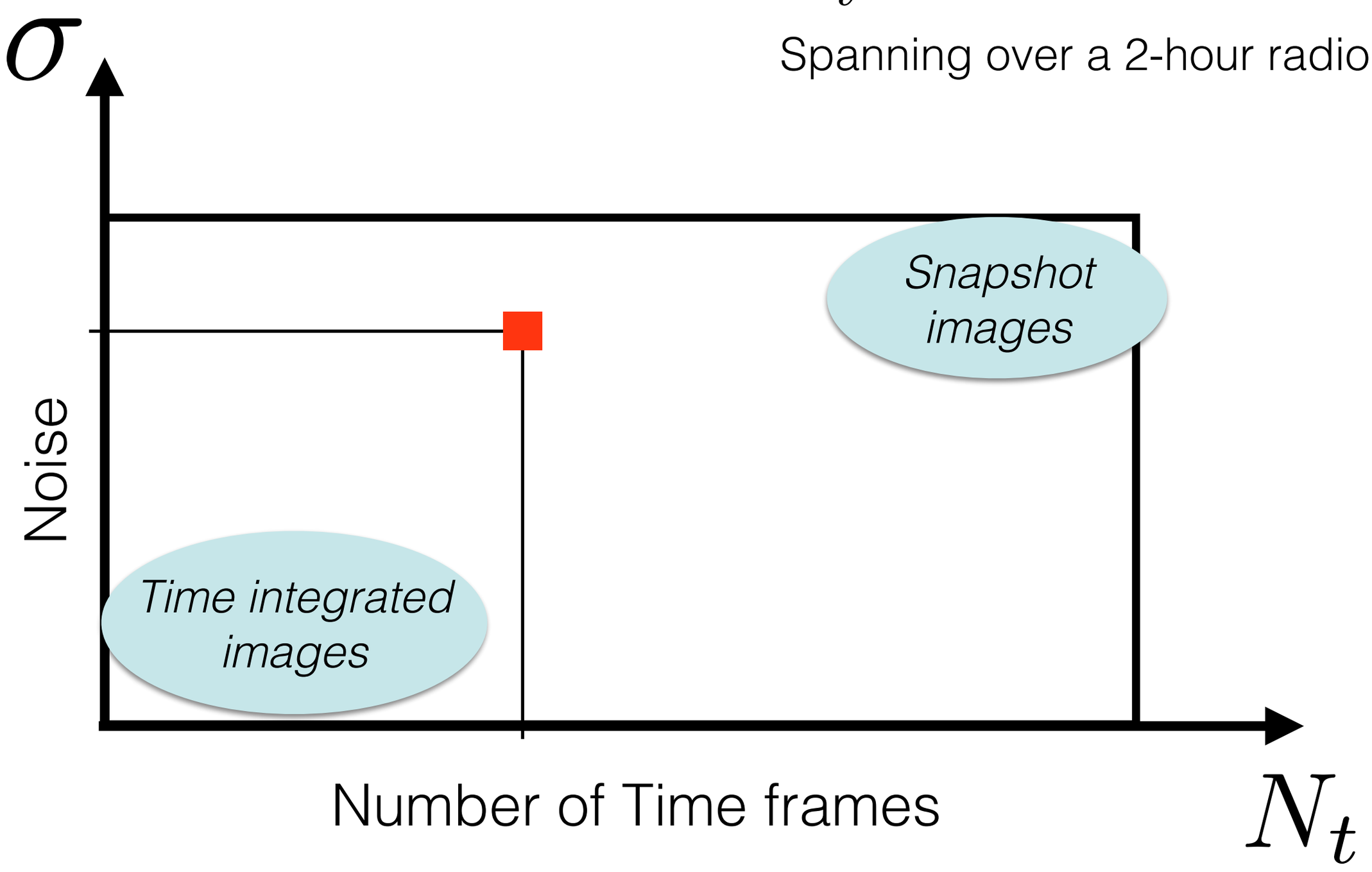
Detection robustness towards **- noise level** σ *detection problem*

- time integration N_t *dilution problem*

→ Probing the parameter space σ **[0. - 2.0] arb. units**

N_t **[2 - 250] time frame**

Spanning over a 2-hour radio simulation



Numerical experiments on simulated data

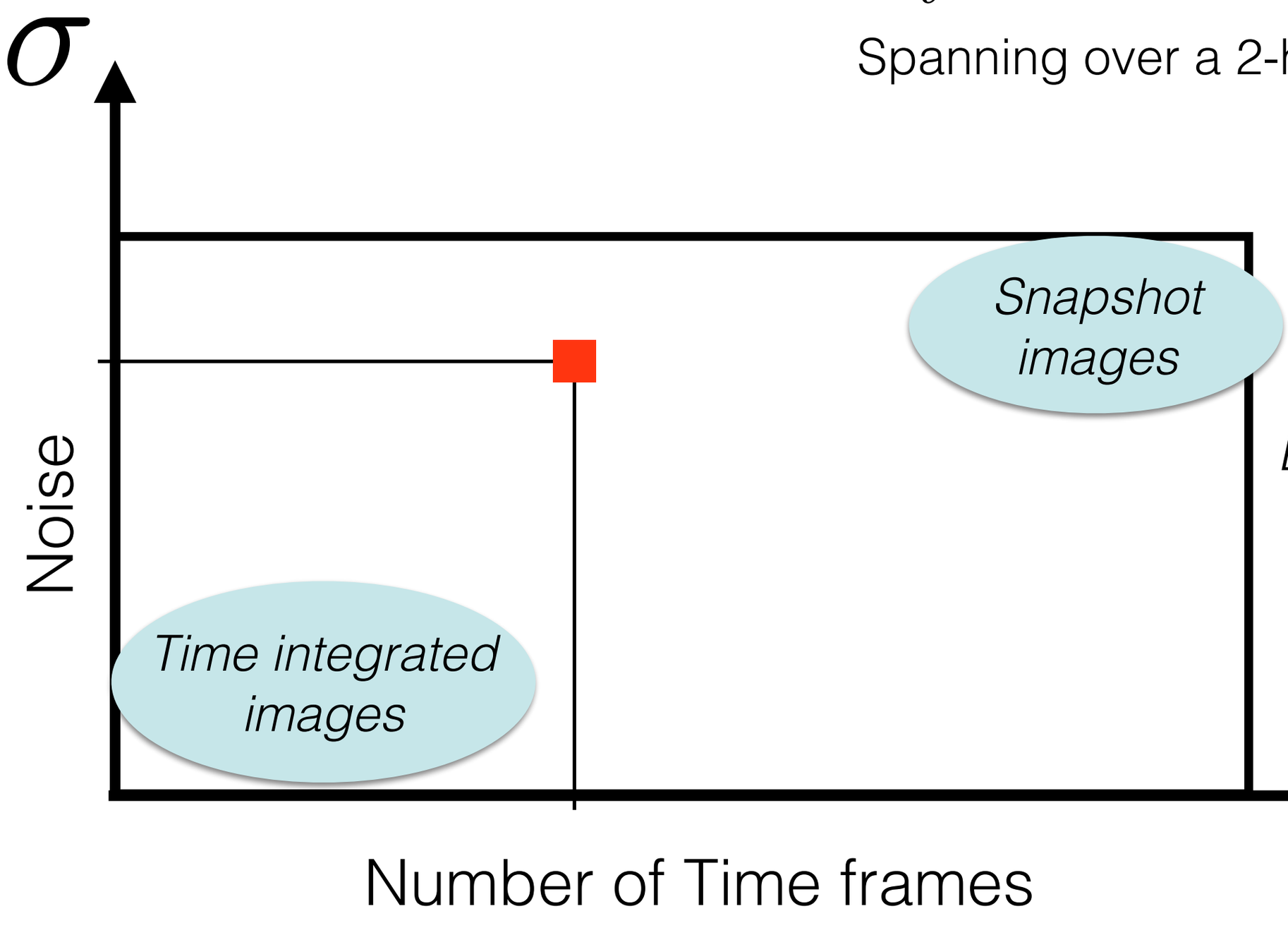
Detection robustness towards **- noise level** σ *detection problem*

- time integration N_t *dilution problem*

→ Probing the parameter space σ [0. - 2.0] arb. units

N_t [2 - 250] time frame

Spanning over a 2-hour radio simulation

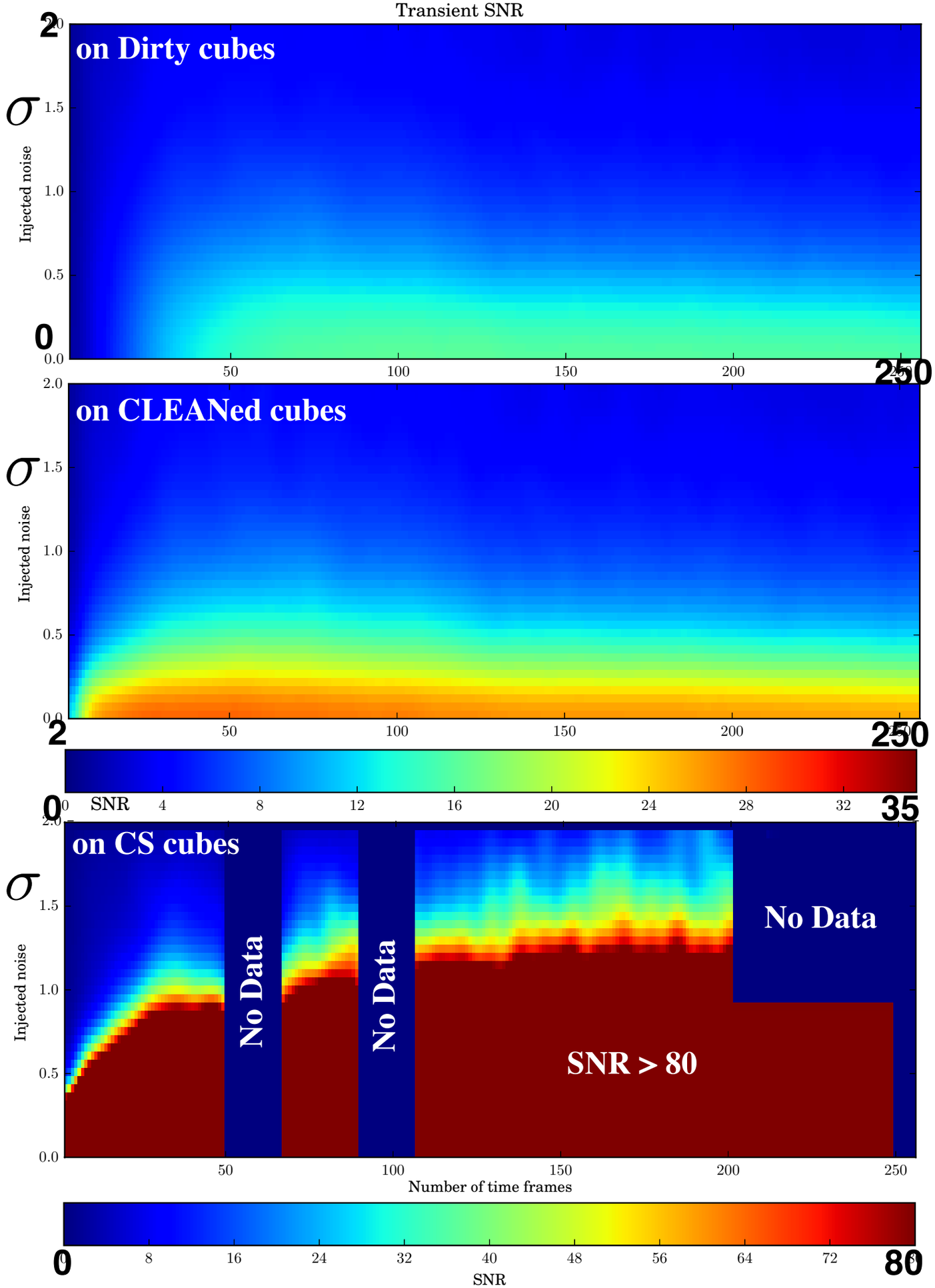


Metrics

Transient source SNR

Error on transient profile

Test #1: SNR - Results



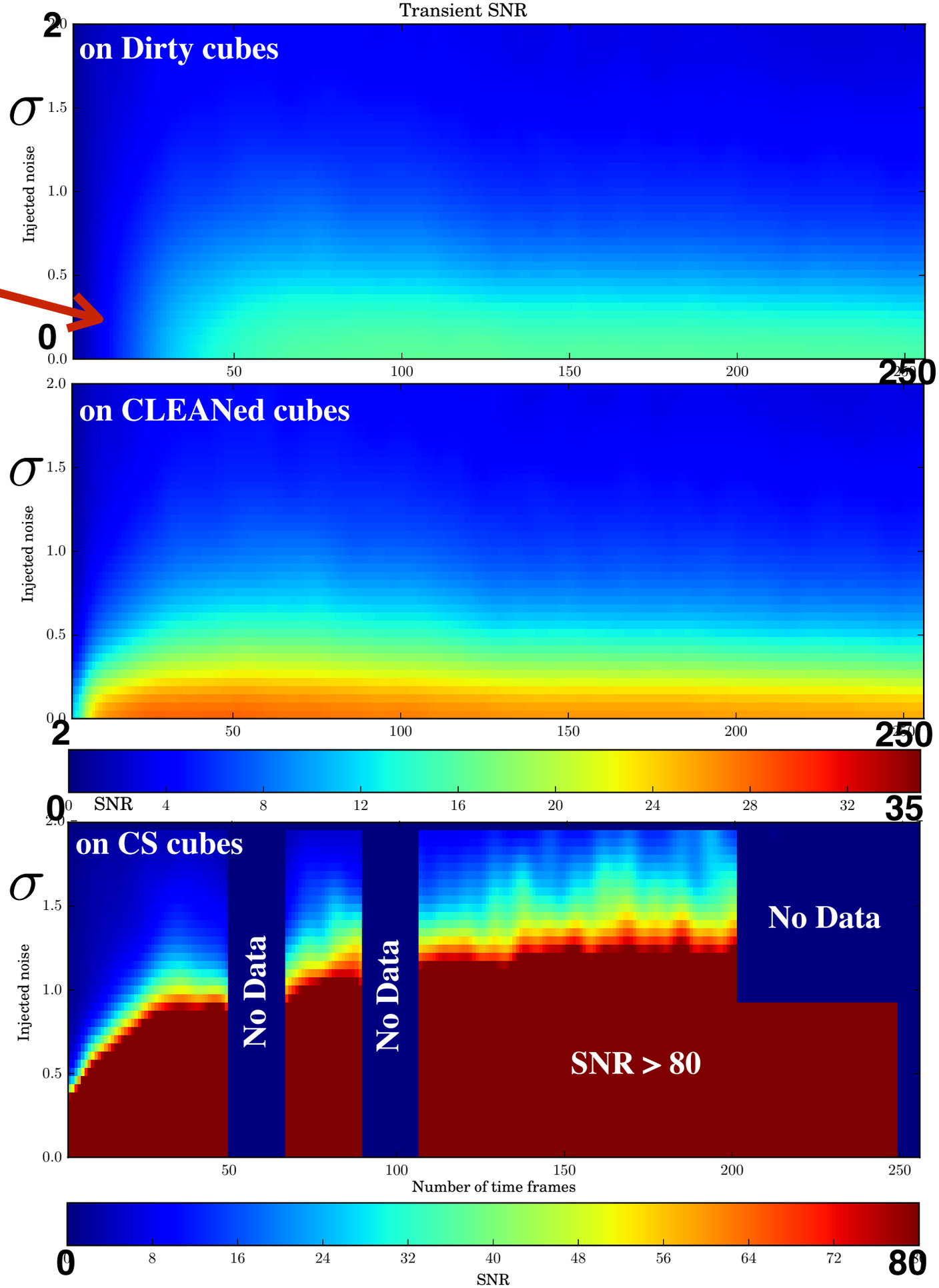
Test #1: SNR - Results

Dirty cubes

Marginal improvement of SNR with time

SNR turn-over below N_t =40

➞ temporal dilution



Test #1: SNR - Results

Dirty cubes

Marginal improvement of SNR with time

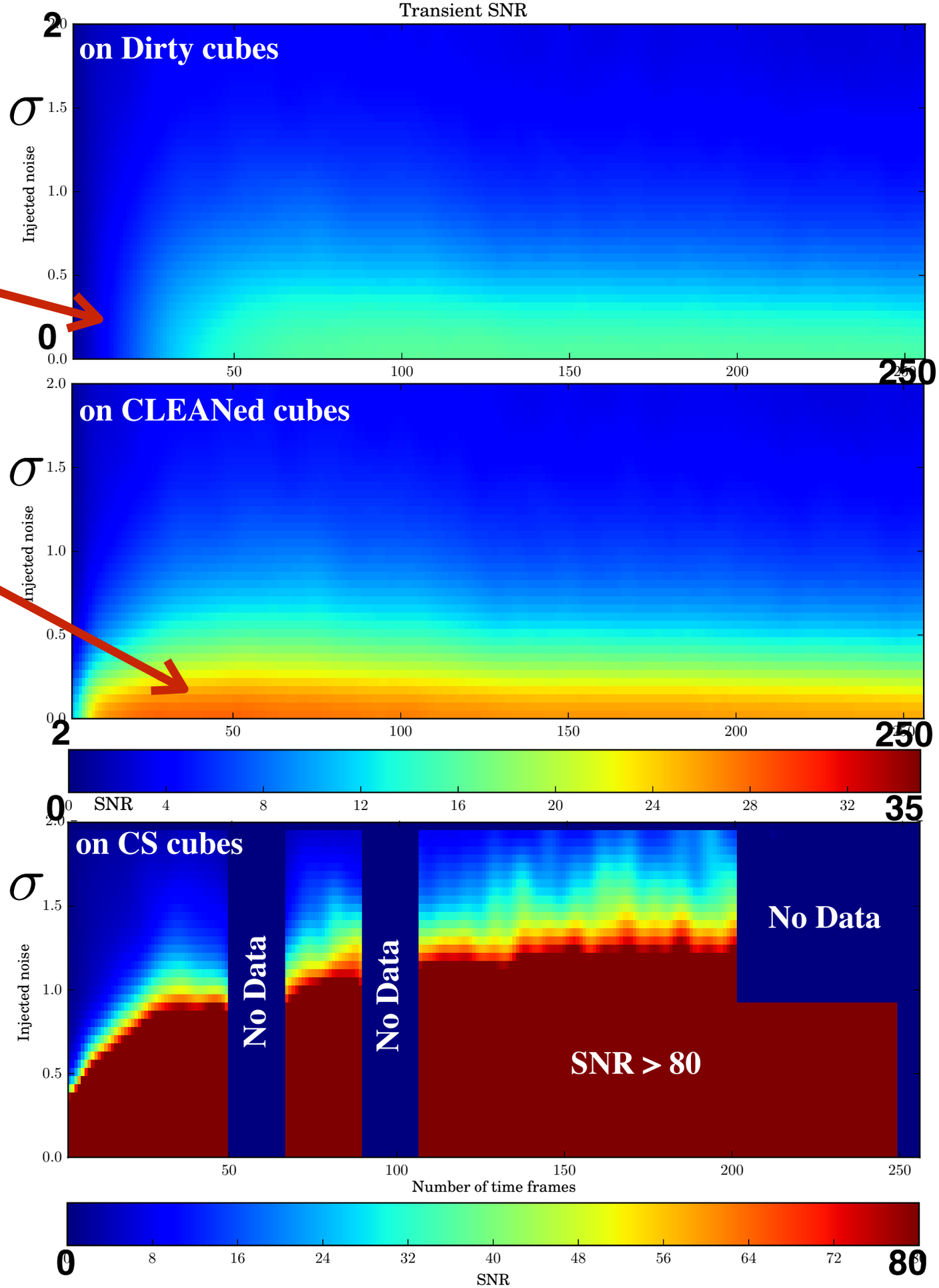
SNR turn-over below N_t =40

➞ temporal dilution

CLEANed cubes

Higher SNR at low noise

Temporal dilution effect reduced



Test #1: SNR - Results

Dirty cubes

Marginal improvement of SNR with time

SNR turn-over below N_t =40

➞ temporal dilution

CLEANed cubes

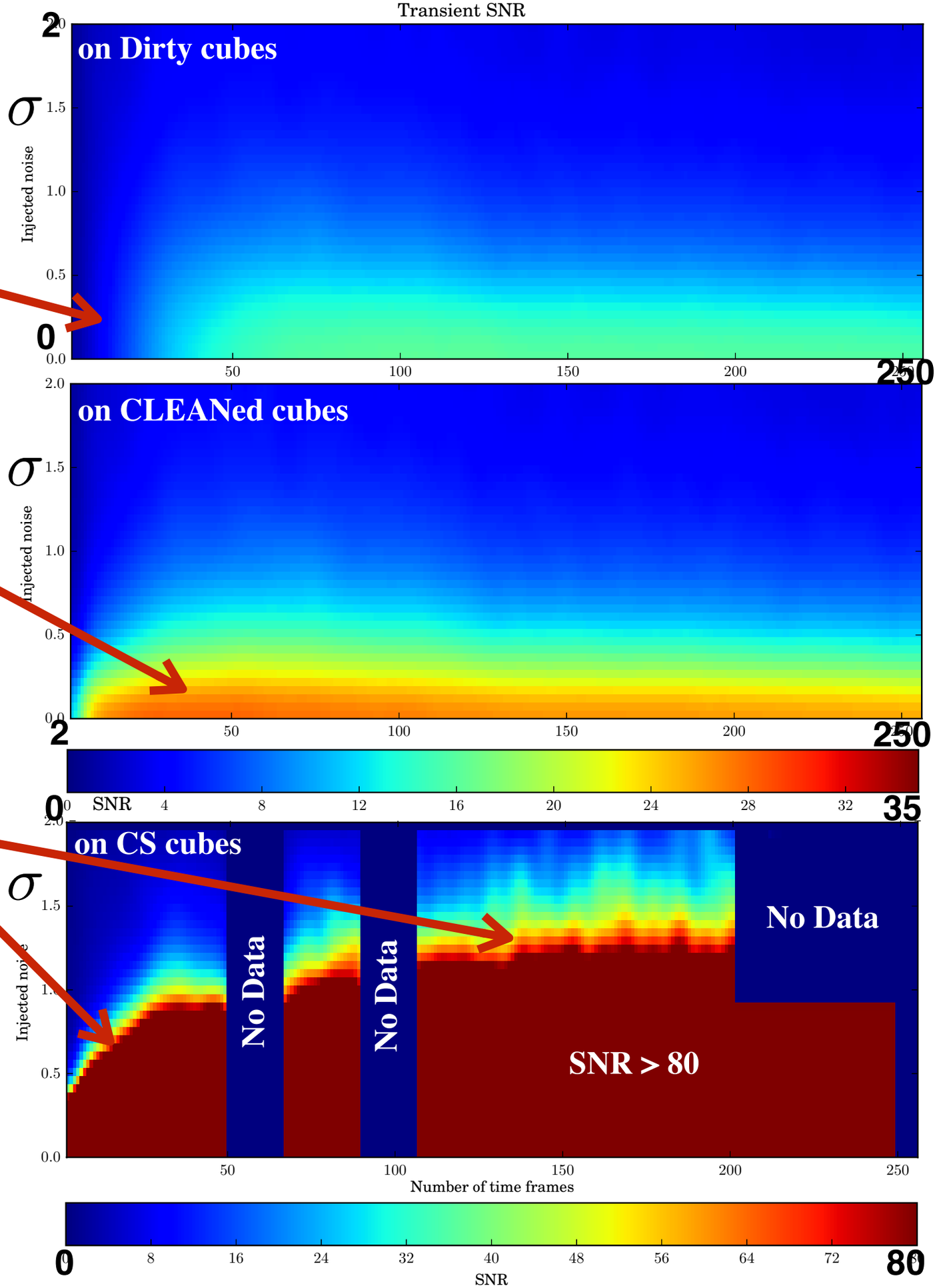
Higher SNR at low noise

Temporal dilution effect reduced

2D1D Sparse cube

Higher SNR at low & high noise

Slow decrease of SNR due to dilution



Test #1: SNR - Results

Dirty cubes

Marginal improvement of SNR with time

SNR turn-over below N_t =40

➞ temporal dilution

CLEANed cubes

Higher SNR at low noise

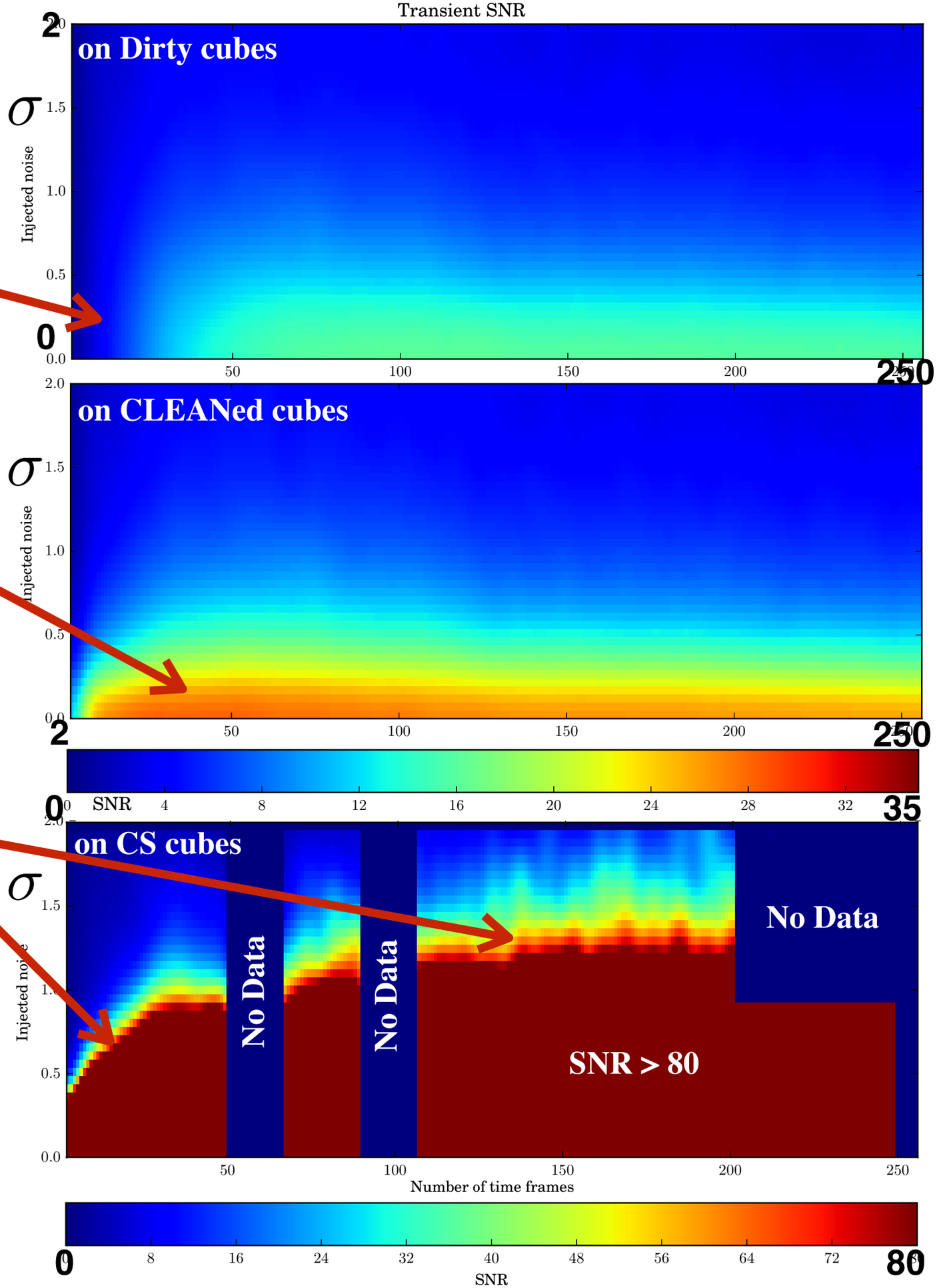
Temporal dilution effect reduced

2D1D Sparse cube

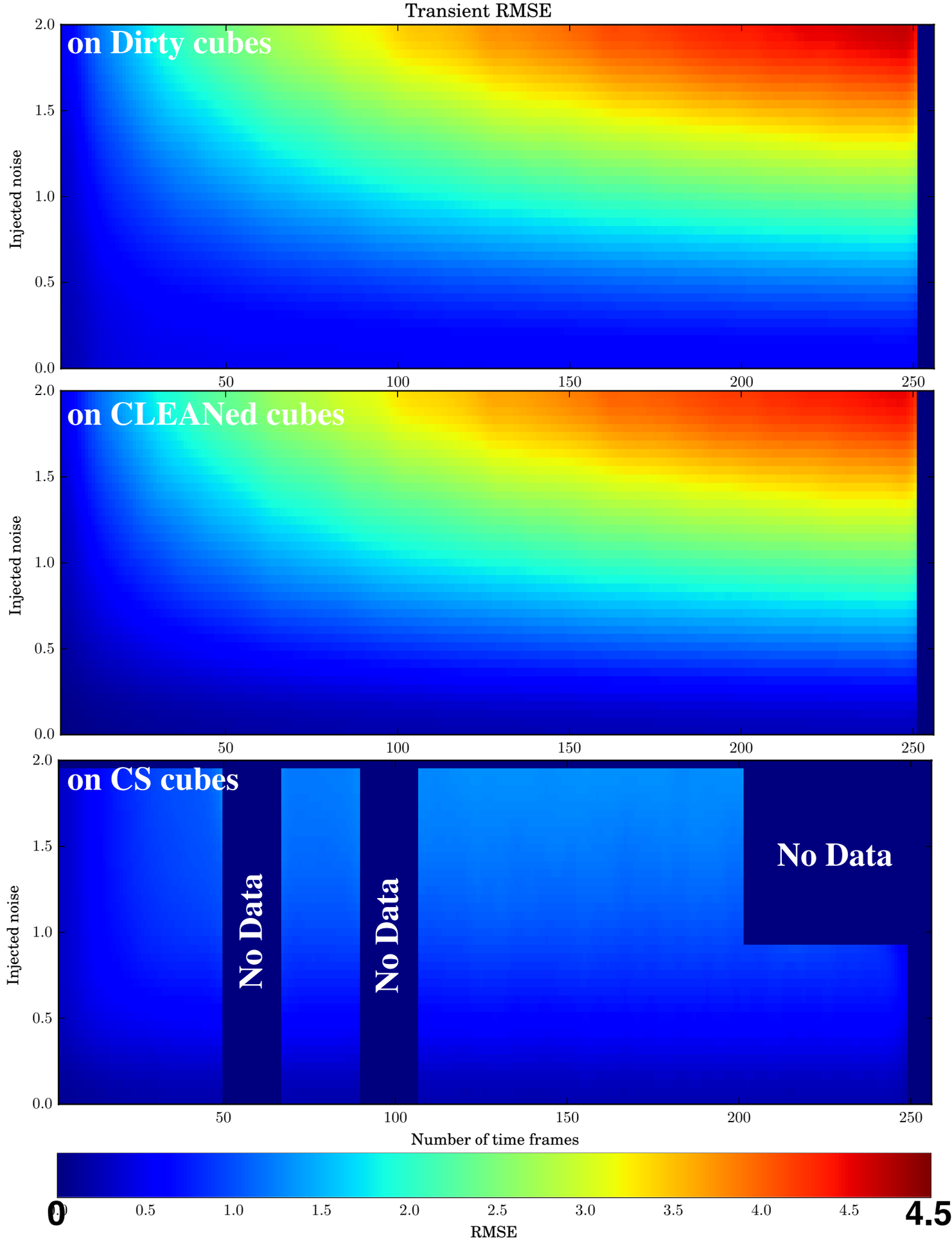
Higher SNR at low & high noise

Slow decrease of SNR due to dilution

One order of magnitude improvement in SNR



Test #2: Time profile

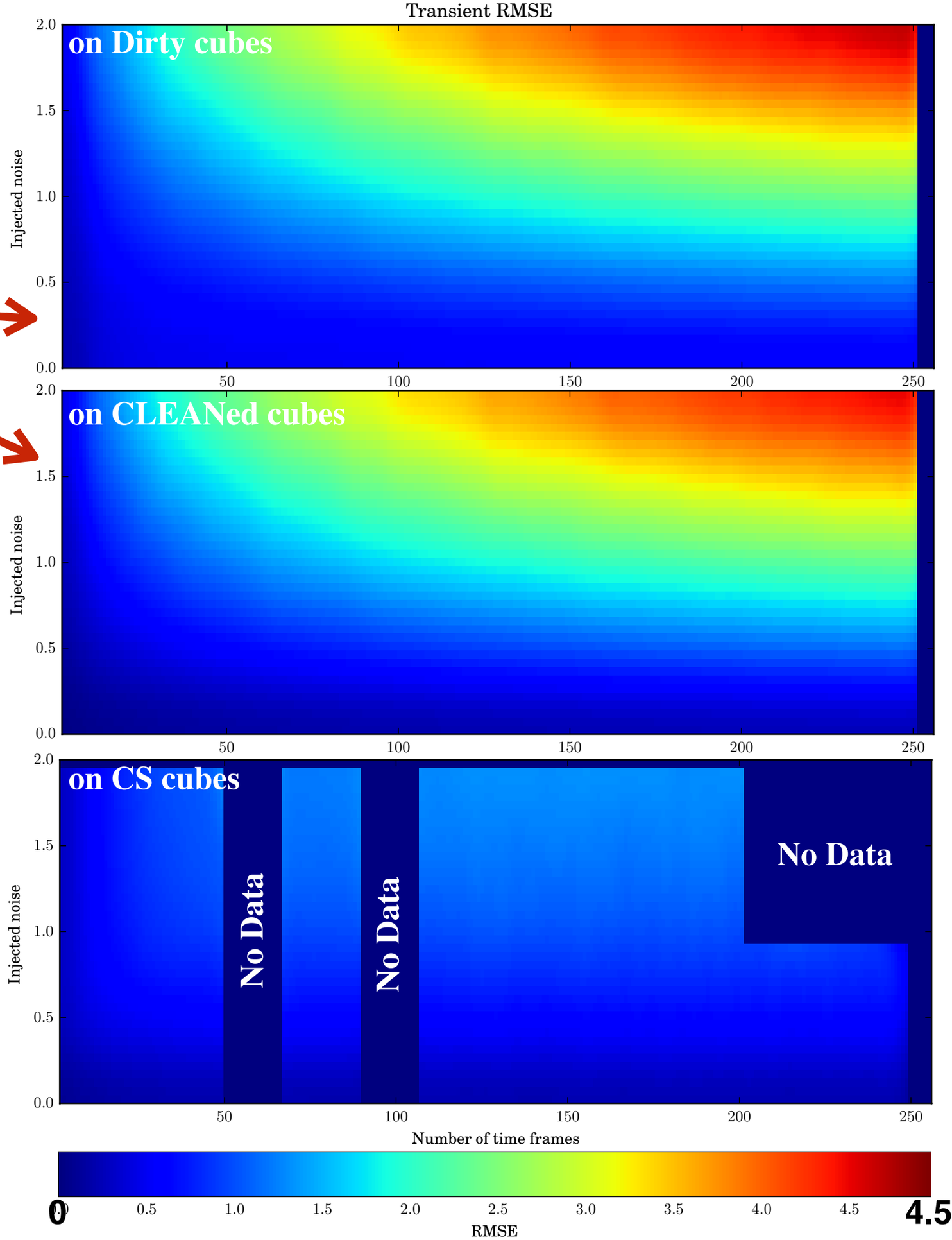


Test #2: Time profile

Dirty & CLEANed cubes

Higher RMSE in high noise snapshots

Similar profile error



Test #2: Time profile

Dirty & CLEANed cubes

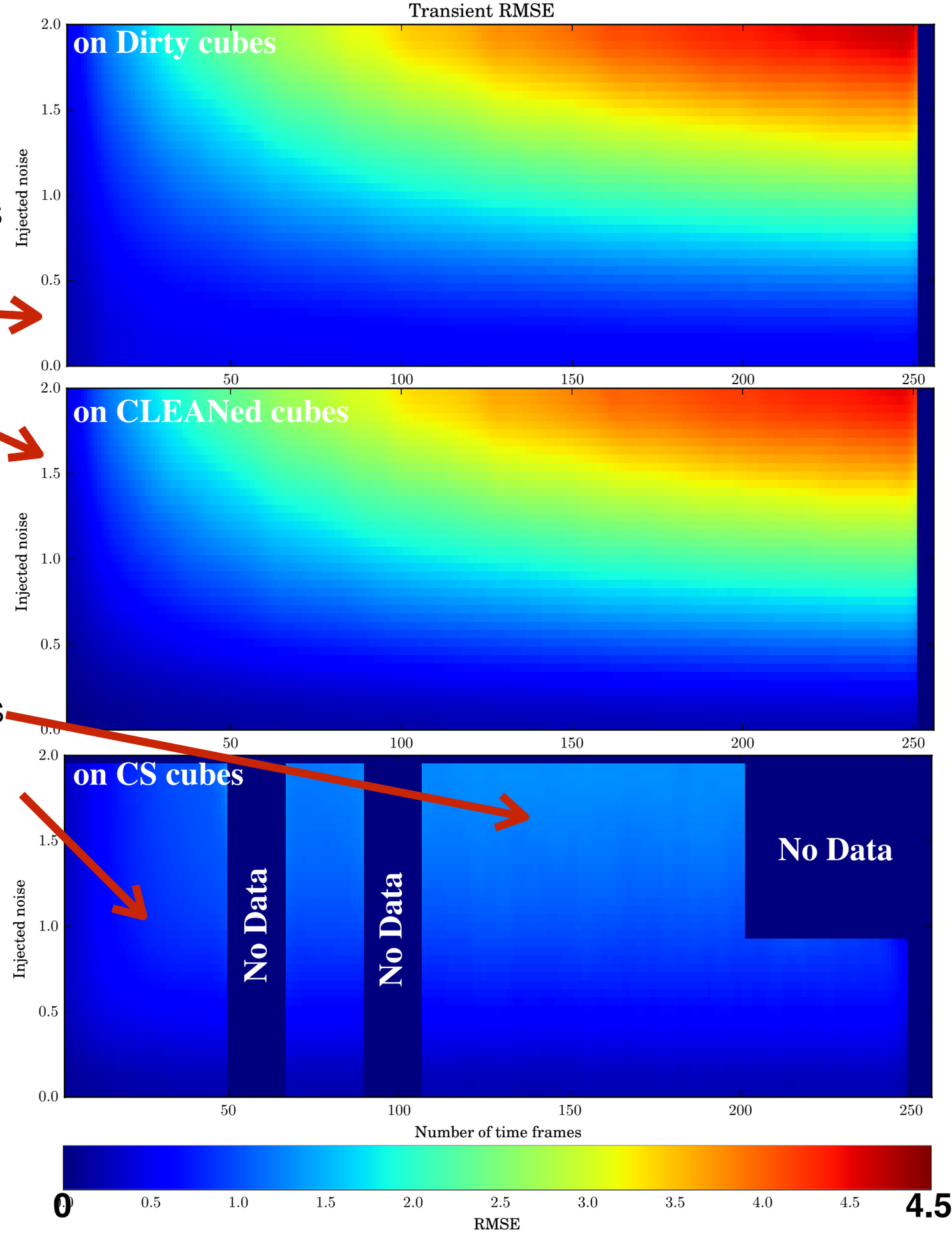
Higher RMSE in high noise snapshots

Similar profile error

2D1D Sparse cube

Higher RMSE in high noise snapshots

Better overall profile reconstruction



Test #2: Time profile

Dirty & CLEANed cubes

Higher RMSE in high noise snapshots

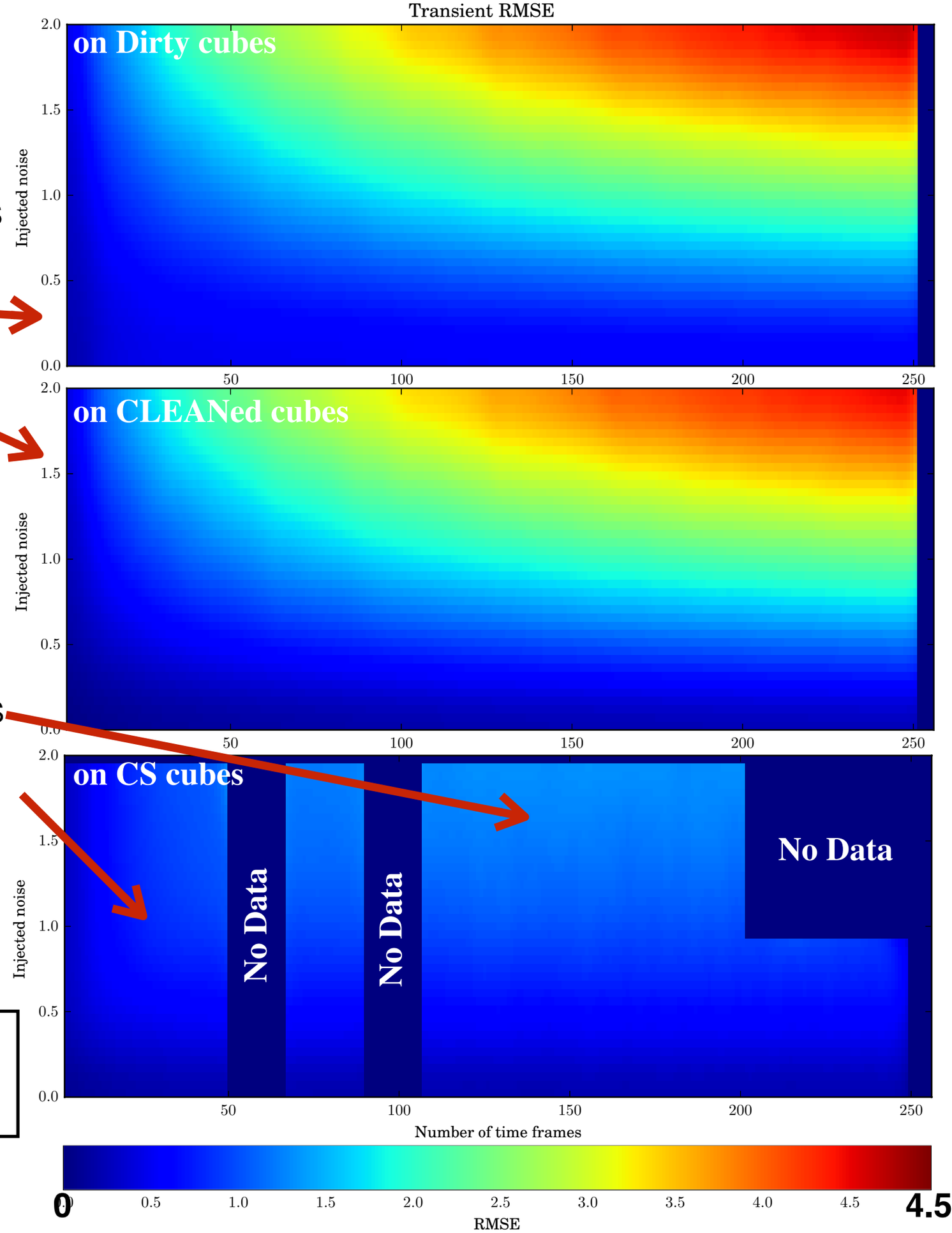
Similar profile error

2D1D Sparse cube

Higher RMSE in high noise snapshots

Better overall profile reconstruction

Factor of ~3 reduction of the RMSE of transient profile

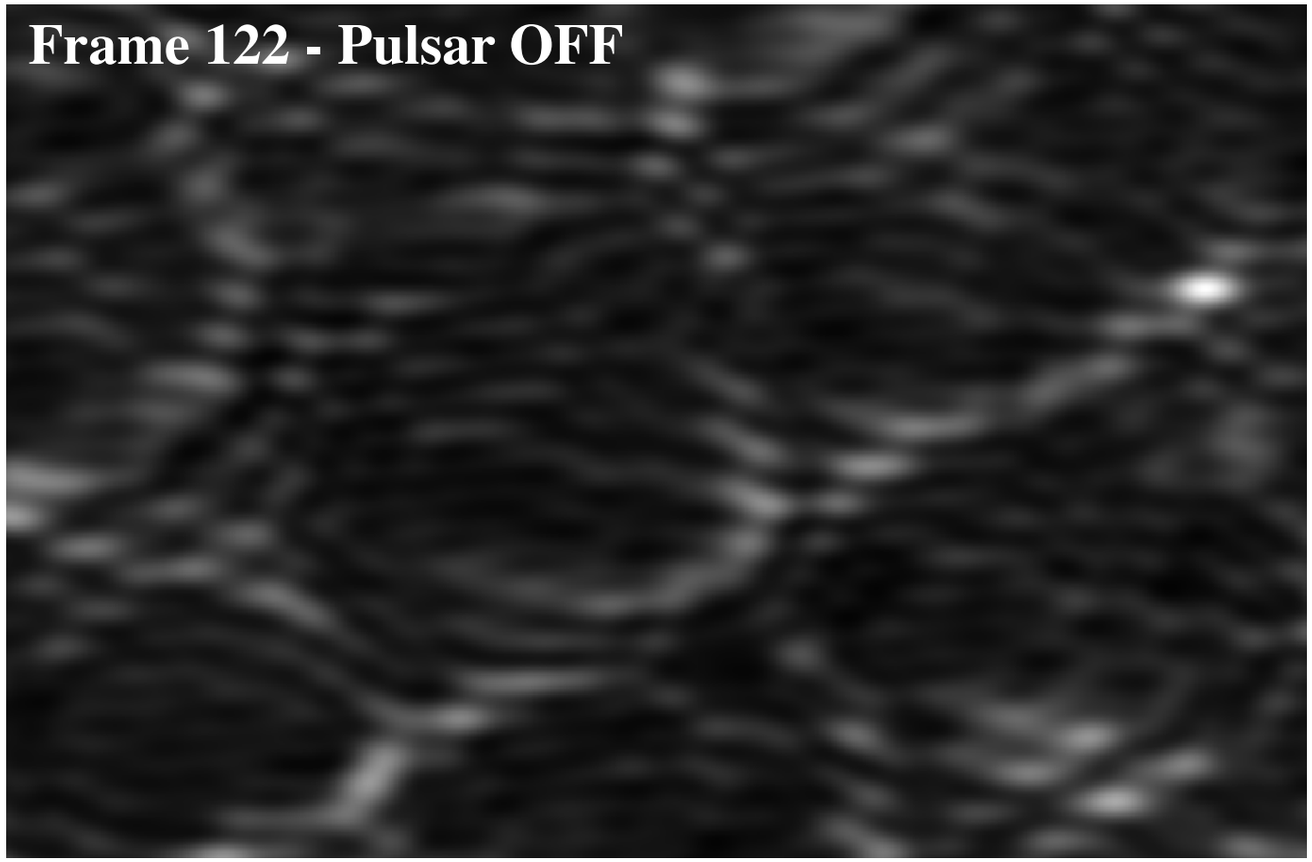


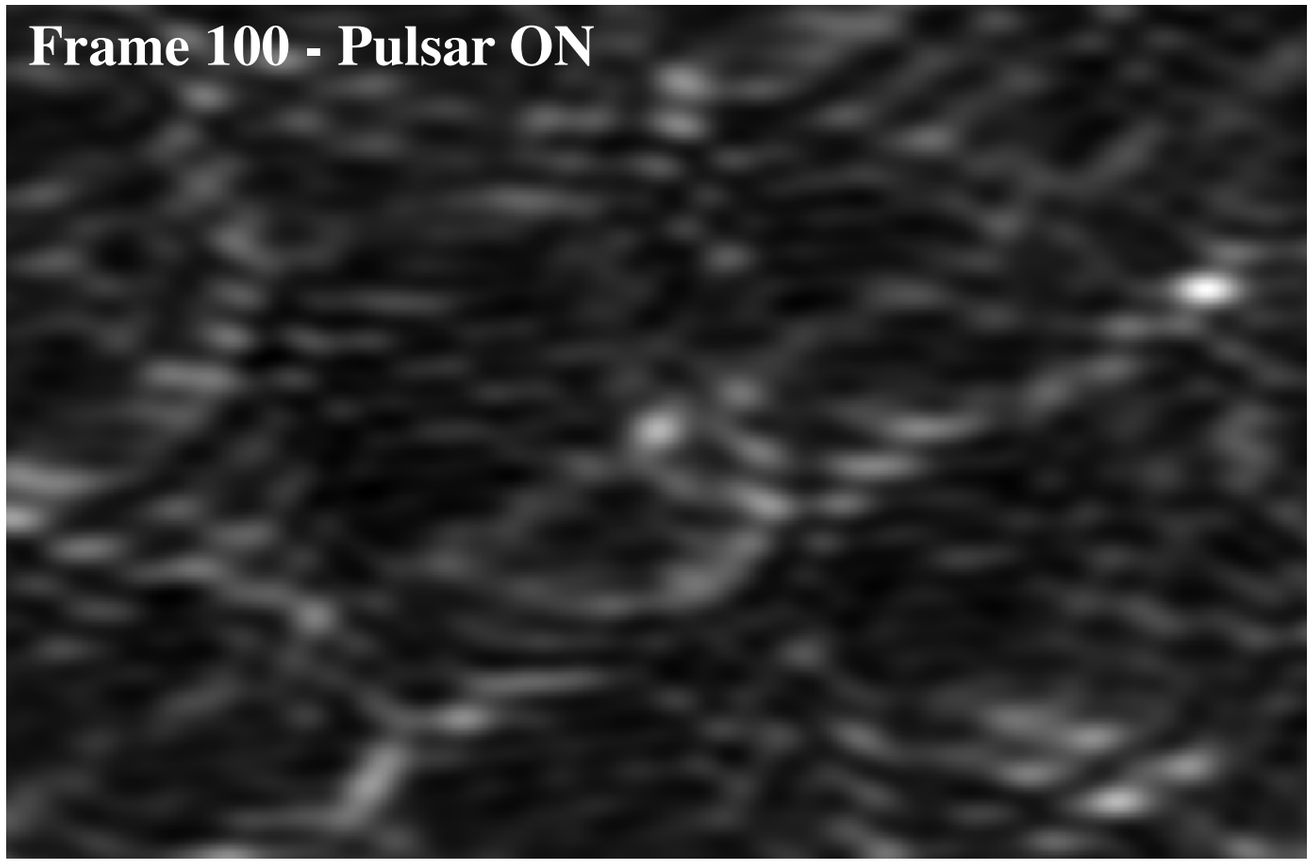
Test #3: Real data: pulsar B0355+55 with the VLA

data $\Delta t = 1.03s$

res. $\delta t = 5ms$

Period $P_{\mathrm{B0355+55}} = 156ms$





- **Transient** takes the form of the PSF
- **Sidelobes** are also transients !

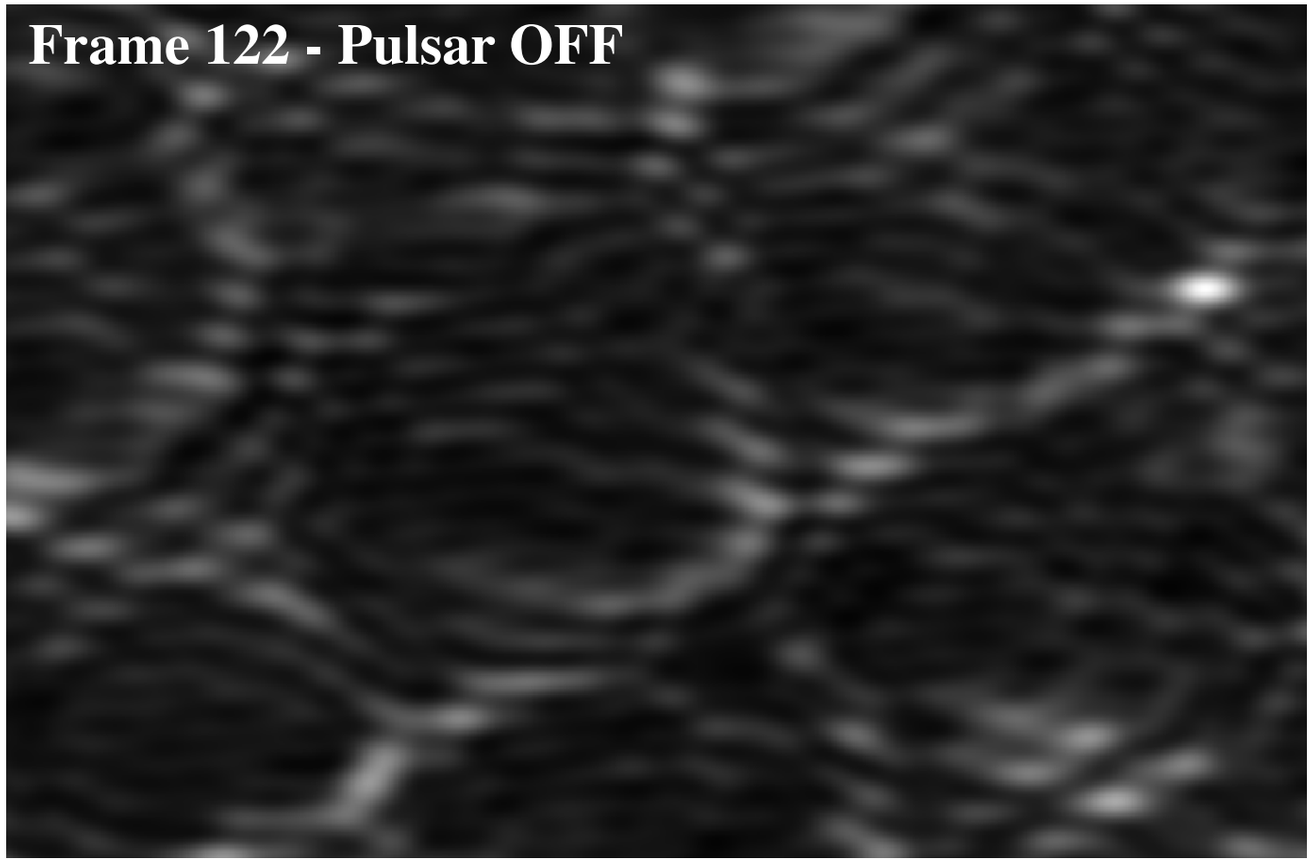
Coll. Casey Law (UC Berkeley)

Test #3: Real data: pulsar B0355+55 with the VLA

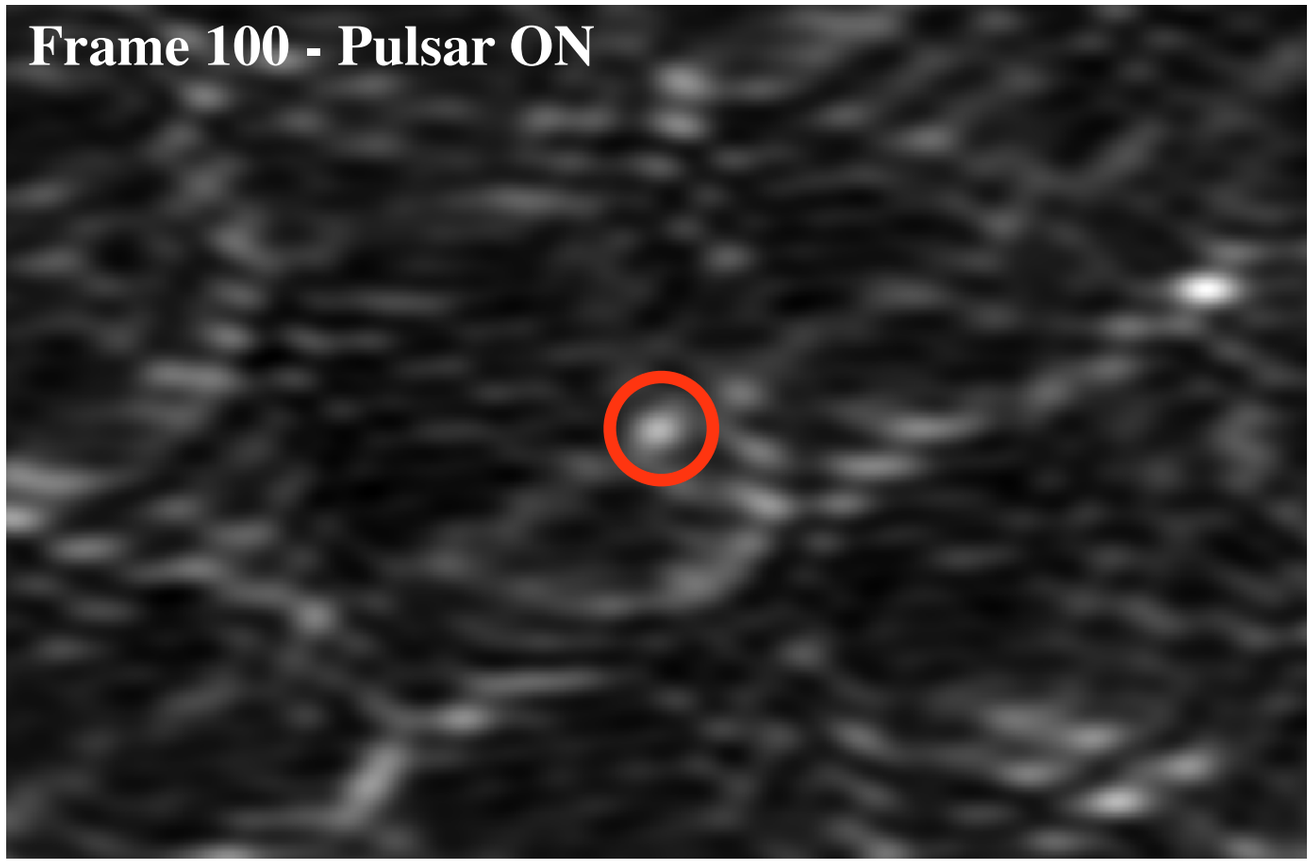
data $\Delta t = 1.03s$

res. $\delta t = 5ms$

Period $P_{\mathrm{B0355+55}} = 156ms$



- **Transient** takes the form of the PSF
- **Sidelobes** are also transients !



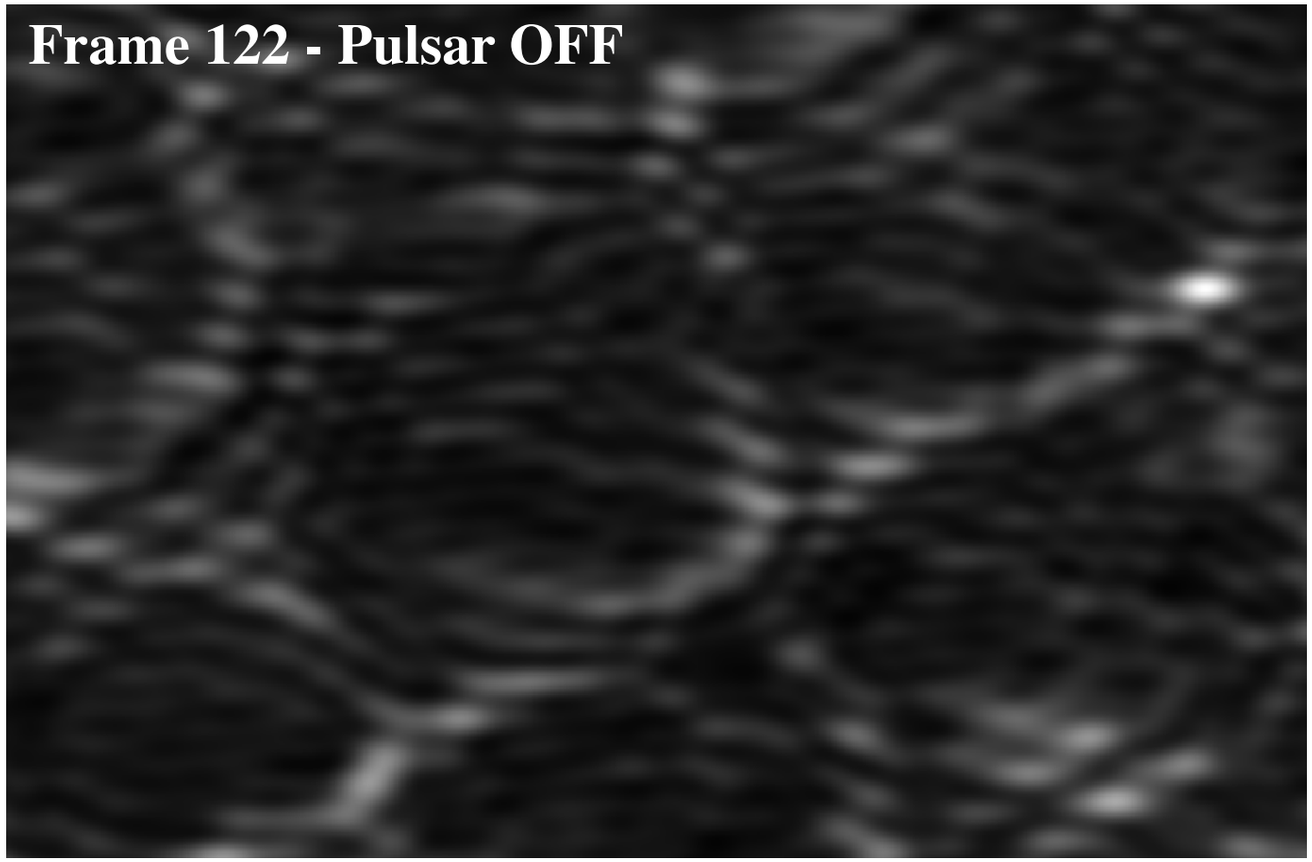
Coll. Casey Law (UC Berkeley)

Test #3: Real data: pulsar B0355+55 with the VLA

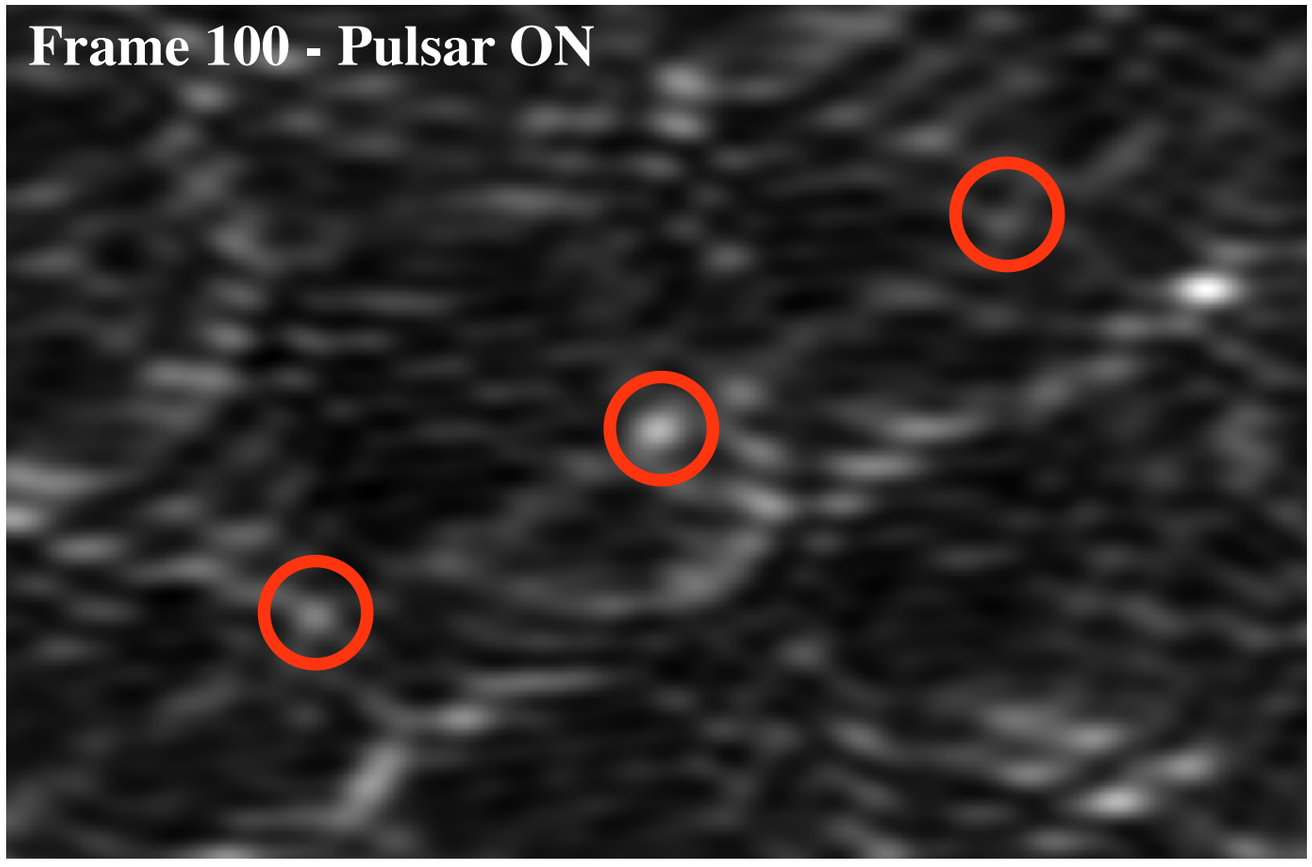
data $\Delta t = 1.03s$

res. $\delta t = 5ms$

Period $P_{\mathrm{B0355+55}} = 156ms$



- **Transient** takes the form of the PSF
- **Sidelobes** are also transients !



Coll. Casey Law (UC Berkeley)

Take-away messages

Take-away messages

SKA-class telescopes ⟶ **gain in raw sensitivity**

enable monitoring of your favorite objects (e.g. during quiescence)

bright slow transients Imaging mode

faint fast transients Beamforming mode

Take-away messages

SKA-class telescopes → **gain in raw sensitivity**

enable monitoring of your favorite objects (e.g. during quiescence)

bright slow transients — Imaging mode

faint fast transients — Beamforming mode

Data calibration → gained in complexity
gained in volume

Large FoV → Instrumental effects = f(t,ν,θ,ϕ)
Biased flux
Fake transients

addressed with Radio Interferometric Measurement Equation

Take-away messages

SKA-class telescopes → **gain in raw sensitivity**

enable monitoring of your favorite objects (e.g. during quiescence)

bright slow transients — Imaging mode

faint fast transients — Beamforming mode

Data calibration → gained in complexity
gained in volume

Large FoV → Instrumental effects = f(t,ν,θ,ϕ)
Biased flux
Fake transients

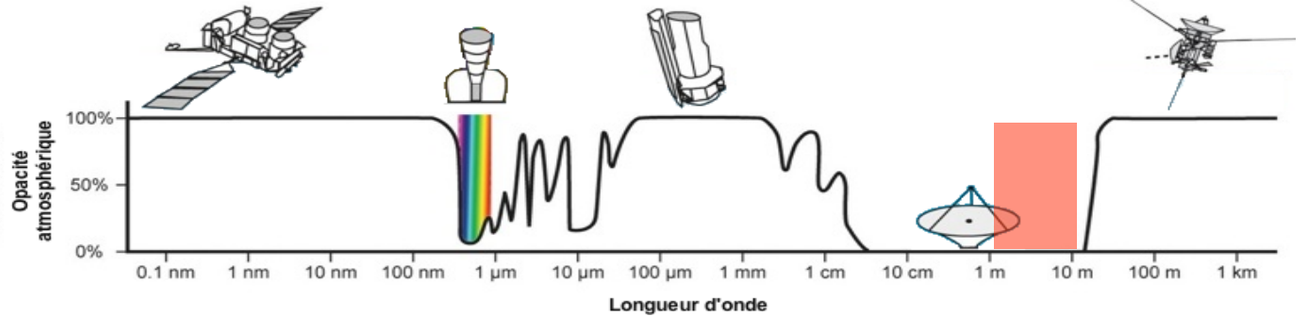
addressed with Radio Interferometric Measurement Equation

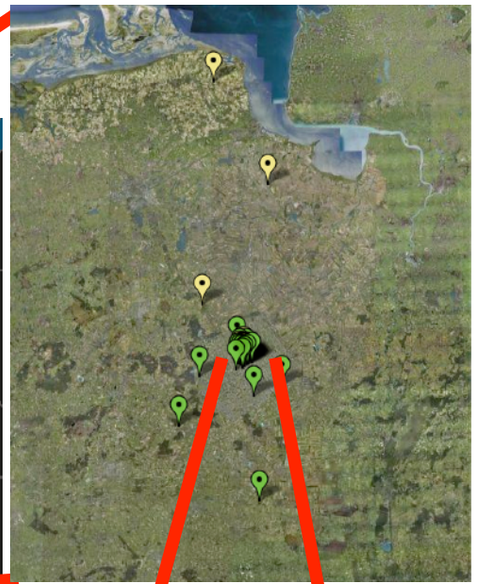
« Compressed Sensing »

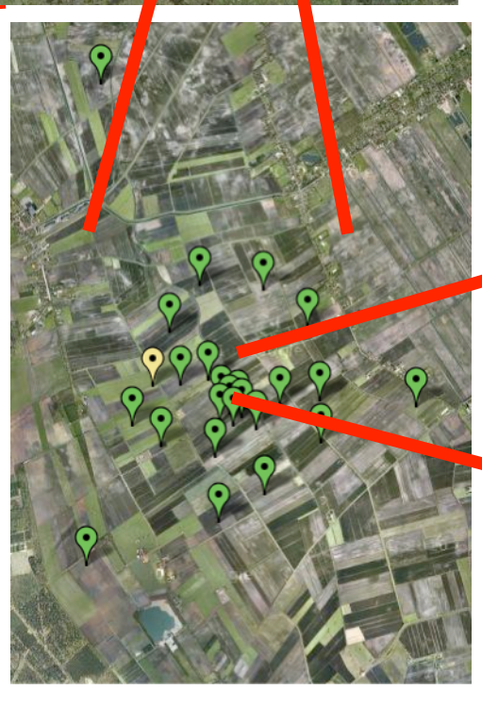
Recent signal processing framework to take the best of your data

(also applicable to X-ray and Gamma-ray deconvolution)

LOFAR
A multiscale instrument





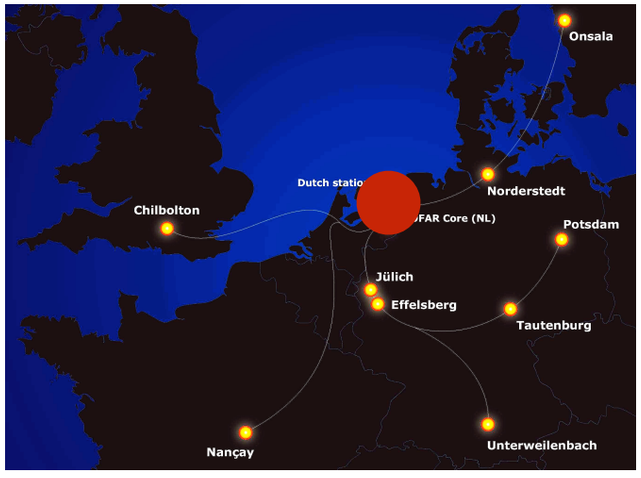


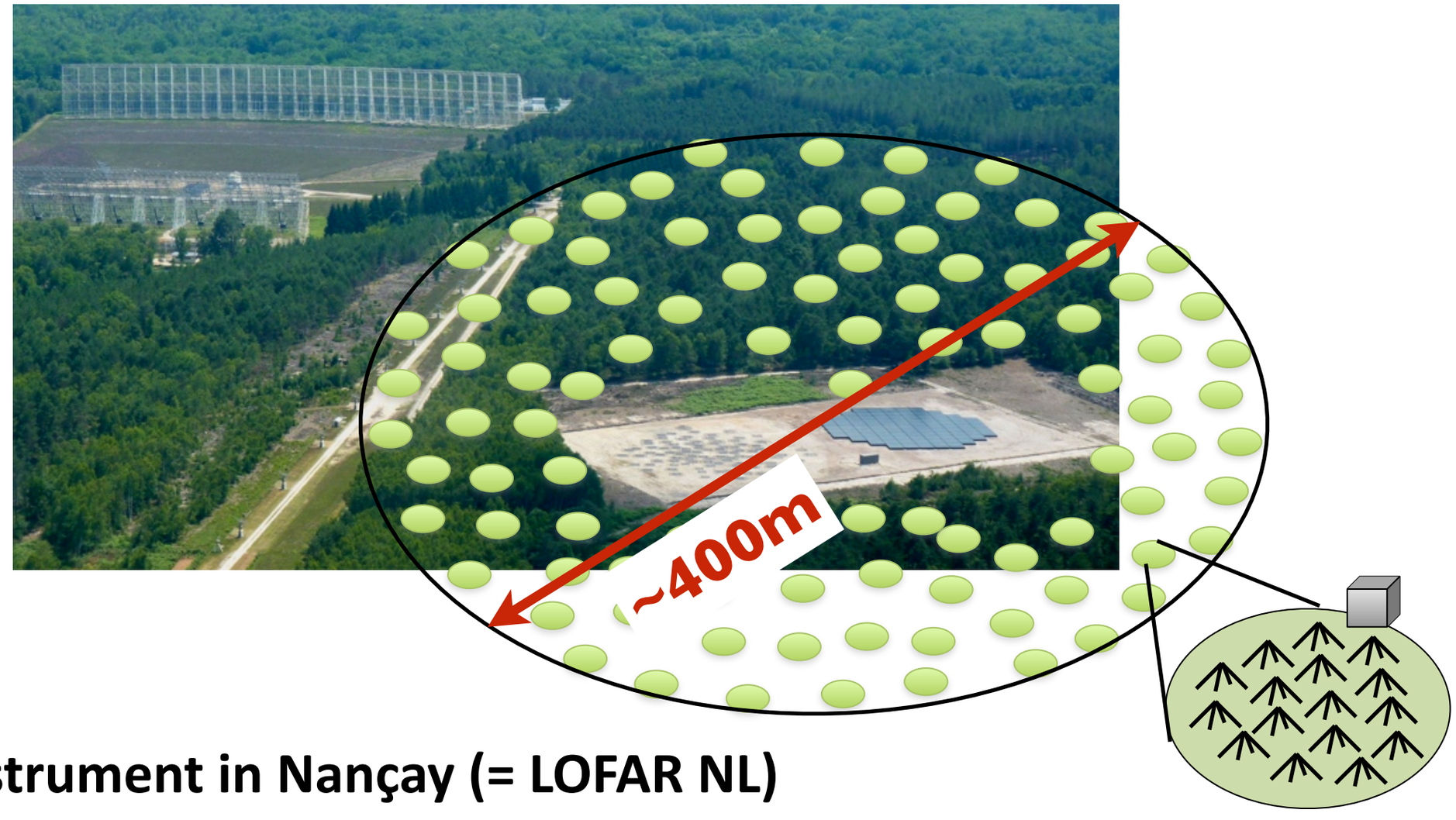
- 1824 antennas / NL tiles + 1248 International
- Imaging, Beamforming, waveforms

Instrumentation

Improving LOFAR ? Instantaneous sensitivity on angular resolution — Access to large structure Field of view

NenuFAR = New Extension in Nançay Upgrading LOFAR





Large stand-alone instrument in Nançay (= LOFAR NL)

Multi-scale instrument

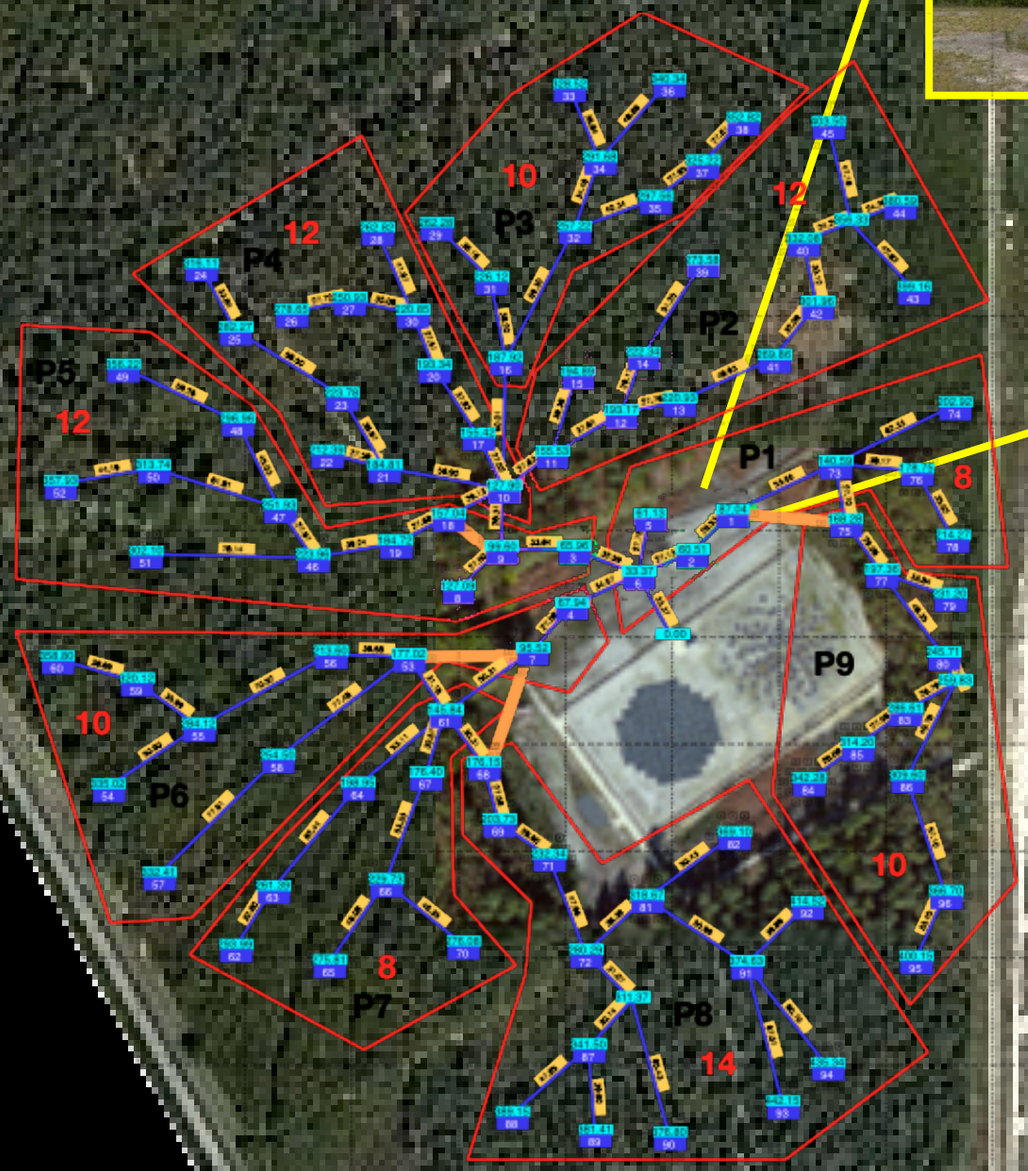
Under construction (~50% by the end of 2017) - SKA Pathfinder

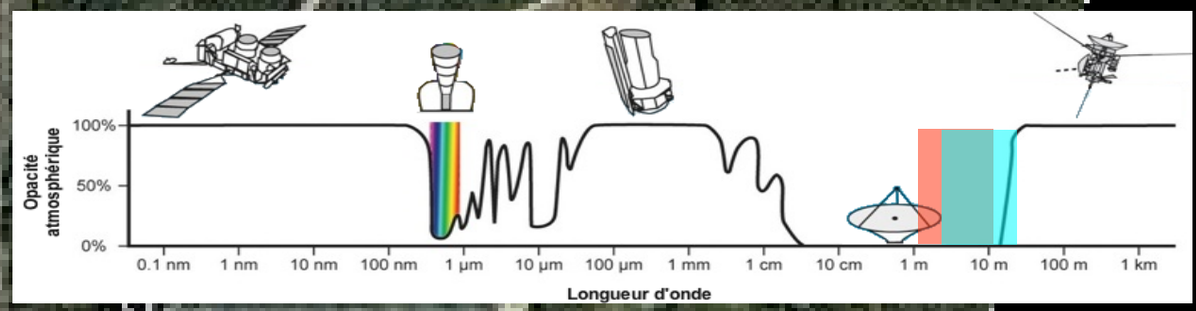
Thèse, 2013 — Girard et al., CRAS, 2012 — Girard et al., SF2A, 2012

Zyma, Girard, Vasko et al., 2016 — Zarka, Girard et al., SF2A 2012 — Zarka, Tagger, Denis, Girard et al., in prep

… NenuFAR

New extension in Nançay upgrading LOFAR





A_{eff} compared to LOFAR, LWA