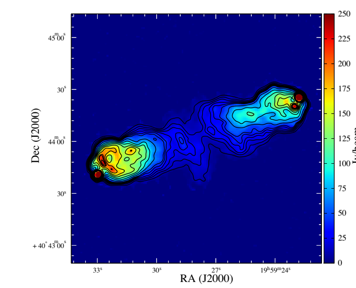
Jean-Luc Starck
http://jstarck.cosmostat.org

Radio-Interferometry & CosmoStat



- Radio Image Reconstruction
  - H. Garsden et al, A&A, 575, A90, 2015.
  - S. Farrens et al, Astronomy and Computing, 32, 2020.

UnivEarthS 2014-2017 (P.I. S. Corbel)
COSMIC 2016-2022 (CO-I J.L. Starck)

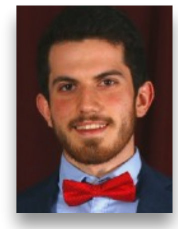
Julien Girard

S. Corbel

H. Garsden

S. Farrens


- **Radio Weak Lensing**
  - F. Nammour, et al, "Galaxy Image Restoration with Shape Constraint", Journal of Fourier Analysis and Applications, 27, 88, 2021.
  - F. Nammour et al, "ShapeNet: Shape Constraint for Galaxy Image Deconvolution", Astronomy and Astrophysics, 663, id.A692022, 2022.

Fadi Namour

François Lanusse

Julien Girard


ANR TOSCA 2023-2027(542k€, P.I. V. Pettorino)
ERA CHAIR TITAN 2023-2027 (2.5M€, P.I. J.-L. Starck)

- Transient sky
  - B. Chiche et al, "Deep Learning-Based Deconvolution for Interferometric Radio Transient Reconstruction", **Astronomy and Astrophysics**, in press, 2023.

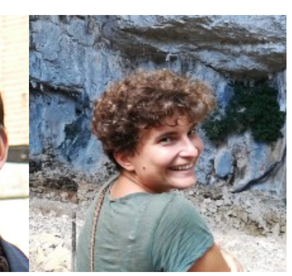
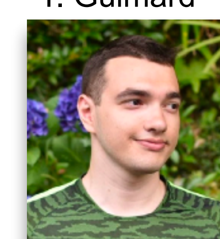
CIFRE 2019-2022
ARGOS 2023-2025 (2.8M€, co-I J.L. Starck)

Julien Girard

Benjamin Chiche


- **Epoch of Reionization (EoR)**
  - E. Chapman et al , "The Scale of the Problem : Recovering Images of Reionization with GMCA", MNRAS, 429, 2013.
  - E. Chapman, et al., "Cosmic dawn and Epoch of Reionization foreground removal with the SKA", SKA science book, 2015.
  - I. Carruci et al, "Recovery of 21-cm intensity maps with sparse component separation", 499, 2020.
  - Y. Guimard et al , "Statistical and morphological component separation of foregrounds in convolved HI skymaps.", IEEE Workshop on Signal Processing, 2022

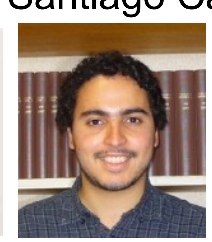
J. Bobin

Isabella Carucci

Y. Guimard


ERC Lena 2016-2021 (1.5M€, P.I. J. Bobin)
ERA CHAIR TITAN 2023-2027

- Theory
  - S. Casas et al, Linear and non-linear Modified Gravity forecasts with future surveys, Physics of the Dark Universe, Volume 18, 2023.
  - S. Casas et al, Constraining gravity with synergies between radio and optical cosmological surveys,Physics of the Dark Universe, Volume 39, 2023

V. Pettorino

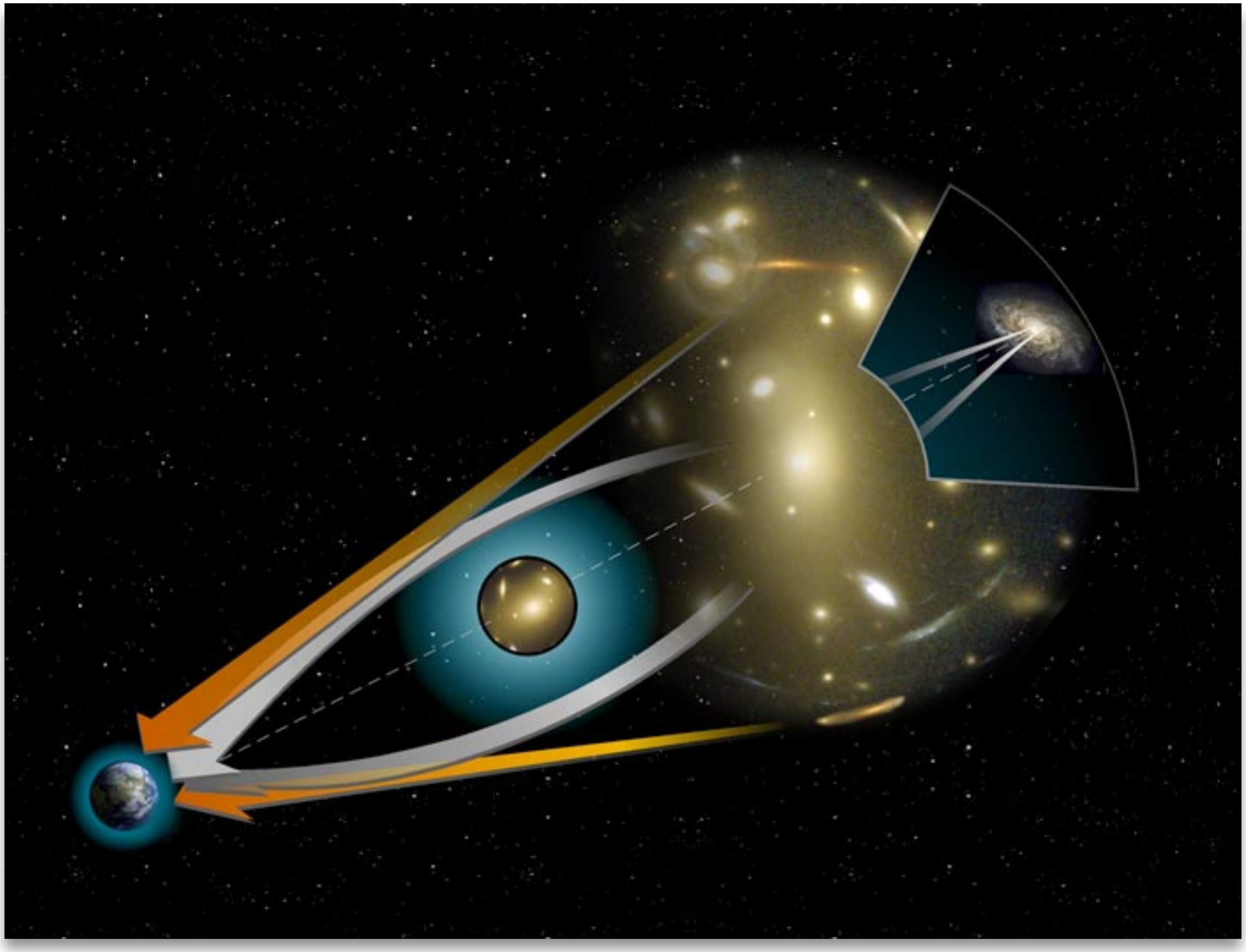
Santiago Casas


ANR TOSCA 2023-2027

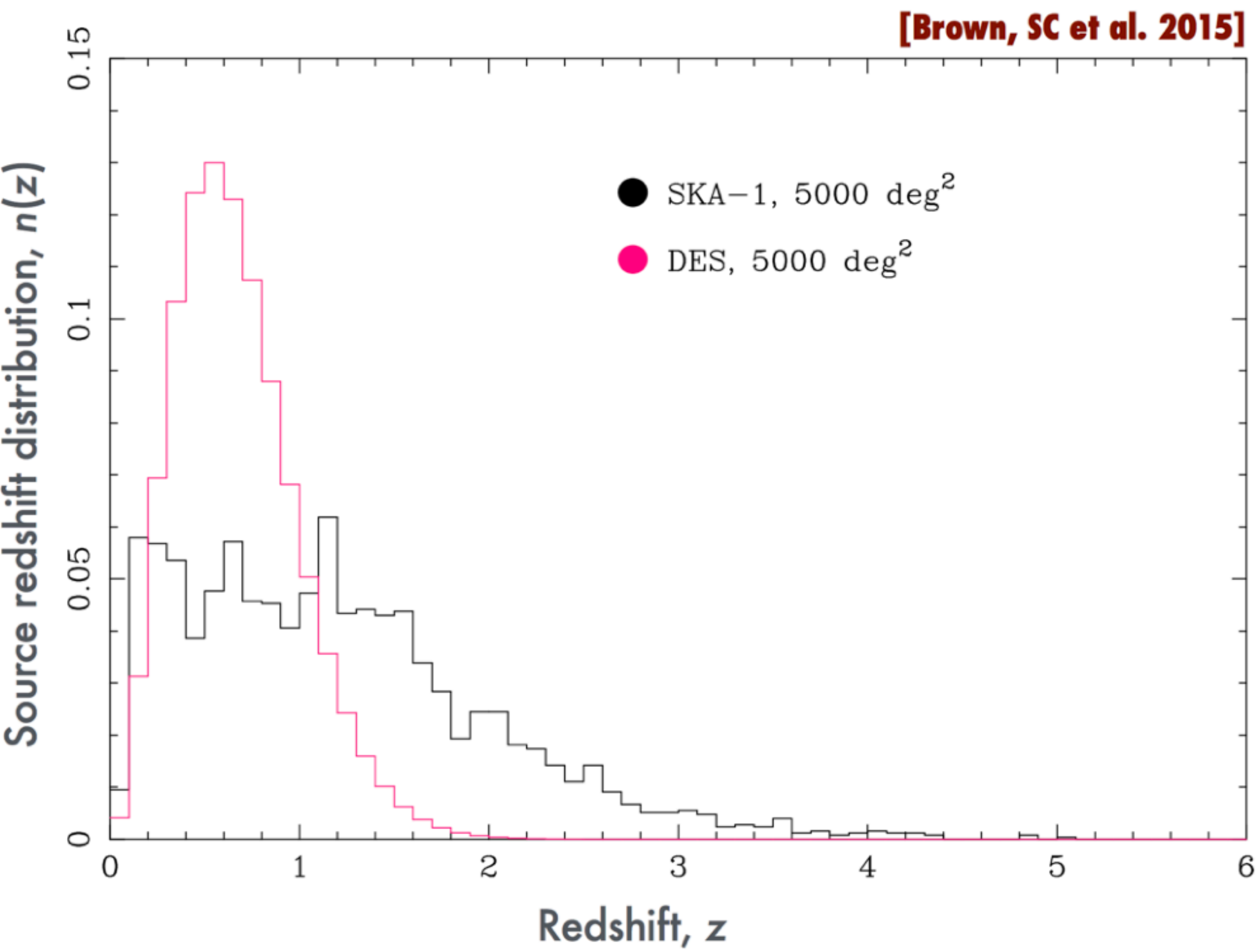
cea

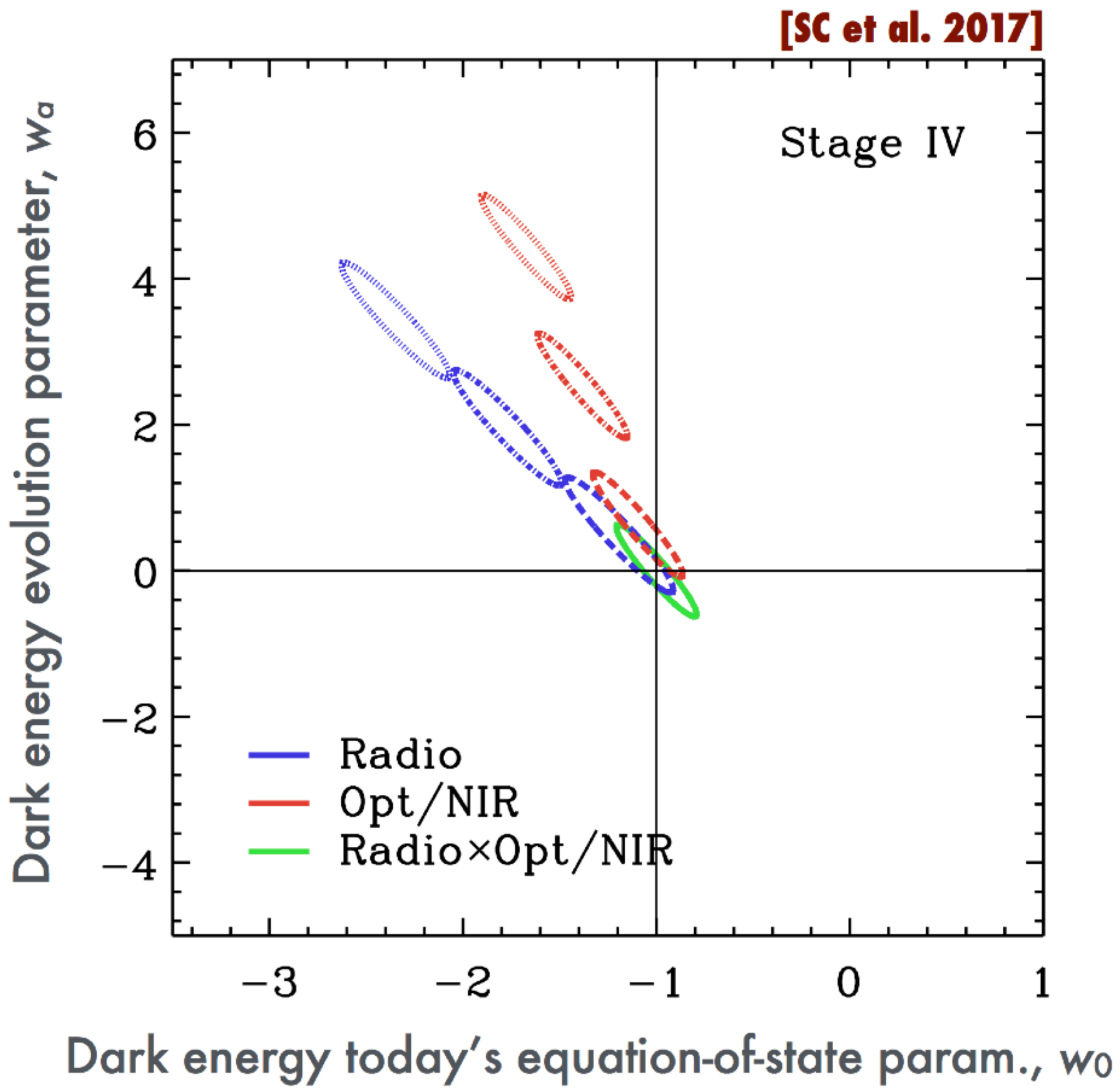
CosmoStat

Dark Matter & Weak Lensing

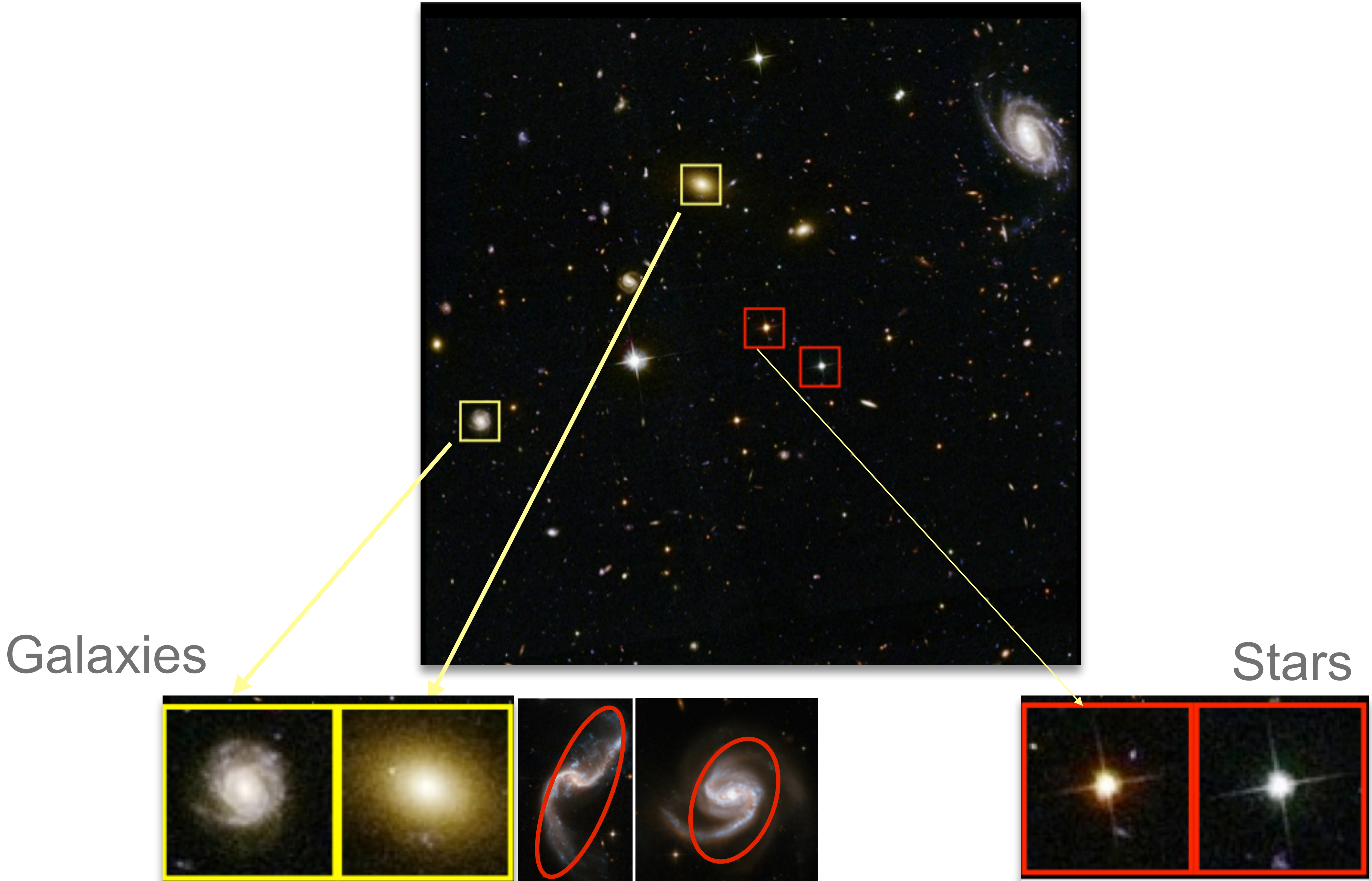


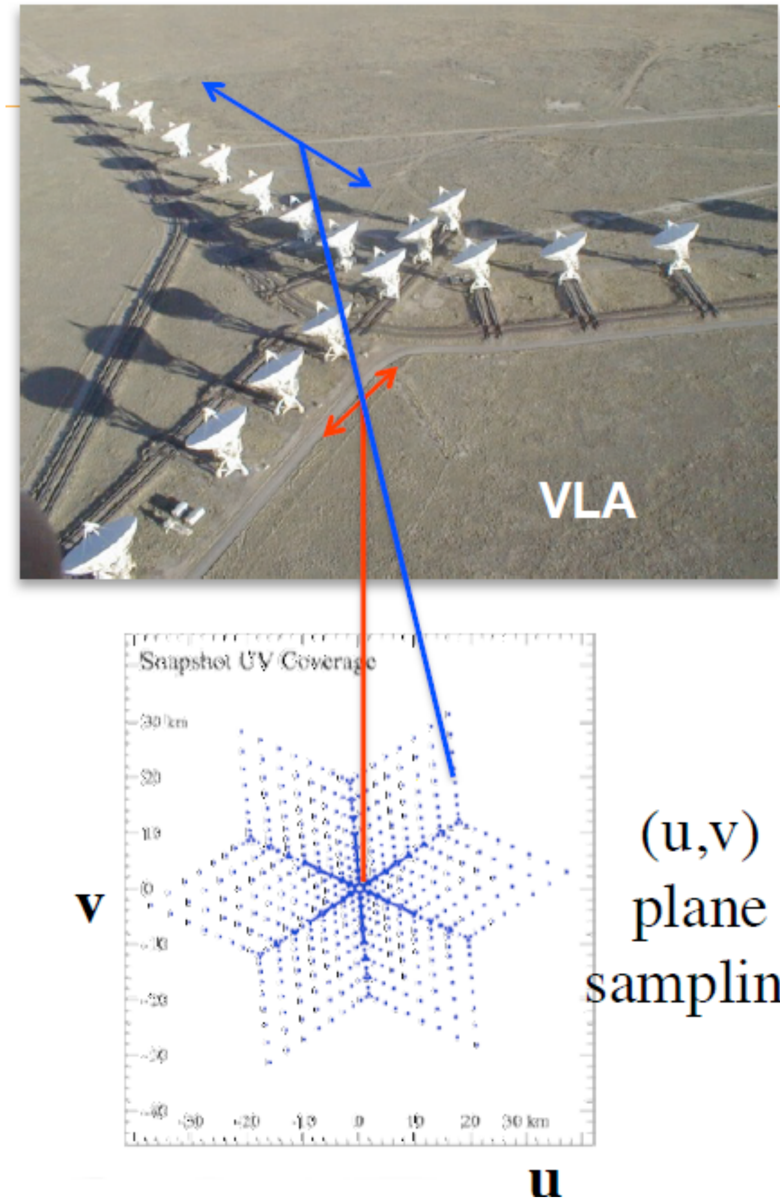
Weak Lensing



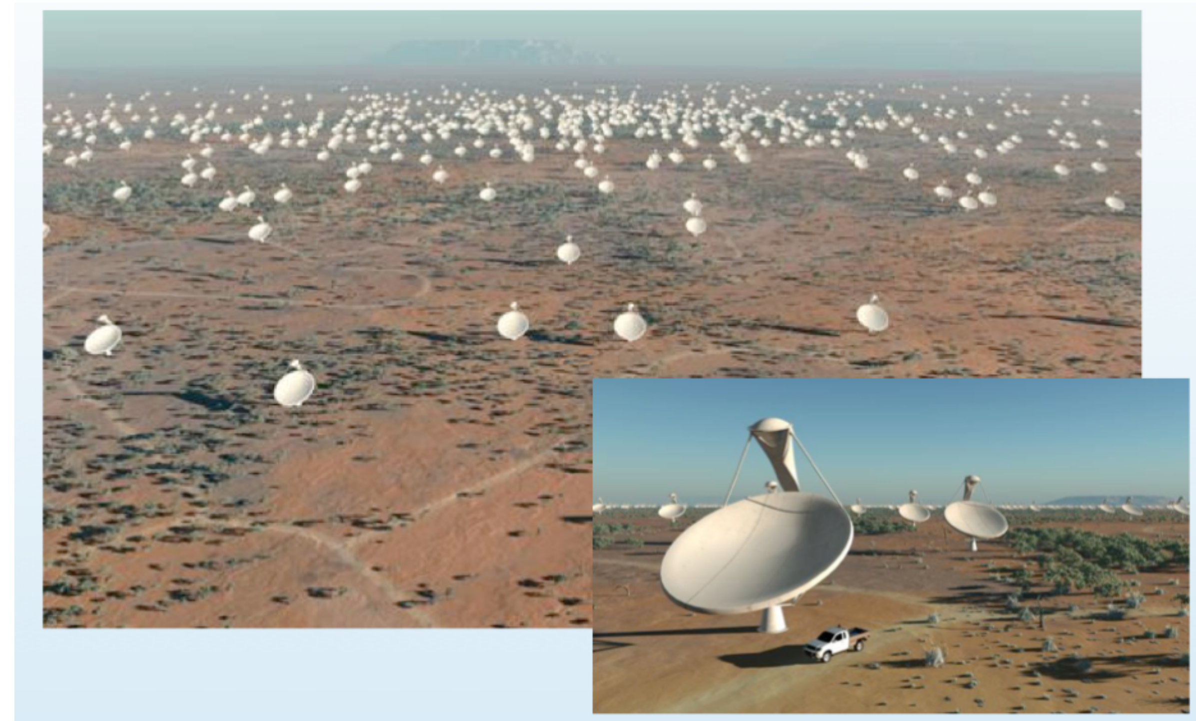


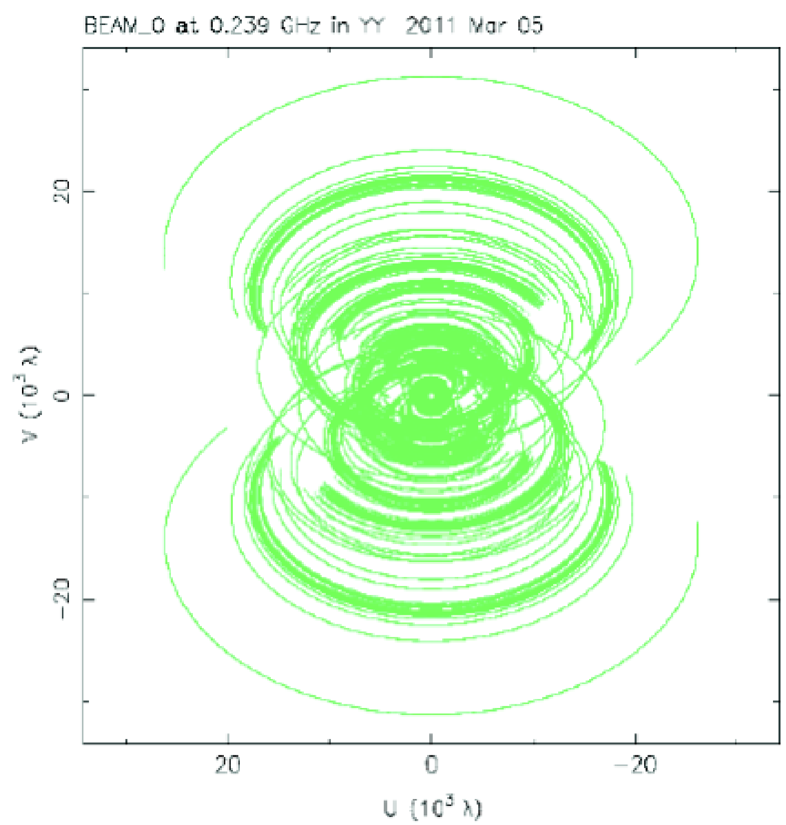
Detection + Classification stars/galaxies

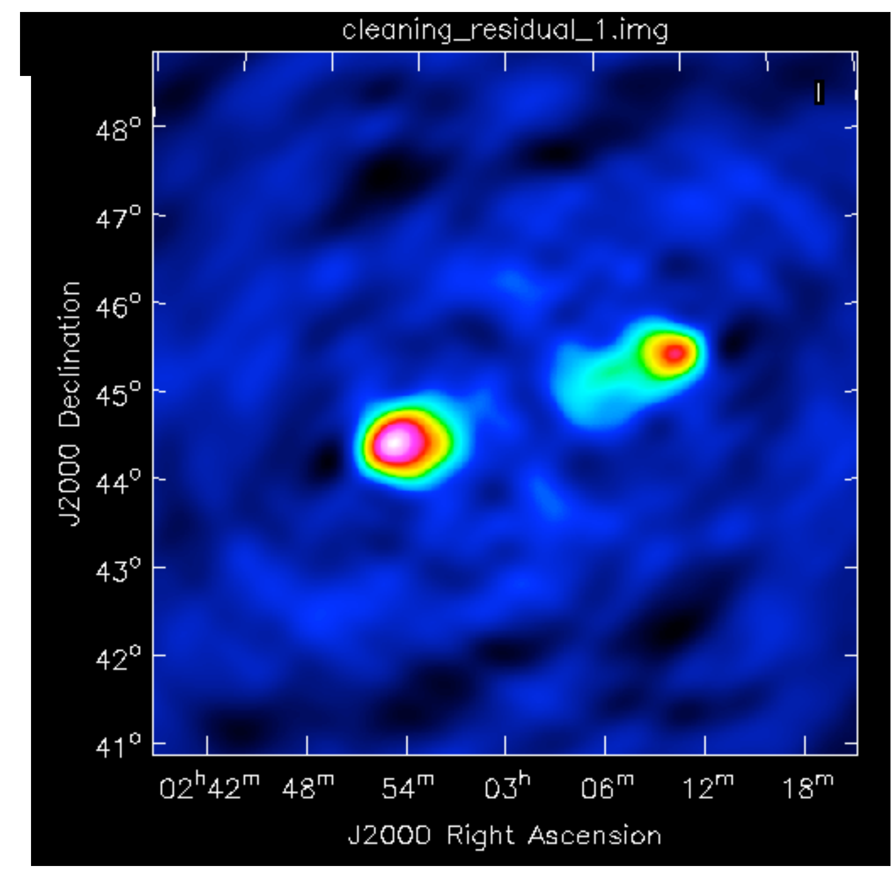




(u,v)
plane
sampling

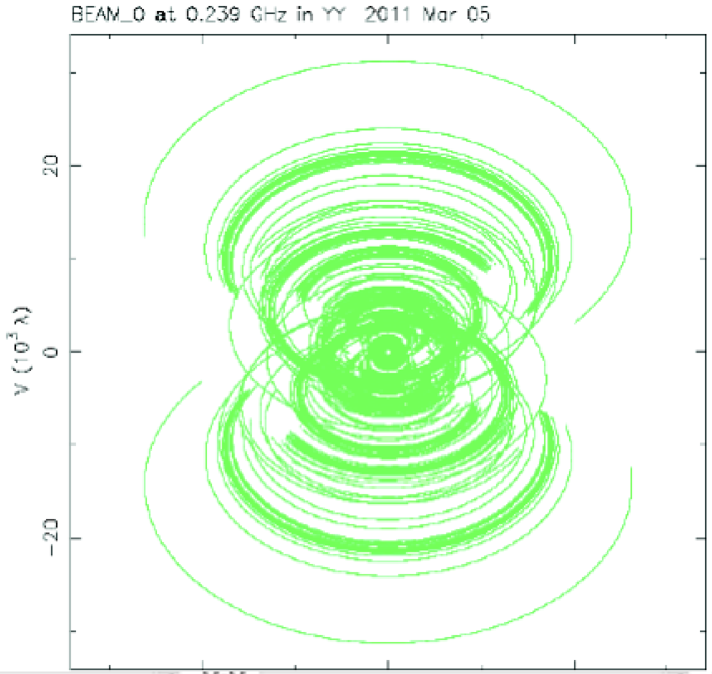


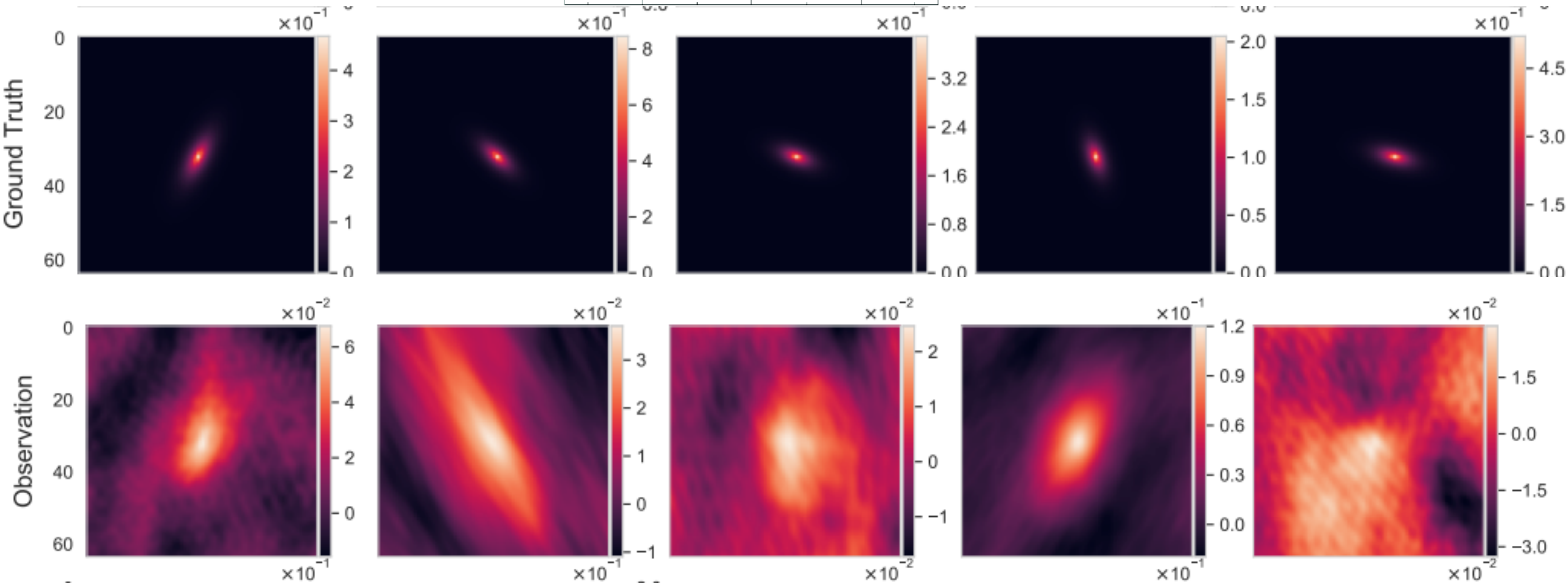




Sampling in the 2D Fourier domain

Radio Galaxies





Radio Shape Measurements

- **Reconstruct images from visibilities and applied standard methods used in optics**

=> iterative deconvolution methods produce images with structures in the residuals that dominate the cosmological signal (Patel et al, 2014,2015).

- **Fit a galaxy model directly to the visibilities (Rivi et al, 2016; Rivi et al, 2018)**

=> Limited by the source number density in the field of view, because of nearby galaxies residuals in the extraction (Rivi et al 2019).

- **Joint fitting of all galaxies directly to the visibilities using an Hamiltonian Monte Carlo (HMC) sampler (Rivi et al, 2019).**

=> Seems promising, however much higher computational cost.

Deconvolution & Shape Constraint

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}$$

- Noise
- True Image
- PSF Convolution
- Observed Image

$$U_1 = \begin{pmatrix} 1 & 1 & \dots & 1 \\ 2 & 2 & \dots & 2 \\ \vdots & \vdots & \ddots & \vdots \\ n & n & \dots & n \end{pmatrix} \quad U_2 = \begin{pmatrix} 1 & 2 & \dots & n \\ 1 & 2 & \dots & n \\ \vdots & \vdots & \ddots & \vdots \\ 1 & 2 & \dots & n \end{pmatrix} \quad U_3 = \begin{pmatrix} 1 & 1 & \dots & 1 \\ 1 & 1 & \dots & 1 \\ \vdots & \vdots & \ddots & \vdots \\ 1 & 1 & \dots & 1 \end{pmatrix}$$

$$U_4 = \begin{pmatrix} 1^2+1^2 & 1^2+2^2 & \dots & 1^2+n^2 \\ 2^2+1^2 & 2^2+2^2 & \dots & 2^2+n^2 \\ \vdots & \vdots & \ddots & \vdots \\ n^2+1^2 & n^2+2^2 & \dots & n^2+n^2 \end{pmatrix} \quad U_5 = \begin{pmatrix} 1^2-1^2 & 1^2-2^2 & \dots & 1^2-n^2 \\ 2^2-1^2 & 2^2-2^2 & \dots & 2^2-n^2 \\ \vdots & \vdots & \ddots & \vdots \\ n^2-1^2 & n^2-2^2 & \dots & n^2-n^2 \end{pmatrix} \quad U_6 = \begin{pmatrix} 1 & 2 & \dots & n \\ 2 & 4 & \dots & 2n \\ \vdots & \vdots & \ddots & \vdots \\ n & 2n & \dots & n^2 \end{pmatrix}$$

$$e_1(X) = \frac{\langle X, U_5\rangle\langle X, U_3\rangle - \langle X, U_1\rangle^2 + \langle X, U_2\rangle^2}{\langle X, U_5\rangle\langle X, U_3\rangle - \langle X, U_1\rangle^2 - \langle X, U_2\rangle^2} \quad , \quad e_2(X) = \frac{2(\langle X, U_6\rangle\langle X, U_3\rangle - \langle X, U_1\rangle\langle X, U_2\rangle)}{\langle X, U_5\rangle\langle X, U_3\rangle - \langle X, U_1\rangle^2 - \langle X, U_2\rangle^2}$$

Statistical properties related to ellipticities are preserved through the blurring operation

$$\begin{bmatrix} < Y, U_1 > \\ \vdots \\ < Y, U_6 > \end{bmatrix} = \begin{bmatrix} < HX, U_1 > \\ \vdots \\ < HX, U_6 > \end{bmatrix}$$

$$M(X) = \sum_{i=1}^{6} \mu_i \left\langle X * H - Y, U_i \right\rangle^2$$

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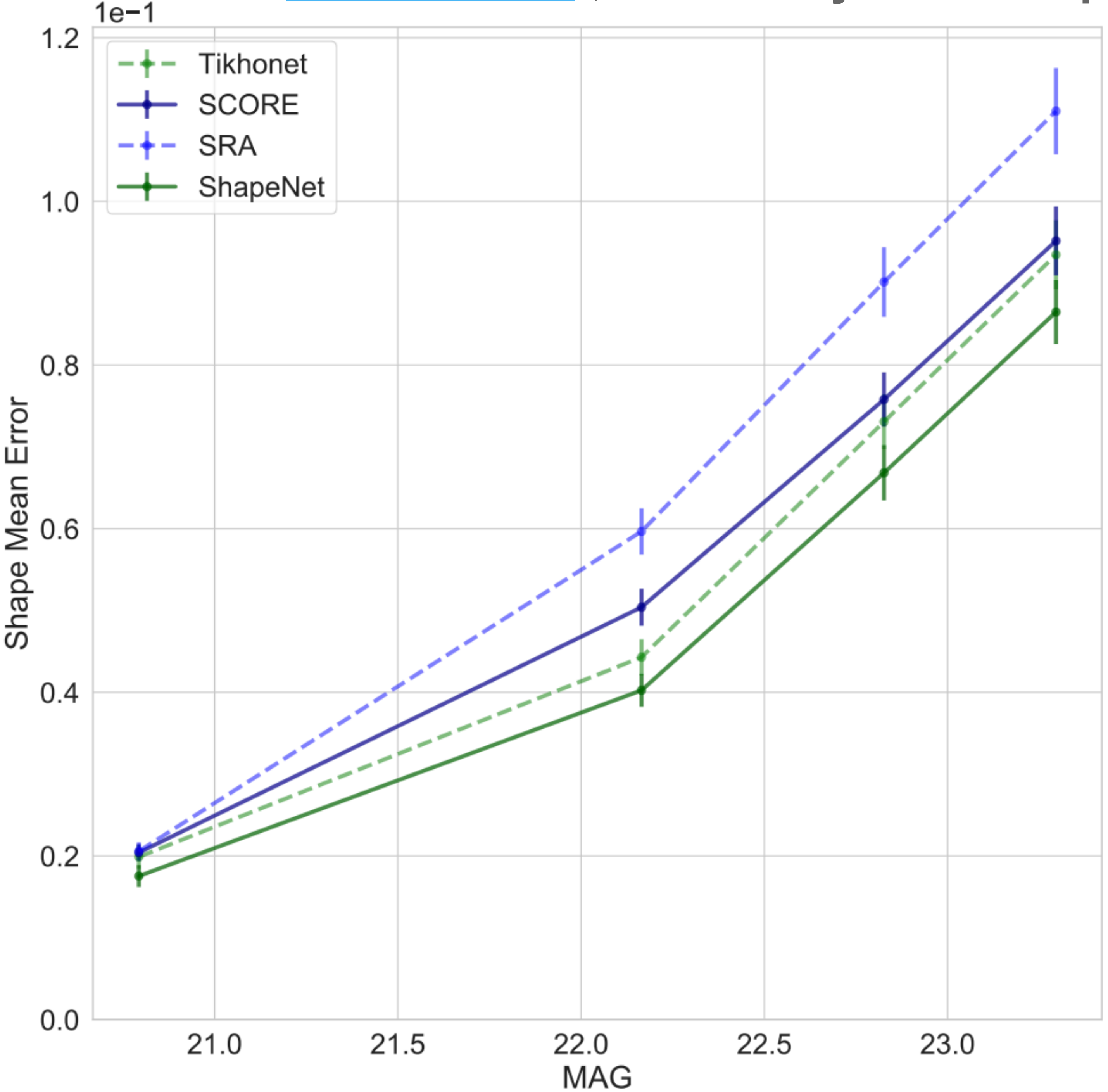
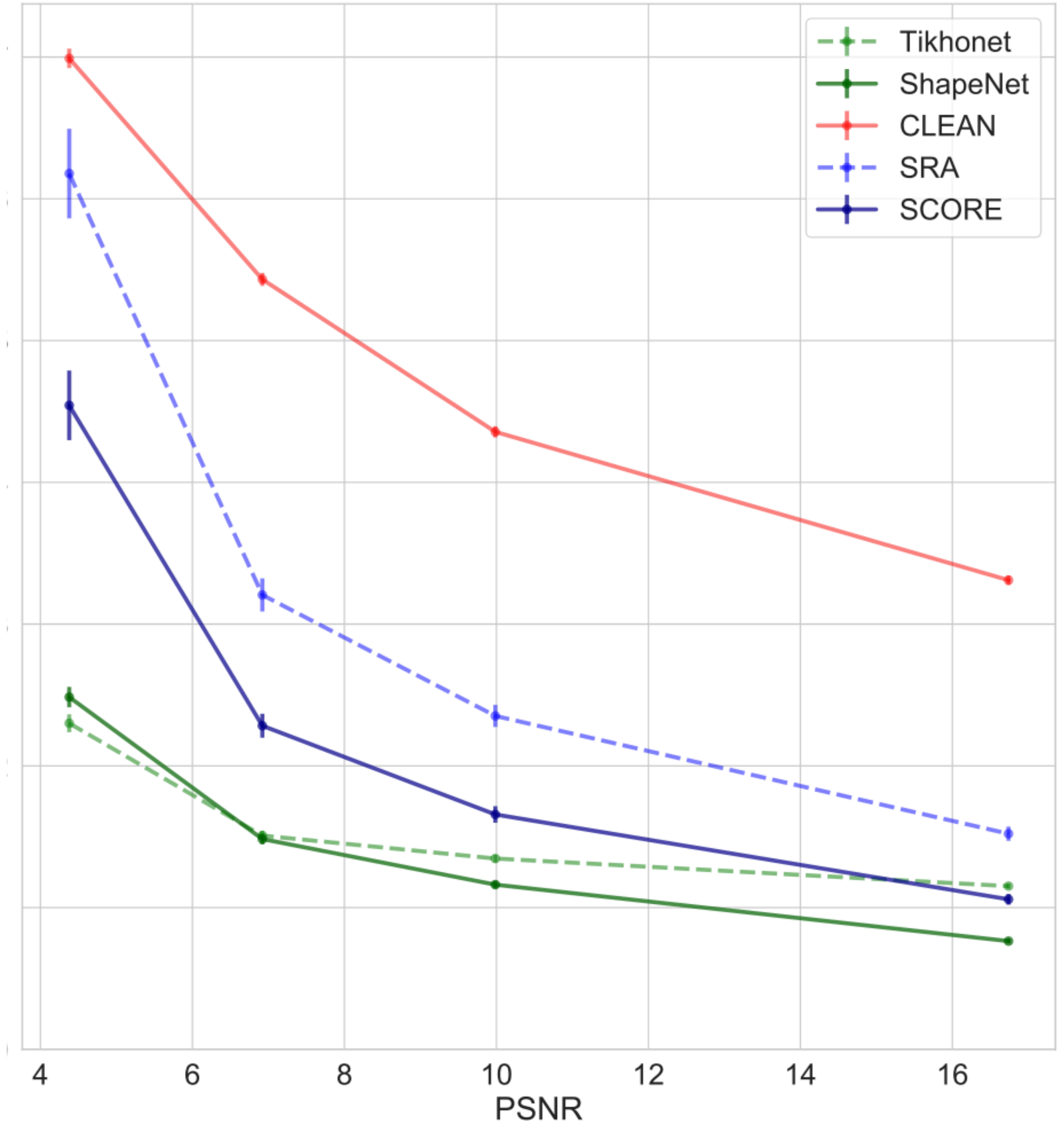
Deep Deconvolution

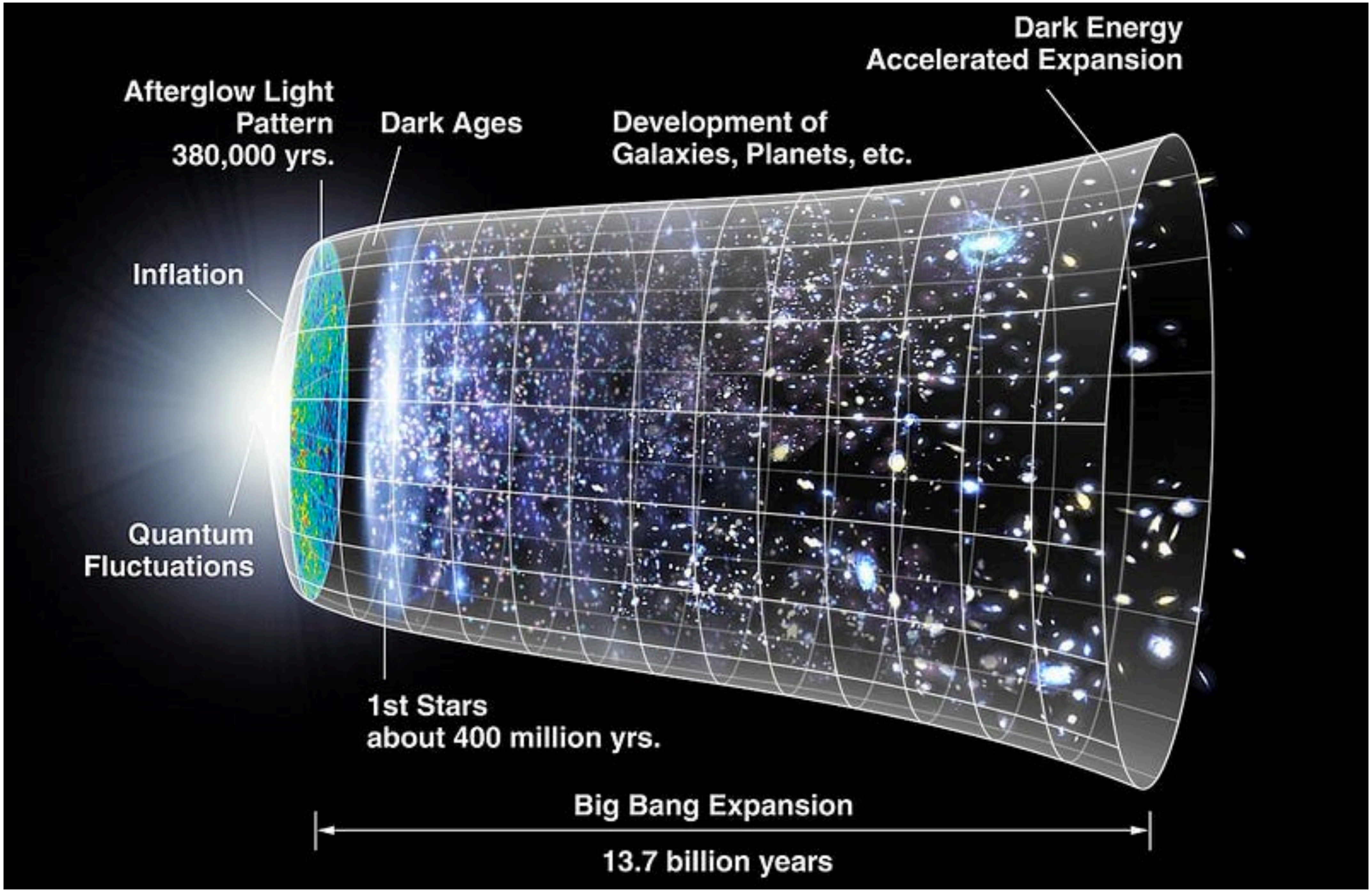
- F. Nammour et al, "ShapeNet: Shape Constraint for Galaxy Image Deconvolution", **Astronomy and Astrophysics**, 663, id.A692022, 2022.





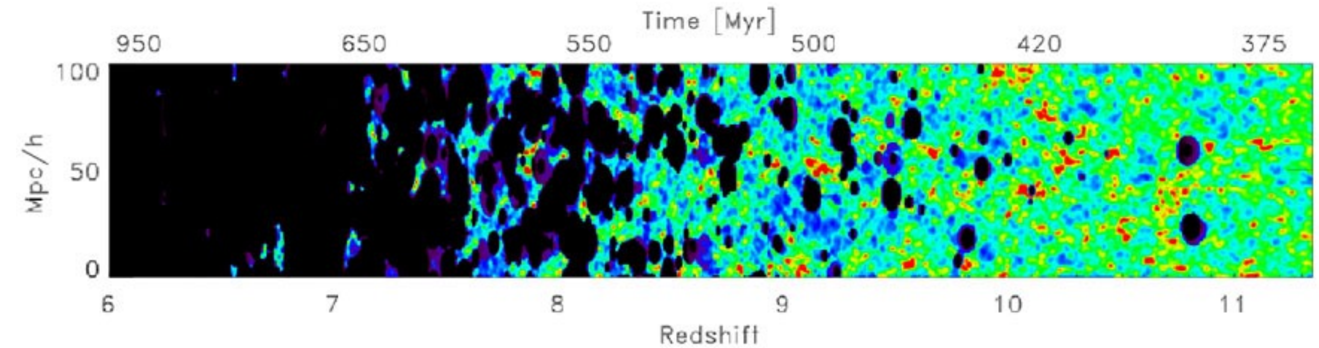
(a) Mean relative error of flux.

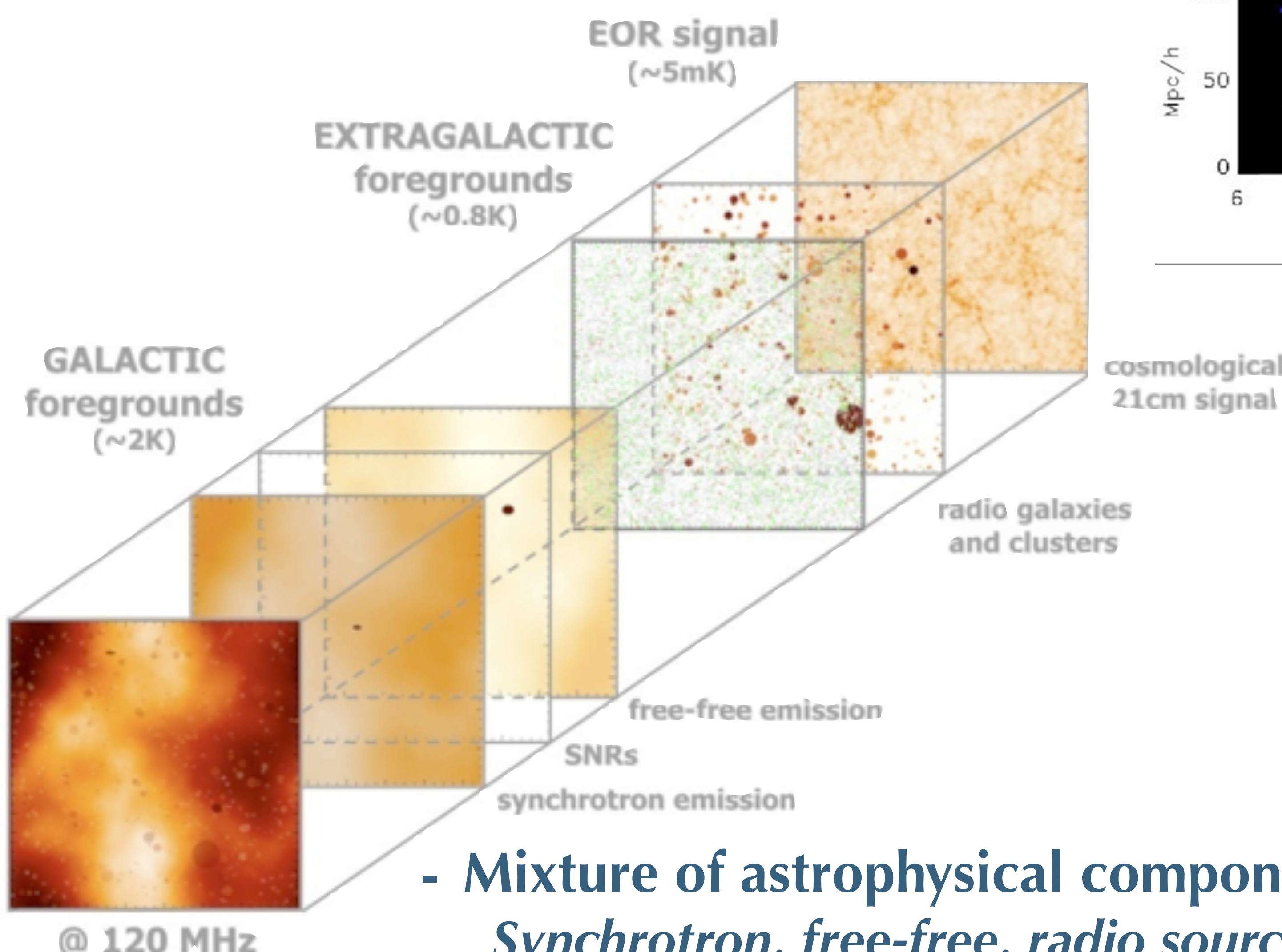
Epoch of Reionization (EoR)

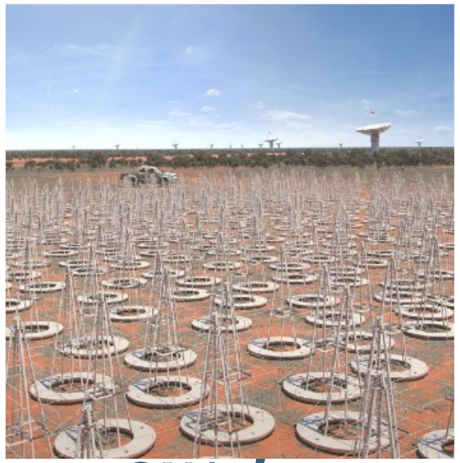


Epoch of Reionization (EoR)

- Imaging the dawn of the Universe at the epoch of reionisation ($6 < z < 12$)
- Mapping out the 21cm emission integrated over unresolved galaxies







SKA-low
Interferometric observations

- Mixture of astrophysical components:
  Synchrotron, free-free, radio sources

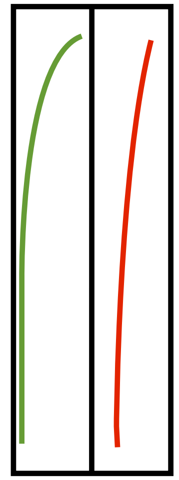
- Very low-level signal

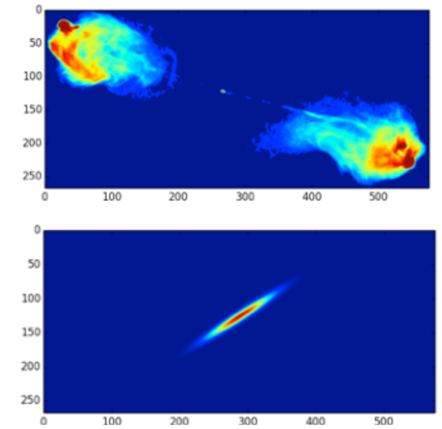
Foregrounds $\sim 1 - 10^2$	$>$	Noise	$>$	EoR signal $\sim 10^{-3}$

A Mixture & Convolution

Ground Truth

A

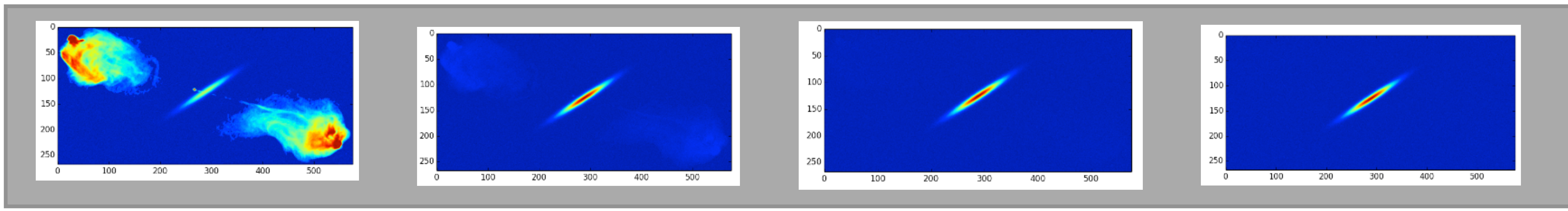




S

Mixtures

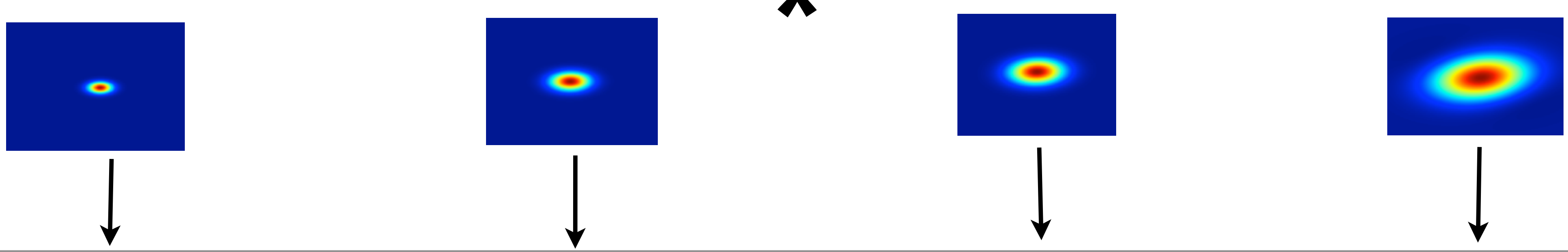
$X = AS$



chan 1 chan 4 chan 7 chan 10

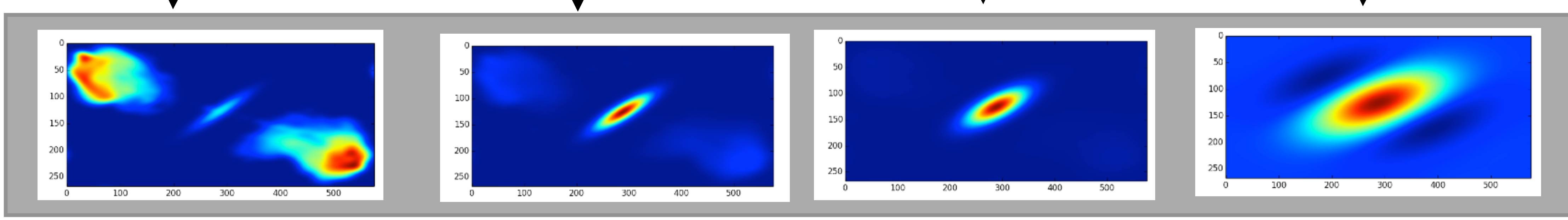
$*$

Beam H



Data

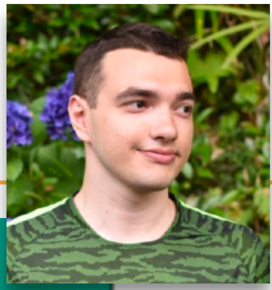
$Y = HX + N$

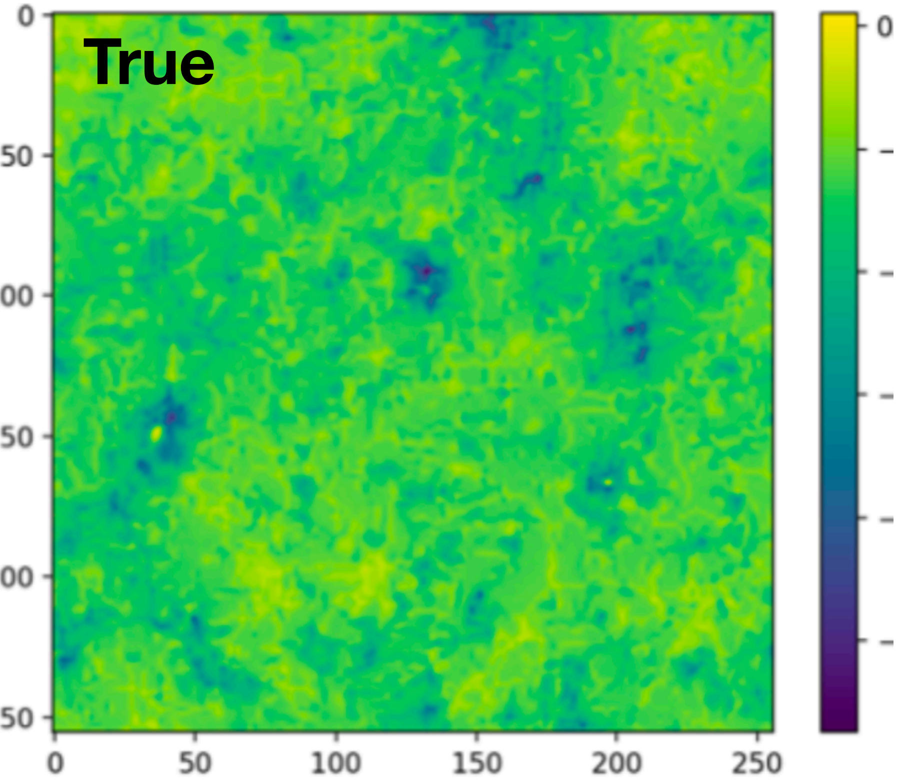


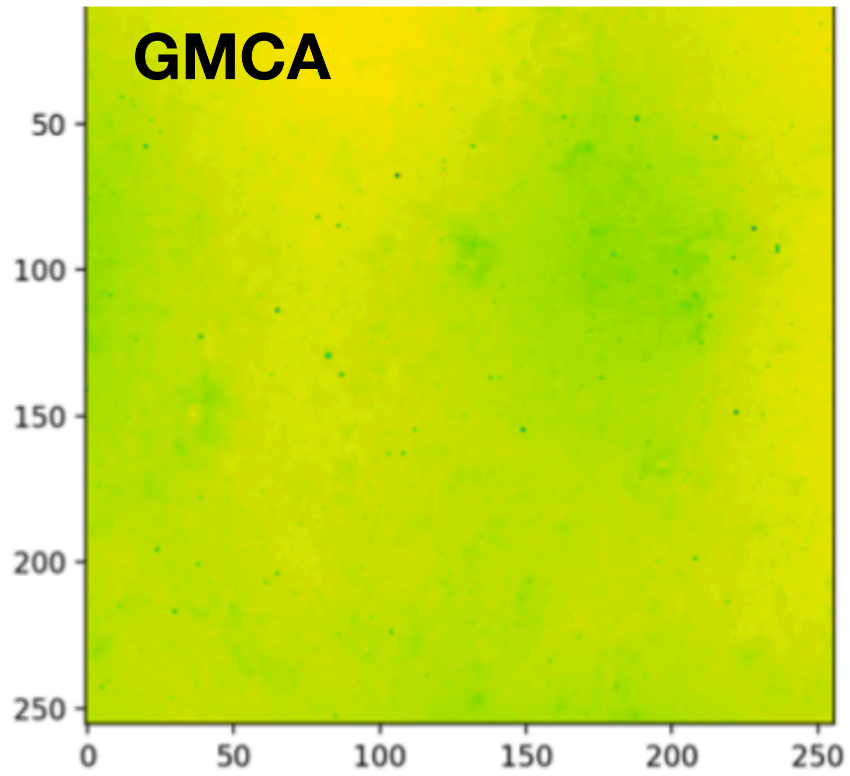
chan 1 chan 4 chan 7 chan 10

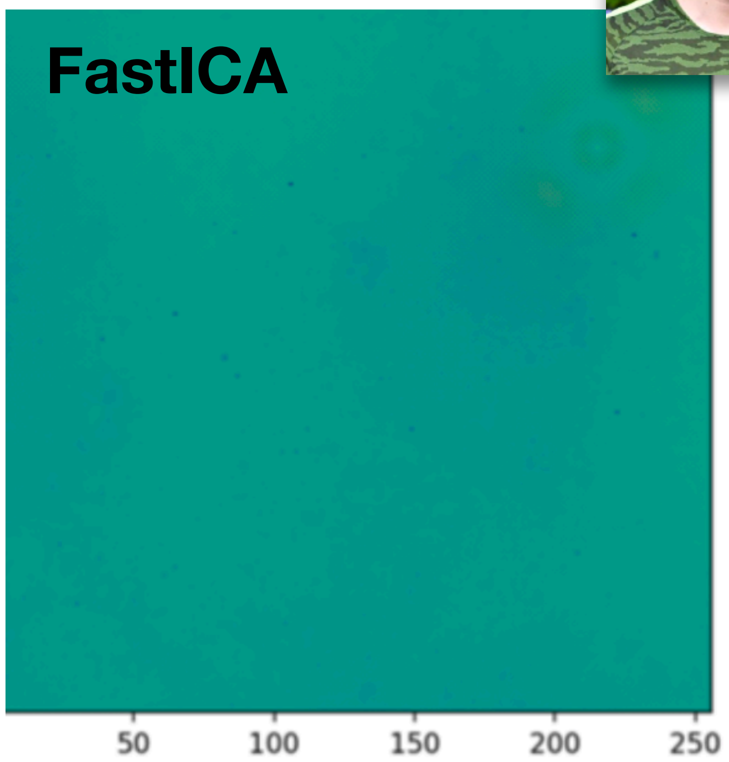
$$\forall i;\ \hat{y}_i = \hat{h}_i \left(\sum_j a_{ij} \hat{x}_j \right) + \hat{n}_i$$

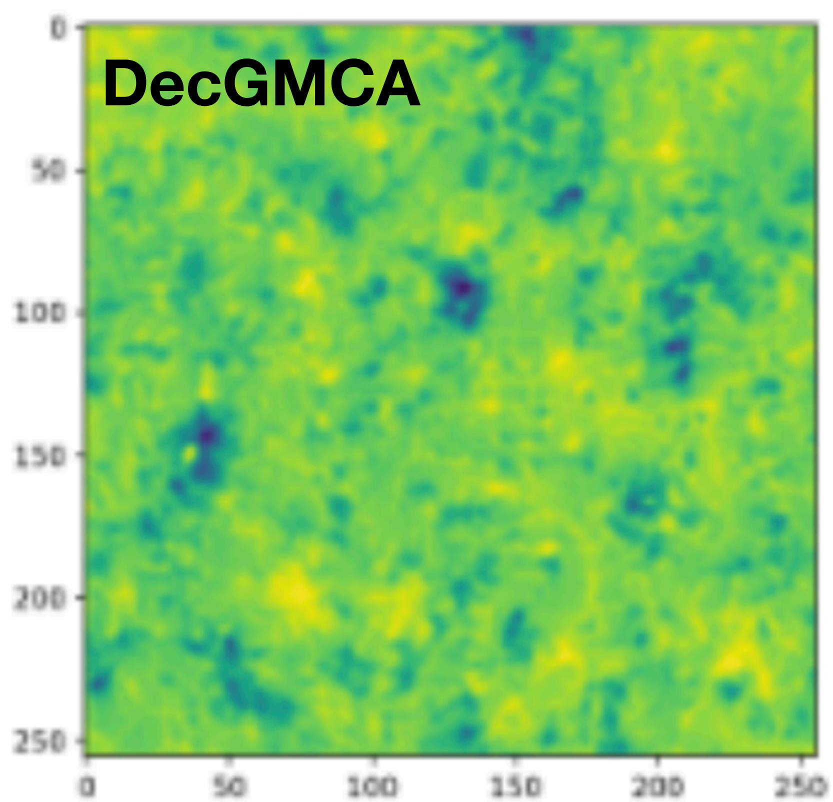
Y. Guimard

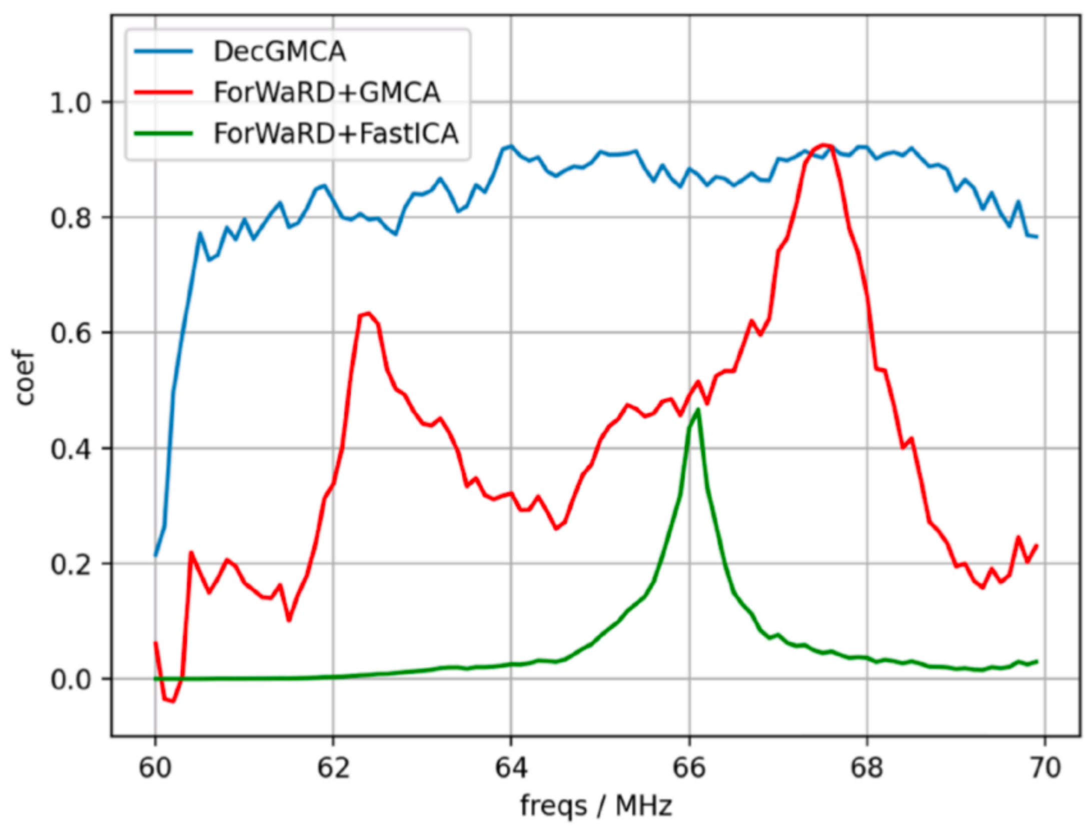



True
0
50
100
150
200
250


GMCA
50
100
150
200
250
0
50
100
150
200
250


FastICA
50
100
150
200
250


DecGMCA
0
50
100
150
200
250

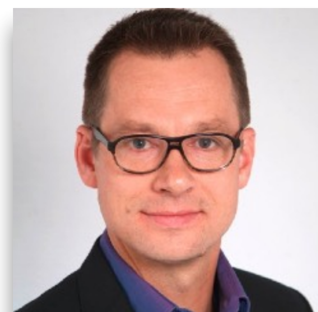

DecGMCA
ForWaRD+GMCA
ForWaRD+FastICA
coef
freqs / MHz
1.0
0.8
0.6
0.4
0.2
0.0
60
62
64
66
68
70

Our SKA research Impact Outside Astrophysics

- Our Astronomical Radio Image Reconstruction paper has led to many collaborations outside astrophysics at CEA:

S. Farrens et al, "PySAP: Python Sparse Data Analysis Package for Multidisciplinary Image Processing", **Astronomy and Computing**, 32, pp 100402, 2020. DOI

Sam Farrens, DAp



Philipe Ciuciu,
Neuropsin, CEA

– DRF Impulsion **COSMIC** (DRF, PI: Ph. Ciuciu, 200 k€) → **Neurospin MRI Imaging**

– DRF Impulsion **Fast FIB-SEM** (DRF Inac, PI: PH Jouneau, 70 k€) → **Electronic Microscopy**

– PTC **ComSET**: (DRT/LETI, PI: Zineb Saghi, 70 k€) → **Spectroscopic Electron Tomography**

– PTC **SILICOSMIC** (DRF, PI: Ph. Ciuciu, 60 k€) → COSMIC's Follow'up
  - NeuroSpin
  - CosmoStat
  - Maison de la Simulation (Pierre Kestener)

– PTC Instrumentation et Détection **CROCUS** (DRF, PI: Ph. Ciuciu, 100 k€) → capteur ultrasons multiélément pour des applications de Contrôle Non Destructif (CND)

Conclusions

SKA Data Analysis will push knowledge on

- Big Data, HPC, Optimization techniques, etc
- 3D Hyperspectral + Time (flux video hyperspectral massif)
- Machine Learning in high Dimension
- Compressed Sensing applications

SKA Data Interpretation will push knowledge on

- EoR, Large scale structures
- Dark Matter & Dark Energy
- Violent Universe

Many ongoing and futur scientific projects at CosmoStat