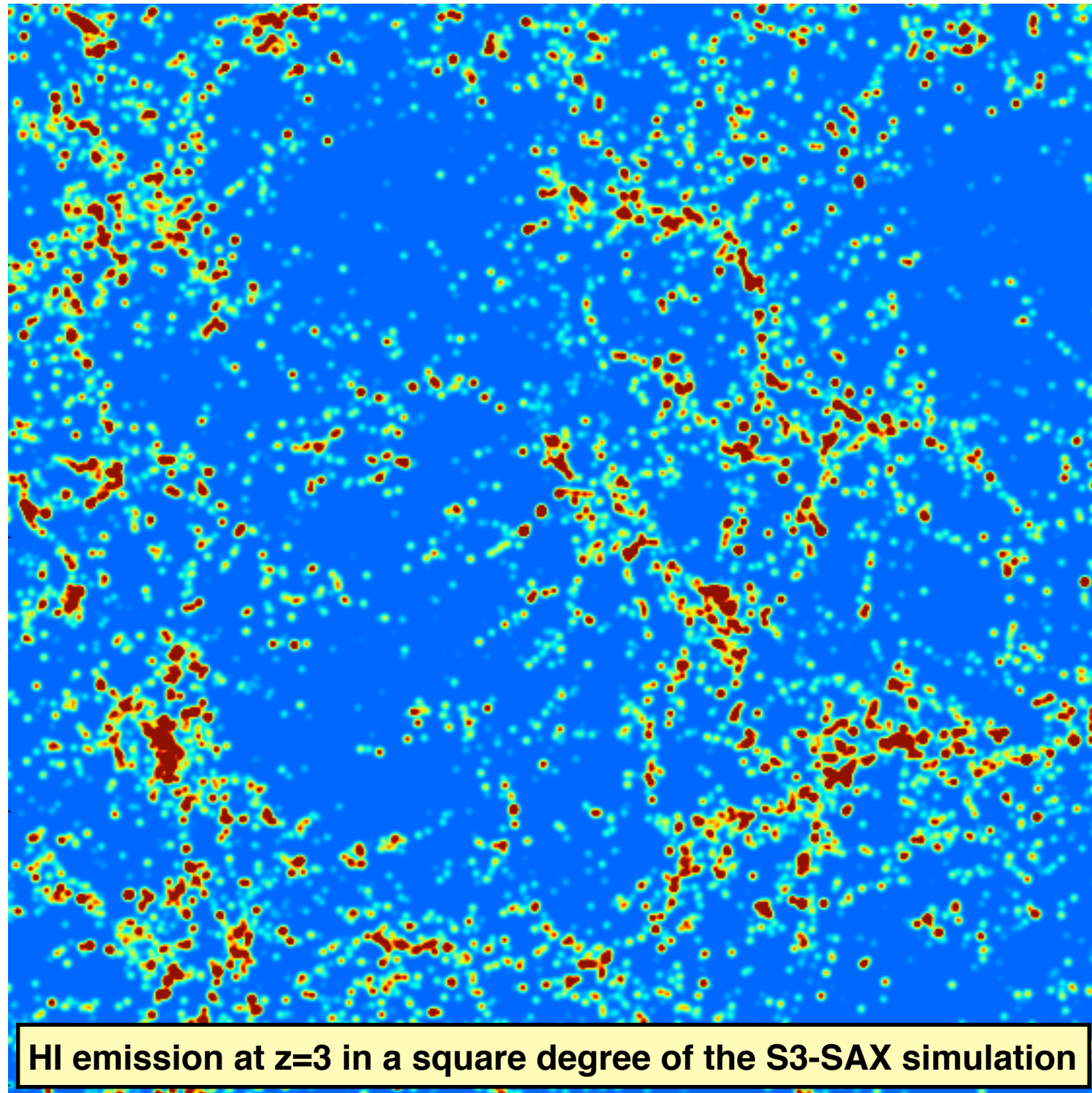


Simulated skies for SKA and its pathfinders



François Levrier
(LERMA - ENS)

Ian Heywood
Hans-Rainer Klöckner
Steve Rawlings
(Oxford)

Danail Obreschkow
(ICRAR)

Richard Wilman
(Melbourne)



Laboratoire d'Étude du Rayonnement et de la Matière en Astrophysique

Outline of the talk

SKA, MeerKAT and ASKAP

Specifications, timelines and key science

SKA Simulated Skies

The goal of end2end sims

The SAX and SEX simulations

S3Map

From simulated catalogues to simulated skies

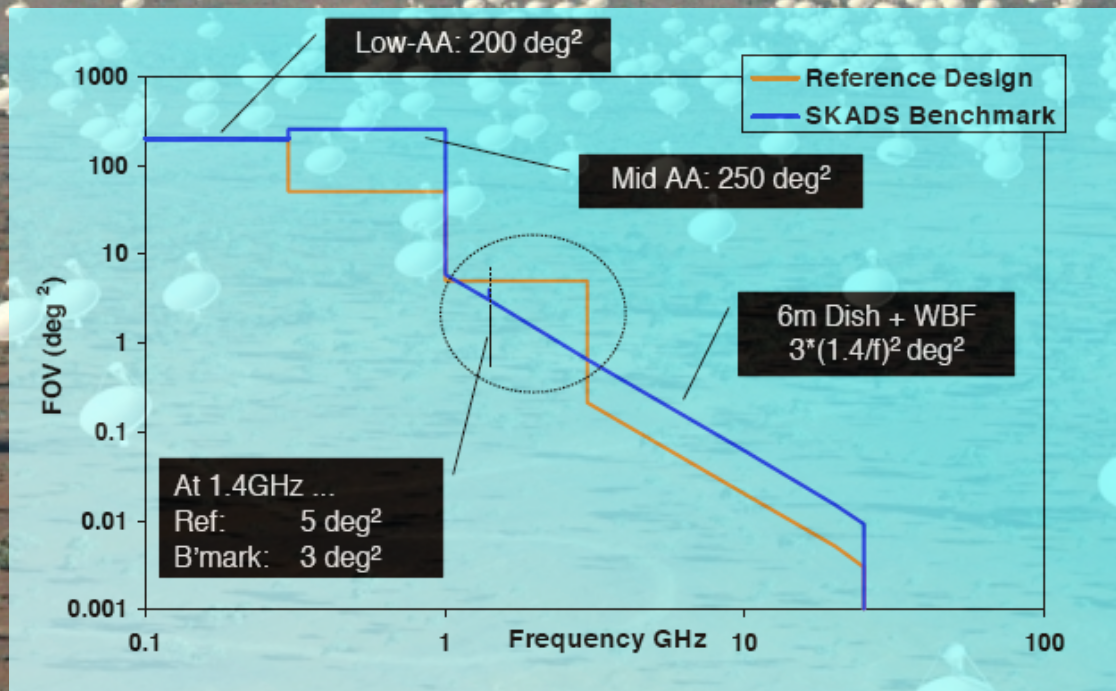
Recent developments

Simulated observations

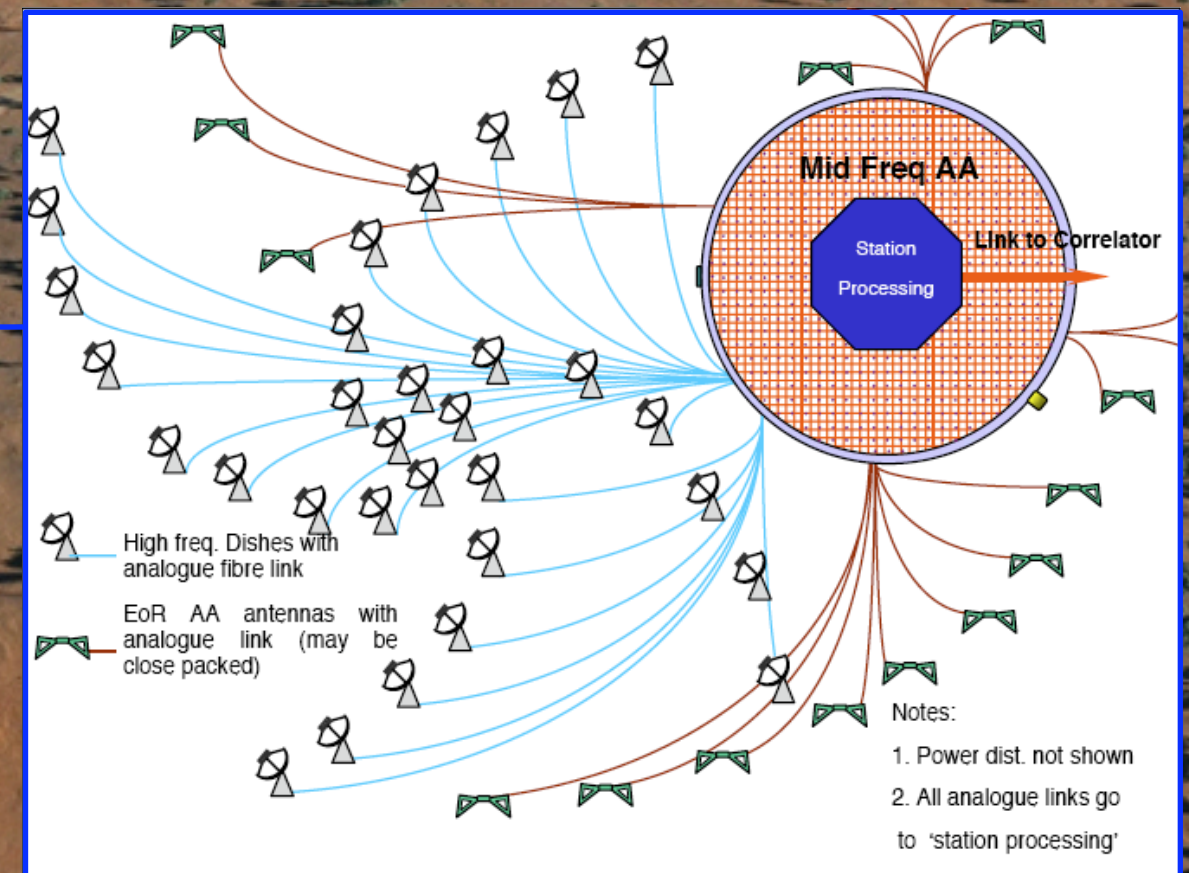
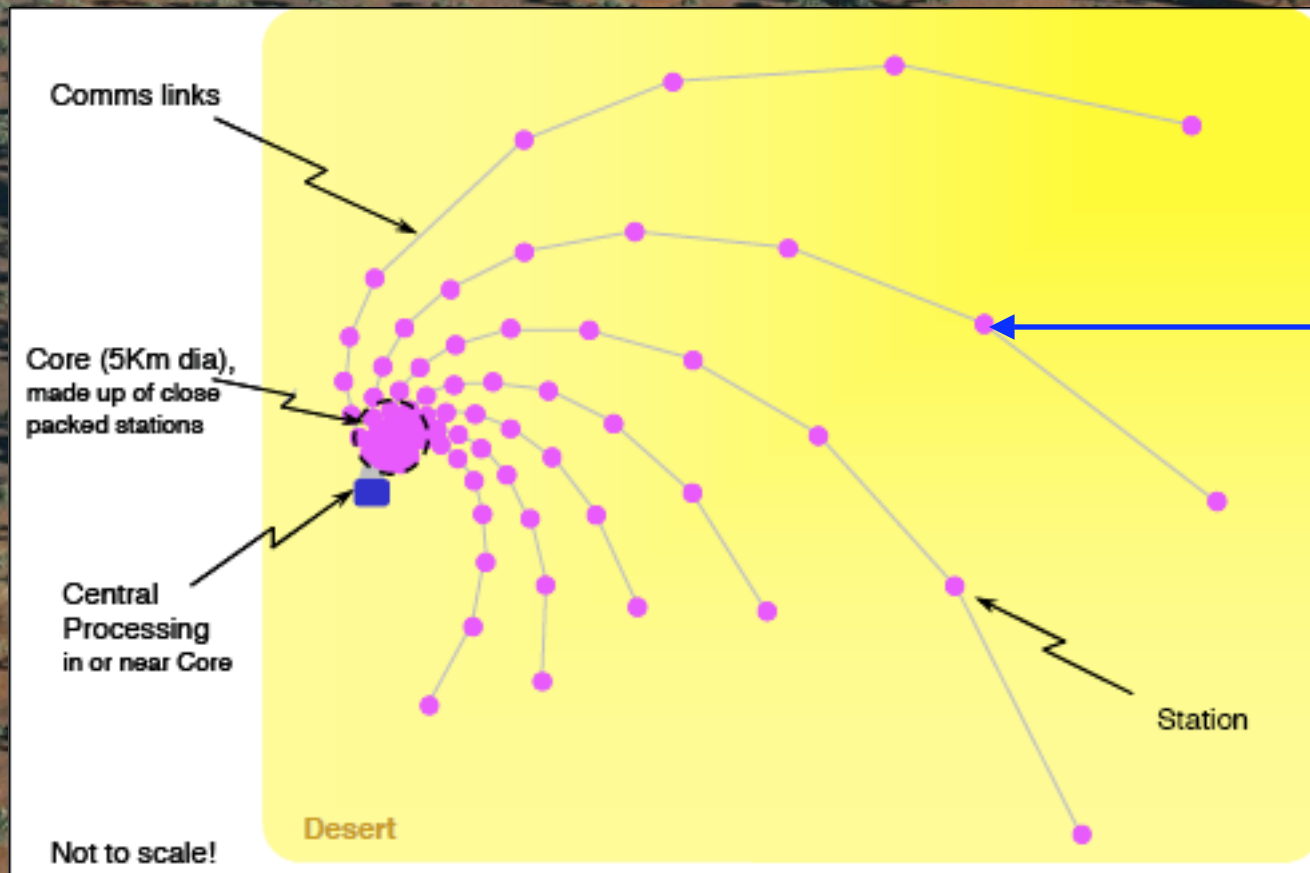
HI and CO mapping at high redshift

Perspectives

The Square Kilometer Array (SKA)

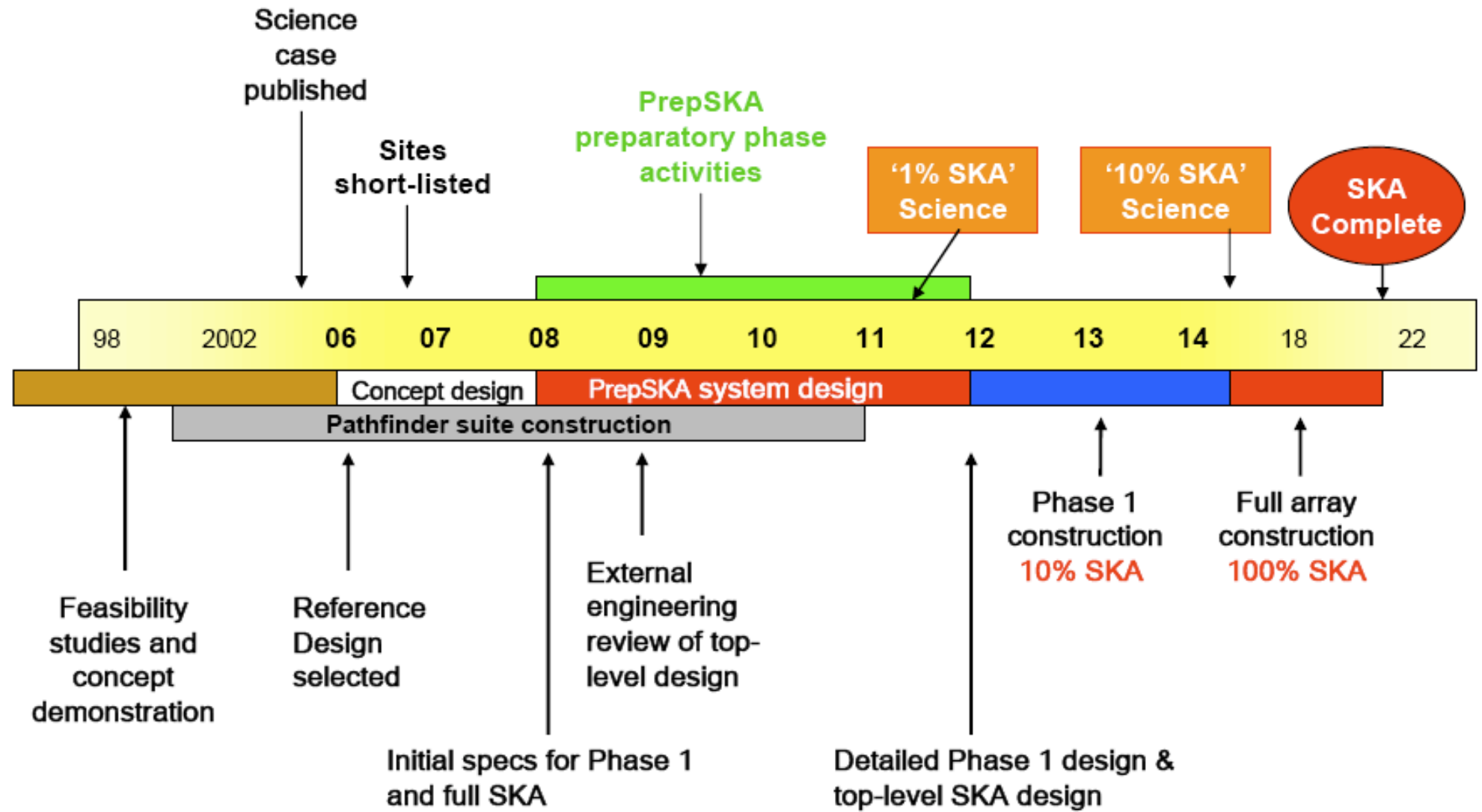


- Low-Frequency Dipole Array (0.1-0.3 GHz)
- Mid-Frequency Aperture Array (0.3-1 GHz)
- Dish Array (0.7-20 GHz)
- Baselines up to 3000 km
- Sensitivity $\sim 10,000 \text{ m}^2/\text{K}$ at 1.4 GHz



The SKA timeline

Back in 2008...



As of 2011...

2011	Established SKA organisation as a legal entity
2012	Site selection
2013-15	Detailed design and pre-construction phase
2016-19	Phase 1 construction
2018-23	Phase 2 construction
2020	Full science operations with Phase 1
2024	Full science operations with Phase 2

23/11/2011

- Australia
- China
- Italy
- Netherlands
- New Zealand
- South Africa
- UK



The SKA Key Science Projects

CRADLE OF LIFE

- Thermal imaging of protoplanetary disks (0.15 AU at 150 pc @ 20 GHz)
- Leakage radiation from ETI

TESTS OF GENERAL RELATIVITY IN STRONG FIELDS

- ~20,000 detectable pulsars : probable pulsar+BH binary
- Timing of millisecond pulsars : GW background

COSMIC MAGNETISM

- 100,000,000 Rotation Measures from extragalactic sources (spacing 60")
- Spectropolarimetric observations of galaxies up to $z > 3$

GALAXY EVOLUTION AND COSMOLOGY

- Detection of HI emission at high redshift ($z \sim 2$)
- Star-formation through continuum emission

EPOCH OF REIONIZATION

- Intergalactic medium HI at high redshift
- Star-formation through studies of molecular gas and dust

MeerKAT

www.ska.ac.za

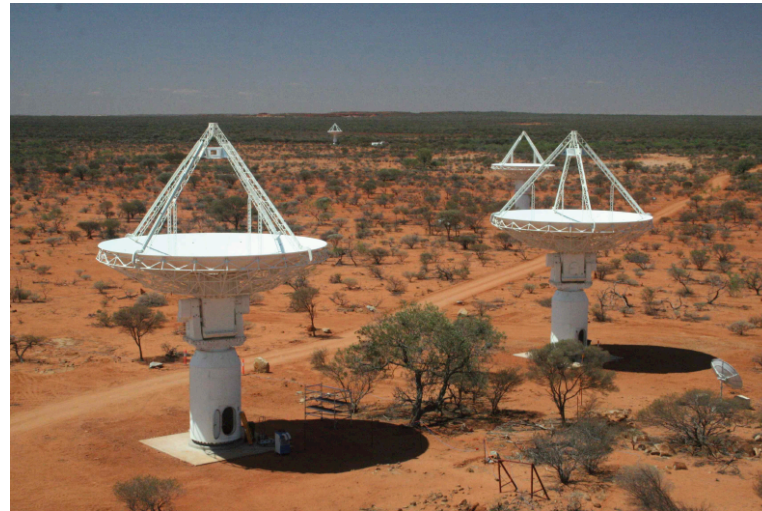


	2011	2016	2018
	Precursor (KAT-7)	MeerKAT Phase 1	MeerKAT Phase 2 & 3
Number of dishes	7	64	64
Receiver bands (GHz)	0.9 - 1.6	1.00 - 1.75	0.58 - 1.015 1.00 - 1.75 8 - 14.5
Max processed BW (GHz)	0.256	0.75	2 (goal 4)
Max baseline (km)	0.2	8	20
Min baseline (m)	20	29	29

Dish diameter : 13.5 m
Sensitivity : 220 m²/K @ 1.4 GHz



MeerKAT science projects	Research leaders
LADUMA (Looking at the Distant Universe with the MeerKAT Array) - An ultra-deep survey of neutral hydrogen gas in the early universe.	Dr Sarah Blyth, University of Cape Town in South Africa; Dr Benne Holwerda, European Space Agency, The Netherlands; Dr Andrew Baker, Rutgers University, United States
MESMER (MeerKAT Search for Molecules in the Epoch of Re-ionisation) - Searching for CO at high red-shift ($z > 7$) to investigate the role of molecular hydrogen in the early universe.	Dr Ian Heywood, Oxford University, UK



2011 : BETA (Boolardy Engineering Test Array)- 6 antennas
2013 : Full 36 antenna array

Number of dishes : 36
Dish diameter : 12 m
Max baseline : 6 km
Sensitivity : 65 m²/K
Observing frequency : 700 – 1800 MHz
Field of View 30 deg²

10 key science projects including :

Evolutionary Map of the Universe (EMU)

Principal Investigator: Ray Norris (CSIRO)

“EMU is a deep (10 μ Jy/beam rms) radio continuum survey of 75% of the entire sky. EMU will probe typical star forming galaxies to redshift 1, powerful starbursts to even greater redshifts, Active Galactic Nuclei to the edge of the Universe, as well as undoubtedly discovering new classes of rare objects. The key science goals for EMU are to trace the evolution of star forming galaxies and massive black holes throughout the history of the Universe and to explore large-scale structure. EMU will create the most sensitive wide-field atlas yet made, and provide a long-lasting legacy survey.”

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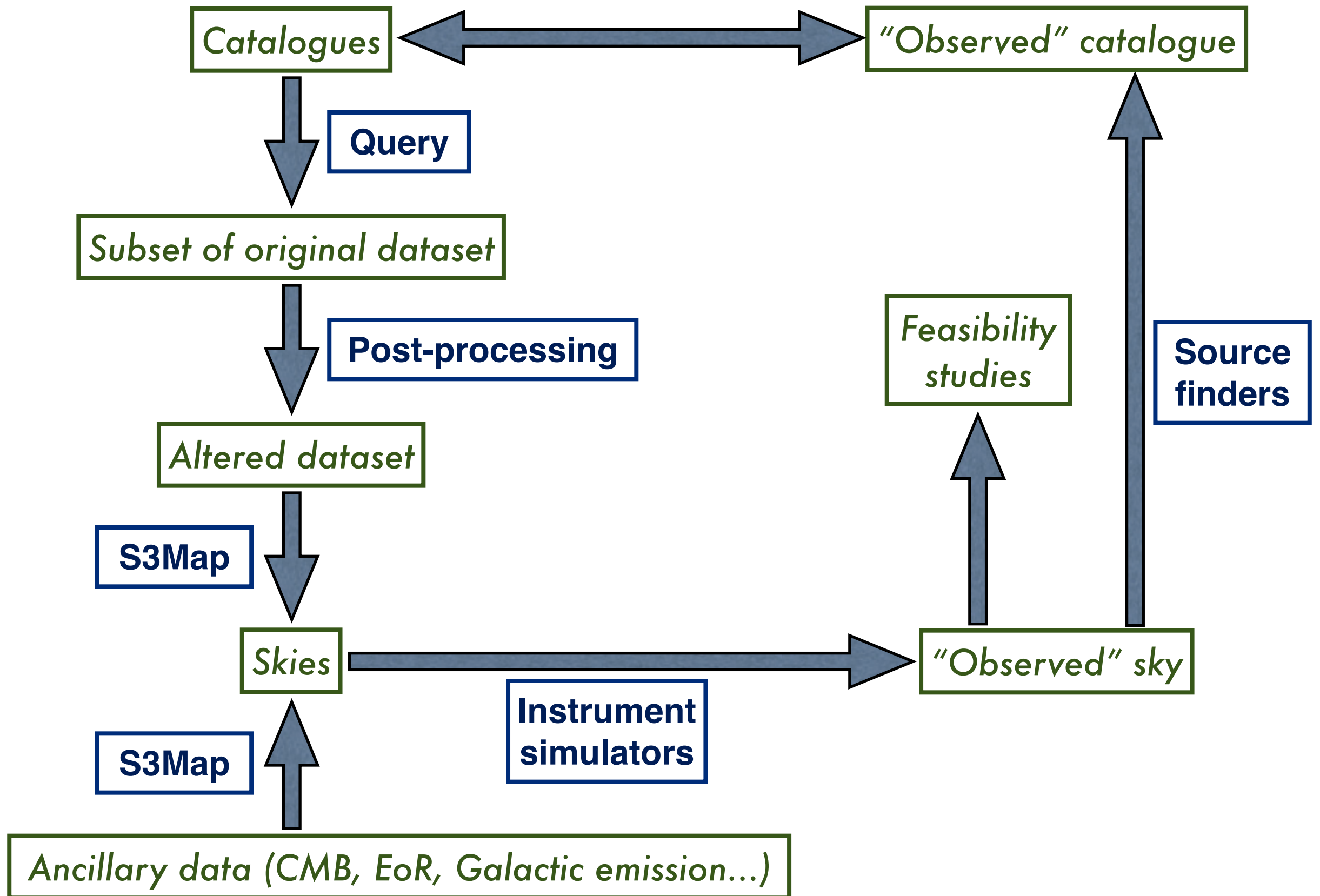
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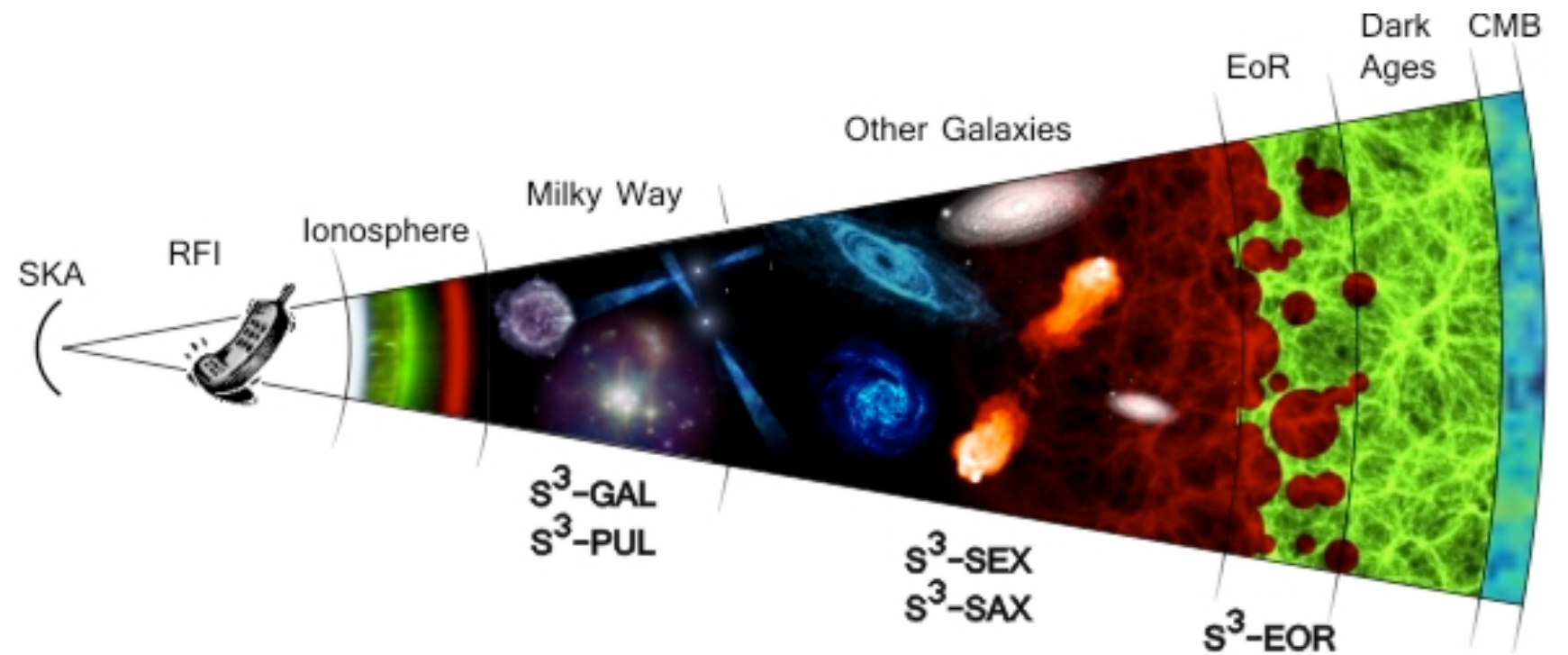
Perspectives

Simulations for SKA and pathfinders



The SKA Simulated Skies (S³)

s-cubed.physics.ox.ac.uk



Semi-Empirical eXtragalactic

Large-scale radio-continuum simulation (150 MHz - 18 GHz)
Wilman et al., 2008

Semi-Analytical eXtragalactic

Small-scale HI and CO lines simulation
Obreschkow et al., 2009

GALactic emission

Galactic radio and submm foregrounds (10 MHz - 100 GHz)
de Oliveira-Costa et al., 2008

PULsar emission

Pulsar emission profiles
Karastergiou & Johnston, 2007

Epoch Of Reionisation

HI line emission and absorption from the IGM in the EoR
Santos (IST Lisbon) - Semelin (LERMA, Paris)

The SKA Simulated Skies (S³)

Semi-Empirical eXtragalactic

'Continuum simulation'

Wilman et al., 2008, MNRAS, 388, 1335

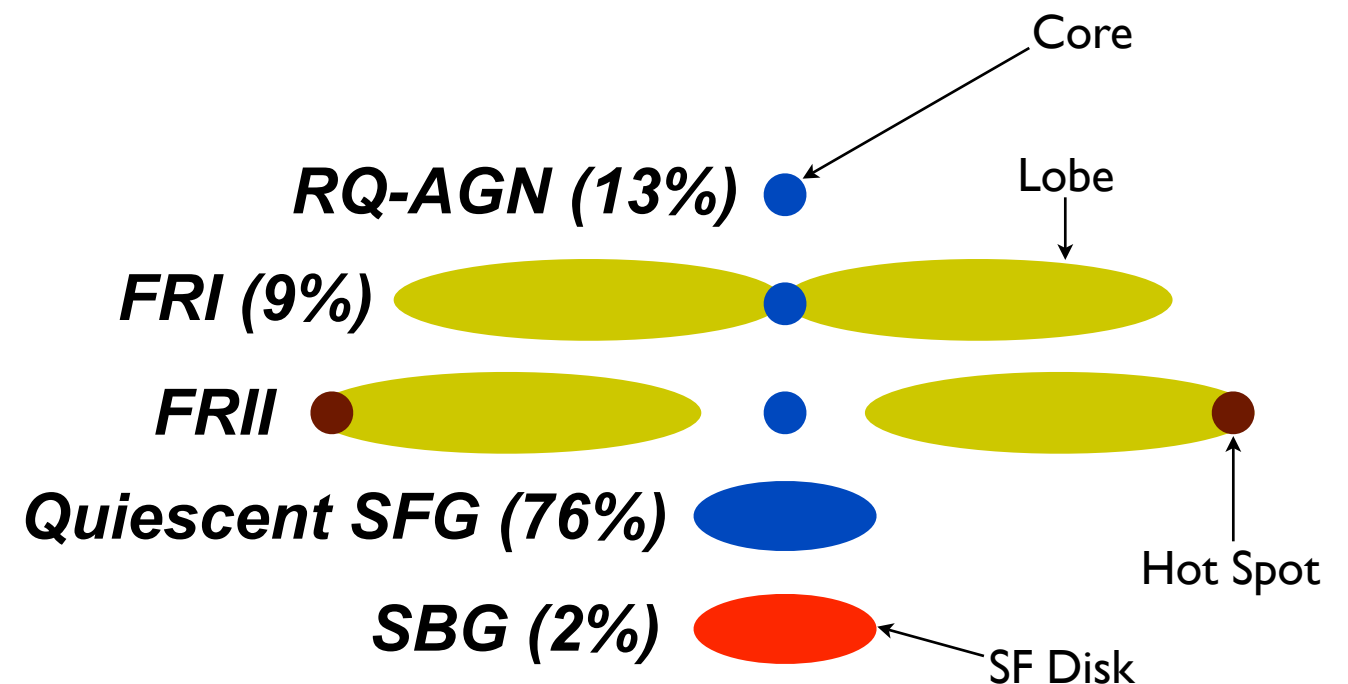
- Underlying dark-matter distribution evolved from linear theory
- Populations of AGN and galaxies drawn randomly from observed/extrapolated luminosity functions down to 10 nJy
- Clusters identified through Press-Schechter filter
- HI mass ascribed via $L_{1.4\text{GHz}}$
- 400 square degrees
- Maximum redshift $z=20$
- 5 different source types : Radio-quiet AGN, Radio-loud FRI, Radio-loud FR II, Quiescent SF galaxies, Starburst galaxies
- Sources described as points and ellipses

$$A = 20^\circ \times 20^\circ$$

$$0 \leq z \leq 20$$

$$S \geq 10 \text{ nJy}$$

$$N_{\text{sources}} \sim 275,000,000$$



2010 update

Infrared flux densities at 24, 70, 100, 160, 250, 350, 450, 500, 850 and 1200 microns

(Wilman et al., 2010)

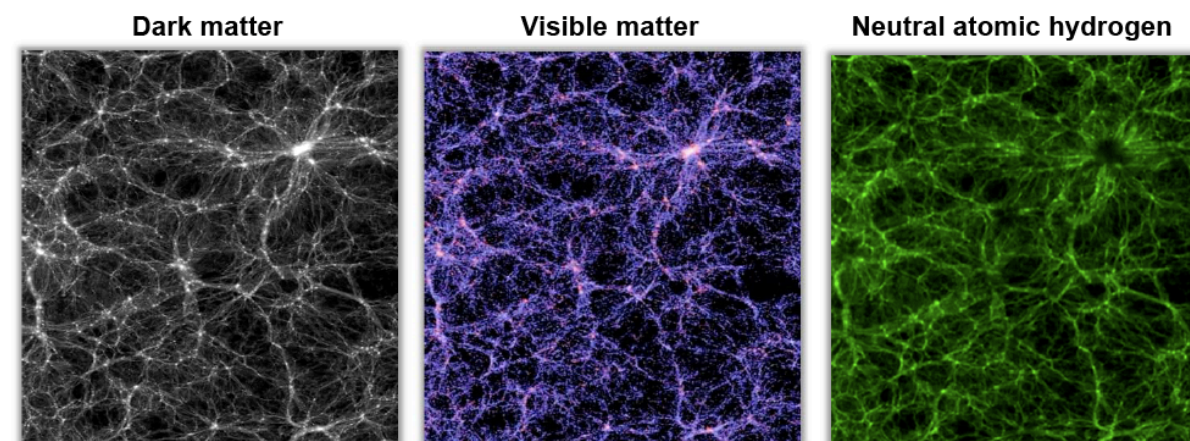
The SKA Simulated Skies (S^3)

Semi-Analytical eXtragalactic

Obreschkow et al., 2009, *ApJ*, 703, 1890

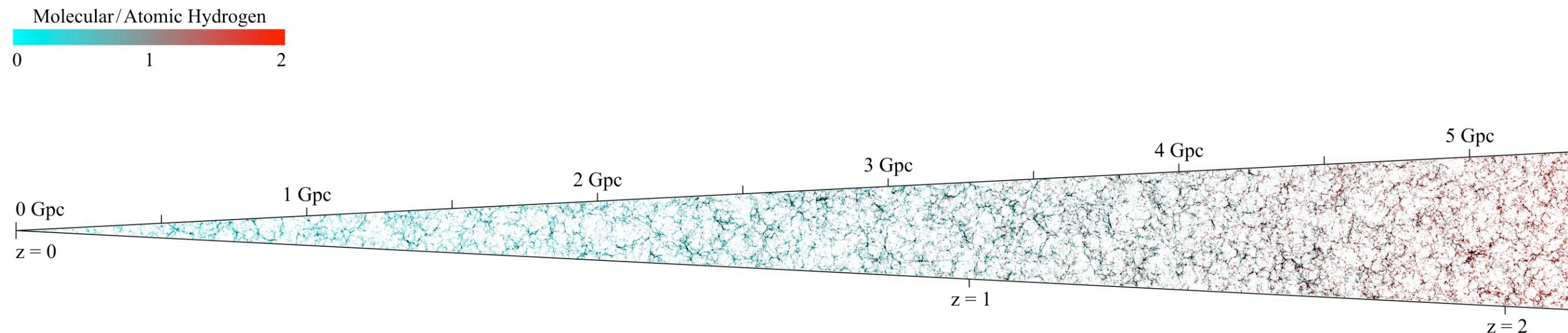
‘Line simulation’

- Dark-matter haloes of galaxies identified in the Millenium simulation
- Gas properties, star-formation and BH accretion rates ascribed
- HI line and 10 rotational lines of CO
- Atomic and molecular contents of galaxies
- 27 square degrees for a maximum redshift $z=4$
- $2.8 \cdot 10^8$ galaxies



SKA Design Studies – Virtual Hydrogen Cone

University of Oxford, D. Obreschkow et al., April 2009



Based on the Millennium simulation (Springel et al. 2005) and a semi-analytic galaxy simulation (Croton et al. 2006, De Lucia et al. 2007)

Accessing the SKA Simulated Skies



- Hosted by OeRC
- MySQL databases

Excerpt from a table structure within S³-SAX

Column	Property	Type	Description	Unit
1	id	BIGINT	Unique galaxy identifier in the mock sky	-
2	galaxyid	BIGINT	Galaxy identifier in the "DeLucia2006a" catalog of the Millennium Database	-
3	box	INT	Box index in the mock observing cone	-
4	ra	FLOAT	Right ascension	deg
5	decl	FLOAT	Declination	deg
6	distance	FLOAT	Comoving distance to the object	Mpc

Sample queries

Limited select

- Get the position, apparent redshift, and integrated HI-flux of the 10 closest galaxies in the cone

HI-fluxes of a galaxy cluster

- This query finds all the galaxies in the most massive cluster in the mock observing cone between $z=1.2$ and $z=1.5$. For each galaxy the output table gives the position, the apparent redshift, the integrated HI-flux (Jy km/s), the HI-peak flux density (Jy), the 50% HI-line width (km/s), the HI-half mass radius (arcsec), the inclination (rad), and the extinction corrected absolute blue magnitude. Only galaxies with stellar masses above 10^9 solar masses are retained.

Custom queries

```
select ra, decl, zapparent, hiintflux
from milli_galaxies_line
order by distance
limit 0,10;
```

Email address for notification

Query result file

```
ra,decl,zapparent,hiintflux
0.145985,0.478183,0.953906,0.0013
-0.102203,0.118672,0.956824,0.0101
0.452566,-0.312153,0.952434,0.0039
-0.119211,-0.319197,0.958274,0.000947
```

S³ on Astrogrid

Eduardo Gonzalez-Solares, Nick Walton [IoA], Anita Richards [Manchester]

The screenshot shows the VO Explorer - SKA interface. The main window displays search results for 'SKADS Simulated Sky'. The left sidebar contains a tree view with 'Resource Lists' and 'Examples' (MERLIN, gemini, SKA, Matching, New Smartlist). The main area shows a table of results with columns for 'Content - Subject', 'Coverage - Waveband', and 'Resource Type'. The selected resource is 'SKADS Simulated Sky'. Below the table, there is an 'Information' tab showing details for 'SKADS Simulated Sky', including its ID, type, creation date, and content type. The 'About' section provides a description of the SKADS Simulated Skies (S3) project.

VO harvests data providers' standard descriptions

- Publishing registries at Cambridge, CDS, HEASARC, ...
- VOExplorer searches Registry of resources
- Look for content description containing 'SKA' and 'simulated'

Choose SKADS Simulated Sky

- Catalogues stored on MySQL at Cambridge
- Browse / sort details of columns etc...
- User types in SQL-like ADQL or uses tree GUI

Query sent to database

- Results returned as standard xml-like VOTable
- Examine, process, convert to ascii e.g. in TopCat

Current status

- S³-SEX out-of-date
- S³-SAX not registered

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From simulated catalogues to simulated skies

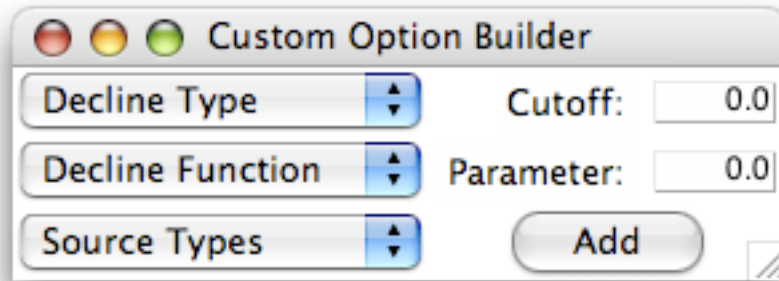
Recent developments

Simulated observations

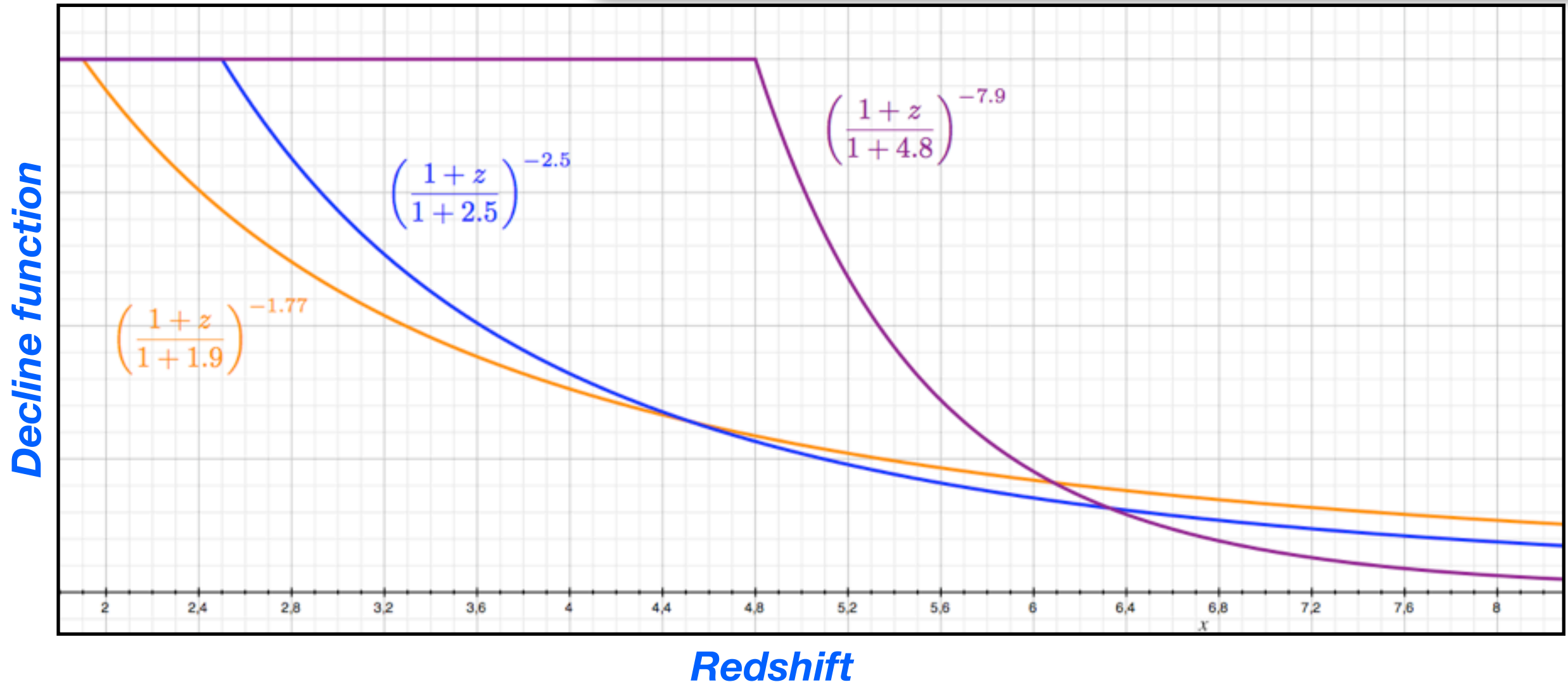
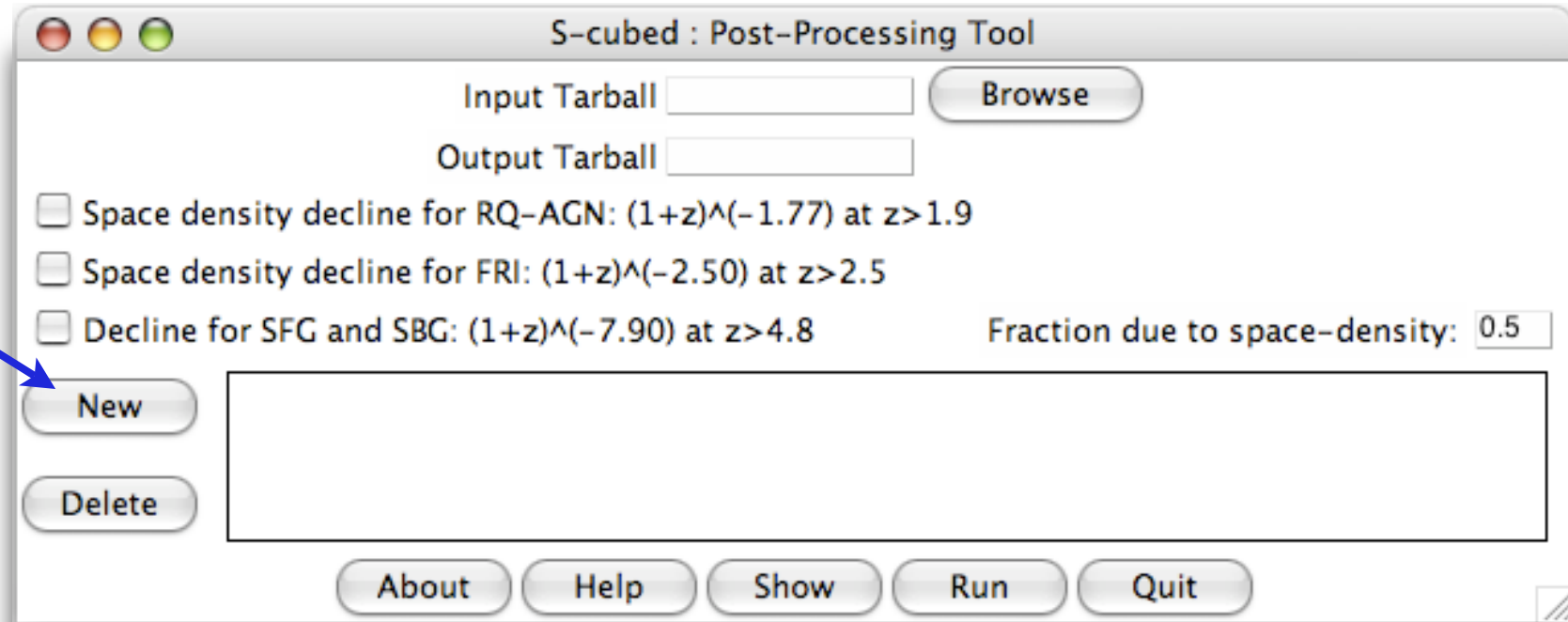
HI and CO mapping at high redshift

Perspectives

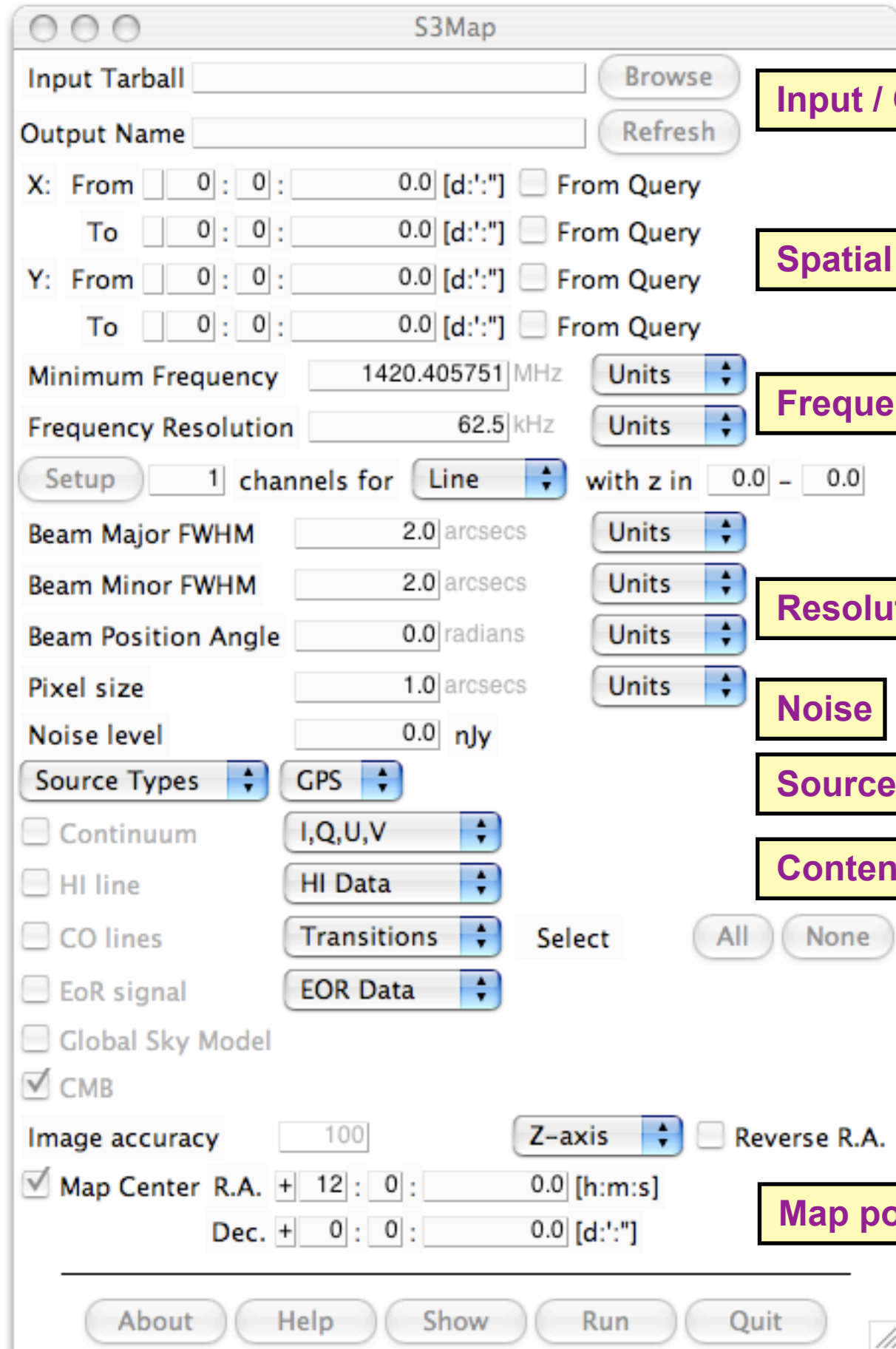
Post-processing query results



- Applies to S³-SEX
- Space density and luminosity declines
- Source type specific
- Power-law and exponential forms
- Default and custom options



Making maps and cubes : S3Map



- Standalone application in Python and C
- GUI layer to python scripts and lower-level routines
- Reads in query results (with or without postprocessing)
- Outputs FITS images and spectral data cubes

Input / Output

Spatial region

Frequency range

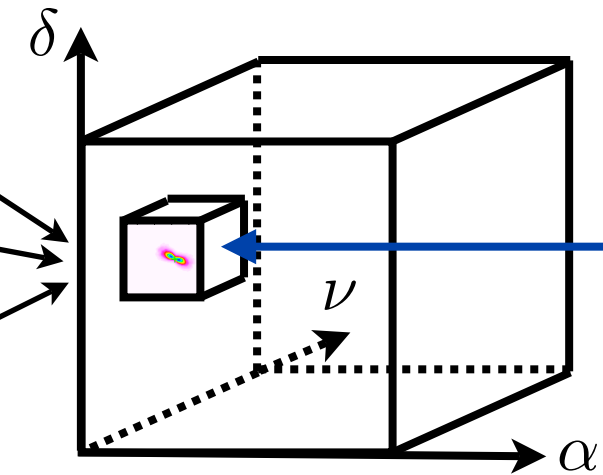
Resolution

Noise

Source types

Contents

Map position

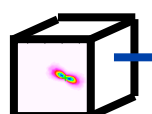
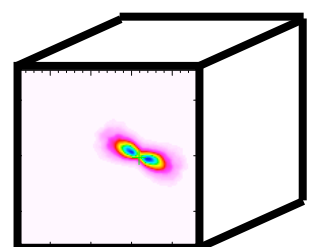


Source data

ra,decl,zapparent,hiintflux,...
0.145985,0.478183,0.953906,0.0013,...

Template from library

Geometrical transforms



Example templates : HI emission

1150 template HI cubes from Rense Boomsma (Kapteyn Institute)

- Galaxy models made of “clouds” placed according to density profile and orbiting according to velocity curve
- 5 galaxy types (spirals and irregulars)
- 46 inclination values (0-90 degrees)
- 5 asymptotic velocities

From template cubes to SAX cubes

SAX information

Action

- Numerical Hubble type
- Inclination angle
- HI line width

Pick template

- HI line width
- Angular size
- HI flux

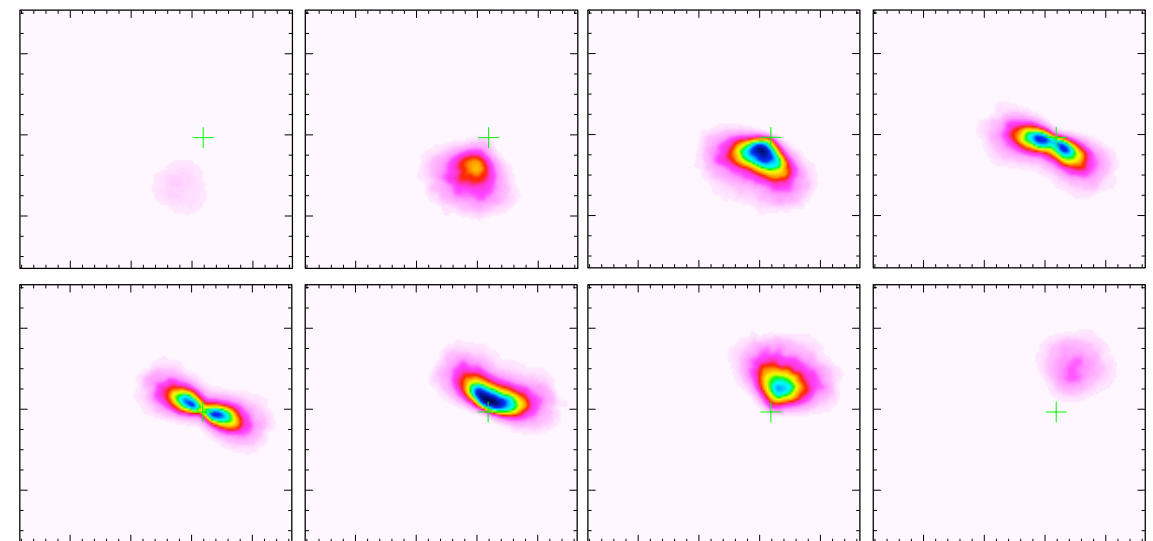
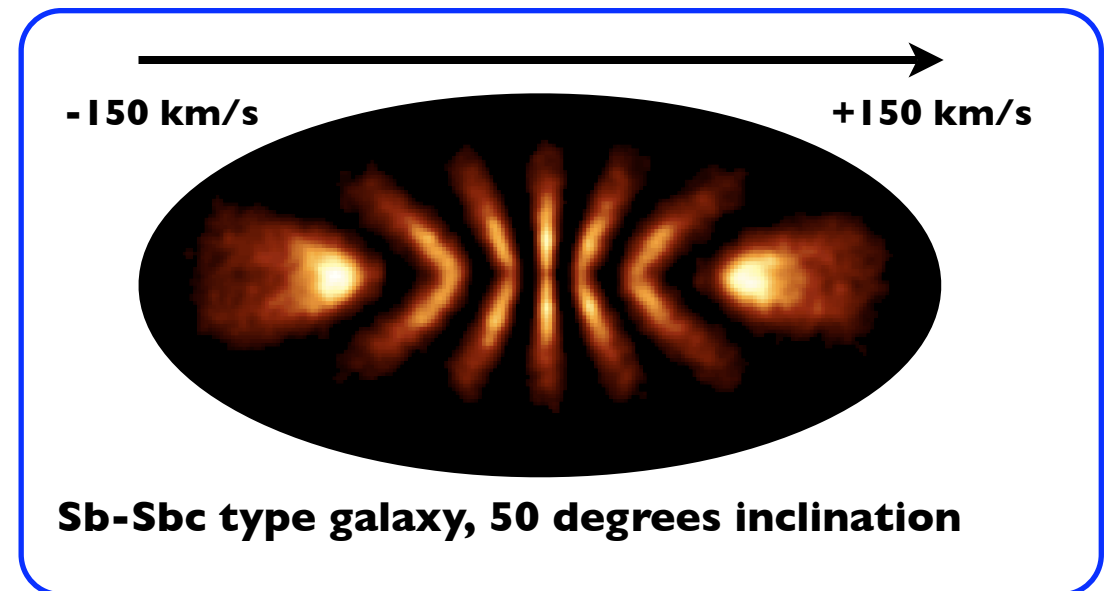
Get scaling factors

- Position angle

Rotate

- Sky position
- Redshift

Paste on master cube

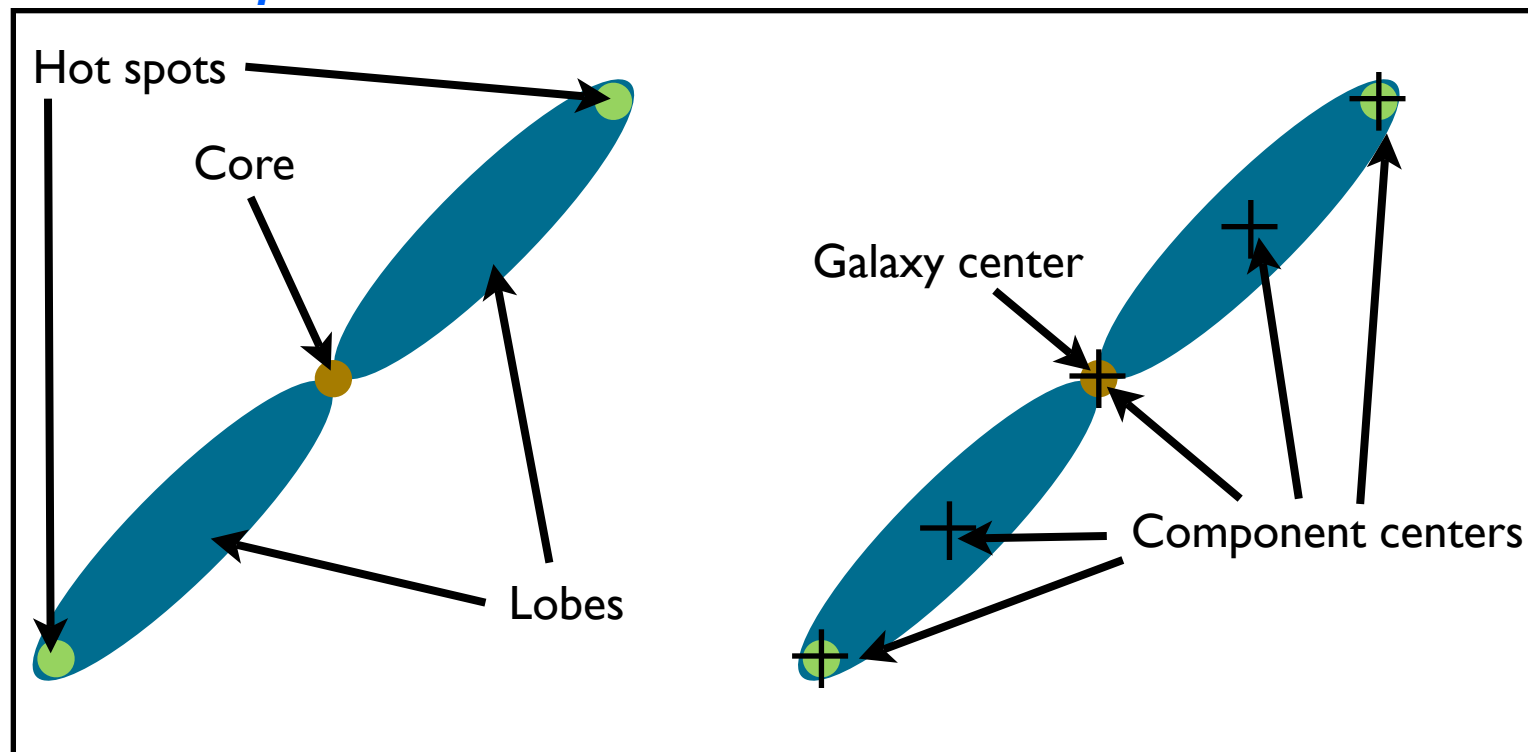


Channel maps from sample SAX cube
[1.2419 to 1.24225 GHz]

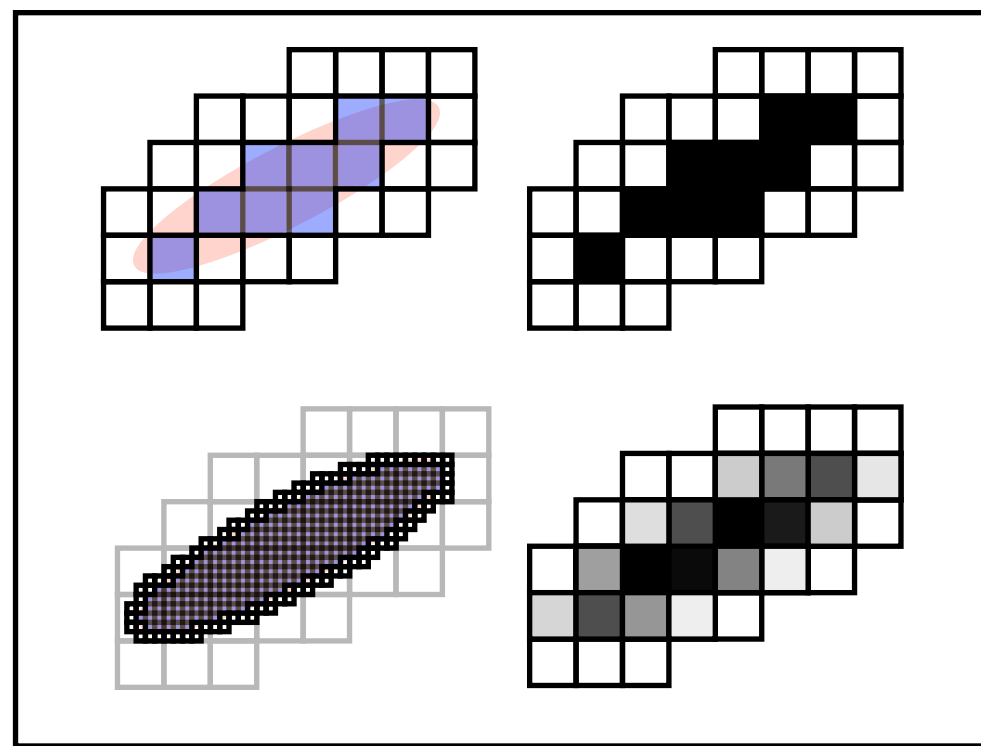
ALSO : 4140 template HI cubes and 4140 template CO cubes from Danail Obreschkow (Oxford)

S³-SEX sources

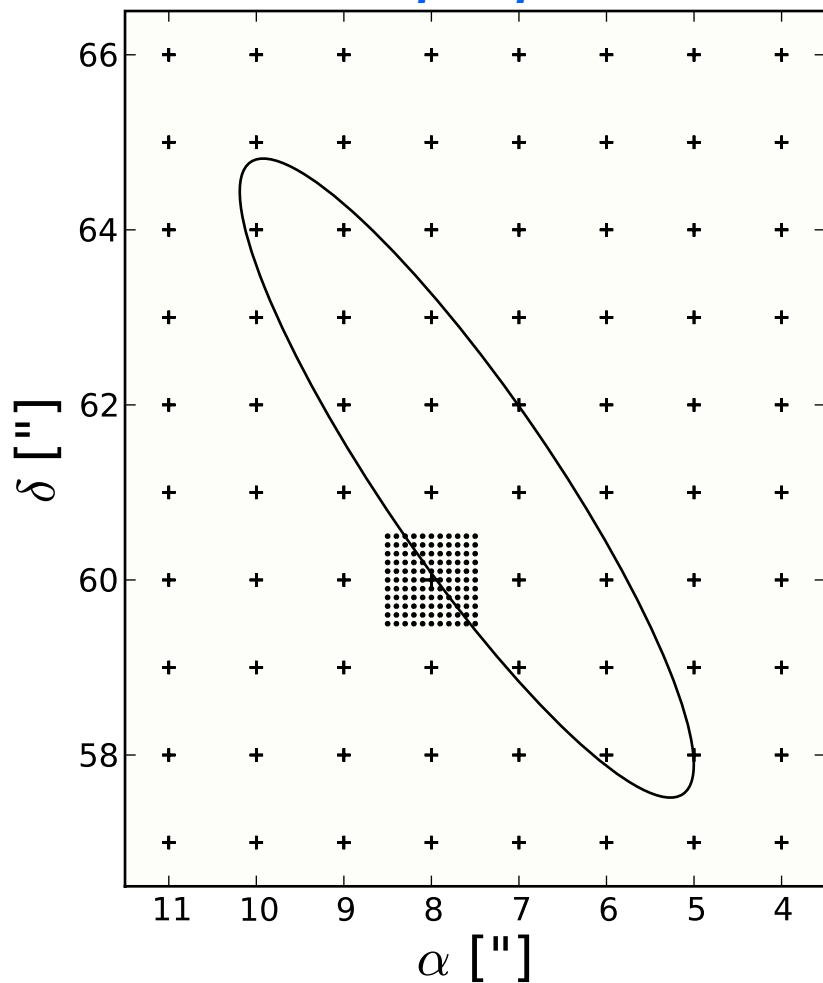
Multi-component sources



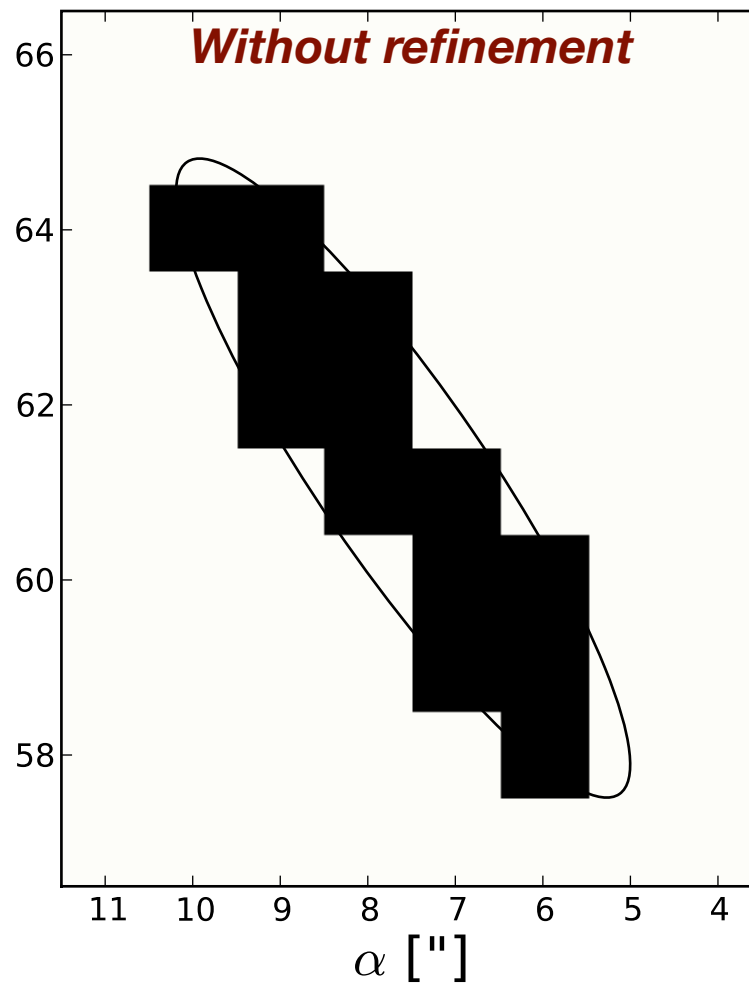
Grid refinement for few-pixel sources



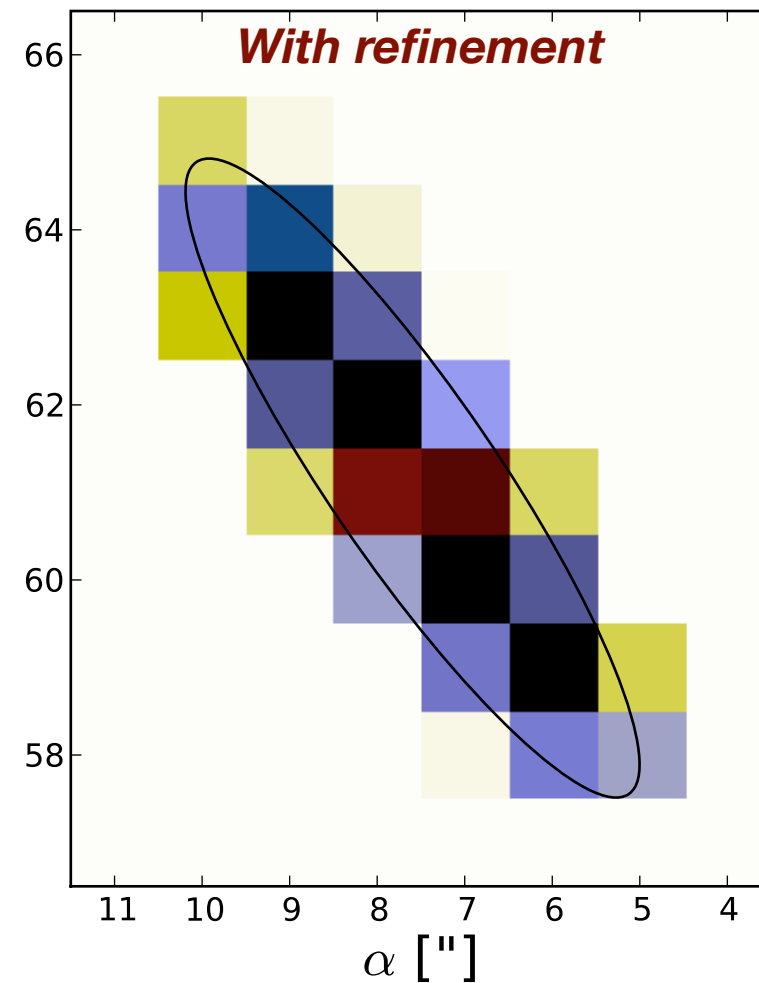
Actual S3Map implementation



Without refinement

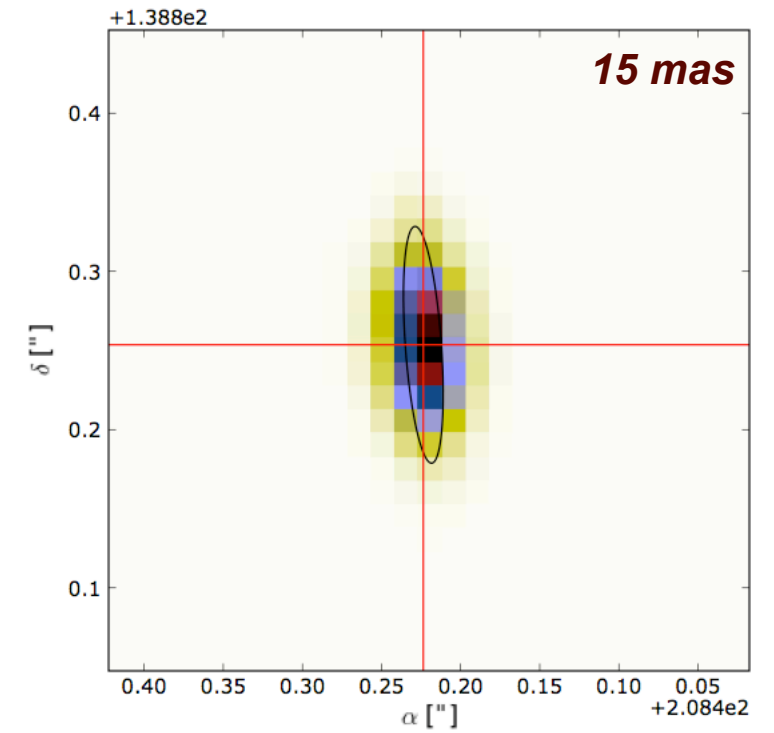
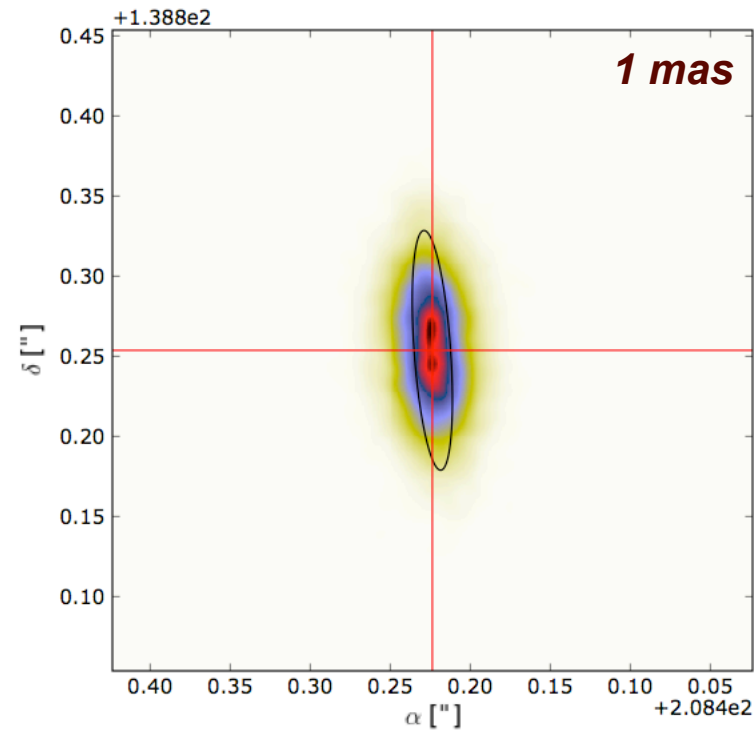
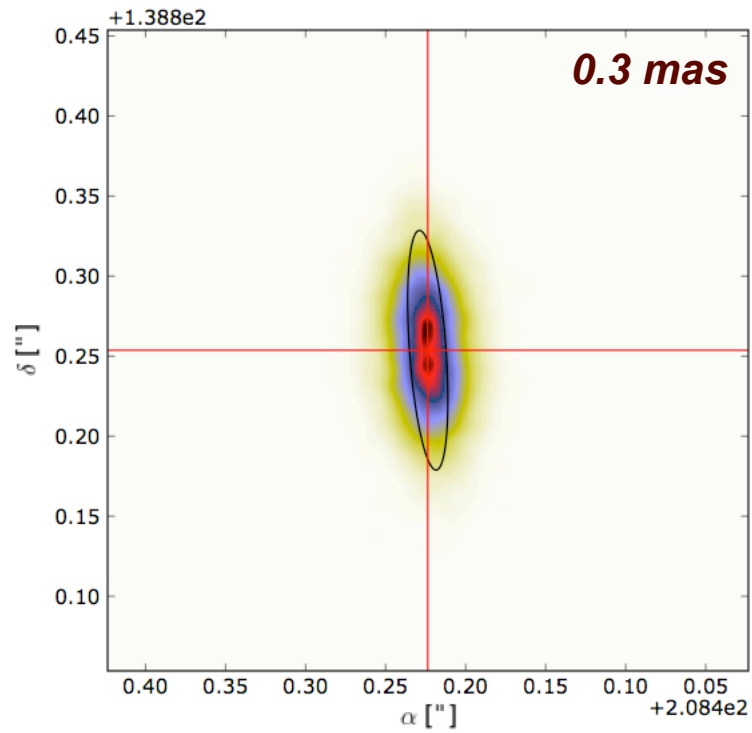


With refinement

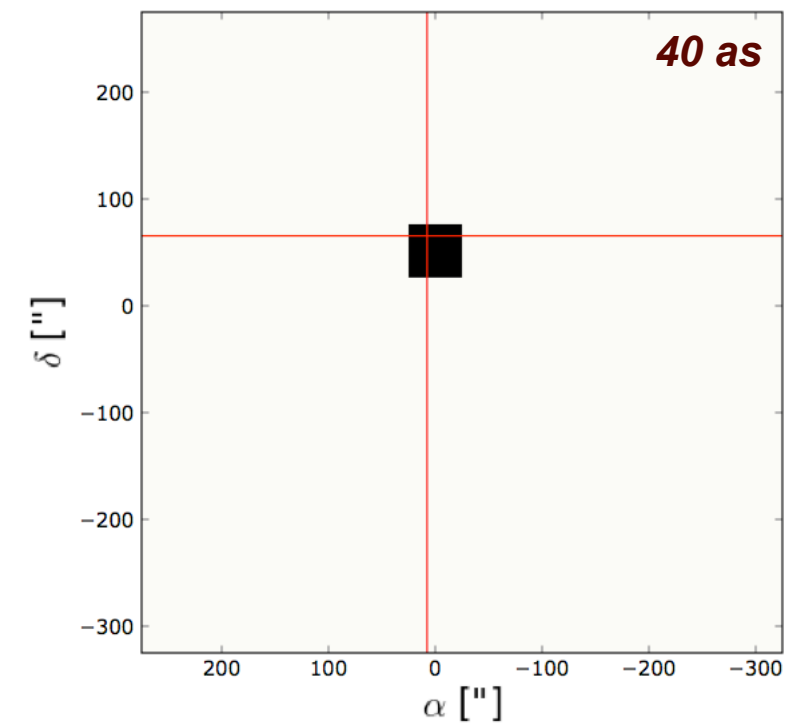
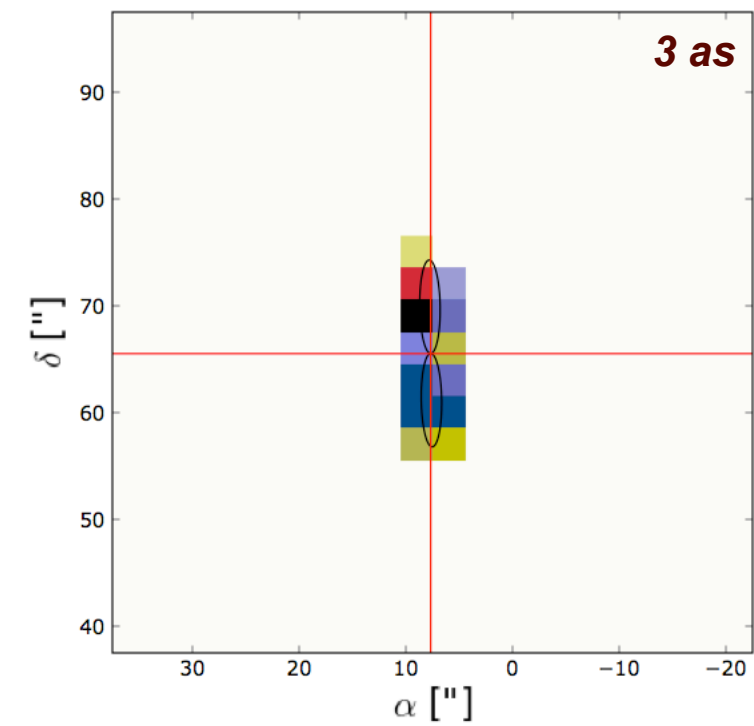
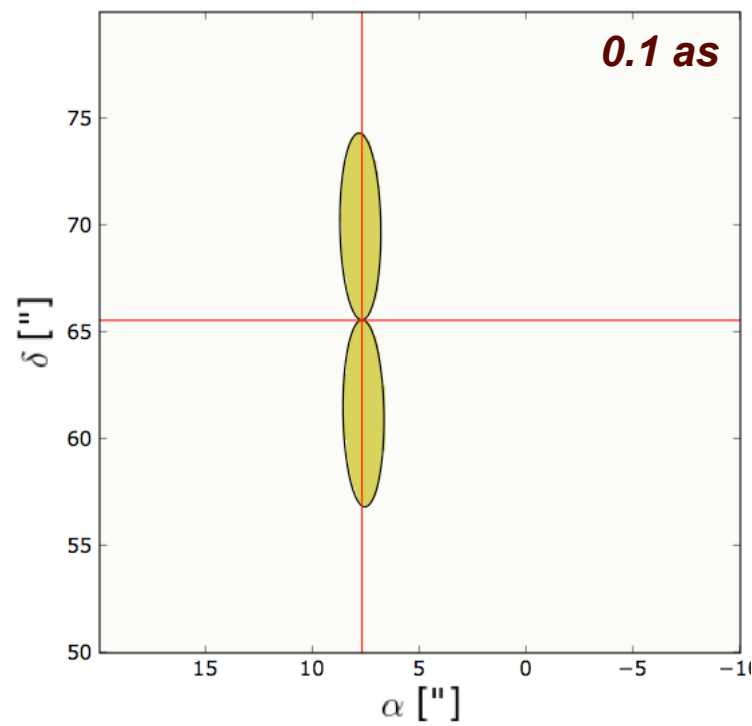


Spatial resolution

HI integrated emission (Kapteyn templates)

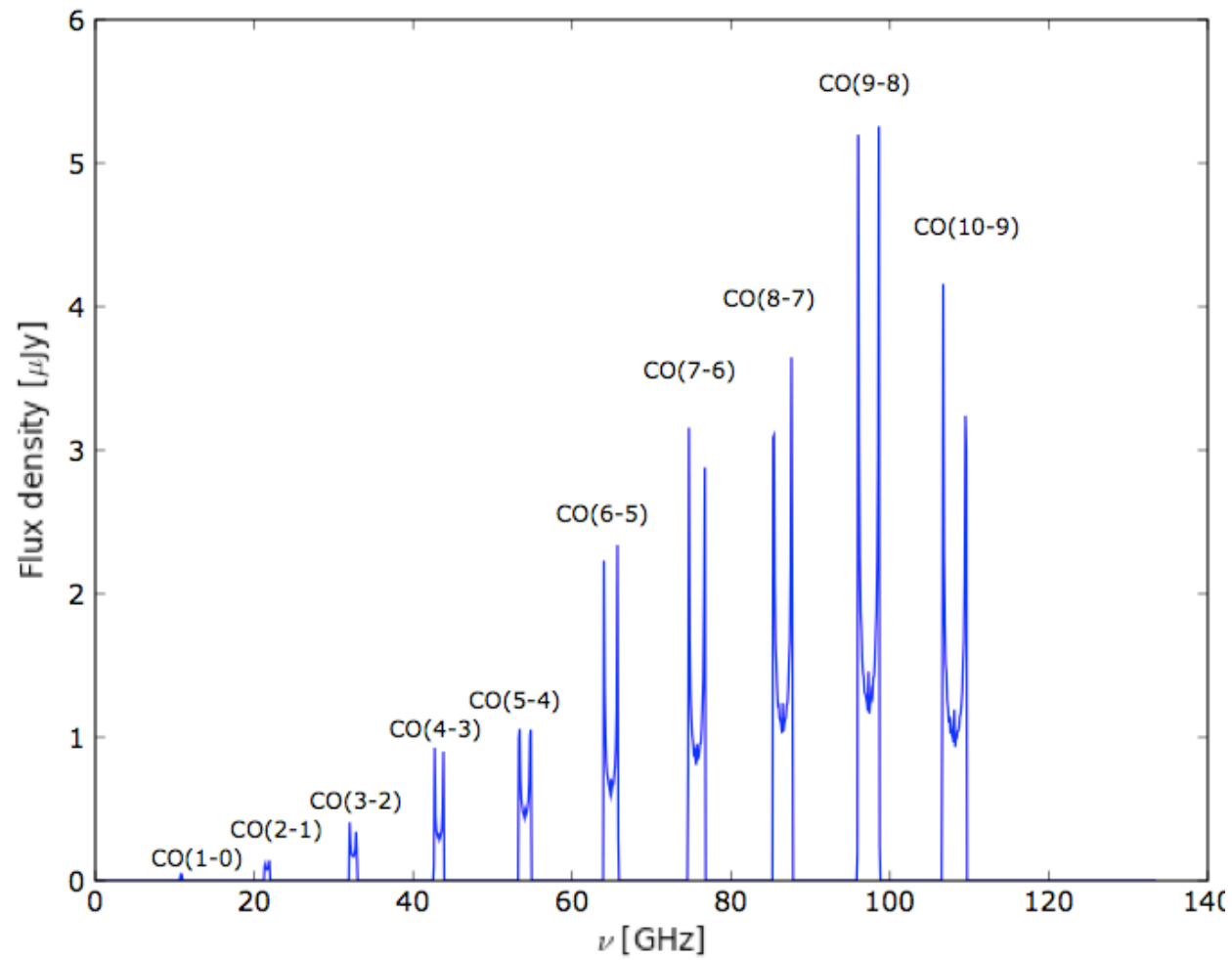


S³-SEX FRI radio-loud source

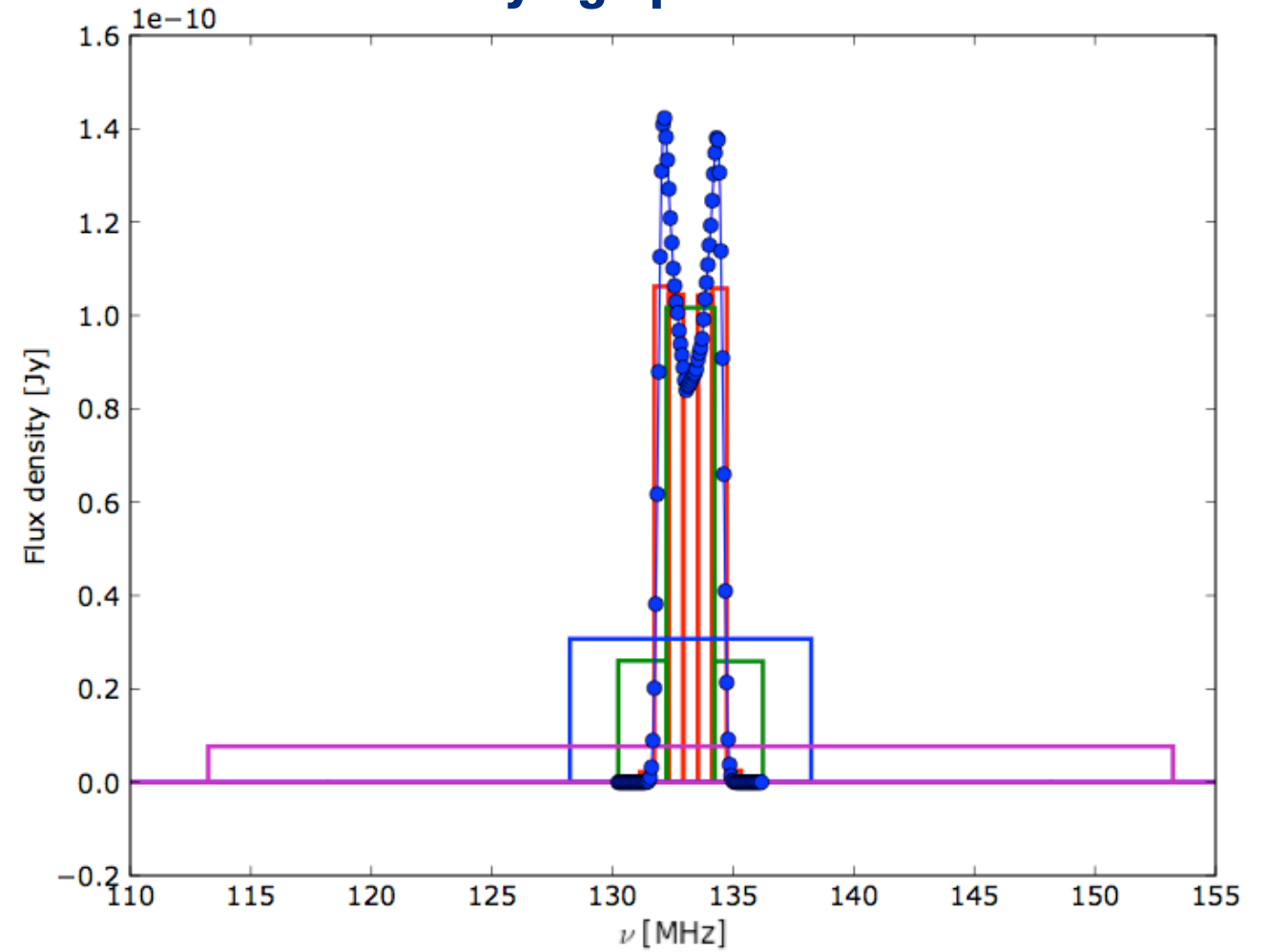


S³-SAX HI and CO line spectra

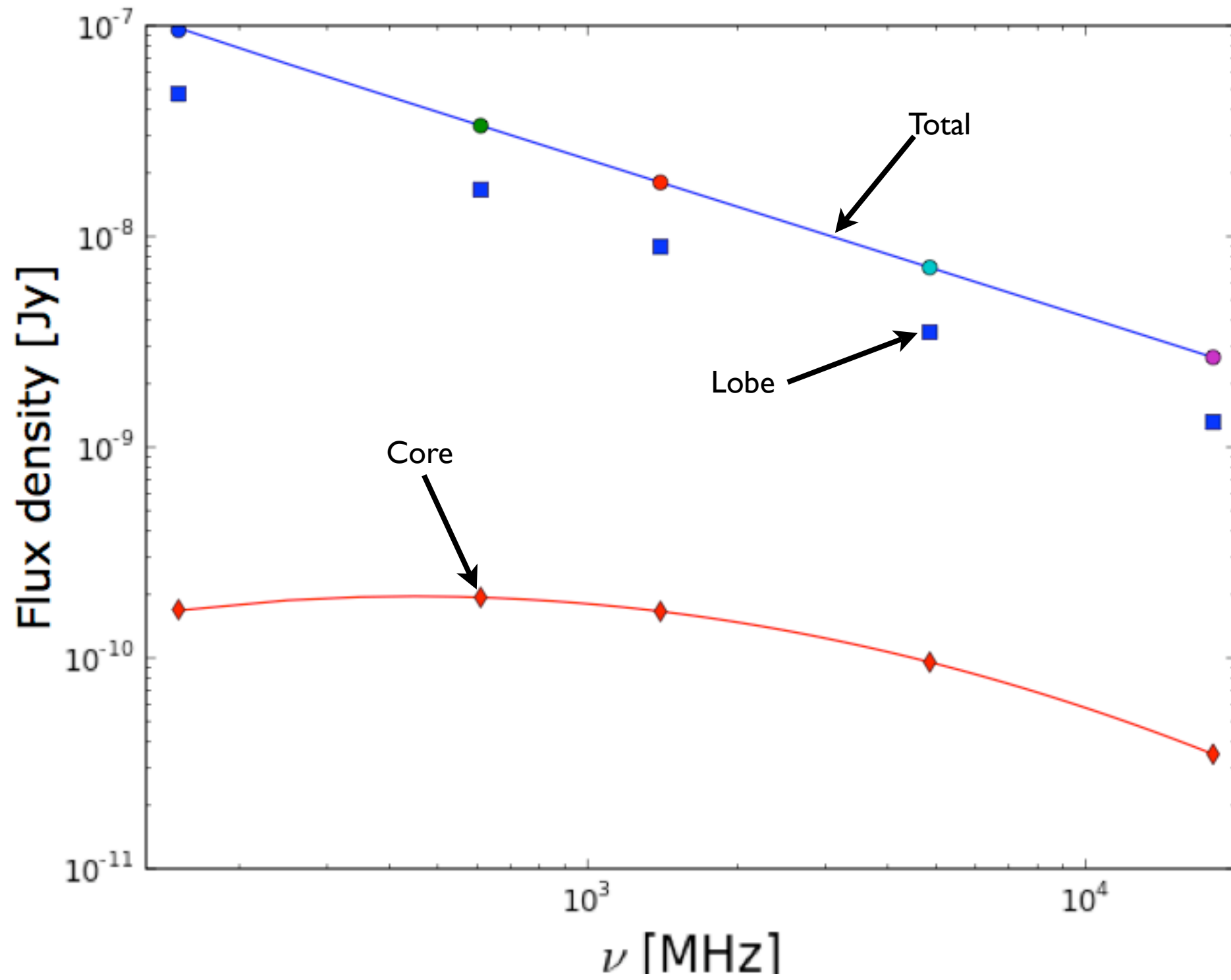
HI and CO lines from a single S³-SAX source



HI line with varying spectral resolution

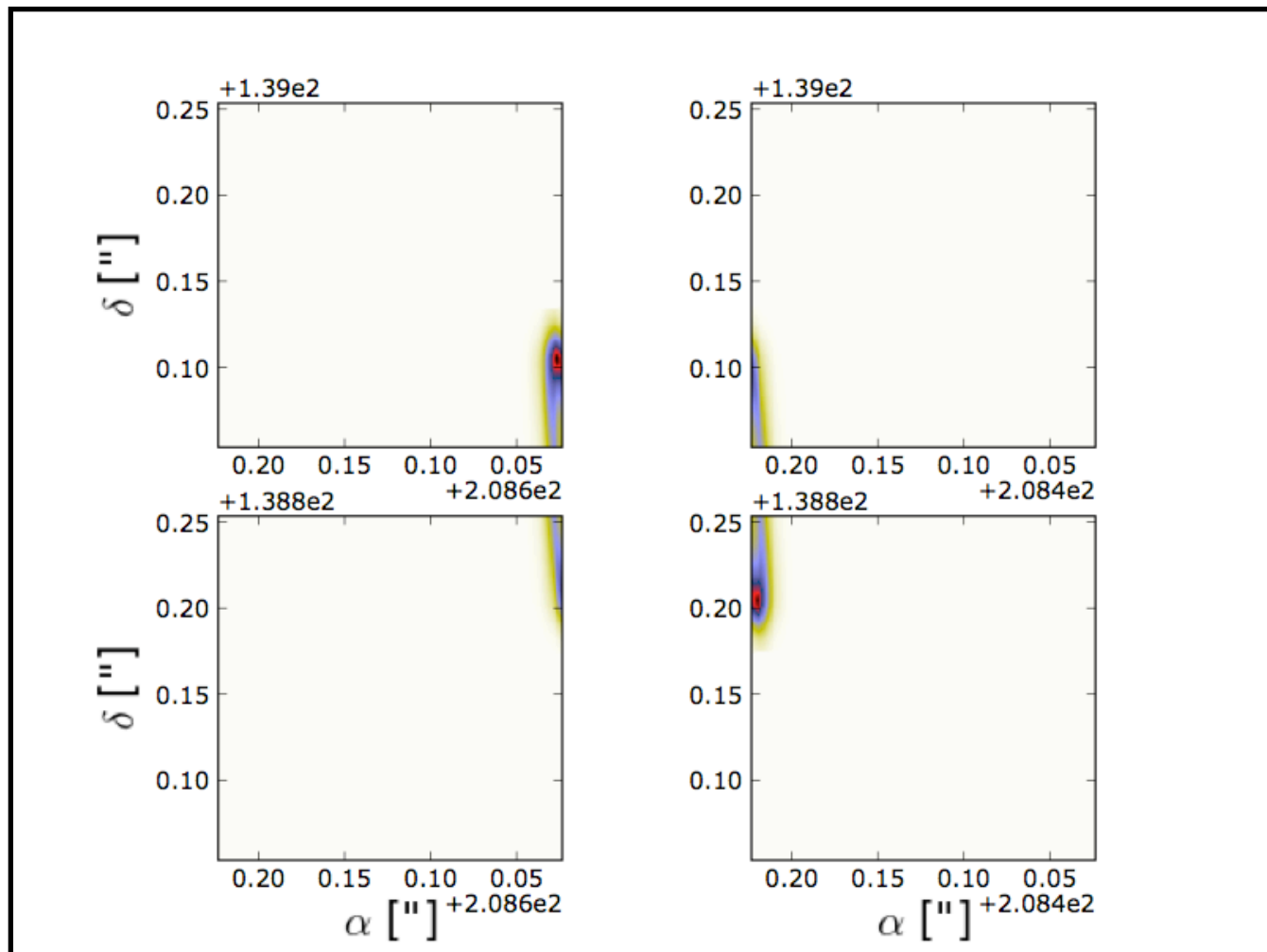


S^3 -SEX continuum spectra

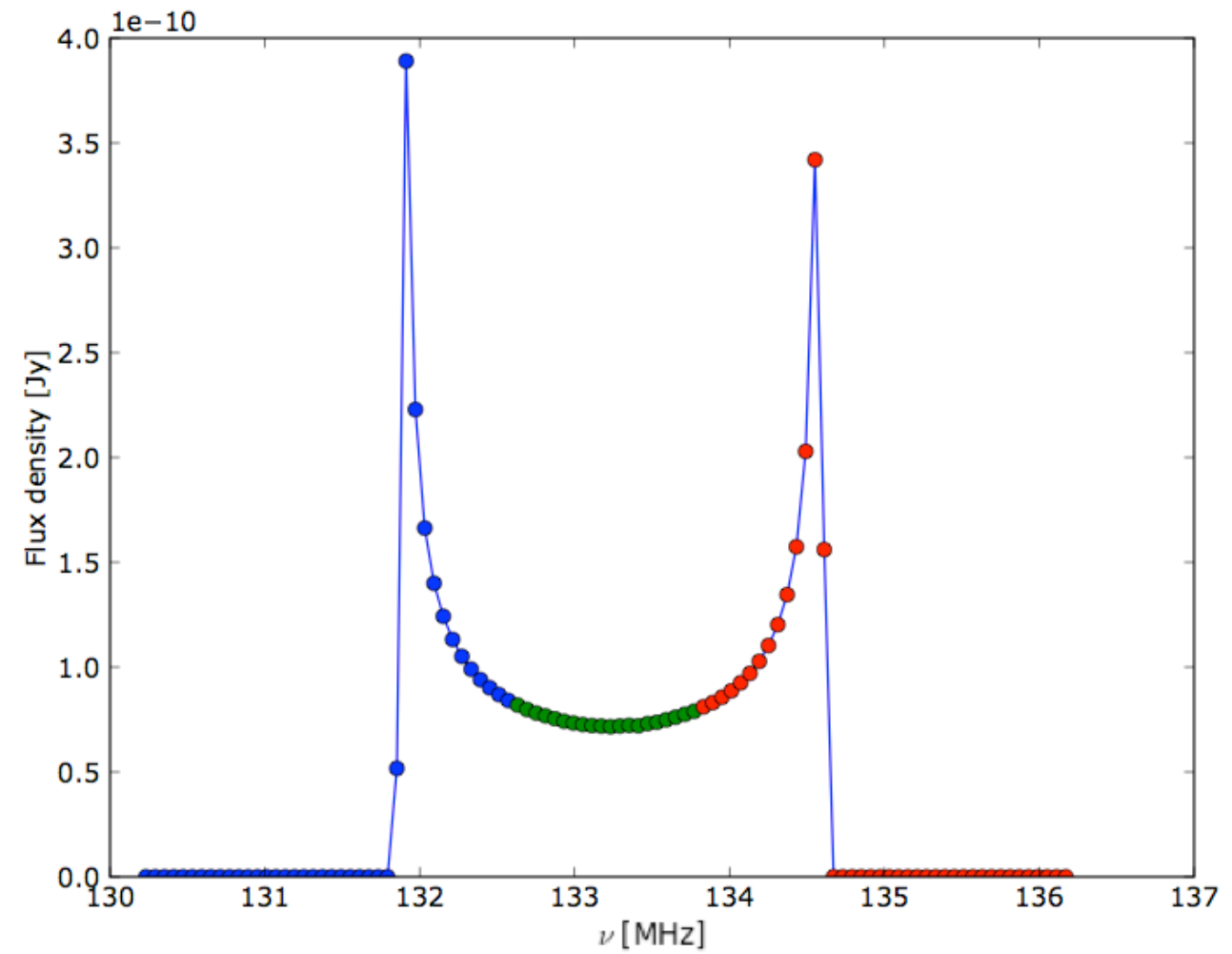


Partially mapped sources

HI integrated emission split over four maps



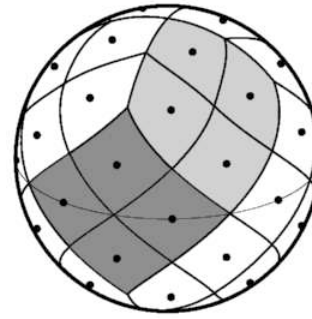
HI line split over three spectral ranges



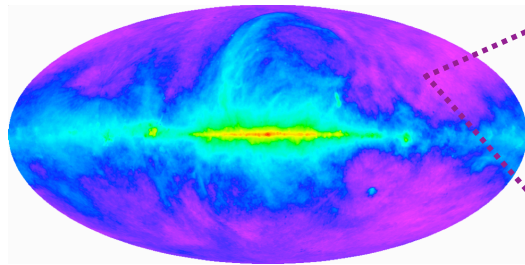
Foreground signals

Global Sky Model (GSM)

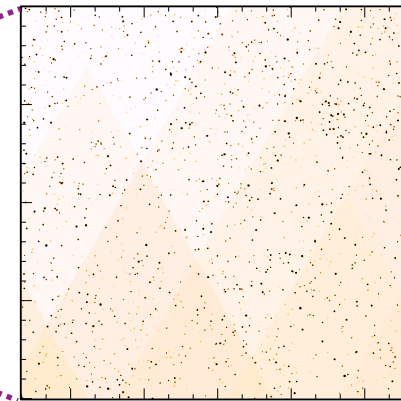
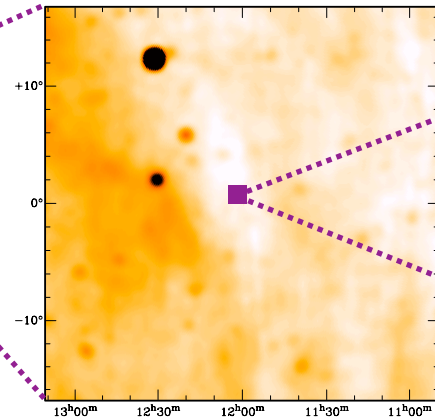
- Courtesy of Angelica de Oliveira-Costa (MIT)
- Compiles publicly available radio surveys
- Covers 10 MHz to 100 GHz
- HEALPIX format
- S3Tools adapted from available IDL routines



<http://space.mit.edu/home/angelica/gsm/>
<http://healpix.jpl.nasa.gov/>

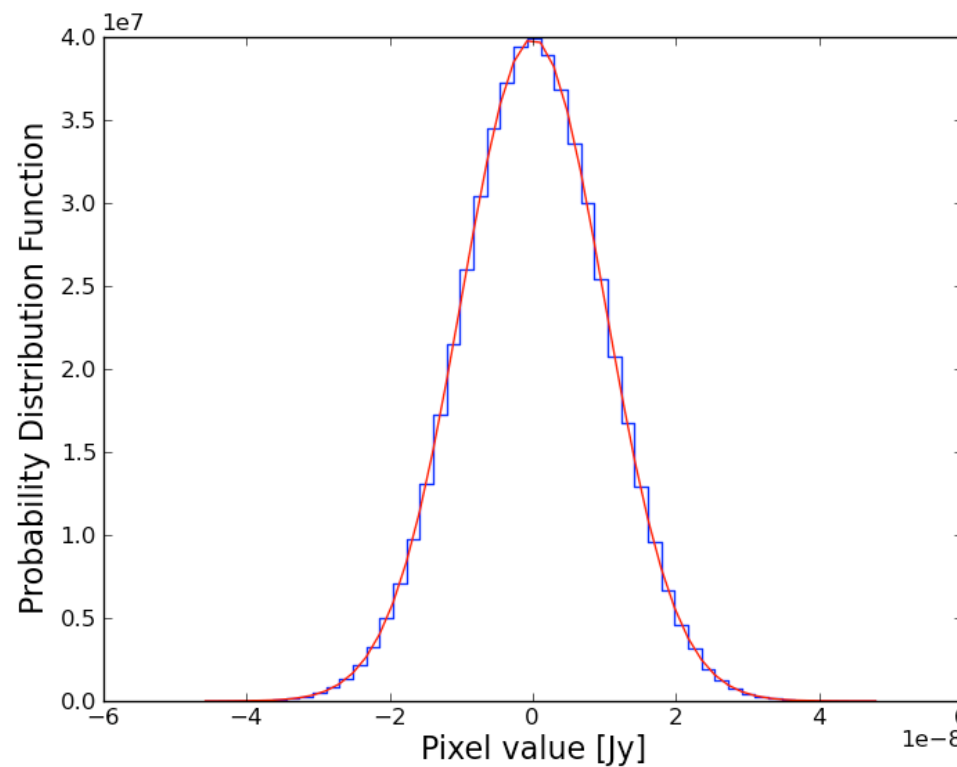
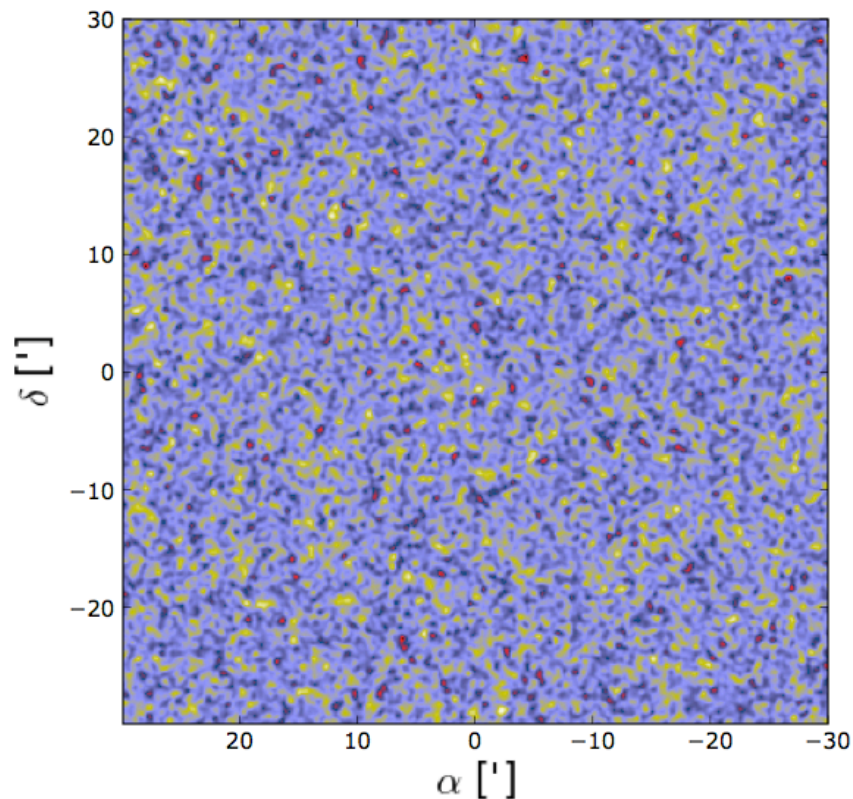


[Haslam et al. @ 408 MHz]



Central 20' by 20' of S-cubed SEX
[only starburst galaxies] overlaid
with GSM @ 1.113 GHz [x 1e15]

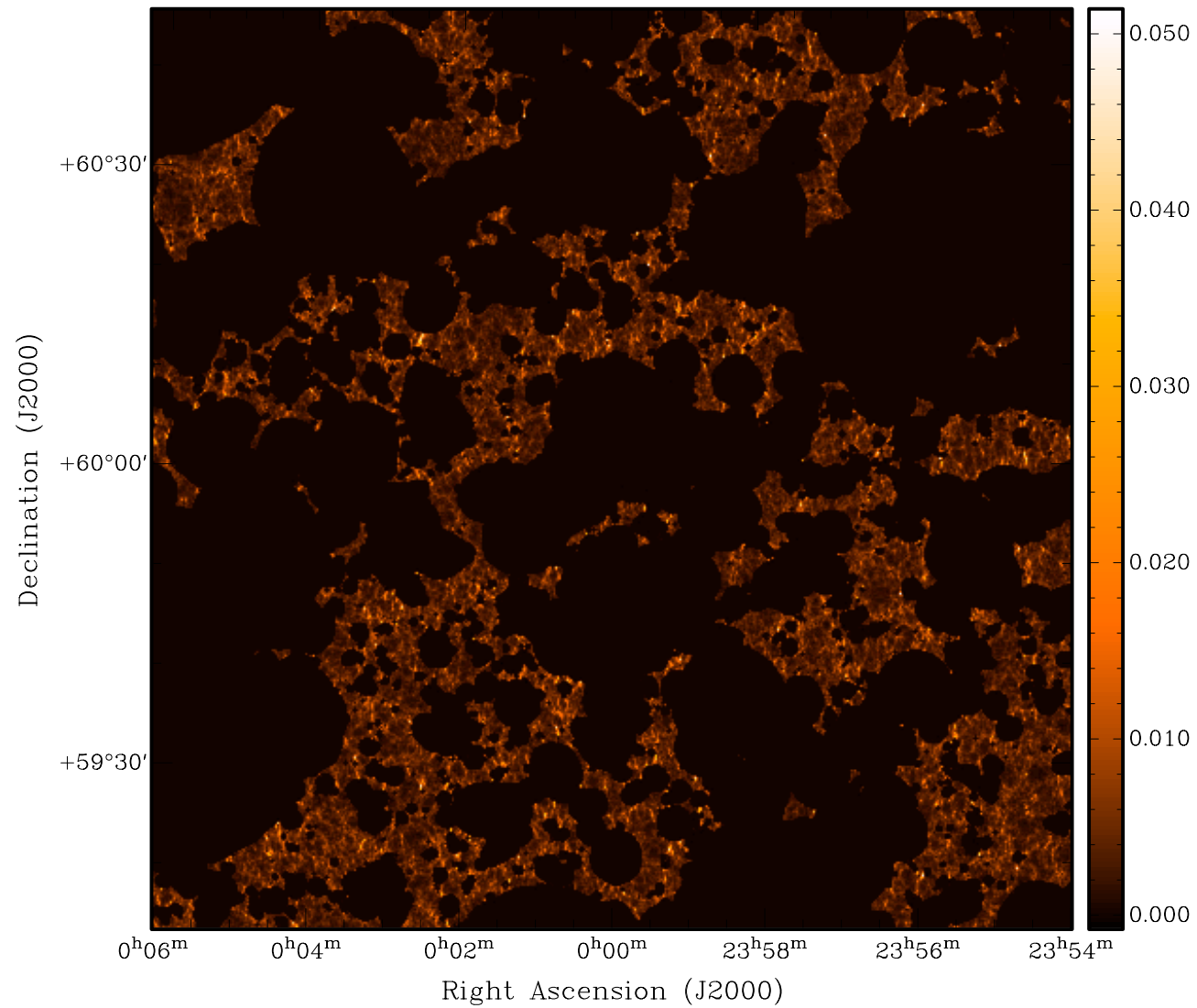
Gaussian noise



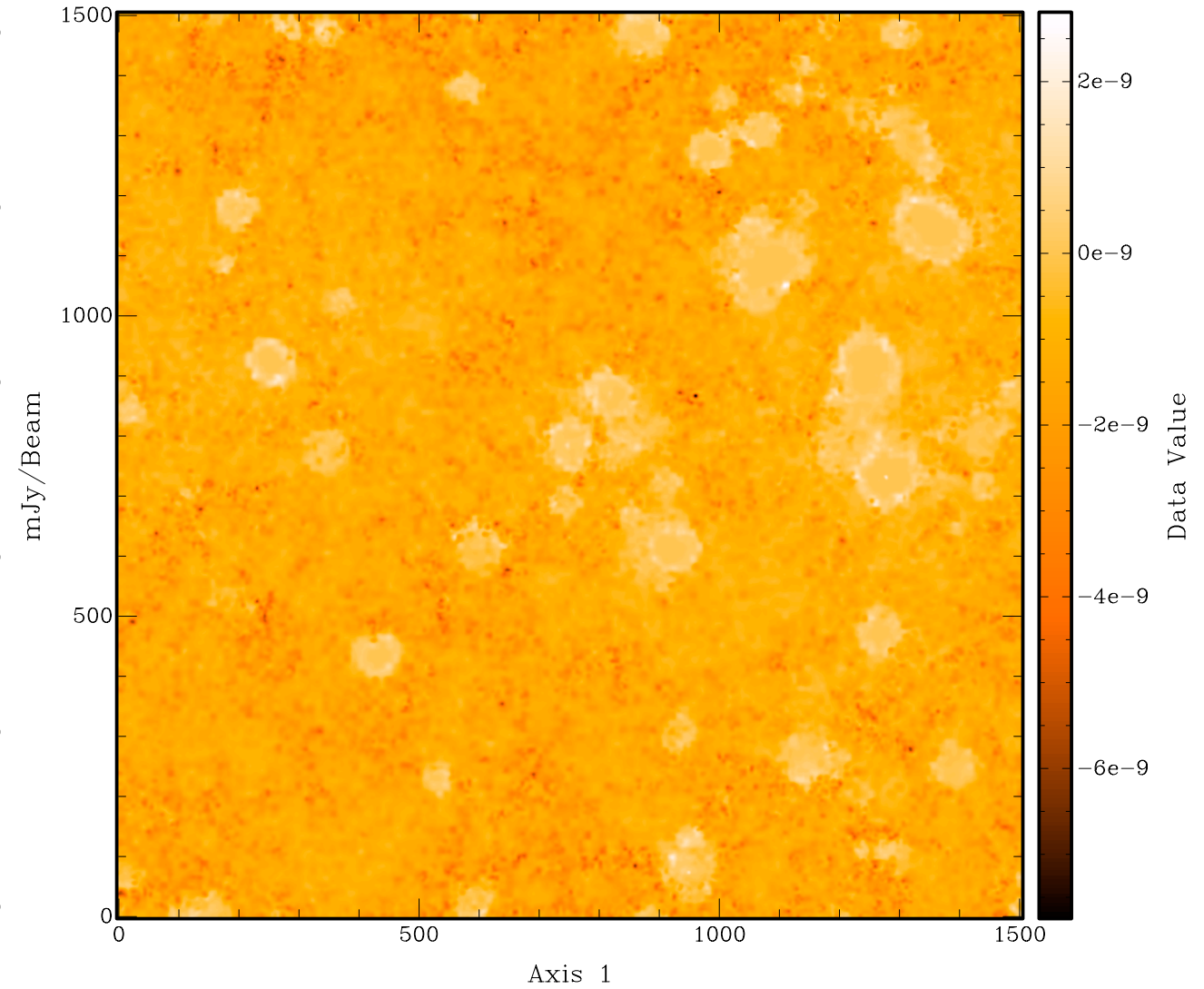
- 1 square degree
- 10 nJy noise level
- 30'' resolution

EoR signals

M. Santos (IST Lisbon)



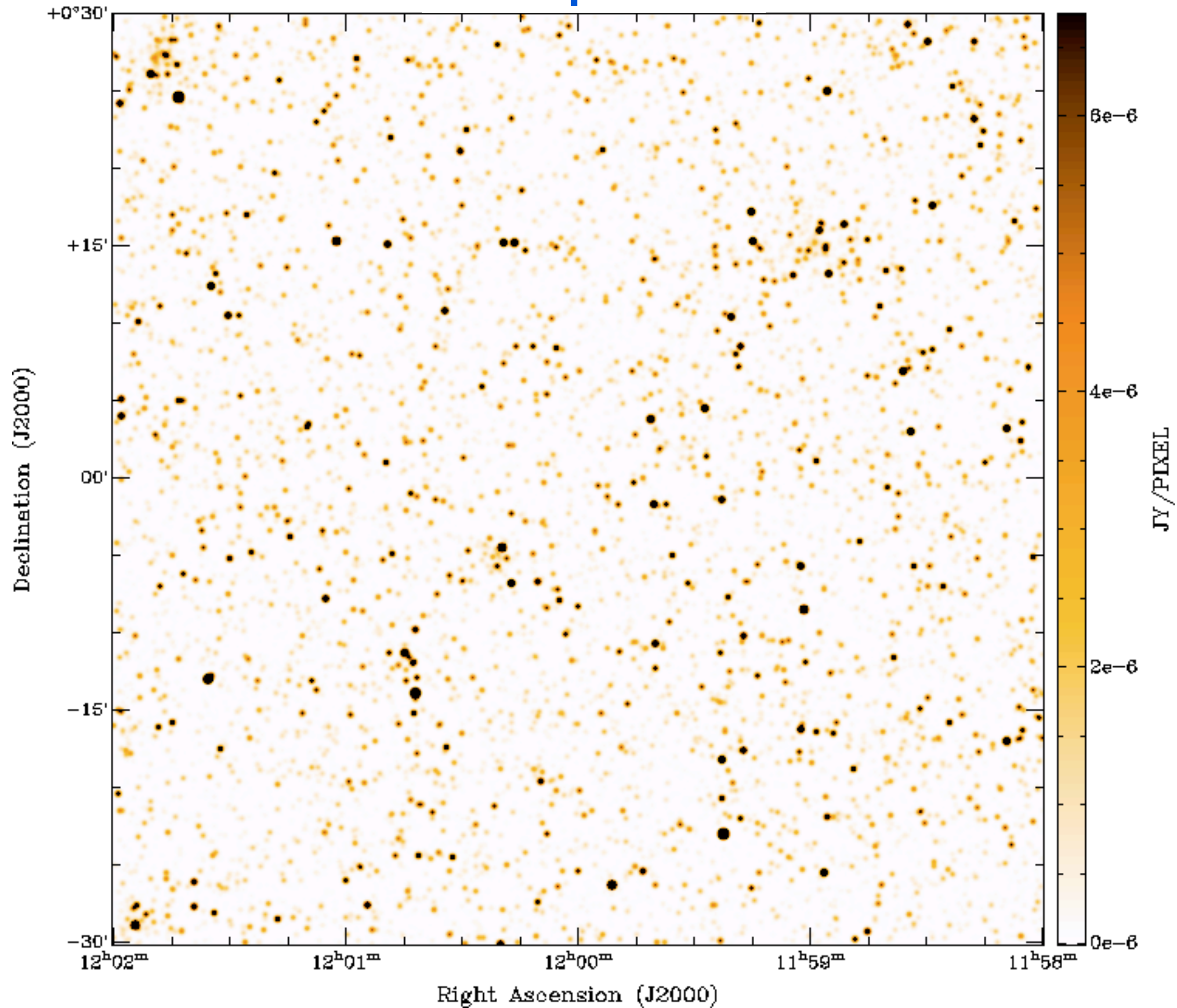
B. Semelin (LERMA)



Implementation in S3Map under way...

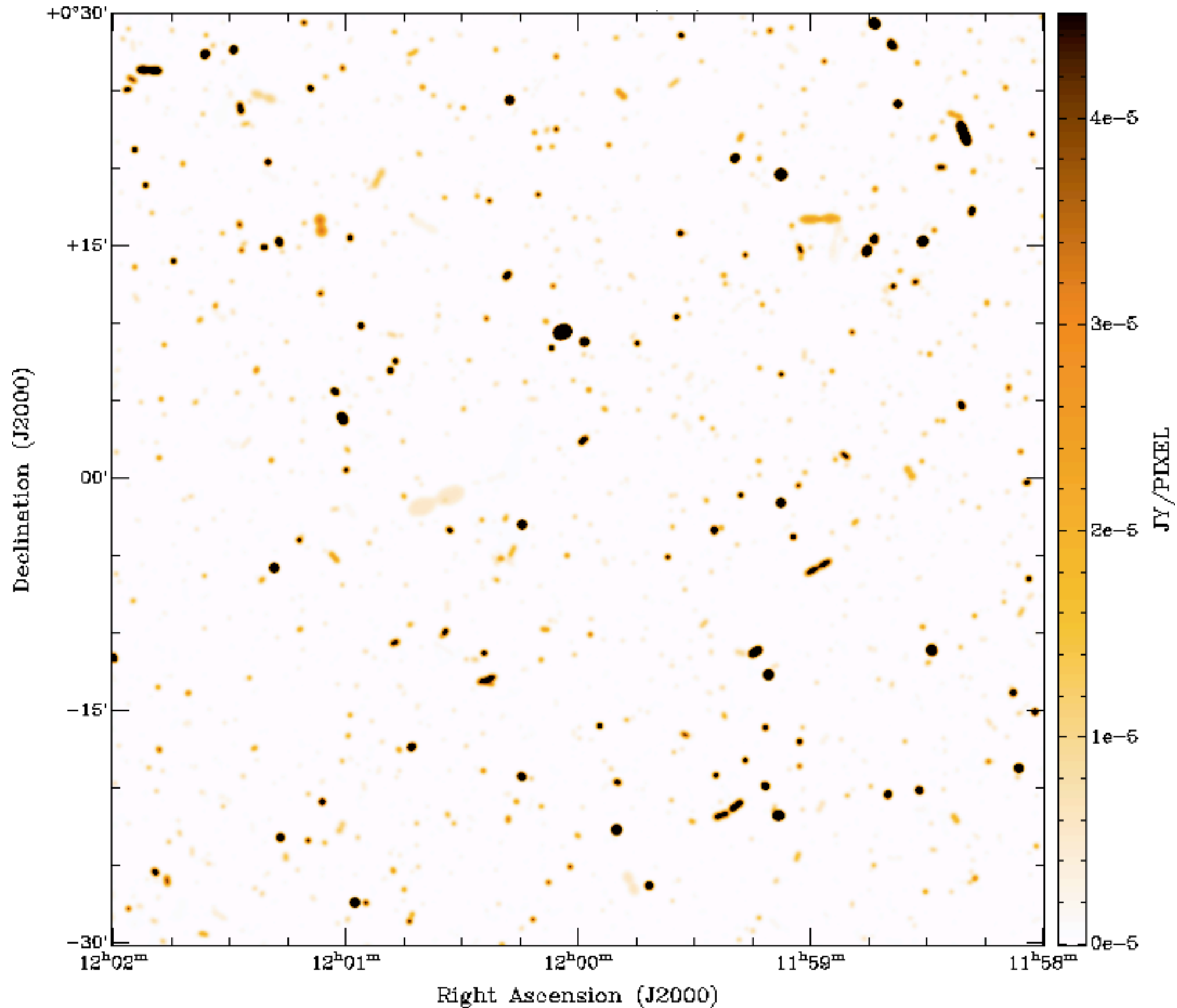
Central square degree of S3-SEX at 1.4 GHz

Radio-quiet AGN



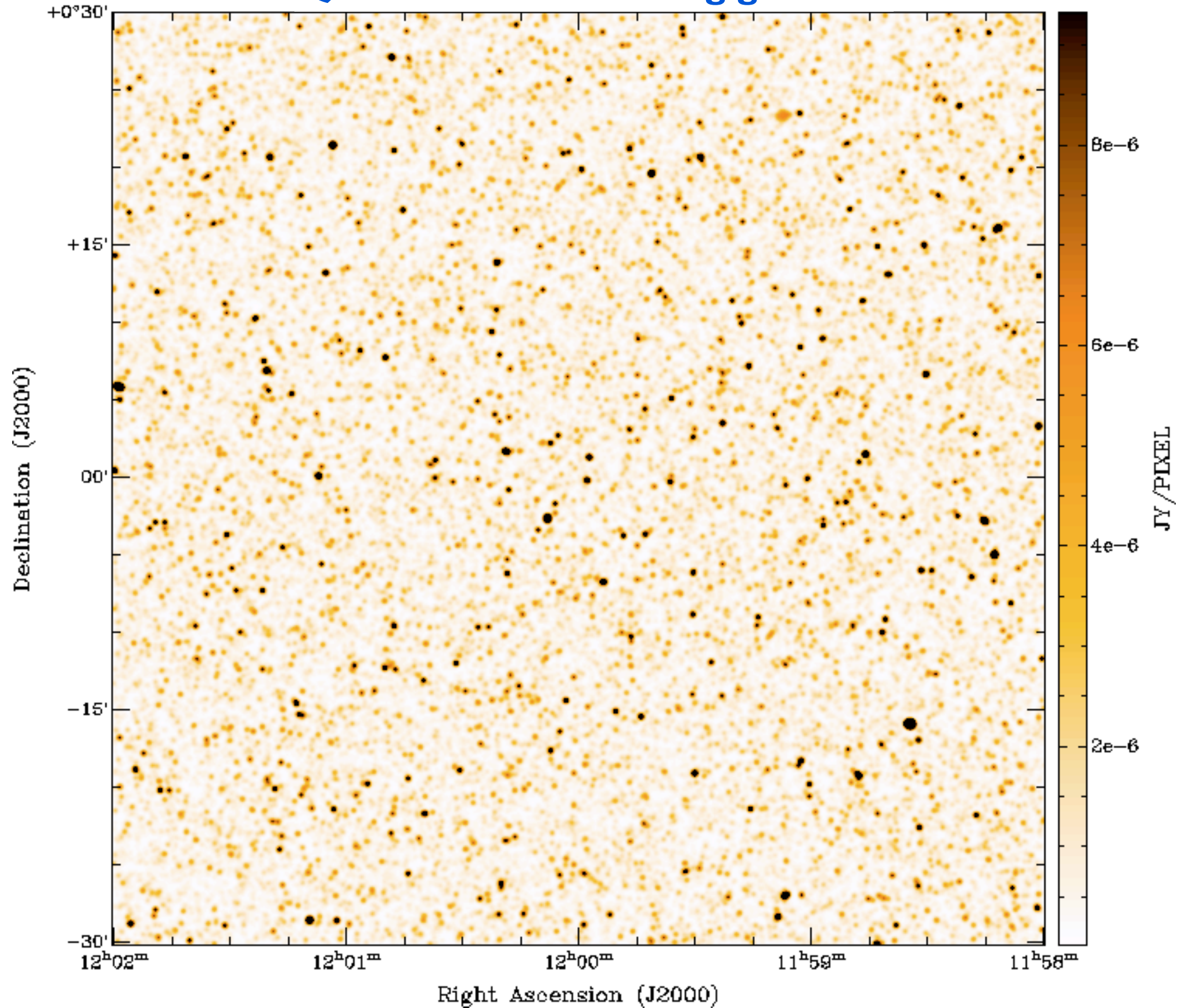
Central square degree of S3-SEX at 1.4 GHz

Radio-loud AGN



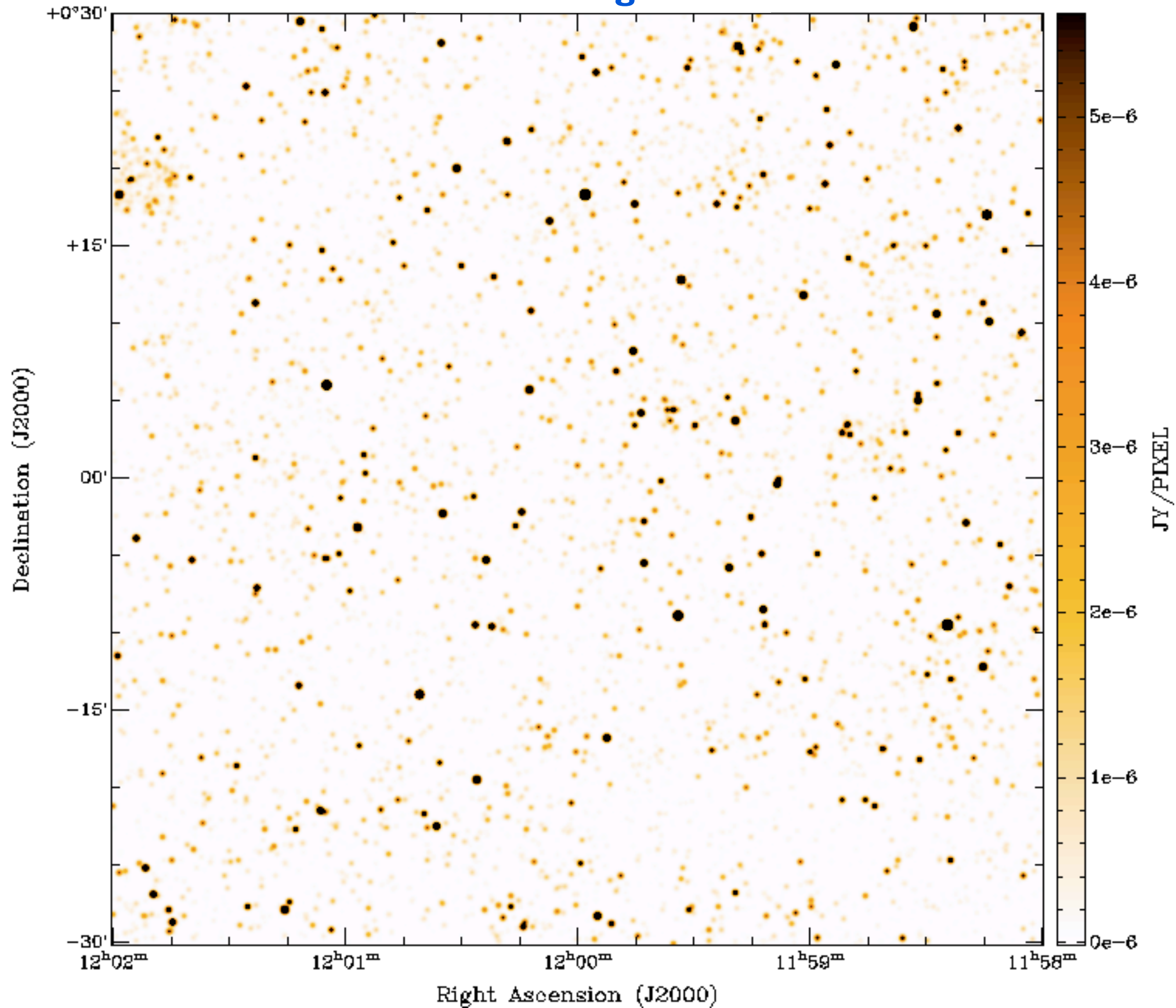
Central square degree of S3-SEX at 1.4 GHz

Quiescent starforming galaxies



Central square degree of S3-SEX at 1.4 GHz

Starburst galaxies



Recent progress

Parallelisation (March 2011)



- SAL : 640 cores
- HAL : 512 cores

Query result file

```
591,591,0,1,0.04334,-0.11014,72.912,0.017089,0,0,0,-3.016,-3.4405
15100,15100,0,1,0.04777,0.14415,281.06,0.066639,0,0,0,-3.3369
18120,18120,0,1,-0.14125,0.06468,312.03,0.074111,0,0,0,-4.6097
36433,36433,0,1,-0.05988,-0.00406,411.744,0.098357,0,0,0,-3.3404
41504,41504,0,1,-0.00709,-0.0059,433.632,0.103718,0,0,0,-4.5923
45233,45233,0,1,6e-05,0.14685,447.945,0.107232,0,0,0,-4.5336
50706,50706,0,1,0.05817,-0.0374,471.256,0.112967,0,0,0,-4.844
56970,56970,0,1,-0.04715,-0.09068,489.218,0.117397,0,0,0,-4.2678
56978,56978,0,1,-0.01053,-0.01773,490.931,0.11782,0,0,0,-4.6987
56986,56986,0,1,0.02769,-0.13346,486.243,0.116663,0,0,0,-4.9642
57004,57004,0,1,0.12275,-0.15084,489.605,0.117493,0,0,0,-4.5191
57020,57020,0,1,0.14047,-0.00797,487.32,0.116929,0,0,0,-4.7824
75840,75840,0,1,0.15066,0.15112,542.249,0.13054,0,0,0,-4.7862
82297,82297,0,1,0.11473,0.02501,551.373,0.132809,0,0,0,-4.6164
119789,119789,0,1,-0.08873,0.0954,633.004,0.15323,0,0,0,-4.0425
123155,123155,0,1,0.1072,0.04925,639.592,0.154888,0,0,0,-4.9336
142127,142127,0,1,0.04104,0.13726,672.862,0.16328,0,0,0,-5.2721
146174,146174,0,1,0.07252,-0.06693,683.864,0.166064,0,0,0,-5.2879
150601,150601,0,1,0.02623,0.02725,685.774,0.166547,0,0,0,-3.9316
```

(...)

Redshift
sorting

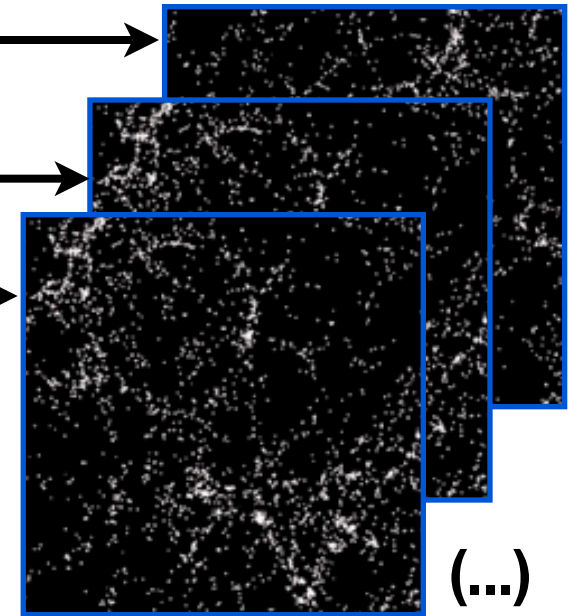
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591,591,0,1,0.04334,-0.11014,72.912,0.017089,0,0,0,-3.016,-3.4405
15100,15100,0,1,0.04777,0.14415,281.06,0.066639,0,0,0,-3.3369
18120,18120,0,1,-0.14125,0.06468,312.03,0.074111,0,0,0,-4.6097
36433,36433,0,1,-0.05988,-0.00406,411.744,0.098357,0,0,0,-3.3404
41504,41504,0,1,-0.00709,-0.0059,433.632,0.103718,0,0,0,-4.5923
45233,45233,0,1,6e-05,0.14685,447.945,0.107232,0,0,0,-4.5336
50706,50706,0,1,0.05817,-0.0374,471.256,0.112967,0,0,0,-4.844
56970,56970,0,1,-0.04715,-0.09068,489.218,0.117397,0,0,0,-4.2678
56978,56978,0,1,-0.01053,-0.01773,490.931,0.11782,0,0,0,-4.6987
56986,56986,0,1,0.02769,-0.13346,486.243,0.116663,0,0,0,-4.9642
57004,57004,0,1,0.12275,-0.15084,489.605,0.117493,0,0,0,-4.5191
57020,57020,0,1,0.14047,-0.00797,487.32,0.116929,0,0,0,-4.7824
75840,75840,0,1,0.15066,0.15112,542.249,0.13054,0,0,0,-4.7862
82297,82297,0,1,0.11473,0.02501,551.373,0.132809,0,0,0,-4.6164
119789,119789,0,1,-0.08873,0.0954,633.004,0.15323,0,0,0,-4.0425
123155,123155,0,1,0.1072,0.04925,639.592,0.154888,0,0,0,-4.9336
142127,142127,0,1,0.04104,0.13726,672.862,0.16328,0,0,0,-5.2721
146174,146174,0,1,0.07252,-0.06693,683.864,0.166064,0,0,0,-5.2879
150601,150601,0,1,0.02623,0.02725,685.774,0.166547,0,0,0,-3.9316
```

(...)

CPU #1

CPU #2

CPU #3



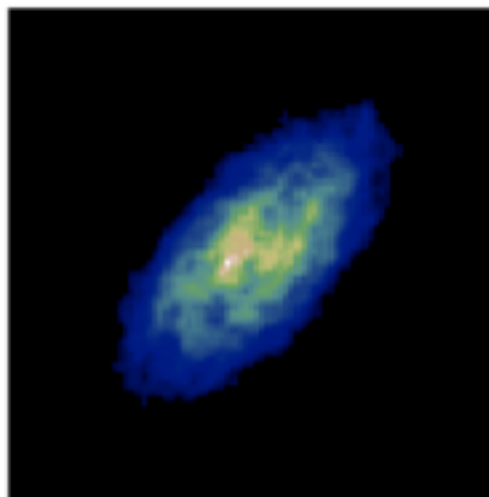
(...)

Pseudo-continuum for S³-SAX (June 2011)

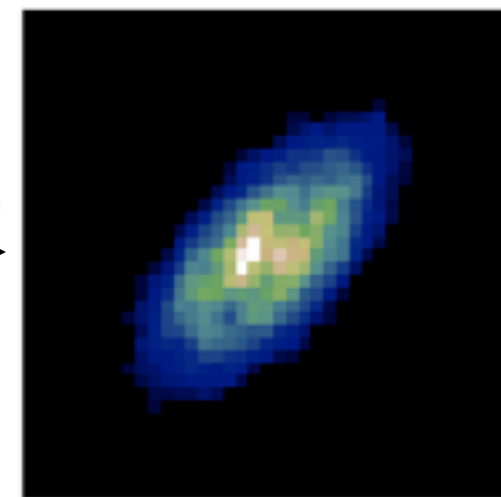
1250 I,Q,U templates from T. Arshakian (MPIfR) [150 MHz-18GHz]

Template parameters

- radius (HI+H2) : 0.1 - 20 kpc
- age : 1 Myr - 15 Gyr
- SFR : 0.001 - 100 solar masses/yr
- inclination : 0-90 degrees



Degraded
spatial
resolution



Work by B. Poillot (M1 student)

Outline of the talk

SKA, MeerKAT and ASKAP

Specifications, timelines and key science

SKA Simulated Skies

The goal of end2end sims

The SAX and SEX simulations

S3Map

From simulated catalogues to simulated skies

Recent developments

Simulated observations

HI and CO mapping at high redshift

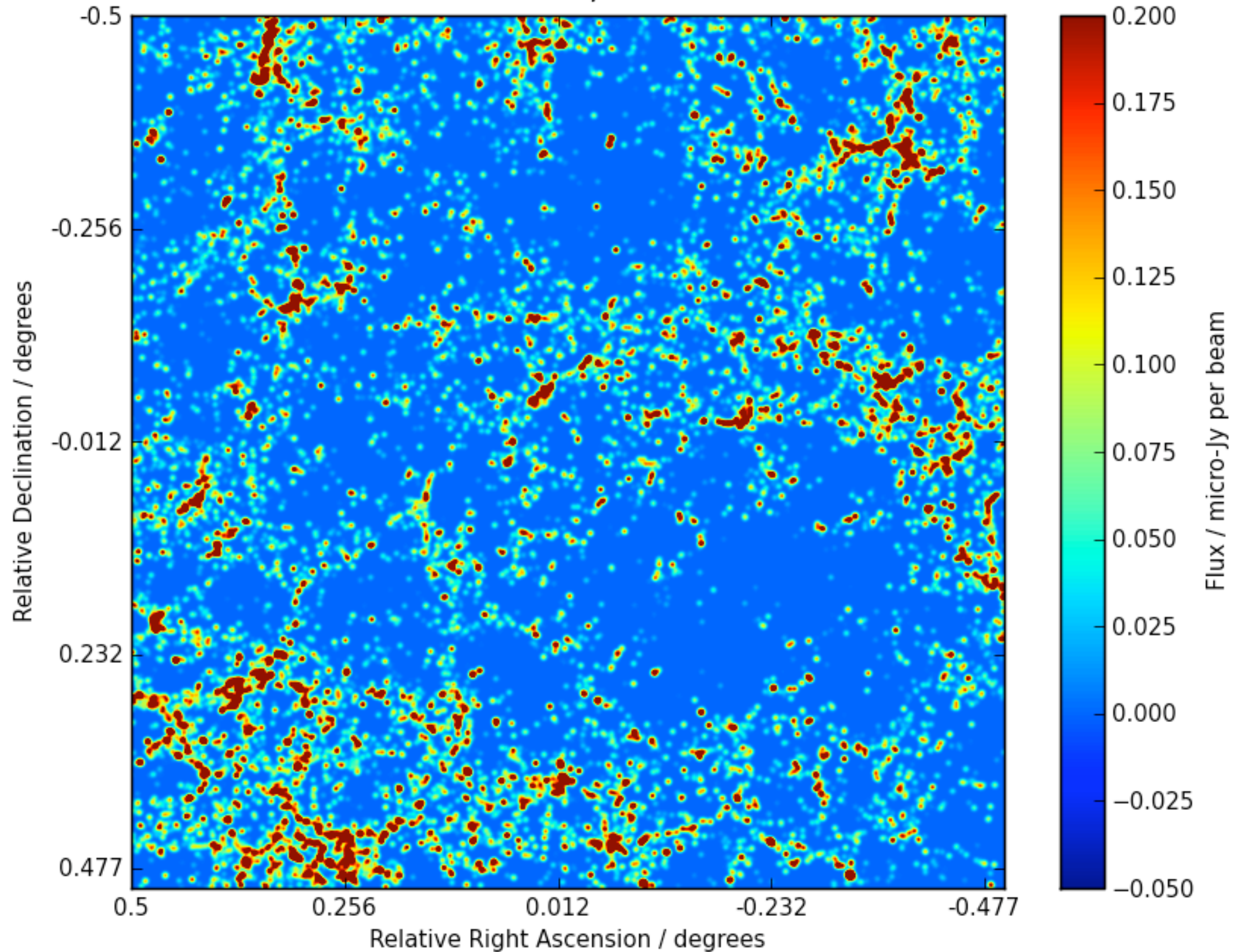
Perspectives

And the sky full of HI...

335.26 MHz, $z = 3.24$

- HI emission
- 1,585,635 galaxies
- 4096x4096 pixels
- 2048 channels
- 20 arcsecond resolution (originally 0.9 arcsecond)

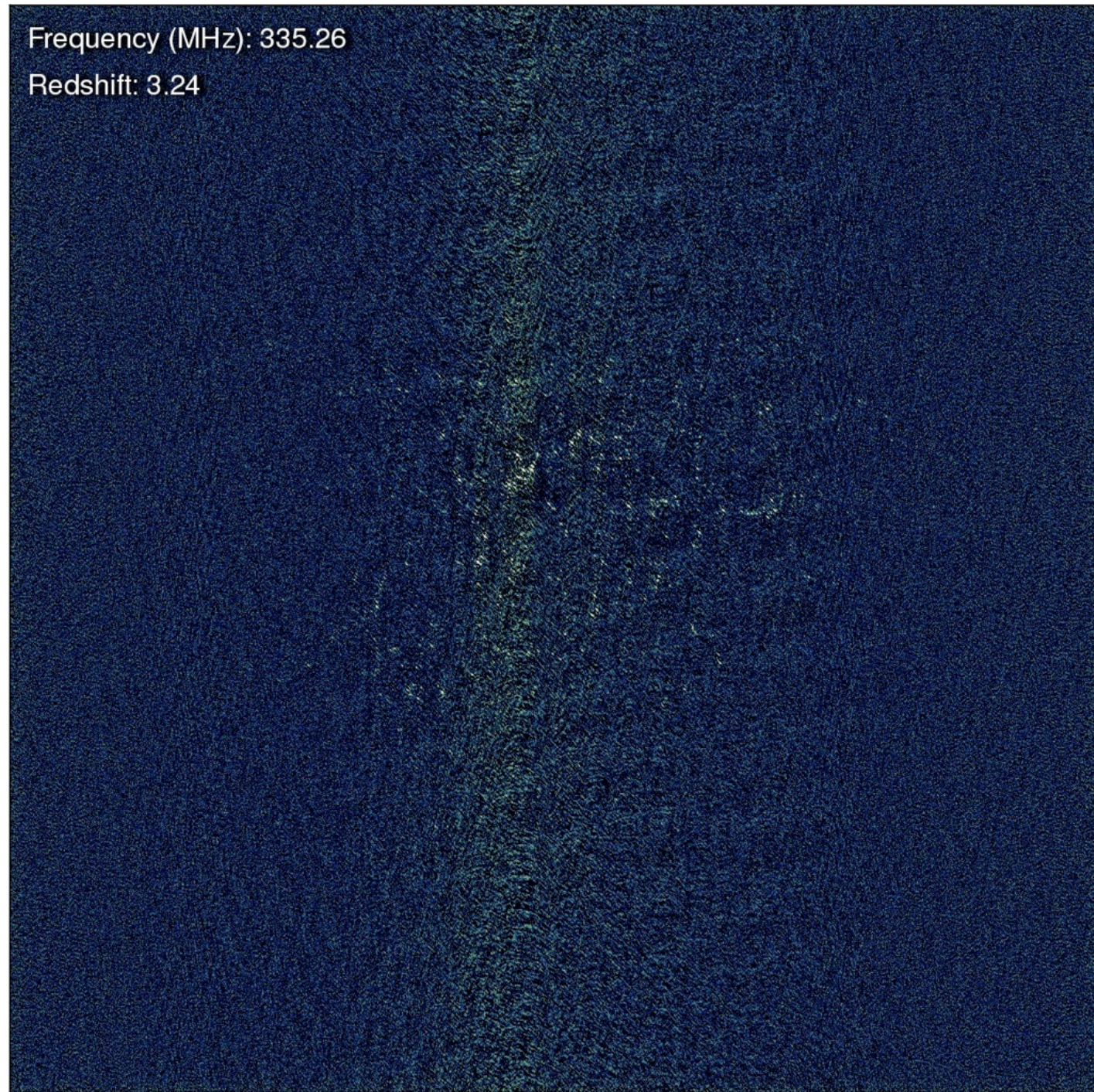
I. Heywood (Oxford)



..as seen by SKA Phase 1 AA

Frequency (MHz): 335.26

Redshift: 3.24



Dirty image - No noise

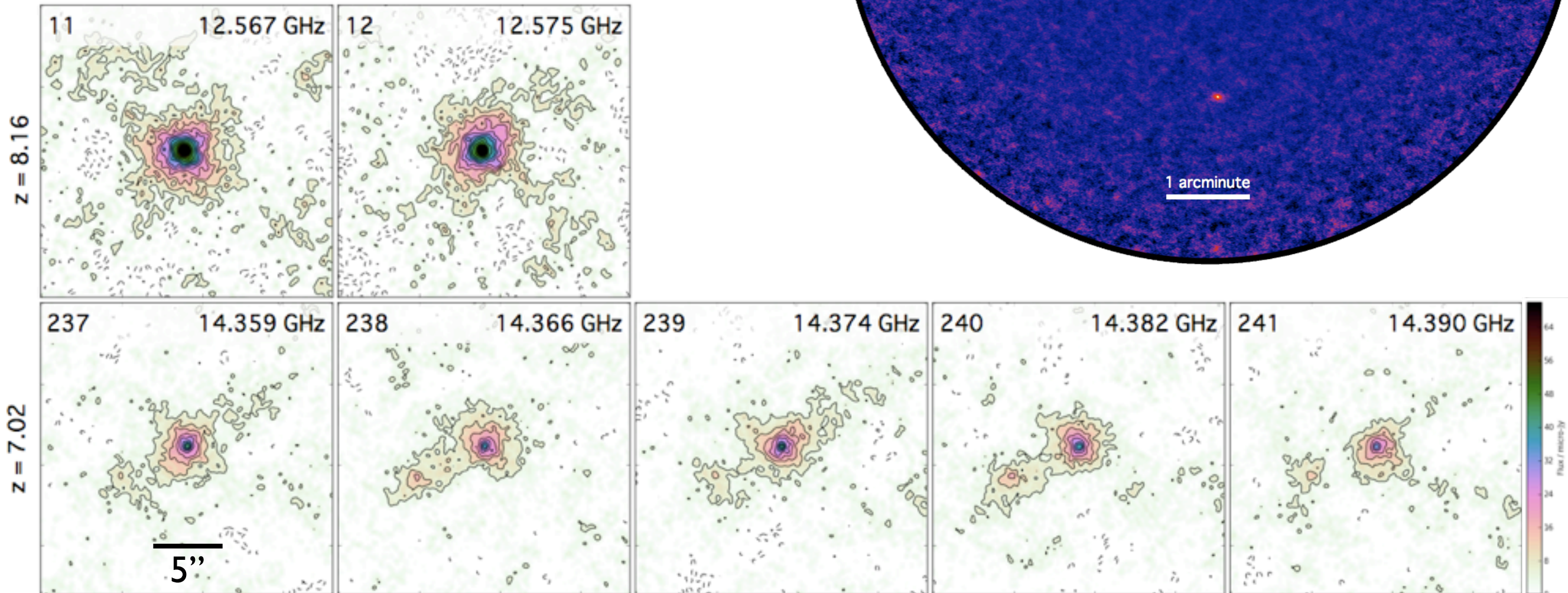
MESMER simulation

MeerKAT Search for Molecules in the Epoch of Reionization

- Approved large survey project for MeerKAT
- High-frequency band imaging (10.5-14.5 GHz)
- Expected direct detection of ~ 400 EoR galaxies in CO(1-0)
- Simulations using S³-SAX, parallelised S3Map, CASA (NRAO) and MeqTrees (ASTRON)
- 4096^2 simulation with 256 channels (2 GHz bandwidth) of a single-pointing 480-hr observation

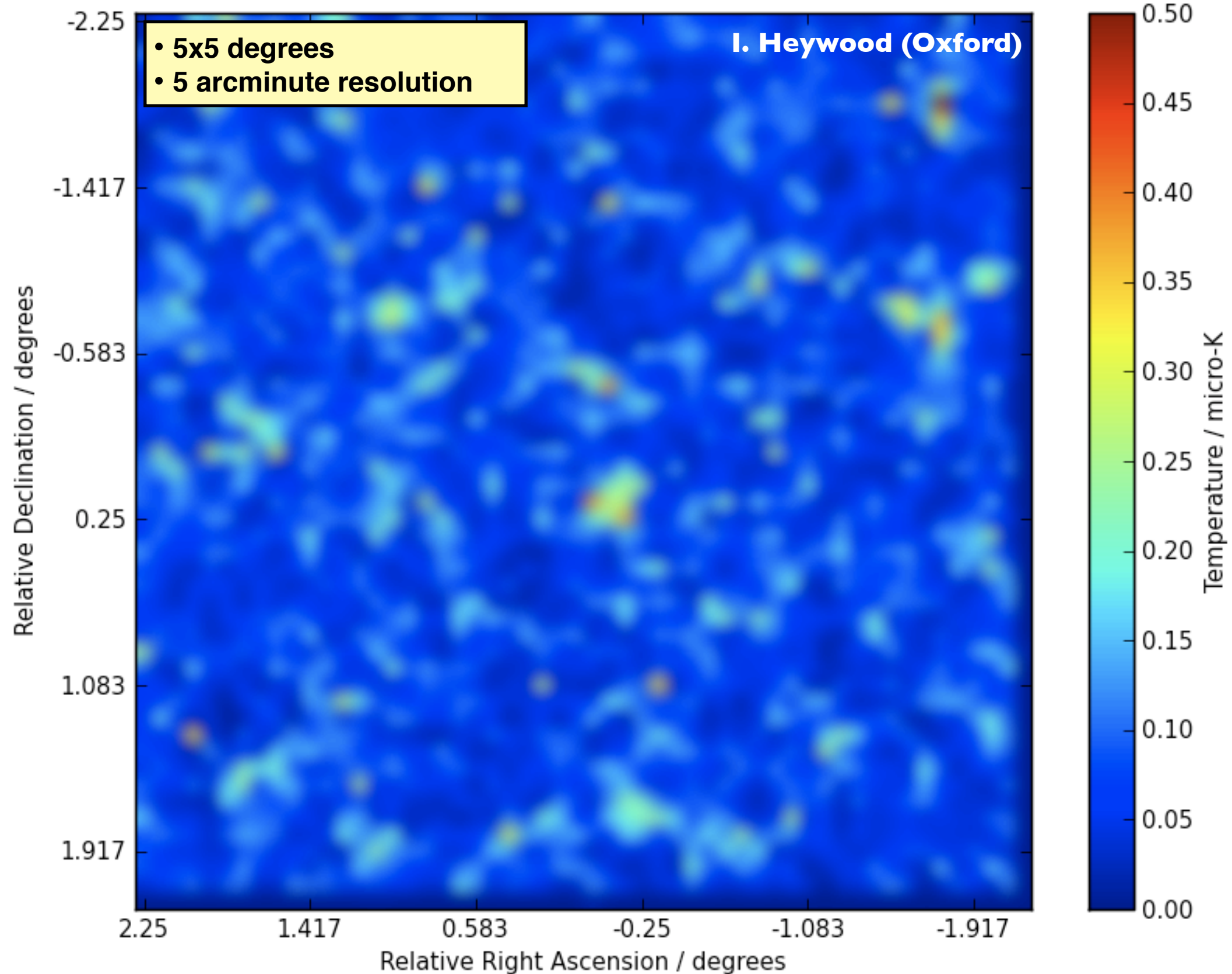
I. Heywood (Oxford)

Example detections in the simulated cube



CO intensity mapping

Freq = 13.82 GHz || Redshift = 7.34



Perspectives

SKA Simulated Skies and S3Map

- Imaging of S3-SEX infrared data (with T. Mauch / R. Wilman)
- Description of polarized emission for S3-SEX (with J. Geisbuech)
- Inclusion of EoR signals (with B. Semelin / M. Santos)
- Update of VO releases and VO-compliant S3Map (mapmaking on the grid ?)

LADUMA HI simulation (with I. Heywood / S. Blyth)

