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Cosmic Magnetism at Low Frequencies and Large Scales

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SALT IV
Sydney, December 2017

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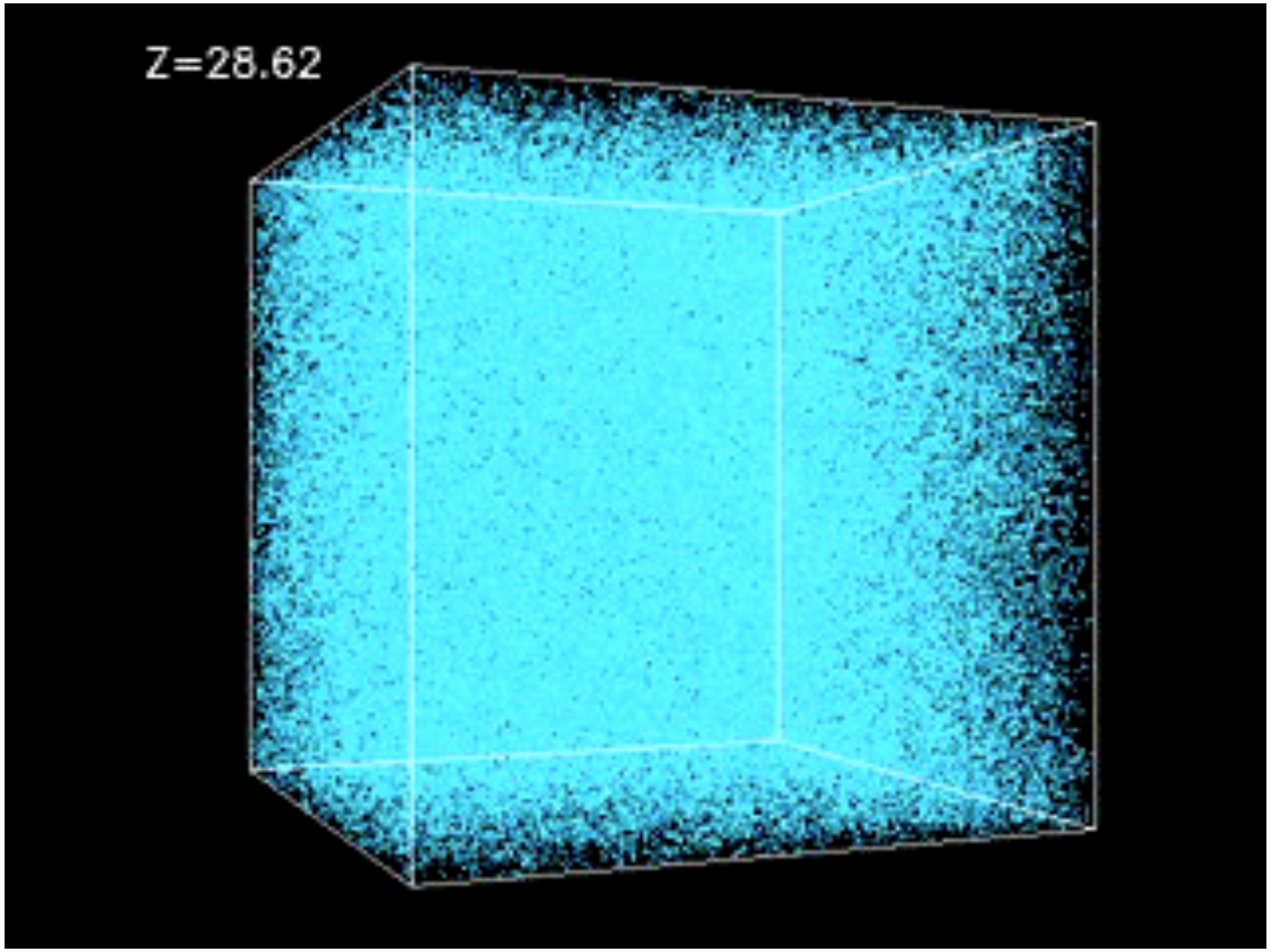
UNIVERSITY OF TORONTO

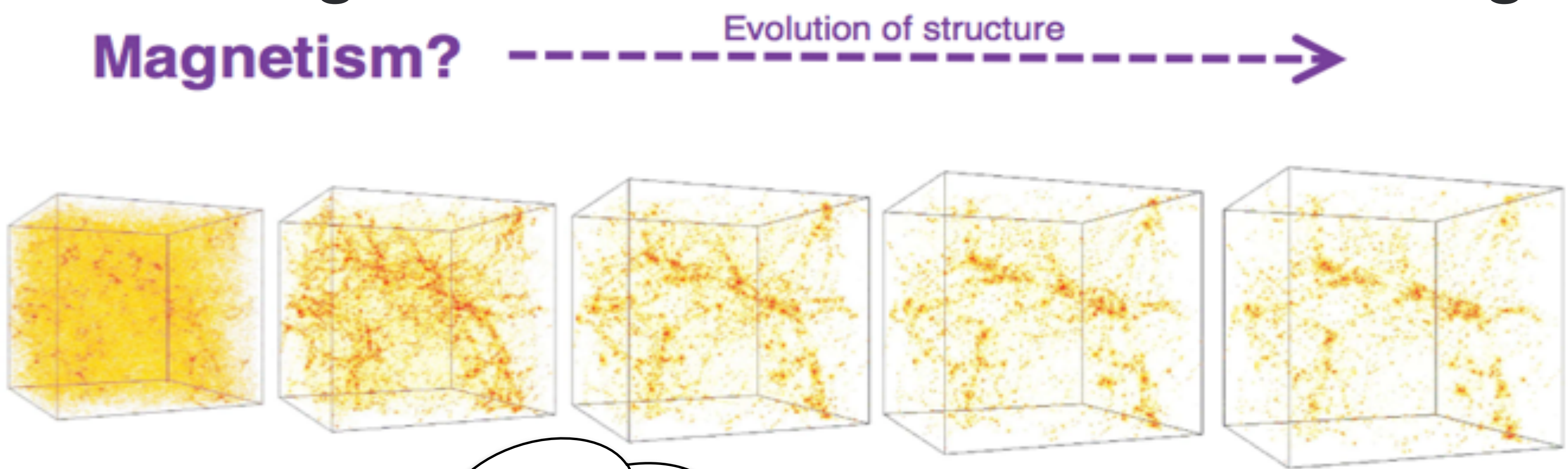
What is the Cosmic Web?

- Fluctuations in the primordial matter density result in the growth of large-scale structure (LSS)
- The CDM theory predicts massive galaxies and galaxy clusters built from smaller galaxies colliding and merging
- Result is clusters, filaments, and voids we see today which form a “web” like structure



(Movie: http://cosmicweb.uchicago.edu/)

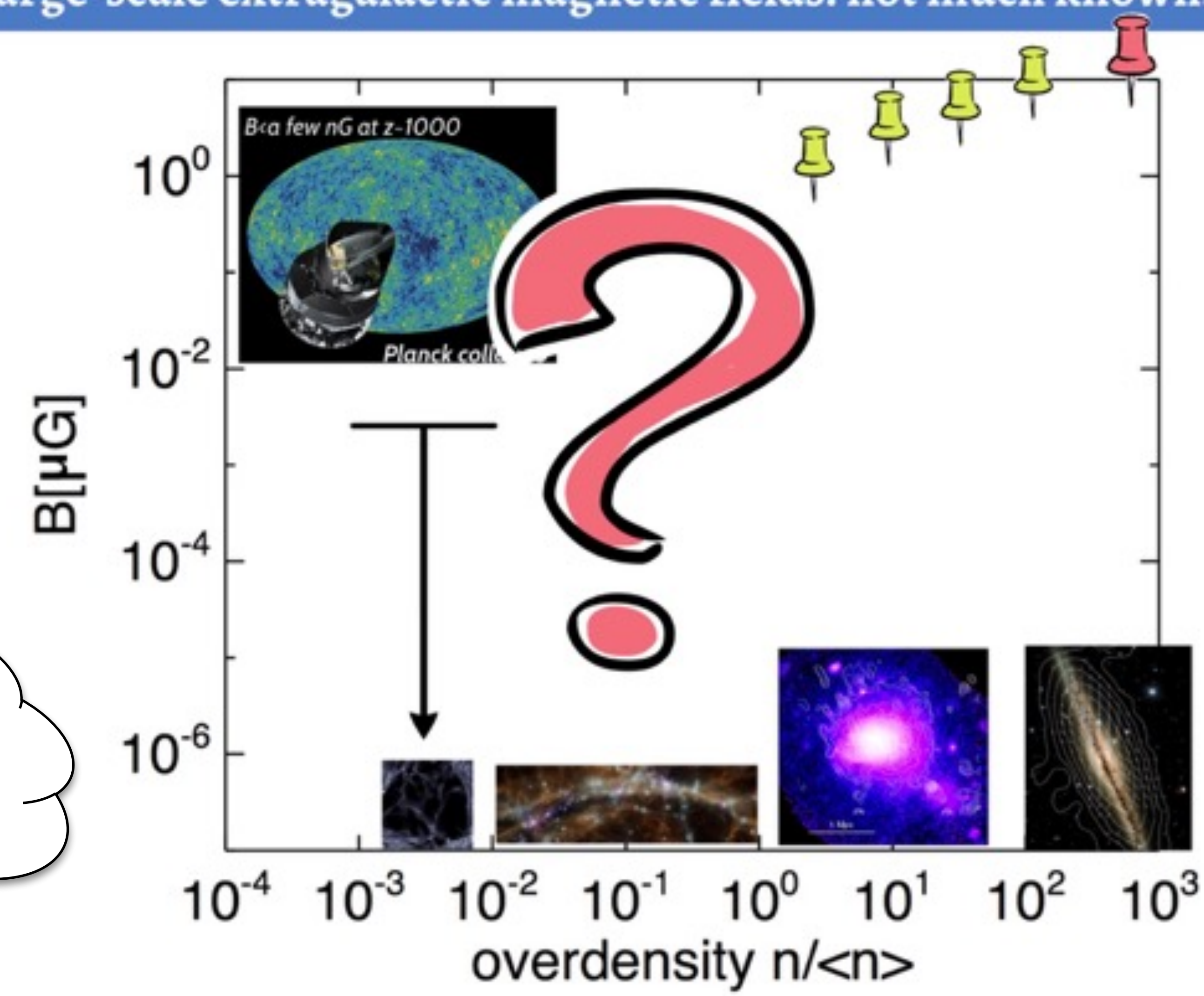
Cosmic Magnetism: a hole in our understanding of the Universe?



What is the origin of cosmic magnetic fields?

What is the role of magnetic fields in structure formation and evolution?

Large-scale extragalactic magnetic fields: not much known.



What is the nature of the IGM and IGMF?

How has IGM / IGMF changed over time?

magnetic fields ~unknown for >99.99% of cosmic volume

Diffuse Emission and The Synchrotron Cosmic Web

- Intergalactic shocks from infall into and along filaments and mergers inside clusters
  →accelerate electrons and amplify magnetic fields
  → producing synchrotron emission

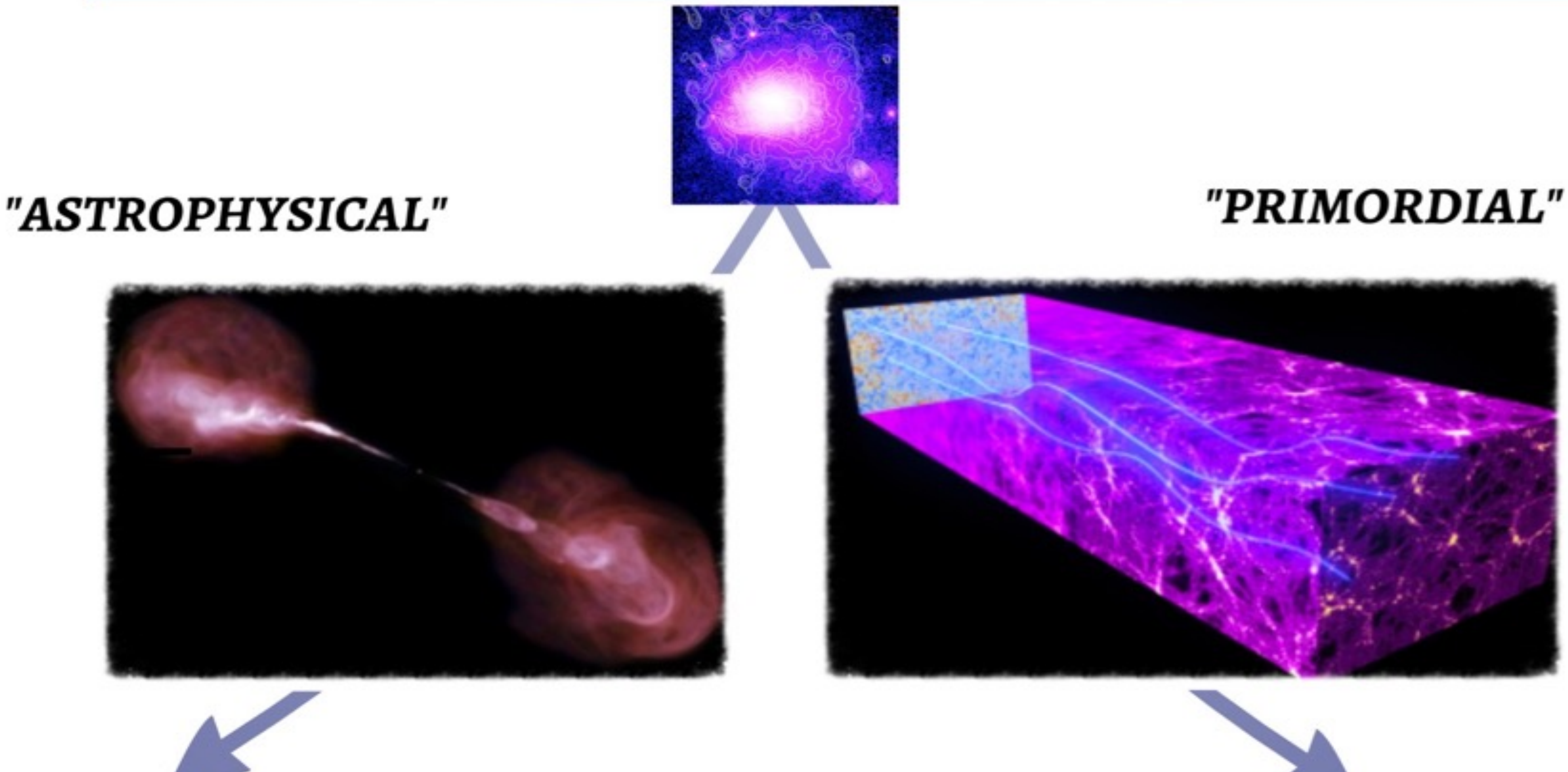
- Synchrotron radiation should trace large-scale structure and cosmic filaments

- Signal should be strongest on scales ~ 10′ to 1° at frequencies ~100 MHz

Blue = B field
Red = Gas

F. Vazza
videos link

What is the origin of extragalactic magnetic fields?



seeds from galaxy formation (z<6)

- "inside-out"
- star formation, AGN
- batteries, CR-dynamos

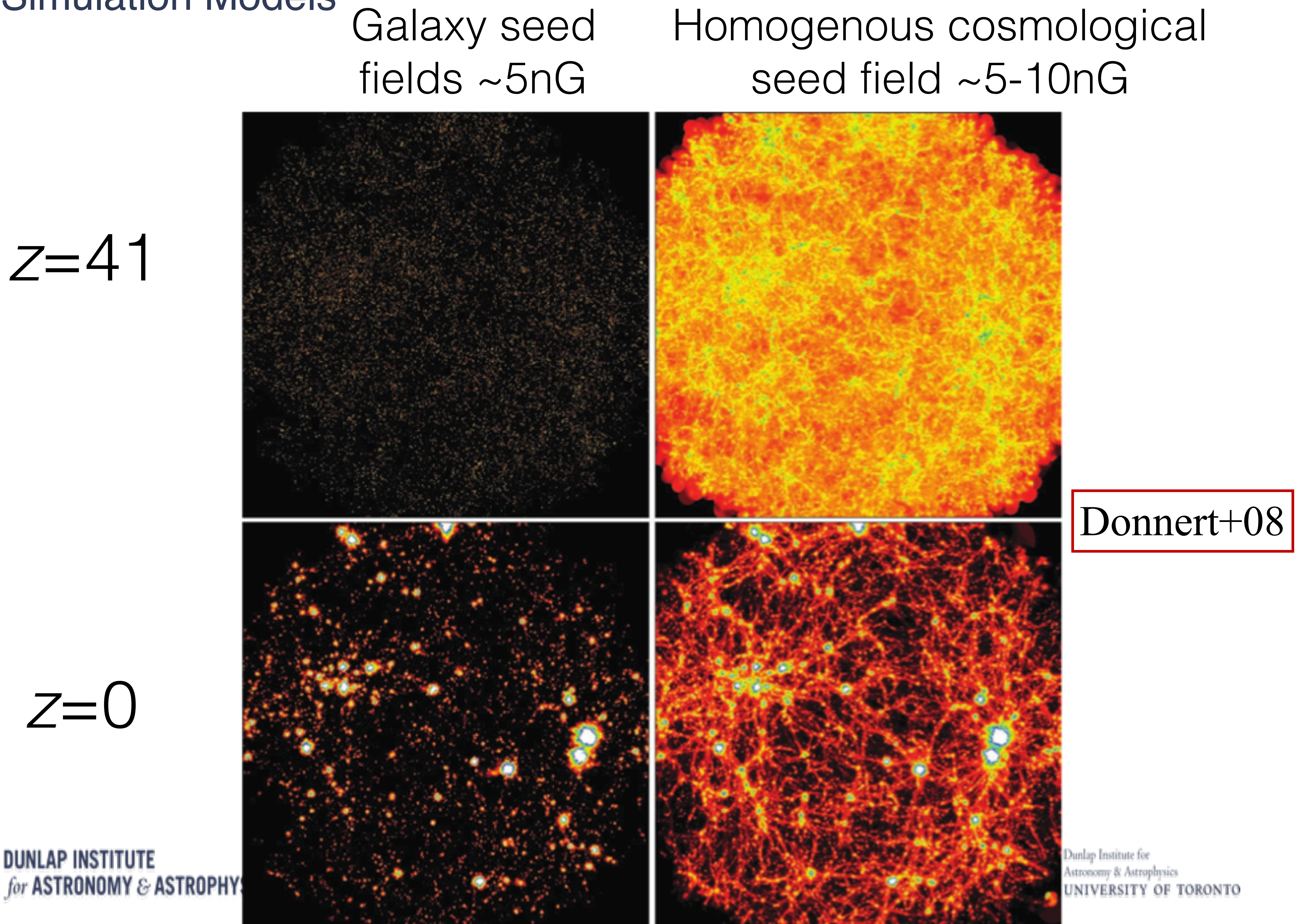
  (sim: Kulsrud+98,Donnert+08,Xu+09,Beck+13)

seeds from early Universe (z>1000):

- spatially unifrom
- inflation/phase transitions/baryogenesis...
- compression + amplification

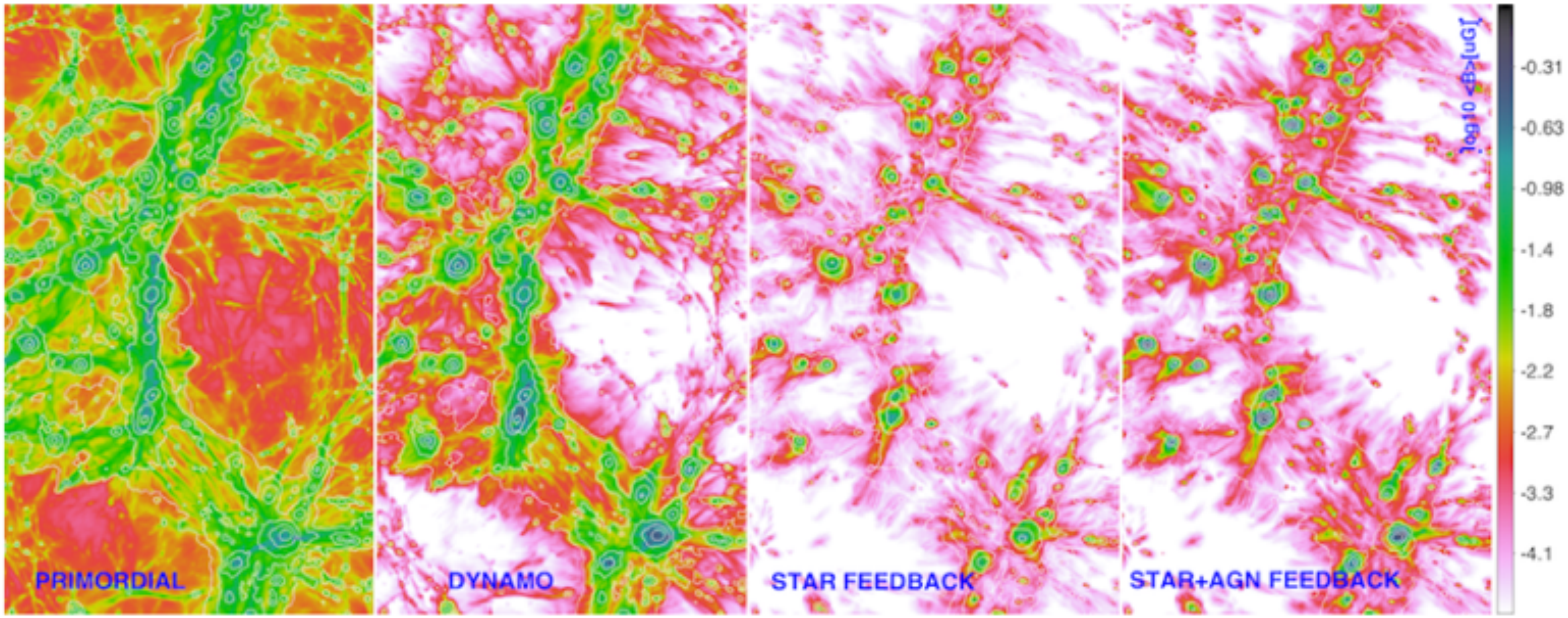
  (sim: Dolag+99,Ryu+08,FV+14,Marinacci+15)

Simulation Models



Simulation Models

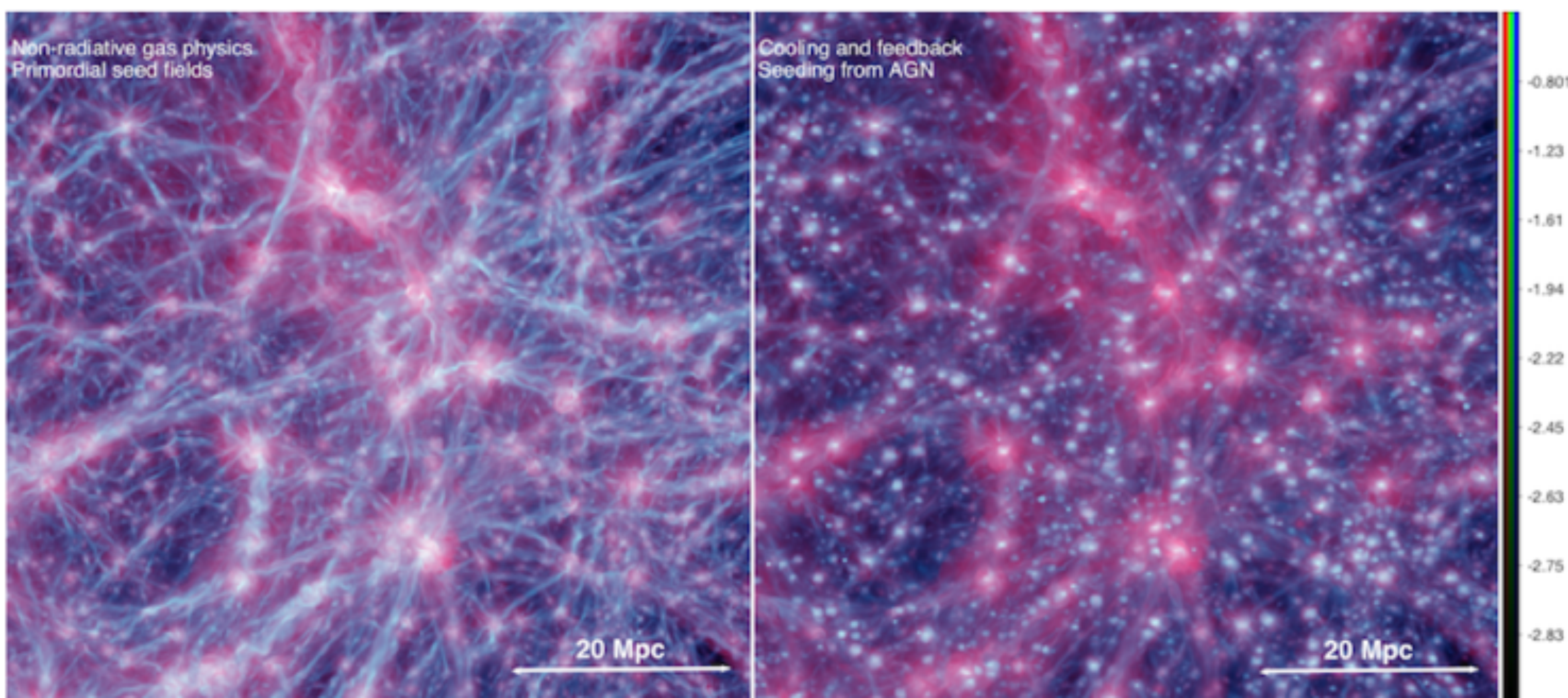
Vazza+17



Mean (mass-weighted) B-field

Primordial

AGN



RED = Temp

Green+Blue= B-field strength

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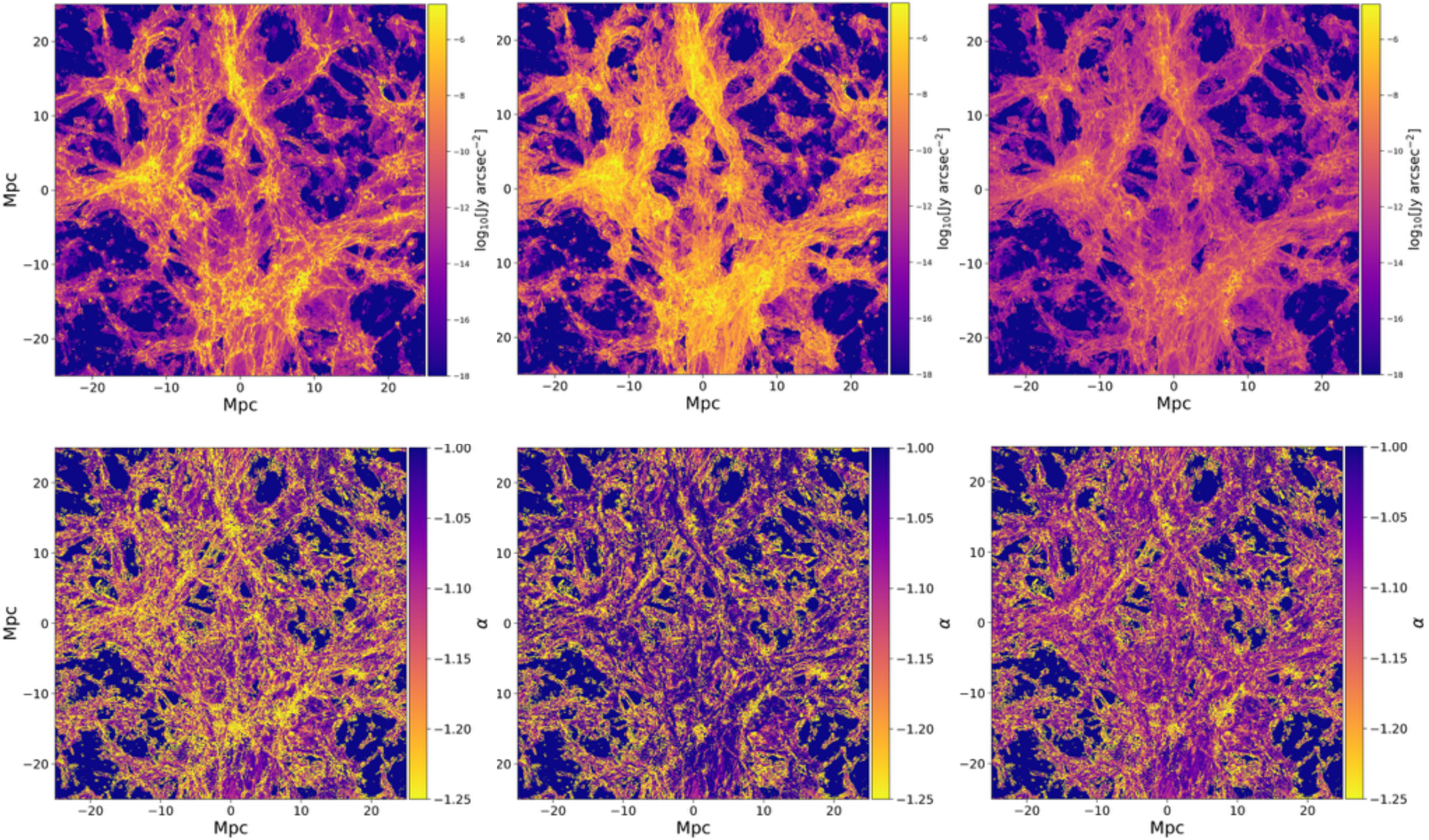
Vazza+15:
ν= 110 MHz, B_0=0.1nG at z=30

Simulation Models

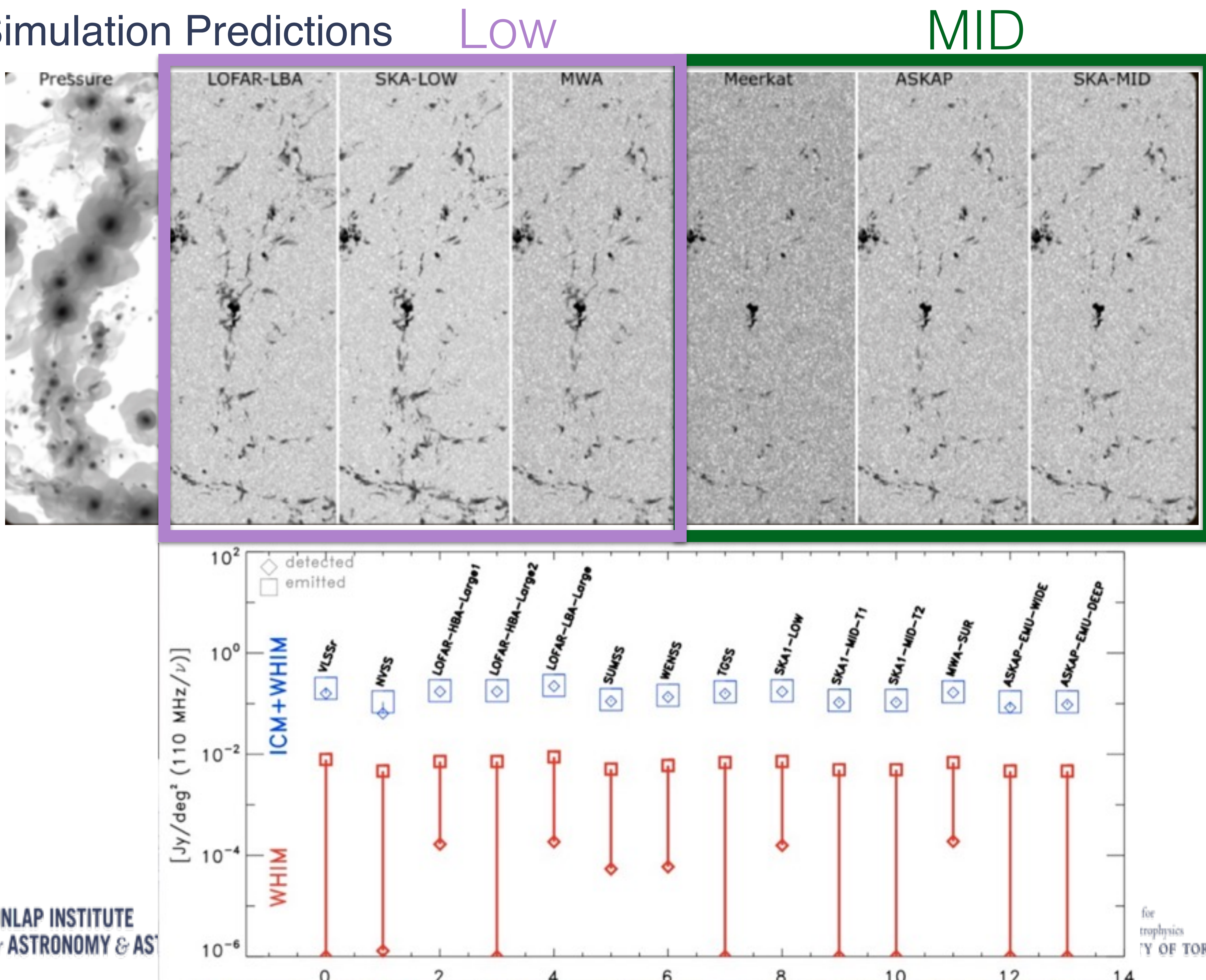
High amp w/reacceleration & shock injection

High amp + CR amp w/reacceleration & shock injection

Low amp w/reacceleration & shock injection

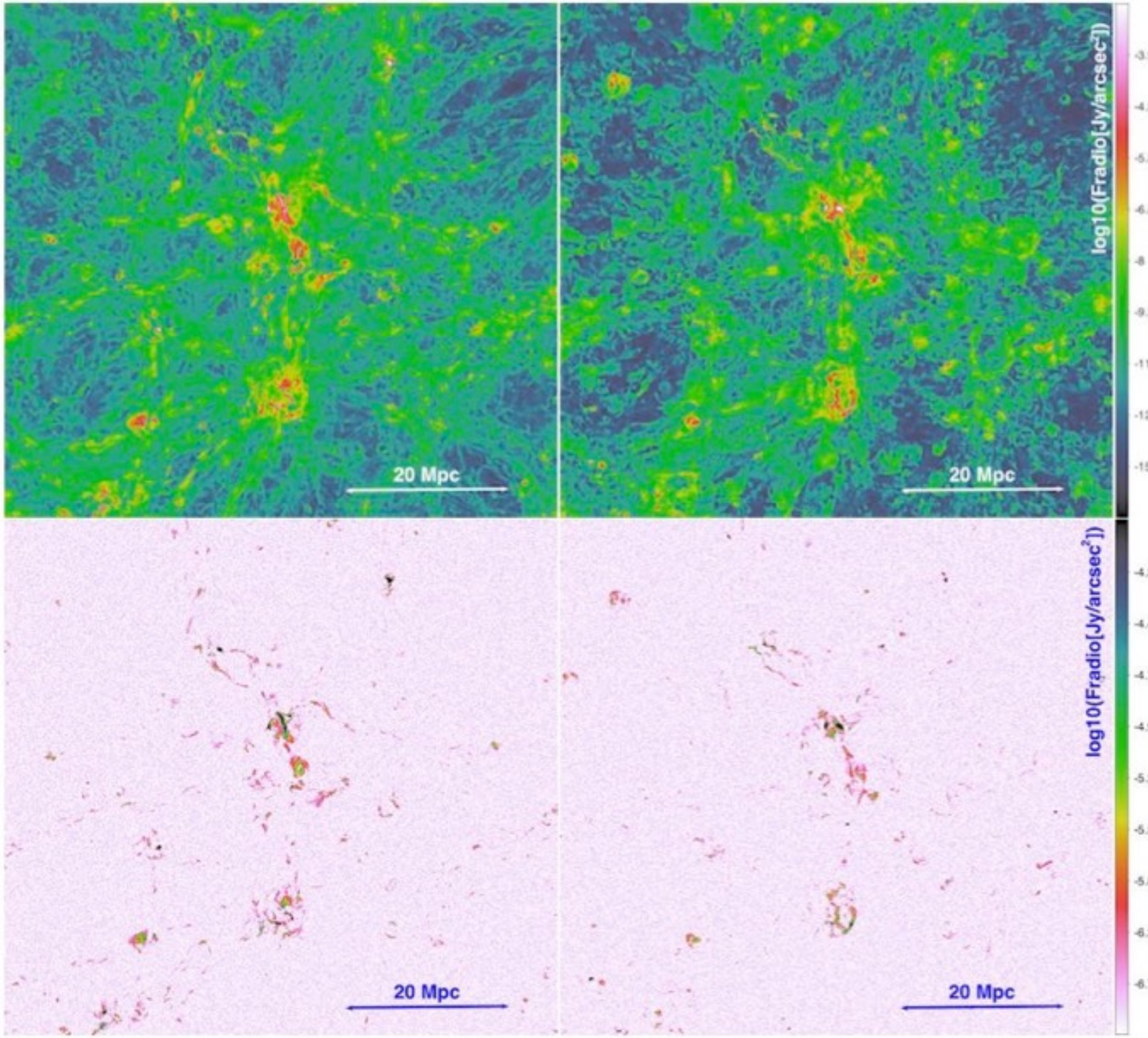


Simulation Predictions

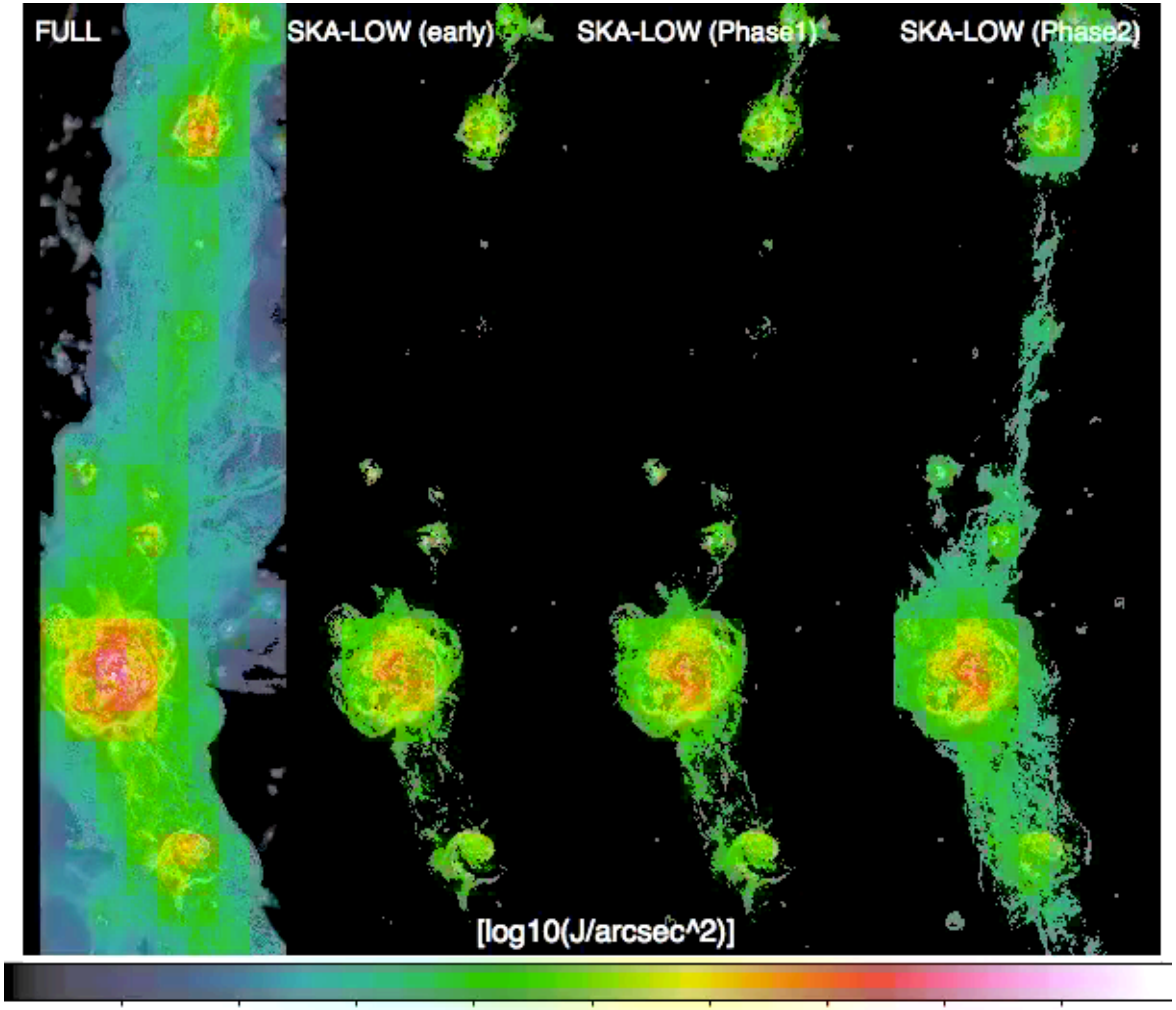


Simulation Predictions

Vazza+17

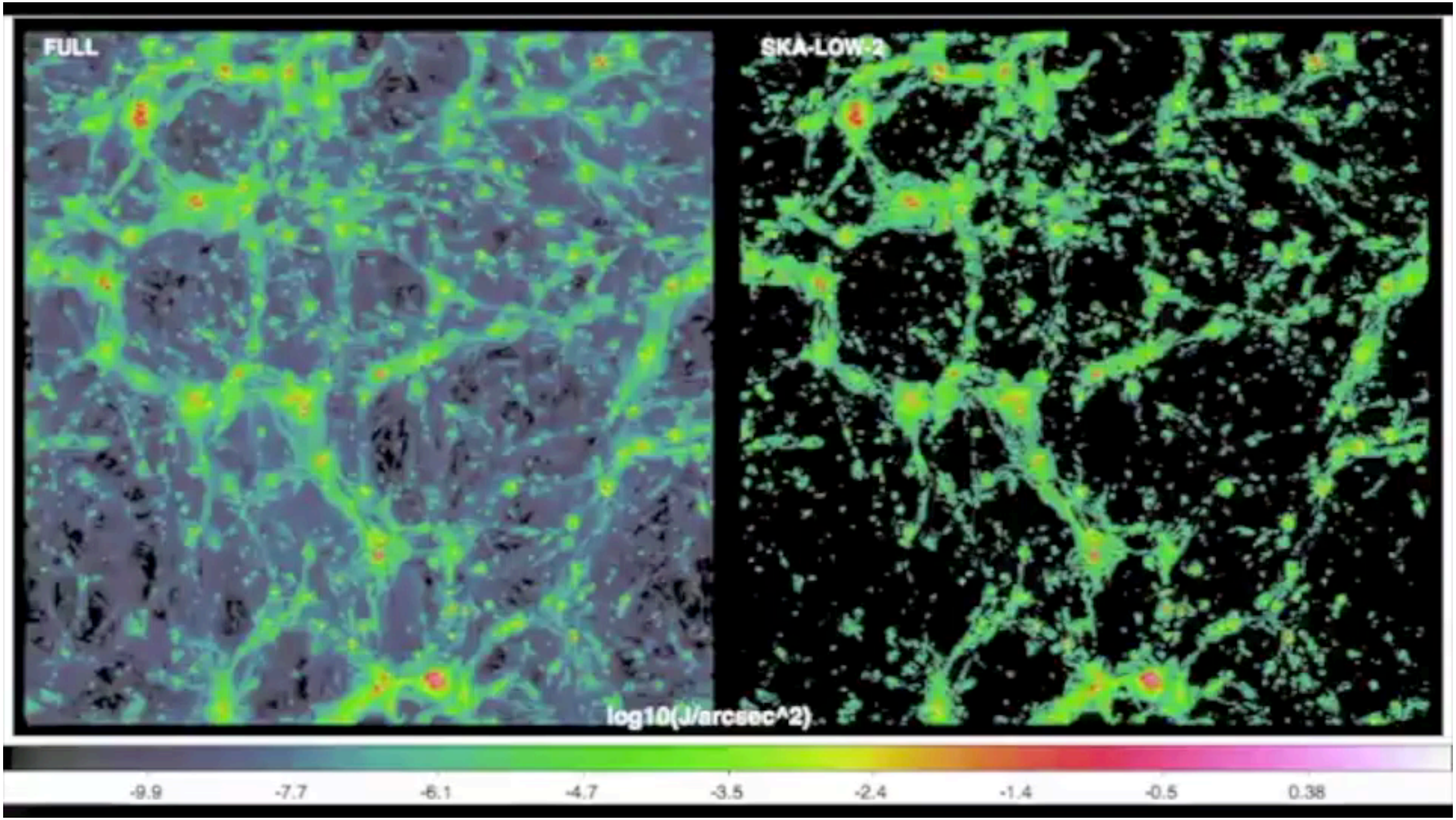


Simulation Predictions



F. Vazza, [videos link]

Simulation Predictions



F. Vazza, videos link

Simulations

- Predictions:
  - 1-2% of magnetised WHIM in filaments detectable by LOFAR, MWA, SKA
  - 5-10% of cluster outskirts may be detected
  - nano to micro Gauss range
  - Very model dependent
  - neglect artefacts, system errors, Galactic emission and point sources

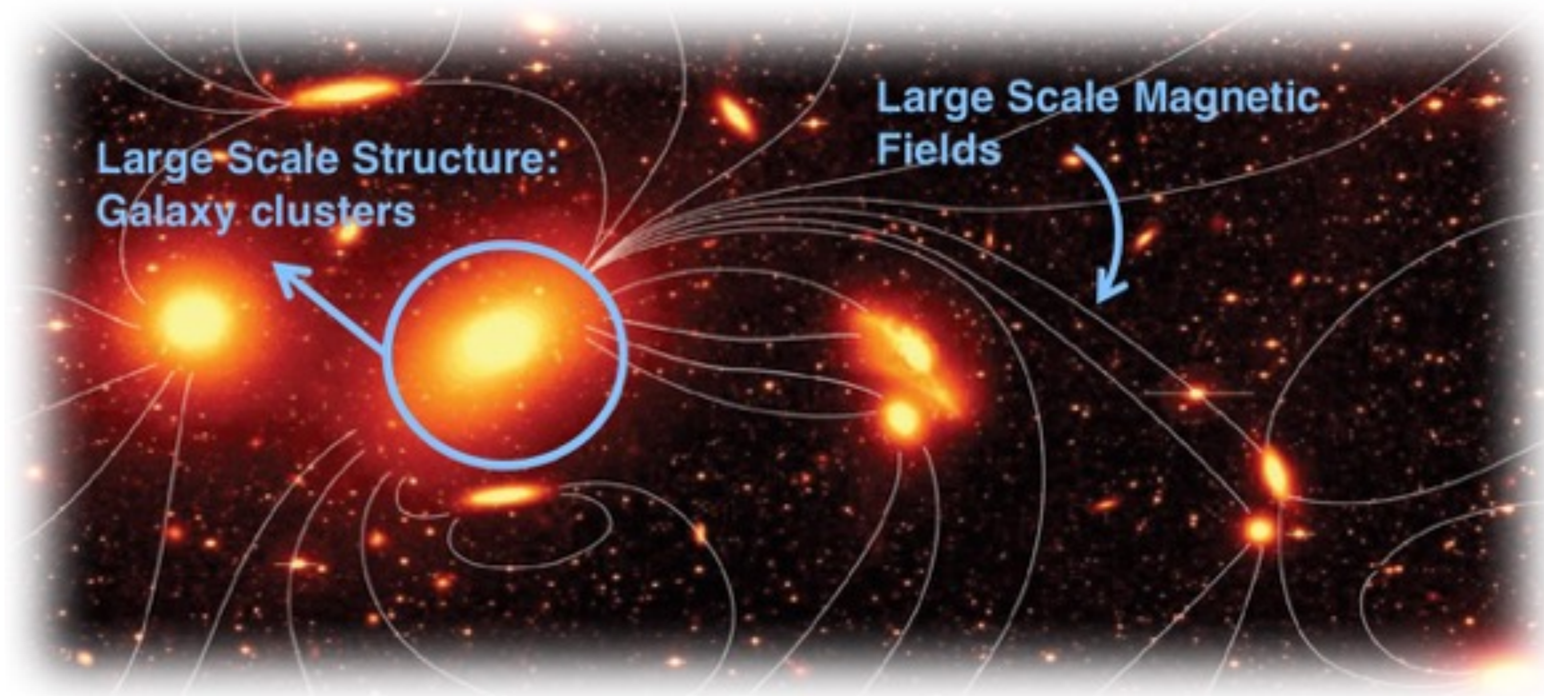
- Low frequency best

- May need to wait for full SKA-low

- Still not many simulations that include magnetism
  → Need more

How can we detect it?

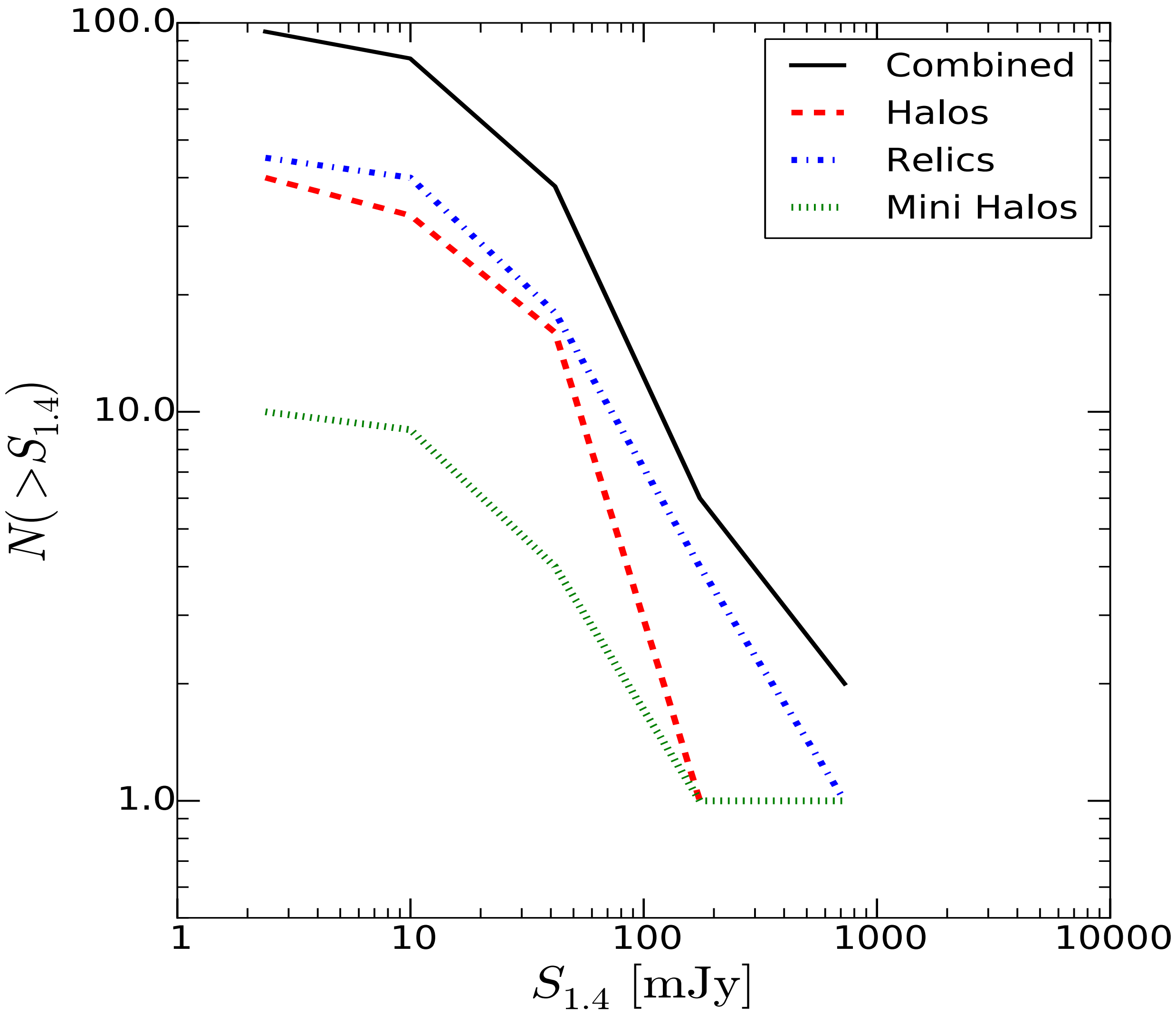
- Direct imaging / detection
- Statistical methods:
  - Cross Correlation
  - Stacking
  - Confusion

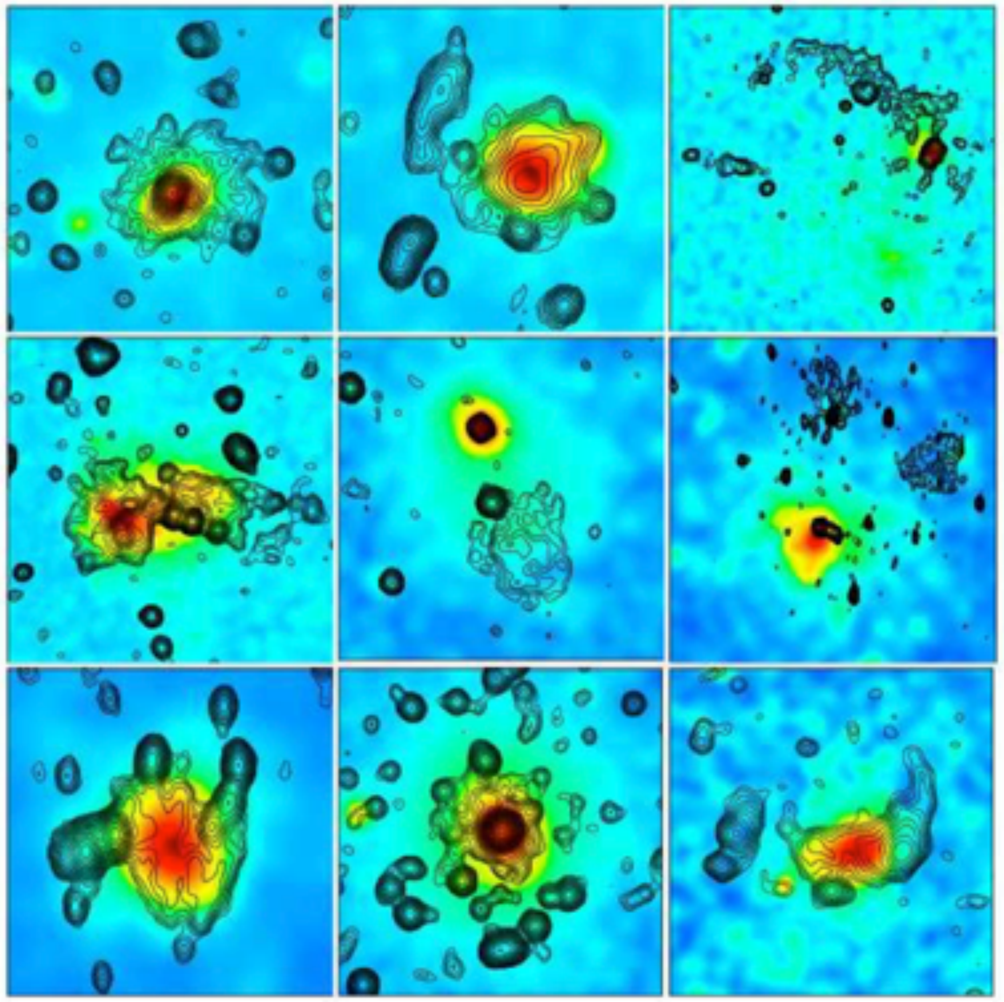


- Polarization:
  - Faraday rotation from background AGN
  - Dispersion from fast radio bursts

Diffuse Emission – Direct Imaging

- Diffuse emission in clusters
  - Halos
  - Mini-halos
  - Relics
  - But only ~100-150 detected (more coming now from low frequency surveys)





Ferretti et al., 2012

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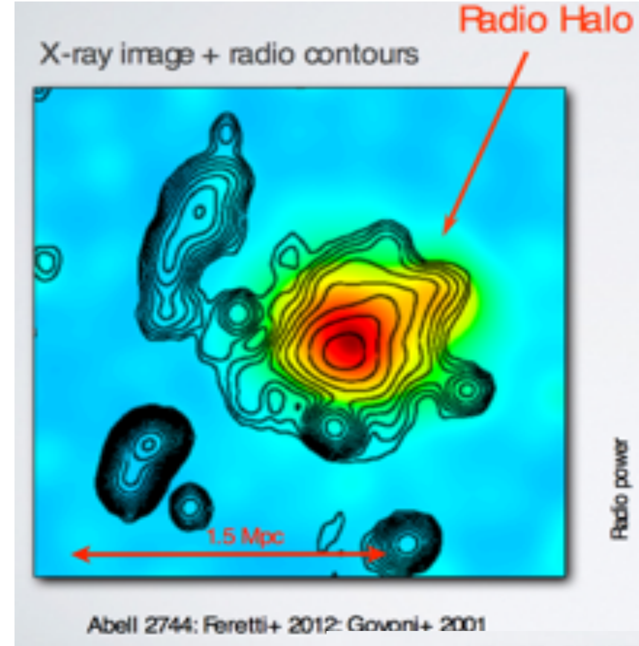
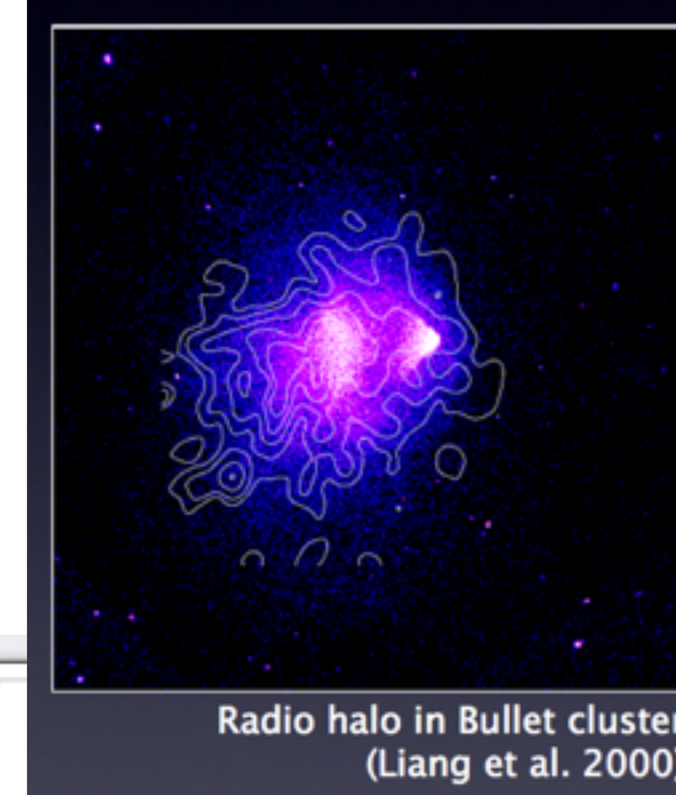
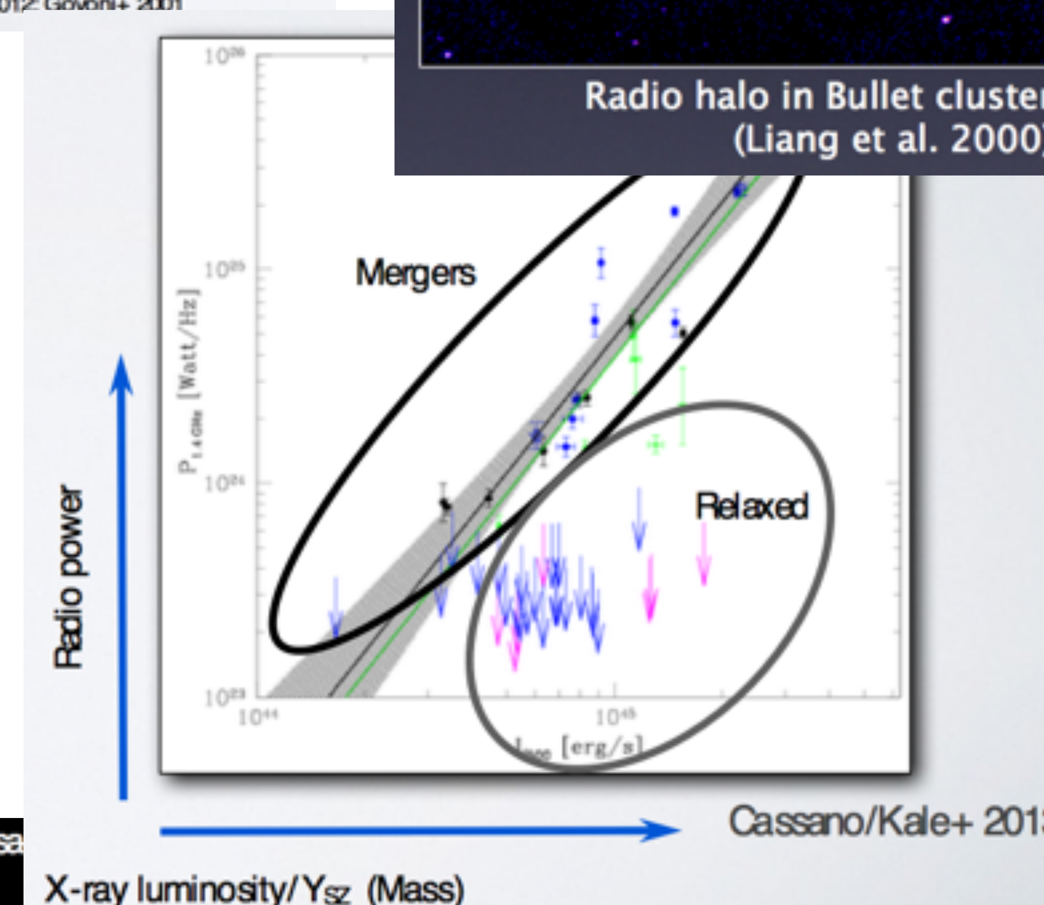
Radio Halos

- Giant and mini halos
- Mpc sizes, centrally located
- Unpolarized
- $L_{1.4\,GHz} \sim 10^{24} - 10^{25}$ W/Hz
  - Radio luminosity scales with cluster mass
- Found in disturbed clusters
- Diffuse, low surface brightness
- Steep spectrum $\alpha \sim -1.2$
  - Can have curved spectra
  - Steepening with radial distance
- Morphology similar to X-ray or SZ emission
  - No severe projection bias
- Particle acceleration mechanisms:
  - Turbulent reacceleration
  - Secondary electrons: products of hadronic collisions




Radio halo in Bullet cluster (Liang et al. 2000)



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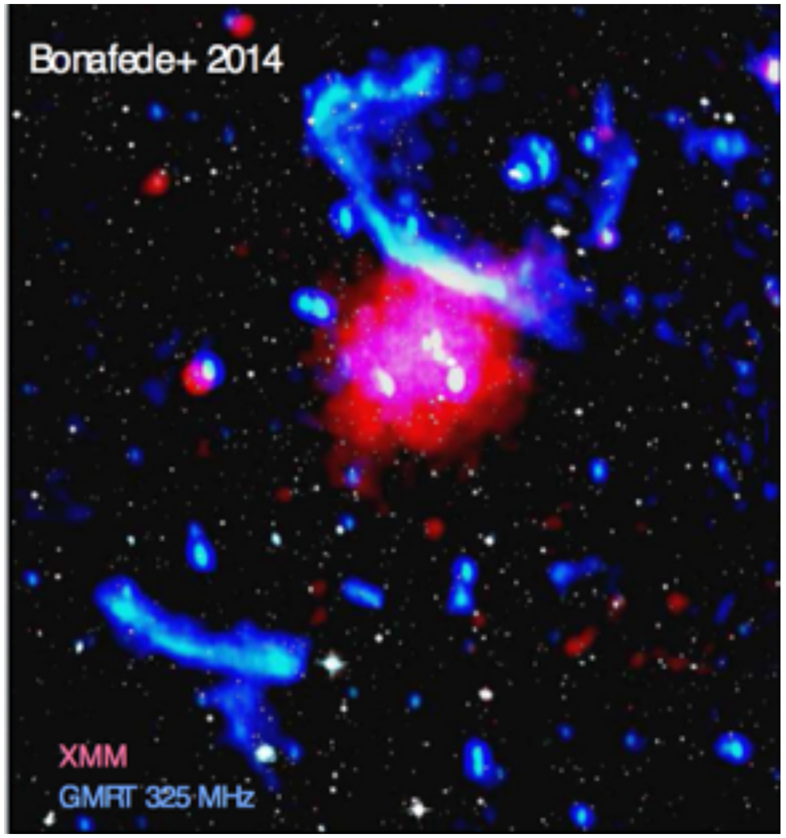
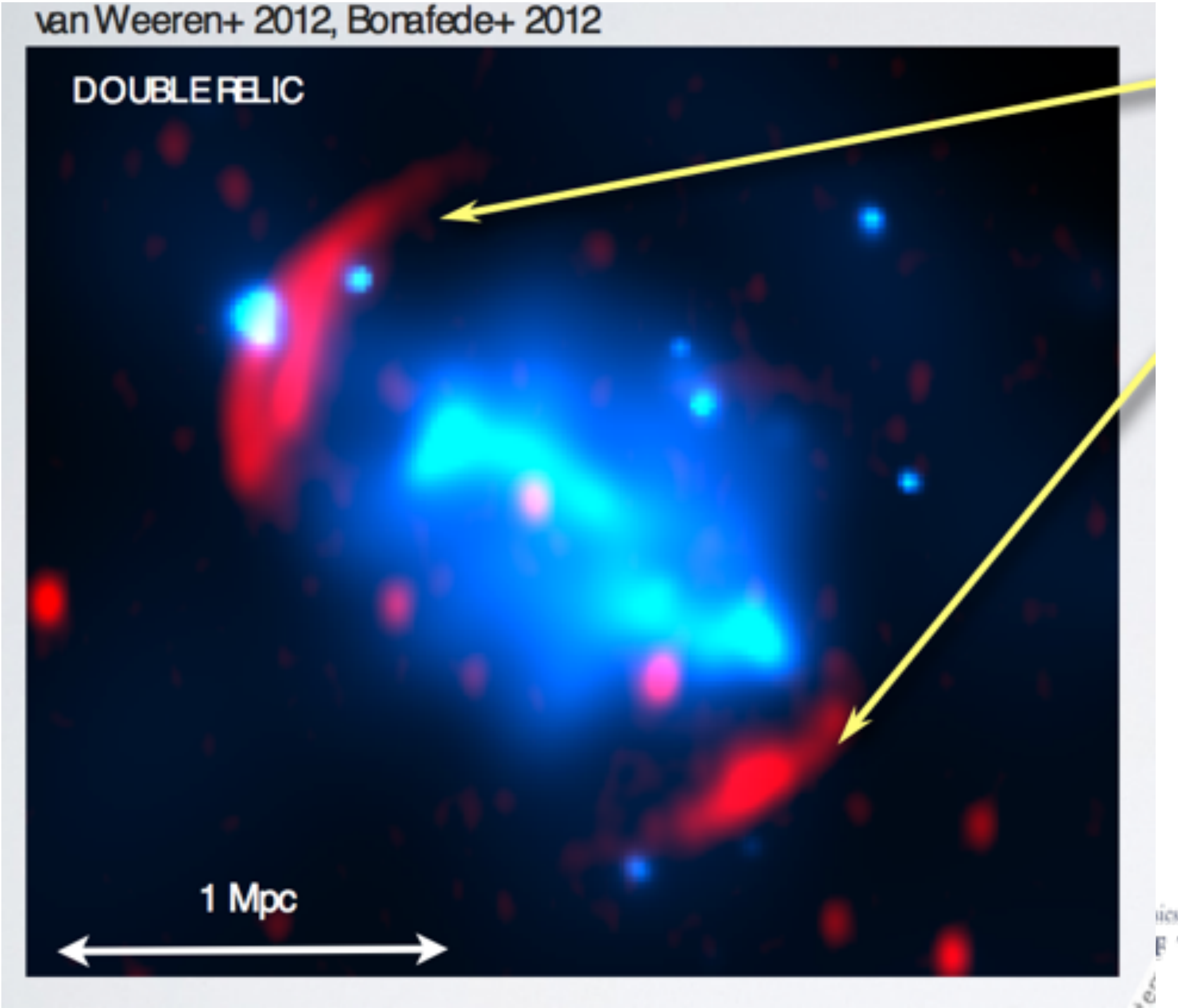
Radio Relics

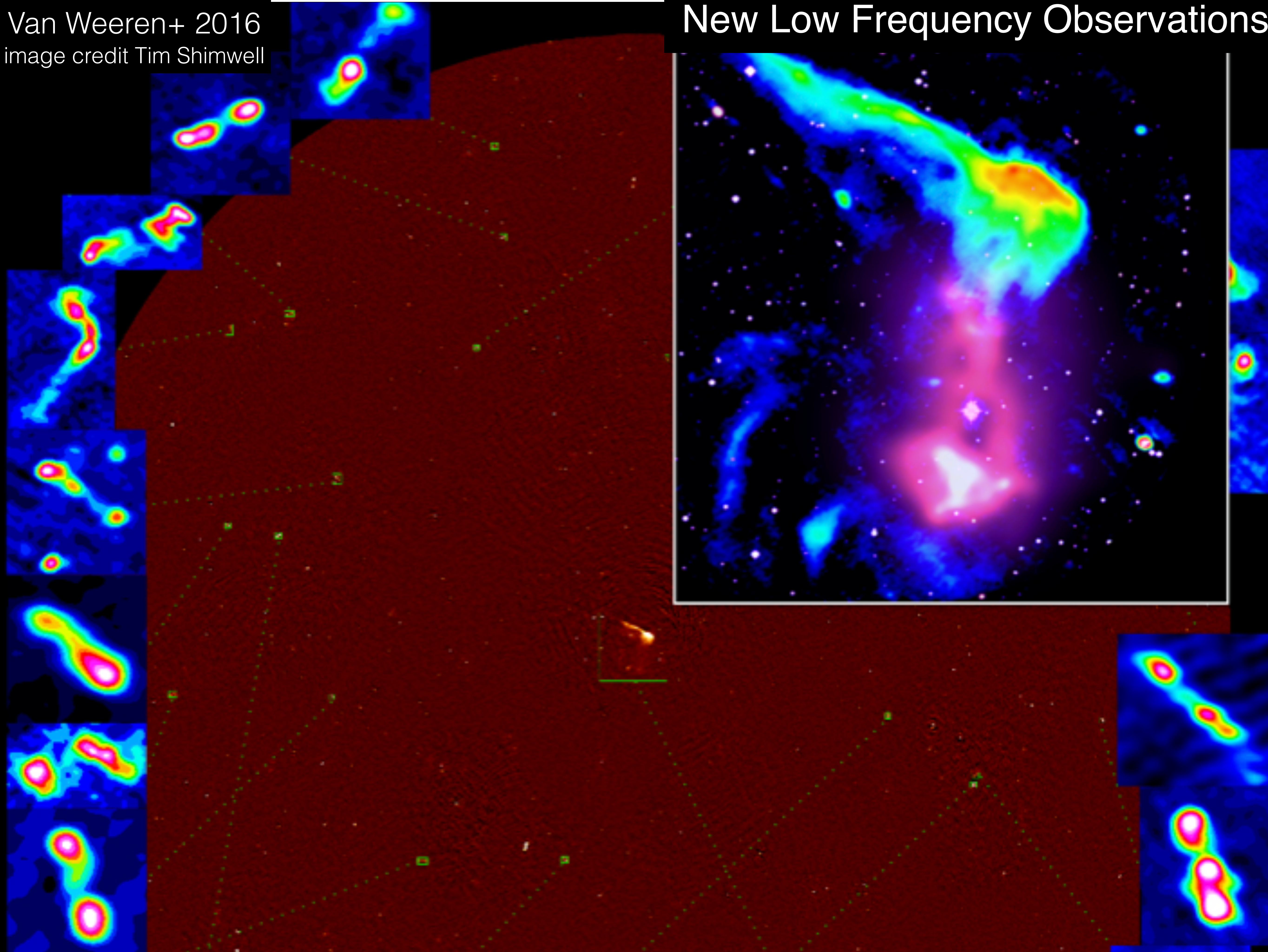
- Elongated or filamentary morphology
- Near cluster periphery
- Higher surface brightness
- Polarized
- $L_{1.4\ GHz} \sim 10^{23} – 10^{25}$ W/Hz
- Also steep spectrum $\alpha \sim -1.2$
- Traces shocks
    - Subject to projection bias

- Particle acceleration mechanisms:
    - Diffusive shock acceleration
    - Shock re-acceleration
    - Adiabatic compression

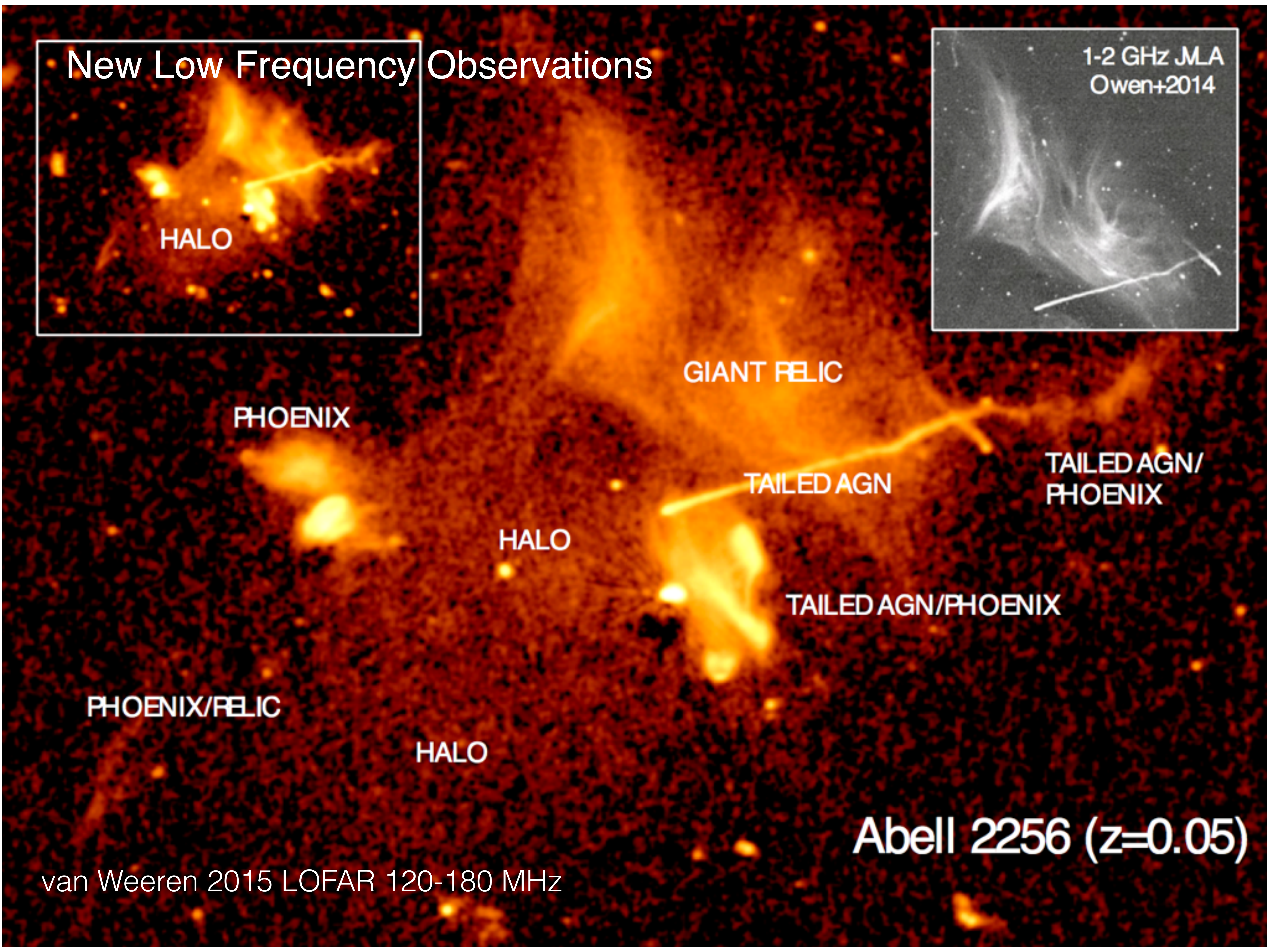




New Low Frequency Observations

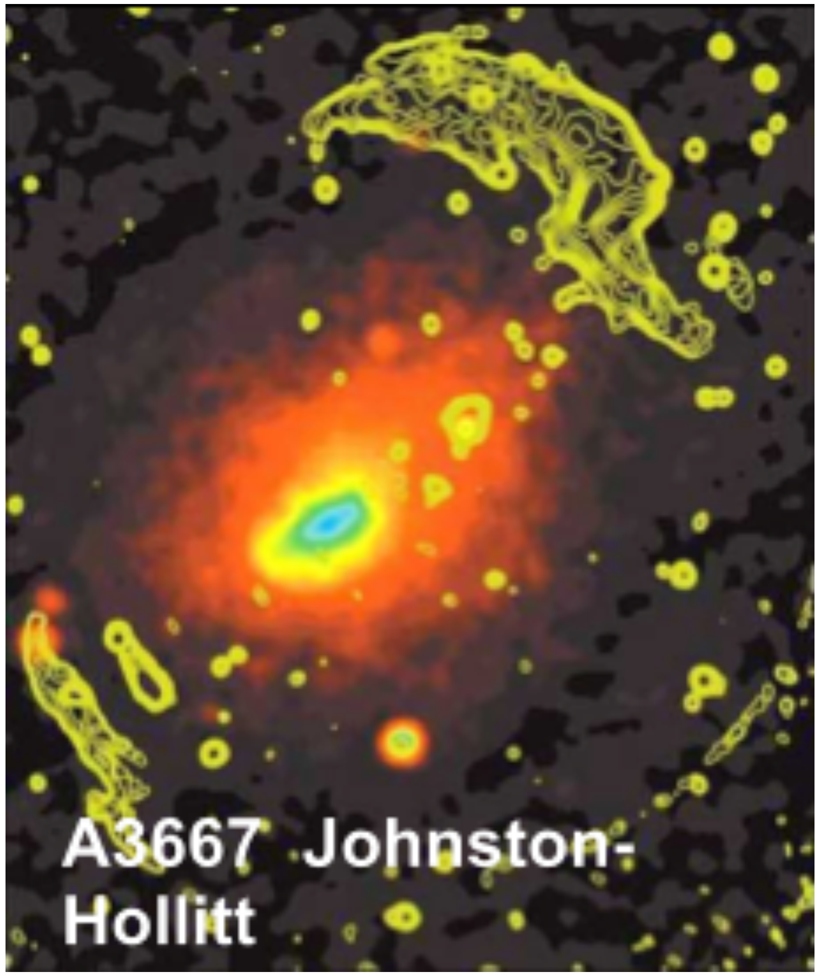


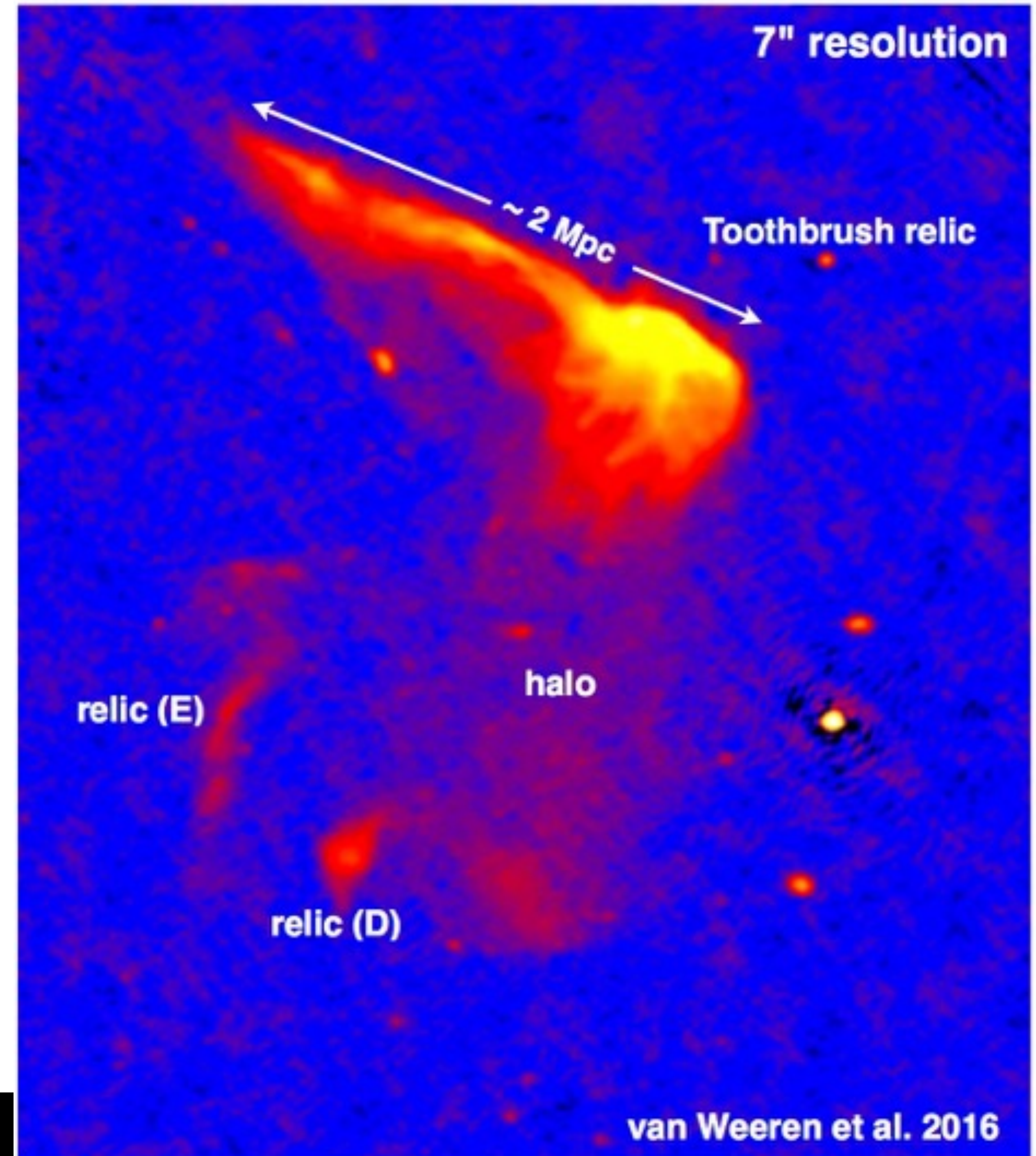
Van Weeren+ 2016
image credit Tim Shimwell

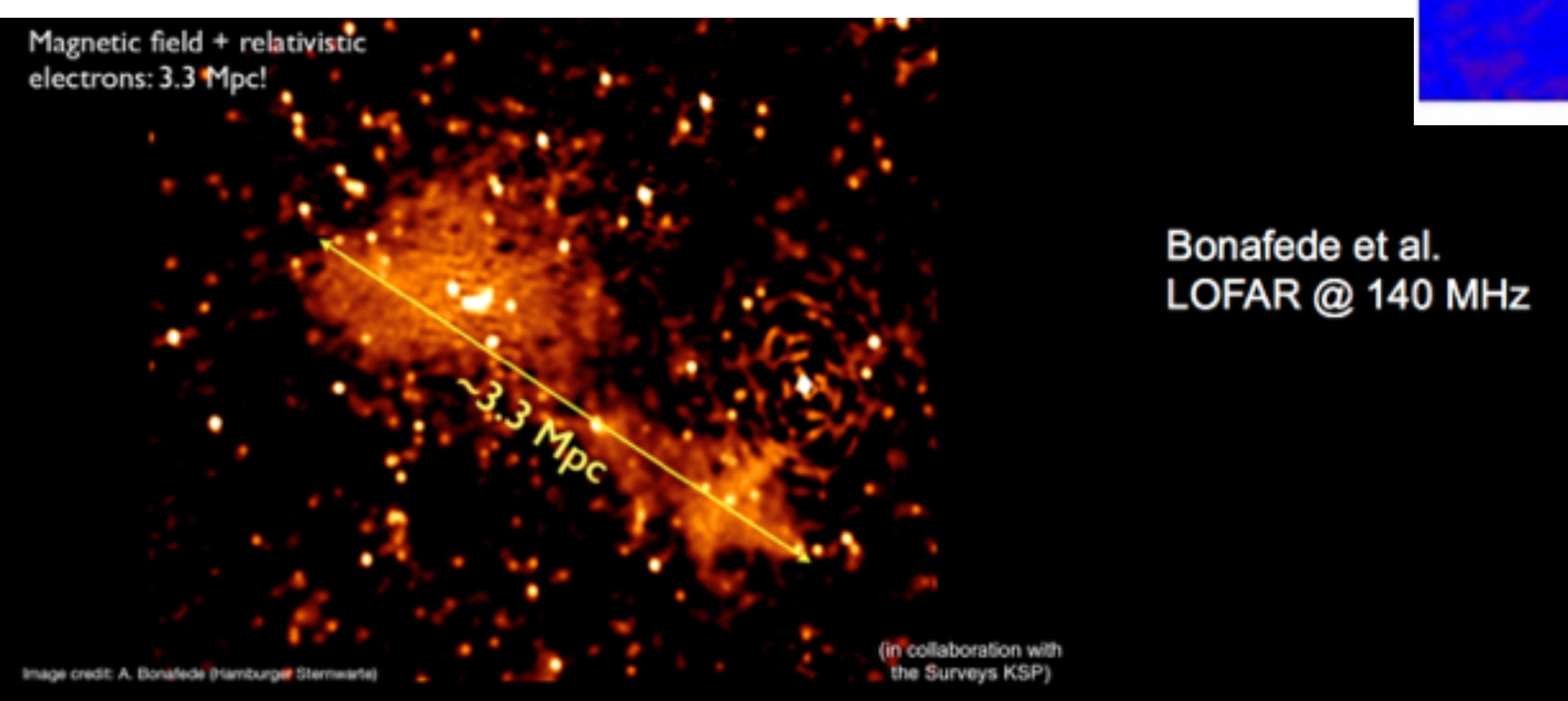


New Low Frequency Observations
HALO
1-2 GHz JVLA
Owen+2014
GIANT RELIC
PHOENIX
TAILED AGN
TAILED AGN/
PHOENIX
HALO
TAILED AGN/PHOENIX
PHOENIX/RELIC
HALO
Abell 2256 (z=0.05)
van Weeren 2015 LOFAR 120-180 MHz

New Low Frequency Observations







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Observations – Magnetic fields

- Dense cool-core clusters, 10–30μG (Kuchar & Enßlin 2011;Laing et al. 2008).

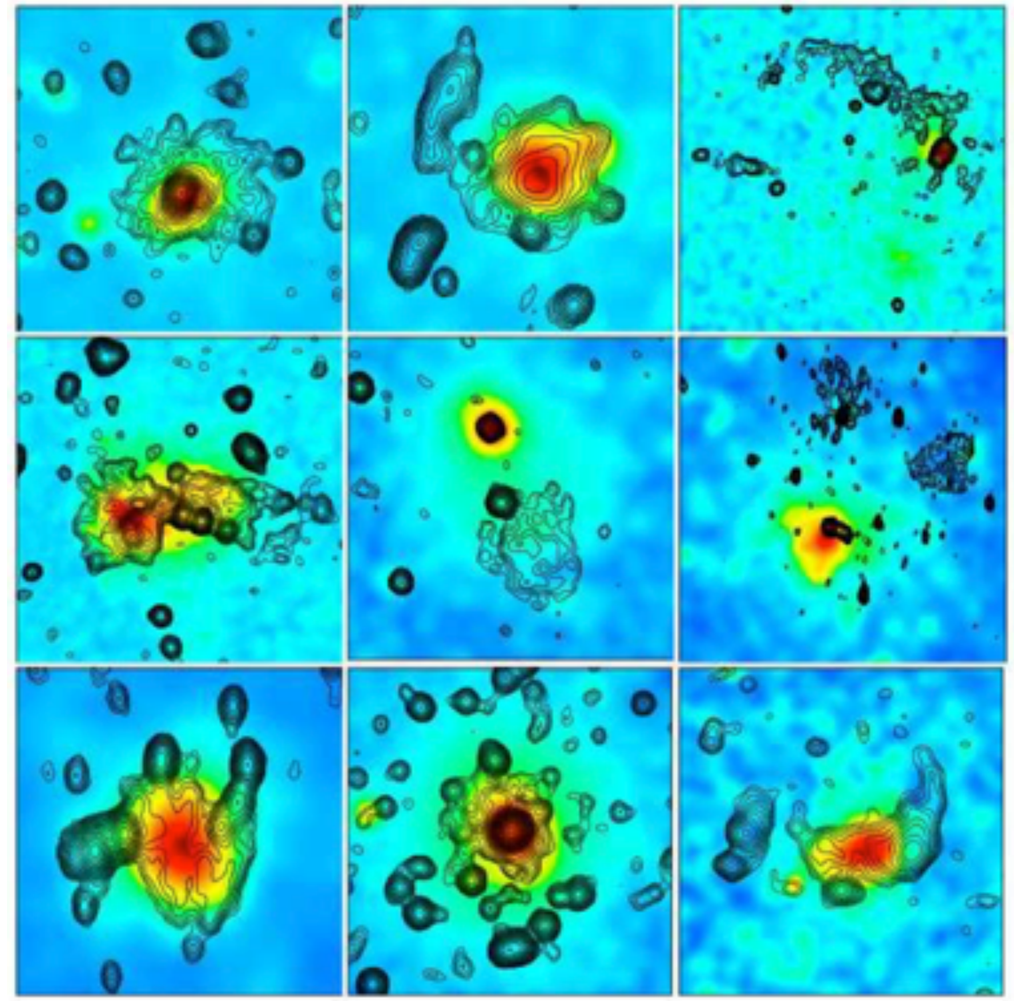
- Lower density clusters, 3–10μG (Feretti et al. 1999a; Guidetti et al. 2010; Kuchar & Enßlin 2011)

- Cluster haloes, 0.1 to 1μG (Feretti et al. 1999b)

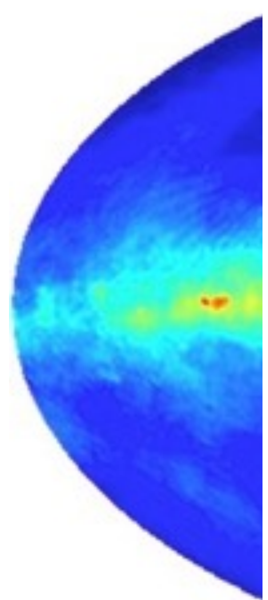
- Coma Cluster
  - 0.4μG (Giovannini et al. 1993)
  - Smoothly varying field with 2±1μG in the cluster centre to 0.3±0.1μG at a distance of 1 Mpc (Brunetti et al. 2001)

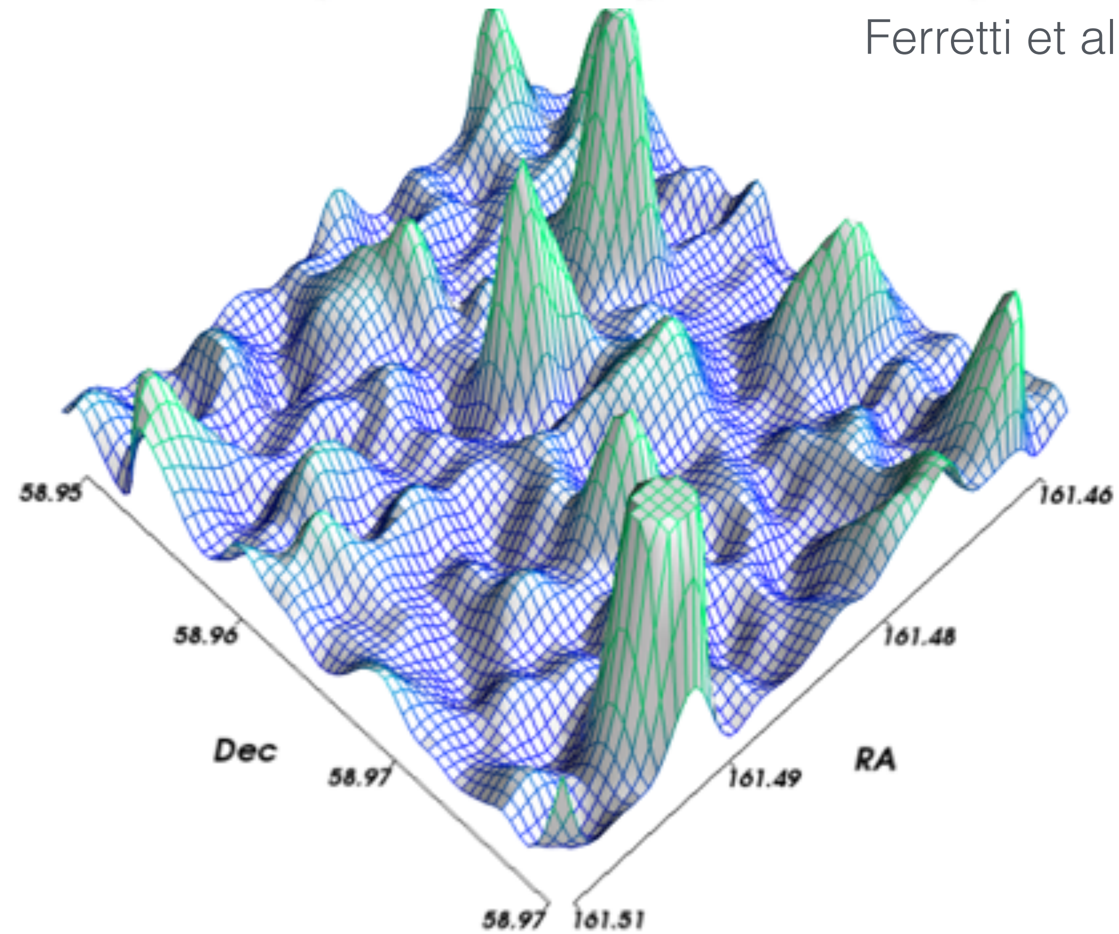
Diffuse Emission – Direct Imaging

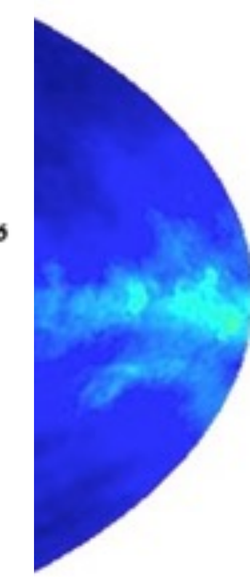
- Diffuse emission in clusters
  - Halos
  - Mini-halos
  - Relics
  - But only ~100-150 detected (more coming now from low frequency surveys)
- Only bright sources (>1mJy) in high(er) mass clusters detected.
- Difficult to directly detect due to:
  - Low surface brightness
  - Low frequencies / steep spectral indices
  - Requires high sensitivity to large angular sca
    - Sizes up to Mpc scales
    - Difficult for radio interferometer tel
  - Bright Galactic foregrounds
  - Bright point sources
  - Faint point source confusion



Ferretti et al., 2012







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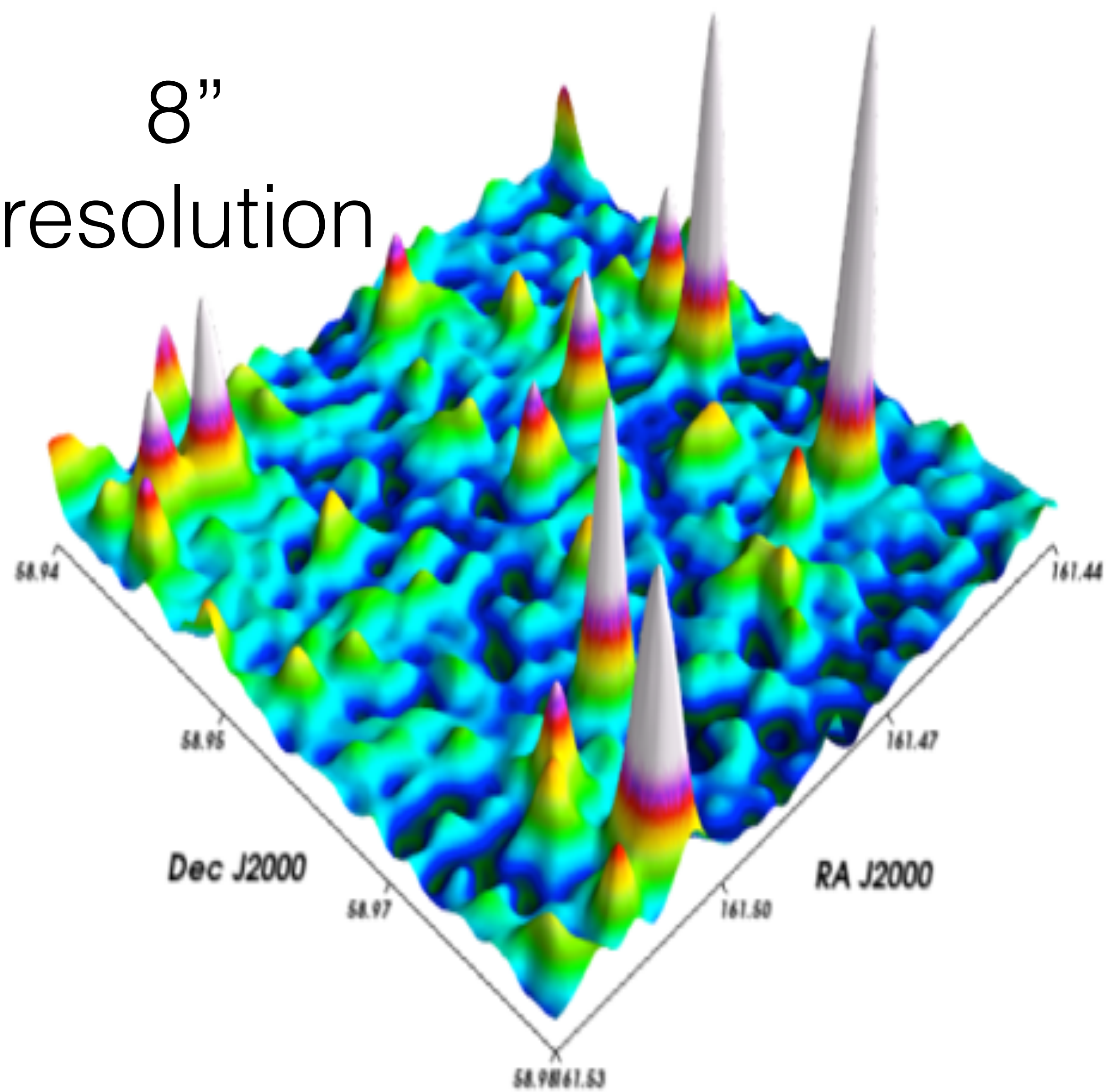
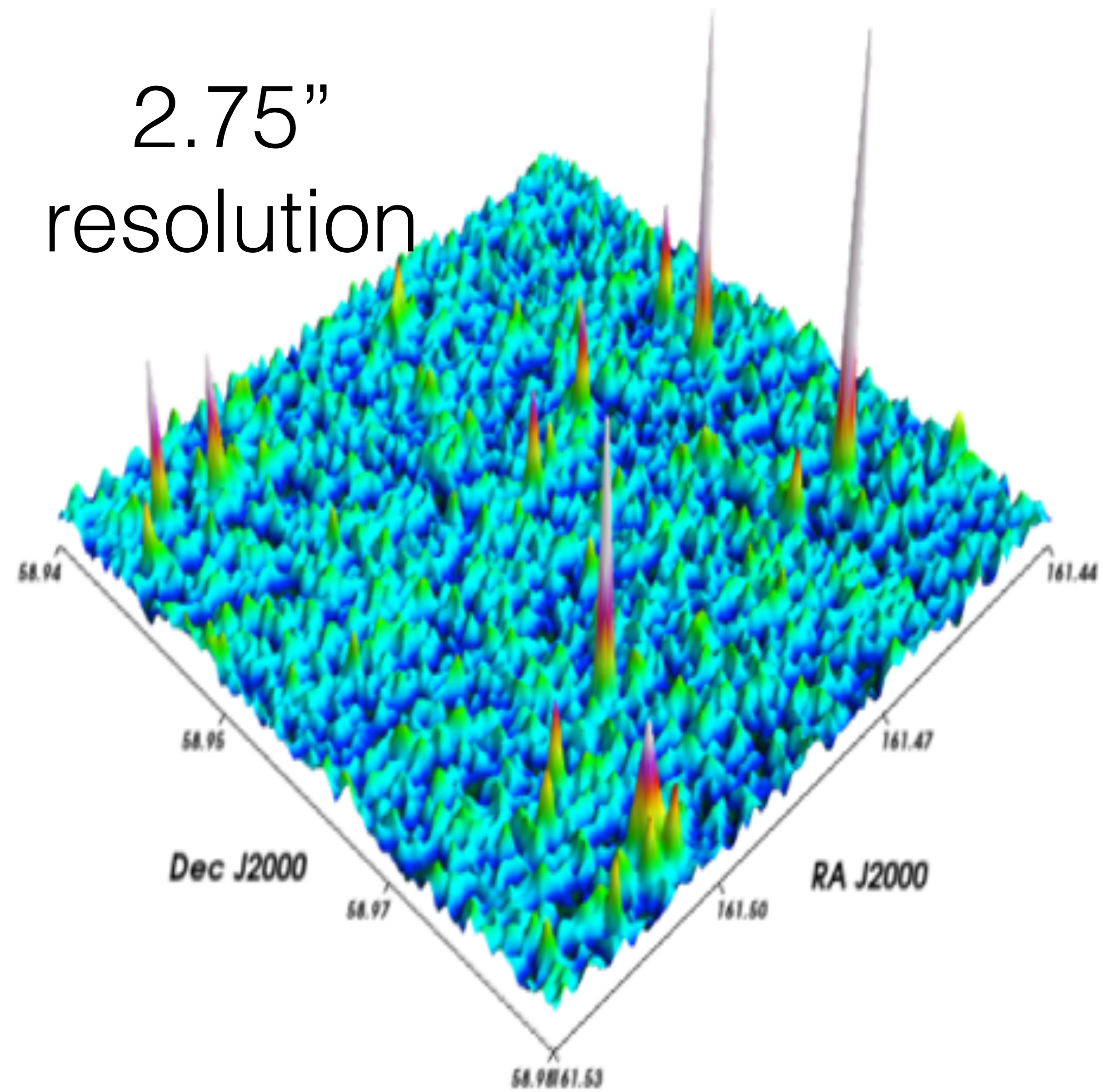
What is Confusion?

- Confusion is the blending of faint sources within a telescope beam

8” resolution

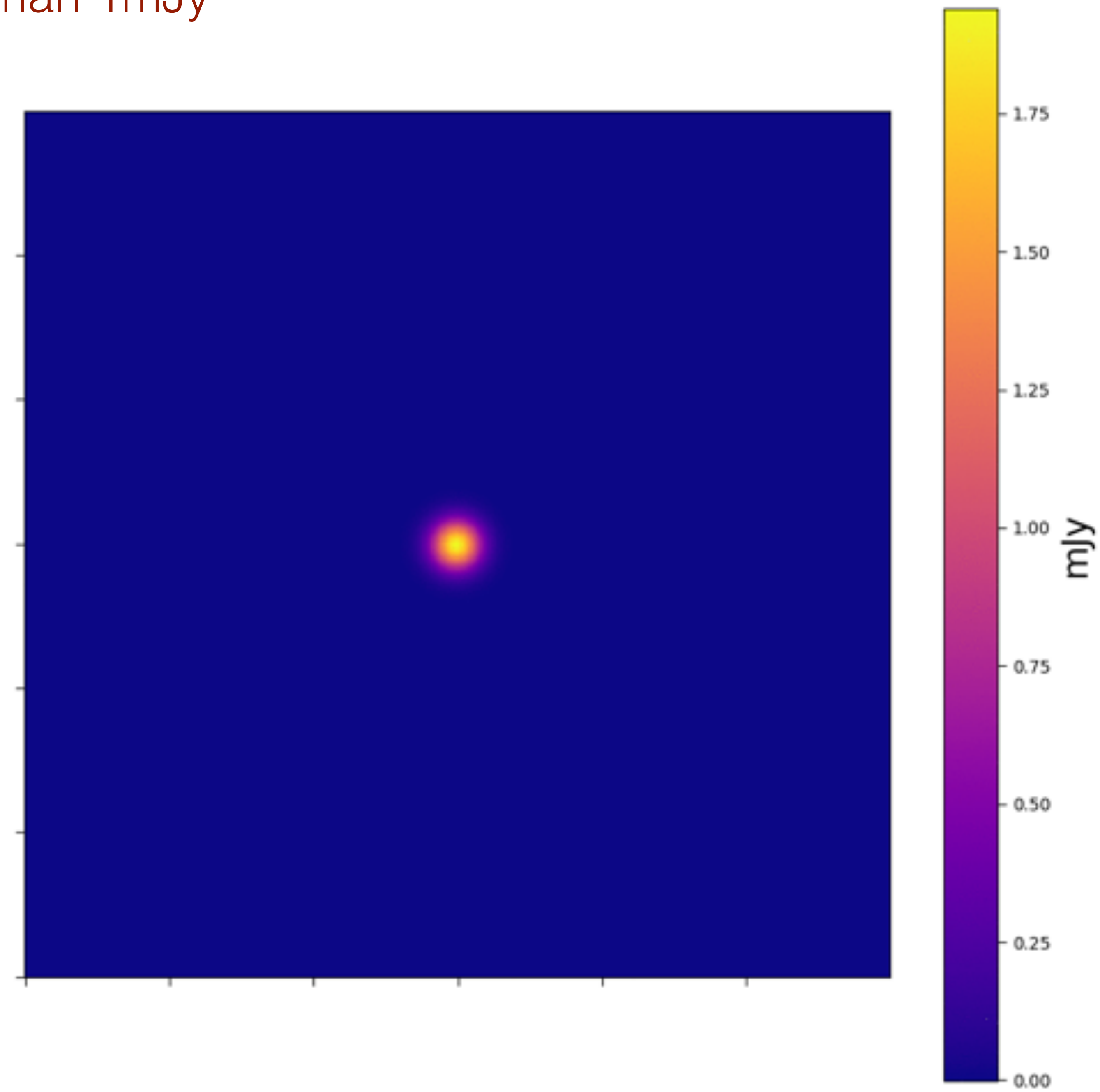


2.75” resolution



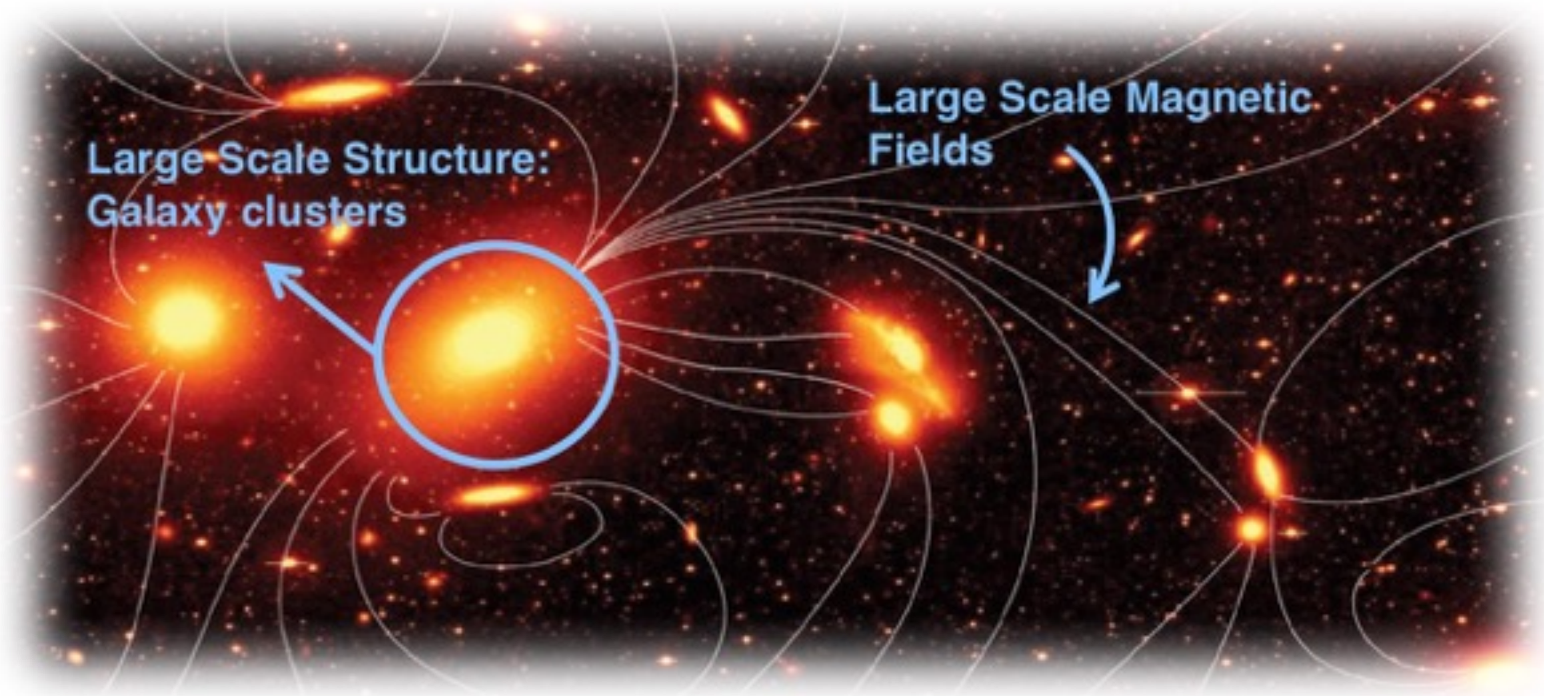
Confusion and Diffuse Emission

- Simulated Gaussian “Halo”
  - 60” size
  - 5 mJy total brightness
  - 45” beam
  - Addition of brighter and brighter point sources
    - None brighter than 1mJy



How can we detect it?

- Direct imaging / detection
- Statistical methods:
  - Cross Correlation
  - Stacking
  - Confusion
- Polarization:
  - Faraday rotation from background AGN
  - Dispersion from fast radio bursts



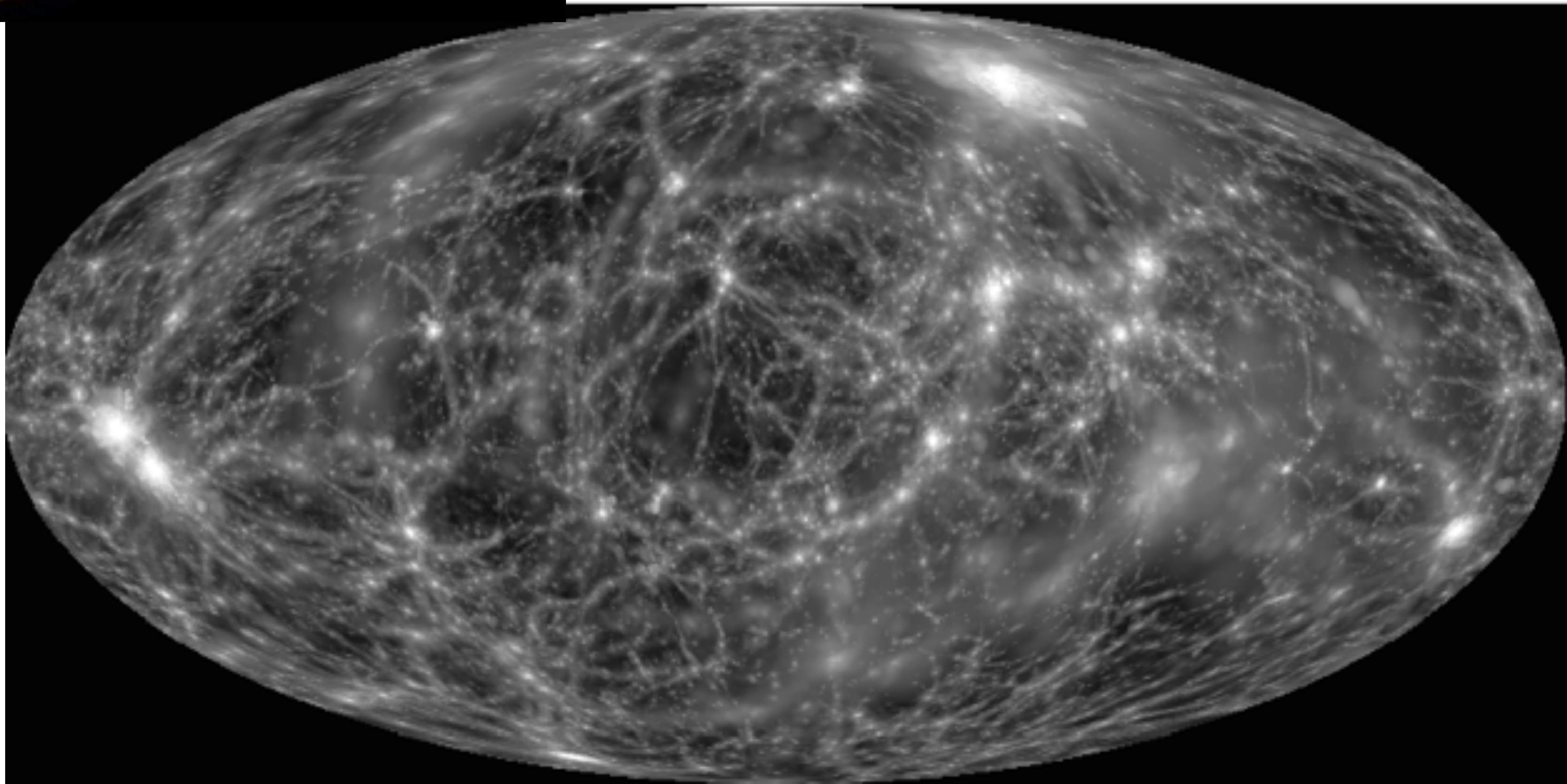
Cosmic Web - Cross Correlation

- Galaxy number density → traces thermal baryon distribution → should correlate with diffuse synchrotron

Cosmic Web - Cross Correlation

- Galaxy number density → traces thermal baryon distribution → should correlate with diffuse synchrotron

2MASS Galaxy Distribution coded by redshift
(photo credit :Thomas Jarrett (IPAC/Caltech)



Simulated radio synchrotron
(credit: Klaus Dolag)

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Cosmic Web - Cross Correlation

- Galaxy number density → traces thermal baryon distribution → should correlate with diffuse synchrotron

- How correlated as a function of distance or angular scale?
  - Unknown

- How correlated?
  - Unknown

- Reasons for a positive correlation:
  - AGN (core)
  - Starbursts and disk emission
  - AGN (WAT and NAT associated with clusters)
  - Cluster halos
  - Cluster relics
  - Synchrotron cosmic web

- Reasons for a negative correlation:
  - Galactic extinction (galaxy number counts down, synchrotron up)

Increasing angular scale

Cross Correlation with MWA

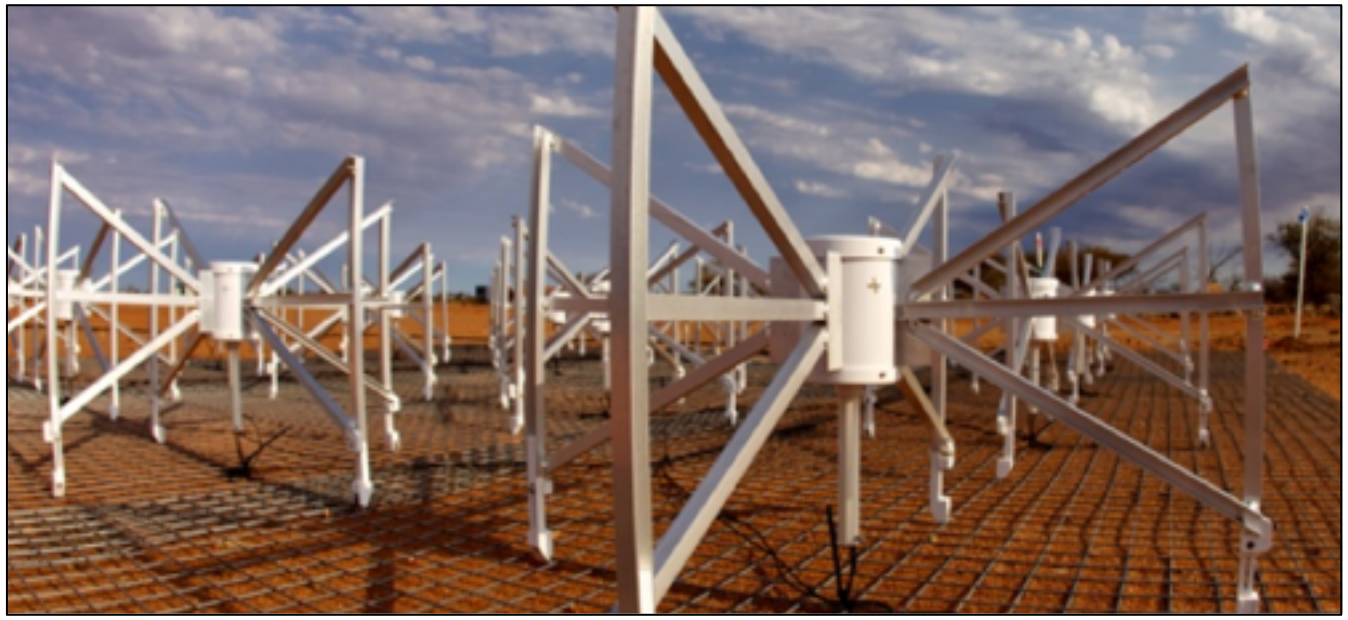


Photo credit: Natasha Hurley-Walker

The MWA:

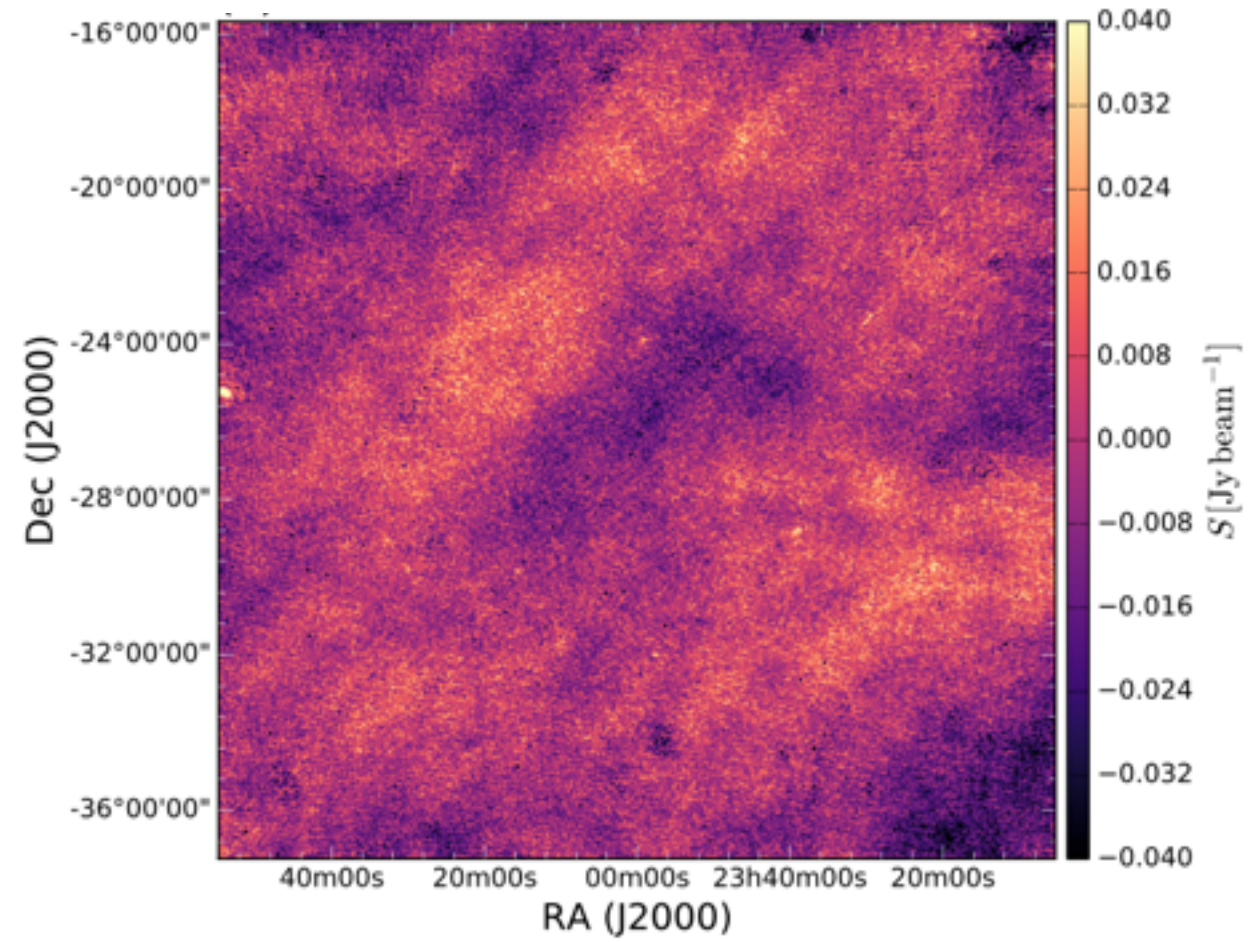
- Frequency range: 80 – 300 MHZ
- 2048 dual polarization dipoles
- Number of antenna tiles: 128
- Number of baselines: 8128
- Approximate collecting area: 2000 sq. meters
- Field of view: 15 - 50 deg. (200 - 2500 sq. deg.)
- Instantaneous bandwidth: 30.72 MHz
- Spectral resolution: 40 kHz
- Temporal resolution: 0.5 seconds
- Polarization: I, Q, U, V

★ Good sensitivity to large angular scales, low frequency, large field of view

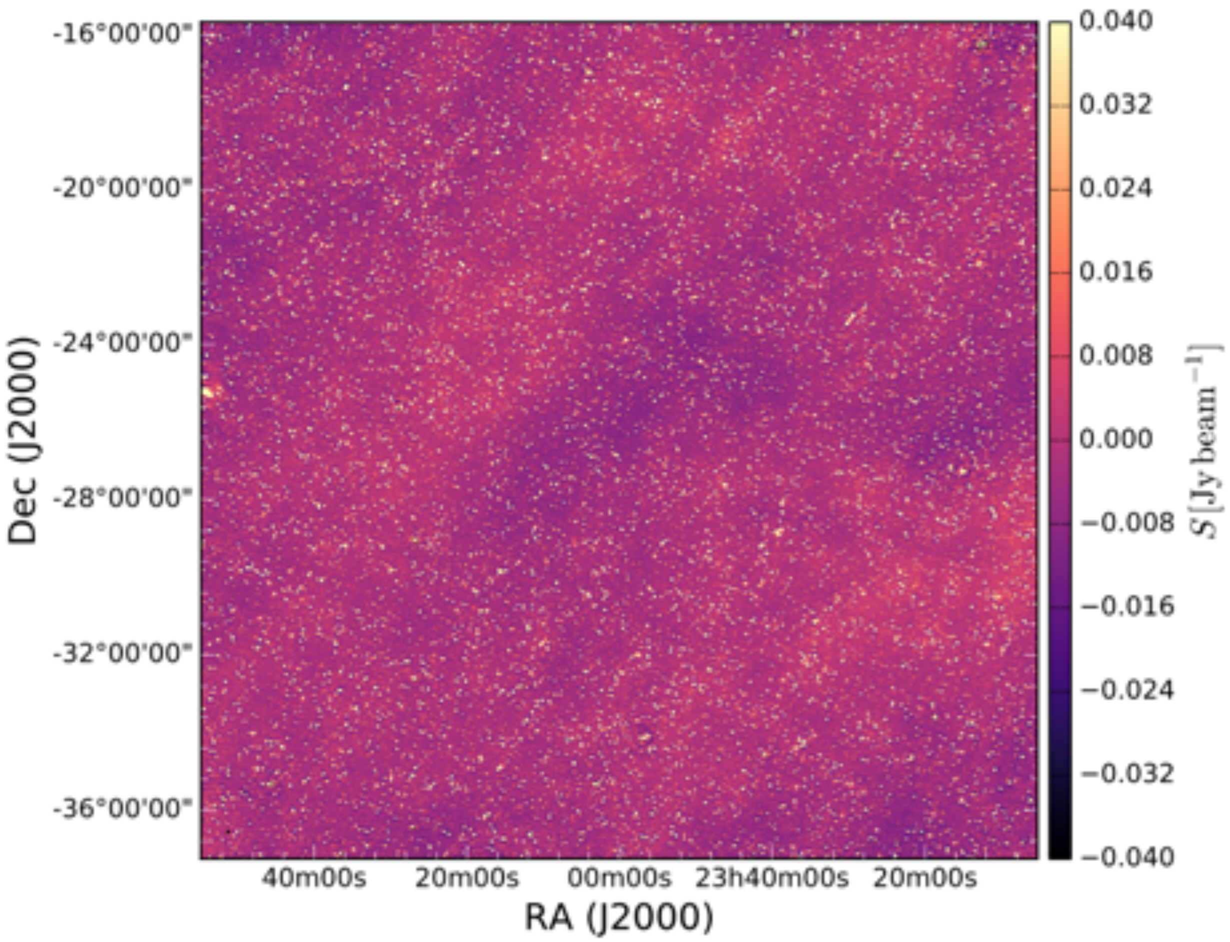
Cross Correlation with MWA - Radio

- Field: EoR0 RA=0 Dec= -27
- υ = 180 MHz
- Beam 2.3' – 2.9'
- σ_n= 0.6 – 0.96 mJy $beam^{-1}$
- σ_c = 4.4 - 9.5 mJy $beam^{-1}$
- Subtraction limit ~ 50 mJy

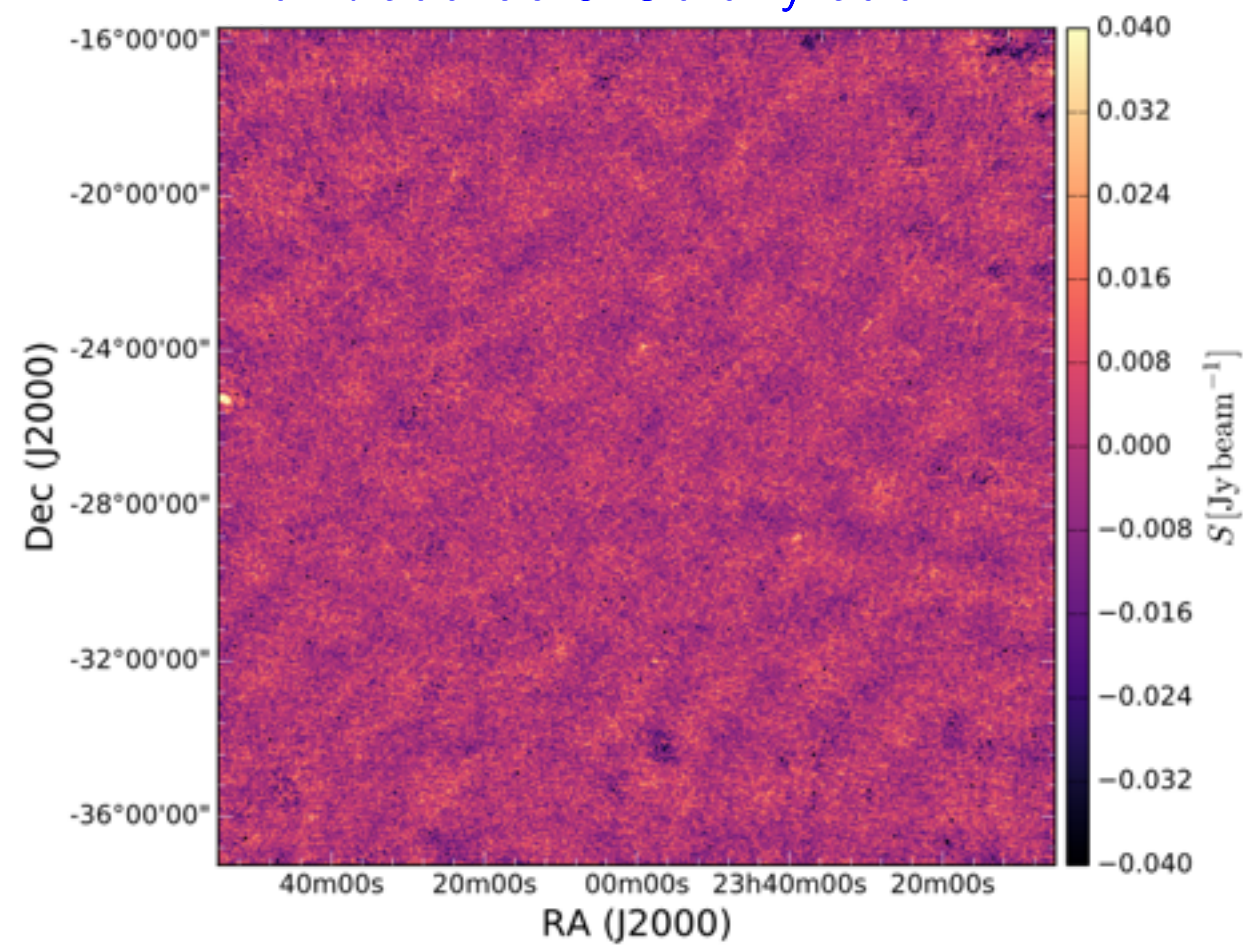
Point source sub



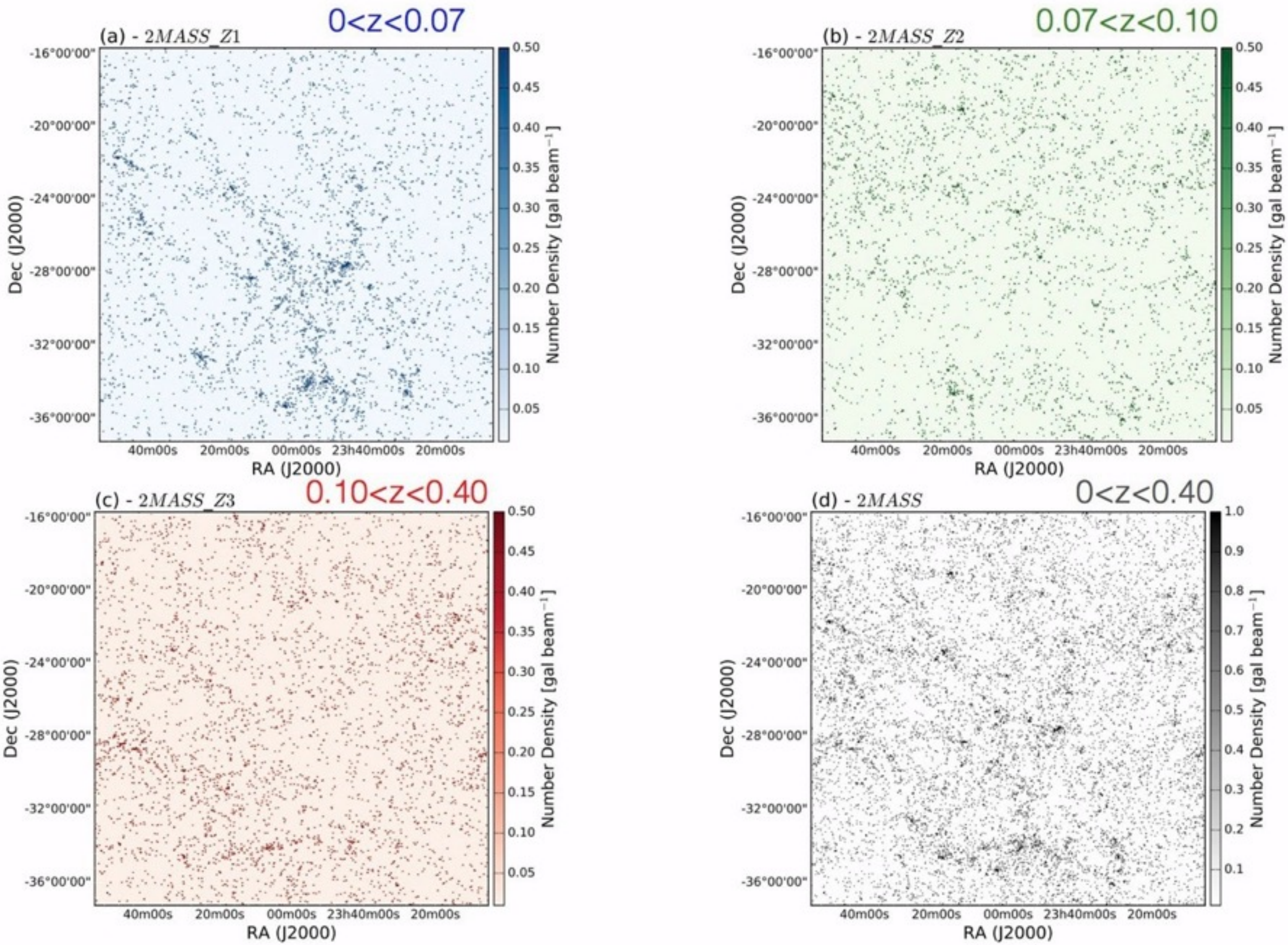
Full



Point source & Galaxy sub

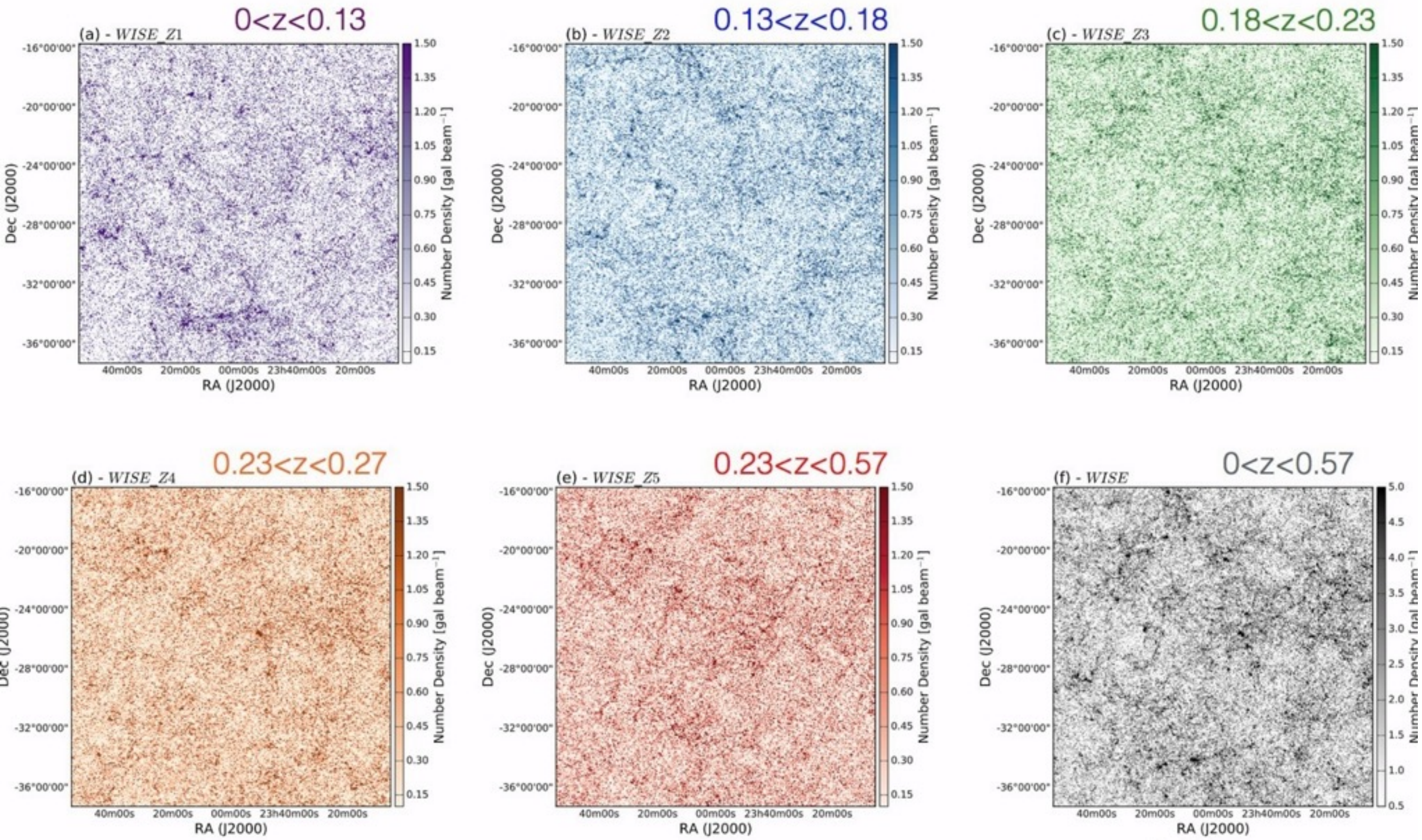


Cross Correlation with MWA - 2MASS Galaxy Density



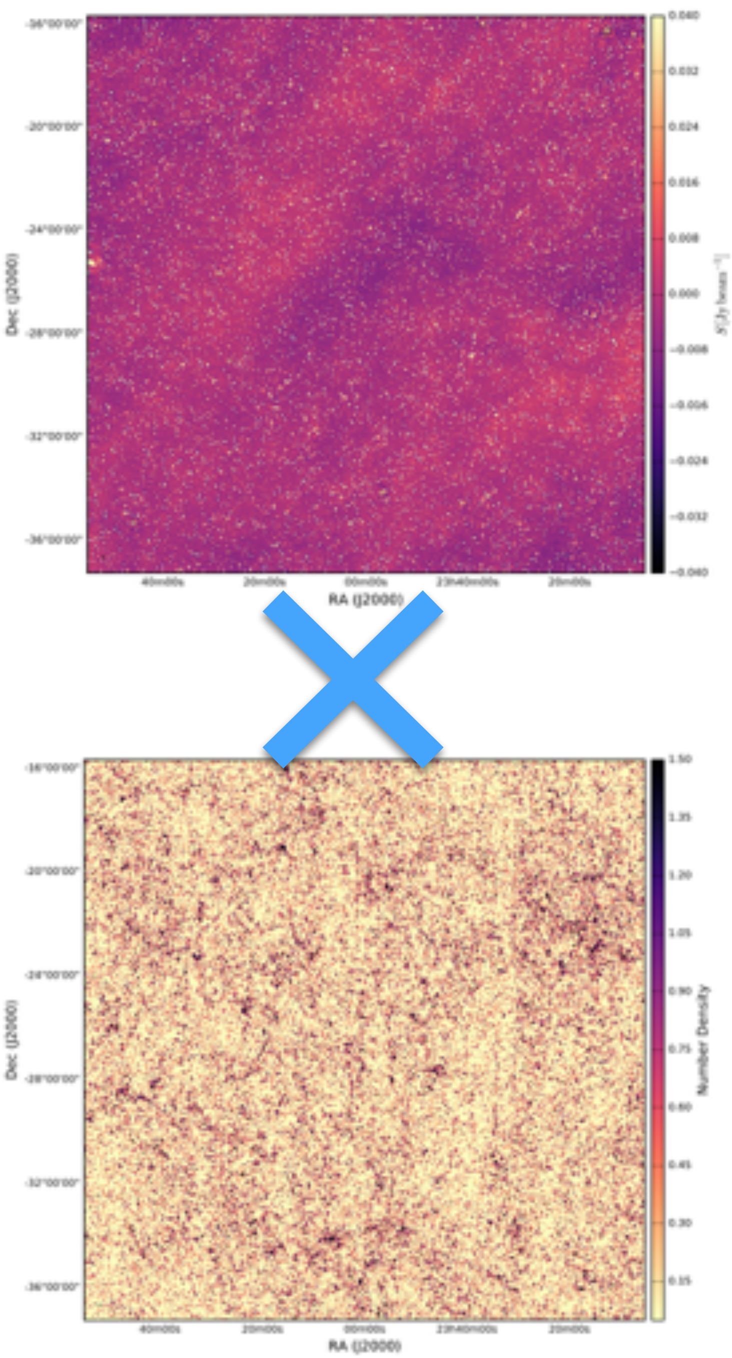
ONTO

Cross Correlation with MWA - WISE Number Density

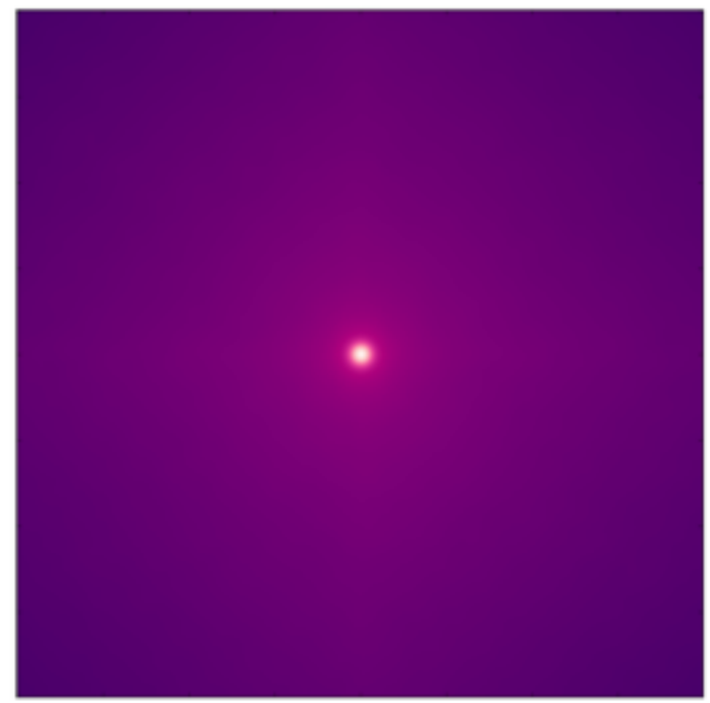


Cross Correlation with MWA

$$CCF\,(xshift, yshift) = \frac{1}{n}\sum(R_{i,j} - \bar{R})(G_{i,j} - \bar{G})$$



Δθ



Δθ

Take radial average

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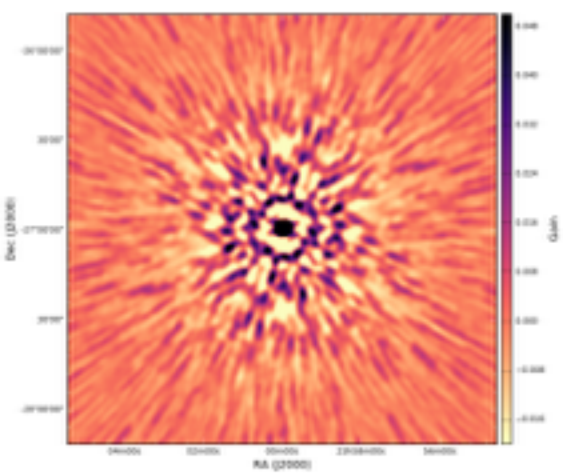
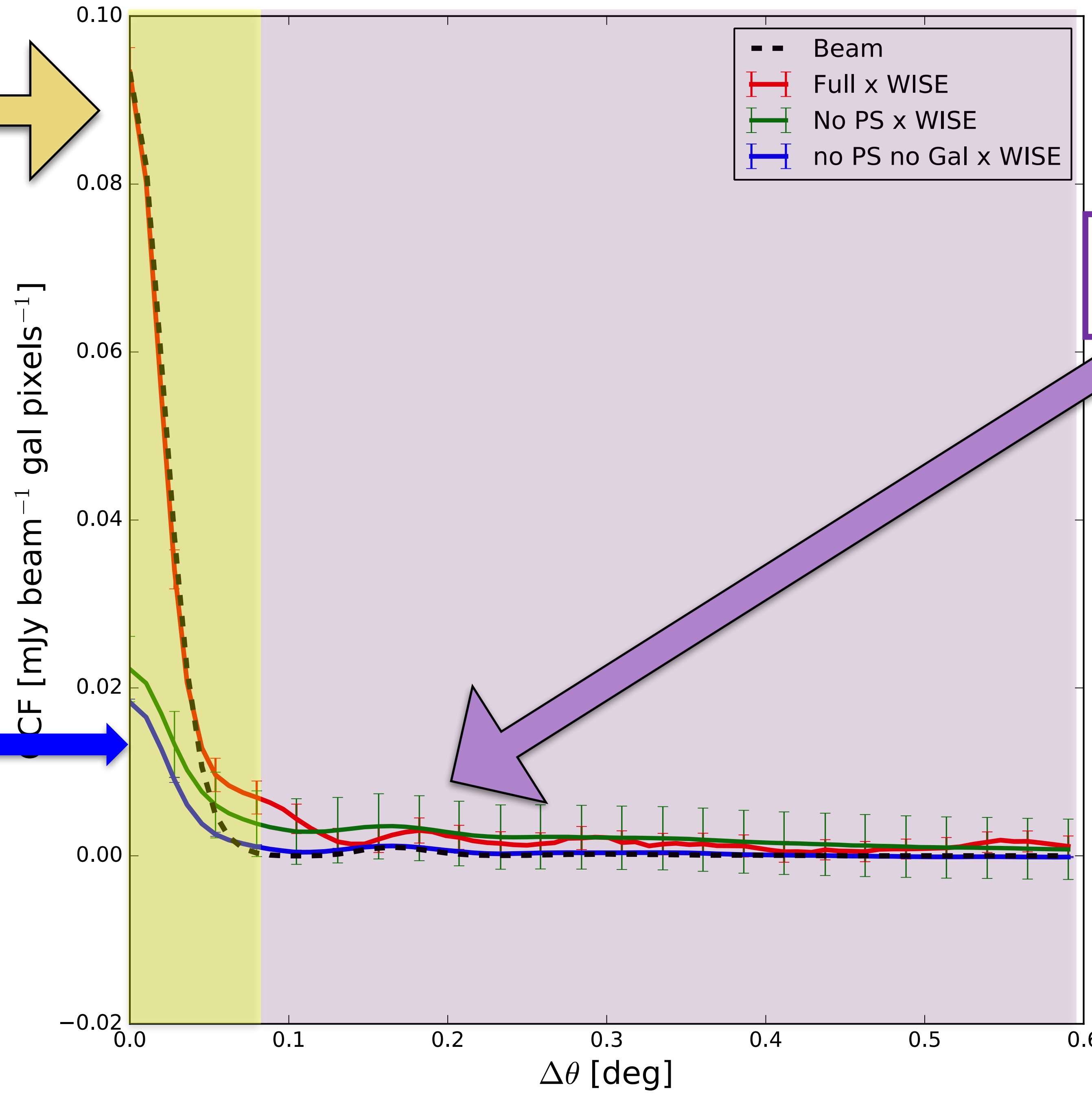
Cross Correlation with MWA

$$CCF\,(xshift, yshift) = \frac{1}{n}\sum(R_{i,j} - \bar{R})(G_{i,j} - \bar{G})$$

Point Sources→ smaller than beam



Still some point source contribution

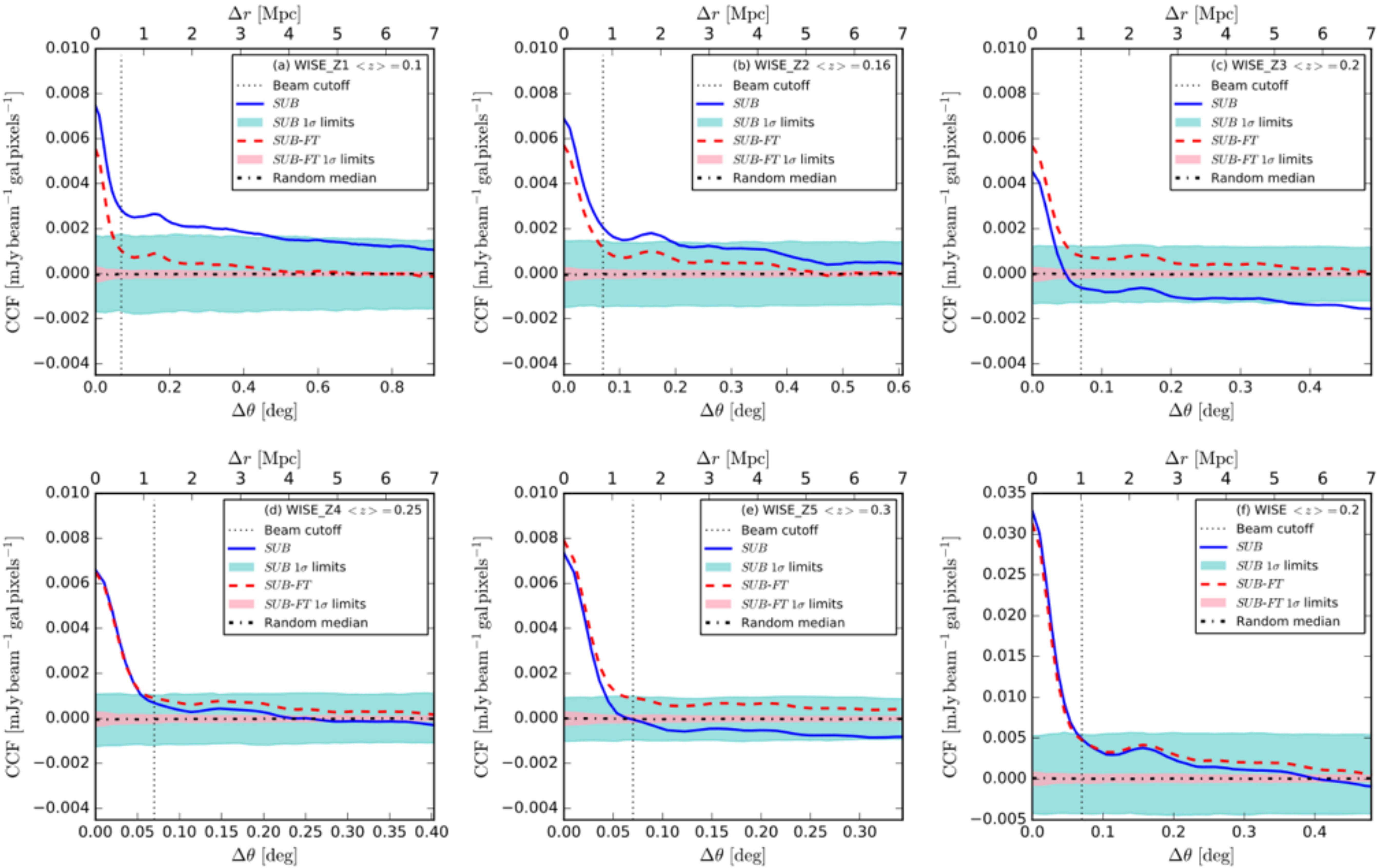


Diffuse emission à larger than beam

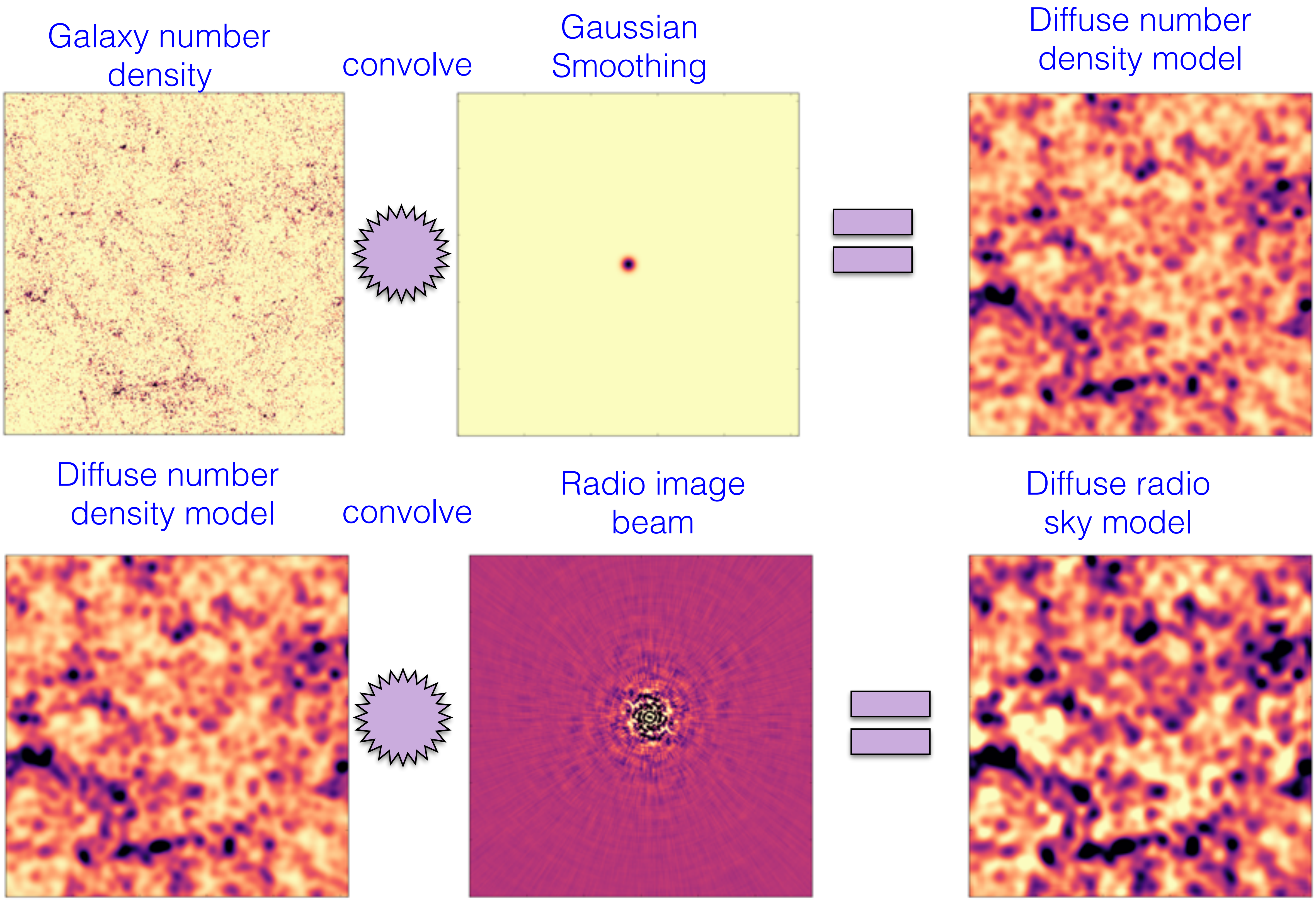
So how much diffuse is there ???

Cross Correlation with MWA

20 total CCFs
(2 radio images x
10 number density maps)

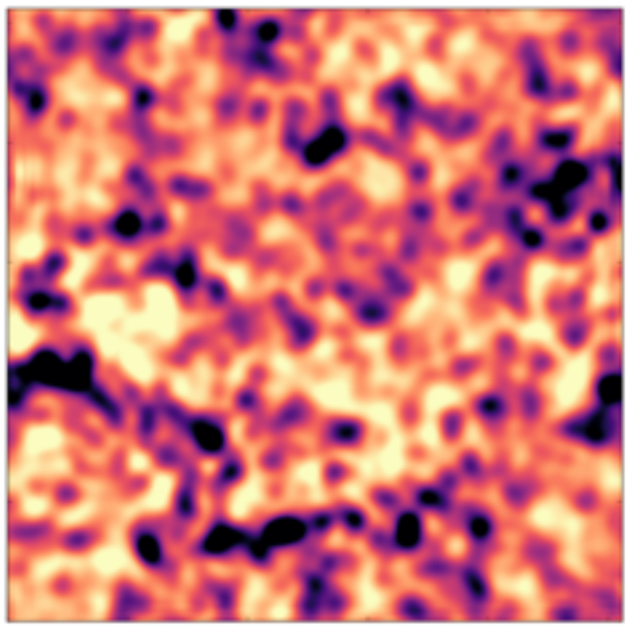


Cross Correlation with MWA – Emission Upper Limits

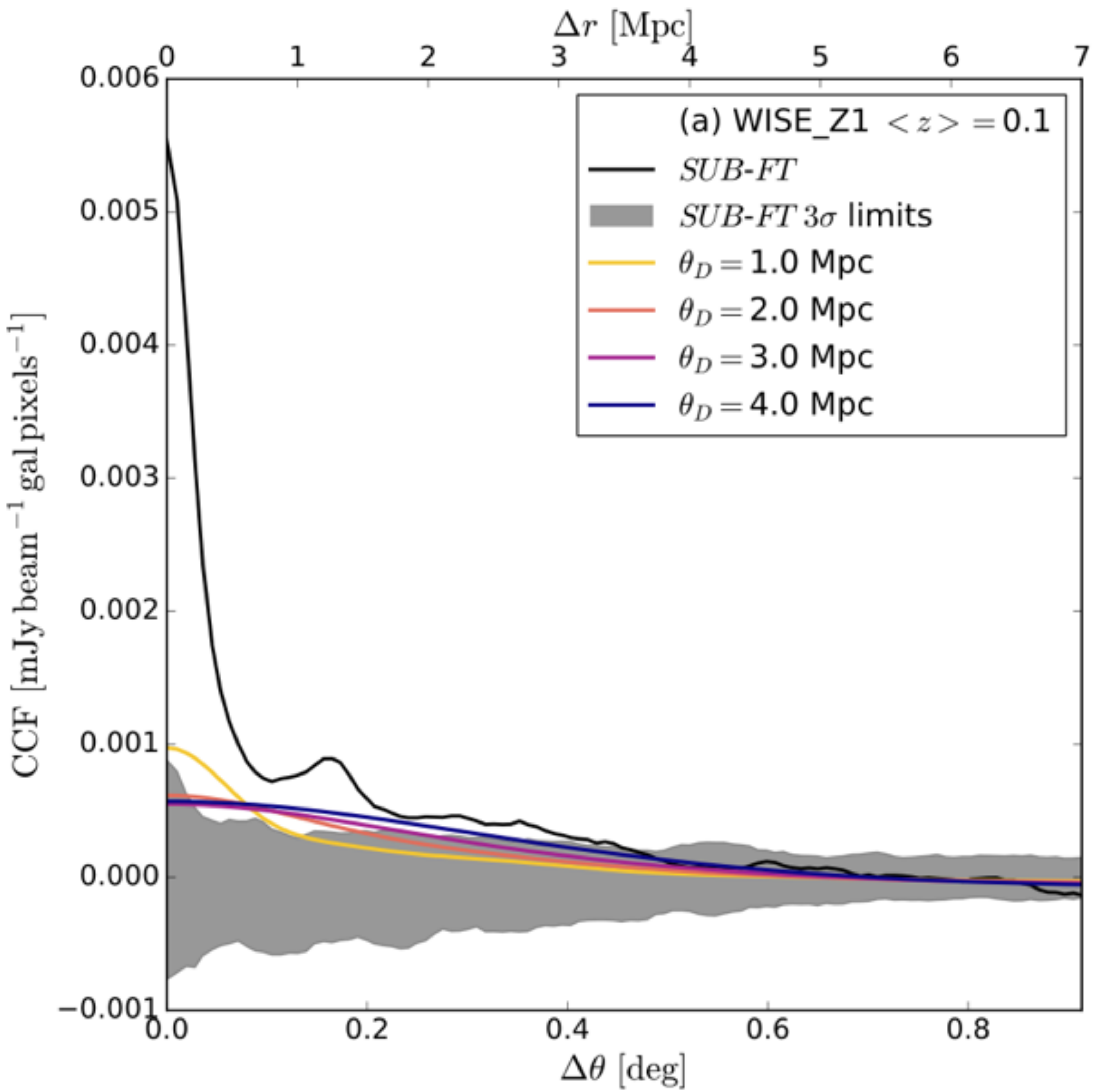


Cross Correlation with MWA – Emission Upper Limits

Diffuse radio sky model



Cross correla



Scale CCF until > 3σ

$0.09 < S$ [mJy beam^{-1}] < 2.2

$0.01 < S$ [mJy arcmin^{-2}] < 0.3

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Cross Correlation with MWA – Magnetic Field Limits

$$B_{\rm eq} = \left[\frac{4\pi(1-2\alpha)(K_0+1)E_{\rm p}^{1+2\alpha}(\nu/2c_1)^{-\alpha}I_\nu(1+z)^{3-\alpha}}{(-2\alpha-1)\,c_2(\alpha)\,l\,\eta\,c_4(i)}\right]^{1/(3-\alpha)}$$

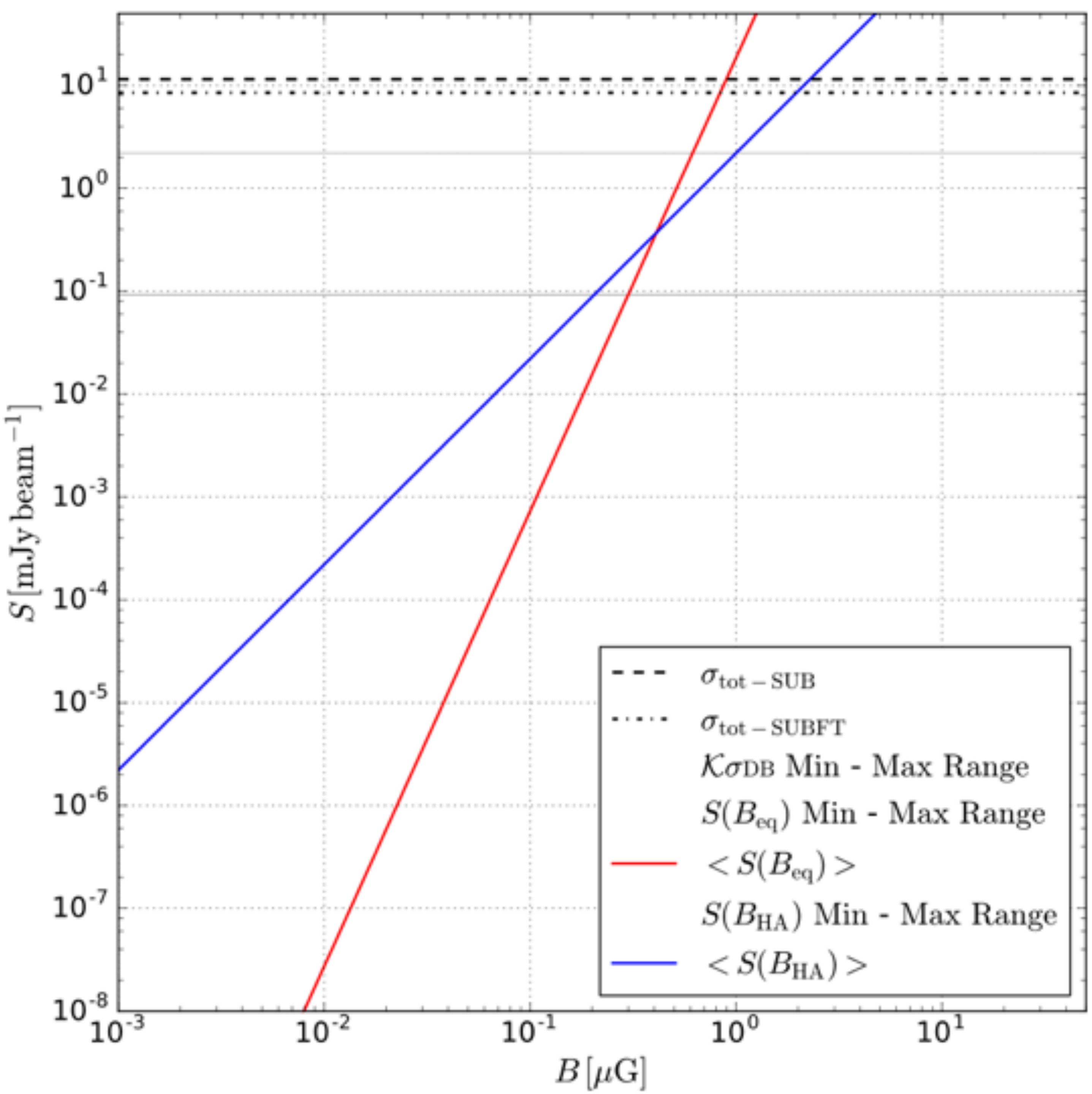
K_0 - ratio of number densities of cosmic ray protons and electrons per particle energy interval

η – Volume filling factor

α – spectral index

Cross Correlation with MWA – Magnetic Field Limits

$$B_{\rm eq} = \left[\frac{4\pi(1-2\alpha)(K_0+1)E_{\rm p}^{1+2\alpha}(\nu/2c_1)^{-\alpha}I_\nu(1+z)^{3-\alpha}}{(-2\alpha-1)\,c_2(\alpha)\,l\,\eta\,c_4(i)}\right]^{1/(3-\alpha)}$$



$1 < K_0 < 300$ $0.01 < \eta < 1$ $-0.6 < \alpha < -2.25$

$0.03 < B_{eq}$ [μG] < 1.98

$K_0 = 100$ $\eta = 1.0$ $\alpha = -1.25$

$0.22 < B_{eq0}$ [μG] < 0.62

$$B_{HA} \simeq 0.05\,\mu G \; \frac{S}{\frac{I_{WHIM}}{5 \times 10^{-3}\,\mathrm{Jy\,deg^{-2}}\left(\frac{100\,\mathrm{MHz}}{\nu}\right)\left(\frac{\cdot}{10^{-3}}\right)}}$$

Vazza et al., 2015

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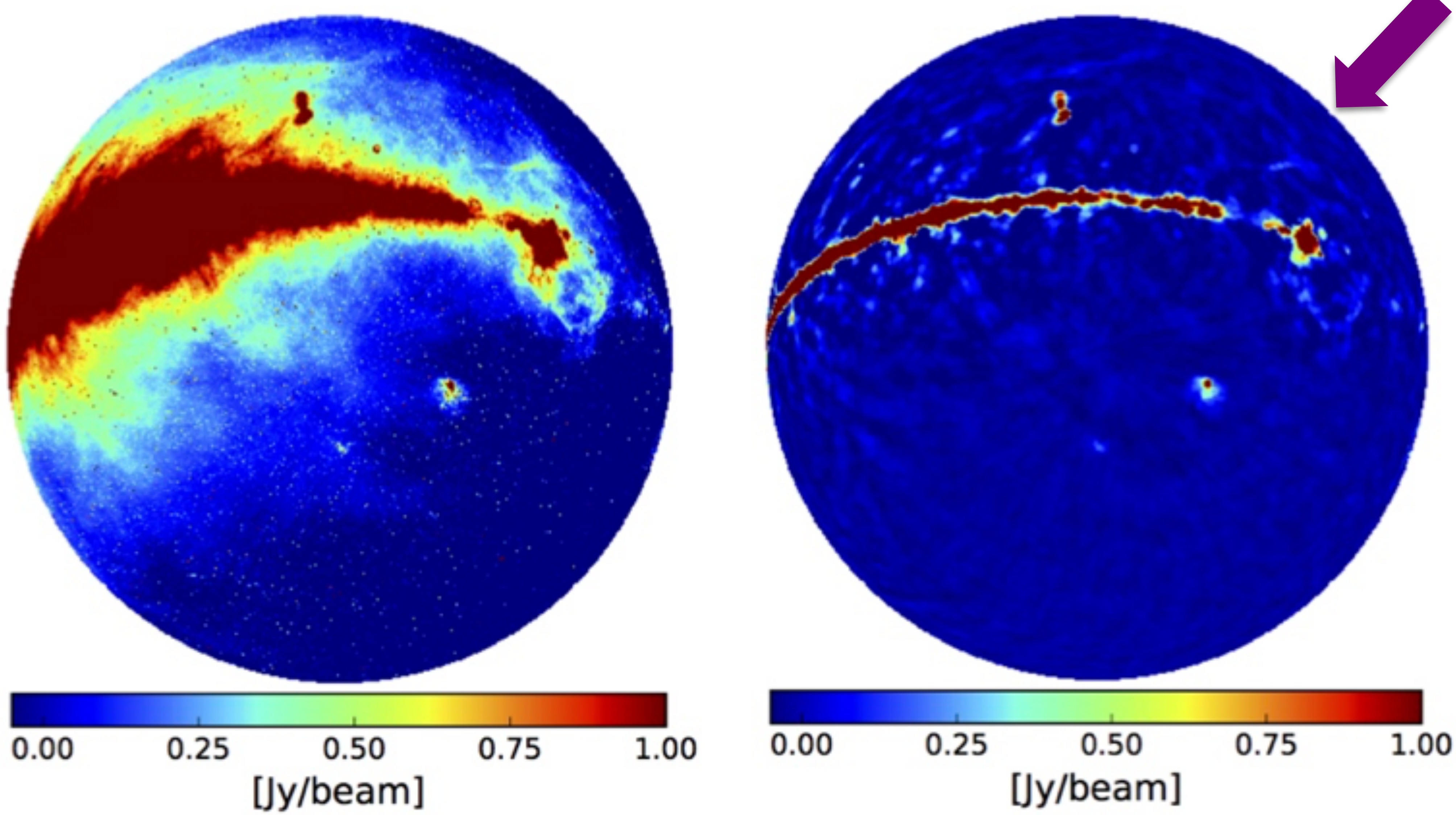
Cross Correlation S-PASS

- Single Dish 2.3 GHz All Sky
- Cross correlate with MHD simulation
  - Brown et al., 2017

Galactic and point source filtering



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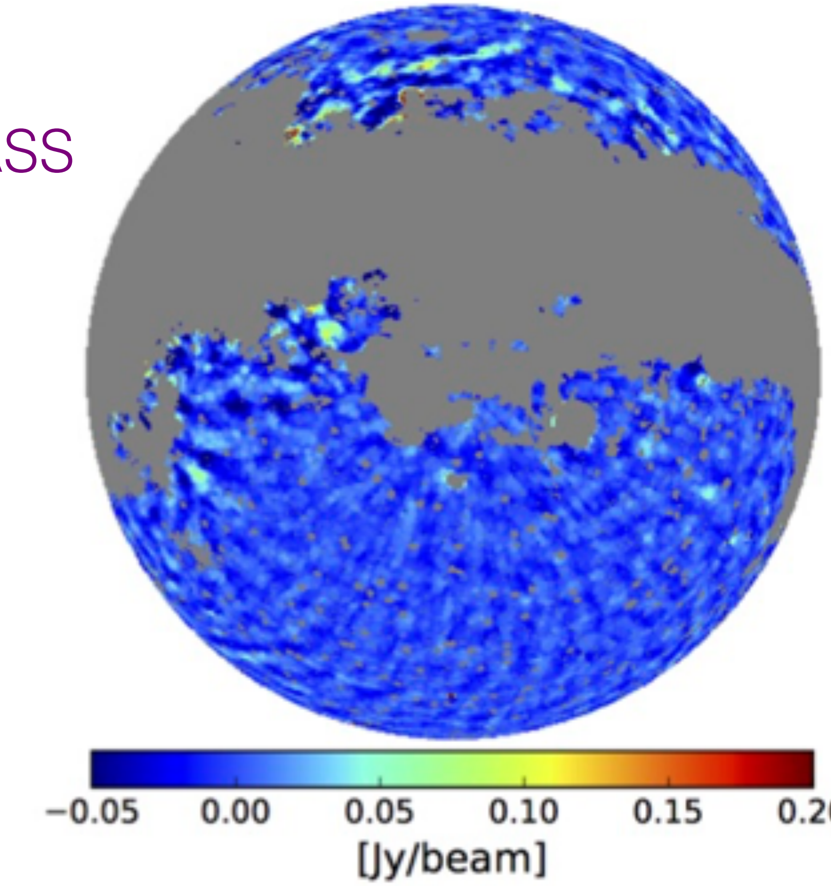
Cross Correlation S-PASS

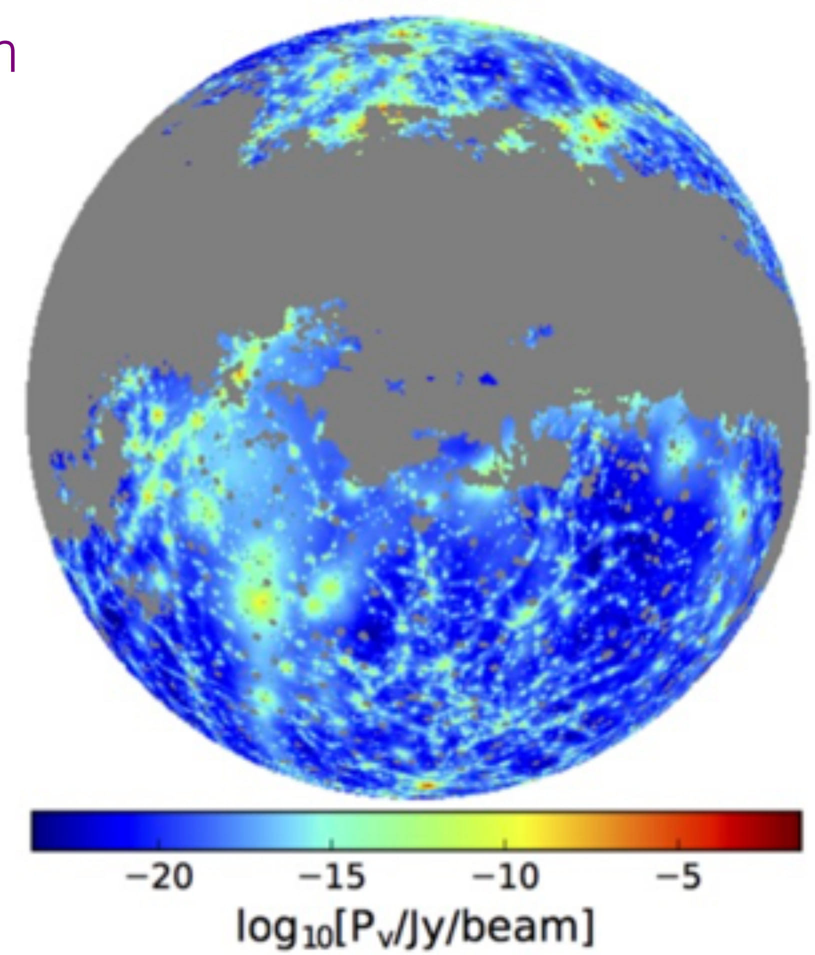
- Single Dish 2.3 GHz All Sky
- Cross correlate with MHD simulation
  - Brown et al., 2017

Masked

SPASS

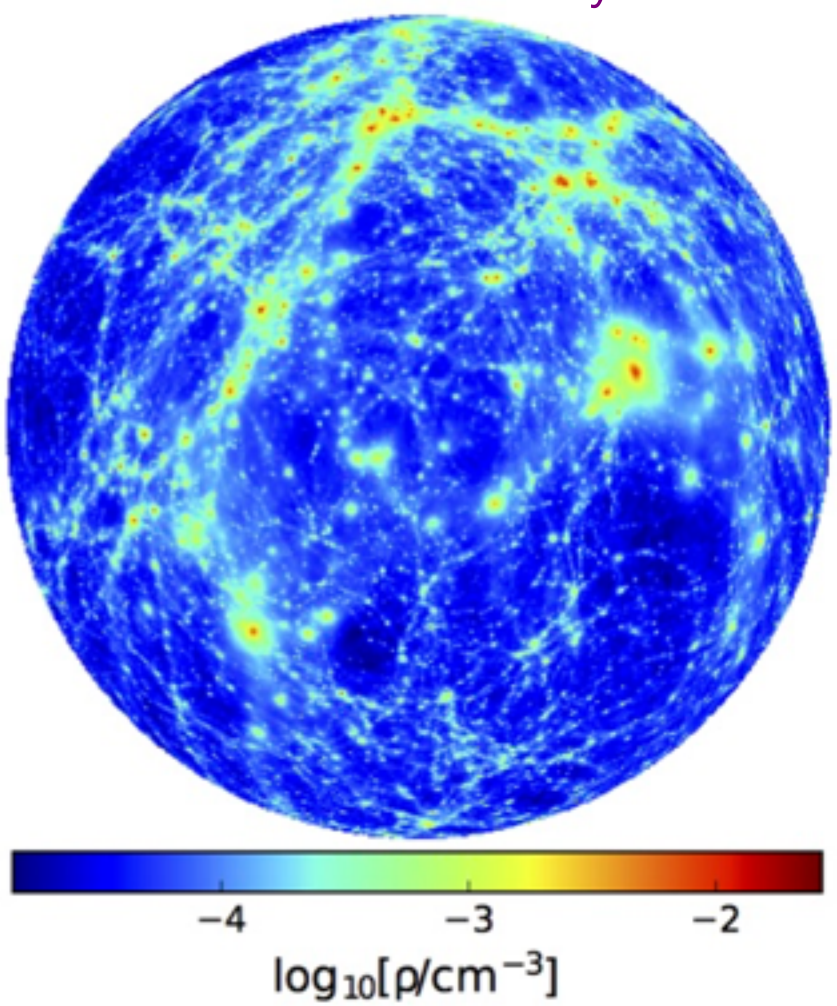


Sim

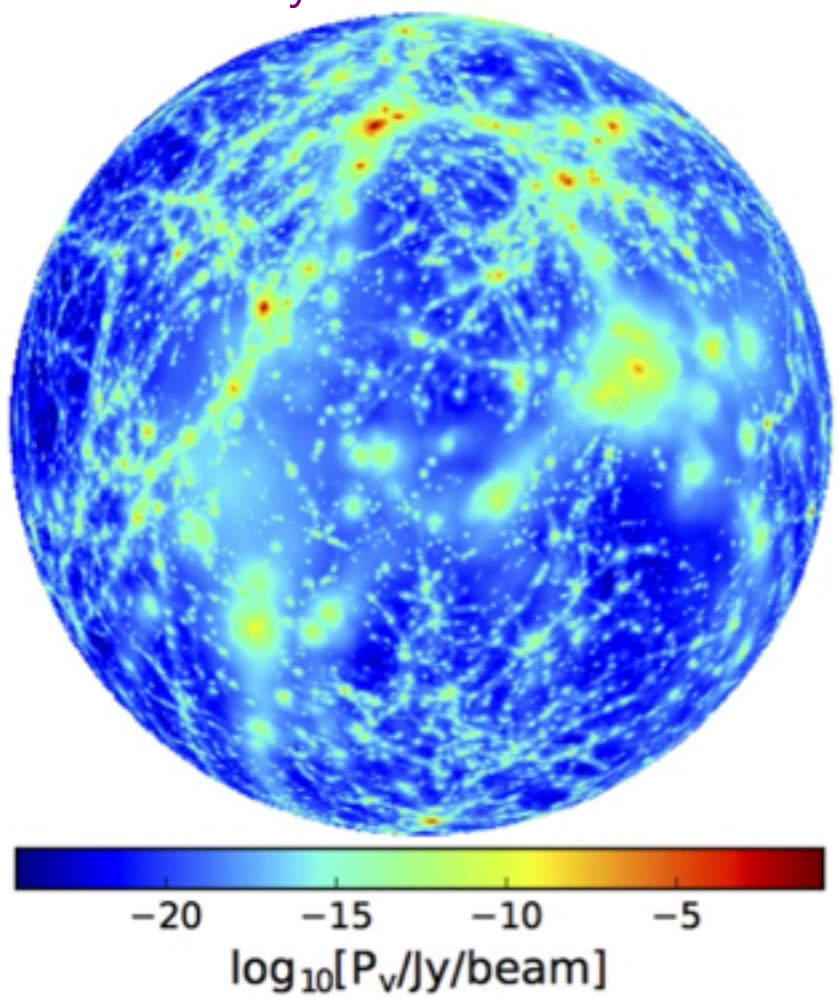


Simulations

Electron density



Synchrotron

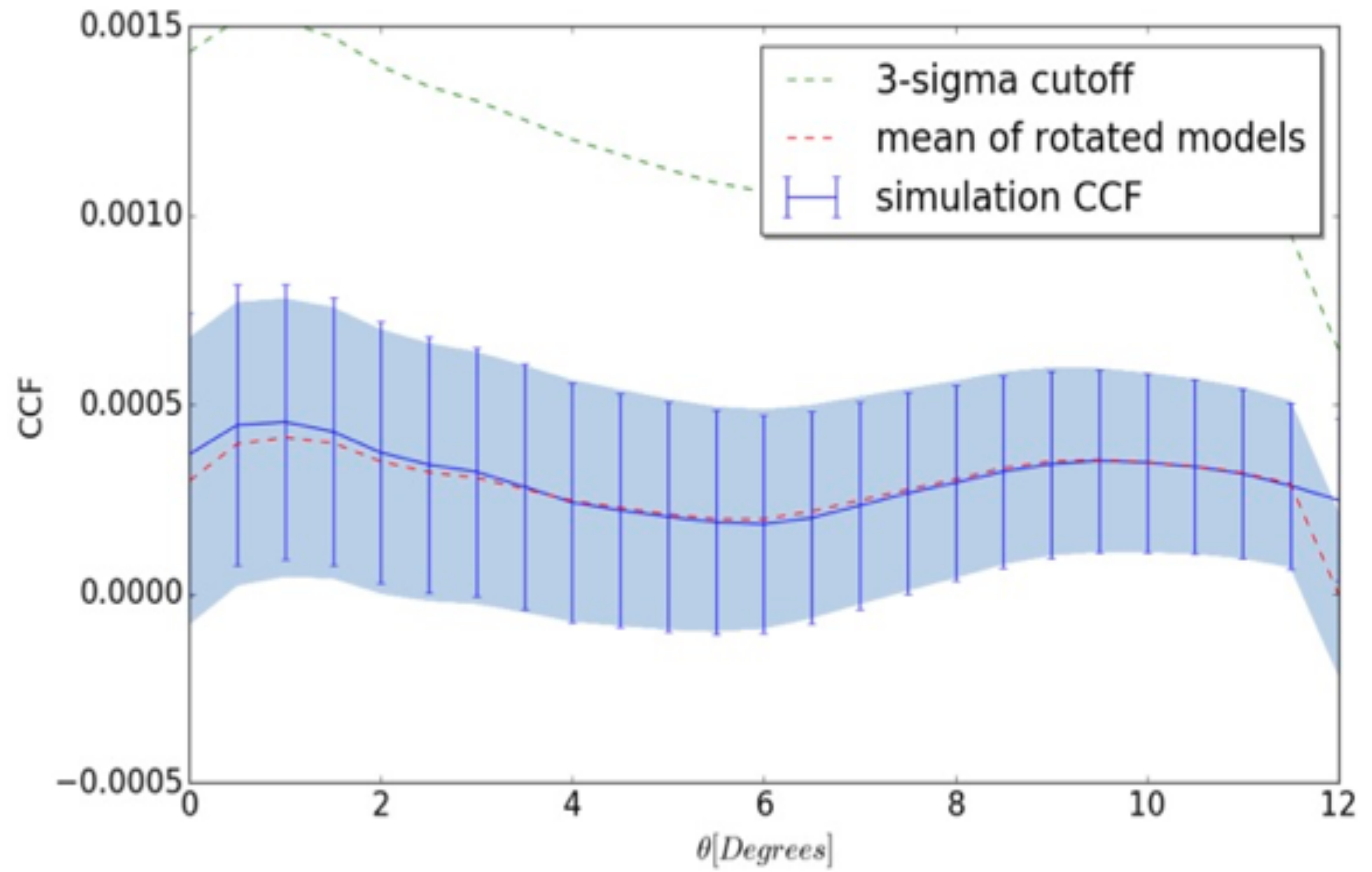


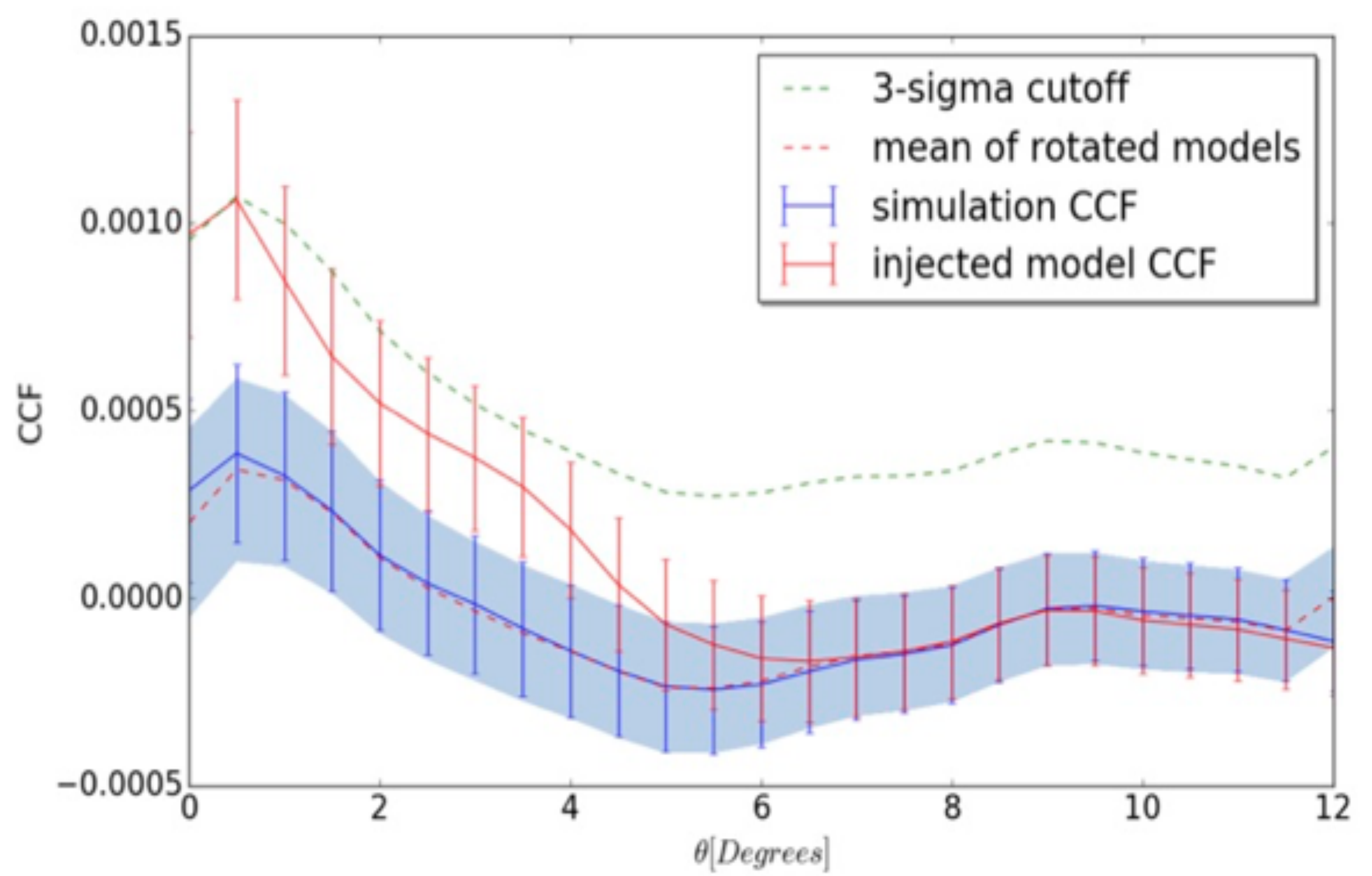
Cross Correlation S-PASS

- Single Dish 2.3 GHz All Sky
- Cross correlate with MHD simulation
  - Brown et al., 2017

Flux upper limit:
0.16 mJy arcmin^{-2}

Magnetic field upper limit:
0.13 μG





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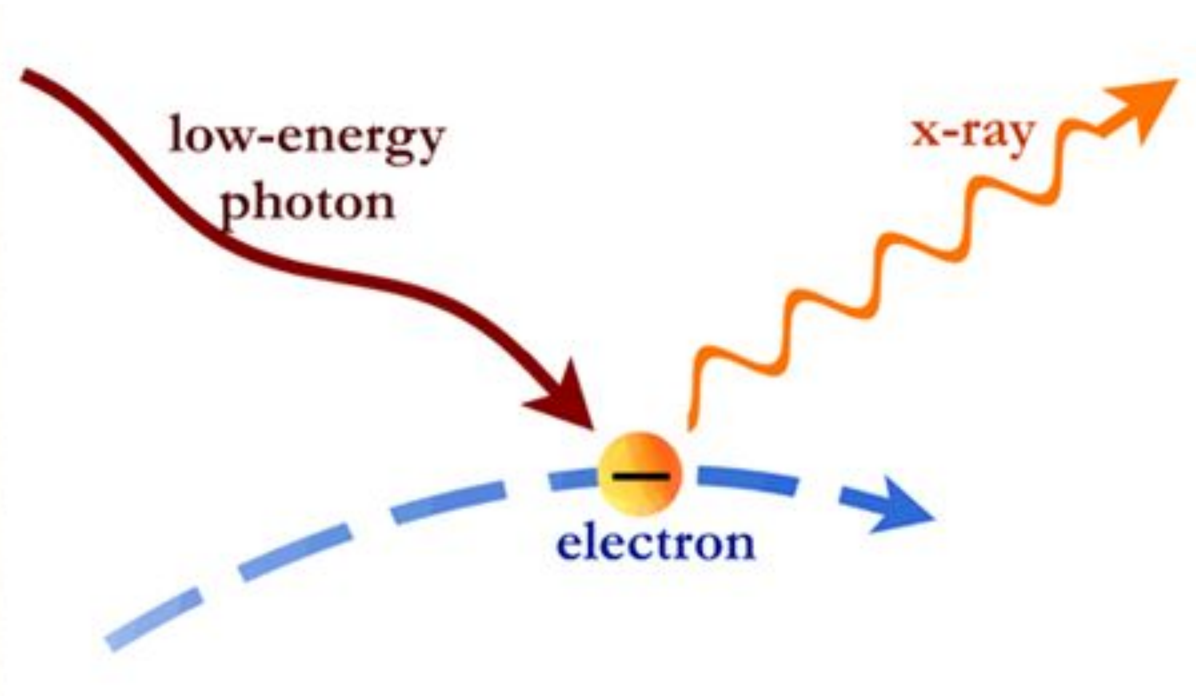
X-ray limits

- Radio emission related to X-ray emission
  - Low energy CMB photons up-scatter from electrons giving off synchrotron emission

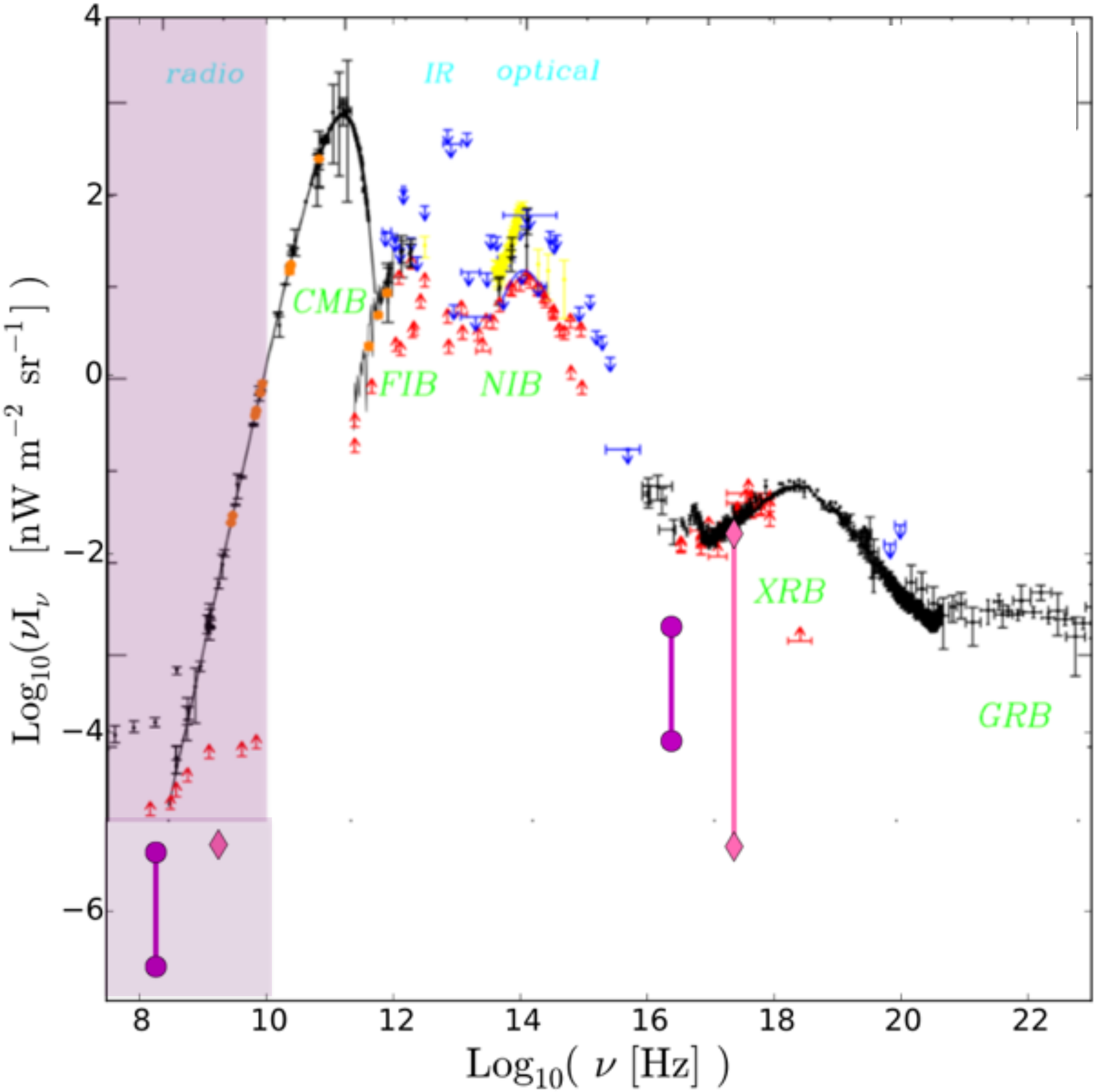
$$\frac{L_{\rm IC}}{L_{\rm sync}} = \frac{U_0(1+z)^4}{U_{\rm B}}$$

  - Can use measurements of X-ray background to constrain radio



X-ray limits

- Assume ultra-relativistic
  - $\Upsilon = 10^4$
- Use median redshift
  - $z = 0.3$
- For cosmic web use flux and magnetic field limits
- For diffuse confusion limit use a range for B of
  - $0.1 < B\ [\mu G] < 6$



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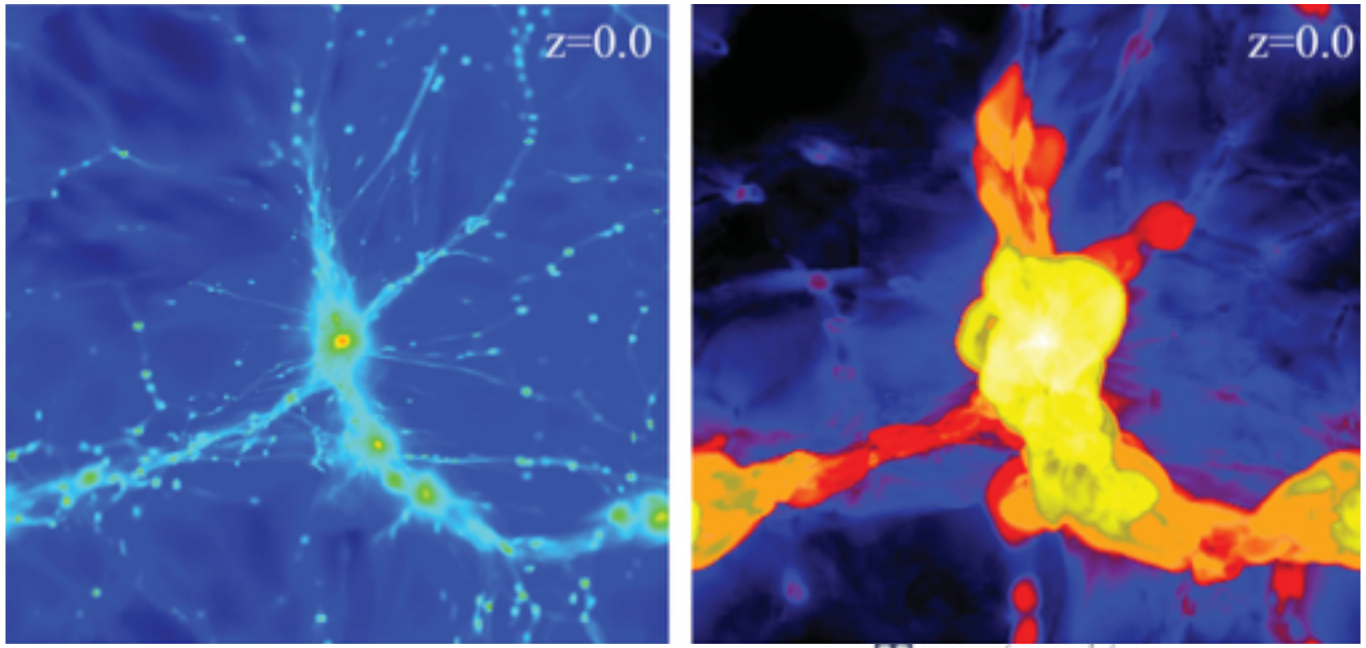
Cross Correlation

Advantages:

- Enhance signals hidden in the noise

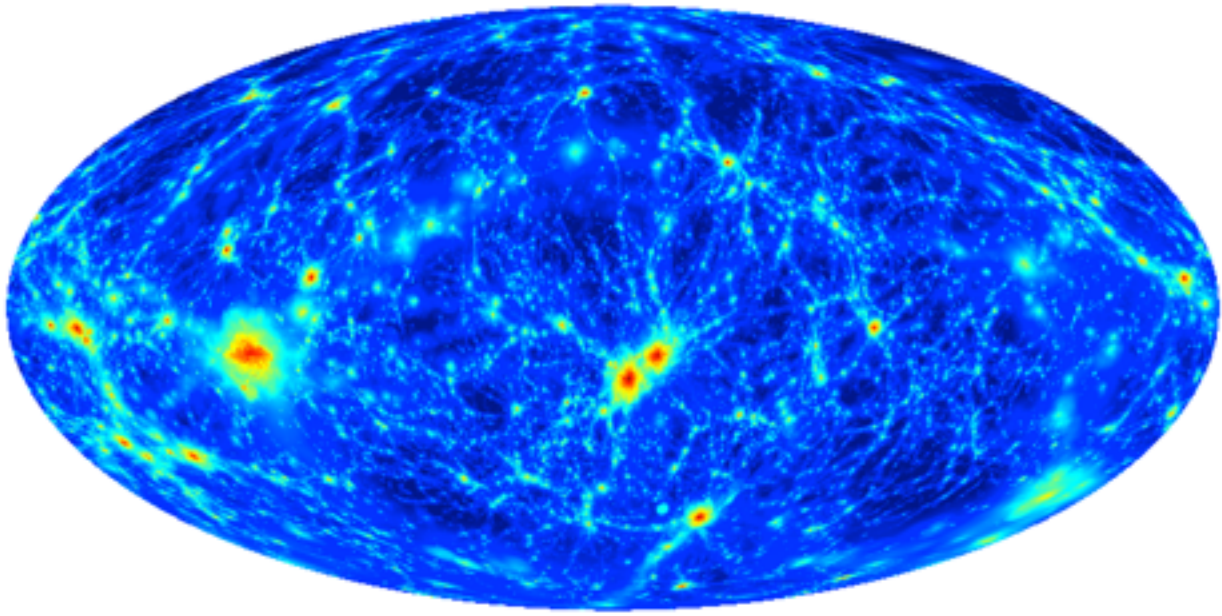
Caveats:

- Need models to interpret results physically
- Need to know (dirty) beam shape well
- Requires point source subtraction and/or model for un-subtracted sources
- Galactic emission can interfere over large areas



Planelles & Quillis (2013)

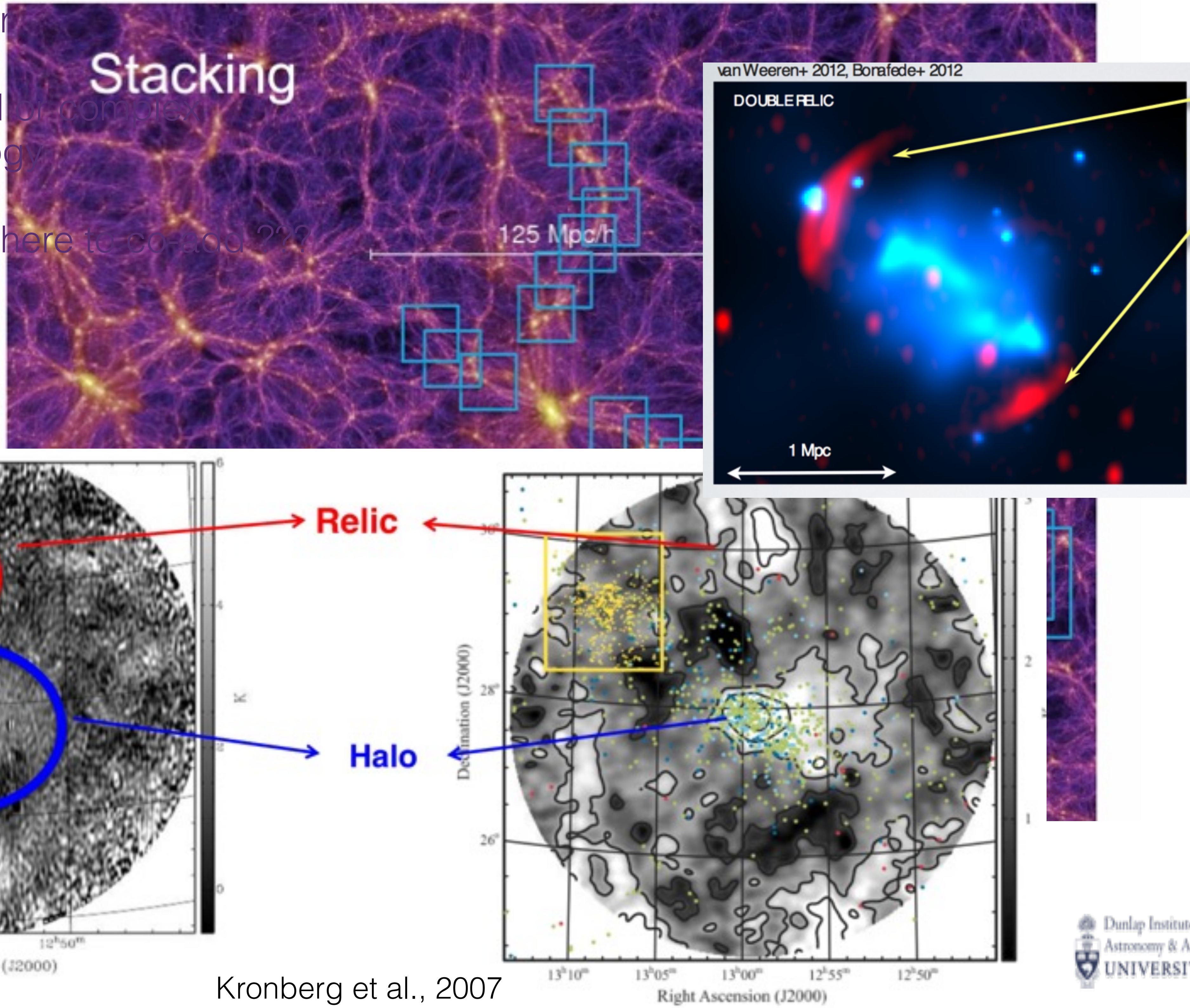
Cross Correlation – Future work

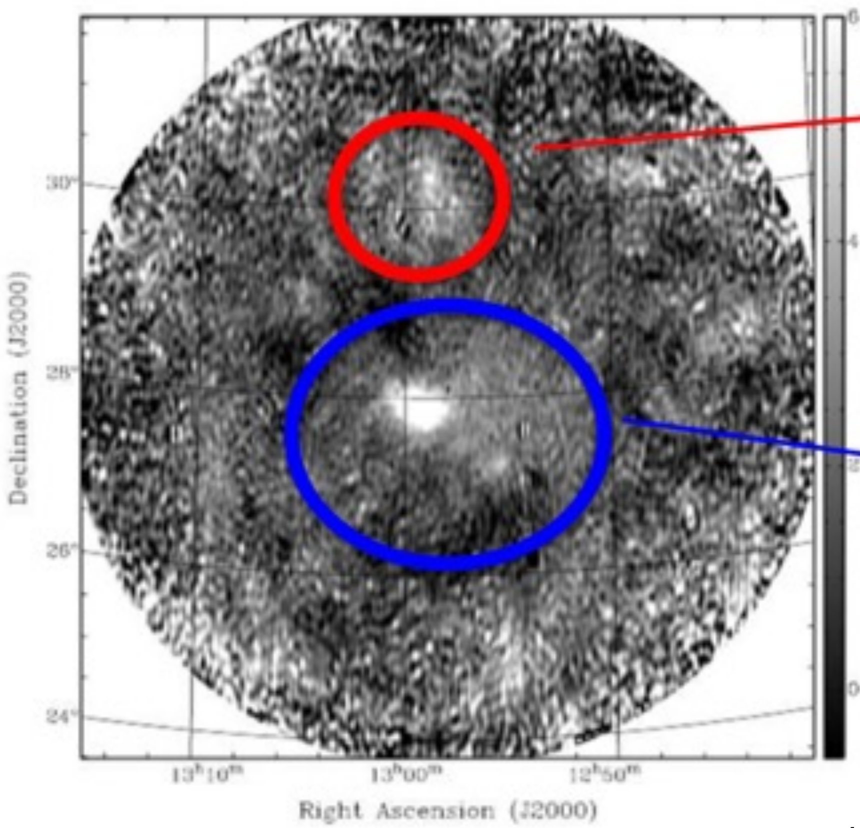


- Repeat with different:
  - area
  - frequency
  - resolution
  - sky coverage
- Other similar tests:
  - cross power correlation
  - wavelet covariance
- New MHD simulations
  - different physical models
  - simulations containing point sources / number densities
- Model for how faint point sources correlate
- Multi-frequency approach
  - combine LOFAR / MWA / GMRT with GMRT/ VLA / EMU / MeerKAT
- New / additional optical / IR data

Other Methods

- Stacking
- But….
  - Off-center
  - Extended or complex morphology
  - How or where to contour ???

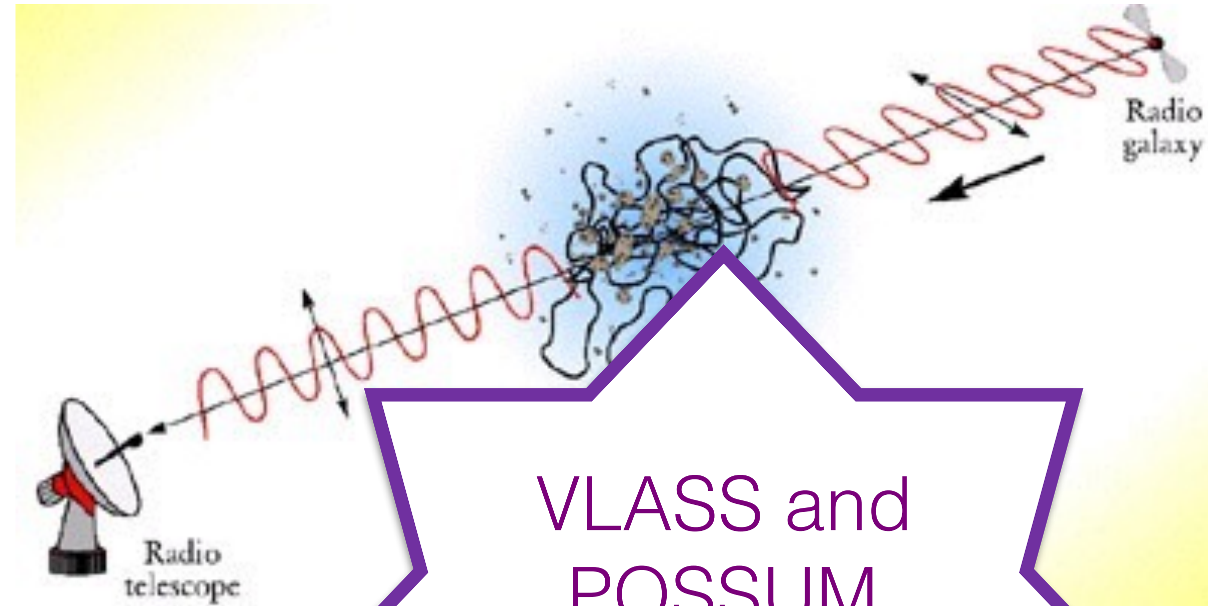




Kronberg et al., 2007

Other Methods

- Stacking
- Rotation measure cross correlation

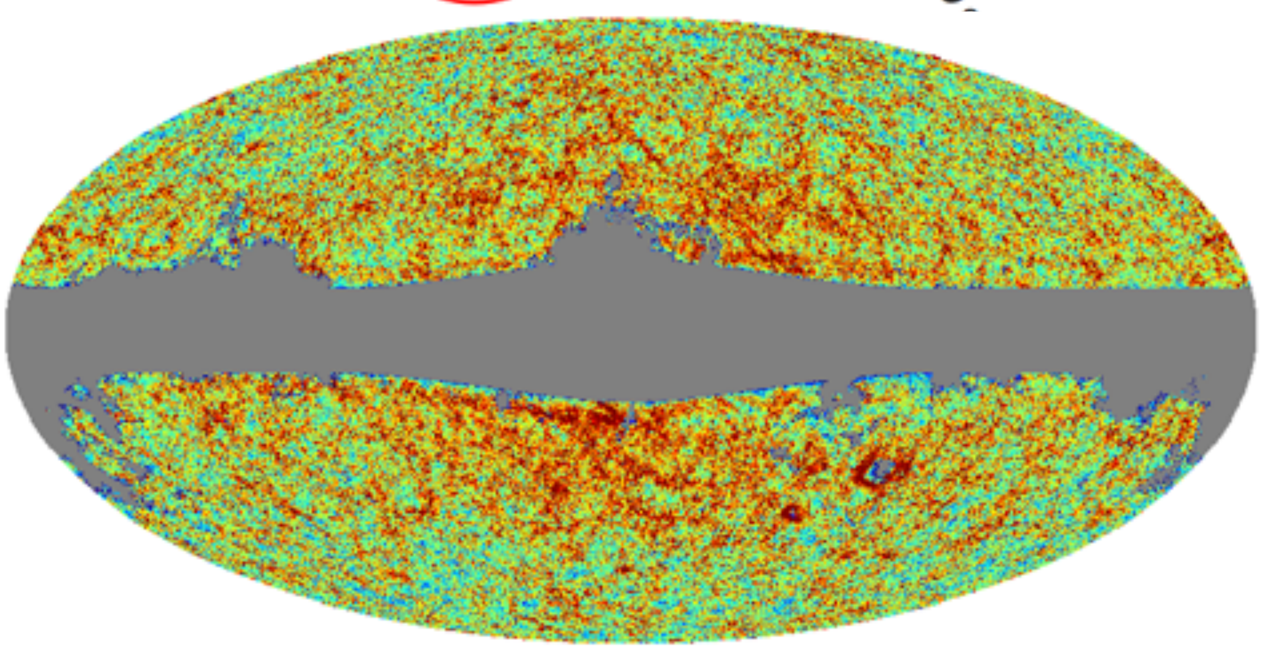


VLASS and POSSUM to add thousands more

Rotation Measure

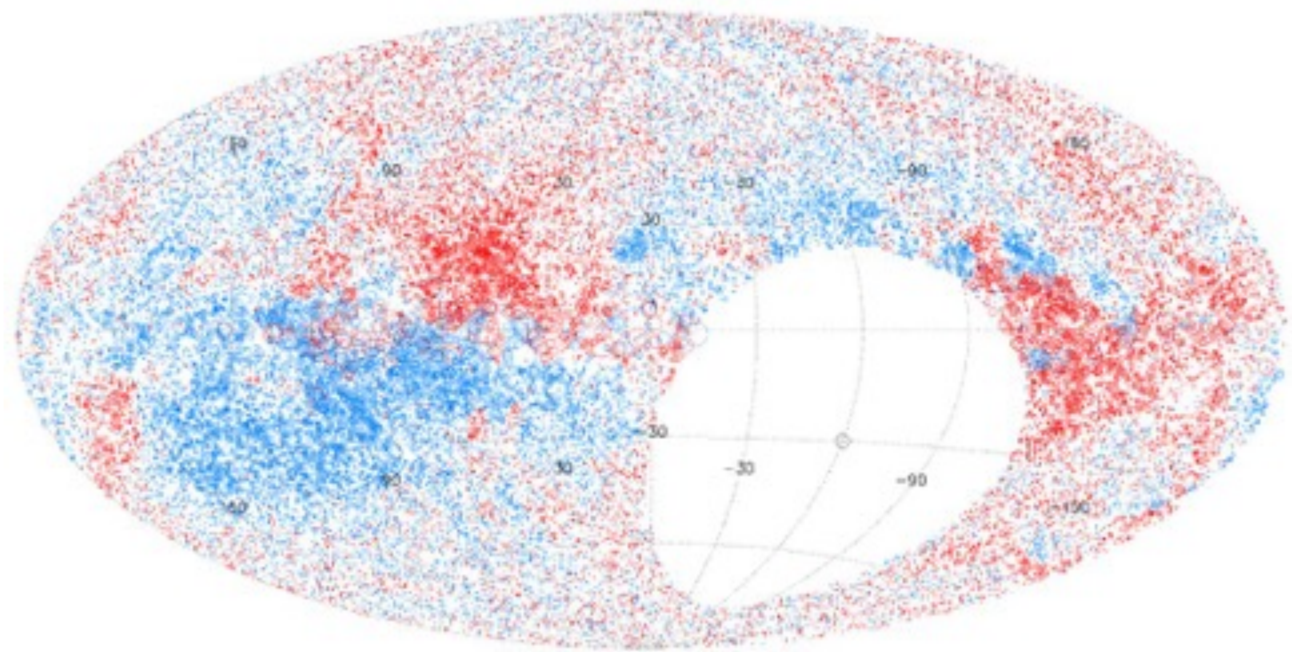
B-field along Line of Sight

$$RM = 8.12 \times 10^5 \int^{z_s} (1+z)^{-2} n_e(z) B_{\parallel}(z) dl(z)$$



WISE galaxy redshift catalog

X



Taylor et al. (2009)
NVSS RM catalogue

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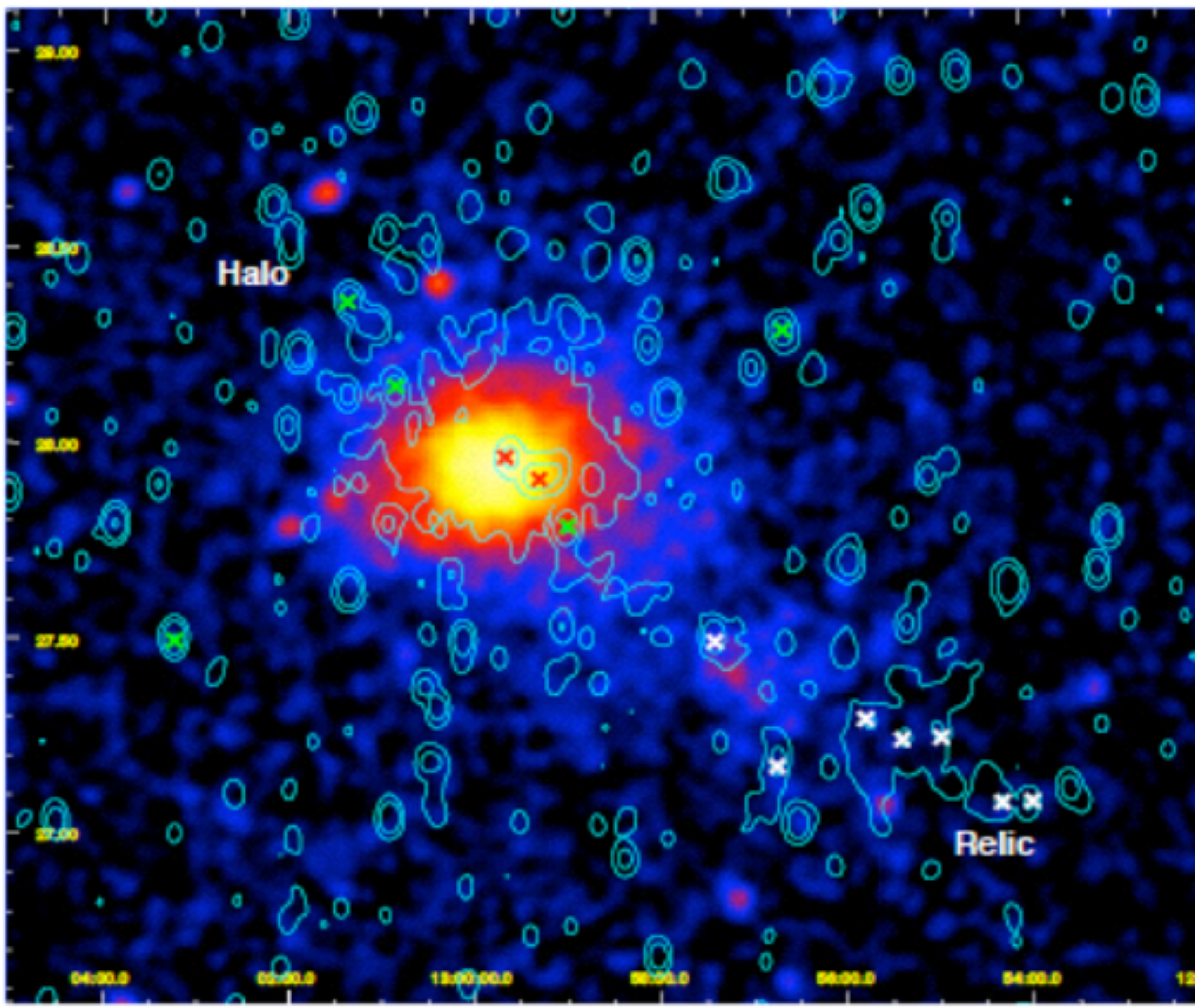
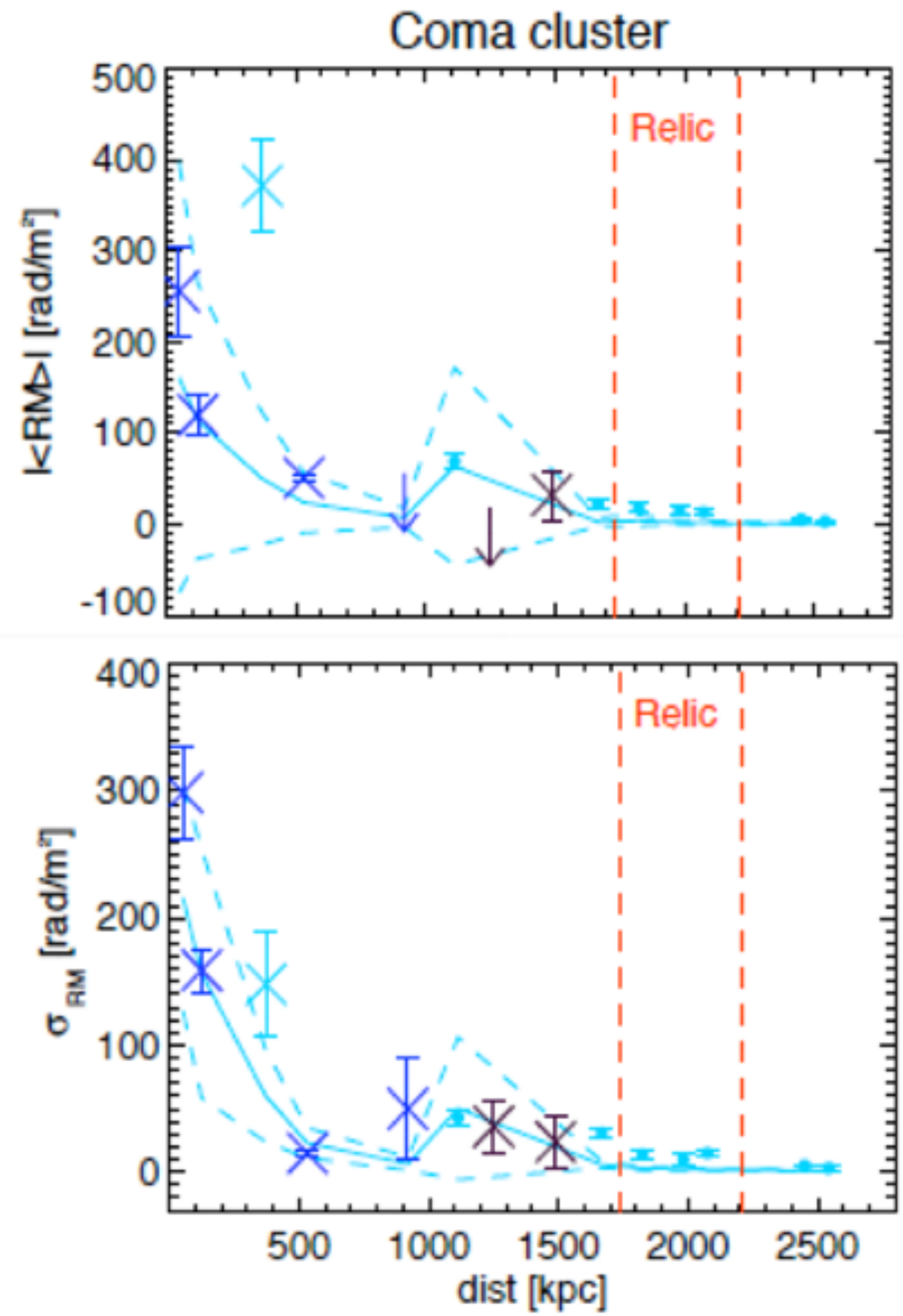
Other Methods

- Stacking
- Rotation measure cross correlation
- RM Grids

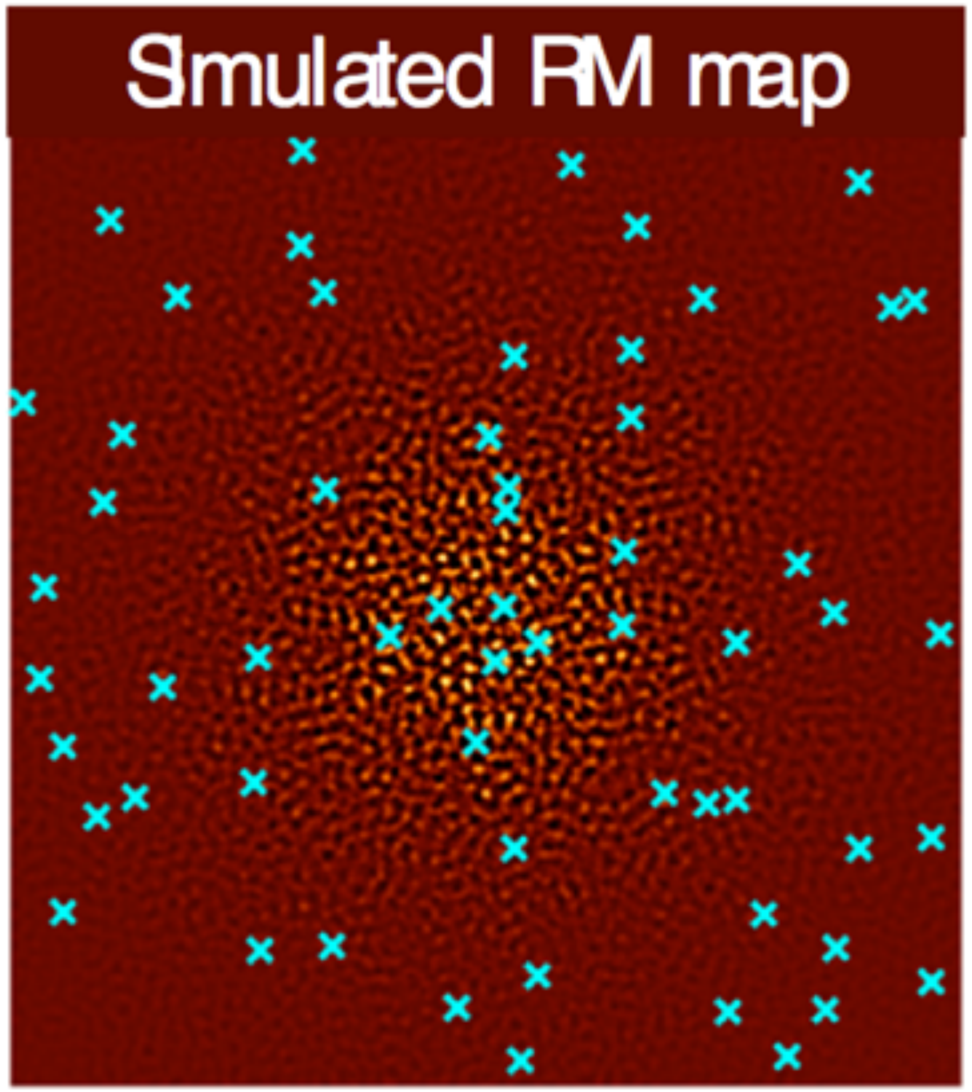


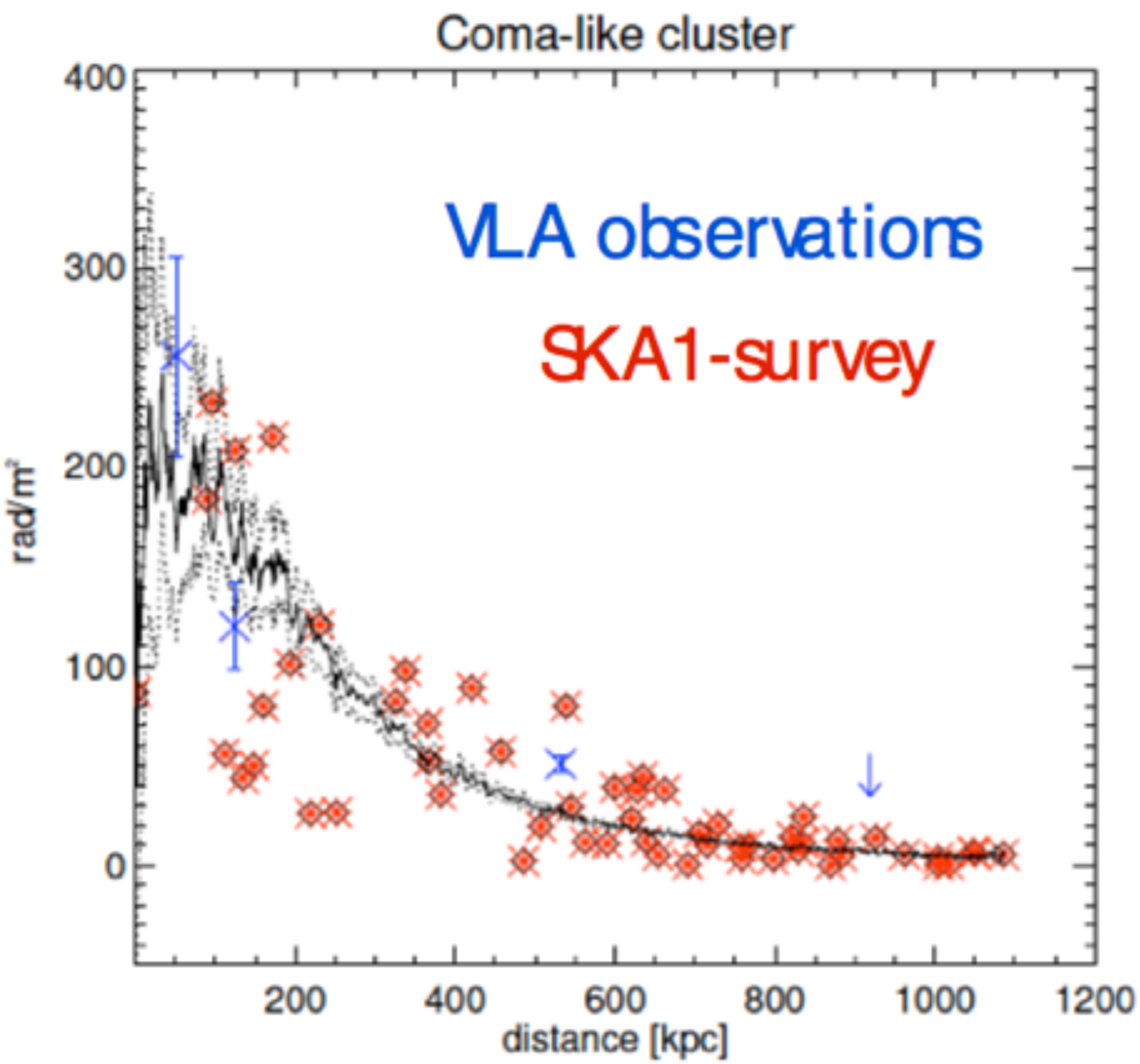


Bonafede et al. 2010,2013

Other Methods

- Stacking
- Rotation measure cross correlation
- RM Grids





Other Methods

- Stacking (e.g. Rudnick, Vazza, Farnes)
- Rotation measure cross correlation (Lee, Amaral, Gaensler et al)
- RM Grids (Vacca, Bonafeda)
- 1D & 2D P(D) confusion analysis (Vernstrom et. al 2015)
- 2D Angular power spectrum
- Cross power spectrum & Wavelet covariance
- Combinations, e.g. confusion analysis + cross correlation

Summary & Conclusions

- Simulations
  - Predict magnetic field values of 10s of nG to ~ a few microG
  - Output very model dependent
  - Likely need SKA-Low for possible WHIM detections
  - Need simulations to include point sources

- Observations
  - Find cluster magnetic fields in range ~0.1-30 μG
  - Many more detections coming from new low frequency data
  - May be limited by confusion for fainter detections

- Cross correlation technique
  - upper limits on IGM of ~0.5 microG
  - Need more/better models to interpret results

- Statistical techniques can be powerful tools for reaching below the noise

- Understanding current and developing new techniques crucial for fully utilizing new large surveys

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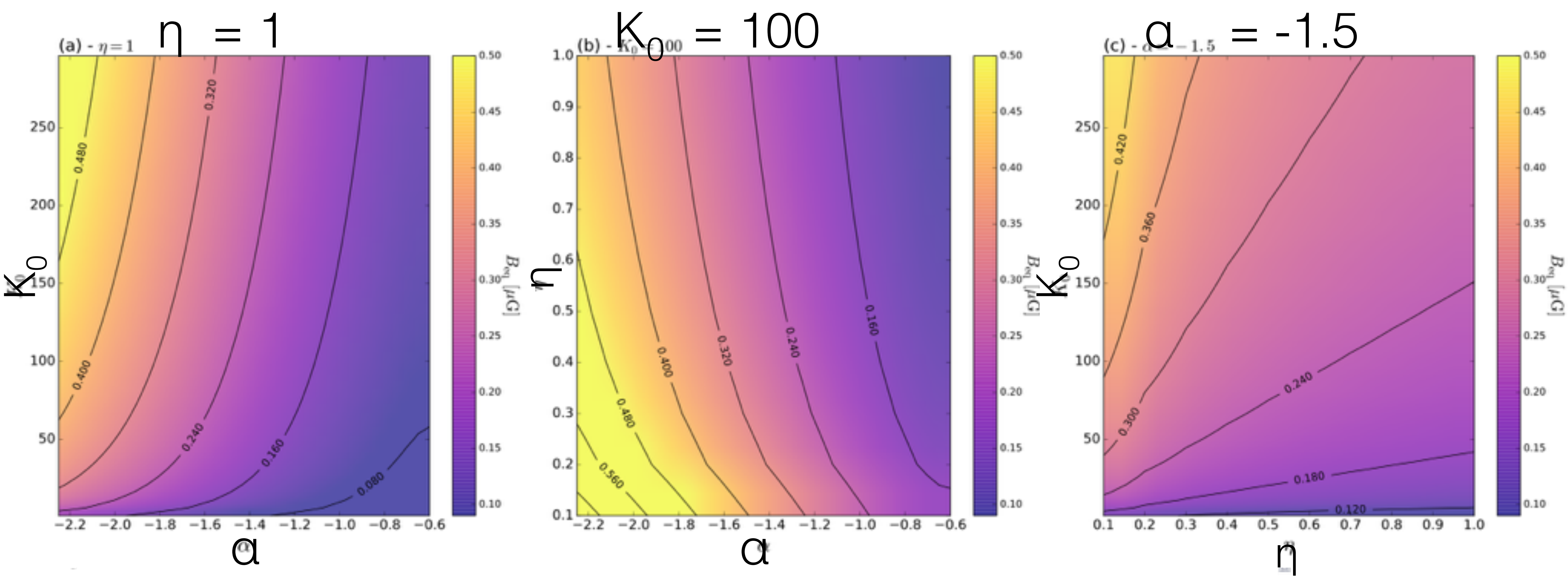
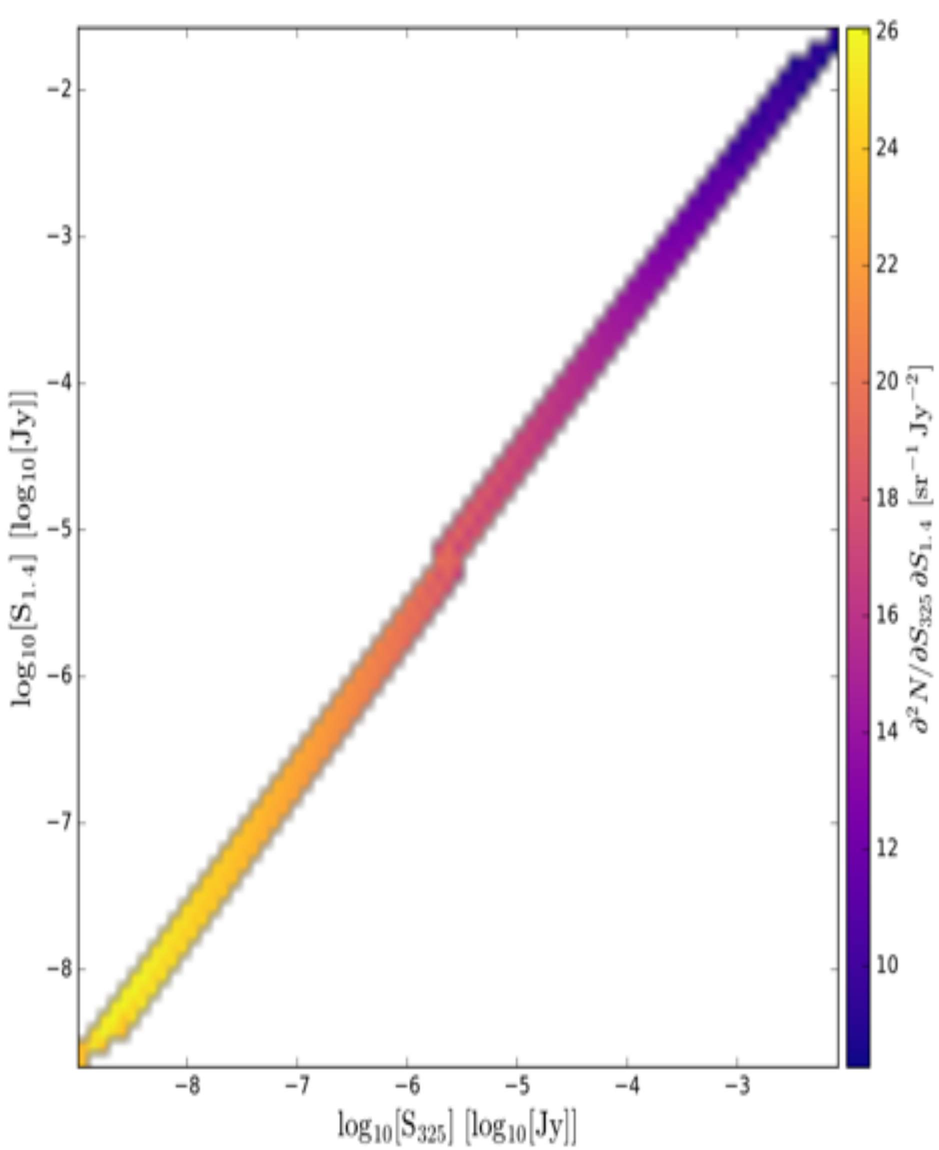


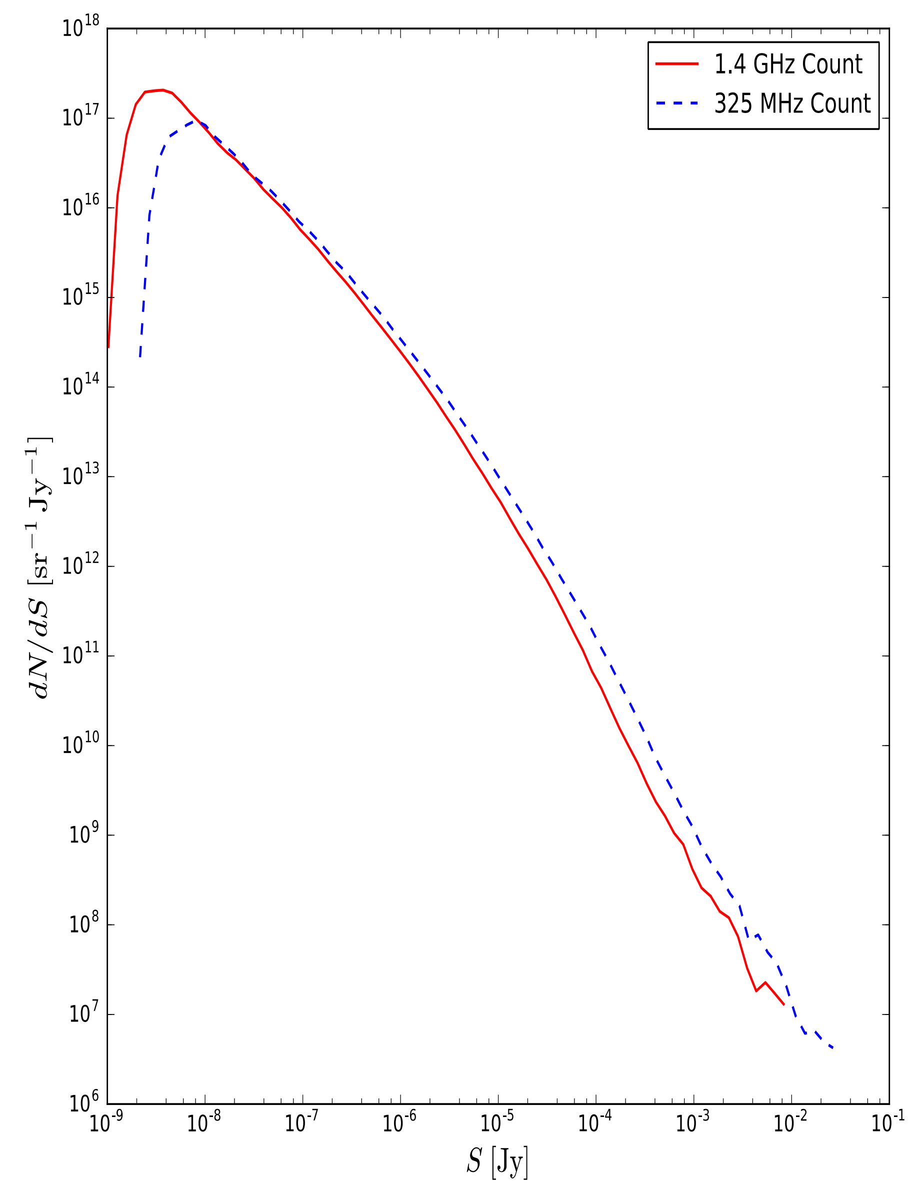
Other Methods

- Stacking
- 2D P(D) analysis

- Fit 2D source count to 2D histogram
- Can be two frequencies, two resolutions, total and polarised intensity
- Provides tighter constraints, uses more data, breaks degeneracies

$$\log_{10}\left[\frac{\partial^2 N(S_1, S_2)}{\partial S_1 \partial S_2}\right]$$





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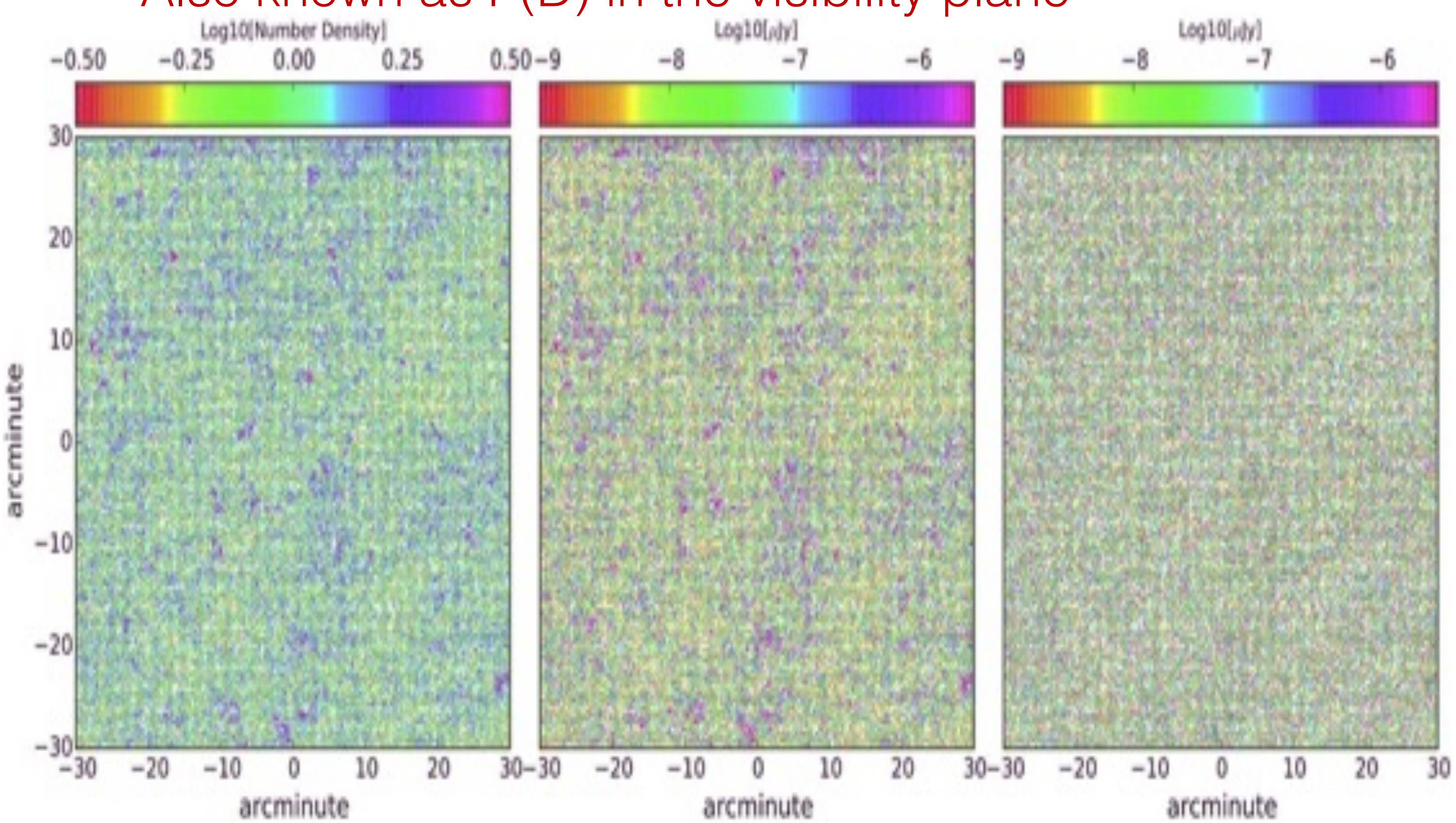
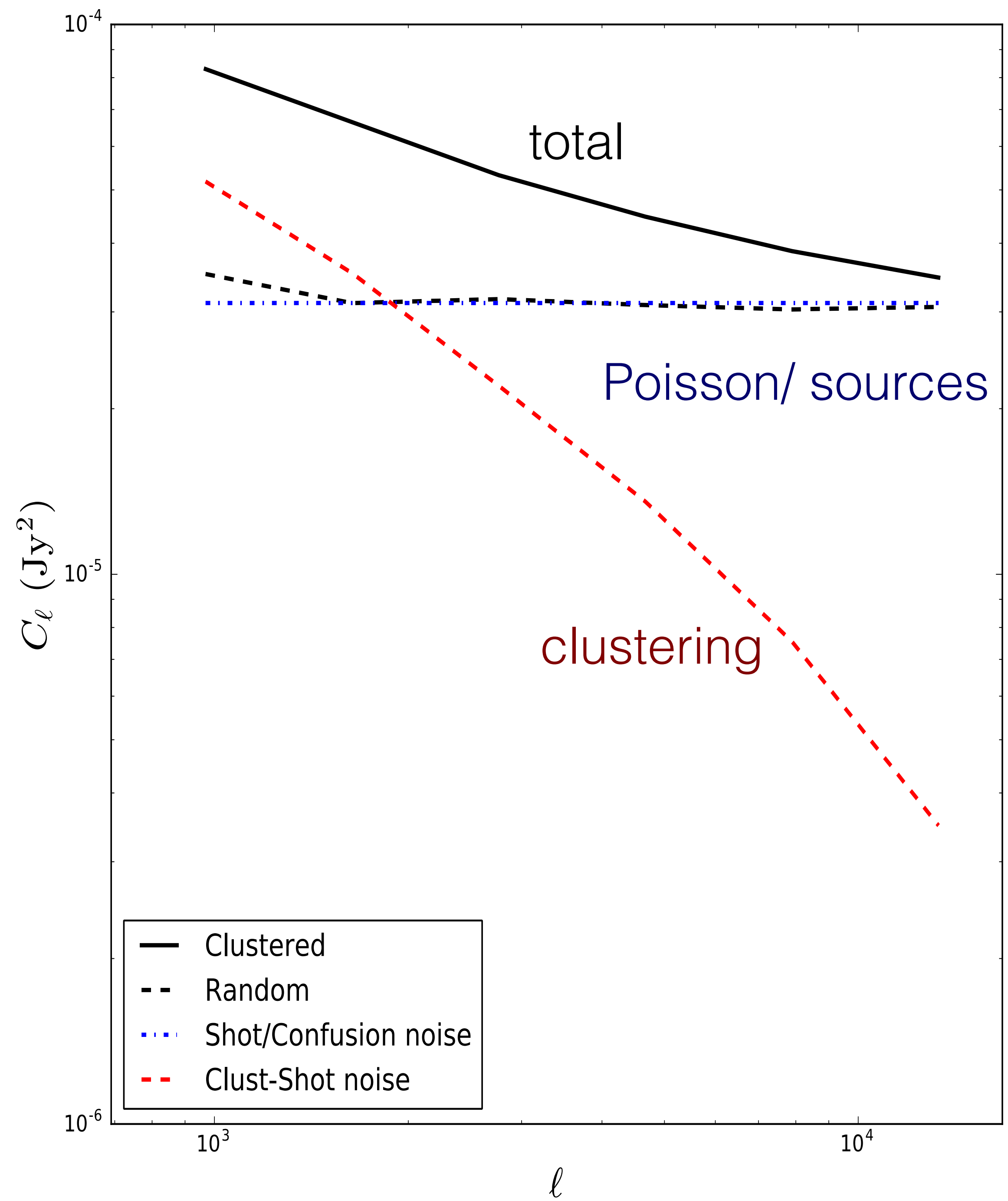
Other Methods

- Stacking
- 2D Angular power spectrum

$$\sigma^2 = \int S^2 \frac{dN}{dS} dS$$

- Can use the confusion noise to estimate Poisson contribution
- Where σ^2 is the (flat) amplitude of the power from sources
- Also known as P(D) in the visibility plane





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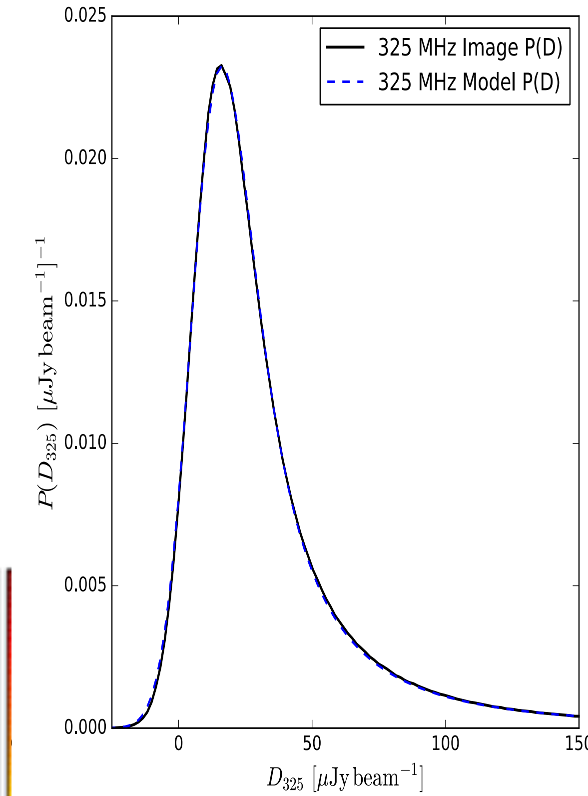

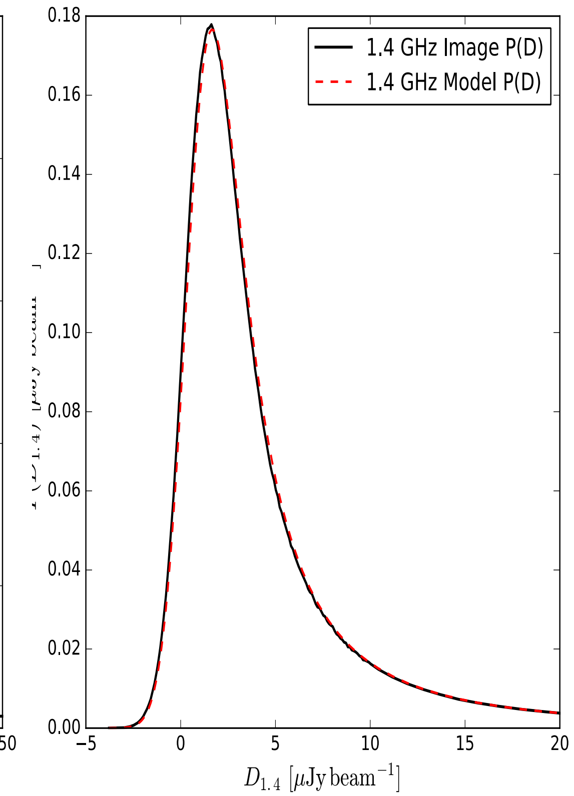

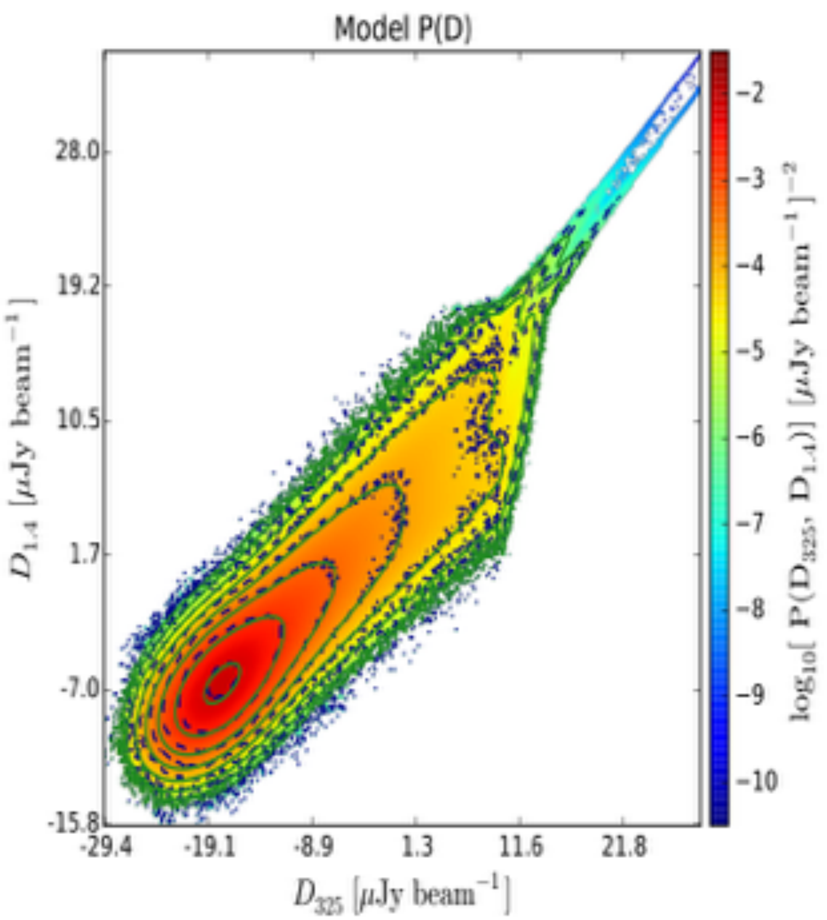

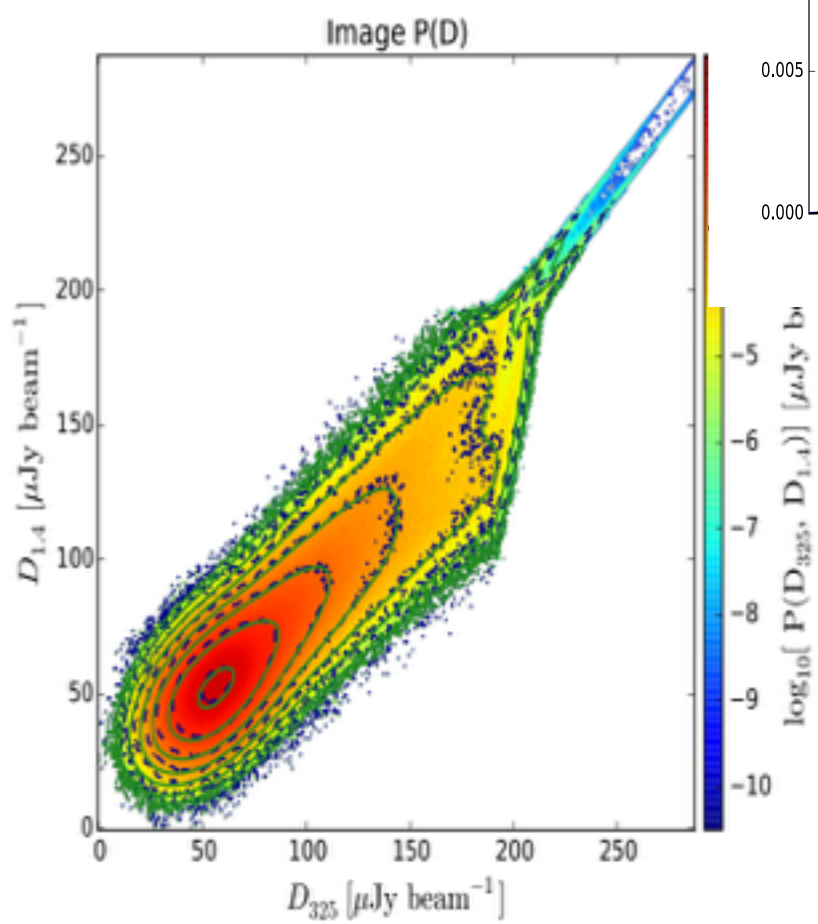

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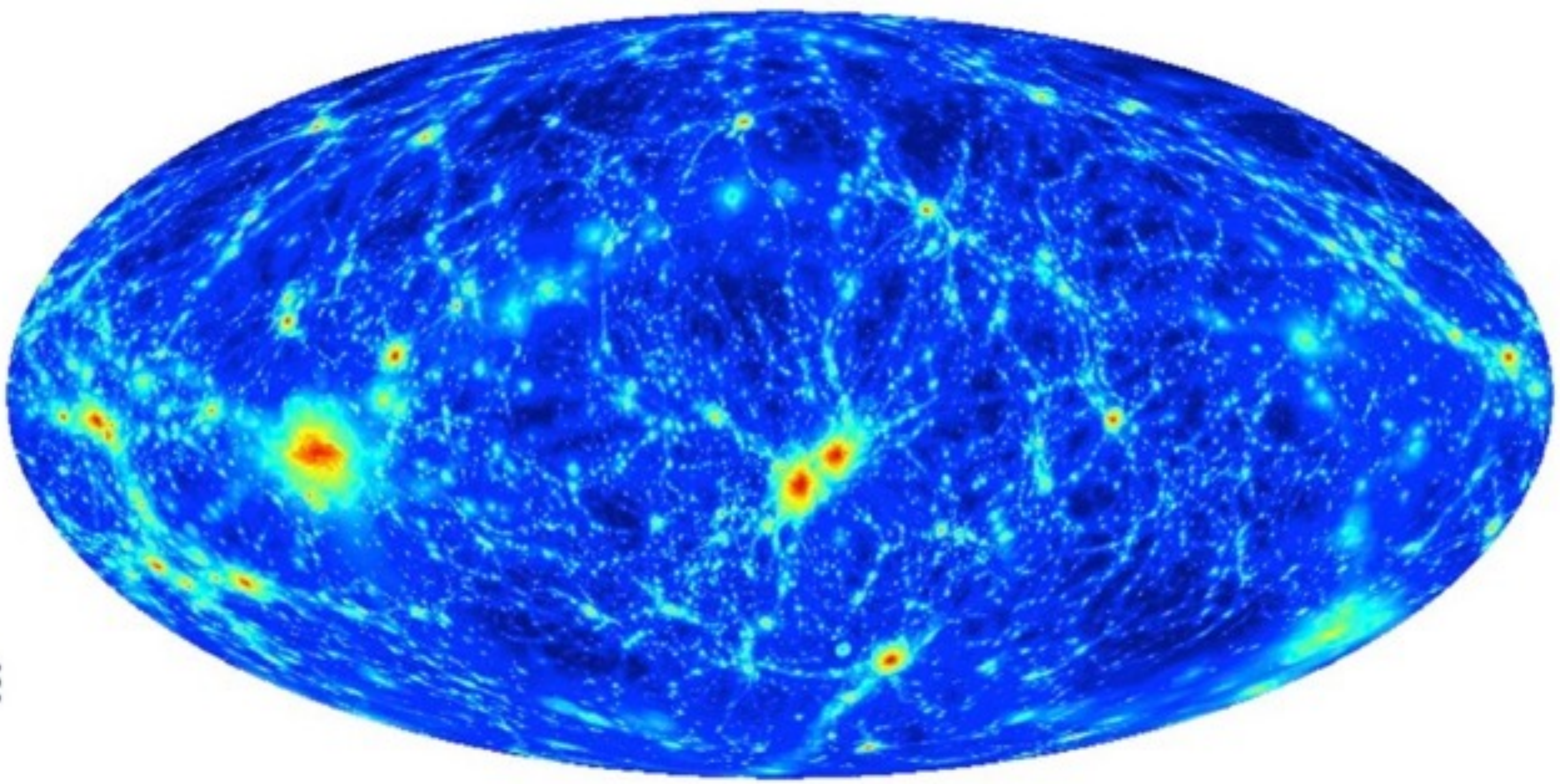
Conclusions

- Many reasons to look for the cosmic web
  - Missing baryons, origin of cosmic magnetism, ….
- Many possible methods of detection
  - Direct imaging, statistical methods, ….
- Many new telescopes/surveys/data coming soon
  - MWA, LOFAR, ASKAP, MeerKAT, SKA, ….

→ Many reasons to think exciting new results in the near future



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Ideal Observational Setup

Frequency

- Low (ish)
  - Too low → stronger Galaxy
  - Too high → weaker signal

Field

- Large area
- Low Galactic contamination
- Multi-wavelength coverage

UV Coverage

- Good (continuous) coverage
  - Minimize sidelobes
  - Deeper cleaning

Resolution

- High (arcsecs)
  - Point source subtraction
- Low (arcmins)
  - Diffuse emission

Sensitivity

- Low instrumental rms
- Good sensitivity to large and small angular scales