FOREGROUNDS: TOWARDS AN UNDERSTANDING OF THE DIFFUSE POLARIZED EMISSION IN THE MILKY WAY

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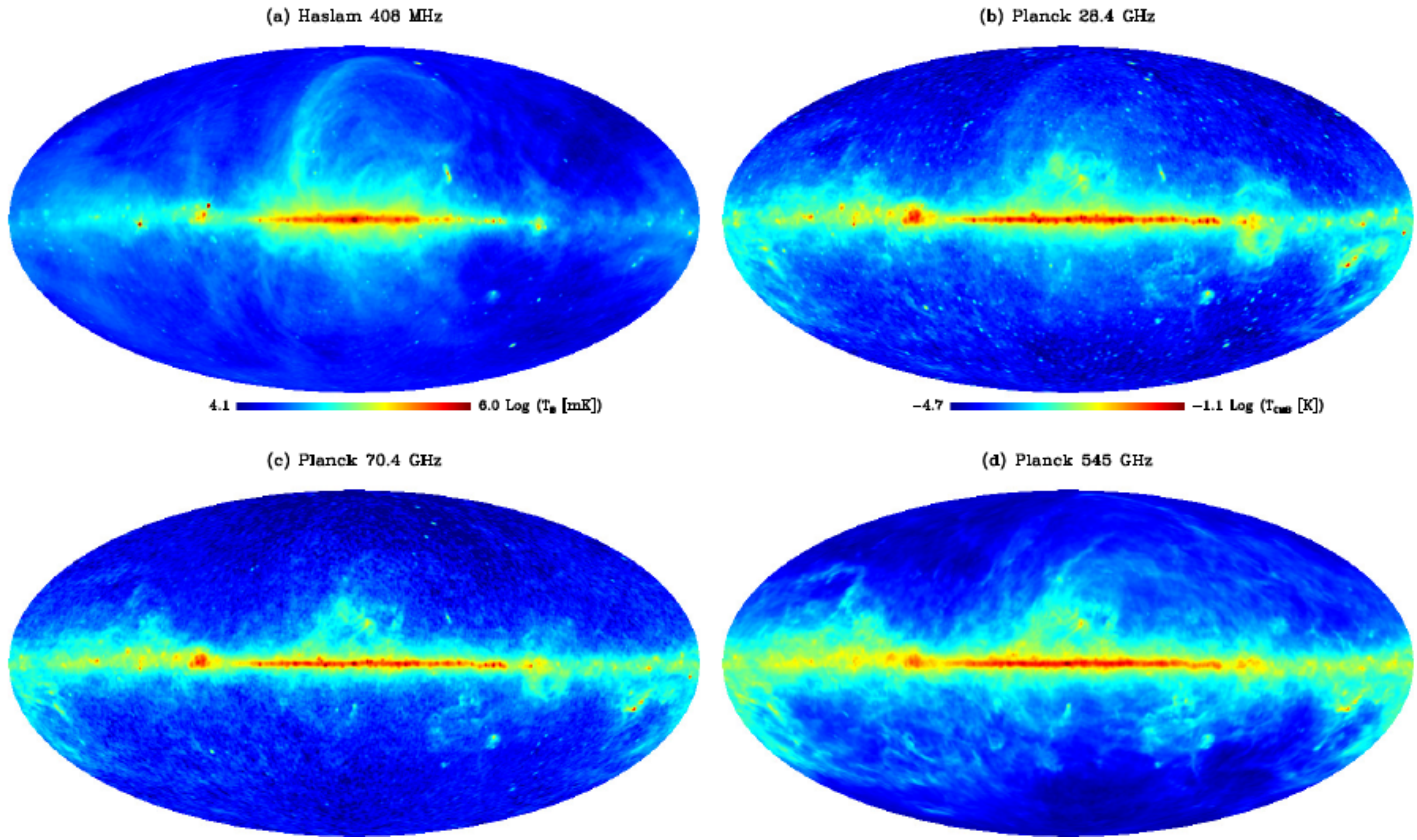
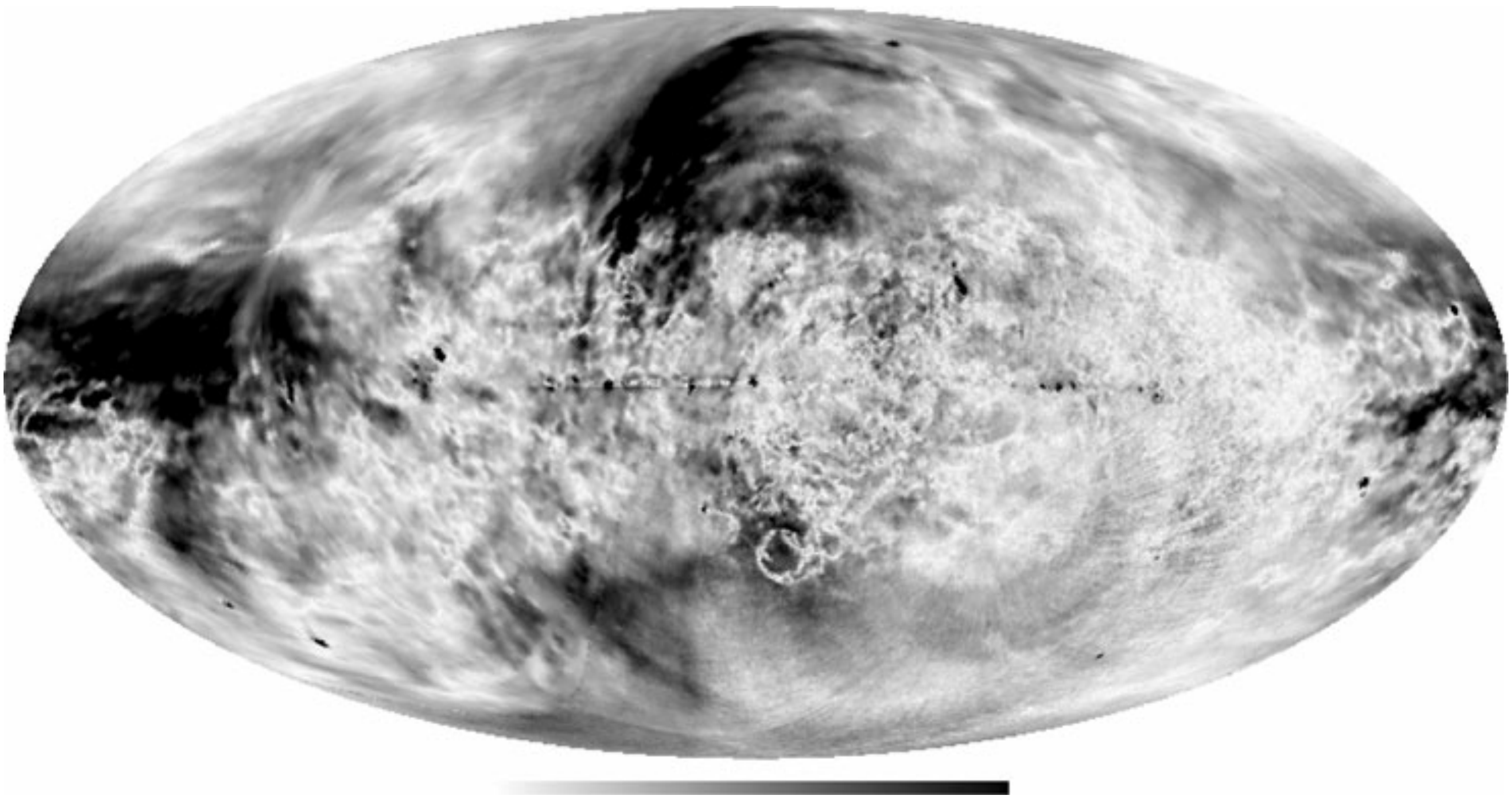
Planck Collaboration: Galactic plane emission from *Planck* with ancillary data



1.4 GHz map (polarized)



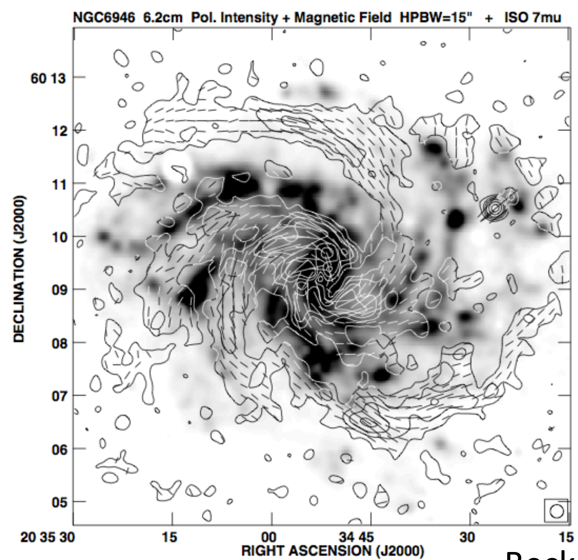
From Caretti (2011)

Can we do a better job of understanding the small scale structure of the polarized diffuse radio emission in the Milky Way?

- Can we construct meaningful models of the synchrotron ISM in other galaxies?
- Can we use rotation measure surveys of polarized extragalactic sources to accurately measure the Galactic foreground?

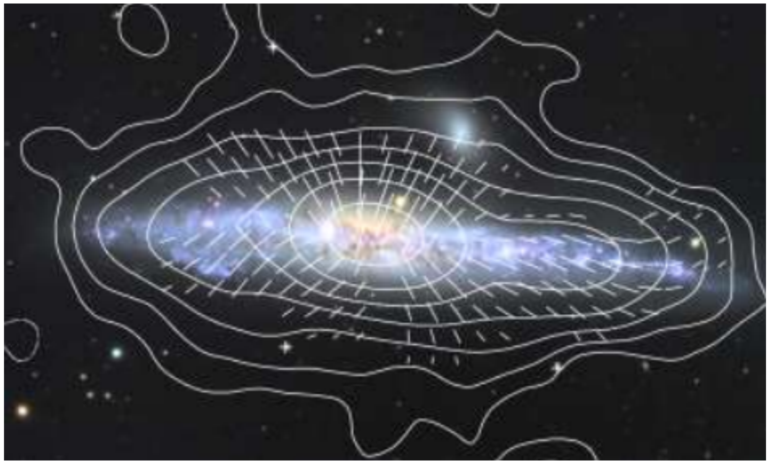
Magnetic Fields in Spiral Galaxies

- Large-scale structure
  - Magnetic arms in face-on galaxies
  - Parallel to disk and X-shape in edge-on galaxies
  - Strength: few uG
  - Scale length: 0.1 – a few kpc



Beck 2007

- Small-scale structure
  - Turbulent
  - Associated with star formation, and in spiral arms
  - Strength: a few to 10s uG
  - Scale Length: sub-pc to 100 pc



M. Krause

Case Study: Observe nearby spiral galaxy NGC 6946, disentangle the magnetic field structure, and see how the structure relates to other galactic processes.

Subaru Telescope, R. Gendler

NGC 6946: FAQ

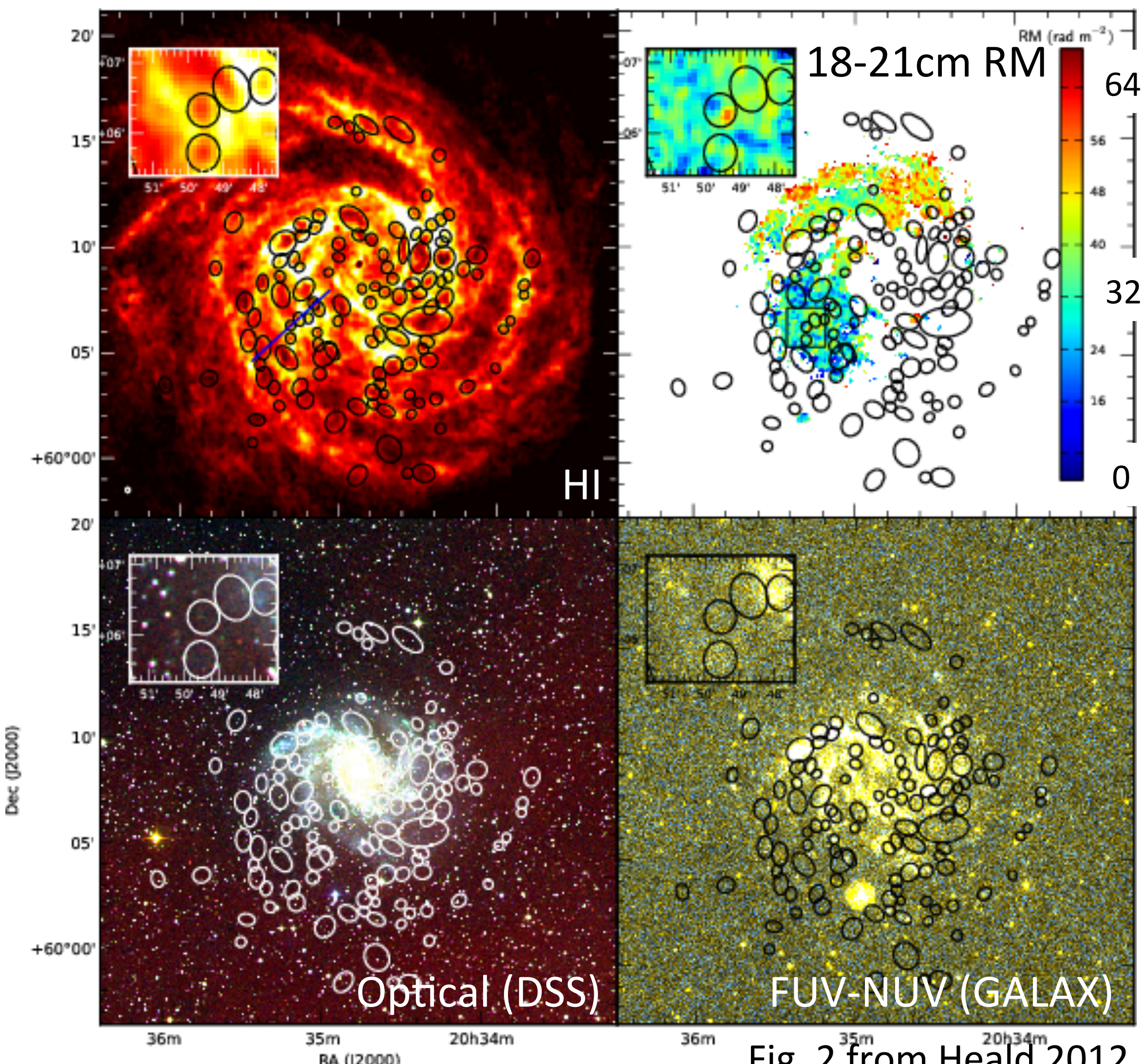


Fig. 2 from Heald 2012

Ellipses are HI bubbles by Boomsma et al. (2008)

-Nearby ~6.8Mpc

1.7kpc ~ 1'

(Karachentsev et al. 2000)

-Nearly face-on

***i*=38deg**

(Boomsma et al. 2008)

-Dynamical mass

~1.9×10^{11} M_{solar}

(Crosthwaite & Turner 2007)

-Integrated SFR

2.8 M_{solar}/yr

(Calzetti et al. 2008)

-Mild SB in nucleus

(e.g. Ball et al. 1985)

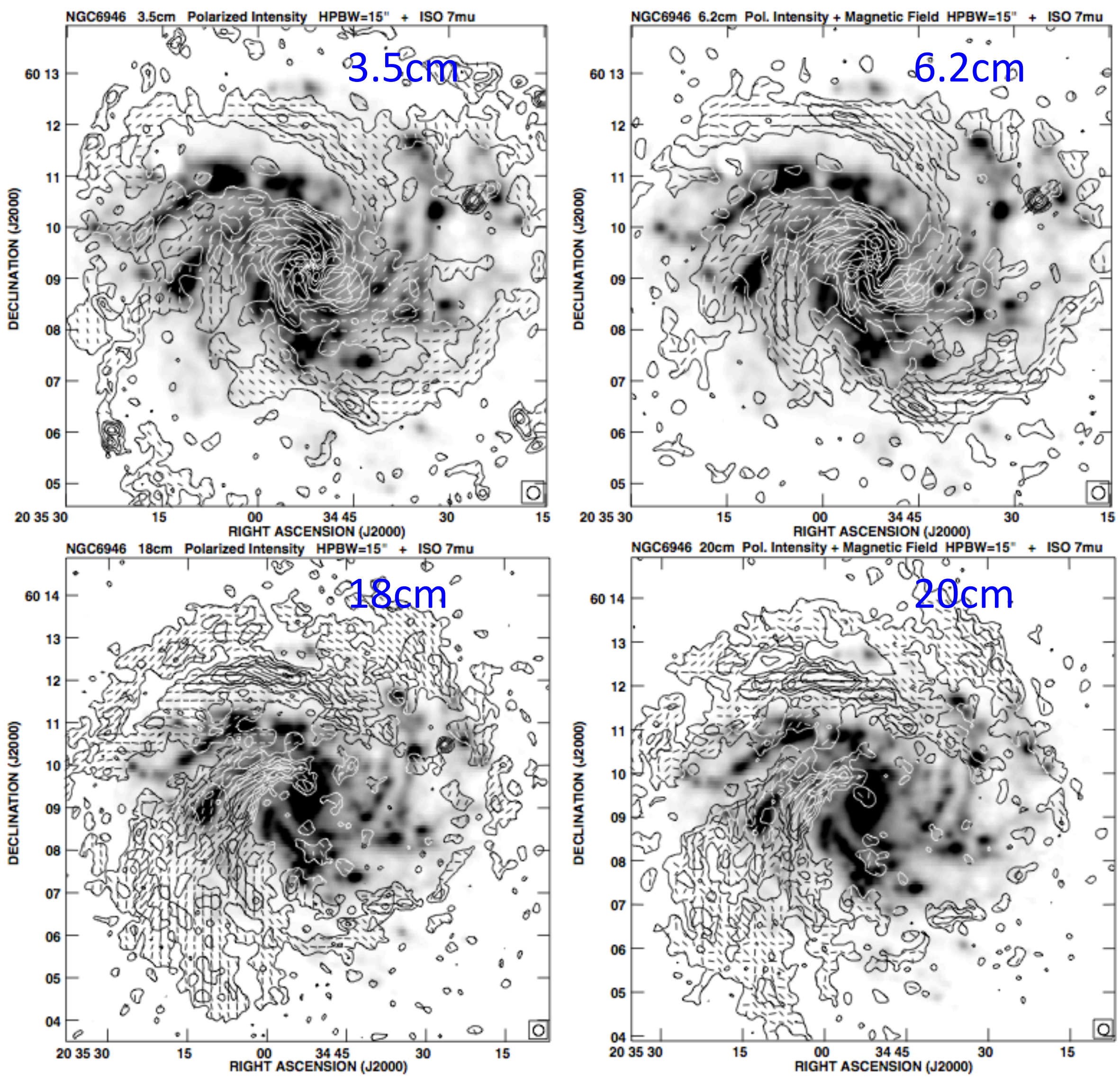
-No strong AGN evidence

(e.g. Tsai et al. 2006)

-Located at low *b*

-Lots of observations available at many different wavelengths!

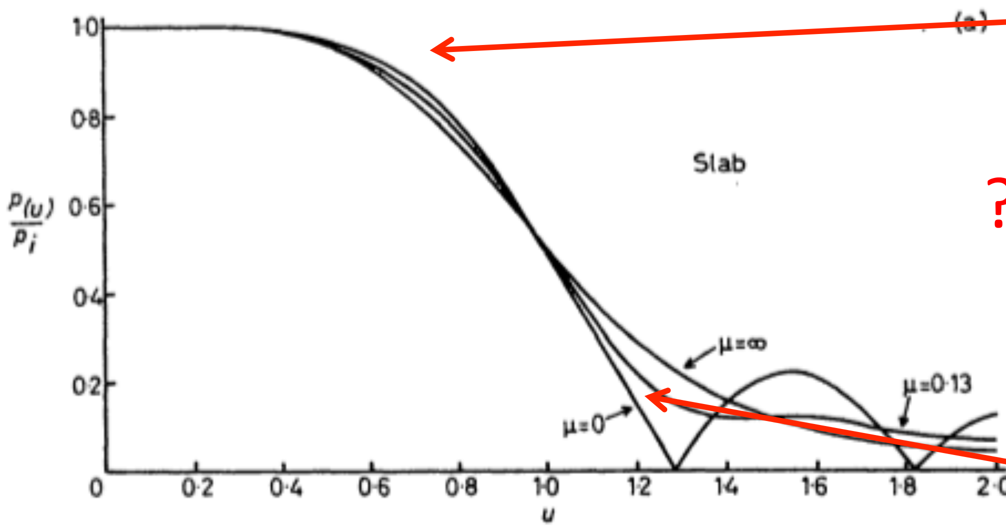
Use wideband polarimetry to probe magnetic field structure in the galaxy.



Beck 2007

Internal Faraday Dispersion

$$P(\lambda^2) = P_0 \frac{1-exp(-S)}{S} \qquad S = 2\lambda^4 \sigma_{RM}^2 - 2i\lambda^2 R$$



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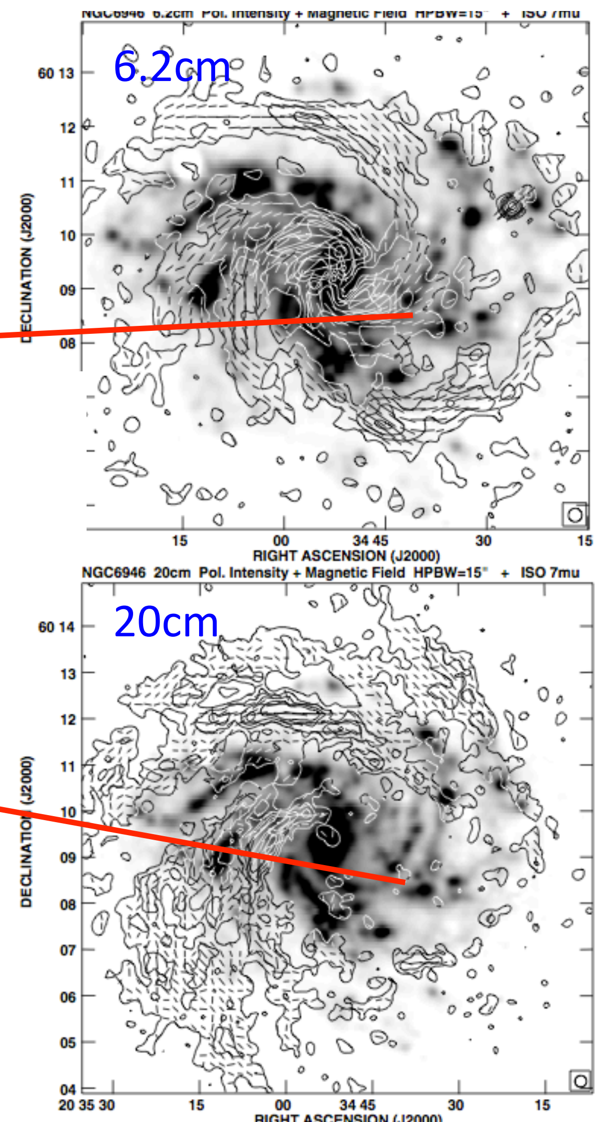
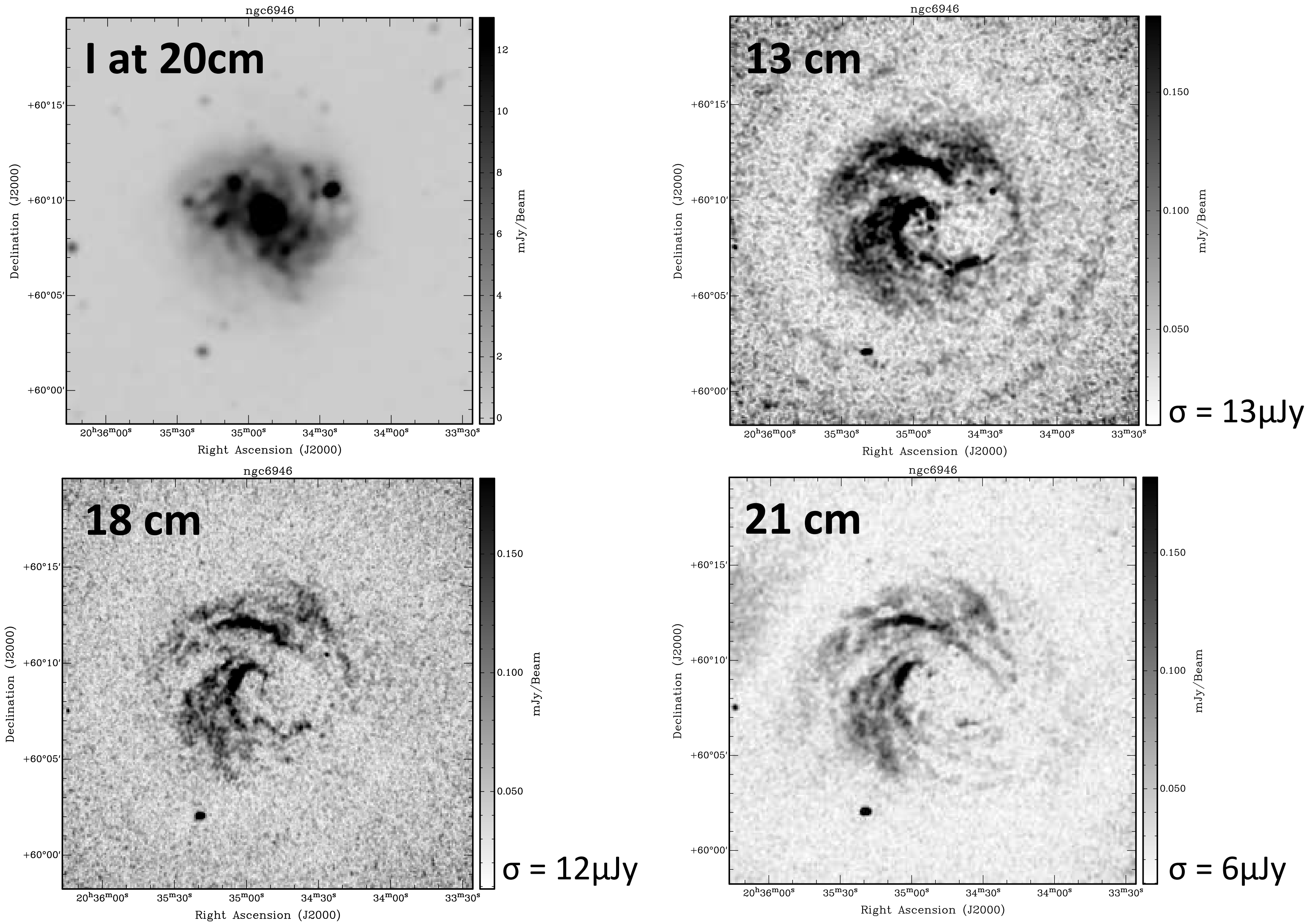


Burn 1966

Beck 2007

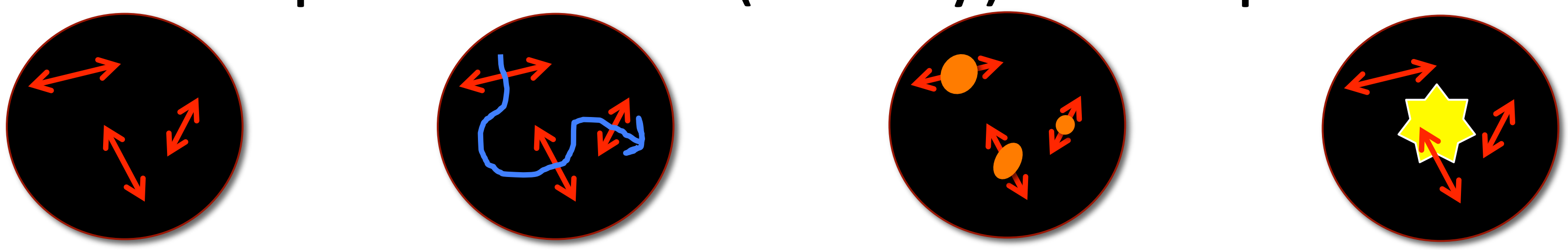
$p(u)/p_i$ percent polarization at u, u proportional to λ

Peak Polarization



What can cause depolarization and complex Faraday structure?

Beam Depolarization: (mostly) λ-independent



E-vectors

Tangled *B*

Different sources

Unresolved background – could depend on λ

Faraday Depolarization: λ^2-dependent

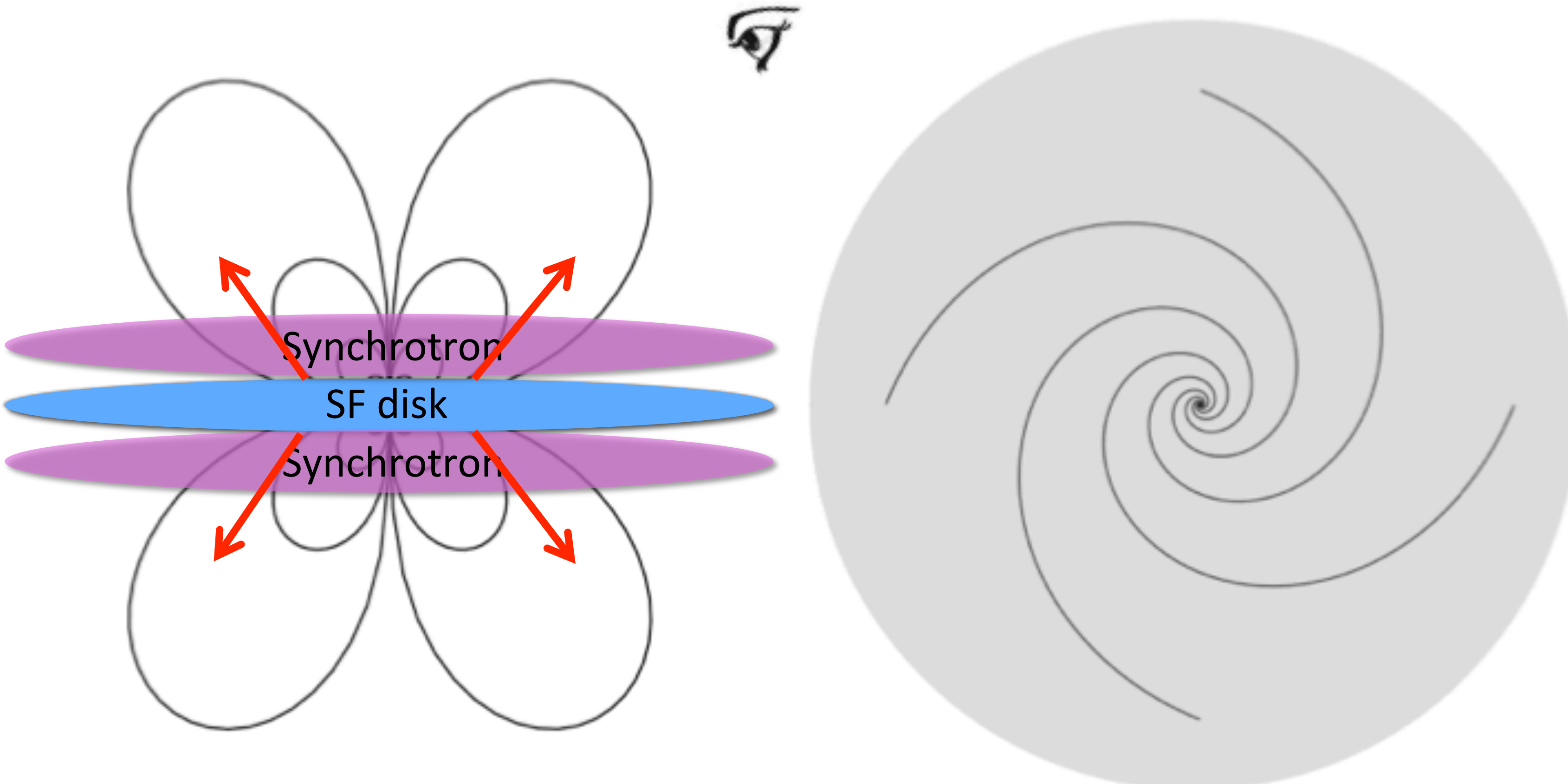
Faraday differential rotation (FDR): Regular field in a medium that is both emitting and rotating

Internal Faraday dispersion (IFD): Turbulent *and* regular field in a medium that is both emitting and rotating

External Faraday dispersion: Emitting and turbulent rotating regions are separated, and the rotating region may cover all or just part of the emitting region--also known as *inhomogeneous Faraday screen (IFS)*

Interpretation

Prediction: azimuthal asymmetry vanishes at higher frequency



Vertical extent of spiral component is ~30% of radius

Braun+2010

Model Fitting

First fit:

$$|\overrightarrow{p}| = p_0 \frac{1 - e^{-S}}{S}$$

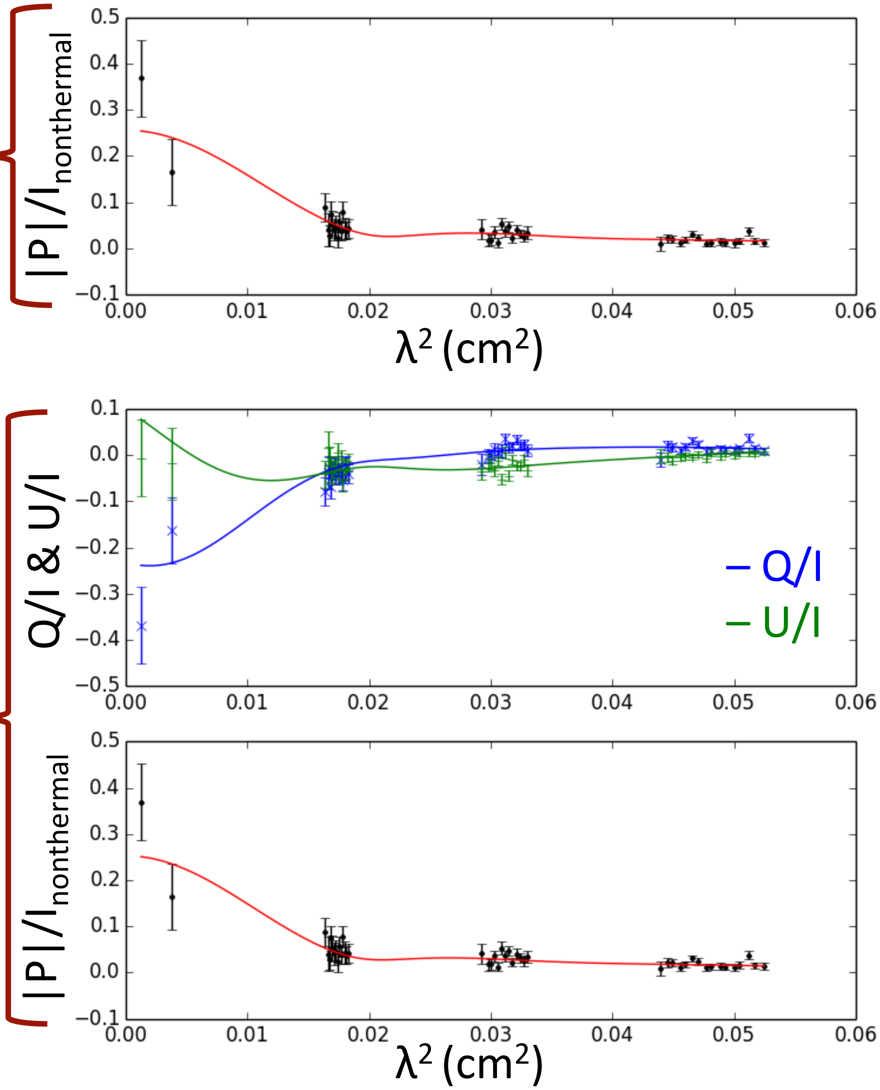
$$S = 2\lambda^4 \sigma_{RM}^2 - 2i\lambda^2 R$$

Second fit:

$$\overrightarrow{p} = p_0 \frac{1 - e^{-S}}{S} \underbrace{e^{2i(\phi_0 + RM\lambda^2)}}$$

$$= \cos\left(2\phi_0 + 2RM\lambda^2\right) + i \sin\left(2\phi_0 + 2RM\lambda^2\right)$$

$$= q + i\ u$$



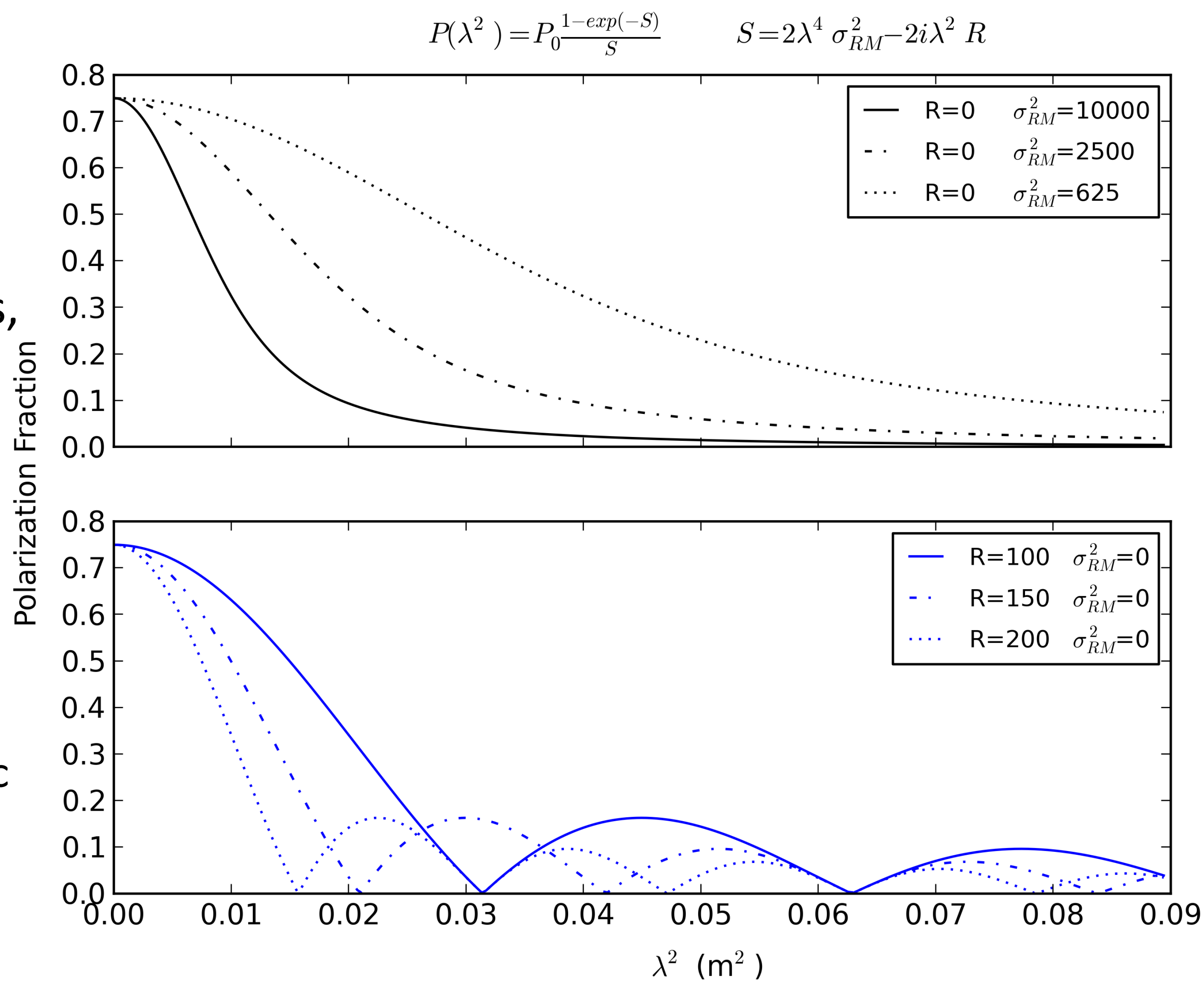
Internal Faraday Dispersion

- Slab of magneto-ionized medium that contains
  - well-mixed thermal and synchrotron emitting gas,
  - and both regular (R) and random fields (σ_{RM}).
  - Typical values

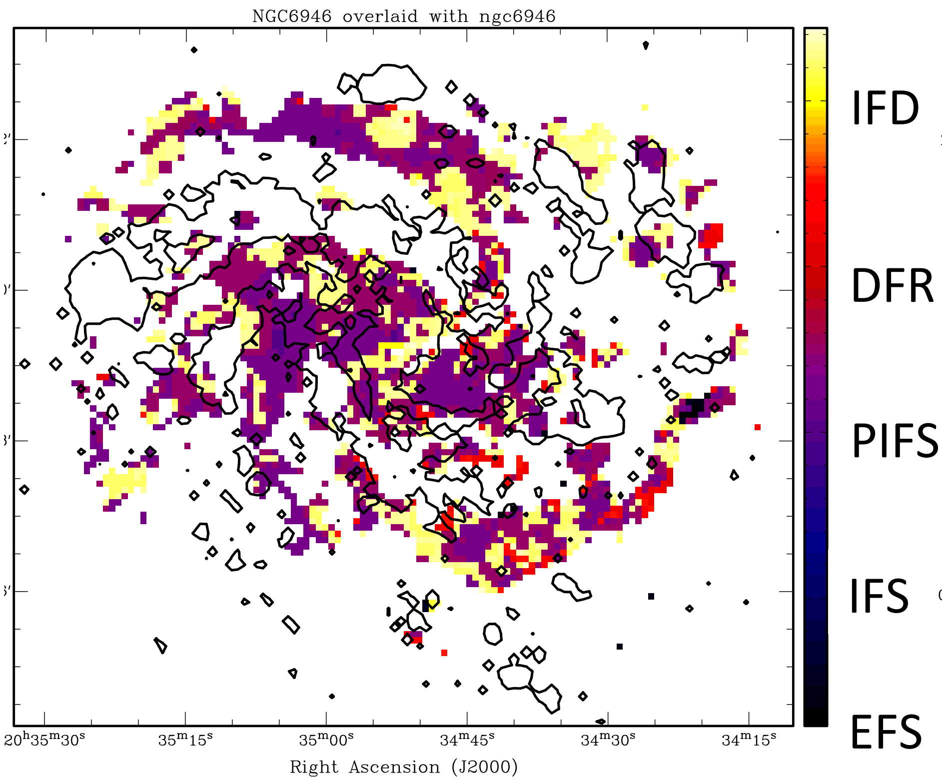
    R ~ 100 rad m^{-2}

    σ^2_{RM} ~ 1000 rad m^{-2}

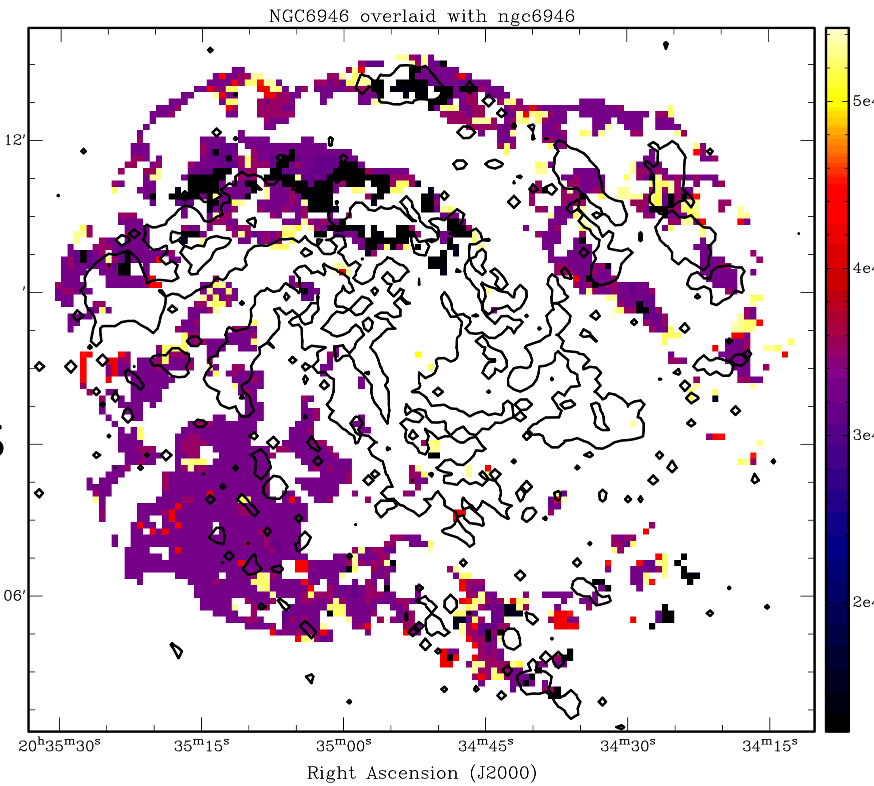
    for n~0.03 cm^{-3}, B_z~2uG, σ_z~3uG, l_m~100pc, h_E~1kpc (Sokoloff et al. 1998)



Best Fit Models

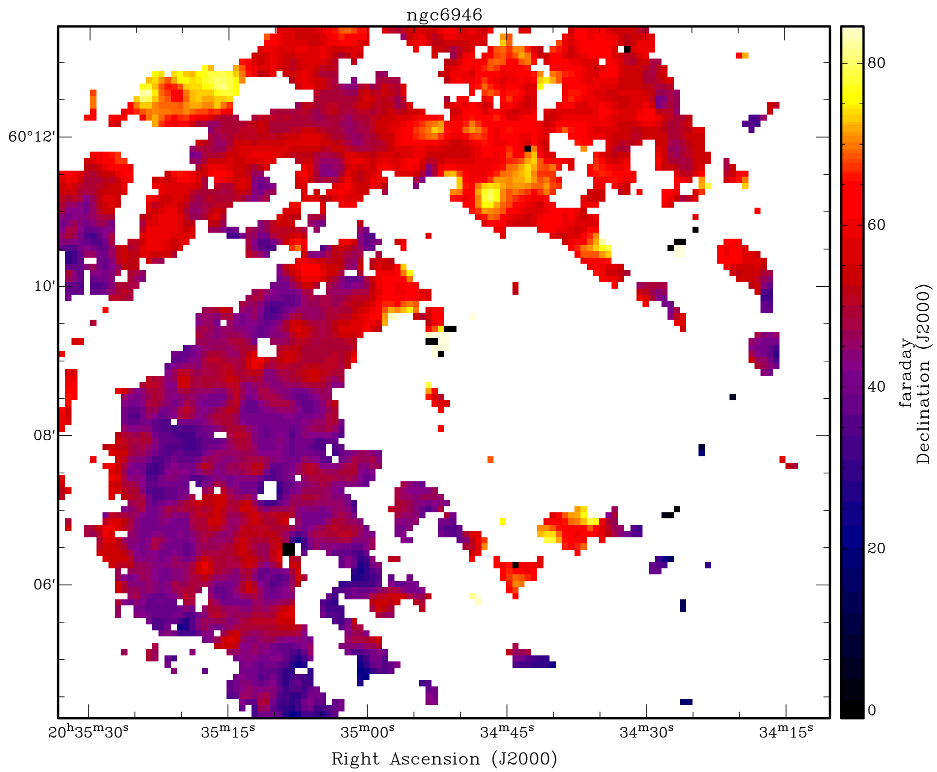


Pixels with polarization at 3 or 6cm has S/N > 8.

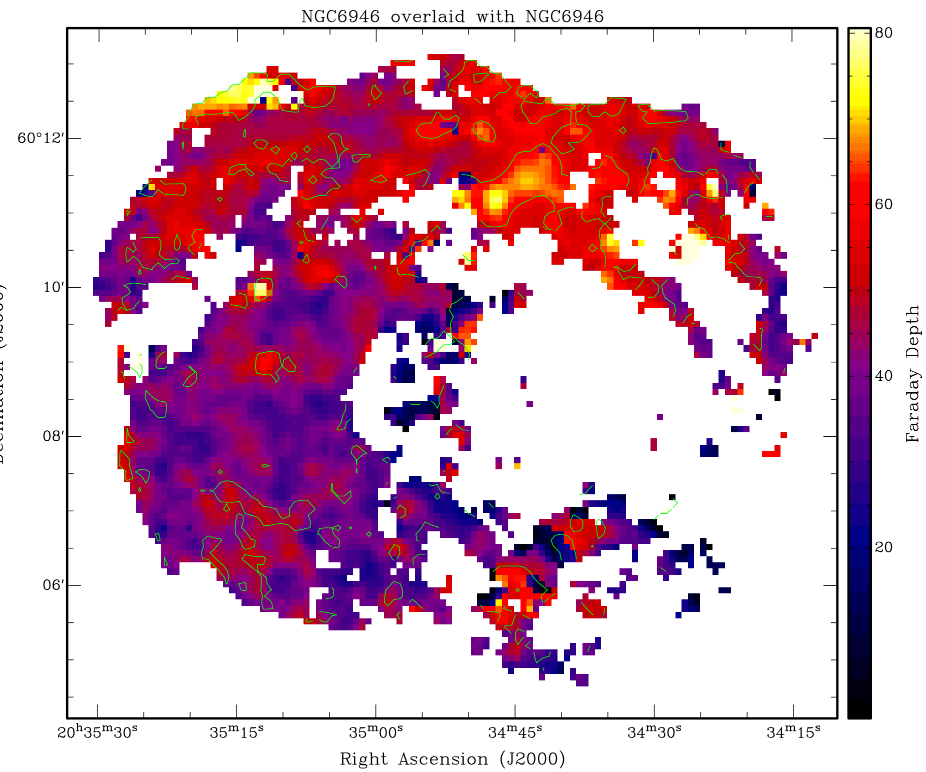


Pixels with polarization at 13, 18, or 21cm has S/N > 8, and excluding pixels with high S/N polarization at 3 & 6cm.

Comparing Faraday depth maps

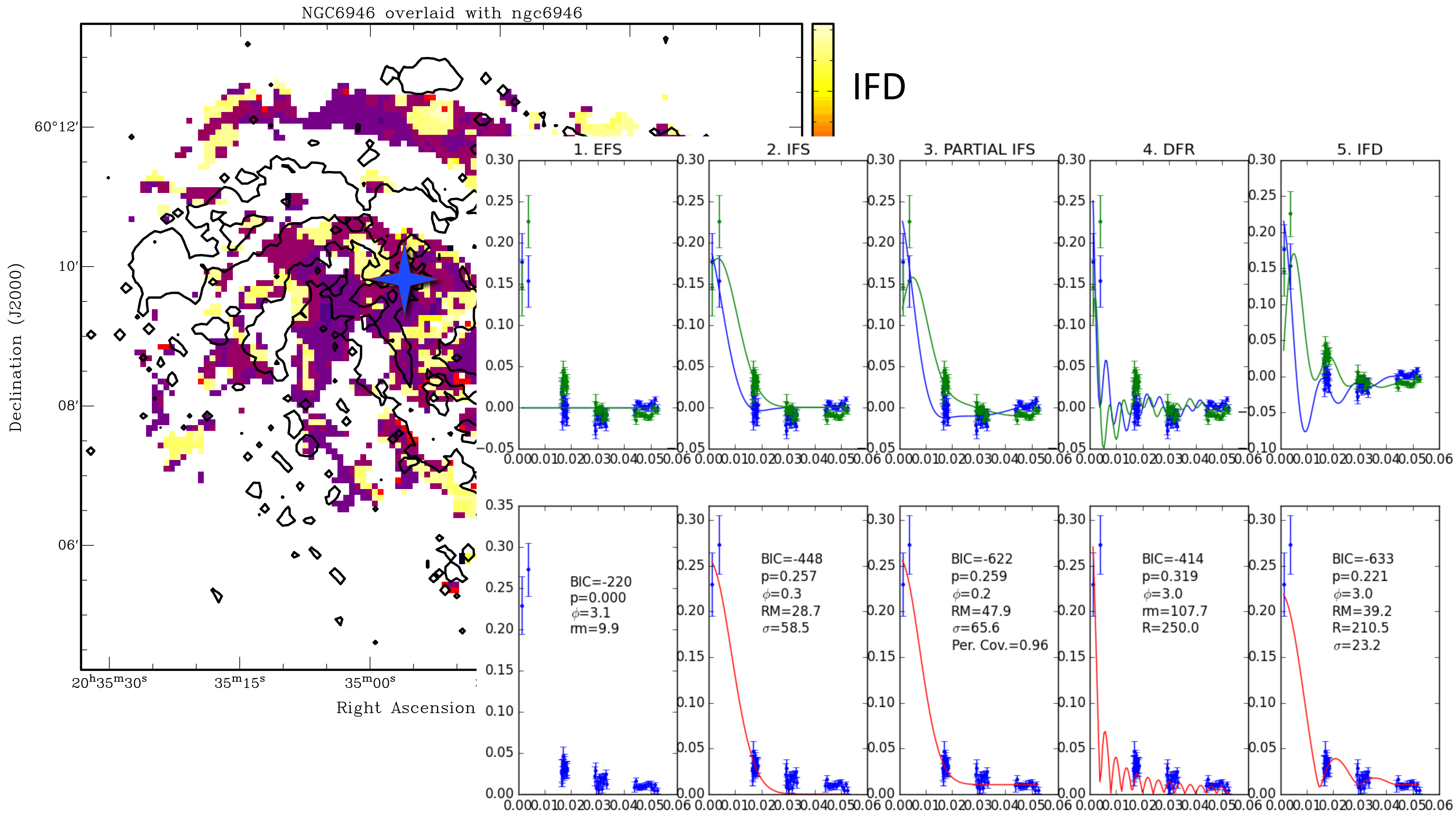


Faraday depth map using
RM synthesis with 13-21cm data

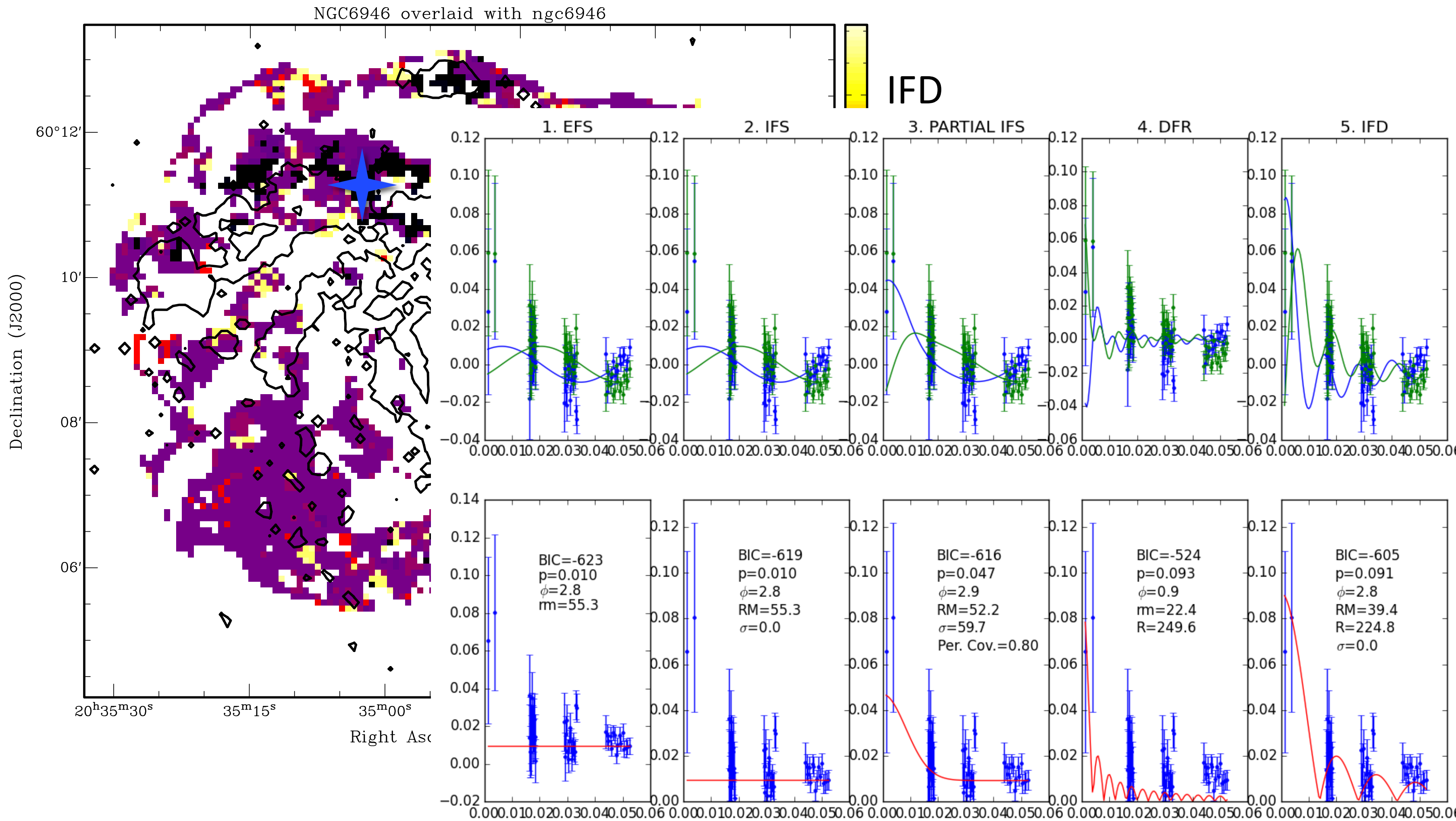


Faraday depth map produced
from best fit RM component in
partial inhomogeneous screen model

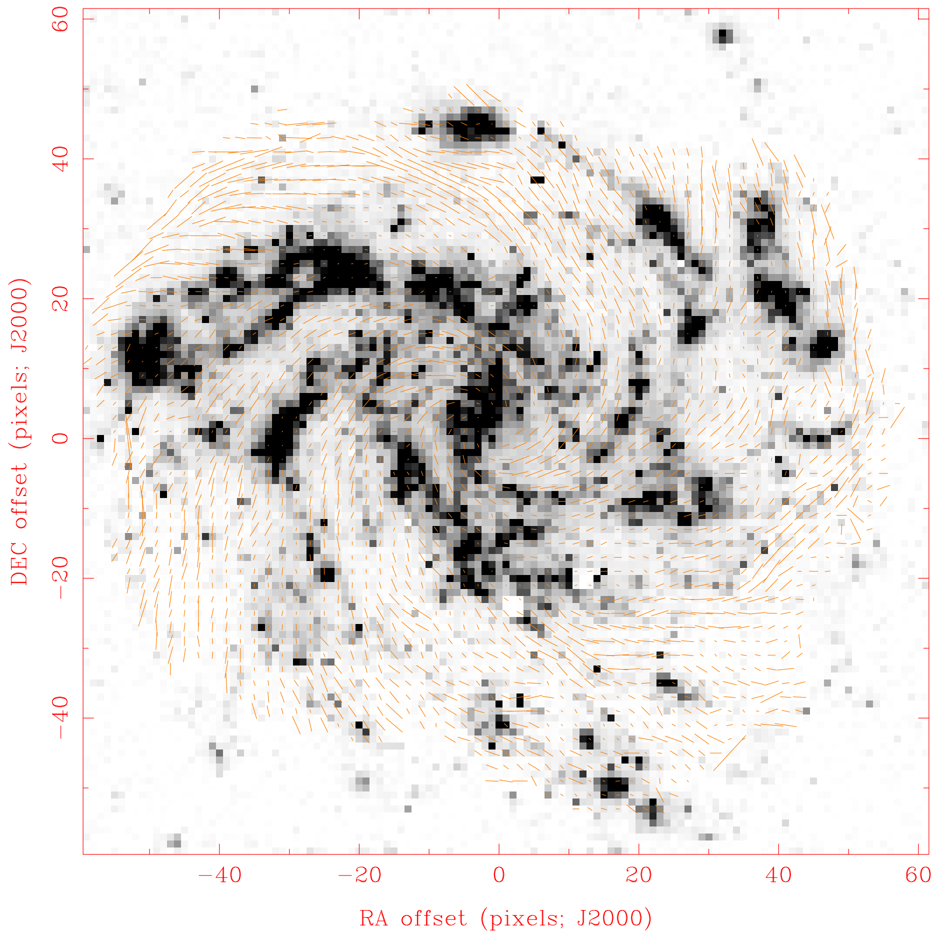
Best Fit Models—point-by-point



Best Fit Models—point-by-point

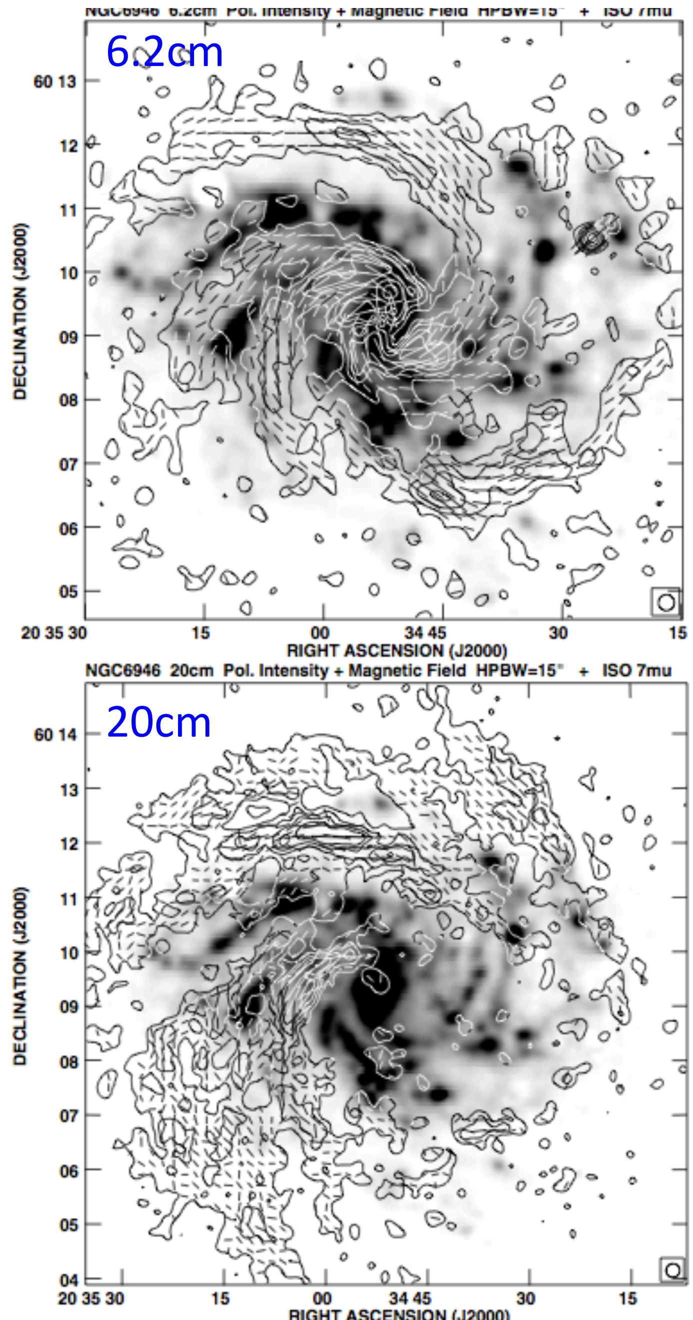


Model Fit: B ‘vectors’



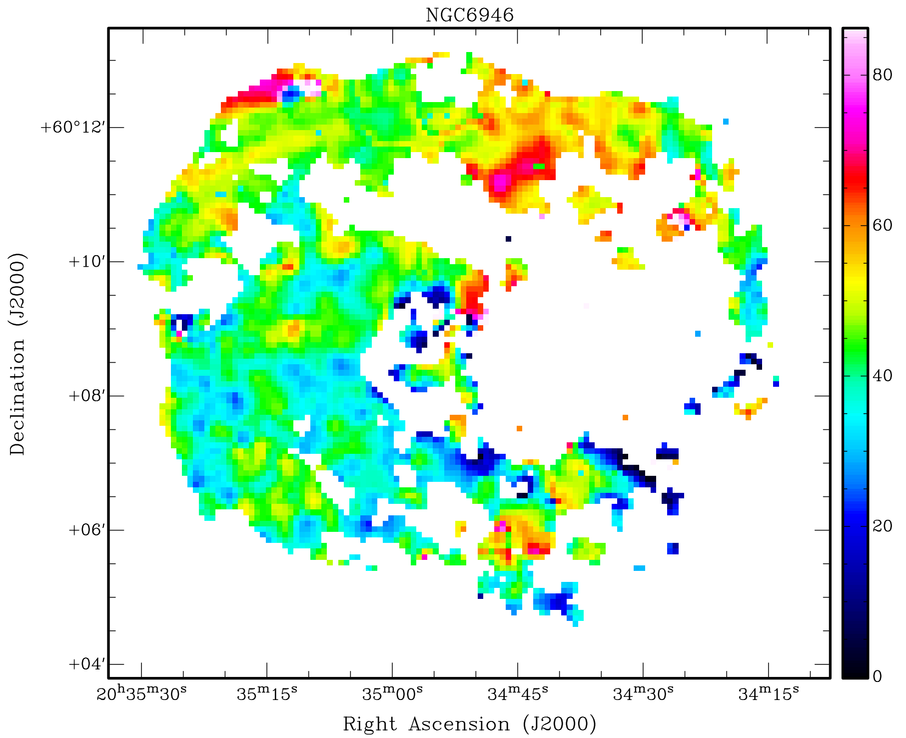
Best fit percent polarization and ϕ from partial inhomogeneous screen fit

(Hα background map courtesy of A. Ferguson)



Beck 2007

New RM map probes different Faraday depths (different layers of ISM!)



RM of Model Fit

RM determined by RM synthesis of 13-21cm data

Colorbar (rad/m^2) and maps are scaled to be equal

Summary

- Using wideband polarization observations at 3-21cm to study magnetic field structure in NGC 6946
- The available data can only be used to rule out models
  - Depolarization cannot be explained with models containing separate emitting and simple, coherent rotating regions
- Most complex models (IFD and PIFS) are better at fitting p_0, ϕ, and RM
- Need expanded wavelength coverage—possible with today's instruments
- Need to explore more physical models

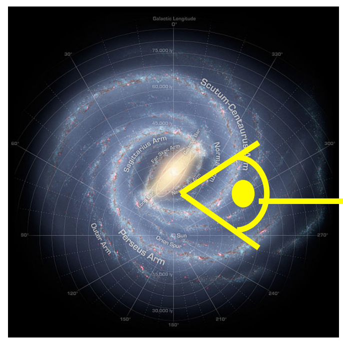
How to study RM in distant galaxies

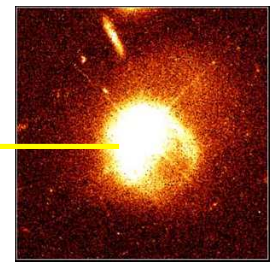
- Theories predicted

(e.g., Parker 1979)

  - μG strength fields to be a relatively recent phenomenon
  - Galactic magnetic fields would be substantially weaker at z~2.0
  - Should see change in RM as function of redshift

$$\phi(r) = 0.81 \int_{there}^{here} n_e(z) B_{\parallel}(z) \frac{1}{(1+z)^2} \frac{dl}{dz} dz$$





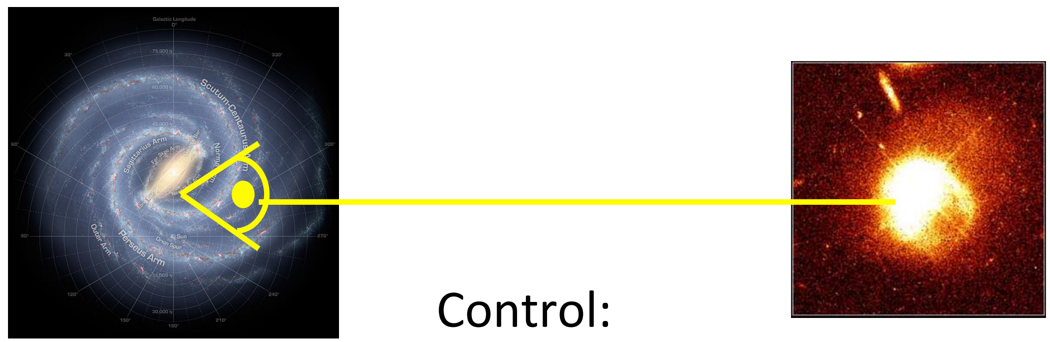
Control:

$RM_{Obs.} = RM_{MW} + RM_{IGM} + RM_{QSO} + \sigma$

How to study RM in distant galaxies

- Theories predicted
(e.g., Parker 1979)
  - μG strength fields to be a relatively recent phenomenon
  - Galactic magnetic fields would be substantially weaker at z~2.0
  - Should see change in RM as function of redshift
- Observational RM experiments were designed with control and target samples (e.g., Oren & Wolfe 1995, Bernet +2010)

$$\phi(r) = 0.81 \int_{there}^{here} n_e(z) B_{\parallel}(z) \frac{1}{(1+z)^2} \frac{dl}{dz} dz$$



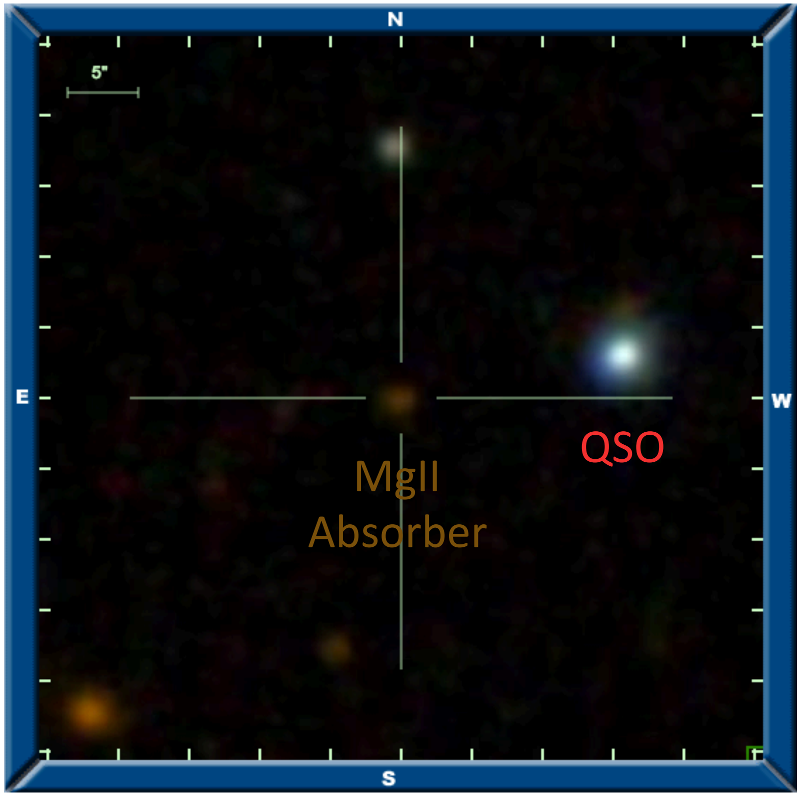
Control:
$RM_{Obs.} = RM_{MW} + RM_{IGM} + RM_{QSO} + \sigma$

Target:
$RM_{Obs.} = RM_{MW} + RM_{INT} + RM_{IGM} + RM_{QSO} + \sigma$

VLA Observations taken during 2014 & 2015

- 38 QSO sightlines with single MgII absorption feature AND photometric detection for absorber!
  - Within 70kpc of QSO
  - $0.38 < z_{MgII} < 0.65$
  - $0.65 < z_{QSO} < 1.9$
- 112 Control sightlines with roughly same distribution in RA and redshift
- S-band (2-4GHz)
  - Mitigate depolarization
  - Broadband for RM synthesis & Q-, U-fitting
- VLA A- & BnA- Configurations
  - Resolve our radio sources!

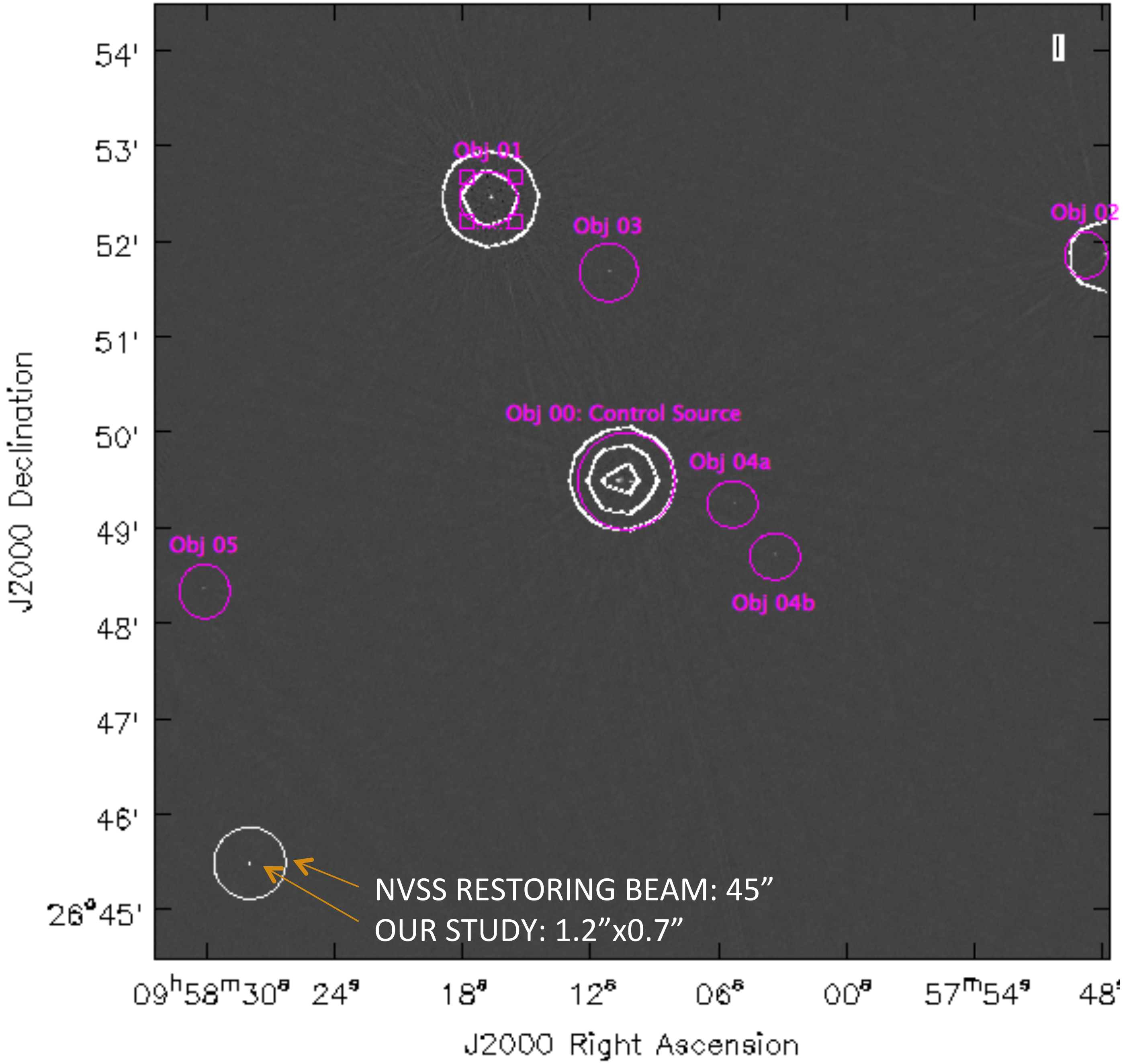
SDSS Image of one target



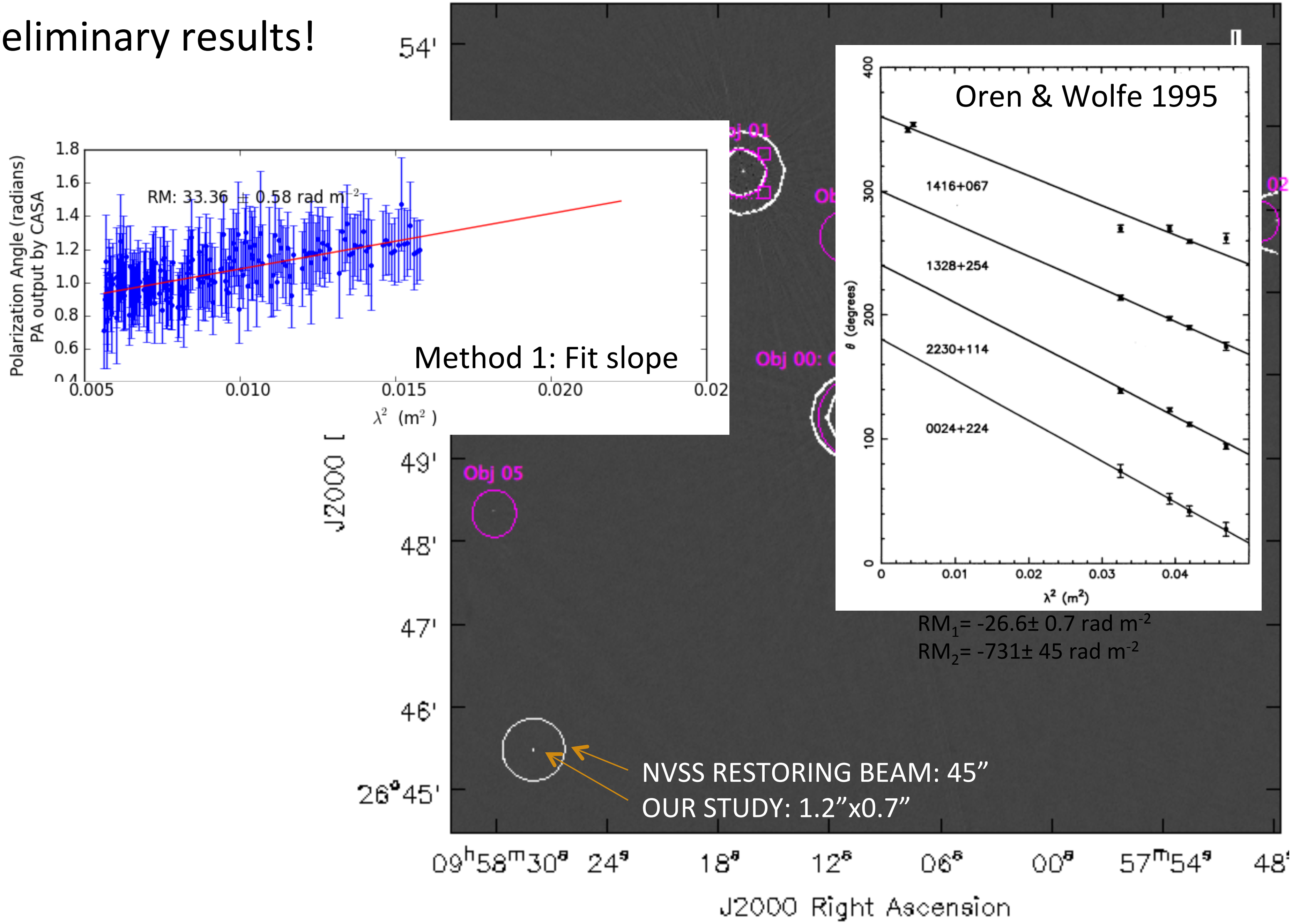
Preliminary results!

Primary beam ~15'
Pixels are 0.2"
20uJy rms

We want to determine RM 3 ways:
1) Fit slope of PA vs. λ^2
2) RM Synthesis
3) Q-,U-fitting



Preliminary results!



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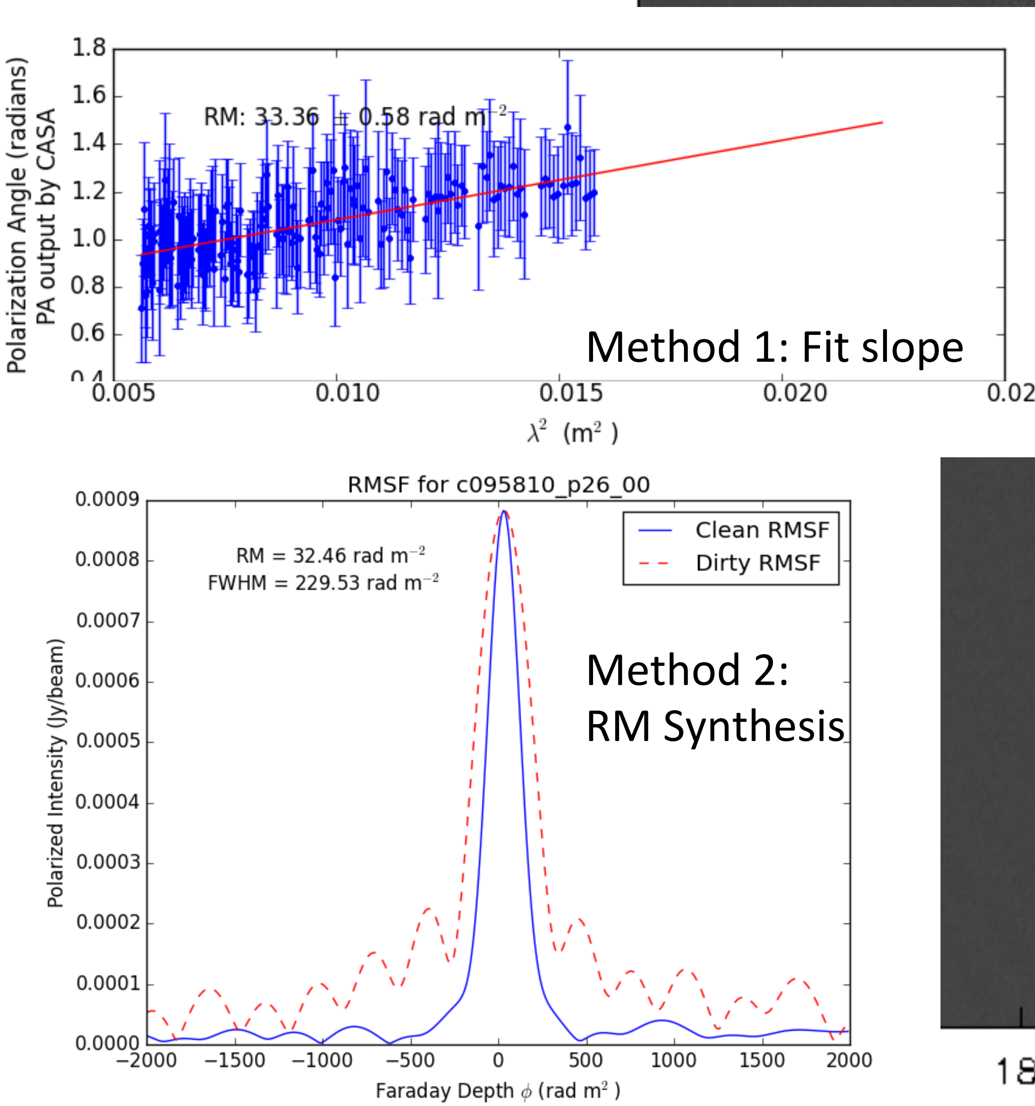
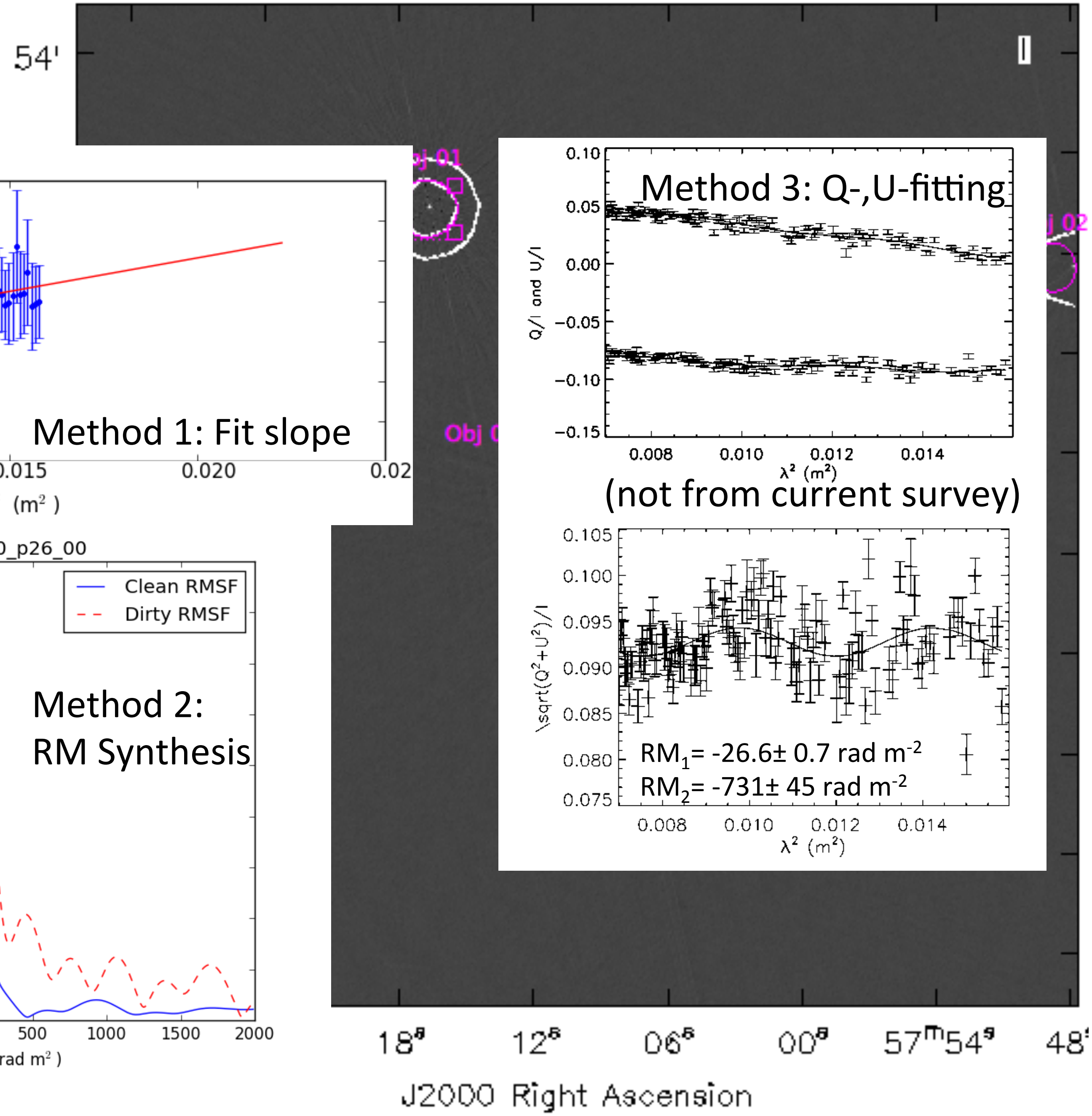
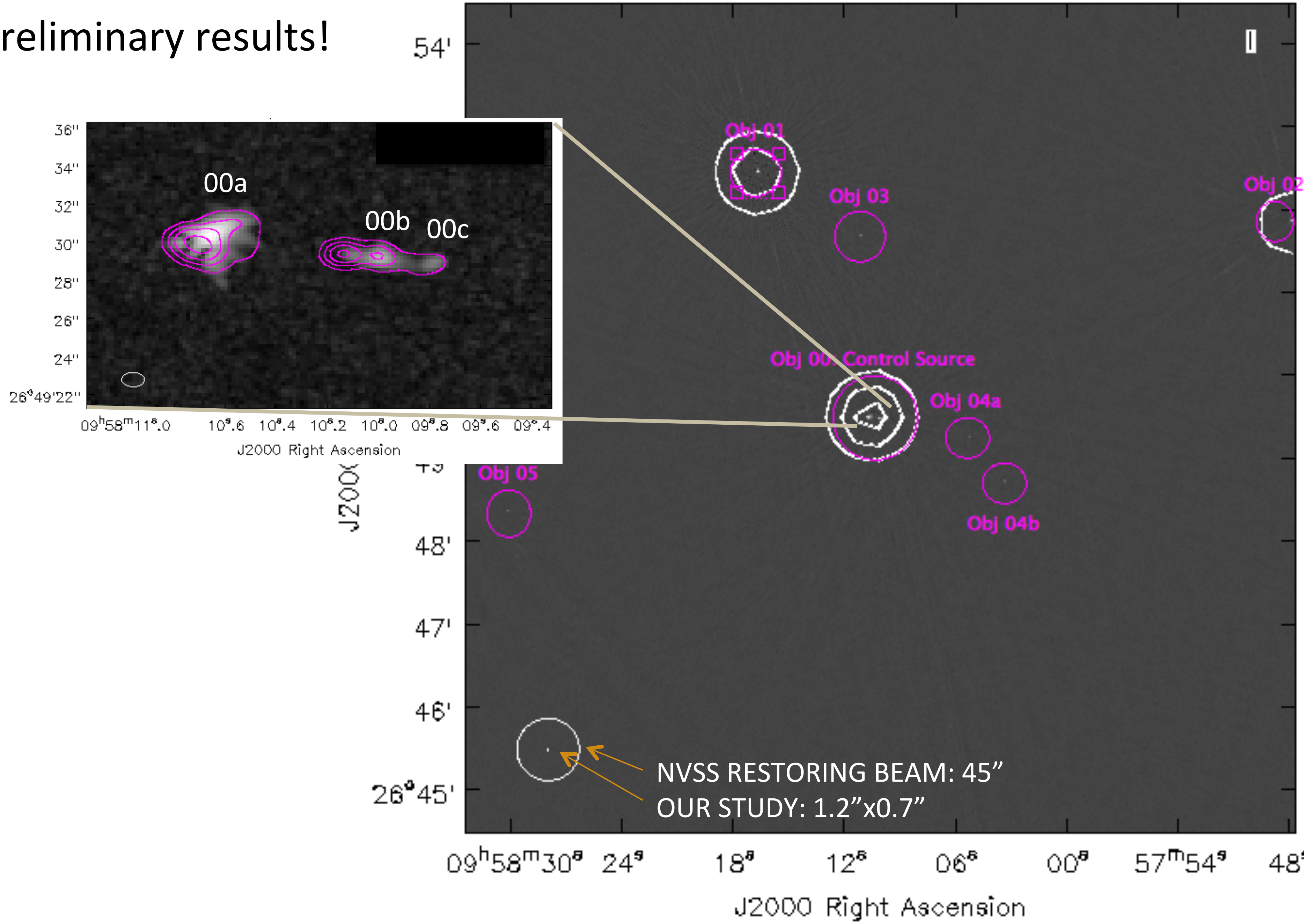
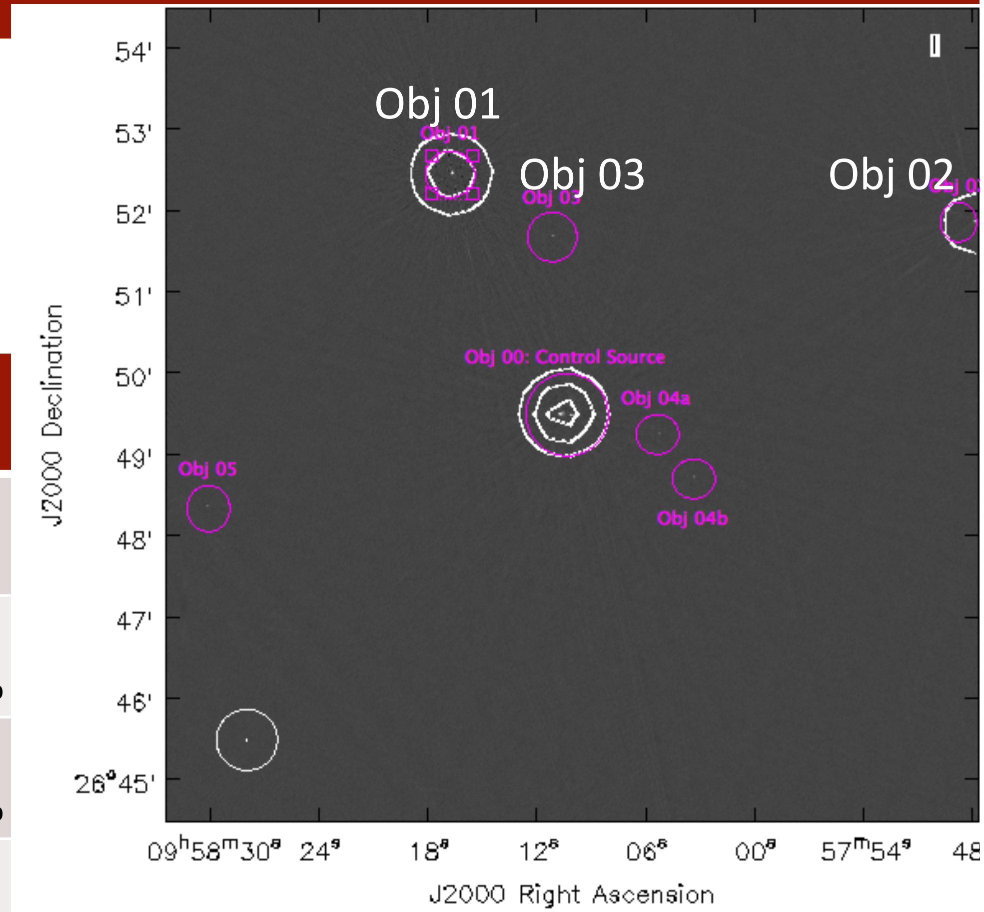




Preliminary results!



Preliminary results!



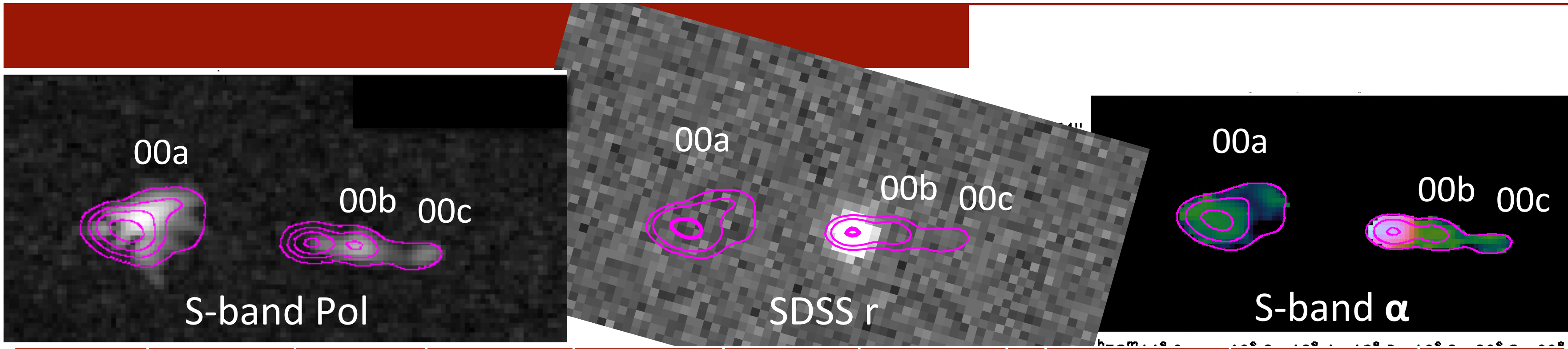
Obj	SDSSz	α	Pol. (mJy/beam)	Pol. S/N	% Pol				
00a	1.5	-0.98	0.88	49	19.5%				
00b	1.5	-0.82	0.36	20	12.2%				
00c	1.5	-1.05	0.19	10	19.5%	[illegible]	[illegible]	[illegible]	[illegible]
01	0.678 (?)	-1.12	0.12	6.8	0.6%	+141 ±16.3	-	-	-
02	(?)	+0.13	0.12	6.7	1.0%	+7 ±16.5	-	-	-
03	0.317	-0.64	0.08	4.6	6.3%	+44 ±25.0	-	-	-

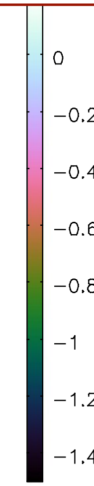
RM

New polarization detections!

→ ~ 200 sources deg^{-2}

RMS~20uJy





Obj	SDSSz	α	Pol.	Pol. S/N	% Pol	RM_{obs}		NVSS Pol.	NVSS % Pol	NVSS RM_{obs}
			(mJy/ beam)			(rad/ m^2)		(mJy/ beam)		(rad/ m^2)
00a	1.5	-0.98	0.88	49	19.5%	+33 ±2.5		3.88 ±0.24	4.01%	+44.1 ±13.1
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00c	1.5	-1.05	0.19	10	19.5%	+40 ±10.6		3.88 ±0.24	4.01%	+44.1 ±13.1
01	0.678 (?)	-1.12	0.12	6.8	0.6%	+141 ±16.3		-	-	-
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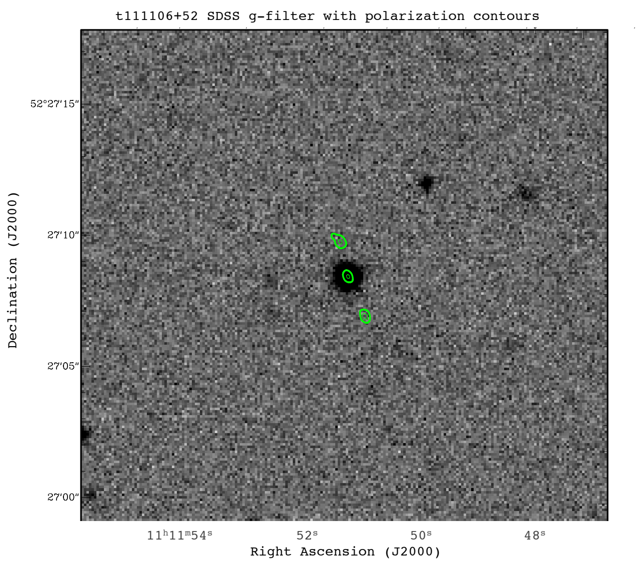
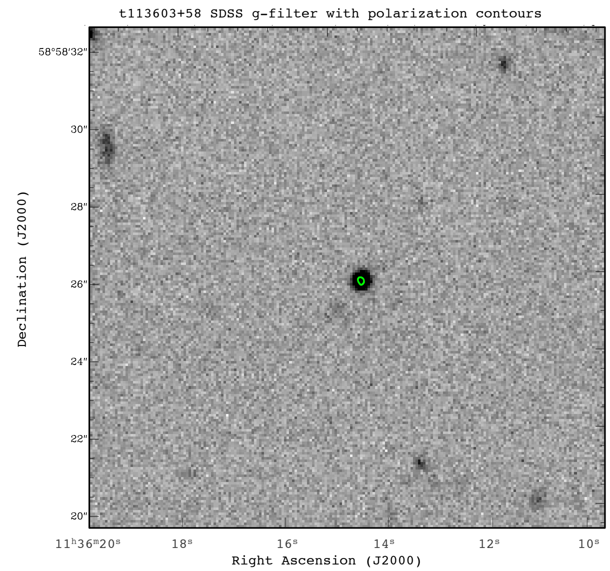
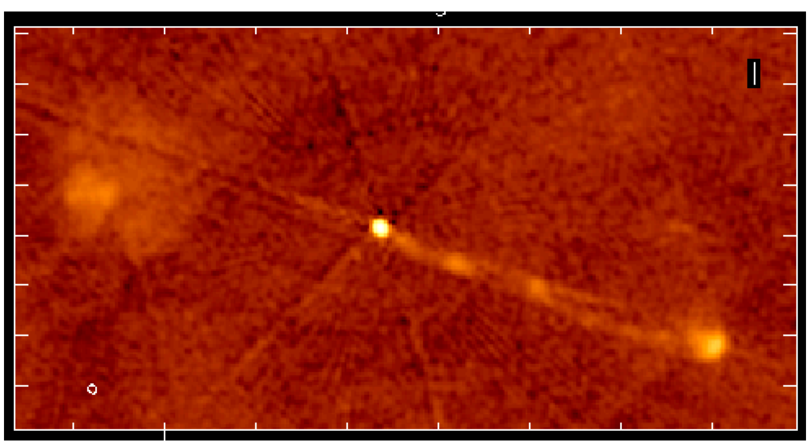
RMS~20uJy

Teaser of what is to come

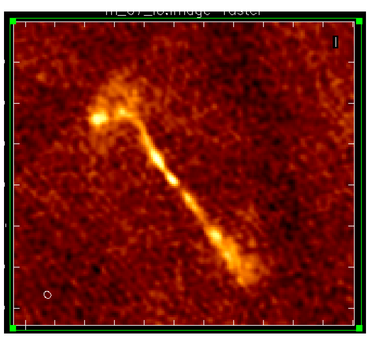


Example target QSOs
←RM~21.1 rad/m²
RM~4.2 rad/m² →





← Target QSO
Field AGN→



Summary

Current best estimates for magnetic fields in and around young, disk-like galaxies is1.8±0.4um (Farnes + 2014) using a broadly sampled data set (599 QSOs with $N_{MgII} \geq 1$, $z(MgII)_{median} \sim 0.8$)

Our Study	Observations	Goals
+38 MgII absorbers ($W \geq 0.3$Å, $z_{MgII} \sim 0.5$), +112 Control (similar z_{QSO} as MgII sample)	+S-band (2-4GHz) +VLA A, BnA configurations (1-2" resolution)	+Determine RMs, compare target vs. control samples +RM vs Impact Parameter +RM vs MgII Eq. width (W) +RM vs z_{MgII} +RM vs other photometric properties

+This is still small-scale, future surveys will improve statistics for sample comparison and our **<u>understanding of foreground (Milky Way) effects – 200 sources per square degree.</u>**
+Wideband observations are vital for us to understand source of polarization and magnetic field structure

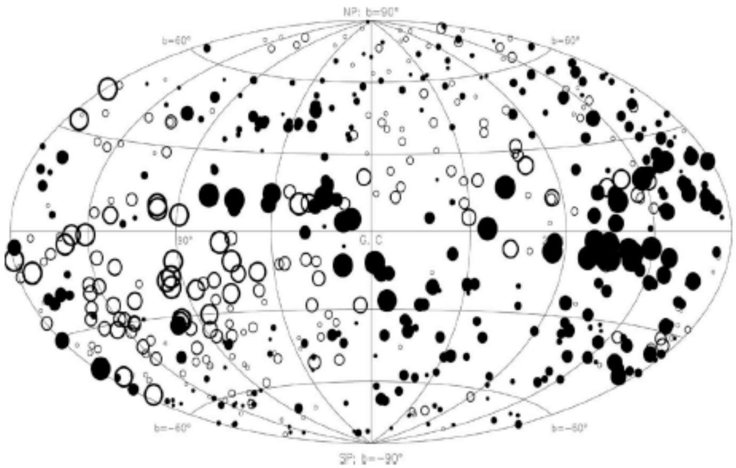
Remaining challenges:
RM_{MW} estimates, k-corrections, understanding polarized beam-shape, managing and accessing data locally…

Next steps?

- VLA All-Sky Survey – getting underway soon (2016)
  - Full polarization all-sky survey at a few GHz
  - Precursor to the EMU survey that will be carried out on ASKAP
- Next Generation radio telescopes
  - RM surveys using ASKAP, MeerKAT
  - Ultimately, SKA
- ngVLA (Next Generation Very Large Array)
  - In proposal stage
  - Fill the gap in frequency coverage between ALMA and the VLA

Increase polarized counts:

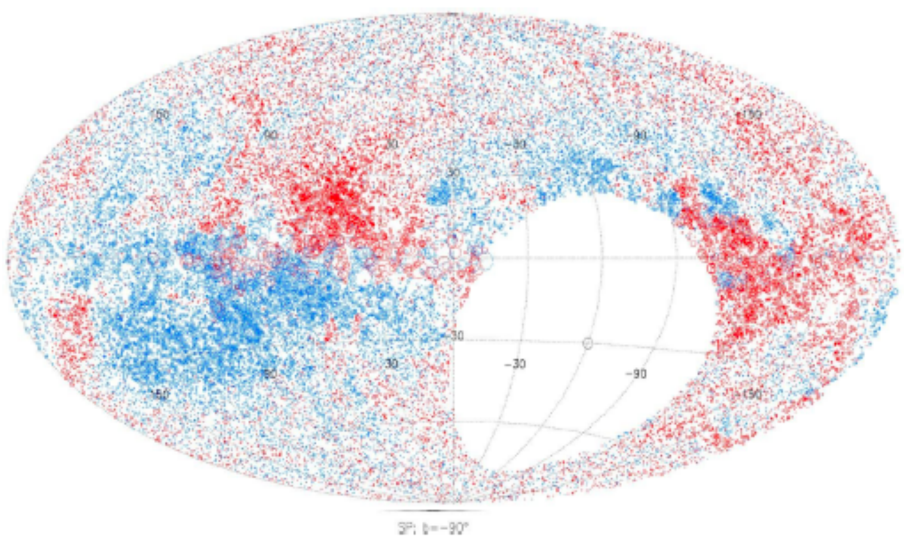
Evolution of the “RM Grid”



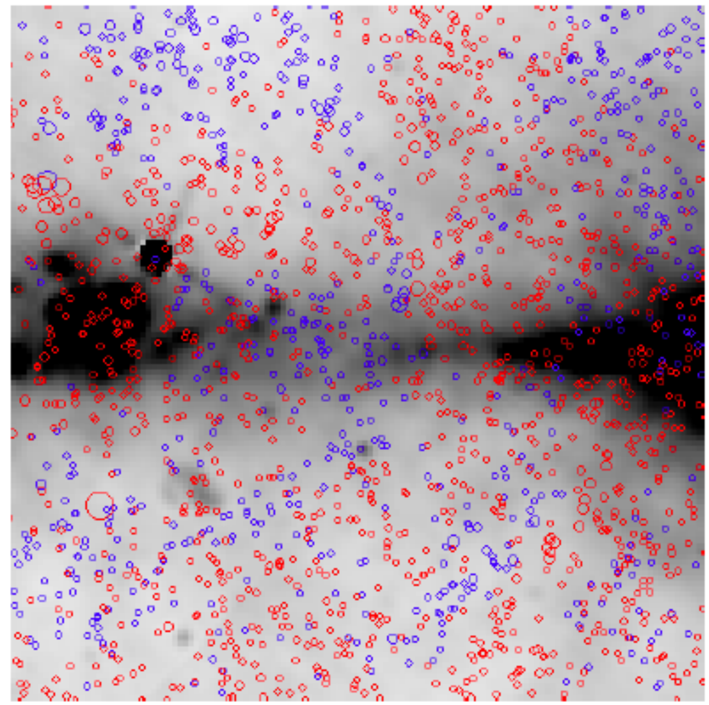
Han+ 1999

Courtesy: L. Rudnick (Minnesota)

Increase polarized counts:
Evolution of the "RM Grid"



NVSS + Taylor, Stil, Sunstrum 2009

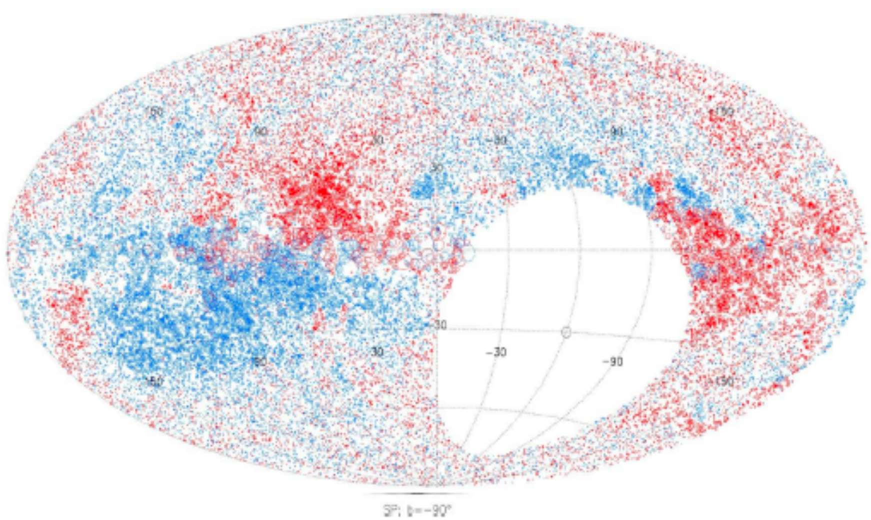


137 refs to date, including

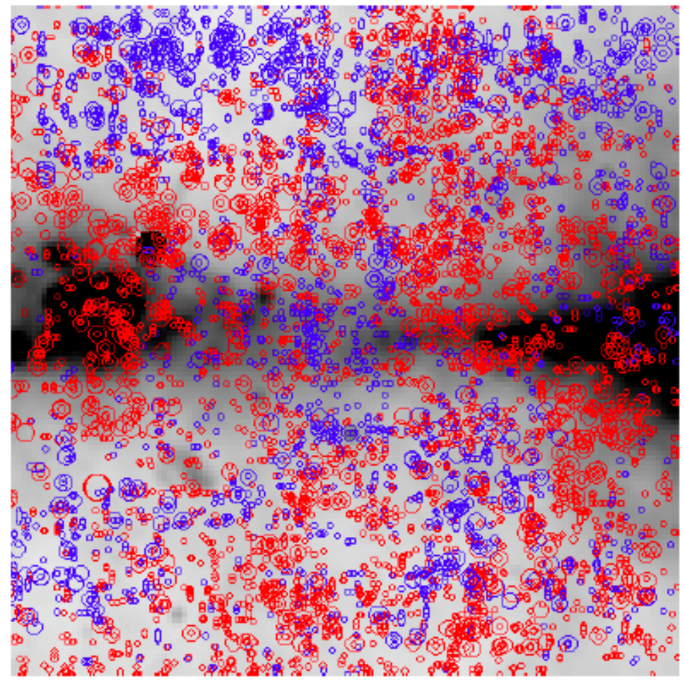
- First determination of local "halo" field component
- Local nature of structures on 10s degree scales
- First estimate of extragalactic intrinsic RM magnitude

VLA SKY SURVEY

Increase polarized counts:
Evolution of the “RM Grid”



End QII: NVSS density comparison.



VLASS

137 refs to date, including

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VLA SKY SURVEY

VLASS Polarization

- ***Goal: a unique, game-changing, polarization survey***
  - High frequency: probe depolarized population
  - High spatial resolution: Faraday maps for most sources
  - Large bandwidth: characterize Faraday complexity in beam and along line of sight; provide k-corrections
  - High sensitivity: [All-sky] increase background probes x6; [Deep] detect new galaxy population
  - Complementary to SKA-precursors

Proposed frequency coverage for the ngVLA

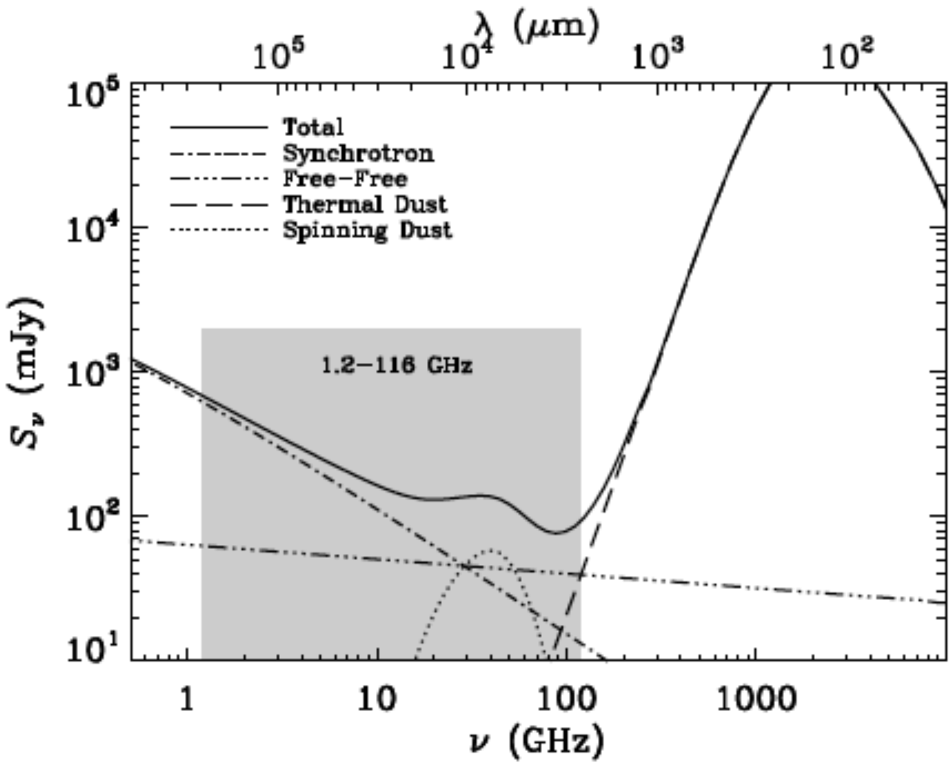

Figure 6: A model spectrum illustrating the various emission processes (non-thermal synchrotron, free-free, spinning dust, thermal dust) that contribute to the observed microwave frequency range to be covered by the ngVLA. Only in the proposed ngVLA frequency range ($1.2 - 116$ GHz, highlighted) do all major continuum emission mechanisms contribute at similar levels, making this range uniquely well-suited to next-generation continuum studies.

Summary

- Using wideband polarization observations at 3-21cm to study magnetic field structure in nearby spiral galaxies – we're learning a lot about the complexity of the ISM in disks.
- RM surveys will soon be delivering estimates of the Galactic foreground contribution to RM on scales of a few hundred sources deg^{-2}.
- The next generation radio facilities and surveys are coming!