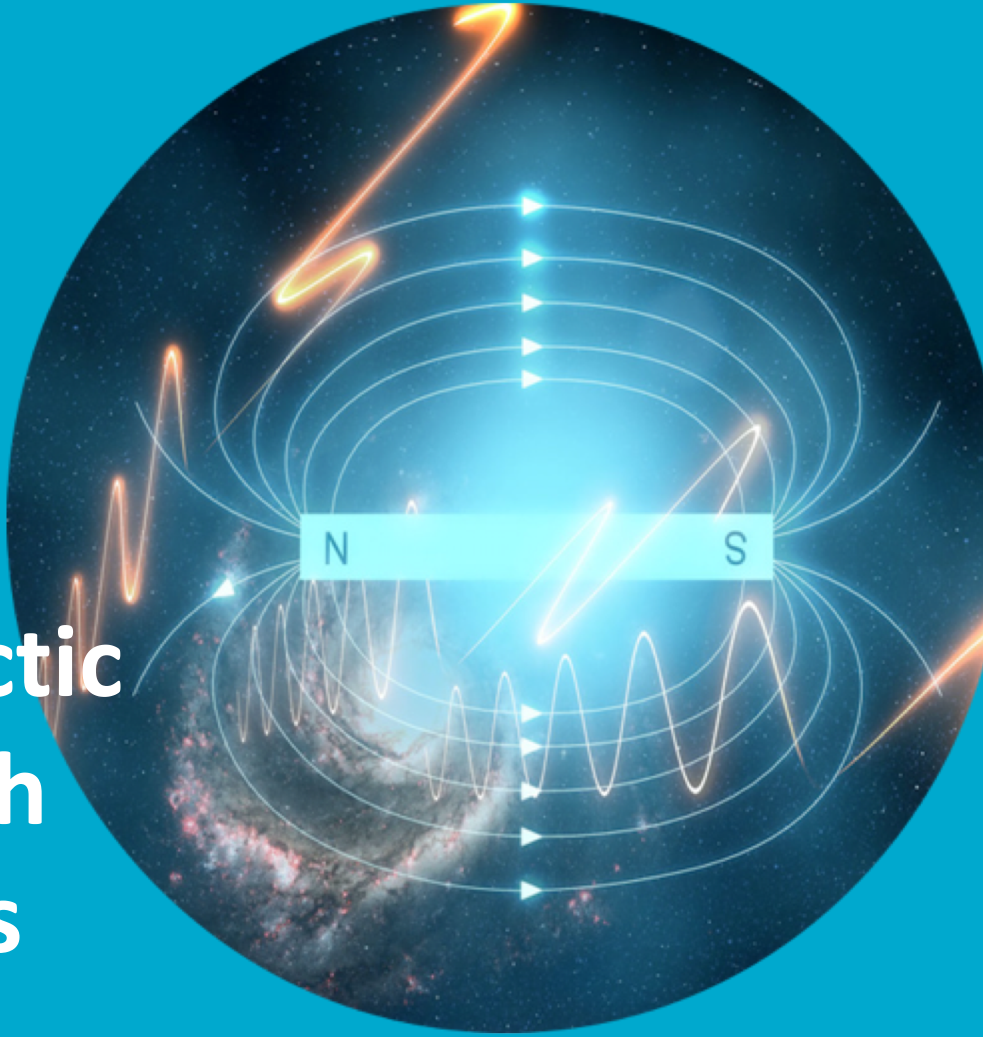


Detecting Intergalactic Magnetic Fields with Polarisation Surveys

Tessa Vernstrom | CSIRO Bolton Fellow

5 December 2018

CSIRO ASTRONOMY & SPACE SCIENCES, CASS
www.csiro.au

DUNLAP INSTITUTE

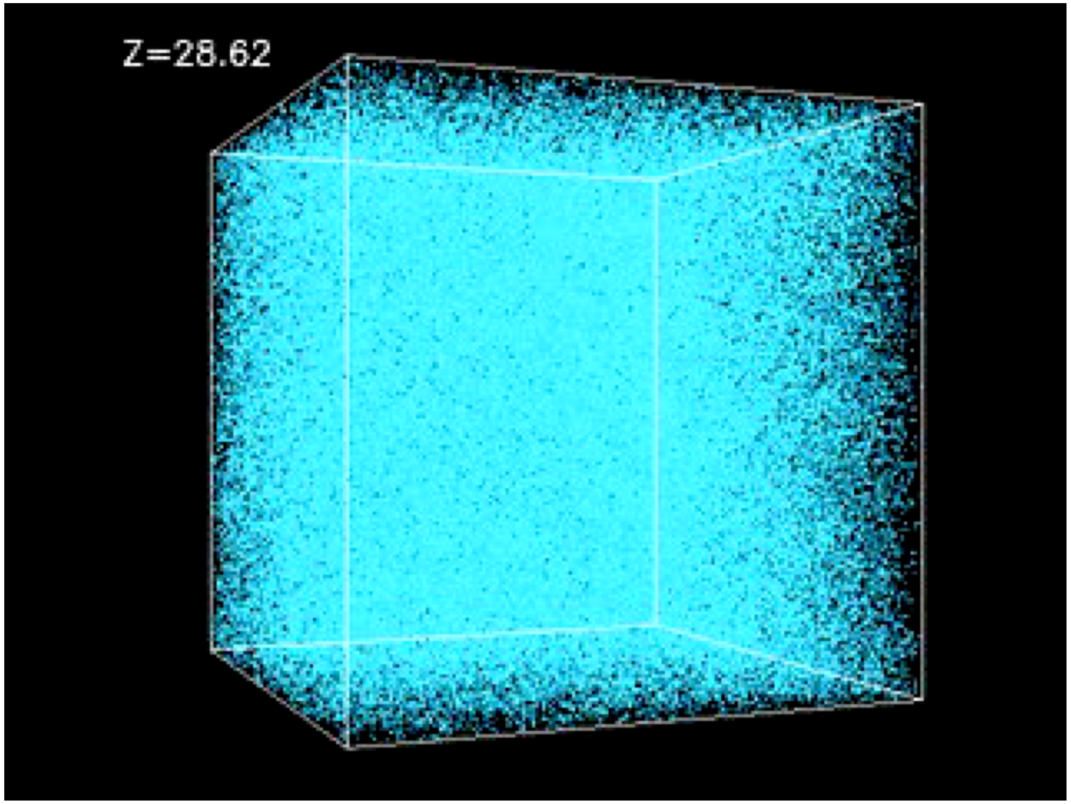
UNIVERSITY OF TORONTO

VLA SKY SURVEY

CSIRO

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/)

The Cosmic Web and Magnetic Fields

- In addition to matter and gravitational forces there are Magnetic fields
  - Primordial seed field
  - Fields from galaxies forming and interacting
  - Within galaxies, clusters, and along filaments
  - Infalling and colliding matter → creates shocks → amplifying magnetic fields

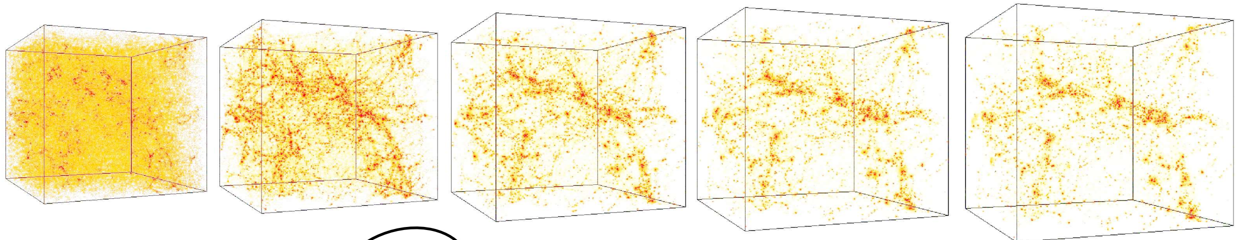
Blue = B field

Red = Gas

F. Vazza

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

Magnetism? - - - - - Evolution of structure - - - - - >



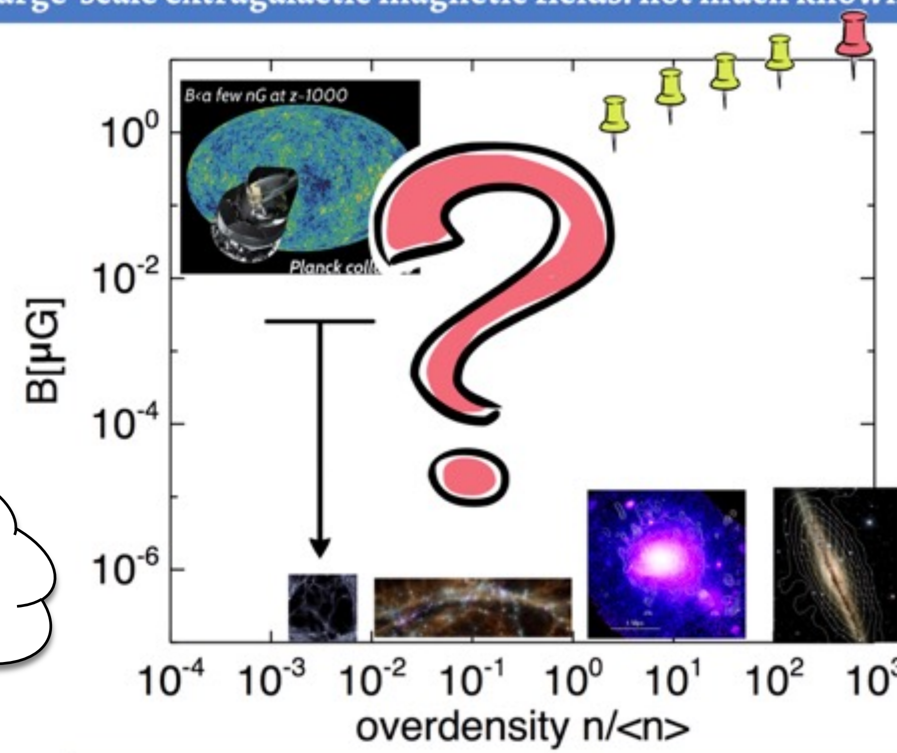
What is the origin of cosmic magnetic fields?

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

What is the nature of the IGM and IGMF?

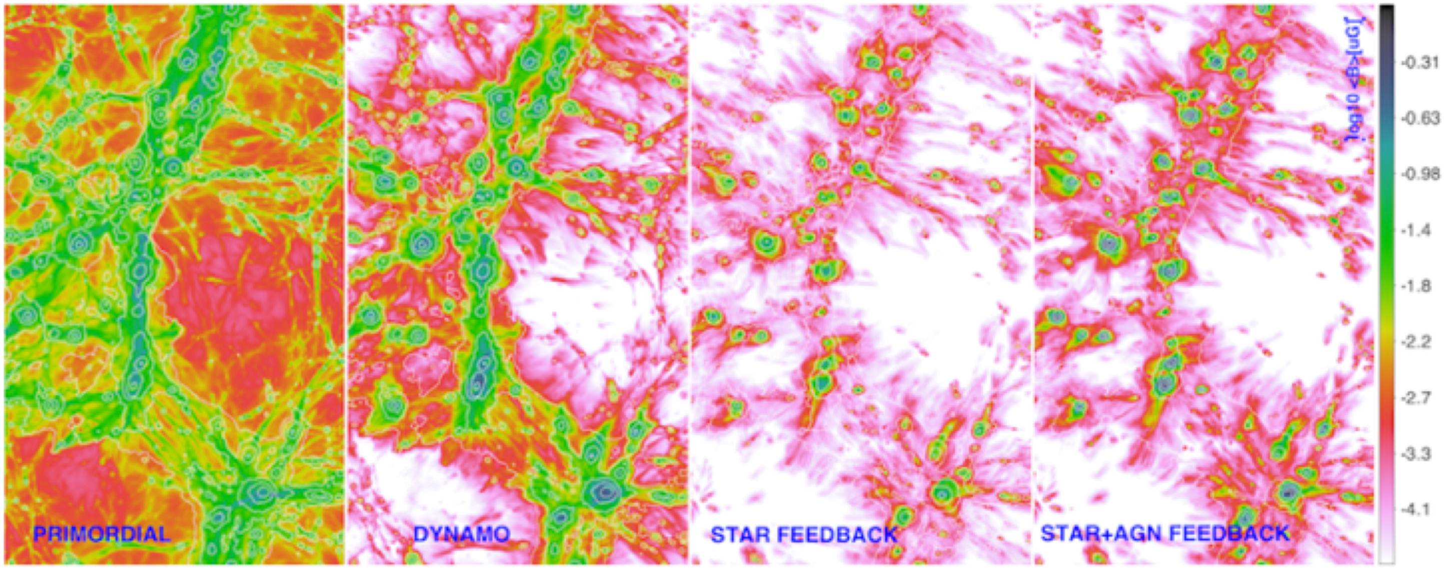
How has IGM / IGMF changed over time?

Large-scale extragalactic magnetic fields: not much known.



magnetic fields ~unknown for >99.99% of cosmic volume

Simulation Models

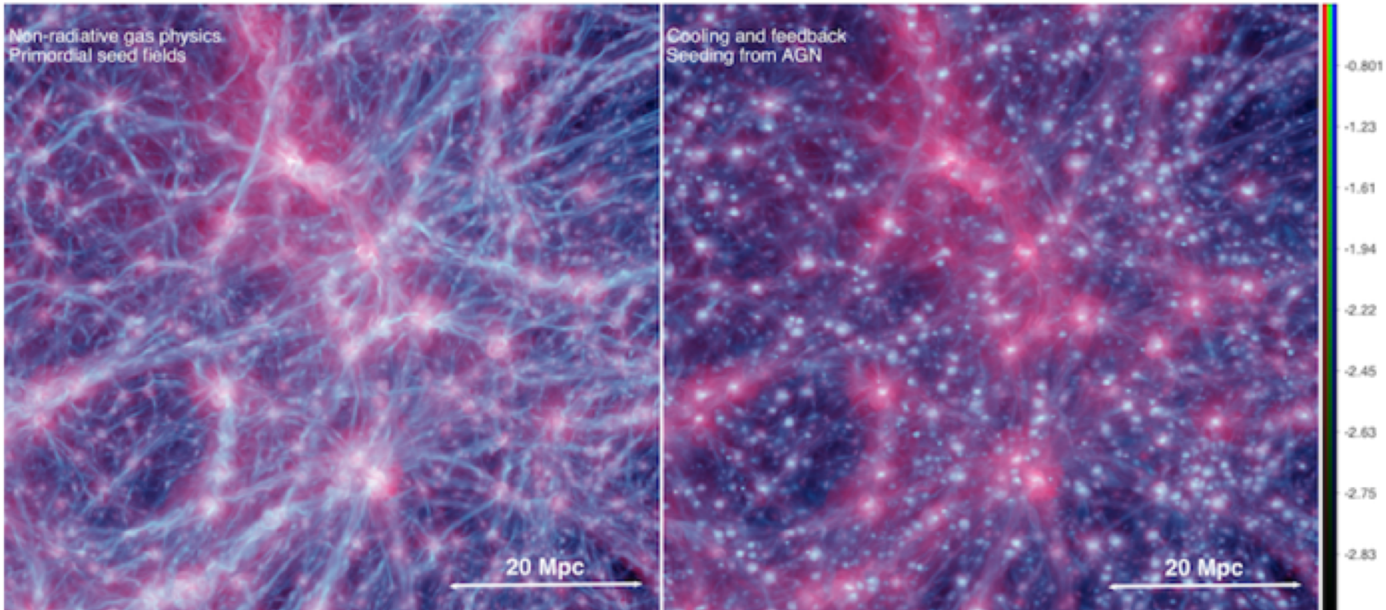


Vazza+17

Mean (mass-weighted) B-field

Primordial

AGN



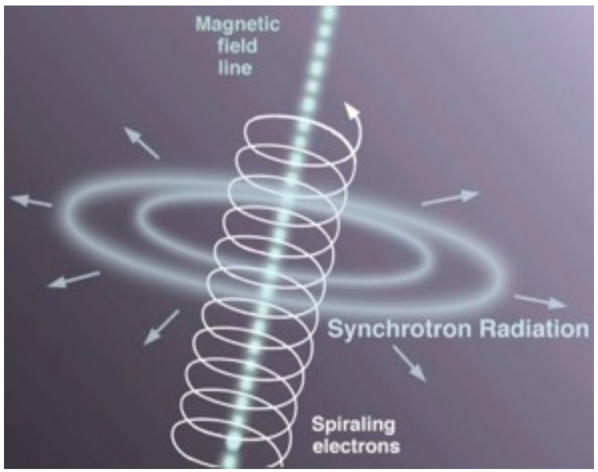
RED = Temp

Green+Blue= B-field strength

How can we study extragalactic magnetic fields?

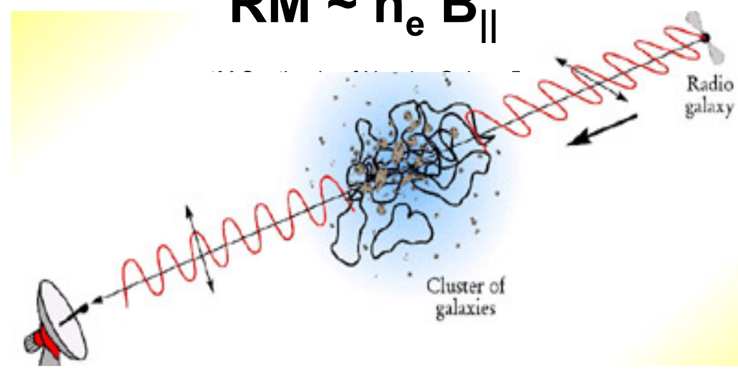
- Synchrotron Emission

$$P = \sqrt{(Q^2+U^2)} \sim n_{CR}\, B_{\perp}$$



- Faraday Rotation

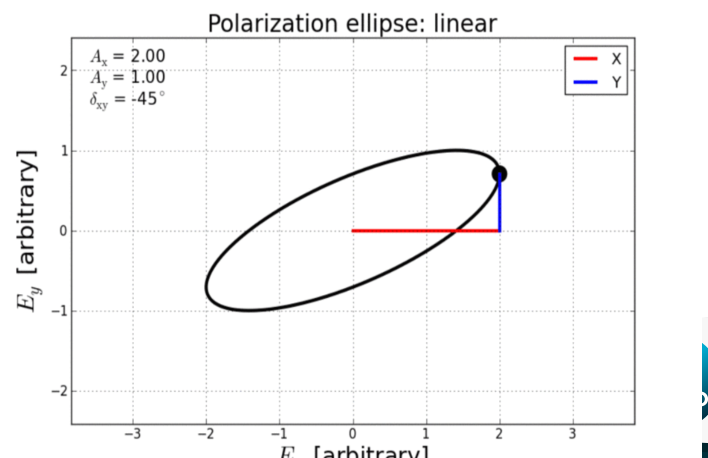
$$RM \sim n_e\, B_{||}$$



Rotation Measure

B-field along Line of Sight

$$RM = 8.12 \times 10^5 \int_0^{z_s} (1+z)^{-2}\, n_e(z)\, B_{||}(z)\, dl(z)$$

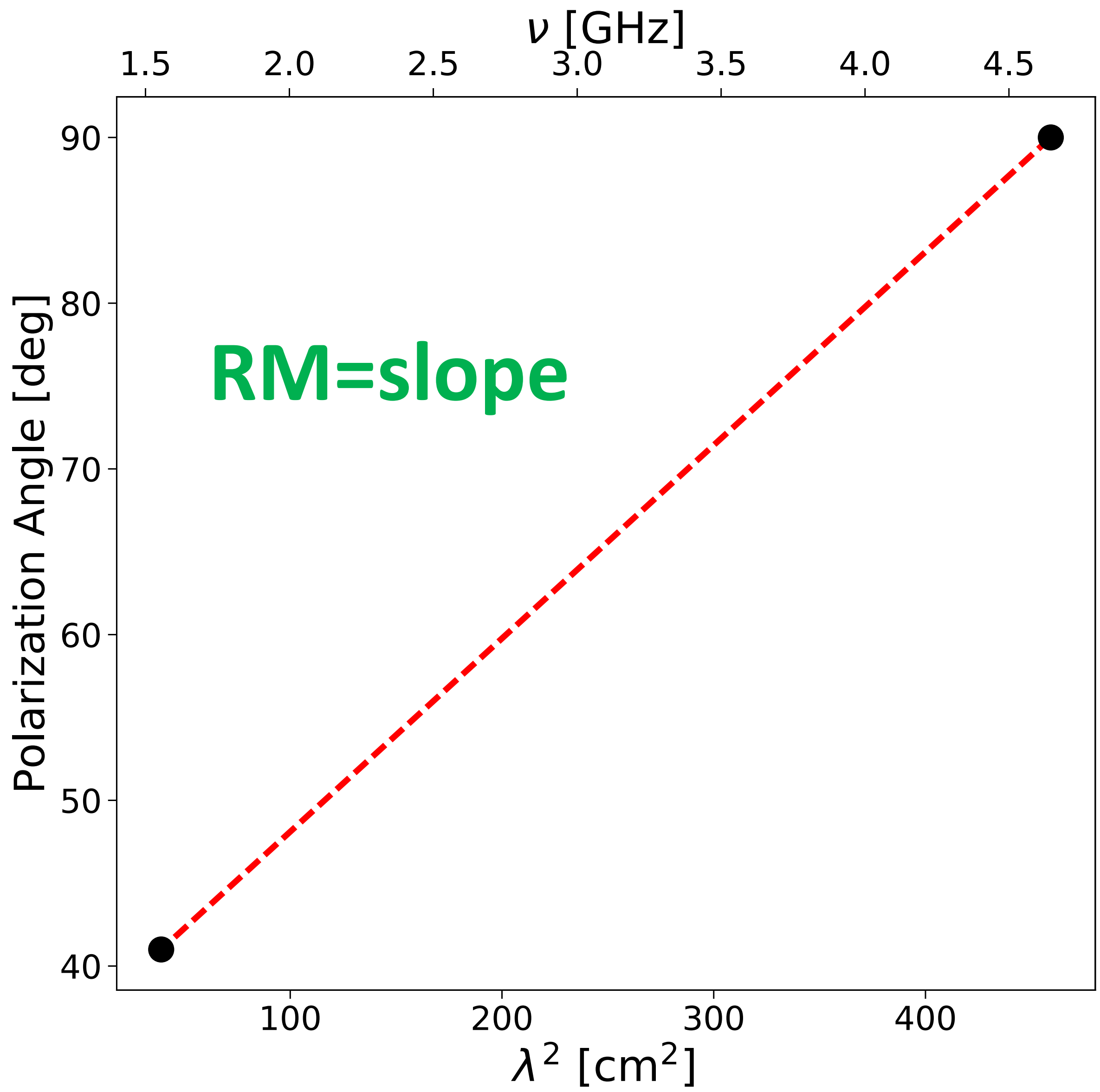


Rotation Measures

- Narrowband data
- Fit slope of Pol angle vs λ^2

$$\chi = \frac{1}{2}\tan^{-1}\left(\frac{S_U}{S_Q}\right)$$

$$\chi = \chi_0 + \mathrm{RM} \times \lambda^2$$



Rotation Measures

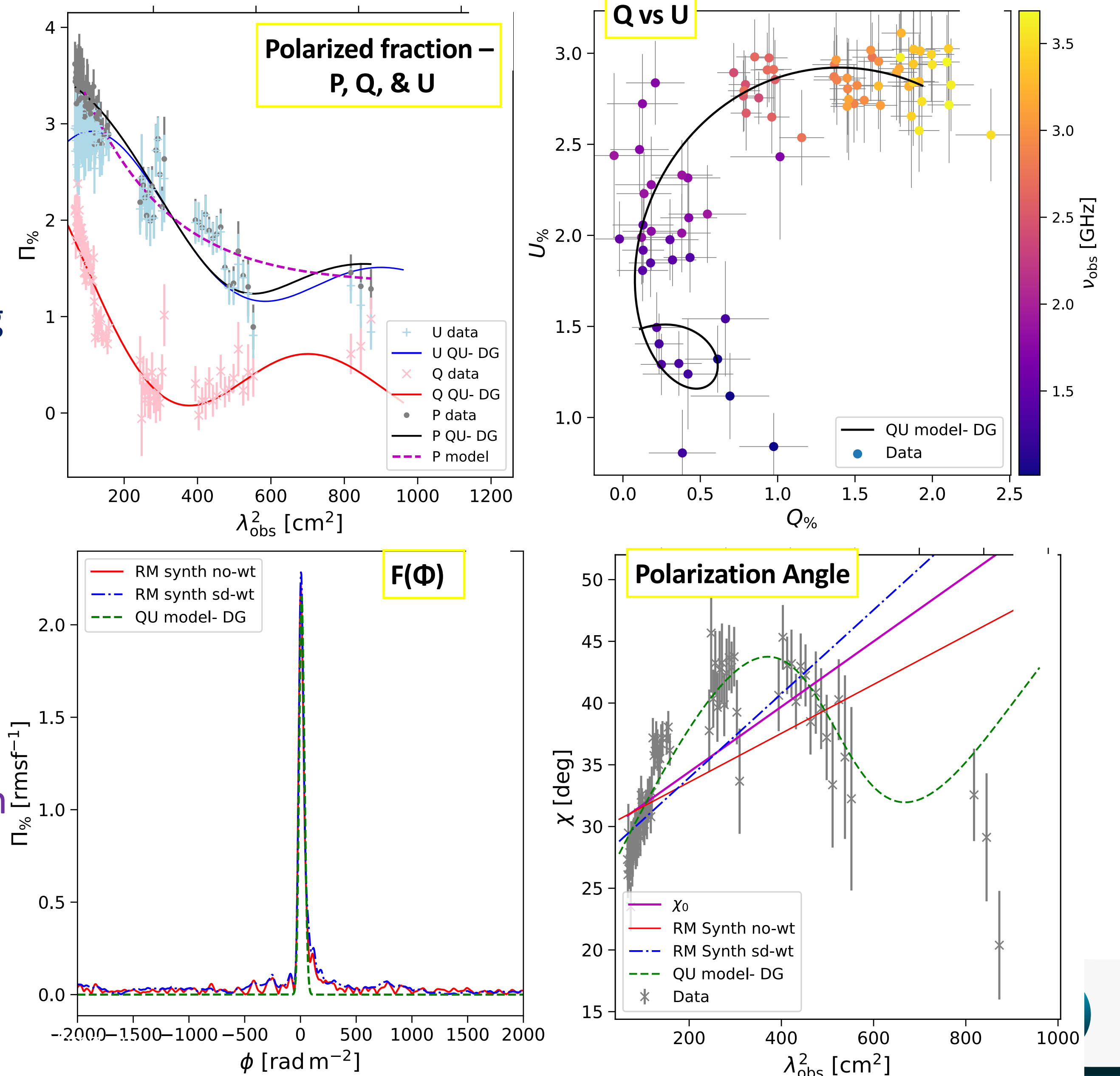
QU fitting

- Wideband data
- Fitting of QU vs λ^2
- RM synthesis and cleaning

$$P(\lambda^2) = \int_{-\infty}^{+\infty} F(\phi) e^{2i\phi\lambda^2} d\phi$$

RM = peak(s) and dispersion of Faraday spectrum

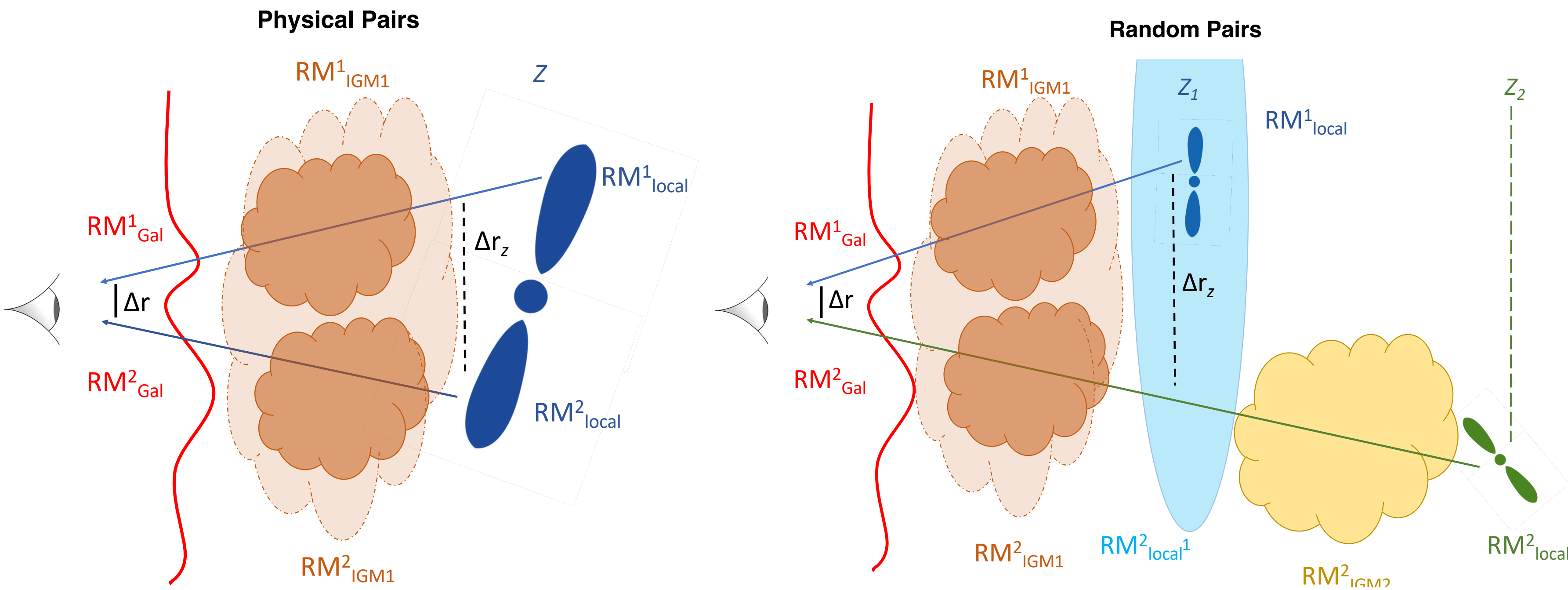
➢ Allows for more detailed fitting of faraday spectrum and polarization angle



IGMF from ΔRM

- Look at the difference in RMs from two sources or two source components

IGMF from ΔRM



For Randoms

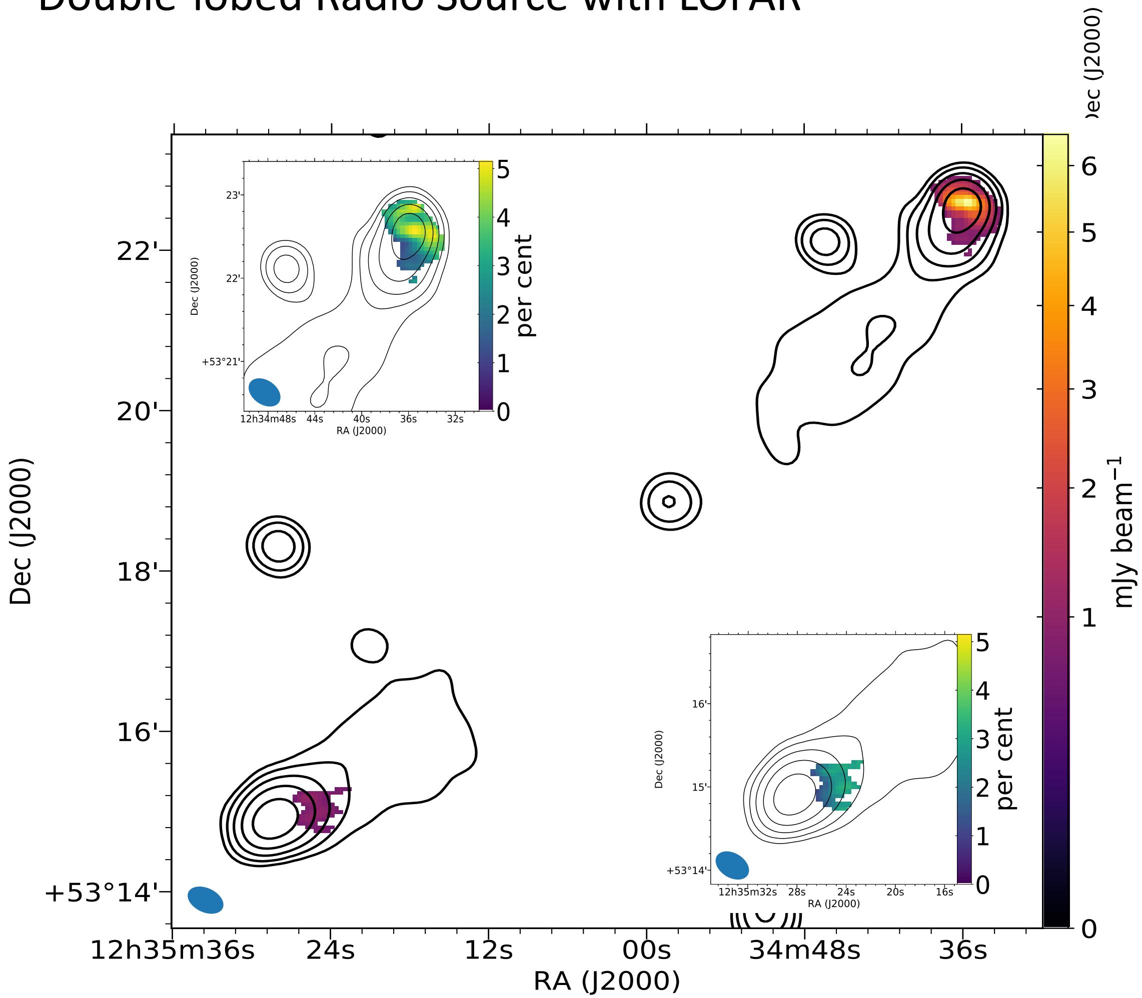
$$\Delta RM_{obs} = \Delta RM_{Gal} + \Delta RM_{IGM1} + \Delta RM^{12}_{local} + RM^{2}_{local1} + RM^{2}_{IGM2} + \Delta RM_{Noise}$$

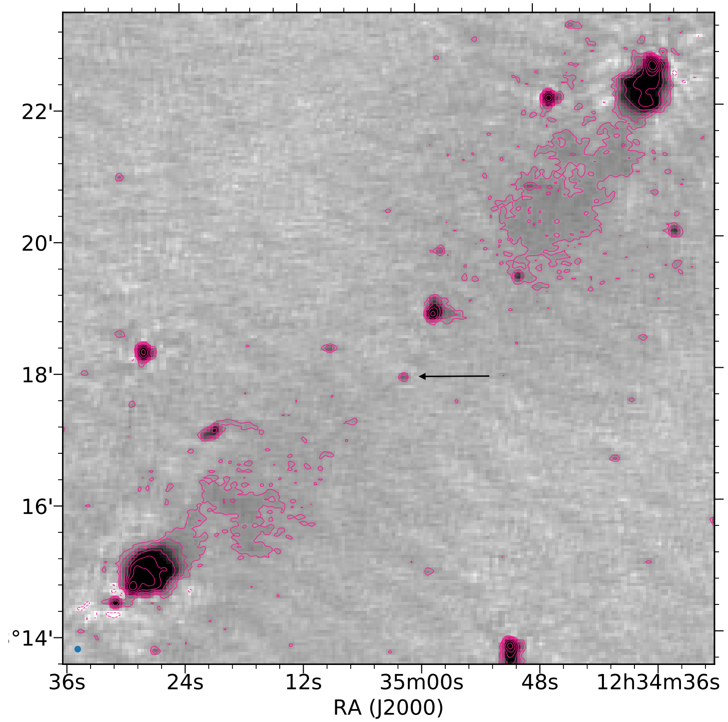
For Physicals

$$\Delta RM_{obs} = \Delta RM_{Gal} + \Delta RM_{IGM1} + \Delta RM^{12}_{local} + \Delta RM_{Noise}$$

IGMF from ΔRM

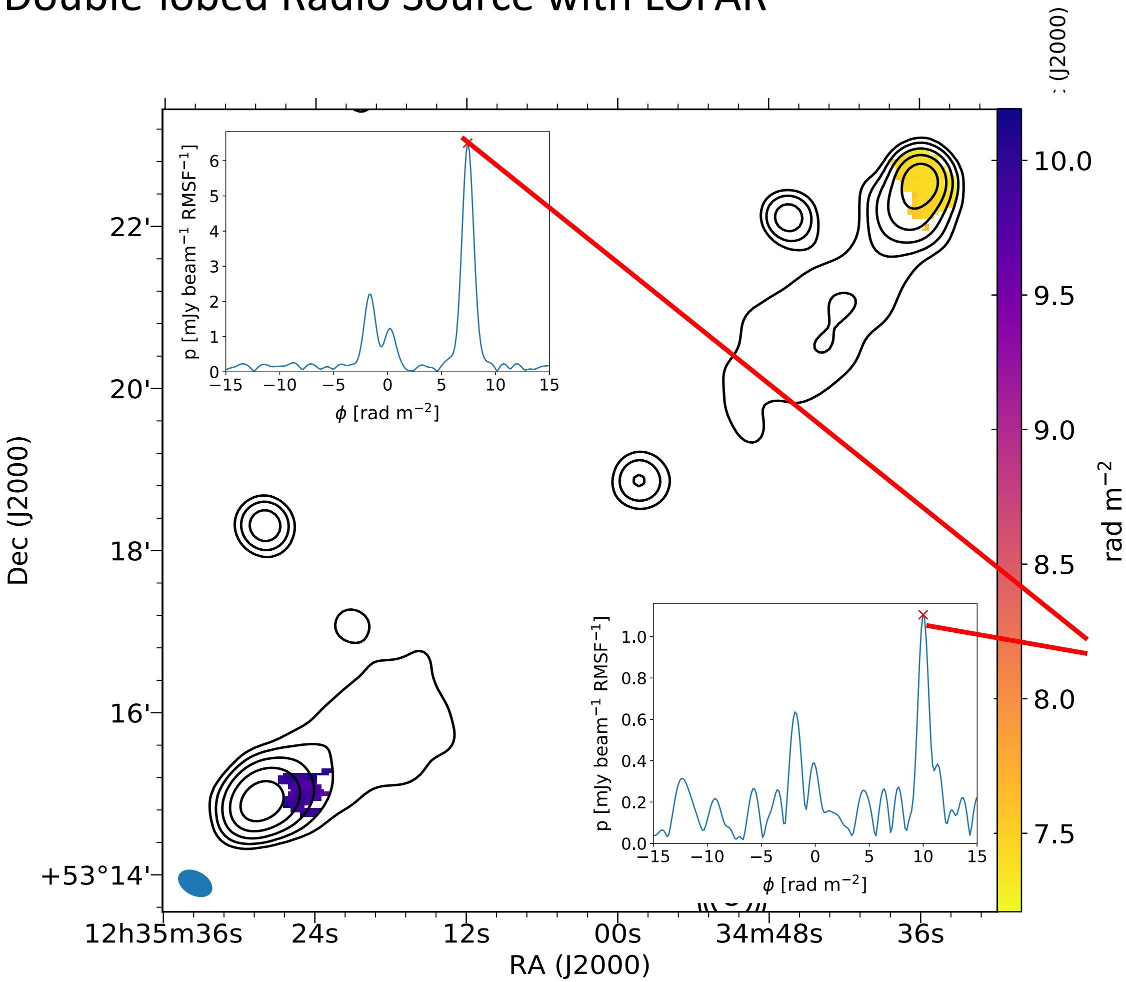
O’Sullivan et al., 2018
Double-lobed Radio Source with LOFAR

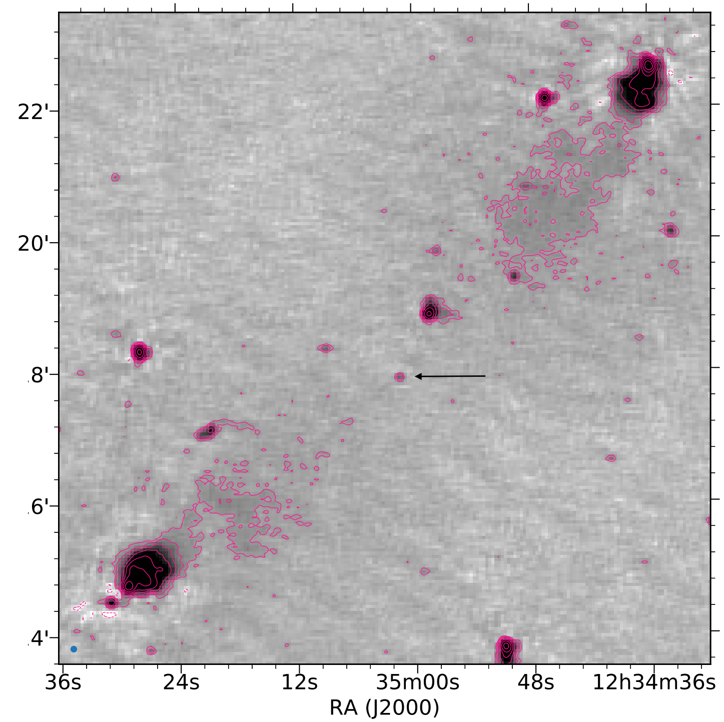




IGMF from ΔRM

O'Sullivan et al., 2018
Double-lobed Radio Source with LOFAR



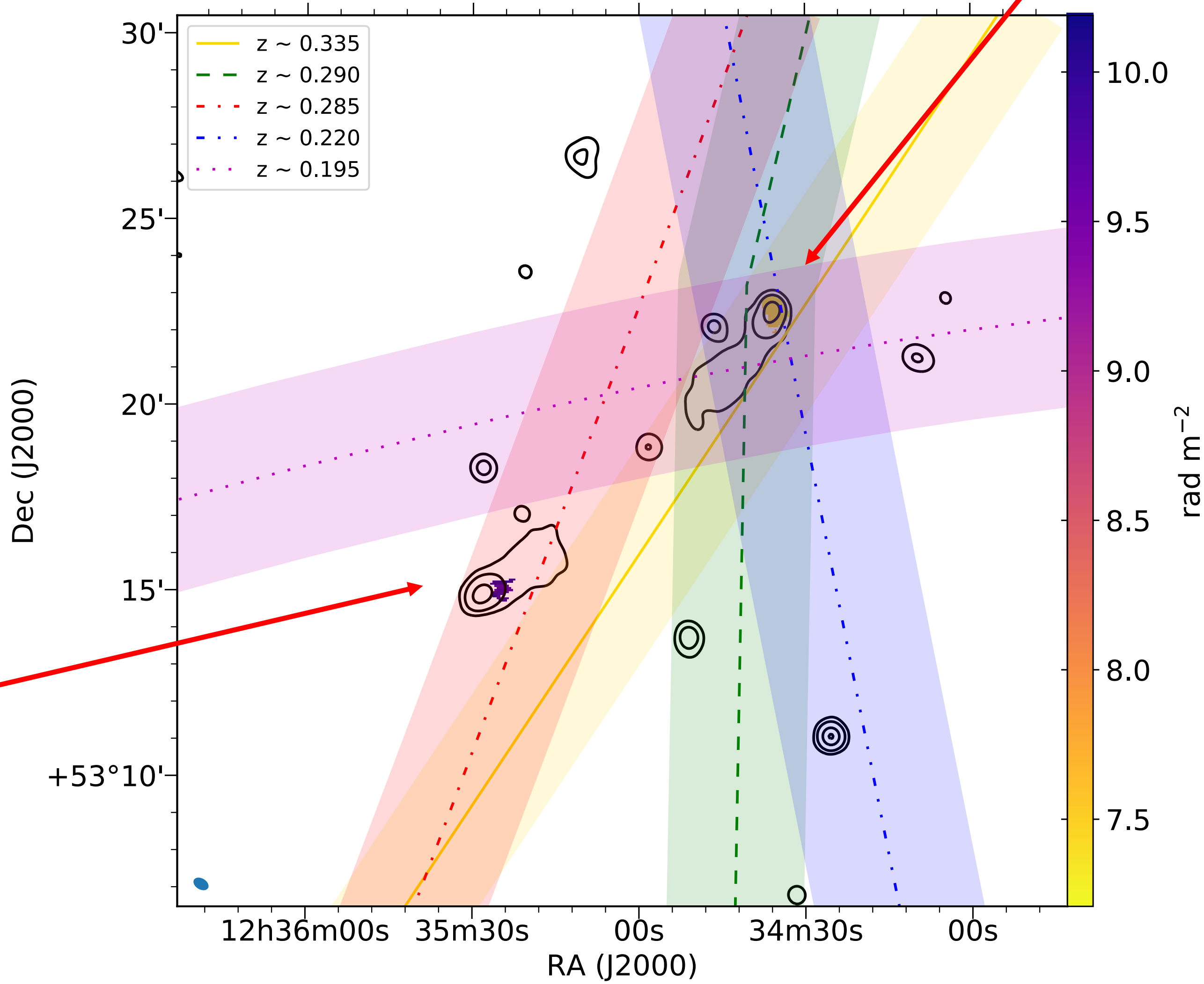


ΔRM = 2.5 +/- 0.1 rad/m^2

IGMF from ΔRM

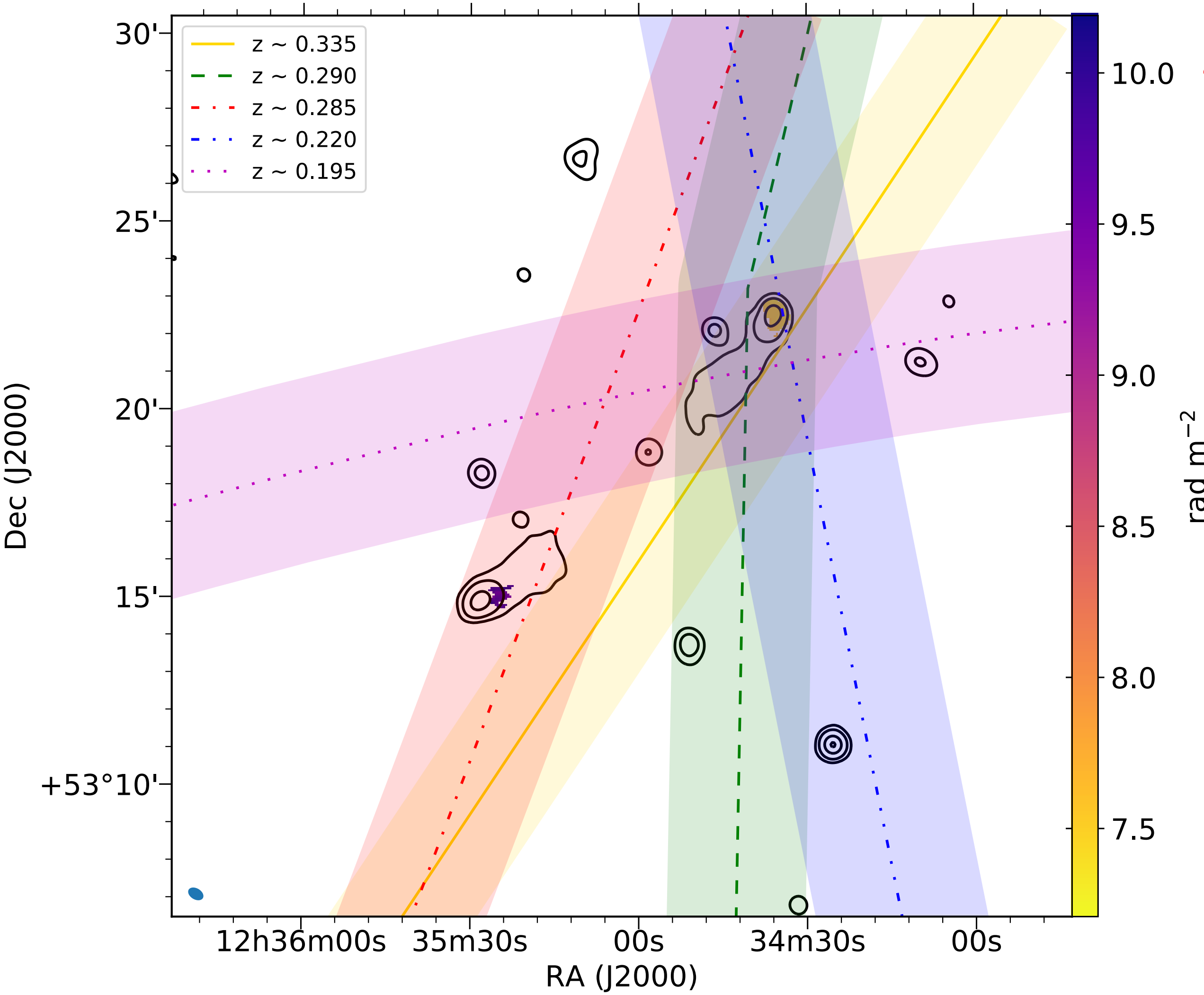
O'Sullivan et al., 2018

Double-lobed Radio Source with LOFAR



IGMF from ΔRM

O'Sullivan et al., 2018
Double-lobed Radio Source with LOFAR



ΔRM = 2.5 +/- 0.1 rad/m^2

N_f = 3

ΔRM ~ 1.5 $N_f^{1/2}$

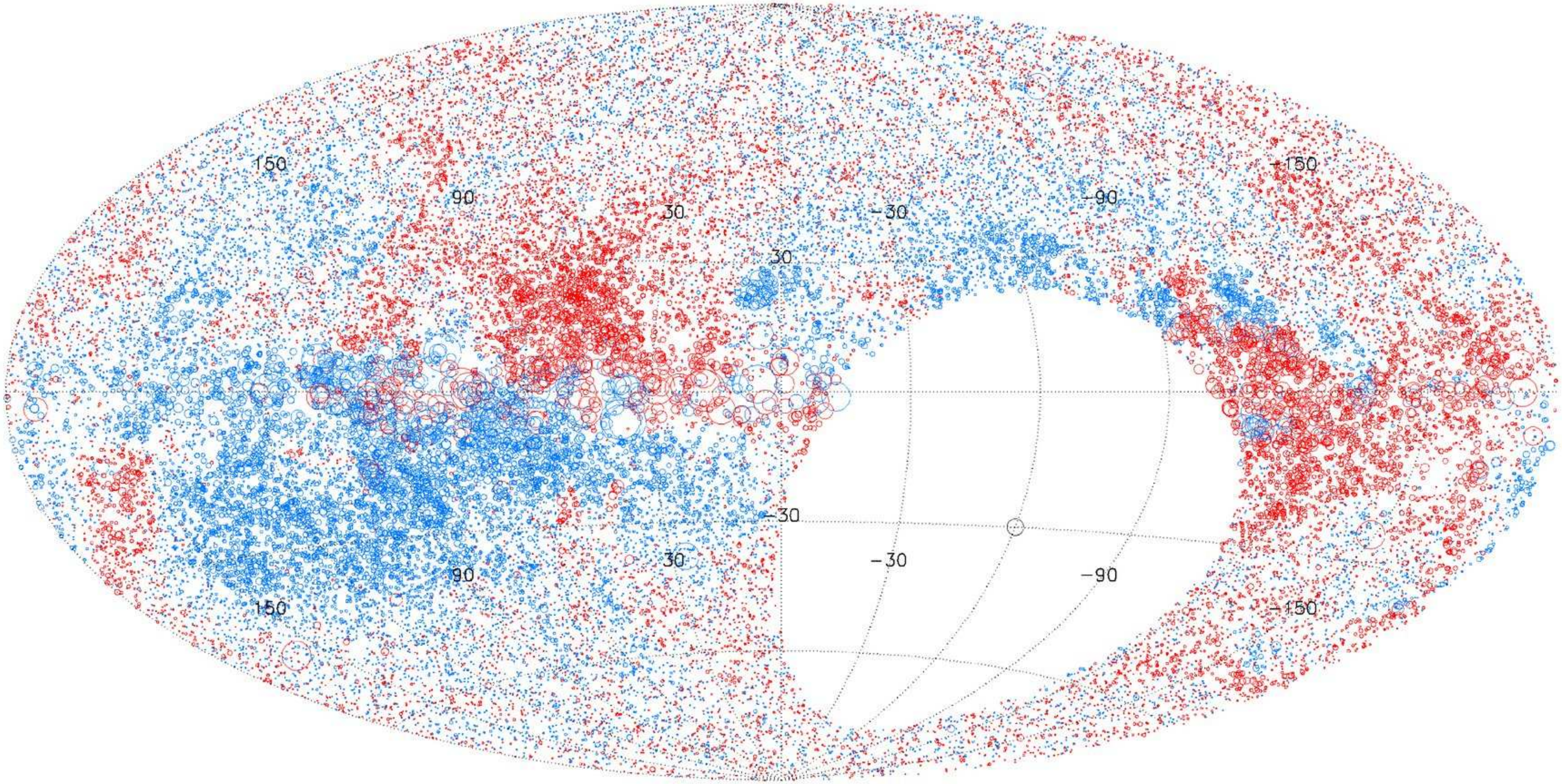
→ 2.6 rad/m^2

→ < B_f > ~ 10nG

IGMF from ΔRM

Vernstrom et al., in prep

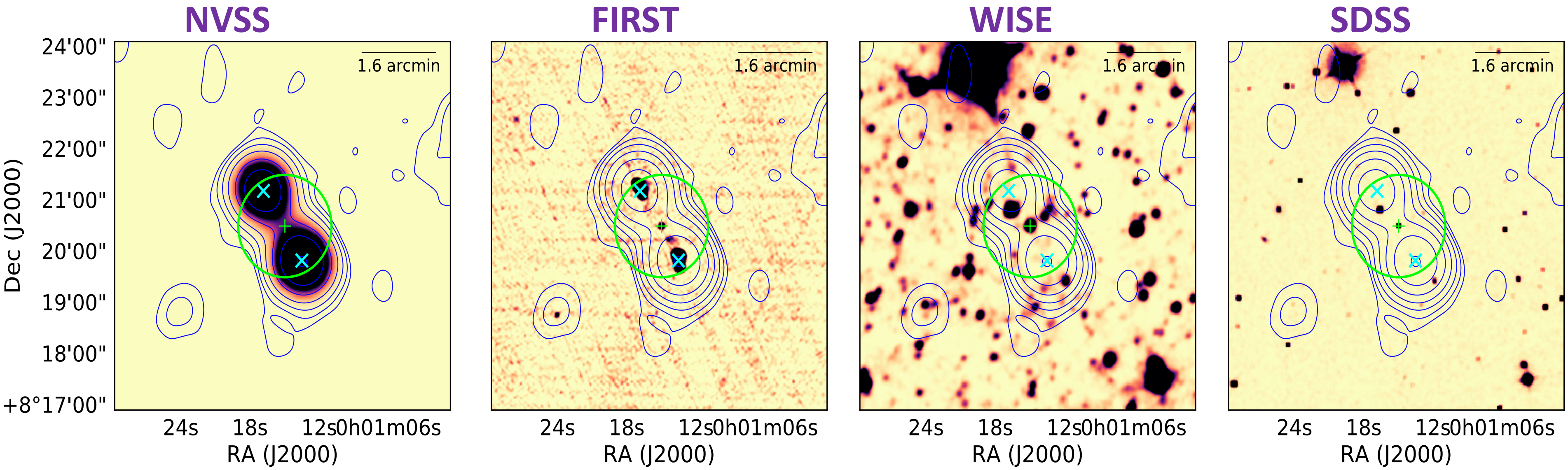
- What about a larger sample and the difference in RM between Random and physical pairs?
- Taylor et al., 2009 catalogue of 37,543 NVSS Rotation Measures



IGMF from ΔRM

Vernstrom et al., in prep

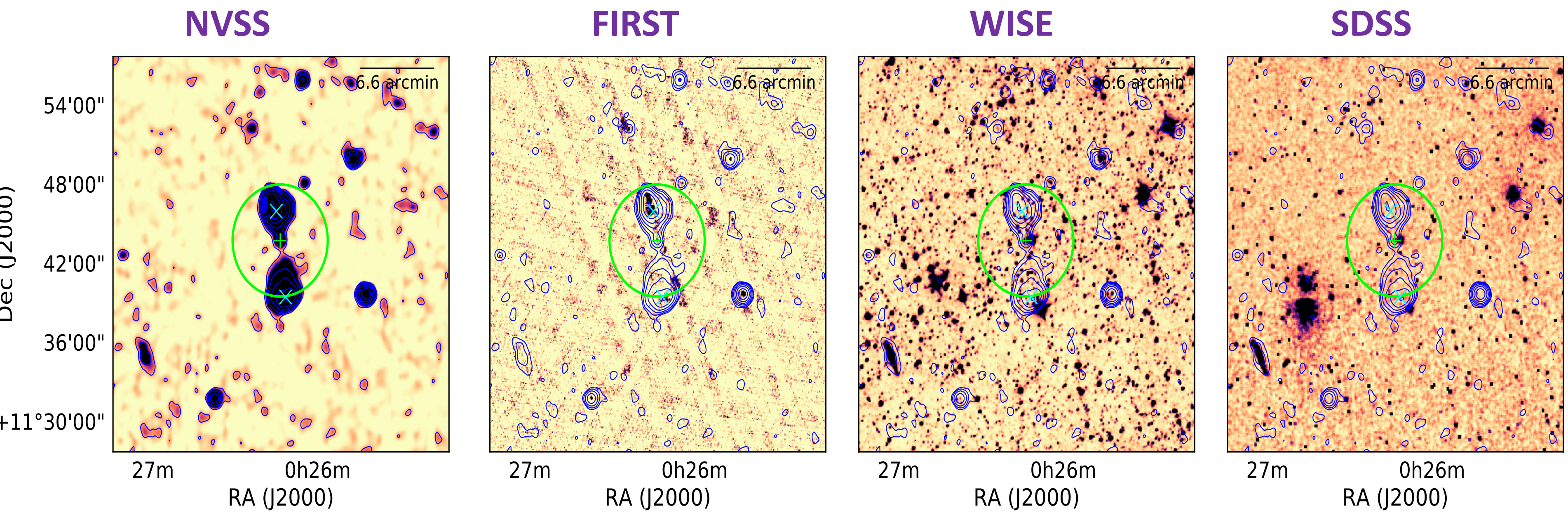
- What about a larger sample and the difference in RM between Random and physical pairs?
- Taylor et al., 2009 catalogue of 37,543 NVSS Rotation Measures
  1. Find pairs of sources (components)
  2. Classify as "random" or "physical" – use radio, optical, IR images and catalog(s) of extended/giant radio galaxies



IGMF from ΔRM

Vernstrom et al., in prep

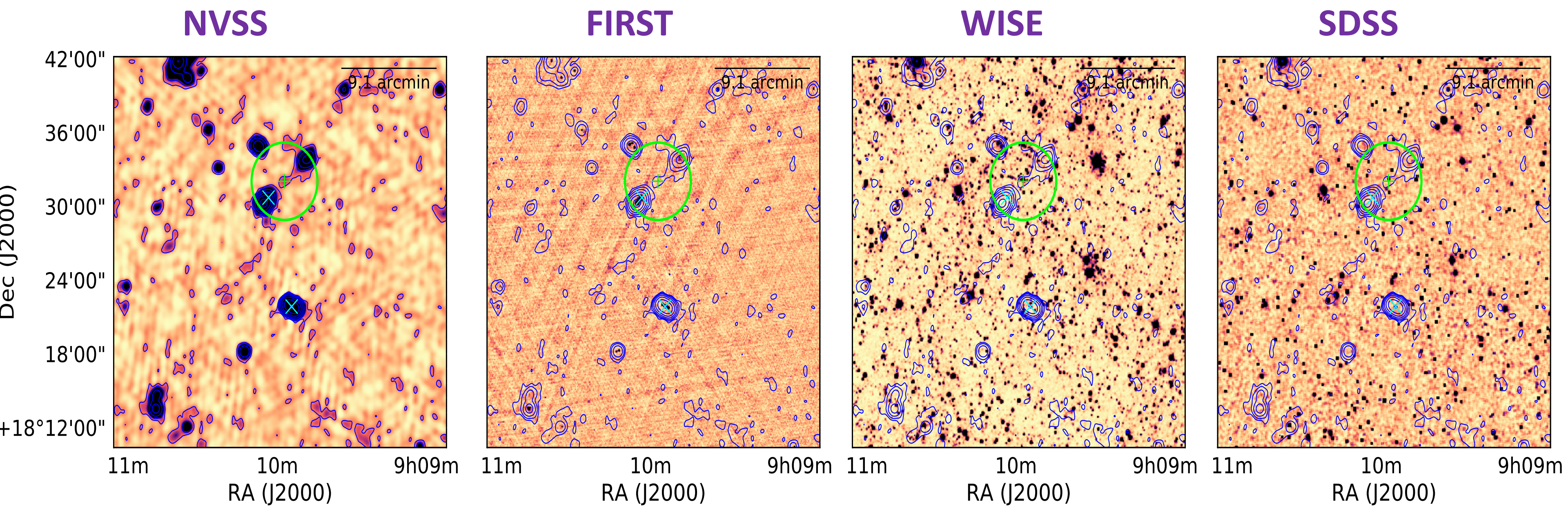
- What about a larger sample and the difference in RM between Random and physical pairs?
- Taylor et al., 2009 catalogue of 37,543 NVSS Rotation Measures
  1. Find pairs of sources (components)
  2. Classify as “random” or “physical” – use radio, optical, IR images and catalog(s) of extended/giant radio galaxies



IGMF from ΔRM

Vernstrom et al., in prep

- What about a larger sample and the difference in RM between Random and physical pairs?
- Taylor et al., 2009 catalogue of 37,543 NVSS Rotation Measures
    1. Find pairs of sources (components)
    2. Classify as “random” or “physical” – use radio, optical, IR images and catalog(s) of extended/giant radio galaxies

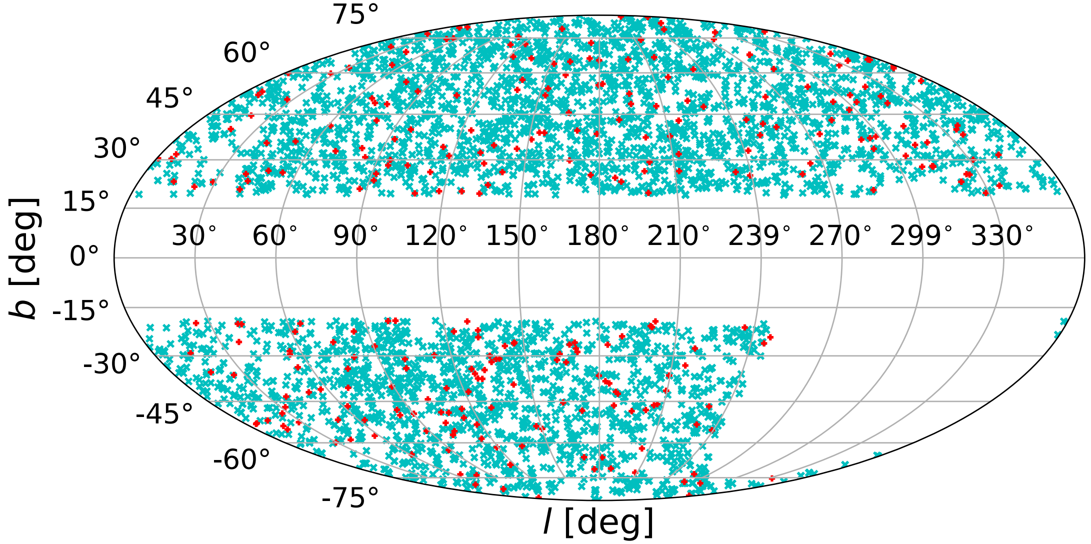


IGMF from ΔRM

Vernstrom et al., in prep

- What about a larger sample and the difference in RM between Random and physical pairs?
- Taylor et al., 2009 catalogue of 37,543 NVSS Rotation Measures
  1. Find pairs of sources (components)
  2. Classify as “random” or “physical” – use radio, optical, IR images and catalog(s) of extended/giant radio galaxies

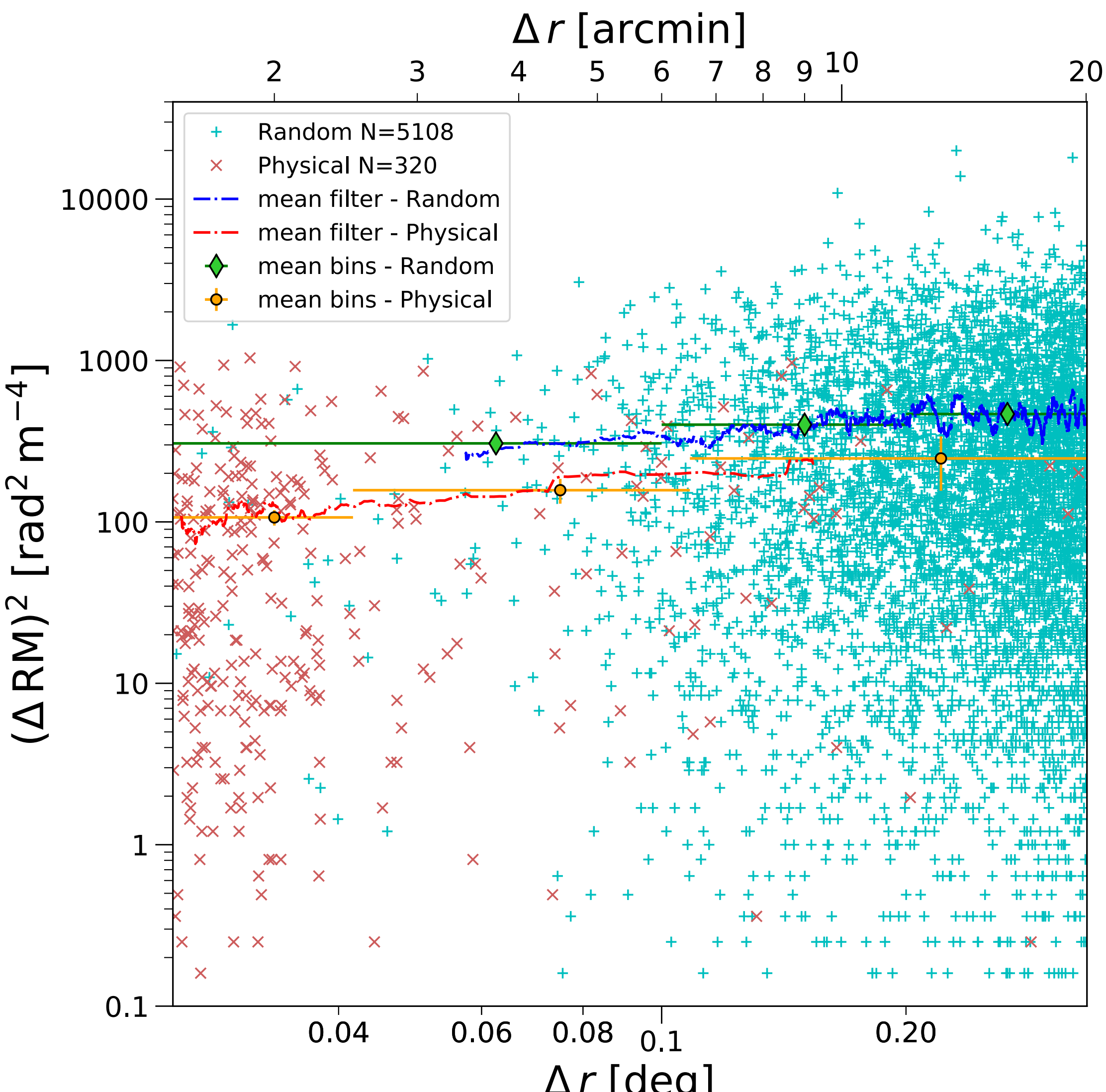
5108 Random pairs
320 Physical pairs
- $1.5 < \Delta r$ [arcminutes] < 20
- $|b| >= 20^0$
- $\Pi >= 2\%$



IGMF from ΔRM

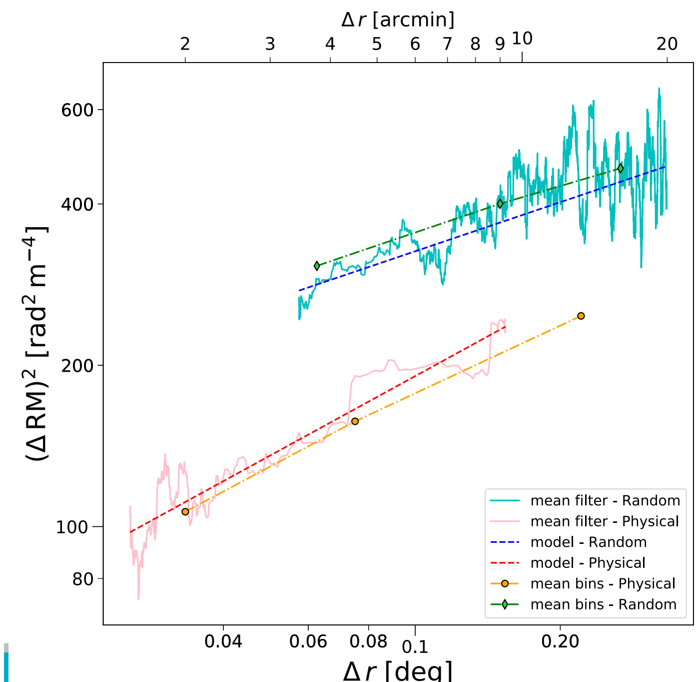
Vernstrom et al., in prep

- What about a larger sample and the difference in RM between Random



Rotation Measures

…tical, IR images and catalog(s) of

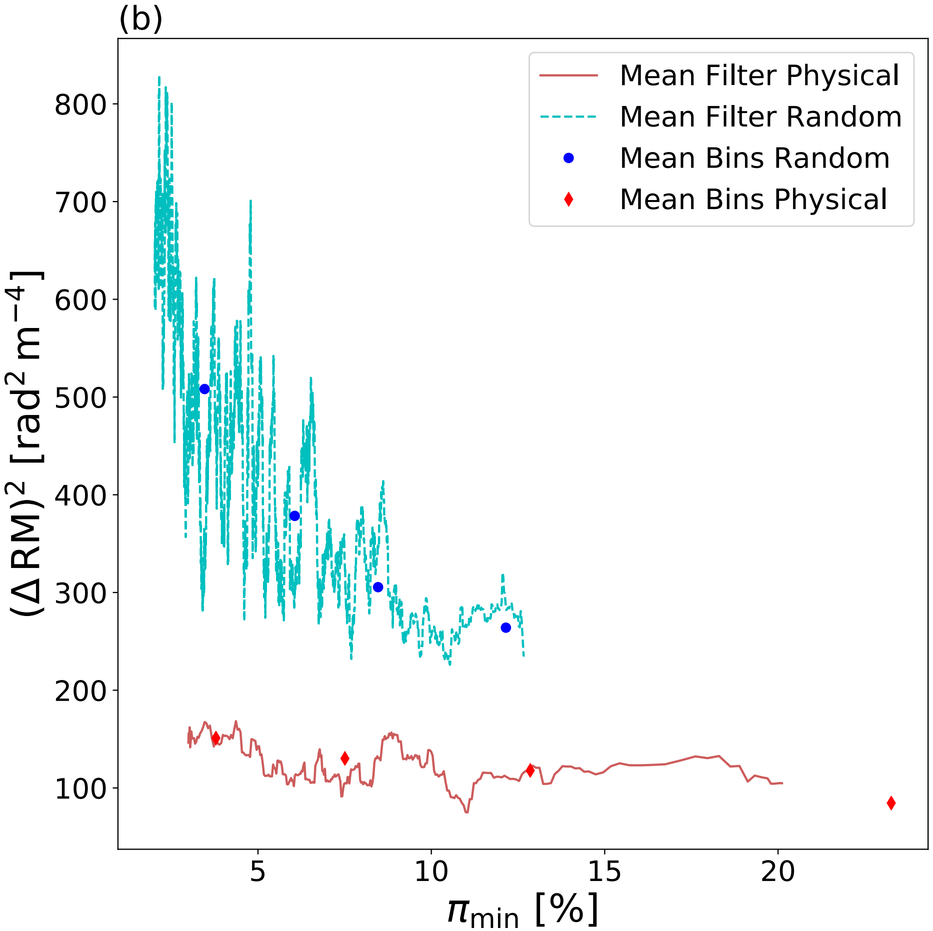


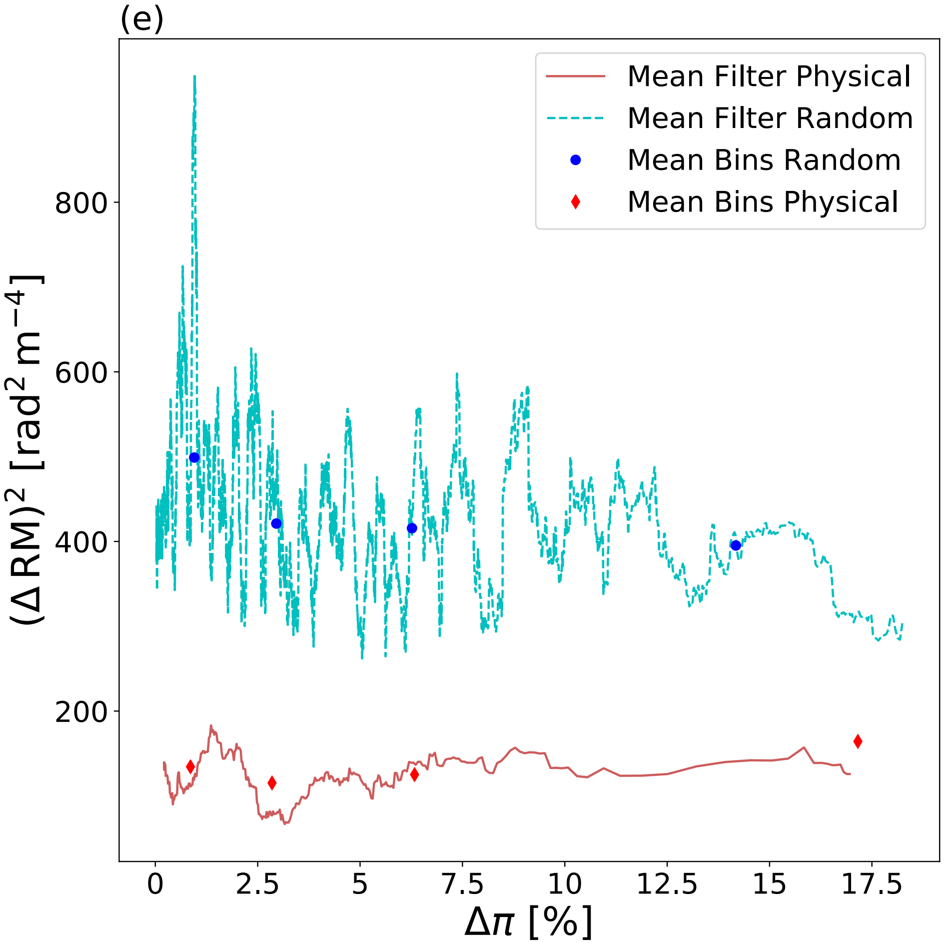
CSIRO

IGMF from ΔRM

Vernstrom et al., in prep

- What about a larger sample and the difference in RM between Random and physical pairs?
- Taylor et al., 2009 catalogue of 37,543 NVSS Rotation Measures



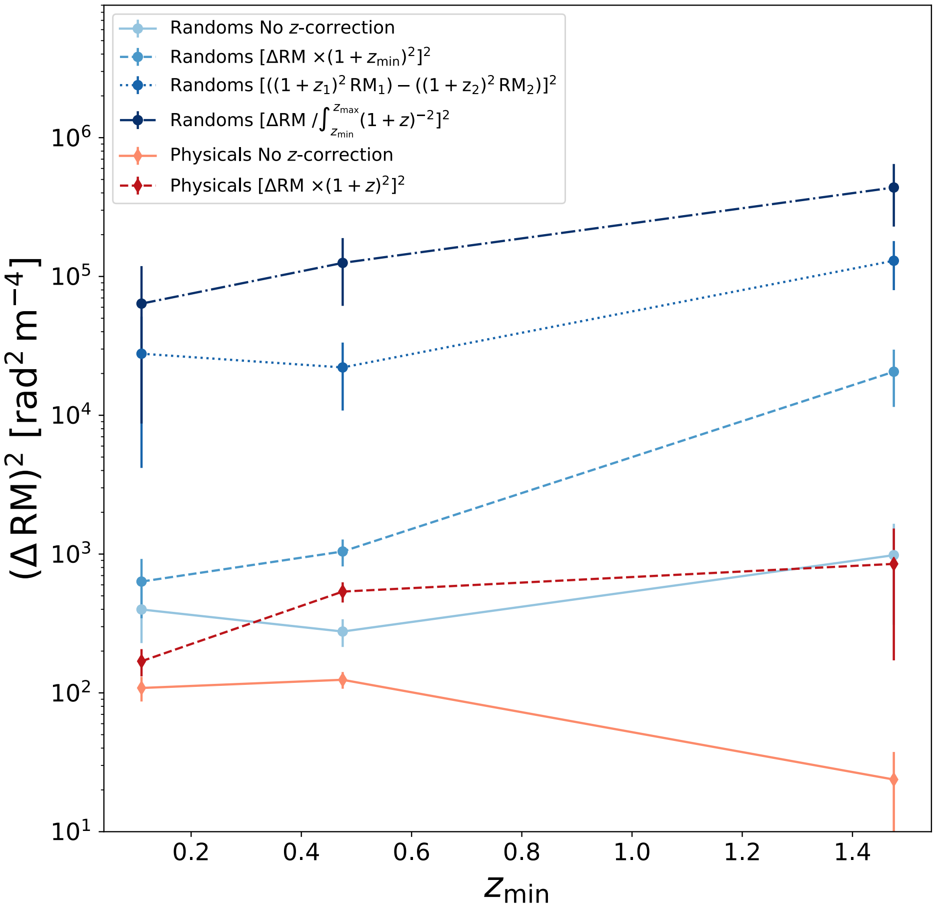


IGMF from ΔRM

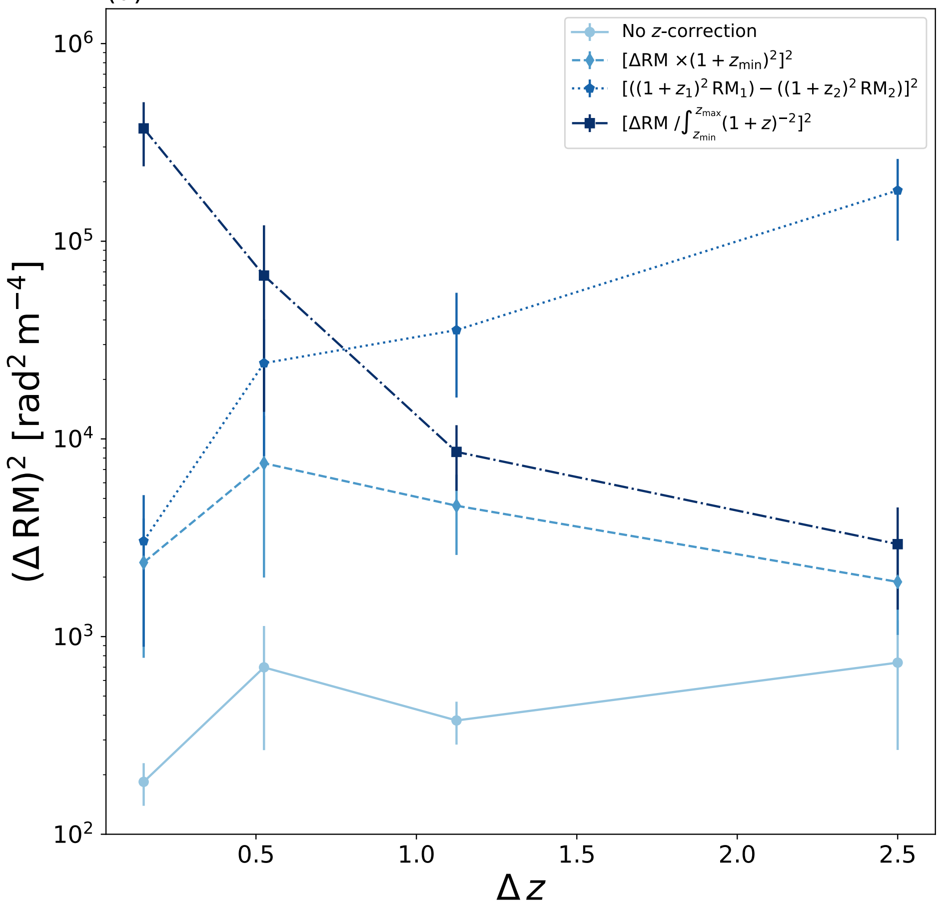
Vernstrom et al., in prep

- What about a larger sample and the difference in RM between Random and physical pairs?
- Taylor et al., 2009 catalogue of 37,543 NVSS Rotation Measures

(b)



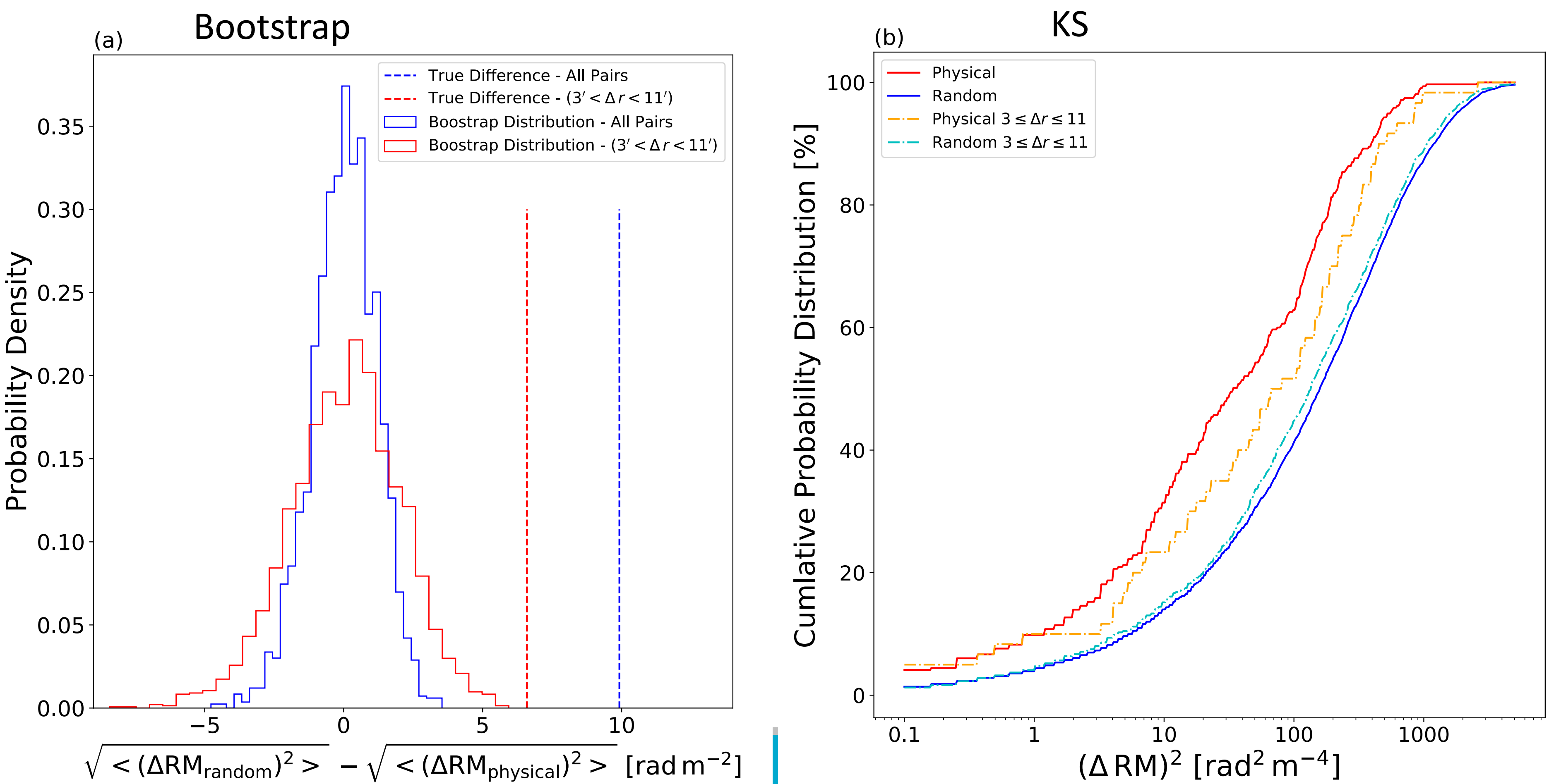
(d)



IGMF from ΔRM

Vernstrom et al., in prep

- **There is a difference in ΔRM between physical and random pairs**



IGMF from ΔRM

Vernstrom et al., in prep

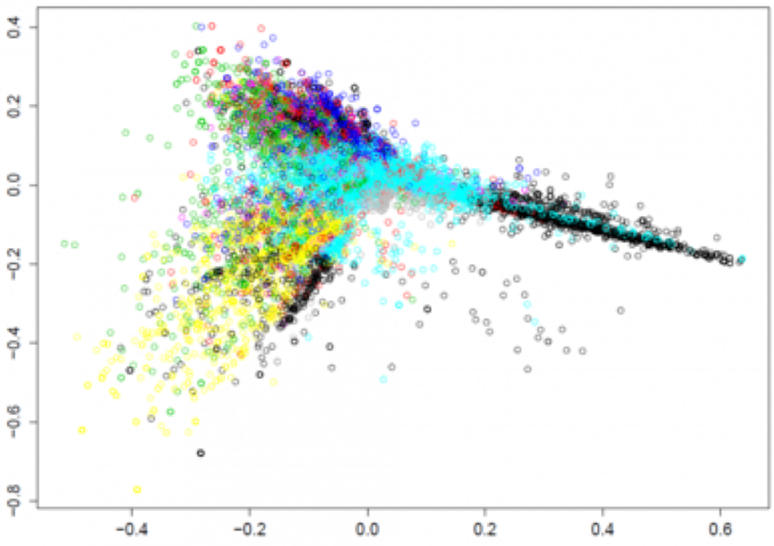
- **There is a difference in ΔRM between physical and random pairs**
- **Possible causes of difference:**
  - **IGMF**
  - **Differences in local source environments**
  - **Differences in types of sources**
  - **Noise / measurement uncertainty**

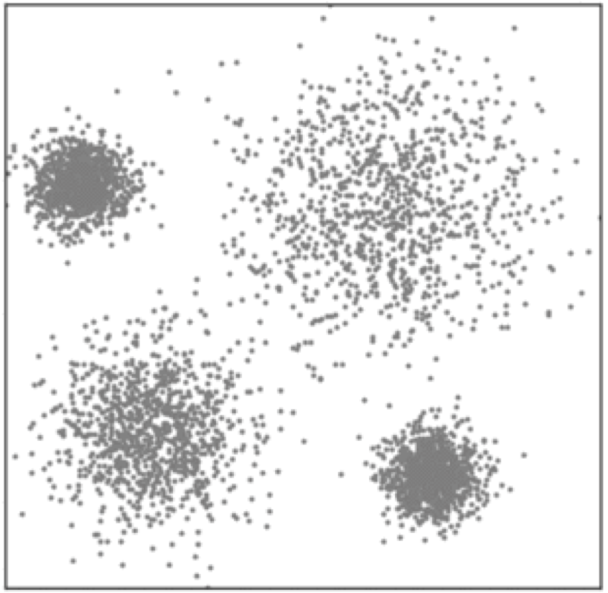
Degenerate with each other

IGMF from ΔRM

- Want to compare like with like
- Parameters:

➢ Redshift
➢ Luminosity
➢ Spectral index
➢ Polarization fraction
➢ Depolarization measure
➢ Rotation Measure
➢ Source type (AGN- FRI, FRII, radio loud/quiet, X-ray loud/quiet, etc)
➢ Cluster proximity (in or out of cluster, passing through a cluster)
➢ Absorbers
➢ Size
➢ ....





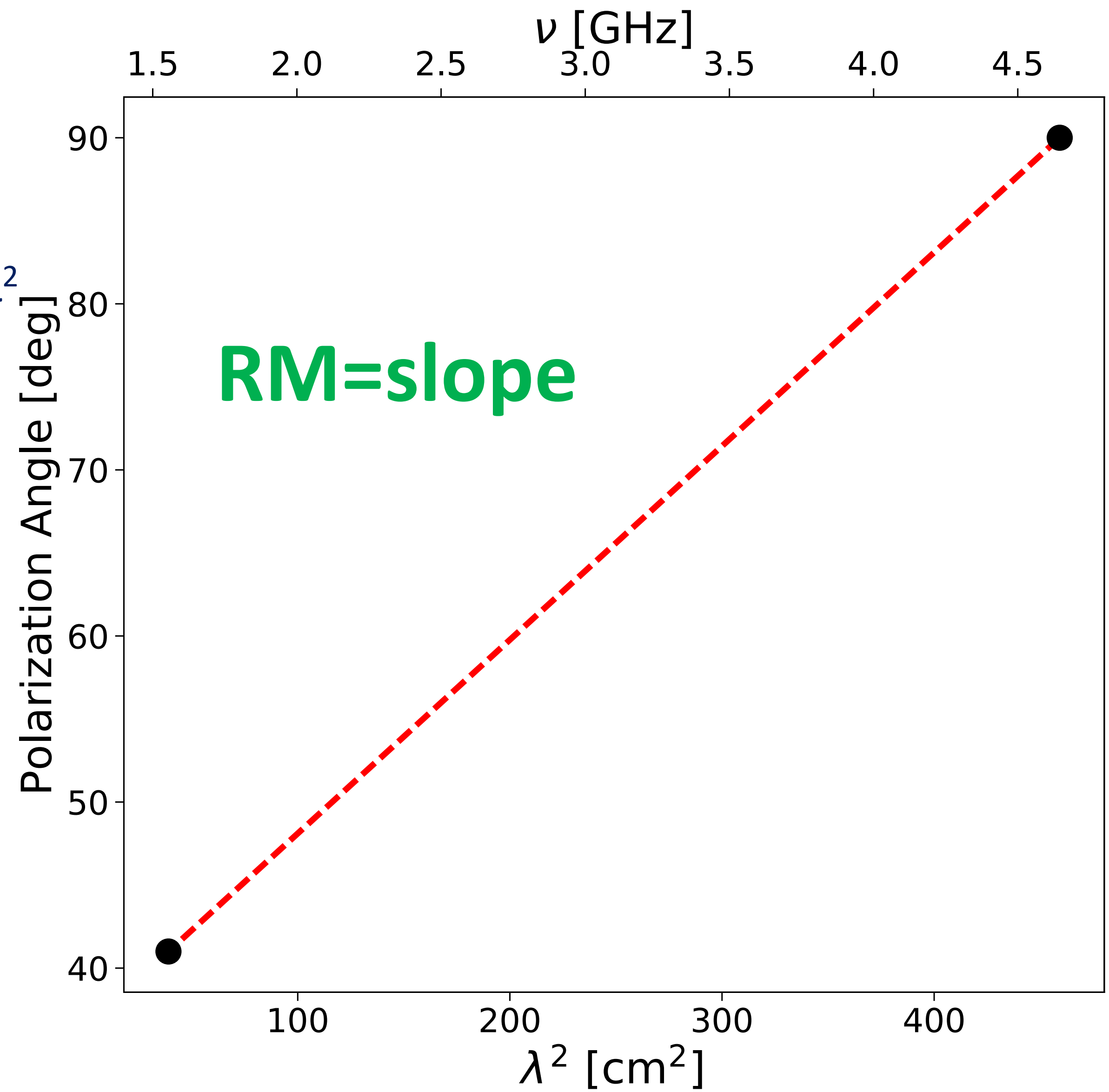
IGMF from ΔRM

Vernstrom et al., in prep

- Narrowband data
- Fit slope of Pol angle vs λ^2

$$\chi = \frac{1}{2}\tan^{-1}\left(\frac{S_U}{S_Q}\right)$$

$$\chi = \chi_0 + \mathrm{RM} \times \lambda^2$$



IGMF from ΔRM

QU fitting

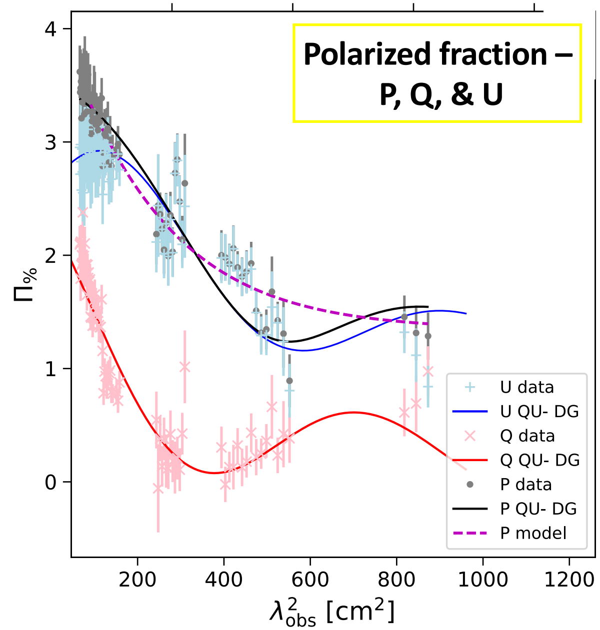
Vernstrom et al., in prep

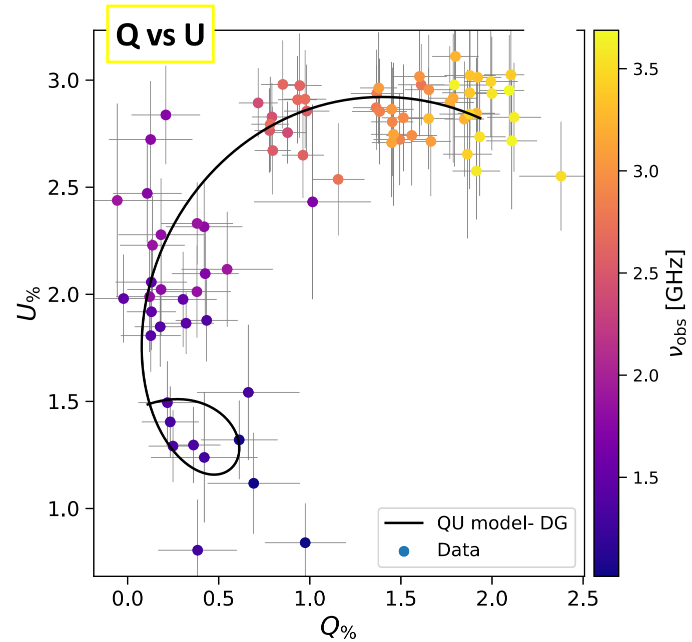
- Wideband data
- Fitting of QU vs λ^2
- RM synthesis and cleaning

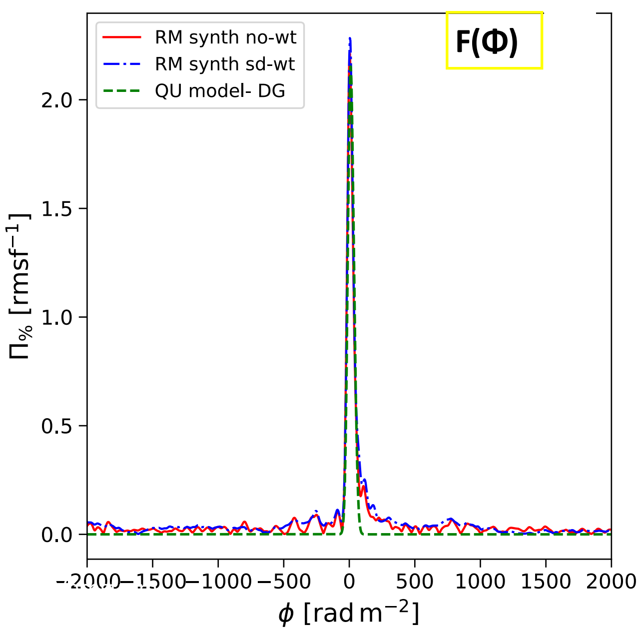
$$P(\lambda^2) = \int_{-\infty}^{+\infty} F(\phi) e^{2i\phi\lambda^2} d\phi$$

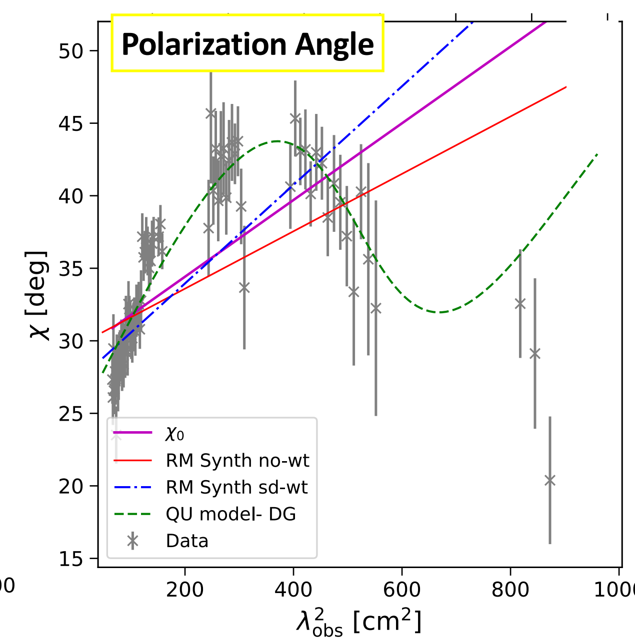
RM = peak(s) and dispersion of Faraday spectrum

➢ Allows for more detailed fitting of faraday spectrun and polarization angle









IGMF from ΔRM

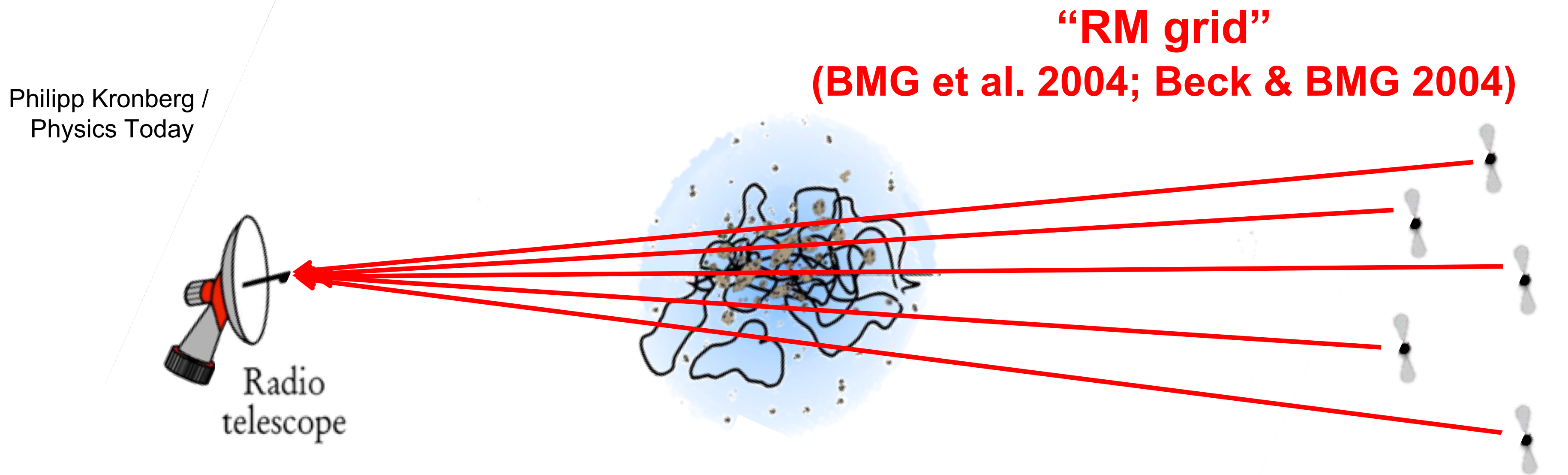
Vernstrom et al., in prep

- **There is a difference in ΔRM between physical and random pairs**
- **Possible causes of difference:**
  - **IGMF**
  - **Differences in local source environments**
  - **Differences in types of sources**
  - **Noise / measurement uncertainty**

Degenerate with each other

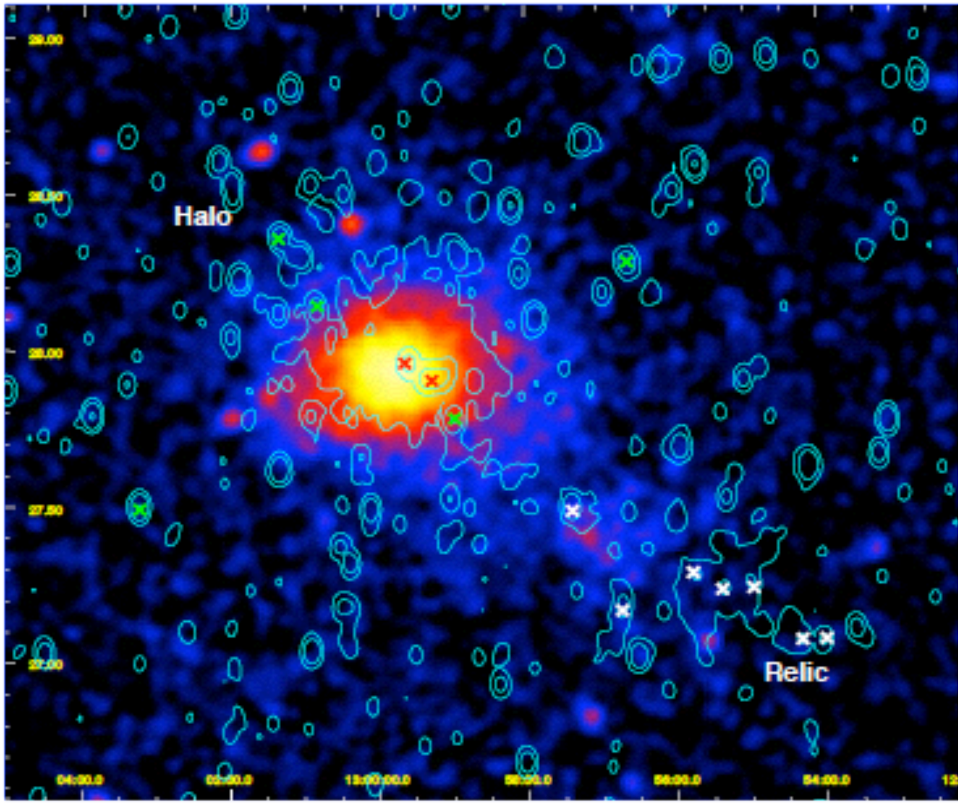
- **How can we improve ?**
  - **Larger sample size**
  - **New data with :**
    - **lower uncertainties**
    - **Larger bandwidth**

Rotation Measure Grids

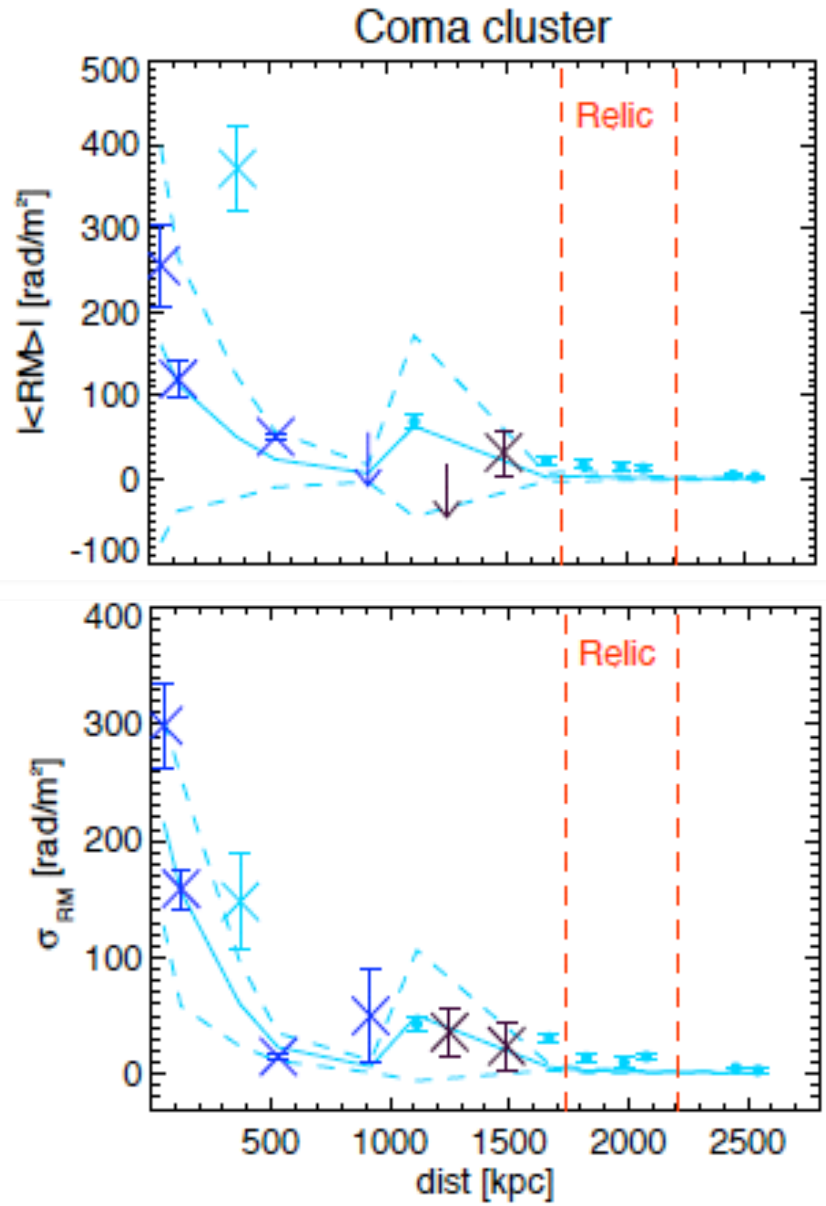


- Requirements for an RM grid:
  - high sensitivity and angular resolution
  - fast mapping speed or wide field of view
  - high polarisation purity (on- and off-axis)
  - broad bandwidth (long "baselines" in Faraday space)

Rotation Measure Grids



Bonafede et al. 2010,2013



Rotation Measure Grids

observed

$$RM = \int_0^d B_{los} n dl$$

model for gas distribution

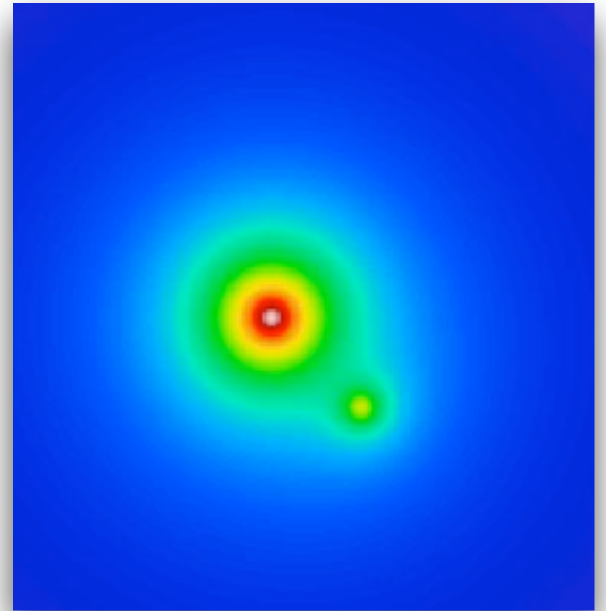
2 isothermal gas spheres in equilibrium matching X-ray observations

3D model for B

B components: Gaussian distribution

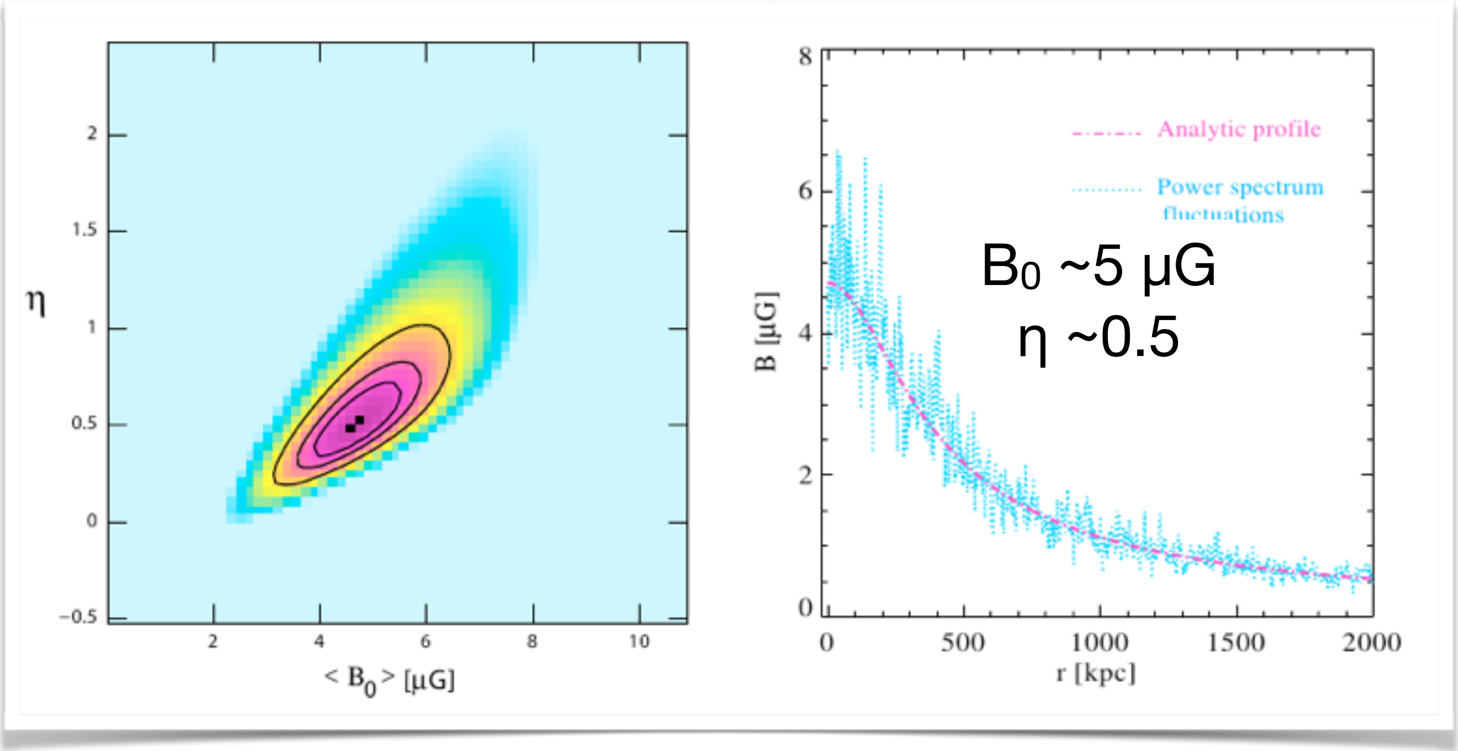
B spectrum: power law $|B_k|^2 \propto k^{-n}$

B profile: $B(r) = B_0 \left(\frac{n_e}{n_0} \right)^{\eta}$



Rotation Measure Grids

$$B \propto B_0 n_{gas}^{\eta}$$

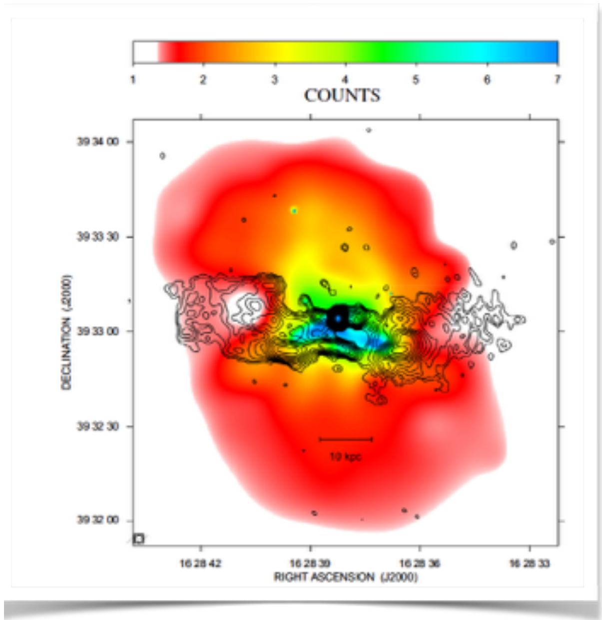


Bonafede et al. 2010.2013

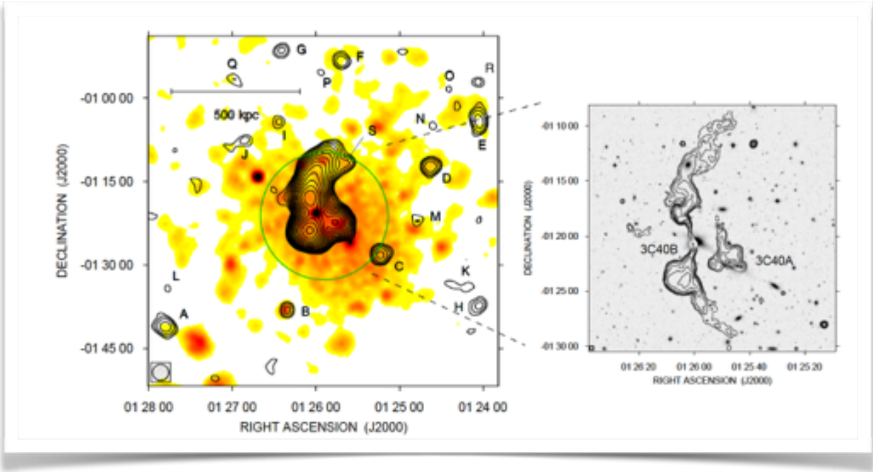
Rotation Measure Grids

SIMILAR APPROACH USED IN OTHER CLUSTERS

+ Bayesian approach



A2199 (Vacca et al. 2012)



A194 (Govoni et al. 2017)

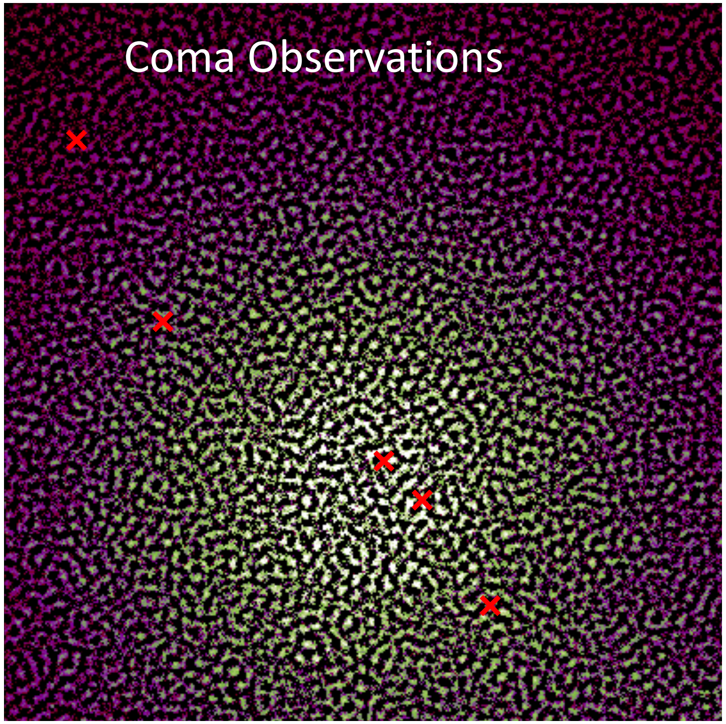
$$B \propto B_0 n_{gas}^{\eta}$$

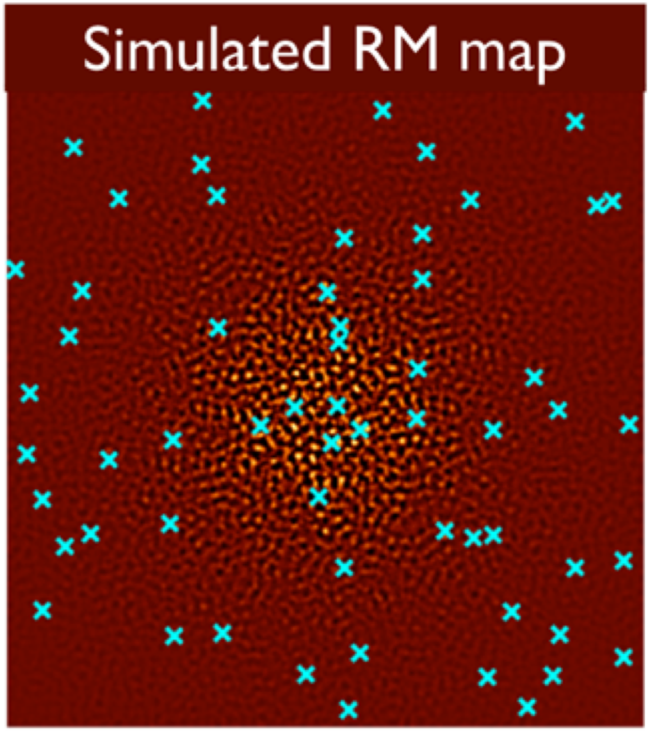
B_0 ~1-5 μG

η ~0.5 - 1

Rotation Measure Grids

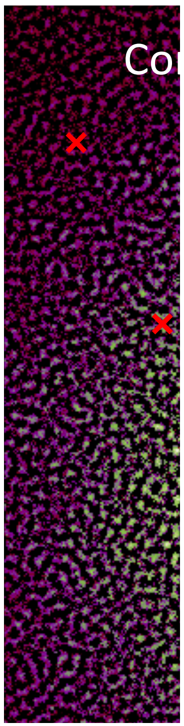
- Limitations → **Need large numbers of RMs !**

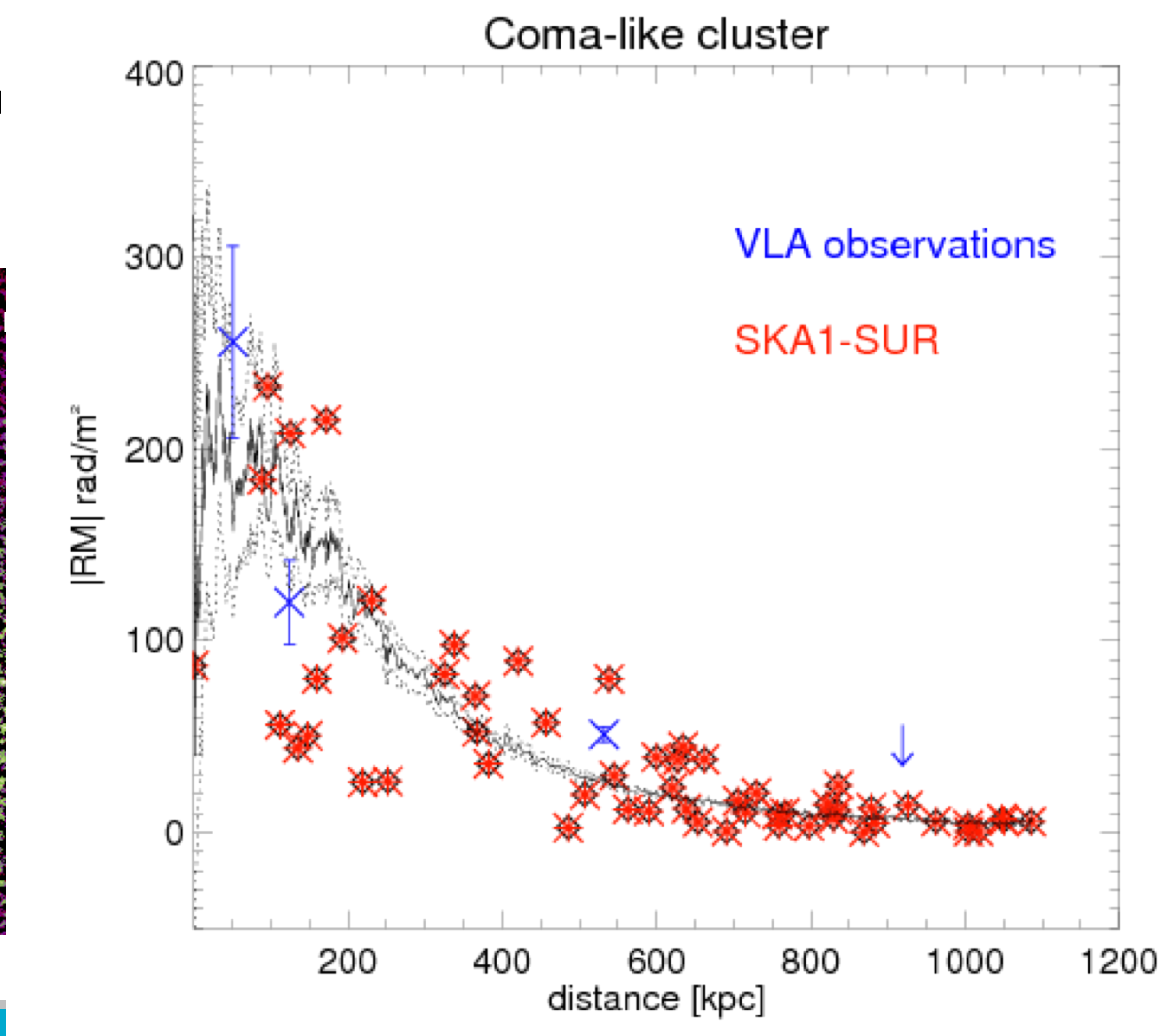


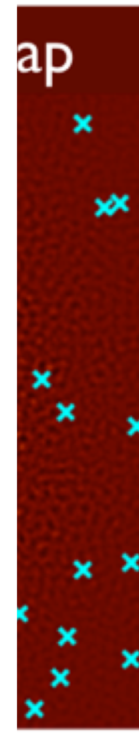


Rotation Measure Grids

- Limita







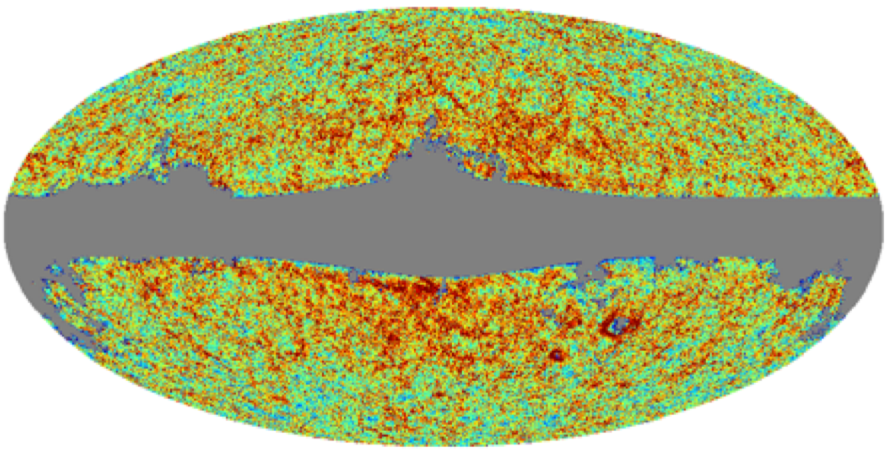
Rotation Measures – Cross Correlation

Amaral, Vernstrom, & Gaensler, in prep

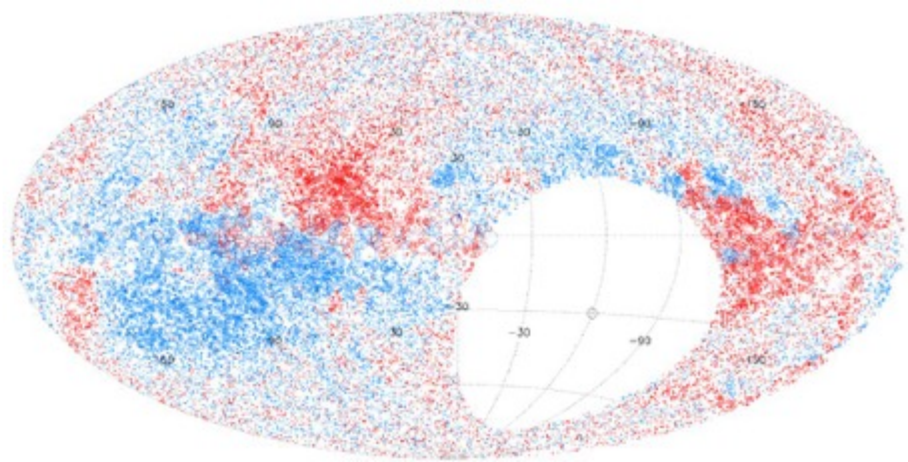
B-field along Line of Sight

Rotation Measure

$$RM = 8.12 \times 10^{5} \int_{0}^{z_s} (1+z)^{-2} n_e(z) B_{\parallel}(z) dl(z)$$



X



WISE galaxy redshift catalog

NVSS RM catalogue

Higher number density → higher electron density/magnetic field strength → larger |RM|

Rotation Measures – Cross Correlation

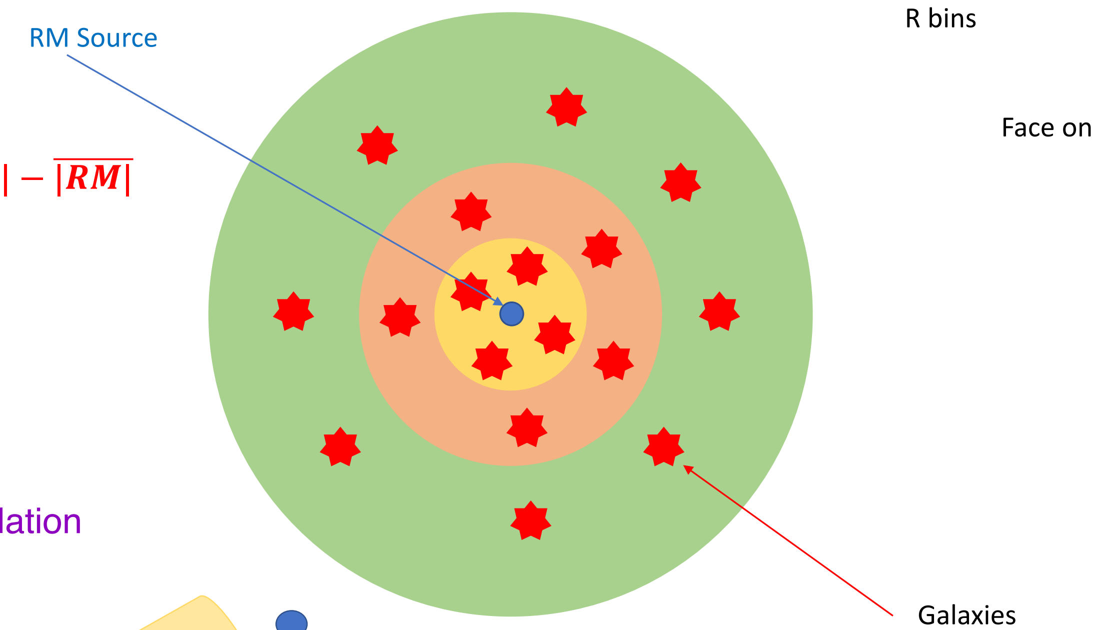
- Compute cross correlation in *z* bins and r bins

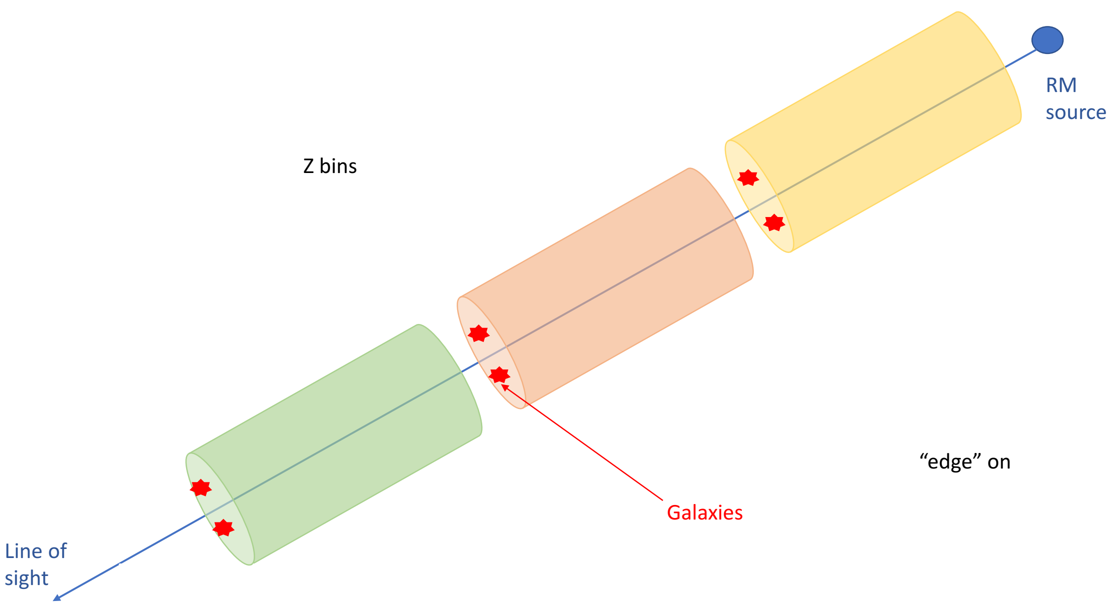
$$\Delta\boldsymbol{\rho}(\boldsymbol{r}) = \boldsymbol{\rho}(\boldsymbol{r}) - \bar{\boldsymbol{\rho}}(\boldsymbol{r})$$

$$\Delta|\boldsymbol{RM}| = |\boldsymbol{RM}| - \overline{|\boldsymbol{RM}|}$$

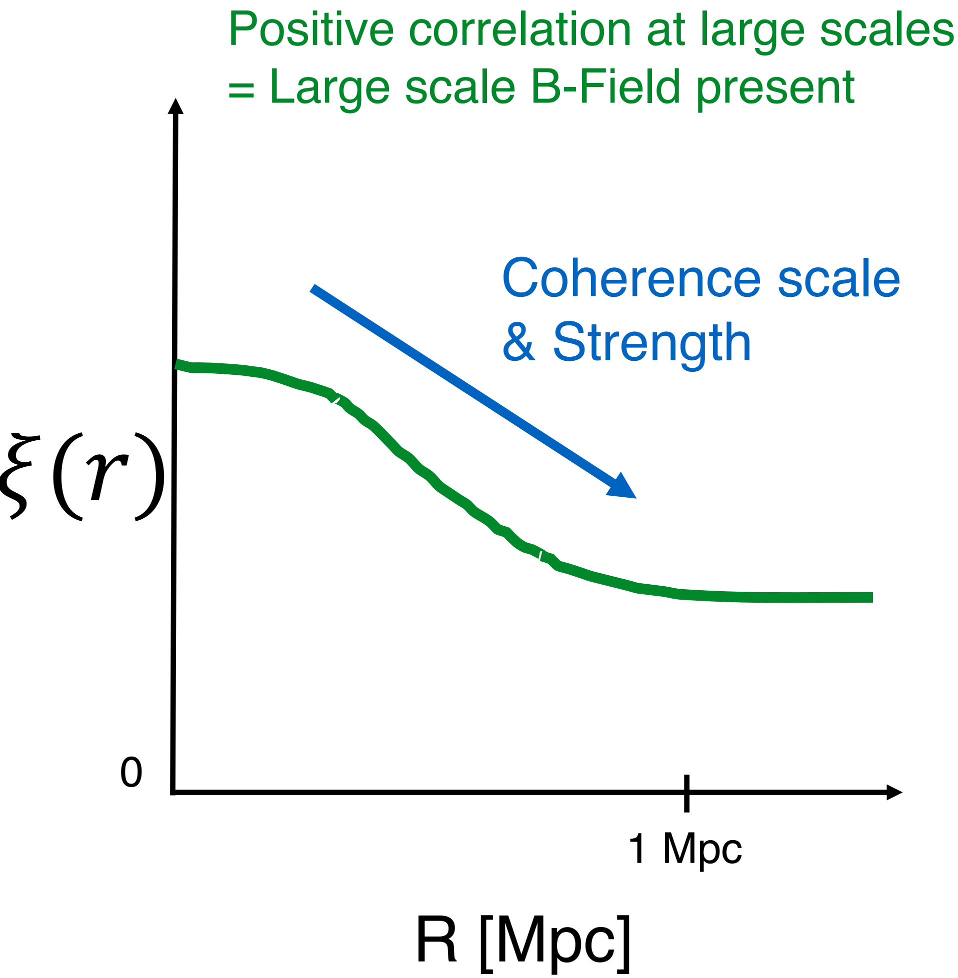
$$\xi(r) = \frac{\langle \Delta\rho(r) \cdot \Delta|RM| \rangle}{\bar{\rho}(r)}$$

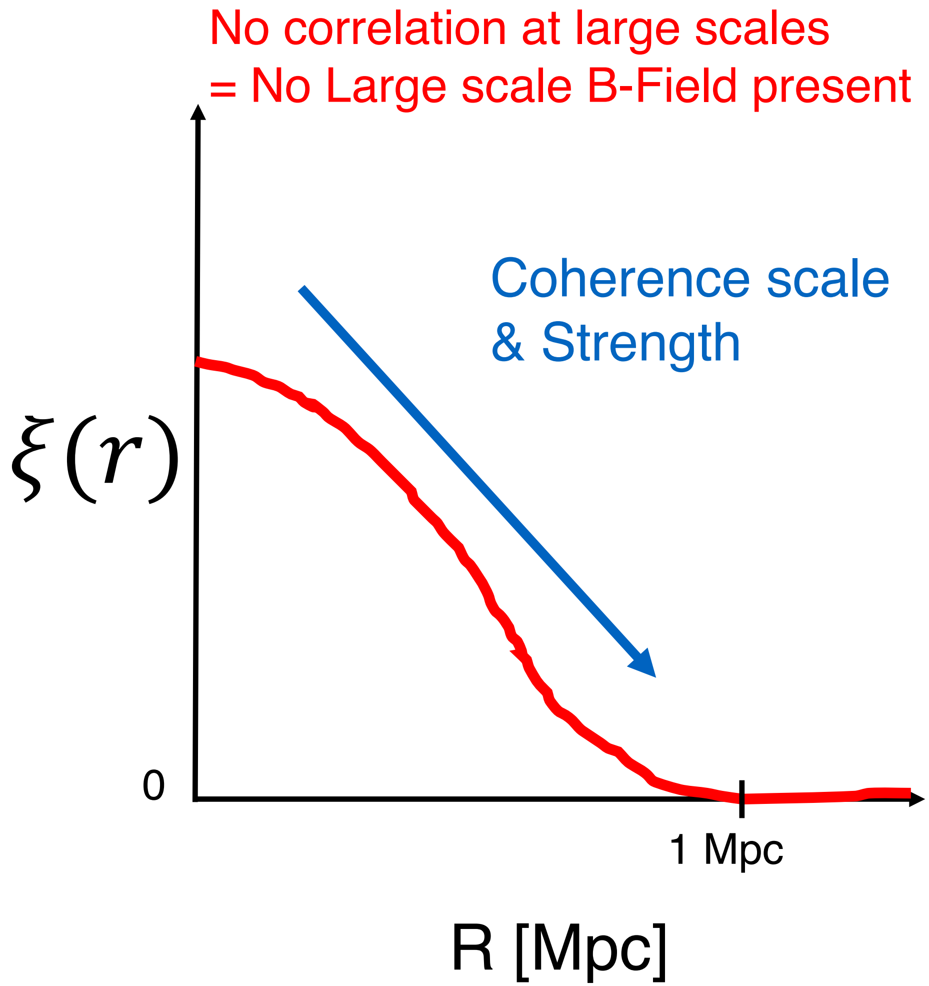
r = array of distance scales to probe correlation between two catalogues (bins)

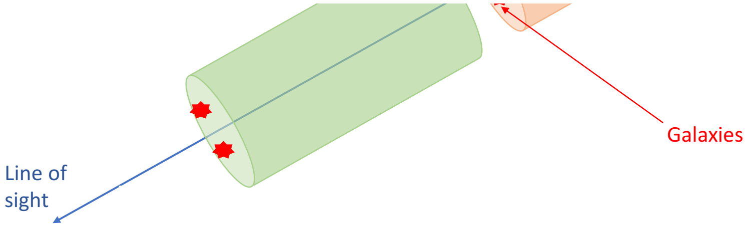




Rotation Measures – Cross Correlation



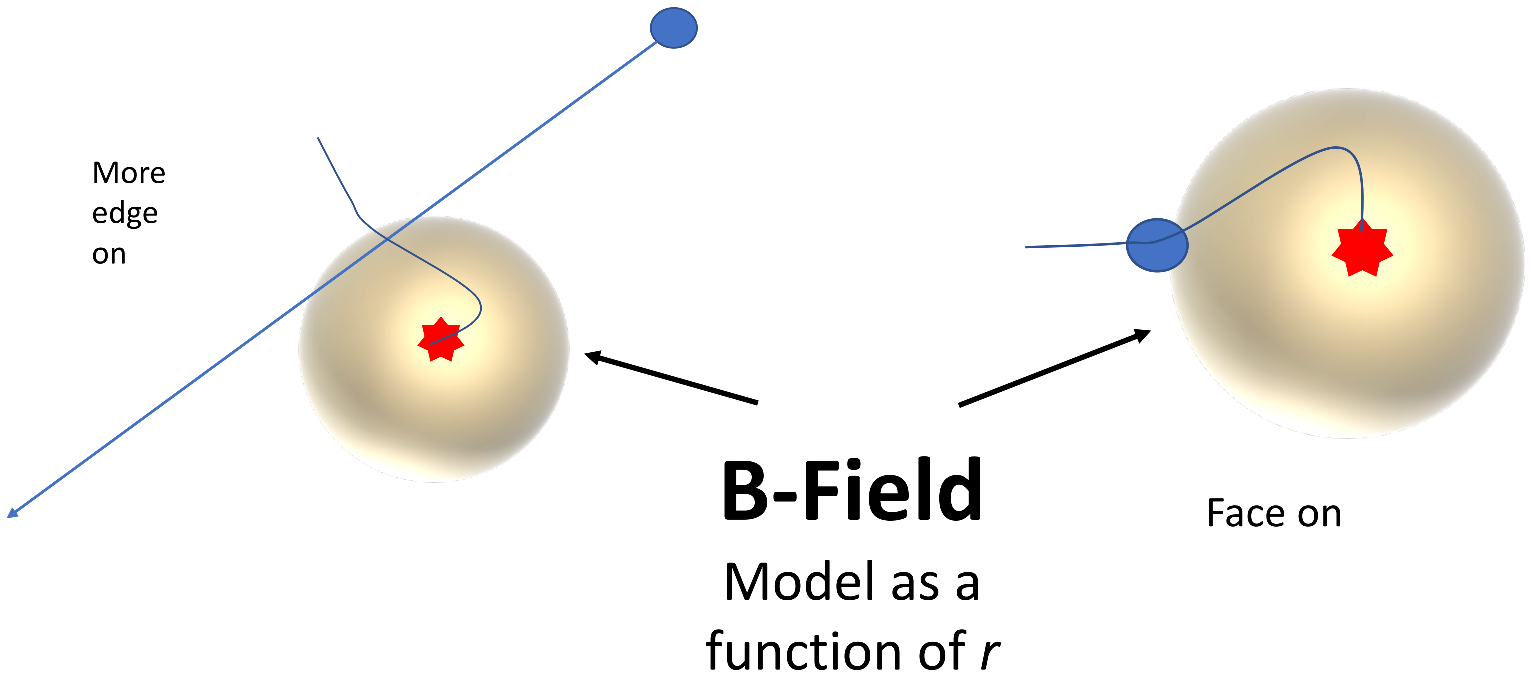




“edge” on

Rotation Measures – Cross Correlation

Assume some b-field model to get predicted cross correlation and compare with observed



Rotation Measures – Cross Correlation

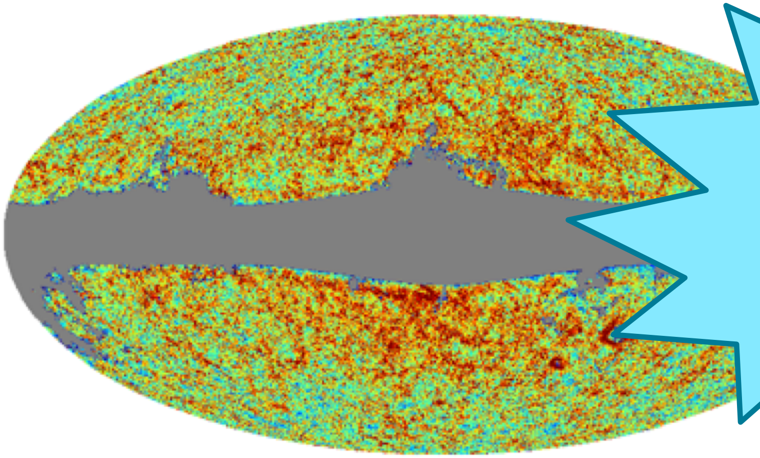
Amaral, Vernstrom, & Gaensler, in prep

B-field along Line of Sight

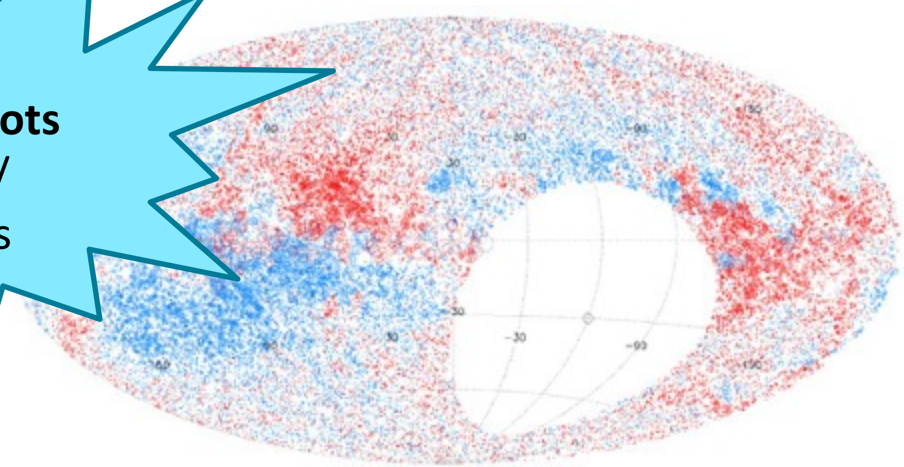
Rotation Measure

$$RM = 8.12\times10^{5}\int_{0}^{z_s}(1+z)^{-2}\,n_e(z)\,B_{\|}(z)\,dl(z)$$

But Need **lots** of RMs / redshifts



WISE galaxy redshift catalog



NVSS RM catalogue

Higher number density → higher electron density/magnetic field strength → larger |RM|

POSSUM and VLASS

- **Australian Square Kilometre Array Pathfinder**
  - 36 12-m dishes, *30-deg^2 field of view,* beginning 2019
  - ***<u>Polarisation Sky Survey of Universe's Magnetism</u>***

    (Gaensler, Landecker & Taylor 2010; askap.org/possum)
  - 3π sr to ~20 μJy/beam, 10” resolution, 1.1-1.4 GHz
  - RM grid at density of ~25 RMs/deg^2 (~10^6 RMs)
  - Early science program: 700-1800 MHz
- **Very Large Array Sky Survey** (Mao et al. 2014)
  - 3π sr to ~70 μJy/beam, 2.5” resolution, 2-4 GHz
  - Three epochs, 2017 to 2024
  - RMs and fractional polarisation for ~200,000 sources
- Extended data products via Canadian Initiative for Radio Astronomy Data Analysis (**CIRADA**)

CSIRO / Swinburne

NRAO/AUI/NSF

CIRADA

- Canadian Initiative for Radio Astronomy Data Analysis (CIRADA), started April 2018
  - CFI Innovation Fund 2017: $10.6M over 5 years
  - six Canadian universities + NRAO + NRC/CADC + international partners
  - 15 software developers and postdocs
- In a nutshell:
  - all-sky surveys with ASKAP, VLASS, CHIME,
  - provided by observatories: 20 PB of basic data products
  - CIRADA: science-ready data products and corresponding public archive
  - ASKAP: polarimetry, HI in external galaxies
  - VLASS: continuum, polarimetry, transients
  - CHIME: continuum, polarimetry, transients, pulsar search, HI absorption

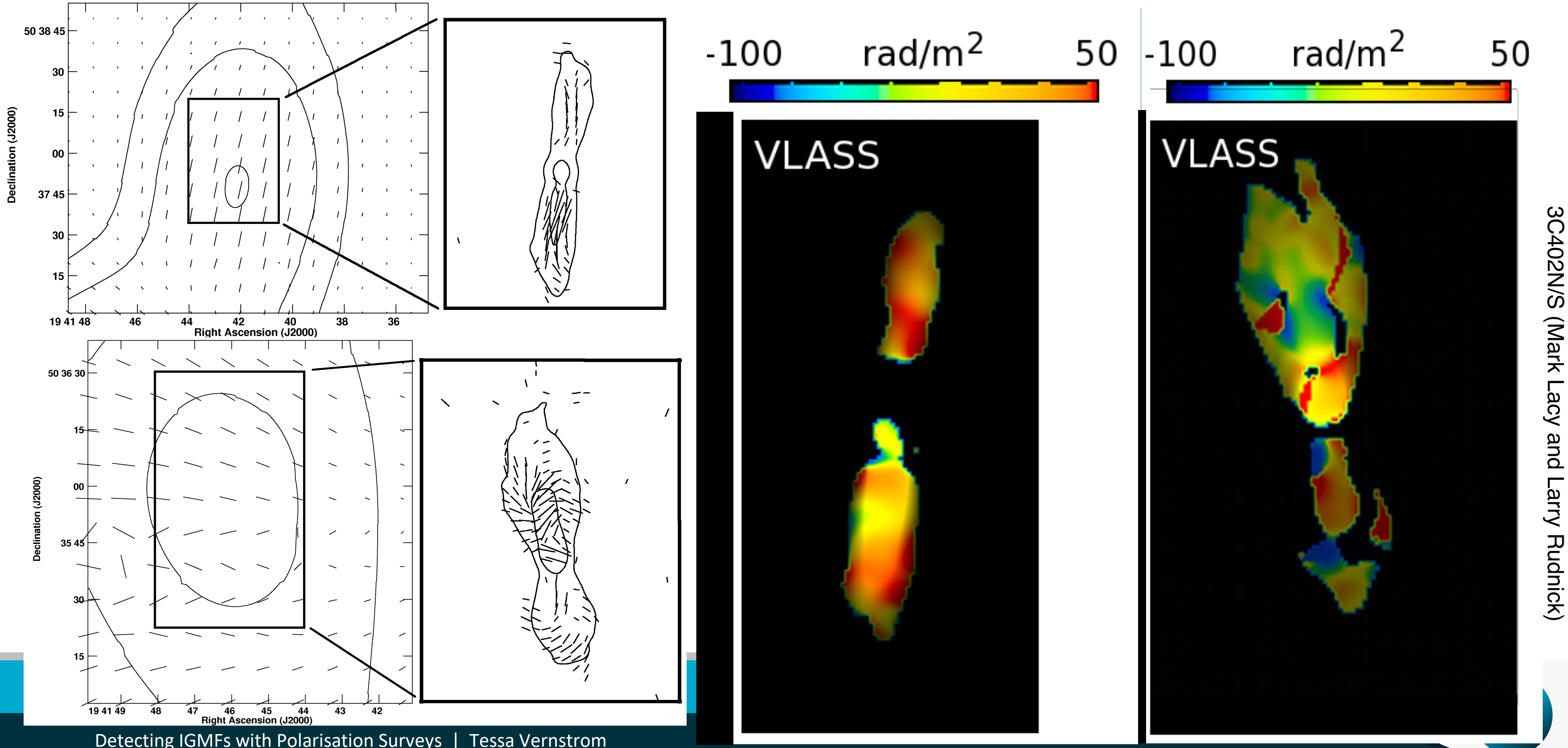

Ant Schinckel


NRAO/AUI/NSF


CHIME

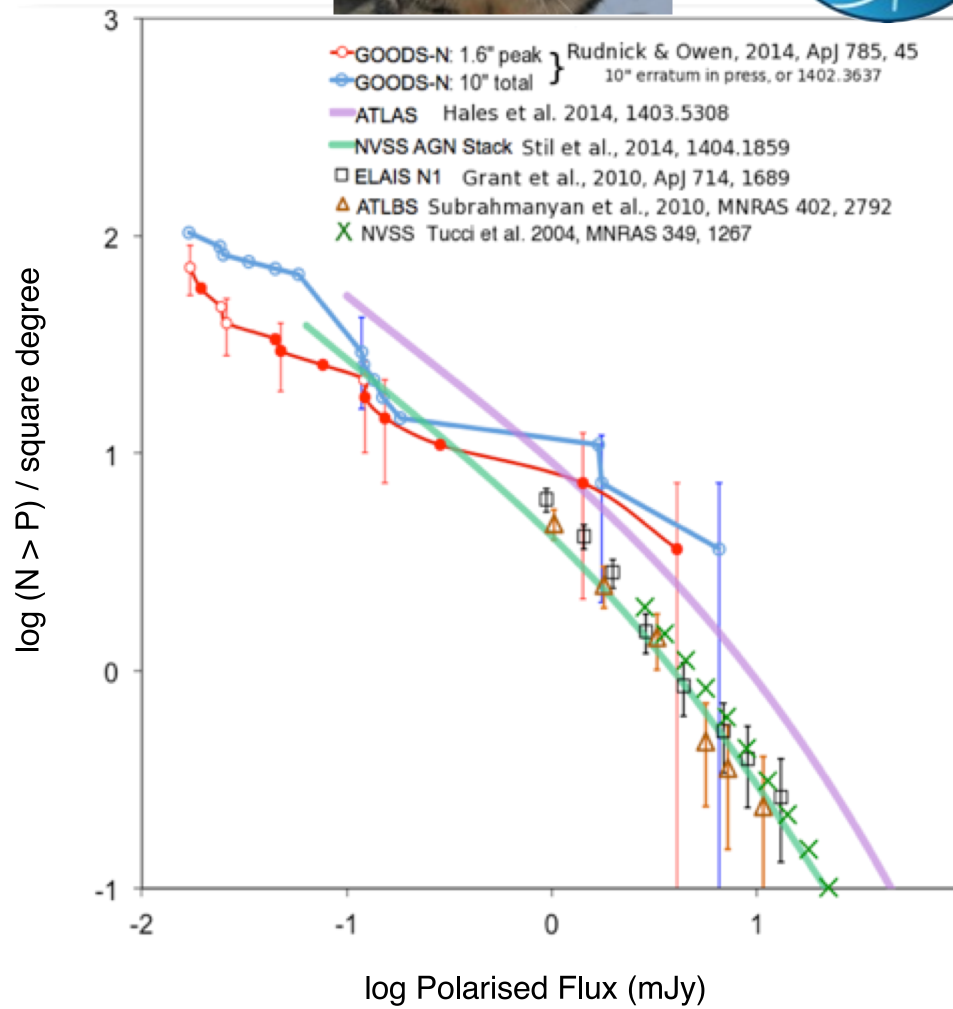
VLASS: First Results

- Epoch 1.1 complete: 50% of VLASS sky (17,000 deg^2)
  - raw visibilities plus “quicklook” data publicly available
  - working on polarisation imaging
  - first results: polarisation in 2 broad channels (bottom & middle thirds of band)



POSSUM Design & Expected Outcomes

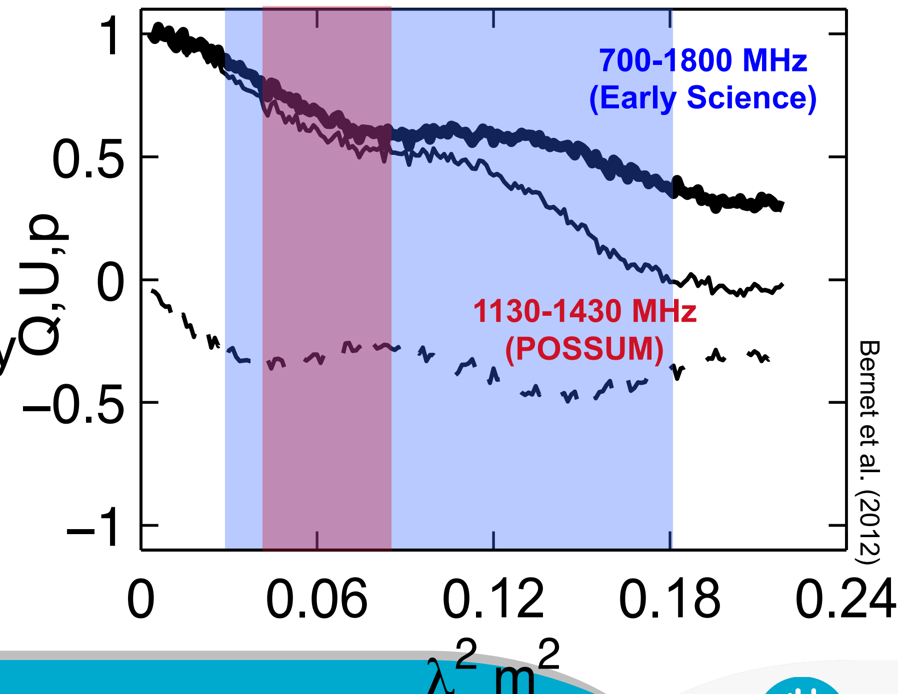
- POSSUM will be fully commensal with EMU
  - *POSSUM Polarisation Catalogue*: polarisation properties of all EMU sources
  - *POSSUM Value-Added Catalogue*: independent polarisation survey
- Frequency coverage 1130-1430 MHz:
  - RM FWHM 131 rad/m^2 ; typical δRM ≤ 7 rad/m^2 (S/N ~ 10) (VLASS: 200 rad/m^2, 10 rad/m^2)
  - maximum RM ~ 14,000 rad/m^2 (plenty!)
  - max RM thickness ~70 rad/m^2
- Sky density of polarised sources at L > 100 μJy will be ~25 deg^{-2}
  - not known: what fraction of sources will be Faraday thin (good for foreground RM grid experiments) vs Faraday thick (intrinsic effects)?



Larry Rudnick (after Rudnick & Owen 2014)

POSSUM Early Science Program

- Full POSSUM: 1130-1430 MHz, 36 antennas
  - narrow bandwidth ($\Delta\nu / \nu \sim 0.25$)
  - rotation measures (foregrounds)
- Early Science: 700-1800 MHz, 28-36 antennas
  - broad bandwidth ($\Delta\nu / \nu \sim 1$)
  - Faraday tomography (intrinsic properties)
- ~16 early science programs (mostly commensal with EMU)
  - radio source structure and evolution
  - broadband Faraday complexity
  - combined ASKAP/MWA polarimetry
  - combined ASKAP/VLASS polarimetry
  - K-corrections
  - ionospheric fluctuations
  - stacking
  - source finding



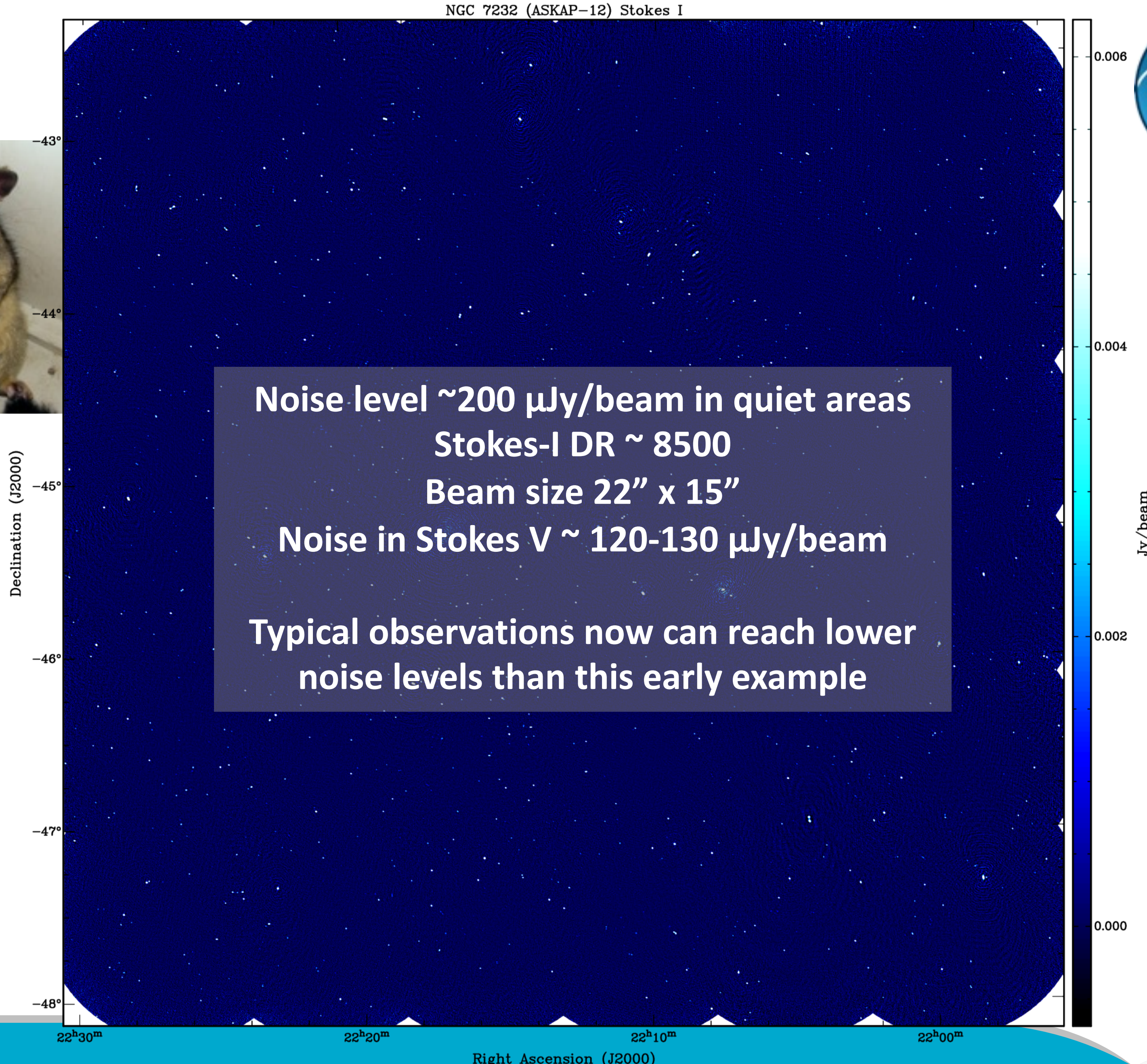
POSSUM Commissioning and Early Science

- Mapping of lobes of Centaurus A
- Pilot RM grid around NGC 7232
- Polarimetry of extended radio galaxies
- Supernova 1006
- Fornax A: comparison with ATCA
- Small Magellanic Cloud
- GAMA fields (broadband counterparts)
- “Cosmology fields”: 2000 deg^2

Kim Steele / Curtin

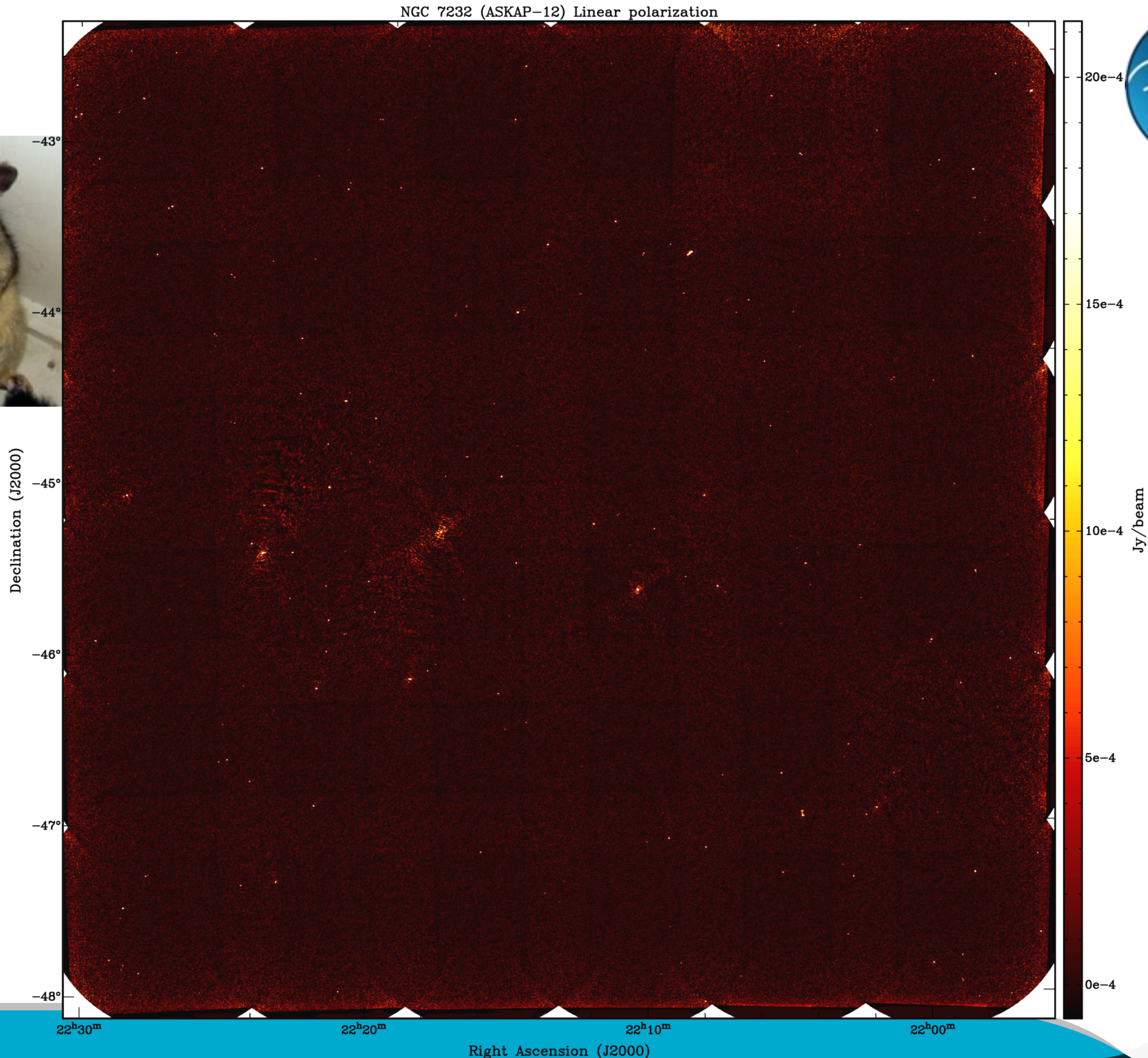
ASKAP's First RM Grid – George Heald

- Data from 11 August 2016: NGC 7232 field (proposed for observation by WALLABY team)
- 48 MHz bandwidth, 12h (but only retained ~half of that time)
- Calibration using
  - Standard ASKAPsoft calibration/selfcal/continuum imaging pipeline
  - Addition of XYphase & leakage calibration using scripts from Craig Anderson
- Residual leakage (I → V) $\lesssim$1% level, strongest at beam edges
- Rotation measures appear to be reliable
  - Starting to give us an indication of data quality

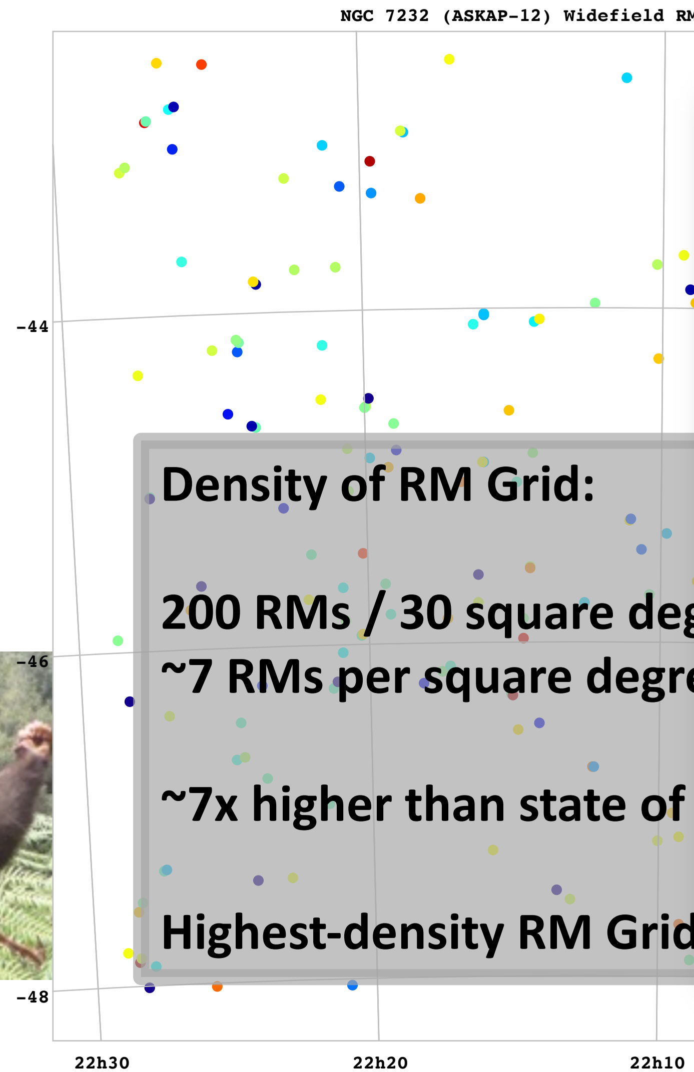


Noise level ~200 μJy/beam in quiet areas
Stokes-I DR ~ 8500
Beam size 22” x 15”
Noise in Stokes V ~ 120-130 μJy/beam

Typical observations now can reach lower noise levels than this early example


NGC 7232 (ASKAP−12) Linear polarization
Declination (J2000)
−43°
−44°
−45°
−46°
−47°
−48°
Right Ascension (J2000)
22h30m
22h20m
22h10m
22h00m
Jy/beam
20e−4
15e−4
10e−4
5e−4
0e−4

ASKAP’s First RM Grid – George Heald



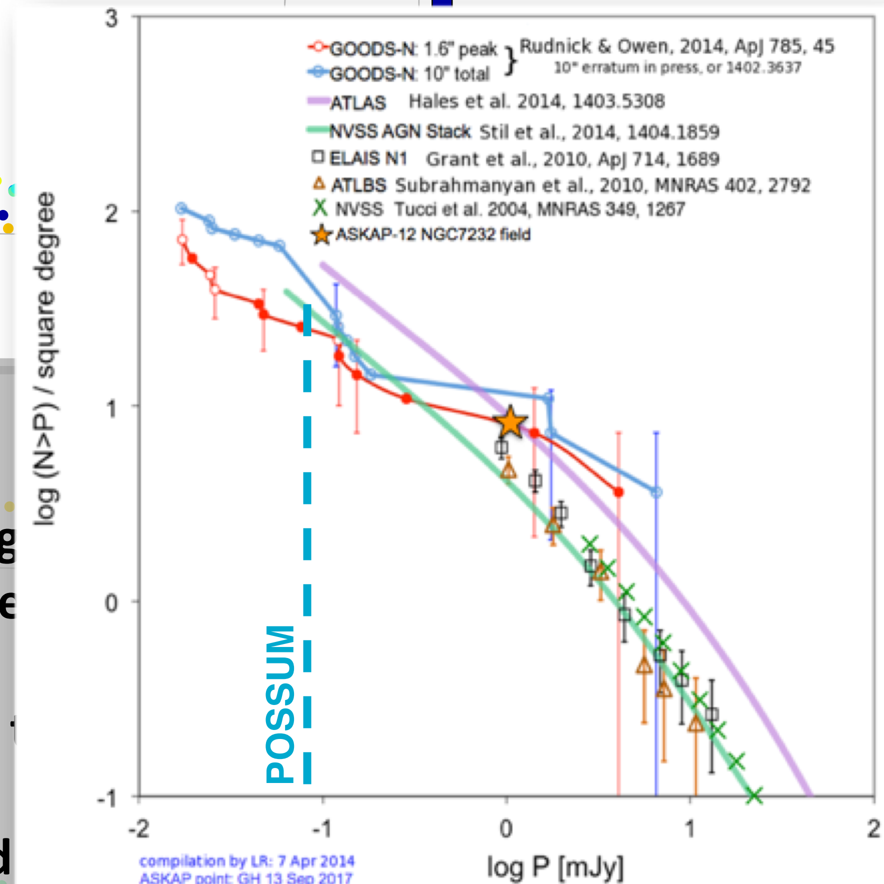
Density of RM Grid:

200 RMs / 30 square deg

~7 RMs per square degre

~7x higher than state of t

Highest-density RM Grid



Other Surveys

- Low Frequencies:
  - **LoTSS**: LOFAR, 144 MHz , ~1 source/ sq deg polarized density, Northern Sky, Shimwell et al
  - **POGS**: MWA GLEAM survey 170 – 230 MHz, Southern Sky – Riseley et al, 2018

- Mid Frequencies:
  - **MIGHTEE**: MeerKAT 1.4 GHz, Deep fields

Summary

- Many possible ways to use RMs to get at magnetic fields of IGM
  - Grids
  - ΔRM
  - Cross correlations
  - And more

- But need:
  - Large sample sizes
  - Faraday spectra
  - Redshifts (& other source properties)

- New polarisation surveys will help a lot with new depths, wide bandwidths, along with new RM measurement techniques