Max-Planck-Institute
for Astrophysics

OAC

Osservatorio
Astronomico
di Cagliari

INAF

Measuring extragalactic magnetic fields

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Main collaborators:

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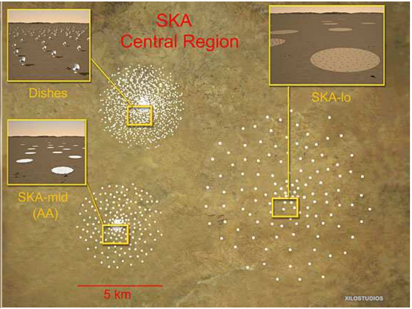
February 16th, 2016
Séminaire Lagrange

Outline

Context

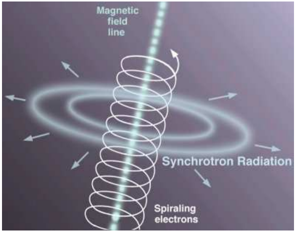
Key Science Project: Origin and evolution of cosmic magnetism

LOFAR-UK station



SKA

Galaxy clusters

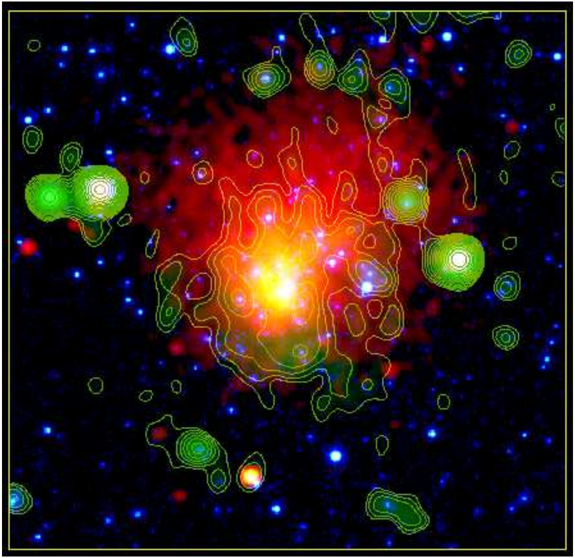


A665

Optical emission

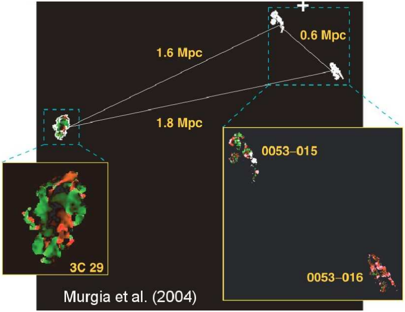
X-ray emission

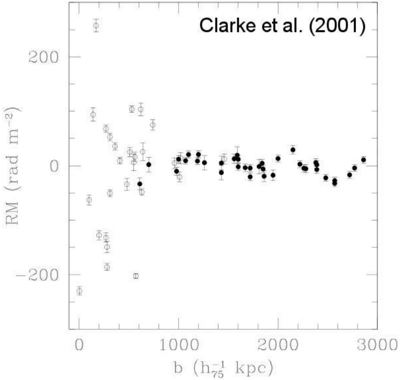
Radio emission



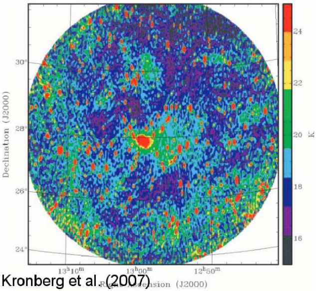
Galaxy clusters

$$\phi \propto \int n_e B dl$$

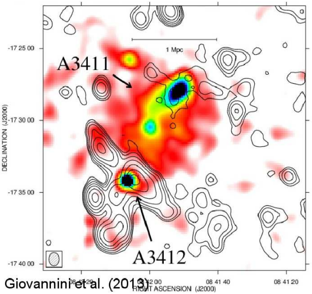




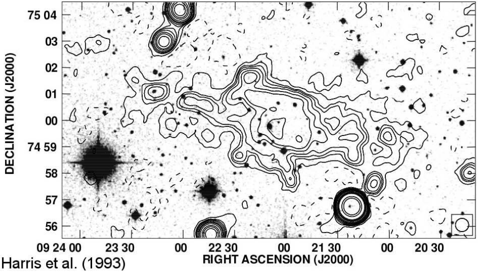
Bridges and Filaments



Kronberg et al. (2007)



Giovannini et al. (2013)



Harris et al. (1993)

PART I

Intracluster magnetic fields from diffuse radio emission

MAGNETIC FIELD INVESTIGATION

Observed Luminosity:

$$L_\nu = J_\nu V$$

Synchrotron emissivity:

$$J_\nu \propto E_{\rm el} B^2 \qquad \alpha = 1$$

Under equipartition

$$E_{\rm el} \approx \frac{B^2}{8\pi}$$

$$\downarrow$$

$$L_\nu \propto B^4 V$$

Average properties

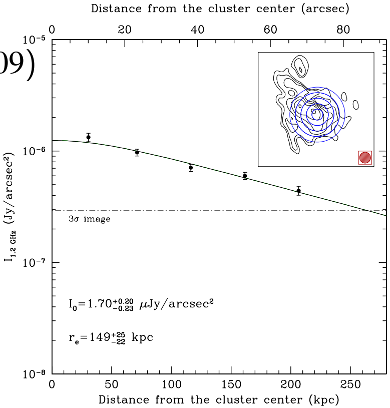
$$I(r) = I_0 e^{-r/r_e} \quad \text{Murgia et al. (2009)}$$

$$V_{cm^3} = \frac{4\pi}{3}(3r_e)^3 = 1.10\times10^{73}\,\text{cm}^3$$

$$L_{1.4\,\text{GHz}} = 1.58\times10^{24}\,\text{W Hz}^{-1}$$

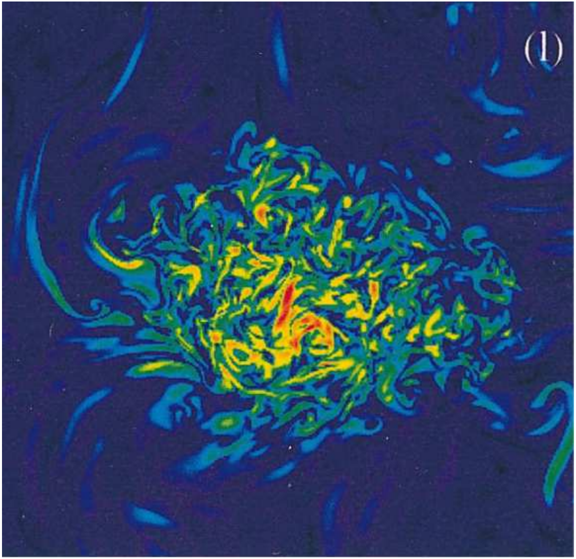
$$\downarrow$$

$$\langle B_0 \rangle \sim few\,\mu\text{G}$$



A1689, Vacca et al. (2011)

Turbulence



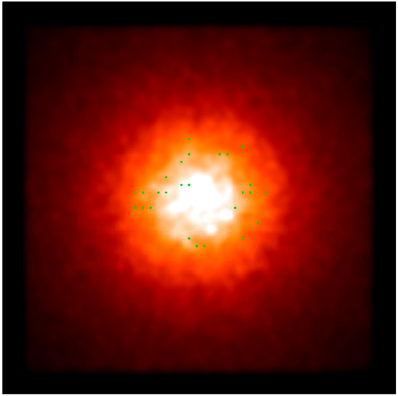
Roettiger et al. (1999)

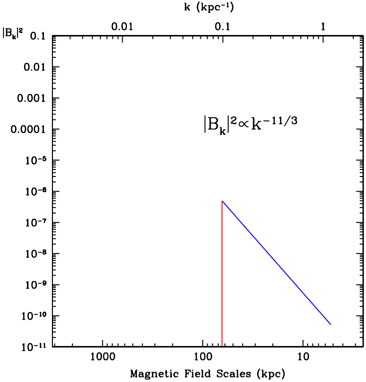
Synthetic images and polarized vectors

for a turbulent Kolmogorov index magnetic field

$$\Lambda_{\max} = 64\ kpc$$

Murgia et al. (2004)



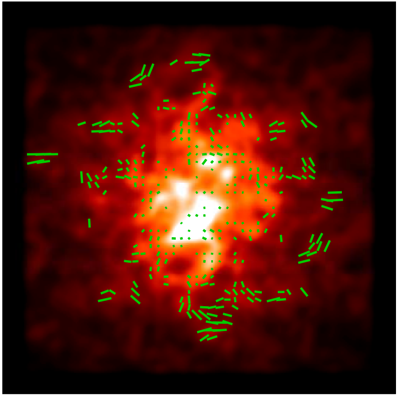


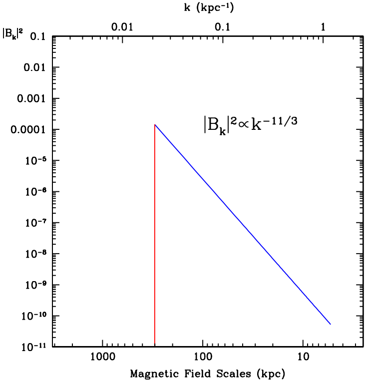
Synthetic images and polarized vectors

for a turbulent Kolmogorov index magnetic field

$\Lambda_{\max} = 300\ kpc$

Murgia et al. (2004)



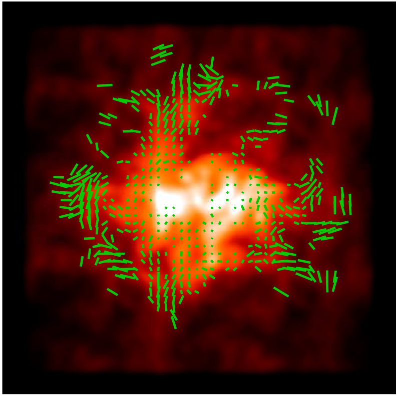


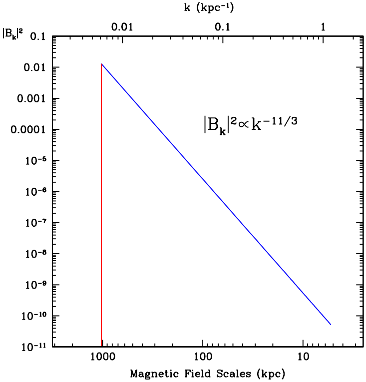
Synthetic images and polarized vectors

for a turbulent Kolmogorov index magnetic field

$\Lambda_{max} = 1024\,kpc$

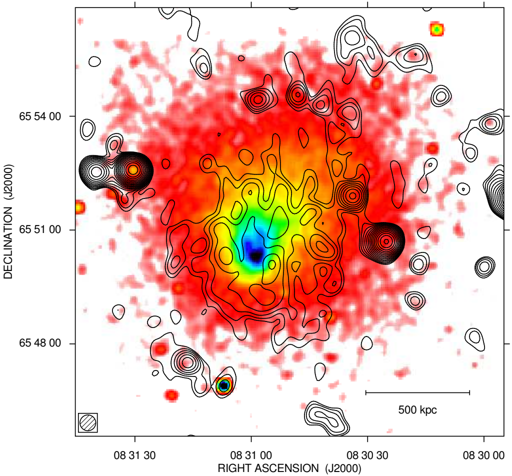
Murgia et al. (2004)





Merging clusters: A665

$\langle B \rangle \simeq 0.75\,\mu\mathrm{G}$, Vacca et al. (2010)



resolution

$25'' \simeq 75\,\mathrm{kpc}$

(1 kpc $= 3.09 \times 10^{19}$ m)

sensitivity

6.35×10^{-8} Jy/arcsec^2

(1 Jy $= 10^{-26}$ W Hz^{-1} m^{-2})

distance

880 Mpc

POLARIZED EMISSION UNDER NOISE LEVEL

Simulations

FARADAY (Murgia et al. 2004)

- Gaussian random field magnetic field

$$|B_{\mathrm{k}}|^2 \propto k^{-\mathrm{n}}, \qquad \langle B(r)\rangle = \langle B_0\rangle \left(\frac{n_{\mathrm{e}}(r)}{n_{\mathrm{e0}}}\right)^{\eta}$$

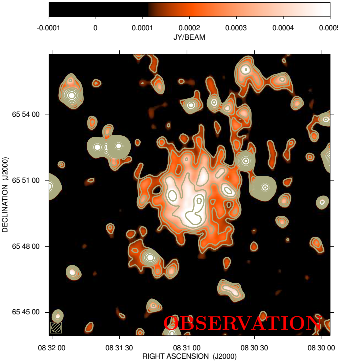
- Relativistic electrons

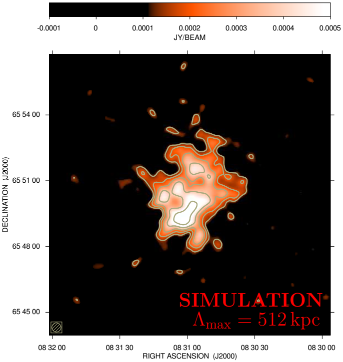
$$N(\gamma)d\gamma = N_0\gamma^{-\delta}d\gamma$$

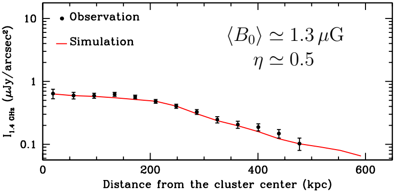
- Thermal gas β-model (Cavaliere & Fusco-Femiano 1976)

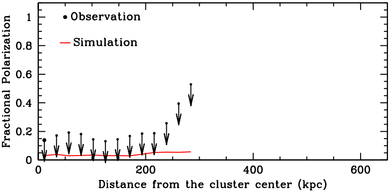
$$n_{\mathrm{e}}(r) = n_0\left[1 + \left(\frac{r}{r_{\mathrm{c}}}\right)^2\right]^{-\frac{3}{2}\beta}$$

Observations vs simulations



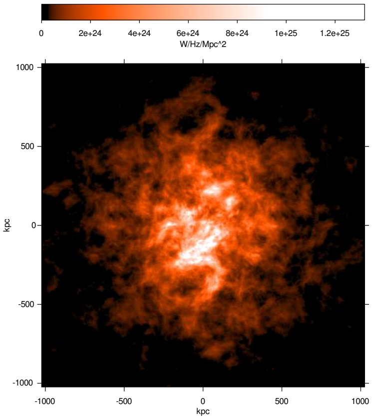


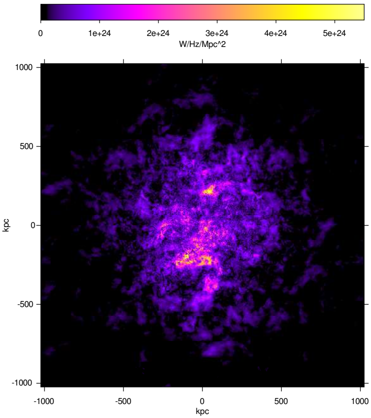




Polarization of radio halos: instrumental limits

FULL RESOLUTION

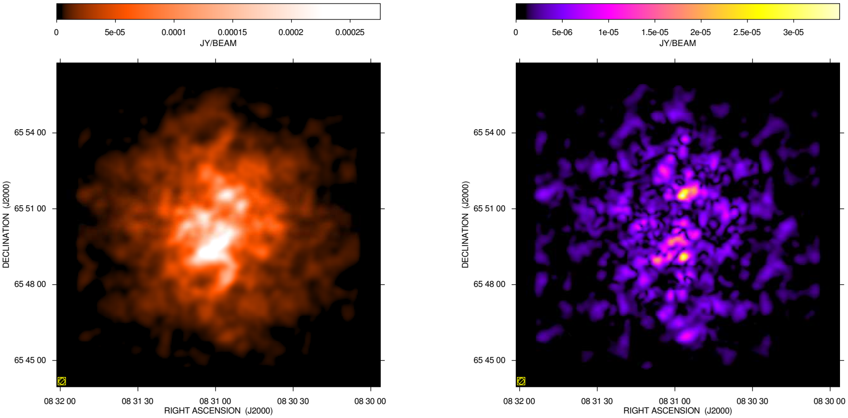




FPOL=24%

Polarization of radio halos: instrumental limits

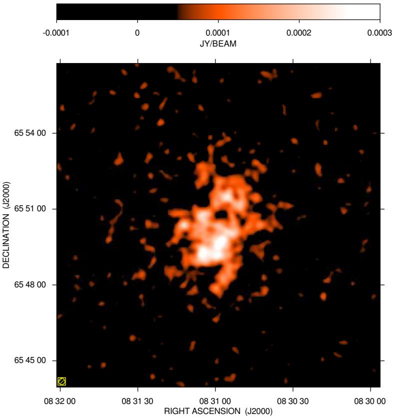
BEAM

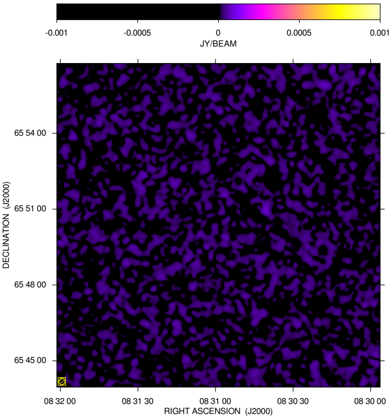


FPOL=7%

Polarization of radio halos: instrumental limits

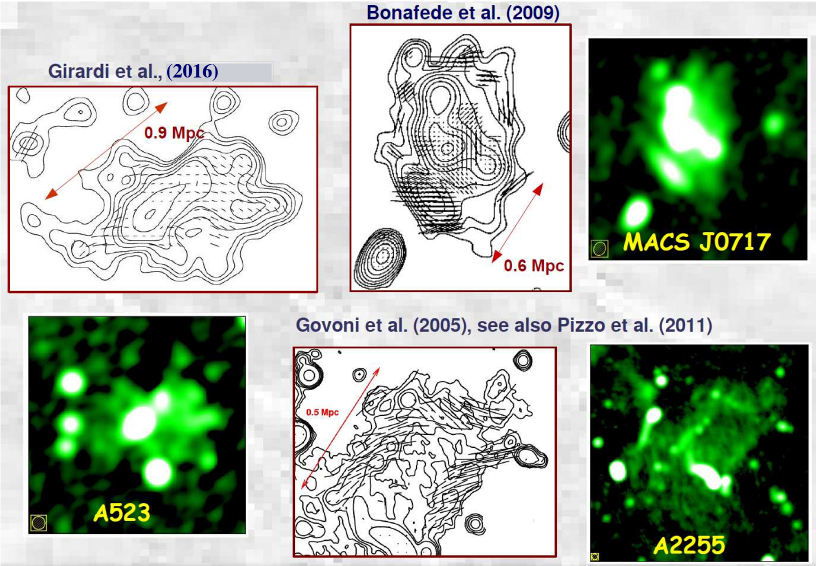
NOISE



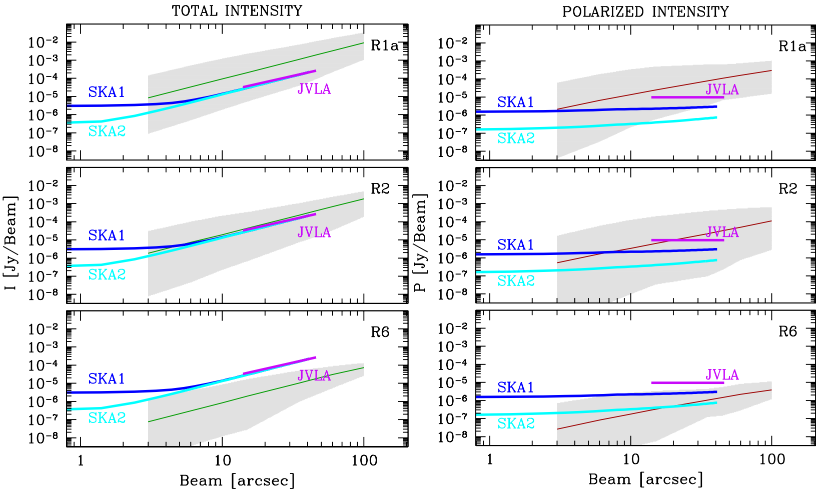


FPOL<noise level

Polarization of radio halos: observations



Polarization of radio halos: simulations

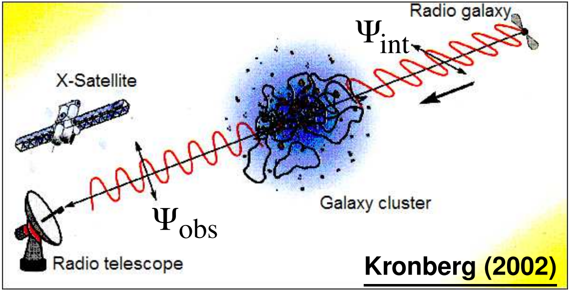


Govoni et al. (2013, 2015)

PART II

Intracluster magnetic fields from radio galaxies

Faraday effect

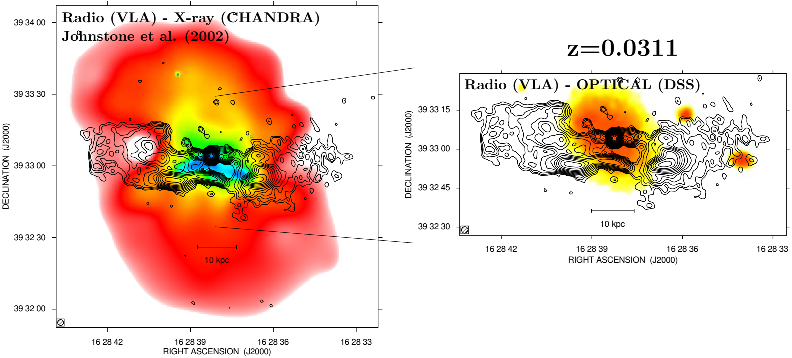


$$\Psi_{obs} = \Psi_{int} + RM\lambda^2$$

$$RM(\mathrm{rad/m^2}) = 812[\mathrm{g^{-1/2}cm^{1/2}s}] \int_0^{\mathrm{L(kpc)}} n_e(\mathrm{cm^{-3}}) B_{\|}(\mu\mathrm{G}) dl$$

Relaxed clusters: A2199

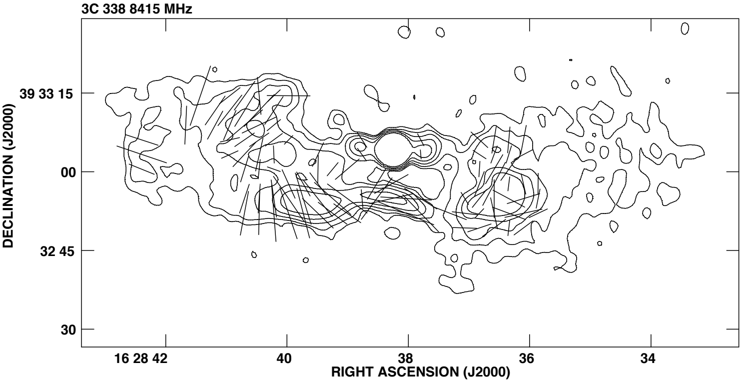
3C 338: the radio galaxy at the center of A2199



Vacca et al. (2012)

Polarization angle vs frequency

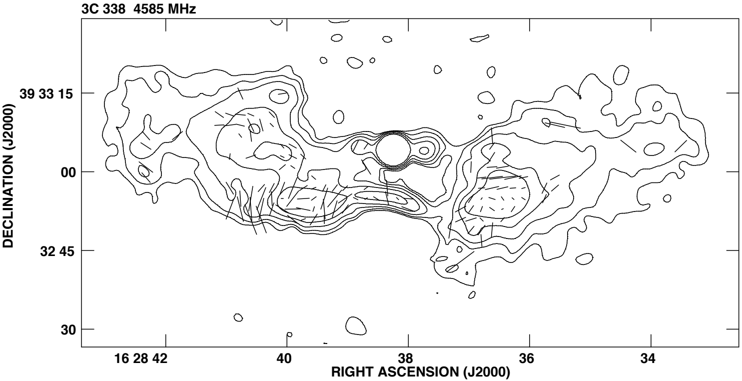
$$\Psi_{\rm obs} = \Psi_{\rm int} + \lambda^2 RM$$



$$FPOL = (41.7 \pm 0.6)\%$$

Polarization angle vs frequency

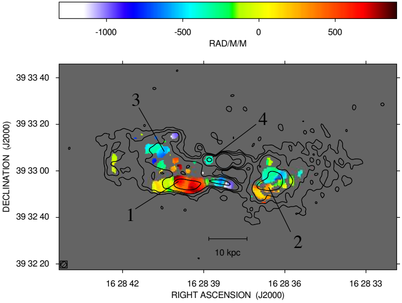
$$\Psi_{\text{obs}} = \Psi_{\text{int}} + \lambda^2 RM$$

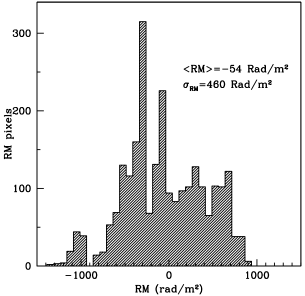


$$FPOL = (13.6 \pm 0.3)\%$$

Rotation measure image

$RM \propto \int_{\rm los} n_e(l) B_{\parallel} dl$ RESOLUTION=2.5″=1.5 kpc





$$\sigma^2_{\rm RM}(r_\perp) = \frac{K^2 B^2 \Lambda_{\rm C} n_0^2 r_{\rm c}}{\left(1+\frac{r_\perp^2}{r_{\rm C}}\right)^{\frac{6\beta-1}{2}}} \frac{\Gamma(3\beta - \frac{1}{2})}{\Gamma(3\beta)}$$

$$\Lambda_{\rm C} = \frac{3\pi}{2} \frac{\int_0^\infty |B_{\rm k}|^2 k dk}{\int_0^\infty |B_{\rm k}|^2 k^2 dk}$$

Felten (1996) Enßlin & Vogt (2003)

Simulations

FARADAY (Murgia et al. 2004)

- Gaussian random field magnetic field

$$|B_{\rm k}|^2 \propto k^{-{\rm n}}, \qquad \langle B(r)\rangle = \langle B_0\rangle \left(\frac{n_{\rm e}(r)}{n_{\rm e0}}\right)^{\eta}$$

- Thermal gas double β-model

$$n_{\rm e}(r) = n_{0,{\rm int}}\left[1+\left(\frac{r}{r_{\rm c,int}}\right)^2\right]^{-\frac{3}{2}\beta_{\rm int}} + n_{0,{\rm ext}}\left[1+\left(\frac{r}{r_{\rm c,ext}}\right)^2\right]^{-\frac{3}{2}\beta_{\rm ext}}$$

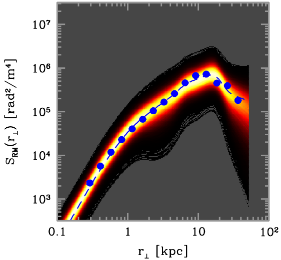
Bayes' Theorem

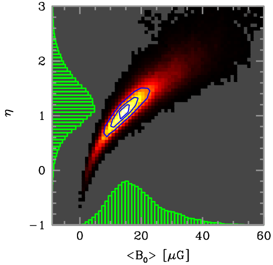
$$P(s|d) = \frac{P(d|s)P(s)}{P(d)}$$

where:

- $P(s|d)$ *posterior*
- $P(d|s)$ *likelihood*
- $P(s)$ *prior*
- $P(d) = \int \mathcal{D}s\, P(d|s)P(s)$ *evidence*

Observations vs simulations





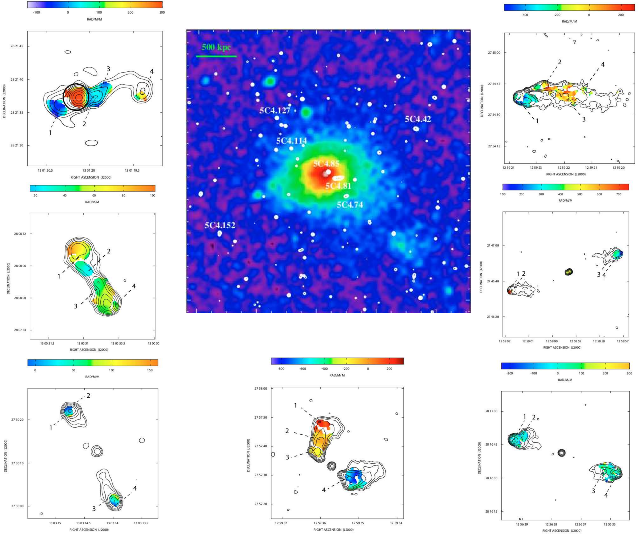
$$|B_\mathrm{k}|^2 \propto k^{-\mathrm{n}}, \qquad \langle B(r)\rangle = \langle B_0\rangle \left(\frac{n_\mathrm{e}(r)}{n_\mathrm{e0}}\right)^\eta$$

$$S_\mathrm{RM} = \left\langle |RM(r'_\perp) - RM(r'_\perp + r_\perp)|^2 \right\rangle_{\mathrm{r}'_\perp} =$$

$$= 2(\sigma^2_\mathrm{RM} + \langle RM\rangle^2) - A_\mathrm{n}\int_0^\infty J_0(kr_\perp)|B_\mathrm{k}|^2 k dk$$

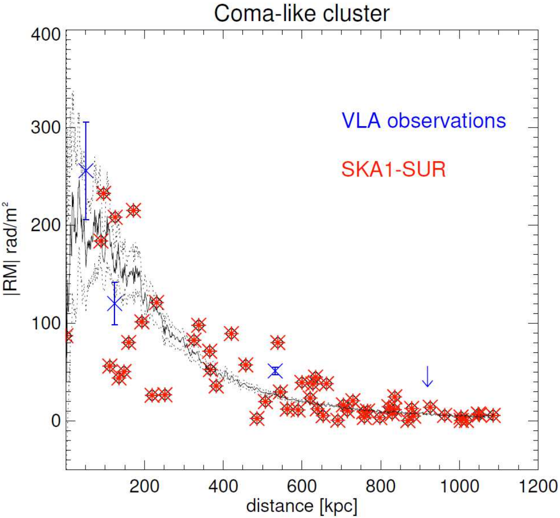
$$n = (2.8 \pm 1.3)$$
$$\Lambda_\mathrm{min} = (0.7 \pm 0.1)\,\mathrm{kpc}$$
$$\Lambda_\mathrm{max} = (35 \pm 18)\,\mathrm{kpc}$$
$$\eta = (0.9 \pm 0.5)$$
$$\langle B_0\rangle = (11.7 \pm 9.0)\,\mu\mathrm{G}$$

A1656-Coma



Bonafede et al. (2010), n=11/3, $\langle B_0 \rangle \simeq 4.7\,\mu$G, $\eta = 0.5$

A1656-Coma

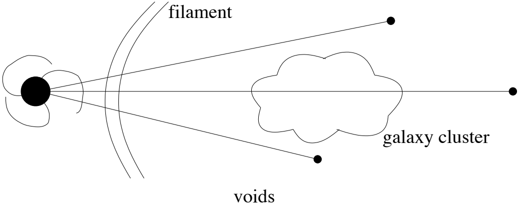


Bonafede et al. (2015)

PART III

Larger scales and statistical approaches

Faraday Depth

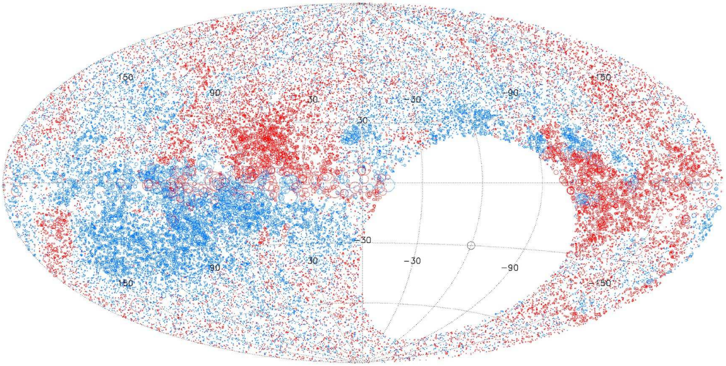


$$\phi_i = a_0 \int_0^{D_i} \mathrm{d}l \frac{n_\mathrm{e} B_\mathrm{l}}{(1+z)^2}$$

$$\phi_i = \phi_{\mathrm{g},i} + \phi_{\mathrm{e},i} + n_i$$

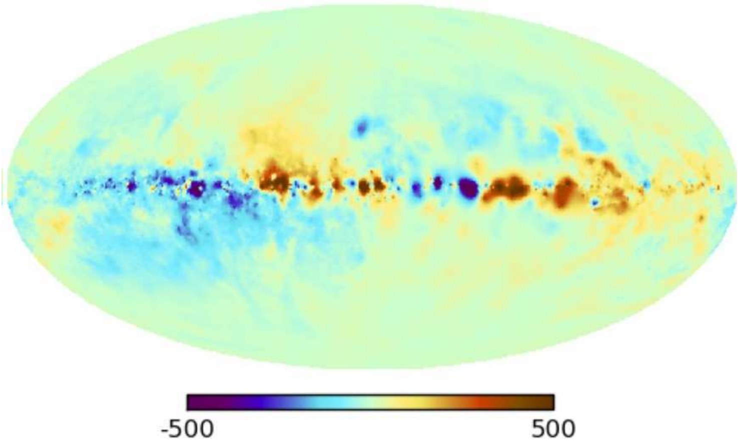
$$\phi_i = \phi_{\mathrm{g},i} + \phi_{\mathrm{intr},i} + \phi_{\mathrm{gc},i} + \phi_{\mathrm{f},i} + \phi_{\mathrm{v},i} + \phi_{\mathrm{s},i} + n_i$$

Observations



Taylor et al. (2009)
(+ Mao et al. 2008, Schnitzeler 2010, Fean et al. 2011, van Eck et al. 2011, etc...)

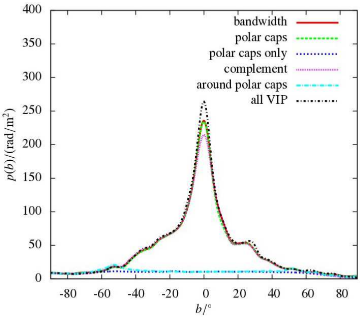
Galactic Foreground



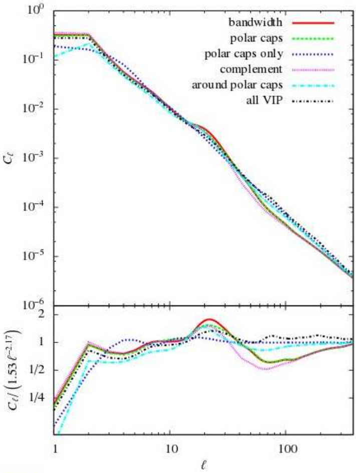
Oppermann et al. (2015)

Galactic Foreground

Latitude Profile



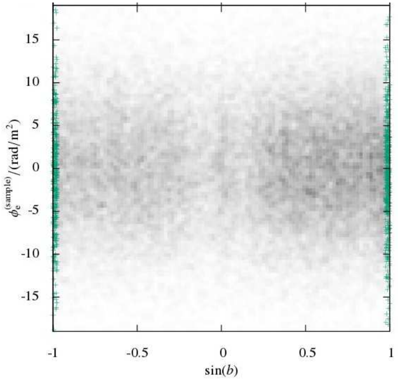
Power Spectrum

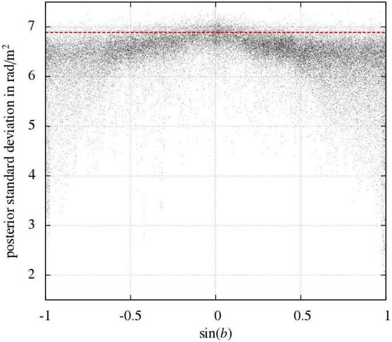


Oppermann et al. (2015)

Extragalactic Faraday depth

Oppermann et al. (2015)

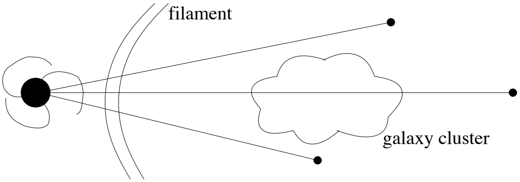




$\sigma_e \approx 7$ rad/m^2

See also Schnitzeler (2010), Dolag et al. (1999)

Approach



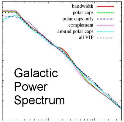
$$\phi_i = \phi_{\mathrm{g},i} + \phi_{\mathrm{e},i} + n_i$$

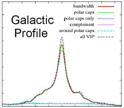
$$\langle \phi_{e,i}^2 \rangle \approx \sigma_{\mathrm{int},i}^2 + \sigma_{\mathrm{env},i}^2$$

$$\approx \left(\frac{L_i}{L_0}\right)^{\chi_{\mathrm{lum}}} \frac{\sigma_{\mathrm{int},0}^2}{(1+z_i)^4} + \frac{D(z_i, \chi_{\mathrm{red}})}{D_0} \sigma_{\mathrm{env},0}^2$$

Vacca et al. (arXiv:1509.00747)

Algorithm: Gibbs sampling





Faraday depth catalog

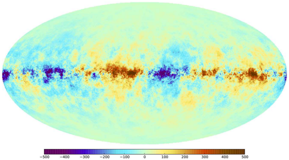
redshift z_i, luminosity L_i

↓

new prior $\sigma_e(z_i, L_i, \sigma_k, \chi_j)$

↑

$\sigma_{\text{int},0}, \sigma_{\text{env},0}, \chi_{\text{lum}}, \chi_{\text{red}}$

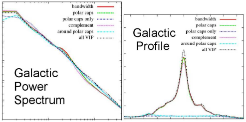


Oppermann et al.

$d_i = \phi_{\text{g},i} + \phi_{\text{e},i} + n_i$

$\phi_{\text{e},i}$ sample → Metropolis-Hasting sampling

Algorithm: Gibbs sampling



Faraday depth catalog

redshift z_i, luminosity L_i

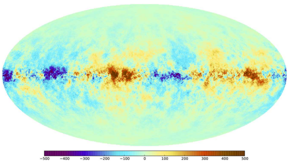
↓

new prior $\sigma_e(z_i, L_i, \sigma_k, \chi_j)$

↑

$\sigma_{\mathrm{int},0}, \sigma_{\mathrm{env},0}, \chi_{\mathrm{lum}}, \chi_{\mathrm{red}}$

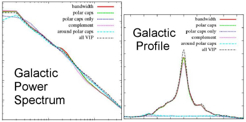
$\phi_{\mathrm{e},i}$ sample → Metropolis-Hasting sampling



Oppermann et al.

$d_i = \phi_{\mathrm{g},i} + \phi_{\mathrm{e},i} + n_i$

Algorithm: Gibbs sampling



Faraday depth catalog

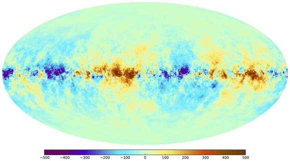
redshift z_i, luminosity L_i

new prior $\sigma_e(z_i, L_i, \sigma_k, \chi_j)$

$\sigma_{\mathrm{int},0}, \sigma_{\mathrm{env},0}, \chi_{\mathrm{lum}}, \chi_{\mathrm{red}}$

$\phi_{\mathrm{e},i}$ sample

Metropolis-Hasting sampling



Oppermann et al.

$d_i = \phi_{\mathrm{g},i} + \phi_{\mathrm{e},i} + n_i$

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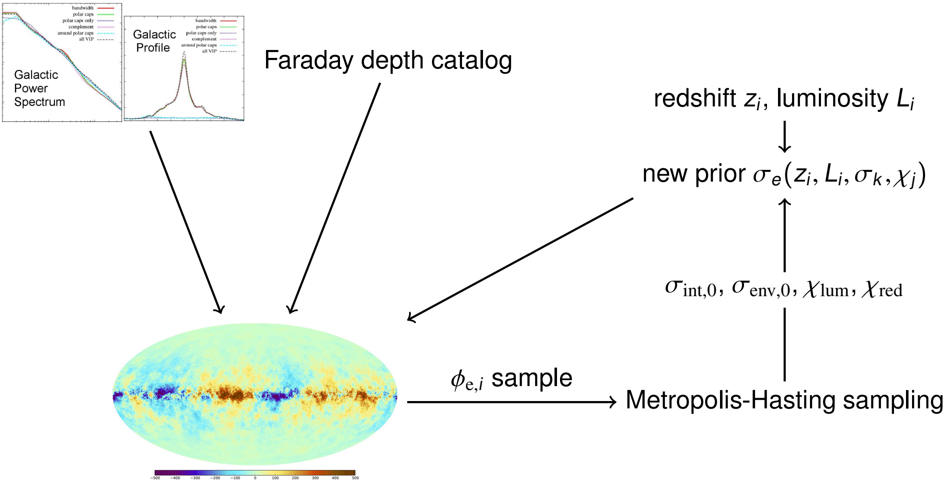
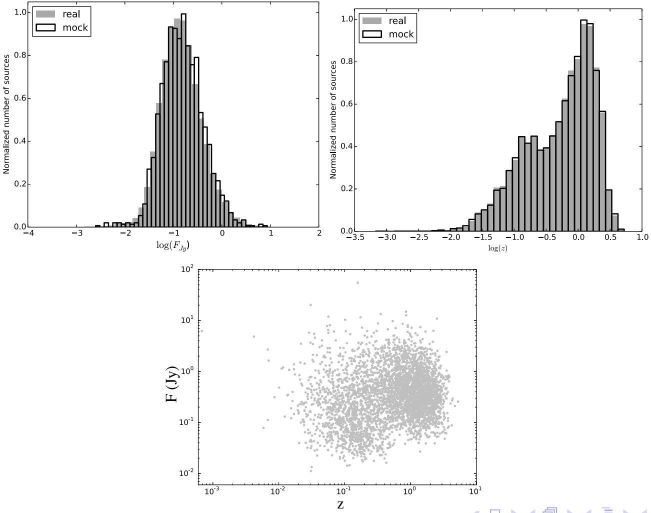


Oppermann et al.

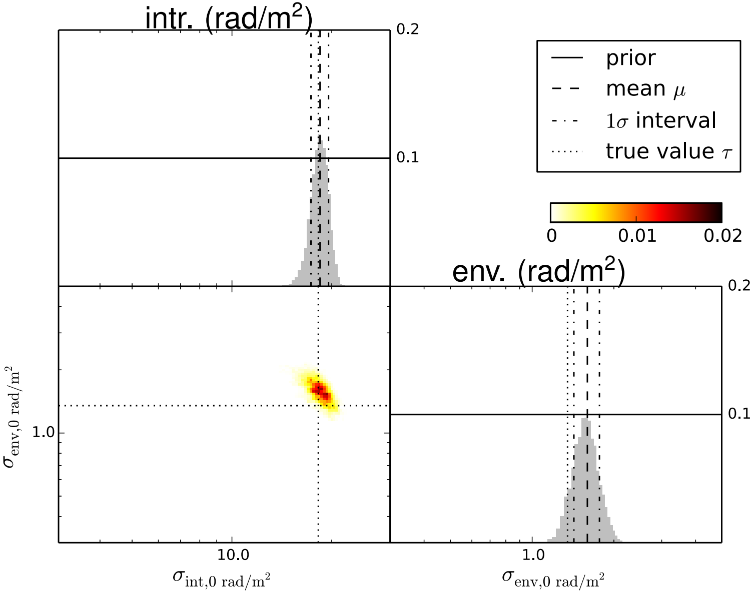
$$d_i = \phi_{\mathrm{g},i} + \phi_{\mathrm{e},i} + n_i$$

Tests

$$\langle \phi^2_{\mathrm{e},i} \rangle = \left(\frac{L_i}{L_0}\right)^{\chi_{\mathrm{lum}}} \frac{\sigma^2_{\mathrm{int},0}}{(1+z_i)^4} + \frac{D_i(z_i,\chi_{\mathrm{red}})}{D_0}\sigma^2_{\mathrm{env},0} \approx (7\,\mathrm{rad/m^2})^2$$

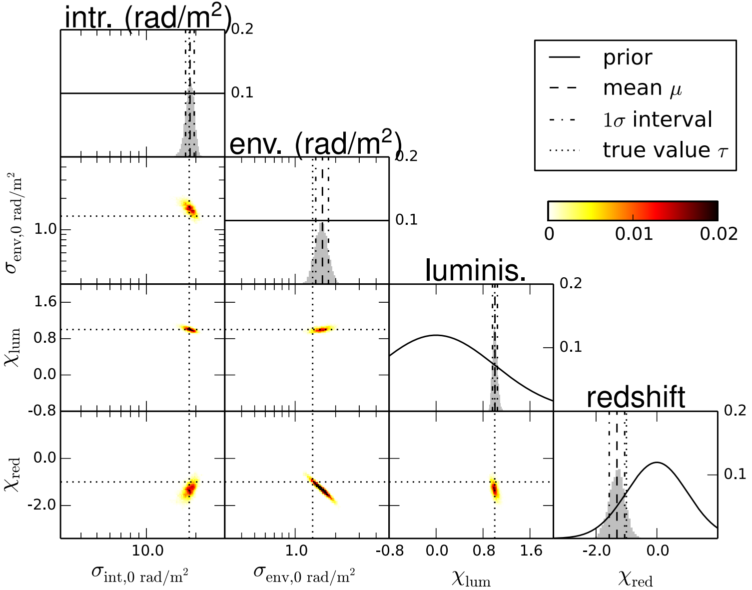


$$\langle \phi_{e,i}^2 \rangle = \left(\frac{L_i}{L_0}\right)^{\chi_\mathrm{lum}} \frac{\sigma_{\mathrm{int},0}^2}{(1+z_i)^4} + \frac{D_i(z_i,\chi_\mathrm{red})}{D_0}\sigma_{\mathrm{env},0}^2 \approx (7\,\mathrm{rad/m^2})^2$$



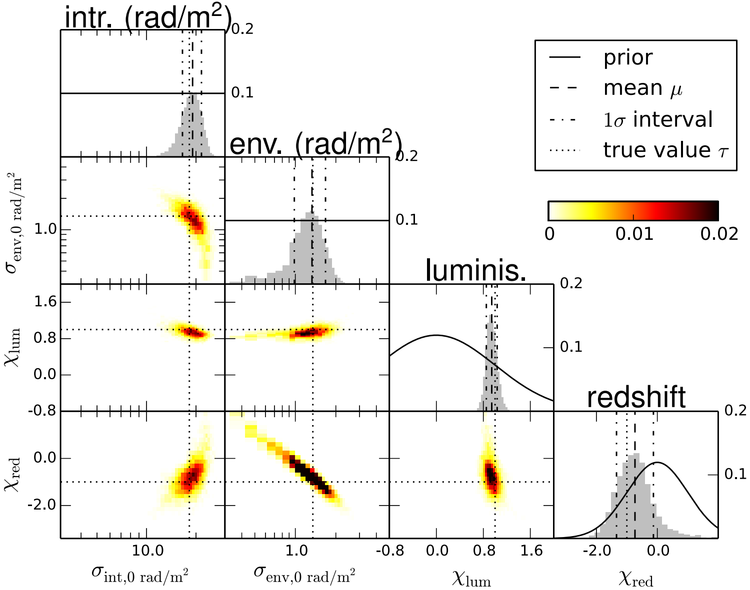
Test: 40000 sources

$$\langle \phi_{e,i}^2 \rangle = \left(\frac{L_i}{L_0}\right)^{\chi_{\rm lum}} \frac{\sigma_{\rm int,0}^2}{(1+z_i)^4} + \frac{D_i(z_i,\chi_{\rm red})}{D_0}\sigma_{\rm env,0}^2 \approx (7\,{\rm rad/m^2})^2$$



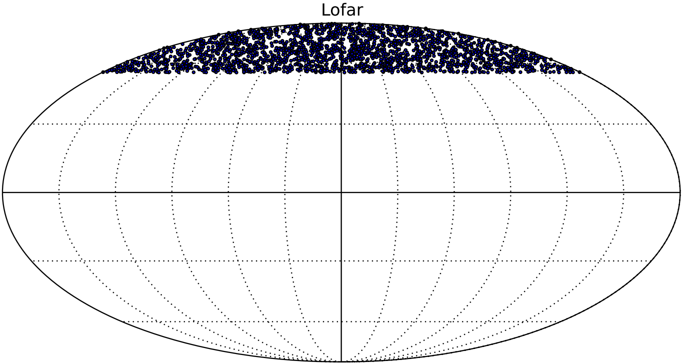
Test: 40000 sources

$$\langle \phi_{\mathrm{e},i}^2 \rangle = \left(\frac{L_i}{L_0}\right)^{\chi_{\mathrm{lum}}} \frac{\sigma_{\mathrm{int},0}^2}{(1+z_i)^4} + \frac{D_i(z_i,\chi_{\mathrm{red}})}{D_0}\sigma_{\mathrm{env},0}^2 \approx (7\,\mathrm{rad/m}^2)^2$$



Test: 4000 sources

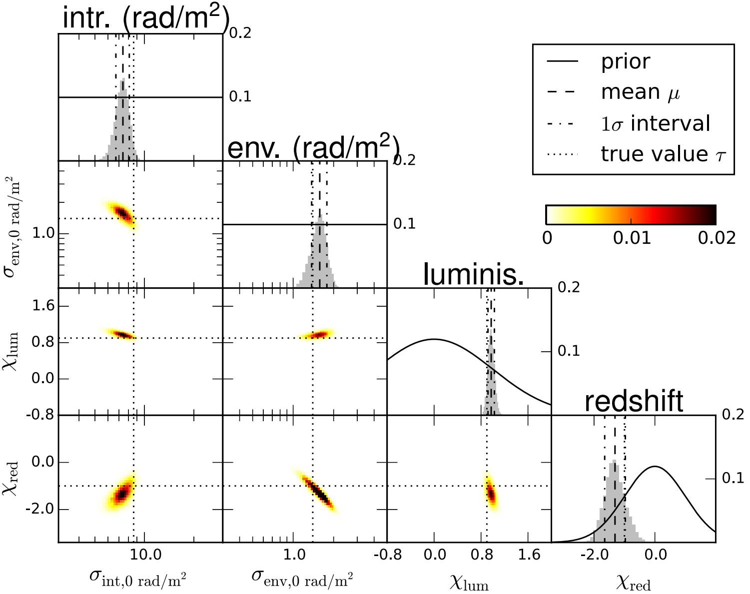
LOFAR HBA 120-160 MHz



1 p. s. / 1.7 deg^2, 8 h (Mulcahy et al. 2014), $b > 55$ deg

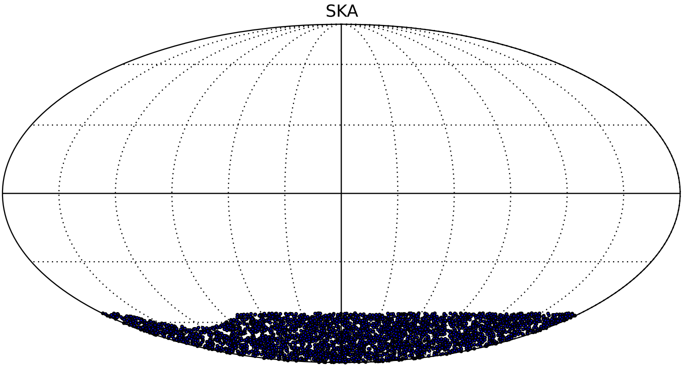
$N_{\rm sources} \sim 2200$

$$\langle \phi_{e,i}^2 \rangle = \left(\frac{L_i}{L_0}\right)^{\chi_{\rm lum}} \frac{\sigma_{\rm int,0}^2}{(1+z_i)^4} + \frac{D_i(z_i,\chi_{\rm red})}{D_0}\sigma_{\rm env,0}^2 \approx (7\,{\rm rad/m^2})^2$$



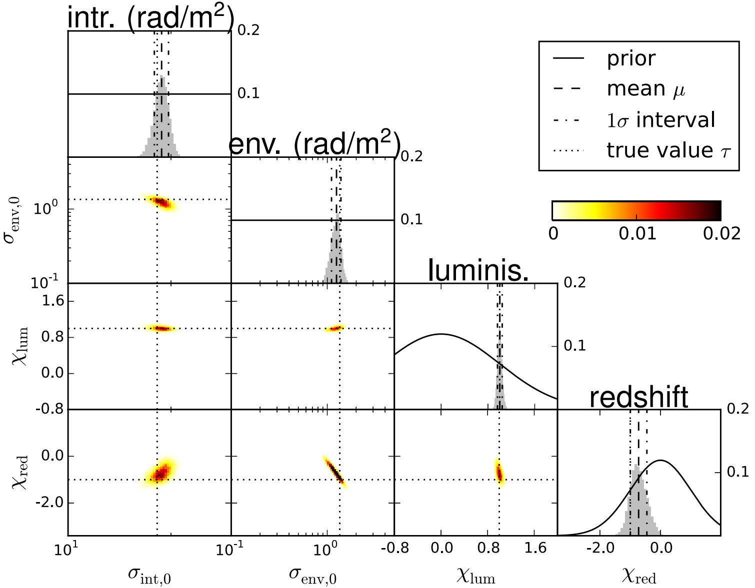
LOFAR HBA 120–160 MHz

SKA MID 0.95–1.76 GHz



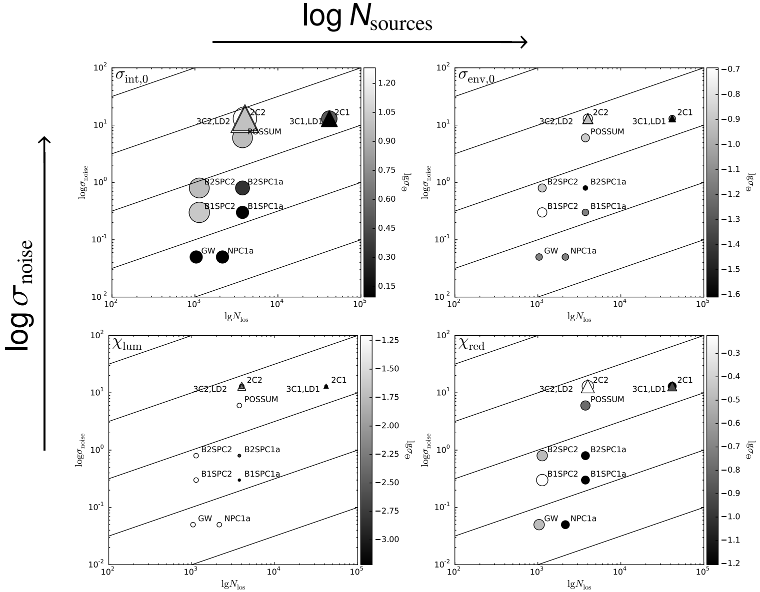
1 p. s. / 1.deg^2, $b < -55$ deg, $N_{\mathrm{sources}} \sim 3500$

$$\langle \phi^2_{e,i} \rangle = \left(\frac{L_i}{L_0}\right)^{\chi_{\rm lum}} \frac{\sigma^2_{\rm int,0}}{(1+z_i)^4} + \frac{D_i(z_i,\chi_{\rm red})}{D_0}\sigma^2_{\rm env,0} \approx (7\,{\rm rad/m^2})^2$$



SKA 0.95–1.76 GHz

Noise vs # Sources, 7 rad/m^2



Strengths

$$\sigma_{\rm e} \sim 7\,\text{rad/m}^2$$

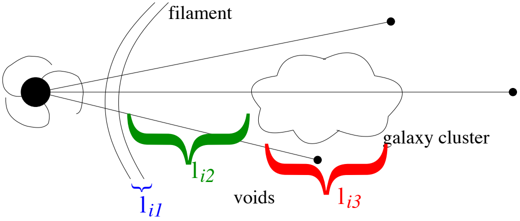
- Radio emitting source (L size of the source)

$$\frac{\sqrt{\langle B_{ox}^2 \rangle}}{\mu\mathrm{G}} \sim 0.5 \div 1 \left(\frac{n_0}{10^{-3}\,\mathrm{cm}^{-3}}\right)^{-1} \left(\frac{\Lambda_{0x}}{5\,\mathrm{kpc}}\right)^{-1} \left(\frac{L}{100\,\mathrm{kpc}}\right)^{-1}$$

- Large scale structure

$$\frac{\sqrt{\langle B_{ox}^2 \rangle}}{\mathrm{nG}} \sim 2 \left(\frac{n_0}{10^{-5}\,\mathrm{cm}^{-3}}\right)^{-1} \left(\frac{\Lambda_{0x}}{5\,\mathrm{Mpc}}\right)^{-1}$$

Further disentagling

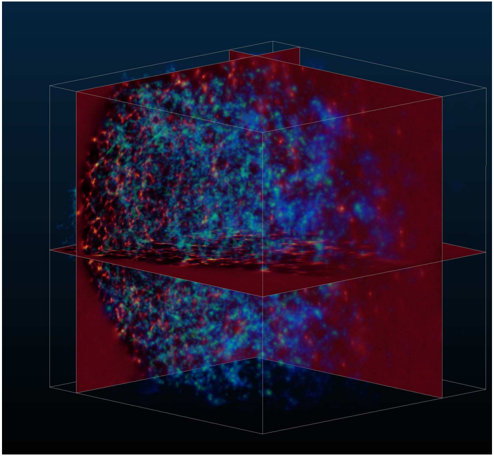


$$\langle \phi_{e,i}^2 \rangle \approx \left[\left(\frac{L_i}{L_0} \right)^{\chi_{\rm lum}} \frac{\sigma_{\rm int,0}^2}{(1+z_i)^4} + \sum_{j=1}^{N_{\rm env}} l_{ij} \sigma_j^2 \right]$$

$$\approx \left[\left(\frac{L_i}{L_0} \right)^{\chi_{\rm lum}} \frac{\sigma_{\rm int,0}^2}{(1+z_i)^4} + l_{i1}\sigma_1^2 + l_{i2}\sigma_2^2 + l_{i3}\sigma_3^2 + l_{i4}\sigma_4^2 + l_{i5}\sigma_5^2 \right]$$

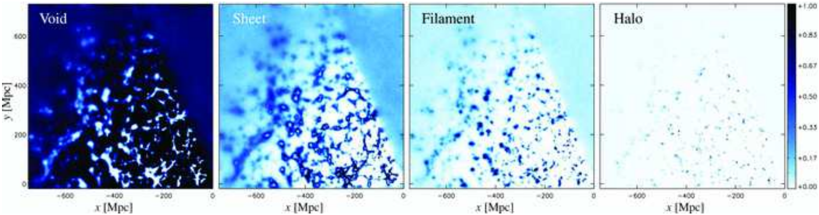
Vacca et al. (2015)

Cosmic web reconstruction



Jasche et al. (2010), see also Leclercq et al. (2015)

Cosmic web classification



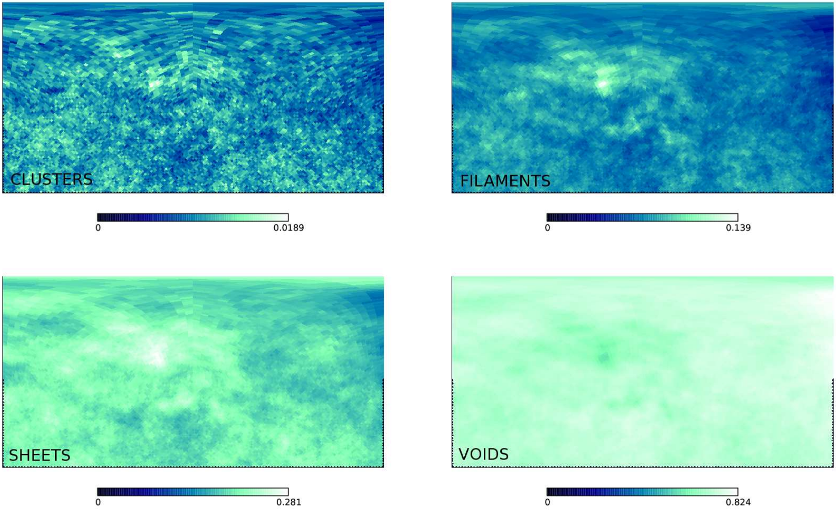
Jasche et al. (2010)

$$\langle \phi^2_{\mathrm{e},i} \rangle \approx \left[\left(\frac{L_i}{L_0} \right)^{\chi_{\mathrm{lum}}} \frac{\sigma^2_{\mathrm{int},0}}{(1+z_i)^4} + \sum_{j=1}^{N_{\mathrm{env}}} l_{ij} \sigma_j^2 \right]$$

Cosmic web structure, redshift catalog → length matrix l_{ij}

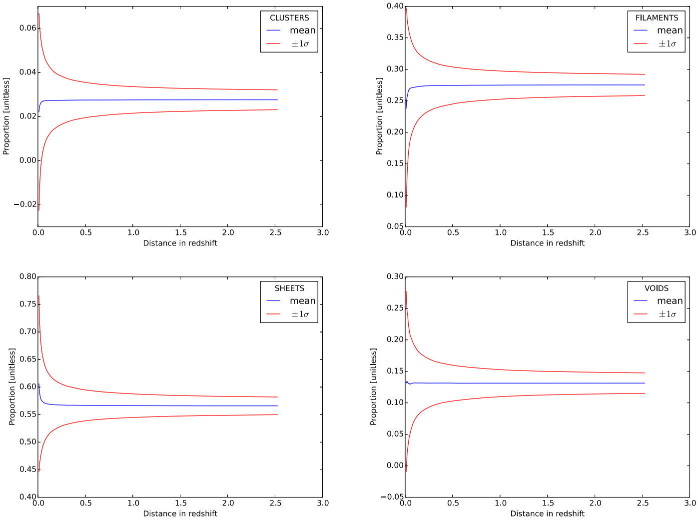
Cosmic web classification

Dupont et al. in preparation



High redshift sources

Dupont et al. in preparation



Summary and conclusions

- ICM magnetic fields can be studied through diffuse radio halo emission and Faraday effect on the signal from radio galaxies;
- Statistically disentangling eg magnetic fields requires: good knowledge of redshift, low observational uncertainty, high number of sources;
- Deriving magnetic fields in different extragalactic enviroments requires the analysis of a sample of sources from the local Universe.

THANK YOU!