The redshift evolution of extragalactic magnetic fields

26.01.2023 Bologna

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https://arxiv.org/abs/2208.01336

Source: ESA

Motivation

- Through its evolution, try to understand origin of cosmic MF

X Dynamo X Primordial X Astrophysical X Combi X Other

→Cosmological simulations already tell us there's a specific morphology, strength and evolution of the MF for each of these cases: *Which one will data single out?*

Our approach to this question:

- **Faraday Rotation Measure (RM) method**: probe along entire LoS, not just at places of particle acceleration (synchrotron radiation methods)

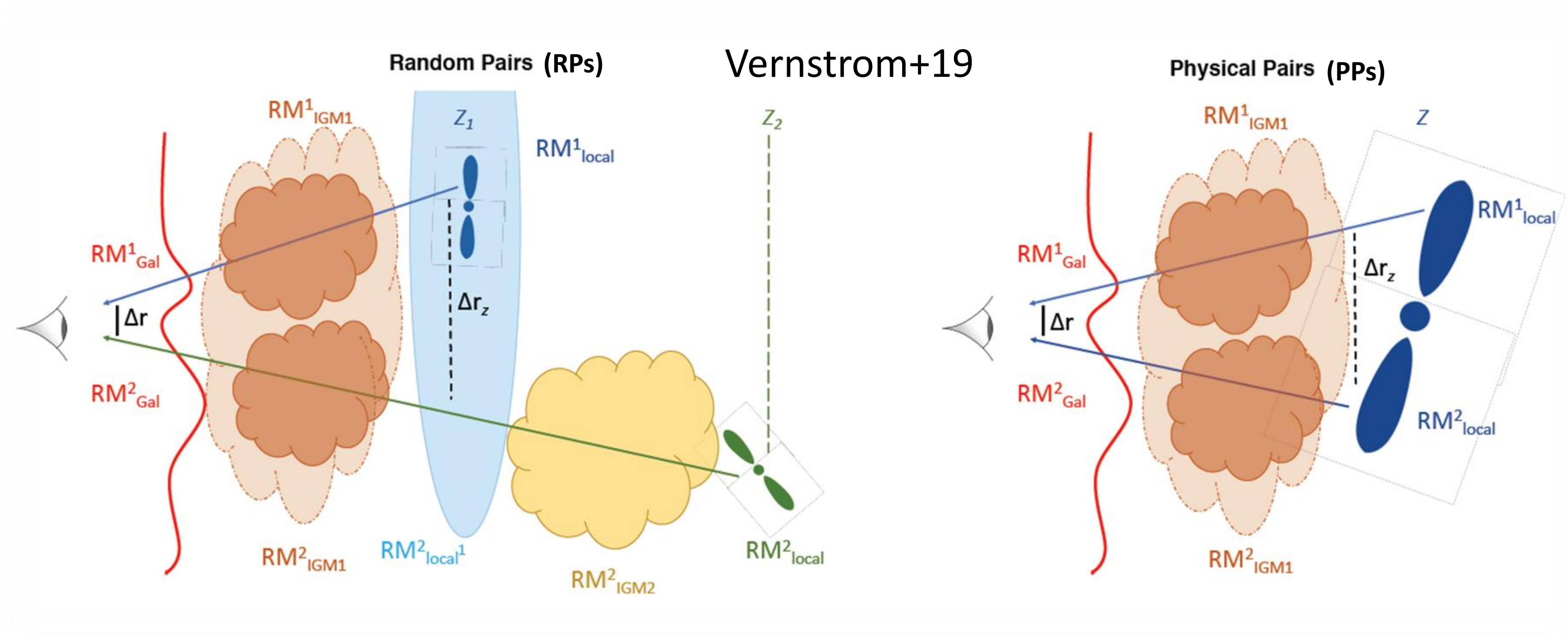
- **MC simulations**: middle-ground between (semi-)analytical approaches and cosmological simulations

The RM and its contributions

$$\mathrm{RM}_{[\mathrm{rad\,m^{-2}}]} = 0.812 \int_{z_s}^{0} \frac{n_{\mathrm{e}\,[\mathrm{cm^{-3}}]}\, B_{\parallel\,[\mu\mathrm{G}]}}{(1+z)^2} \frac{\mathrm{d}l_{[\mathrm{pc}]}}{\mathrm{d}z}\,\mathrm{d}z$$

- $RM = GRM + RM_{IGM} + RM_{local}$

$|\Delta \boldsymbol{RM}| = |\Delta GRM + \Delta RM_{IGM} + \Delta RM_{local}|$



Motivation for RM **pair** analysis: minimize GRM

Carretti+22 and 23: complementary work using single-source analysis

Observational Data

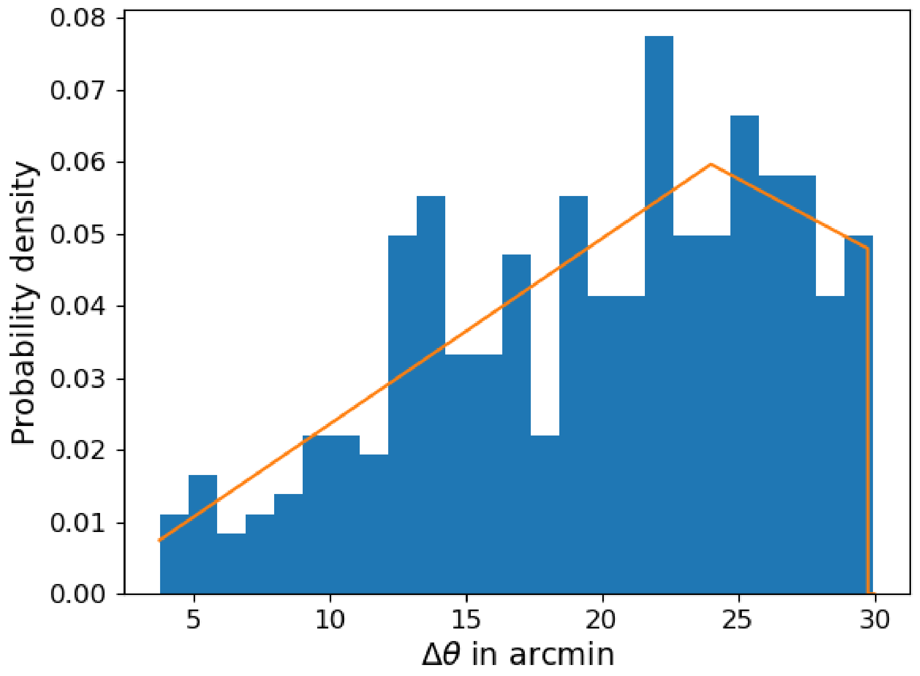
Raw data: (for more details see O'Sullivan et al. 2023, https://arxiv.org/abs/2301.07697v1)

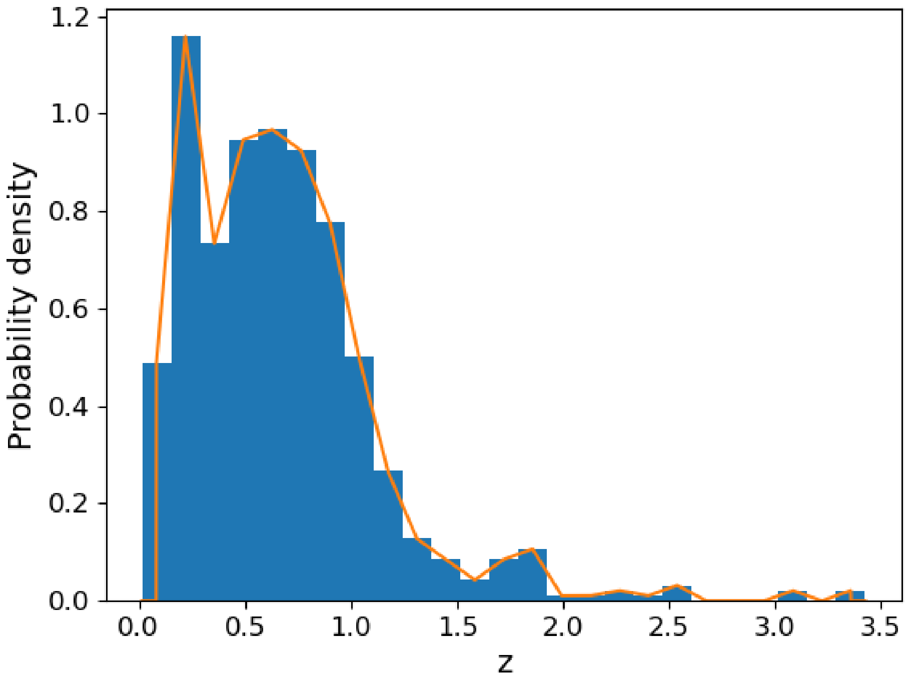
- RM Grid catalogue derived from LoTSS DR2

RM pair data:

- Cross-match RM grid catalogue with itself to get pairs with a $\Delta\theta_{max} = 30$ arcmin
- Final sample:

- 345 RPs with redshift for both sources
- 168 PPs with host galaxy redshift (control sample)





Methodology of data analysis

- Main quantity of interest: $|\Delta RM| = |RM_1 - RM_2|$.
- Use medians and a bootstrap uncertainty rather than mean and std

Redshift analysis:

- Evaluate dependence of random pairs' $|\Delta RM|$ in 10 bins in
  - $z_<$
  - $\Delta z = z_< - z_<$ → Focus on this here

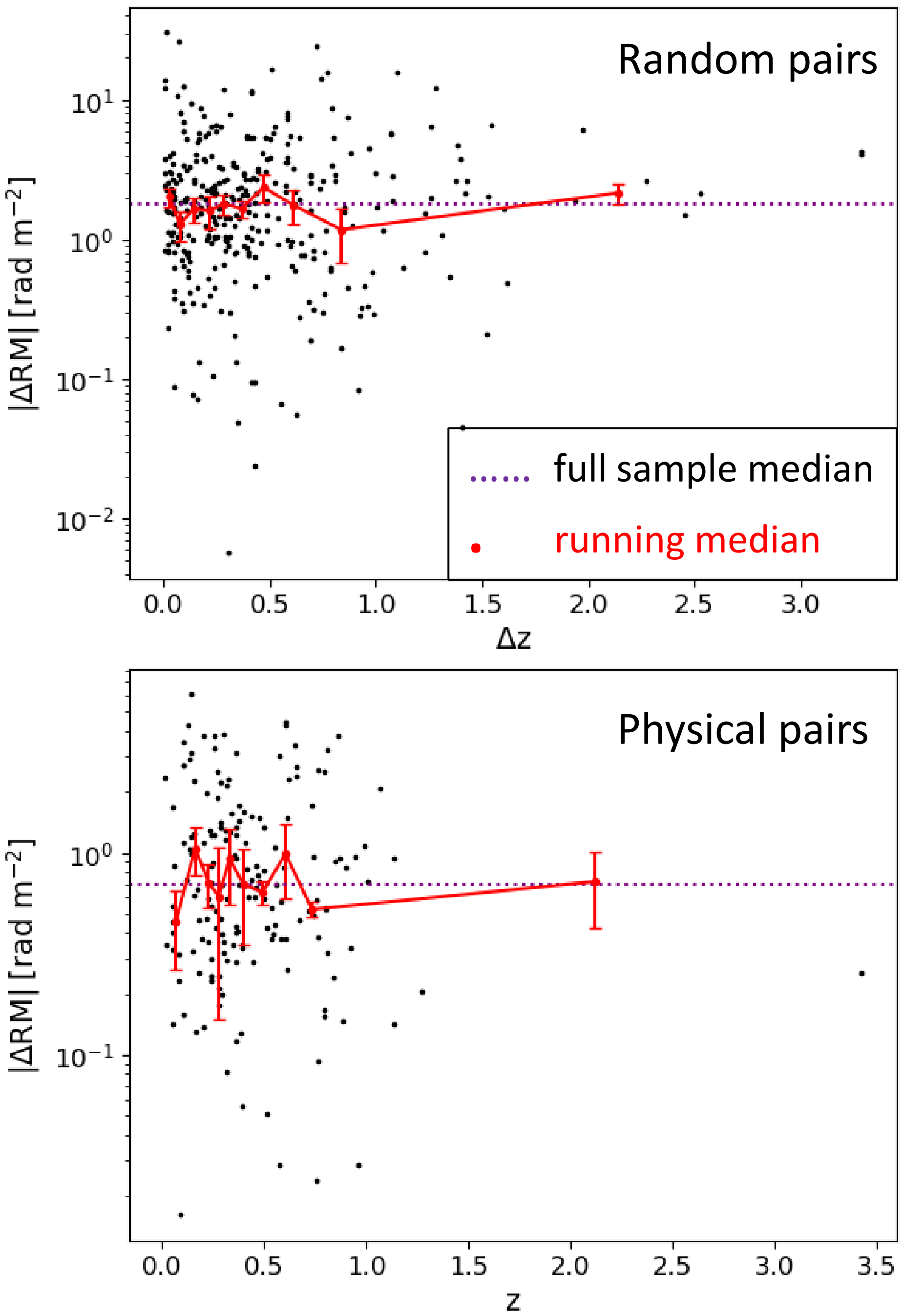
Results from data analysis

$$|\Delta RM|_{RP} = (1.79 \ \pm 0.09) \text{ rad } m^{-2}$$
$$|\Delta RM|_{PP} = (0.70 \ \pm 0.08) \text{ rad } m^{-2}$$

Remove local contributions by taking the *excess median* of RPs over PPs:

$$|\Delta RM|_{ex} = (|\Delta RM|^2_{med,\,RPs} - |\Delta RM|^2_{med,\,PPs})^{\,1/2}$$
$$|\Delta RM|_{ex} = (1.65 \ \pm 0.10) \text{ rad } m^{-2}$$

→ This is an estimate of the IGM contribution



Implications of a flat $|\Delta RM(\mathrm{z})|$

$$\mathrm{RM}_{[\mathrm{rad\,m^{-2}}]} = 0.812 \int_{z_s}^{0} \frac{n_{\mathrm{e}\,[\mathrm{cm^{-3}}]} B_{\parallel\,[\mu\mathrm{G}]}}{(1+z)^2} \frac{\mathrm{d}l_{[\mathrm{pc}]}}{\mathrm{d}z} \mathrm{d}z$$

- For this to be flat with redshift, the mean **comoving** intergalactic field must evolve with redshift, ansatz power law: $\boldsymbol{B_0(z) = B_0(1+z)^{-\gamma}}$
- Test this in MC simulations:

Monte-Carlo simulations

$$\mathrm{RM}_{[\mathrm{rad\,m^{-2}}]} = 0.812 \int_{z_s}^{0} \frac{n_{\mathrm{e}\,[\mathrm{cm^{-3}}]}\, B_{\parallel\,[\mu\mathrm{G}]}}{(1+z)^2} \frac{\mathrm{d}l_{[\mathrm{pc}]}}{\mathrm{d}z}\, \mathrm{d}z$$

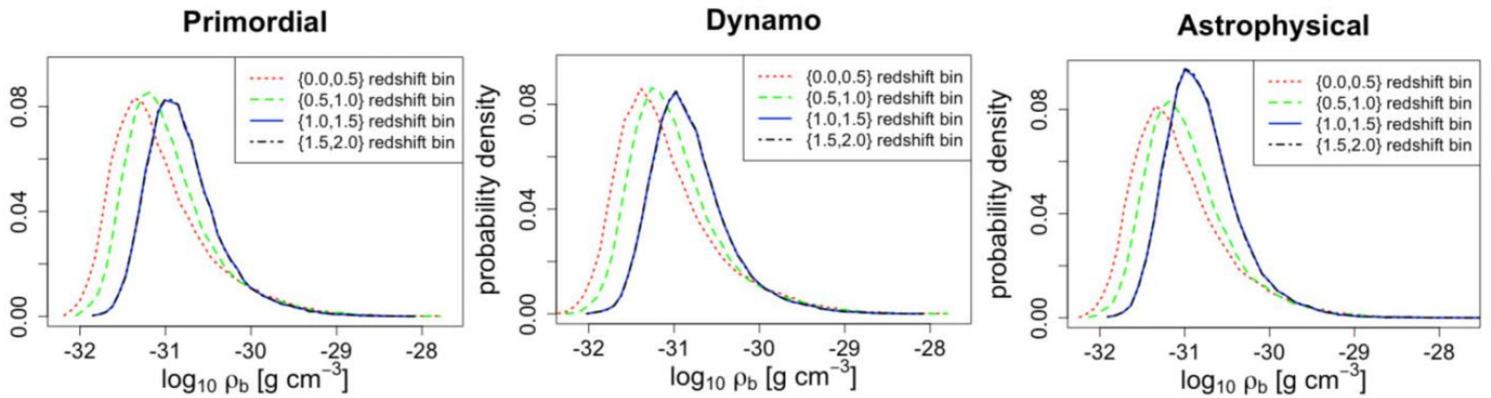
- Sim **only IGM** contribution of **10 000** RPs

Parameter	Explored values	Effect on RM
B_0	$\{0.5, 1.0, 1.5, 2.0\}$ nG	$\mathrm{RM} \propto B_0$
l_0	$\{0.1, 1, 10, 100\}$	$\mathrm{RM} \propto l_0^{1/2}$
γ	$\{1.5(0.5)5.0\}$	$\mathrm{RM} \propto (1+z_s)^{1.5-\gamma}$ for $\gamma \neq 1.5$
		$\mathrm{RM} \propto \ln(1+z_s)$ for $\gamma = 1.5$
dd	*prim*, *dyn*, *astro*	

- The **ingredients** for simulating RM pairs
- z-values (draw from observed distribution)
- comoving n_e-values (draw from cosmo sims of Vazza+17)
- $\mathrm{B(z)} = B_0(z)(n_e/n_{ref})^{2/3}$ and then **evolve** the **comoving field** as

$$\boldsymbol{B_0(z) = B_0(1+z)^{-\gamma}}$$

- Change MF orientation every coherence length $L_c = l_0 \Delta l$



Results from comparing sims and data

- Use a maximum-likelihood method, see table
- Overall preference for *dyn*, higher γ and higher B_0 and/or l_0
- Overall good fit:
  - Overall flat
  - 1σ difference between sim and data's total median
- Preference for higher γ values, coupled with higher B_0 and/or l_0 , seeks to ensure flatness while also avoiding too great a suppression of the median

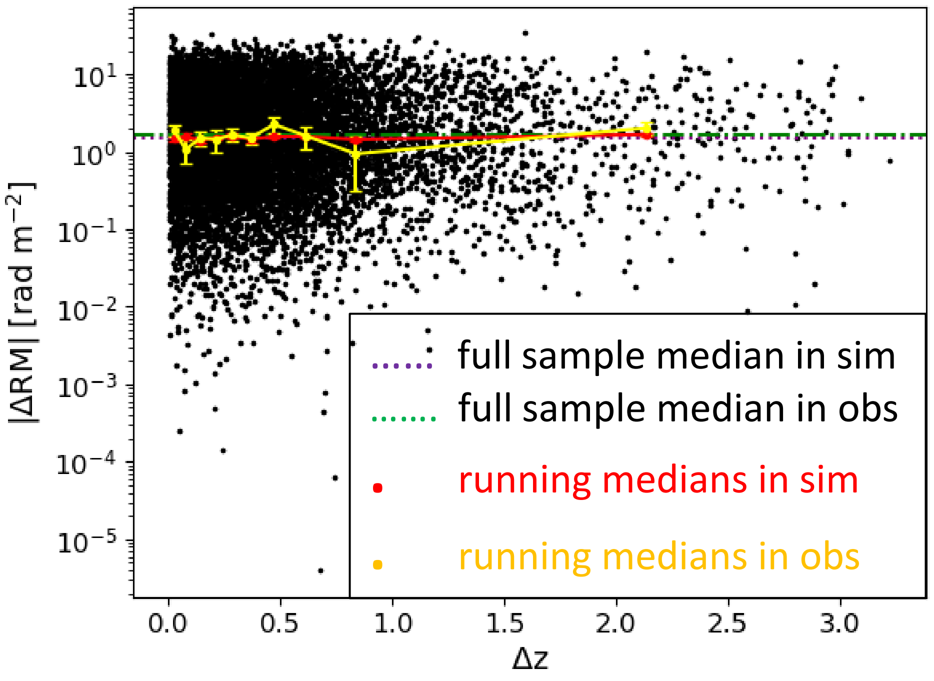
→Compensation effects between parameters ☹

→Quote results as upper limits: $\boldsymbol{B_0} \lesssim (\mathbf{2.0} \ \pm \mathbf{0.2})$ nG and $\boldsymbol{\gamma} \lesssim \mathbf{4.5} \ \pm \mathbf{0.2}$

$\boldsymbol{B_0(z) = B_0(1+z)^{-\gamma}}$ → higher gamma reduces RM more for big z than for small z → FLAT RM

Model: | dd | B_0/nG | l_0 | γ |	$\|\Delta\mathrm{RM}\|_{\mathrm{med}}$ [rad m^{-2}]	$\log P(d\|m)$
D1: | dyn | 2.0 | 0.1 | 4.5 |	1.52 ± 0.03	-7.86
P1: | prim | 1.0 | 10 | 4.5 |	1.62 ± 0.03	-8.03
P2: | prim | 0.5 | 100 | 2.5 |	1.42 ± 0.03	-8.35
D2: | dyn | 2.0 | 1 | 4.5 |	1.48 ± 0.03	-8.84
A1: | astro | 2.0 | 10 | 3.0 |	1.57 ± 0.03	-8.93

Data: $|\Delta RM|_{ex} = (1.65 \ \pm 0.10)$ rad m^{-2}



Implications for magnetogenesis

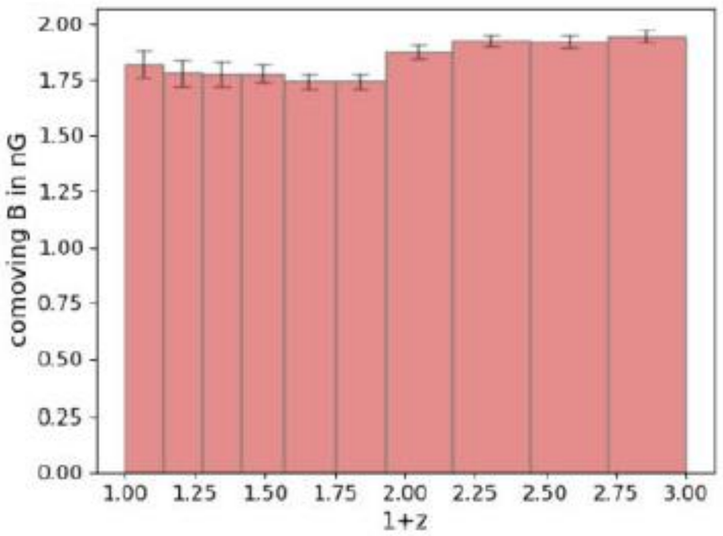
- Use Vazza+17's cosmological sims again
- If we take our parameters to be at the upper limits we derived: $\boldsymbol{B_0 = 2.0}$ nG and $\boldsymbol{\gamma = 4.5}$
- At z=2 comoving MF value has dropped to 0.01 nG

→Uniform primordial seed fields disfavored

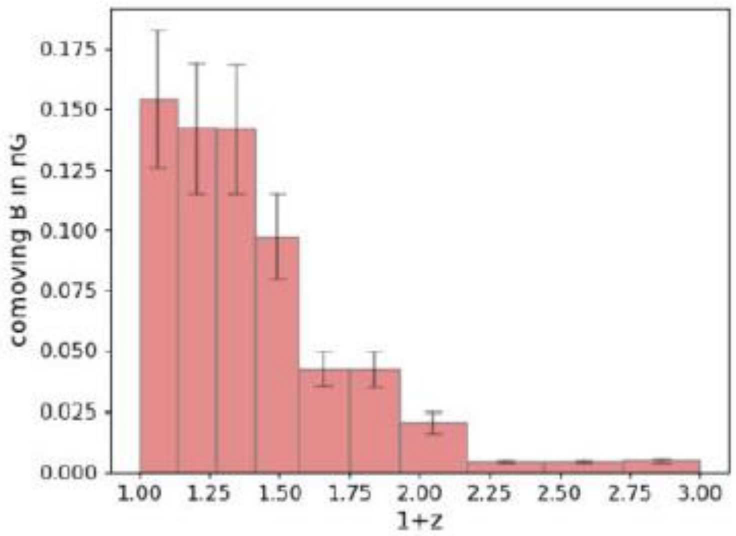
Table 6. Results for γ averaged over 100 LoSs for each magnetogenesis model in cosmological simulations (Vazza et al. 2017).

Model	γ
Primordial	-0.26 ± 0.02
Dynamo	4.18 ± 0.11
Astrophysical	2.32 ± 0.16

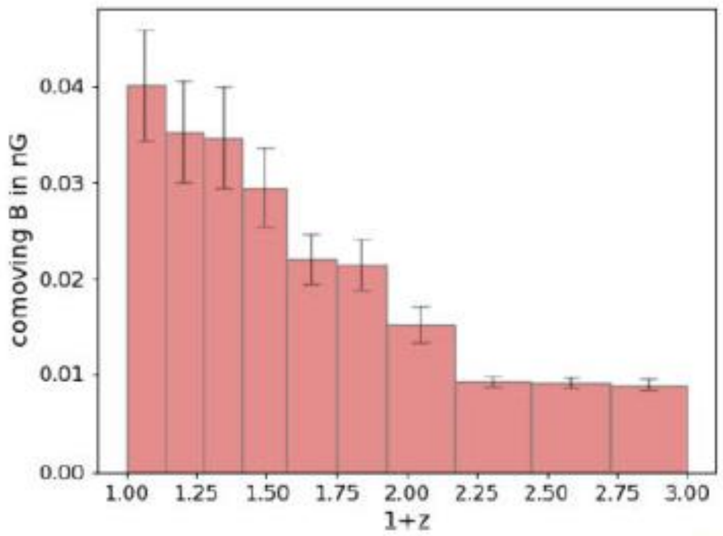
prim



dyn



astro



Summary and Lessons Learned

- $|\Delta RM|$ flat w.r.t. $z_<$ and Δz
- $|\Delta RM|_{ex} = (1.65 \ \pm 0.10)$ rad m^{-2} to remove local contributions

as much as possible

- $\boldsymbol{B_0} \lesssim (\mathbf{2.0} \ \pm \mathbf{0.2})$ nG and $\boldsymbol{\gamma} \lesssim \mathbf{4.5} \ \pm \mathbf{0.2}$
- Uniform primordial model as taken from cosmo sims. disfavored

Other models to consider:

- primordial with tangled, turbulent fields

- combined models, e.g. primordial + dynamo

Thank you!

The redshift evolution of intergalactic magnetic fields

https://arxiv.org/abs/2208.01336

Questions?

Results from data analysis

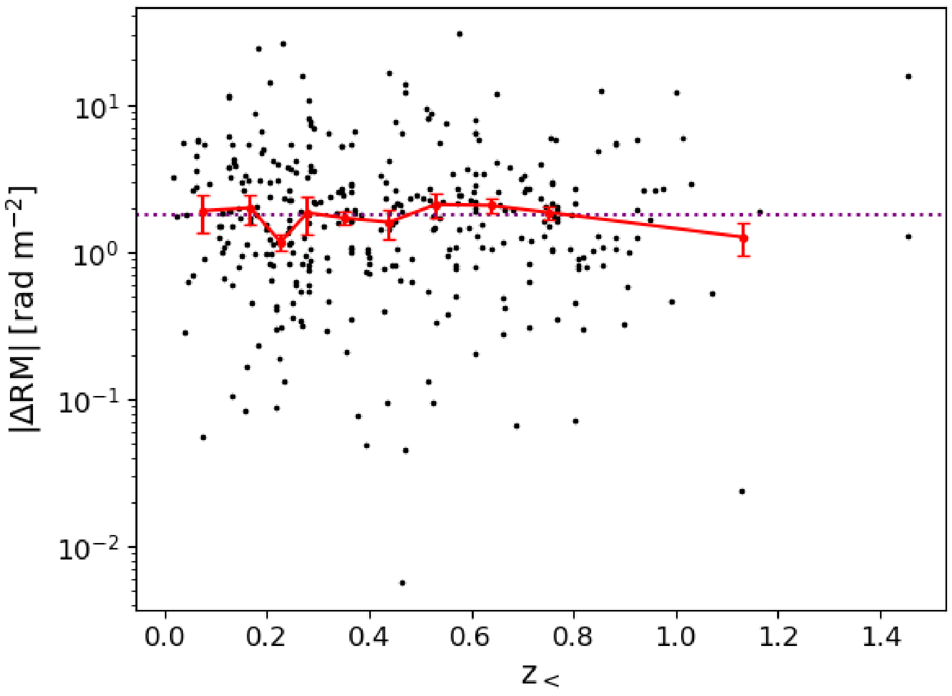
Table 2. Median $|\Delta\mathrm{RM}|_{\mathrm{med}}$ in units of (rad m^{-2}) for the entire sample of RPs and PPs before and after the foreground subtraction. The uncertainty is estimated by bootstrapping.

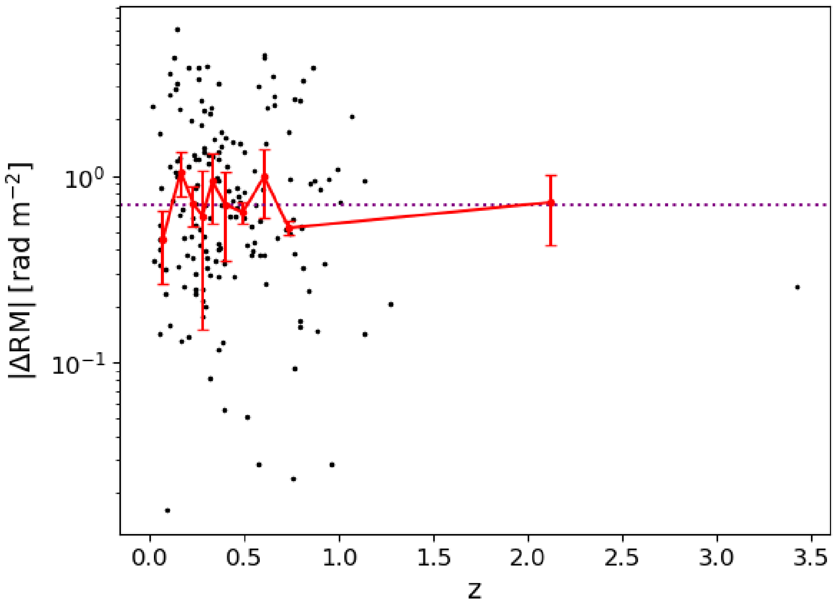
	RPs before	RPs after	PPs before	PPs after
$\lvert\Delta\mathrm{RM}\rvert_{\mathrm{med}}$	2.17 ± 0.15	1.79 ± 0.09	0.68 ± 0.06	0.70 ± 0.08

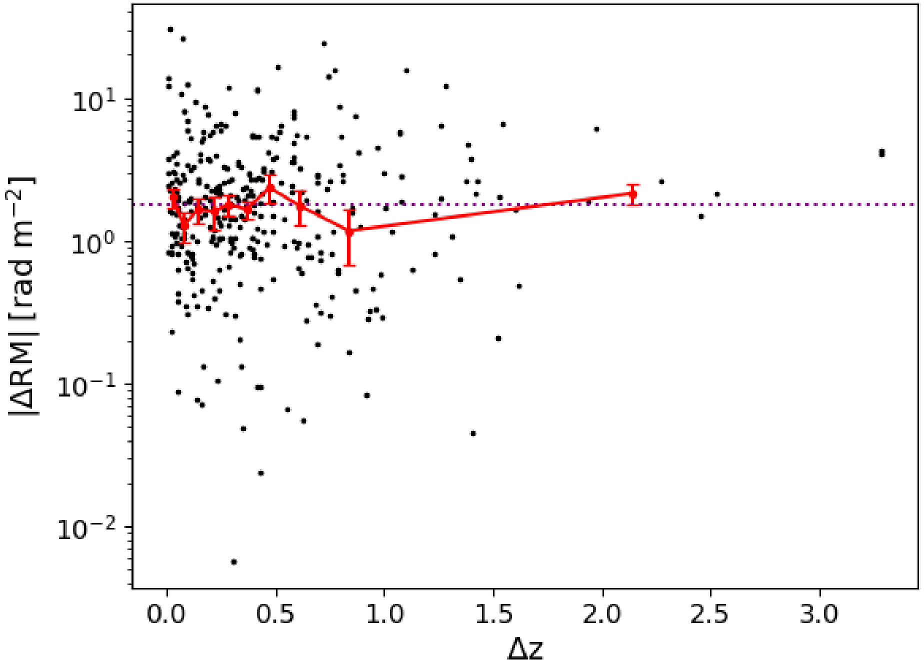
Make sure local contributions are removed:

$$|\Delta RM|_{ex} = (|\Delta RM|^2_{med,\,RPs} - |\Delta RM|^2_{med,\,PPs})^{1/2}$$

$$|\Delta RM|_{ex} = (1.65 \pm 0.10)\ \mathrm{rad}\ m^{-2}$$







Assessing agreement between sims and data: Maximum log-likelihood

We want to compare sims to the *excess* of RPs over PPs in the data:

- Compute $|\Delta RM|_{ex}$ bin-wise in the data for both z-spaces
- Divide both simulated z-spaces into the same 10 bins as data
- Compute $|\Delta RM|$ bin-wise in the simulations
- Build the bin-wise likelihood function

$$P_i(d|m) = \frac{1}{2\pi\,\sigma_{a_{\mathrm{tot,i}}}\sigma_{b_{\mathrm{tot,i}}}}\exp\left(-\frac{(a_{\mathrm{d,i}}-a_{\mathrm{m,i}})^2}{2\sigma^2_{a_{\mathrm{tot,i}}}}-\frac{(b_{\mathrm{d,i}}-b_{\mathrm{m,i}})^2}{2\sigma^2_{b_{\mathrm{tot,i}}}}\right),$$

- Build product of the 10x P_i
- Take log and select model with the highest $logP$

Results from comparing sims and data

- Use a maximum-likelihood method
- Overall preference for *dyn*, higher γ and higher B_0 and/or l_0
- Overall good fit:

- Overall flat, BUT see low $z_<$ range
- 1σ difference between sim and data's total median

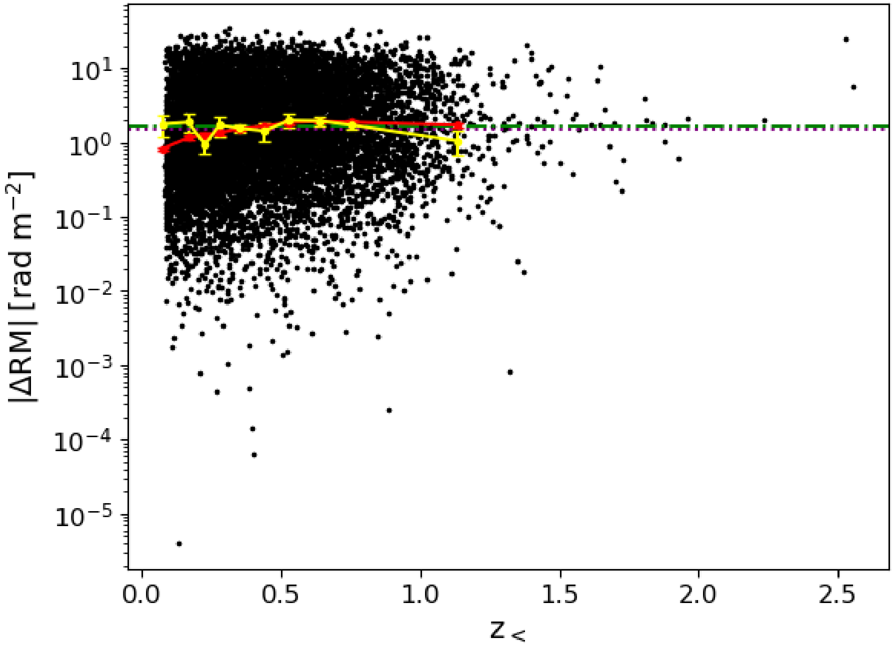
- HOWEVER this difference is very systematic: Is it telling us something although it's not statistically significant?
- Could be related to the preference for higher γ values that tries to ensure flatness, coupled with higher B_0 and/or l_0 in order to avoid too great a suppression of the median

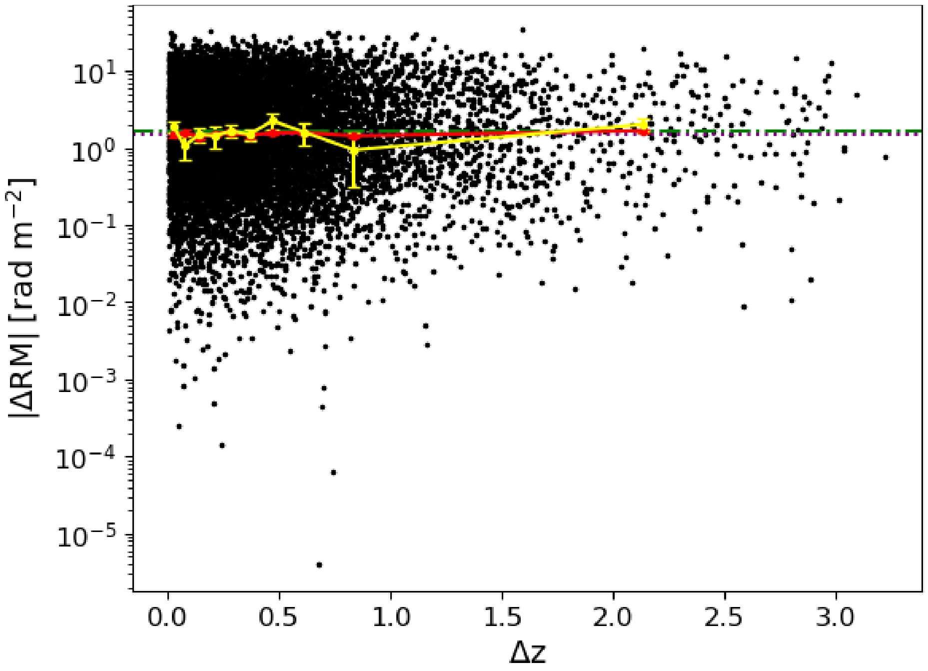
→ Compensation effects between parameters ☹

Table 5. Results for the top five best-fitting models D1, P1, P2, D2, and A1 out of 384 models in total. Included are the full-sample absolute RM difference median, the likelihood, the correlation coefficients, and p-values from a Spearman rank test for $|\Delta\mathrm{RM}|$ with Δz and $z_<$, respectively.

Model: | *dd* | B_0/nG | l_0 | γ |	$|\Delta\mathrm{RM}|_{\mathrm{med}}$ [rad m^{-2}]	$\log P(d|m)$	$\rho_{\Delta z}$	$p_{\Delta z}$	$\rho_{z_<}$	$p_{z_<}$
D1: | dyn | 2.0 | 0.1 | 4.5 |	1.52 ± 0.03	−7.86	0.012	0.22	0.11	$\ll 10^{-6}$
P1: | prim | 1.0 | 10 | 4.5 |	1.62 ± 0.03	−8.03	0.022	0.03	0.05	$\ll 10^{-6}$
P2: | prim | 0.5 | 100 | 2.5 |	1.42 ± 0.03	−8.35	0.0007	0.95	0.09	$\ll 10^{-6}$
D2: | dyn | 2.0 | 1 | 4.5 |	1.48 ± 0.03	−8.84	0.021	0.03	0.10	$\ll 10^{-6}$
A1: | astro | 2.0 | 10 | 3.0 |	1.57 ± 0.03	−8.93	0.046	$<10^{-5}$	0.13	$\ll 10^{-6}$

Data: $|\Delta RM|_{ex} = (1.65 \pm 0.10)$ rad m^{-2}





Caveats of model and methodology

Let’s summarize:

- Our models can’t provide perfect fit in terms of both flatness and the median
- Remedy: select models with potentially overestimated parameter values
- Why is this possible? → Compensatory effects between parameters

→ Quote our results on parameters as upper limits

→ Small local contribution as in Goodlet & Kaiser 2005 (increase with z)

- Didn’t we remove local contributions by considering $|\Delta RM|_{ex}$?
- Almost, BUT: local contrib of PPs (both sources at same redshift) are different than for RPs (the two sources have different redshift)

⇒A small local contribution is justified and it could alleviate both of our problems!

New results by Carretti+23

- Single-source approach, compare data directly to upgraded cosmological simulations, without MC simulations
- Cosmo sim upgrades: longer LoS, radiative cooling in all magnetogenesis scenarios, explore 5 magnetogenesis scenarios
- Look at MF evolution in filaments only (not the entire IGM)
- Tangled primordial model agrees best with data, with a $\gamma_f = 2.15 \pm 0.5$ and a $B_{f,0}^{10} = 8 - 26$ nG in filaments
- Transforming from just filaments to the general IGM:

  $\gamma = 4.3 \pm 0.5$ and a $B_0 = 1.7 - 5.6$ nG, cf. our results

  $\gamma \lesssim 4.5 \pm 0.2$ and a $B_0 \lesssim 2.0$ nG