Linearly-Polarized FRB as a tool of exploring cosmic magnetism

1. Prediction of the IGMF
2. Observing Strategy
3. Observations

Thank Alvina for an excellent talk!
I can skip some background.

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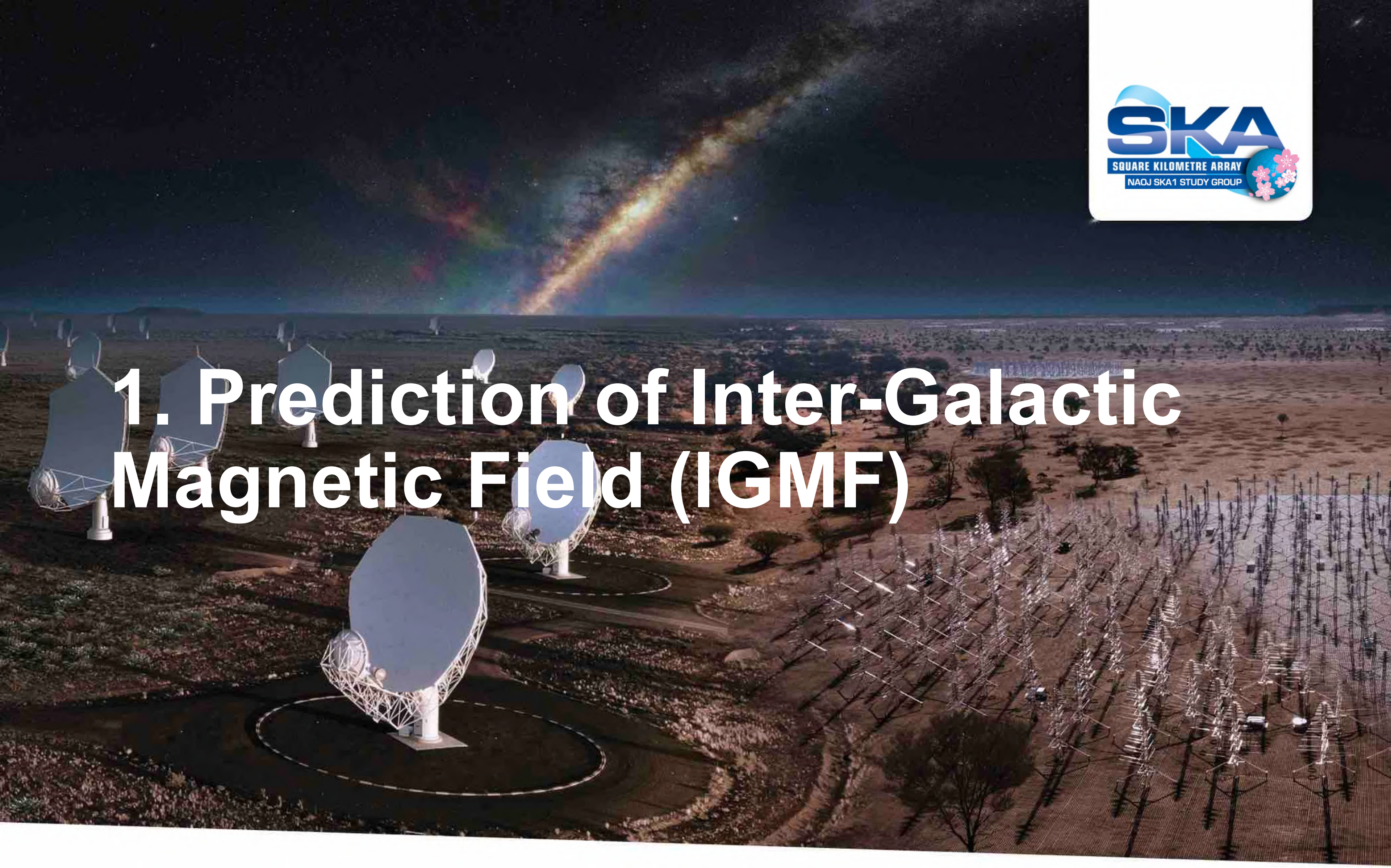
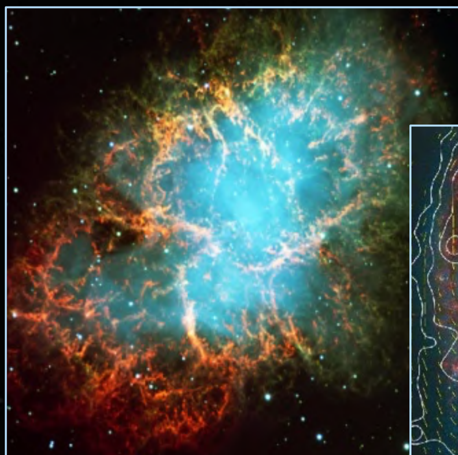


1. Prediction of Inter-Galactic Magnetic Field (IGMF)

1. Prediction of IGMF

Magnetic Field (B) is Ubiquitous

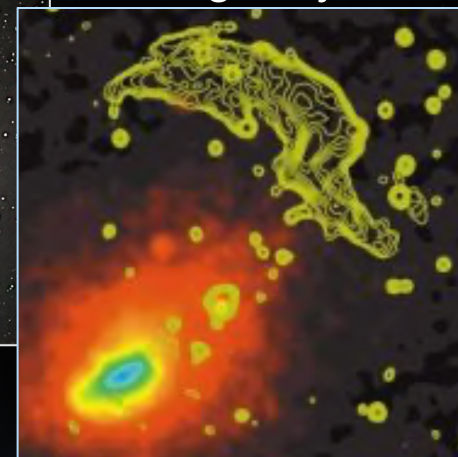
✓Make **diversity** and **universality** of the Universe



Instability, Morphology

Star Formation, Supernova

Particle acceleration
Missing baryon



Accretion disk, Jet, Feedback

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Invited Review

TA+ (2018a)

Invited Review

Cosmic magnetism in centimeter- and meter-wavelength radio astronomy

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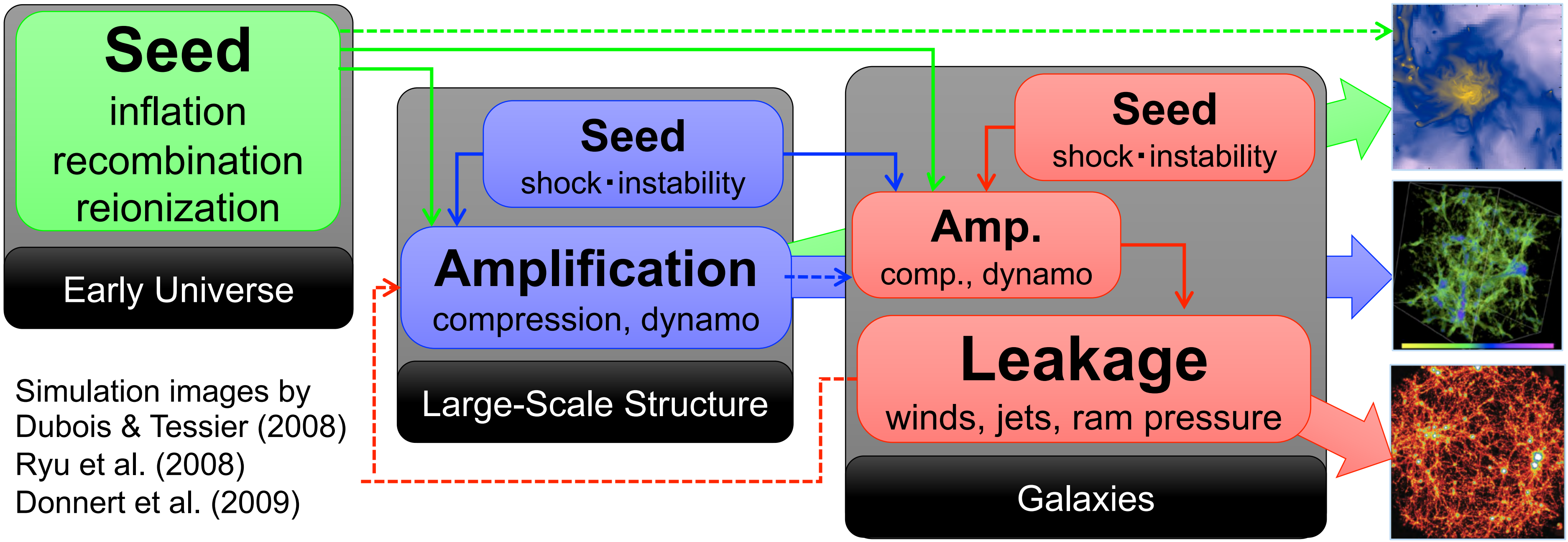
What is the origin of B?
When did B emerge in our Universe?
How does B evolve in redshift?
How does B work in matter evolution?

The IGMF in the WHIM



Simulation images by
Dubois & Tessier (2008)
Ryu et al. (2008)
Donnert et al. (2009)

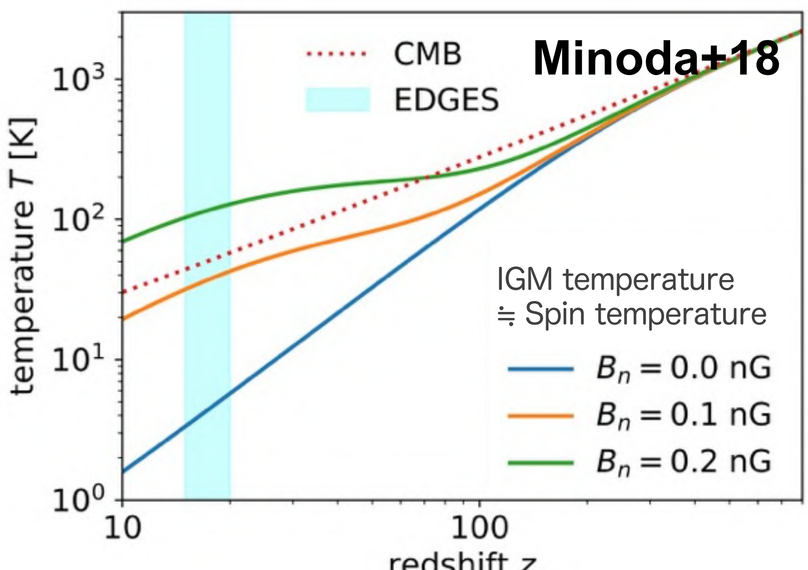
Reviews – Ryu+12; Widrow+12 & Recent works - Vazza+17; Gheller & Vazza 19

- **There are various possibilities of field generation & amplification → the Warm-Hot Intergalactic Medium (WHIM) most likely magnetized**
- **If μG in clusters of galaxies → *1-100 nG in filaments***

Importance of the IGMF

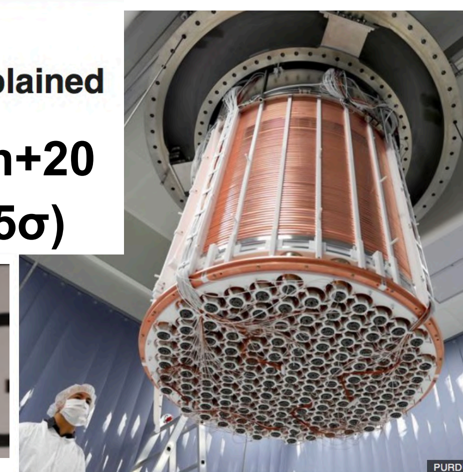
■Epoch of Reionization?

- B can heat the IGM through ambipolar diffusion and turbulent dissipation (e.g., Minoda+18, MNRAS)



■Axion Dark Metter?

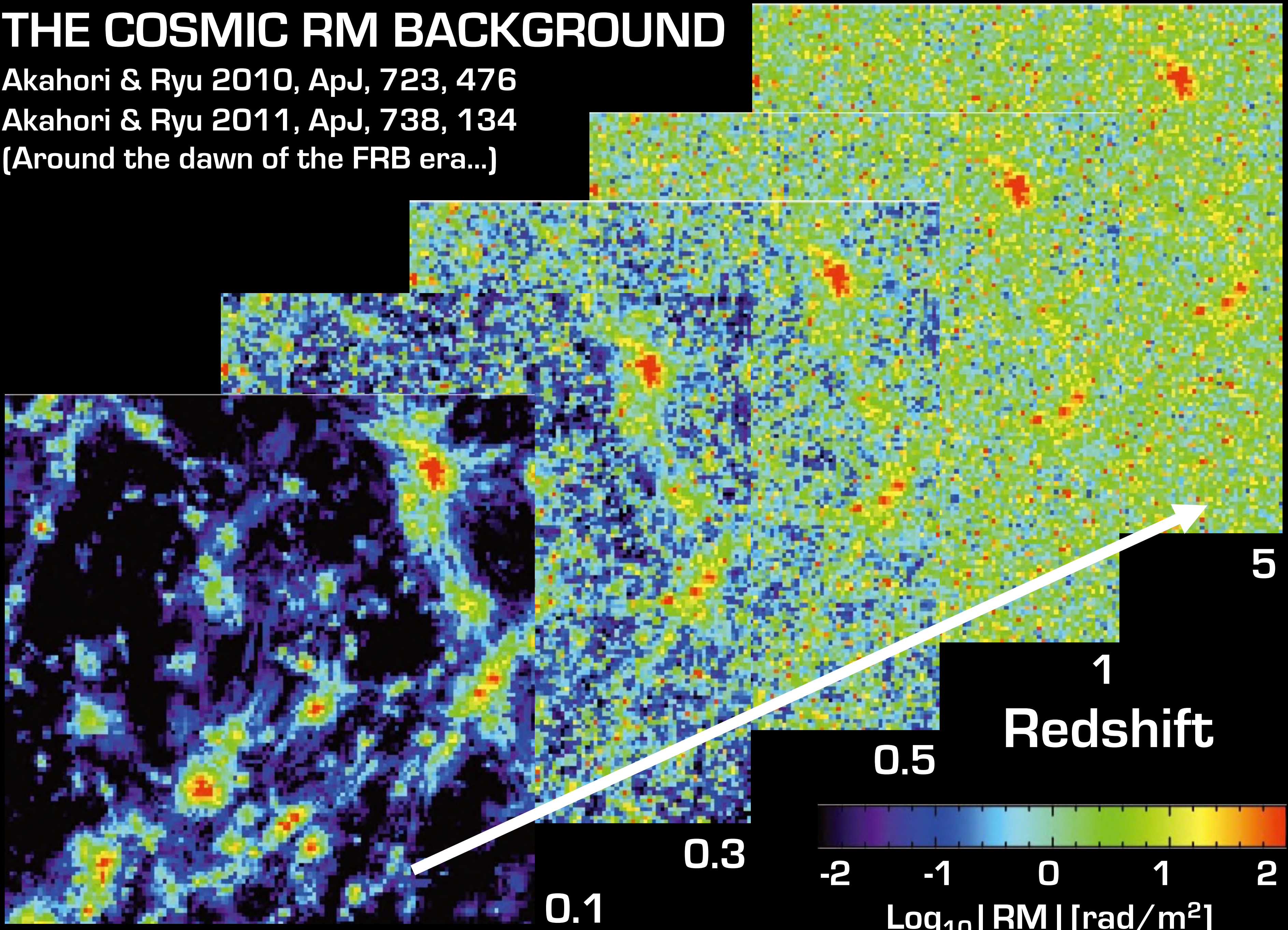
- Axion dark matter in B induces λ-independent rotation of the polarization angle by the effect of vacuum birefringence (e.g., Fujita+2019, PRL)



Wikipedia: birefringence

THE COSMIC RM BACKGROUND

Akahori & Ryu 2010, ApJ, 723, 476
Akahori & Ryu 2011, ApJ, 738, 134
(Around the dawn of the FRB era...)



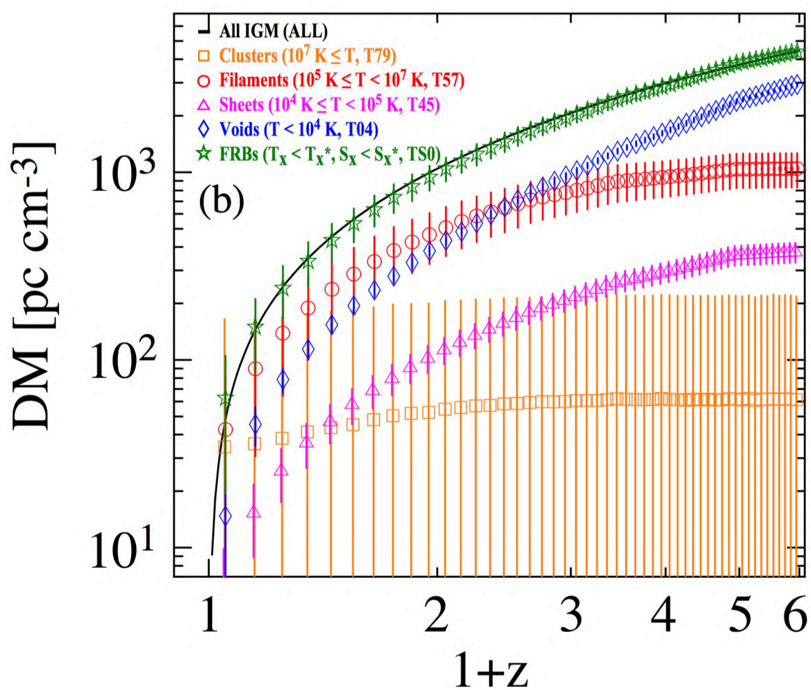
1. Prediction of IGMF

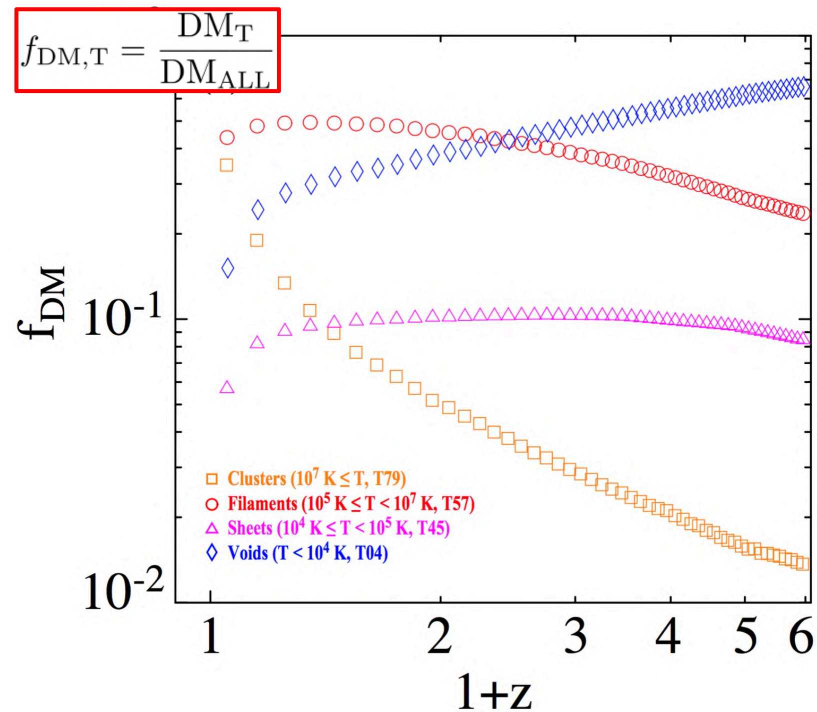
DM and DM fraction

The average (mark) and standard deviation (error bar) for simulated FRBs

— ALL IGM — ICM ($T_x > 10^7$ K) — WHIM (10^5 K < $T_x < 10^7$ K)

— Sheet gas (10^4 K < $T_x < 10^5$ K) — Void gas ($T_x < 10^4$ K) — Selected FRBs





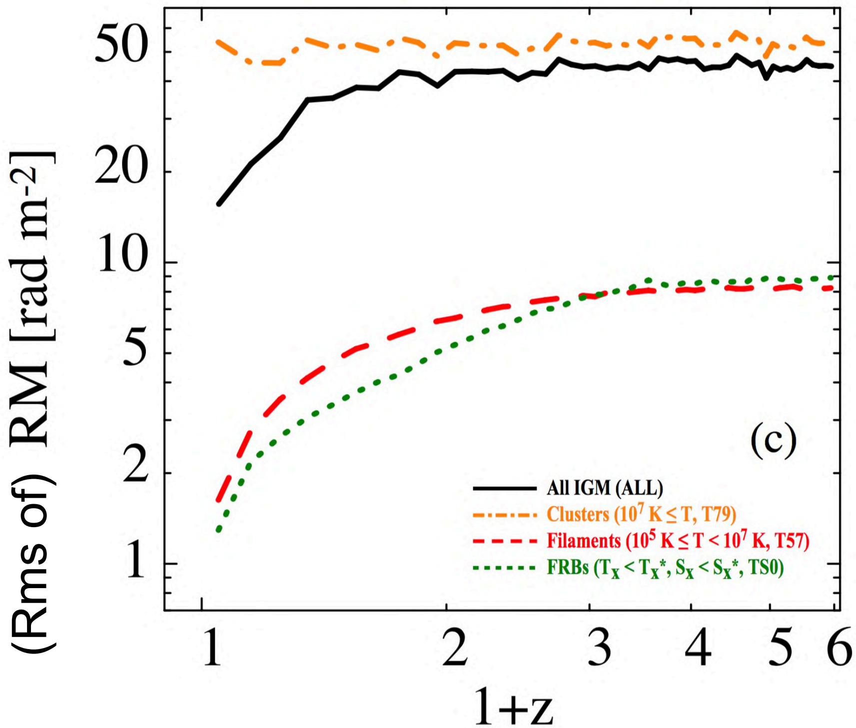
- **WHIM (z<1) and the void gas (z>1) dominate DM**
  - Note: Voids dominate >90% of the path length
- **DM fraction $f_{DM,WHIM}$ ~ 0.5 in z < 1 for the std. cosmology**

Akahori, Ryu, Gaensler (2016)

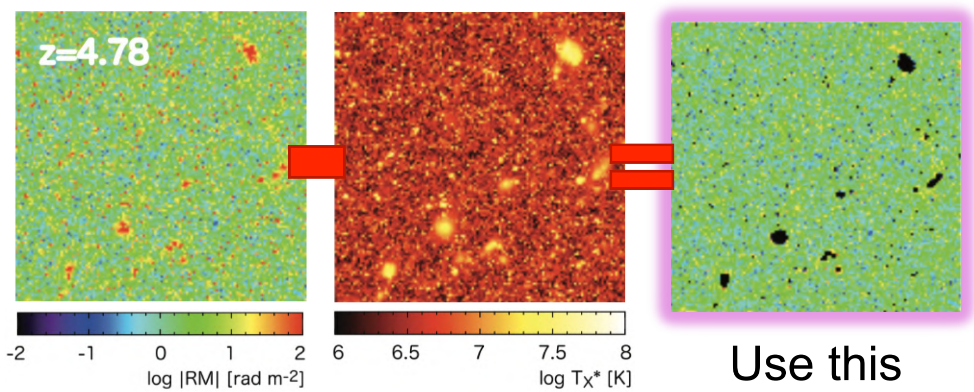
1. Prediction of IGMF

RM and Cluster Subtraction

The average (mark) and standard deviation (error bar) for simulated FRBs
— ALL IGM — ICM ($T_x > 10^7$ K) — WHIM (10^5 K < T_x < 10^7 K)
— Sheet gas (10^4 K < T_x < 10^5 K) — Void gas (T_x < 10^4 K) — Selected FRBs



- ICM dominates RM
- Referring Sx & Tx, we can safely remove clusters. Then, WHIM dominates RM



Use this

Akahori, Ryu, Gaensler (2016)
See also a similar work by Hackstein et al. (2020)

Estimation of the IGMF

■Galactic context

$$B_{||}^{\dagger} = \frac{C_{\rm D} RM}{C_{\rm R} DM} = 12.3 \left(\frac{RM}{10 \text{ rad m}^{-2}}\right)\left(\frac{DM}{10^3 \text{ pc cm}^{-3}}\right)^{-1} \text{ nG}$$

■Cosmological context

$$DM = C_{\rm D} \int_0^{z_i} \frac{n_{\rm e}(z)}{(1+z)} \frac{dl(z)}{dz} dz \quad \text{pc cm}^{-3}$$

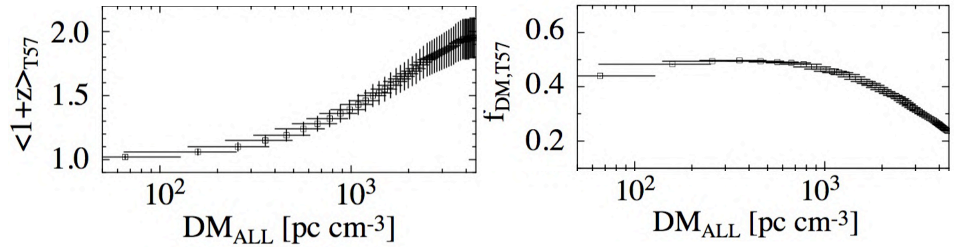
$$RM = C_{\rm R} \int_{z_i}^{0} \frac{n_{\rm e}(z) B_{||}(z)}{(1+z)^2} \frac{dl(z)}{dz} dz \quad \text{rad m}^{-2}$$

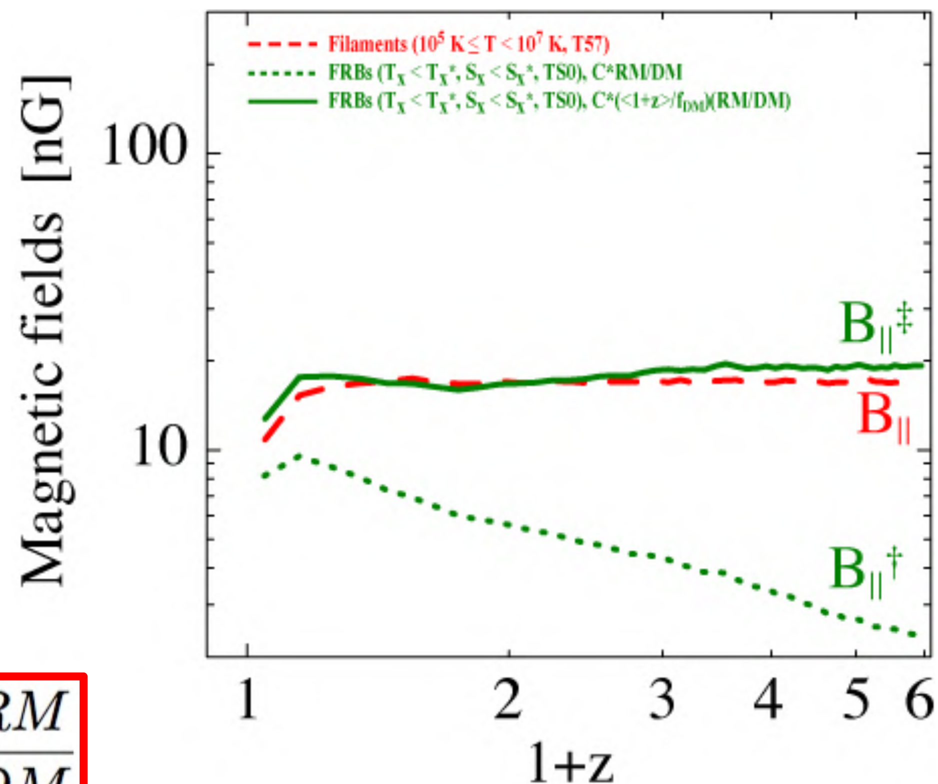
$$\langle 1+z \rangle = \int_0^{z_i} \frac{n_{\rm e}(z)}{(1+z)} \frac{dl(z)}{dz} dz \Big/ \int_0^{z_i} \frac{n_{\rm e}(z)}{(1+z)^2} \frac{dl(z)}{dz} dz.$$

$$\langle B_{||} \rangle \sim RM \langle 1+z \rangle / DM$$

+ Remember DM → $f_{\rm DM,WHIM}$ * DM

$$B_{||}^{\ddagger} = \frac{\langle 1+z \rangle}{f_{DM}} B_{||}^{\dagger} = \frac{\langle 1+z \rangle}{f_{DM}} \frac{C_{\rm D} RM}{C_{\rm R} DM}$$





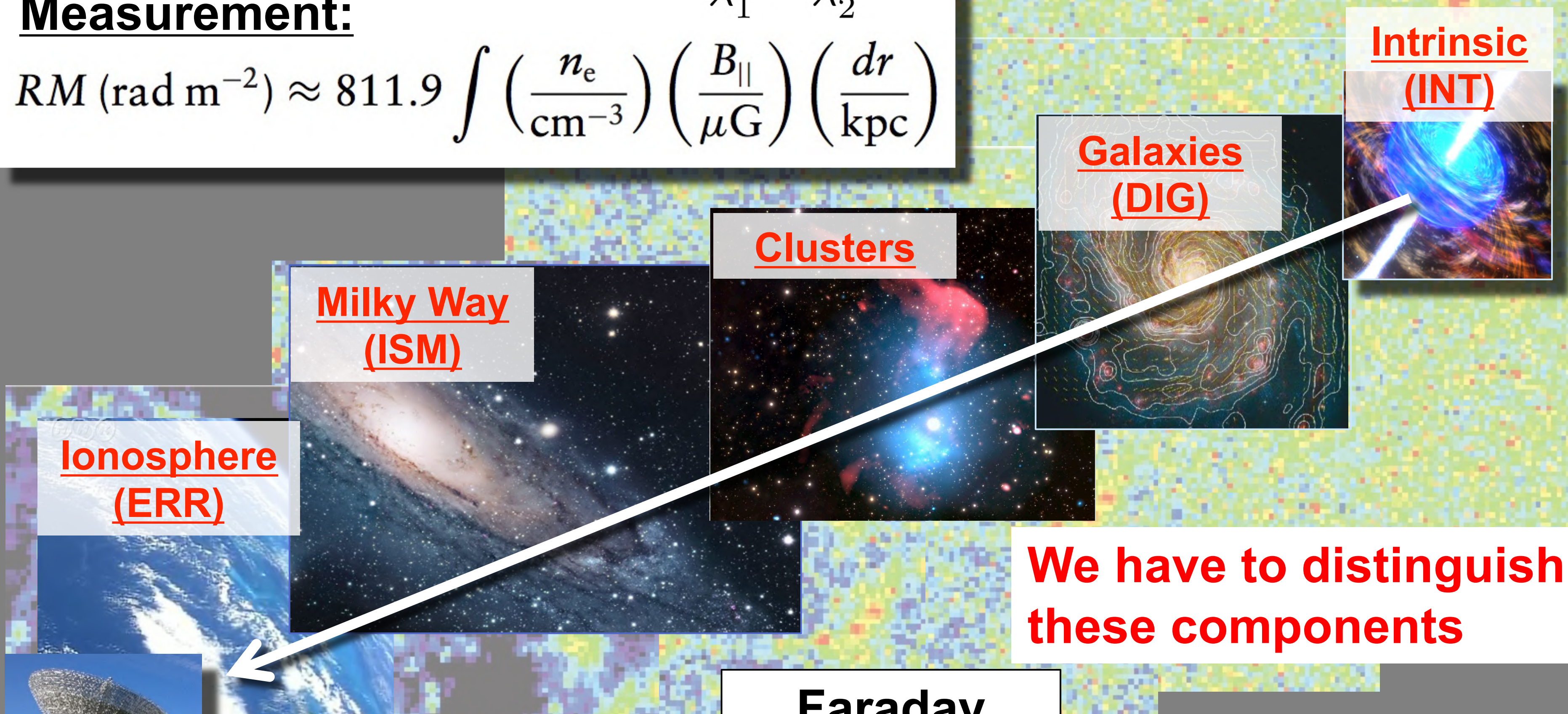
Akahori, Ryu, Gaensler (2016)

2. Observing Strategy

RM Measurement:

$$\mathrm{RM_{obs}} \equiv \frac{\Psi(\lambda_1) - \Psi(\lambda_2)}{\lambda_1^2 - \lambda_2^2}$$

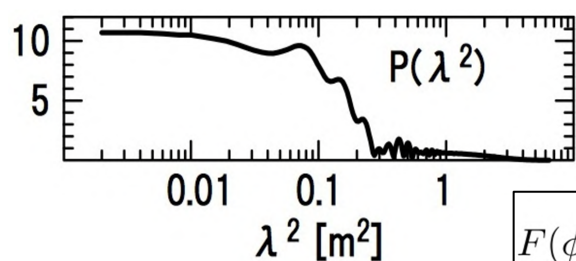
$$RM\,(\mathrm{rad\,m^{-2}}) \approx 811.9 \int \left(\frac{n_e}{\mathrm{cm^{-3}}}\right)\left(\frac{B_{||}}{\mu\mathrm{G}}\right)\left(\frac{dr}{\mathrm{kpc}}\right)$$



We have to distinguish these components

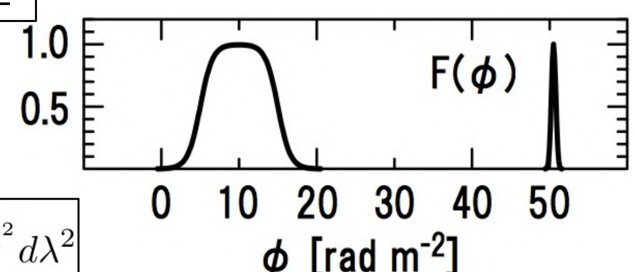
Faraday Tomography

Pol. Int. $P(\lambda^2)=Q(\lambda^2)+iU(\lambda^2)$

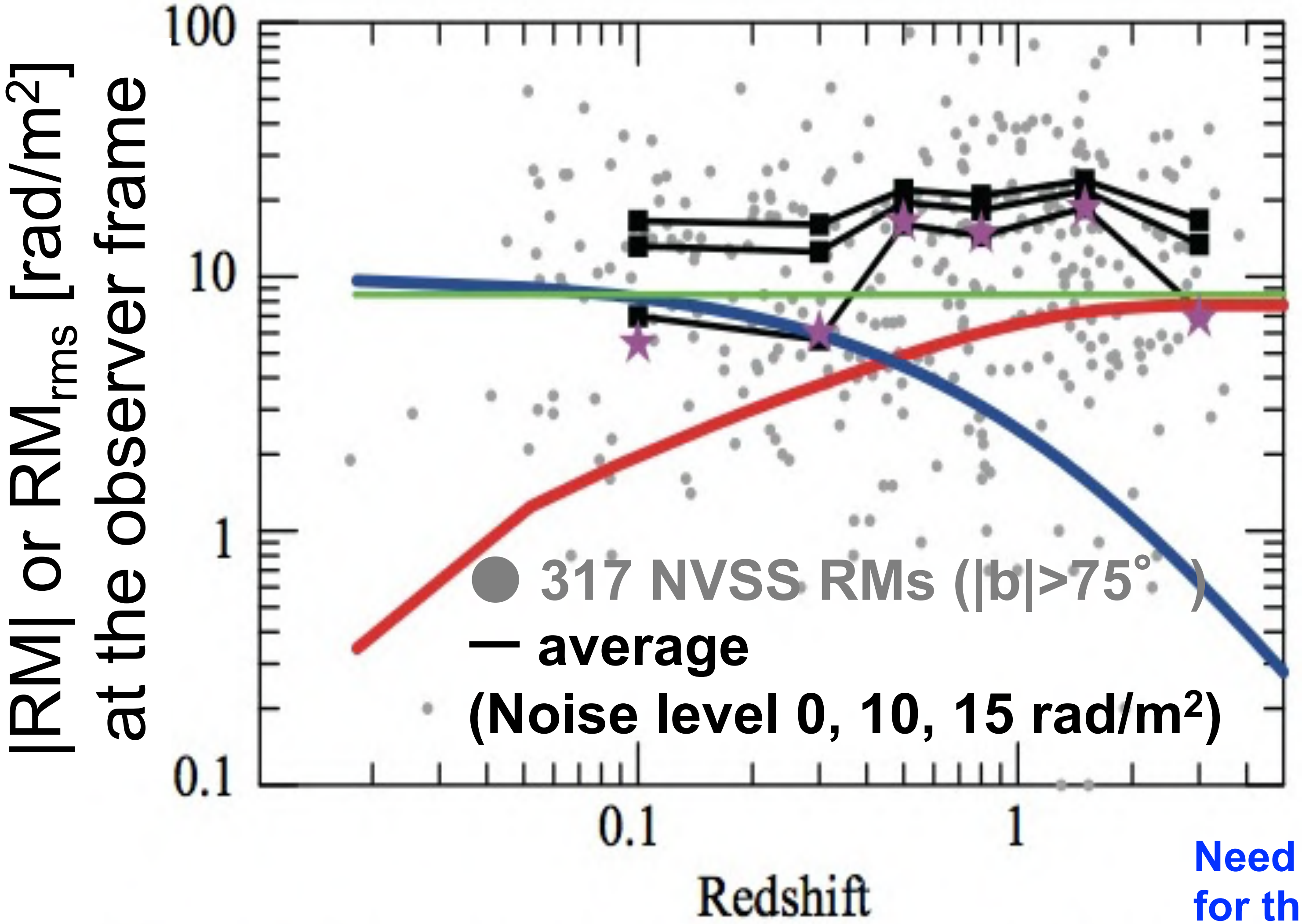


$$F(\phi) = \int_{-\infty}^{+\infty} P(\lambda^2) e^{-2i\phi\lambda^2} d\lambda^2$$

Faraday Spectrum F(φ)



INT Cut: Use high-z sources



DIG (depolarizing intervening galaxies) ~unknown

ISM ~ 9 rad/m^2

IGMF ~1-7 rad/m^2

INT ~10 $(1+z)^{-2}$ rad/m^2

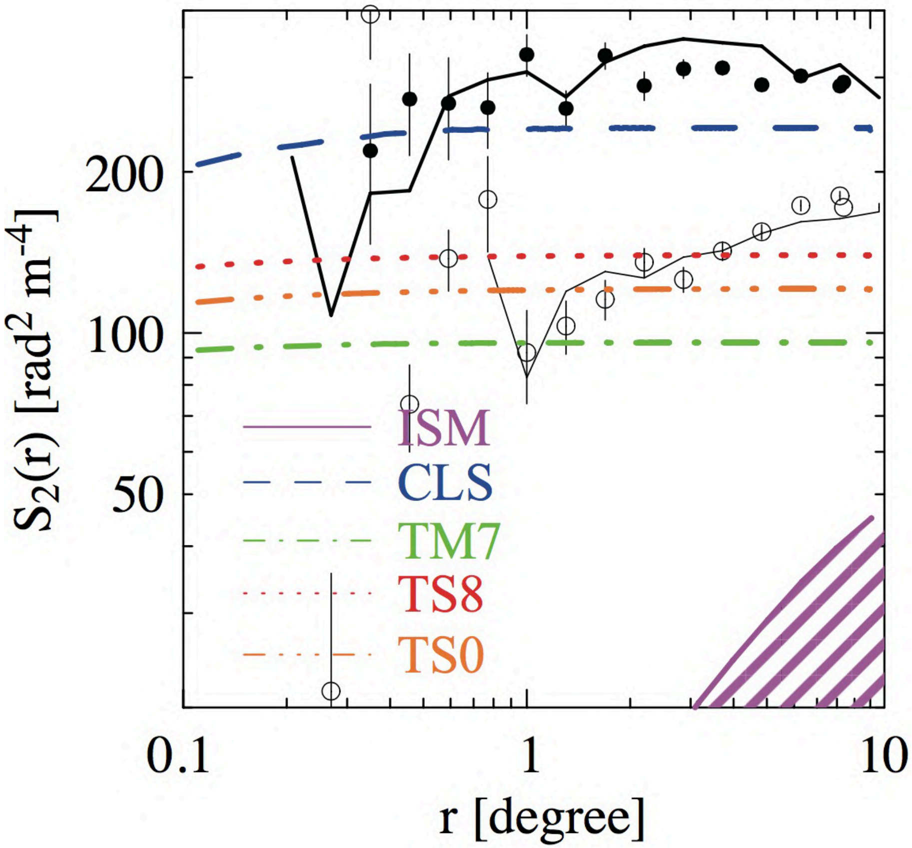
Need more works for the case of FRBs

Akahori, Gaensler, Ryu (2014a), ApJ, 790, 123

2. Observing Strategy
ISM Cut: Use spatial filter

n-th order structure function (SF)

$$S_n(r) = \langle |RM(\vec{x}+\vec{r}) - RM(\vec{x})|^n \rangle_{\vec{x}} \propto r^\eta$$

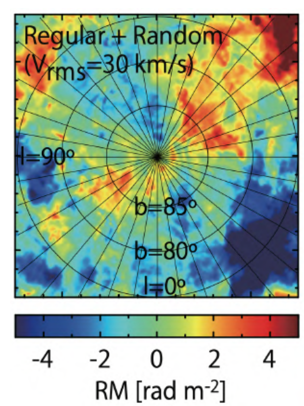


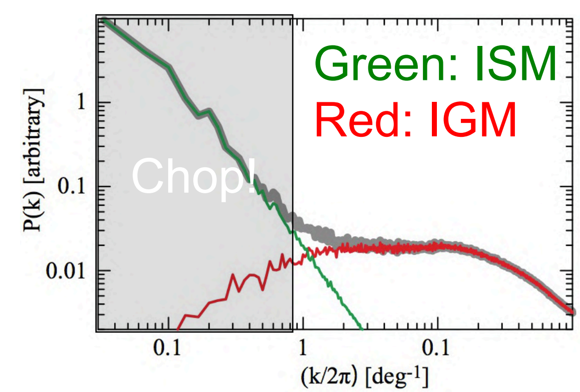
←South Galactic Pole
●: Mao+ (2010), —: Stil+ (2011)

←North Galactic Pole
○: Mao+ (2010), —: Stil+ (2011)

←IGMF
—: flat S_2 at >0.2° with ~100 [rad^2/m^4]

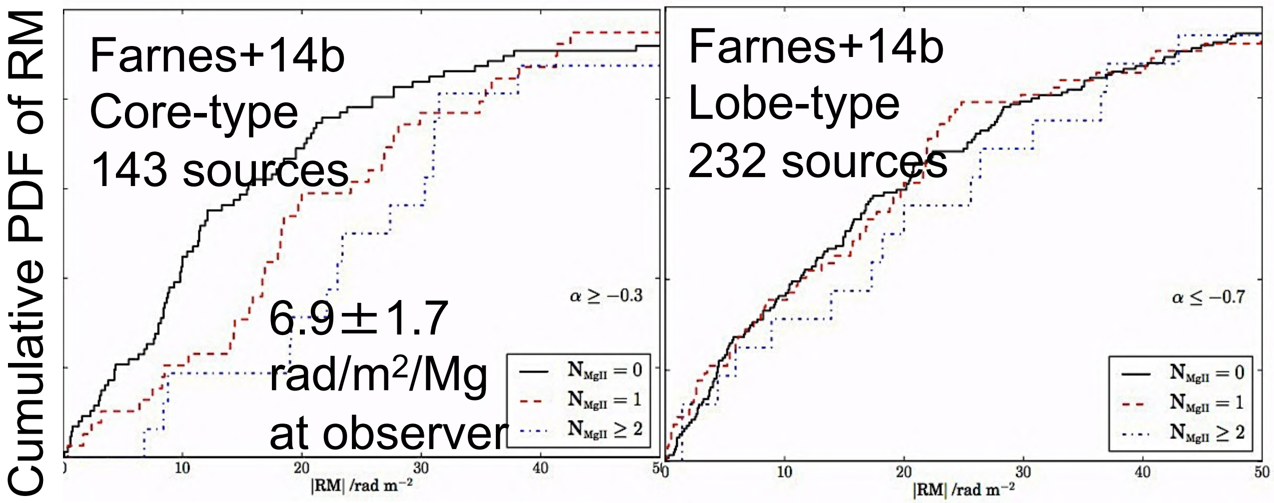
←ISM is small & steep!
—: steep S_2 with < 50 [rad^2/m^4]

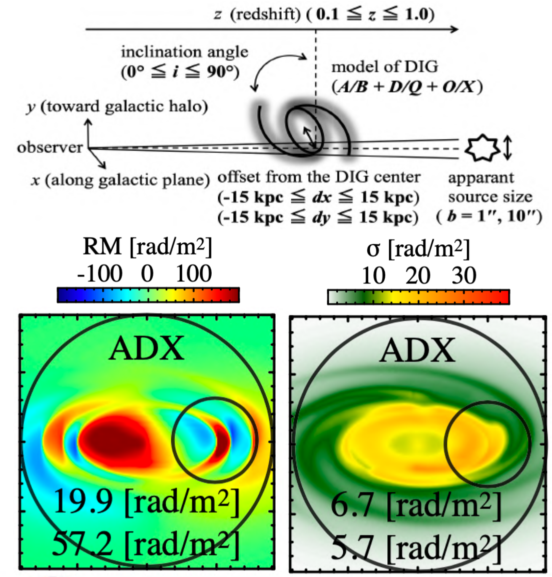




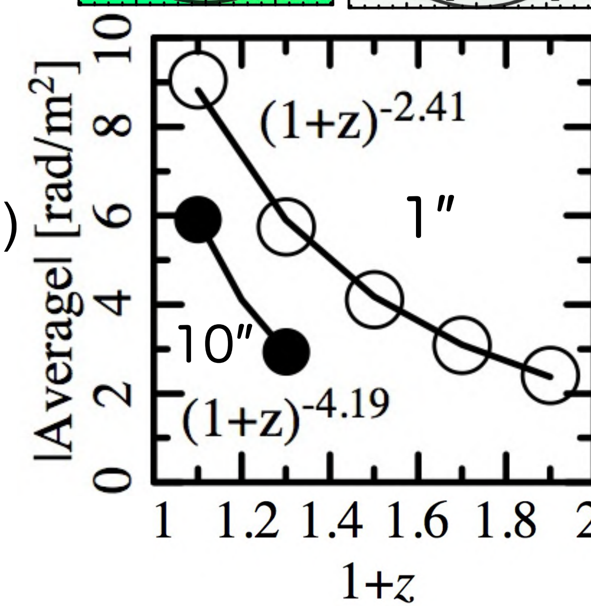
Akahori, Ryu, Kim, Gaensler 2013, ApJ, 767, 150

2. Observing Strategy
DIG Cut: Use un-DP sources





- **~1/2 of SDSS galaxies exhibit MgII absorber systems (DIG)**
  - 40429/107194 QSOs (Zhu&Merald13)
  - Foreground galaxies (Adam's talk: Simha+20)
- **Monte-Carlo simulation of DIG (Omae, TA+ in prep.)**
  - 1″ (Core) $|RM_{DIG}| < 2$ rad/m^2 if $z_{DING} > 1$
  - 10″ (Lobe) $|RM_{DIG}| < 2$ rad/m^2 if $z_{DING} > 0.4$

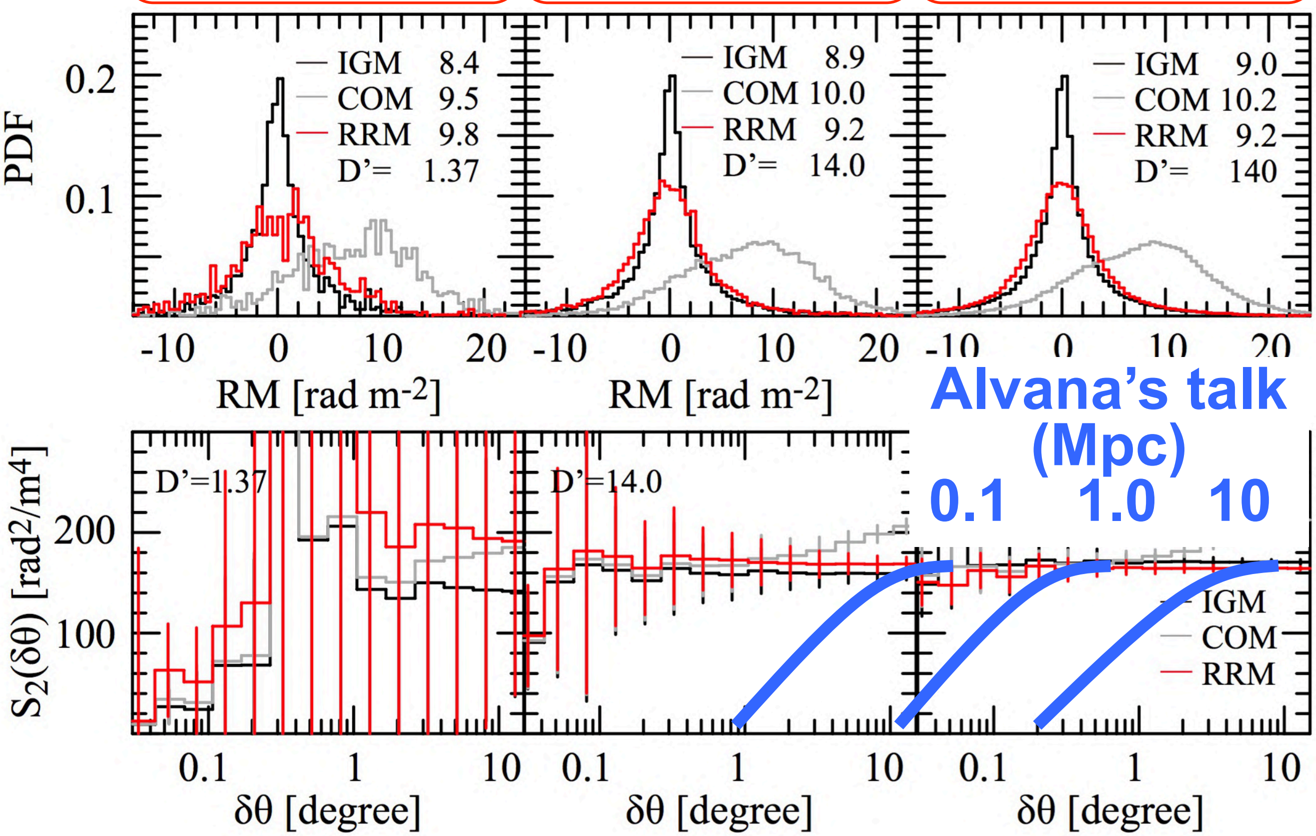


2. Observing Strategy

Can we find the IGMF?

900 deg^2 FOV, South Galactic Pole, z>2, θ=2°
— IGM — COM(ALL) — RRM

Precursor	SKA1	SKA2
10 RM/deg^2	**100 RM/deg^2**	**1000 RM/deg^2**
~10 μJy level	~μJy level	~100 nJy level



- Our selection criteria discard **~86%** of sources
- **100 RM/deg^2 → we can study $\sigma_{RM,WHIM}$**
- **1000 RM/deg^2 →we can study $S_{2,RM,WHIM}$**
- Need to select ideal sources from a large population

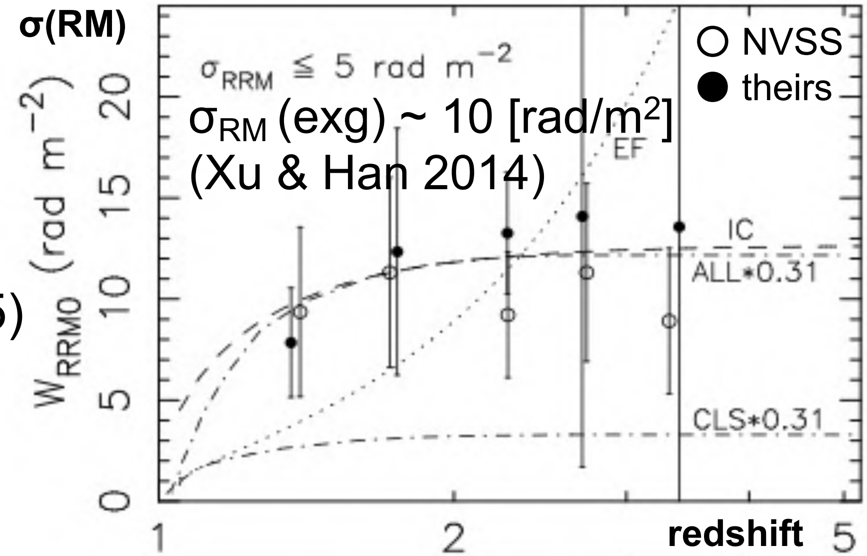
Akahori, Gaensler, Ryu (2014a)

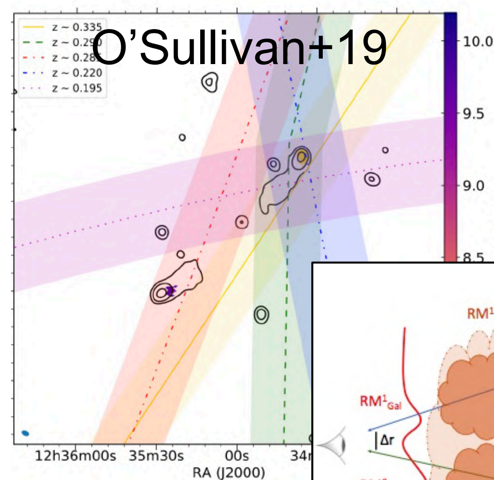
3. Observations

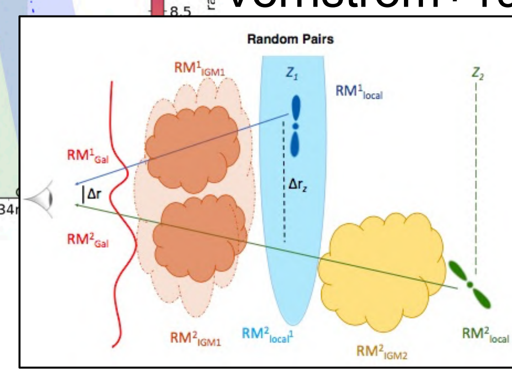
Constraints on IGMF

■ RM < 2-15 rad/m^2 → B < 4-100 nG

- Superclusters (Xu+06); cluster outskirts (Govoni+10, Bonafede+10); Galactic poles (Mao+10, Stil+11)
  - ✓ RM fluctuation analysis (On+19)
- All-sky RM grids (Oppermann, TA+15)
- RM(latitude) (Schnitzeler 10)
- RM(z) (Hammond+12; Xu & Han 14)
- RM(MgII) (Farnes+ 14ab)
- The differential RM ~2.5 rad/m^2 for radio lobes, 10-50 nG (O'Sullivan+18); < 4 nG (<1.9 rad/m^2, O'Sullivan+20)
- The differential RM ~ 10 rad/m^2 for physical/random pairs, 40 nG (Vernstrom+19)







■ Synchrotron emission

- <30nG?? (Vernstrom+17; Brown+17)
- <200 nG (LOFAR, Locatelli+21)
- 30-60 nG (Vernstrom+21)

SQUARE KILOMETRE ARRAY
NAOJ SKA1 STUDY GROUP

3. Observations

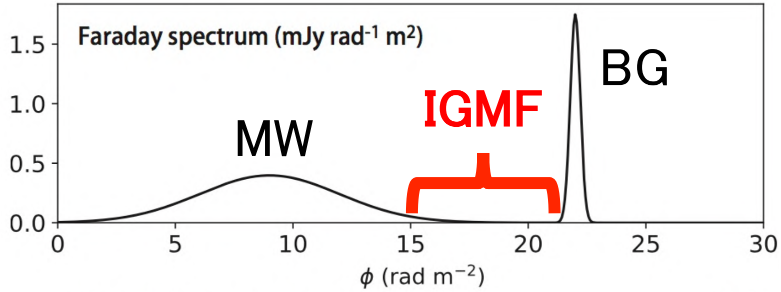
Linearly-Polarized FRBs

	ID	Facility	P (%)	RM (rad/m²)	Reference
1	110523	Parkes	44±3	-186.1±1.4	Masui+15
2	150807	Parkes	80±1	12.0±7	Ravi+16
3	150215	Parkes	43±5	1.6±10	Petroff+17
4	150418	Parkes	9±2	36±52	Keane+16
5	151230	Parkes	35±13	0	Caleb+18
6	160102	Parkes	84±15	-221±6	Caleb+18
7	121102	Arecibo/GBT	~100	1×10^5	Michilli+18
8	180924	ASKAP	80	14±1	Bannistar+19
9	181226	CHIME	~100	-114.6±0.6	CHIME/FRB+19

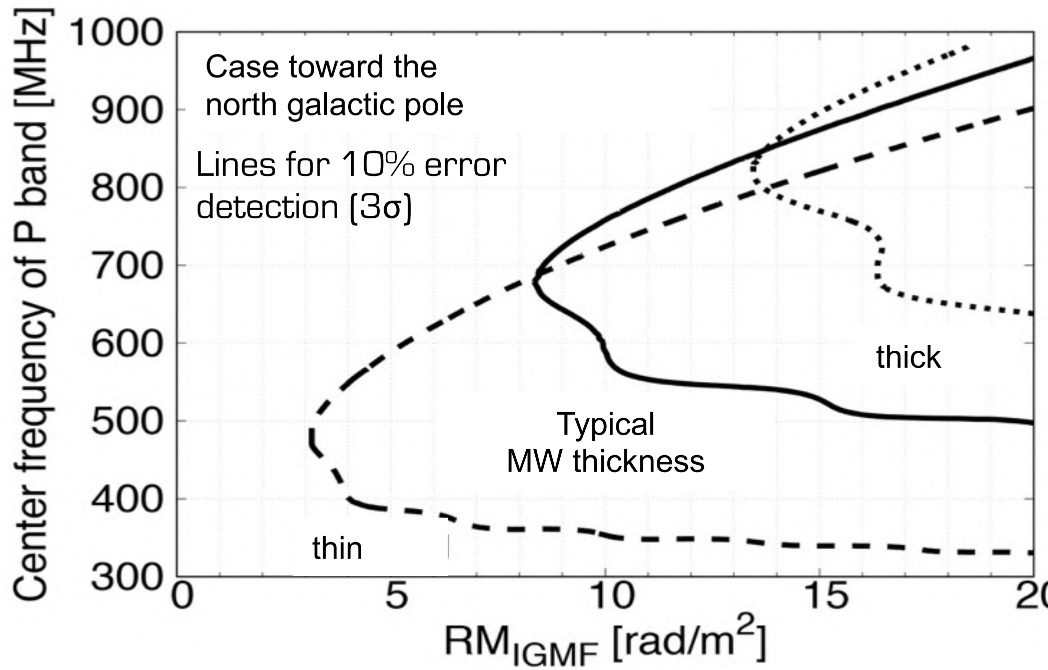
■ **Upper limit of extragalactic magnetic field:**

- **B < 21 nG (Ravi+16), B < 30 nG (Bannistar+19)**
- Faraday tomography is a key to derive the RMs

Optimum Frequency for FT



$$F(\phi) = \sum_{i=\mathrm{MW,BG}} \frac{f_i e^{2i\theta_i}}{\sqrt{2\pi}\delta\phi_i} \exp\left\{-\frac{(\phi-\phi_i')^2}{2\delta\phi_i^2}\right\}$$



■**Given the data at**

- 1.4 GHz (20MHz BW),
- 1.6 GHz (100MHz BW),

we explored the optimum frequency at P band

■**Is there the optimum frequency at P band?**

- Yes. It depends on the thickness of MW foreground
- To detect RM_{IGMF}, try to observe linearly-polarized FRB at 0.7 GHz + 1.4 GHz + 1.6 GHz simultaneously

Akahori+14b; 18d

Summary

■Exploring magnetized cosmic web

- Various possibilities of field generation/amplification
- 1-100 nG for the IGMF in filaments of galaxies
- Not RM/DM, but $<1+z>RM/\ f_{DM,WHIM}{}^{*}DM$

■How can we explore the IGMF?

- Source selection (w/ redshift, broadband, MgII)
- Sufficient statistics available in the SKA era
- The differential RM grids
- Linearly-polarized FRBs with Faraday tomography
  - ✓Where 0.7/1.4/1.6 GHz simultaneous observation is a key

Not only FRB Cosmology with DM

but also <u>FRB Magnetism with RM</u>