How many RM grids do we need to study the IGMF?

TA, Gaensler, Ryu (2014a), ApJ, 790, 123
TA, Kumazaki, Takahashi, Ryu (2014b), PASJ, 66, 65
TA, Ryu, Gaensler (2016), ApJ, 824, 105

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SPARCS 2016
16.11.3-5 @ Goa, India

1. Introduction
Missing Baryon and the IGMF

BigBang Cosmolgy
Observations

Total baryon content in the Universe

galaxies・clusters・H_I・Lyα・O_{VI} | Gas in filaments? | MOND?

Seed
inflation
recombination
reionization

Early Universe

Seed
shock・instability

Amplification
compression, dynamo

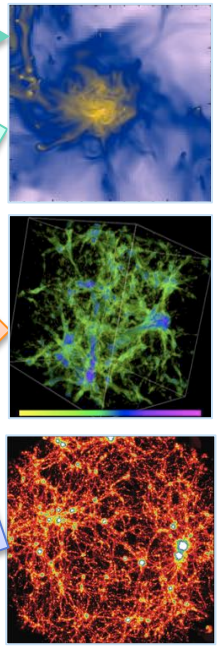
Large-Scale Structure

Seed
shock・instability

Amp.
comp., dynamo

Leakage
winds, jets, ram pressure

Galaxies



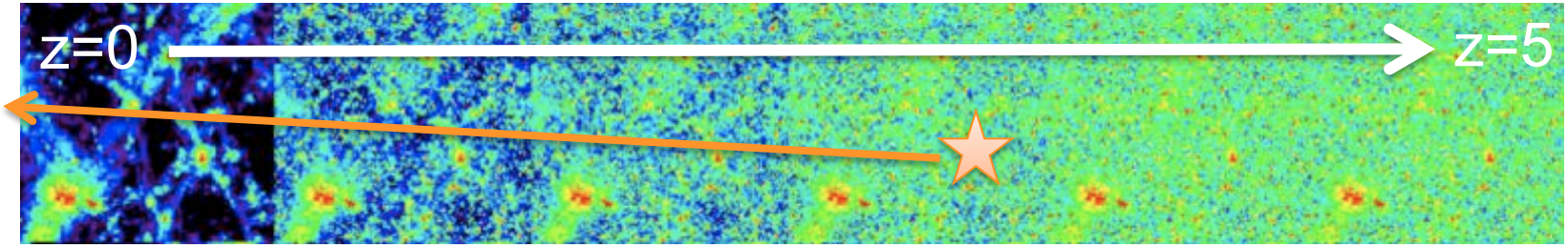
See reviews:
Ryu+11;Widrow+11

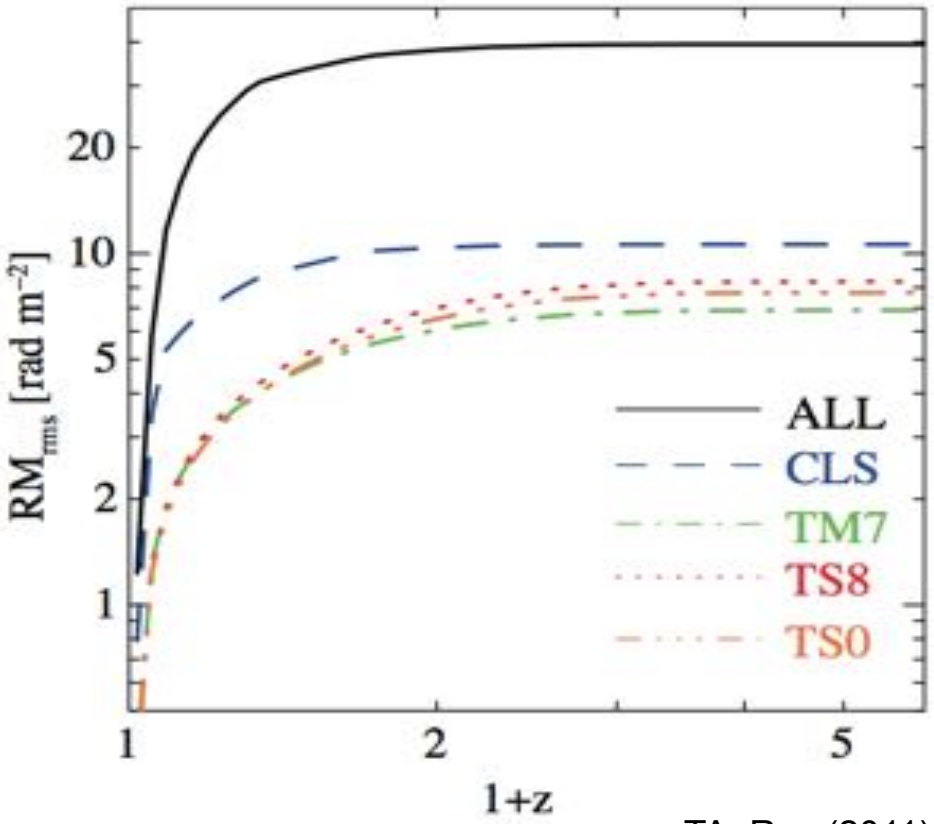
❖**IGMF could be a probe of missing baryon**

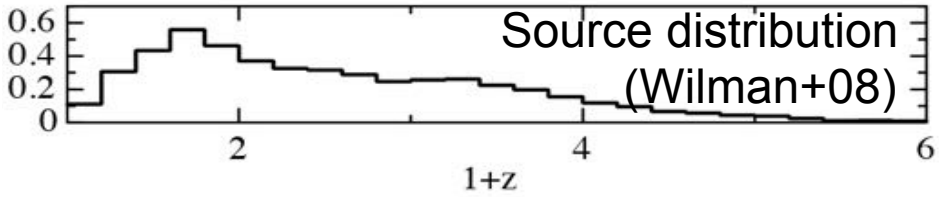
❖**If μG in clusters → 1-10 nG in filaments?**

Dubois & Tessier 08
Ryu+08
Donnert+09

1. Introduction
Simulation of IGMF RM







❖IGMF RM_{rms}~7-10 [rad/m^2] ($T_x=10^{5\text{-}7}$ K)

※Galaxy Cluster Subtraction

CLS: ALL – grids (<1 Mpc of Tx>2 keV)

TM7: ALL – grids ($T>10^7$)

TS8: ALL – pixels ($Tx^*>10^7$ & $Sx^*>10^{-8}$)

TS0: ALL – pixels ($Tx^*>10^7$ & $Sx^*>10^{-10}$)

T in [K], S in [erg/s/cm^2/sr]

TA, Ryu (2011), ApJ, 738, 134

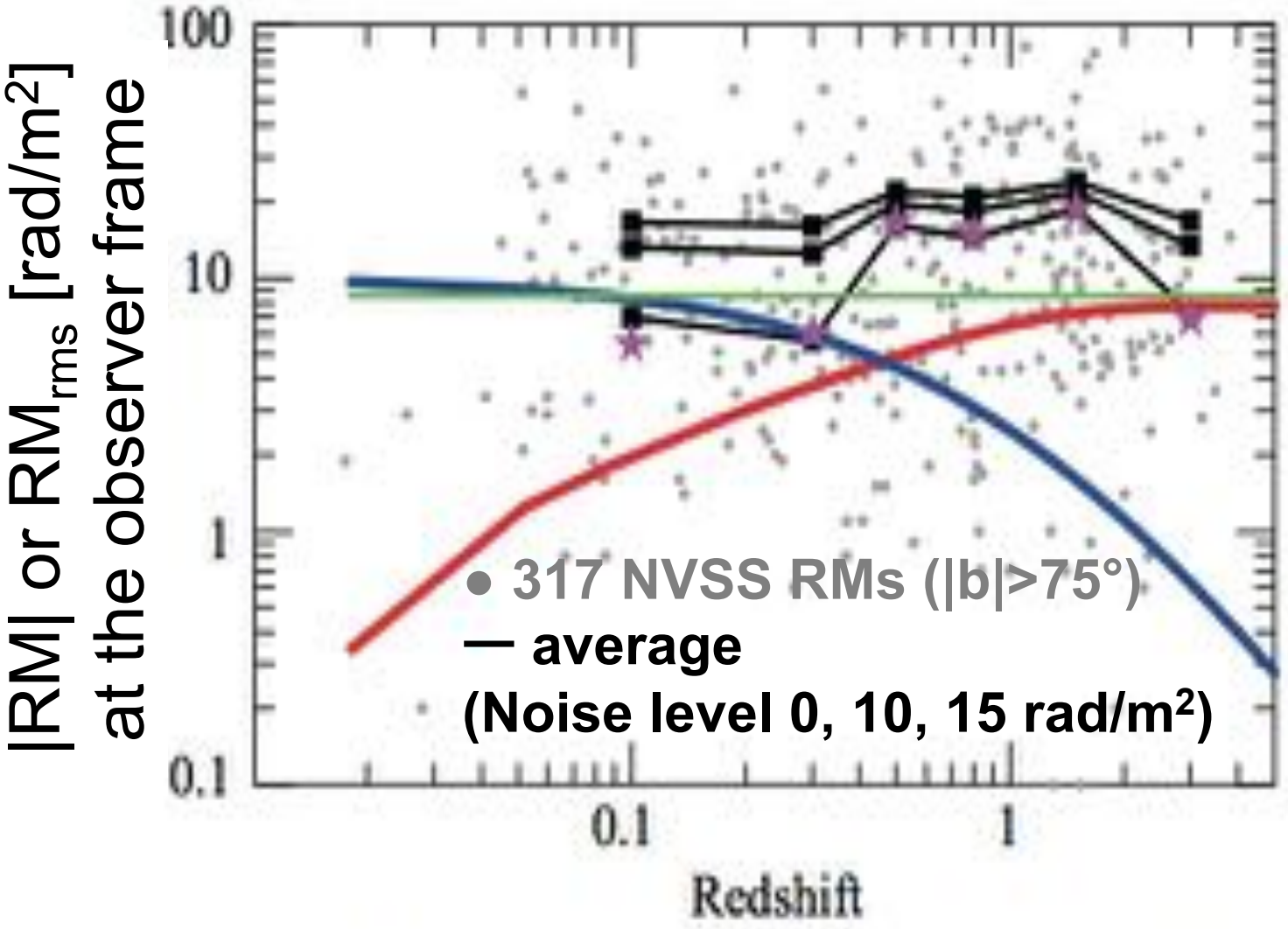
2. Model and Calculation

RM of Background Source

- **Observation of extragalactic polarized sources**
- **Multiple contributions of Faraday rotation measures (RMs) along a line of signt (LOS)**
  - RM due to the Intergalactic magnetic field (IGM)
  - RMs of the source (INT), intervening galaxies (DIG), the Milky Way (ISM), and others (ERR)

2. Model and Calculation

RMs toward Galactic Poles



RM of Ext. Gal.

RM of Our Gal. ~ 9 rad/m²

RM of the IGMF ~1-7 rad/m²

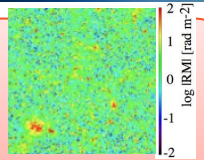
RM of the source ~10 (1+z)$^{-2}$ rad/m²

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

2. Model and Calculation
The Simulation

900 deg^2 South GP

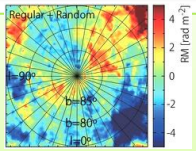
IGM
map
Akahori, Ryu 2011



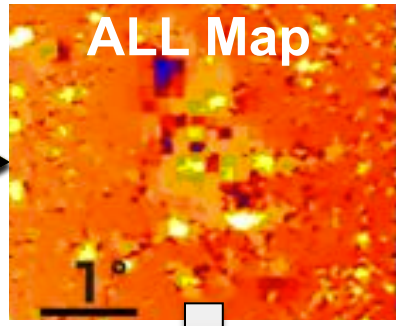
INT
random
$\sigma_{INT}=\sigma_{INT,0}/(1+z)^2$
$\sigma_{INT,0}$=10 rad/m^2

DIG
random, 50% MgII

ISM
map
Akahori+ 2013



ERR
random
σ_{ERR}=1 rad/m^2



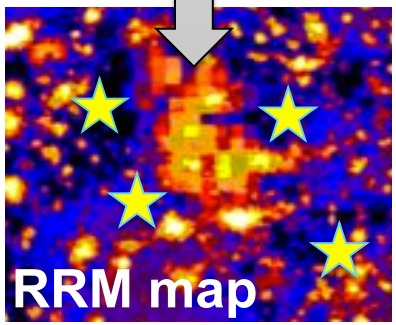
ICM filter

INT filter

DIG filter

ISM filter

ERR filter

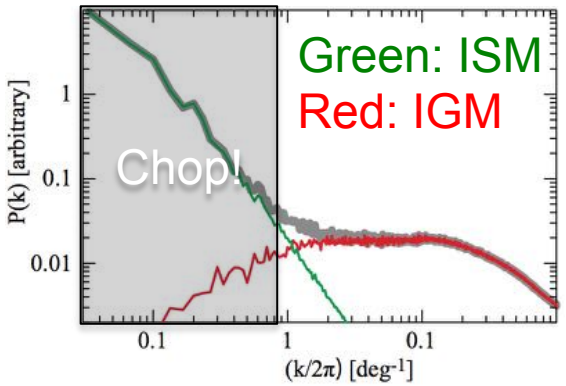


Remove clusters of galaxies
X-ray brightness & temperature

Choose high-z sources
$\sigma_{INT}(z=2)$ ~ 1 rad/m^2

Discard 50 % of sources
they have large DIG RMs

Cut large-scale component
filtering scale at ~1°-10°

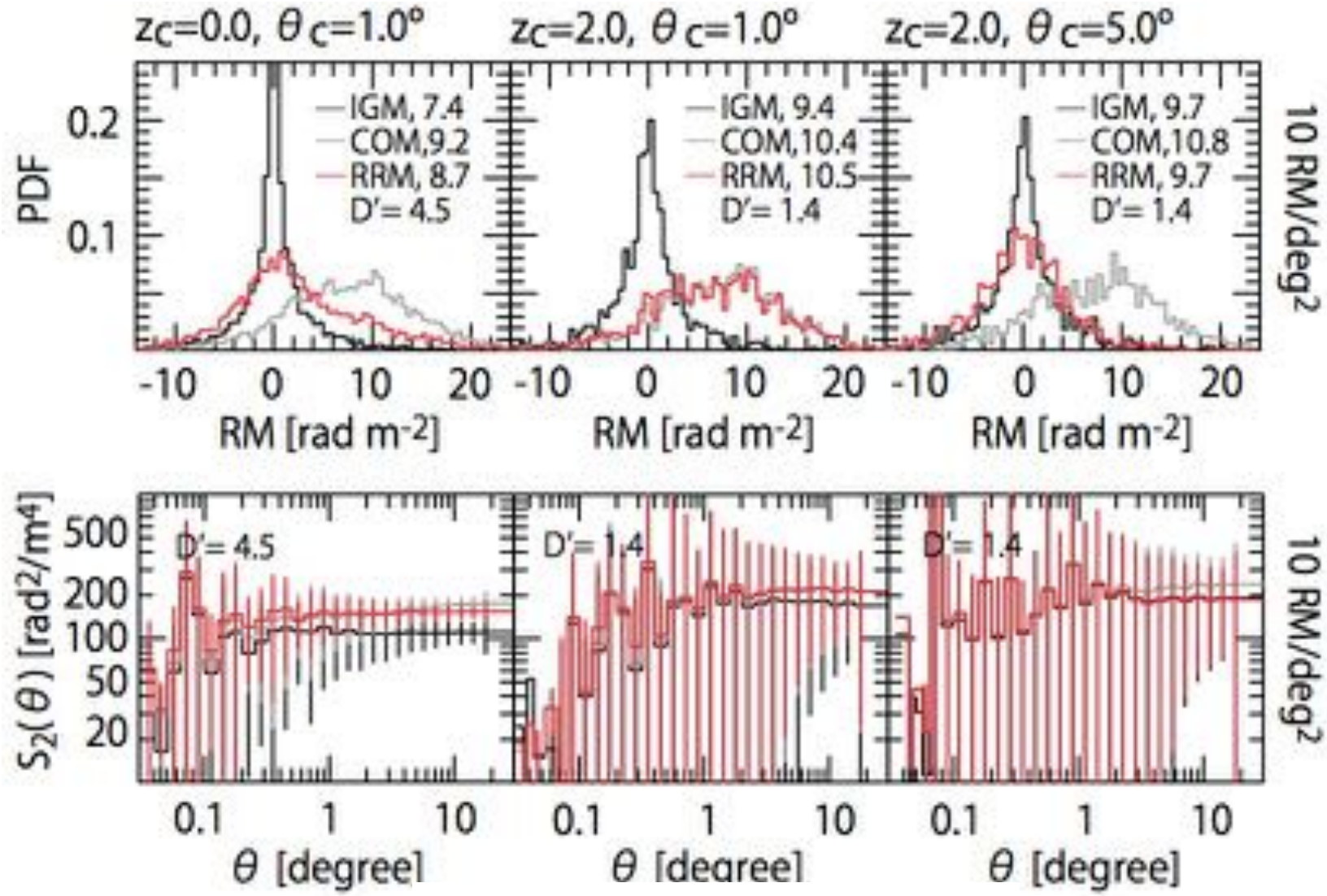


Assume sources have
mean RM error ~1 rad/m^2

3. Results

Choice of High-z Sources

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

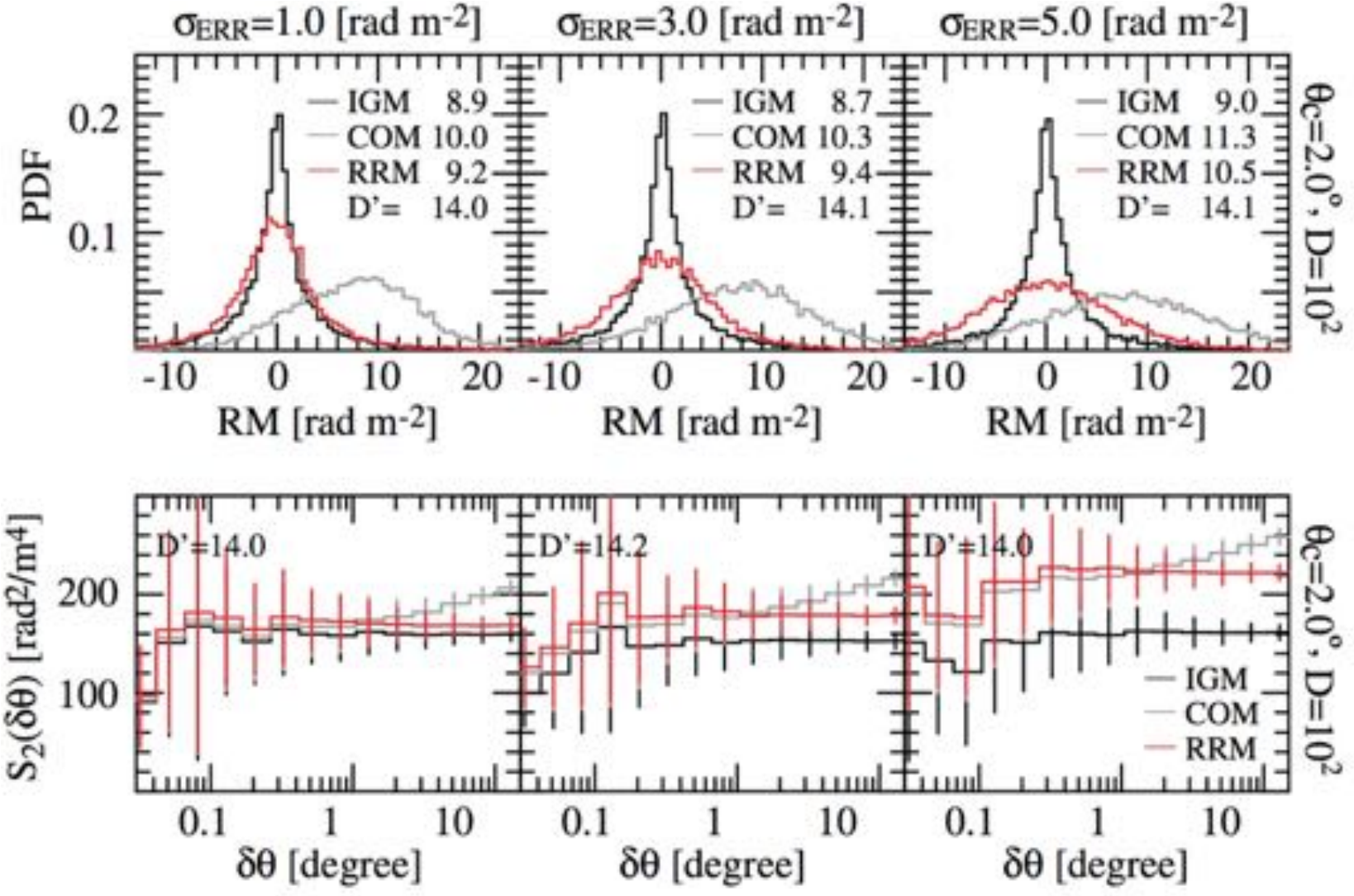


TA, Gaensler, Ryu (2014a), ApJ, 790, 123

3. Results

Choice of Low-Noise Sources

z_c=2



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

3. Results
RM-Grid Density

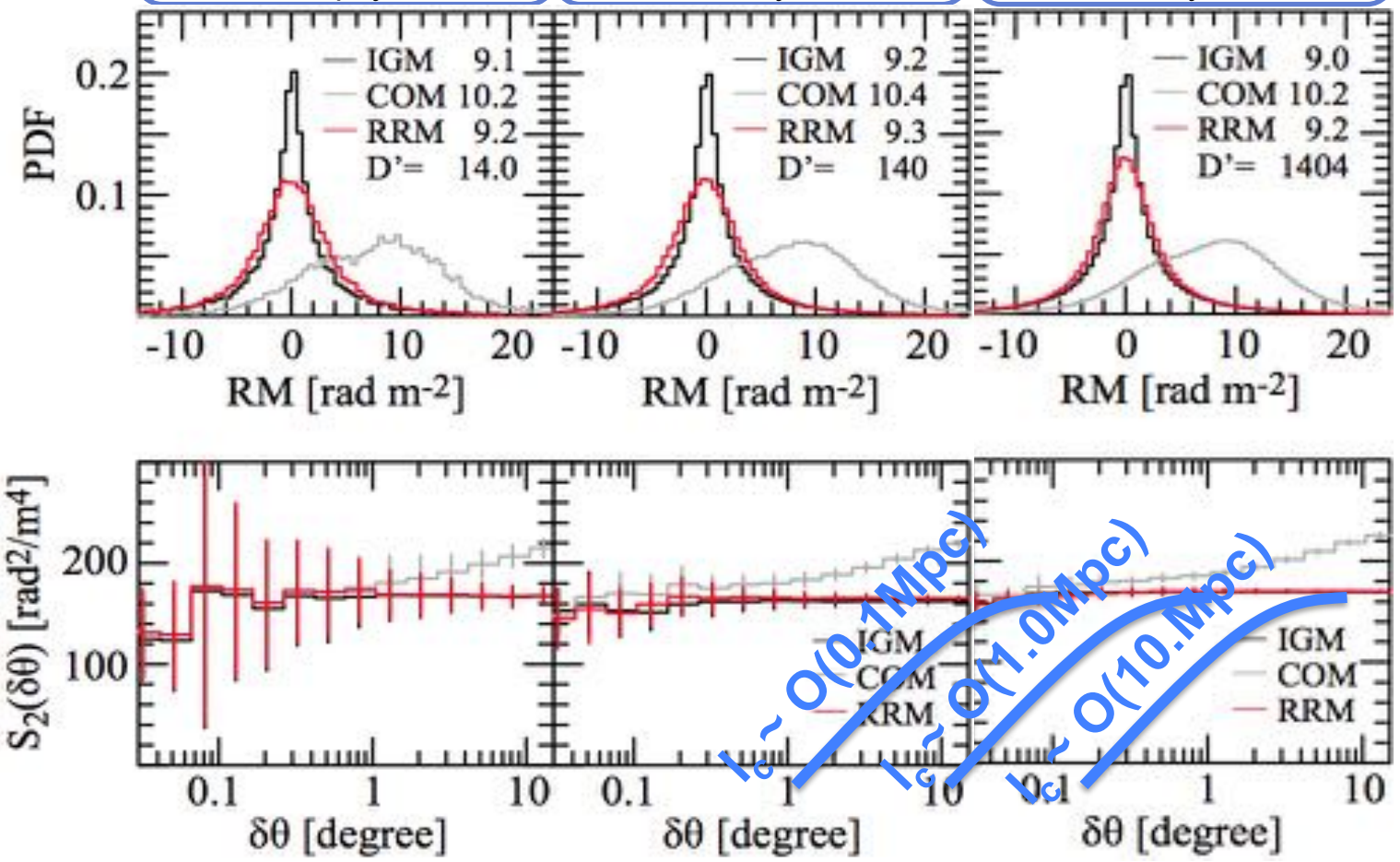
SKA1 (Survey?)
100 RM/deg²
~a few μJy level

SKA1 (Deep?)
1,000 RM/deg²
~100 nJy level

SKA2 (Deep?)
10,000 RM/deg²
~10 nJy level

$z_c=2$

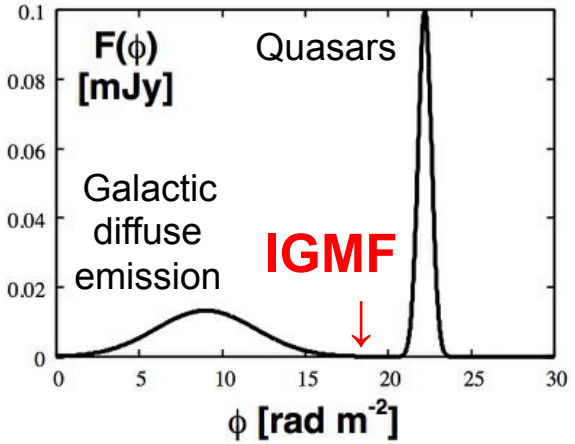
RM_{err} = 1 rad/m²



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

4. Discussion
Faraday Tomography

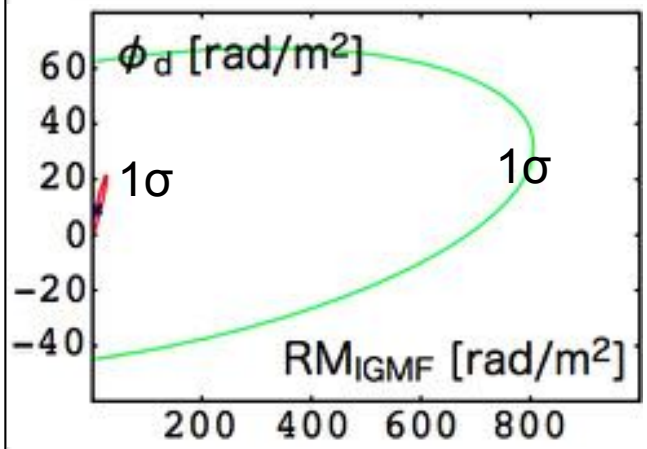
model

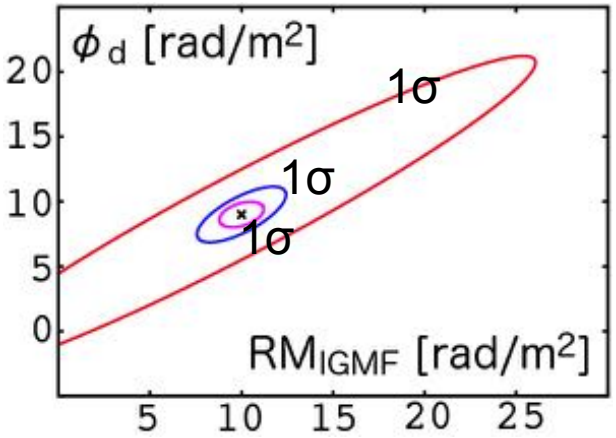


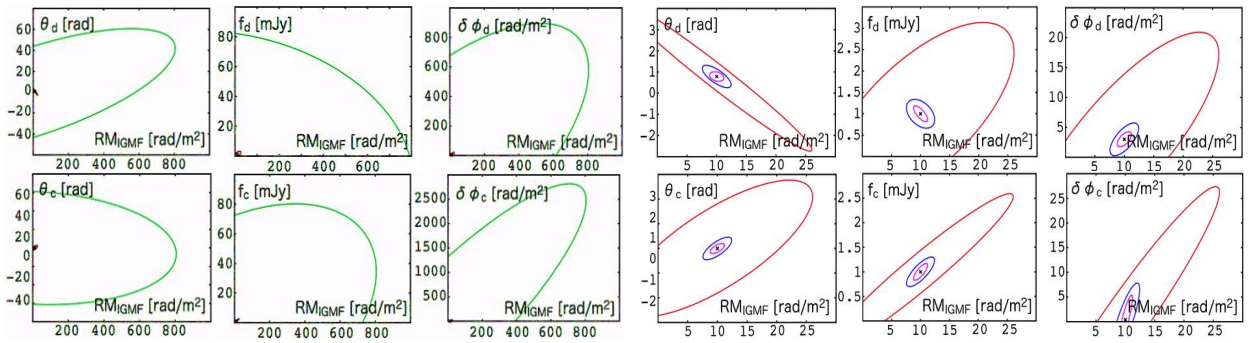
$$F(\phi) = \frac{f_{\rm d}}{\sqrt{2\pi}\delta\phi_{\rm d}} e^{2i\theta_{\rm d}} \exp\left\{-\frac{(\phi-\phi_{\rm d})^2}{2\delta\phi_{\rm d}^2}\right\} + \frac{f_{\rm c}}{\sqrt{2\pi}\delta\phi_{\rm c}} e^{2i\theta_{\rm c}} \exp\left\{-\frac{(\phi-\phi_{\rm c})^2}{2\delta\phi_{\rm c}^2}\right\}$$

2 Gaussians, 8 params

ASKAP-12, 1 hour, 1 mJy source, RM_{IGMF}=10 rad/m²
—700-1000 MHz —1150-1450 MHz
—(700-1000+1150-1450) MHz —700-1800 MHz







❖Null IGMF can be excluded at ~3σ significance

TA+ (2014b), PASJ, 66, 65; Govoni, TA+ (2014)

Utilizing extragalactic FRBs

❖ Two steps to evaluate the IGMF from FRBs

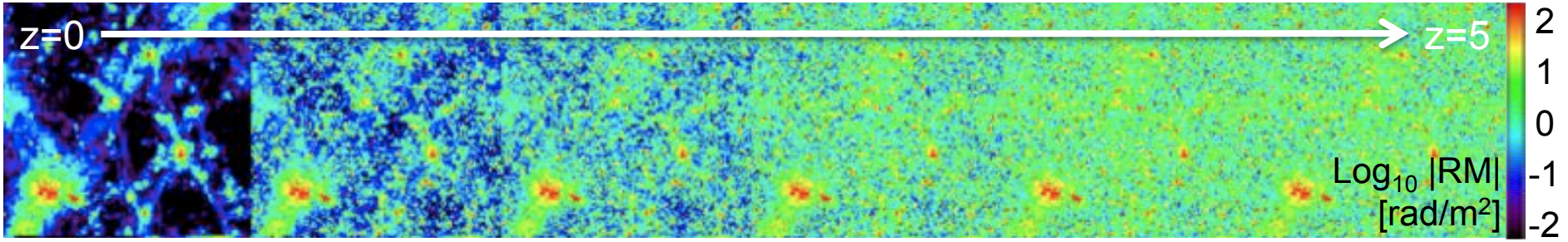
Extraction of IGMF's DM and RM from observed ones

+

Estimation of the IGMF strength from the extracted DM and RM

Traditionally,

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



❖ Numerical simulations

- Ryu et al. (2008)
- ΛCDM (Ω_{m0}=0.27,$\Omega_{\Lambda 0}$=0.73, H_0=70)
- IGMF only

❖ Mock Observations

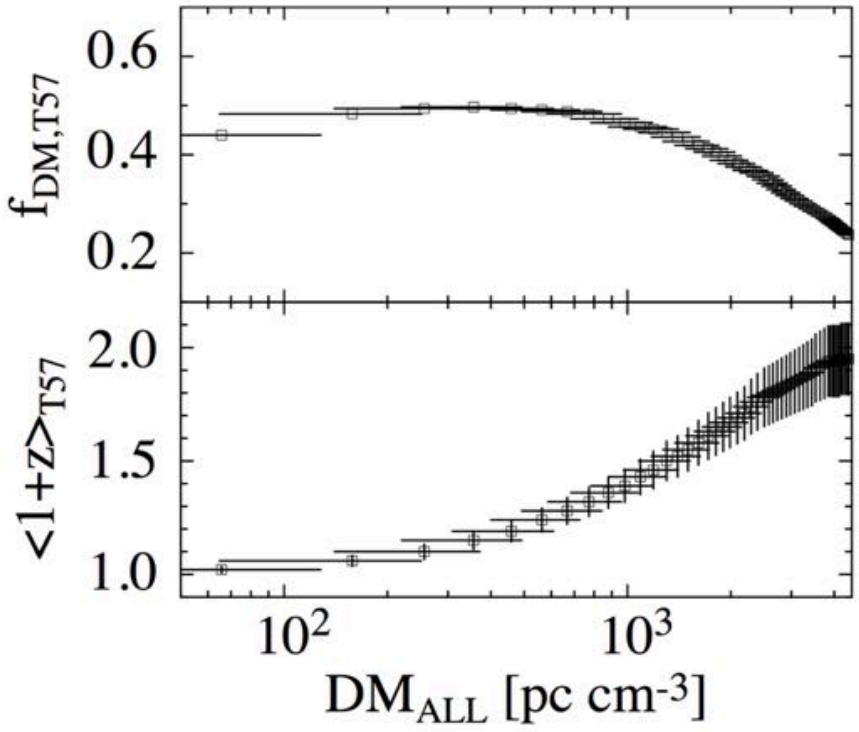
- Akahori & Ryu (2011)+
- Random distribution of FRBs
- 400 FRBs/deg^2

TA, Ryu, Gaensler (2016) ApJ, 824, 105

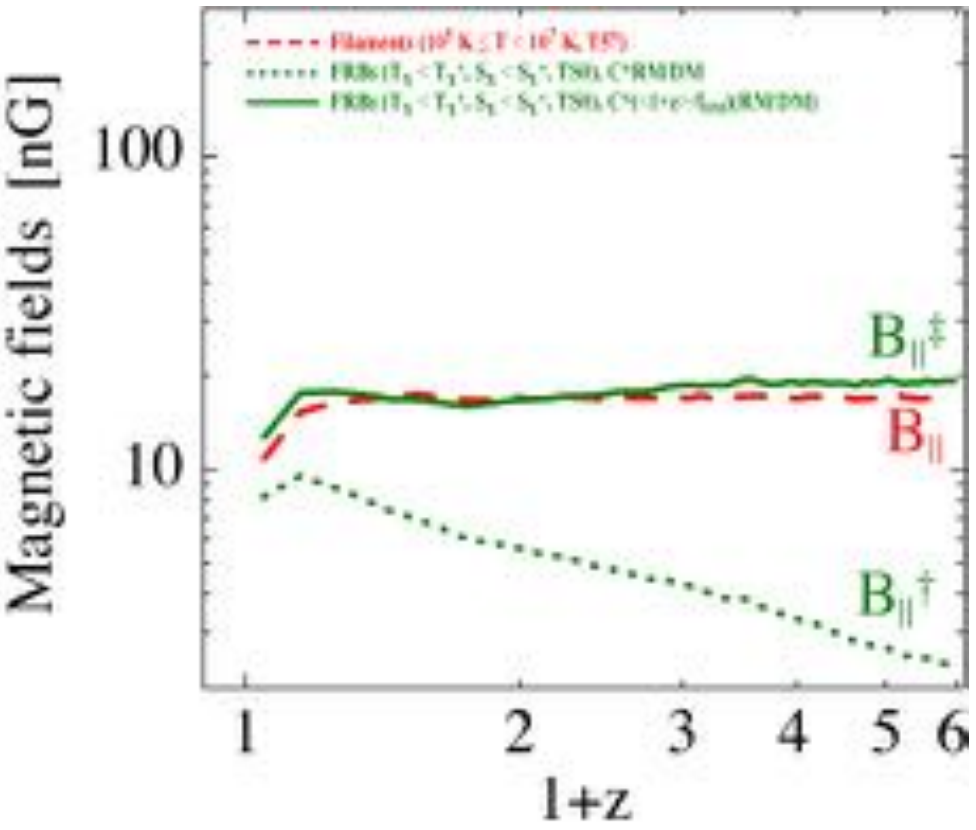
Utilizing extragalactic FRBs

- **DM & RM of Pol. FRB (but $B_{||} \neq B_{||}^{\dagger} \sim RM/DM$)**
  - RM grids ~ *O*(10-100)/deg^2/yr?

$$B_{||}^{\ddagger} = \frac{\langle 1+z \rangle}{f_{DM}} B_{||}^{\dagger} = \frac{\langle 1+z \rangle}{f_{DM}} \frac{C_D RM}{C_R DM}$$



Ω_{M0}=0.27, $\Omega_{\Lambda 0}$=0.73, H=70

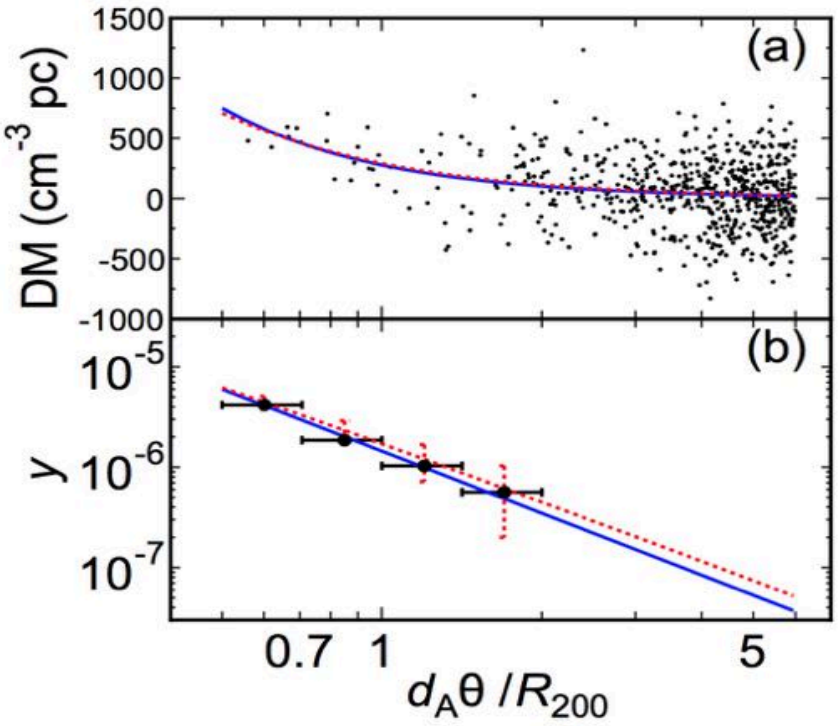


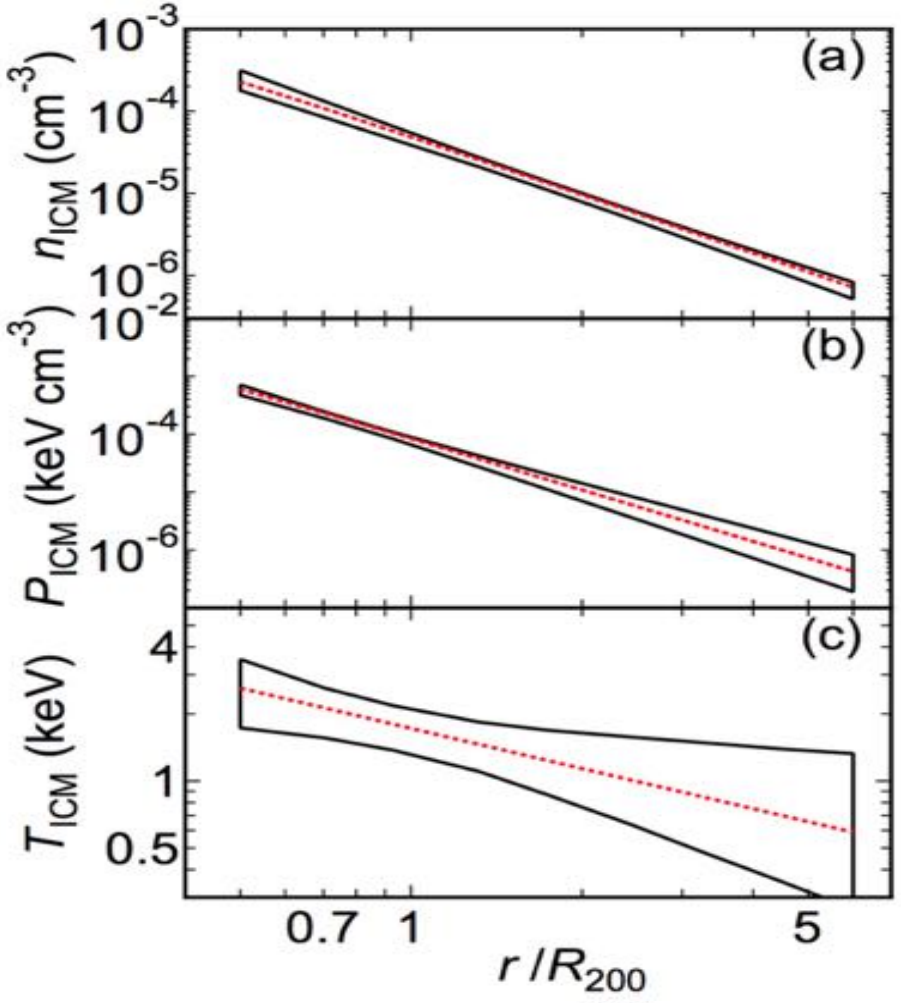
TA, Ryu, Gaensler (2016) ApJ, 824, 105

Utilizing extragalactic FRBs

- **Probing WHIM *around* galaxy clusters**
  - ***n*** from FRBs, ***P*** (∝nT) from SZ effects → **T** beyond r_{vir}

N_{FRB} = **20** events /deg^2





Fujita, TA+ 2016, submitted (arXiv:1609.03566)

Summary

- **Introduction**
  - IGM: σ_{RM} ~ several rad/m^2 through filaments up to z=5, 0.1° - 1° scales
- **Model**
  - ISM: σ_{RM} ~ 2-5 rad/m^2 toward Galactic poles, > 1°
  - DIG: σ_{RM} ~ 1-2 rad/m^2 if z>1 or extended (10″) INT
  - INT: σ_{RM} ~ 10/(1+z)^2 rad/m^2 → ~1 rad/m^2 @ z=2
- **Result**
  - RM_{IGMF} → ASKAP, SKA1 (100 /deg^2)
  - SF_{IGMF} → SKA2 (10^3-10^4 /deg^2)
- **Discussion**
  - Faraday Tomography is a very powerful tool
  - FRB can be utilized for this work