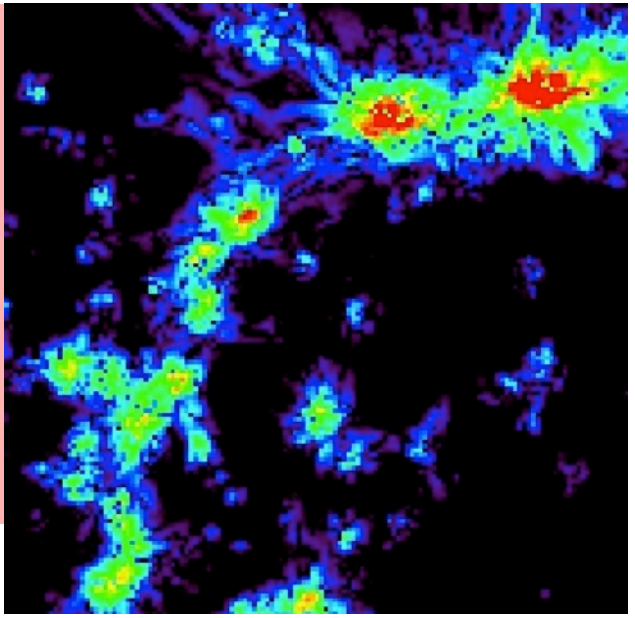
Probing RMs due to Magnetic Fields in the Cosmic Web



SKA-JP
Square Kilometre Array Japanese Consortium

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Cosmic Magnetism Assessment Workshop

2014/1/22-24 @ Jodrell Bank, UK

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Probing RM due to Magnetic Fields in the Cosmic Web

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Key Messages

- Magnetic fields in the cosmic web is a good science case for SKA1
- Better sensitivity & wide frequency coverage are key parameters

1. Science Overview

SKA-JP
Square Kilometre Array
Japanese Consortium

1.1 Background
1.2 Theoretical predictions

1.1 Background (1/3): Inter-Galactic Medium (IGM)

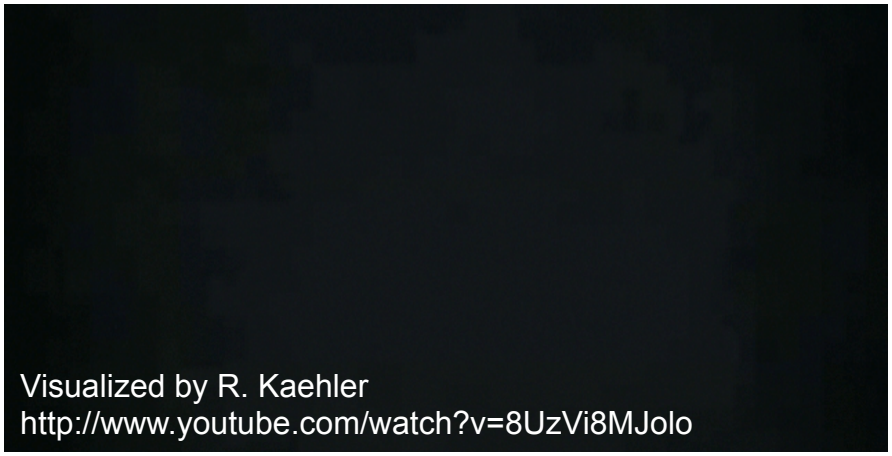
IGM Family

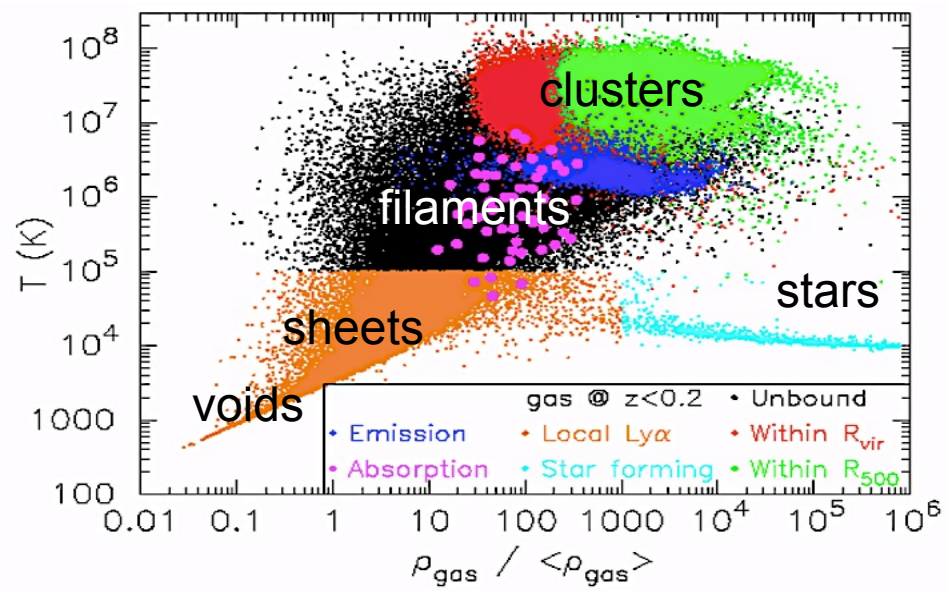
- **Intra-Cluster Medium (ICM)**
  - Galaxy clusters, $T>10^7$ [K]
  - $n\sim10^{-4}$ –10^{-1} [cm^{-3}]
- **Warm-Hot IGM (WHIM)**
  - Galaxy filaments, $T\sim10^{5\text{-}7}$ [K]
  - $n\sim10^{-6}$ –10^{-4} [cm^{-3}]
- **Warm Ionized Medium**
  - Sheets and voids, $T<10^5$ [K]
  - $n\sim10^{-7}$ –10^{-5} [cm^{-3}]

Missing Baryons

Is IGM magnetized?
Can we probe the IGM with SKA1?

Yes!



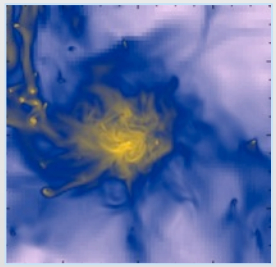


Baryon phase distribution (Piro+07)

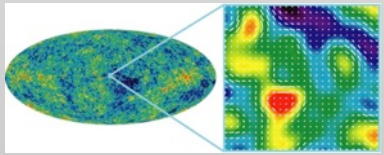
1.1 Background (2/3): Inter-Galactic Magnetic Field (IGMF)

Early Universe

Seeds (10 pG)
Dubois & Tessier 08



Seed Fields
inflation
recombination
reionization

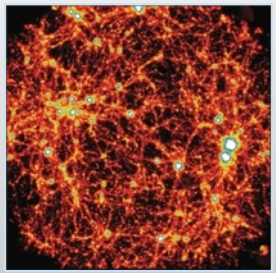


Takahashi+05
Ichiki+06

Galaxy Formation

seed?

Amplification
galactic dynamo



Injections
Donnert+09
Stasyszyn+10

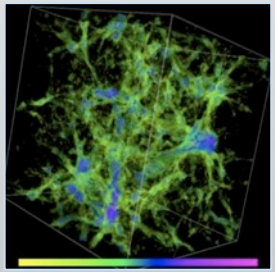
Leakage
jet/wind/ram pressure

Large-scale Structure Formation

Amplification
turbulence dynamo
adiabatic compression

Battery
shocks/instabilities

survive
near galaxies?



Dynamo
Ryu+08

survive
at vold?

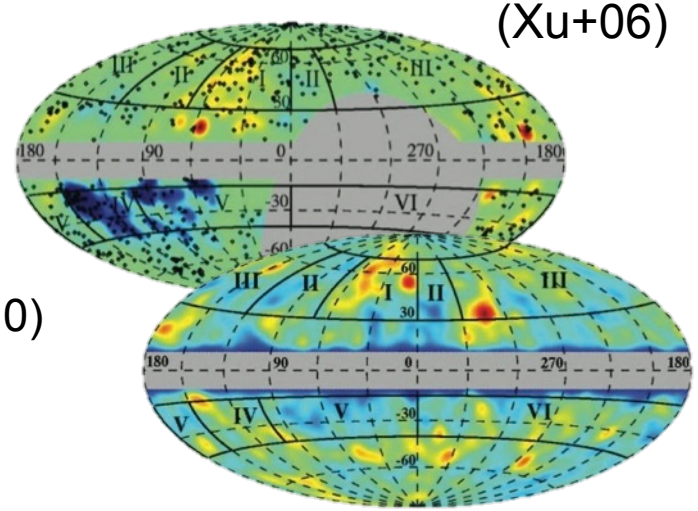
IGMF

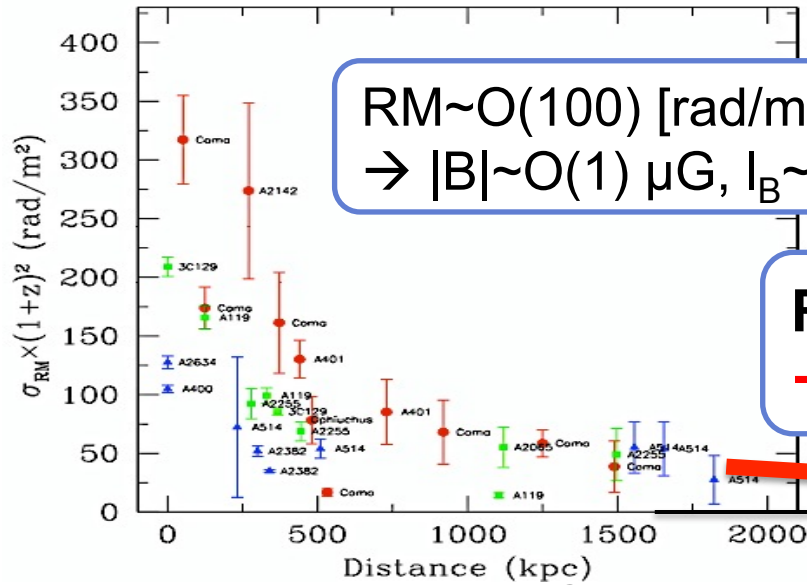
Widrow et al. (2012); Ryu et al. (2012)

1.1 Background (3/3): Faraday Rotation Measure (RM)

- **Local superclusters: RM~9-60 [rad/m^2]**
  - Hercules and Perseus-Pisces (Xu+06)
- **Residual RM: RRM~7-15 [rad/m^2]**
  - Between radio sources and the Galaxy (Hammond+12; See also Kronberg+08)
- **Latitude dependence: RM~6-7 [rad/m^2]**
  - Independent on Gallactic latitude (Schnitzeler 10)
- **Cluster outskirts: RM<50 [rad/m^2]**
  - Radial profile (Clarke+01; Govoni+10)

RM vs galaxies (Xu+06)





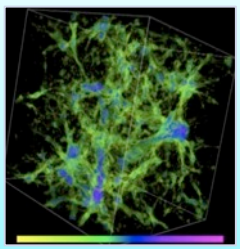
RM~O(100) [rad/m^2] in galaxy clusters
→ |B|~O(1) μG, l_B~O(1-10) kpc?

RM~O(1-10) [rad/m^2] in filaments?
→ |B|~O(1-100) nG?, l_B~O(100) kpc?

3Mpc 4Mpc 5Mpc

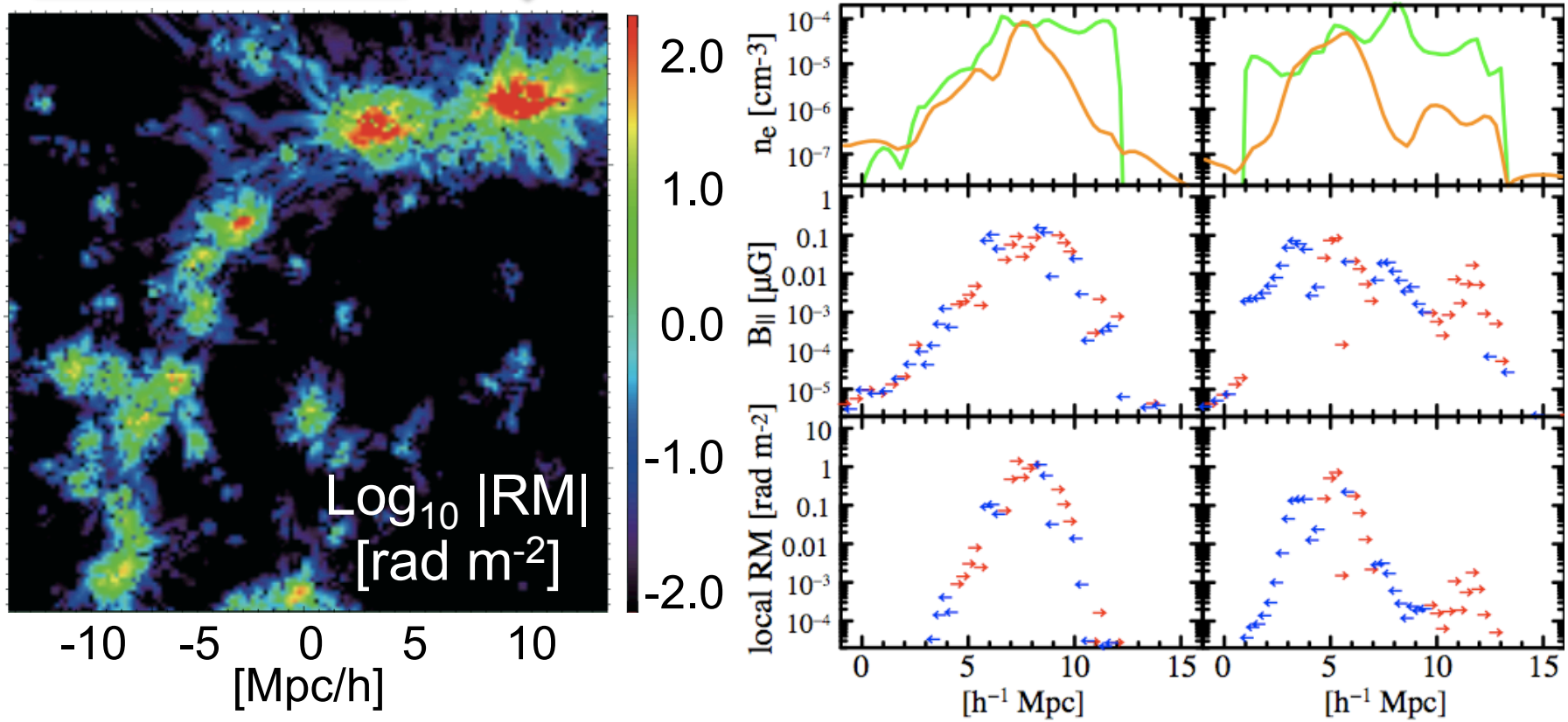
Govoni+10

1.2 Prediction (1/3): IGMF-RM in the Local Universe (100 h^{-1} Mpc)



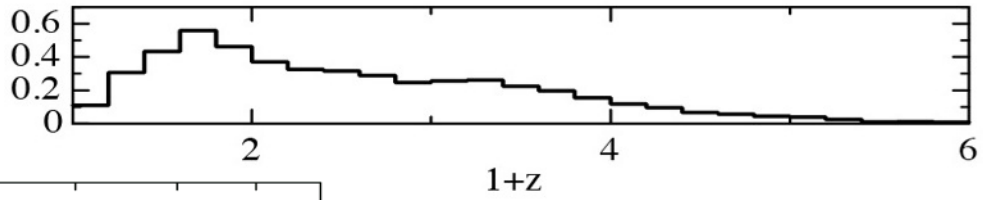
IGMF model Ryu+08

- RM_{rms}~1.4 [rad/m^2] (T_x=10^{5-7} K)
- l_{RM}~ several × 100 [h^{-1} kpc]

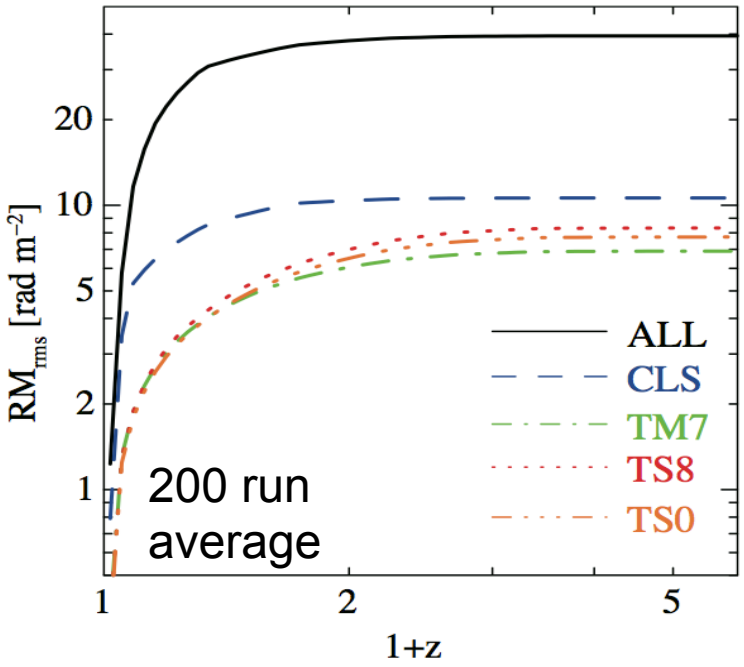


TA, Ryu (2010), ApJ, 723, 476

1.2 Prediction (2/3): IGMF-RM Integrated up to z=5



Source distribution (Wilman+08)



- **Random walk & saturation**
- **RM_{rms}~7-10 [rad/m^2] ($T_x=10^{5-7}$ 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]

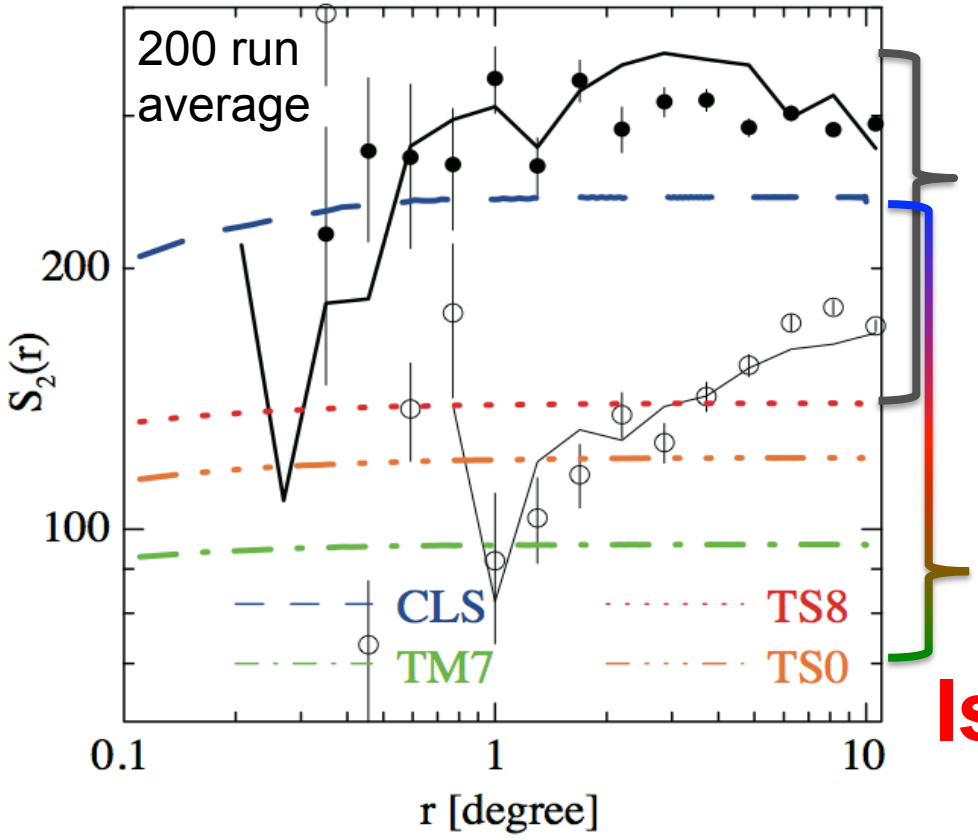
TA, Ryu (2011), ApJ, 738, 134

1.2 Prediction (3/3): IGMF-RM Integrated up to z=5

n-th order structure function (SF)

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

❖ **Flat S_2 at >0.2° with 100-200 [rad²/m⁴]**



- 900 deg² FOV -

←South Galactic Pole
●: Mao+ (10) WSRT+ACTA
—: Stil+ (11) NVSS(VLA)

←North Galactic Pole
◯: Mao+ (10) WSRT+ACTA
—: Stil+ (11) NVSS(VLA)

←Predictions
Color: Akahori, Ryu (2011)

Is RM_{IGMF} measurable?
→Yes!

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

2. Cosmic Web Science Assessment

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Square Kilometre Array Japanese Consortium

2.1 Statistical Approach (Sensitivity)

2.2 Faraday RM Synthesis (Frequency)

2.1 Statistical Approach (1/4): Multiple RM Components

- **Observed RM contains multiple RM contributions**
  - INT: intrinsic RM associated with the polarized source
  - IGM: RM due to the intergalactic magnetic field
  - EXG: RM of intervening galaxies/clouds
  - ISM: RM due to the Galactic magnetic field
  - ERR: RM of ionospheric, instrumental, etc
- **COM: combined RM (observed RM)**
  - $\mu_{COM} = \mu_{INT} + \mu_{IGM} + \mu_{EXG} + \mu_{LGG} + \mu_{ISM} + \mu_{ERR}$
  - $\sigma_{COM}^2 = \sigma_{INT}^2 + \sigma_{IGM}^2 + \sigma_{EXG}^2 + \sigma_{LGG}^2 + \sigma_{ISM}^2 + \sigma_{ERR}^2$

2.1 Statistical Approach (2/4): Can we extract RM due to the IGMF?

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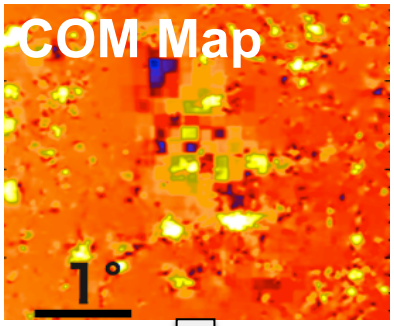
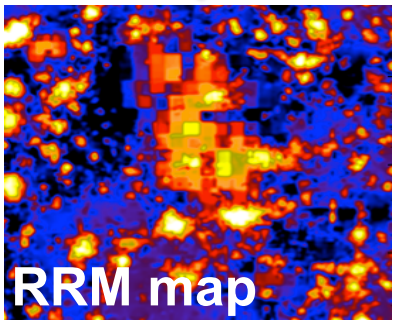


INT filter

EXG filter

ISM filter

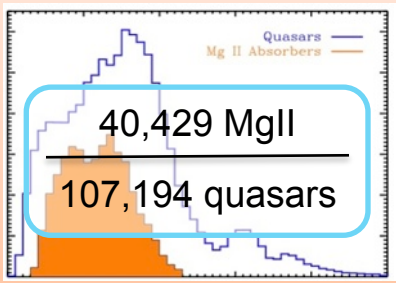
ERR filter



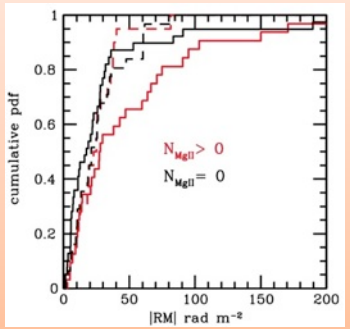
Remove "obscured" sources
which indicate depolarization signals

Spatial resolution & high frequency

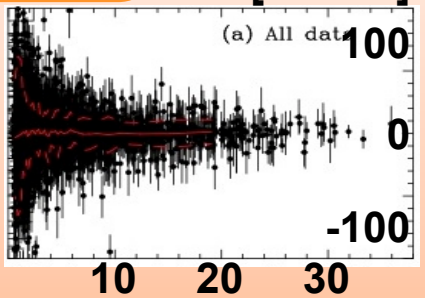
Remove suspicious LOSs
MgII absorber system & depolarization



Zhu, Merand 13



Bernet+ 12



Hammond+ 12

Look Galactic Pole &
Apply high-pass filter (~1°-2°)

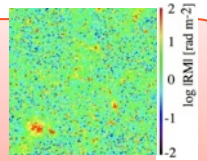
FOV at least a couple of tens deg^2

Remove low S/N sources
Need, say, 10 ± 0.1 rad/m^2 level

Polarization purity & sensitivity

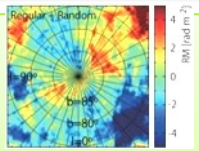
TA, Gaensler, Ryu submitted

2.1 Statistical approach (3/4): Extraction Model/Assumption

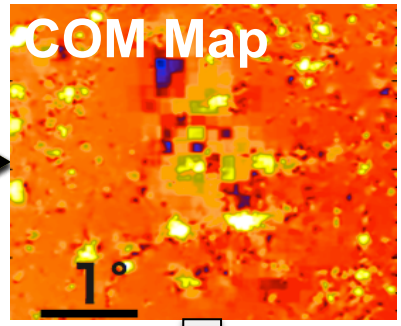
IGM map

Akahori, Ryu 2011

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

EXG map
not available

ISM map

Akahori+ 2013

ERR map
random
σ_{ERR}=1 rad/m^2

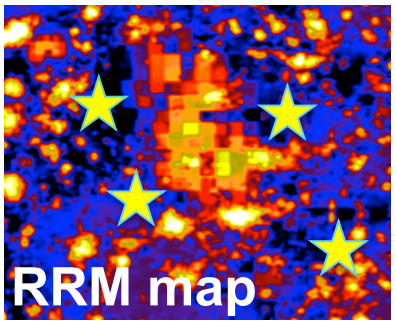


INT filter

EXG filter

ISM filter

ERR filter



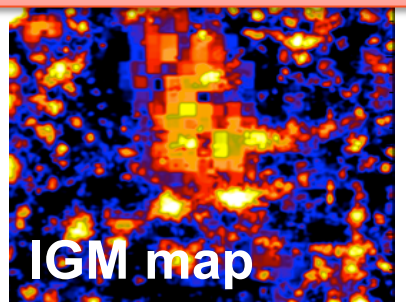
Choose high-z sources
$\sigma_{INT}(z=2)$~1 rad/m^2

Assume 50 % of sources
are no EXG sources

Apply high-pass filter
filtering scale at ~1°-2°

Use all sources
mean RM error ~1 rad/m^2

How many sources do we need to extract statistics of IGMF-RM?



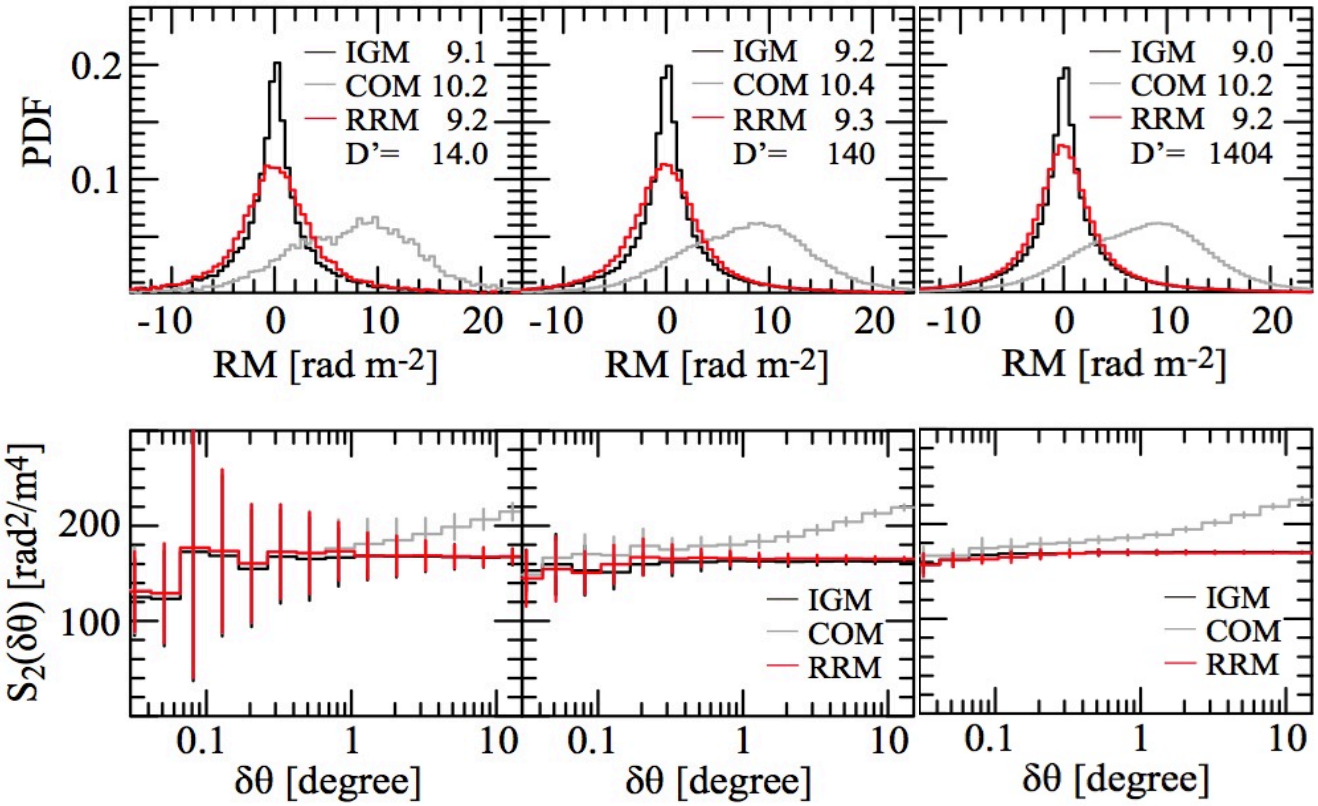
TA, Gaensler, Ryu submitted

2.1 Statistical approach (4/4): Results

900 deg² FOV, south Galactic pole, z>2 sources only
— IGM — COM — RRM

※Number under discussion (See Larry's talk & §3.1 of our memo)

SKA1-Sur 100 RM/deg²	SKA1-Sur 1000 RM/deg²	SKA2 Deep? 10000 RM/deg²
3h, 2 μJy/bm, S/N=8	300h, 0.2 μJy/bm, S/N=8	



- Our selection criteria: **~14%** of sources are available
- **100 RM/deg²** data may allow to extract σ_{IGM}
- **1000 RM/deg²** data may allow to extract $S_{2,IGM}$ **down to ~0.1°**

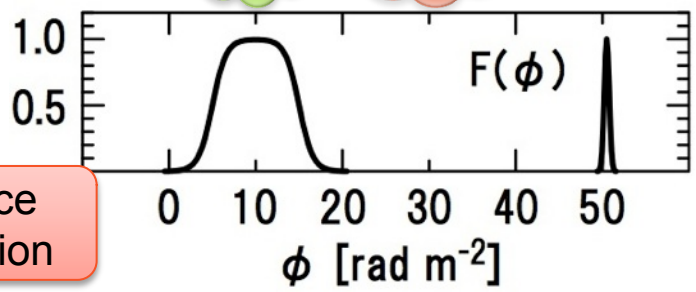
TA, Gaensler, Ryu submitted

2.2 Faraday RM Synthesis (1/4): Concept & Direct Reconstruction

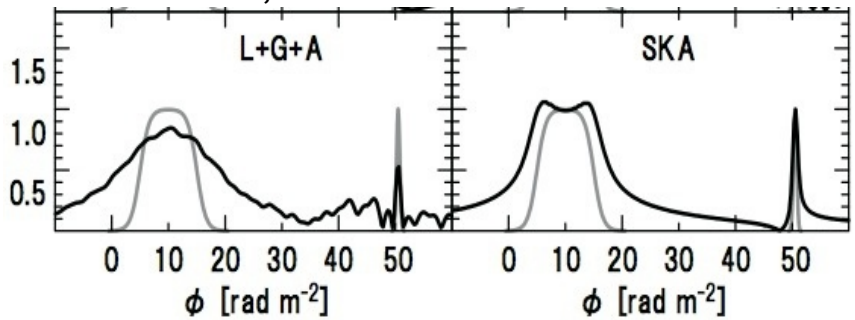
Strategy A

Galactic IGMF Quasars

Source selection

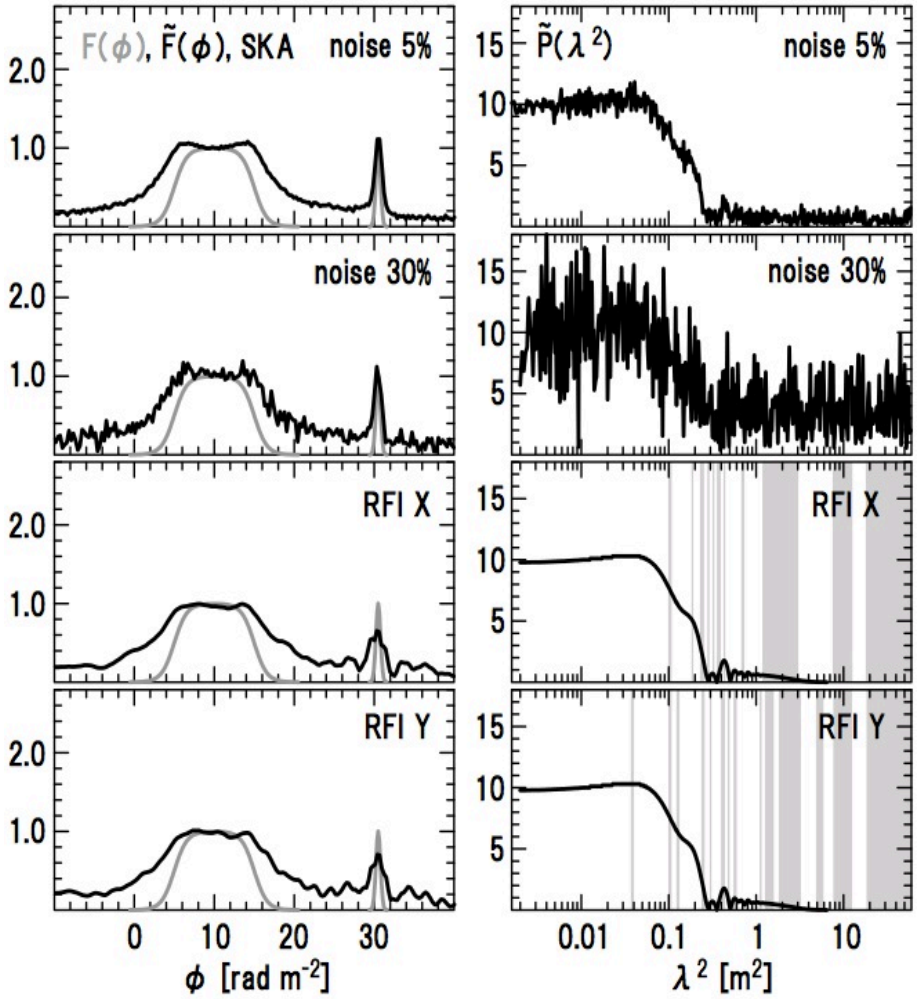


— model, — reconstructed



❖ **SKA full band (0.07-10 GHz) is very powerful**

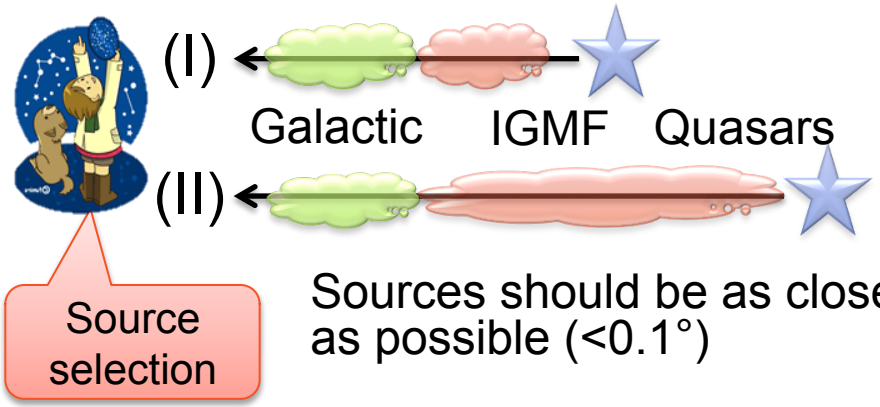
Strategy A, SKA, RM_{IGMF}=10 rad/m²



TA, Takahashi+, submitted

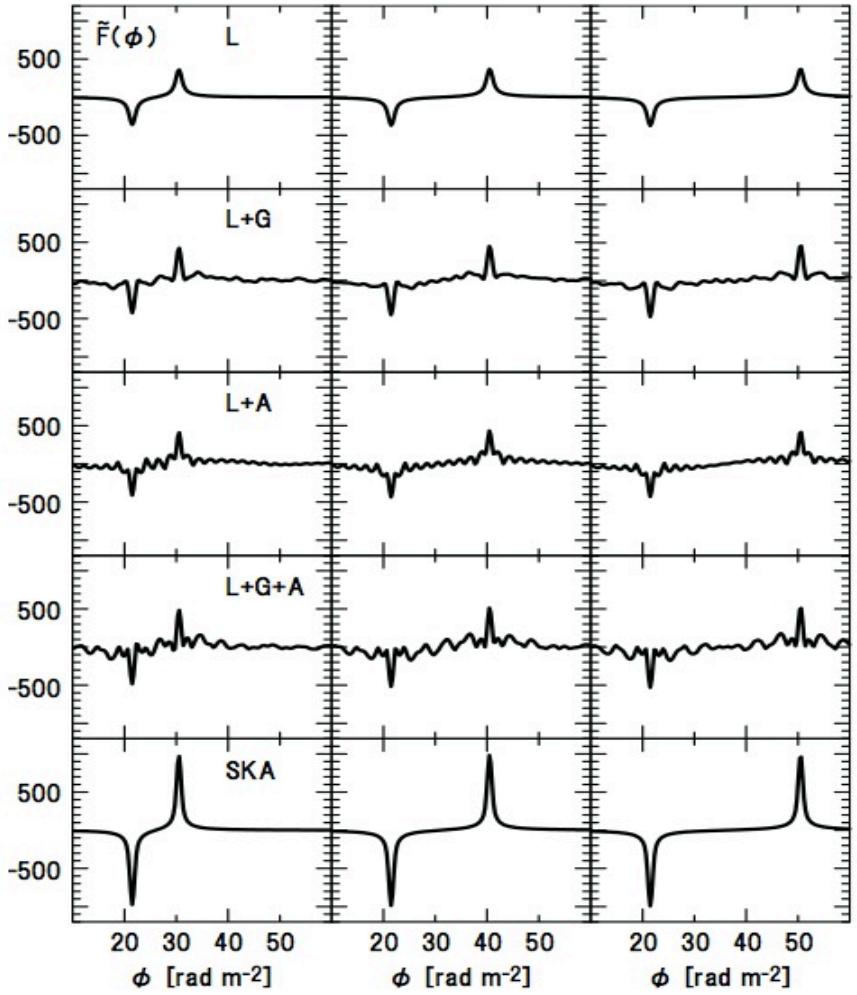
2.2 Faraday RM Synthesis (2/4): Concept & Direct Reconstruction

Strategy B



❖ **SKA full band (0.07-10 GHz) is very powerful**

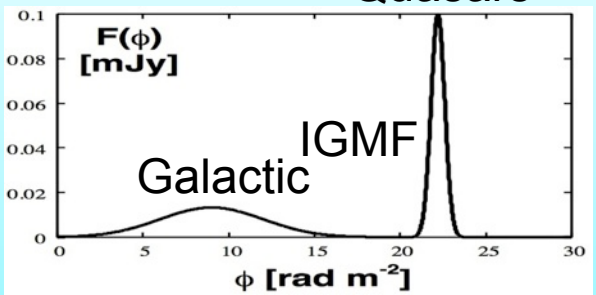
Strategy B, SKA, RM_{IGMF}=10 rad/m²



TA, Takahashi+, submitted

2.2 Faraday RM Synthesis (3/4): QU-fitting decomposition

Model FDF



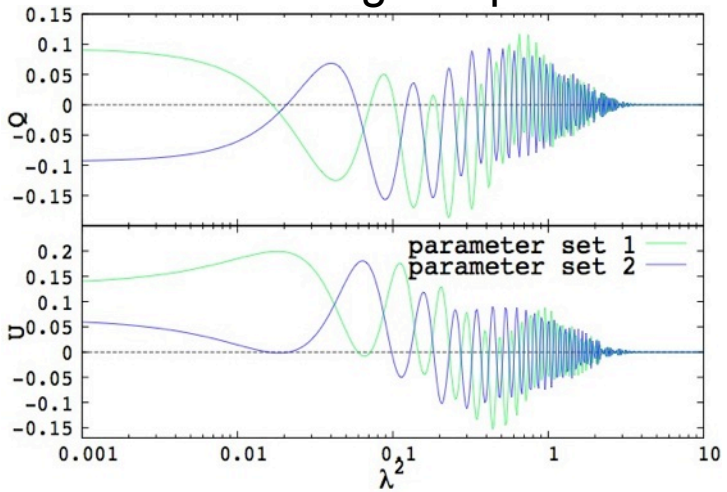
$$F(\phi) = \frac{f_{\rm d}}{\sqrt{2\pi}\delta\phi_{\rm d}} e^{2i\theta_{\rm d}} \exp\left\{-\frac{(\phi-\phi_{\rm d})^2}{2\delta\phi_{\rm d}^2}\right\} + \frac{f_{\rm c}}{\sqrt{2\pi}\delta\phi_{\rm c}} e^{2i\theta_{\rm c}} \exp\left\{-\frac{(\phi-\phi_{\rm c})^2}{2\delta\phi_{\rm c}^2}\right\}$$

Definisions of model parmeters

$$RM_{\rm IGMF} = (\phi_{\rm c} - 3\delta\phi_{\rm c}) - (\phi_{\rm d} + 3\delta\phi_{\rm d})$$

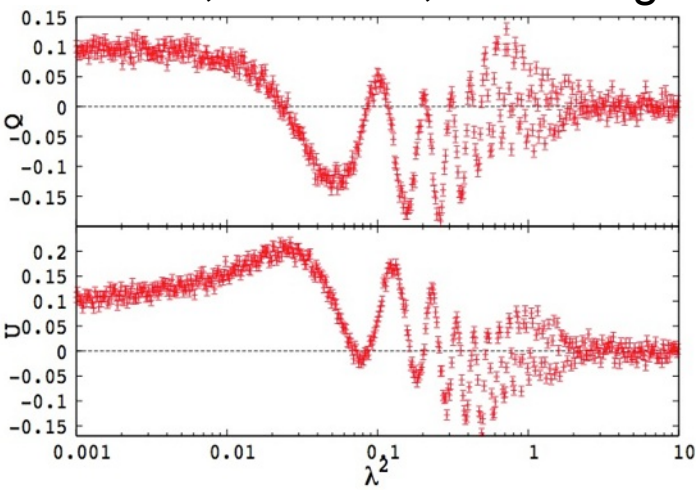
Fourier transform

Model Q & U for given parameters



fit & seek the best parameters

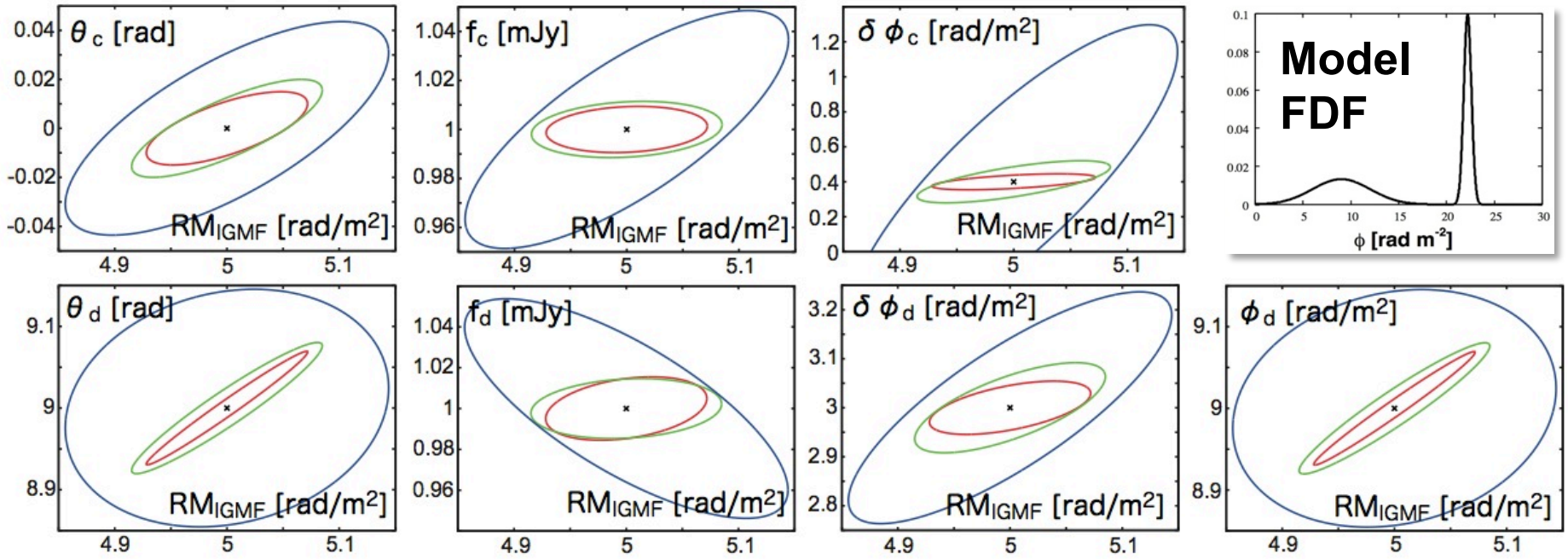
Mock Q & U
Noise, channels, λ-coverage



Ideguchi, Takahashi, TA+ (2013)

2.2 Faraday RM Synthesis (4/4): QU-fitting decomposition Results

SKA1-Survey, 1 hr, 1 mJy source, RM_{IGMF}= 5 rad/m², 3σ confidence
—650-1670 MHz —500-1500 MHz —350-1350 MHz



- Full frequency coverage is desirable. But if it is not initially feasible, going to lower frequencies would be better for SKA1-Survey PAF Band 2

Ideguchi, private communication

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Summary

- **RM due to magnetic fields in the cosmic web**
  - σ_{RM}~1 rad/m^2 for a filament, σ_{RM}~several-10 rad/m^2 up to z=5
- **Key specification (major/minor)**
  - **Sensitivity:** as better as possible. Proposing continuum sensitivities (Sur-3.72, Low-2.06, Mid-0.72 μJy/hr$^{1/2}$) are essential
  - **Frequency**: as wide as possible in λ^2 space. If we survey with Low +Sur, we should apply both PAF band1 (350-900 MHz) and band 2 (650-1670 MHz), or band 2 should go to e.g., 500-1500 MHz
  - **Polarization purity:** 10±0.1 rad/m^2 (so <1%?) but 1 rad/m^2 error OK
  - **FOV:** Toward the poles. ~900 deg^2 is reasonable (prev. observations)
  - **Spatial resolution:** need to dignose depolarization effects
  - **High Frequency:** need to dignose depolarization effects
  - **Largest angular scale:** proposing spec. (~1°) is satisfactory
- **Remarks**
  - Need to develop source selection schemes/criteria
  - How many sources will we obtain with SKA1?