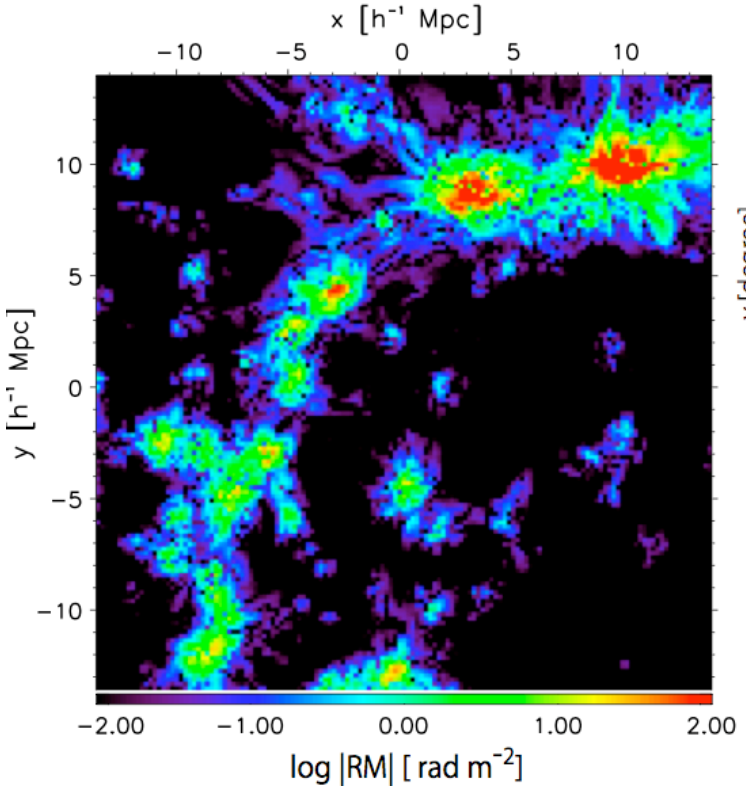
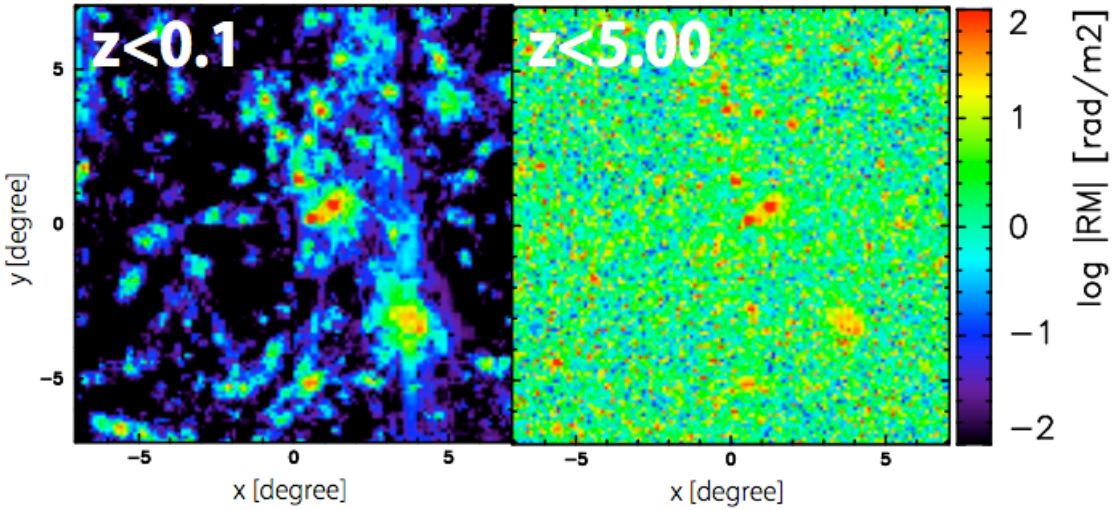
Exploring Faraday Rotation Measure due to the Intergalactic Magnetic Field with the SKA





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Contents

- **Self-Introduction**
- **Introduction**
- **Faraday Rotation Measure (RM) due to the Intergalactic Magnetic Field (IGMF)**
  - Part 1. present-day local universe
  - Part 2. cosmological effects
  - Part 3. galactic foreground
- **Summary**
- **Toward the SKA**

Introduction: Baryon in Our Universe

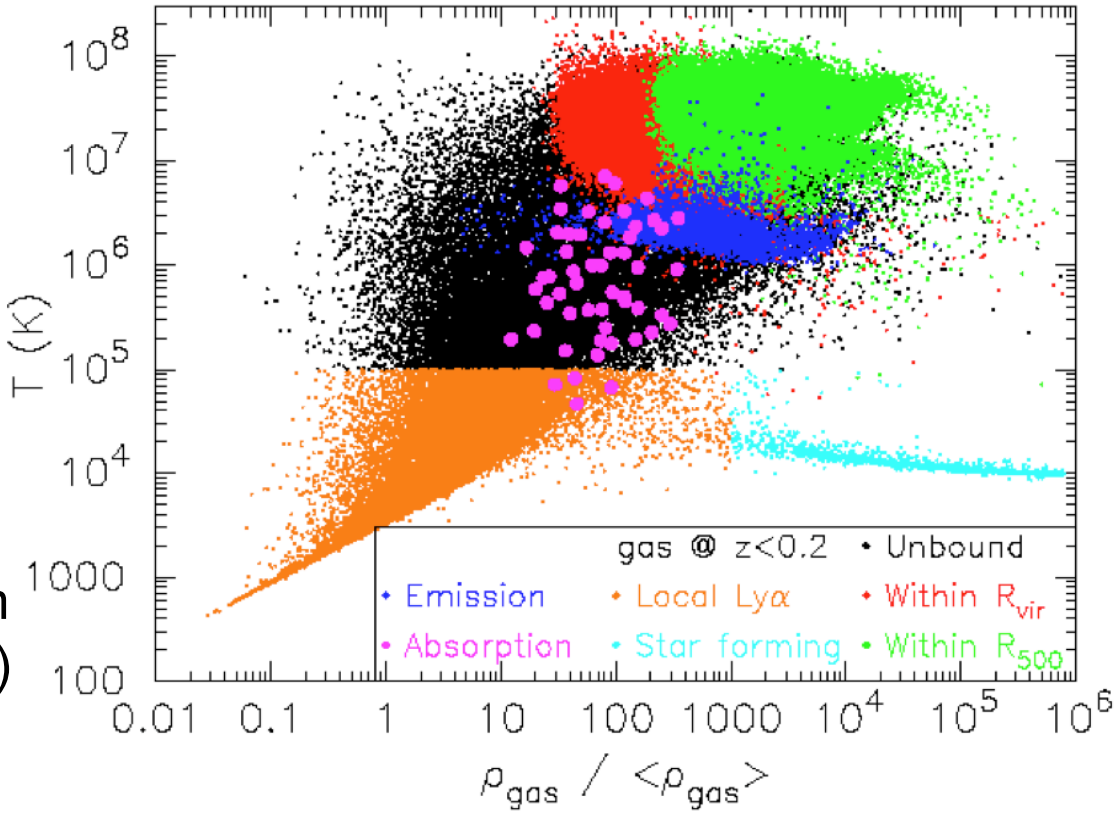
Ionized Medium
ICM/WHIM

Magnetized?
Inter-Galactic Magnetic Field
IGMF

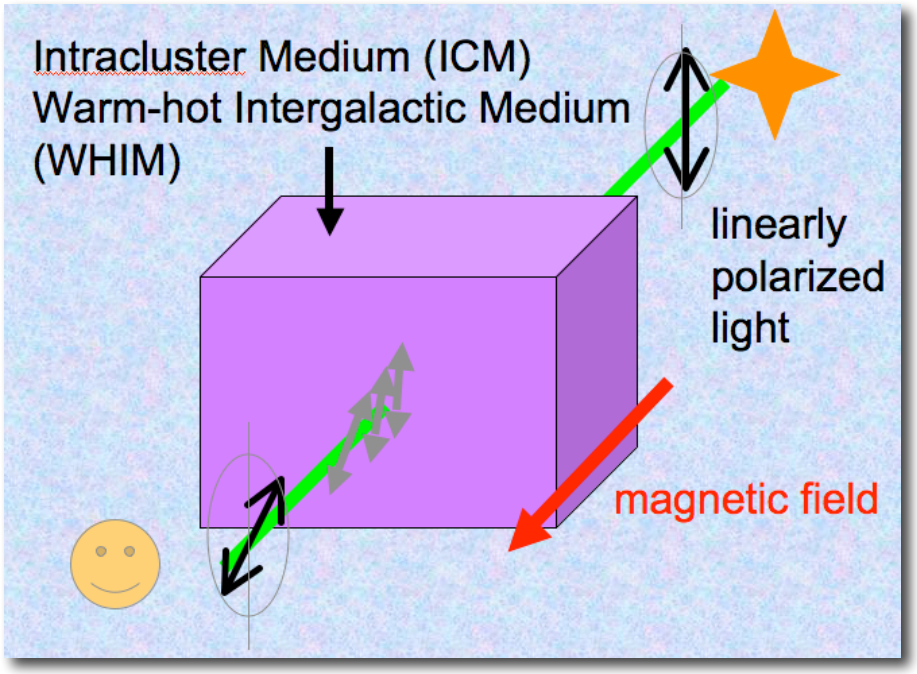
Baryon Phase

- **ICM (>10^7K)**
  Intra-Cluster Medium
- **WHIM ($10^{5\text{-}7}$K)**
  Warm-Hot Intergalactic Medium
- **Others**

Baryon Phase Diagram from cosmo. simulation (Piro+ 07)



Introduction: Faraday Rotation Measure



One of a few methods to explore the intergalactic mangetic field (IGMF)

$$\Phi(\lambda) = \mathrm{RM} \times \lambda^2 + \Phi_0(\lambda)$$

Φ: rotation angle [rad]
Φ_0: intrinsic rotation angle [rad]
λ: wavelength [m]

Theory

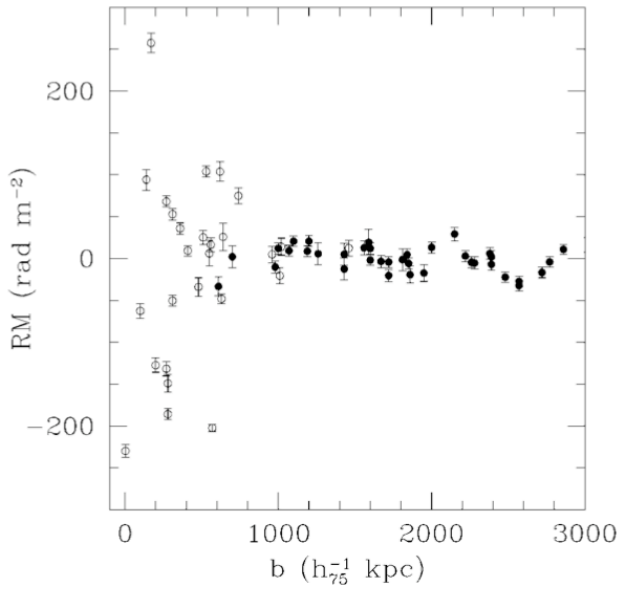
$$\mathrm{RM} = 811.9 \int_0^L n_e B_{||} dl \ \ \mathrm{rad\ m^{-2}}$$

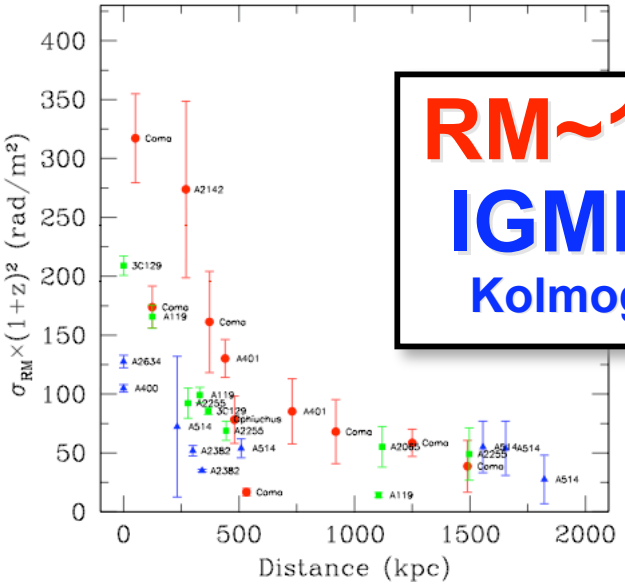
n_e: thermal electron density [cm^{-3}]
$B_{||}$: line-of-sight IGMF strength [μG]
L : depth along the line-of-sight [kpc]

Observation

$$\mathrm{RM} = \frac{\Phi(\lambda_1) - \Phi(\lambda_2)}{\lambda_1^2 - \lambda_2^2}$$

Introduction: RM in Galaxy Clusters





RM~100 [rad m^{-2}]
IGMF~1-10 [μG]
Kolmogorov Spectrum (?)

Radial RM profiles of 16 Abell clusters (Clarke, Kronberg, Bohringer 01)

Radial RM profiles and model fitting (Govoni+ 10)

Power-law IGMF model

$$\langle \boldsymbol{B} \rangle(r) = \langle \boldsymbol{B} \rangle_0 \cdot \left(1 + r^2/r_c^2\right)^{-\frac{3}{2}\mu}$$

$$|B_k|^2 = C_n^2 k^{-n}$$

(e.g., Murgia+ 04)

Kolmogorov spectrum (n=11/3)

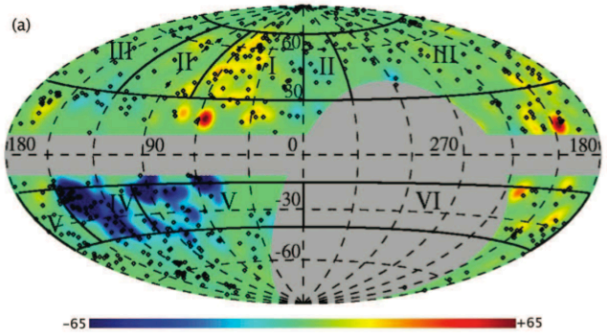
(e.g., Guidetti+ 08)

turbulent amplification of the IGMF?

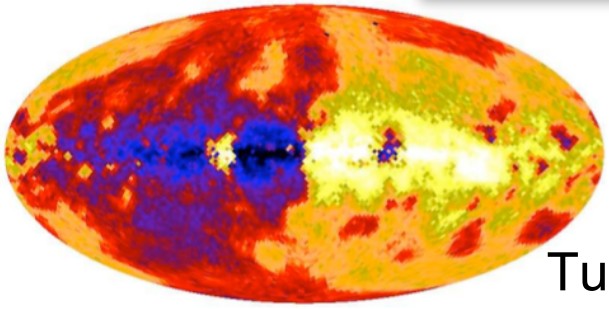
Introduction: RM in Filaments of Galaxies

Observation & Theory

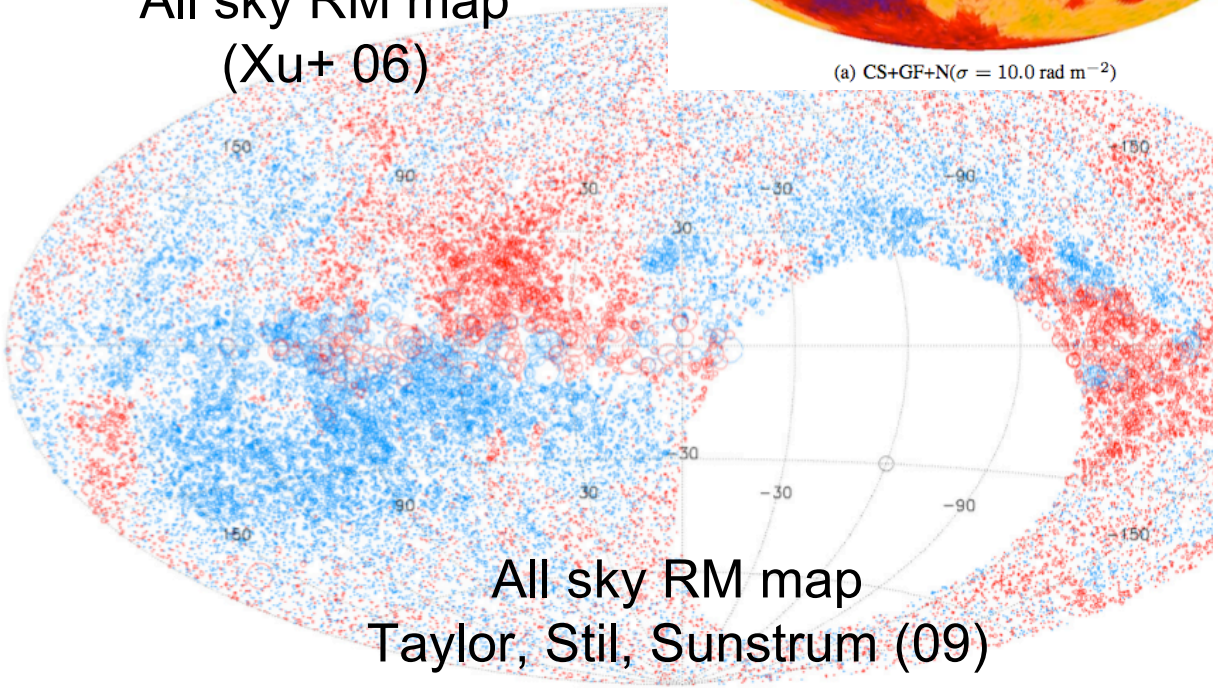
RM<10 [rad m^{-2}]?
IGMF<1 [μG]?



All sky RM map
(Xu+ 06)

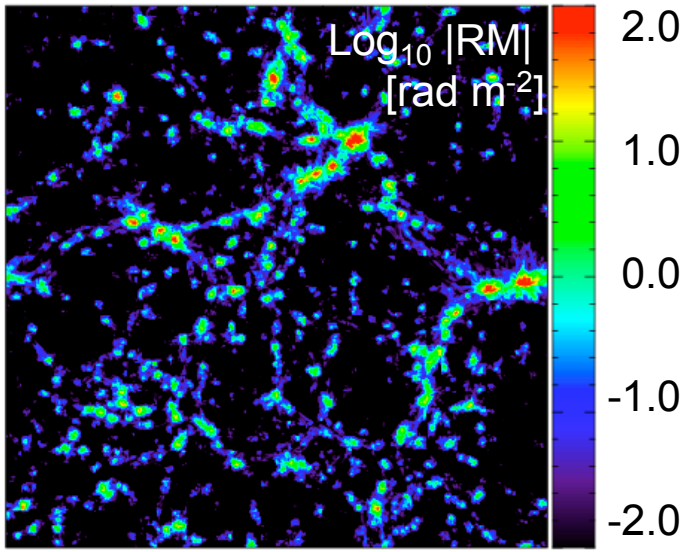


SPMHD simulation
Stasyszyn+ (10)



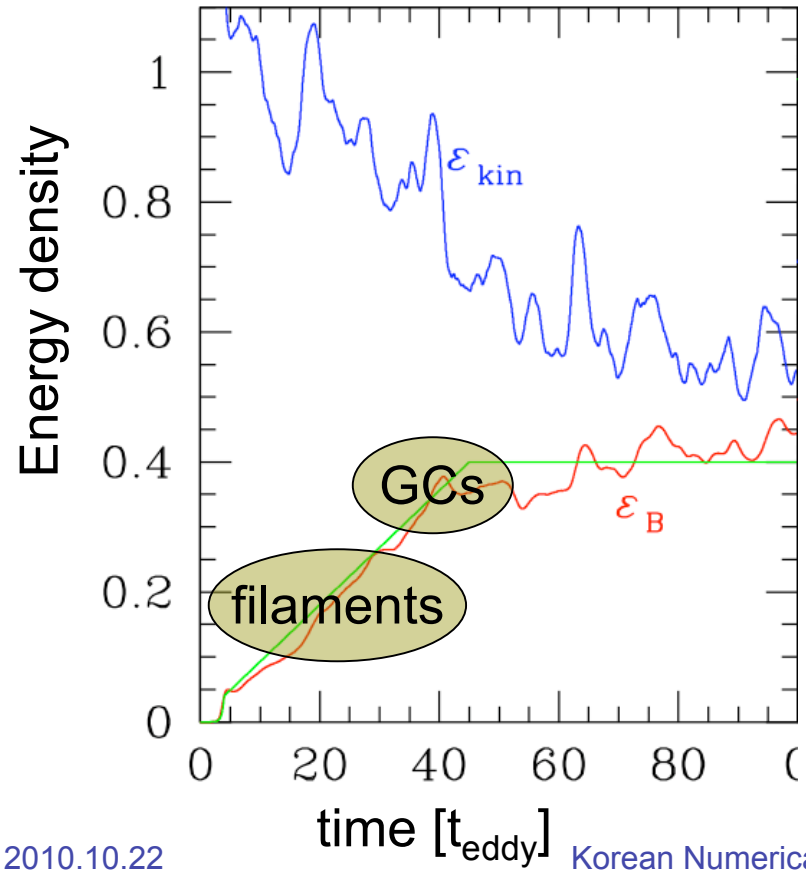
All sky RM map
Taylor, Stil, Sunstrum (09)

Turbulence dynamo model
Akahori, Ryu (10)



Model: Our Model for the IGMF

- **Goal:** Predict RM of WHIM & test it by future obs.
- **Method:** Simulation of the cosmological structure formation + turbulence dynamo model (Ryu+ 08)
  - MHD…still hard to treat evolution of turbulence and amplification of the IGMF correctly



① Calculate curl component of flow motion & its energy ε_w

② Regard ε_w as the turbulence energy ε_{turb}

③ Adopt the growth model $\varepsilon_B/\varepsilon_{turb}=f(t/t_{eddy})$ & $B=(8\pi\varepsilon_B)^{1/2}$

④ Direction … passive field

Model: Prediction of RM

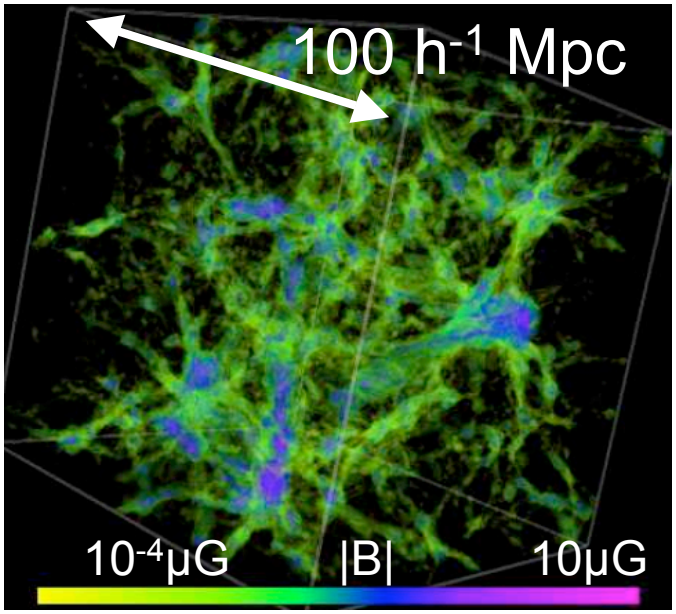
- Estimation of RM in filaments (Cho, Ryu 09)

$$\sigma_{RM} \sim 1.5 \left(\frac{\bar{n}_e}{10^{-5}\mathrm{cm}^{-3}}\right)\left(\frac{B_{rms}}{0.3\ \mu\mathrm{G}}\right)\left(\frac{L_{int}}{300\mathrm{kpc}}\ \frac{L}{5\mathrm{Mpc}}\right)^{1/2} \mathrm{rad\ m}^{-2}$$

typical value in filaments

density-weighted average (Ryu+ 08)
$\langle(\rho B)^2\rangle^{1/2}/\langle\rho\rangle$

expected length scales based on MHD turbulence simulations (Cho & Ryu 09)

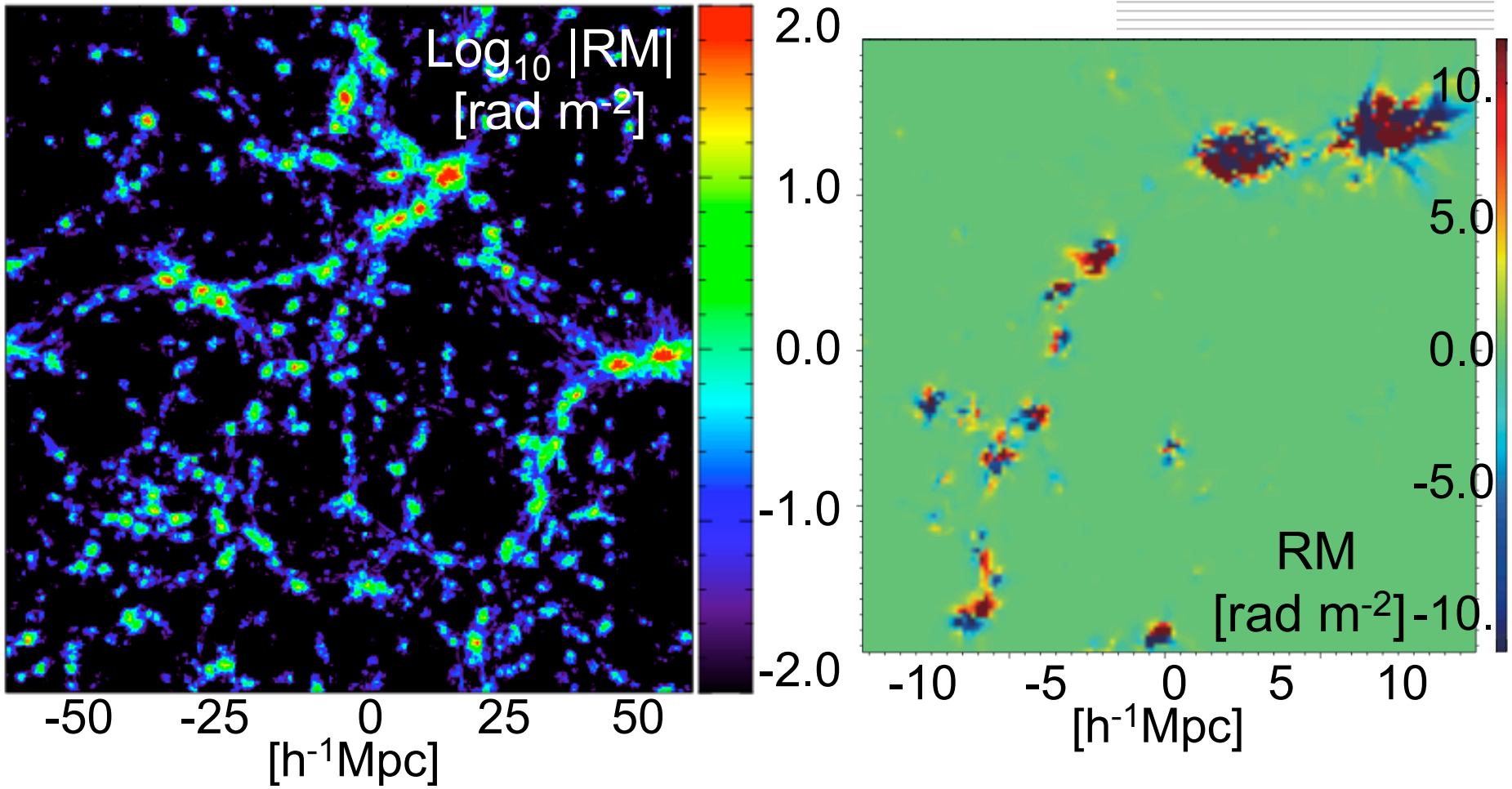


Ryu+ (08)

My work

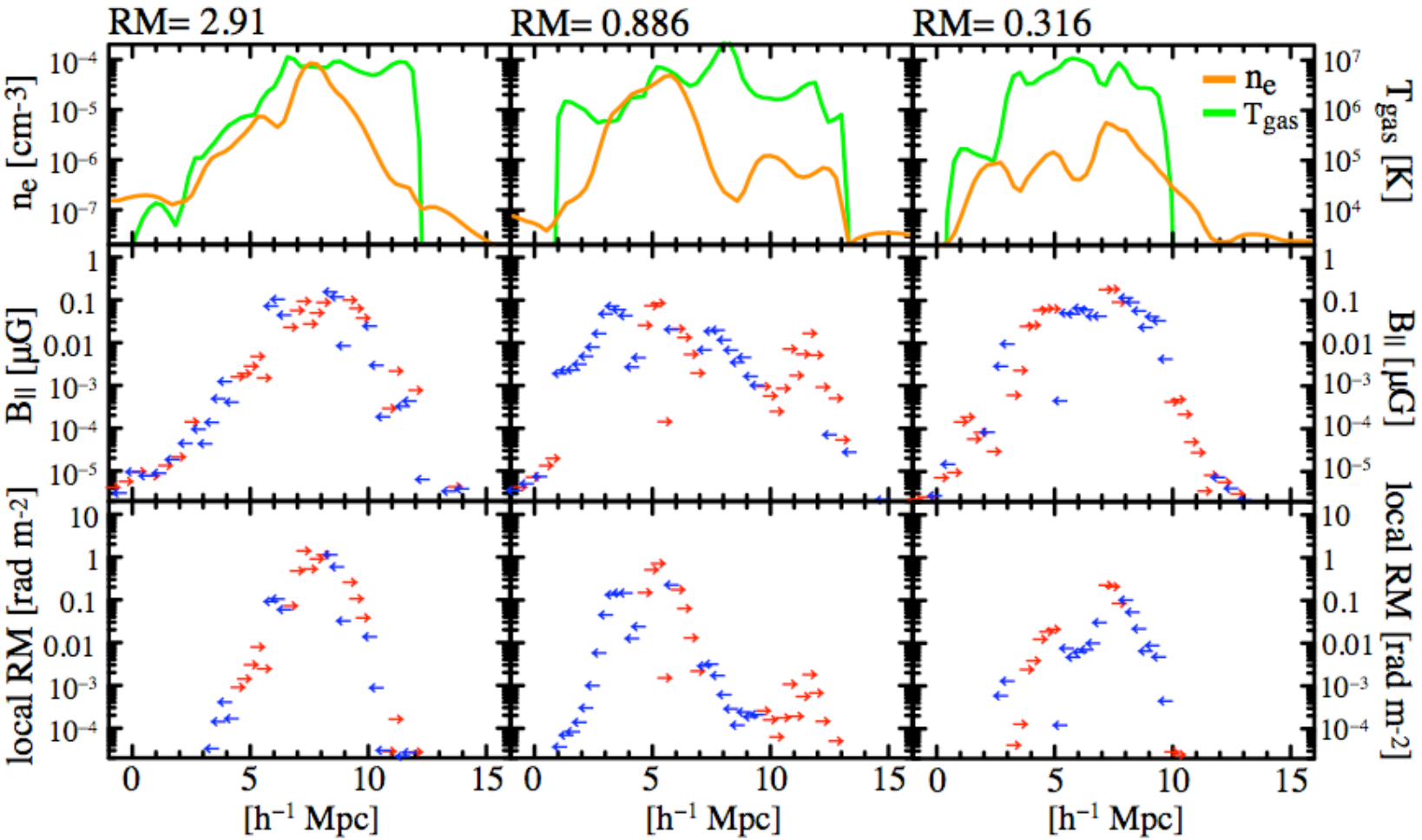
Using a model IGMF, we explore detailed structure and statistical properties of RM due to the IGMF in filaments

1 Present-day Local Universe: 2D Map



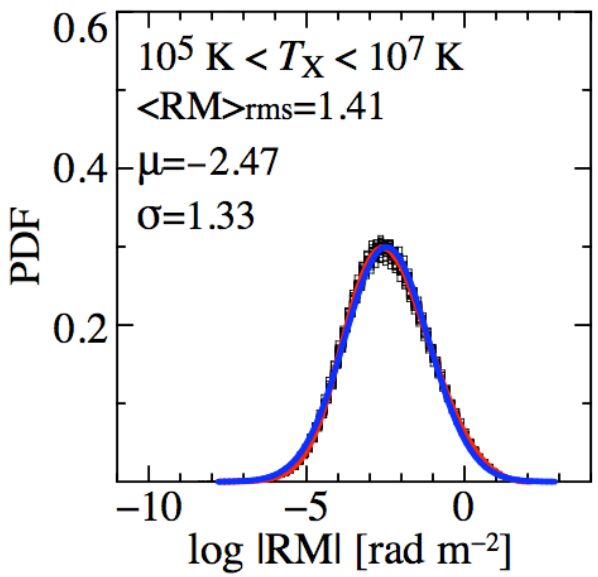
- **RM ~100 (GCs), ~10 (Groups), ~0.01-1 (filaments)**
- Mixture of positive and negative RM, that reflects the randomness and the coherence scale of IGMFs in the LSS

1 Present-day Local Universe: 1D Profile



- Inducement of RM is a random walk process with the coherence length < path length, but is dominated by the contribution from the density peak along LOS

1 Present-day Local Universe: Statistics



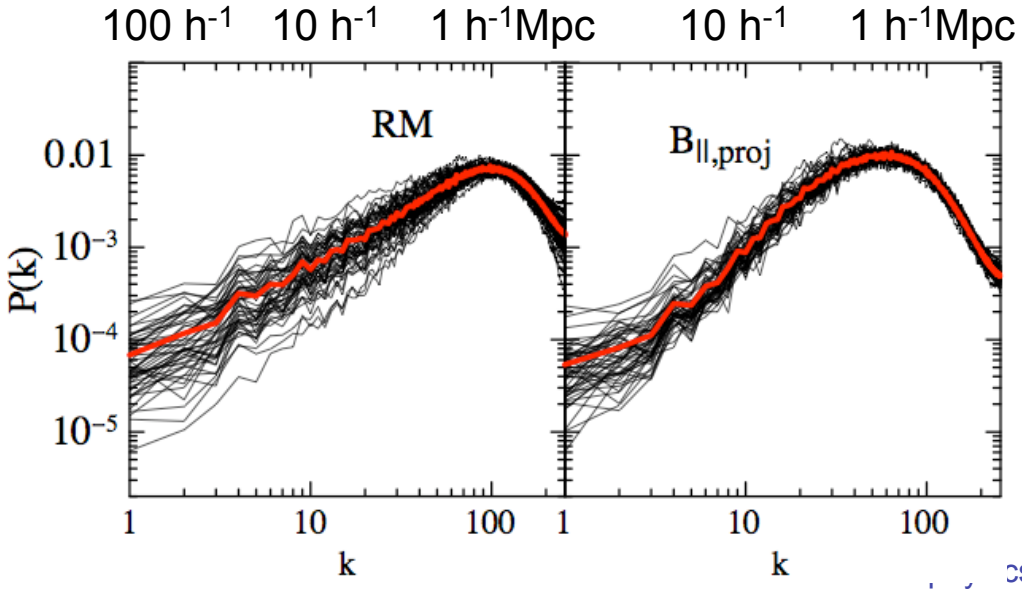
PDF of |RM| for WHIM (10^5 K<Tx<10^7 K)

Tx: emissivity weighted temperature.

Black: 3×16 runs, Red: average, Blue: best-fit

$$PDF(\log_{10}|\mathrm{RM}|) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{(\log_{10}|\mathrm{RM}| - \mu)^2}{2\sigma^2}\right]$$

- Lognormal profile of PDF
- rms **~ 1.4 [rad m^{-2}]** for WHIM



2D power spectra of RM and the projected IGMF

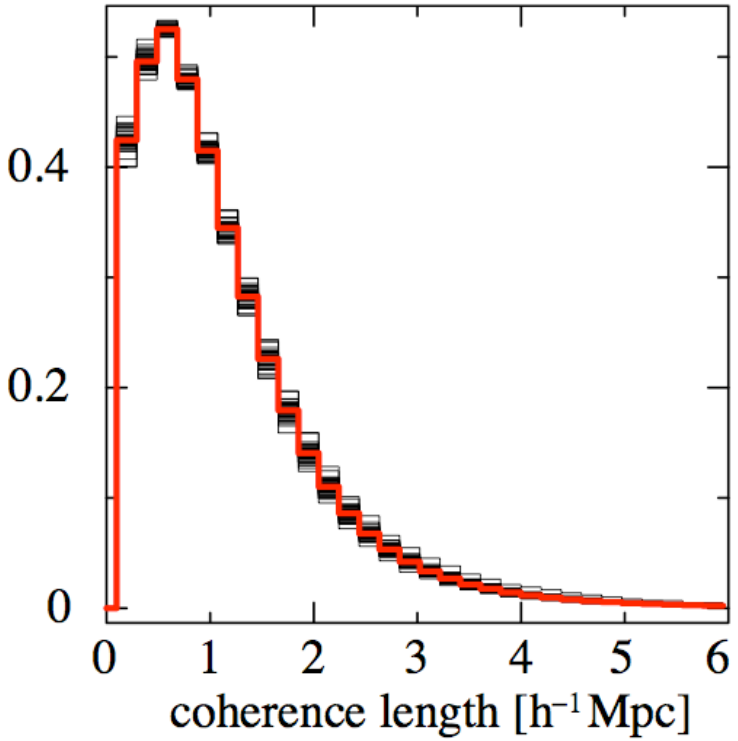
Black: 3×16 runs, Red: average

- Peaked at **~Mpc scale**
- $P^{RM}(k)$ traces $P^{B||,proj}(k)$

1 Present-day Local Universe: Discussion

- RM depends on the strength as well as the coherence length of the IGMF
  - Check 1: PDF of the length with the same sign of $B_{||}$ along LOSs for WHIM
    ~600 h^{-1} kpc
  - Check 2: From "the integral scale"
    ~800 h^{-1} kpc
  - Check 3: largest energy containing scale
    ~900 h^{-1} kpc
  - Cho & Ryu (09):
    ~a few × 100 h^{-1} kpc
- May be due to the resolution effect
  - Although grid size=200 h^{-1} kpc < the above coherence length…
- RM is dominantly contributed by the density peak along LOS --> would be not too large to invalidate the results

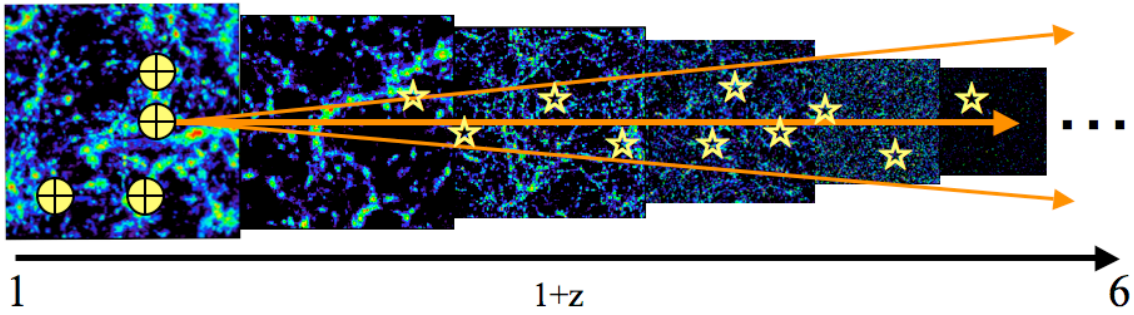
PDF of the coherence length

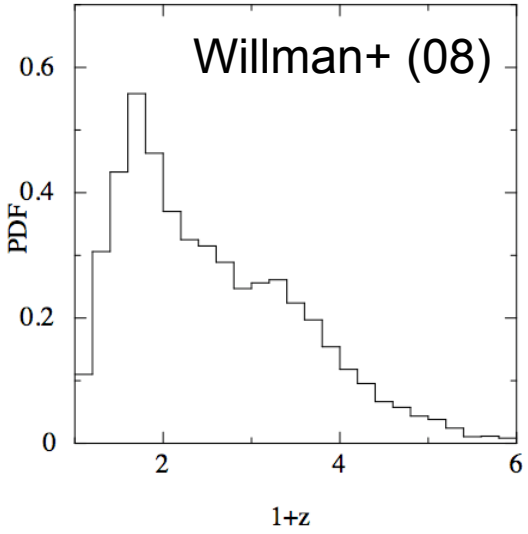


coherence length of B for RM

$$\frac{3}{4} \times 2\pi \frac{\int P_B^{3D}(k)/k \; dk}{\int P_B^{3D}(k) \; dk}$$

2 Cosmological Effects: RM Stacking

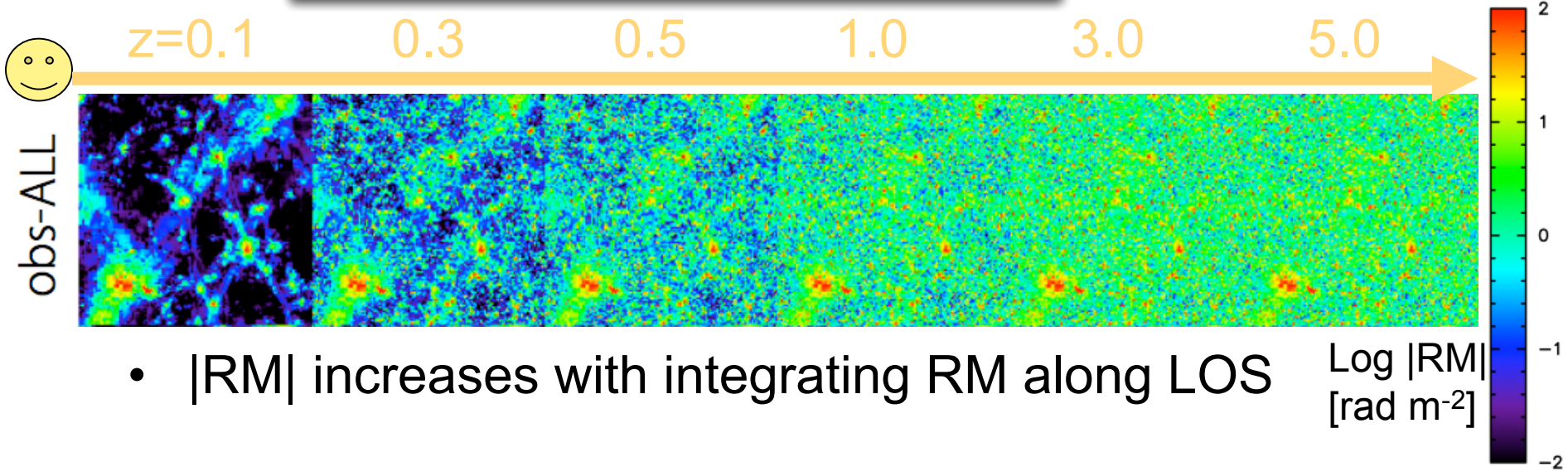




Simulation boxes are stacked up to z=5

Redshift distribution of radio sources are considered

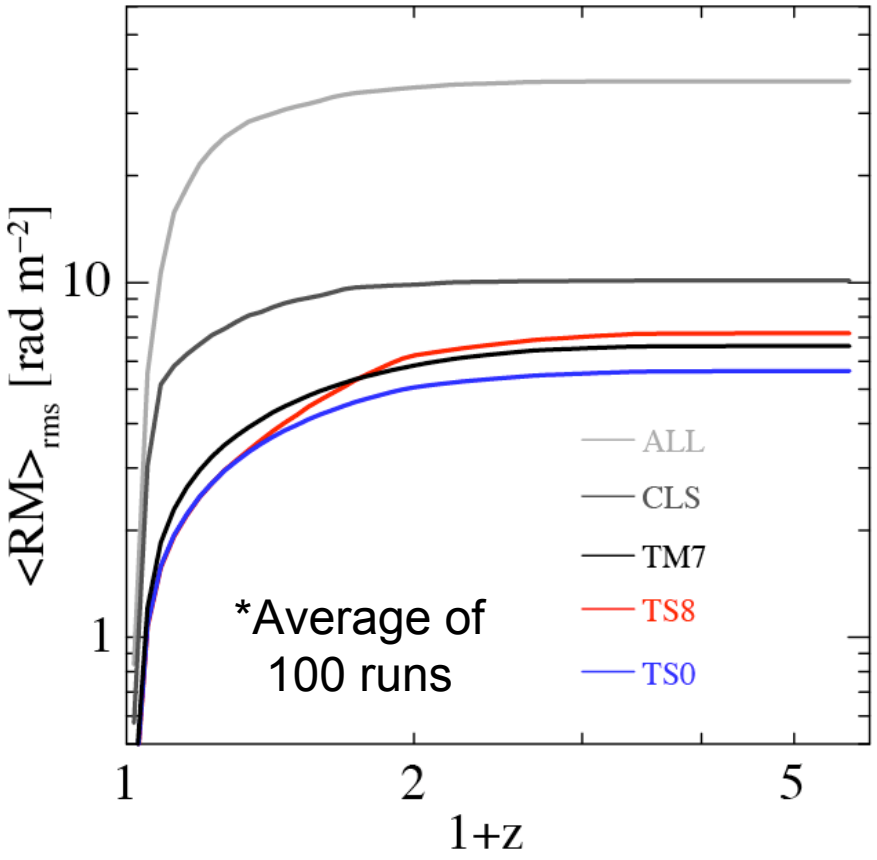
$$RM = \frac{e^3}{2\pi m_e^2 c^4} \int_{l_s(z_s)}^{0} (1+z)^{-2} n_e(z) B_{\parallel}(z) dl(z)$$



- |RM| increases with integrating RM along LOS

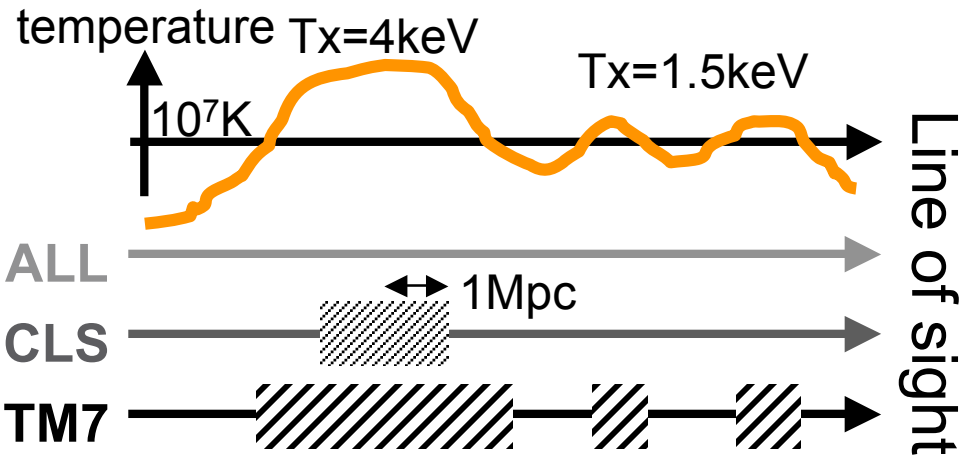
Log |RM| [rad m^{-2}]

2 Cosmological Effecs: rms Value



	[rad m^{-2}]
RM of WHIM (in)	7-10
RM of WHIM (after)	6-7

Subtl. of ICM **in** the integration

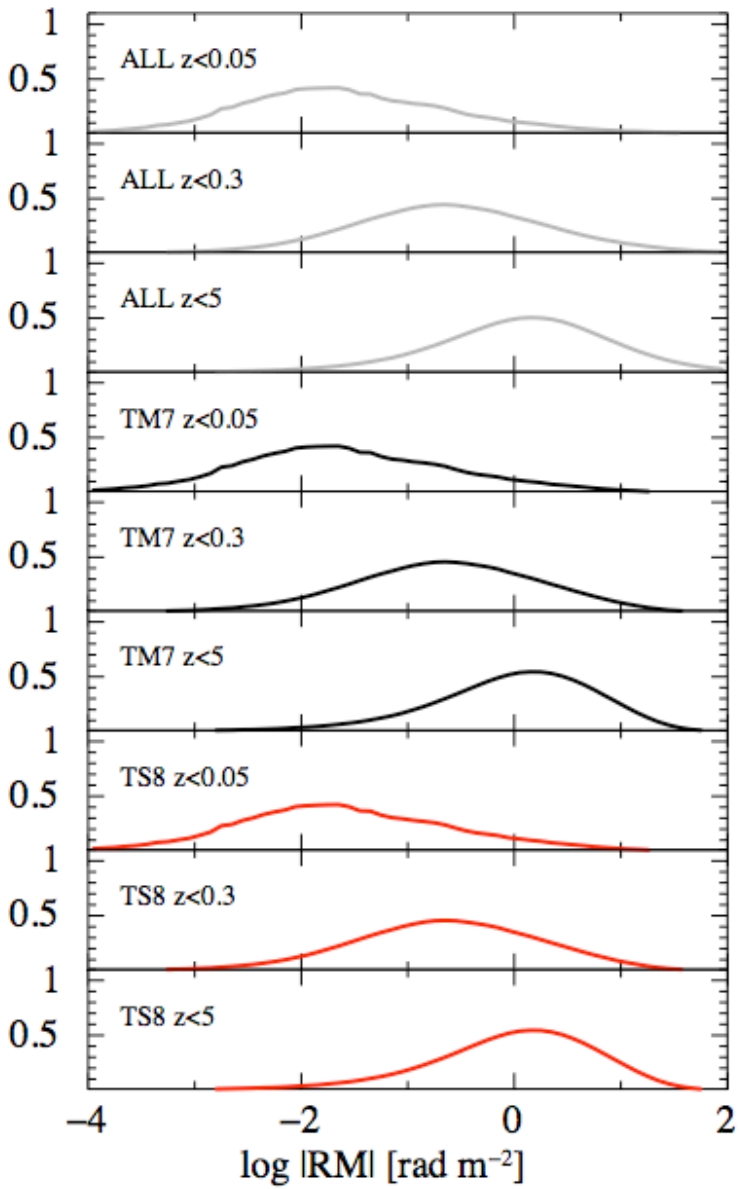


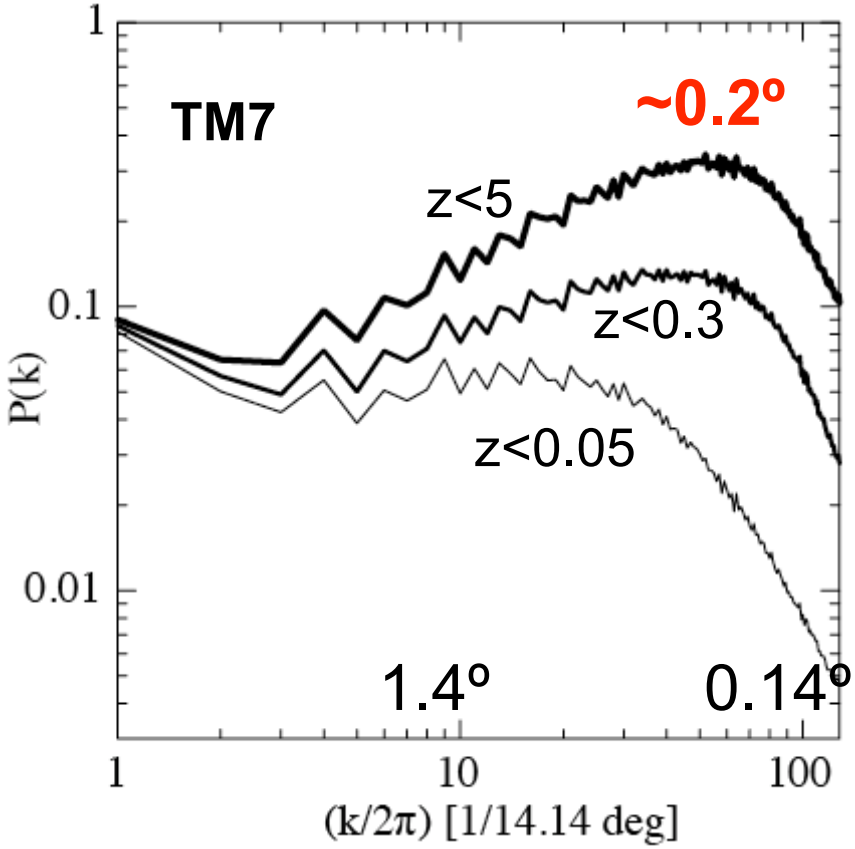
Subtl. of ICM **after** the integration

TS8 ALL Map − **Pixcels w Tx>10^7K & Sx>10^{-8} e/s/cm^2/sr**

TS0 ALL Map − **Pixcels w Tx>10^7K & Sx>10^{-10}e/s/cm^2/sr**

2 Cosmological Effects: Statistics





- PDF of |RM| follows the log-normal distribution
- Power spectrum peaks at ~0.2° scale

2 Cosmological Effect: Discussion

- **Estimation of RM through filaments**

(1) RM (z=0)~1.4 rad m^{-2} (AR10)

(2) z < ~3

(3) Random walk process:

(RM ∝ √N)

N the number of passage

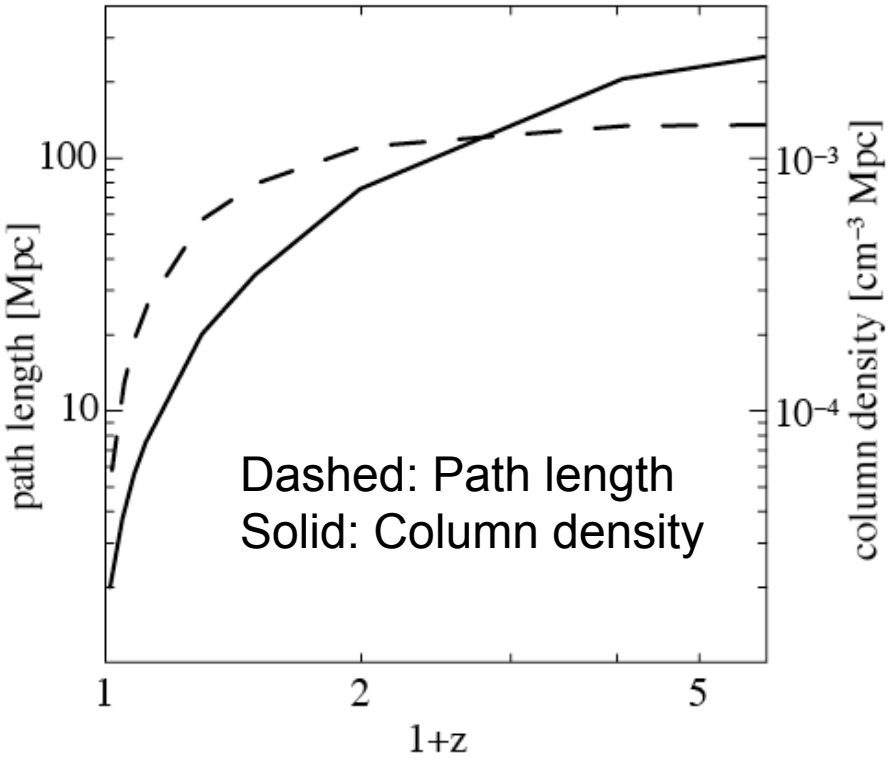
N ~10 passages→

rms ~1.4× √10 ~4.4 rad m^{-2}

N the column density

N increases by ~40 times→

rms ~1.4× √40 ~8.8 rad m^{-2}

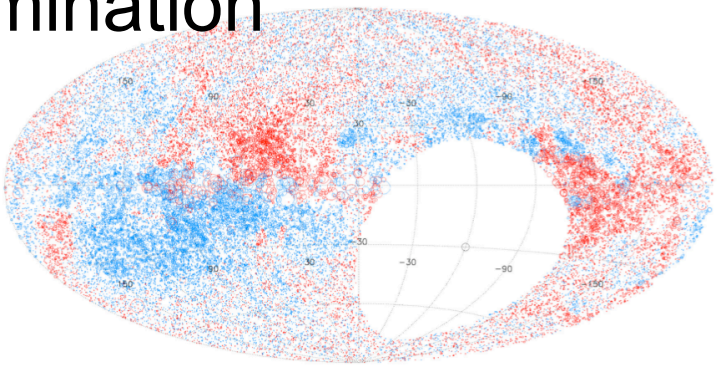


RM through filaments
several [rad m^{-2}]

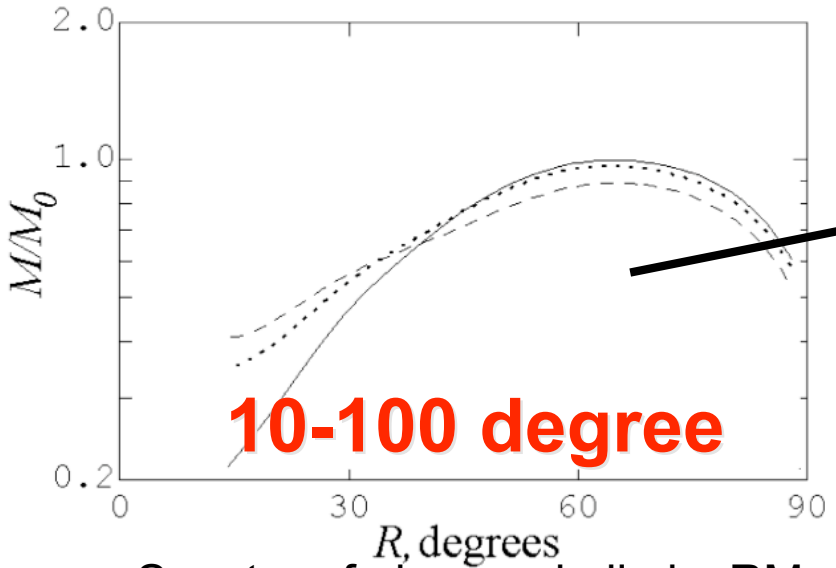
3 Galactic Foreground: Concept of Analysis

- Galactic RM is a serious contamination for studying RM in filaments
  - galactic RM ~10-100 [rad m^{-2}]

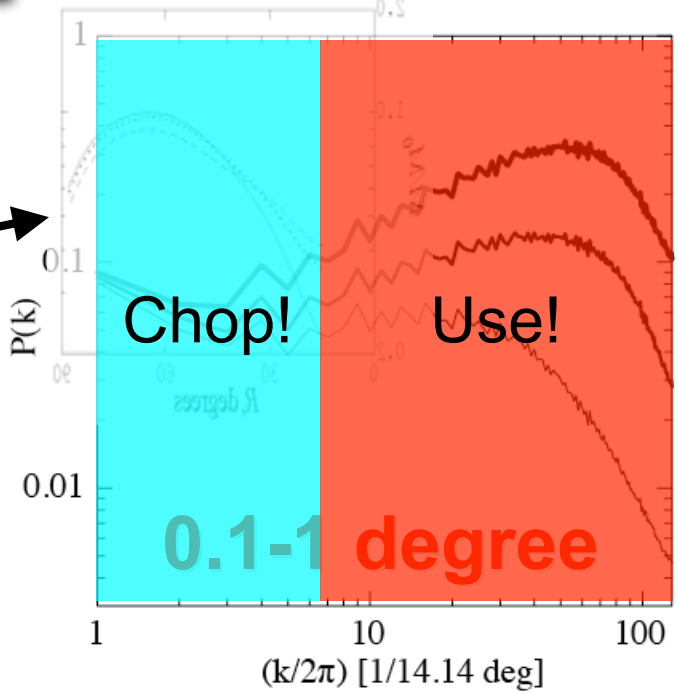
Key point:
peak scales are different



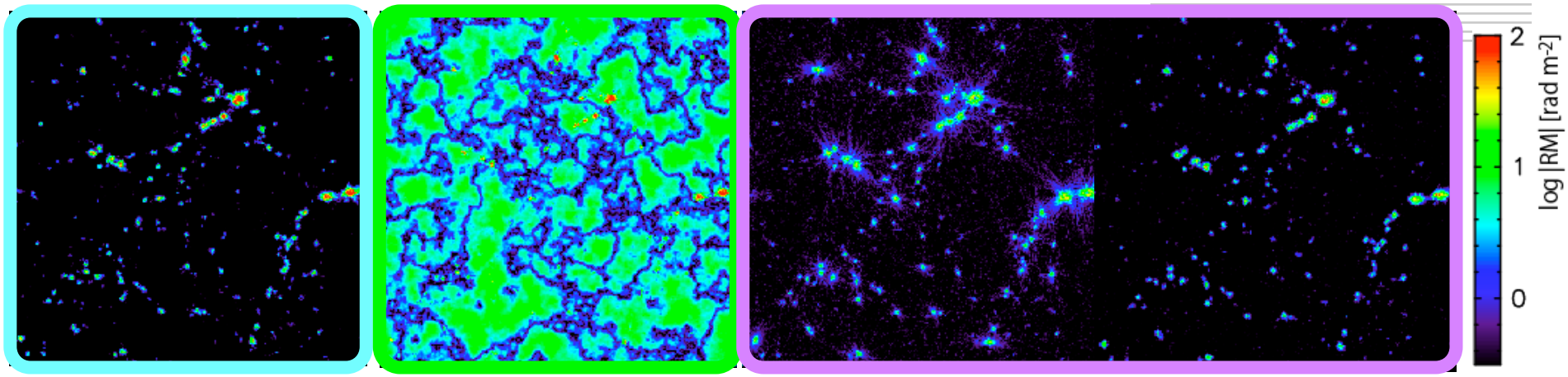
All sky RM (Taylor+ 09)



Spectra of observed all-sky RM (Frick+ 01)



3 Galactic foreground: High-pass filters



Intrinsic RM

Noise RM

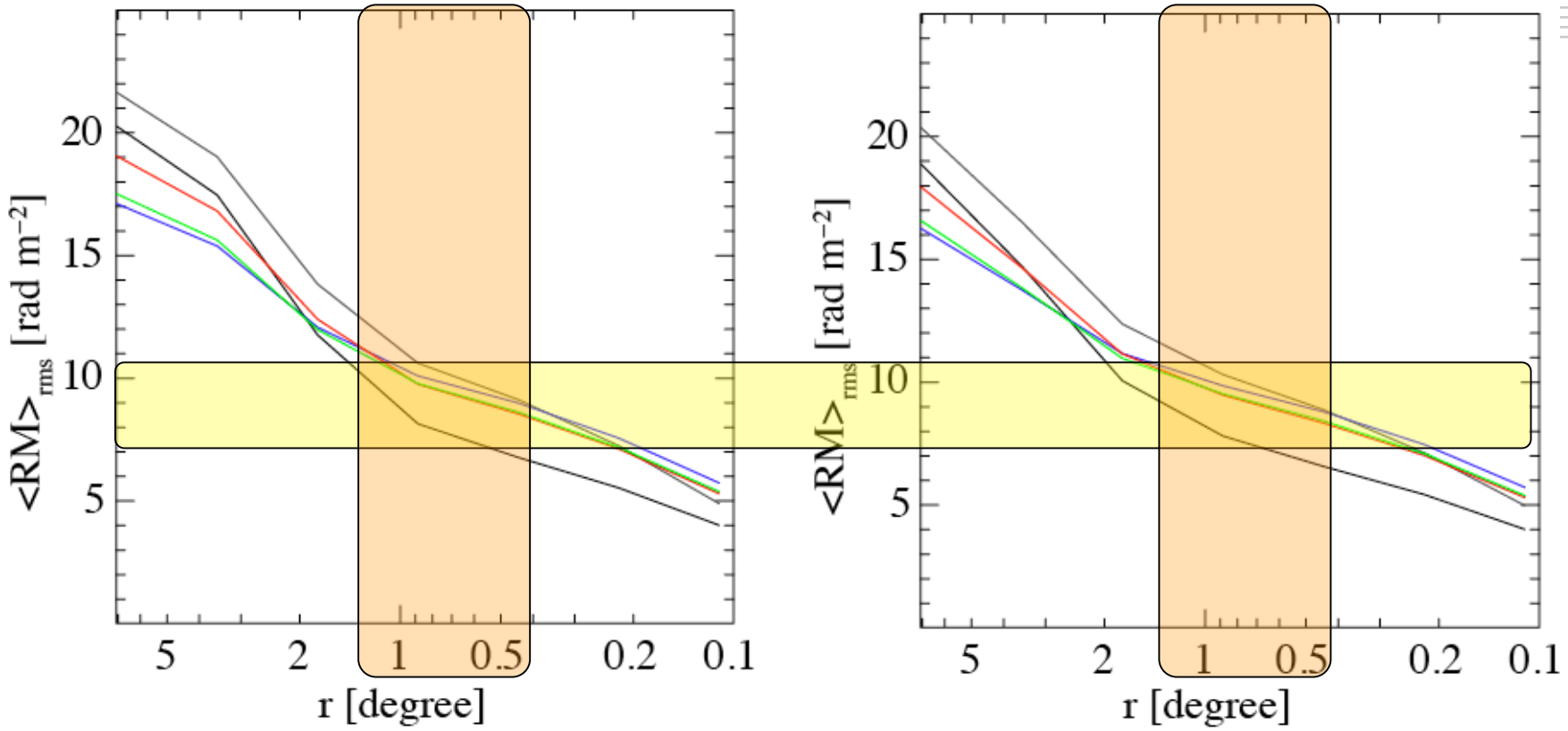
→ Intrinsic +Noise → High-pass filter → Filtered RM (FFT/FWT)

- Gaussian random fluctuation
- Kolmogorov spectrum
  $|Q(k)|^2 \propto k^{-11/3} (k>k_n)$, $k^{-1} (k<k_n)$
- $\langle RM \rangle = 0$, $\langle RM \rangle_{rms} = \sigma_n$
- Parameters: σ_n & k_n

- Fast Fourier transformation (FFT)
- Fast Wavelet transformation (FWT)
- Transform → low frequency cut at k_f
  → inverse-Transform
- Parameter: k_f

High-pass filters have potential to subtract galactic component

3 Galactic foreground: What's the Best k_f?



rms of RM as a function of the filter scales of FFT (left) and FWT (right)

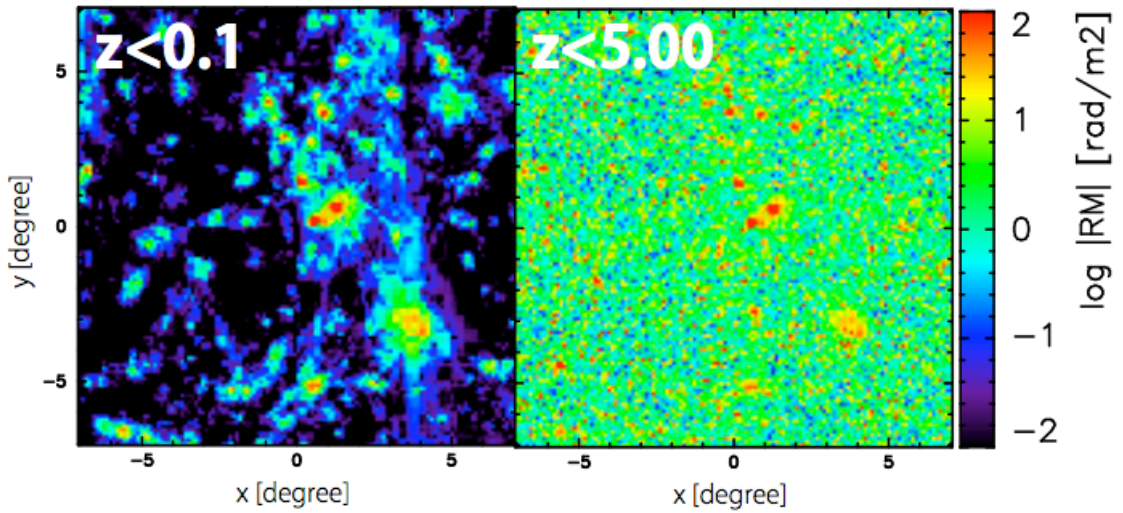
Noise model: k_n= 5 (2.8º scale), $\langle RM \rangle_{rms,\ noise}$= 20 [rad m^{-2}]

- A high-pass filter with **k_f ~ degree** would effectively reduce the galactic foreground contamination

Summary

RM in filaments is discussed using a model IGMF

- **Present-day local universe**
  - rms **~ 1 [rad m^{-2}]**, **lognormal**, peak at **~Mpc**
- **Cosmological effects** (stcking up to z=5)
  - rms **~ several [rad m^{-2}]**, **lognormal**, peak at **~0.2º**
- **Galactic Foreground**
  - **Degree-scale high-pass filters (FFT/FWT)** works well

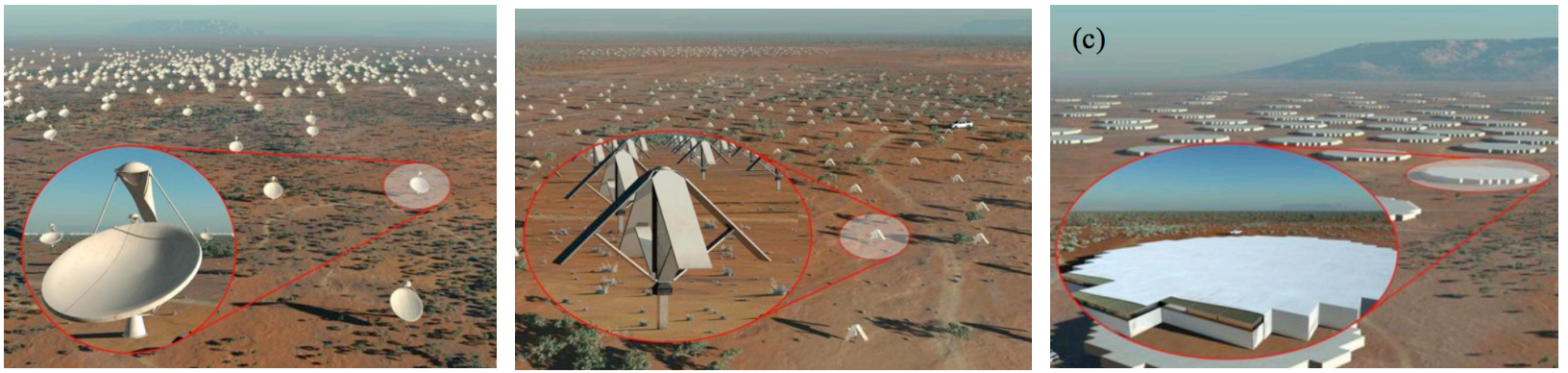


Future Observations

- **Square Kilometer Array**
  - mid 2020s, $2-3 billion
  - 70-300MHz (200deg^2), 0.3-10GHz (>30deg^2), 5-25GHz (>1deg^2)
  - 3000 antennas, d_{max}~3000 km
  - ~0.1” resolution, ~100×VLA sensitivity (1 source/arcmin^2)

SKA movie here
http://www.skatelescope.org/video/SKA_Animation_2010.mov

Our estimated RM could be tested with the SKA!



Dishes, sparse aperture arrays, and dense aperture arrays,
Garrett+ 10, a concept design for SKA Phase 1