RMs due to the IGMF and GMF

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Fundamental Science and Technology

Intro.

review

RM due to the IGMF
- Turbulence
- RM structures

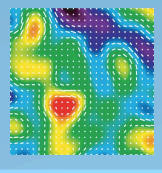
new

RM due to the GMF
- Turbulence
- RM structures

Summary

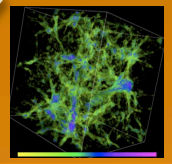
Possible Origins of the IGMF

Cosmological Seed Fields



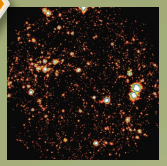
Inflation, Phase transition, Perturbation

MHD in Structure Formation



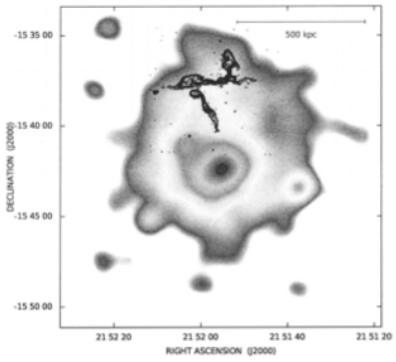
Shock, Battery effect, Dynamo

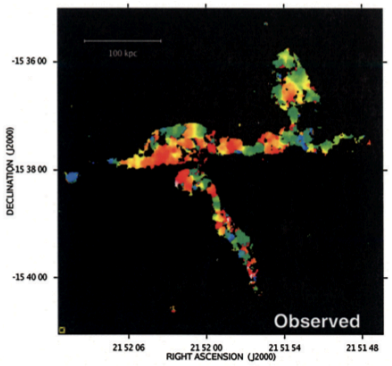
Leakage from Stars & Galaxies

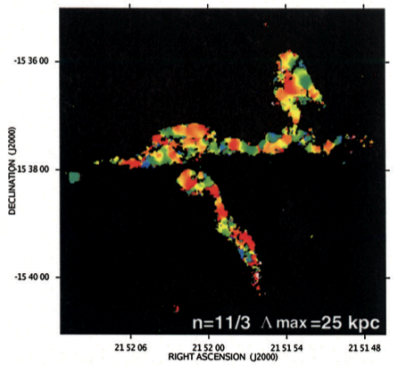


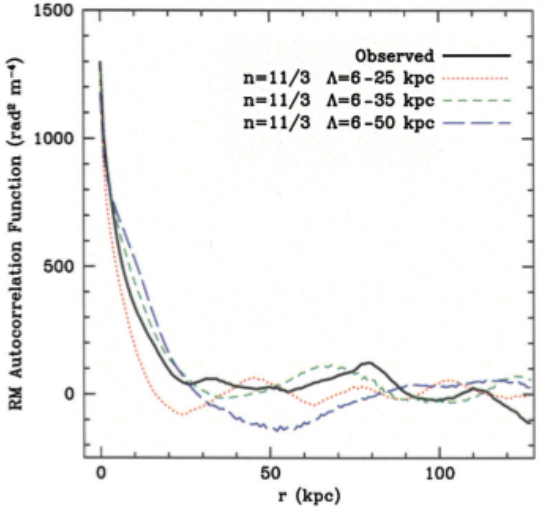
AGN jet, Supernova, wind, Stripping

- A **Kolmogorov** model can explain the observed RM map → **Existence of turbulence?**





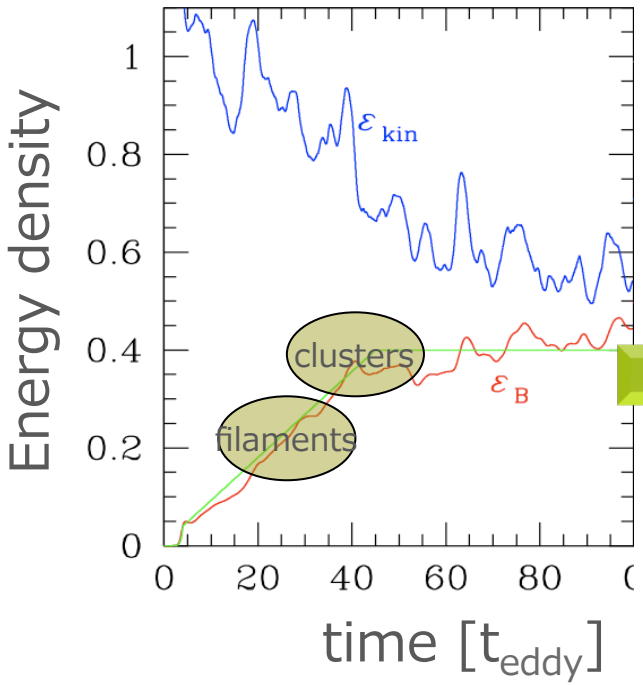




PKS2149-158 & 158C in Abell 2383 (Guidetti+ 08)
ROSAT 0.1-2.4 keV (gray), VLA 4.88 GHz (contour)

Structure Formation and the IGMF

- Cosmological MHD simulations…
  - still suffers from large numerical dissipation & lack of resolution to treat small-scale cascading of eddies
- **Cosmological structure formation simulations + turbulence dynamo model (Ryu+ 08)**



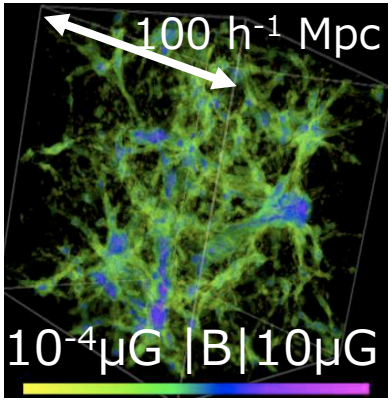
1. Curl component of flow: $\vec{\omega} \equiv \vec{\nabla} \times \vec{v}$
2. Turbulent energy: $\varepsilon_{\rm turb} = \varepsilon_{\omega}$
3. Adopt the growth model $t' = t/t_{\rm eddy}$

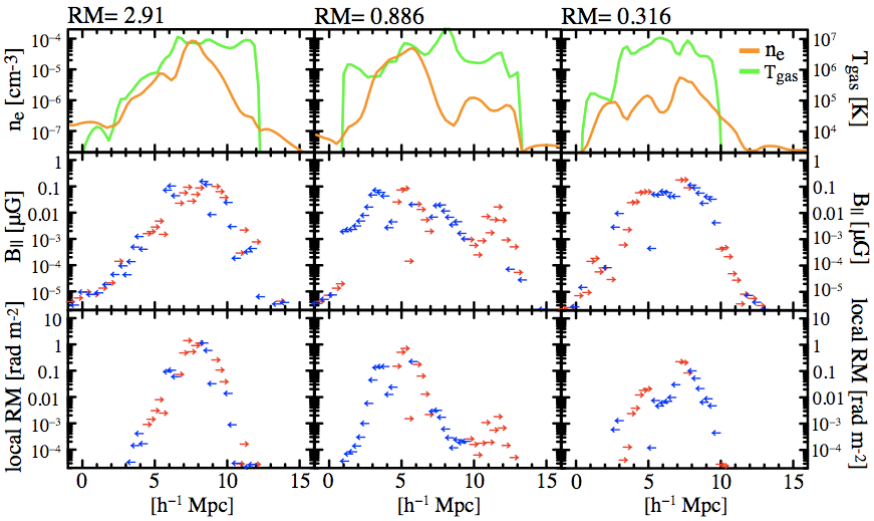
$$\frac{\varepsilon_B}{\varepsilon_{\rm turb}} = \begin{cases} 0.04 \times \exp[(t'-4)/0.36] & \text{for } t' < 4, \\ 0.00878 \times (t'-4) + 0.04 & \text{for } 4 < t' < 45, \\ 0.4 & \text{for } 45 < t', \end{cases}$$

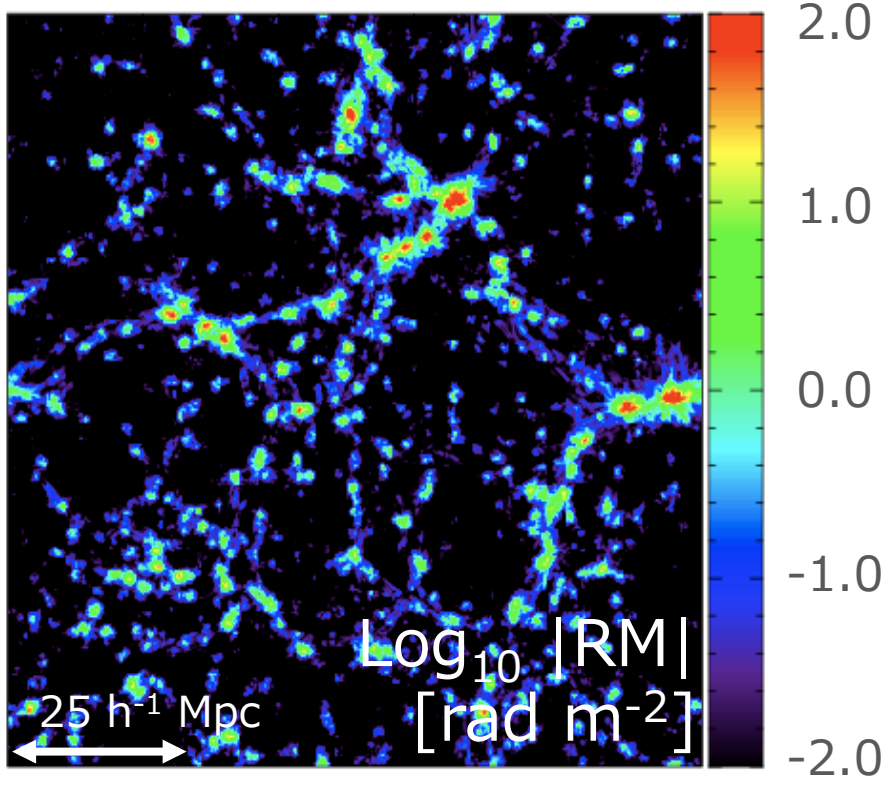
4. Magnetic field strength: $B = (8\pi\varepsilon_B)^{1/2}$
5. Direction: assume passive field

IGMF-RM: Local Universe

- $\sigma_{RM,IGMF}$ through a filament ~1 [rad m^{-2}]
- Coherence length~a few*100 [kpc], random walk

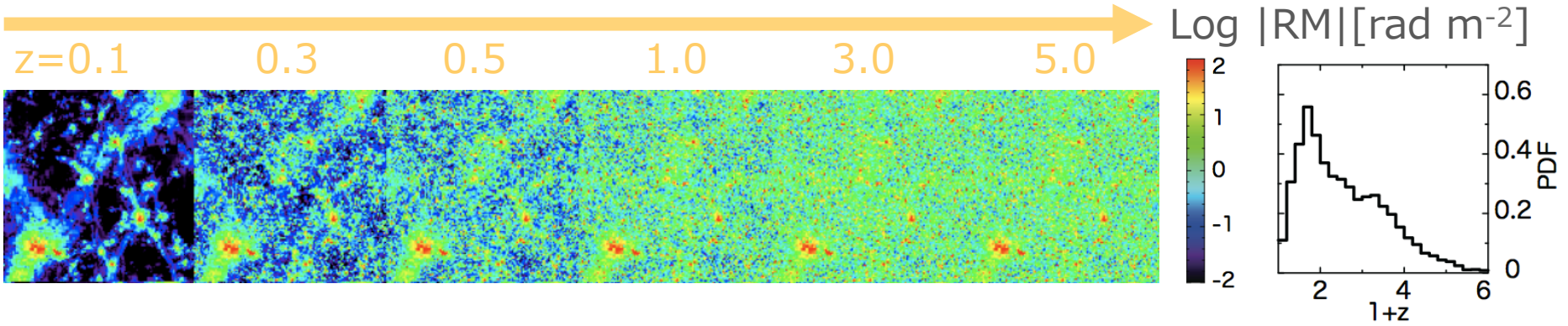




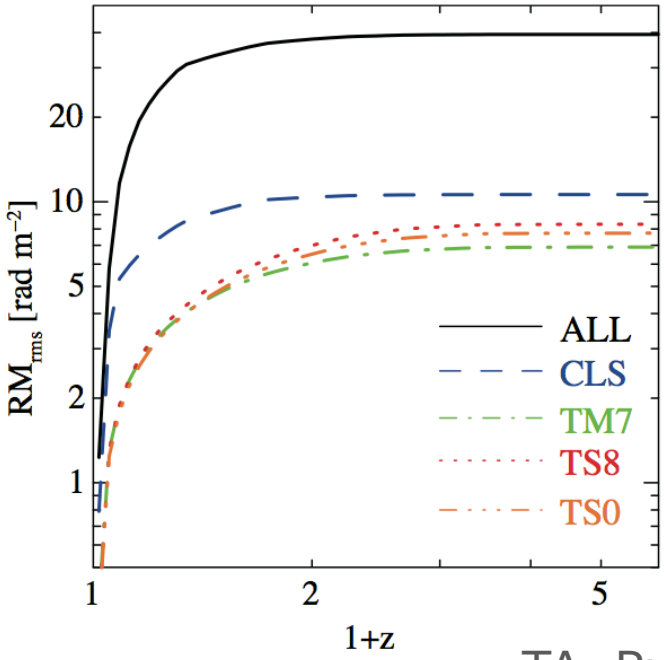


TA, Ryu 2010, ApJ, 723, 476

IGMF-RM: Up to z=5



- $\sigma_{RM,IGMF}$ through filaments ~several [rad m^{-2}]



※Galaxy Cluster Subtraction

-In the integration

CLS:ALL-grids(1Mpc around Tx >2 keV)

TM7:ALL-grids(T>10^7K)

-After the integration

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

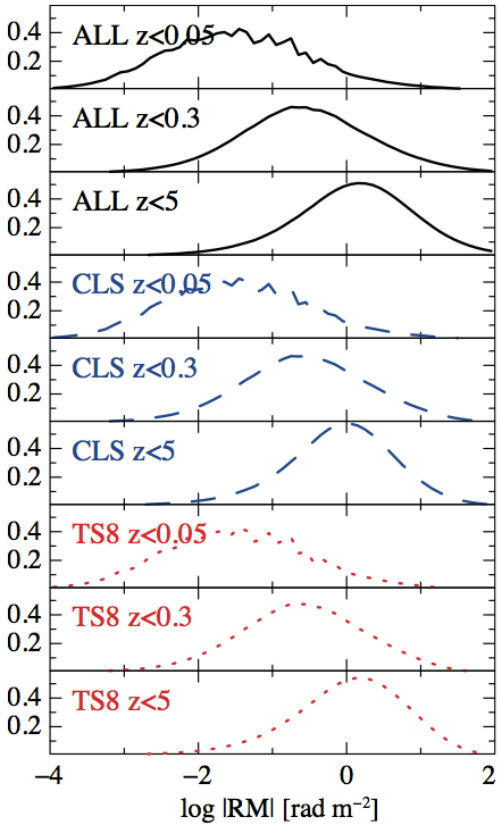
TS0:ALL-pixels(Tx*>10^7K & Sx*>10^{-10})

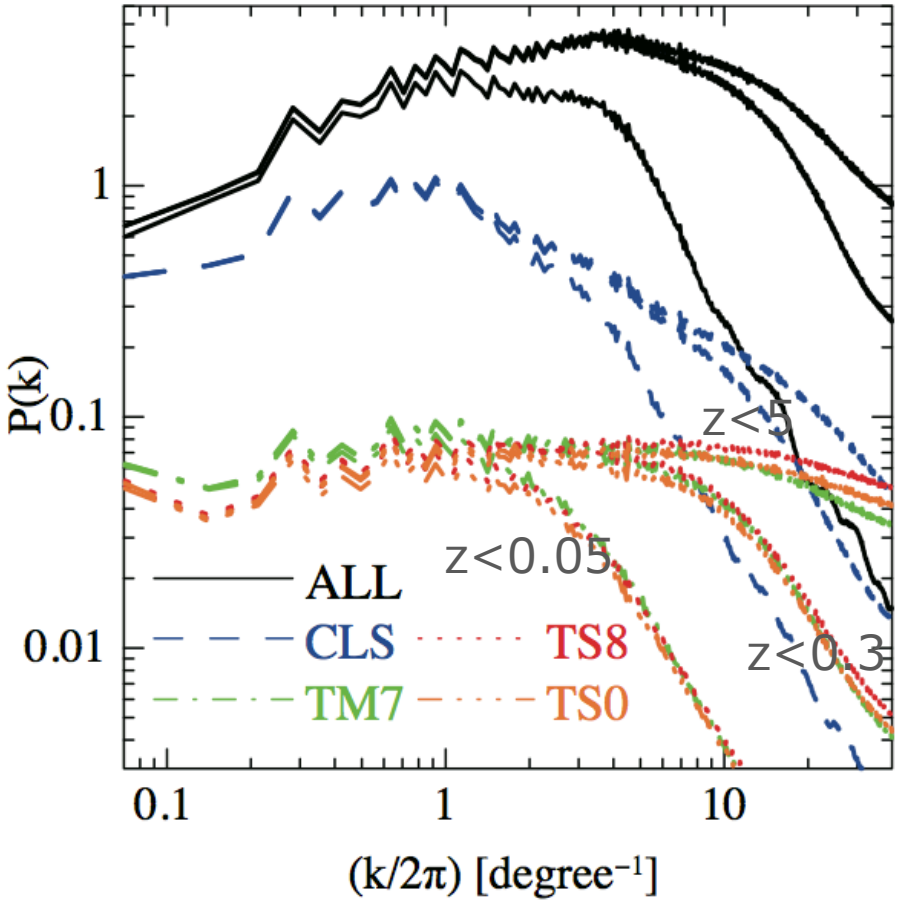
erg/s/cm^2/sr

TA, Ryu 2011, ApJ, 738, 134

IGMF-RM: Up to z=5

- PDF follows the lognormal profile
- PS peaks at 0.1º-0.2º scales

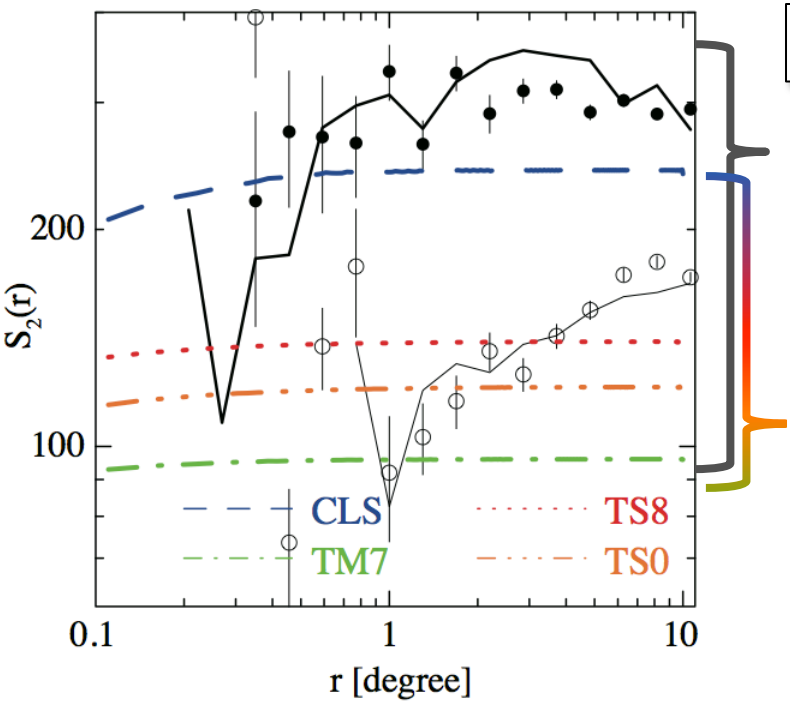




TA, Ryu 2011, ApJ, 738, 134

IGMF-RM: Up to z=5

- SF is flat at >0.2° with 100-200 [rad^2 m^{-4}]



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

← **Observed Structure Functions**

circles: Mao+ (10) WSRT+ACTA

lines: Taylor+ (09) NVSS

← **Simulation Results (IGMF)**

colors: Akahori, Ryu (11)

4 models of diff. cluster subtraction

Next:

How much is the Galactic contribution in the data?

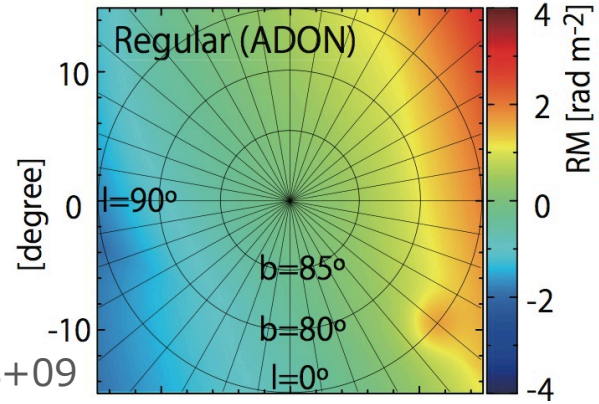
TA, Ryu 2011, ApJ, 738, 134

GMF-RM: Toward Galactic Poles

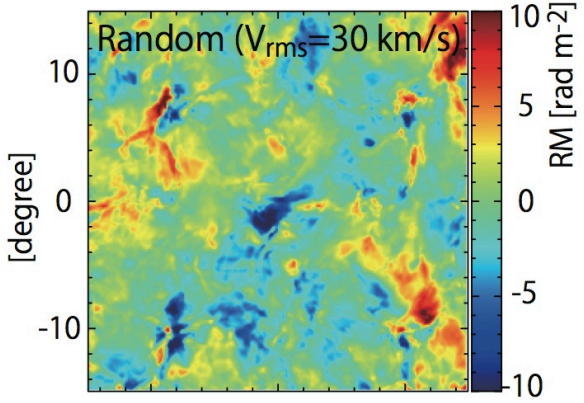
- Random magnetic field, b, seems to be stronger than vertical, regular magnetic field, $B_{||}$
  - ✓ $|b| \sim 1$ μG ⇔ $|B_{||}| \sim$-0.14-0 (N), 0.2-0.3 μG (S) (Taylor+ 08; Mao+ 10; Stil+11)
  - ✓ Careful treatment of the random component is needed
- But the modeling is not trivial
  - ✓ Distribution of b ⇔ uniform b at disk, halo, everywhere
  - ✓ Correlation between the density and b ⇔ parameter
  - ✓ Phase ⇔ random phase (no sheet/filamentary structures)
  - ✓ No 900 deg^2 FOV has been studied
- **Analytical regular field model + stack the results of turbulence simulations (TA+ 12)**

GMF-RM: Toward Galactic Poles

- Analytic regular field + MHD turbulence data



Sun+08;
Waelkens+09



Regular Component

- NE2001 (h_1=1.8 kpc)
- Disk spiral (ASS/BSS)
- Halo toroidal (DP/QP)
- Galactic center poloidal (on/off)
- Temperature profile

$$T_e(R,z) = 5780 + 287R - 526|z| + 1770z^2$$

- V_{rms}=15,30 [km/s]

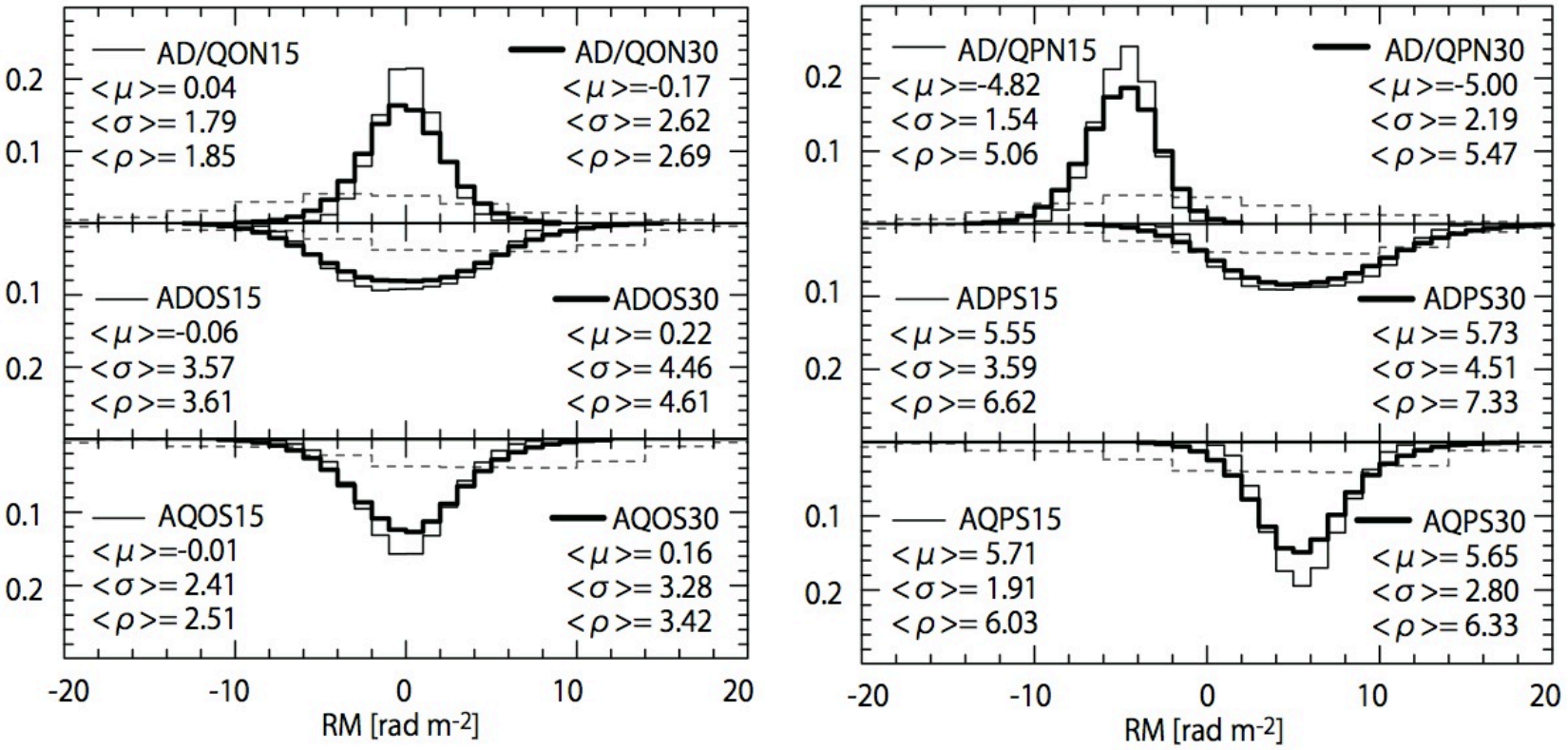
Random Component

- Isothermal, compressible MHD
- Saturation stage
- L_{box} = 500 [pc], L_{drive} = 330 [pc]
- M_{rms}=0.5,1,2,4, β_{rms}=0.1,1,3,10
- |b| is given by B_0, M_{rms}, β_{rms}
- Alignment of regular field direction

TA, Ryu, Kim, Gaensler, to be submitted

GMF-RM: Result 1

- <RM>~0 (no vertical) or ±6 (±1) [rad m^{-2}]
- $\sigma_{RM,GMF}$~5 (±0.5) [rad m^{-2}]



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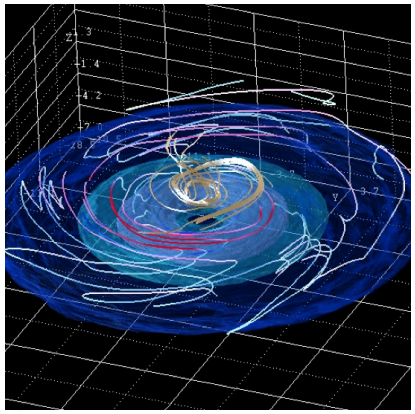
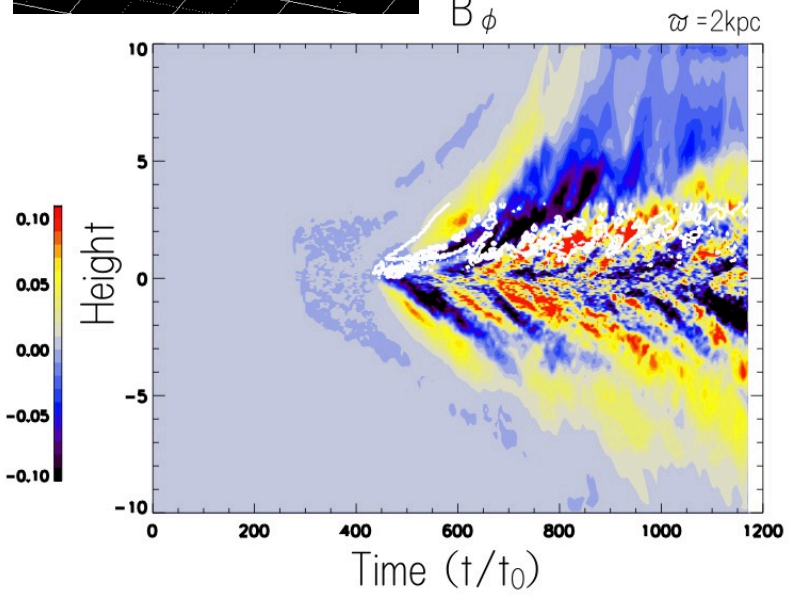
Discussion 1 (Average)

- **The mixed regular field geometry (e.g., Mao+ 10)**
  - $\langle RM \rangle_{NGP} \sim 0$ [rad m^{-2}]
  - $\langle RM \rangle_{SGP} \sim +6$ [rad m^{-2}]
- If $L_{drive} \sim 2$ [kpc], $\sigma_{\langle RM \rangle} \sim 6$ [rad m^{-2}] → inconsistent with EM observations (L_{drive} should be ~500 pc)
- Difficulties of producing a mixed field geometry in a steady state (e.g., Moss, Sokoloff 2008)
- **Transient regular field geometry?**



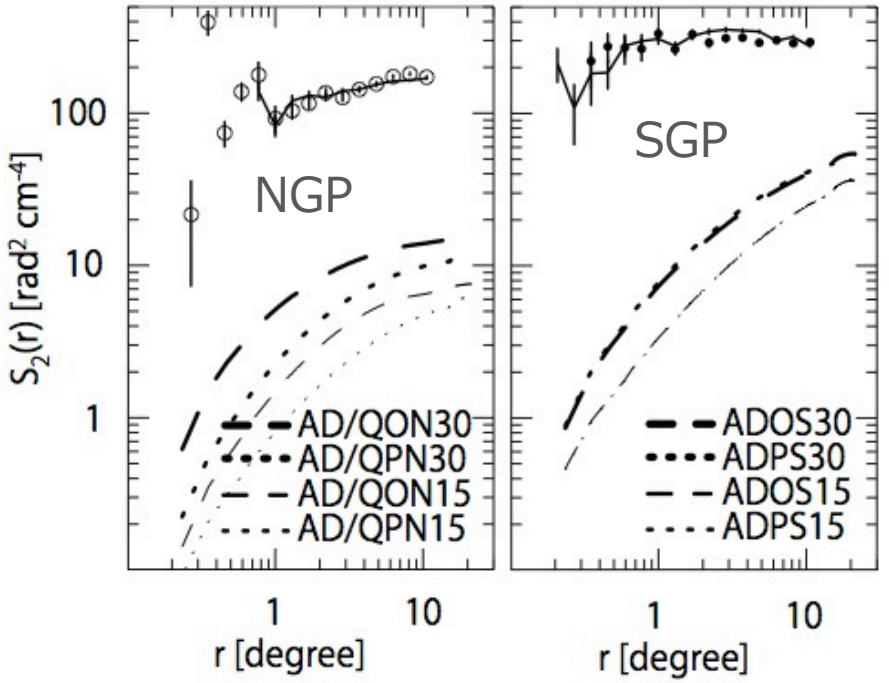
$t_0 \sim 5$Myr



MHD simulations of the galactic disk (Machida,TA, et al. submitted)

GMF-RM: Results 2

- Regular → large-scale structure (>10º scales)
  random → filaments/clumps (1-several º scales)
- SF is up to ~50 [rad^2 m^{-4}] at 10º, and has a slope ($\propto r^{\zeta}$) with ζ>0.6 at a few degree



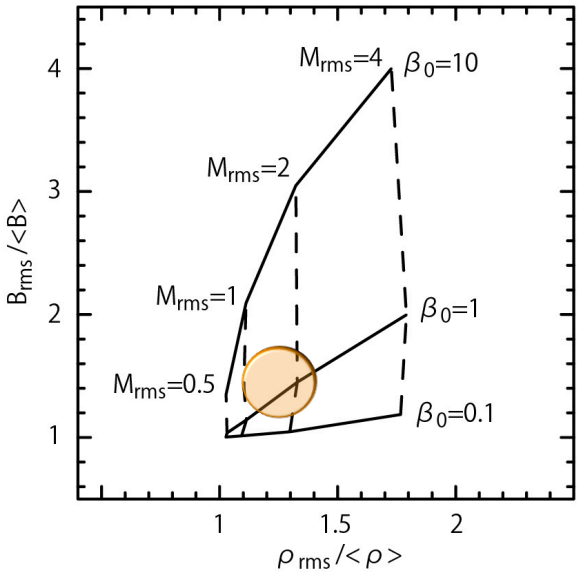
← **Observed SFs**
circles: Mao+(10) WSRT+ACTA
lines: Taylor+ (09) NVSS

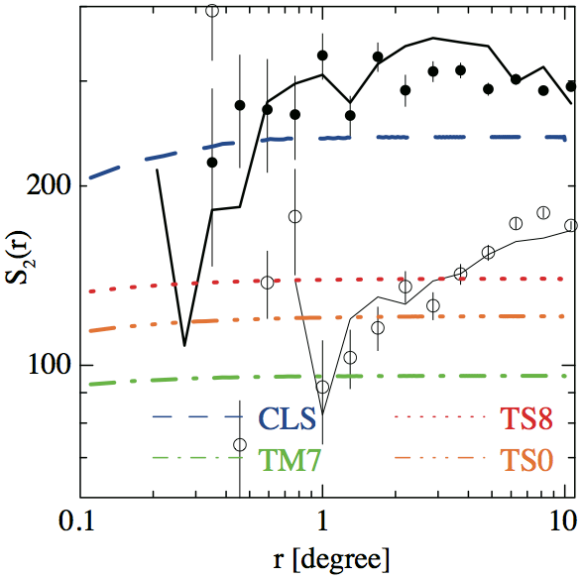
← **Our Results (GMF)**
colors: my work
4 different regular field & V_{rms}

TA, Ryu, Kim, Gaensler, to be submitted

Discussion 2 (Deviation & SF)

- **Observed σ_{RM}~9 [rad m^{-2}] (Mao+ 10) and 14-20 [rad m^{-2}] (Stil+ 11)**
- **GMF RM?**
  - σ_{MW}~7 [rad m^{-2}] (Schnitzeler 10) ⇔ σ_{GMF}~2-5 [rad m^{-2}] (our results)
  - If M_{rms}~3-4, σ_{GMF}~7 [rad m^{-2}] → inconsistent with EM observations (M_{rms} should be ~1-2)
  - Even if we input additional Galactic local structures, only the Galactic origins would be hard to explain SF~100-200 [rad^2 m^{-4}] at 0.1-1º
- **Noise RM, σ_{err}~3-5 [rad m^{-2}]?**
  - If we assume white Gaussian noise, SF~2*σ^2~100 [rad^2 m^{-4}] for σ~7 [rad m^{-2}] → not enough
- **Intrinsic RM?**
  - 2D white Gaussian
  - RM difference ~10 [rad^2 m^{-4}] at $\Delta\Theta$~0.01º (Simonetti & Cordes 86) → inconsistent? We need more samples
- **IGMF RM, σ_{IGMF}~several [rad m^{-2}]**
  - Flat SF~100-200 [rad^2 m^{-4}] at > 0.1º
  - Likely decreases to order ~ 10 [rad^2 m^{-4}] at 0.01º



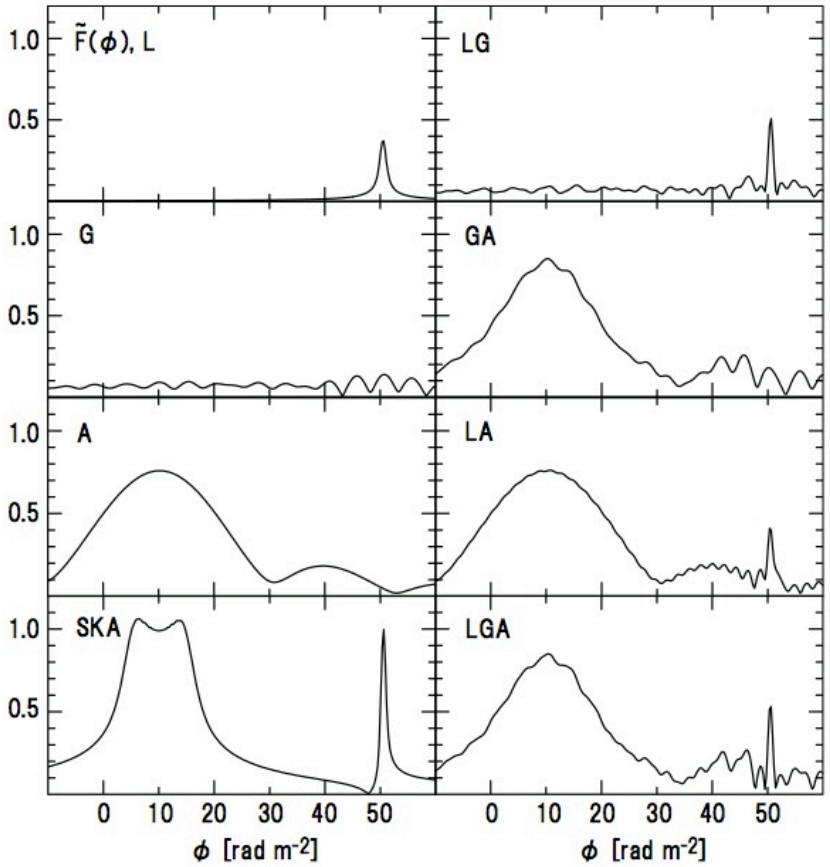


Summary

- Origin and nature of the IGMF
  - Observational test for the IGMF is quite important
- RM due to the IGMF
  - $\sigma_{RM,IGMF}$~1 [rad m^{-2}] through a filament
  - $\sigma_{RM,IGMF}$~several [rad m^{-2}] through filaments (z<5)
  - A flat SF>0.2º with 100-200 [rad^2 m^{-4}]
- RM due to the GMF toward the Poles
  - <RM> ~0 or ±6 (±1) [rad m^{-2}]
  - $\sigma_{RM,GMF}$~5 (±0.5) [rad m^{-2}]
  - SF is up to ~50 [rad^2 m^{-4}] at 10º, and has a slope with ζ>0.6 at a few degree
- POSSUM observation!

Future: How to Discover the IGMF by POSSUM

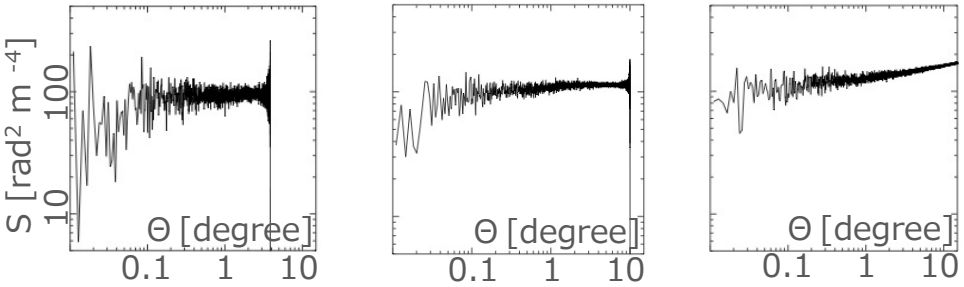
Faraday Tomography



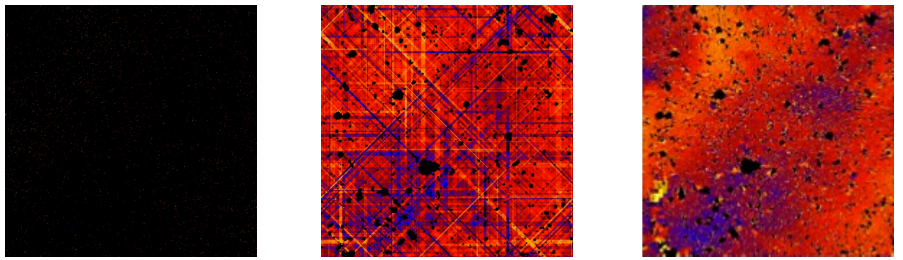
TA, Kumazaki, Takahashi, Ryu
to be submitted

Image Processing

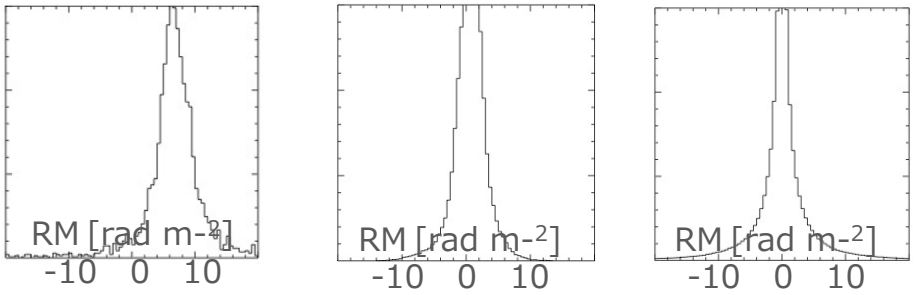
FOV 30 deg² → 200 deg² → 900 deg²



Observed → interpolated ⇔ Original



Observed → interp.+Filter ⇔ Original



TA & anybody in this room!

Cosmic Magnetism and the IGMF

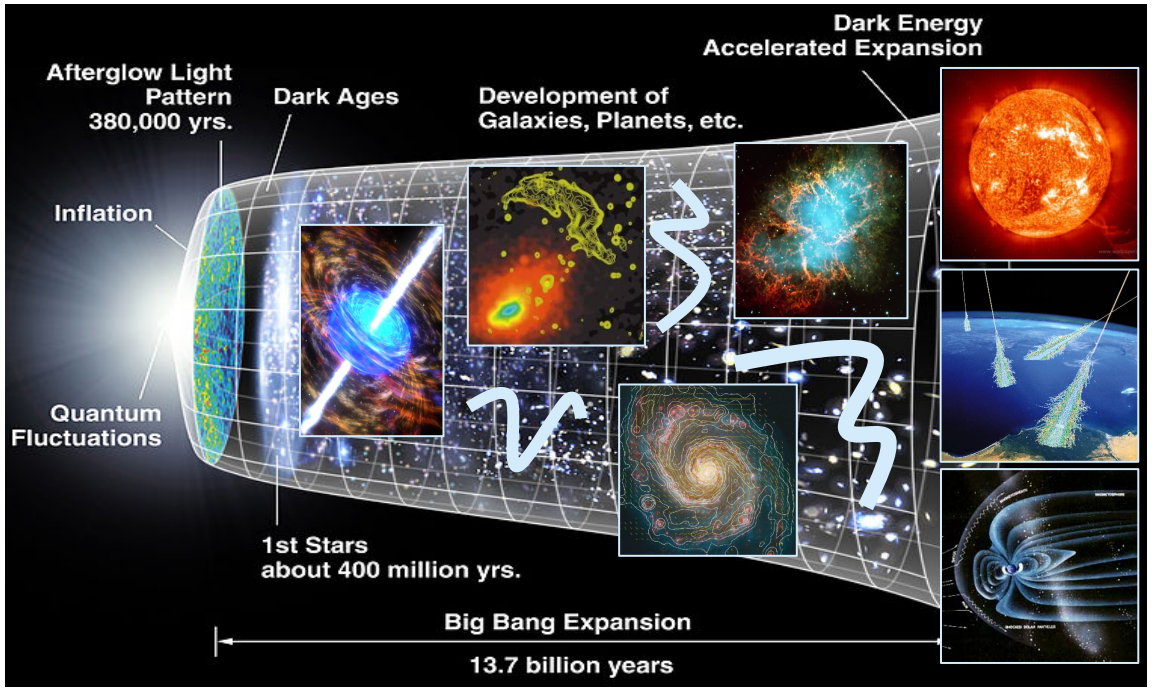
- Inter-Galactic Magnetic Field (IGMF)

Propagations of…
- UHECRs
- γ-ray halo/echo

Evolutions of…
- Galaxy clusters
- Large-scale structure

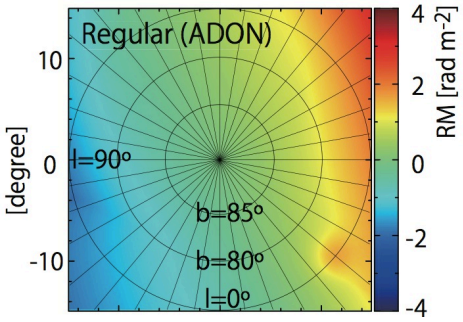
Seed Fields of…
- First objects
- Proto-galaxies

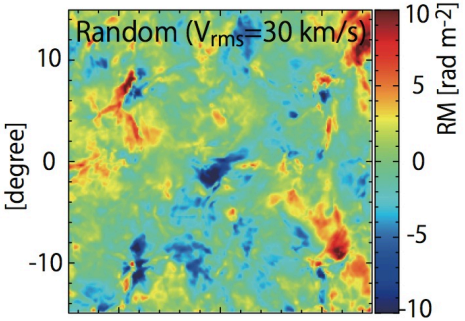
- ICM
  - RM ~ 100 rad m^{-2}
  - B_{IGMF} ~ 1-10 μG
  - L_{int} ~ 20 kpc
- WHIM
  - RM ~ 1? rad m^{-2}
  - B_{IGMF} ~ 10-100? nG
  - L_{int} ~ 300? kpc

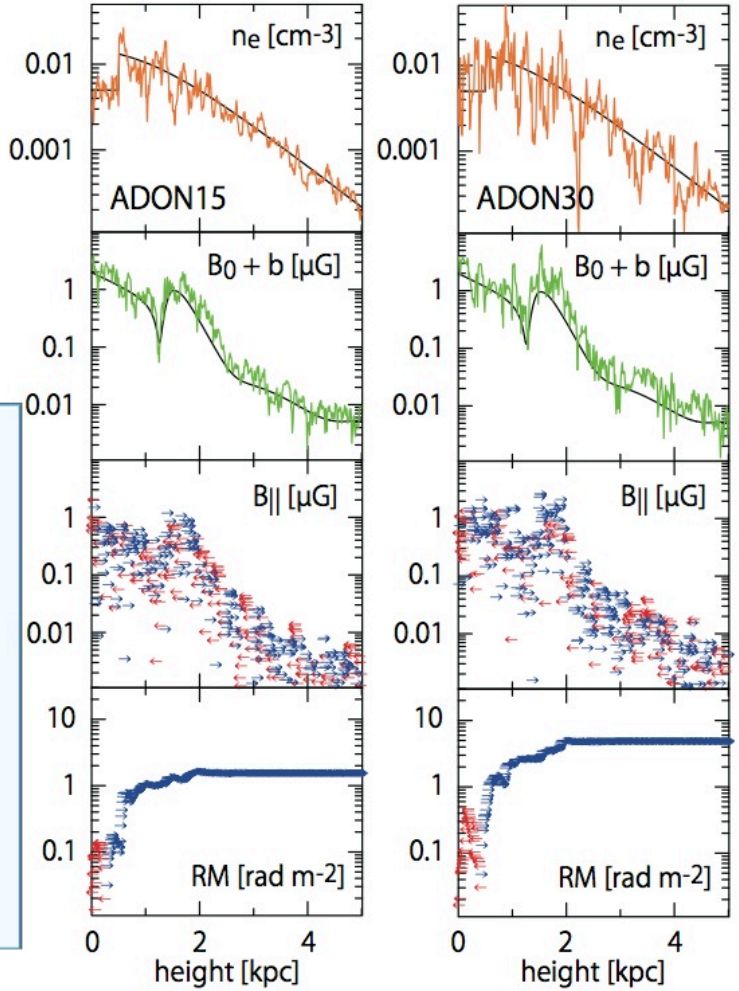


GMF-RM: Toward Galactic Poles

- Analytic regular field + MHD turbulence data







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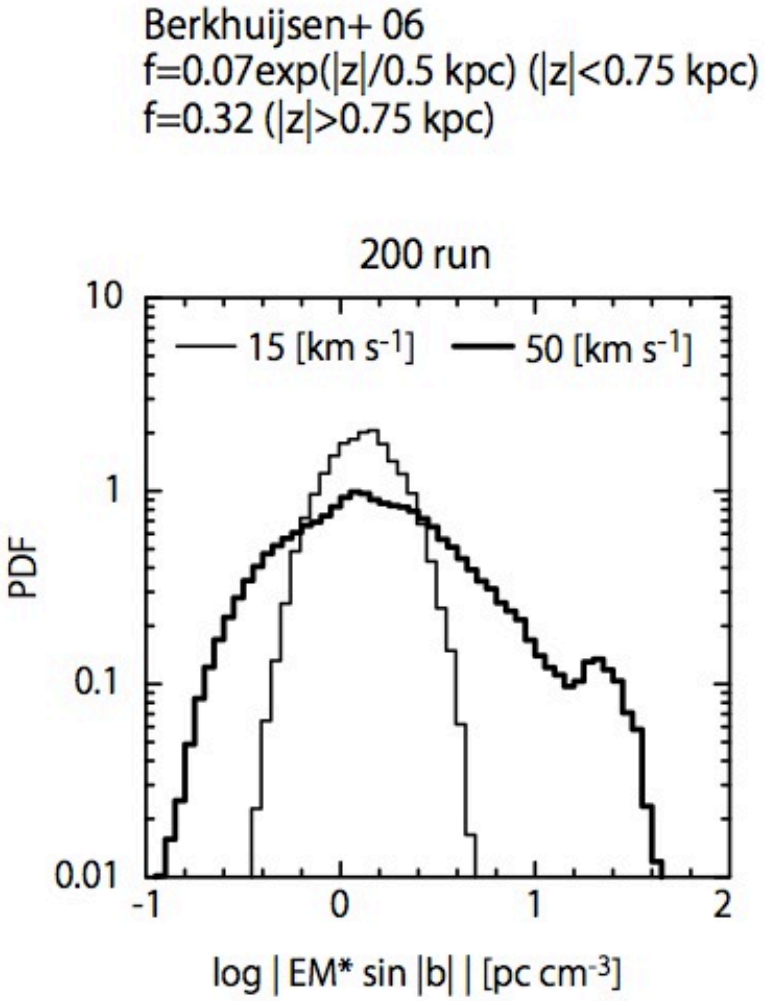
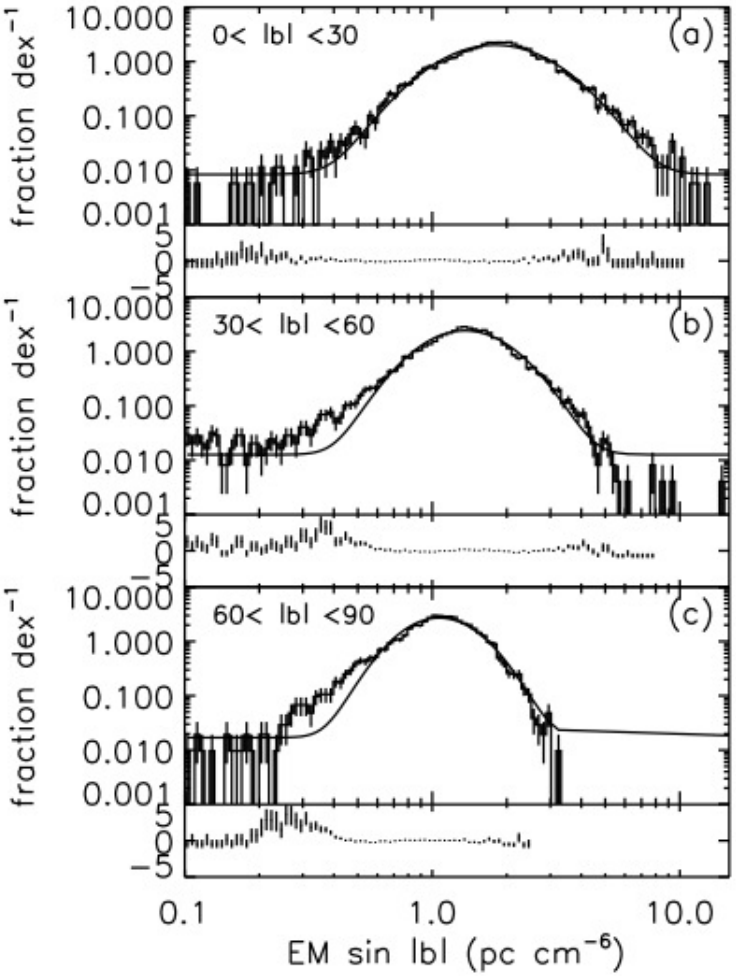
TA, Ryu, Kim, Gaensler, to be submitted

GMF-RM: Toward Galactic Poles

- PDF of EMs for our model





TA, Ryu, Kim, Gaensler, to be submitted