# Shock and Turbulence in Galaxy Clusters and the Large-Scale Structure

**Takuya Akahori[1,2]**

[1]Korea Astronomy and Space Science Institute (KASI)

[2]Research Fellow for Young Scientist, Korea Research Council of Fundamental Science and Technology (KRCF)

筑波大学 計算科学研究センター Center for Computational Sciences

CHUNGNAM NATIONAL UNIVERSITY

KASI 한국천문연구원 Korea Astronomy & Space Science Institute

KRCF

# Contents

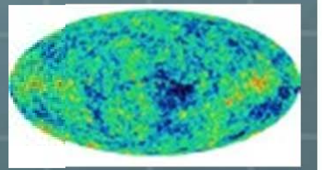
# 1. Introduction of Galaxy Clusters and the Large-Scale Structure

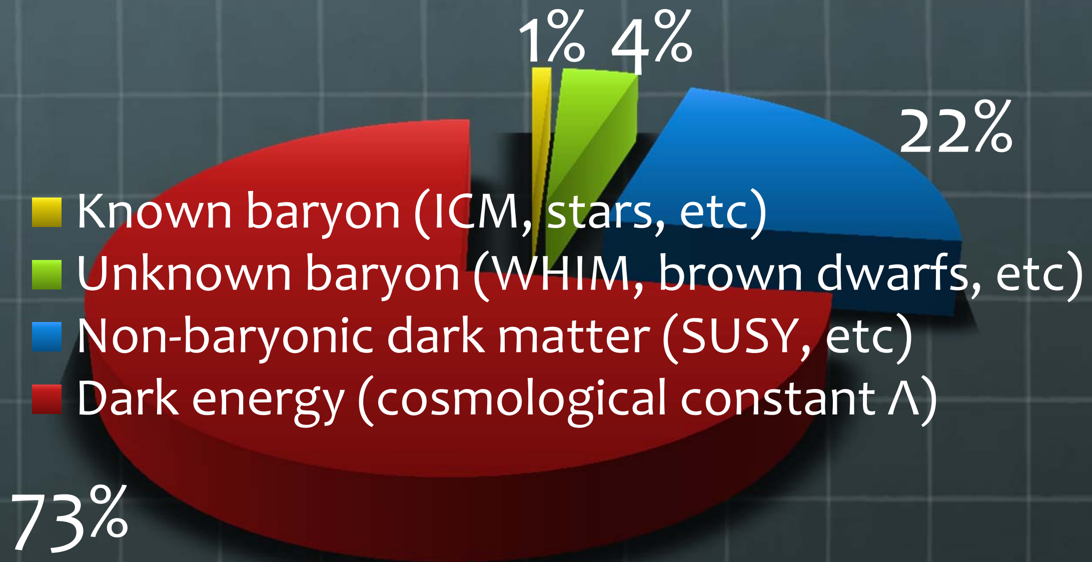
# 1. Cosmological Structure Formation



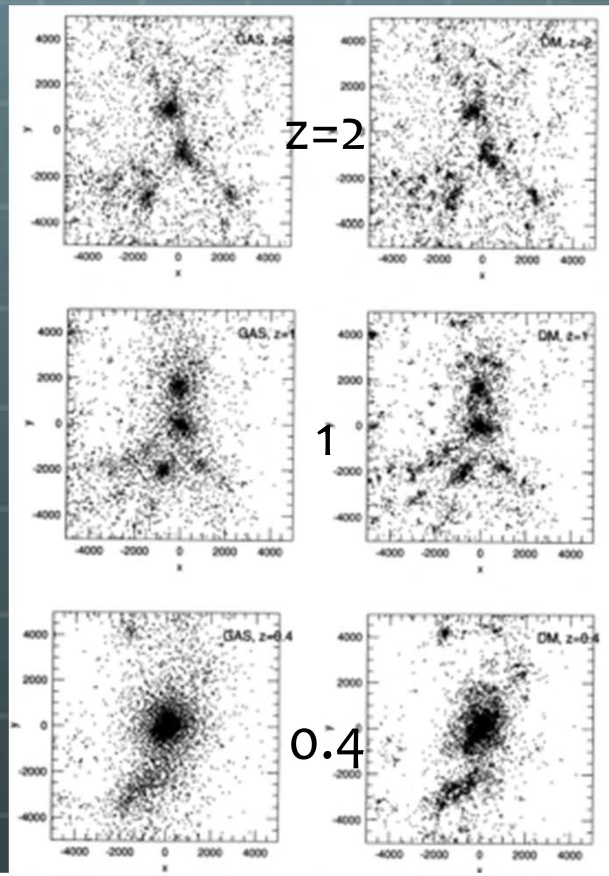
- ΛCDM cosmology
  - Primordial perturbation
  - Jeans instability
  - Sheet/filament structures
  - Mergers of smaller objects
  - Intersections → Galaxy clusters

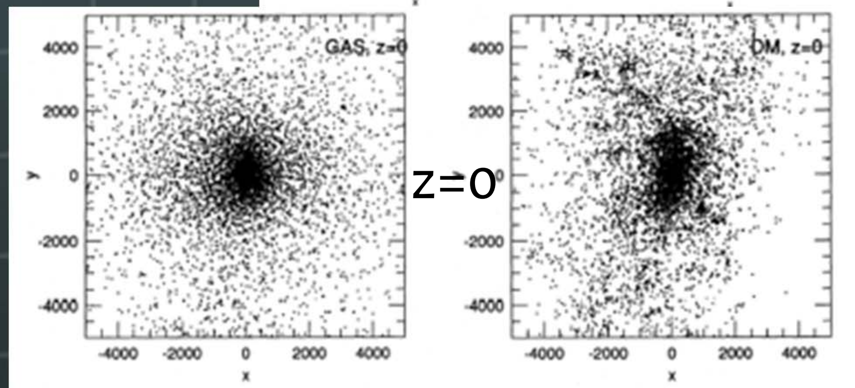
3K CMB (WMAP)






Navarro+ 95

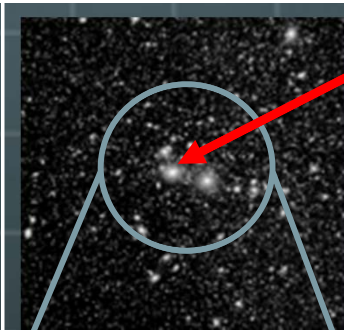
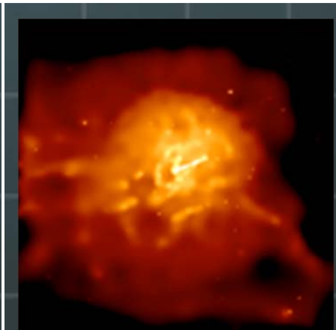
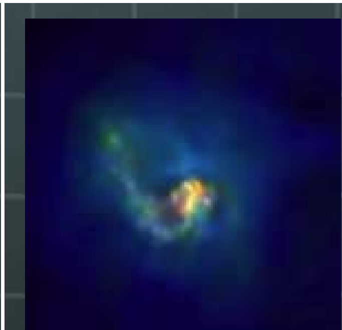
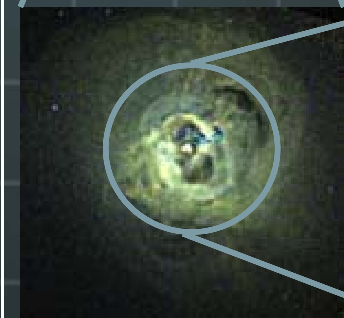


# 1. Galaxy Clusters

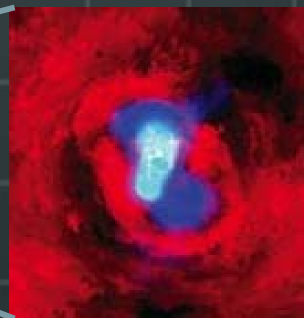


- Galaxy cluster consists of
  - **Galaxies** (1) – Radio, IR, visible, UV, (X-ray, γ-ray)
  - **Intracluster medium (ICM)** (5) – X-ray
  - **Dark matter** (30) – indirect evidences ($\sigma_{gal}$, $T_{ICM}$)

| | Virgo | Centaurus | Perseus |
|---|---|---|---|
| Visible |  |  |  |
| X-ray |  |  |  |

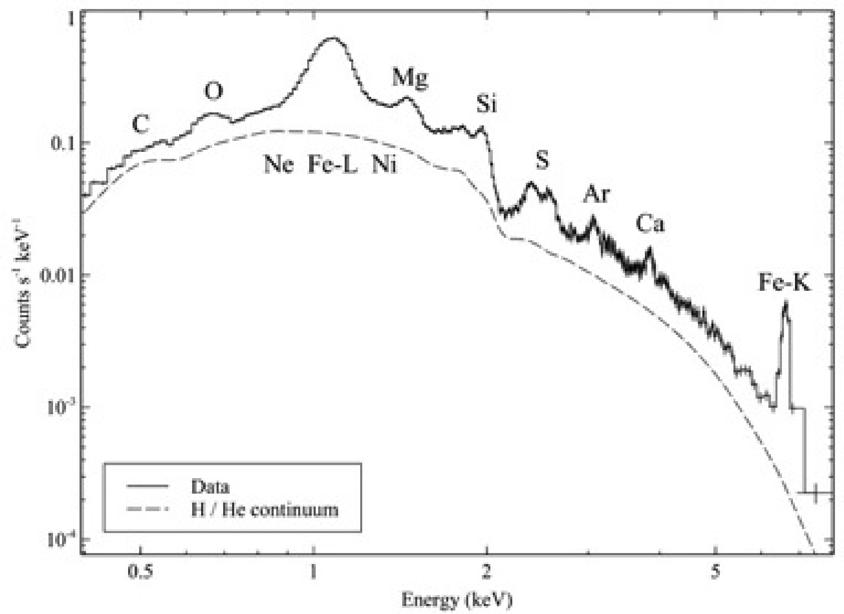
cD galaxy NGC1275
Radio source 3C85

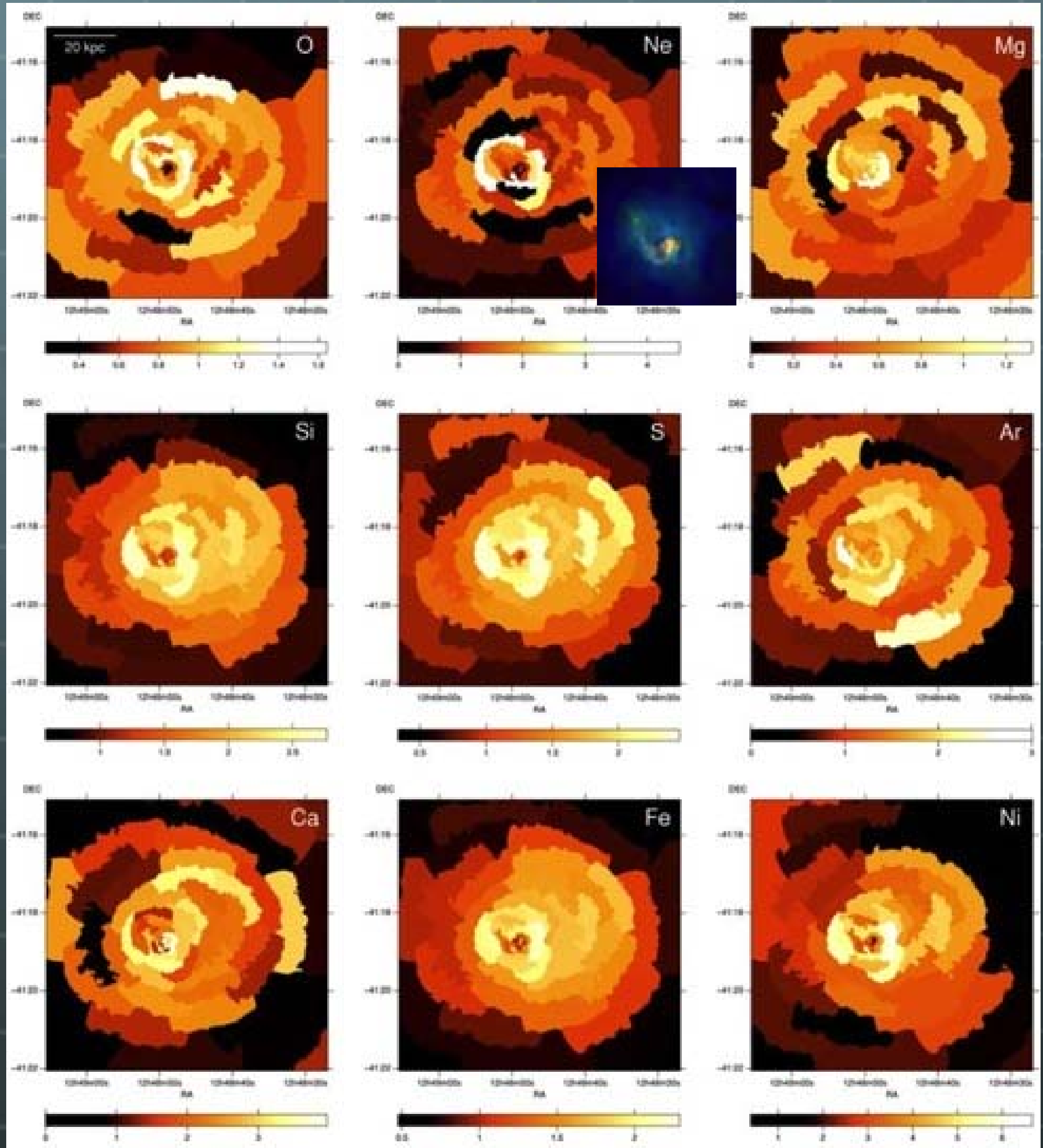
1.4 GHz intensity (blue)
Thermal Gas Pressure (red)
Fabian+ 06



# 1. Intracluster Medium (ICM)

- X-ray emissions
  - Bremsstrahlung
  - Lines (O, Si, Fe, … )
  - $T \sim 10^7$-$10^8$ K
  - $Z \sim 0.1$-$1.0\ Z_{sun}$



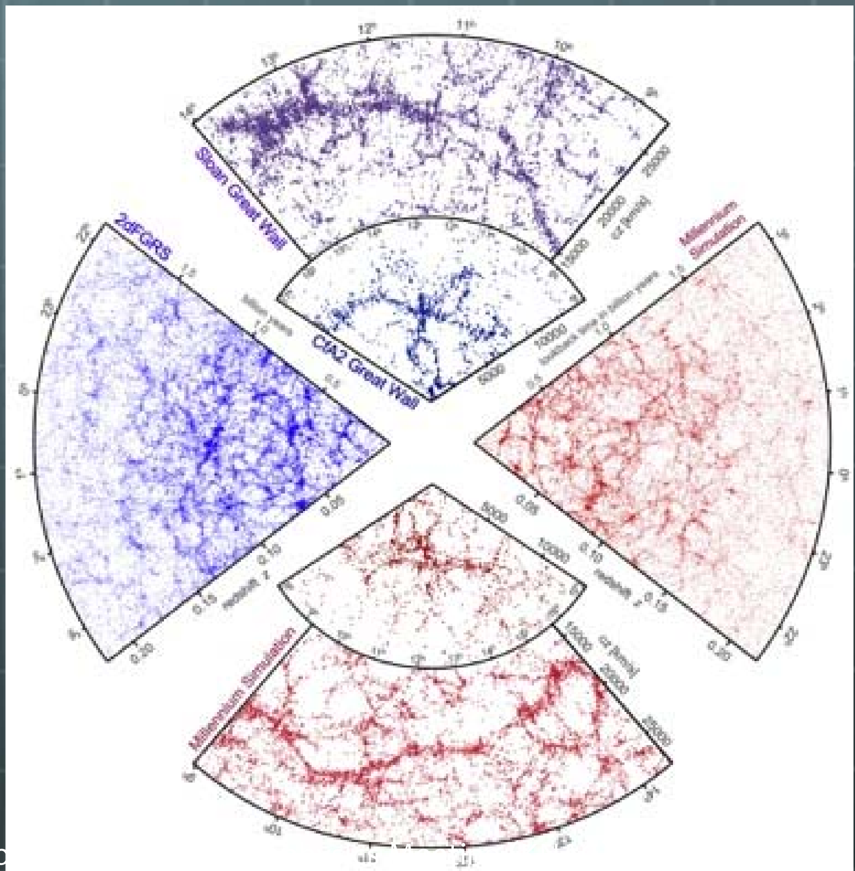



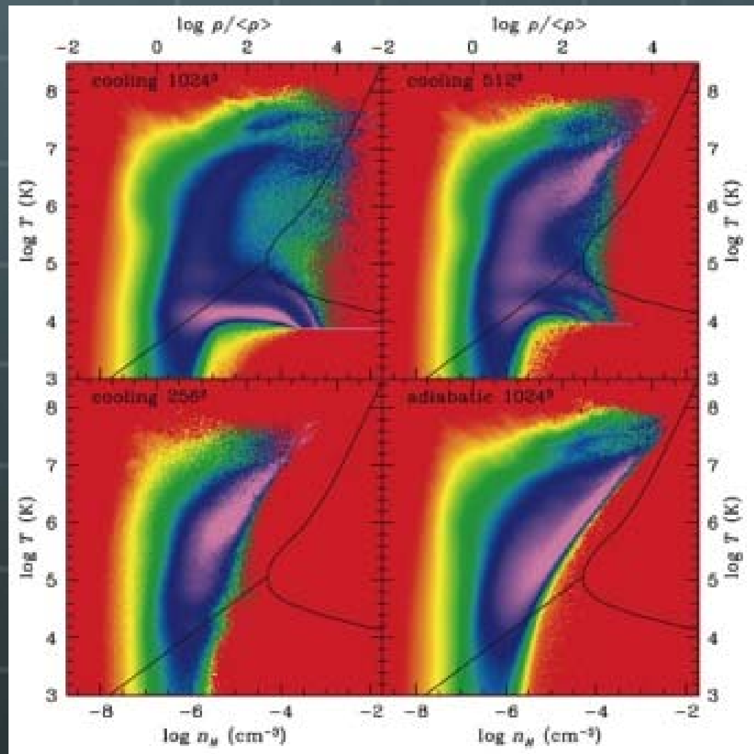

Centaurus (Sanders+ 06)

# 1. Large-Scale Structure



- The large-scale structure consists of
  - **Galaxies** – Radio, IR, visible, UV, (X-ray, γ-ray)
  - **Warm-Hot Intergalactic medium (WHIM)** – UV, X-ray
  - **Dark matter** – (theoretically predicted)

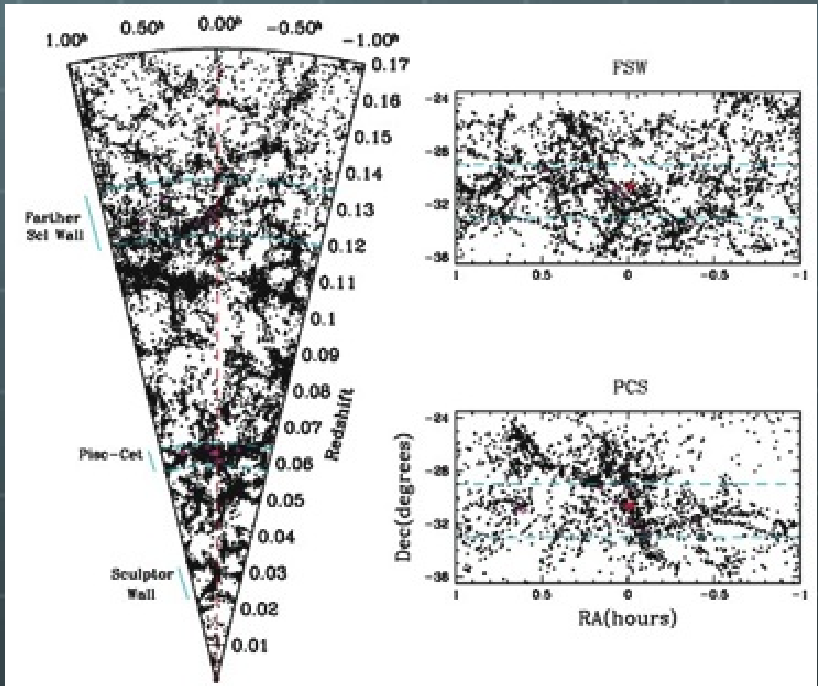


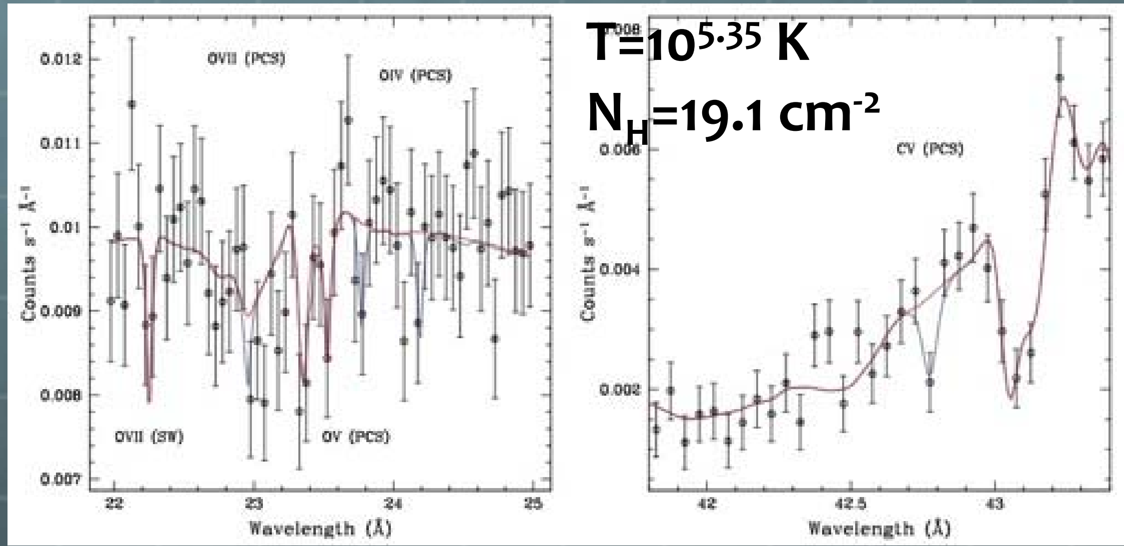



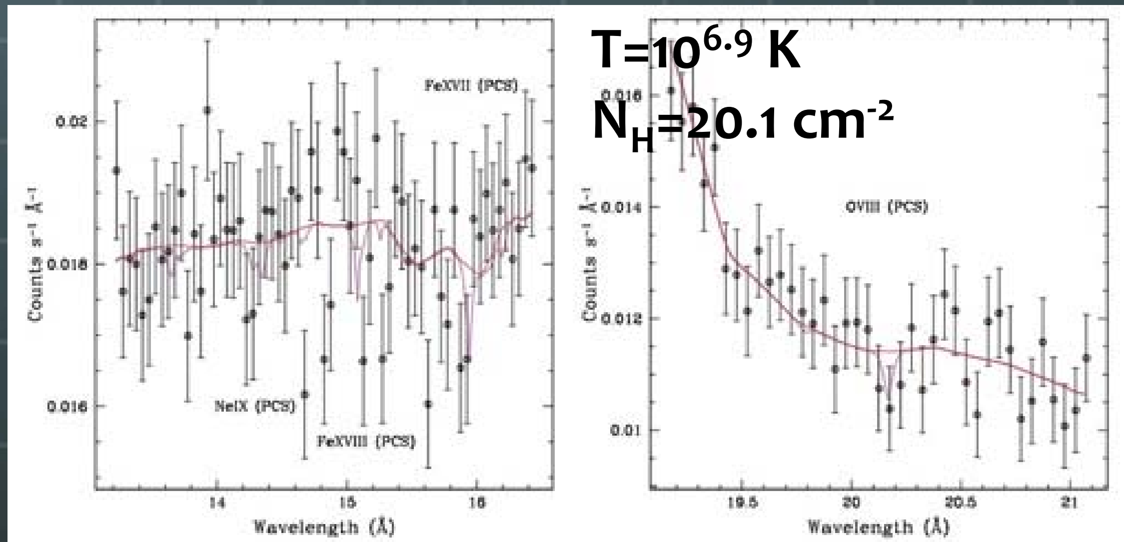

Virgo consortium
http://www.mpa-garching.mpg.de/millennium/

Kang+ 05

- X-ray emissions
  - detection?
- Absorption Lines
  - Some "detections"




500 ksec Chandra obs. of Blazar H2356-309 (Zappacosta+ 10)

# 2. Shock

2.1 As a Heating Mechanism

2.2 Non-Equilibrium Plasma

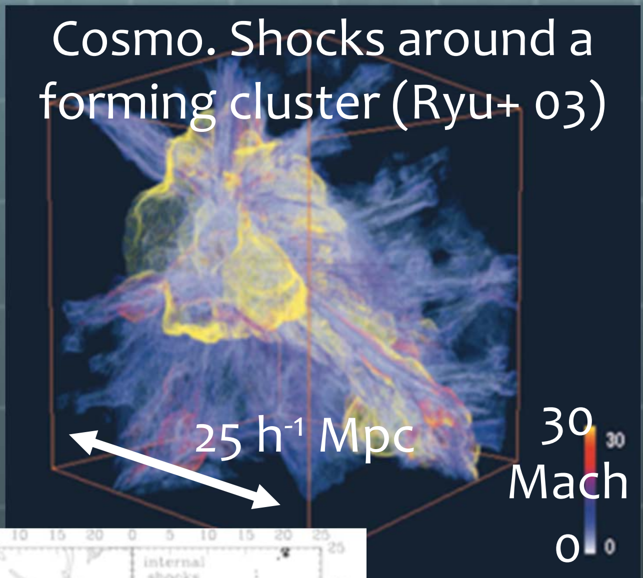
2.3 Sunyaev-Zel'dovich effect

# 2.1 Shocks as Heating Mechanism

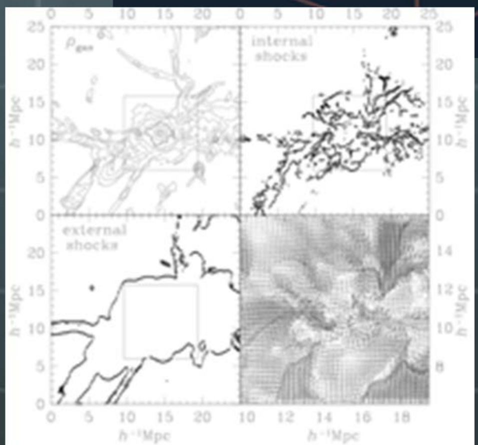


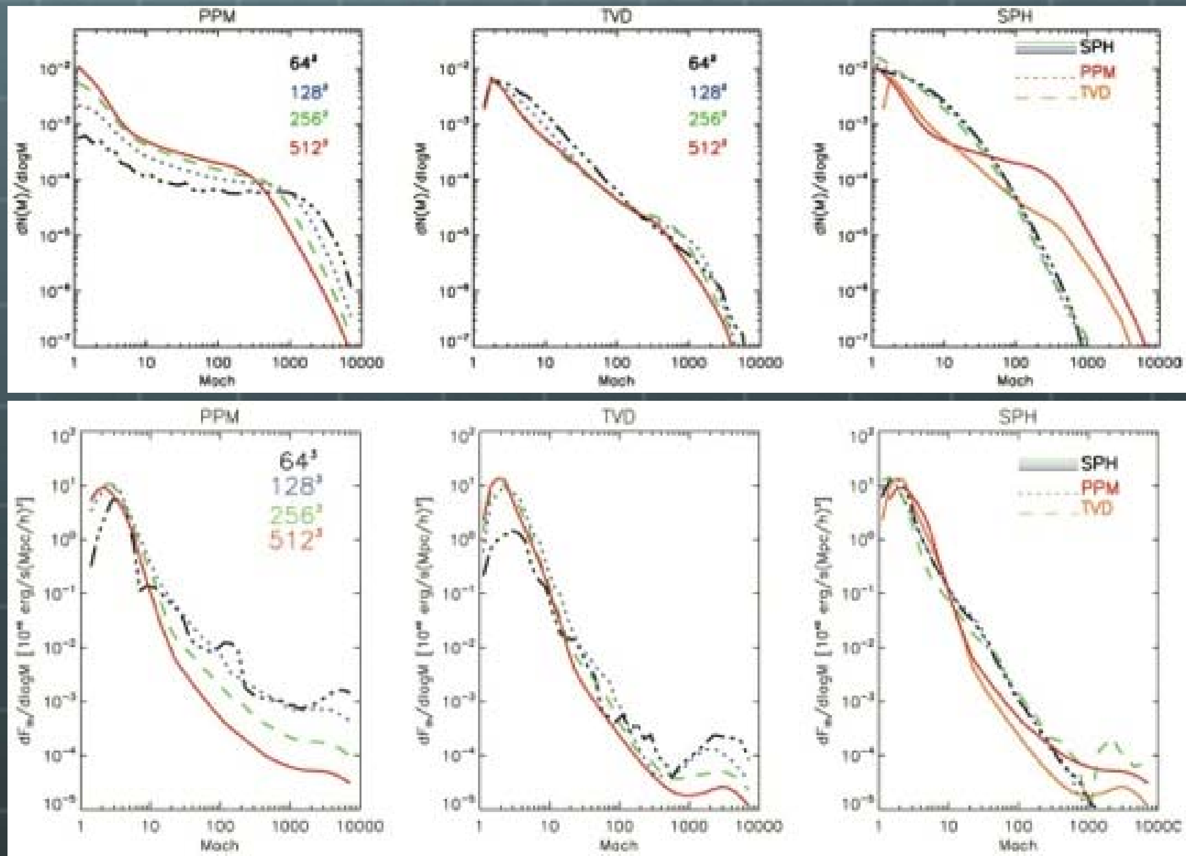
- Shocks are ubiquitous
  - Usually, $V_{infall} > V_{sound}$

| | Clusters | Filaments |
|---|---|---|
| Temperature | $10^7 – 10^8$ K | $10^5 – 10^7$ K |
| Mach number | a few | 10 - 100 |




Cosmo. Shocks around a forming cluster (Ryu+ 03)

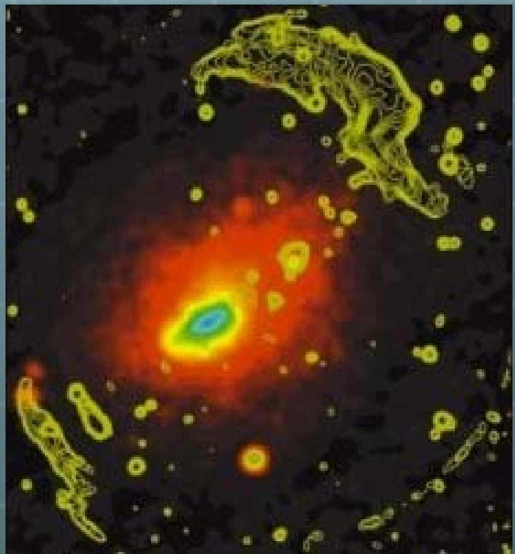


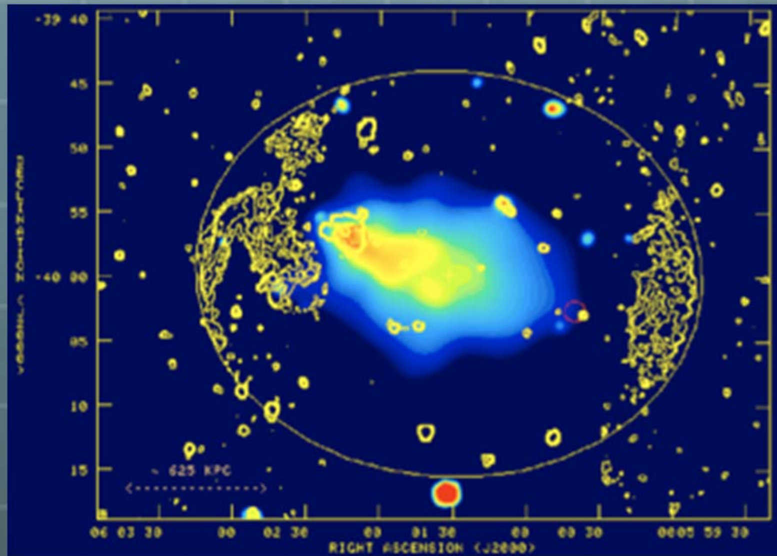




Volume-weighted number distribution of shocks and thermalized energy flux through shocks (Vazza+ 11)

# 2.1 Clues for Shocks (Radio)



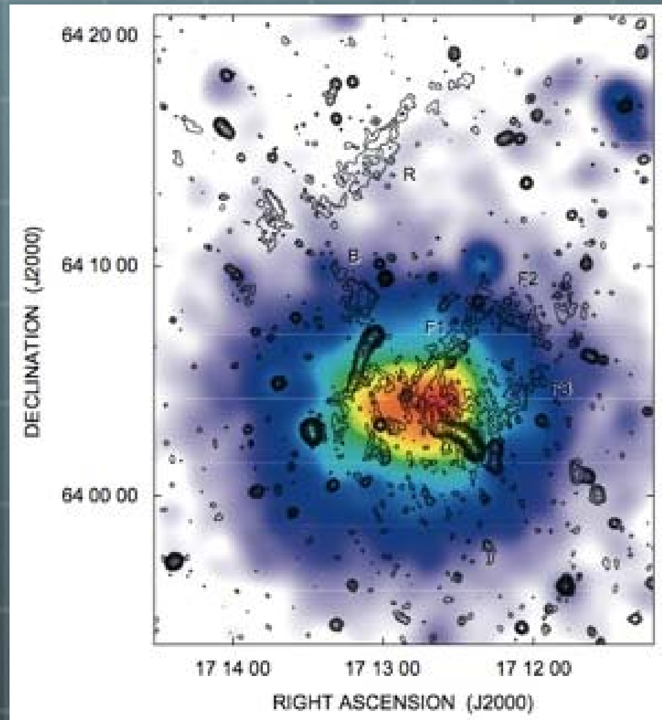


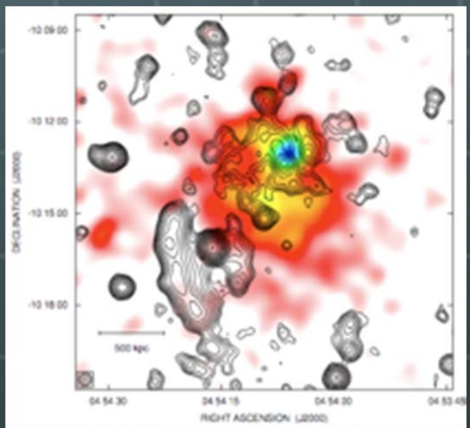


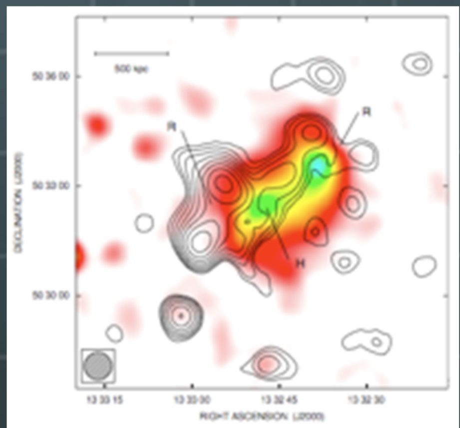

Abell 3667
(Roettiger+ 99)

Abell 3376
(Bagchi+ 06)

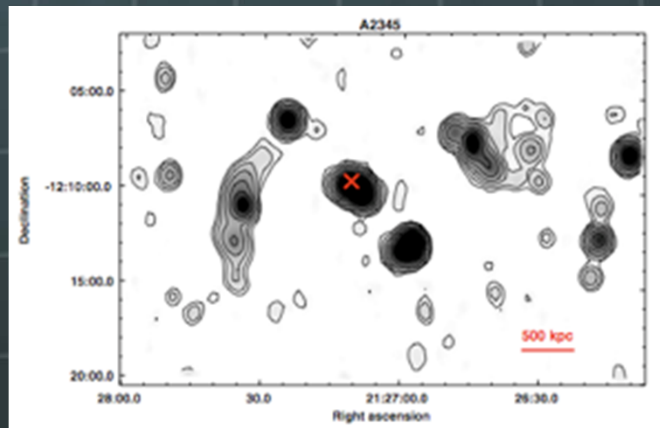
Abell 2255
(Govoni+ 05)

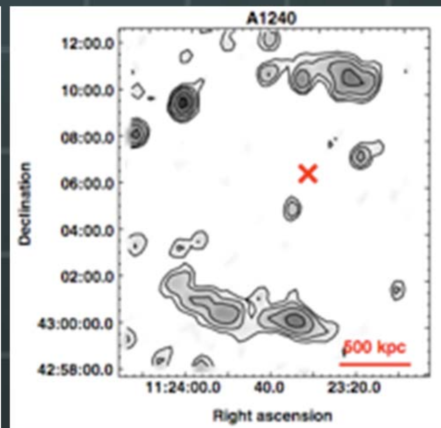




A521, A1758 (Giovanini+ 09)

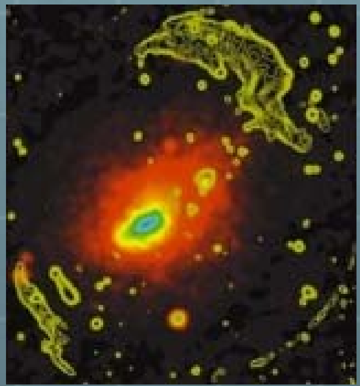


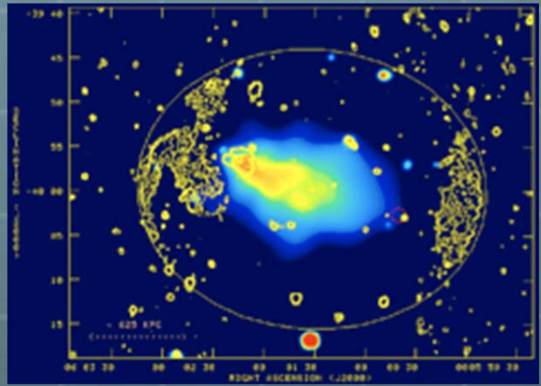



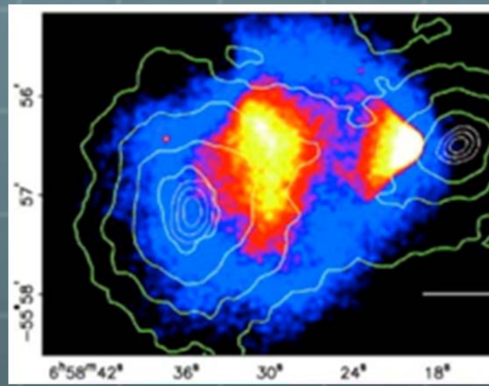

A2345, A1240 (Bonafede+ 09)
✕=X-ray peak

# 2.1 Clues for Shocks (X-ray)

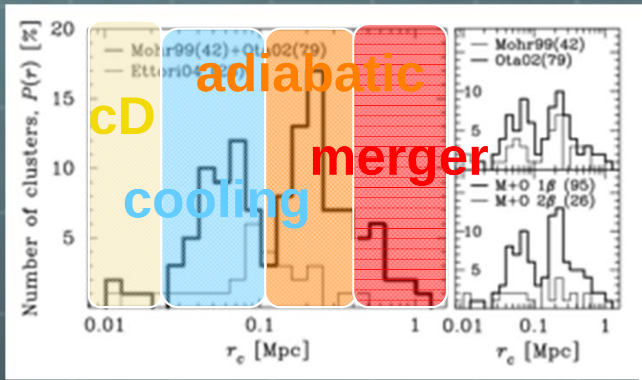




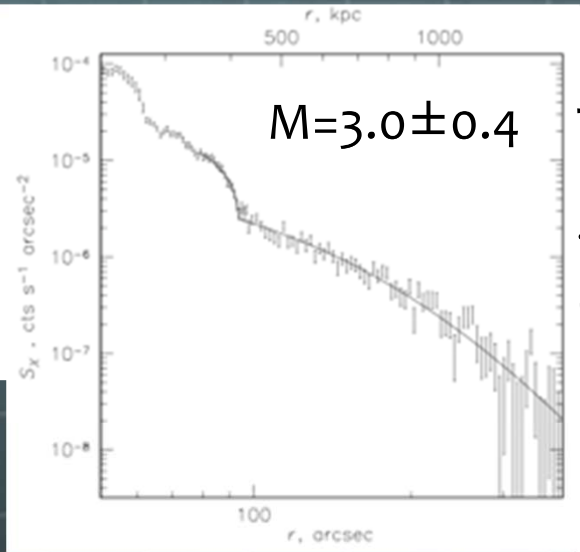


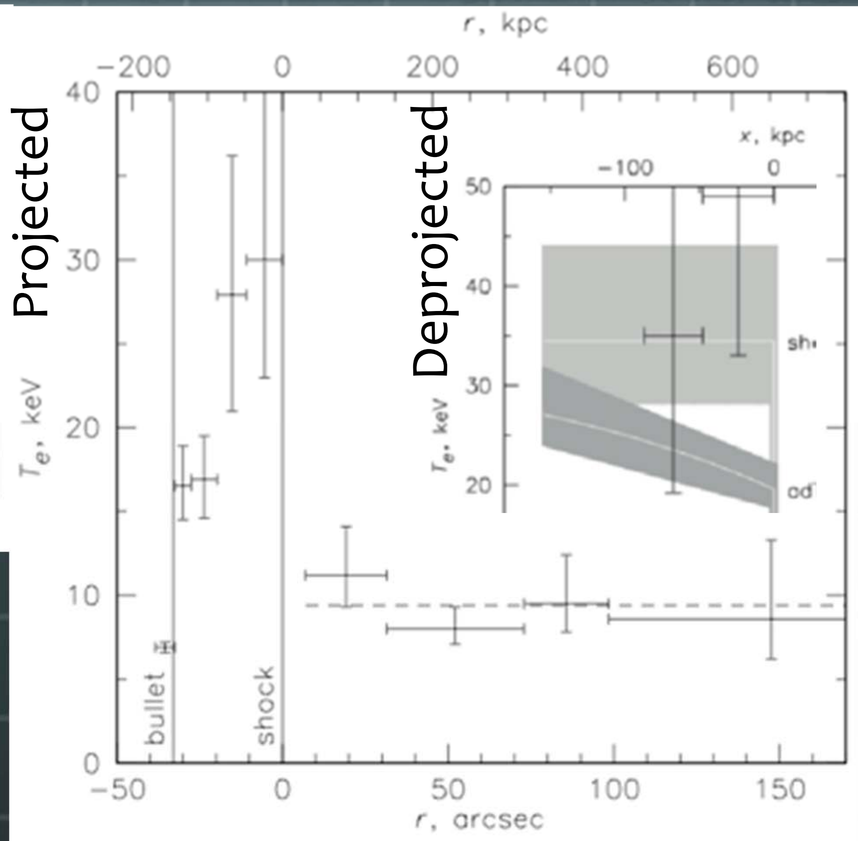


1E0657-56
Chandra 0.8-4.0 keV (color)
Lensing mass (contour)
Markevitch 06; Clowe+ 06




TA, Masai 05;06




Markevitch 06

**<u>X-ray merging cluster candidates</u>**

Abell 85, 399/401, 520, 665, 2065, 2142, 2256, 3376, 3395, 3667, ZwCl 0024+1652, RXJ 0658.5-5556, RXJ 1347.5-1145, RXJ 1720.1-2638, MACSJ 0025.4-1222, MACSJ 0717.5+3745

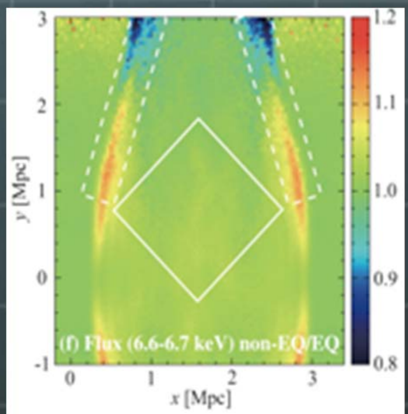
# 2.2 Non-Equilibrium Plasma

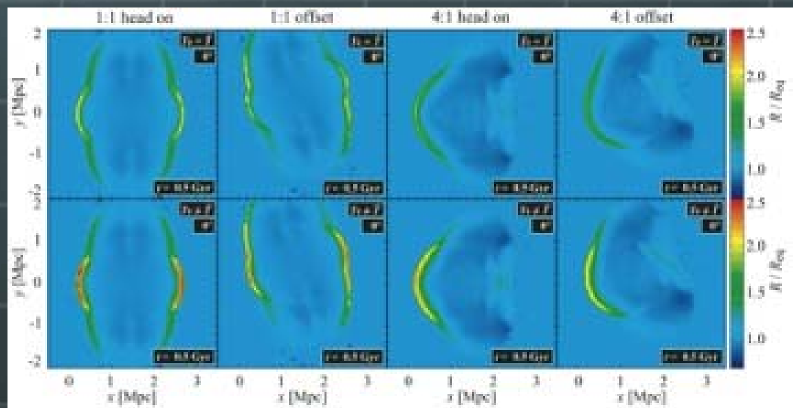


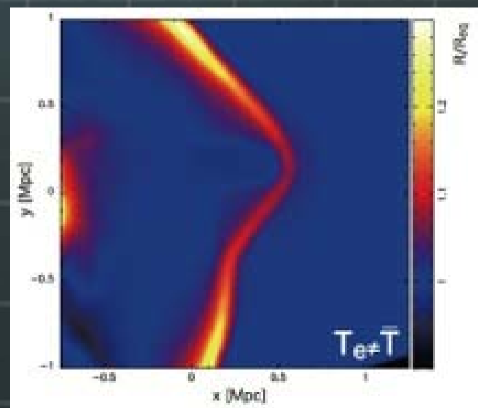
- How the ICM/WHIM is heated by the shock?
  - Particle acceleration (non thermal)
    - Non-thermal emissions
  - Thermalization ($T_i \geqq T_e > T_{ionize}$)
    - Thermal but non-equilibrium emissions
  - Equilibration ($T_i = T_e = T_{ionize}$)
    - Thermal emissions

Importance
2T: for discussing T & M
NEI: for discussing T & Z

$t_{el} \sim 2$ Gyr $(n_e{}^{-4}\text{cm}^{-3})^{-1}(T_e{}^{8}\text{K})^{3/2}$
$t_{CIE} \sim 3$ Gyr $(n_e{}^{-4}\text{cm}^{-3})^{-1}$



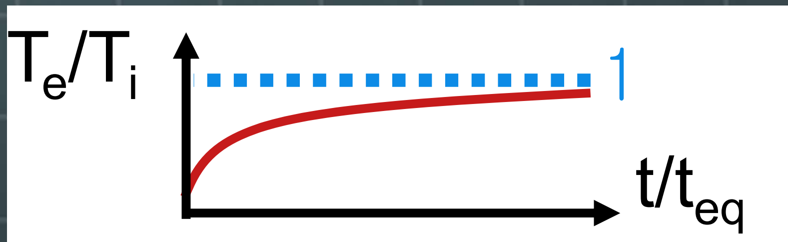



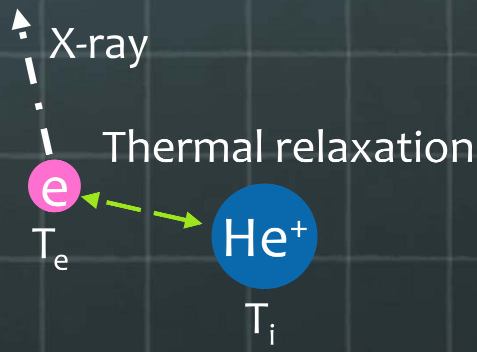

TA, Yoshikawa 08; 10; 12

# 2.2 Electron-Ion Two Temperatures 

- Thermal relaxation at the post-shock
  I. Typically, $E_e \sim m_e V_s^2$ $E_p \sim m_i V_s^2$ at the post shock ($V_s$ the shock velocity)
  II. Since $m_i \sim 1830\ m_e$, ions mainly get the energy ($T_i >> T_e$)
  III. Electrons get energy from ions through Coulomb collisions, where $t_{ei} \sim 43 t_{ii} \sim 1830 t_{ee}$

$$\frac{dT_e}{dt} = \frac{T_i - T_e}{t_{eq,ei}}$$




$$t_{eq,ei} = 7.97 \times 10^9 yr \frac{(T_e/10^8\ \mathrm{K})^{3/2}}{(n_i/10^{-3}\ \mathrm{cm}^{-3}) \ln \Lambda}$$

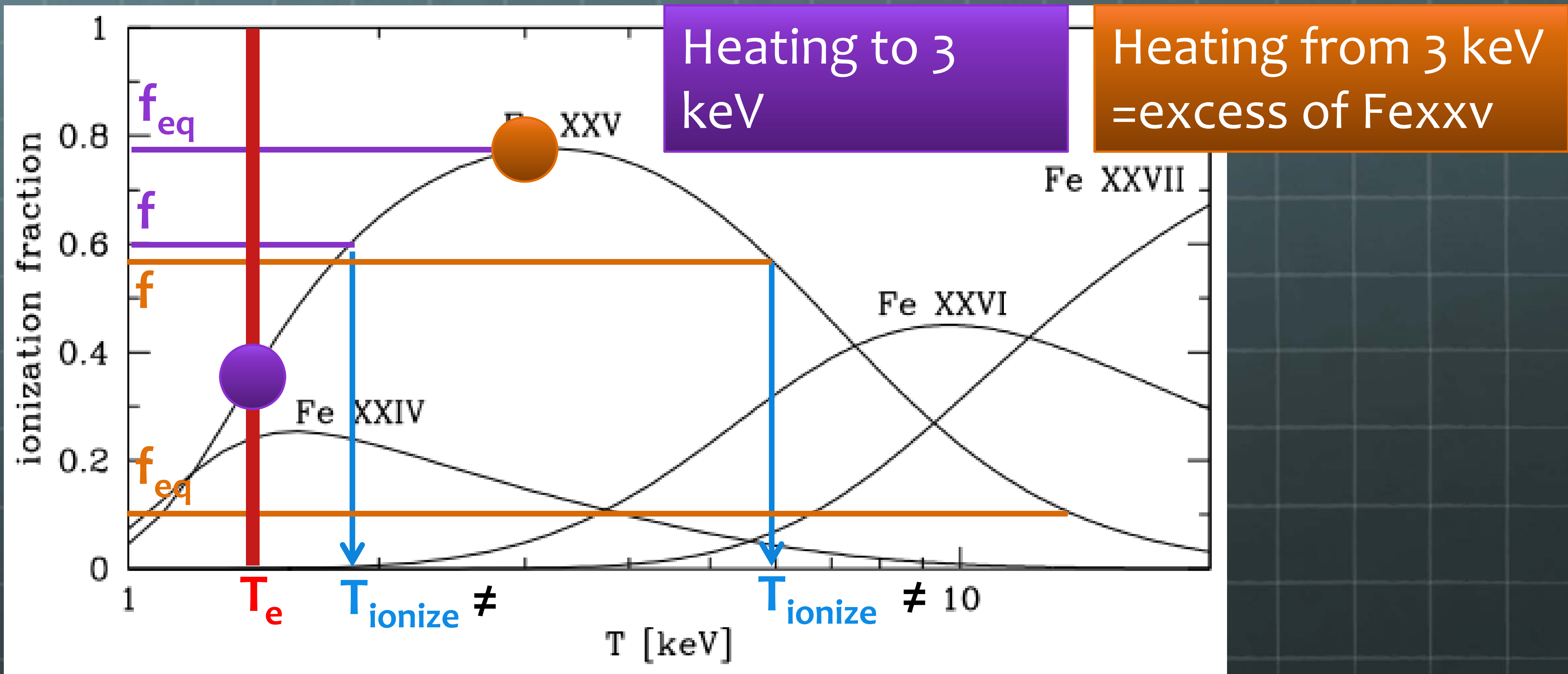
~40

# 2.2 Non-Equilibrium Ionization (NEI)



- **Actual ionization state with the temperature T differs from the state of the CIE with T**

Ionization fraction of Fe in the CIE

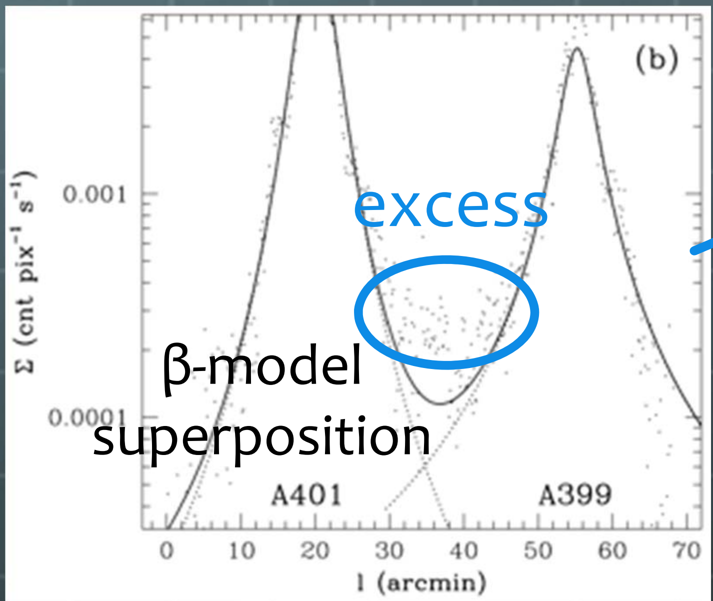


# 2.2 Abell 399/ Abell 401 Linked Region

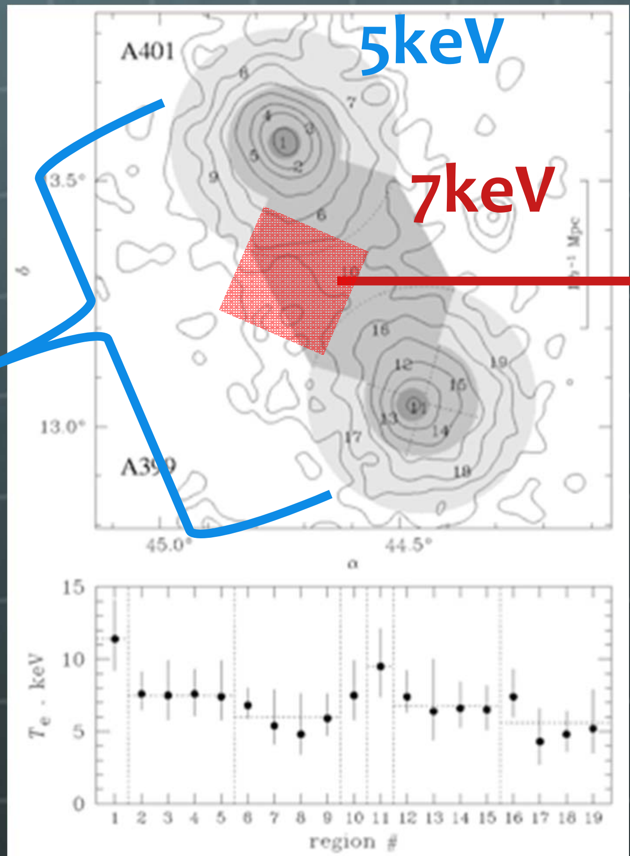


- **Compression makes the outskirts visible!**
  - **Metallicity ~ 0.2 $Z_{sun}$ … Is it real?**

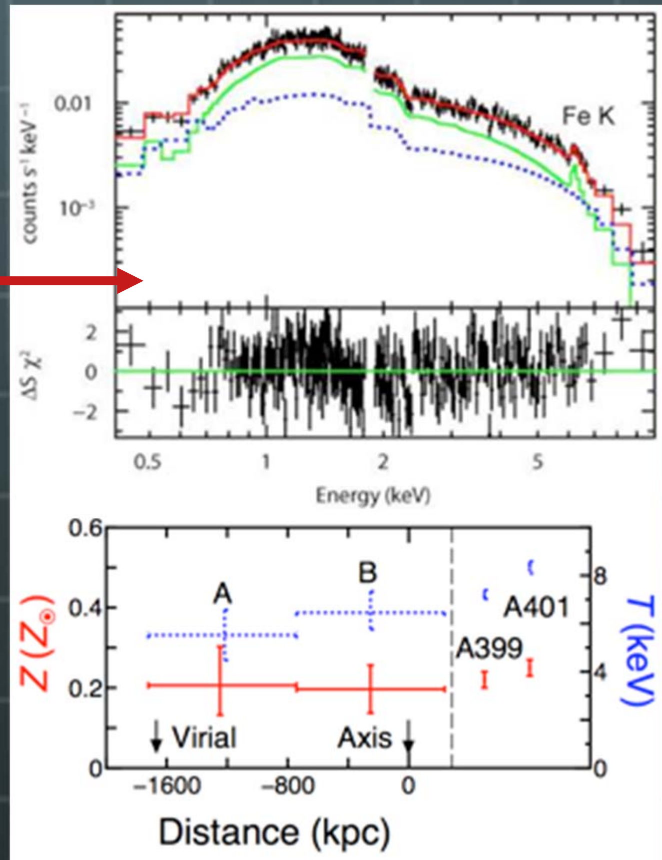
XMM-Newton: Brightness (Sakelliou, Ponman 04)




ASCA: Temperature (Markevitch+ 98)

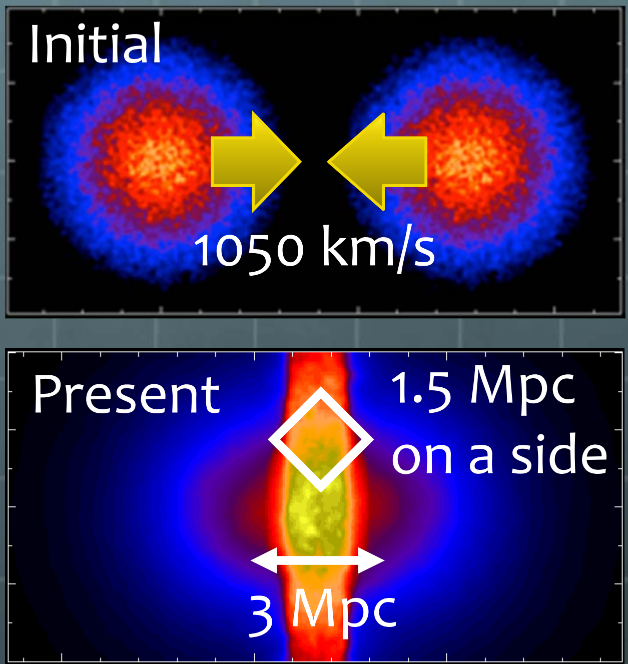



Suzaku: Metallicity (Fujita+ 08)

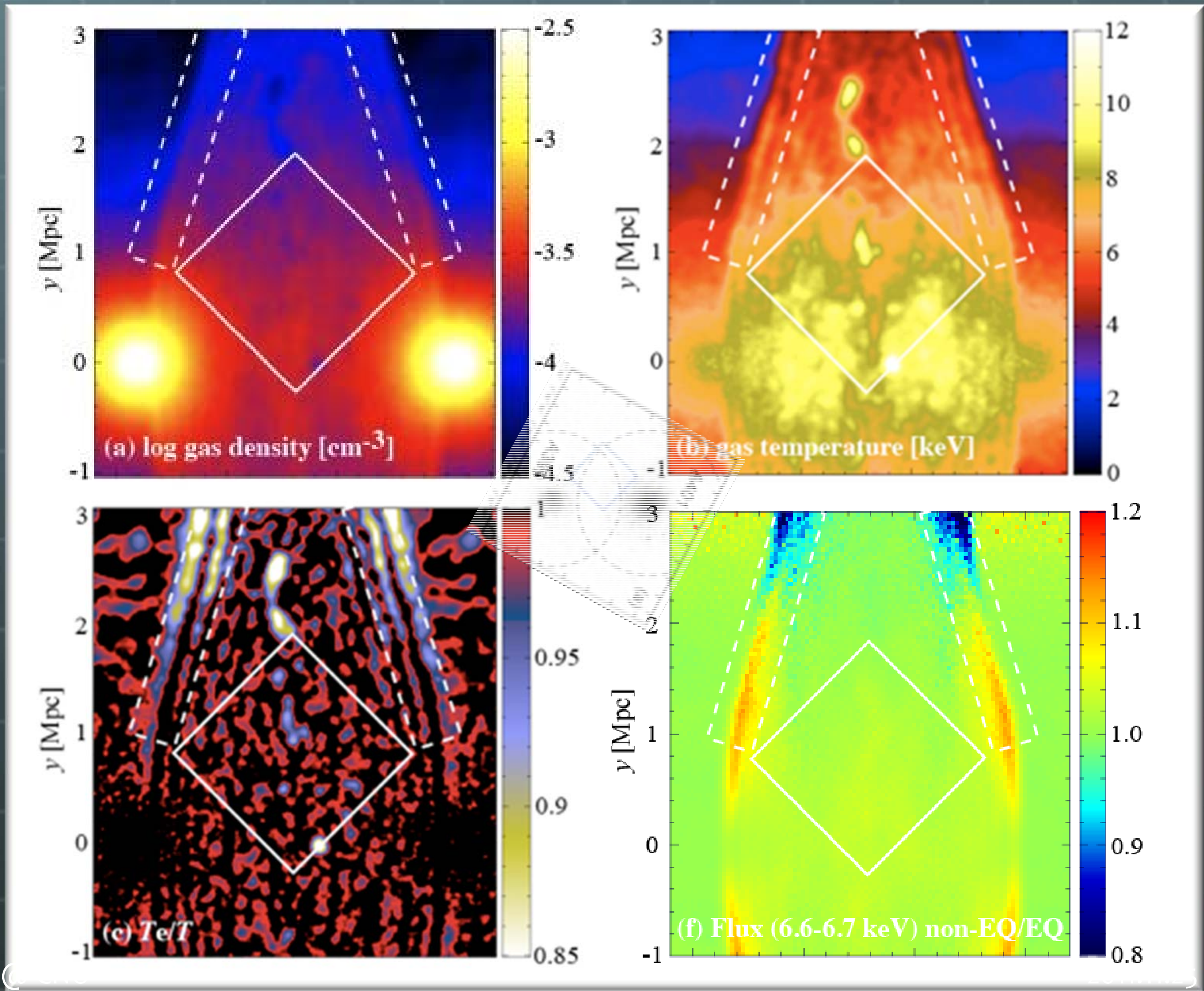


# 2.2 Abell 399/ Abell 401 Linked Region

- Suzaku region already have relaxed → CIE/1T OK.
- Shock layers are newly predicted → NEI/2T




TA, Yoshikawa 08

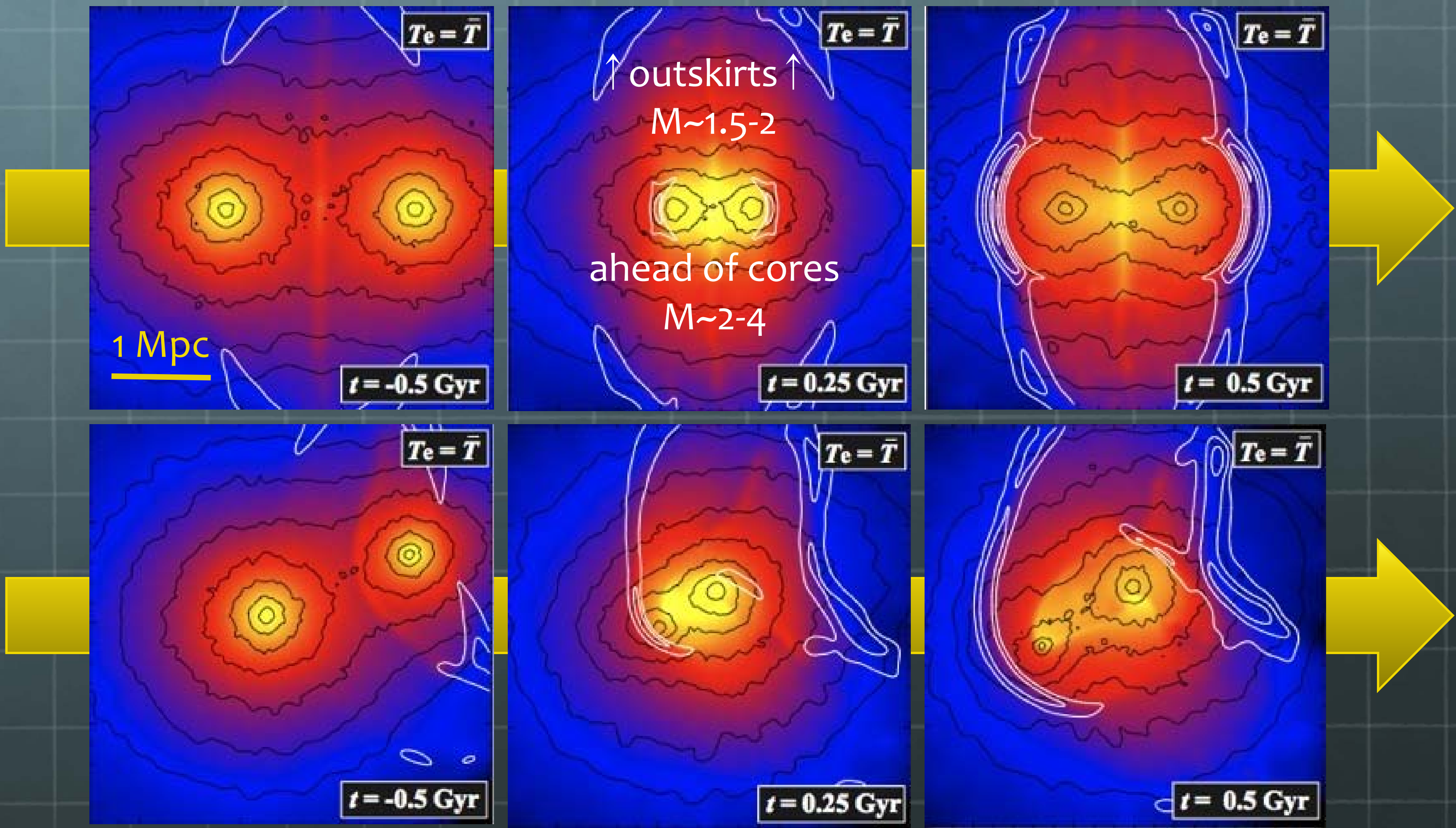


# 2.2 Merging Cluster Simulations



## Shocks in merging clusters

White contour : Mach number (1.4, 2.0, 2.6,..)



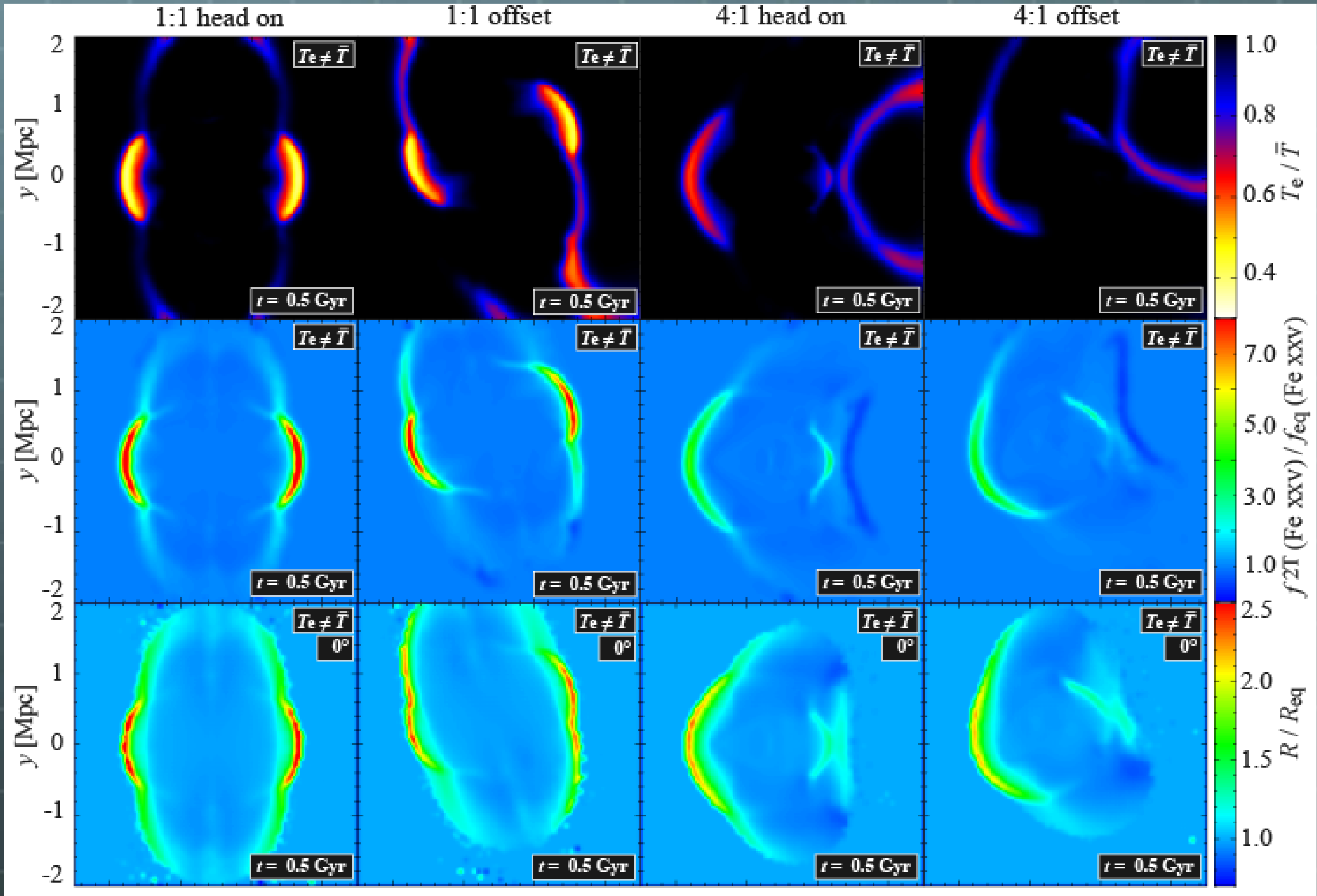

TA, Yoshikawa 10

# 2.2 Merging Galaxy Clusters



- Behind the shock layers → NEI/2T

$$\frac{R}{R_{eq}} = \frac{[I_{6.6-6.7}/I_{6.9-7.0}]}{[I_{6.6-6.7}/I_{6.9-7.0}]_{eq}}$$




$T_e/T$

0.8-0.9 (outskirts)

0.5-0.8 (core)

$f/f_{eq}$ Fe xxv

2-4 (outskirts)

3-8 (core)

$R/R_{eq}$

1.2-1.4 (outskirts)

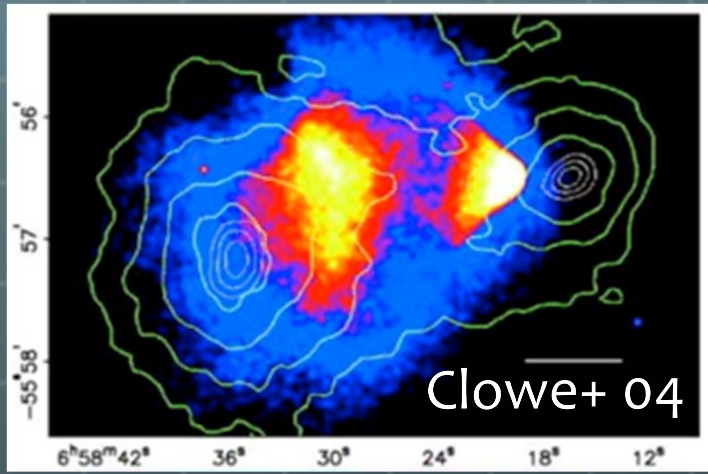
1.6-2.2 (core)

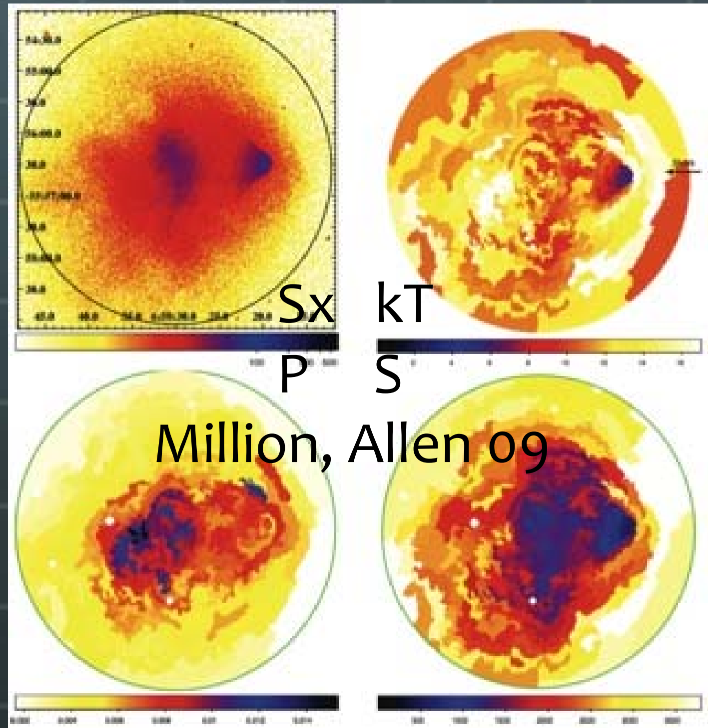
TA, Yoshikawa 10

# 2.2 The Bullet Cluster 1E0657-56



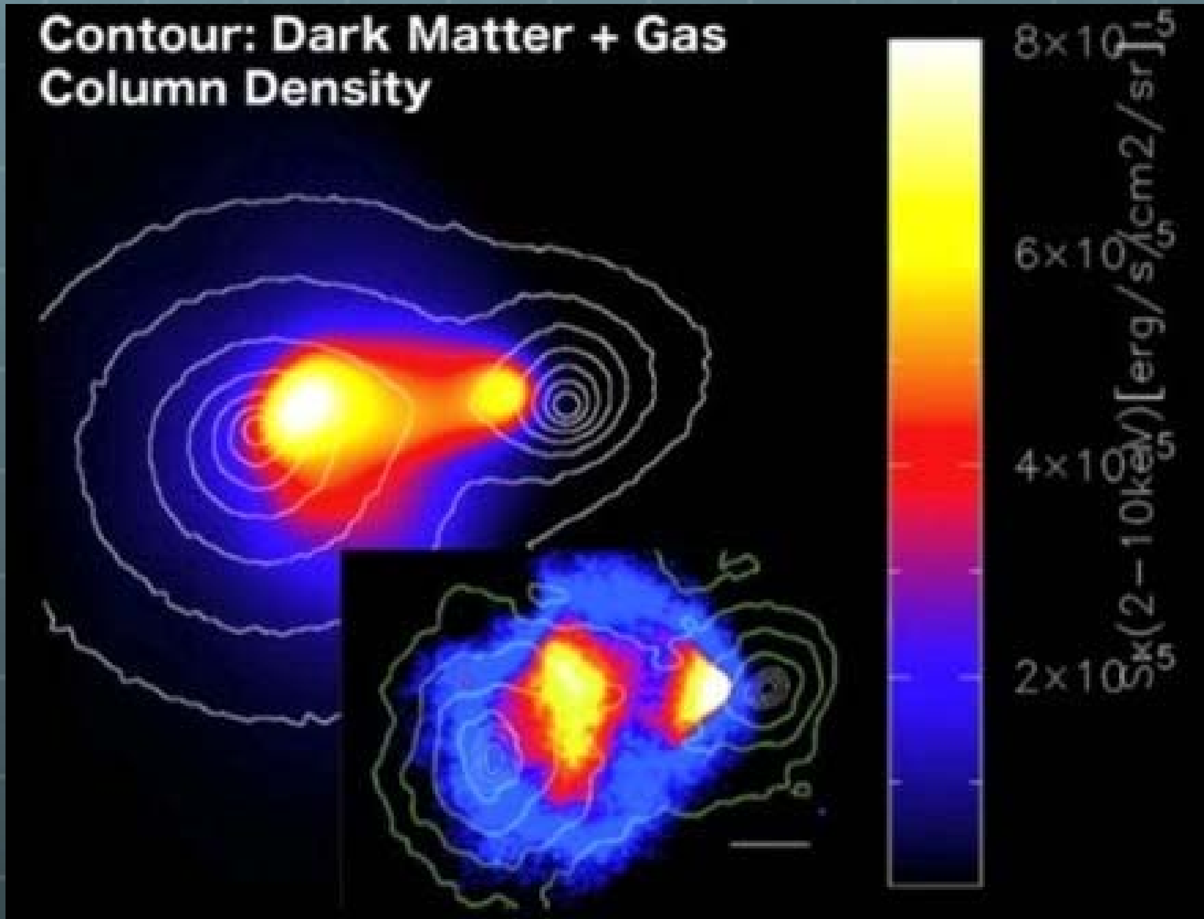
- Textbook of cluster merger
  - Two distinct peaks → evidence of merger
  - Offset of weak lensing → evidence of dark matter (pressure-less matter)
  - Very-high average temperature → evidence of shock heating to the ICM
  - Brightness jump → evidence of the shock with M~3.0±0.4
- 1E0657-56 is suited to "test" standard cosmology and plasma relaxation processes



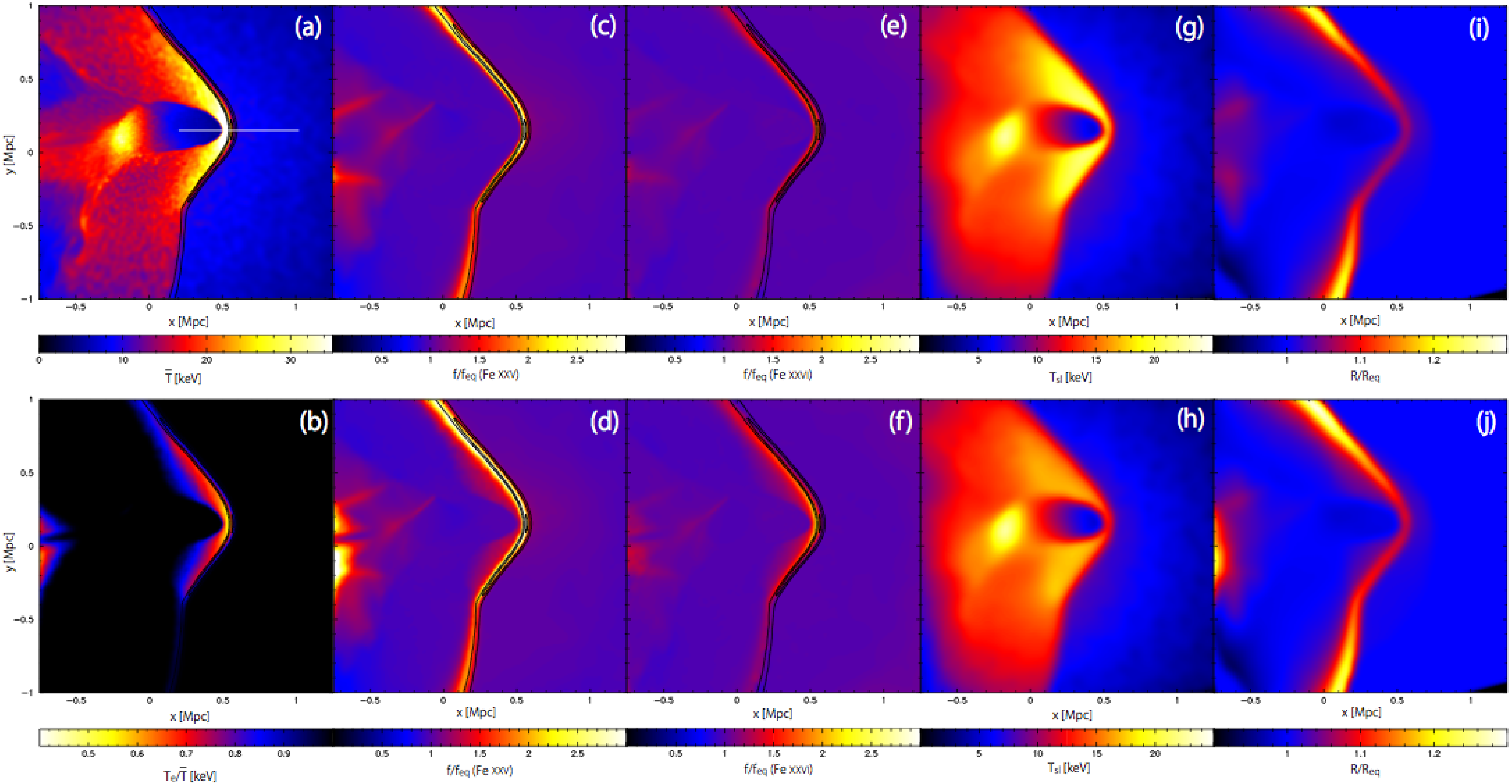
# 2.2 Simulating Bullet Cluster 1E0657-56



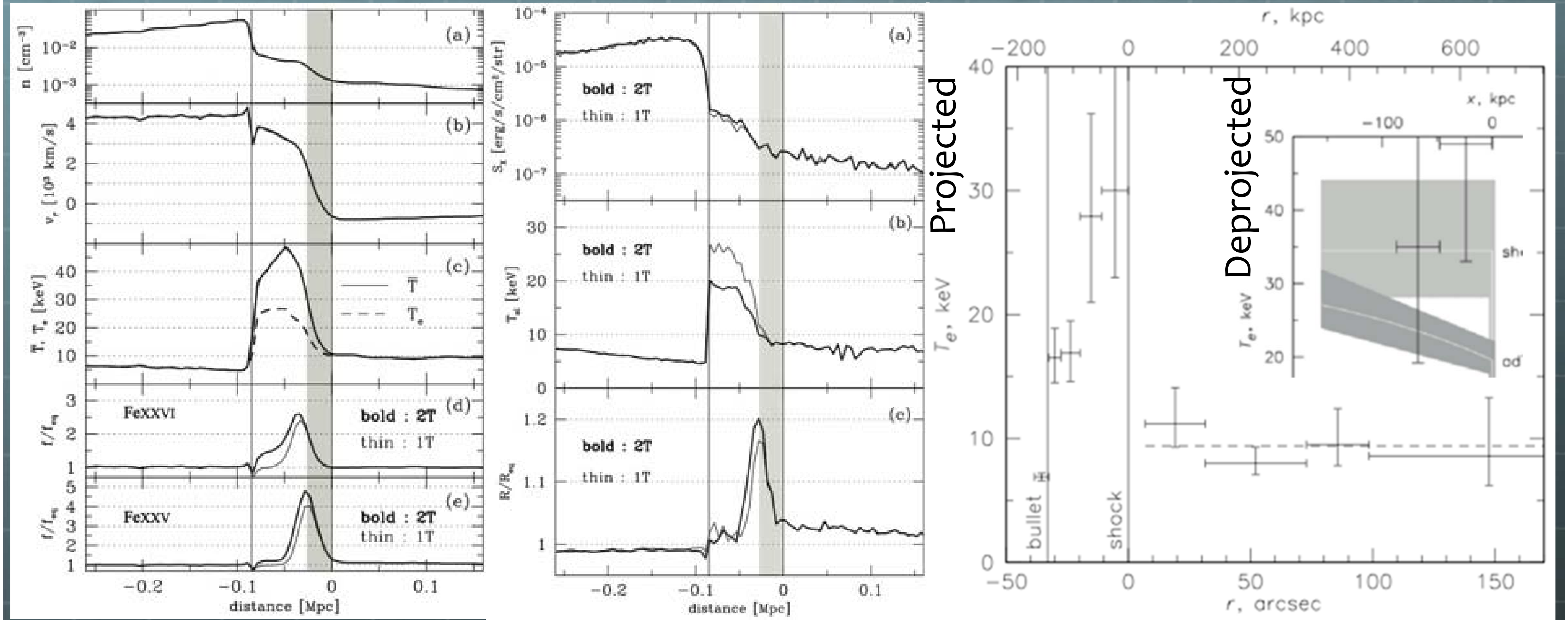



Simulation Movie
Please visit http://canopus.cnu.ac.kr/akataku/Activity.html

- NEI/2T appear behind the shock front



# 2.2 Simulating Bullet Cluster 1E0657-56 




- **If $T_e$ > 30 keV or narrow line with $T_i$~$T_e$ → 1T is plausible**
  - Fast relaxation processes @ M=3
- **If $T_e$ < 25 keV or broad line with $T_i$>>$T_e$ → 2T is plausible**
  - No fast relaxation & Coulomb relaxation?

TA, Yoshikawa 12

# 2.3 Sunyaev-Zel'dovich Effects

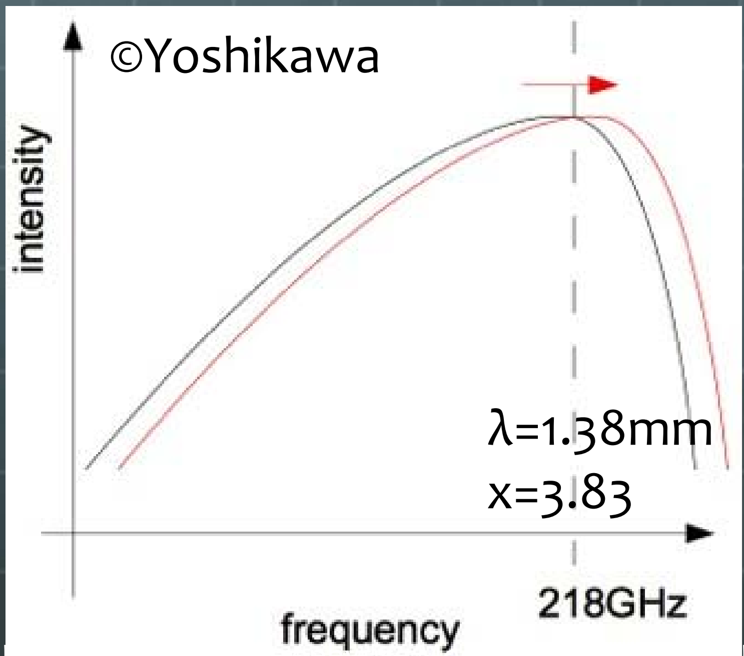
CMB photon distortion caused by IC scattering

Non-relativistic diffusion approximation

- SZ effect
  - Thermal SZ
    - ①Kampaneets Formalism
    - Wright Formalism
      - ②Maxwell-Blotzmann DF
      - ③Relativistic Juttner DF
  - ④Kinematic SZ

Relativistically correct

## ①Thermal SZ (Kampaneets Formalism)




$$x = \frac{h\nu}{k_B T_{CMB}}$$

$$I_0 = \frac{2(k_B T_{CMB})^3}{(hc)^2}$$

$$\Delta I(x) = I_0 \int g(x) \frac{k_B T_e(l)}{m_e c^2} n_e(l) \sigma_T dl$$

$$\Delta I(x) = I_0 g(x) y$$

$$y = \int \frac{k_B T_e(l)}{m_e c^2} n_e(l) \sigma_T dl$$

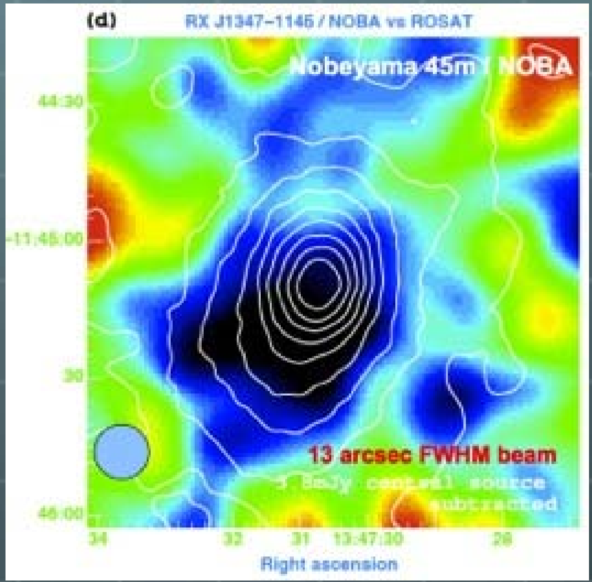
$$g(x) = \frac{x^4 \exp(x)}{[\exp(x) - 1]^2} \left[ x \frac{\exp(x) + 1}{\exp(x) - 1} - 4 \right]$$

Suyaev & Zel'dovich 70

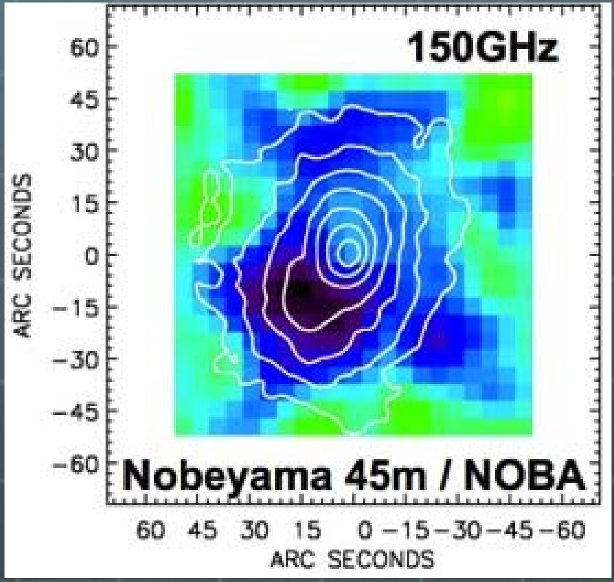
# 2.3 Sunyaev-Zel'dovich Effects

## RXJ1347-1145

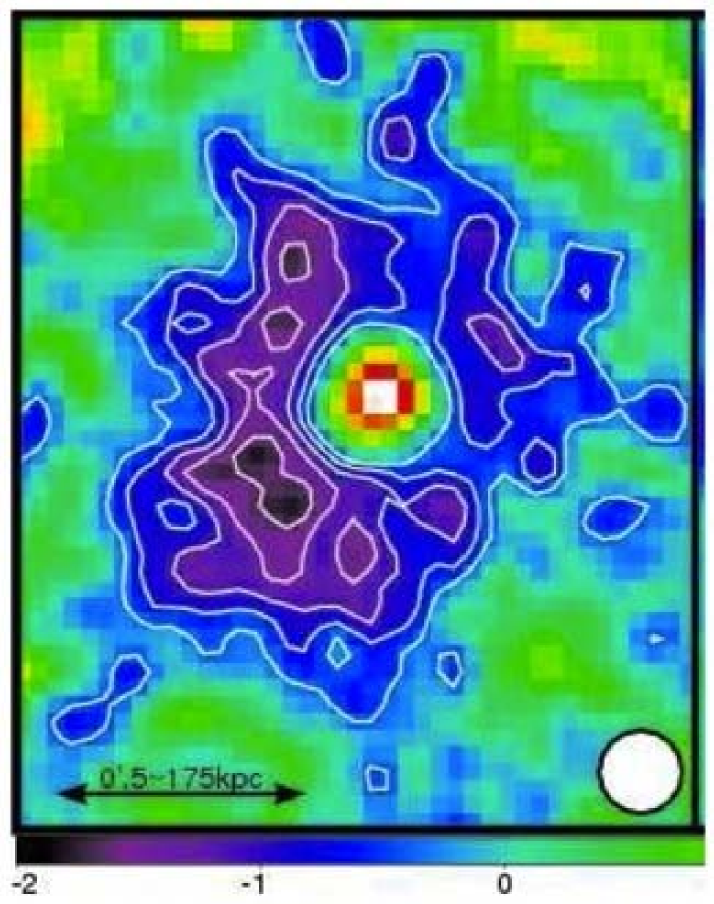
$$\frac{\Delta I}{I_0} \sim 10^{-4} \left( \frac{k_{\rm B} T_{\rm e}}{10 \text{ keV}} \right) \left( \frac{n_{\rm e}}{10^{-3} \text{ cm}^{-3}} \right) \left( \frac{L}{1 \text{ Mpc}} \right)$$




NRO 45m/150GHz
Komatsu+ 01




NRO 45m/150GHz
Kitayama+ 04




GreenBank 100m/90GHz
Mason+ 10

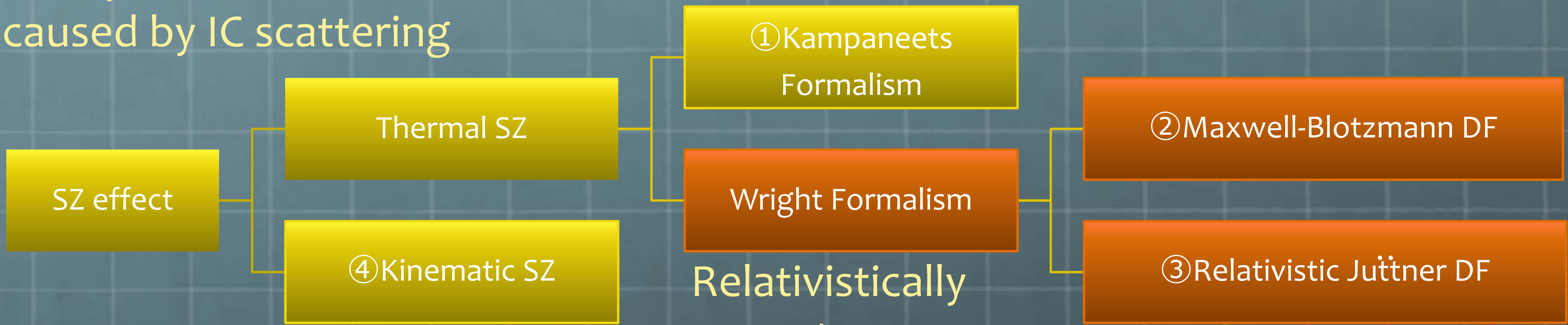
M~2 (Kitayam+ 04)

c.f. $kT=25.3^{+6.1}_{-4.5}$ keV (Suzaku, Ota+ 08)

# 2.3 Sunyaev-Zel'dovich Effects

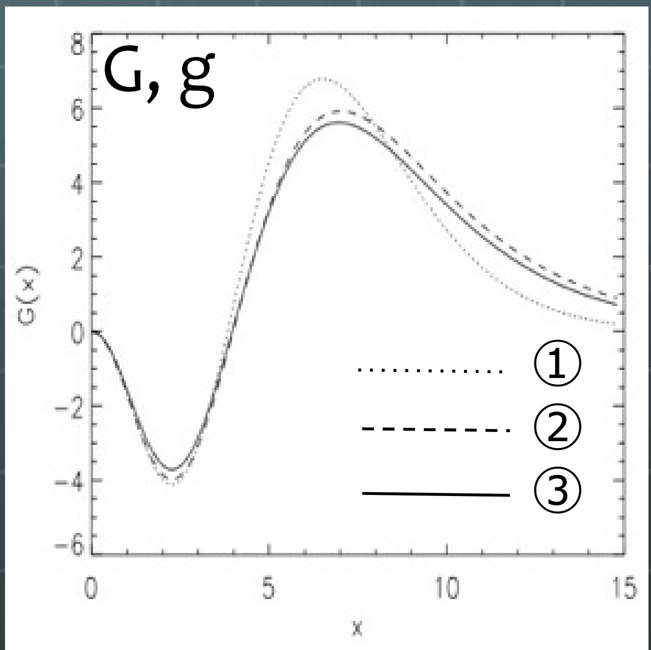
CMB photon distortion caused by IC scattering

Non-relativistic diffusion approximation




Relativistically correct

## ②③Thermal SZ (Wright Formalism)




$$\Delta I^{\rm rmb}(x) = I_0 \int G(x, T_{\rm e}) \frac{k_{\rm B} T_{\rm e}(l)}{m_{\rm e} c^2} n_{\rm e}(l) \sigma_{\rm T} dl$$

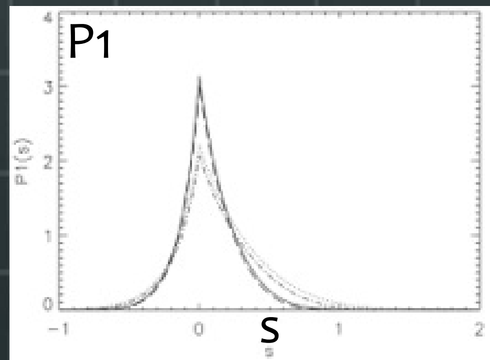
$$x = \frac{h\nu}{k_{\rm B} T_{\rm CMB}}$$

$$I_0 = \frac{2(k_{\rm B} T_{\rm CMB})^3}{(hc)^2}$$

$$G(x, T_{\rm e}) = \int \frac{P_1(s, T_{\rm e})}{\Theta(T_{\rm e})} \left[ \frac{x^3 \exp(-3s)}{\exp\{x \exp(-s)\} - 1} - \frac{x^3}{\exp(x) - 1} \right] ds$$

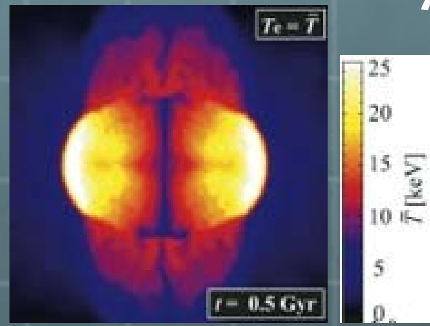
$$\Theta(T_{\rm e}) = \frac{k_{\rm B} T_{\rm e}(l)}{m_{\rm e} c^2}$$

S the logarithmic frequency shift caused by a scatter, P the scattering kernel (the distribution of frequency shift for single scattering)

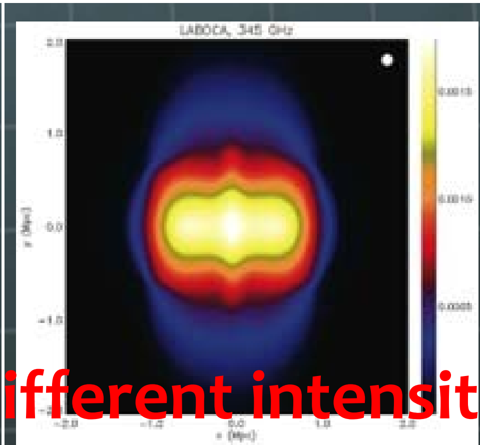
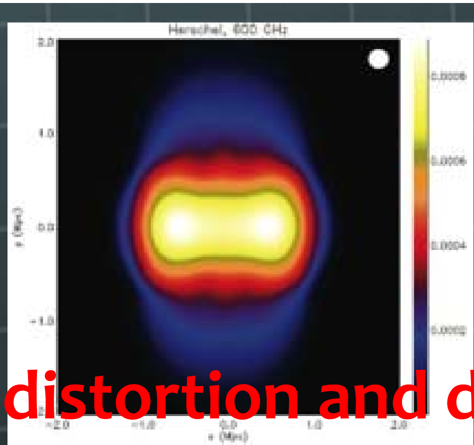
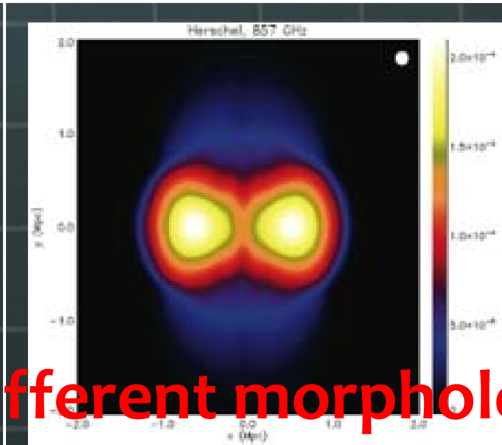



Wright 79; Prokhorov, TA+ 2011abc

# 2.3 Sunyaev-Zel'dovich Effects




- Kampaneets vs Wright
  - Wright: I increases @ T > 10 keV

| | 345GHz | 600GHz | 857GHz |
|---|---|---|---|
| Kampaneets | Different intensity distortion but same morphology | | |
| Wright |   |   |   |

Different intensity distortion and different morphology

Prokhorov, TA+ 2011c

# 2.3 Sunyaev-Zel'dovich Effects

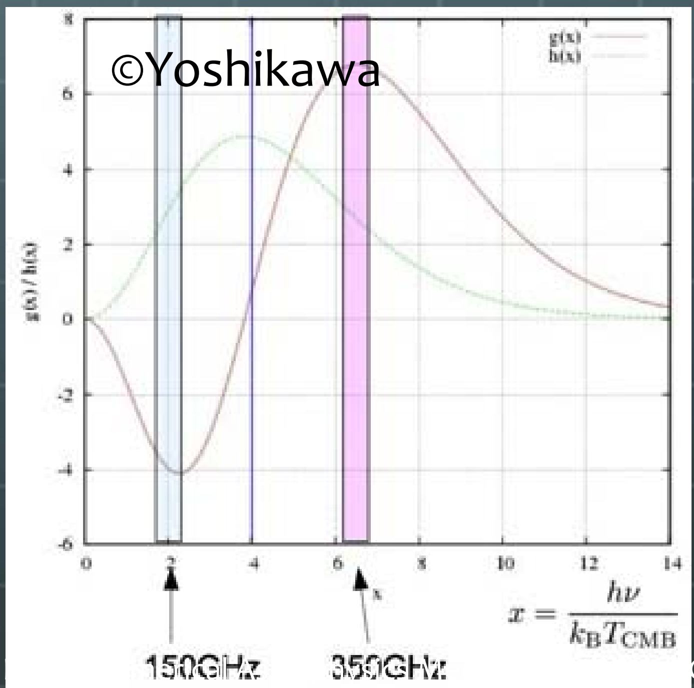
CMB photon distortion caused by IC scattering

Non-relativistic diffusion approximation

- SZ effect
  - Thermal SZ
    - ①Kampaneets Formalism
    - Wright Formalism
      - ②Maxwell-Blotzmann DF
      - ③Relativistic Juttner DF
  - ④Kinematic SZ

Relativistically correct

## ④Kinematic SZ




$$\Delta I^{\rm kin}(x) = -I_0 \int h(x) \frac{v_r}{c} n_e(l) \sigma_T dl$$

$$x = \frac{h\nu}{k_B T_{CMB}}$$

$$I_0 = \frac{2(k_B T_{CMB})^3}{(hc)^2}$$

$$\Delta I^{\rm kin}(x) = I_0 h(x) y \qquad y^{\rm kin} = \int \frac{v_r}{c} n_e(l) \sigma_T dl$$

$$\frac{y^{\rm kin}}{y} \sim 0.05 \left(\frac{v_r}{300\ {\rm km/s}}\right) \left(\frac{k_B T_e}{10\ {\rm keV}}\right)^{-1}$$

$$h(x) = \frac{x^4 \exp(x)}{[\exp(x) - 1]^2}$$

Suyaev & Zel'dovich 72; Challinor, Lasenby 98

Yoshikawa, TA, Kitayama, Komatsu in prep.

# 2.3 Sunyaev-Zel'dovich Effects

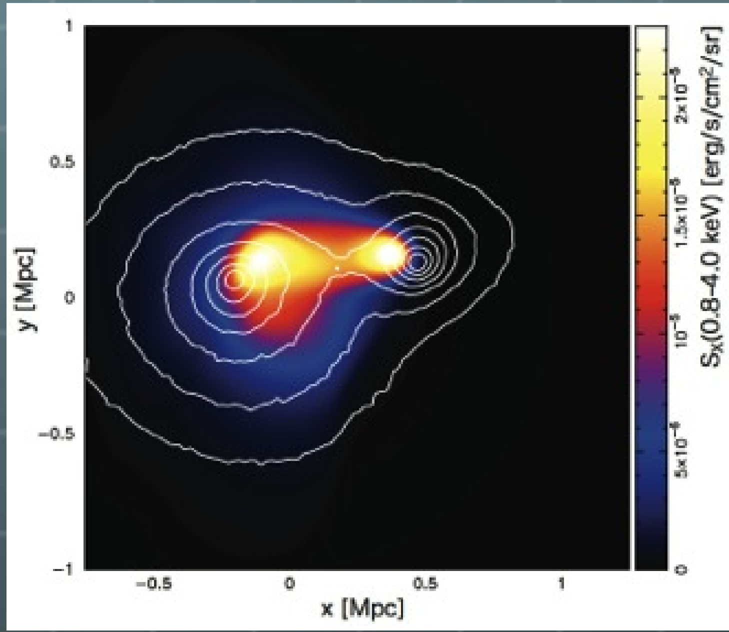


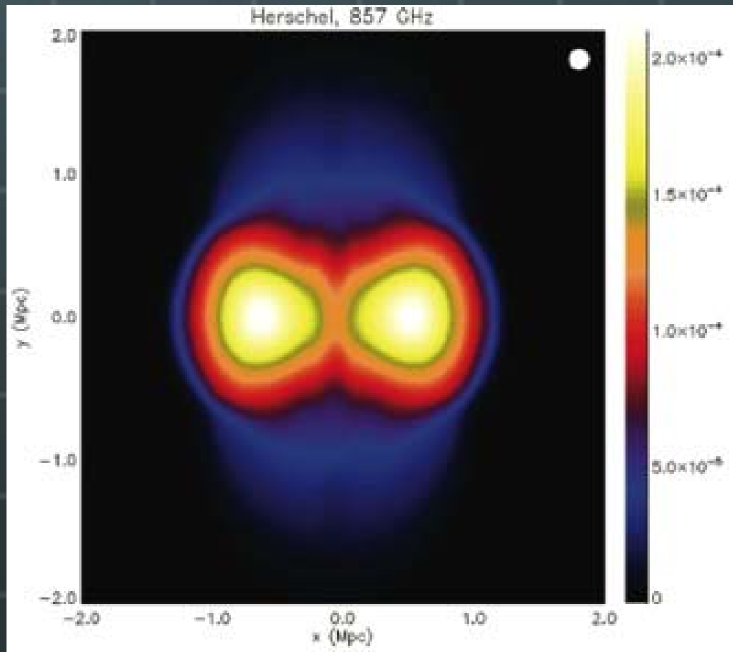
- **Simulated Bullet cluster**

Yoshikawa, TA, Kitayama, Komatsu in prep.

# Section 2 Summary

- Shocks are ubiquitous
  - Mechanism of heating
  - Laboratory of plasma
- Non-Equilibrium effects are significant behind the shocks even in galaxy clusters
- Relativistic correction of SZ effect is important for very hot ICM heated by the shocks
- Astro-H/ALMA observations



# 3. Turbulence

1. As a Driving Mechanism of IGMF
2. Faraday Rotation Measure
3. Galactic Foreground

# 3.1 As Driving Mechanism of the IGMF 

## Cosmic Magnetism – an unresolved problem of astrophysics –

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

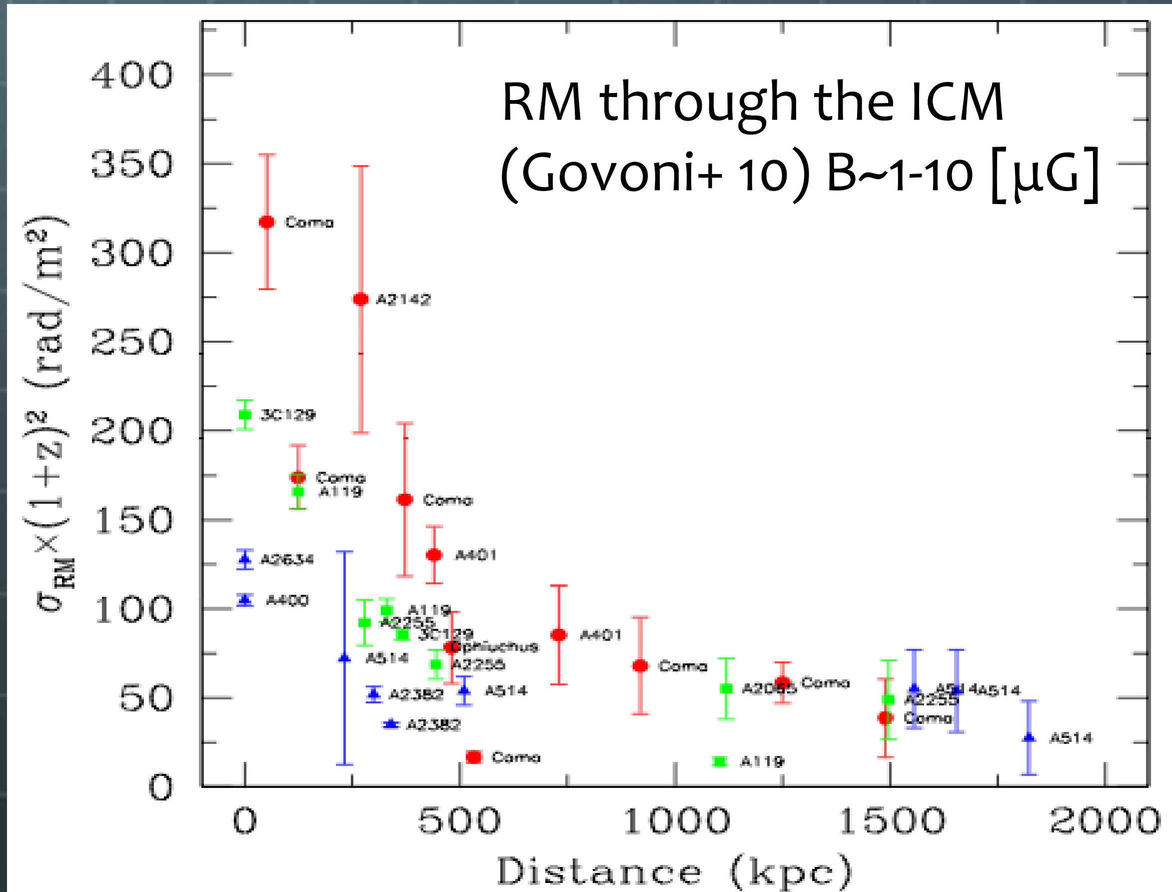
**Evolutions of…**
- Galaxy clusters
- Large-scale structure

**Seed Fields of…**
- First objects
- Proto-galaxies

## IGMF

**– Inter-Galactic Magnetic Field –**

- **ICM → *partly known***
  - **|RM| ~ 100 [rad m$^{-2}$]**
  - **IGMF ~ 1-10 [μG]**
- **WHIM → *unknown***
  - **|RM| ~ 1?? [rad m$^{-2}$]**
  - **IGMF ~ 1-10?? [nG]**

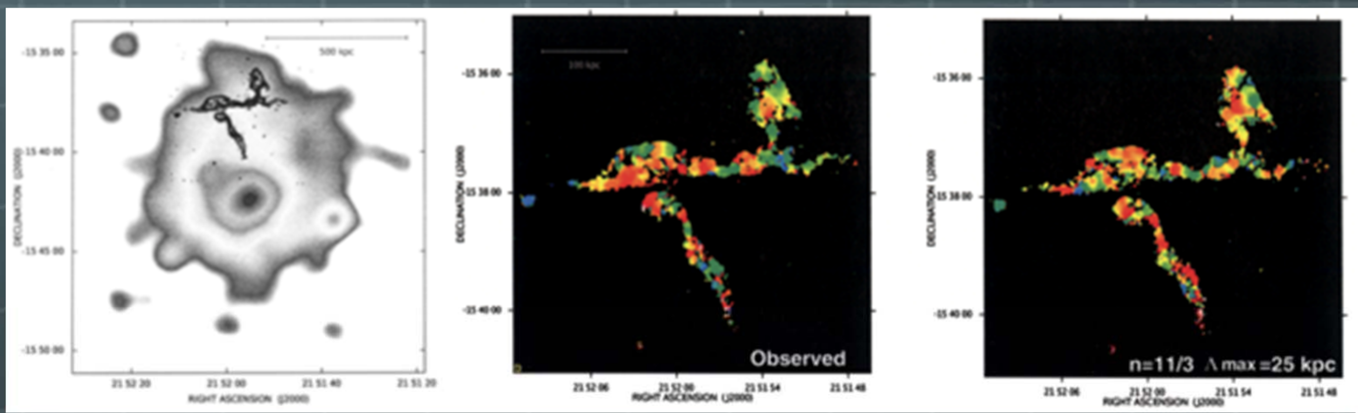


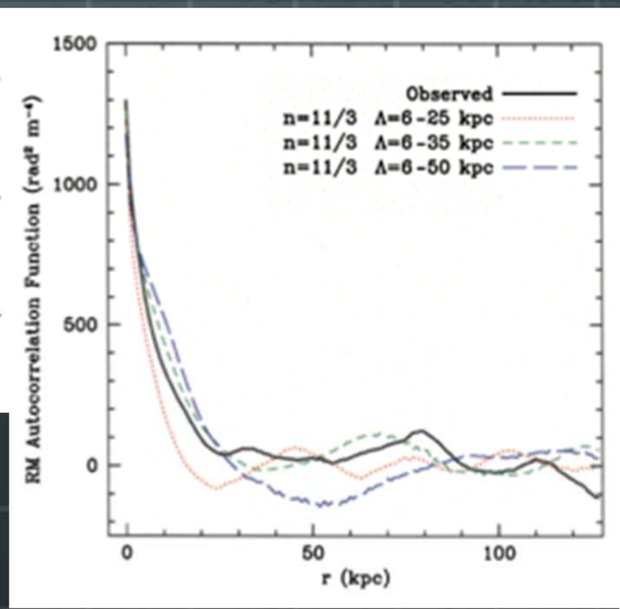
# 3.1 As Driving Mechanism of the IGMF

- **Turbulence Dynamo in the Universe**

| Cosmological Seed Fields | → | MHD in LSS | ↔ | Leakage from Galaxies |
| --- | --- | --- | --- | --- |
| Inflation, Phase transition, Perturbation | | Cosmological shock, Biermann effect, Turbulence dynamo | | Supernova, Galactic wind, AGN Jet |

- **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)

# 3.2 As Driving Mechanism of the IGMF

## Expected turbulence dynamo action

Gravitational energy

Shock Wave

↓

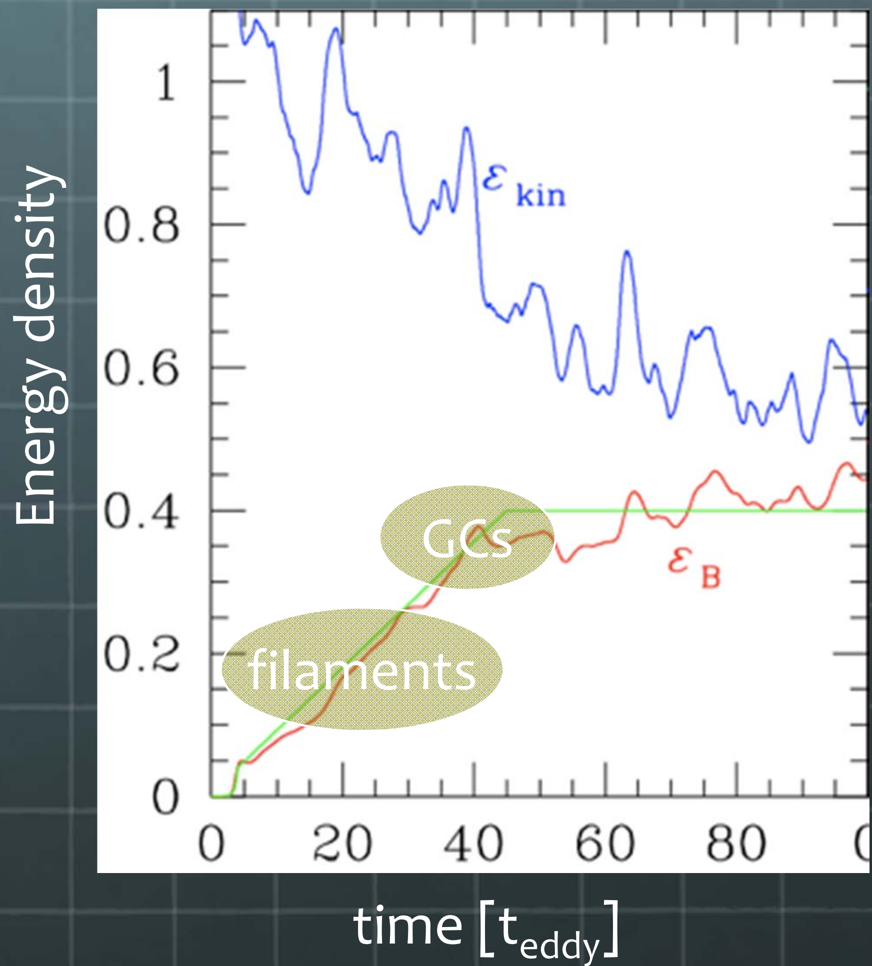
Vorticity energy

Cascading

↓

IGMF energy

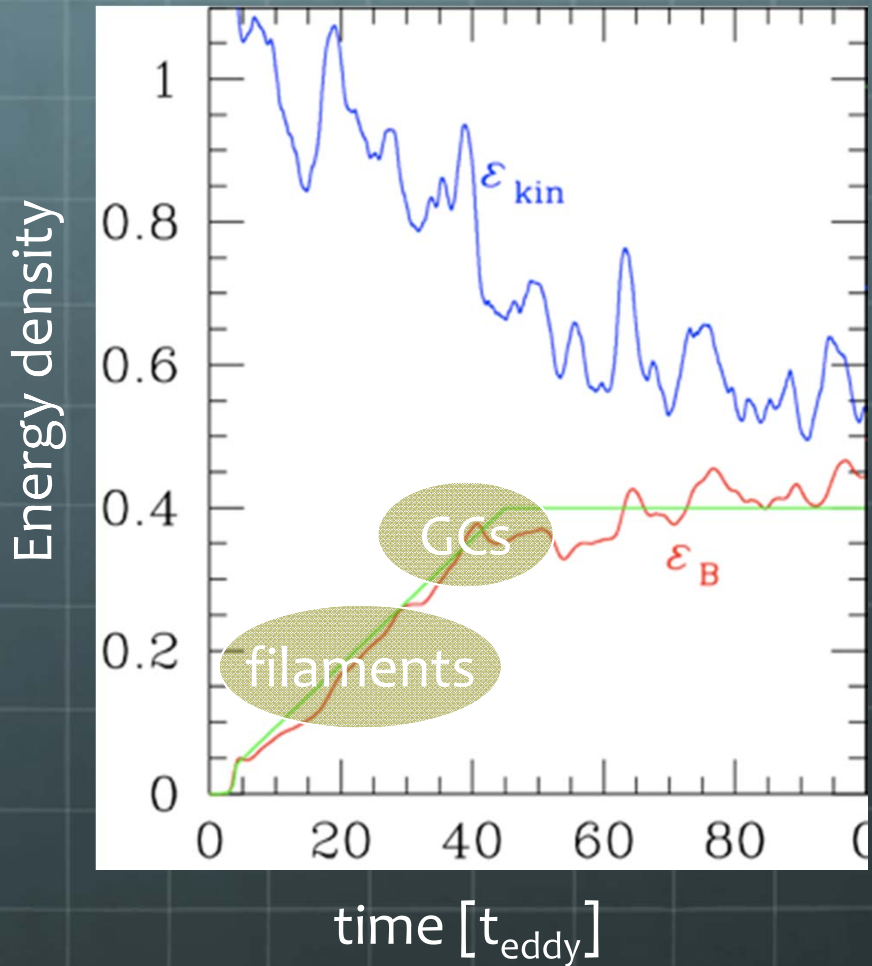
Dynamo action




Ryu+ 08

# 3.2 As Driving Mechanism of the IGMF

- **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 $\varepsilon_w$

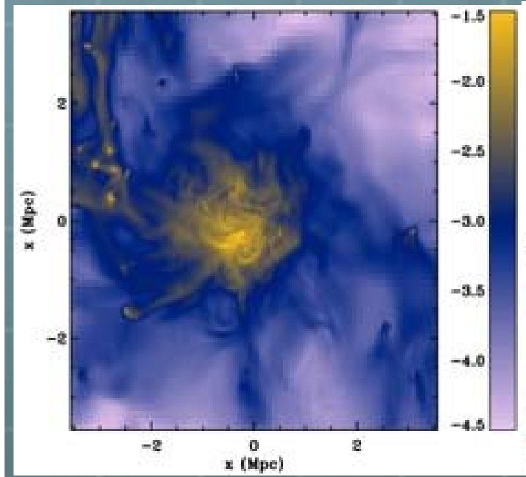
② Regard $\varepsilon_w$ as the turbulence energy $\varepsilon_{turb}$

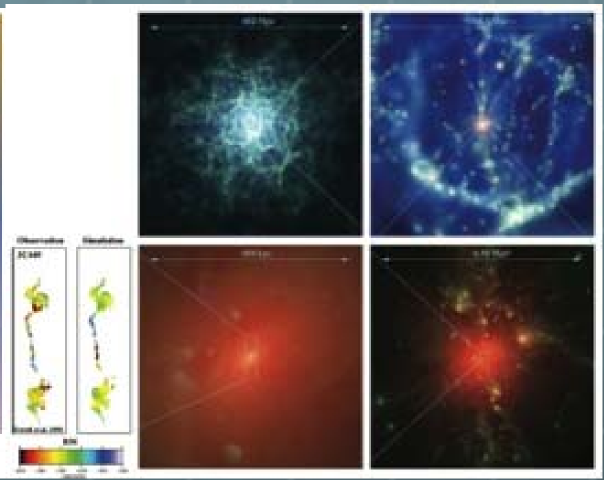
③ Adopt the growth model $\varepsilon_B/\varepsilon_{turb}=f(t/t_{eddy})$ & $B=(8\pi\varepsilon_B)^{1/2}$

④ Direction … passive field

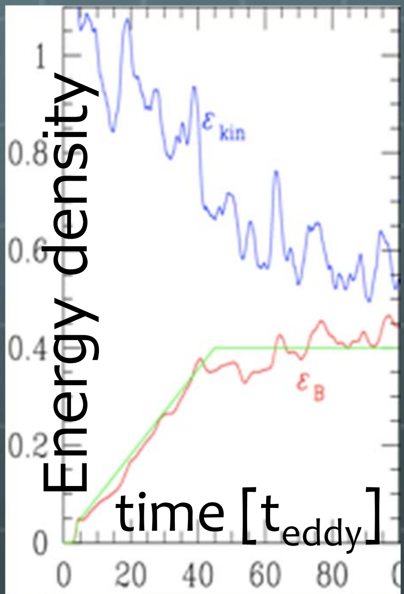
# 3.2 As Driving Mechanism of the IGMF

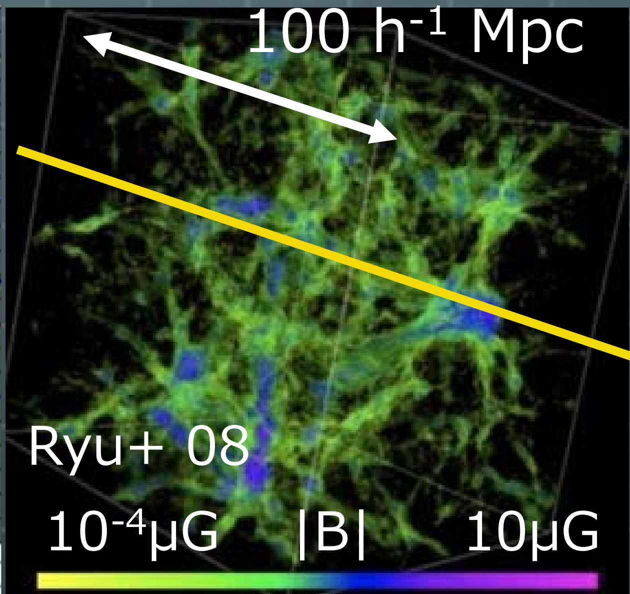




- Cosmological simulations
  - AMR-MHD (Dubois, Teyssier 08)
  - SPH-MHD (Dolag, Stasyszyn 09)
  - MHD(passive) + turbulence dynamo model (Ryu, Kang, Cho, Das 08, science)




**My Work**

Faraday Rotation Measure (RM)

$n_e$ [$cm^{-3}$], $B_{||}$ [$\mu$G], l [kpc]

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

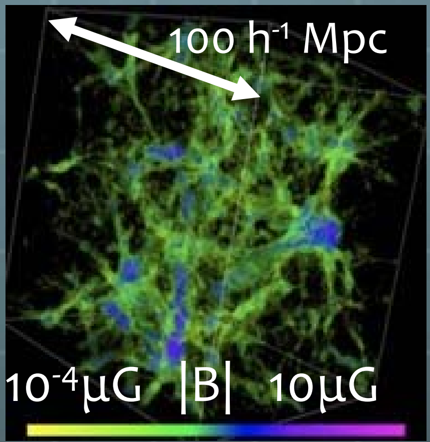
⇔ current/future observations

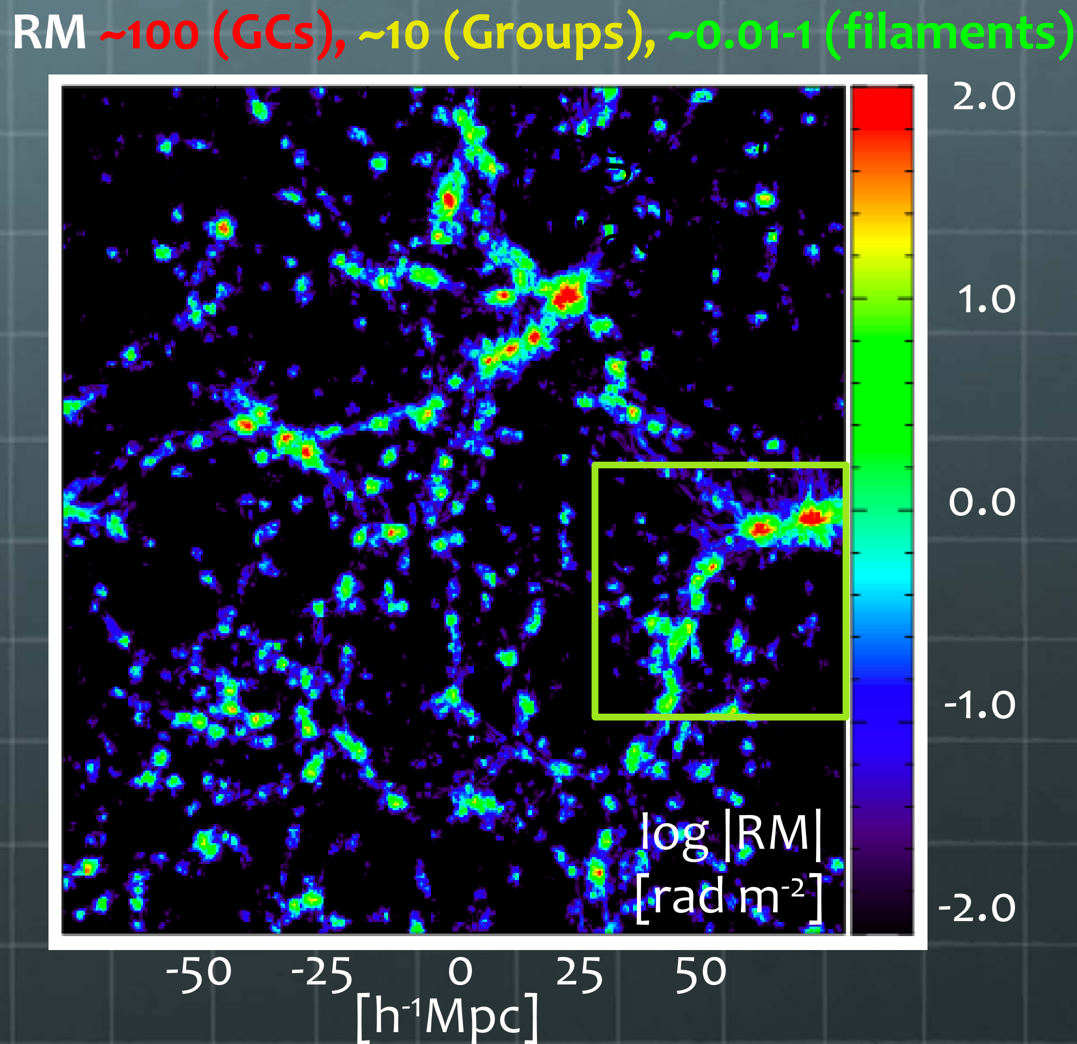
$$\sigma_{RM} \sim 1.5 \left(\frac{\bar{n}_e}{10^{-5}\mathrm{cm}^{-3}}\right)\left(\frac{B_{rms}}{0.3\ \mu\mathrm{G}}\right)\left(\frac{L_{int}}{300\mathrm{kpc}}\frac{L}{5\mathrm{Mpc}}\right)^{1/2} \mathrm{rad\ m^{-2}}$$

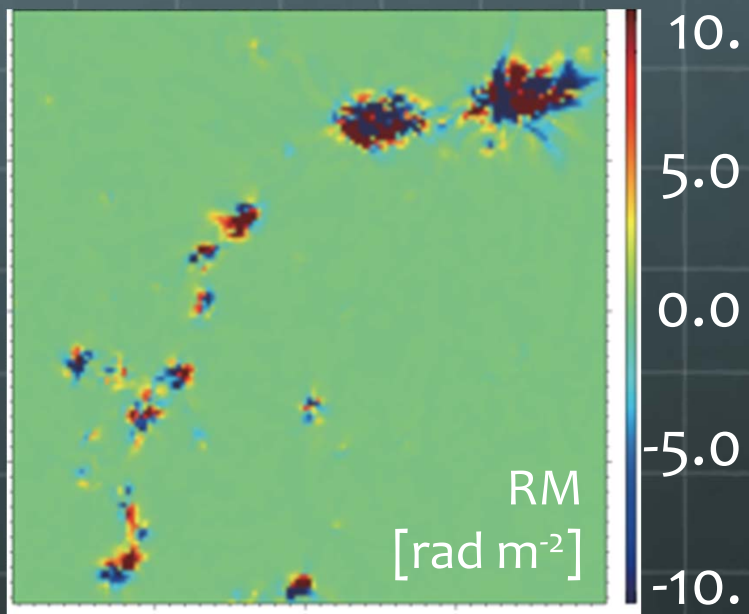
Cho, Ryu 09

# 3.2 IGMF RM – Local Universe –

- RMS of RM through a filament ~1 [rad m$^{-2}$]



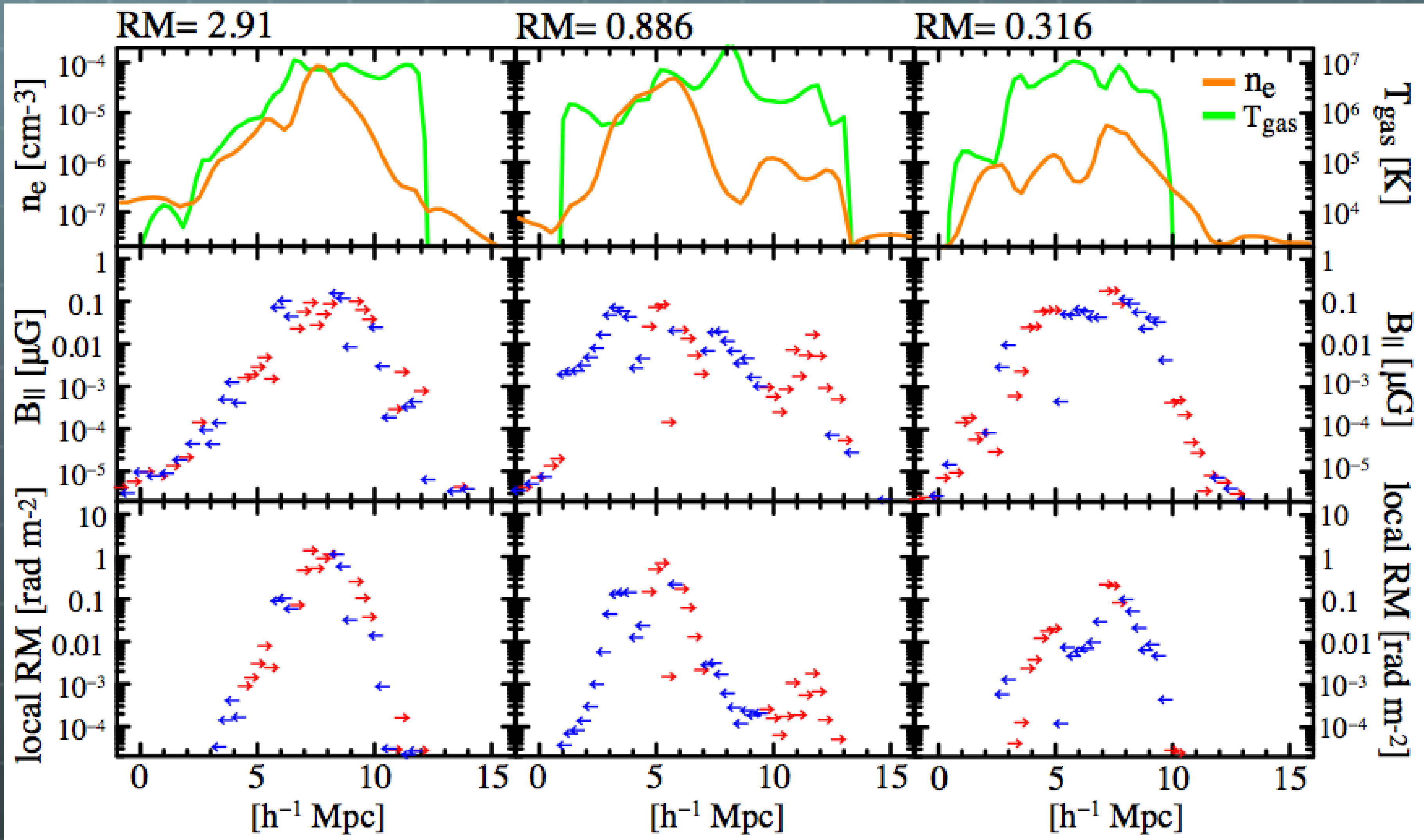




TA, Ryu 10

# 3.2 IGMF RM – Local Universe –



- Coherence length~ a few*100 kpc, random walk

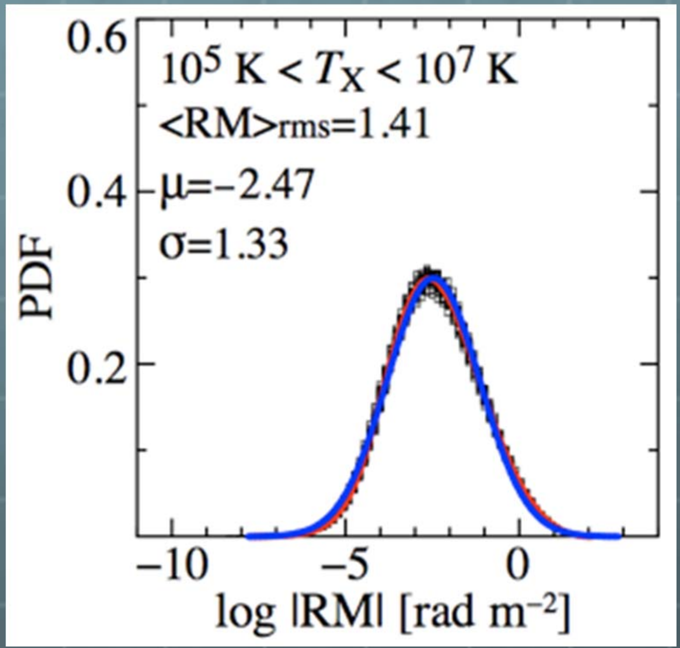





TA, Ryu 10

# 3.2 IGMF RM – Local Universe –





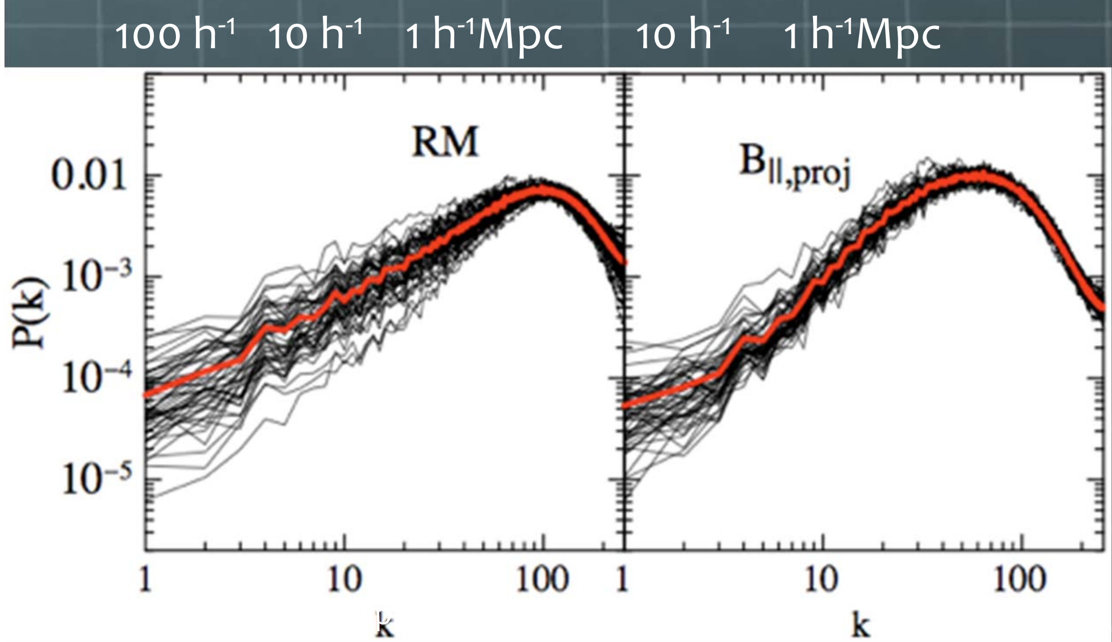

PDF of |RM| for WHIM ($10^5$ K<Tx<$10^7$ K)

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

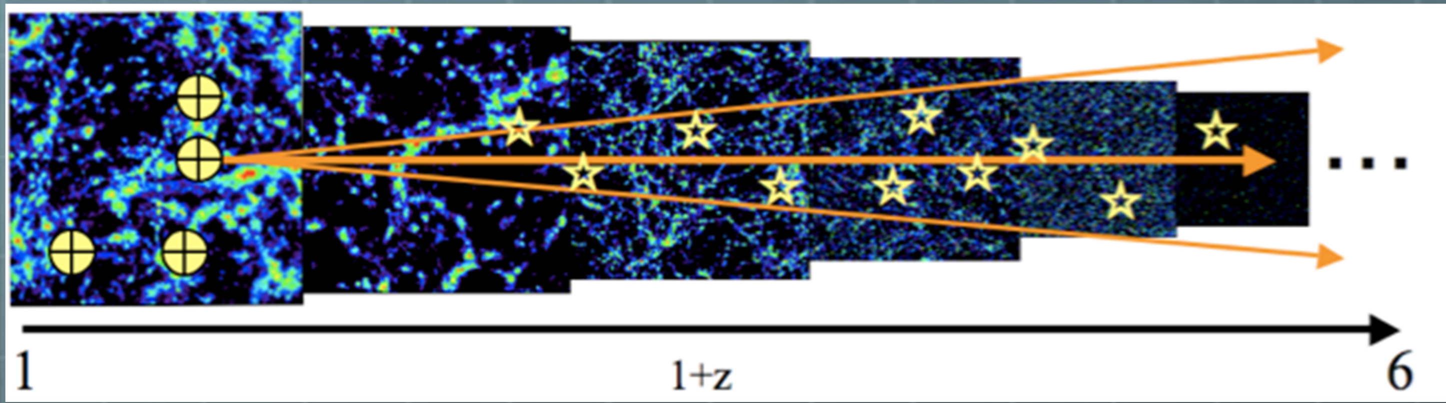
**Black: 3×16 runs, Red: average**

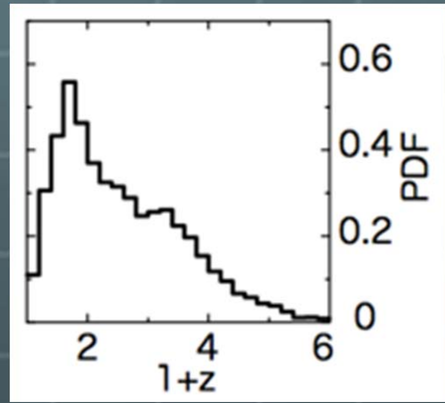
- Peaked at **~Mpc scale**
- $P^{RM}(k)$ traces $P^{B||,proj}(k)$

TA, Ryu 10

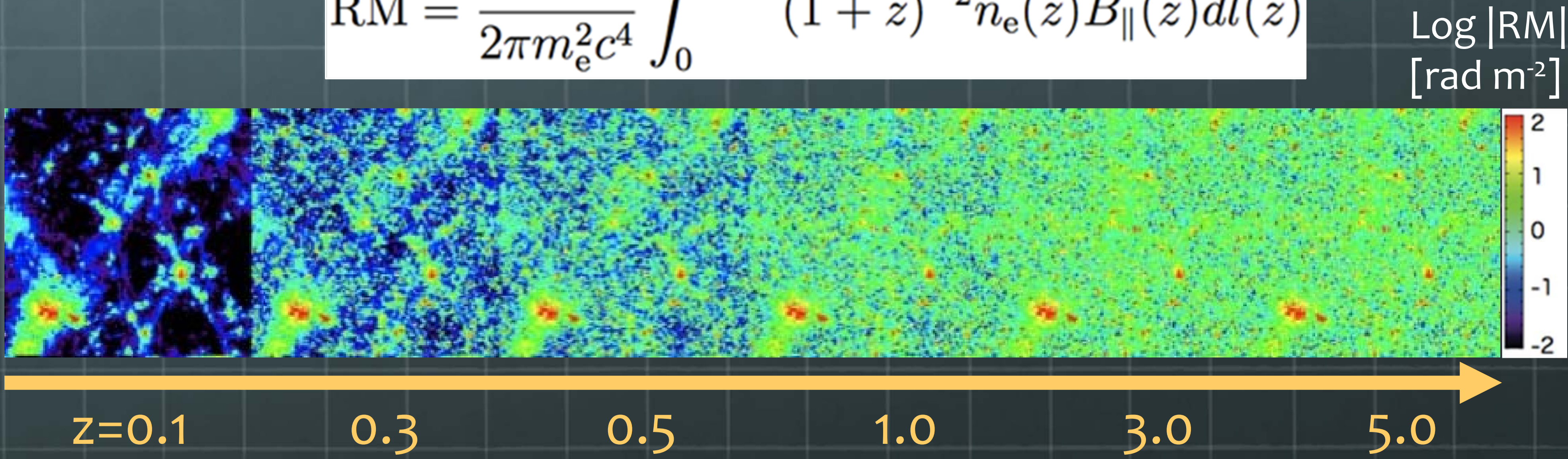
# 3.2 IGMF RM – Up to z=5 –

- Integrating RM up to redshift of 5



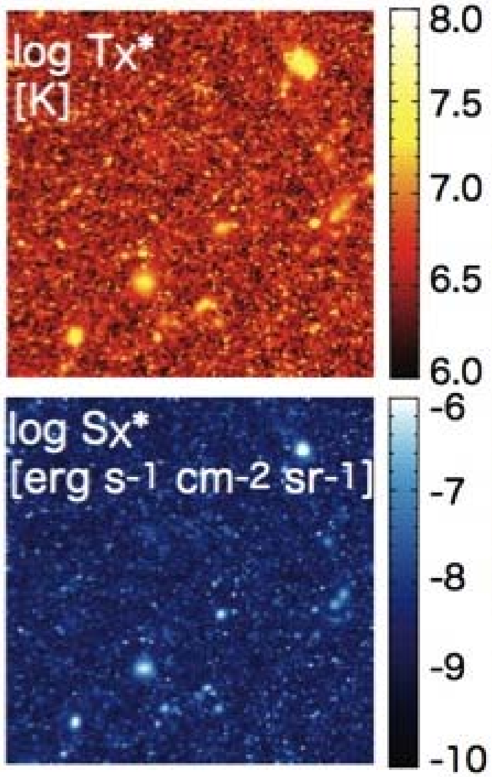

$$\mathrm{RM} = \frac{e^3}{2\pi m_e^2 c^4} \int_0^{l_s(z_s)} (1+z)^{-2} n_e(z) B_{\parallel}(z) dl(z)$$

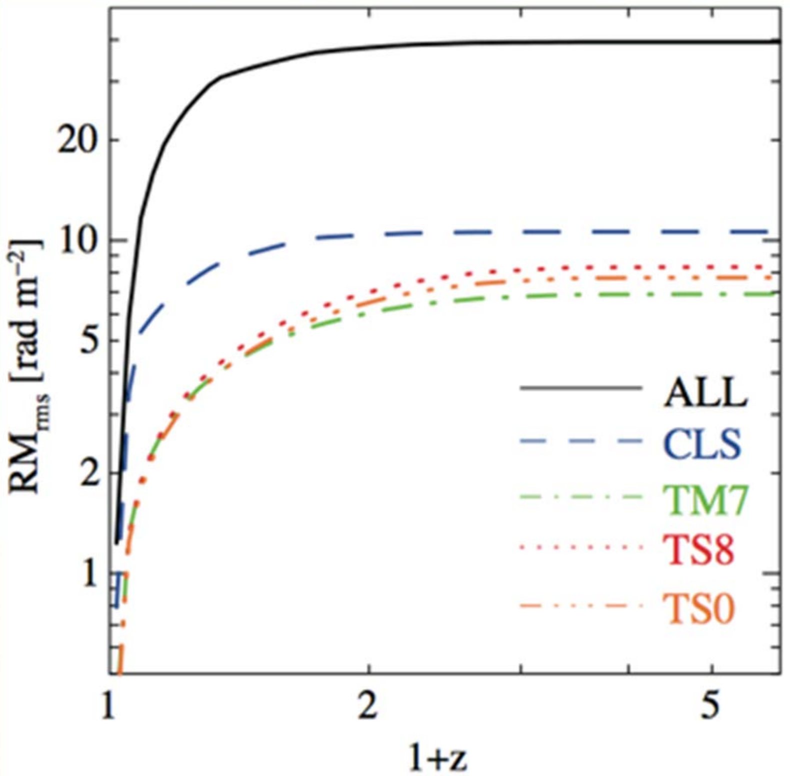



TA, Ryu 11

# 3.2 IGMF RM – Up to z=5 –

- RMS of RM through filaments ~several-10 [rad m$^{-2}$]

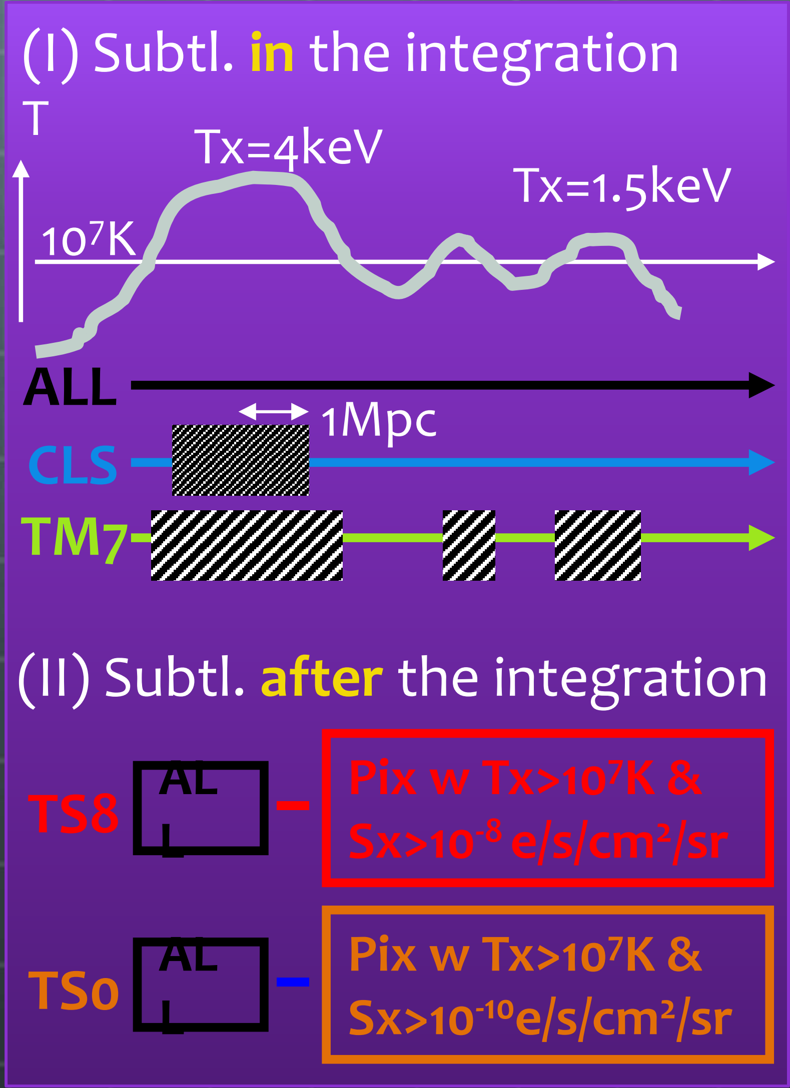



Sx, Tx maps (z<5) 200 deg$^2$ FOV

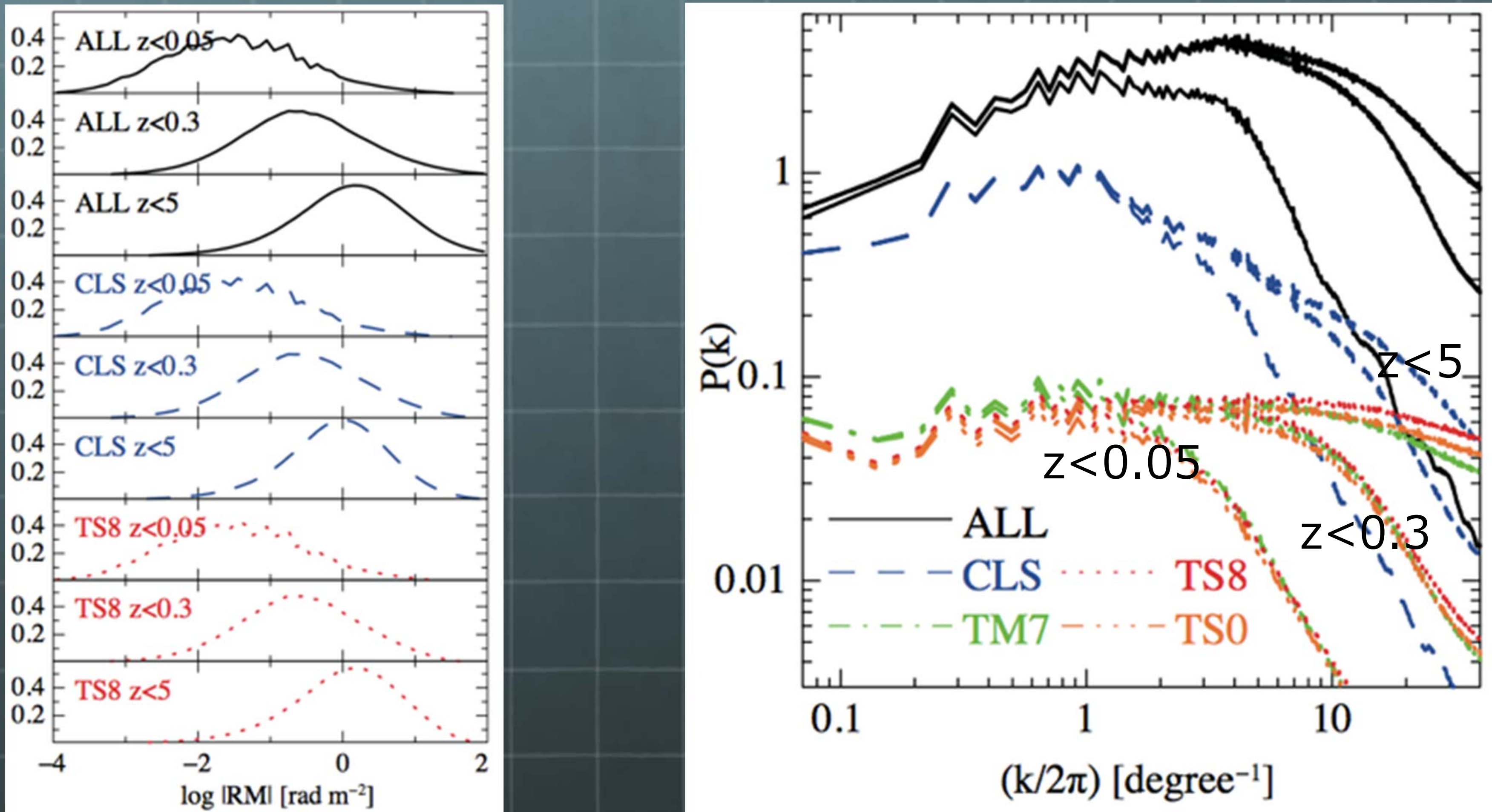
RMS of RM(<z)

(Ave. of 200 maps = average of 2048*2048*200 pixels)



# 3.2 IGMF RM – Up to z=5 –

- PDF follows lognormal profile
- Power spectrum peaks at 0.1-0.2° scales



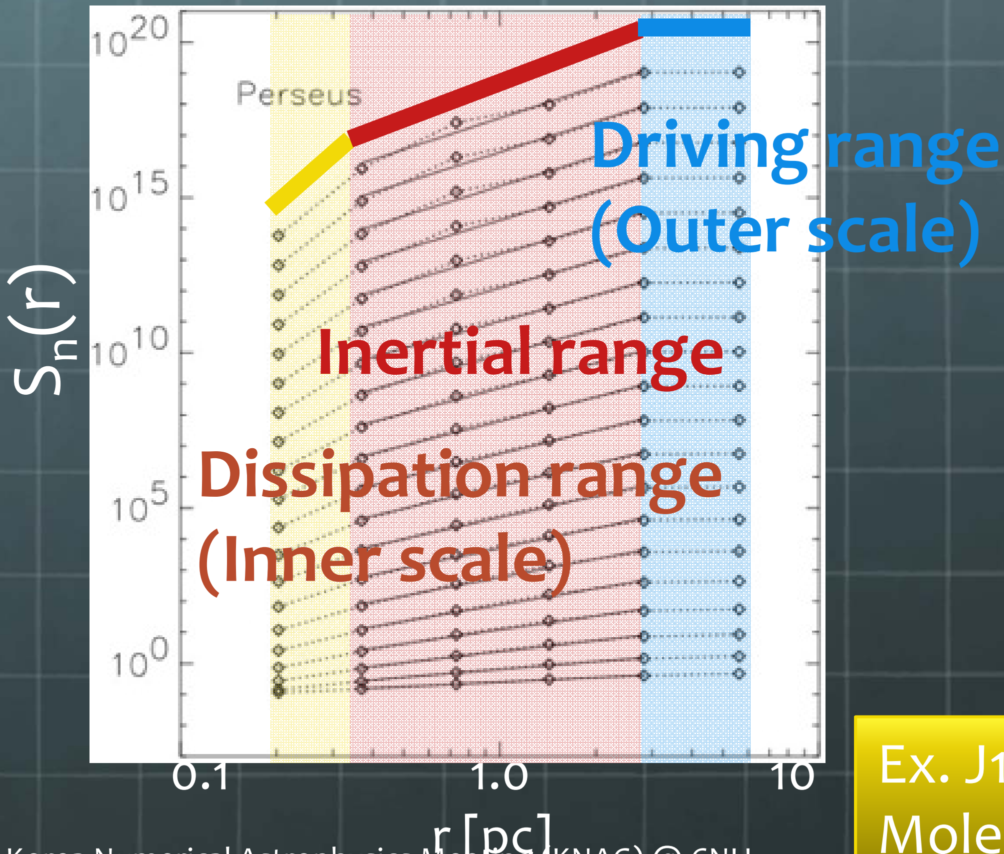

PDFs and Power spectra of RM map (ave. of 200 maps)

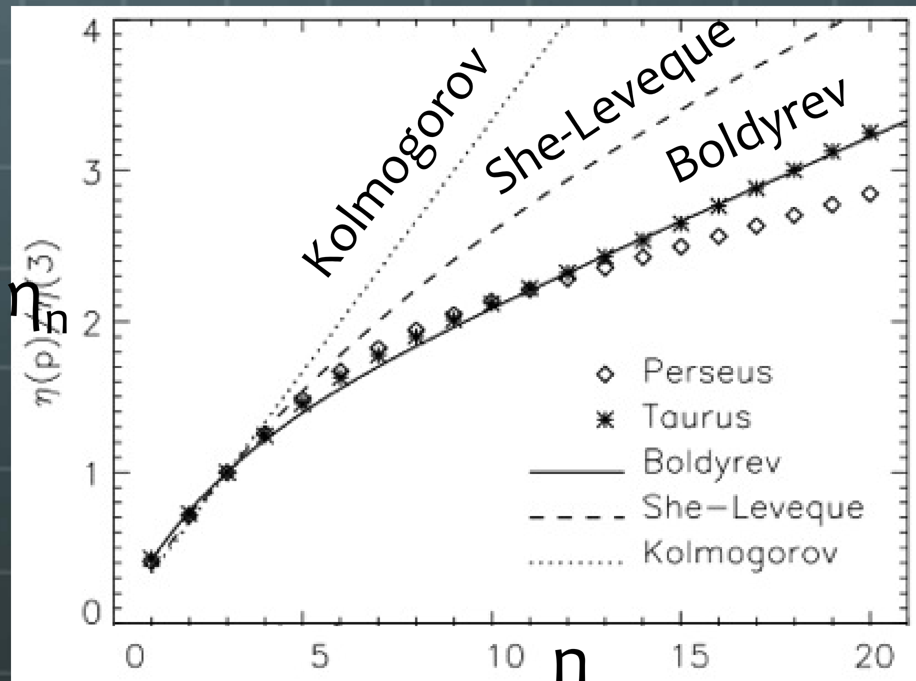
# 3.2 Structure Function (SF) of RM

- Structure Function (SF) of Rotation Measure (RM)

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

  - Available even for coarse-spacing data without errors
  - Shape & Exponents reveal the nature of turbulence

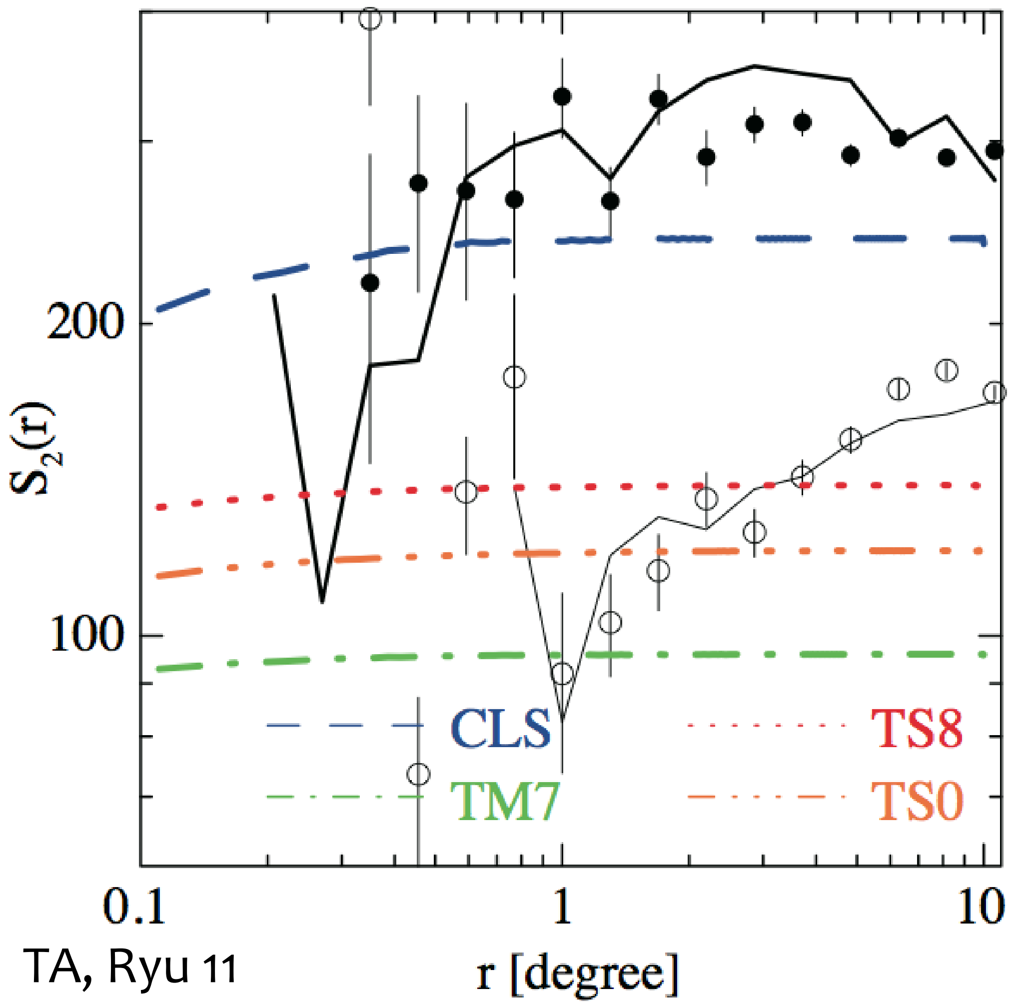



Ex. J1-0 [13]CO Intensity SF and SF exponents of Molecular Cloud Complexes (Padoan+ 03)

# 3.2 IGMF RM – Up to z=5 –

## SFs of RM toward the Galactic Poles (Stil+ 11)




TA, Ryu 11

← South Galactic Pole (SGP)
circles: Mao+ (10) WSRT+ACTA
lines: Taylor+ (09) NVSS

← North Galactic Pole (NGP)
circles: Mao+ (10) WSRT+ACTA
lines: Taylor+ (09) NVSS

← Simulation Results (IGMF)
colors: Akahori, Ryu (11)

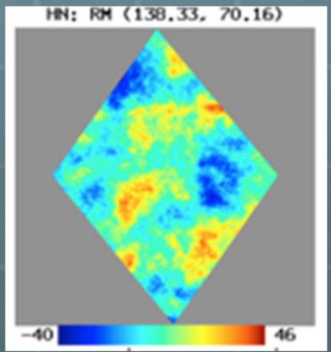
- ✓ Flat @ r > 0.2°
- ✓ 100-200 [rad² m⁻⁴]

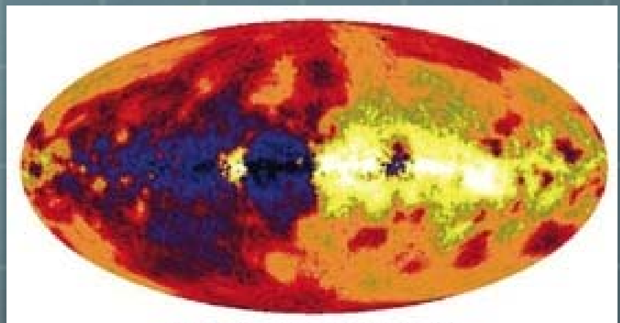
**Conclusion** IGMF significantly contributes to the RMs!

# 3.3 Galactic Foreground RM



- **GMF** – Galactic Magnetic Field –
- **Analytical model of the Galaxy "HAMMURABI"**



(a) CS+GF+N($\sigma$ = 10.0 rad m$^{-2}$)

RM map toward (l,b)=(140,70) with 1.5°x1.5° FOV (Sun, Reich 09)
All-sky RM map (Stasyszyn+ 10) using cosmological SPH-MHD simulation (Dolag+ 09) + HAMMURABI (Waelkens+ 09)

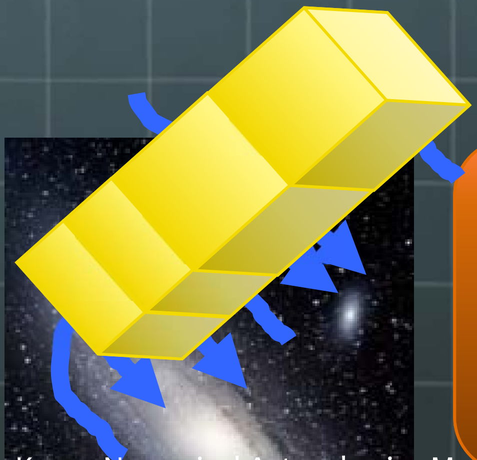
- **But, unsolved issues…**
  - ✓ Coupling factor for the thermal electron density fluctuation
  - ✓ Suppose uniform |b|~a few μG at disk, halo, everywhere
  - ✓ Suppose random phase (no sheet/filamentary structures)

Analytic model for regular component + Results of MHD simulations for random component

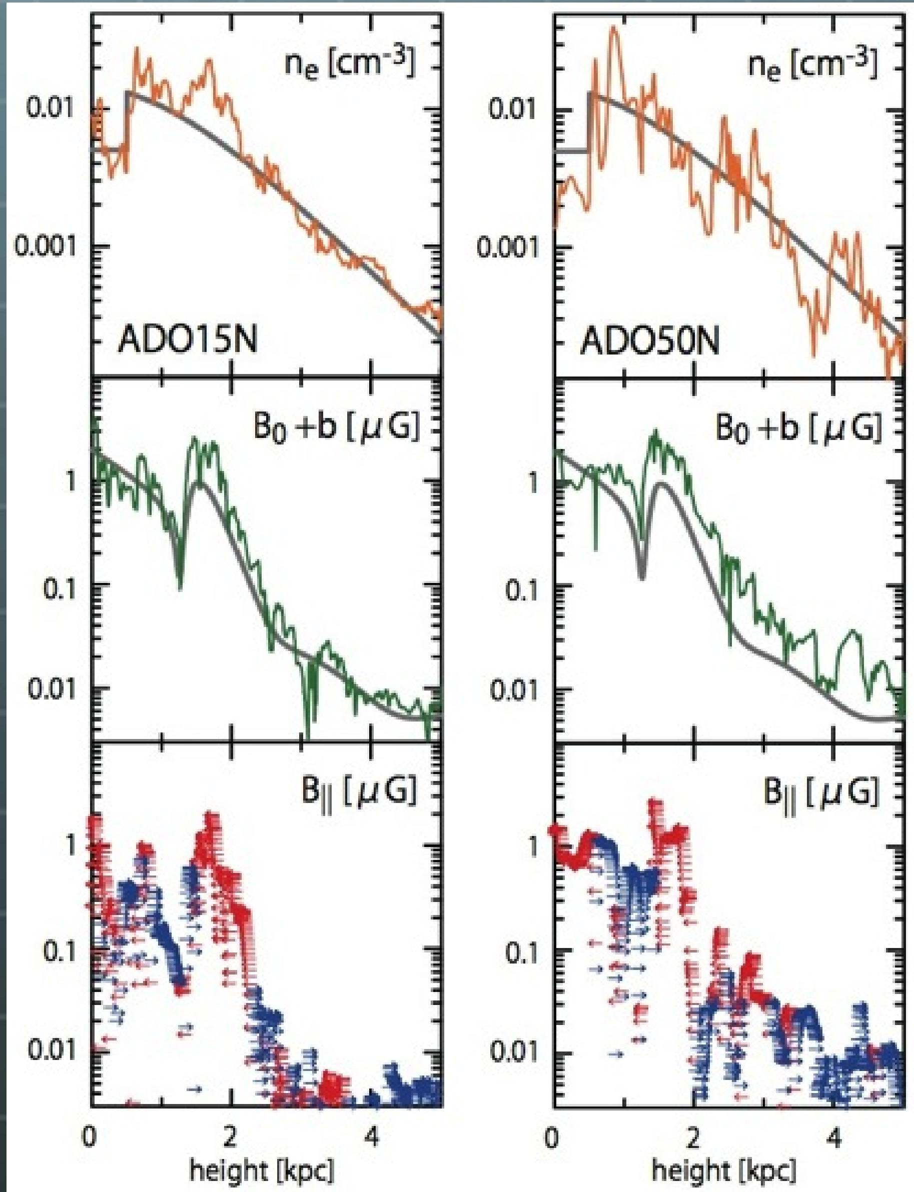
**My Work**

# 3.3 Galactic Foreground RM

- Regular compoent
  - NE2001 (Cordes, Lazio 02;03)
  - ASS or BSS, DP or QP, w/o Vertical (Waelkens+09; Sun, Reich 09; 10)
- Random component
  - stack boxes of MHD turbulence simulations (Kim+ 93; Wu+ 09)



Examples of line-of-sight properties toward the NGP




$V_{rms}$ = 15 - 50 [km/s]
(Tufte+ 99; Haffner+ 03, 10)

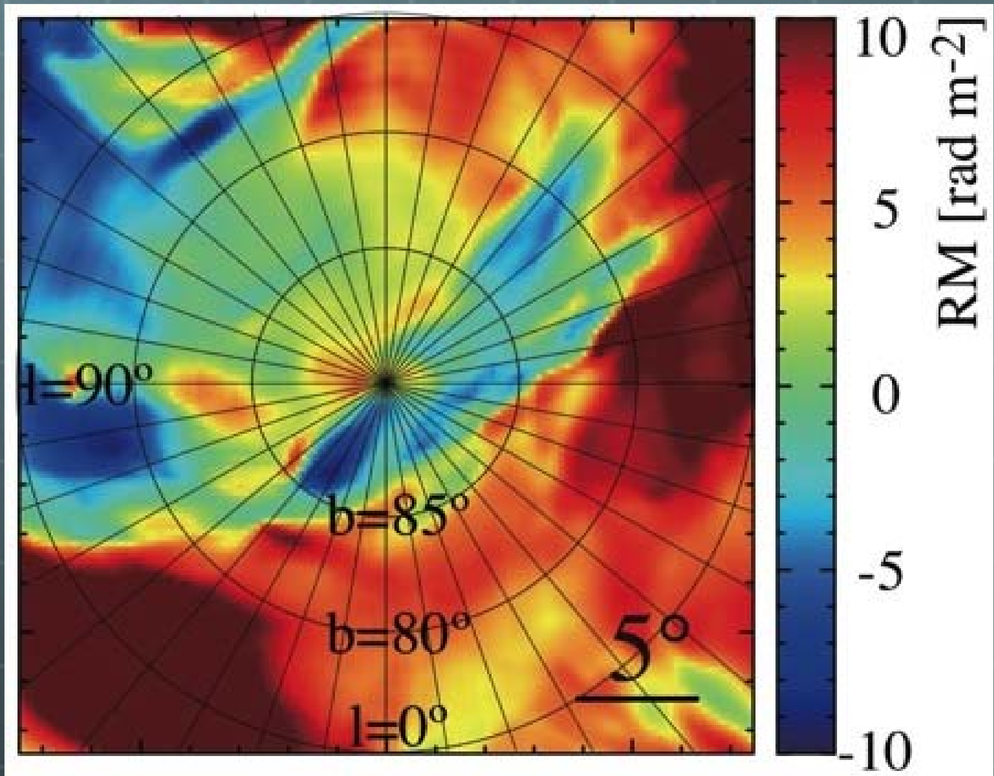
$L_{drive}$ = 1.67 [kpc]
(Gaensler+ 08 & Wu+ 09)

TA, J. Kim, Ryu, Gaensler in prep.

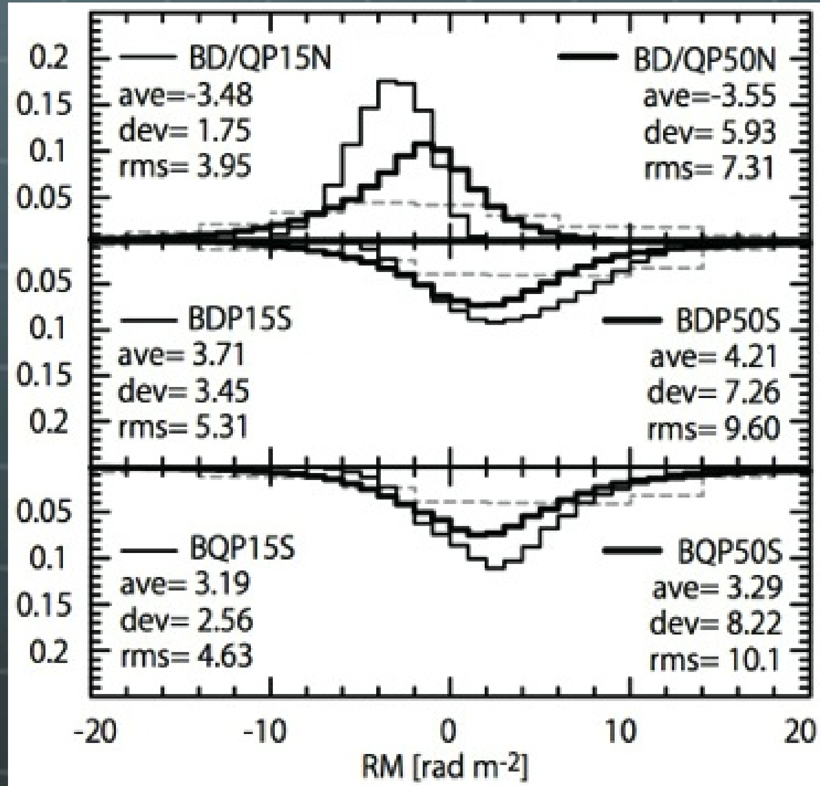
# 3.3 Galactic Foreground RM



- Regular: Large-scale structure > 10° scales
- Random: Filament/clump structures ~ 1-several° scales
- Ave. ~ ±several [rad m$^{-2}$], std. ~serveral [rad m$^{-2}$]




RM map toward NGP




PDF of RMs (Ave. of 200 maps)

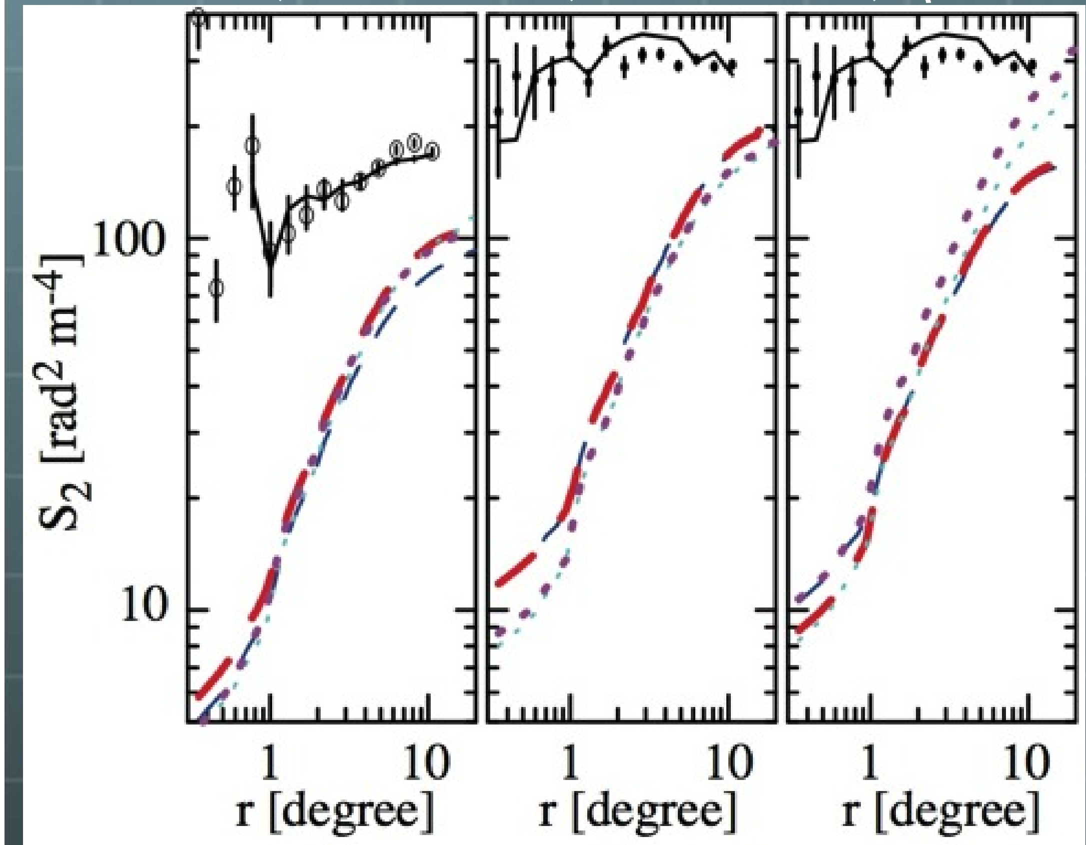
TA, J. Kim, Ryu, Gaensler in prep.

# 3.3 Galactic Foreground RM

## SFs of RM toward the Galactic Poles (Stil+ 11)

$V_{rms}$ ~50 km/s, $L_{drive}$=1.7 kpc

NGP, DP    SGP,DP    SGP, QP




TA, J. Kim, Ryu, Gaensler in prep.

← South Galactic Pole (SGP)
- circles: Mao+ (10) WSRT+ACTA
- lines: Taylor+ (09) NVSS

← North Galactic Pole (NGP)
- circles: Mao+ (10) WSRT+ACTA
- lines: Taylor+ (09) NVSS

← **Simulation Results (IGMF)**
- colors: Akahori+ (11)

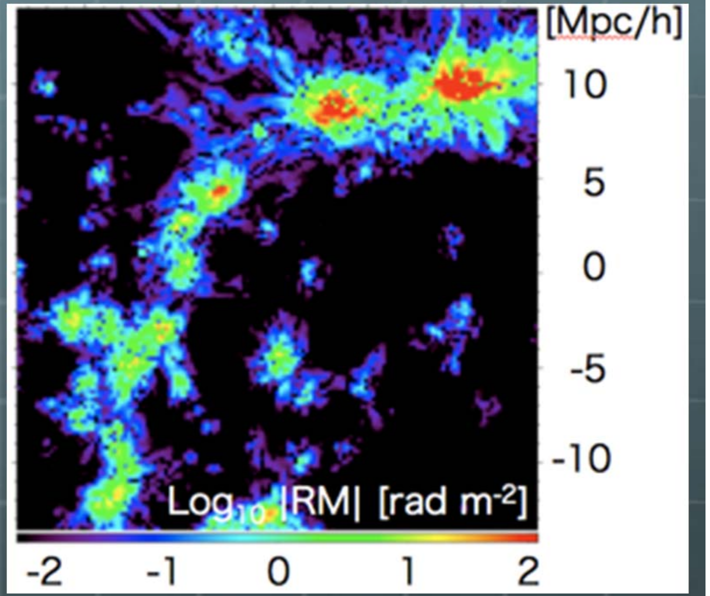
✓ Steeper slope
✓ 100-200 [rad² m-4]

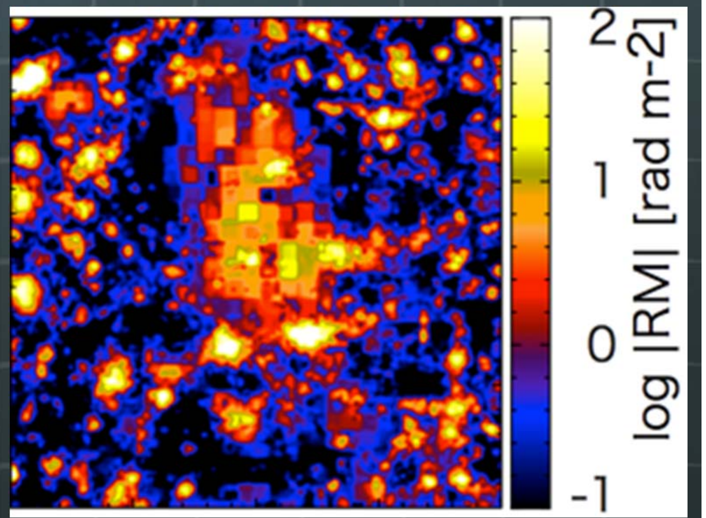
Conclusion **IGMF dominates RMs at small angular scales!**

# Summary



- Cosmic Magnetism
- IGMF-RM
  - RMS ~ 1-10 [rad $m^{-2}$]
  - SF ~ 100-200 [$rad^2$ $m^{-4}$], flat
- GMF-RM toward Galactic poles
  - RMS ~ several [rad $m^{-2}$] ($V_{rms}$=50km/s)
  - SF ~ 100-200 [$rad^2$ $m^{-4}$]@10°, slope
- SKA observations



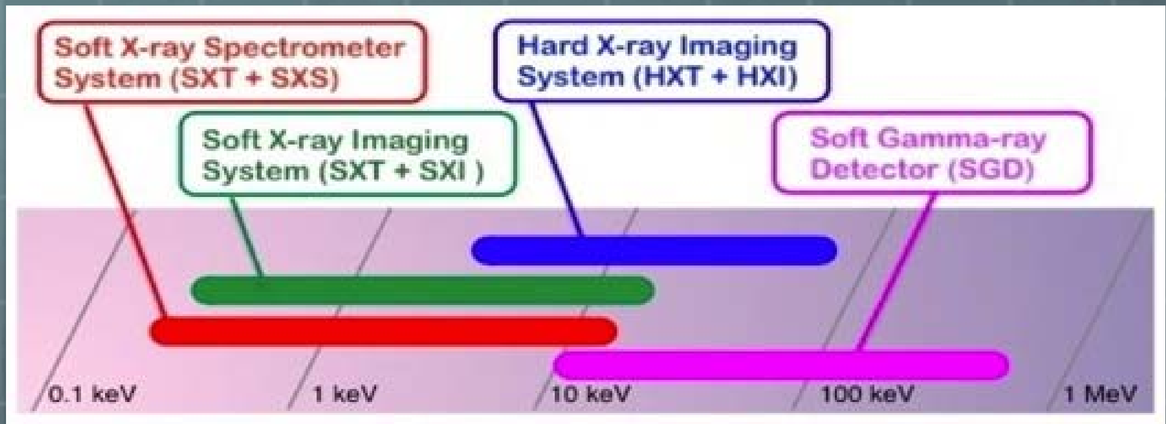



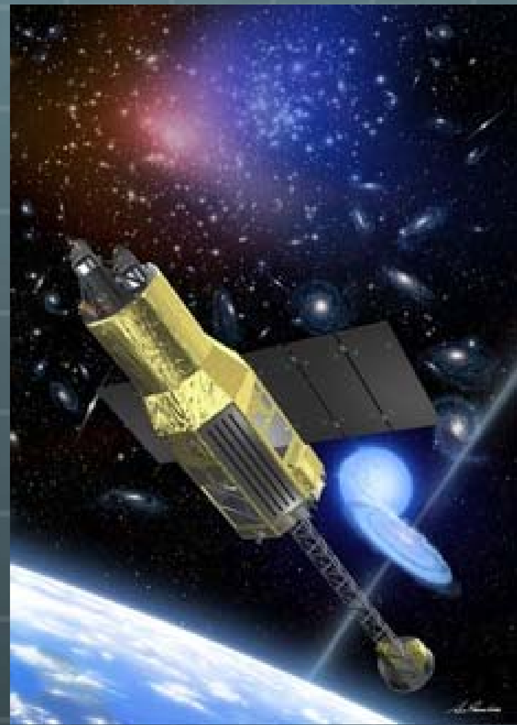
# 4. Future Observations

1. Astro-H
2. ALMA
2. SKA

# 4.1 Astro-H

- Astro-H (NeXT) 2013-observation
  - "Revealing the LSS" is one of the key science projects



| | SXS | SXI | HXI |
|---|---|---|---|
| FOV (resolution) [arcmin²,arcmin] | 9 (1.3) | 1440 (1.3) | 81 (1.7) |
| Energy range [keV] | 0.3-12 | 0.4-12 | 5-80 |
| Energy resolution in FWHM [eV] | 5 | 150 @6keV | 2000 @60keV |

***We enter the era of observing the LSS!***

# 4.2 ALMA



- ALMA cycle 0 (16) in operation
  - 25 antennas in observatory
  - 66 antennas finally
  - "SZ effect" may be an important science project (but no proposals are approved in cycle 0…?)

| | ALMA |
|---|---|
| Frequency range [GHz] | 80-950 |
| FOV (resolution) @ 900 GHz [arcsec$^2$,arcsec] | 49 (0.005) |
| Sensitivity [mJy] | 0.005-1 |

***We enter the era of observing the shock!***

# 4.2 ASKAP and SKA



- The Square Kilometer Array (SKA)
  - 2020- observation (2 trillion won project)
  - "Cosmic Magnetism" is one of the five key science projects

- Australia SKA Pathfinder (ASKAP)
  - 2013- observation
  - Polarization Sky Survey of the Universe's Magnetism (POSSUM)

| | VLA | ASKAP | SKA |
|---|---|---|---|
| Observational uncertainty [rad $m^{-2}$] | 10 | 1 | 0.1 |
| Average separation of sources [degree] | 1 | 0.1 | 0.01 |

***We enter the era of observing the IGMF!***

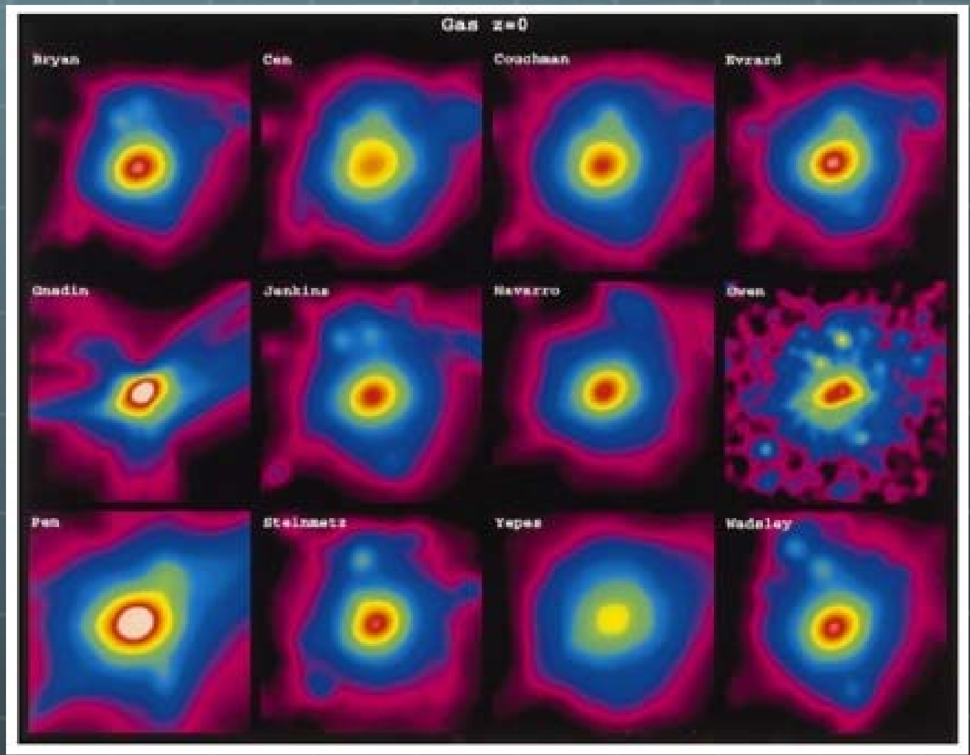
# Supporting material

# 1. Convergence of Simulations

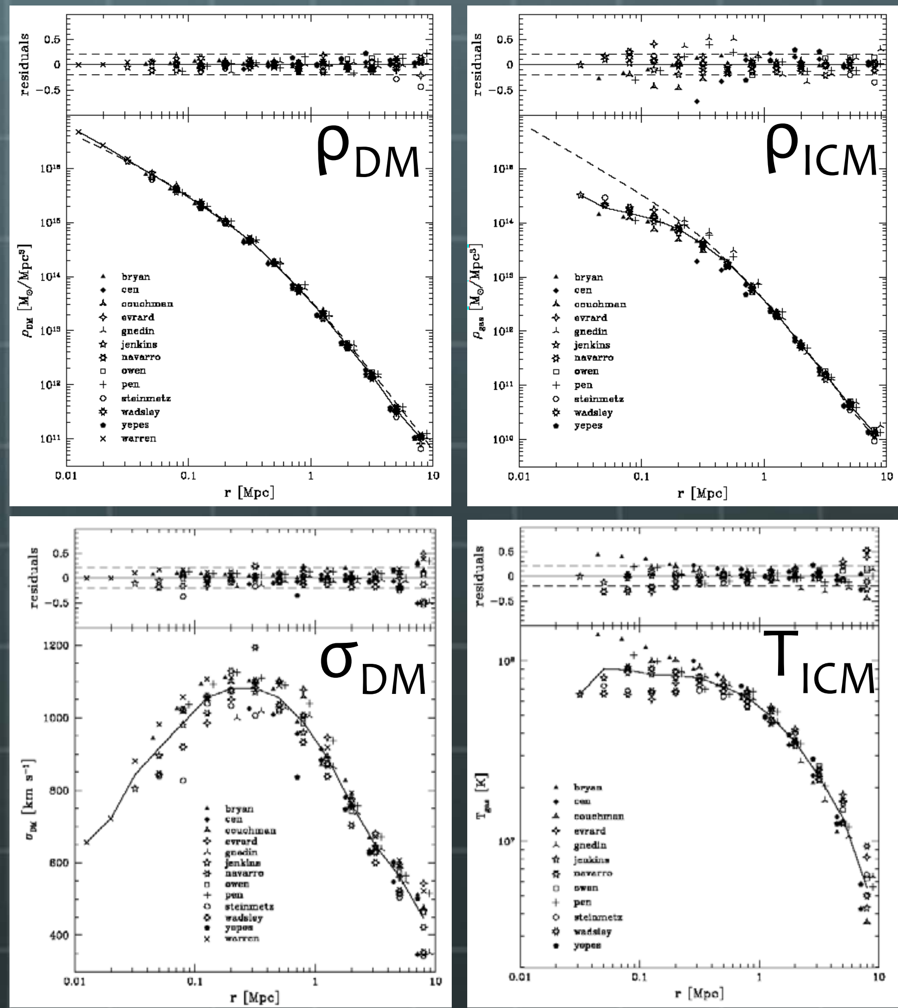


## SBCC Project (Frenk et al. 1999)

- 12 different codes on 7 different algorithms from the same ΛCDM

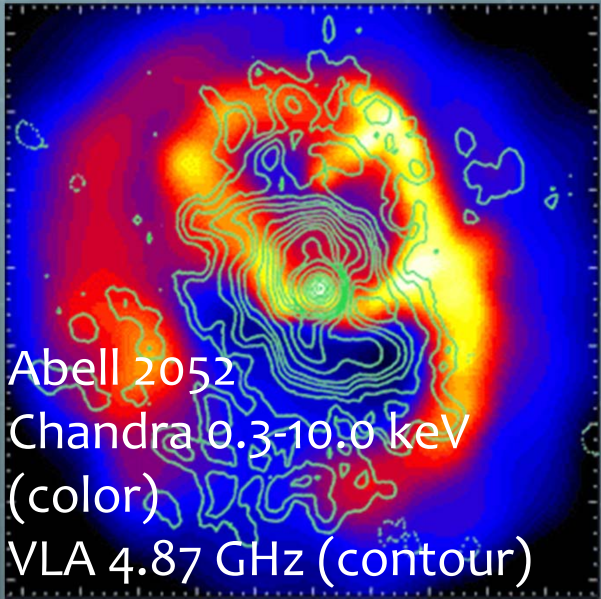



$\rho_{ICM}$@z=0



# 2.1 Clues for Shocks (Radio)





Abell 2052
Chandra 0.3-10.0 keV (color)
VLA 4.87 GHz (contour)
Burns 90, Blanton+ 03)

Existence of
- High-energy electrons
- Magnetic field

Abell 3667
ROSAT 0.1-2.4 keV (color)
MOST 843 MHz (contour)
Roettiger+ 99, Owers+ 09

**Synchrotron emissions**

- **Radio Halo** — spherical shape — Close to X-ray peak
  - **Mini Halo?** — Tend to no-polarize?
  - **Halo?** — Tend to polarize?
- **Radio Relic** — arc shape — Far from X-ray peak — Tend to polarize?

AGN Jet?
Turbulence?

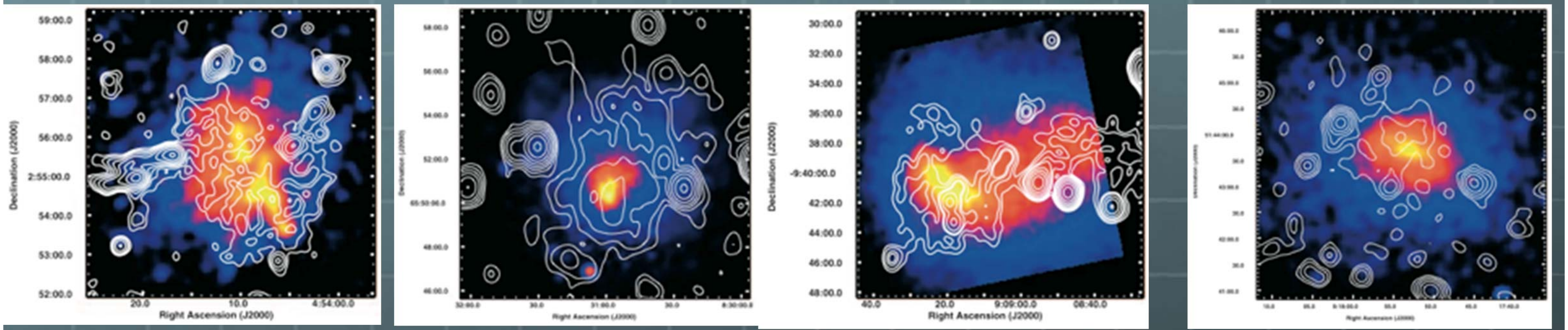
Cosmological shocks?

viewing angle??

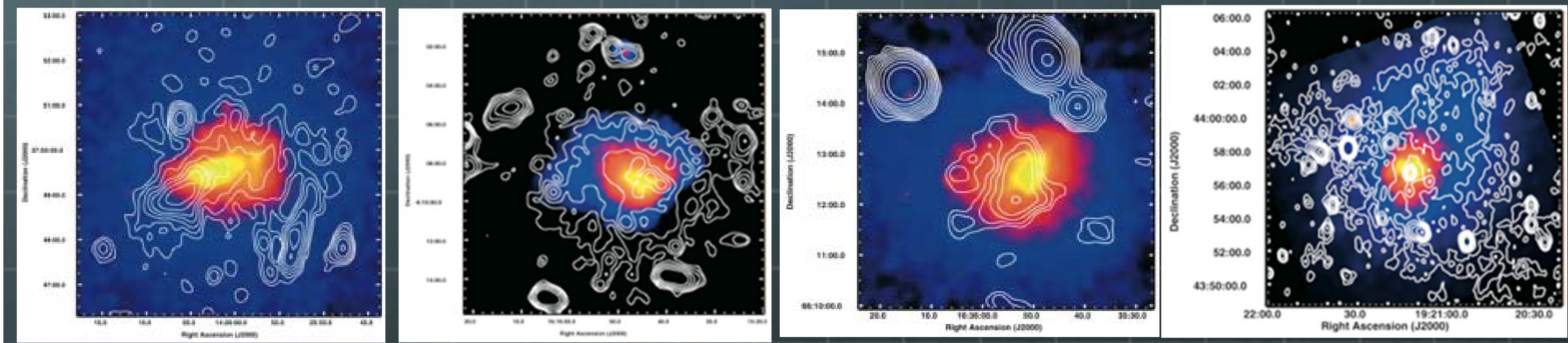
# 2.1 Radio Halo



**Chandra 0.8-4.0 keV (color) VLA 1.4 GHz (contour) Govoni+ 04**

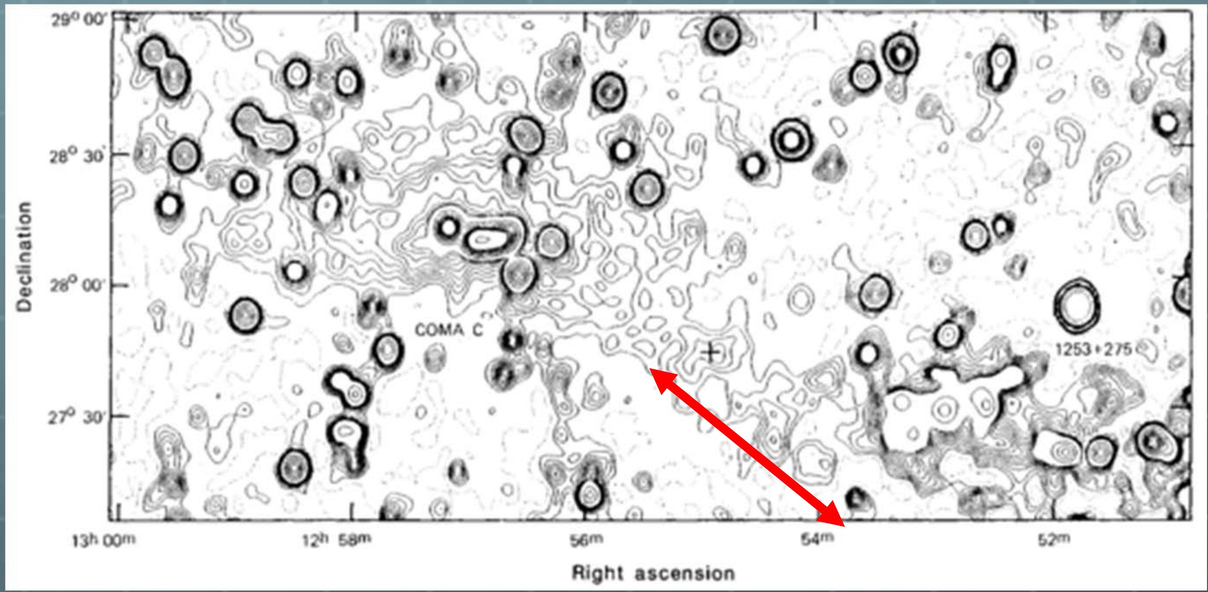



A520, A665, A754, A773

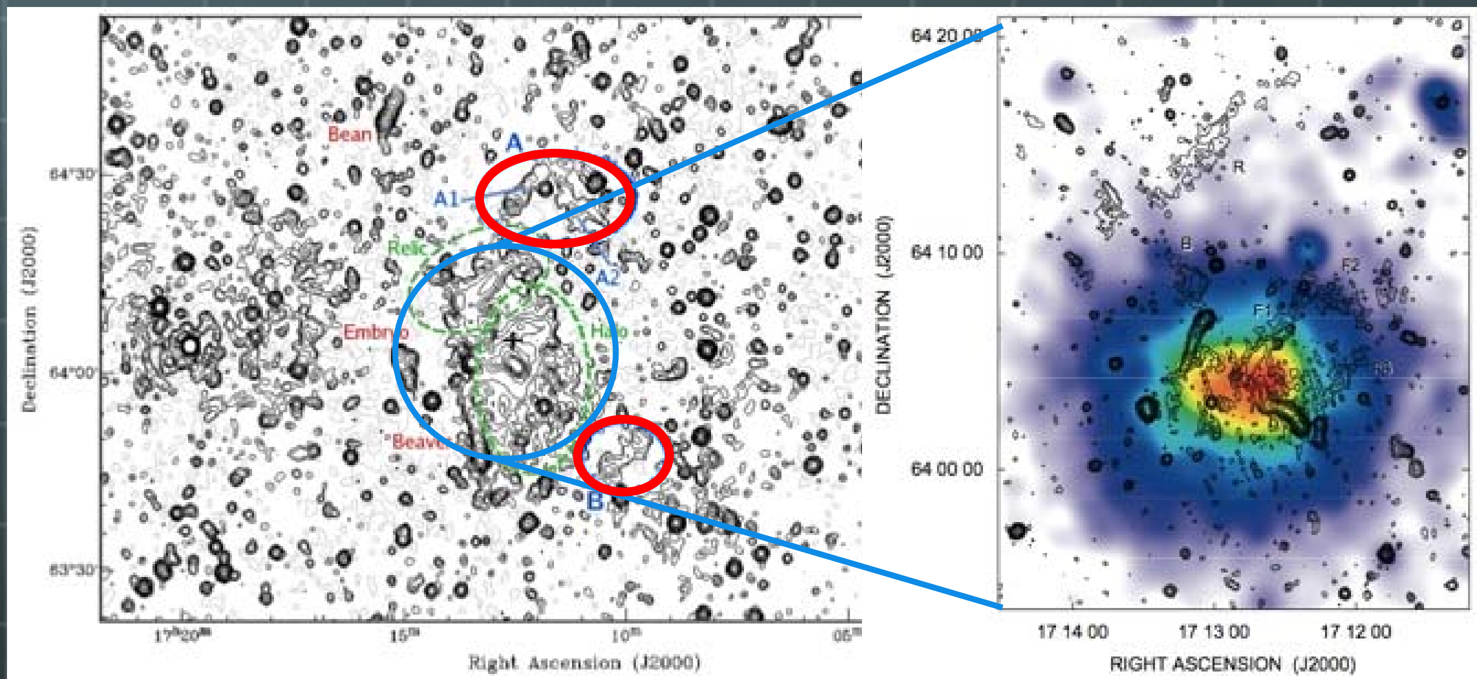



A1914, A2163, A2218, A2319

# 2.1 Clues for Shocks (Radio)




Coma cluster
WSRT 324 MHz (contour)
(Kim+ 89)
Extending~4Mpc, B~0.1-0.2 μG

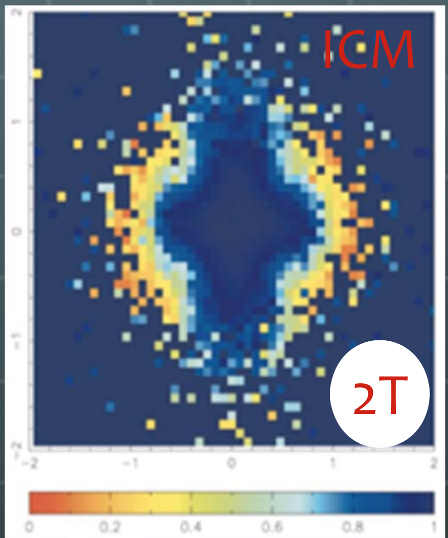



Abell 2255
Radio 85cm (coutour)
(Pizzo+ 08)

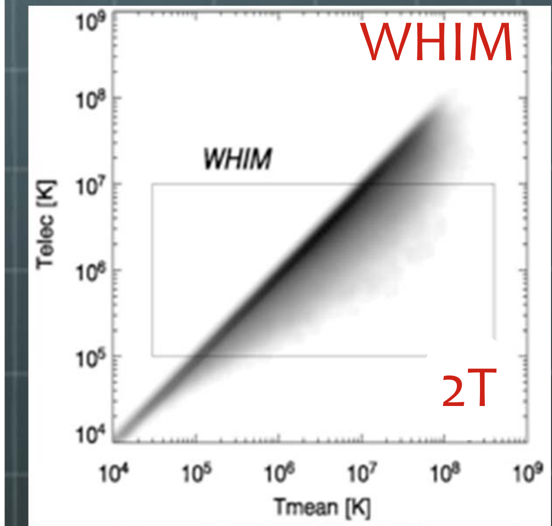
# 2.2 Non-Equilibrium Plasma



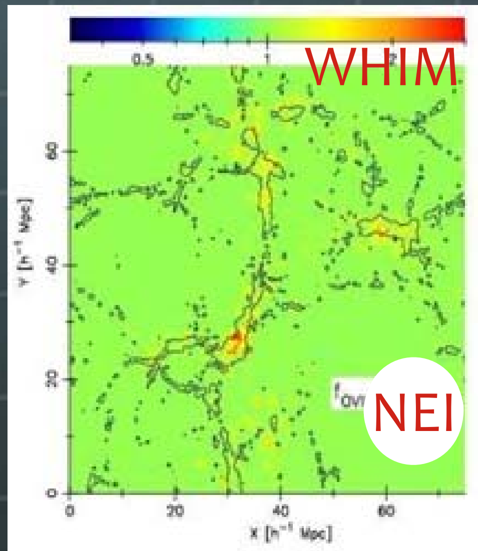
- **NEI and 2T** → the relaxation timescales are longer than the dynamical timescale of the merger
  - Timescale of collisional ionization equilibrium (Masai 84)
    - $t_{CIE} \sim 3$ Gyr $(n_e/10^{-4}\mathrm{cm}^{-3})^{-1}$
  - Timescale of e-i temperature equilibration (Spitzer 56)
    - $t_{e\text{-}I} \sim 2$ Gyr $(n_e/10^{-4}\mathrm{cm}^{-3})^{-1}(T_e/10^8\mathrm{K})^{3/2}$



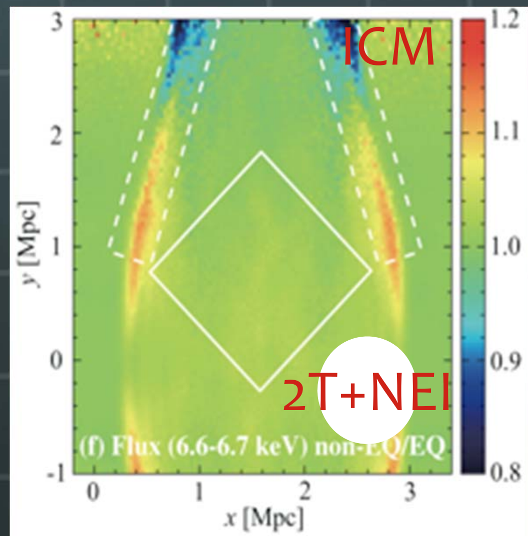
Takizawa 98, 99, 00



Yoshida+ 05



Yoshikawa, Sasaki 06



TA, Yoshikawa 08;10;12

# 2.2 Thermal Relaxation

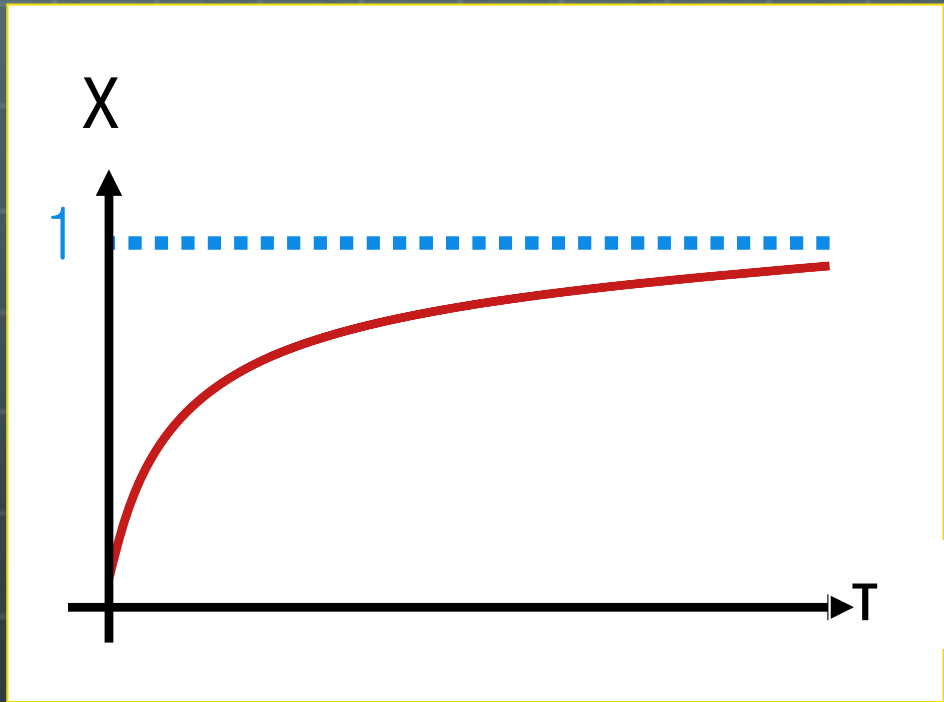
- **Energy exchange between a field ($T_f$) and a test particle (T) follows**

$$\frac{dT}{dt} = \frac{T_{\rm f} - T}{t_{\rm eq}}$$

$$\tau = t/t_{\rm eq}, \chi = T/T_{\rm f}$$

$$\frac{d\chi}{d\tau} = 1 - \chi$$

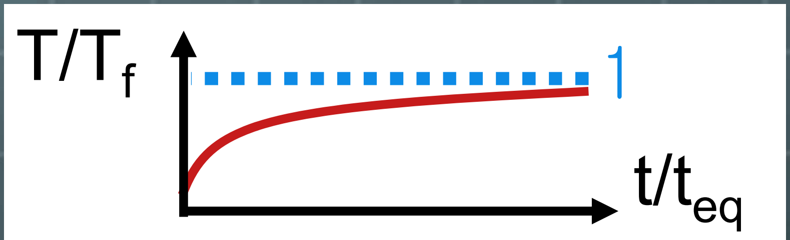
$$\chi = 1 - Ce^{-\tau}$$



# 2.2 Thermal Relaxation

- Spitzer thermal relaxation
  - Energy exchange between field particles ($T_f$) and test particles (T) follows

$$\frac{dT}{dt} = \frac{T_{\rm f} - T}{t_{\rm eq}}$$




  - Particle distribution becomes 1T Maxwell-Boltzmann at most within the following relaxation time

If there are no any other relaxation processes

$$t_{\rm eq} = \frac{3m^{-1/2}m_{\rm f}}{8(2\pi)^{1/2}Z^2Z_{\rm f}^2e^4\ln\Lambda}\frac{(kT)^{3/2}}{n_{\rm f}}\left(1+\frac{m}{m_{\rm f}}\frac{T_{\rm f}}{T}\right)^{3/2}$$

$$t_{\rm eq,ep} \sim (m_{\rm p}/m_{\rm e})^{1/2}t_{\rm eq,pp} \sim (m_{\rm p}/m_{\rm e})t_{\rm eq,ee}$$

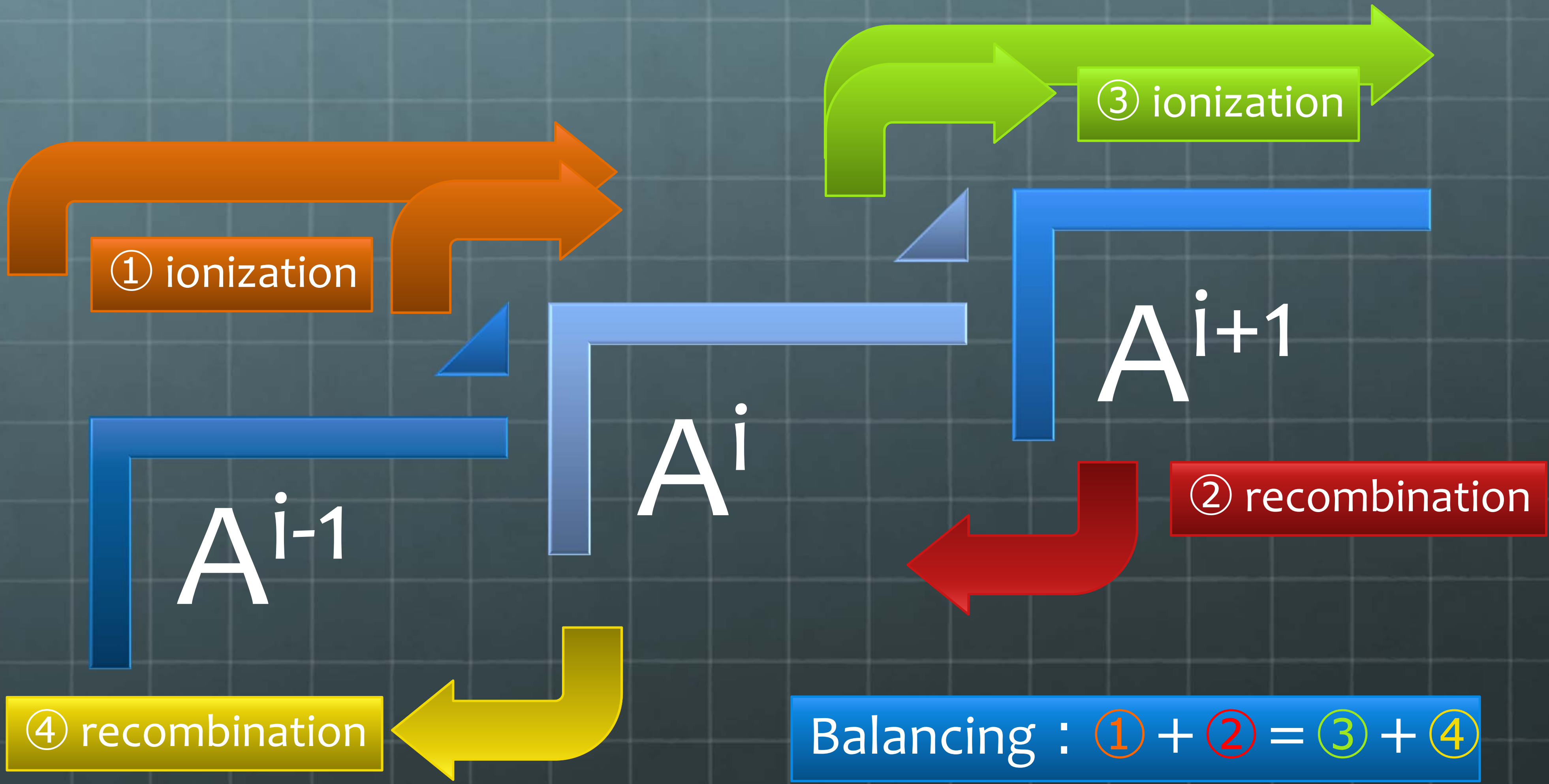
~43 ~1830

Spitzer, L., Jr. "Physics of Fully Ionized Gases", 1962, New York: Wiley

# 2.2 Ionization/Recombination Processes

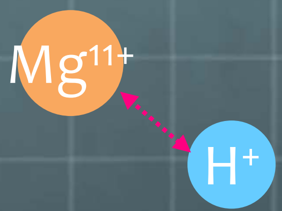


- For i times ionized ion A



# 2.2 Ionization/Recombination Processes 

- **Ionization**
  - (1)Direct Collisional Ionization
  - (2)Excitation-Autoionization
  - (3)Auger Effect ionization
  - (4)Charge-Exchange ionization
  - (5)Photo-Ionizations


- **Recombination**
  - [1]Radiative recombination
  - [2]Dielectric recombination
  - [3]C-E recombination


$$(1)\quad A^{i+} + e^- \rightarrow A^{(i+1)+} + 2e^- + \Delta E$$

最外殻電子をぶっ叩きBinding energyだけエネルギーを失う

$$(2)\quad A^{i+} + e^- \rightarrow A_*^{i+} + 2e^- + \Delta E_1$$
$$(2)\quad A_*^{i+} \rightarrow A_*^{(i+1)+} + e^- + \Delta E_2$$
$$(2)\quad A_*^{(i+1)+} \rightarrow A^{(i+1)+} + h\nu$$

外殻電子がわずかで内殻電子の多い重元素で起こりやすい。

(3) 空乏内殻に対するカスケードの際に、放射が外殻電子にあたって飛び出す

$$(4)[3]\quad A^{i+} + H^+ \leftrightarrow A^{(i+1)+} + H$$

水素がイオンにあたって電子を奪う/与える。ヘリウムの寄与もある。

$$(5)\quad A^{i+} + h\nu \rightarrow A_*^{(i+1)+} + e^- + \Delta E$$
$$(5)\quad A_*^{(i+1)+} \rightarrow A_*^{(i+1)+} + h\nu_1 + h\nu_2 + \ldots$$

外殻電子の光電離の場合。光子のエネルギーによっては励起状態を起こす

$$(5)\quad A^{(i+1)+} + h\nu \rightarrow A_{**}^{(i+1)+} + e^- + \Delta E_1$$
$$(5)\quad A_{**}^{i+} + h\nu \rightarrow A_*^{(i+m+1)+} + me^- + \Delta E_2$$
$$(5)\quad A_*^{(i+m+1)+} \rightarrow A_*^{(i+m+1)+} + h\nu_1 + h\nu_2 + \ldots$$

内殻電子の光電離の場合。Auger ionizationがよりprobable

$$[1]\quad A^{i+} + e^- \rightarrow A_*^{(i-1)+} + h\nu$$
$$[1]\quad A_*^{(i-1)+} \rightarrow A^{(i-1)+} + h\nu_1 + h\nu_2 + \ldots$$

イオンの回りで高い軌道角運動量を持って電子がとっ捕まる。前半は再結合連続線、後半はΔl=±1の選択則に従い再結合特定線

$$[2]\quad A^{i+}(1s, 2s, \ldots) + e^- \rightarrow A_*^{(i-1)+}(n_1 l_1; n_2 l_2)$$
$$[2]\quad A_*^{(i-1)+}(n_1 l_1; n_2 l_2) \rightarrow A_*^{(i-1)+}(n_3 l_3; n_2 l_2) + h\nu$$
$$[2]\quad A_*^{(i-1)+}(n_3 l_3; n_2 l_2) \rightarrow A^{(i-1)+}(n_3 l_3; n_4 l_4) + h\nu_1 + h\nu_2 + \ldots$$

束縛電子のひとつをautoionization stateにする再結合

# 2.2 Non-Equilibrium Ionization (NEI)

- Collisional Ionization Equilibrium (CIE)
  - Balancing between ionization and recombination

$$0 = \frac{dn_{A,i}}{dt} = -n_e n_{A,i} R_{\mathrm{coll}}^{A,i} - n_e n_{A,i} \alpha_{\mathrm{rec}}^{A,i} + \ldots$$

$$\tau_{\mathrm{CIE}} \sim n_{\mathrm{e}}^{-1} (R_{\mathrm{coll}}^{A,i} + \alpha_{\mathrm{rec}}^{A,i})^{-1}$$

  - Generally, time evolution of the ionization fraction $f_{A,i}$ for i times ionized ion A is

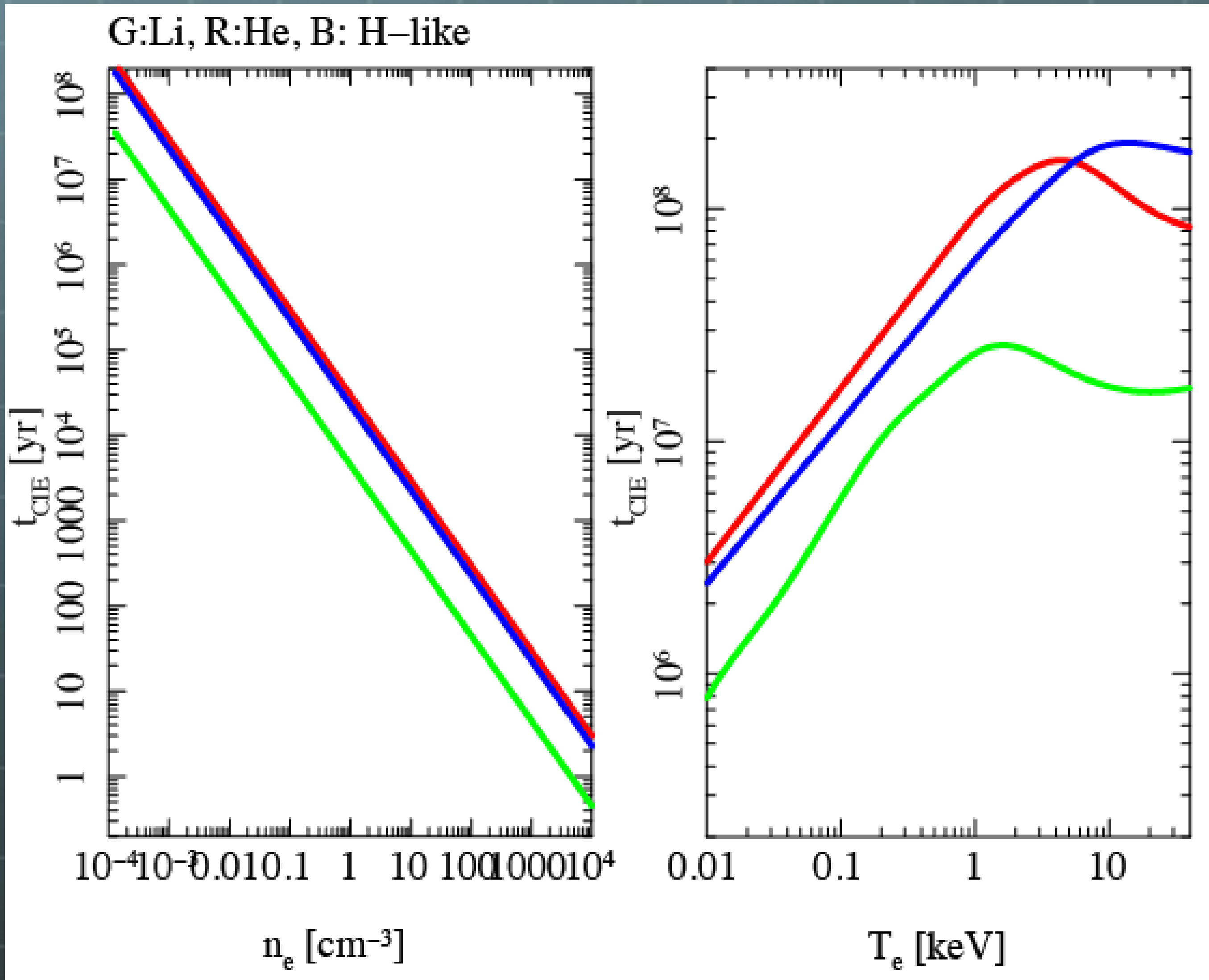
$$\frac{df_{A,i}}{dt} = \sum_{k=1}^{i-1} S_{i-k,k} f_{A,k} - \sum_{k=i+1}^{z+1} S_{k-i,i} f_{A,i} - \alpha_i f_{A,i} + \alpha_{i+1} f_{A,i+1}$$

$$\tau_{\mathrm{CIE}} \sim \left( \sum S_{,i} + \alpha_i \right)^{-1}$$

Ref: Dopita, M. A., & Sutherland, R. S. "Astrophysics of the Diffuse Universe", 2003, Springer

# 2.2 Ionization Equilibrium Timescale

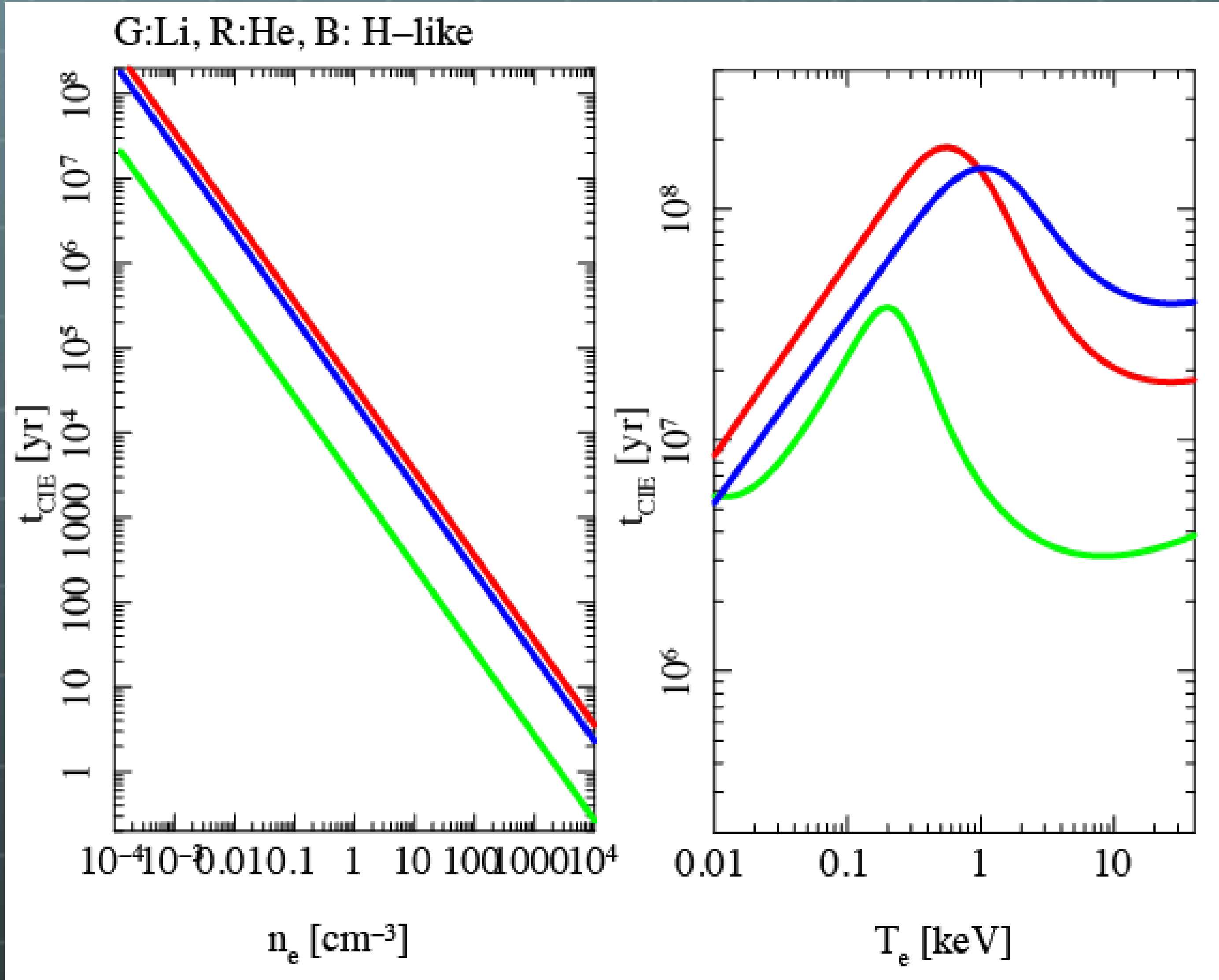
- For Fe, $T_e$=3 keV or $n_e$=$10^{-4}$ $cm^{-3}$



# 2.2 Ionization Equilibrium Timescale



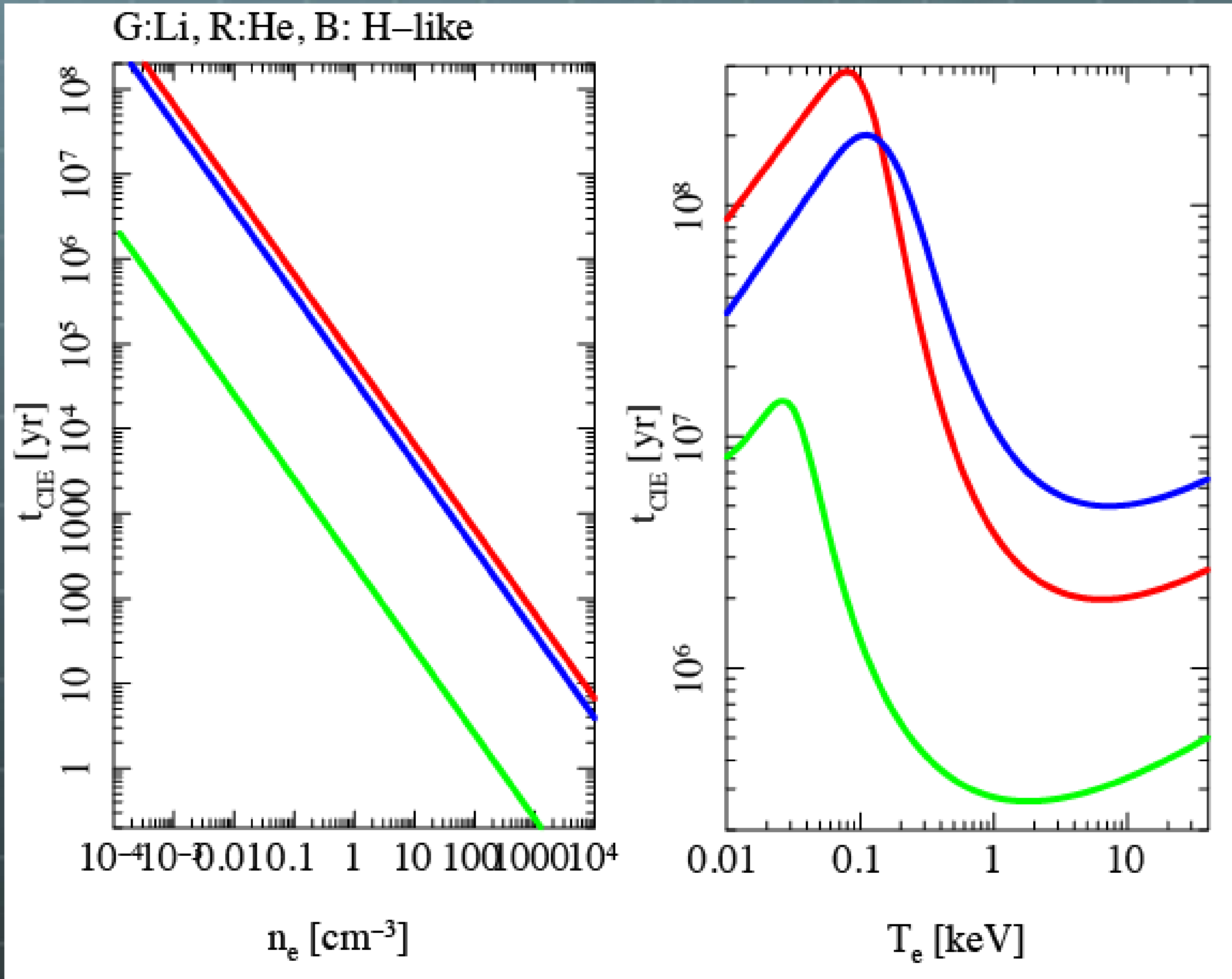
- For S, $T_e$=0.5 keV or $n_e$=$10^{-4}$ $cm^{-3}$



# 2.2 Ionization Equilibrium Timescale



- For O, $T_e$=0.1 keV or $n_e$=$10^{-4}$ $cm^{-3}$



# 2.2 The Simulations

## SPH/N-body Calculations

Based on Springel Hernquist 02

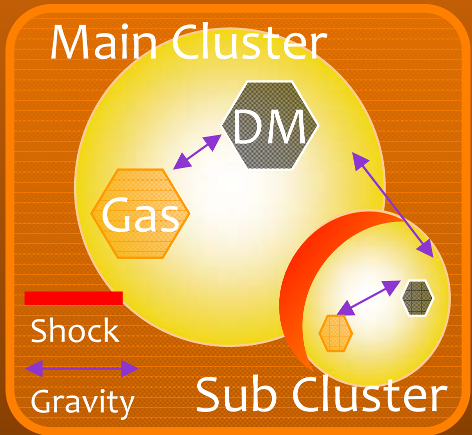
Original code optimized for cluster simulations (TA, Masai 05; 06; TA, Yoshikawa 08; 10; 12). MPI/OpenMP hybrid parallel, Burns-Hut Tree (monopole, θ=0.4), artificial viscosity (Monaghan, Gingold 83, Balsara 95) with β=2α, α=1

Initial condition

ICM: β-model (Cavaliere & Fusco-Femiano 76) + hydrostatic temperature profile, or Isothermal + hydrostatic density profile,

DM: NFW (Navarro+ 97) profile + Jeans equation

Two clusters contact at virial radius for each other with initial velocity V (free parameter, or Sarazin 02)




## Mach Number Calculation

Based on Pflommer+ 06

$$1+\frac{f_h h}{M_1 c_1 A_1}\frac{dA_1}{dt}=\frac{2\gamma M_1^2-(\gamma-1)}{\gamma+1}\left[\frac{(\gamma-1)M_1^2+2}{(\gamma+1)M_1^2}\right]^{\gamma}$$

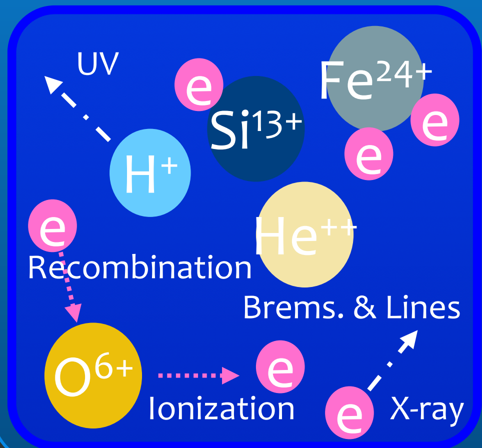
M: Mach number, c: sound velocity, A: entropic function ($P=A\rho^{\gamma}$), h: smoothing length of SPH, $f_h$=1

## NEI/Spectra Calculations

Based on Yoshikawa, Sasaki 06

$$\frac{df_j}{dt}=\sum_{k=1}^{j-1}S_{j-k,k}f_k-\sum_{i=j+1}^{Z+1}S_{i-j,j}f_j-\alpha_j f_j+\alpha_{j+1}f_{j+1}$$

$f_j$: ionization fraction of ion j ( j-1 times ionized ion), $S_{i,j}$: Ionization rate that ion j ejects i electrons, $\alpha_j$: Recombination rate for ion j




Backward difference formula (sequentially updated in the order of increasing ionization states)

Atomic data/spectra: SPEX ver. 1.10 (http://www.sron.nl/divisions/hea/spex)

UV+X background radiation: CUBA code (Haardt, Madau 01)

H, He, C, N, O, Ne, Mg, Si, S, Fe (112 ionization states) for all SPH particles are calculated

## 2T Calculation

Based on Takizawa 99

$$\frac{d\tilde{T}_e}{dt}=\frac{\tilde{T}_i-\tilde{T}_e}{t_{ei}}-\frac{\tilde{T}_e}{u}Q_{sh}$$

$$t_{ei}=\frac{3m_e m_i}{8(2\pi)^{1/2}n_i Z_i^2 e^4\ln\Lambda}\left(\frac{kT_e}{m_e}+\frac{kT_i}{m_i}\right)^{3/2}$$

Ti, Te: the ion and electron temperatures, ~: normalized by the gas mean temperature T, u: the internal energy of the gas, Qsh: the shock heating rate, μ=0.6, lnΛ: Coulomb logarithm, mi, me: the ion and electron mass

# 2.2 Simulation Details

- Electron-Ion Two Temperature structure
  - Fox, Loab 97; Takizawa 98
  - Coulomb two-body relaxation (with $T_e$ and $T_i$)

$$\rho \frac{du_e}{dt} = -P_e \nabla \cdot v + Q_{rad} + Q_{ex}$$
$$\rho \frac{du_i}{dt} = -P_i \nabla \cdot v + Q_{vs} - Q_{ex}$$

$$Q_{ex} = \frac{n_e k}{\gamma - 1} \frac{T_i - T_e}{t_{ei}} \qquad Q_{sh} = -\frac{\Pi}{2} \nabla \cdot v$$

$$t_{ei} = 7.97 \times 10^9 \ \mathrm{yr} \frac{(T_e/10^8 \ \mathrm{K})^{3/2}}{(n_i/10^{-3} \ \mathrm{cm}^{-3})} \cdot \frac{1}{\ln \Lambda}$$

We assume that the mean molecular weight μ is constant (H and He are normally fully-ionized).

$$\mu \equiv \frac{m_p n_p + m_{He} n_{He} + \dots}{m_p (n_e + n_p + n_{He} + \dots)}$$

$$\begin{aligned} n_i &= \left( \frac{\rho X}{m_p} + \frac{\rho Y}{m_{He}} \right) \\ &= \frac{\rho}{m_p} (X + Y/4) \\ &= \mu (X + Y/4) n \\ &\equiv \mu' n \\ n_e &= (1 - \mu') n \end{aligned}$$

$$nT = n_e T_e + n_i T_i$$
$$T = (n_e T_e + n_i T_i)/(n_e + n_i)$$
$$X_e = T_e/T、 X_i = T_i/T$$
$$X_i = \frac{1 - (1 - \mu') X_e}{\mu'}$$

$$\frac{du}{dt} = -\frac{P}{\rho} \nabla \cdot v + \frac{1}{\rho} (Q_{rad} + Q_{vs})$$
$$\frac{dX_e}{dt} = \frac{X_e - X_i}{t_{ei}} - \frac{X_e}{\rho u} (Q_{rad} + Q_{vs}) + \frac{Q_{rad}}{(1 - \mu') \rho u}$$

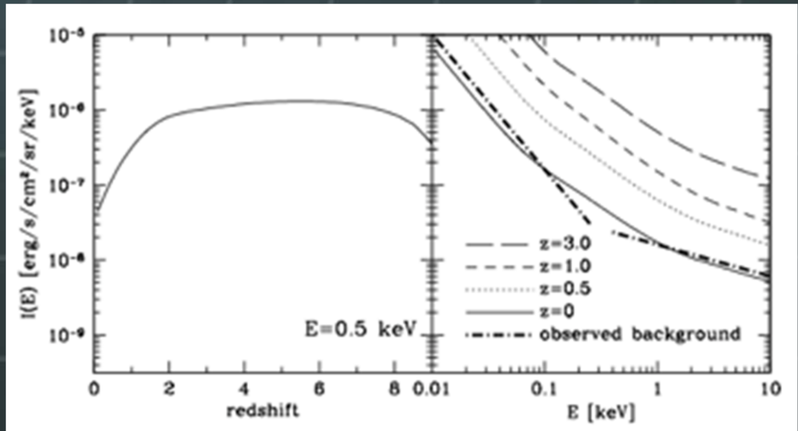
# 2.2 Simulation Details

- Non-Equilibrium Ionization
  - Yoshikawa, Sasaki 06
  - SPEX package ver. 1.10
    - Ionization: collisional, Auger, charge-exchange, photo-ionization
    - Recombination: radiative, dielectric, charge-transfer
    - H, He, C, N, O, Ne, Mg, Si, S, Fe
  - CUBA code
    - Haardt, Madau 01
    - UV, X-ray background
  - Backward difference formula
    - Implicit. Ex. Anninos+ 97
    - Sequentially updated in the order of increasing ionization states

$$\frac{df_j}{dt} = \sum_{k=1}^{j-1} S_{j-k,k} f_k - \sum_{i=j+1}^{Z+1} S_{i-j,j} f_j - \alpha_j f_j + \alpha_{j+1} f_{j+1}$$

$f_j$: ionization fraction of j-1times ionized ion, Z: atomic number, $S_{i,j}$: Ionization rate that ion j ejects i e, $\alpha_j$: Recombination rate for ion j

Intensity




redshift E(keV)

# 2.2 Simulation Details



- Mach number estimator
  - Pflommer 06
  - Entropy increase law
    - Entropic function A(s), 1 and 2 the upstream and downstream

$$P = A(s)\rho^\gamma$$

$$\Delta t = f_h h / v_1$$

$$\Delta A_1 \simeq \Delta t \mathrm{d} A_1 / \mathrm{d}t$$

$$M_1 = v_1 / c_1$$

$$c_1 = \sqrt{\gamma P_1 / \rho_1}$$

$$\frac{A_2}{A_1} = \frac{A_1 + \Delta A_1}{A_1} = 1 + \frac{f_h h}{M_1 c_1 A_1} \frac{\mathrm{d}A_1}{\mathrm{d}t}$$

  - Rankine-Hugoniot law

$$\frac{\rho_2}{\rho_1} = \frac{(\gamma+1)M_1^2}{(\gamma-1)M_1^2+2}$$

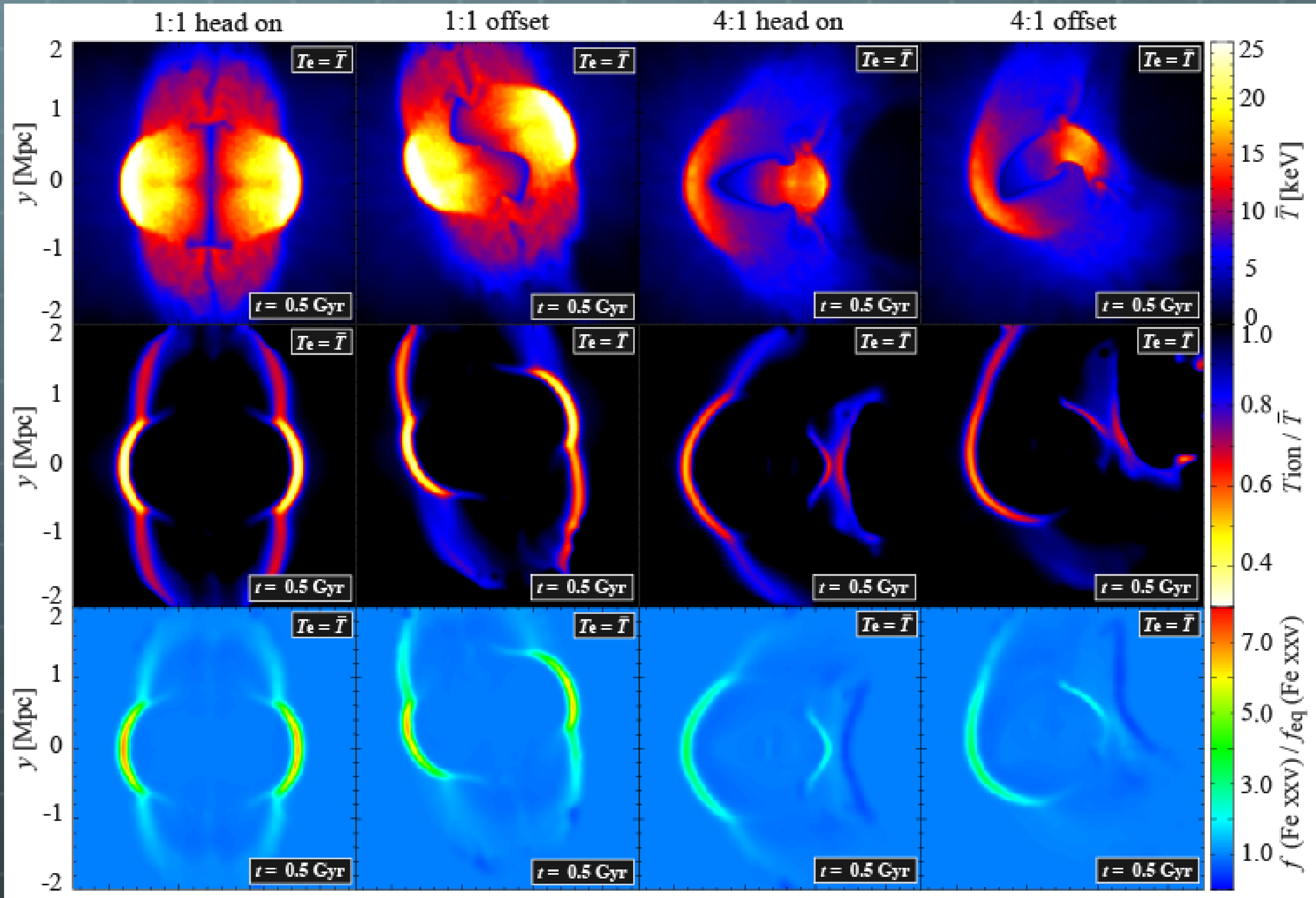
$$\frac{P_2}{P_1} = \frac{2\gamma M_1^2 - (\gamma-1)}{\gamma+1}$$

$$\frac{T_2}{T_1} = \frac{[2\gamma M_1^2 - (\gamma-1)][(\gamma-1)M_1^2+2]}{(\gamma+1)^2 M_1^2}$$

$$\frac{A_2}{A_1} = \frac{P_2}{P_1}\left(\frac{\rho_1}{\rho_2}\right)^\gamma = \frac{2\gamma M_1^2 - (\gamma-1)}{\gamma+1}\left[\frac{(\gamma-1)M_1^2+2}{(\gamma+1)M_1^2}\right]^\gamma$$

# 2.2 Merging Galaxy Clusters

- **Behind the shock layers → NEI/2T**




TA, Yoshikawa 10

# 2.2 Line Spectrum Width

- Line width δ due to the Doppler shift
  - Emission of rest-frame wavelength $\lambda_0$ ($\omega_0=2\pi c/\lambda_0$) at the atom A with forward velocity v
  - ω at the observer is $$\omega = \omega_0(1+v/c)$$
  - Probability that A with the mass M and temperature T has a velocity within v - v+dv is $$\sqrt{\frac{M}{2\pi kT}}\exp\left(-\frac{Mv^2}{2kT}\right)dv$$
  - Thus, Doppler broadening is $$I_{\rm D}(\omega)d\omega = \sqrt{\frac{Mc^2}{2\pi kT\omega_0^2}}\exp\left[-\frac{Mc^2}{2kT\omega_0^2}(\omega-\omega_0)^2\right]d\omega$$
  - Half width δ is

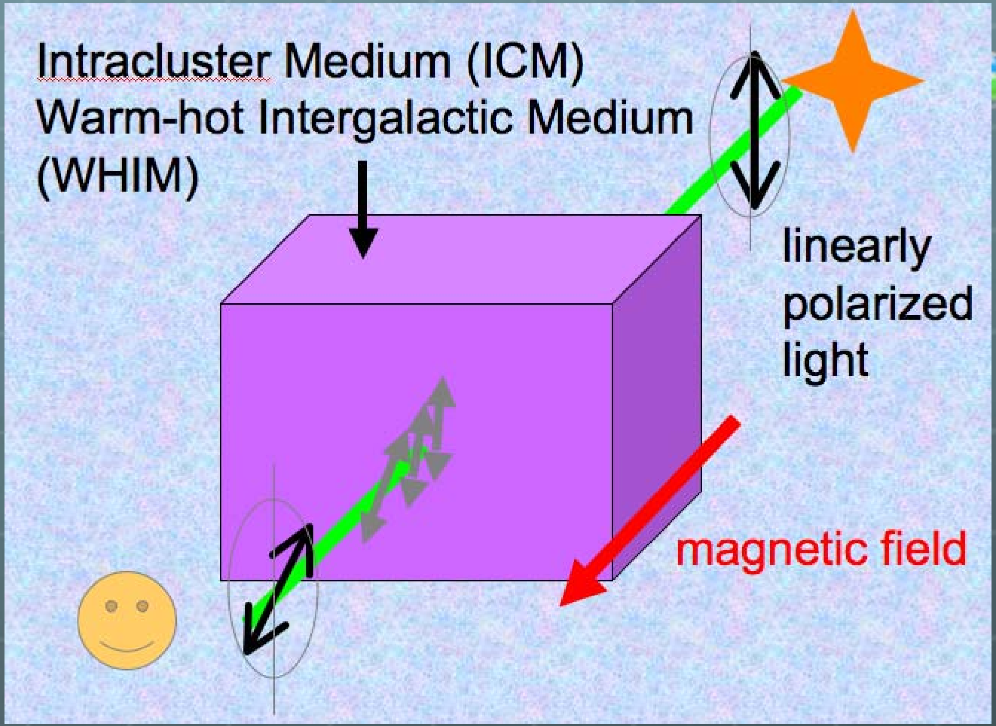
$$\delta(\omega_0) = 2\omega_0\sqrt{(2kT/Mc^2)\ln 2}$$

$$\frac{\delta(\lambda_0)}{\lambda_0} = 7.16\times10^{-7}\sqrt{\frac{T}{A}} = 0.967\times10^{-3}\sqrt{\left(\frac{T}{10^8\ {\rm K}}\right)\left(\frac{56}{A}\right)}$$

Ref: 原子物理学II, 白土釥二, 日本理工出版会

# 3.2 Faraday Rotation Measure






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

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

$\Phi$: rotation angle [rad]
$\Phi_o$: intrinsic rotation angle [rad]
$\lambda$: 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

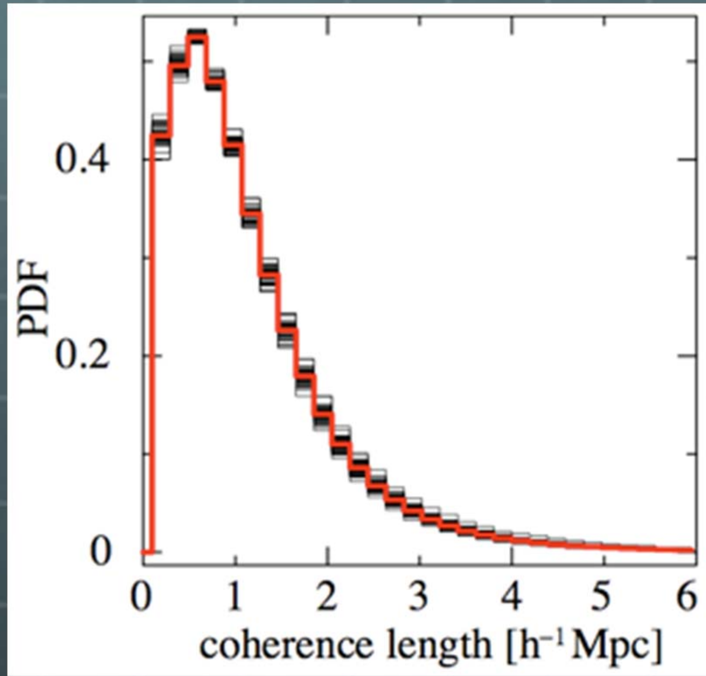
$$\mathrm{RM} = \frac{\Phi(\lambda_1) - \Phi(\lambda_2)}{\lambda_1^2 - \lambda_2^2}$$

# 3.2 IGMF RM – Local Universe –



- 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



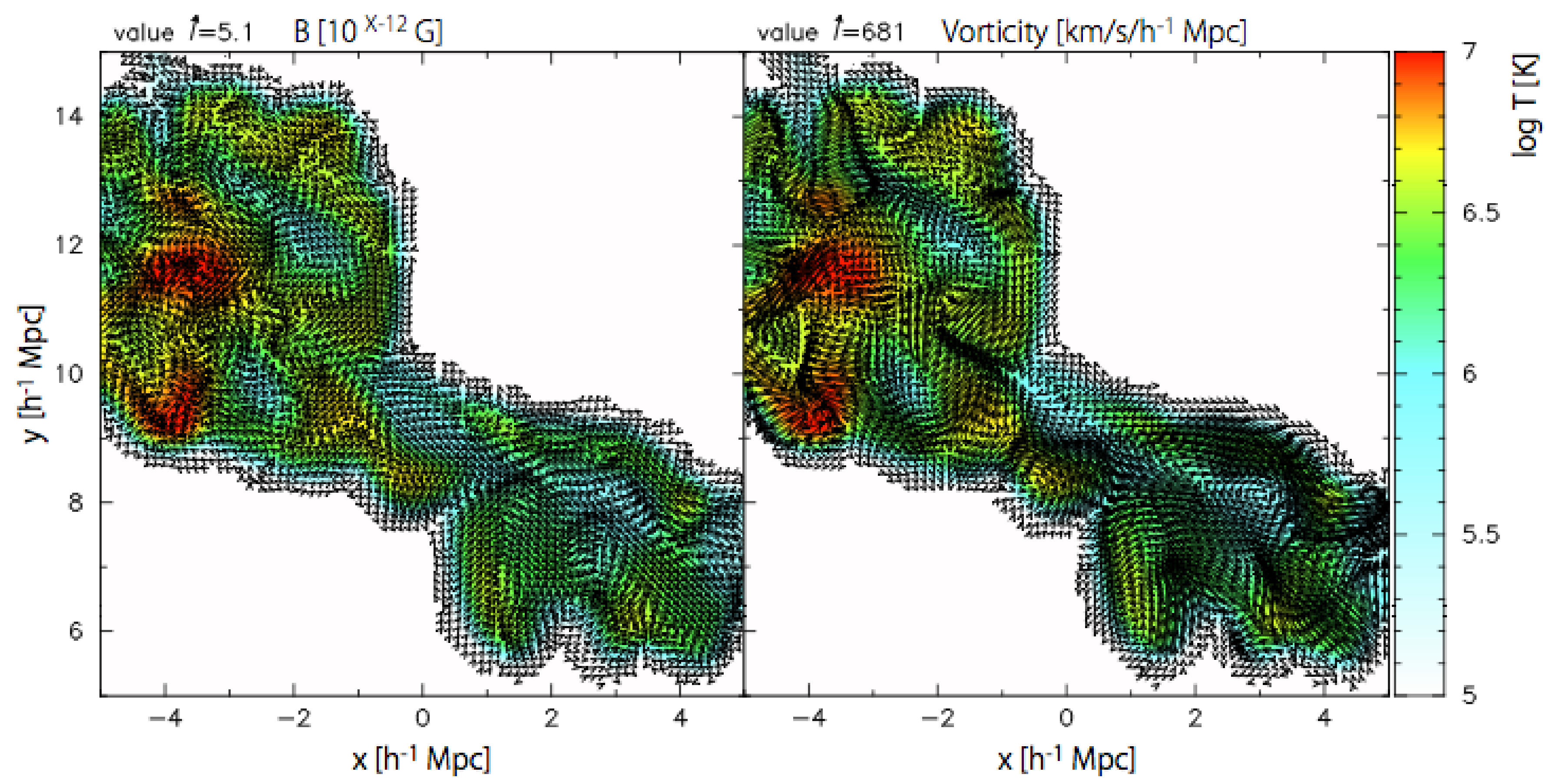

coherence length of B for

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

# 3.2 IGMF RM – Local Universe –



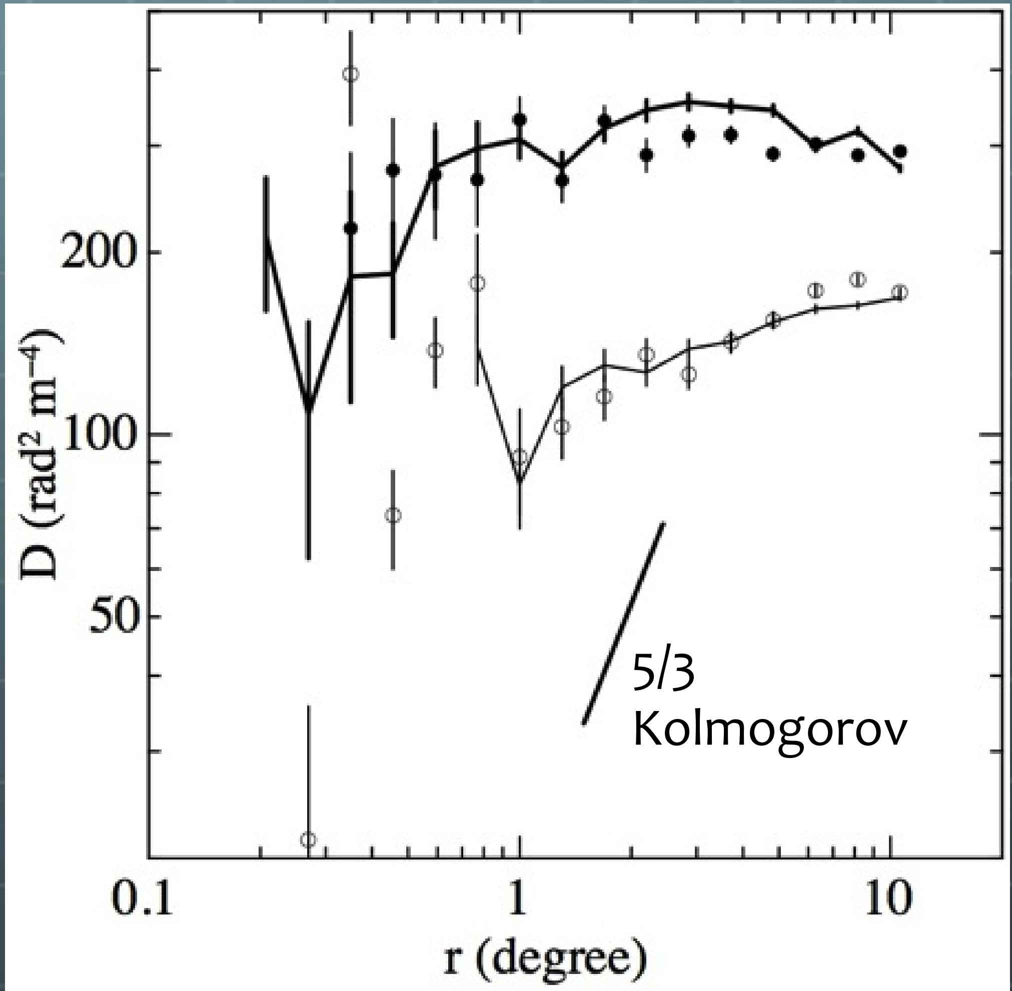
## Passive field and vorticity




Distributions of IGMF (left) and the vorticity (right) in the 2D slice. The length of arrows for IGMF corresponds to x of $10^{x-12}$ G. The color shows the gas temperature. The direction of magnetic field correlates with the direction of vorticity in a passive field model.

# 3.2 Structure Function (SF) of RM

## SFs of RM toward the Galactic Poles (Stil+ 11)




← South Galactic Pole (SGP)

circles: Mao+ (10) WSRT+ACTA

lines: Taylor+ (09) NVSS

← North Galactic Pole (NGP)

circles: Mao+ (10) WSRT+ACTA

lines: Taylor+ (09) NVSS

- ✓ Very flat profile
- ✓ 100-400 [$rad^2\ m^{-4}$]
- ✓ $SF_{SGP}$ > 1.5-2 $SF_{NGP}$

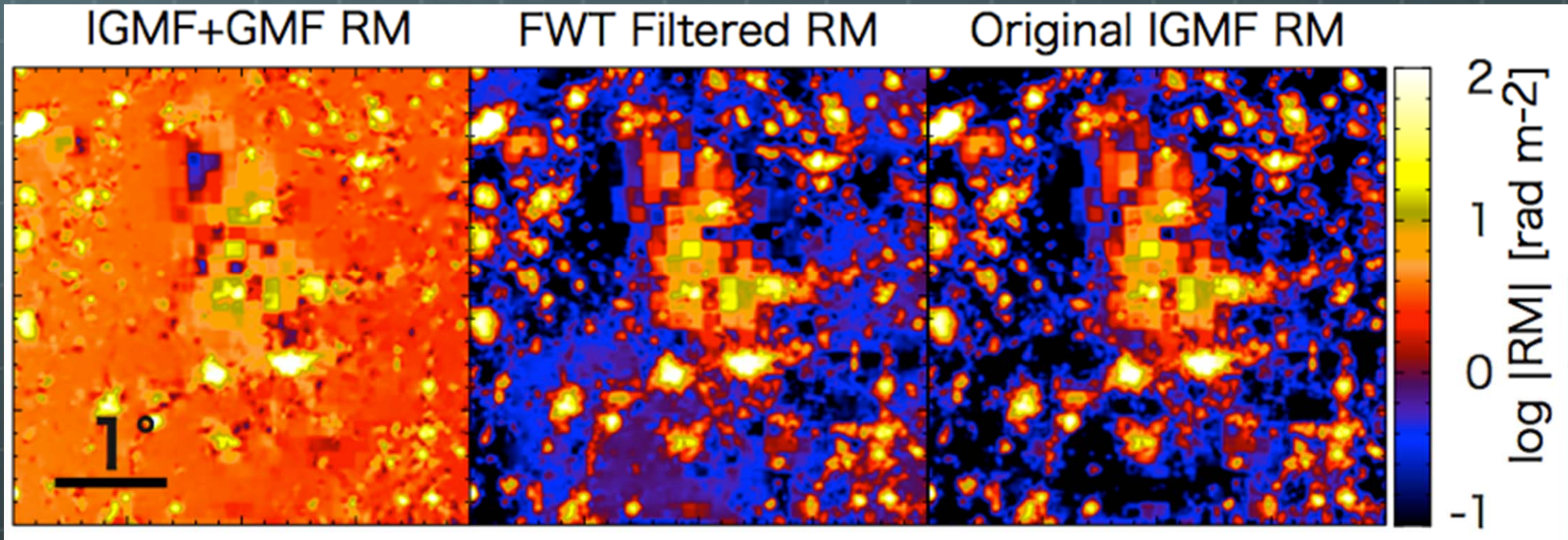
**Motivation** How much is the contribution from the IGMF?

# Toward ASKAP and SKA



- **Development of Image Processing**
  - **High-pass filter technique**

Fourier transformation of RM map → **Chop** the large-scale power in Fourier space → Inverse Fourier transformation



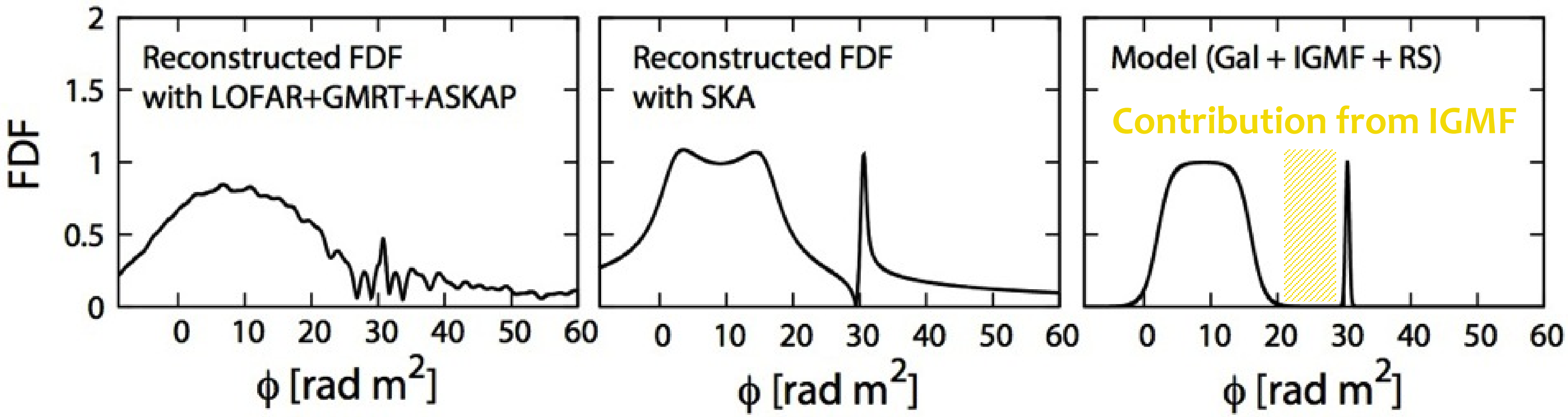

Akahori et al. in prep.

# Toward ASKAP and SKA



- **Development of Image Processing**
  - **Faraday RM tomography (e.g., Brentjens, de Bruyn 2005)**

Polarized intensity map $P(\lambda^2)$ → Fourier transformation → Faraday dispersion function F(RM)




Kumazaki, Akahori, Takahashi, Ryu in prep.