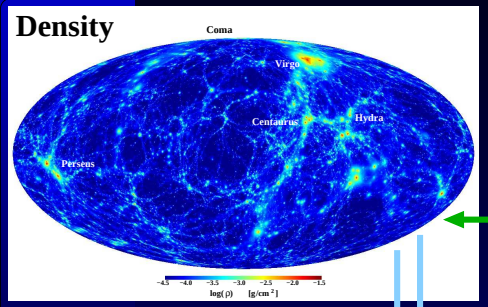
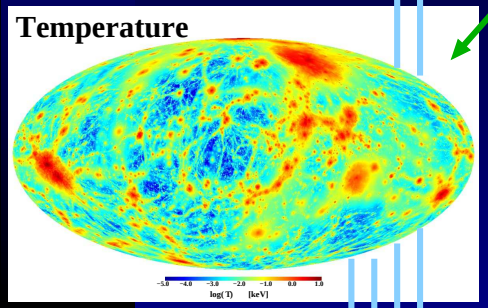
Lecture II
Cosmological Magnetic Fileds and the propagation of CRs

Klaus Dolag

Universitäts-Sternwarte München, LMU

Process Network





ICs (Cosmology)

Primordial

Seed Magnetic Field

Coupling to Star Formation

Structure Formation
- Star Formation ?
- Feedback ?
- AGN ?

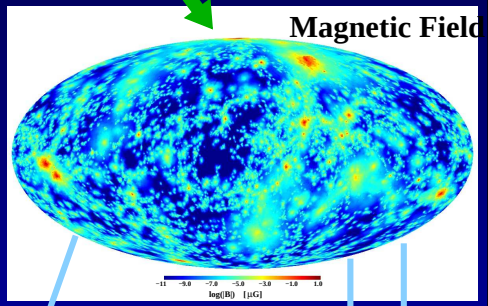
Magnetic Pressure

Compression

Magnetic Field Evolution
- Dissipation ?
- Numerics ?
- Resolution ?

Shock Statistics
- Detection ?
- Numerics ?

Turbulence
- Viscosity ?
- Numerics ?
- Sub−Grid Model ?



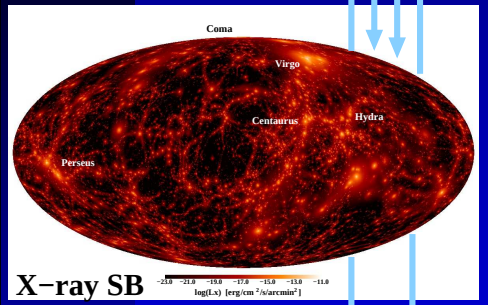
Efficiency δ(M) ???

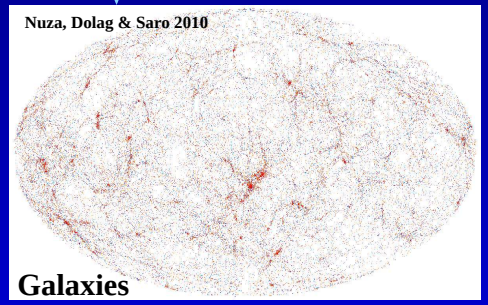
Mechanism ???

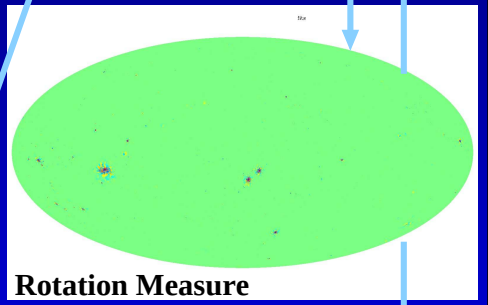
Cosmic Rays
- Description ?
- Diffusion ?

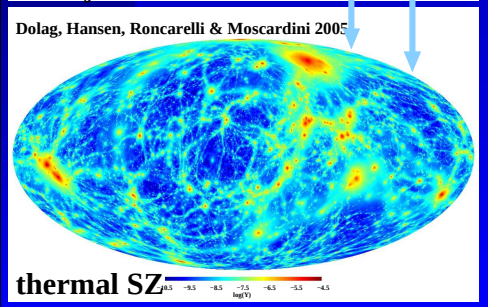
CR−p CR−e

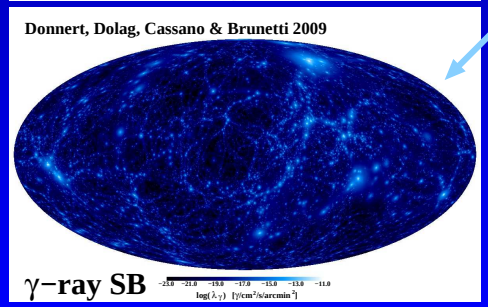
Observables

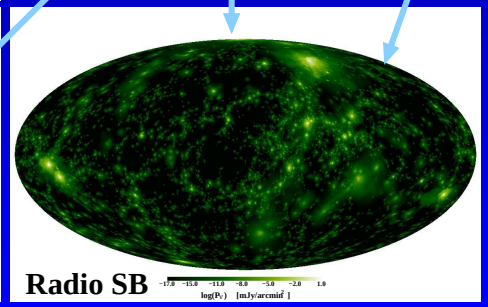


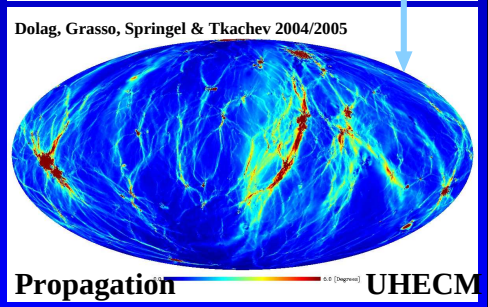




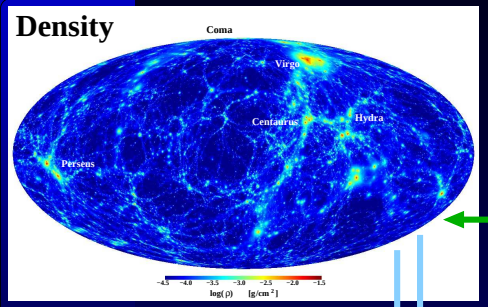


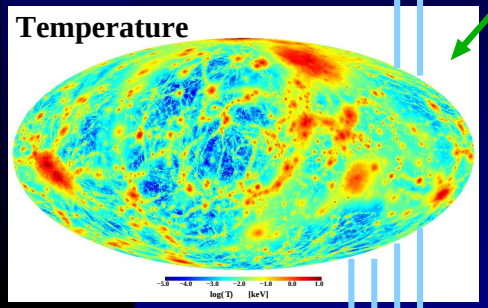






Process Network





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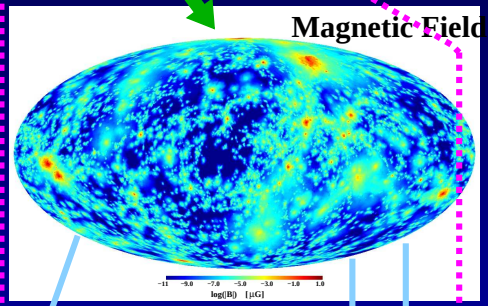
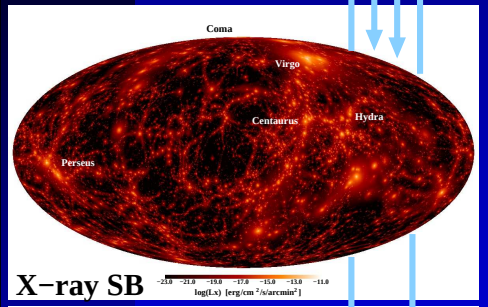
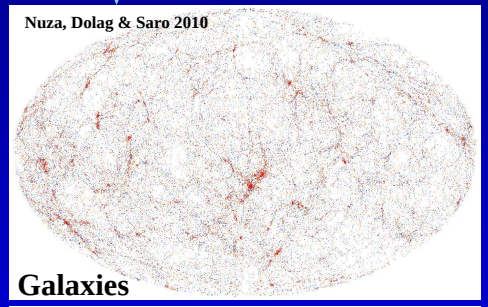
Mechanism ???



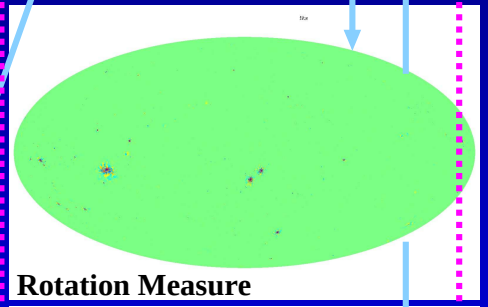
Observables

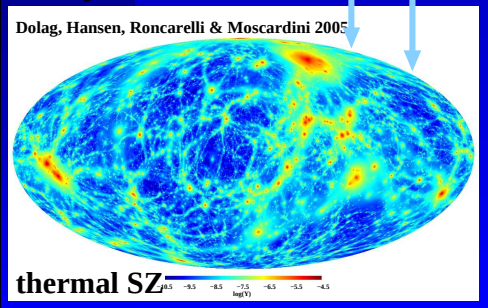


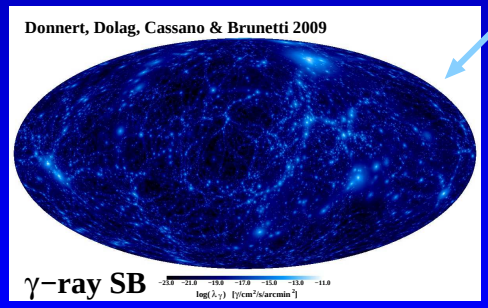


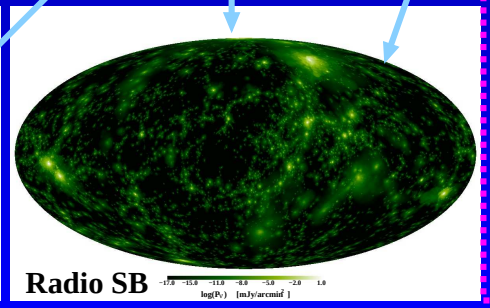
Cosmic Rays
- Description ?
- Diffusion ?

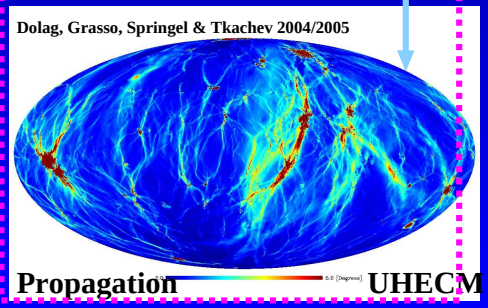
CR−p CR−e







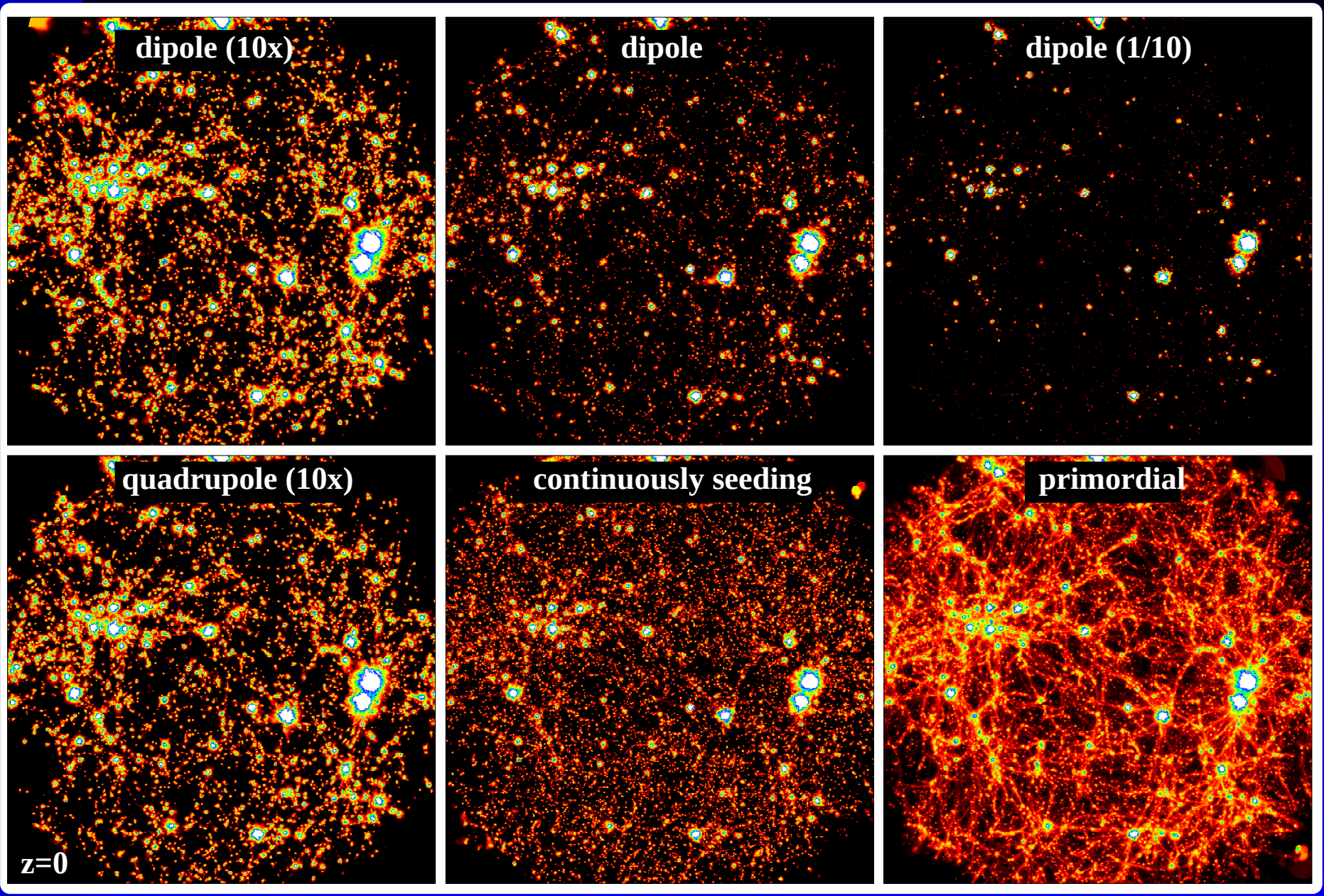




Outline

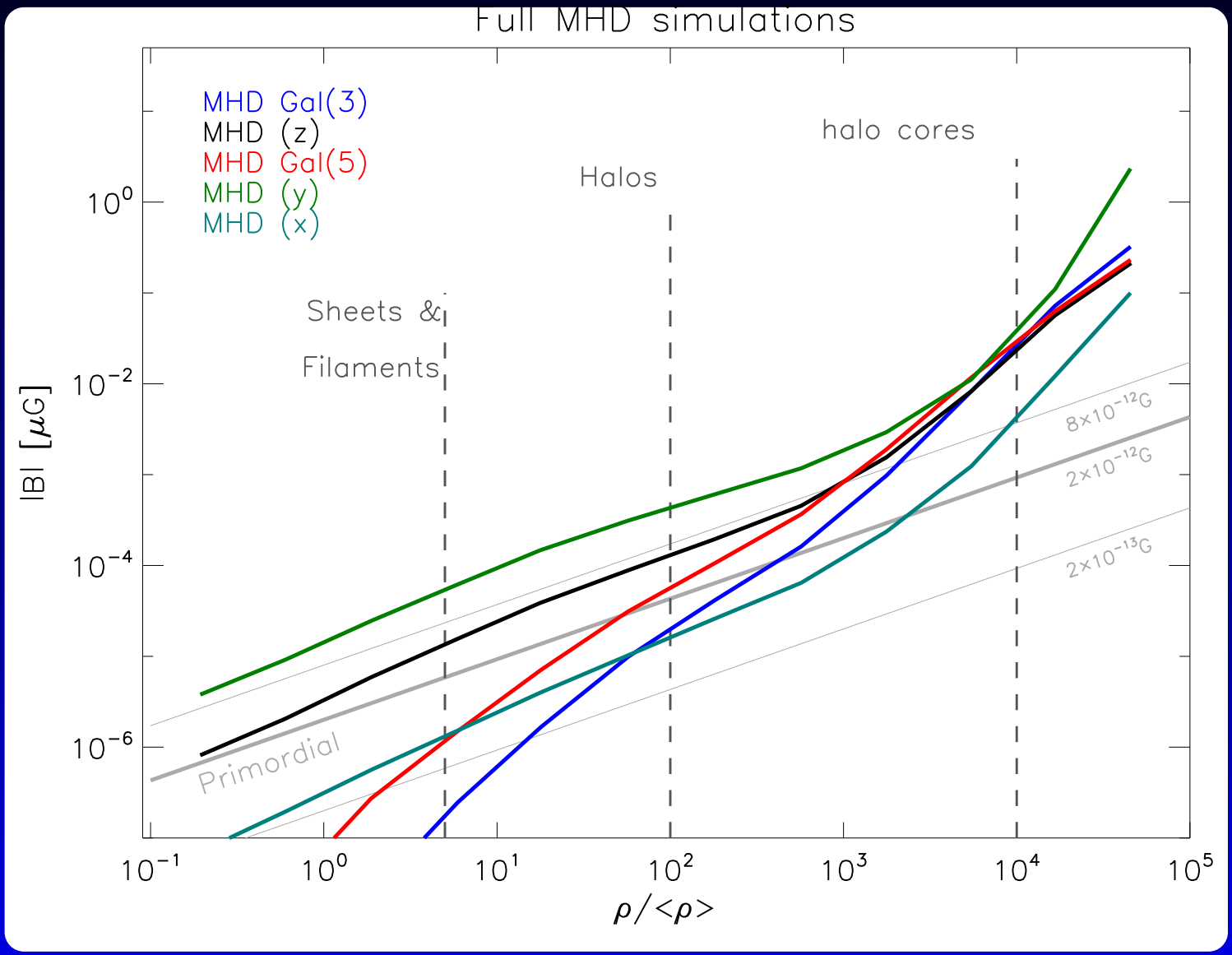
- Introduction
  - Magnetization quest
  - Windows to cosmic magnetism
- Faraday Rotation Measures
- UHECR propagation
- TeV photons
  - Deflection of electro magnetic cascade
  - Attenuation of electro magnetic cascade
- Summary

Cosmic Magnetization Quest



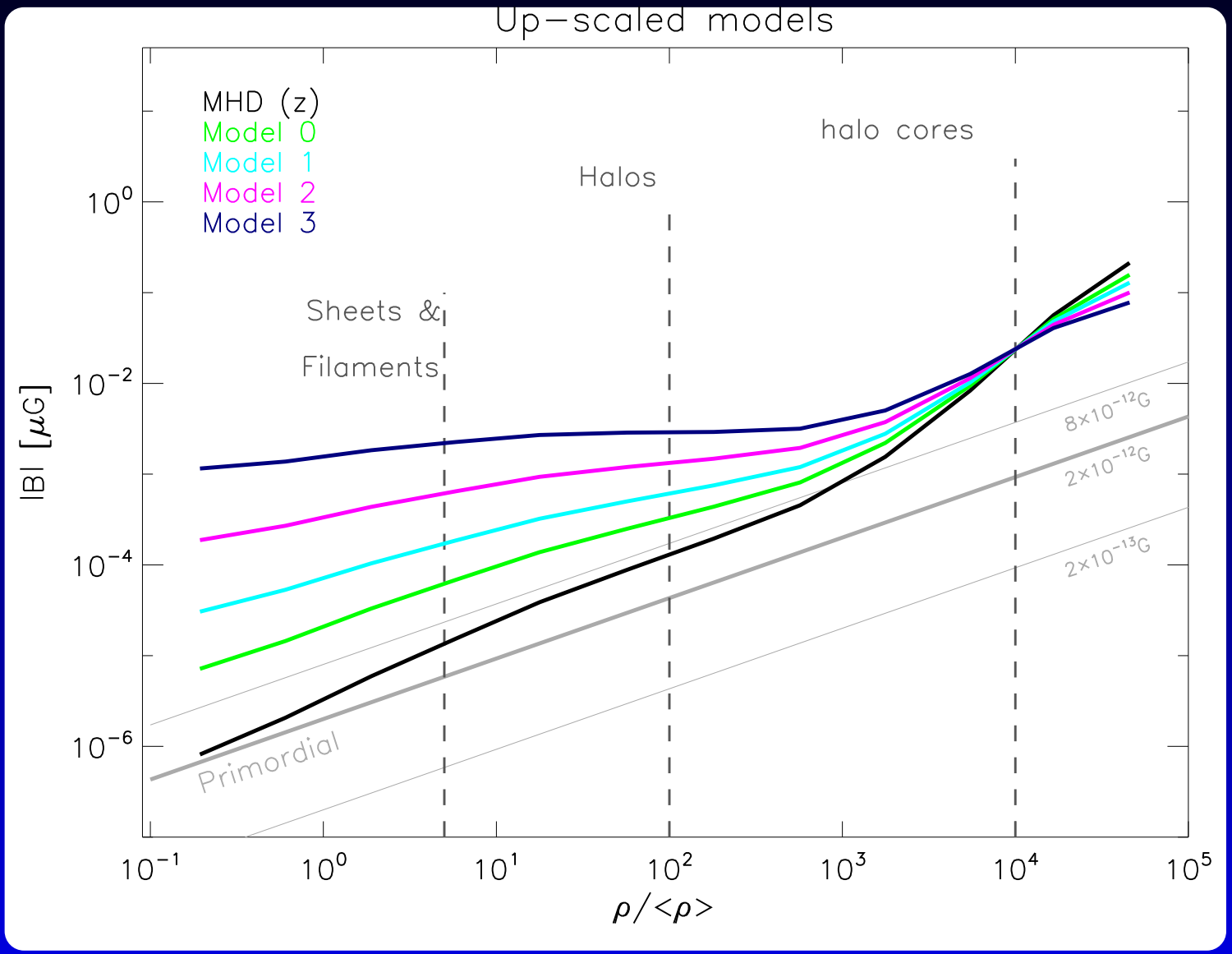
Different wind parameters (Donnert et al. 2009) $\Rightarrow$ Lecture IV.

Cosmic Magnetization Quest



Predictions from **different** models for **origin** of cosmic magnetism ⇒ Lecture IV.

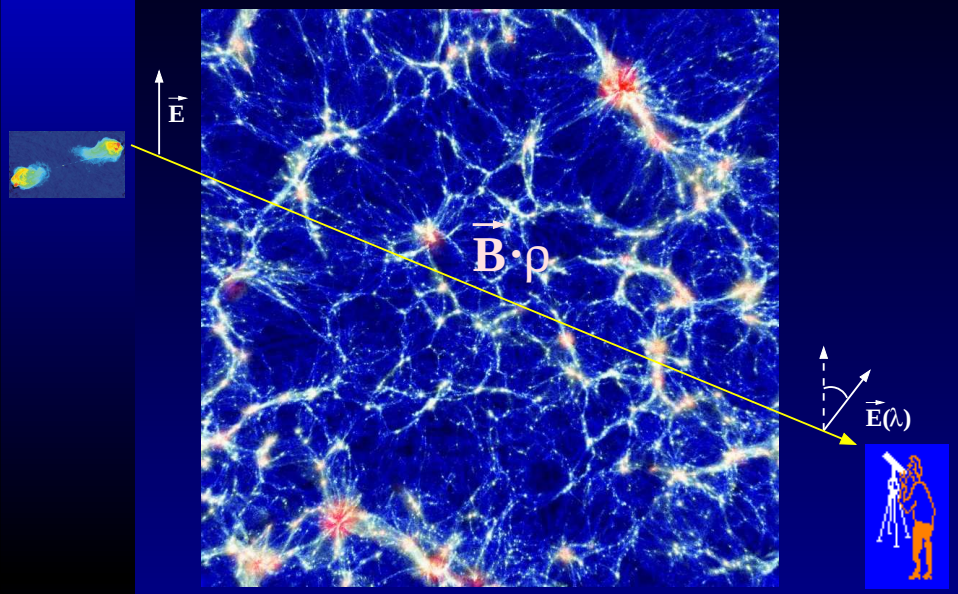
Cosmic Magnetization Quest



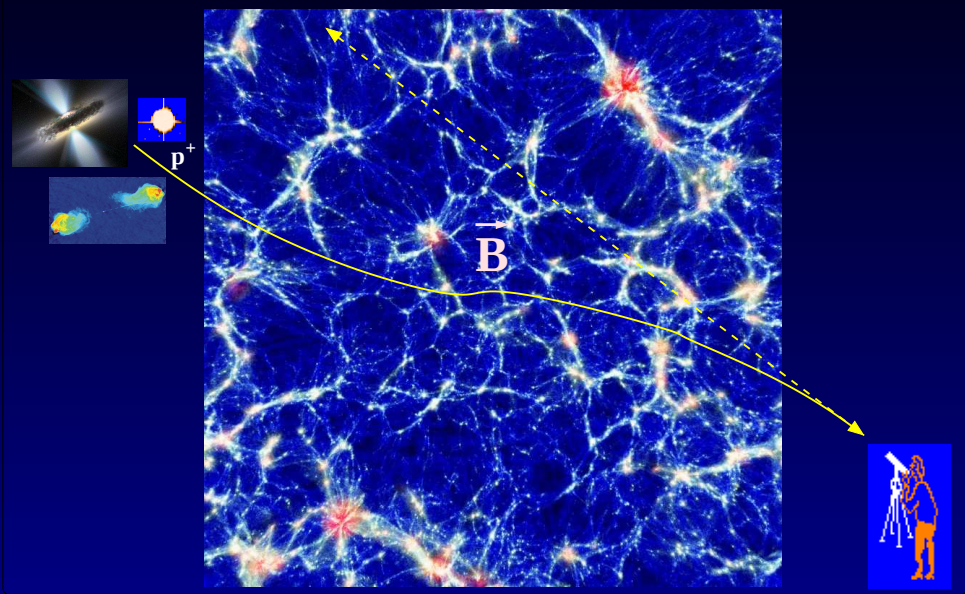
Synthetic models for testing **extreme** cases.

Cosmic Magnetization Quest

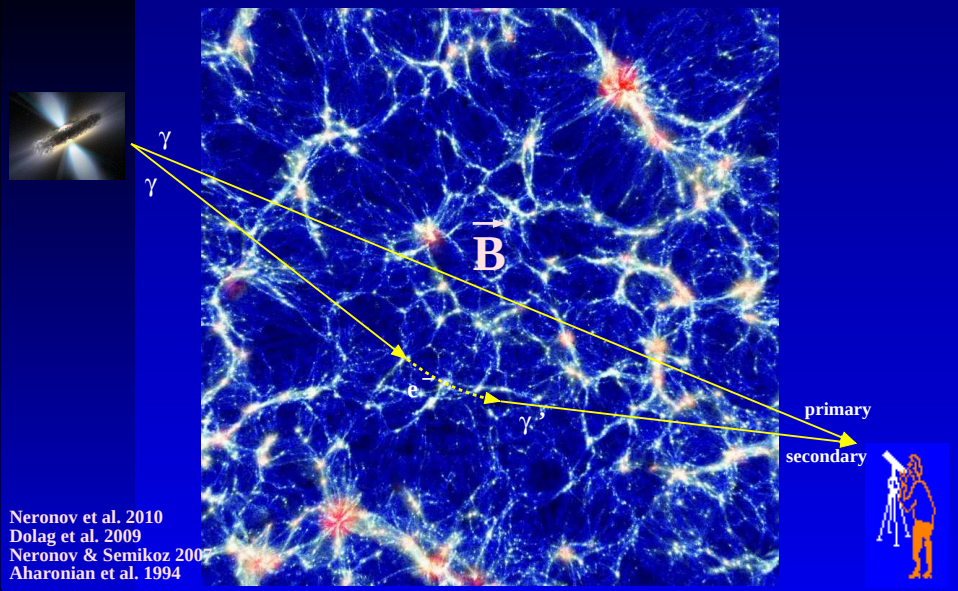
Faraday Rotation (RM) of polarized radio emission



Propagation of ultra high energy cosmic rays (UHECR)

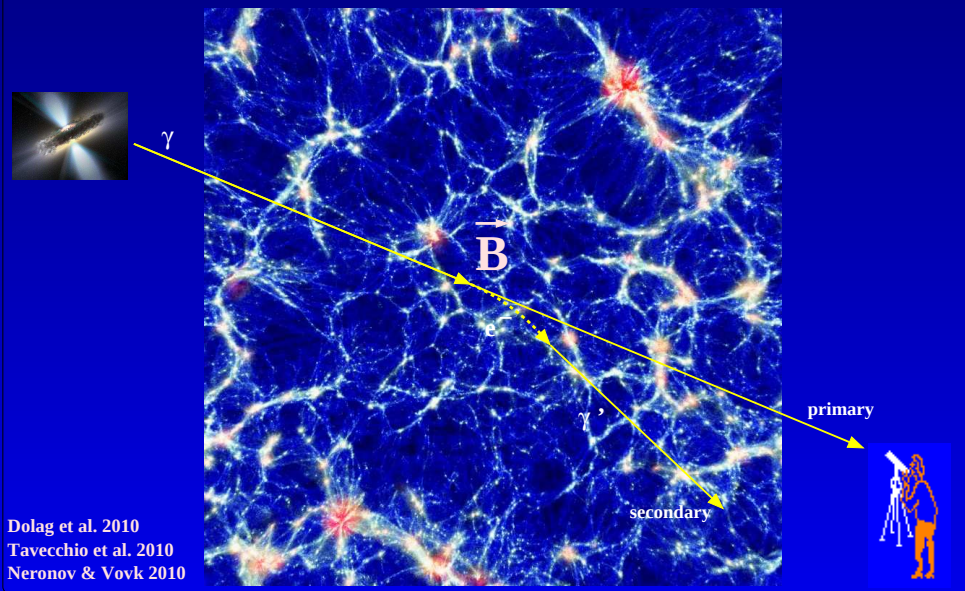


Deflection of electromagnetic cascade of TeV photons



Neronov et al. 2010
Dolag et al. 2009
Neronov & Semikoz 2007
Aharonian et al. 1994

Attenuation from electromagnetic cascade of TeV photons

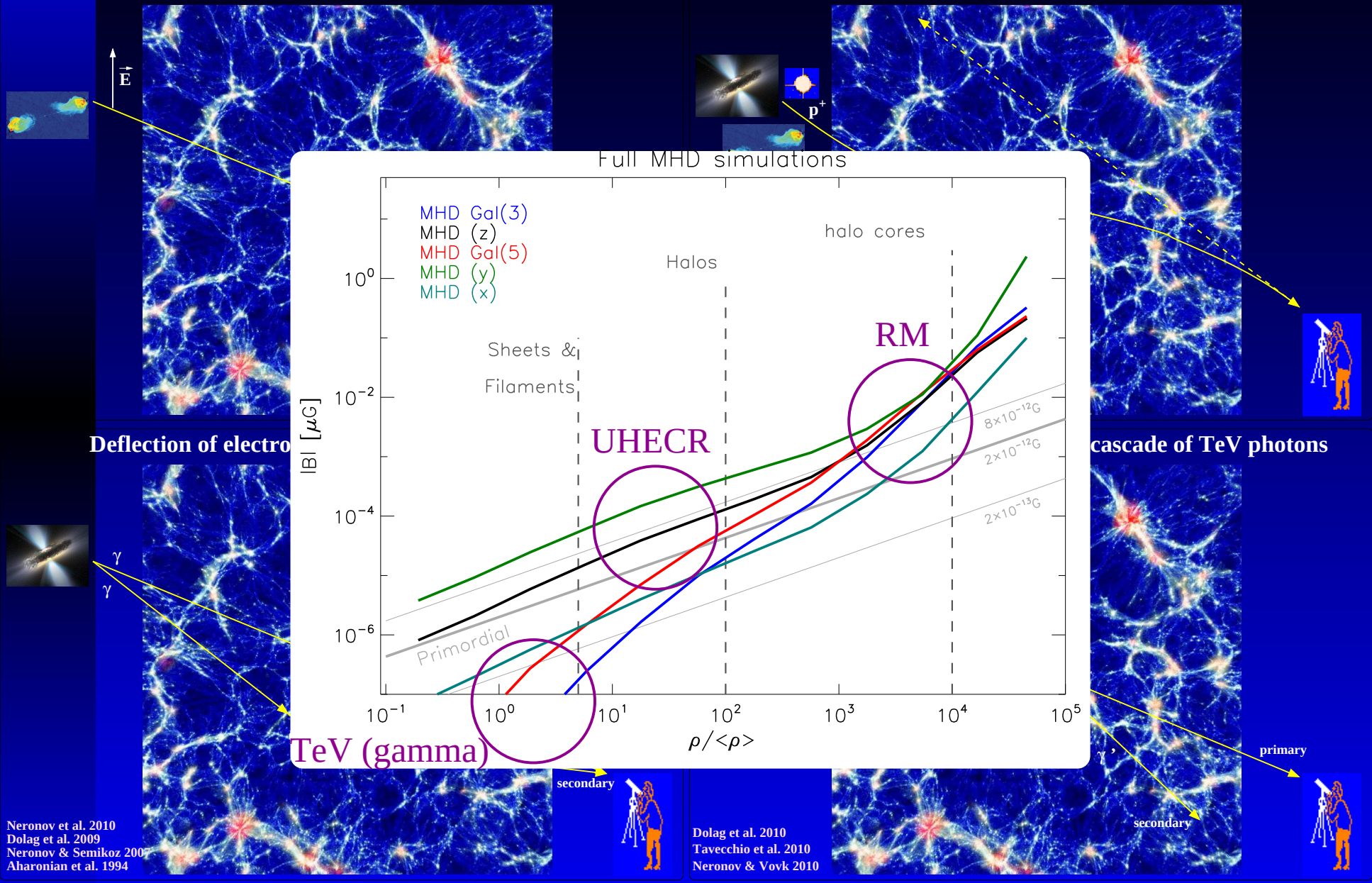


Dolag et al. 2010
Tavecchio et al. 2010
Neronov & Vovk 2010

Cosmic Magnetization Quest

Faraday Rotation (RM) of polarized radio emission

Propagation of ultra high energy cosmic rays (UHECR)



Deflection of electro

cascade of TeV photons

Neronov et al. 2010
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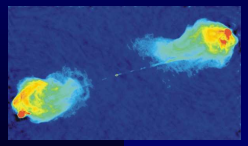
Neronov & Vovk 2010

UHECMessengers open **new** window to Cosmic Magnetism !

Method I: RM statistics (μG)

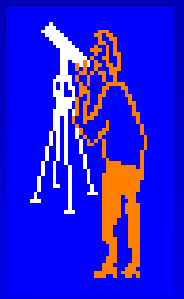
Faraday Rotation (RM) of polarized radio emission



$\vec{E}$

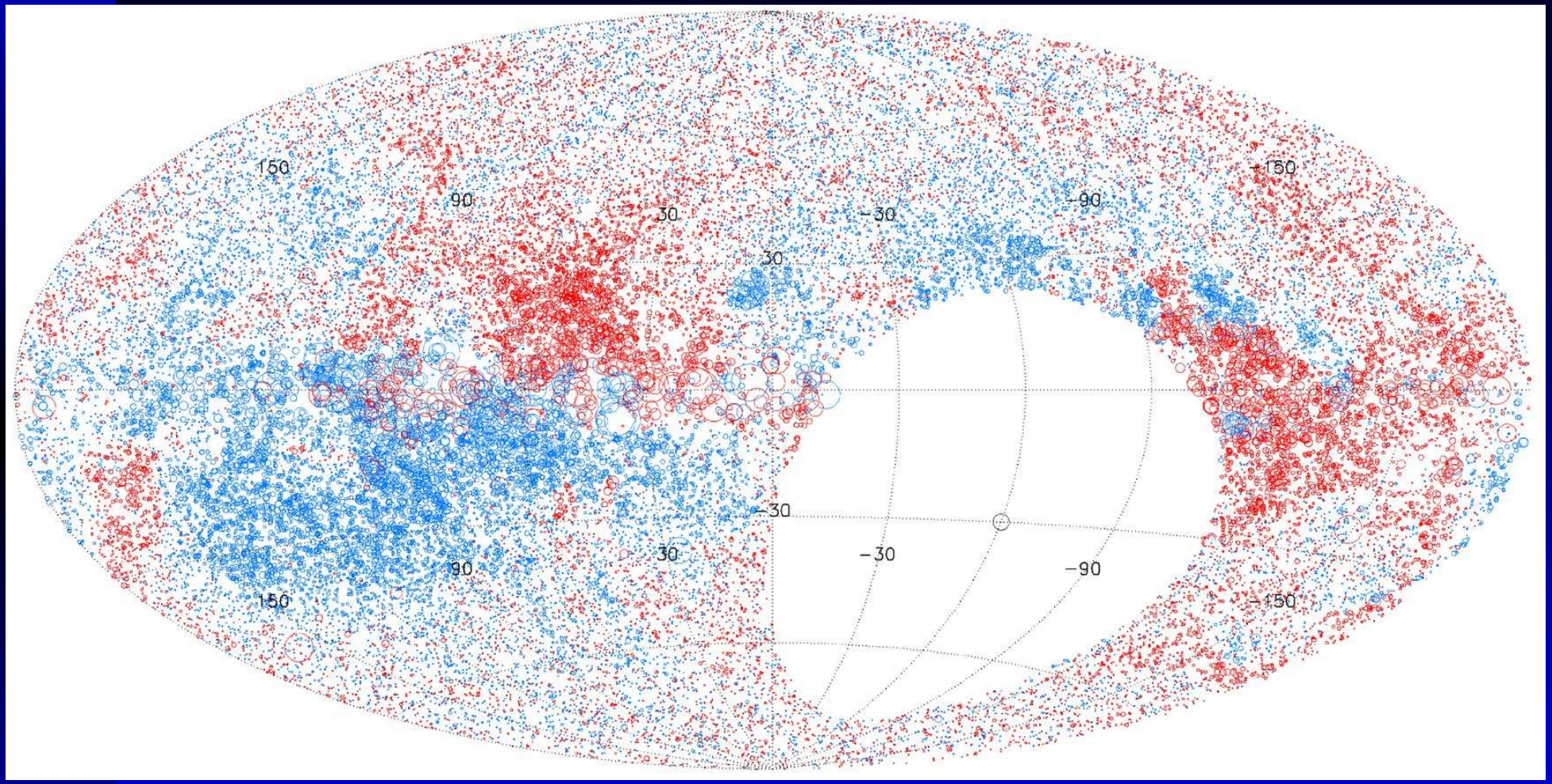
$\vec{B} \cdot \rho$

$\vec{E}(\lambda)$



Method I: RM statistics (μG)

RMs sensitive to $(.1 - 1) \times 10^{-6}$G, statistical methods 10^{-9}G (?)

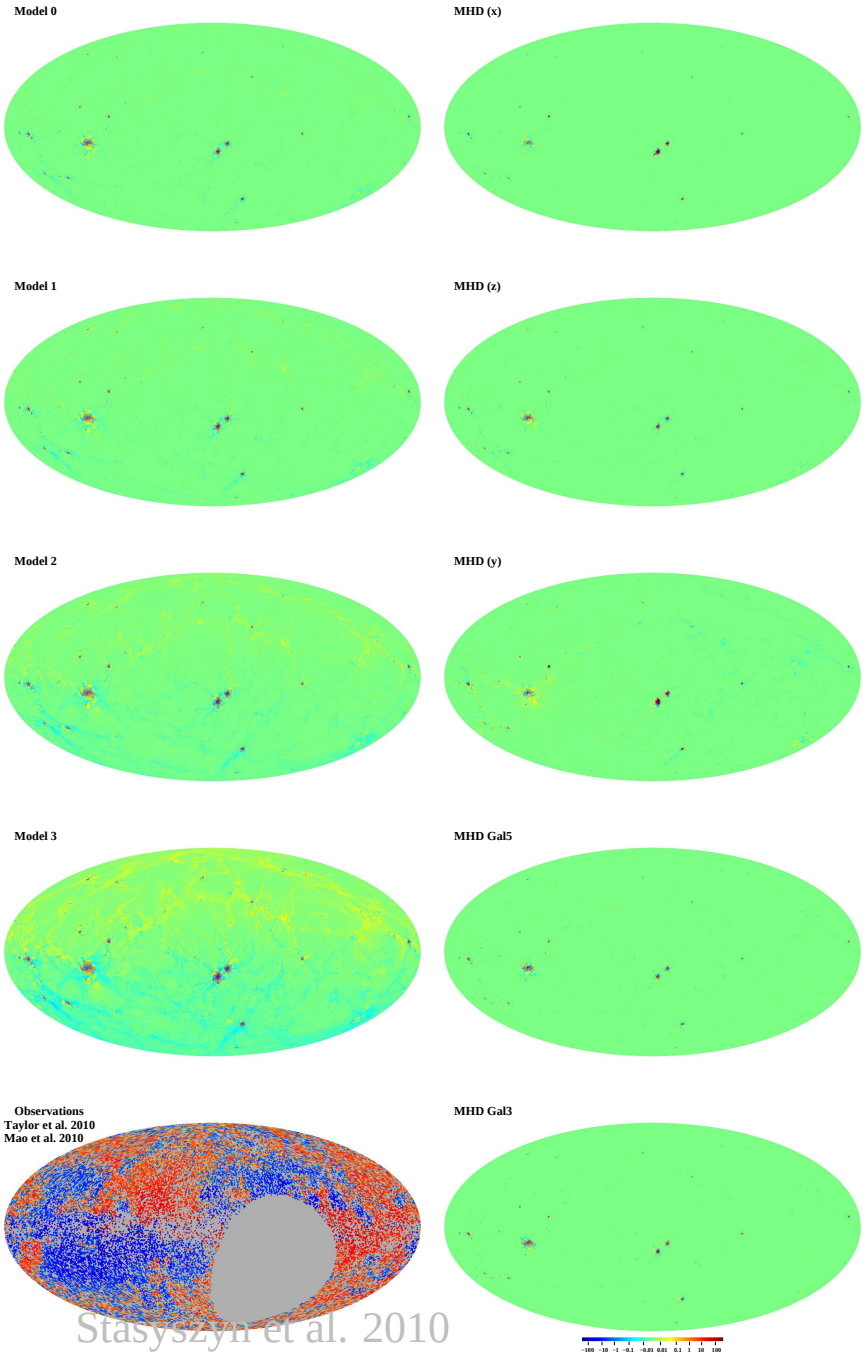


Observed, full sky RM signal (Taylor et al. 2009)

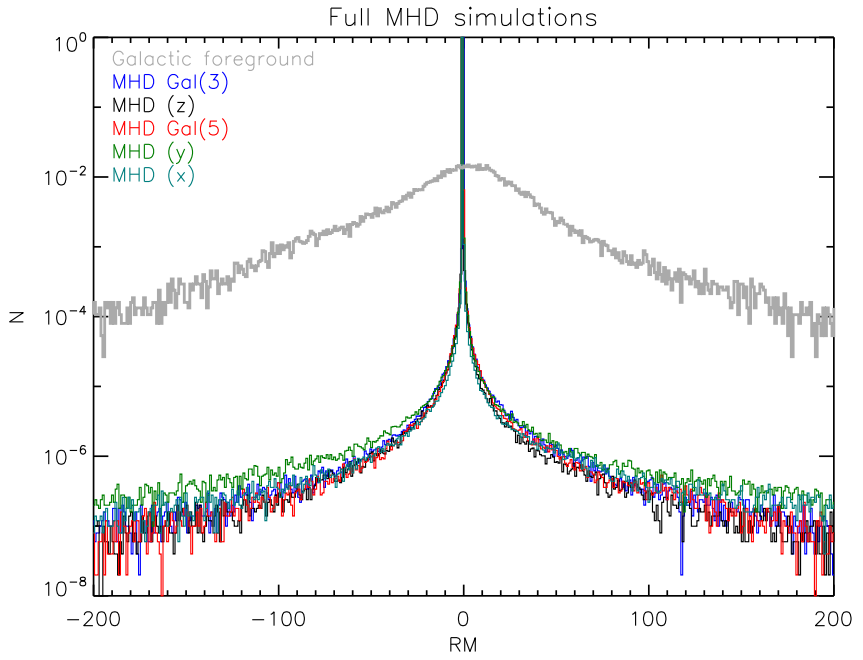
$\Rightarrow B_{cosmic} \approx 30 \times 10^{-9}$G (Lee et al. 2009) **???**.

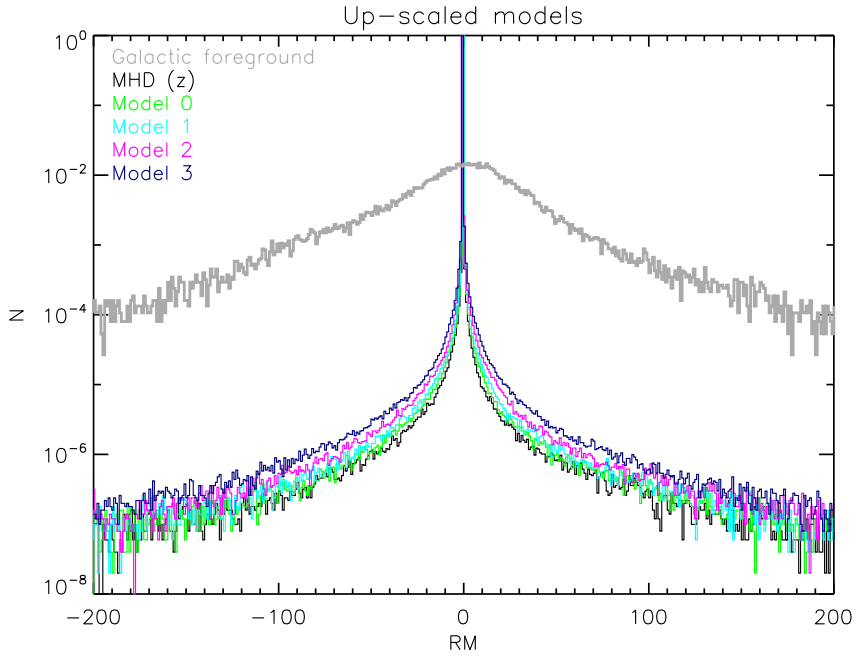
But **Galactic foreground** critical !!!

Method I: RM statistics (μG)

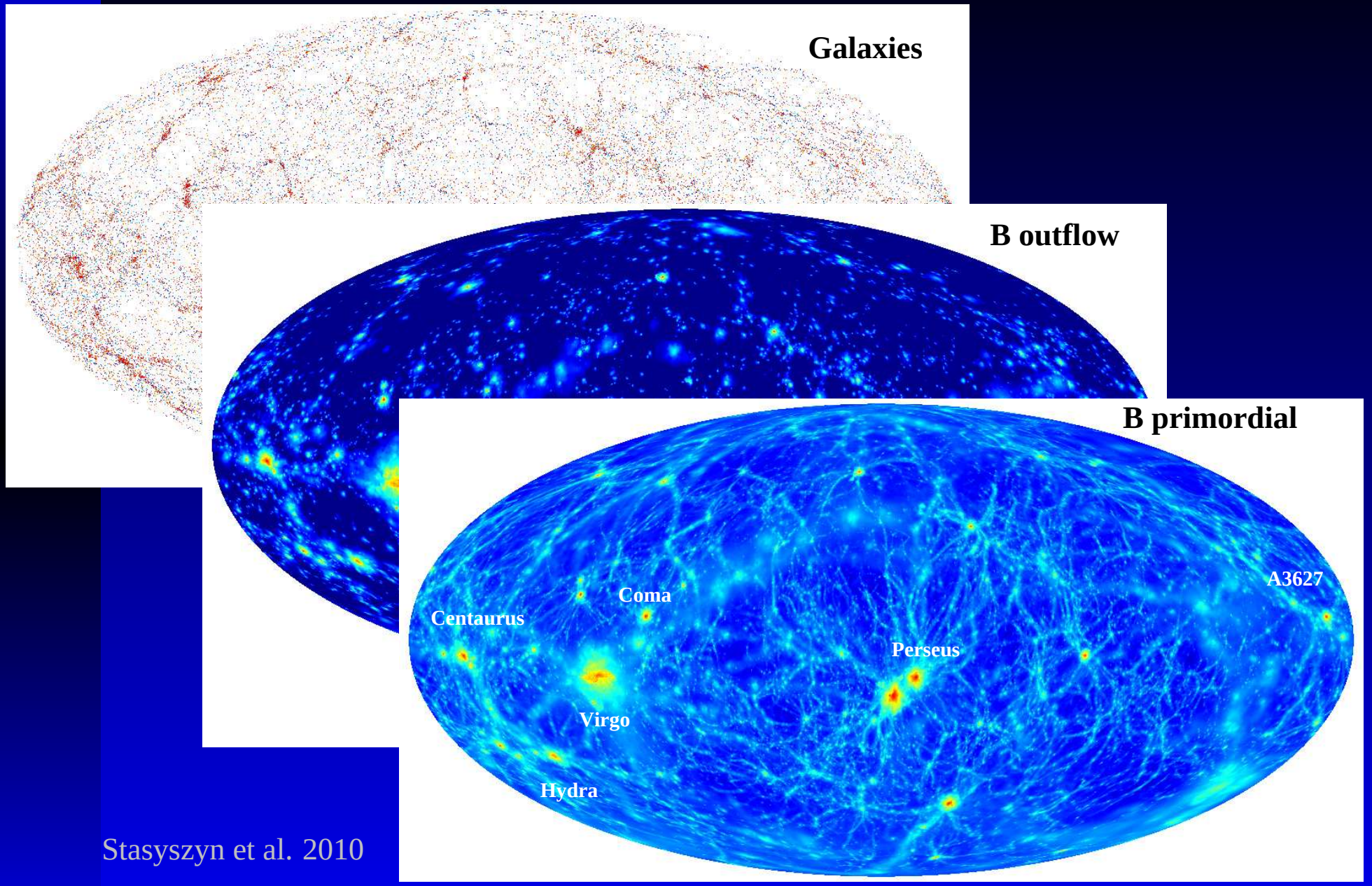


Stasyszyn et al. 2010





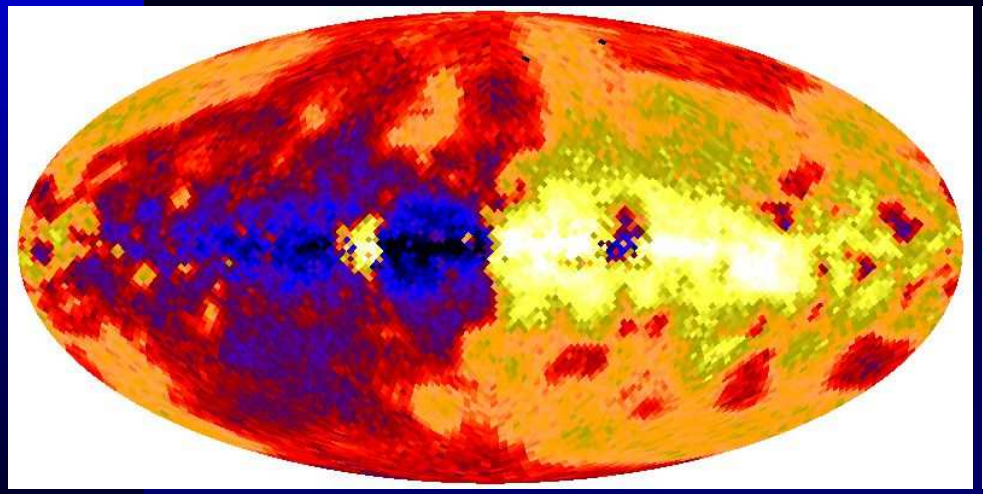
Method I: RM statistics (μG)

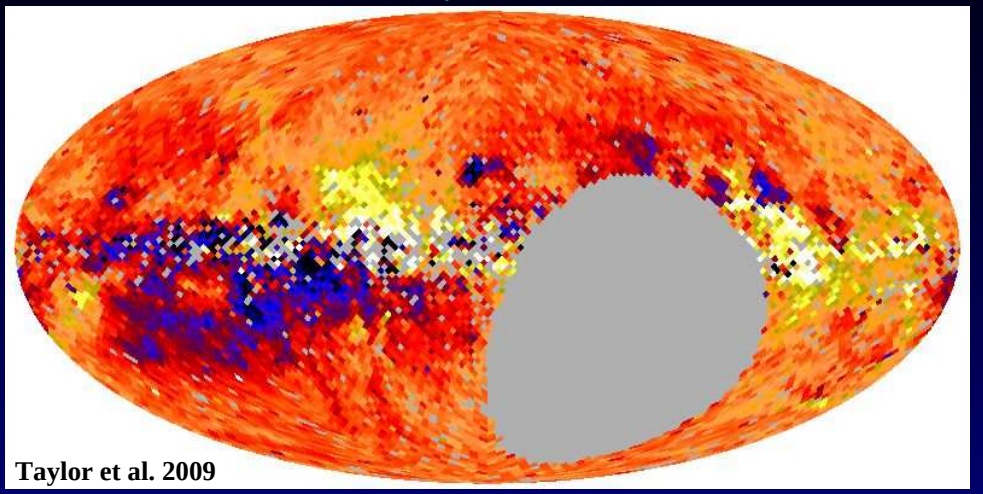


Stasyszyn et al. 2010

Full sky maps for the local universe showing the **magnetic field** and **galaxy distribution**.

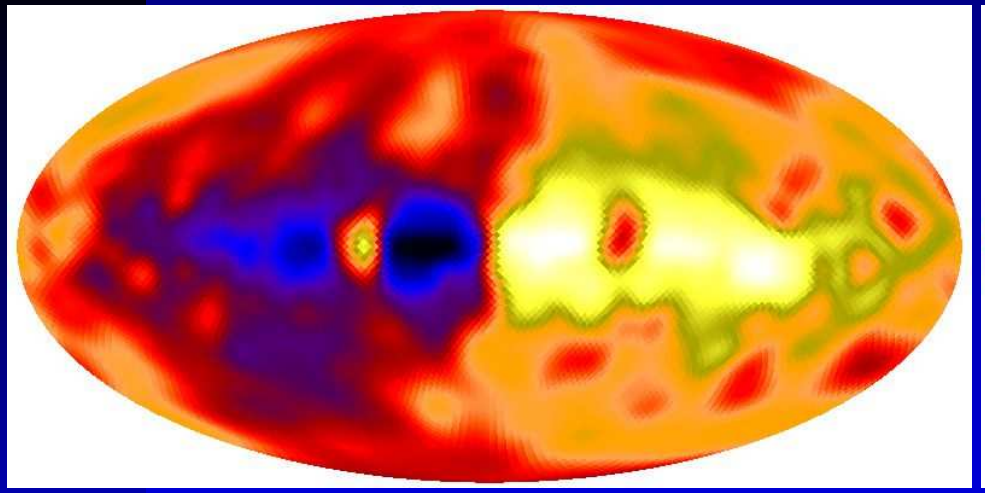
Method I: RM statistics (μG)

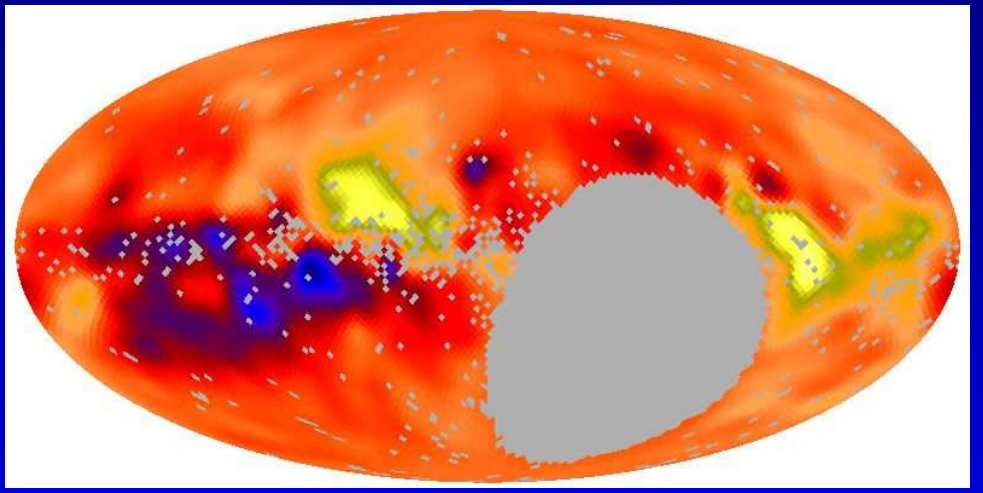




Taylor et al. 2009

Model foreground based on HAMMURABI (Waelkens et al. 2009), cosmic signal and observational noise compared to observations.

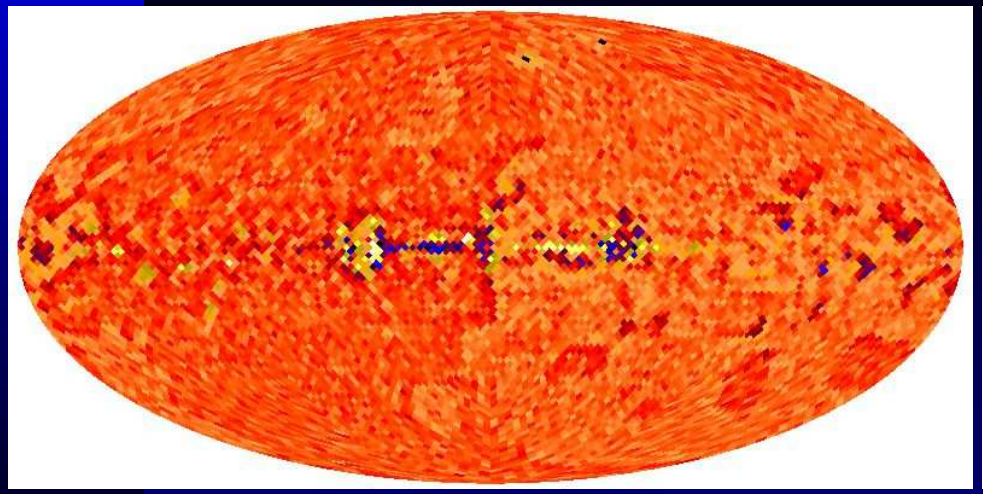


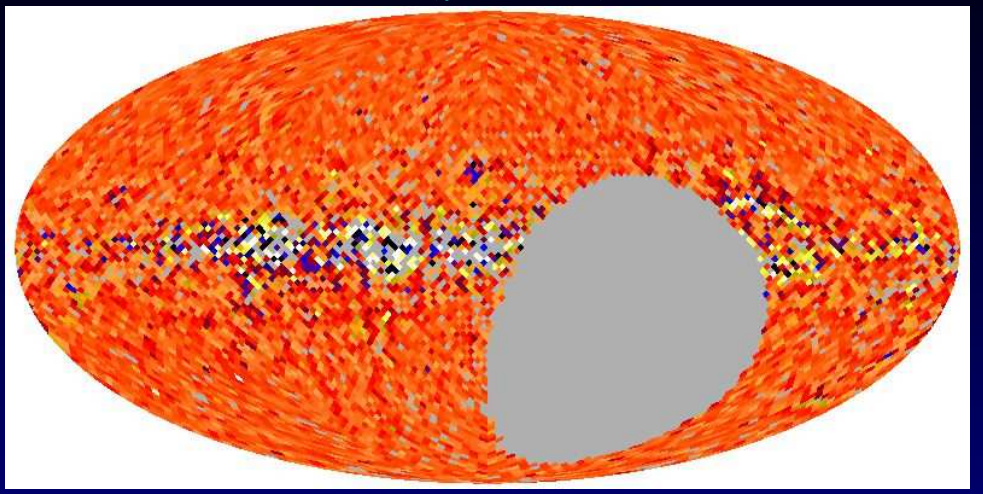


Same but smoothed by 8 degrees.

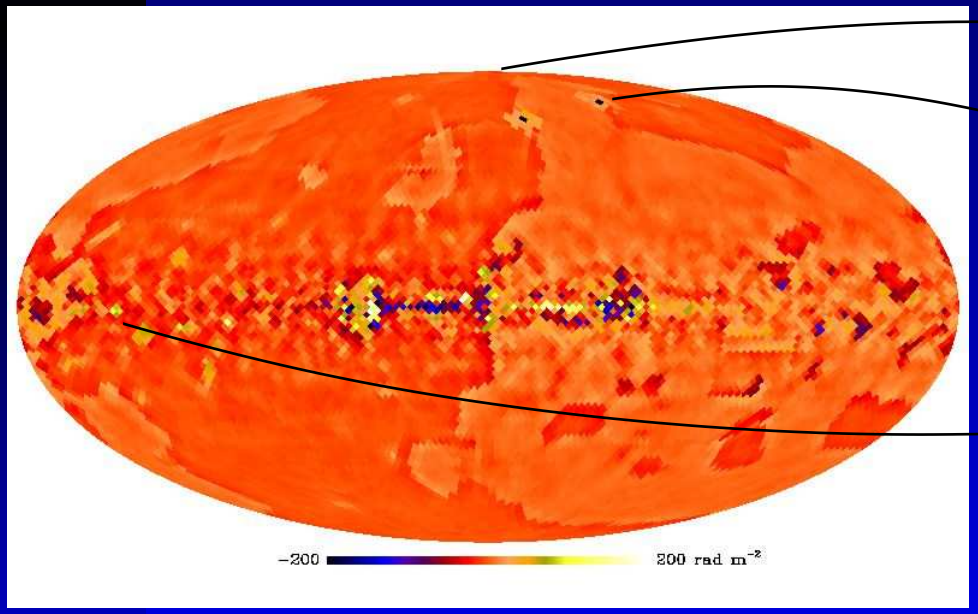
Stasyszyn et al. 2010

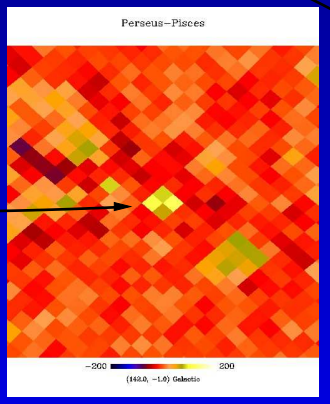
Method I: RM statistics (μG)

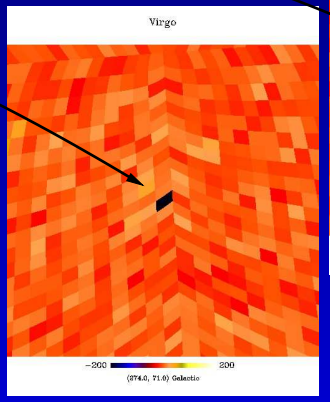


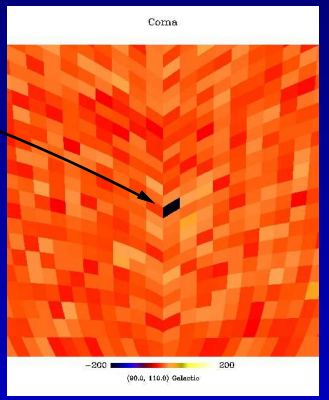


Same as before, but with foreground removal.





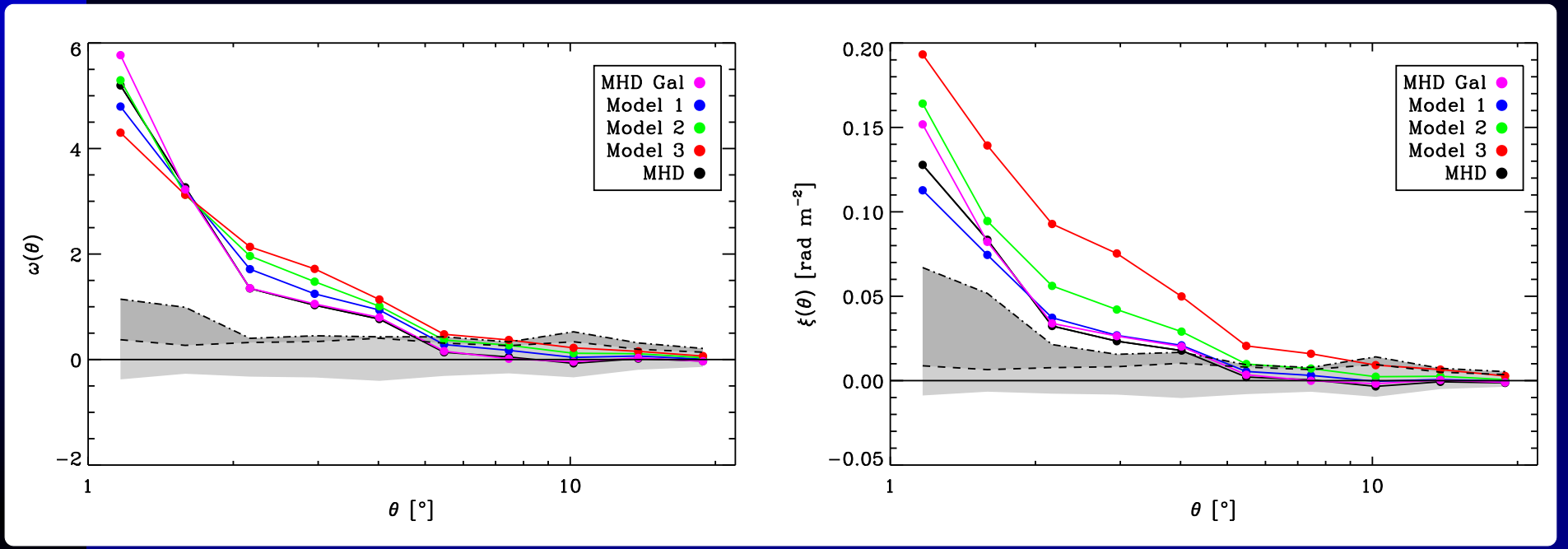




Reduced noise (1 rad$/m^2$) and zoom on several clusters.

Stasyszyn et al. 2010

Method I: RM statistics (μG)



Correlation functions (based on 3072 RMs):

$$\omega_{\rm RM}(\theta) \equiv \frac{\langle \Delta n(\theta) |{\rm RM}| \rangle}{\bar{n}\overline{|{\rm RM}|}},$$

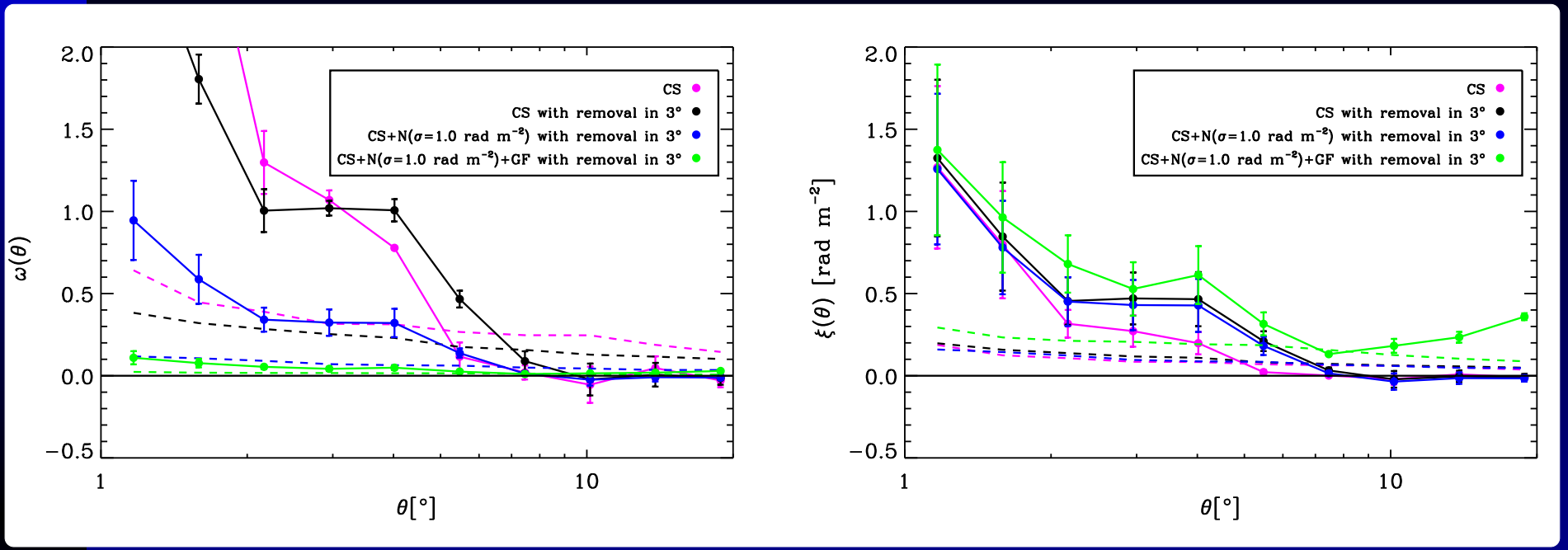
(normalized)

$$\xi_{\rm RM}(\theta) \equiv \frac{\langle \Delta n(\theta) |{\rm RM}| \rangle}{\bar{n}}.$$

(unnormalized).

Stasyszyn et al. 2010

Method I: RM statistics (μG)

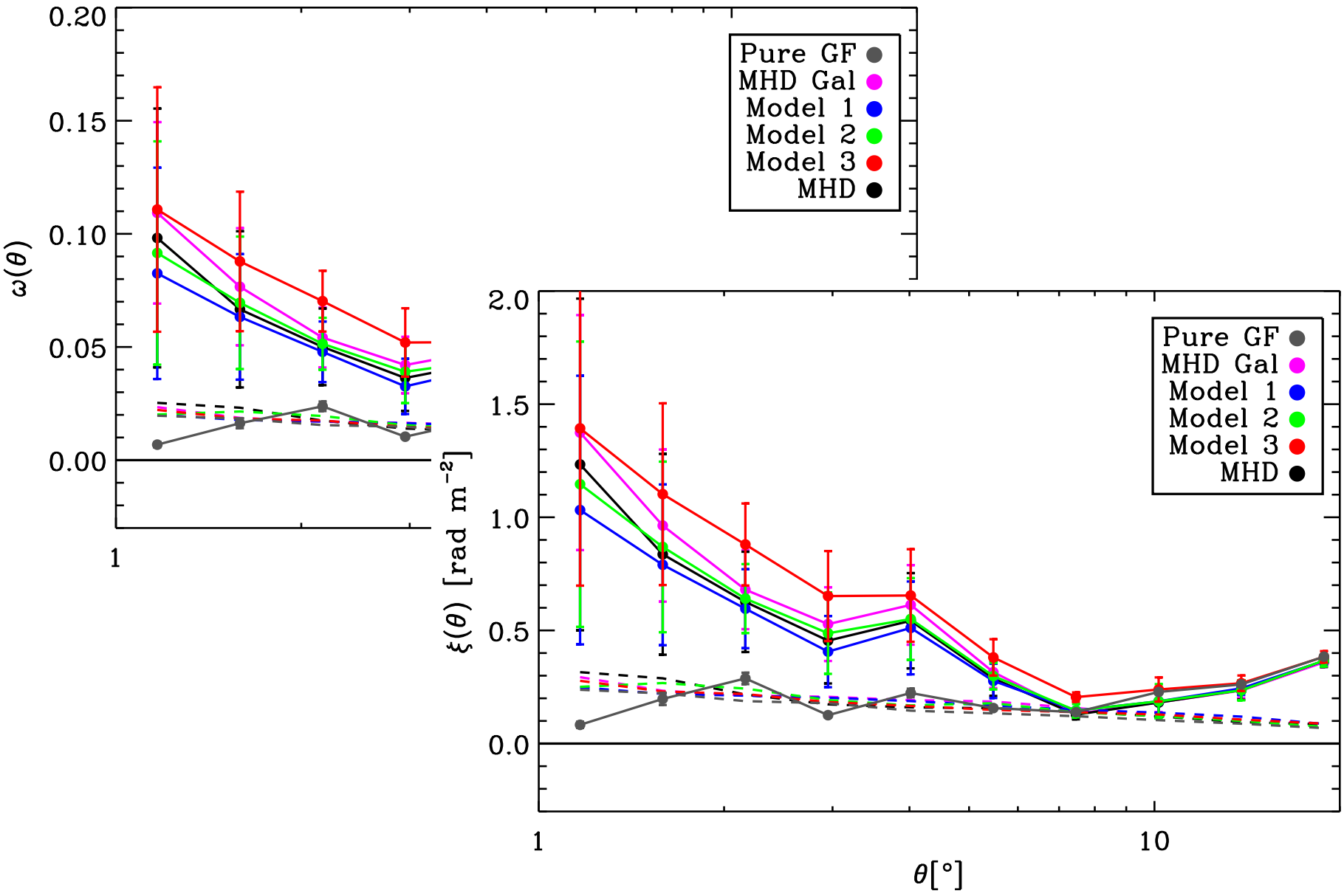


Influence of the different components onto the correlation signal:

- Cosmological signal (CS)
- Including galactic foreground and applying removal
- Adding only noise (1 rad/m^2) to the signal (CS+N)
- All effects together

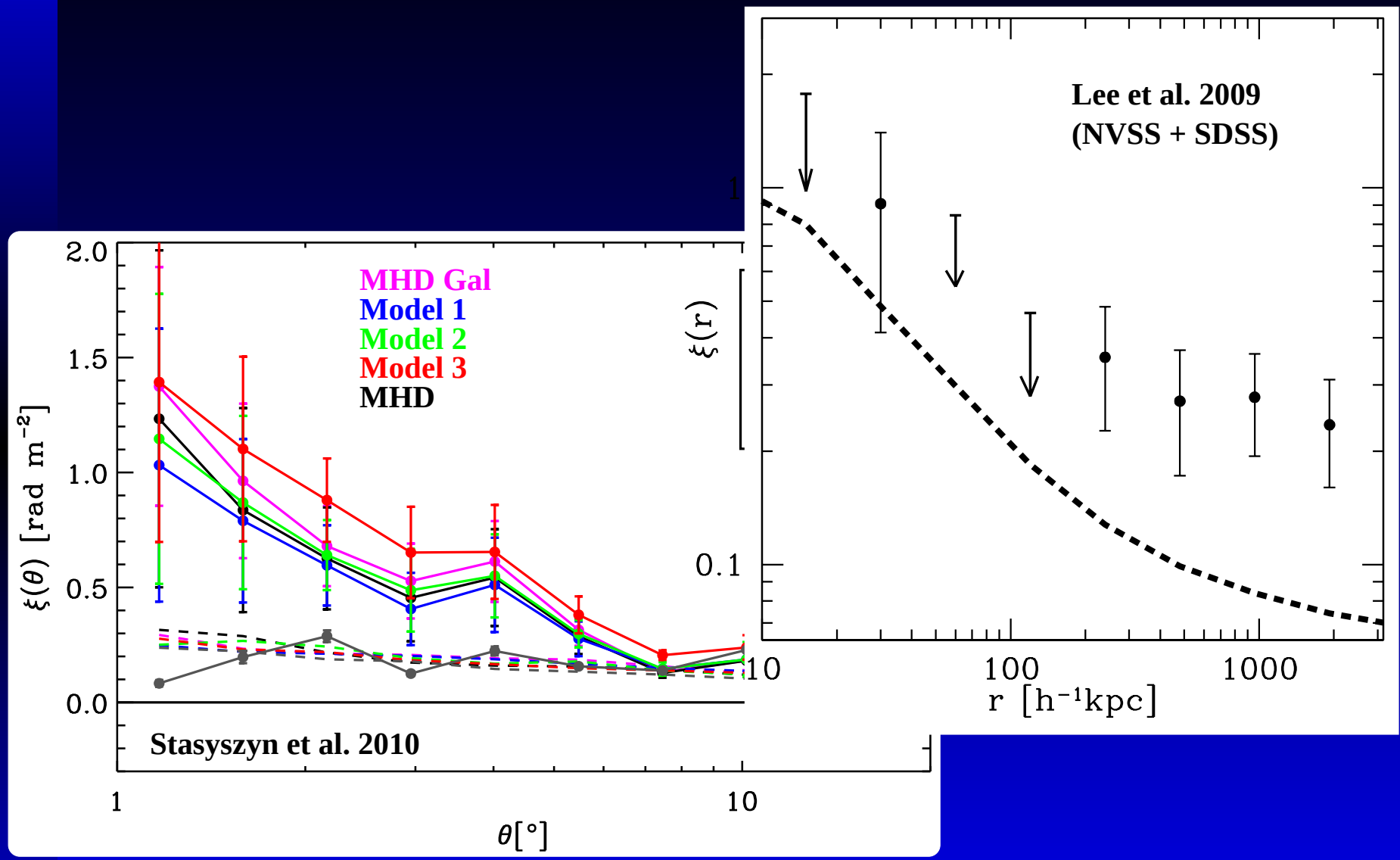
Stasyszyn et al. 2010

Method I: RM statistics (μG)



Correlation signal from different model (Stasyszyn et al. 2010).

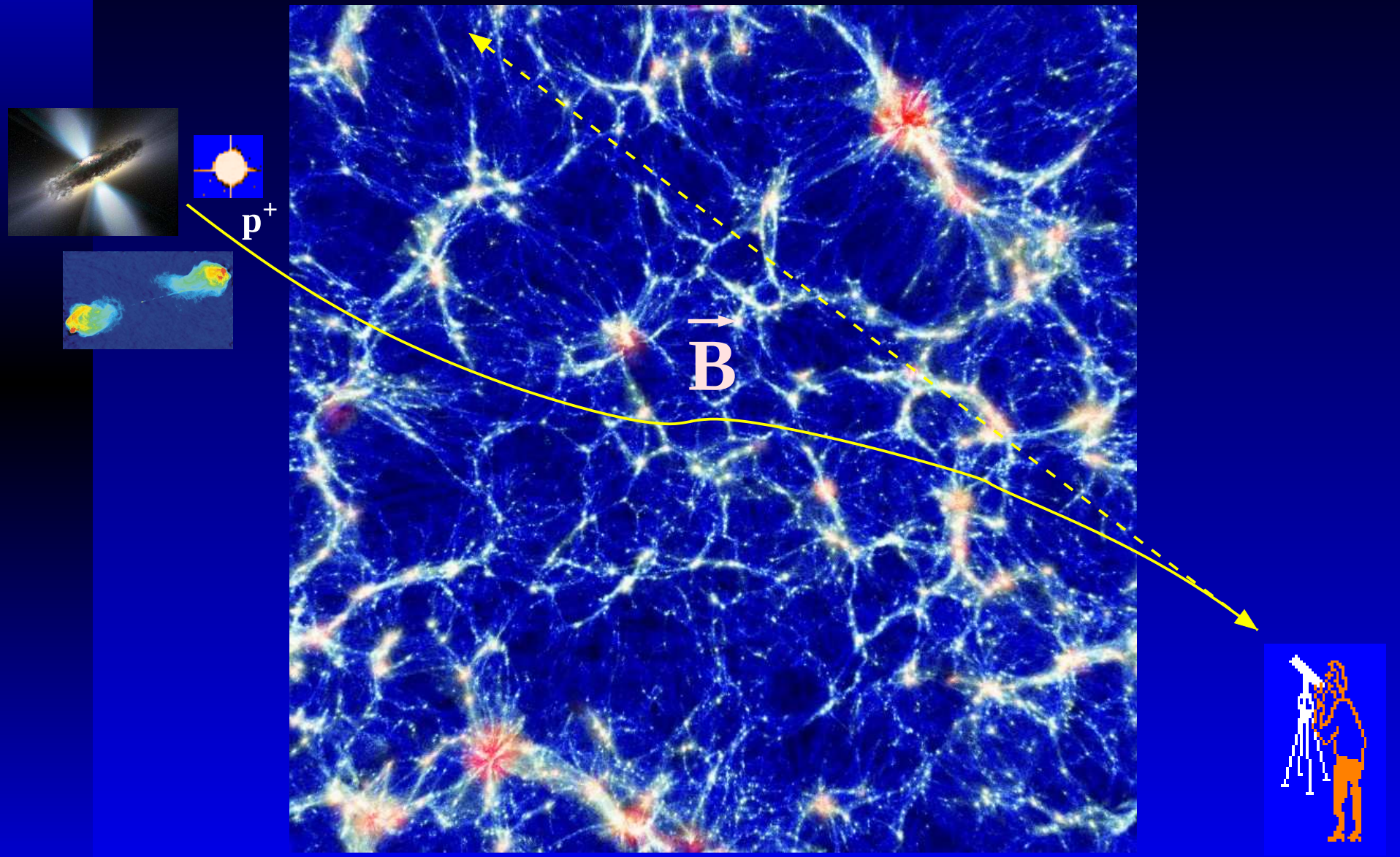
Method I: RM statistics (μG)



Correlation signal predicted by simulations, but the amplitude is driven by the foreground and observational noise !

Method II: UHECR defl. (nG)

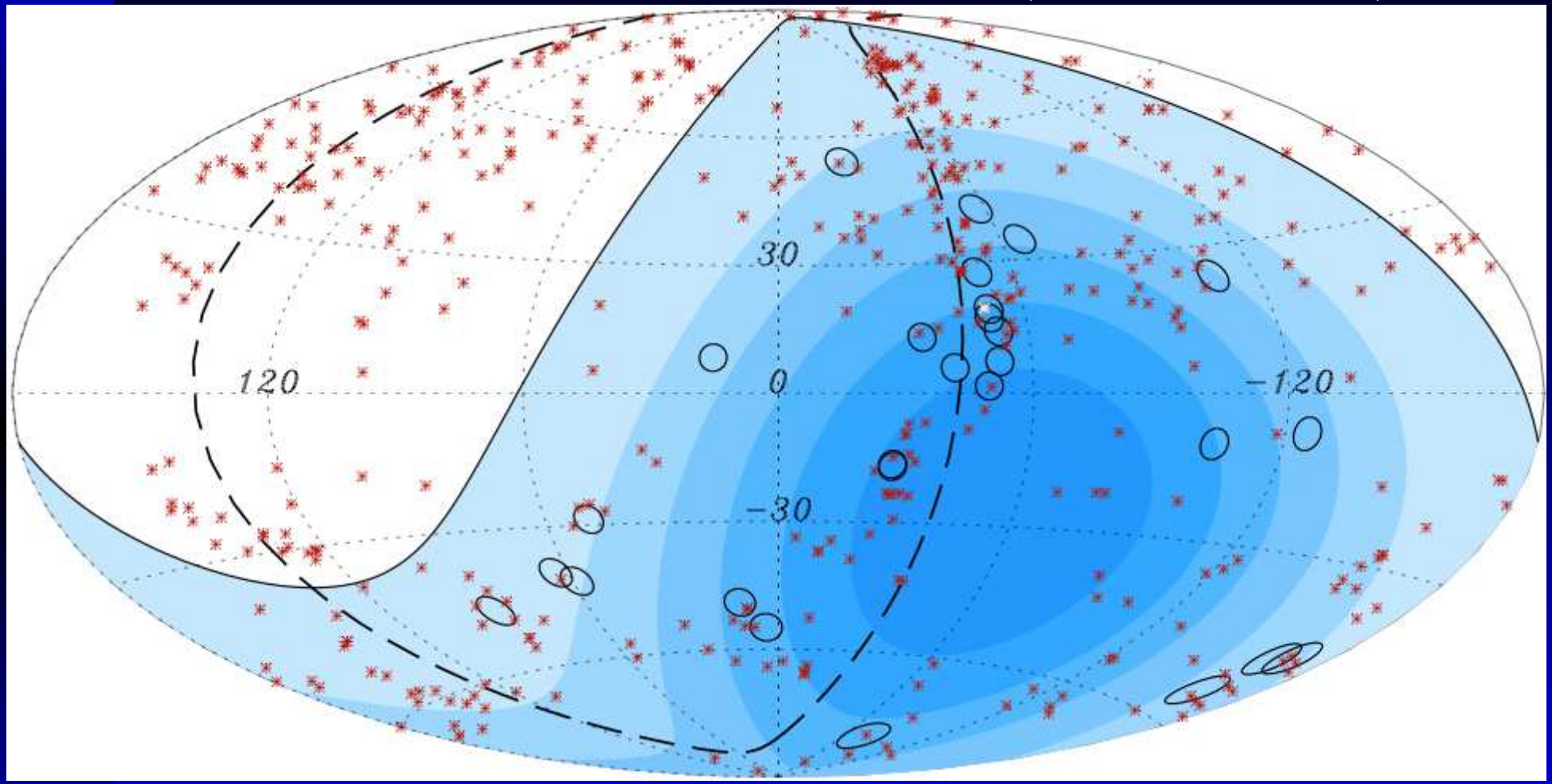
Propagation of ultra high energy cosmic rays (UHECR)



Cooling: photo-pion production in collisions with CMB
Secondary particles: ν from pion decay

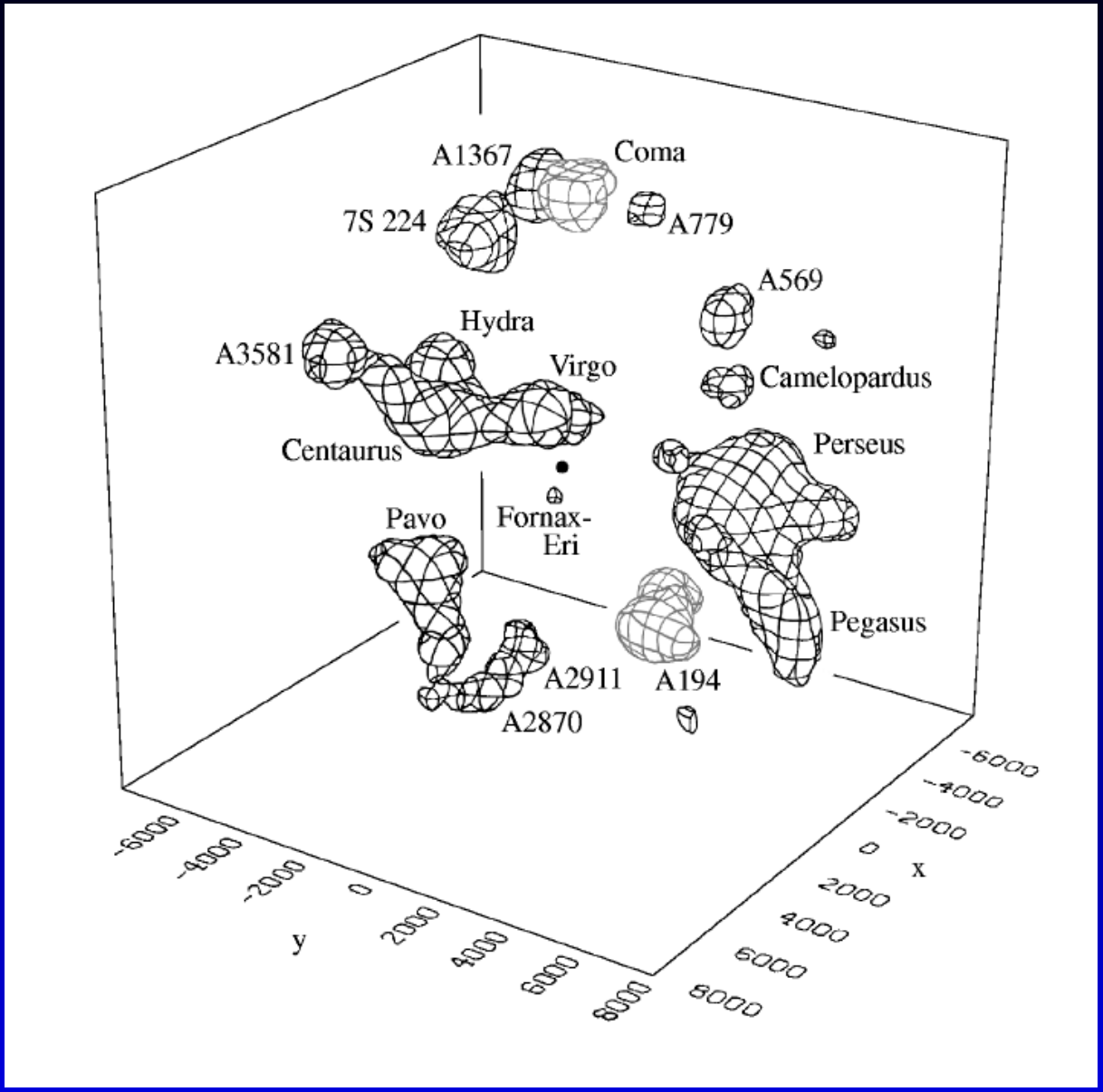
Method II: UHECR defl. (nG)

Propagation of CRp, sensitive to $(10^{-9} - 10^{-12})$G



Pierre Auger Observatory provides evidence for anisotropy in the arrival directions of the Cosmic Rays with the highest energies, which are correlated with the positions of relatively nearby active galactic nuclei (AGNs). **But still under discussion !**

Method II: UHECR defl. (nG)

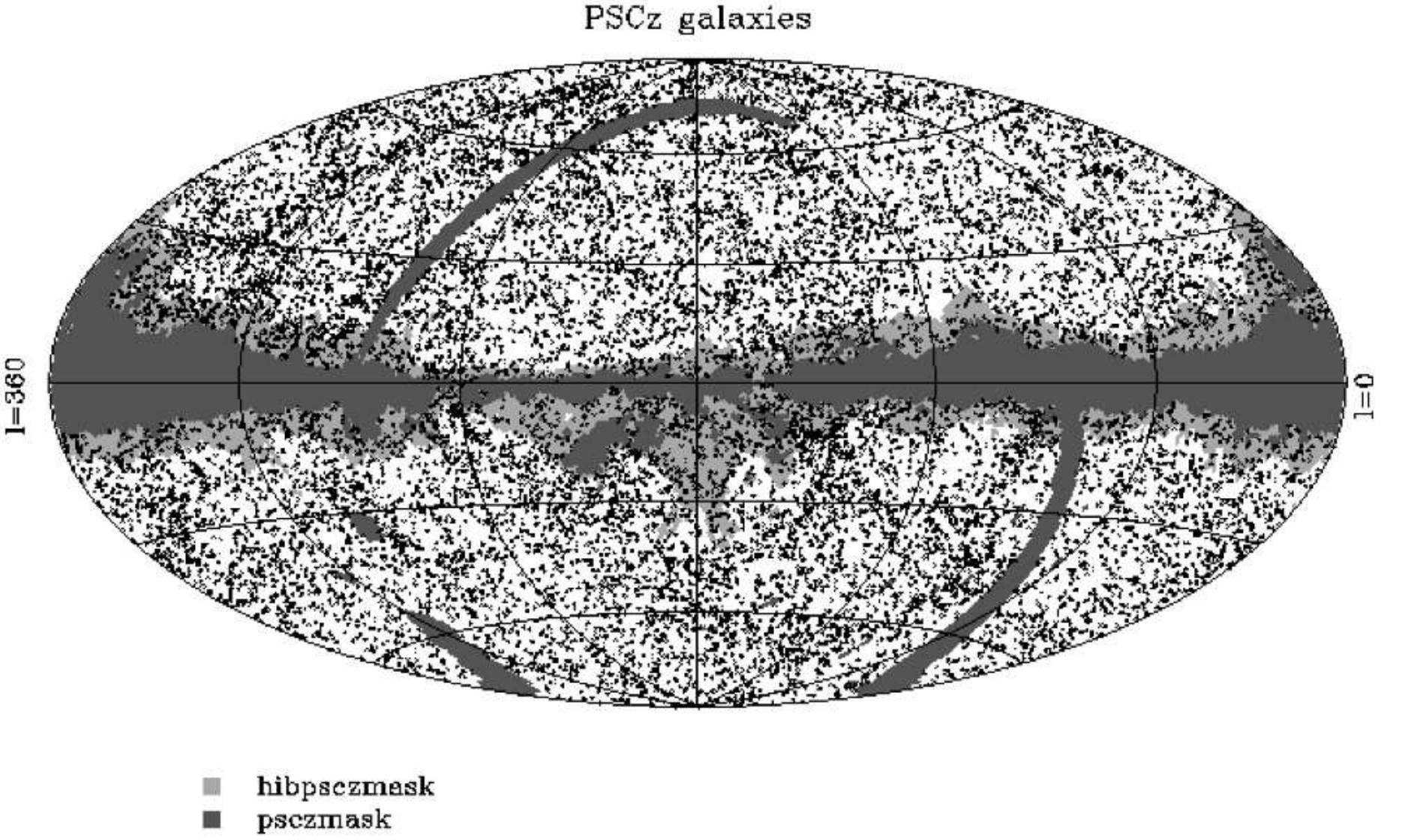


Hudson 1993

Magnetic Field structure in **Local Universe** ?

Charged particle astronomy possible ?

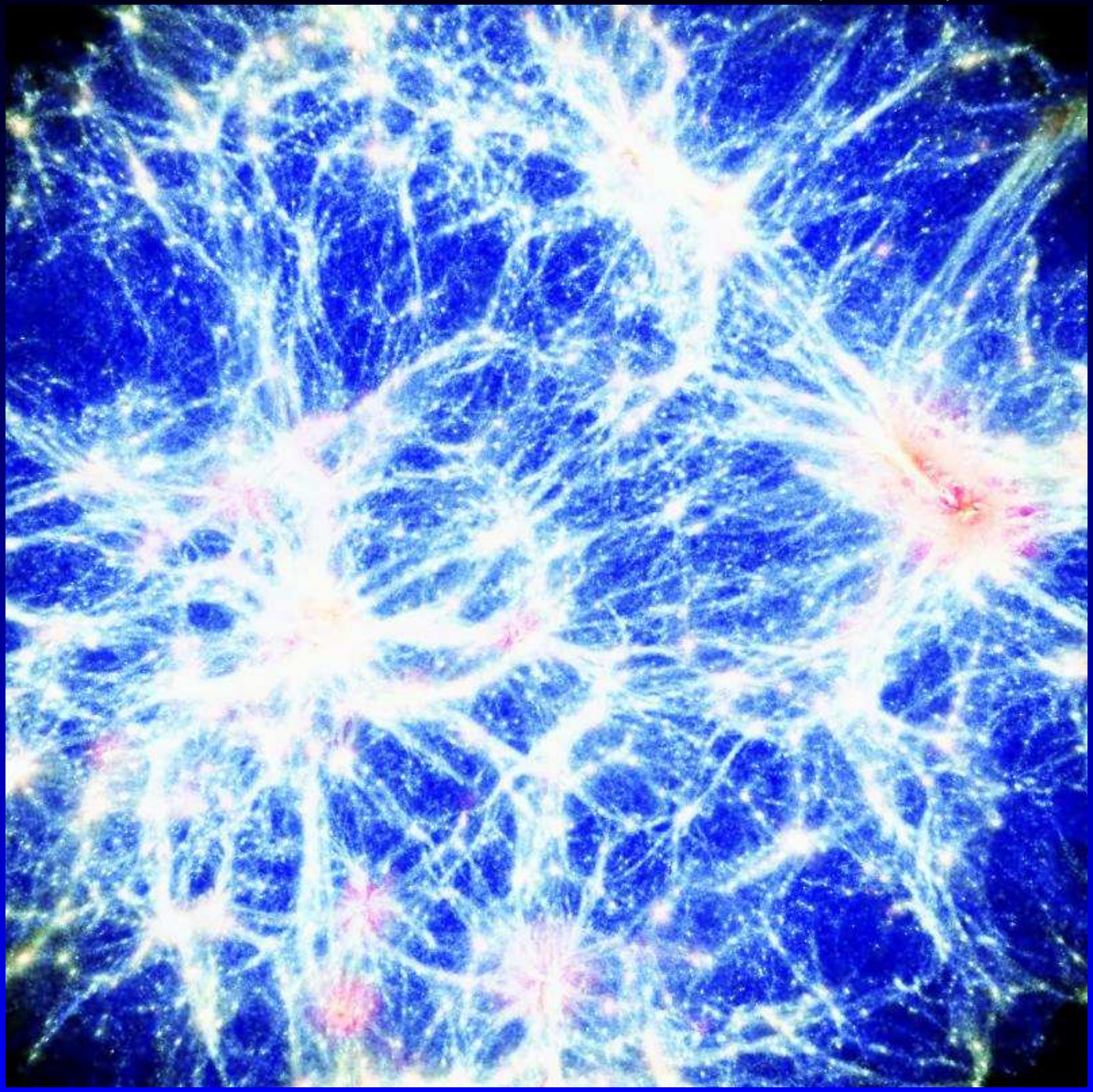
Method II: UHECR defl. (nG)



Saunders et al. 2000

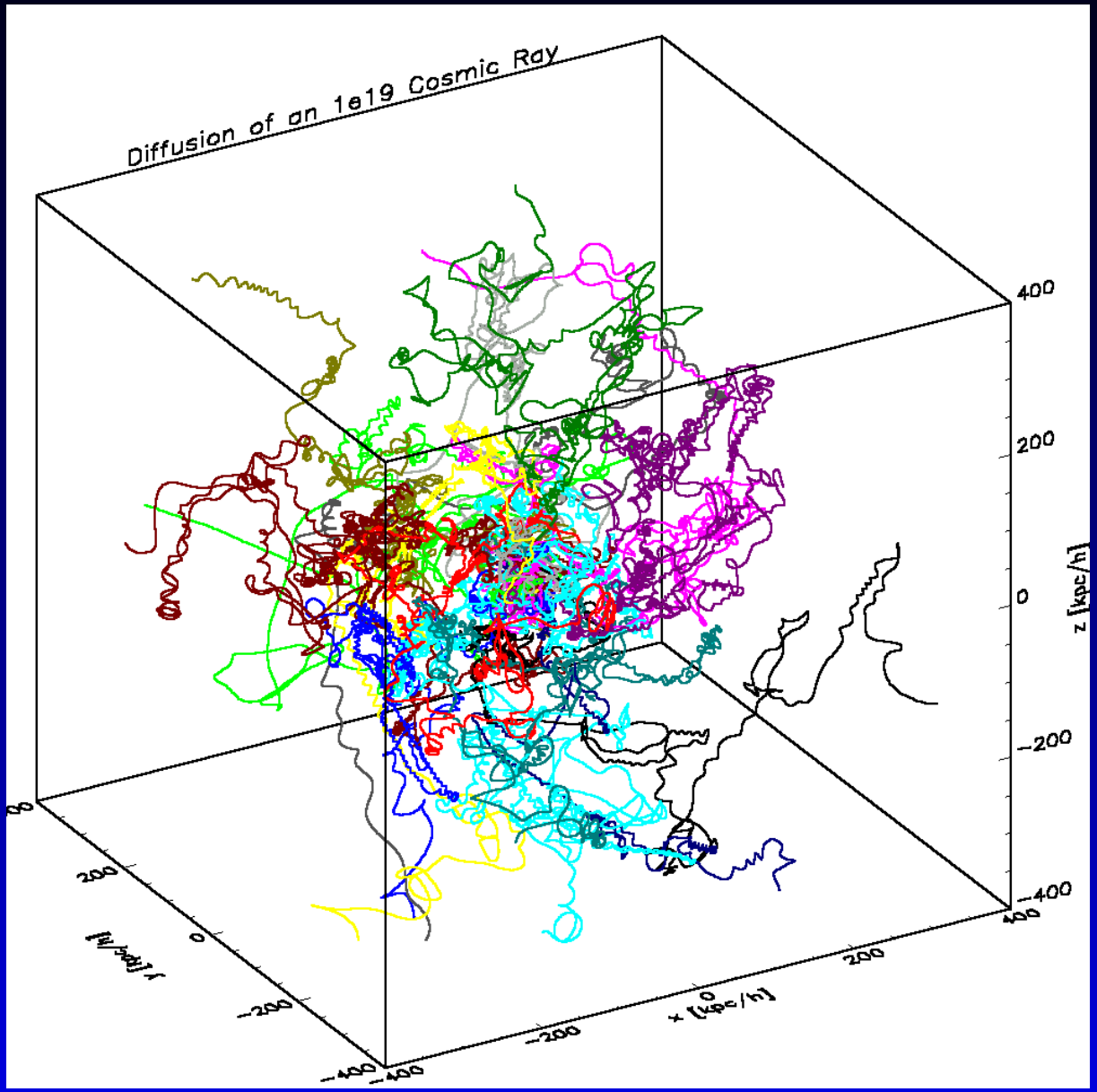
15000 IRAS Galaxies

Method II: UHECR defl. (nG)



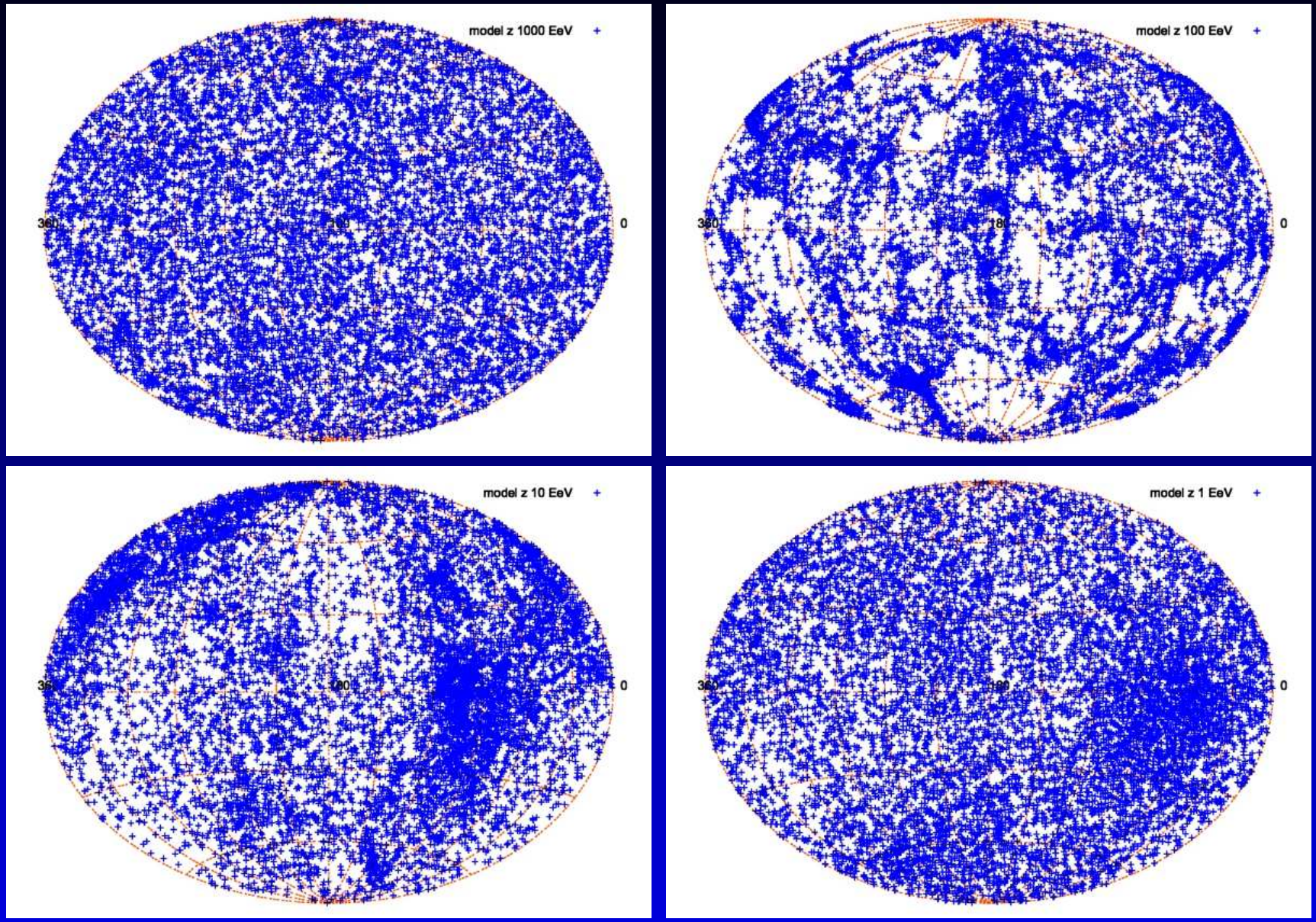
Run movie

Method II: UHECR defl. (nG)



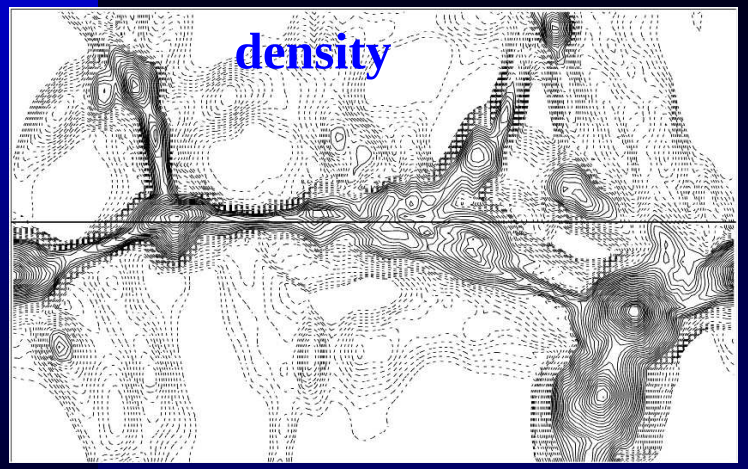
Trajectories of Cosmic Rays diffusing through the cluster core (Rordorf, Grasso & Dolag 2004) $\Rightarrow$ **whole cluster looks like the source !**

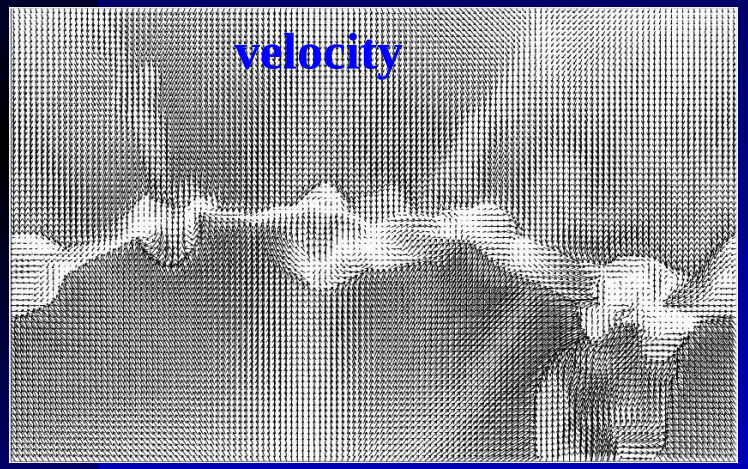
Method II: UHECR defl. (nG)

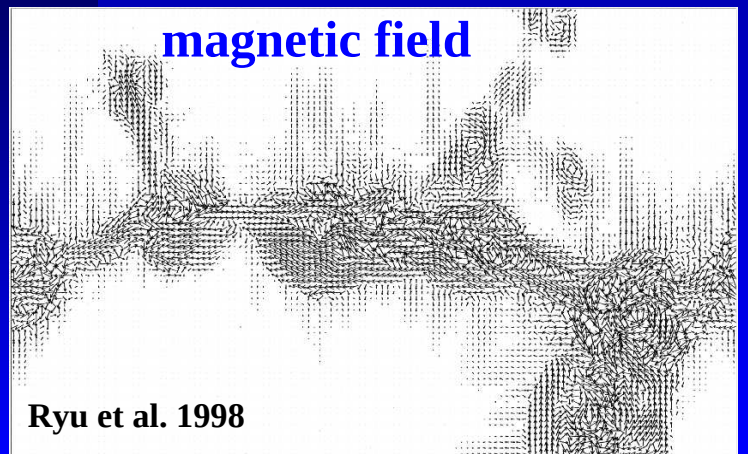


Sky maps of UHECRs emitted uniformly from M87 with 1000 (upper right), 100, 10 and 1 EeV (lower left)
(Dolag, Kachelriess, Semikoz 2008)

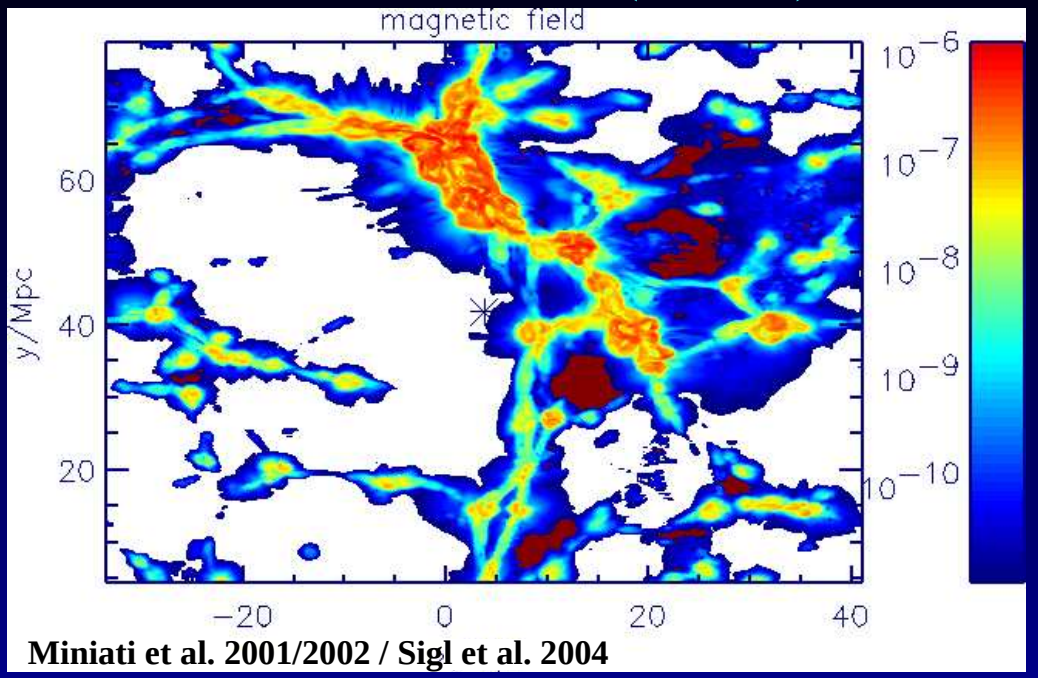
Method II: UHECR defl. (nG)



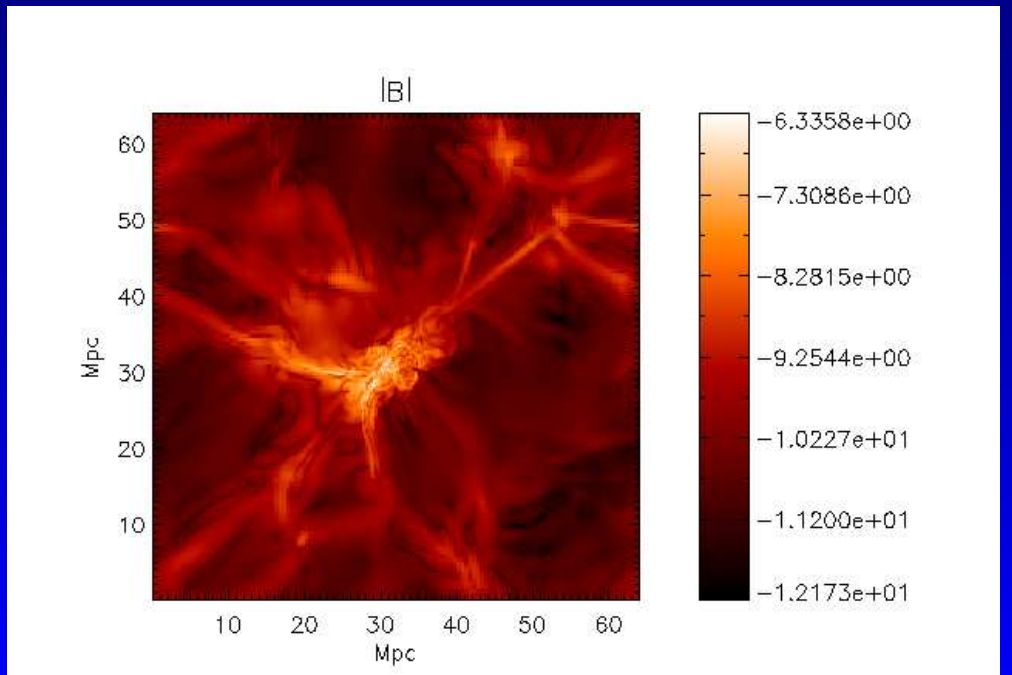




Ryu et al. 1998

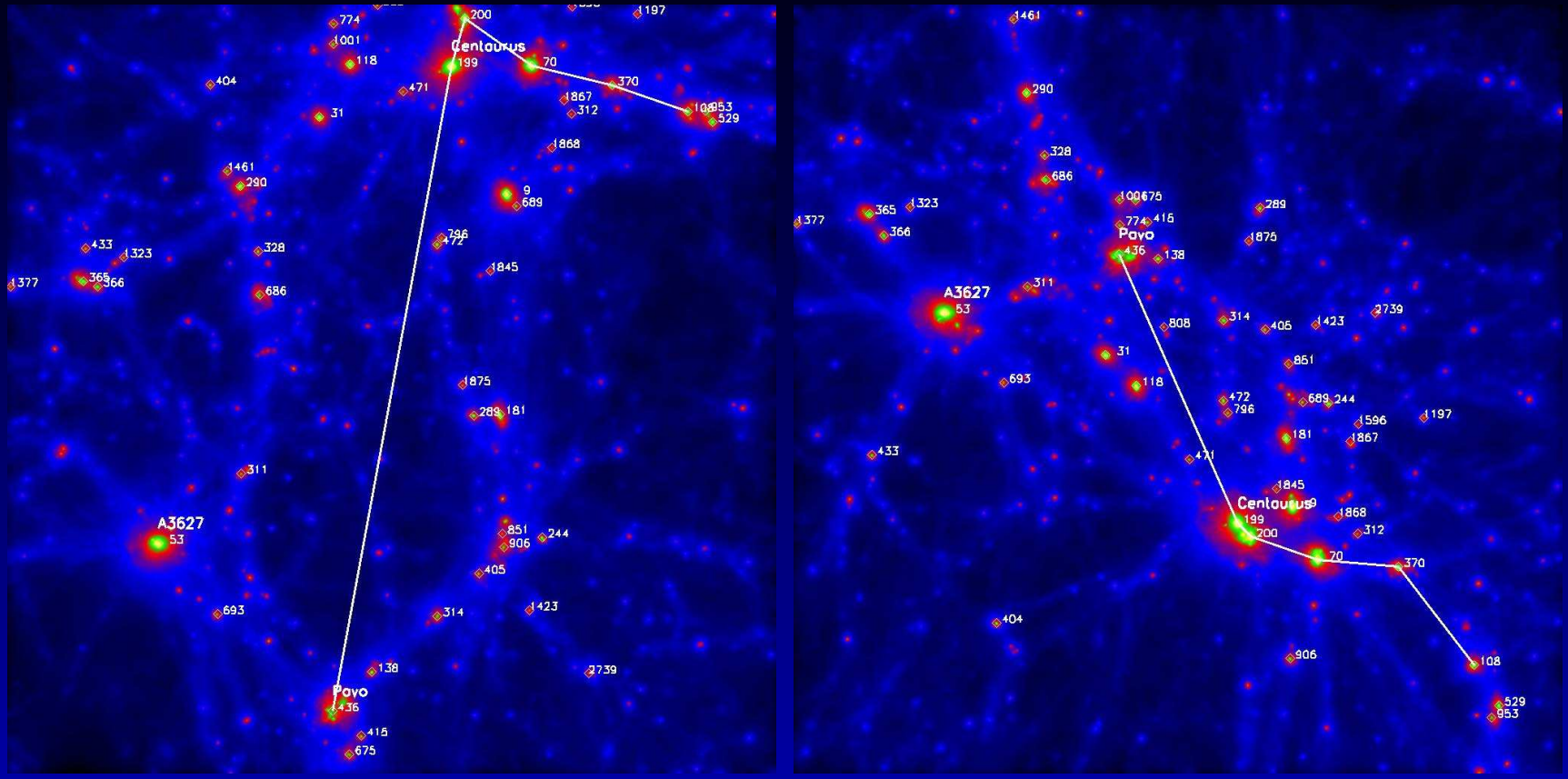


Miniati et al. 2001/2002 / Sigl et al. 2004



Brueggen et al. 2005

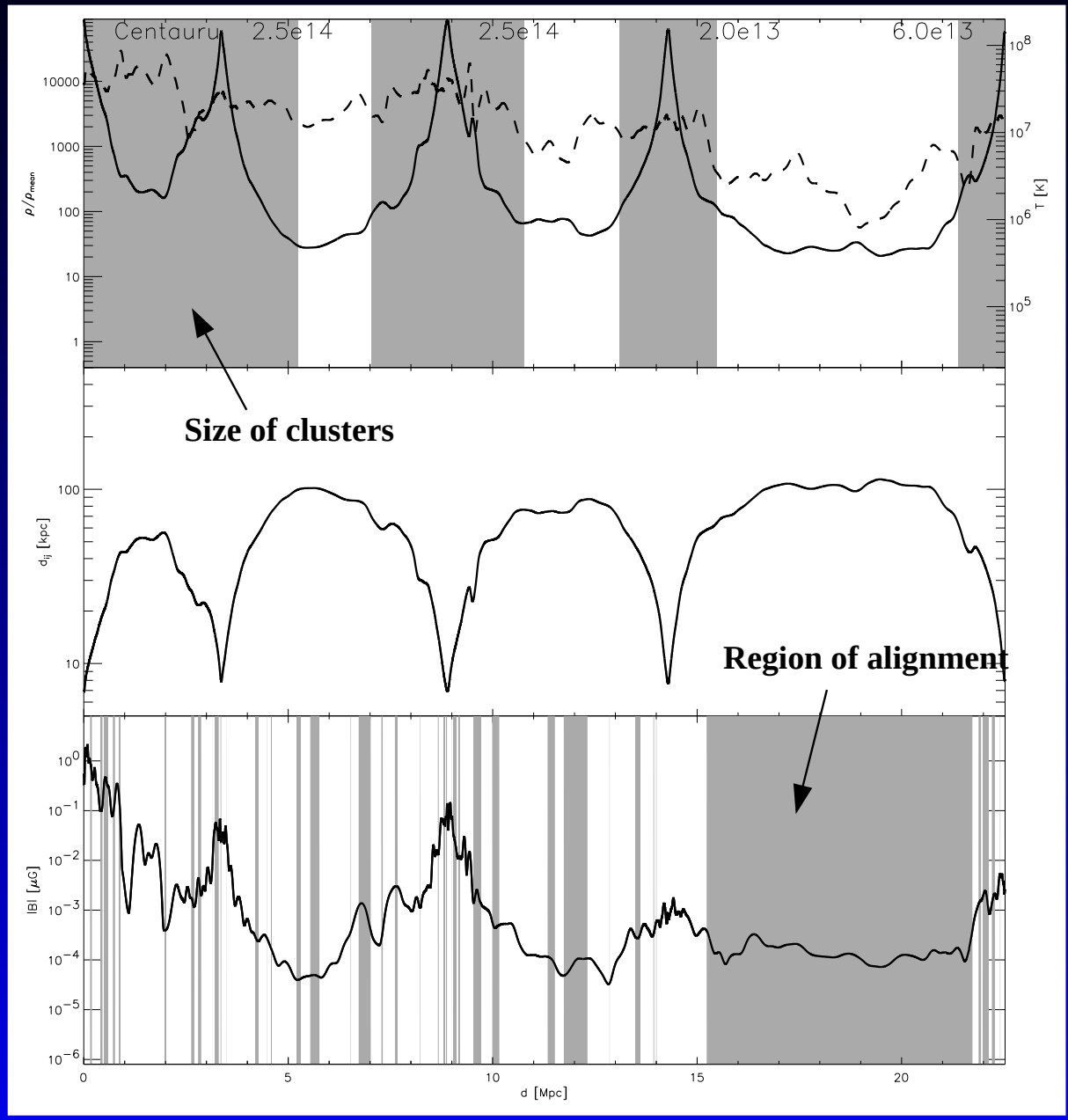
Method II: UHECR defl. (nG)



Region shown is $(50\ \mathrm{Mpc})^3$ centered between **Centaurus** and Pavo. Filaments and bridges between clusters, but be careful:

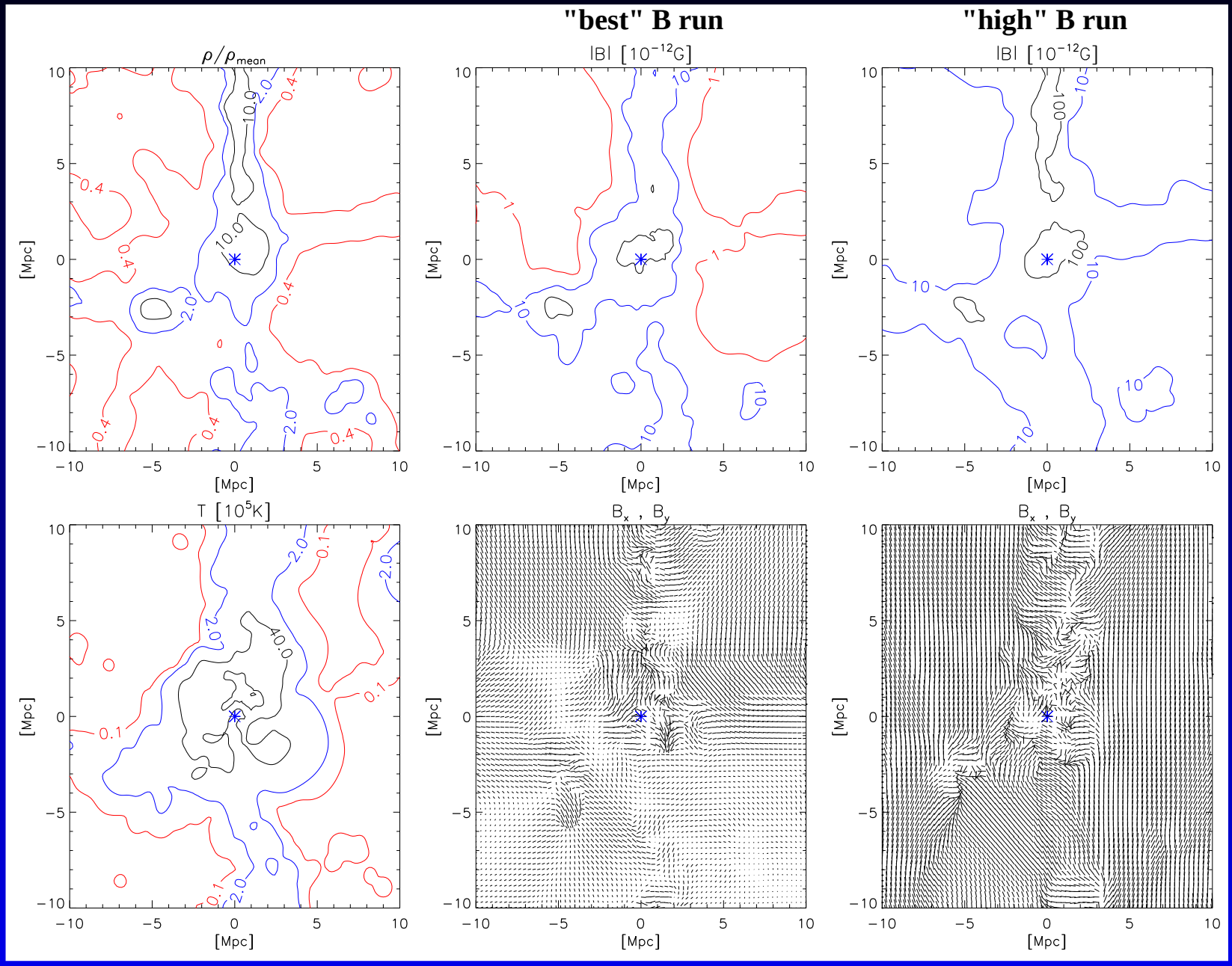
- Never straight lines !
- Always junctions of sheets !
- Sometimes projections of sheets !

Method II: UHECR defl. (nG)



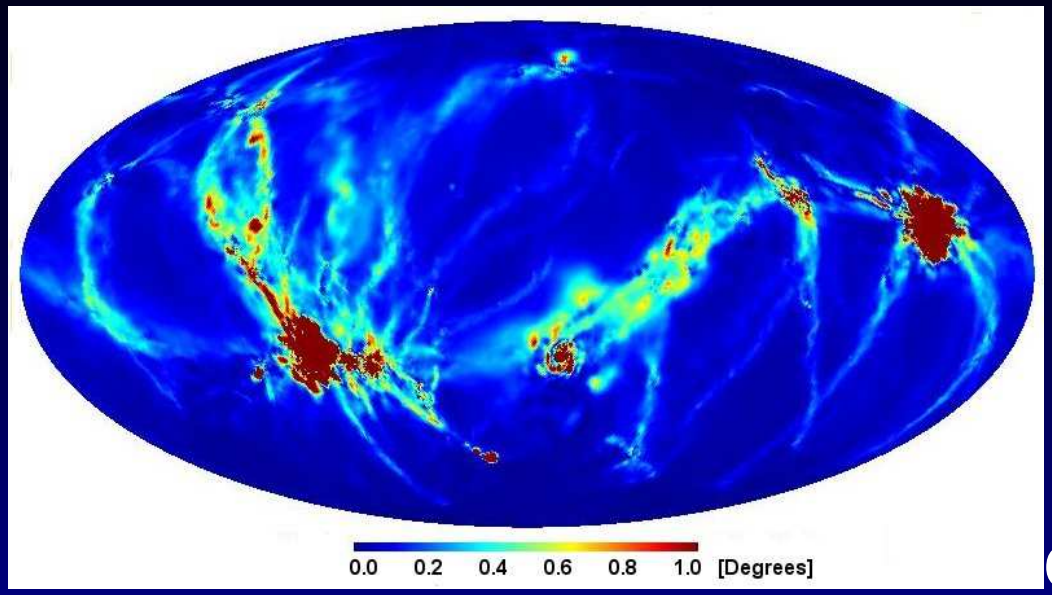
Going along a **filament**, regions of alignment.

Method II: UHECR defl. (nG)

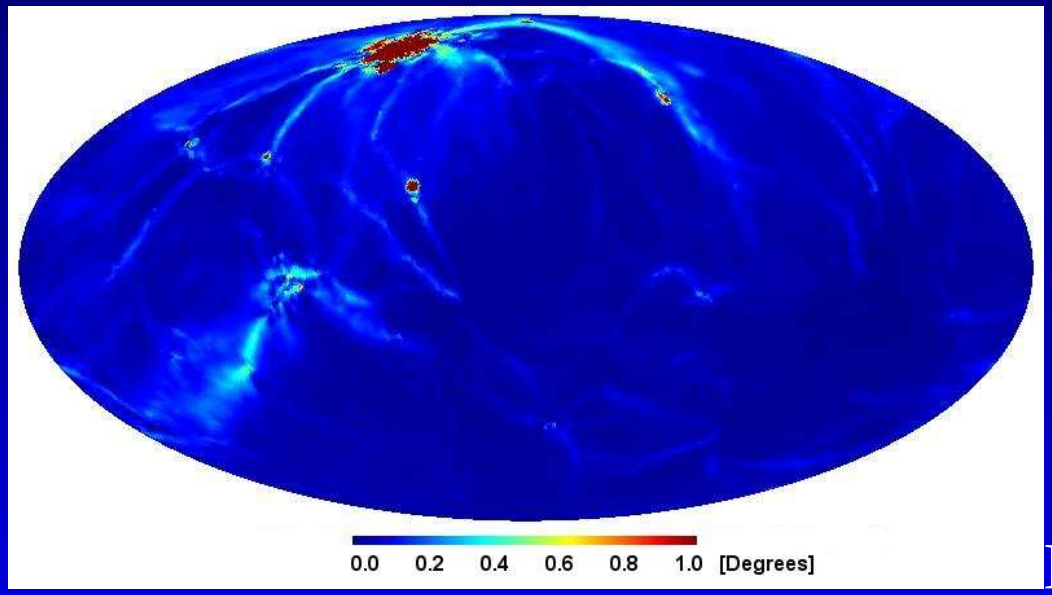


Slice perpendicular to a **filament**, complex geometry.

Method II: UHECR defl. (nG)



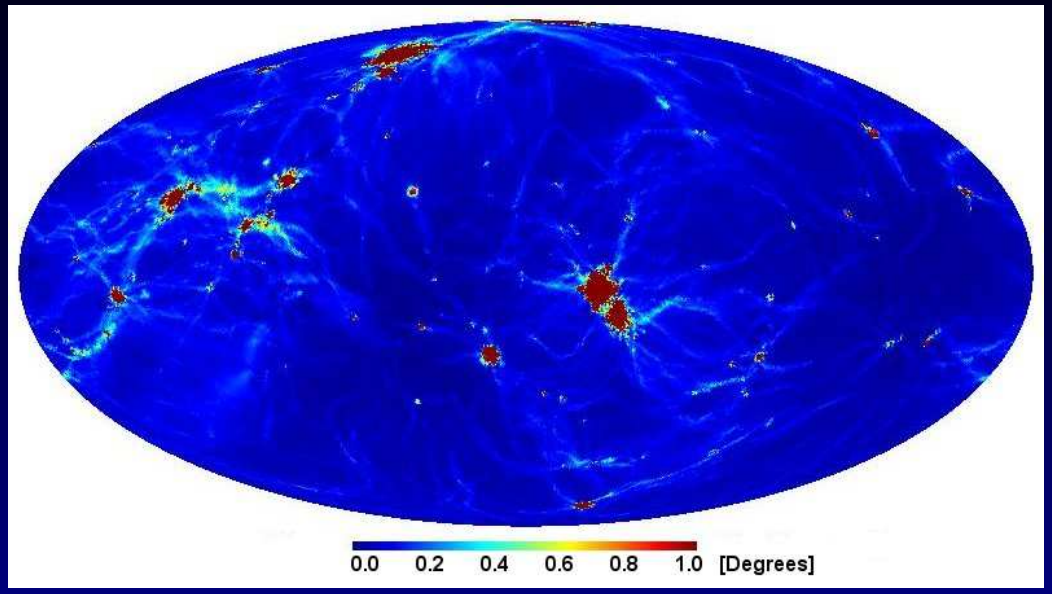
Centaurus



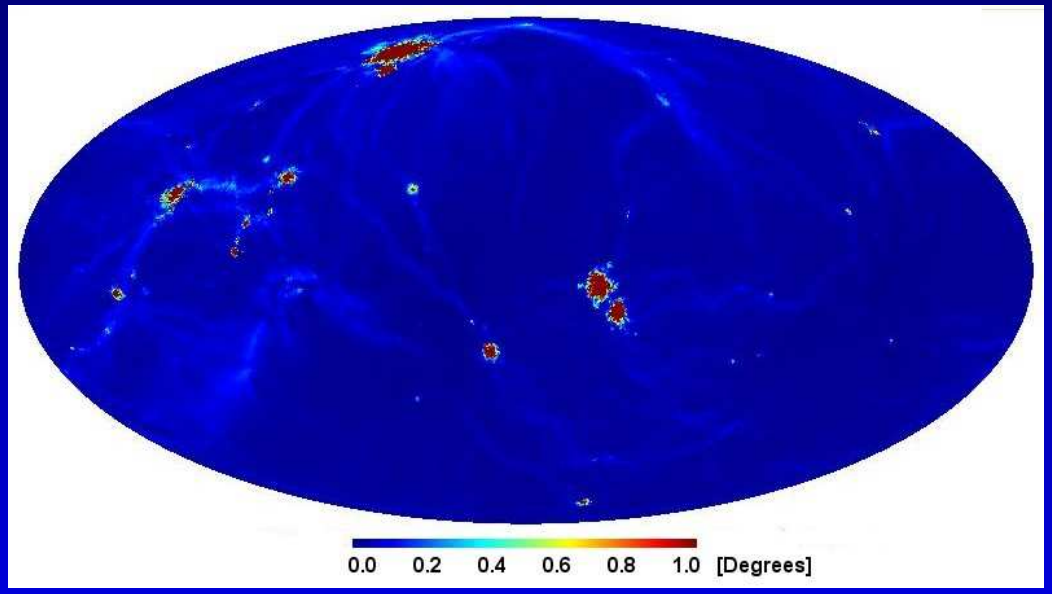
Milky Way

Full sky deflection signal for 4×10^{19}eV Cosmic Rays for two different observer position, using a sphere with radius 35Mpc.

Method II: UHECR defl. (nG)



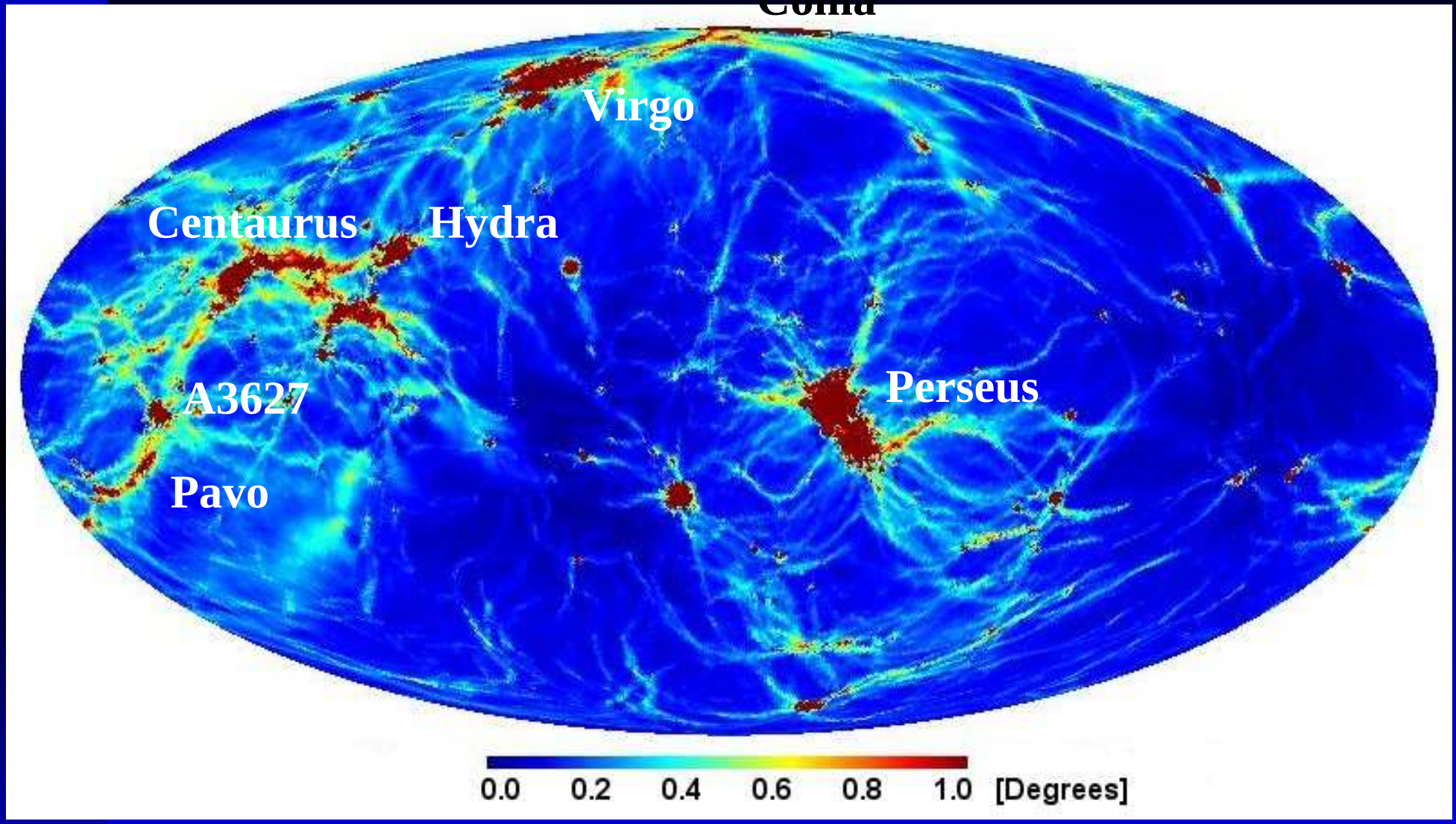
no losses



with losses

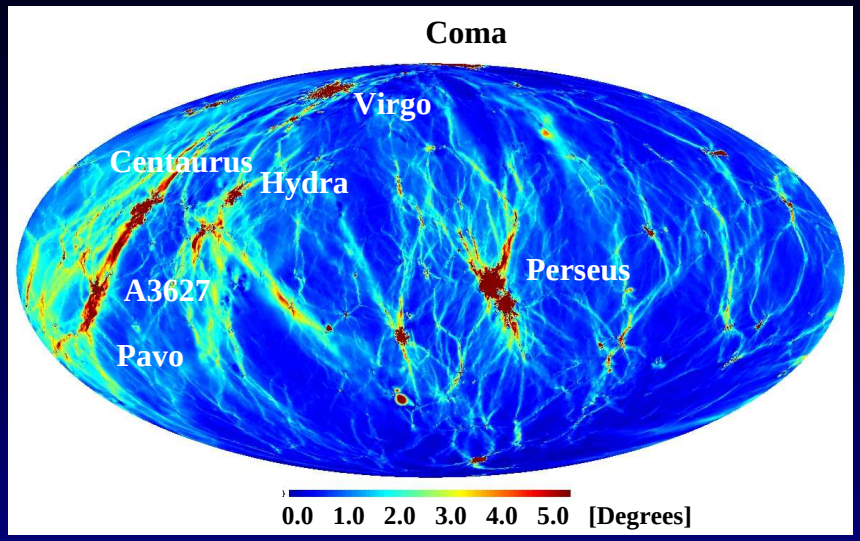
Full sky deflection signal for 1×10^{20}eV Cosmic Rays with and without losses by photo-pion production in collisions with CMB, using a sphere of 100Mpc radius.

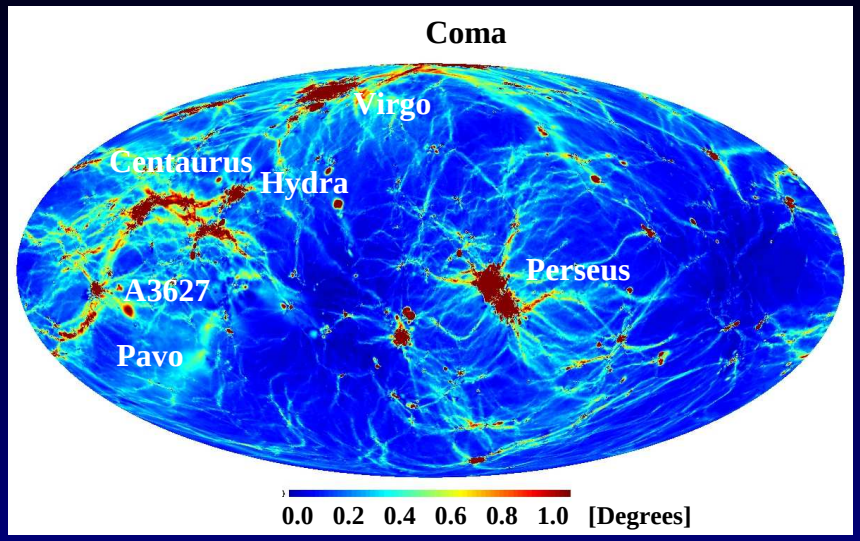
Method II: UHECR defl. (nG)

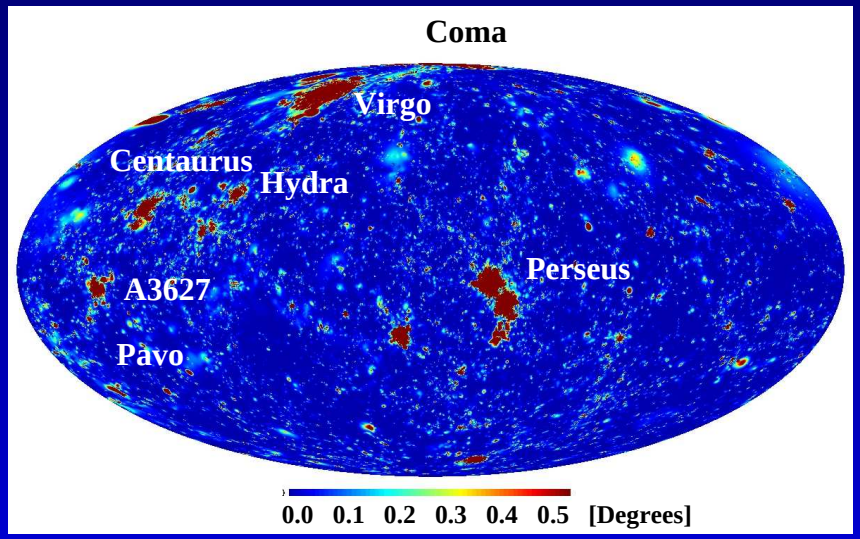


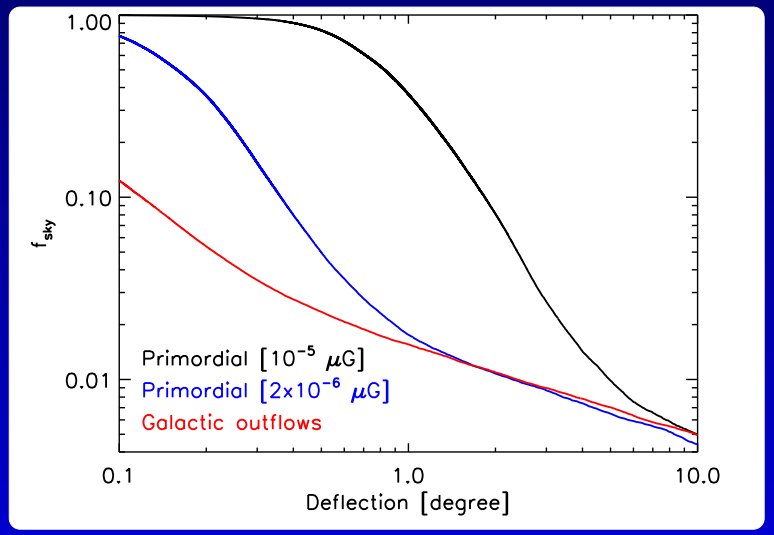
Full sky deflection signal for 4×10^{19}eV Cosmic Rays without losses, using a sphere of 110Mpc radius.

Method II: UHECR defl. (nG)



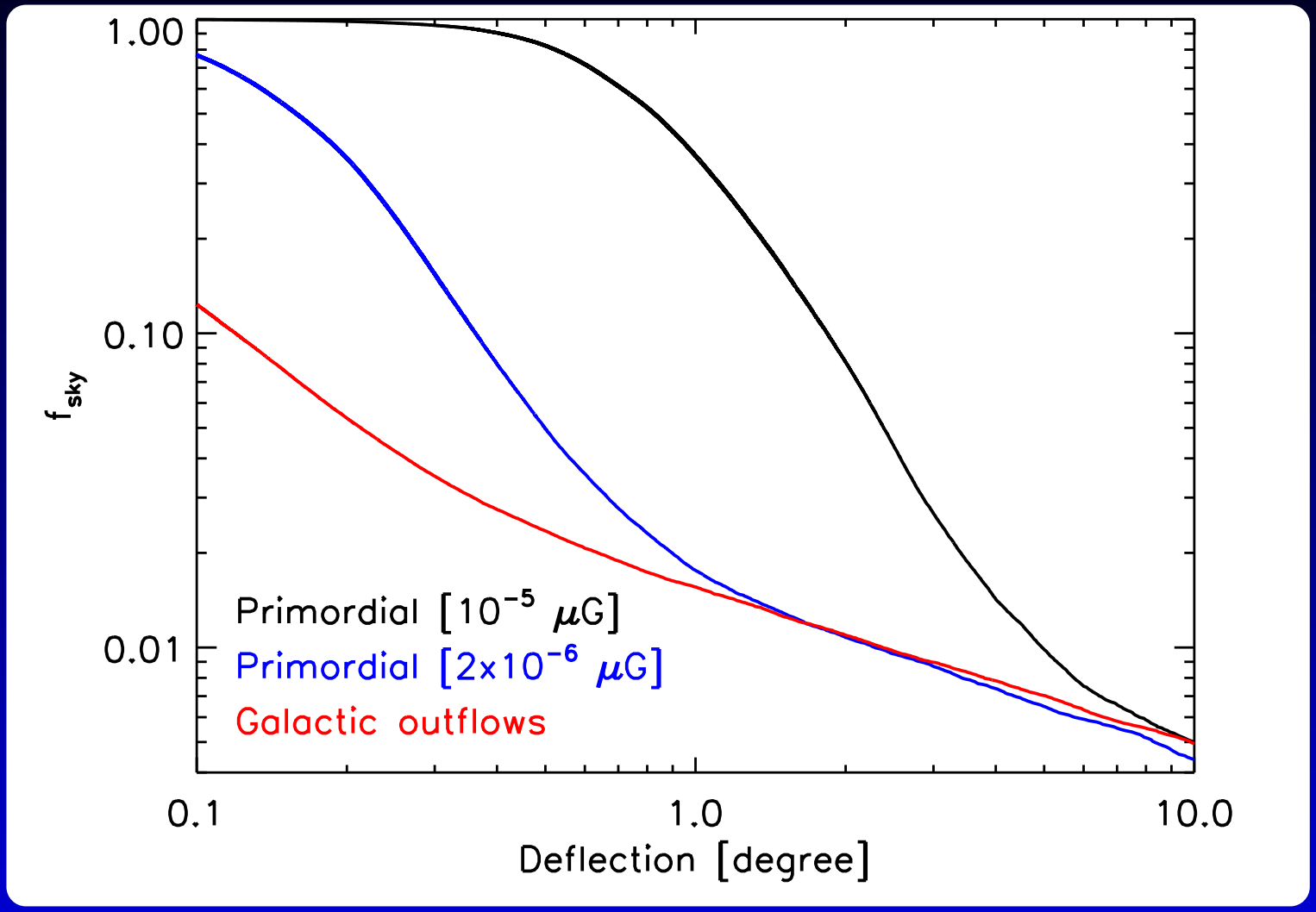






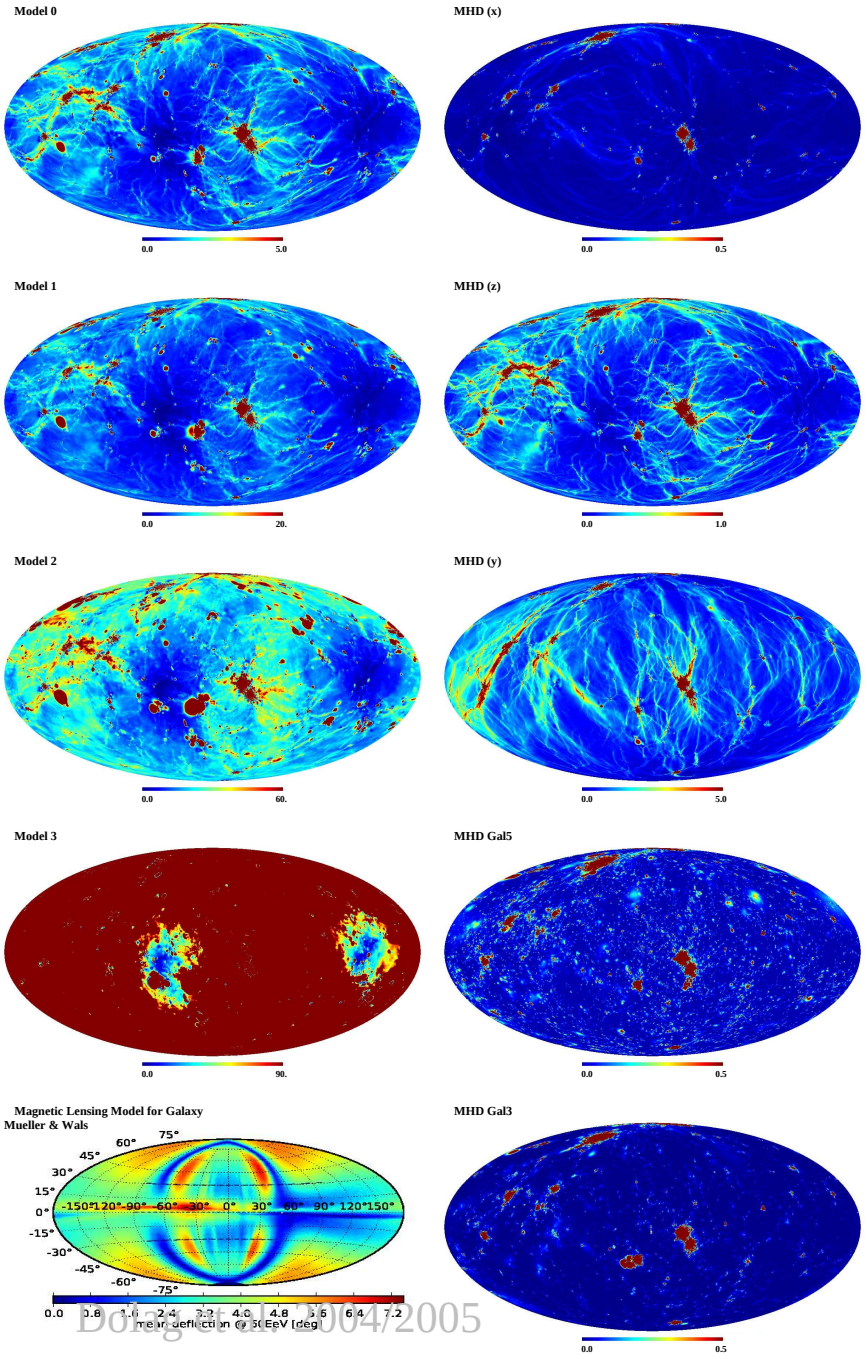
Full sky deflection signal for 4×10^{19}eV **Cosmic Rays** without losses, using a sphere of 110 Mpc radius for **different** magnetic seed models (Dolag, Grasso, Springel & Tkachev 2004/2005).

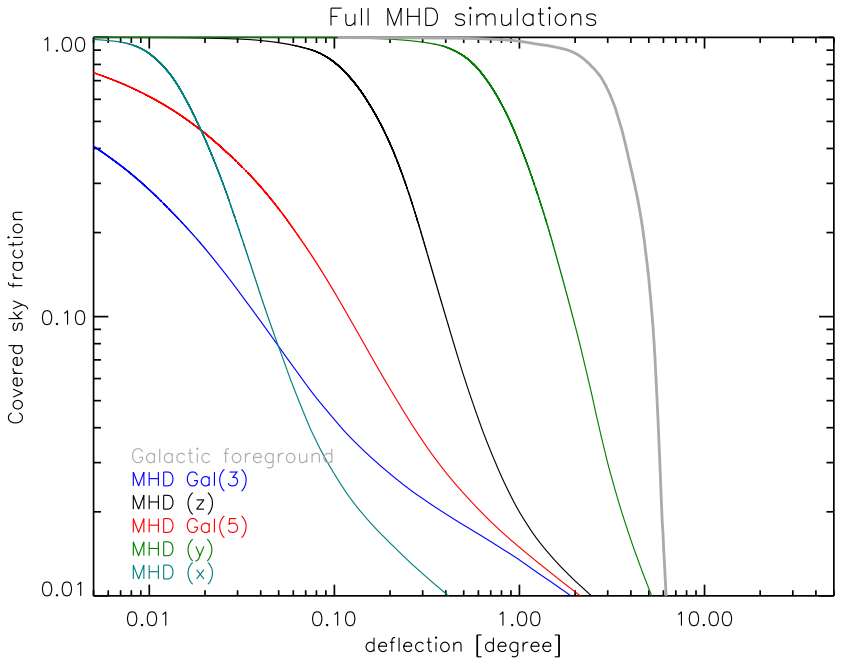
Method II: UHECR defl. (nG)

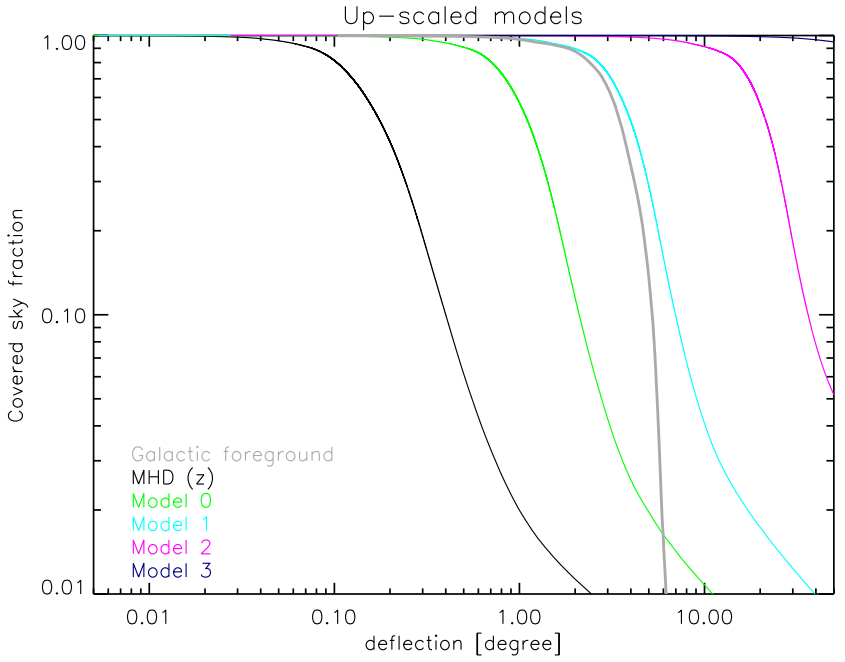


Sky coverage of deflection signal for 4×10^{19}eV Cosmic Rays without losses, using a sphere of 110 Mpc radius for all **models**
Allows to probe cosmic magnetic fields !?

Method II: UHECR defl. (nG)

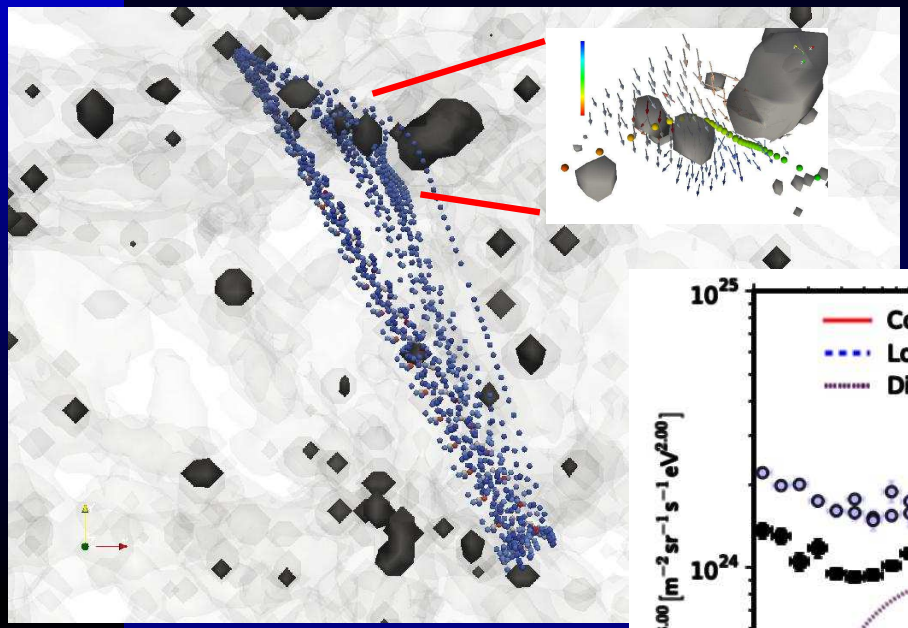


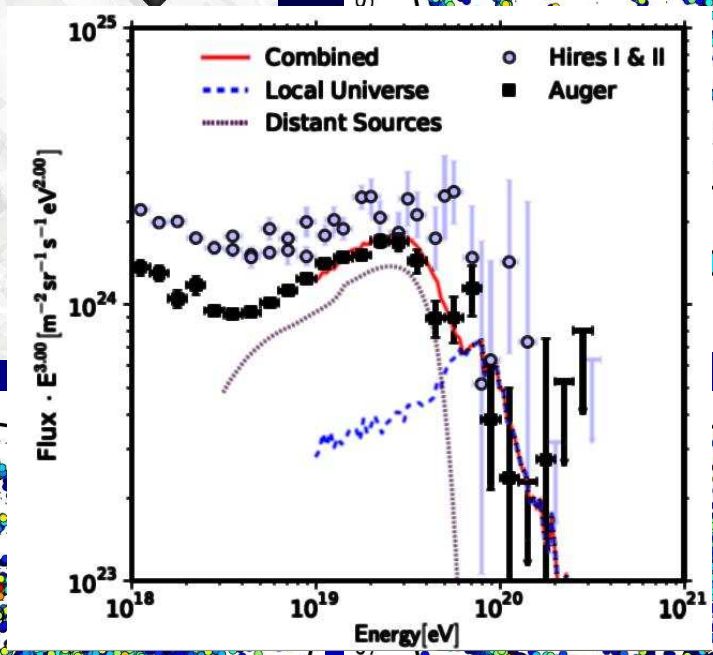


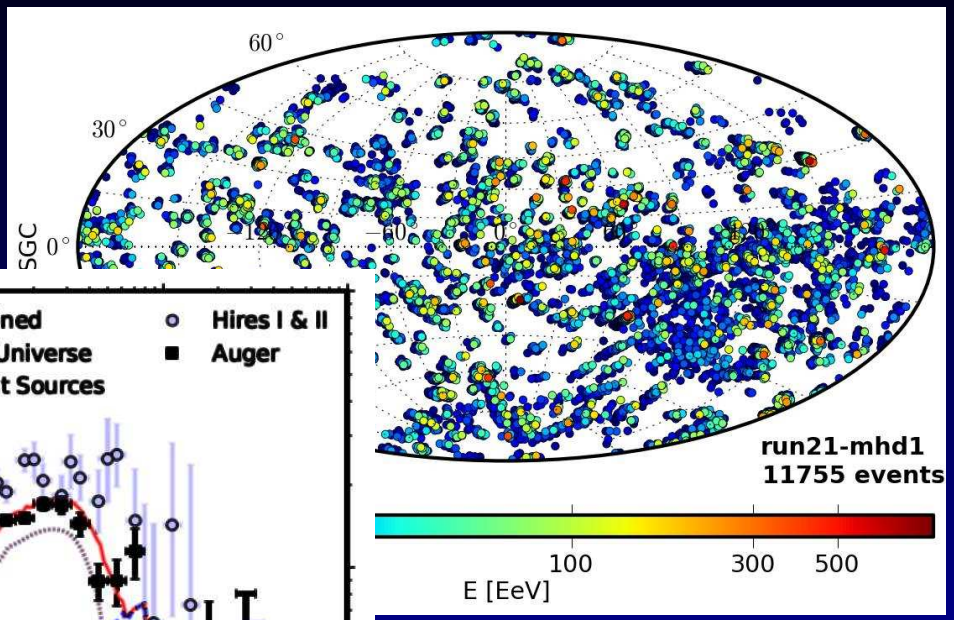


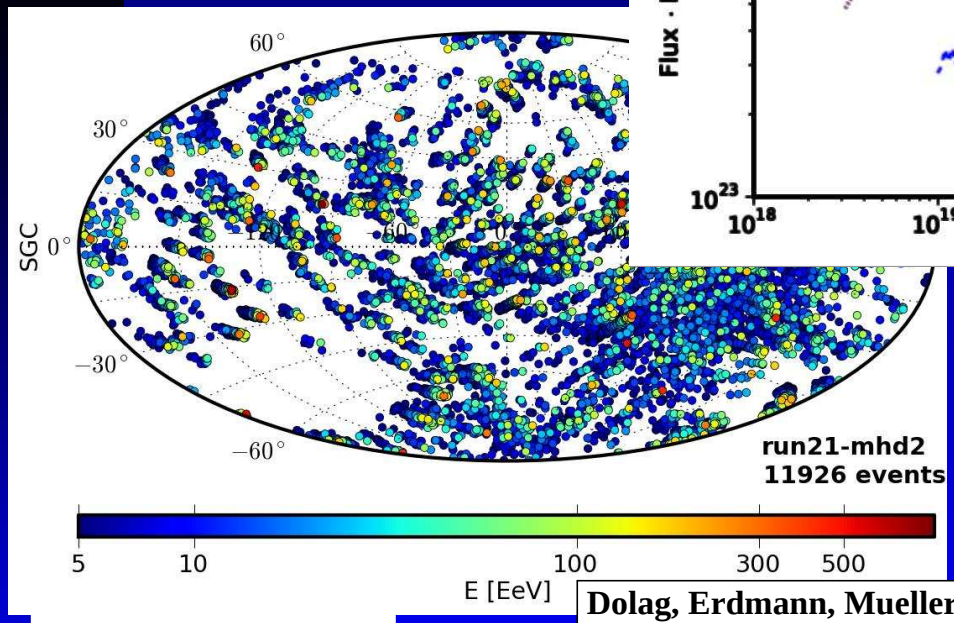
Bonaguri 2004/2005

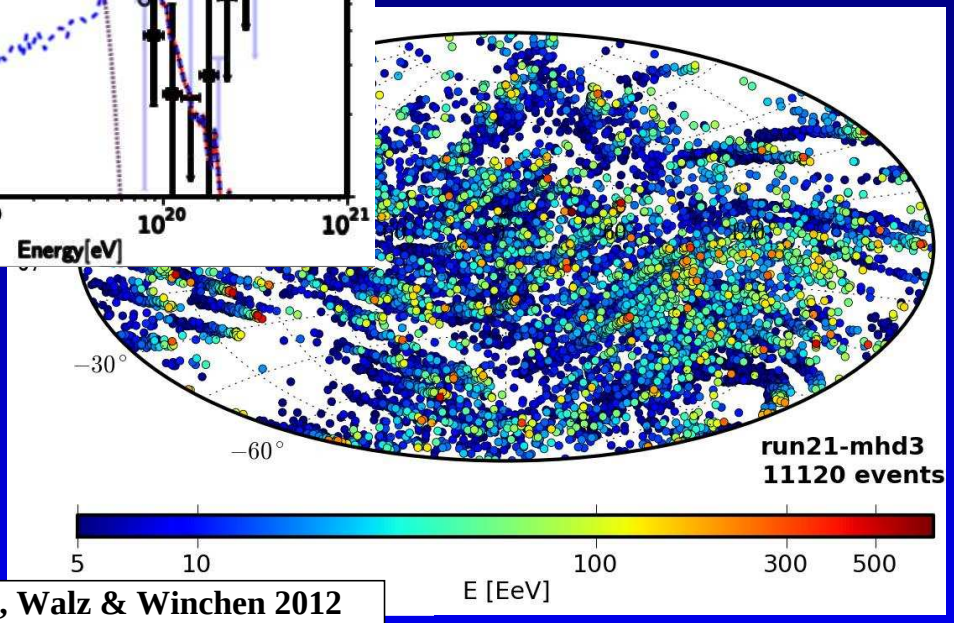
Method II: UHECR defl. (nG)







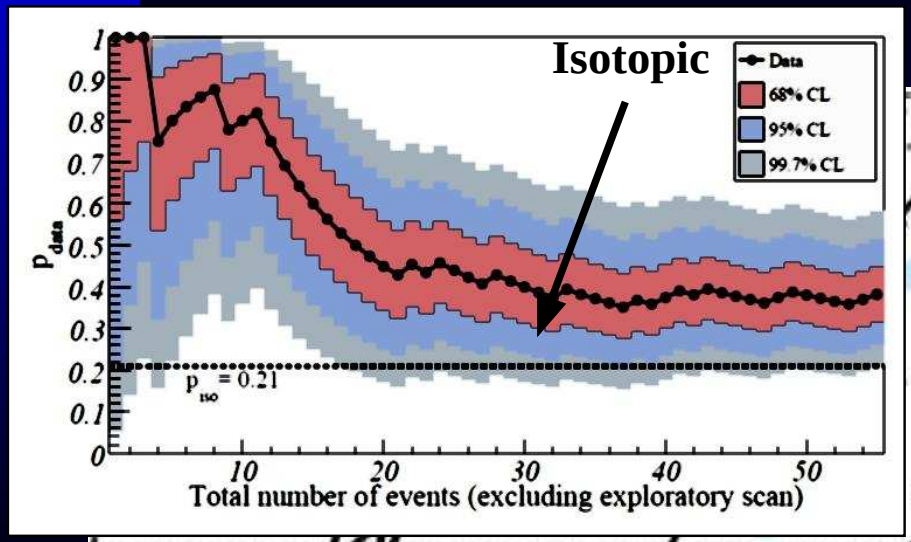




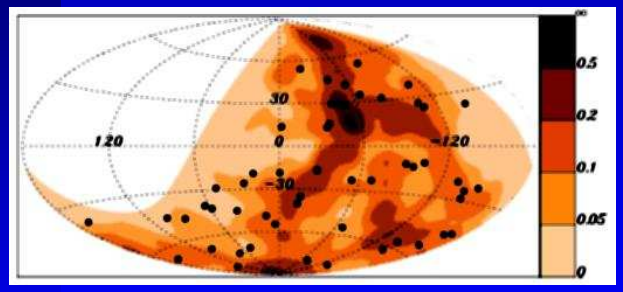
Dolag, Erdmann, Mueller, Walz & Winchen 2012

Full **tracking** of UHECRs in cosmological MHD simulation.

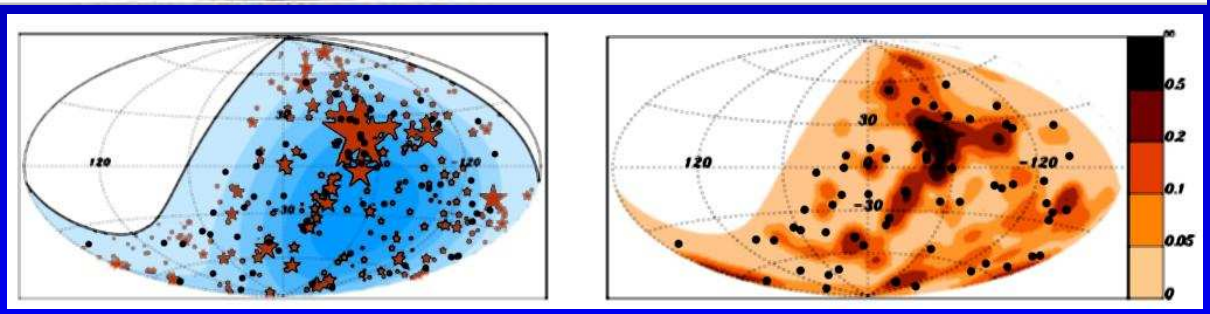
Method II: UHECR defl. (nG)



AUGER 2010



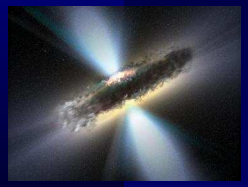
2MASS



Swift−BAT (AGNs)

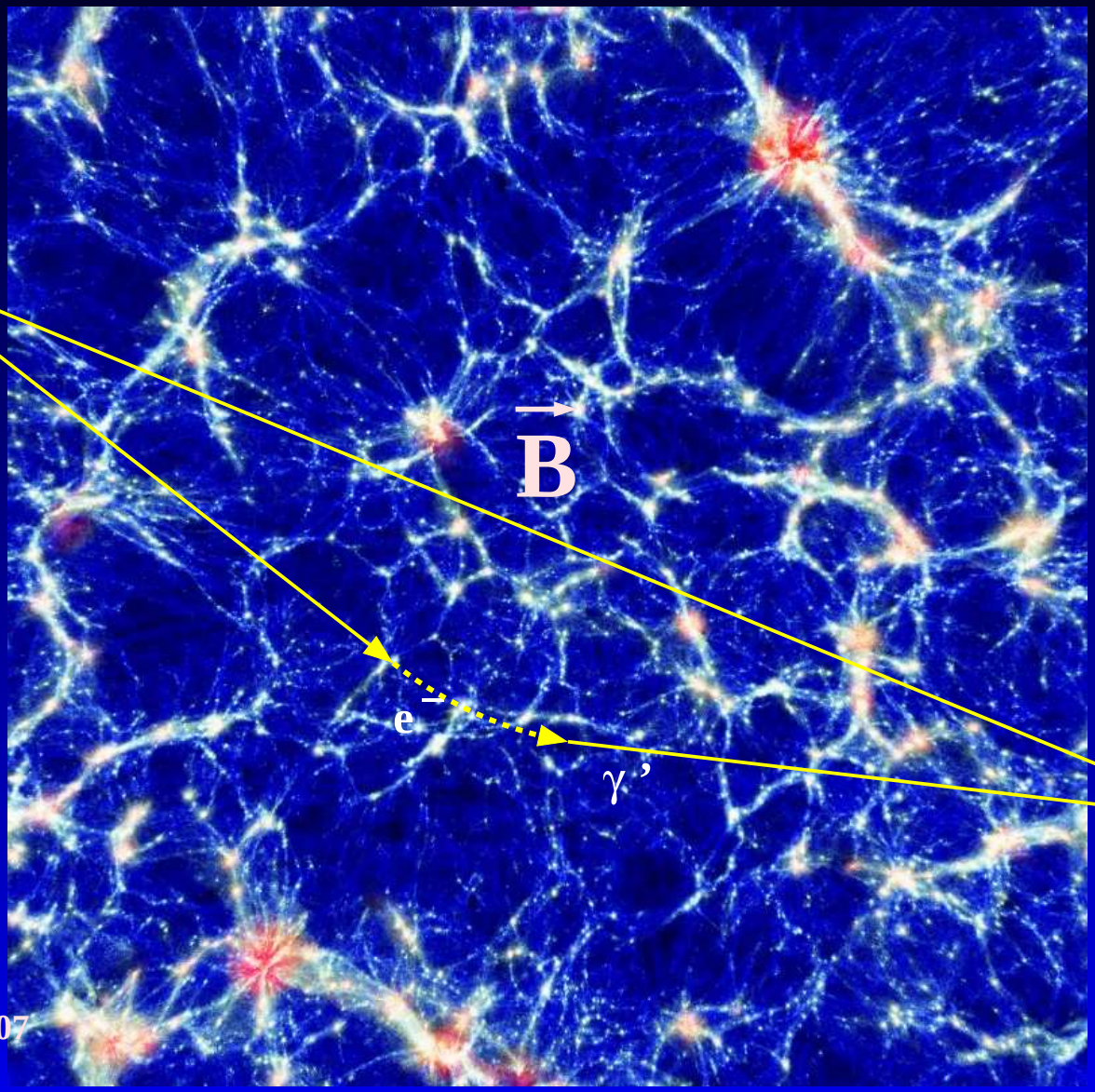
Method III: γ-rays (pG-fG)

Deflection of electromagnetic cascade of TeV photons



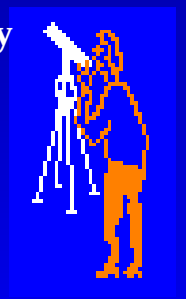
γ

γ



primary

secondary

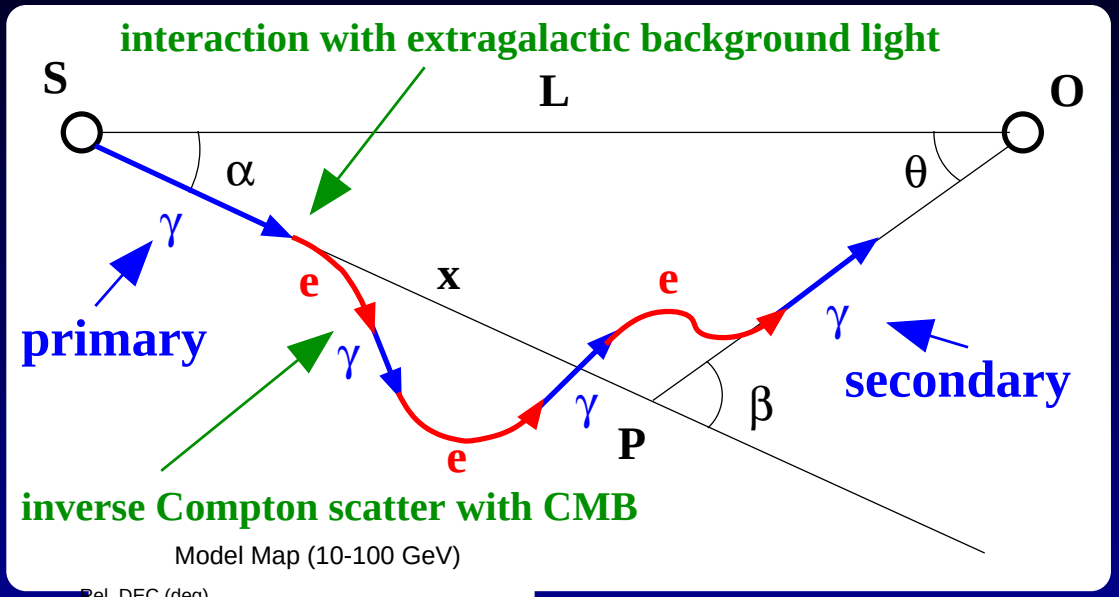


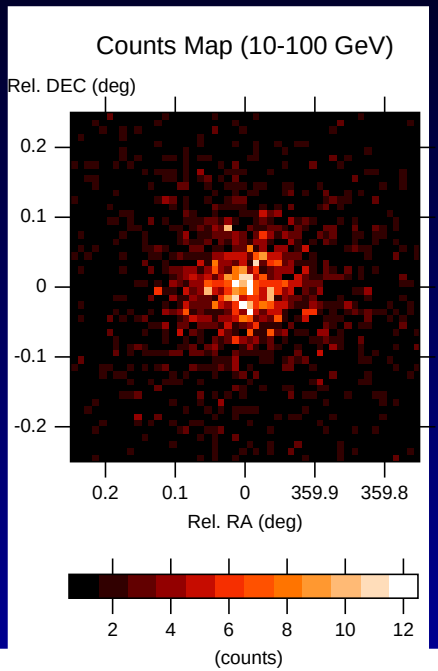
Neronov et al. 2010
Dolag et al. 2009
Neronov & Semikoz 2007
Aharonian et al. 1994

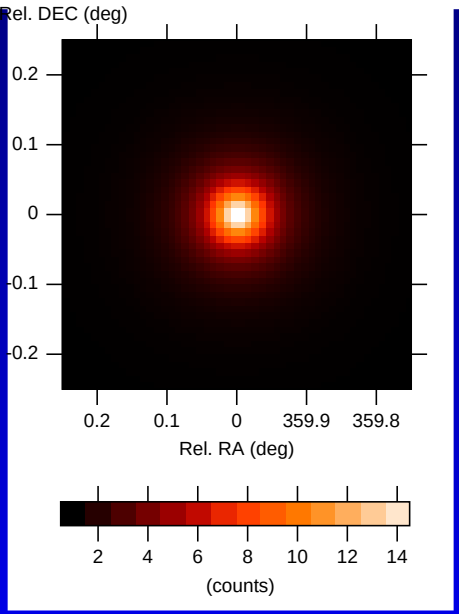
electromagnetic cascade: electron pair production interaction with EBL
cooling of electrons: inverse compton scatter with CMB photons

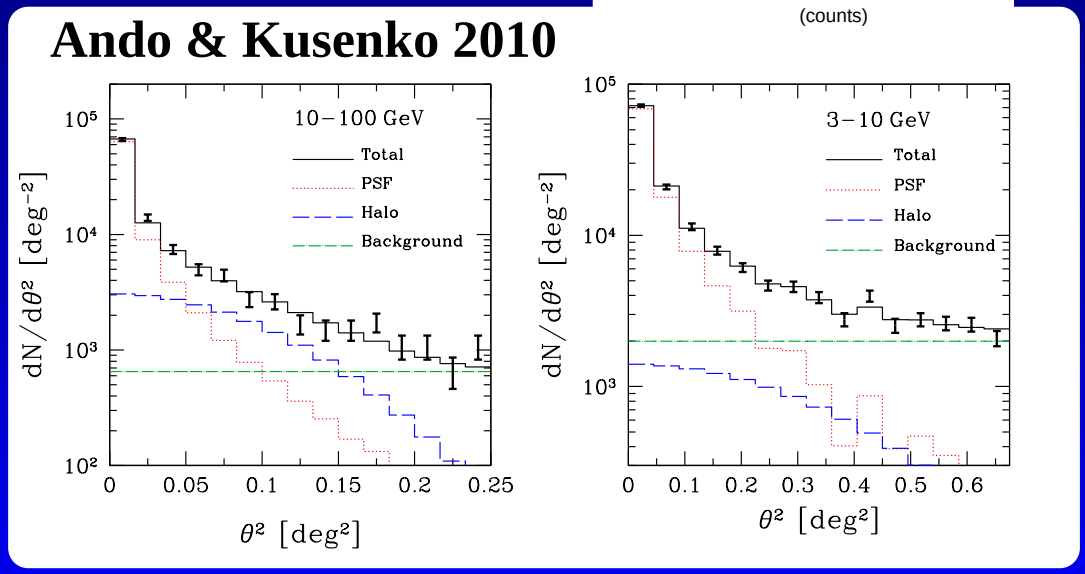
Method III: γ-rays (pG-fG)

Propagation of γ-rays, sensitive to $(10^{-12} - 10^{-16})$G



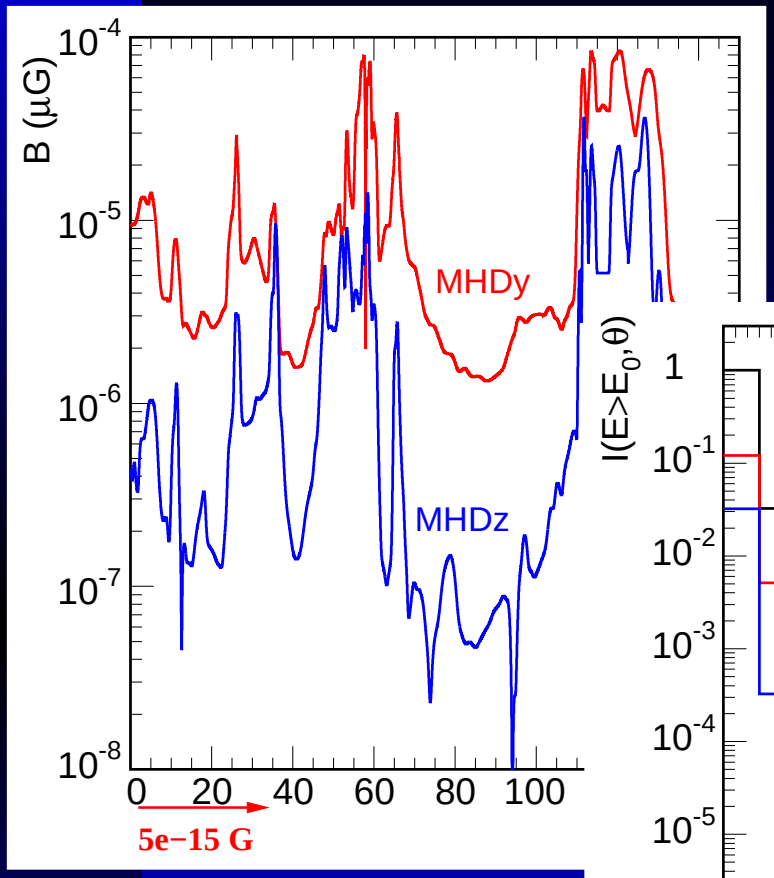




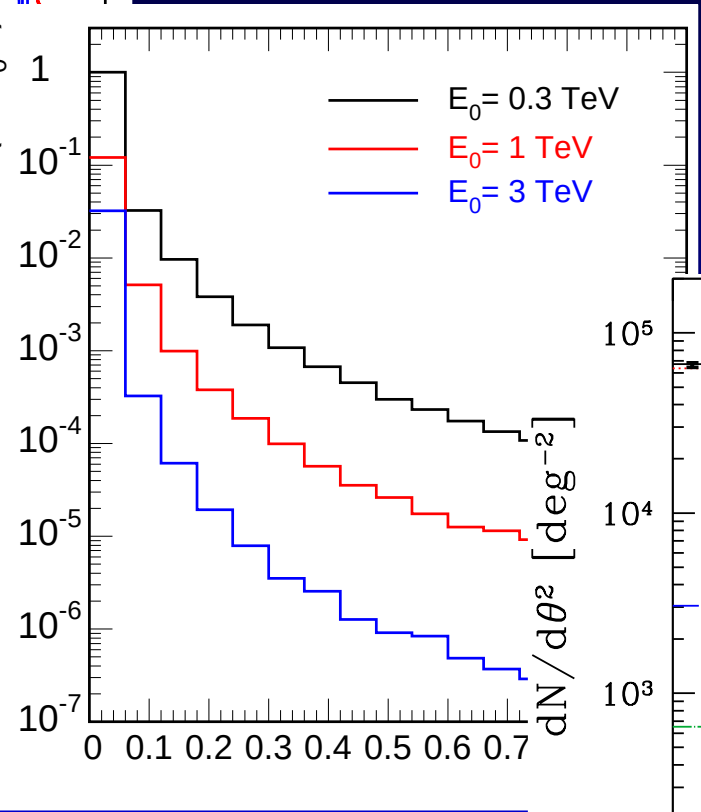


Halo found **stacking** 170 AGNs with FERMI: $B \approx 10^{-15}$G.

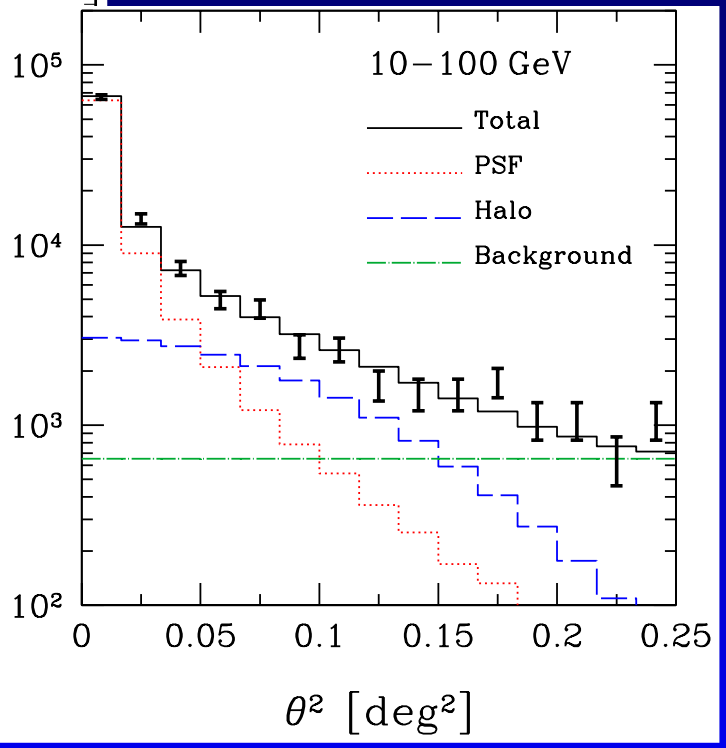
Method III: γ-rays (pG-fG)



Dolag et al. 2009

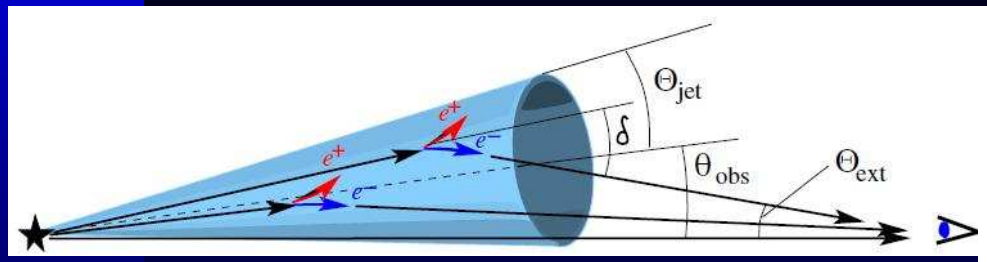


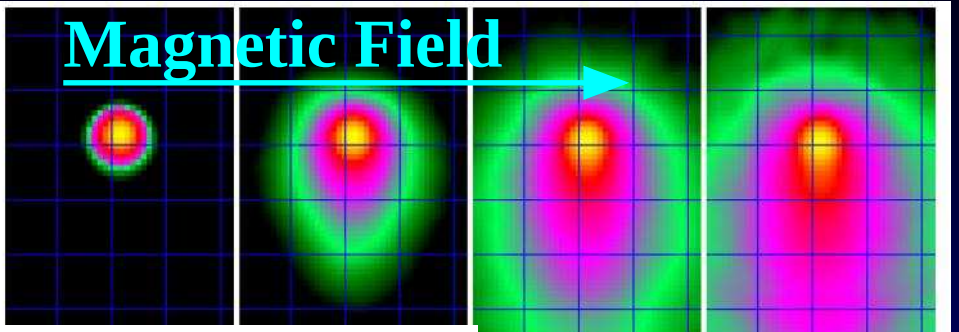
Ando & Kusenko 2010

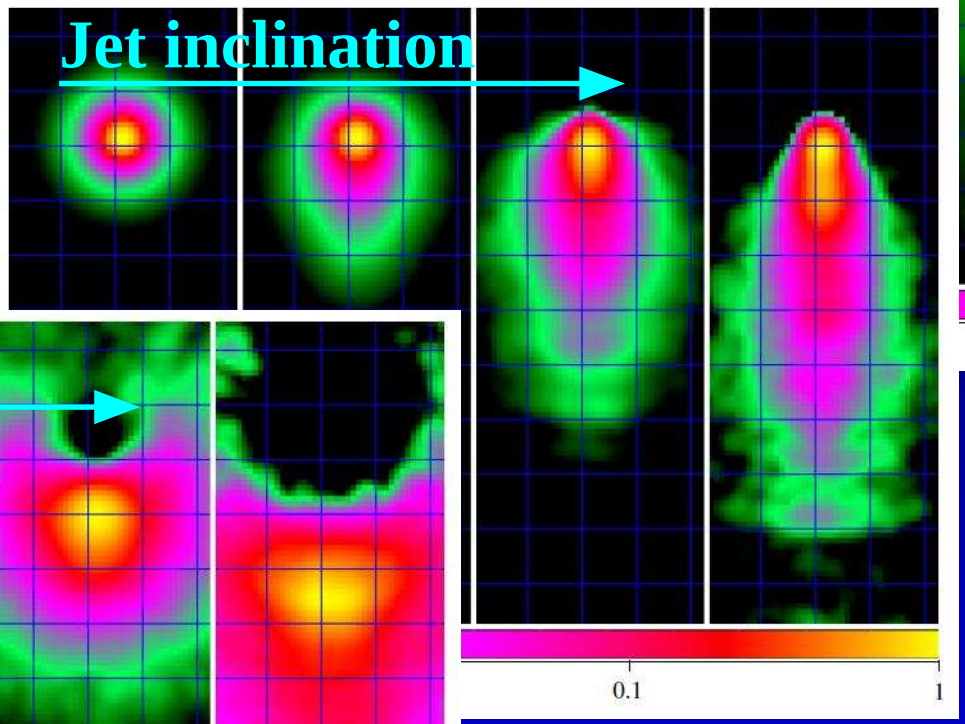


But false detection due to inperfect beam ! (Neronov et al. 2010)

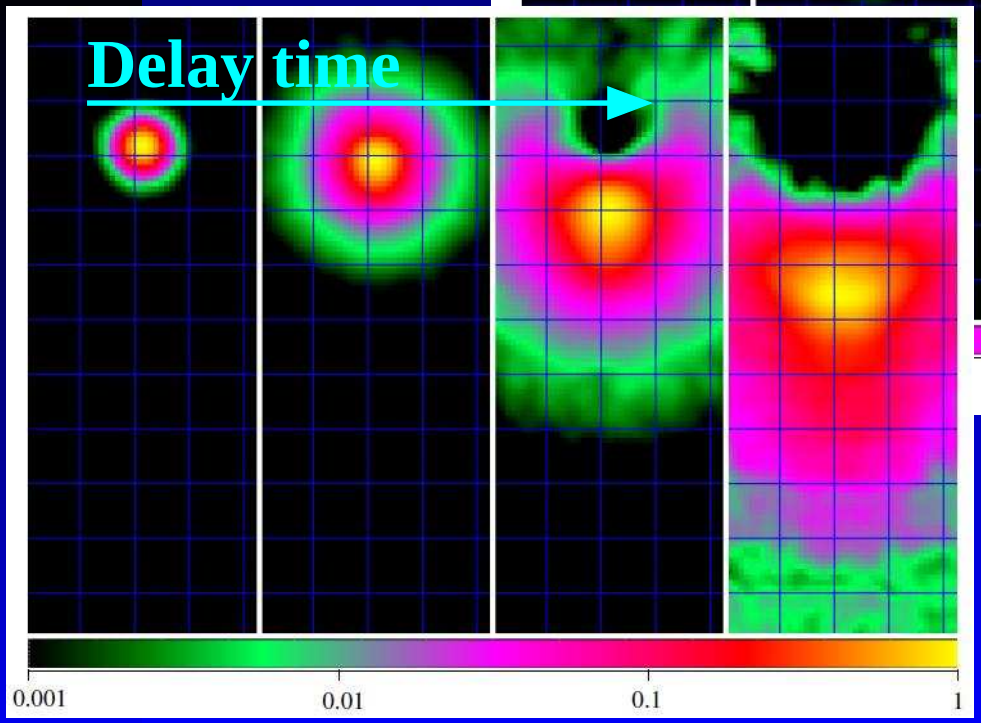
Method III: γ-rays (pG-fG)







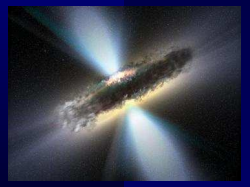
Neronov et al. 2010

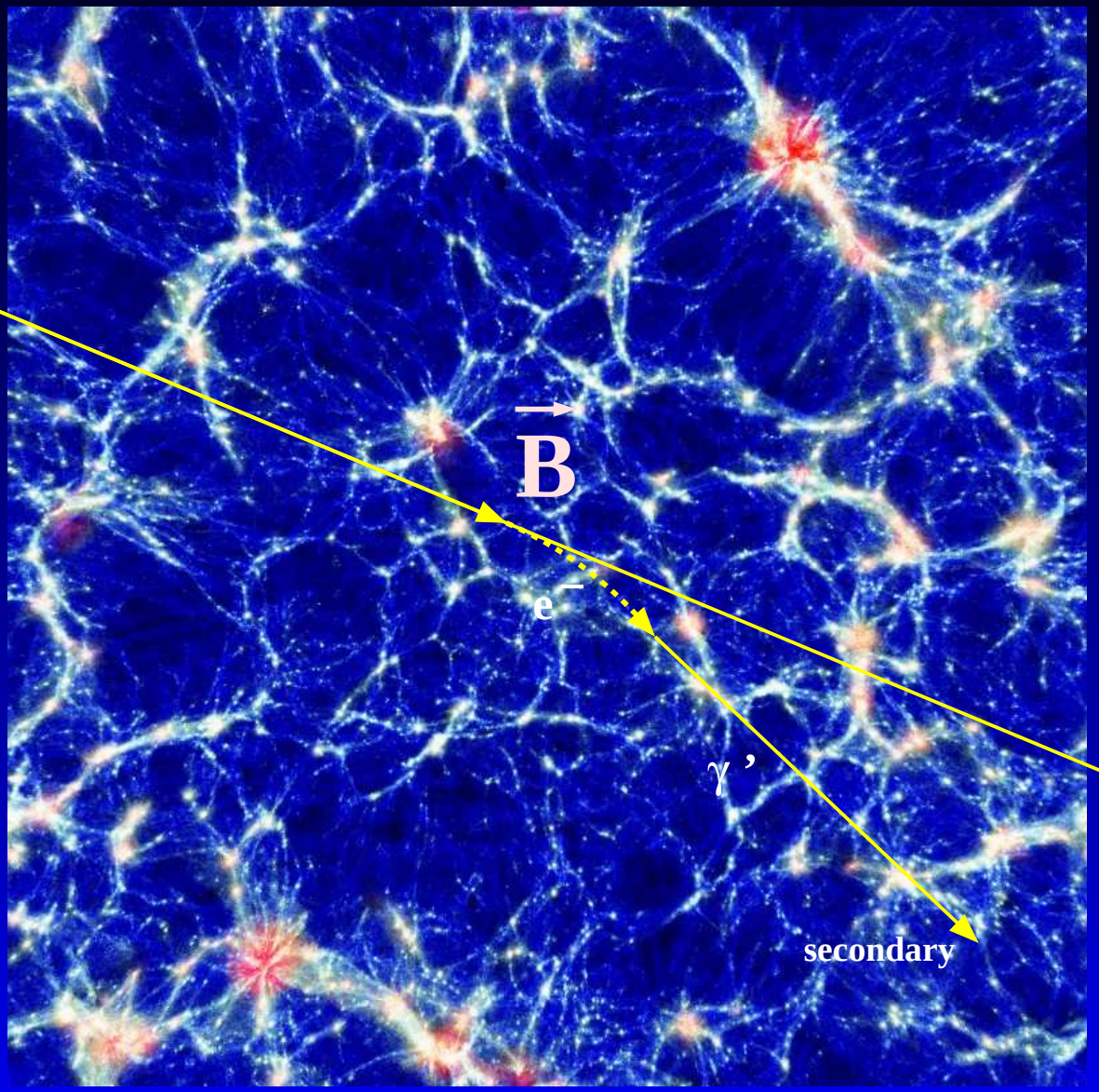


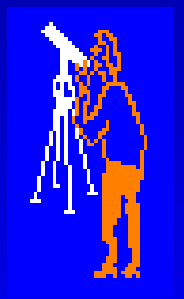
Real detection will be difficult due to **source/geometry** details.

Method IV: γ-rays (fG)

Attenuation from electromagnetic cascade of TeV photons



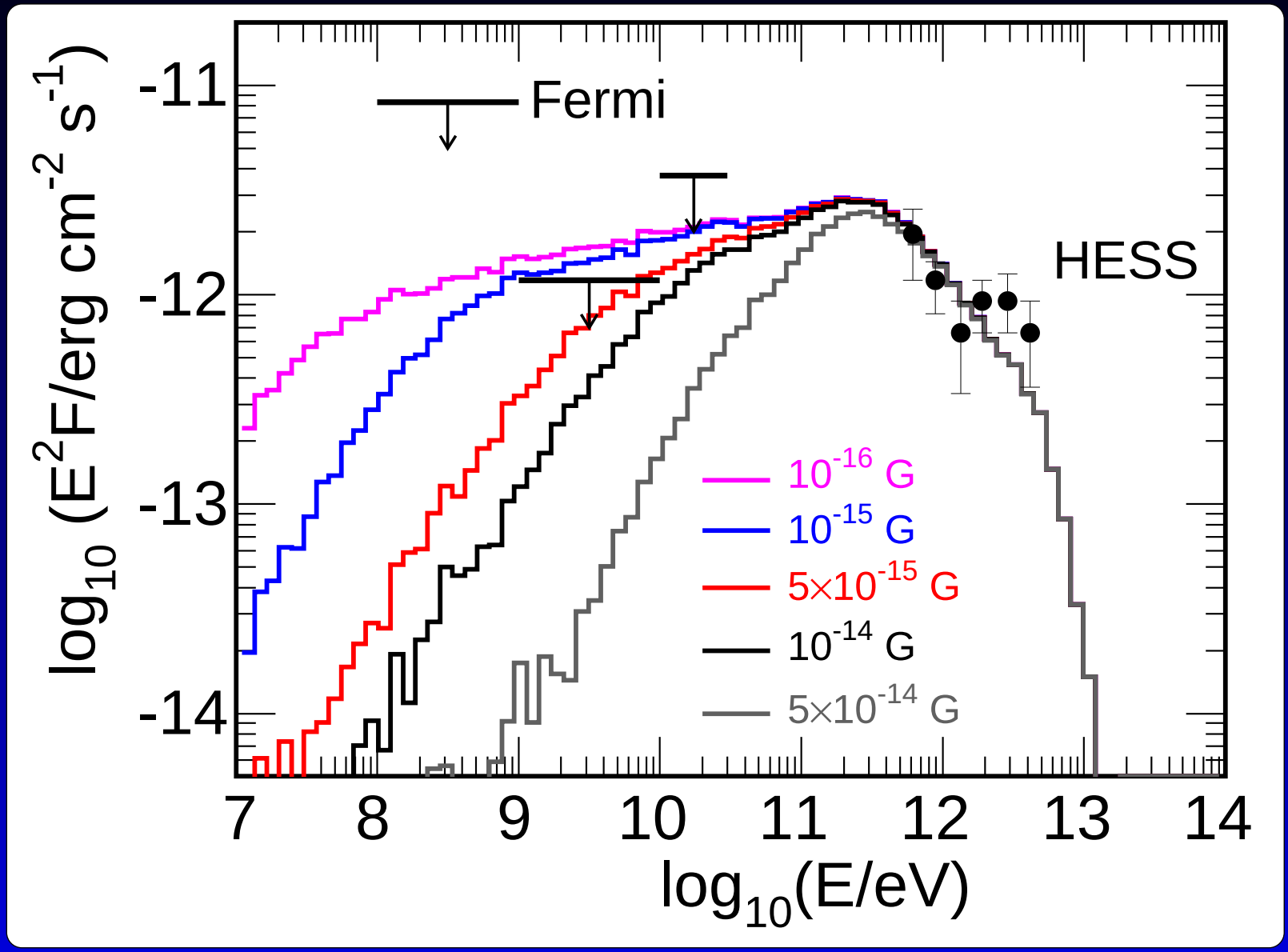




Dolag et al. 2010
Tavecchio et al. 2010
Neronov & Vovk 2010

electromagnetic cascade: electron pair production interaction with EBL
cooling of electrons: inverse compton scatter with CMB photons

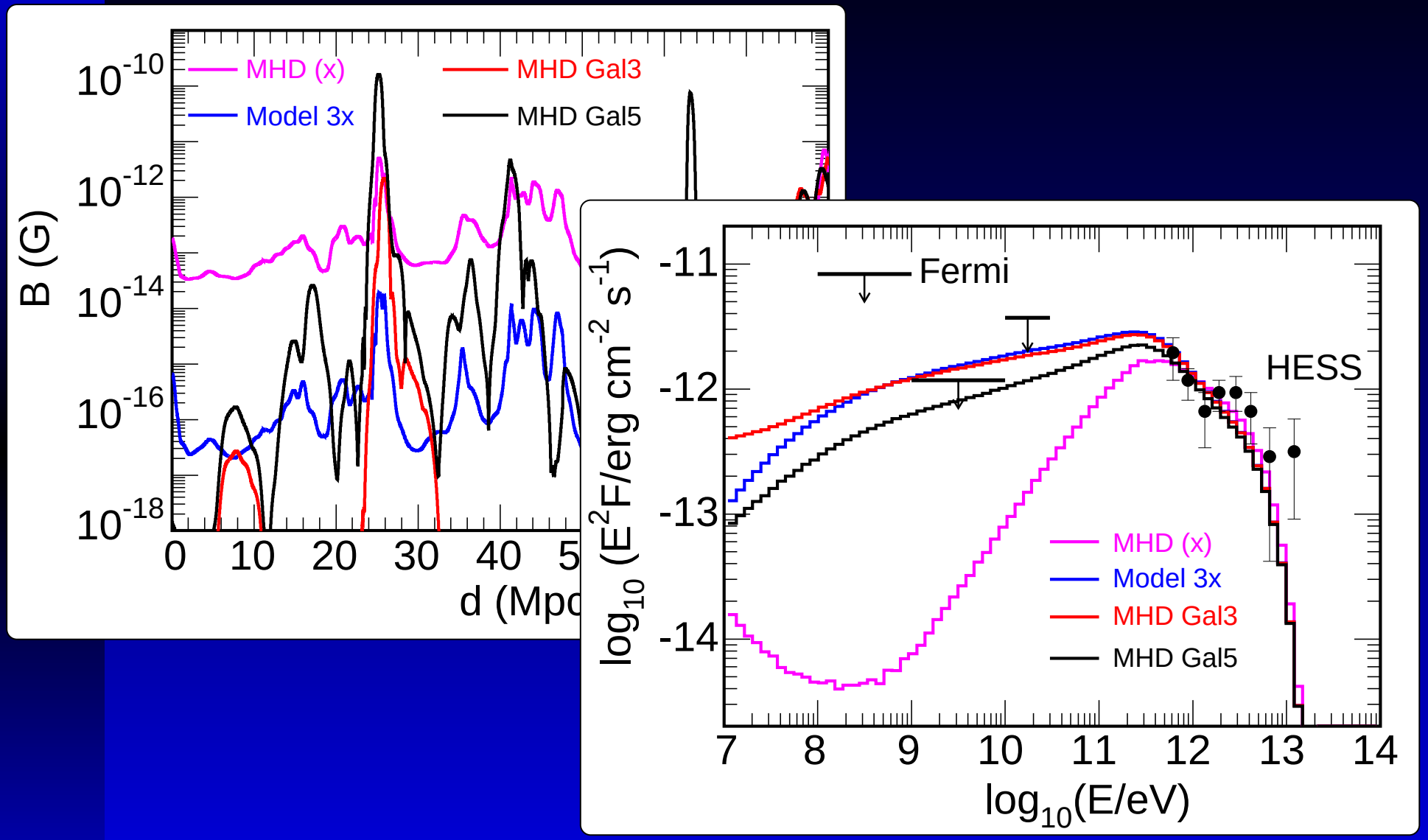
Method IV: γ-rays (fG)



Combing FERMI and HESS give **lower limit** of

$B > 5 \times 10^{-15}$G (Neronov & Vovk 2010, Tavecchio et al. 2010)

Method IV: γ-rays (fG)

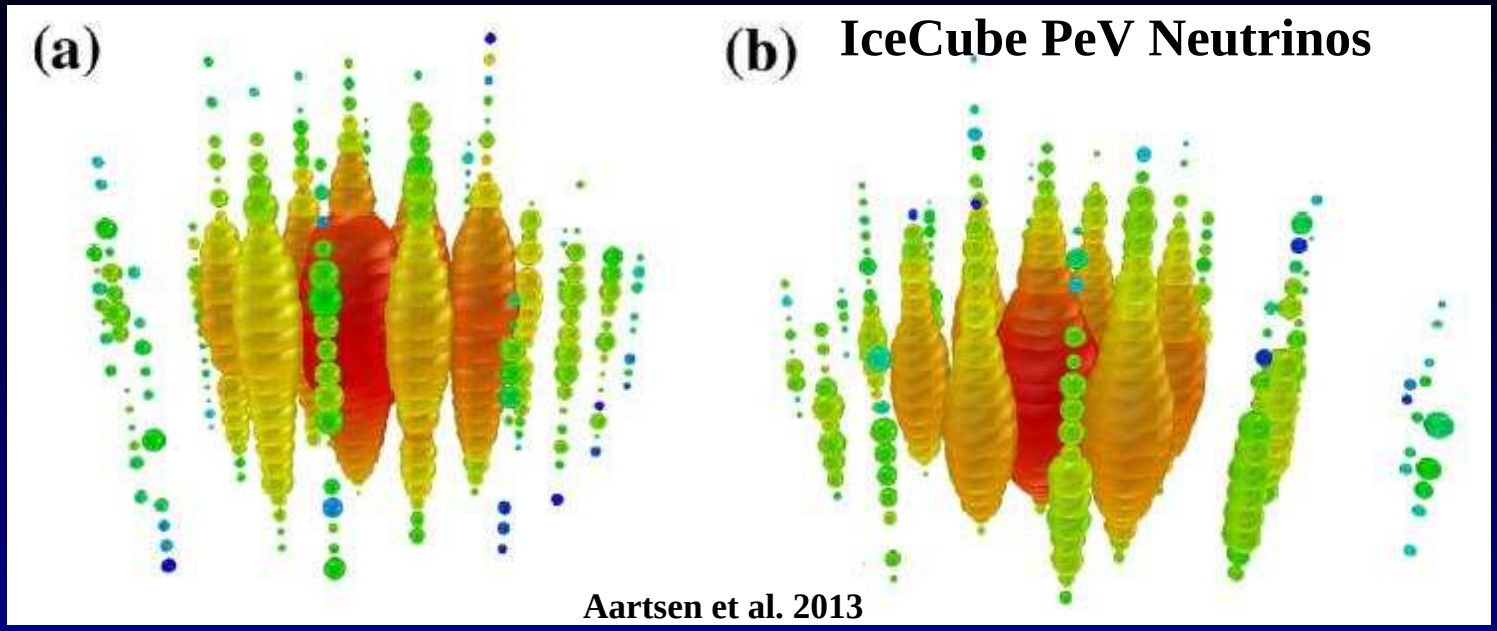


$\Rightarrow B > 3 \times 10^{-15}$ G in at least 40% of space !

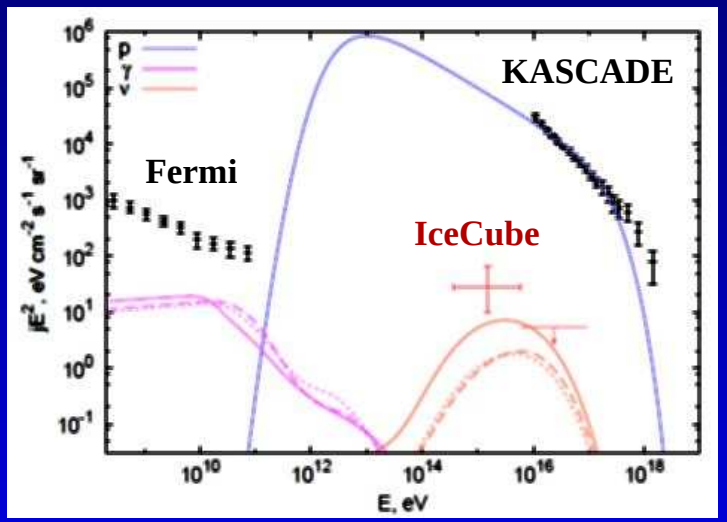
$\Rightarrow$ Strong **constrains** on the **origin** of EGMFs

(Dolag, Kachelriess, Ostapchenko & Tomàs 2010)

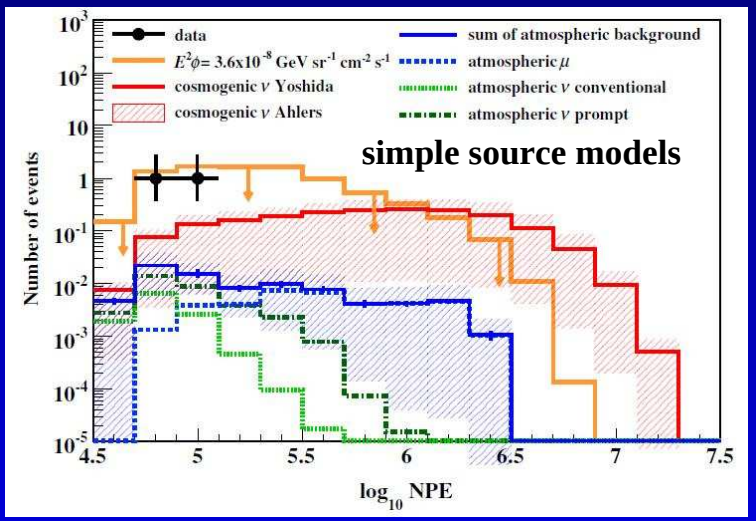
Method V: Neutrinos



Aartsen et al. 2013



Kalashev, Kusenko & Essey 2013



Electromagnetic cascade will also produce neutrino signal.

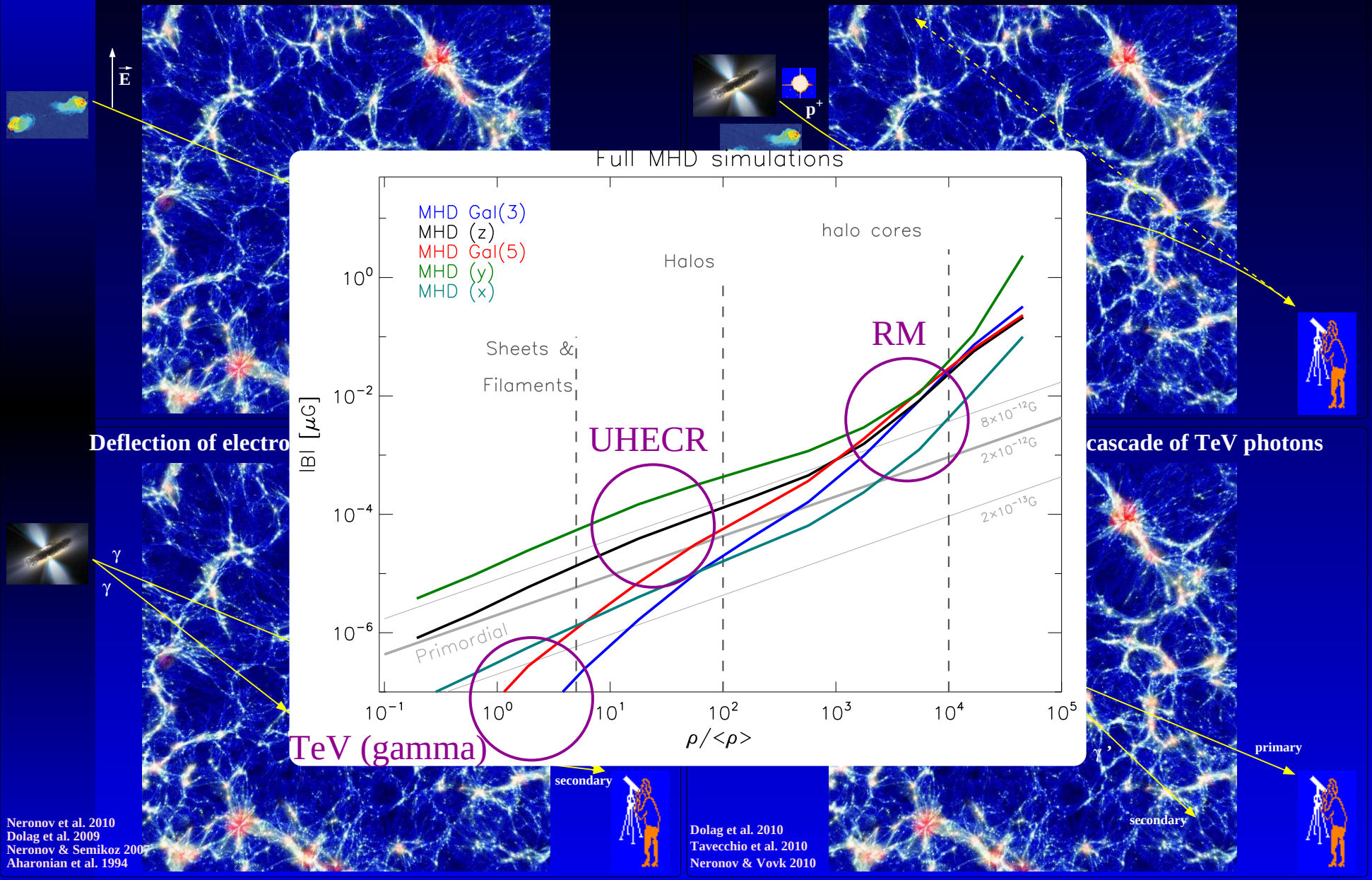
IceCube detected 2 Neutrinos with PeV energies !

⇒ Compatible with attenuation signal !

Summary

Faraday Rotation (RM) of polarized radio emission

Propagation of ultra high energy cosmic rays (UHECR)



Deflection of electro

cascade of TeV photons

Neronov et al. 2010
Dolag et al. 2009
Neronov & Semikoz 2007
Aharonian et al. 1994

Dolag et al. 2010
Tavecchio et al. 2010
Neronov & Vovk 2010

UHECMessengers open **new** window to Cosmic Magnetism !

Summary

Observations (**RM & Radio probes μG, maybe nG**)

- Measurement of magnetic field power spectra
- Clear indication of magnetic field topology
- Indications for minimum/maximum length scale
- RM-Galaxy correlation consistent (but foreground / noise)

Observations (**UHECR & γ-rays probes $10^{-16} - 10^{-9}$G**)

- High Energy Astronomy helps probing their origin
- UHECR propagation consistent (still under discussion)
- TeV observations of halos would exclude significant contribution from primordial fields (but observations challenged)
- TeV observations of attenuation probes filling factor in voids (but observations challenged by plasma physics)
- First cosmological neutrinos detected (ICE cube) opens independent probe of UHECRM propagation.

$\Rightarrow$ **growing field of research !**