Galactic and intergalactic magnetic fields

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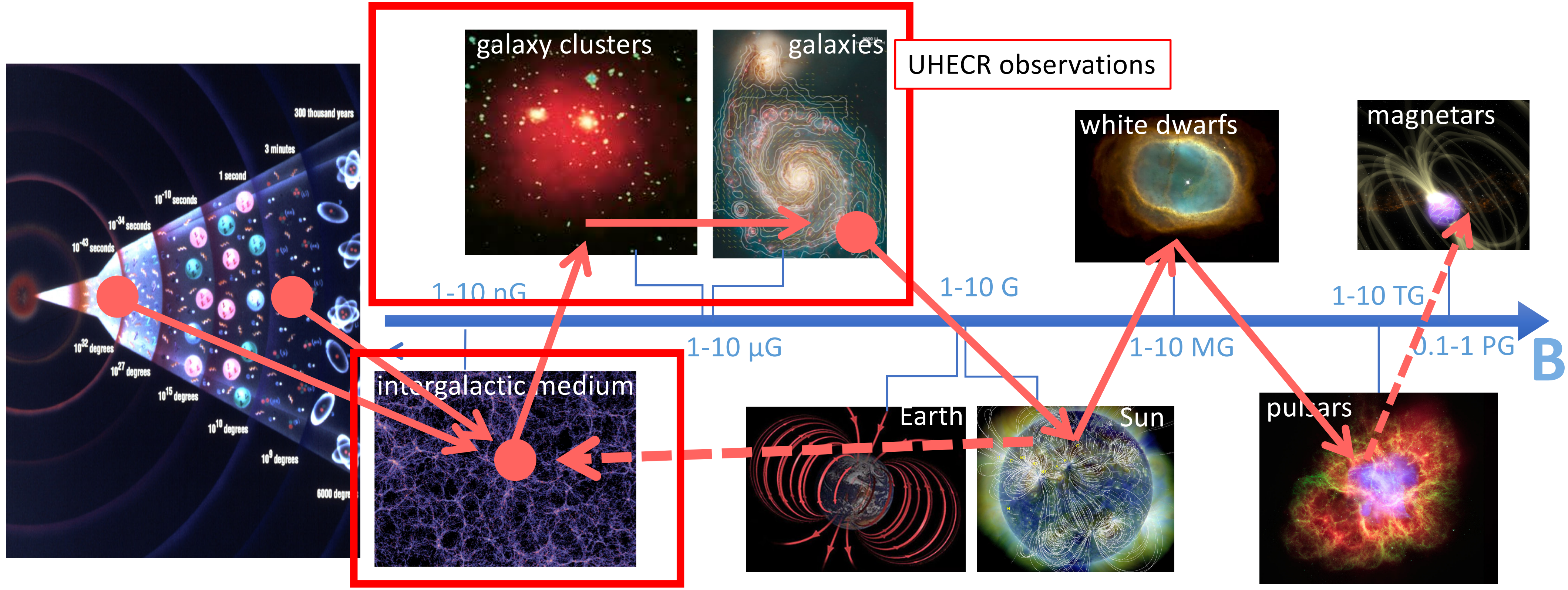
APC, Paris & University of Geneva



Ubiquity of cosmic magnetic fields is due to the common presence of charged particles forming high-conductivity plasma in astrophysical environments. Magnetic field – charged plasma dynamics is governed by MHD effects, which include turbulence, dynamos, viscous and Ohmic dissipation .

Galactic magnetic fields

Structure of large and small scale components of magnetic field in galaxies could be probed via different measurement techniques.

* Synchrotron total intensity

– strength of total field $B_{tot,\perp}$; $E_s \sim \frac{eB_{tot,\perp}E_e^2}{m_e^3}$; $I_s \sim \frac{e^4 B_{tot,\perp}^4 E_e^2}{m_e^4}$

* Polarized synchrotron intensity

– strength and orientation of regular field $B_{reg,\perp}$

* Faraday rotation measure

– strength and orientation of regular field $B_{reg,||}$

– strength and scale of turbulent field $B_{turb,||}$

$$\Delta\psi \sim \frac{e^3}{m_e^2}\lambda^2 RM; \quad RM = \int_{los} B_{||} n_e dl$$

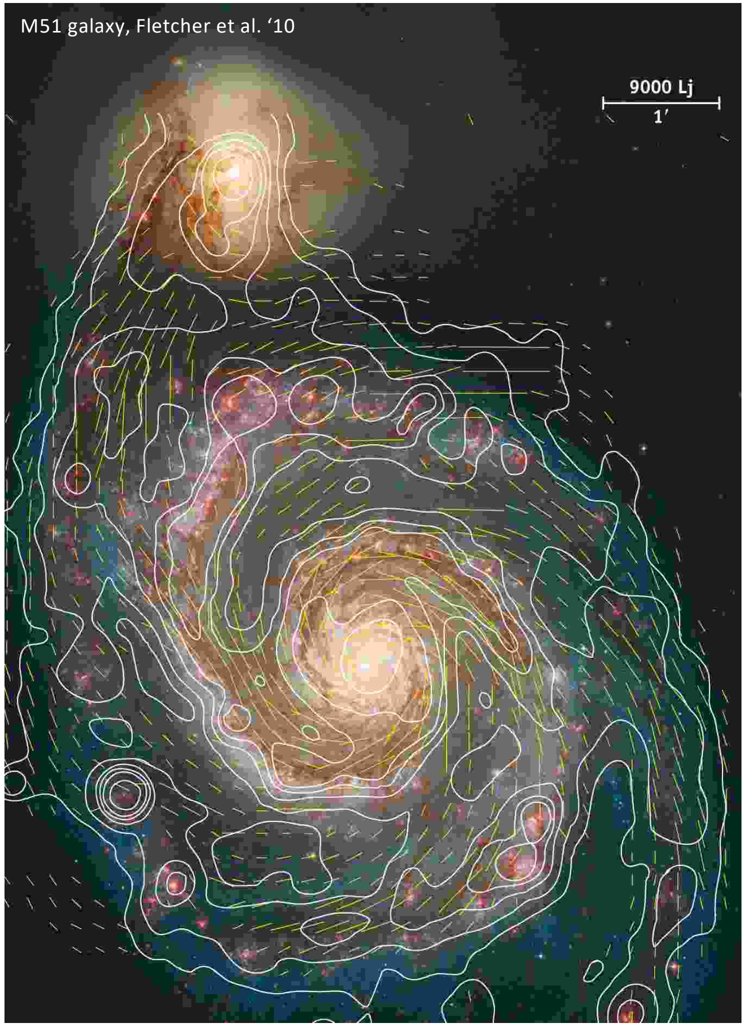
* Polarization of dust emission; polarization of starlight emission by intervening dust

– orientation of regular field $B_{reg,\perp}$

– scale of turbulent field $B_{turb,\perp}$

* Zeeman splitting

–strength and orientation of regular field $B_{reg,||}$; $\Delta E_z \sim \frac{eB}{m_e}$



Milky Way magnetic field

Structure of large and small scale components of magnetic field in galaxies could be probed via different measurement techniques.

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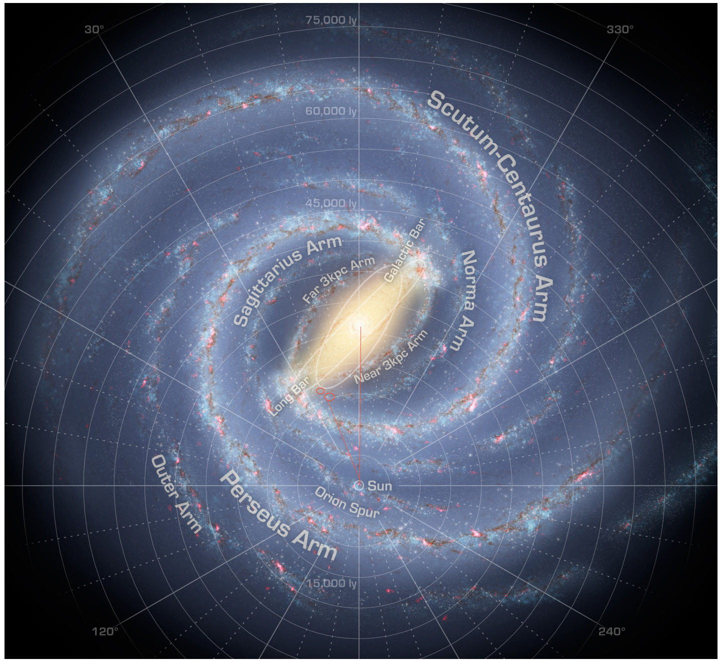
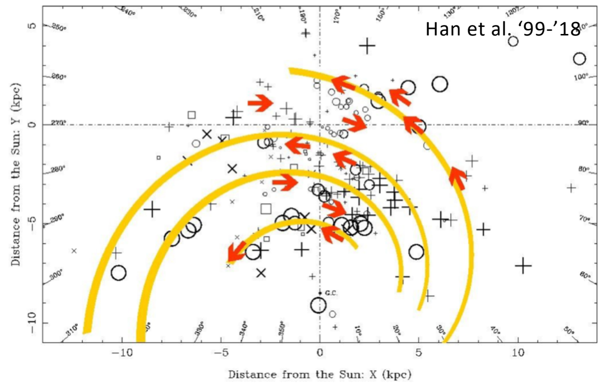
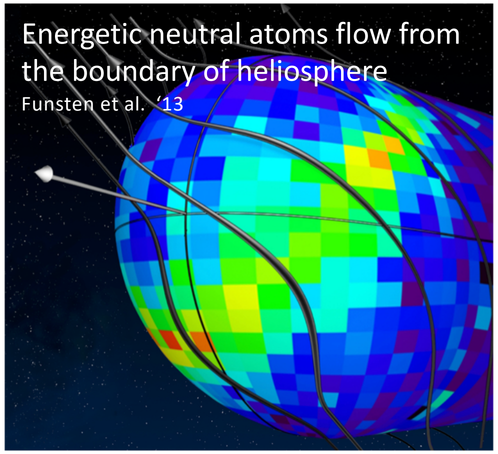


Most of techniques provide field characteristics integrated along the line of sight. Projection effects prevent measurements of global magnetic field structure in the Milky Way.



Study of Faraday rotation in pulsars is and starlight polarization could provide "tomography" type measurements of magnetic field across the Galaxy.

Local Galactic magnetic fields

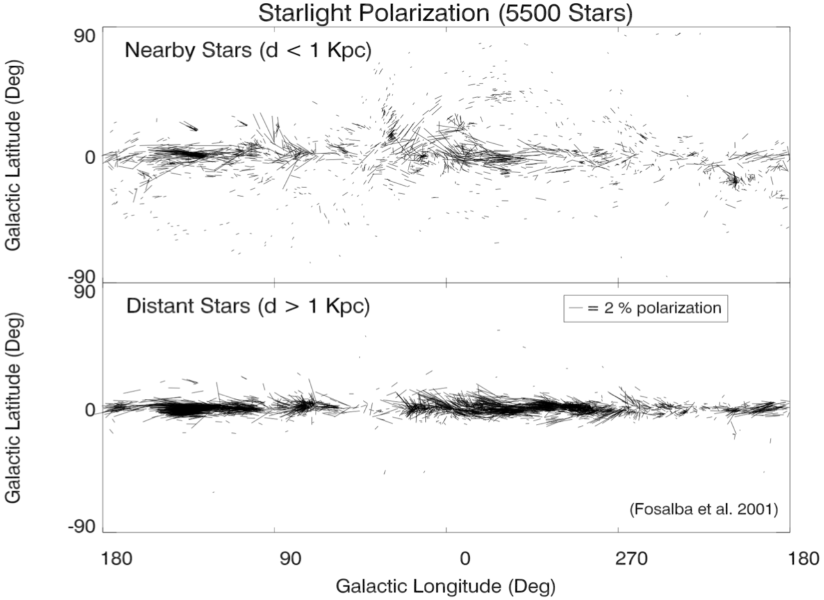


Magnetic field at the boundary of Heliosphere: $(l_0, b_0) = (35^\circ \pm 4^\circ, 56^\circ \pm 1^\circ)$.

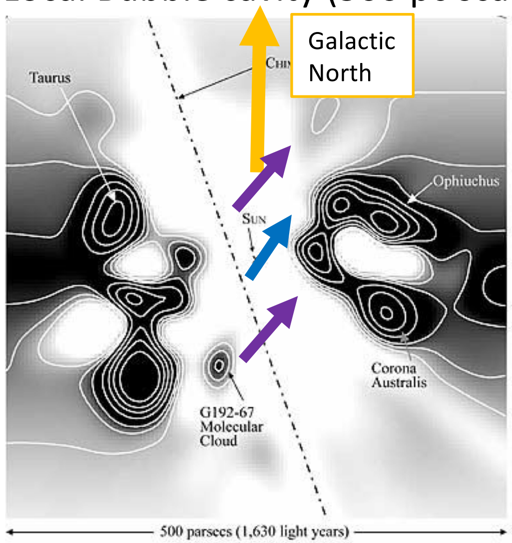
Magnetic field within 40 pc from the Sun: $(l_0, b_0) = (36^\circ \pm 16^\circ, 49^\circ \pm 16^\circ)$.

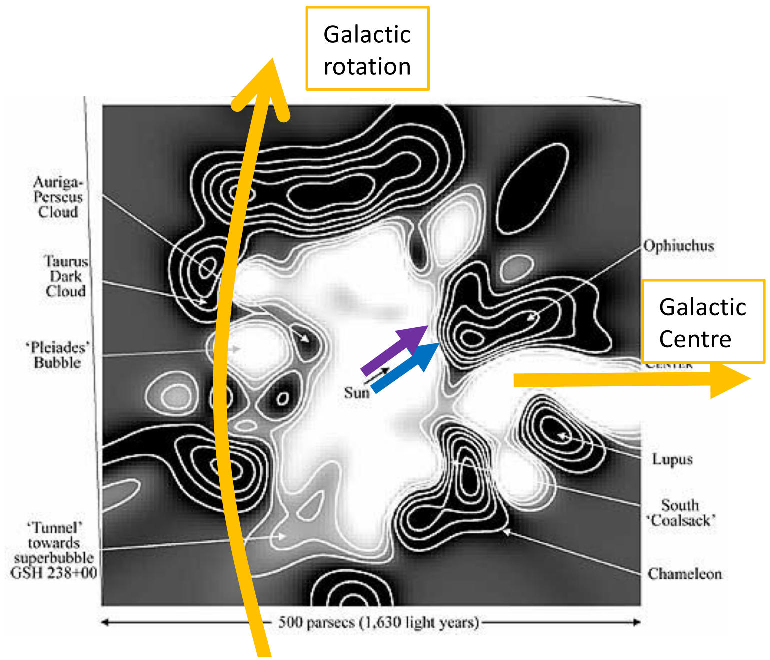
Starlight polarization map

Fosalba et al. '01; Frisch et al. 15



Local Bubble cavity (500 pc scale)





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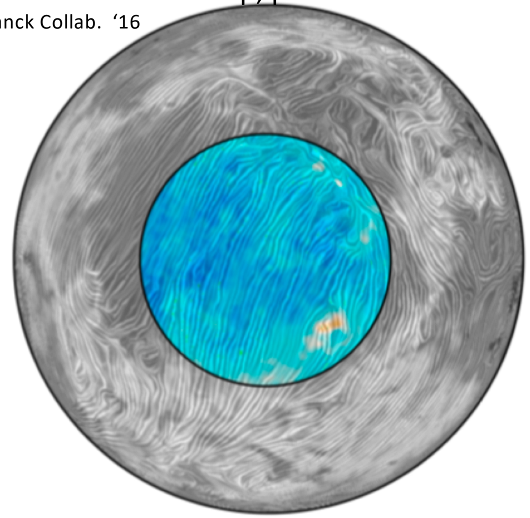
Magnetic field within 200 pc from the Sun (Southern Galactic cap):
$(l_0, b_0) = (70^\circ \pm 5^\circ, 24^\circ \pm 5^\circ)$

$B_{random}/B_{regular} \simeq 0.9$ (field significantly changes direction on $100\ pc$ scale).

Southern Galactic cap, polarized dust emission

Planck Collab. ‘16



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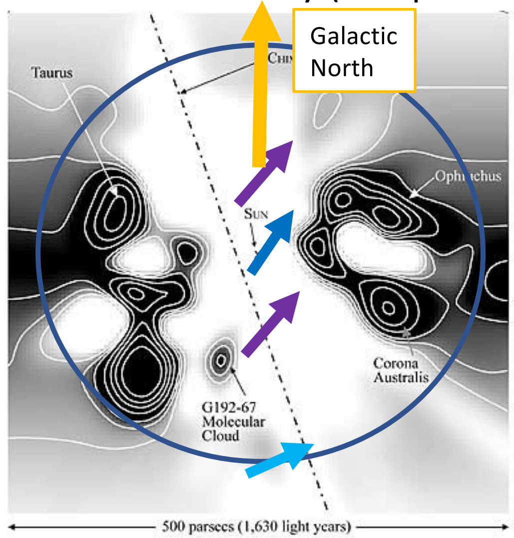
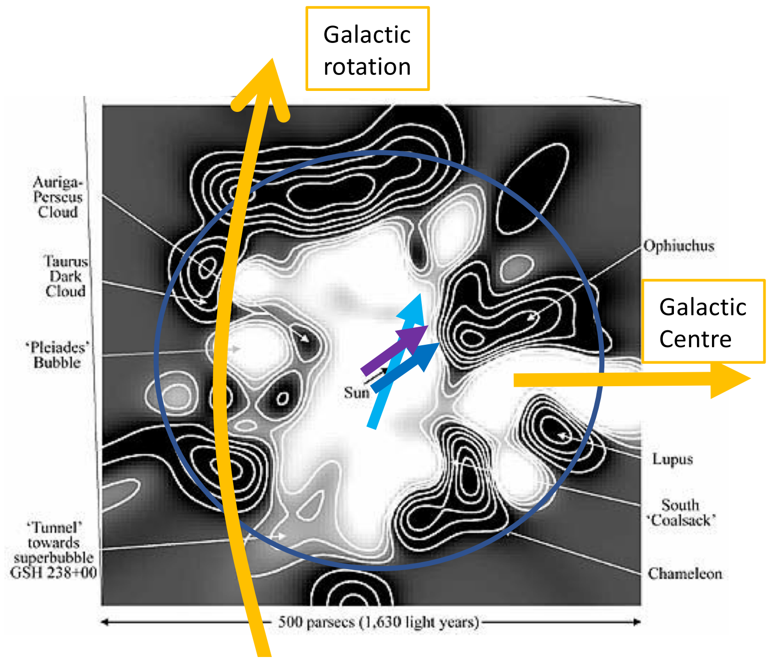
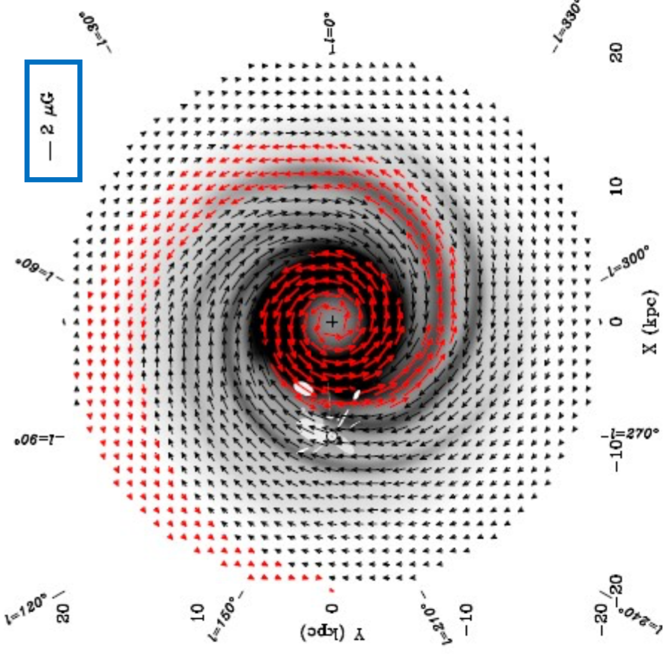


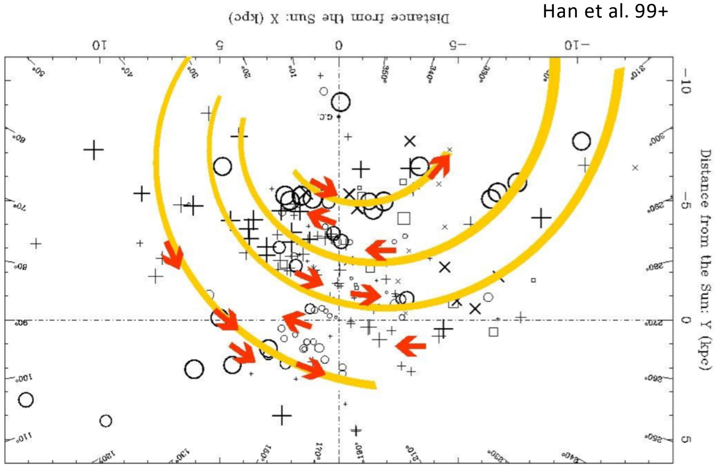


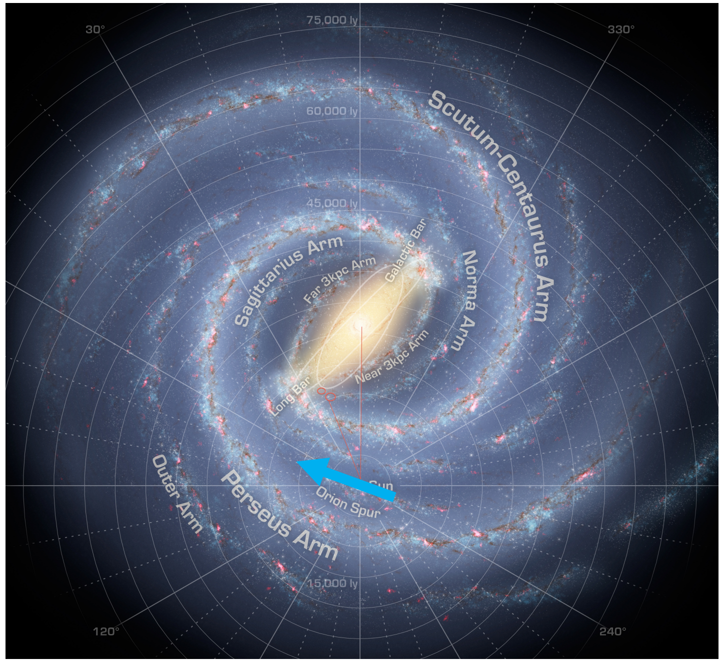
Galactic magnetic field on kiloparsec scales

Sun et al. 08



Han et al. 99+

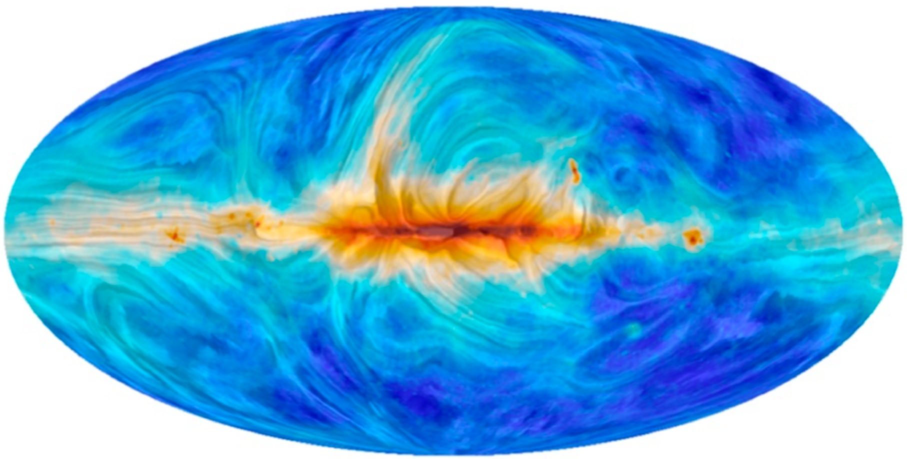




Magnetic field on larger scales (kpc) could be measured based on pulsar rotation measures.
Changes in the rotation measure indicate regular field alignment along spiral arms (in tangential direction) and presence of field reversals.

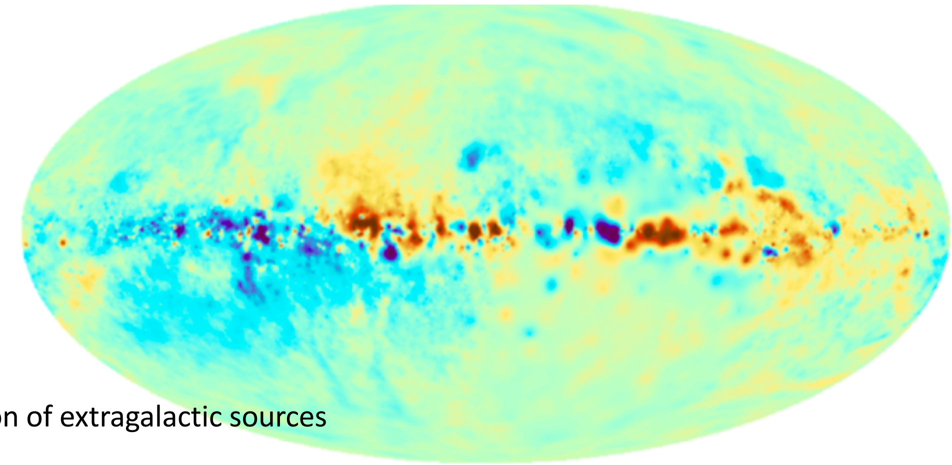
Contrary to stralight / dust polarization, Faraday rotation measurements provide estimate of the field strength (possible if assumptions about density of electrons are made).

Large scale structure of Galactic magnetic field



Synchrotron emission at 30 GHz

Planck Collab. '16



Faraday rotation of extragalactic sources

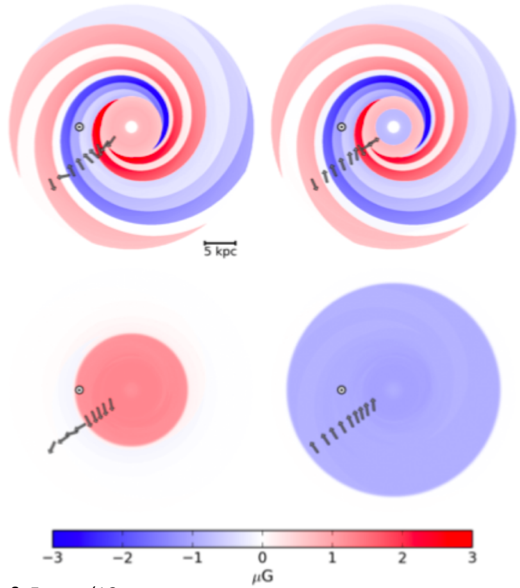
Taylor et al. '09

Oppermann et al. '12

Only line-of-sight integrated field characteristics are measured. Study of 3D field structure not possible, one could only constrain parameters of pre-defined global magnetic field models

Modelling:

* Regular field component B_{reg}
  – disk / halo components
  – toroidal / poloidal components
  – spiral arms
* Isotropic turbulent field component B_{turb1}
  – coherence length L_{coh1}
* Anisotropic turbulent field component B_{turb2}
  – coherence length L_{coh2}, anisotropy ξ



Jansson & Farrar '12

Large scale structure of Galactic magnetic field

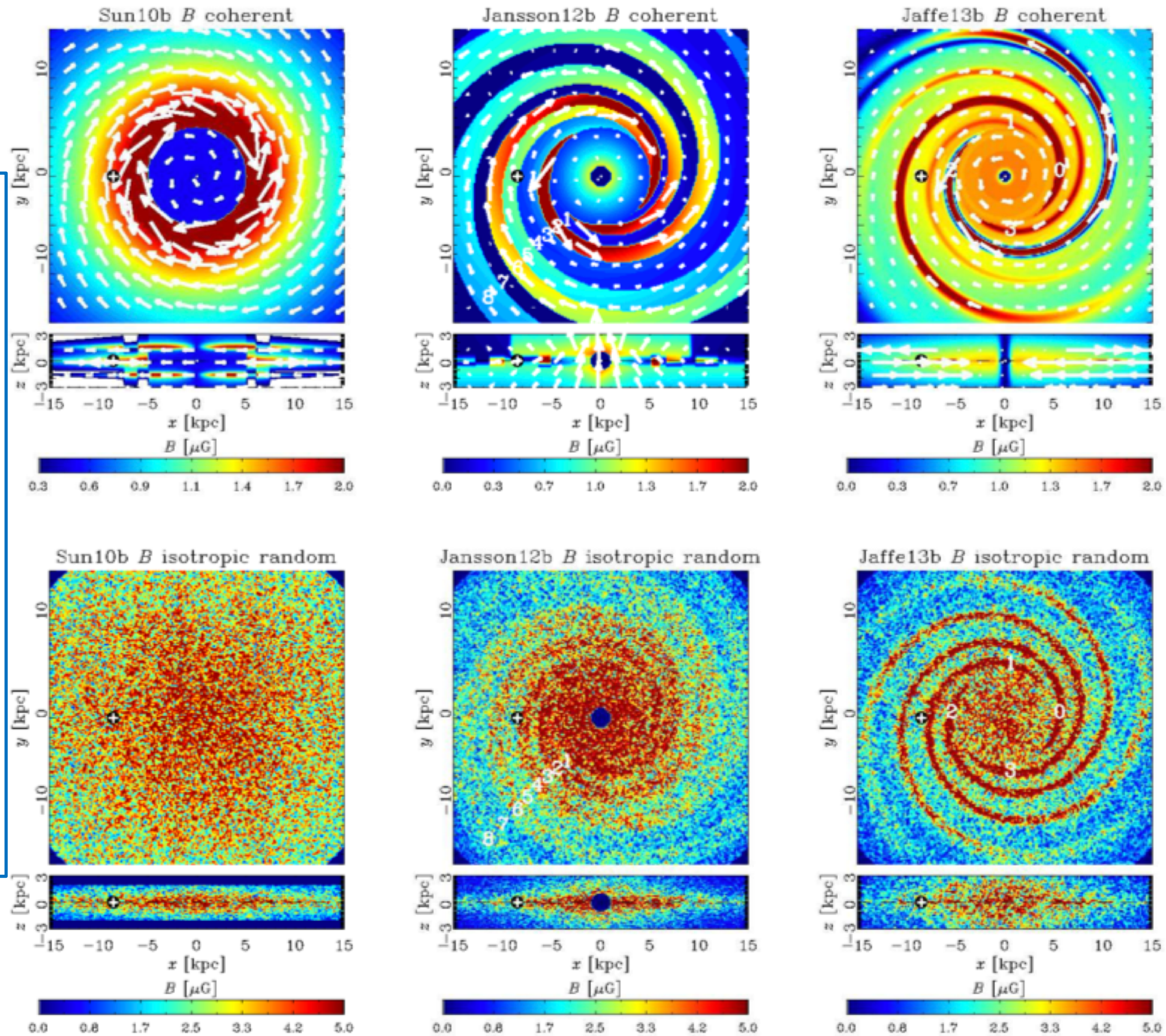
Simultaneous fits to synchrotron, Faraday rotation and dust polarization maps provide constraints on parameters of global magnetic field models.

*Data are consistent with diverse global model choices

* Parameter reconstruction depends on unknown 3d distribution of thermal and cosmic ray electrons.

* Turbulent field is more difficult to estimate than the regular field; JF12 turbulent field estimate revised to lower values by Planck Collab. ‘16

* Even for regular field, details of the field structure not well constrained…



Planck Collab. XLII ‘16

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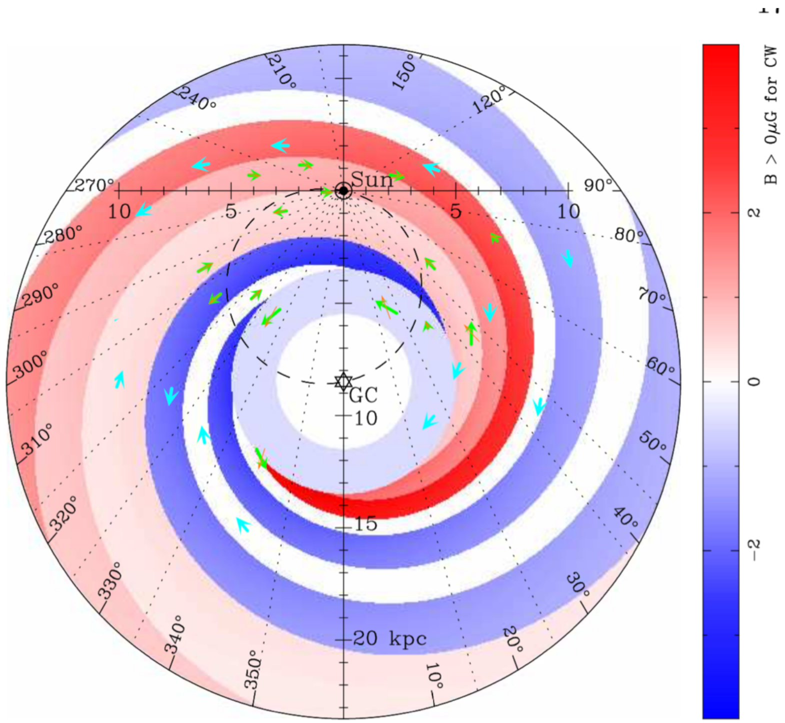
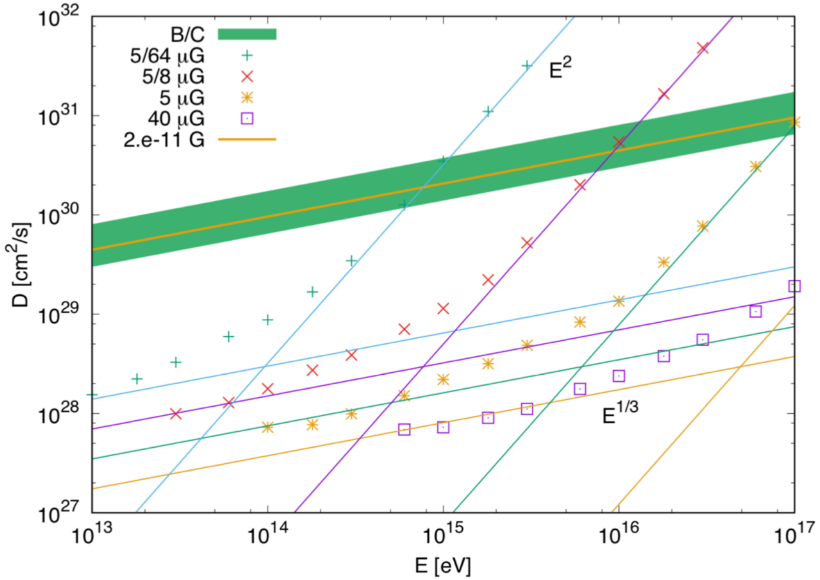
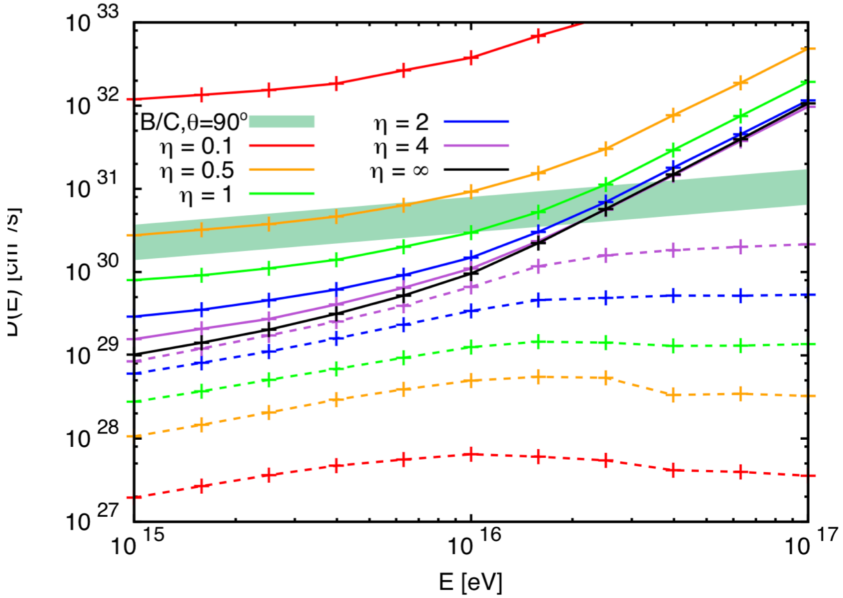


Han et al. ’18
Jansson & Farrar ‘12

Turbulent component of Galactic magnetic field





Existence of large strength of turbulent field component $B_{turb} > B_{reg}$ with correlation length about 100 pc would prevent cosmic ray escape from the Galactic halo on time scales indicated by the measurement of primary / secondary nuclei ratios.

Cosmic ray data indicate that turbulent field is. $B_{turb} < 0.5 B_{reg}$. This implies strongly anisotropic diffusion of cosmic rays spreading / escaping along ordered magnetic field lines.

Presence of out-of-the-plane ordered field component is important in such cosmic ray escape model.

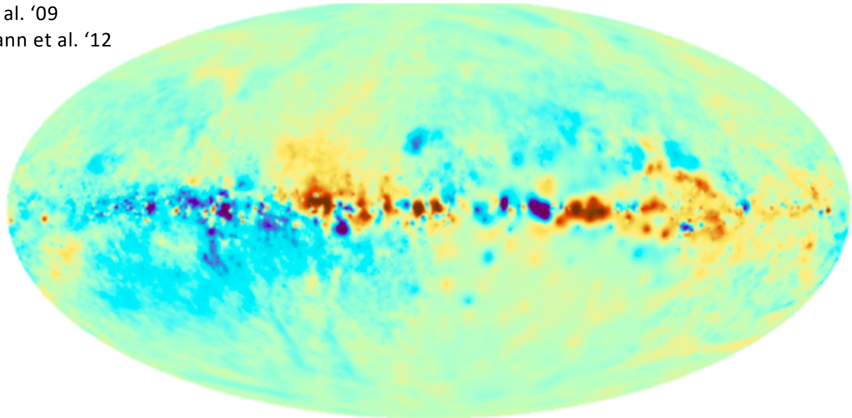
Giacinti et al. ‘18
Snodin et al. ’15
Casse et al. ‘01

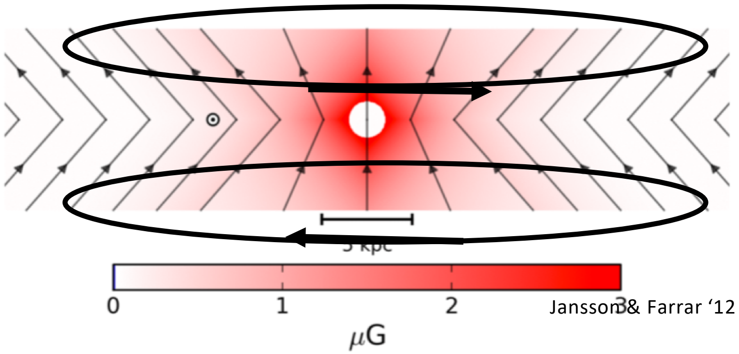
Galactic halo magnetic field

Faraday rotation of extragalactic sources

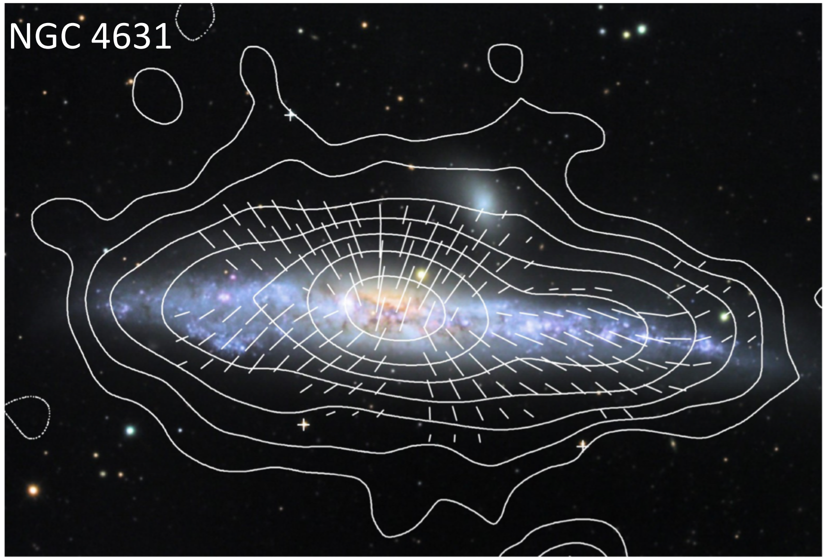
Taylor et al. '09

Oppermann et al. '12



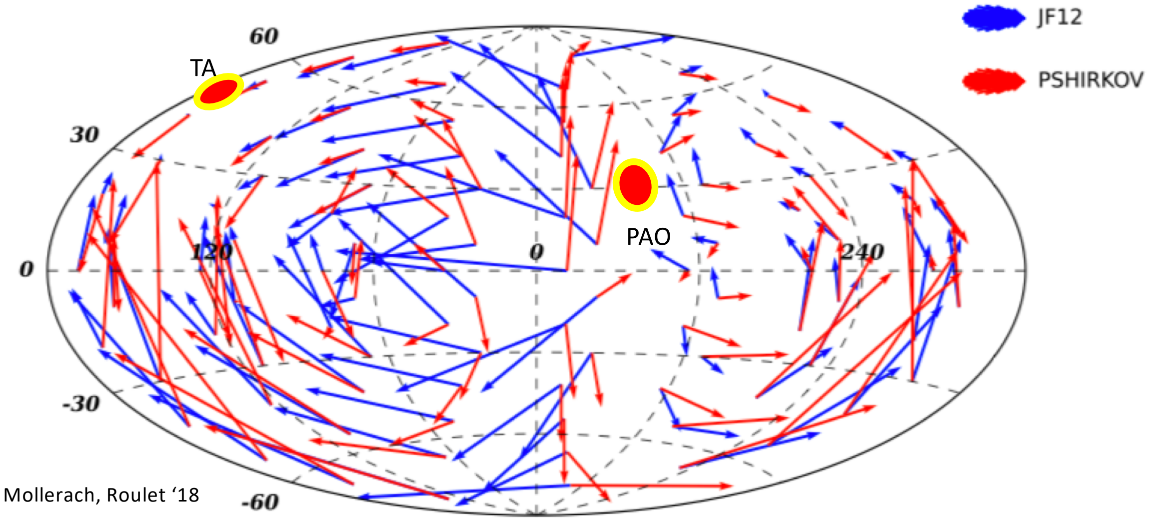


Jansson & Farrar '12



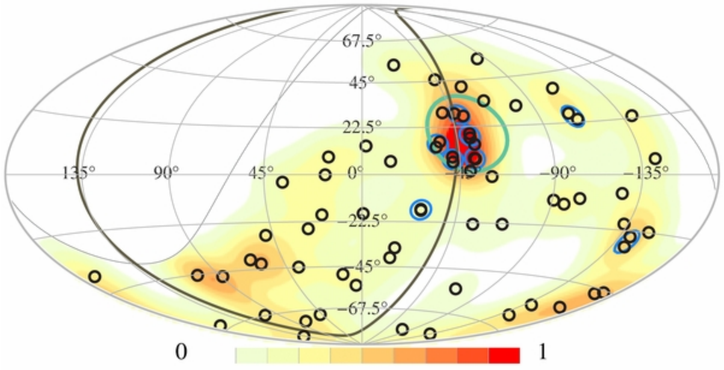
Out-of-the-plane field model inspired by observations of other galaxies ("X-shaped" field); Rotation measure data suggest existence of a toroidal component counter-rotating above / below the Galactic Plane.

UHECR deflections by Galactic magnetic field

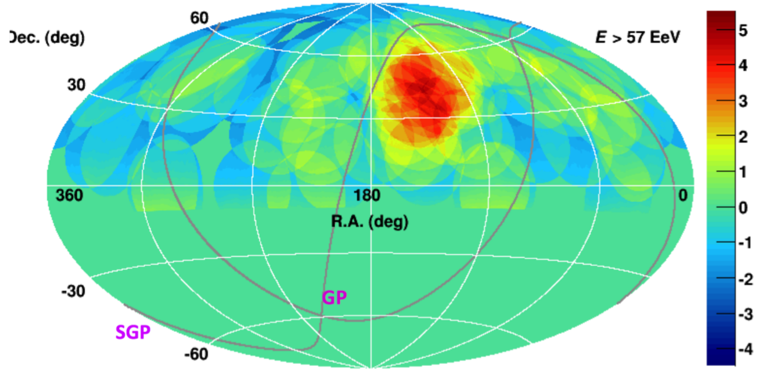


Mollerach, Roulet ‘18

Pierre Auger Observatory “hot spot” Abraham et al. ‘08



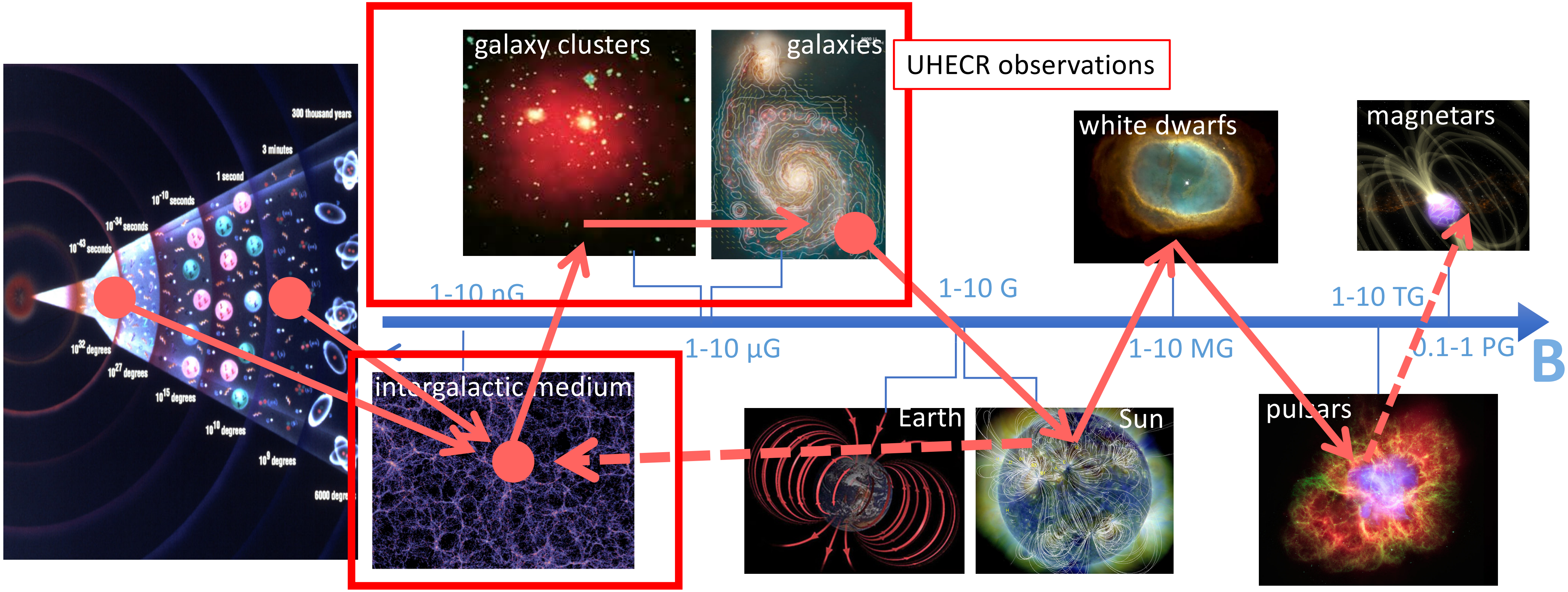
Telescope Array “hot spot” at 20º angular scale, Fukushima et al. ‘13



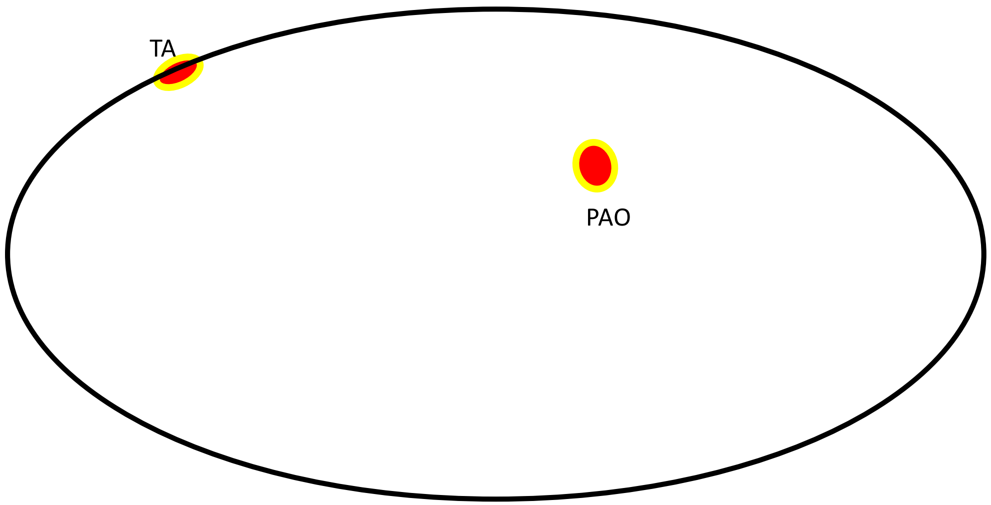
Large uncertainties in modelling of both regular and turbulent Galactic magnetic result in uncertainties of predictions of UHECR deflection patterns.

UHECR measurements have potential to test / constrain global Galactic magnetic field models

Galactic and intergalactic magnetic fields



UHECR deflections by intergalactic magnetic field



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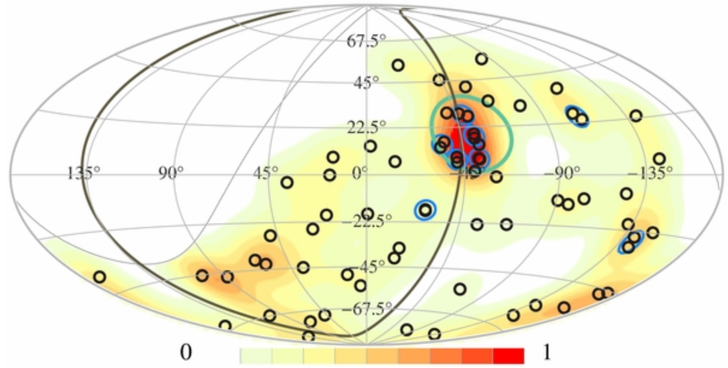

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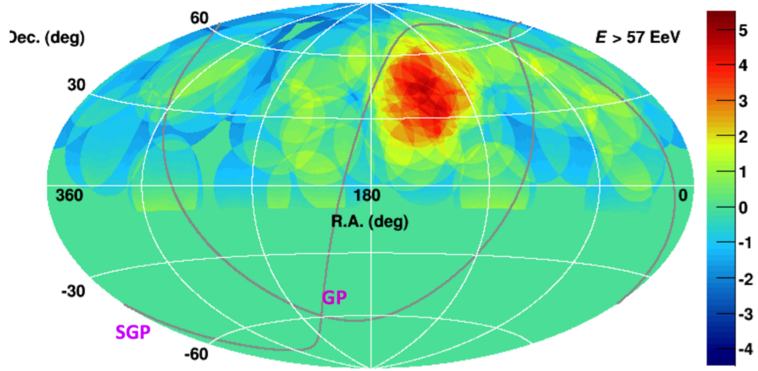


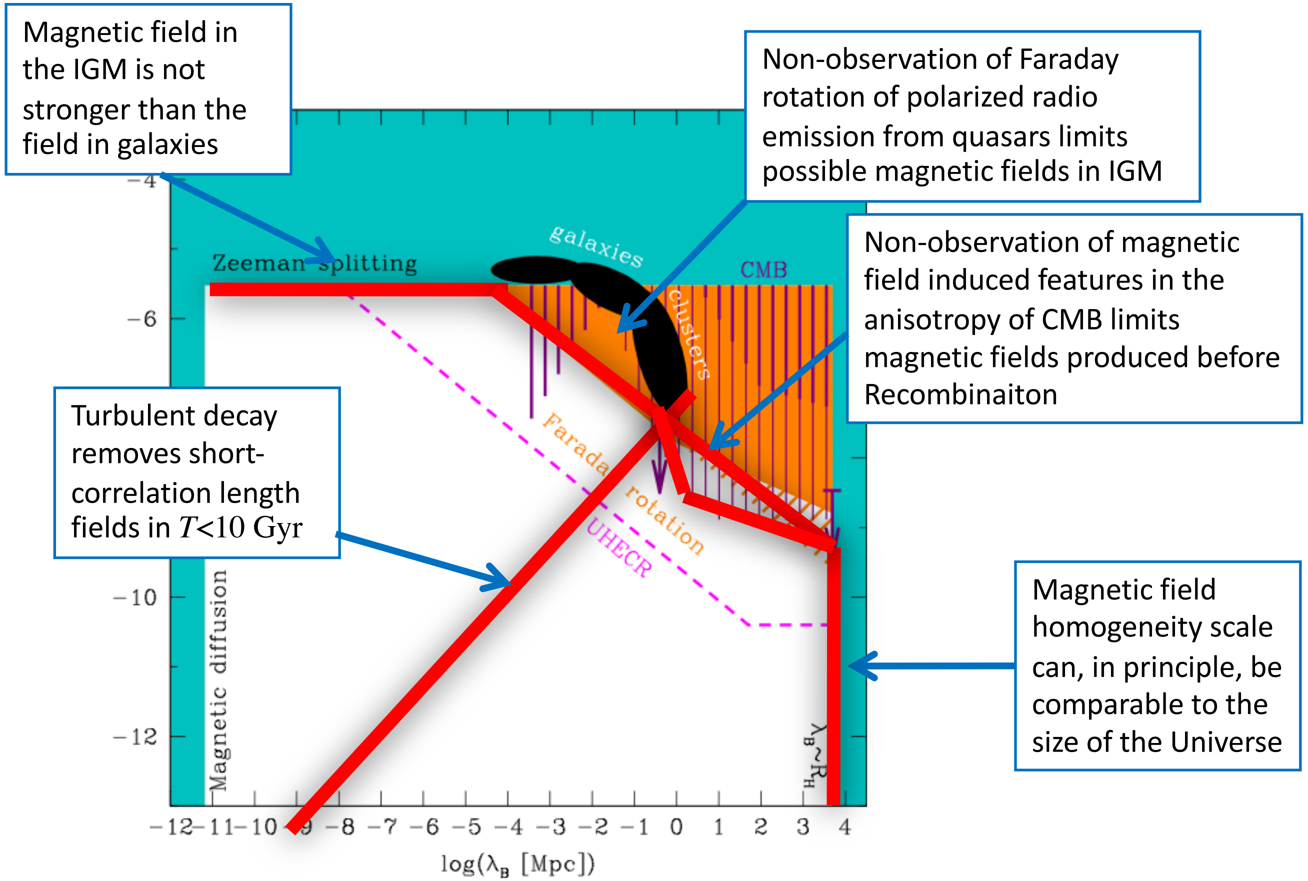
The deflection angle by intergalactic magnetic field with strength *B*

$$\theta = \frac{eBD}{E} \simeq 3^\circ \left[\frac{B}{10^{-6}G}\right]\left[\frac{D}{5\ kpc}\right]\left[\frac{E}{10^{20}eV}\right]^{-1}$$

$$\theta = \frac{eBD}{E} \simeq 3^\circ \left[\frac{B}{10^{-10}G}\right]\left[\frac{D}{50\ Mpc}\right]\left[\frac{E}{10^{20}eV}\right]^{-1}$$

Magnetic field with nG strength in intergalactic medium could produce UHECR deflections comparable to those by Galactic magnetic field.

Intergalactic magnetic field measurement techniques



Neronov & Semikoz '09

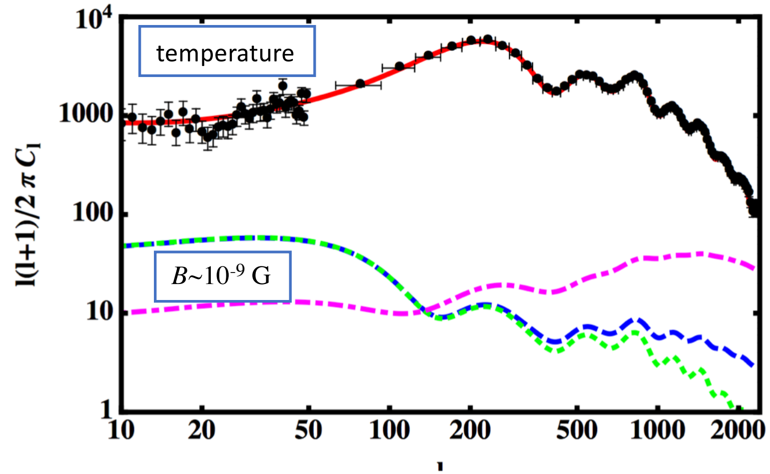
Intergalactic magnetic field measurement techniques

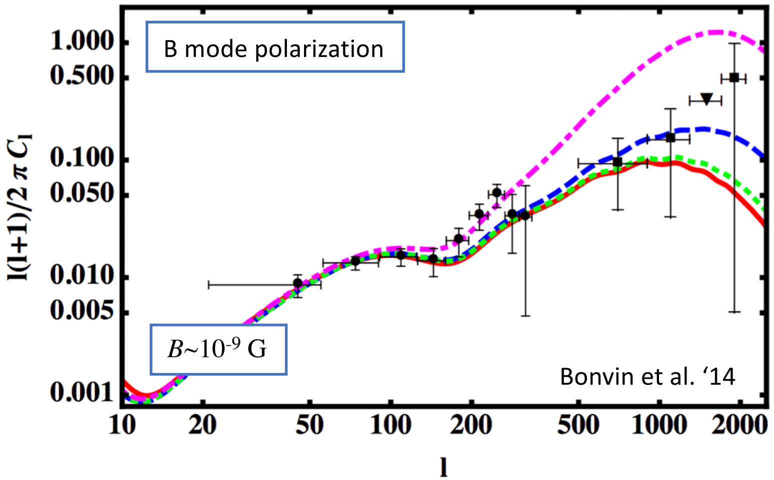
Presence of magnetic field affects CMB anisotropies and polarization in multiple ways: generation of vector and tensor perturbations, generation of magnetosonic waves, Faraday rotation of polarization, …

Magnetic field does not dominate the structure of CMB anisotropies:
$\varrho_B < 10^{-6}\varrho_{cr} \sim (3\times10^{-9}\ \mathrm{G})^2/8\pi$

Magnetic field drives compressible turbulence in the medium and induces inhomogeneities during the recombination. This leads to additional density fluctuations.

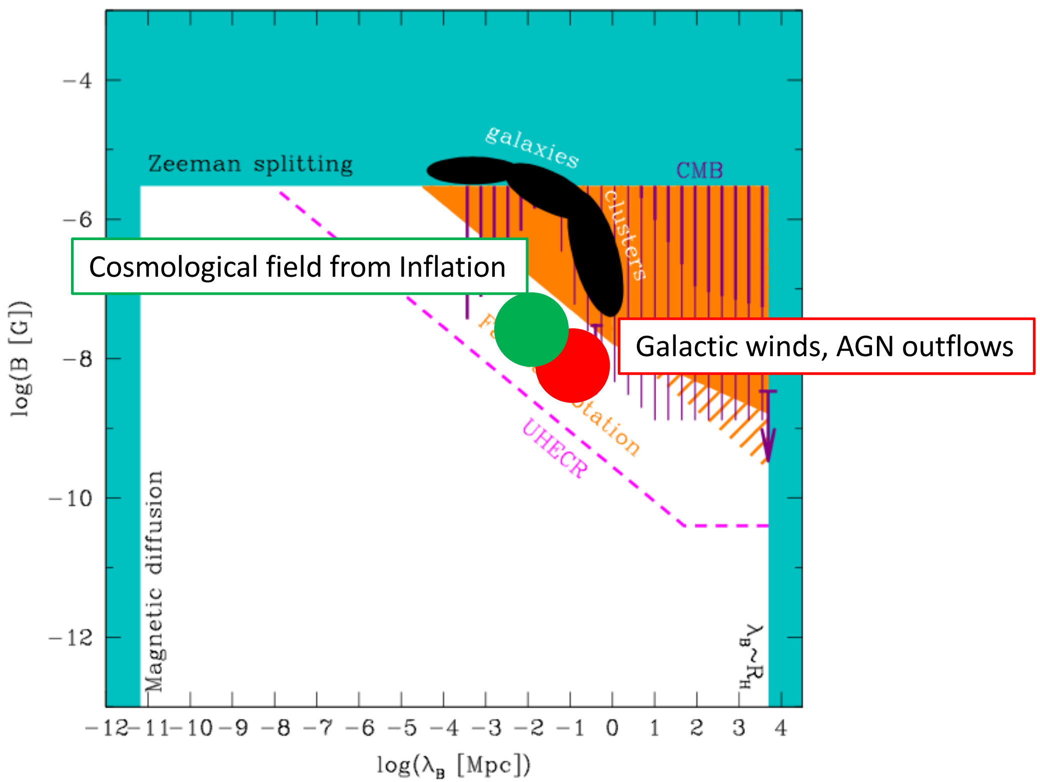
Magnetic field also induces B-mode polarization. A 10^{-9} G field would produce polarization at the level close to existing upper bound.





Barrow et al '97, Seshadri & Subramanian '01, Lewis '04, Kahniashvili & Ratra '07, Durrer '07, Shaw & Lewis '10, '12, …

Intergalactic magnetic field measurements



Furnaleto & Loeb '01
Bertone et al. '06
Durrer, Neronov '13
Neronov & Semikoz '09

Intergalactic magnetic field measurement with gamma-rays

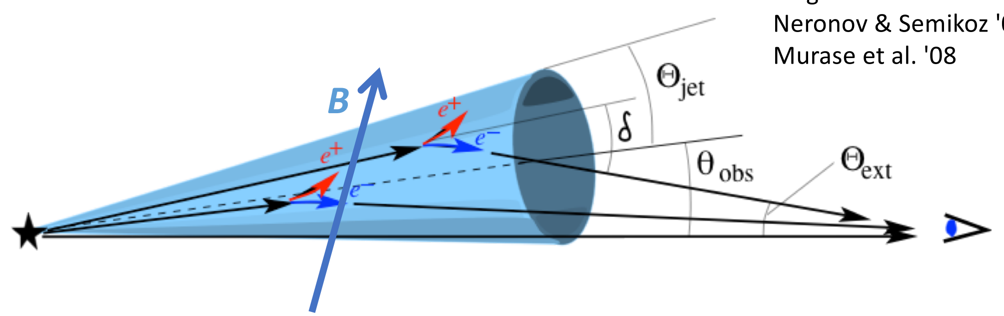
γ-rays could interact on the way from the source:

$\gamma + \gamma_b \rightarrow e^+ + e^-$

Mean free path of gamma-rays: $\lambda_\gamma \sim 1 \left|\frac{E_\gamma}{0.3\ \mathrm{TeV}}\right|^{-1}$ Gpc

Energy threshold: $E_\gamma > \frac{m_e^2 c^4}{E_b} \simeq 0.25 \left[\frac{E_b}{1\ \mathrm{eV}}\right]^{-1}$ TeV

Aharonian, Coppi & Voelk '94
Plaga '95
Neronov & Semikoz '07, '09
Murase et al. '08



Electrons / positrons convert low energy photons in gamma-rays via inverse Compton scattering

$\gamma_b + e \rightarrow \gamma + e$

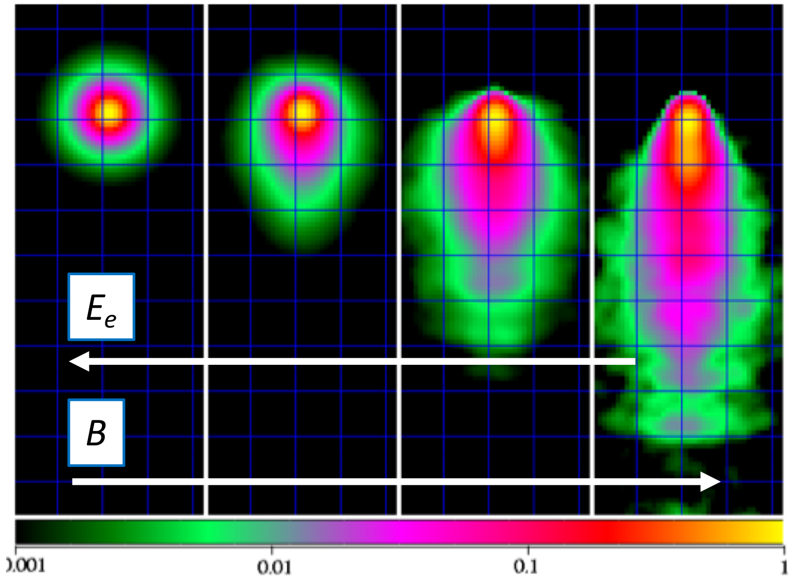
Energy loss rate and cooling distance:

$$\frac{dE_e}{dt} = \sigma_T U_b \frac{E_e^2}{m_e^2} \qquad l_e = \frac{E_e}{dE_e/dt} \simeq 10^{21} \left|\frac{E_e}{10\ TeV}\right|^{-1} \mathrm{cm}$$

Energy of upscattered gamma-rays:

$$E_\gamma \simeq \frac{E_e^2}{m_e^2} E_b \simeq 10^2 \left|\frac{E_e}{10\ TeV}\right|^2 \mathrm{GeV}$$

Neronov et al., Ap.J., 719, L130 (2010)



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Deflection angle: $\delta \sim r_g / l_e$.

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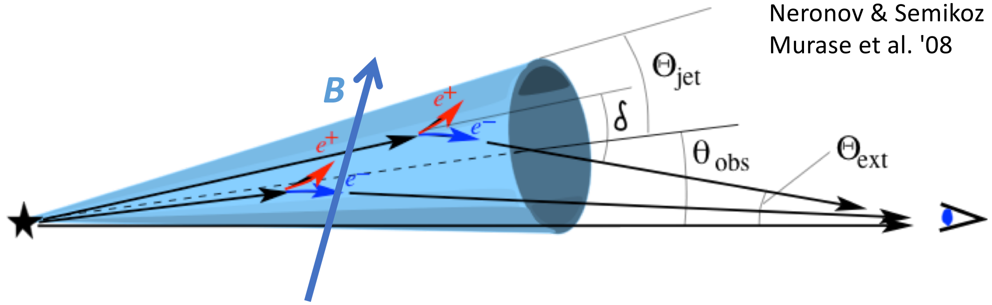

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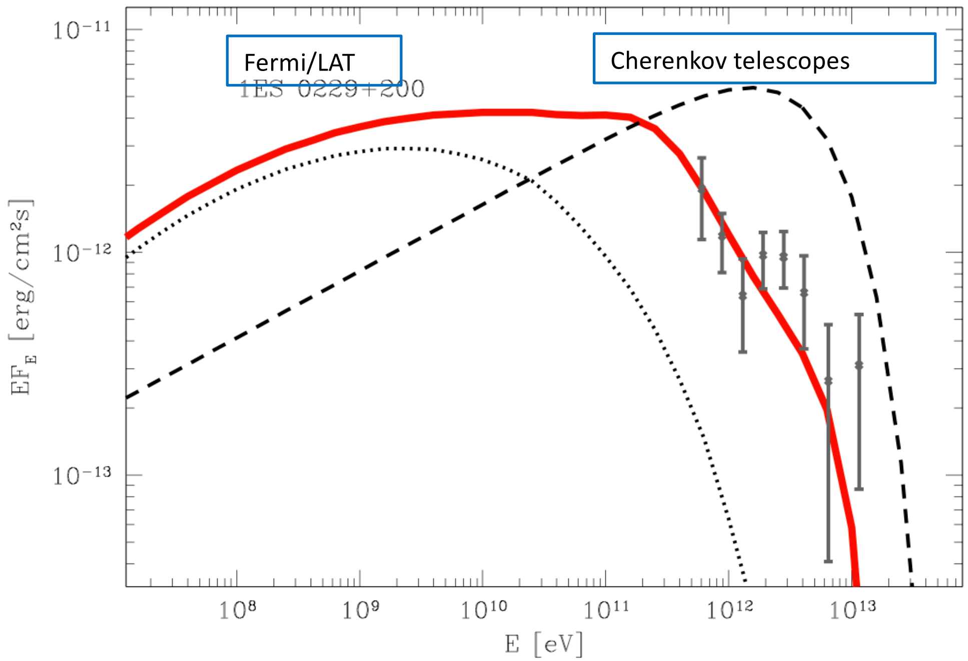

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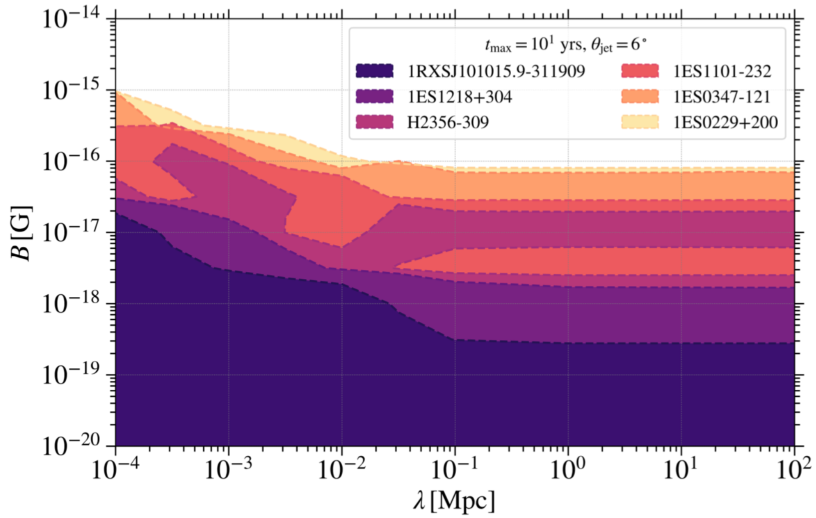
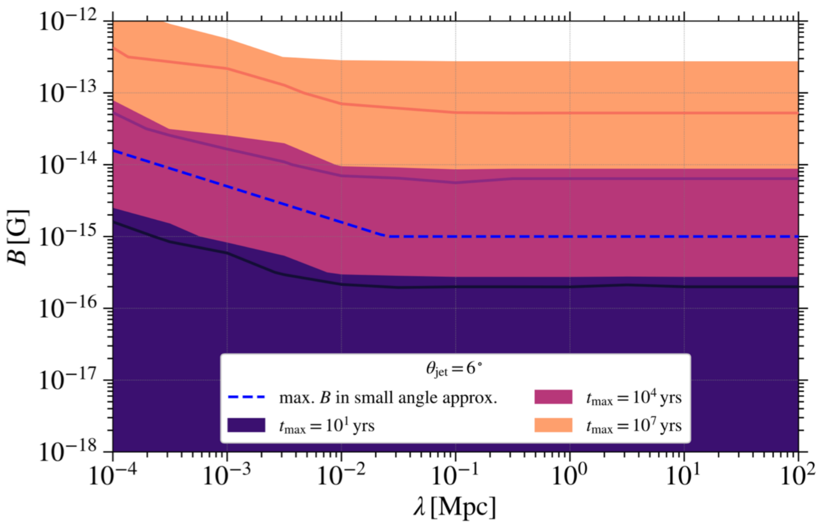
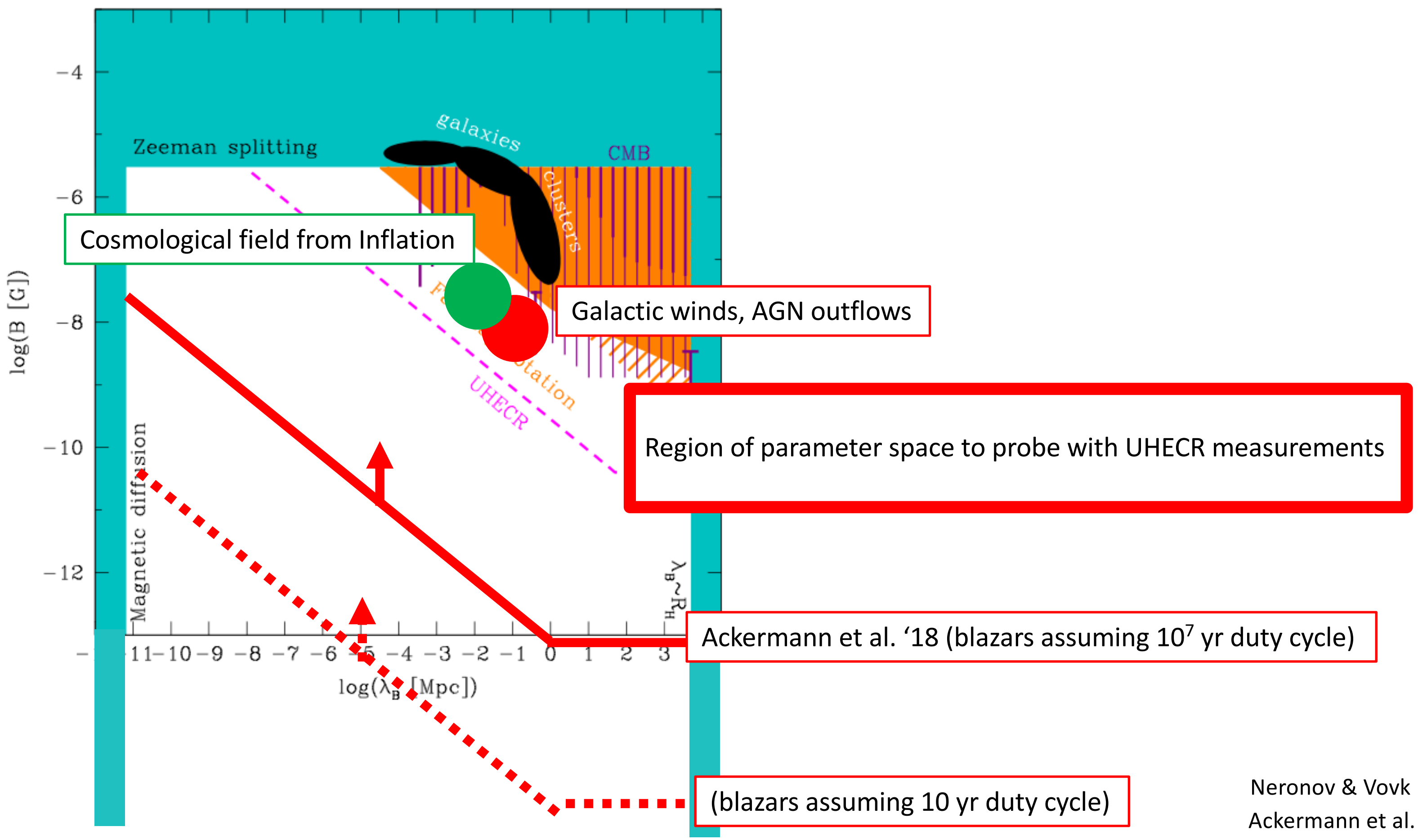




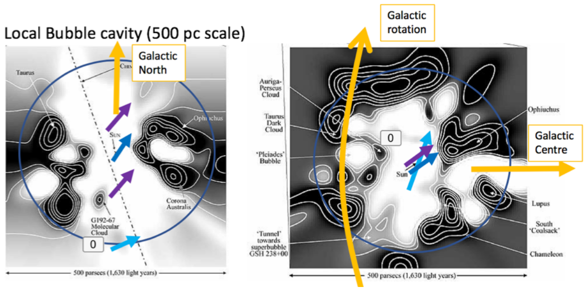
Ackermann et al. '18

Intergalactic magnetic field measurements

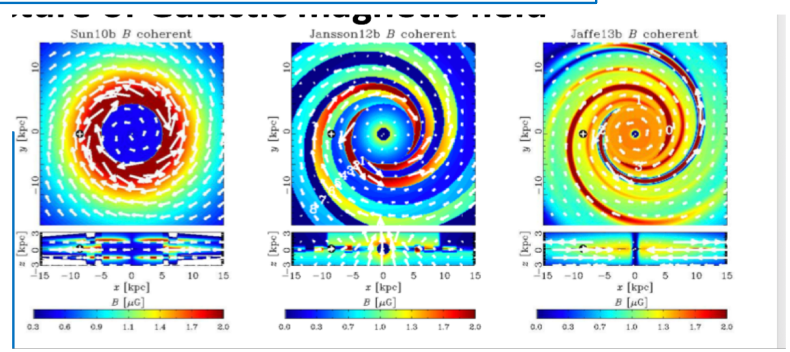


Neronov & Vovk '10
Ackermann et al. '18

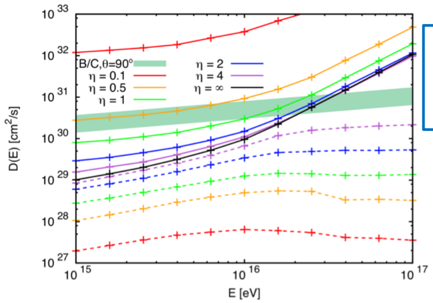
Summary



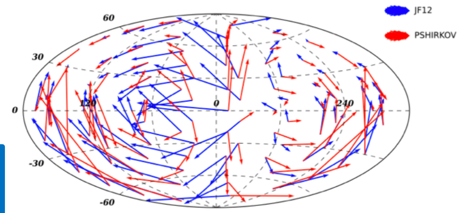
Local interstellar medium magnetic field is affected by Local Bubble environment



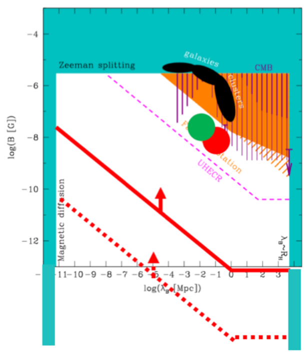
Global geometry of Galactic magnetic field is uncertain, only constraints on different analytical models are constrained



Turbulent field component is constrained by low-energy cosmic ray diffusion characteristics



UHECR measurements (still) have potential to test / constrain global Galactic magnetic field models



Distance between upper and lower bounds on intergalactic magnetic fields is shrinking. UHECR observations have potential to probe still allowed range of magnetic field strengths and correlation lengths