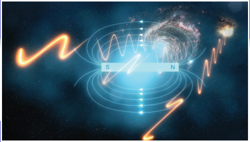

Magnetic fields and UHECR propagation

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6^{th} *International Symposium*
on Ultra High Energy Cosmic Rays
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Outline

Outline

Magnetic fields and cosmic rays

The existence of interstellar magnetic fields was first predicted as a means to *confine* and *accelerate* Galactic cosmic rays

- Alfvén (1937)
  Cosmic-ray confinement implies
  ”the existence of a magnetic field in interstellar space”

- Fermi (1949)
  ”The main process of [cosmic-ray] acceleration
  is due to [interstellar] magnetic fields ...
  The magnetic field in the dilute matter is $\sim 5\ \mu\mathrm{G}$,
  while its intensity is probably greater in the heavier clouds”

☞ The history of interstellar magnetic fields
is intimately linked to the history of cosmic rays

Magnetic fields and cosmic rays

The Galactic magnetic field, $\vec{B}$, deflects the trajectories of cosmic rays

This deflection is measured by the Larmor radius, $r_{\rm g}$

- 1 GeV CR

  $$r_{\rm g} \simeq (0.2\,{\rm AU})\,(B_{\mu{\rm G}})^{-1} \simeq (10^{-6}\,{\rm pc})\,(B_{\mu{\rm G}})^{-1} \lll L_B\,,\ H_{\rm Gal}$$

  ☞ CR has *helical* motion along field lines (negligible drift)
  with some diffusion due to small-scale $\delta\vec{B}$ and collisions

- 1 EeV CR

  $$r_{\rm g} \simeq (1\,{\rm kpc})\,(B_{\mu{\rm G}})^{-1} \sim L_B\,,\ H_{\rm Gal}$$

  ☞ CR motion is *moderately deflected* by $\vec{B}$
  such that trajectory is neither straight nor helical

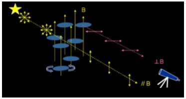
Outline

Observational tools

- **Polarization of starlight & dust thermal emission**

  Due to *dust grains* → general (dusty) ISM

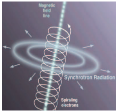
  ☞ $\vec{B}_\perp$ (orientation only)



- **Synchrotron emission**

  Produced by *CR electrons* → general (CR-filled) ISM

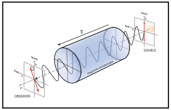
  ☞ $\vec{B}_\perp$ (strength & orientation)



- **Faraday rotation**

  Caused by *thermal electrons* → ionized regions

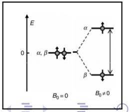
  ☞ $B_\parallel$ (strength & sign)



- **Zeeman splitting**

  Molecular & atomic *spectral lines* → neutral regions

  ☞ $B_\parallel$ (strength & sign)

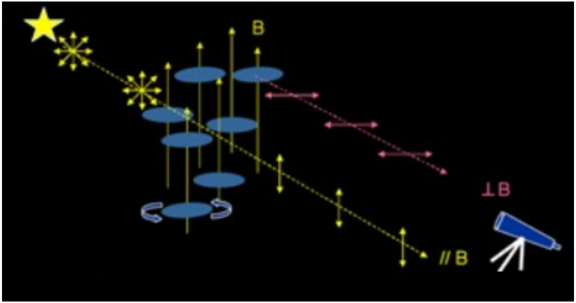


Outline

Physical concept

Dust grains tend to spin about their short axes
& to align their spin axes with $\vec{B}$

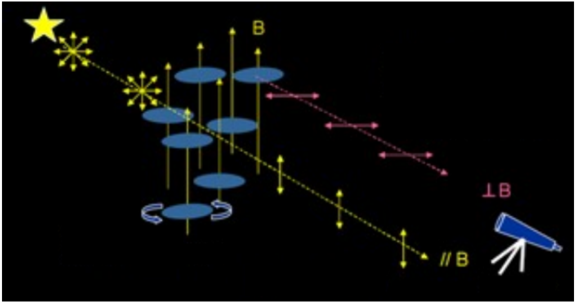
This grain alignement leads to *linear polarization*



Credit: Wen-Ping Chen

Polarization orientation

- Starlight attenuated by dust *(optical)* is polarized $\parallel \vec{B}_\perp$
- Dust thermal emission *(infrared)* is polarized $\perp \vec{B}_\perp$



Credit: Wen-Ping Chen

Polarization fraction

$$p \equiv \frac{P}{I}$$

- Starlight attenuated by dust : $p \simeq \tau \, p_0 \cos^2 \gamma$
- Dust thermal emission : $p = p_0 \cos^2 \gamma$

↳ $p_0 = p_{max} \, F_{align} \, F_{\delta B}$

$\vec{B} \in \mathrm{PoS}$

$\left(\cos^2 \gamma = 1\right)$

$\Rightarrow \; p = p_0$

$\vec{B} \perp \mathrm{PoS}$

$\left(\cos^2 \gamma = 0\right)$

$\Rightarrow \; p = 0$

Credit: Vincent Guillet

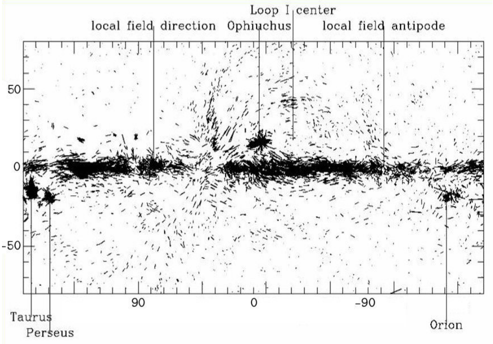
Dust polarization

Altogether

- Polarization *orientation* ☞ *orientation* of $\vec{B}$ *in* PoS
- Polarization *fraction* ☞ *inclination* of $\vec{B}$ *to* PoS (for ideal conditions)

Polarization of starlight

$\vec{B}_\perp$ segtors from 8 662 stars



Heiles (2000)

☞ Near the Sun - In the disk : $\vec{B}_{\rm ord}$ is horizontal

$\vec{B}_{\rm ord}$ is nearly azimuthal ($\simeq -7°$ from $\hat{e}_\phi$)

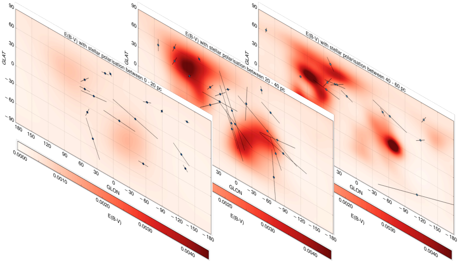
- In the halo : $\vec{B}_{\rm ord}$ has a vertical component

Polarization of starlight

Stars have accurately measured distances (with Gaia)

☞ Possible to probe $\vec{B}$ in 3D

Stellar polarization cube of nearby ISM



3 layers at

0 – 20 pc

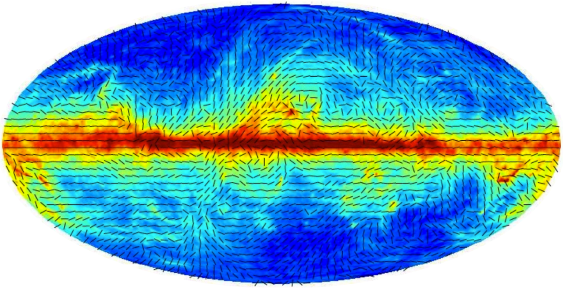
20 – 40 pc

40 – 60 pc

Credit: Marta Alves

Polarization of dust thermal emission

Total intensity & $\vec{B}_\perp$ segtors at 353 GHz (Planck)



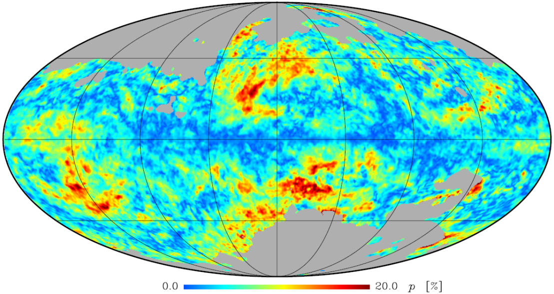
Planck collaboration (2015)

☞ - In the disk : $\vec{B}_{\rm ord}$ is horizontal

- In the halo : $\vec{B}_{\rm ord}$ has a vertical component

Polarization of dust thermal emission

Polarization fraction at 353 GHz (Planck)



Planck collaboration (2015)

☞ Info on - Inclination of $\vec{B}_{\rm ord}$ to PoS : $\cos^2\gamma$

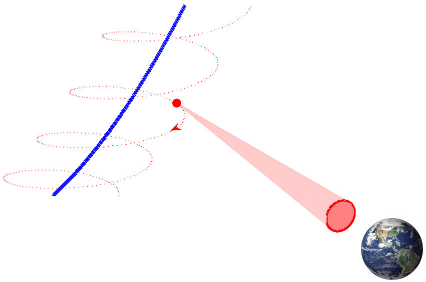
- Magnetic fluctuations : $\frac{B_{\rm fluct}}{B_{\rm ord}}$

- Grain properties & alignment efficiency : $p_{\rm max}$ & $F_{\rm align}$

Outline

Physical concept

Relativistic electrons gyrating about magnetic field lines emit *synchrotron radiation*

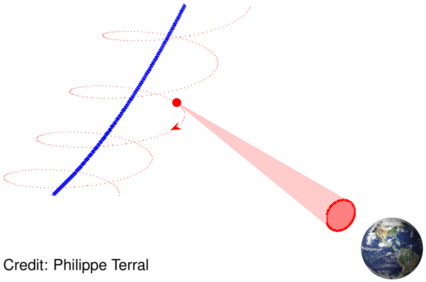


Credit: Philippe Terral

Total & polarized intensities

Emissivity : $\mathcal{E} = f(\alpha)\, n_{\rm CRe}\, B_\perp^{\alpha+1}\, \nu^{-\alpha}$ & $\mathcal{E}_{\rm pol} = p_{\rm syn}\, \mathcal{E}$ & $\overleftrightarrow{\mathcal{E}}_{\rm pol} \perp \overrightarrow{B}_\perp$

- Total intensity : $I = \int \mathcal{E}\, ds$ ☞ $B_\perp$
- Polarized intensity : $\overleftrightarrow{P} = \int \overleftrightarrow{\mathcal{E}}_{\rm pol}\, ds$ ☞ $(\overleftrightarrow{B}_\perp)_{\rm ord}$



Credit: Philippe Terral

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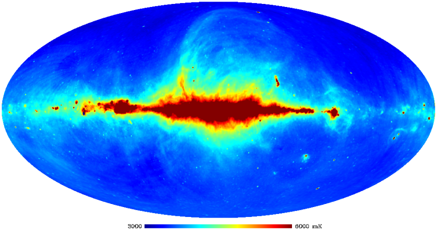
- Polarized intensity : $\overleftrightarrow{P} = \int \overleftrightarrow{\mathcal{E}}_{\rm pol}\, ds$ ☞ $(\overleftrightarrow{B}_\perp)_{\rm ord}$

↳ $Q + i\,U = \int \mathcal{E}_{\rm pol}\, e^{2i\psi}\, ds$

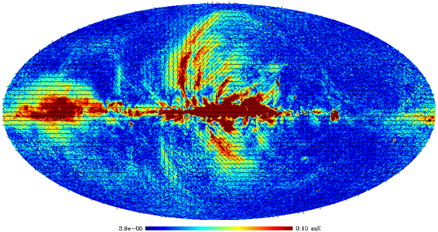
Total & polarized intensities

TI at 1.4 GHz (25m Stockert + 30m Villa Elisa)



Credit: Tess Jaffe

PI & $\vec{B}_\perp$ sectors at 23 GHz (WMAP)



Credit: Tess Jaffe

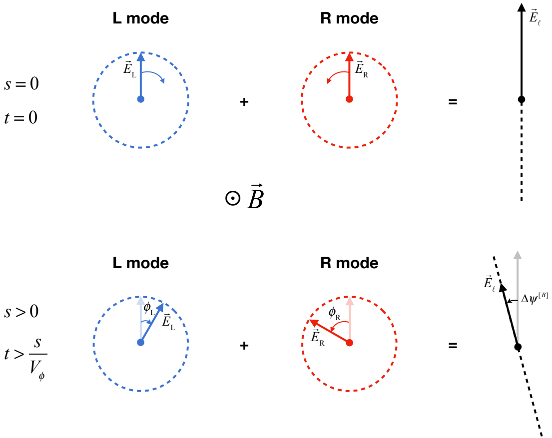
☞ - Near the Sun : $B_{\rm ord} \sim 3\ \mu{\rm G}$ & $B_{\rm tot} \sim 5\ \mu{\rm G}$

- In the disk : $\vec{B}_{\rm ord}$ is horizontal
- In the halo : $\vec{B}_{\rm ord}$ has a vertical component

Outline

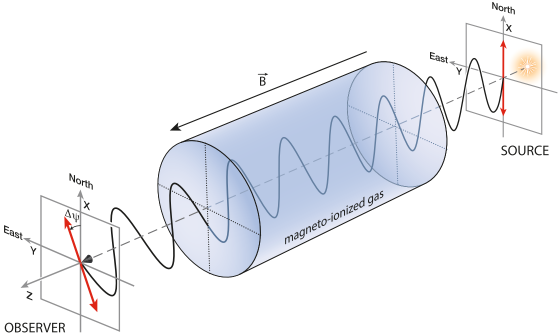
Physical concept

When a linearly polarized radio wave travels through a magneto-ionized medium, the orientation of linear polarization undergoes *Faraday rotation*



Physical concept

When a linearly polarized radio wave travels through a magneto-ionized medium, the orientation of linear polarization undergoes *Faraday rotation*

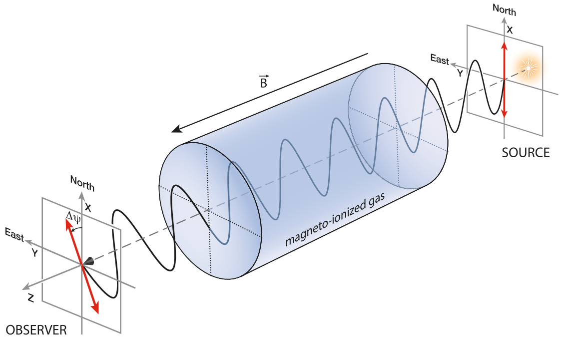


Credit: Theophilus Britt Griswold (NASA Goddard)

Rotation angle & rotation measure

Rotation angle : $\Delta\psi = \mathrm{RM}\ \lambda^2$

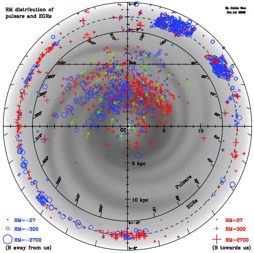
Rotation measure : $\mathrm{RM} = C \int n_e\, B_{\parallel}\, ds$ ☞ $B_{\parallel}$



Credit: Theophilus Britt Griswold (NASA Goddard)

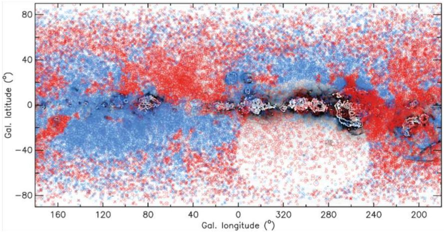
Rotation measures

RMs of pulsars & EGRSs with $|b| < 8^\circ$



Han (2009)

RMs of EGRSs [NVSS ($\delta > -40^\circ$) + S-PASS ($\delta < 0^\circ$)]



Schnitzeler et al. (2019)

☞ - Near the Sun : $B_{\rm reg} \simeq 1.5\ \mu$G & $B_{\rm tot} \sim 5\ \mu$G

$\vec{B}_{\rm reg}$ is nearly azimuthal ($\simeq -8^\circ$ from $\hat{e}_\phi$)

- In the disk : $\vec{B}_{\rm reg}$ is horizontal & mostly azimuthal, with *reversals* in B_ϕ

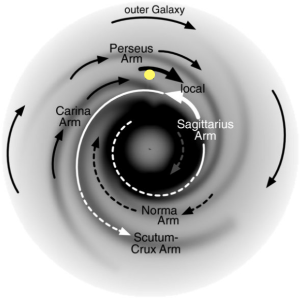
$\vec{B}_{\rm reg}$ probably has a spiral shape

- In the halo : $\vec{B}_{\rm reg}$ is CCW at $z > 0$ & CW at $z < 0$

$\vec{B}_{\rm reg}$ possibly has an upward spiraling shape

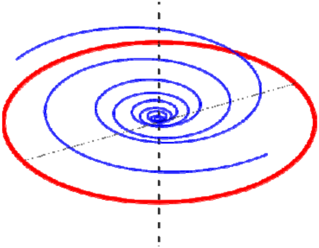
Rotation measures

In the disk



van Eck et al. (2011)

In the halo



Terral & Ferrière (2017)

☞ - Near the Sun : $B_{\rm reg} \simeq 1.5\ \mu{\rm G}$ & $B_{\rm tot} \sim 5\ \mu{\rm G}$

$\vec{B}_{\rm reg}$ is nearly azimuthal (≃ -8° from $\hat{e}_\phi$)

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Outline

Physical concept

- Underlying processes

  - Galactic synchrotron emission : linearly polarized

  - Faraday rotation : λ-dependent

- General idea

  - Measure synchrotron polarized intensity at many different λ

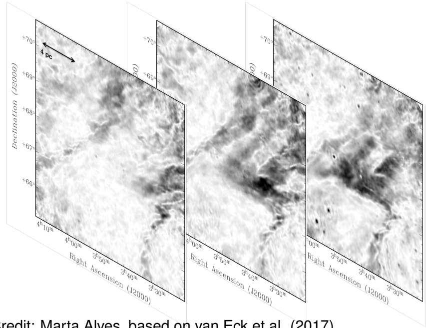
  - Convert λ-dependence into s-dependence [Φ-dependence]

- Output

  Faraday cube = 3D cube of synchrotron polarized emission as fc(α, δ, Φ)

Output

Faraday cube toward Fan region (LOFAR)



Credit: Marta Alves, based on van Eck et al. (2017)

3 slices at

$$\Phi_1 = -2.0 \text{ rad m}^{-2}$$
$$\Phi_2 = -1.5 \text{ rad m}^{-2}$$
$$\Phi_3 = -1.0 \text{ rad m}^{-2}$$

What can be learned

- In Faraday cube
  - Uncover synchrotron-emitting & Faraday-rotating features
  - Identify these features with interstellar matter structures
- For synchrotron-emitting regions

  $\int \vec{F}(\Phi)\, d\Phi$ ☞ $\overleftrightarrow{B}_{\perp}$
- For Faraday-rotating regions

  $\Delta\Phi$ ☞ $B_{\|}$

Outline

Outline

Observational tools

- Synchrotron emission
  ☞ $\vec{B}_{\perp}$ (strength & orientation)
- Faraday rotation
  ☞ $B_{\parallel}$ (strength & sign)
- Polarization of dust thermal emission
  ☞ $\vec{B}_{\perp}$ (orientation only)

Main characteristics

Spiral galaxies

- $\vec{B}$ has an ordered component
- $B_{\rm tot} \sim$ a few μG
- $*$ *Face on*
  - Disk : $\vec{B}_{\rm ord}$ follows the spiral arms

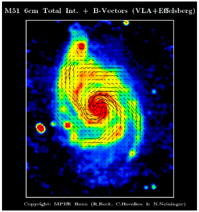
  $*$ *Edge on*
  - Disk : $\vec{B}_{\rm ord}$ is horizontal
  - Halo : $\vec{B}_{\rm ord}$ has an X shape

Elliptical galaxies

- $\vec{B}$ has only fluctuating component
- $B_{\rm tot} \sim$ a few μG

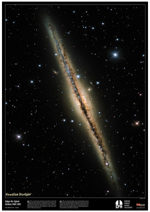
M 51

HST

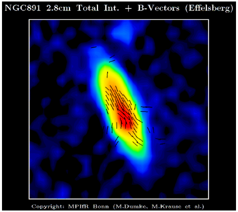


Effelsberg + VLA (6.2 cm)

NGC 891



CFHT



Effelsberg (2.8 cm)

Main characteristics

Spiral galaxies

- $\vec{B}$ has an ordered component
- $B_{\rm tot} \sim$ a few μG
- ∗ *Face on*
  - Disk : $\vec{B}_{\rm ord}$ follows the spiral arms

  ∗ *Edge on*
  - Disk : $\vec{B}_{\rm ord}$ is horizontal
  - Halo : $\vec{B}_{\rm ord}$ has an X shape

Elliptical galaxies

- $\vec{B}$ has only fluctuating component
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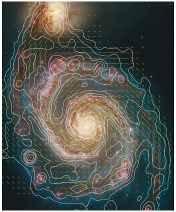
M 51

HST



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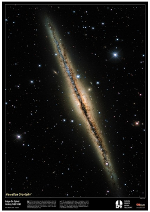
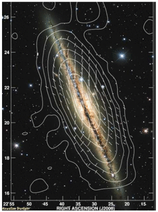


CFHT



Effelsberg (3.6 cm)

Outline

Clusters of galaxies

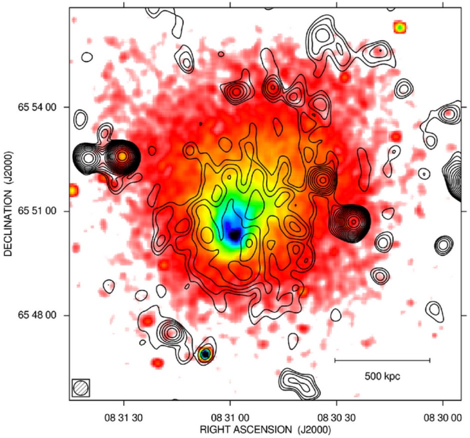
Observational tools

- Synchrotron emission
- Faraday rotation

Main characteristics

- $\vec{B}$ has only fluctuating component
- $B_{\rm tot} \sim (0.1 - \text{a few})\ \mu\text{G}$

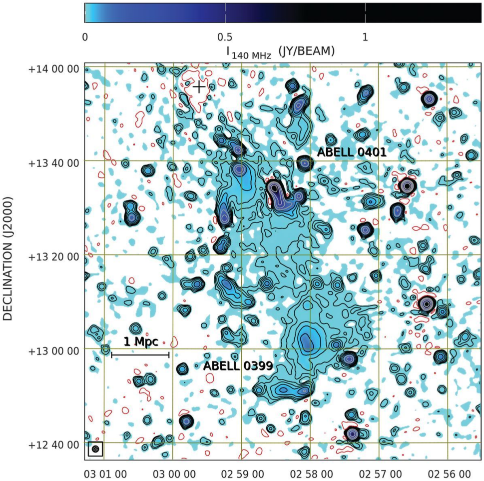
Cluster A 665



Radio 1.4 GHz + X-ray 0.8-4 keV (Vacca et al. 2018)

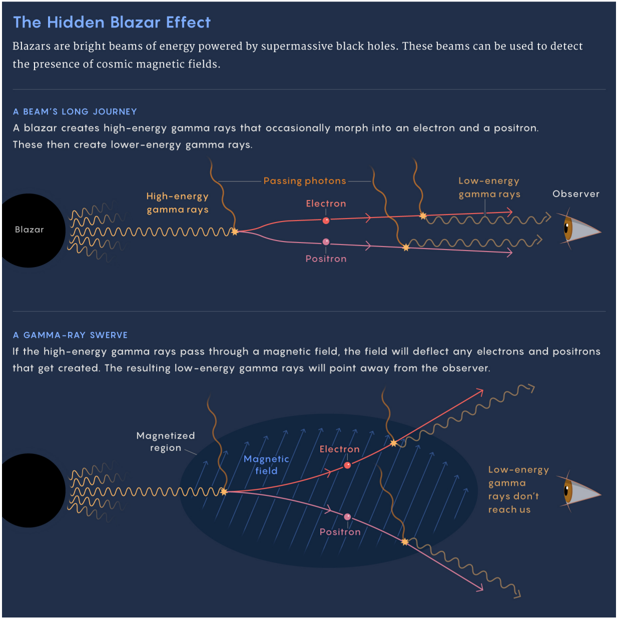
Cosmic filaments

Radio synchrotron filament between Abell 399 & Abell 401 (LOFAR)



Govoni et al. (2019)

Cosmic voids



Credit: Samuel Velasco/Quanta Magazine

- Delay of GeV echo

  ☞ $B \gtrsim 10^{-20.5}$ G

  (Takahashi et al. 2013)

- Size of GeV halo

  ☞ $B \sim (10^{-17} - 10^{-15})$ G

  (Chen et al. 2015)