CREDO and cosmology

Mikhail Medvedev (KU)

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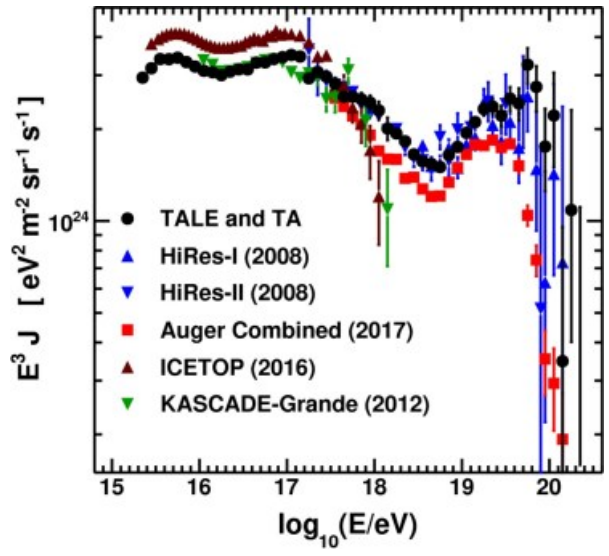
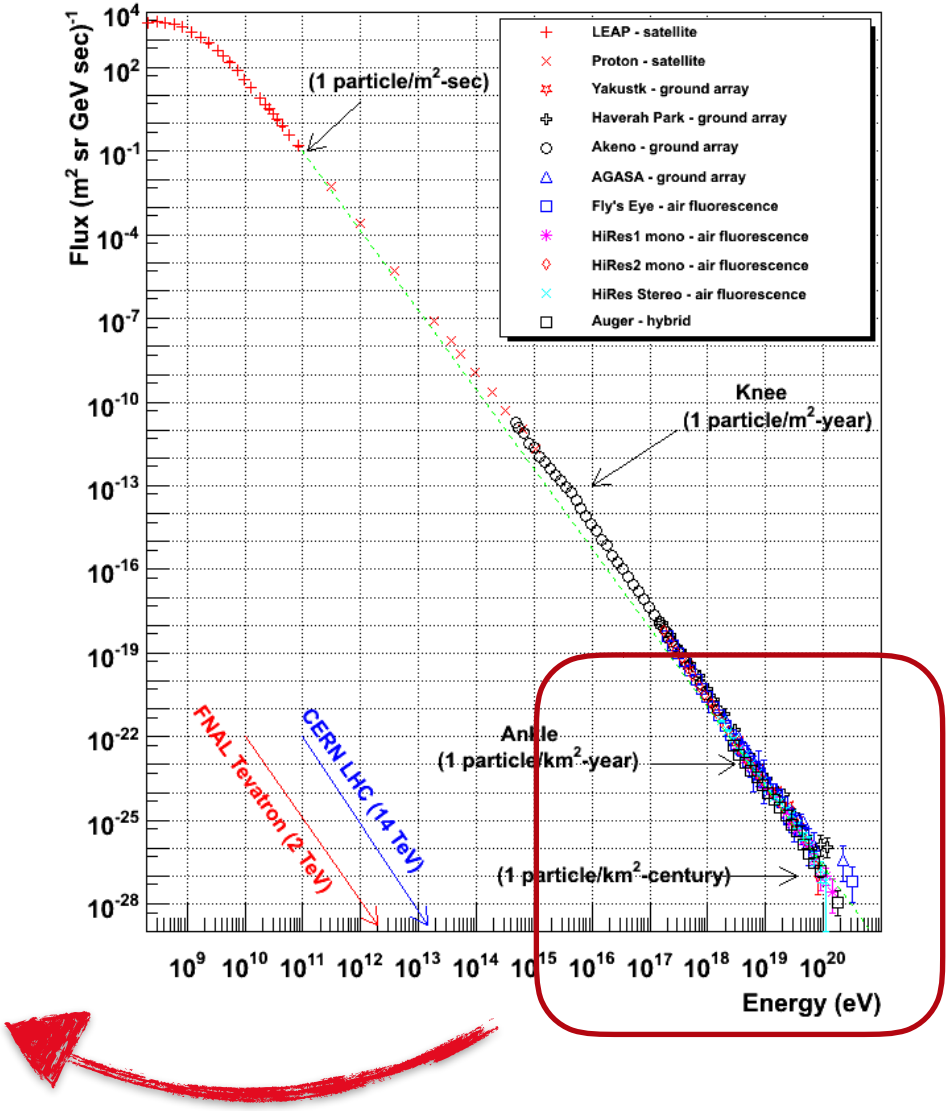
Motivation

Cosmic Ray energy spectrum



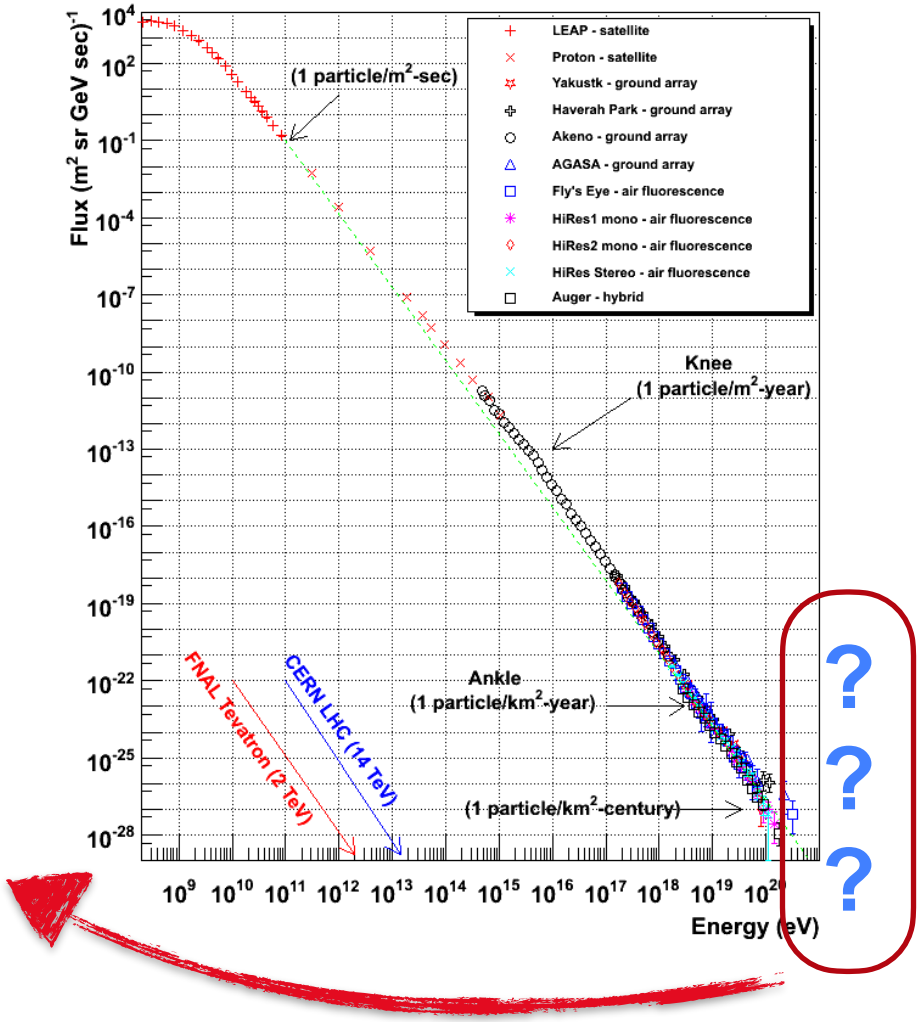


Motivation

Possible interesting sources of CREDO signal:

This talk →

- **"Super UHECR"**
- **Dark Matter**
- **Mag. Monopoles**
- **???**



Monopole concept

1931 Dirac

$$eg = n\hbar c/2$$

explains electric charge quantization

$$g_D = \frac{\hbar c}{2e} = \frac{1}{2\alpha}e \approx \frac{137}{2}e$$

elementary magnetic `Dirac charge'

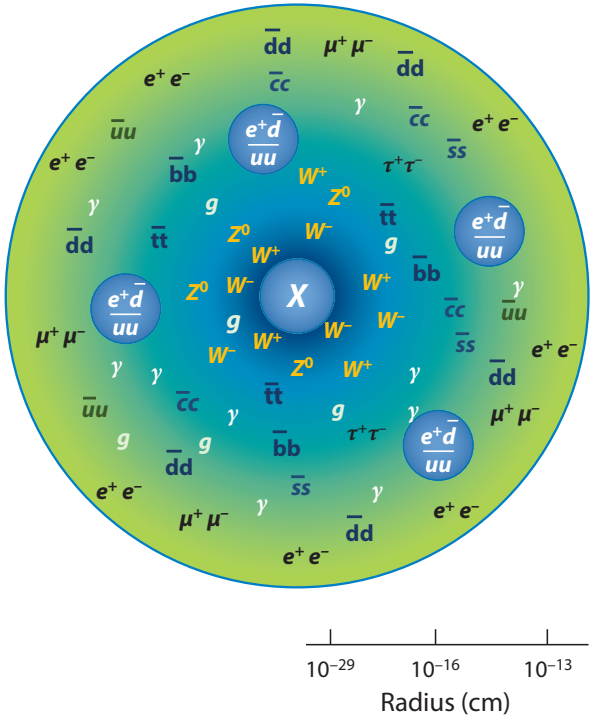
1974 Polyakov; 't Hooft

monopoles are inevitable in GUT

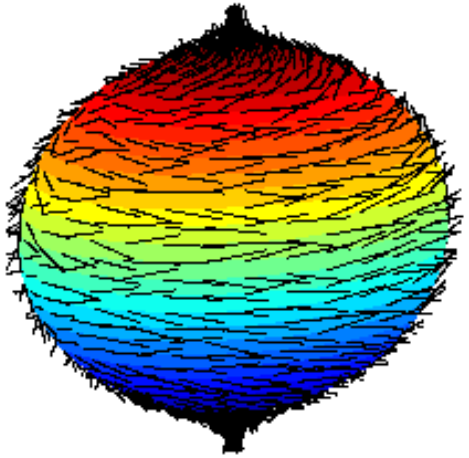
- they are topological defects
- mass ~ GUT ~10^{17} GeV
- copiously produced

$$\Omega_M h^2 \simeq 10^{15} \left(T_c/10^{15}\ \mathrm{GeV}\right)^3 m_{17}$$

"monopole catastrophe"

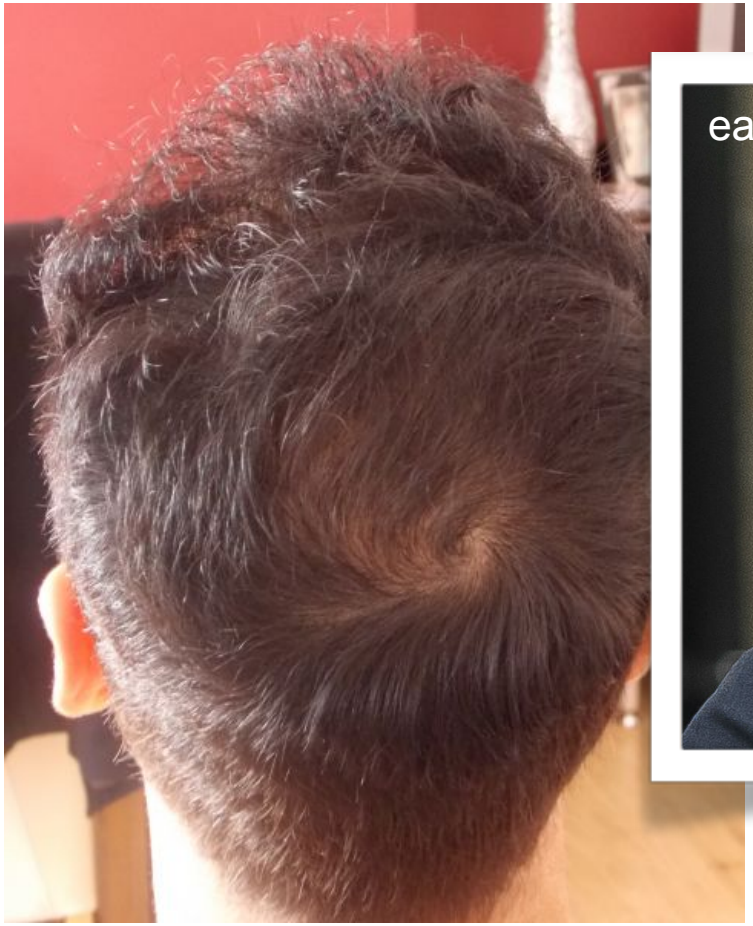


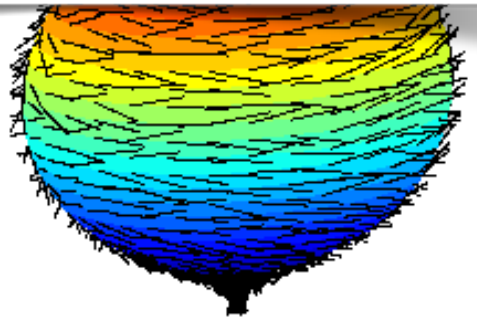
Topological defect - example



The hairy ball theorem:
you can't comb a hairy ball flat without creating a cowlick

Topological defect - example





The hairy ball theorem:
you can't comb a hairy ball flat without creating a cowlick

Monopoles restore EM symmetry

Maxwell's eqns.

$$\partial_\alpha F^{\alpha\beta} = \frac{4\pi}{c} J_e^\beta,$$

Gauss + Ampere

$$\partial_\alpha \tilde{F}^{\alpha\beta} = \frac{4\pi}{c} J_m^\beta$$

Faraday + div.B

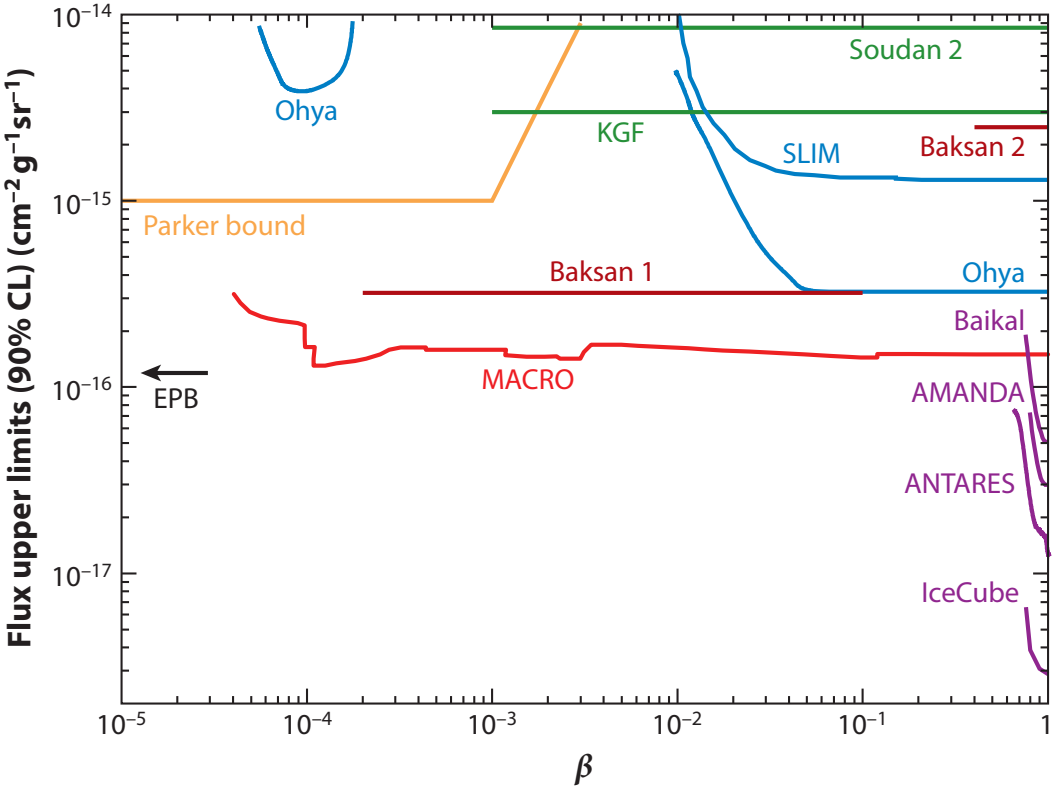
Lorentz force

$$\frac{dp_\alpha}{d\tau} = \left(q_e F_{\alpha\beta} + q_m \tilde{F}_{\alpha\beta}\right) \frac{v^\beta}{c}$$

Duality transformation restores full symmetry:
'electric' or 'magnetic' is now a matter of convention

$$\begin{pmatrix} \mathbf{E} \\ \mathbf{B} \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \mathbf{E}' \\ \mathbf{B}' \end{pmatrix} \qquad \begin{pmatrix} J_e \\ J_m \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} J'_e \\ J'_m \end{pmatrix}$$

Searches

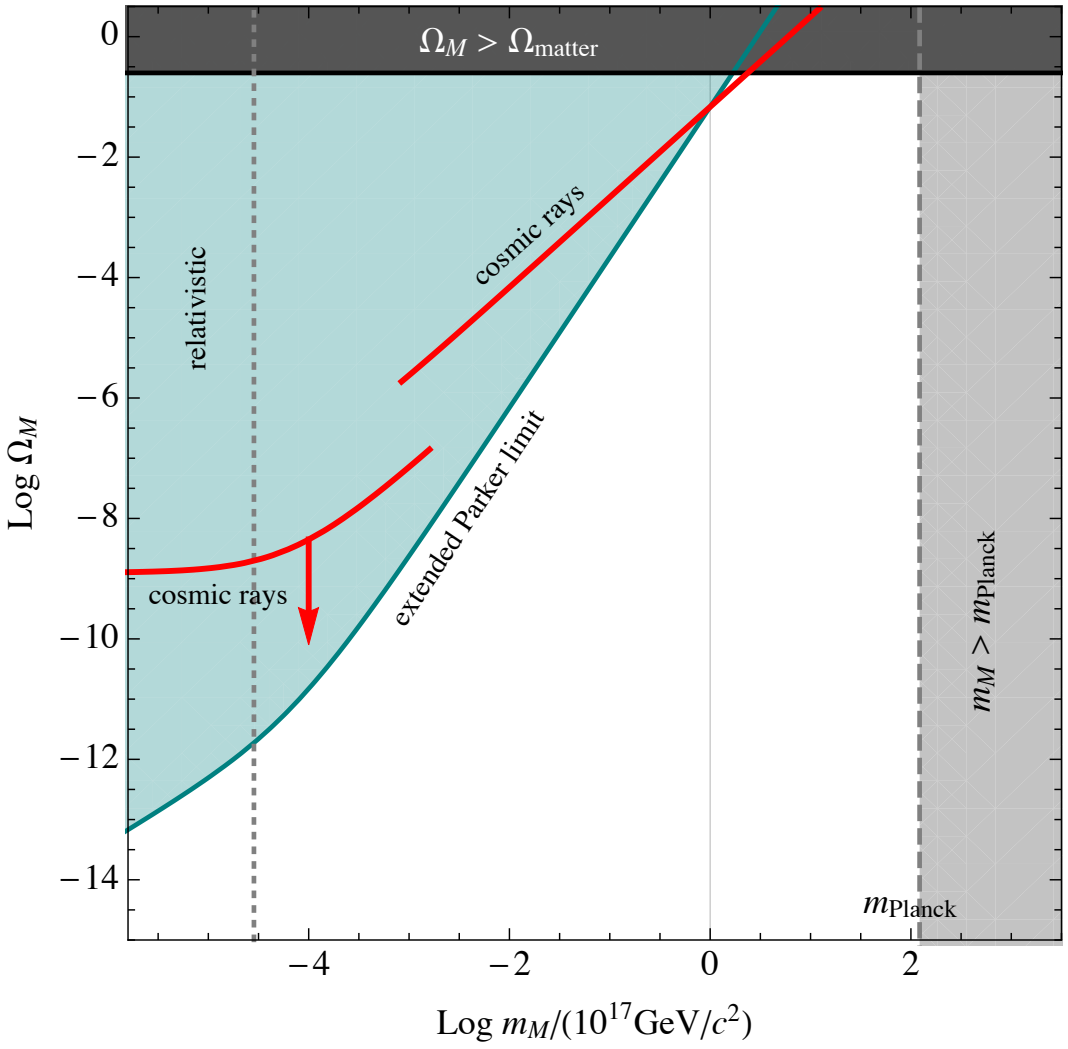


Observational constraints on monopole flux

$$F_M \lesssim \begin{cases} 10^{-16}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1} & \text{for } v/c \lesssim 0.8, \\ 3 \times 10^{-18}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1} & \text{for } v/c \gtrsim 0.8. \end{cases}$$

Patrizii & Spurio, ARNPS, 2015

Existing constraints



Parker limit:

survival of galactic and protogalactic B-fields

$$\mathbf{j_m} \cdot \mathbf{B} \lesssim (B^2/8\pi)\tau_{dynamo}^{-1}$$

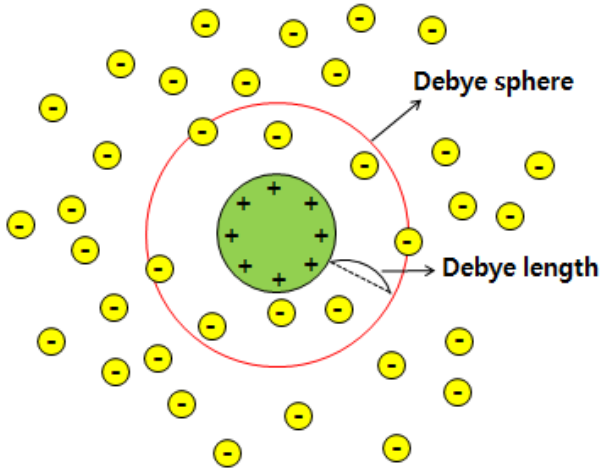
Monopole plasma

Ensemble of particles interacting electromagnetically -- plasma (like ionized gas)

Monopoles in the Universe behave *like*:

collisionless, non-magnetized electron-positron plasma (just, very heavy)

- collective motions -- waves, instabilities
- Debye shielding

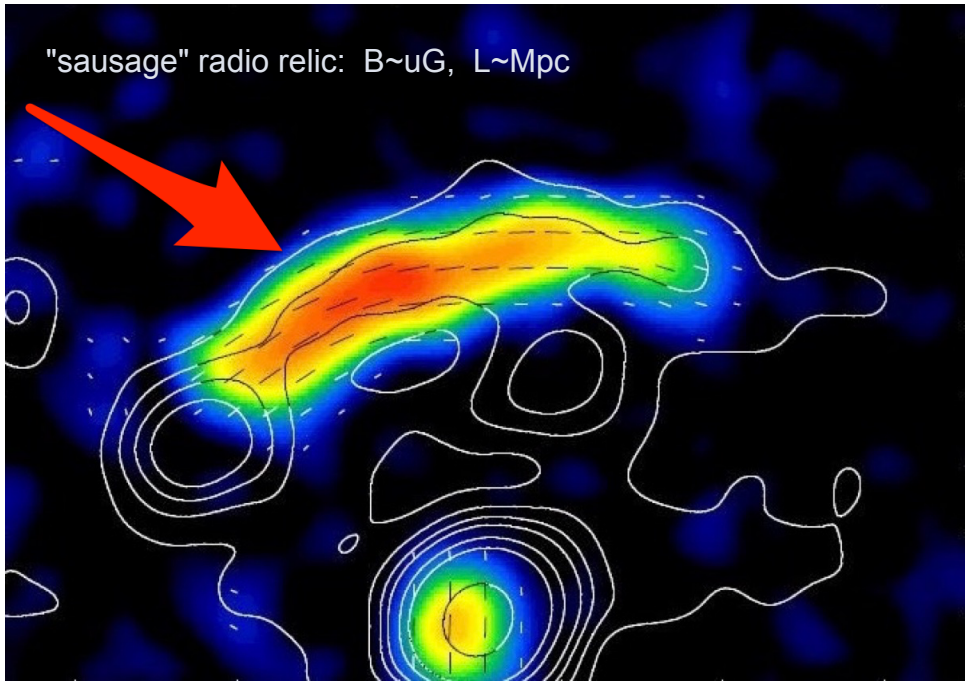


$$\phi(r) = \frac{q}{r}\, e^{-r/\lambda_D}$$ Yukawa-type potential

$$\lambda_D = \left(\frac{k_B T}{4\pi e^2 n}\right)^{1/2}$$ Debye length

(MM & Loeb, JCAP, 2017)

Largest-scale B-fields observed



B-fields accelerate monopoles

$$(\gamma - 1)m_M c^2 = gBl,$$

$$v_{th}/c \simeq \begin{cases} 1, & \text{if } m_M \lesssim 10^{13}\ \text{GeV}, \\ 10^{-2} m_{17}^{-1/2}, & \text{if } m_M \gtrsim 10^{13}\ \text{GeV}. \end{cases}$$

Debye length

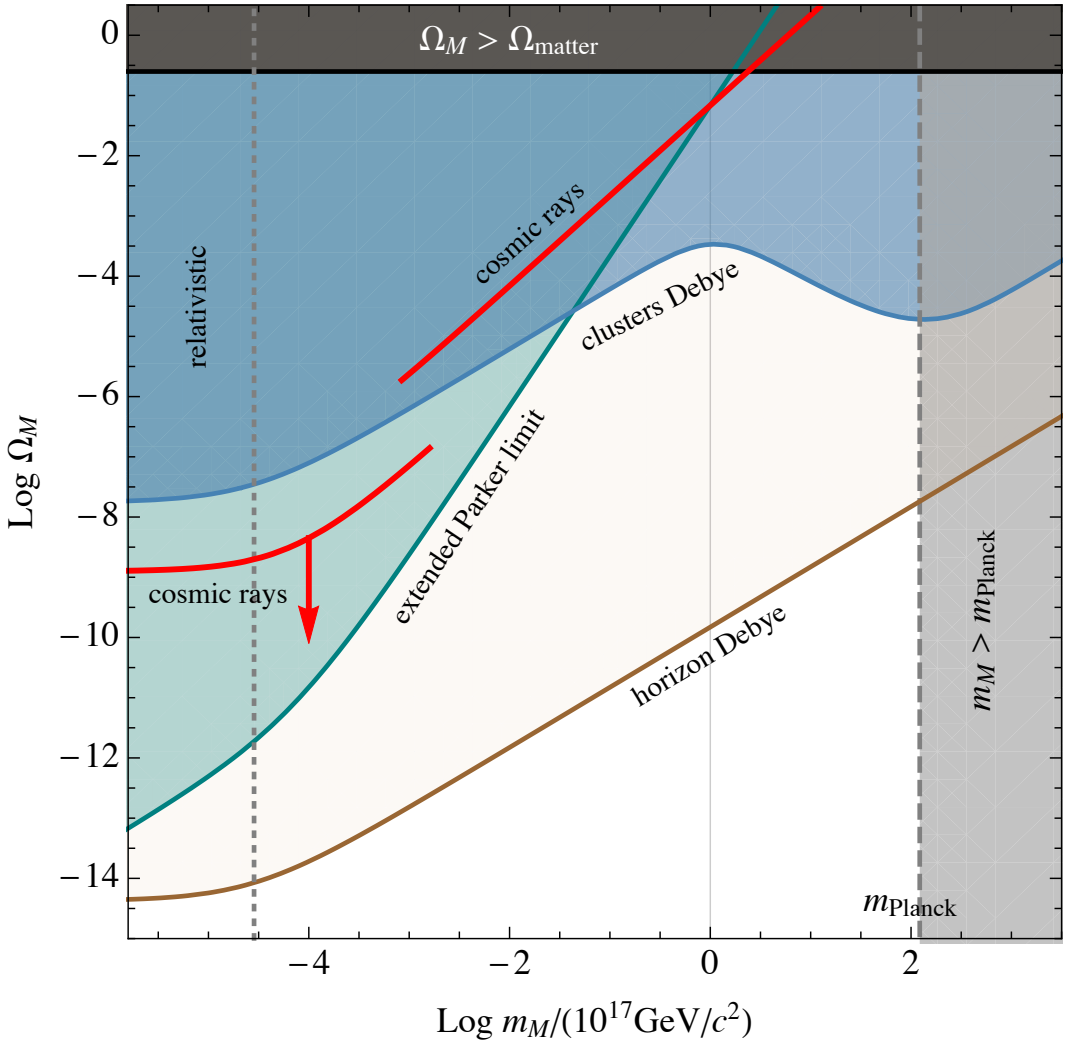
$$\lambda_D = \frac{v_{th}}{\omega_{p,M}} \simeq (10^{23}\text{cm})\,(\Omega_M h^2 \Delta)^{-1/2} m_{17}^{1/2}$$

No shielding on L~Mpc: $\lambda_D > L.$

$$\Omega_M h^2 < 10^{-3} \Delta^{-1} m_{17}.$$

image: Kierdorf et al., A&A, 2017

Debye constraint



Absolute limit:

$$\Omega_M \lesssim 3 \times 10^{-4}$$

Monopoles cannot constitute dark matter

($n<10^{-26}$ cm^{-3})

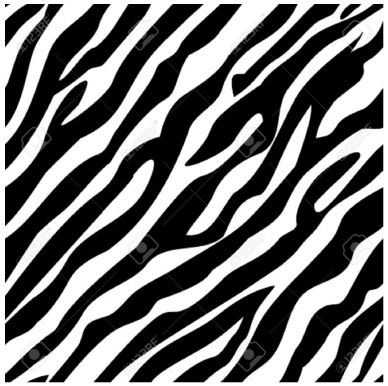
(MM & Loeb, JCAP, 2017)

Magnetic Langmuir waves

As in any plasma, magnetic Langmuir waves must exist in monopole plasma

$$\omega^2 = \omega_{p,M}^2 + 3k^2 v_{th}^2, \qquad \omega_{p,M} = \left(\frac{4\pi g_D^2 n_M}{\gamma m_M}\right)^{1/2} \simeq (3\times 10^{-15}\mathrm{s}^{-1})\,(\Omega_M h^2 \Delta)^{1/2} m_{17}^{-1}$$

Must be seen as "zebra pattern" of an alternating B-field with wavelength



$$\lambda_D \sim \lambda_{wave} \sim 1/|\mathbf{k}|$$

"Smoking gun" -- alignment of k and B, because B is not divergence-free

$$\mathbf{k}\cdot\mathbf{B} \neq 0$$

Origin of galaxy cluster B-fields

Monopole plasma accreting onto a cluster, should produce collisionless shock -- just like ionized gas

The collisionless accretion shock is mediated by **magnetic Langmuir turbulence**

This turbulence is absolutely necessary because the "Coulomb" mean-free-path exceeds the size of the system by orders of magnitude

The field strength must be close to equipartition in order to scatter particle efficiently

$$B^2/8\pi \simeq m_M n_M u^2/2$$

$$B \simeq (3\times 10^{-7}\ \mathrm{Gauss}) \left(\frac{\Omega_M}{3\times 10^{-4}}\frac{\Delta}{200}\right)^{1/2} \left(\frac{u}{10^3\ \mathrm{km\ s^{-1}}}\right),$$

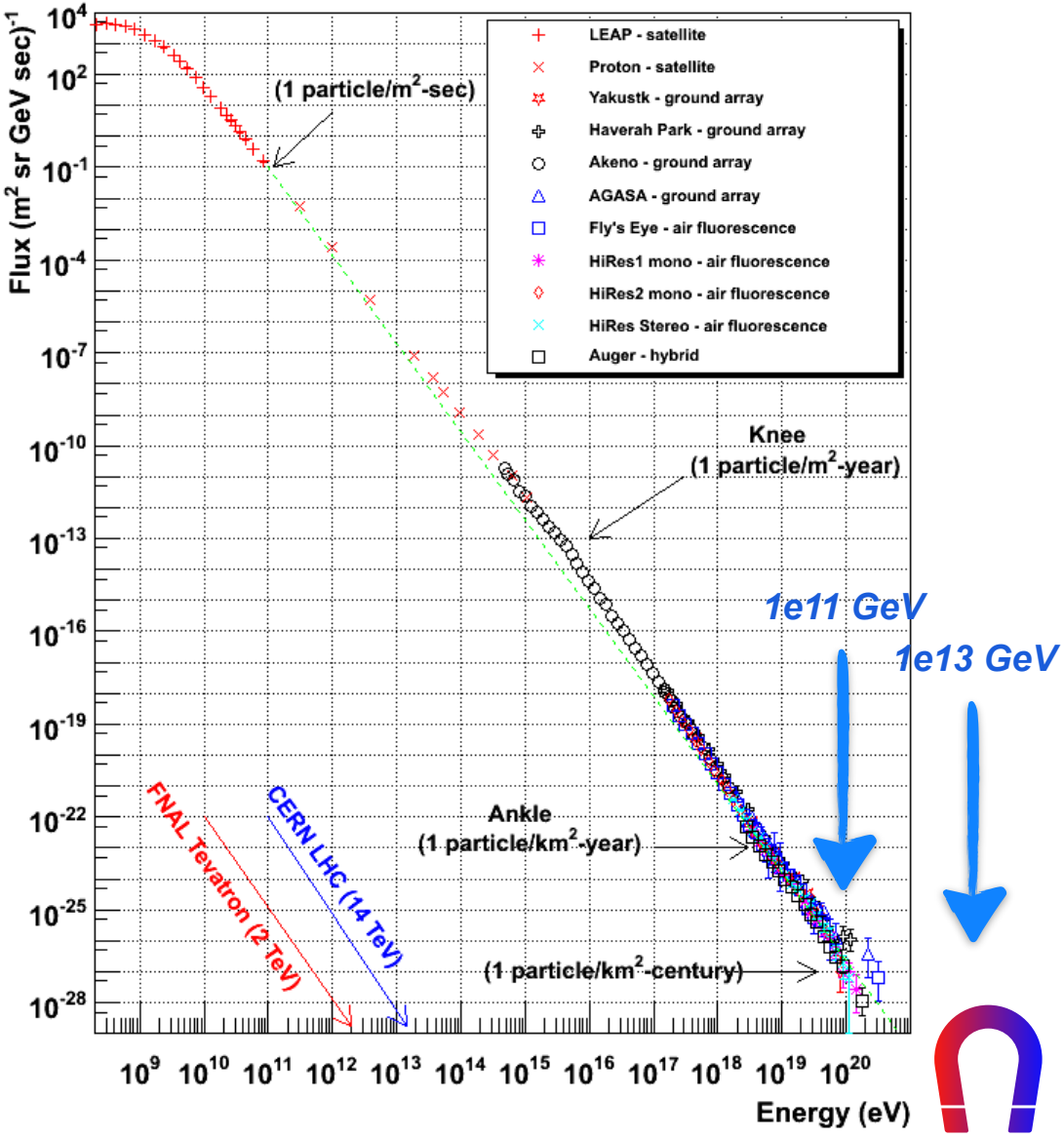
$$\lambda_B \sim 1/k_{max} \sim u/\omega_{p,M} \sim 60\, m_{17}\ \mathrm{kpc}$$

0.3 micro-Gauss, 100 kpc fields at the accretion shock radius (!)

+ can be further amplified by further compression of the flow

and turbulent motions in ionized gas of IGM

Monopoles for CREDO



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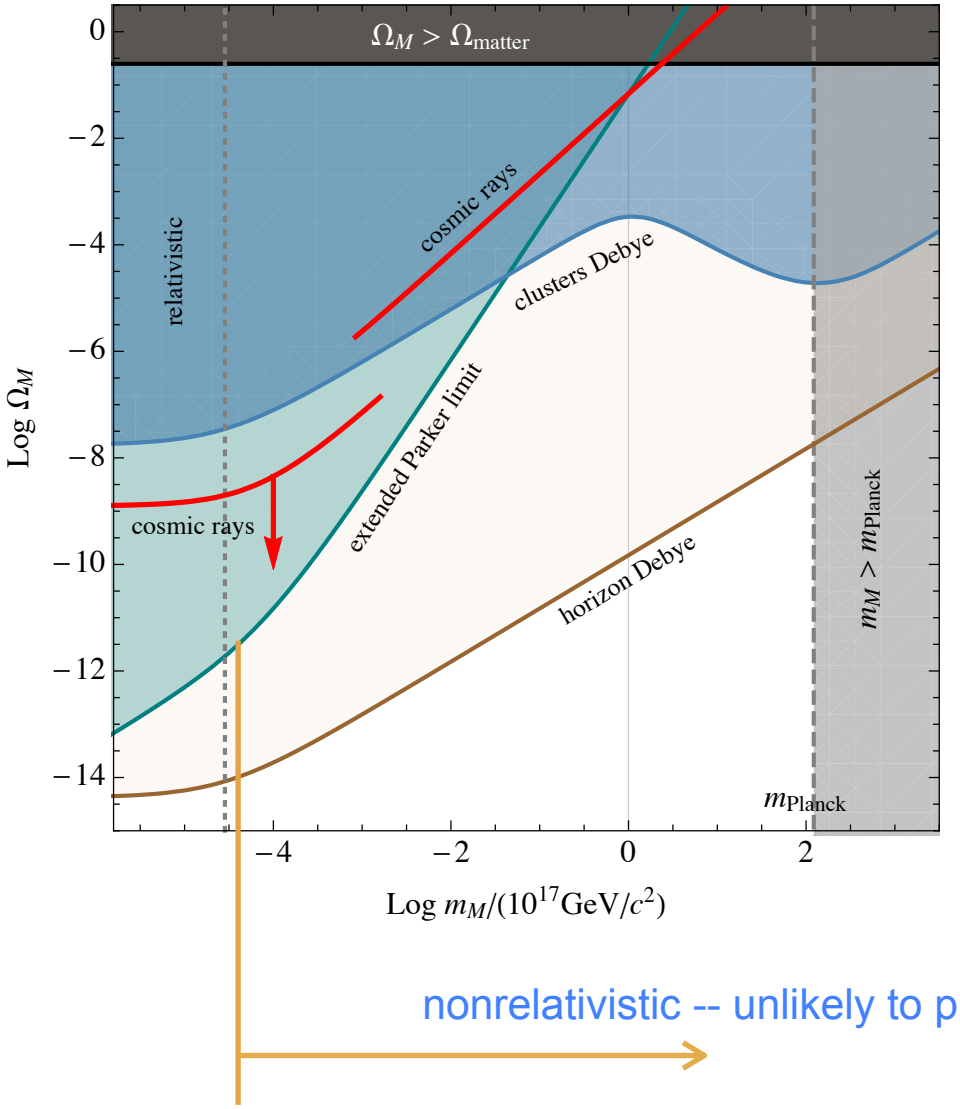
Therefore, realistic energies are about (below) 1e13 GeV

Monopoles for CREDO?



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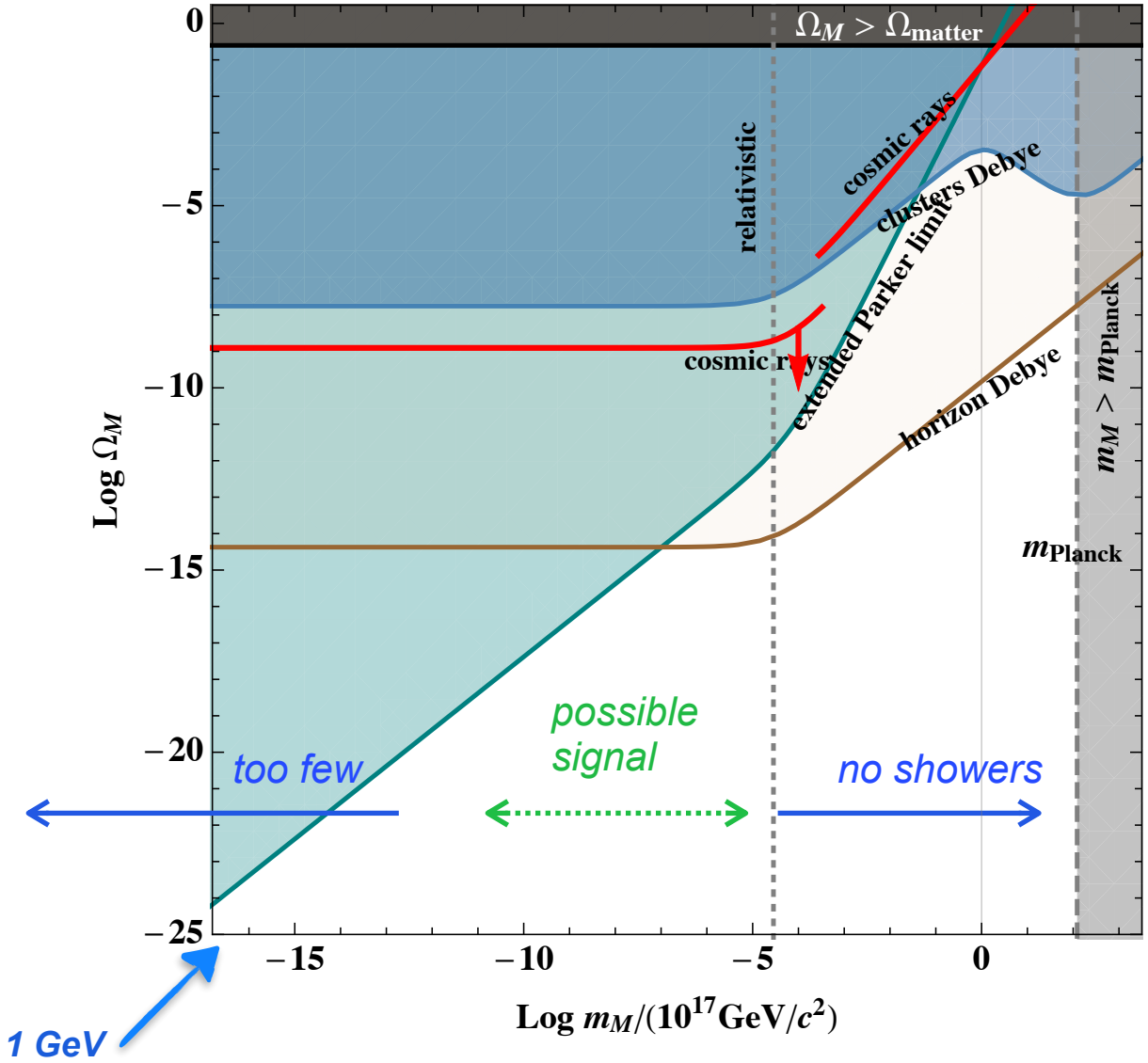
Therefore, realistic energies are about (below) 1e13 GeV

(monopoles would behave simply as multiply charged dust particles)

nonrelativistic -- unlikely to produce showers

Monopoles for CREDO?



Take home messages

If magnetic monopoles exist:

Observed cluster and radio relic fields strongly constrain monopole abundance:

$$\Omega_M \lesssim 3 \times 10^{-4}$$

"Smoking gun" of monopoles -- *"zebra pattern"* of alternating B-field with

$$\mathbf{k} \cdot \mathbf{B} \neq 0$$

Typical energies of astro monopoles are <~ 1e22 eV (just above the GZK cutoff)

Hard to observe with CR detectors:

--monopoles are either too slow or there're too few of them

--possible range of masses there there is hope is *roughly* ~ 1e8 - 1e12 eV