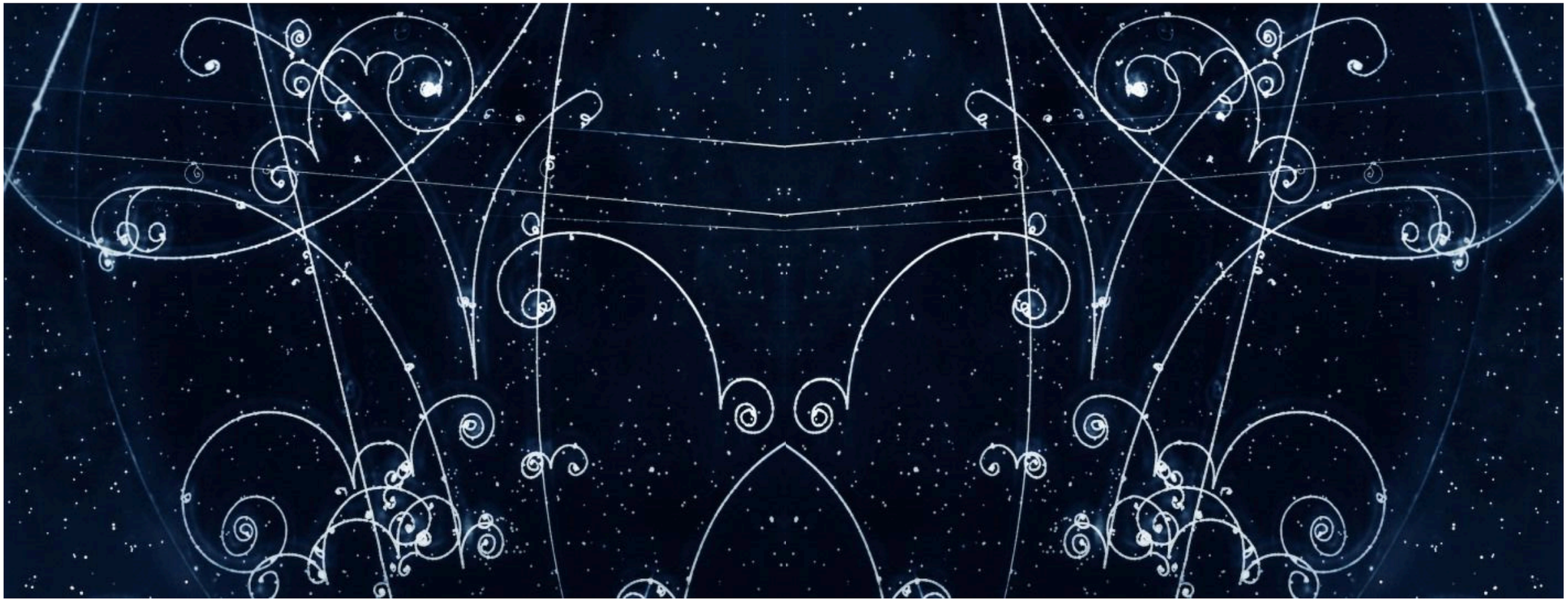


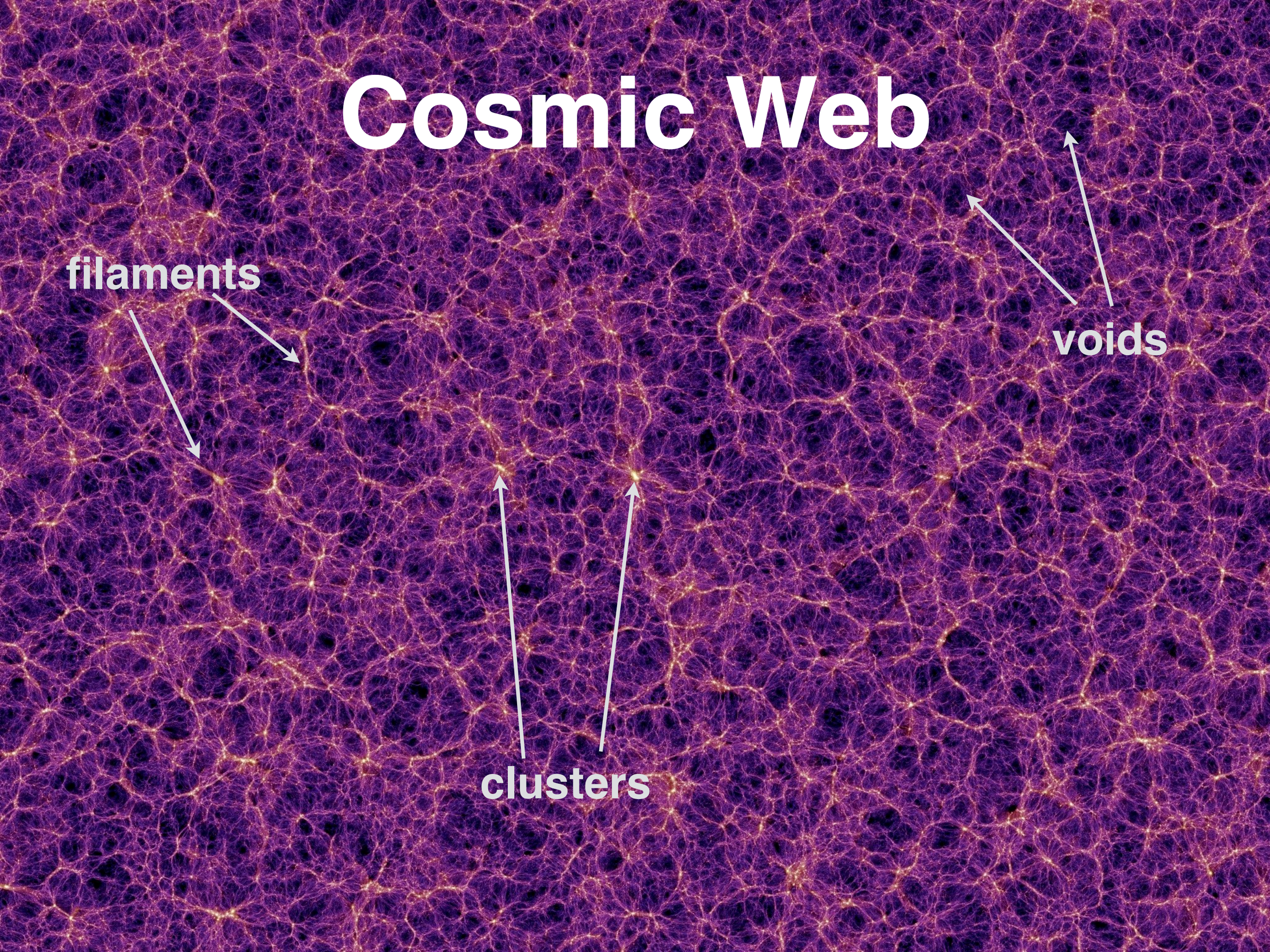
FRANCESCO MINIATI (OXFORD)

CTA SYMPOSIUM, MAY 9 2019, BOLOGNA (IT)

TESTING PRIMORDIAL (AXION) MAGNETOGENESIS WITH CTA

BASIC QUESTION

- What is the origin of the magnetic field in cosmic voids ?
- Can it be a relic of the early universe ?


Cosmic Web
filaments
voids
clusters

E.M. CASCADE IN VOIDS

$\gamma_{Blz}\gamma_{EBL} \rightarrow e^+e^-$

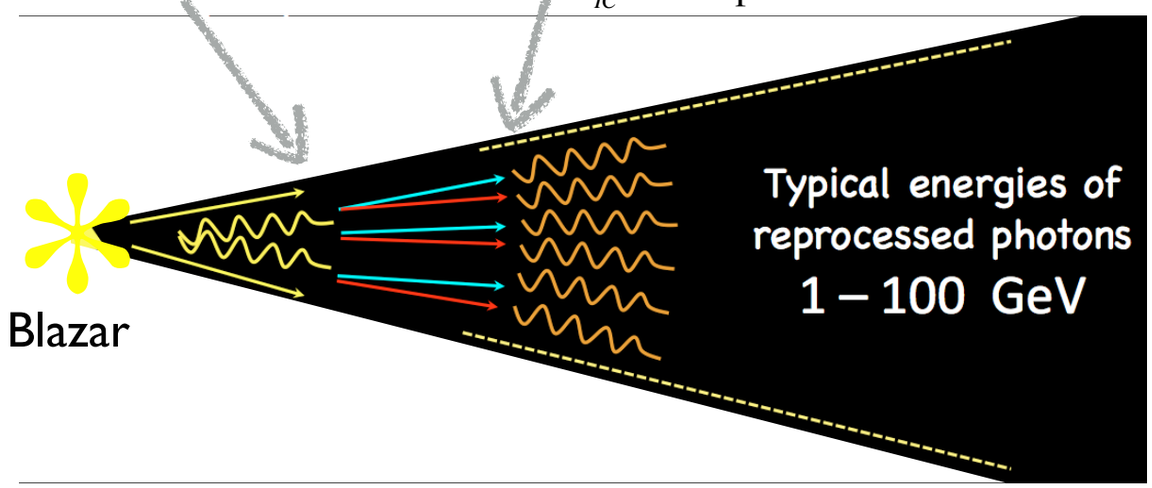
$\Gamma_{e^\pm} = E_{\gamma_{Blz}} / 2m_e c^2 \approx 10^6 E_{\gamma_{Blz},TeV}$

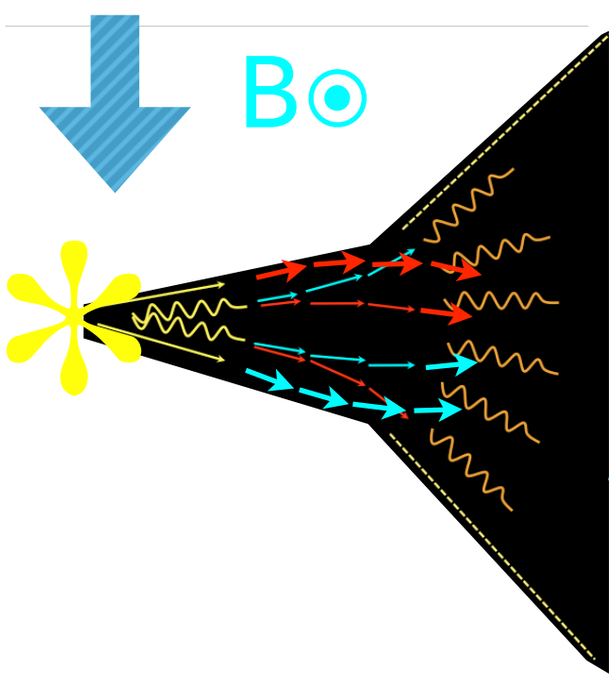
$\ell_{\gamma\gamma} \sim 100$ Mpc

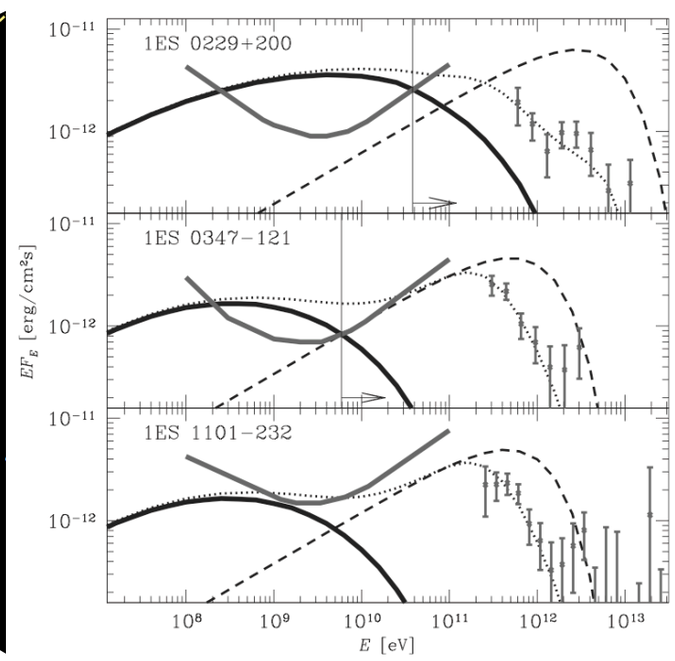
$e^\pm\gamma_{CMB} \rightarrow e^\pm\gamma$

$E_\gamma \approx 1.3\varepsilon_{CMB}\Gamma^2_{e^\pm} \approx 88\left(E_{\gamma,Blz}/10\text{TeV}\right)^2$ GeV

$\ell_{IC} \sim 30$ kpc







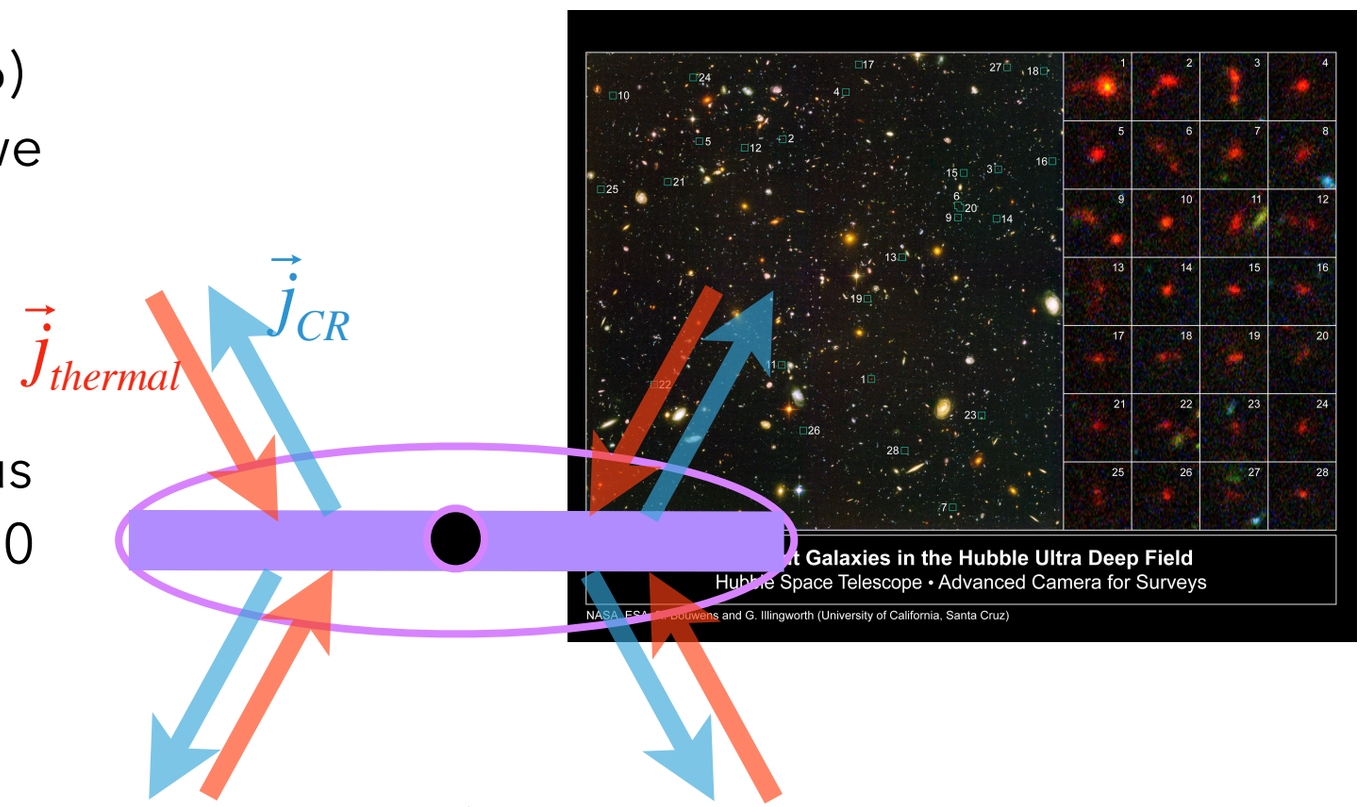
Neronov and Vovk, Science 328 73 (2010)
see also Tavecchio et al (2010, 2011)

- Relativistic pair-beams are produced in cosmic voids by high energy TeV photons from blazars
- The pairs inverse Compton scatter on the CMB to produce GeV bump in the blazar spectra
- A non vanishing B-field deflects secondary e± such that
  - i) B >10^{-7} G no secondary gamma-rays
  - ii) 10^{-7} G > B >10^{-12} G **pair halo** (Aharonian, Coppi, Völk 1994)
  - iii) B<10^{-14} G modified SED, **pair echo**, Magnetically Broadened Cascade (Plaga 1995, Elyiv et al. 2009, Neronov, Semikov 2009)
- SED analysis: lack of such GeV bumps is ascribed to: **B ≳10^{-18} - 10^{-17} G** (Dermer et al 2010, Taylor et al 2011)

RESISTIVE MECHANISM AT BREAK OF COSMIC DAWN

(*FM* & Bell, ApJ 2011, 729, 73; arXiv:1001.2011)

- young galaxies at high redshift (z>6) reionize the universe, remarkably, we can now measure their Schechter function
- massive stars, emit the ionising ph, eventually go SN producing copious CRs which escape to the IGM in 1-10 Myr
- the CR current, j_{cr}, causes charge imbalance driving a return current carried by the thermal plasma, j_{th}, that tends to cancel j_{cr} itself, i.e. $j_{th} \approx -j_{cr}$ (Bell & Kingham 2003)
- the return current is associated with an electric field



$$\vec{E}' = \frac{\vec{j}_{th}}{\sigma} \qquad \sigma_{Spitzer} \simeq 10^7 \left(\frac{T}{K}\right)^{3/2} s^{-1}$$

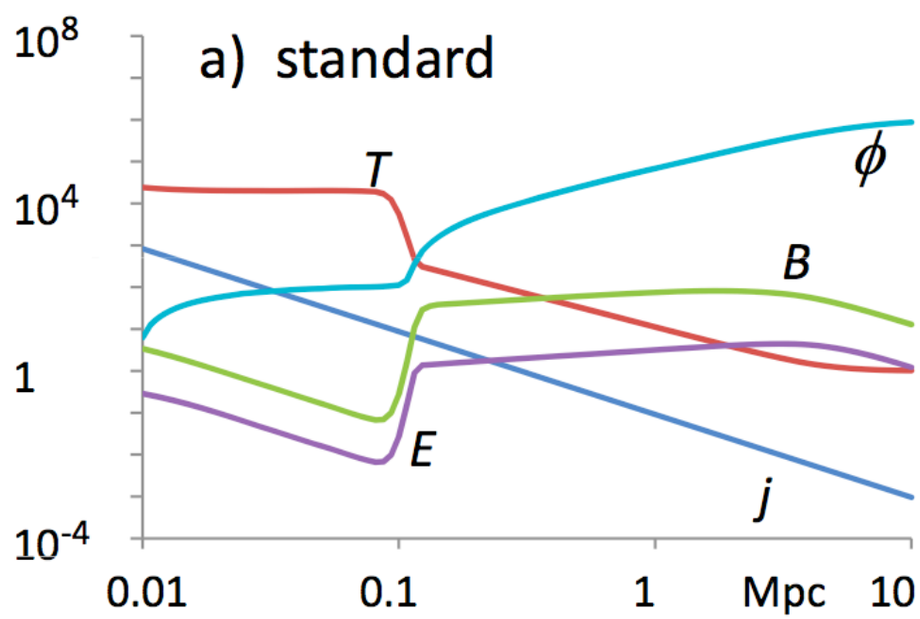
$$\boxed{\frac{\partial \vec{B}}{\partial t} = -c\vec{\nabla} \times \vec{E} \simeq c\frac{\vec{j}_{cr}}{\sigma} \times \frac{\vec{\nabla} T}{T}}$$

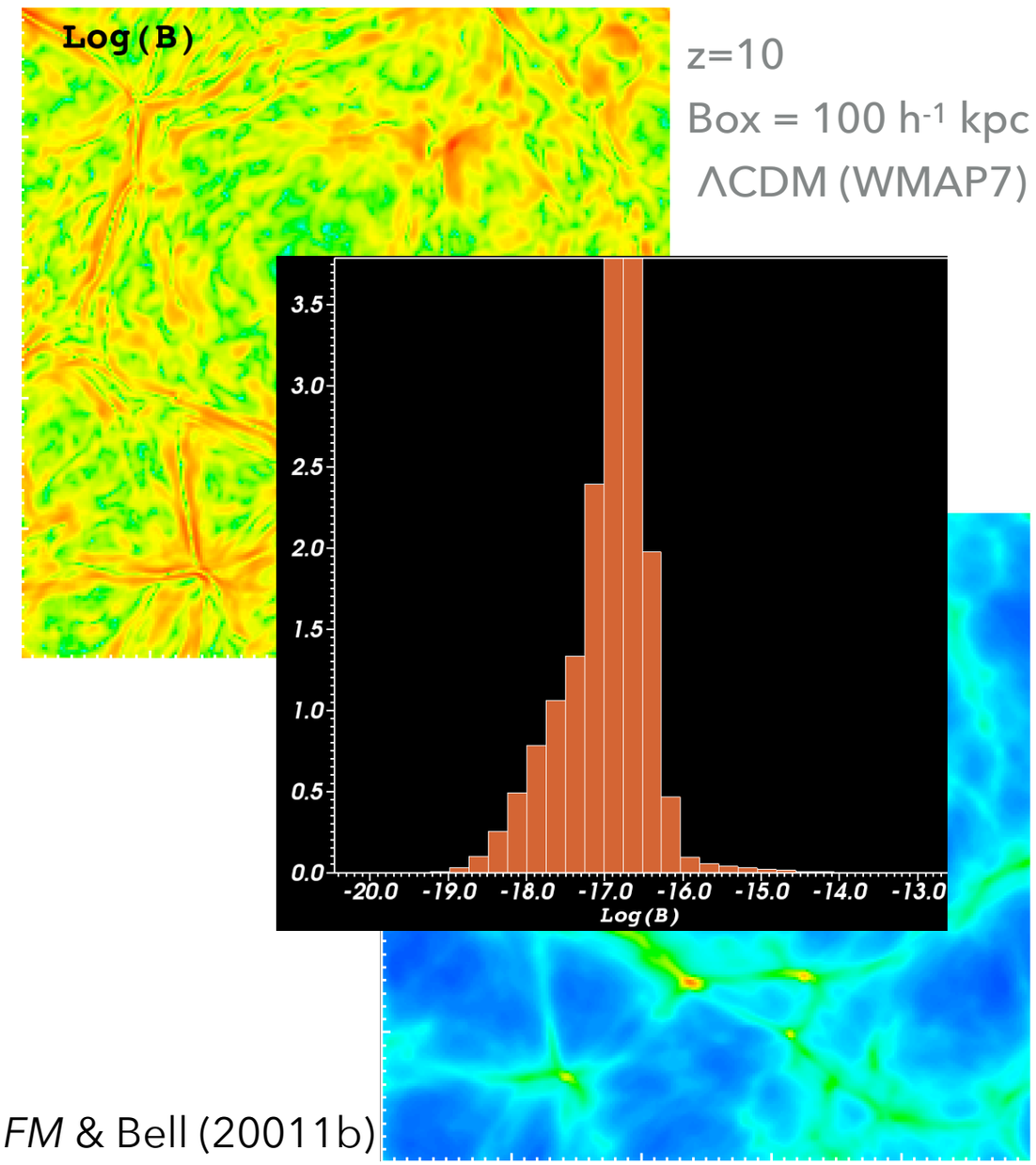
RESULTS

(*FM* & Bell, ApJ 2011, 729, 73; arXiv:1001.2011)

$$\frac{\partial B}{\partial t} \approx \frac{c j_{CR}}{\sigma \ell_T} \approx \left(10^{-17} - 10^{-16}\right)\left(\frac{\ell_T}{\mathrm{kpc}}\right)^{-1} \frac{\mathrm{Gauss}}{\mathrm{Gyr}}$$

$[j] = 10^{-18}\,\mathrm{Am}^{-2}$
$[\mathrm{T}] = \mathrm{K}$
$[\mathrm{B}] = 10^{-18}\,\mathrm{G}$
$[\mathrm{E}] = 10^{-18}\,\mathrm{Vm}^{-1}$
$[\phi] = \mathrm{Volt}$





- inclusive of Ohmic heating
- T-scale ~ 1kpc
- weekly dependent on j_{CR}

B ~ 10^5 larger than Bierman's
λ_B ~ $10^{12\text{-}14}$ larger than Weibel's

FM & Bell (20011b)

QCD CROSSOVER

(*FM*, Gregori, Reville, Sarkar, PRL **121**, 021301 (2018), arXiv:1708.07614)

- t ≈10^{-5} s, T≈150 MeV
- nucleation of quark-gluon plasma due to hadronic confinement at T<1 GeV
- pressure gradients at interface of bubbles formed from heat released in the above process
- charge, energy density and EoS asymmetry of quarks and leptons lead to thermoelectric fields (Quashnock et al '89)

$$\boldsymbol{E}_{te} \approx -\epsilon \frac{\nabla P}{en}$$

- bubble collisions non-null baroclinic term generates field via Biermann's battery (Quashnock et al '89)
- but lattice calculations show QCD crossover is smooth process (Aoki et al. 2006)

AXION DRIVEN MAGNETO GENESIS

(*FM*, Gregori, Reville, Sarkar, PRL **121**, 021301 (2018), arXiv:1708.07614)

- Axions introduced to account for lack of CP violation in strong interactions
- candidate dark matter particle (generalised to ALPs)
- axion field "a" couples to the E.M. field through $\mathscr{L} = -g_{a\gamma}\, \mathbf{E}\cdot\mathbf{B}\, a$ (e.g., Harari & Sikivie 1992)

(Ohm's law) $$\boldsymbol{E} \approx \eta_p \boldsymbol{J} + \boldsymbol{E}_{te}$$

$$\boldsymbol{E}_{te} \approx -\epsilon \frac{\nabla P}{en}$$

(Ampère's law) $$\boldsymbol{J} \approx g_{a\gamma} \nabla a \times \boldsymbol{E}$$

$$\boldsymbol{E} \approx \boldsymbol{E}_{te} + \eta_p g_{a\gamma} \nabla a \times \boldsymbol{E}_{te}$$

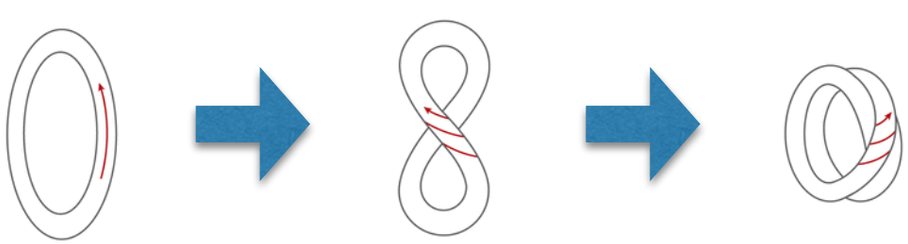
AXION DRIVEN MAGNETO GENESIS

(*FM*, Gregori, Reville, Sarkar, PRL **121**, 021301 (2018), arXiv:1708.07614)

- fluctuations induced by QCD crossover stir up fluid motions

$$\frac{1}{\sqrt{g_*}} \approx \frac{\delta P}{P} \approx \frac{\delta u}{c_s}$$

- which decay into turbulence below causally connected scale $L_u \approx \delta u L_H$
- turbulent cascade follows Kolmogorov scaling in mildly relativistic regime (Zhang et al 2009, Radice & Rezzolla 2013) and turbulent dynamo appears to operate as in classical case (Zhang et al 2009, Mizuno et al 2014)



$$\frac{d}{dt}\langle B^2 \rangle \approx \frac{\delta u_\ell^3}{\ell} \approx \varepsilon_{turb}$$

AXION DRIVEN MAGNETO GENESIS

(*FM*, Gregori, Reville, Sarkar, PRL **121**, 021301 (2018), arXiv:1708.07614)

- We can compute B, Alfvén speed, v_A, and Alfvén scale L_B at t_{QCD}
- After that turbulence dissipates, dynamo stops, so begins the phase of unwinding of magnetic field lines and the decay of magnetic energy

Flux conservation
(Hogan 1983)

$$BR^2 \propto \frac{R}{L_B} \quad \rightarrow \quad Lu_M \propto v_A L_B \propto BL_B$$

Unwinding
(Dimopoulos & Davis 1997)

$$\frac{d}{dt}\frac{L_B}{R} = \frac{v_A}{R} \quad \rightarrow \quad L_B \propto t^{1/2}$$

- This behaviour summarised by the constancy of *Lundquist* number and square root time evolution is confirmed by numerical simulations both in the classical (Brandenburg et al 2015) and relativistic regime (Zrake 2014)

RESULTS

(*FM*, Gregori, Reville, Sarkar, PRL **121**, 021301 (2018), arXiv:1708.07614)

- fast forward through periods of radiation dominated, matter dominated, radiation drag, recombination… (see also Adshead et al 2016; Choi, Kim, Sekiguchi 2018)

$$B_0 \approx 5 \times 10^{-14} \left(\frac{\eta_B}{0.05}\right) \mathrm{G}$$

$$L_0 \approx 25 \left(\frac{\eta_B}{0.05}\right) \left(\frac{g_*}{30}\right)^{-1/2} \mathrm{pc}$$

- Gamma ray observations can distinguish between

Primordial (axion)

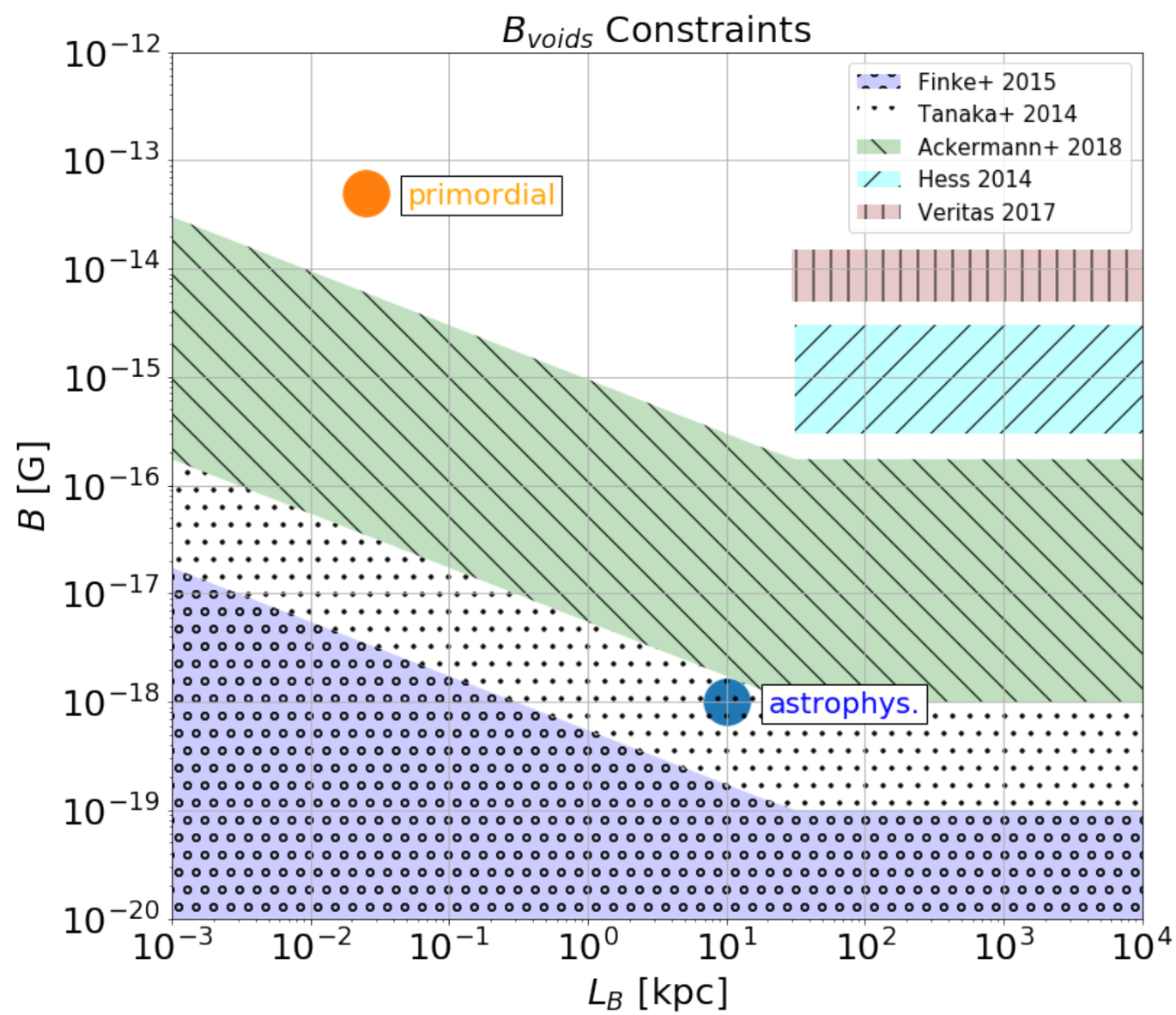
$$\left(\frac{B_0}{\mathrm{G}}\right) \left(\frac{L_0}{\mathrm{kpc}}\right)^{1/2} \approx 10^{-14} \left(\frac{\eta_B}{0.05}\right)^{3/2} \left(\frac{g_*}{30}\right)^{-1/4}$$

Astrophysical

$$\left(\frac{B_0}{\mathrm{G}}\right) \left(\frac{L_0}{\mathrm{kpc}}\right)^{1/2} \approx 10^{-18}$$

GAMMA-RAY OBSERVATIONS

- lack of such GeV bumps is ascribed to **$B \gtrsim 10^{-18}$ - 10^{-17} G** (Dermer et al 2010, Taylor et al 2011)
- EGMF range (0.3–3) $\times 10^{-15}$ G, L_B~1Mpc excluded for PKS 2155-304 (HESS collab. 2014)
- 1ES 0347−121: EGMF~10^{-18}–10^{-17}G (Tanaka et al. 2014)
- EGMF>10^{-19} G at L_B~Mpc (Finke et al. 2015)
- preliminary detection (2.3σ) EGMF ~ 10^{-17} –10^{-15} G from stacking 24 sync peaked BL Lacs at 1GeV (Cheng 2015)
- EGMF~10^{-14} G excluded by non-detection of MBC emission to 1ES 1218+304 (Veritas Coll. 2017)
- Stacking: EGMF~3x10^{-16}G at L_B k~10 kpc (Ackerman et al. 2018)



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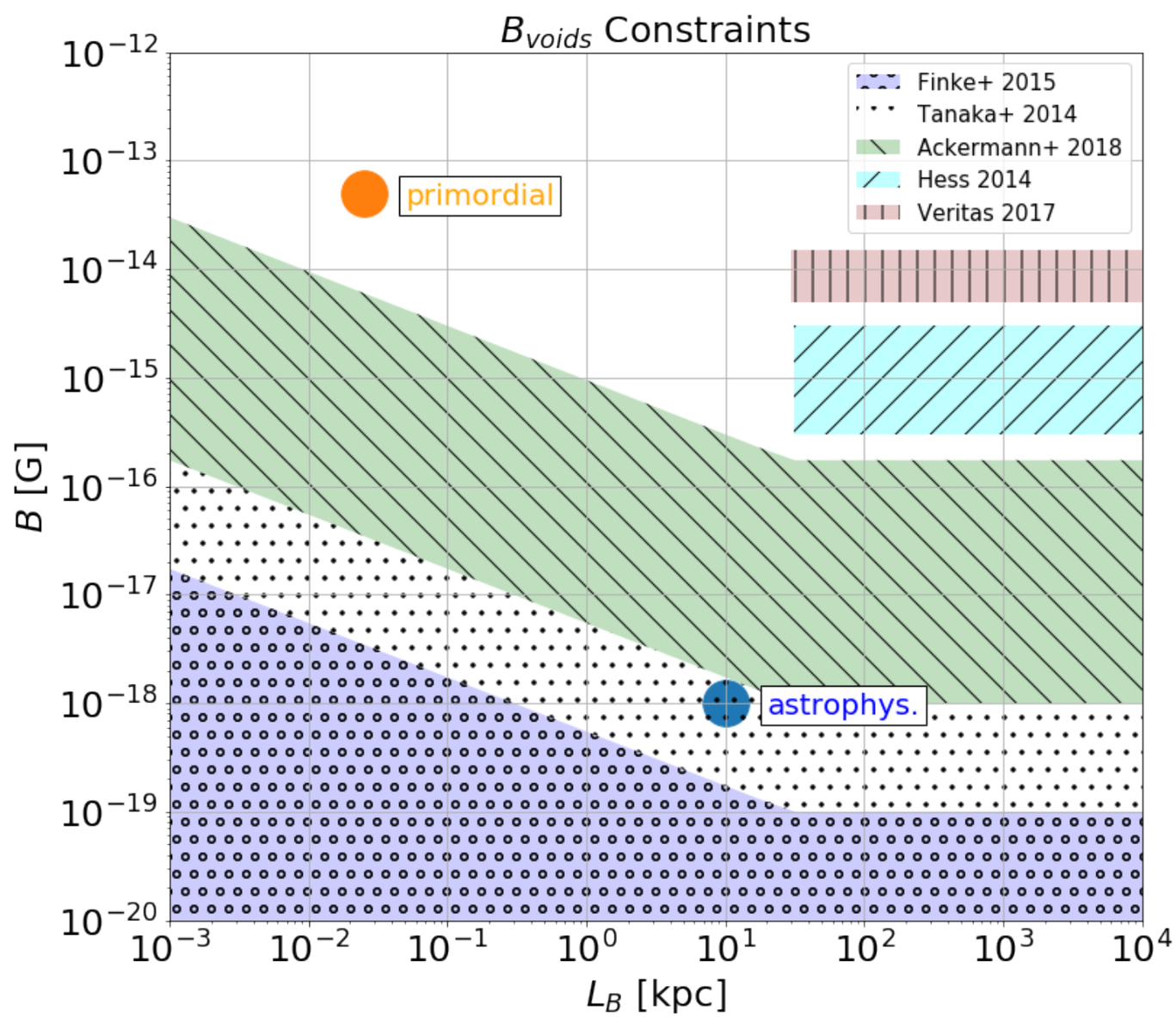
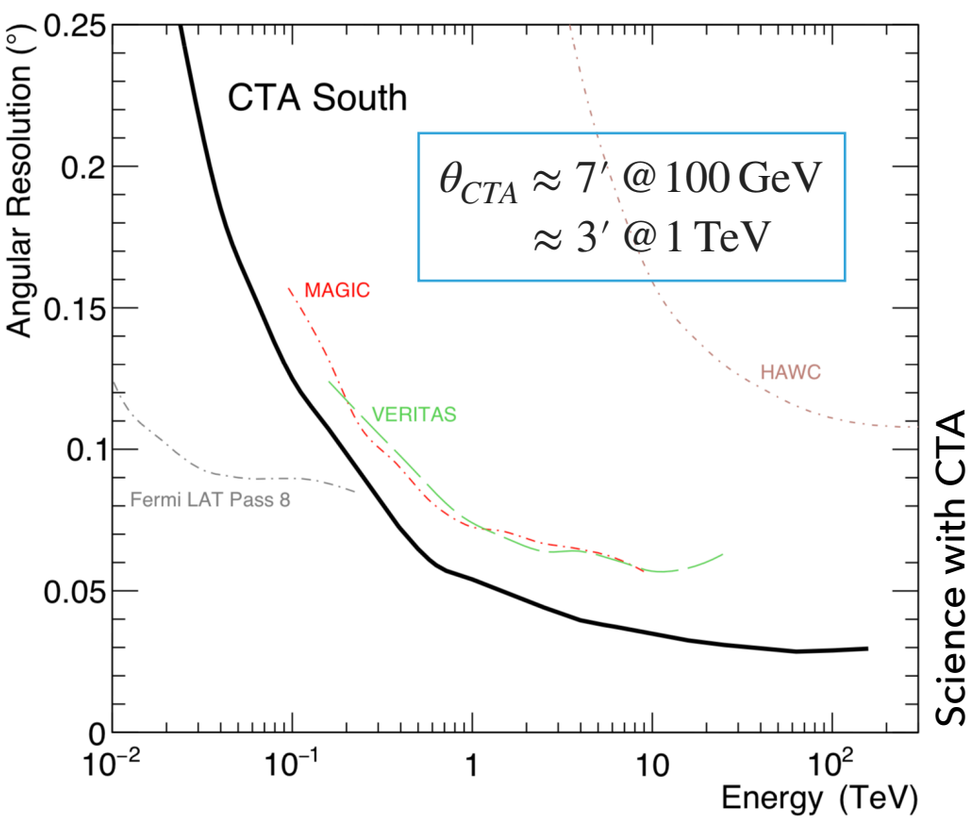


PS: "… presently available data are compatible with a zero-IGMF hypothesis" (Arlen et al. 2014)

FORECAST

- Primordial B-scenario can be probed by the angular distribution (MBC) of the secondary gamma-rays or time delay (pair echo) for a time-dependent (flaring) source
- pair echo on variable sources is promising for weaker fields given CTA's time-differential flux sensitivity
- produce PDF of expected effect corresponding to different l.o.s. based on numerical models of actual physical scenarios that account on varieties of conditions, B inhomogeneities
- CTA improved measurements of EBL will provide more accurate estimate of $\ell_{\gamma\gamma}$



Primordial

$$\theta_{halo} \approx 2' \, \frac{\ell_{\gamma\gamma 100}}{d_{*\mathrm{Gpc}}} \left(\frac{E}{100\,\mathrm{GeV}}\right) \left(\frac{B_0}{10^{-13}\,\mathrm{G}}\right) \left(\frac{L_0}{25\,\mathrm{pc}}\right)^{1/2}$$

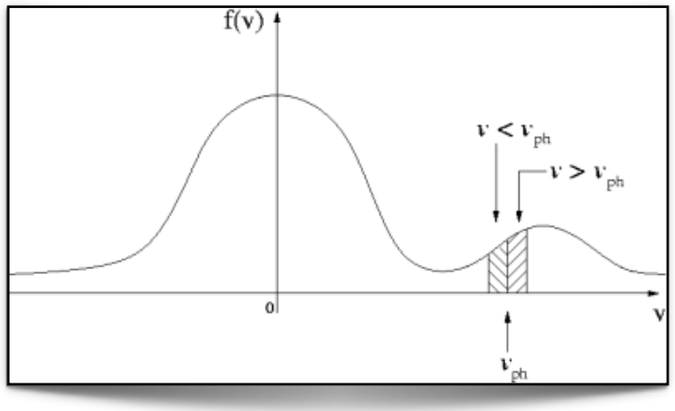
$$\Delta t \approx 66\,\mathrm{yr}\, \ell_{\gamma\gamma 100} \left(\frac{E}{100\,\mathrm{GeV}}\right)^{-1} \left(\frac{B_0}{10^{-14}\,\mathrm{G}}\right) \left(\frac{L_0}{25\,\mathrm{pc}}\right)$$

Astrophysical

$$\theta_{halo} < 0.3''$$

$$\Delta t \approx 1\,\mathrm{w}\, \ell_{\gamma\gamma 100} \left(\frac{E}{10\,\mathrm{GeV}}\right)^{-1} \left(\frac{B_0}{10^{-18}\,\mathrm{G}}\right) \left(\frac{L_0}{10\,\mathrm{kpc}}\right)$$

ALTERNATIVE



- Alternatively caused by pair-beam instability, with dramatic consequences for the thermal history of the IGM (Broderik et al 2012).
- Nonlinear analysis by *FM* & Elyiv (2013) show that the beam is stable on timescales ≫ inverse Compton timescale. This was questioned by Chang et al. (2014) but confirmed by simulations of Vafin et al. (2018, 2019)
- PIC simulations (Sironi and Giannios 2014; Kempf, Kilian, Spanier, F. 2016, Rafighi et al. 2017) show that the beam is stable even at the linear stage (contrary to 50-100 τ_{inst} from 1-D simulations Grognard 1975).

CONCLUSIONS

- exciting discovery of magnetic field in voids
- tentative case for primordial vs astrophysical (resistive) mechanism, CTA expected to probe broadening of the E. M. cascade / time delay (pair echo), however detailed (numerical) modelling and PDF of expected effects on E.M. cascade necessary for interpretation of the data
- in principle important details testable or calculable from first principles/simulations, general framework to test other possibilities

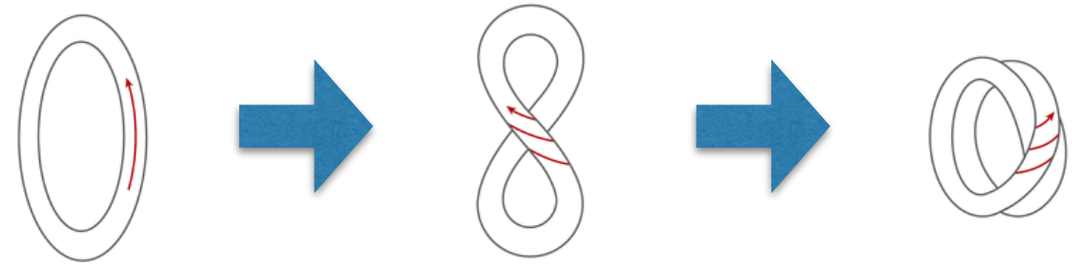
THANKS!

- A.R. Bell
- A. Elyiv
- G. Gregori
- B. Reville
- S. Sarkar

GROWTH OF MAGNETIC FIELD

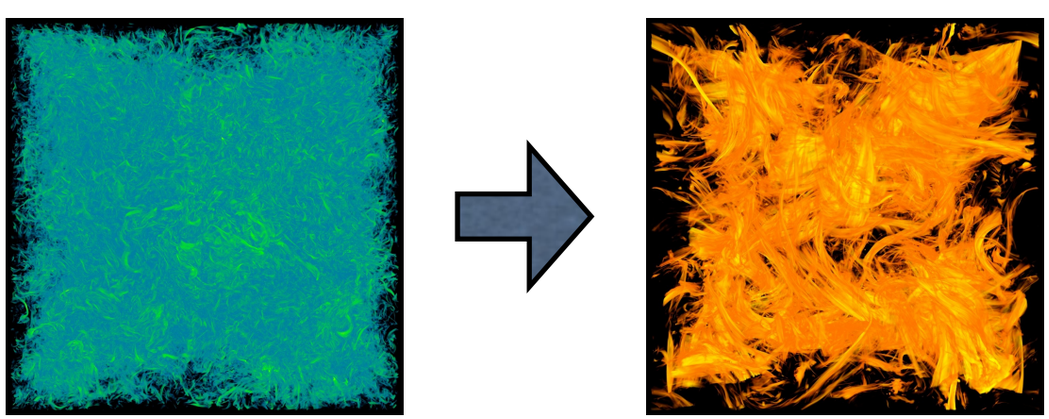
Stretch, twist and fold dynamo mechanism

- if ℓ_s is the scales where stretching is most efficient so that roughly: $\delta u^2_{\ell s} \sim \langle B^2 \rangle$
- C_E~4-5 % according to recent numerical simulations (Beresnyak 2012, Beresnyak and Miniati 2016)
- Finally, $E_B \sim E_K$ and E_B growth saturates

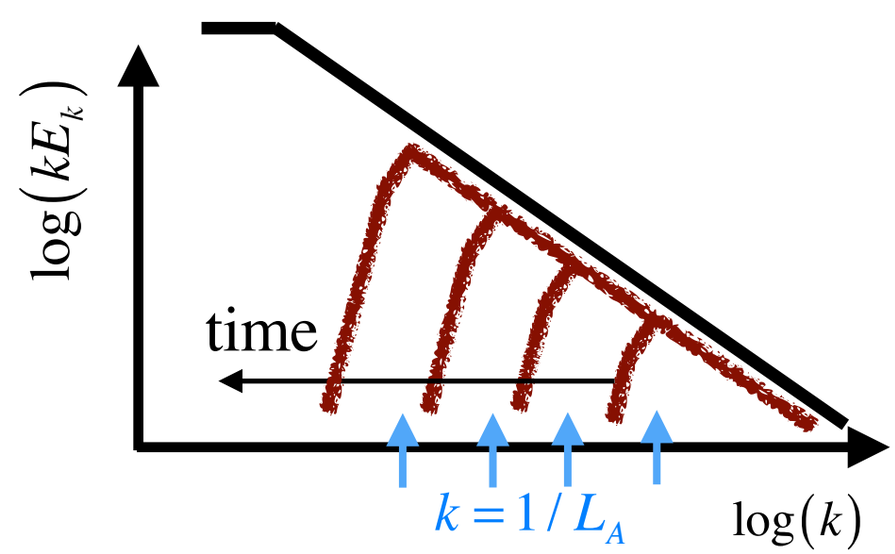


$$\frac{d}{dt}\langle B^2 \rangle \approx \frac{\delta u_{\ell_s}}{\ell_s}\langle B^2 \rangle \approx \frac{\delta u^3_{\ell_s}}{\ell_s} \sim \varepsilon_{turb}$$

$$\Rightarrow \langle B^2 \rangle(t) \approx C_E \int^t \varepsilon_{turb}(\tau)\, d\tau$$



Jones et al. (2011)



Kulsrud & Anderson (1992), Cho & Vishniac (2000), Schekochihin & Cowley (2007), Jones et al. (2011)