Multi-messenger constraints on cosmological magnetic fields

Andrii Neronov

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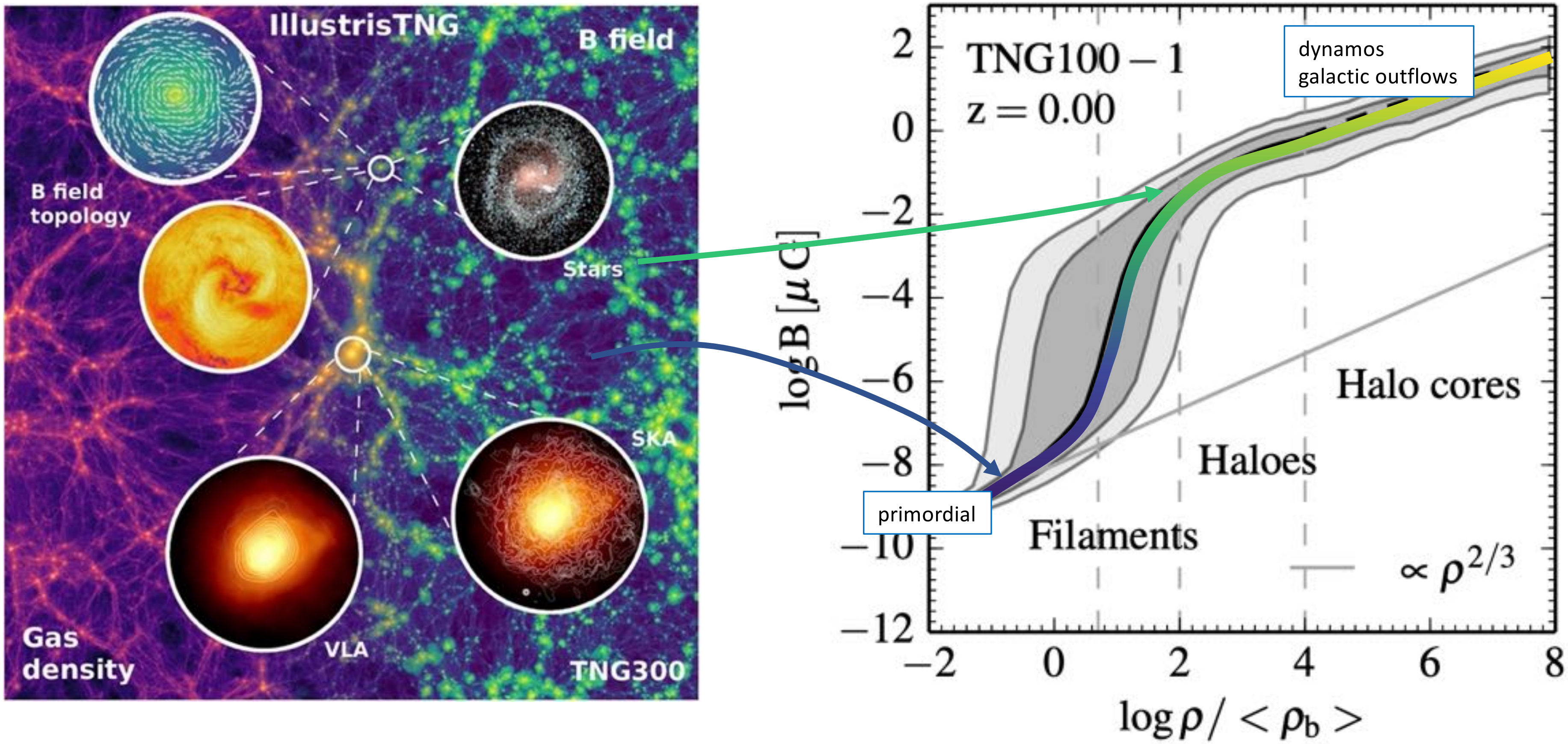
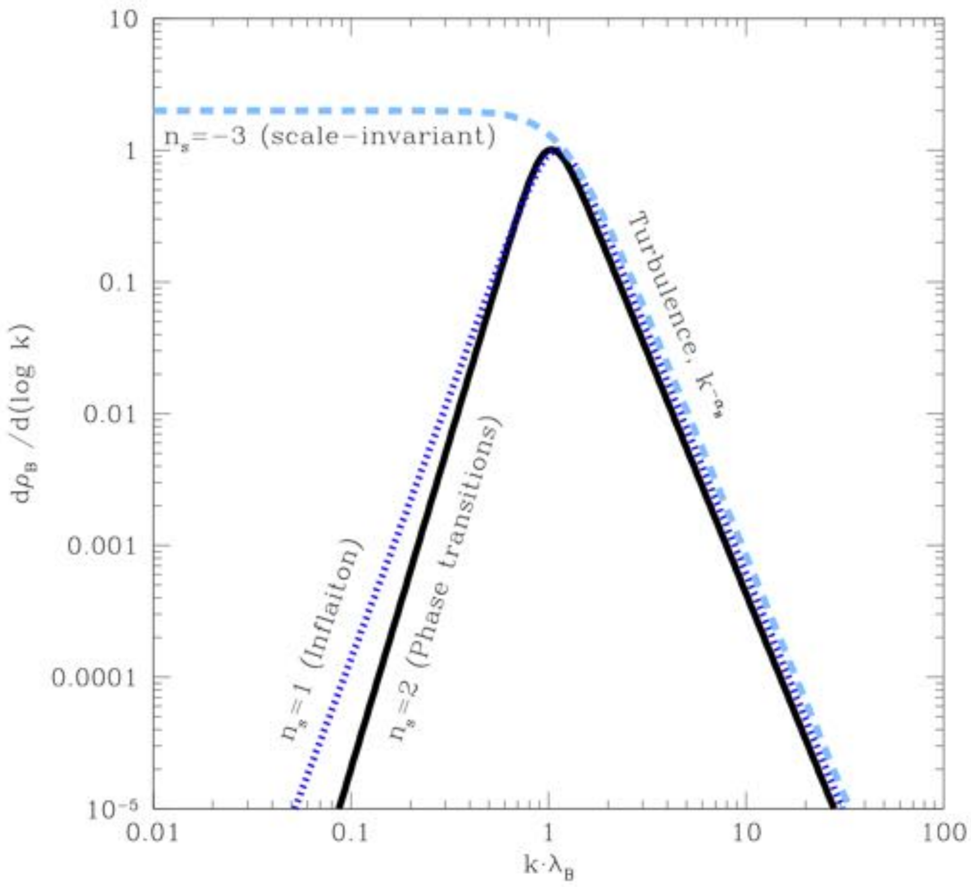
Where to look for cosmological magnetic fields?

Marinacci et al. 18

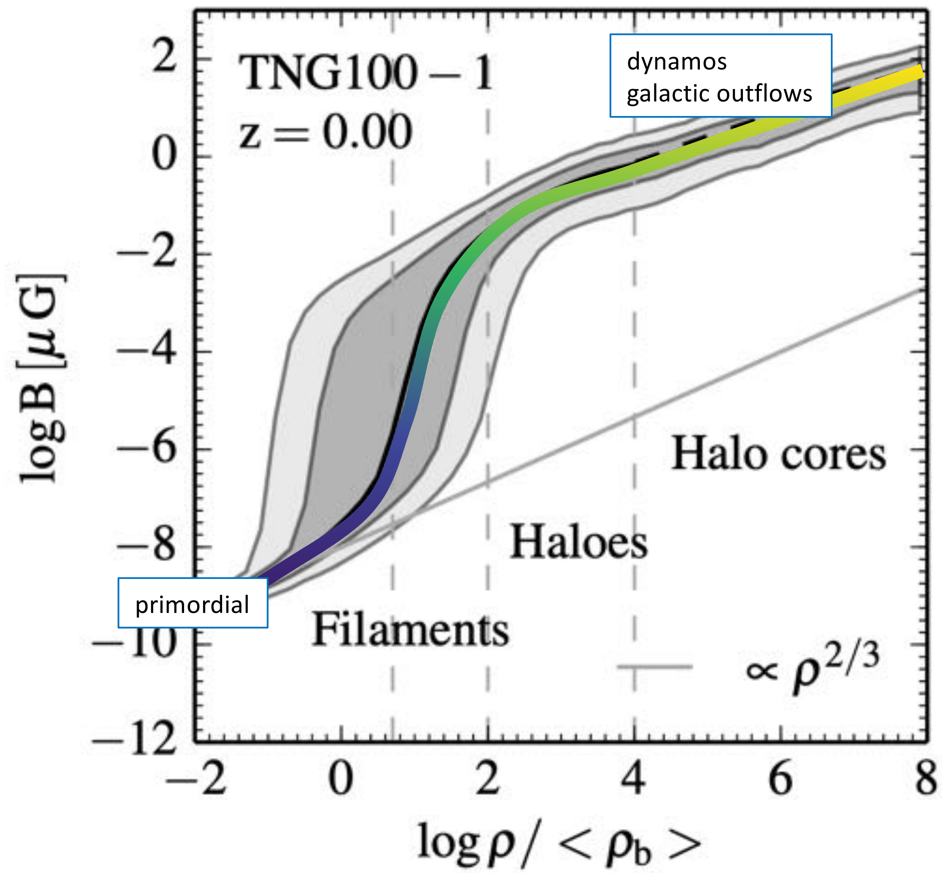


Constraints on cosmological magnetic fields can be derived from magnetic fields in the voids (least affected by outflows from galaxies, turbulent dynamos etc).

What are cosmological magnetic field characteristics?

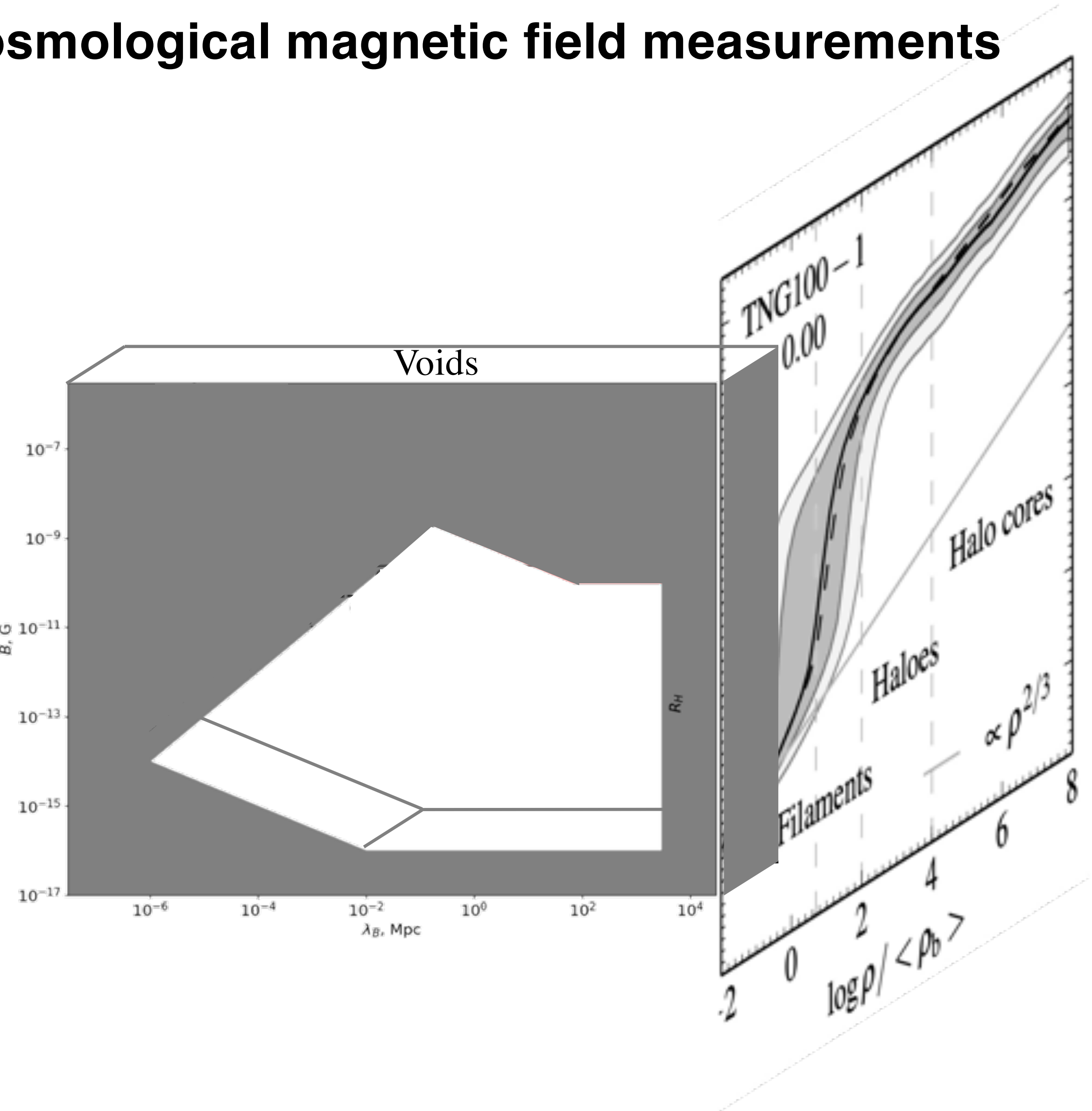


Marinacci et al. 18

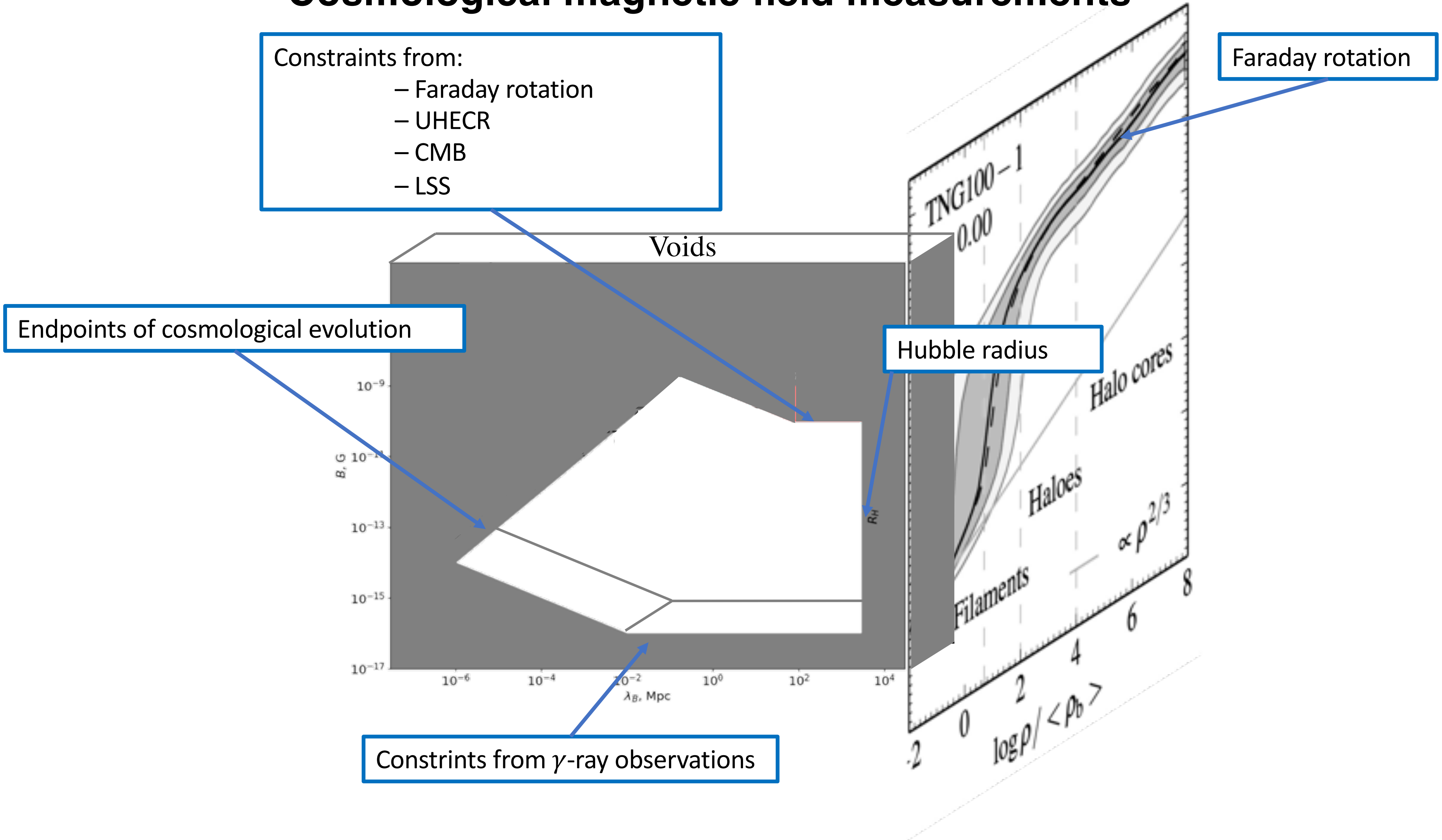


Magnetic field is characterised by energy and helicity power spectrum, with parameters strength, fractional felicity, correlation length, slope(s) of the power spectr(a). Not all of them are measurable from observational data.

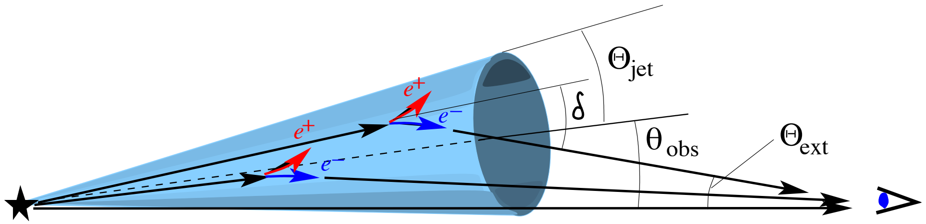
Cosmological magnetic field measurements

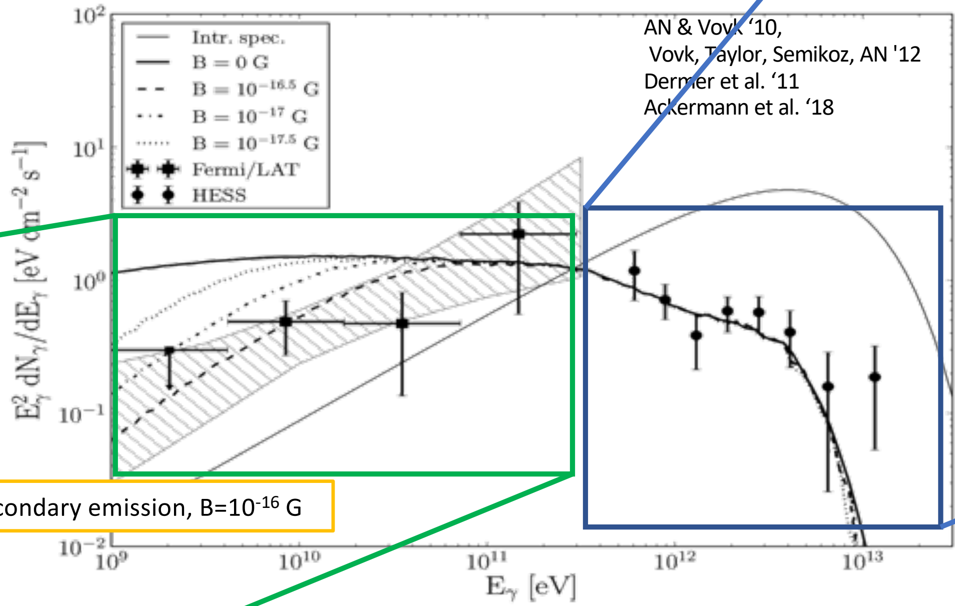


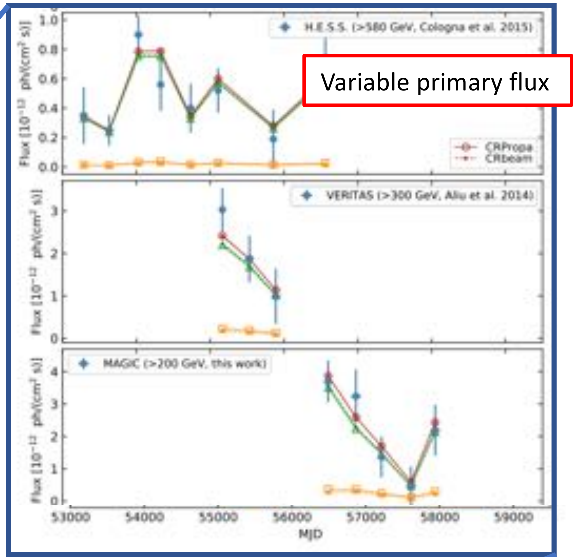
Cosmological magnetic field measurements

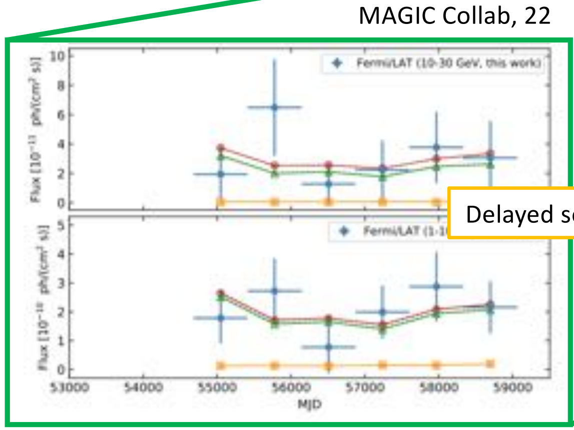


Constraints from gamma-ray observations





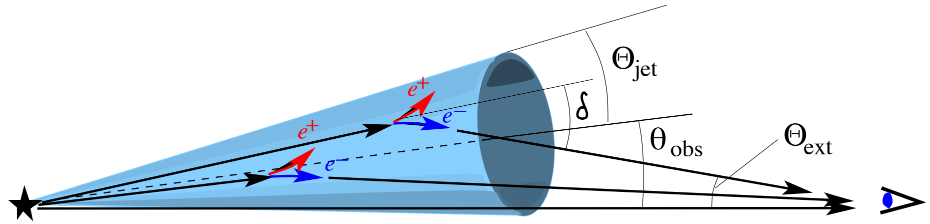




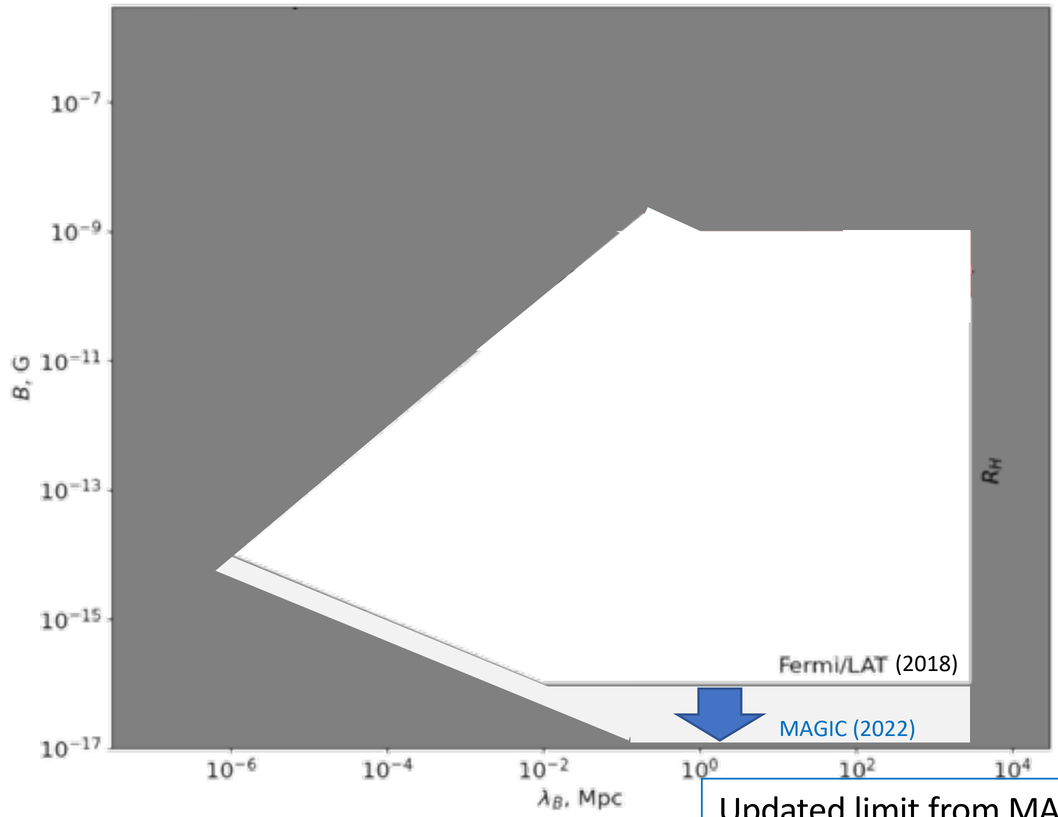
Monitoring of TeV and GeV flux from blazars on decade-long time span is now available. It allows to refine the search of delayed IGMF dependent secondary emission.

talk by P. da Vela

Constraints from gamma-ray observations



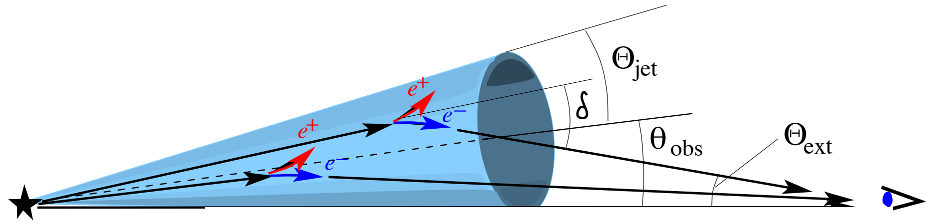
Plaga '95
Neronov & Semikoz '07, '09



talk by P. da Vela

Updated limit from MAGIC is weaker than Fermi/LAT 2018 limit

Constraints from gamma-ray observations



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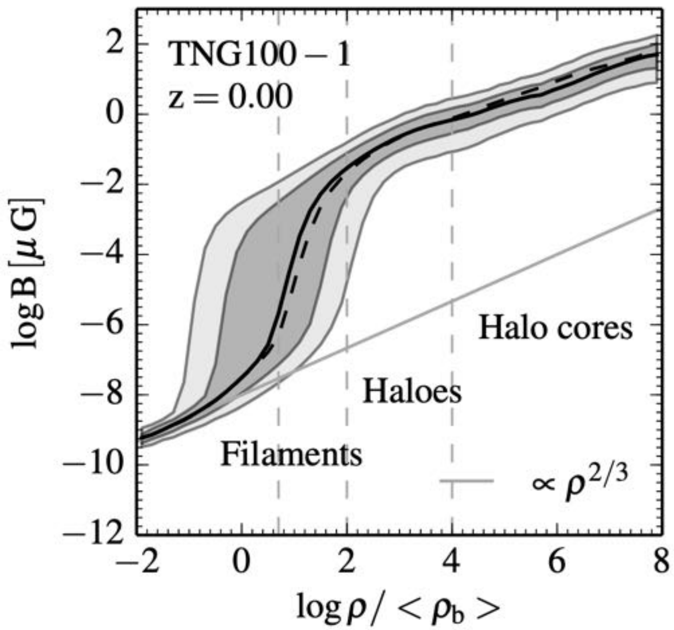
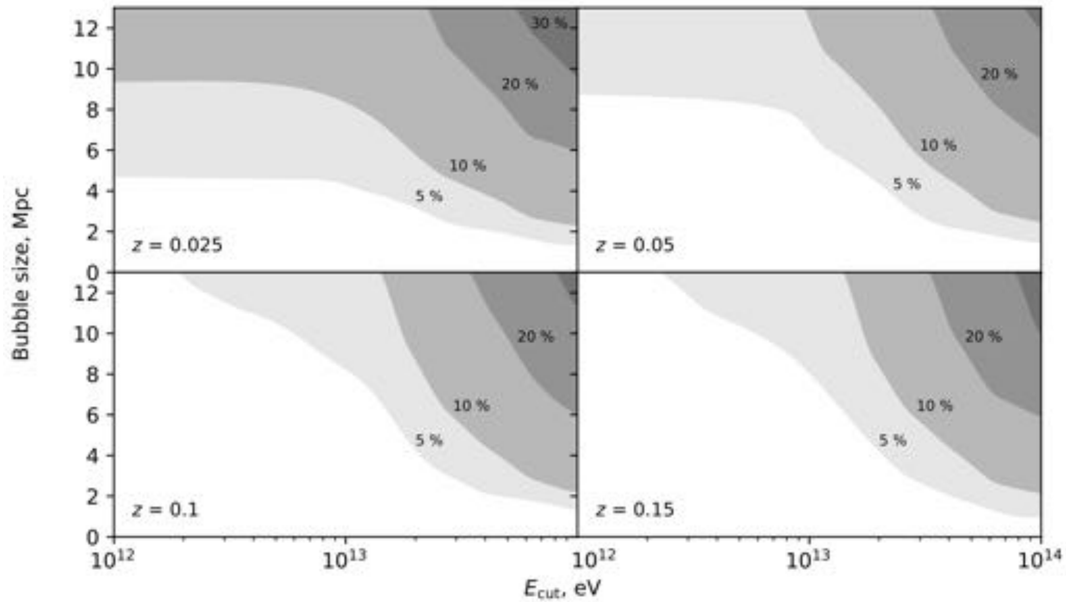


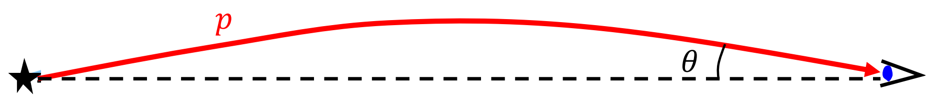
Bondarenko et al. 22

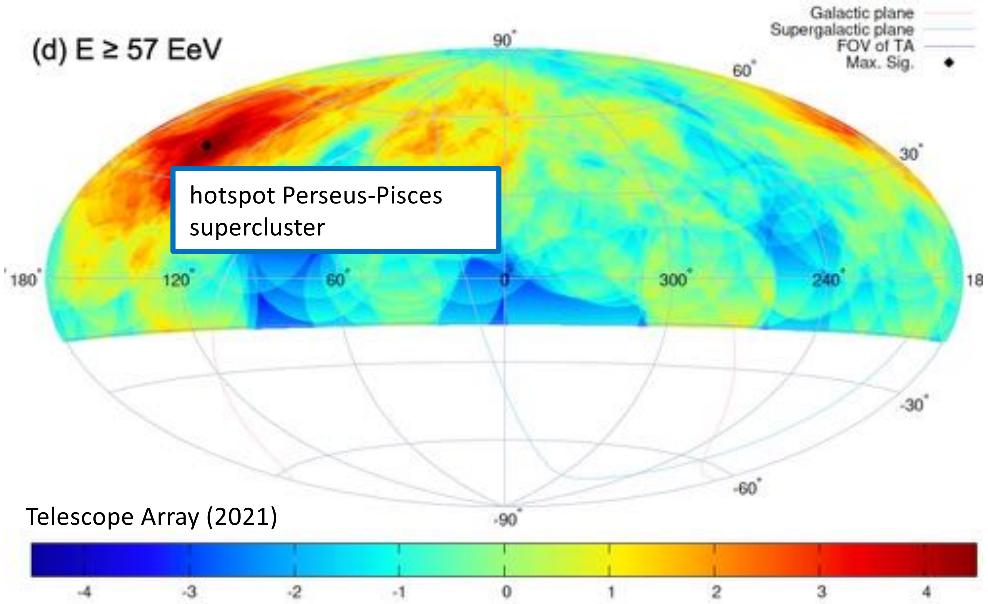


Gamma-ray measurements may be affected by the presence of magnetized bubbles produced by galactic outflows. Estimates from Illustris—TNG suggest that the effect is at 5-10% level for primary gamma-rays in the 1-10 TeV energy range, but can be more important at E>20 TeV.

talk by K.Bondarenko

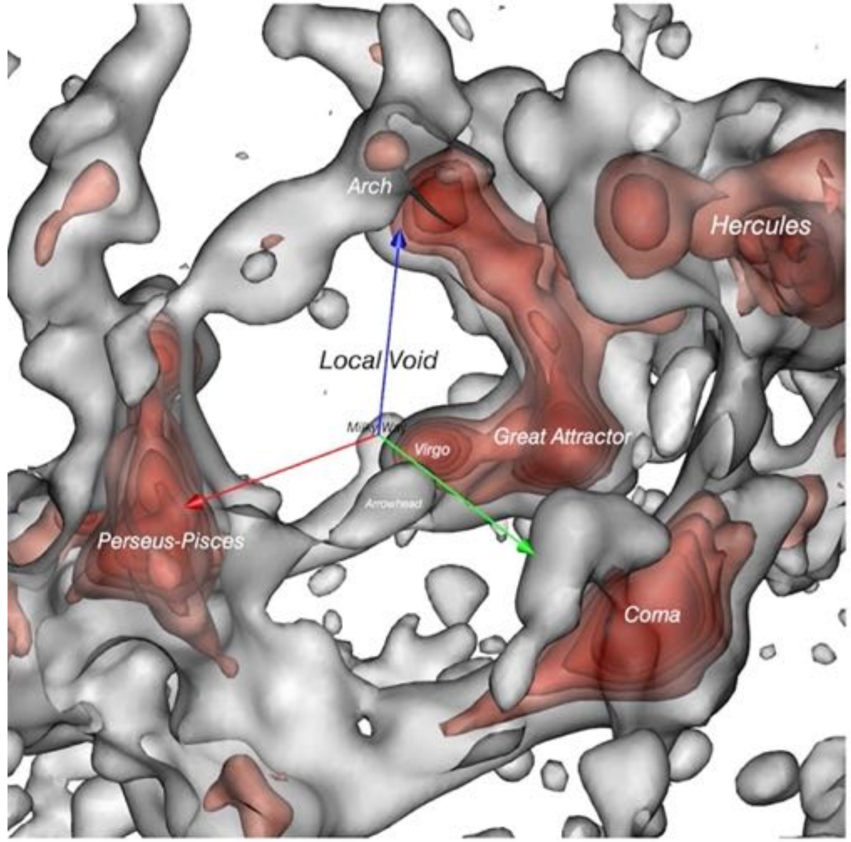
Constraints from UHECR





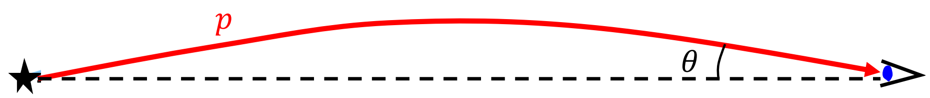
Telescope Array (2021)

Tully et al. 19

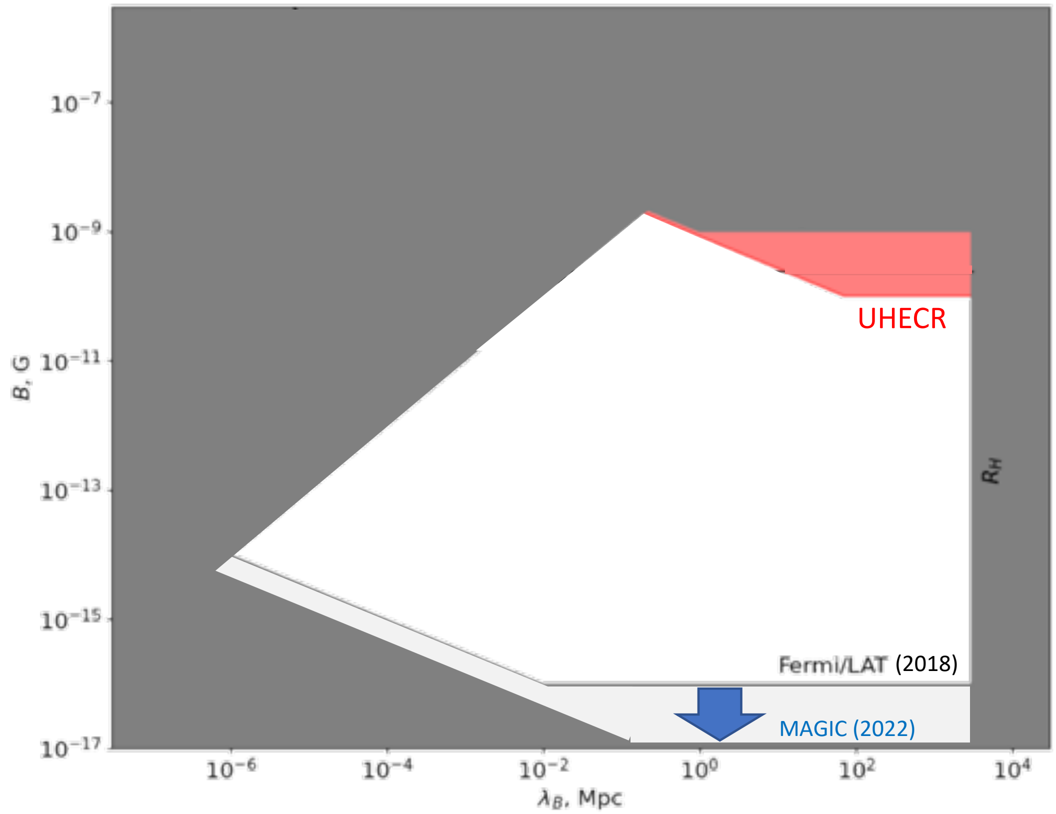


Detection of even one UHECR source immediately implies a constraint on magnetic field between the source and the Earth. TA has reported evidence for an extended (20 degree) excess in the direction of Perseus-Pisces supercluster, at the distances ~ 70 Mpc, behind the Local Void. This imposes a constraint on magnetic field in the Local Void.

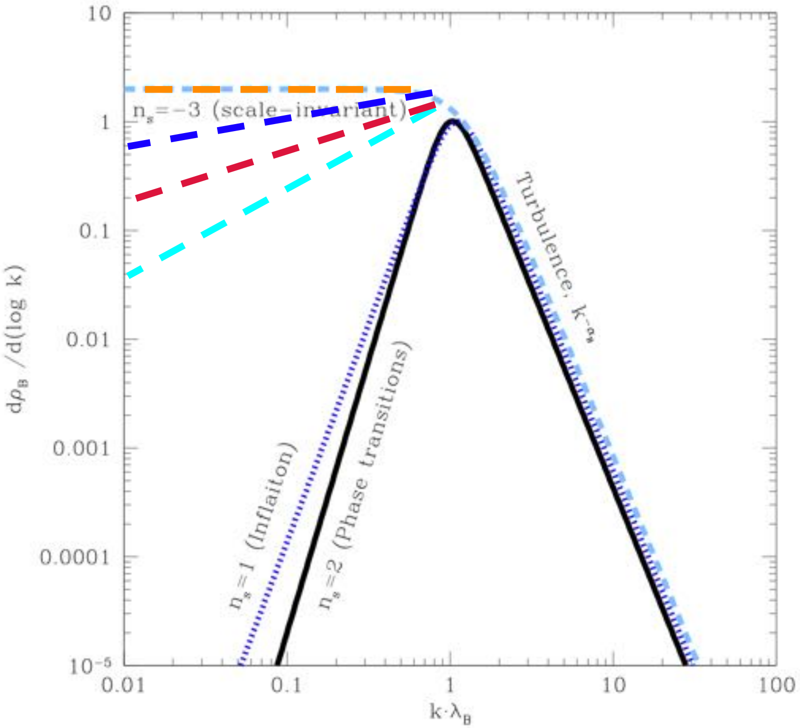
Constraints from UHECR

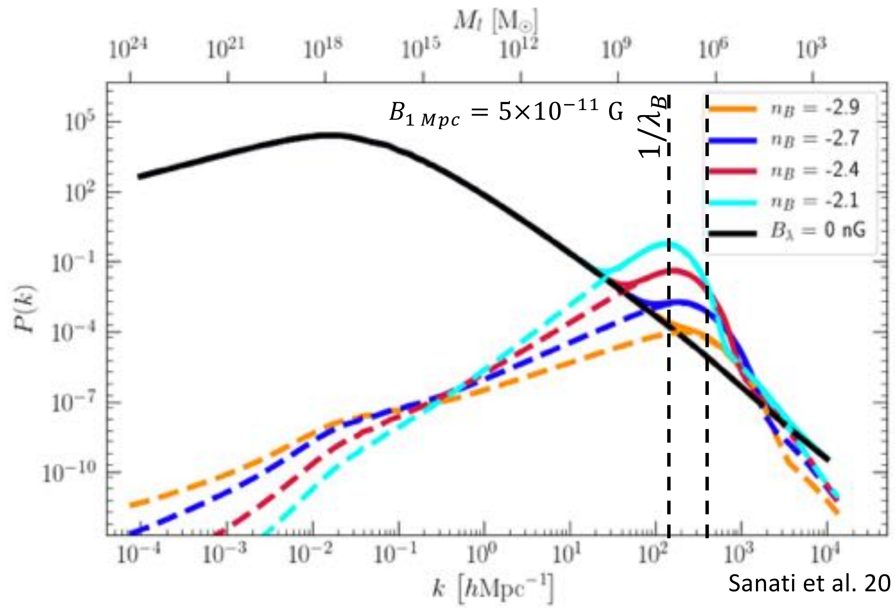


Neronov, Semikoz 21



Constraints from LSS





Sanati et al. 20

Magnetic field has a broken power spectrum peaking at $k \sim \lambda_B^{-1}$ with the correlation length λ_B corresponding to the "largest processed eddy" scale, which small at the moment of recombination, $\lambda_B \leq v_A t_{rec} \sim 5\left[\frac{B}{5\times10^{-11}\mathrm{G}}\right]$ kpc. Short correlation length magnetic field induces plasma motions and affects matter power spectrum on the scales $k \sim \lambda_B^{-1}$.

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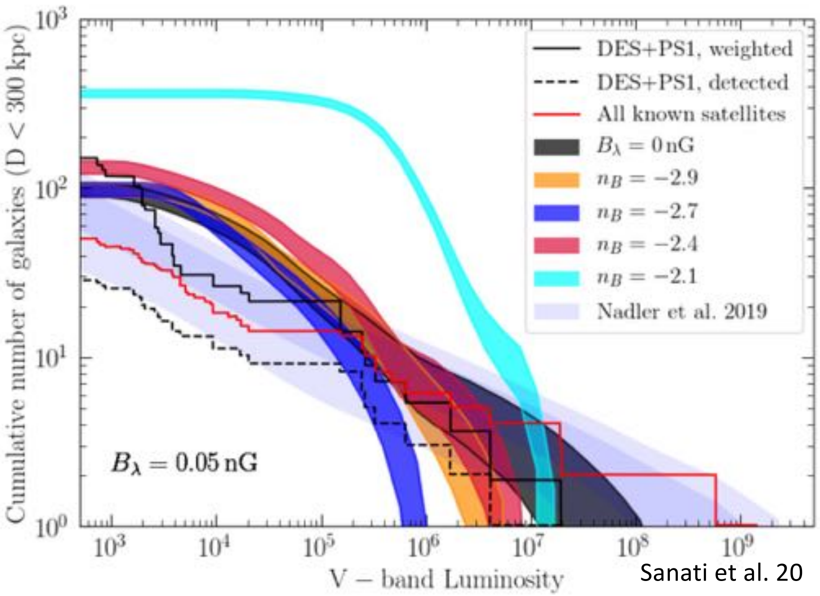

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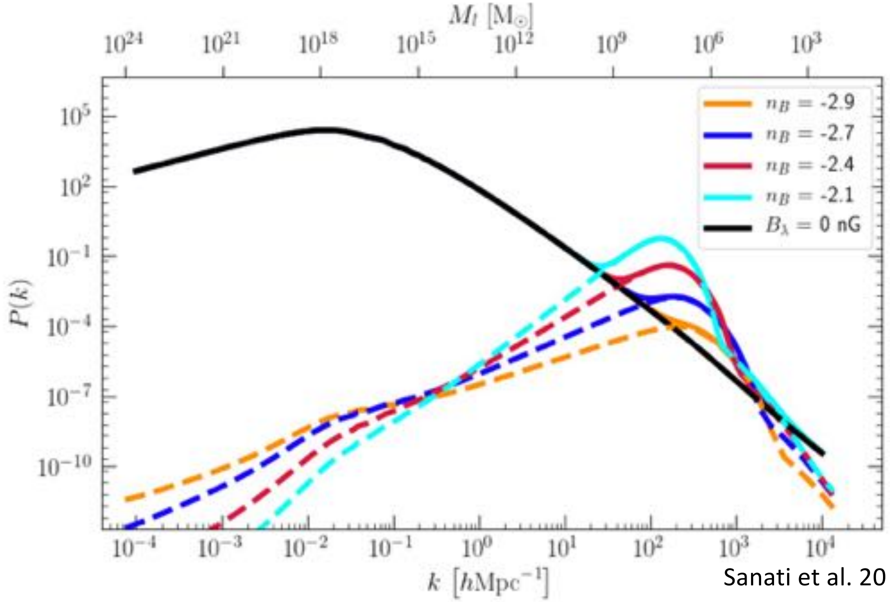

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Excess in the matter power spectrum leads to larger abundance of dwarf galaxy scale halos and to earlier on-set of star formation in these halos, resulting in earlier re-ionisation.

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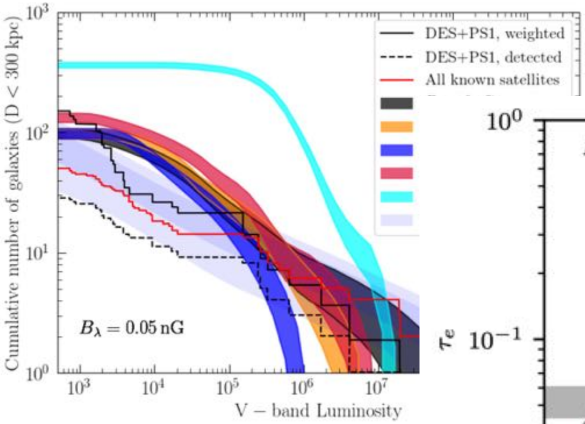
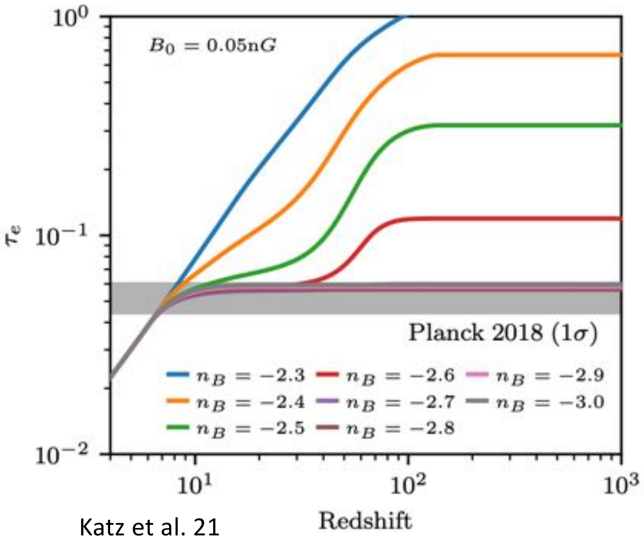
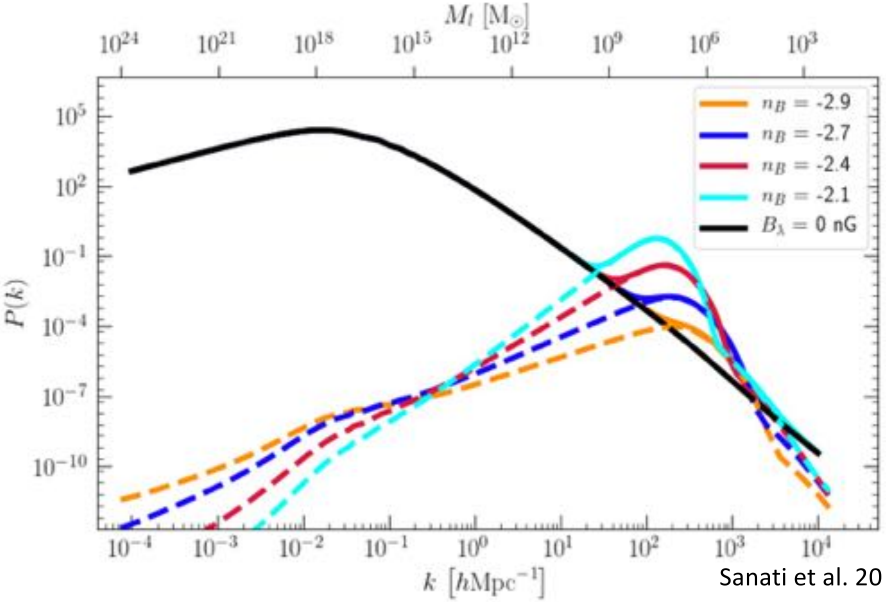


Sanati et al. 20



Katz et al. 21



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This increases the free electron density in the intergalactic medium and CMB optical depth w.r.t. Compton scattering on these free electrons.

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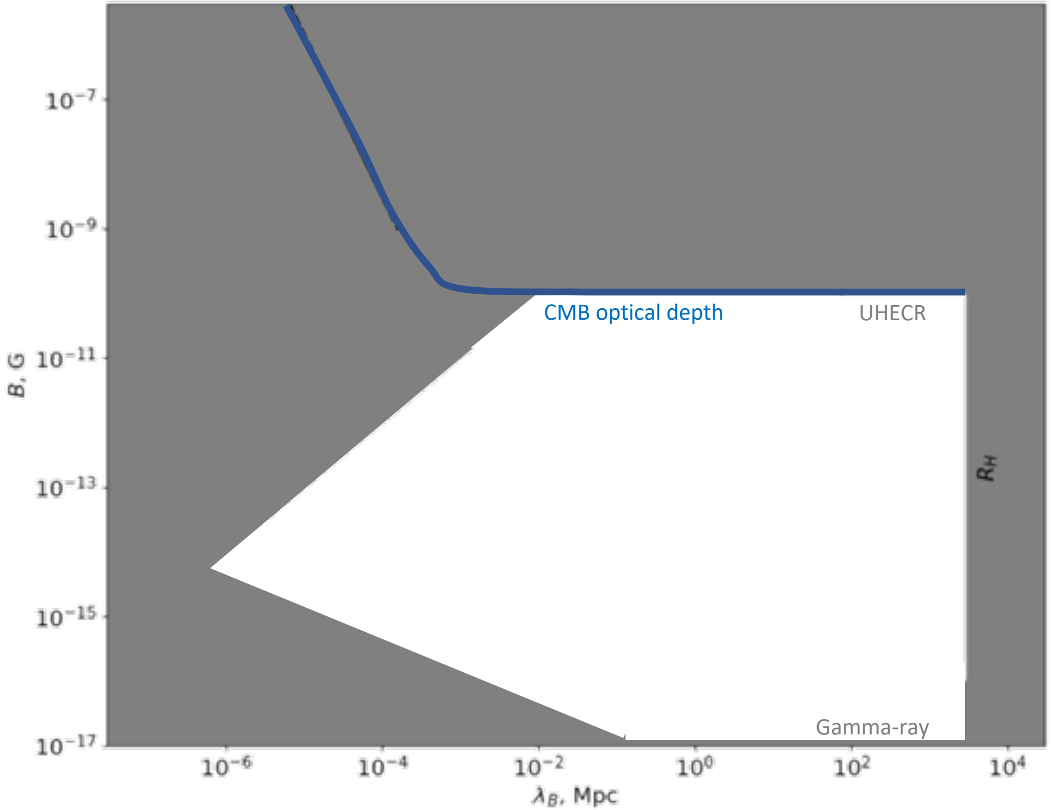

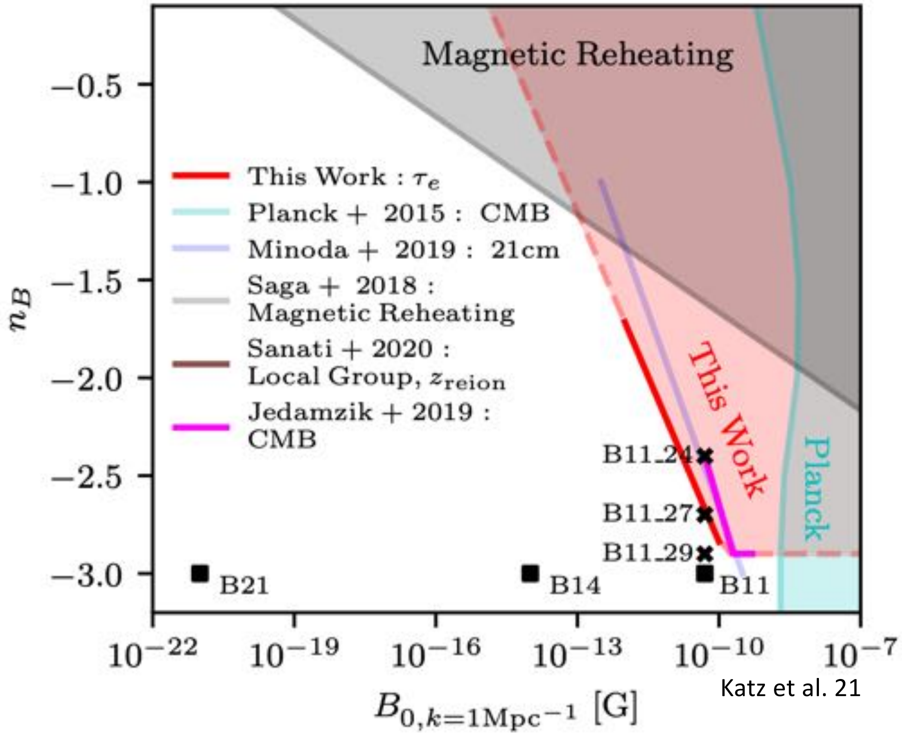

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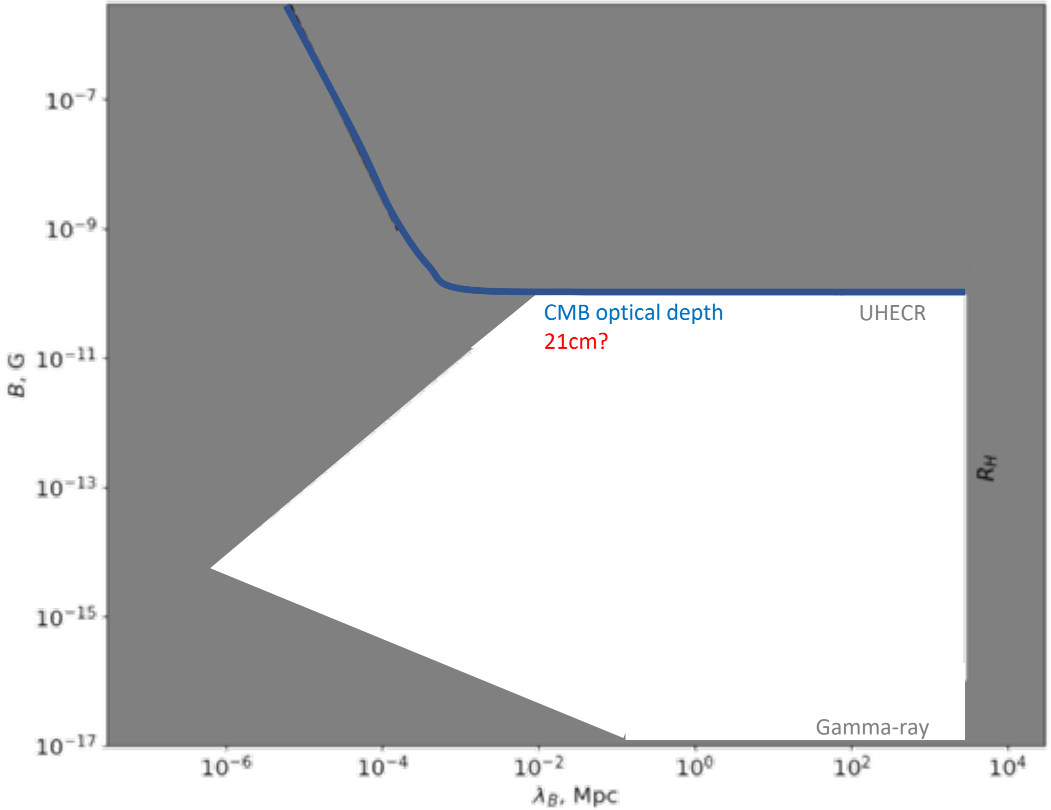

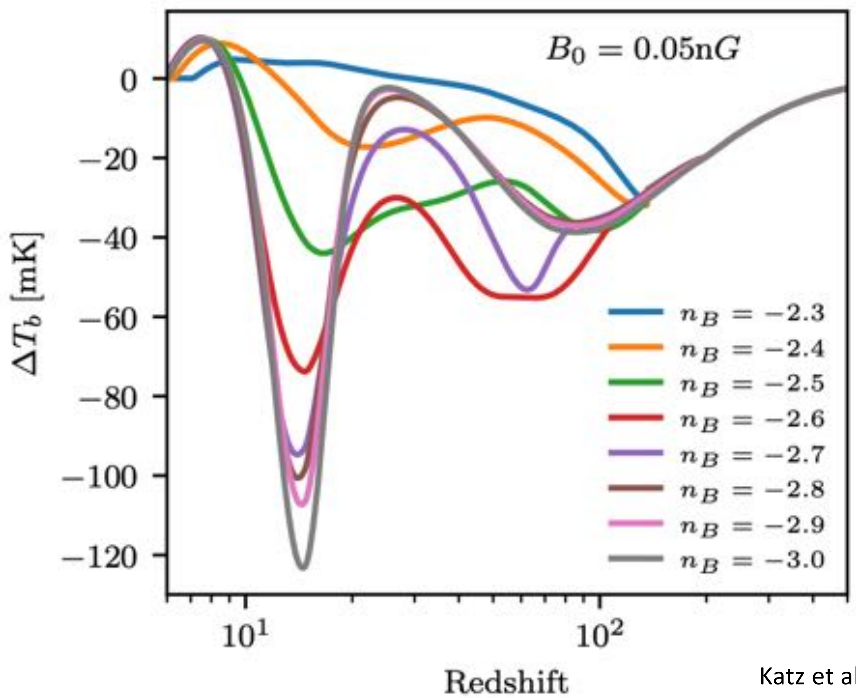

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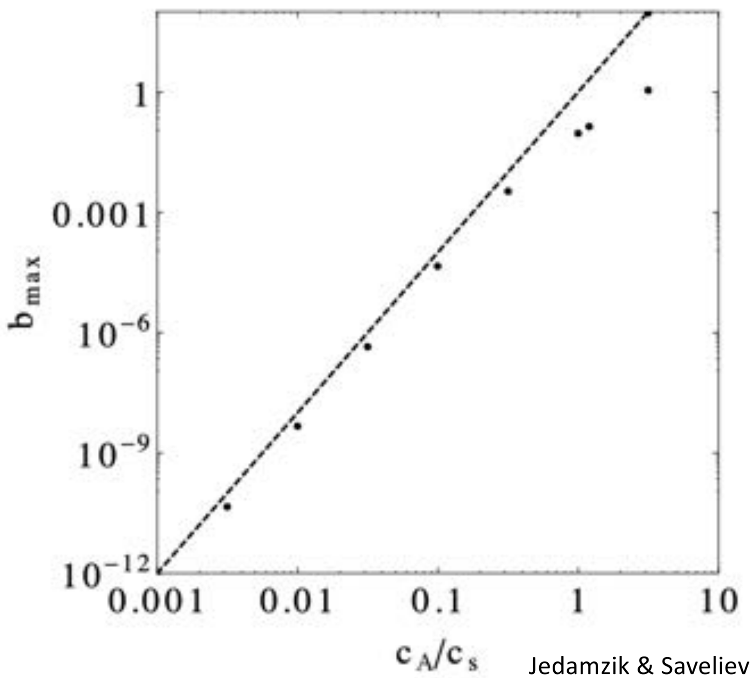
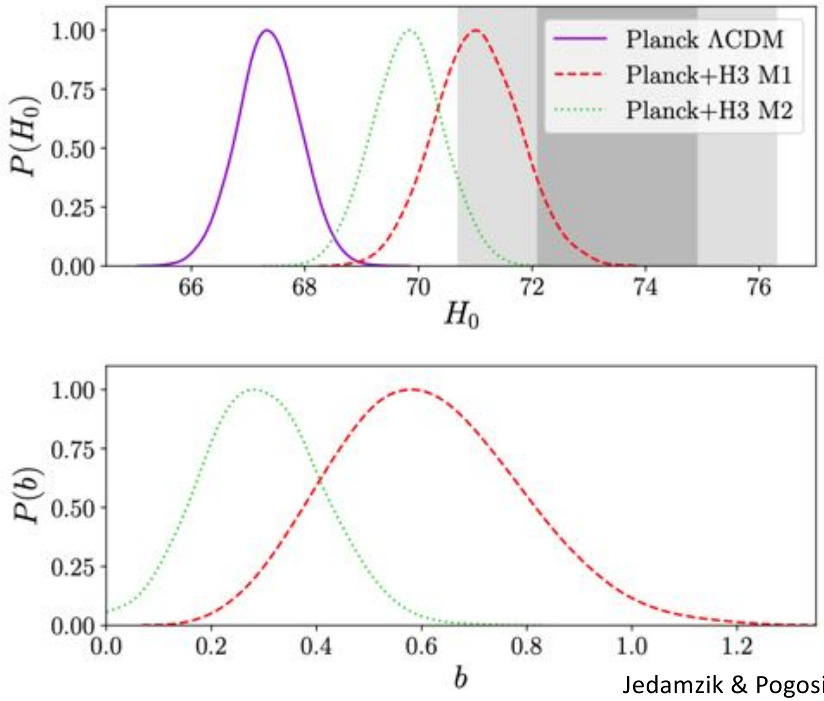
Constraints from CMB clumping



Jedamzik & Saveliev 19

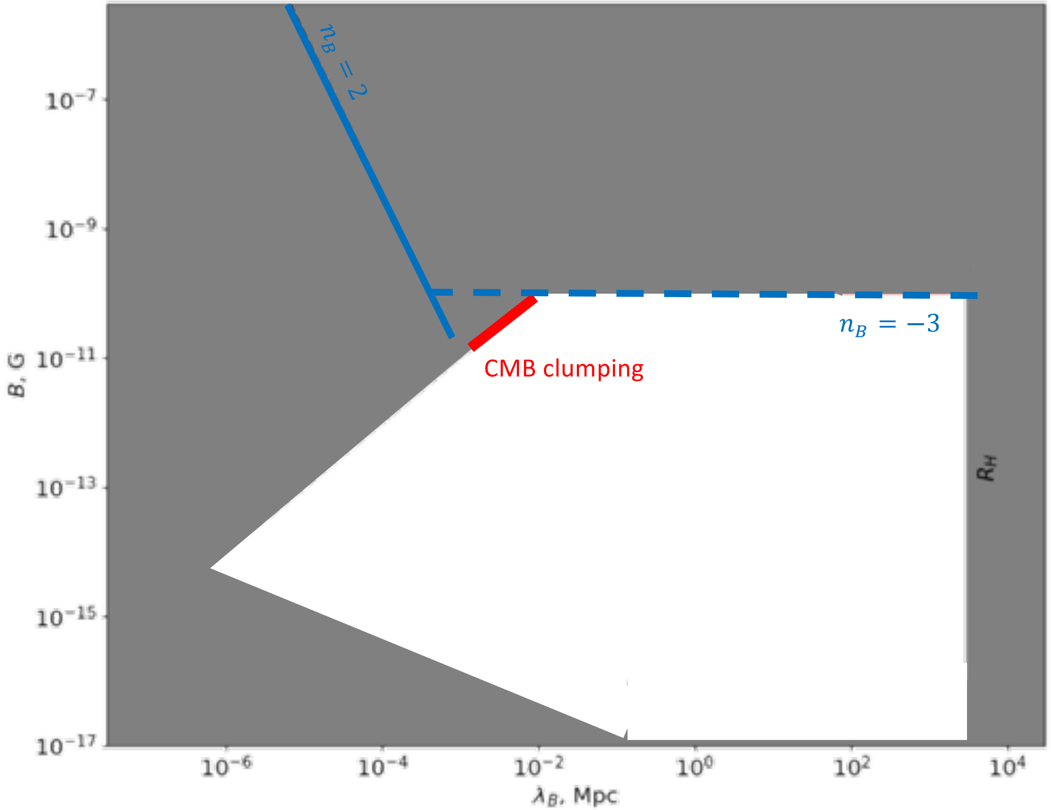


Jedamzik & Pogosian 20

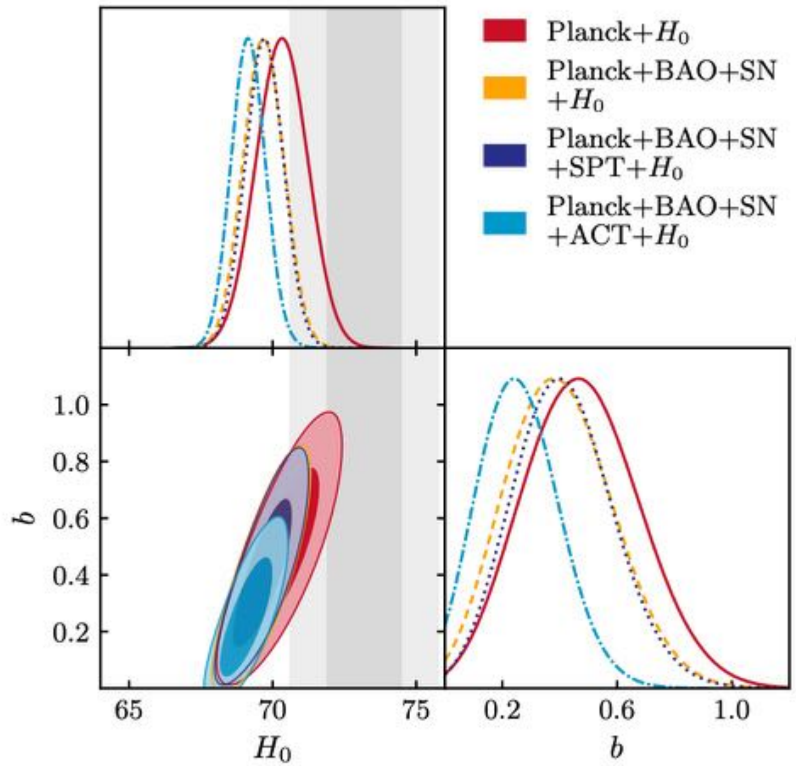
Magnetic field induces clumping of baryonic fluid during recombination, $b = \langle \delta\rho^2/\rho^2 \rangle$, which changes the recombination history, which in turn leads to revision of the estimate of the Hubble constant from CMB. $b \sim 1$ are allowed and possibly favoured by the CMB data.

talk by K.Jedamzik

Constraints from CMB clumping



Galli et al 22



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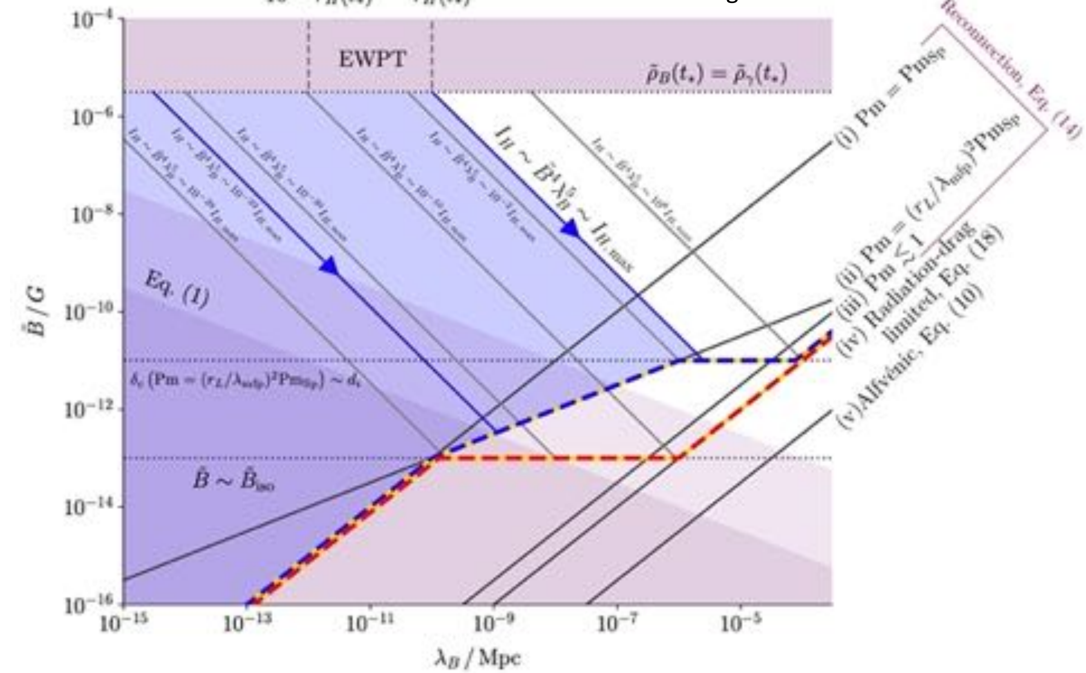
This imposes constraint on the possible strength of magnetic field during recombination epoch, possibly an estimate of it strength and correlation length at recombination.

For a field with scale-invariant power spectrum ($n_B = -3$), the UHECR, LSS and CMB upper limits are comparable!

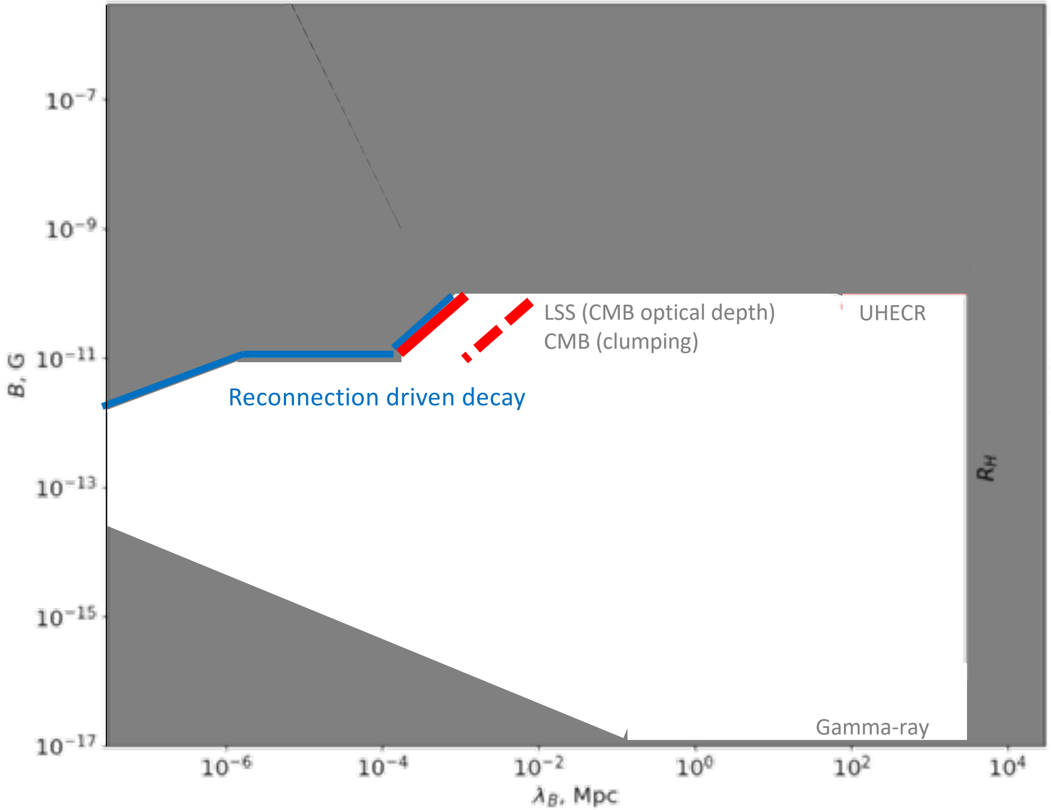
Constraints from cosmological evolution

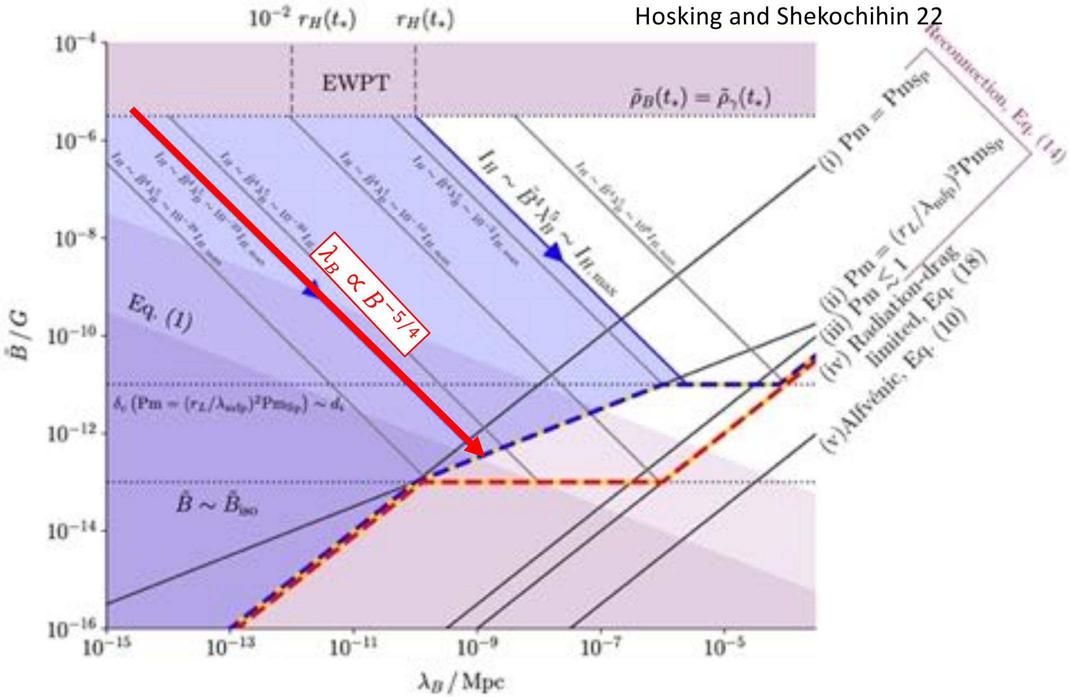
Hosking and Shekochihin 22



Magnetic field correlation length at any cosmological epoch may be of the order of the "largest processed eddy" scale, $\lambda_B \sim v_A t \sim 1[B/10^{-8}\mathrm{G}]$ Mpc (Banerjee & Jedamzik 2004). Hosking and Shekochihin (2022) have challenged this conjecture, suggesting that turbulent decay of magnetic field is guided by reconnection, which has smaller processed eddy scales, at most $\widetilde{\lambda_B} \sim 0.1\lambda_B$ (still smalled for magnetic field strength lower than 10^{-11} G).

Constraints from cosmological evolution





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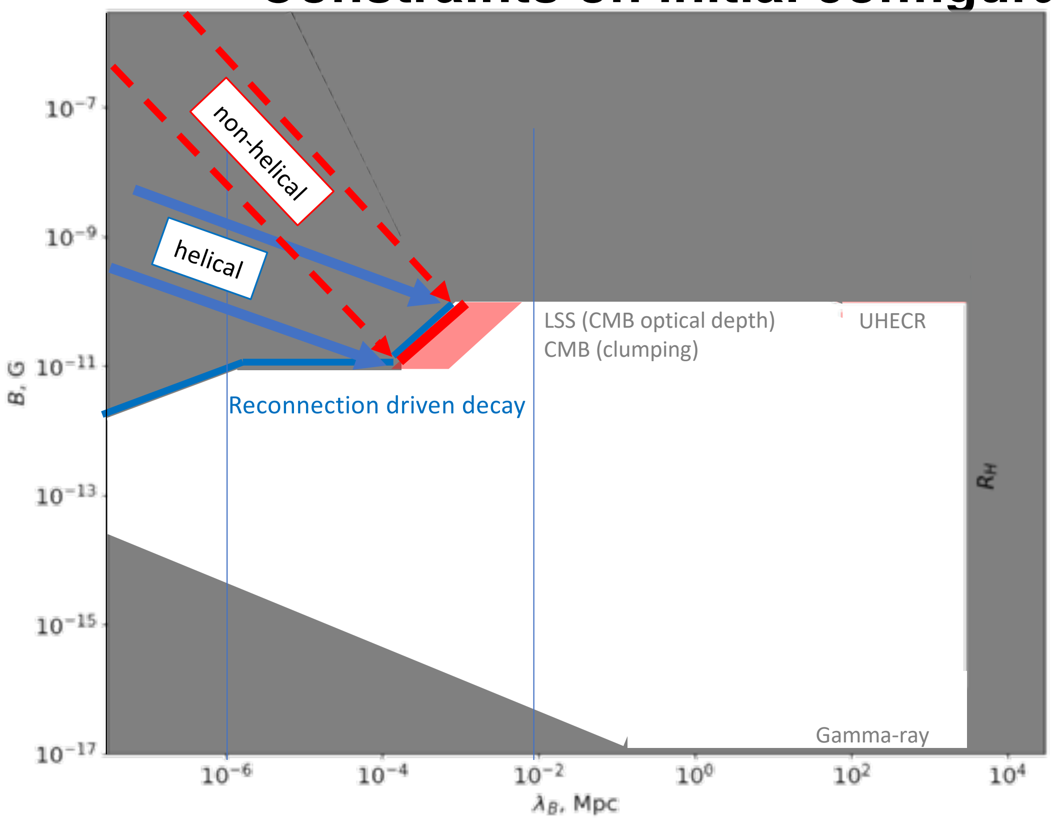
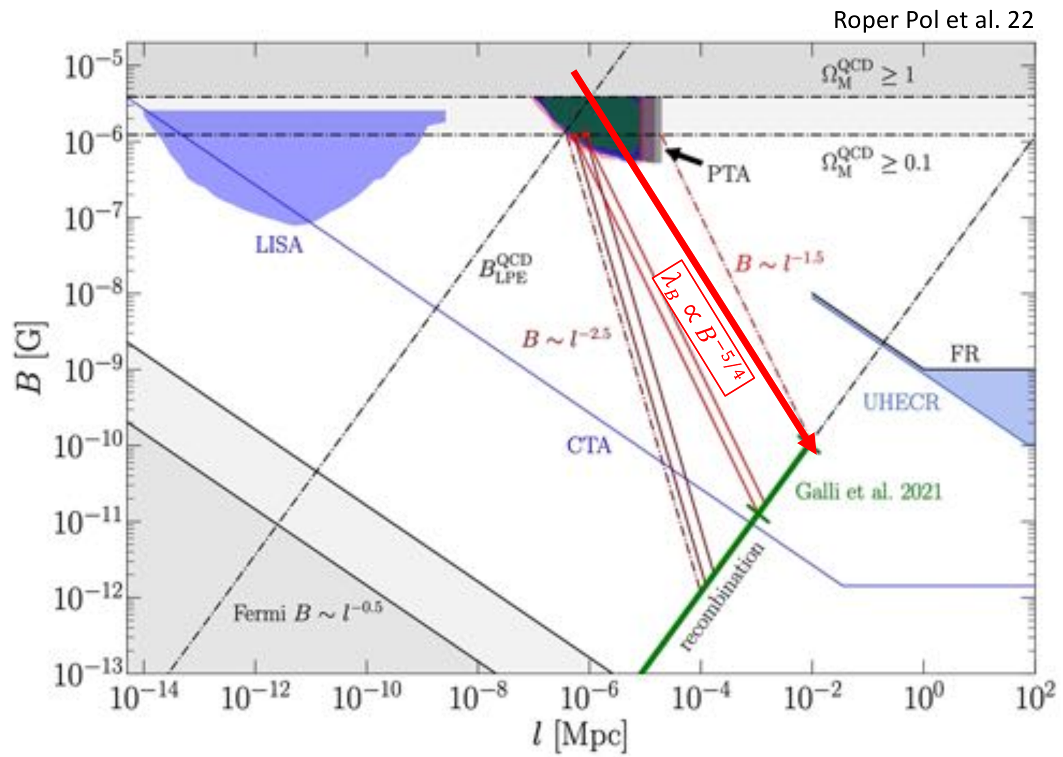
Much smaller correlation lengths are observationally allowed. How would this affect CMB clumping and LSS bounds?

Constraints on initial configuration of cosmological magnetic?

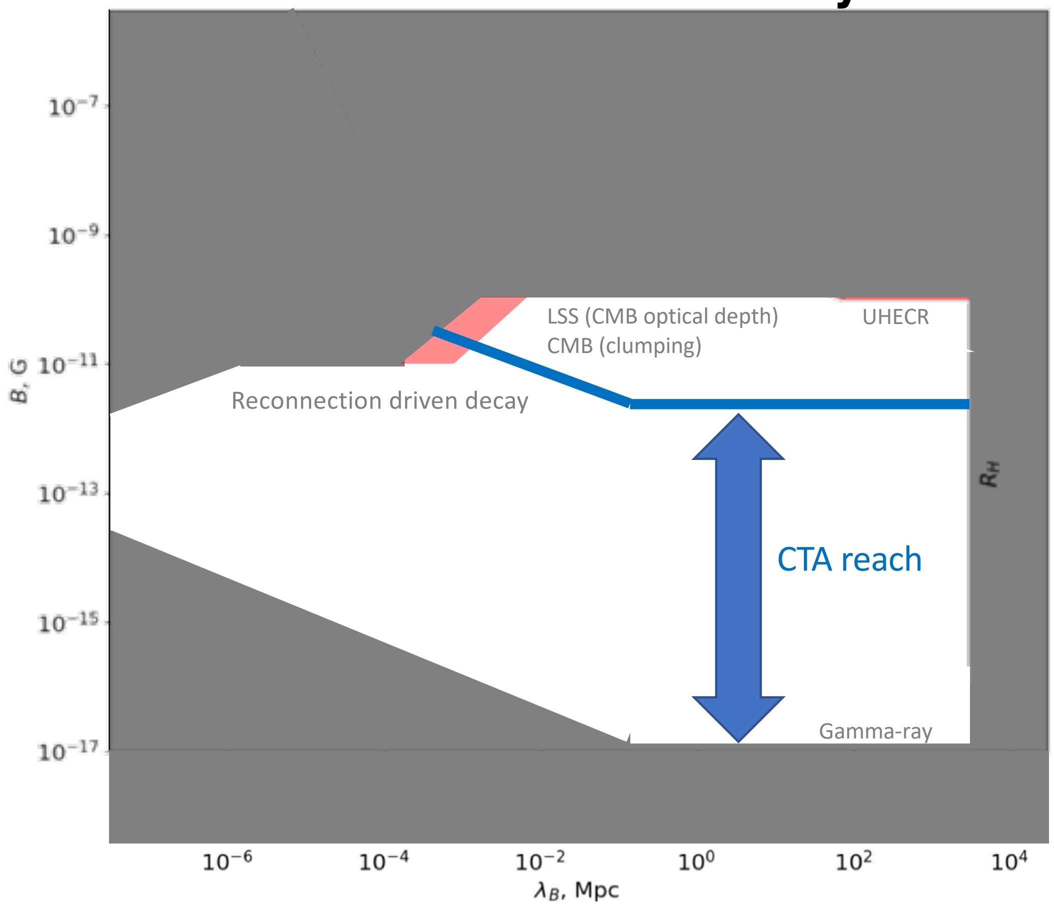


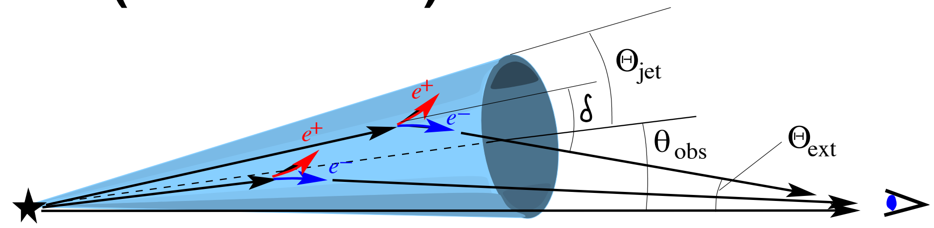


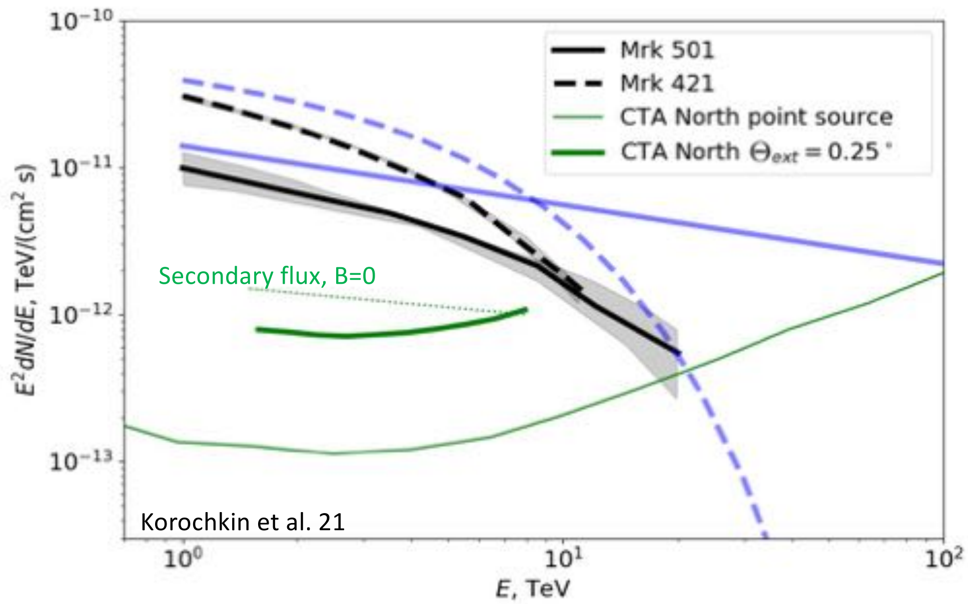
It is possible to detect the stochastic gravitational wave background produced by plasma motions in the Early Universe, simultaneously with magnetic field generation. Gravitational wave detectors LISA and pulsar timing arrays (PTA) are sensitive to magnetic fields from the Electroweak and QCD phase transitions, respectively.

talks by T.Kahnishvili, C.Caprini, A.Brandenburg

Sensitivity reach of CTA (+LHAASO?)

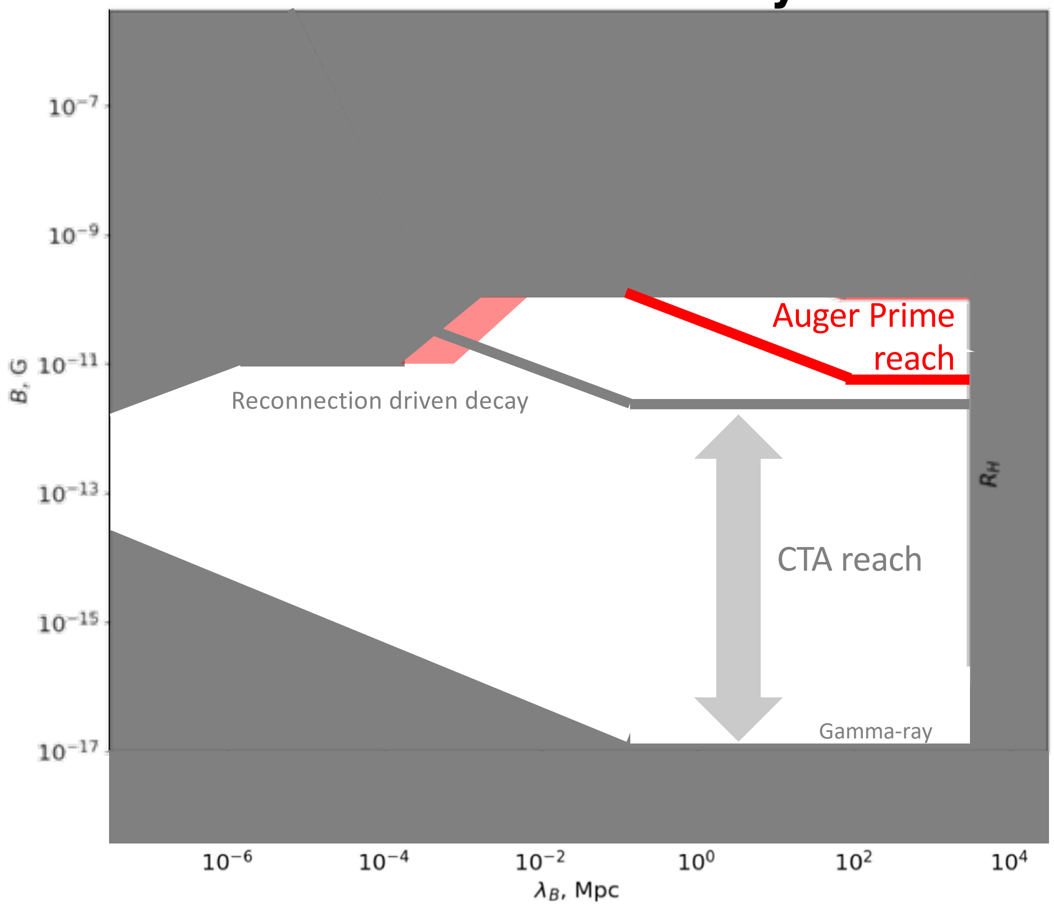


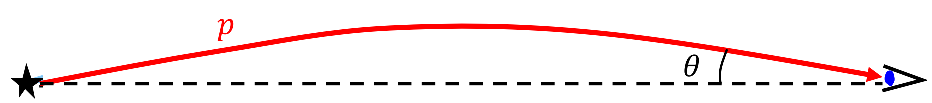




Void IGMF measurements will be improved by next-generation gamma-ray instruments, able to observe secondary signal in 0.1-1 TeV range: $E_\gamma \simeq 7 \left[\frac{E_{\gamma 0}}{100\text{TeV}}\right]^2$ TeV. The most promising is search for IGMF-dependent extended emission around relatively nearby extragalactic sources (Mrk 501?), for which reliable estimates of the primary source flux in 10-100 TeV range can be available (e.g. from LHAASO).

Sensitivity reach of TAx4 and Auger Prime

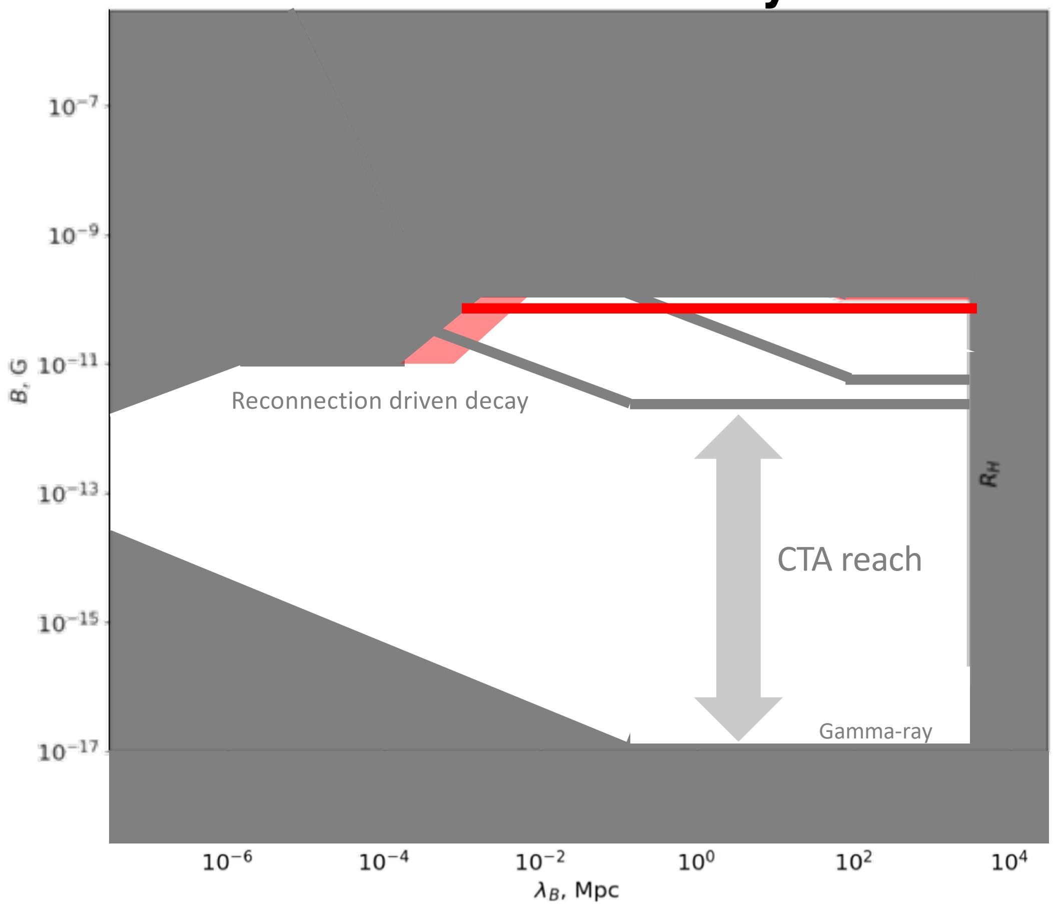




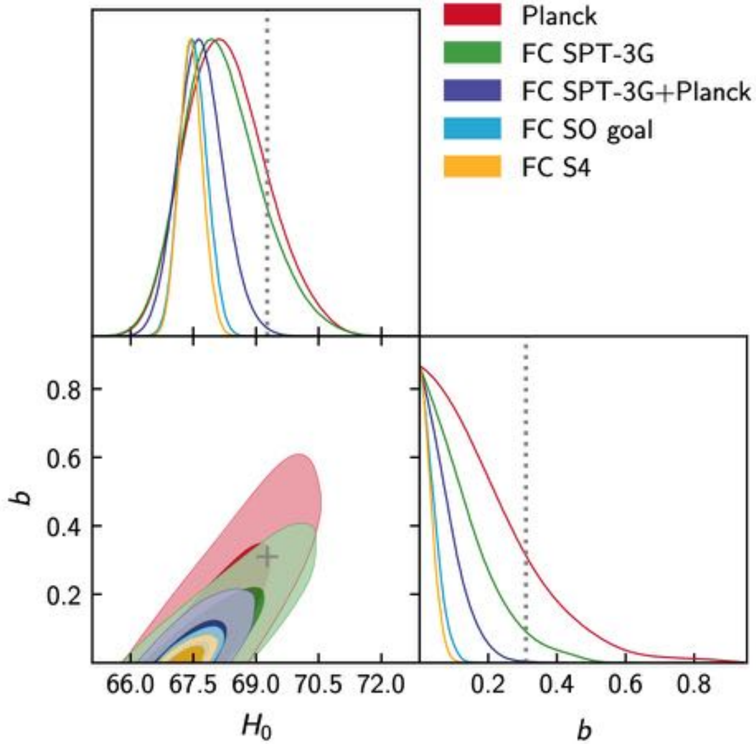
Auger Prime station

Deflection angle of UHECR proton from a source at the distance 70 Mpc is $\theta \simeq 0.4^{\circ}[B/10^{-11}\text{G}]$, in principle accessible for Auger Prime (that will be able to single out proton component of UHECR flux.

Sensitivity reach of CMB, LSS experiments



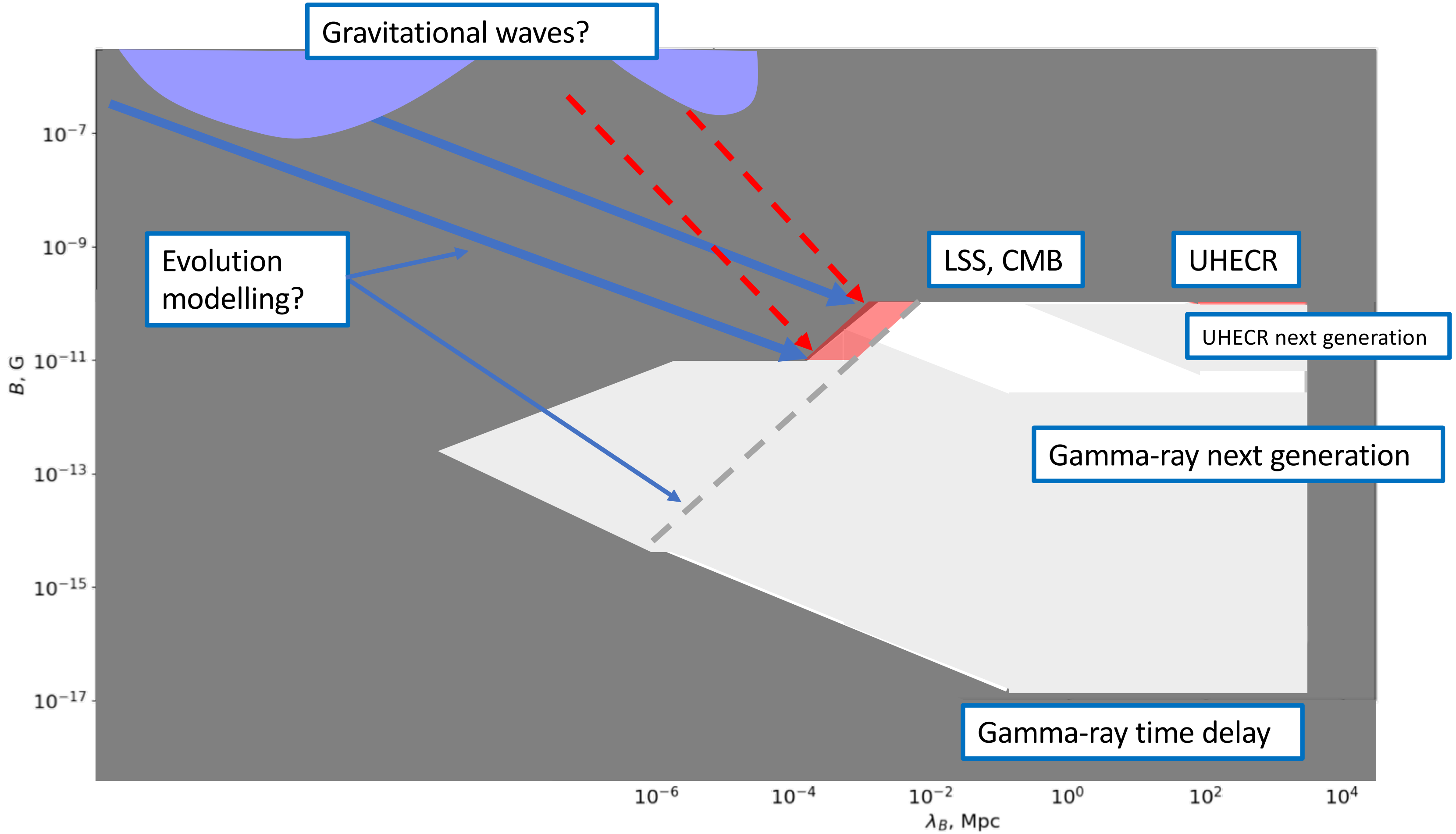
Galli et al. 22



Tighter constraints on the baryon clumping factor b will be available with next-generation CMB experiments. However, this would not necessarily result in much better constraints on the magnetic field, because of $b \propto B^4$ scaling.

Sensitivity reach of 21cm, CMB optical depth, dwarf galaxy abundance measurements?

Summary



Current status of constraints of cosmological magnetic fields (dark grey), sensitivity reach of gamma-ray, UHECR techniques (light grey) for $z = 0$ field, sensitivity of gravitational wave detectors for the initial field configurations (blue).