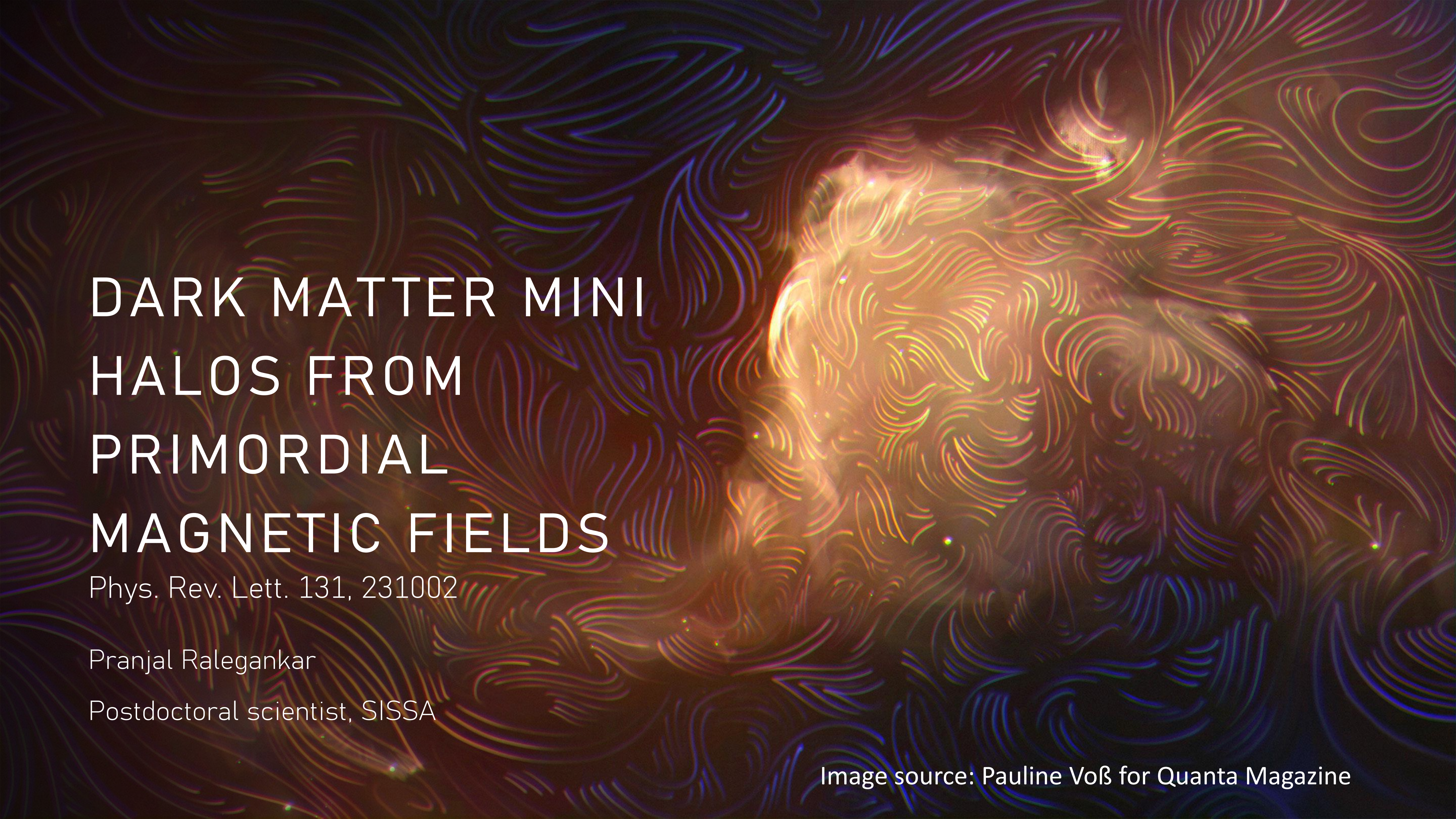


DARK MATTER MINI HALOS FROM PRIMORDIAL MAGNETIC FIELDS

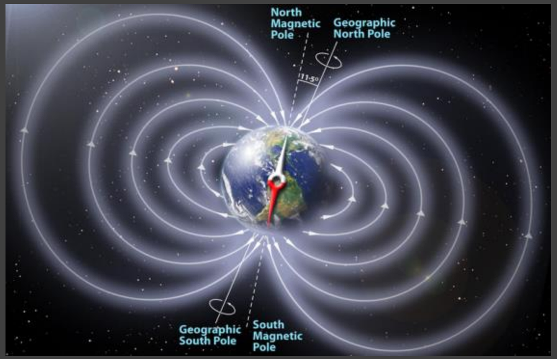
Phys. Rev. Lett. 131, 231002

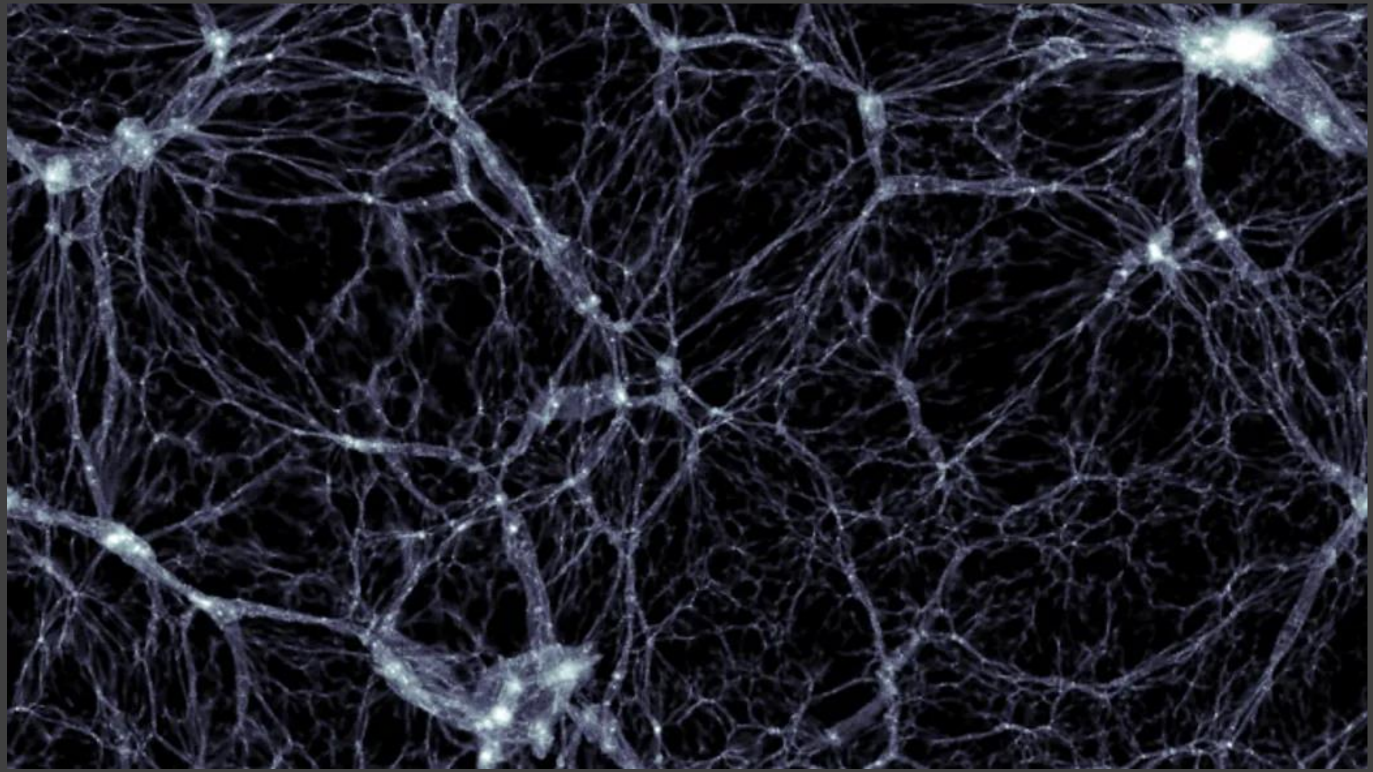
Pranjal Ralegankar

Postdoctoral scientist, SISSA

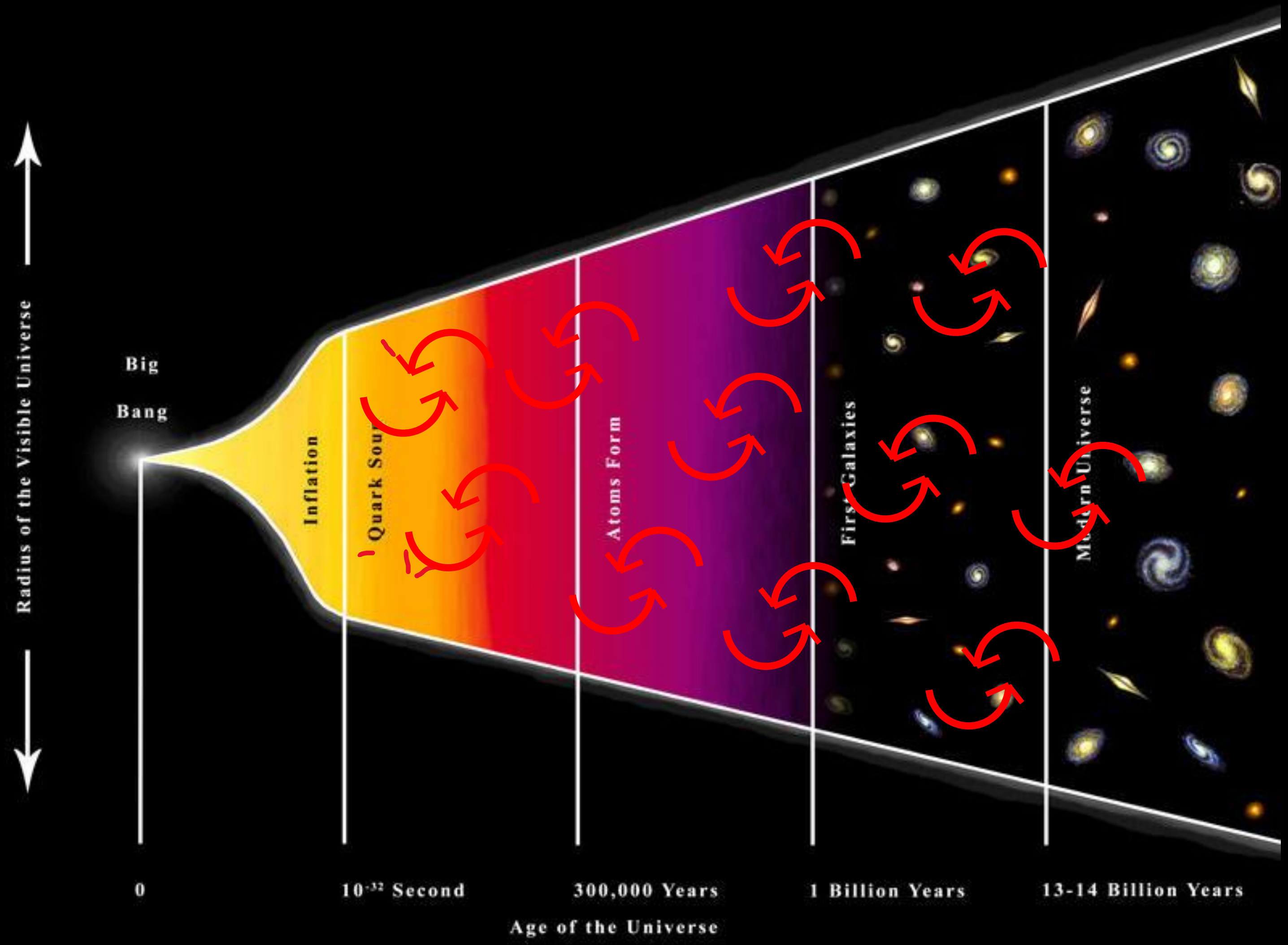
Image source: Pauline Voß for Quanta Magazine

UBIQUITOUS MAGNETIC FIELDS





PRIMORDIAL: PRODUCED BY BIG BANG PLASMA



PRIMORDIAL MAGNETIC FIELDS ENHANCE DENSITY PERTURBATIONS

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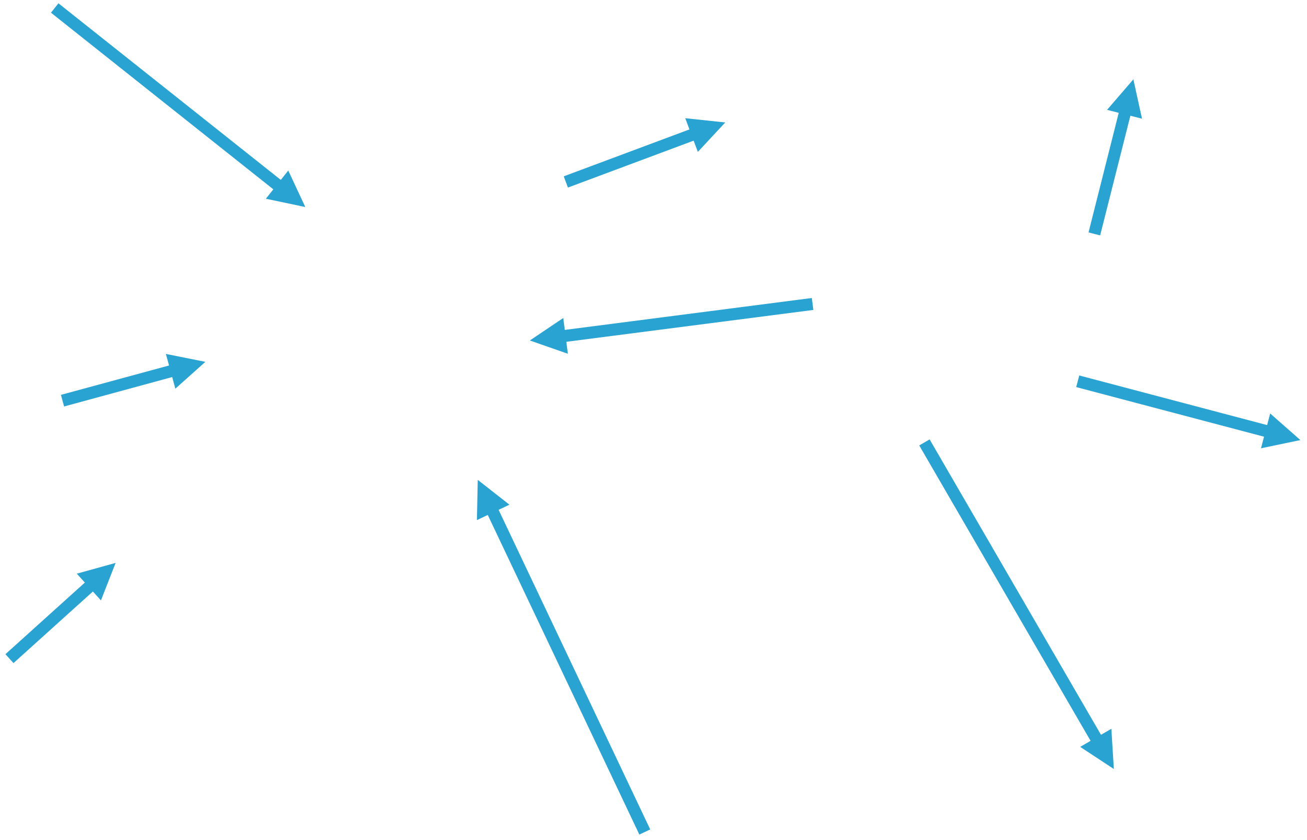
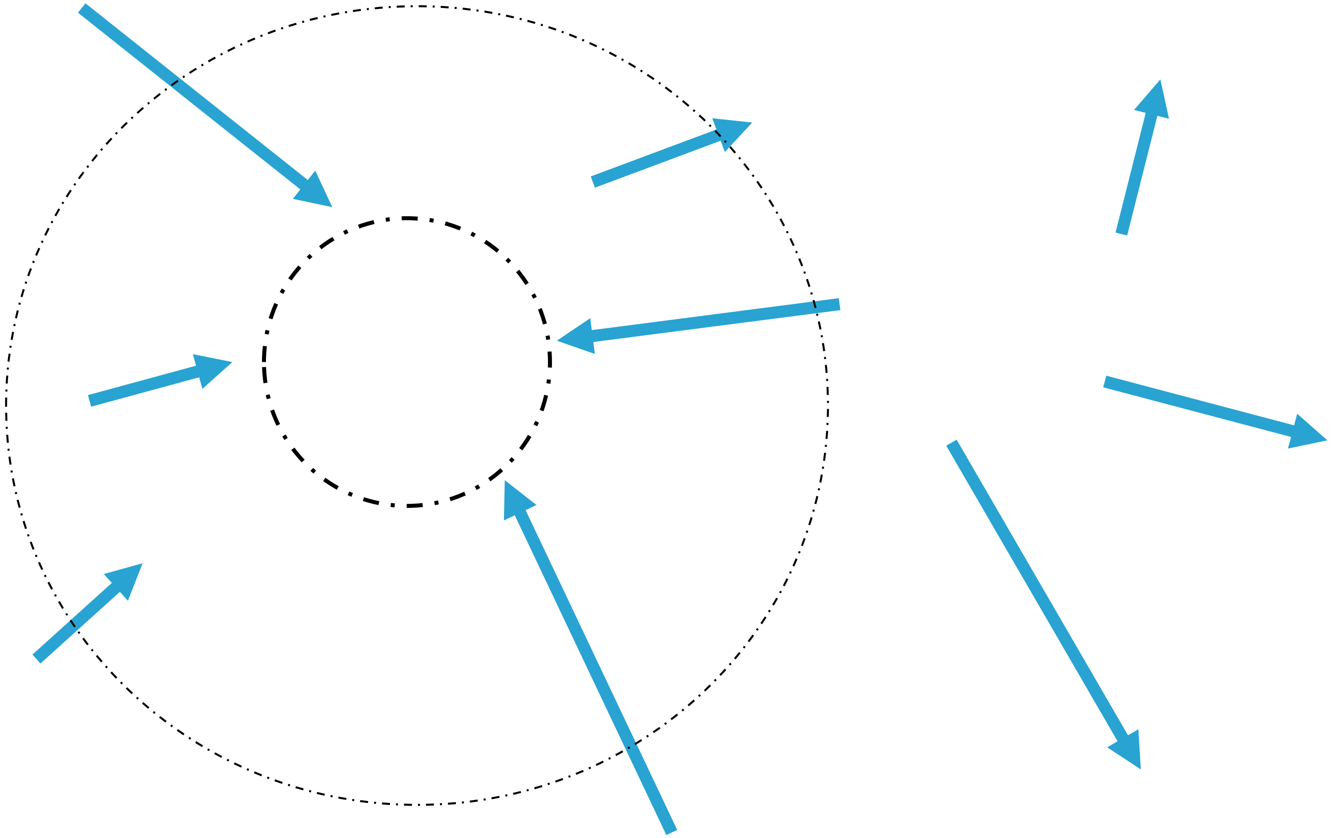
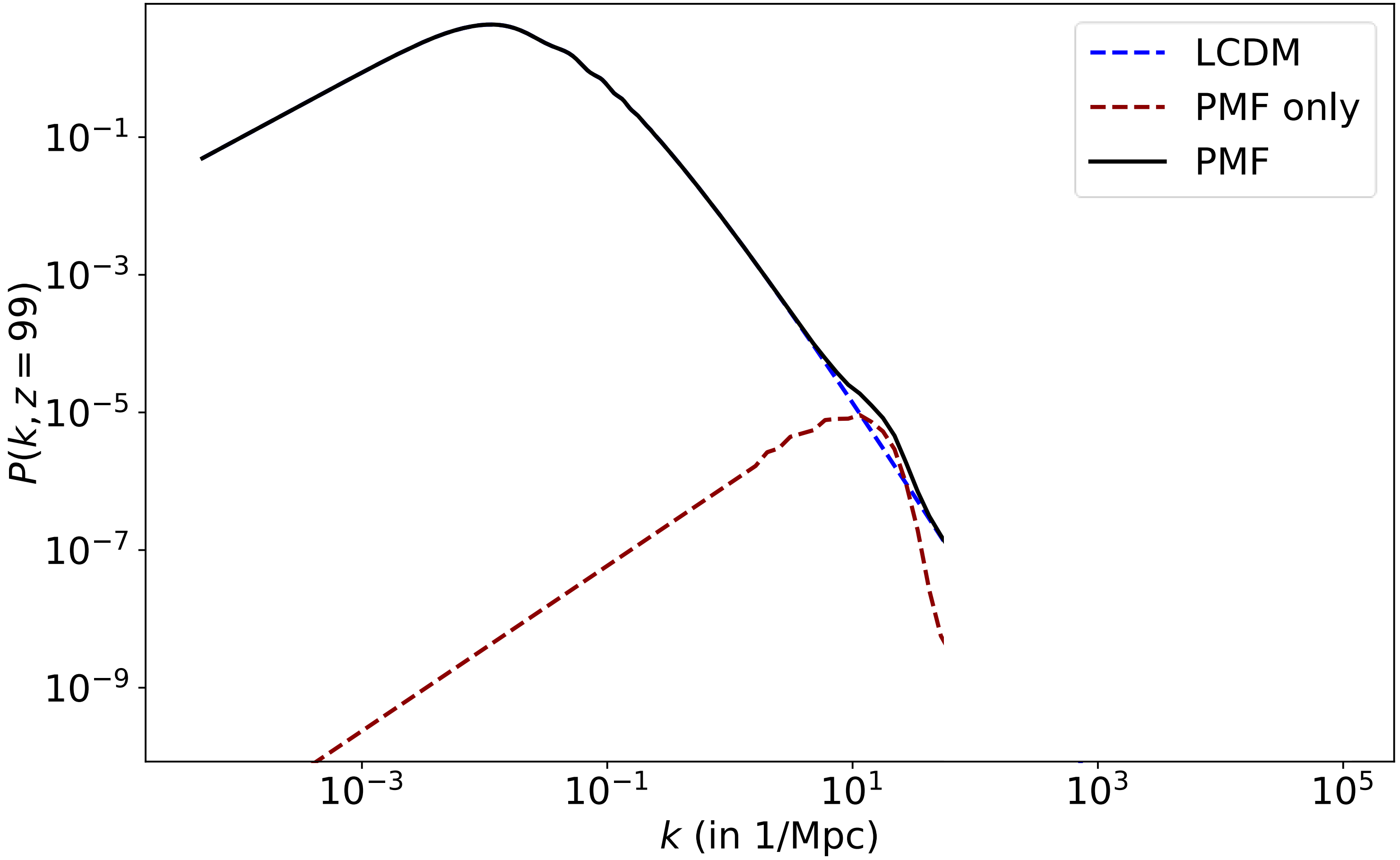


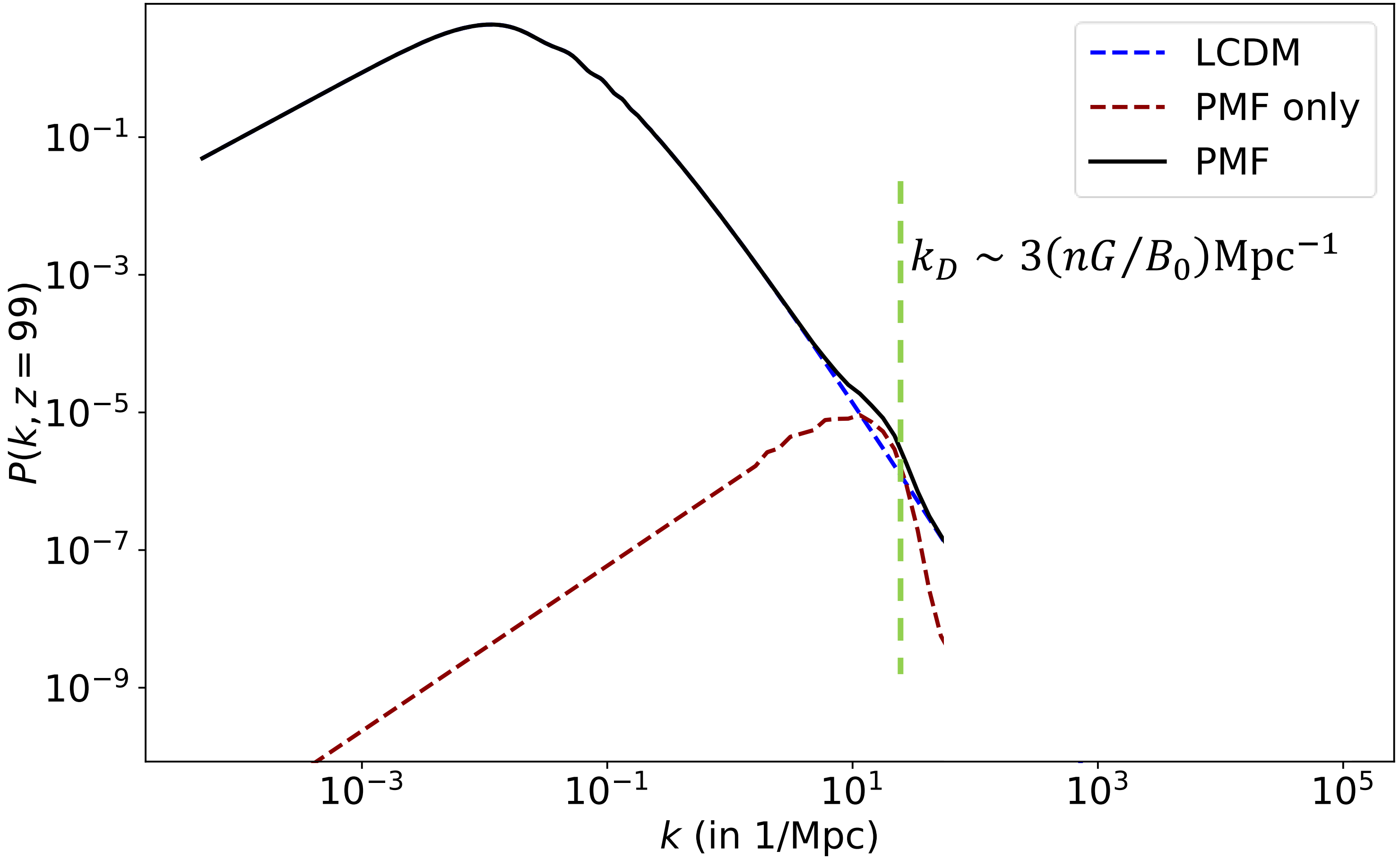
PRIMORDIAL MAGNETIC FIELDS ENHANCE DENSITY PERTURBATIONS



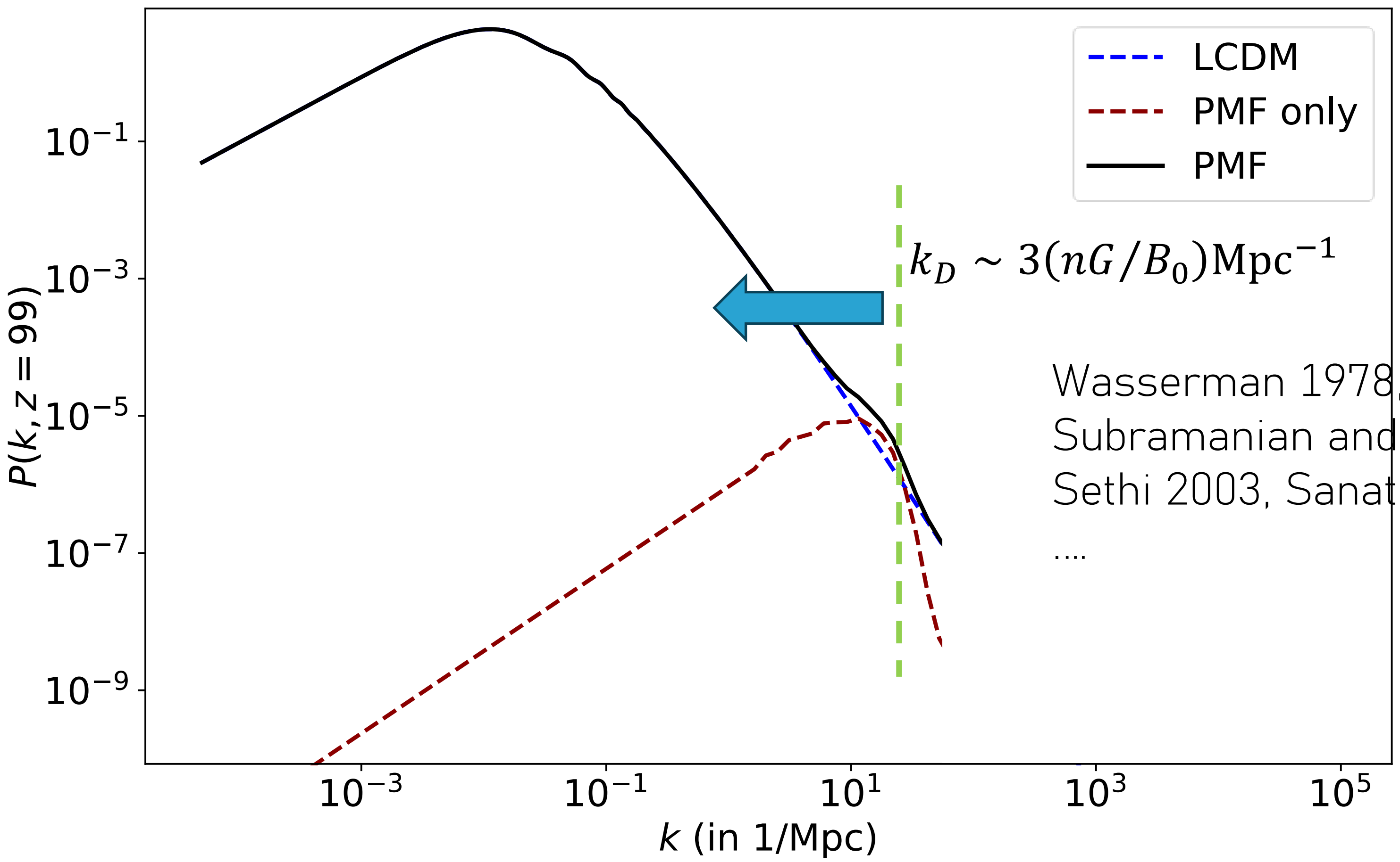
PRIMORDIAL MAGNETIC FIELDS ENHANCE POWER SPECTRUM ON SMALL SCALES



BACKREACTION FROM BARYONS SUPPRESSES BARYON DENSITY PERTURBATIONS BELOW MAGNETIC DAMPING (JEANS) SCALE

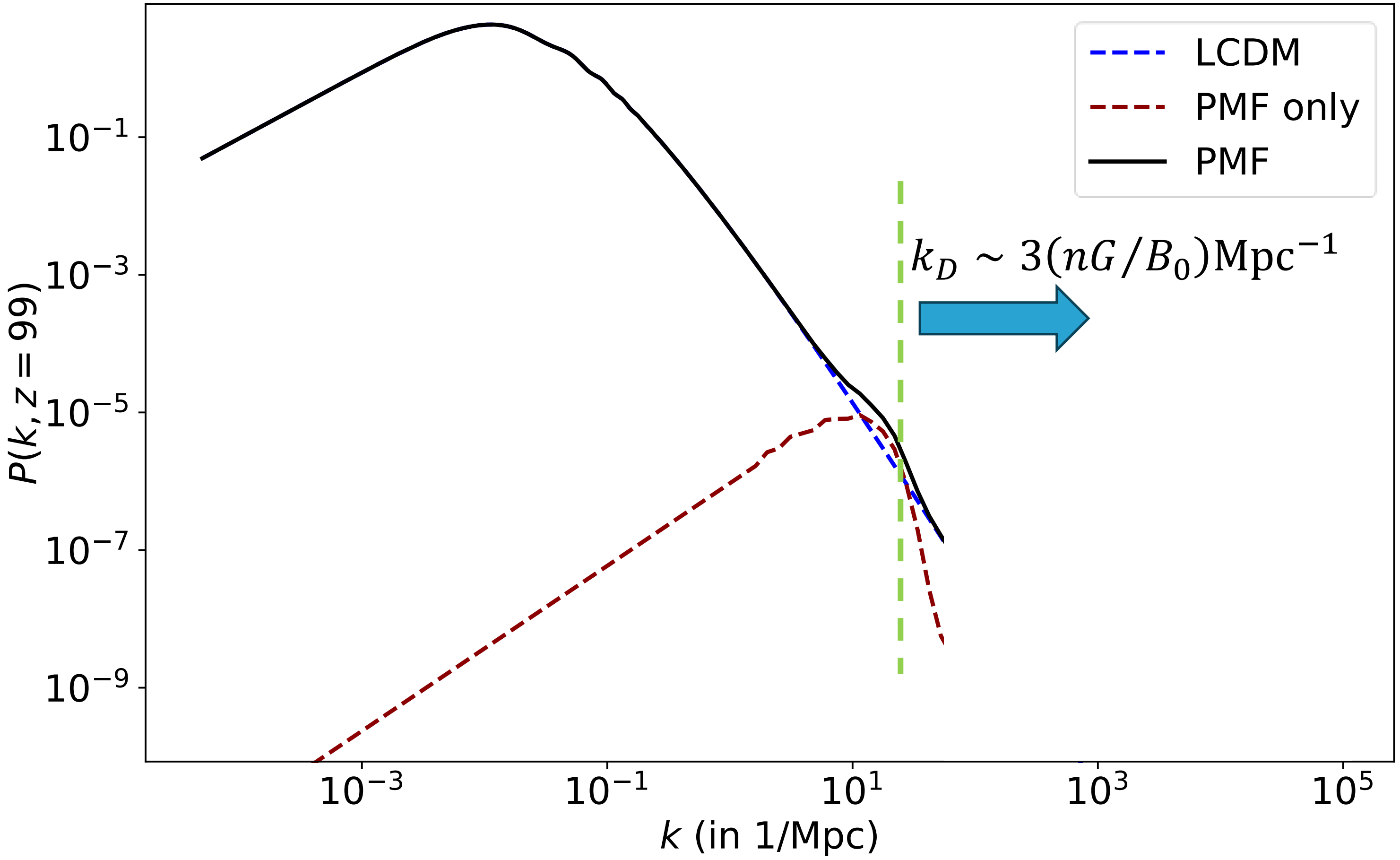


EARLIER WORKS FOCUSED ON SCALES BELOW MAGNETIC DAMPING (JEANS) SCALE

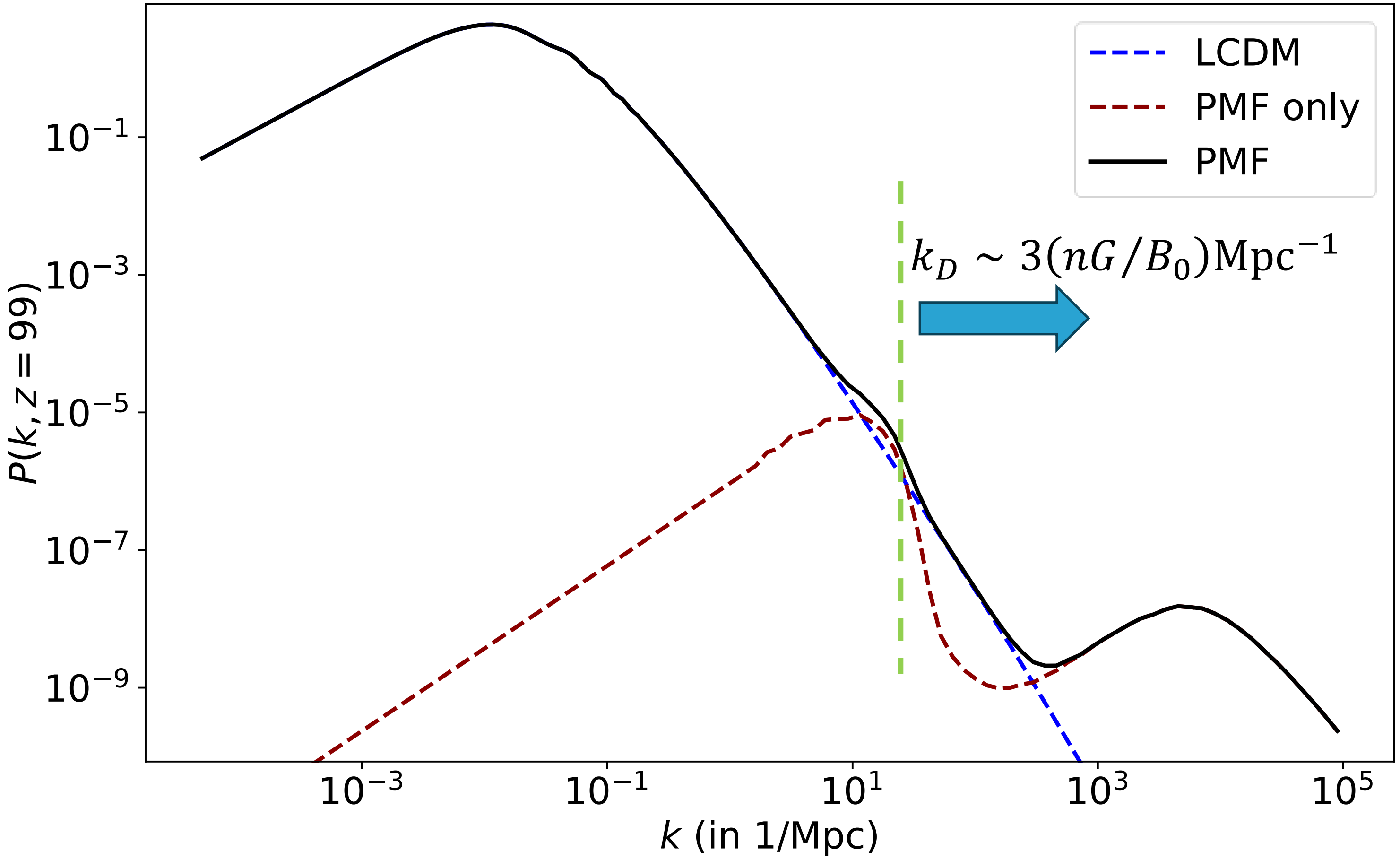


Wasserman 1978, Kim et al 1996, Subramanian and Barrow 1997, Gopal and Sethi 2003, Sanati 2020 (2024), Katz 2021 ....

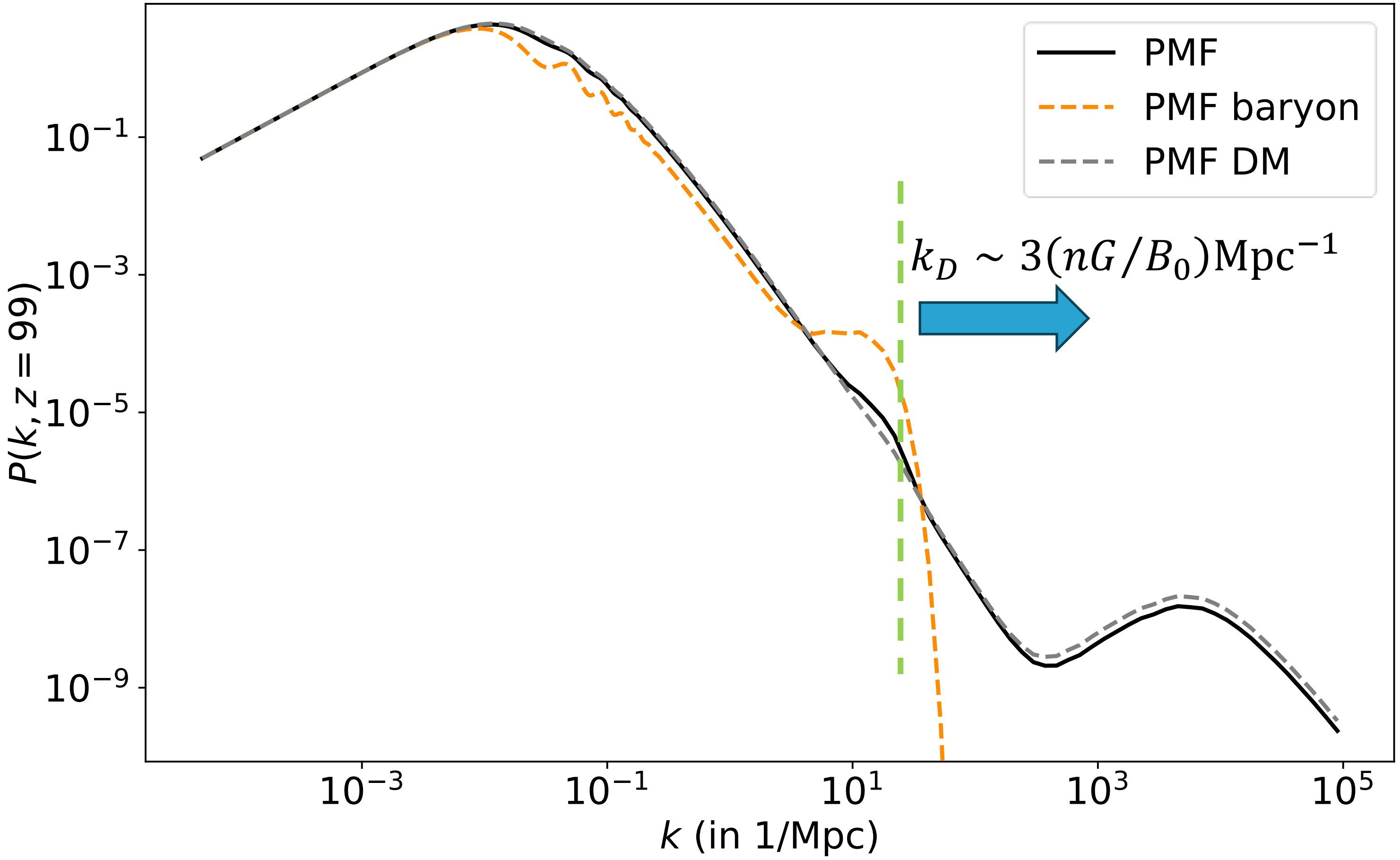
MY STUDY FOCUSES ON SCALES BELOW MAGNETIC DAMPING (JEANS) SCALE



FINDING: HIGHLY ENHANCED POWER SPECTRUM BELOW JEANS SCALE



FINDING: BARYON PERTURBATION SUPPRESSED BELOW JEANS SCALE BUT NOT DARK MATTER!



NON-RELATIVISTIC IDEAL MHD IN PHOTON DRAG REGIME

$$\frac{\partial\,(a^2\vec{B})}{\partial t} = \frac{\nabla\times(\vec{v}_b\times a^2\vec{B})}{a}$$

$$\frac{\partial\vec{v}_b}{\partial t} + (H+\alpha)\vec{v}_b + \frac{(\vec{v}_b.\nabla)\vec{v}_b}{a} = \frac{\left(\nabla\times\vec{B}\right)\times\vec{B}}{4\pi a\rho_b} - \frac{\mathrm{c}_\mathrm{b}^2\nabla\delta_b}{a} - \frac{\nabla\phi}{a}$$

$$\frac{\partial\delta_b}{\partial t} = -\frac{\nabla.\vec{v}_b}{a} - \frac{\nabla.(\delta_b\vec{v}_b)}{a}$$

$$\nabla^2\phi = \frac{a^2}{2M_{Pl}^2}(\rho_b\delta_b + \rho_{DM}\delta_{DM})$$

$$\frac{\partial^2\delta_{DM}}{\partial a^2} + \left[\frac{\partial\ln(a^2H)}{\partial\ln a} + 1\right]\frac{\partial\delta_{DM}}{a\partial a} = \frac{\nabla^2\phi}{(a^2H)^2}$$

NON-RELATIVISTIC IDEAL MHD IN PHOTON DRAG REGIME

$$\frac{\partial\,(a^2\vec{B})}{\partial t} = \frac{\nabla\times(\vec{v}_b\times a^2\vec{B})}{a}$$

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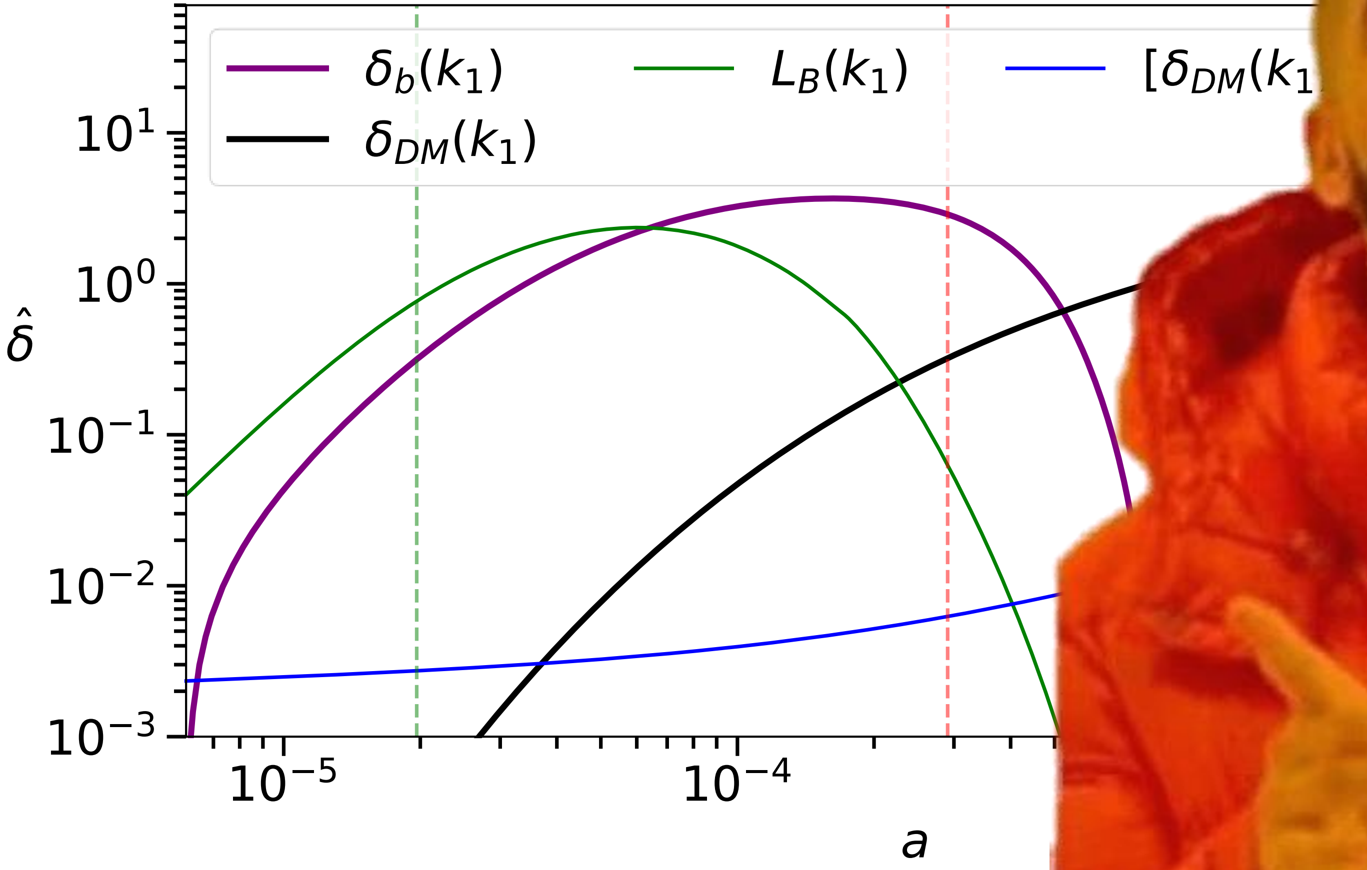
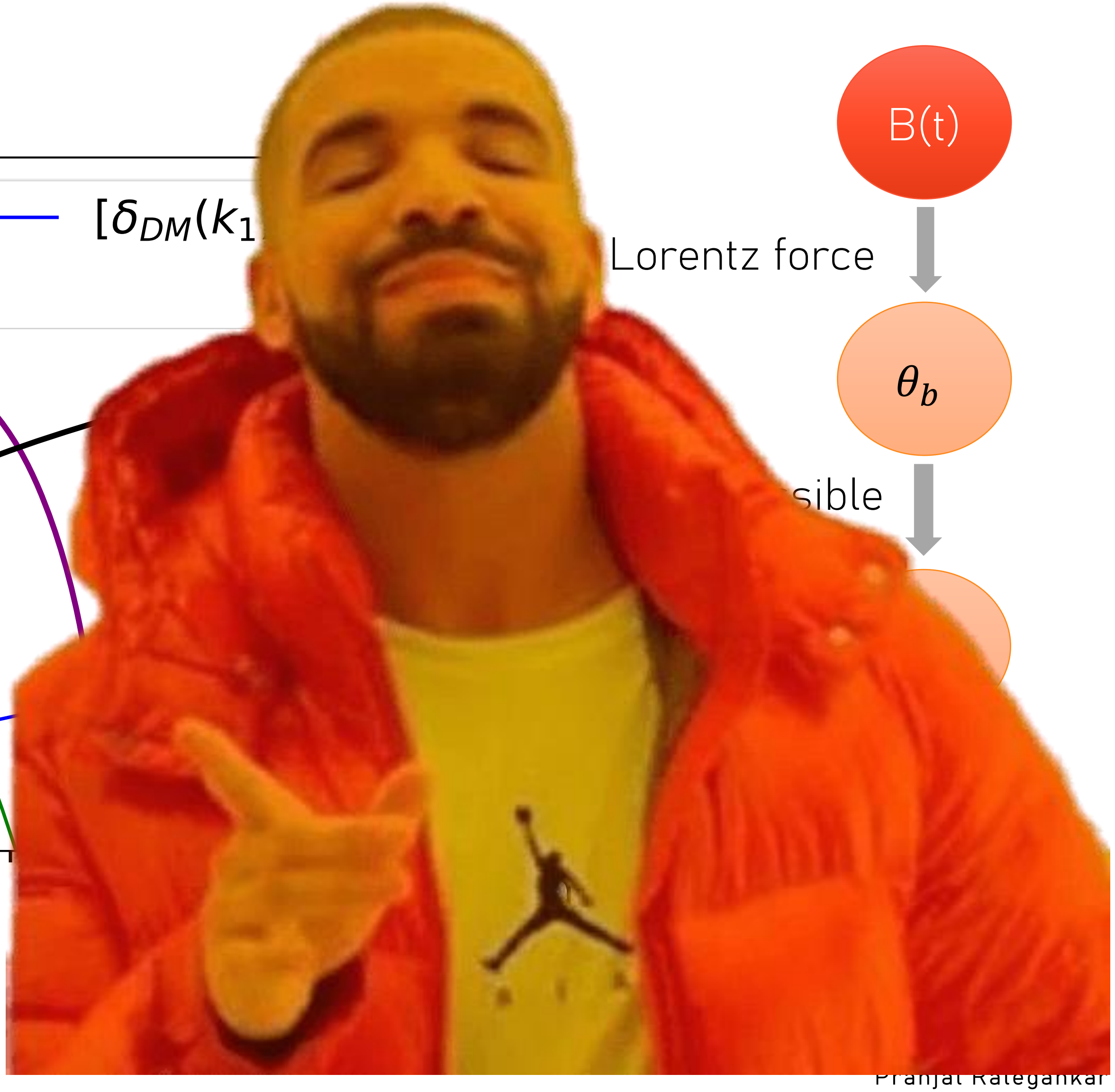
$$\frac{\partial\delta_b}{\partial t} = -\frac{\nabla.\vec{v}_b}{a} - \frac{\nabla.(\delta_b\vec{v}_b)}{a}$$

$$\nabla^2\phi = \frac{a^2}{2M_{Pl}^2}(\rho_b\delta_b + \rho_{DM}\delta_{DM})$$

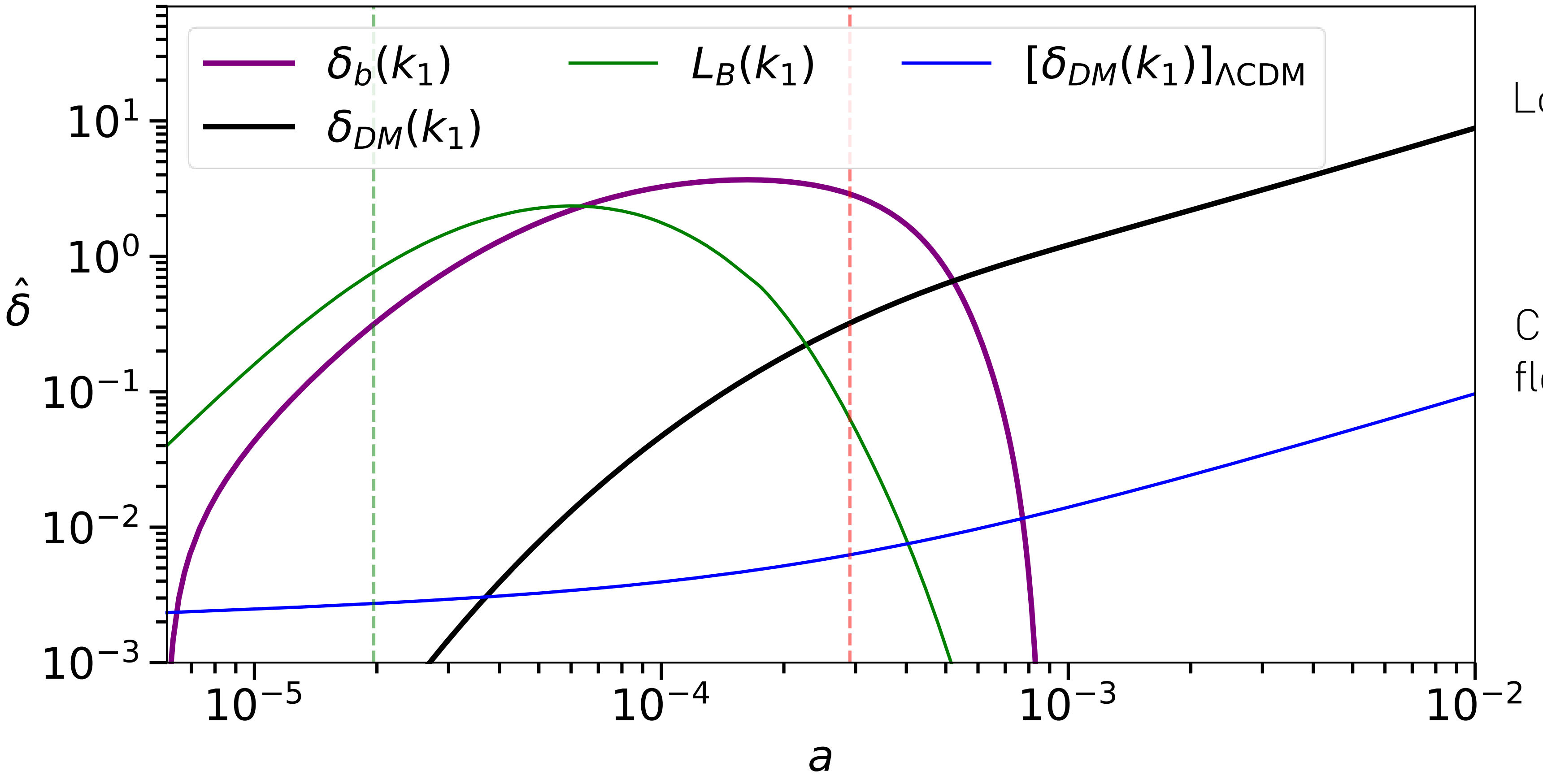
$$\frac{\partial^2\delta_{DM}}{\partial a^2} + \left[\frac{\partial\ln(a^2H)}{\partial\ln a} + 1\right]\frac{\partial\delta_{DM}}{a\partial a} =$$

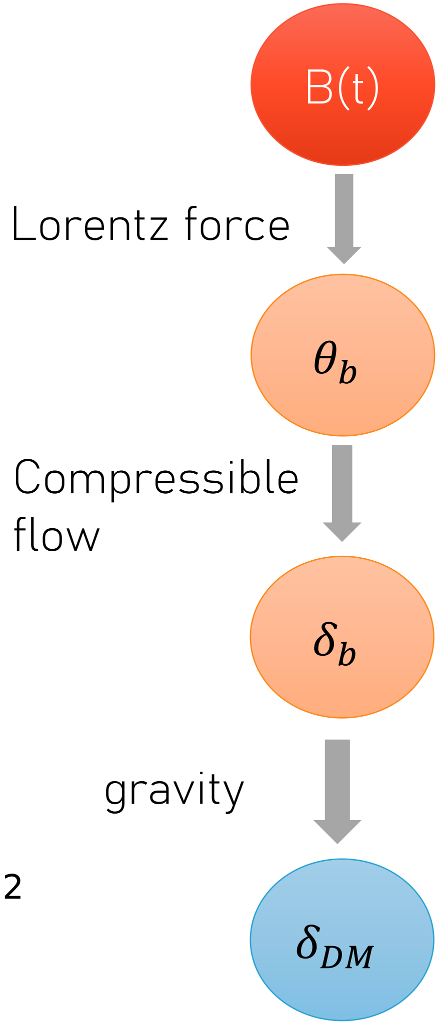
PERTURBATION EVOLUTION PLOT



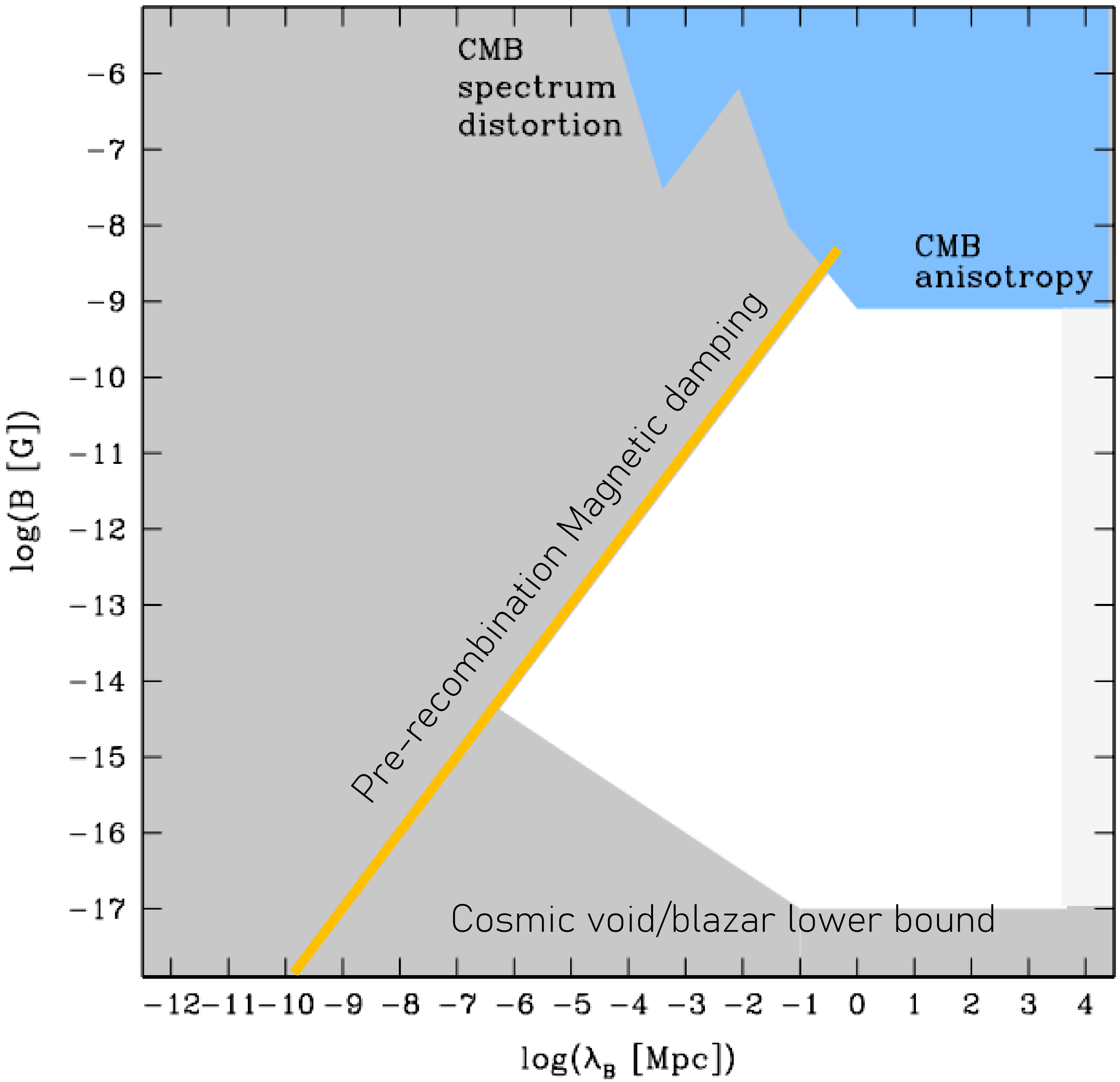


PERTURBATION EVOLUTION PLOT



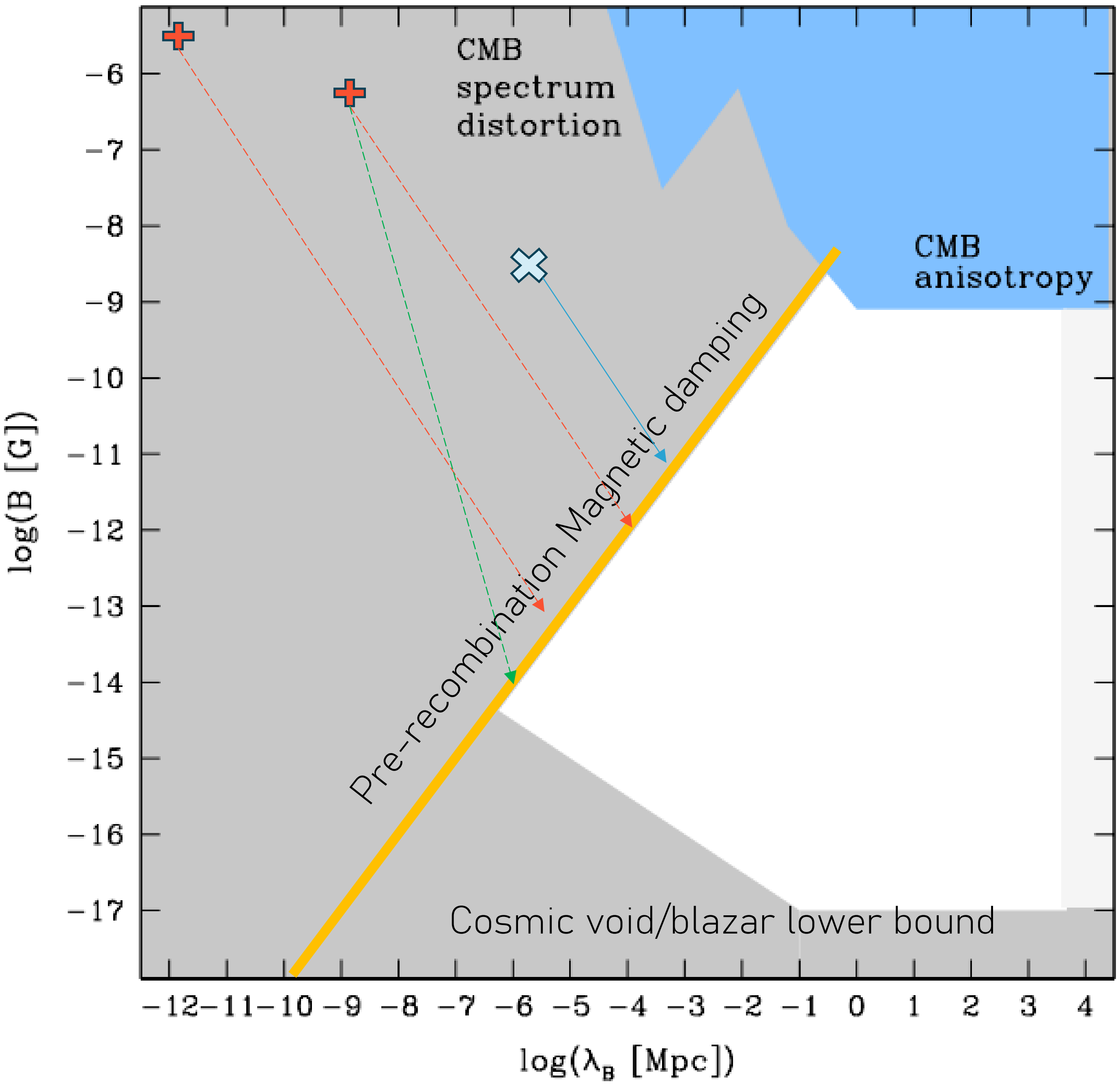


CONSTRAINTS ON PMF

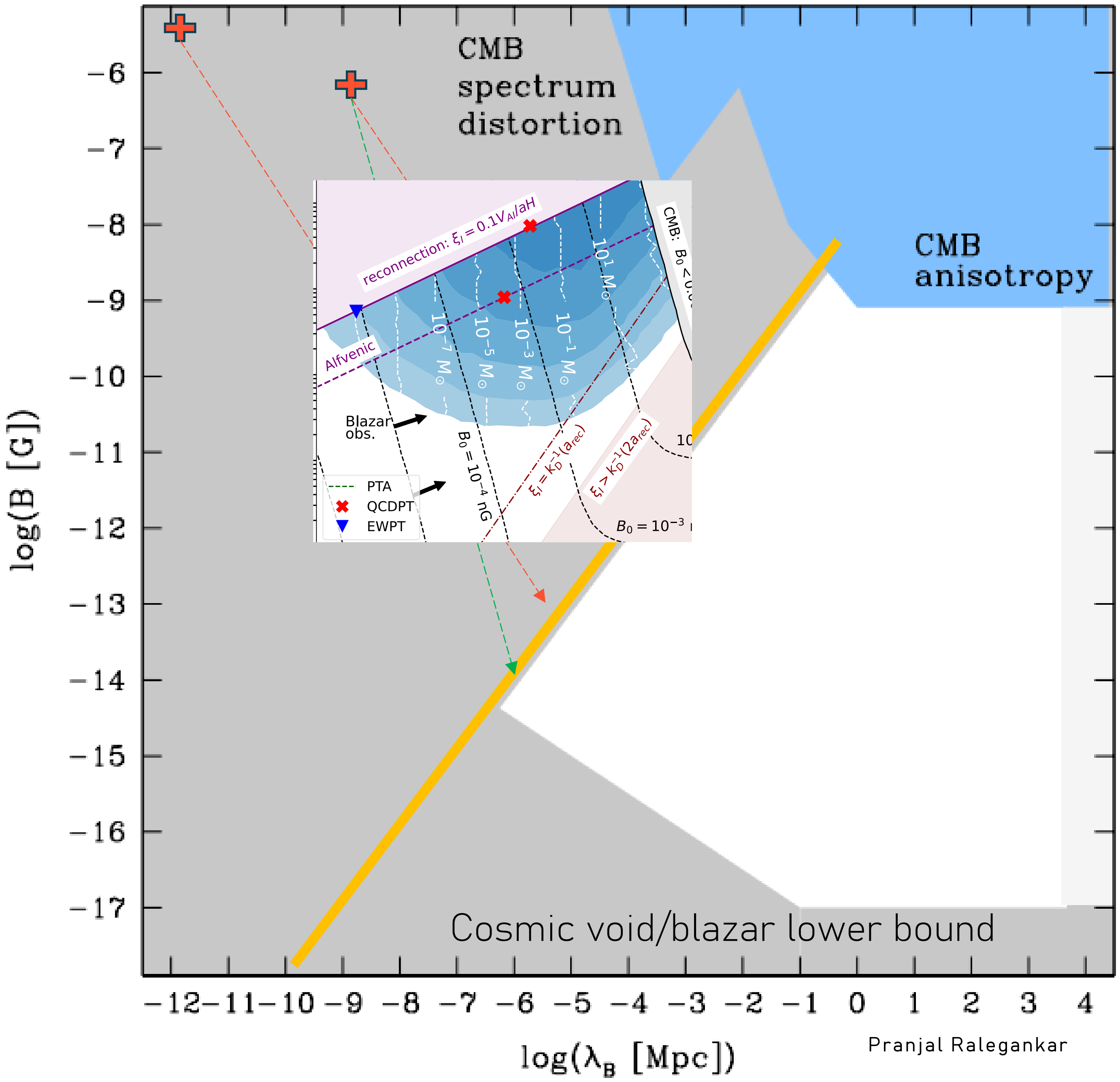


Durrer and Neronov 2013

EVOLUTION OF EARLY UNIVERSE PMFS

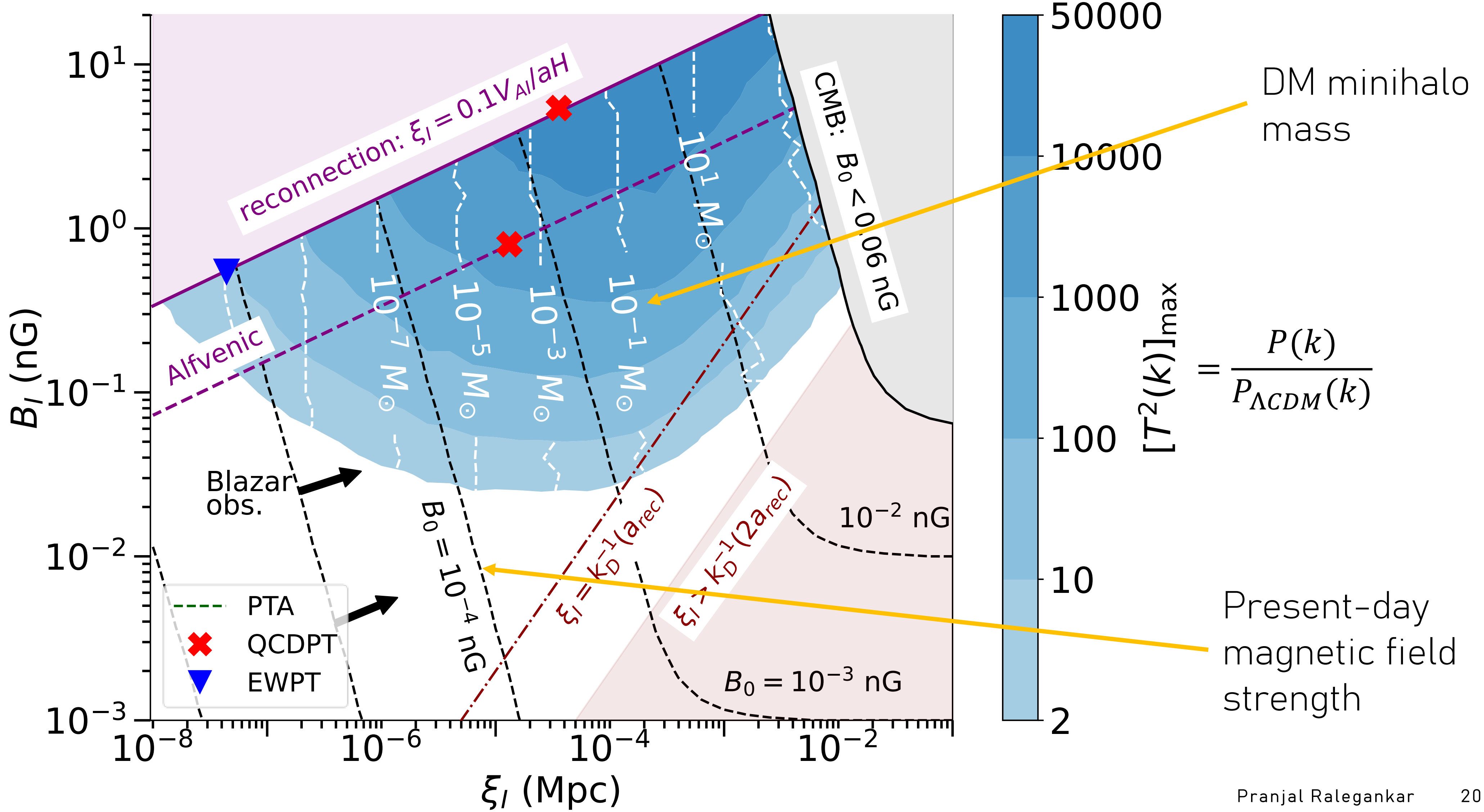


RELEVANCE OF DARK MATTER MINIHALO GENERATION



PARAMETER SPACE WITH ENHANCED POWER ON SMALL SCALES

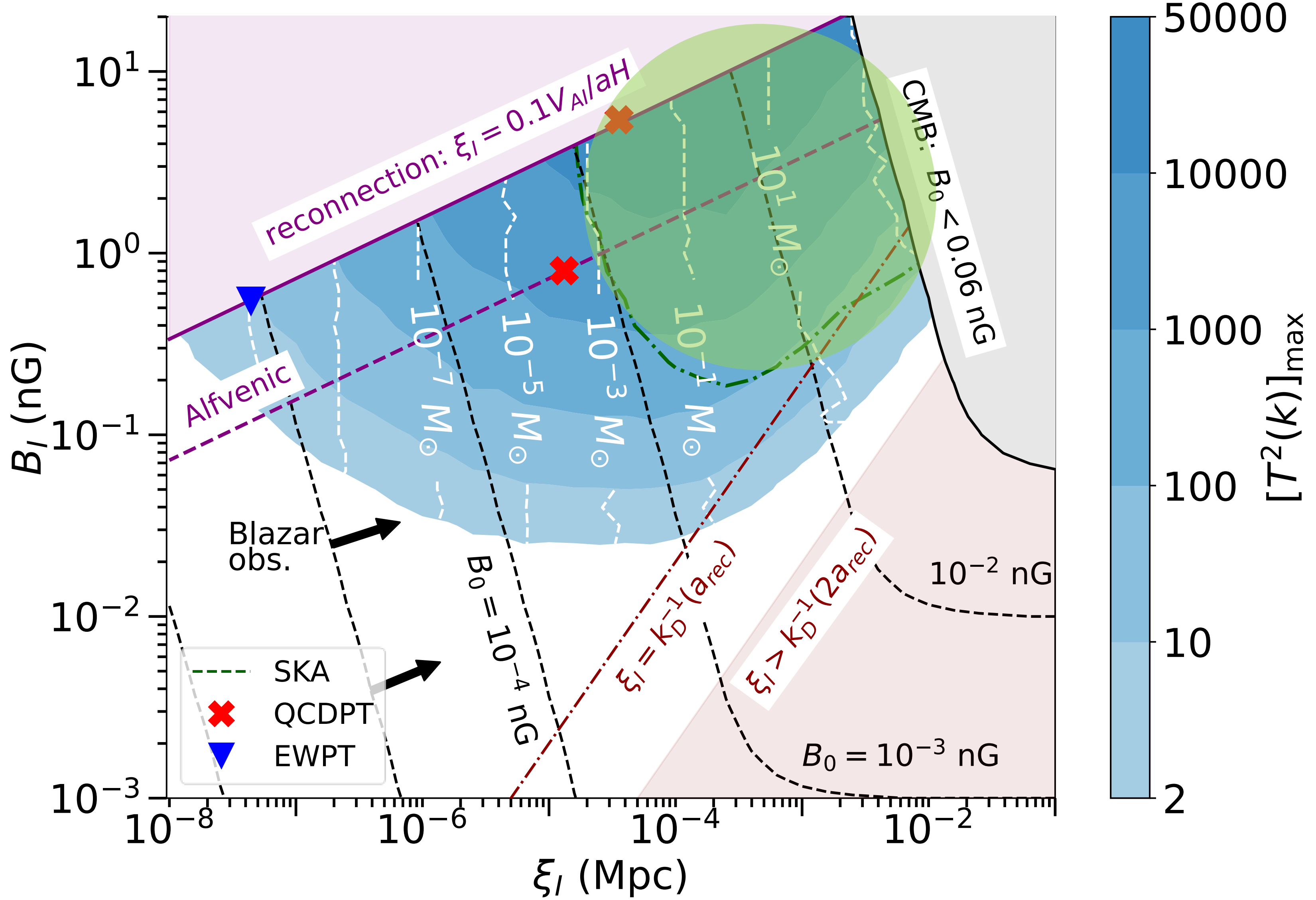
Subscript I refers to the time at the beginning of laminar flow regime



$$= \frac{P(k)}{P_{\Lambda CDM}(k)}$$

PARAMETER SPACE WITH ENHANCED POWER ON SMALL SCALES: THEIA SKA SENSITIVITY

Subscript I refers to the time at the beginning of laminar flow regime



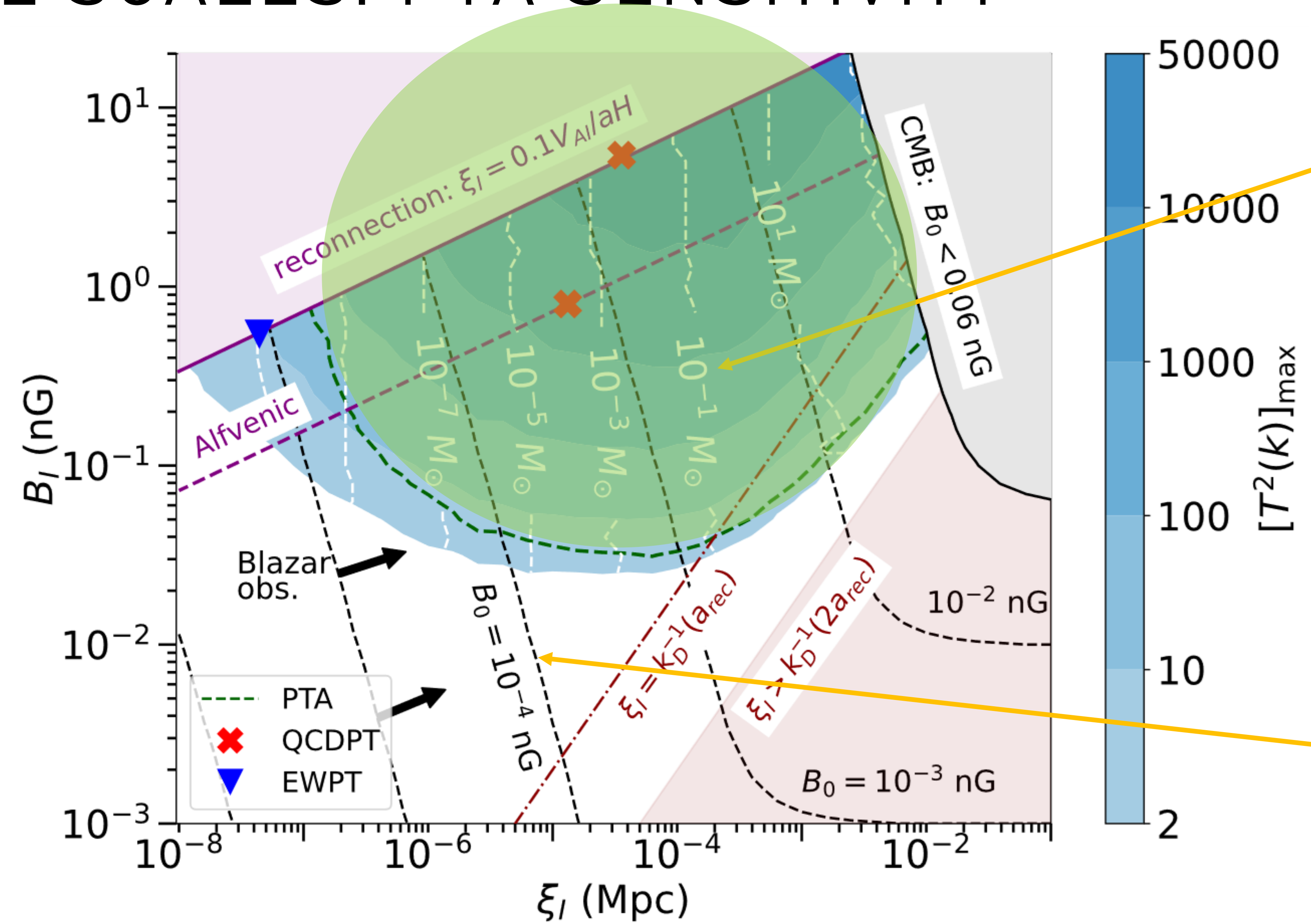
DM minihalo mass

$$= \frac{P(k)}{P_{\Lambda CDM}(k)}$$

Present-day magnetic field strength

PARAMETER SPACE WITH ENHANCED POWER ON SMALL SCALES: PTA SENSITIVITY

Subscript I refers to the time at the beginning of laminar flow regime

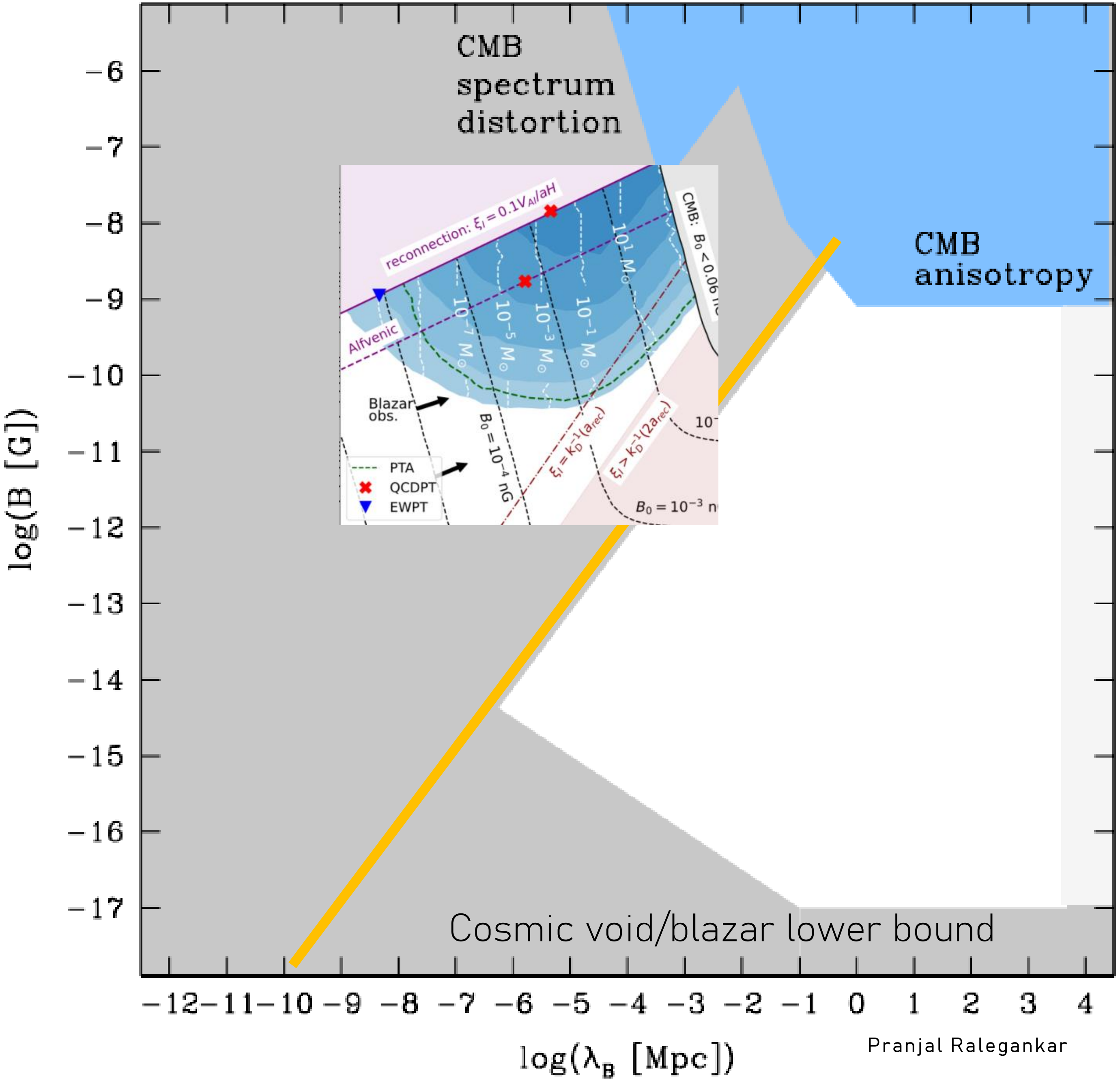


$$= \frac{P(k)}{P_{\Lambda CDM}(k)}$$

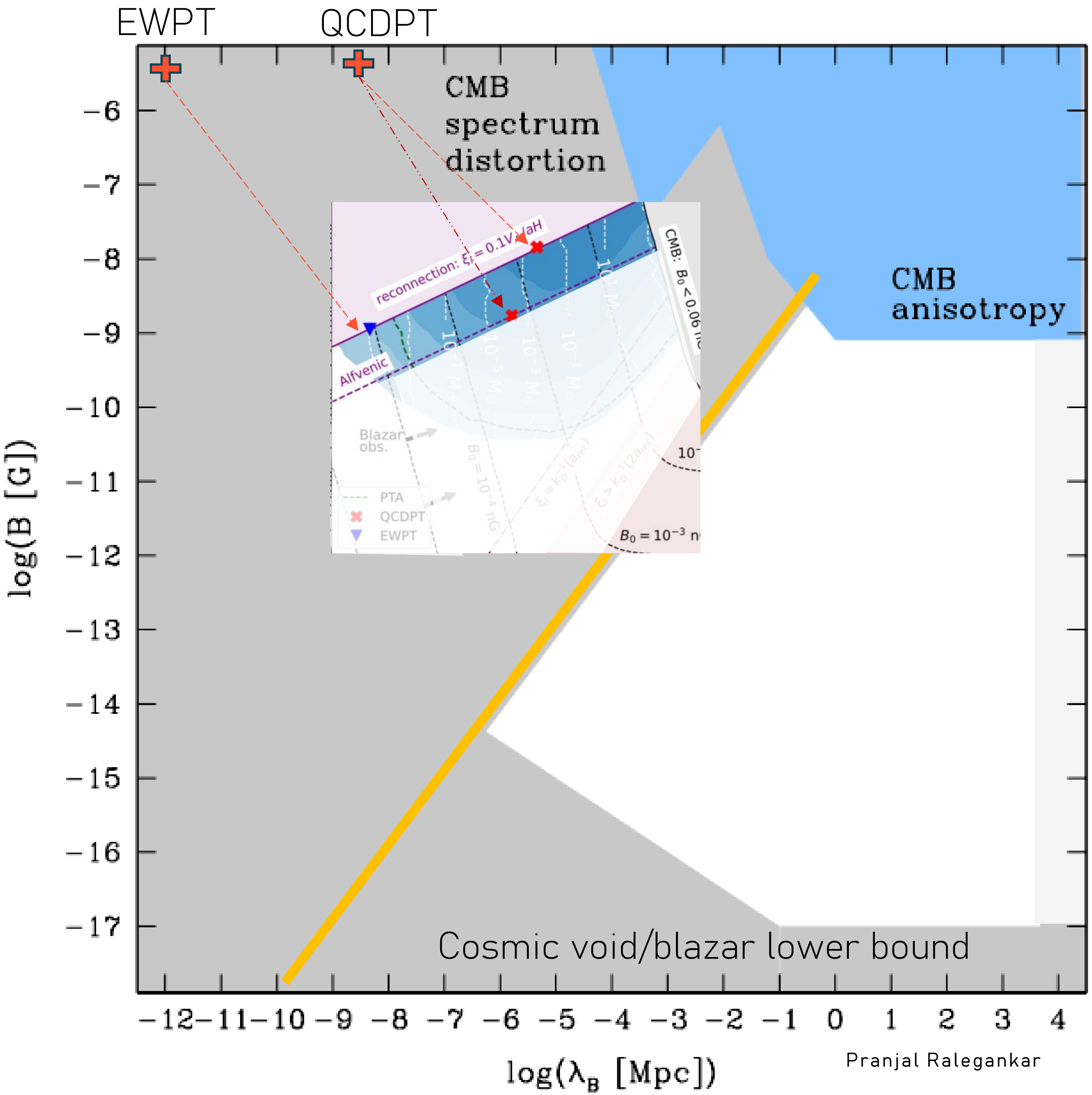
DM minihalo mass

Present-day magnetic field strength

MINIHALOS FROM CAUSALLY GENERATED PMFS

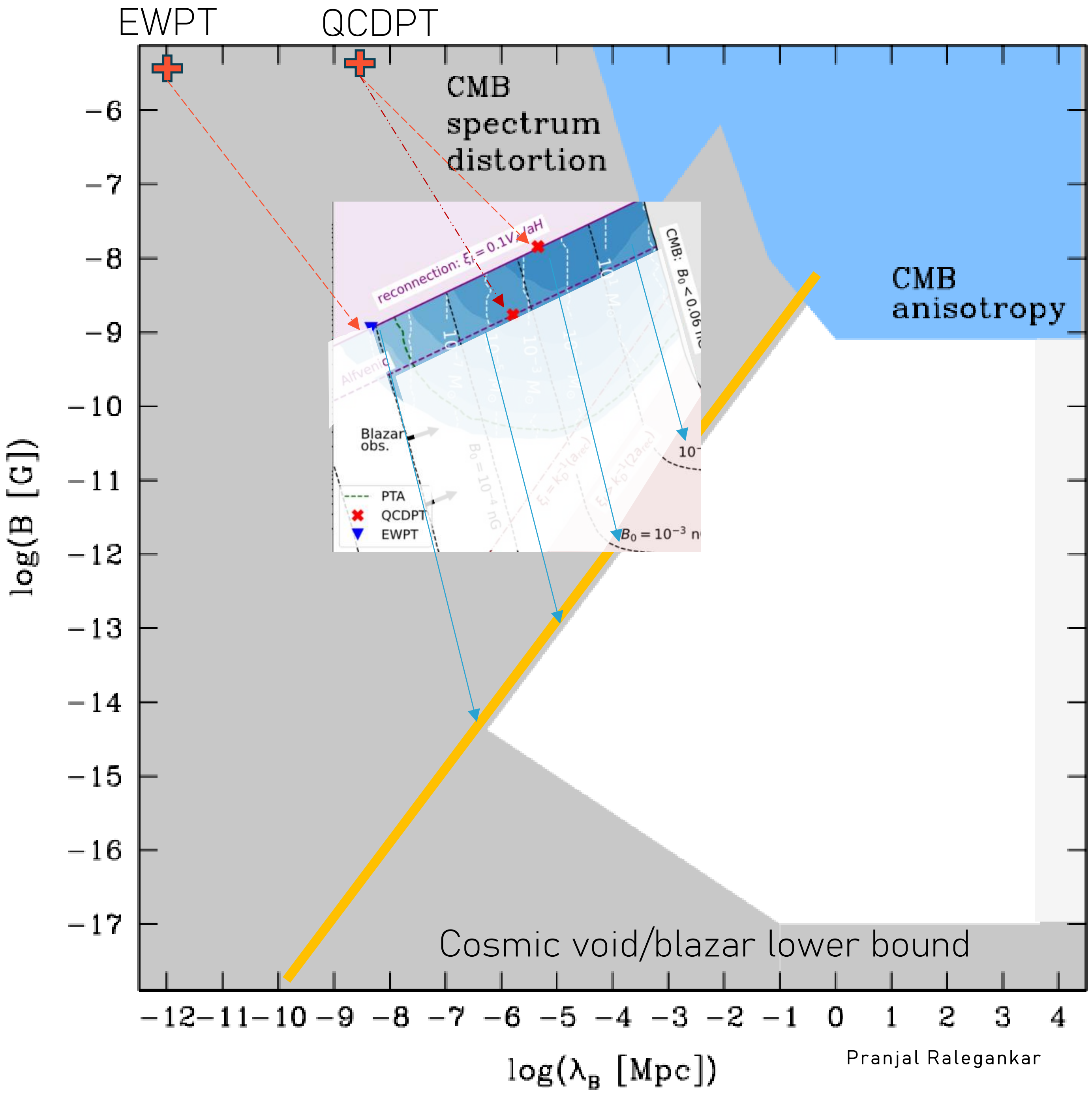


MINIHALOS FROM CAUSALLY GENERATED PMFS



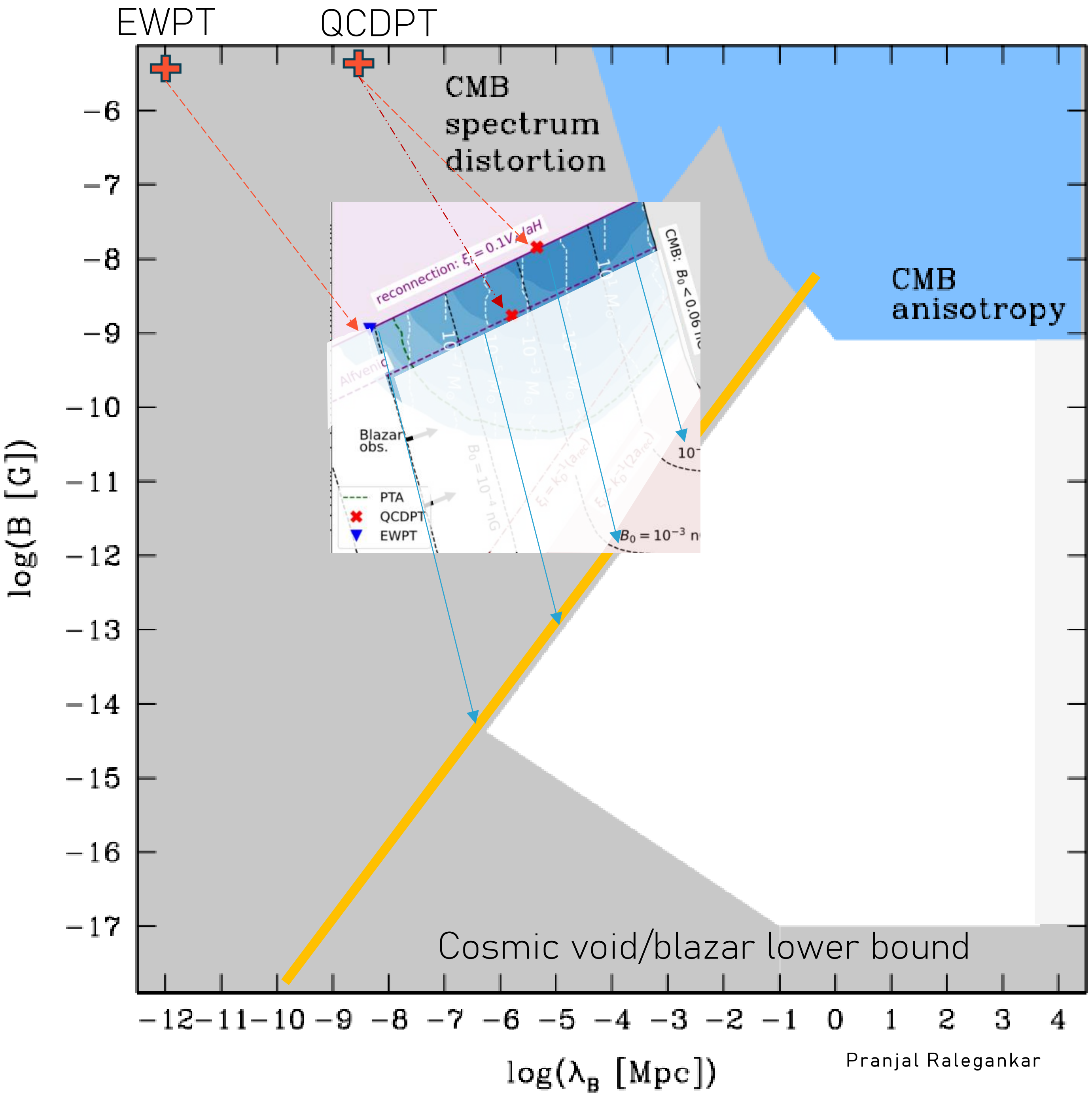
PMFS TO EXPLAIN COSMIC VOID OBSERVATIONS

Assuming Batchelor spectrum!



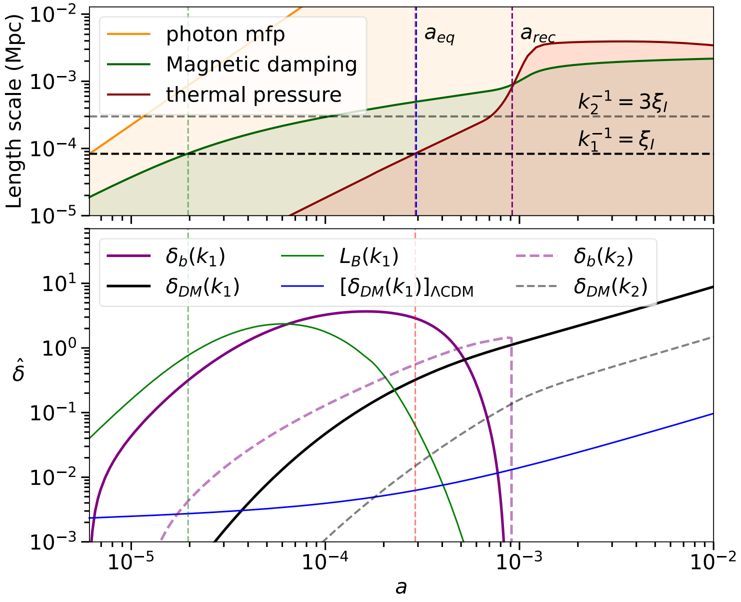
UNIVERSE MAYBE FILLED WITH DARK MATTER MINIHALOS!!

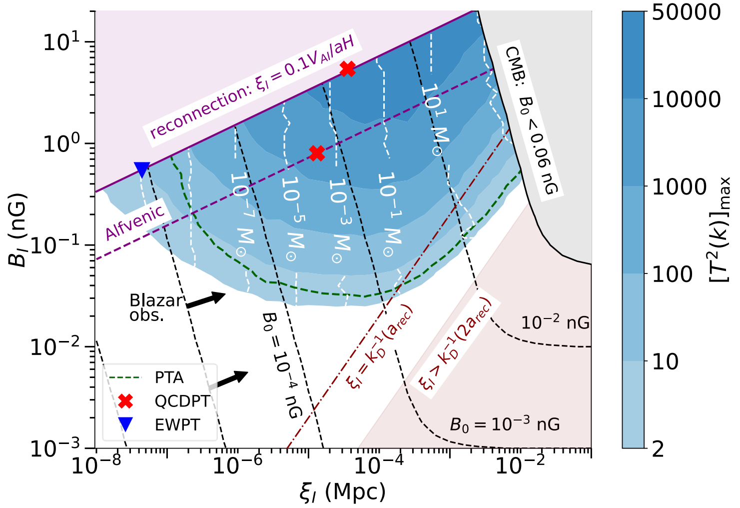
Assuming Batchelor spectrum!



SUMMARY AND CONCLUDING REMARKS

- Magnetic fields can enhance power on small scale dark matter distribution gravitationally.
- PTA/GAIA detection of DM minihalos can provide best probe of primordial magnetic fields
- PMFs resolving Hubble tension likely produce minihalos
- Ironic: how invisible dark matter can help look for visible entity: magnetic fields





BACKUP SLIDES

SOLVING MHD EQUATIONS ANALYTICALLY

NON-RELATIVISTIC IDEAL MHD IN PHOTON DRAG REGIME

$$\frac{\partial\,(a^2\vec{B})}{\partial t} = \frac{\nabla \times (\vec{v}_b \times a^2\vec{B})}{a}$$

$$\frac{\partial \vec{v}_b}{\partial t} + (H + \alpha)\vec{v}_b + \frac{(\vec{v}_b.\nabla)\vec{v}_b}{a} = \frac{\left(\nabla \times \vec{B}\right) \times \vec{B}}{4\pi a \rho_b} - \frac{\mathrm{c}_\mathrm{b}^2 \nabla \delta_b}{a} - \frac{\nabla \phi}{a}$$

$$\frac{\partial \delta_b}{\partial t} = -\frac{\nabla.\vec{v}_b}{a} - \frac{\nabla.(\delta_b \vec{v}_b)}{a}$$

$$\nabla^2 \phi = \frac{a^2}{2M_{Pl}^2}(\rho_b \delta_b + \rho_{DM}\delta_{DM})$$

$$\frac{\partial^2 \delta_{DM}}{\partial a^2} + \left[\frac{\partial \ln(a^2 H)}{\partial \ln a} + 1\right]\frac{\partial \delta_{DM}}{a \partial a} = \frac{\nabla^2 \phi}{(a^2 H)^2}$$

NON-RELATIVISTIC IDEAL MHD IN PHOTON DRAG REGIME: PHOTON DRAG SUPPRESS CONVECTION

$$\frac{\partial\,(a^2\vec{B})}{\partial t} = \frac{\nabla \times (\vec{v}_b \times a^2\vec{B})}{a}$$

$$\frac{\partial \vec{v}_b}{\partial t} + (H + \alpha)\vec{v}_b + \frac{(\vec{v}_b.\nabla)\vec{v}_b}{a} = \frac{(\nabla \times \vec{B}) \times \vec{B}}{4\pi a \rho_b} - \frac{\mathrm{c}_\mathrm{b}^2 \nabla \delta_b}{a} - \frac{\nabla \phi}{a}$$

$$\frac{\partial \delta_b}{\partial t} = -\frac{\nabla.\vec{v}_b}{a} - \frac{\nabla.(\delta_b \vec{v}_b)}{a}$$

$$\nabla^2 \phi = \frac{a^2}{2M_{Pl}^2}(\rho_b \delta_b + \rho_{DM}\delta_{DM})$$

$$\frac{\partial^2 \delta_{DM}}{\partial a^2} + \left[\frac{\partial \ln(a^2 H)}{\partial \ln a} + 1\right]\frac{\partial \delta_{DM}}{a \partial a} = \frac{\nabla^2 \phi}{(a^2 H)^2}$$

SOLVING MAGNETIC FIELD EVOLUTION ANALYTICALLY

$$\frac{\partial\,(a^2\vec{B})}{\partial t} = \frac{\nabla\times(\vec{v}_b\times a^2\vec{B})}{a}$$

$$\frac{\partial\vec{v}_b}{\partial t} + (H+\alpha)\vec{v}_b + \frac{(\vec{v}_b.\nabla)\vec{v}_b}{a} = \frac{\left(\nabla\times\vec{B}\right)\times\vec{B}}{4\pi a\rho_b} - \frac{\mathrm{c}_\mathrm{b}^2\nabla\delta_b}{a} - \frac{\nabla\phi}{a}$$

SOLVING MAGNETIC FIELD EVOLUTION ANALYTICALLY: LARGE B AND LARGE DRAG LIMIT

$$\frac{\partial\,(a^2\vec{B})}{\partial t} = \frac{\nabla \times (\vec{v}_b \times a^2\vec{B})}{a}$$

$$(H + \alpha)\vec{v}_b \approx \frac{\left(\nabla \times \vec{B}\right) \times \vec{B}}{4\pi a \rho_b}$$

SOLVING MAGNETIC FIELD EVOLUTION ANALYTICALLY: FOCUS ON CORRELATIONS

$$\frac{\partial\,(a^2\vec{B})}{\partial t} = \frac{\nabla \times (\vec{v}_b \times a^2\vec{B})}{a}$$

$$(H + \alpha)\vec{v}_b = \frac{\left(\nabla \times \vec{B}\right) \times \vec{B}}{4\pi a \rho_b}$$

$$\langle \vec{B}_0 \frac{\partial \vec{B}_0}{\partial t} \rangle = \langle \frac{\nabla \times (\vec{v}_b \times \vec{B}_0)}{a} \vec{B}_0 \rangle$$

SOLVING MAGNETIC FIELD EVOLUTION ANALYTICALLY: FOCUS ON CORRELATIONS

$$\frac{\partial\,(a^2\vec{B})}{\partial t} = \frac{\nabla \times (\vec{v}_b \times a^2\vec{B})}{a}$$

$$(H+\alpha)\vec{v}_b = \frac{\left(\nabla \times \vec{B}\right) \times \vec{B}}{4\pi a \rho_b}$$

$$\frac{d \ln P_B(k,t)}{d \ln a} = -\frac{4}{3}\frac{k^2 v_A^2}{a^2 H(\alpha + H)} \sim -(k\tau v_b)^2$$

$$\langle \vec{B}_0 \frac{\partial \vec{B}_0}{\partial t} \rangle = \langle \frac{\nabla \times (\vec{v}_b \times \vec{B}_0)}{a} \vec{B}_0 \rangle$$

SOLVING MAGNETIC FIELD EVOLUTION ANALYTICALLY: FOCUS ON CORRELATIONS

$$\frac{\partial\,(a^2\vec{B})}{\partial t} = \frac{\nabla \times (\vec{v}_b \times a^2\vec{B})}{a}$$

$$(H+\alpha)\vec{v}_b = \frac{\left(\nabla \times \vec{B}\right) \times \vec{B}}{4\pi a \rho_b}$$

$$\frac{d \ln P_B(k,t)}{d \ln a} = -\frac{4}{3}\frac{k^2 v_A^2}{a^2 H(\alpha + H)} \sim -(k\tau v_b)^2$$

$$\langle \vec{B}_0 \frac{\partial \vec{B}_0}{\partial t} \rangle = \langle \frac{\nabla \times (\vec{v}_b \times \vec{B}_0)}{a} \vec{B}_0 \rangle$$

$$P_B(k,t) = P_B(k,t_I) e^{-\frac{k^2}{k_D^2}}$$

$$k_D^{-1}(a) \sim \tau v_A \sqrt{\frac{H}{\alpha + H}}$$

Jedamzik et al 1996,
Subramanian and Barrow 1997

SOLVING MAGNETIC FIELD EVOLUTION ANALYTICALLY: FOCUS ON CORRELATIONS

$$\frac{\partial\,(a^2\vec{B})}{\partial t} = \frac{\nabla \times (\vec{v}_b \times a^2\vec{B})}{a}$$

$$(H+\alpha)\vec{v}_b = \frac{(\nabla\times\vec{B})\times\vec{B}}{4\pi a \rho_b}$$

$$\langle \vec{B}_0 \frac{\partial \vec{B}_0}{\partial t}\rangle = \langle \frac{\nabla\times(\vec{v}_b\times\vec{B}_0)}{a}\vec{B}_0\rangle$$

<u>ASSUMED</u>

B_0 Gaussian

$$\frac{\ldots P_B(k,t)}{\ldots \ln a} = -\frac{4}{3}\frac{k^2 v_A^2}{a^2 H(\alpha+H)} \sim -(k\tau v_b)^2$$

$$P_B(k,t) = P_B(k,t_I)e^{-\frac{k^2}{k_D^2}}$$

$$k_D^{-1}(a) \sim \tau v_A\sqrt{\frac{H}{\alpha+H}}$$

Jedamzik et al 1996,
Subramanian and Barrow 1997

MODELLING BARYON DENSITY PERTURBATIONS

$$\frac{d\ln P_B(k,t)}{d\ln a} = -\frac{4}{3}\frac{k^2 v_A^2}{a^2 H(\alpha + H)} \sim -(k\tau v_b)^2$$

INTO NON-LINEAR REGIME: MODELLING BARYON DENSITY PERTURBATIONS

$$\frac{d\ln P_B(k,t)}{d\ln a} = -\frac{4}{3}\frac{k^2 v_A^2}{a^2 H(\alpha + H)} \sim -(k\tau v_b)^2$$

Divergence of Lorentz force

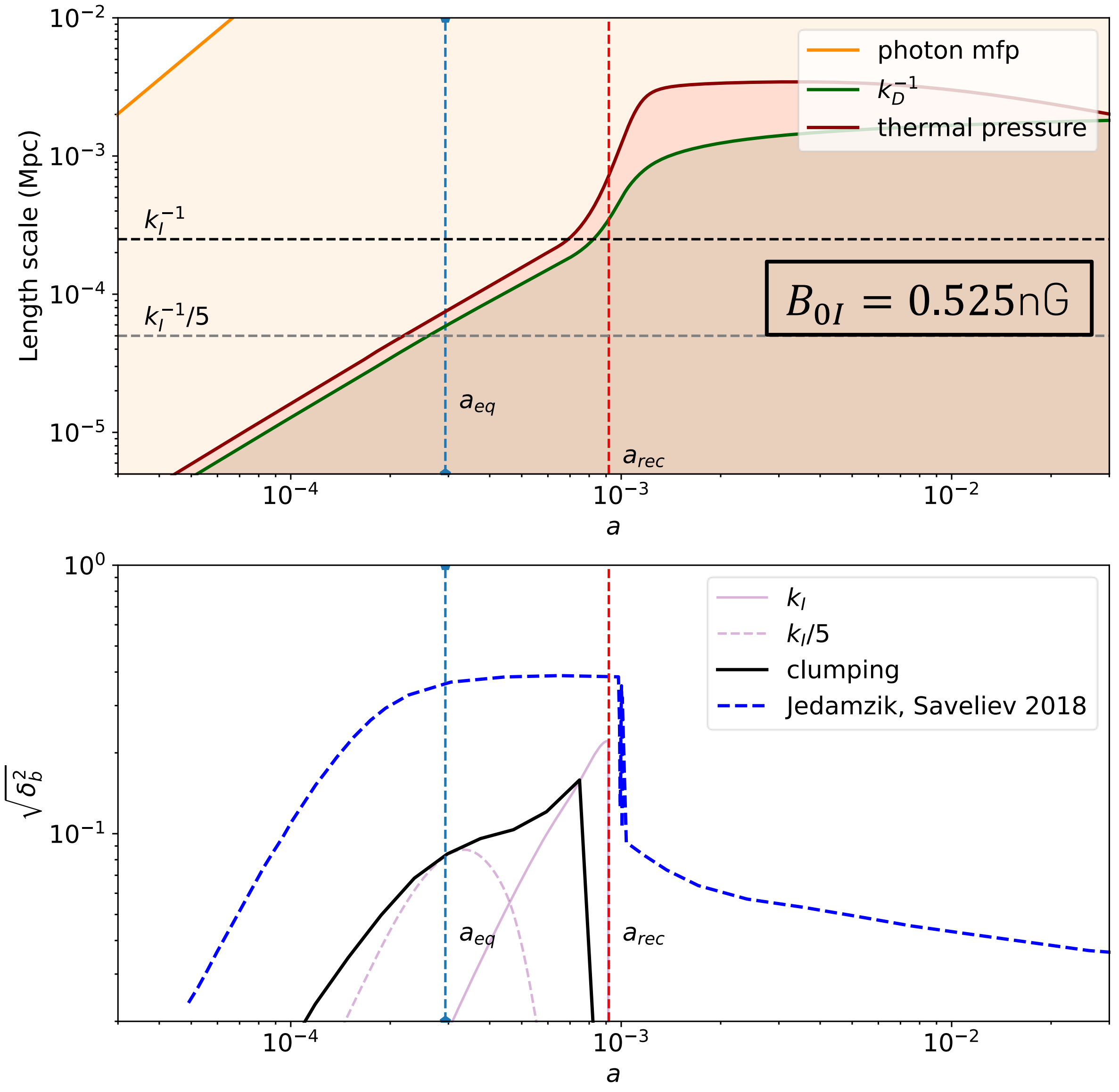
$$\frac{\partial \theta_b}{\partial t} + (H+\alpha)\theta_b = \frac{S_0(k)}{a^2} + \frac{c_b^2 k^2 \delta_b}{a}$$

$$\frac{\partial \delta_b}{\partial t} = -\frac{\theta_b}{a} - \frac{\nabla.(\delta_b \vec{v}_b)}{a}$$

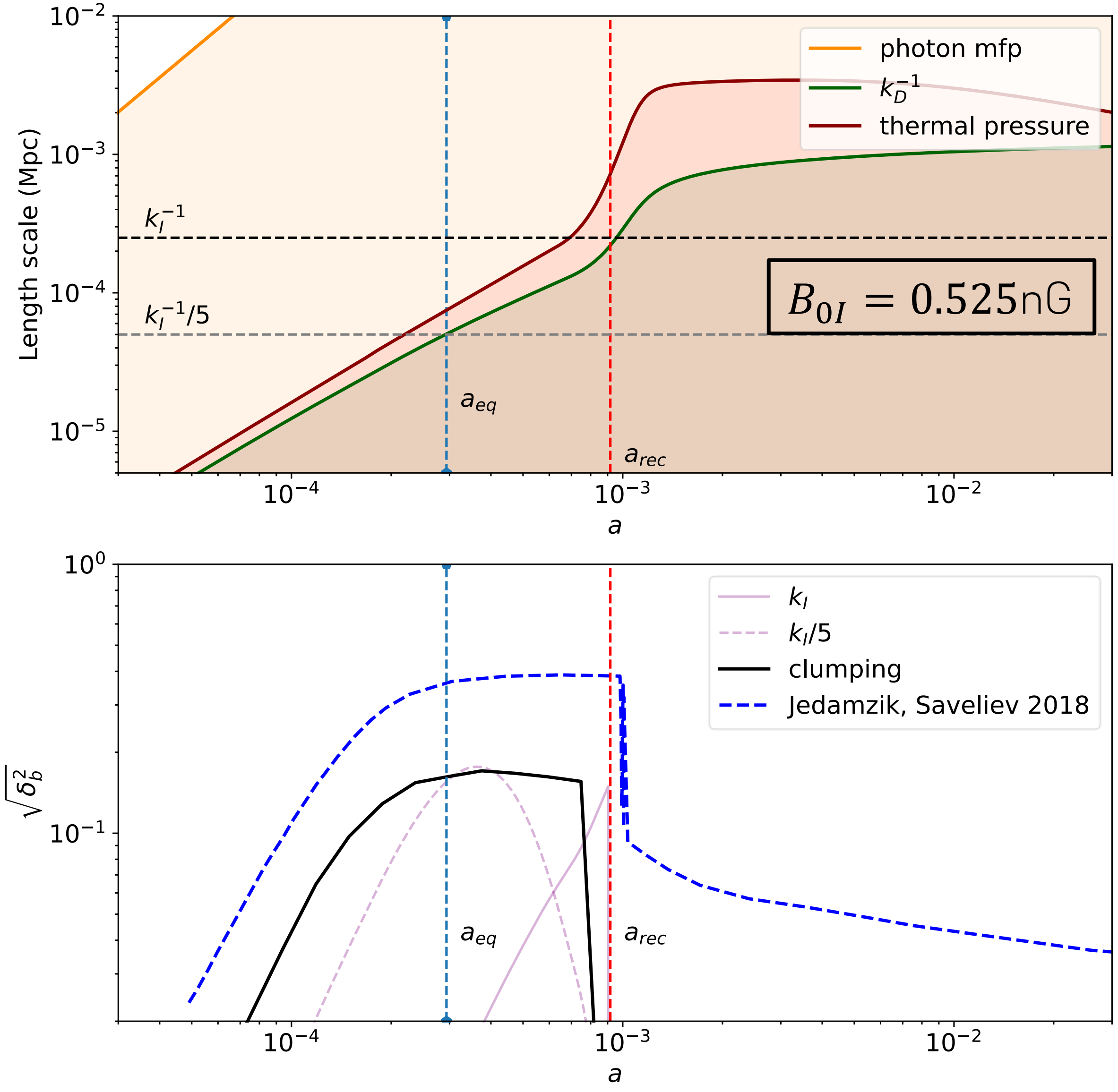
Ignored non-linear terms in δ_b

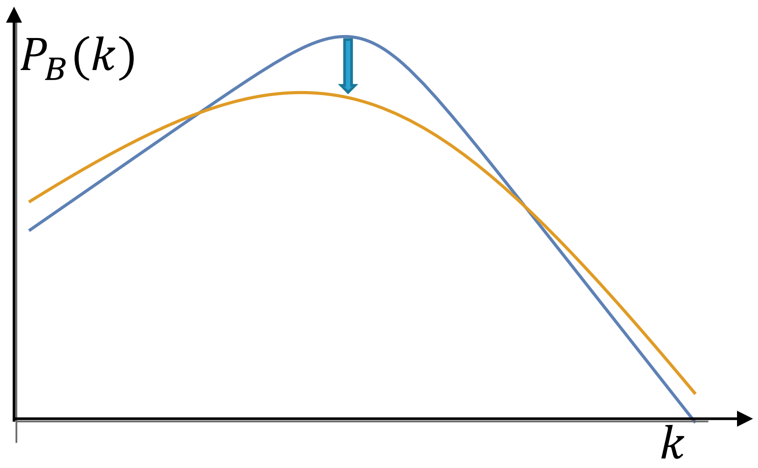
COMPARING WITH FULL MHD SIMULATIONS

COMPARING WITH SIMULATIONS: SENSITIVE TO INITIAL POWER SPECTRUM

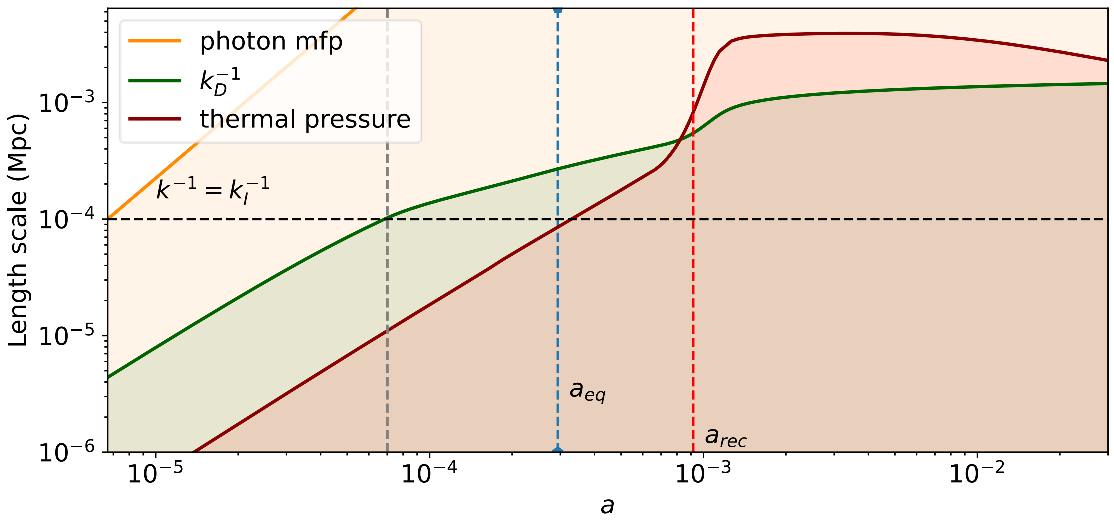


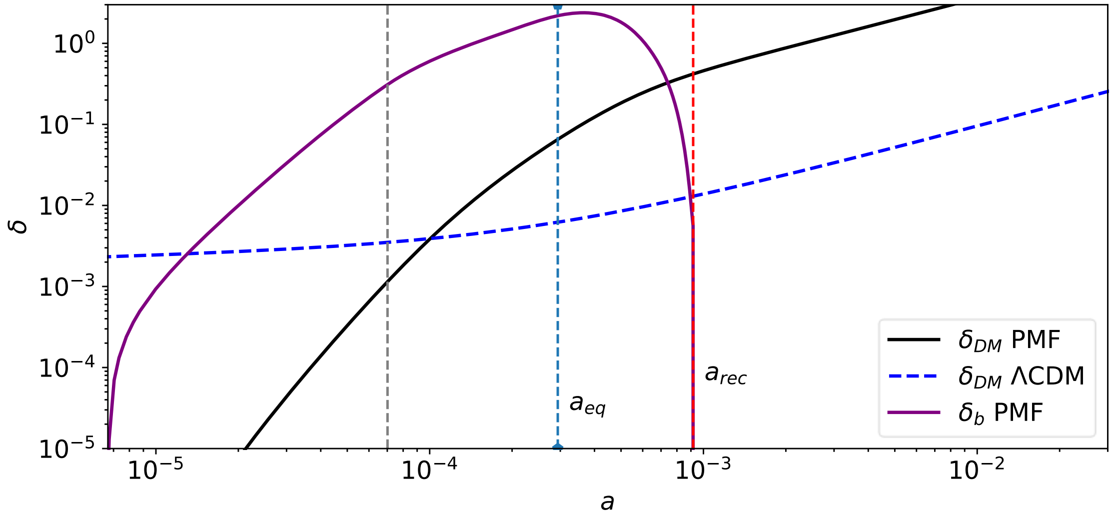
COMPARING WITH SIMULATIONS: SENSITIVE TO INITIAL POWER SPECTRUM





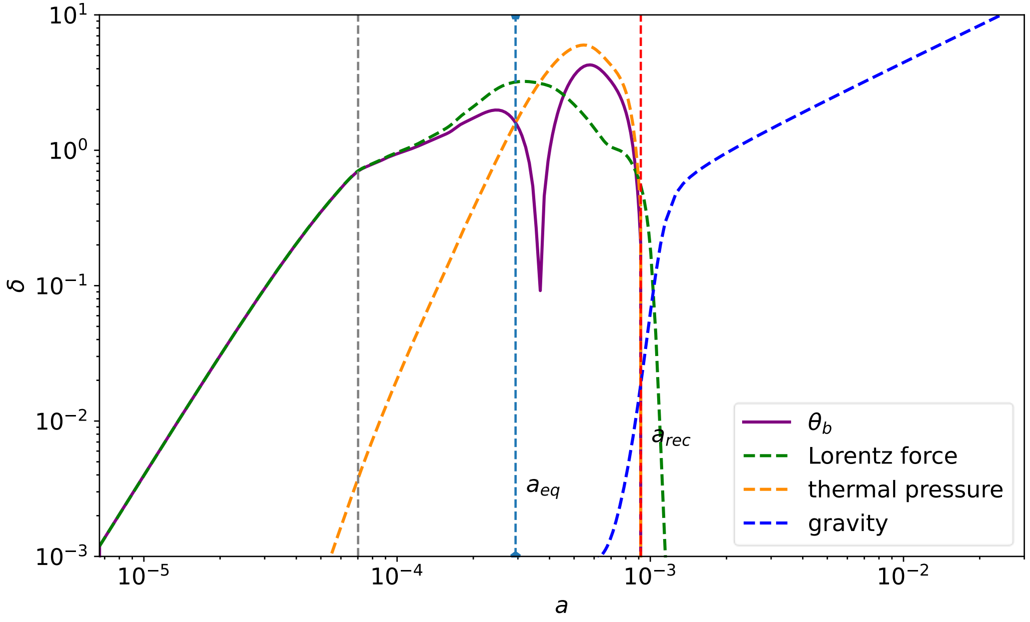
MORE PERTURBATION PLOTS



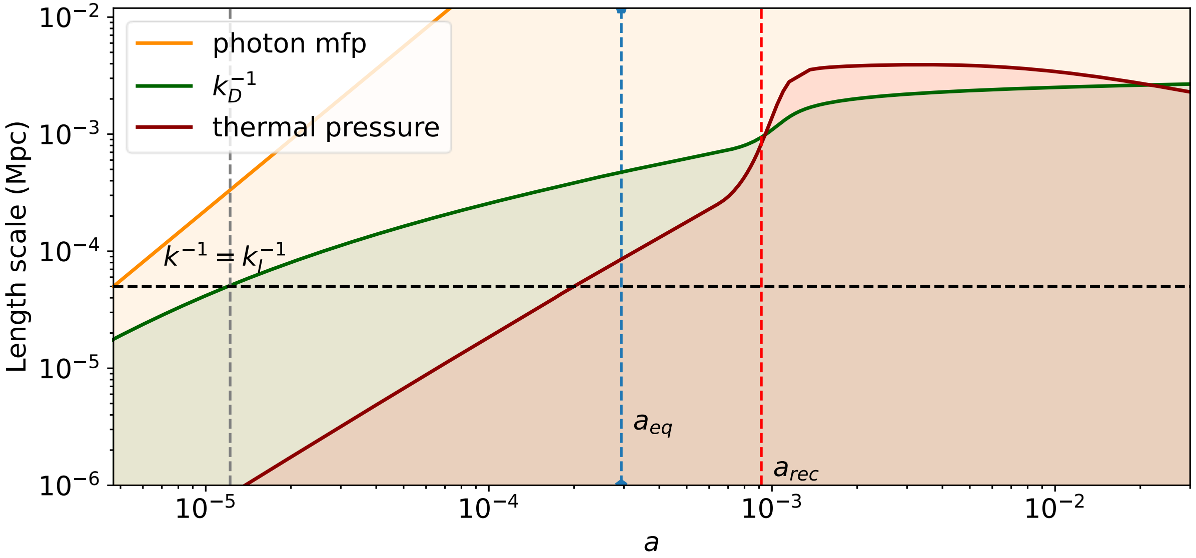


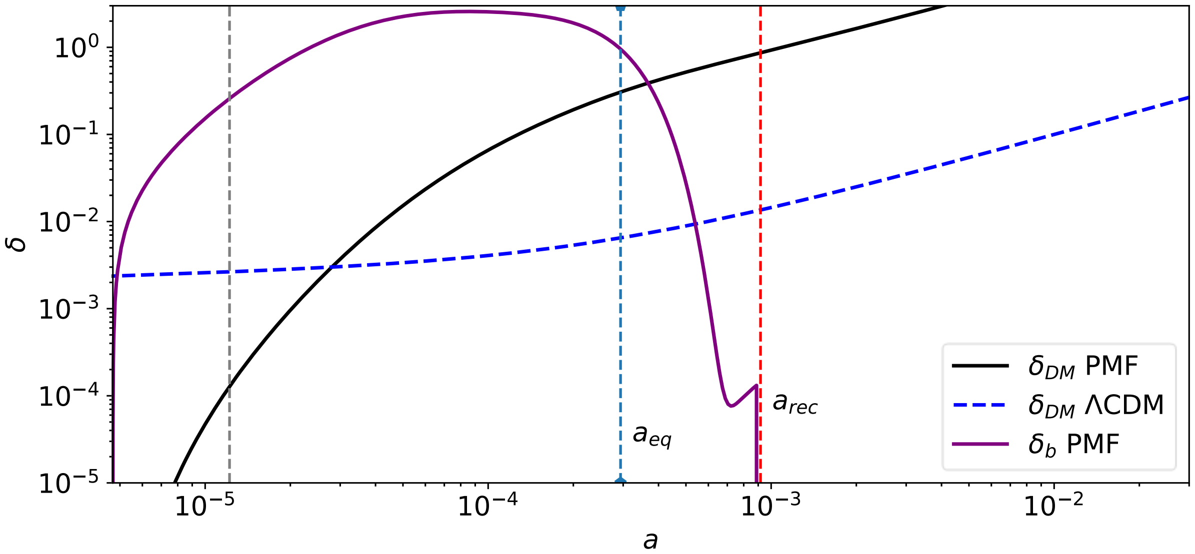
$B_0 = 1\text{nG}$

$k_I = 10^4\ Mpc^{-1}$



MORE PERTURBATION PLOTS





$B_0 = 8\text{nG}$

$k_I = 10^4\ Mpc^{-1}$