PRIMORDIAL MAGNETIC FIELDS AND THE MATTER POWER SPECTRUM

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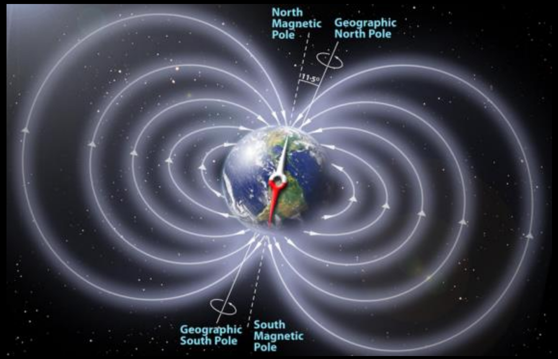
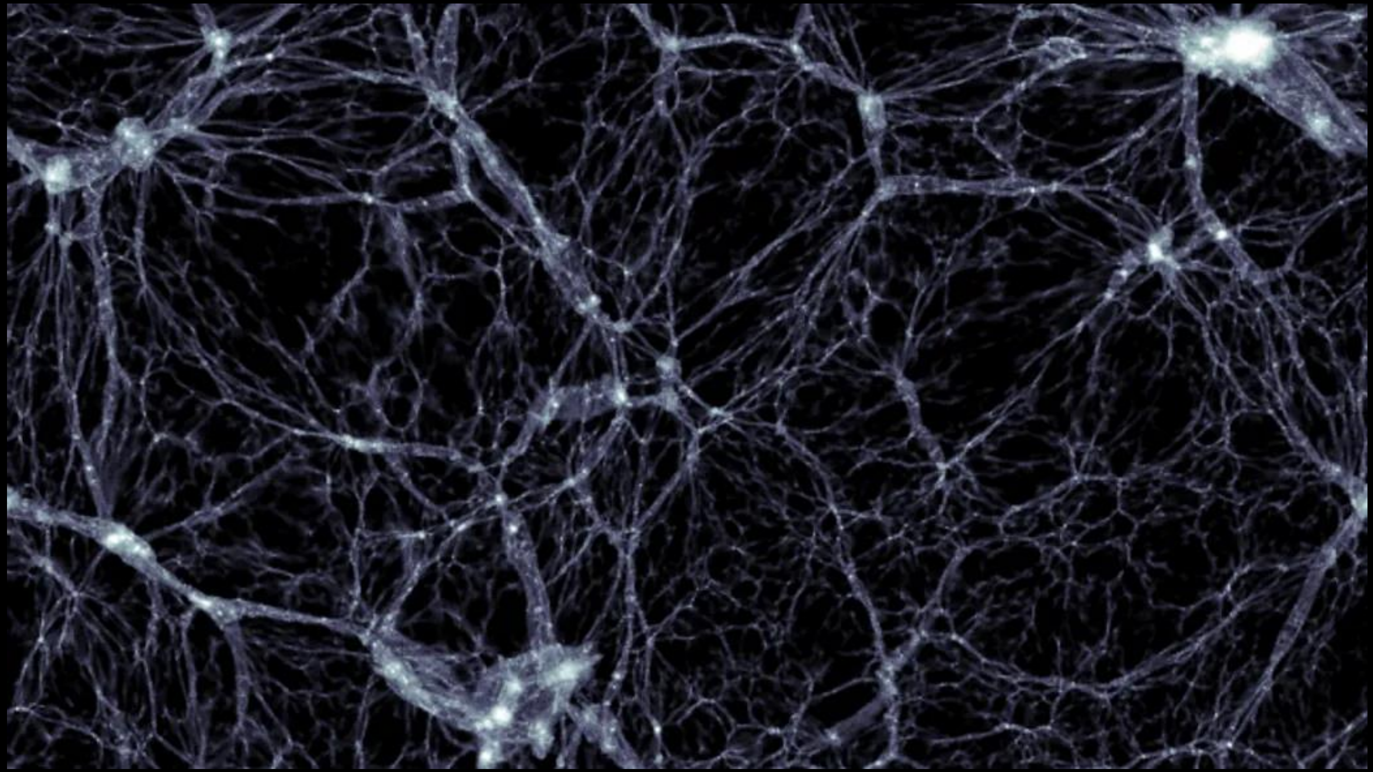
Pranjal Ralegankar

Postdoctoral scientist, SISSA

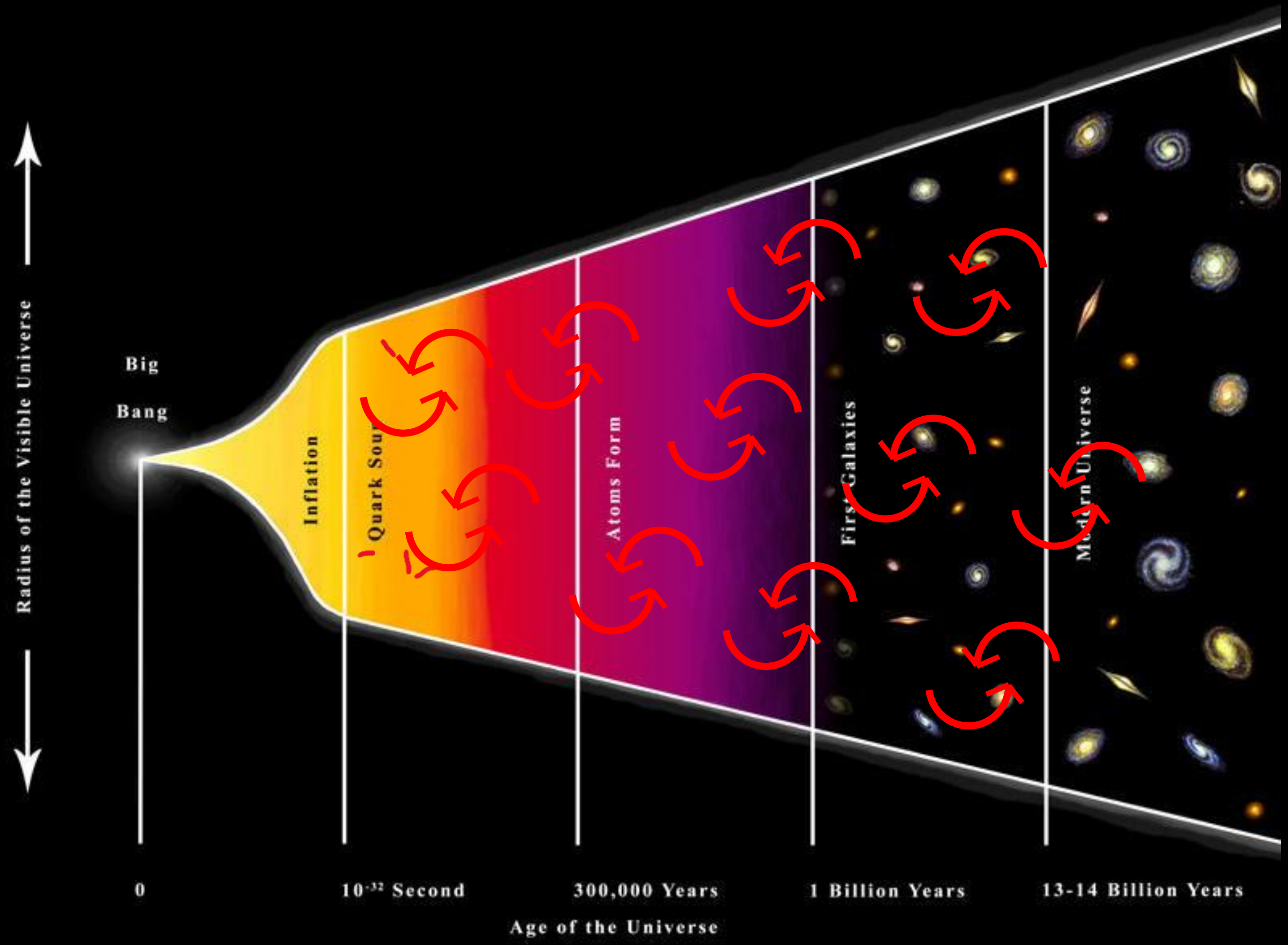
Image source: Pauline Voß for Quanta Magazine

UBIQUITOUS MAGNETIC FIELDS

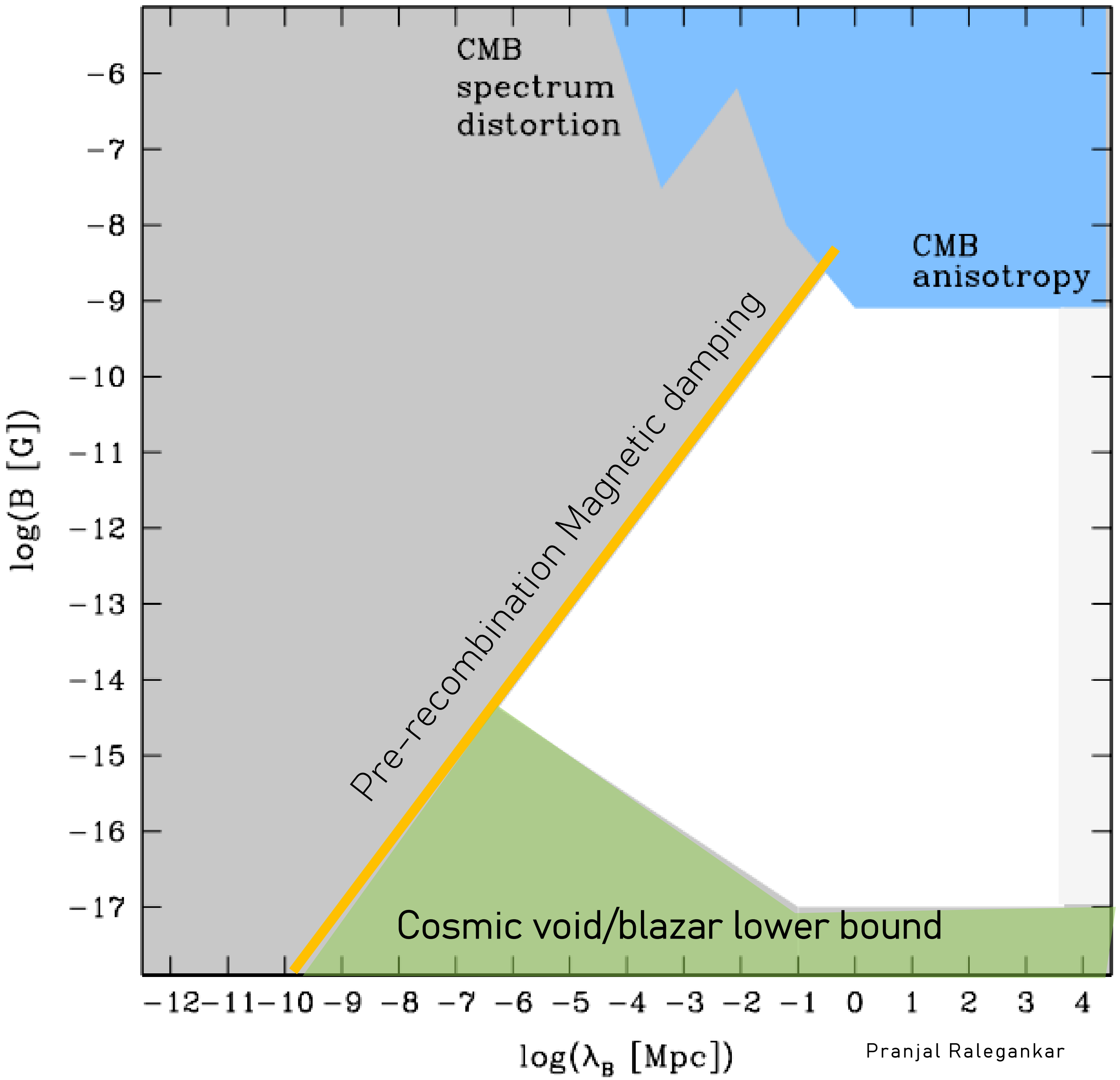




PRIMORDIAL: PRODUCED BY BIG BANG PLASMA

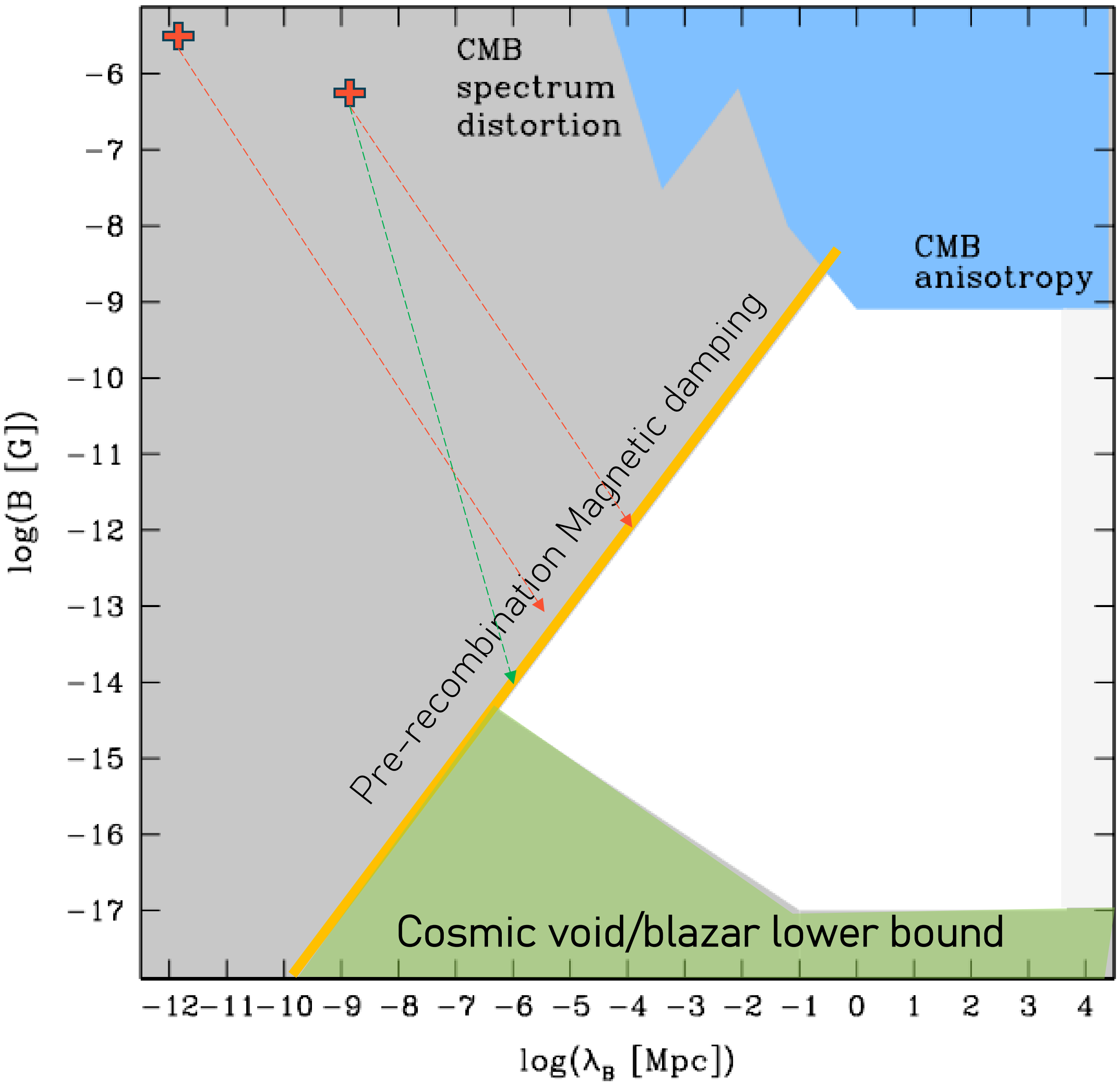


ALLOWED PMF PARAMETER SPACE

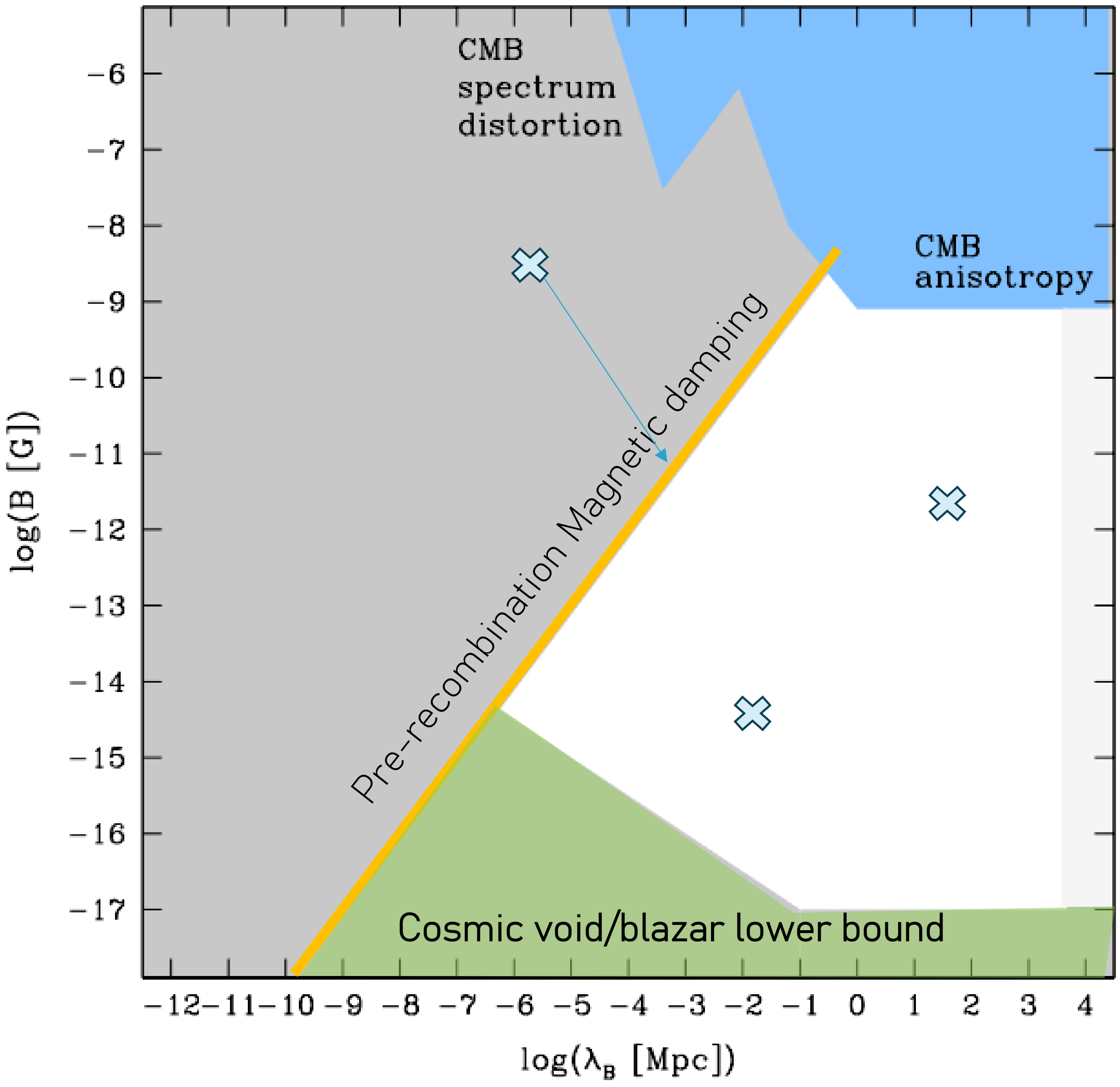


Durrer and Neronov 2013

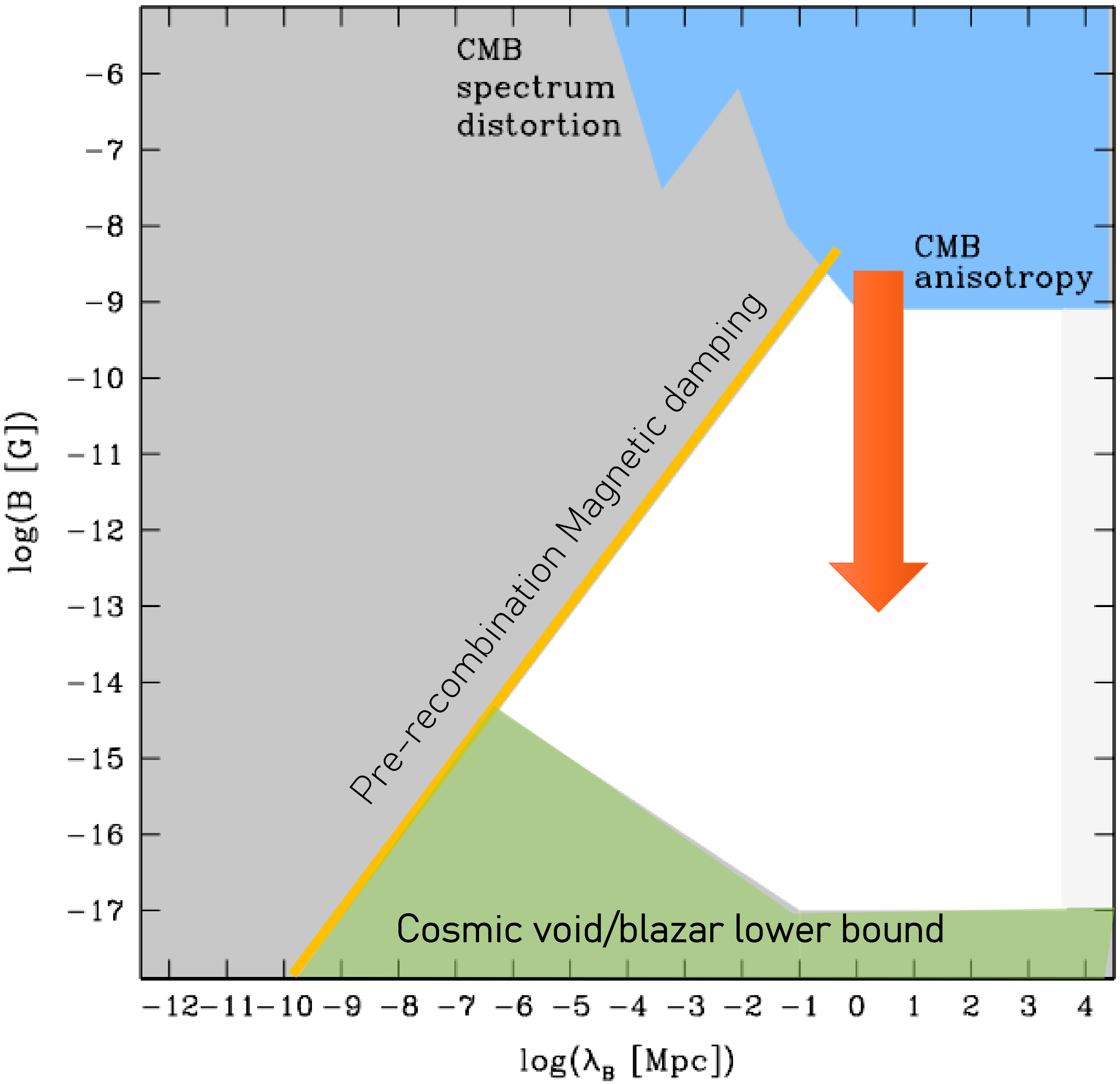
PMFS GENERATED POST INFLATION LIE ON THE DAMPING LINE



INFLATION GENERATED PMFS CAN BE ANYWHERE ON THE RIGHT OF DAMPING LINE



GOAL: TEST THE PRIMORDIAL HYPOTHESIS OF MAGNETIC FIELDS



PRIMORDIAL MAGNETIC FIELDS ENHANCE DENSITY PERTURBATIONS

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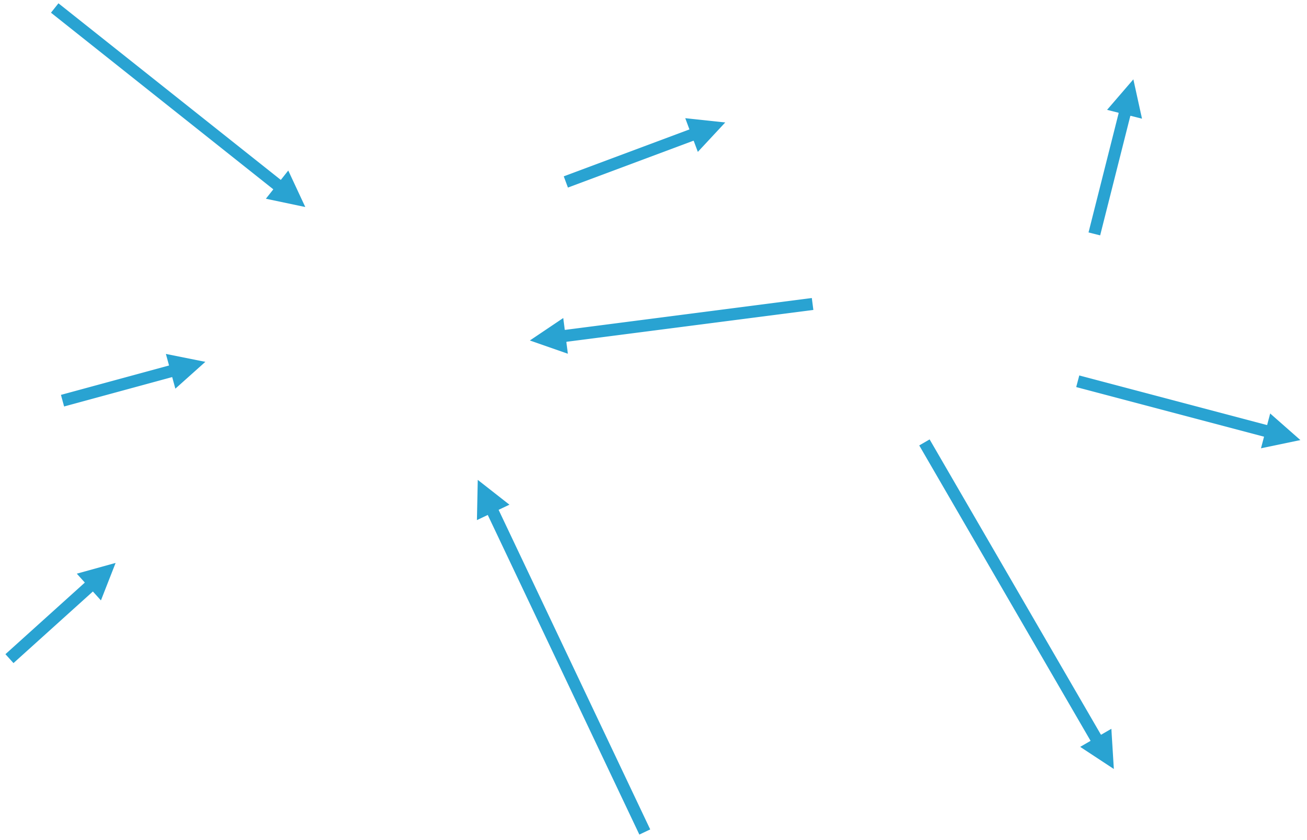
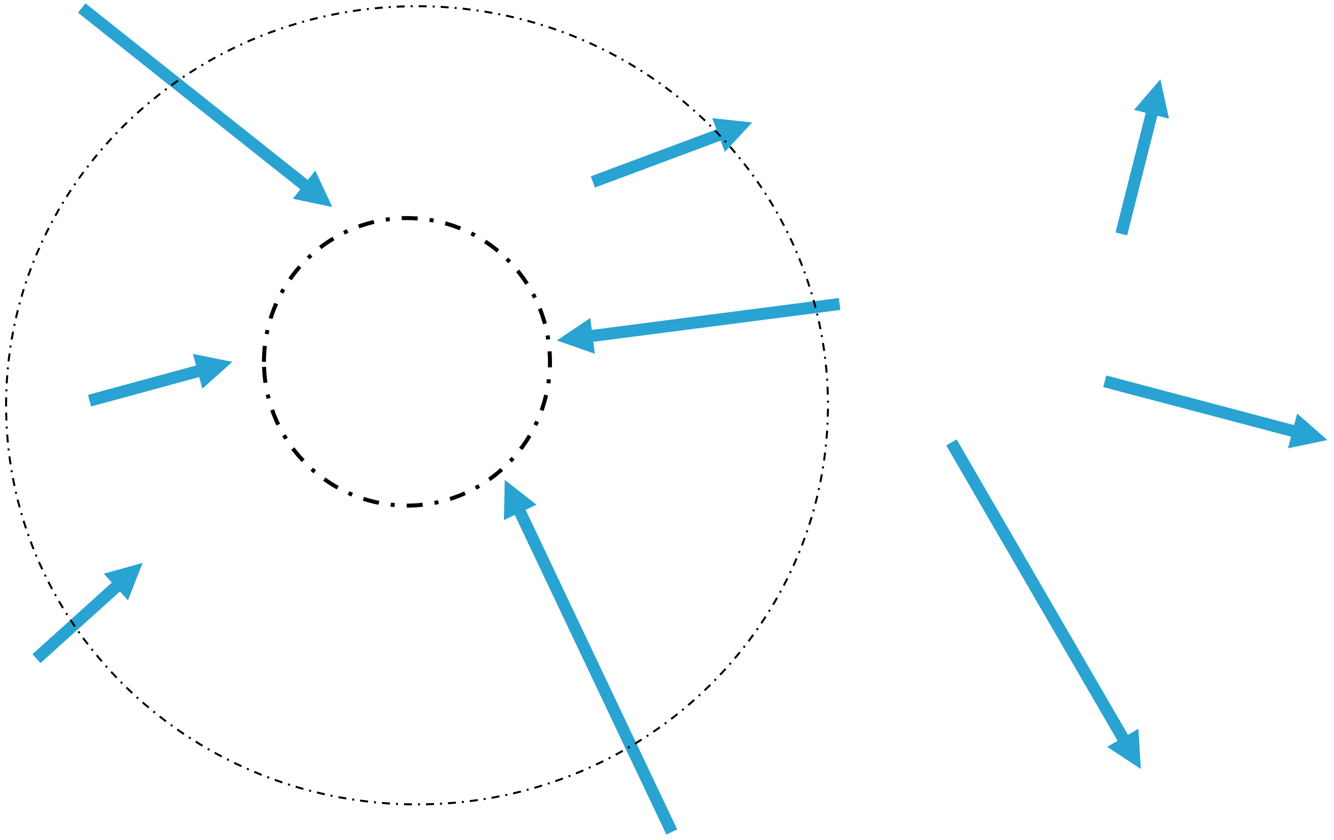
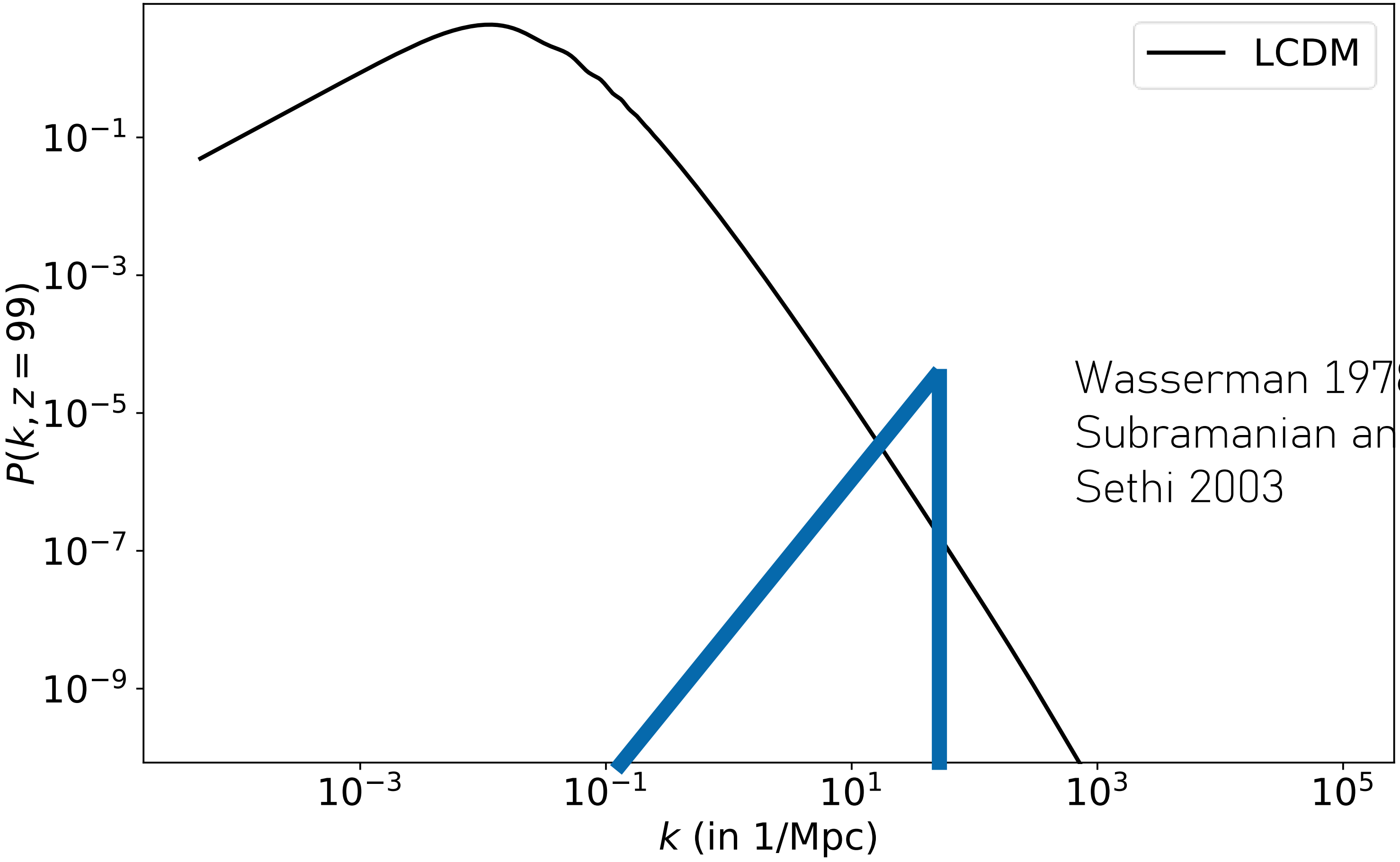


PRIMORDIAL MAGNETIC FIELDS ENHANCE DENSITY PERTURBATIONS

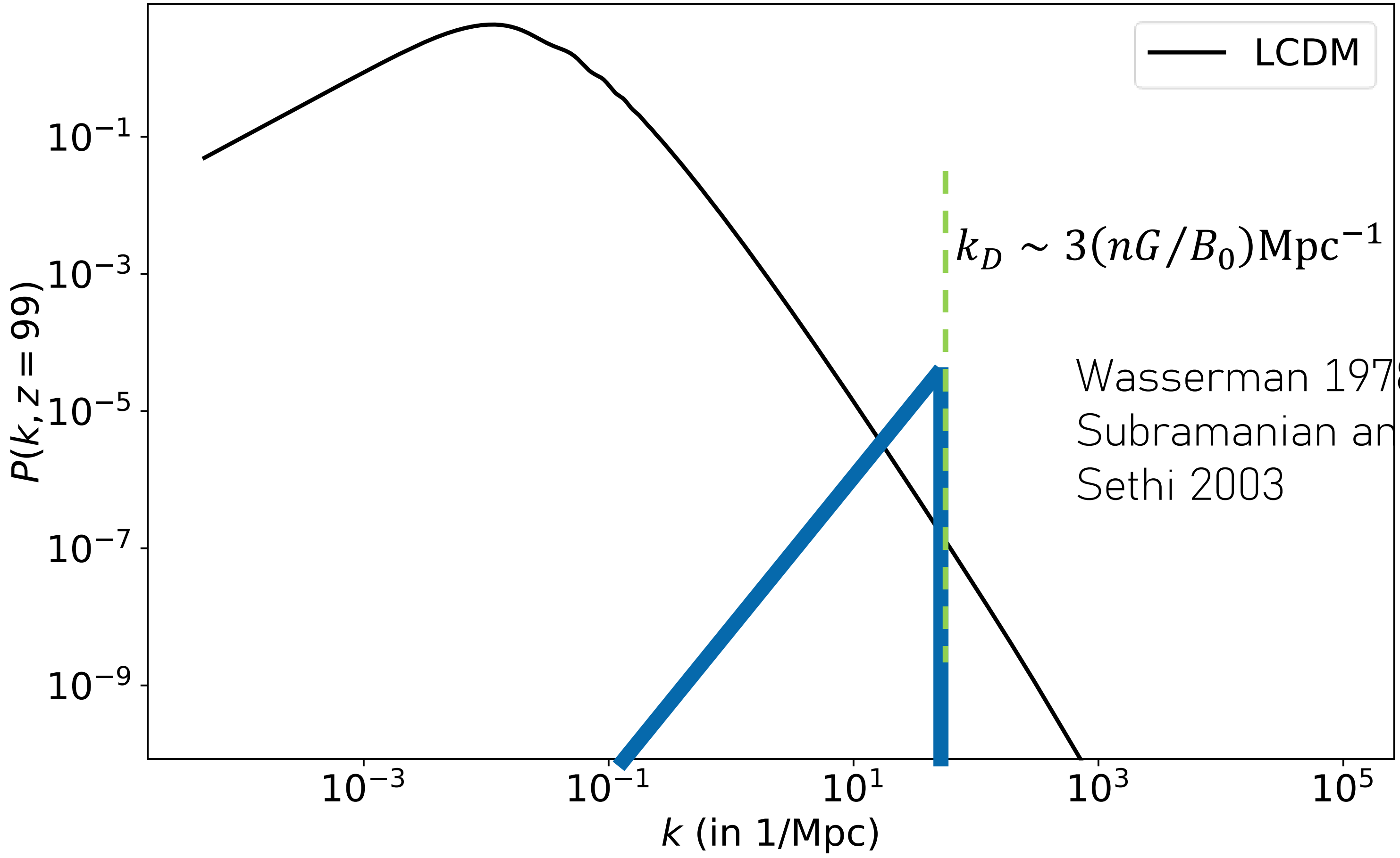


PRIMORDIAL MAGNETIC FIELDS ENHANCE POWER SPECTRUM ON SMALL SCALES



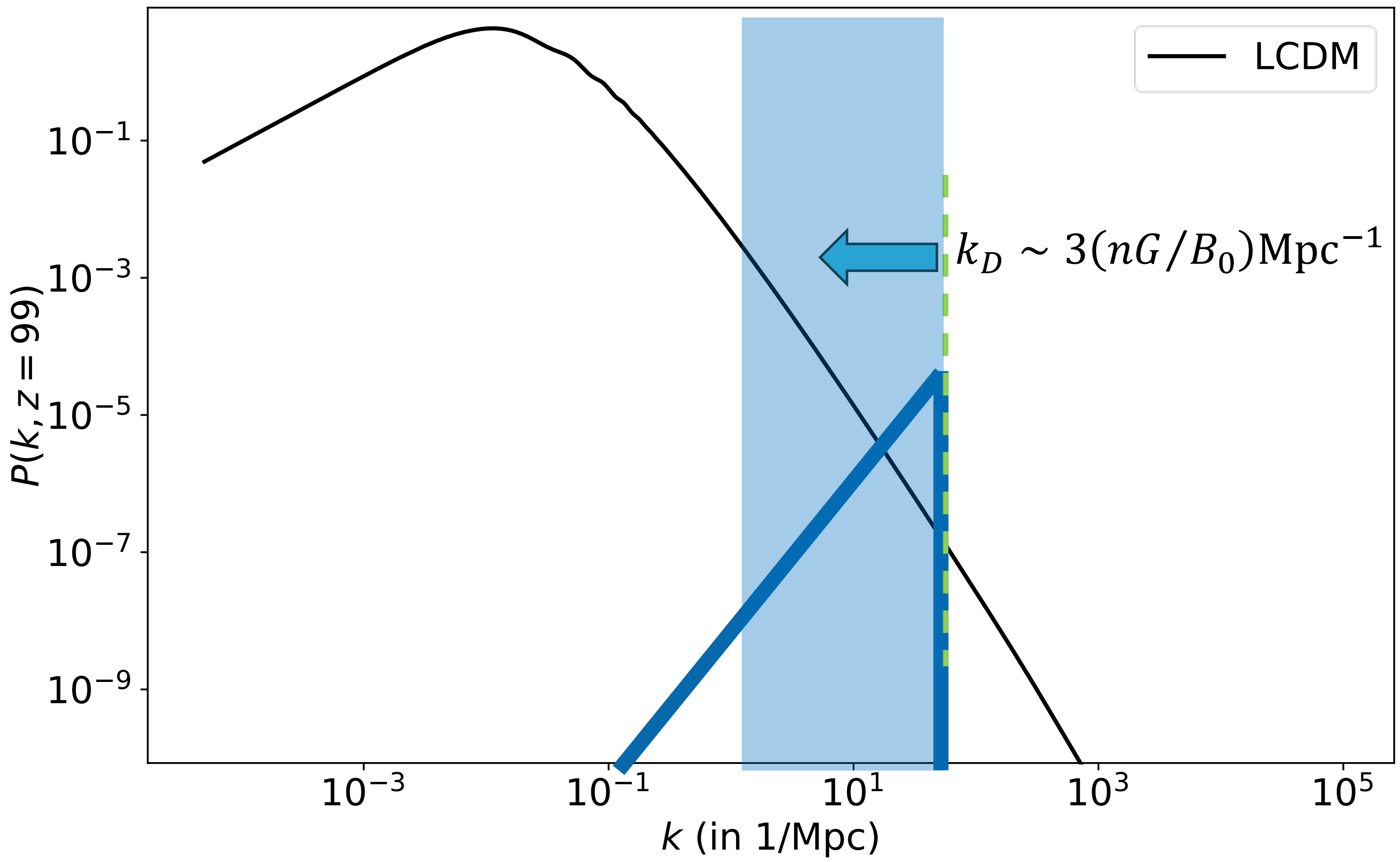
Wasserman 1978, Kim et al 1996, Subramanian and Barrow 1997, Gopal and Sethi 2003

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

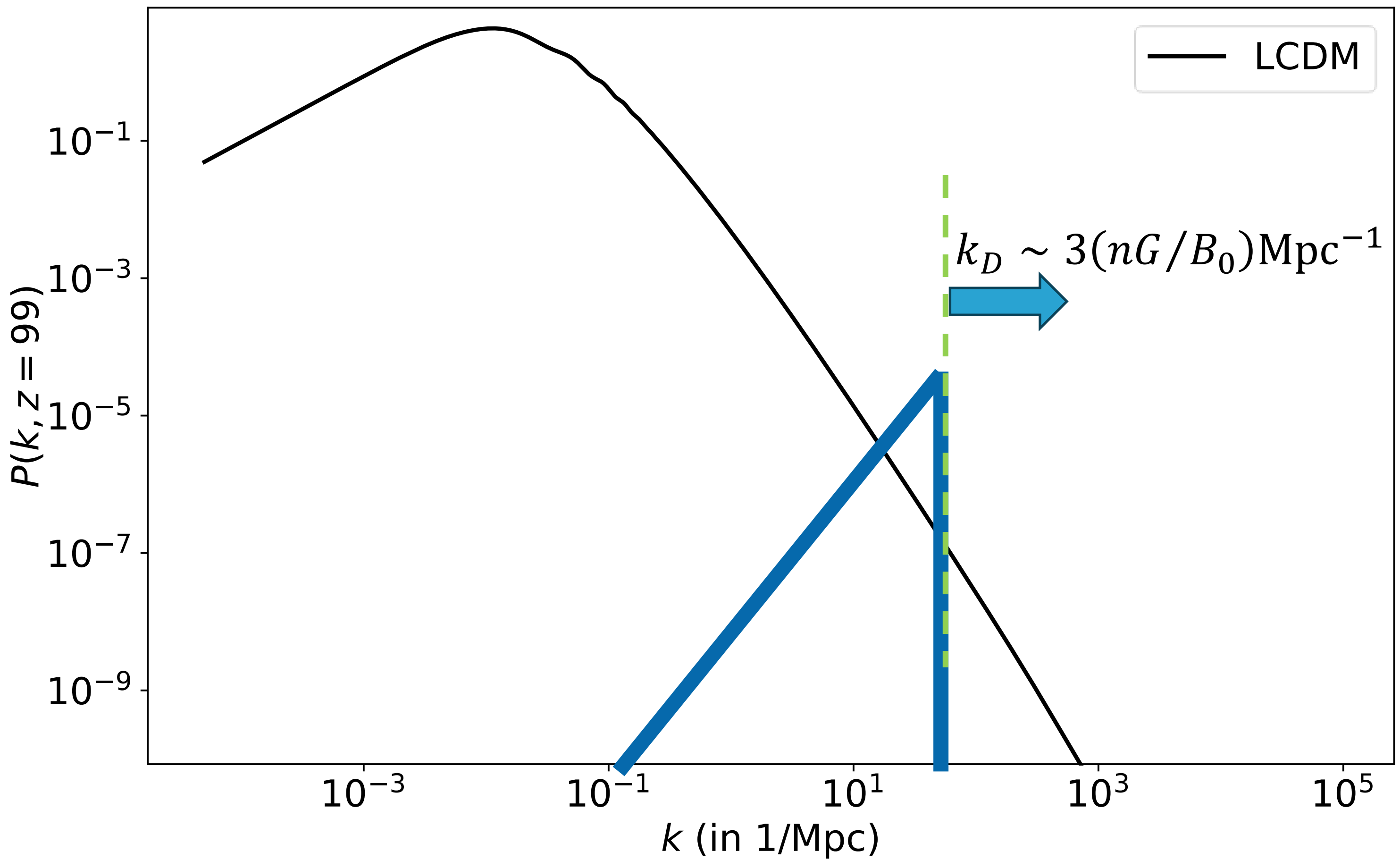


Wasserman 1978, Kim et al 1996, Subramanian and Barrow 1997, Gopal and Sethi 2003

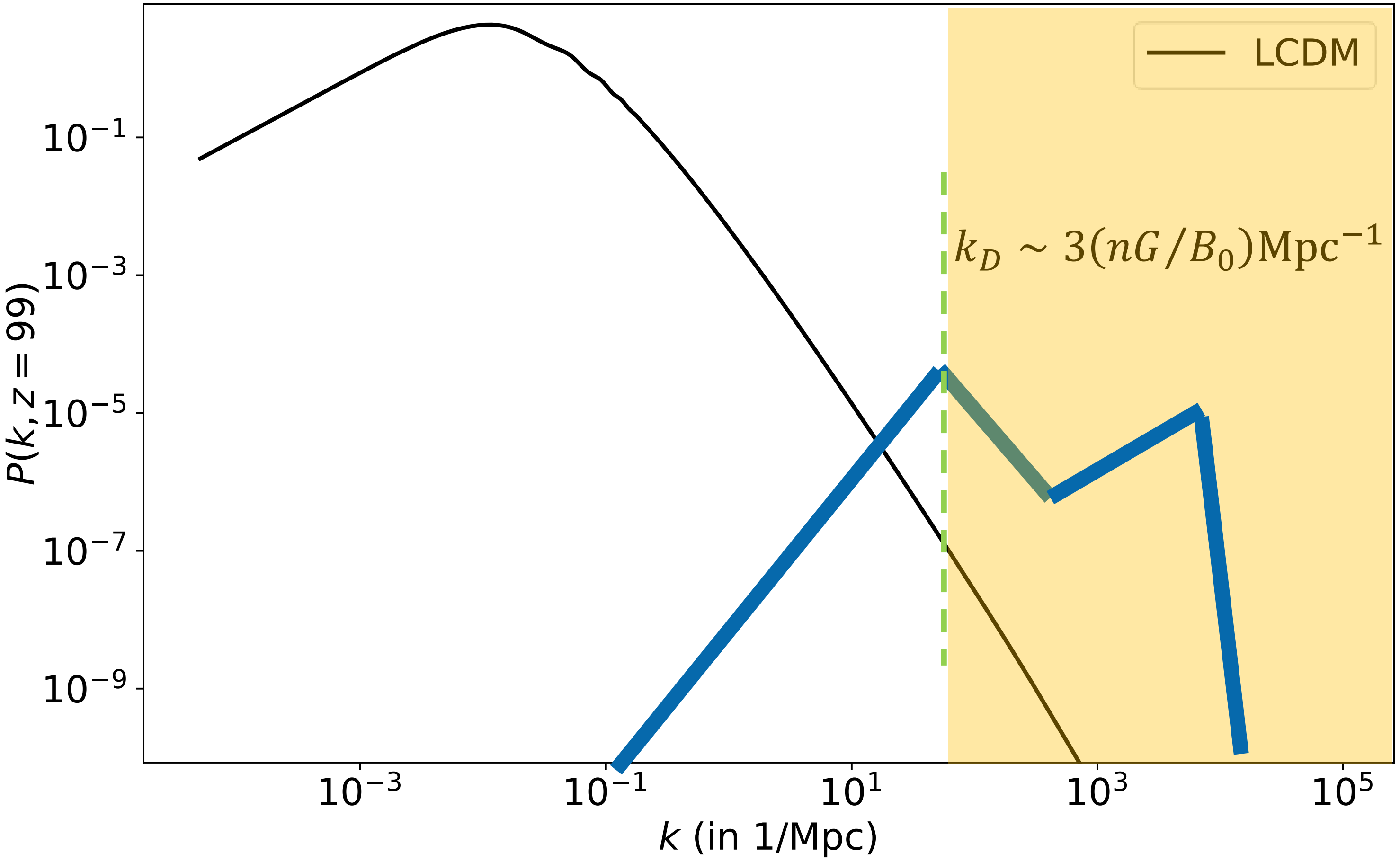
EARLIER WORKS FOCUSED ON SCALES BELOW MAGNETIC DAMPING (JEANS) SCALE



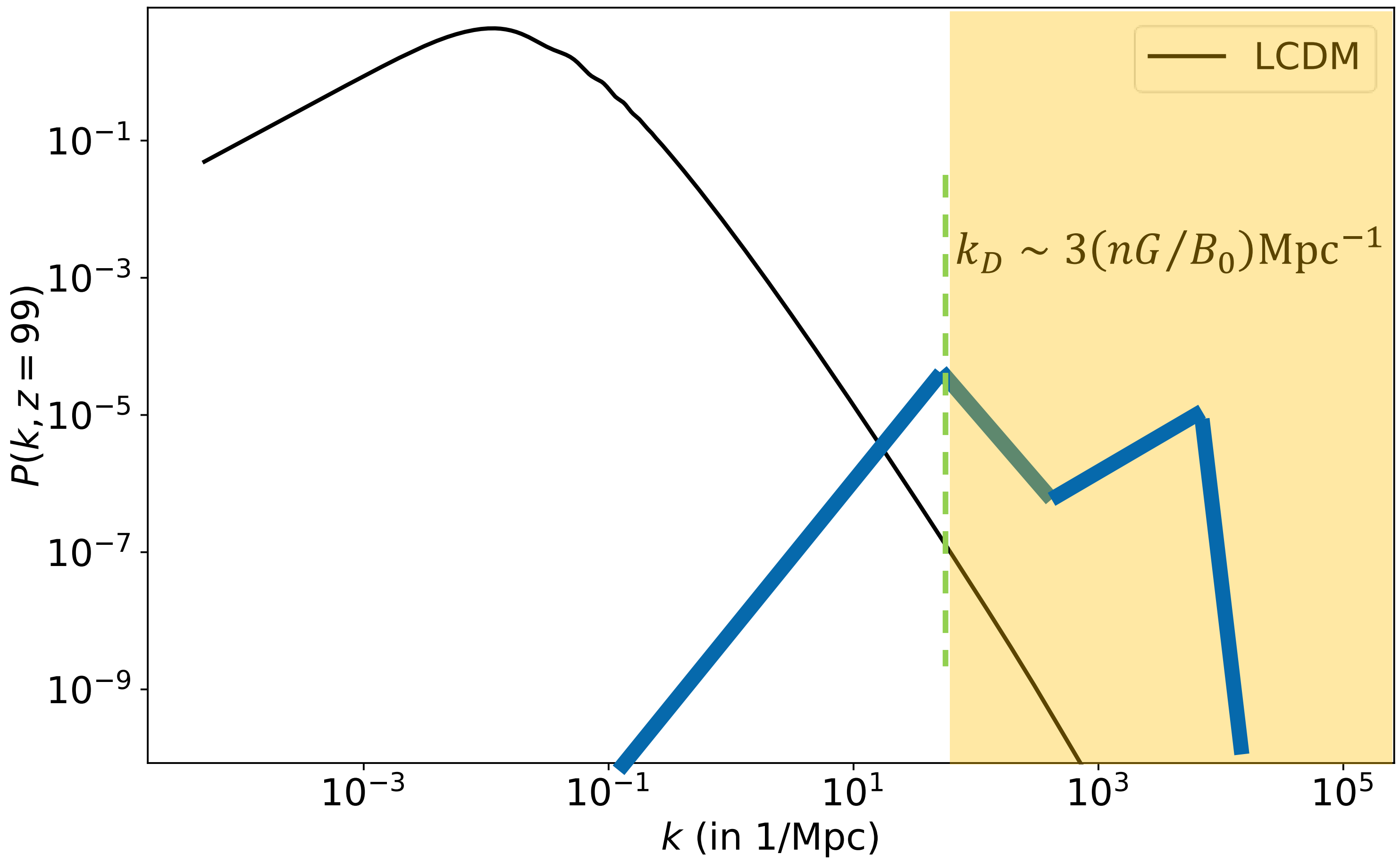
MY STUDY FOCUSES ON SCALES BELOW MAGNETIC DAMPING (JEANS) SCALE



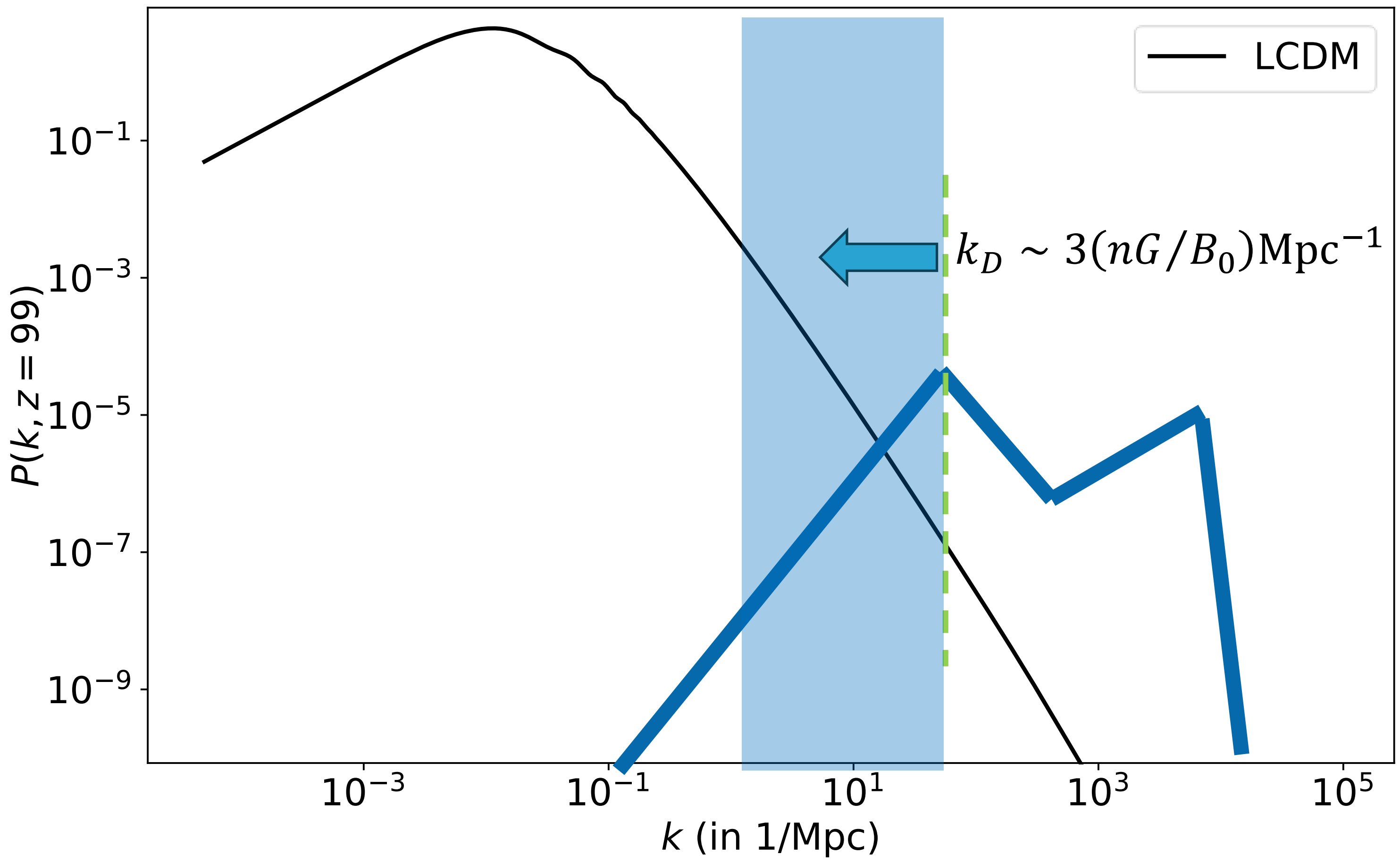
FINDING: HIGHLY ENHANCED POWER SPECTRUM BELOW JEANS SCALE



PART 1: DARK MATTER MINIHALOS BELOW JEANS SCALE



(MAYBE) PART 2: LARGE SCALES RELEVANT FOR JWST

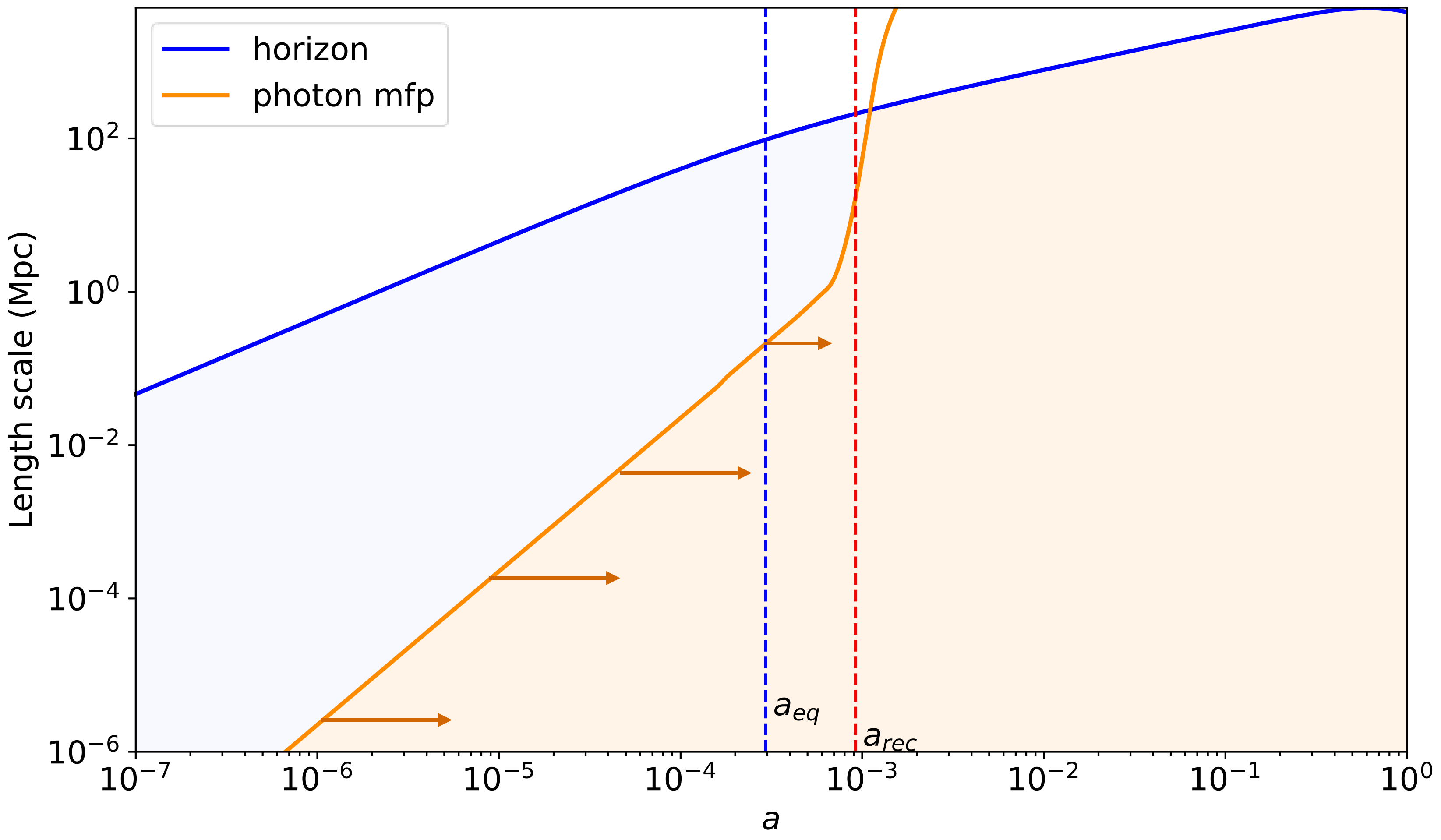


PART 1

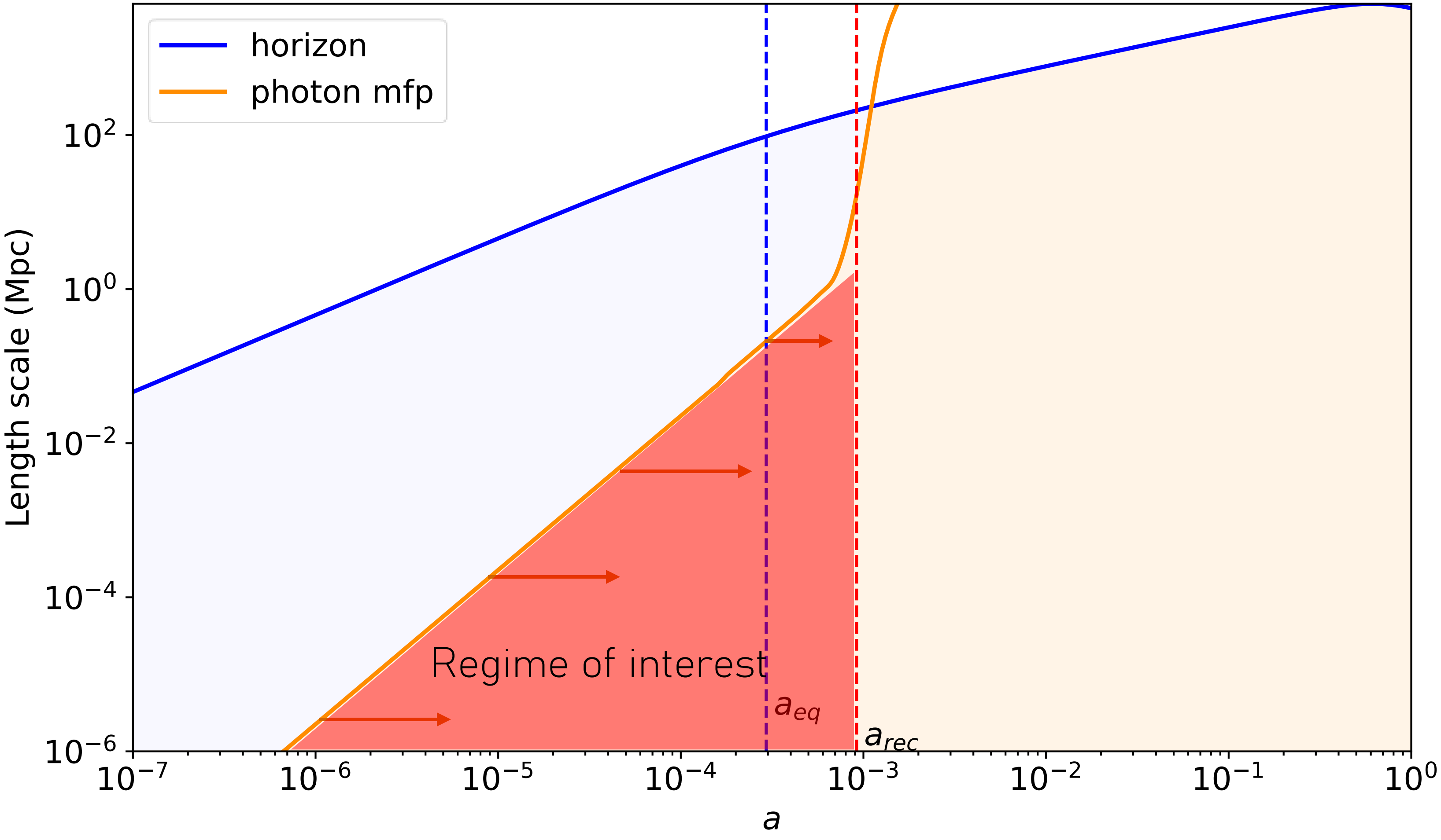
Probing Primordial magnetic fields through dark matter minihalos

ARXIV: 2303.11861

SCALES OF INTEREST: PRE-RECOMBINATION AND SCALES SMALLER THAN PHOTON MFP



SCALES OF INTEREST: PRE-RECOMBINATION AND SCALES SMALLER THAN PHOTON MFP



IDEAL MHD IN PHOTON DRAG REGIME

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

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

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

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

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

IDEAL MHD IN PHOTON DRAG REGIME

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

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

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

PRE-RECOMBINATION IDEAL MHD: MAGNETIC FIELDS INFLUENCE BY BARYON FLOW

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

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

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

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PRE-RECOMBINATION IDEAL MHD: BARYONS PUSHED BY LORENTZ FORCE

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

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

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

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

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

PRE-RECOMBINATION IDEAL MHD: REMAINING EQUATIONS SAME!

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

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

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

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

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PRE-RECOMBINATION IDEAL MHD: LARGE PHOTON DRAG

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

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

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

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

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

PRE-RECOMBINATION IDEAL MHD: LARGE PHOTON DRAG MAKES FLOW LAMINAR

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

$$\frac{\partial \vec{v}_b}{\partial t} + (H + \alpha)\vec{v}_b + \cancelto{0}{\frac{(\vec{v}_b.\nabla)\vec{v}_b}{a}} = \frac{\left(\nabla \times \vec{B}\right) \times \vec{B}}{4\pi a \rho_b} - \frac{\mathrm{c}_\mathrm{b}^2 \nabla \delta_b}{a} - \frac{\nabla \phi}{a}$$

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CAN ANALYTICALLY SOLVE MHD EQS: VISCOUS DAMPING

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

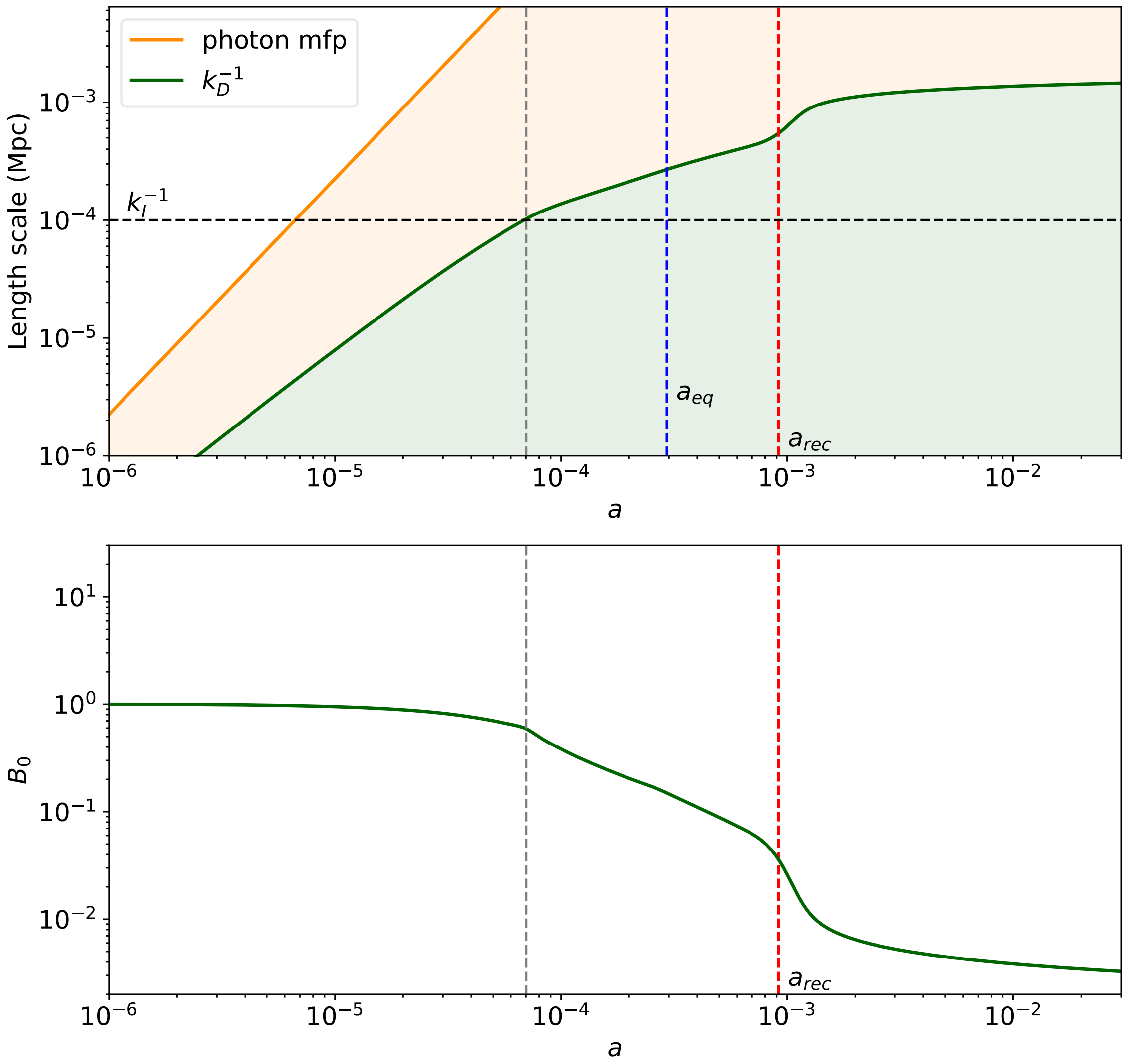
$$k_D^{-1}(a) \sim \tau v_b$$

Assumed B is always Gaussian!

EVOLUTION OF MAGNETIC DAMPING SCALE

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

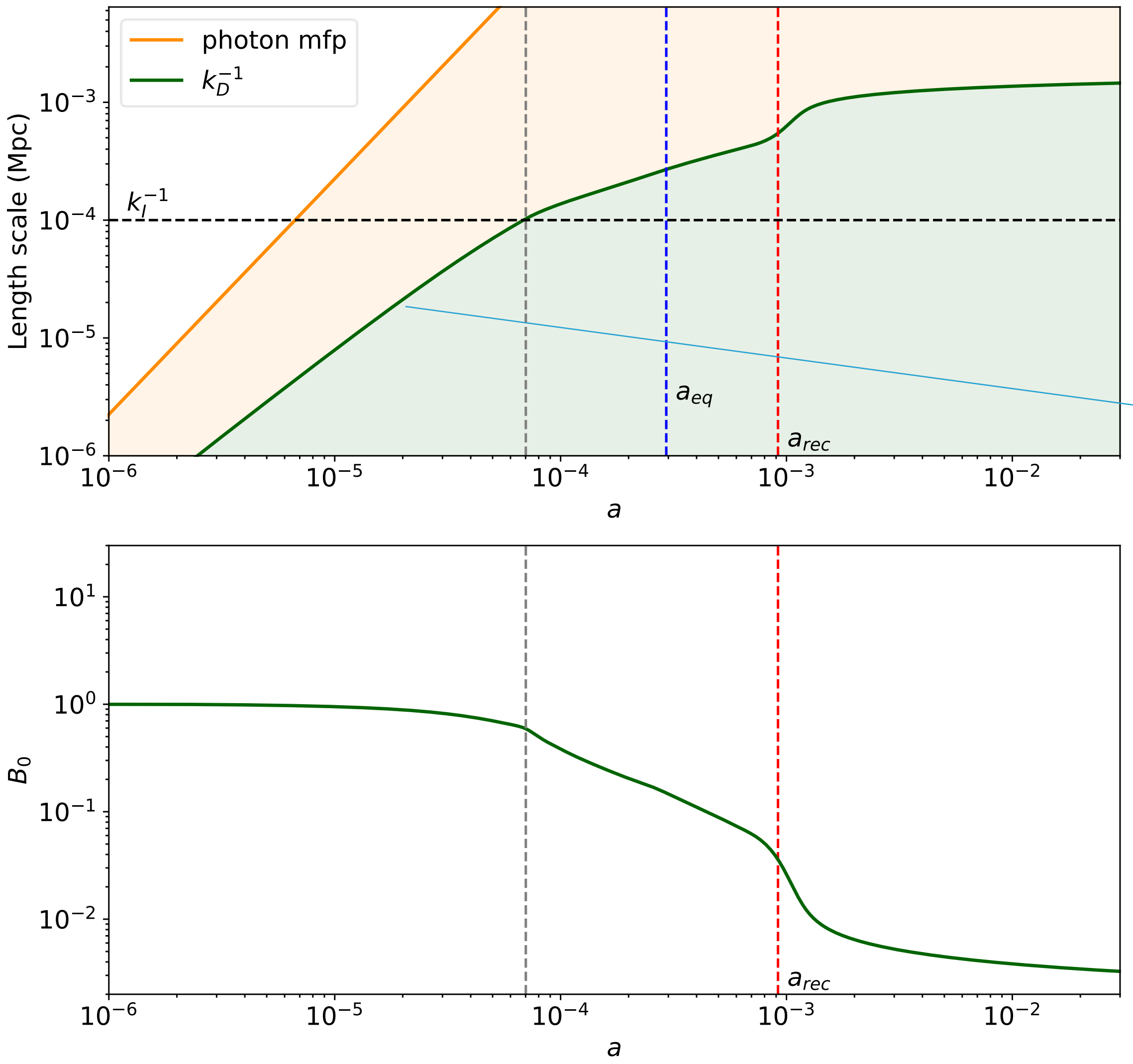
$$k_D^{-1}(a) \sim \tau v_b$$

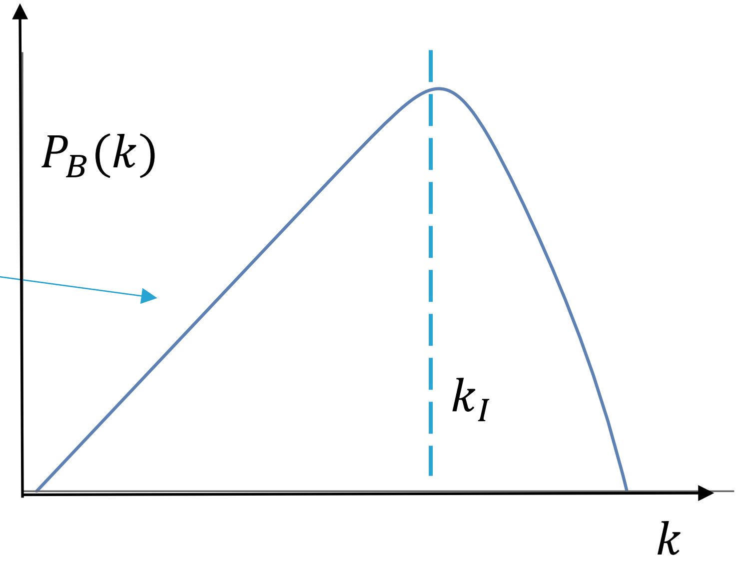


EVOLUTION OF MAGNETIC DAMPING SCALE

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

$$k_D^{-1}(a) \sim \tau v_b$$





EVOLUTION OF MAGNETIC DAMPING SCALE

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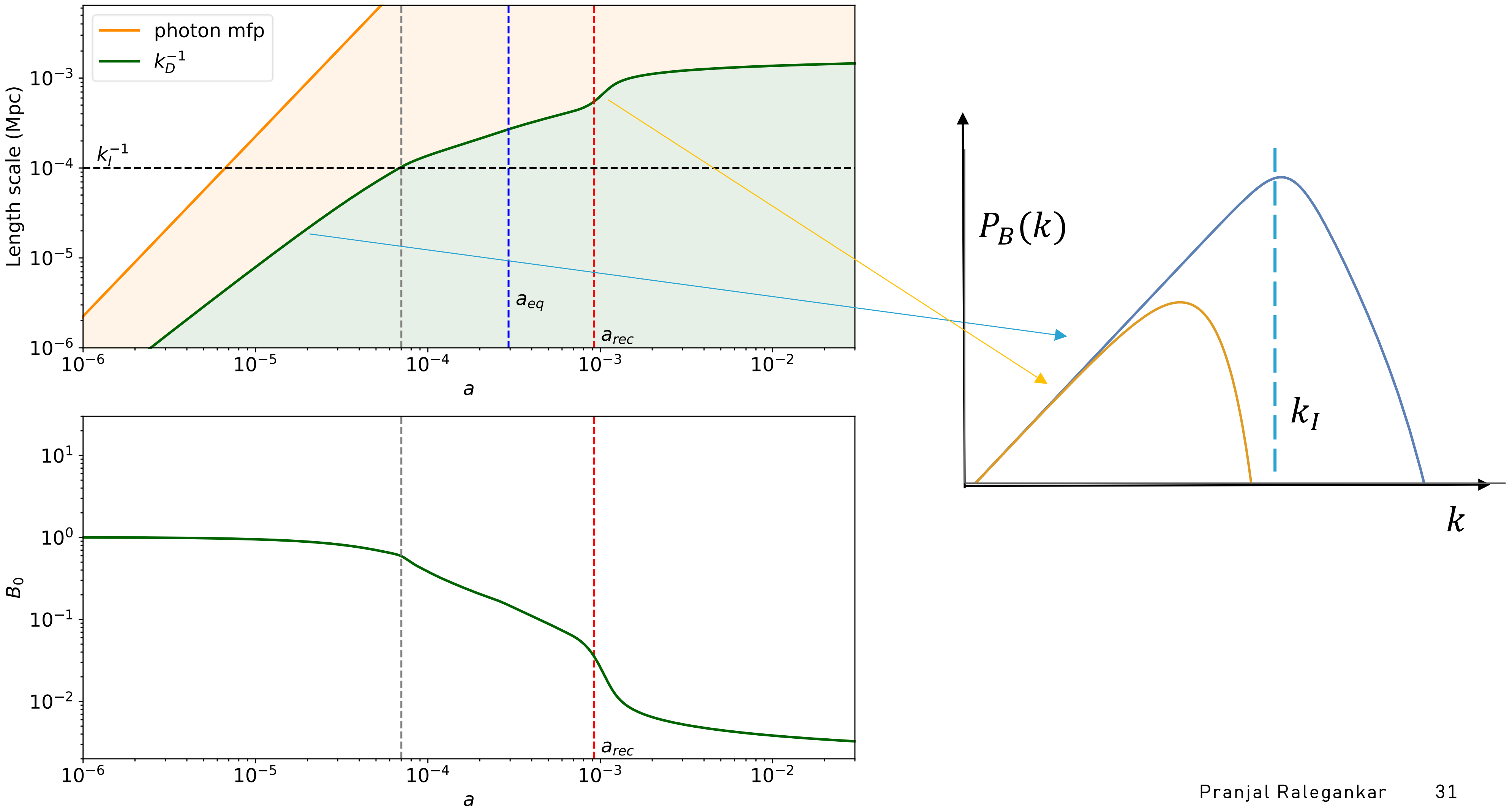
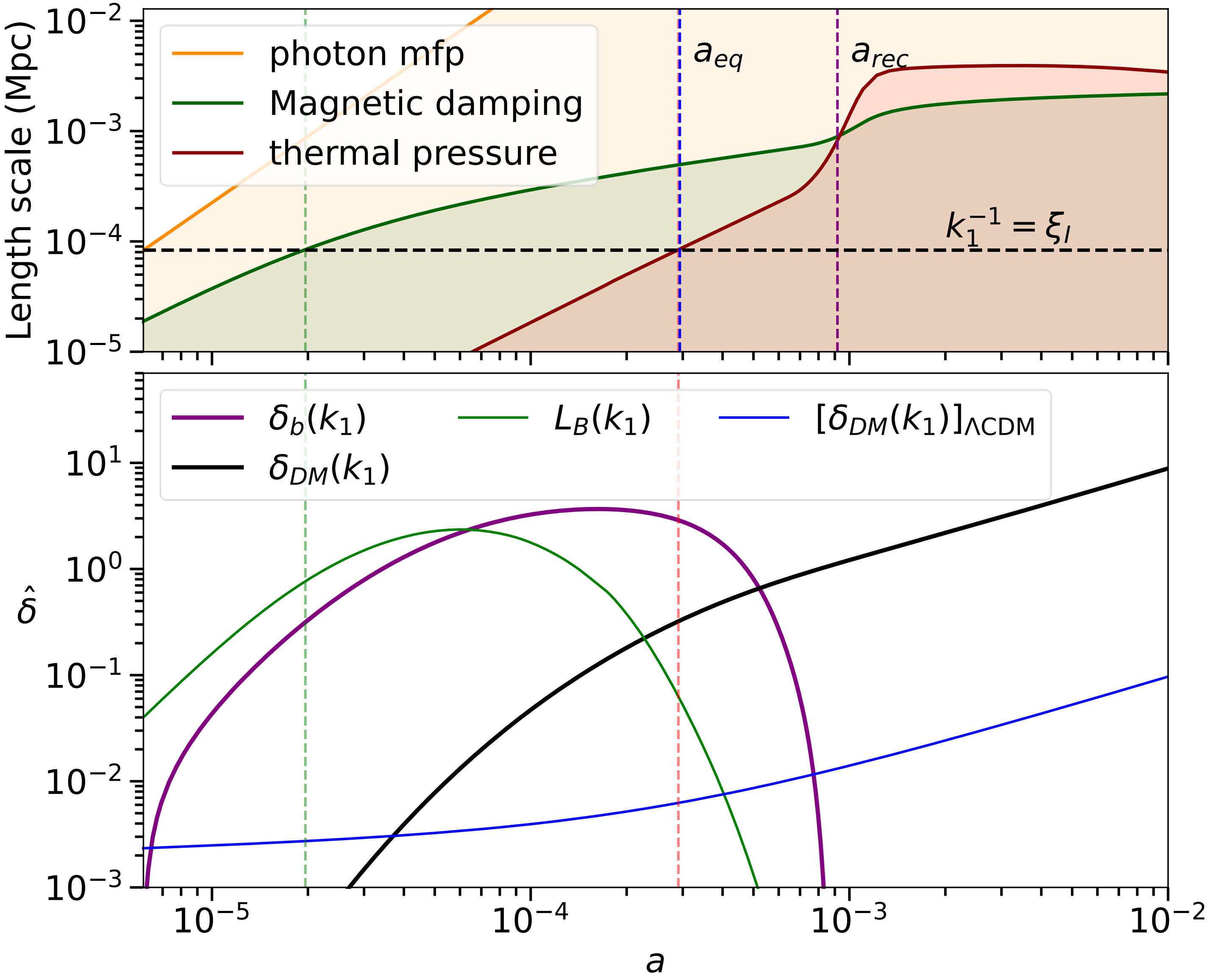
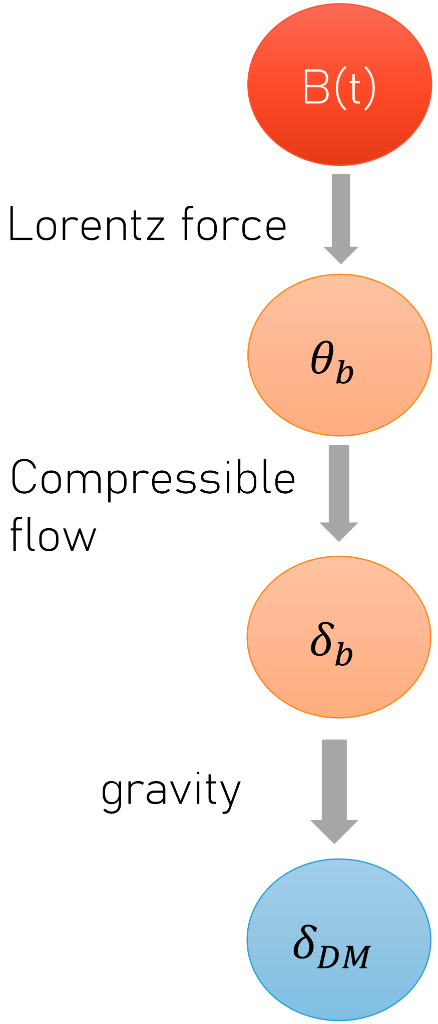
$$k_D^{-1}(a) \sim \tau v_b$$



PERTURBATION EVOLUTION PLOT

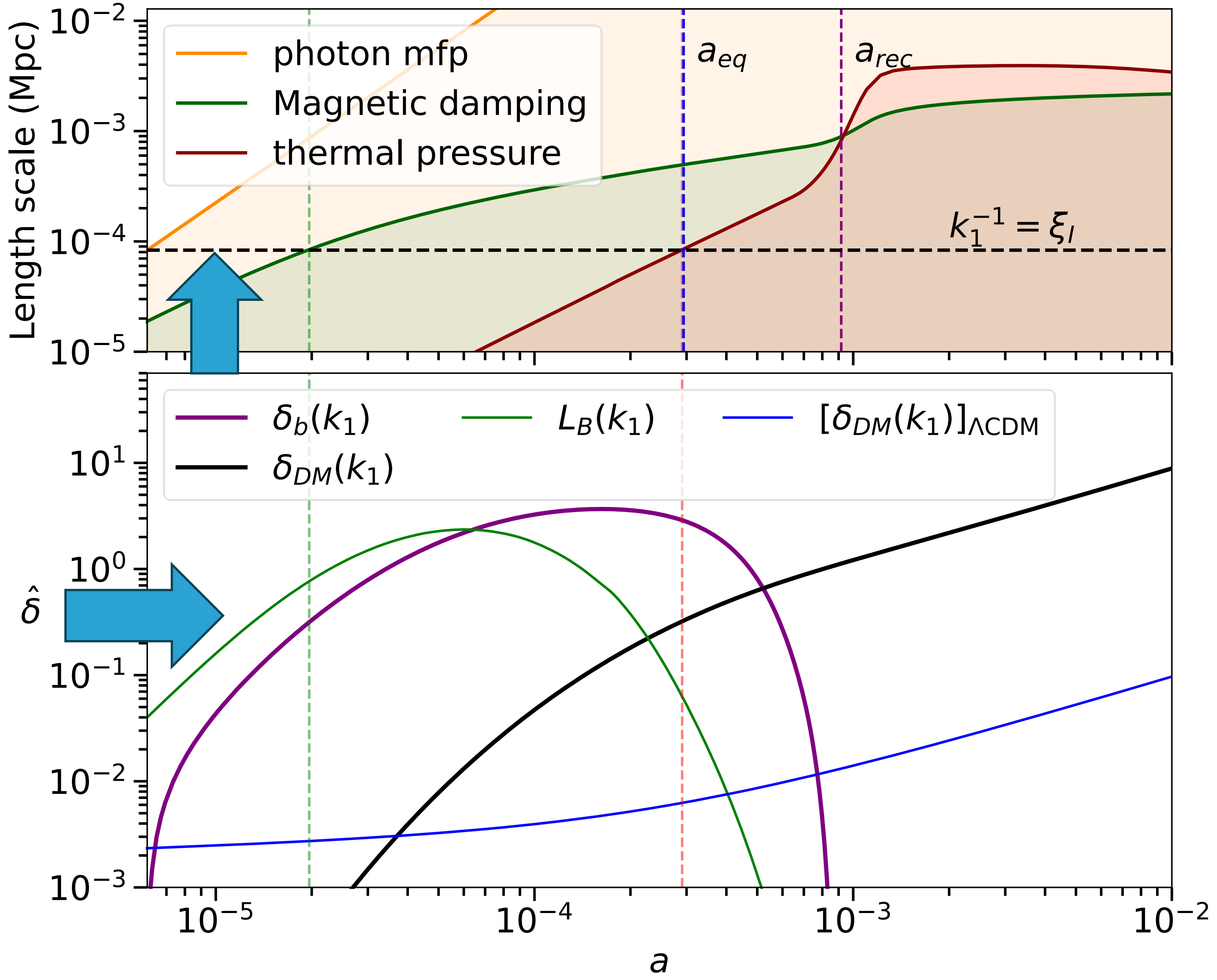
$B_I = 5$ nG

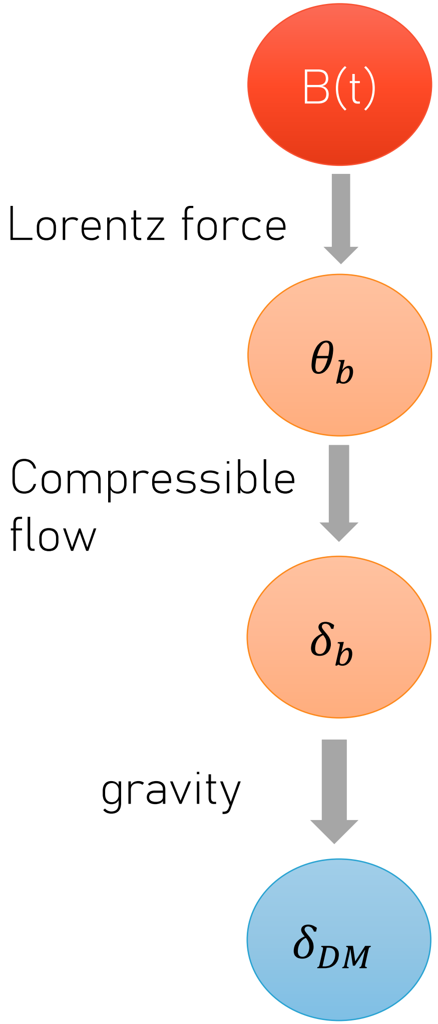




LORENTZ FORCE ENHANCES BARYON PERTURBATIONS FOR MODES OUTSIDE k_D^{-1}

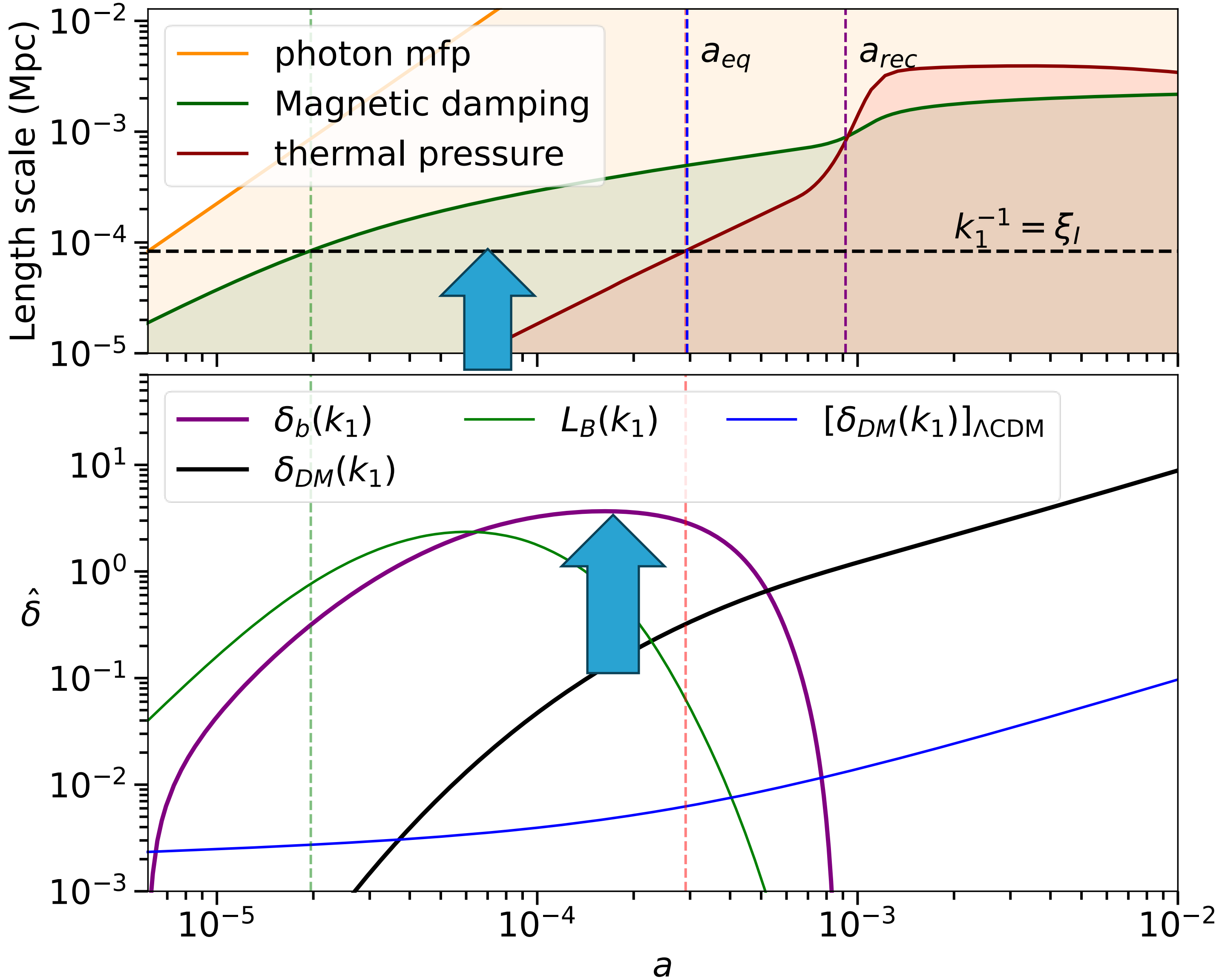
$B_I = 5$ nG

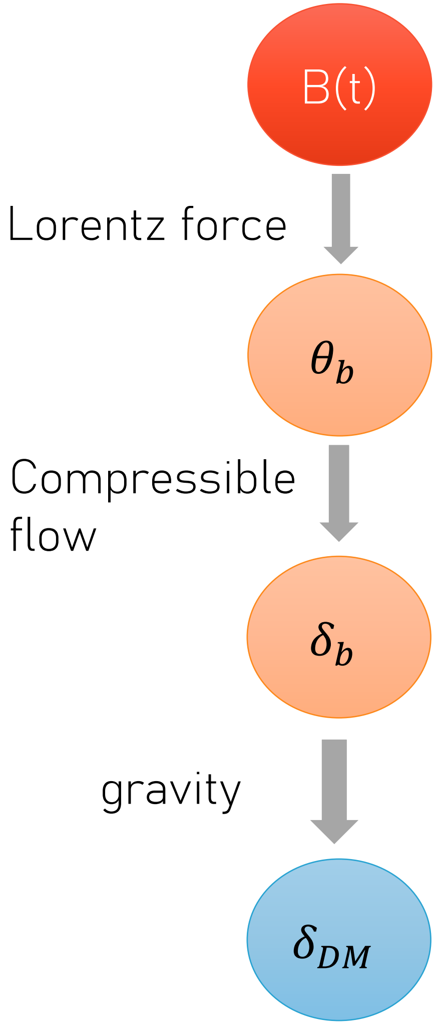




BARYON PERTURBATIONS ASYMPTOTE ONCE MODE ENTERS k_D^{-1}

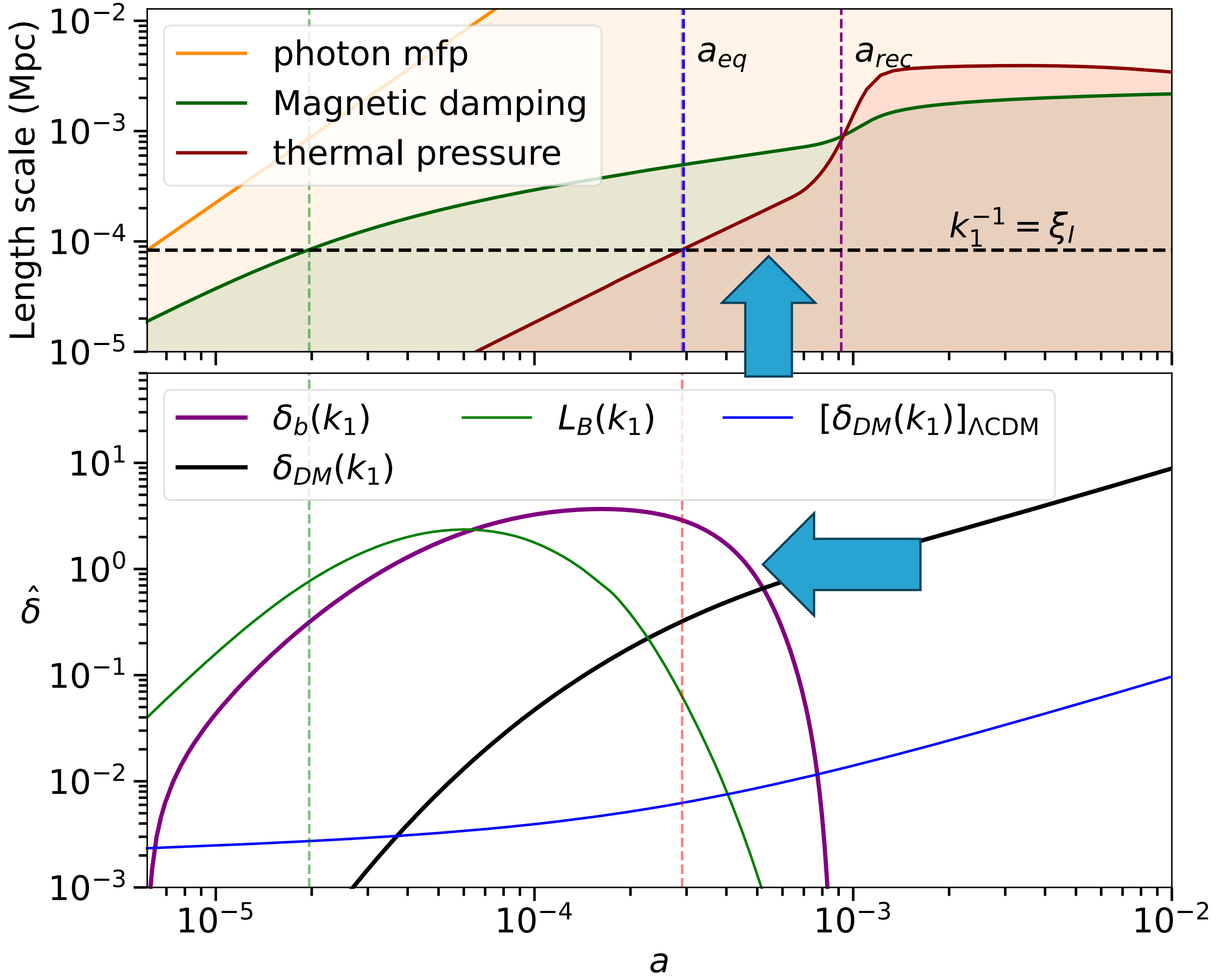
$B_I = 5$ nG

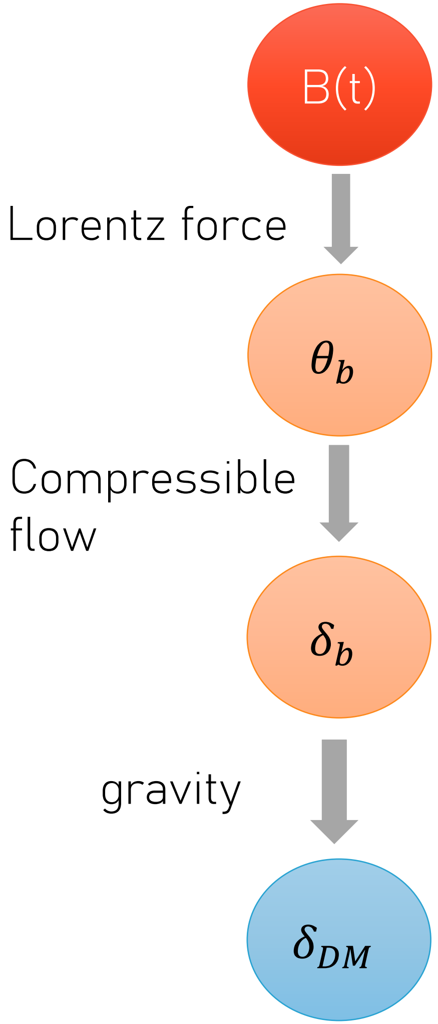




BARYON PERTURBATIONS DAMPED BY THERMAL PRESSURE

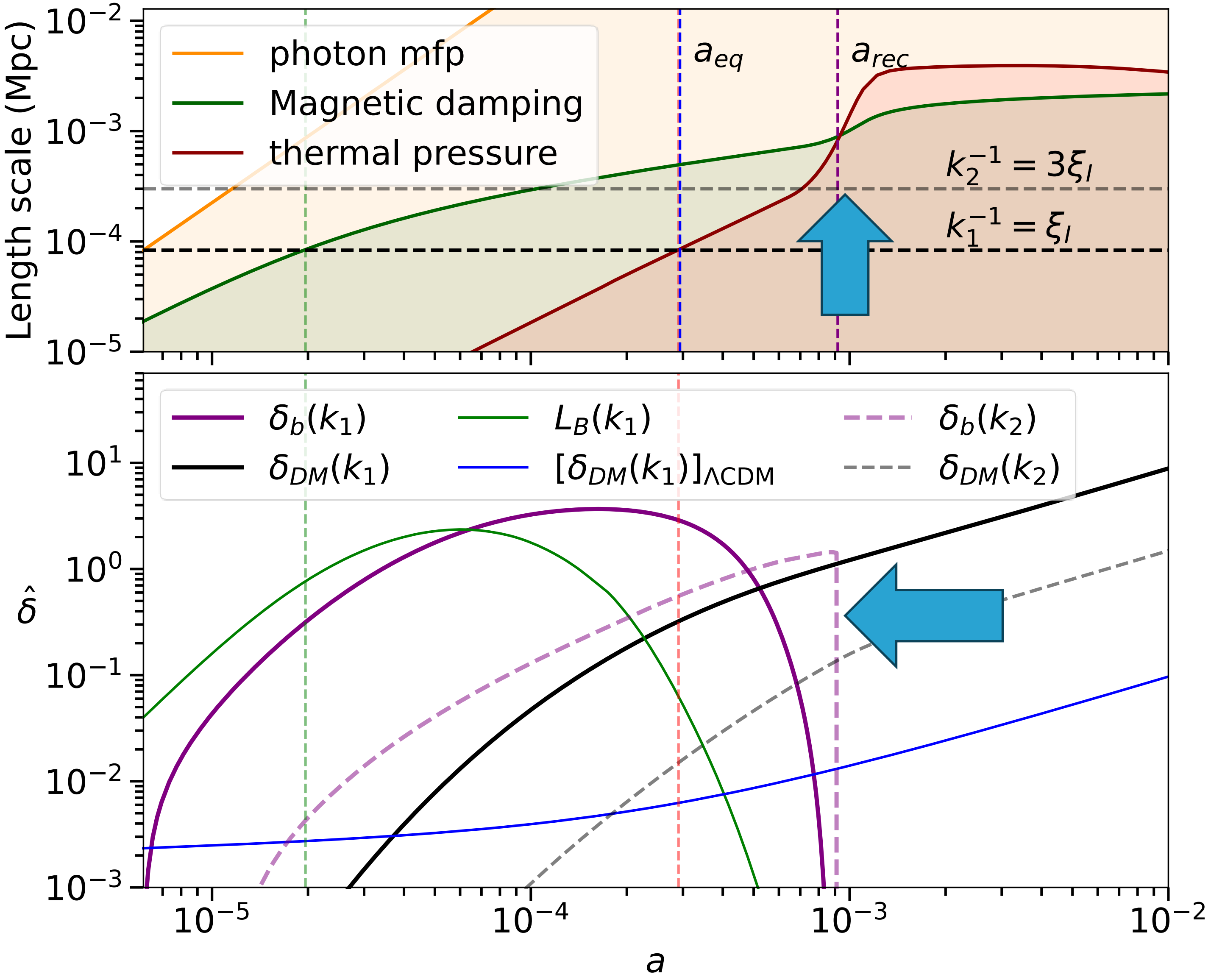
$B_I = 5$ nG

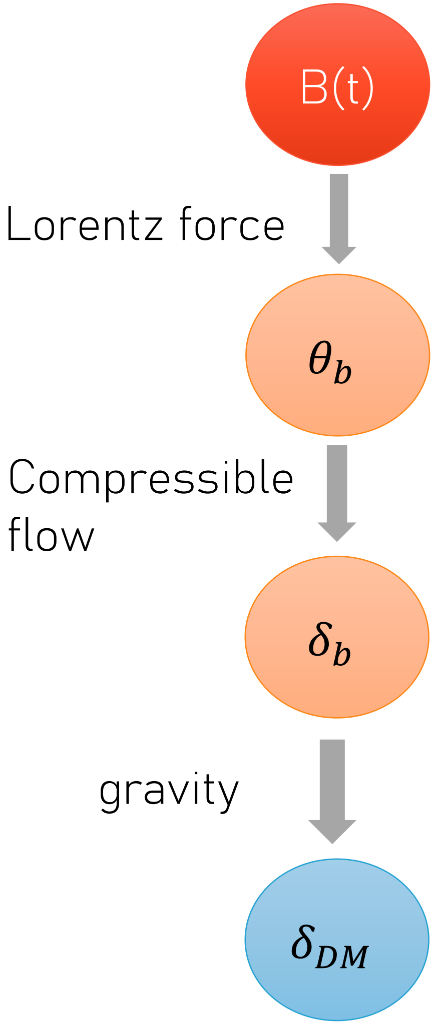




BARYON PERTURBATIONS DAMPED BY TURBULENCE AT RECOMBINATION

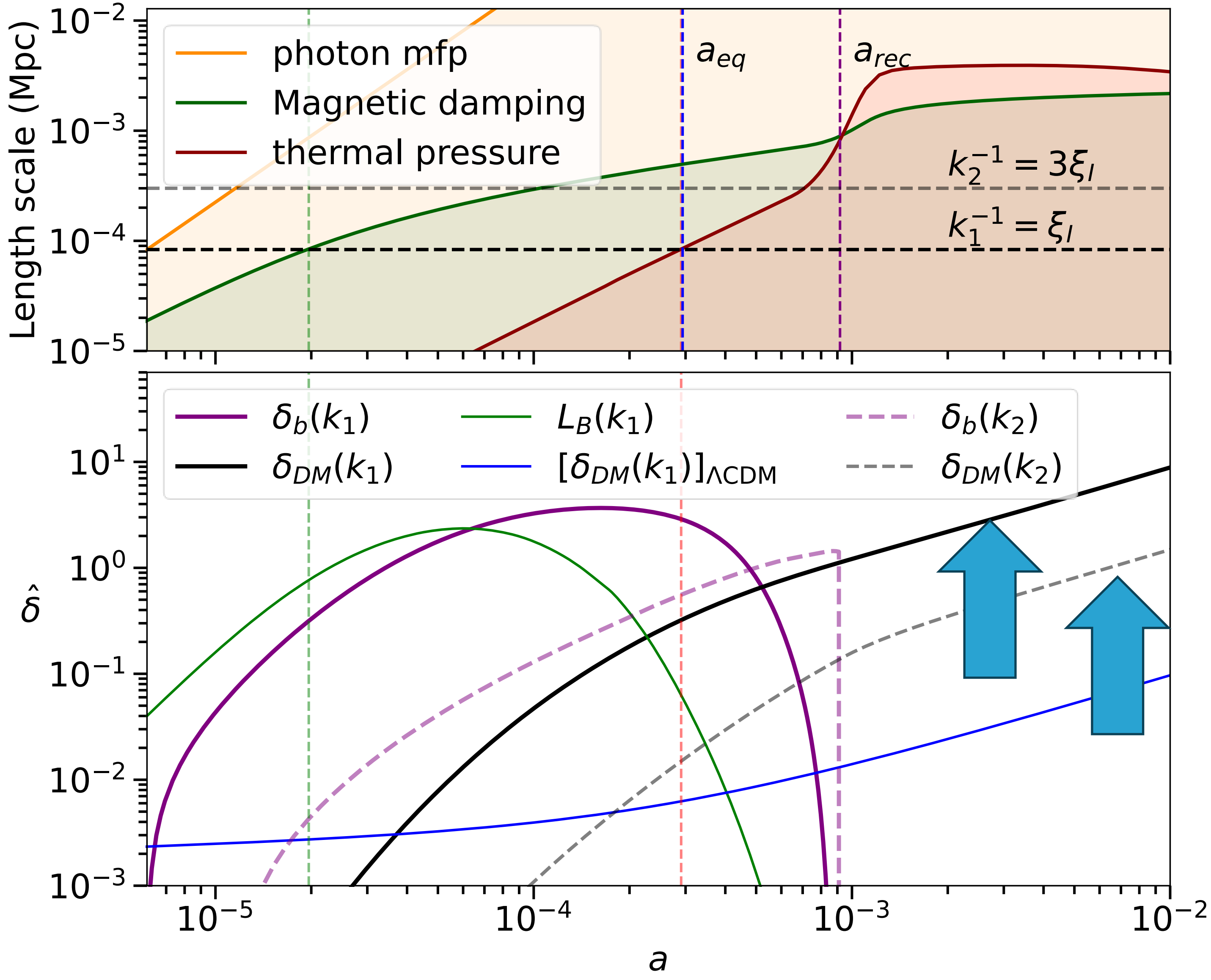
$B_I = 5$ nG

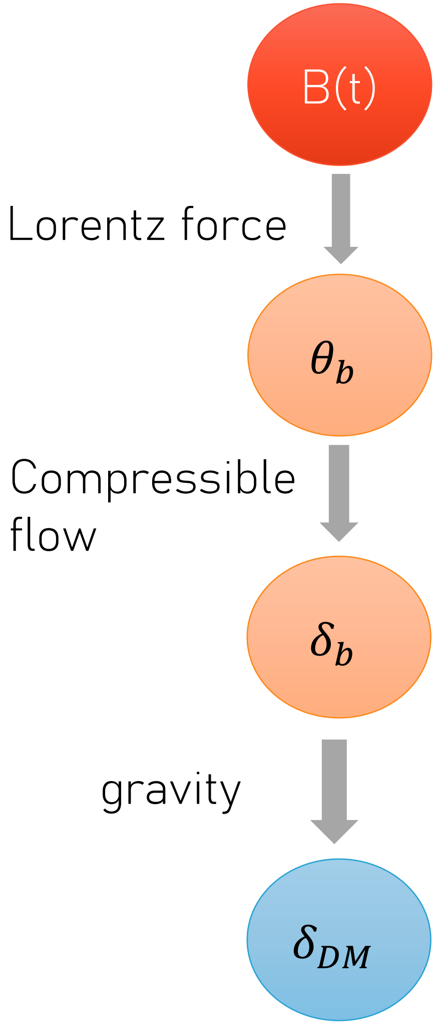




DARK MATTER PERTURBATIONS CONTINUES TO GROW!

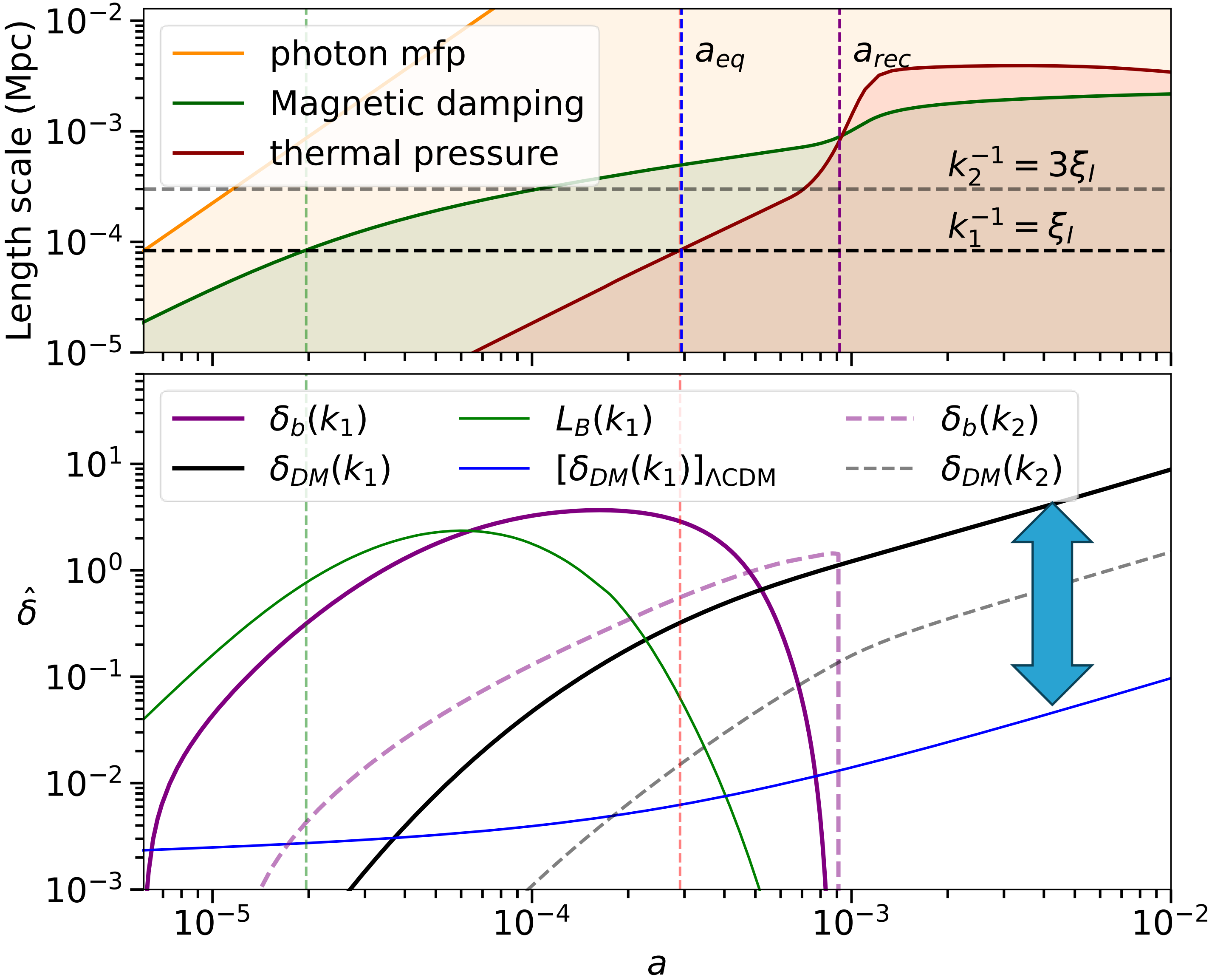
$B_I = 5$ nG

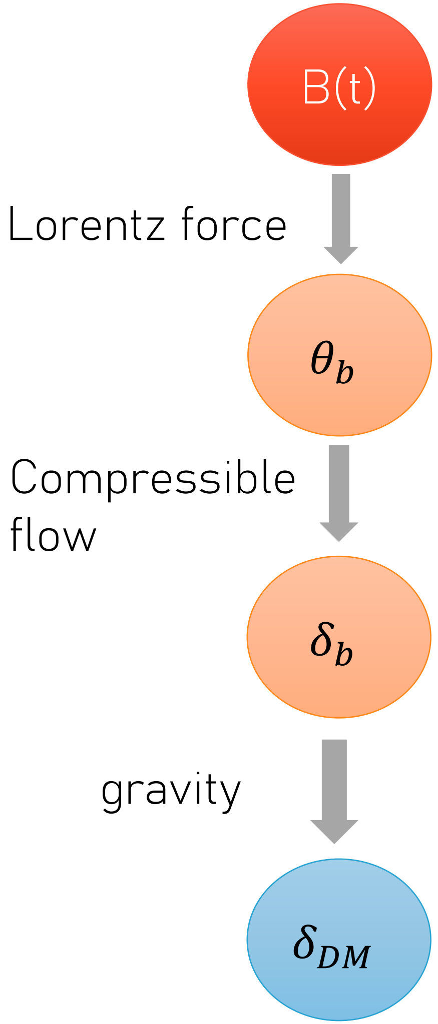




DARK MATTER PERTURBATIONS ENHANCED BY ORDERS OF MAGNITUDE COMPARED TO ΛCDM

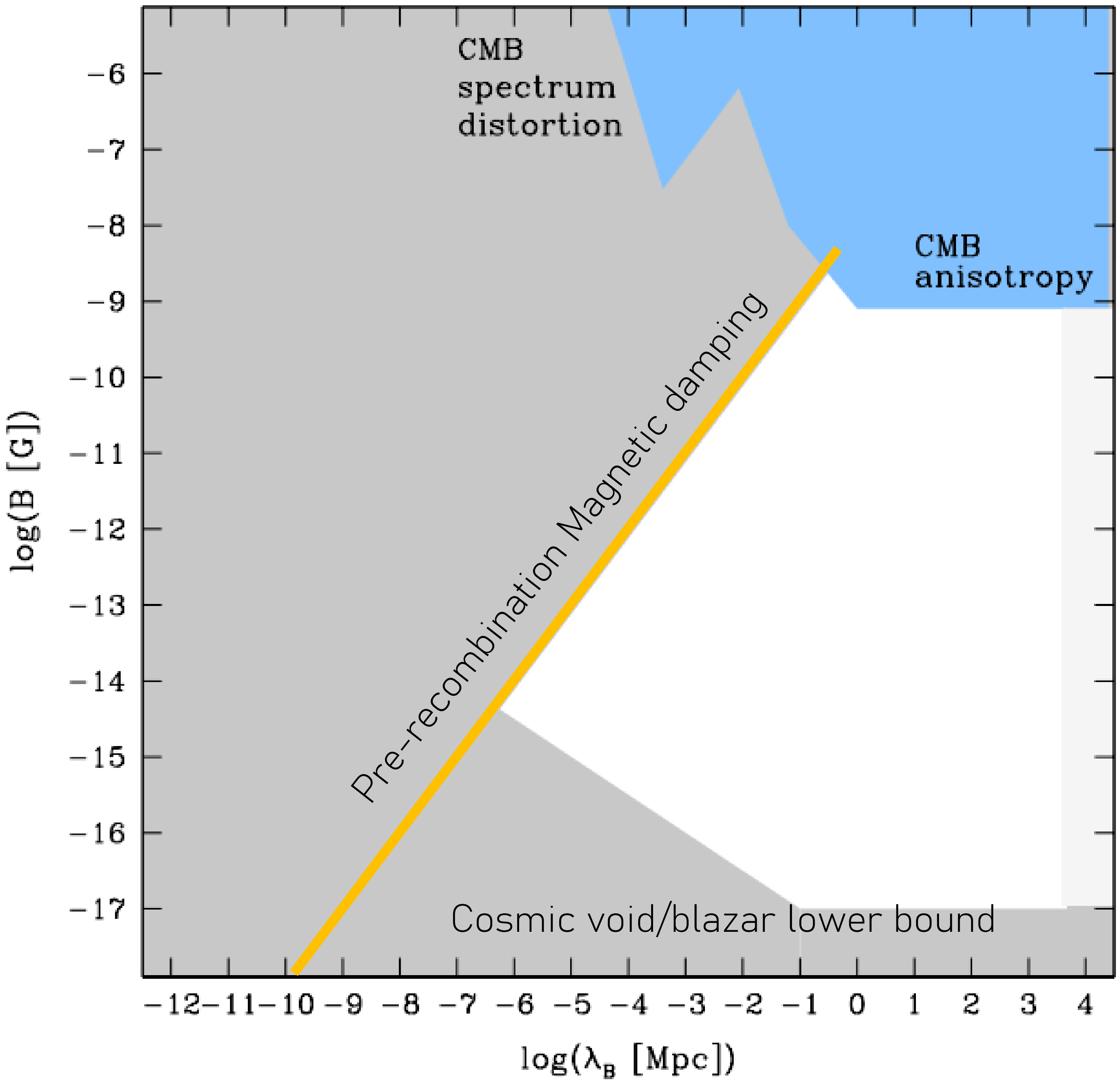
$B_I = 5$ nG



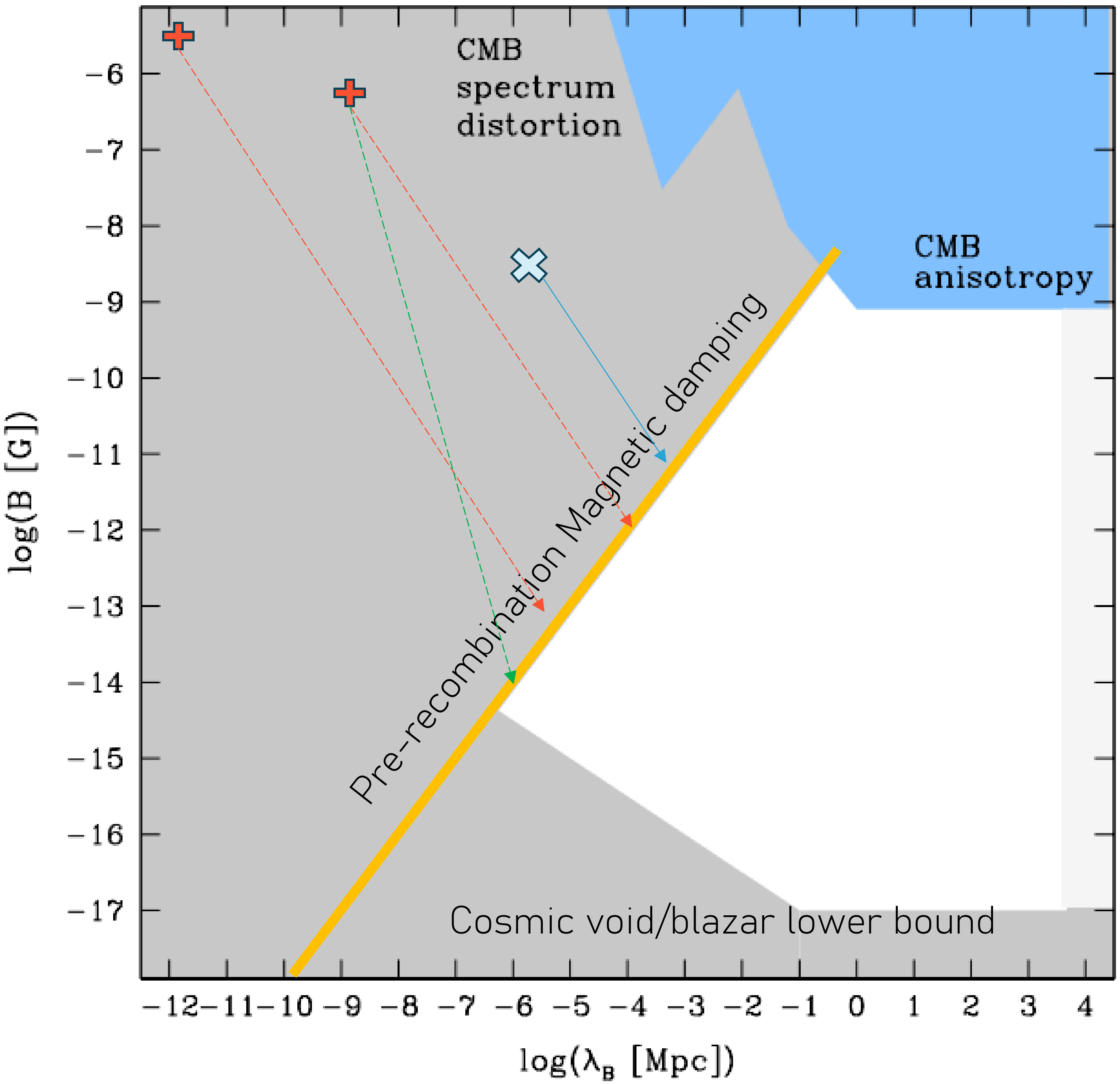


CONSTRAINTS ON PMF

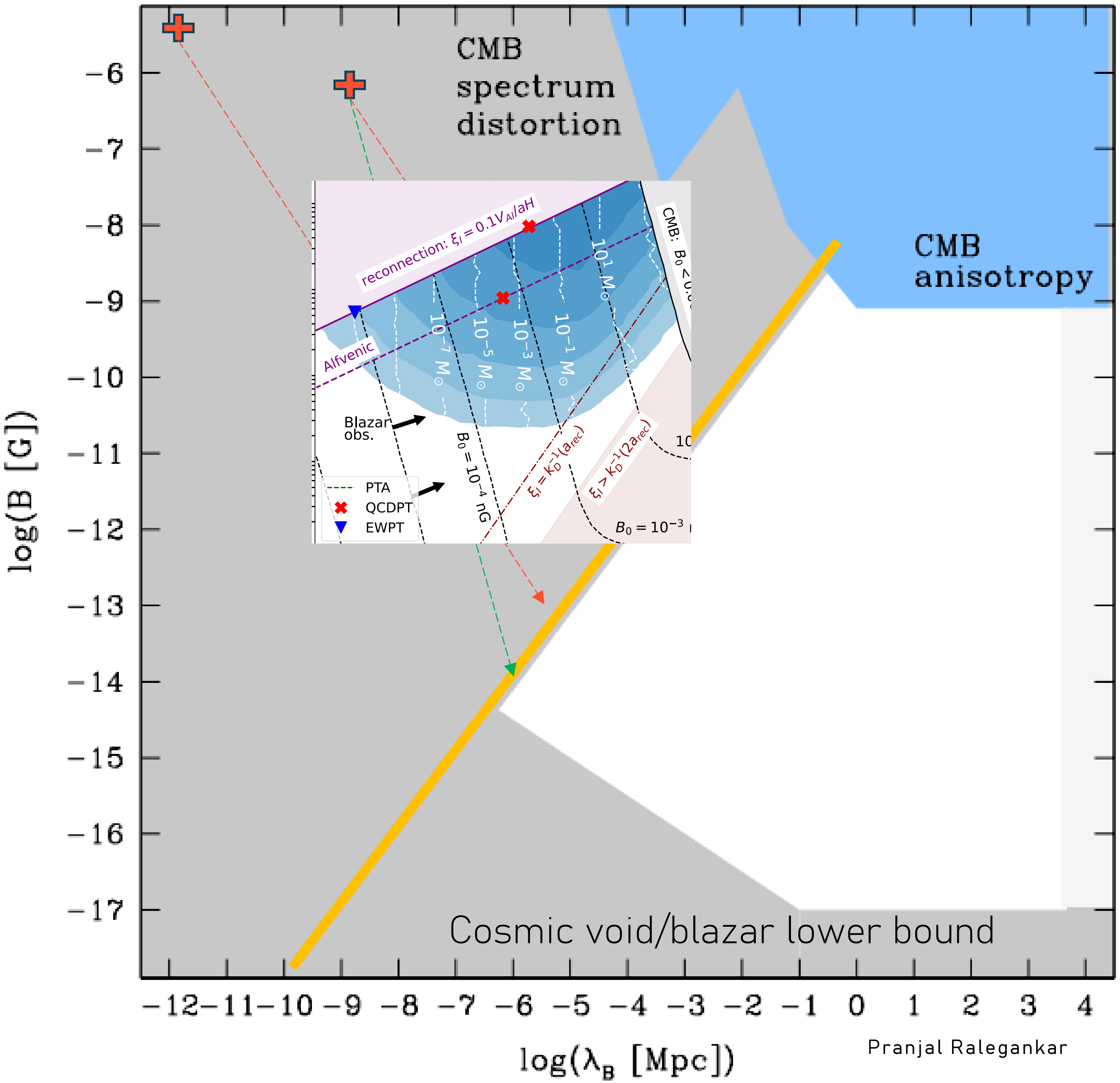
Durrer and Neronov 2013



EVOLUTION OF EARLY UNIVERSE PMFS

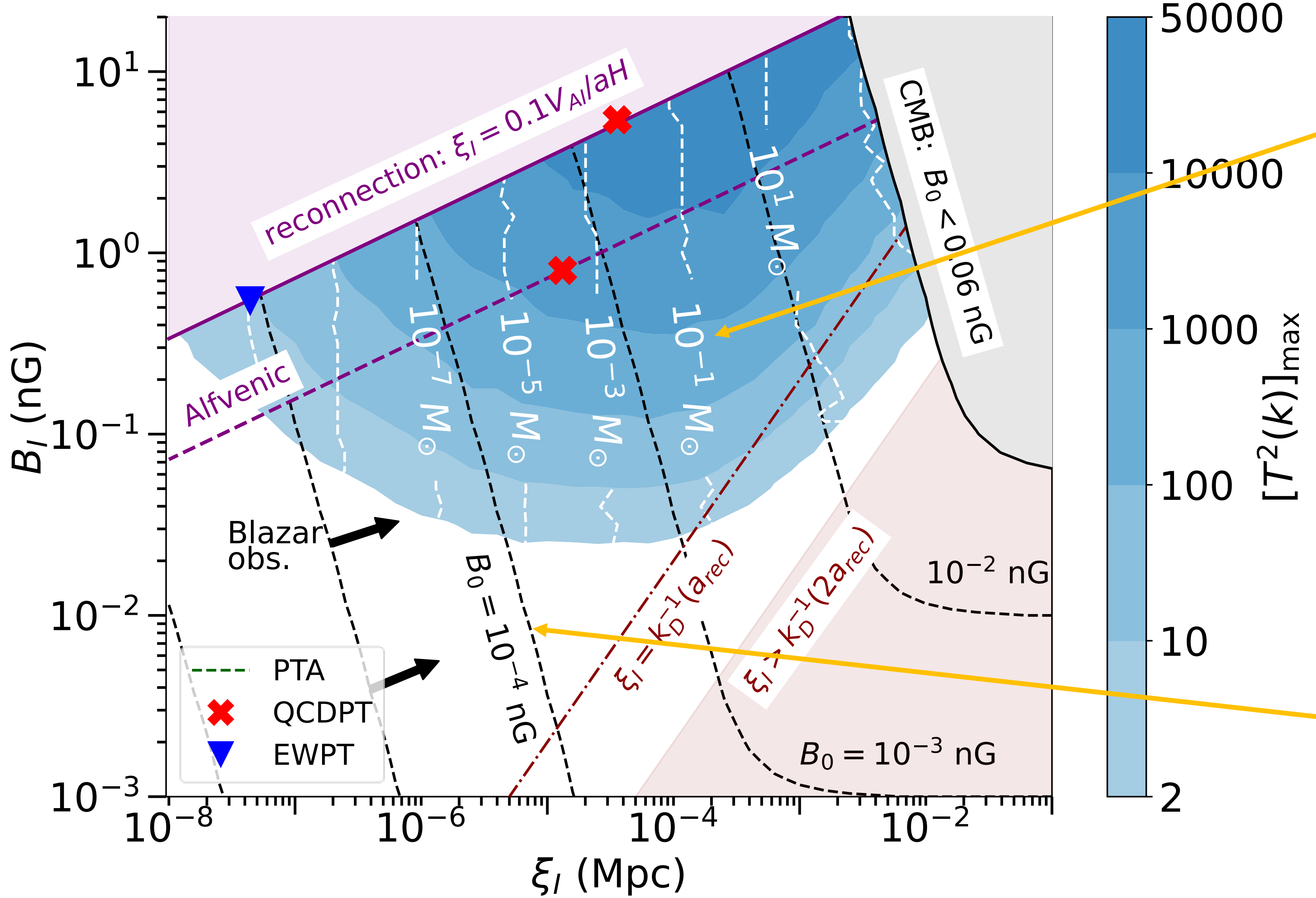


RELEVANCE OF DARK MATTER MINIHALO GENERATION



PARAMETER SPACE WITH ENHANCED POWER ON SMALL SCALES

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



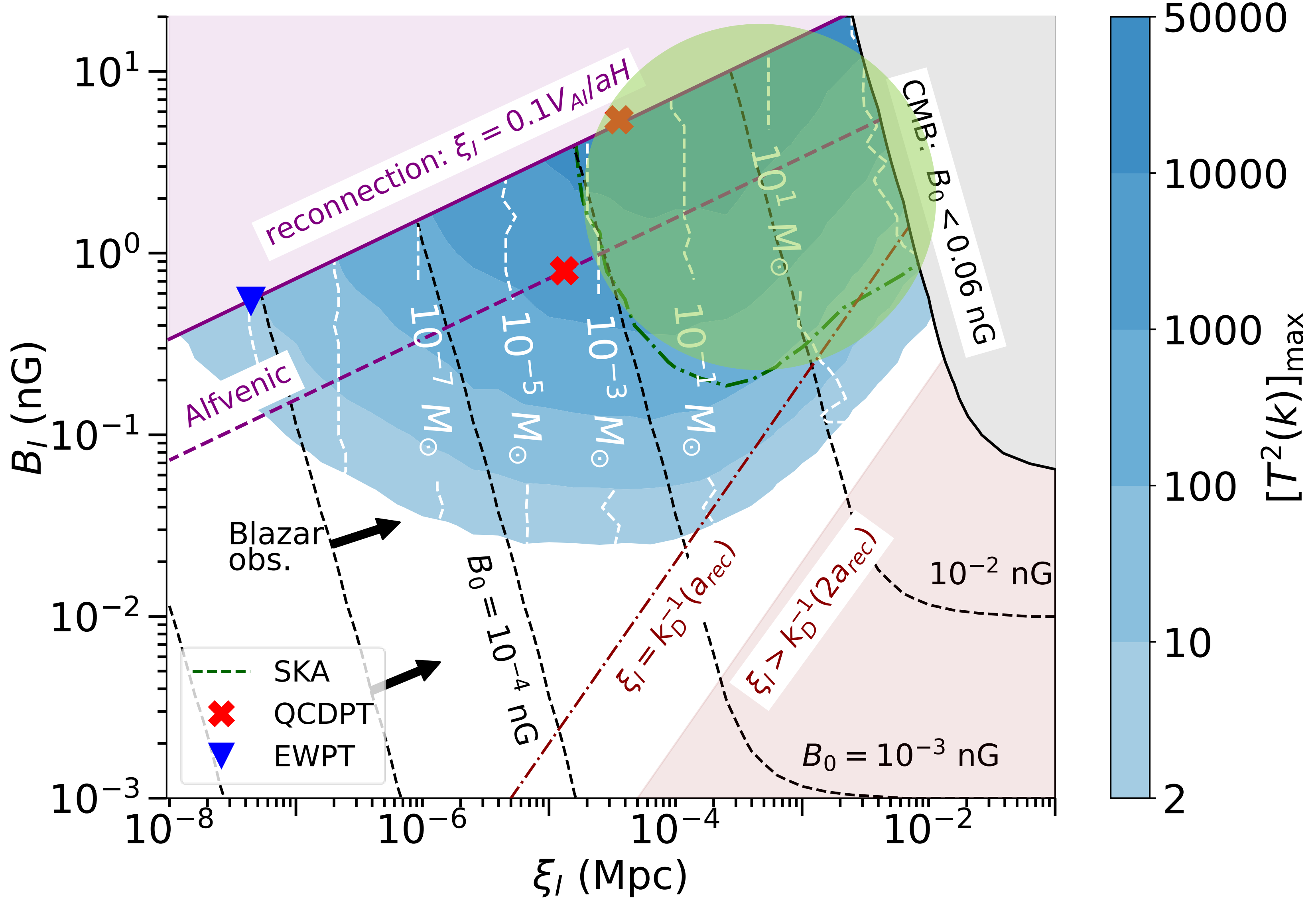
$$= \frac{P(k)}{P_{\Lambda CDM}(k)}$$

DM minihalo mass

Present-day magnetic field strength

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

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



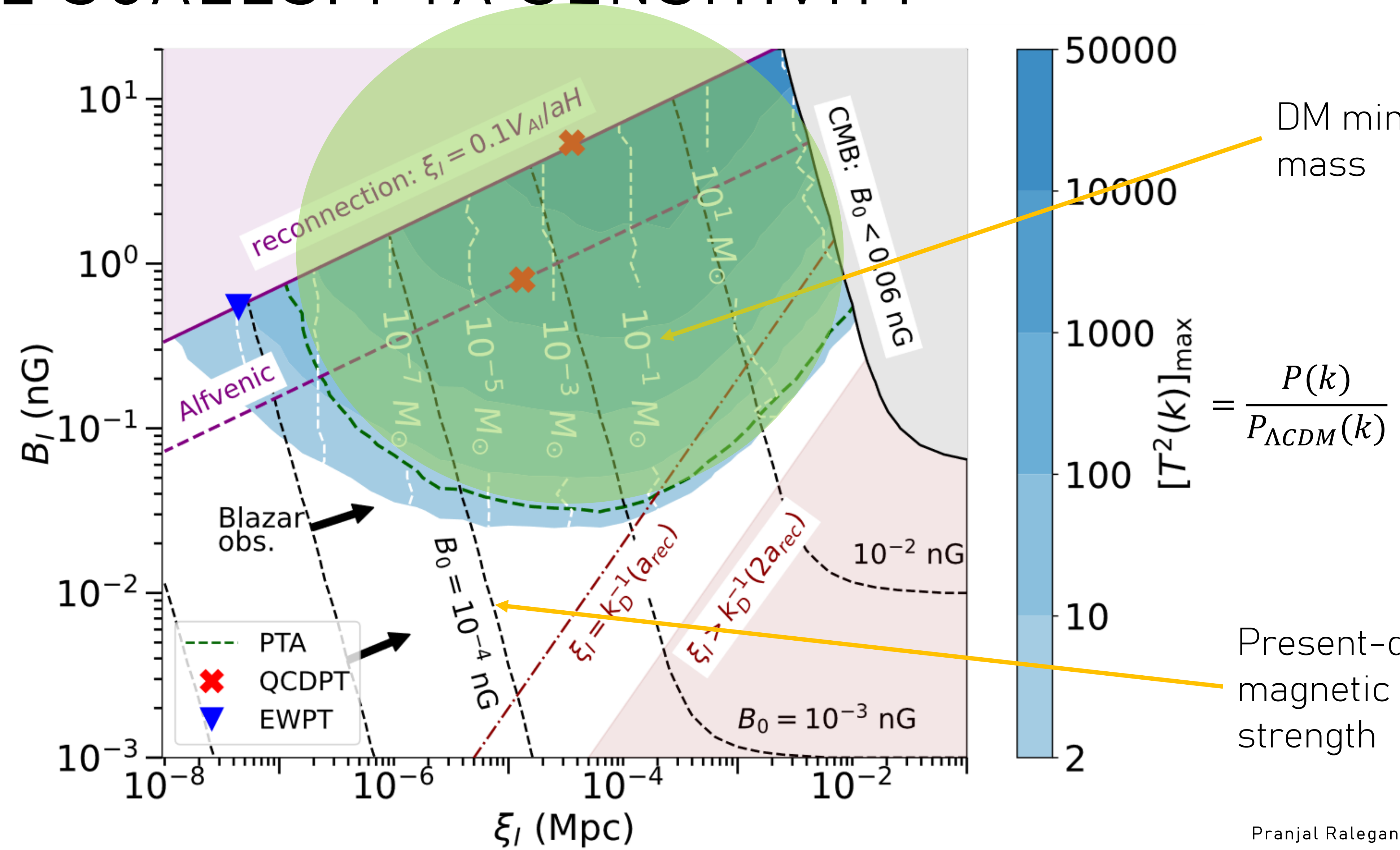
DM minihalo mass

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

Present-day magnetic field strength

PARAMETER SPACE WITH ENHANCED POWER ON SMALL SCALES: PTA SENSITIVITY

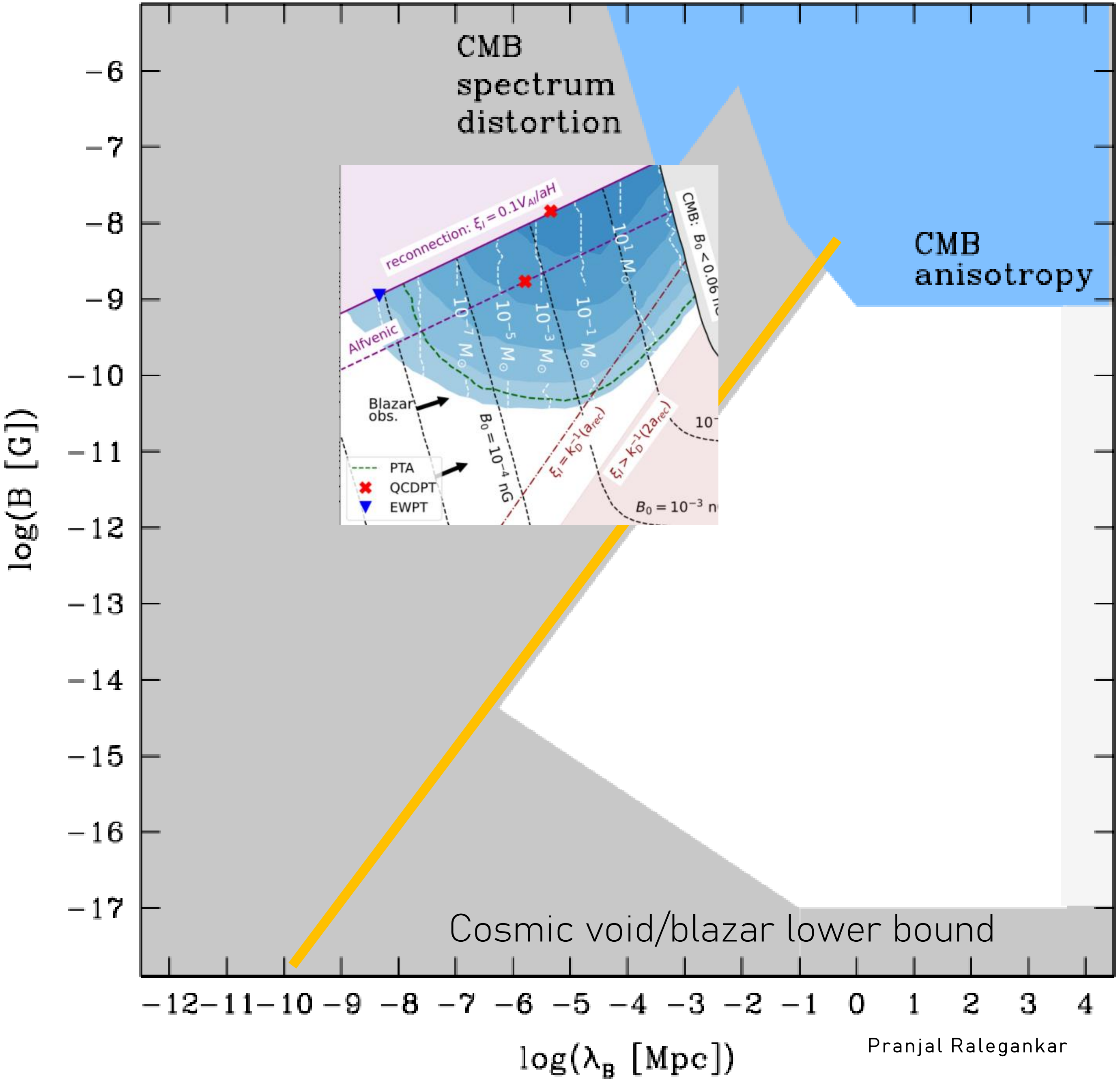
Subscript I refers to the time at the beginning of laminar flow regime



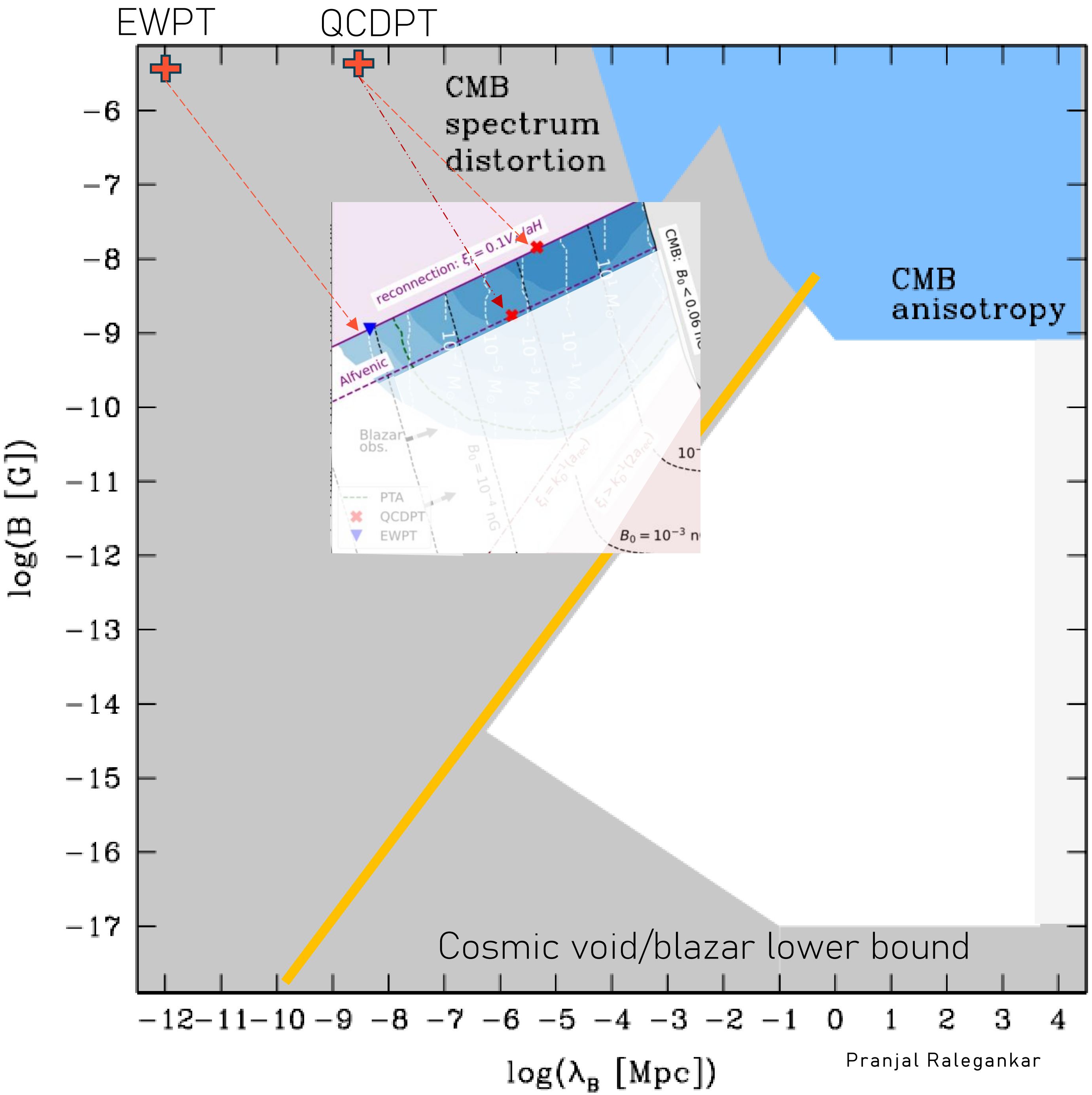
DM minihalo mass

Present-day magnetic field strength

MINIHALOS FROM CAUSALLY GENERATED PMFS

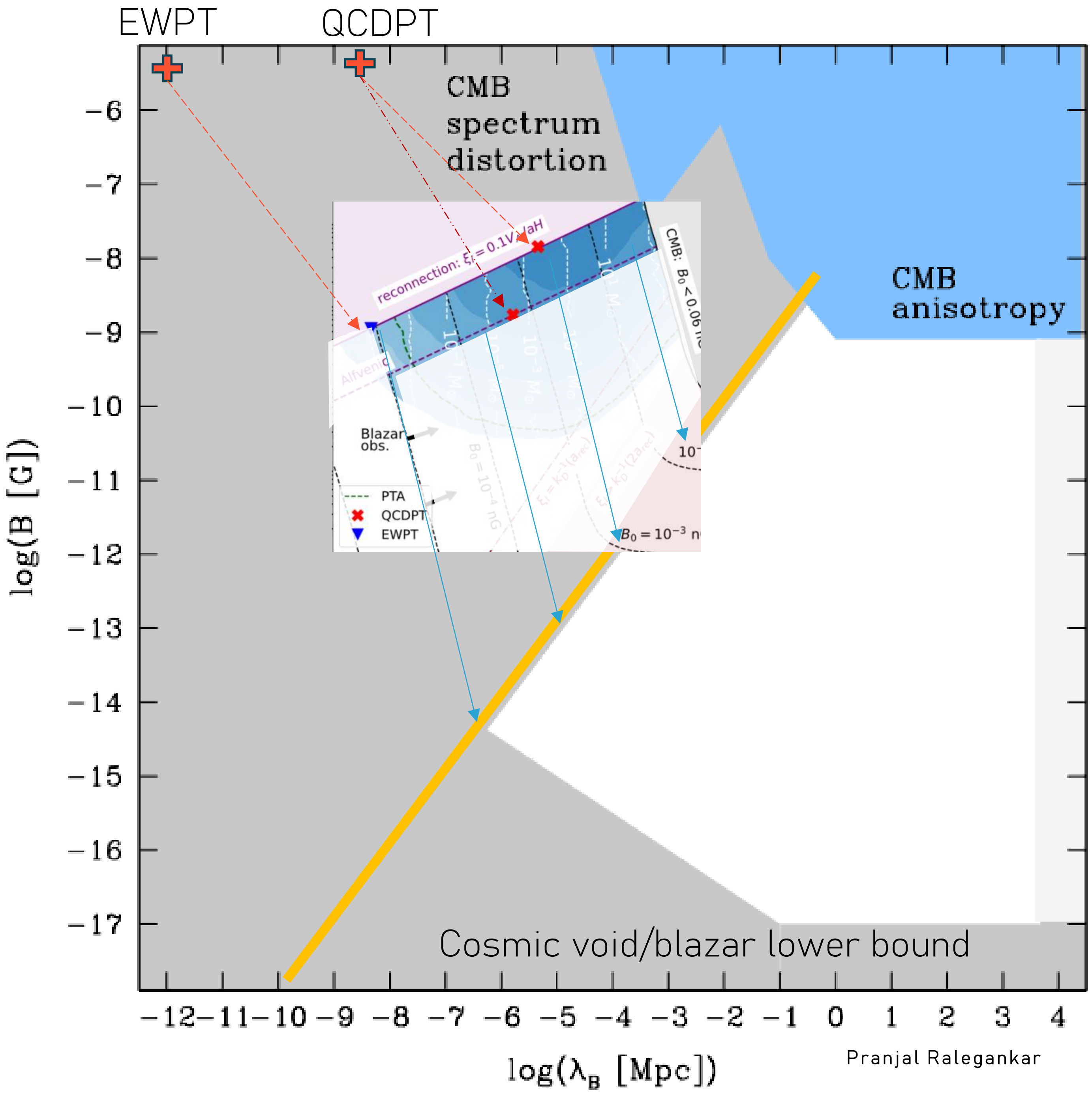


MINIHALOS FROM CAUSALLY GENERATED PMFS



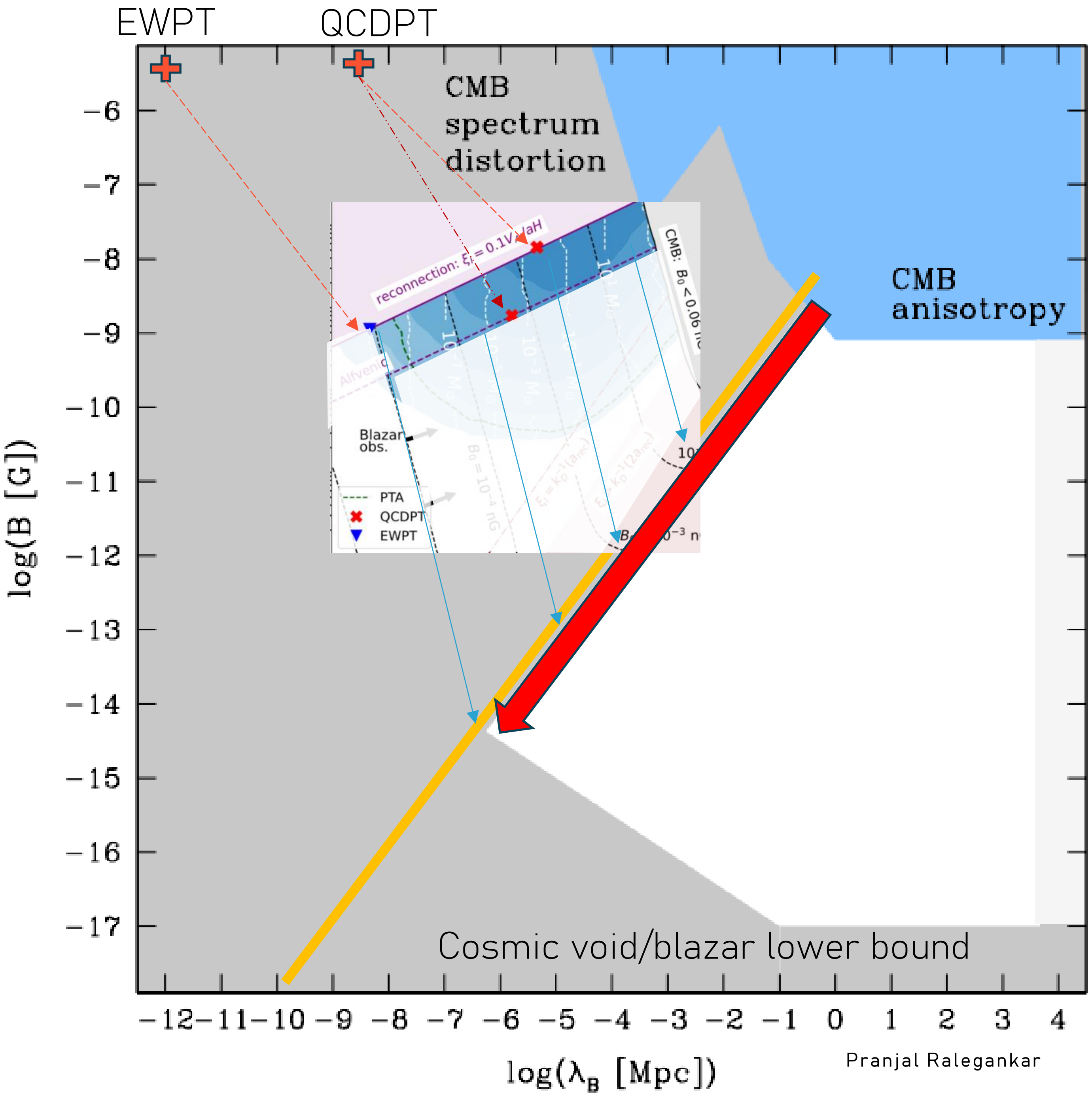
PMFS TO EXPLAIN COSMIC VOID OBSERVATIONS

Assuming Batchelor spectrum!



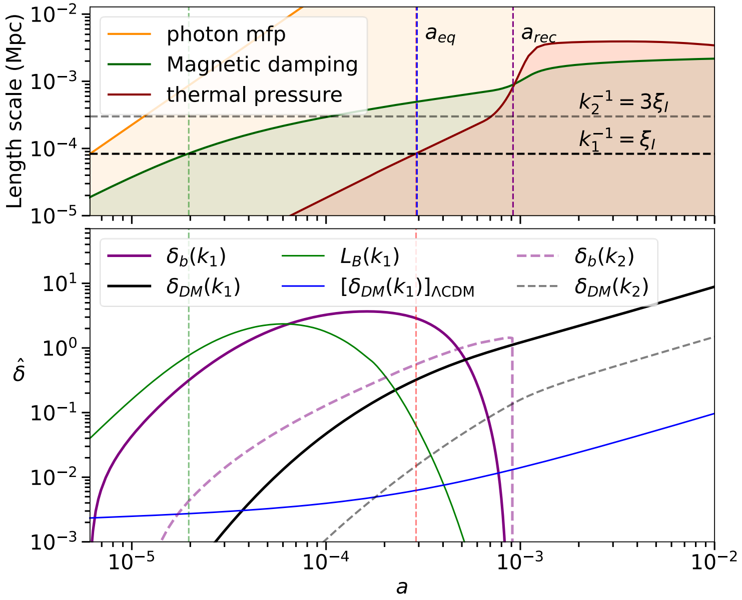
UNIVERSE MAYBE FILLED WITH DARK MATTER MINIHALOS!!

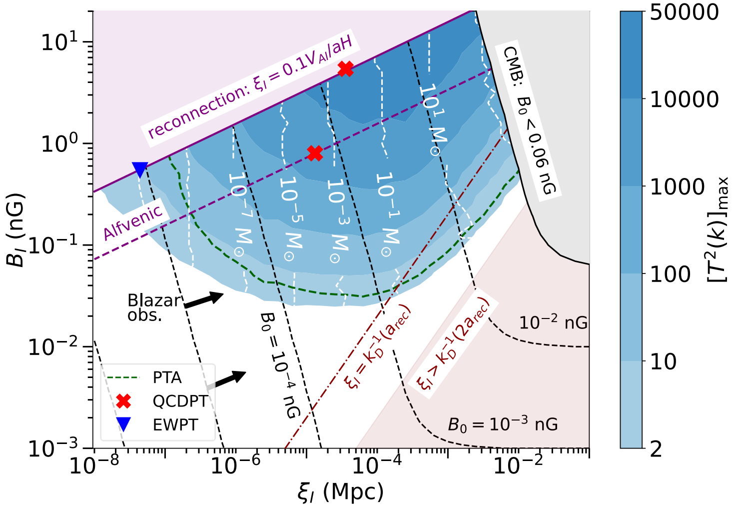
Assuming Batchelor spectrum!



SUMMARY AND CONCLUDING REMARKS

- Magnetic fields can enhance power dark matter power spectrum below magnetic Jeans scale.
- PTA/GAIA detection of DM minihalos can provide best probe of primordial magnetic fields
- Results are qualitative: Need MHD simulations to get accurate quantitative answers.
- Ironic: how invisible dark matter can help look for visible entity: magnetic fields



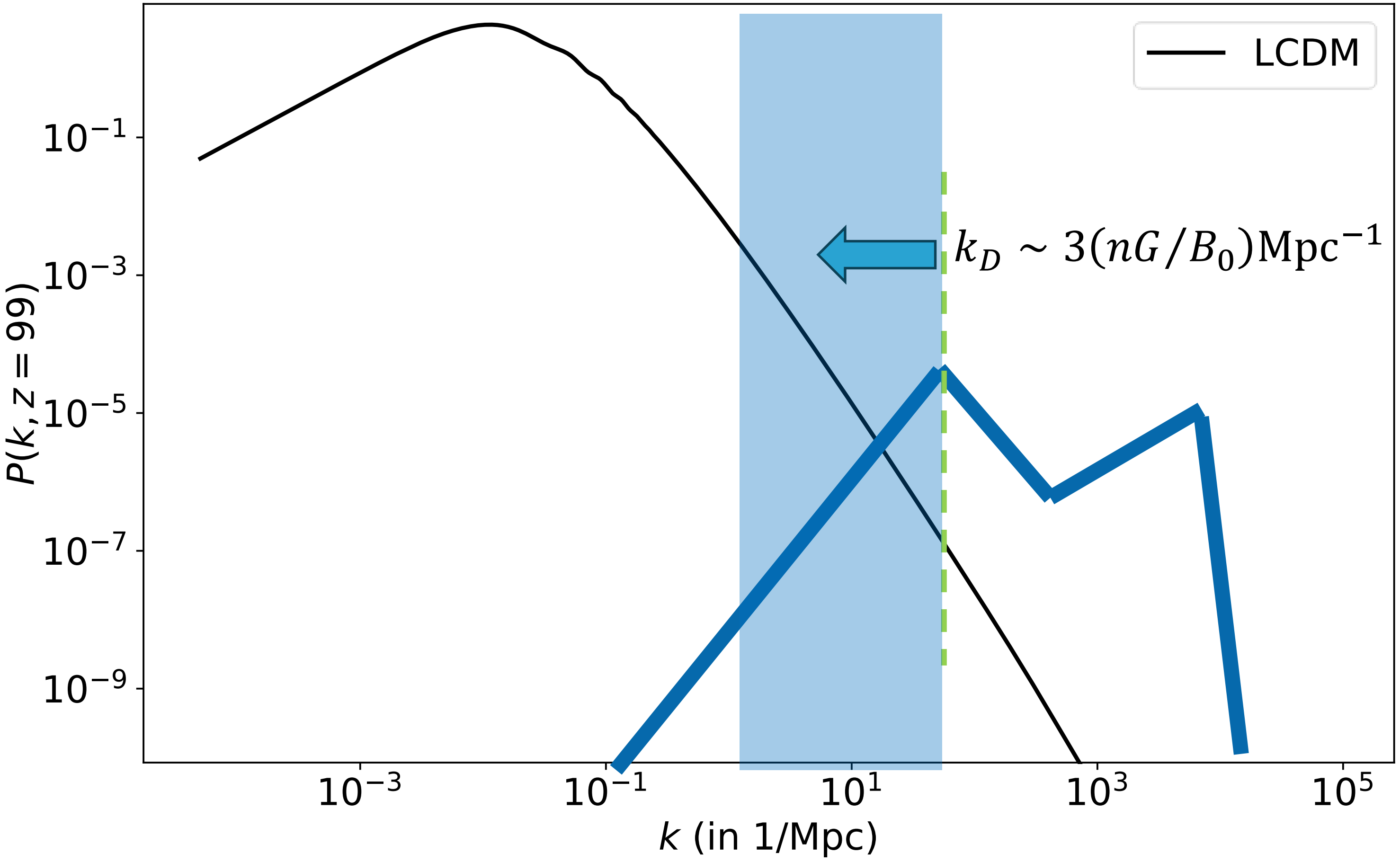


PART 2

Baryon fraction enhanced on Large scales

Arxiv: 2402.14079

PART 2: LARGE SCALES RELEVANT FOR JWST



POST-RECOMBINATION IDEAL MHD

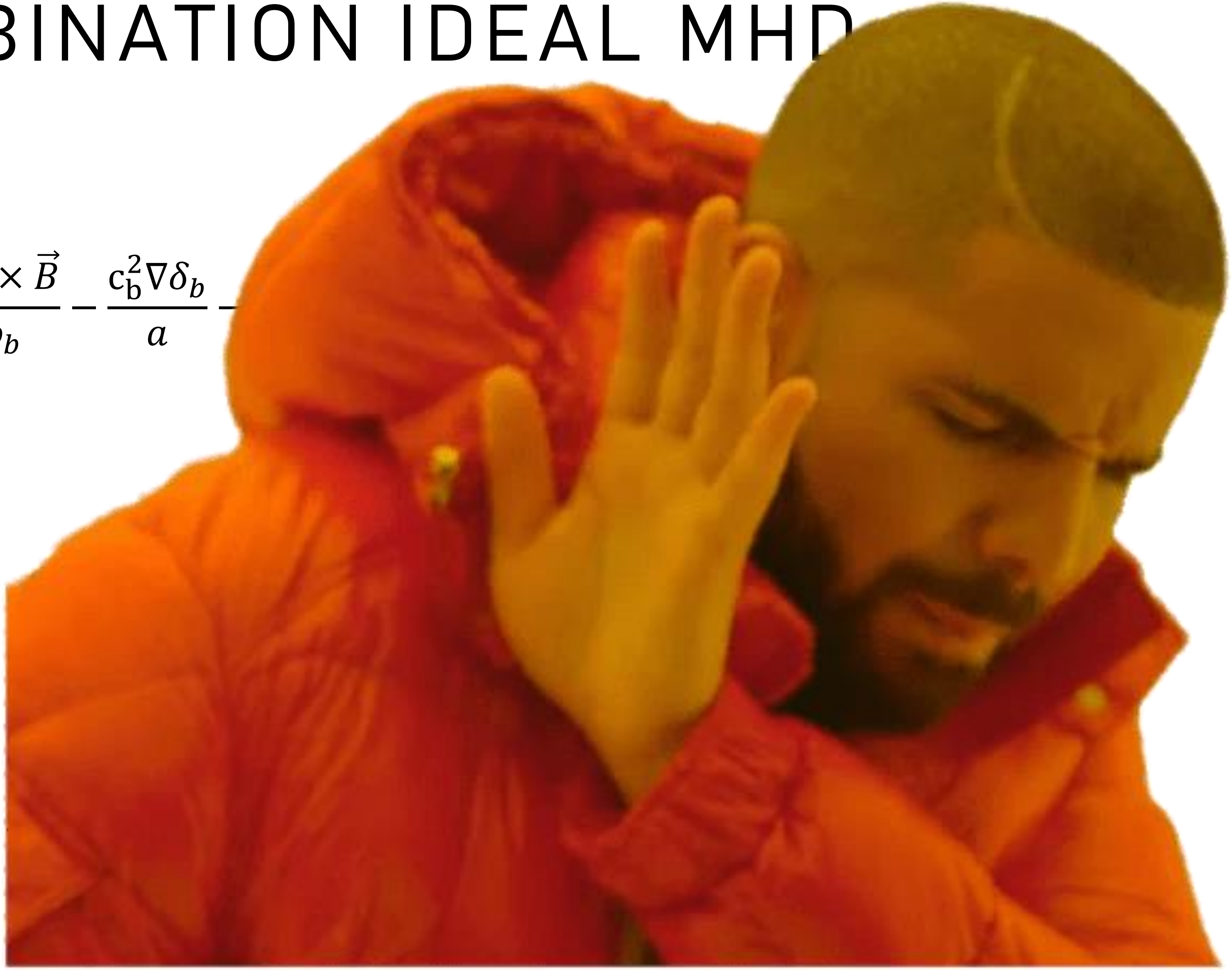
$$\frac{\partial\,(\vec{B})}{\partial t} = \frac{\nabla \times (\vec{v}_b \times \vec{B})}{a}$$

$$\frac{\partial \vec{v}_b}{\partial t} + H\vec{v}_b + \frac{(\vec{v}_b.\nabla)\vec{v}_b}{a} = \frac{\left(\nabla \times \vec{B}\right) \times \vec{B}}{4\pi a^5 \rho_b} - \frac{\mathrm{c}_\mathrm{b}^2 \nabla \delta_b}{a} -$$

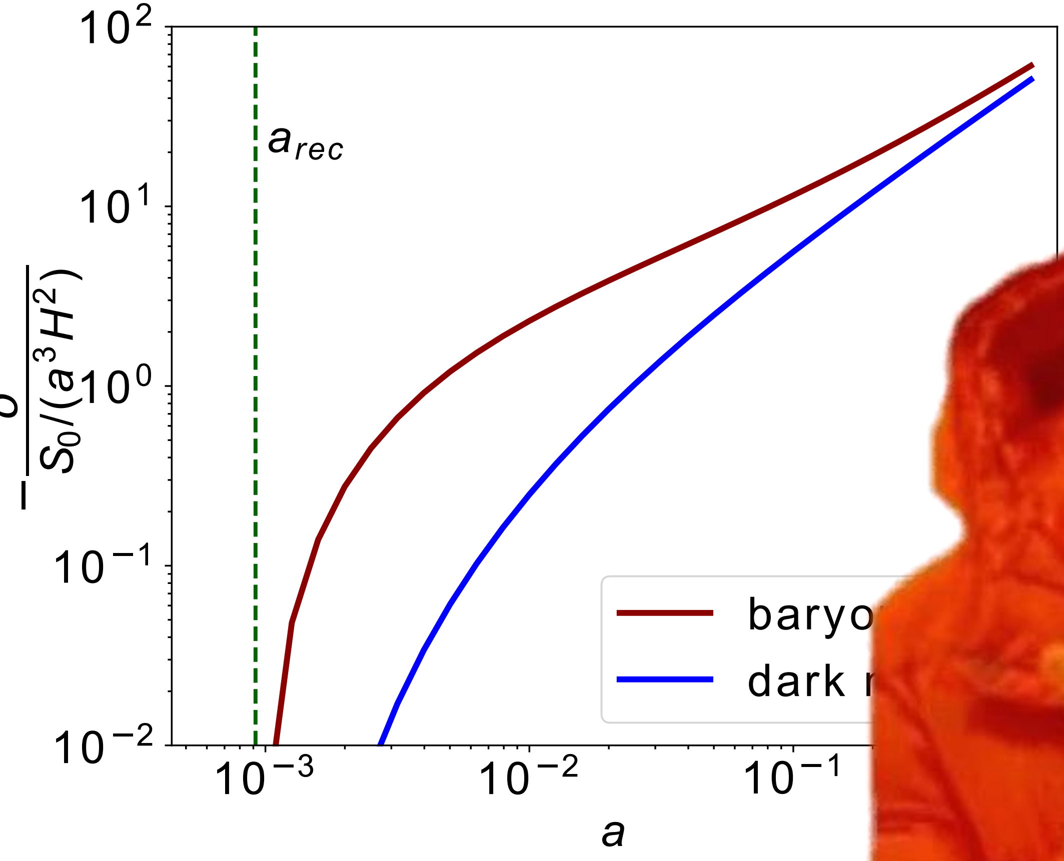
$$\frac{\partial \delta_b}{\partial t} = -\frac{\nabla.\vec{v}_b}{a} - \frac{\nabla.(\delta_b \vec{v}_b)}{a}$$

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

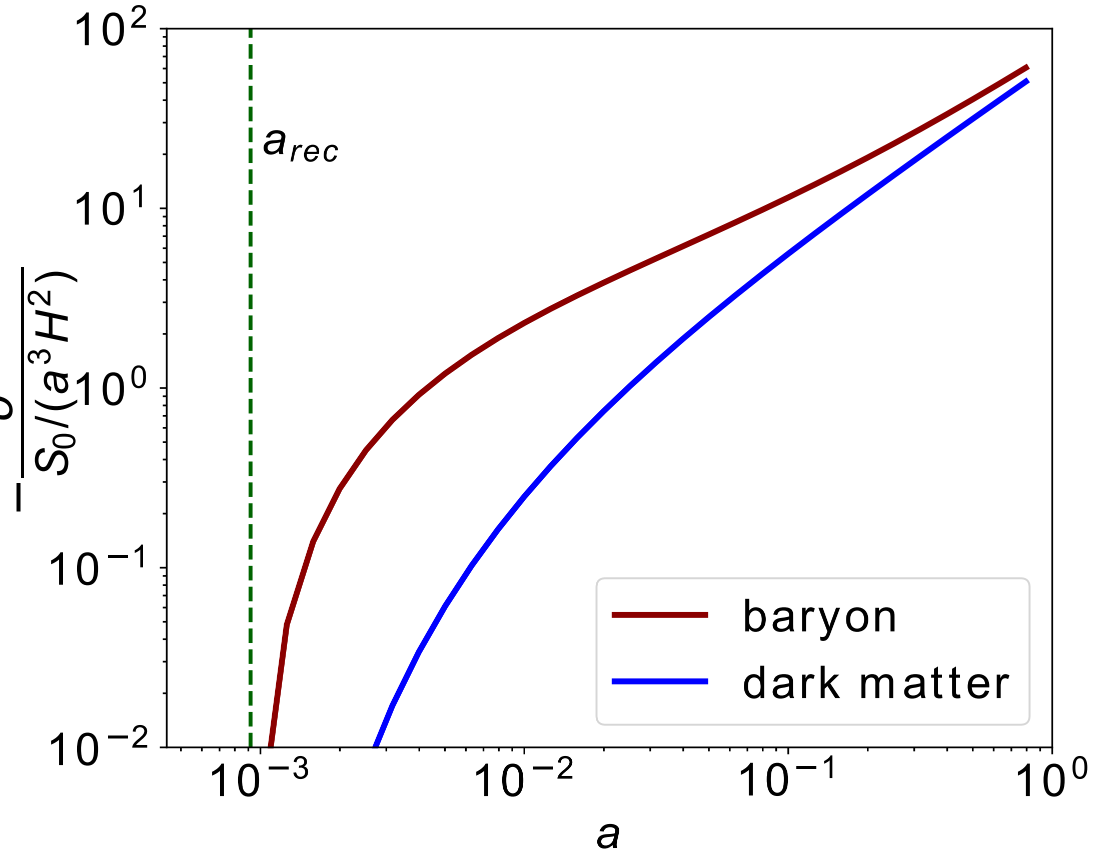
$$\frac{\partial^2 \delta_{DM}}{\partial a^2} + \left[\frac{\partial \ln(a^2 H)}{\partial \ln a} + 1\right]\frac{\partial \delta_{DM}}{a \partial a} =$$



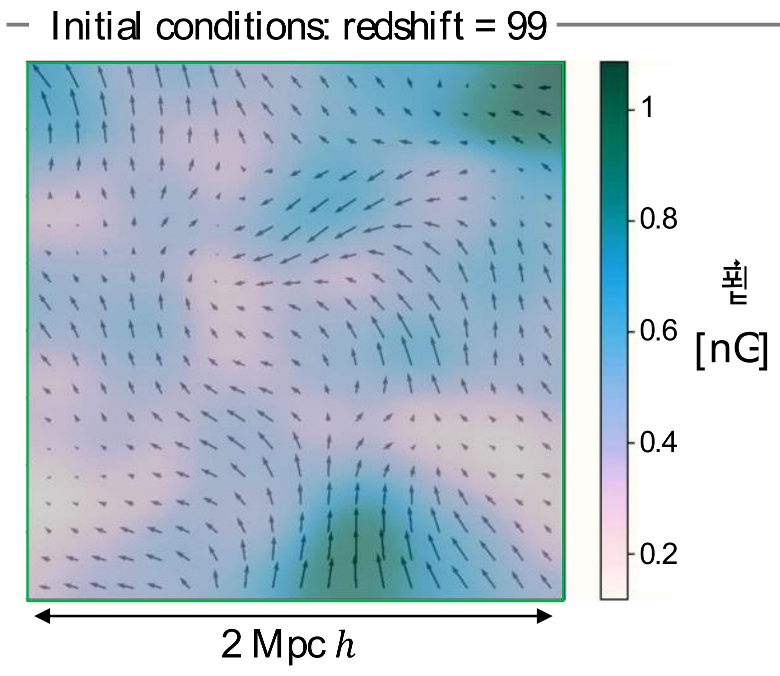
POST RECOMBINATION: BARYON PERTURBATIONS MORE ENHANCED THAN DARK MATTER

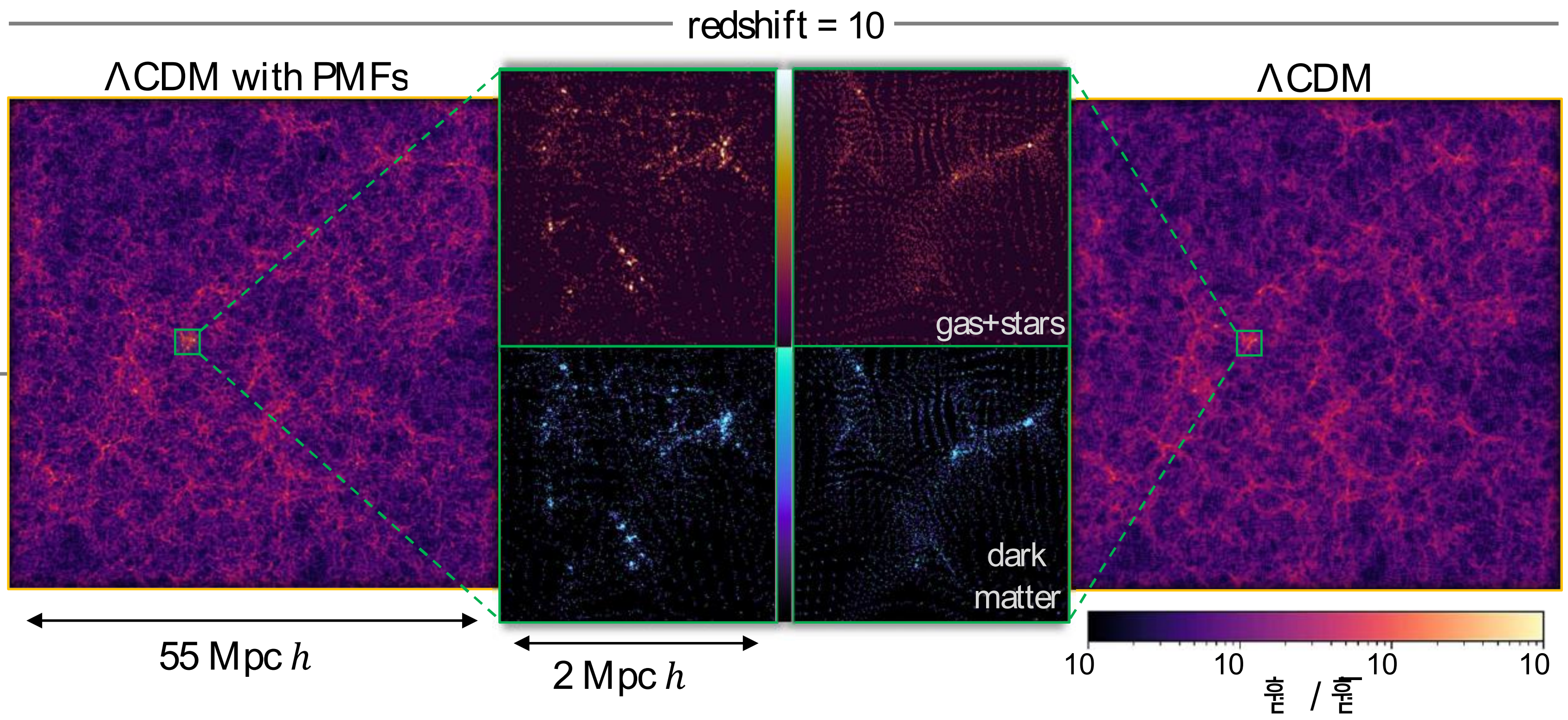


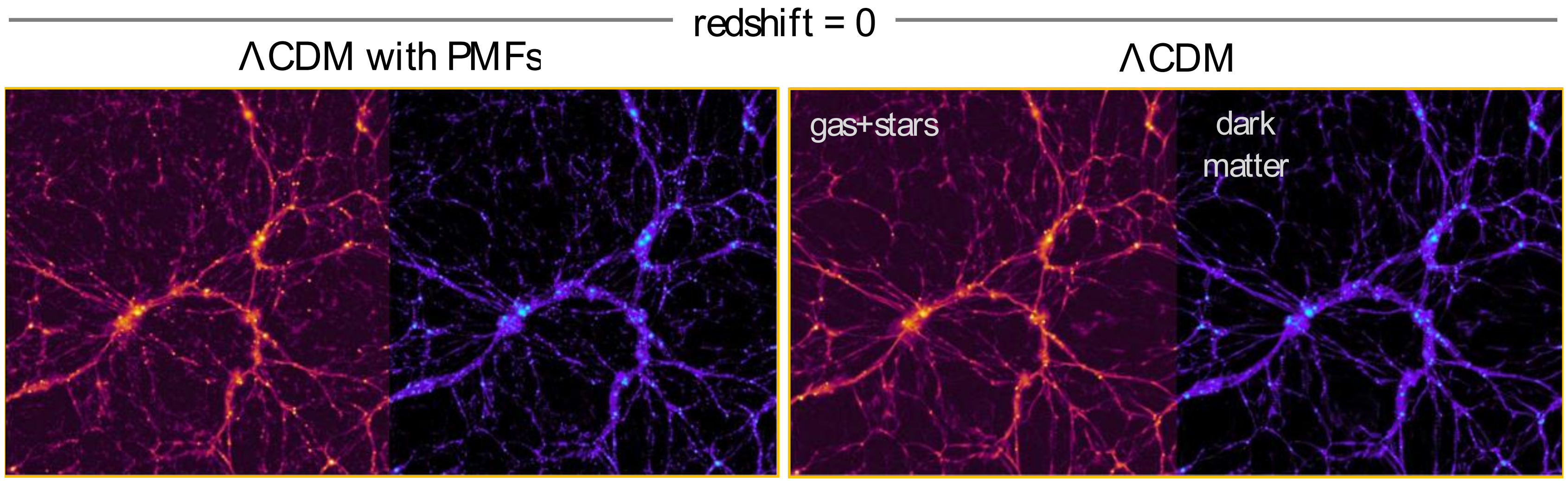
POST RECOMBINATION: BARYON PERTURBATIONS MORE ENHANCED THAN DARK MATTER



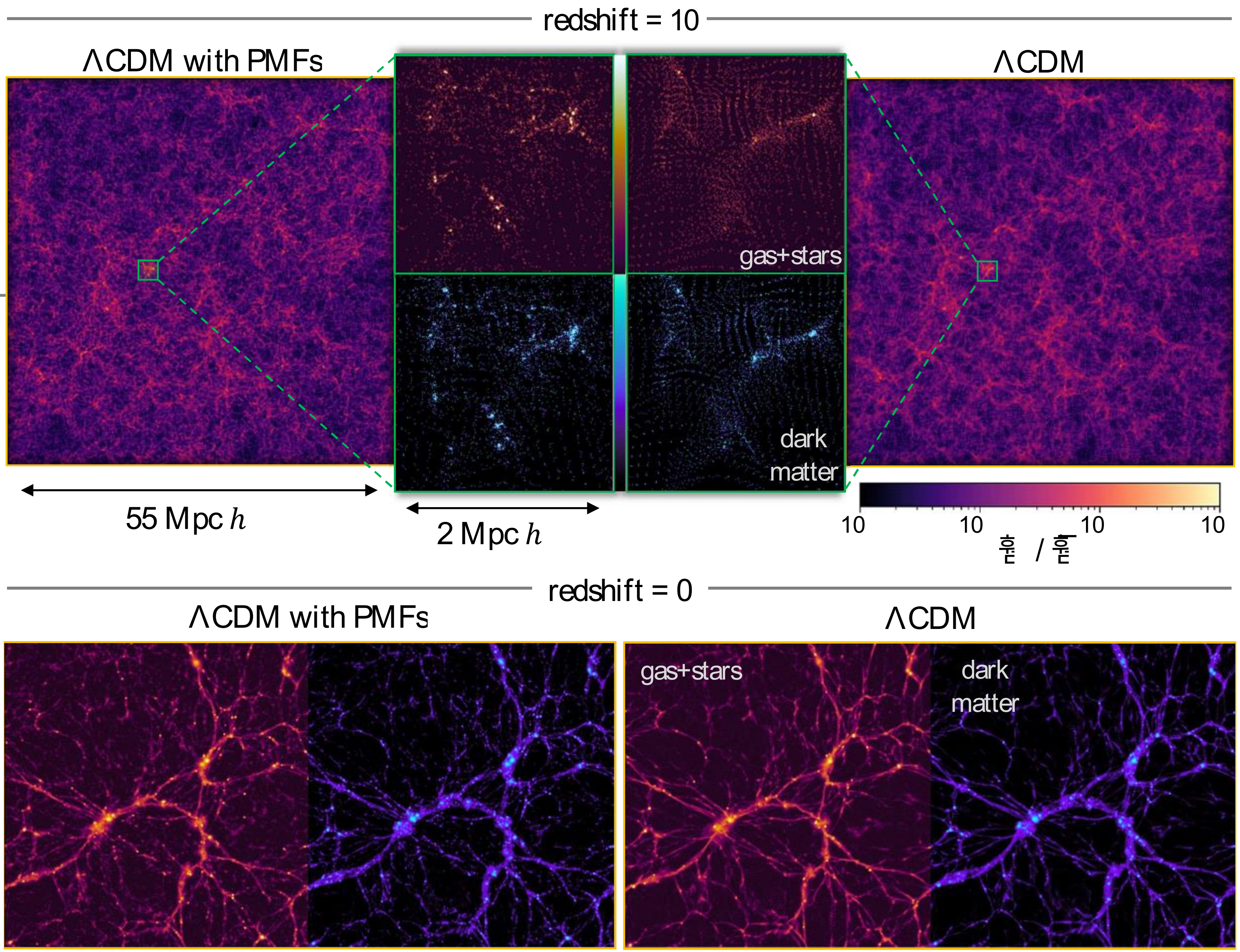
SIMULATIONS





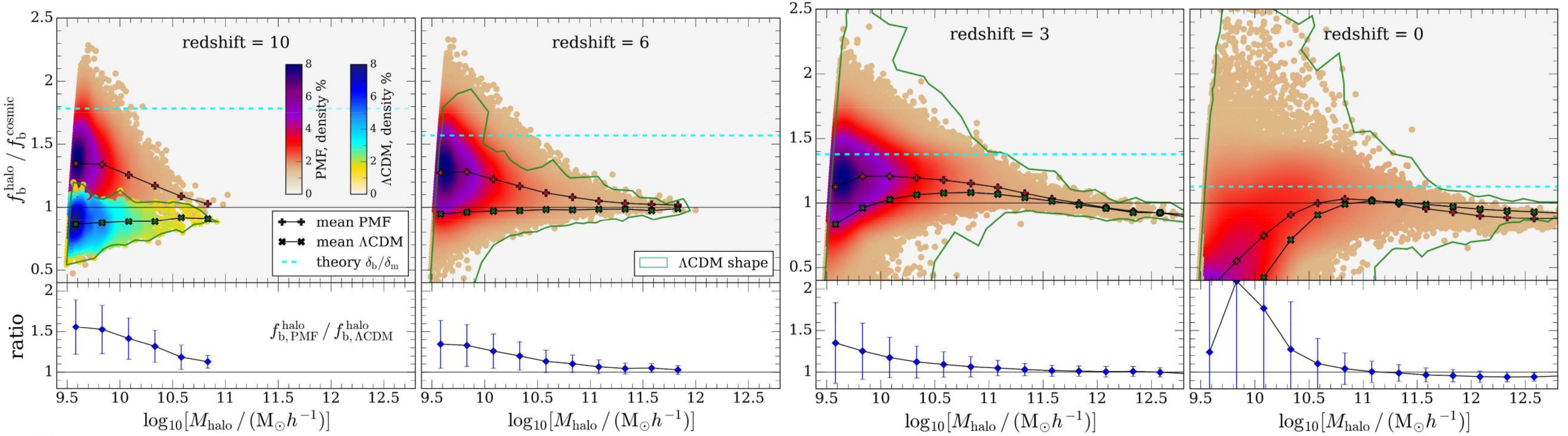


SIMULATIONS



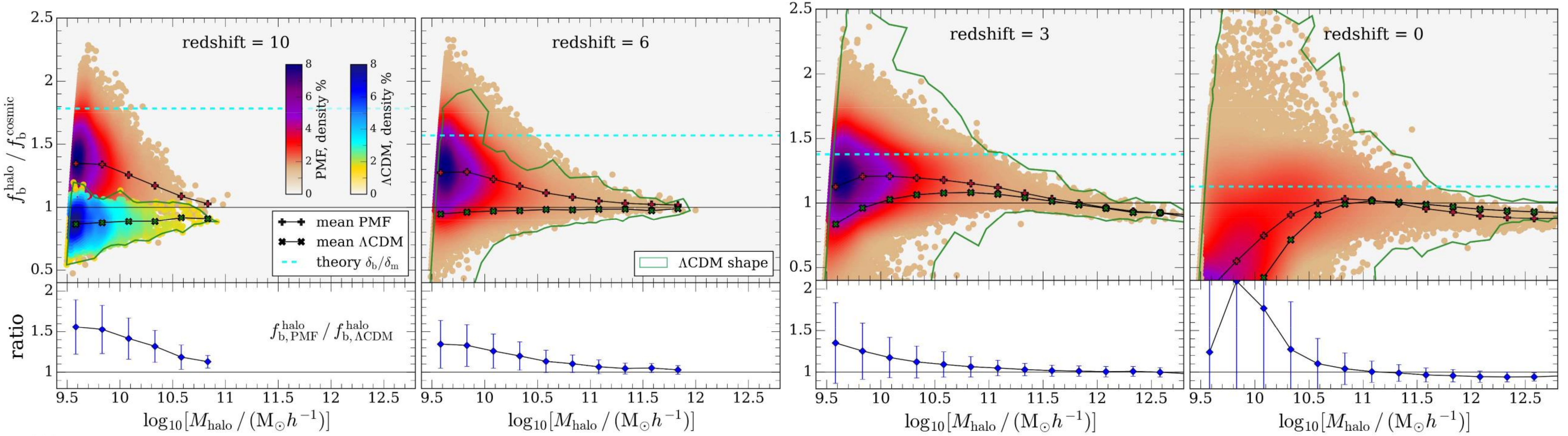
BARYON FRACTION IN HALOS: ENHANCED BY PMFS

BARYON FRACTION IN HALOS: ENHANCED BY PMFS



Scale invariant 1 nG PMFs

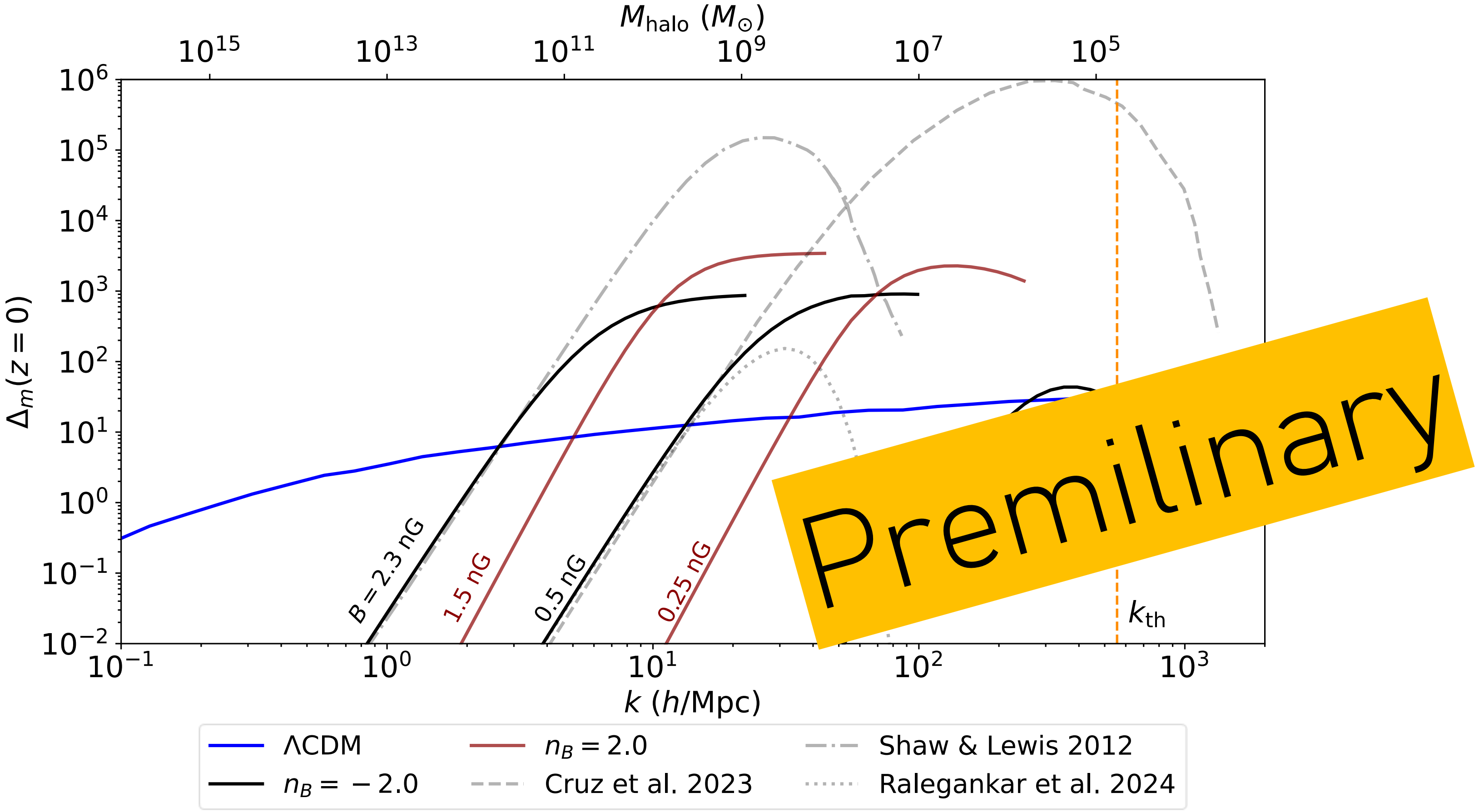
BARYON FRACTION IN HALOS: STOCHASTIC NATURE



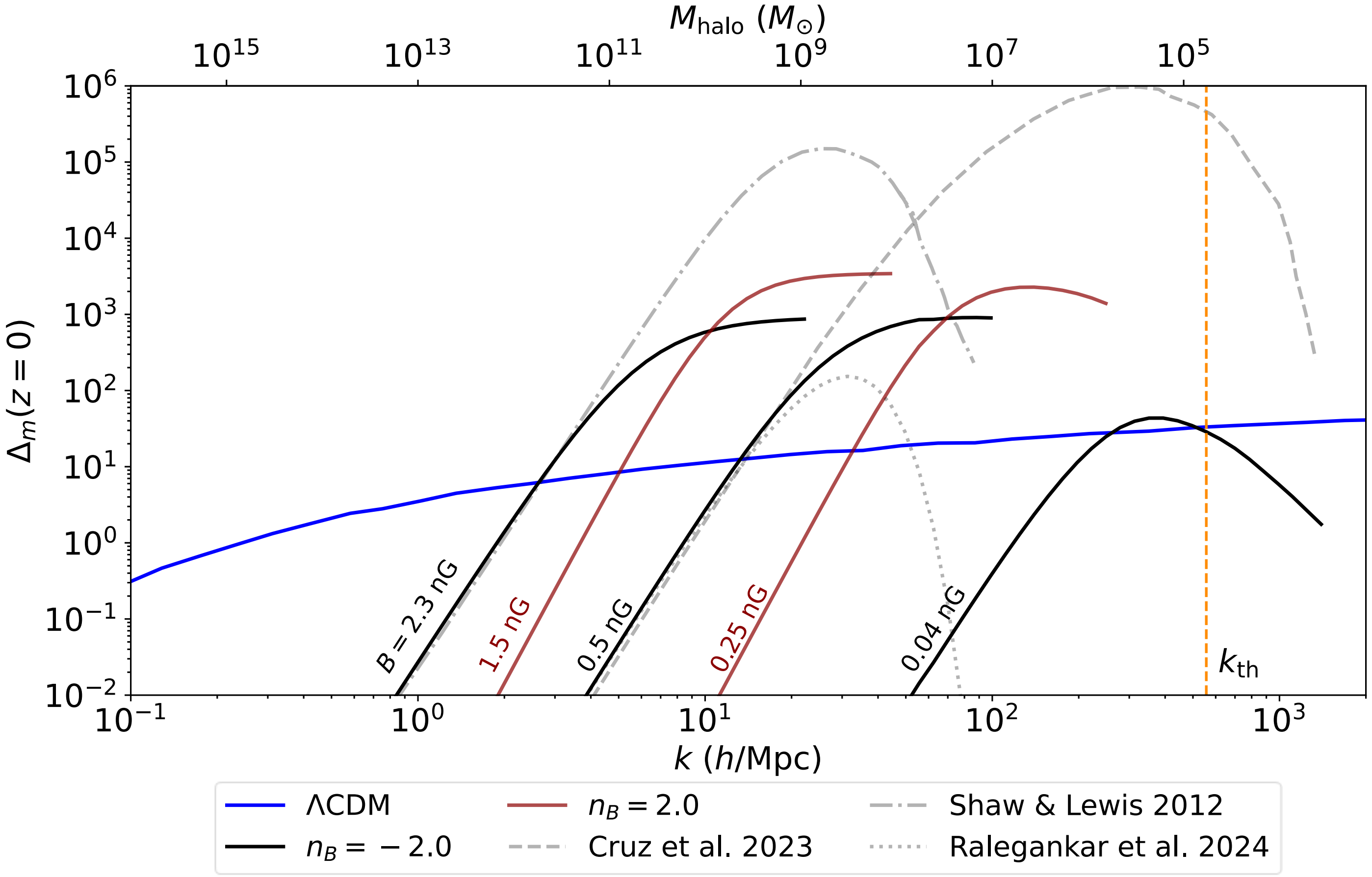
Scale invariant 1 nG PMFs

$$\frac{f_b^{halo}}{f_b^{cosmic}} = \frac{\delta_b^{PMF} + \delta_b^{\Lambda CDM}}{\delta_m^{PMF} + \delta_m^{\Lambda CDM}}$$

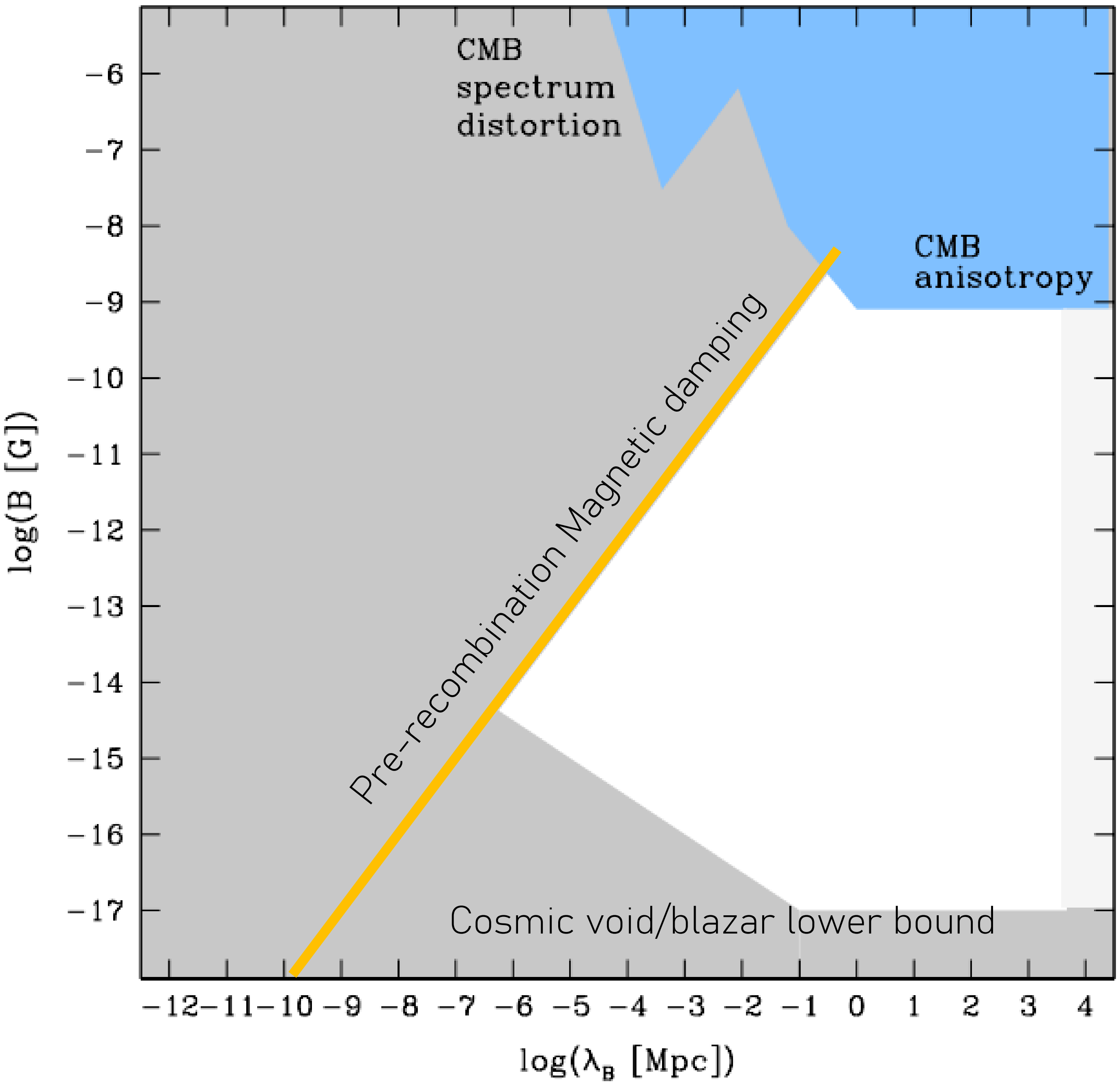
ENHANCEMENT MOVES TO SMALLER SCALES WITH SMALLER PMF STRENGTH



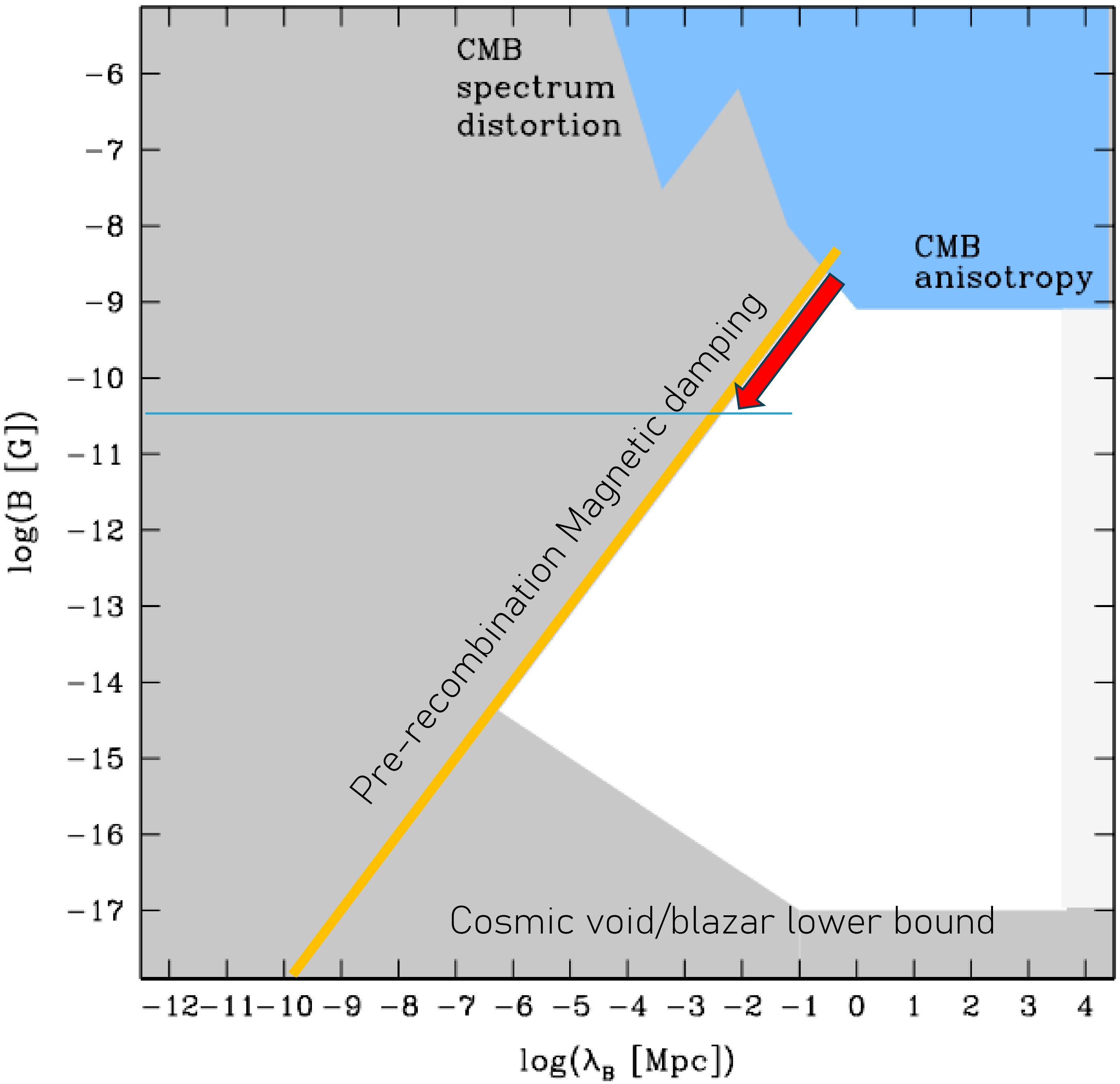
ENHANCEMENT MOVES TO SMALLER SCALES WITH SMALLER PMF STRENGTH



IMPLICATIONS FOR PMFS

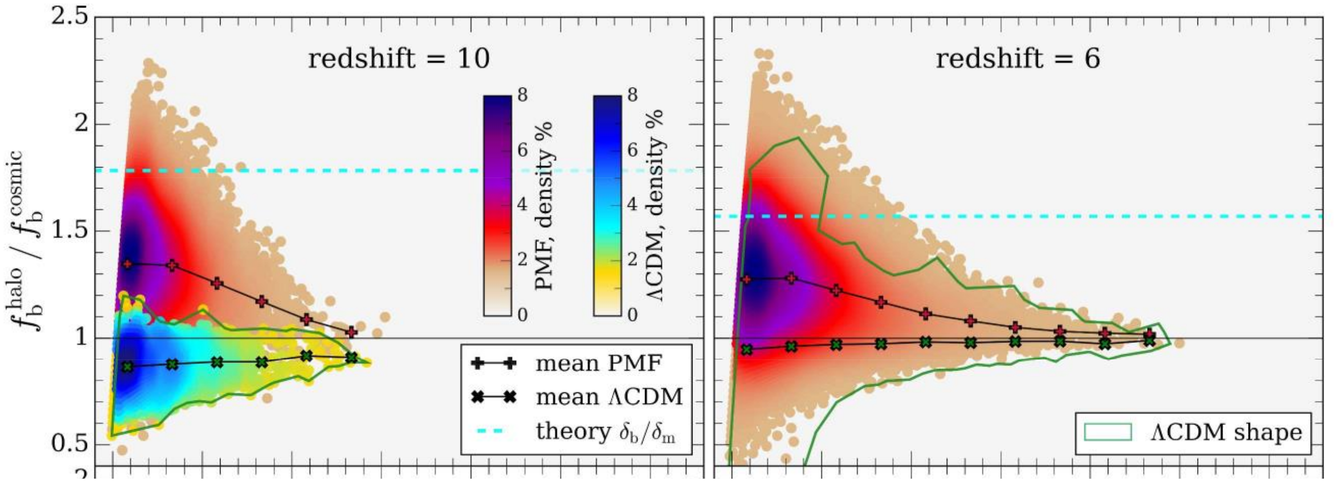


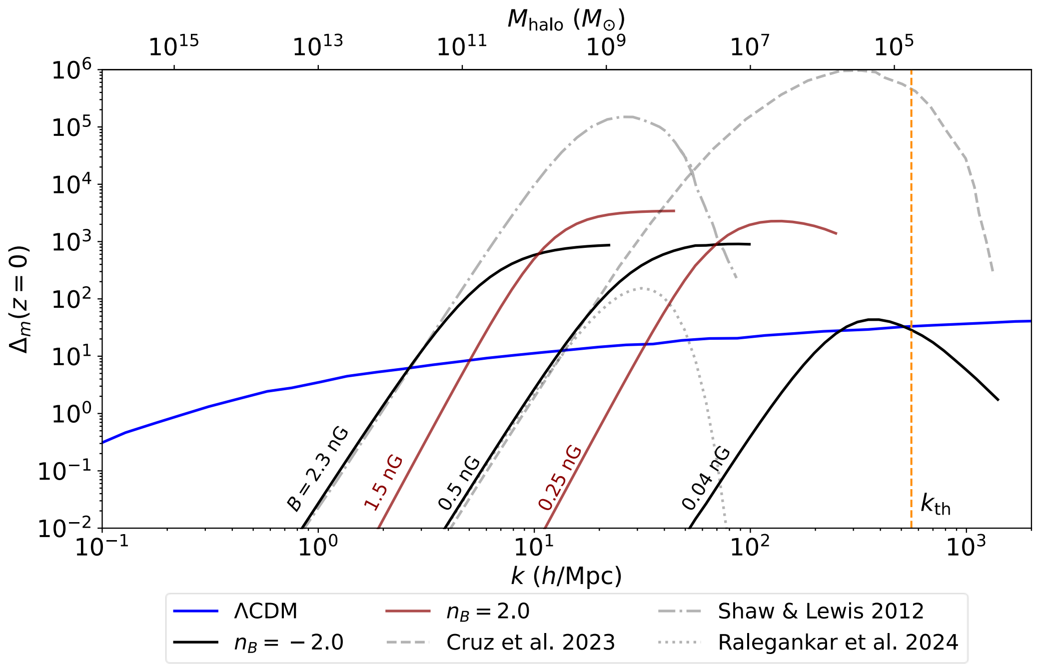
POWER SPECTRUM ABOVE MAGNETIC JEANS SCALE IS SENSITIVE UPTO 0.05 NG PMFS



PART 1: SUMMARY

- PMFs can enhance baryon fraction apart from enhancing matter power spectrum
- Can affect star formation efficiency, black hole formation etc. Need dedicated MHD sims.
- The final conclusion of enhanced baryon fraction in halos does not depend on MHD.
- Observing high baryon fraction at high redshift will be smoking gun signal for PMFs

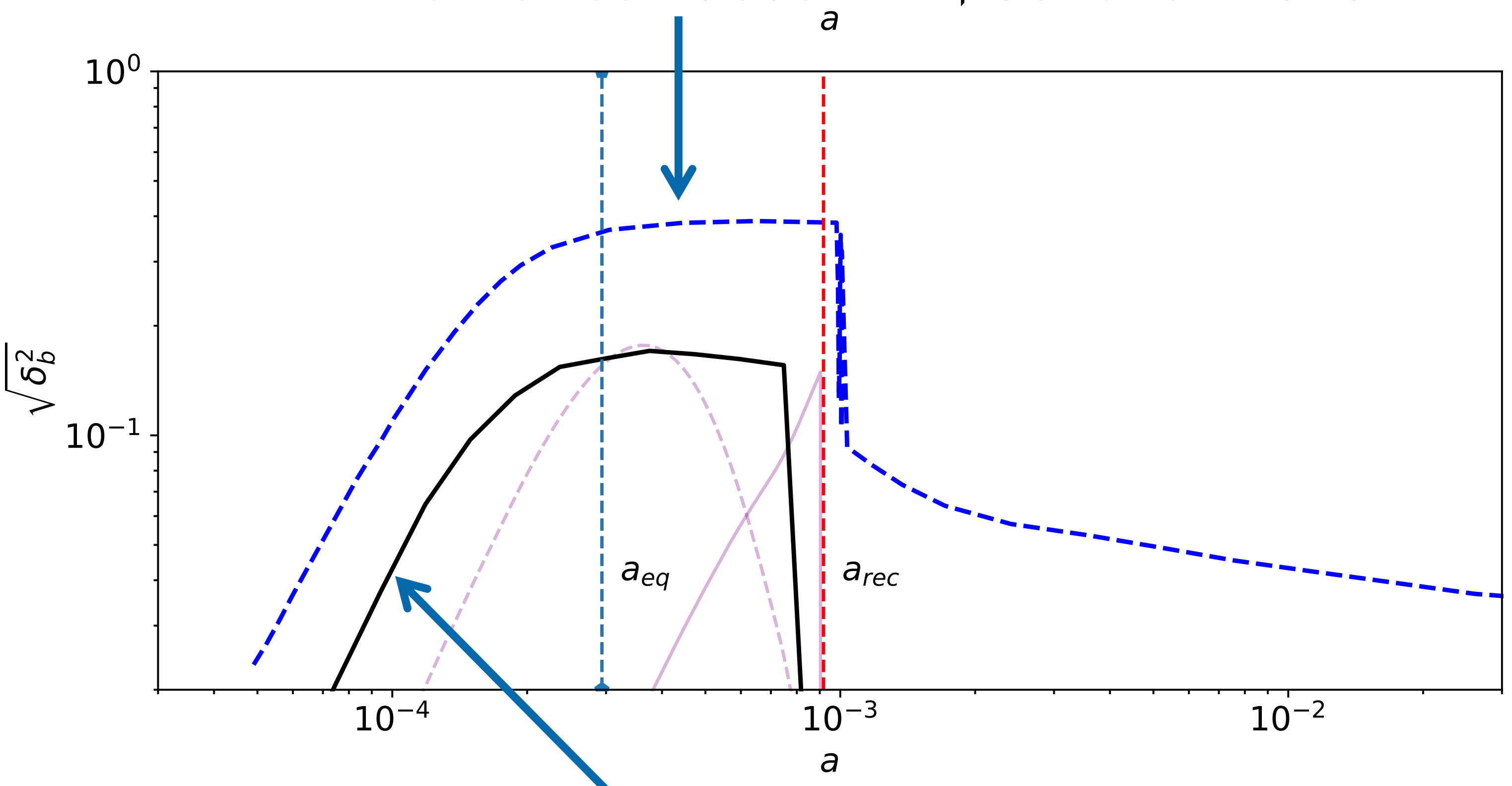




BACKUP SLIDES

COMPARING WITH SIMULATIONS: ANALYTICAL NOT THAT BAD

Numerical: Jedamzik, Saveliev 2018



analytical

$B_{0I} = 0.525$nG

BACKUP: ANALYTIC DERIVATION IN PRE-RECOMBINATION FLUID

IDEAL MHD IN PHOTON DRAG REGIME:

IDEAL MHD IN PHOTON DRAG REGIME: LAMINAR FLOW IN BARYONS

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

IDEAL MHD IN PHOTON DRAG REGIME: LAMINAR FLOW IN BARYONS

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

Abel and Jedamzik 2010,
Campanelli 2013,
Jedamzik and Saveliev 2018

IDEAL MHD IN PHOTON DRAG REGIME: KEY FORCES

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

Gravity

Lorentz force

Thermal pressure

IDEAL MHD IN PHOTON DRAG REGIME: LARGE LORENTZ FORCE LIMIT

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

IDEAL MHD IN PHOTON DRAG REGIME: LARGE LORENTZ FORCE LIMIT

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

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

IDEAL MHD IN PHOTON DRAG REGIME: MAGNETIC DAMPING SCALE

$$\left.\begin{aligned} (H+\alpha)\vec{v}_b &\approx \frac{\left(\nabla\times\vec{B}\right)\times\vec{B}}{4\pi a\rho_b} \\ \frac{\partial\,(a^2\vec{B})}{\partial t} &= \frac{\nabla\times(\vec{v}_b\times a^2\vec{B})}{a} \end{aligned}\right\}$$

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

$$k_D^{-1}(a) \sim \tau v_b$$

Campanelli 2013

IDEAL MHD IN PHOTON DRAG REGIME: MAGNETIC DAMPING SCALE

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

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

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

$$k_D^{-1}(a) \sim \tau v_b$$

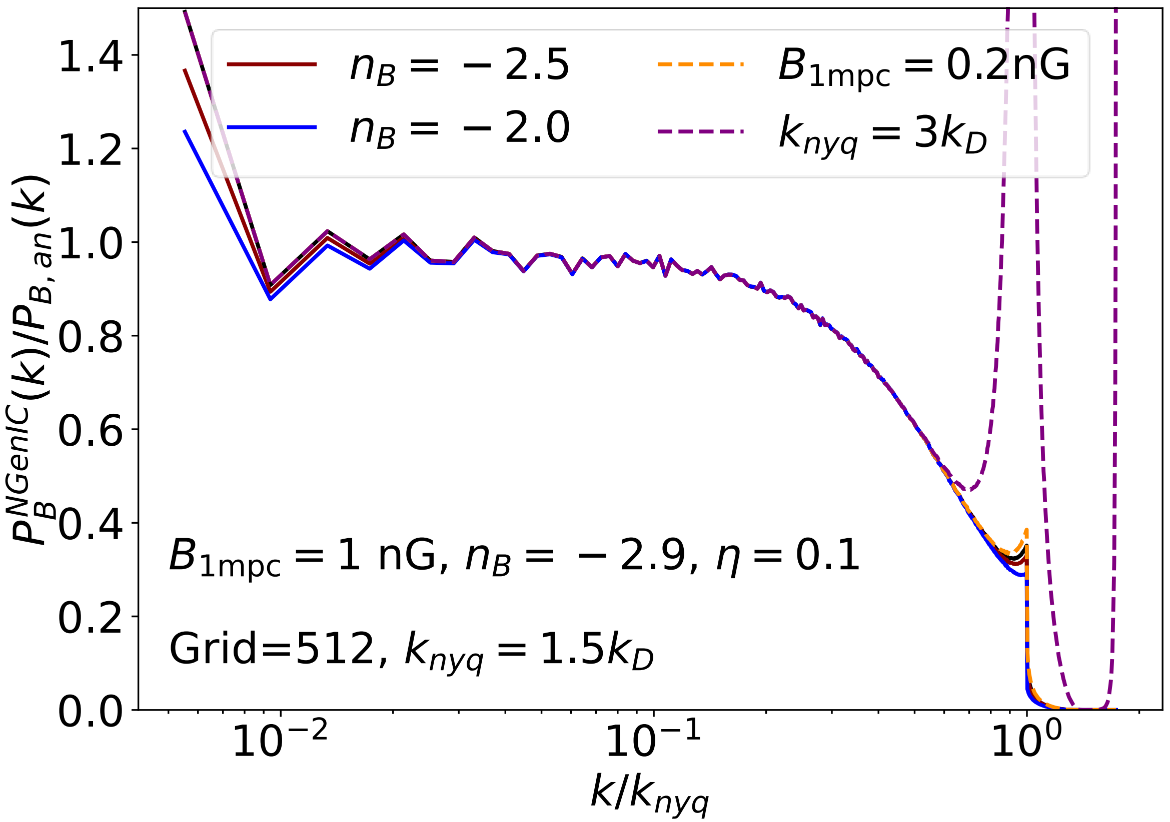
Campanelli 2013

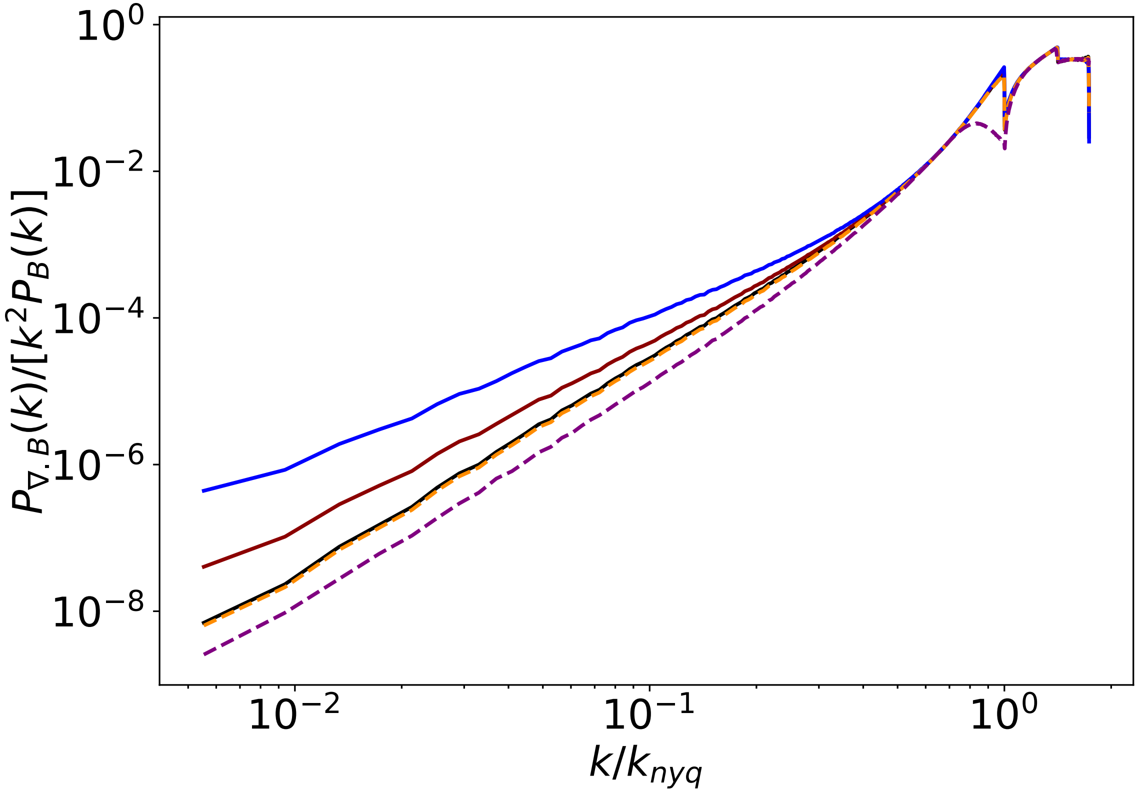
ASSUMED

B_0 Gaussian

PROBLEM WITH LORENTZ FORCE IN MY LATTICE

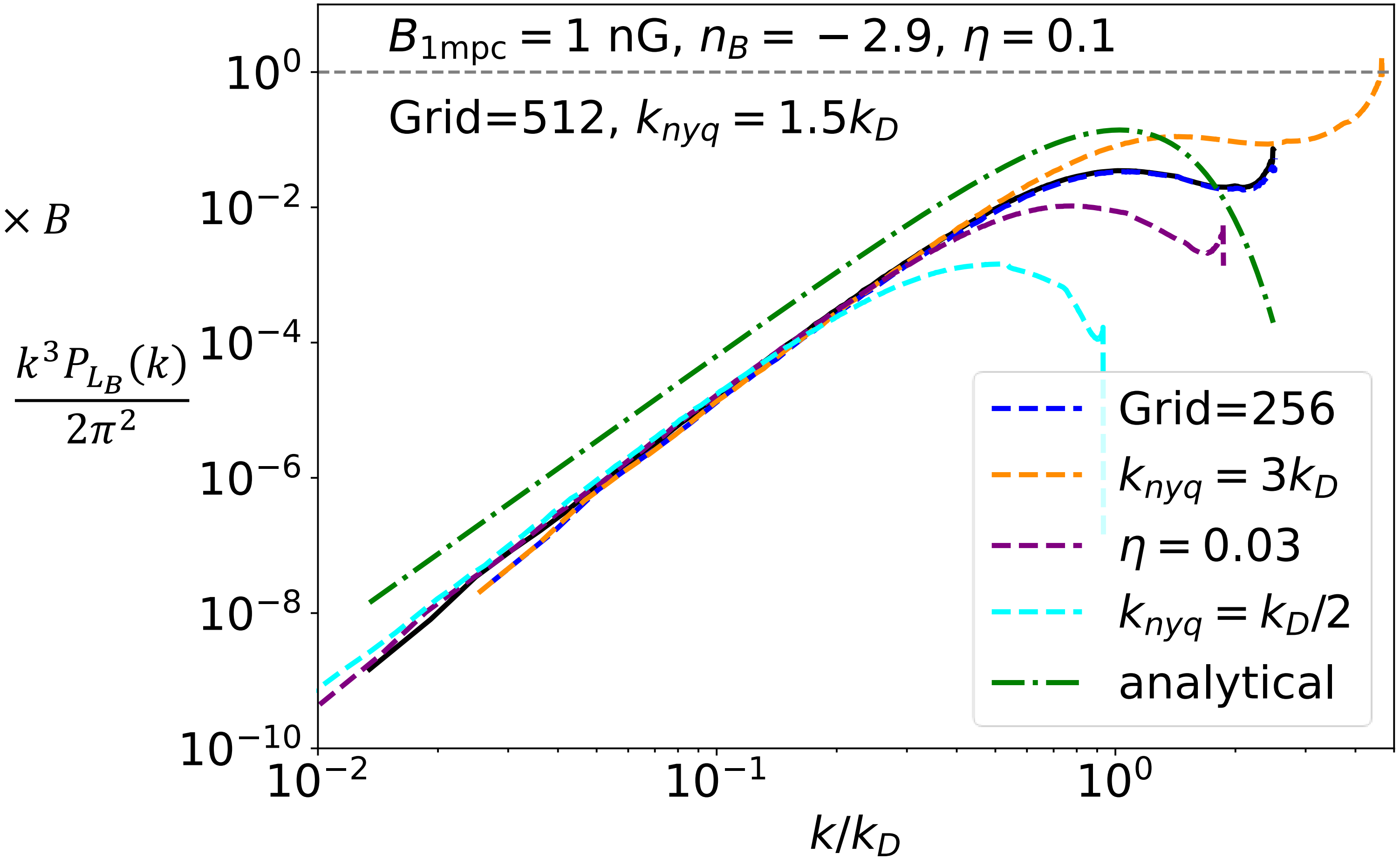
INITIALIZING STOCHASTIC PMFS ON LATTICE



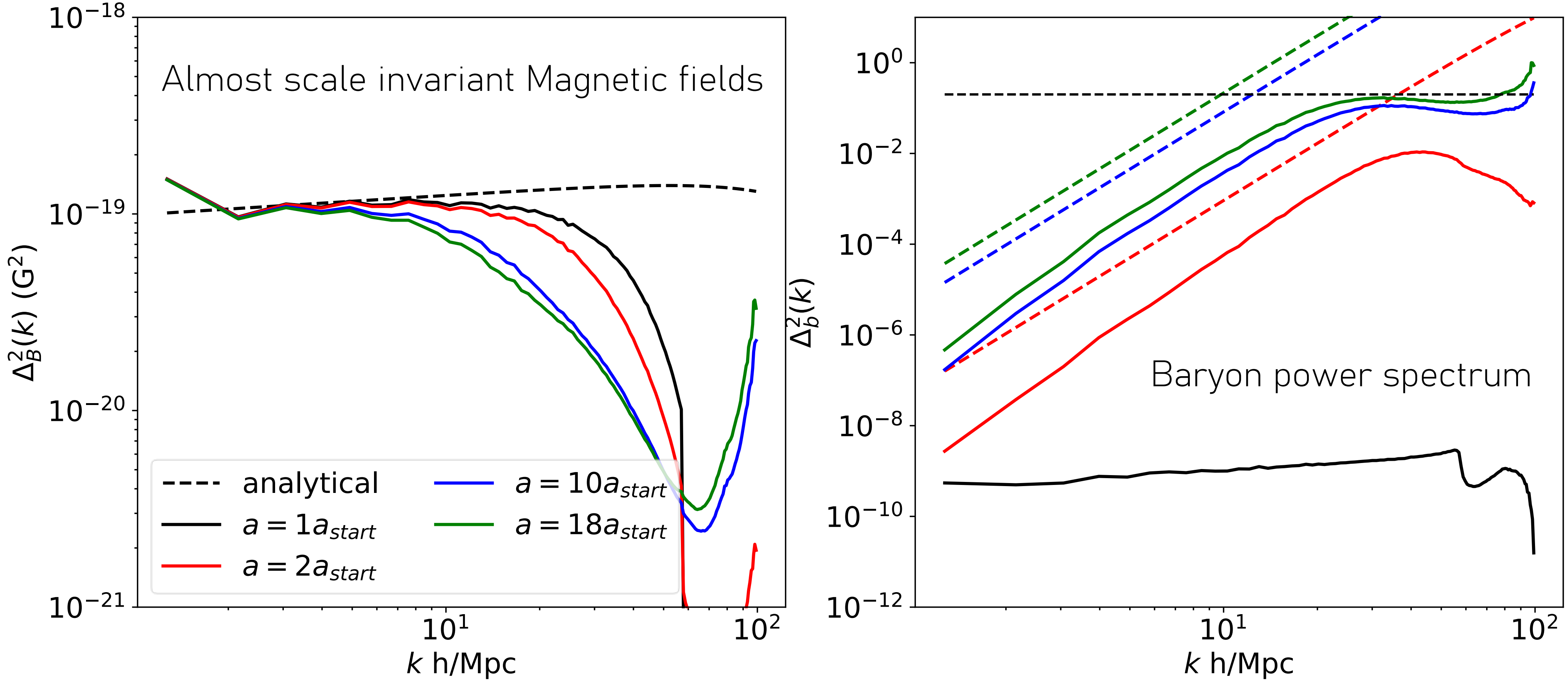


LORENTZ FORCE POWER SPECTRUM DOESN'T AGREE WITH THEORY

$L_B \propto \nabla.(\nabla \times B) \times B$

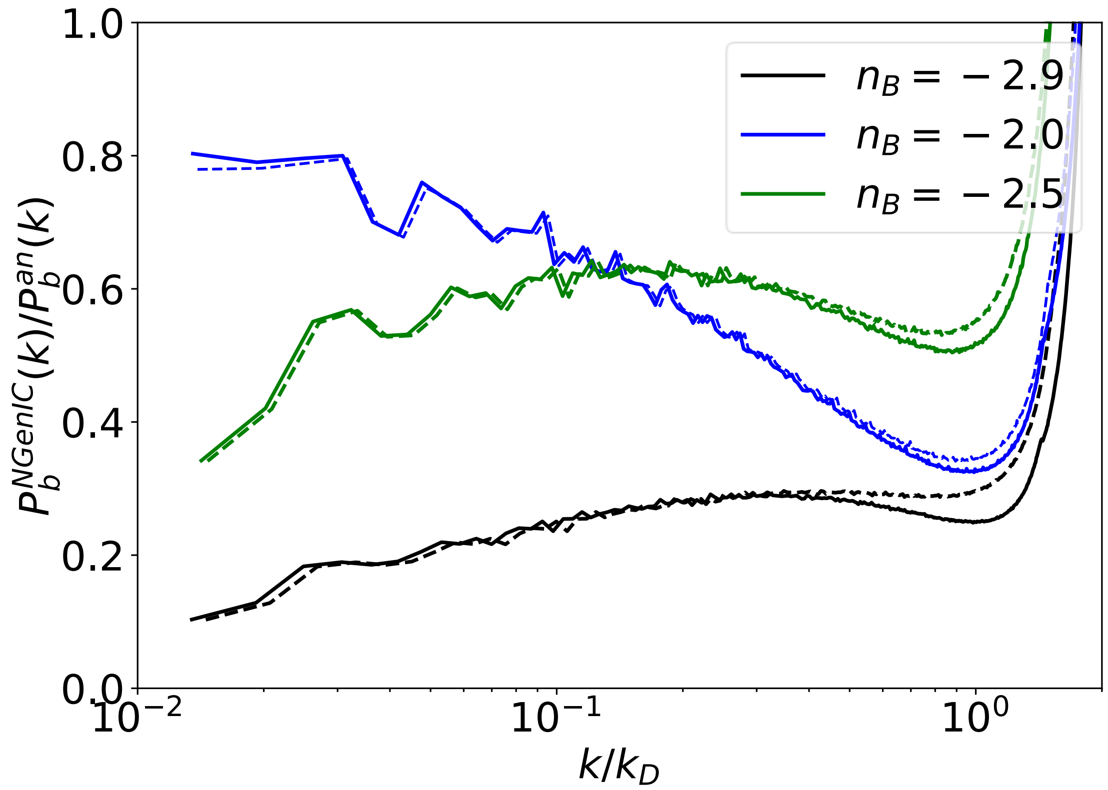


THE SUPPRESSION OF POWER IS ALSO SEEN IN AREPO (PRELIMINARY!!)



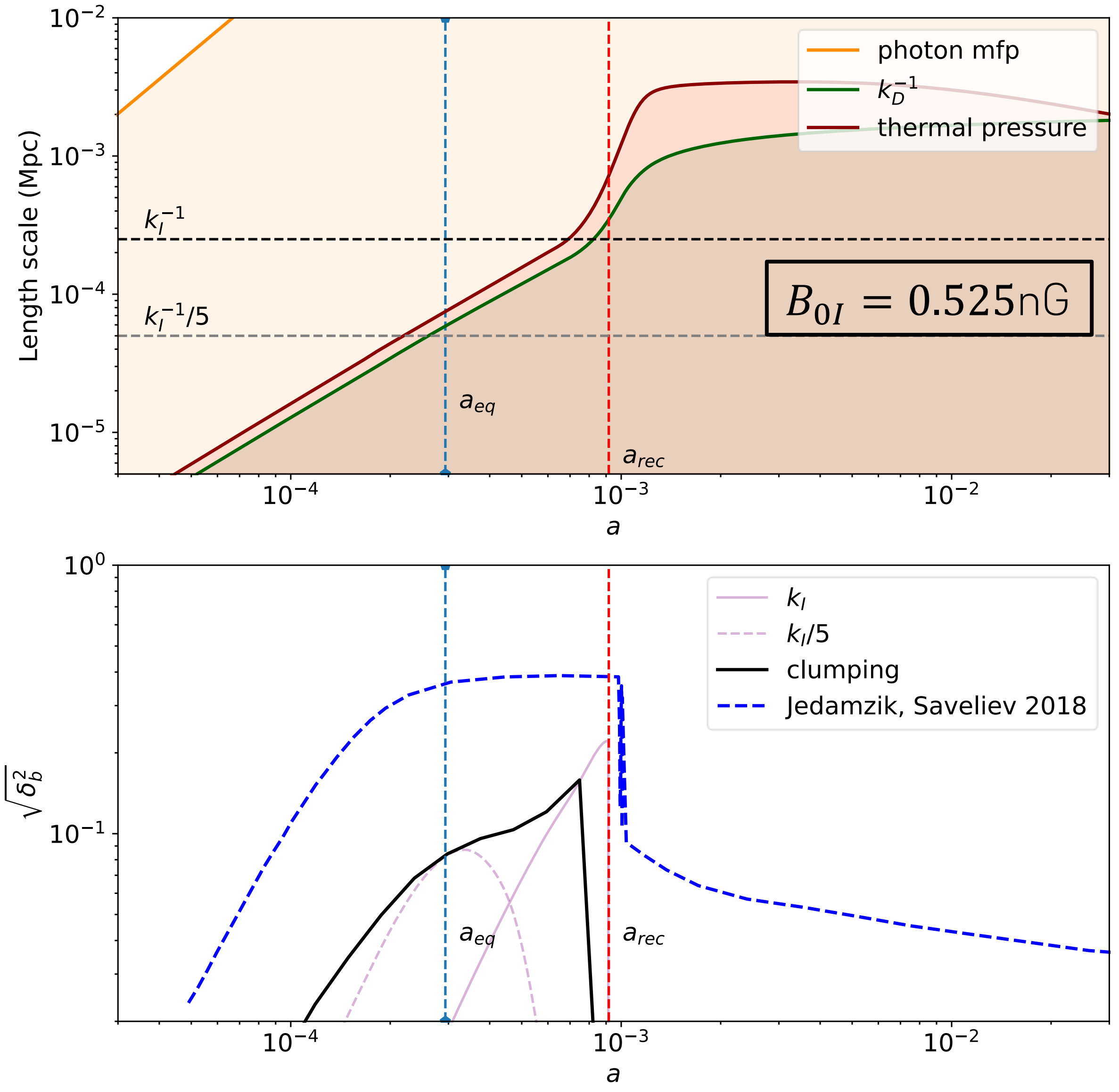
BACKUP SLIDES

SPECTRUM SHAPE DEPENDENCE OF SHIFT

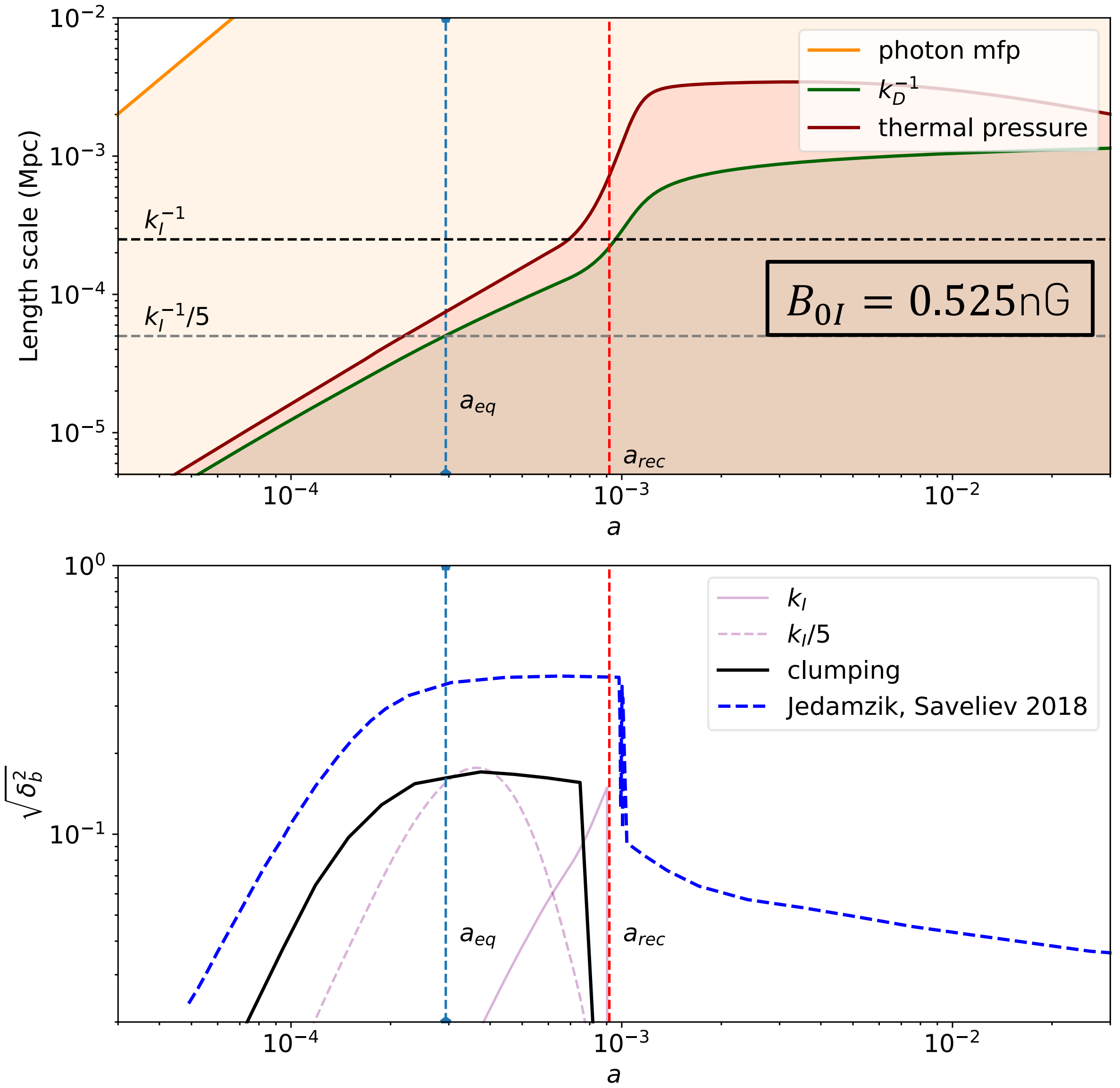


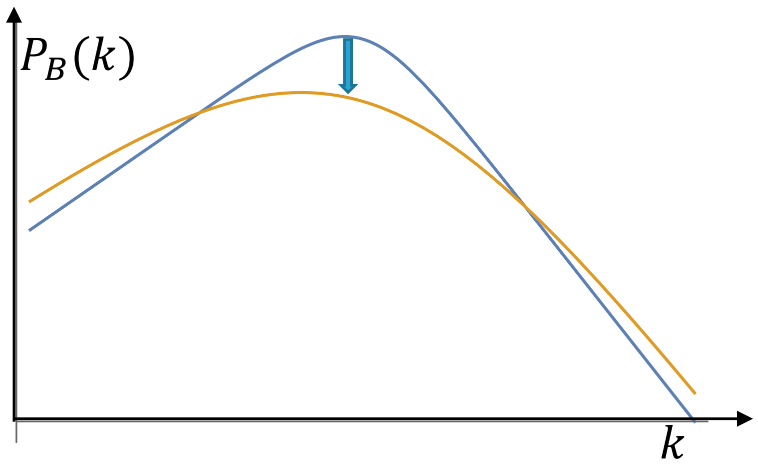
COMPARING WITH FULL MHD SIMULATIONS

COMPARING WITH SIMULATIONS: SENSITIVE TO INITIAL POWER SPECTRUM

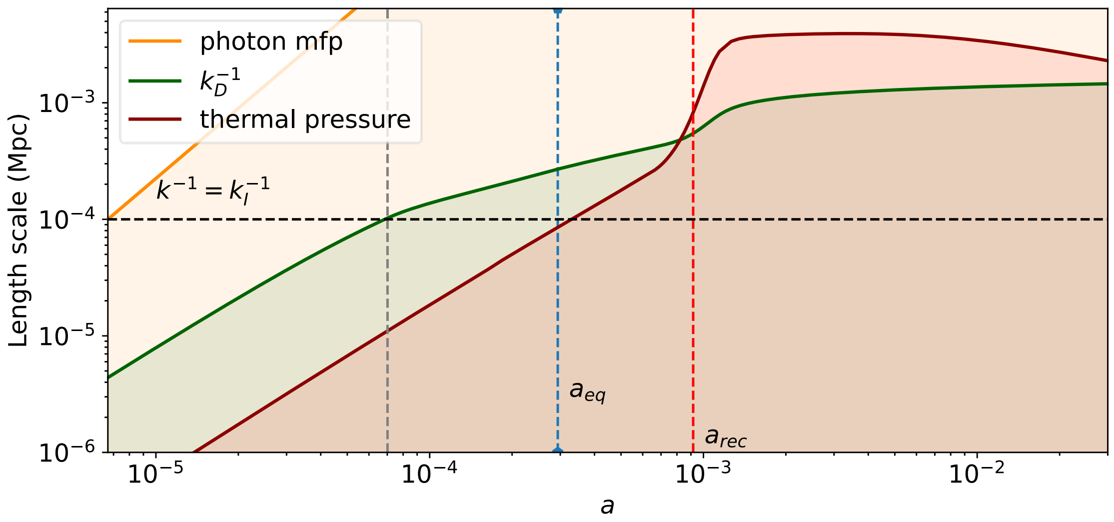


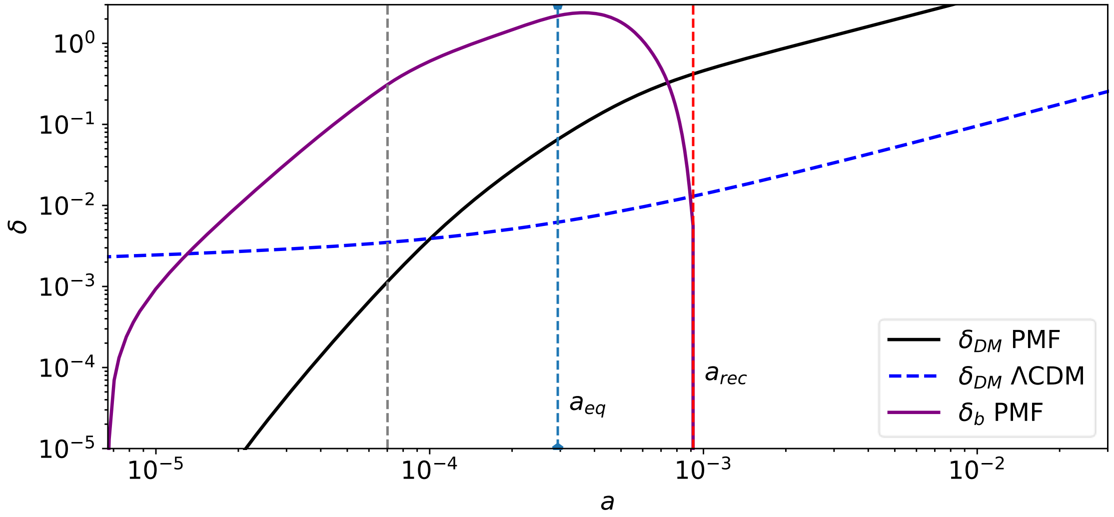
COMPARING WITH SIMULATIONS: SENSITIVE TO INITIAL POWER SPECTRUM



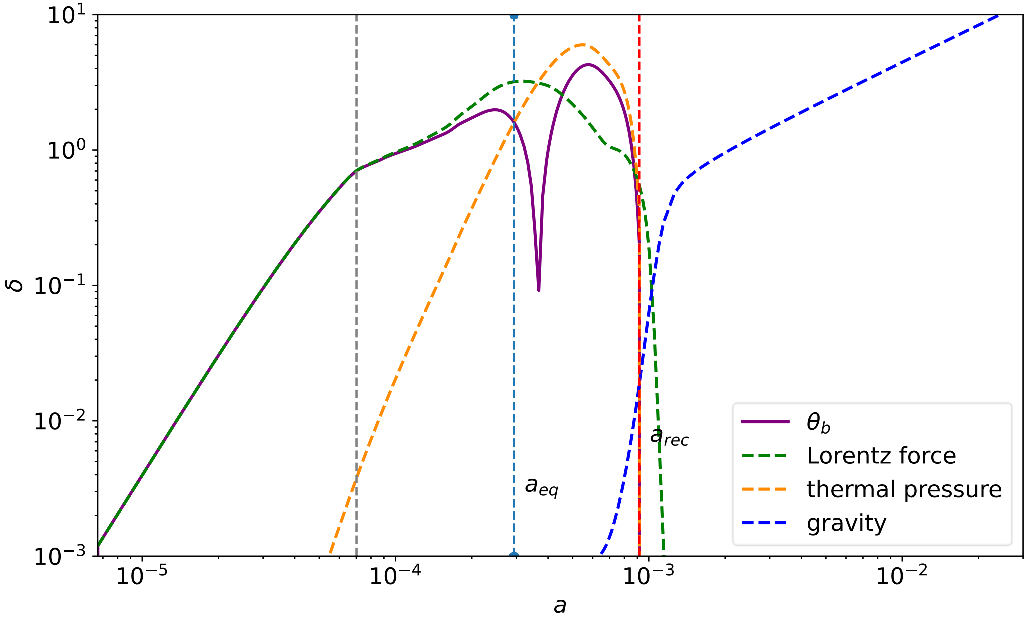


MORE PERTURBATION PLOTS

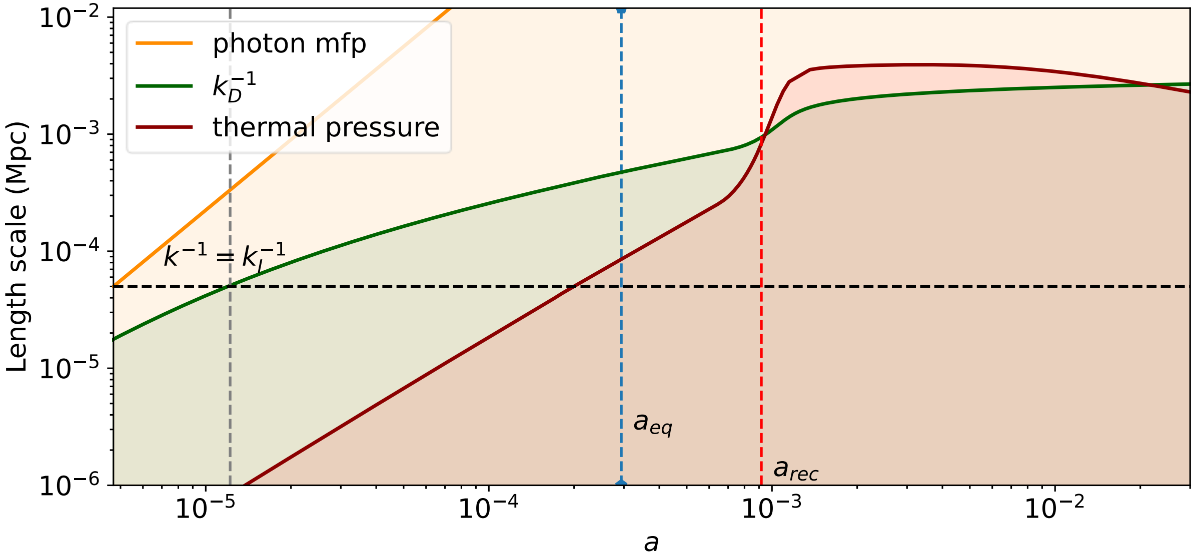


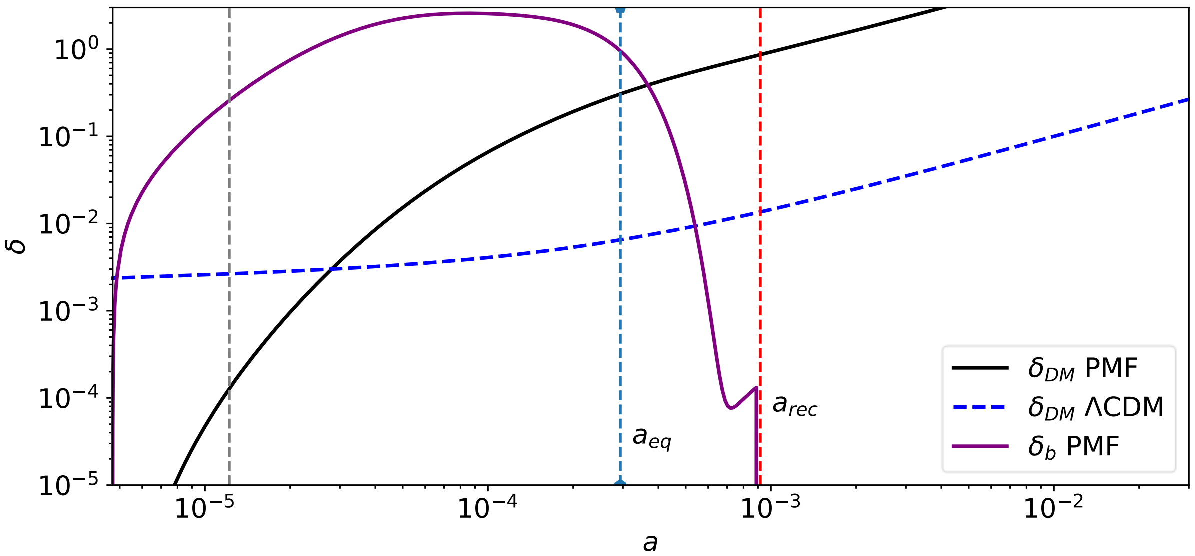


$$B_0 = 1\text{nG}$$
$$k_I = 10^4\ Mpc^{-1}$$



MORE PERTURBATION PLOTS





$B_0 = 8\text{nG}$

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