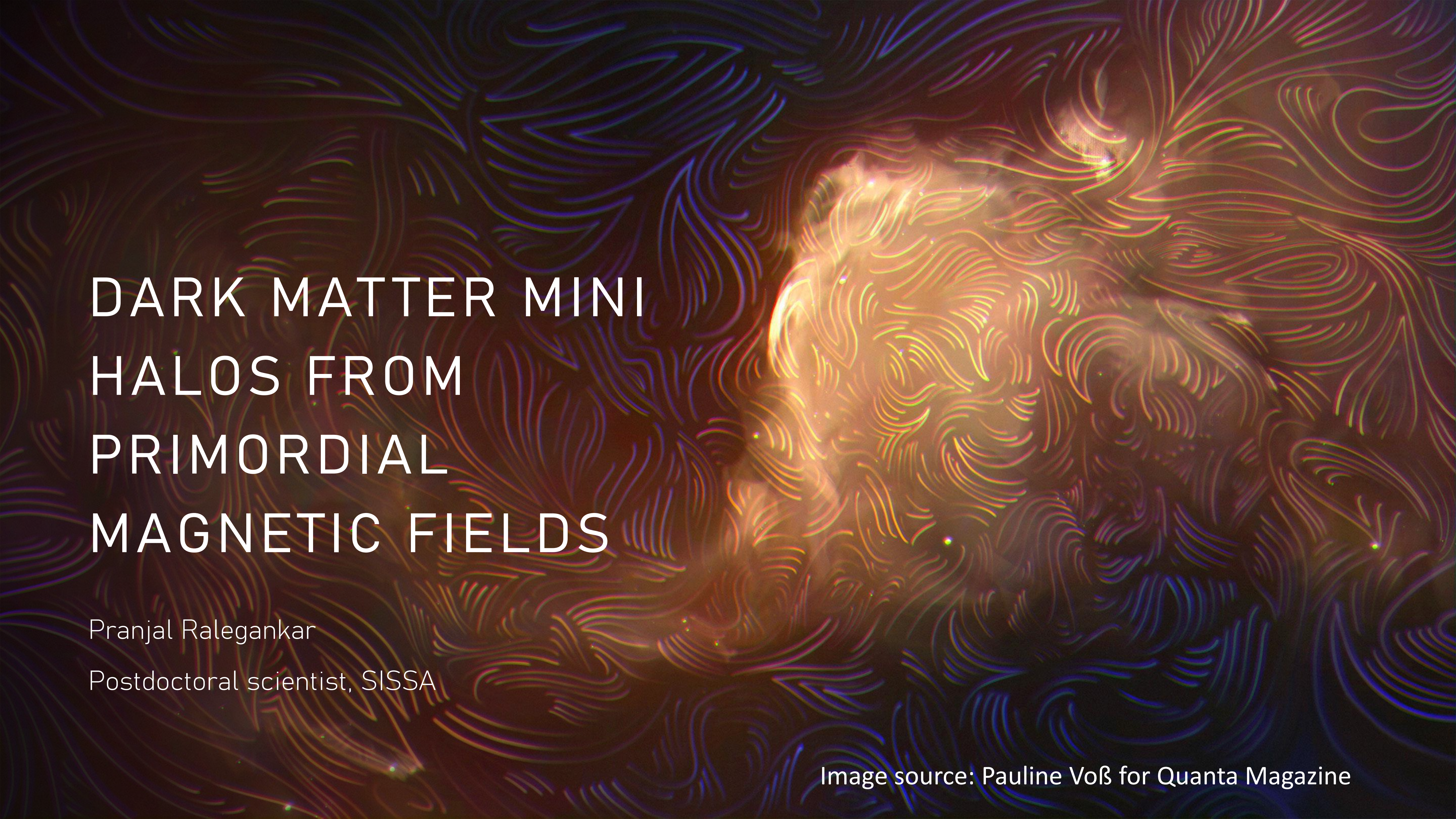


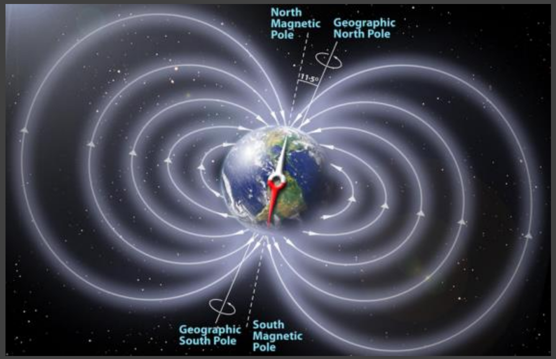
DARK MATTER MINI HALOS FROM PRIMORDIAL MAGNETIC FIELDS

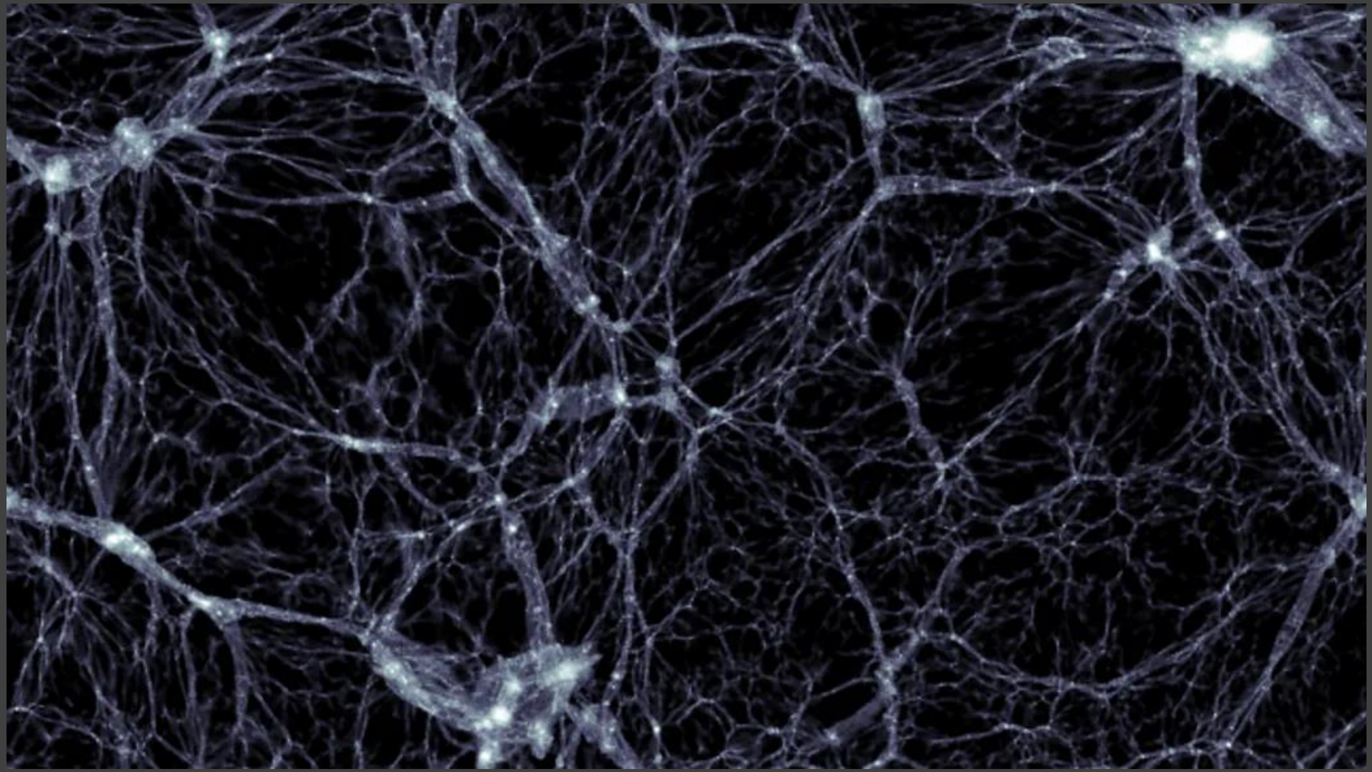
Pranjal Ralegankar

Postdoctoral scientist, SISSA

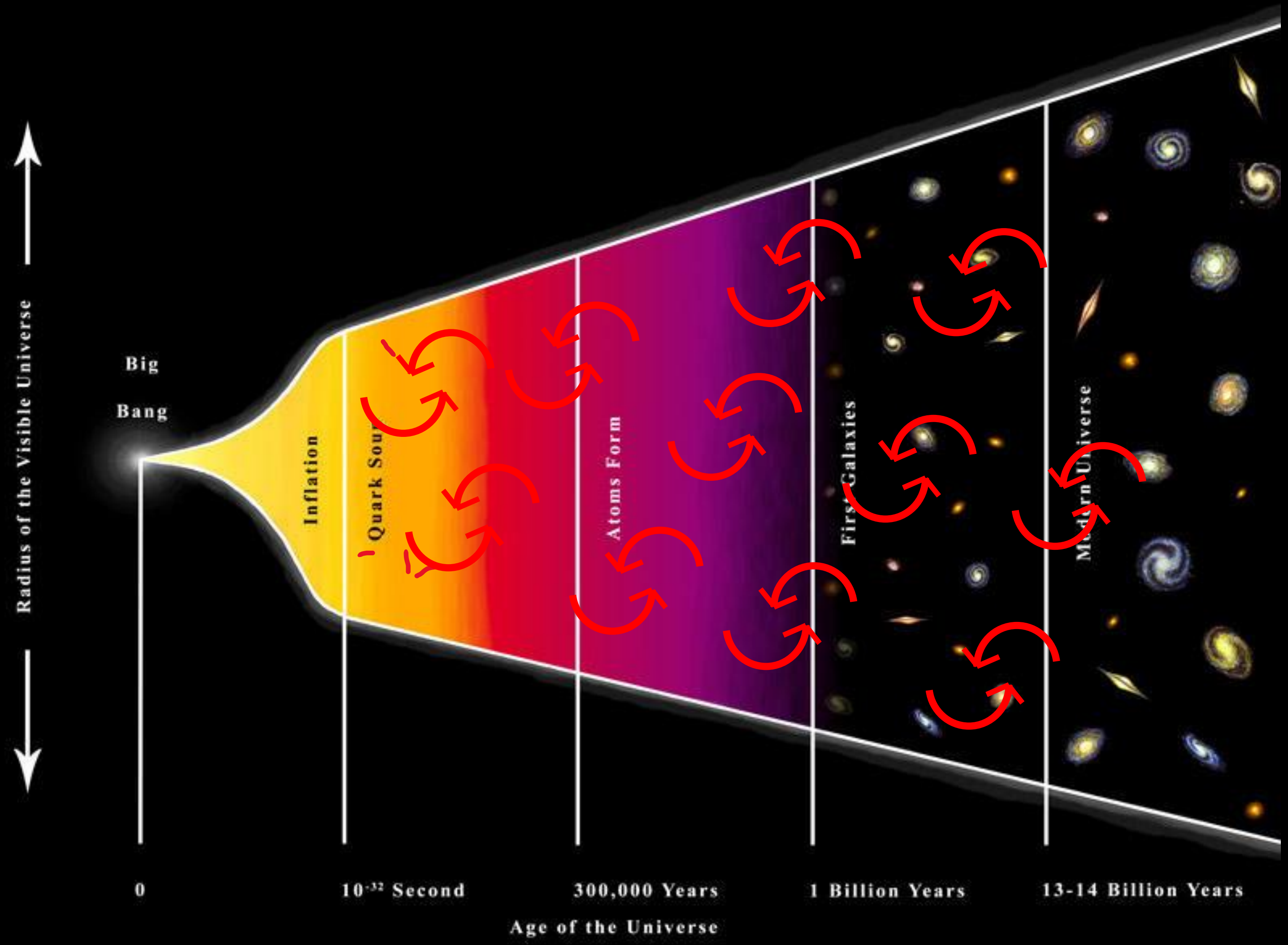
Image source: Pauline Voß for Quanta Magazine

UBIQUITOUS MAGNETIC FIELDS



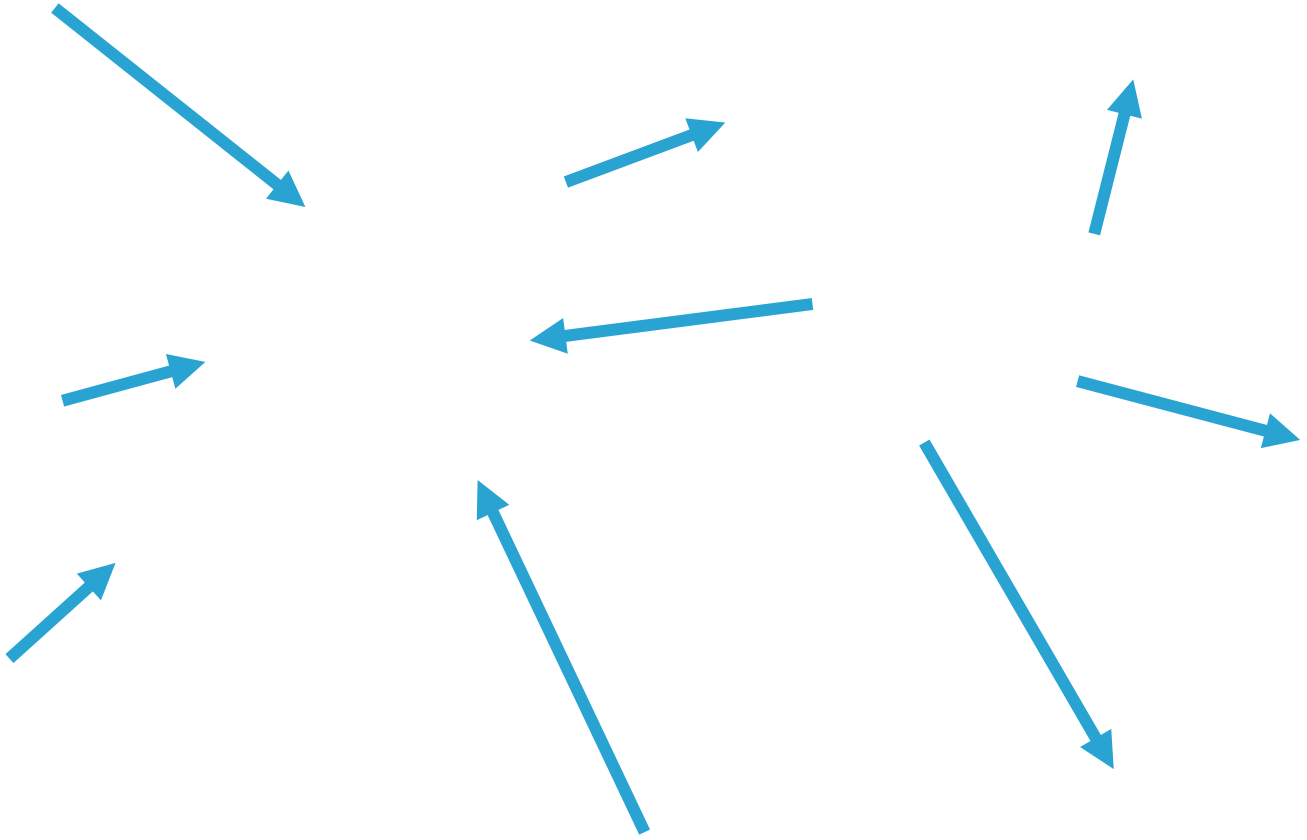


PRIMORDIAL: PRODUCED BY BIG BANG PLASMA

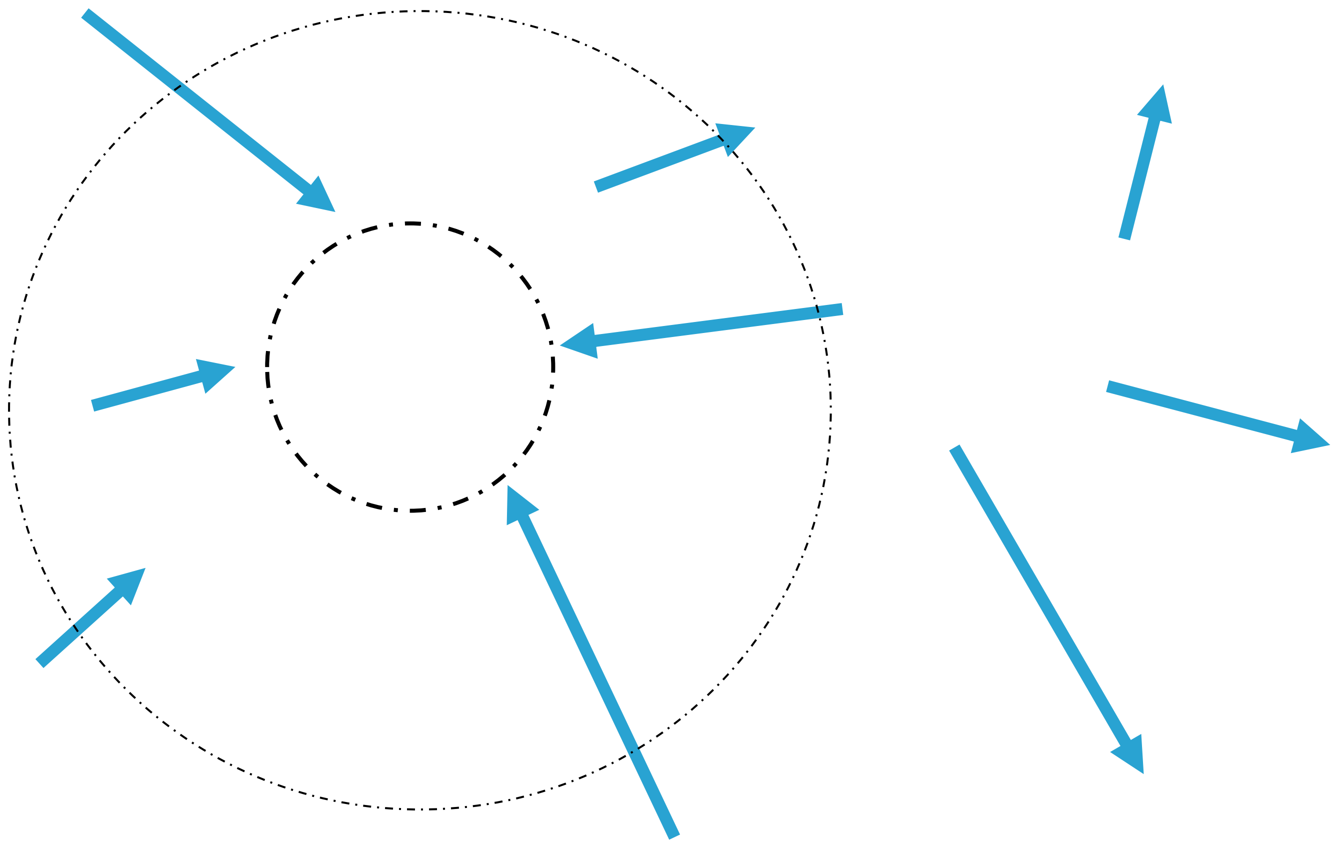


PRIMORDIAL MAGNETIC FIELDS ENHANCE DENSITY PERTURBATIONS

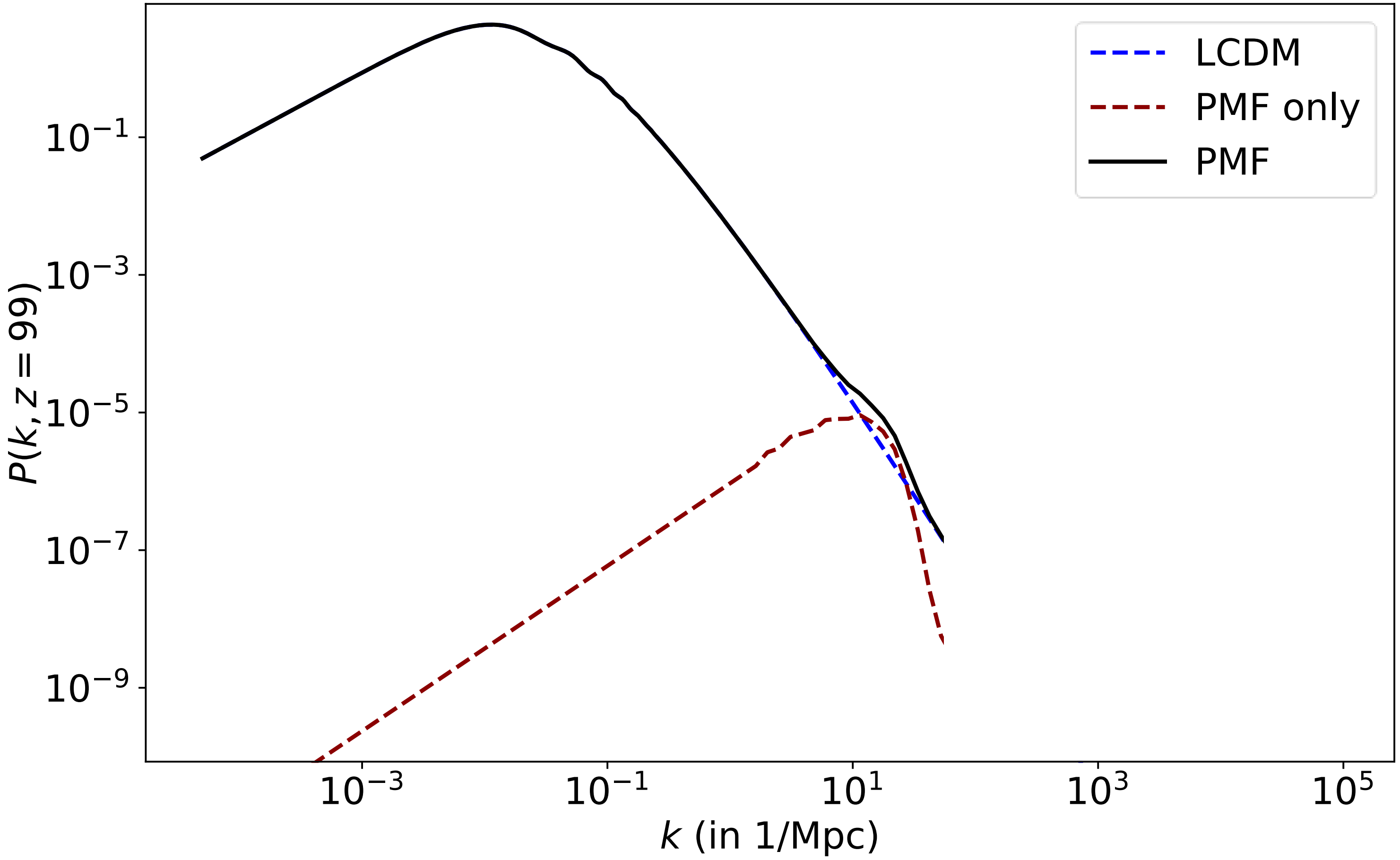
PRIMORDIAL MAGNETIC FIELDS ENHANCE DENSITY PERTURBATIONS



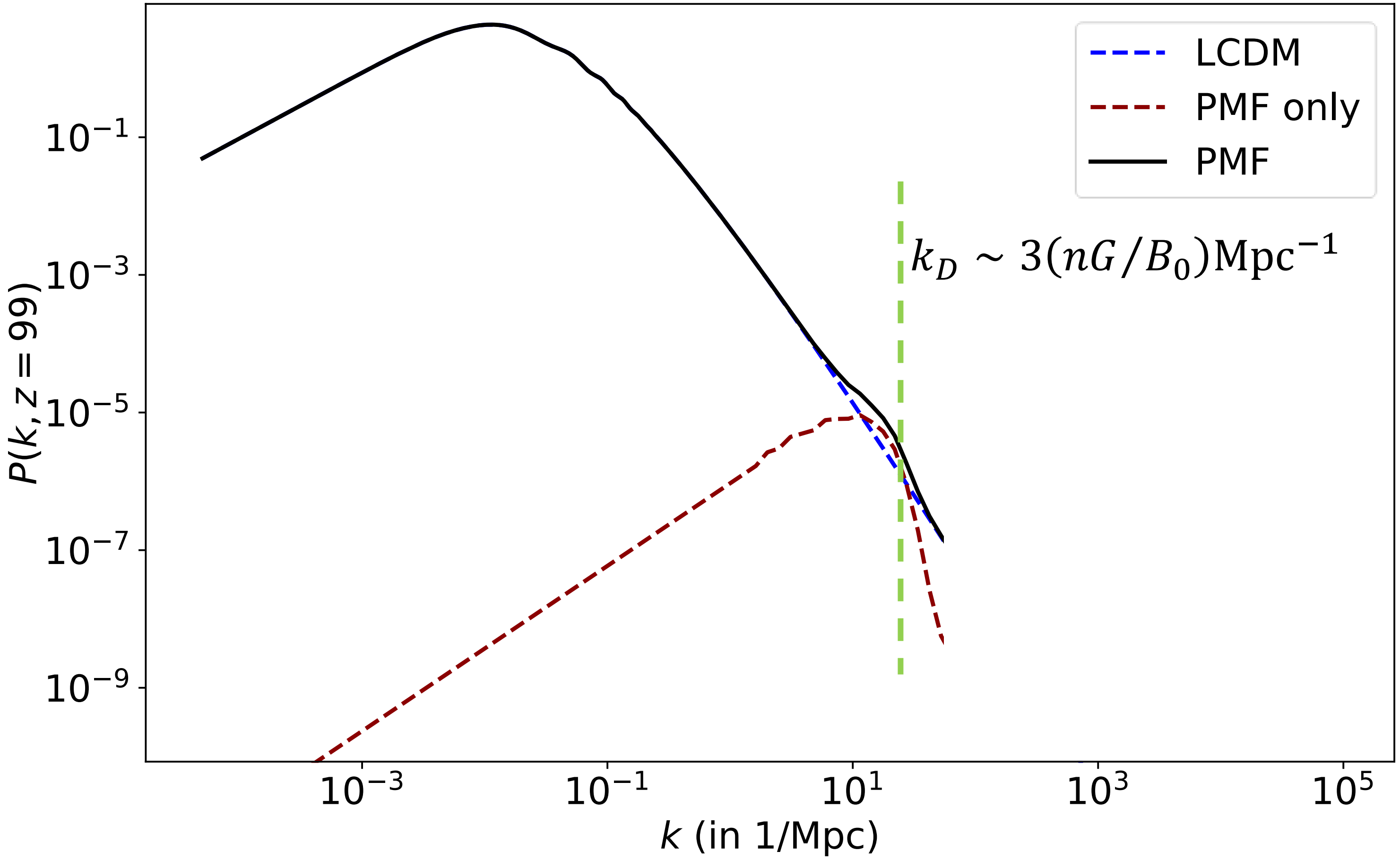
PRIMORDIAL MAGNETIC FIELDS ENHANCE DENSITY PERTURBATIONS



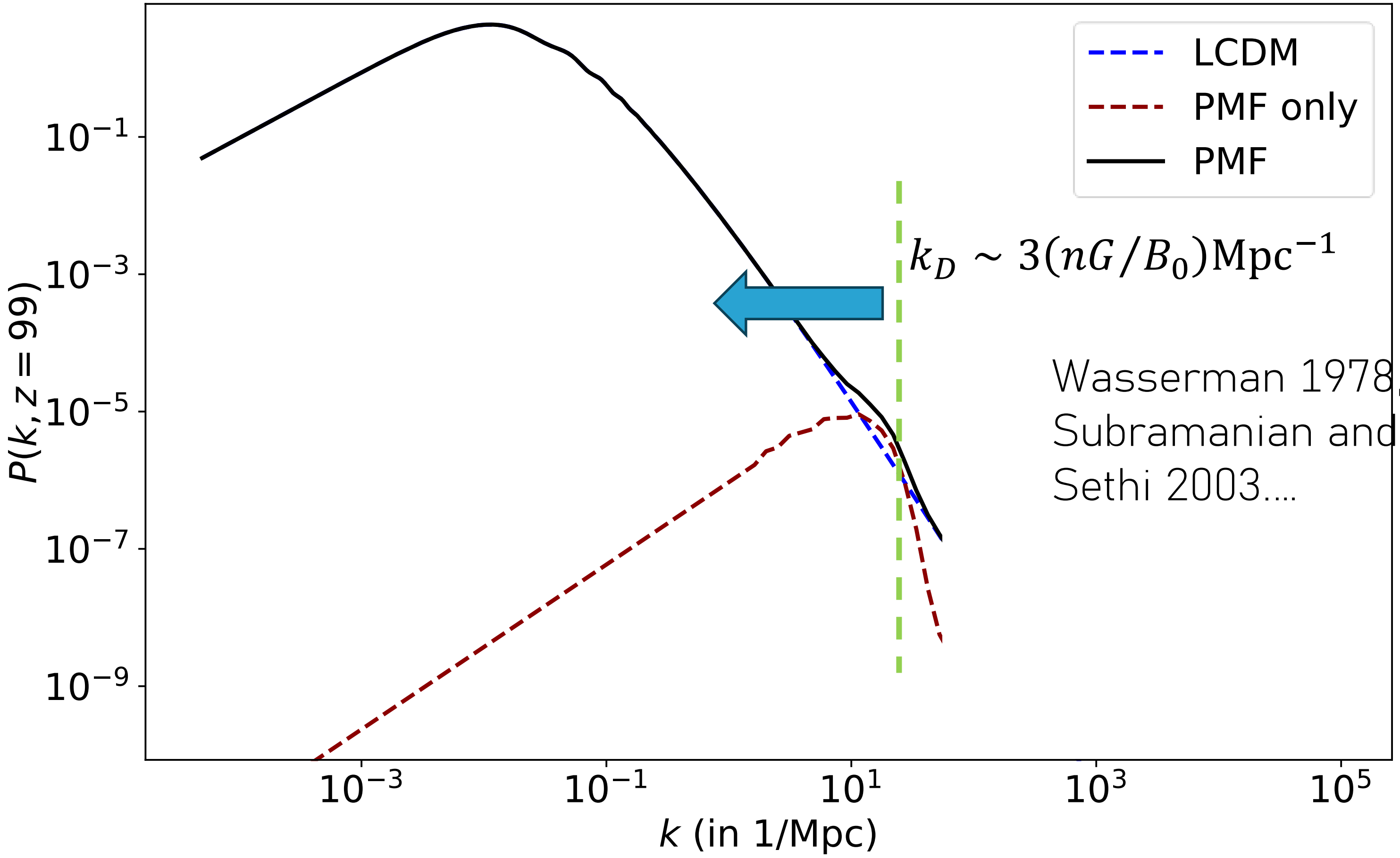
PRIMORDIAL MAGNETIC FIELDS ENHANCE POWER SPECTRUM ON SMALL SCALES



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

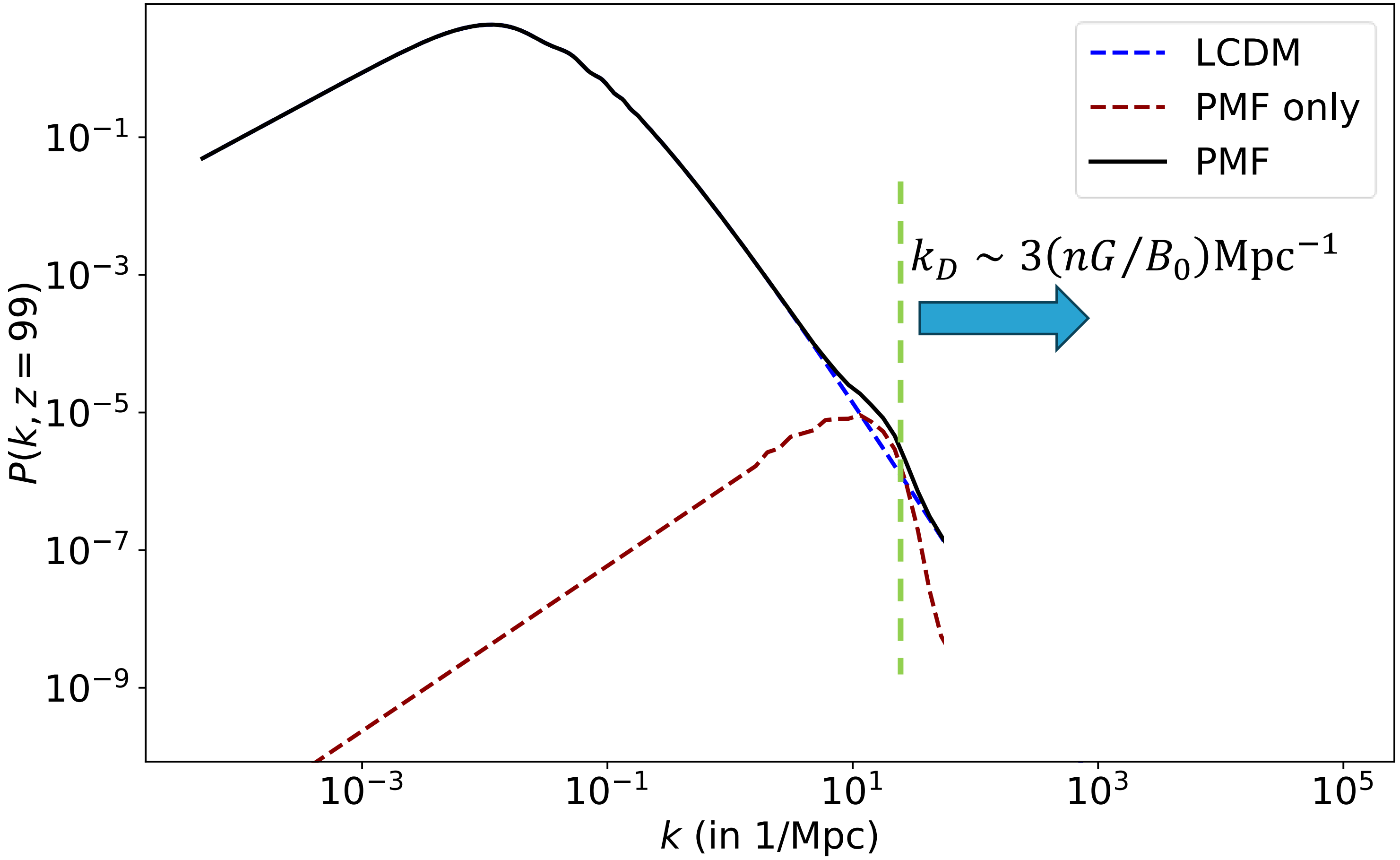


EARLIER WORKS FOCUSED ON SCALES BELOW MAGNETIC DAMPING (JEANS) SCALE

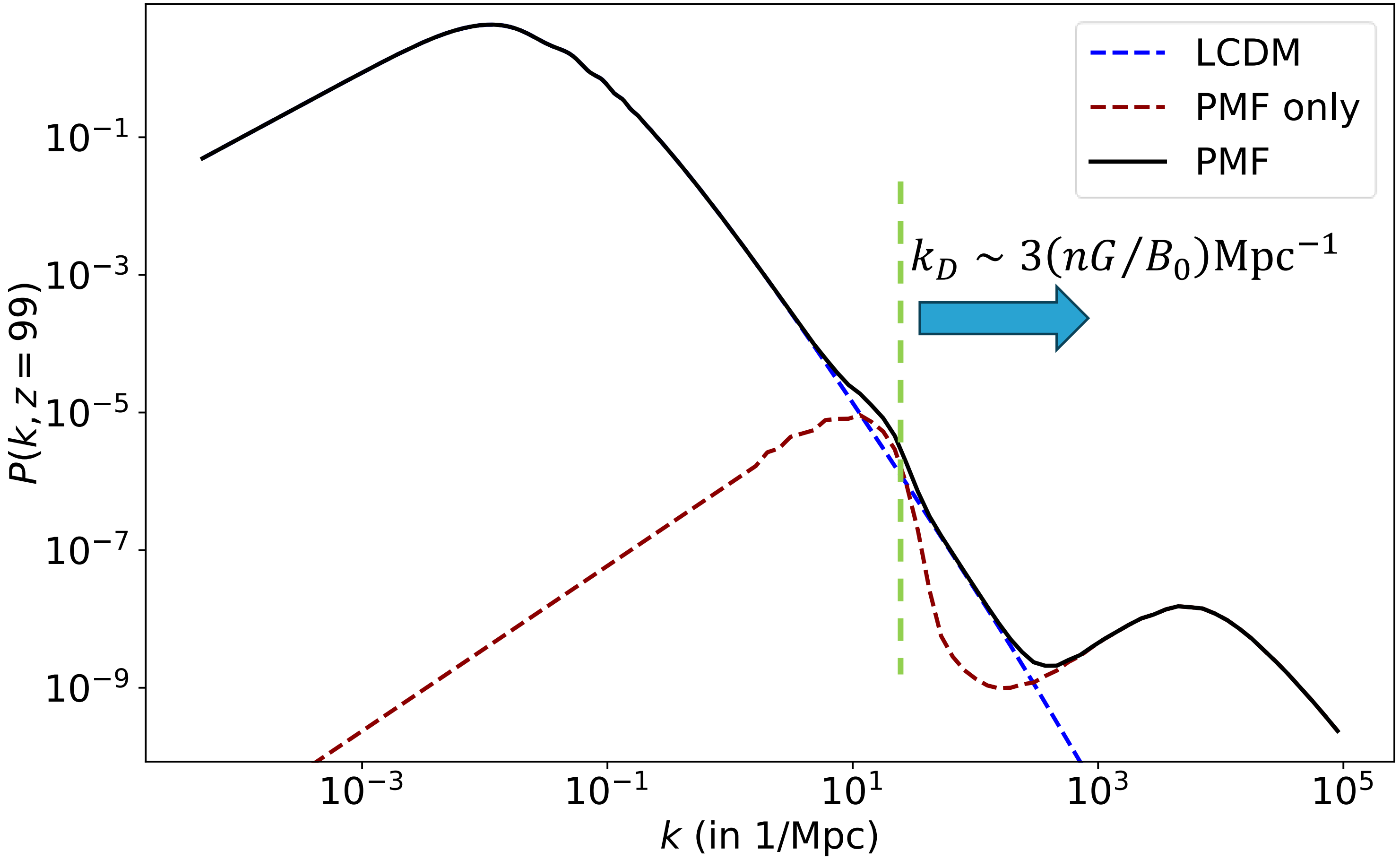


Wasserman 1978, Kim et al 1996, Subramanian and Barrow 1997, Gopal and Sethi 2003....

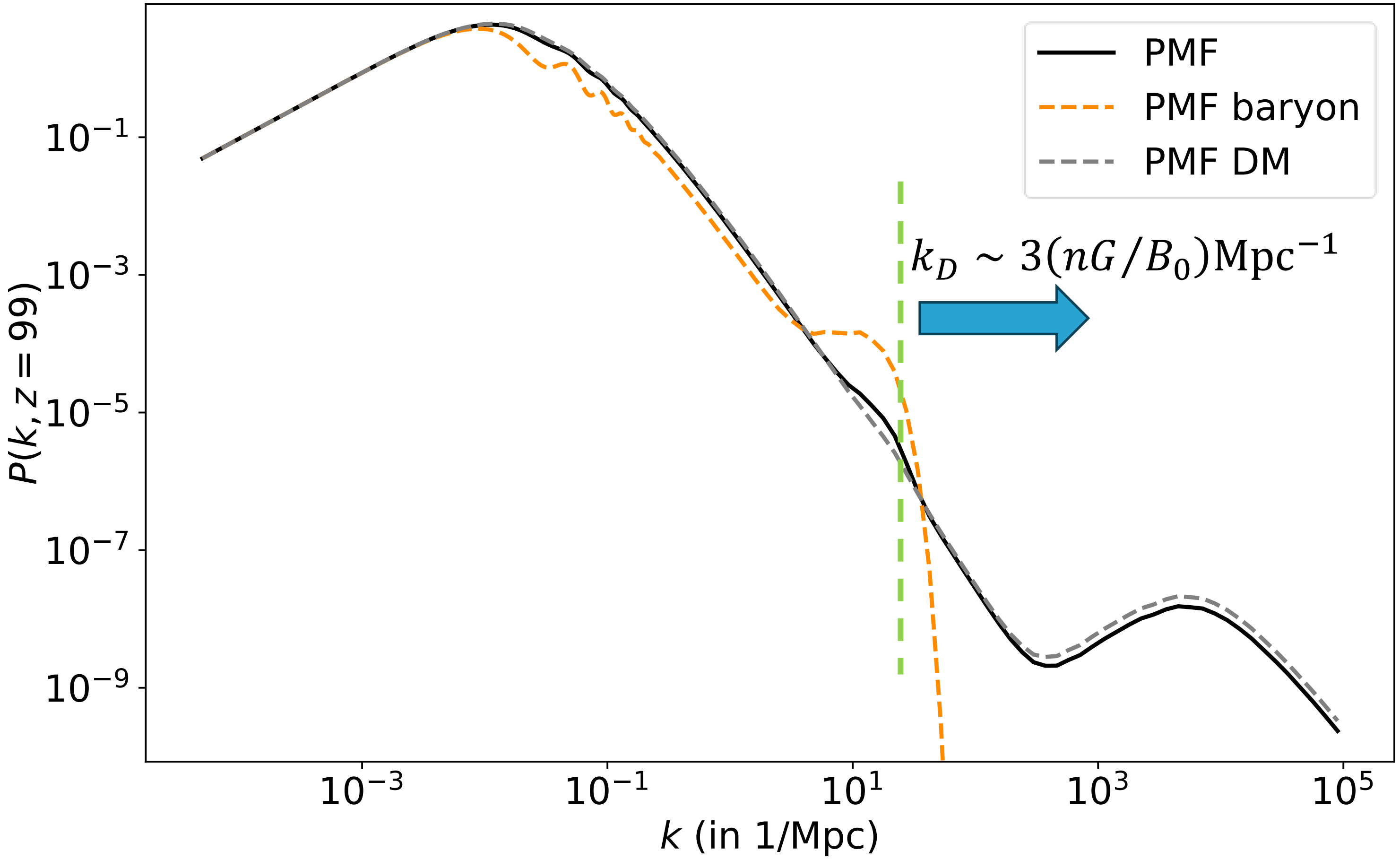
MY STUDY FOCUSES ON SCALES BELOW MAGNETIC DAMPING (JEANS) SCALE



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

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

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

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

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

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

NON-RELATIVISTIC IDEAL MHD IN PHOTON DRAG REGIME

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

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

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

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

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

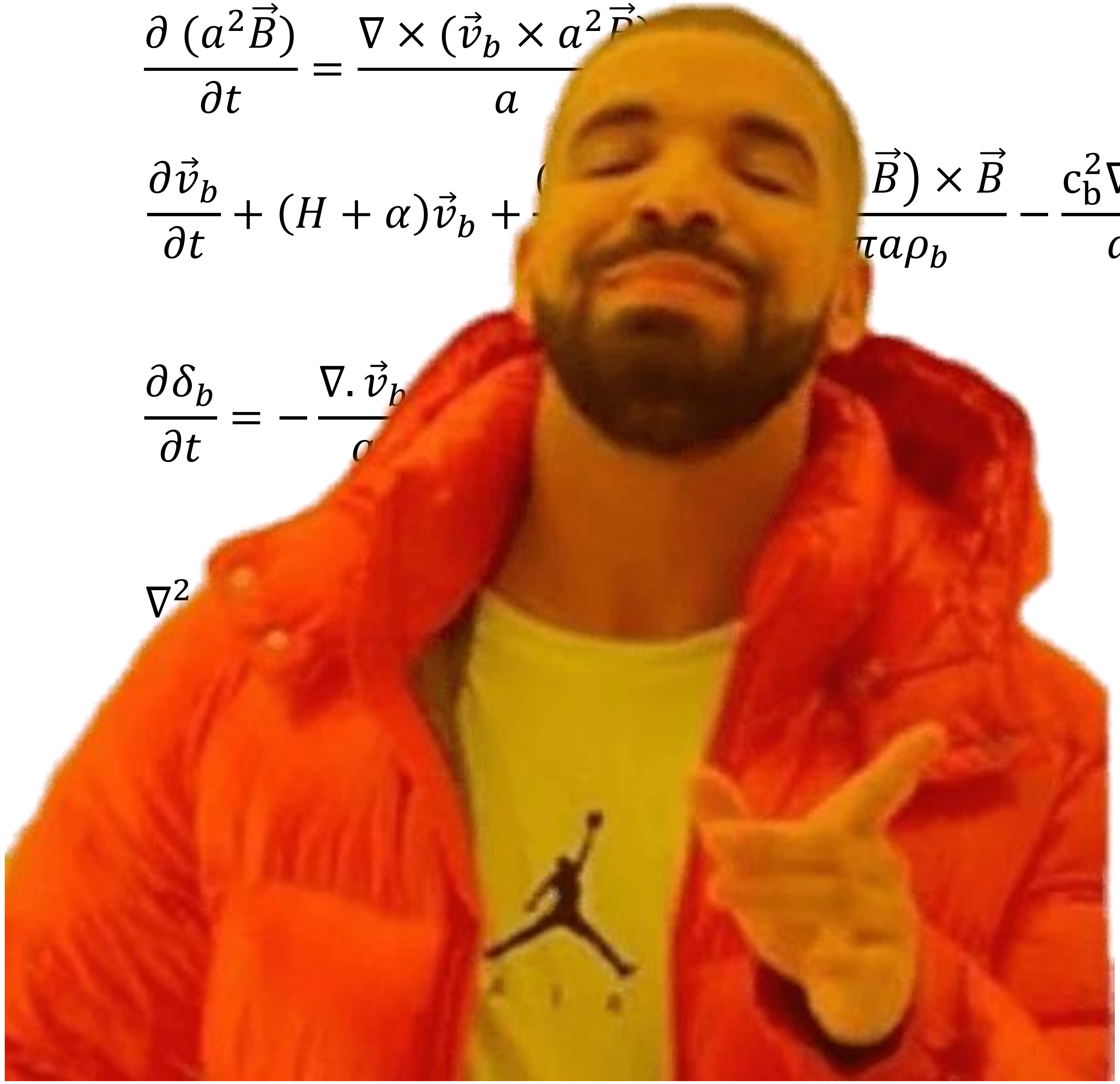
NON-RELATIVISTIC IDEAL MHD IN PHOTON DRAG REGIME

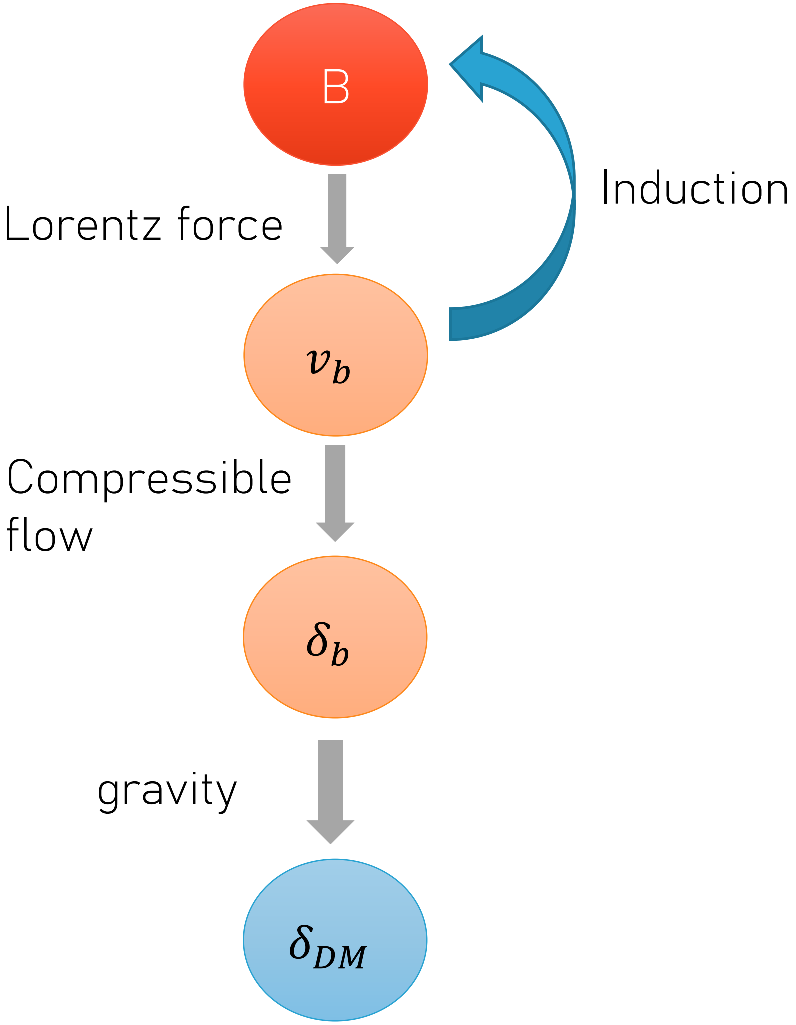
$$\frac{\partial\,(a^2\vec{B})}{\partial t} = \frac{\nabla \times (\vec{v}_b \times a^2\vec{B}\ldots}{a}$$

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

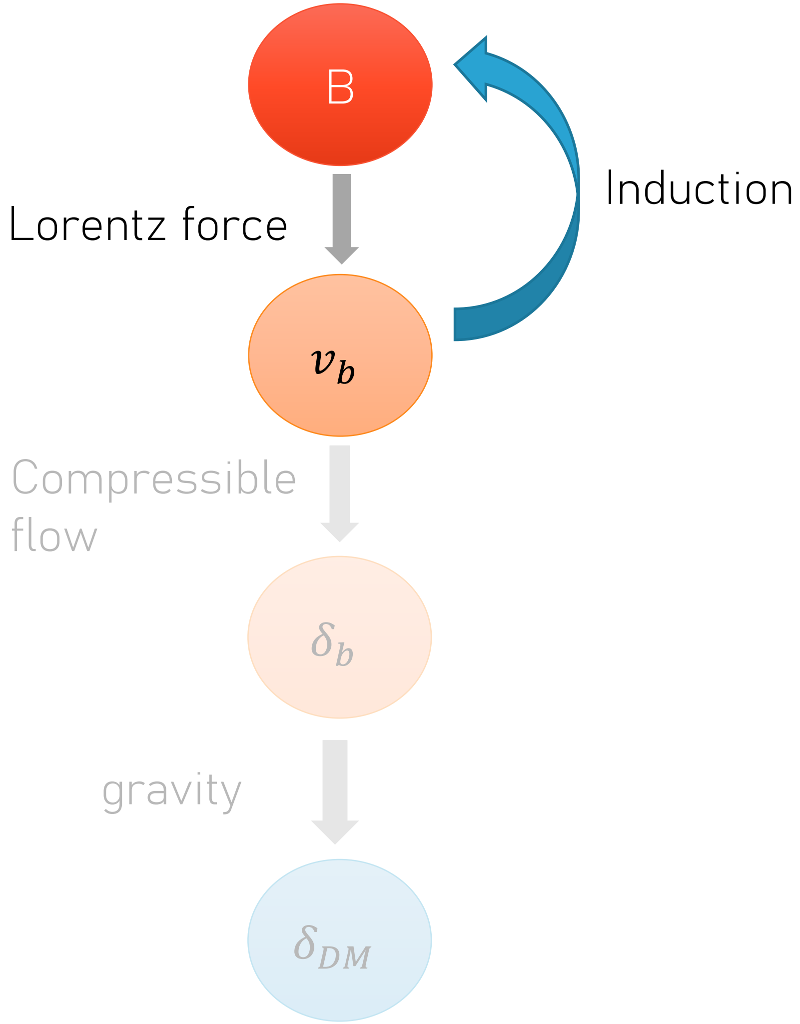
$$\frac{\partial \delta_b}{\partial t} = -\frac{\nabla . \vec{v}_b}{a}$$

∇^2 …





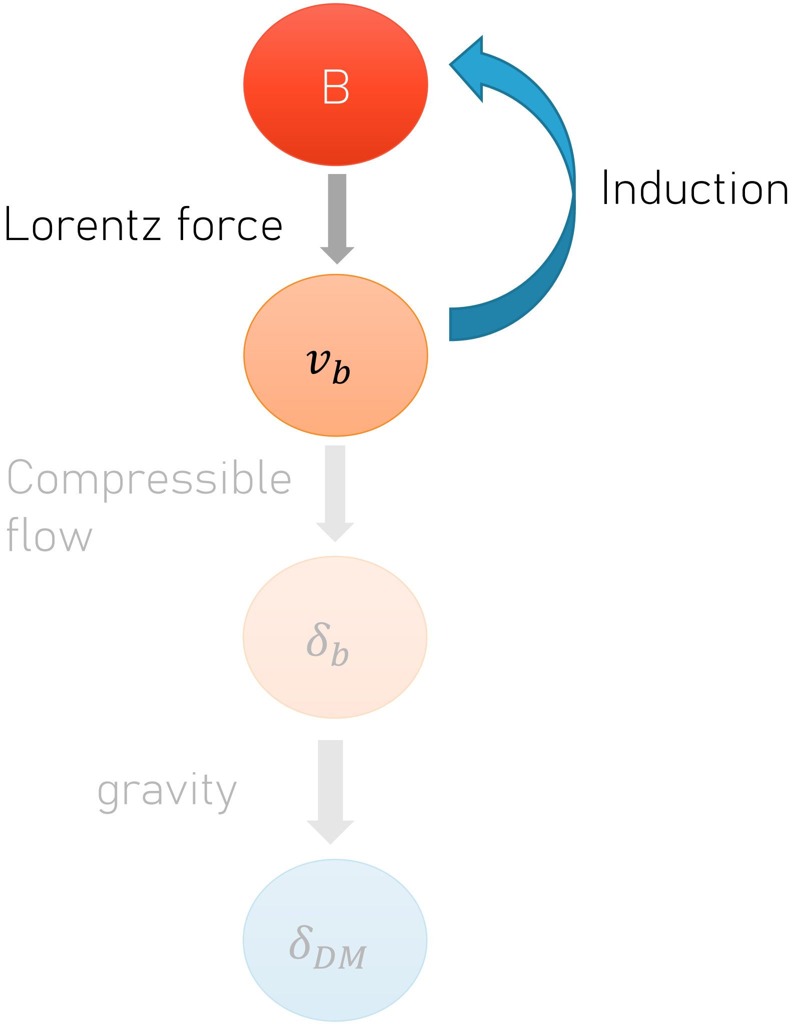
NON-RELATIVISTIC IDEAL MHD IN PHOTON DRAG REGIME: CAN SOLVE B ANALYTICALLY!!



MAGNETIC DAMPING SCALE

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

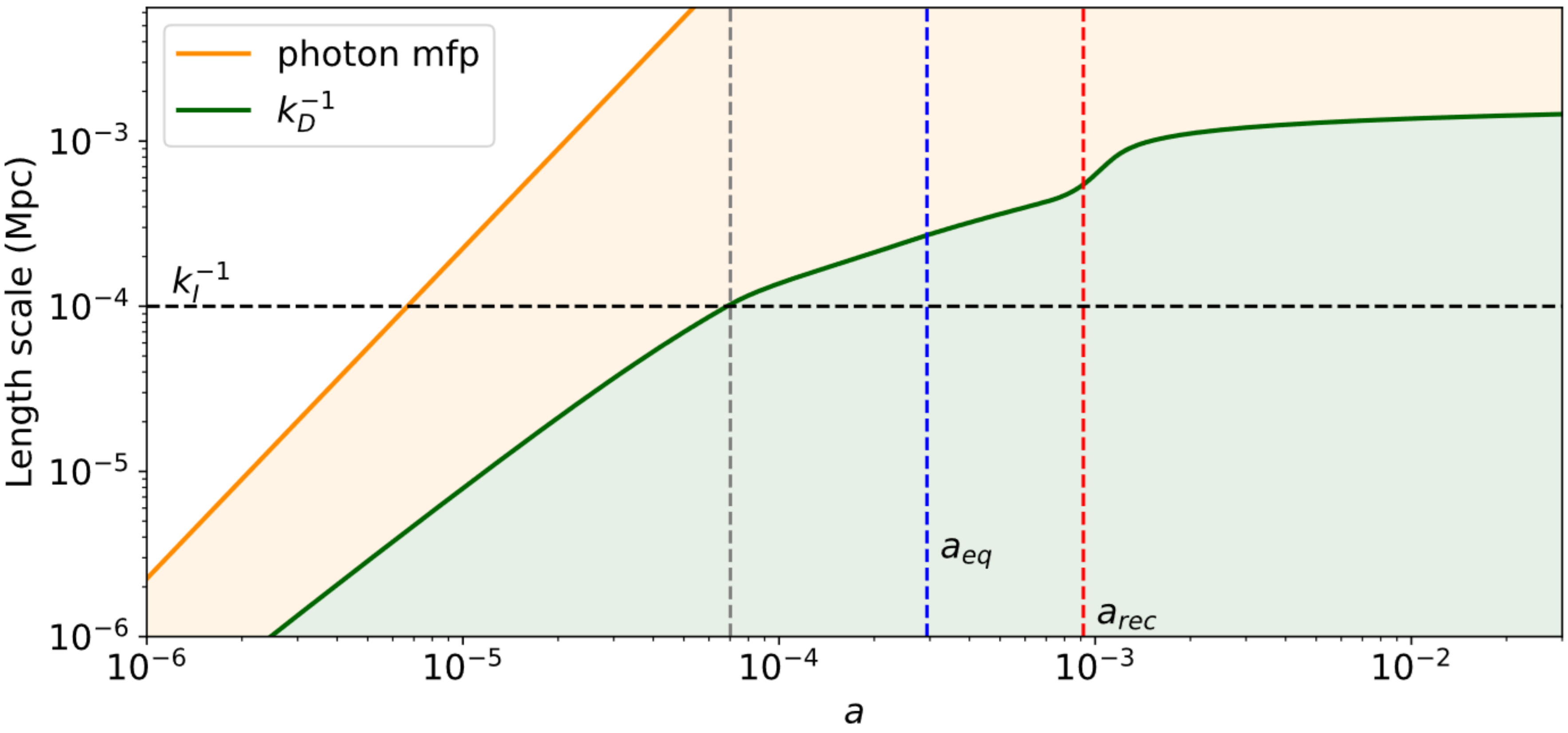
$$k_D^{-1}(a) \sim \tau v_b$$



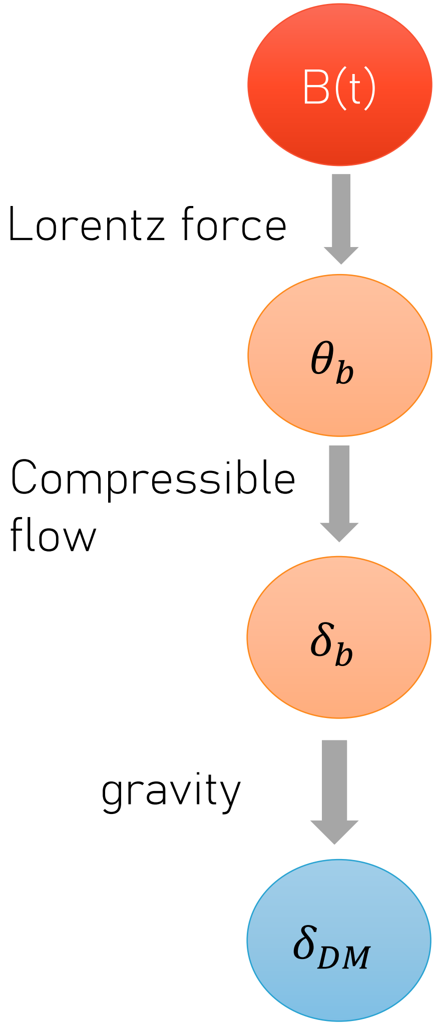
MAGNETIC DAMPING SCALE EVOLUTION

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

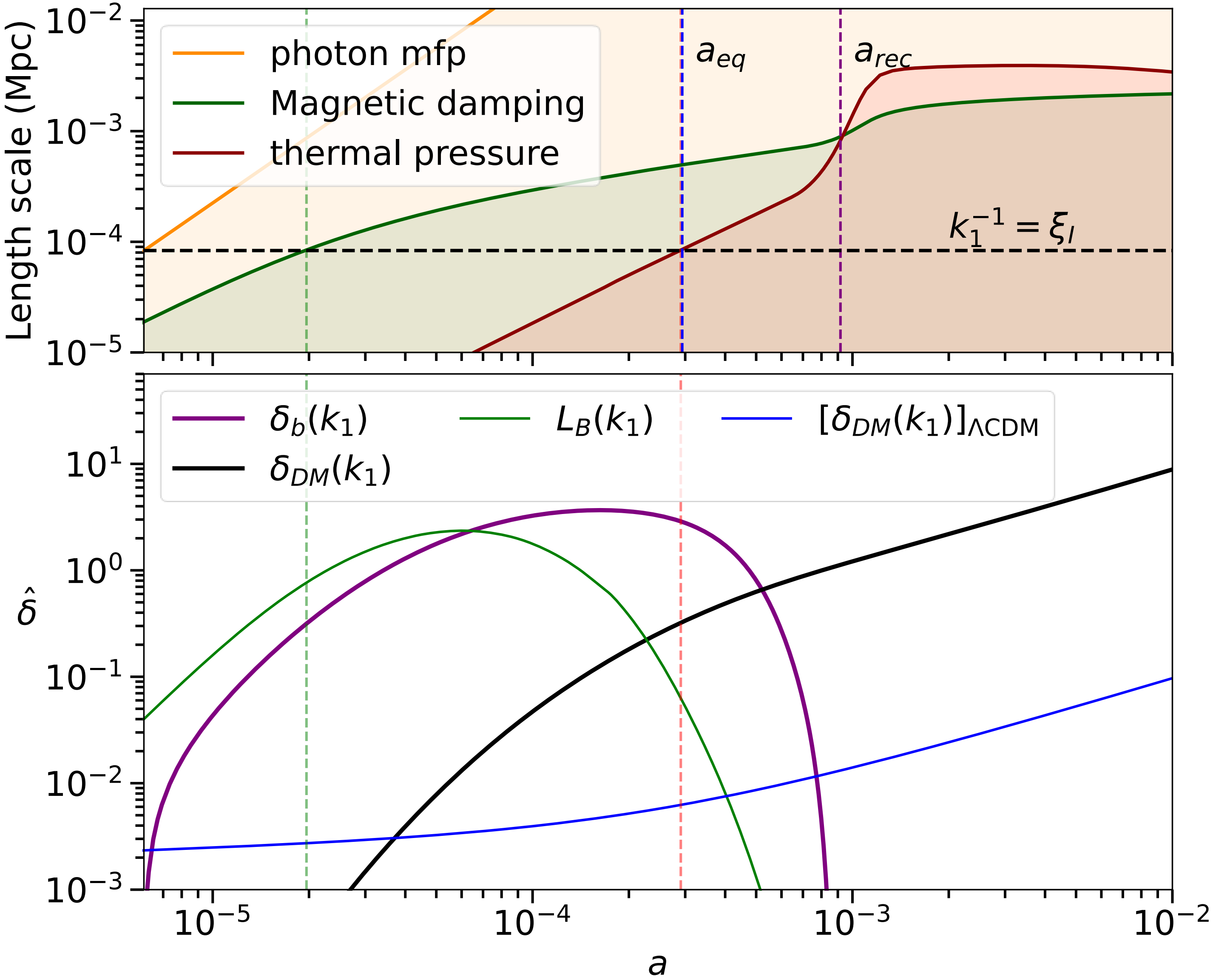
$$k_D^{-1}(a) \sim \tau v_b$$

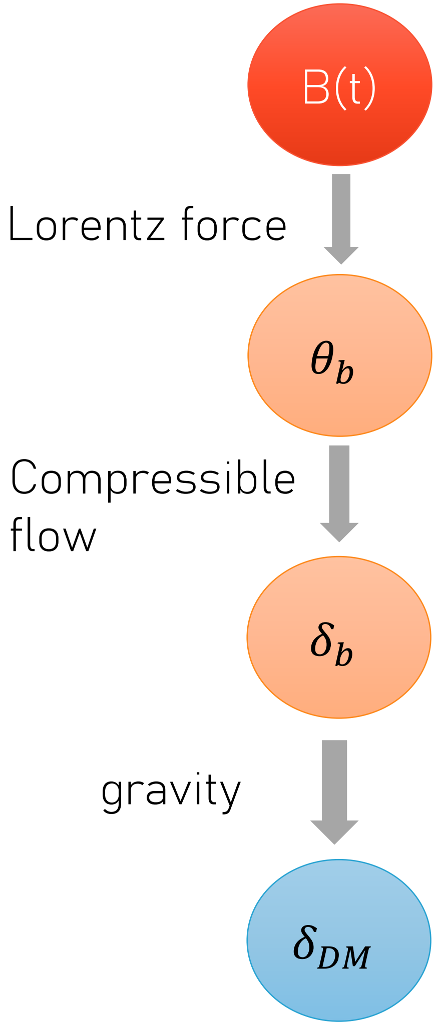


SOLVE PERTURBATIONS WITH MAGNETIC FIELDS AS EXTERNAL SOURCE

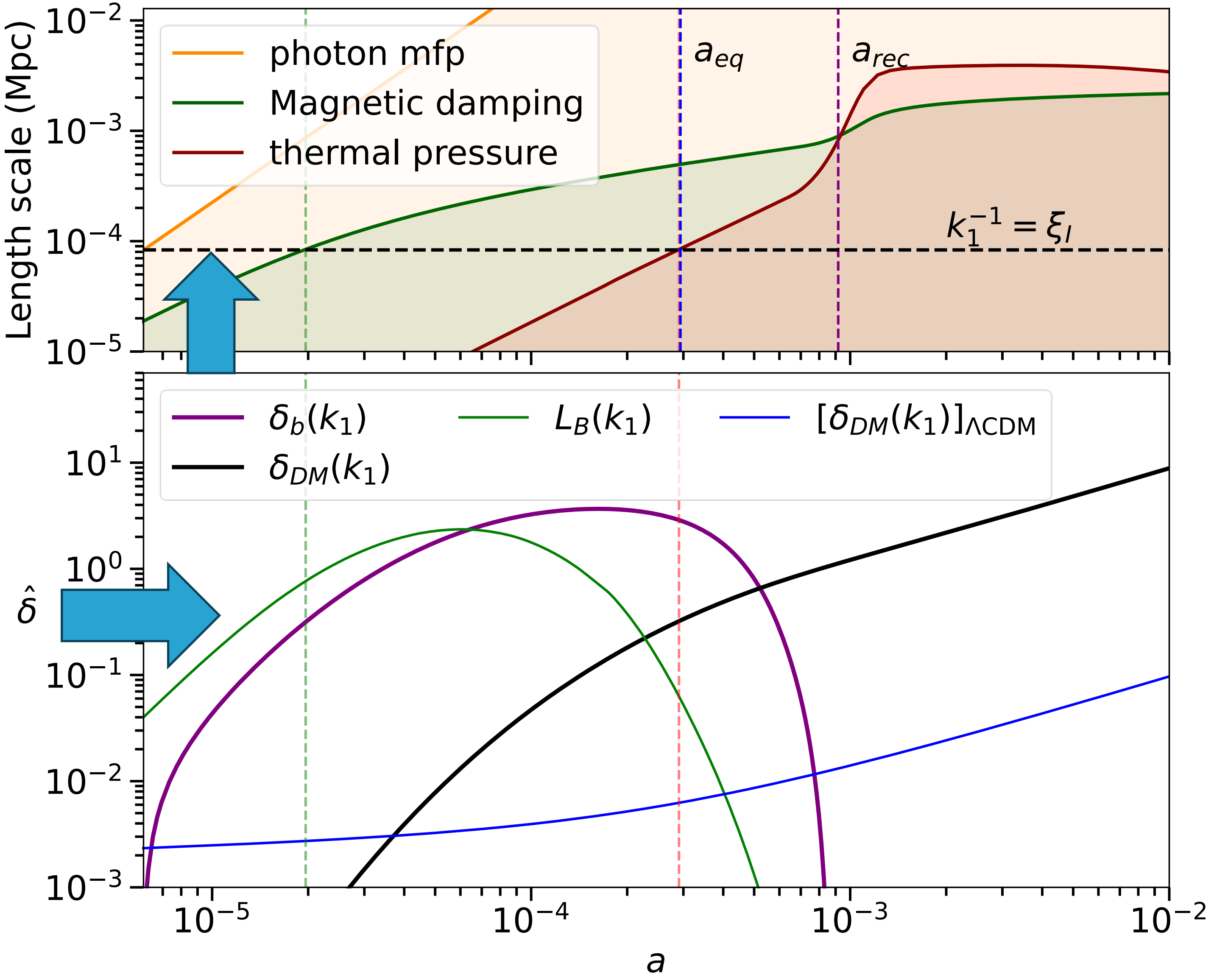


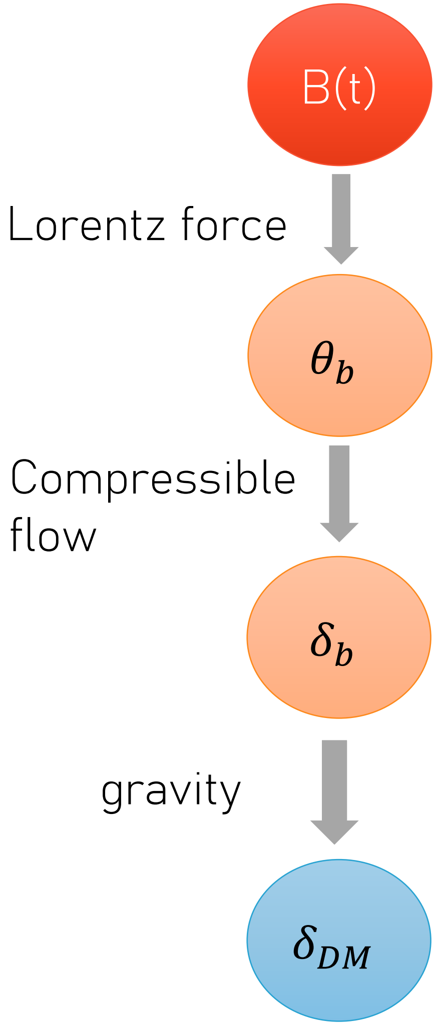
PERTURBATION EVOLUTION PLOT



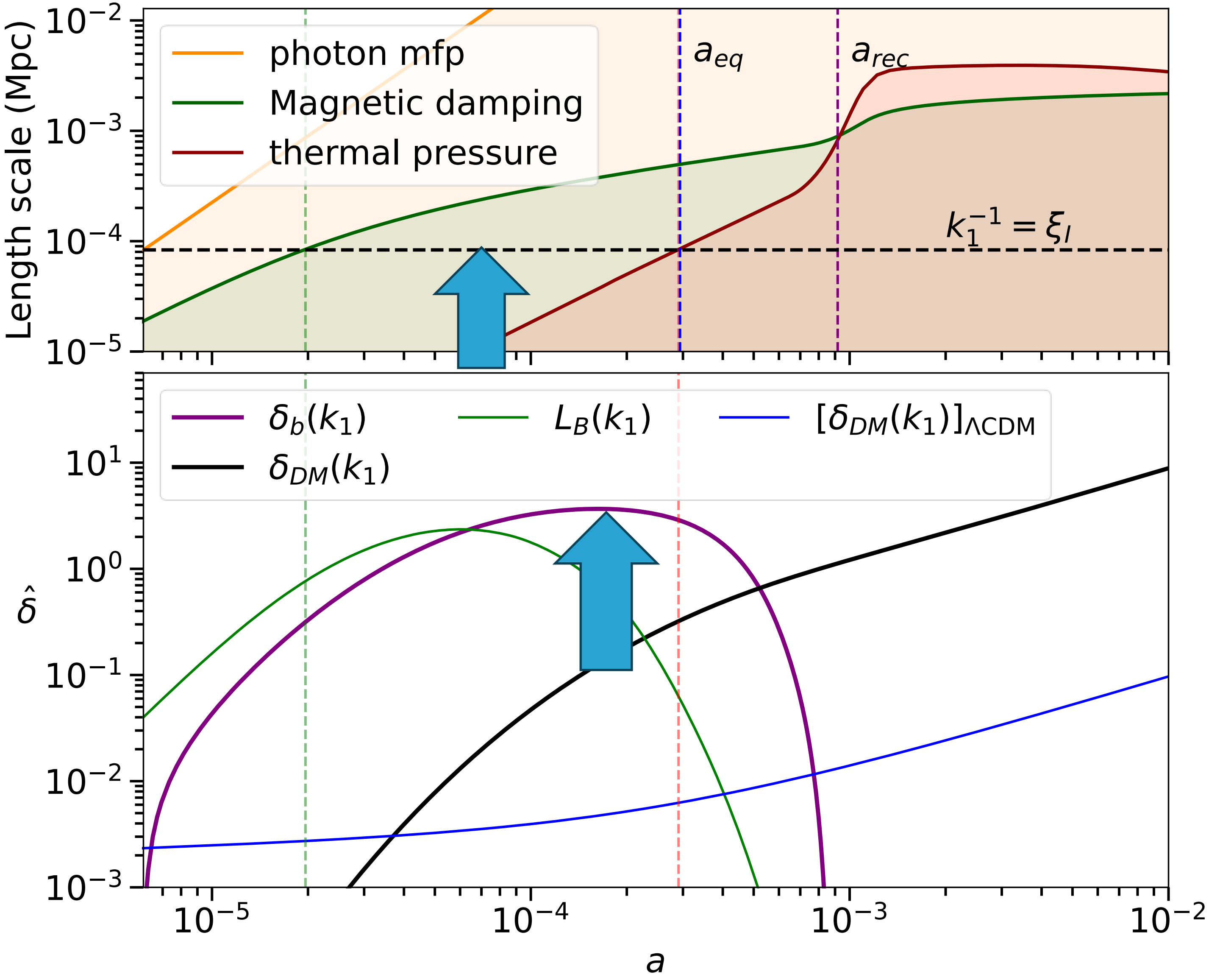


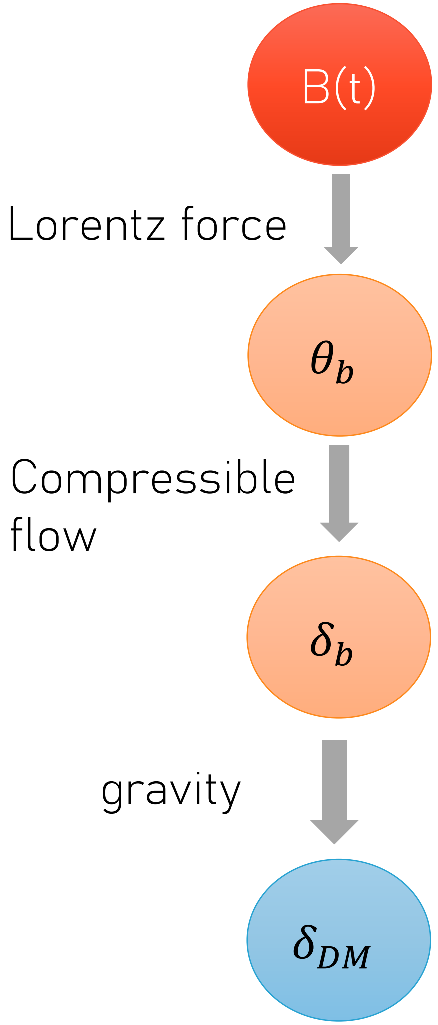
LORENTZ FORCE ENHANCES BARYON PERTURBATIONS FOR MODES OUTSIDE k_D^{-1}



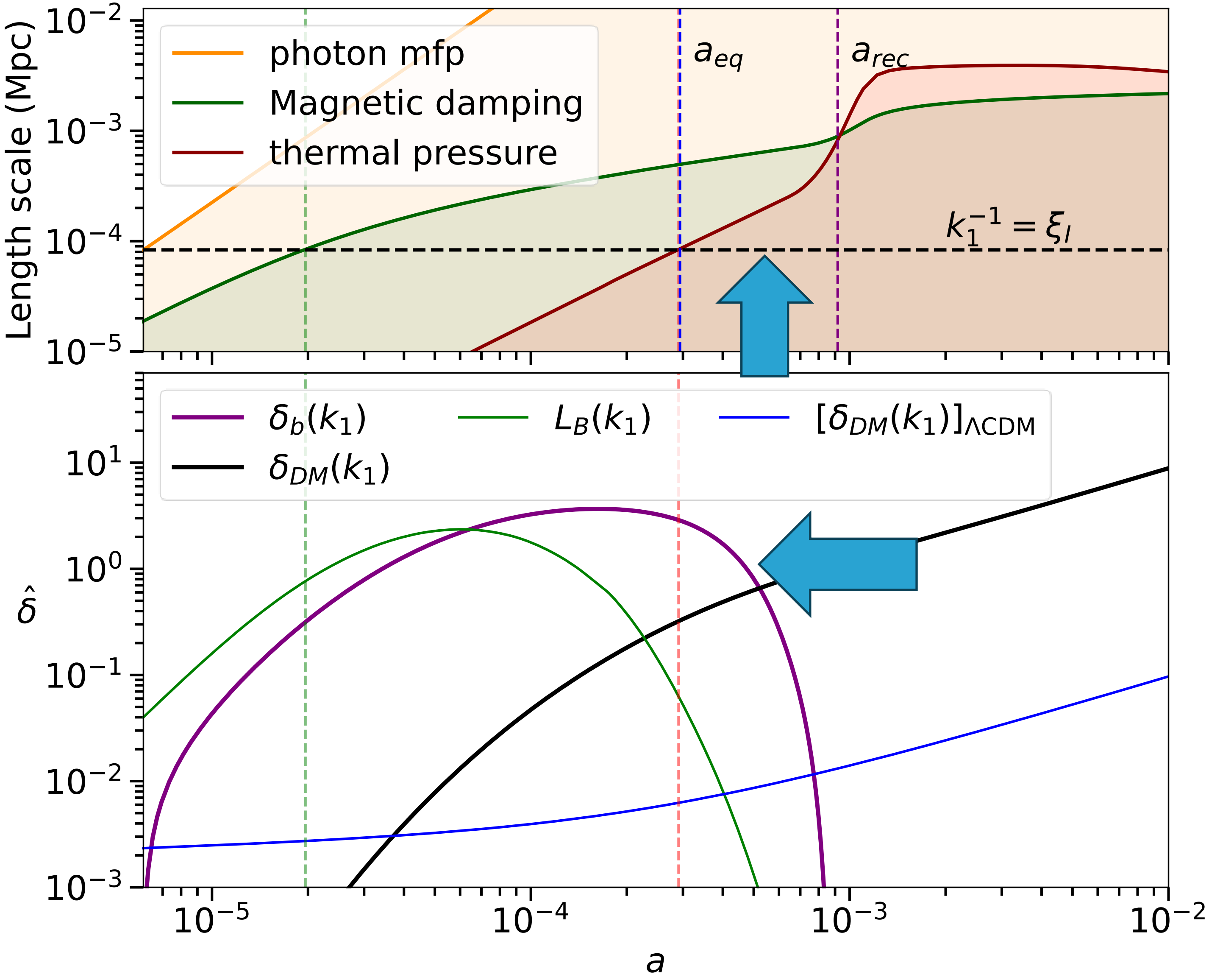


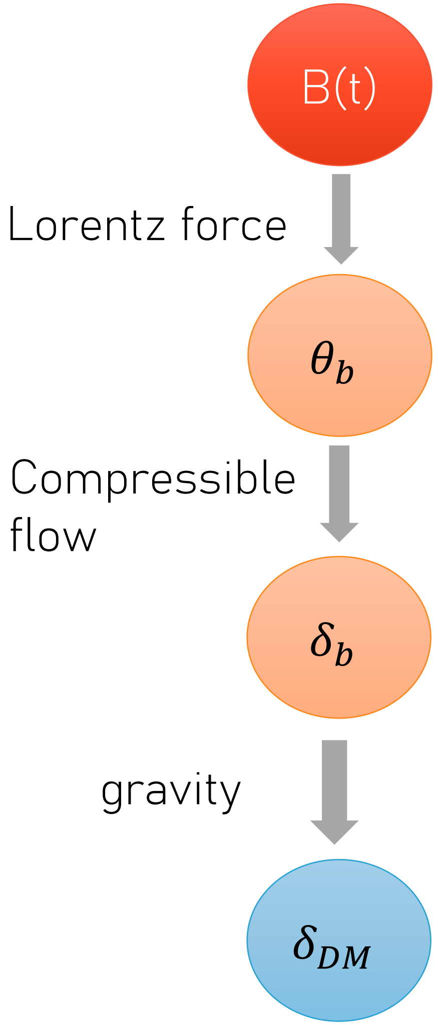
BARYON PERTURBATIONS ASYMPTOTE ONCE MODE ENTERS k_D^{-1}



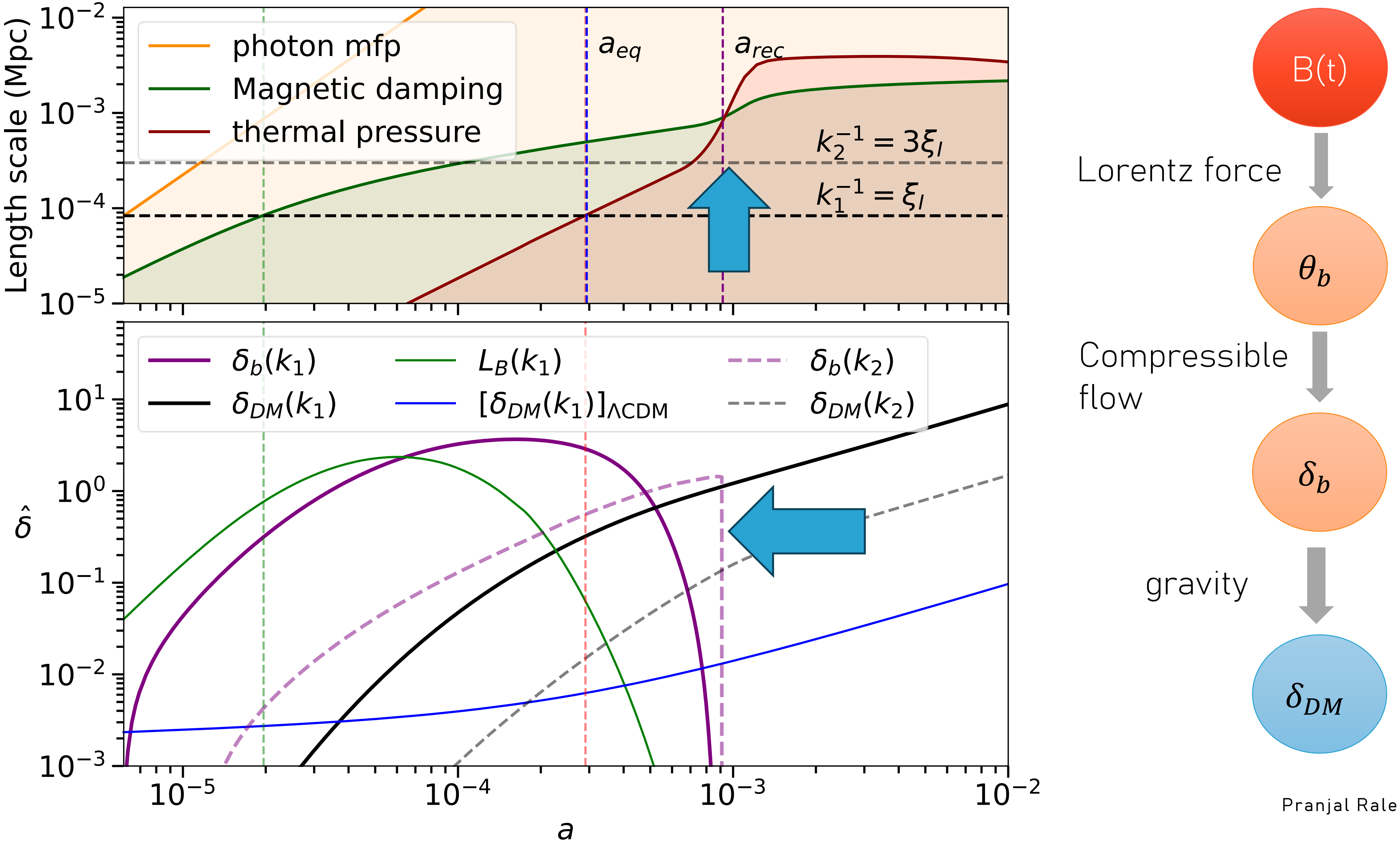


BARYON PERTURBATIONS DAMPED BY THERMAL PRESSURE

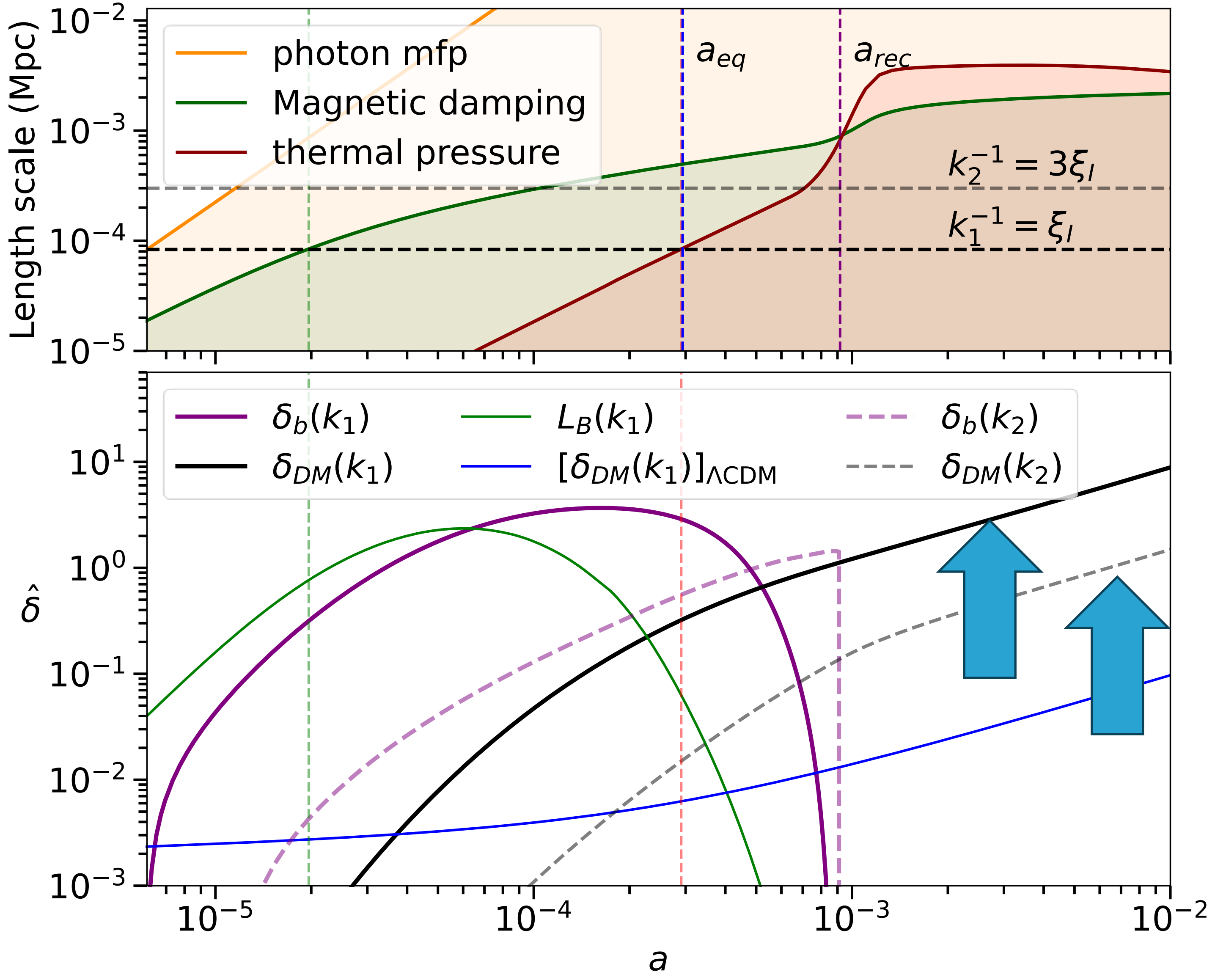


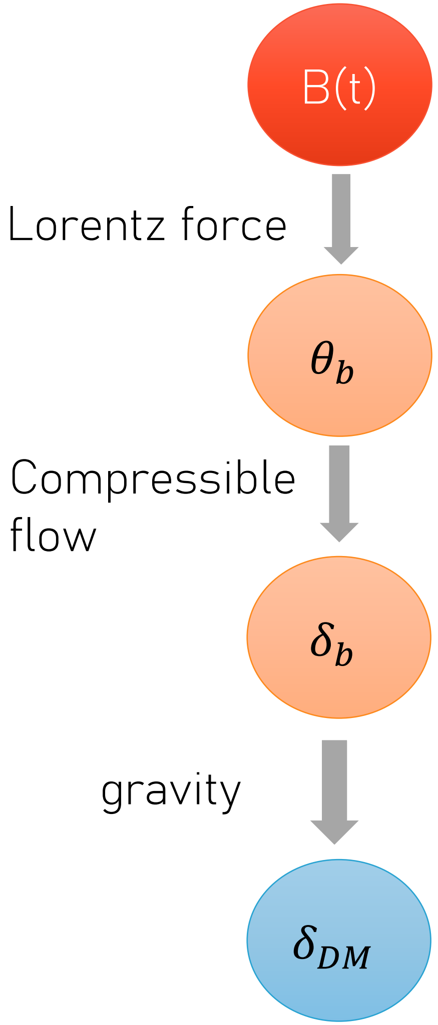


BARYON PERTURBATIONS DAMPED BY TURBULENCE AT RECOMBINATION

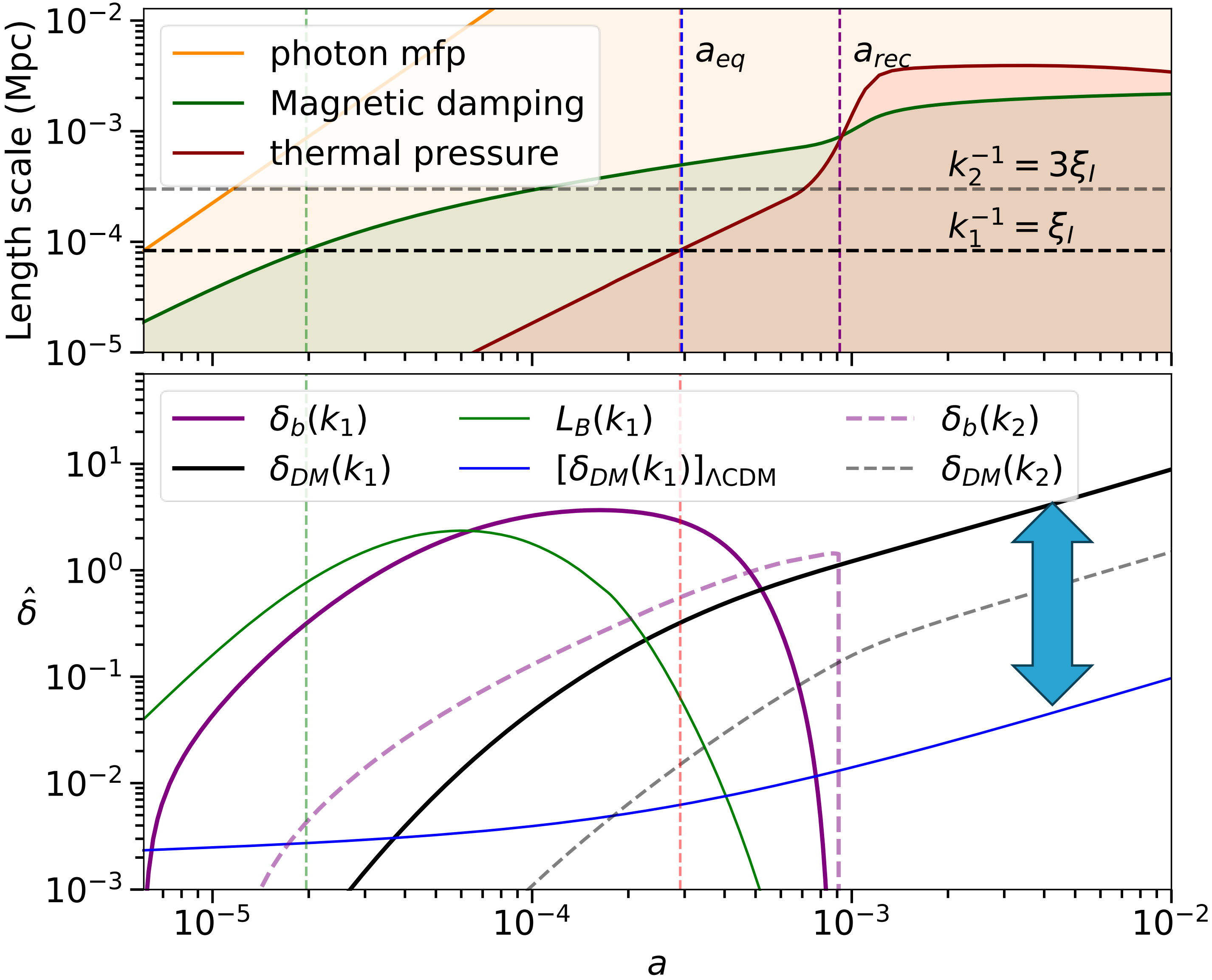


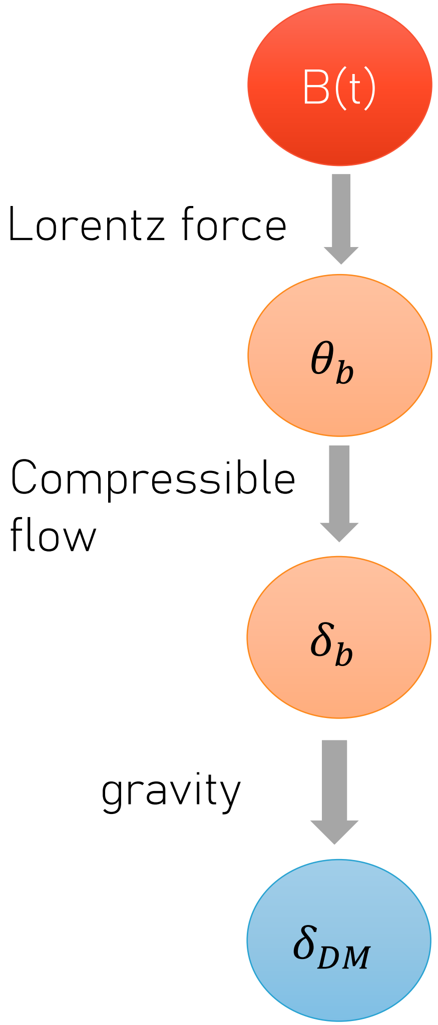
DARK MATTER PERTURBATIONS CONTINUES TO GROW!





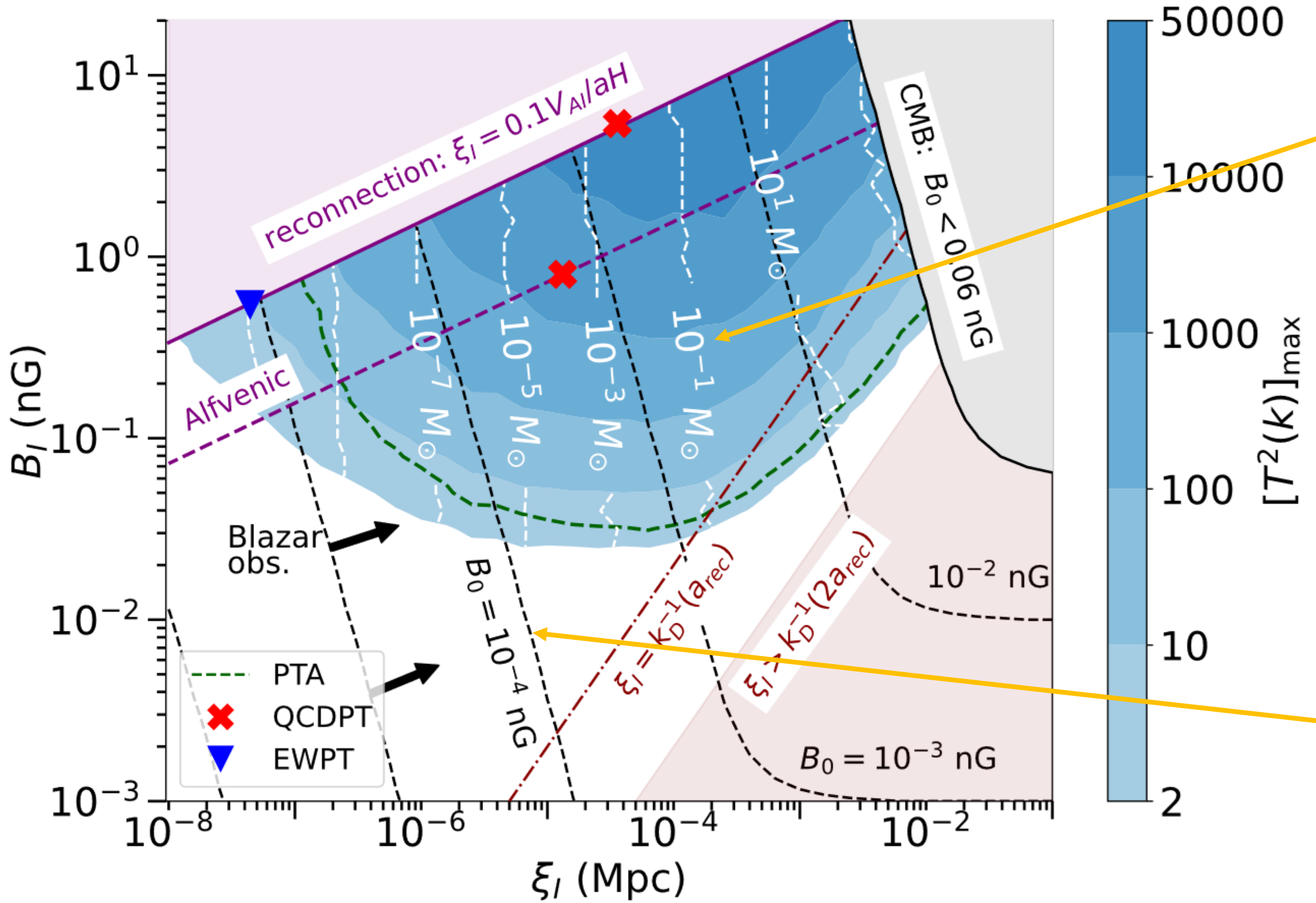
DARK MATTER PERTURBATIONS ENHANCED BY ORDERS OF MAGNITUDE COMPARED TO ΛCDM





CONNECTING WITH OBSERVABLES

PARAMETER SPACE WITH ENHANCED POWER ON SMALL SCALES

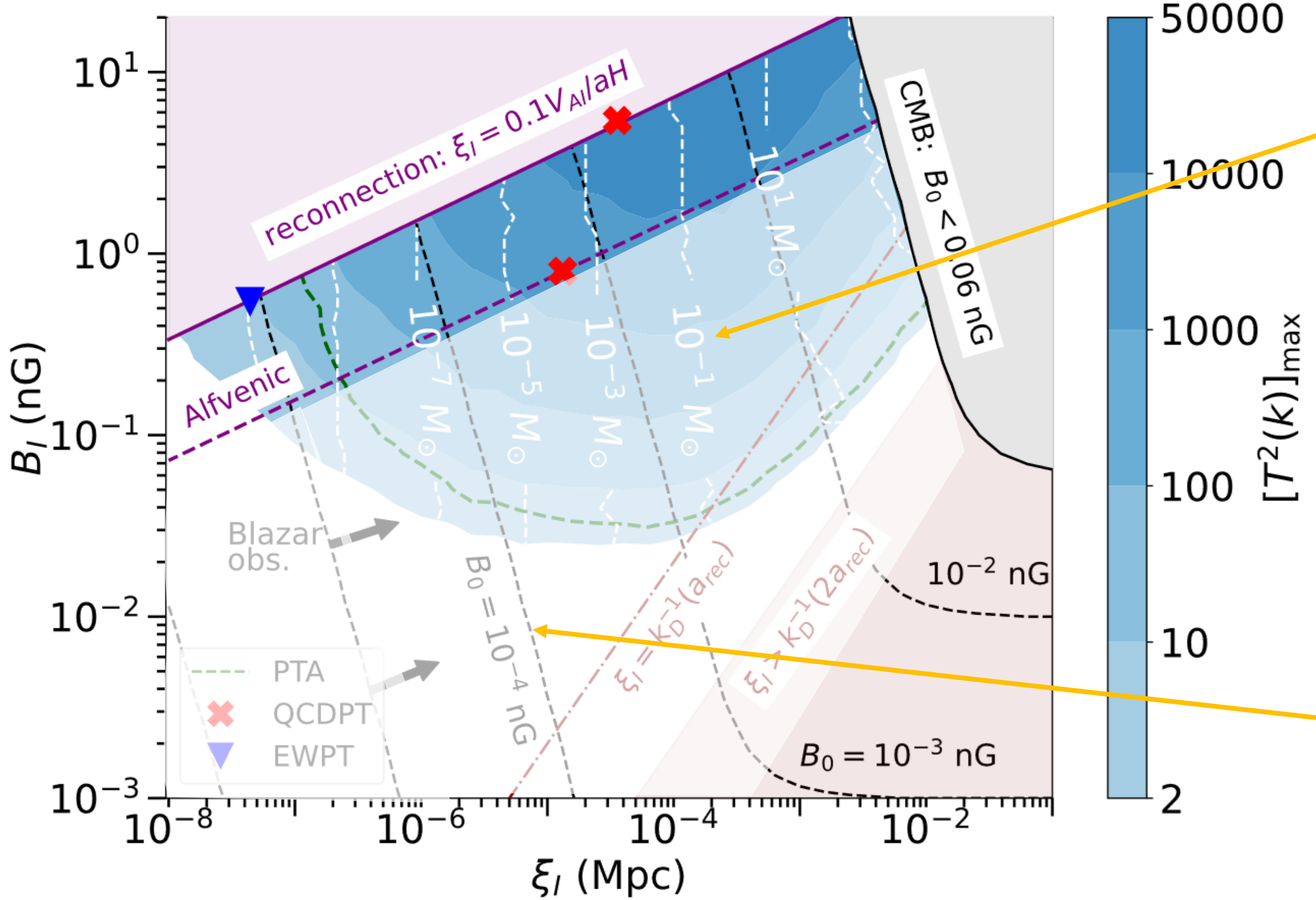


$= \frac{P(k)}{P_{\Lambda CDM}(k)}$

DM minihalo mass

Present-day magnetic field strength

PARAMETER SPACE EXPECTED FROM MAGNETOGENESIS FROM PHASE TRANSITIONS

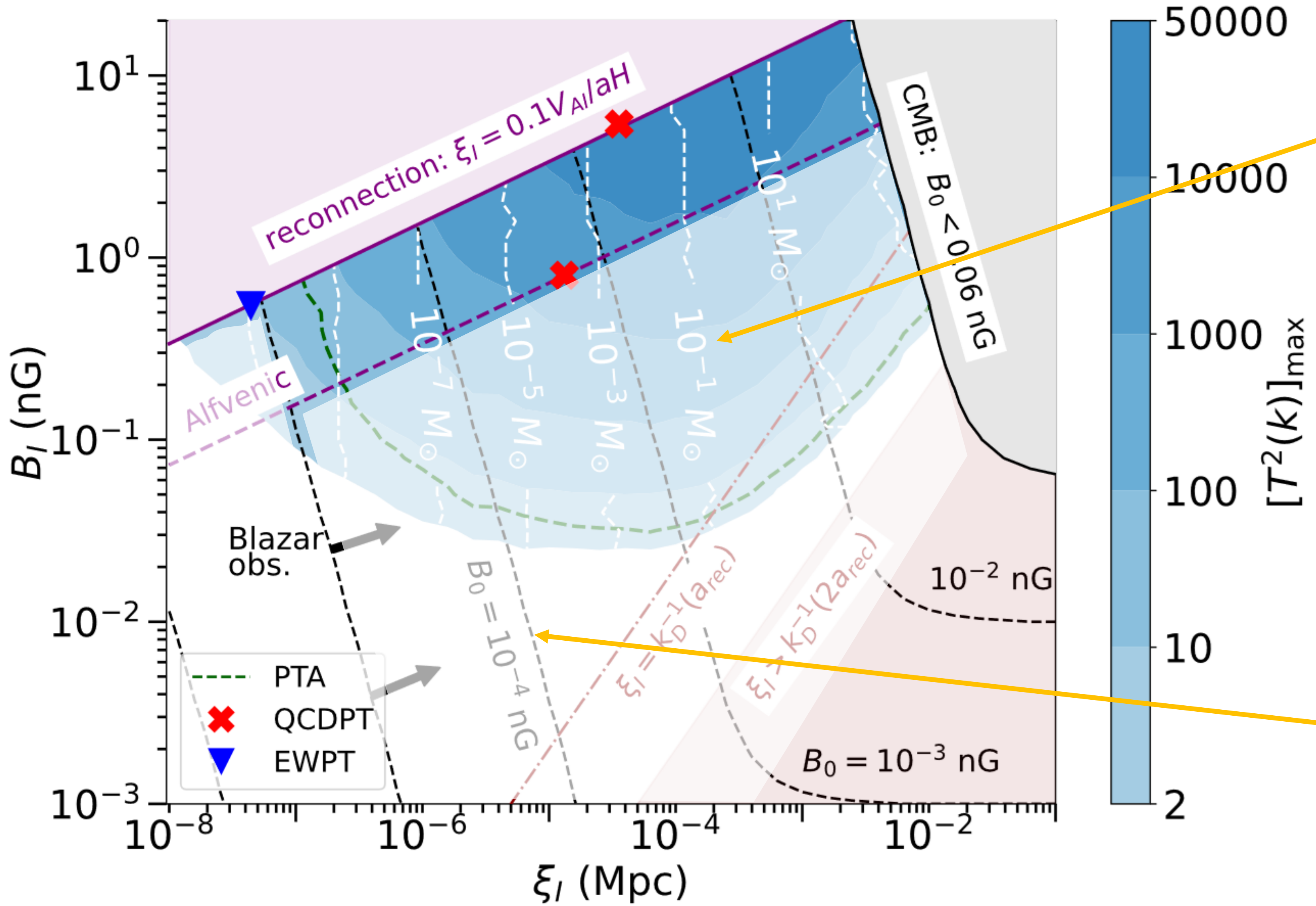


DM minihalo mass

$$[T^2(k)]_{max} = \frac{P(k)}{P_{\Lambda CDM}(k)}$$

Present-day magnetic field strength

PARAMETER SPACE TO EXPLAIN BLAZAR OBSERVATIONS

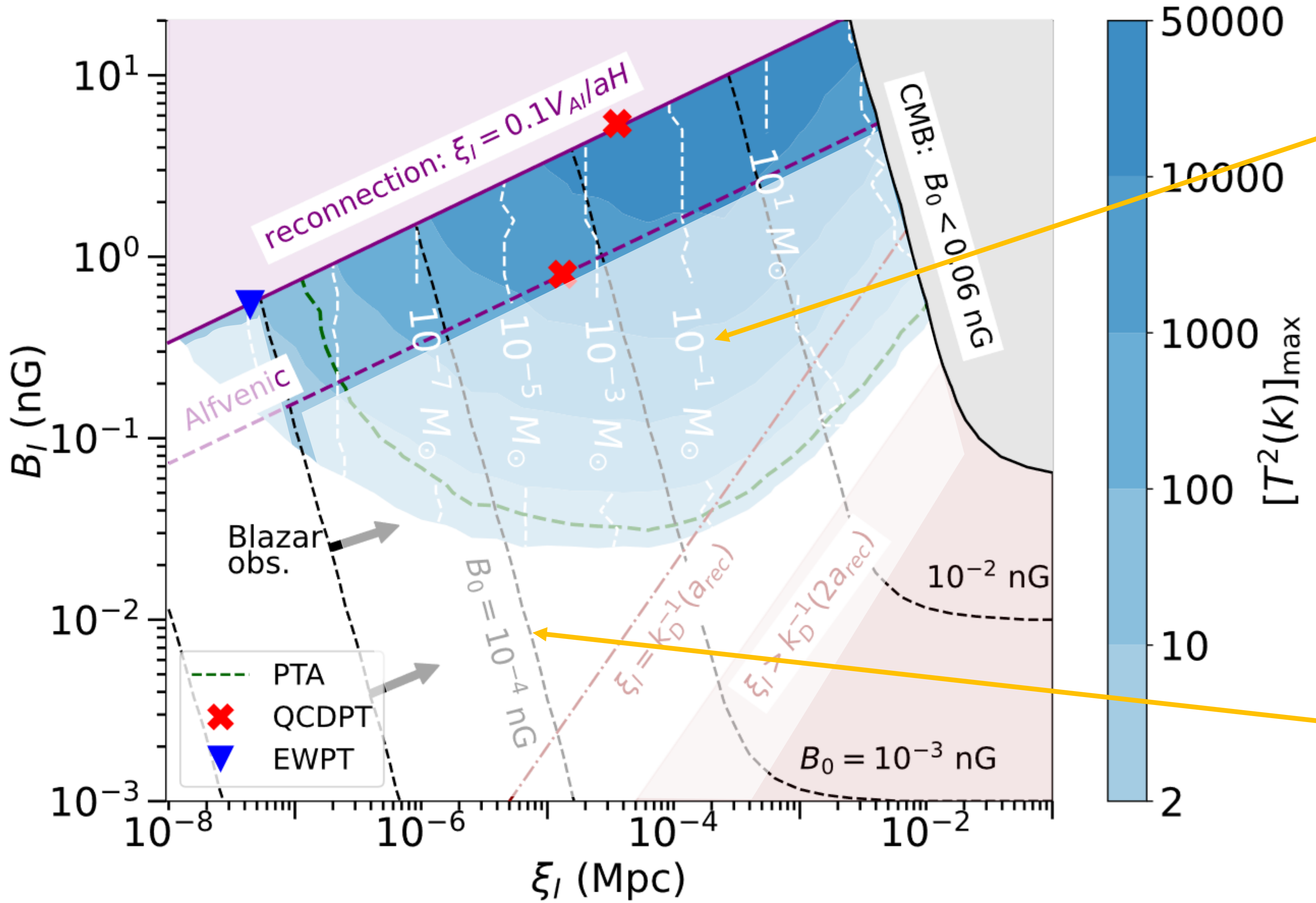


$= \frac{P(k)}{P_{\Lambda CDM}(k)}$

DM minihalo mass

Present-day magnetic field strength

UNIVERSE MAYBE FILLED WITH DARK MATTER MINIHALOS!!



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

DM minihalo mass

Present-day magnetic field strength

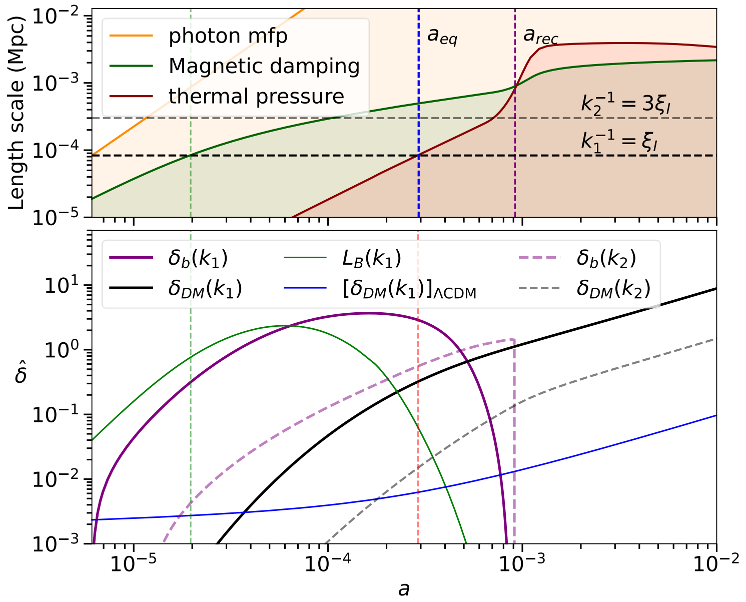
SUMMARY AND CONCLUDING REMARKS

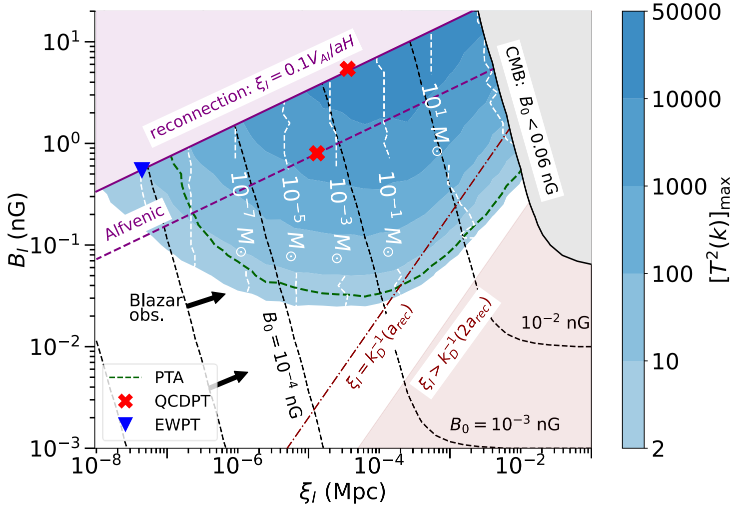
- Magnetic fields can enhance power on small scale dark matter distribution gravitationally.

- PTA/GAIA detection of DM minihalos can provide best probe of primordial magnetic fields

- Results are qualitative: Need MHD simulations to get accurate quantitative answers.

- 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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

ASSUMED

B_0 Gaussian

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

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

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

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

Jedamzik et al 1996,
Subramanian and Barrow 1997

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

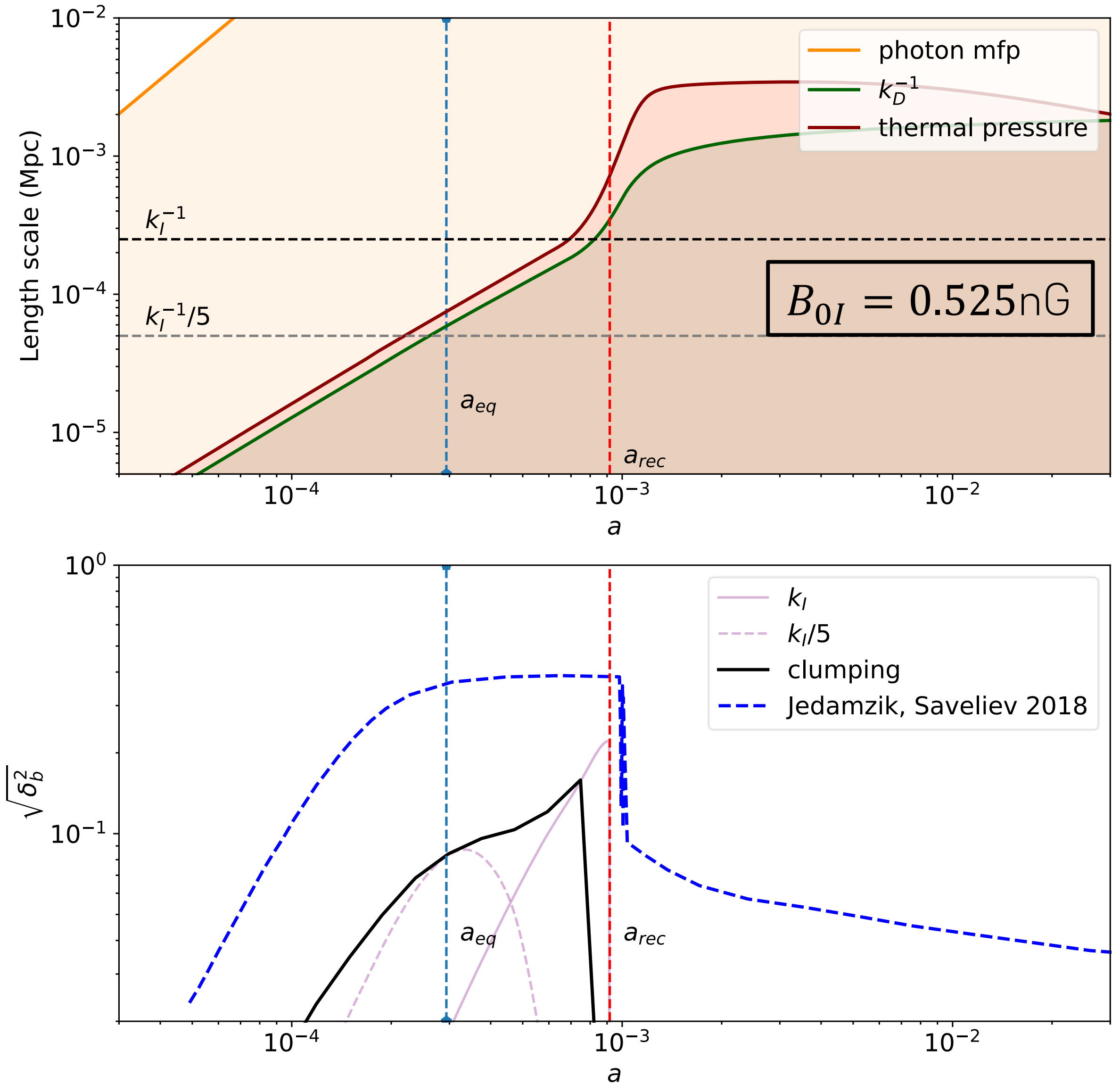
$$\frac{\partial \theta_b}{\partial t} + (H + \alpha)\theta_b = \frac{S_0(k)}{a^2} + \frac{c_b^2 k^2 \delta_b}{a}$$

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

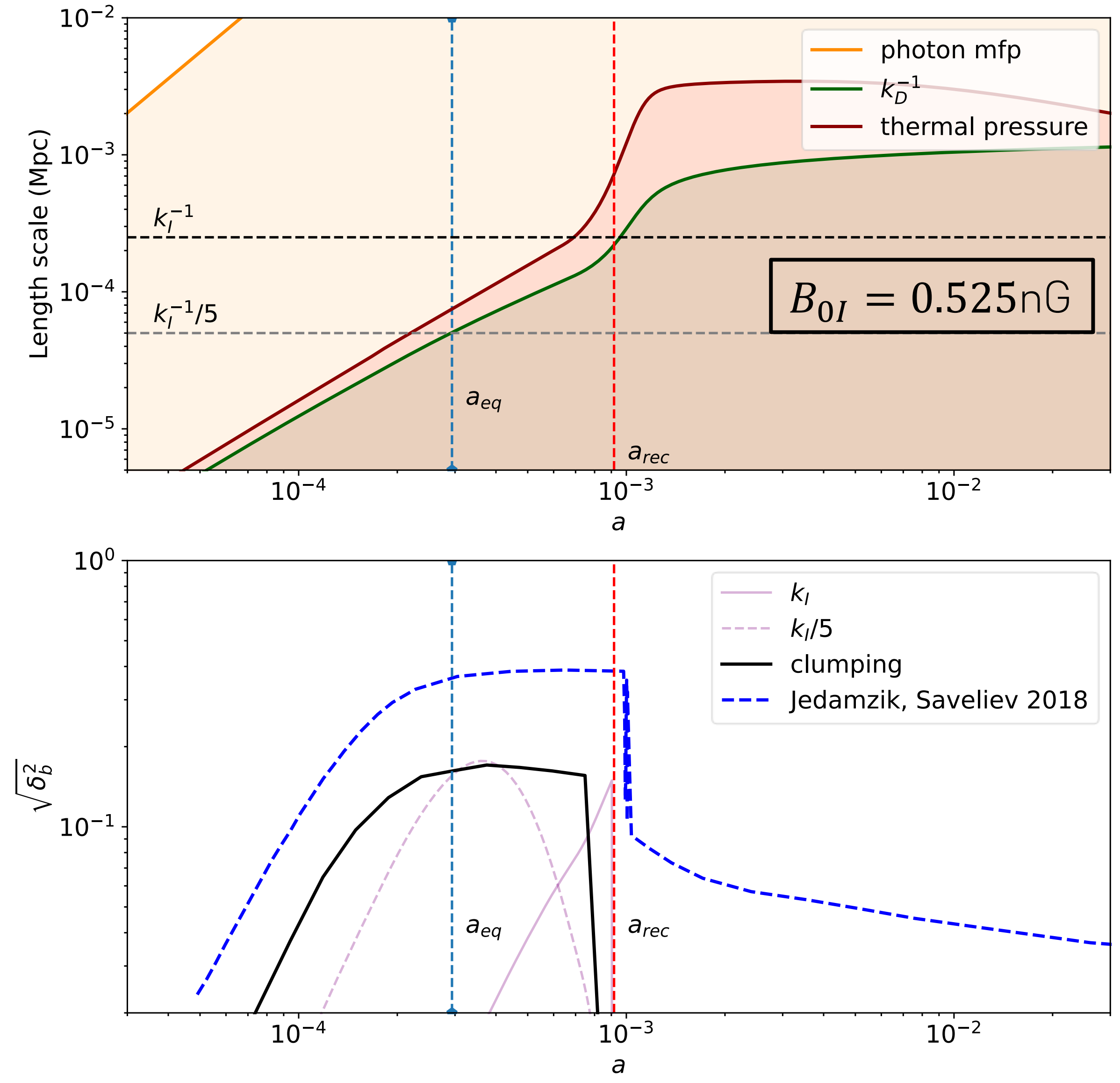
Ignored non-linear terms in δ_b

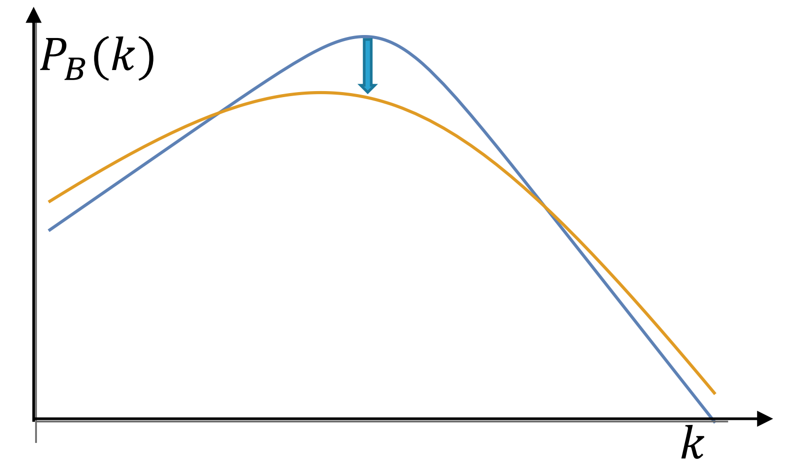
COMPARING WITH FULL MHD SIMULATIONS

COMPARING WITH SIMULATIONS: SENSITIVE TO INITIAL POWER SPECTRUM

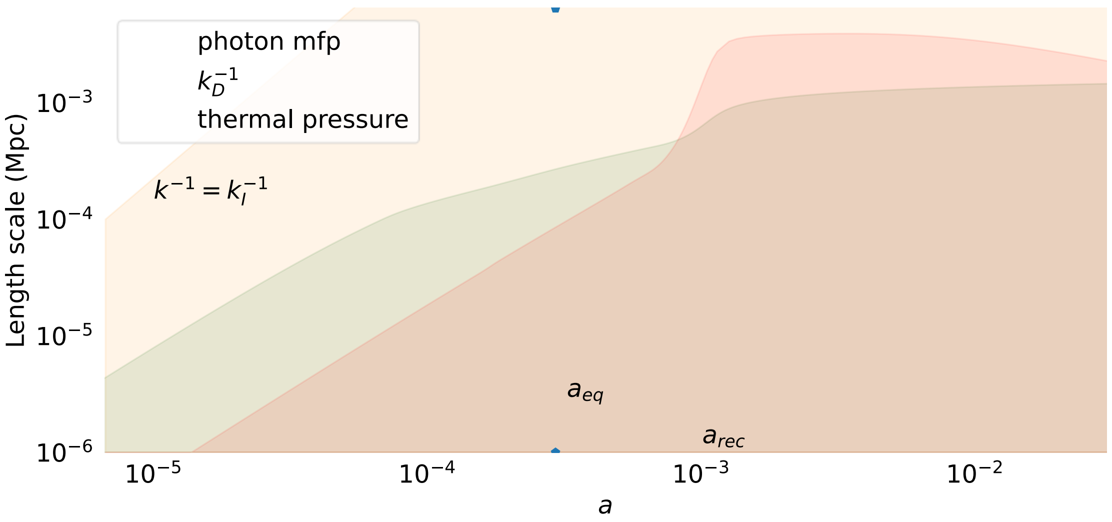


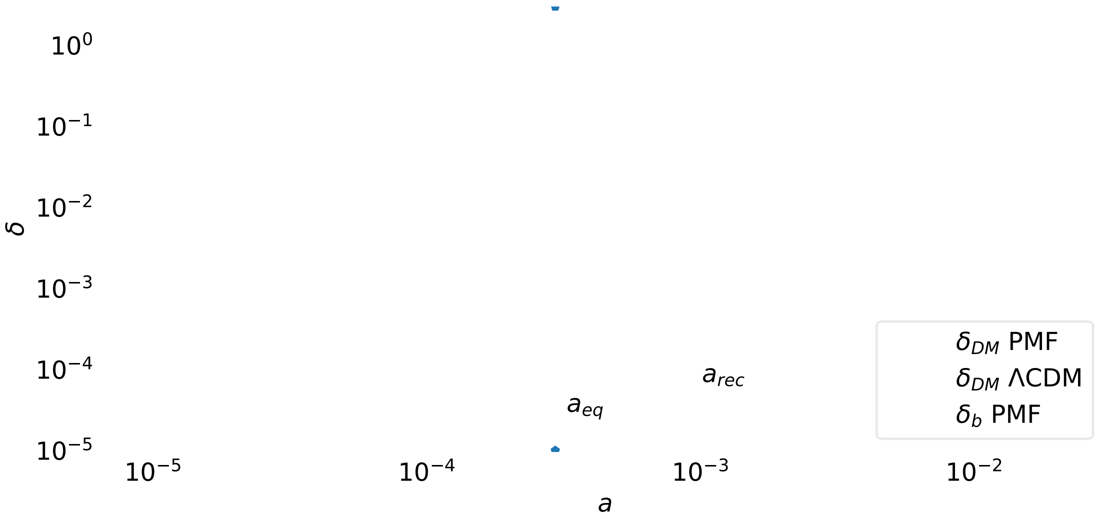
COMPARING WITH SIMULATIONS: SENSITIVE TO INITIAL POWER SPECTRUM





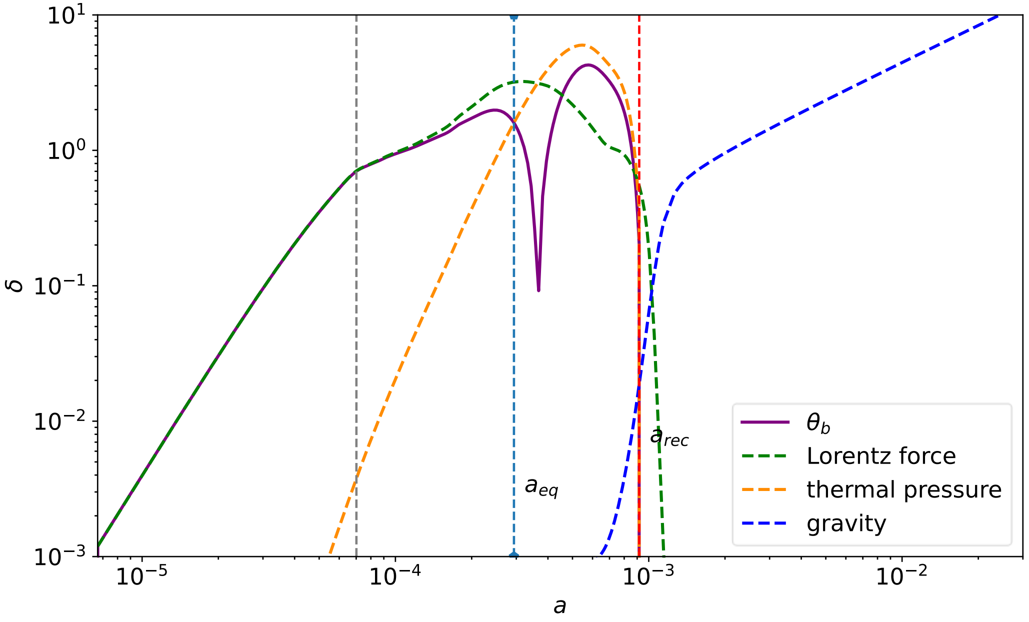
MORE PERTURBATION PLOTS



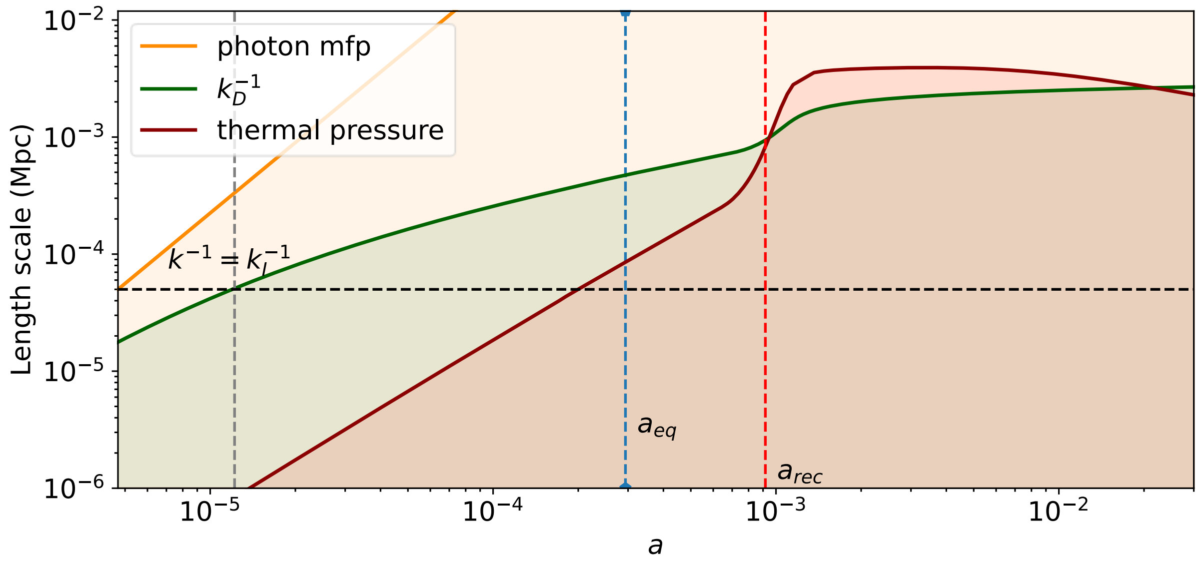


$B_0 = 1\text{nG}$

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



MORE PERTURBATION PLOTS



$B_0 = 8\text{nG}$
$k_I = 10^4\ Mpc^{-1}$