Primordial magnetic fields and the matter power spectrum

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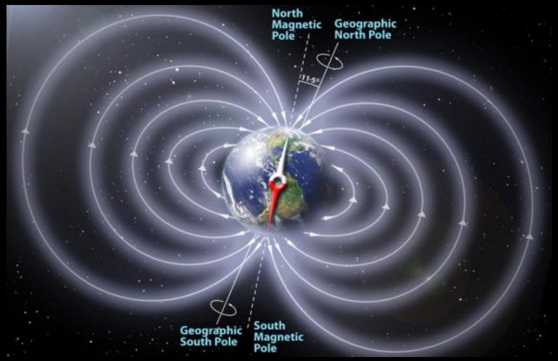
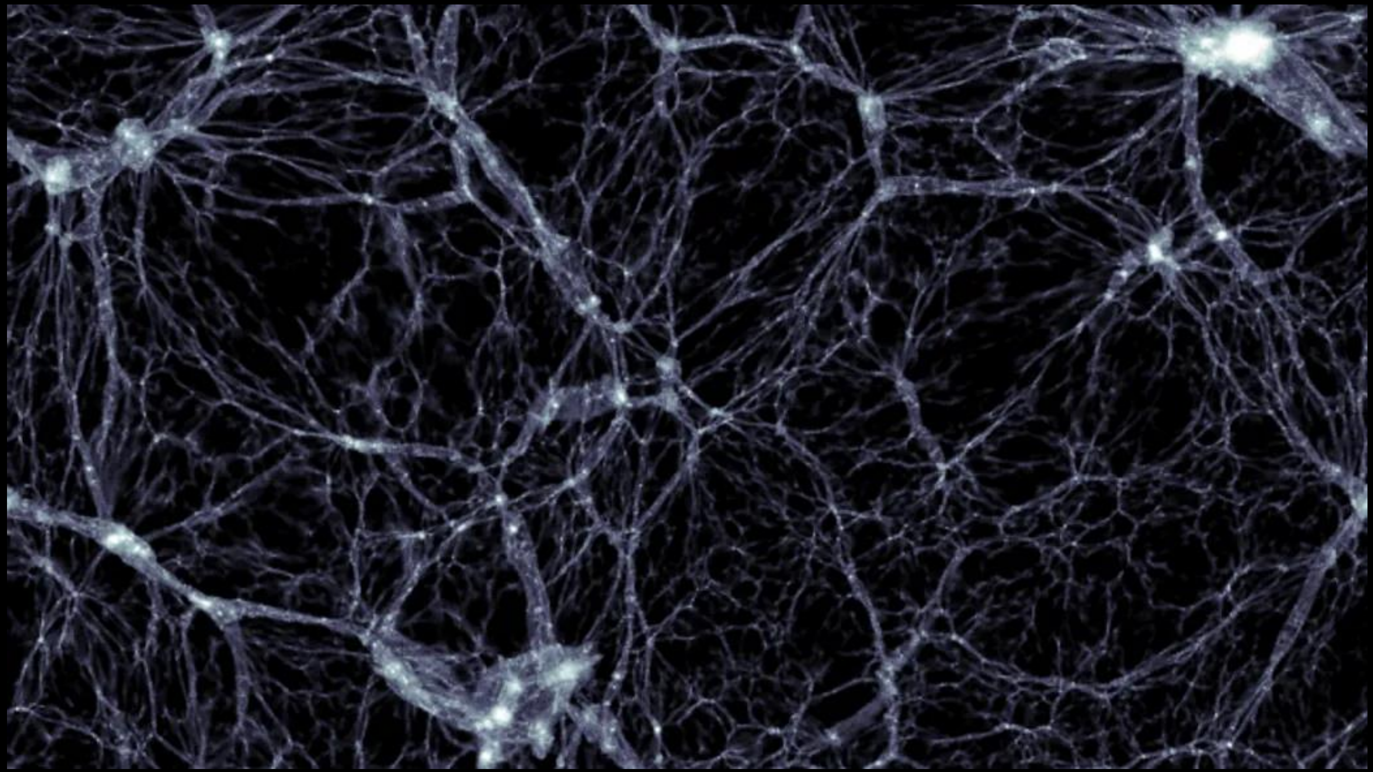
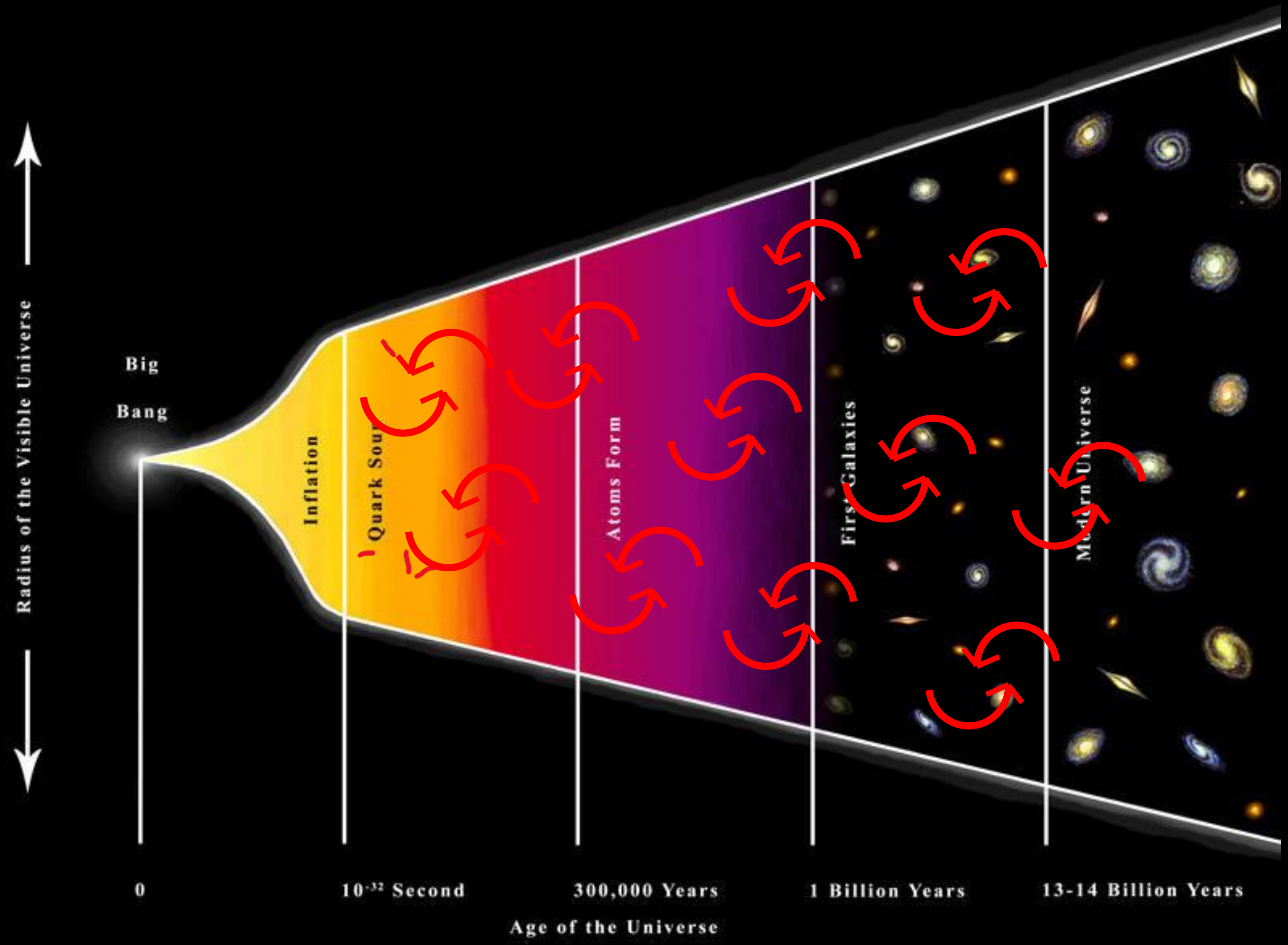
Image source: Pauline Voß for Quanta Magazine

Ubiquitous Magnetic Fields

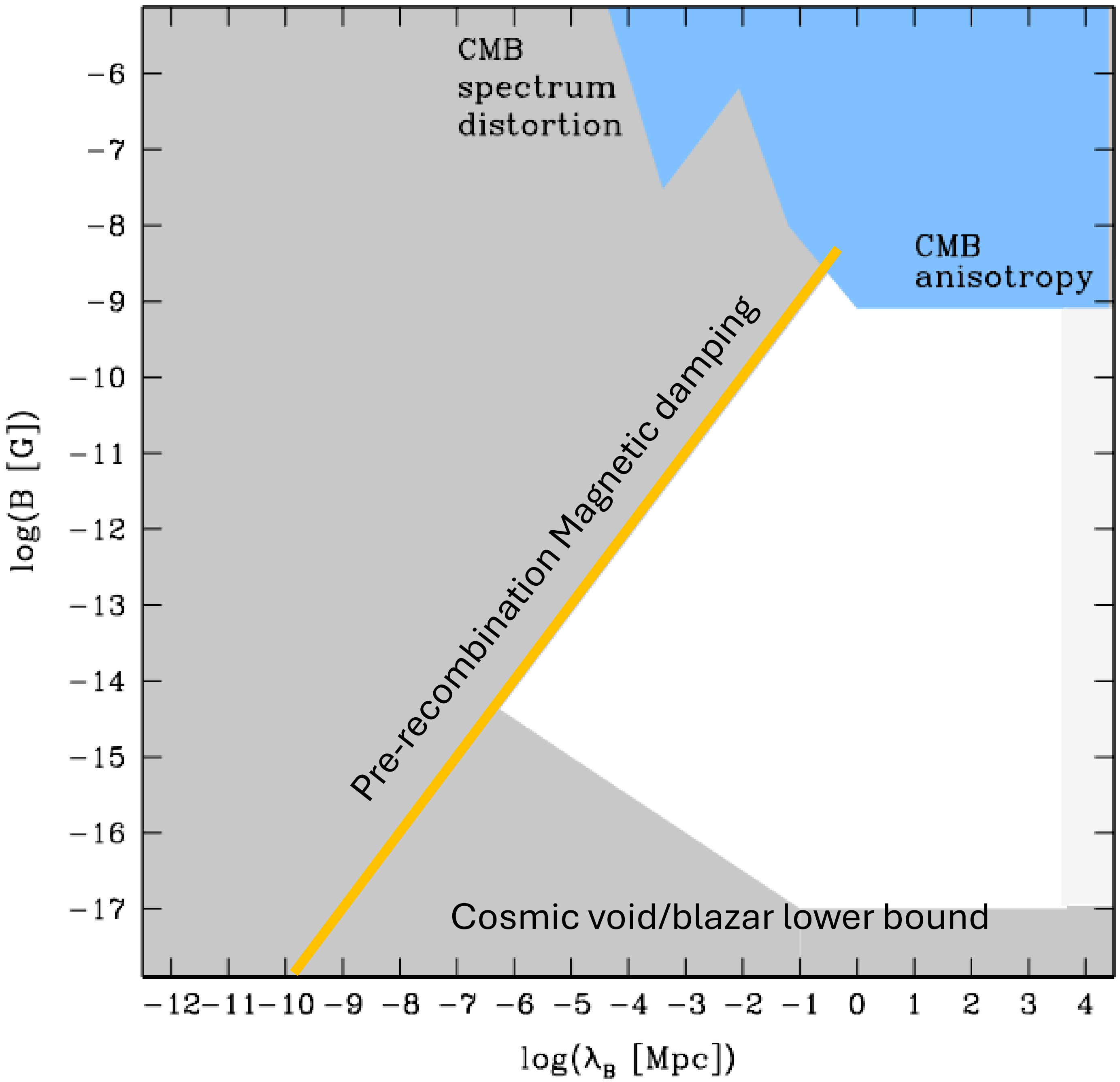




Primordial: Produced by Big Bang plasma

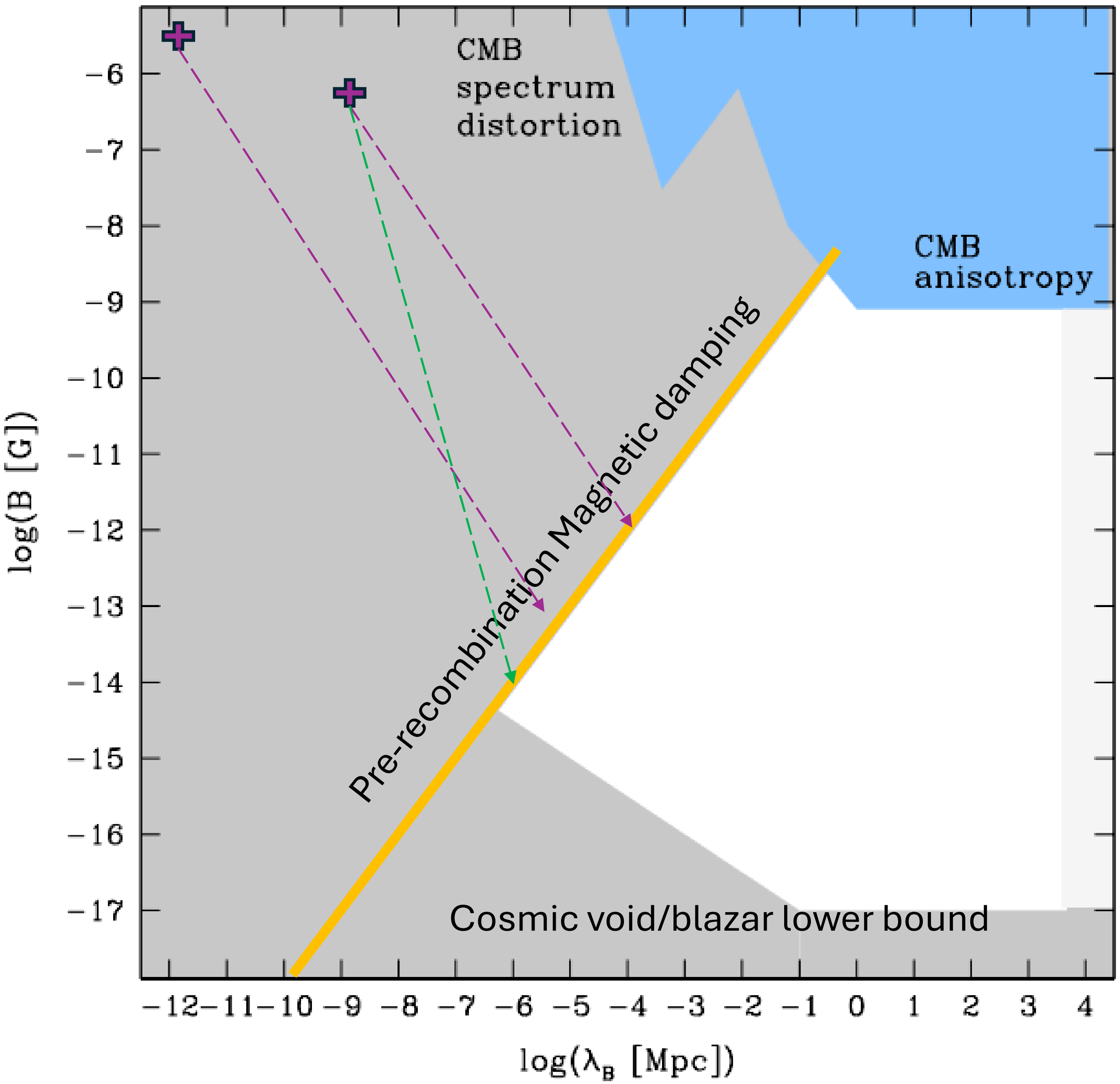


Allowed PMF parameter space

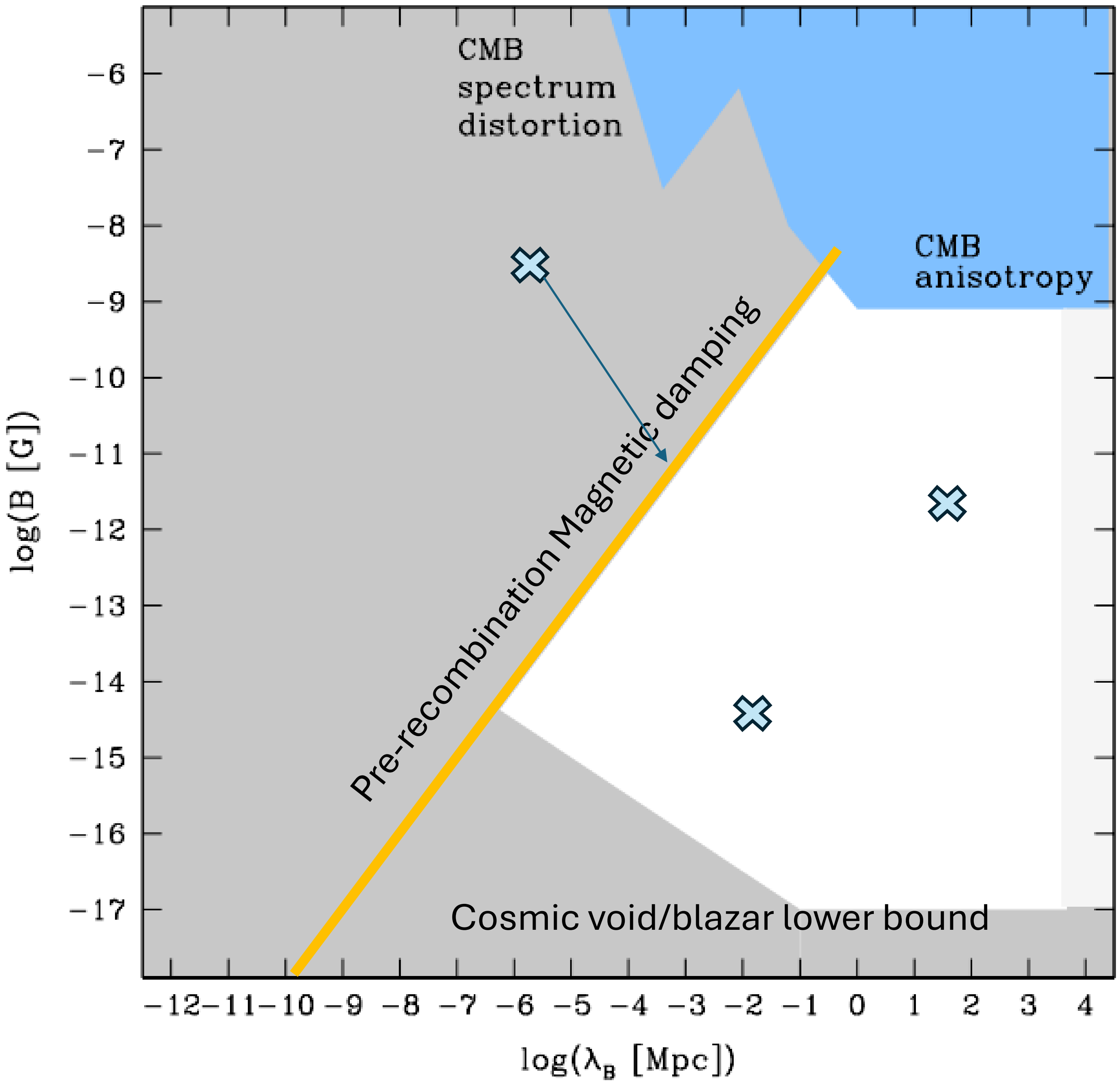


Durrer and Neronov 2013

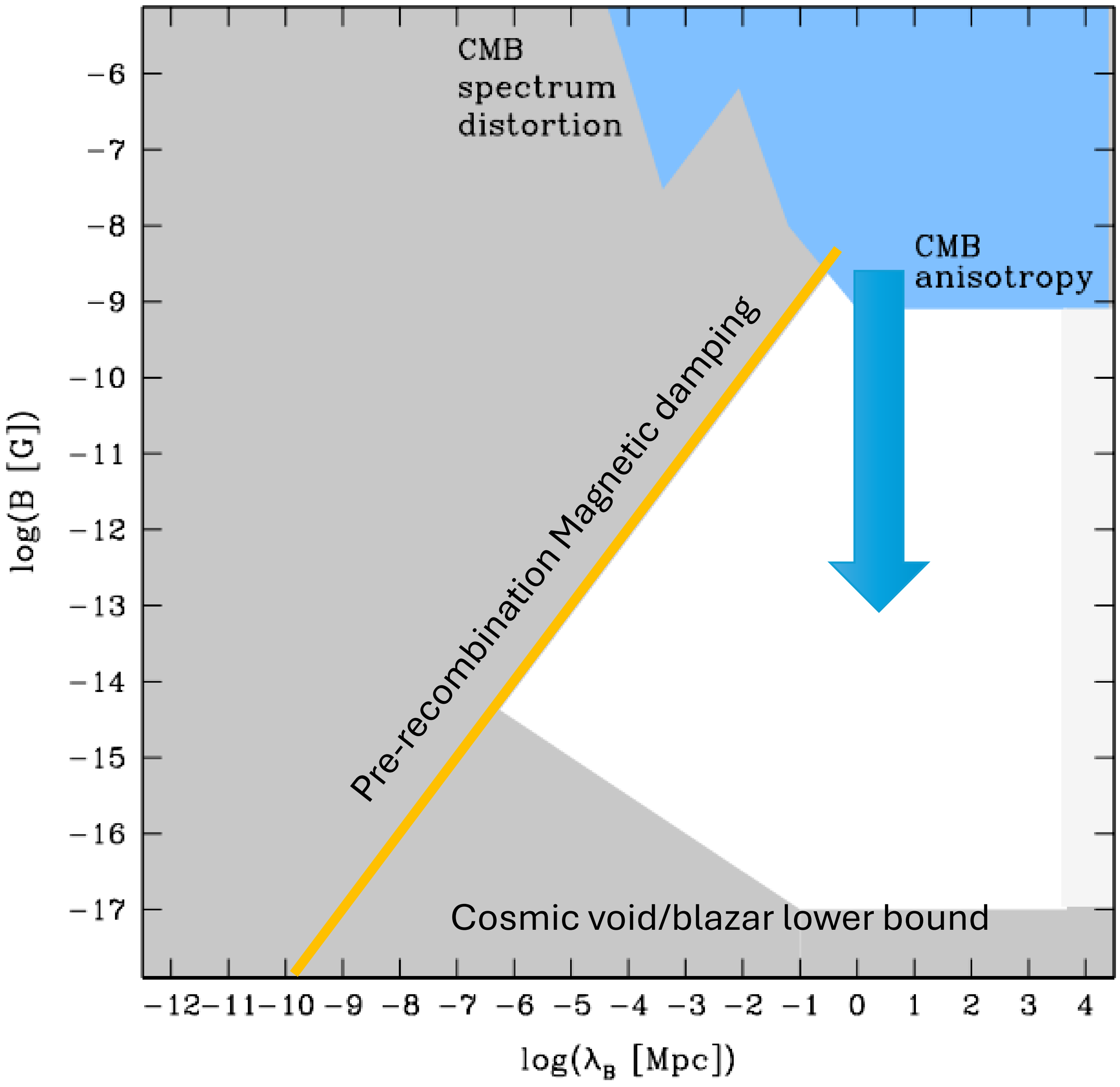
PMFs generated post inflation lie on the damping line



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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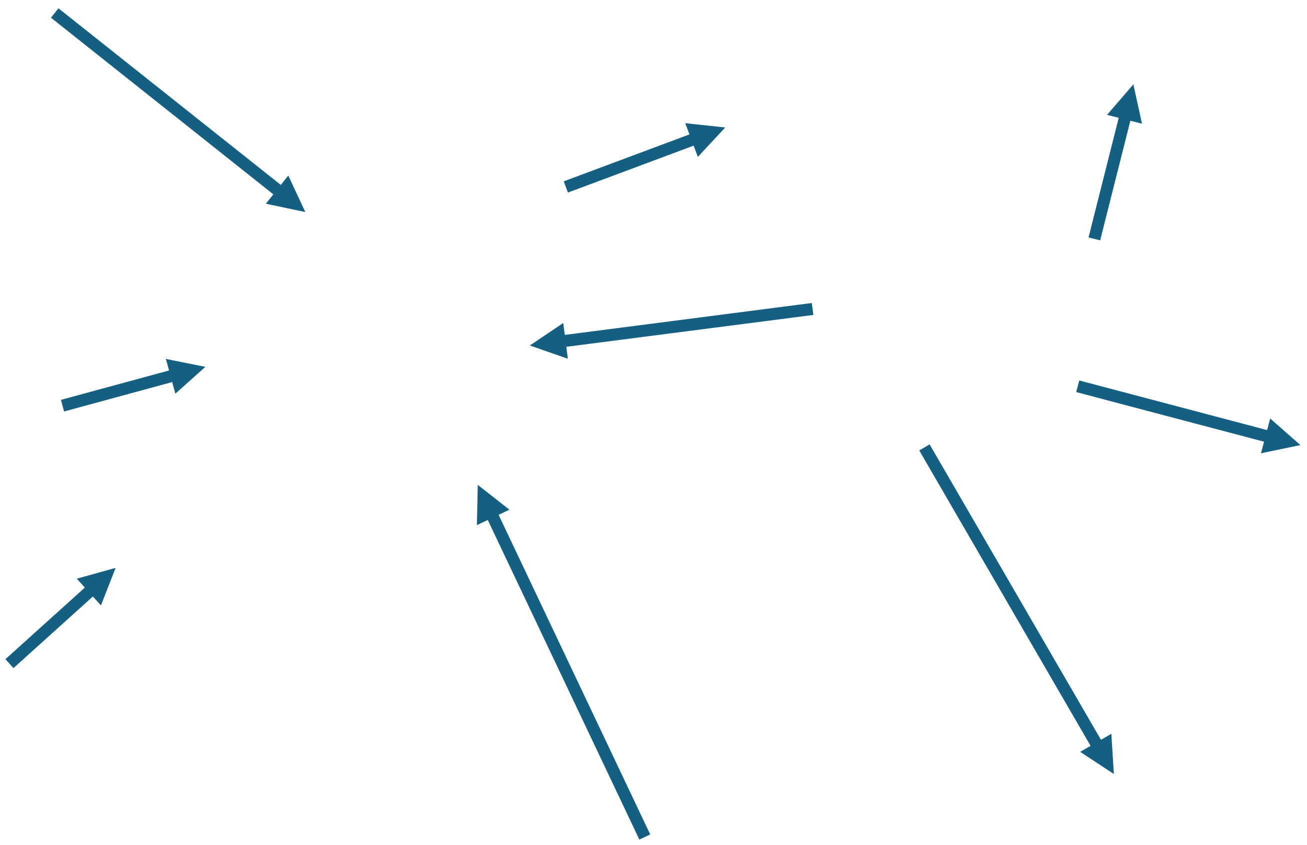
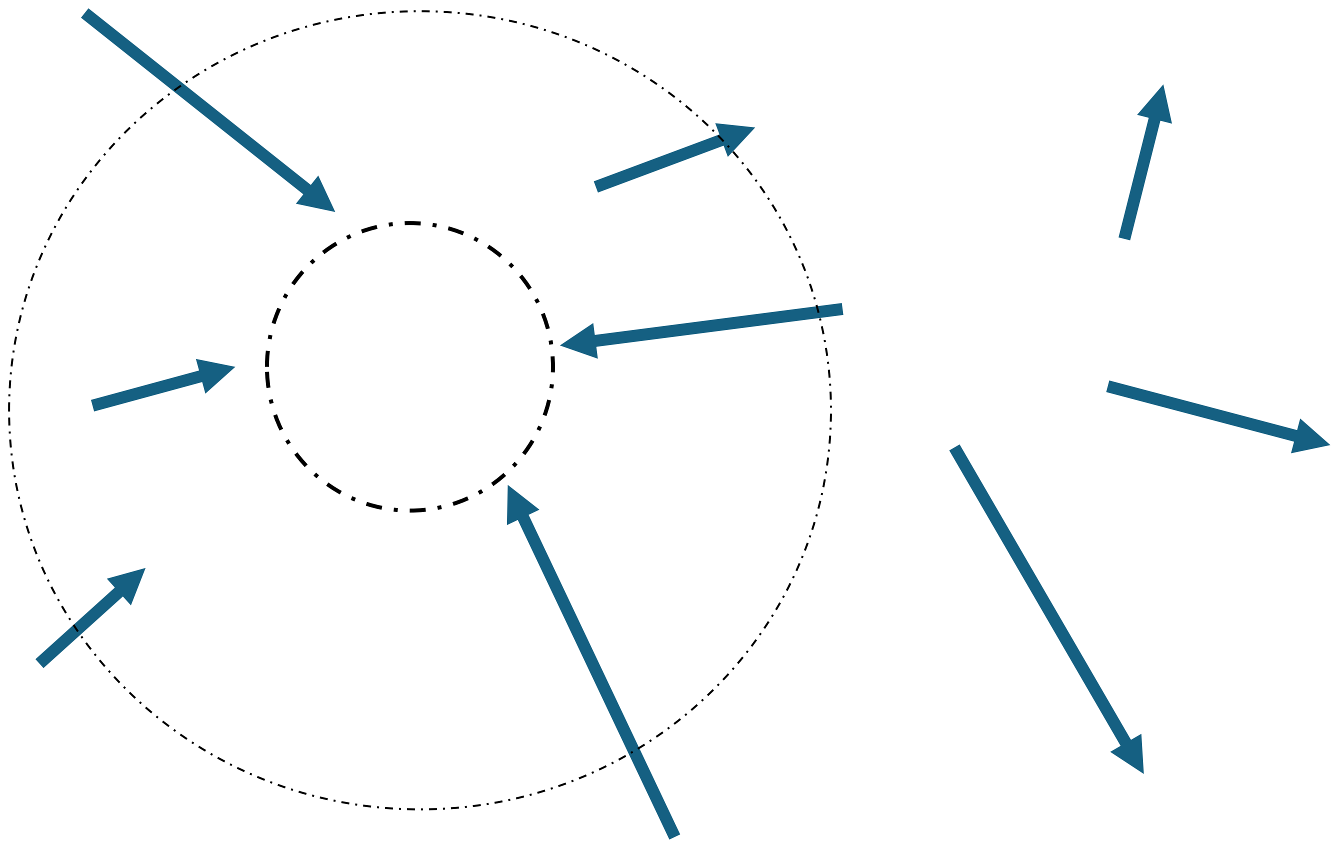
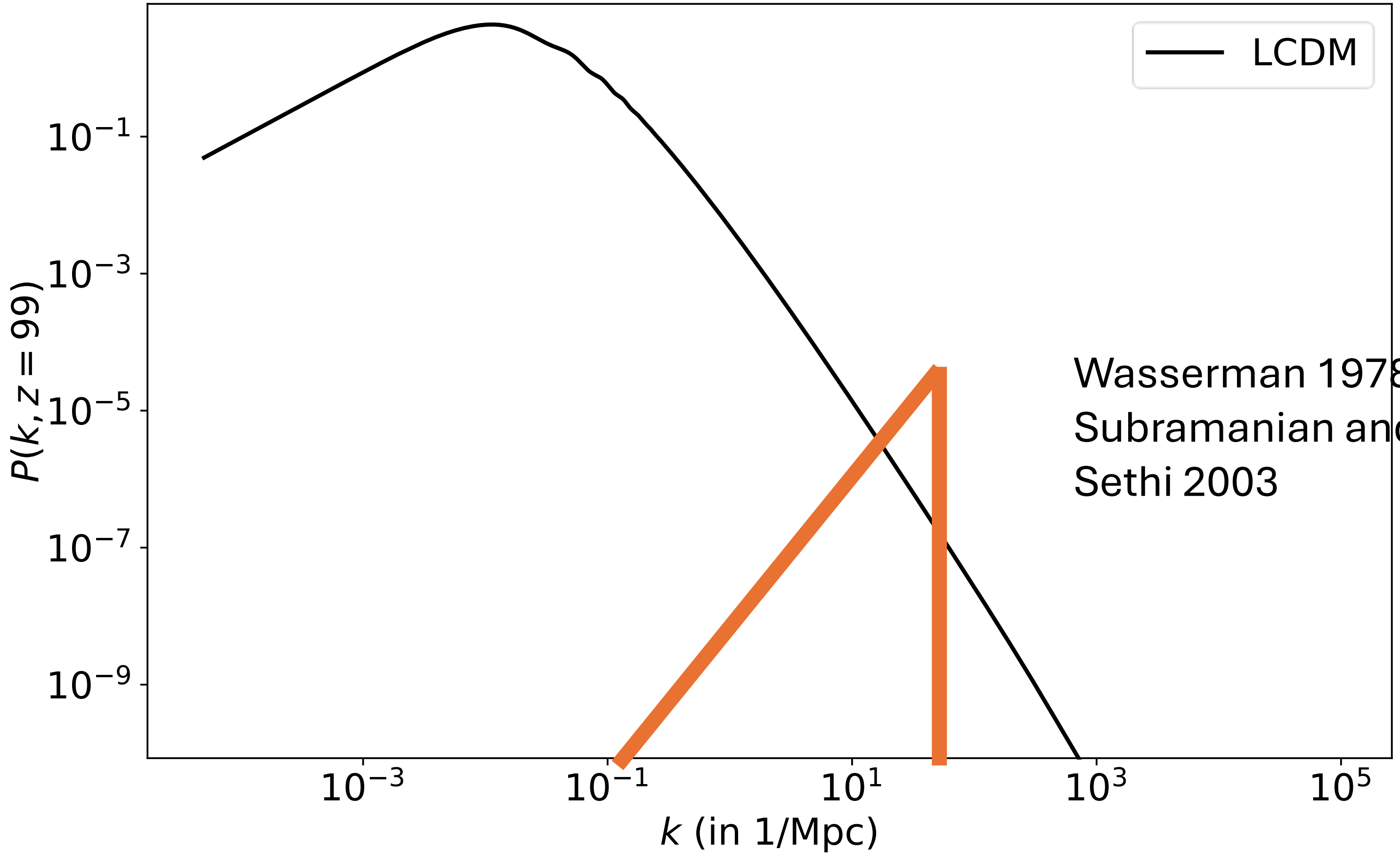


Primordial Magnetic Fields enhance density perturbations

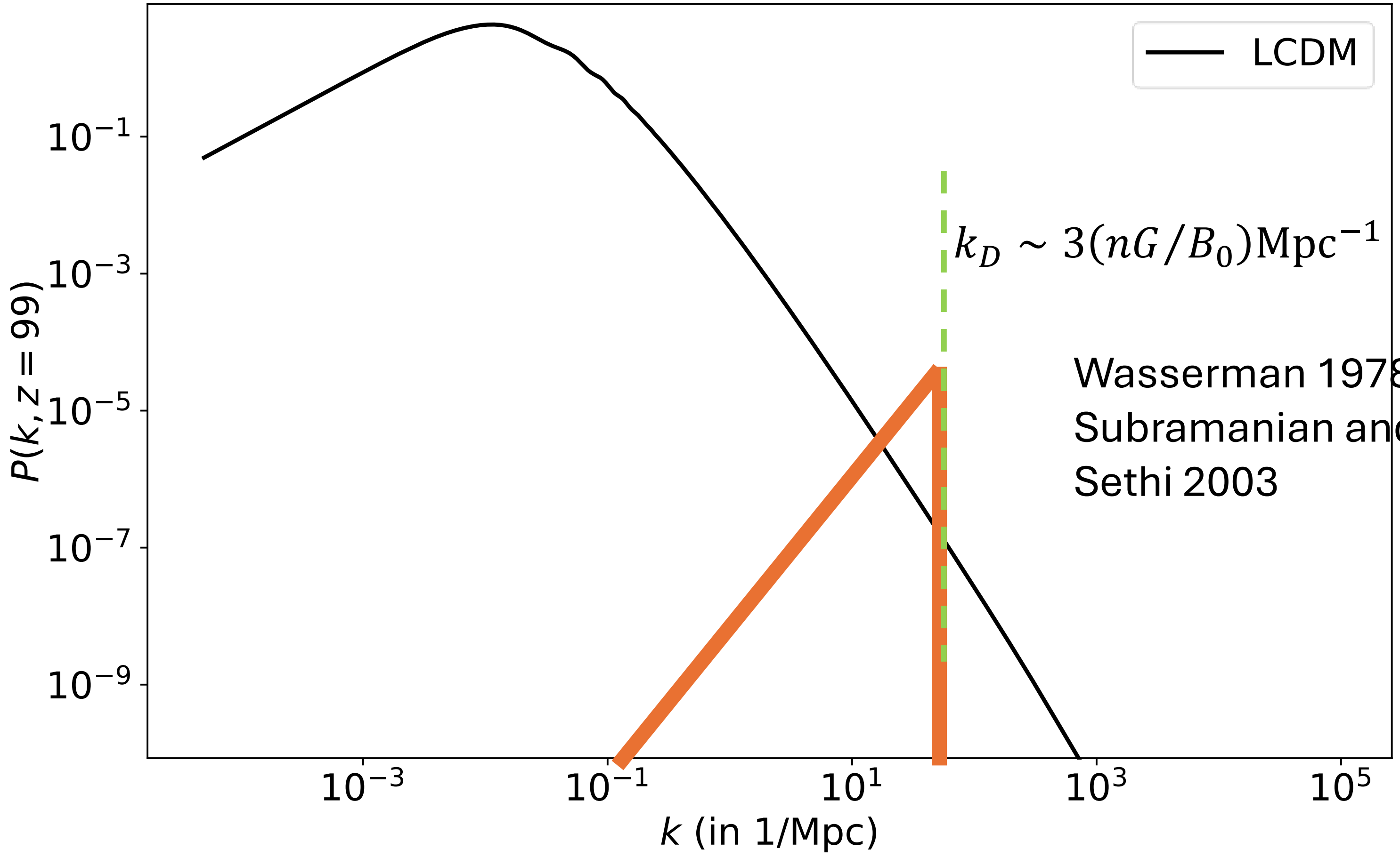


Primordial Magnetic Fields enhance power spectrum on small scales



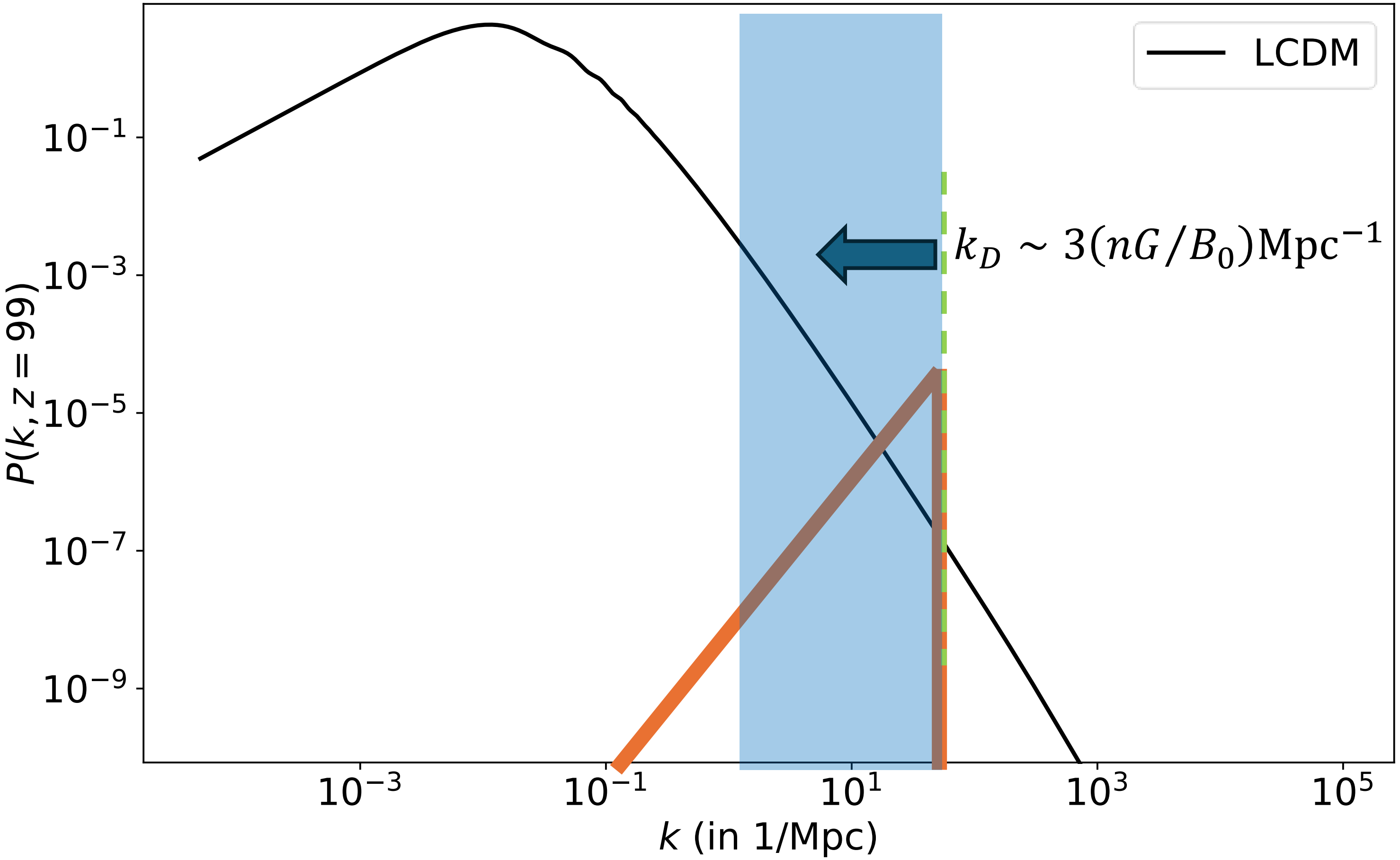
Wasserman 1978, Kim et al 1996, Subramanian and Barrow 1997, Gopal and Sethi 2003

Backreaction from baryons suppresses baryon density perturbations below Magnetic damping (Jeans) scale

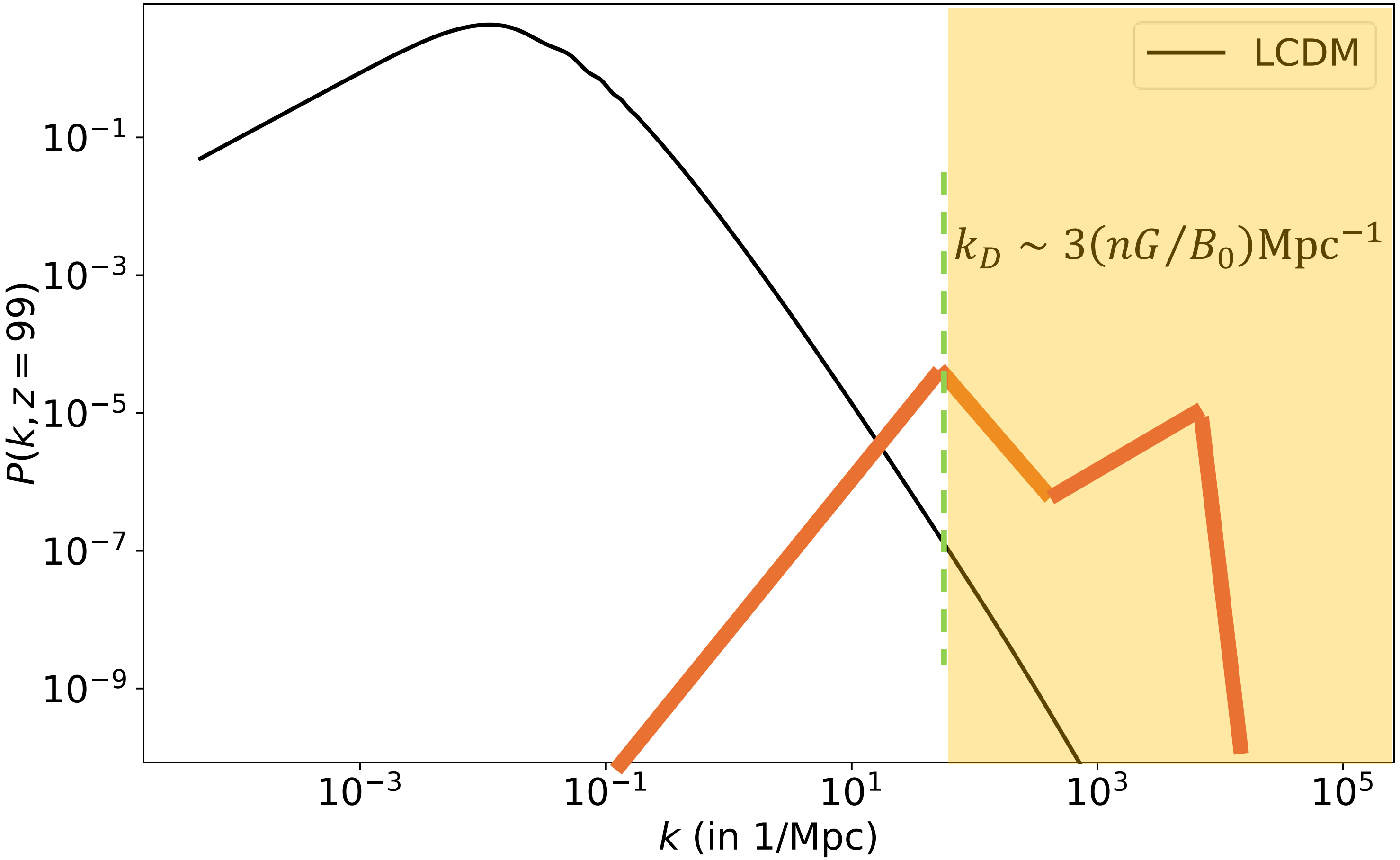


Wasserman 1978, Kim et al 1996, Subramanian and Barrow 1997, Gopal and Sethi 2003

Part 1: Enhanced baryon fraction above jeans scale



Part 2: Dark matter minihalos below jeans scale



Part 1

Enhancing baryon fraction through Primordial magnetic fields

Arxiv: 2402.14079

Post-recombination Ideal MHD

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

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

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

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

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

Post-recombination Ideal MHD

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

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

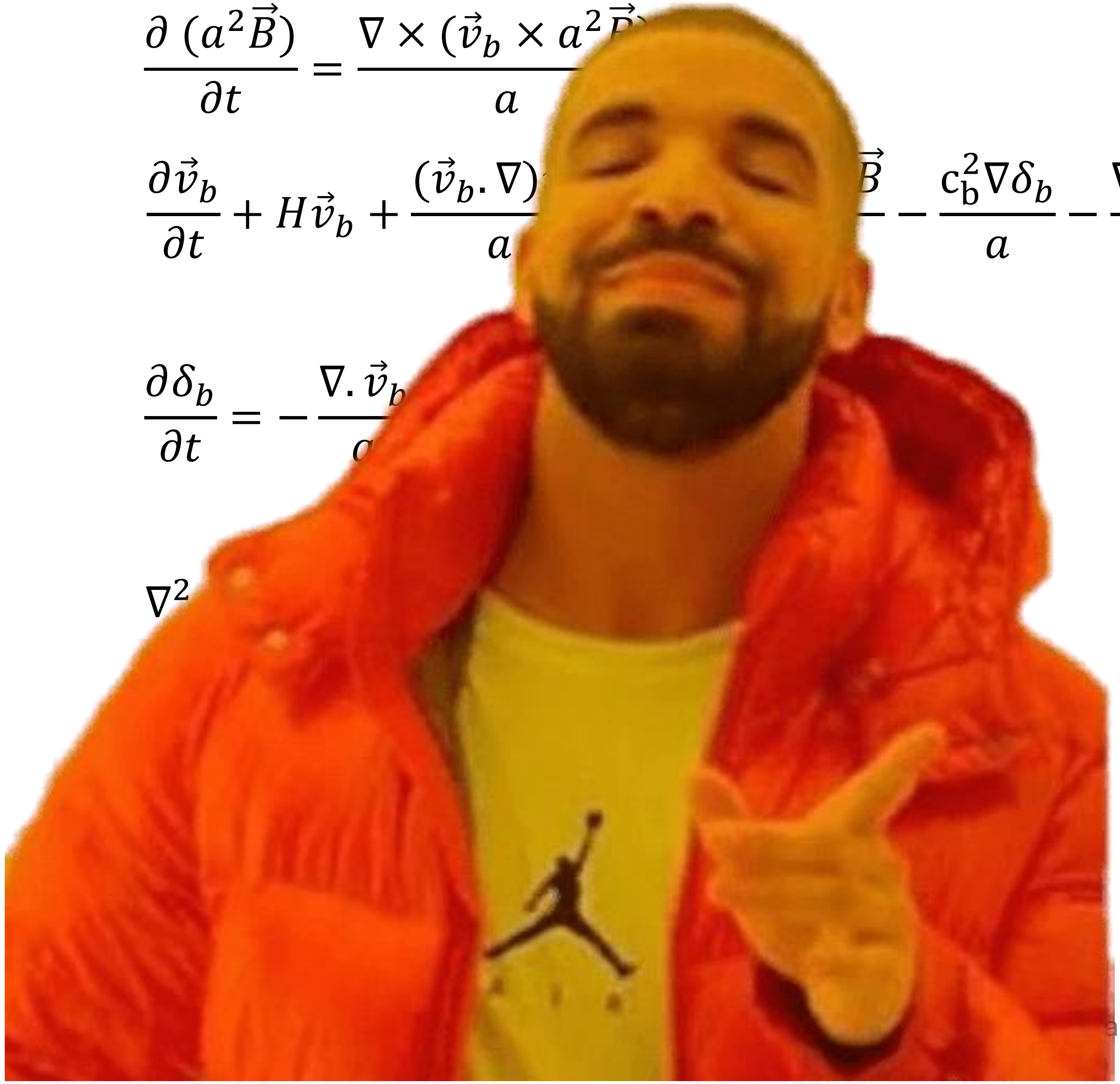
Post-recombination Ideal MHD

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

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

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

$\nabla^2 \ldots$



Focus on large scales, linear limit

$$\delta \ll 1,\, v_b \ll aH$$

Post-recombination Ideal MHD linear limit

$$\frac{\partial\,(\vec{B})}{\partial t} = 0$$

$$\frac{\partial^2 \delta_b}{\partial a^2} + \frac{3}{2}\frac{\partial \delta_b}{a\partial a} = -\frac{\nabla \cdot \left(\nabla \times \vec{B}\right) \times \vec{B}}{(4\pi a^3 \rho_b) a^5 H^2} + \frac{\nabla^2 \phi}{(a^2 H)^2}$$

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

$$\frac{\partial^2 \delta_{DM}}{\partial a^2} + \frac{3}{2}\frac{\partial \delta_{DM}}{a\partial a} = \frac{\nabla^2 \phi}{(a^2 H)^2}$$

Comoving Magnetic fields are frozen

$$\frac{\partial\,(\vec{B})}{\partial t} = 0$$

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$$\frac{\partial^2 \delta_{DM}}{\partial a^2} + \frac{3}{2}\frac{\partial \delta_{DM}}{a \partial a} = \frac{\nabla^2\phi}{(a^2 H)^2}$$

Baryons driven by Lorentz force and gravity

$$\frac{\partial\,(\vec{B})}{\partial t} = 0$$

$$\frac{\partial^2 \delta_b}{\partial a^2} + \frac{3}{2}\frac{\partial \delta_b}{a \partial a} = -\frac{\nabla \cdot \left(\nabla \times \vec{B}\right) \times \vec{B}}{(4\pi a^3 \rho_b) a^5 H^2} + \frac{\nabla^2 \phi}{(a^2 H)^2}$$

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

$$\frac{\partial^2 \delta_{DM}}{\partial a^2} + \frac{3}{2}\frac{\partial \delta_{DM}}{a \partial a} = \frac{\nabla^2 \phi}{(a^2 H)^2}$$

Dark matter only influenced by gravity

$$\frac{\partial\ (\vec{B})}{\partial t} = 0$$

$$\frac{\partial^2 \delta_b}{\partial a^2} + \frac{3}{2}\frac{\partial \delta_b}{a \partial a} = -\frac{\nabla \cdot \left(\nabla \times \vec{B}\right) \times \vec{B}}{(4\pi a^3 \rho_b) a^5 H^2} + \frac{\nabla^2 \phi}{(a^2 H)^2}$$

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

$$\frac{\partial^2 \delta_{DM}}{\partial a^2} + \frac{3}{2}\frac{\partial \delta_{DM}}{a \partial a} = \frac{\nabla^2 \phi}{(a^2 H)^2}$$

Star of the show: S_0 term

$$\frac{\partial\ (\vec{B})}{\partial t} = 0$$

$$\frac{\partial^2 \delta_b}{\partial a^2} + \frac{3}{2}\frac{\partial \delta_b}{a \partial a} = -\frac{\nabla \cdot \left(\nabla \times \vec{B}\right) \times \vec{B}}{(4\pi a^3 \rho_b) a^5 H^2} + \frac{\nabla^2 \phi}{(a^2 H)^2}$$

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Star of the show: S_0 term

$$\frac{\partial\,(\vec{B})}{\partial t} = 0$$

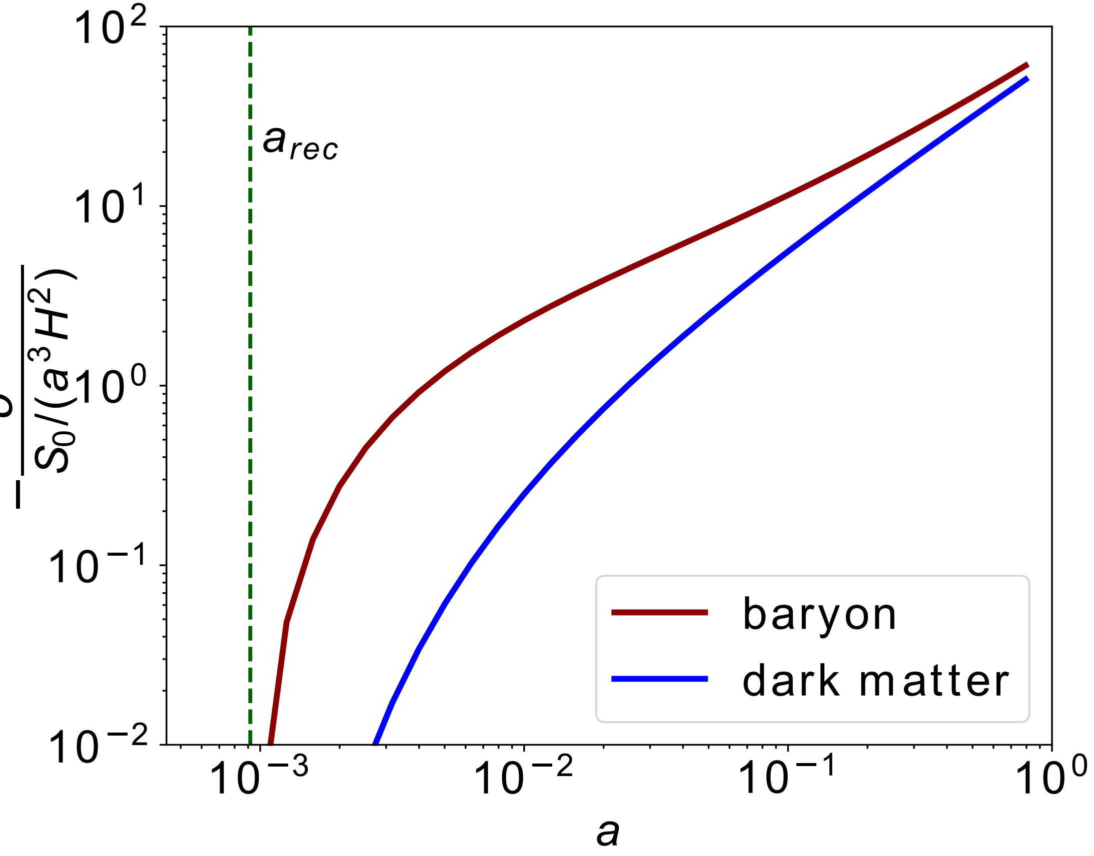
$$\frac{\partial^2 \delta_b}{\partial a^2} + \frac{3}{2}\frac{\partial \delta_b}{a\partial a} = -\frac{S_0}{a^2(a^3H^2)} + \frac{\nabla^2\phi}{(a^2H)^2}$$

$$\frac{S_0}{a^3H^2} = \frac{\nabla\cdot(\nabla\times\vec{B})\times\vec{B}}{4\pi a^3\rho_b(a^3H^2)} = \text{constant}$$

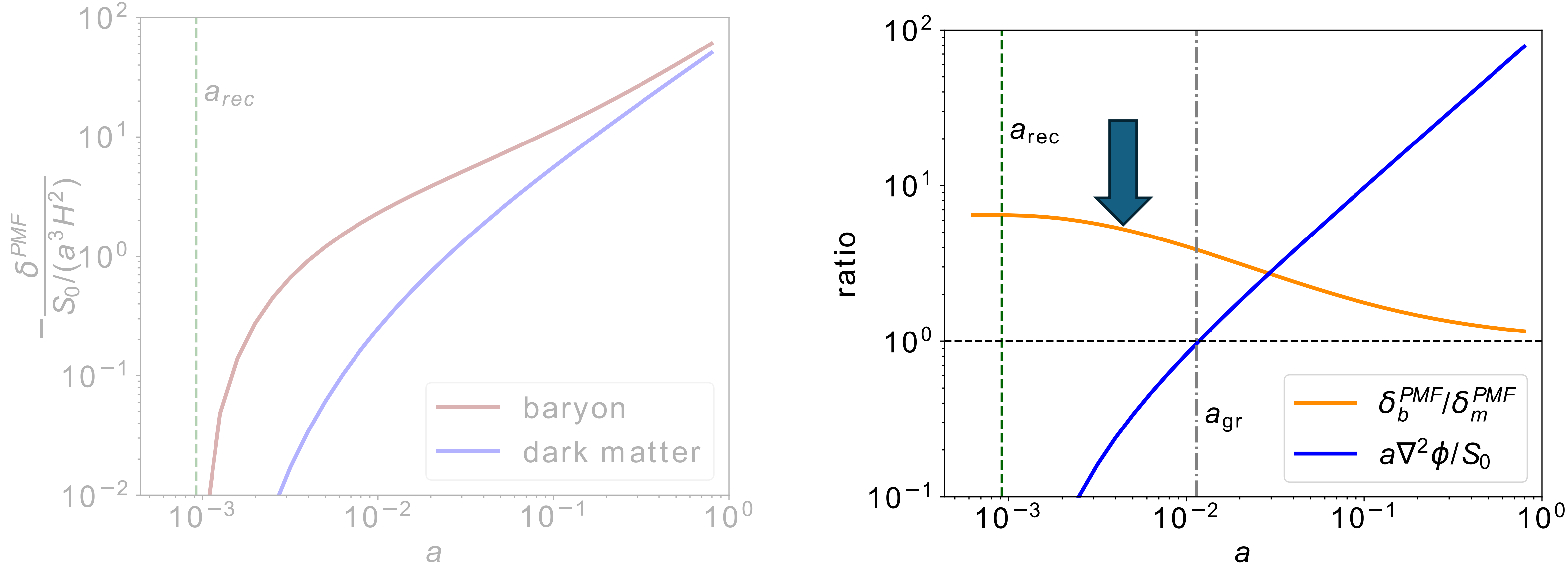
$$\nabla^2\phi = \frac{a^2}{2M_{Pl}^2}(\rho_b\delta_b + \rho_{DM}\delta_{DM})$$

$$\frac{\partial^2 \delta_{DM}}{\partial a^2} + \frac{3}{2}\frac{\partial \delta_{DM}}{a\partial a} = \frac{\nabla^2\phi}{(a^2H)^2}$$

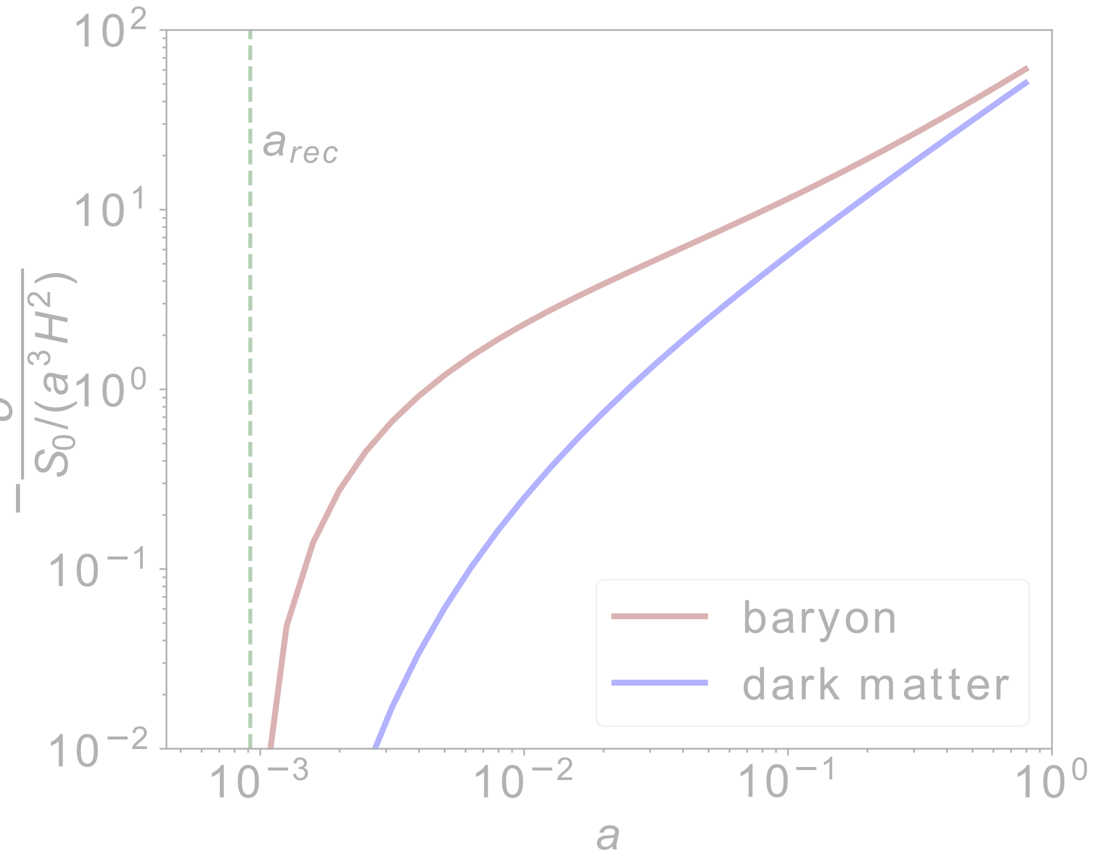
S_0 sources baryon perturbations

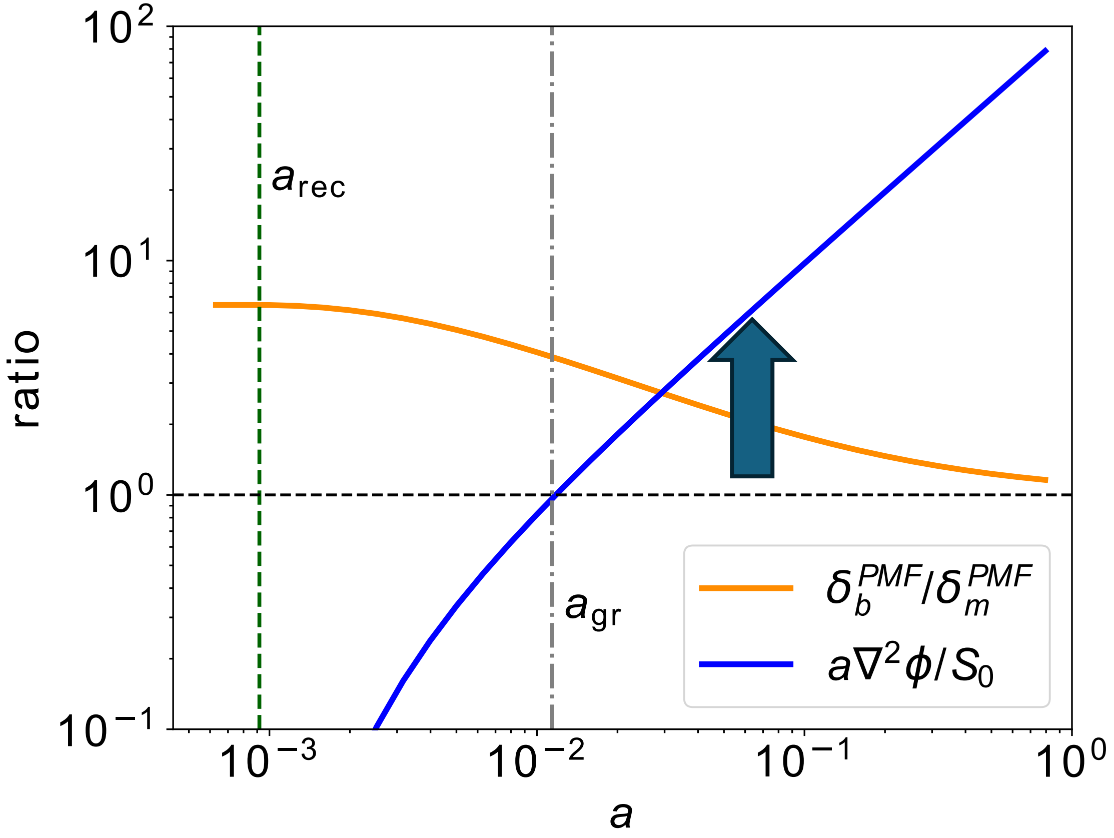


Baryon fraction decreases with time



Gravity quickly overcomes Lorentz force





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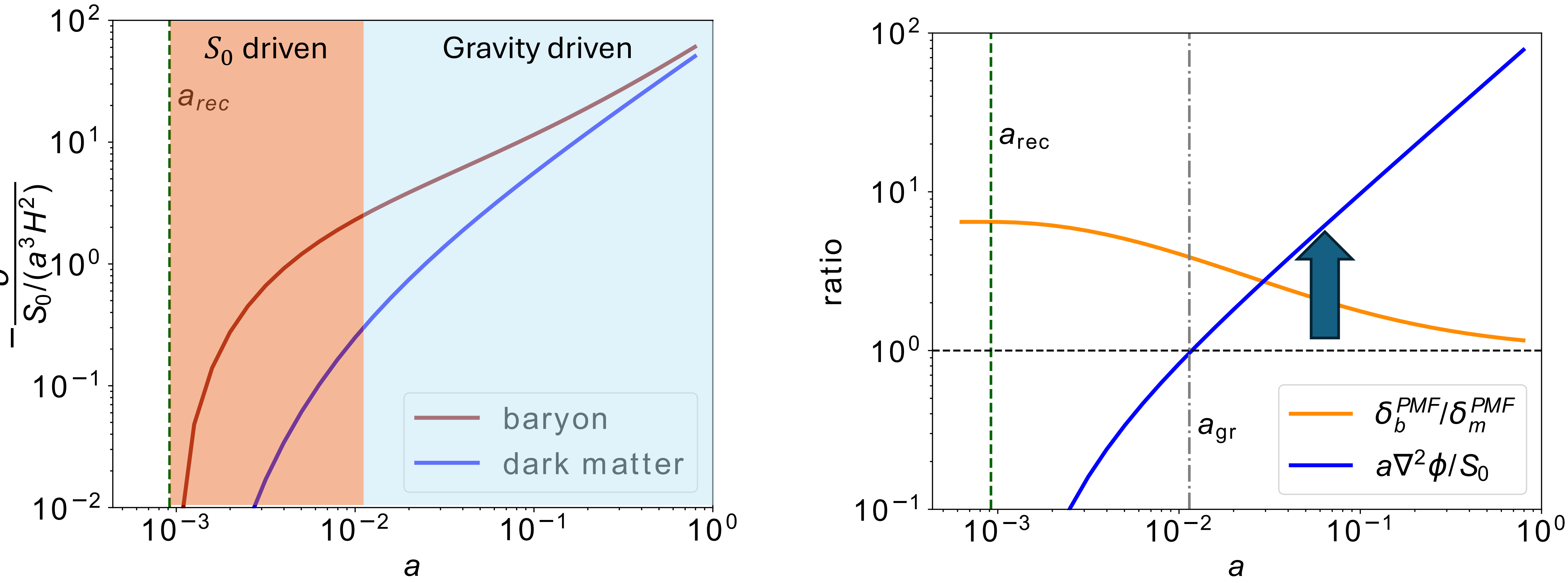
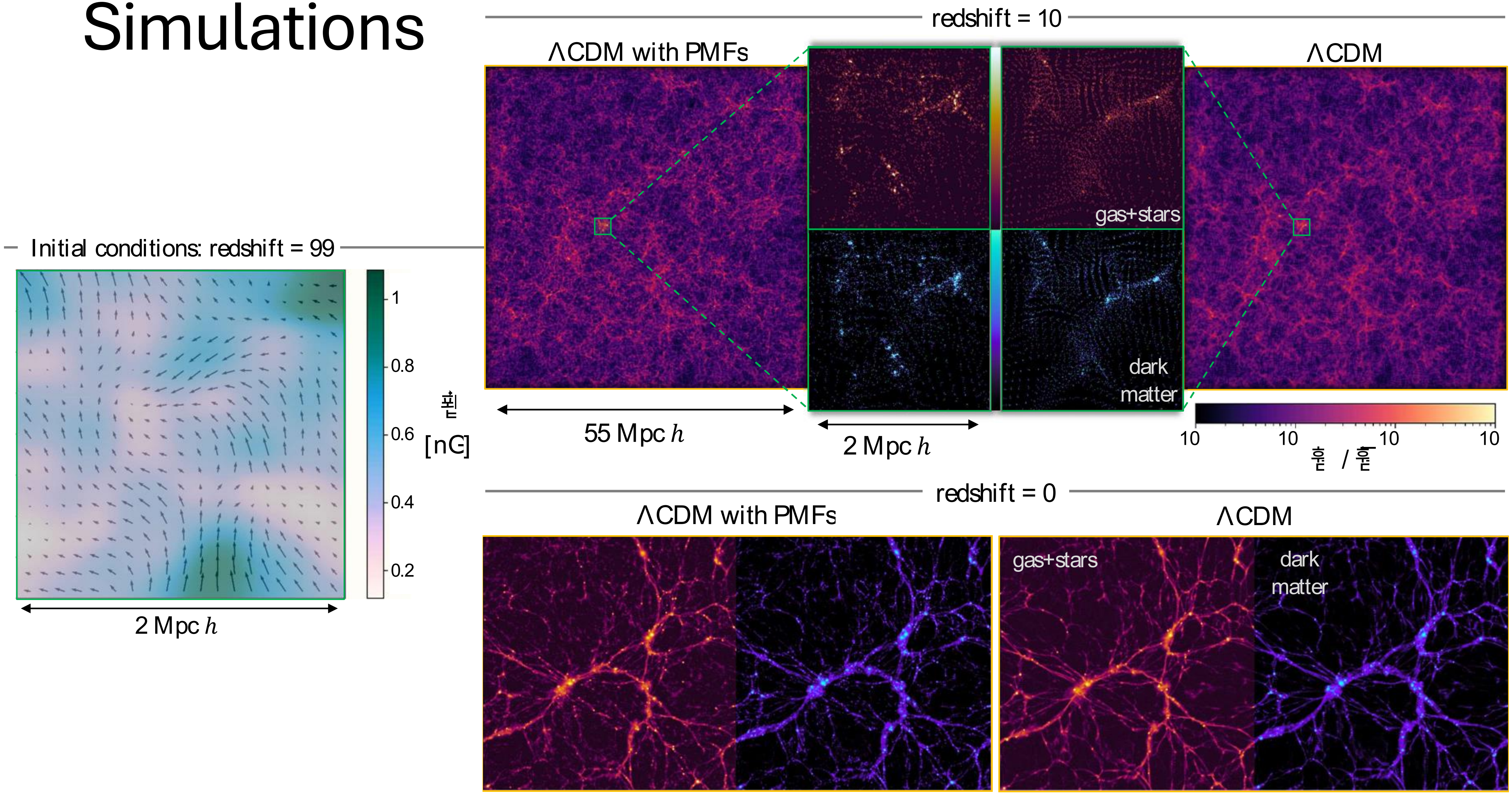
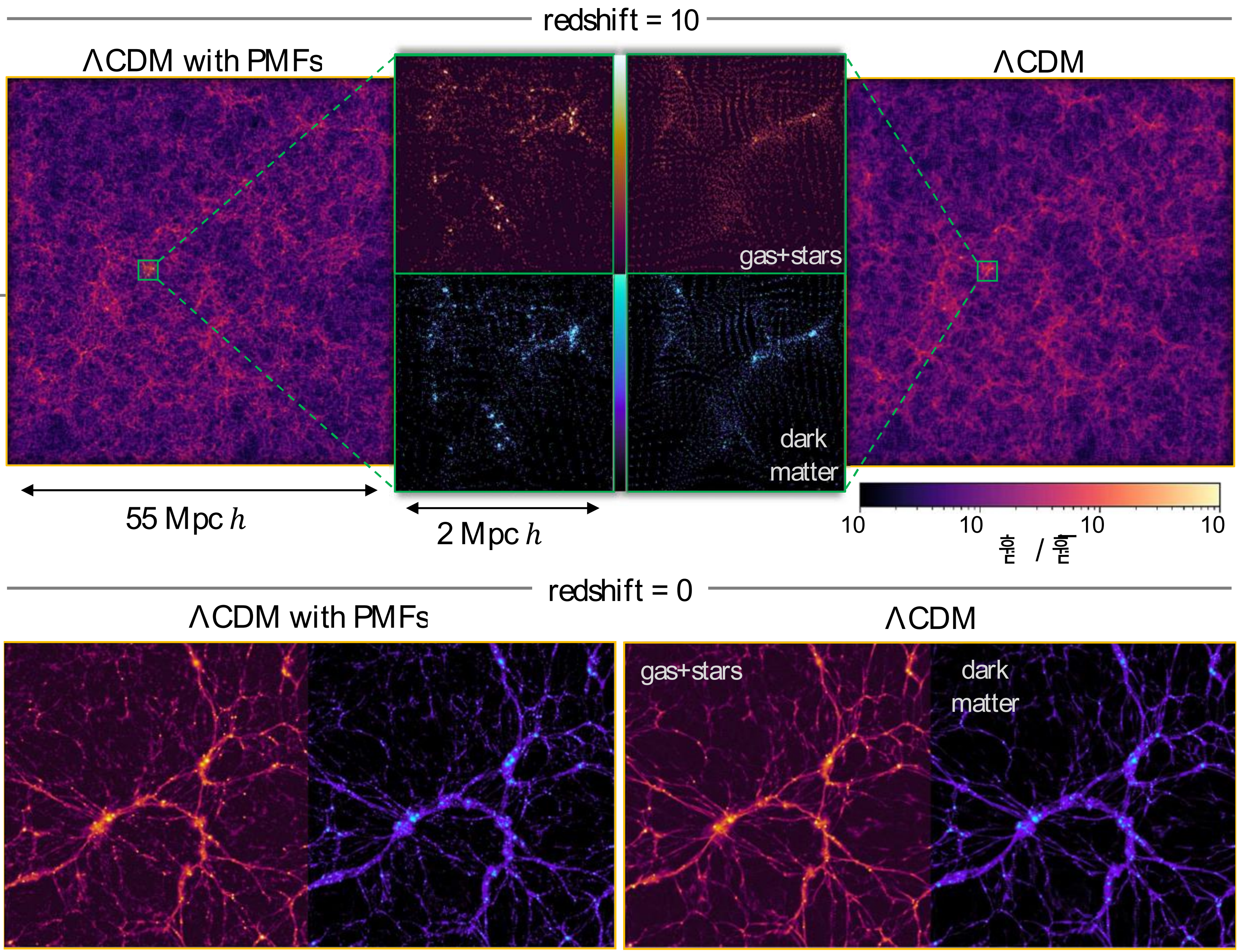


Simulations



Simulations



Baryon fraction in halos: enhanced by PMFs

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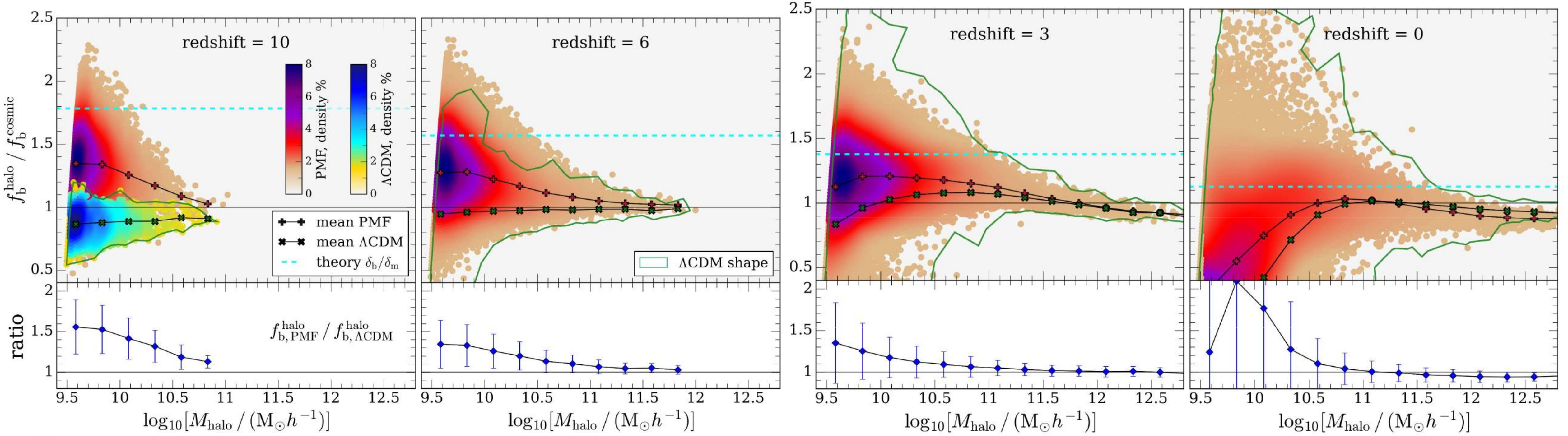
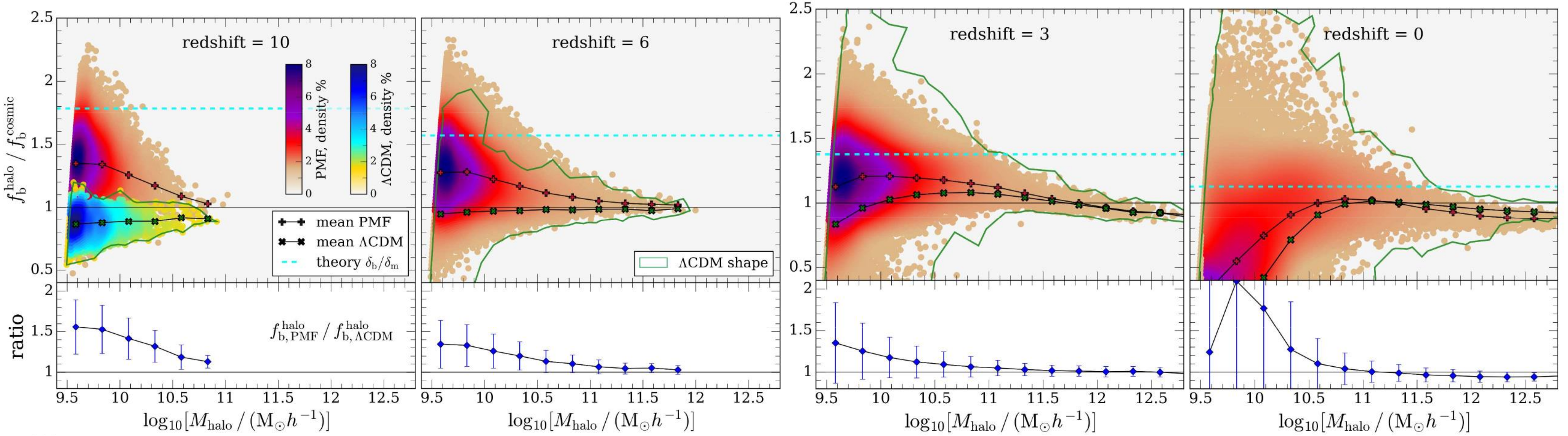


Scale invariant 1 nG PMFs

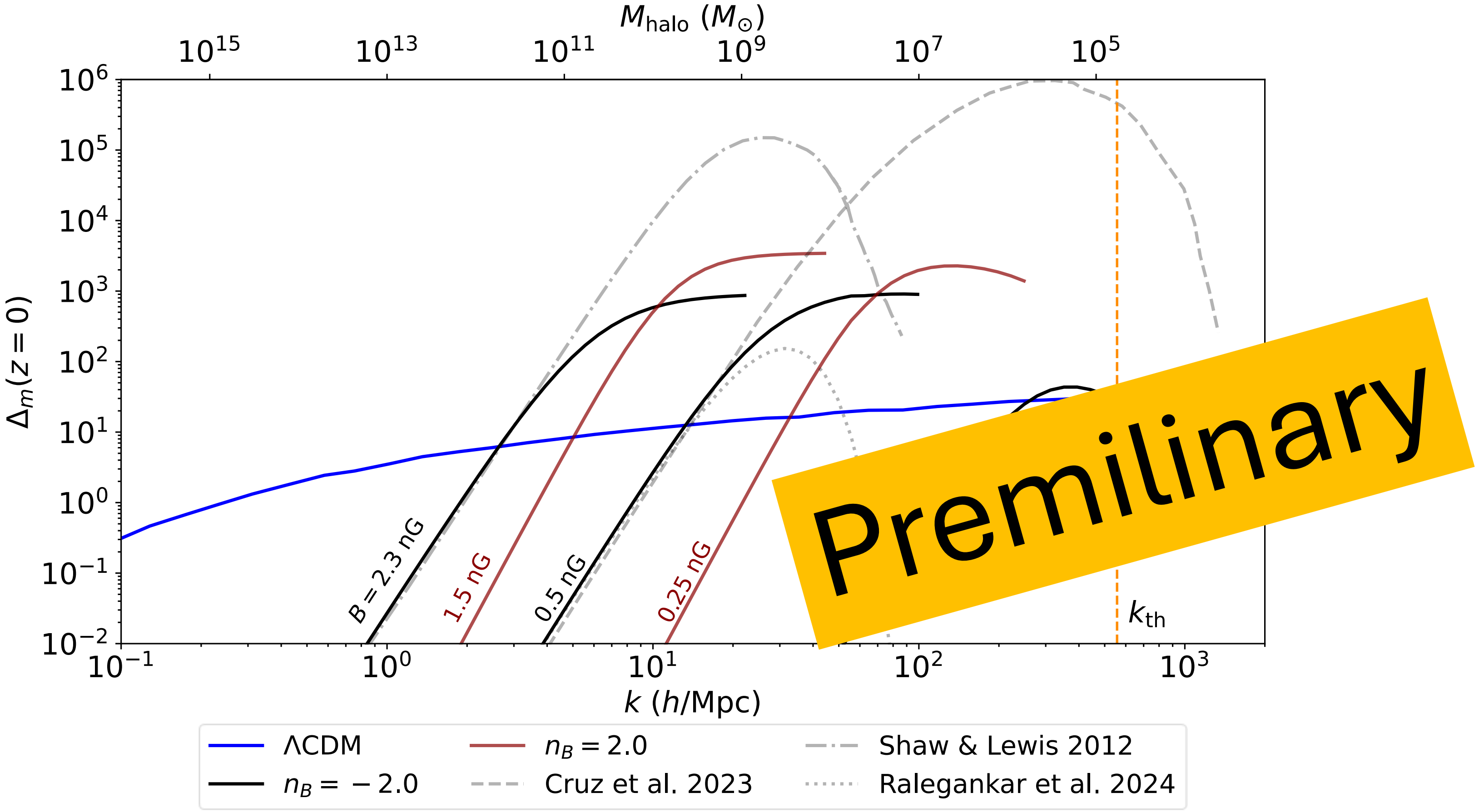
Baryon fraction in halos: stochastic nature



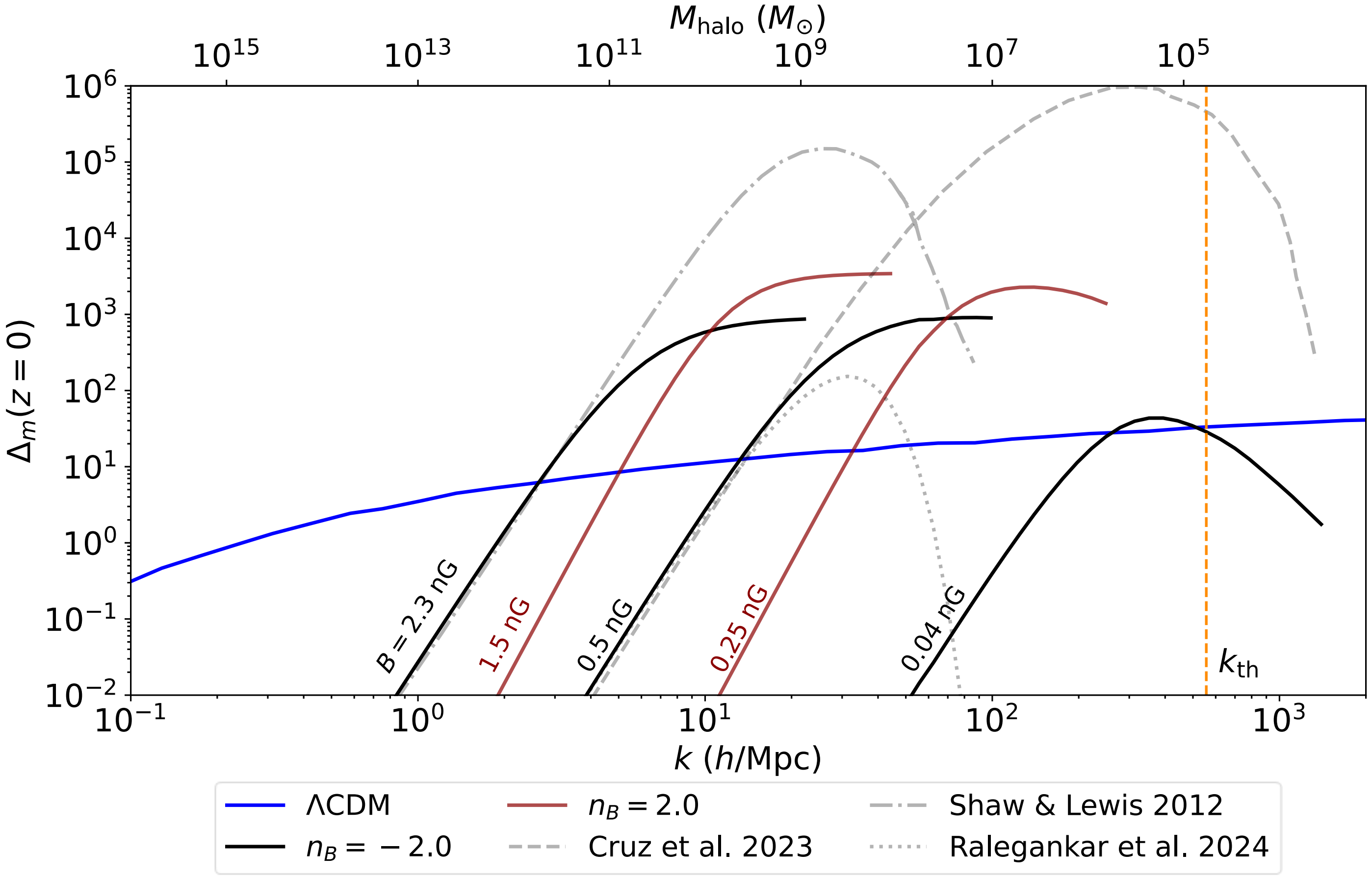
Scale invariant 1 nG PMFs

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

Enhancement moves to smaller scales with smaller PMF strength

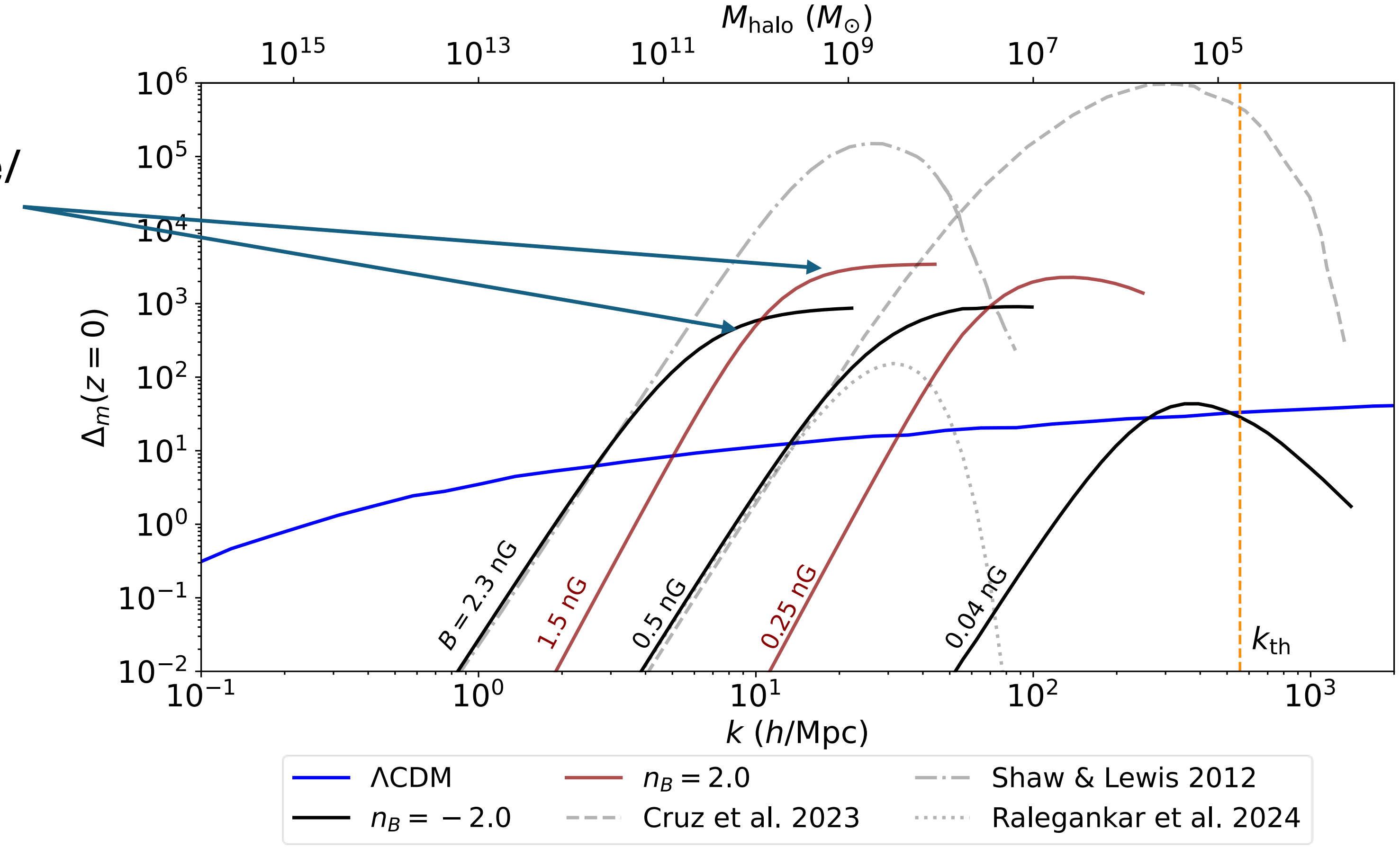


Enhancement moves to smaller scales with smaller PMF strength

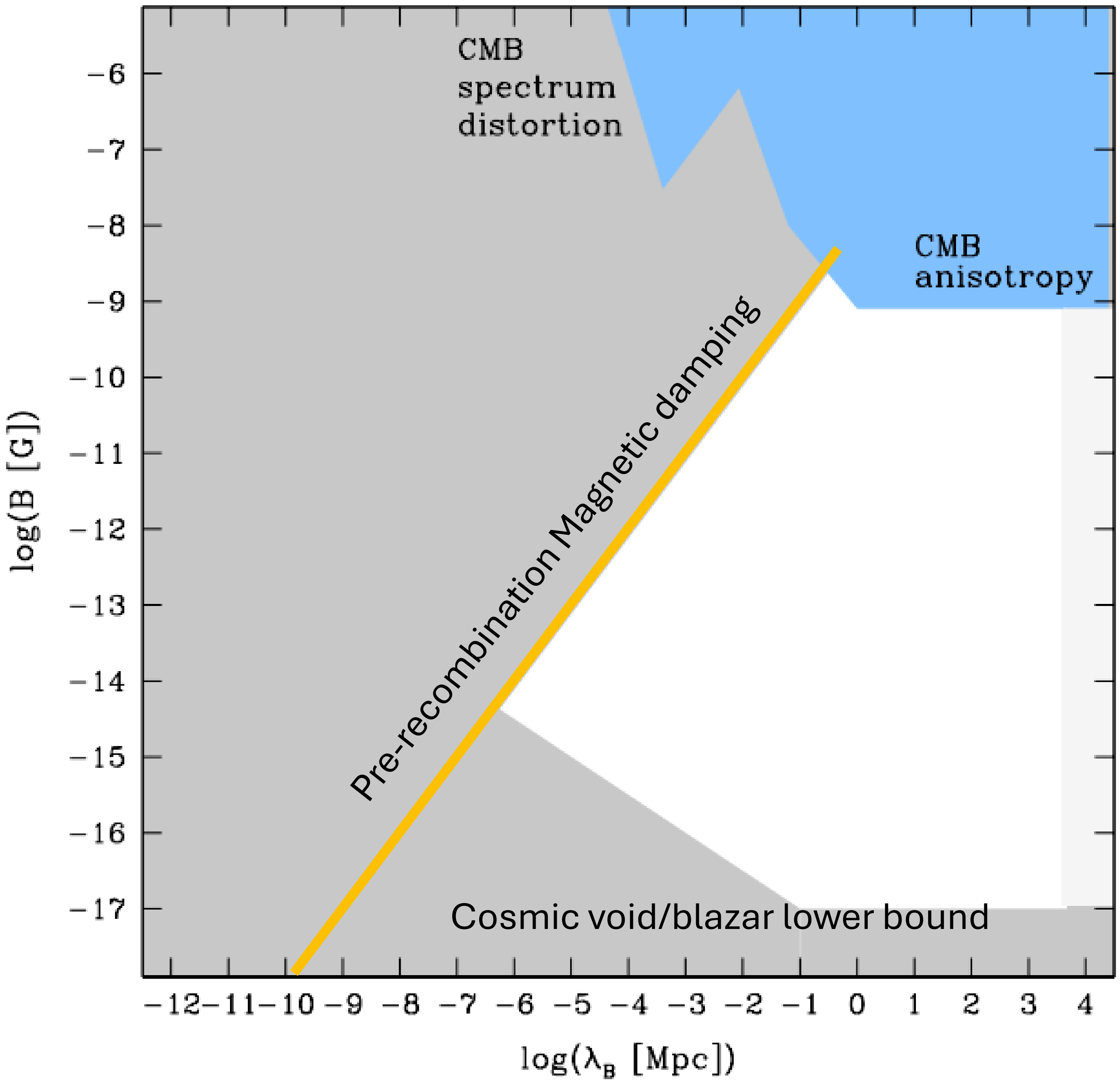


Enhancement moves to smaller scales with smaller PMF strength

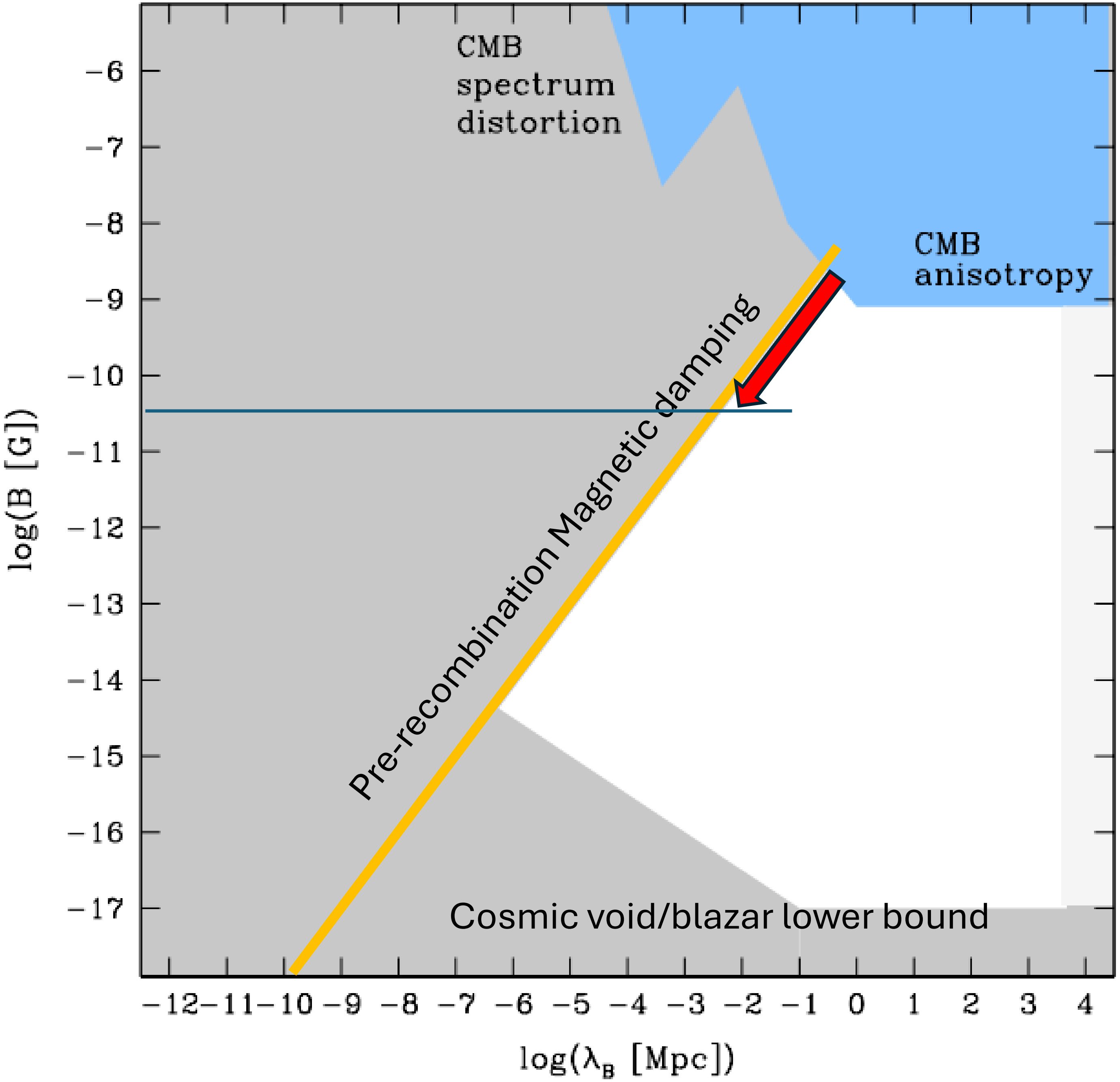
Magnetic Jeans scale/ non-linear regime



Implications for PMFs

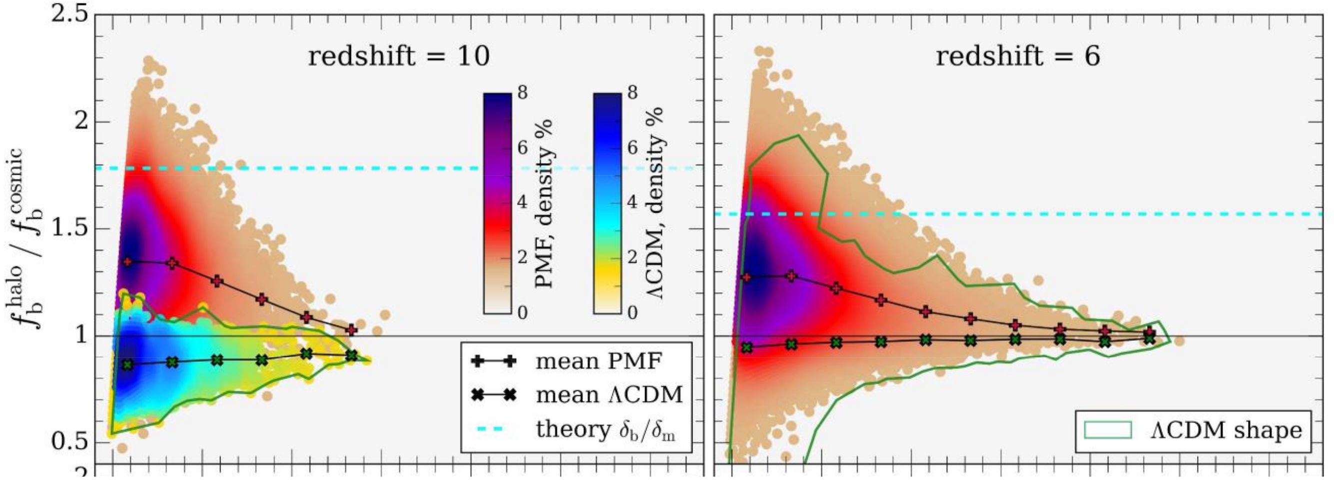


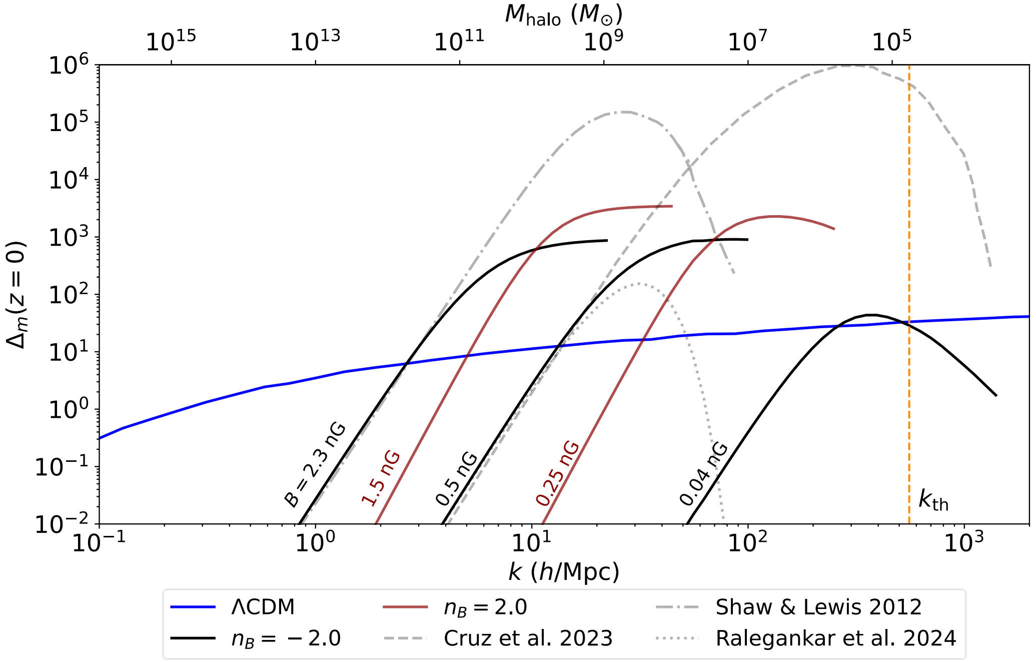
Power spectrum above magnetic jeans scale is sensitive upto 0.05 nG PMFs



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



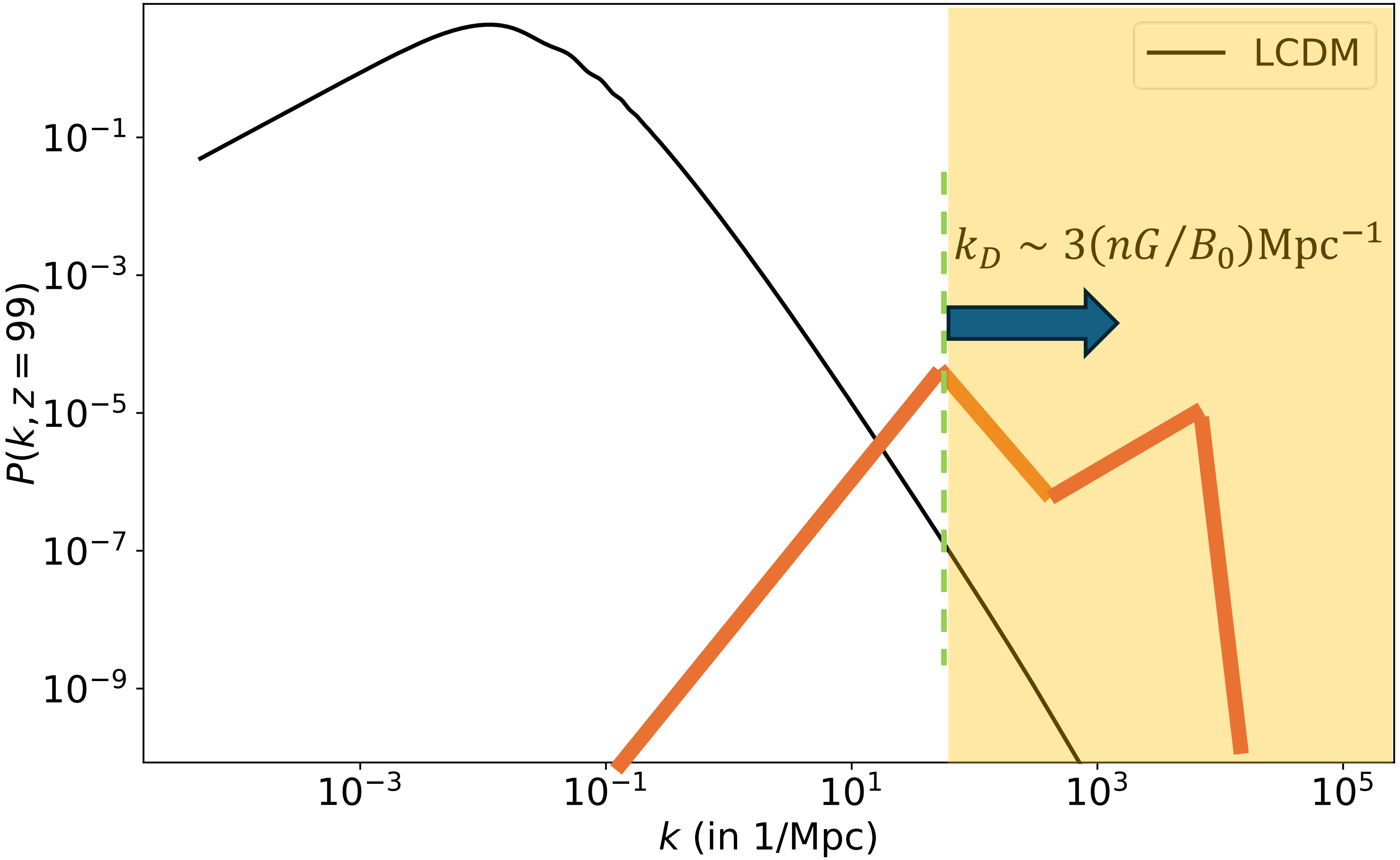


Part 2

Probing Primordial magnetic fields through dark matter minihalos

ARXIV: 2303.11861

Part 2: Dark matter minihalos below jeans scale



Pre-recombination Ideal MHD.. With non-linear terms

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

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

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

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

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

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Pre-recombination Ideal MHD: laminar flow due to photon drag

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

0

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

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

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

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

Can analytically solve MHD eqs: viscous damping

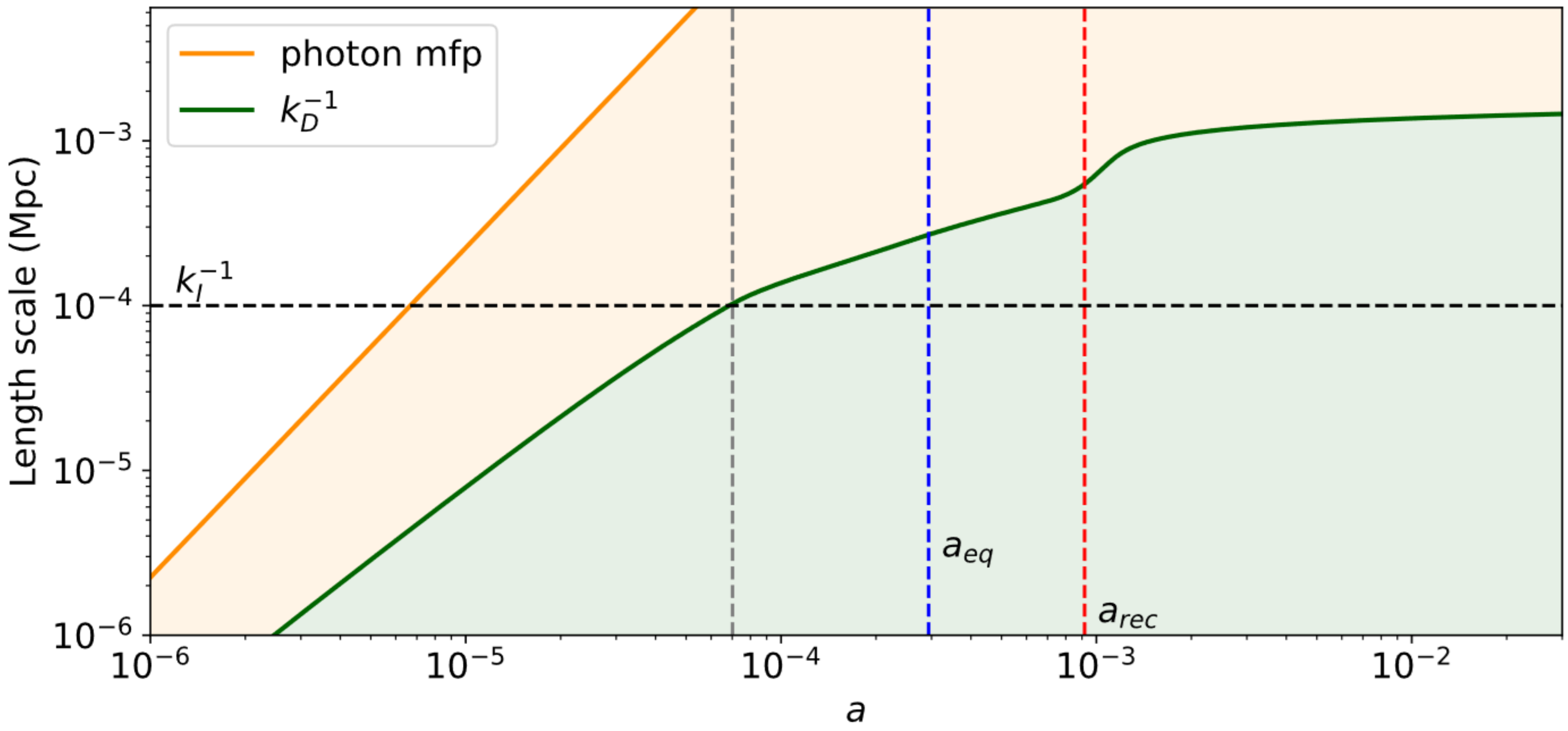
$$P_B(k,t) = P_B(k,t_I)e^{-\frac{k^2}{k_D^2}}$$

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

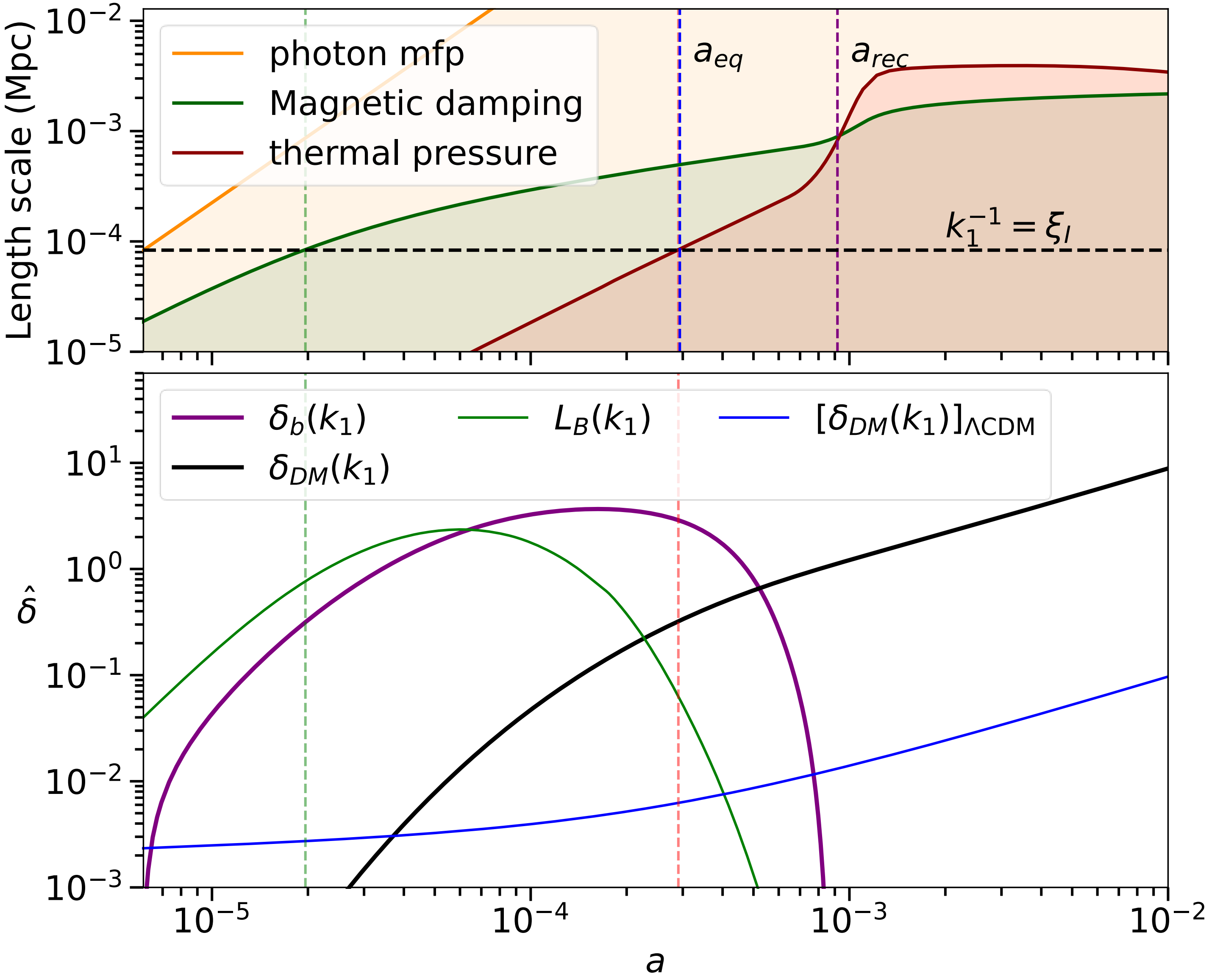
magnetic damping scale Evolution

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

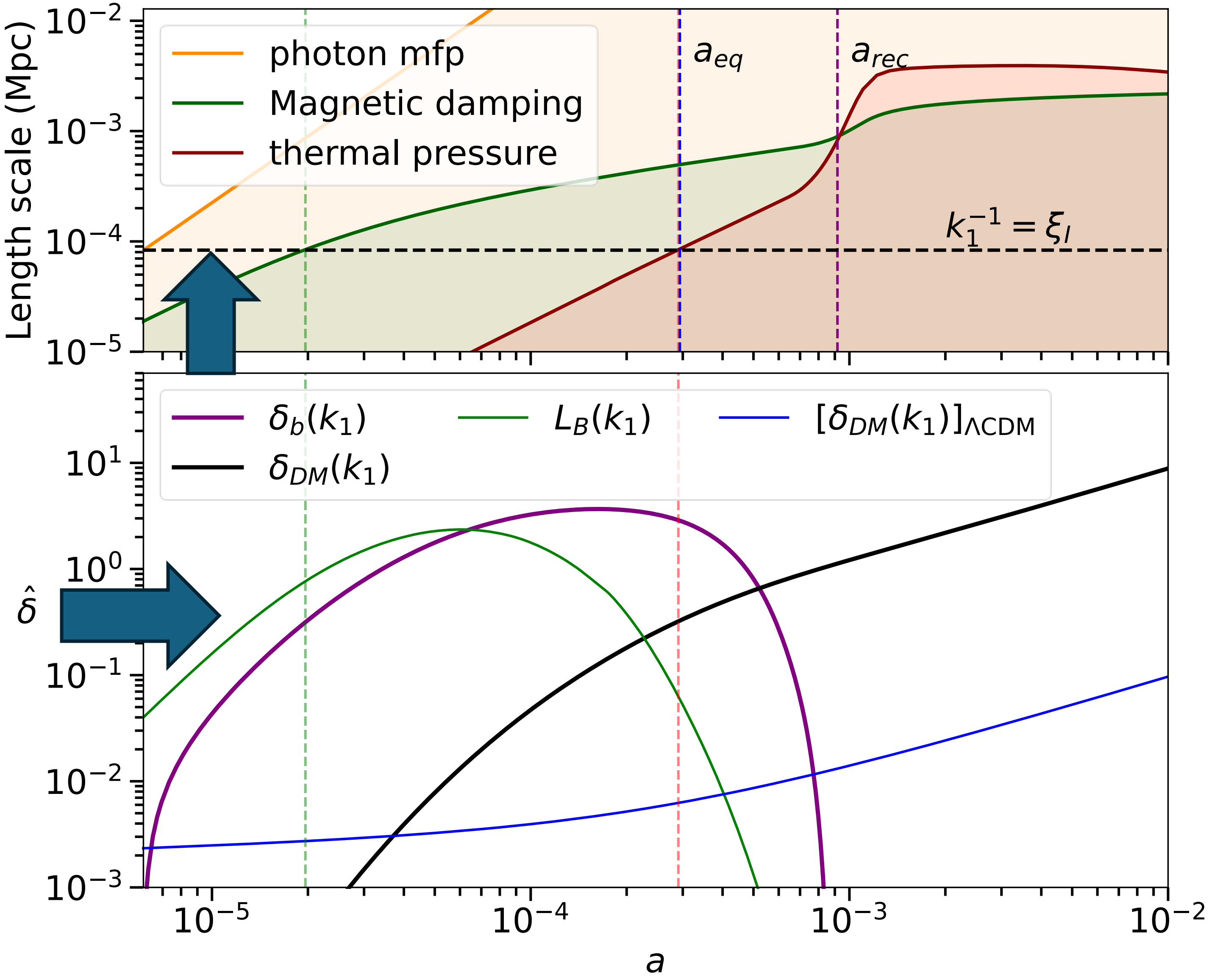
$$k_D^{-1}(a) \sim \tau v_b$$



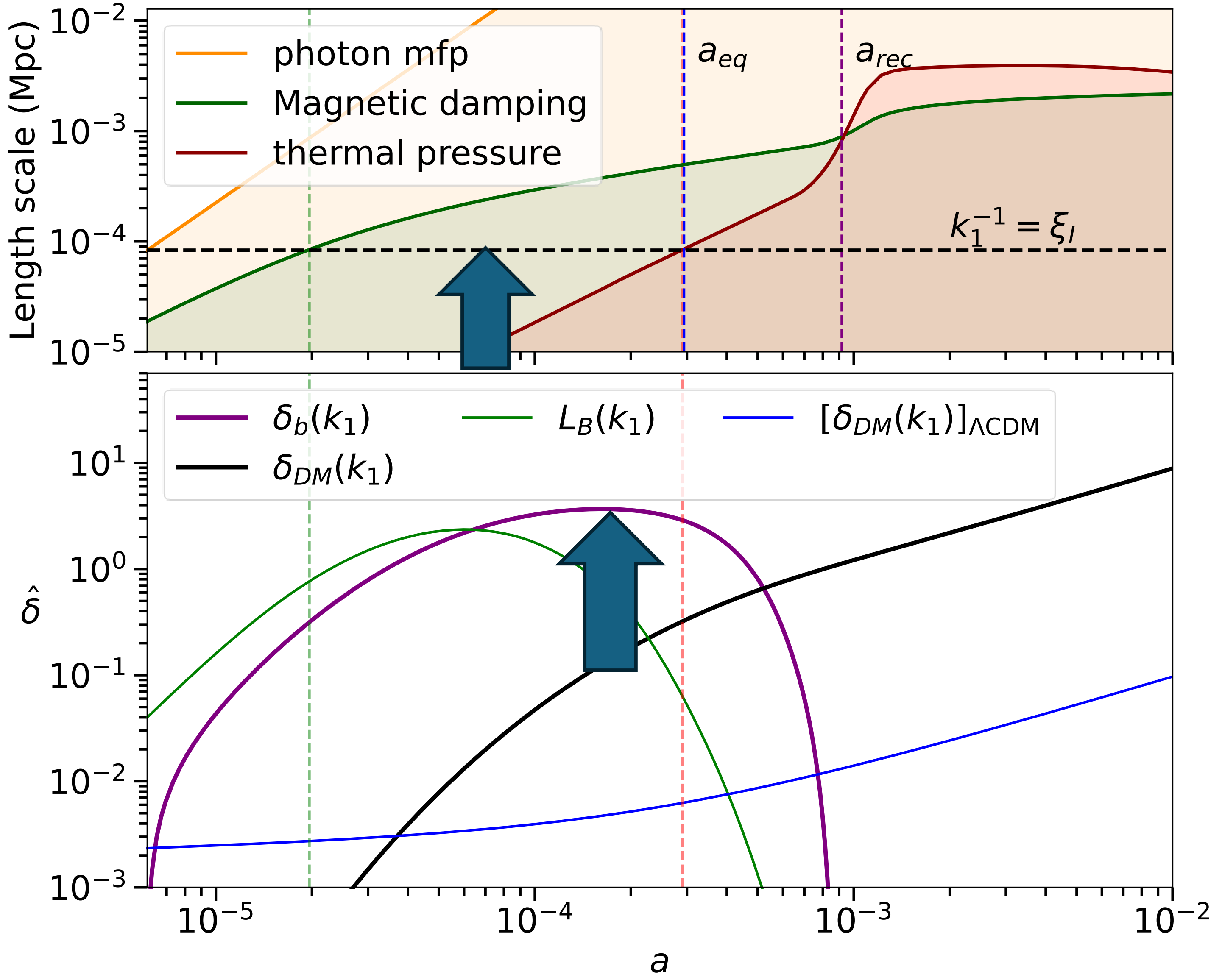
Perturbation evolution plot



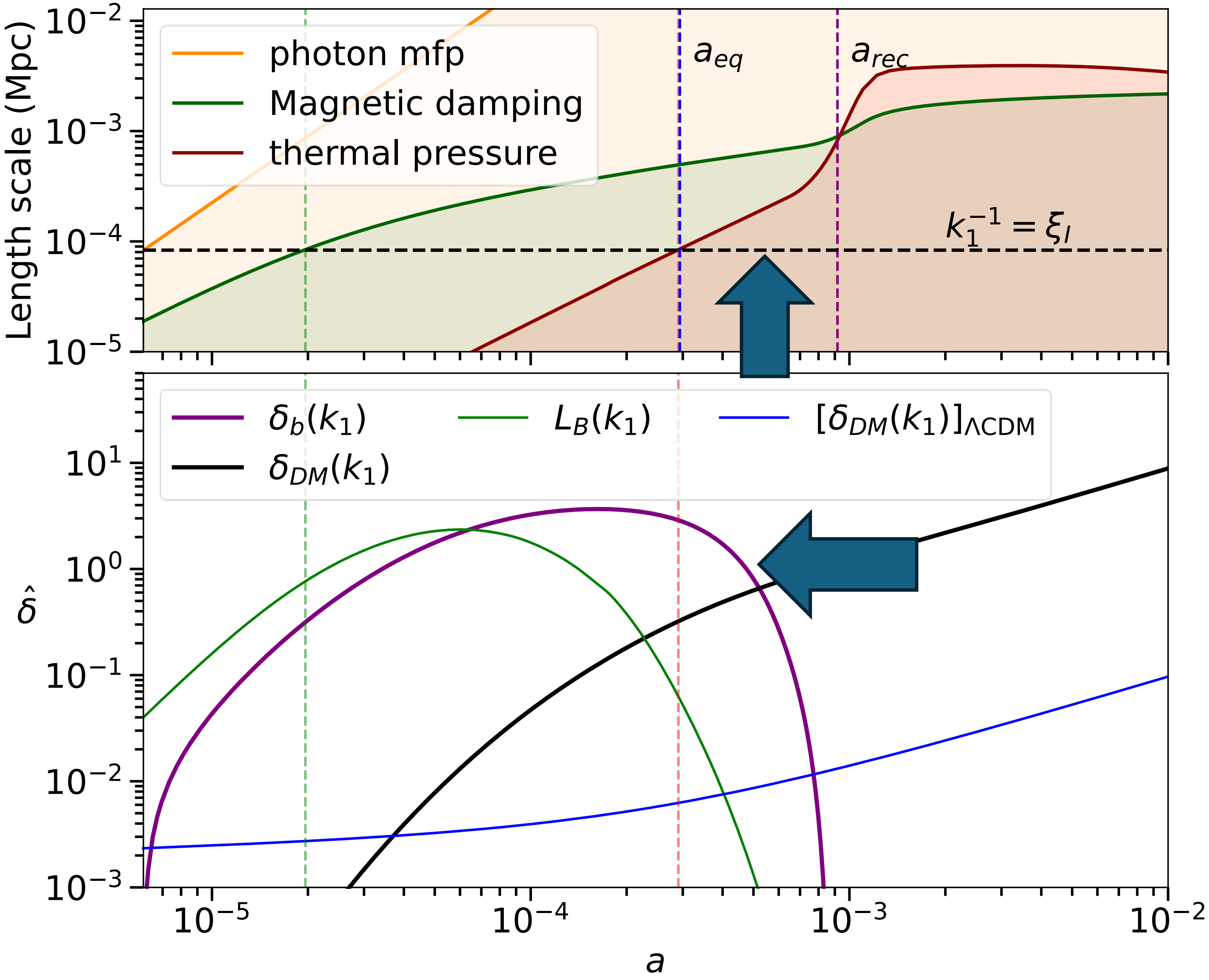
Lorentz force enhances baryon perturbations for modes outside k_D^{-1}



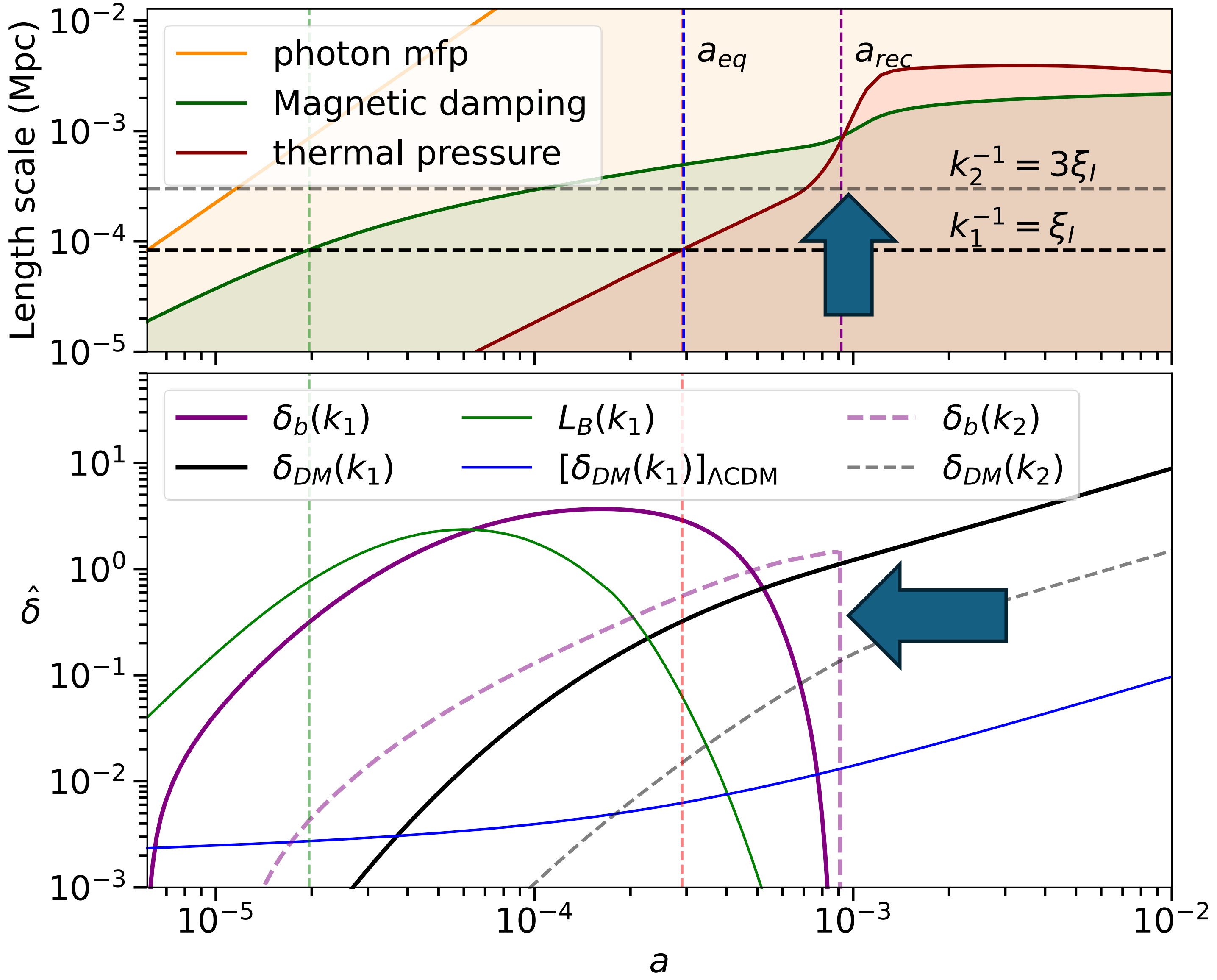
baryon perturbations asymptote once mode enters k_D^{-1}



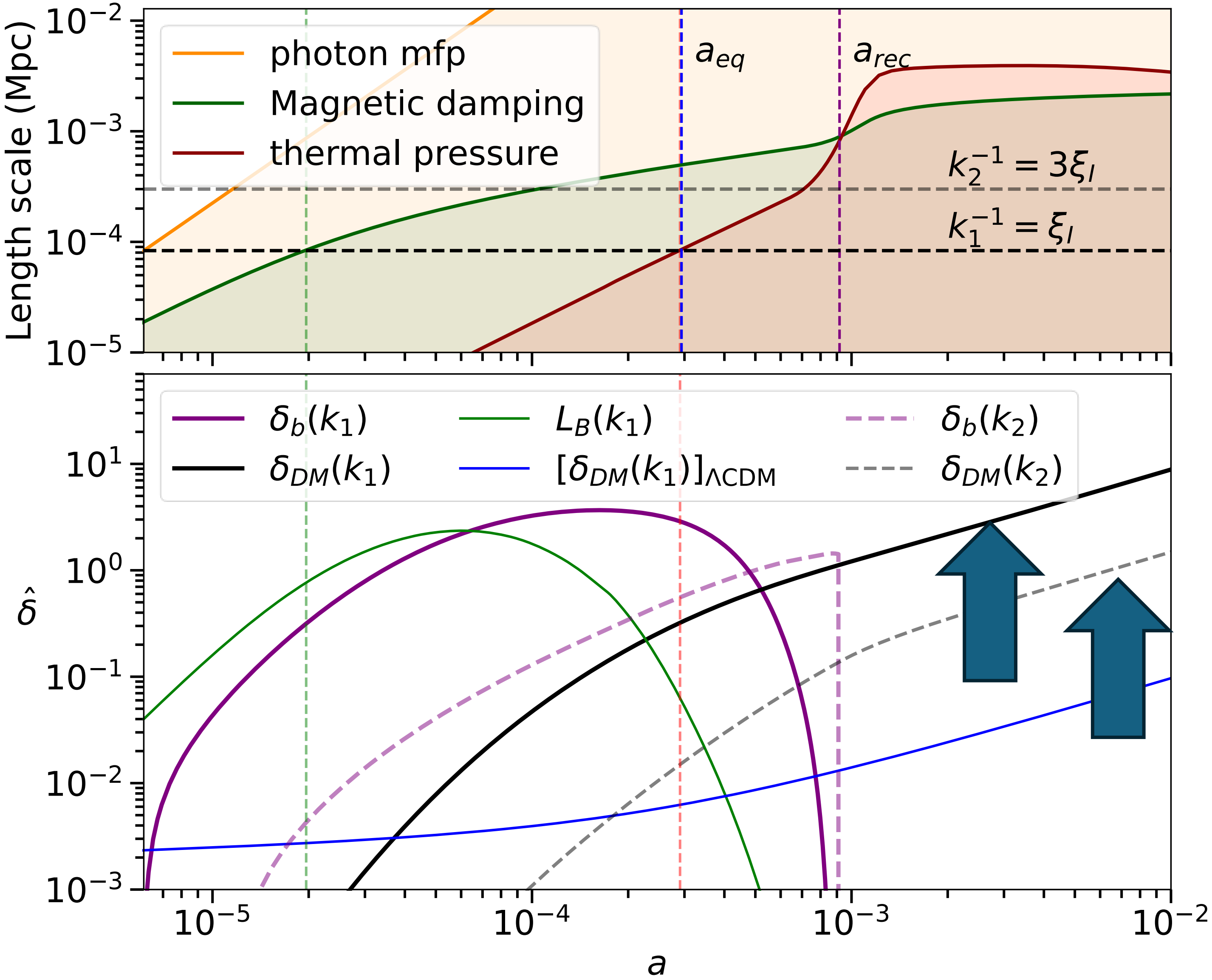
baryon perturbations damped by thermal pressure



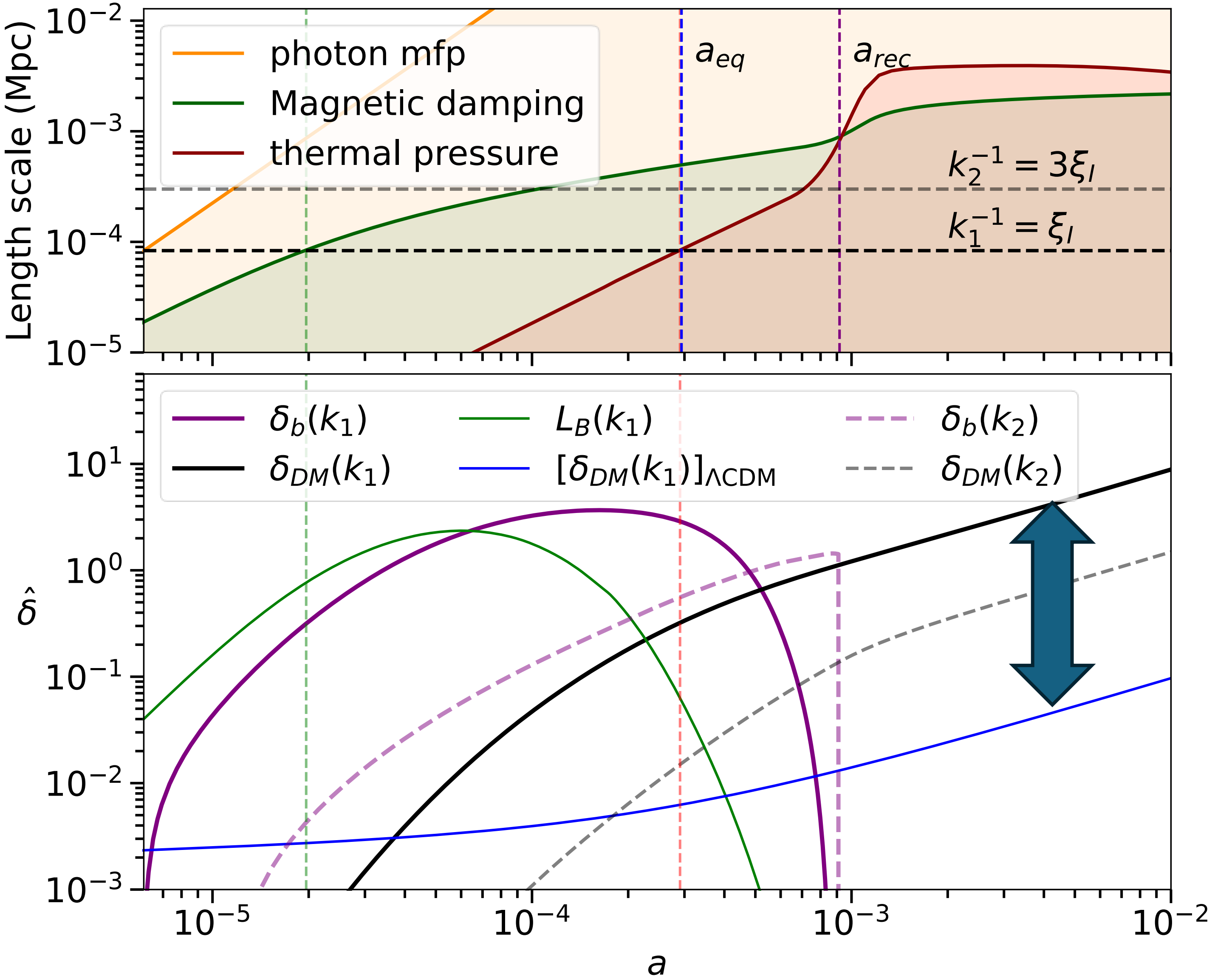
baryon perturbations damped by turbulence at recombination



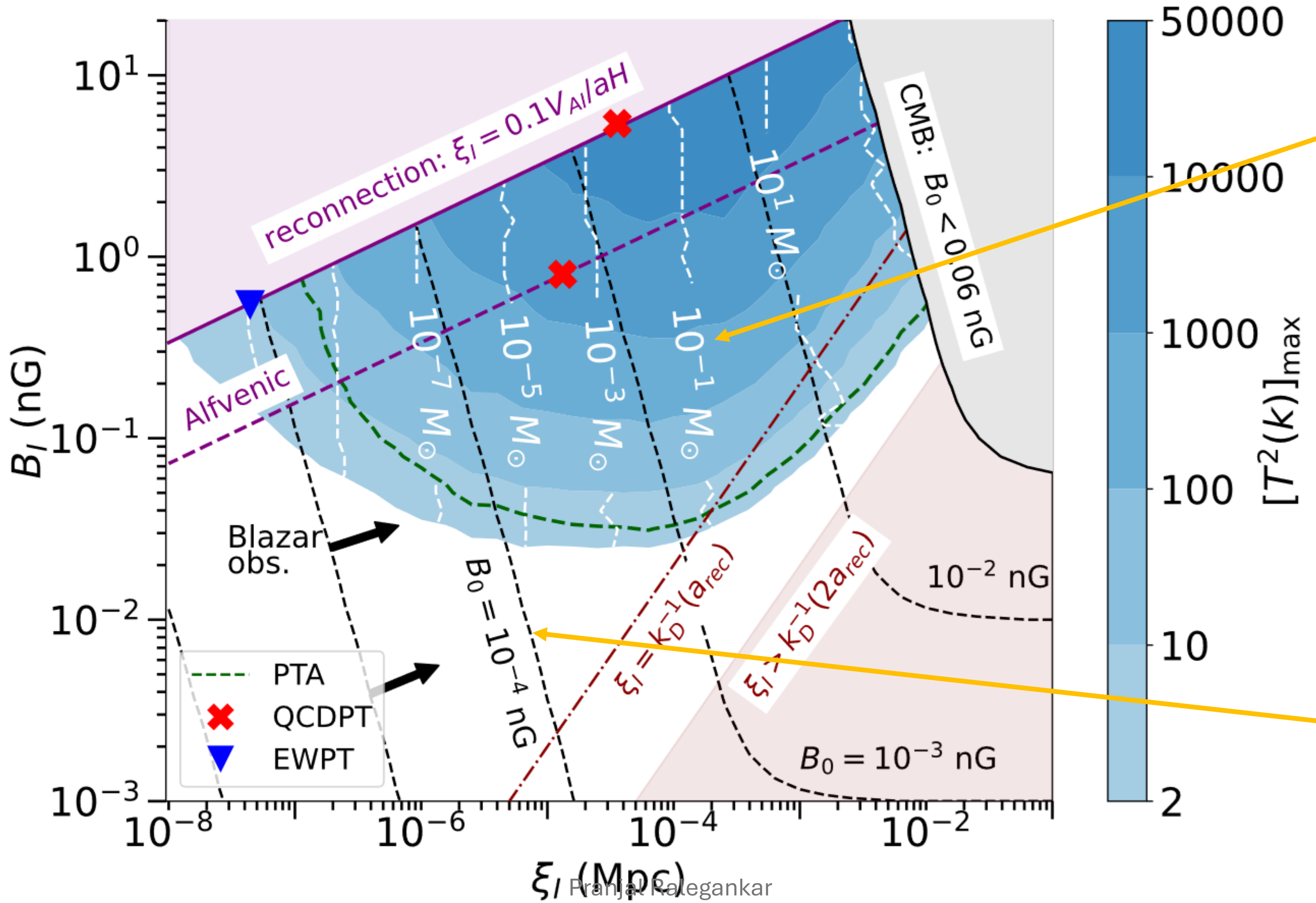
Dark matter perturbations continues to grow!



Dark matter perturbations enhanced by orders of magnitude compared to ΛCDM



Parameter Space with Enhanced Power on Small scales



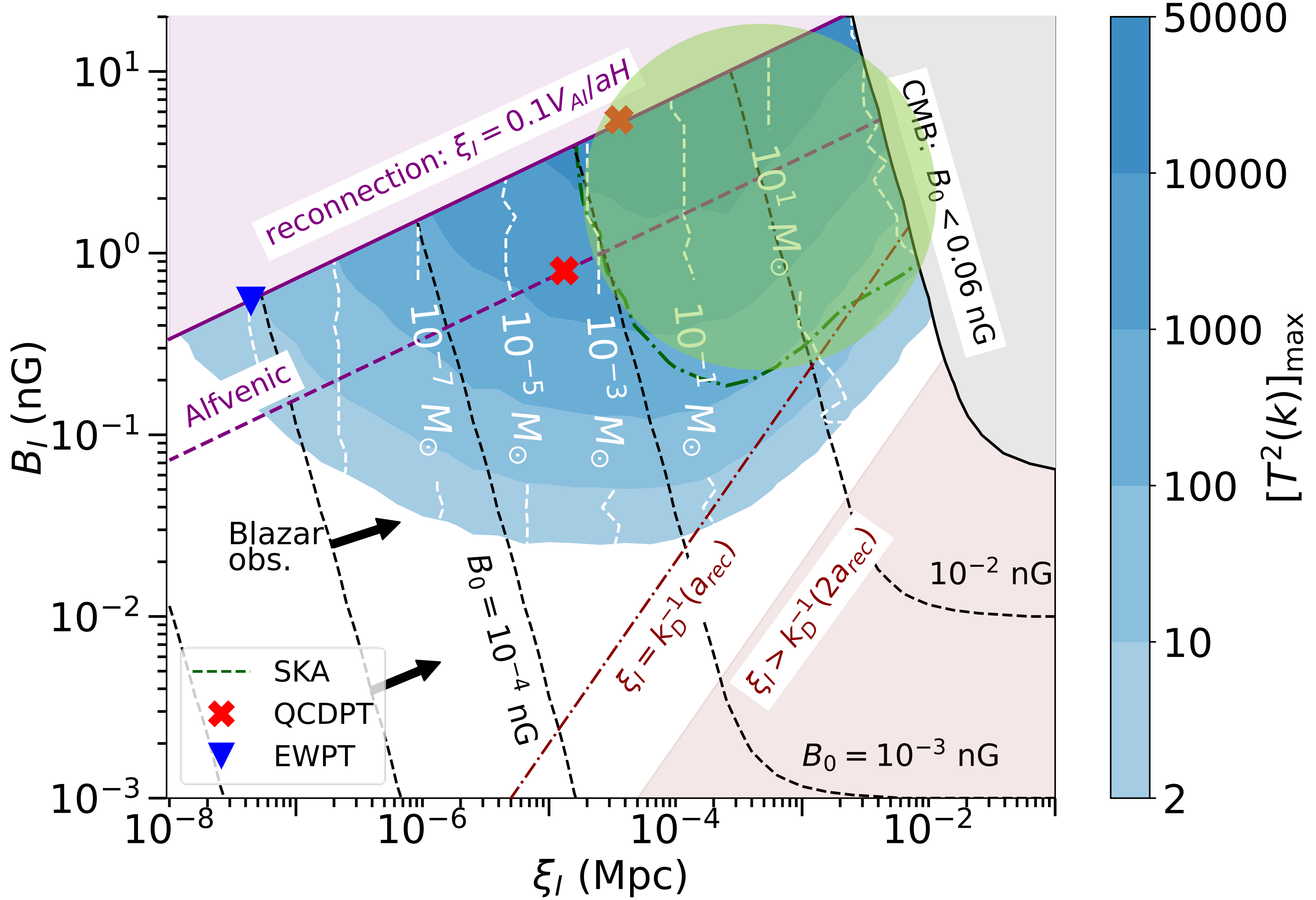
$= \frac{P(k)}{P_{\Lambda CDM}(k)}$

DM minihalo mass

Present-day magnetic field strength

Parameter Space with Enhanced Power on Small scales: THEIA SKA sensitivity

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



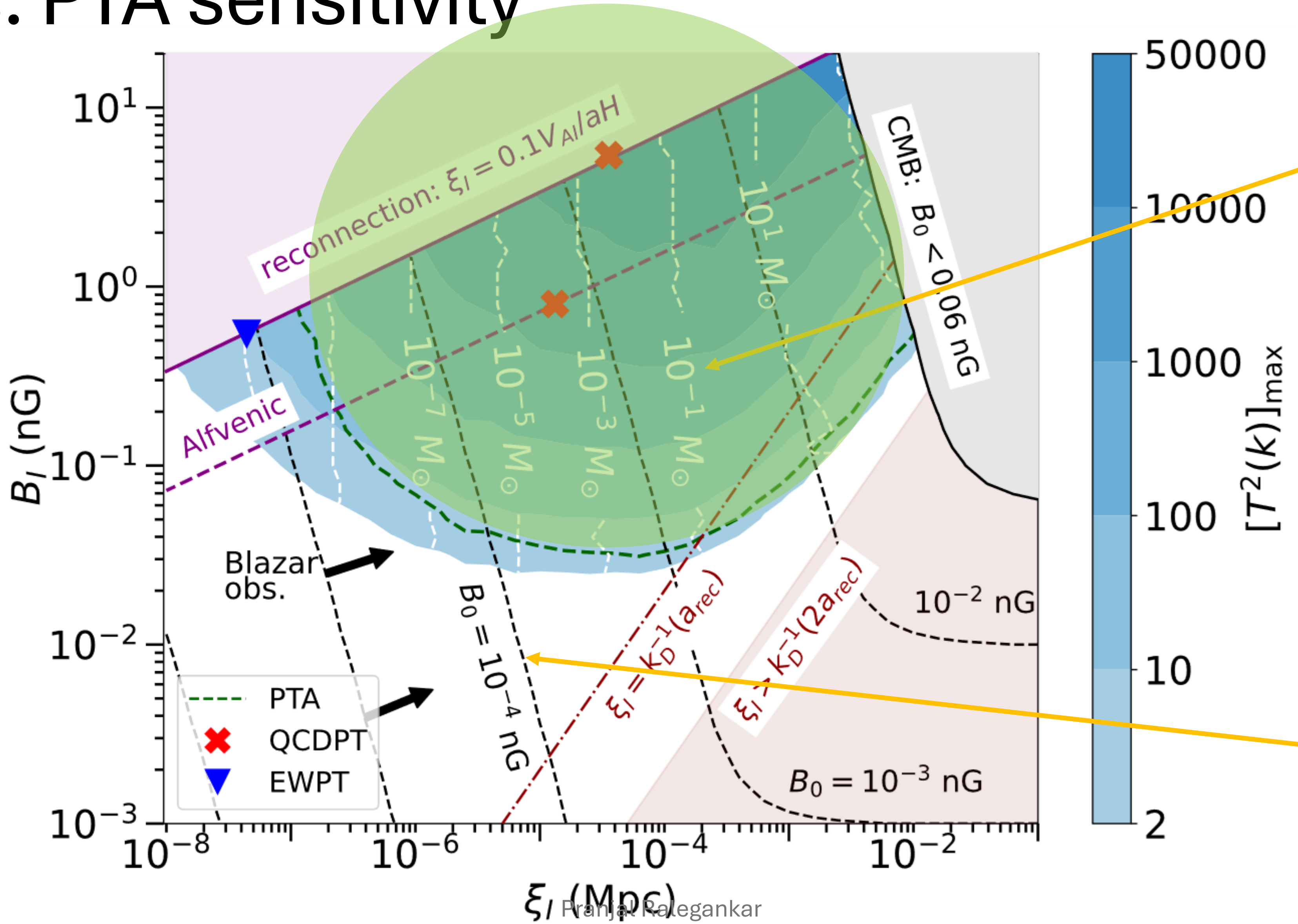
DM minihalo mass

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

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

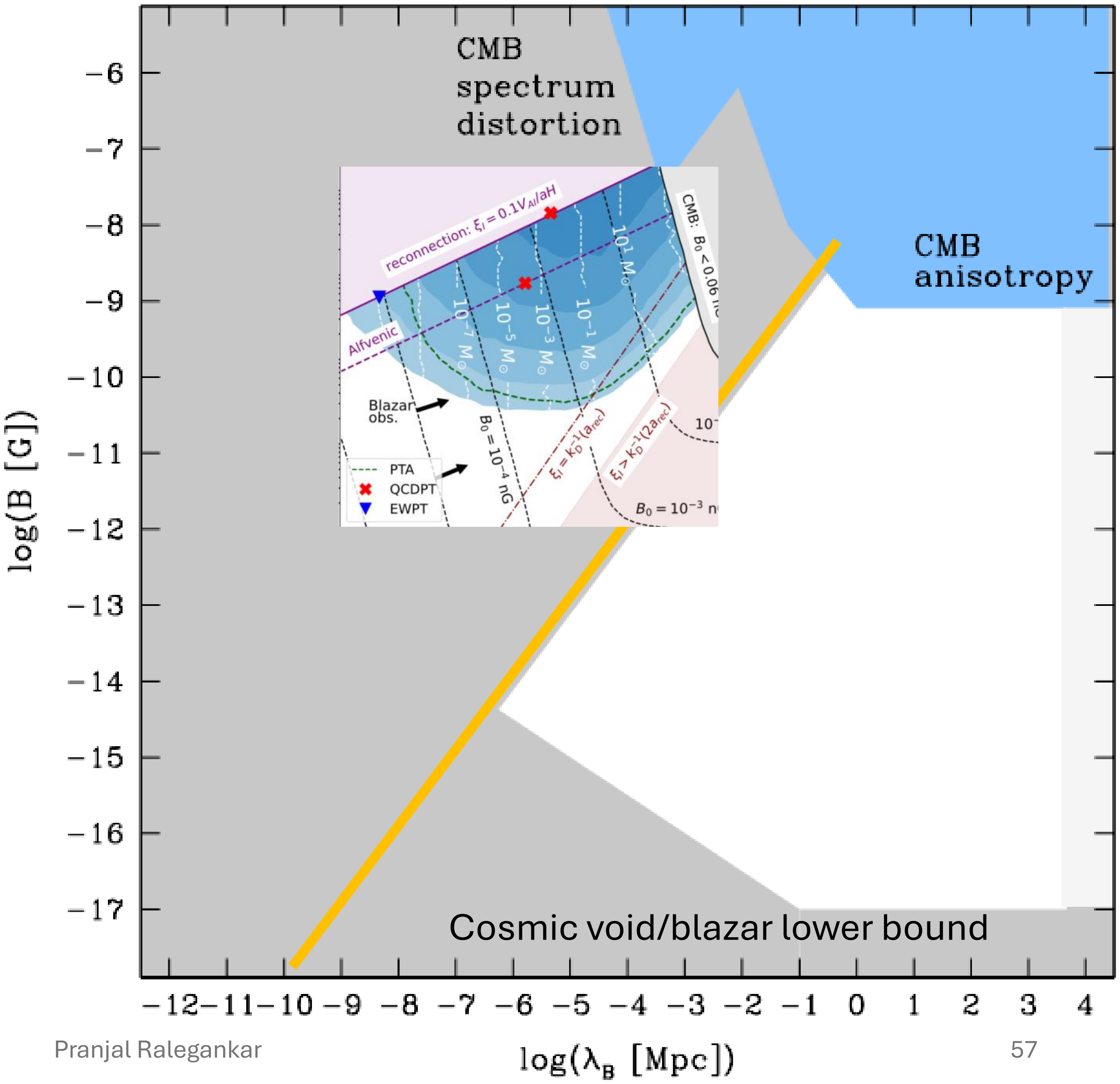


$$= \frac{P(k)}{P_{\Lambda CDM}(k)}$$

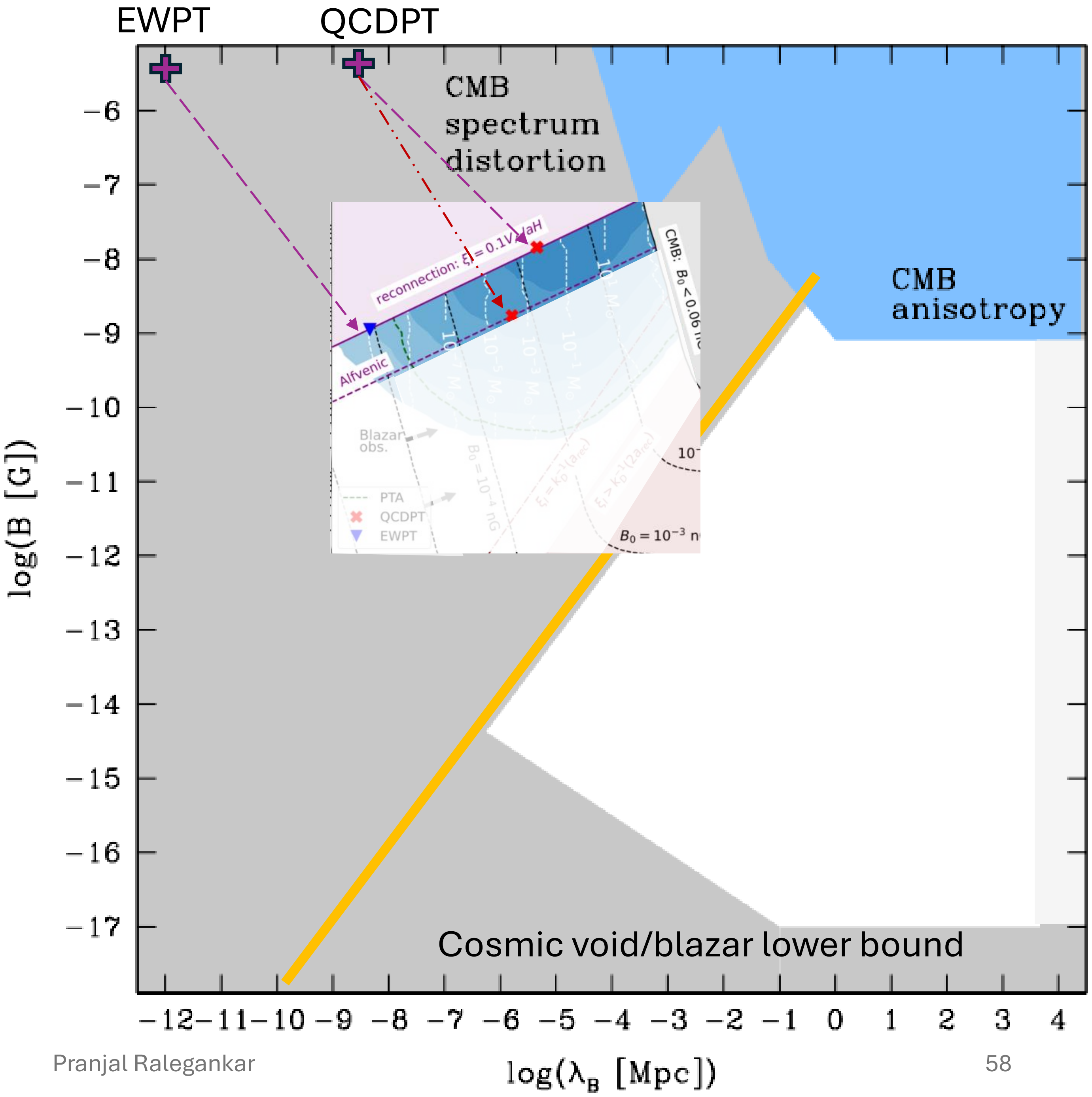
DM minihalo mass

Present-day magnetic field strength

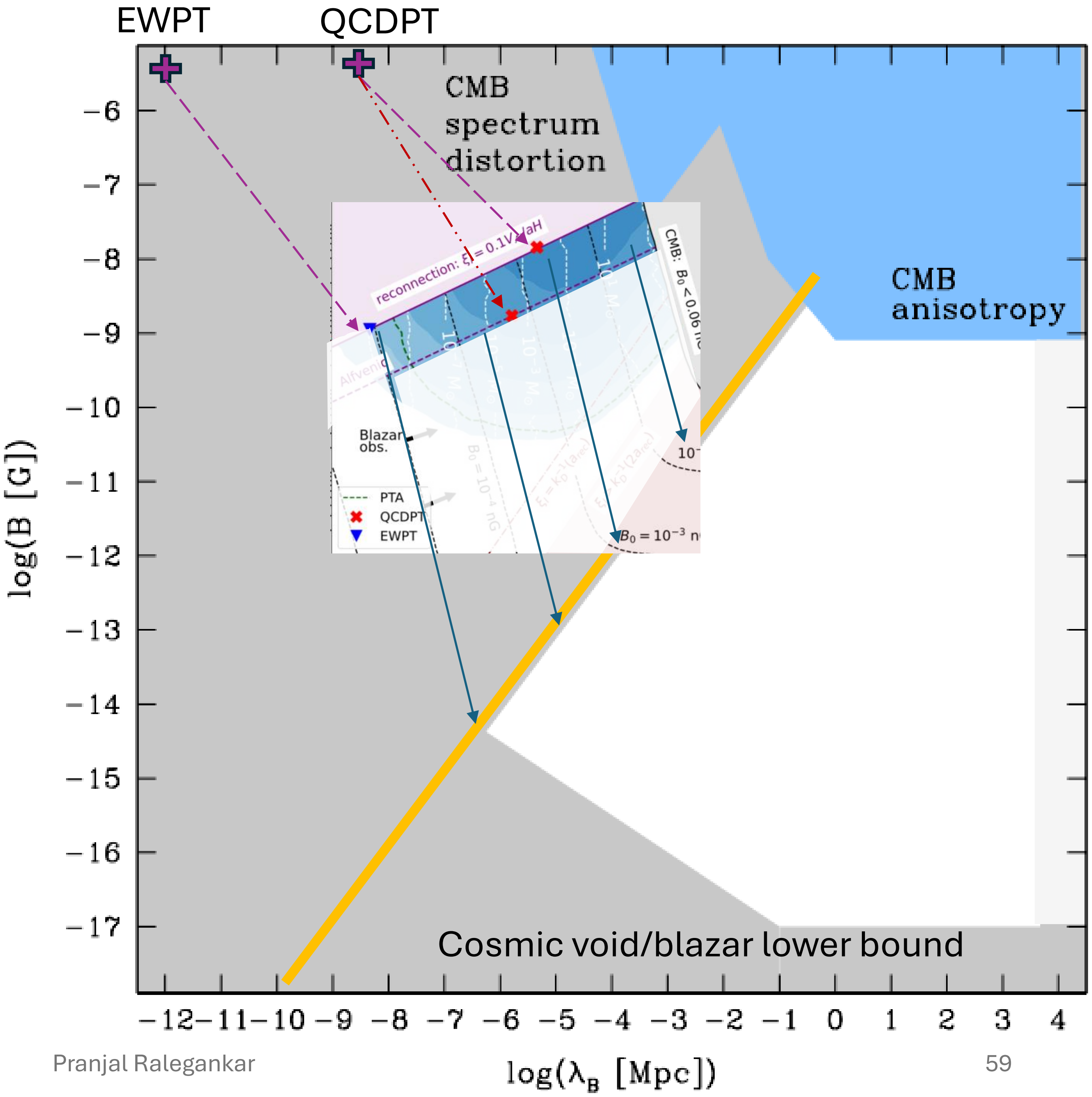
Minihalos from causally generated PMFs



Minihalos from causally generated PMFs



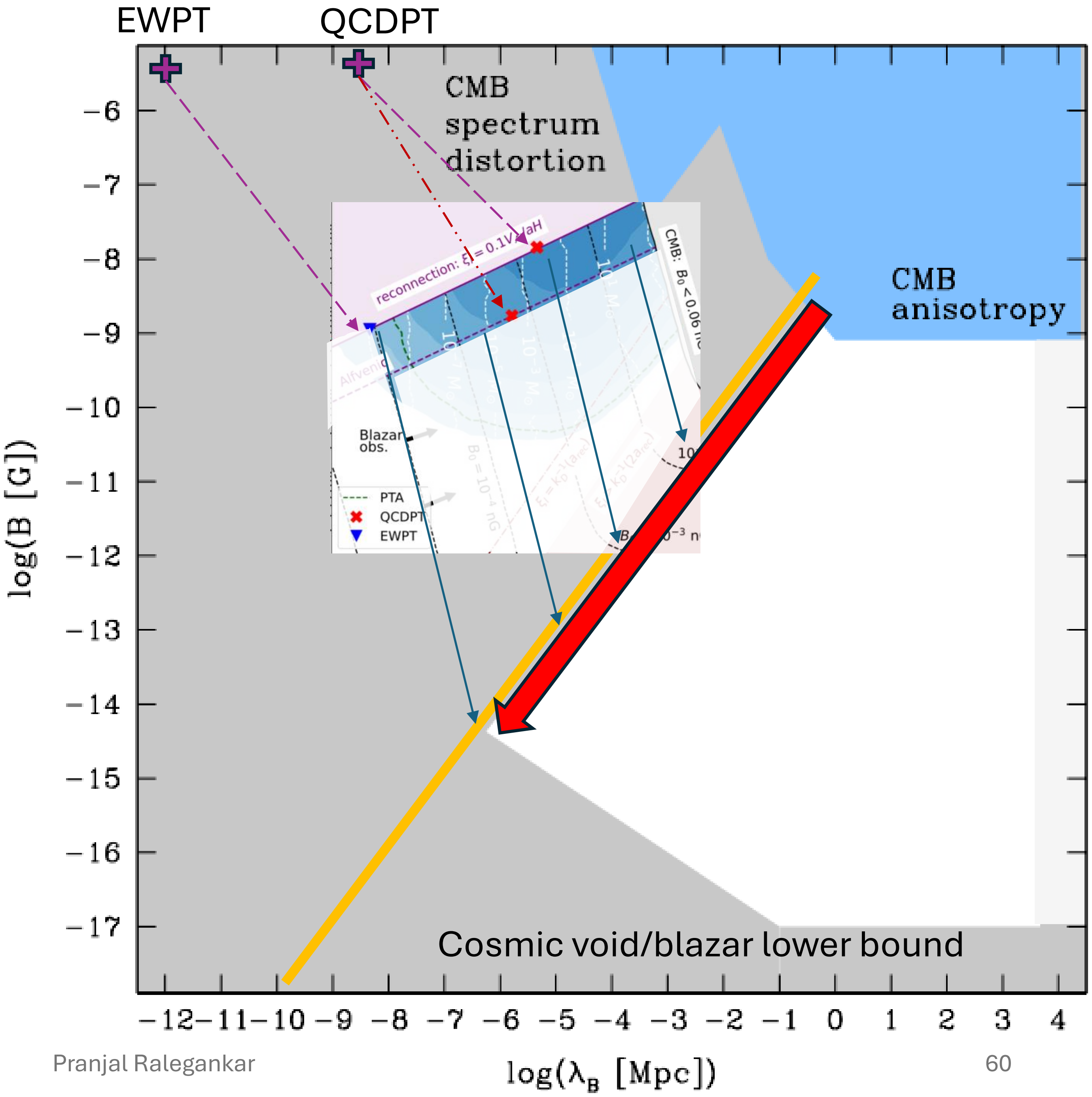
PMFs to explain cosmic void observations



Assuming Batchelor spectrum!

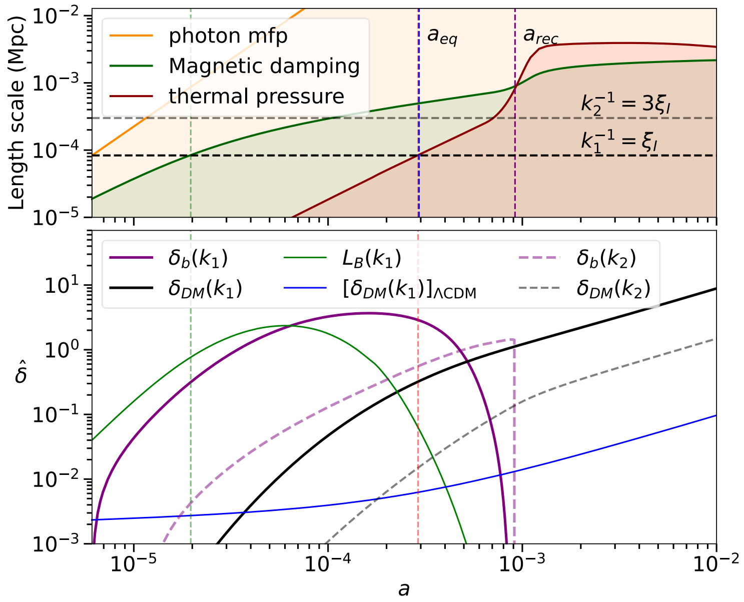
Universe Maybe filled with dark matter minihalos!!

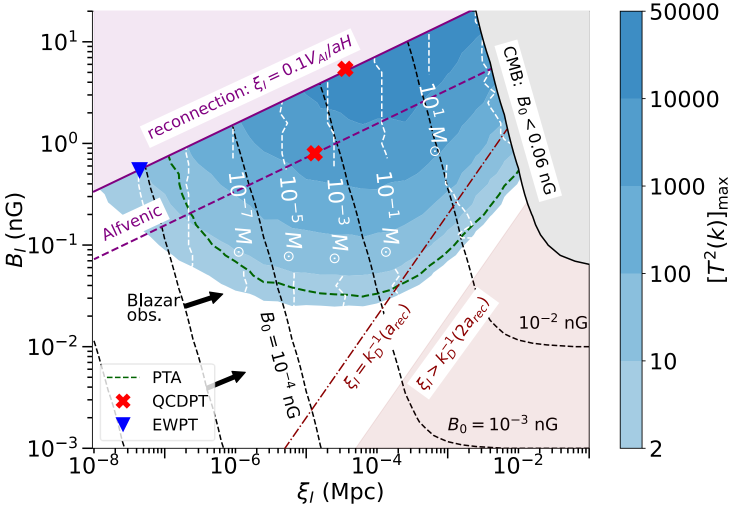
Assuming Batchelor spectrum!



Part 2: 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

Back to power spectrum