Probing Axionic Instabilities in the late Universe via CMB-B mode

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UNIVERSITY OF NOTRE DAME

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Latest topics in particle physics and related issues in astrophysics and cosmology

University of Pittsburgh May 8-10, 2023

Introduction

~~Direct detection~~ → Nightmare Scenario?

Dark Sector

Standard Model

GRAVITY

Gravitational Waves

CMB

Secluded Dark Sector: Axion + Dark Photon

$$\frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - V(\phi) - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\alpha}{4f}\phi X_{\mu\nu}\widetilde{X}^{\mu\nu} \longrightarrow \text{Dark photon}$$

Initial condition:
$\Omega_\phi \neq 0$
$\Omega_X \approx 0$

$$V(\phi) \longrightarrow \Lambda^4 \cos\left(\frac{\phi}{f}\right) \rightarrow \boxed{m = \frac{\Lambda^2}{\sqrt{2}f}}$$

Axion E.O.M $\rightarrow$

$$\phi'' + \underbrace{2aH\phi'}_{\text{Hubble friction}} + \underbrace{a^2\frac{\partial V}{\partial\phi}}_{m^2\phi} = \frac{\alpha}{f}a^2\mathbf{E}\cdot\mathbf{B}$$

$m > H(z)$ at Matter Domination $\longrightarrow$ $m \lesssim 10^{-28}$ eV

Geller et al, 2104.08284

Caution: $\phi \neq$ DM

Tachyonic instability: Exponential production of Dark Photon

$$\hat{X}^i(\mathbf{x},\tau) = \int \frac{d^3k}{(2\pi)^3}\hat{X}^i(\mathbf{k},\tau)e^{i\mathbf{k}\cdot\mathbf{x}} = \sum_{\lambda=\pm}\int \frac{d^3k}{(2\pi)^3} v_\lambda(k,\tau)\,\varepsilon^i_\lambda(\mathbf{k})\,\hat{a}_\lambda(\mathbf{k})\,e^{i\mathbf{k}\cdot\mathbf{x}} + \text{h.c.}$$

Dark Photon E.O.M →
(k mode)

$$v''_\pm(k,\tau) + \omega^2_\pm(k,\tau)\,v_\pm(k,\tau) = 0$$

$$v_\pm(k,\tau)\,|_{\text{in}} = \frac{e^{ik\tau}}{\sqrt{2k}}$$

Bunch Davis Vacuum

Time dependent frequency →

$$\omega^2_\pm(k,\tau) = k^2 \mp k\frac{\alpha}{f}\phi'$$

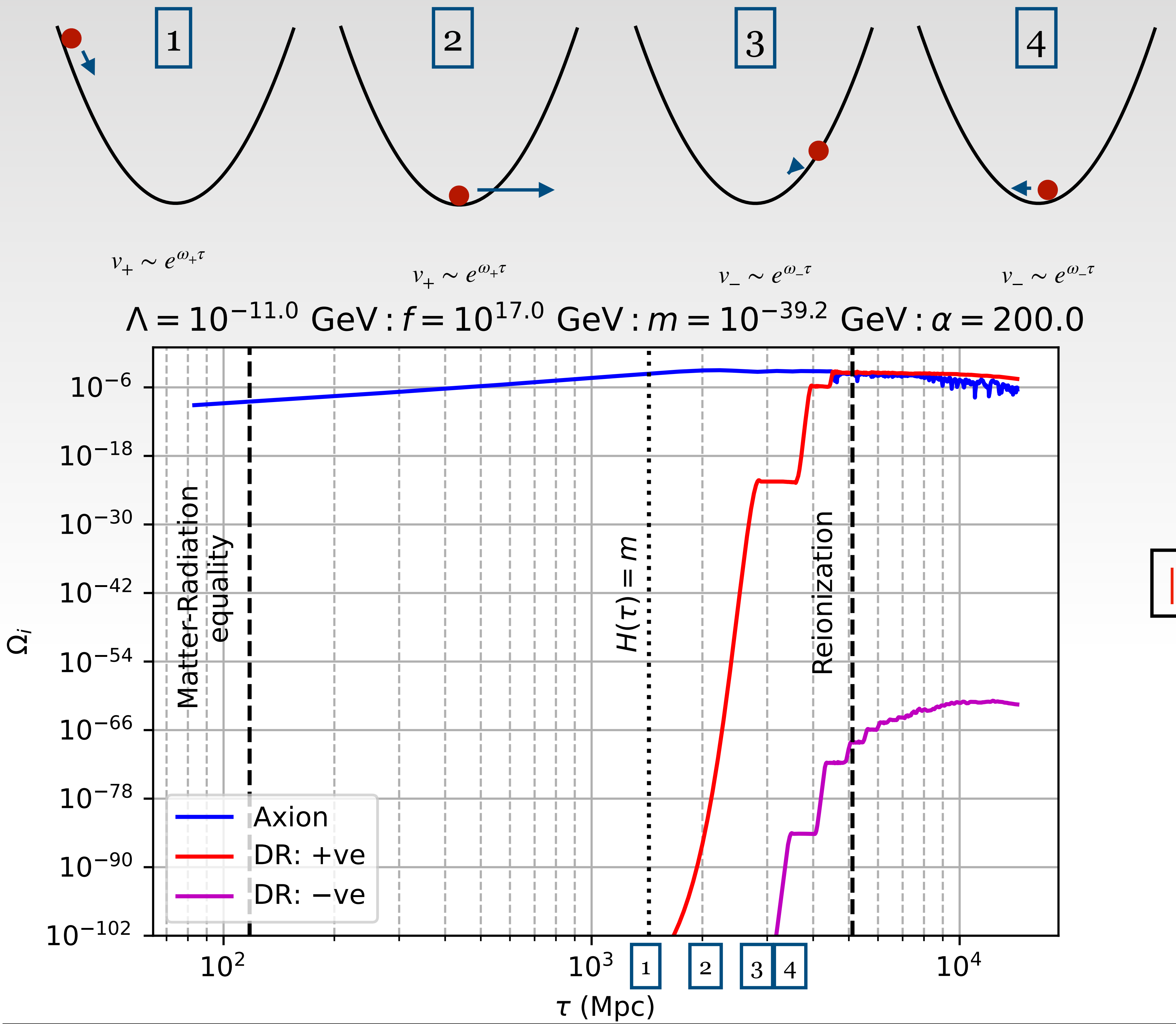
$\boxed{\text{Tachyonic Band}}$ $\quad 0 < k < \dfrac{\alpha|\phi'|}{f} \longrightarrow \omega^2_\pm < 0 \longrightarrow \boxed{v_\pm \sim e^{|\omega_\pm|\tau}}$

Exponential growth

Machado et al, 1811.01950

Geller et al, 2104.08284

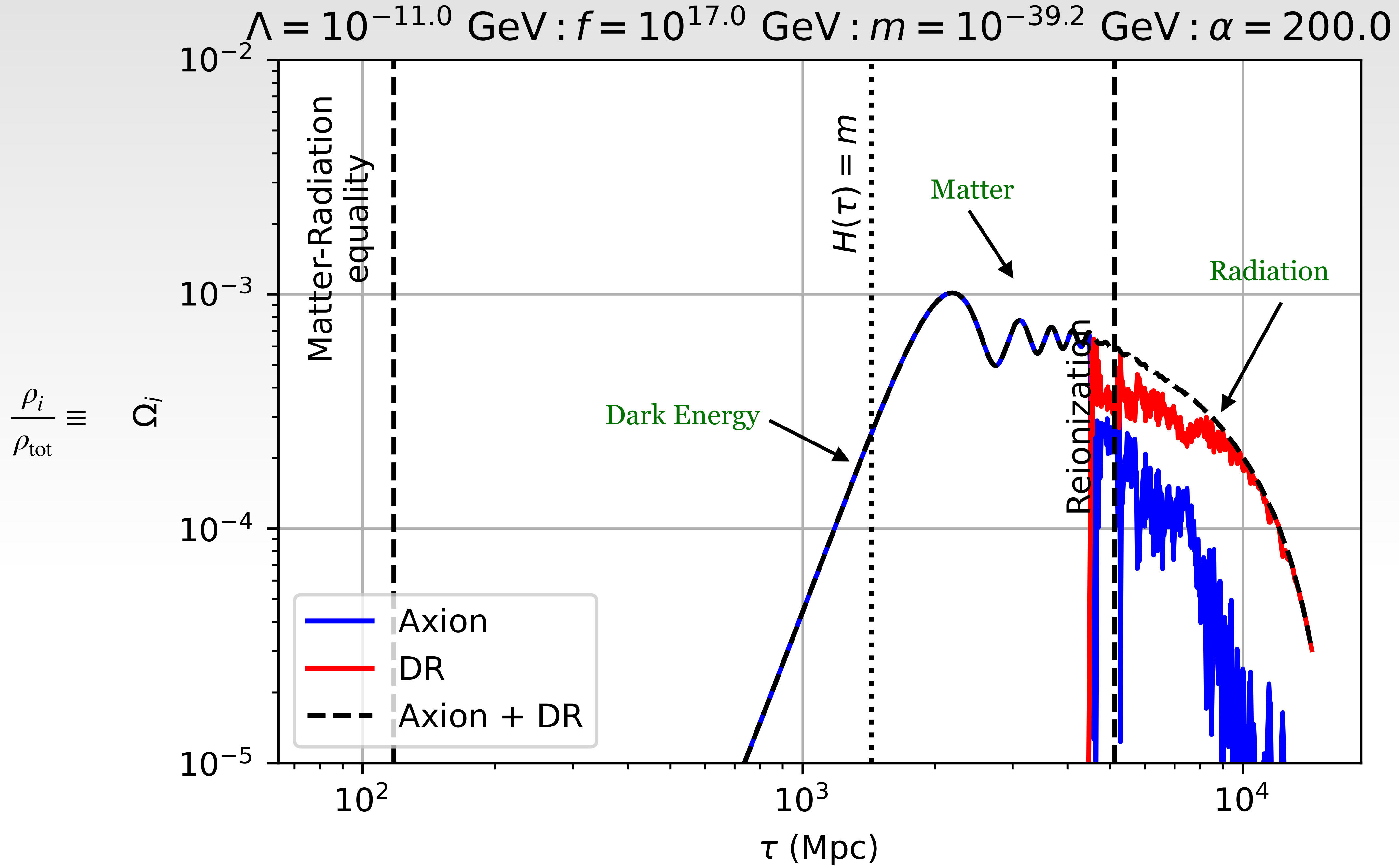
Tachyonic instability: Enhancement of one helicity



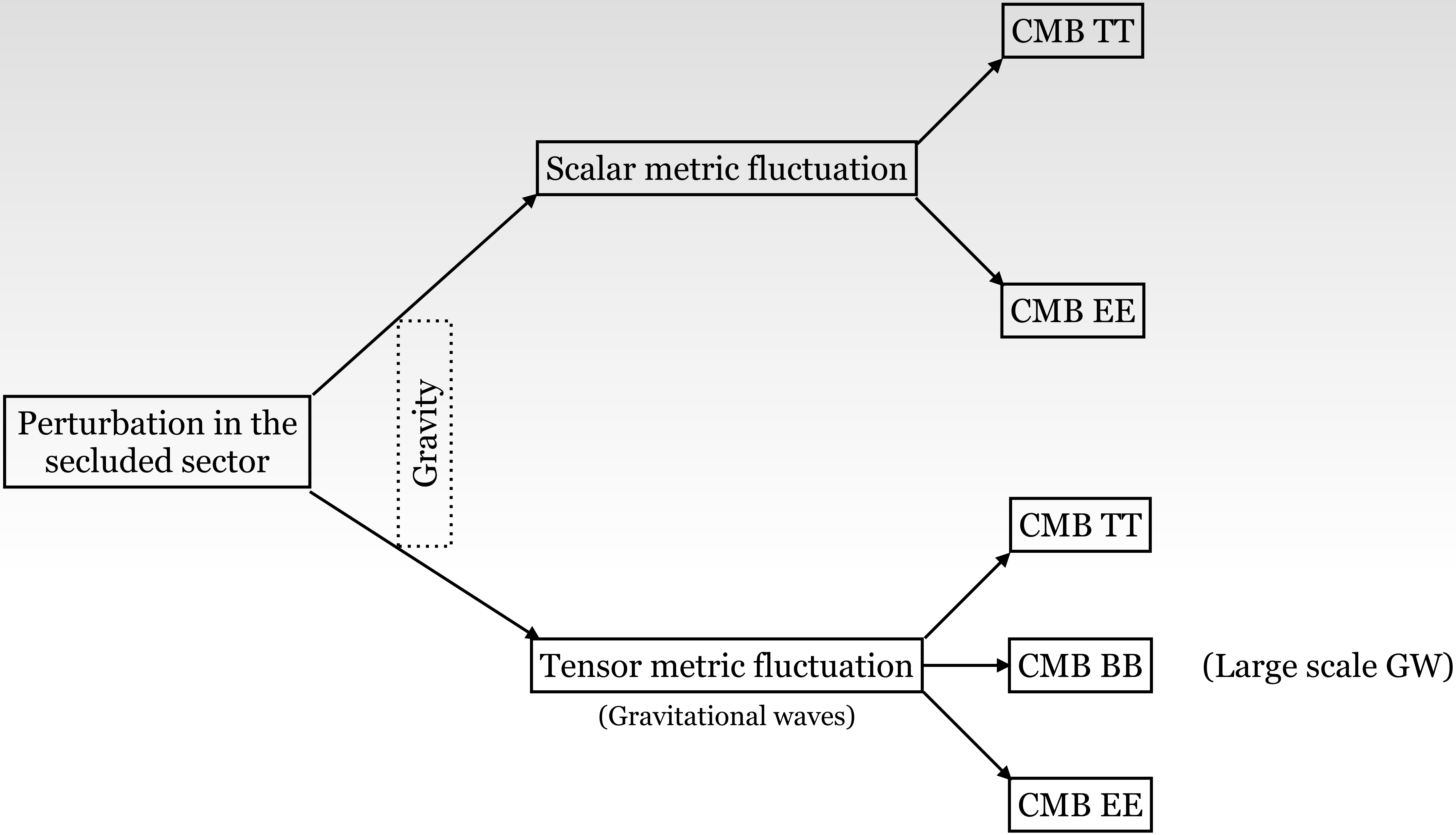
$|v_+| \gg |v_-|$

In our numerical calculation we only consider +ve helicity for simplicity

Tachyonic instability: Energy transfer from Axion to DR



Effects on CMB



Metric fluctuation : Isocurvature modes

The perturbation in Dark Photon is very high due exponential particle production

$$\frac{\langle \delta\rho_{\rm DR}^2 \rangle^{1/2}}{\rho_{\rm DR}} \sim 0.1$$

Matter domination: $\rho_{\rm DR} \sim (1\ ,\ 10^{-3})\ \rho_{\rm Axion}$

$$\langle \delta\rho_{\rm DR}^2 \rangle^{1/2} \sim 0.1\rho_{\rm DR} \sim (10^{-2},10^{-4})\rho_{\rm Axion} \sim 10^{-5}\rho_{DM} \sim \delta\rho_{DM}|_{\rm inflation}$$

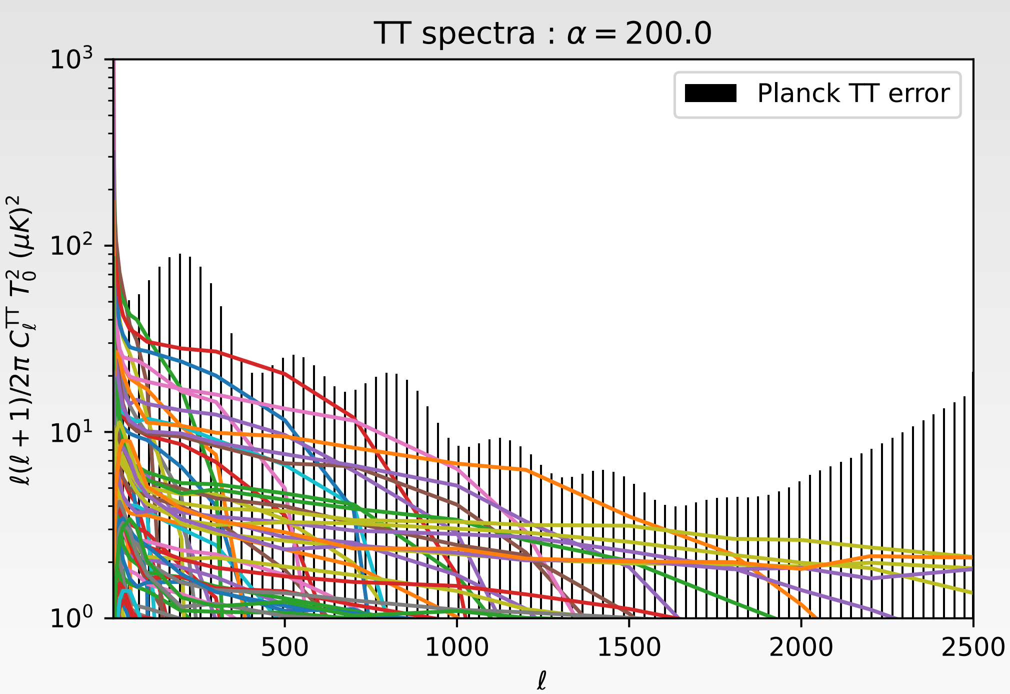
Assuming $\rho_{\rm Axion} \sim 10^{-2}\rho_{DM}$

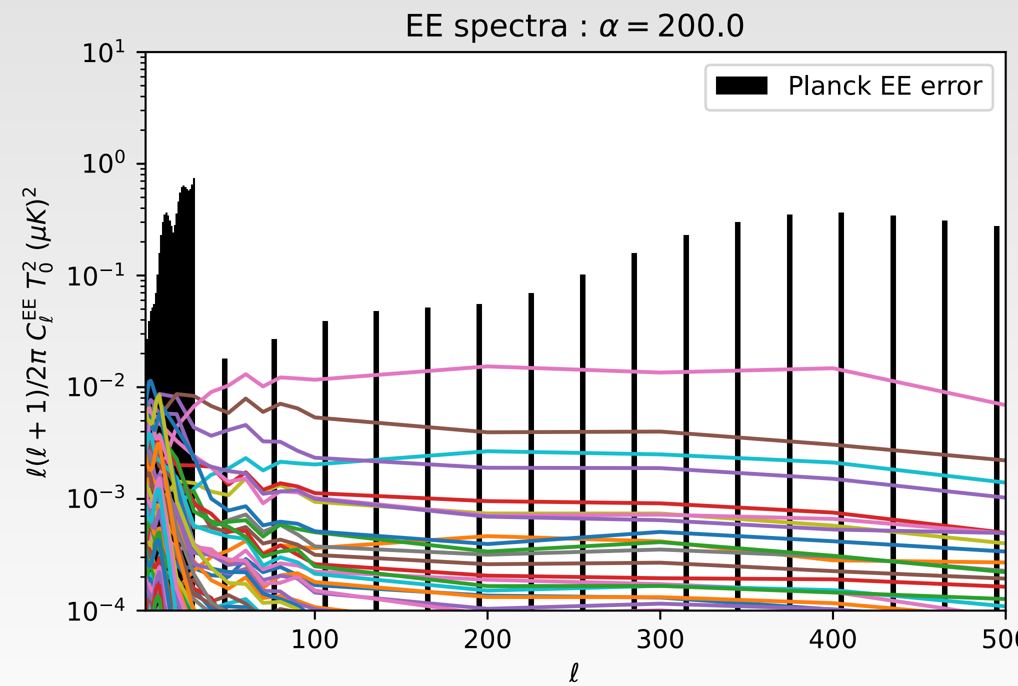
Subdominant DR in Matter domination can source high metric fluctuation

These fluctuations are uncorrelated from inflationary fluctuations → Isocurvature fluctuation

CMB Constraints

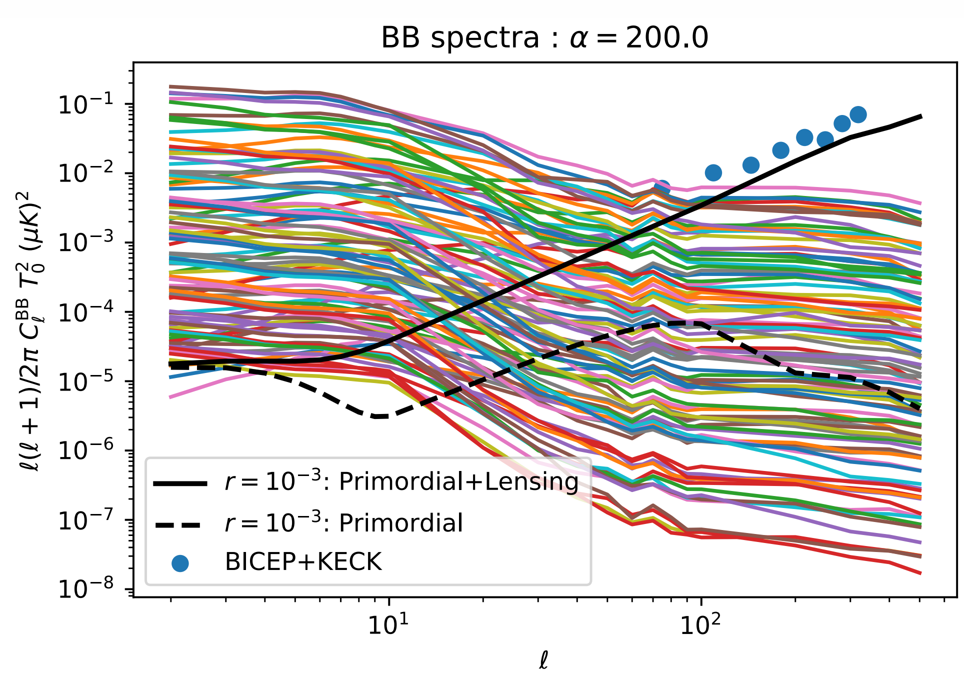
TT/EE signal $<1\sigma$ error-bar on Planck 2018 dataset





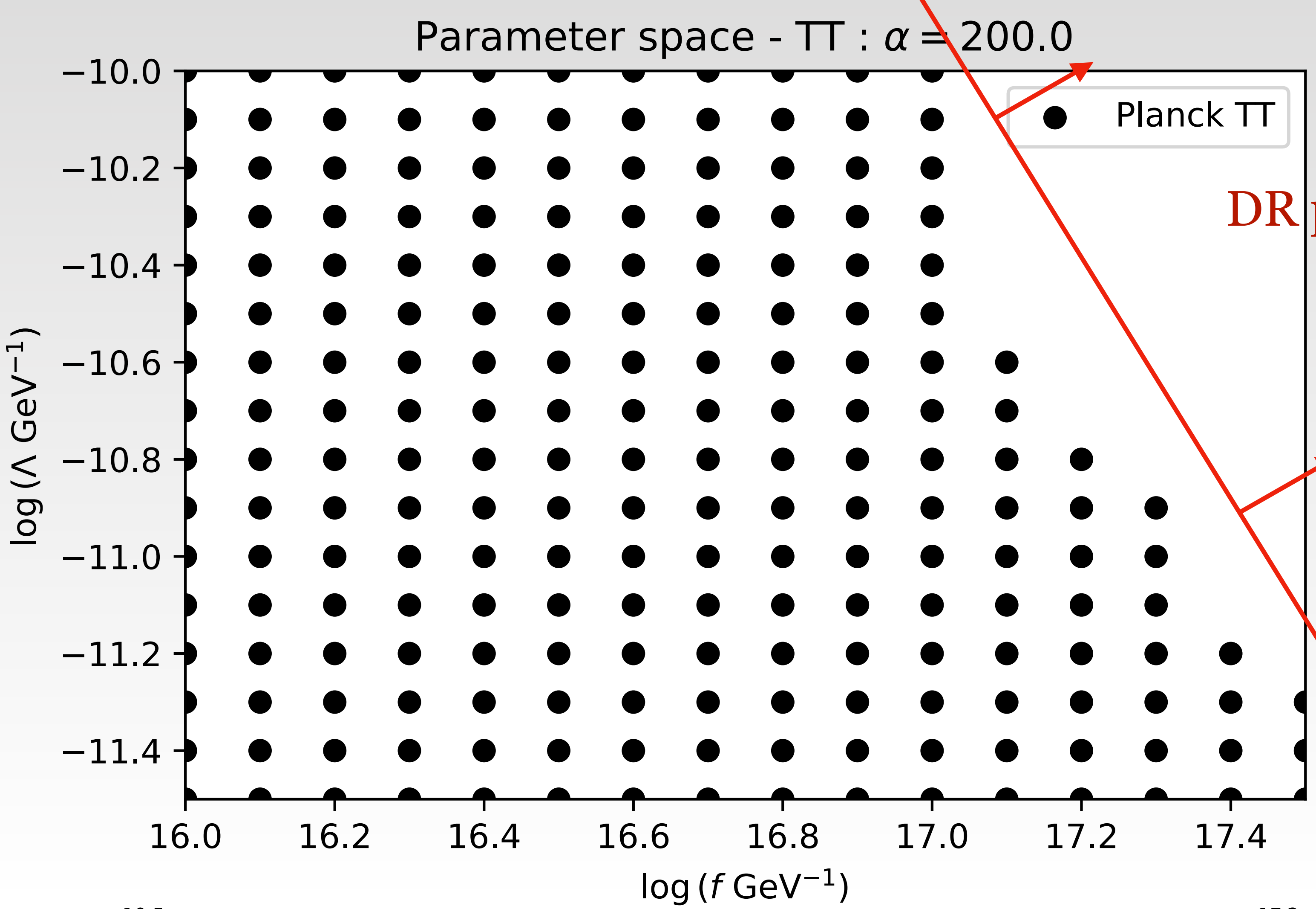
Sensitivity of future B mode experiments

B mode signal for $r = 10^{-3} <$ BB Signal $<$ BICEP+KECK bound



The spectrum calculation is highly computation intensive

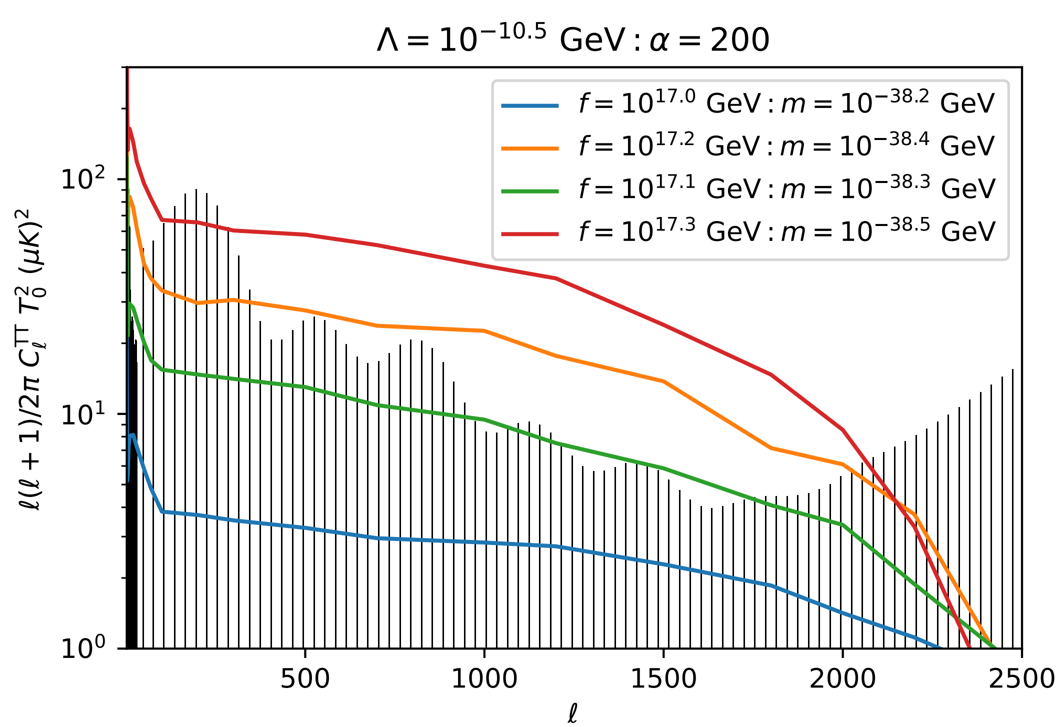
Parameter space: Constraints from TT : $\alpha = 200$

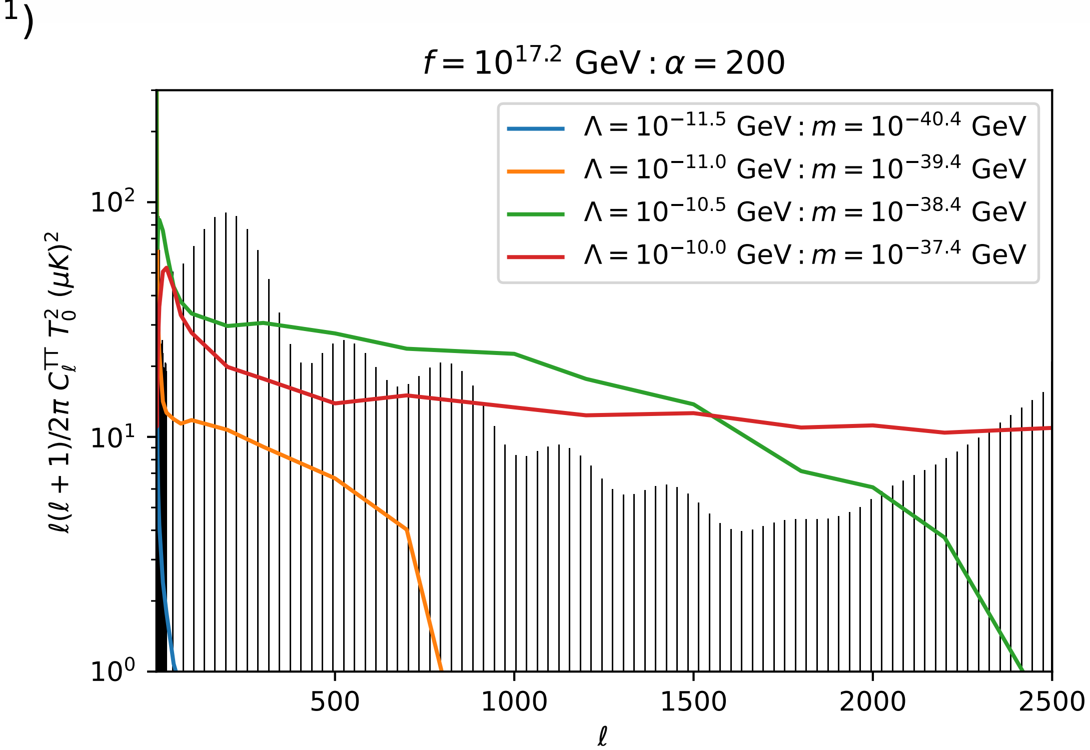


DR production happens late

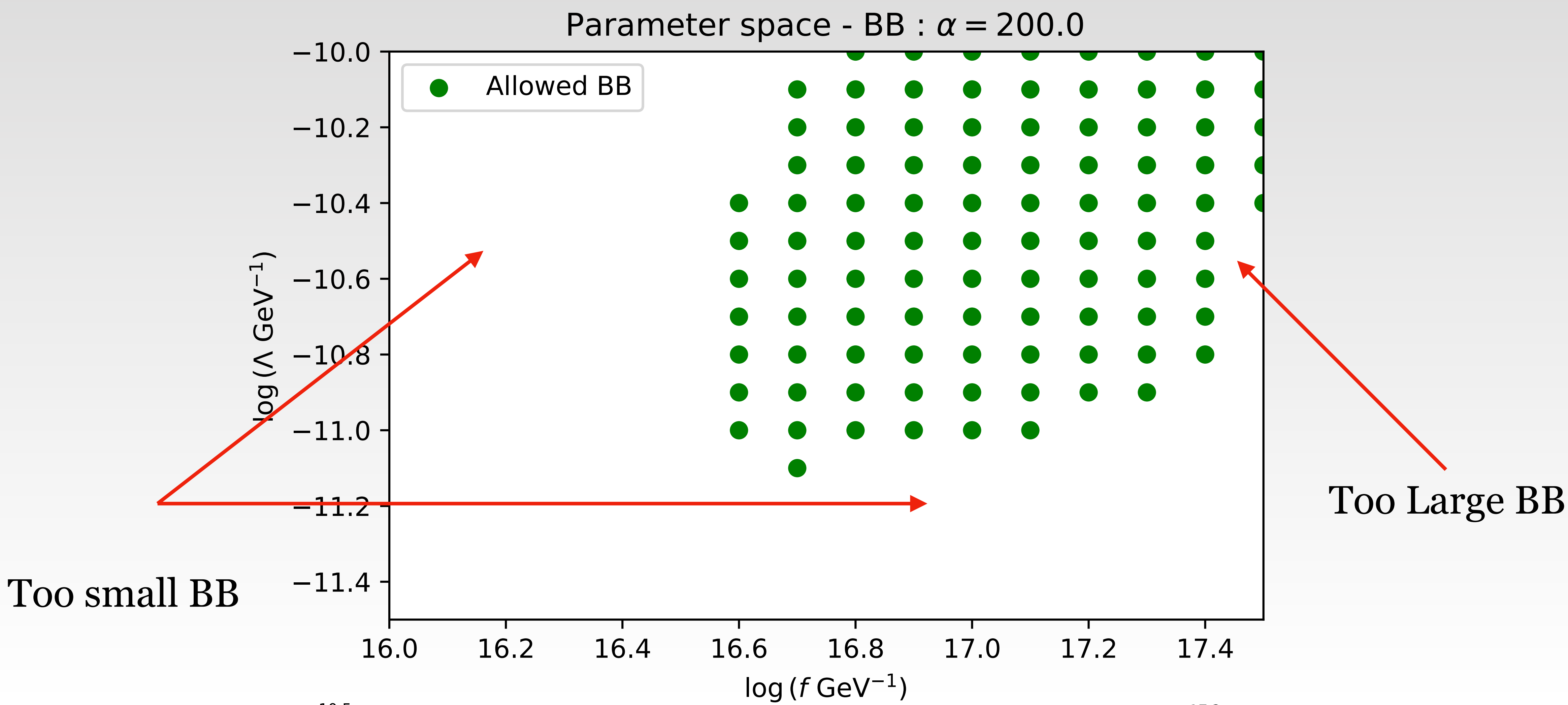
&

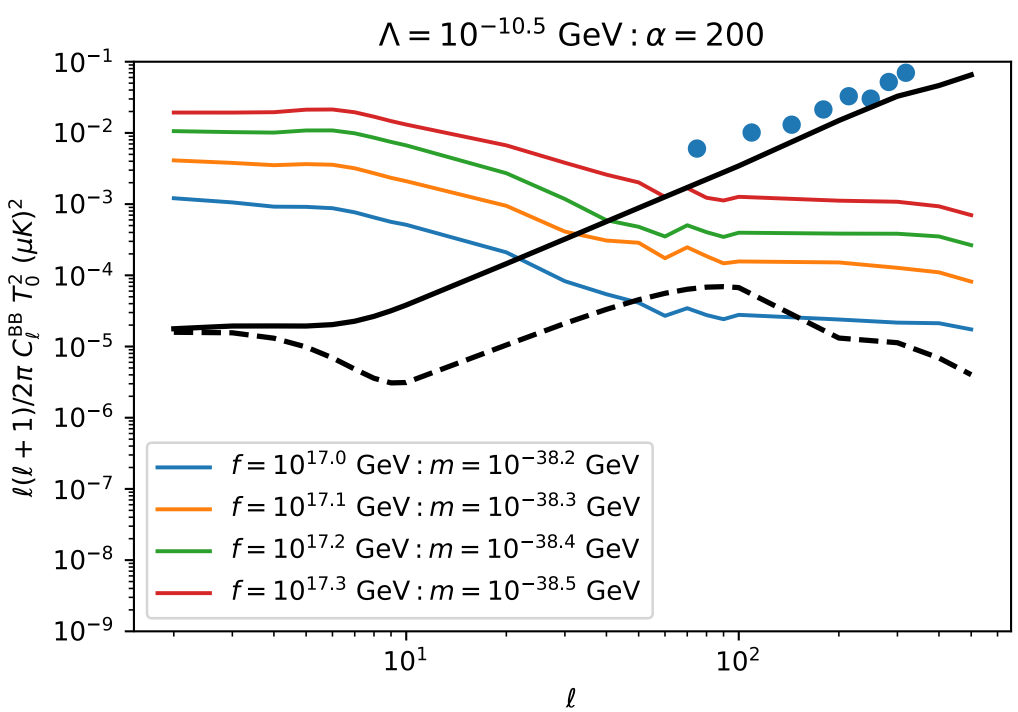
Large Ω_{Axion} (Ω_{DR})

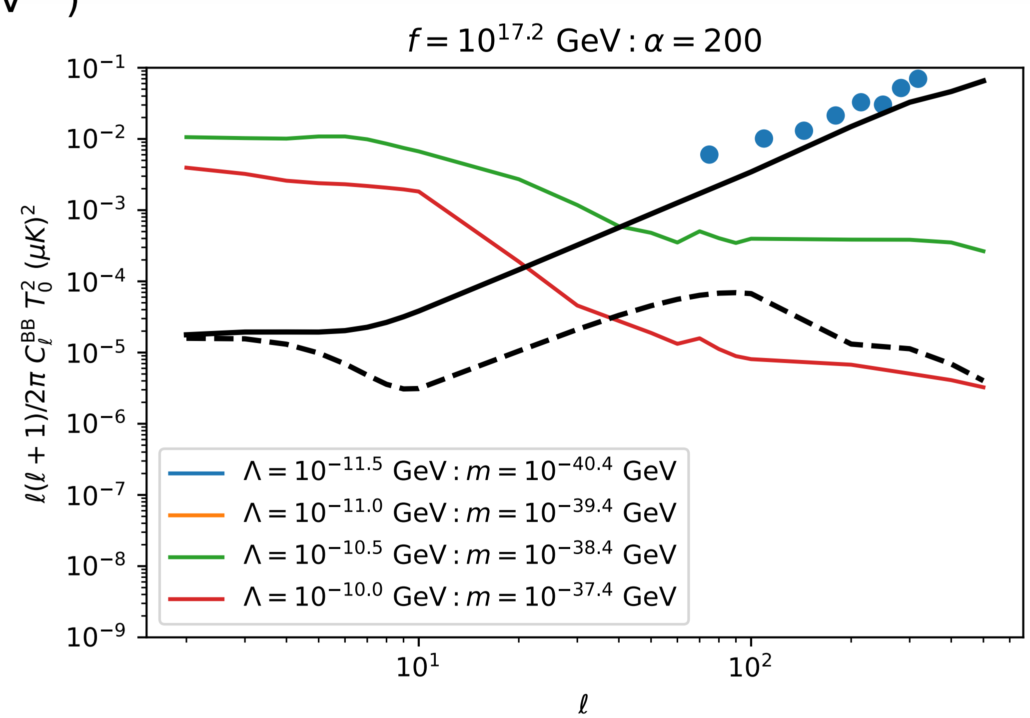




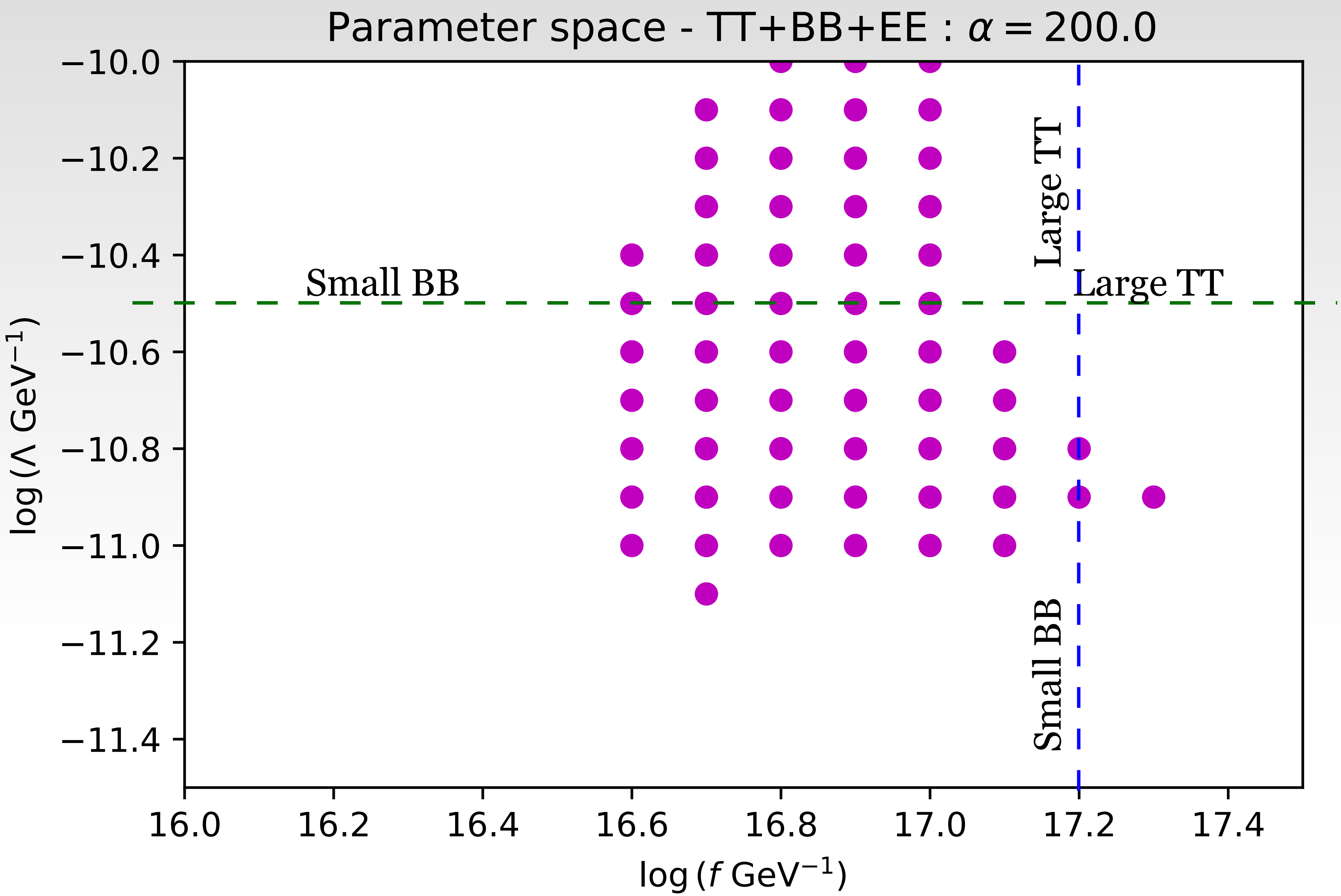
Parameter Space: Sensitivity of BB : $\alpha = 200$



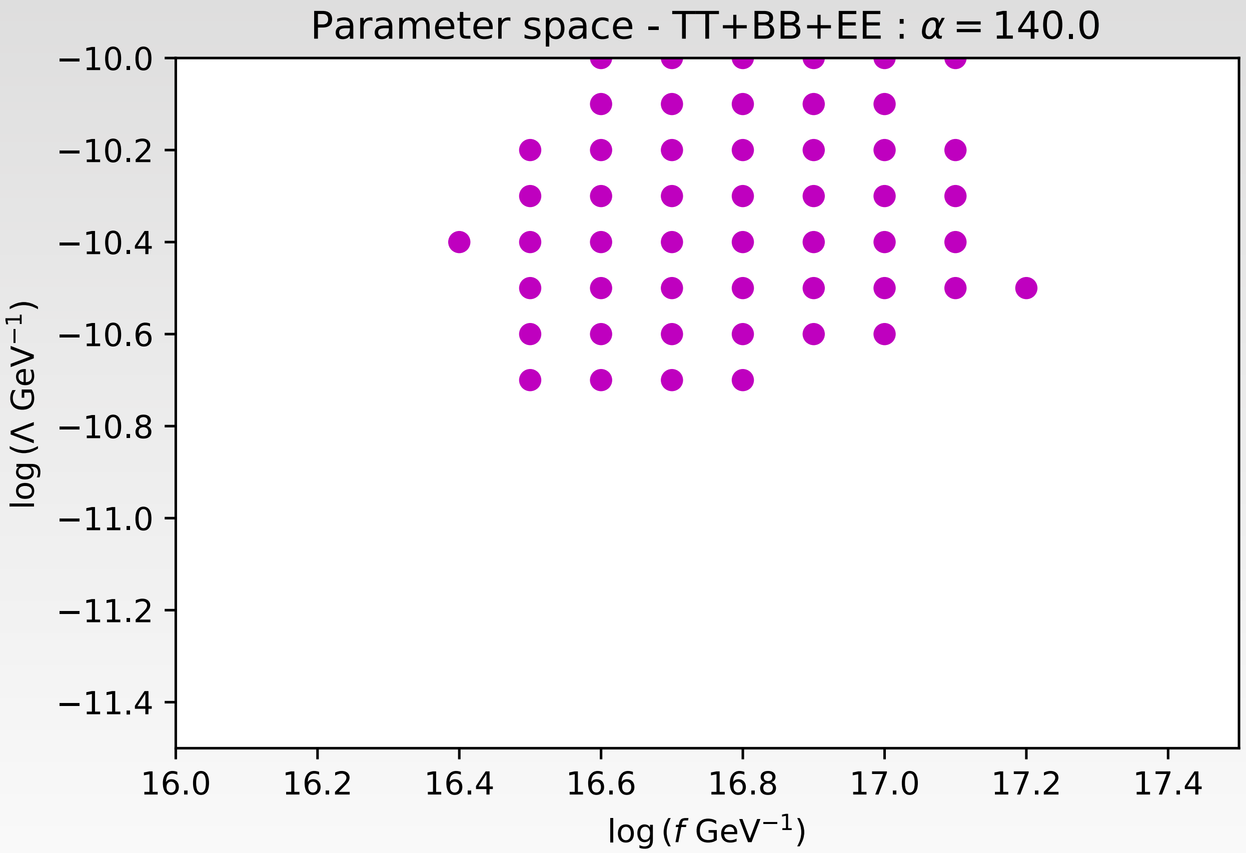


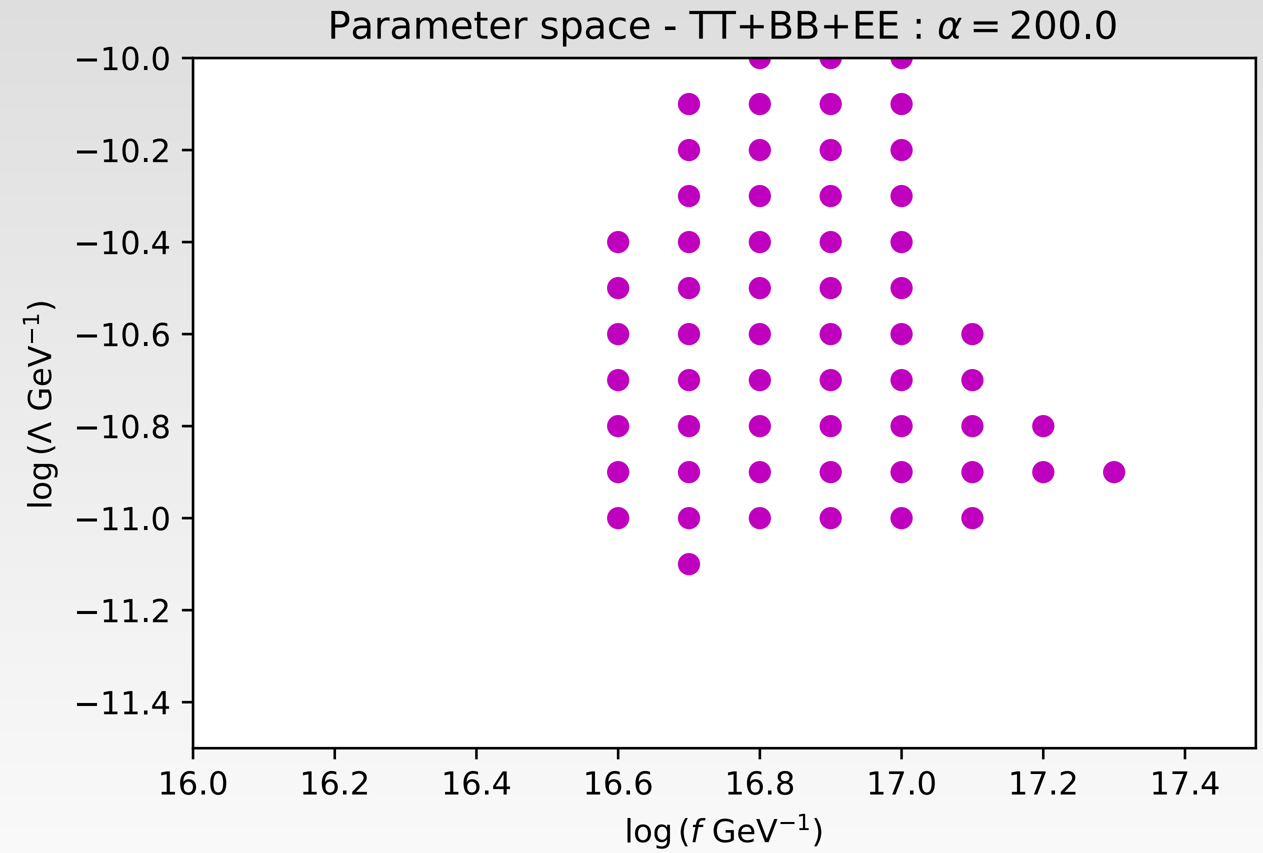


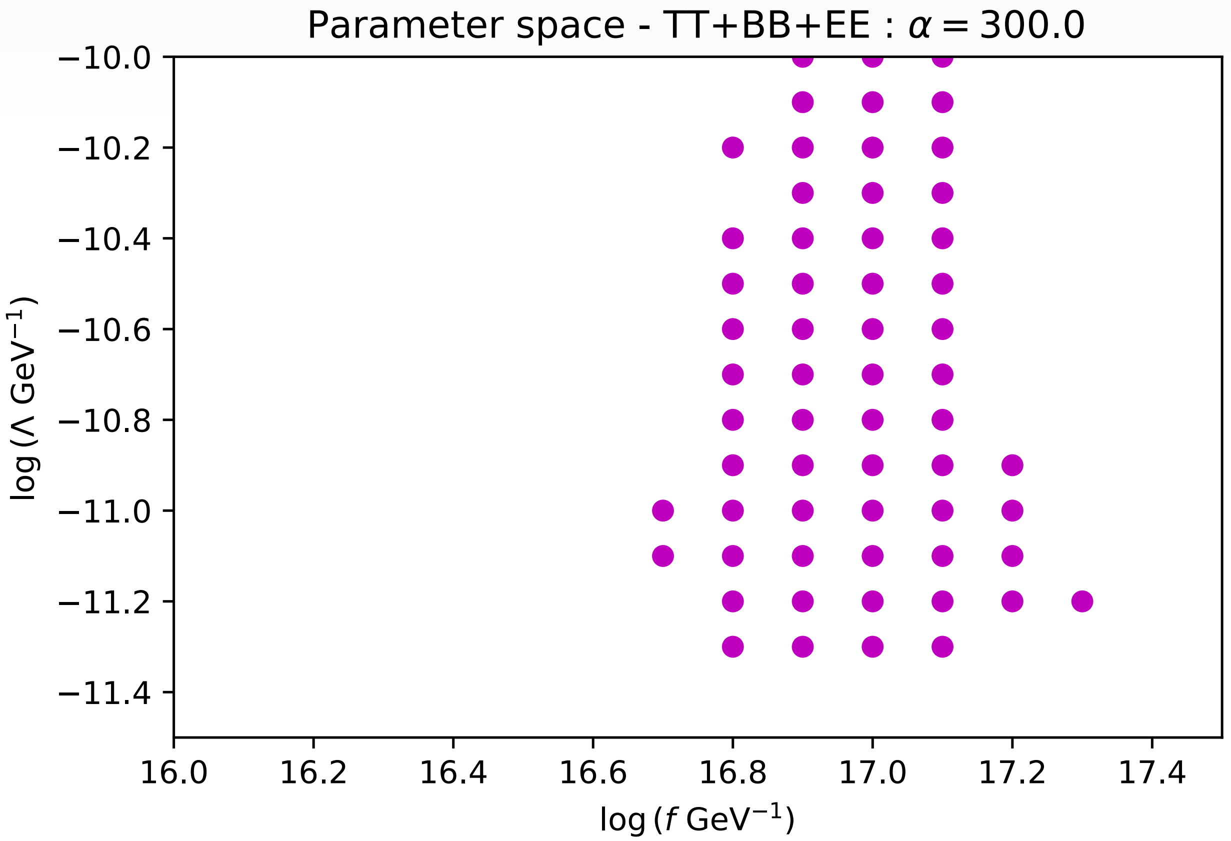
Parameter space: Dependence on Λ

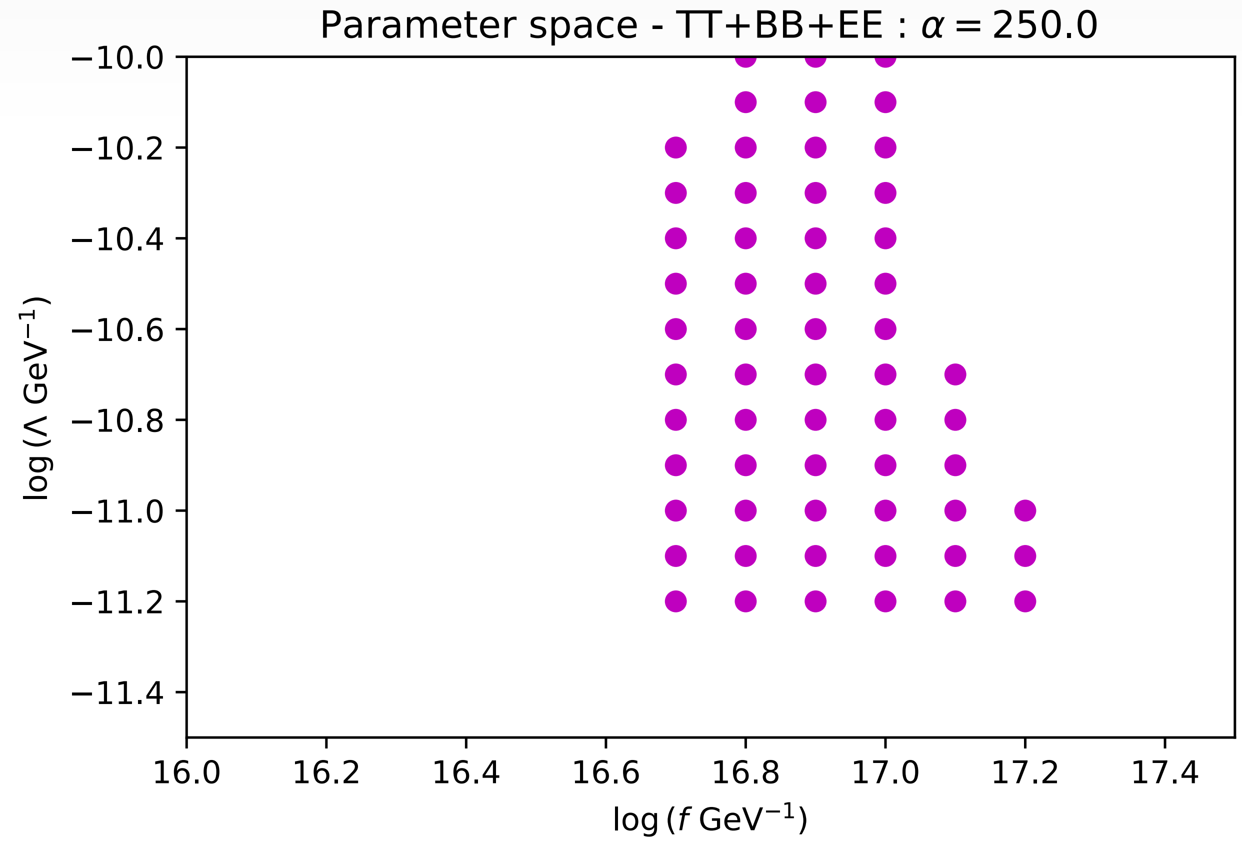


Parameter Space: TT+BB+EE









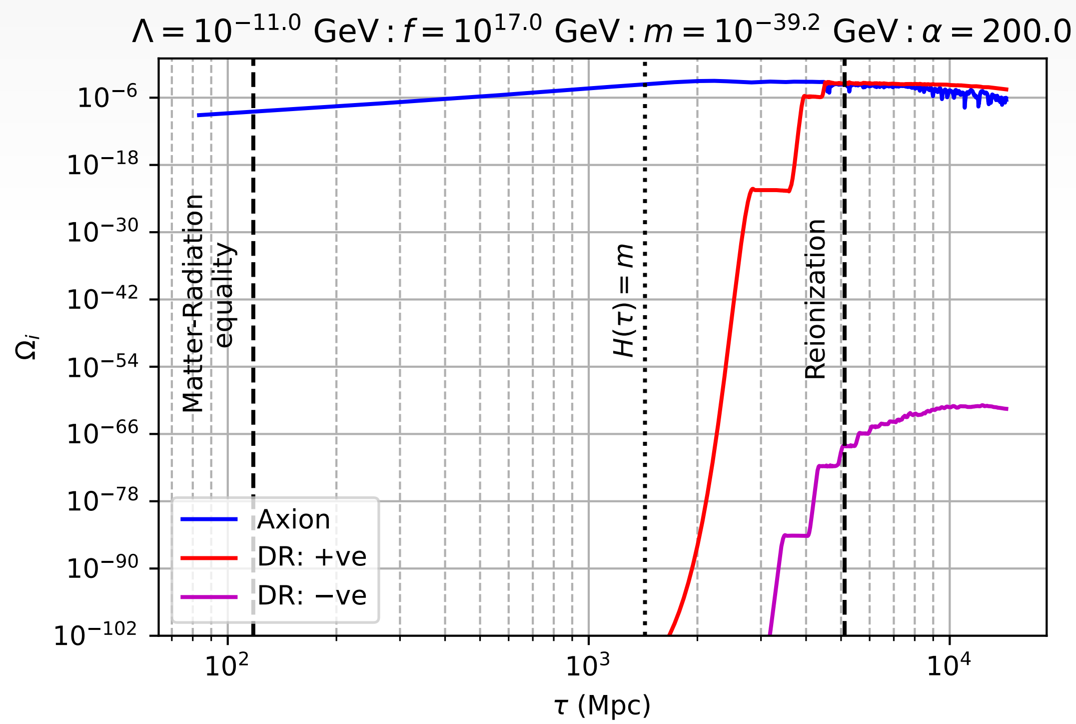
Non-zero EB correlation from Axion oscillation

$$\frac{\alpha}{4f}\phi X_{\mu\nu}\widetilde{X}^{\mu\nu}$$

Breaks CP as ϕ takes a background value

One helicity is enhanced compared to other $\equiv$ CP Violation

CP Violation $\propto$ Difference in helicities



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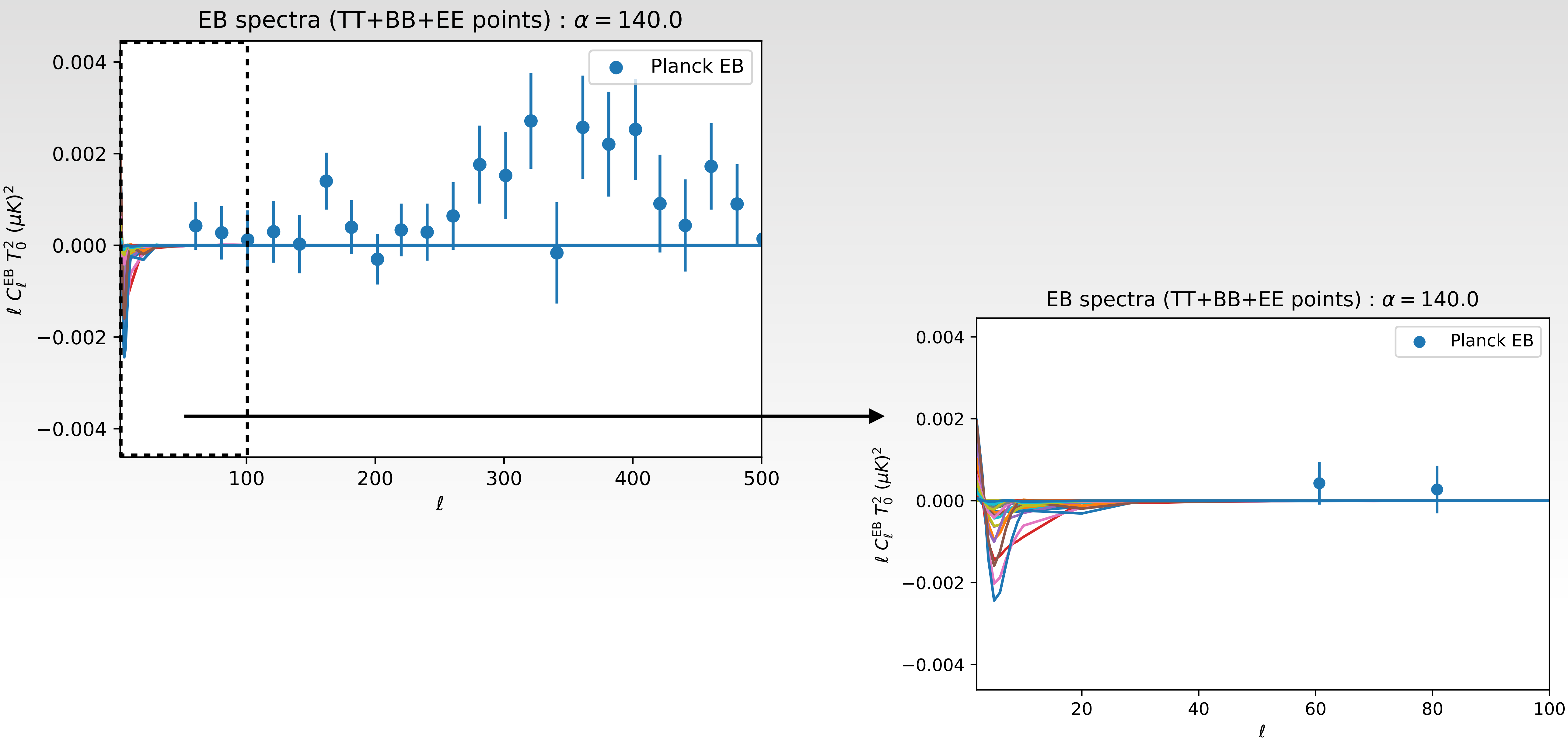


The signal does not have large support at small scale (unable to explain the CP violation)

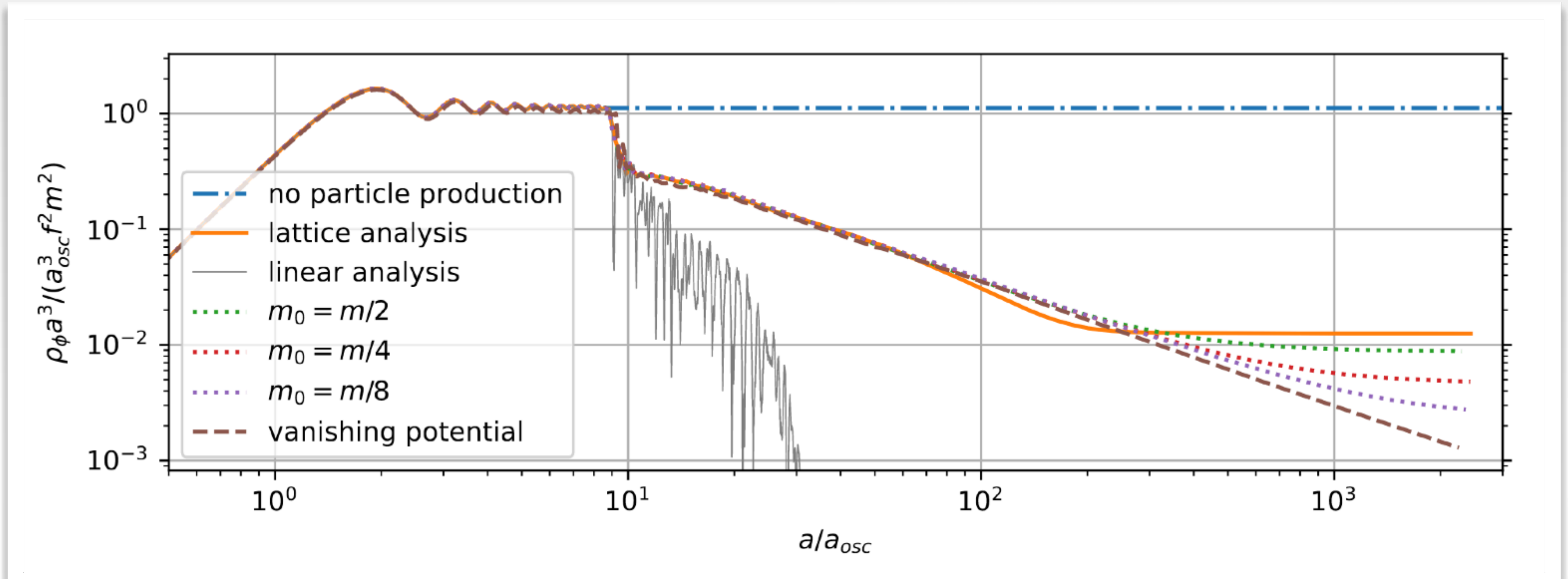
Predicts large CP violation at large scale

Back-reaction of DR to Axion

Back-reaction → Inverse decay of DR to Axion, DR axion scattering

Back-reaction is studied (for convenience) on position space with spacetime discretized into lattices

Ratzinger et al., 2012.11584



*This is for axion oscillation in radiation domination

Effects

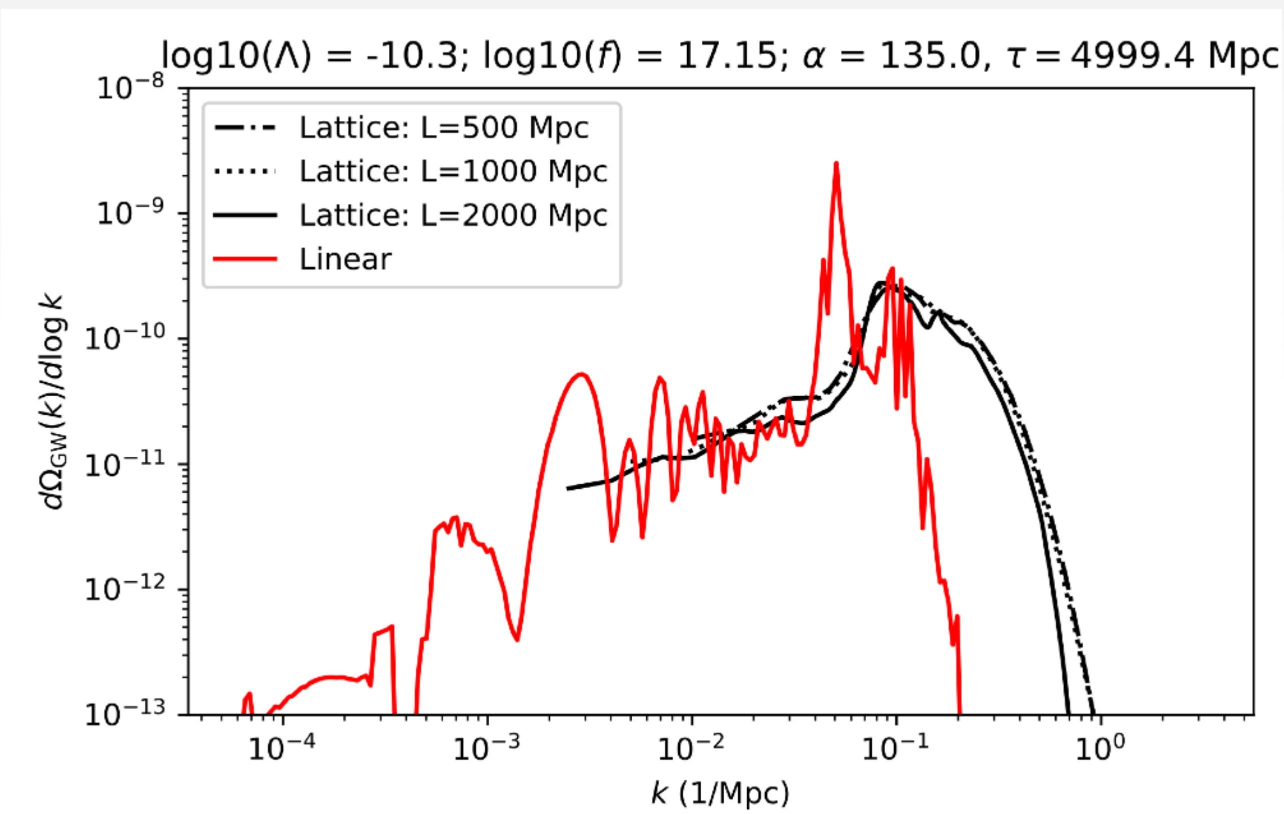
Only allows depleting Axion abundance by factor of 10^{-2}

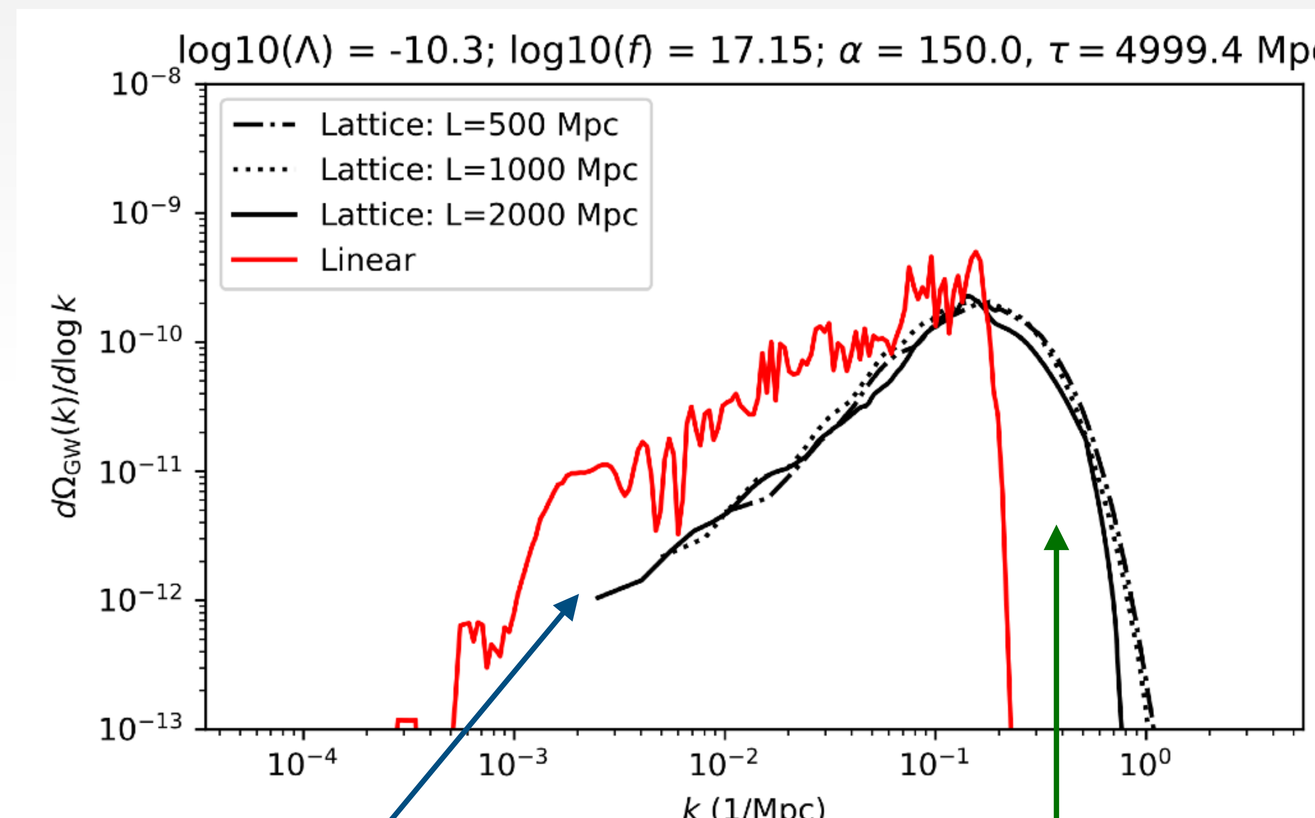
Wash out CP violation (helicity difference) for small k

Back-reaction of DR to Axion

Backreaction → Inverse decay of DR to Axion, DR axion scattering

$\boxed{\text{Only relevant for high interaction} \rightarrow \text{high } \alpha}$





Slight suppression of B mode signal at small ℓ

Only affects the high ℓ
spectra where signal is weak

Conclusion

- Completely secluded dark sectors can be probed via gravitational effects: Tachyonic instability generates exponential growth for dark photon
- CMB T & E measurements put constraints on the parameter space
- Axion - Dark photon system generates sizable B mode signal for future B mode experiments
- The signal is not strongly affected by back-reaction
- Produces CP violating EB signal at large scale

Stay tuned for the complete analysis (arXiv: 2306.xxxxx)

Future Directions

- Integrate Axion-DR system as a module in CLASS

  Full parameter scan with ΛCDM parameter variation, fast spectrum calculation
- Investigate EB signal keeping future CMB experiments in mind
- Include back reaction of DR to axion in the analysis

THANK YOU

Post ~~Credit~~ Conclusion

Mechanism of Particle production

Relaxion friction from particle production, 1607.01786

Allows large values of f_a: 1708.05008

Relaxion

QCD Axion DM

... Particle production via Axion/ALP rolling ...

Inflation

Gravitational Waves

Friction for inflation rolling, 0908.4089

GWs from Dark photon, 1811.01950

Example model for producing large α

Kim-Nilles-Peloso (KNP) Mechanism

$$\mathcal{L} = \frac{\alpha_s}{8\pi f} a\, G^{a,\mu\nu} \widetilde{G}^a_{\mu\nu} + \frac{\alpha_d}{8\pi f} b\, F_D^{\mu\nu} (\widetilde{F}_D)_{\mu\nu} + \Lambda^4 \cos\left(\frac{na+b}{f}\right)$$

Kim et al, hep-ph/0409138
Agrawal et al, 1708.05008

Mass eigenstates :

$$\phi = \frac{1}{\sqrt{1+n^2}}(a - nb), \qquad \phi_h = \frac{1}{\sqrt{1+n^2}}(na+b)$$

Coupling with light eigenstate $\longrightarrow$

$$\mathcal{L} = \frac{\alpha_s}{8\pi f_a} \phi\, G^{a,\mu\nu} \widetilde{G}^a_{\mu\nu} + \frac{\alpha_d n}{8\pi f_a} \phi\, F_D^{\mu\nu} (\widetilde{F}_D)_{\mu\nu}$$

$$f_a = f\sqrt{1+n^2}$$

Large $n \rightarrow$ hierarchical coupling

UV models

Clockwork, extra dimension etc.

Why CMB?

Axion-DR Particle production

Effects of Axion-DR energy exchange

+ Effects of spatial (k -dependent) fluctuation

Depletion of Axion energy (e.g., Axion DM)

Creation of DR (e.g., Reheating)

Friction/slow rolling of Axion (e.g, inflation, relaxion)

$\vdots$

Gravitational waves

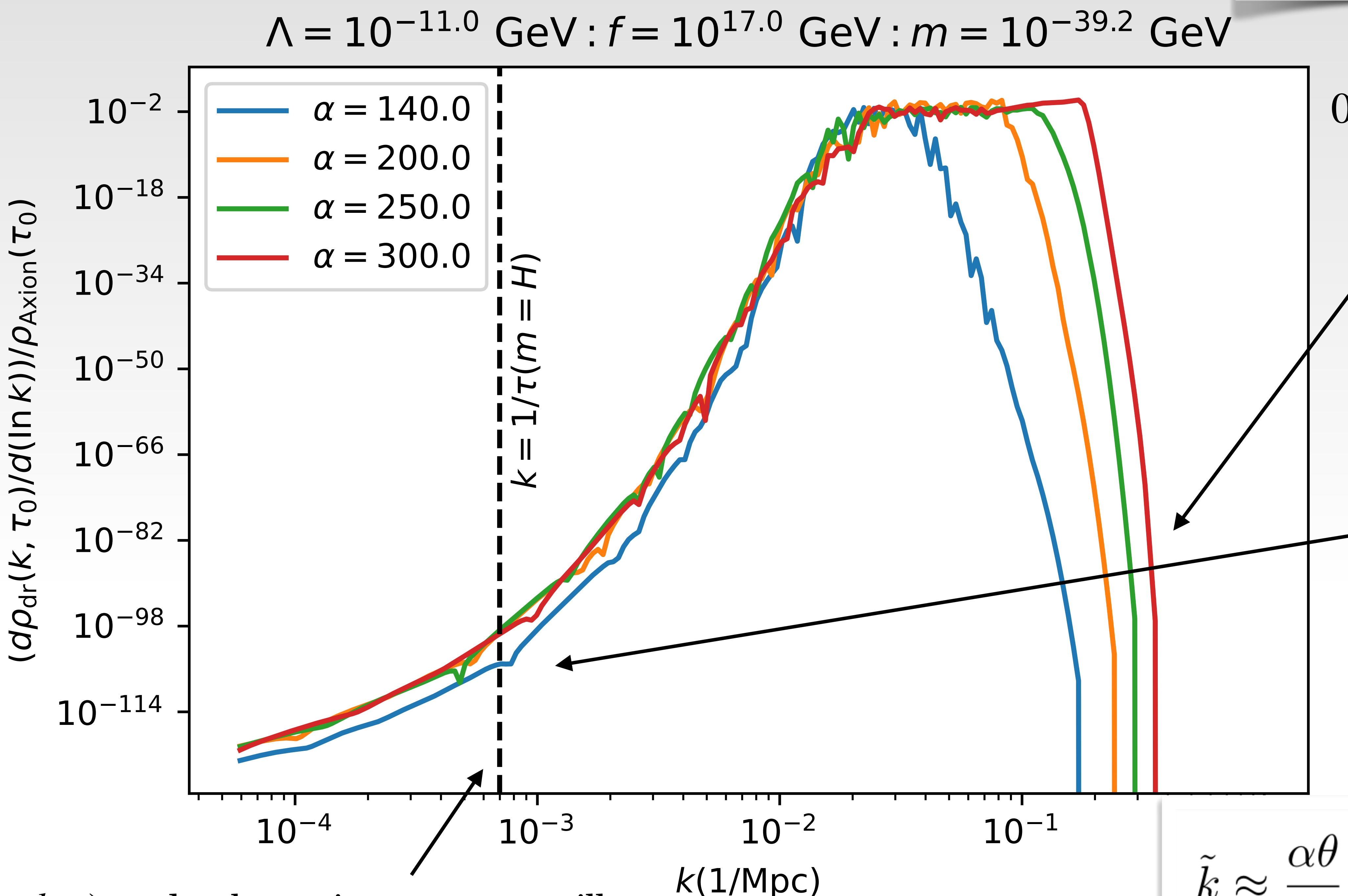
Gravity induced fluctuation/perturbation of SM plasma $\equiv$ effects in CMB

$\vdots$

Excitation of small scale modes

Energy fraction in k modes today

$$\omega_{\pm}^2(k,\tau) = k^2 \mp k\frac{\alpha}{f}\phi'$$



$$0 < k < \frac{\alpha|\phi'|}{f}$$

$\omega^2 > (am)^2$

$k\ (\equiv k_{\rm osc})$ mode when axion starts to oscillate

$$\tilde{k} \approx \frac{\alpha\theta}{2}\left(\frac{a_{\rm osc}}{a}\right)^{\frac{3}{2}} am$$

Tachyonic band peak

$\boxed{k \gg k_{\rm osc} \text{ are excited}}$

Scalar metric fluctuations

Axion(m) and DR(e) Boltzmann equation: Calculate ϕ

$$\delta'_m + \theta_m = 3\Phi' ,$$
$$\theta'_m + \frac{a'}{a}\theta_m = -\Phi ,$$
$$k^2\Phi + 3\frac{a'}{a}\Phi' + 3\left(\frac{a'}{a}\right)^2 \Phi = -4\pi G_N\, a^2(\delta\rho_e + \delta\rho_m)$$

C_ℓ^{TT} from ISW Effect (Change of late time potential)

$$\Theta_0(\mathbf{n}) = \sum_l i^l\,(2l+1)\int \mathcal{D}k\,\tilde{\Theta}_l(\mathbf{k})P_l\left(\frac{\mathbf{k}\cdot\mathbf{n}}{k}\right)$$
$$\tilde{\Theta}_l(\mathbf{k}) = 2\int_{\tau_{rec}}^{\tau_0} d\tau\,\Phi'(\mathbf{k},\tau)j_l[k(\tau_0-\tau)] ,$$

$$C_l^{TT} = \frac{1}{4\pi}\int d\mathbf{n}'d\mathbf{n}''\Theta_0(\mathbf{n}')\Theta_0(\mathbf{n}'')P_l(\mathbf{n}'\cdot\mathbf{n}'')$$

Similar C_ℓ^{EE} expressions

Scalar contribution to TT and EE spectra is subdominant

Tensor metric fluctuations

$$\bar{h}''_{ij} + \left(k^2 - \frac{a''}{a}\right)\bar{h}_{ij} = \frac{2}{M_{Pl}^2} a\,\Pi_{ij}(\mathbf{k},\tau)$$

DR Mode functions source

$$C_l^{TT} = \frac{9\pi}{2}\frac{(l+2)!}{(l-2)!}\int \mathcal{D}k\mathcal{D}k' \cdot \left\langle \left\{ \int_{\tau_r}^{\tau_0} d\tau\, h'_{ij}(\mathbf{k},\tau)\frac{j_l[(\tau_0-\tau)k]}{(\tau_0-\tau)^2 k^2} \right\}^2 \right\rangle$$

$\frac{j_\ell(x)}{x^2}$ peaks at $x \sim \ell$

Most contributions at given ℓ ($\ell > 2$)from

$$l \approx (\tau_0 - \tau)k \Rightarrow \tau = \tau_0 - \frac{\ell}{k}$$

Contribution from wider k modes

$$C_l^{BB} = 36\pi\, \mathcal{T}_{\rm rei}^2 \int \mathcal{D}k\mathcal{D}k'\, \mathcal{J}_{l,B}^2(k) \cdot \left\langle \left\{ \int_{\tau_{\rm rec}}^{\tau_{\rm rei}} d\tau\, h'_{ij}(k,\tau)\frac{j_2[(\tau_{\rm rei}-\tau)\,k]}{(\tau_{\rm rei}-\tau)^2\,k^2} \right\}^2 \right\rangle$$

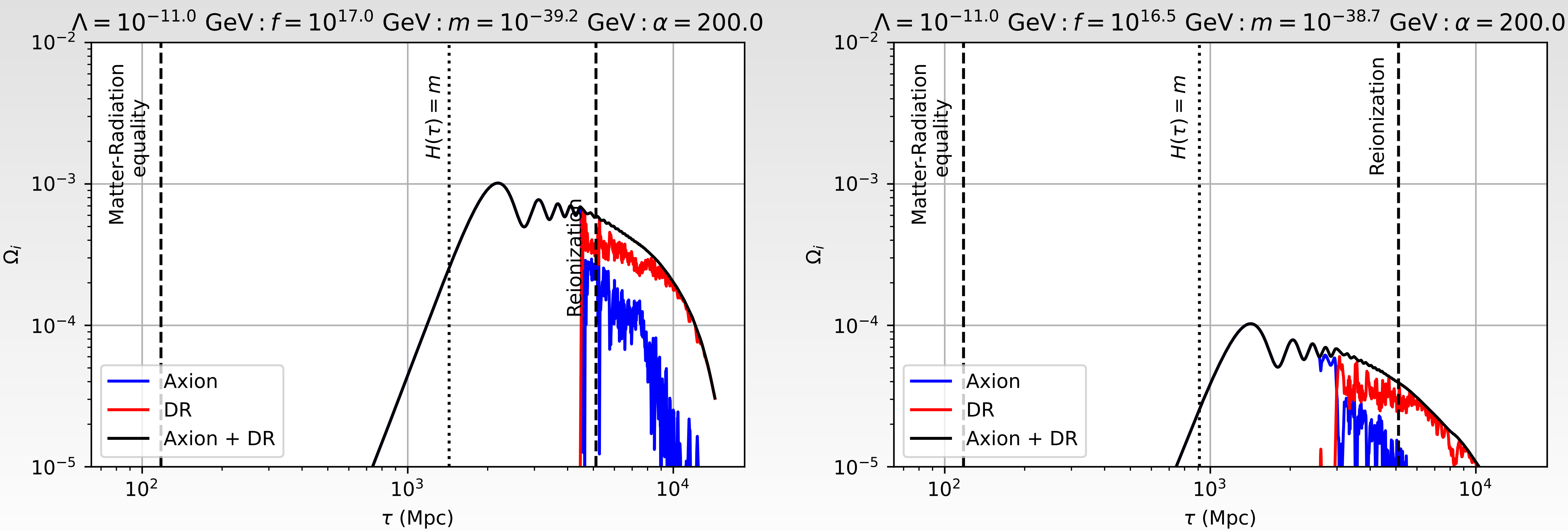
Most contributions at given ℓ from

$$\tau \approx \tau_{\rm rei}$$

Contribution from mode functions at reionization

$\frac{j_2(x)}{x^2}$ peaks at $x = 0$

Energy transfer : Dependence on f



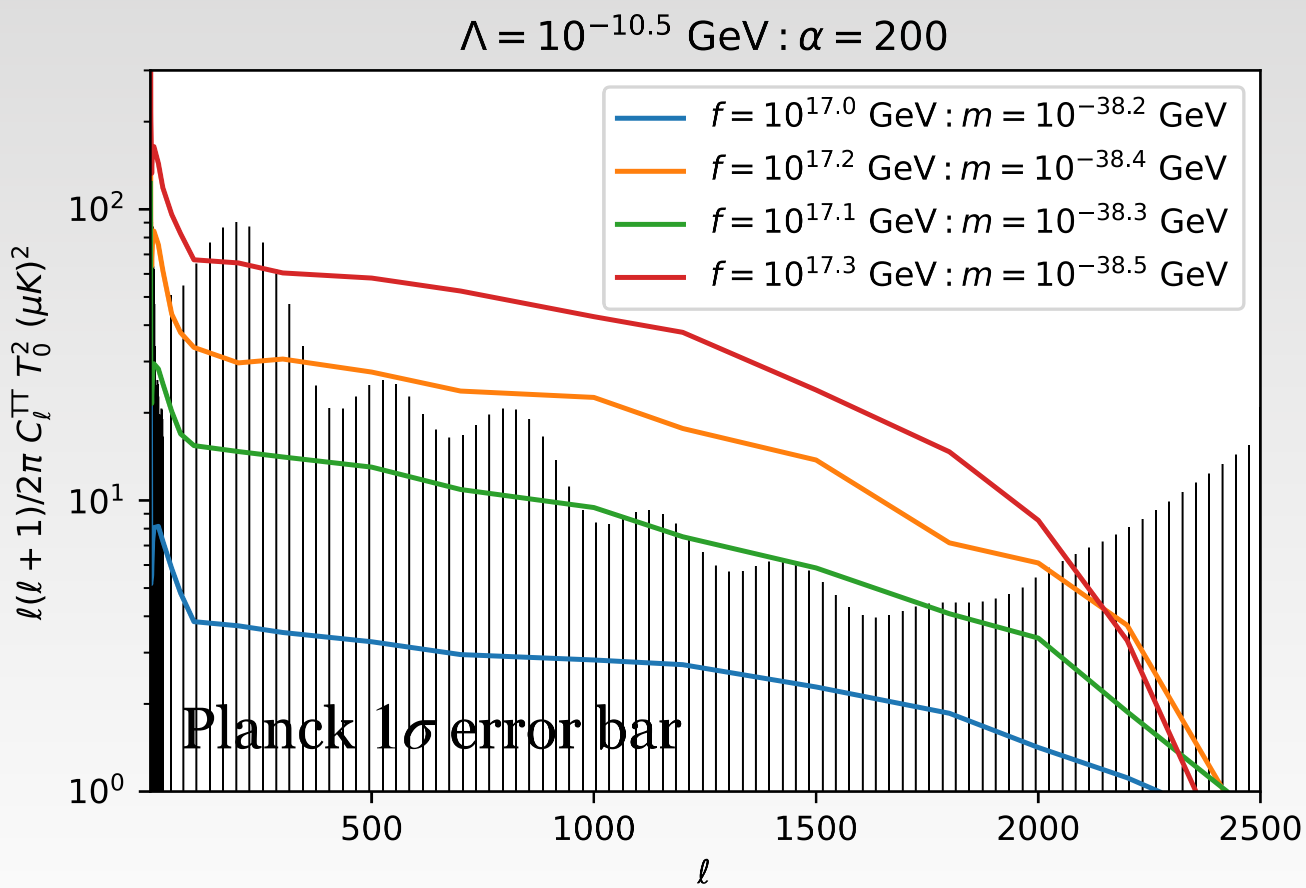
Fixed Λ : Smaller f → Higher m → lower Ω_{axion} (& higher interaction strength) → lower Ω_{DR}

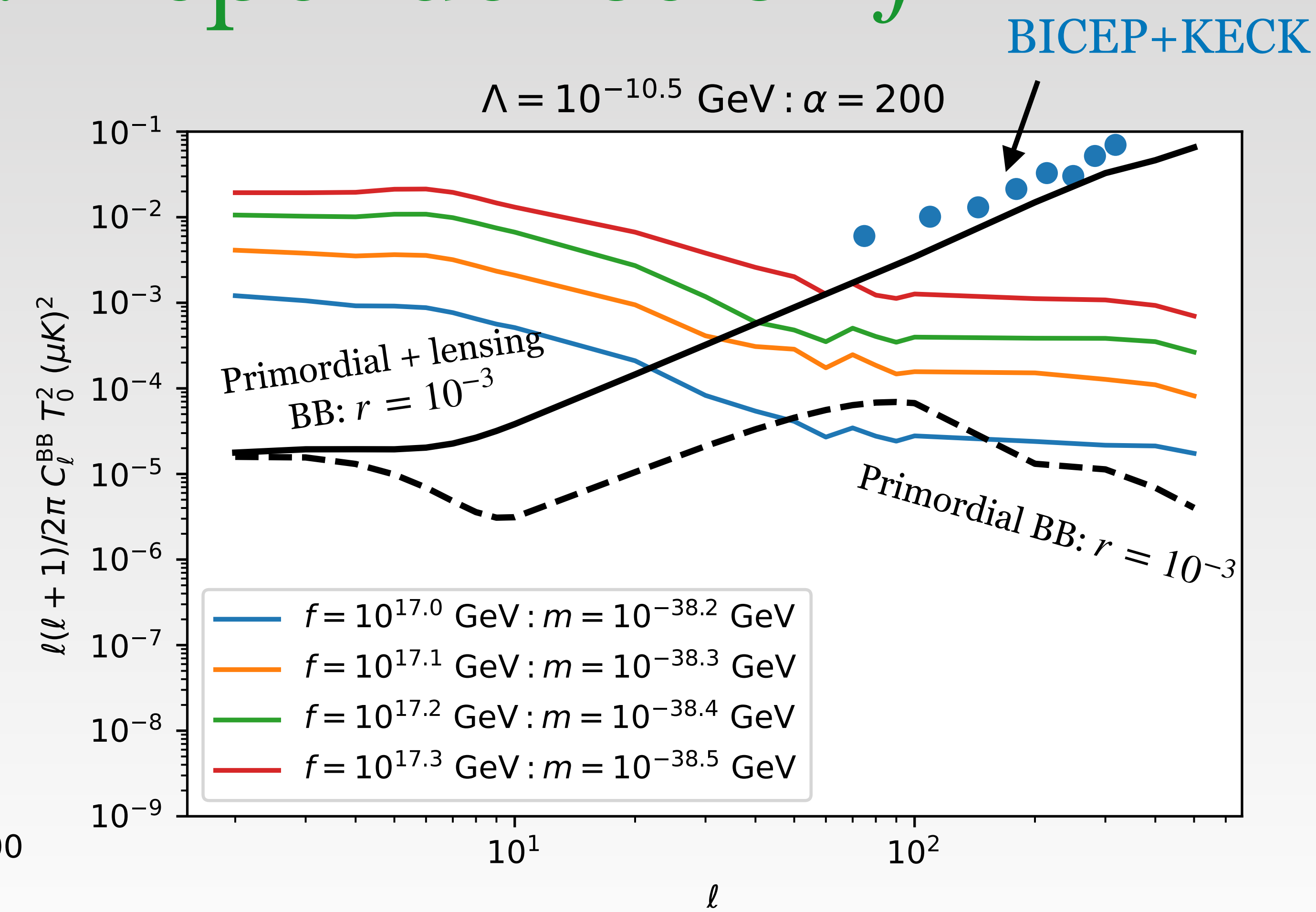
$$\phi'' + 2aH\phi' + a^2\frac{\partial V}{\partial \phi} = \frac{\alpha}{f}a^2 \mathbf{E}\cdot\mathbf{B}$$

$m^2\phi$

$$\boxed{m = \frac{\Lambda^2}{\sqrt{2}f}}$$

CMB Spectrum: Dependence on f





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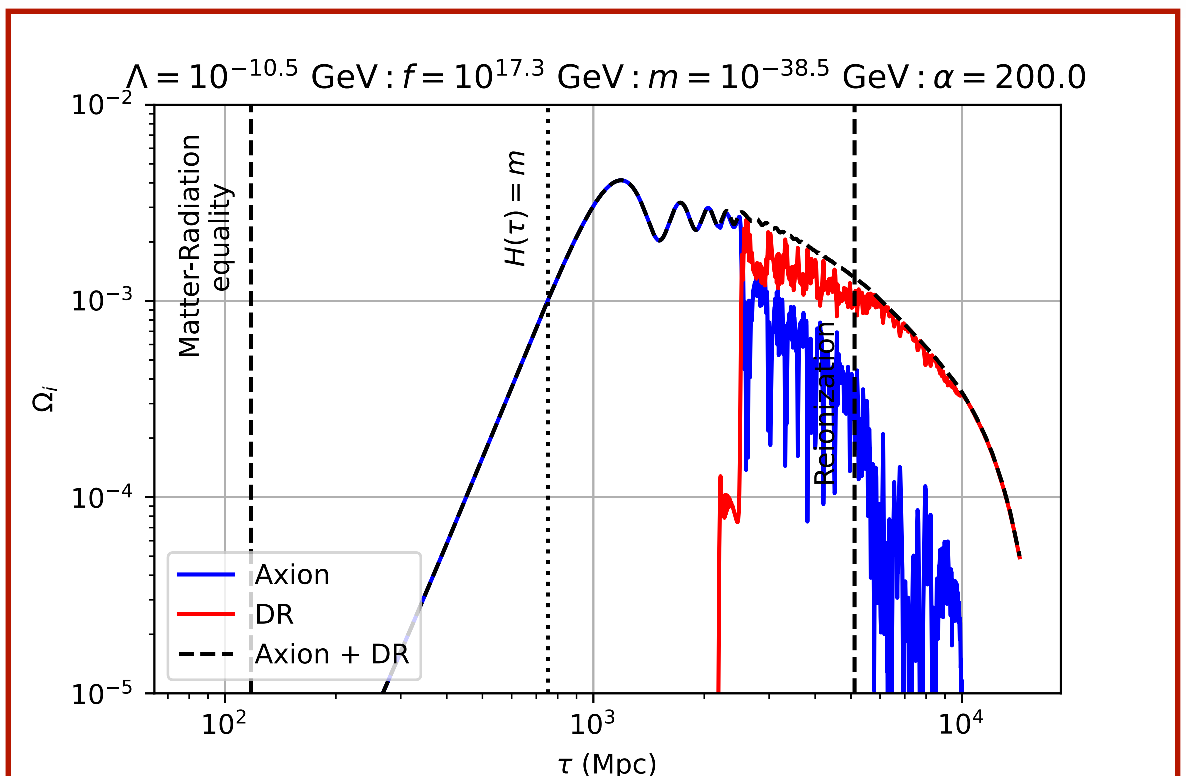
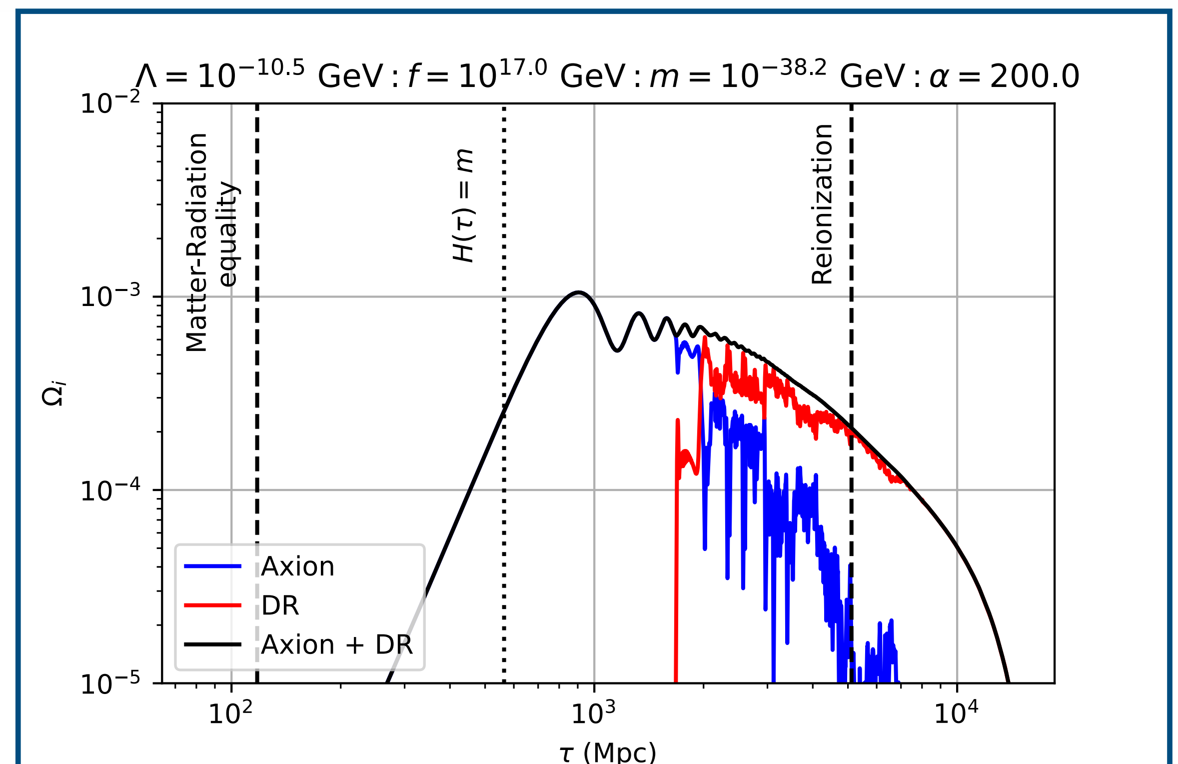
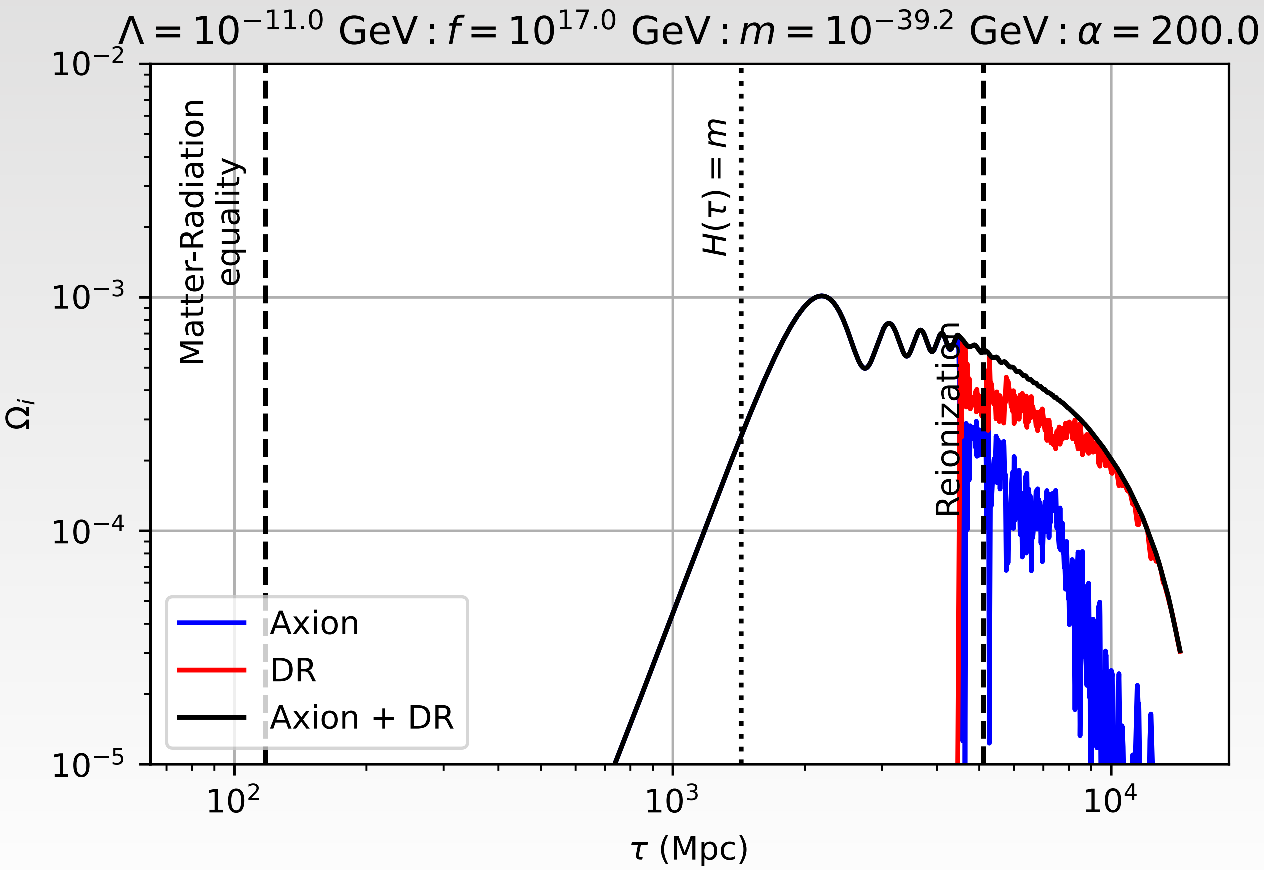
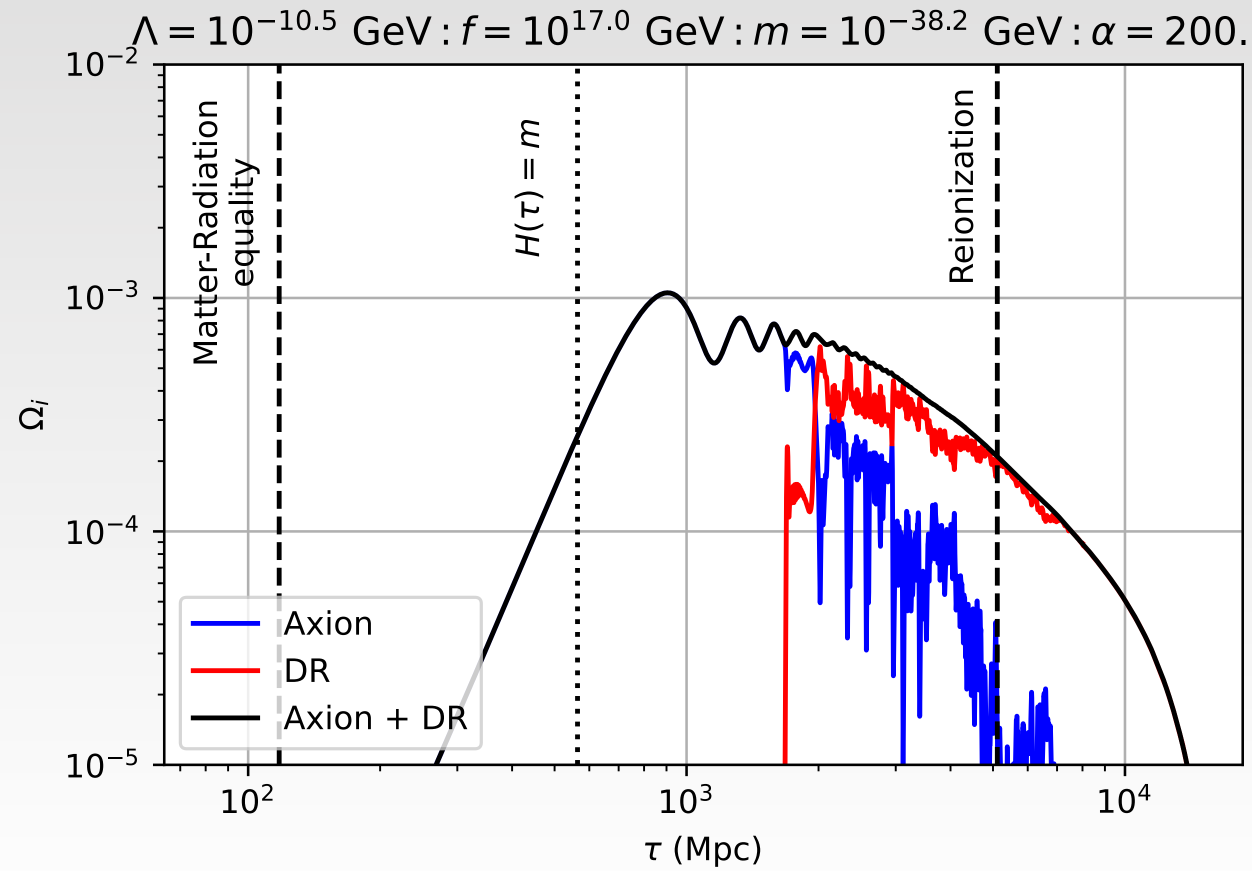




Energy transfer : Dependence on Λ





Fixed f : Higher $\Lambda \rightarrow$ Higher m $\rightarrow$ same $\Omega_{\rm axion}$ (& same interaction strength)$\rightarrow$ lower $\Omega_{\rm DR}$ (at late times)

$$m = H(a) \sim a_{\rm trans}^{-3/2} \qquad \text{(Matter domination)}$$

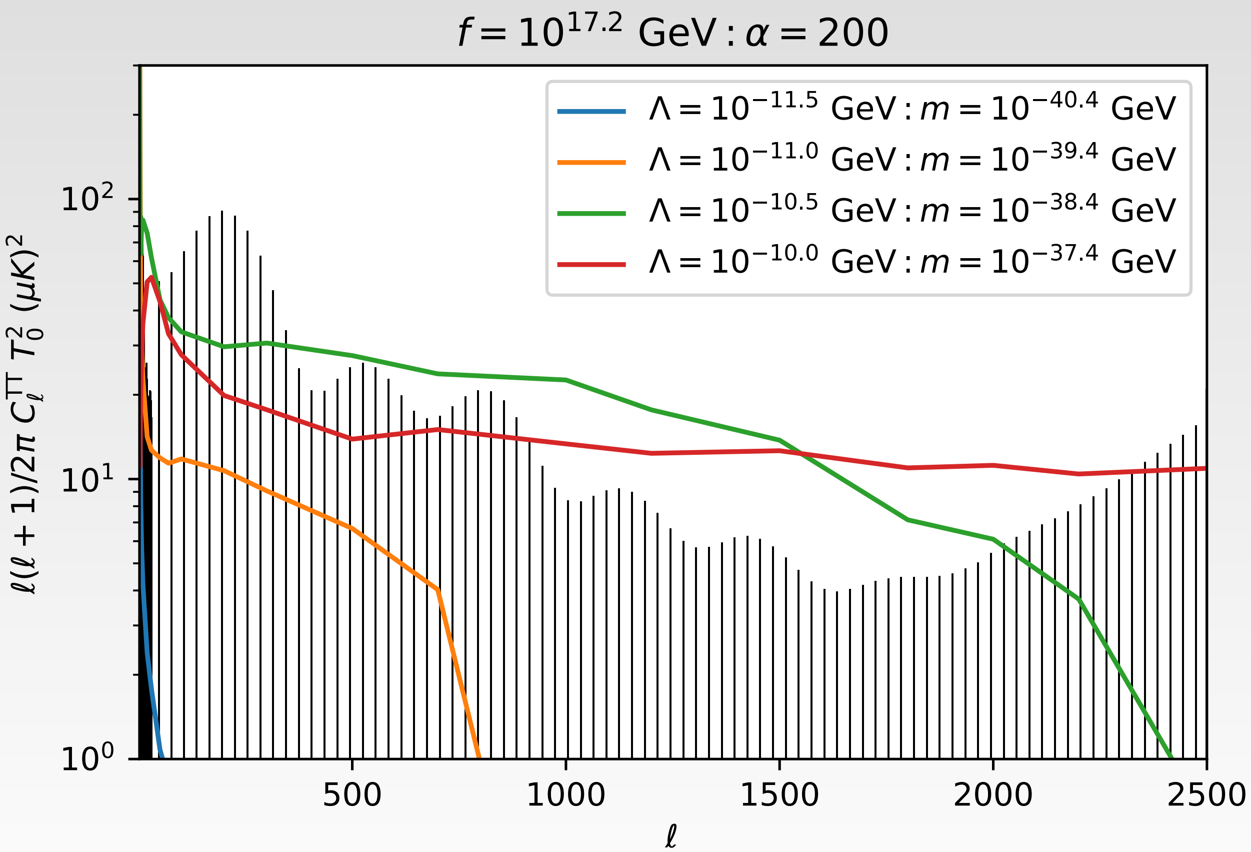
$$\Omega_i \sim \frac{\Lambda^4}{\rho_{\rm tot}\; a_{\rm trans}^{-3}} \sim \frac{\Lambda^4}{m^2} \sim f^2$$

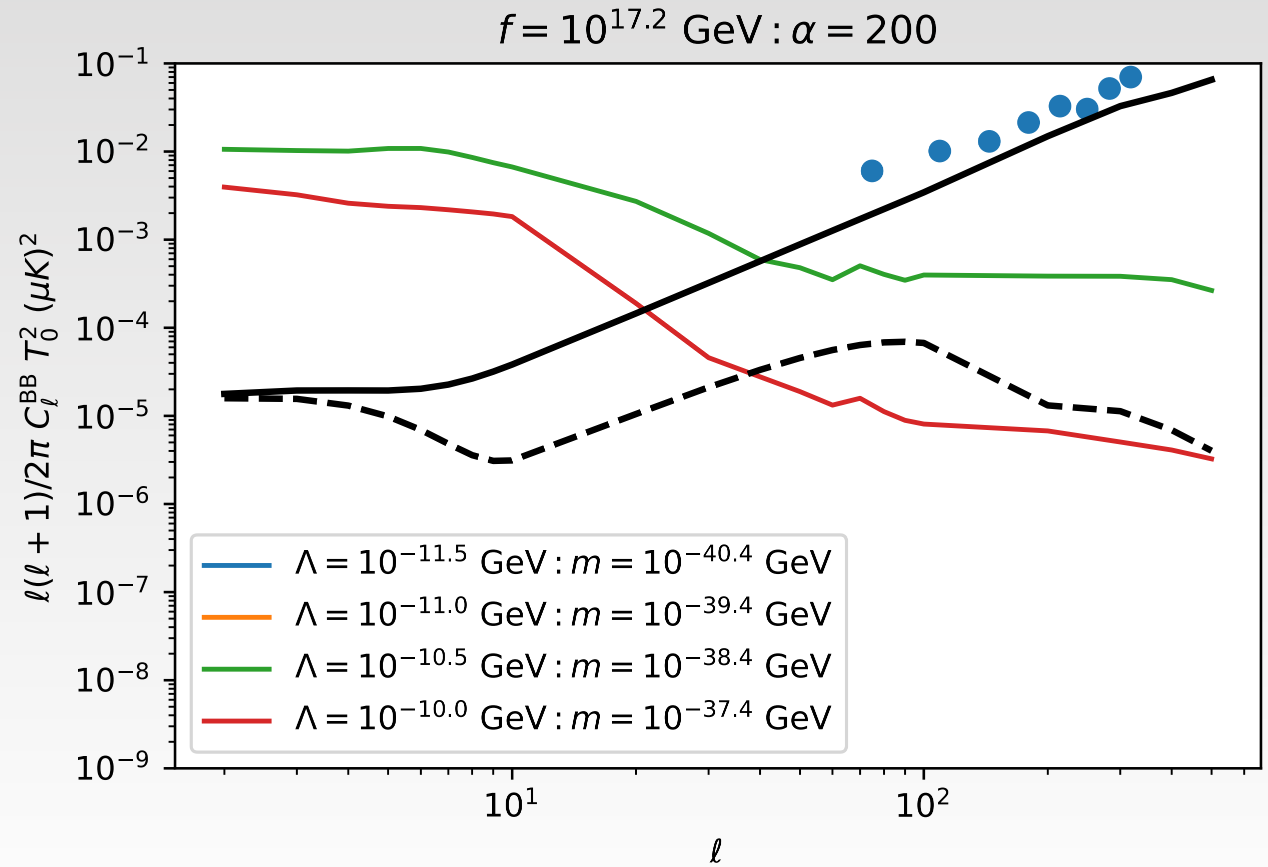
$$\phi'' + 2aH\phi' + a^2\frac{\partial V}{\partial \phi} = \frac{\alpha}{f}a^2\mathbf{E}\cdot\mathbf{B}$$

$$m^2\phi$$

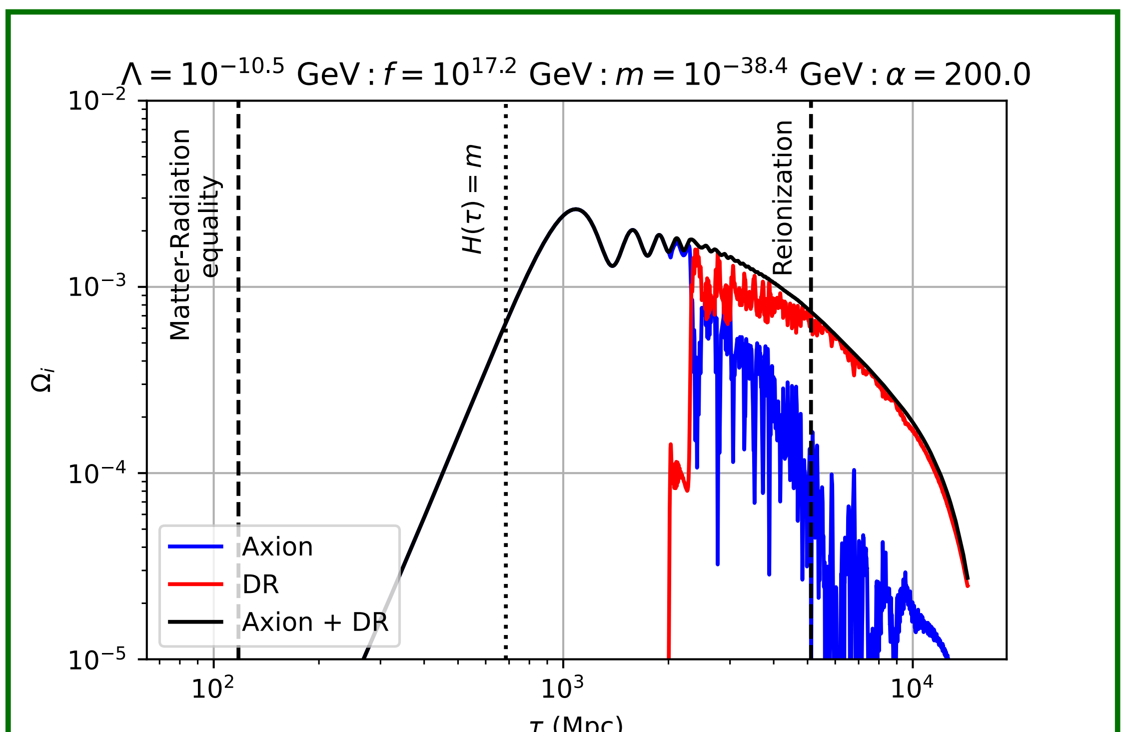
$$\boxed{m = \frac{\Lambda^2}{\sqrt{2}f}}$$

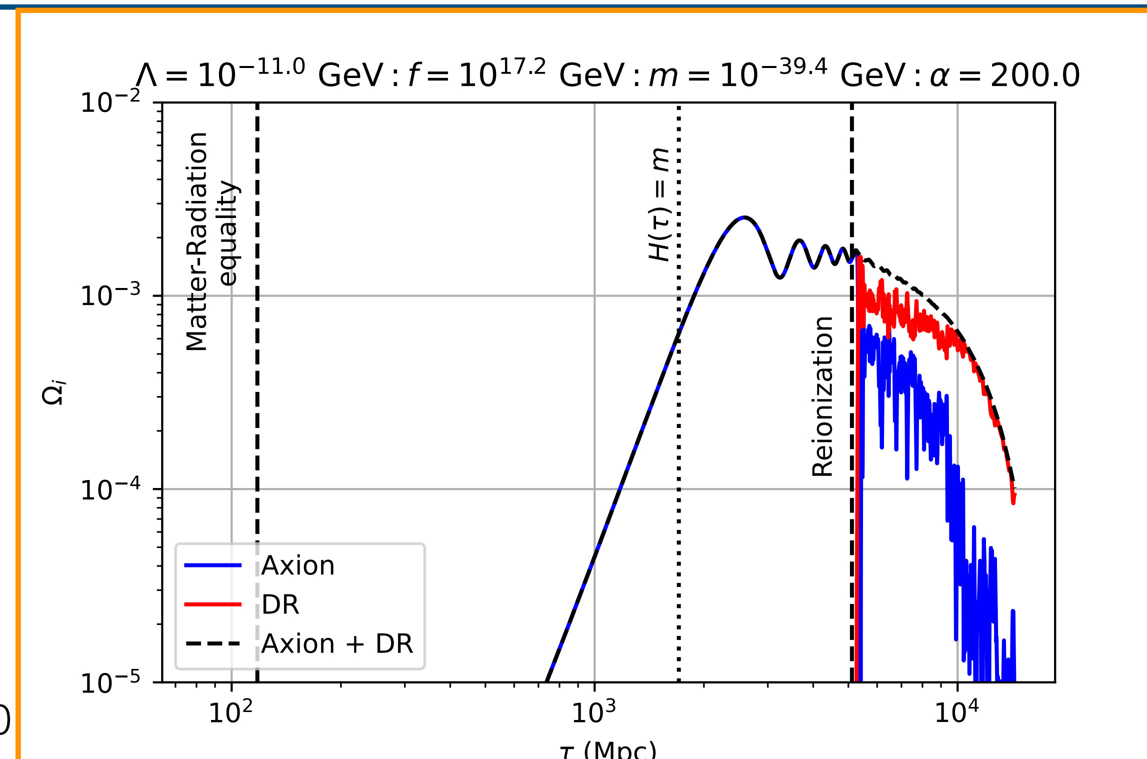
CMB Spectrum: Dependence on Λ



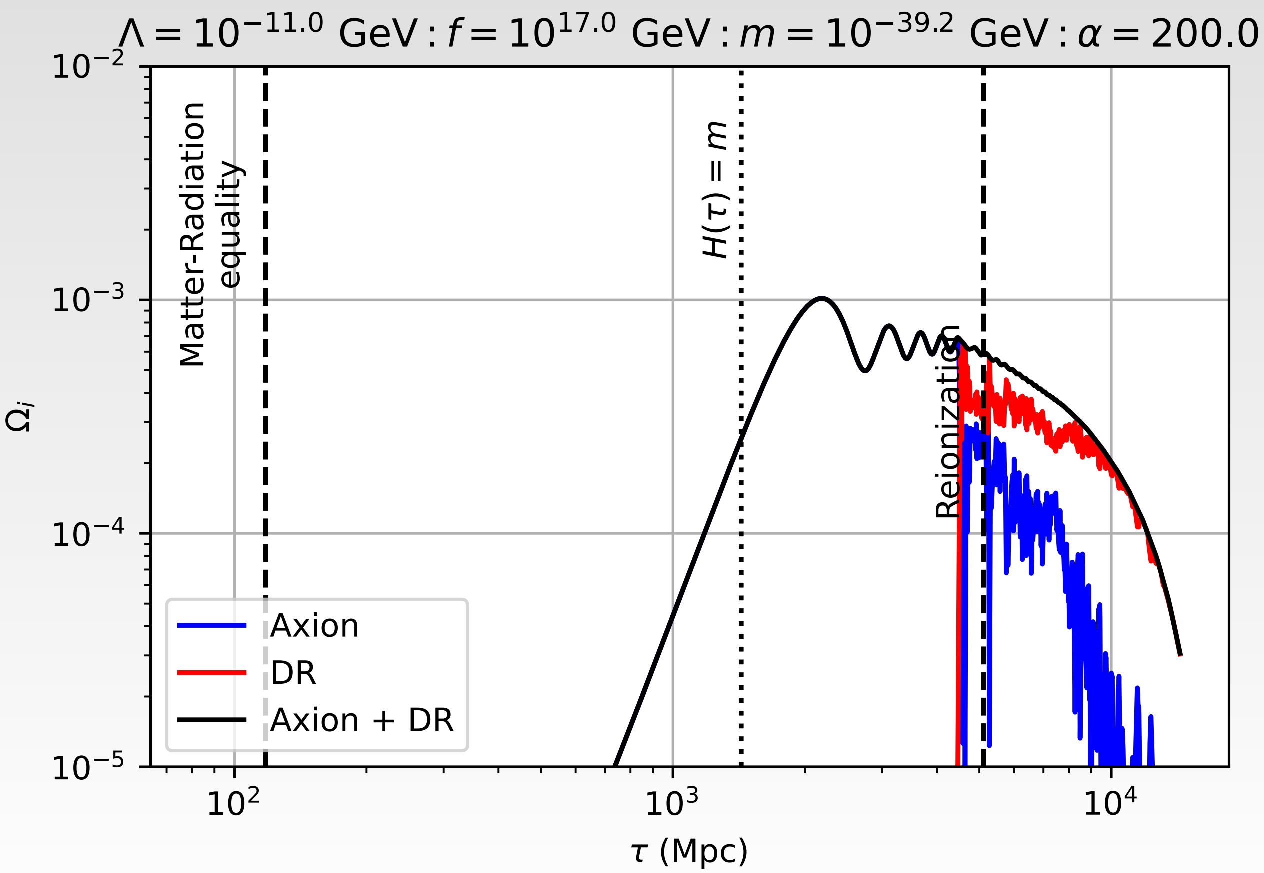


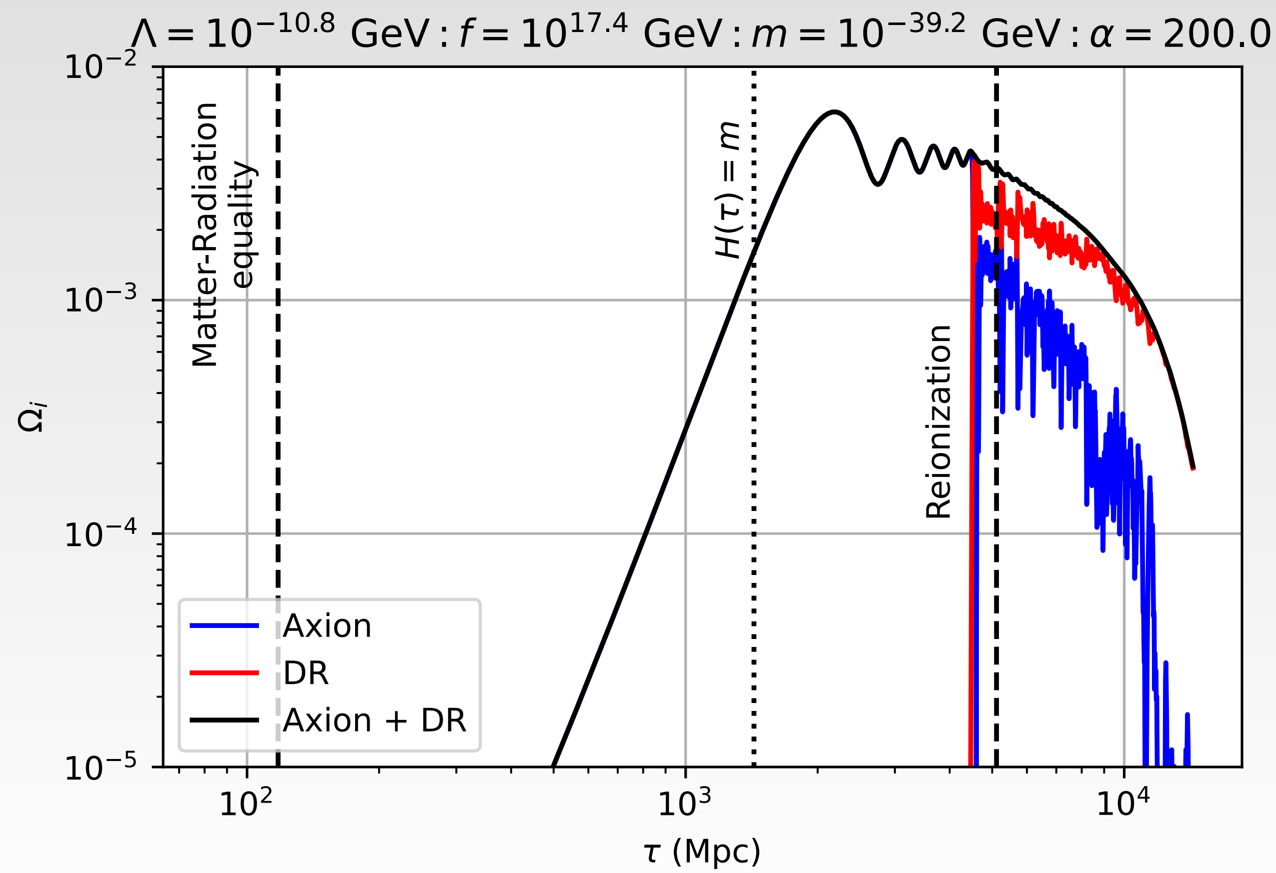
Fixed f : Higher $\Lambda \rightarrow$ Higher m $\rightarrow$ same Ω_{axion} (& same interaction strength)$\rightarrow$ lower Ω_{DR} (at late times)





Energy transfer : Dependence on Λ with fixed m





Fixed m : Higher $\Lambda \rightarrow$ Higher Ω_{axion} (& higher interaction strength - due to lower f)

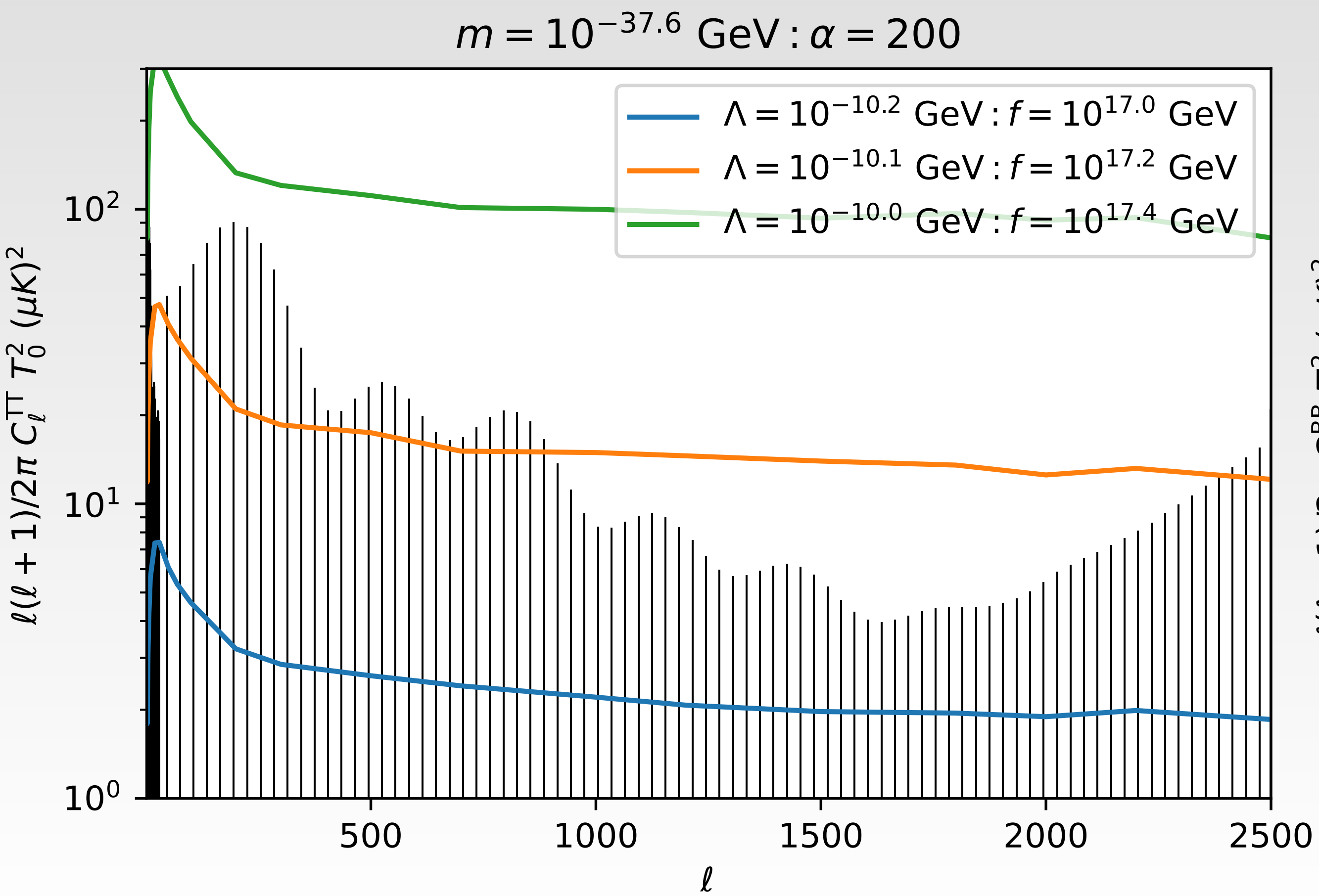
$$\Omega_{\text{Axion}} \sim m^2 f^2 \sim \Lambda^4$$

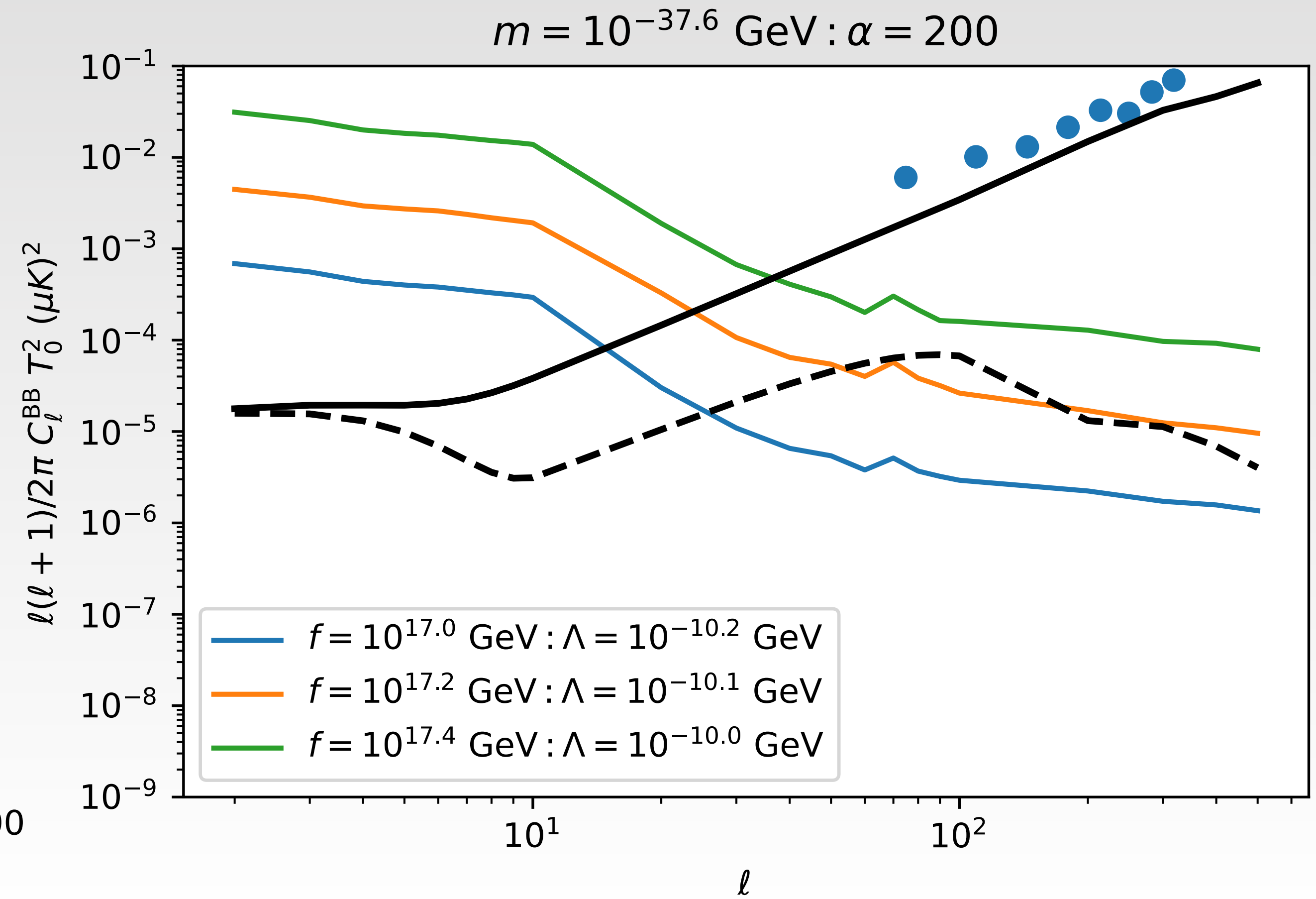
$$\phi'' + 2aH\phi' + a^2 \frac{\partial V}{\partial \phi} = \frac{\alpha}{f} a^2 \mathbf{E} \cdot \mathbf{B}$$

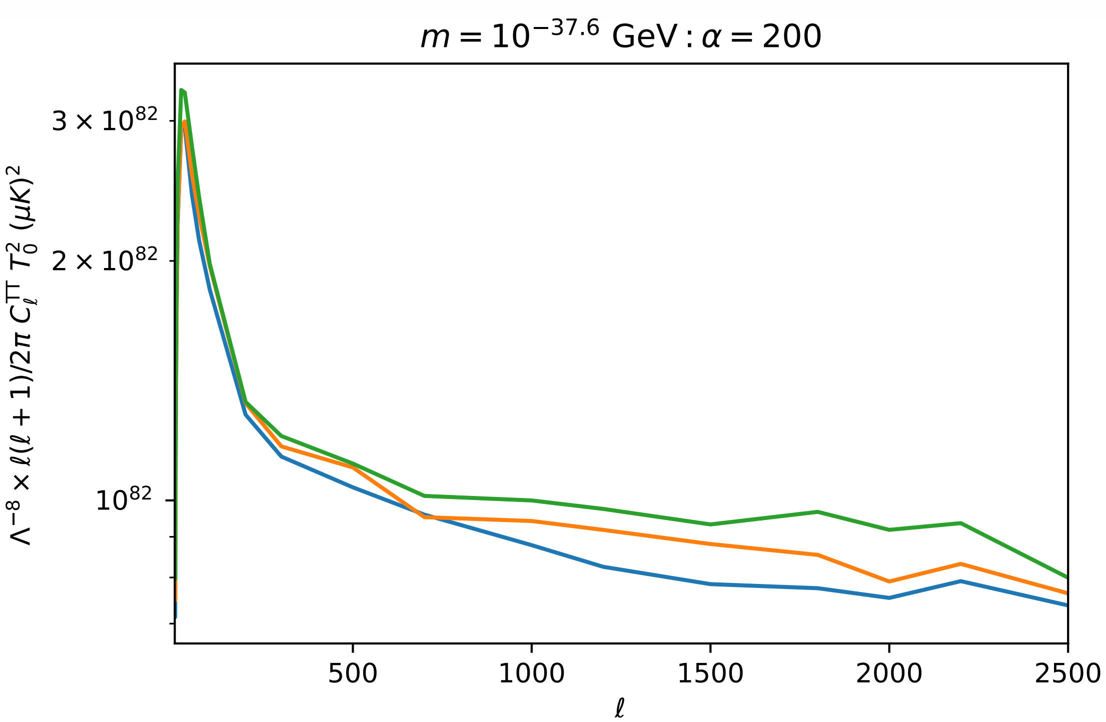
$$m^2 \phi$$

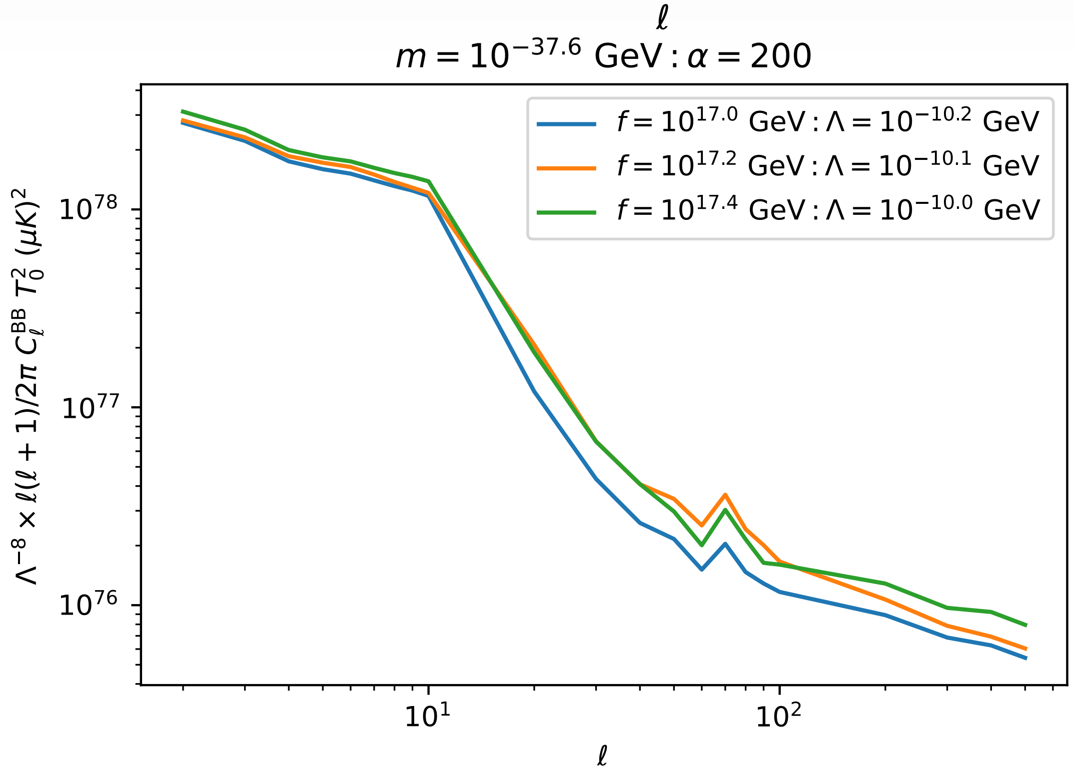
$$\boxed{m = \frac{\Lambda^2}{\sqrt{2}f}}$$

CMB Spectrum: Dependence on Λ with fixed m

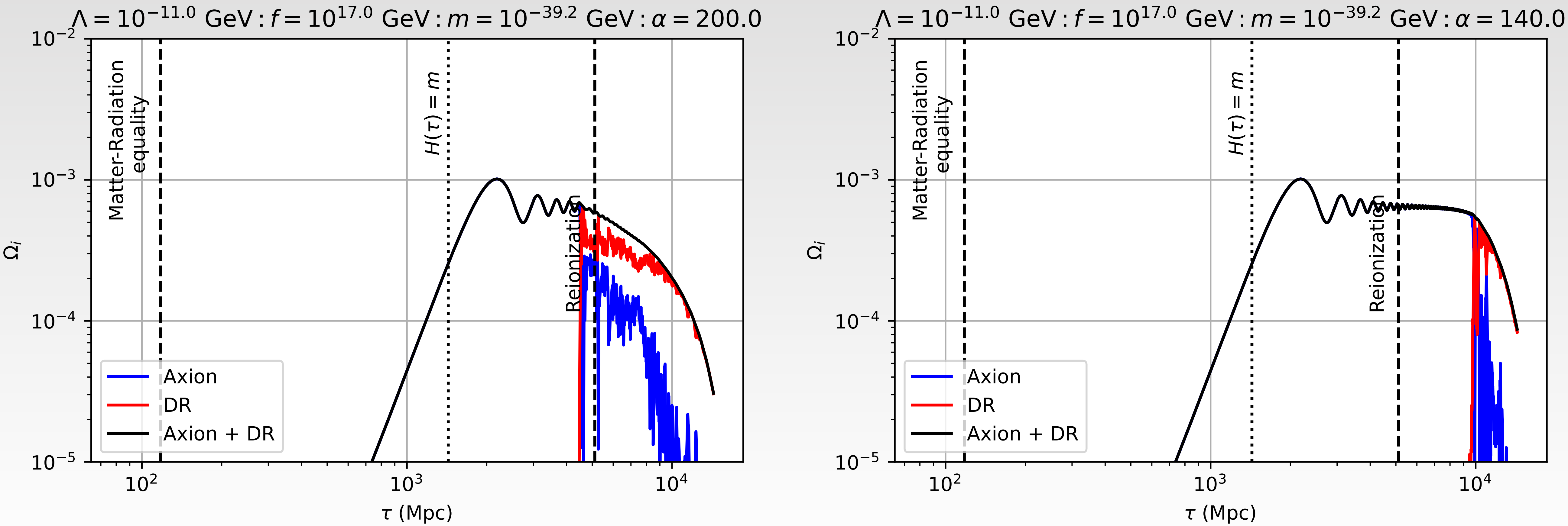








Energy transfer : Dependence on α



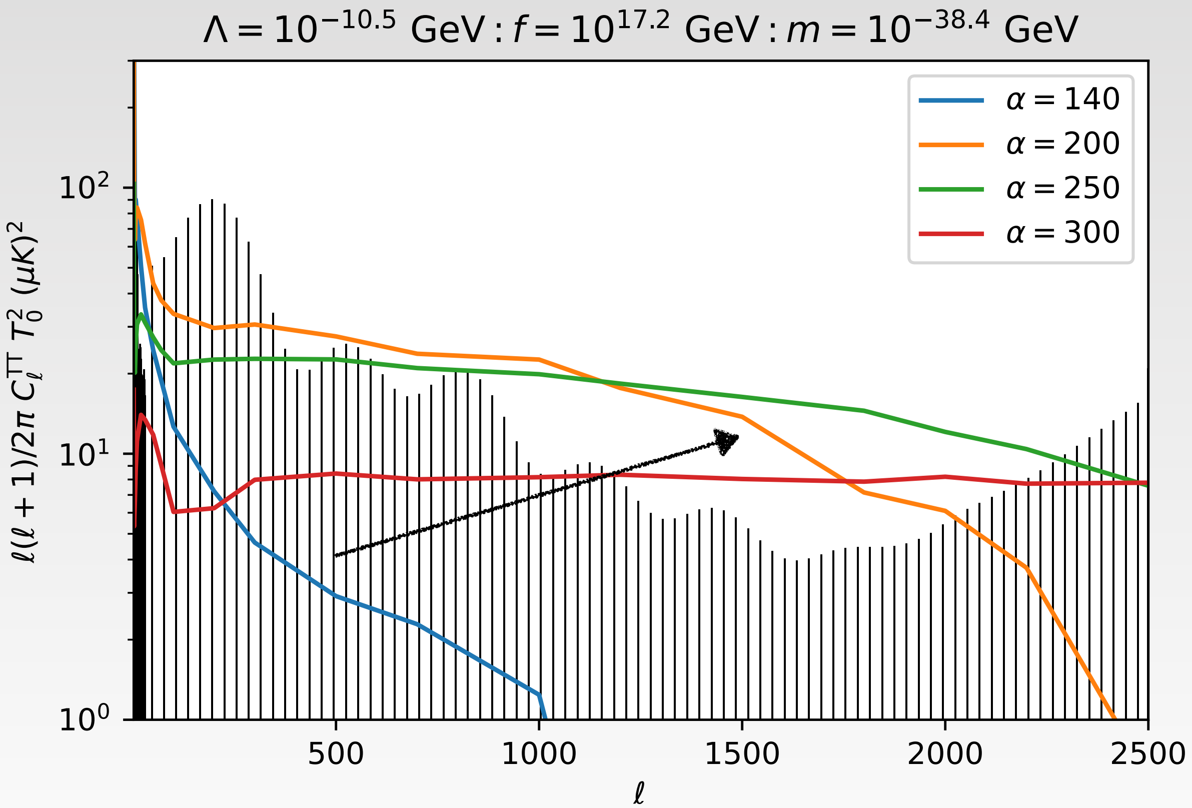
Lower α → lower interaction strength → delayed energy transfer

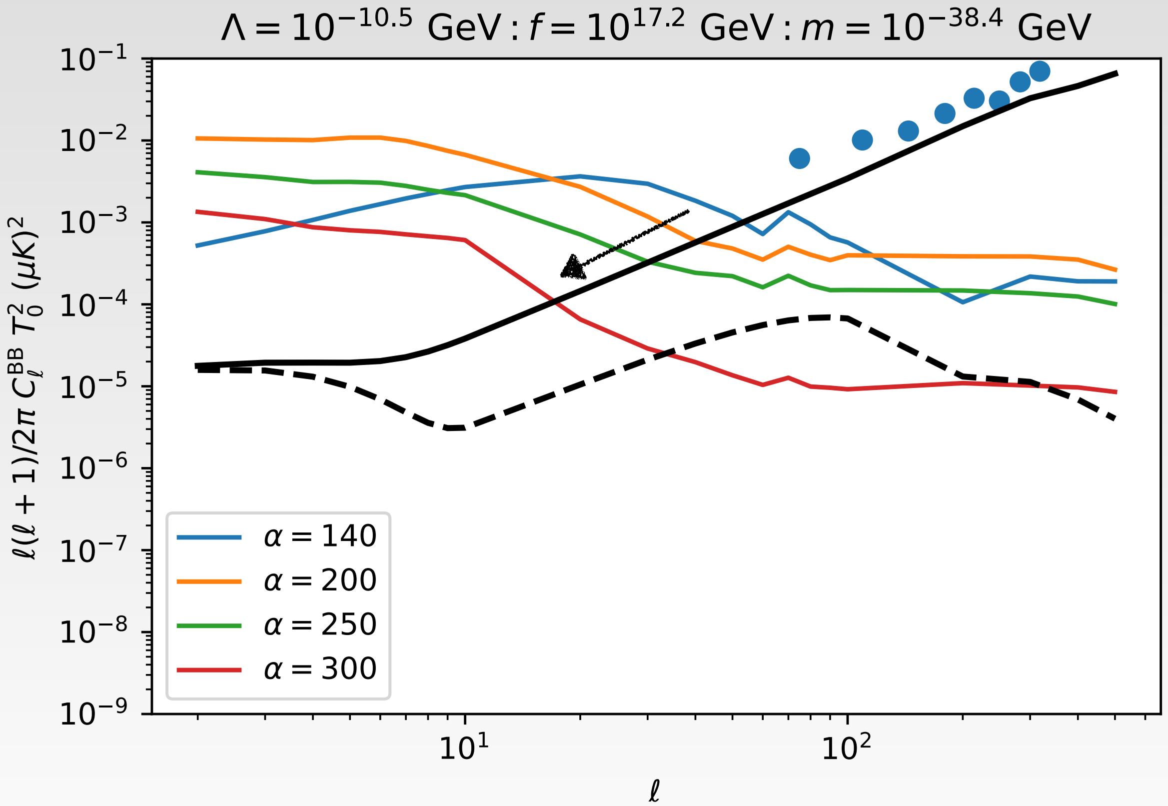
$$\phi'' + 2aH\phi' + a^2\frac{\partial V}{\partial \phi} = \frac{\alpha}{f}a^2\mathbf{E}\cdot\mathbf{B}$$

$m^2\phi$

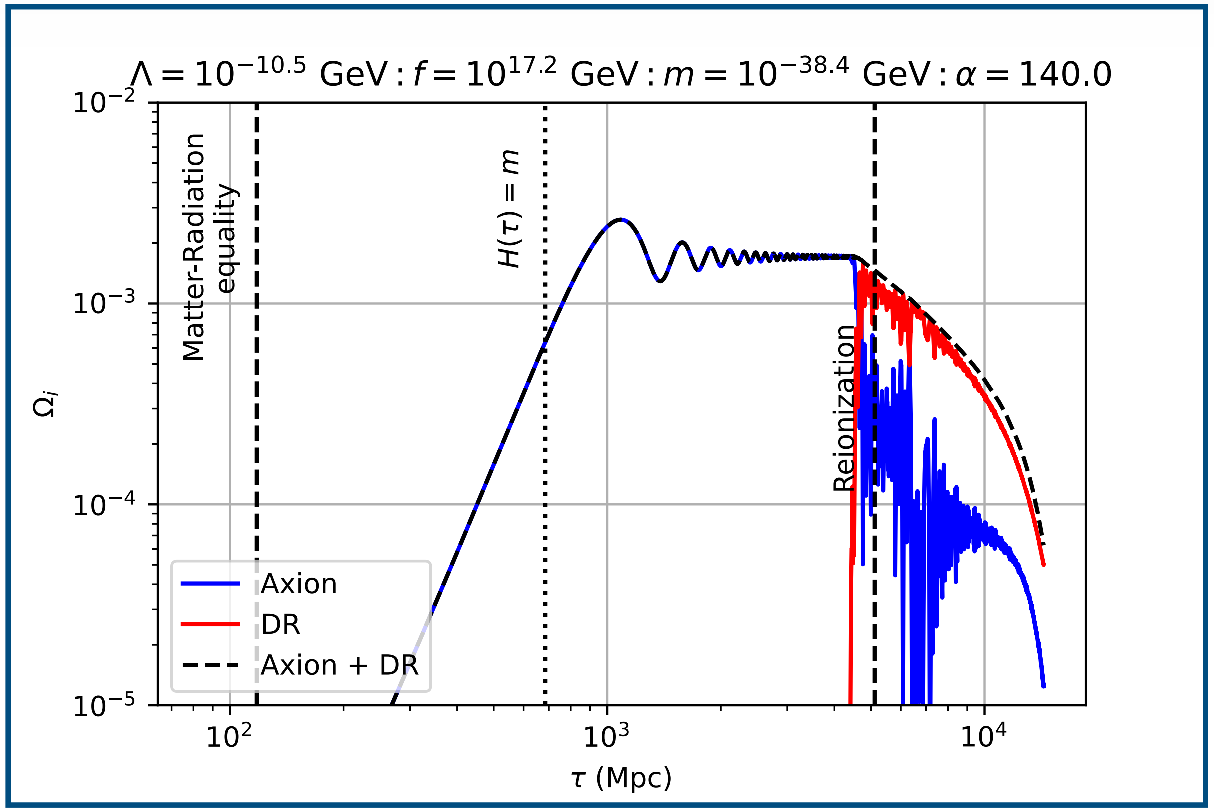
$$\boxed{m = \frac{\Lambda^2}{\sqrt{2}f}}$$

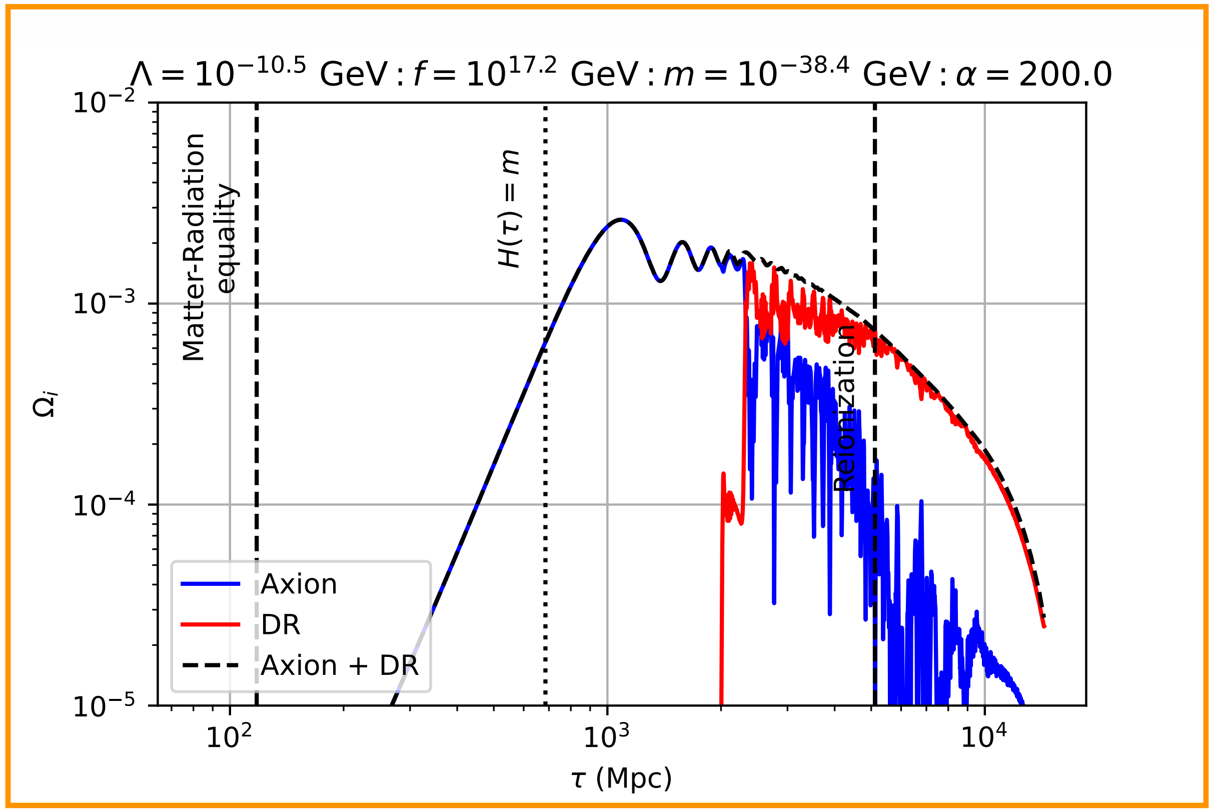
CMB Spectrum: Dependence on α



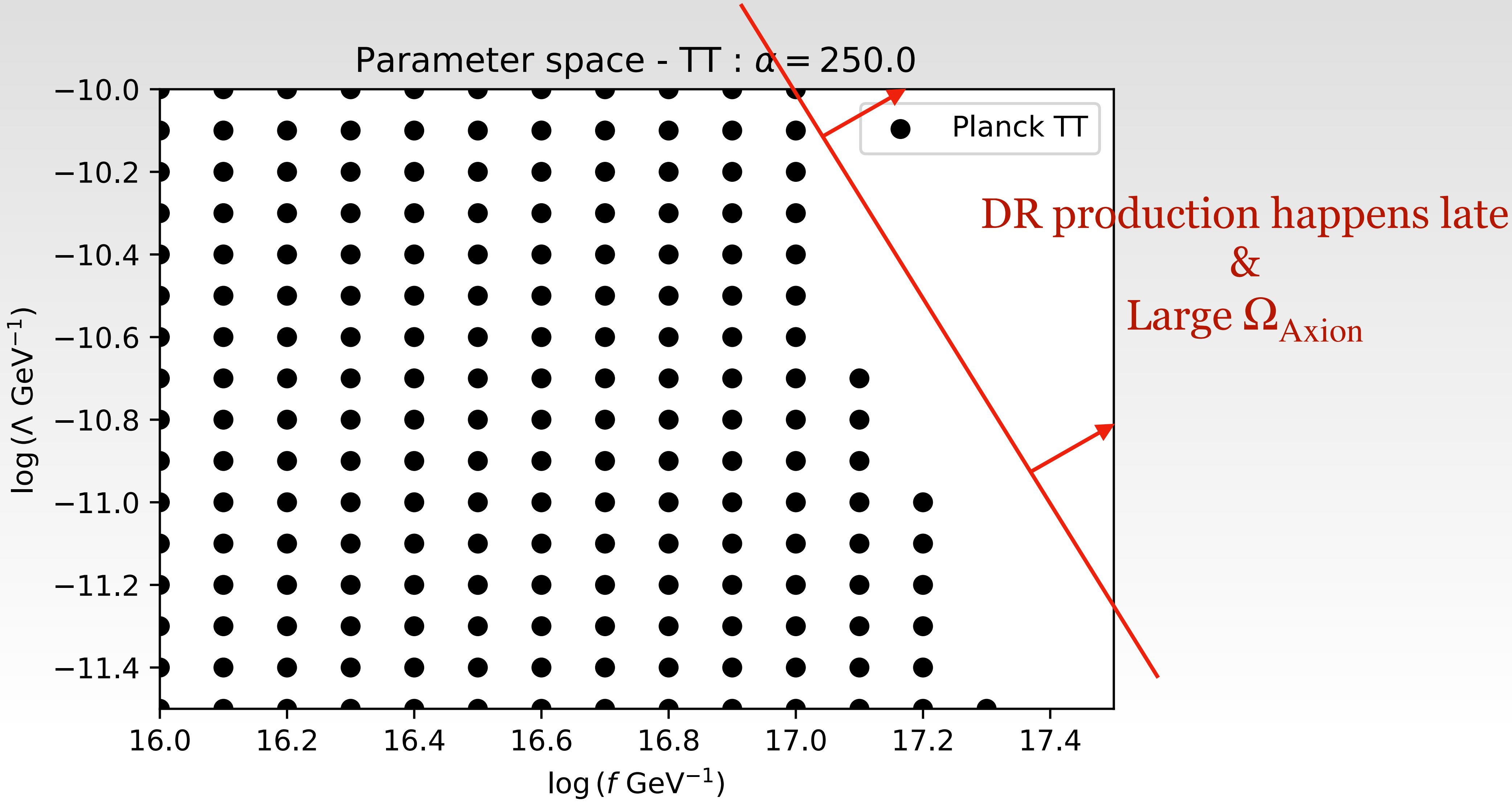


Lower $\alpha \rightarrow$ lower interaction strength $\rightarrow$ delayed energy transfer

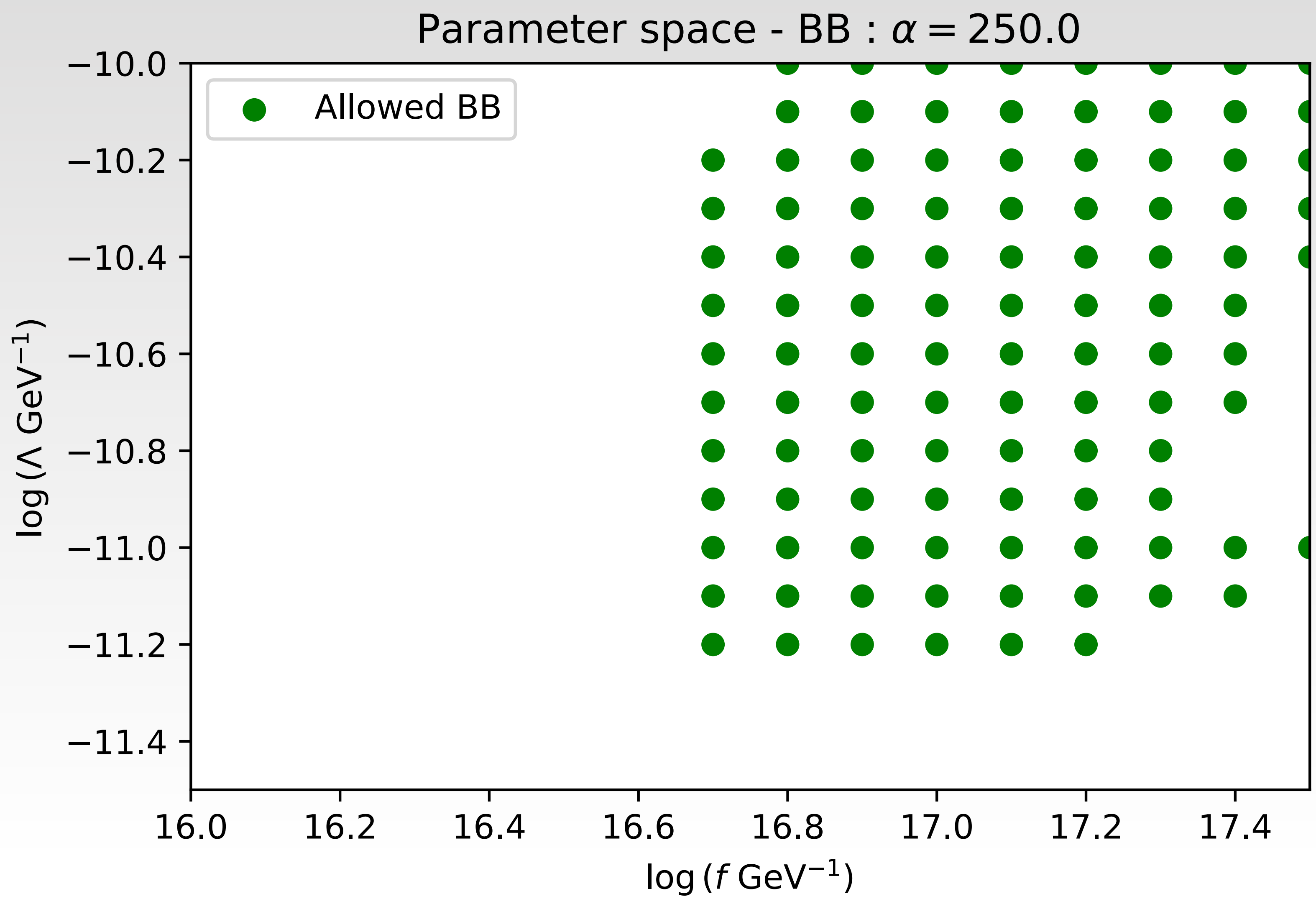




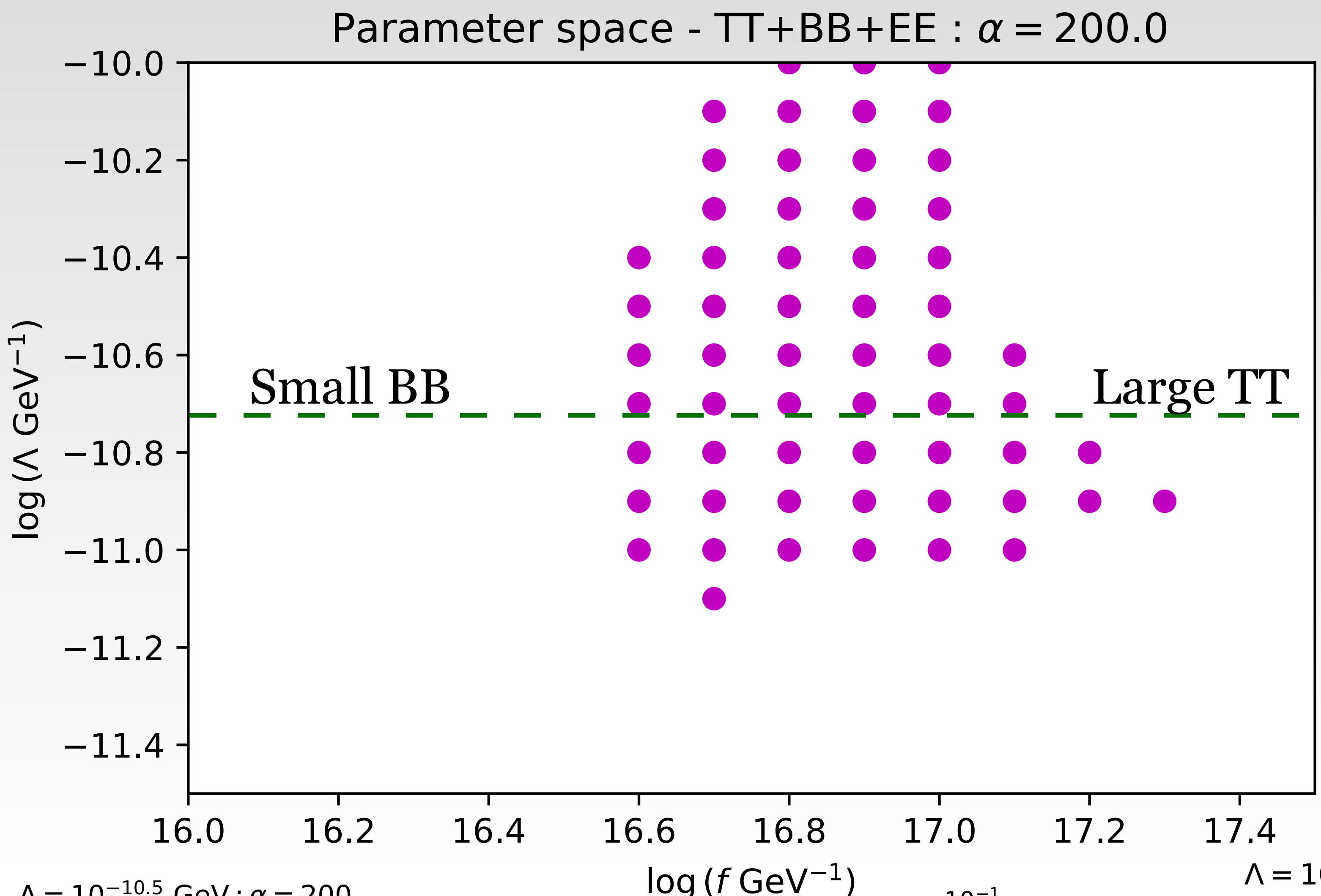
Parameter space: Constraints from TT : $\alpha = 250$

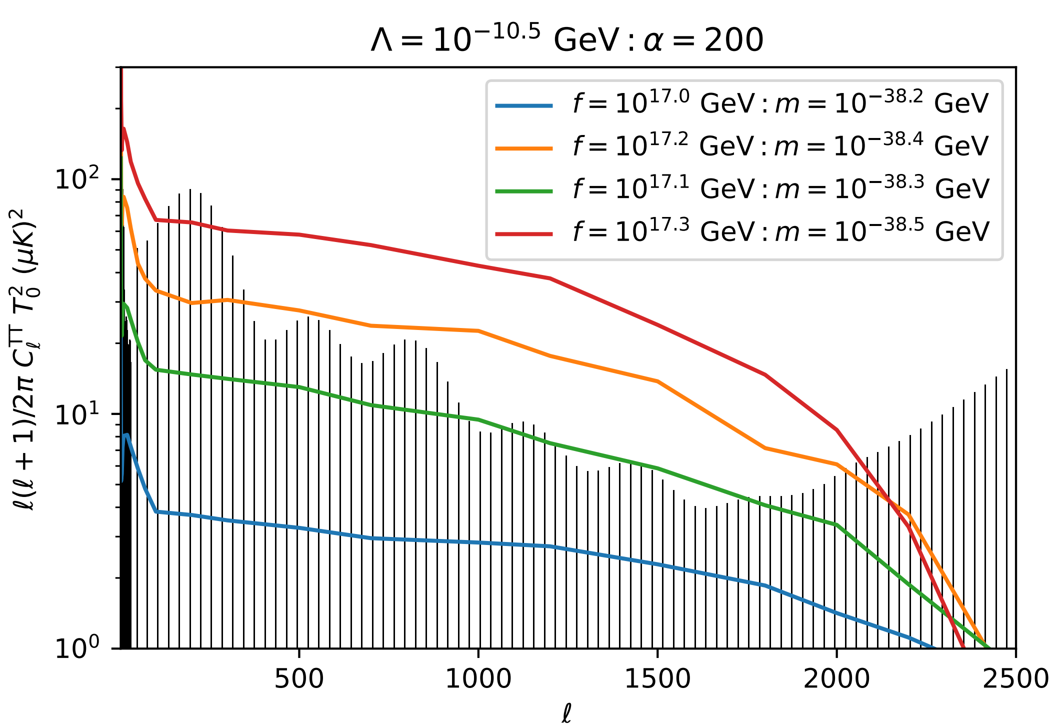


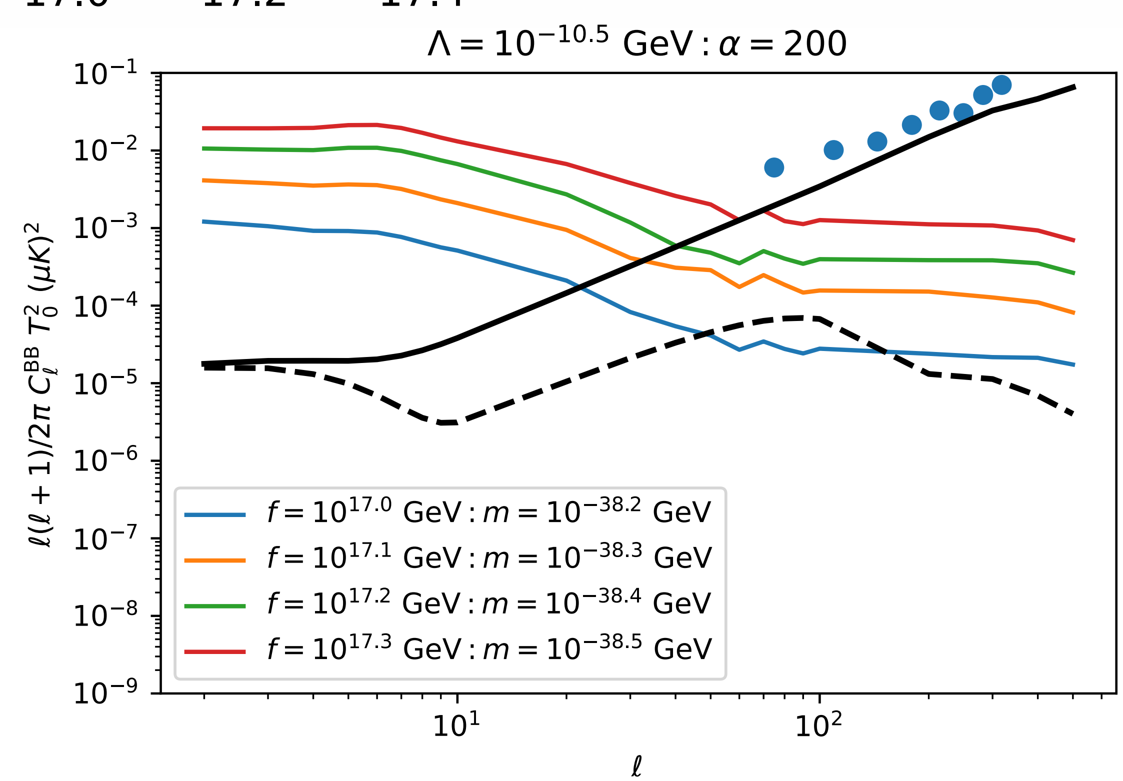
Parameter Space: Sensitivity of BB : $\alpha = 200$



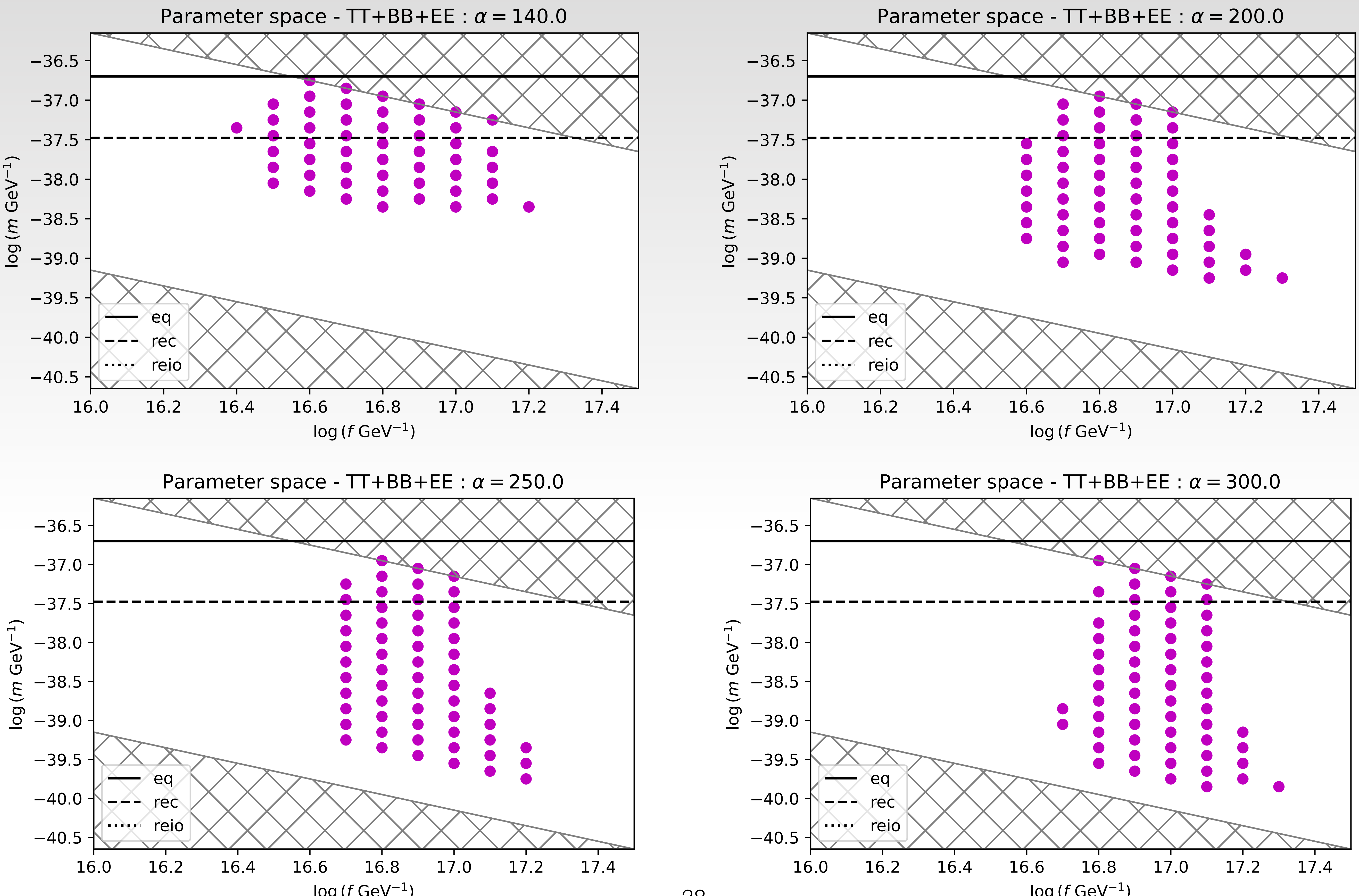
Parameter space: Dependence on f







Parameter Space: TT+BB+EE



Numerical Challenges

We solve the mode functions numerically for total $N = 200$ modes

Mode functions are highly oscillatory and we solved them from $\tau_{\rm osc}$ to today τ_0

We calculated the CMB spectrum from scratch numerically

$\sim N_\ell \times N^3$ steps of computations (with highly oscillatory functions)

Optimization

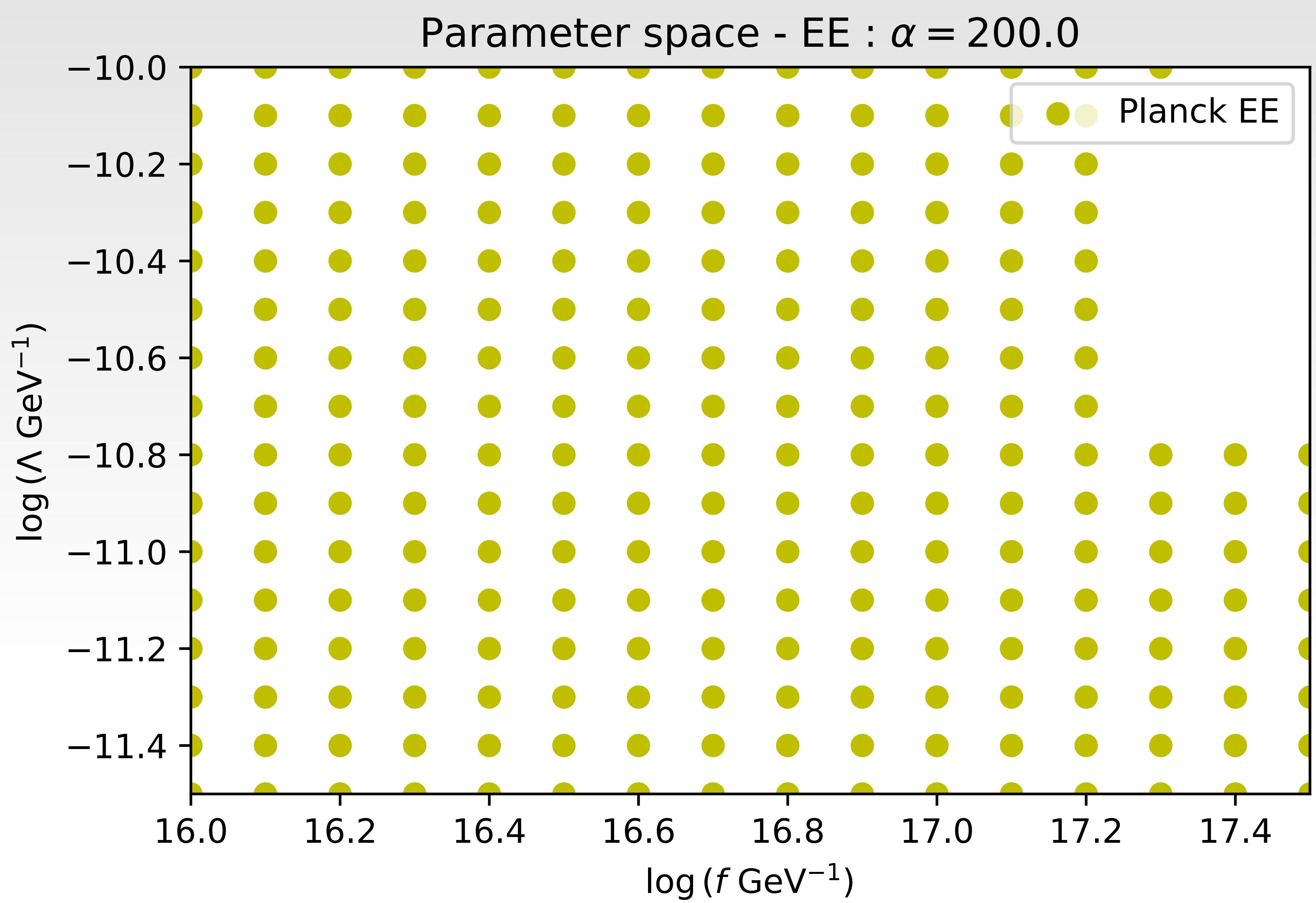
Physics: change of unit, redefinition of variable (to make equations less stiff)

Numerical: Numerical integration using SciPy, paralization using OPENMP and MPI

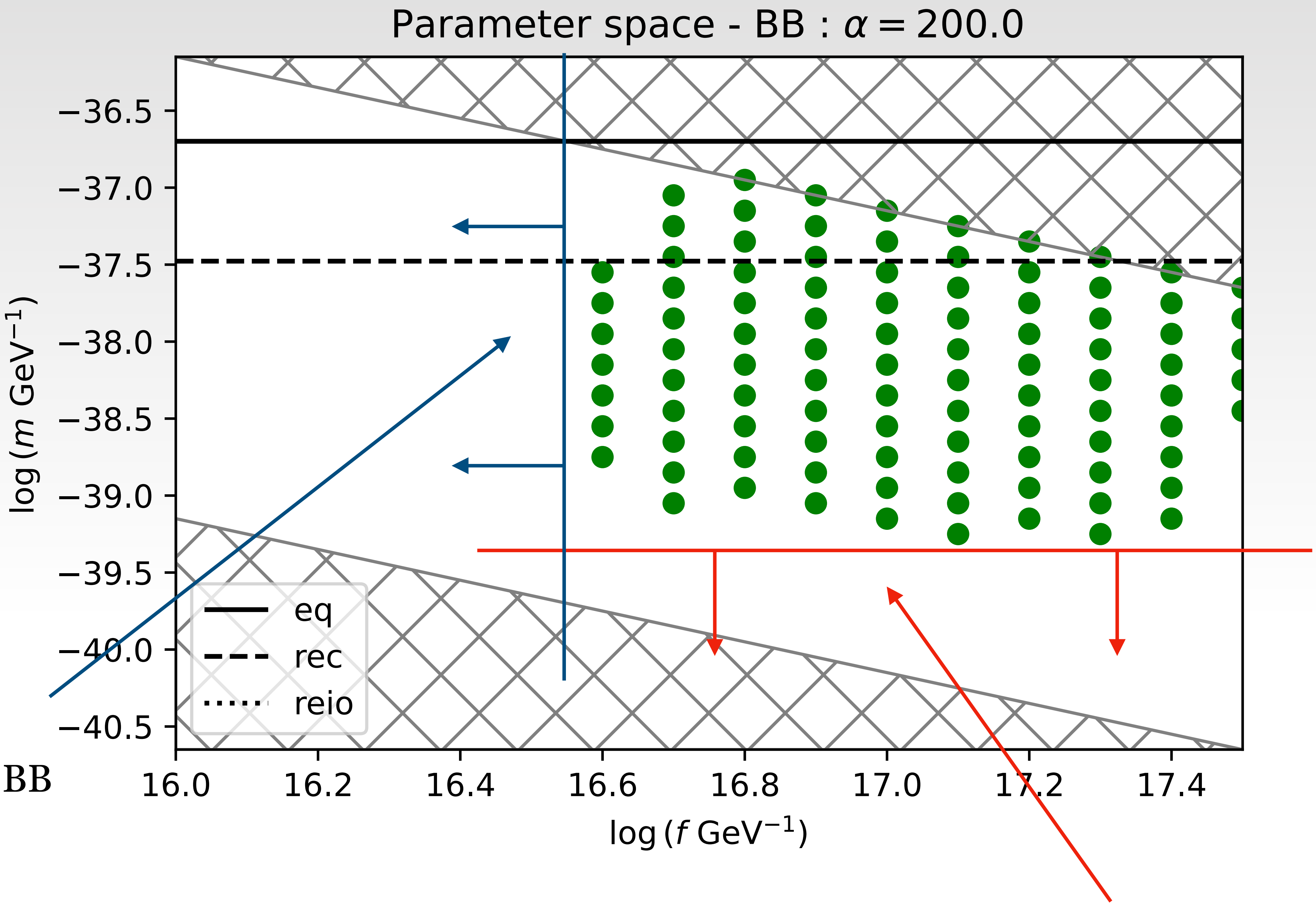
Typical computation time: BB/EE ~ 6 mins, TT ~ 30 mins

Optimization was necessary for parameter scans

Parameter Space: EE : $\alpha = 200$



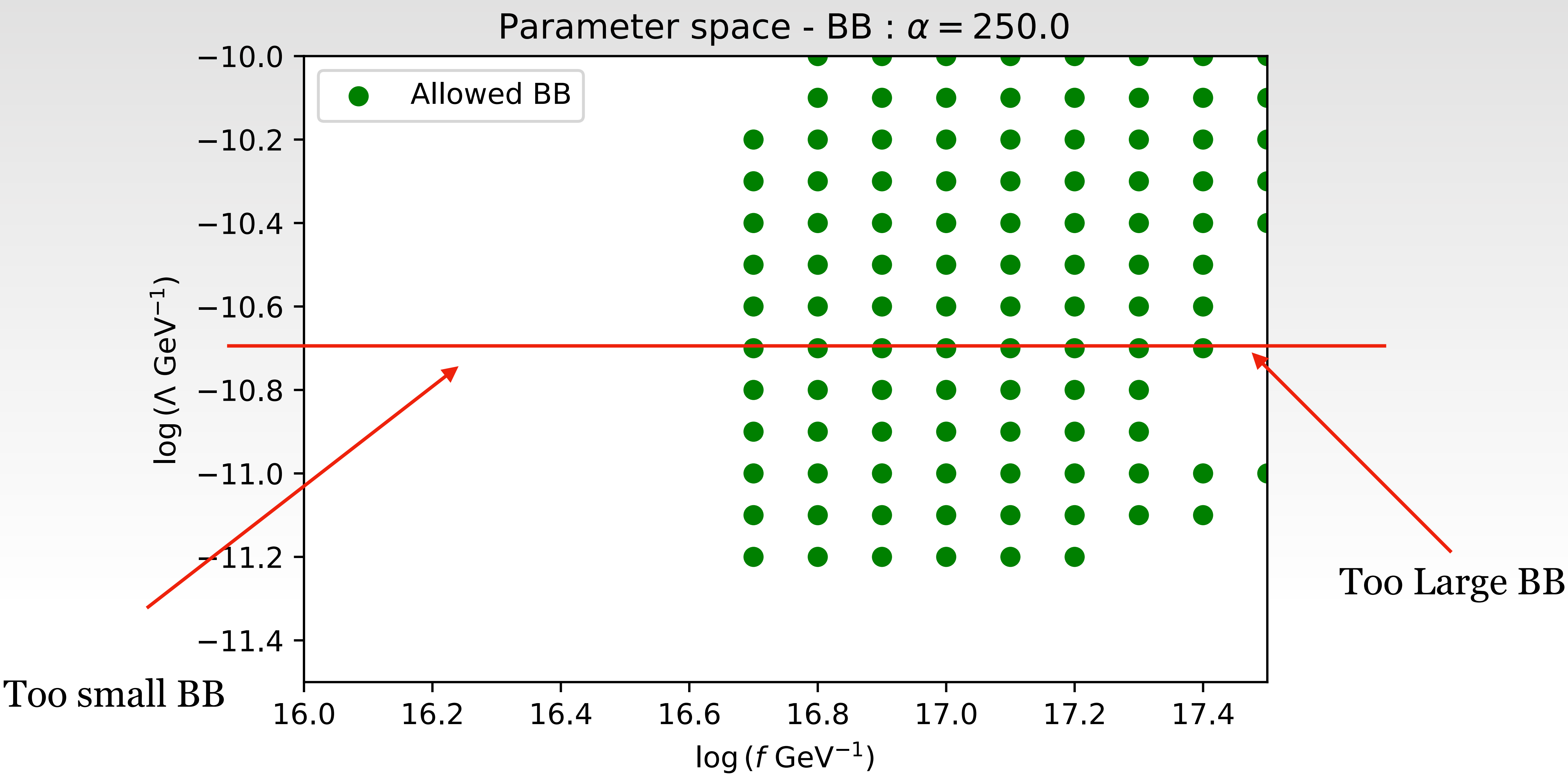
Parameter Space: BB : $\alpha = 200$



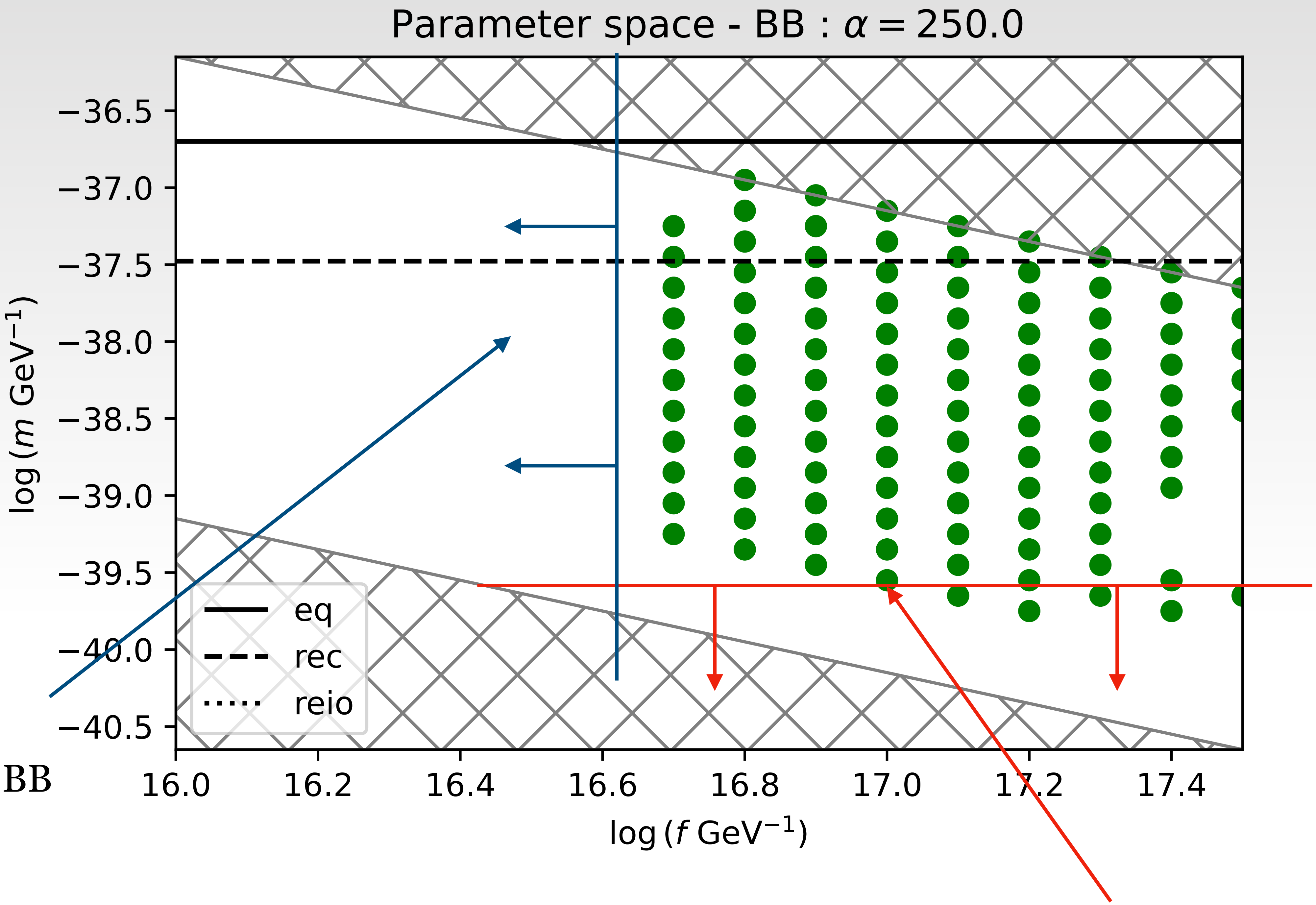
Too small BB

DR production happens after reionization

Parameter Space: BB : $\alpha = 250$



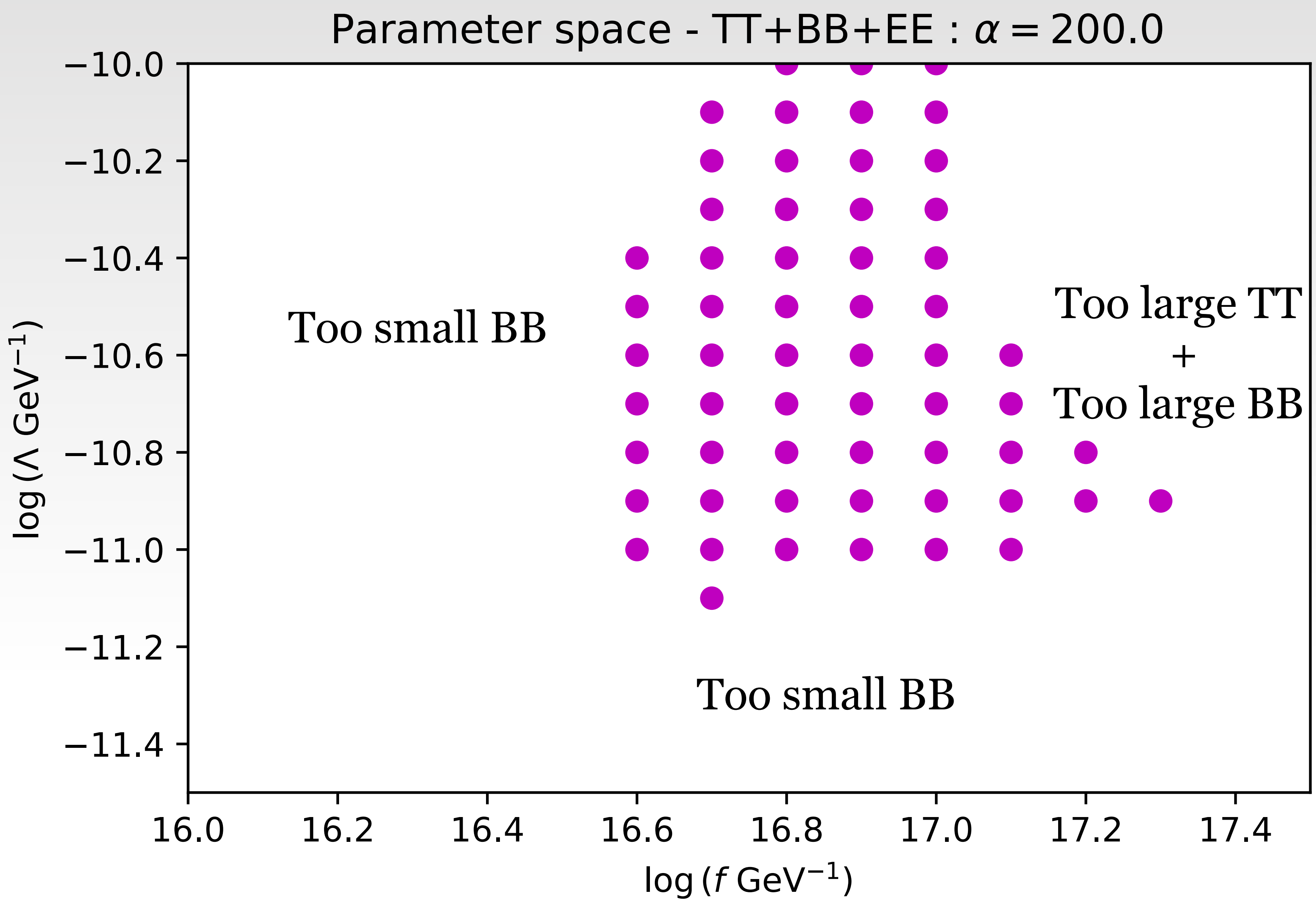
Parameter Space: BB : $\alpha = 250$



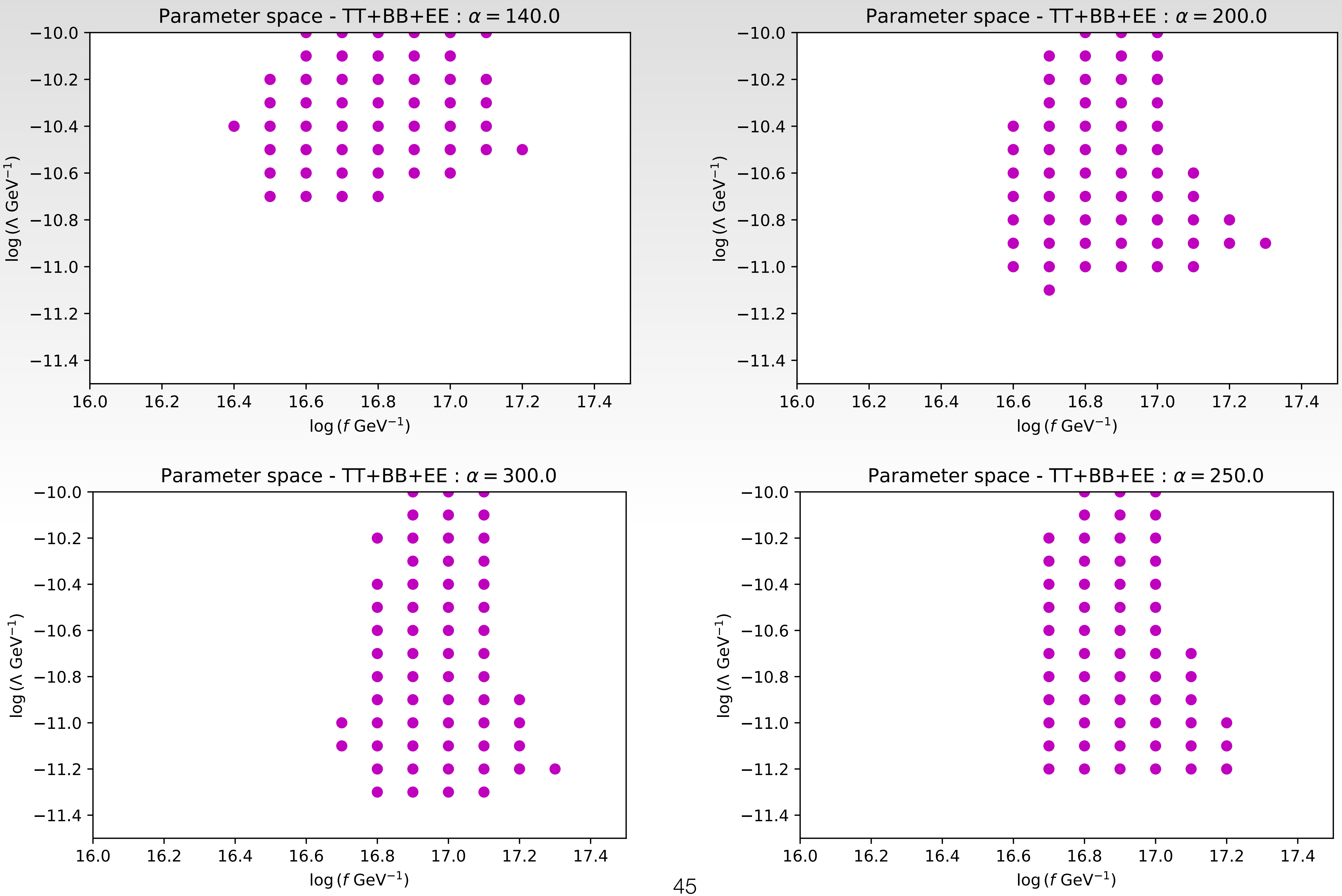
Too small BB

DR production happens after reionization

Parameter Space: TT+BB+EE



Parameter Space: TT+BB+EE



CMB EB measurement: Cosmic Birefringence

⚠️ Different Model

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - V(\phi) - \frac{1}{4}F^2 - \frac{\alpha}{4f}\phi F\tilde{F}$$

Axion DM

SM Photon

Rotates the plane of linear polarization of CMB photon

Birefringence angle

$$\beta(\hat{\mathbf{n}}) = \frac{\alpha}{2f}\left[\phi(\eta_{\rm o}) - \phi(\eta_{\rm e}, r\hat{\mathbf{n}})\right]$$

Intrinsic EB at LSS

$$C_\ell^{EB,{\rm o}} = \frac{\tan(4\beta)}{2}\left(C_\ell^{EE,{\rm o}} - C_\ell^{BB,{\rm o}}\right) + \frac{C_\ell^{EB}}{\cos(4\beta)}$$

Observed EB

CMB EB measurement: Miscalibration Angle

Miscalibration angle (systematics) : α

The unknown angle of orientation of polarization detectors

Arises because the orientation of detectors in sky coordinate is not precisely known
&
due to rotation of light by optical component

$\boxed{\alpha \text{ is degenerate with } \beta}$

Rotation at instrument level

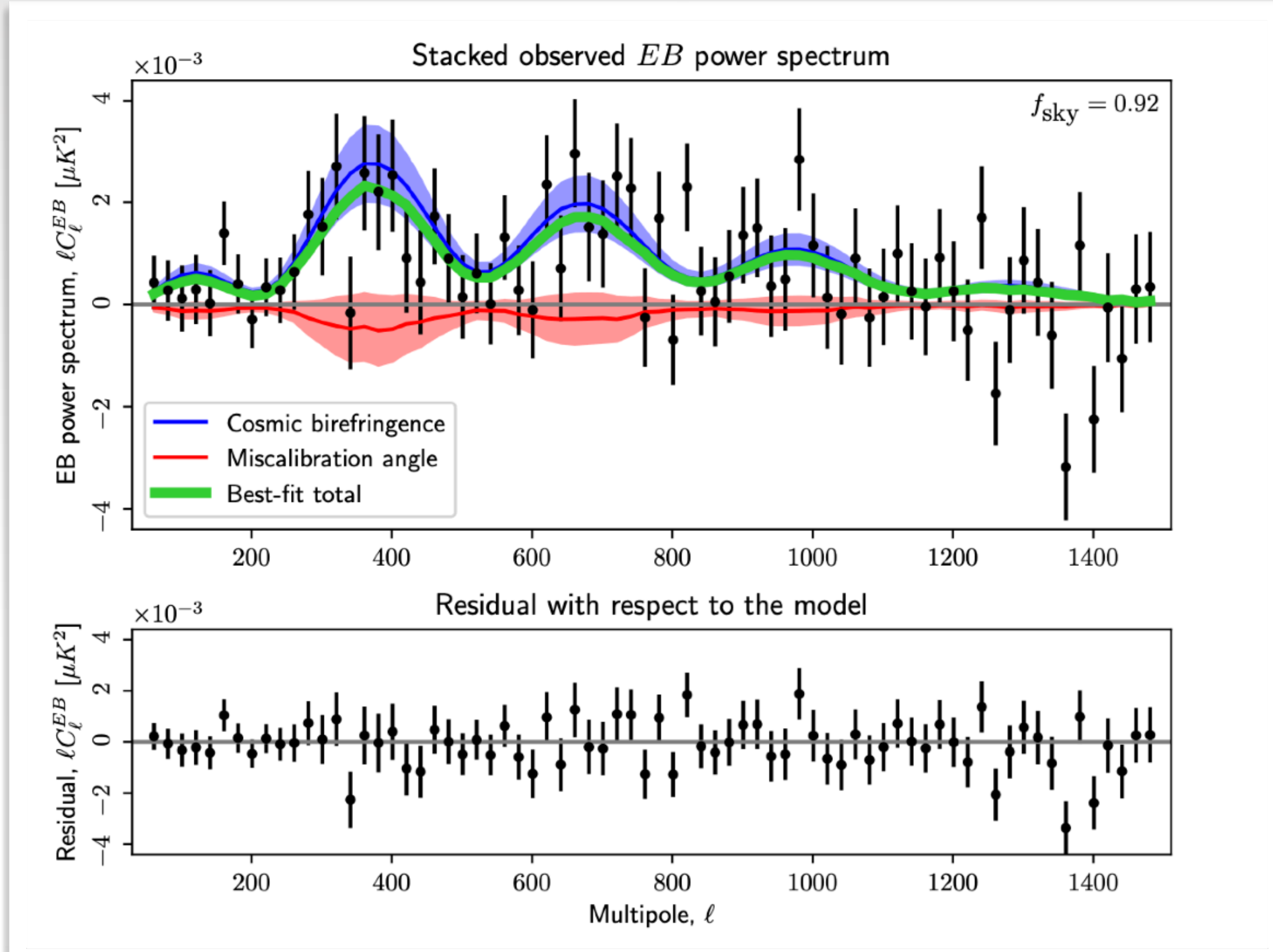
Rotation due to birefringence

CMB is only sensitive to $(\alpha + \beta)$

CMB EB measurement: Breaking degeneracy

CMB is only sensitive to $(\alpha + \beta)$

Foreground (emission due to galaxy) is only sensitive to α (it's a local effect)



Eskilt et. al., arXiv: 2205.13962

$$\beta = 0.342^\circ \,{}^{+0.094^\circ}_{-0.091^\circ} \quad (68\% \quad \text{C.L.})$$

$\boxed{\beta = 0 \text{ is excluded at } 3.6\sigma}$

Non-zero EB correlation from Axion oscillation

Since we only solved for the +ve helicity the mode function sources are same for EB or BB/EE

(Maximum CP violation → for assumption)

$$C_l^{EB} = 36\pi\, \mathcal{T}_{\rm rei}^2 \int \mathcal{D}k\mathcal{D}k'\, \mathcal{J}_{l,E}(k)\, \mathcal{J}_{l,B}(k) \cdot \left\langle \left\{ \int_{\tau_{\rm rec}}^{\tau_{\rm rei}} d\tau\, h'_{ij}(k,\tau) \frac{j_2[(\tau_{\rm rei}-\tau)\,k]}{(\tau_{\rm rei}-\tau)^2\, k^2} \right\}^2 \right\rangle$$

$$\mathcal{J}_{B,l}(k) = \frac{l+2}{2l+1} j_{l-1}(\kappa) - \frac{l-1}{2l+1} j_{l+1}(\kappa)$$

$$\mathcal{J}_{E,l}(k) = \frac{(l+2)(l+1)}{(2l+1)(2l-1)} j_{l-2}(\kappa) - \frac{6(l+2)(l-1)}{(2l+3)(2l-1)} j_l(\kappa) + \frac{l(l-1)}{(2l+3)(2l+1)} j_{l+2}(\kappa)\,,$$