Probing Dark Matter Decays to Axions via Axion-Photon Conversion in Filaments

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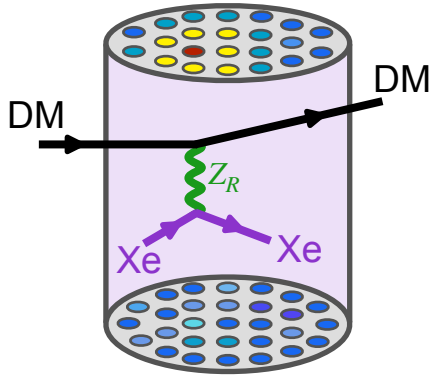
University of Chicago

PHENO 2026

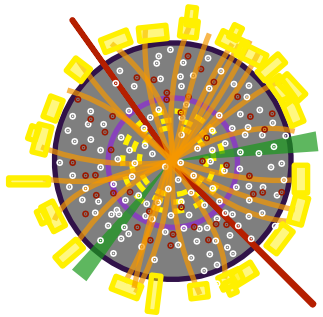
Based on: arXiv 2605.xxxxx with *G. Krnjaic and D. Rocha*

Previous Searches for Dark Matter

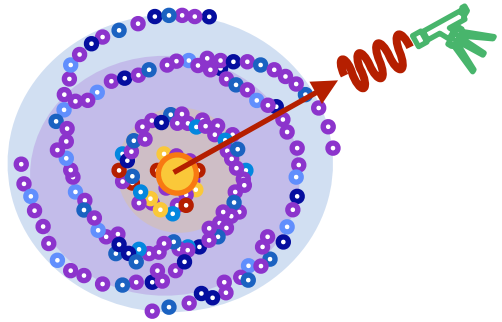
TeV mass dark matter has been extensively searched for:



Direct Detection



Collider



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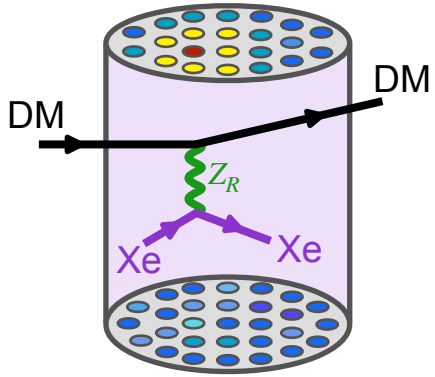

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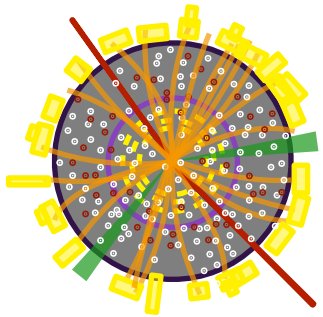

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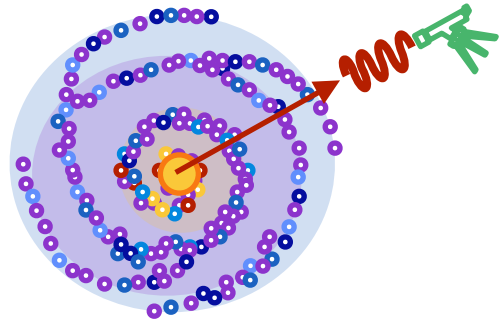

Indirect Detection

Bounds on coupling between dark matter and standard model are **very strong**

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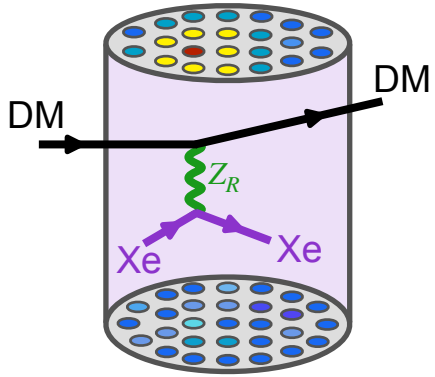

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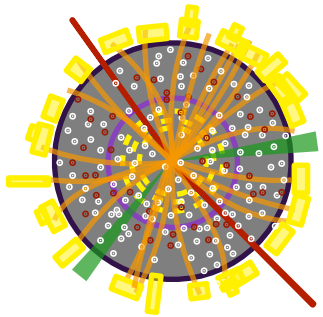

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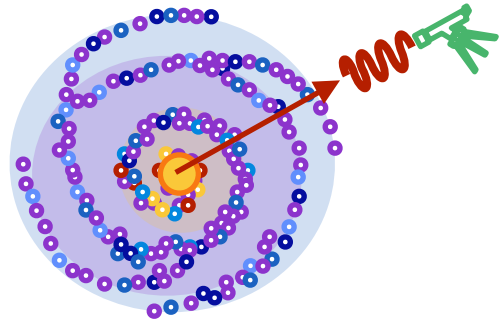

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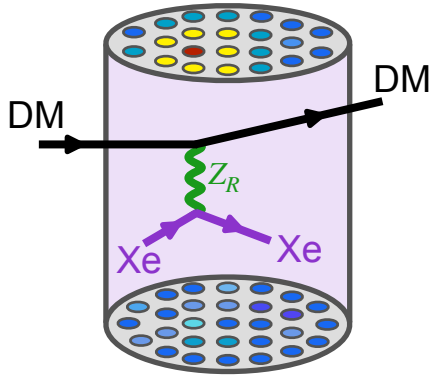

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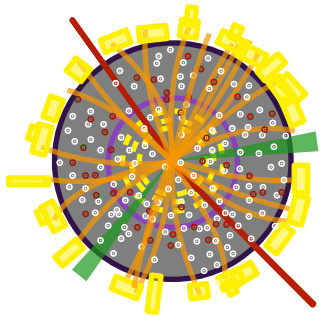

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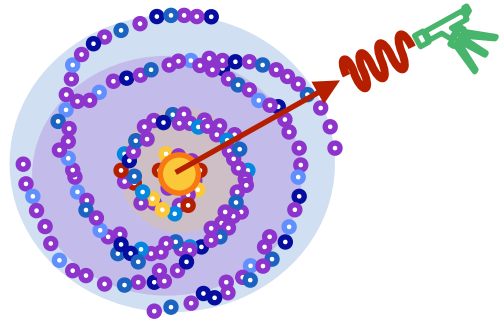

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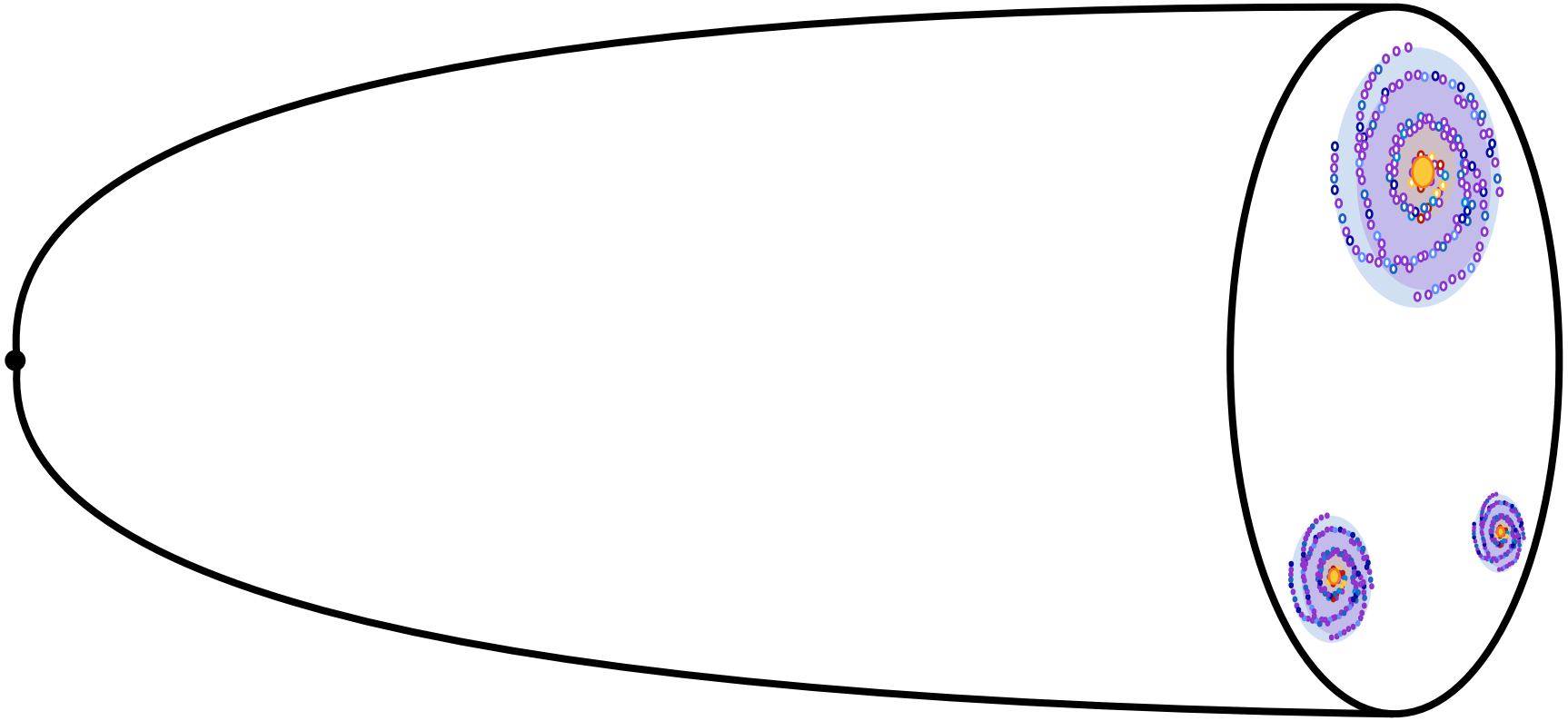
What if dark matter couples instead to BSM fields?

Can we set constraints on dark matter coupled to **axions**?

Photon Flux from Dark Matter Decays via Axions



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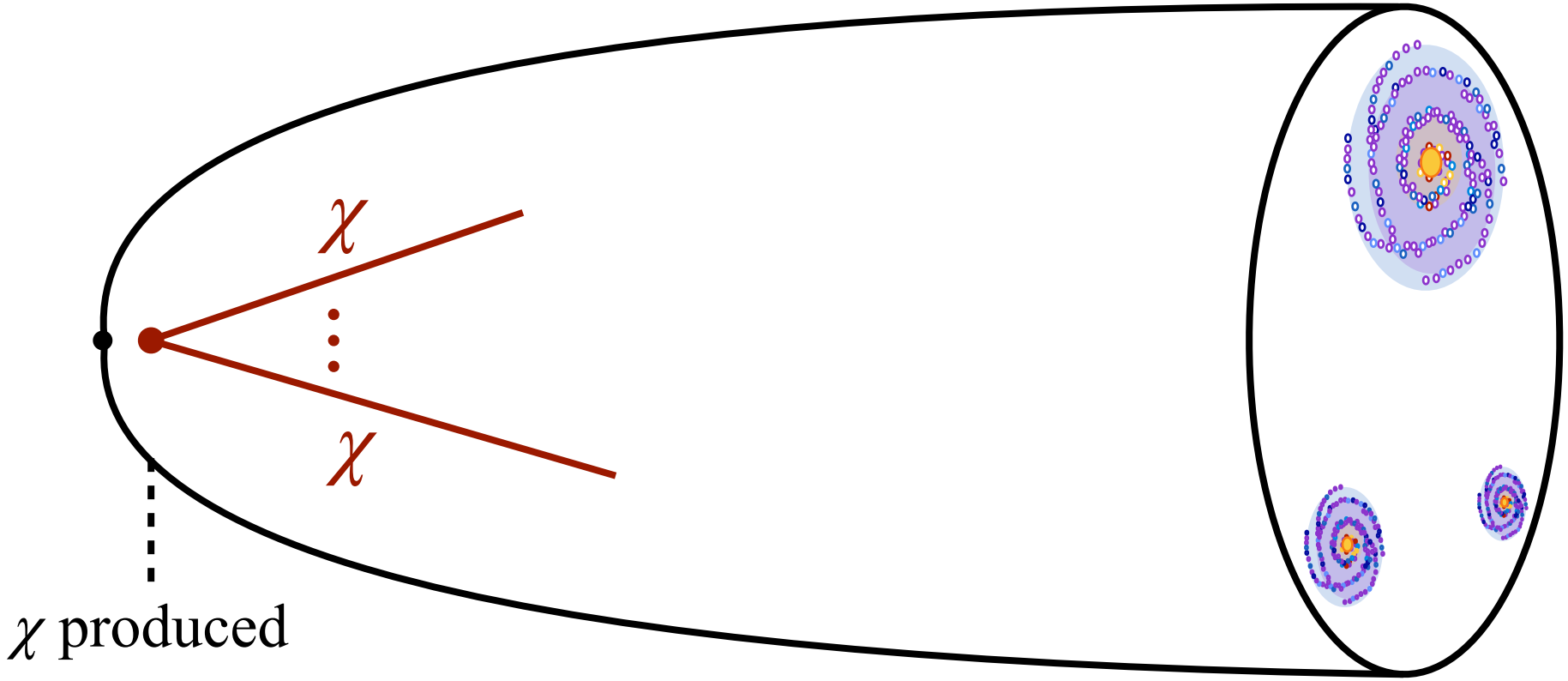

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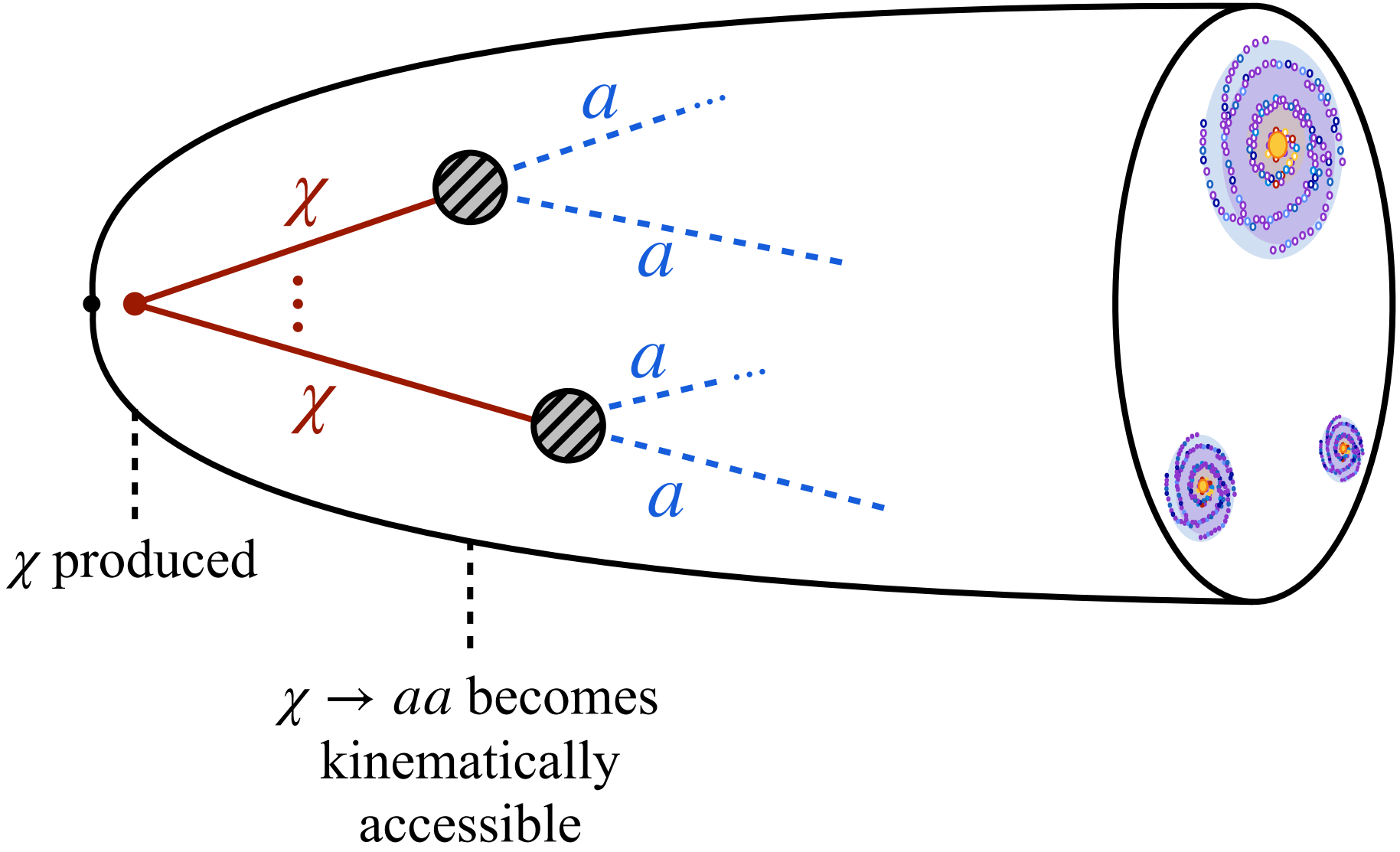

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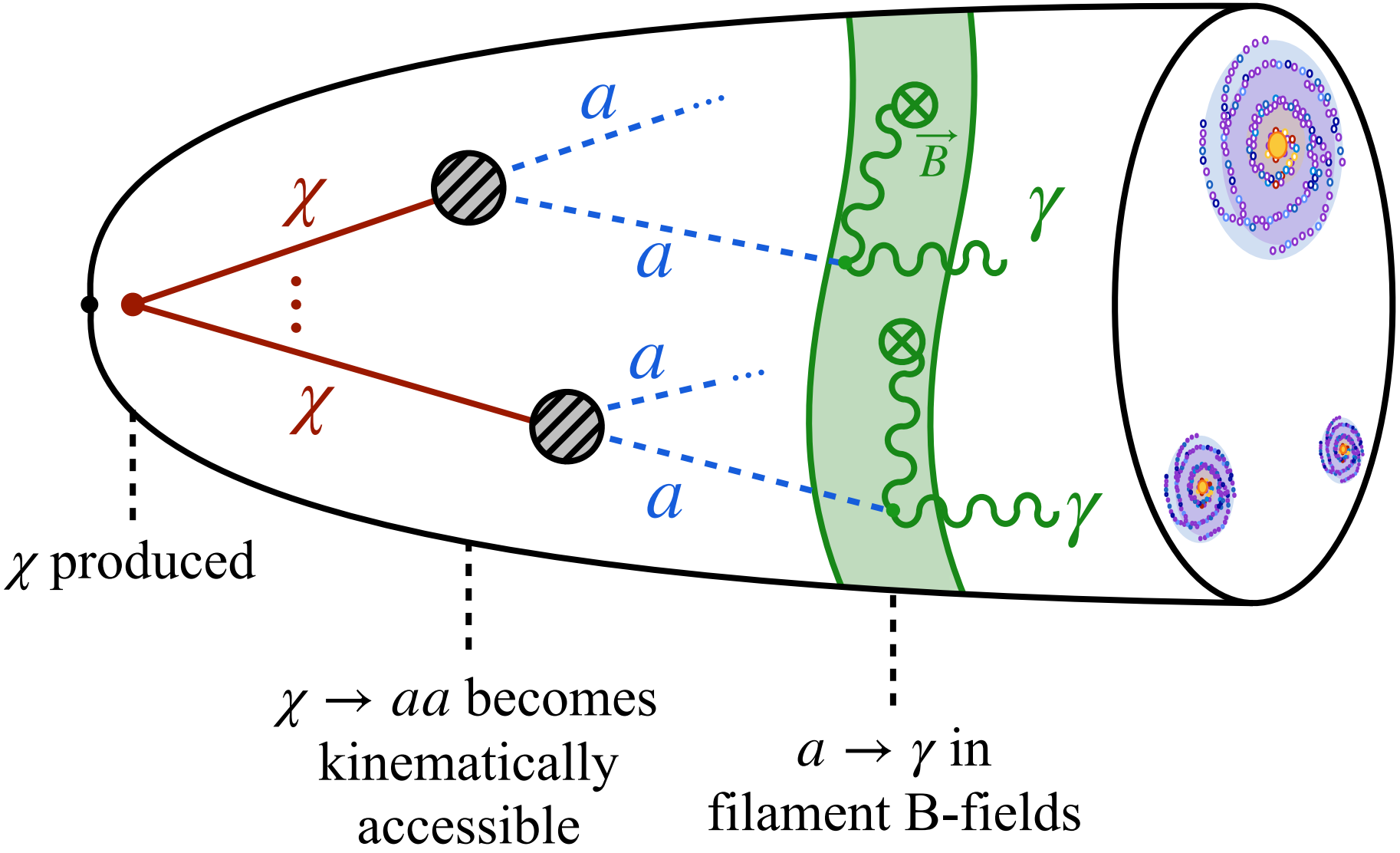

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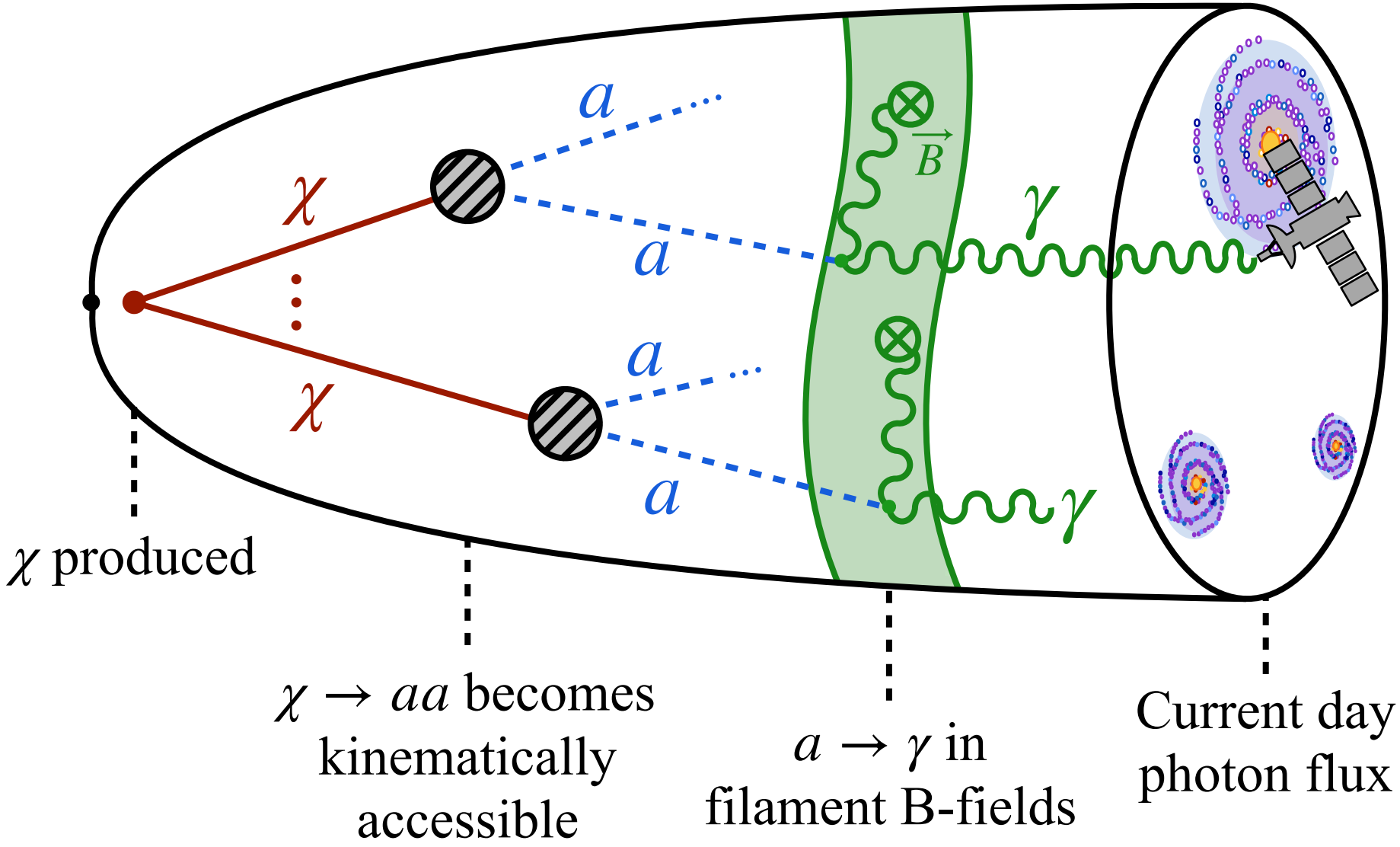

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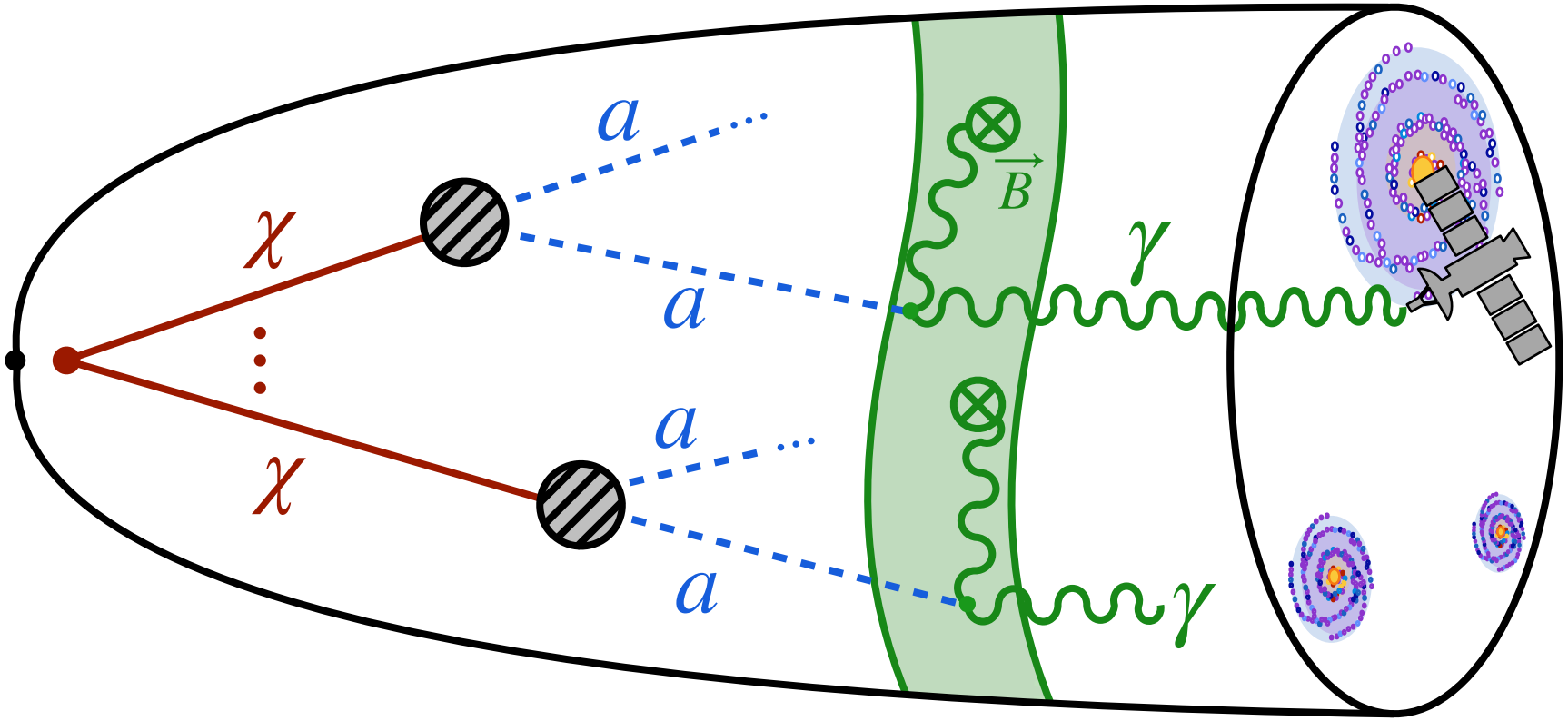
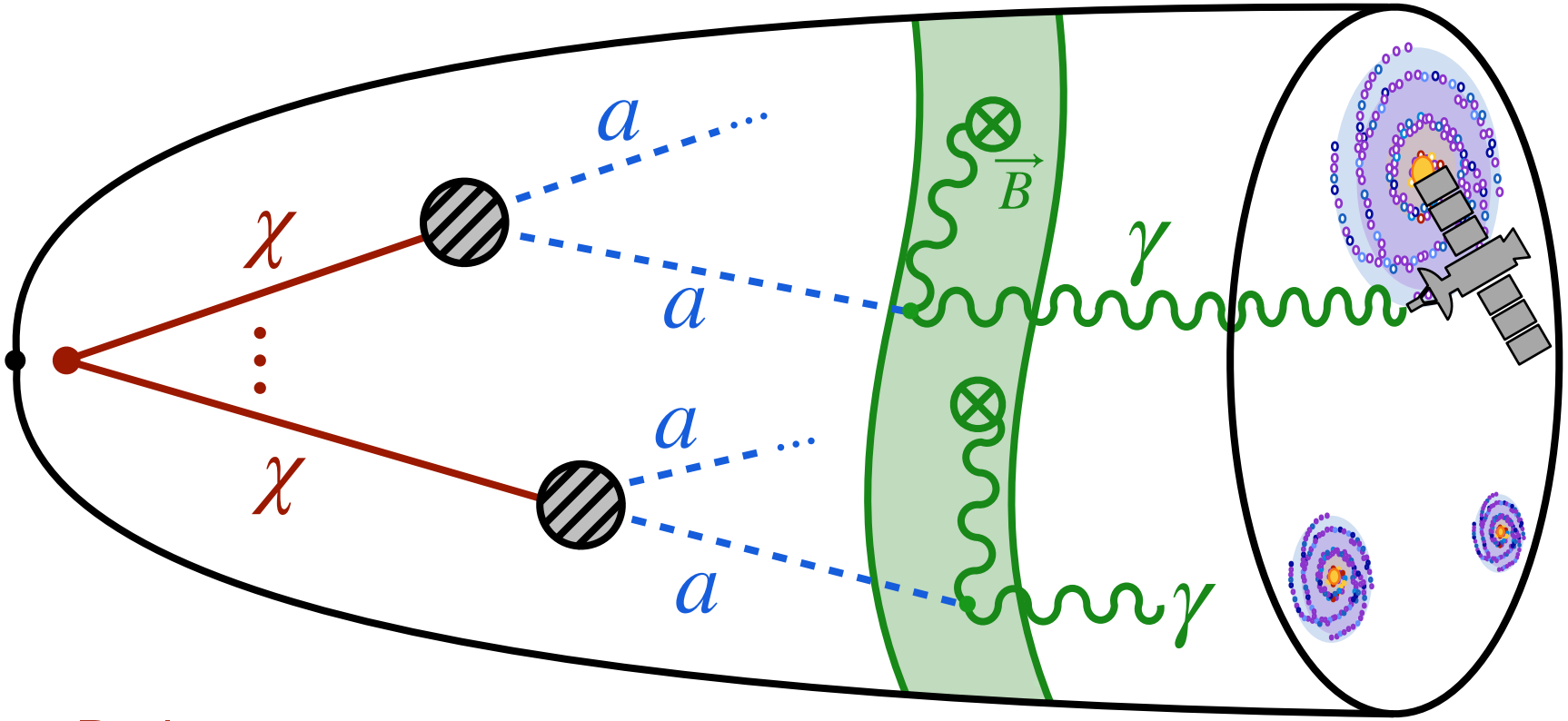


$\mathscr{L}$

Photon Flux from Dark Matter Decays via Axions



Dark matter mass

$$\mathscr{L} \supset \boxed{\mathscr{L}_{m_\chi}}$$

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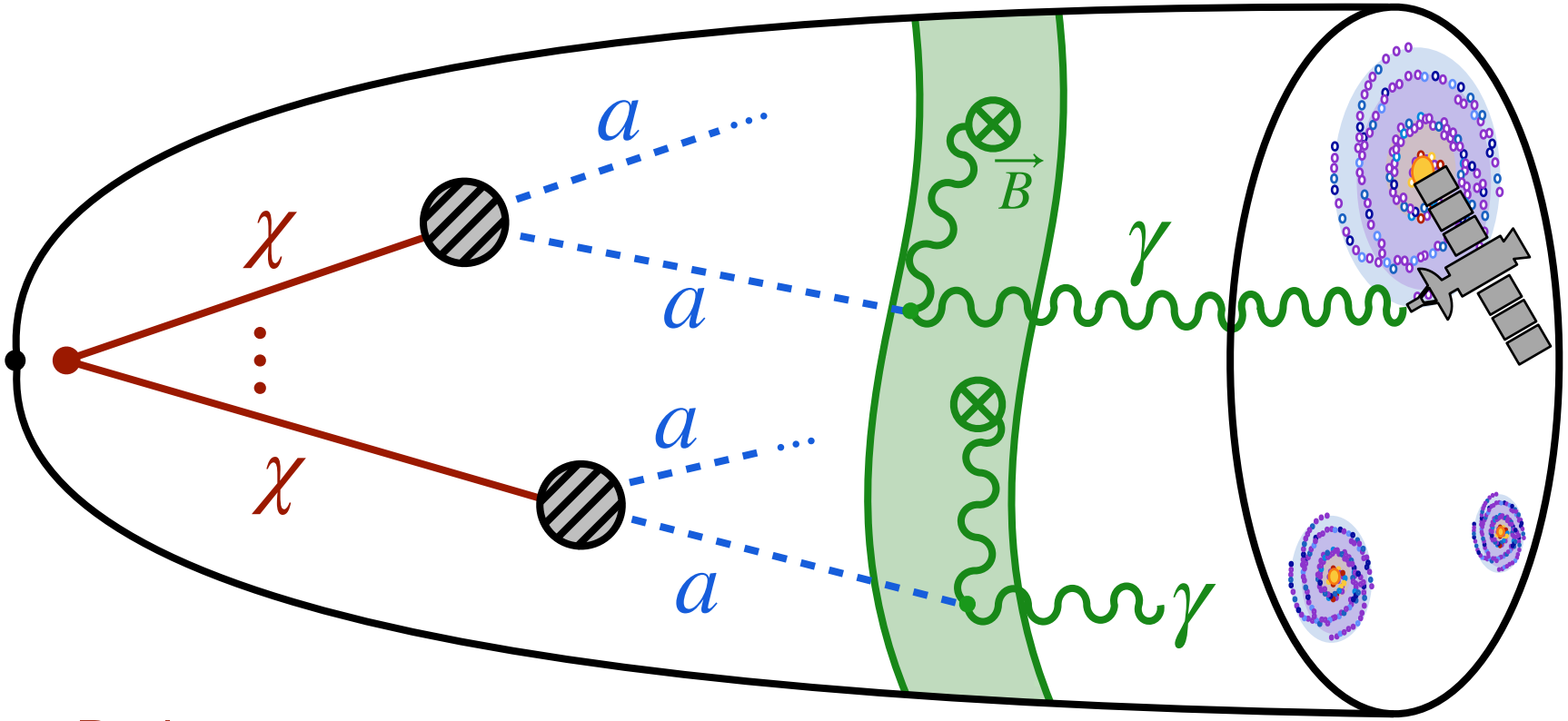

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Dark matter decay

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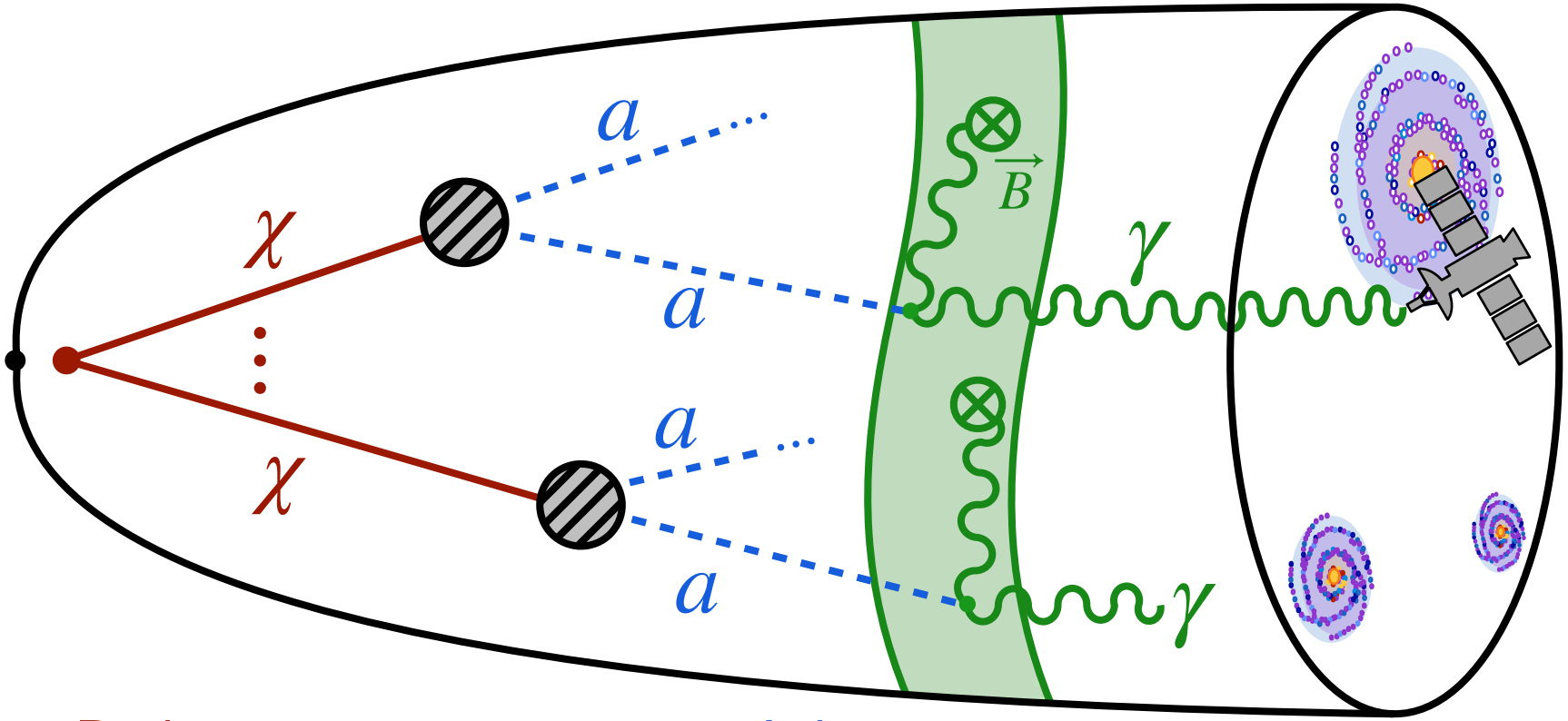

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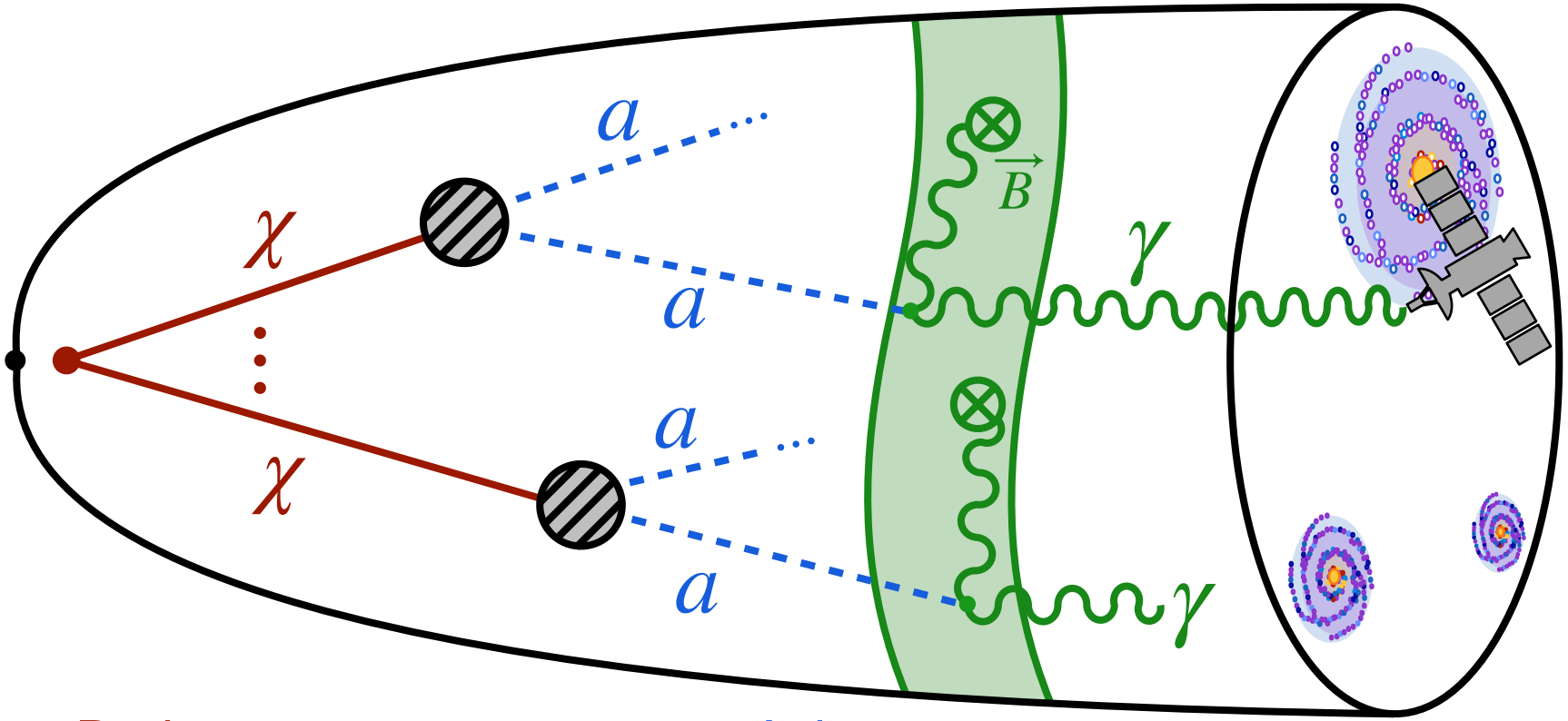

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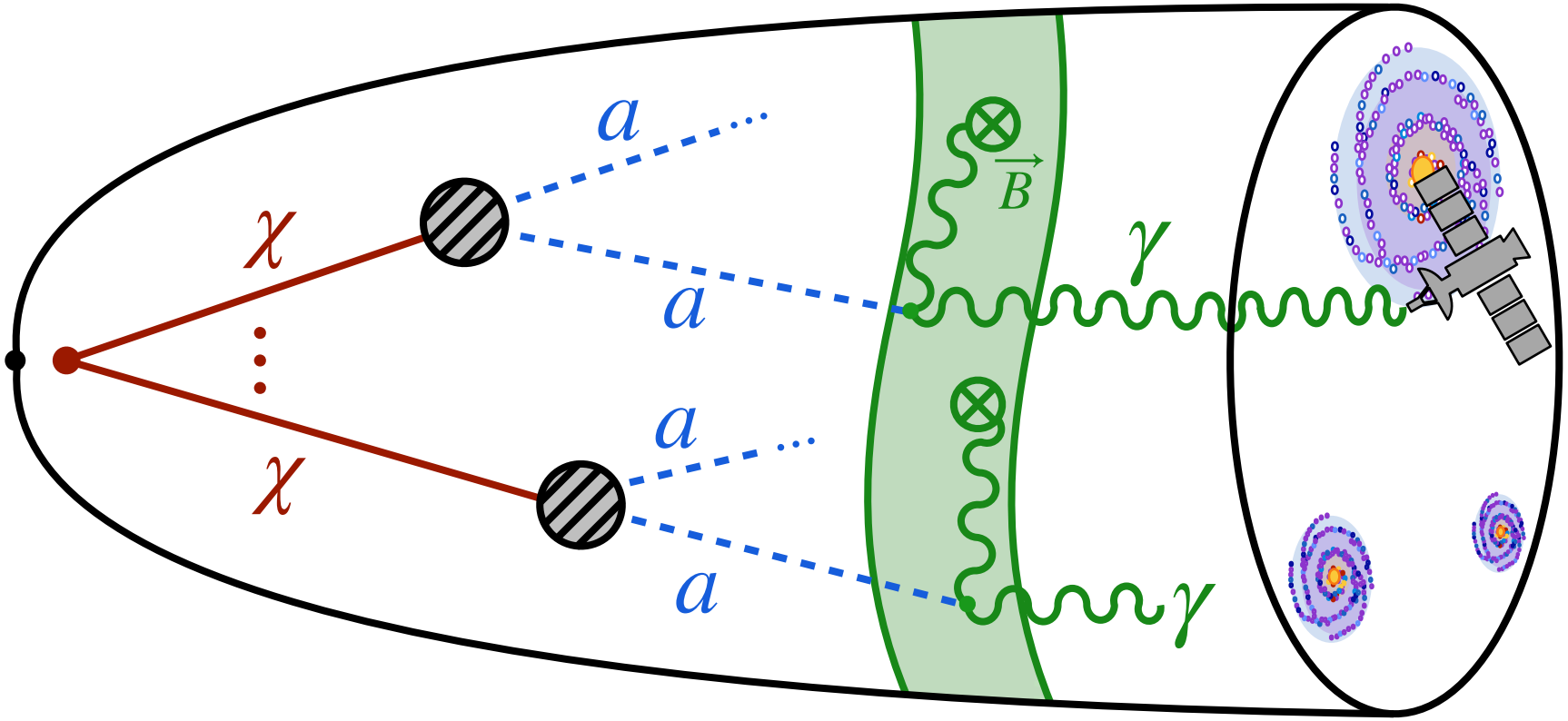
$$\mathscr{L} \supset \mathscr{L}_{m_\chi} + \mathscr{L}_{\chi \to aa} - \frac{1}{2} m_a^2 a^2 + \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Dark matter decay

Axion-photon vertex

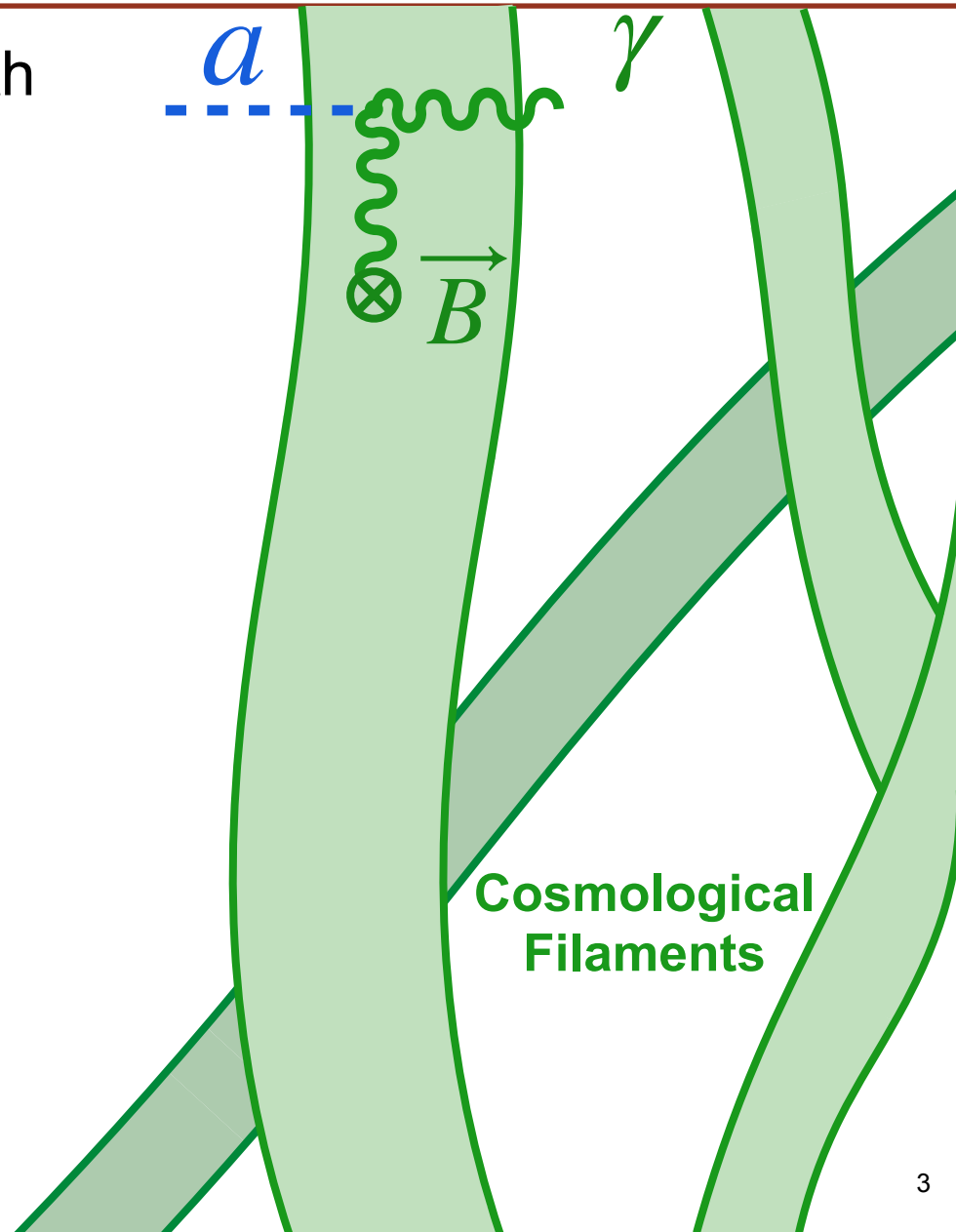
Photon Flux from Dark Matter Decays via Axions



Cosmological filaments provide an **indirect probe** of models with **dark matter** coupled to **axions**

Axion-Photon Conversion in Cosmological Filaments

Cosmological filaments fill $\mathcal{O}(10\%)$ of universe with magnetic fields $B(z)$ up to $\mathcal{O}(100)$ nG



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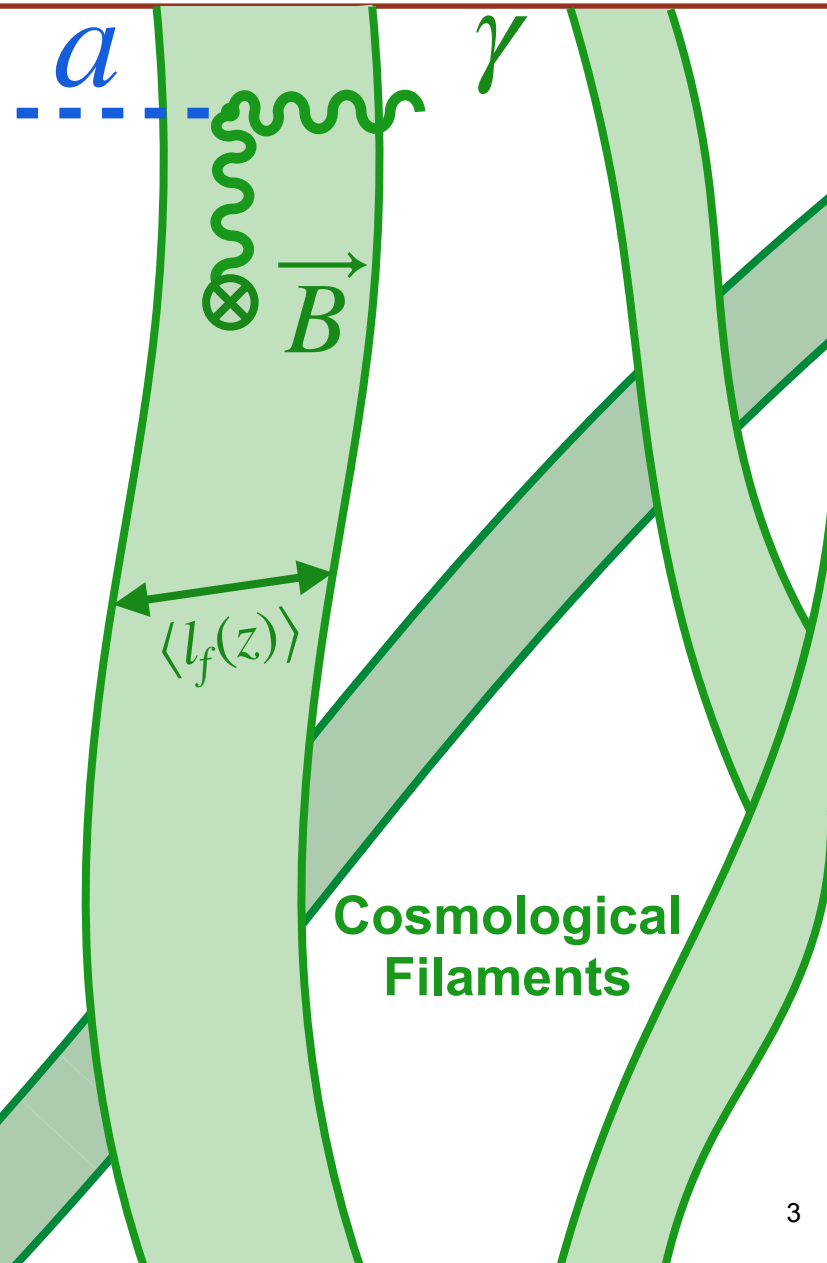

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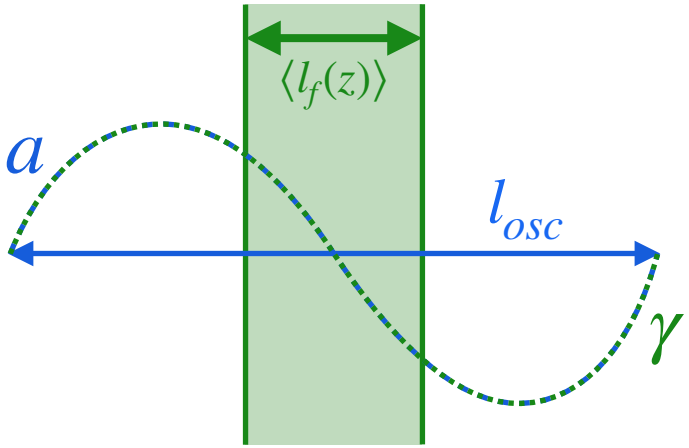

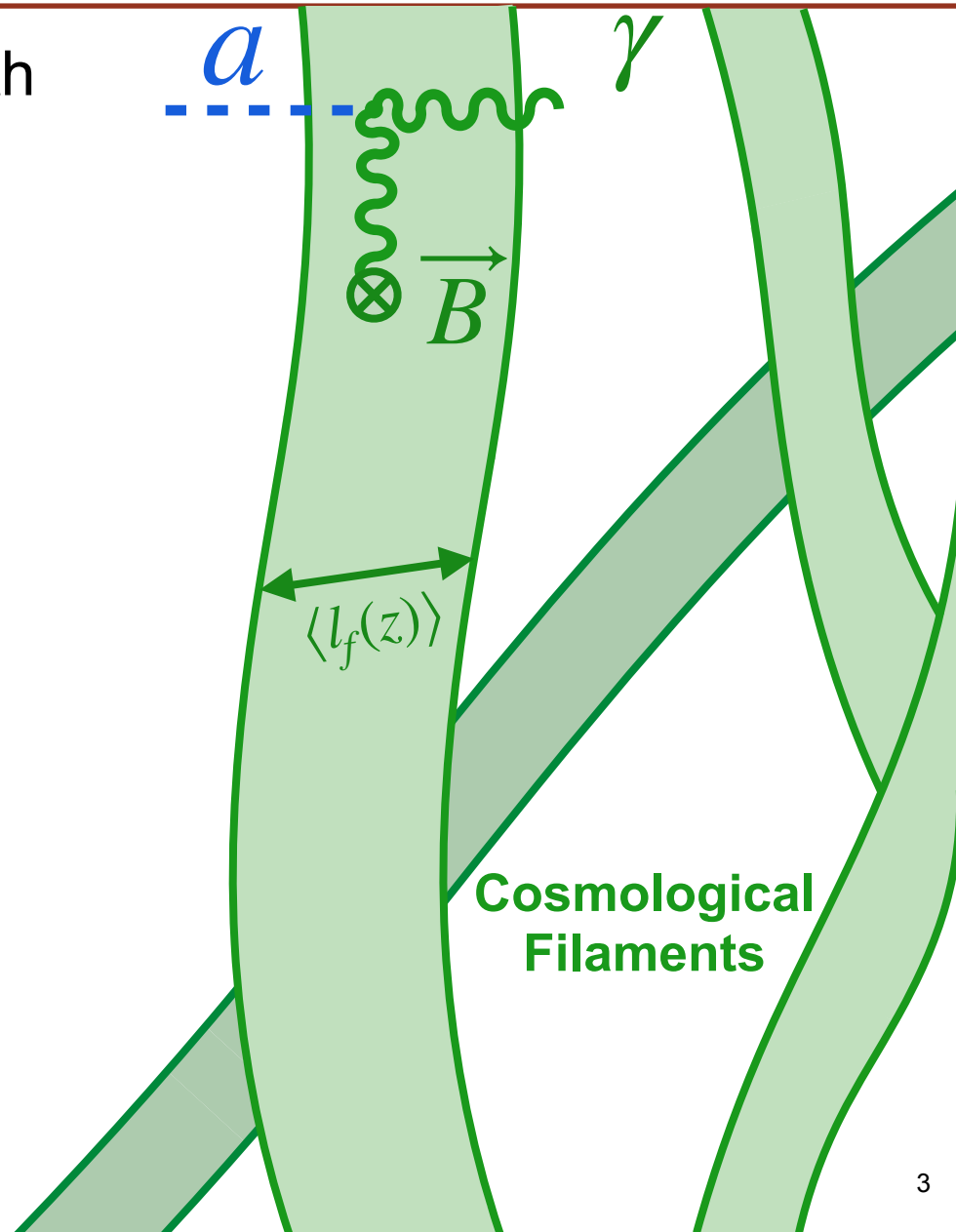

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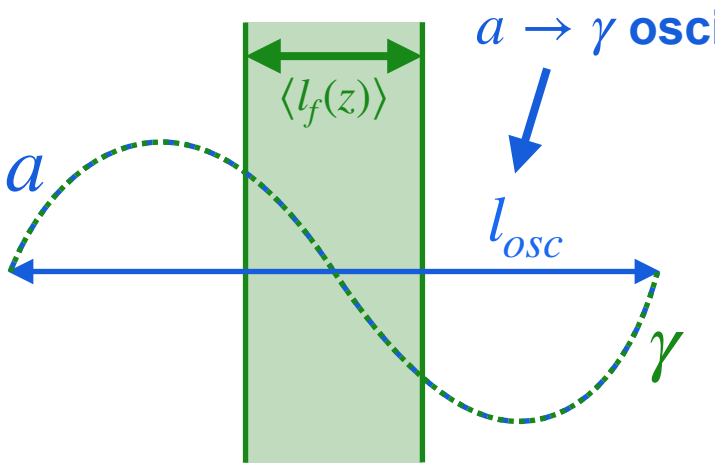

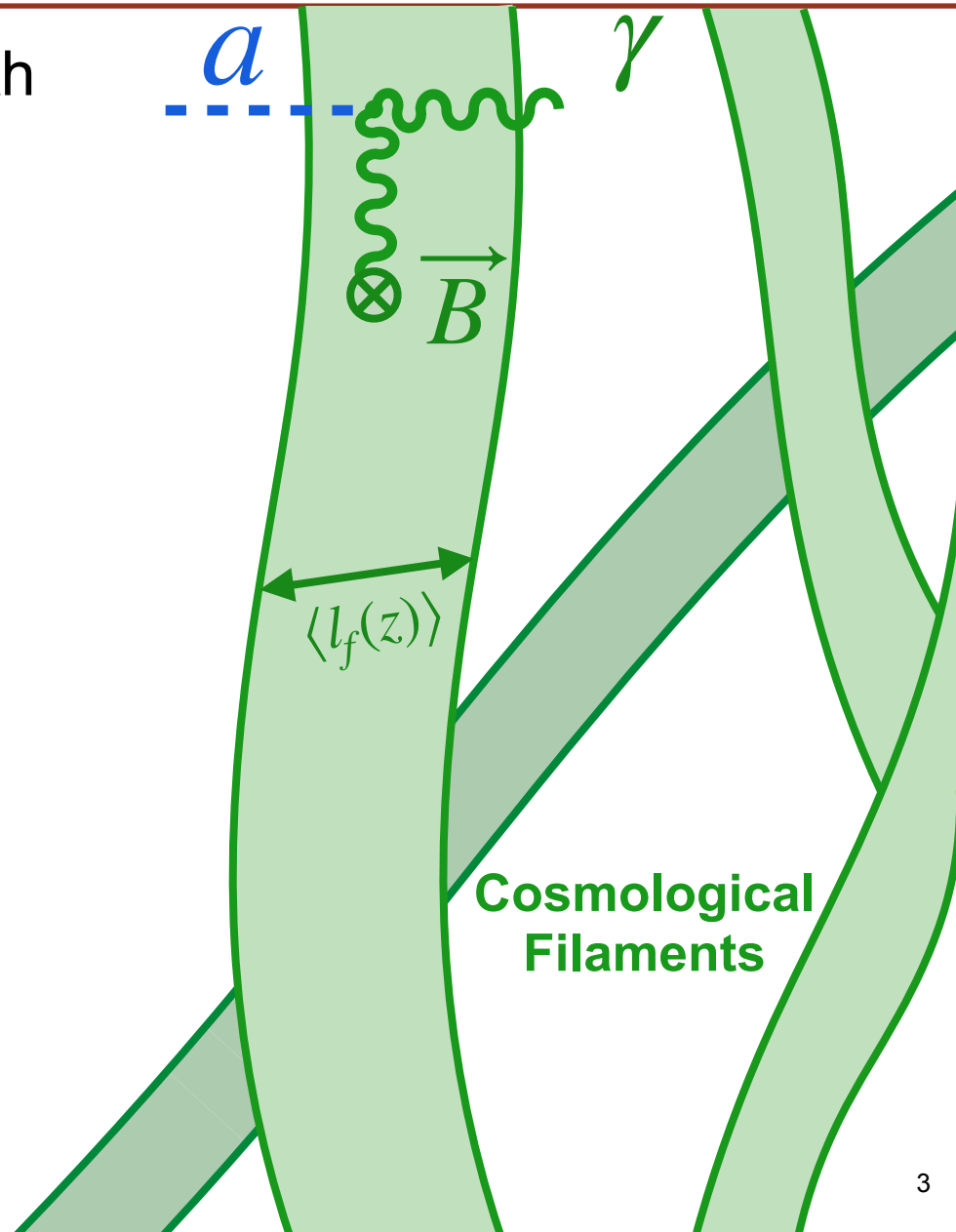

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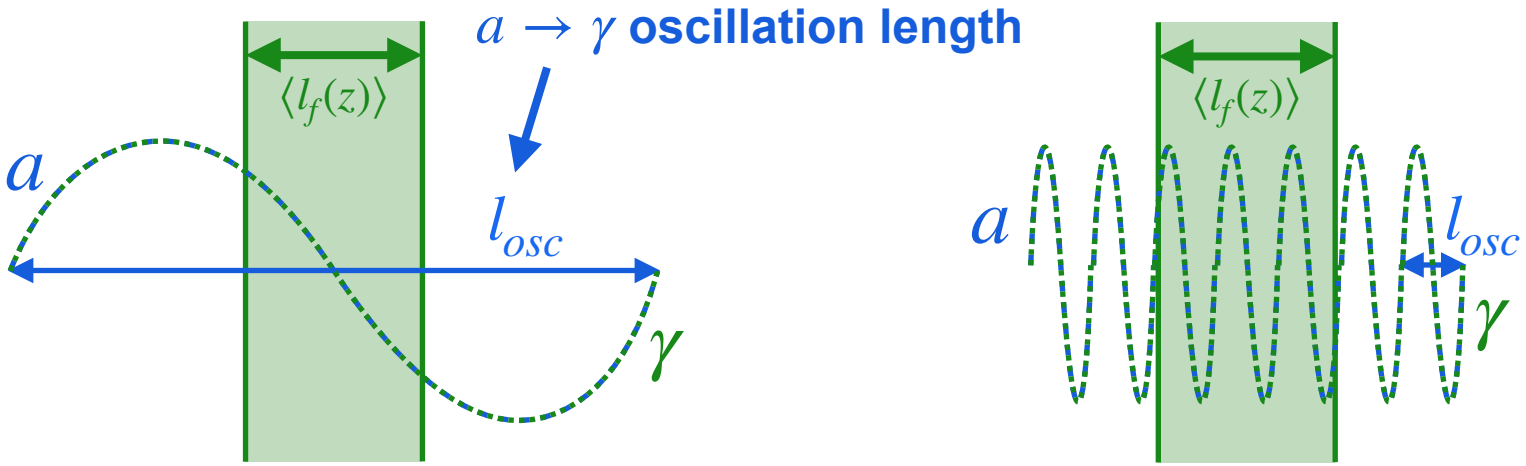

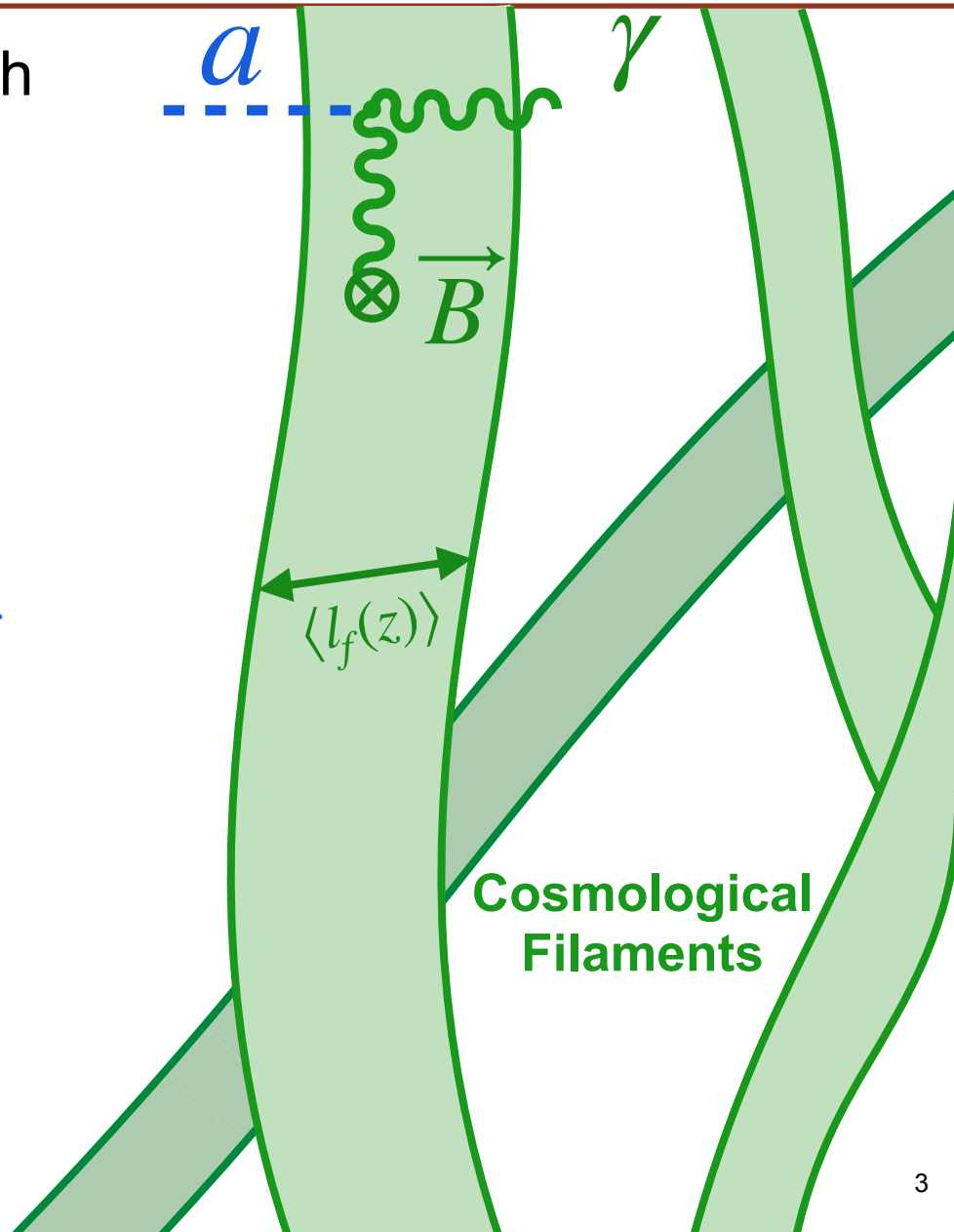

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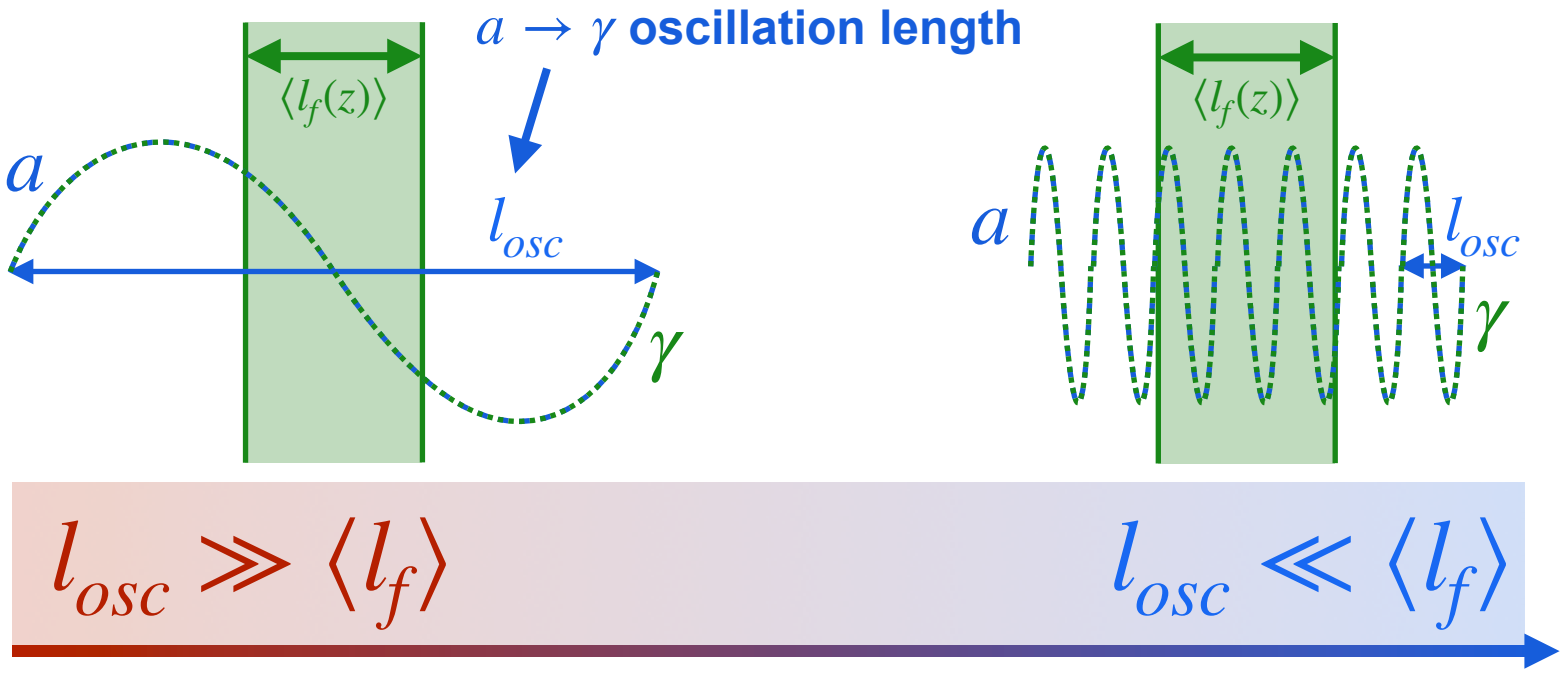

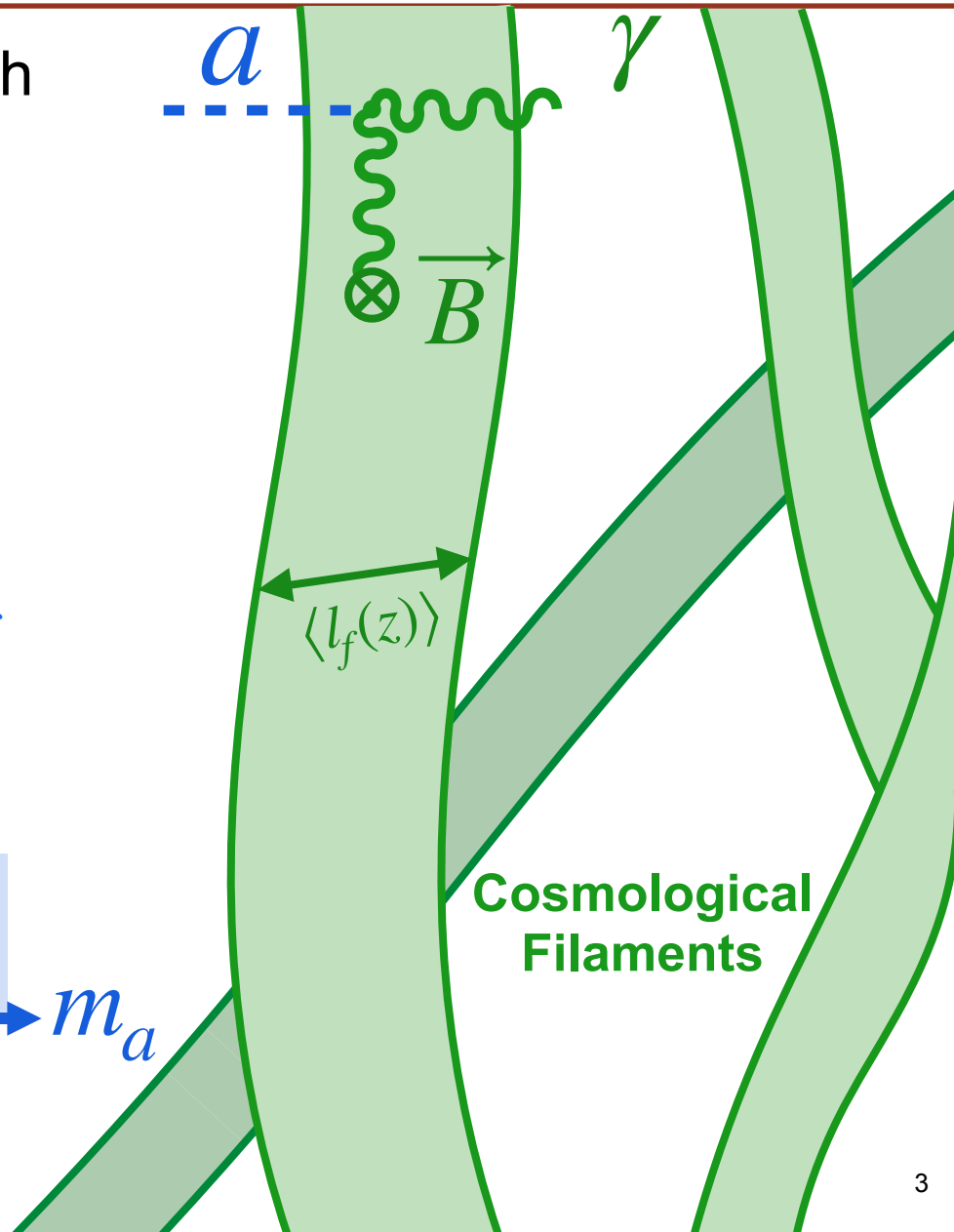

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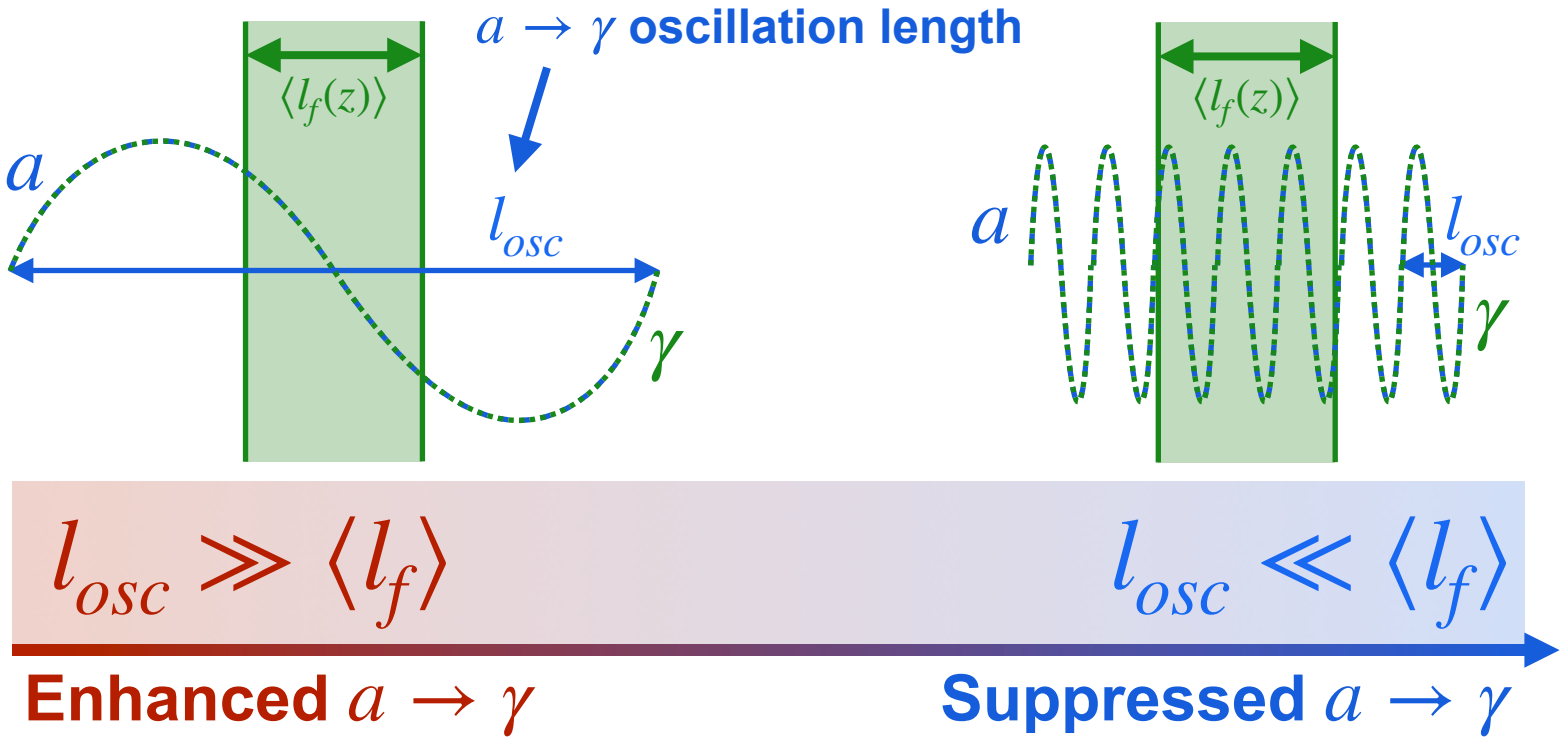

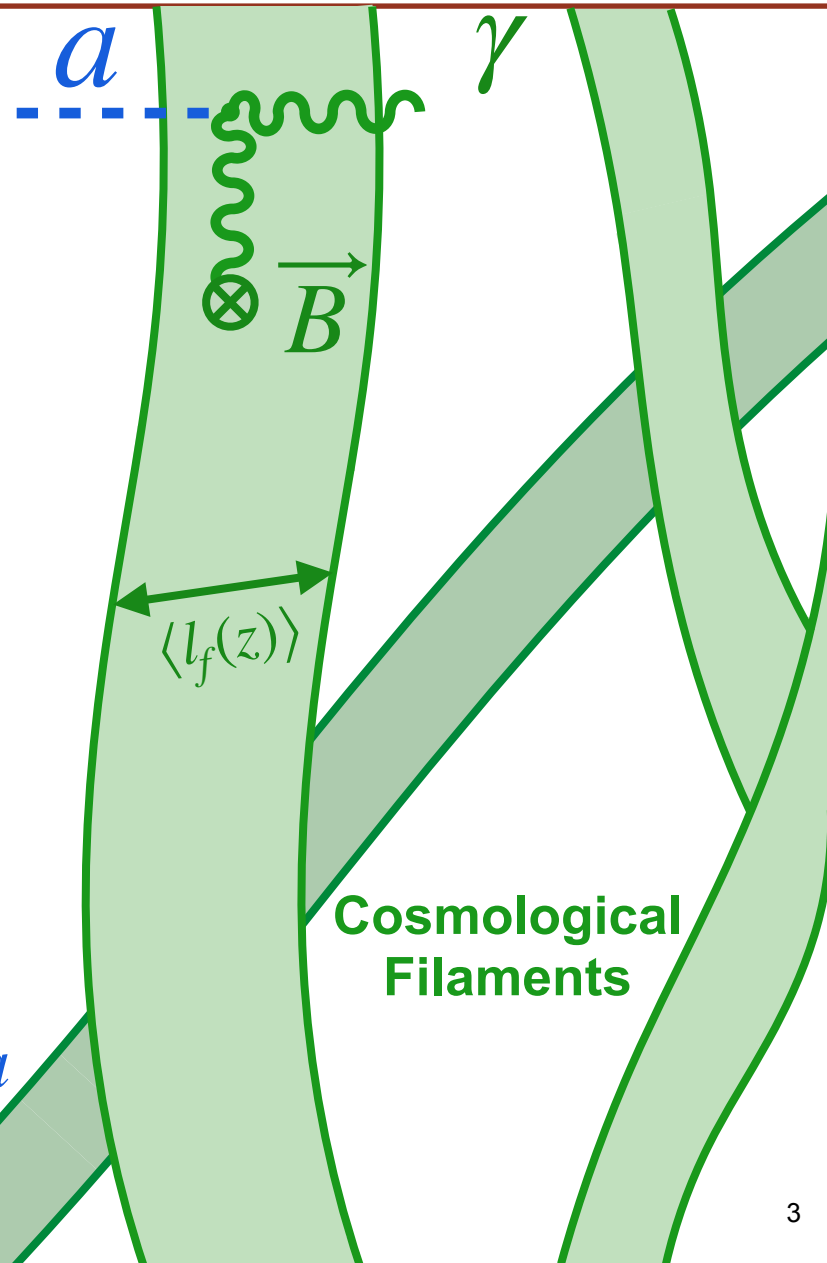

Axion-Photon Conversion in Cosmological Filaments

Single $a \to \gamma$ conversion probability

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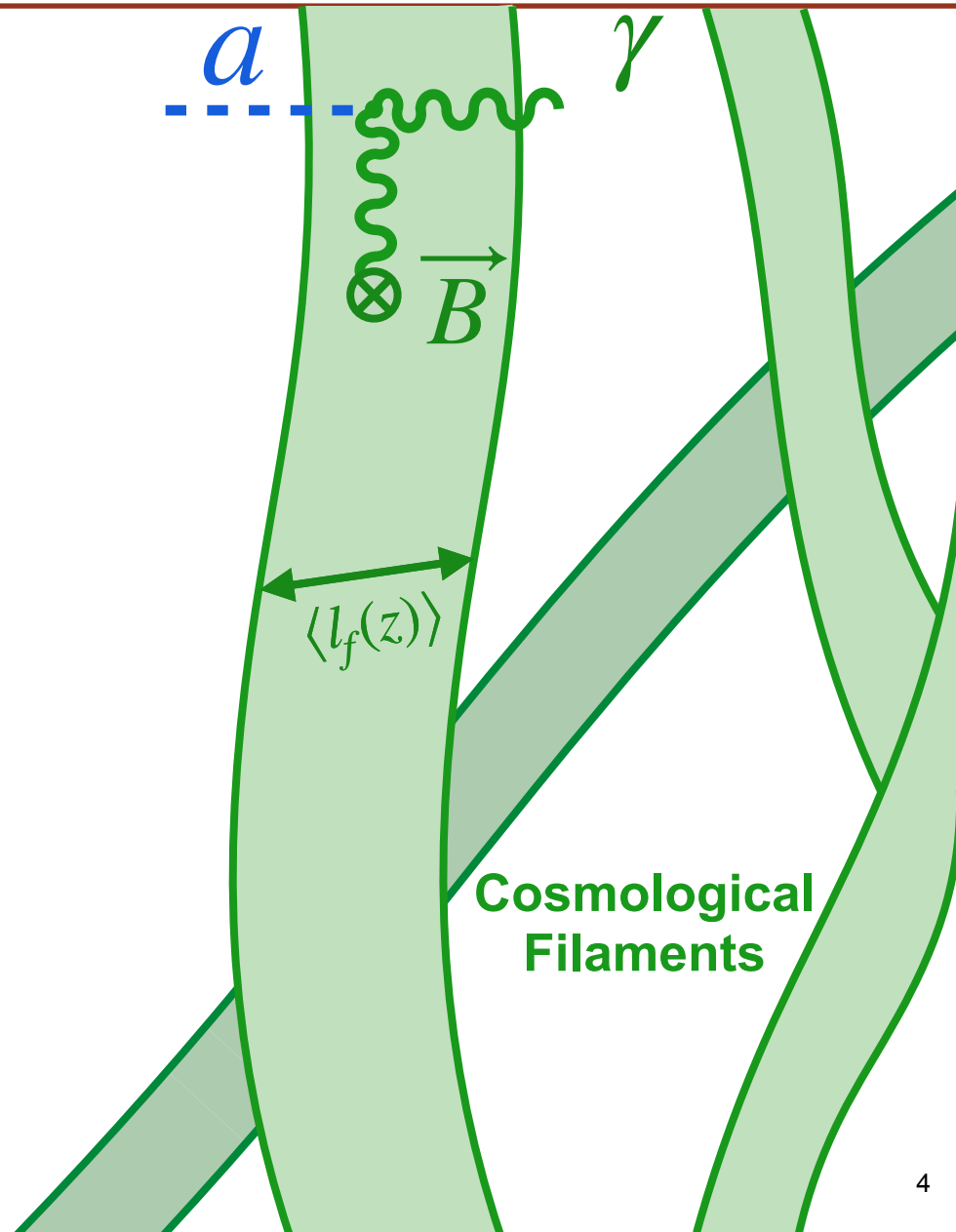

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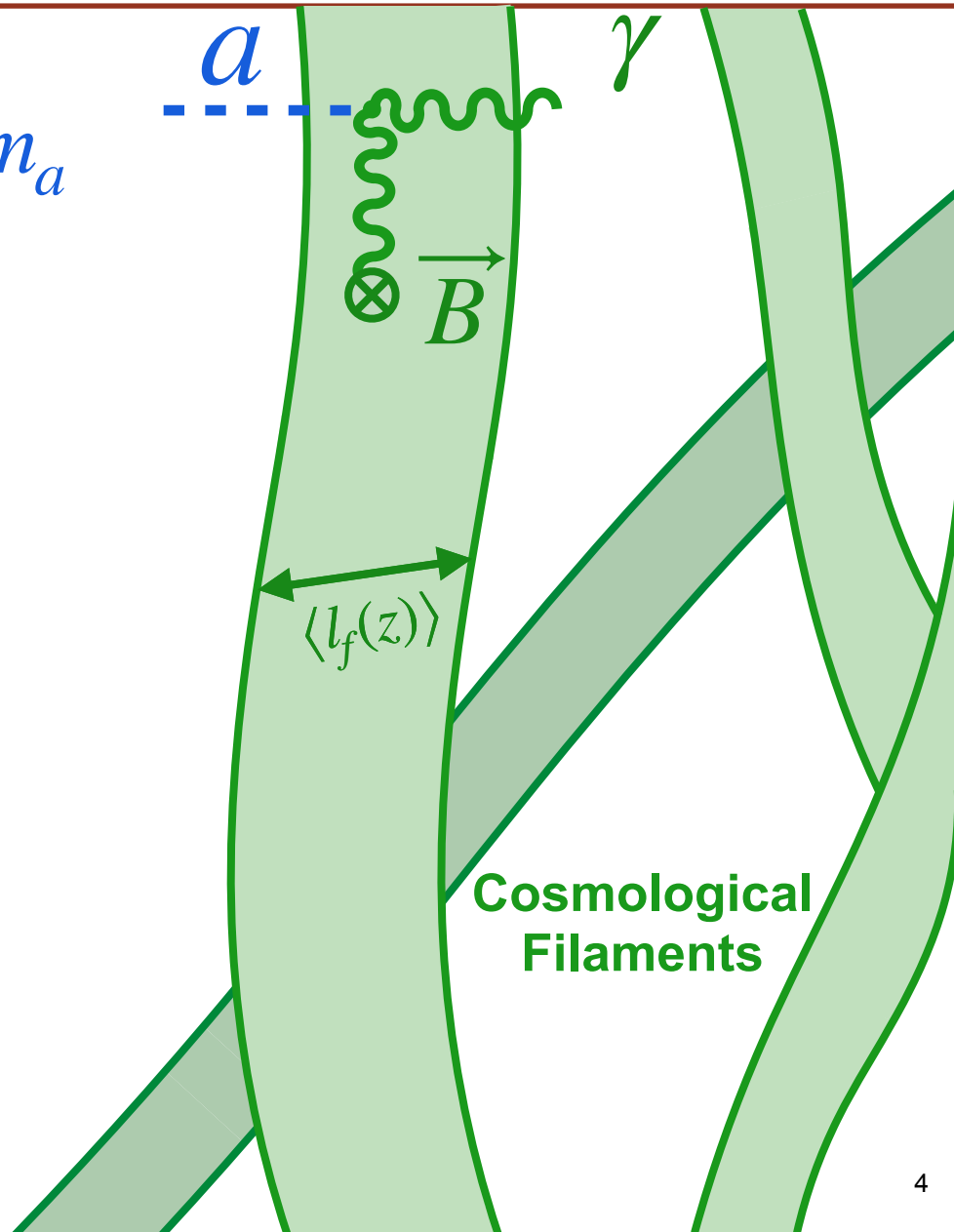
m_a



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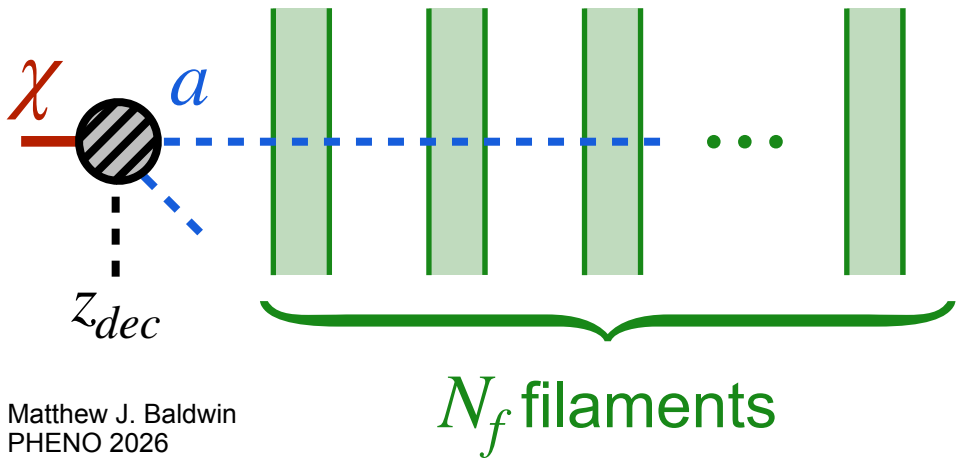

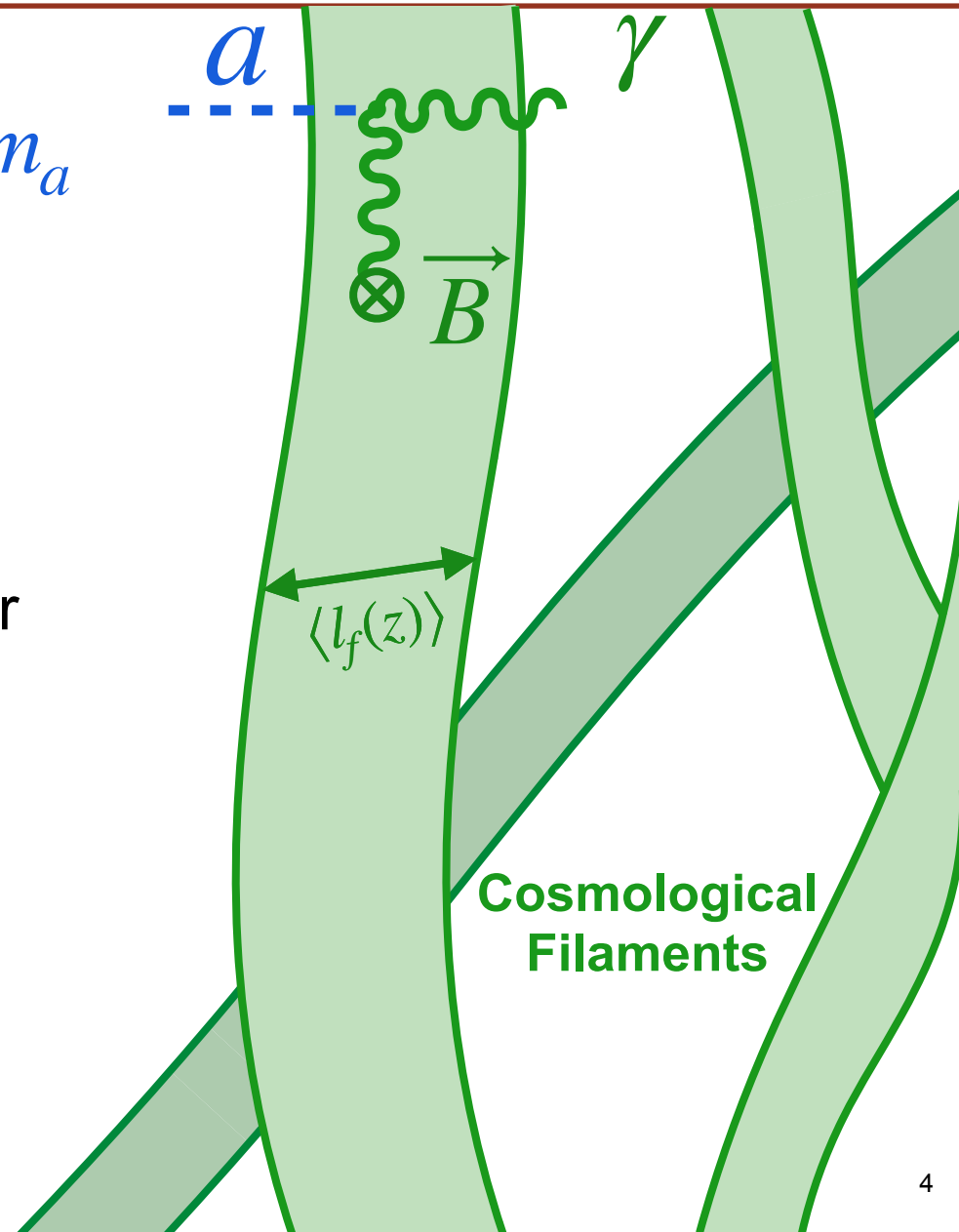

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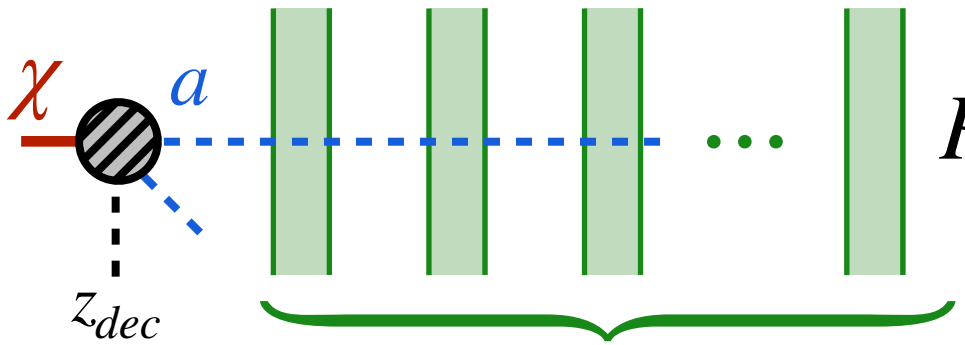
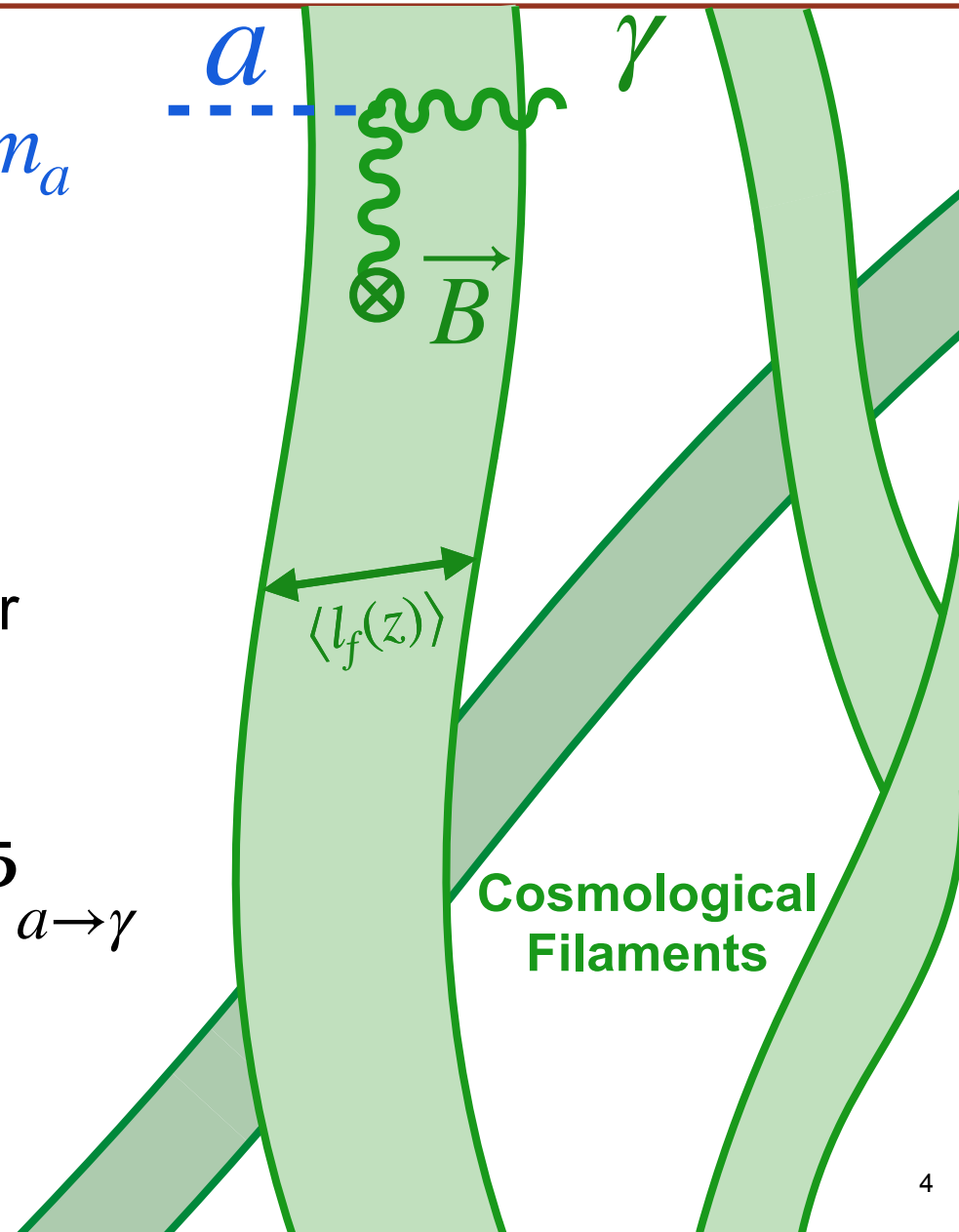
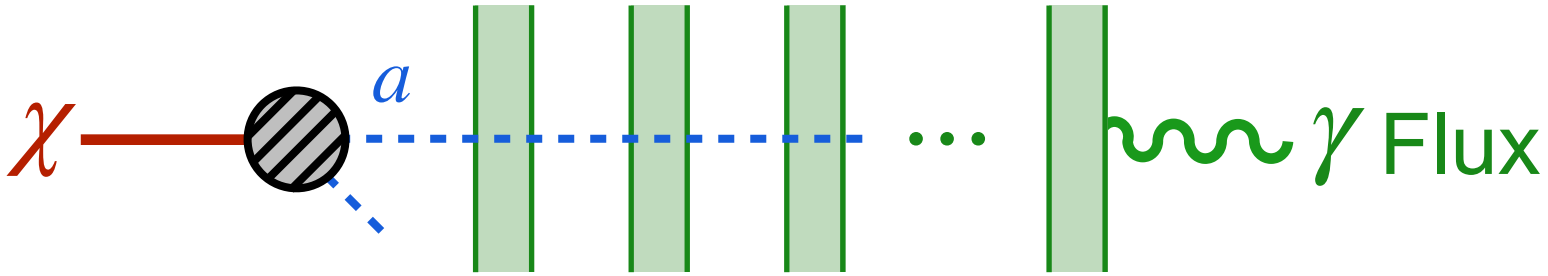


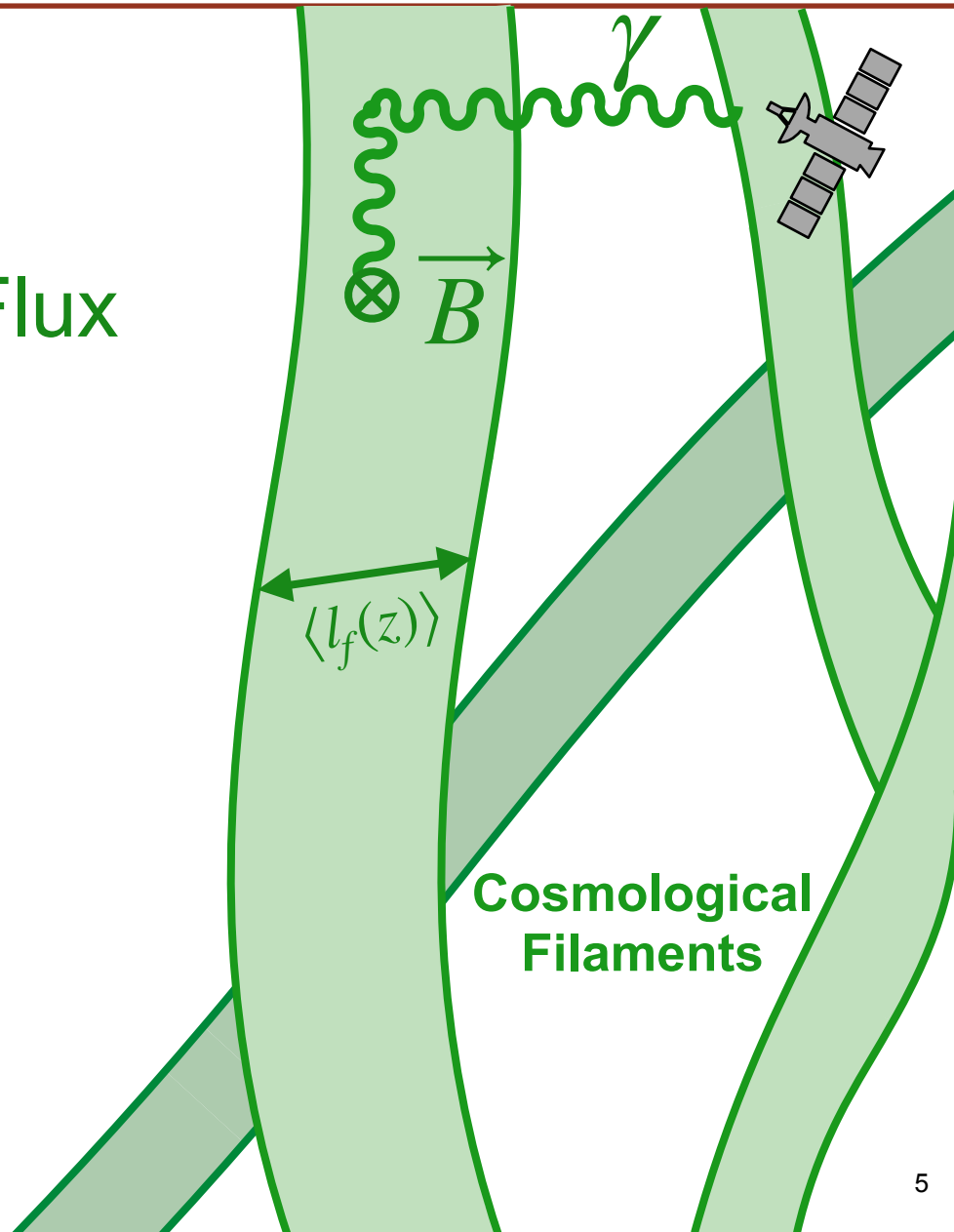
$$P_{a\to\gamma} = \int_{z_{dec}}^{0} dN_f \bar{P}_{a\to\gamma}$$



Photon Flux Connects Dark Matter and Axion Properties

Resulting photons produce a flux





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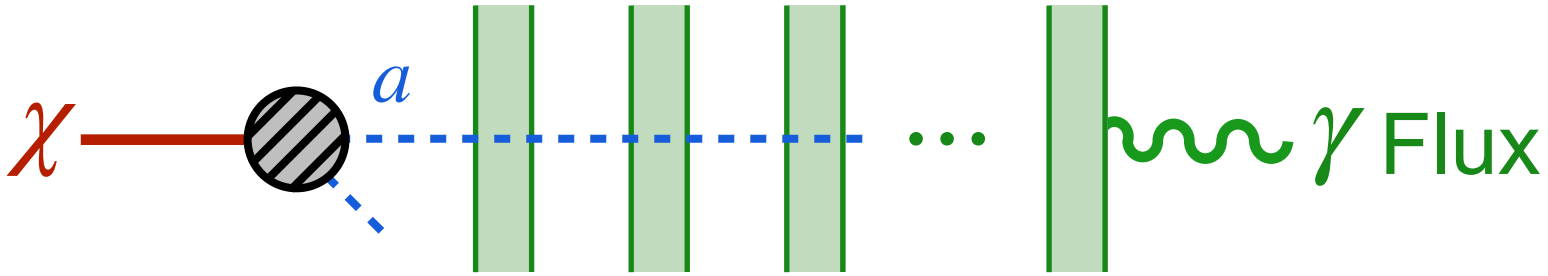

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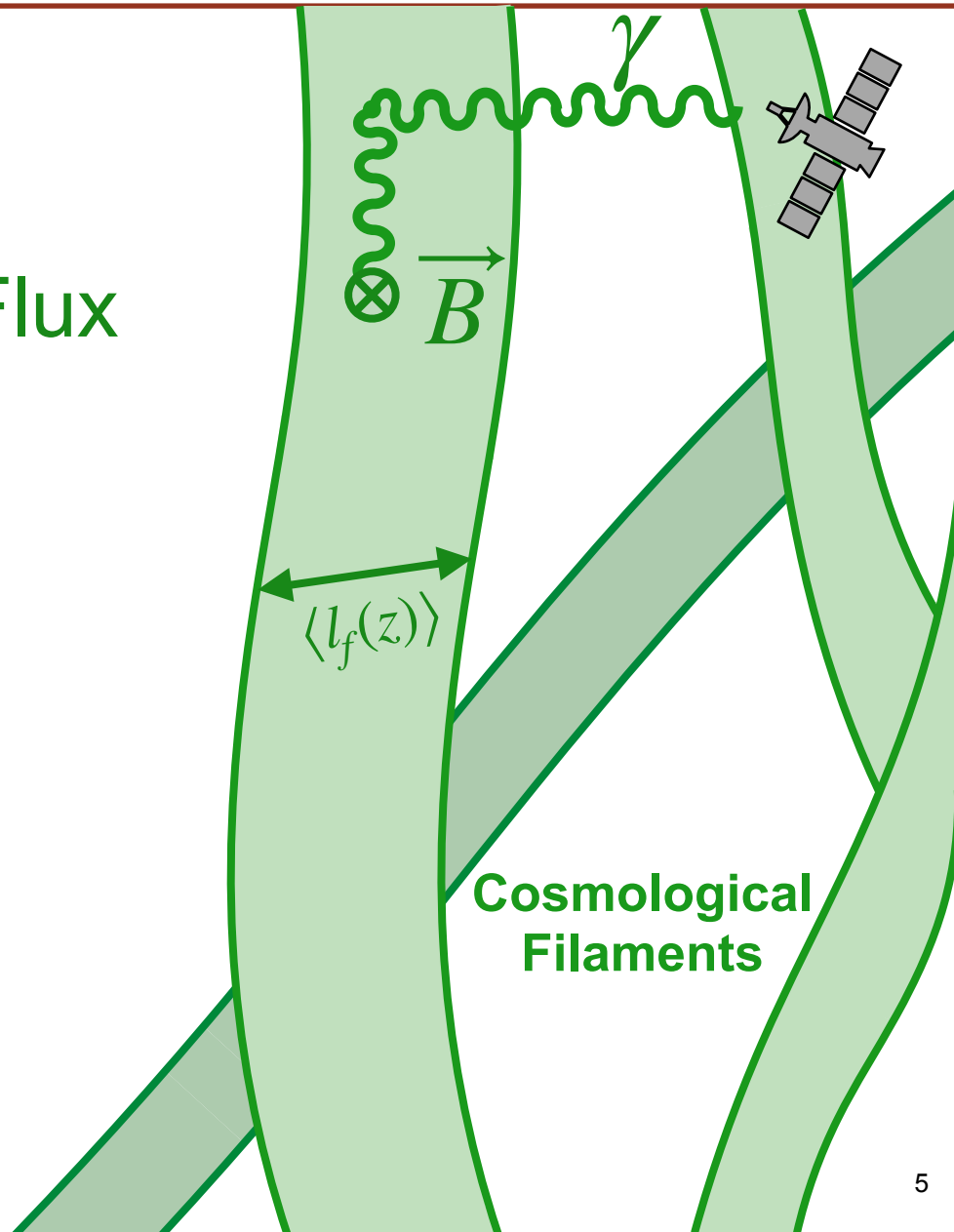

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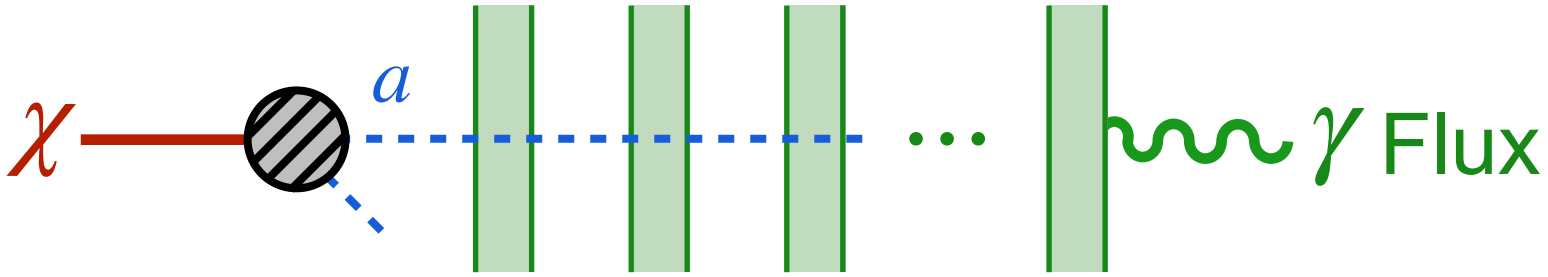

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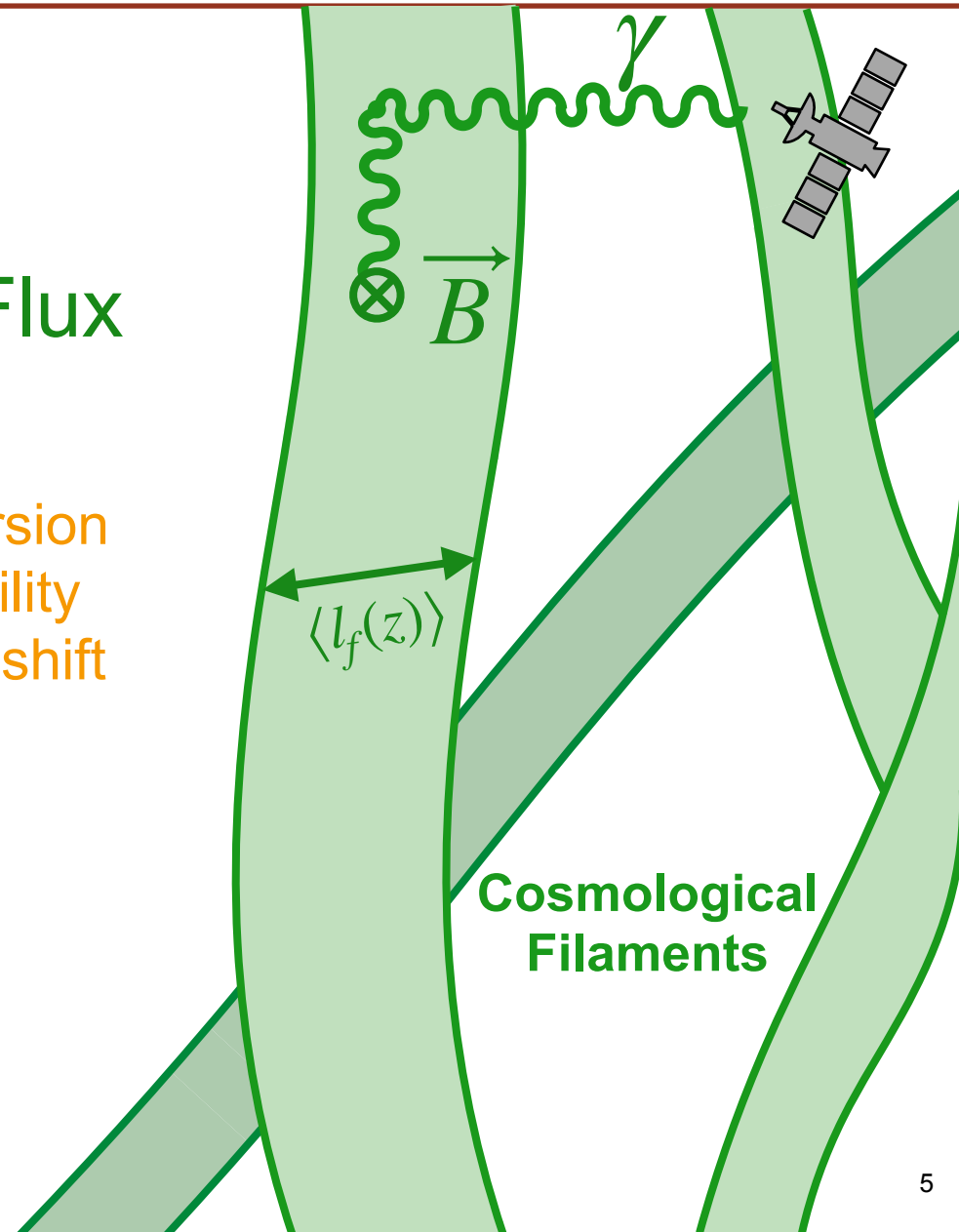
Conversion probability per redshift

$$g_{a\gamma\gamma},\ m_a$$



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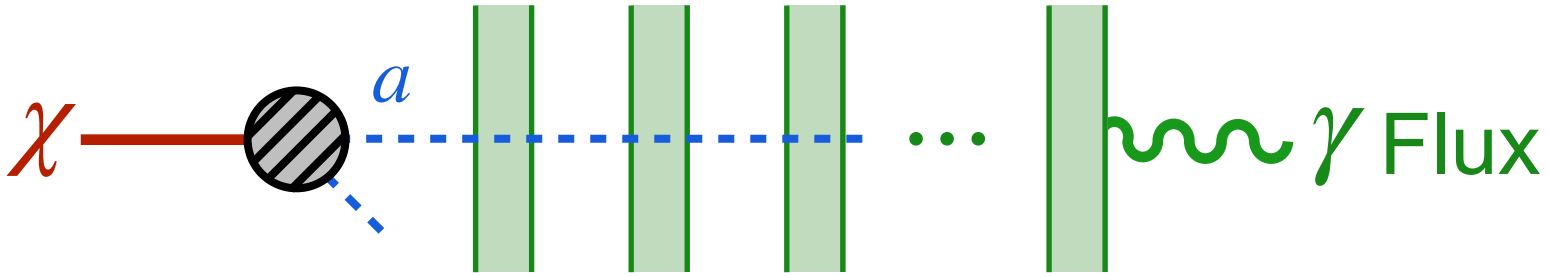

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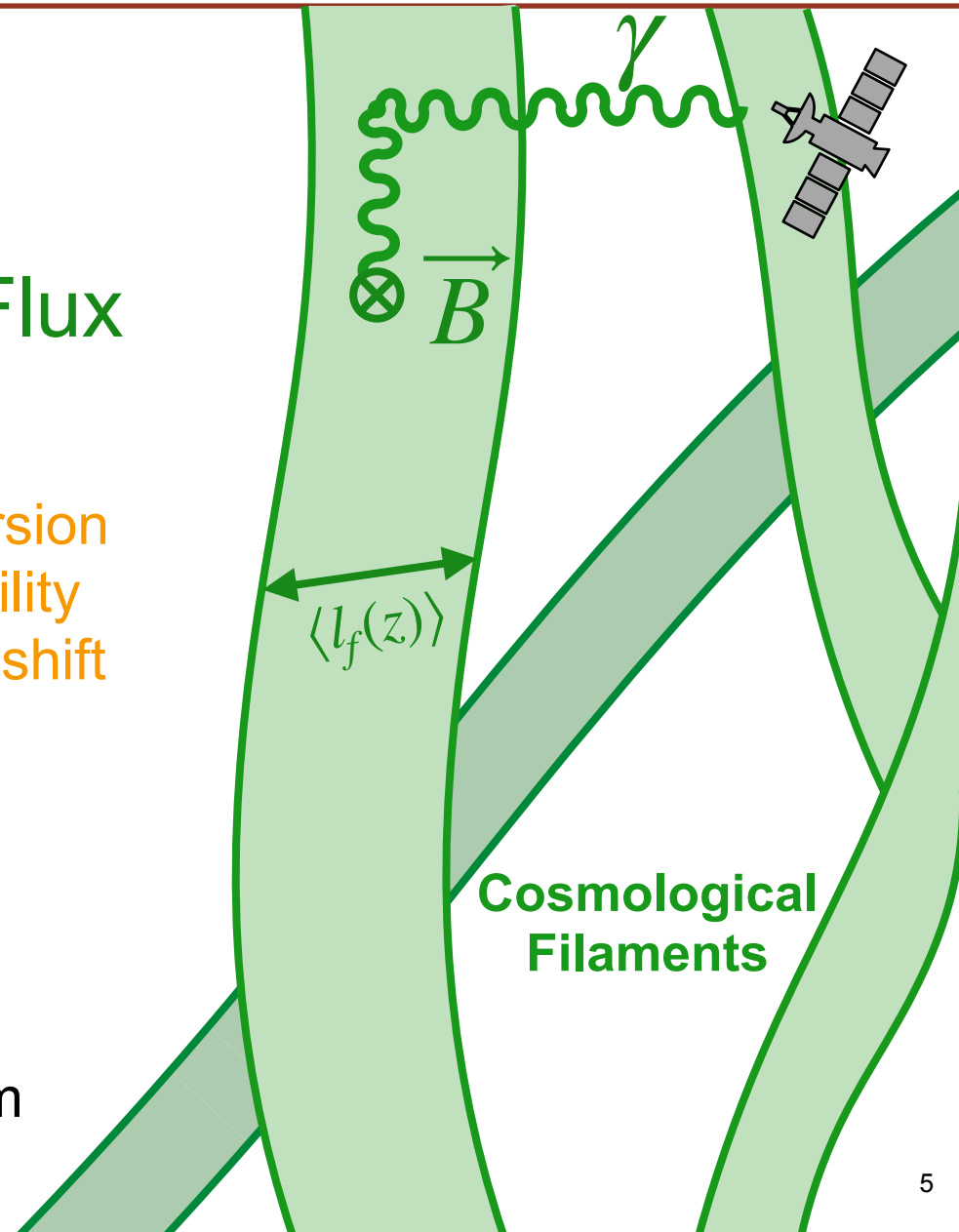
Conversion probability per redshift

Axion flux from DM decays

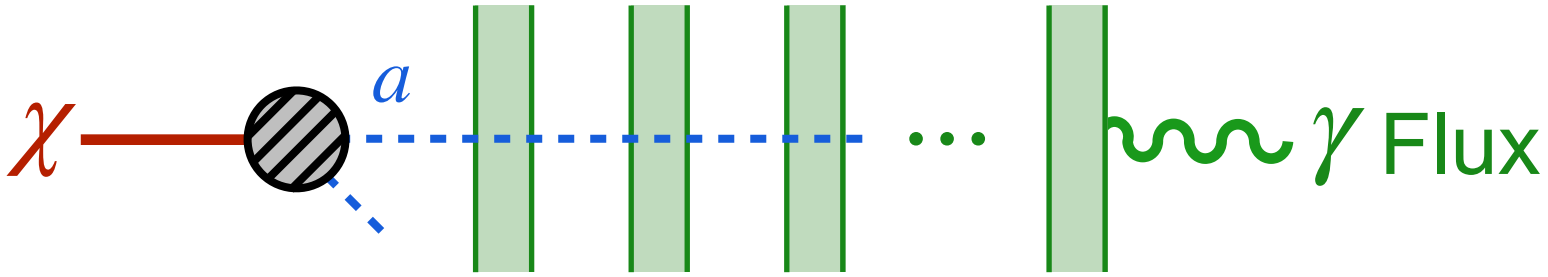
$$\boxed{\frac{d\Phi_a}{dE_a}} = \frac{1}{\tau_\chi}\frac{\Omega_\chi \rho_c}{m_\chi}\int_z^\infty \frac{dz'}{H(z')}\frac{dN_a}{dE_a}(z')$$

Axion spectrum



Photon Flux Connects Dark Matter and Axion Properties

Resulting photons produce a flux



$$\gamma \text{ Flux} = \int_0^\infty dz \, \frac{d\Phi_a}{dE_a} \, \frac{dP_{a\to\gamma}}{dz}$$

$\frac{dP_{a\to\gamma}}{dz}$: Conversion probability per redshift

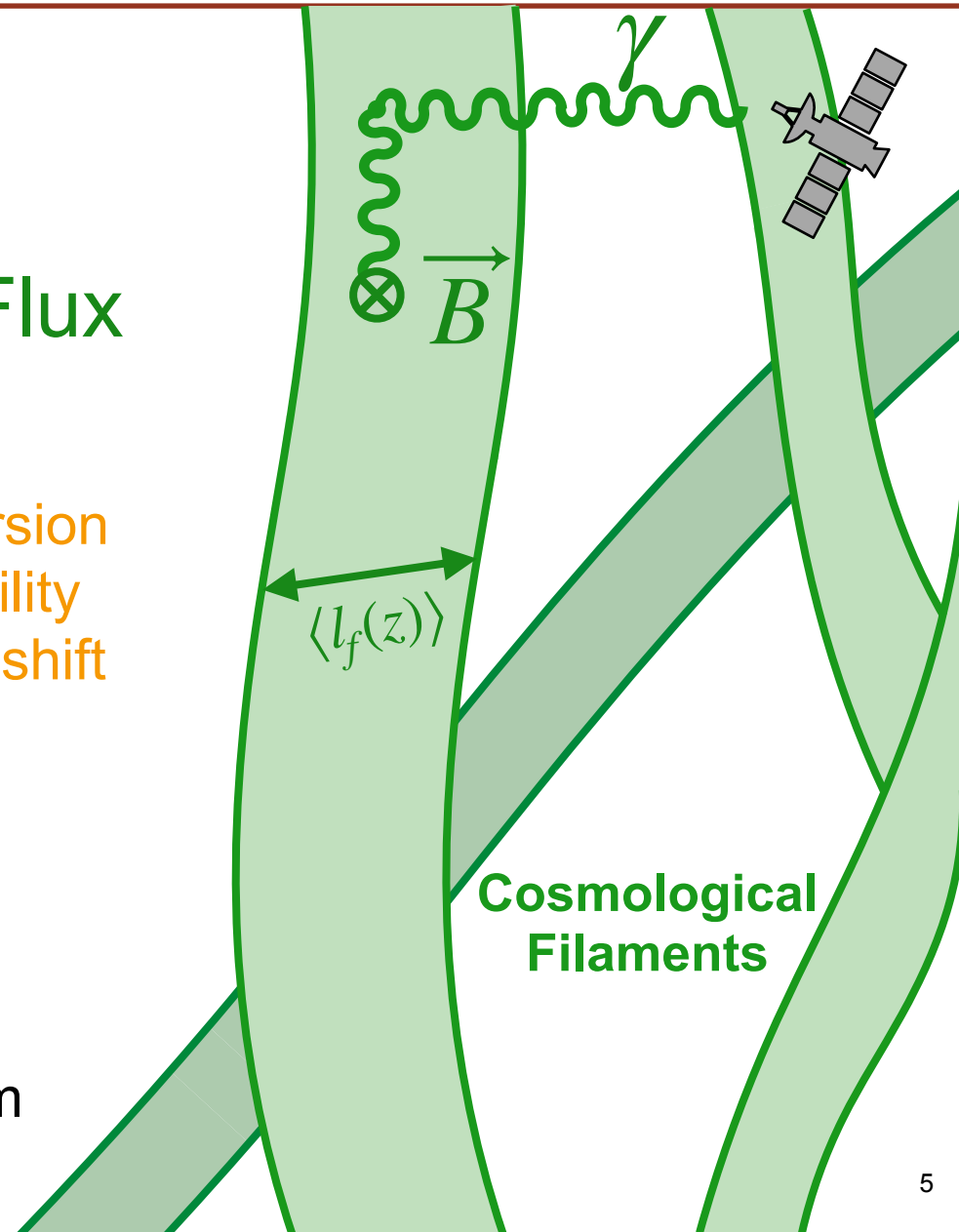
$\frac{d\Phi_a}{dE_a}$: Axion flux from DM decays

$$\frac{d\Phi_a}{dE_a} = \frac{1}{\tau_\chi} \frac{\Omega_\chi \rho_c}{m_\chi} \int_z^\infty \frac{dz'}{H(z')} \frac{dN_a}{dE_a}(z')$$

τ_χ: DM lifetime

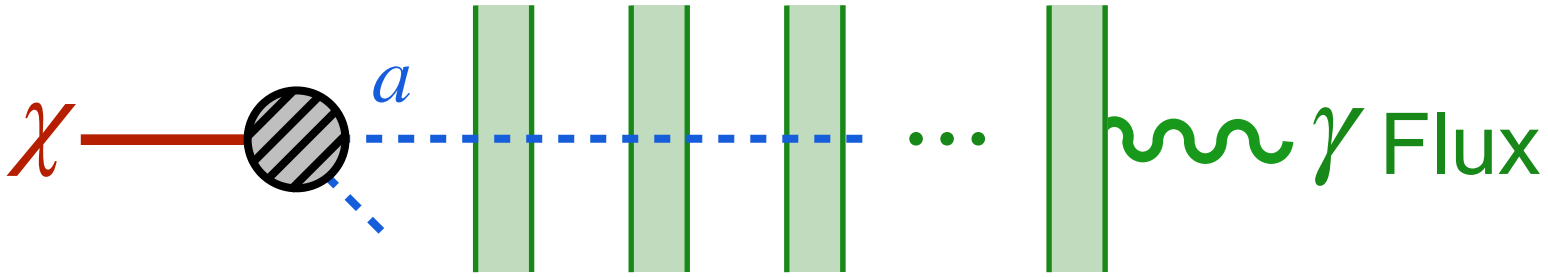
m_χ: DM mass

$\frac{dN_a}{dE_a}(z')$: Axion spectrum



Photon Flux Connects Dark Matter and Axion Properties

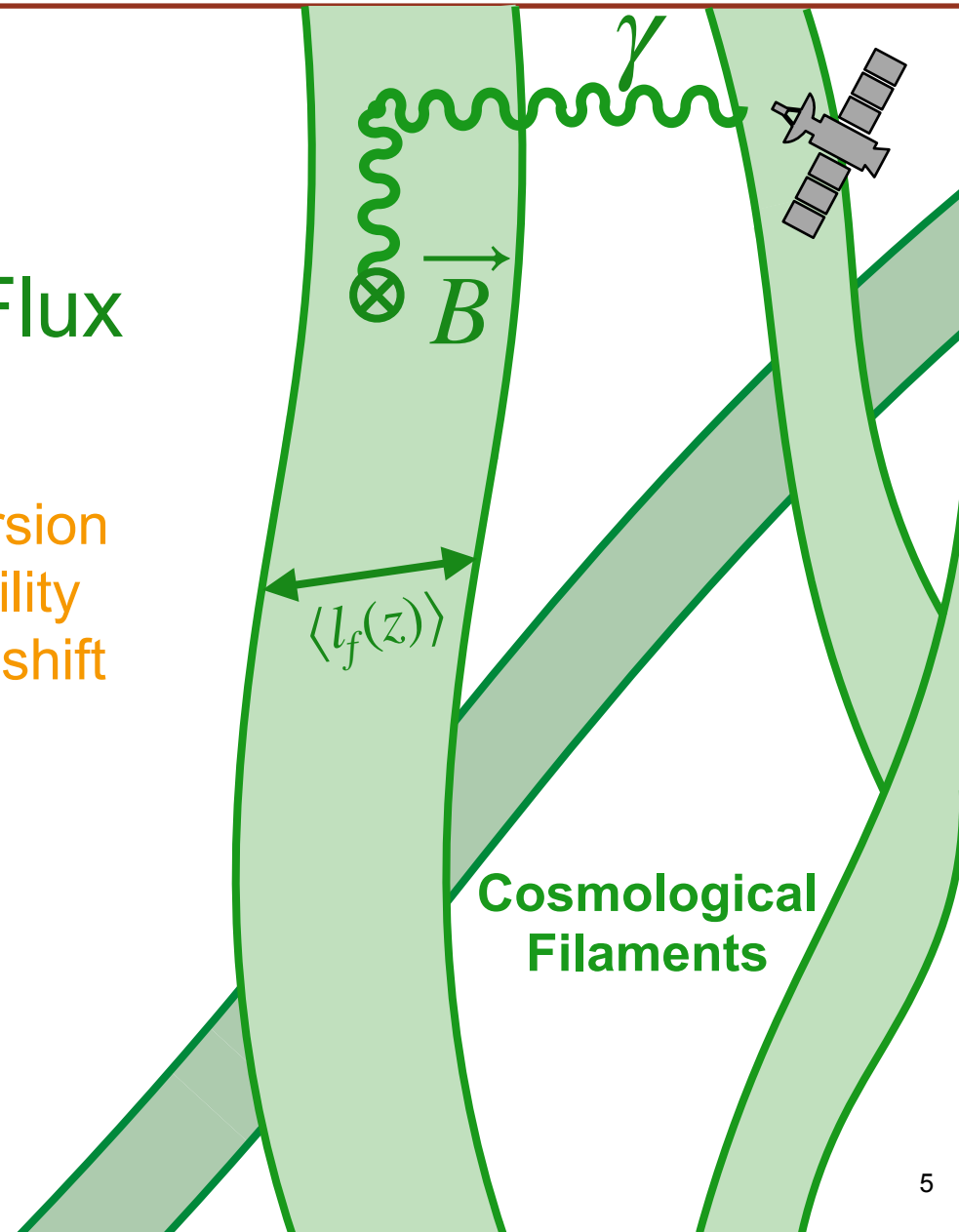
Resulting photons produce a flux



$$\gamma \text{ Flux} = \int_0^\infty dz \, \frac{d\Phi_a}{dE_a} \, \frac{dP_{a\to\gamma}}{dz}$$

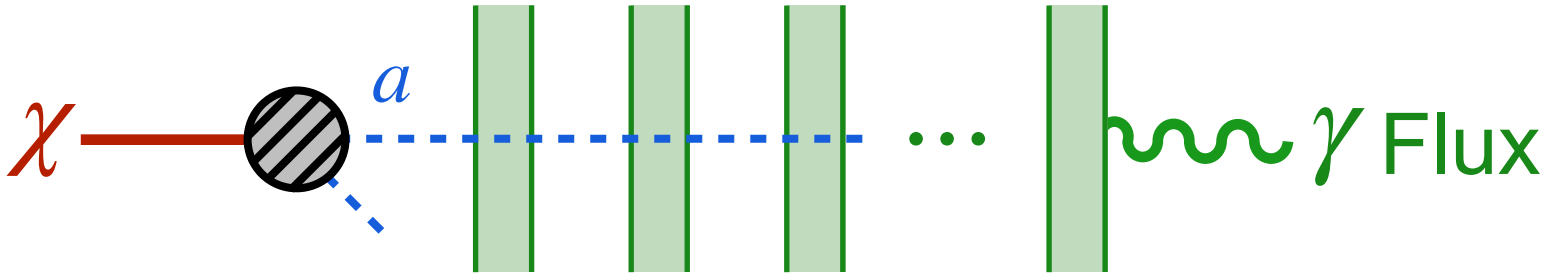
Conversion probability per redshift

m_χ, τ_χ $\quad$ $g_{a\gamma\gamma}, m_a$



Photon Flux Connects Dark Matter and Axion Properties

Resulting photons produce a flux



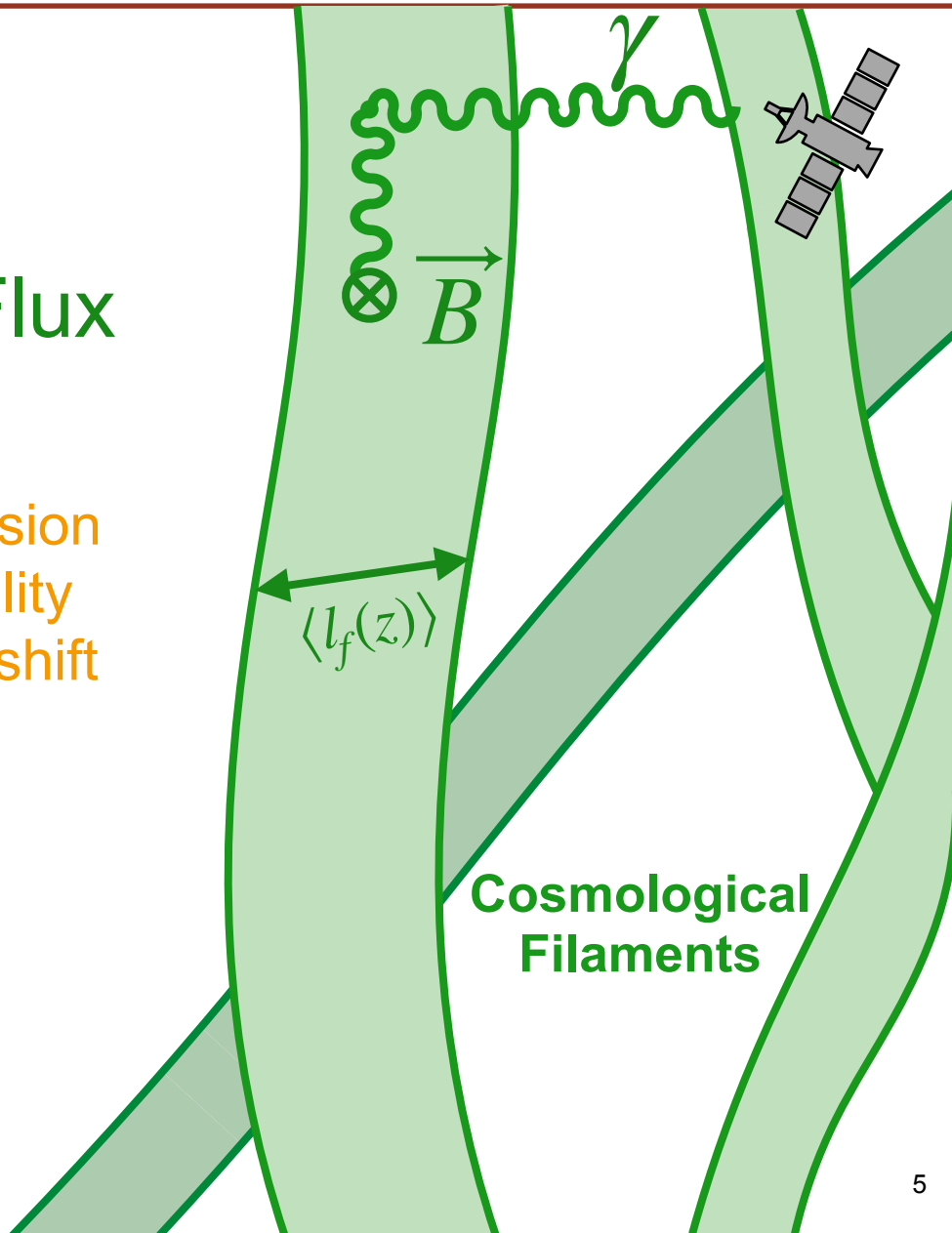
$$\gamma \text{ Flux} = \int_0^\infty dz \, \frac{d\Phi_a}{dE_a} \, \frac{dP_{a\to\gamma}}{dz}$$

Conversion probability per redshift

$\frac{d\Phi_a}{dE_a}$: m_χ, τ_χ

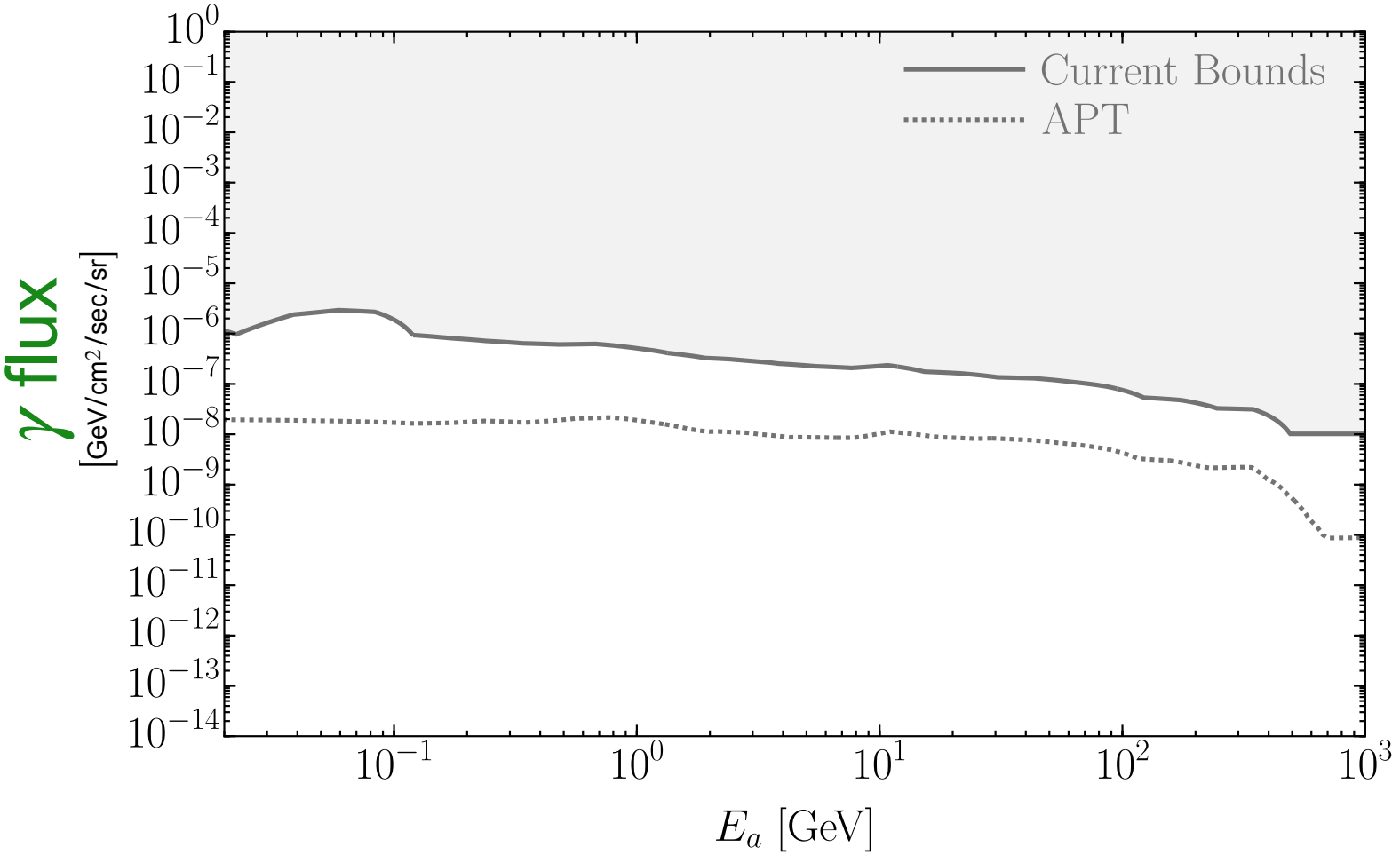
$\frac{dP_{a\to\gamma}}{dz}$: $g_{a\gamma\gamma}$, m_a

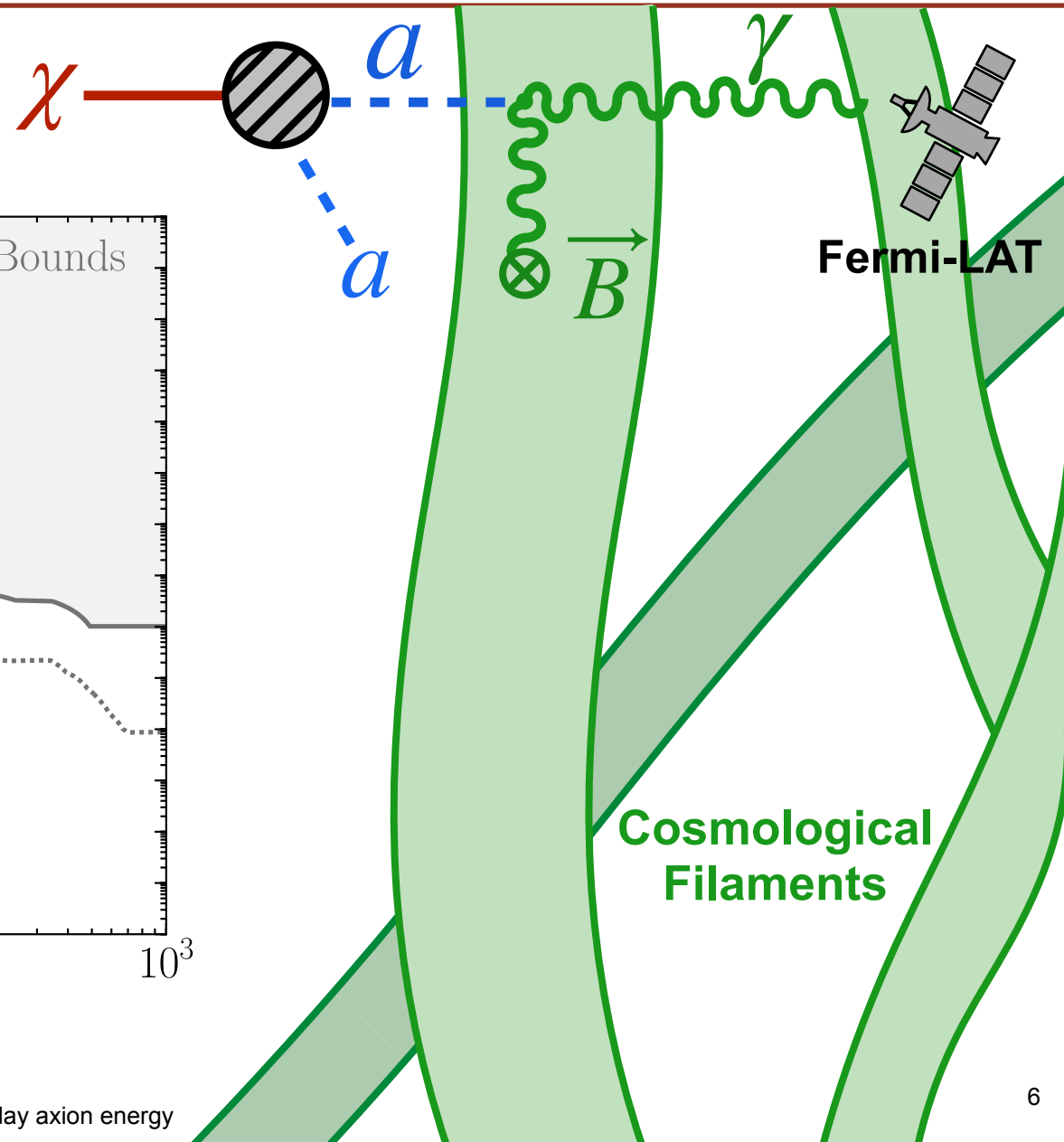
Given m_χ, τ_χ, constrain $g_{a\gamma\gamma}$, m_a by measuring γ flux



Photon Flux Connects Dark Matter and Axion Properties

γ flux constrained by Fermi-LAT, INTEGRAL, EGRET, COMPTEL

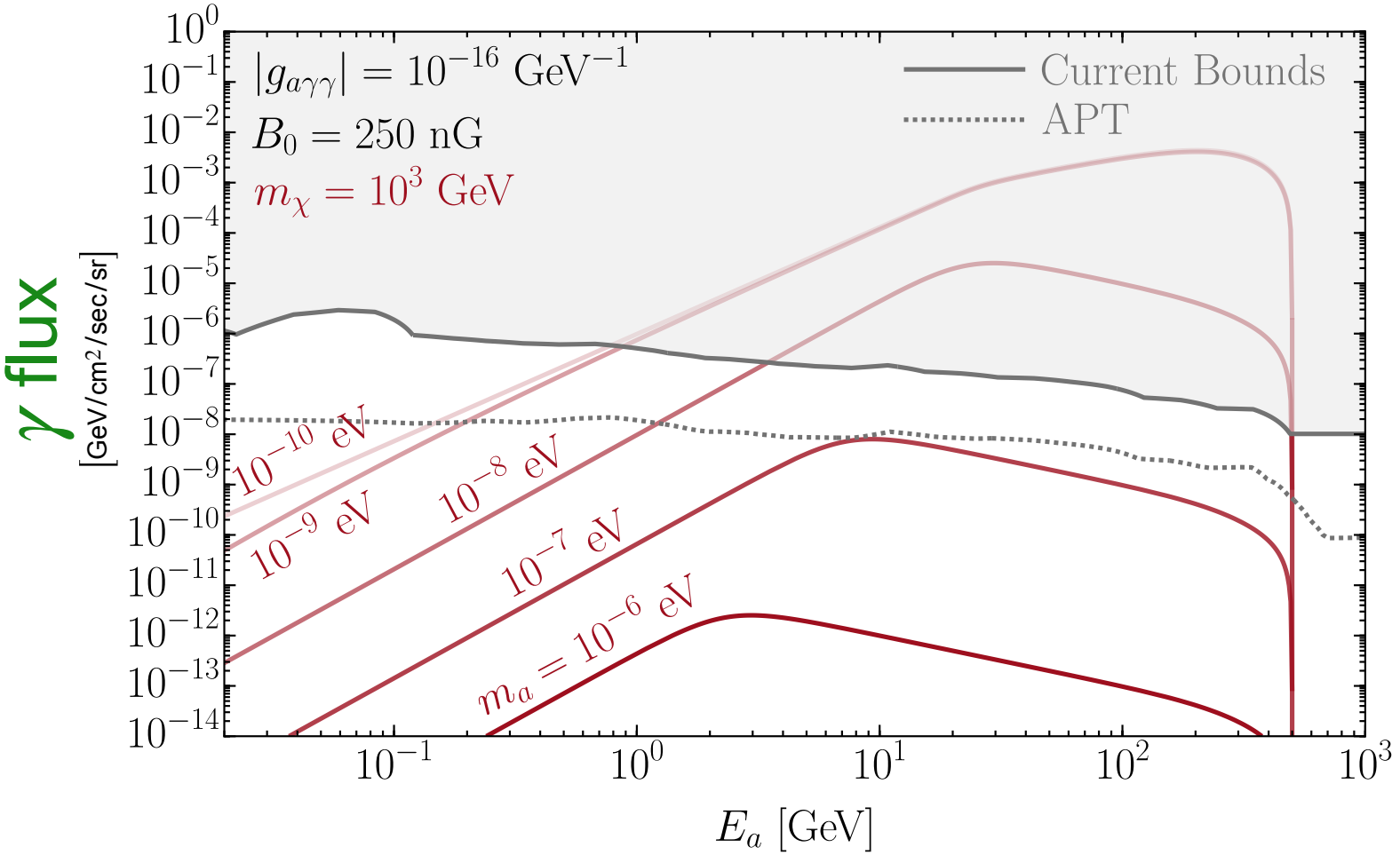


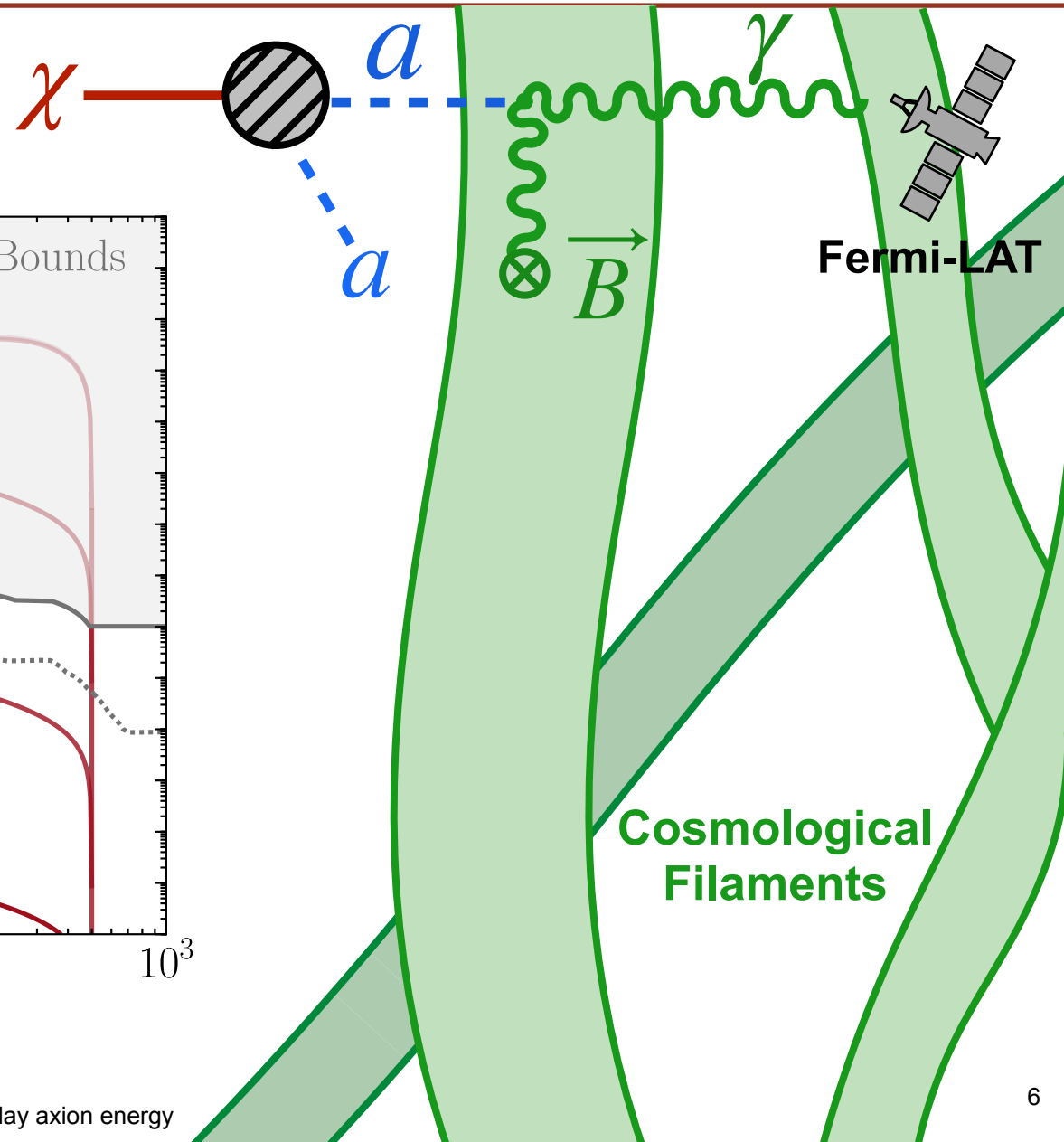


*or present-day axion energy

Photon Flux Connects Dark Matter and Axion Properties

γ flux constrained by Fermi-LAT, INTEGRAL, EGRET, COMPTEL





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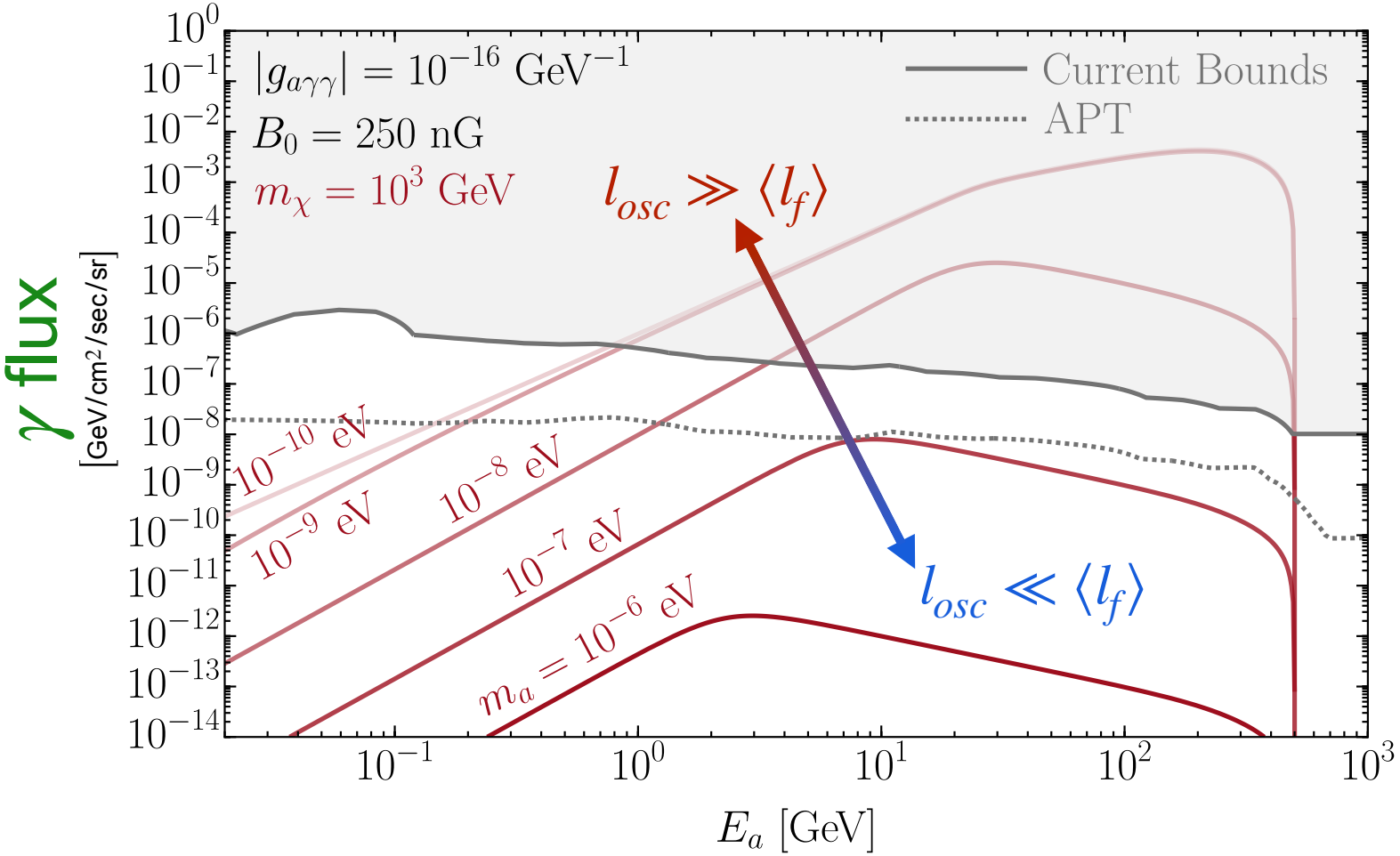
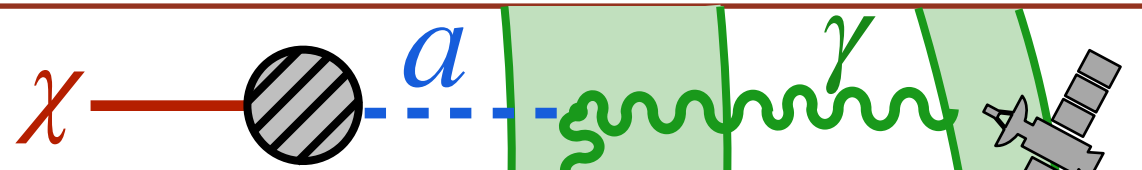
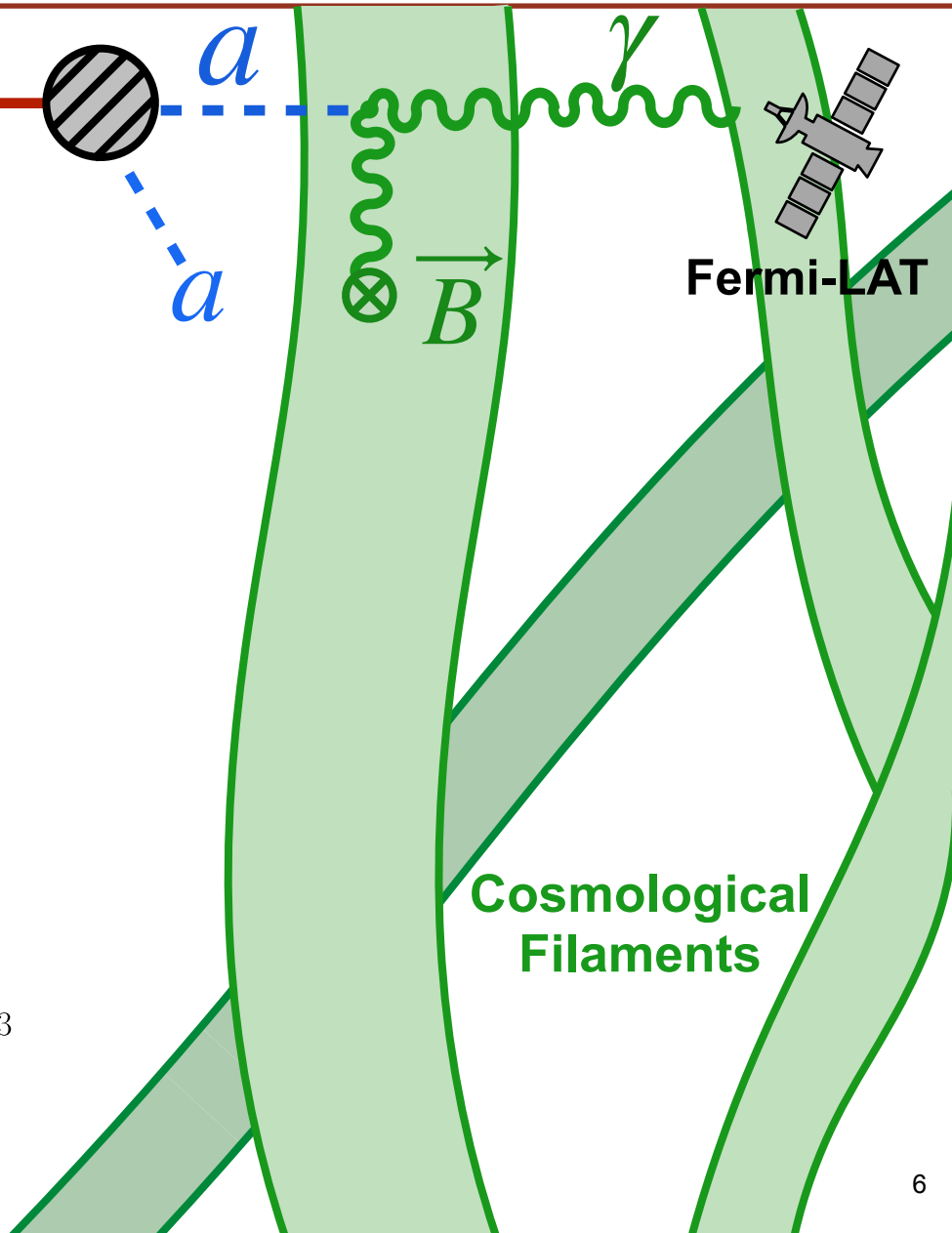
Photon Flux Connects Dark Matter and Axion Properties

γ flux constrained by Fermi-LAT, INTEGRAL, EGRET, COMPTEL



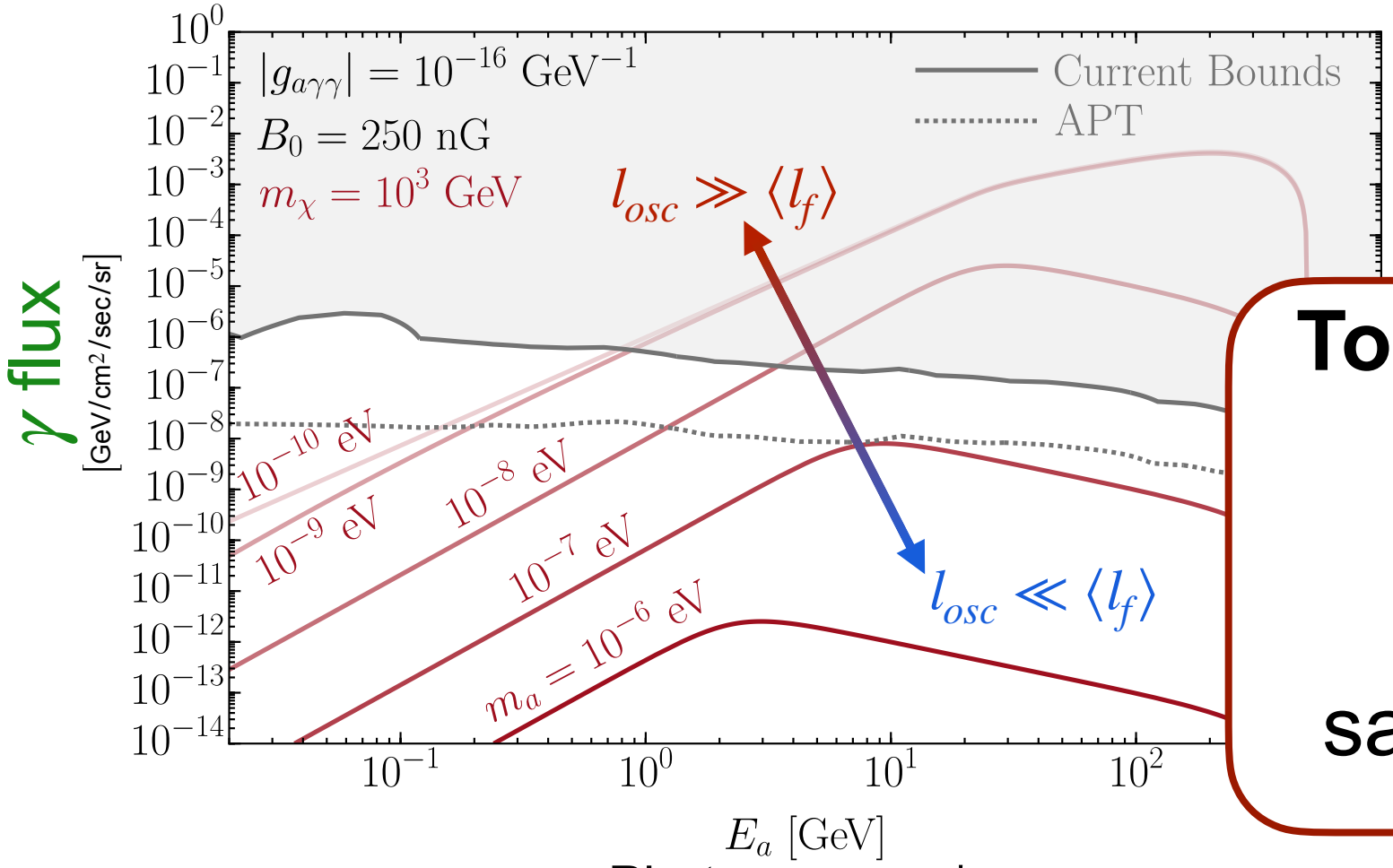


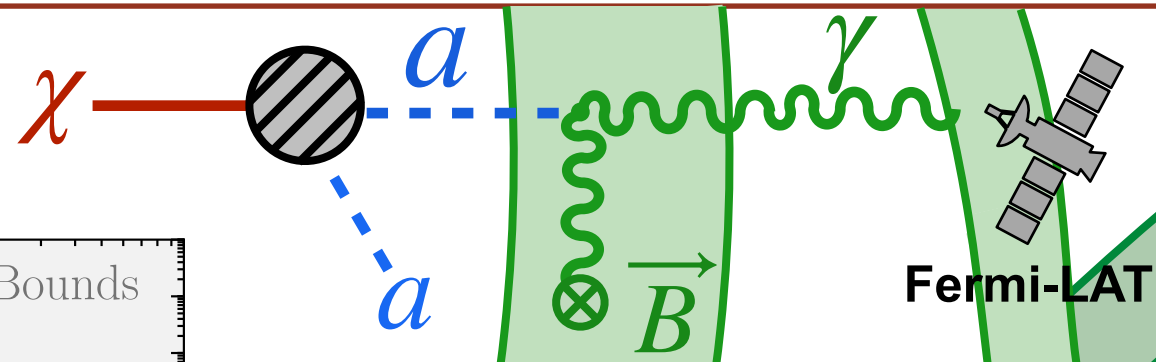


*or present-day axion energy

Photon Flux Connects Dark Matter and Axion Properties

γ flux constrained by Fermi-LAT, INTEGRAL, EGRET, COMPTEL



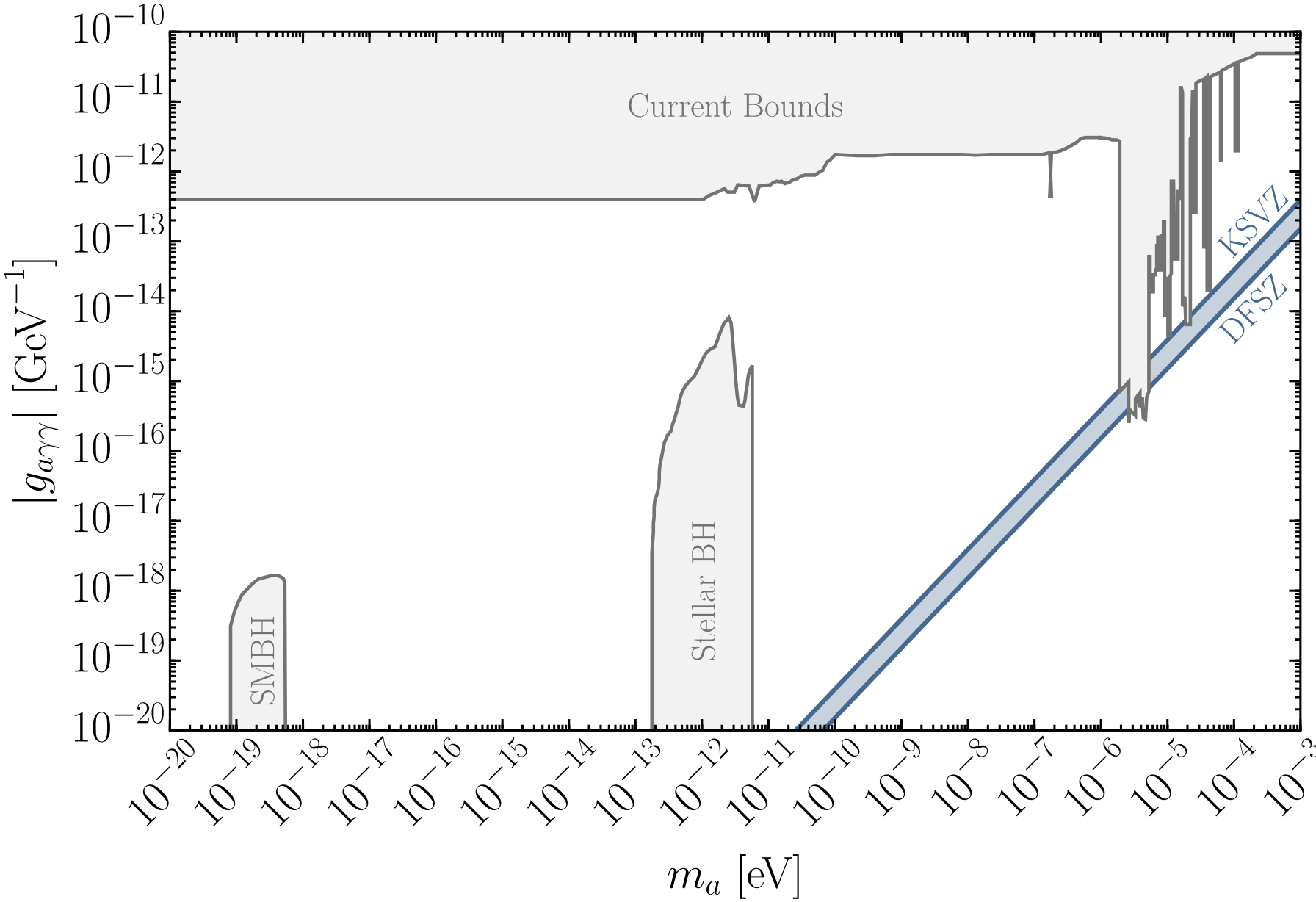


To obtain bounds for a given m_χ, τ_χ:

Find m_a, $g_{a\gamma\gamma}$ that saturate γ flux bound

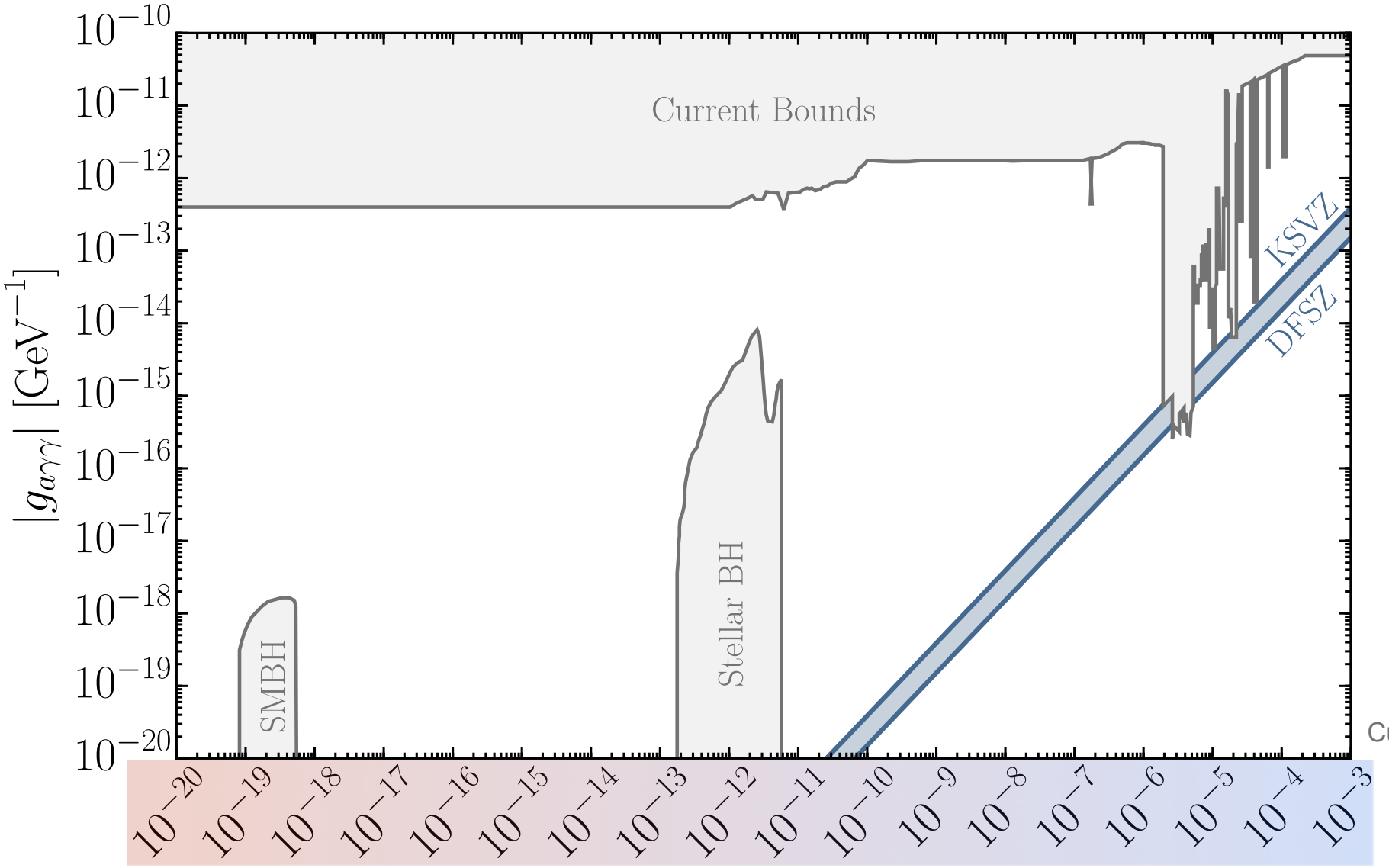
*or present-day axion energy

Optimistic benchmark probes QCD axion



Current bounds: O'Hare

Optimistic benchmark probes QCD axion



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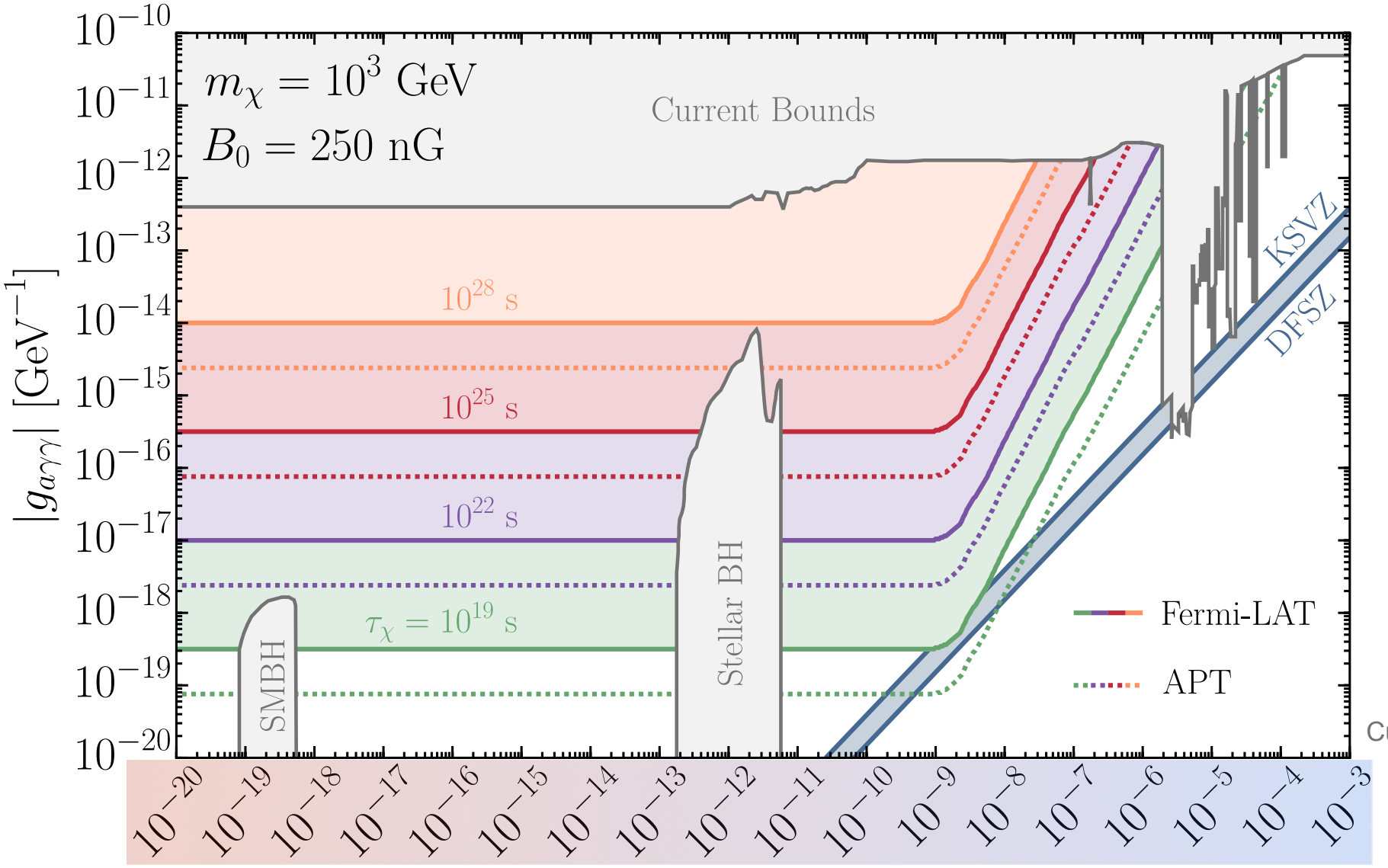
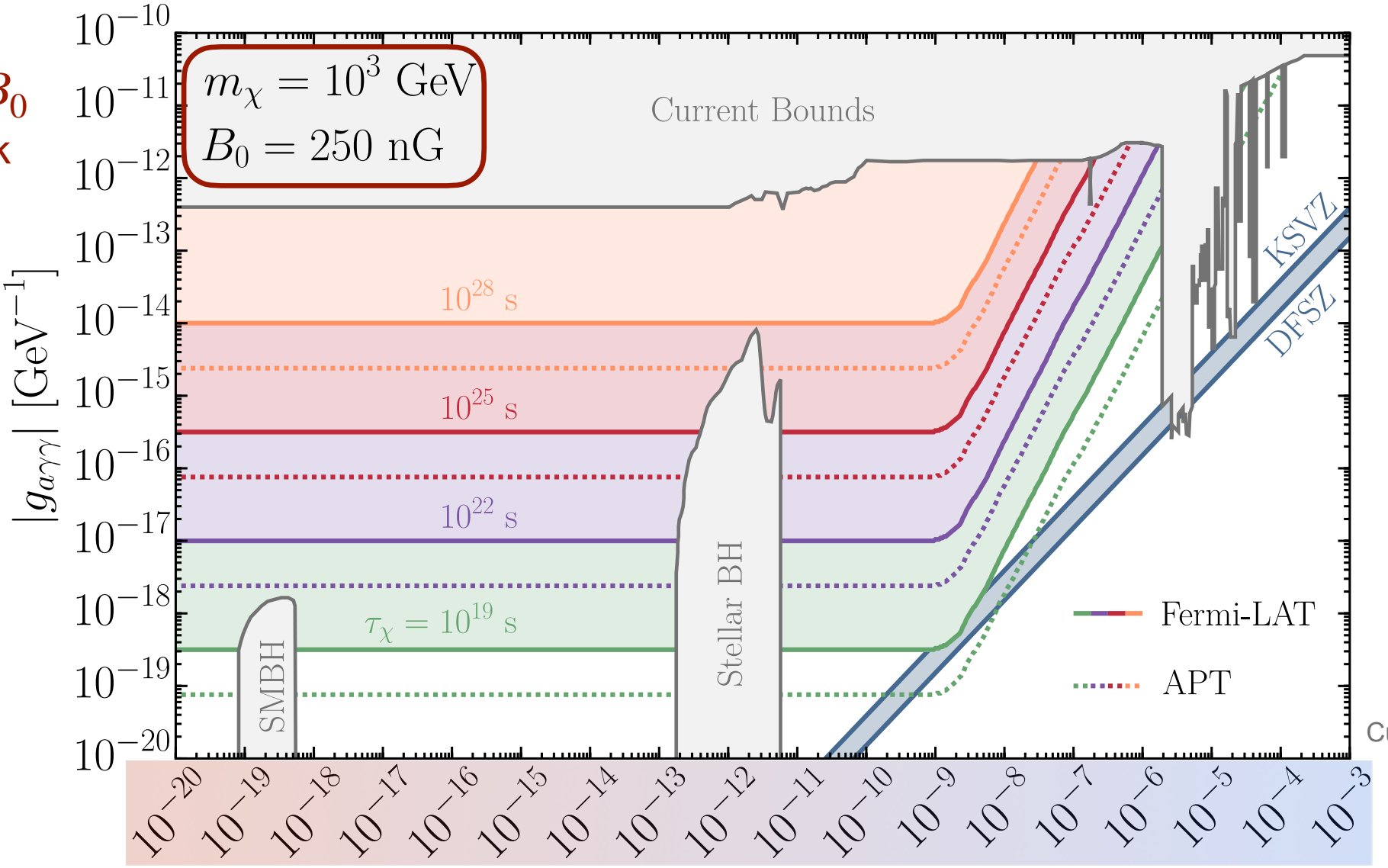
Optimistic benchmark probes QCD axion



Current bounds: O'Hare

Optimistic benchmark probes QCD axion

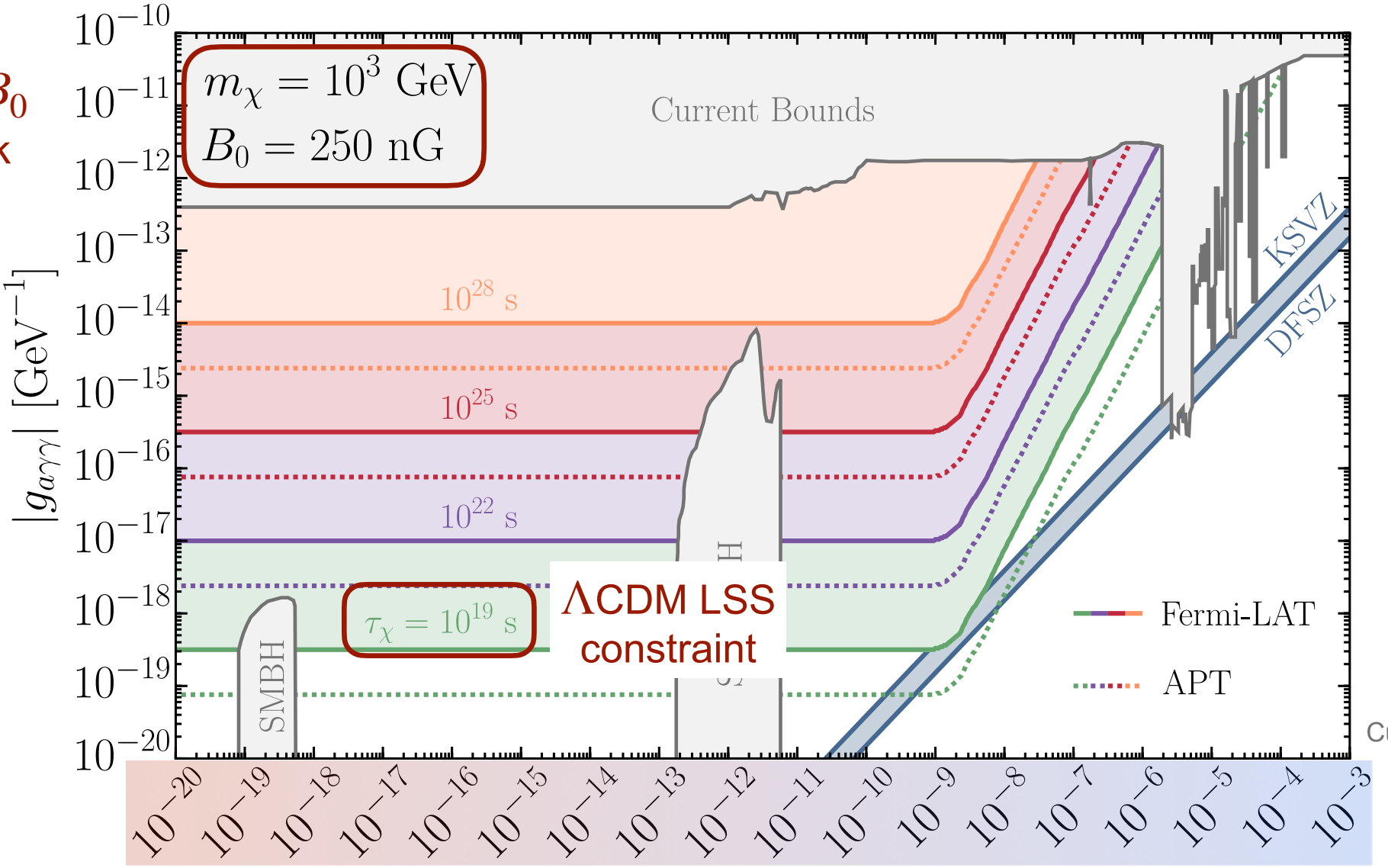
Large m_χ, B_0 benchmark



Current bounds: O'Hare

Optimistic benchmark probes QCD axion

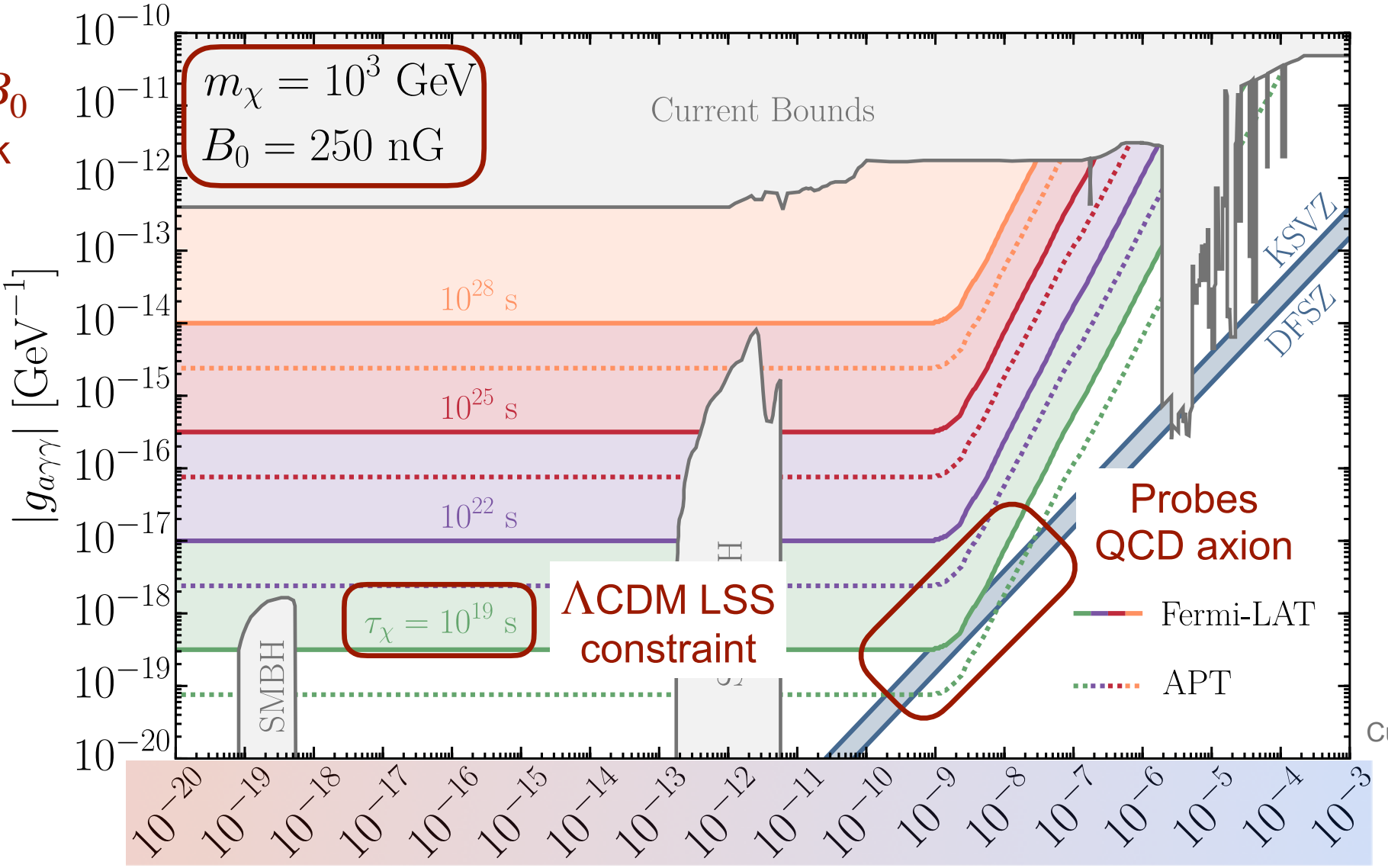
Large m_χ, B_0 benchmark



Current bounds: O'Hare

Optimistic benchmark probes QCD axion

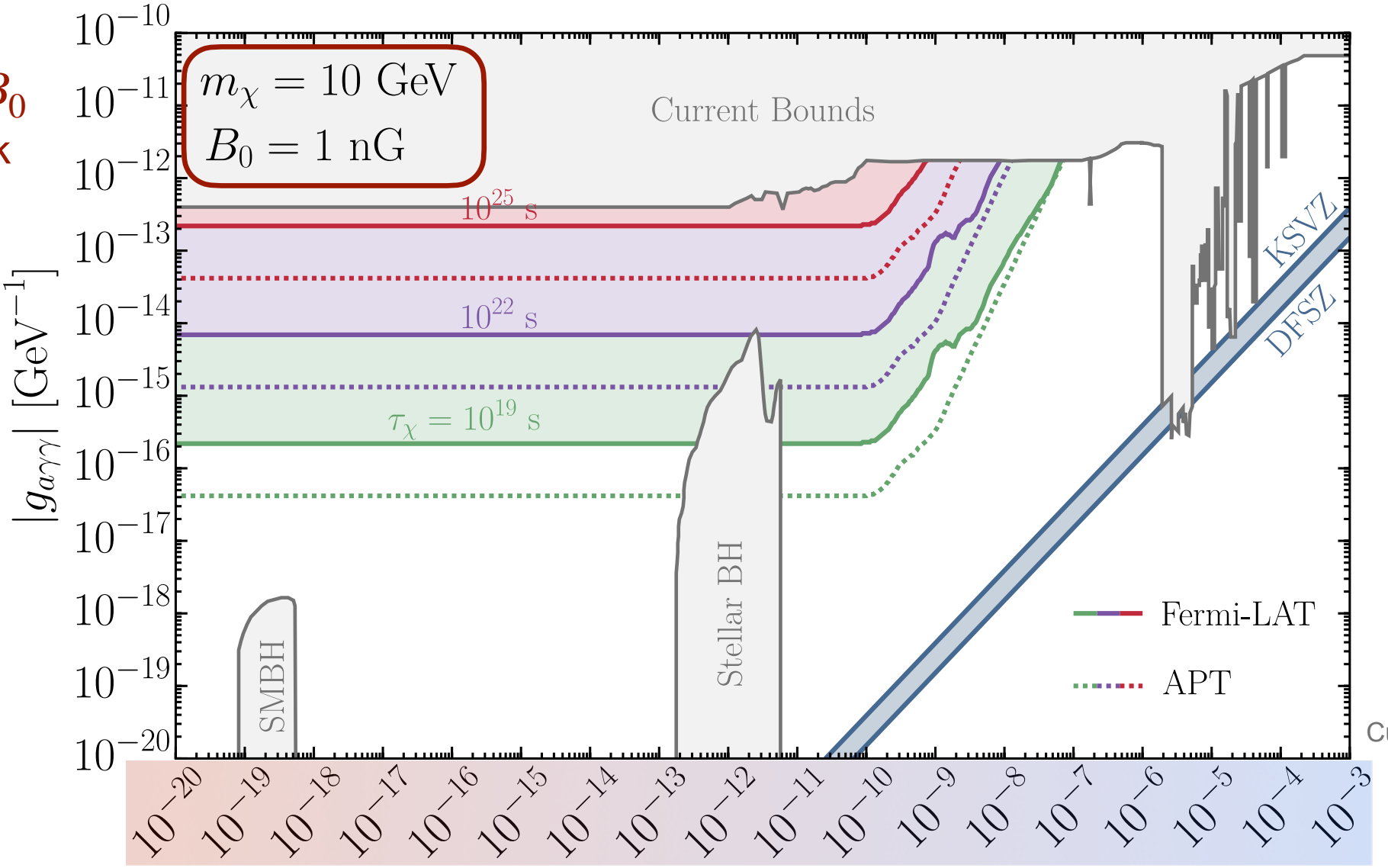
Large m_χ, B_0 benchmark



Current bounds: O'Hare

Conservative benchmark improves current bounds

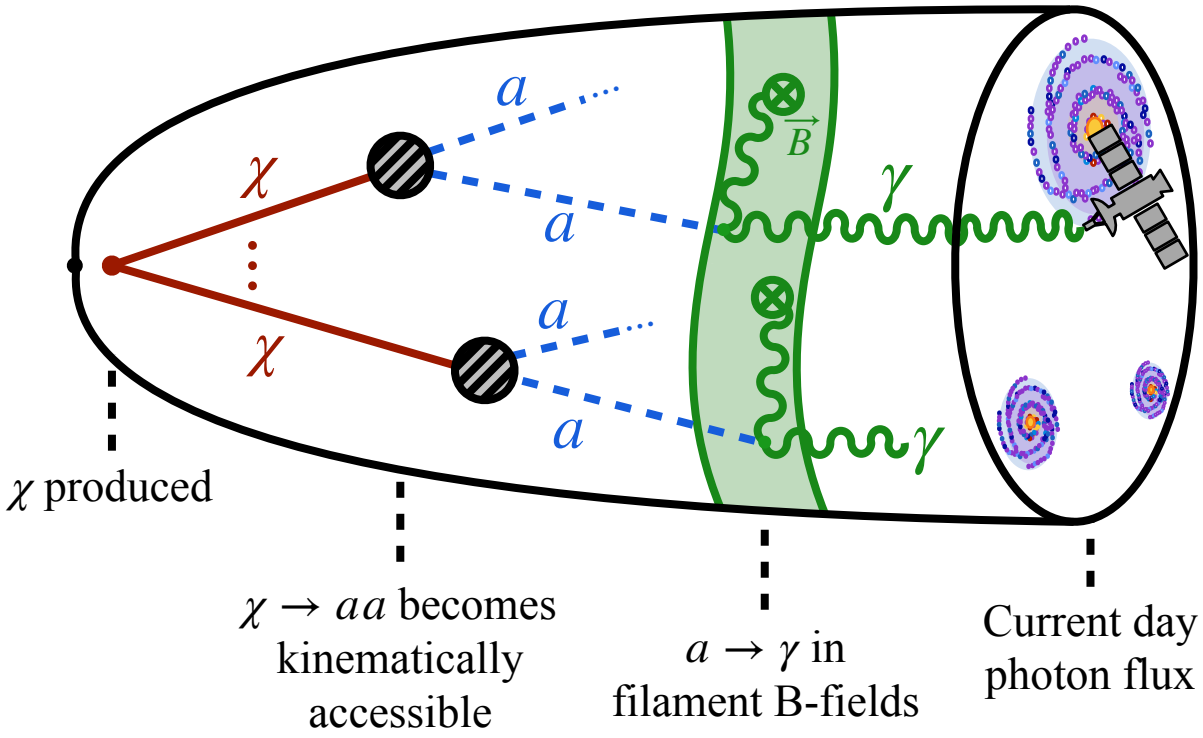
Small m_χ, B_0 benchmark

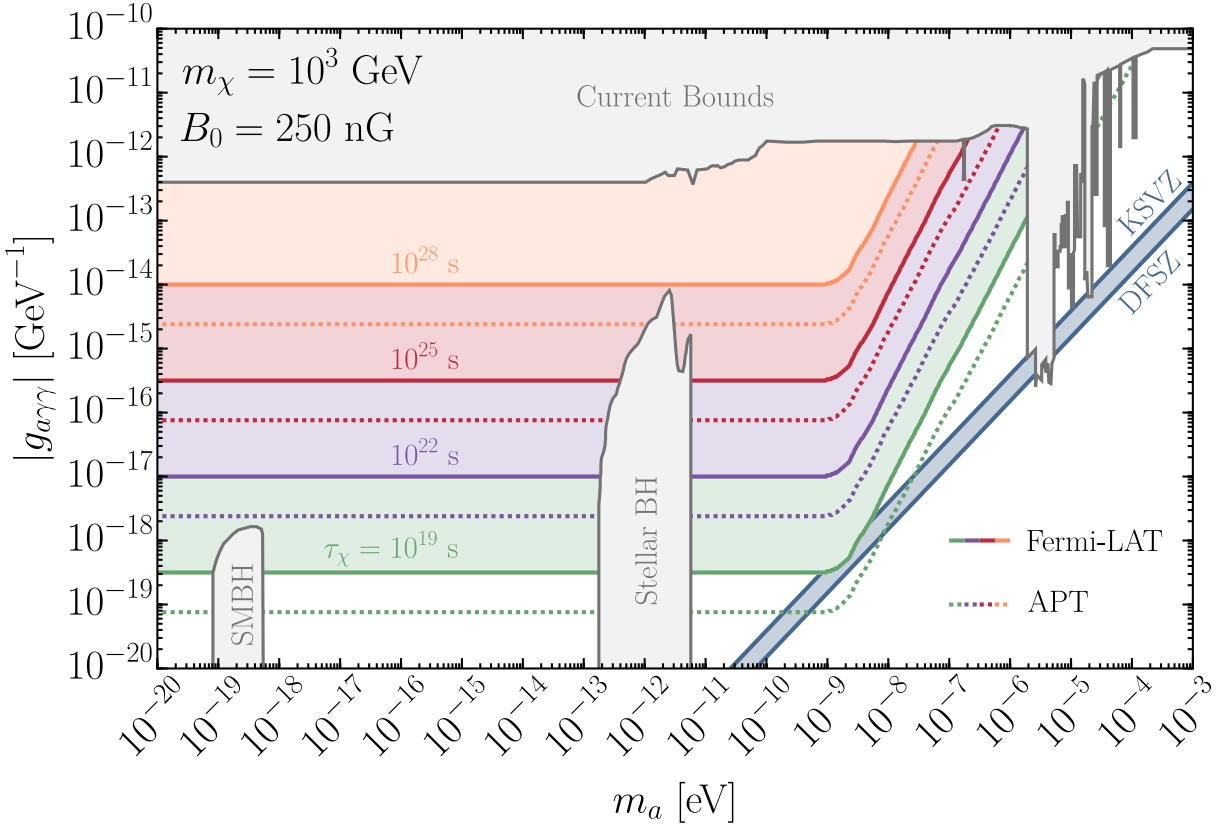


Current bounds: O'Hare

Conclusion

Cosmological filaments provide an **indirect probe** of models with **dark matter** coupled to **axions**





Next: survey of models that give rise to $\chi \to aa$ decays

Backup Slides

Gaussian Approximation to Filament Diameter

Axion photon conversion probability

$$P^{(1)}_{a\to\gamma} = \frac{g^2_{a\gamma\gamma}B^2(z)l^2_{osc}(z)}{4}\sin\left(\frac{l_f(z)}{l_{osc}(z)}\right)$$

We can model length axions travel through filaments as Gaussian variable l_f with average $\langle l_f\rangle$, second moment $\langle l_f^2\rangle$ and deviation $\sigma = \langle l_f^2\rangle - \langle l_f\rangle^2$.

$$\bar{P}^{(1)}_{a\to\gamma}(z) \approx \frac{g^2_{a\gamma\gamma}B^2(z)l^2_{osc}(z)}{8}\left[1 - e^{-\frac{2\sigma^2}{l^2_{osc}(z)}}\cos\left(\frac{2\langle l_f(z)\rangle}{l_{osc}(z)}\right)\right]$$

$$\langle l_f(z)\rangle \approx \frac{4}{1+z}\ \text{Mpc}, \qquad \langle l_f^2(z)\rangle \approx \frac{64}{3(1+z)^2}\ \text{Mpc}^2$$

Axion-Photon Conversion in Cosmological Filaments

Oscillation length plays important role

$$l_{osc}(z) = \frac{4E_a(1+z)}{\left| m_\gamma^2(z) - m_{EH}^2(z) - m_a^2 \right|}$$

Axion energy ($z = 0$)

Axion mass

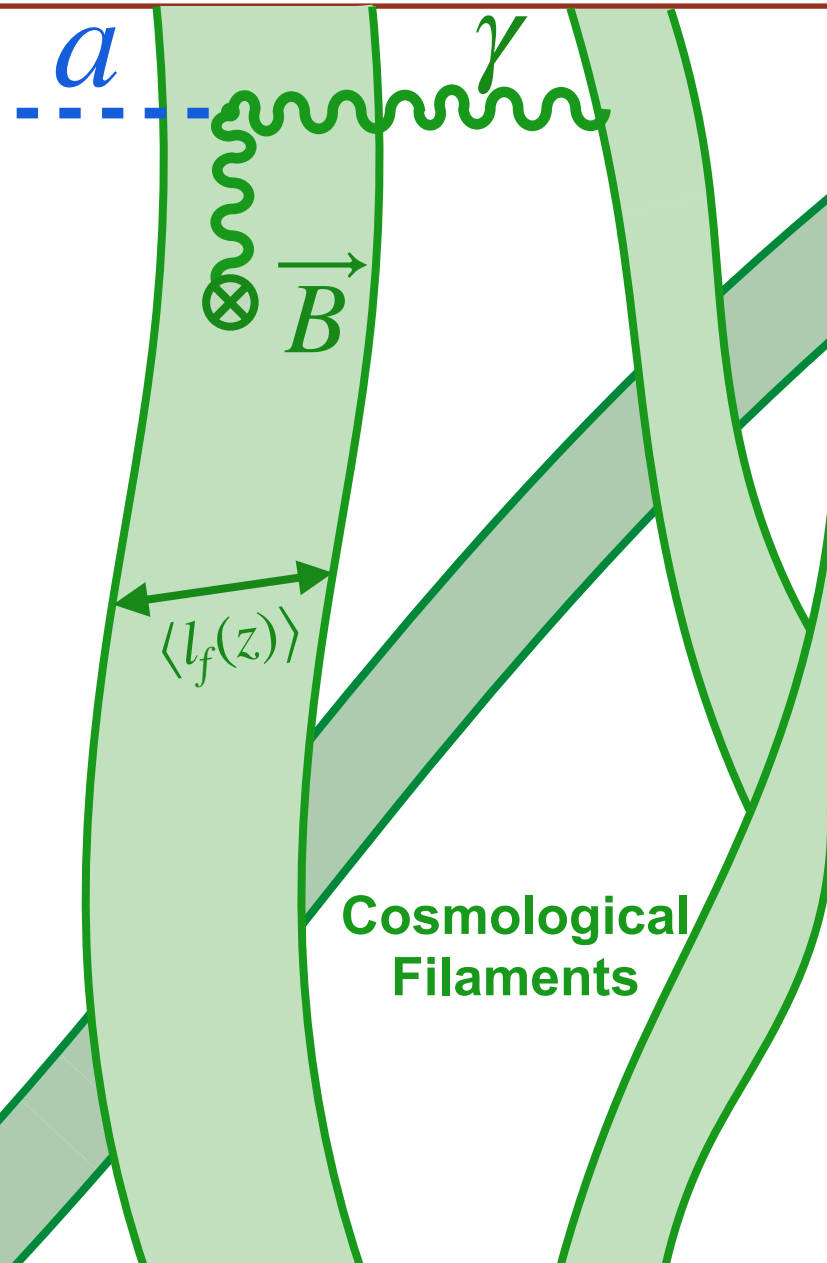
Photon plasma mass

Euler-Heisenberg mass

Two regimes*:

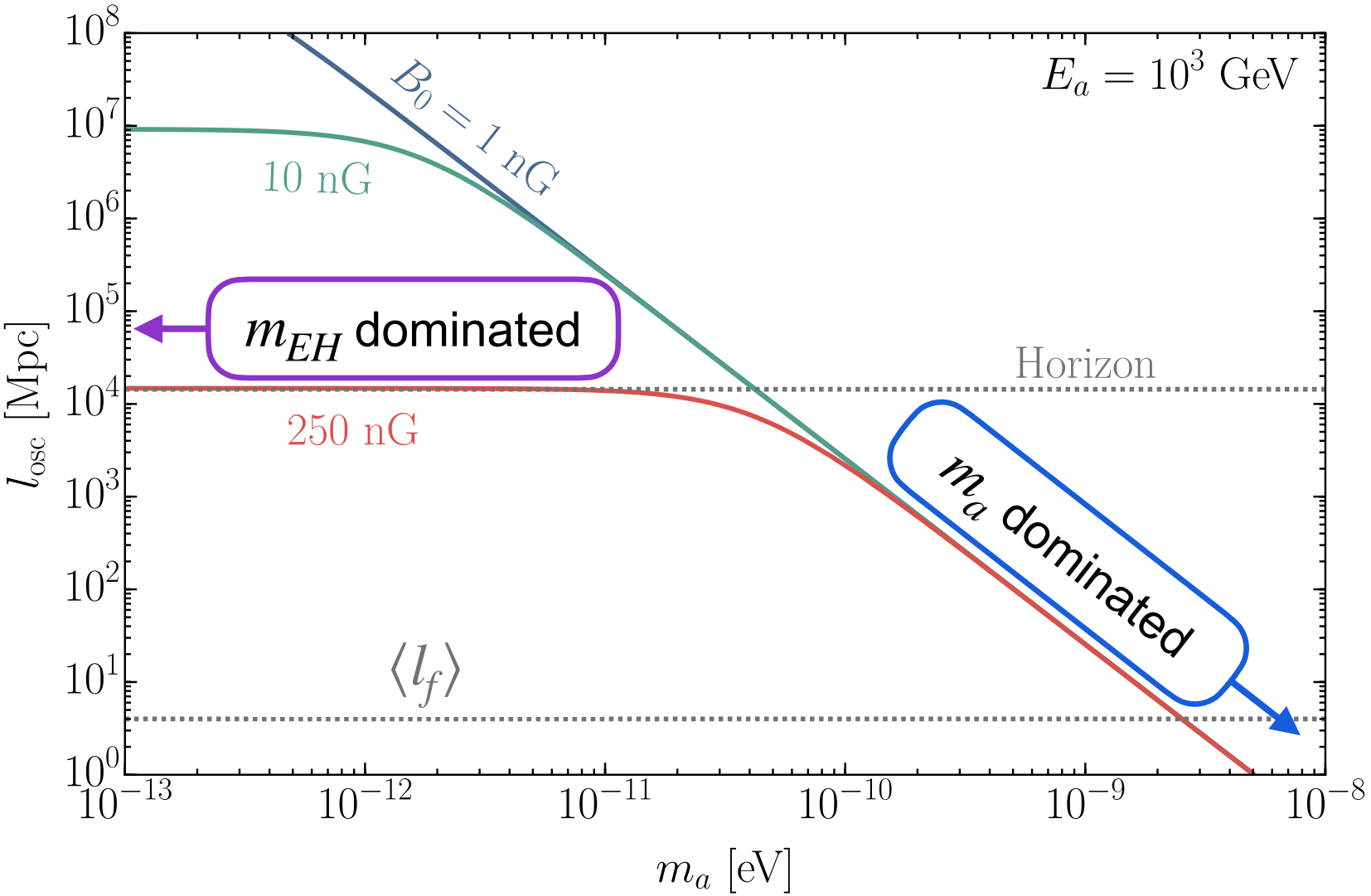
$m_a \gg m_{EH}$ — m_a dominated

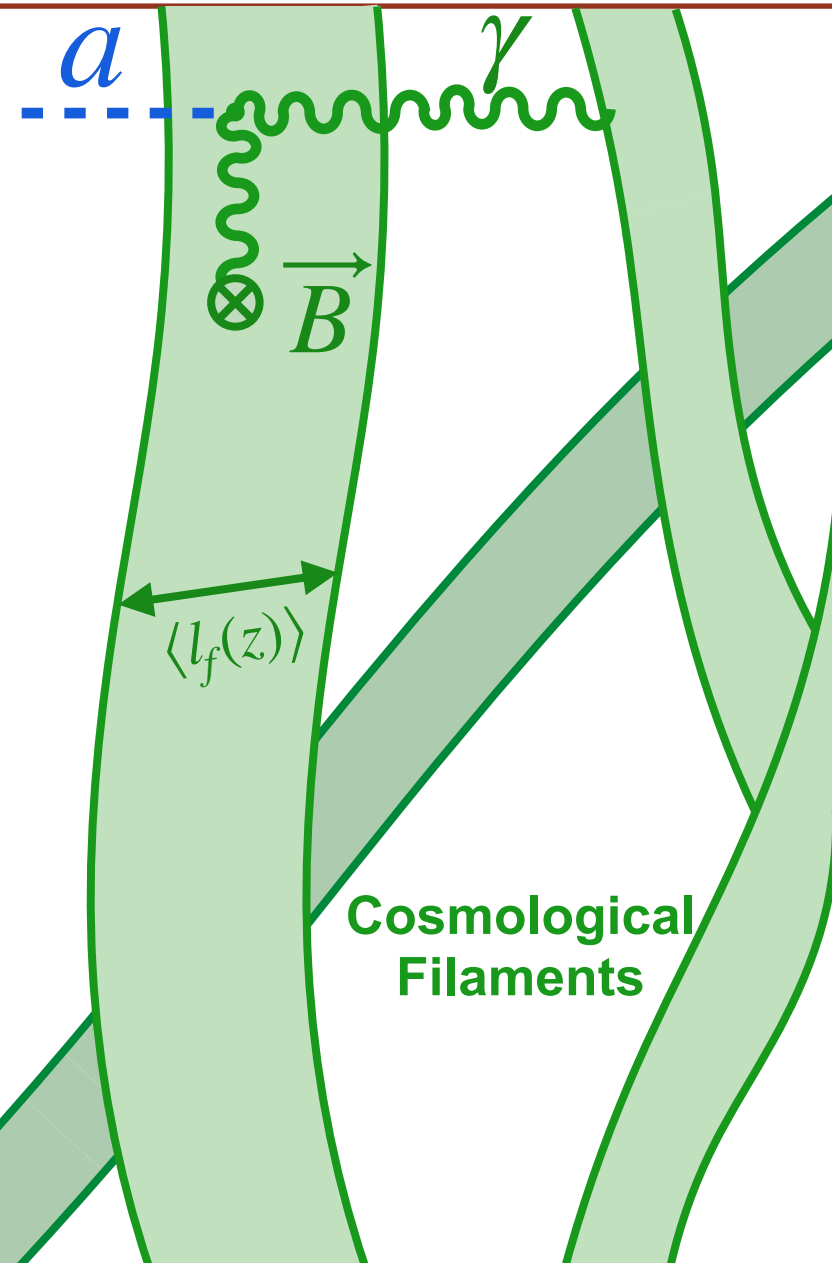
$m_a \ll m_{EH}$ — m_{EH} dominated



*For all relevant redshifts $m_\gamma \ll m_a, m_{EH}$

Axion-Photon Conversion in Cosmological Filaments





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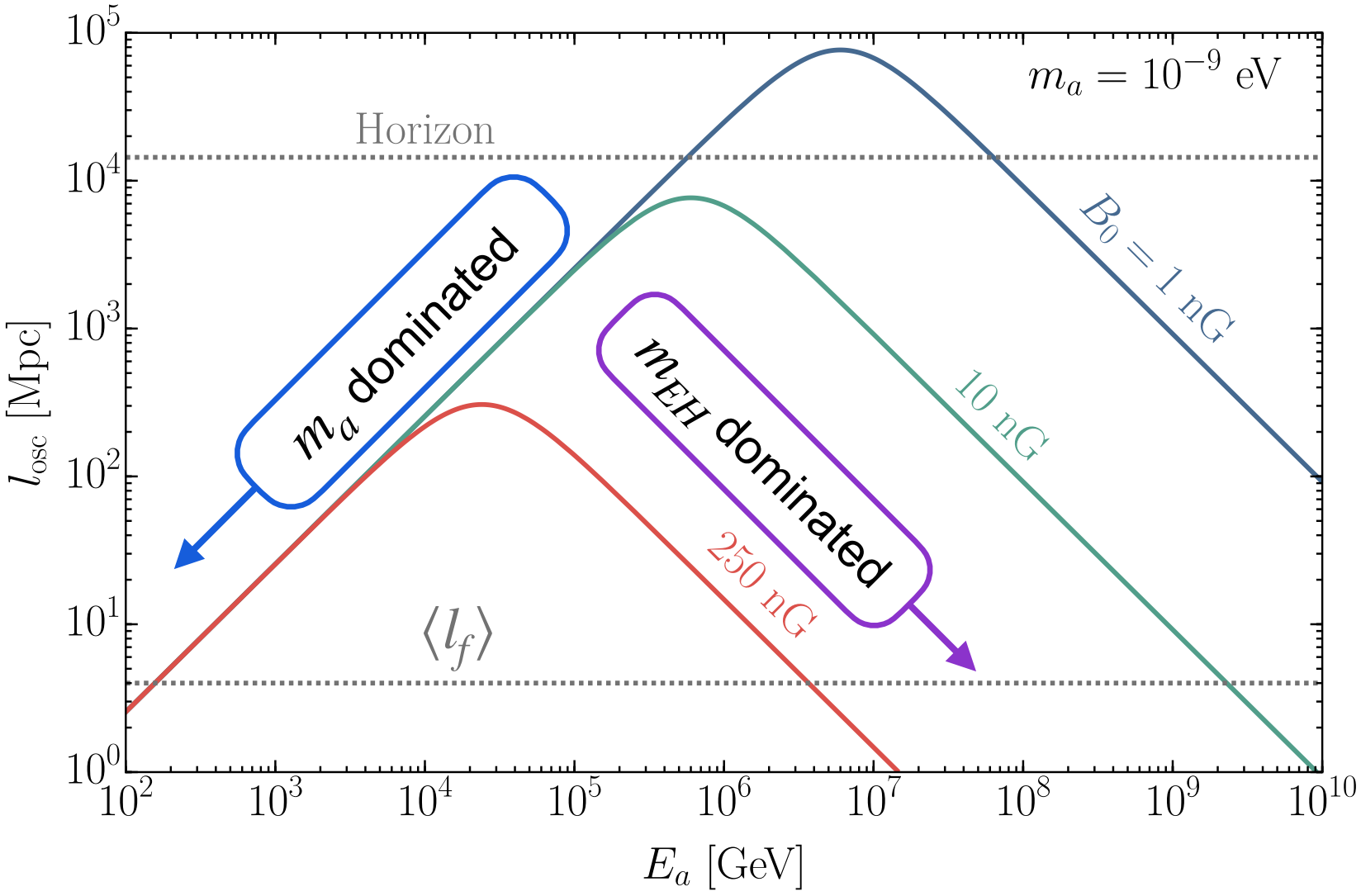
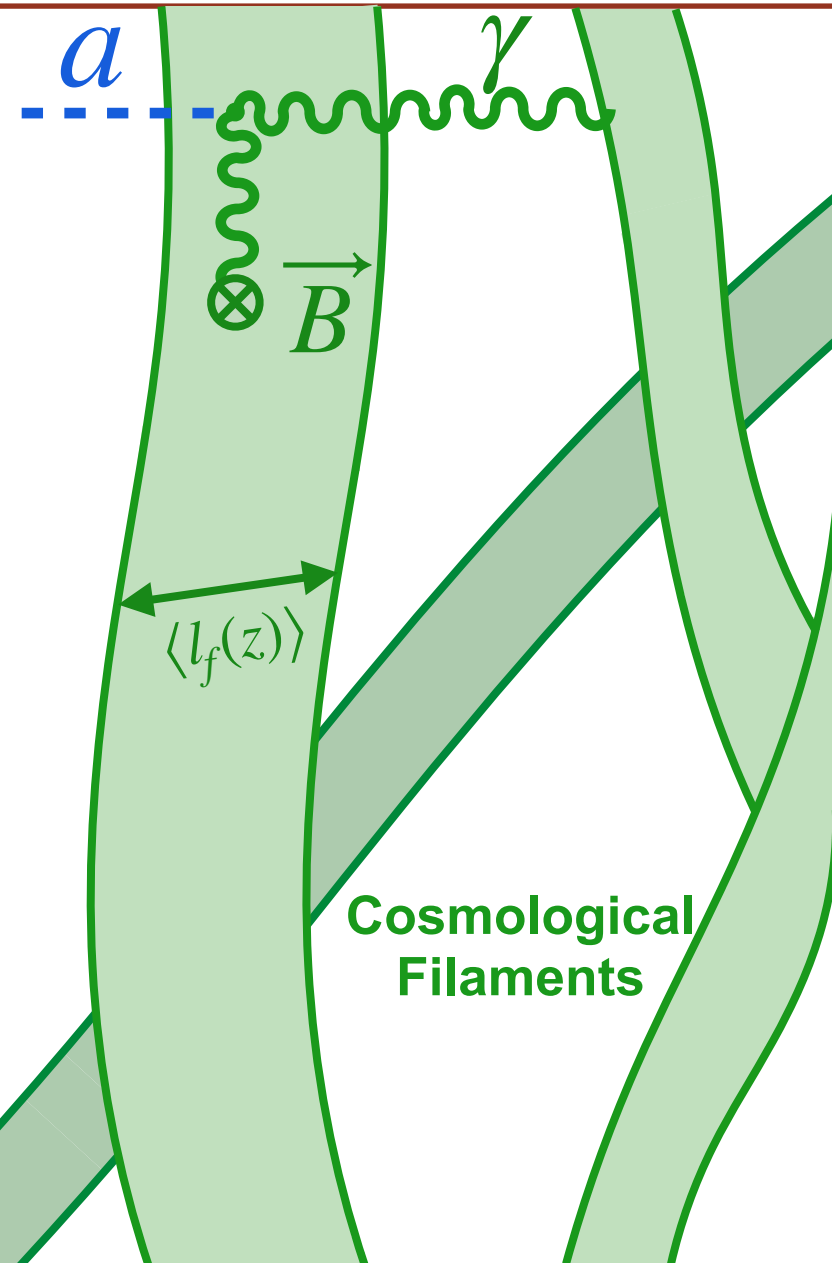
Axion-Photon Conversion in Cosmological Filaments





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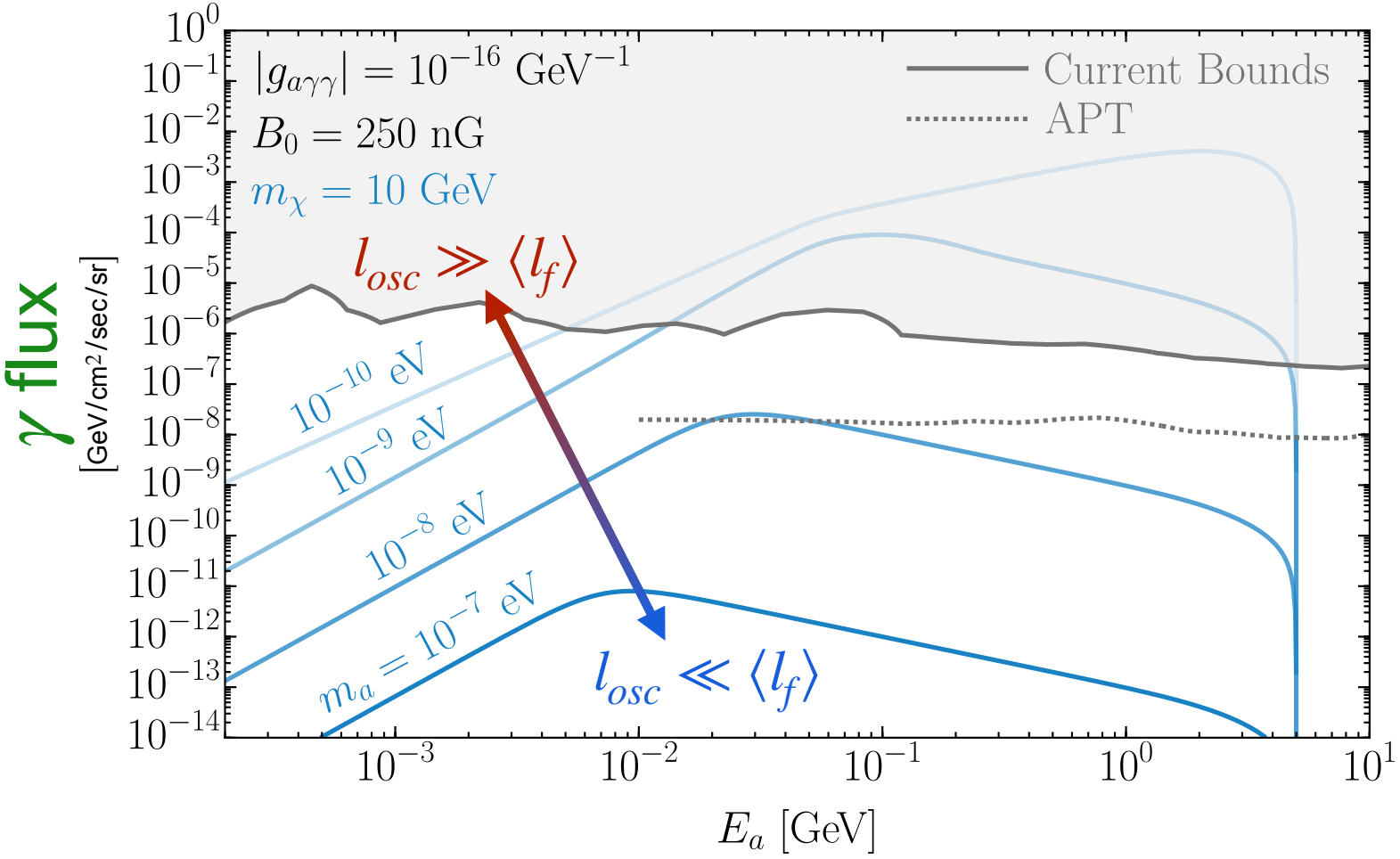
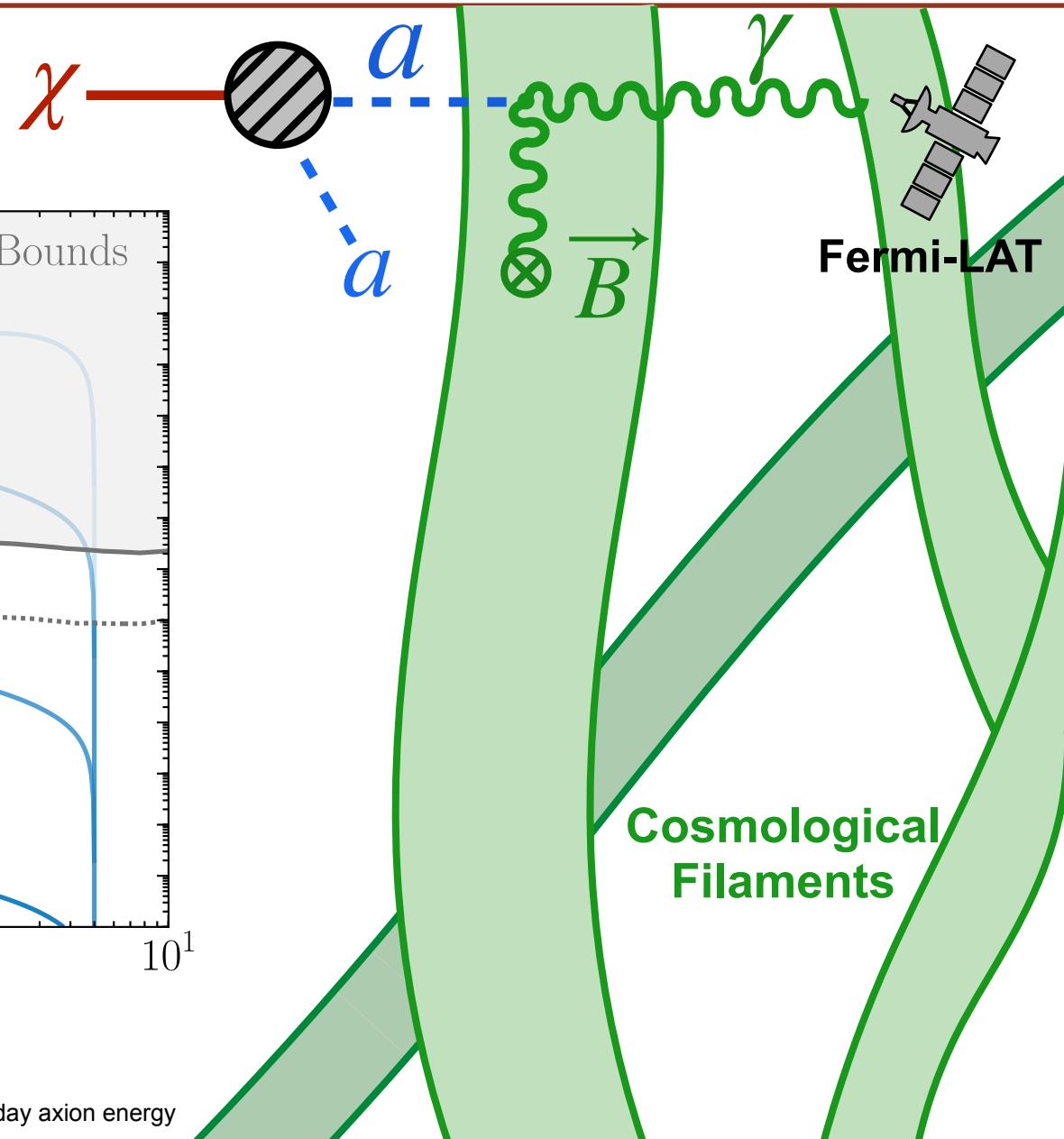
Photon Flux For 10 GeV Dark Matter

γ flux constrained by Fermi-LAT, INTEGRAL, EGRET, COMPTEL





*or present-day axion energy