coupling axion-like particles to photons during propagation: the ALPinist plug-in

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axion-like particles

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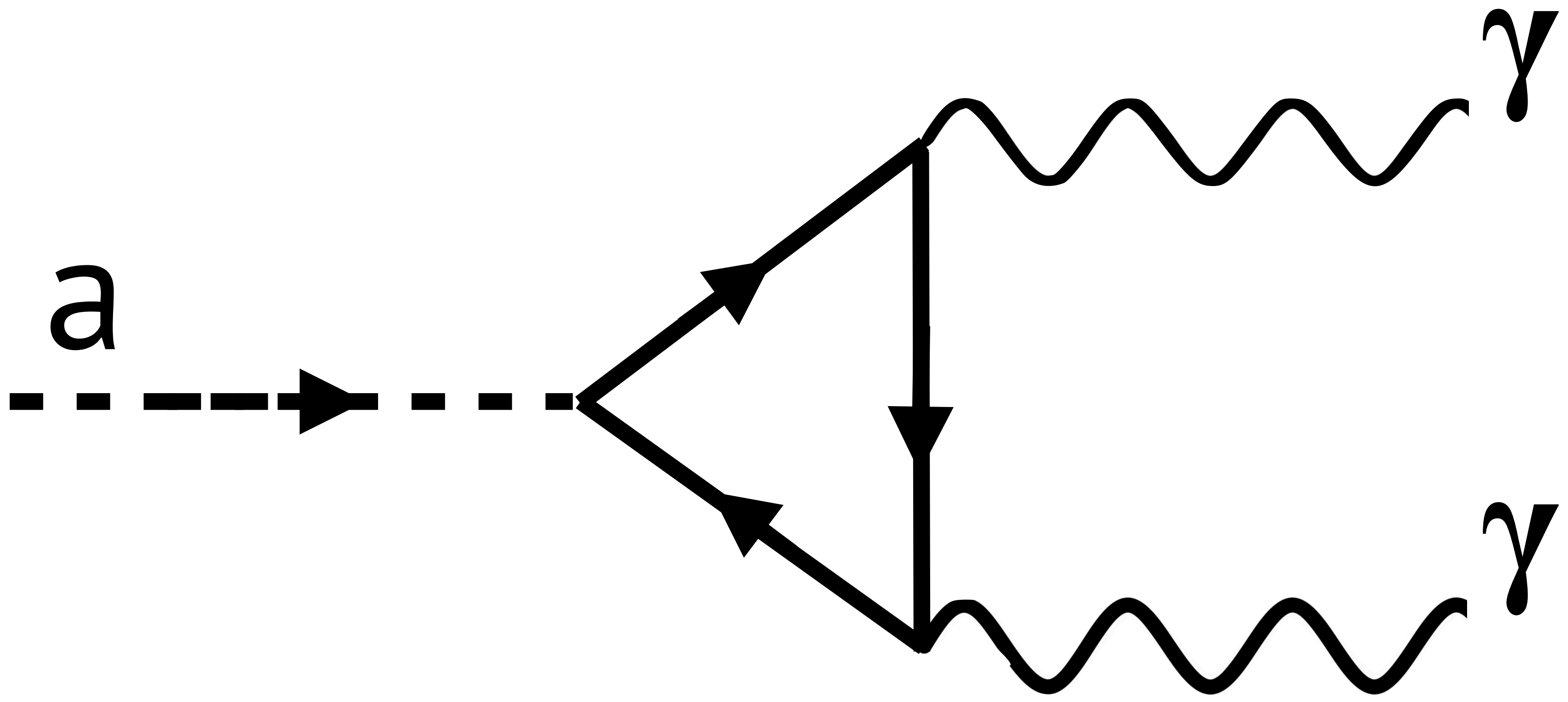

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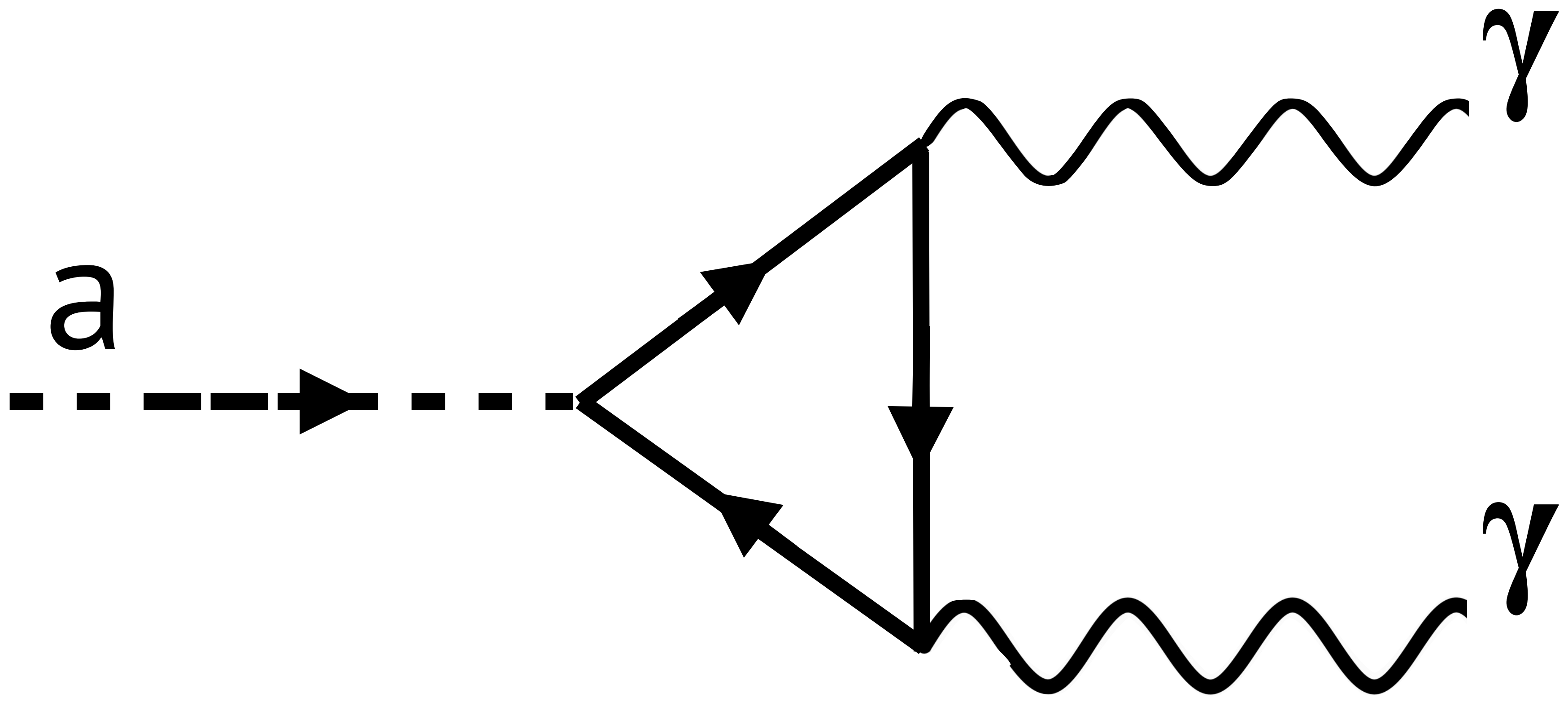
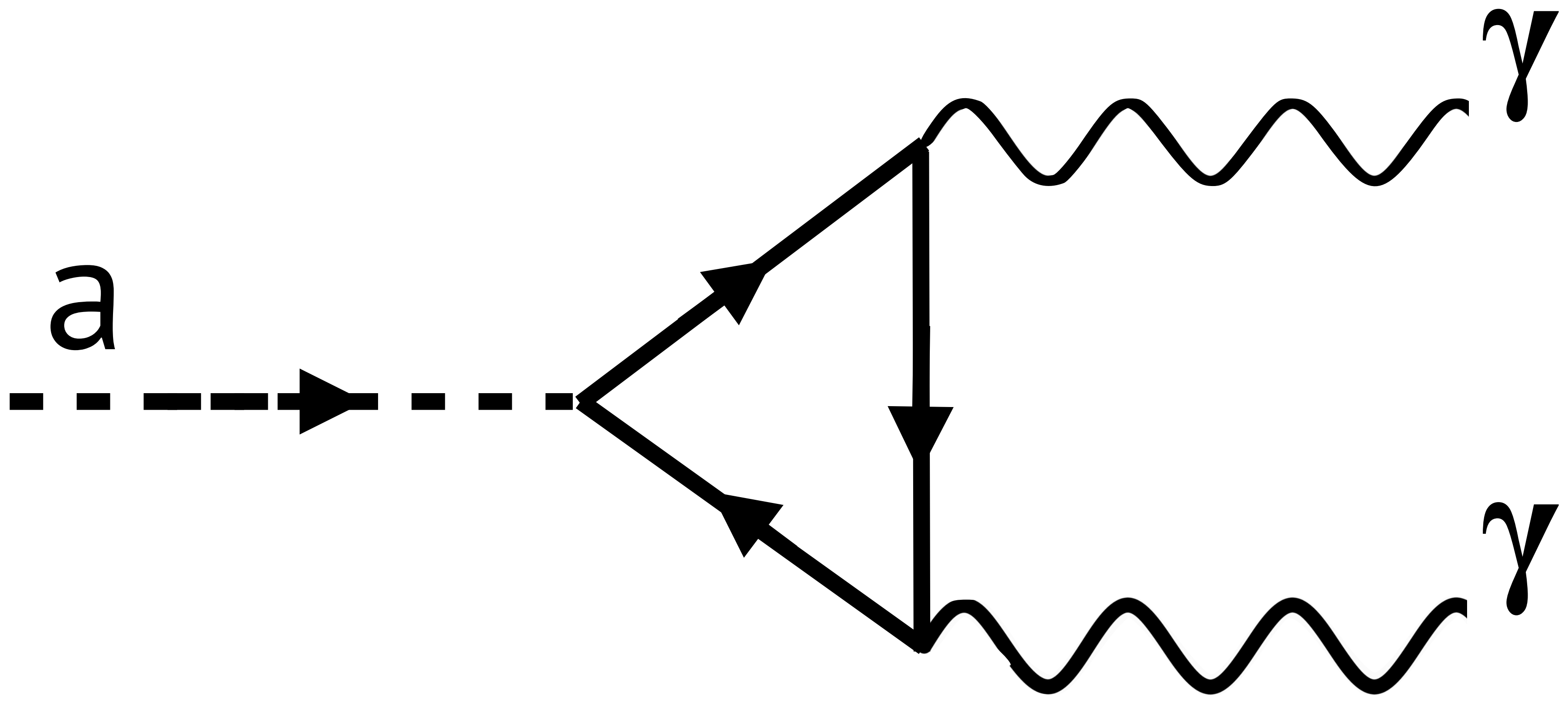


Lagrangian ALP-photon mixing



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$$\mathscr{L}_{a\gamma} = g_{a\gamma} \overrightarrow{E}_{\gamma} \cdot \overrightarrow{B} \, a$$

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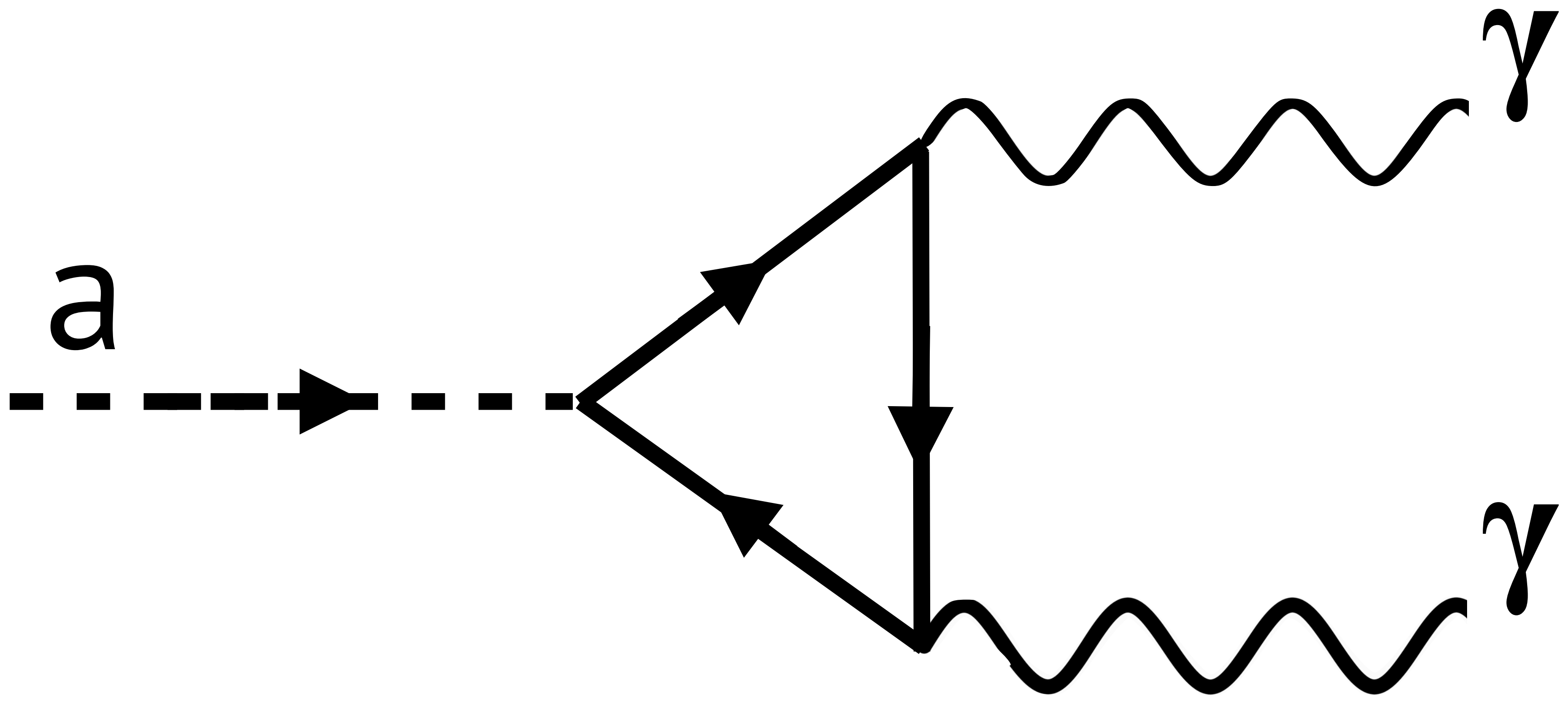

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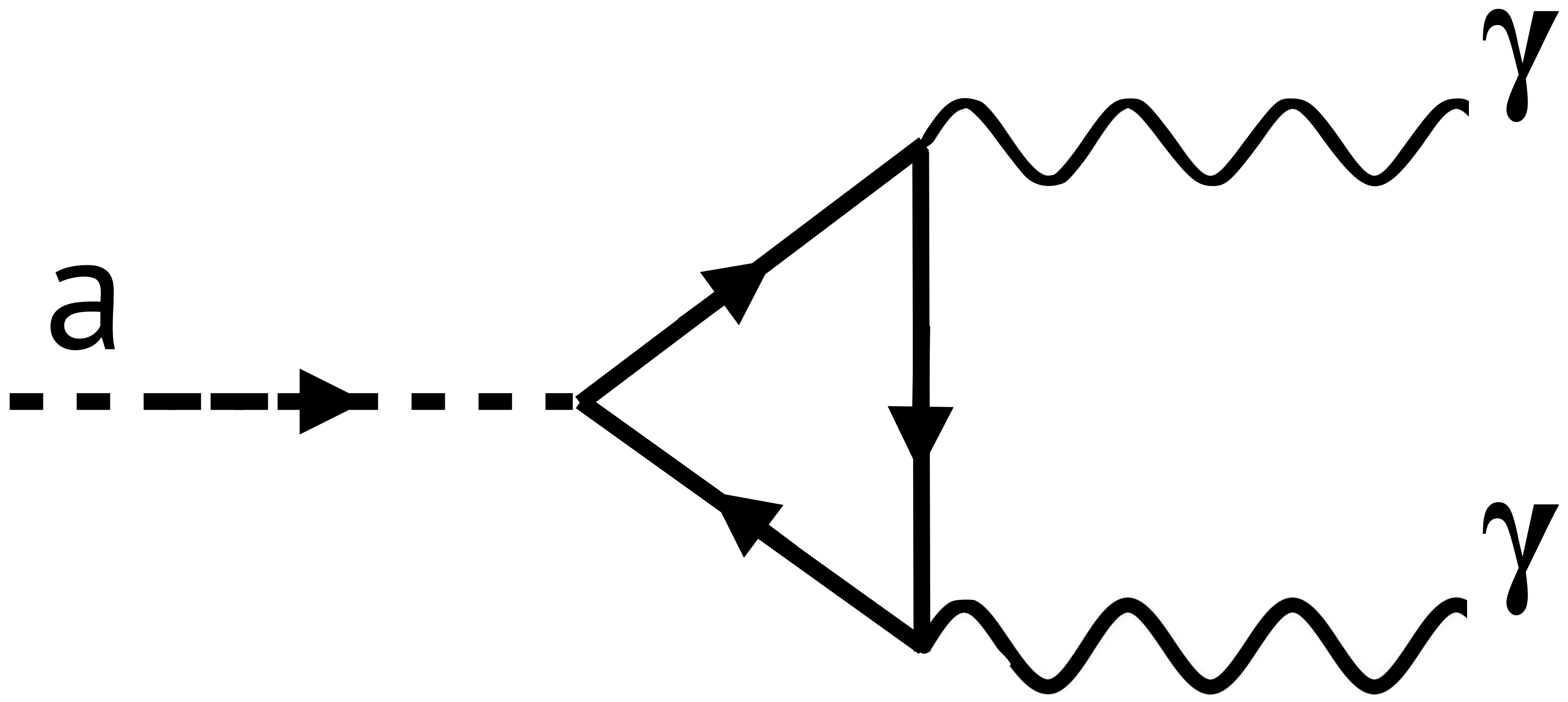

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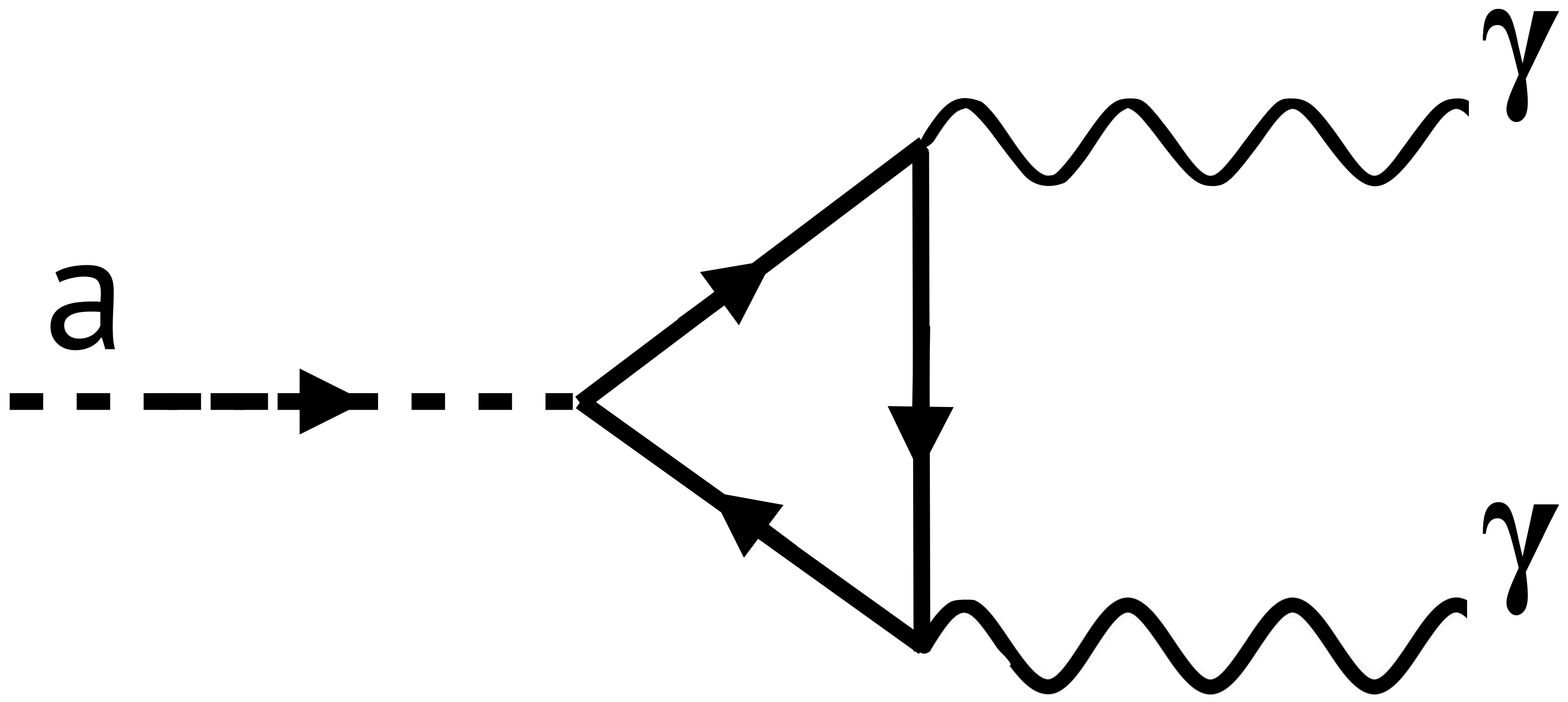

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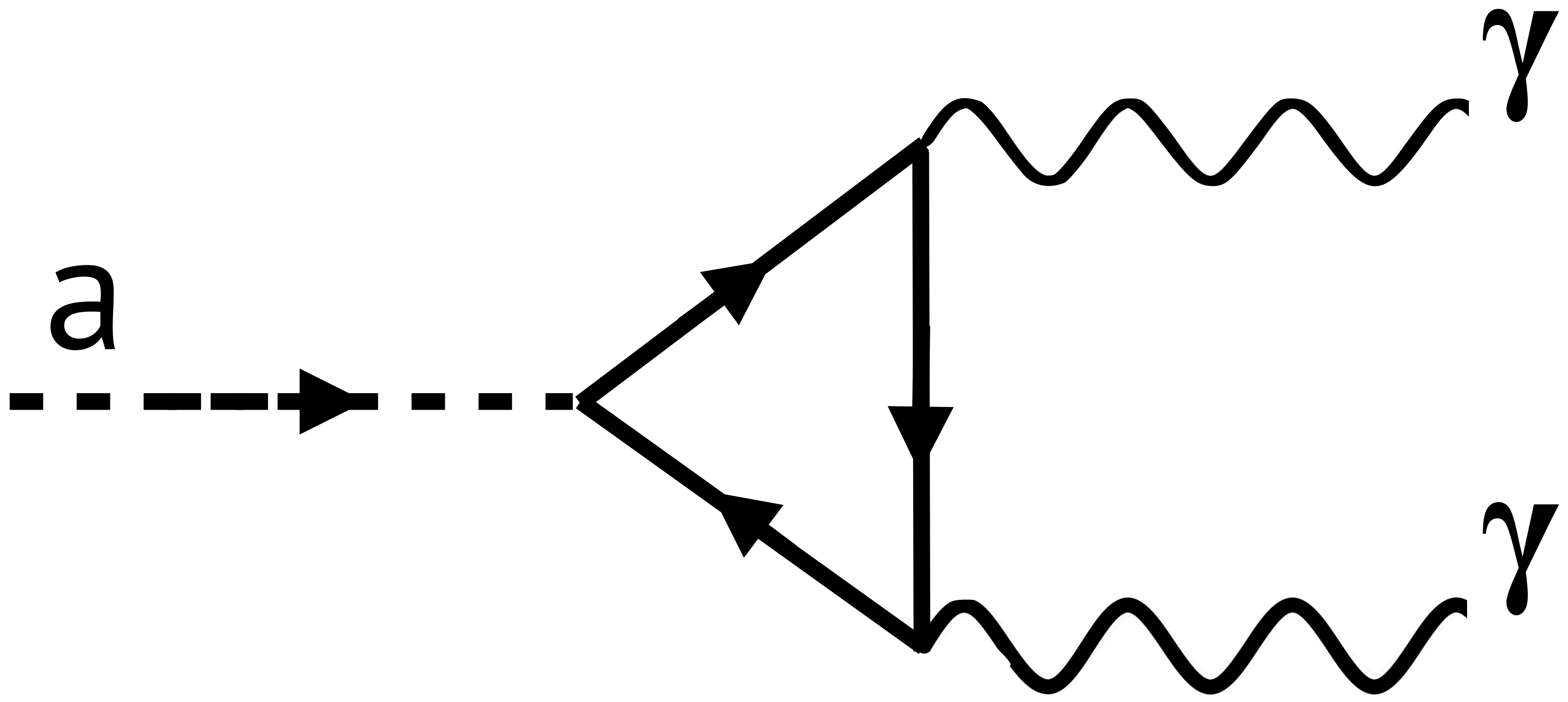

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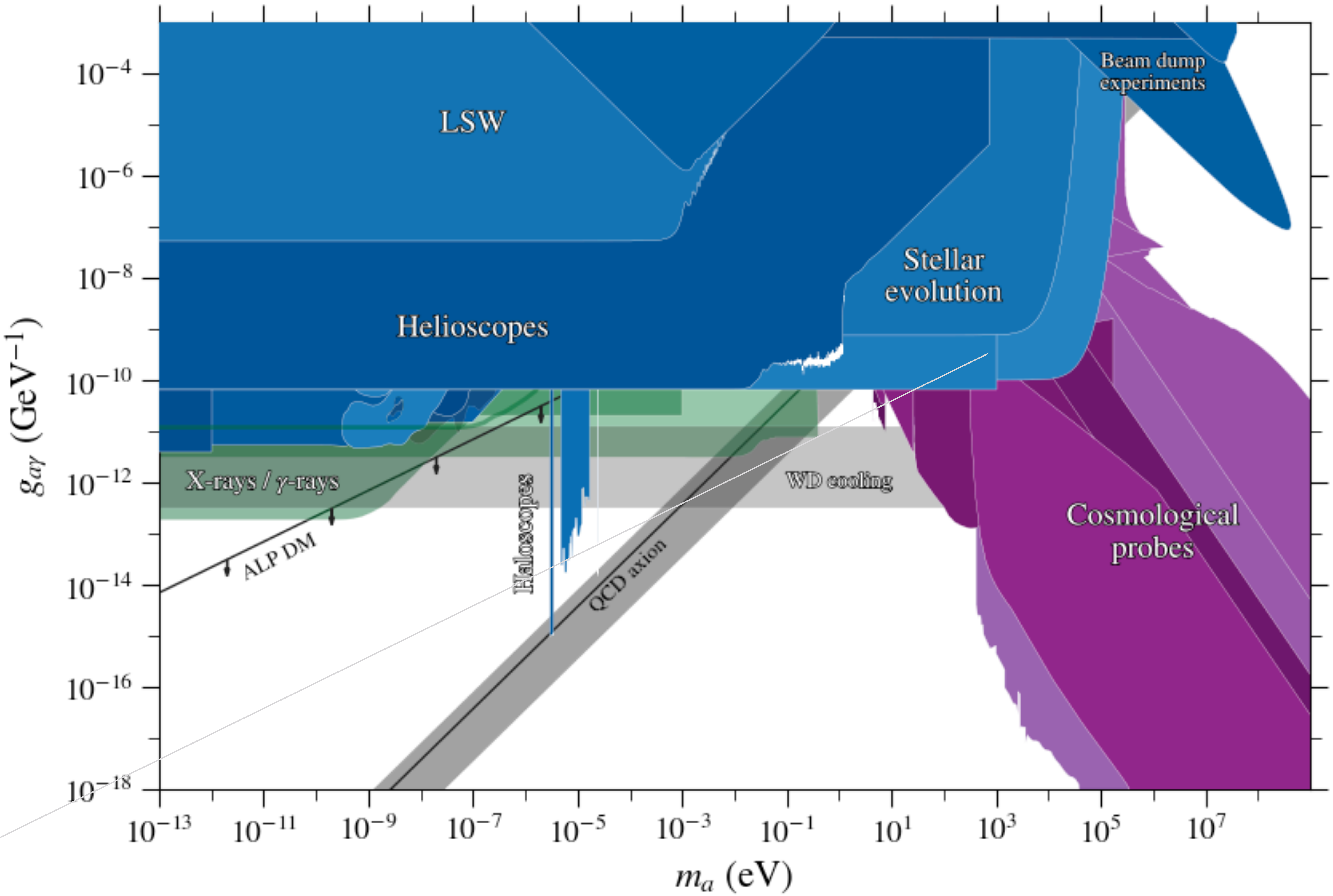
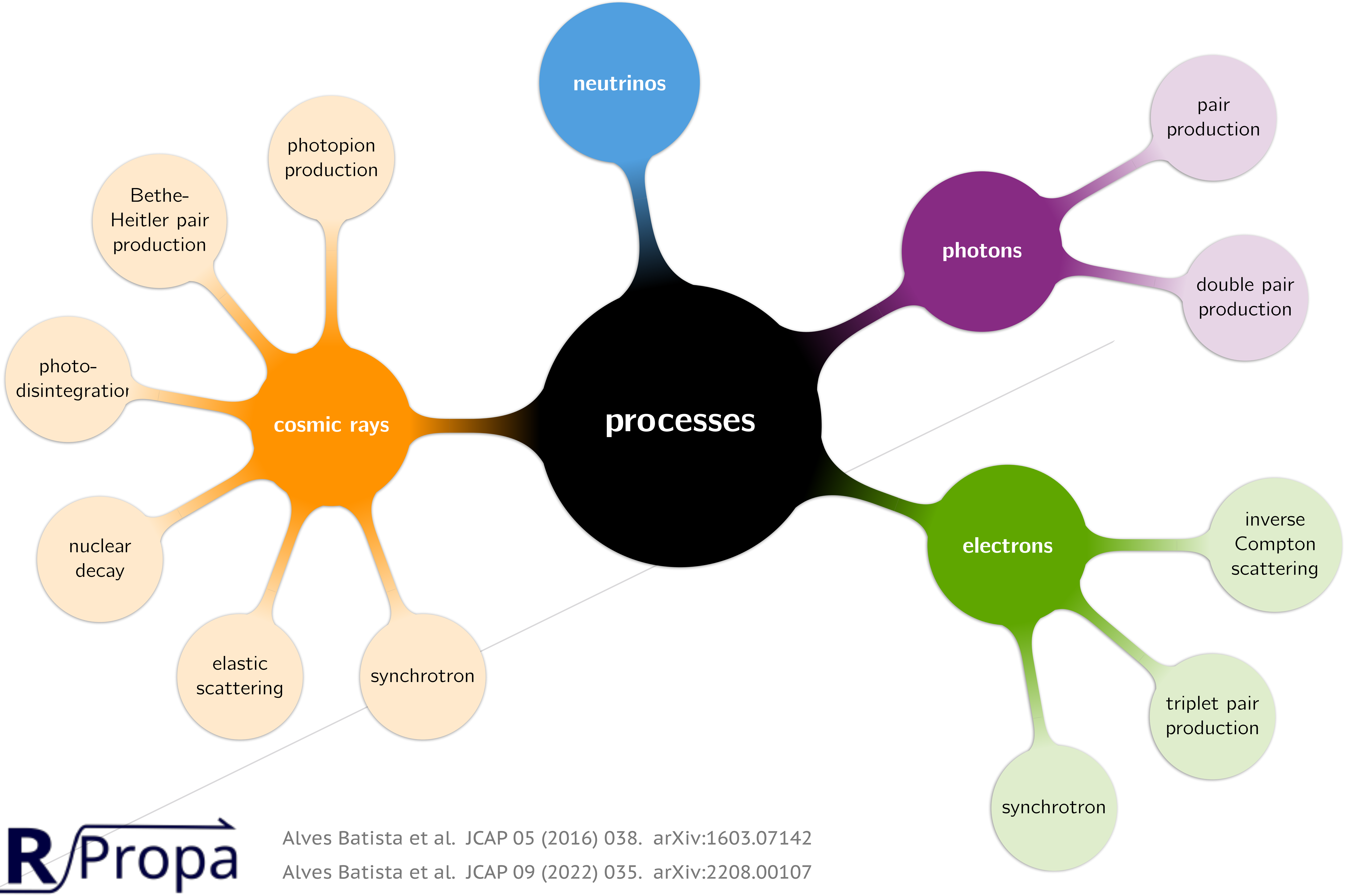
ALP field

axion-like particles: parameter space



https://github.com/me-manu/gammaALPsPlot

Monte Carlo simulations of ALP-photon mixing



CRPropa

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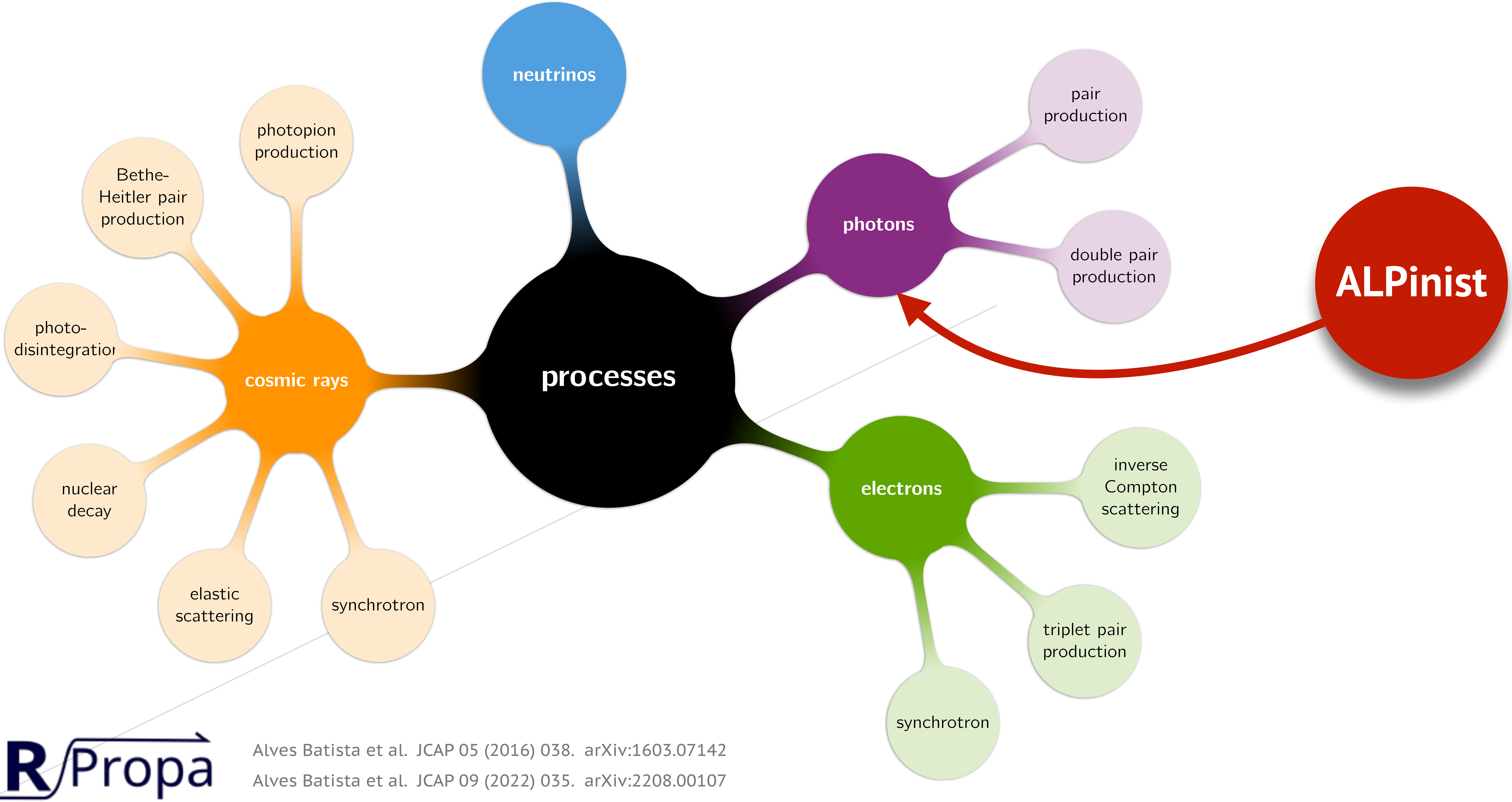

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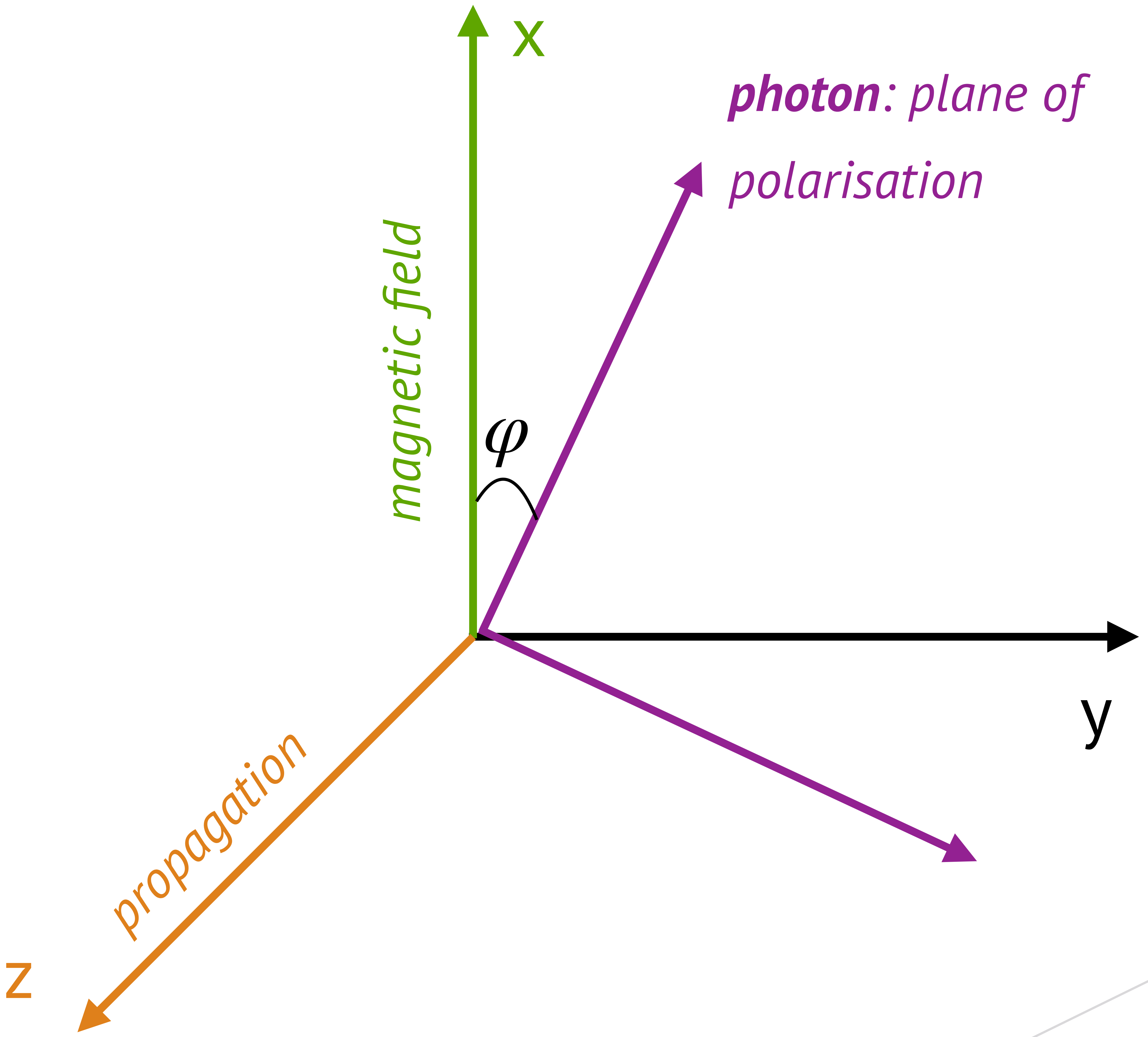
ALPinist: implementation



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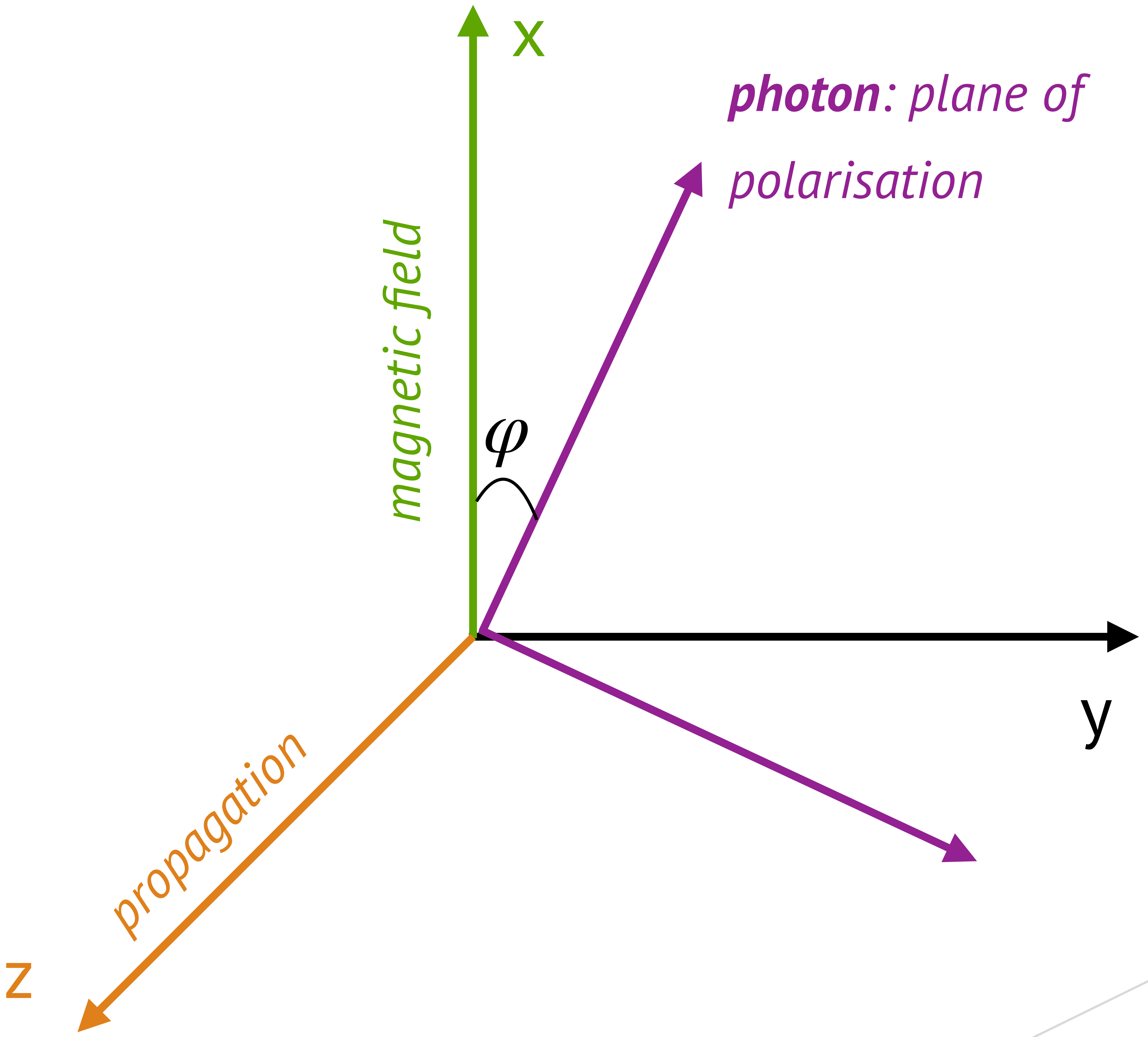

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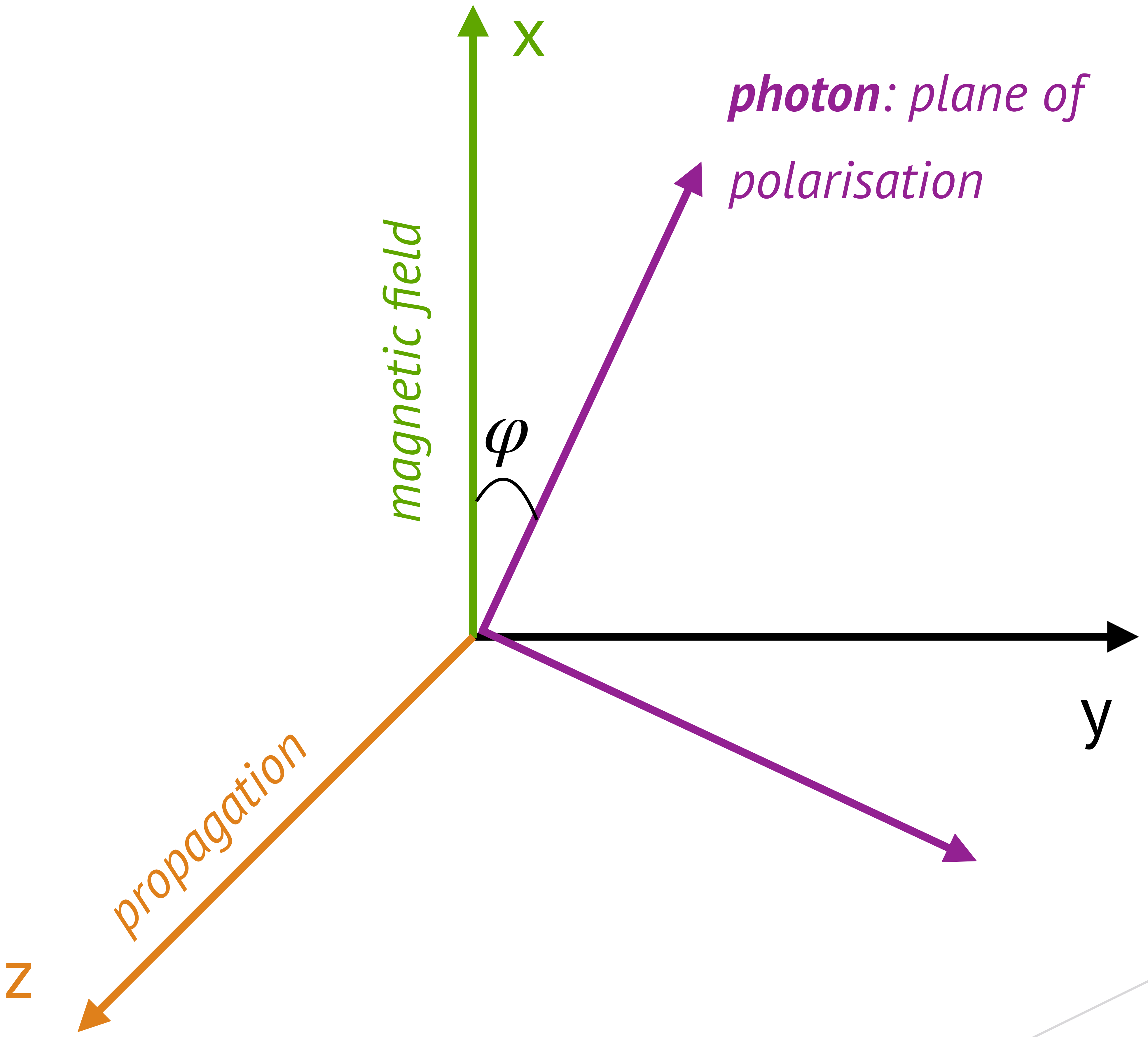

three-state quantum system

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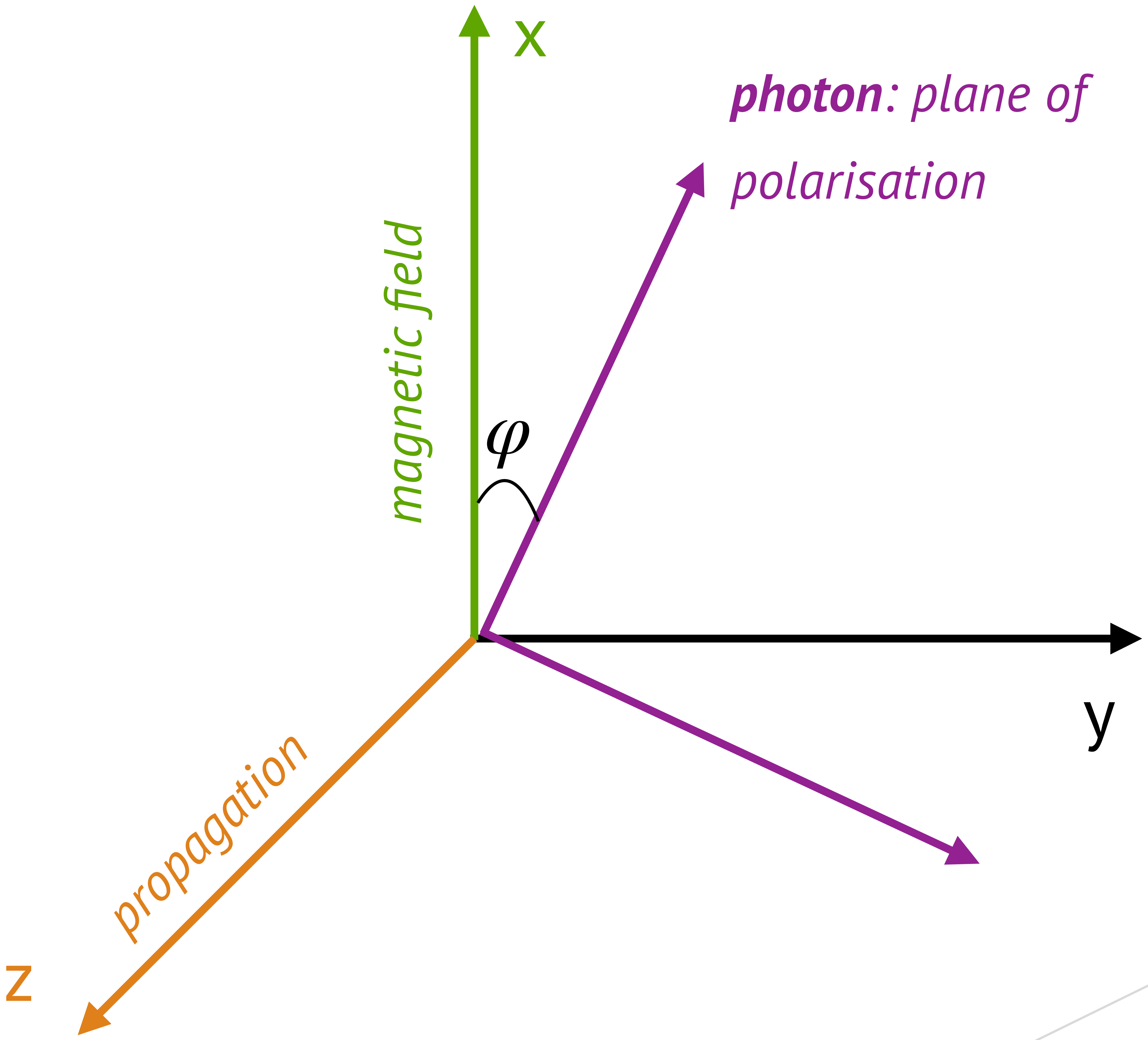

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$$\mathscr{A}(z) = \begin{pmatrix} A_1(z) \\ A_2(z) \\ a(z) \end{pmatrix}$$

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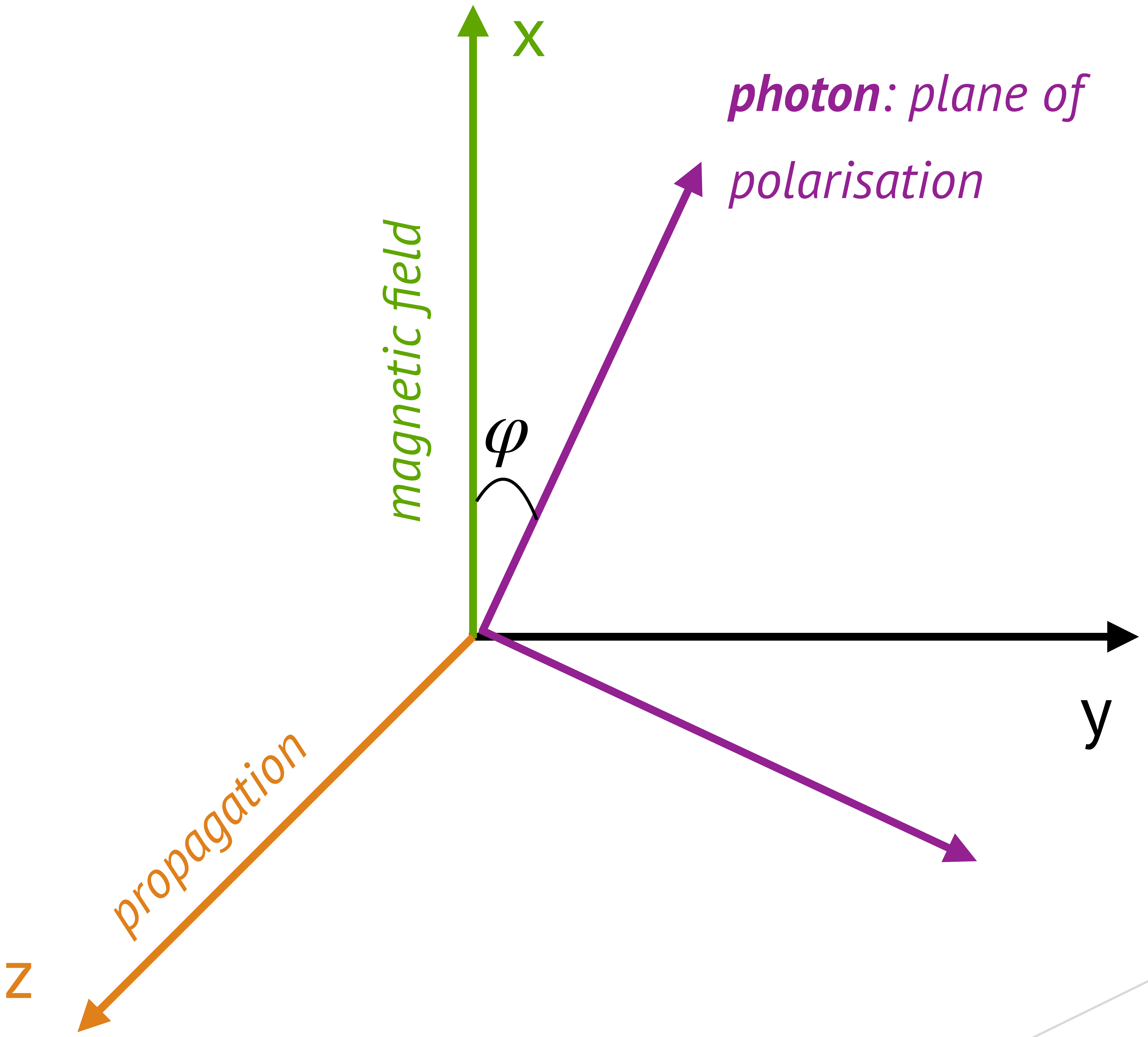

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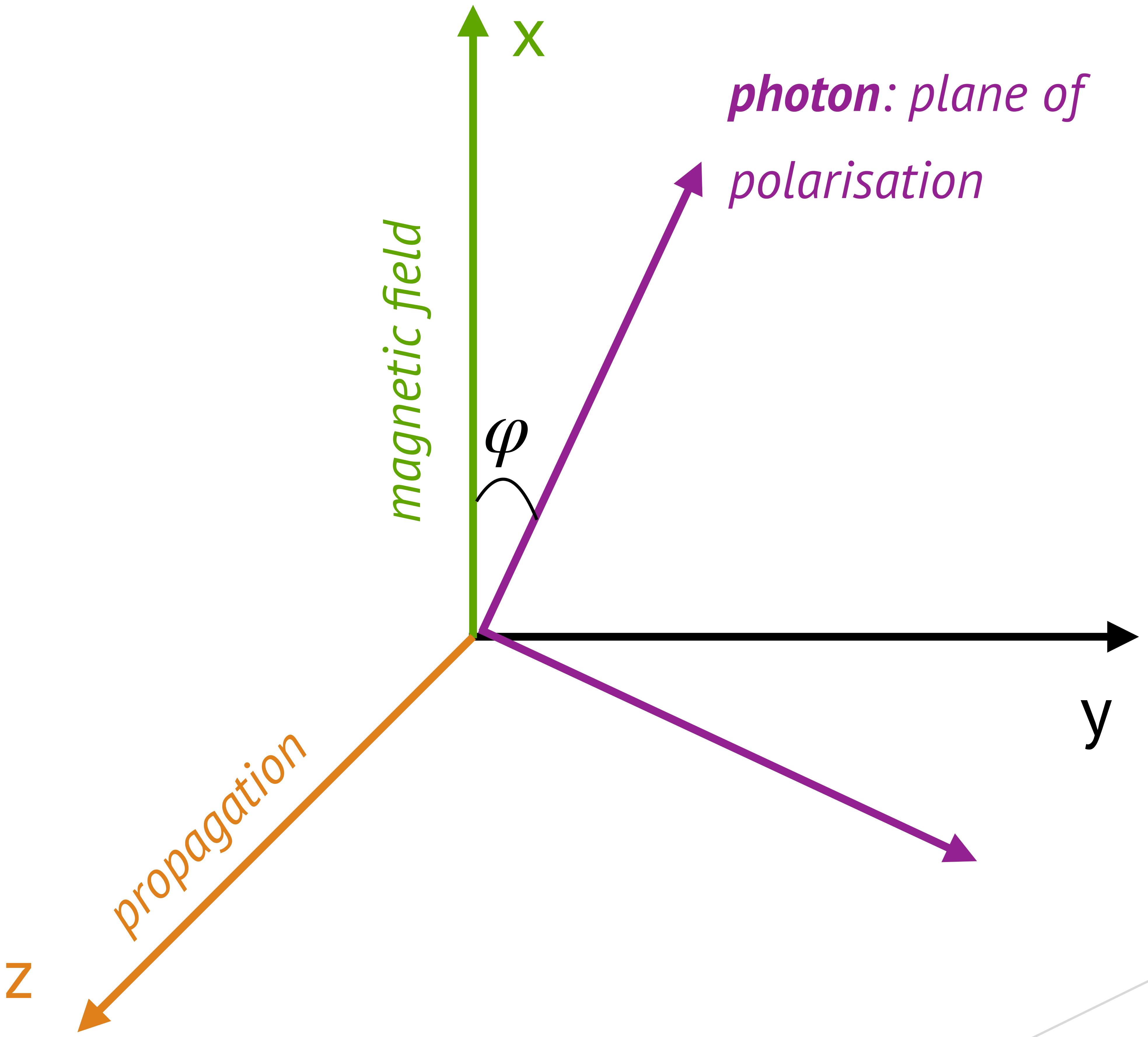

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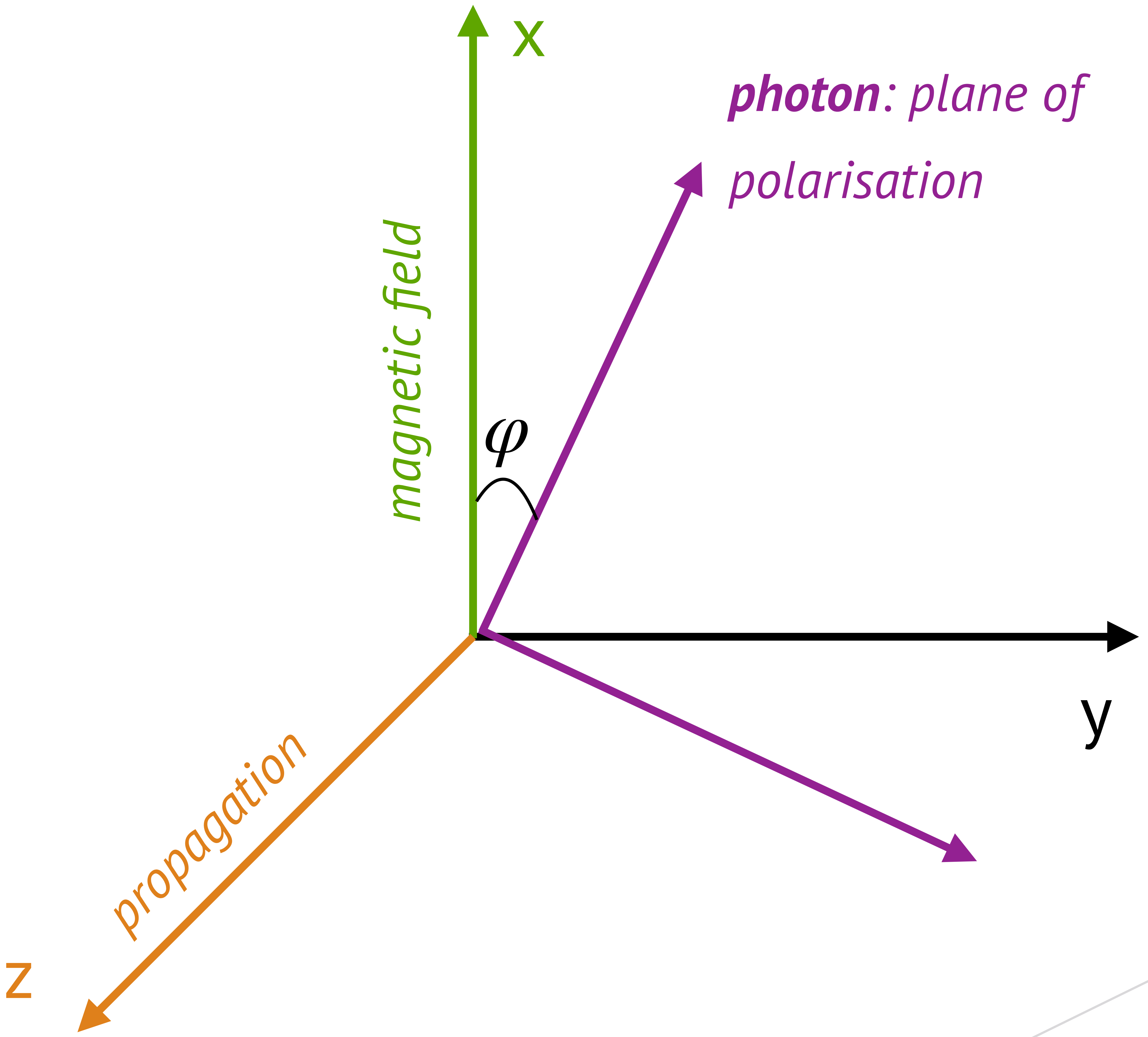

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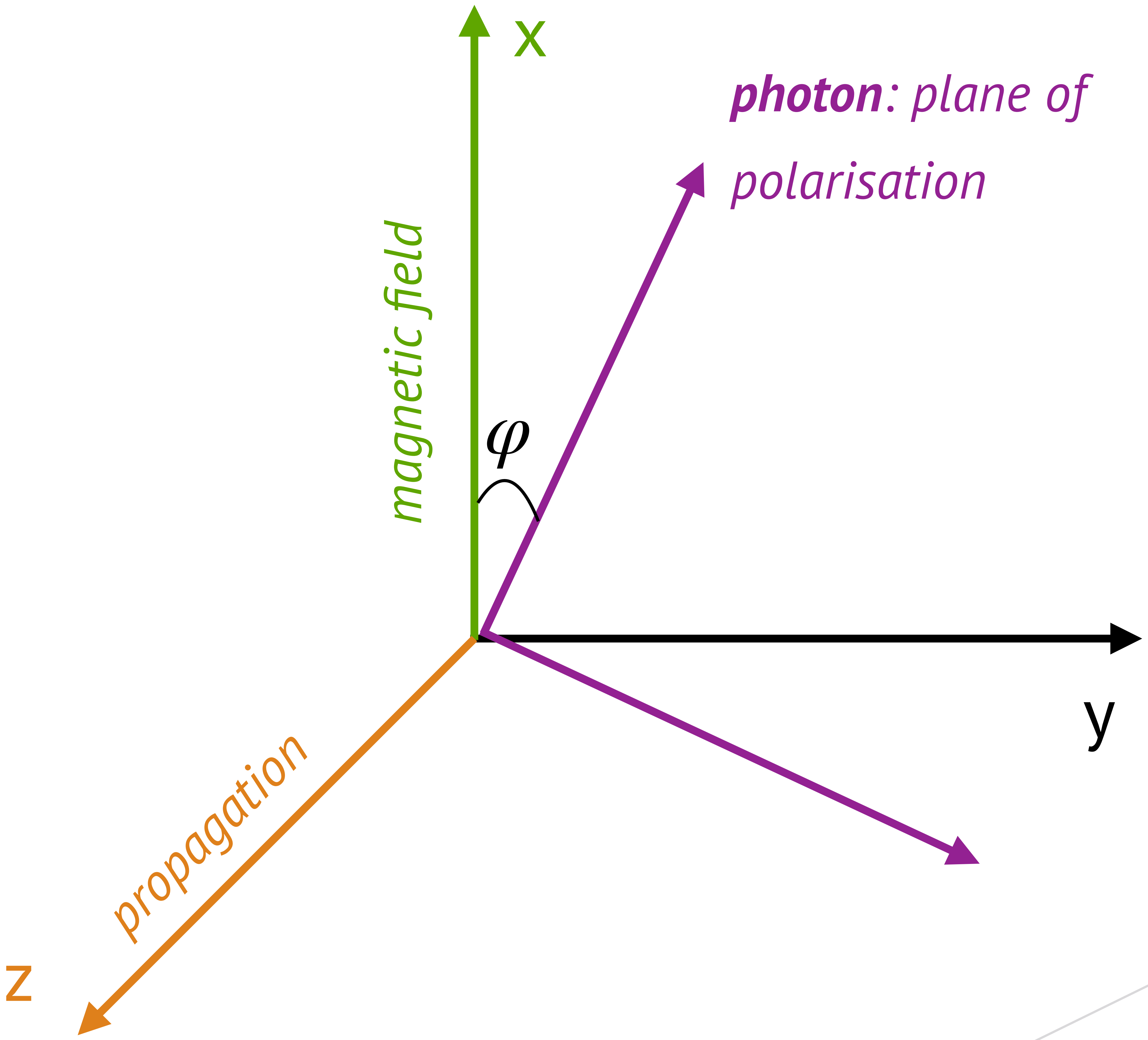

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- initial ALP state needed to build wave function
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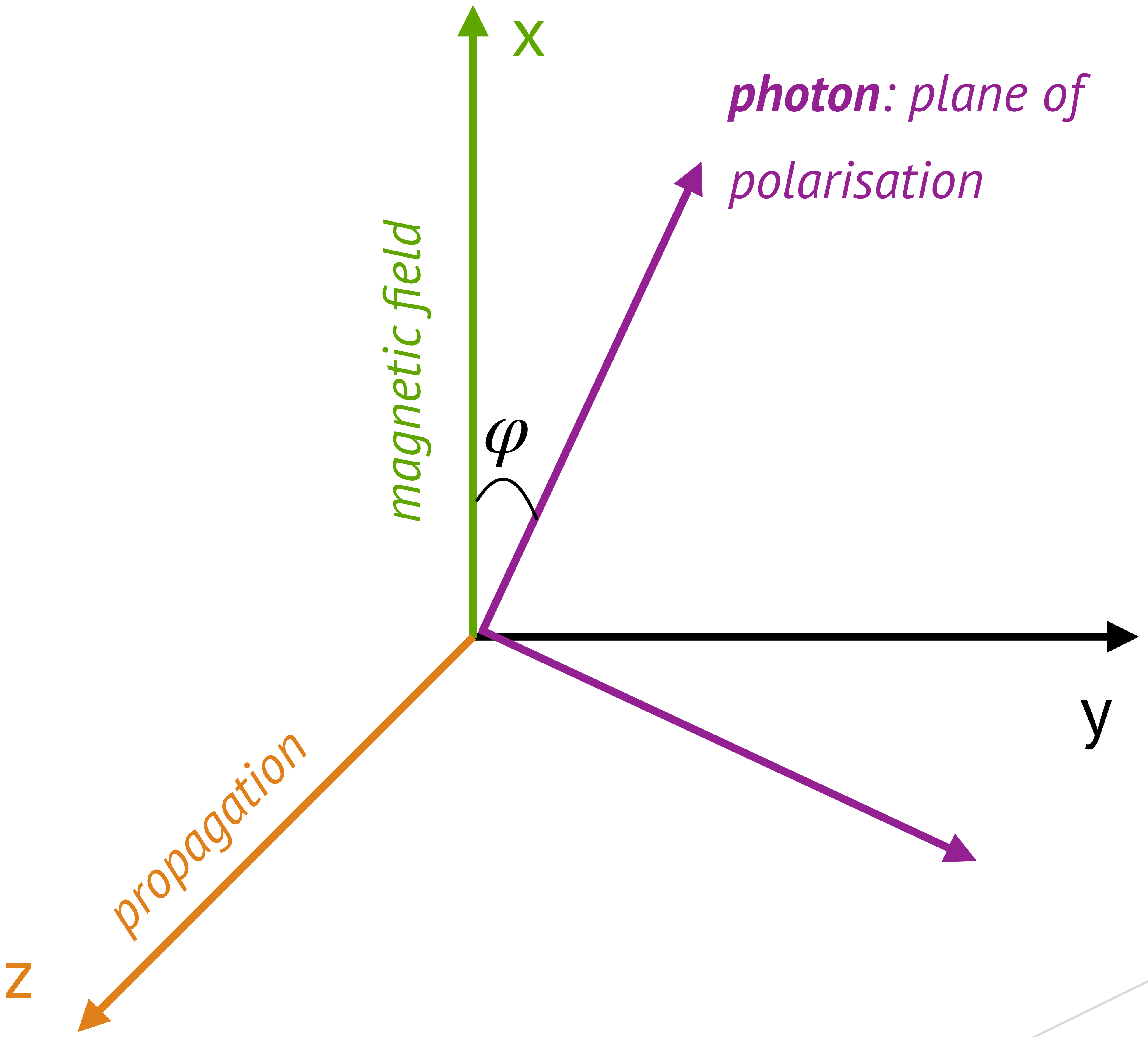

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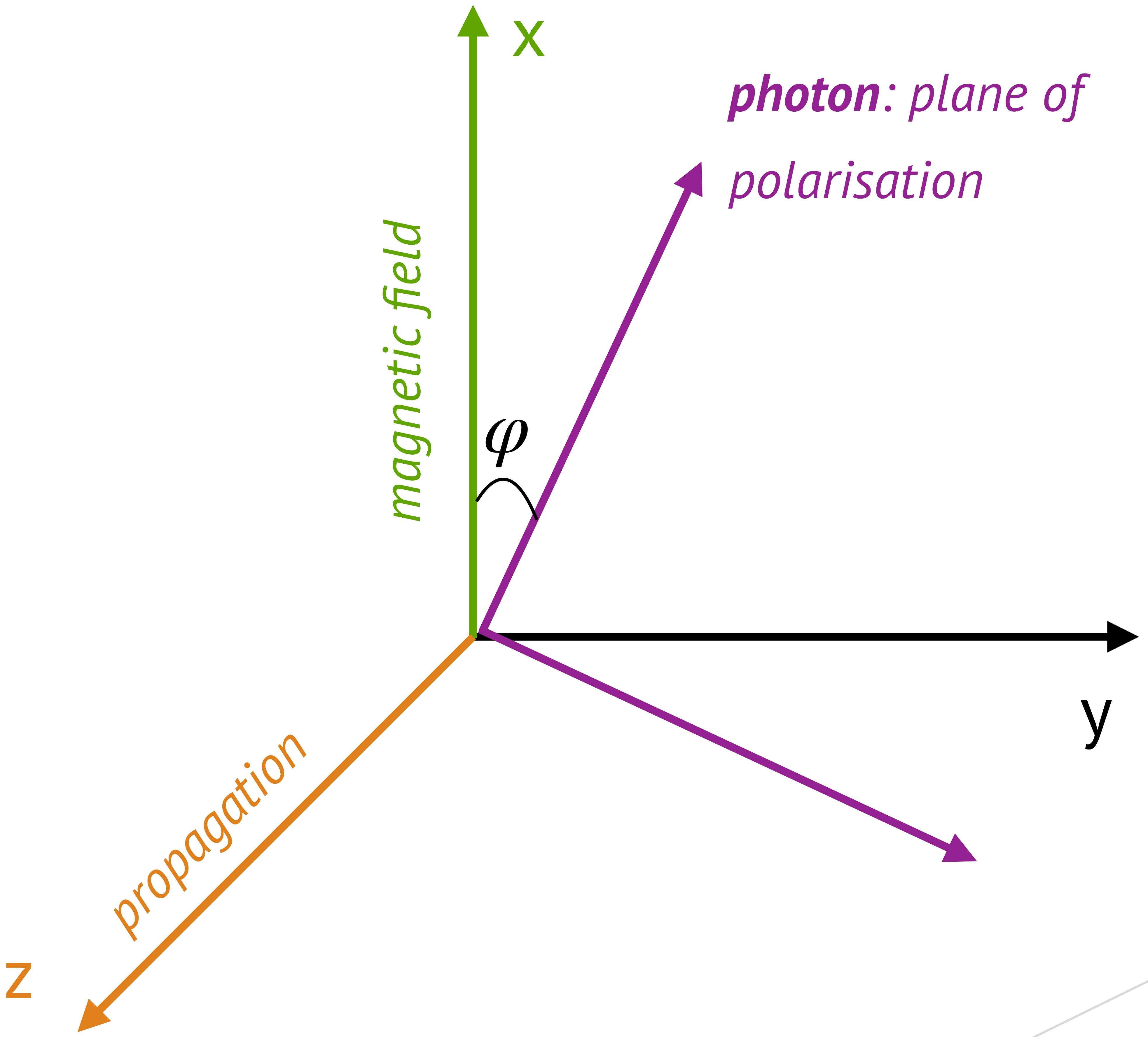
```
source.add(alp.SourceALPState(0., 0.))
source.add(alp.SourceNoPolarisation())
```

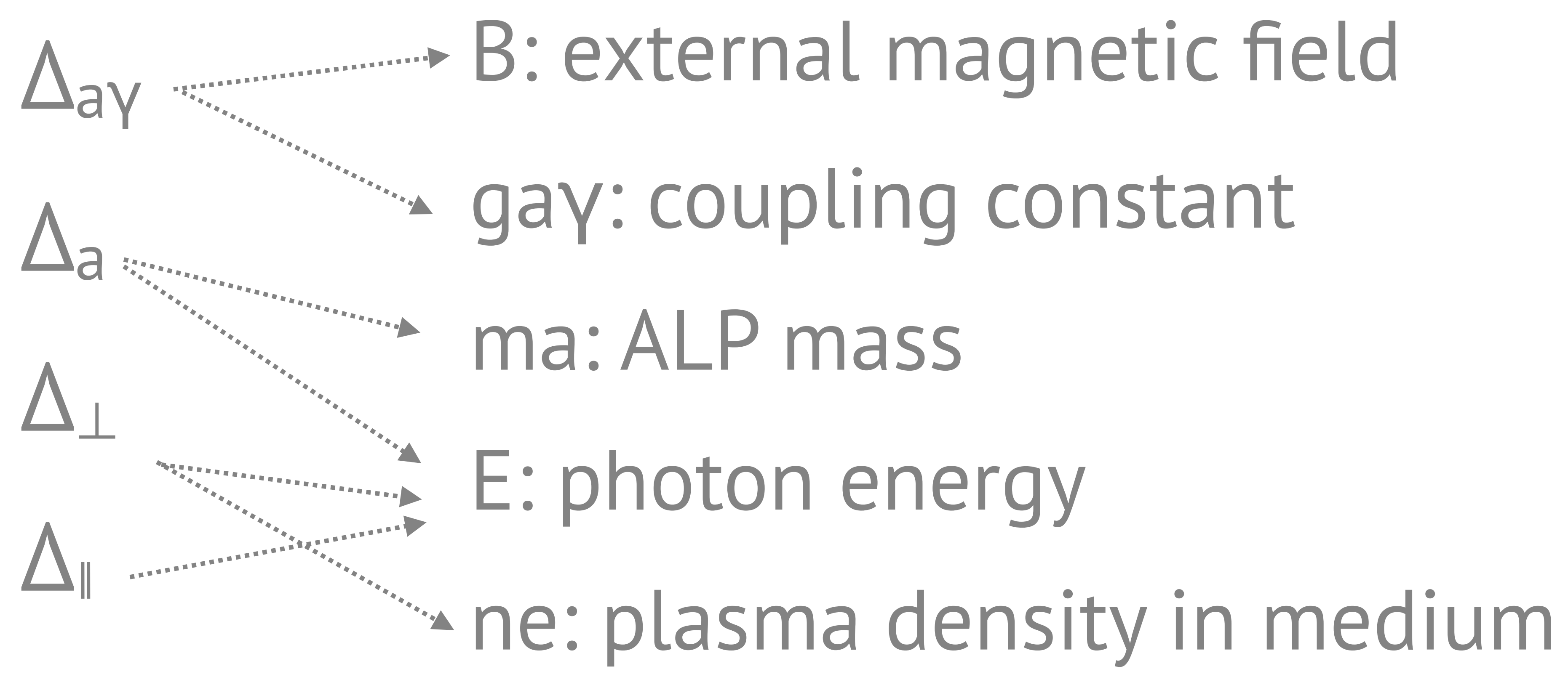
ALPinist: implementation



mixing matrix

$$
\mathbb{M} = \begin{pmatrix} \Delta_{\parallel} \cos^2 \varphi + \Delta_{\perp} \sin^2 \varphi & \left(\Delta_{\parallel} - \Delta_{\perp}\right) \sin \varphi \cos \varphi & \Delta_{a\gamma} \cos \varphi \\ \left(\Delta_{\parallel} - \Delta_{\perp}\right) \sin \varphi \cos \varphi & \Delta_{\parallel} \sin^2 \varphi + \Delta_{\perp} \cos^2 \varphi & \Delta_{a\gamma} \sin \varphi \\ \Delta_{a\gamma} \cos \varphi & \Delta_{a\gamma} \sin \varphi & \Delta_{a} \end{pmatrix}
$$

depends on



B: external magnetic field

gaγ: coupling constant

ma: ALP mass

E: photon energy

ne: plasma density in medium

equation of motion

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ALPinist: implementation

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density = alp.PlasmaDensityUniform(densityIGM)
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```
alpPhoton = alp.ALPPhotonMixing(axionMass * eV / c_light ** 2, coupling / eV, bField, density, .5)
```

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- random numbers compared to probability of photon-ALP conversion to decide if oscillation occurs

ALPinist: code validation

For a homogeneous magnetic field and medium, the equations of motion can be solved analytically to determine the conversion probability.

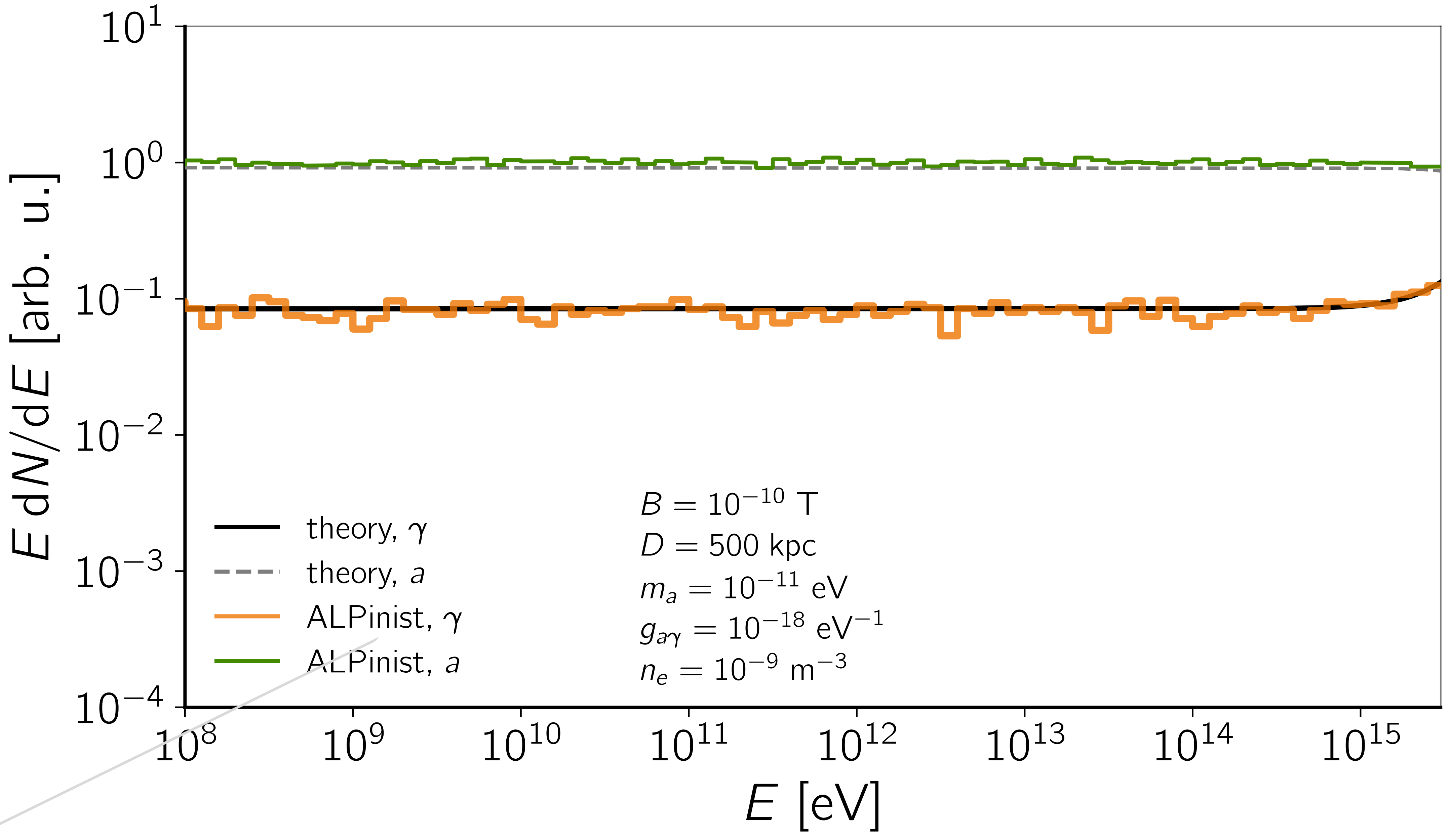
conversion probability

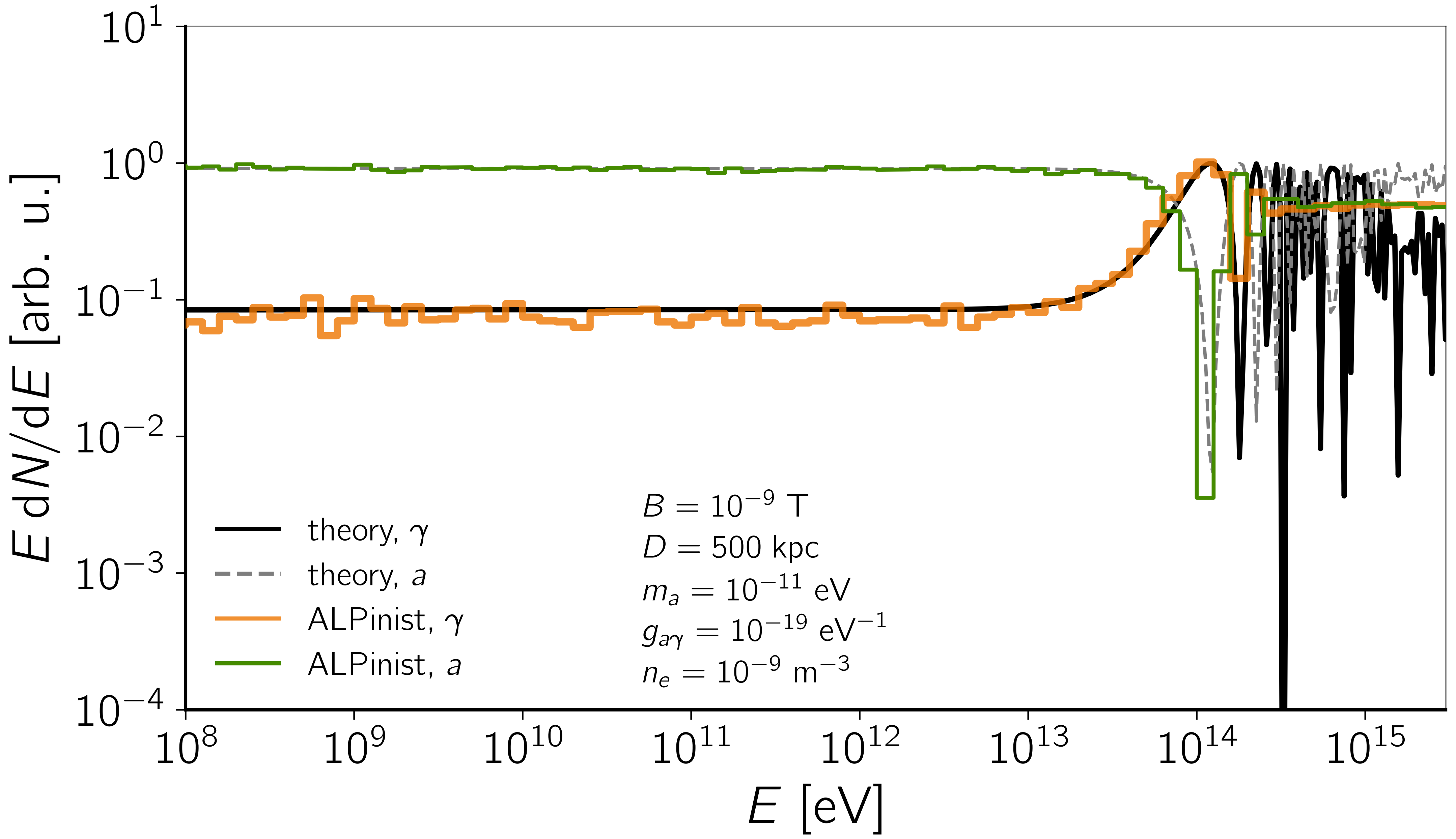
$$P_{a\gamma}(z) = \sin^2\theta \sin^2\left(\frac{z}{2}\sqrt{\left(\Delta_a - \Delta_{\rm pl}\right)^2 + 4\Delta_{a\gamma}}\right)$$

mixing angle

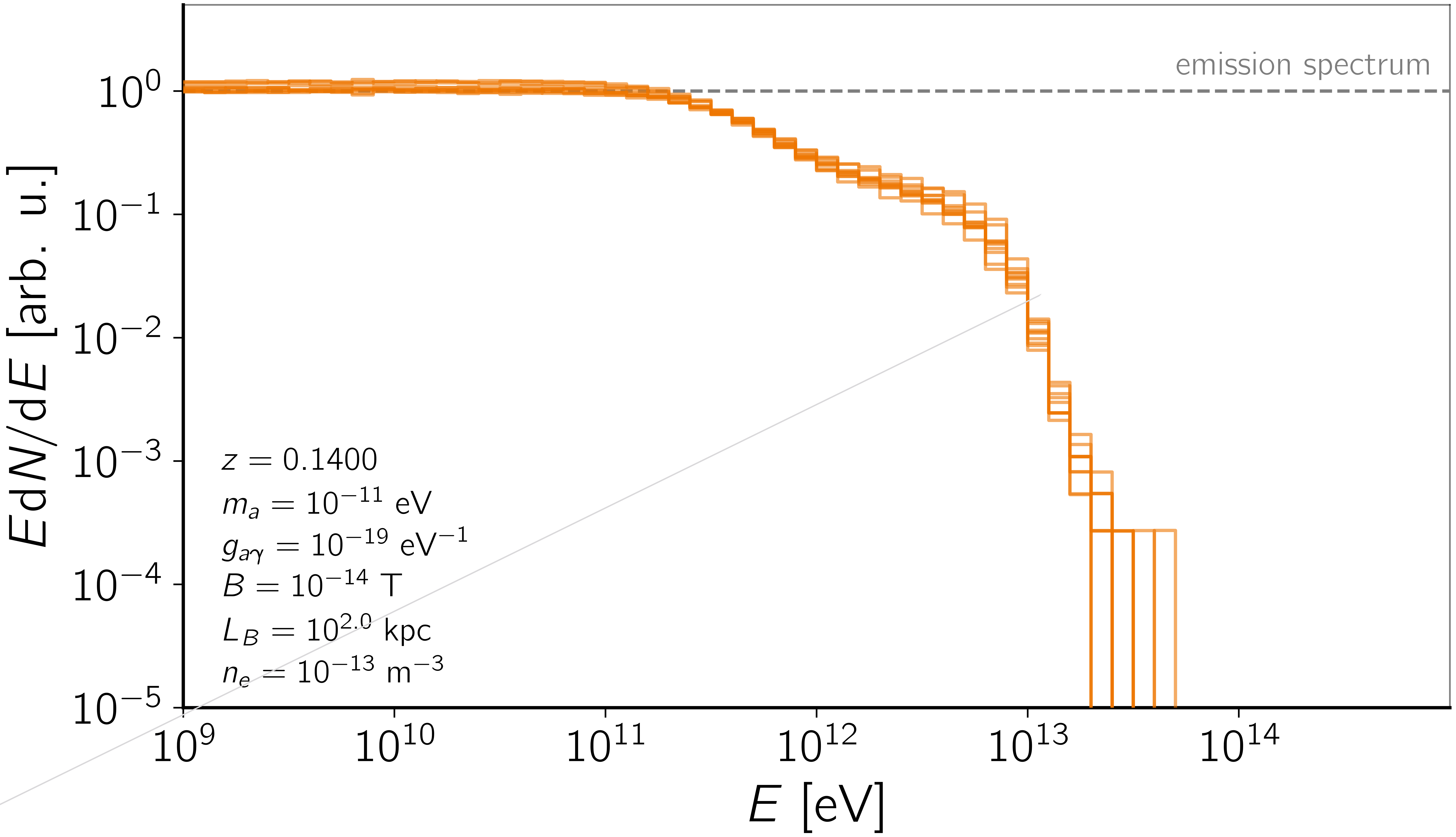
$$\theta = \frac{1}{2}\arcsin\left(\frac{2\Delta_{a\gamma}}{\sqrt{\left(\Delta_a - \Delta_{\rm pl}\right)^2 + 4\Delta_{a\gamma}}}\right)$$

For θ=45° mixing is maximal and an oscillatory behaviour sets in.

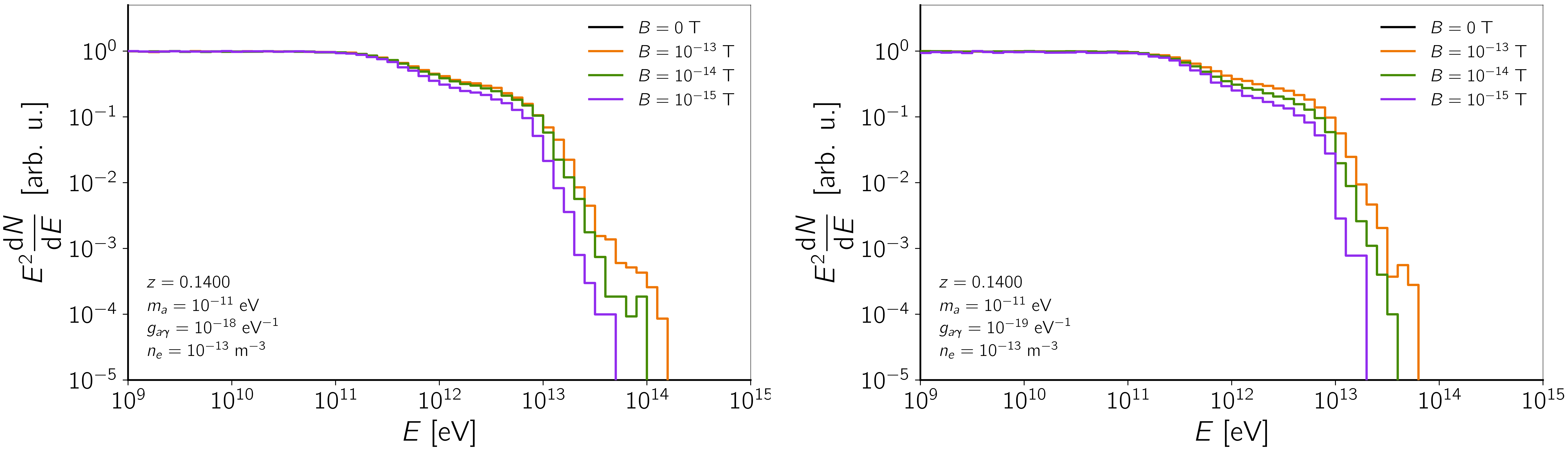




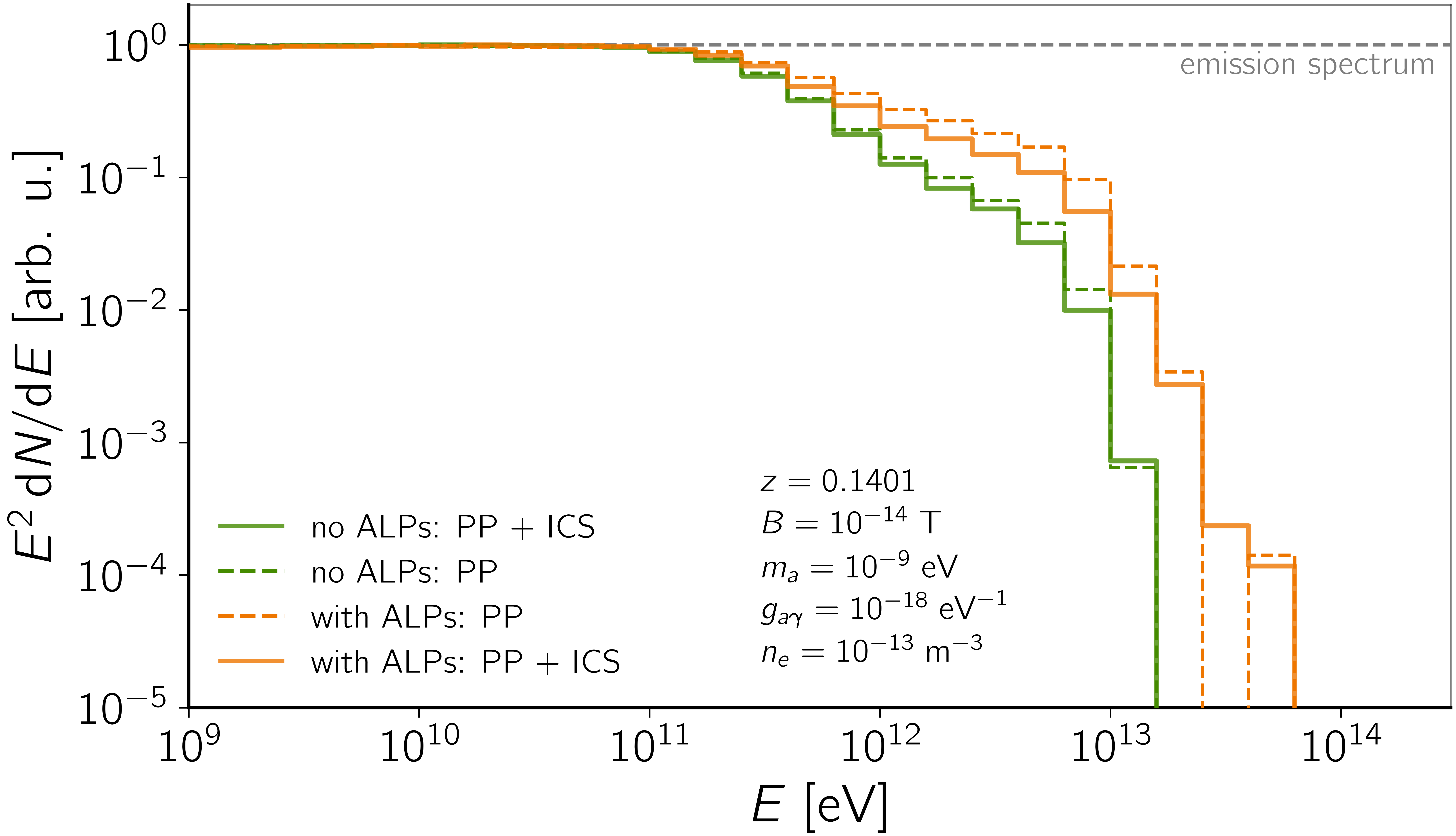
simulations with turbulent magnetic fields



simulations with pair production and turbulent magnetic fields



adding inverse Compton scattering



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  - inverse Compton scattering can only be treated if the initial photons are *unpolarised*
- first-ever simulations of electromagnetic cascades including all effects: pair production + inverse Compton scattering + ALP-photon mixing
  - cascades initiated via inverse Compton can provide an additional contribution to the gamma-ray flux