PHOTON-ALP WIGGLES IN PHOTON SPECTRA

(www.tuhogar.com)

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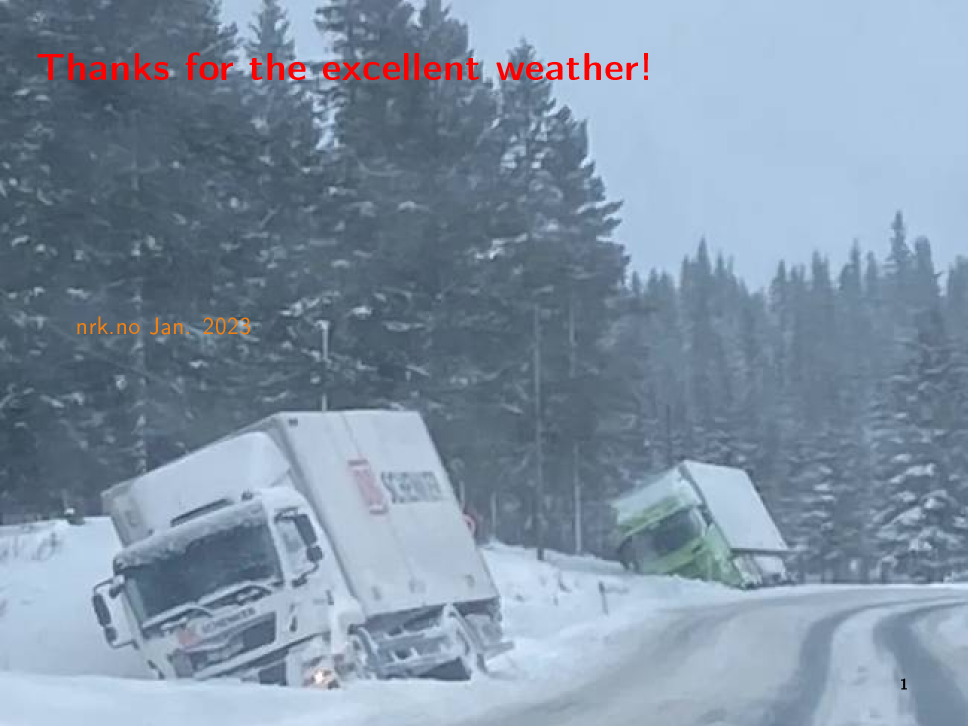
Supervisor: Michael Kachelrieß
Norwegian University of Science and Technology

TMEX 2023

Thanks for the excellent weather!



nrk.no Jan. 2023

Content

Why axions and axion-like particles (ALPs)?

Signatures of photon-ALP oscillations

Detecting “ALP wiggles”

Comment on the modeling of the magnetic field

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Warning: I have a tendency to refer to ALPs as both axion and ALP...

The strong CP problem and axions

$$\mathcal{L}_{\mathrm{SM}} \supset \frac{\vartheta g^2}{8\pi^2} G\tilde{G}, \quad \vartheta \in [0, 2\pi)$$

- Measurements of the neutron dipole moment $\Rightarrow |\vartheta| \lesssim 10^{-10}$

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- Measurements of the neutron dipole moment $\Rightarrow |\vartheta| \lesssim 10^{-10}$
- Fine tuning: Why not $\vartheta = \mathcal{O}(1)$?!
- The Peccei-Quinn solution: (Peccei, Quinn 1977)
  Promote ϑ to a field which dynamically relaxes to 0 (by introducing a U(1) chiral symmetry spontaneously broken)

Peccei and Quinn overlooked an important, testable consequence of their idea. The particles produced by their neutralizing field – its quanta – are predicted to have remarkable properties. Since they didn't take note of these particles, they also didn't name them. That gave me an opportunity to fulfill a dream of my adolescence.

Frank Wilczek (Quanta Magazine 2016)

A few years before, a supermarket display of brightly colored boxes of a laundry detergent named Axion had caught my eye. It occurred to me that “axion” sounded like the name of a particle and really ought to be one. So when I noticed a new particle that “cleaned up” a problem with an “axial” current, I saw my chance.

Frank Wilczek (Quanta Magazine 2016)

...testable consequence...

$$\mathcal{L} \supset \frac{g^2}{16\pi^2} \frac{a}{f_a} G \tilde{G}$$

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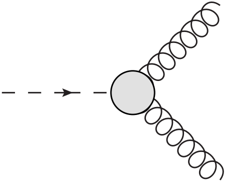

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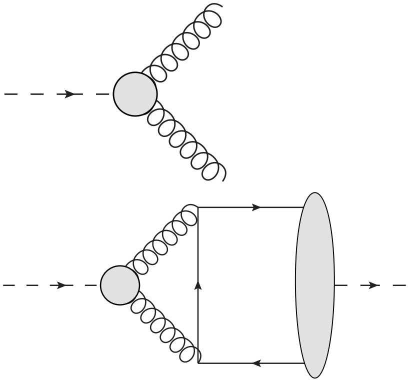

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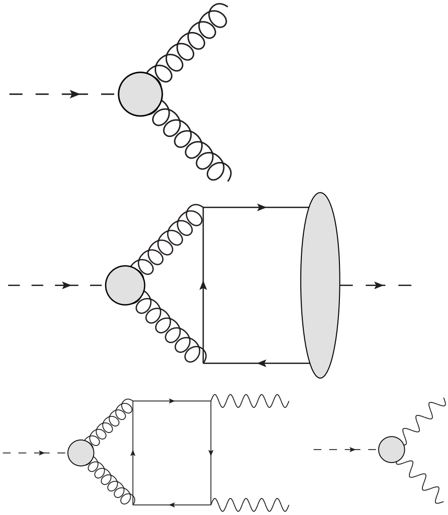
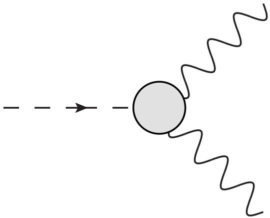
- Photon-coupling



Axion-like particles (ALPs)



- Scalar particles with spin 1, mass m_a, coupling $g_{a\gamma}$

$$\mathcal{L}_{\mathrm{SM}} \supset \frac{1}{2}\partial^{\mu} a \partial_{\mu} a - \frac{1}{2} {m_a}^2 a^2 \left[1 - \cos(a/f_a)\right] - \frac{1}{4} g_{a\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a$$

- Common in theories with spontaneous symmetry breakings
- QCD axion: $g_{a\gamma} \approx 10^{-19} m_a/\mathrm{eV}^2$
- Can explain inflation (inflaton), dark energy, dark matter, ...

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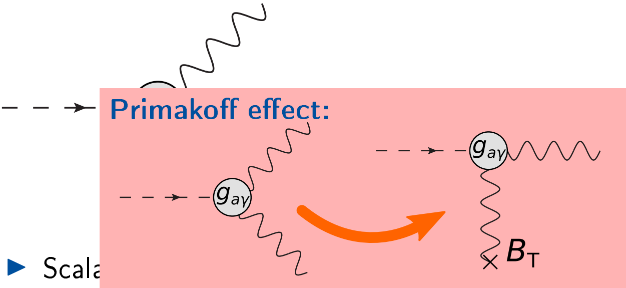

- Scala … $g_{a\gamma}$

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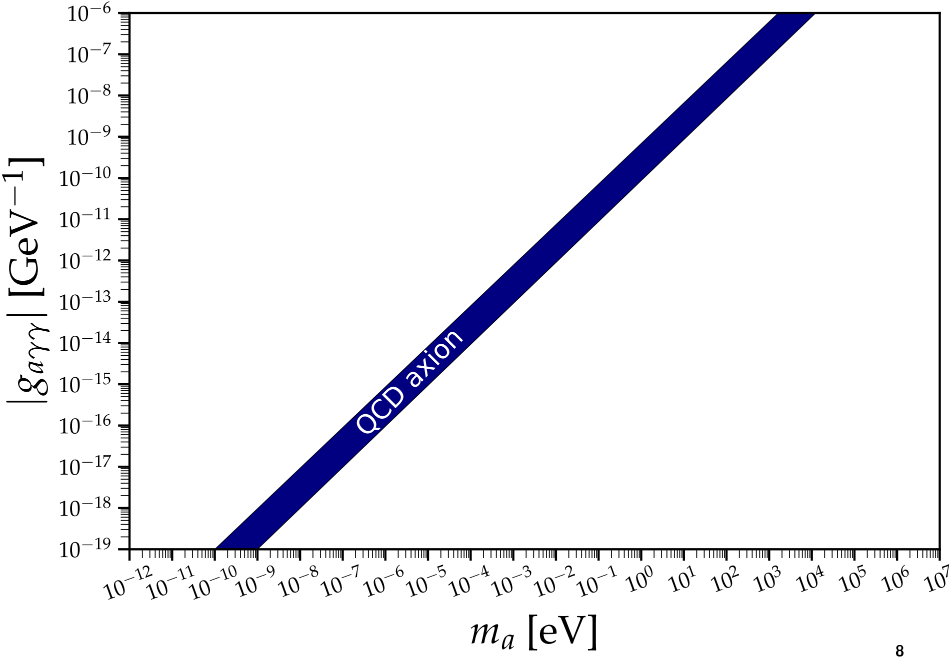

QCD axion
$|g_{a\gamma\gamma}|$ [GeV^{-1}]
m_a [eV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
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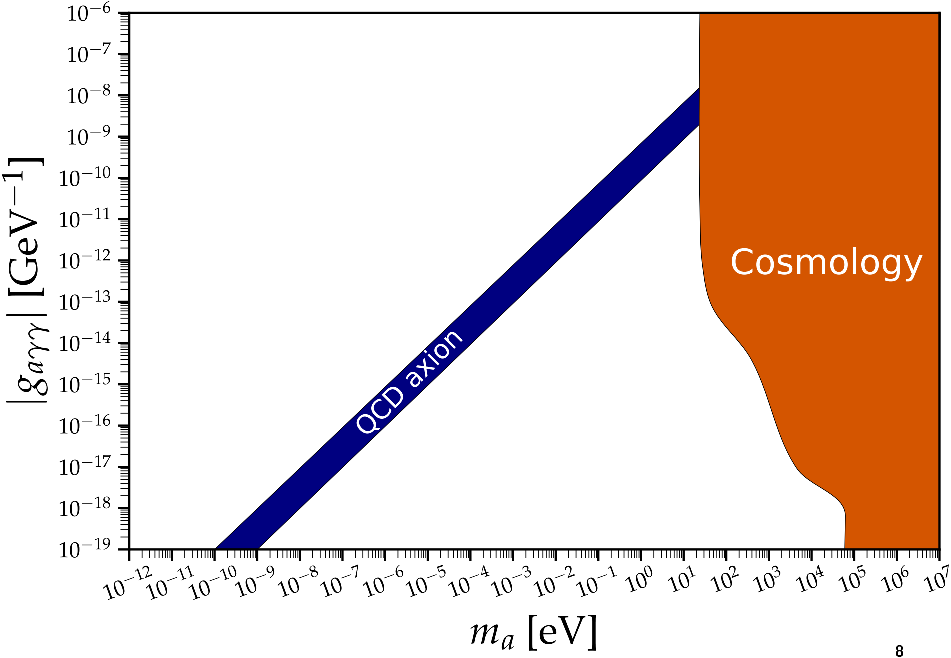
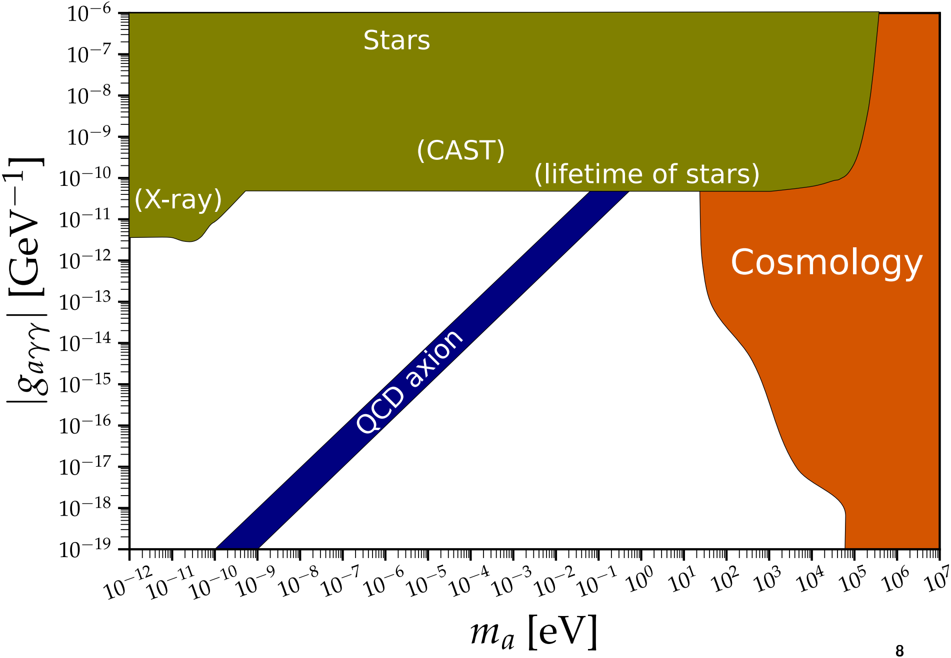


QCD axion
Cosmology
$|g_{a\gamma\gamma}|$ [GeV^{-1}]
m_a [eV]


Stars
(CAST)
(lifetime of stars)
(X-ray)
Cosmology
QCD axion
$|g_{a\gamma\gamma}|$ [GeV^{-1}]
m_a [eV]
10^{-6}
10^{-7}
10^{-8}
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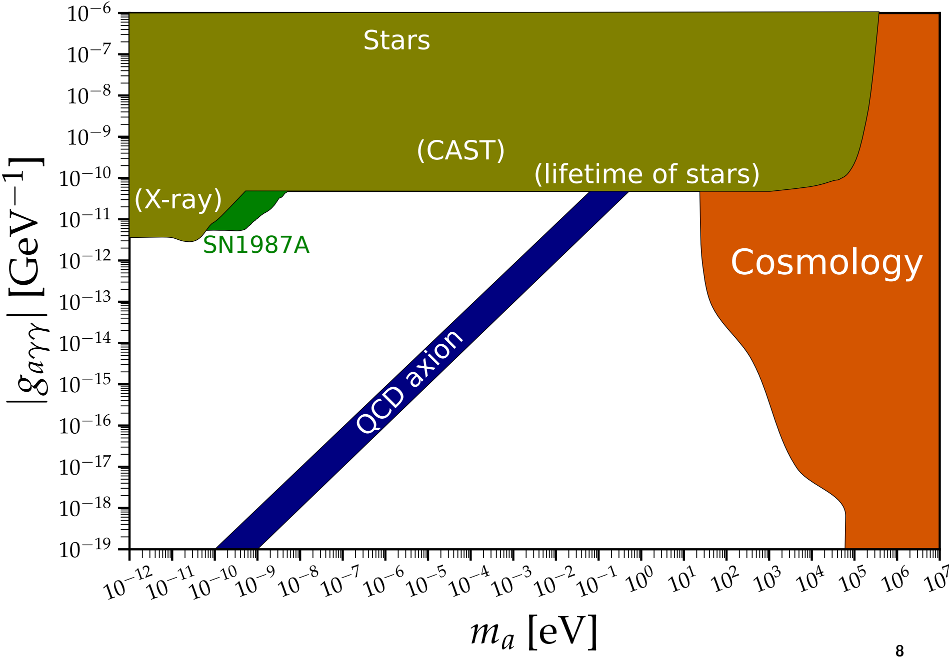
Stars
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SN1987A
Cosmology
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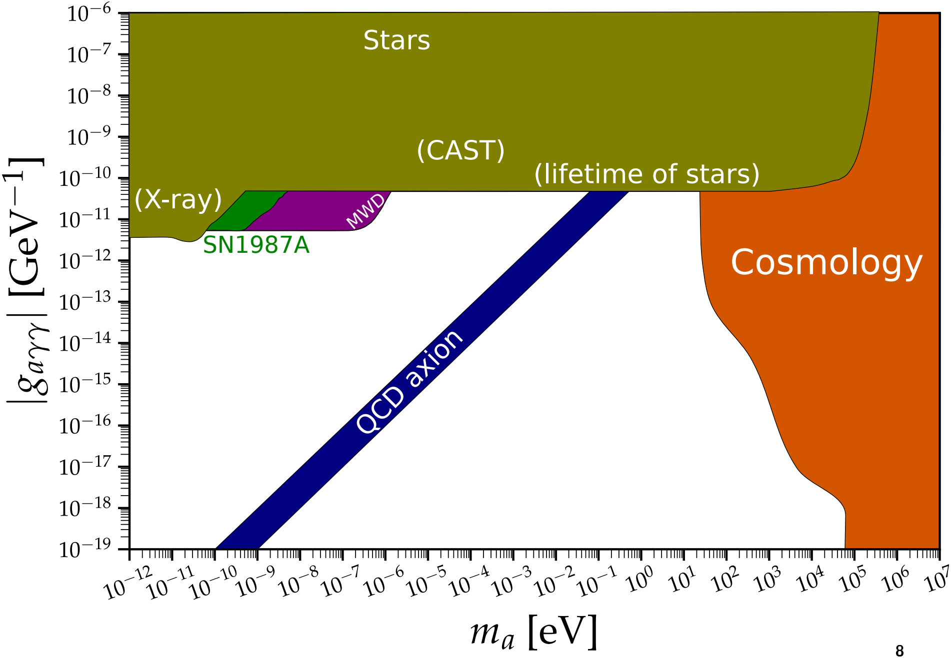
Stars
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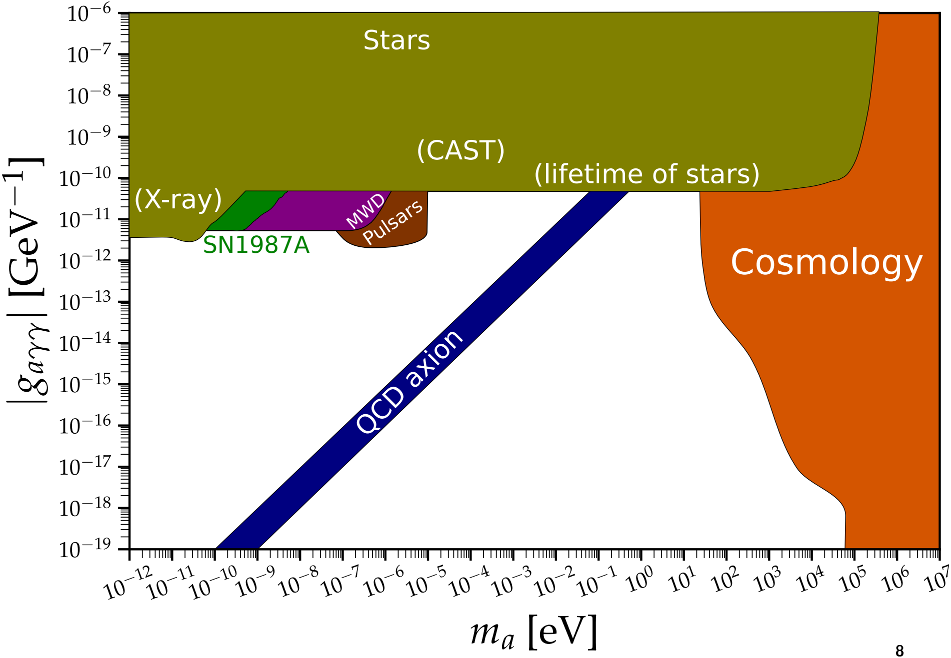
Stars
(CAST)
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(X-ray)
SN1987A
MWD
Pulsars
Cosmology
QCD axion
$|g_{a\gamma\gamma}|$ [GeV^{-1}]
m_a [eV]
10^{-6}
10^{-7}
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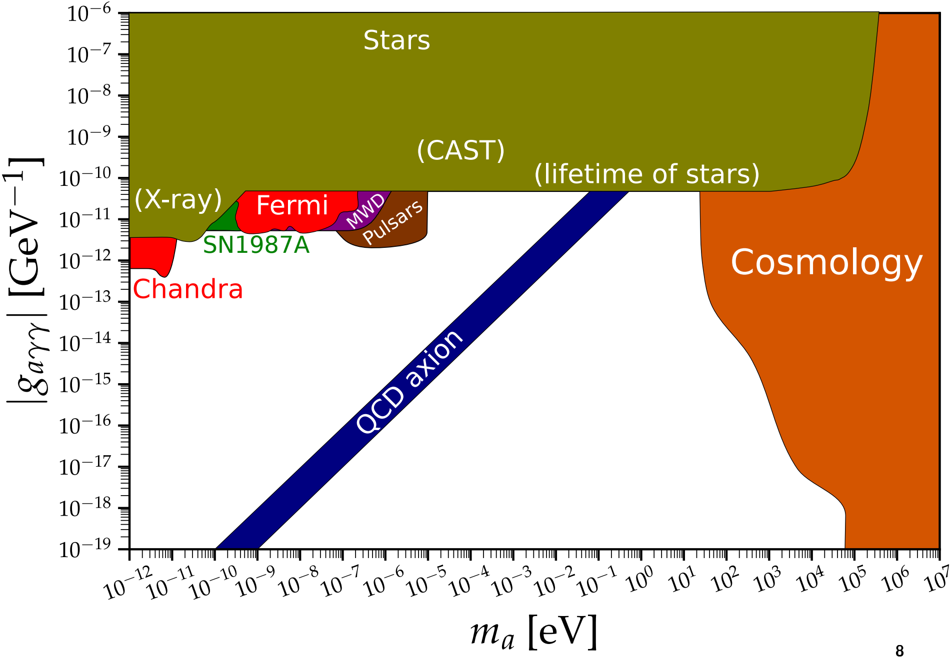
Stars
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Chandra
Cosmology
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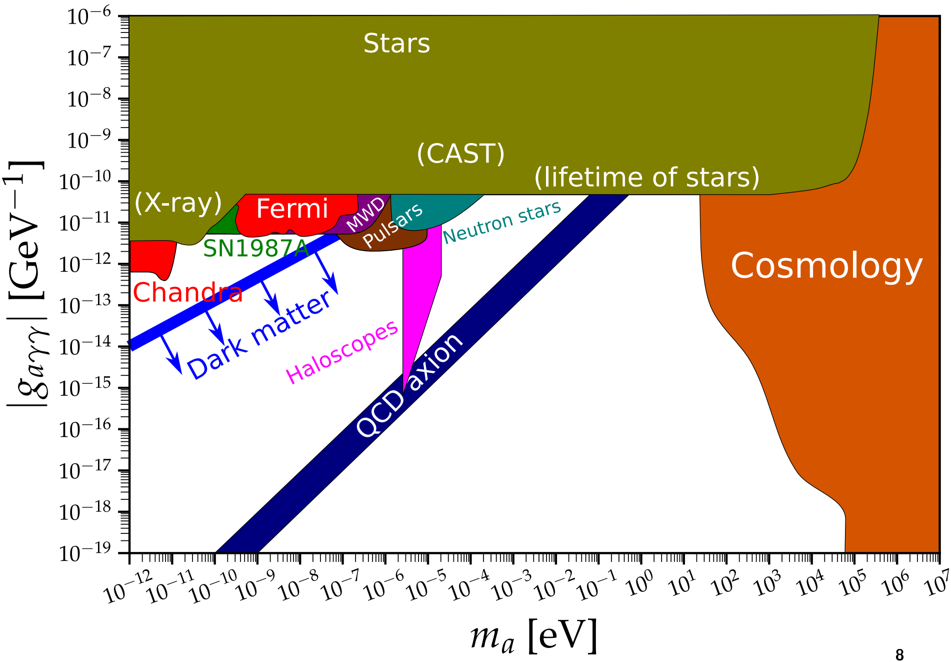
Stars
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Fermi
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Pulsars
Neutron stars
SN1987A
Chandra
Dark matter
Haloscopes
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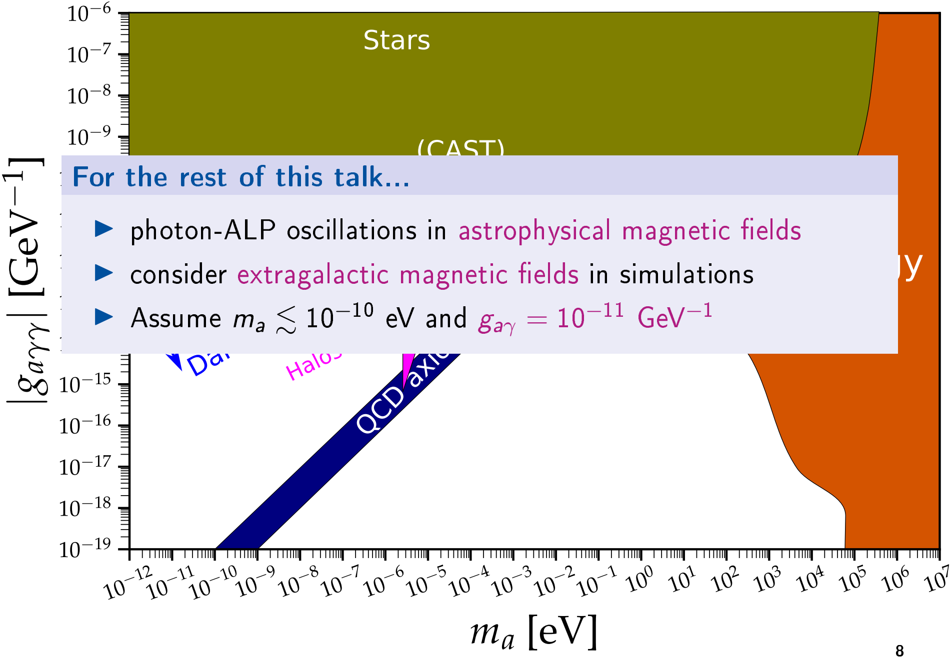
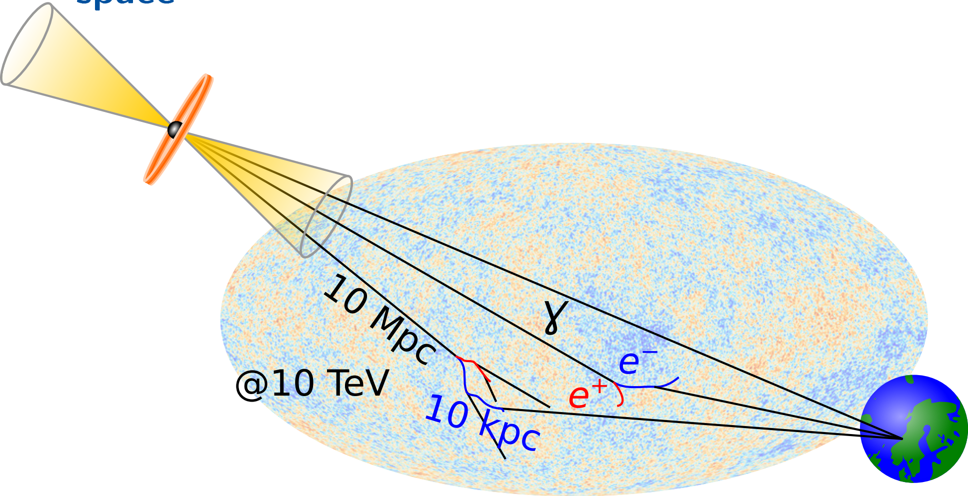


For the rest of this talk...

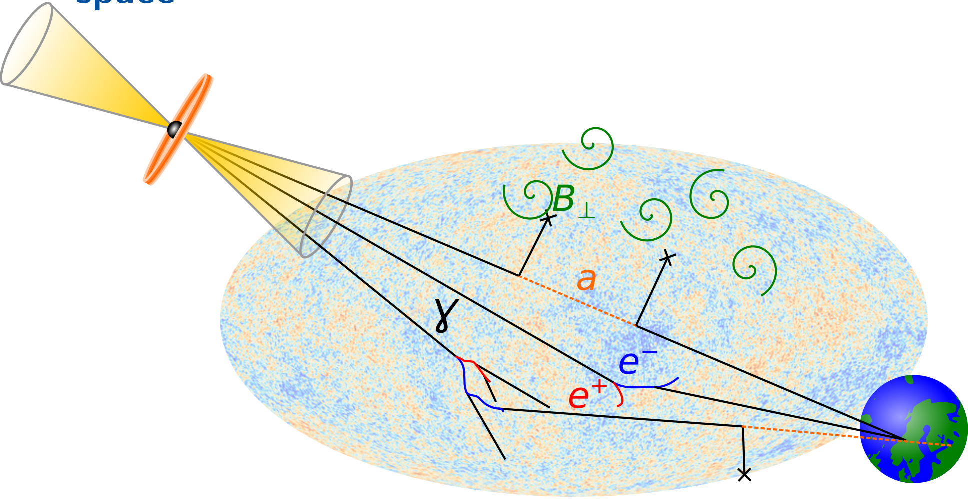
- photon-ALP oscillations in astrophysical magnetic fields
- consider extragalactic magnetic fields in simulations
- Assume $m_a \lesssim 10^{-10}$ eV and $g_{a\gamma} = 10^{-11}$ GeV^{-1}

SIGNATURES OF PHOTON-ALP OSCILLATIONS IN PHOTON SPECTRA

Electromagnetic cascades in extragalactic space



Electromagnetic cascades in extragalactic space



ELMAG [1106.5508, 1909.09210]

Monte Carlo simulation tool for electromagnetic cascades of high-energy photons and electrons

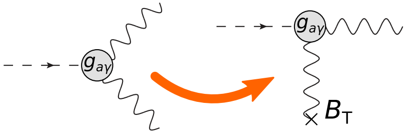
- $\gamma + \gamma_{\mathrm{EBL}} = e^+ + e^-$ (pair production $[E \lesssim 10^{15}\ \mathrm{eV}]$)
- $e^\pm + \gamma_{\mathrm{EBL}} = e^\pm + \gamma$ (inverse Compton scattering)
- Photon-axion oscillations in a magnetic field ($a \leftrightarrow \gamma$)

Alternative Python codes:

GammaALP [2108.02061] and ALPro [2202.08875]

The physics of photon-ALP oscillations

Primakoff effect:



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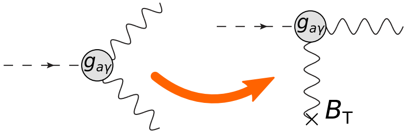

Oscillation due to a mass difference of two mass eigenstates

$$\Rightarrow P_{\gamma\to a} = |\langle a|\Psi(t)\rangle|^2 = \sin^2(2\vartheta)\sin\left(\frac{L}{2E}\left(m_1^2 - m_2^2\right)\right)$$

$\Rightarrow$ The oscillation length depends on the refractive index!

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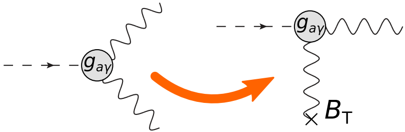

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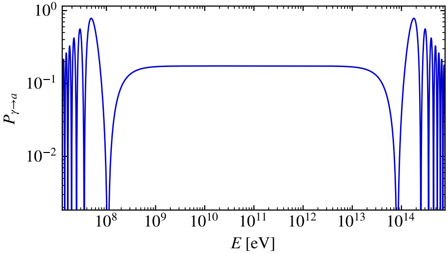
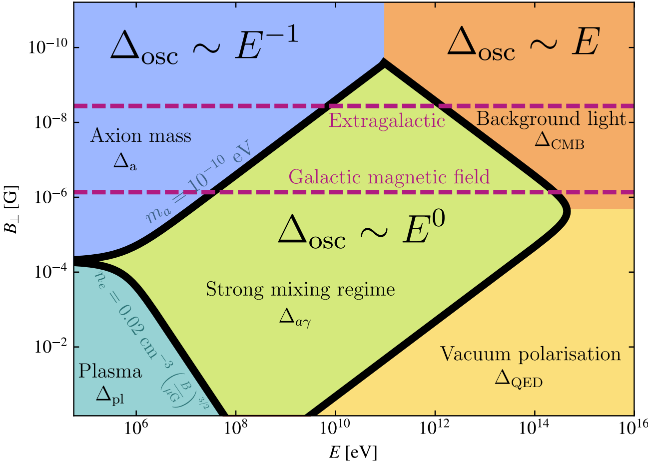


Contribution to the dispersion

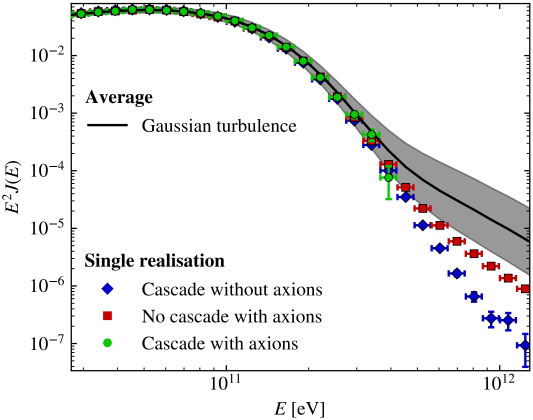


Signatures of photon-ALP oscillations in photon spectra

1. Decreased opacity of the Universe
2. Irregularities in photon spectra

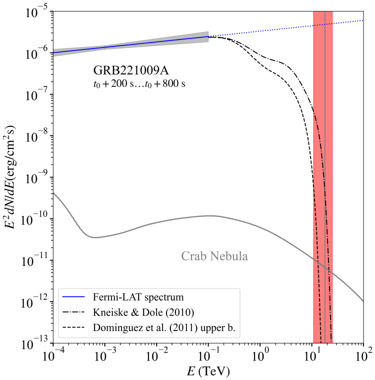
1. Decreased opacity of the Universe

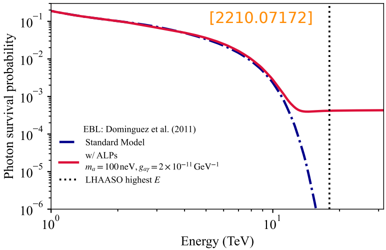
ALPs are not attenuated by the EBL!



Example: GRB221009A

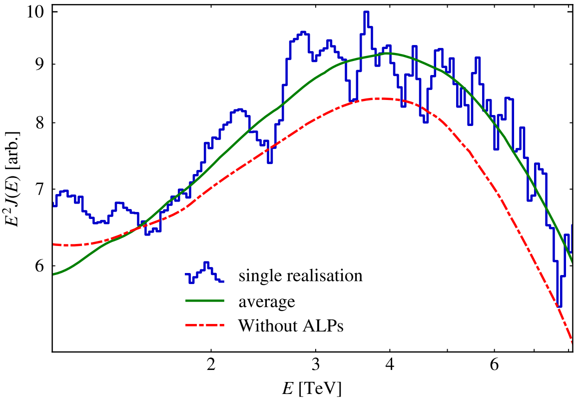
Photon-ALP oscillations can explain the 18 TeV LHAASO events!





Galanti et al. [2210.05659], Baktash et al. [2210.07172], Carenza & Marsh [2211.02010], Troitsky [2210.09250]...

2. Wiggles (“irregularities”) in photon spectra



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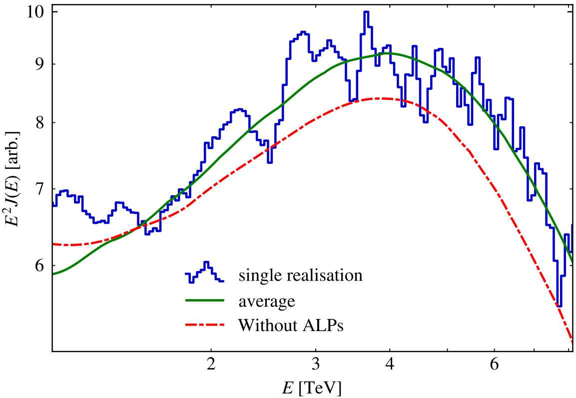

The "irregularities" have the same regular behaviour as in a homogeneous magnetic field

A direct detection of ALP wiggles

- **Idea:** Use the energy dependence of the wiggles as observable

$$G(k) = \left| \int_{\eta_{\rm min}}^{\eta_{\rm max}} \mathrm{d}\eta \, q(\eta) \mathrm{e}^{\mathrm{i}\eta k} \right|^2 \approx \left| \frac{1}{N} \sum_{\rm events} \exp\left\{\mathrm{i}\eta k\right\} \right|^2$$

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  - Peak in $G(k)$ for $\eta \sim E^{-1}$ at "low" energies
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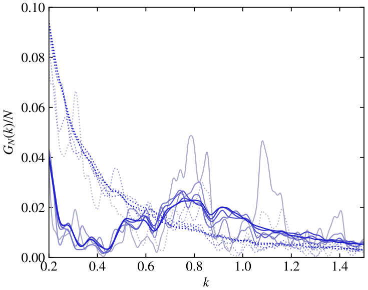
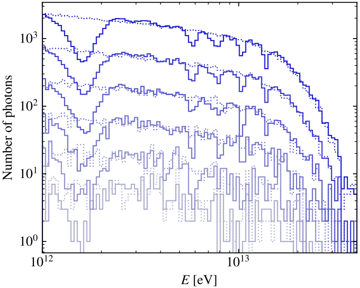
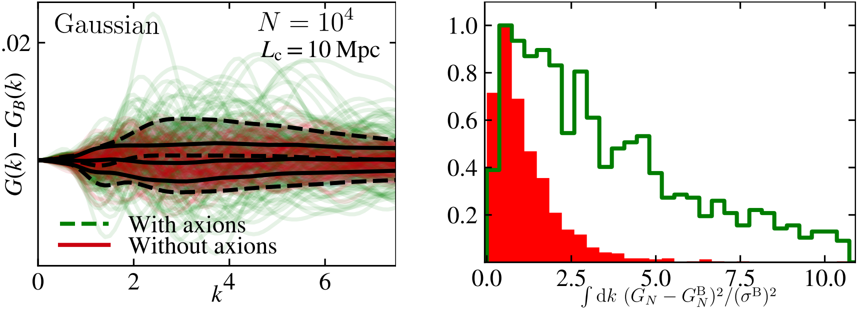
- This leads to a detection method independent of the modeling of the magnetic fields
- The signal can be used to infer information about the magnetic field

Example: detecting axion wiggles





Test-statistic example

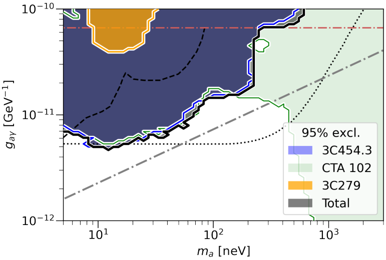


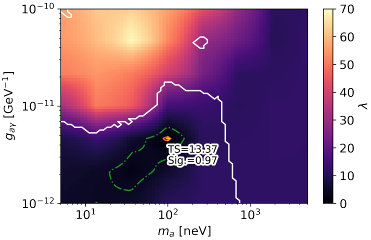
- $z = 0.1$, $\mathrm{d}N/\mathrm{d}E \sim E^{-1.2}$, $L_c = 10$ Mpc
- The background is estimated by minimising the MLE of a parametrisation
- Smearing according to the energy resolution of CTA is included!

Is there a signal in the Fermi data?

with M. Meyer

A small (1σ) preference for ALPs in a new Fermi analysis of the quasar CTA102 Davies, Meyer & Cotter (2022):





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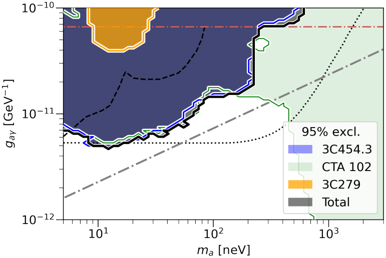
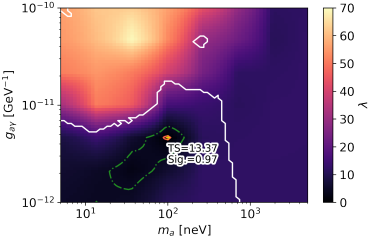
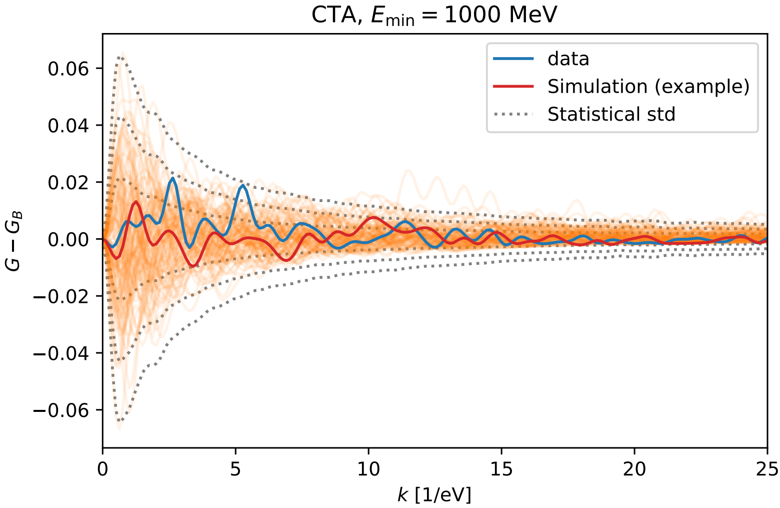




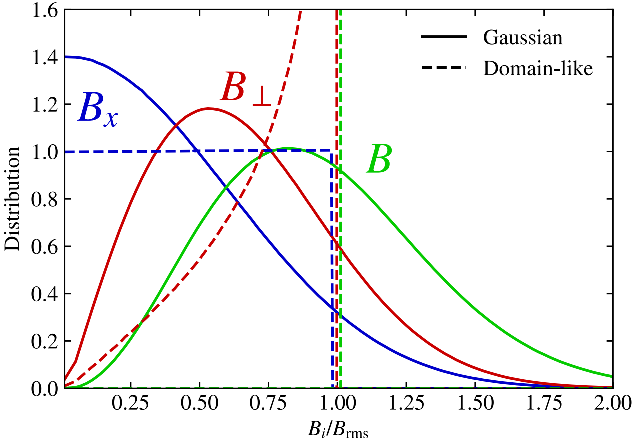
The Fermi tools gtobssim and gtselect makes it easy to look for ALP wiggles!


CTA, $E_{\min} = 1000$ MeV
data
Simulation (example)
Statistical std
0.06
0.04
0.02
0.00
−0.02
−0.04
−0.06
$G - G_B$
0
5
10
15
20
25
k [1/eV]

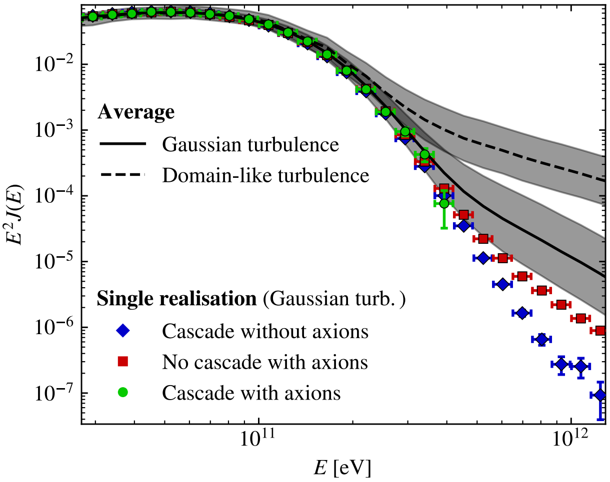
COMMENT ON THE MODELING OF THE MAGNETIC FIELD

Simplified magnetic field models are often used

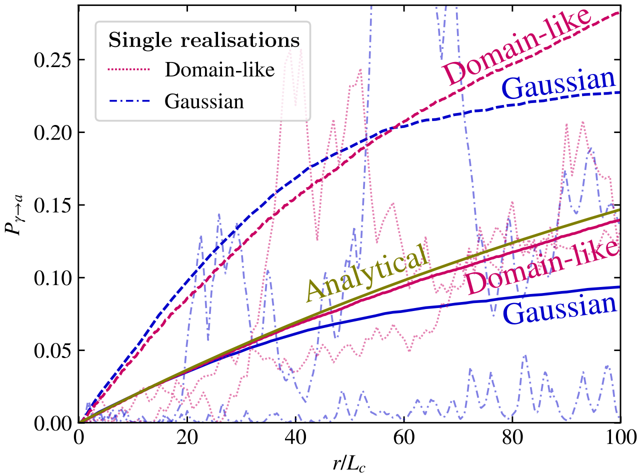
- In previous plots, the turbulent magnetic field was described as a Gaussian turbulent field
- In the literature, a domain-like field is oftentimes used



The opacity depend on the modeling



Convergence of conversion probability



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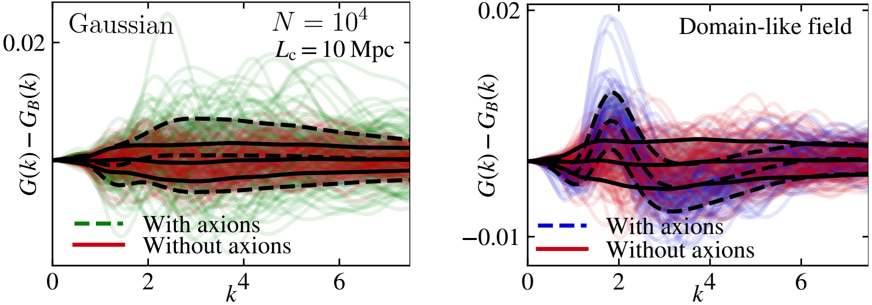
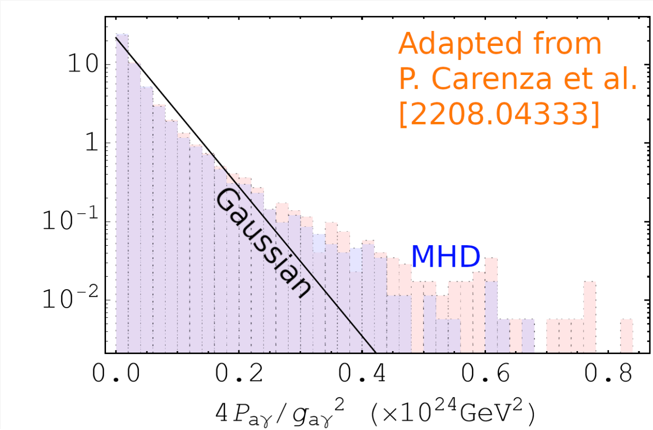


The lack of variation may lead to a bias in the modeled spectra!

A positive view of the world



We might be lucky with the magnetic fields in our Universe!

Summary

- ALPs are interesting particles
- Photon-ALP oscillations will make characteristic wiggles in photon spectra with a known energy dependence
- Axion wiggles can be detected using the discrete power spectrum
- Care should be taken when interpreting results based on simplified models of the magnetic field
- The variation in realistic magnetic field models might increase the sensitivity for photon-ALP oscillations

BACKUP

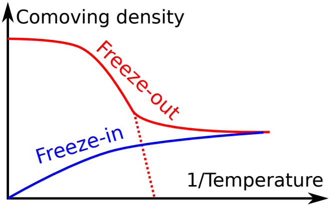
Axionic dark matter

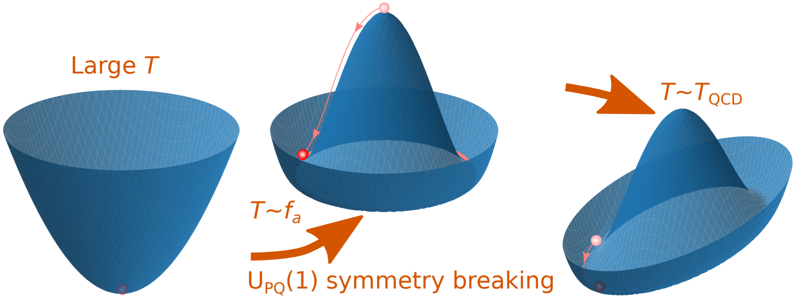
- Very light, $m_a \lesssim \mathrm{eV}$

⇒ Thermal production gives hot dark matter...

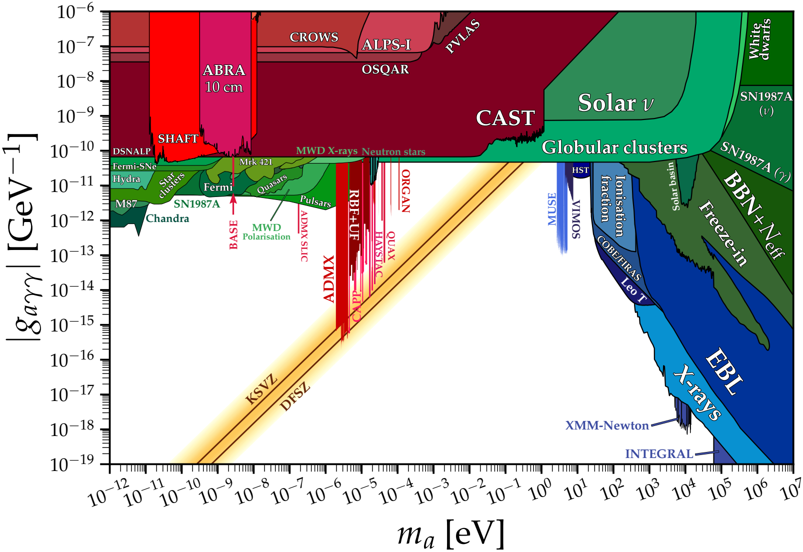
- Misalignment mechanism
  (Preskill, Wise, Wilczek 1983, ++)

→ The axion field oscillates coherently and looses energy by producing physical axions





The ALP parameter space



(adapted from [10.5281/zenodo.3932430])