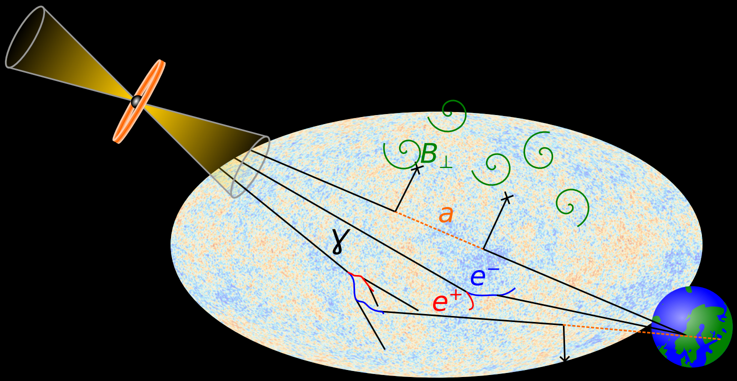
ALPs, High-Energy Gamma-Rays and Magnetic Fields

Michael Kachelrieß NTNU, Trondheim



Outline of the talk

1. Introduction
2. Signature of ALPs
   - Optical depth of the Universe
   - Irregularities
3. Magnetic field:
   - Galactic magnetic field
   - Extragalactic magnetic fields
4. Summary

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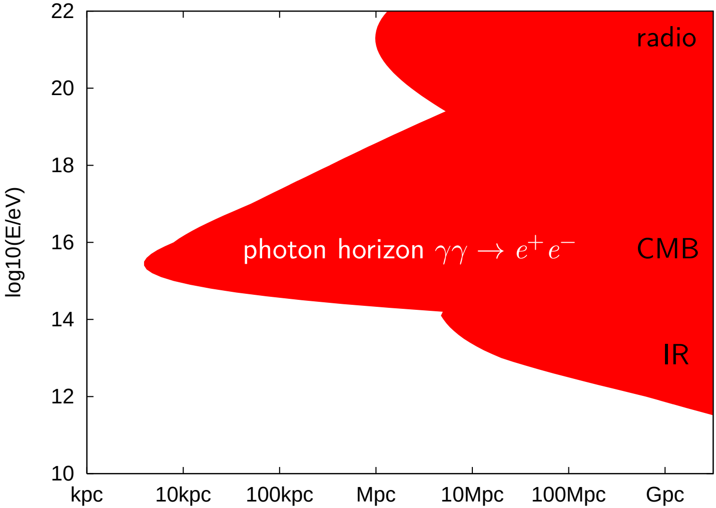
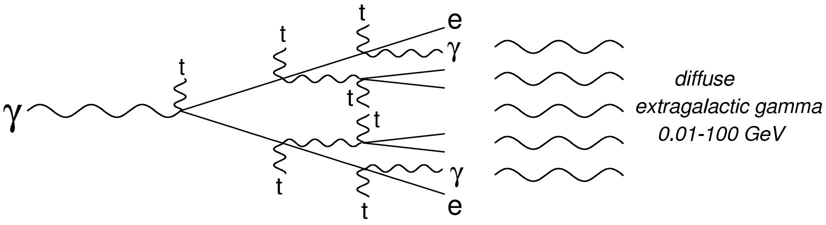
Photon horizon and electromagnetic cascades



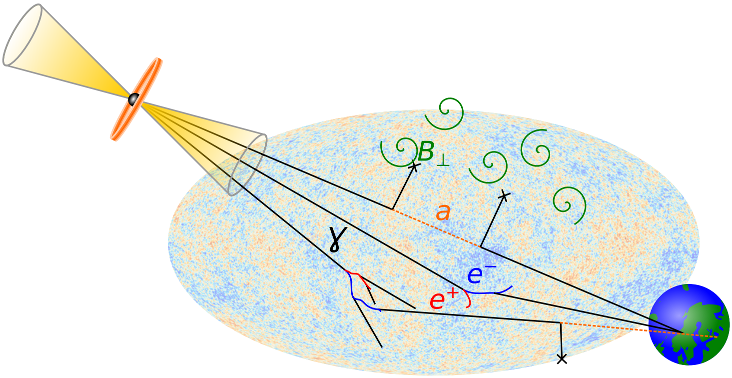
Photon horizon and electromagnetic cascades

Development of elmag. cascade



Photon horizon and electromagnetic cascades

Development of elmag. cascade from TeV blazar



History: IR crisis around 2000

- first observations of Mkn 501 up to 20 TeV by HEGRA
- observations/lower limits on IR background by DIRBE,...

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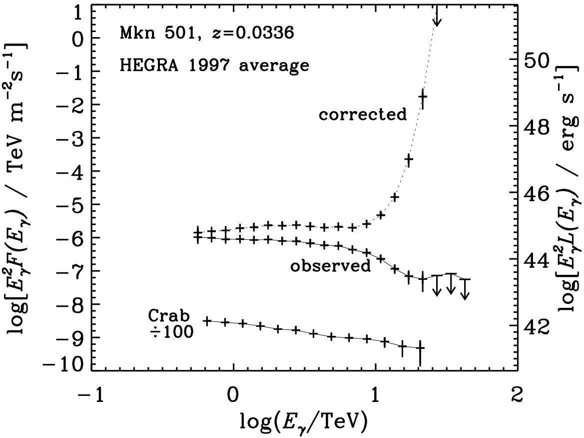

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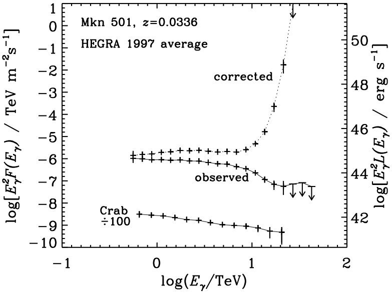
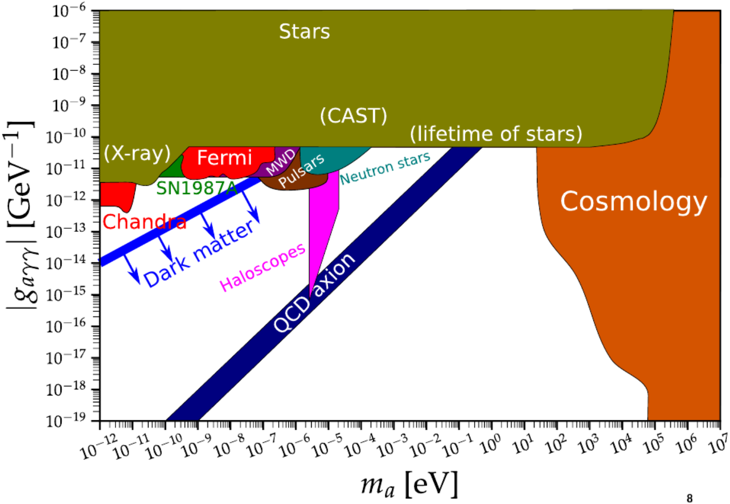


- proposed solutions:
  - LIV
  - BE condensate
  - ALPs?

ALP space:


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

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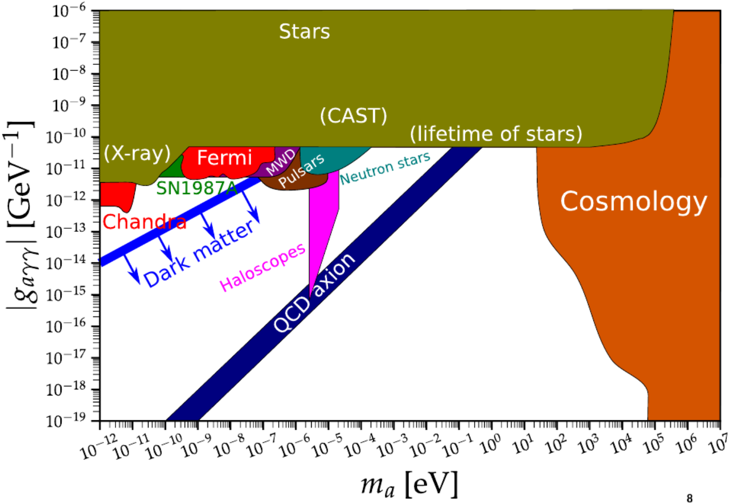
ALP space: $g_{a\gamma} \sim 10^{-11}$/GeV and $m_a \lesssim 10^{-9}$ eV for HE γ-ray astronomy



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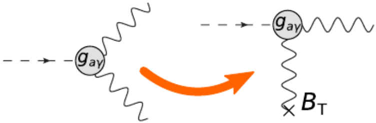
ALP-photon oscillations

Primakoff effect:



Oscillation due to a mass difference of two mass eigenstates

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

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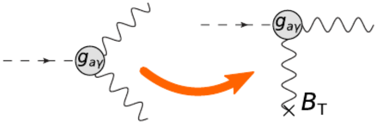

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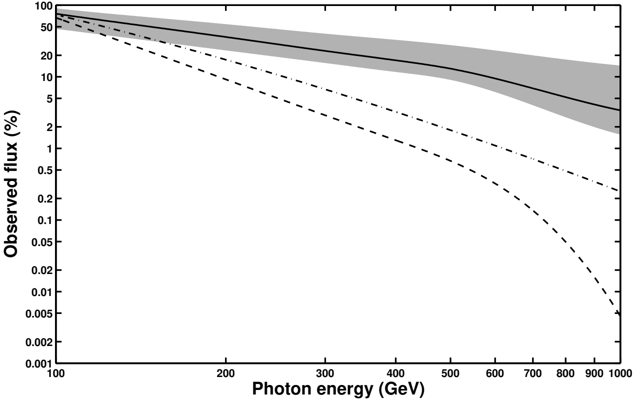
signatures:

- increased mean-free path of photons
- irregularities in energy spectra

Decreased opacity due to ALP-photon oscillations

source 3C279 at $z = 0.538$ and Kneiske EBL:



[De Angelis, Roncadelli, Mansutti '07]

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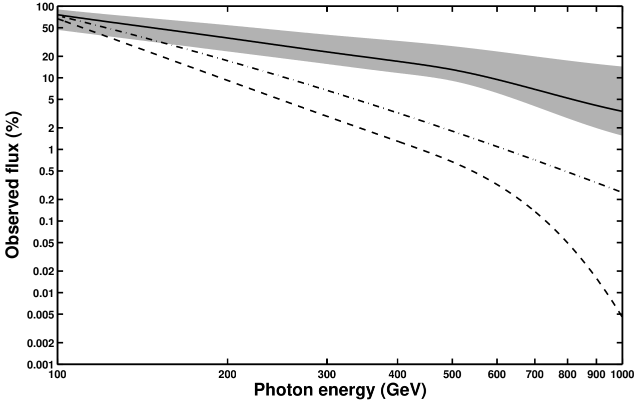
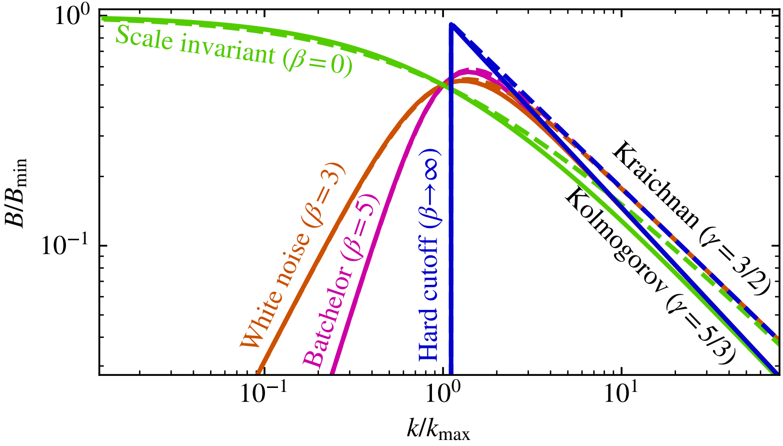


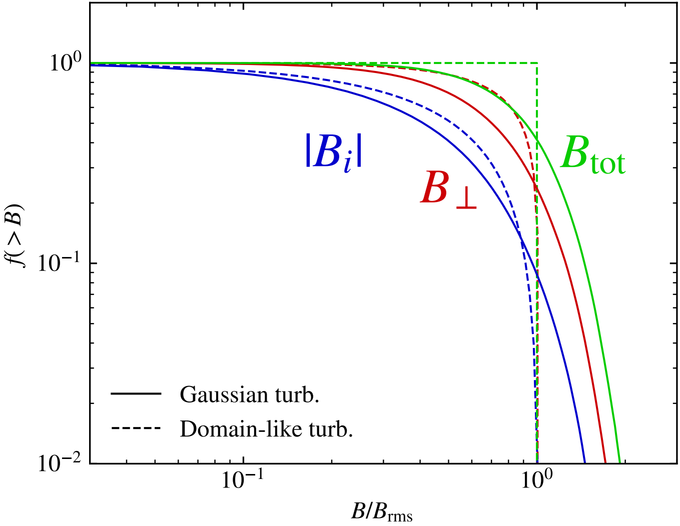
[*De Angelis, Roncadelli, Mansutti '07*]

EGMF modelled as domain-like $L = 1\,\mathrm{Mpc}$

Modelling the turbulence

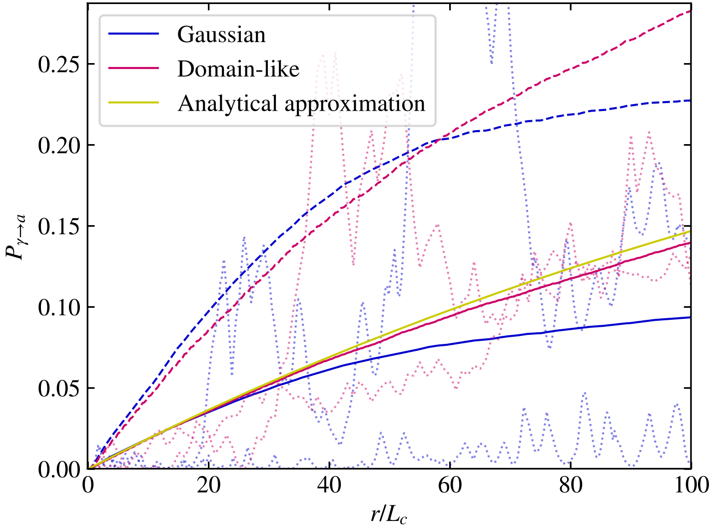


Modelling the turbulence



Effect on oscillation probability:

[MK, Tjemsland '21]



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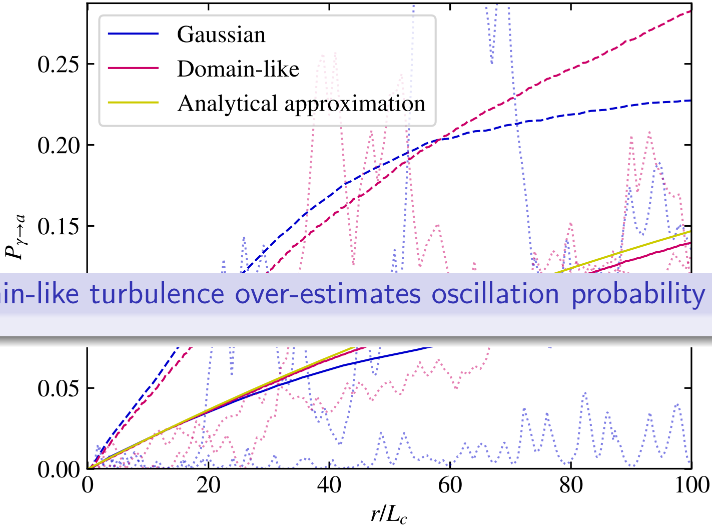
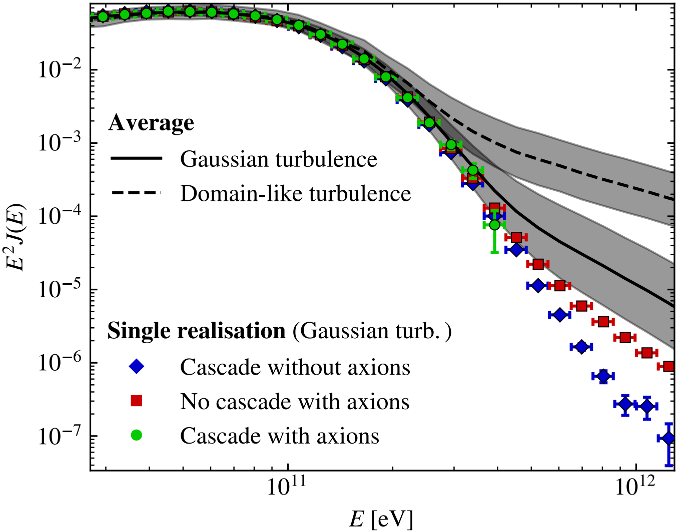
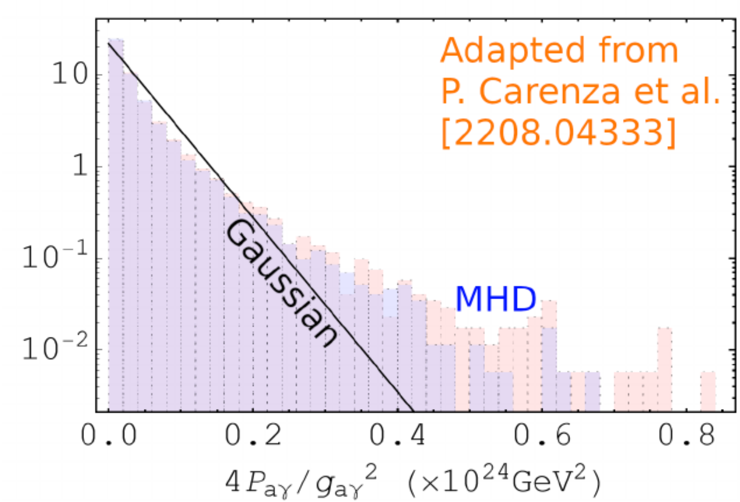


domain-like turbulence over-estimates oscillation probability

Decreased opacity: domain vs Gaussian turbulence

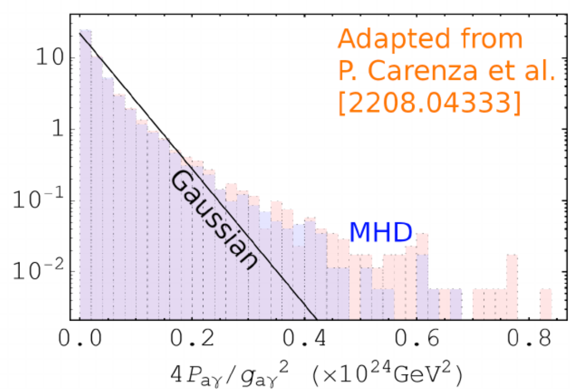


MHD vs Gaussian turbulence



- MHD fields have larger tails – even less domain-like

MHD vs Gaussian turbulence



- MHD fields have larger tails – even less domain-like
  - – smaller change of opacity
  - + larger irregulrities, maybe lucky L.o.S.
- how to implement? Multiplicative chaos [Durrive, Leaffre, Ferrière '20]

LHAASO and GRB 221009A

- exceptionally brigh GRB at redshift $z = 0.1505$
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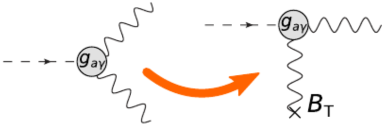
- required value of $g_{a\gamma}$ disfavoured?

ALP-photon oscillations

Primakoff effect:



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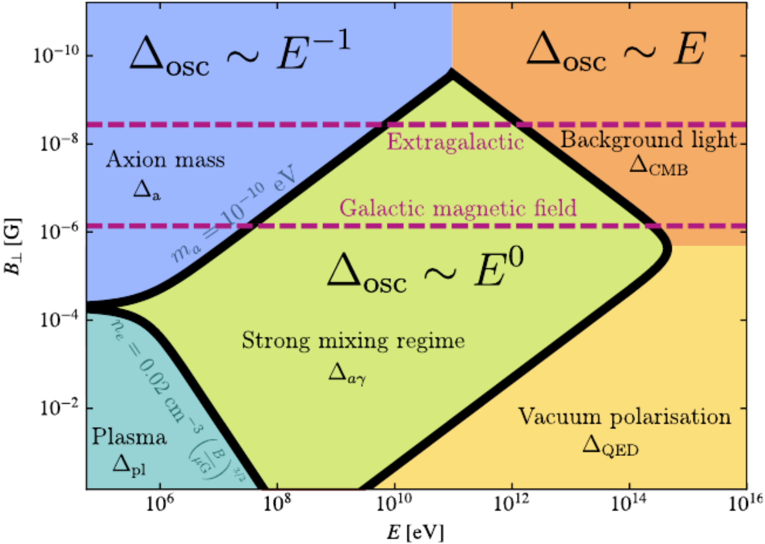
$\Rightarrow$ The oscillation length depends on the refractive index!

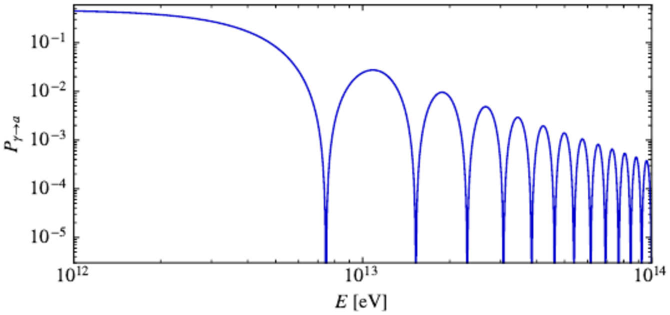
various contributions to n:

m_a, $\vec{B}$, EBL, QED vacuum, plasma

Dispersion space



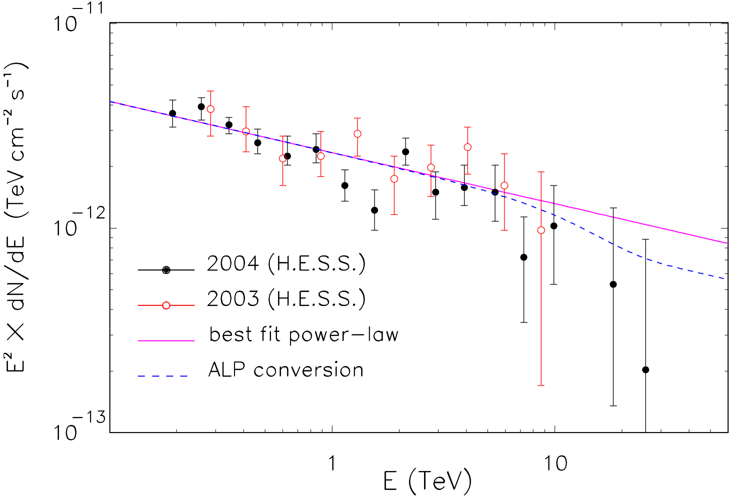
Oscill. probability for uniform $B = 5\,\text{nG}$ and $l = 10\,\text{Mpc}$



- oscillations induce "regular irregularities" in energy spectra

ALP induced wiggles

- non-detection ⇒ exclusion of parameter space



[Mirizzi, Raffelt, Serpico '07]

ALP induced wiggles

[*Liang et al. '18*]

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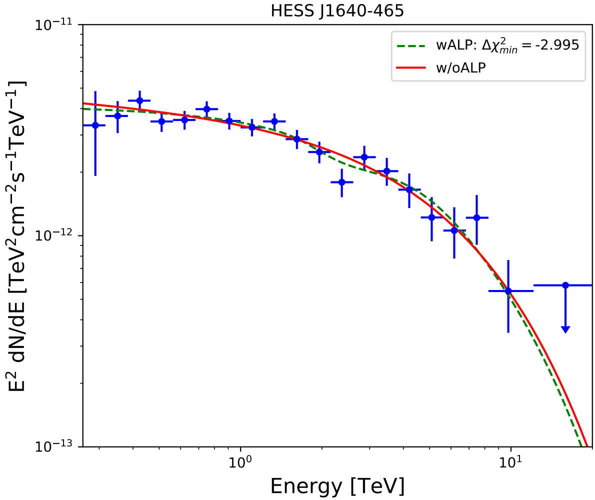

ALP induced wiggles: prospects for CTA

[*Liang et al. '18*]

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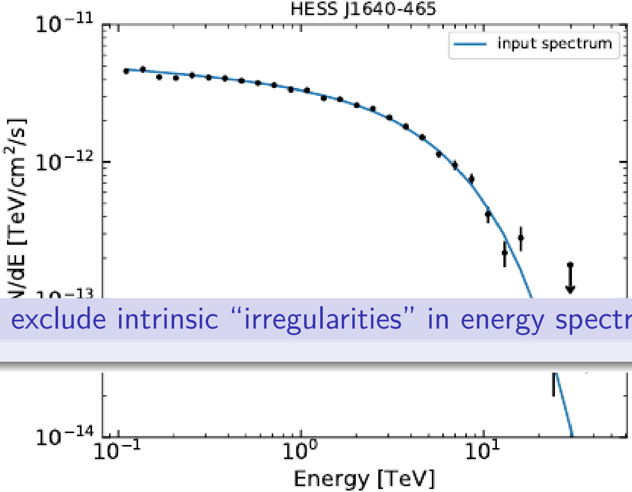
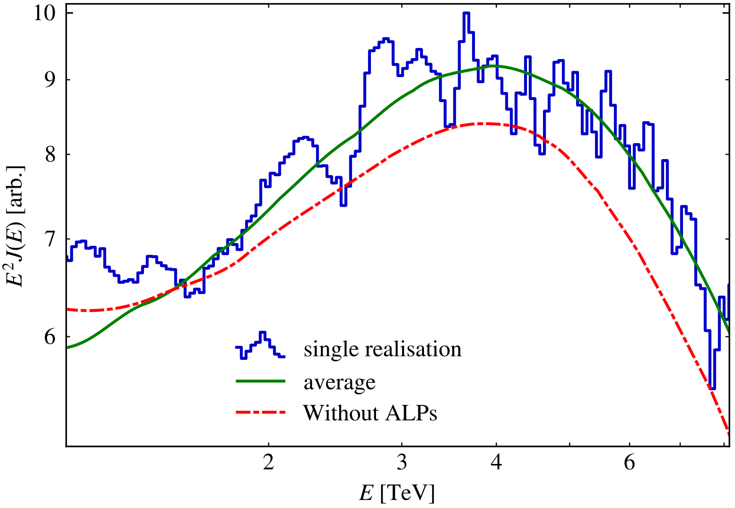


how to exclude intrinsic "irregularities" in energy spectra?

Oscillation wiggles have definite energy dependence



- but reduced in turbulent fields

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$$G(k) = \left| \int_{\eta_{\min}}^{\eta_{\max}} \mathrm{d}\eta \, \mathrm{q(k)e^{i\eta k}} \right|^2 \simeq \left| \sum_{\text{events}} \mathrm{e^{i\eta k}} \right|^2$$

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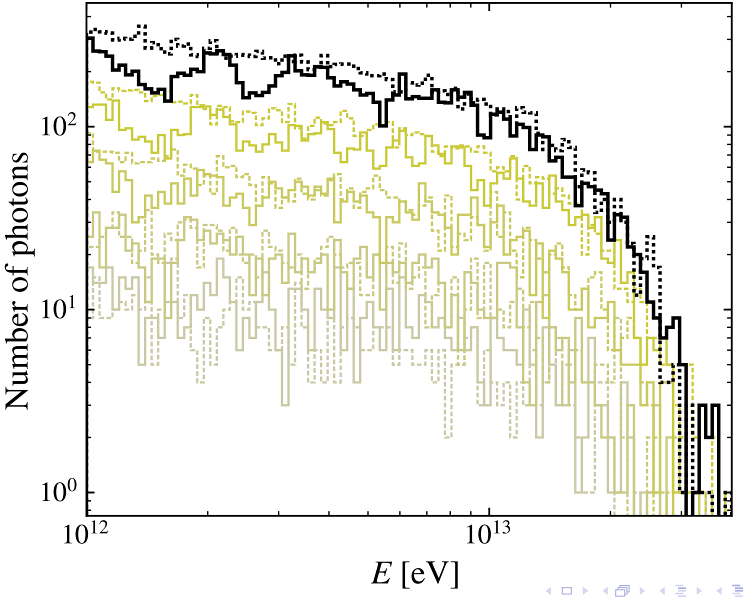
- signature:
  - low energies: peak in "inverse" energy spectrum $\eta \sim 1/E$
  - high energies: peak in energy spectrum $\eta \sim E$
- independent of B modelling
- $G(k)$ contains info on B

Axion wiggles –PKS 2155–304



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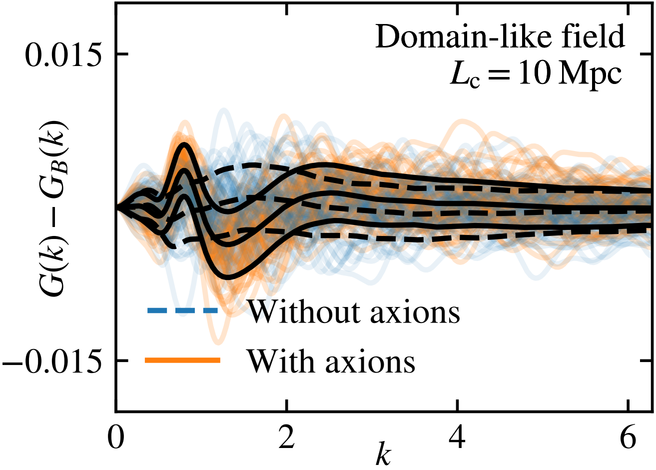

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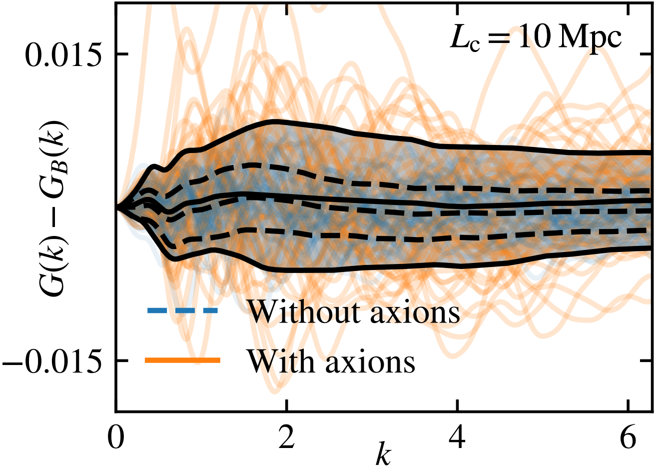

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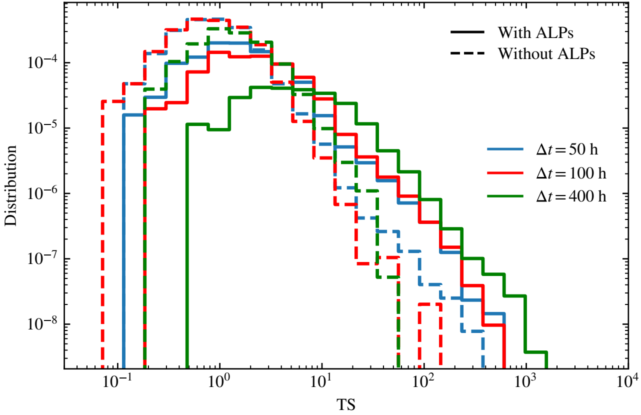
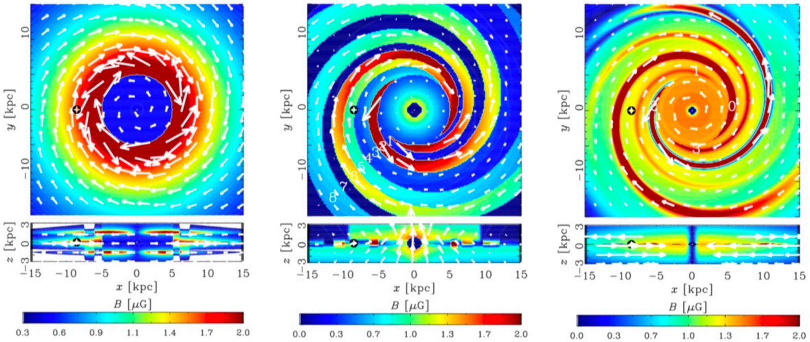


Status of GMF models

- JF12 has become a "standard"
- but data are too sparse to constrain models



Limits on extragalactic magnetic fields (EGMF)

- Origin of seed for EGMF is unknown
- Observations only in cluster cores,
  - synchrotron halo: $\Rightarrow B \sim (0.1 - 1)\,\mu$G
  - Faraday rotation: $\Rightarrow B \sim (1 - 10)\,\mu$G
- Aharonian, Coppi, Völk '94: Pair halos around AGNs
- Plaga '95: EGMFs deflect and delay cascade electrons
  $\Rightarrow$ search for delayed "echoes" of multi-TeV AGN flares/GRBs
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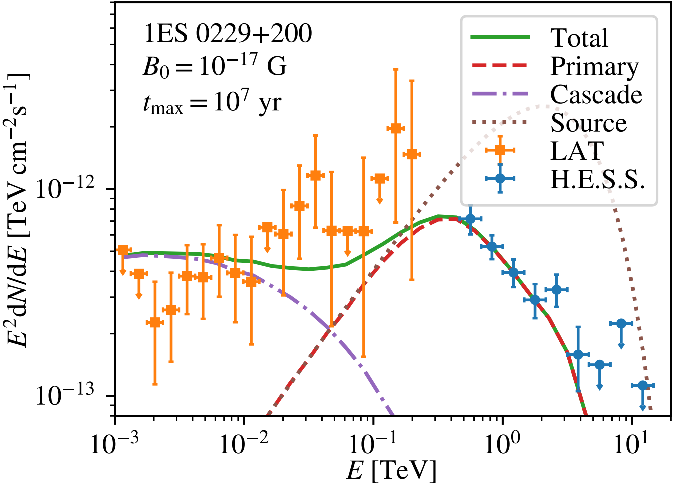
- Alternative: plasma instabilities [*Broderick et al.'12*]

1ES0229+200 reloaded: best-fit spectra

[*Tjemsland, Meyer, Vazza, in prep.*]



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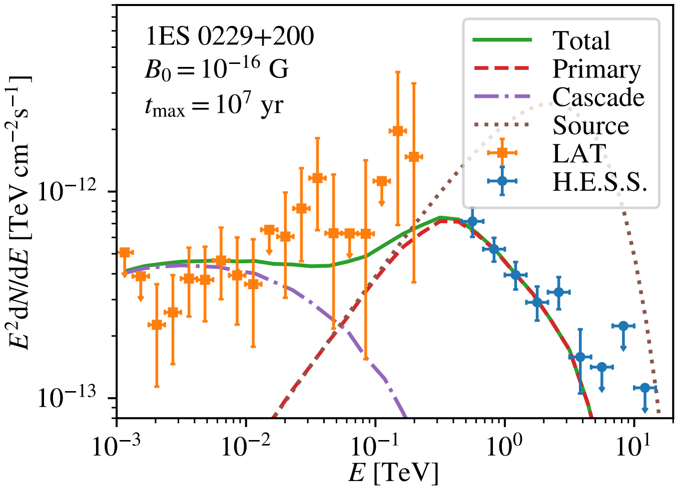

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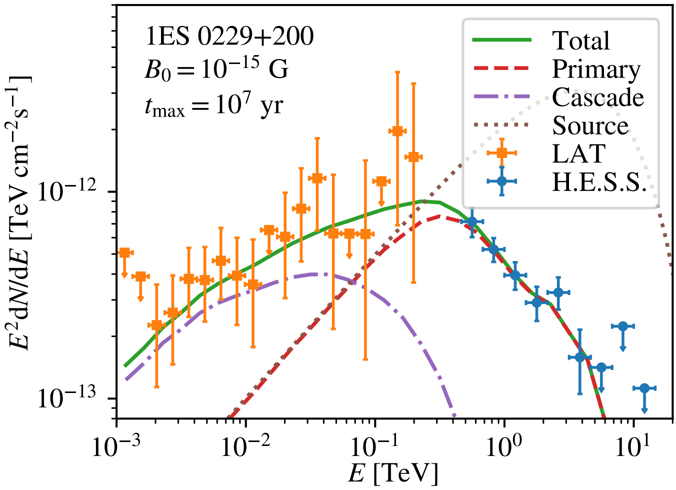

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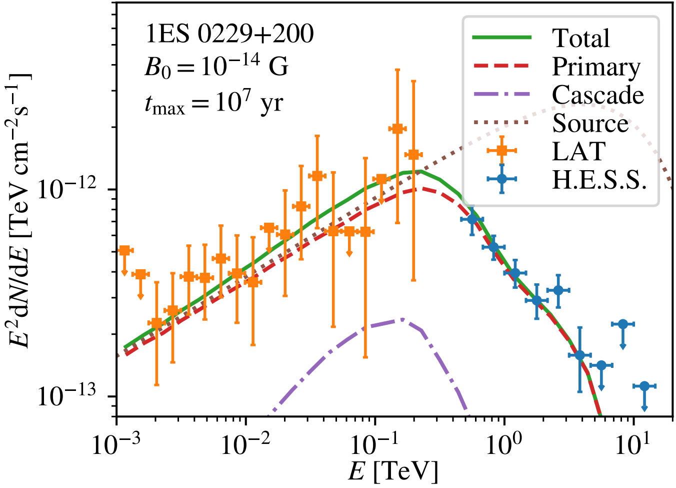

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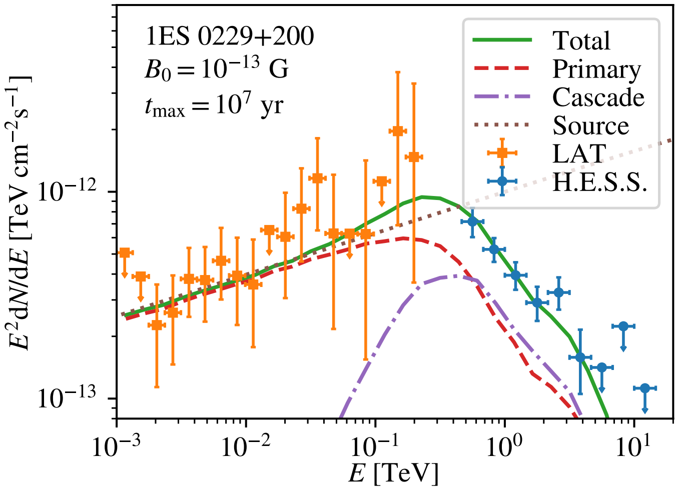

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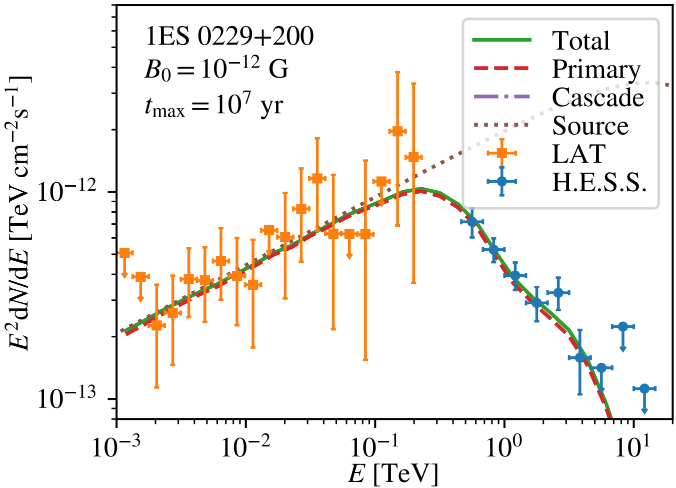

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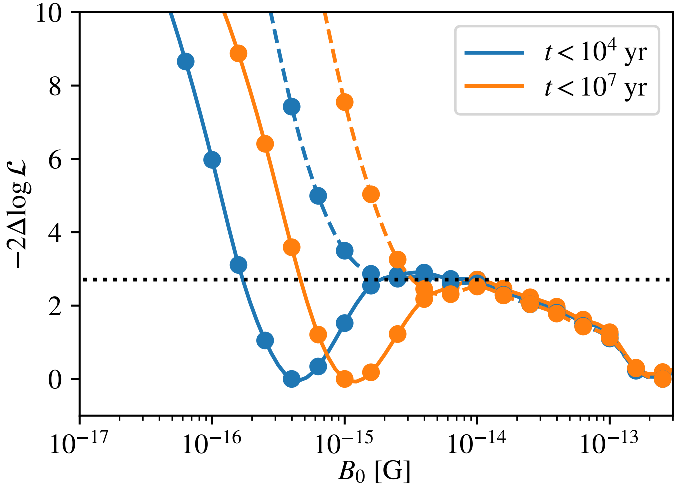

Acknowledgements

most work done by Jonas Tjemsland – defended his PhD 3 weeks ago

Summary

- ALP-photon oscillations lead to
  - decreased opacity
    - + EBL with smaller errors
  - regular wiggles in γ-ray spectra
    - + energy dependence as signature
    - + improved exp. sensitivity: CTA and ATHENA
- lower limit on EGMF is becoming stronger:
  - (but) no direct evidence (halos, time-delays)
  - plasma instabilities?