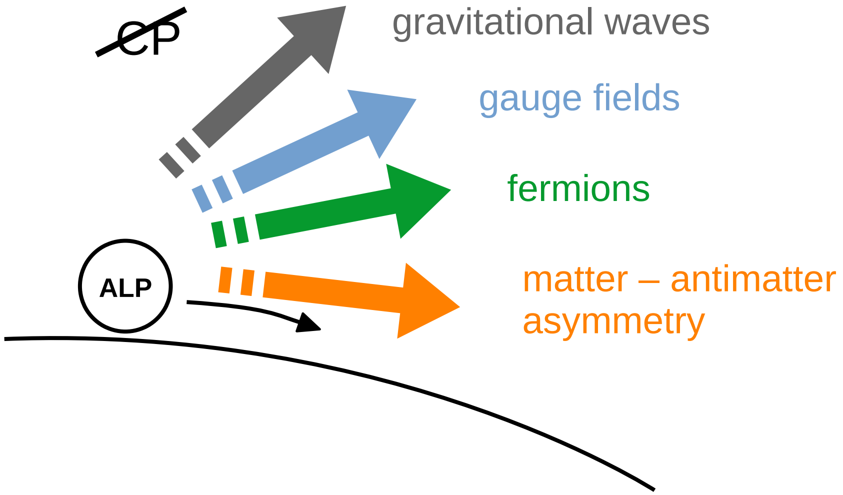
Particle production in axion inflation



Valerie Domcke
CERN

@ cosmic magnetic field workshop
EPFL, Lausanne, 01.05.2024

based on work with
Yohei Ema, Veronica Guidetti,
Kohei Kamada, Kyohei Mukaida,
Stefan Sander, Kai Schmitz,
Yvette Welling, Alexander Westphal
and Masaki Yamada

‘axion’ inflation

slow-roll inflation → very flat scalar potential

reheating after inflation → coupling to the SM

↓

inflaton as Pseudo Goldstone Boson (PNGB, ALP) with shift-symmetric couplings:

$$\boxed{\phi F_{\mu\nu}\tilde{F}^{\mu\nu}} \qquad \boxed{(\partial_\mu\phi)\underbrace{\bar{\psi}\gamma^\mu\gamma^5\psi}_{J_5^\mu}}$$

related by chiral anomaly equation:

$$0 \neq \partial_\mu J_5^\mu = -\frac{\mathcal{A}}{16\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Outline

1) Fermion production and backreaction to gauge fields

2) Gauge field production and backreaction to axion dynamics

‘axion’ inflation

- a minimal setup for SM + inflation:

axion with scalar potential

(hyper charge) U(1) gauge field

massless (SM) fermions

axion gauge field coupling

$$\mathcal{L} = \sqrt{-g}\left[\frac{1}{2}\partial^\mu\phi\partial_\mu\phi - V(\phi)\right] - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \sum_\alpha \bar{\psi}_\alpha(i\partial\cdot\gamma - gQA\cdot\gamma)\psi_\alpha + \underline{\frac{\alpha\phi}{4\pi f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}}$$

SM chiral anomaly forces us to consider gauge fields and fermions simultaneously

after chiral fermion rotation:

$$\underline{(\partial_\mu\phi)\bar{\psi}\gamma^\mu\gamma^5\psi}$$

shift-symmetric coupling to ϕ

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shift-symmetric coupling to ϕ

see Lorenzo's talk

- axion – hypercharge coupling leads to exponential helical gauge field production (ignoring fermion backreaction for the moment):

$$\frac{d^2}{d\tau^2}A_\pm(\tau,k) + \left[k^2 \pm 2k\frac{\xi}{\tau}\right]A_\pm(\tau,k) = 0\,, \qquad \xi = \frac{\alpha\dot\phi}{2Hf_a}$$

Turner, Widrow `88
Garretson, Field, Caroll `92

- gravitational waves, PBHs, magnetic fields ….

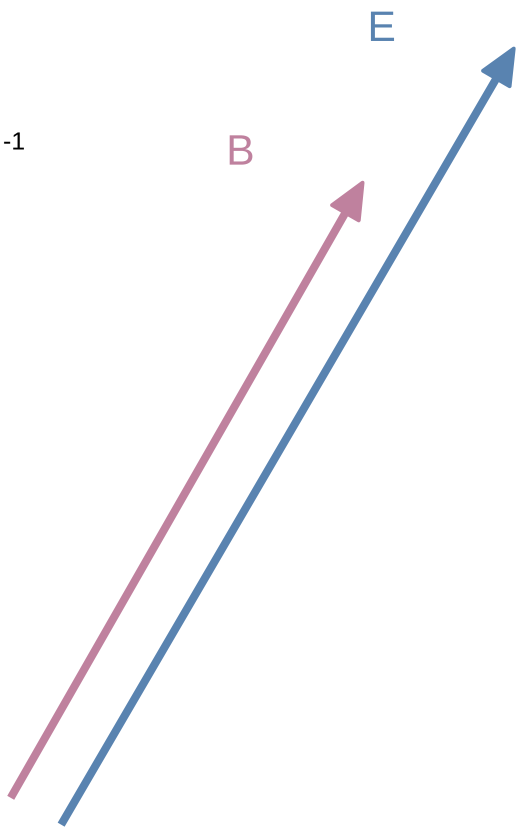
VD, Pieroni, Binétruy `16,
VD, Muia, Pieroni, Witkowski `17

fermion production

VD, Mukaida `18

helical gauge field production

- one gauge field helicity acquires tachyonic mass
- parallel E & B fields, constant & homogeneous on scales << H^{-1}



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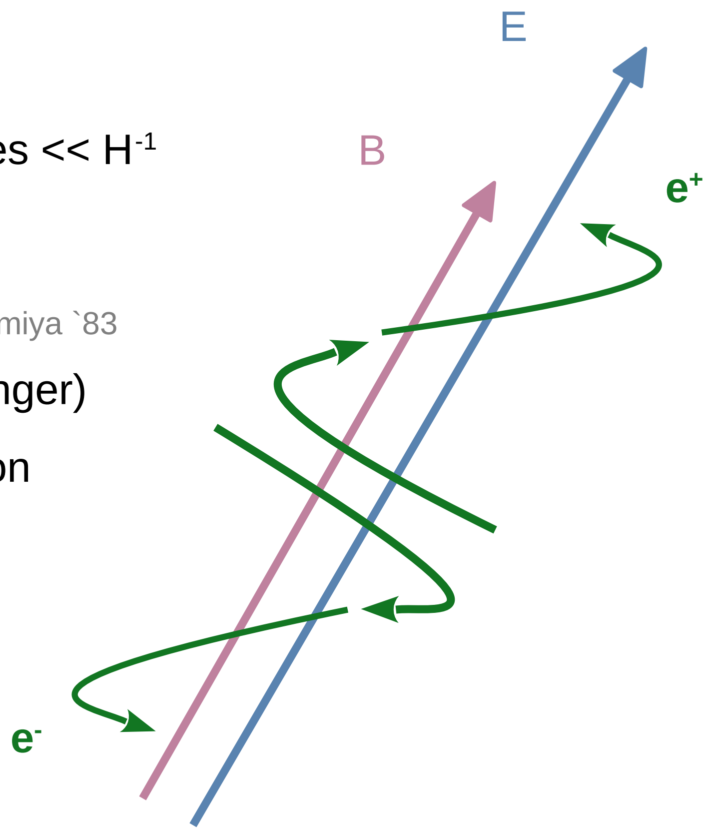
(chiral) fermion production

Nielsen, Ninomiya `83

- fermion production in constant E,B background (Schwinger)
- asymmetric production consistent with anomaly equation



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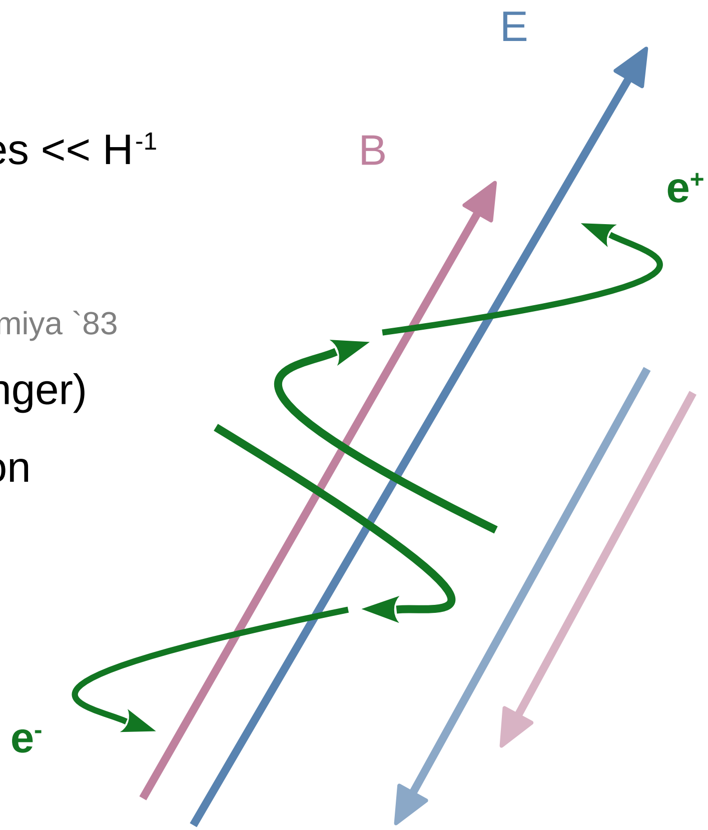
backreaction on gauge field production

- fermions are accelerated in gauge field background
- induced current inhibits gauge field production



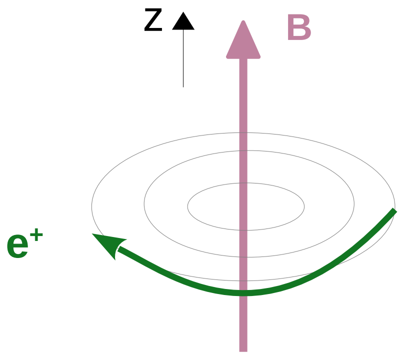
any light charged particles will be produced and induce backreaction

Landau Levels in the sky

Dirac equation: $$\left(i\partial_0 \pm i\vec{\nabla}\cdot\vec{\sigma} \pm gQ\vec{A}\cdot\vec{\sigma}\right)\psi_{R/L} = 0$$

constant B-field : quantized energy levels

constant E-field : time-dependent energy levels



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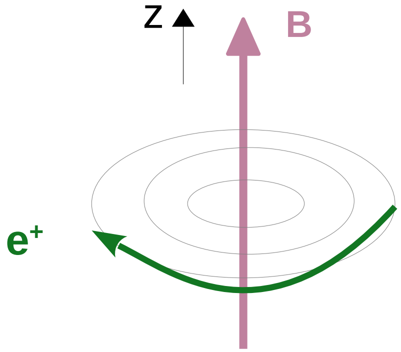

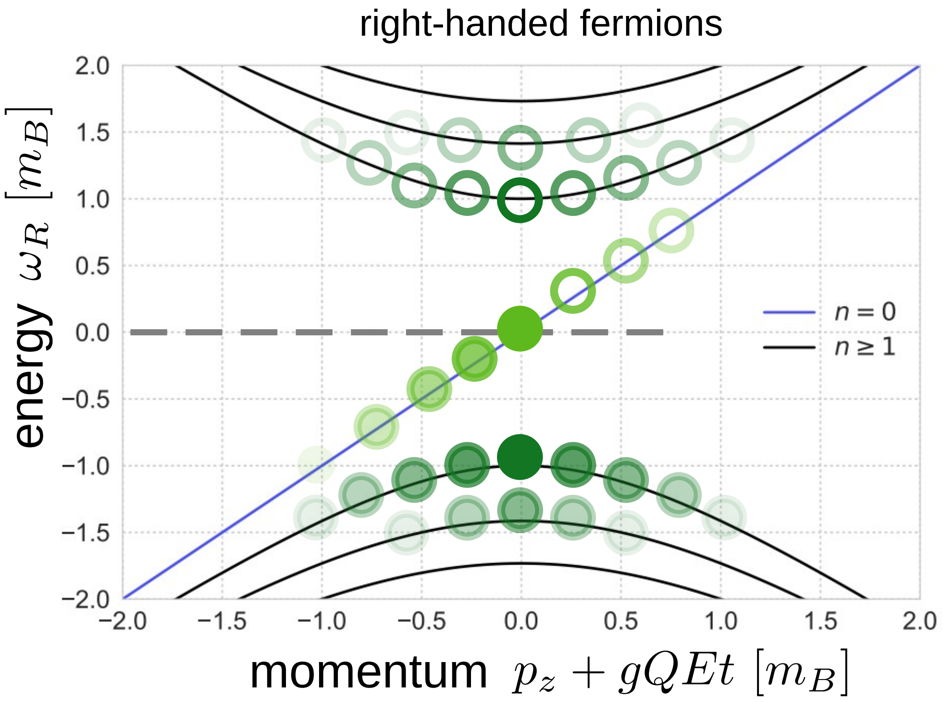

dispersion relation:

$$\omega = \pm\sqrt{(p_z + gQEt)^2 + n\,m_B^2}$$

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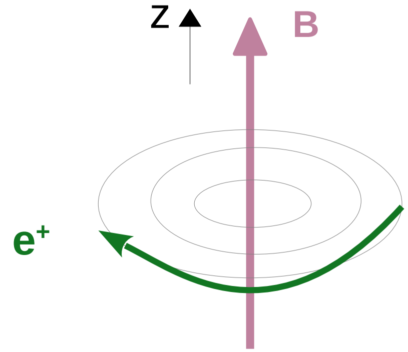
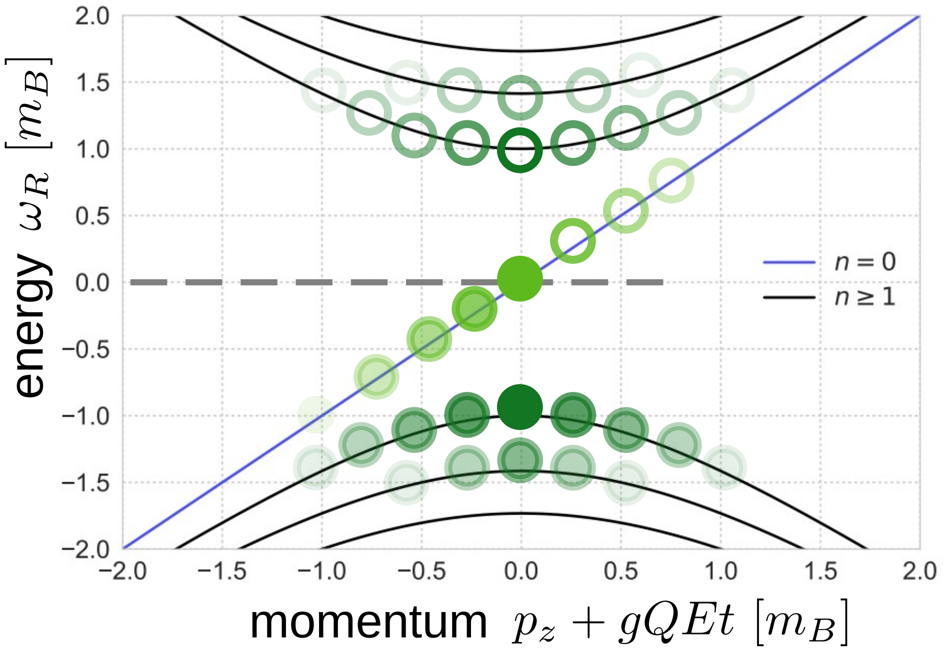


right-handed fermions



dispersion relation:

$$\omega = \pm\sqrt{(p_z + gQEt)^2 + n\, m_B^2}$$

harmonic oscillator with
time – dependent frequency

- non-perturbative particle production
- induced current: VD, Mukaida `18

$$\langle |J^z_\psi| \rangle \propto \coth\left(\frac{\pi B}{E}\right) EB$$

fermion back-reaction

VD, Mukaida `18

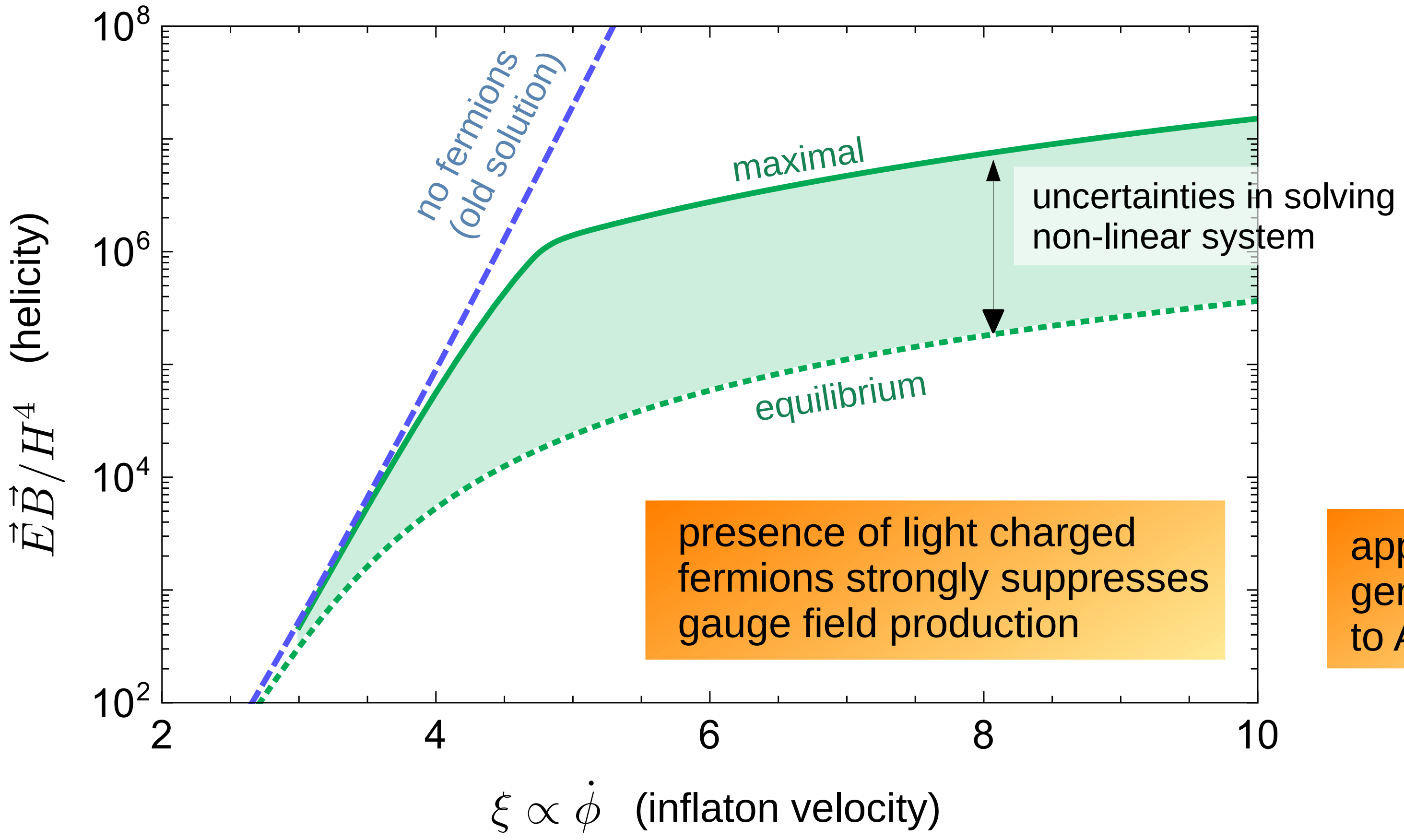
fermion production inhibits gauge field production

$$0 = \dot{\rho}_A = -4H\rho_A + 2\xi H\vec{E}\cdot\vec{B} - \vec{E}gQ\langle\vec{J}_\psi\rangle$$

from solving Dirac equation

$$\langle|J^z_\psi|\rangle \propto \coth\left(\frac{\pi B}{E}\right)EB$$

→ non-linear system, search for stationary solution :



uncertainties in solving non-linear system

presence of light charged fermions strongly suppresses gauge field production

applies generically to ALP models

implications for axion inflation

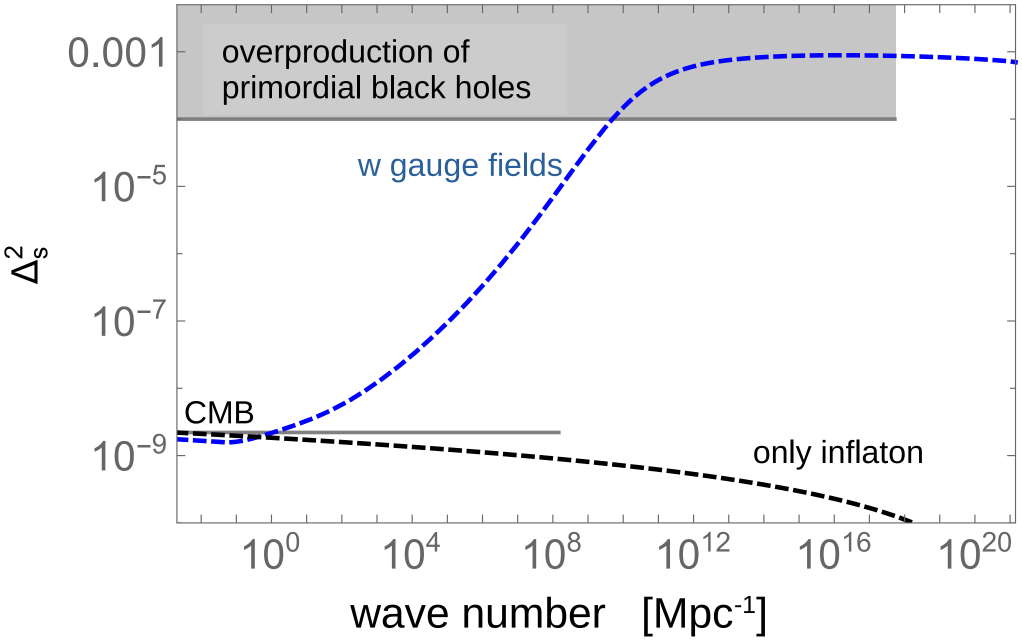
$V(\phi) = \mu^3 \phi\,, \quad \mu \sim 10^{-3} M_P$

$\alpha/(\pi f_a) = (0.02\, M_P)^{-1}$

VD, Mukaida `18; VD, Ema, Mukaida `19

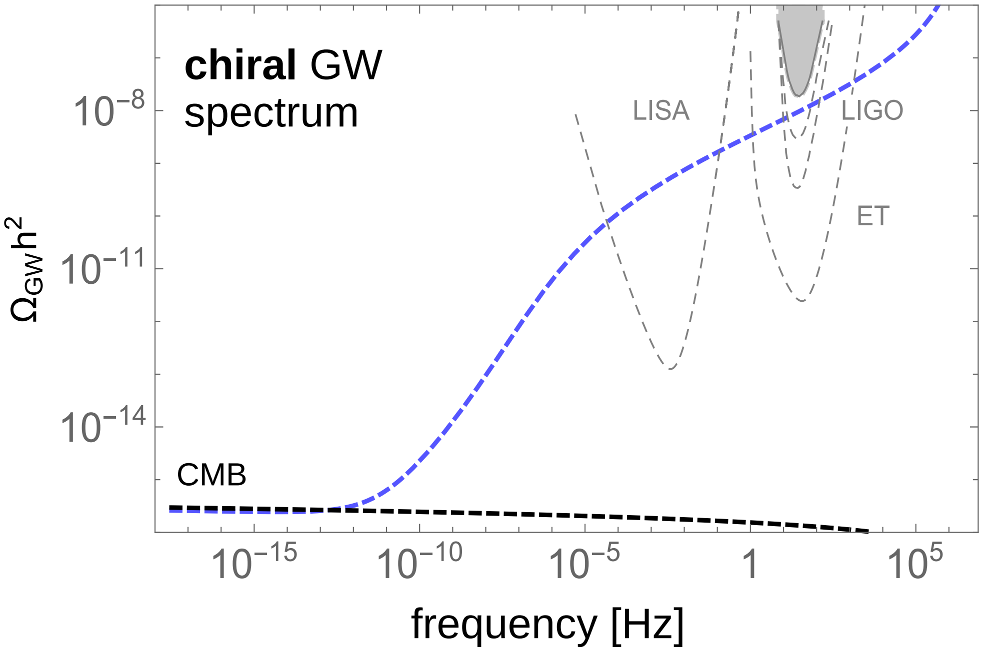
scalar power spectrum

maximal/ equ. solution for EB



tensor power spectrum

equilibrium solution for EB



see Gorbar, Schmitz, Sobol, Vilchinskii `21
for fermion backreaction in the electric picture

see Adshead, Giblin, Pieroni, Weiner `19
for preheating GW signal

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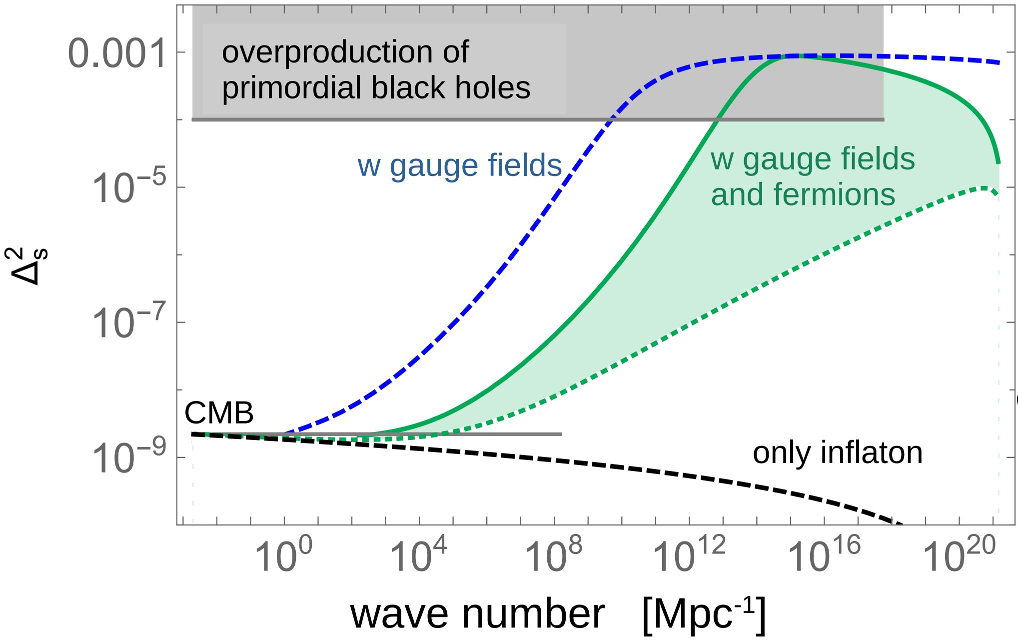

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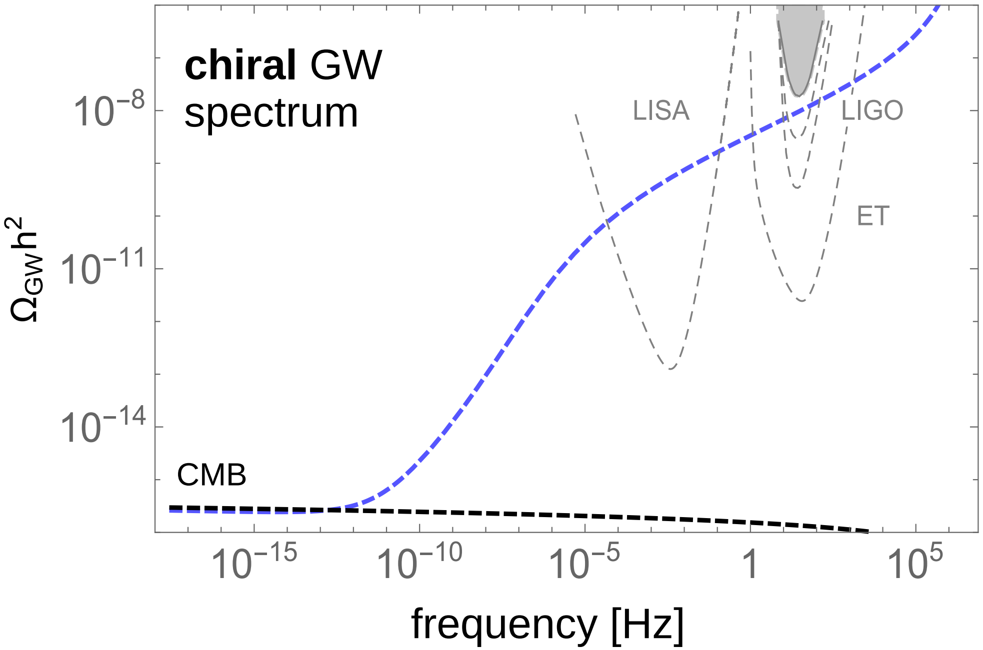

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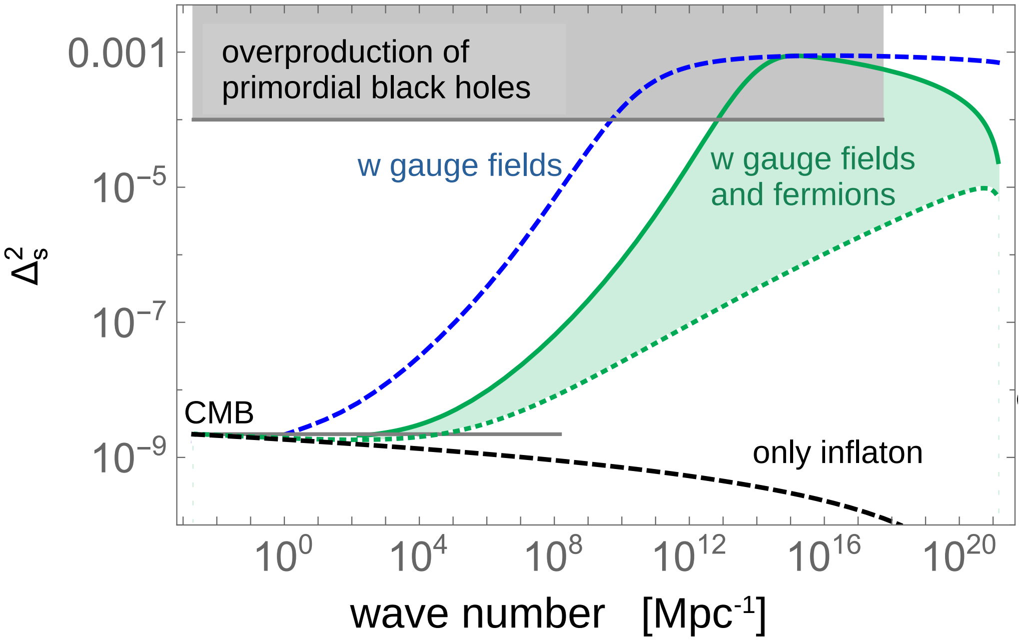

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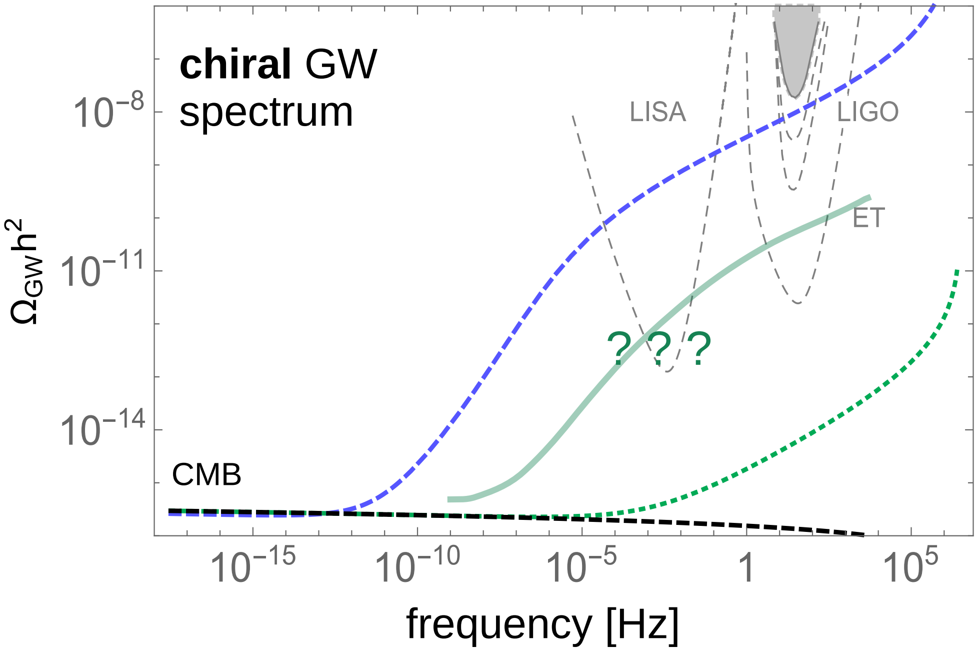

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Implications for late universe

Reduces efficiency of magnetogenesis models based on axionic coupling?

Opens up new avenues for baryogenesis (see Kohei's talk):

Baryogenesis from decaying magnetic fields
(Kamada, Long `16, Jimenez, Kamada, Schmitz, Xu `17)

Baryogenesis from dual gauge field and fermion production
(VD, v. Harling, Morgante, Mukaida `19)

Spontaneous baryogenesis
(VD, Ema, Mukaida, Yamada)

Wash-in Leptogenesis
(VD, Kamada, Mukaida, Schmitz, Yamada `20)

Fermion backreaction - assumptions

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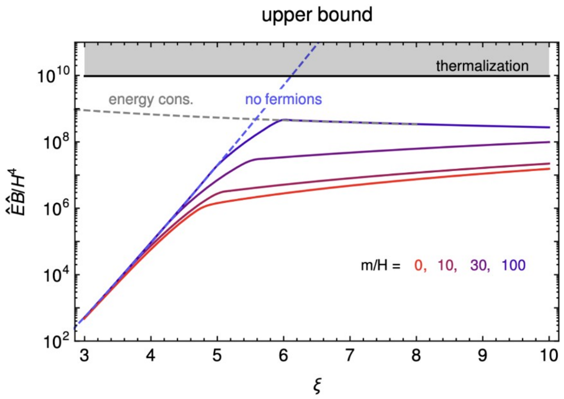
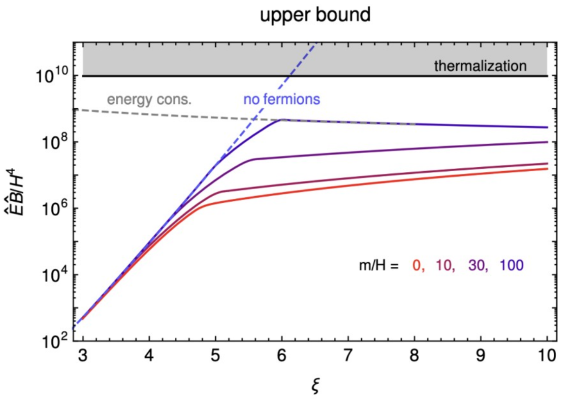


- massless fermions, no thermalization

valid for m « H

Fermion backreaction - assumptions



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- Adiabatic evolution of inflaton velocity

  ok in slow-roll inflation and weak gauge field backreaction

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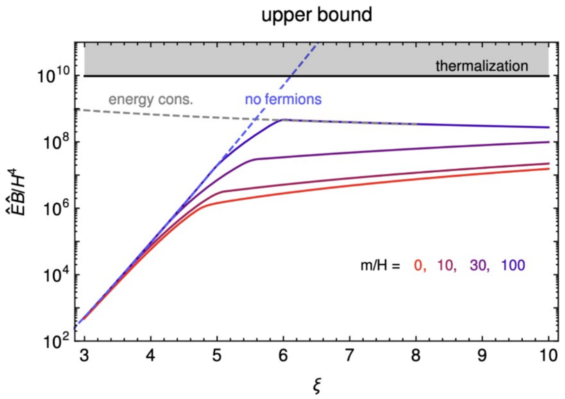

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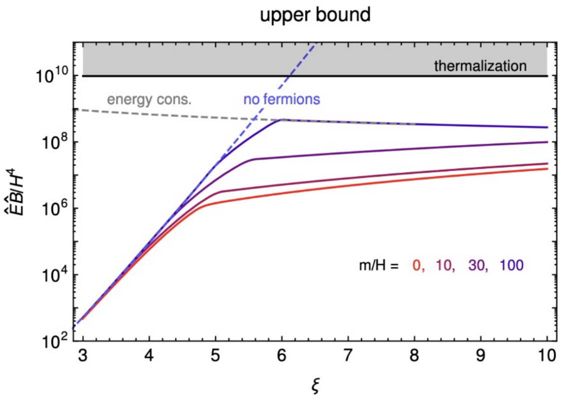

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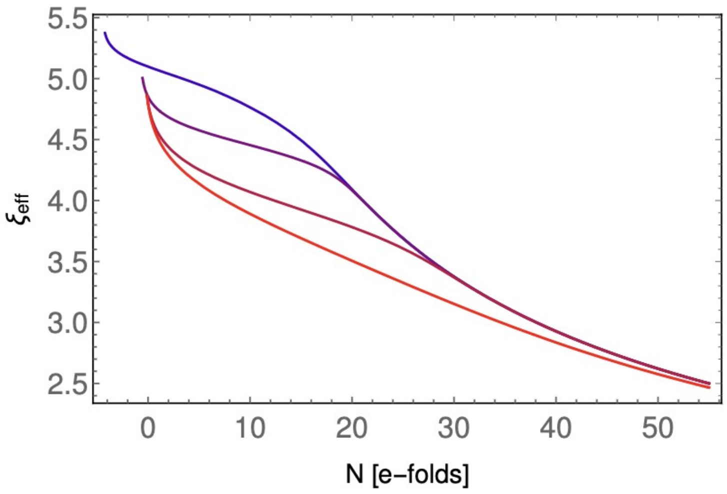
- Approximations made in solving non-linear EM equations

  introduces significant uncertainties

Outline

1) Fermion production and backreaction on to gauge fields

2) Gauge field production and backreaction on to axion dynamics (no fermions)



Luckily, it seems we might not have to worry about both at the same time...

more backreaction challenges

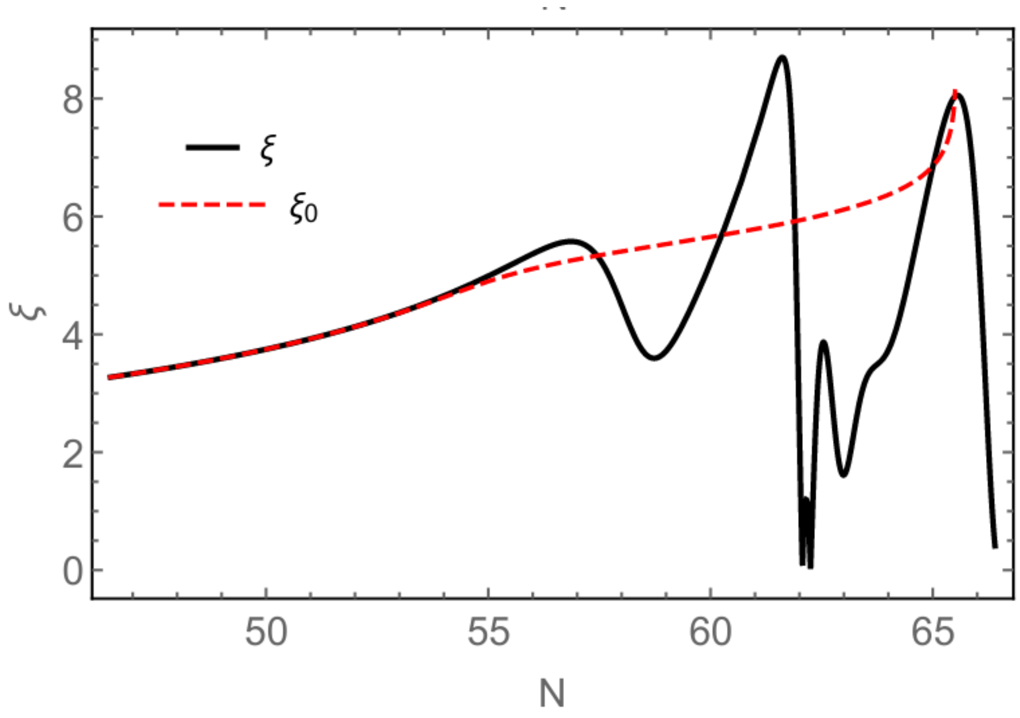
Resonant backreaction of gauge fields on inflaton (no fermions)

VD, Guidetti, Welling, Westphal `20

Gorbar, Schmitz, Sobol, Vilchinskii `21
(gradient expansion formalism)

Figueroa, Lizarraga, Urio, Urrstilla `23
(lattice calculation)

perturbative stability analysis: Peloso, Sorbo `22;
v.Eckardstein, Peloso, Schmitz et al `23



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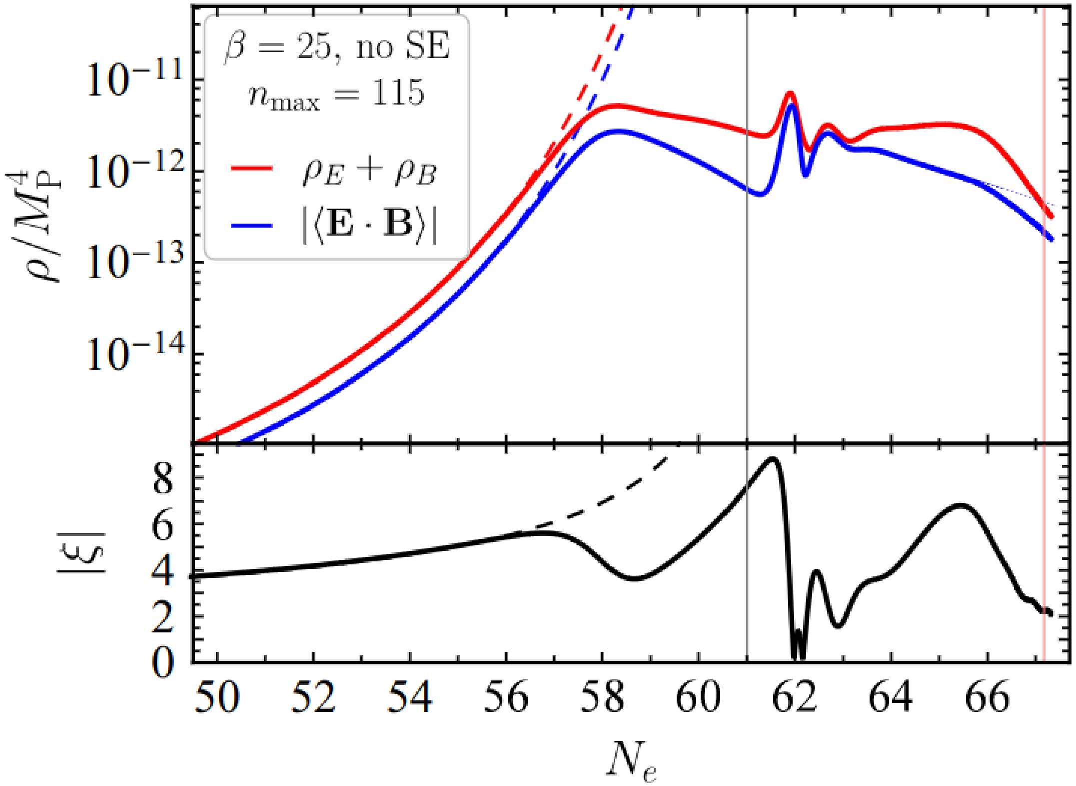

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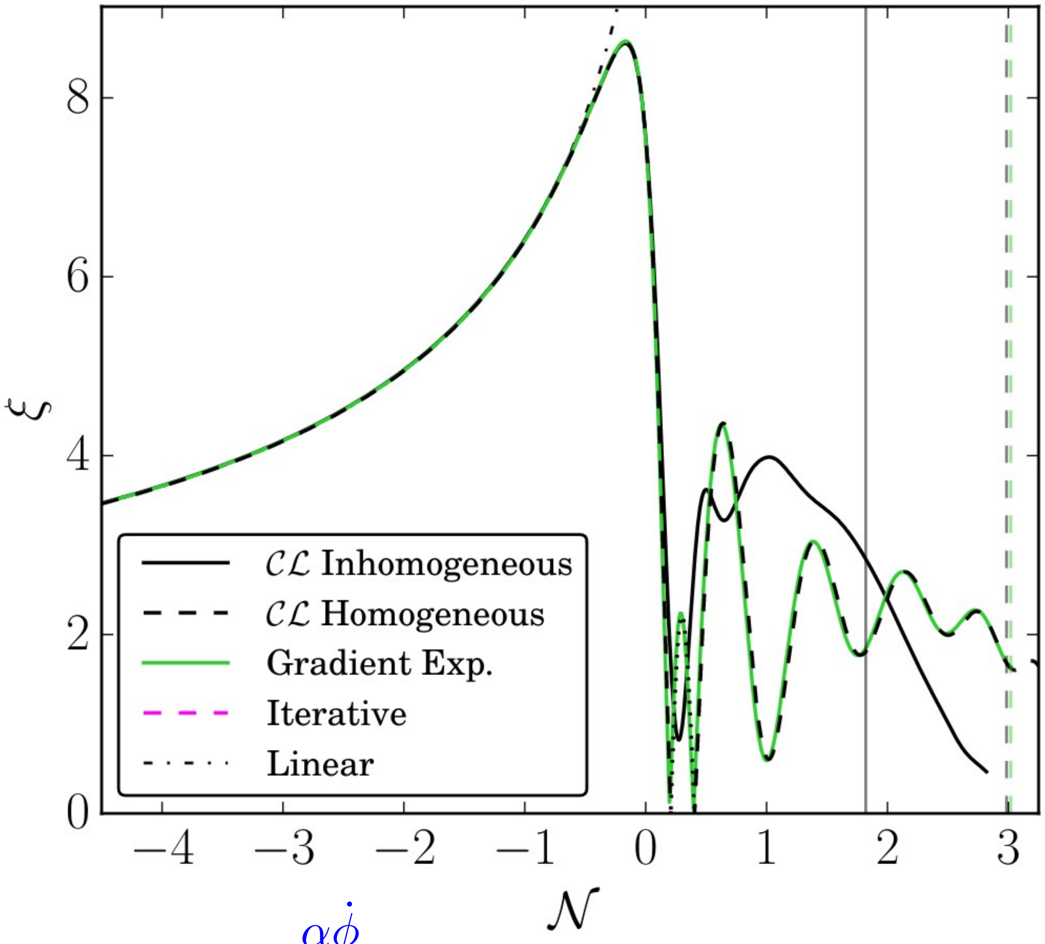

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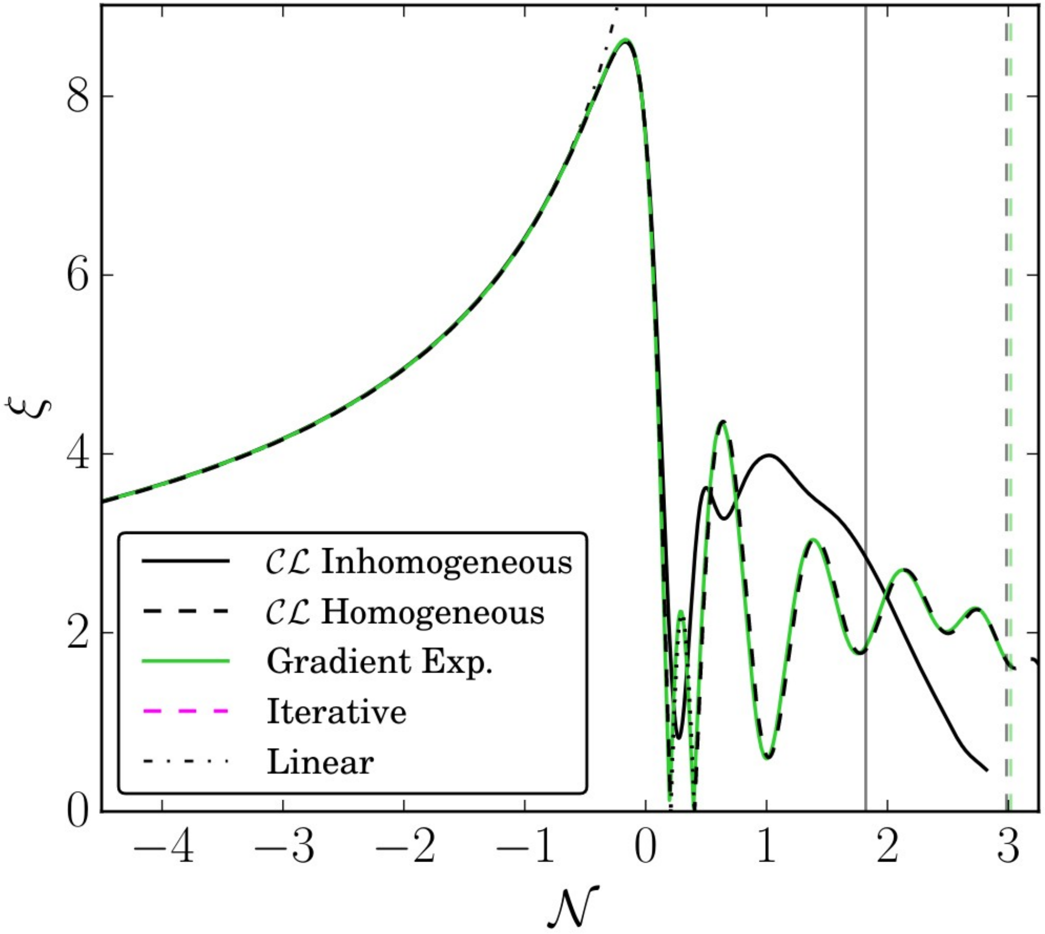
gauge fied gradients ✓

axion gradients relevant too

→ can they be included perturbatively?



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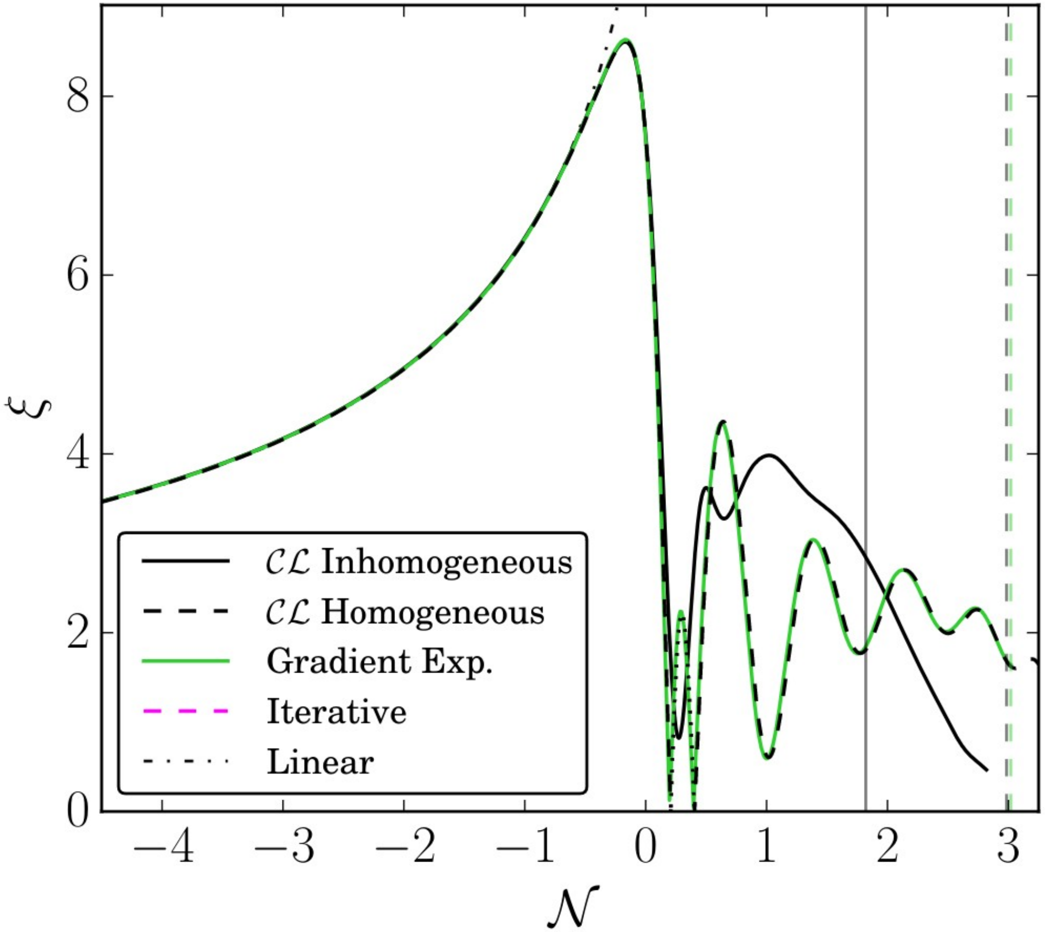


non-abelian gauge groups (w & w/o fermions): non-linear gauge field interactions:

Lozanov, Maleknejad, Komatsu `18, **VD**, Mares, Muia, Pieroni `18, **VD**, Ema, Mukaida, Sato `18,
Mirzagholi, Maleknejad, Lozanov `19, **VD,** Sandner `19

warm/thermalized inflation: Ferreira, Notari `17, Berghaus, Graham, Kaplan `19

towards accounting for axion gradients

Gradient expansion formalism:

Gorbar, Schmitz, Sobol, Vilchinskii `21

EOMs in position space,

$$0 = \ddot\phi + 3H\dot\phi + m_\phi^2\phi - \frac{\beta}{M_P}\left\langle \vec E\cdot\vec B\right\rangle,$$

$$0 = \ddot\chi + 3H\dot\chi - \frac{\nabla^2\chi}{a^2} + m_\phi^2\chi - \frac{\beta}{M_P}\left(\vec E\cdot\vec B - \left\langle\vec E\cdot\vec B\right\rangle\right),$$

$$0 = \dot{\vec E} + 2H\vec E - \frac{1}{a}\vec\nabla\times\vec B + \frac{\beta}{M_P}\left(\dot\phi+\dot\chi\right)\vec B + \frac{\beta}{M_P}\frac{1}{a}\vec\nabla\chi\times\vec E,$$

$$0 = \dot{\vec B} + 2H\vec B + \frac{1}{a}\vec\nabla\times\vec E,$$

$$0 = \vec\nabla\cdot\vec E + \frac{\beta}{M_P}\vec\nabla\chi\cdot\vec B, \quad 0 = \vec\nabla\cdot\vec B,$$

$$\phi(x,t)\mapsto\phi(t)+\chi(x,t)$$

$$\mathcal{P}_X^{(n)} = \frac{1}{a^n}\left\langle \vec X\cdot(\vec\nabla\times)^n\vec X\right\rangle$$

$$\mathcal{P}_{XY}^{(n)} = -\frac{1}{a^n}\left\langle \vec X\cdot(\vec\nabla\times)^n\vec Y\right\rangle$$

$\vec\nabla\chi = 0$

boundary terms

$$\dot{\mathcal{P}}_E^{(n)} + (n+4)H\mathcal{P}_E^{(n)} - \frac{2\beta\dot\phi}{M_P}\mathcal{P}_{EB}^{(n)} + 2\mathcal{P}_{EB}^{(n+1)} = \left[\dot{\mathcal{P}}_E^{(n)}\right]_b,$$

$$\dot{\mathcal{P}}_B^{(n)} + (n+4)H\mathcal{P}_B^{(n)} - 2\mathcal{P}_{EB}^{(n+1)} = \left[\dot{\mathcal{P}}_B^{(n)}\right]_b,$$

$$\dot{\mathcal{P}}_{EB}^{(n)} + (n+4)H\mathcal{P}_{EB}^{(n)} - \mathcal{P}_E^{(n+1)} + \mathcal{P}_B^{(n+1)} - \frac{\beta\dot\phi}{M_P}\mathcal{P}_B^{(n)} = \left[\dot{\mathcal{P}}_{EB}^{(n)}\right]_b$$

+ truncation condition

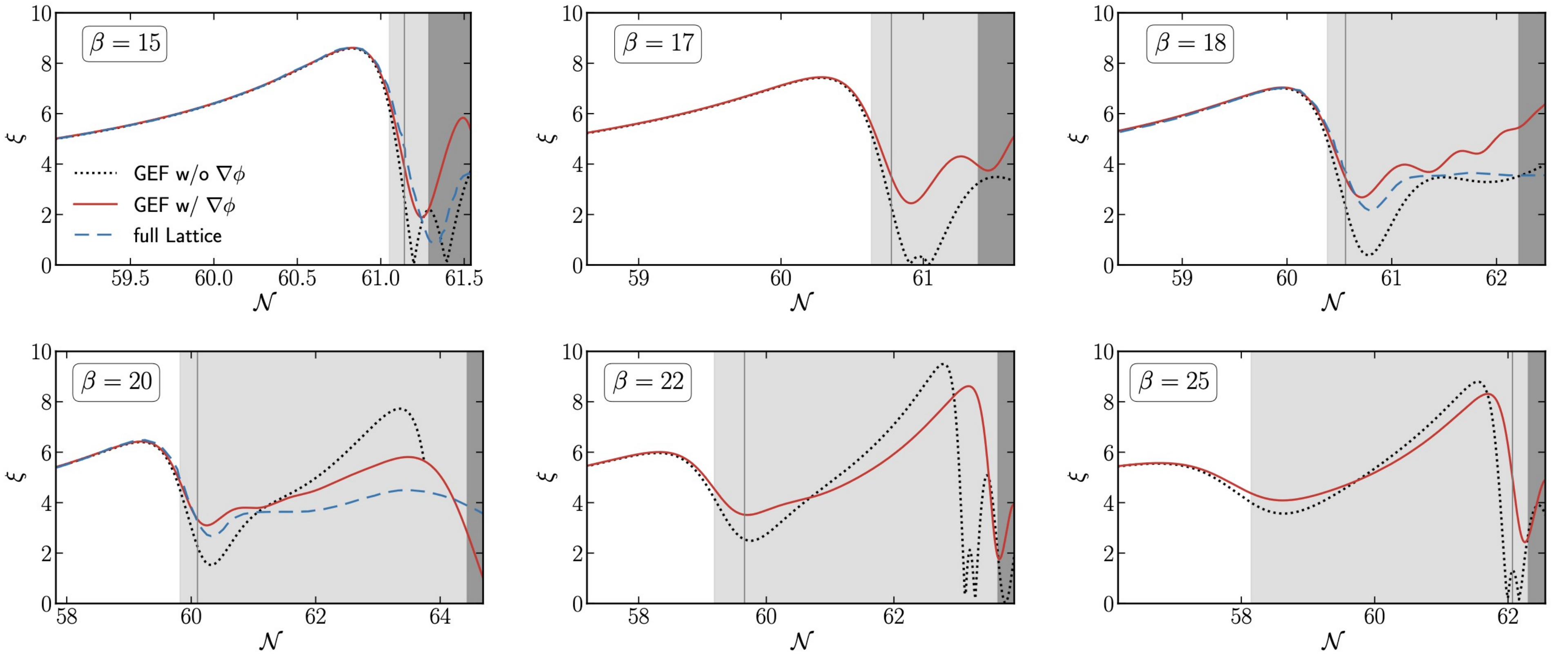
→ large, coupled system of ODEs

towards accounting for axion gradients

VD, Ema, Sandner `23

Figueroa, Lizarraga,
Urio, Urrstilla `23
(lattice calculation)

include axion gradients perturbatively → evolve 2-pt and 3-pt functions:

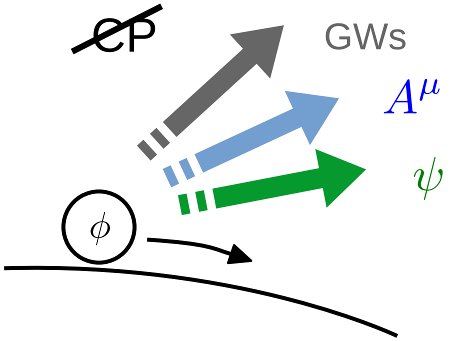


axion gradient energy > 1 % , axion gradient energy > 50 %

Few e-folds of perturbative regime, but eventually axion gradients dominate

conclusions

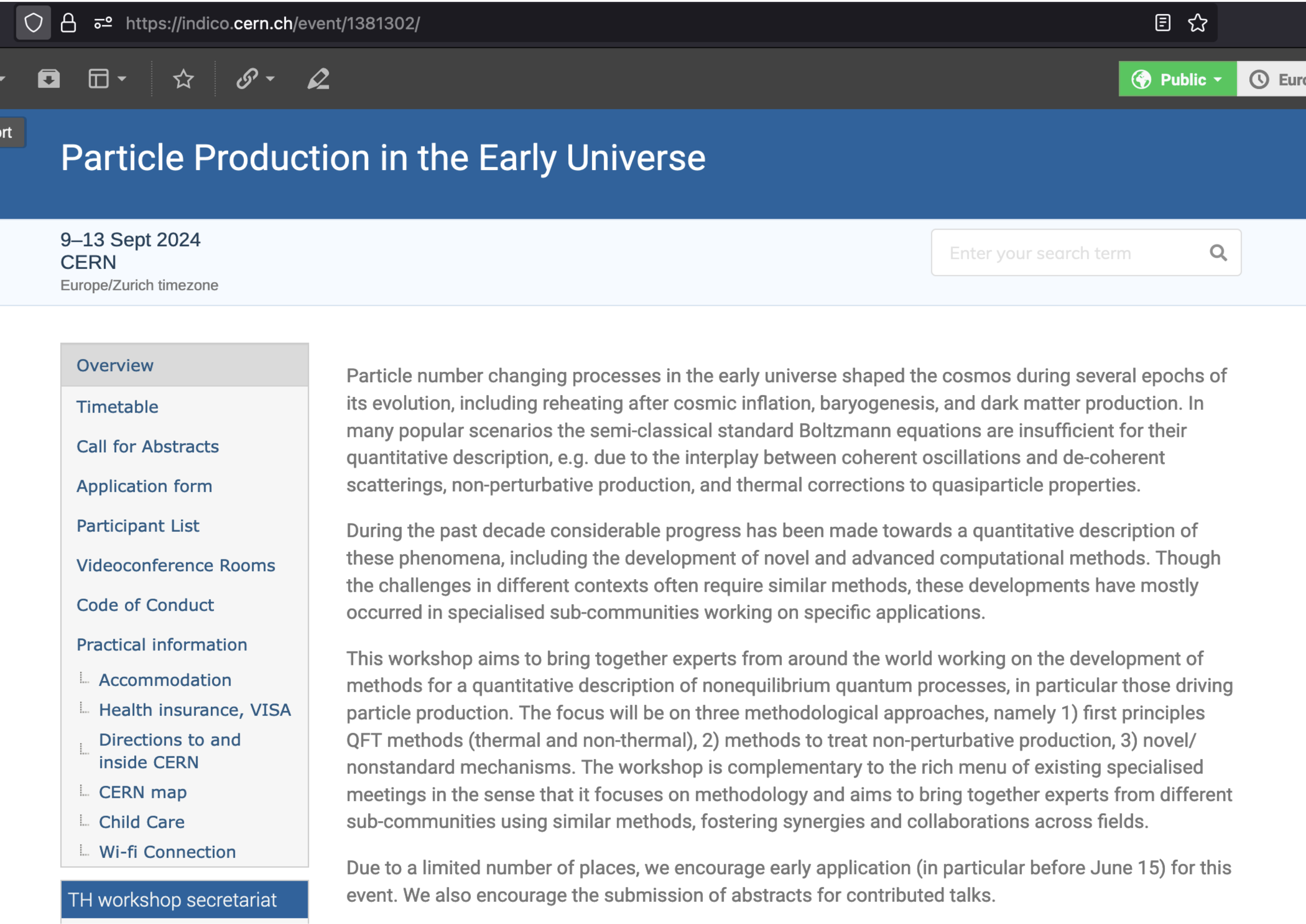
axion inflation: dual production of gauge fields and fermions



- enhanced scalar power spectrum and chiral GW spectrum at small scales
- interactions between different components crucial
- non-vanishing chemical potentials for SM fermions

Open questions: most interesting phenomenology occurs in regimes where some backreaction is relevant. More work needed for quantitative predictions.

Thank you!



Particle Production in the Early Universe

9–13 Sept 2024
CERN
Europe/Zurich timezone

- Overview
- Timetable
- Call for Abstracts
- Application form
- Participant List
- Videoconference Rooms
- Code of Conduct
- Practical information
  - Accommodation
  - Health insurance, VISA
  - Directions to and inside CERN
  - CERN map
  - Child Care
  - Wi-fi Connection

Particle number changing processes in the early universe shaped the cosmos during several epochs of its evolution, including reheating after cosmic inflation, baryogenesis, and dark matter production. In many popular scenarios the semi-classical standard Boltzmann equations are insufficient for their quantitative description, e.g. due to the interplay between coherent oscillations and de-coherent scatterings, non-perturbative production, and thermal corrections to quasiparticle properties.

During the past decade considerable progress has been made towards a quantitative description of these phenomena, including the development of novel and advanced computational methods. Though the challenges in different contexts often require similar methods, these developments have mostly occurred in specialised sub-communities working on specific applications.

This workshop aims to bring together experts from around the world working on the development of methods for a quantitative description of nonequilibrium quantum processes, in particular those driving particle production. The focus will be on three methodological approaches, namely 1) first principles QFT methods (thermal and non-thermal), 2) methods to treat non-perturbative production, 3) novel/nonstandard mechanisms. The workshop is complementary to the rich menu of existing specialised meetings in the sense that it focuses on methodology and aims to bring together experts from different sub-communities using similar methods, fostering synergies and collaborations across fields.

Due to a limited number of places, we encourage early application (in particular before June 15) for this event. We also encourage the submission of abstracts for contributed talks.