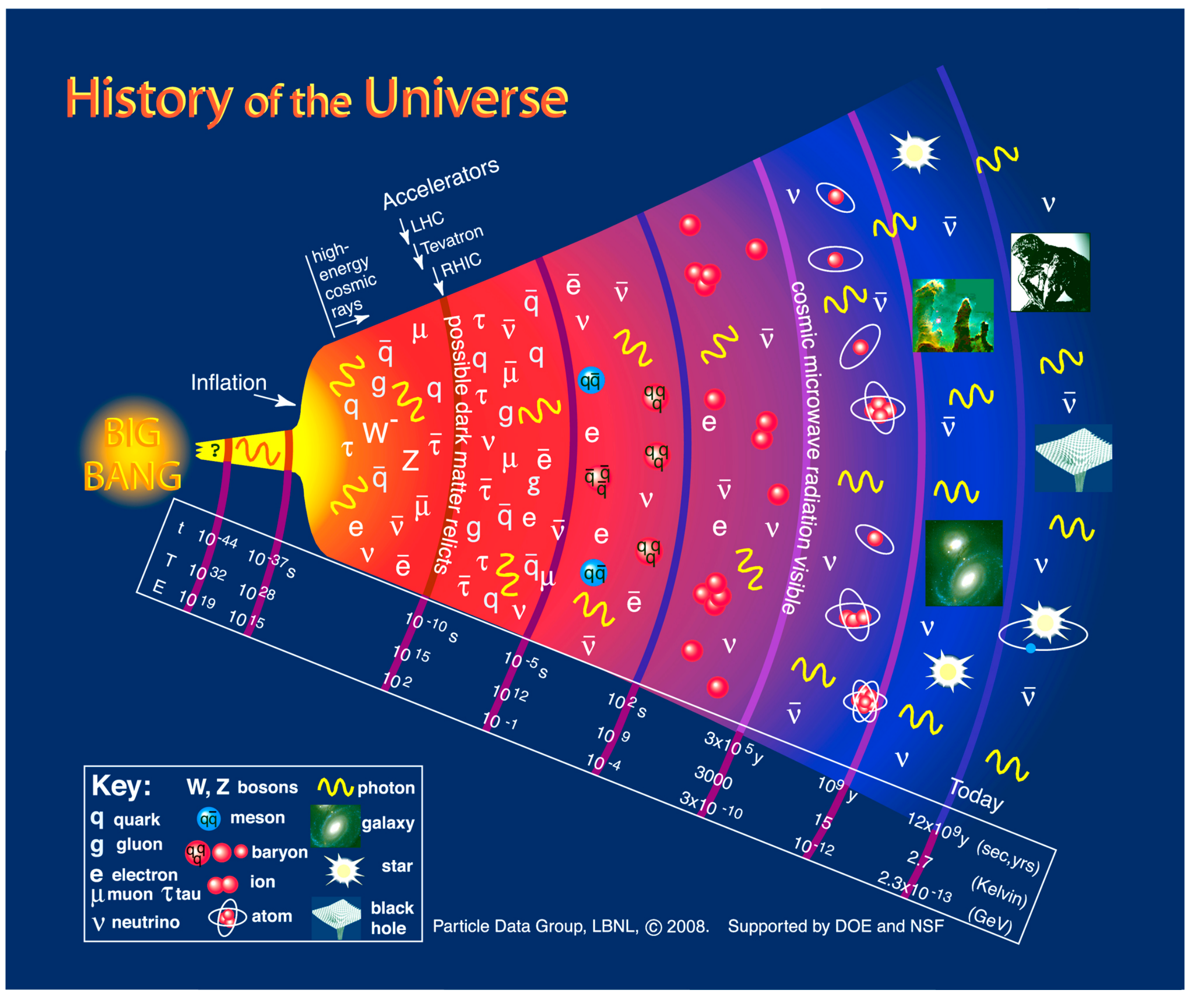
Particle Production during Axion Inflation

New probes of inflation ?



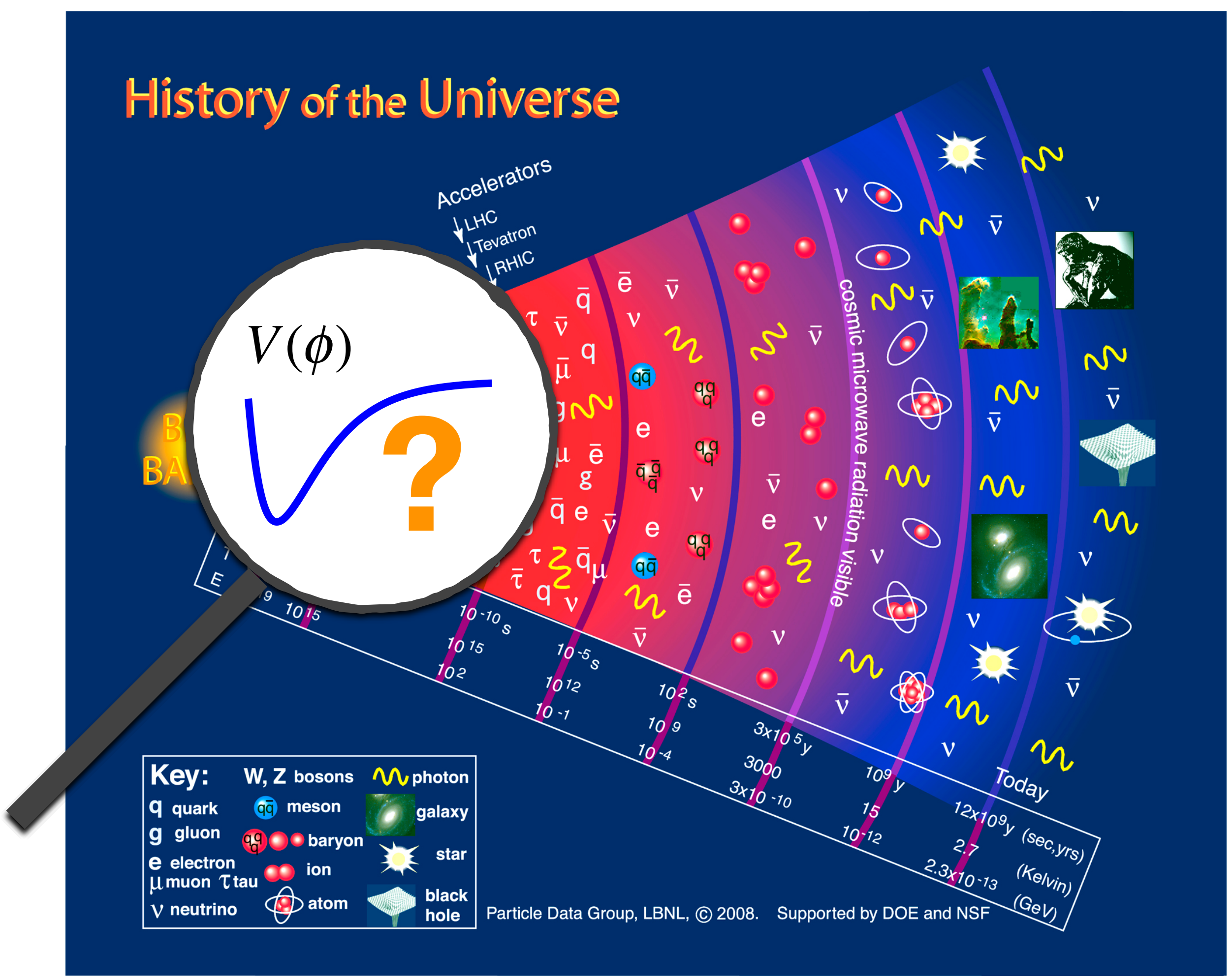
Valerie Domcke
DESY Hamburg

DAMTP-Cavendish HEP seminar,
09.11.2018

based on arXiv: 1806.08769
in collaboration with Kyohei Mukaida

Particle Production during Axion Inflation

New probes of inflation ?



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‘Axion’ inflation

Slow-roll inflation → **very flat scalar potential**

Reheating after inflation → **coupling to the SM**

↓

Inflaton as Pseudo Goldstone Boson (PNGB) with shift-symmetric couplings

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

Particle production during inflation is irrelevant, because everything is diluted exponentially !

Really…?

Outline

- PNGB couplings to gauge fields and fermions
- Dual production of helical gauge fields and chiral fermions
- Consequences for inflation and leptogenesis

coupling to gauge fields

$$\mathcal{L} = -\partial_\mu \phi \partial^\mu \phi - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} - V(\phi) - \boxed{\frac{\alpha}{4 f_a} \phi F_{\mu\nu} \tilde{F}^{\mu\nu}}$$

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

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

explosive helical gauge boson production

additional friction modifies dynamics of inflation

strongly blue-tilted non-gaussian scalar and tensor power spectrum

production of PBHs and UCMHs
Linde, Mooji, Pajer ’13
Muia, VD, Pieroni ‘17

polarized SGWB at LISA and LIGO
Cook, Sorbo ’11/’12
Barnaby, Pajer, Peloso ‘12 ,
Binetruy, VD, Pieroni ‘16

baryogenesis from decaying helical gauge fields
Jiminez, Kamada, Schmitz, Xu ‘17

inflation on steep potentials Anber, Sorbo ’09

relaxion mechanism
Hook, Marques-Tavares ’16

coupling to fermions

$$\mathcal{L} = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) + i\bar{\psi}\gamma^\mu\partial_\mu\psi - \boxed{\frac{\phi}{2f_a}\partial_\mu \underbrace{\left(\bar{\psi}\gamma^\mu\gamma_5\psi\right)}_{J_5^\mu}}$$

Dolgov, Freese '94

$$\phi\,\partial_\mu J_5^\mu \to \dot{\phi}\,J_5^0$$

chiral fermion production

spontaneous CPT violation

add. contribution to scalar and tensor power spectrum

Anber, Sabancilar '16
Adshead, Pearce, Peloso, Roberts, Sobrbo '18

spontaneous baryogenesis

Kusenko, Schmitz, Yanagida '14
Adshead, Sfakianakis '15/'16

QFT anomalies in a nutshell

anomaly = classical symmetry broken at the quantum level

global symmetry

gauge symmetry

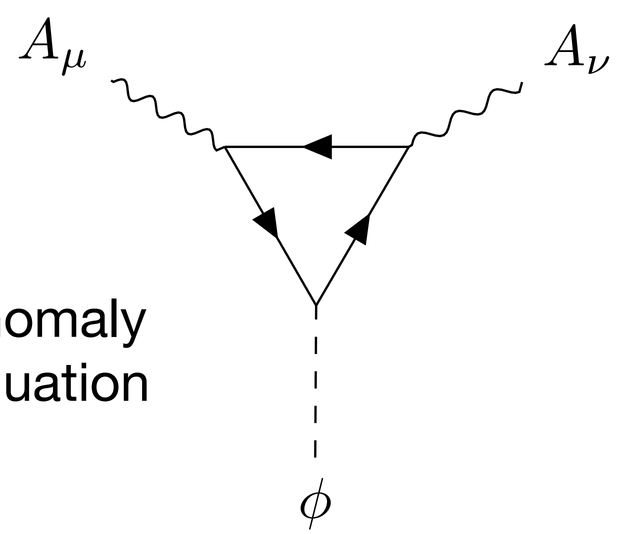
inconsistent QFT

chiral anomaly, e.g. in the SM

- pion decay $\pi^0 \to \gamma\gamma$
- baryon and lepton number (B + L)

$$0 \neq \partial_\mu J_5^\mu = -\frac{1}{16\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

anomaly equation



In the presence of a chiral anomaly (SM!), the shift-symmetric couplings to gauge fields and fermions are not independent

Setup

U(1) gauge symmetry + massless Dirac fermion + pseudo Goldstone boson + chiral anomaly:

$$S = \int \mathrm{d}^4 x \left\{ \sqrt{-g} \left[\frac{g^{\mu\nu}}{2} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right] - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \overline{\psi} \left(i \partial\!\!\!/ - g Q A\!\!\!/ \right) \psi + \boxed{\frac{\alpha \phi}{4 \pi f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}} \right\}.$$

chiral rotation

$$S = \int \mathrm{d}^4 x \left\{ \sqrt{-g} \left[\frac{g^{\mu\nu}}{2} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right] - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \overline{\psi} \left(i \partial\!\!\!/ - g Q A\!\!\!/ \right) \psi \boxed{- \frac{\phi}{2 Q^2 f_a} \partial_\mu J_5^\mu} \right\}$$

Two different frames describing the same physics

conserved currents & charges

ϕ

shift symmetry

$$\phi \mapsto \phi + \theta$$

$$\partial_\mu \left(\sqrt{-g} J^\mu_\phi + \frac{1}{2Q^2} J^\mu_5 \right) = \partial_\mu \left(\sqrt{-g} J^\mu_\phi - \frac{1}{2} K^\mu_{\rm CS} \right) = -\sqrt{-g} f_a V'(\phi) \simeq 0$$

$$\dot\phi \neq 0$$

axial U(1)

$$\psi_R \mapsto e^{i\theta_A} \psi_R$$

$$\psi_L \mapsto e^{-i\theta_A} \psi_L$$

q_5

$$\partial_\mu (J^\mu_5 + Q^2 K^\mu_{\rm CS}) = 0$$

$q_{\rm CS}$

$$J^\mu_\phi \equiv f_a g^{\mu\nu} \partial_\nu \phi \sim f_a \dot\phi$$

$$J^\mu_5 \equiv \overline{\psi} \gamma^\mu \gamma_5 \psi$$

$$K^\mu_{\rm CS} \equiv \frac{\alpha}{\pi} \epsilon^{\mu\nu\rho\sigma} A_\nu \partial_\rho A_\sigma .$$

$$J^\mu_\psi \equiv \overline{\psi} \gamma^\mu \psi$$

vector U(1)

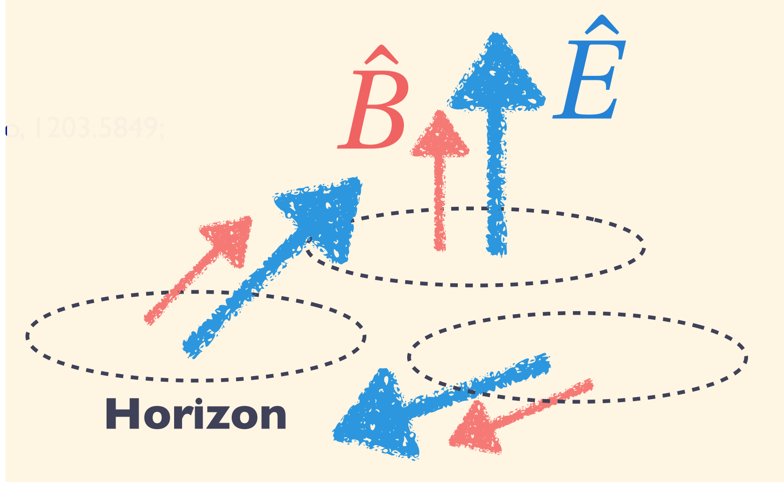
$$0 = \partial_\mu J^\mu_\psi ,$$

$$\psi_R \mapsto e^{i\theta_V} \psi_R$$

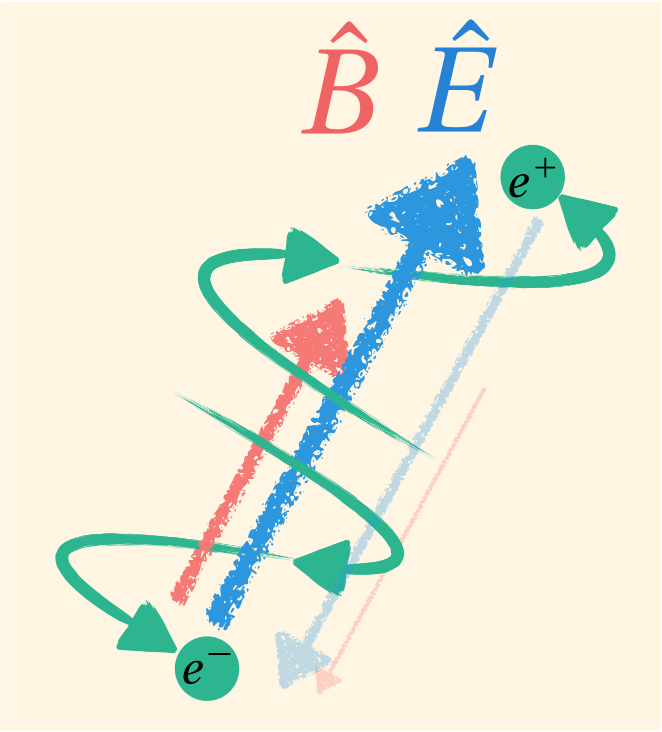
$$\psi_L \mapsto e^{i\theta_V} \psi_L$$

Dual fermion and gauge field production driven by rolling inflaton

the microphysics - overview



figures by K. Mukaida



helical gauge field production

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

(chiral) fermion production

- fermion production in constant E,B background
- quantum `Schwinger - type’ production (-> anomaly equation)

backreaction on gauge field production

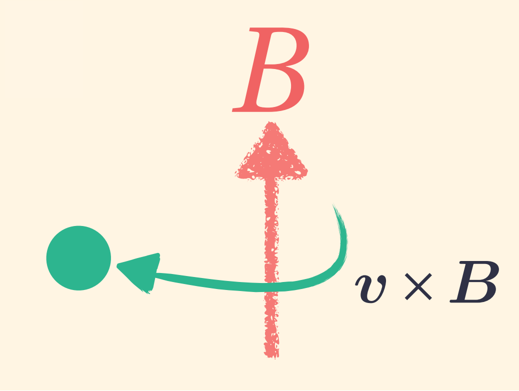
- fermions are accelerated in gauge field background
- induced current inhibits gauge field production

$$\Box A^\nu - \partial_\mu \left(\frac{\alpha \phi}{\pi f_a} \tilde{F}^{\mu\nu} \right) \boxed{- g Q J^\nu_\psi} = 0$$

fermion production

Nielsen, Ninomiya '83
Bavarsad, Kim, Stahl, Xue '18

eom: $$0 = (i\partial_\eta \pm i\boldsymbol{\nabla}\cdot\boldsymbol{\sigma} \pm gQ\boldsymbol{A}\cdot\boldsymbol{\sigma})\,\psi_{\mathrm{R/L}} \equiv D_{\mathrm{R/L}}\psi_{\mathrm{R/L}}$$



differentiate with $\tilde{D}_{\mathrm{R/L}} \equiv i\partial_\eta \pm i\boldsymbol{\nabla}\cdot\boldsymbol{\sigma} \mp gQ\boldsymbol{A}\cdot\boldsymbol{\sigma}$

assume constant E,B in z-direction: $(A_\mu) = (0, 0, -Bx, Et)$

auxiliary eom:

$$0 = \tilde{D}_{\mathrm{R/L}}D_{\mathrm{R/L}}\psi_{\mathrm{R/L}} = \left[-\frac{\partial^2}{\partial t^2} + \frac{\partial^2}{\partial x^2} - (gQBx + p_y)^2 - (gQEt - p_z)^2 - gQ\,(B \pm iE)\,\sigma_z\right]\Psi_{\mathrm{R/L}}$$

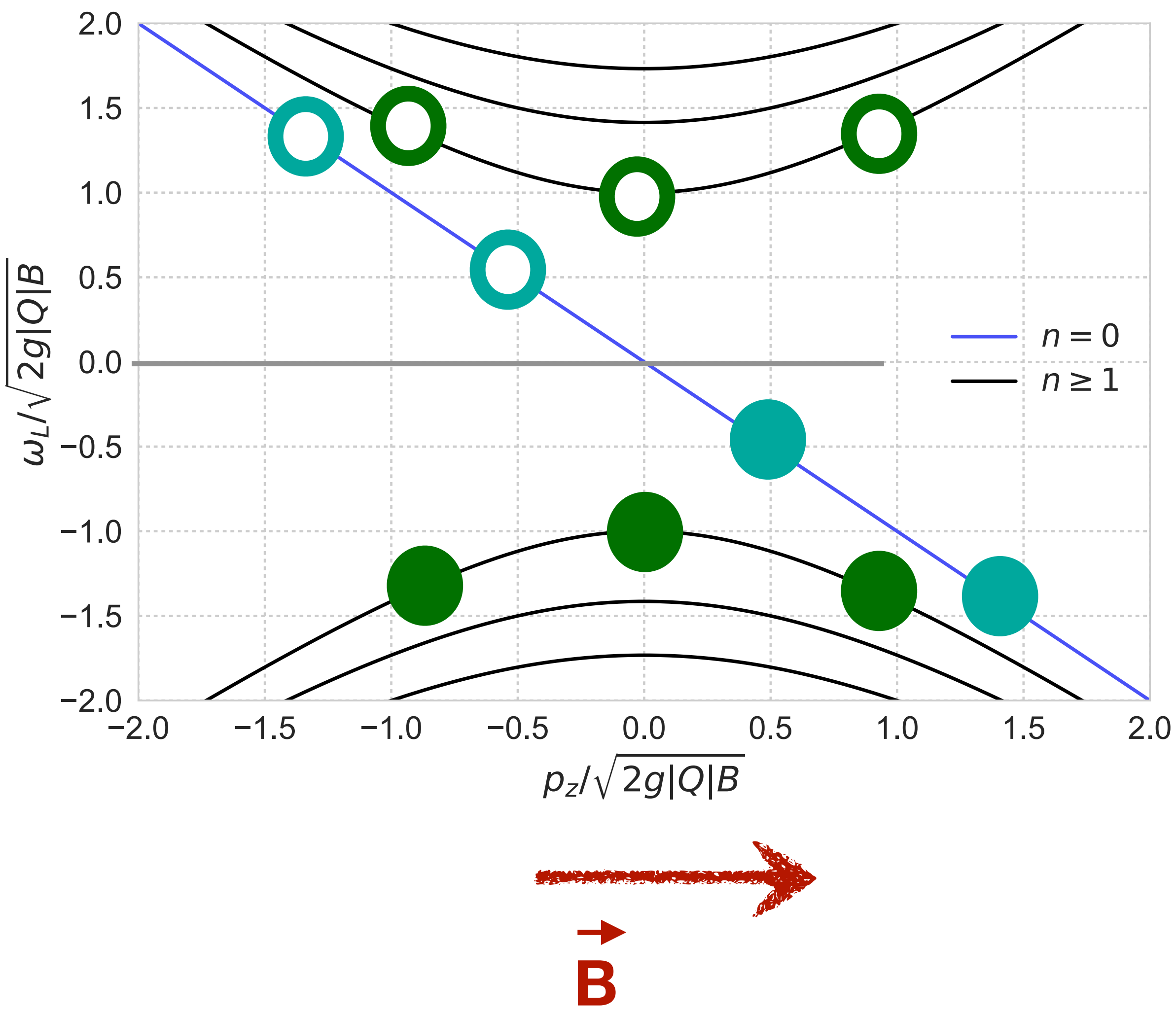
separable differential equation with **discrete energy levels** (Landau levels)**:**

$$\vec{E} = 0 \qquad \omega_{\mathrm{L}} = \begin{cases} \pm\sqrt{p_z^2 + 2ngQB} & \text{for} \quad n = 1, 2, \ldots\,, \\ -p_z & \text{for} \quad n = 0\,, \end{cases} \qquad \omega_{\mathrm{R}} = \begin{cases} \pm\sqrt{p_z^2 + 2ngQB} & \text{for} \quad n = 1, 2, \ldots\,, \\ p_z & \text{for} \quad n = 0\,, \end{cases}$$

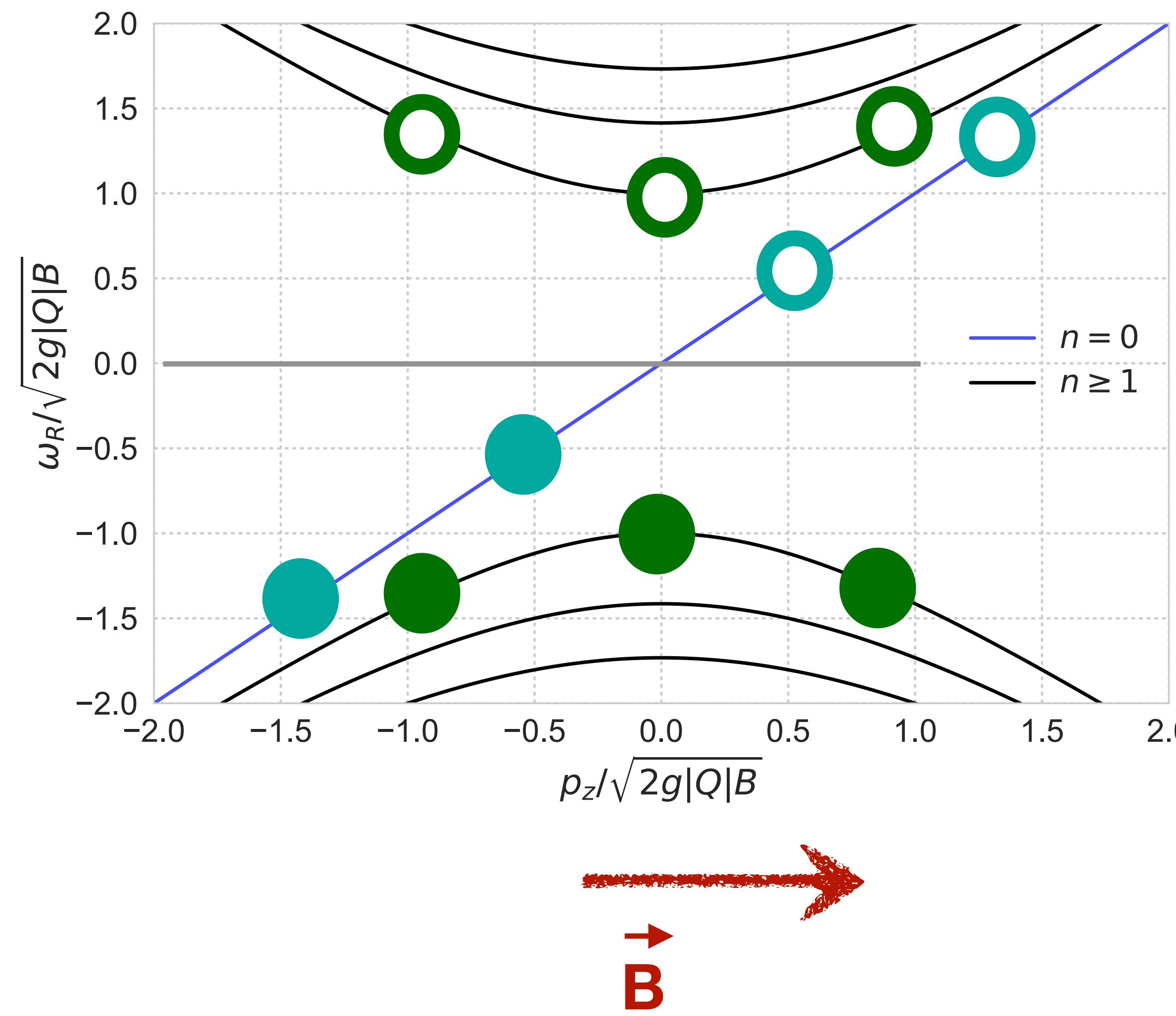
determine particle production induced by E-field

fermion production (LLL)

left-handed fermions

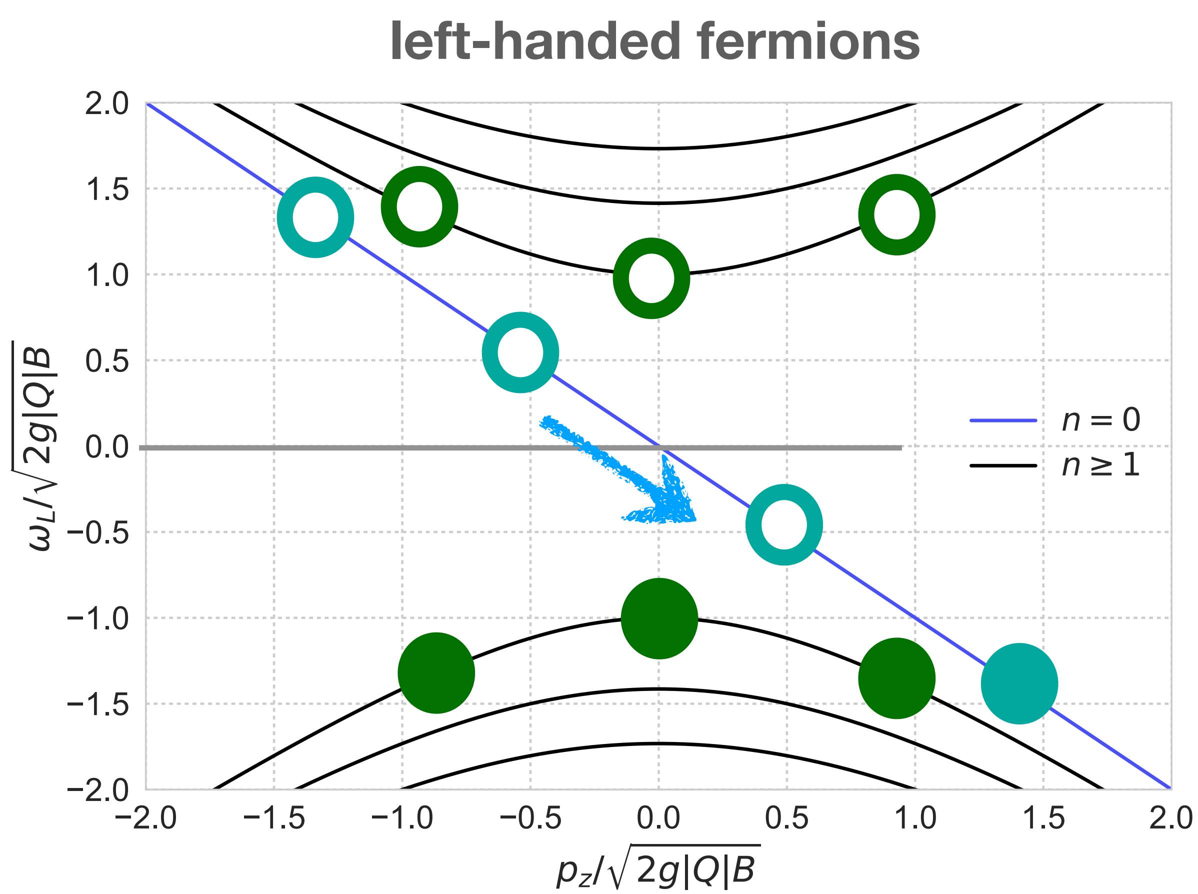


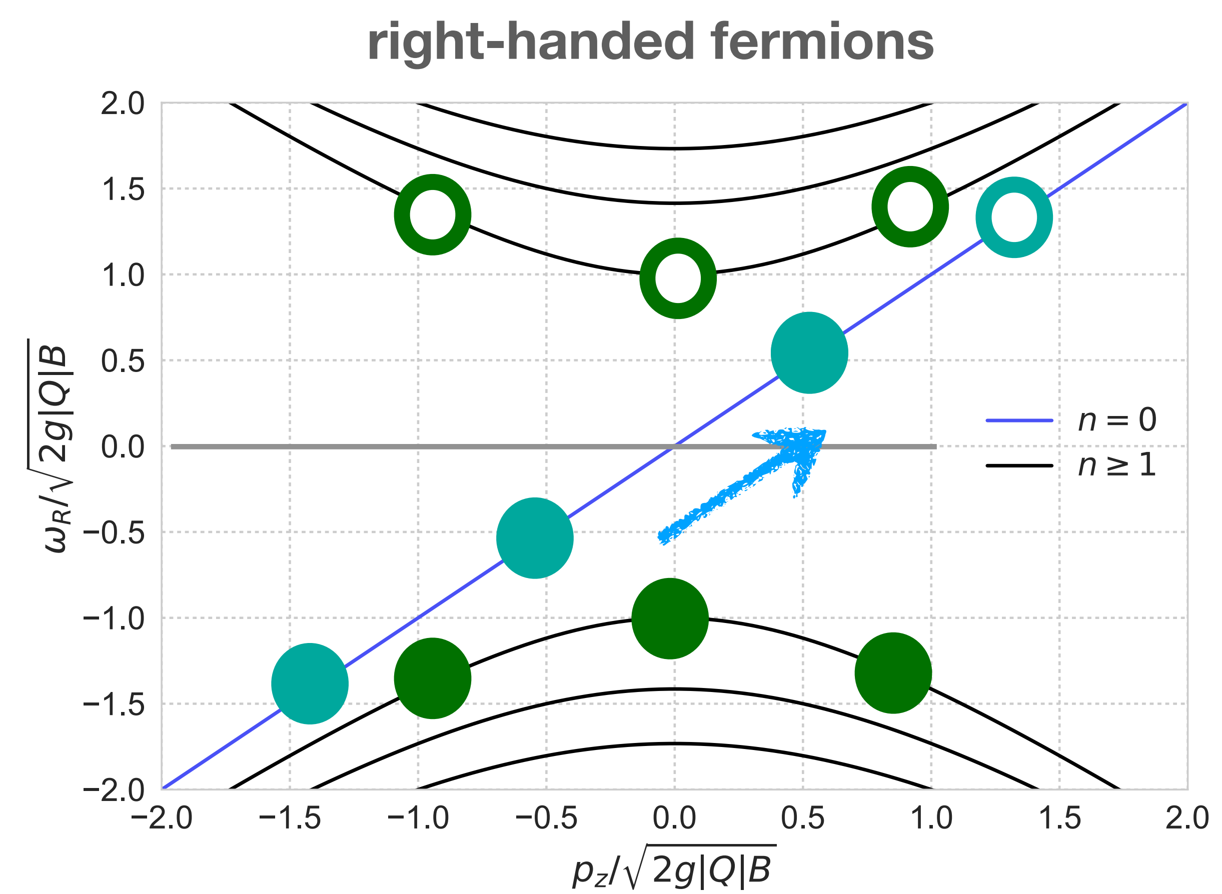
right-handed fermions

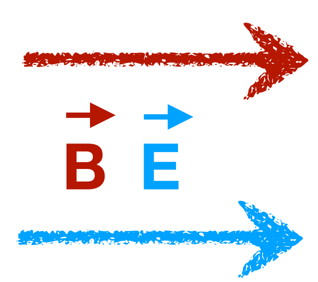


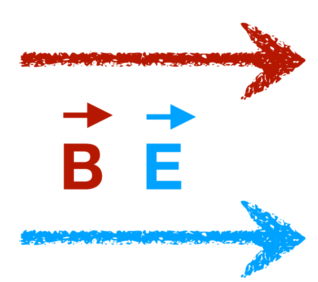
asymmetric fermion production

fermion production (LLL)





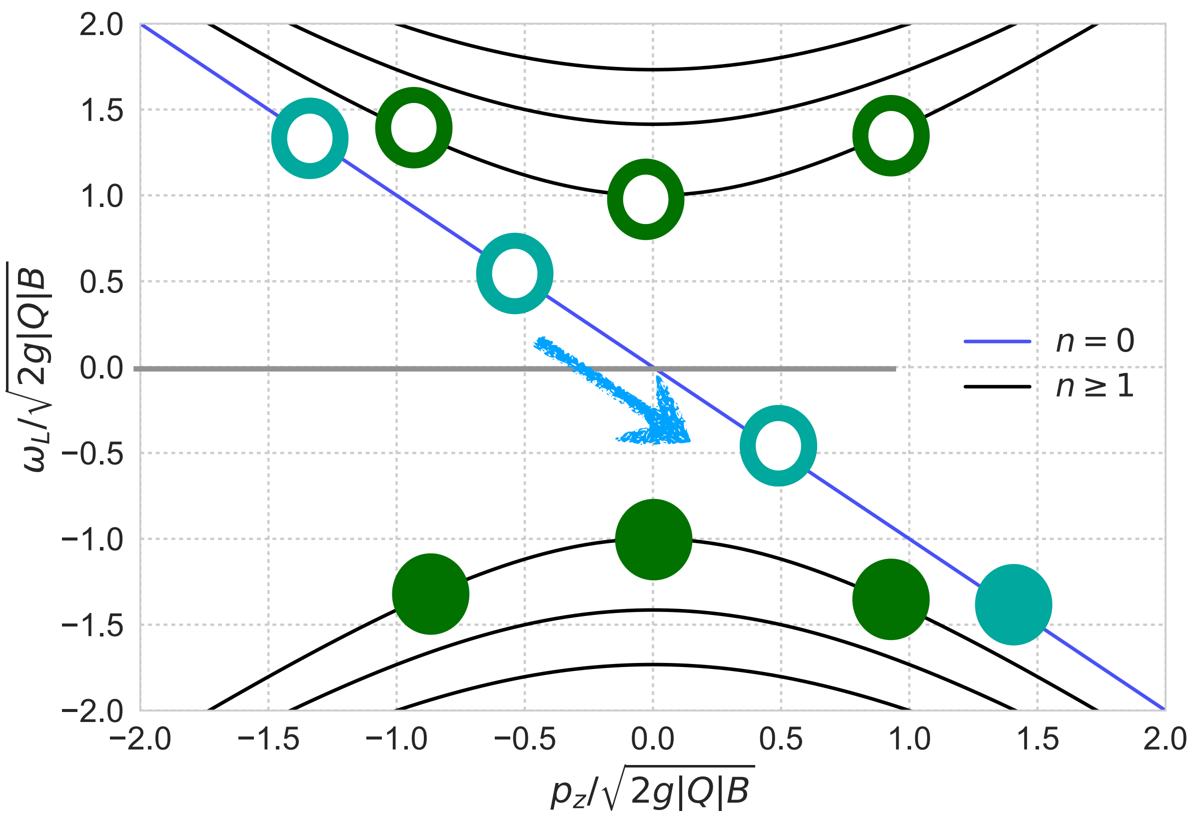


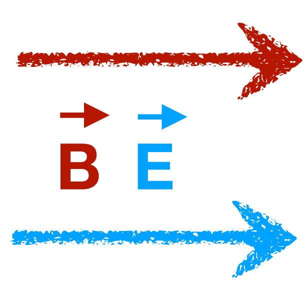


asymmetric fermion production

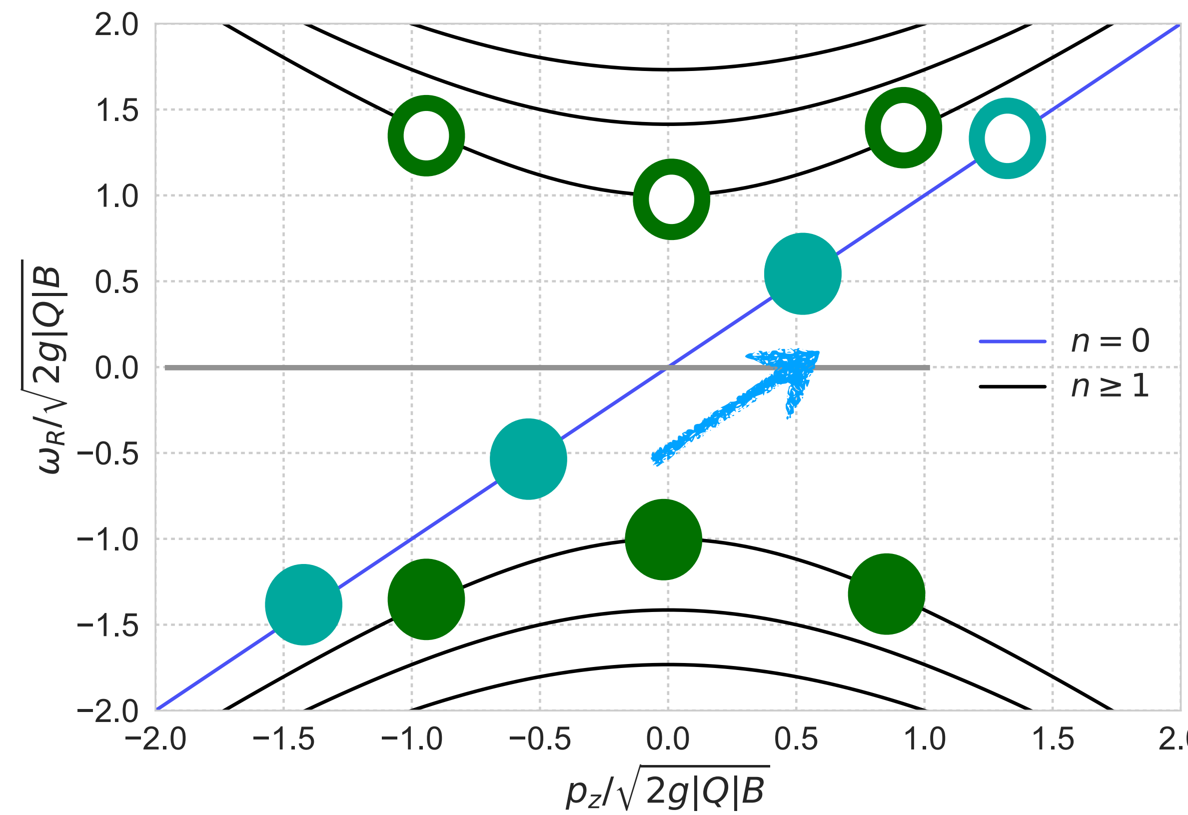
fermion production (LLL)

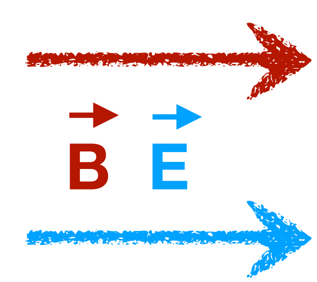
left-handed fermions





right-handed fermions





asymmetric fermion production

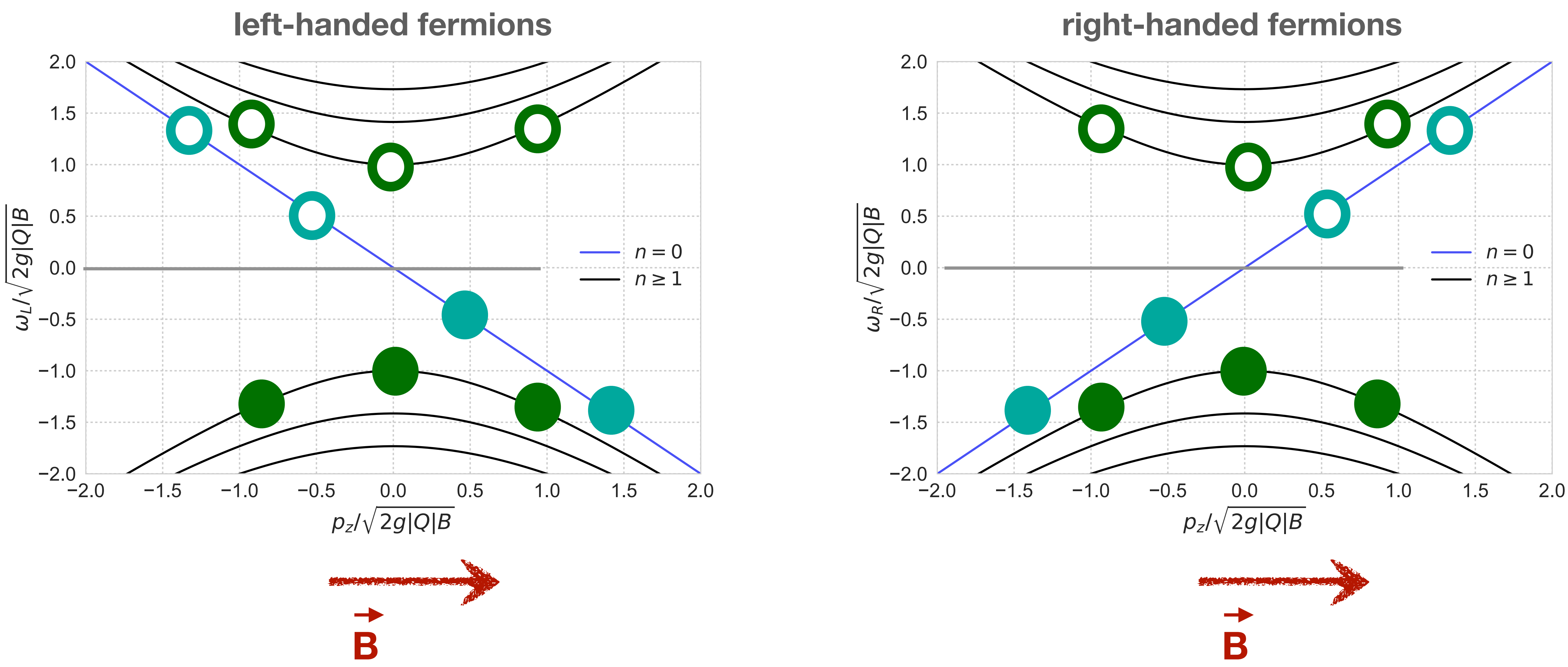
anomaly equation !

Nielsen, Ninomiya ’83

$$\dot{q}_5 = \dot{q}_{\mathrm{R}}\big|_{n=0} - \dot{q}_{\mathrm{L}}\big|_{n=0} = -\frac{\alpha Q^2}{2\pi} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\dot{n}_\psi^{\mathrm{LLL}} = 2 \times \frac{g^2 Q^2}{4\pi^2} E\, B$$

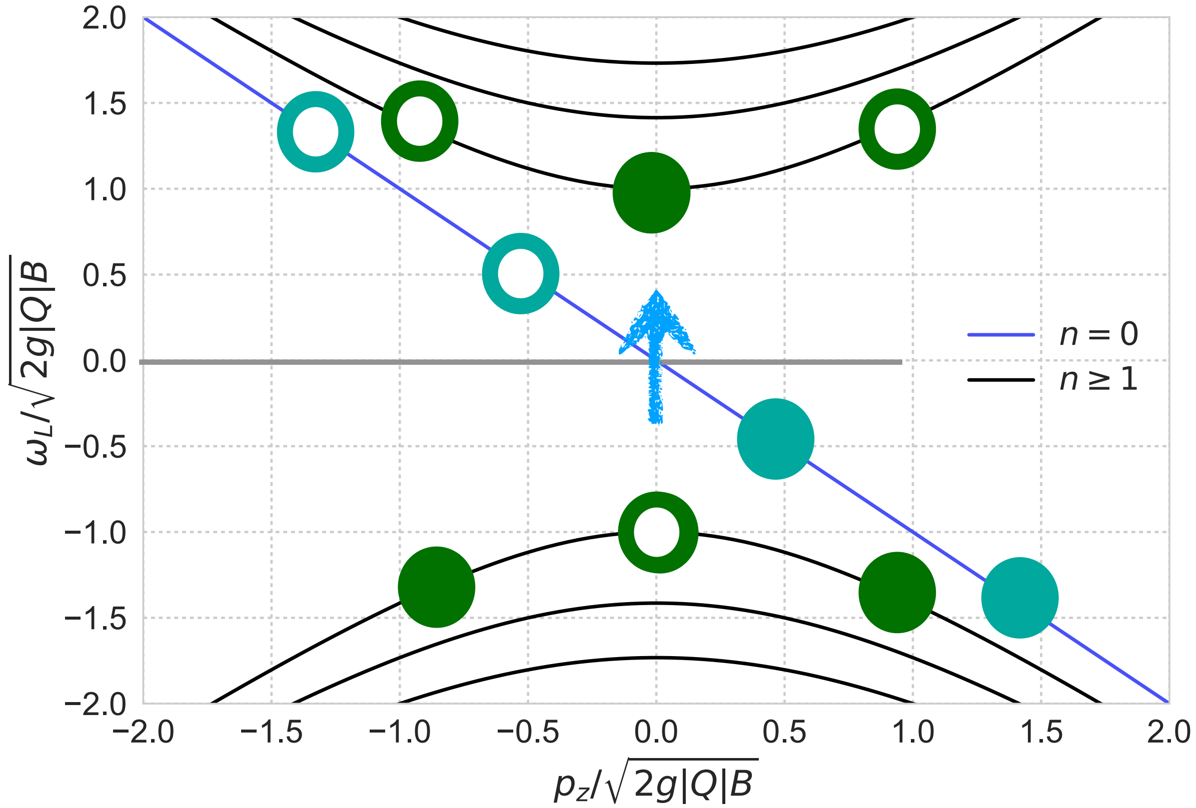
fermion production (HLL)



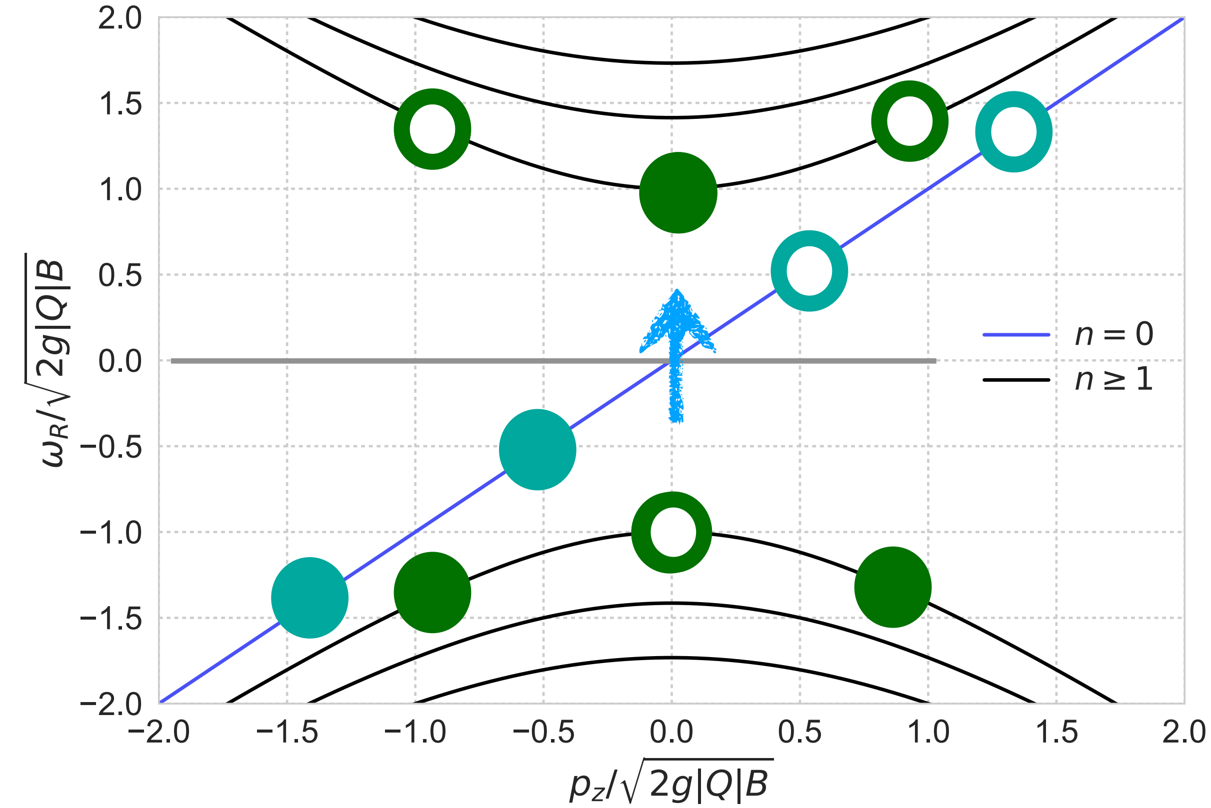
symmetric fermion production

fermion production (HLL)

left-handed fermions



right-handed fermions

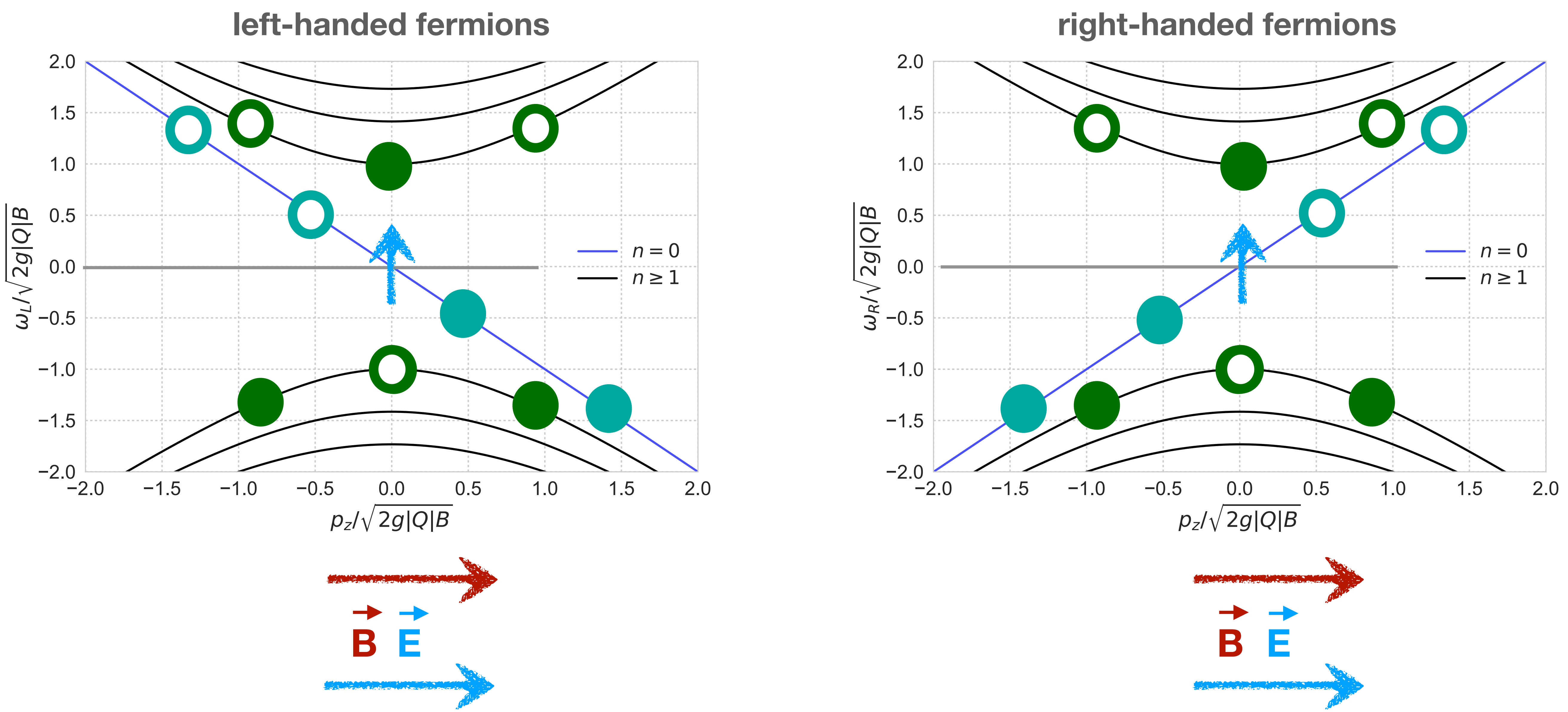


$\vec{B}$ $\vec{E}$

$\vec{B}$ $\vec{E}$

symmetric fermion production

fermion production (HLL)

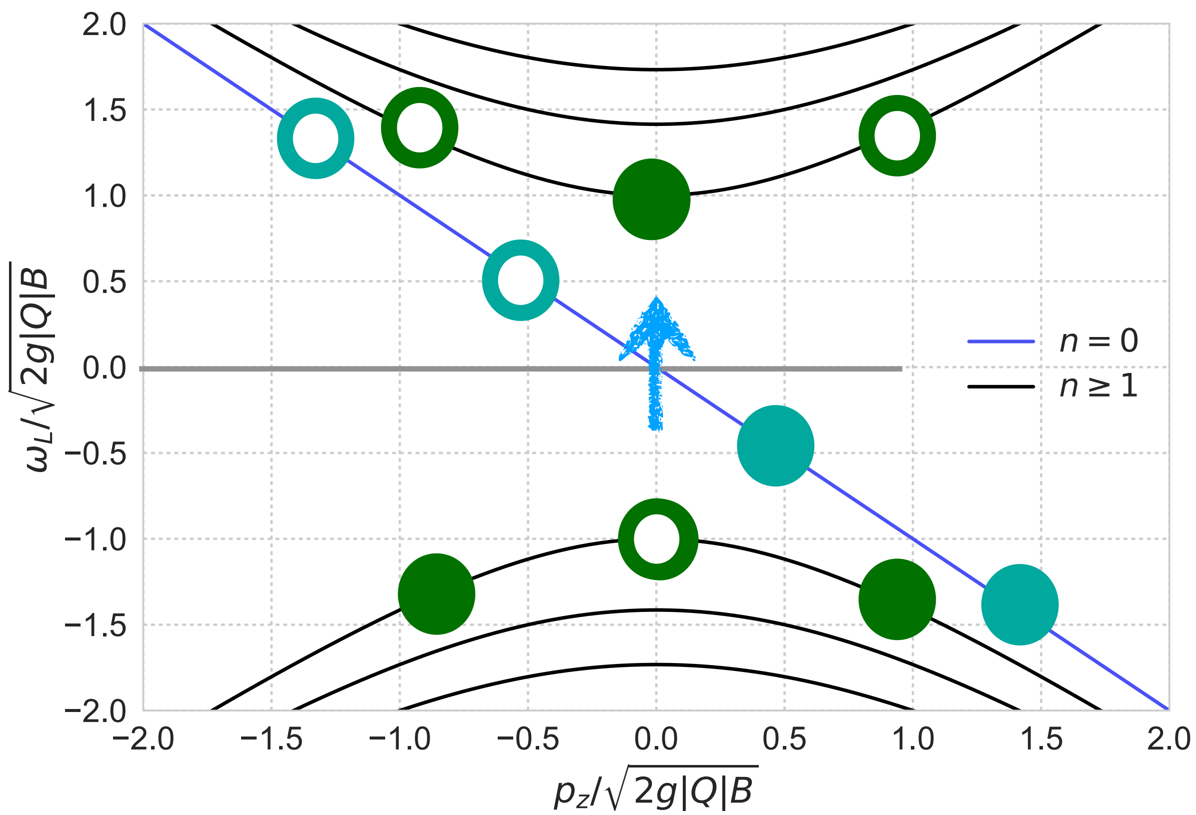


symmetric fermion production

$$\dot{n}_\psi^{\rm HLL} = 4 \times \frac{g^2 Q^2}{8\pi^3}\left(E^2 - \pi E B + \frac{\pi^2}{3} B^2 + \cdots\right)$$

fermion production (HLL)

left-handed fermions



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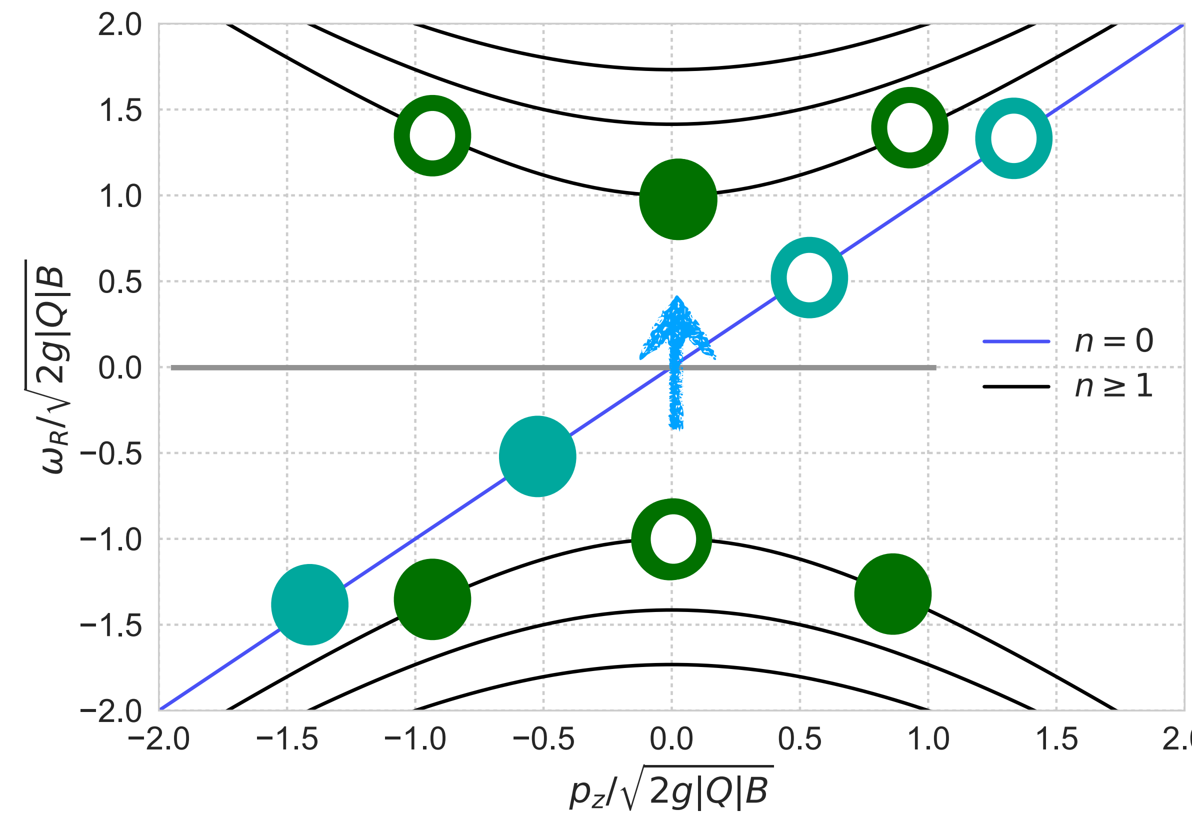
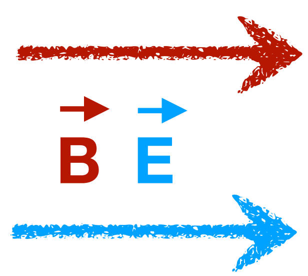
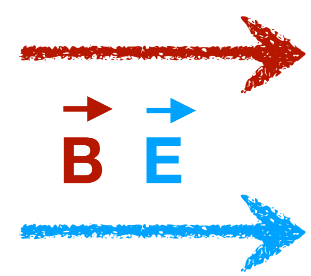






symmetric fermion production

B = 0 : Schwinger production

$$\dot{n}_\psi^{\rm HLL} = 4 \times \frac{g^2 Q^2}{8\pi^3}\left(E^2 - \pi E B + \frac{\pi^2}{3} B^2 + \cdots\right)$$

induced current

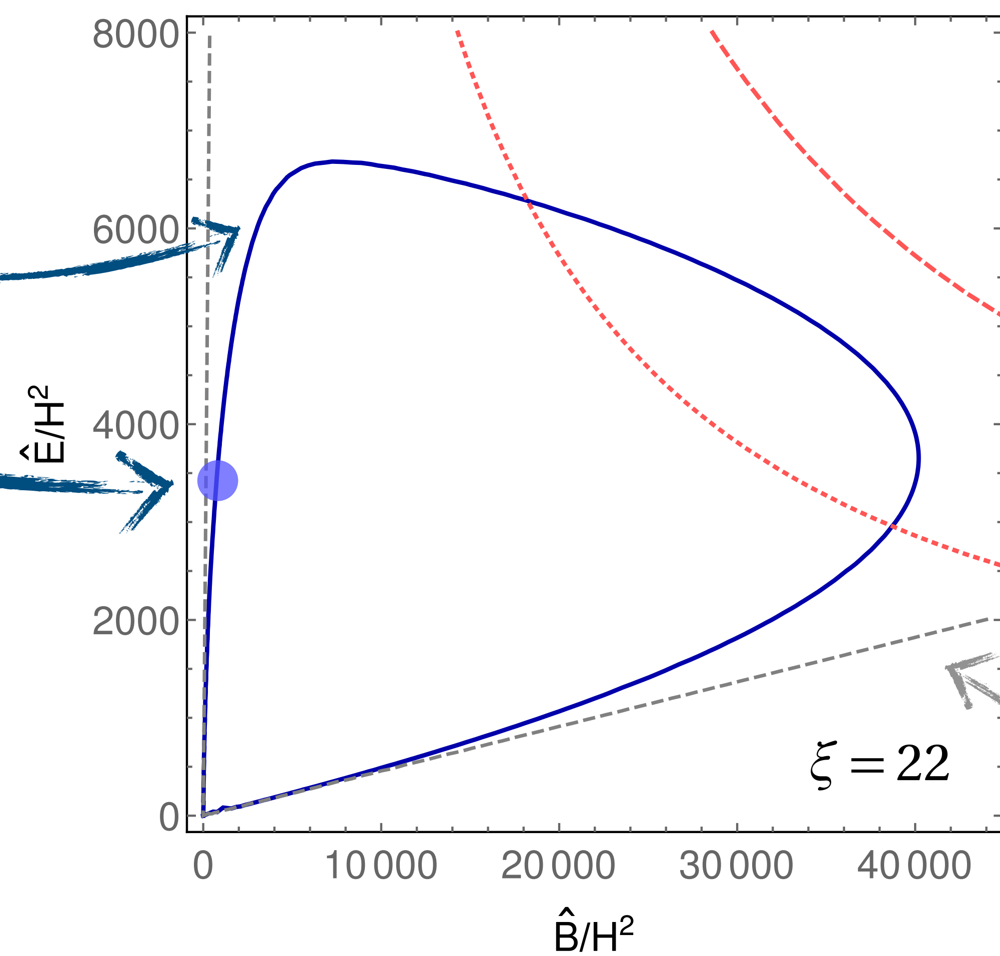
backreaction on gauge field production: $\Box A^\nu - \partial_\mu \left(\frac{\alpha\phi}{\pi f_a} \tilde{F}^{\mu\nu} \right) \boxed{- gQ J^\nu_\psi} = 0$

in **equilibrium:**

$$0 = \dot{\rho}_A = -4H\rho_A + 2\xi H \hat{\boldsymbol{E}} \cdot \hat{\boldsymbol{B}} - \hat{\boldsymbol{E}} \cdot gQ \overbrace{\langle \boldsymbol{J}_\psi \rangle}^{\sim n_\psi}$$

upper bound

estimate

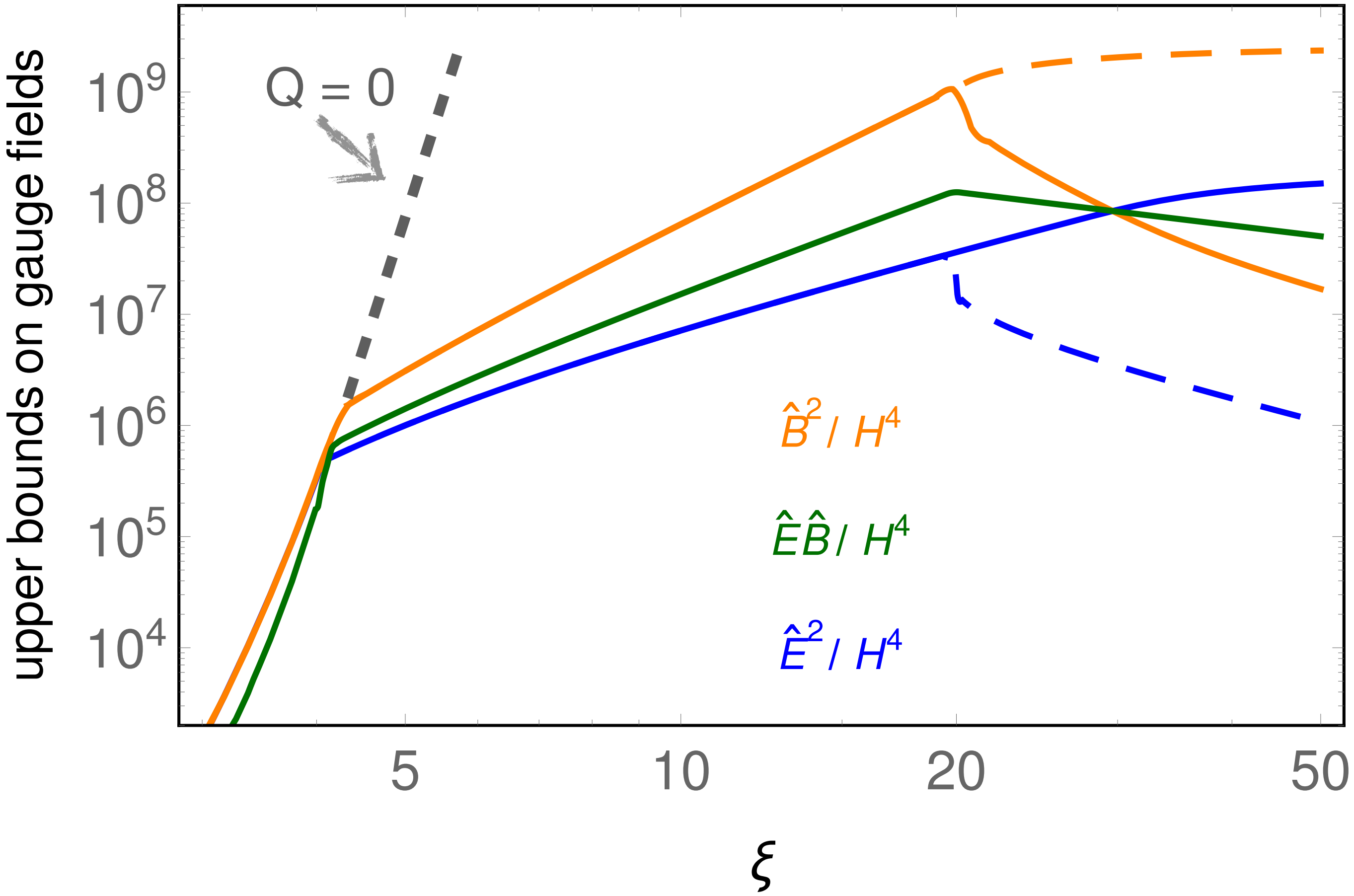


constraints from inflation with
r = 0.1
r = 0.05

Q = 0

upper bounds on E- and B-fields

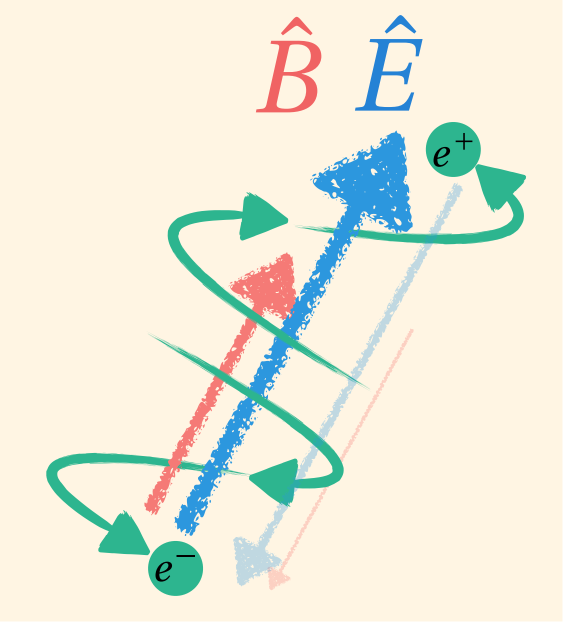
upper bounds on gauge fields



fermion production dampens gauge field production

Outline

- PNGB couplings to gauge fields and fermions
- Dual production of helical gauge fields and chiral fermions

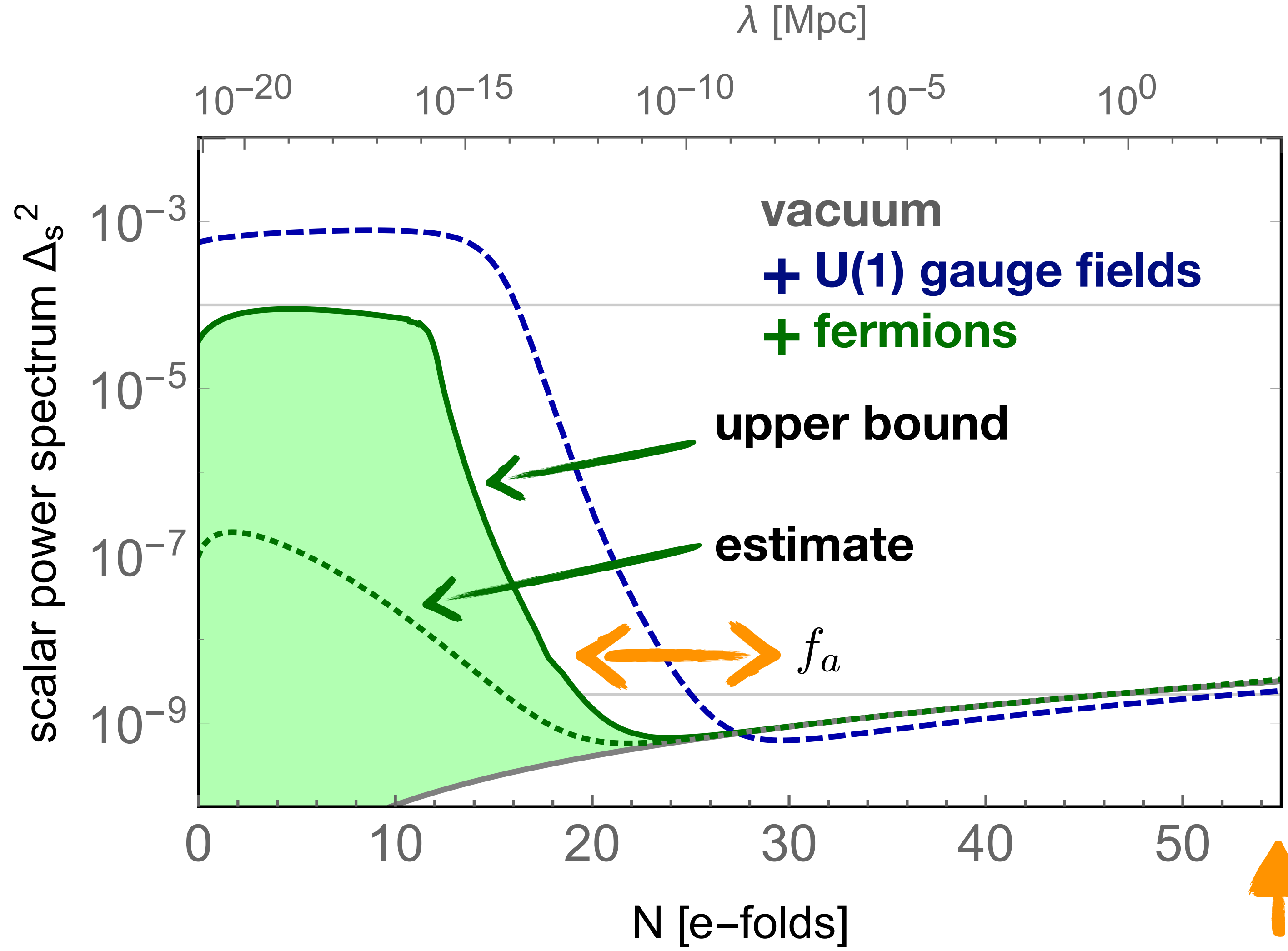


- Consequences for inflation and leptogenesis

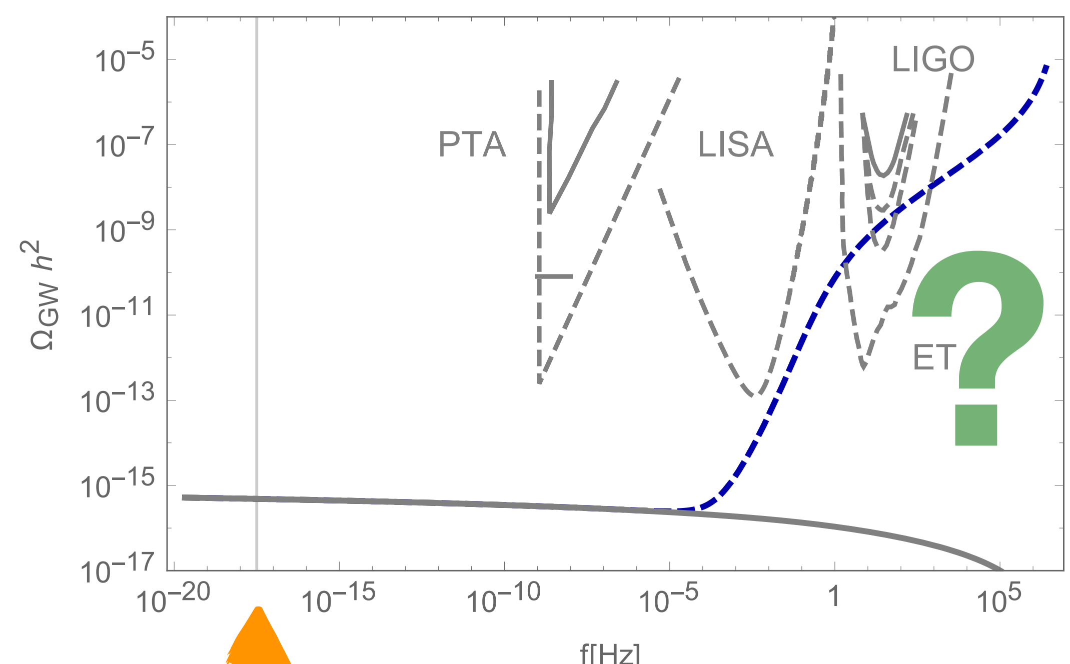
Axion inflation

helical gauge fields and chiral fermions source scalar and tensor fluctuations:

$Q = 1\,, \quad g = 1/\sqrt{2}$



CMB



CMB

we need small-scale probes of the scalar and tensor power spectrum

Leptogensis

If they survive until EW phase transition, helical magnetic fields may source baryon asymmetry of the universe

Giovannini, Shaposhnikov '98,
Boyarsky, Ruchayskiy, Shaposhnikov '12,
Kamada, Long '16,
Jiminez, Kamada, Schmitz, Xu '17,
Kamada '18, …..

Presence of chiral charge induces plasma instability → erasure of helicity

Toy model presented here → total erasure of helicity & chiral charge

More realistic SM setup → Sphalerons & Yukawas erase chiral charge

→ incomplete cancellation of chiral charge and helicity

→ viable baryogenesis ?

Conclusion and Outlook

PNGB couplings to gauge fields and/or fermions during inflation can have significant phenomenological implications

Chiral anomaly triggers fermion production which dampens the helical gauge field production

Impacts predictions of inflation and leptogenesis from helical gauge fields

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Outlook:

- Tensor spectrum -> GW interferometers sensitive at small scales
- Relaxation of the EW scale
- Toy model -> realistic model (-> leptogenesis ?)

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Impacts predictions of inflation and leptogenesis from helical gauge fields

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- Tensor spectrum -> GW interferometers sensitive at small scales
- Relaxation of the EW scale
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Thank you !

Backup slides

Tensor power spectrum

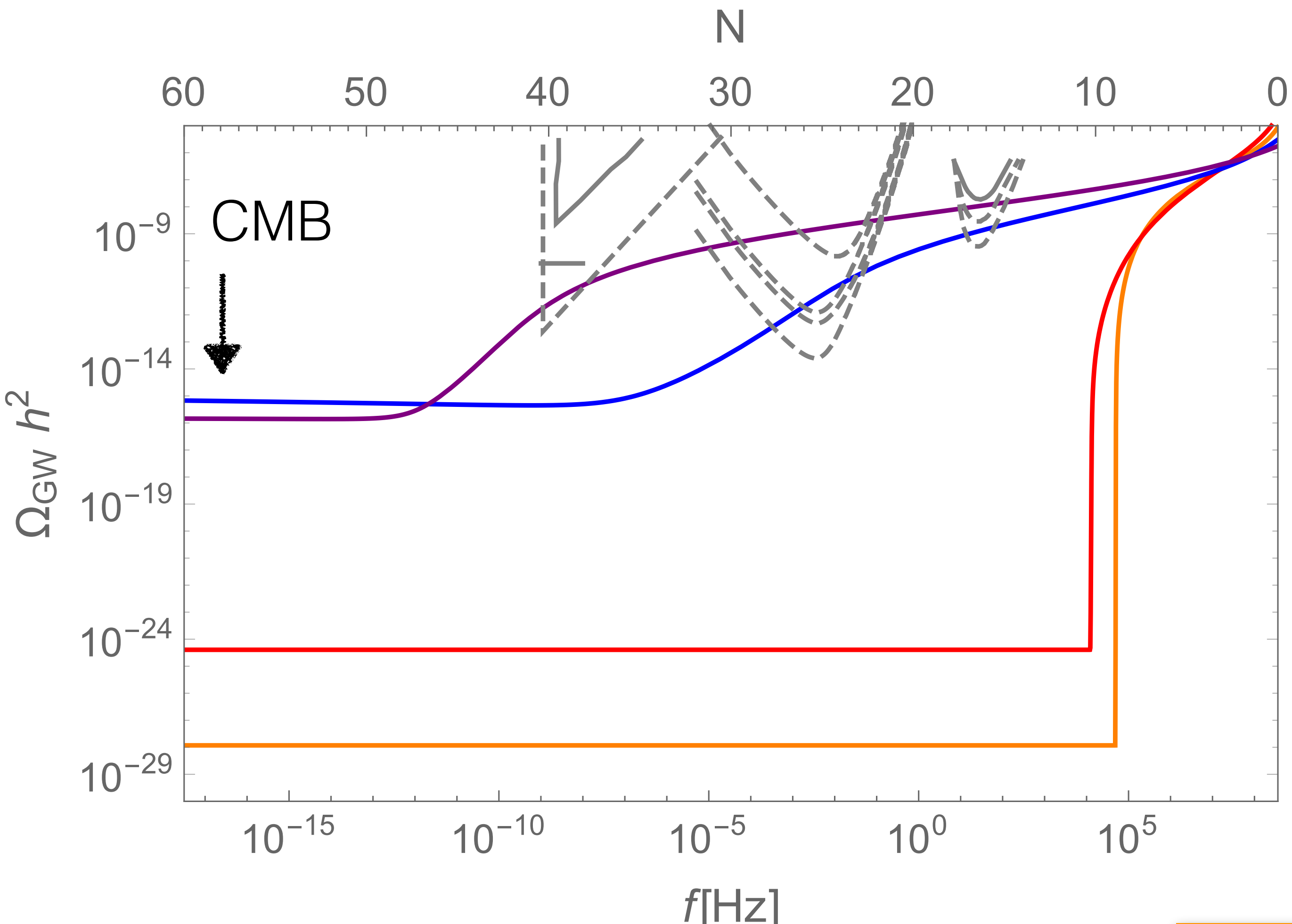
vacuum + sourced contribution:

$$\Omega_{\mathrm{GW}} = \frac{1}{12}\left(\frac{H}{\pi M_P}\right)^2 \left(1 + 4.3\times 10^{-7}\frac{H^2}{M_P^2 \xi^6} e^{4\pi\xi}\right)$$

a simple parametrization of the scalar potential:

$$\epsilon_V = \frac{1}{2M_P^2}\left(\frac{V'(\phi)}{V(\phi)}\right)^2 \simeq \frac{\beta}{N^p}$$

Mukhanov '13



Binetruy, VD, Pieroni '16

p = 1 (Quadratic)
p = 2 (Starobinsky)
p = 3 (Hilltop)
p = 4 (Hilltop)

strong enhancement on small scales

Tensor power spectrum

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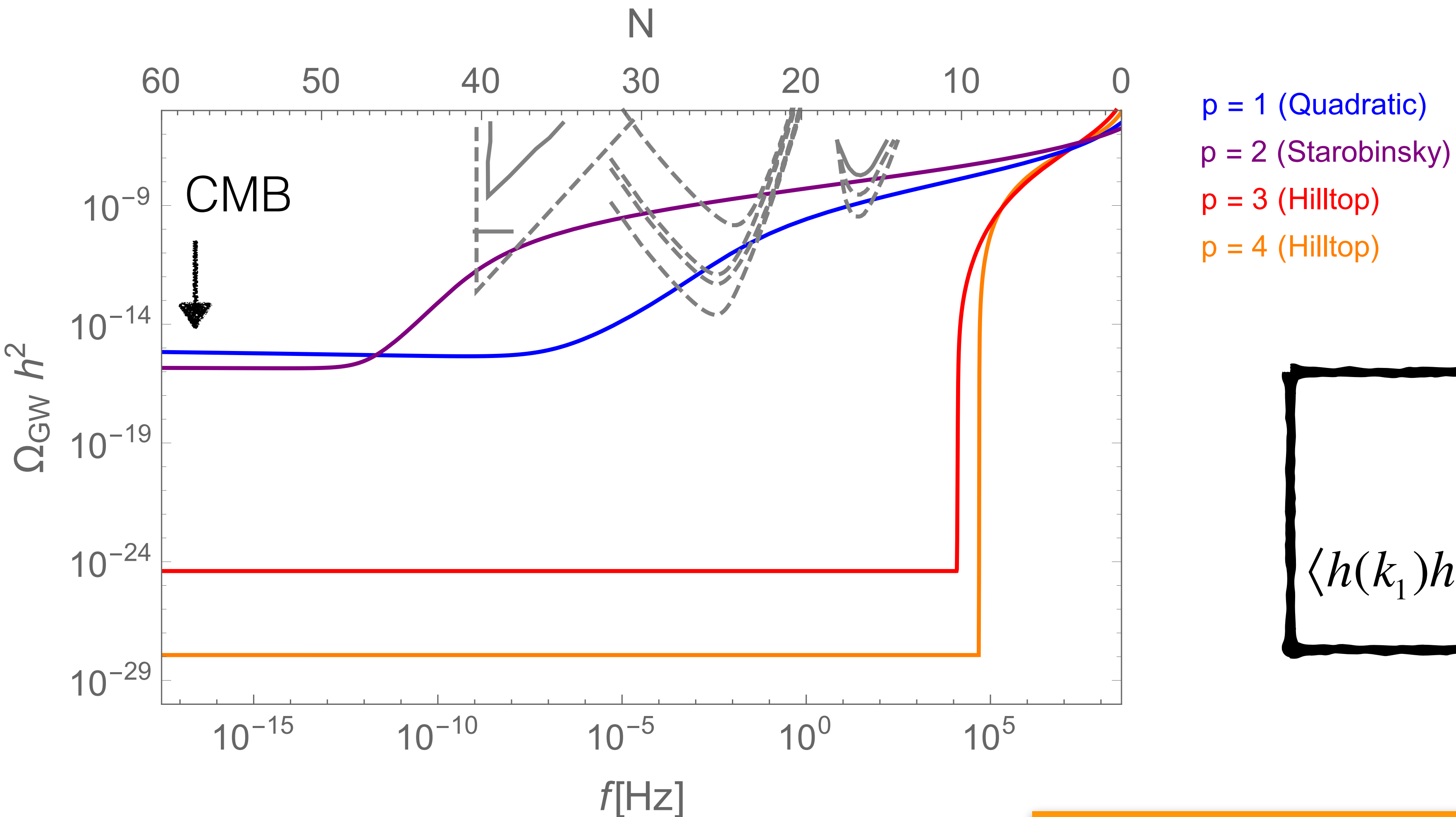


Binetruy, VD, Pieroni '16

polarized
non-gaussian
$\langle h(k_1)h(k_2)h(k_3)\rangle_{\rm equil} \propto \Omega_{\rm GW}(k)^{3/2}$

strong enhancement on small scales

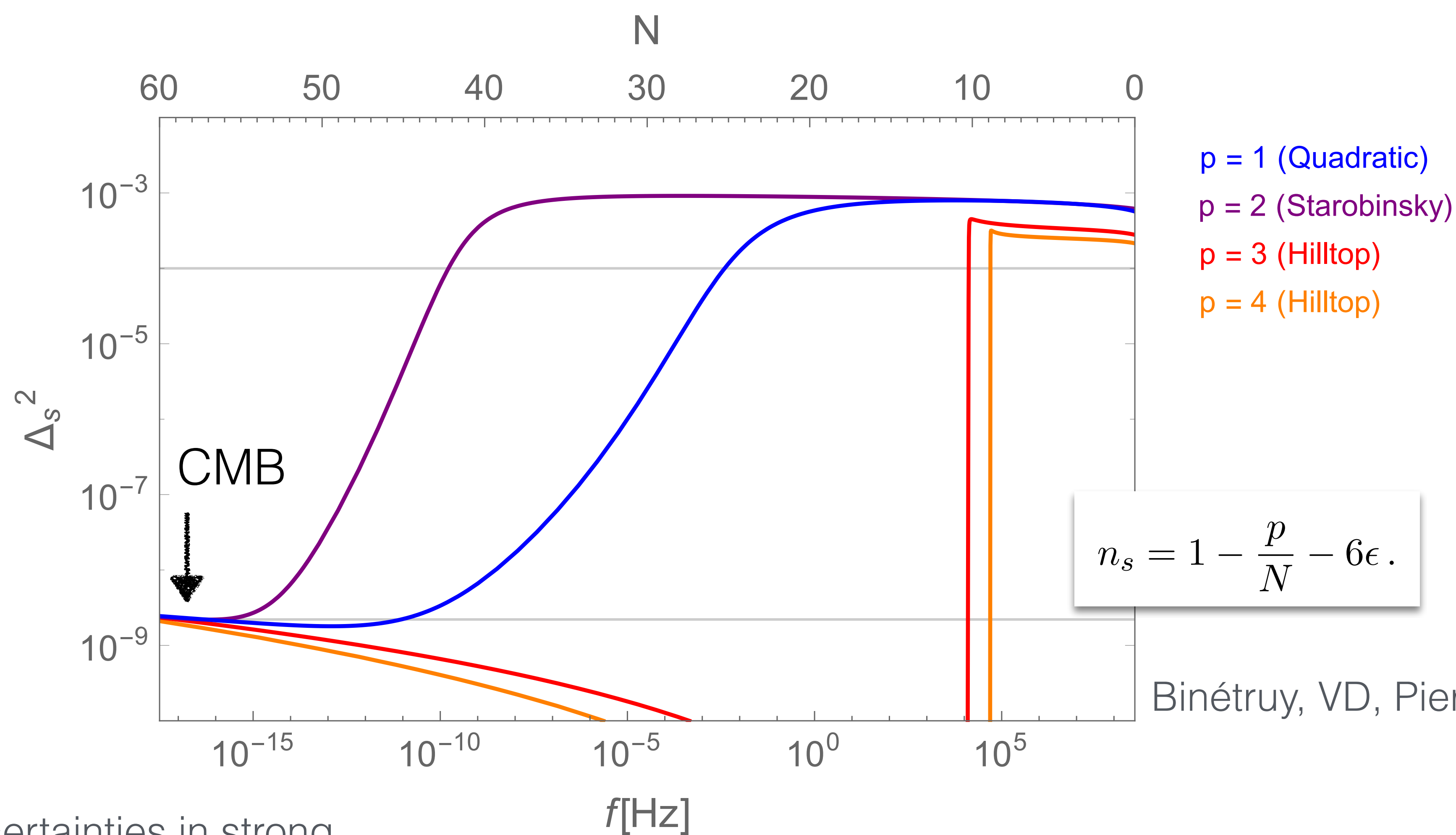
Scalar power spectrum

vacuum + sourced contribution:

$$\Delta_s^2(k) = \Delta_s^2(k)_{\mathrm{vac}} + \Delta_s^2(k)_{\mathrm{gauge}} = \left(\frac{H^2}{2\pi|\dot\phi|}\right)^2 + \left(\frac{\alpha\langle\vec E\vec B\rangle}{3bH\dot\phi}\right)^2$$

$$b = 1 - 2\pi\xi\frac{\alpha\langle\vec E\vec B\rangle}{3\Lambda H\dot\phi},$$

$$\langle\vec E\vec B\rangle \simeq \mathcal{N}\cdot 2.4\cdot 10^{-4}\frac{H^4}{\xi^4}e^{2\pi\xi}$$



$$n_s = 1 - \frac{p}{N} - 6\epsilon\,.$$

Binétruy, VD, Pieroni '16

3 parameters: $\alpha/\Lambda, \beta, p$

uncertainties in strong back reaction regime, Sloth '15, Peloso '16

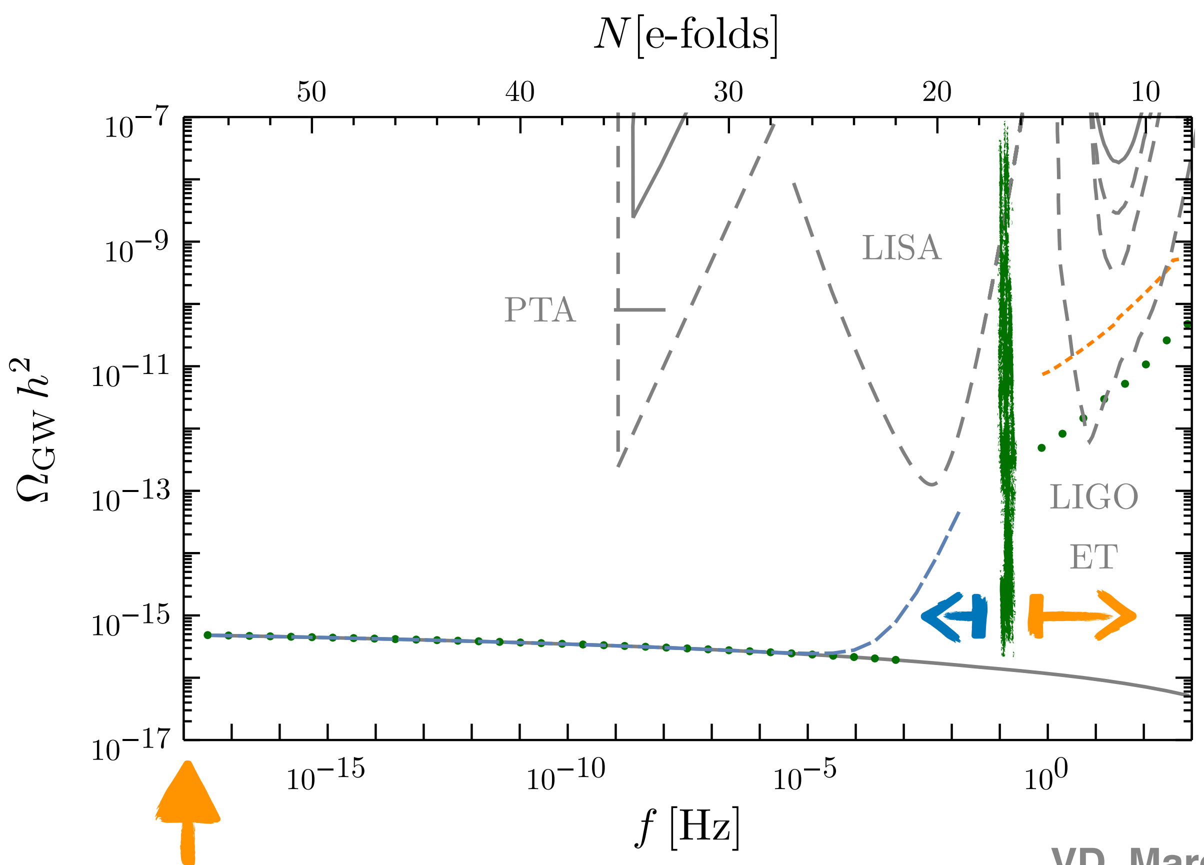
strong, quasi-universal enhancement at small scales

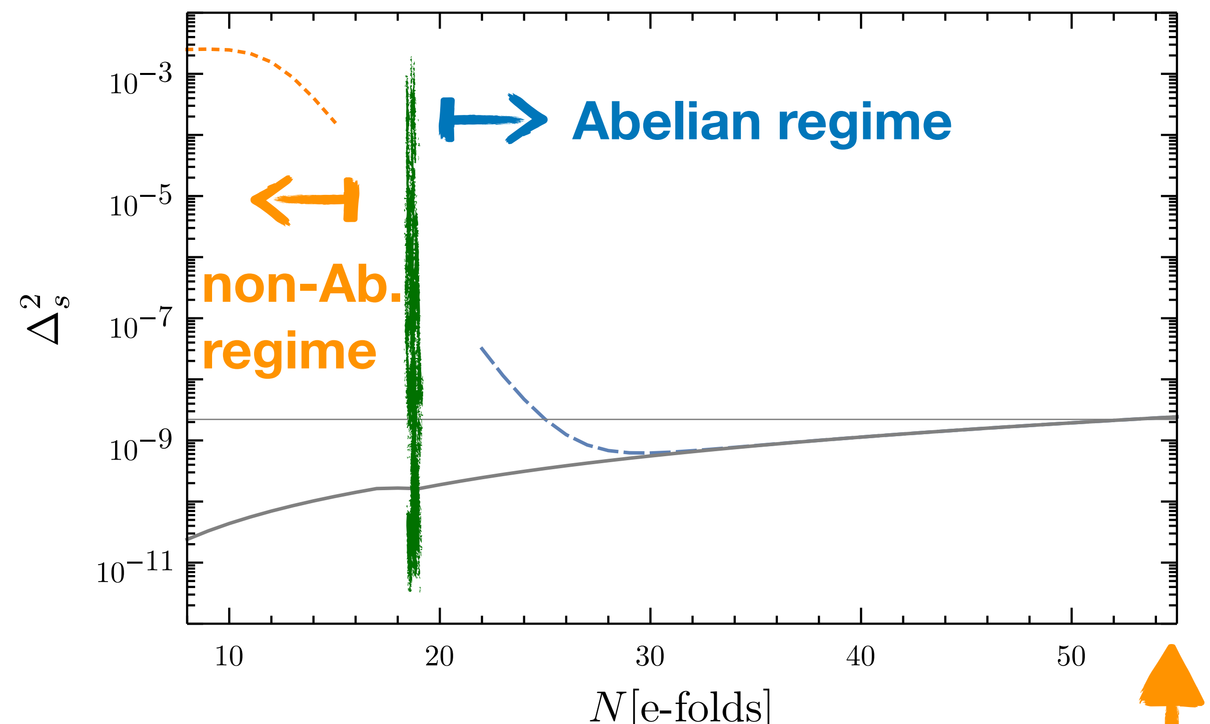
coupling to SU(2) gauge fields

tensor power spectrum

$e = 5 \times 10^{-3}$

scalar power spectrum





VD, Mares, Muia, Pieroni '18

CMB

CMB

strongly enhanced GW spectrum at small scales

maximally polarized

strongly enhanced scalar power spectrum at small scales

spectral shape different than for U(1) case