# Stochastic Gravitational Wave Background

Challenges & opportunities


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Theory Seminar
University of Oslo
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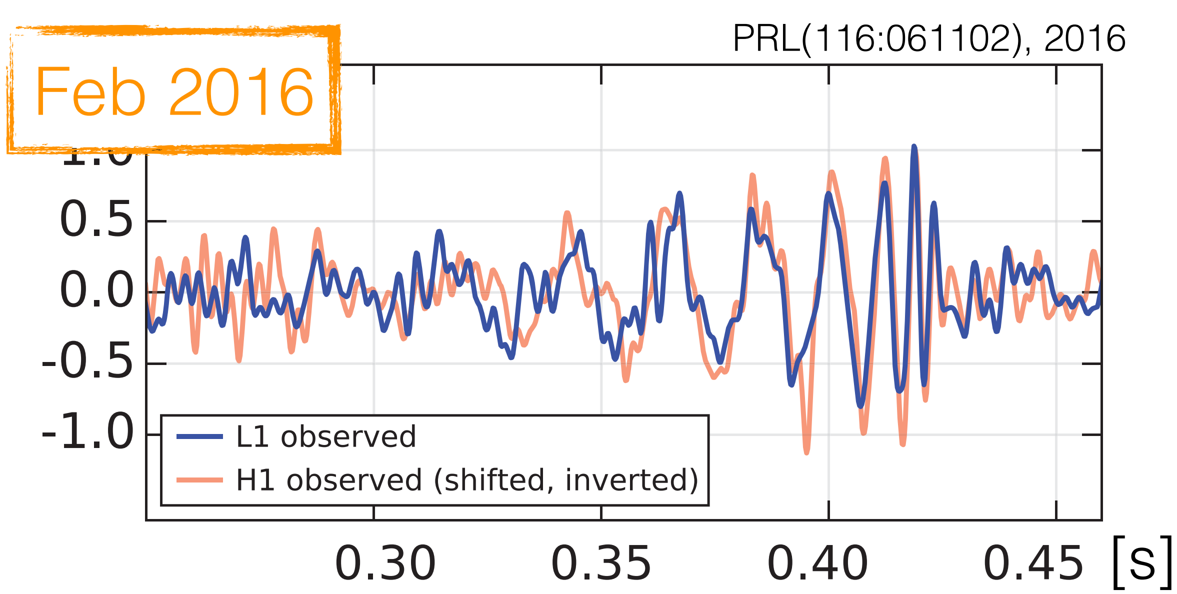
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

DESY.

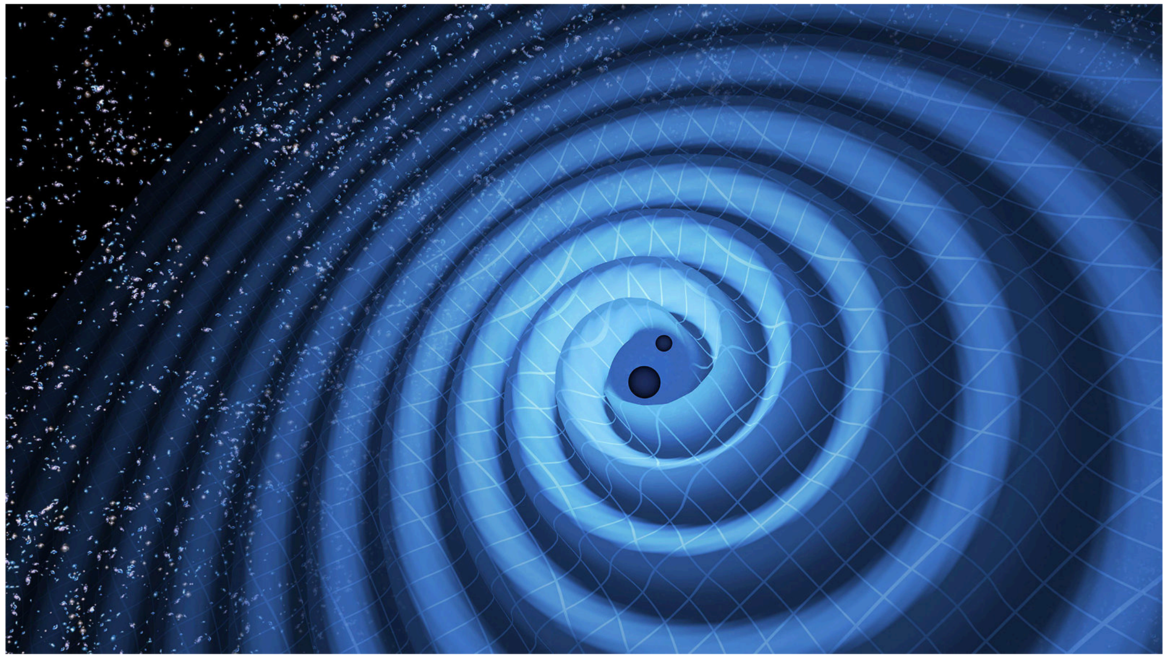
# A new window of observation?

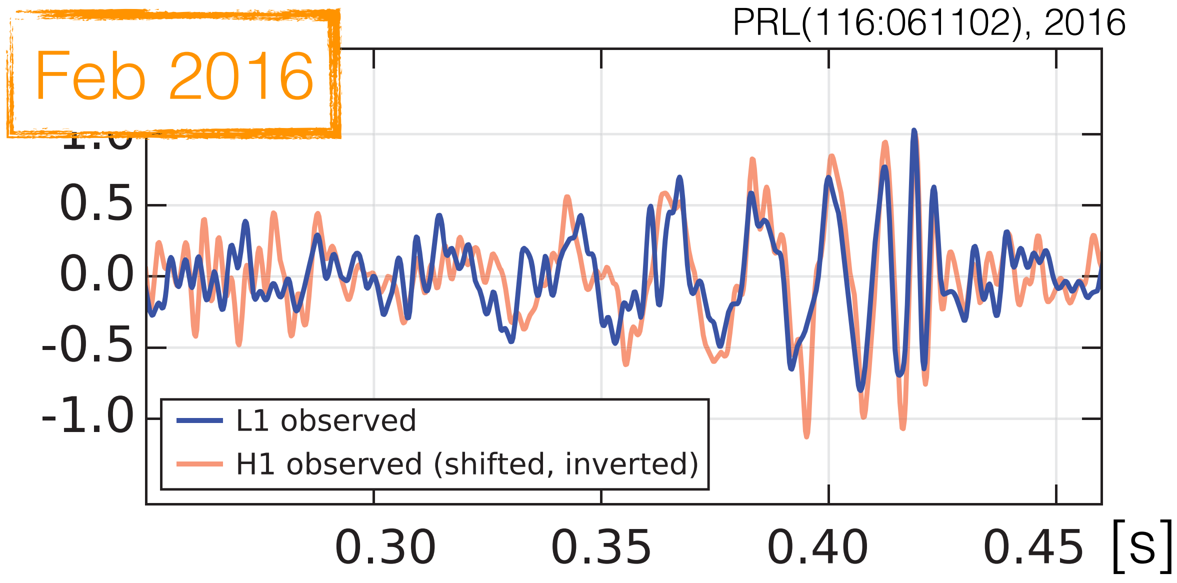



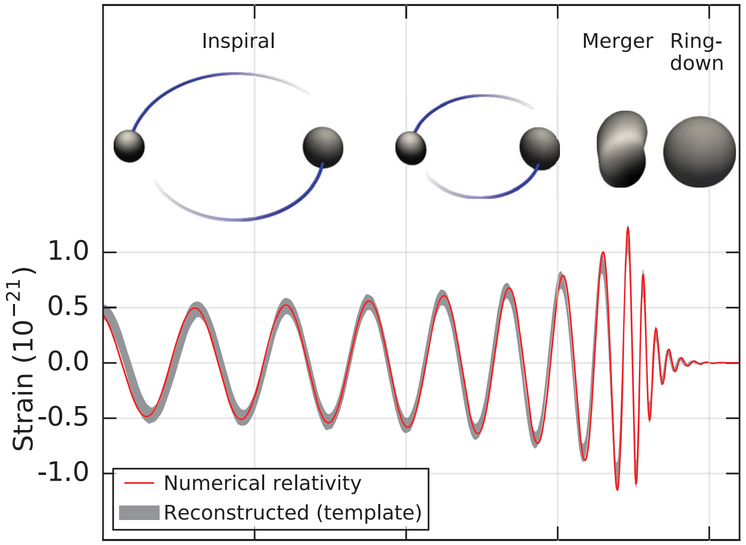

**extremely precise Michelson interferometer**

**measures relative length of the two 4 km arms**

# A new window of observation?




BH - BH merger,

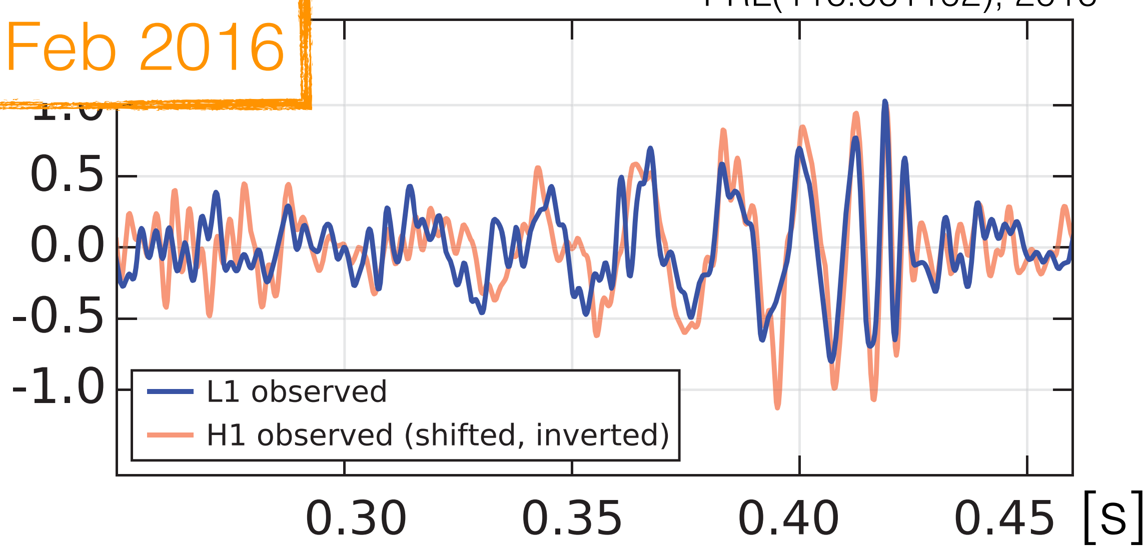
GW150914

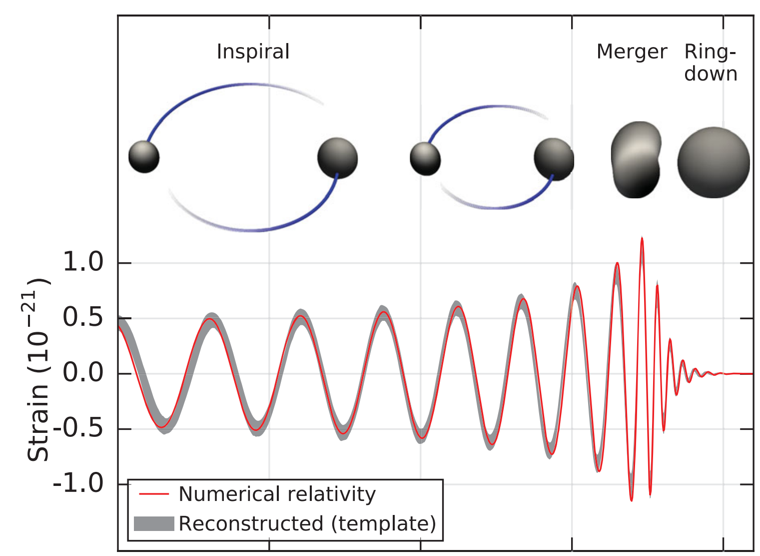
# A new window of observation?

2017 Nobel prize for Weiss, Barish (LIGO/VIRGO) and Thorne


Feb 2016

PRL(116:061102), 2016

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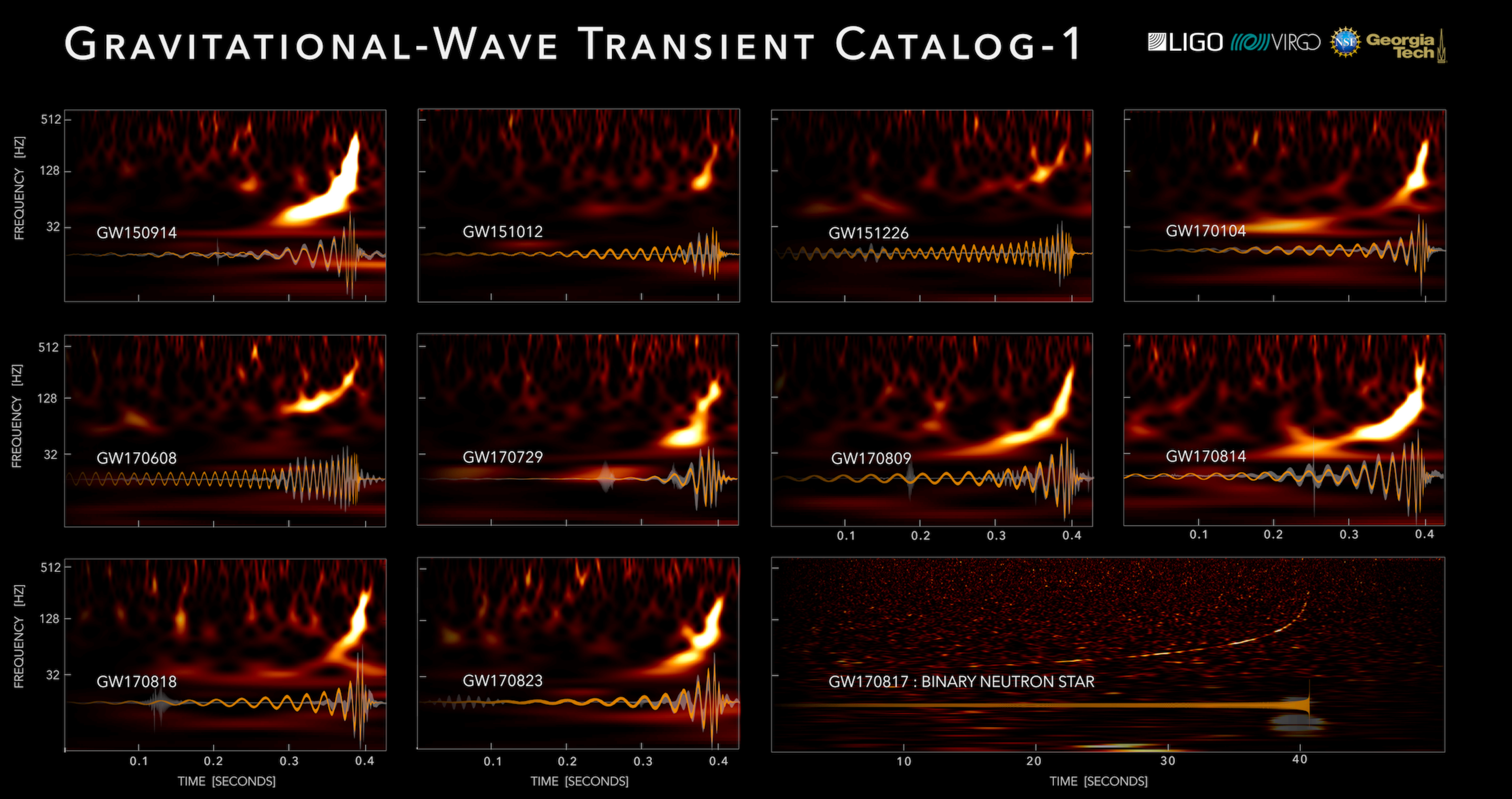

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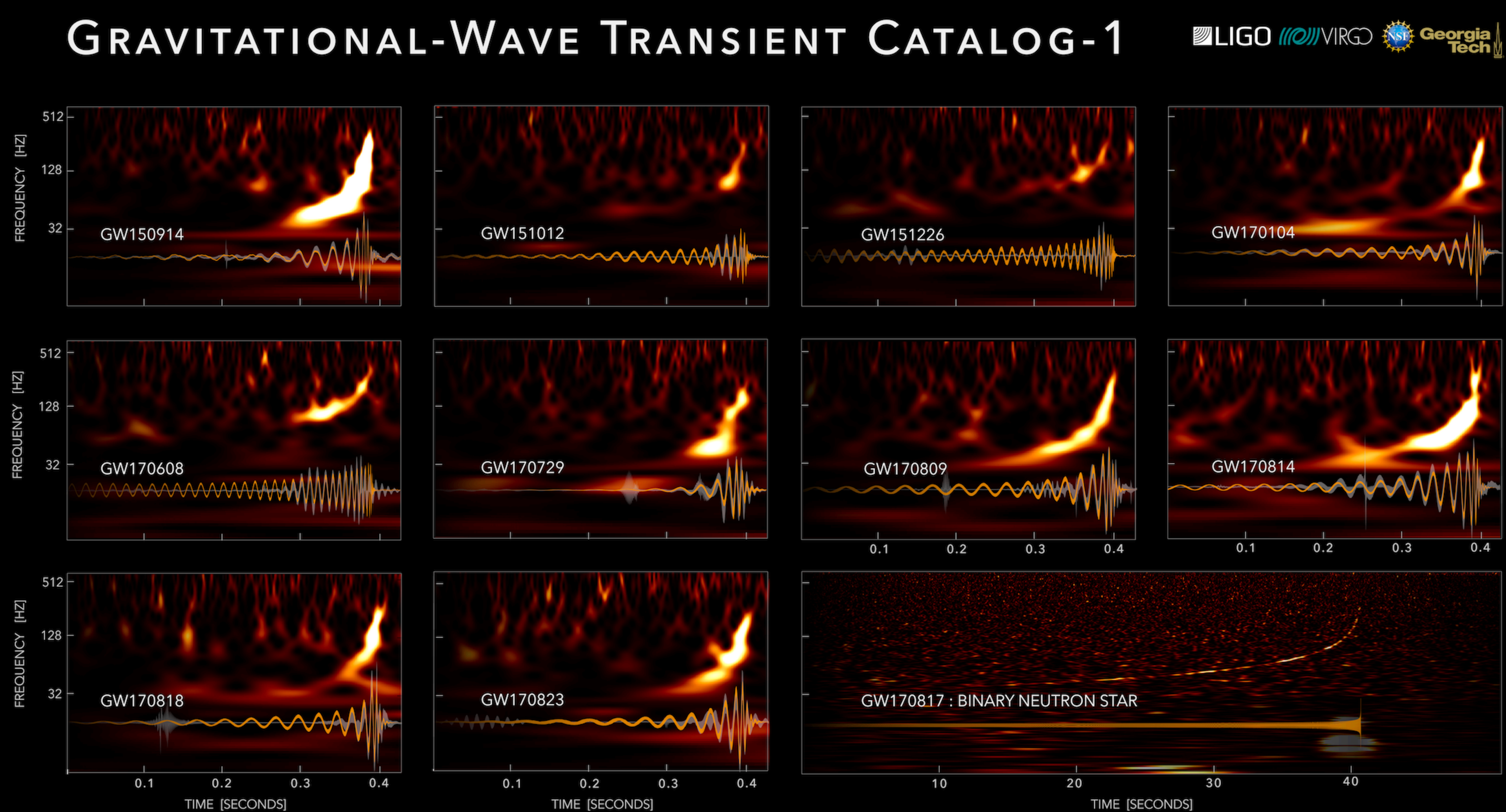
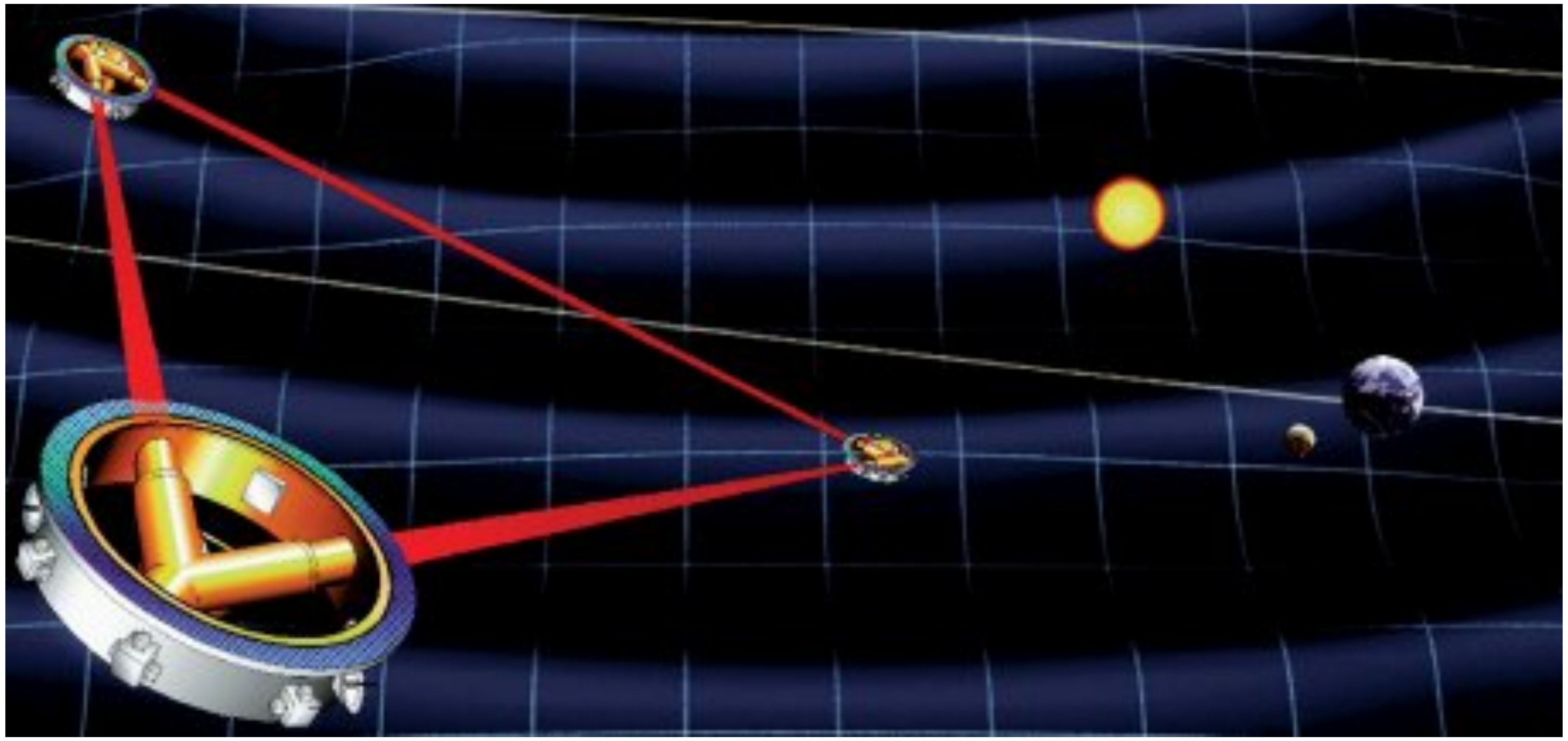


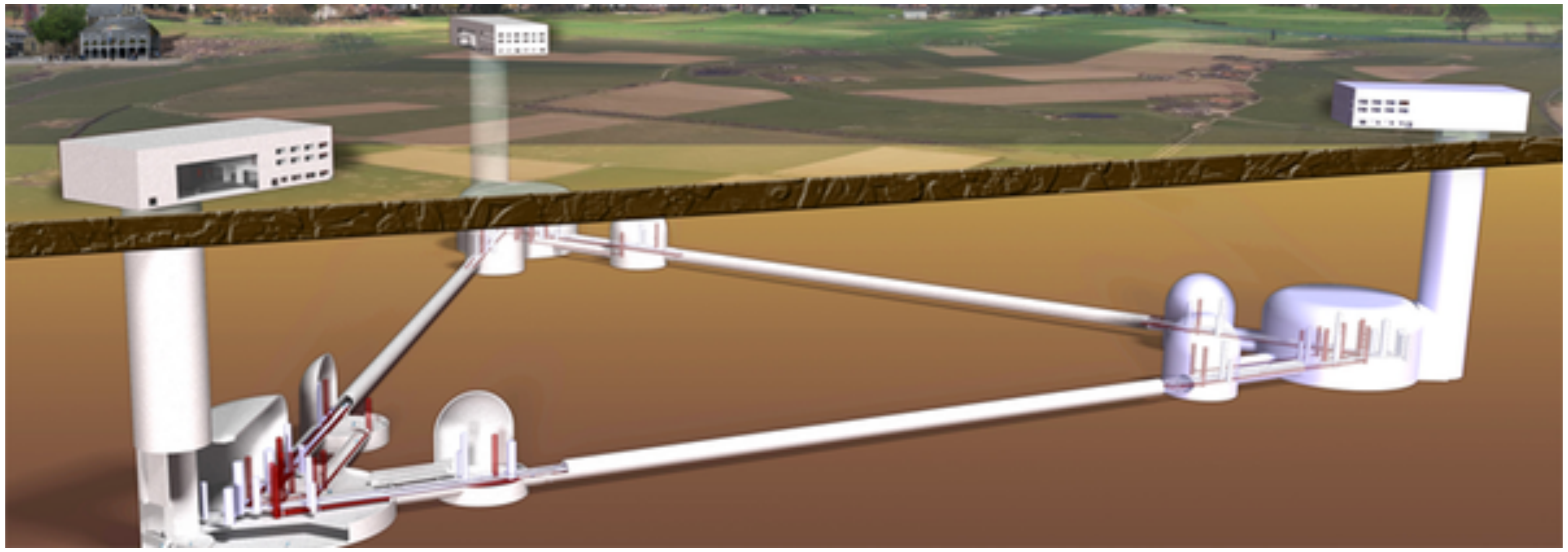

stay tuned - 3rd run started April 2019

# Coming soon: LISA

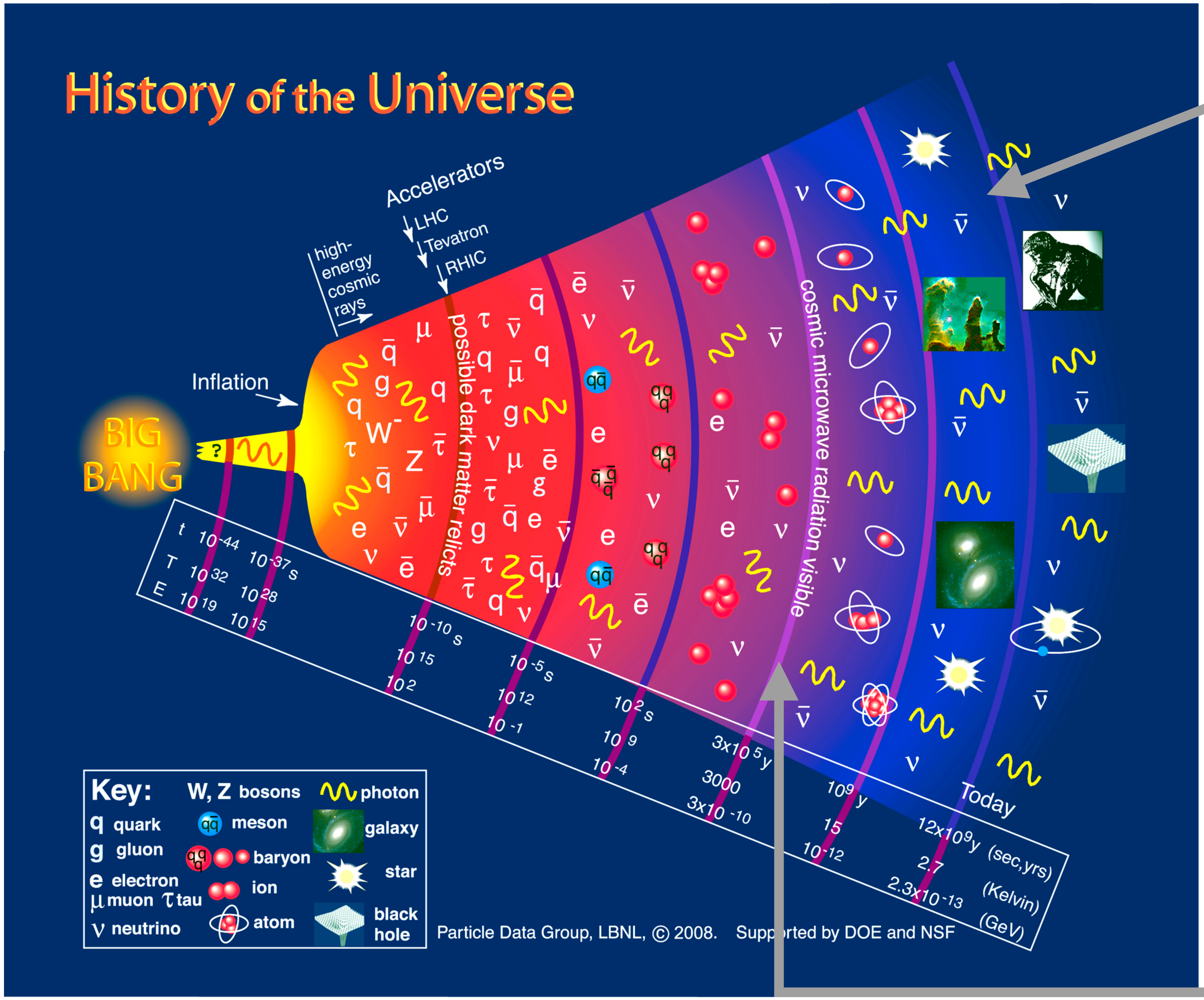


- 3 satellites, 2.5 mio km apart
- ESA mission
- launch ~ 2030

currently ideas for
3rd generation of
ground based detectors
are being developed
(ET, Cosmic Explorer)



# Cosmic history

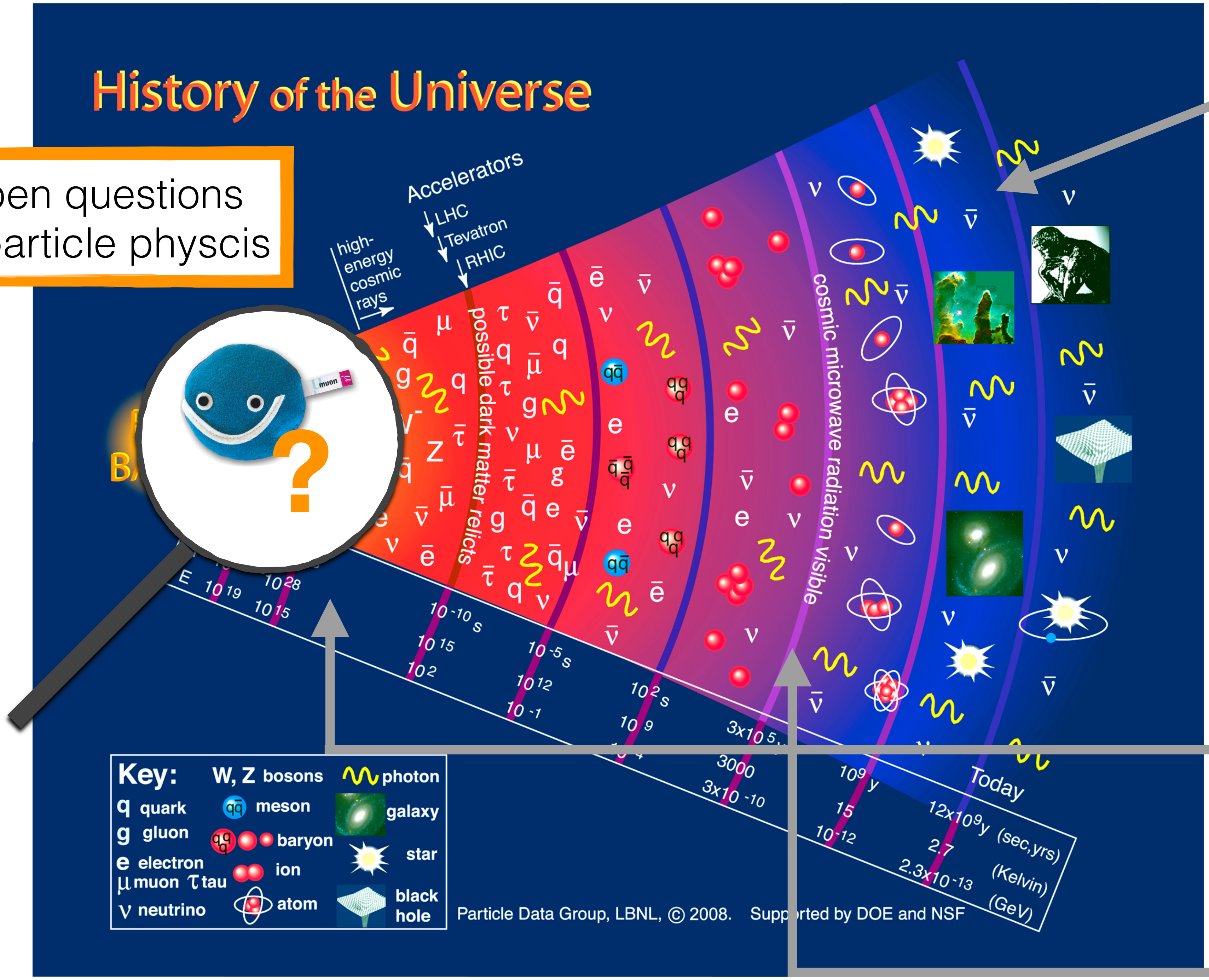



GW150914
(400 Mpc = $10^9$ ly away)

**how far back can we probe?**

CMB
(photon decoupling)

# Cosmic history




open questions of particle physcis

GW150914 (400 Mpc = $10^9$ ly away)

**how far back can we probe?**

primordial gravitational waves

CMB (photon decoupling)

# Outline

Introduction to gravitational wave physics

The stochastic gravitational wave background (SGWB)

Probing the particle physics driving cosmic inflation

# Some useful properties of GWs

perturbations of the background metric: $ds^2 = a^2(\tau)(\eta_{\mu\nu} + h_{\mu\nu}(\mathbf{x},\tau))dx^\mu dx^\nu$

scale factor: cosmological expansion — flat metric — GW

governed by linearized Einstein equation $(\tilde{h}_{ij} = a h_{ij}, \text{ TT - gauge})$

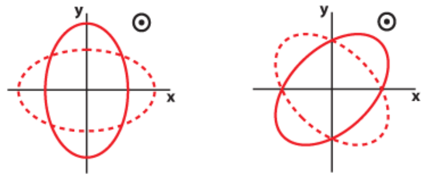
$$\tilde{h}''_{ij}(\boldsymbol{k},\tau) + \underbrace{\left(k^2 - \frac{a''}{a}\right)}_{\sim a^2 H^2} \tilde{h}_{ij}(\boldsymbol{k},\tau) = \underbrace{16\pi\, G\, a\, \Pi_{ij}(\boldsymbol{k},\tau)}_{\text{source term from } \delta T_{\mu\nu}}$$

source: anisotropic (not spherical symmetric) stress-energy tensor

$$k \gg aH : \; h_{ij} \sim \cos(\omega\tau)/a\,, \quad k \ll aH : \; h_{ij} \sim \text{const.}$$

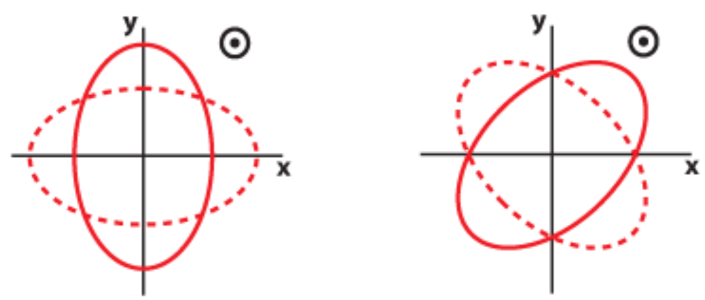
a useful plane wave expansion: $h_{ij}(\boldsymbol{x},\tau) = \sum_{P=+,\times} \int_{-\infty}^{+\infty} \frac{dk}{2\pi} \int d^2\hat{\boldsymbol{k}}\; h_P(\boldsymbol{k}) \underbrace{T_k(\tau)}_{\sim a(\tau_i)/a(\tau)} e^{P}_{ij}(\hat{k})\, e^{-ik(\tau - \hat{\boldsymbol{k}}\boldsymbol{x})}$

transfer function , expansion coefficients , polarization tensor $P = +, \times$




**Any GW signal is a convolution of a primordial spectrum with the subsequent cosmological evolution**

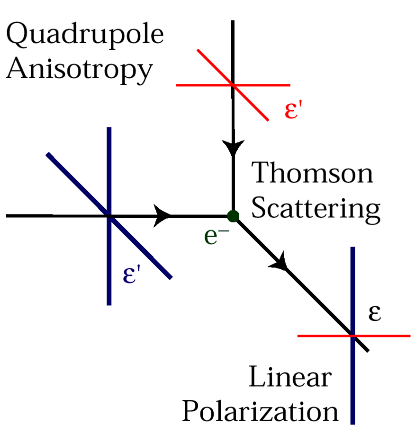
# Hunting for primordial GWs



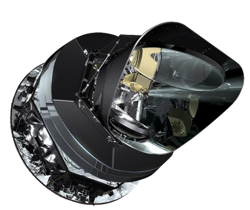

CMB

tensor anisotropies
on last scattering surface

polarization of CMB photons
through Thomson scattering




- Lensing: T -> E
- dust contaminates primordial signal
- B - modes most sensitive

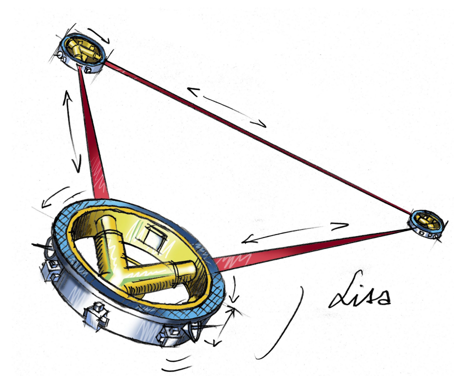


sensitive to CMB scales

direct

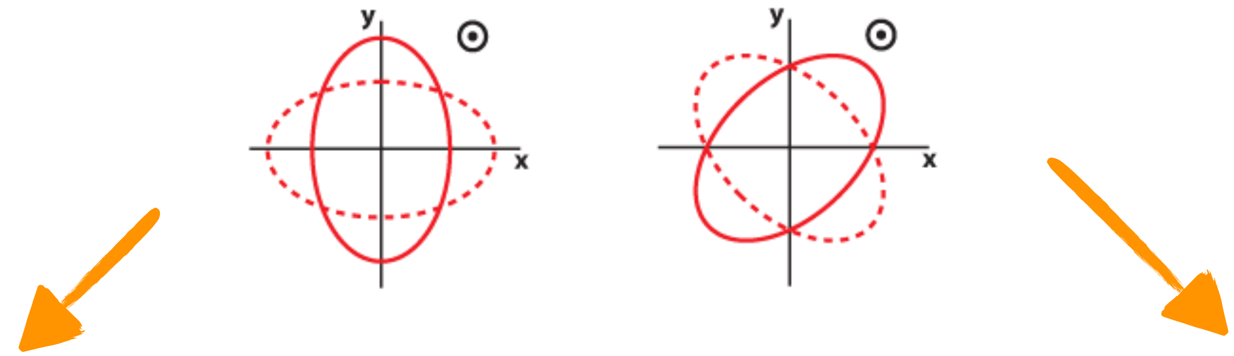
GW travels freely until today

distortion of space as GW
passes detector




- ground-based interferometers
- space-based interferometers
- pulsar timing arrays

# Hunting for primordial GWs

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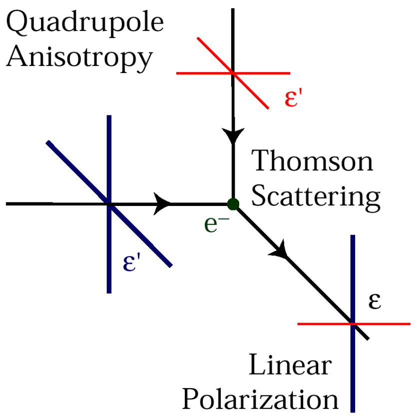


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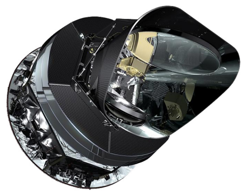

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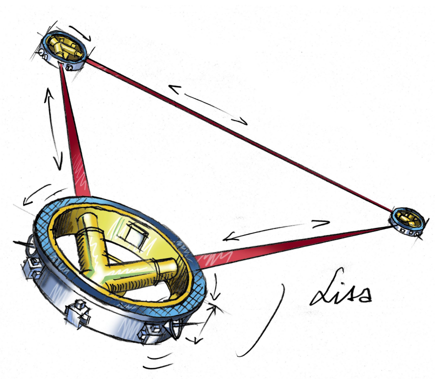


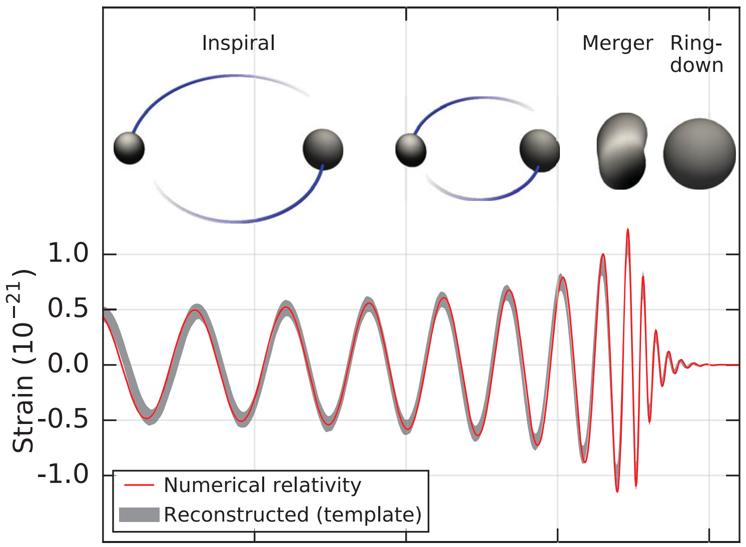

- ground-based interferometers
- space-based interferometers
- pulsar timing arrays

sensitive to GW with f ~1 / (detector size)

# Sources of GWs

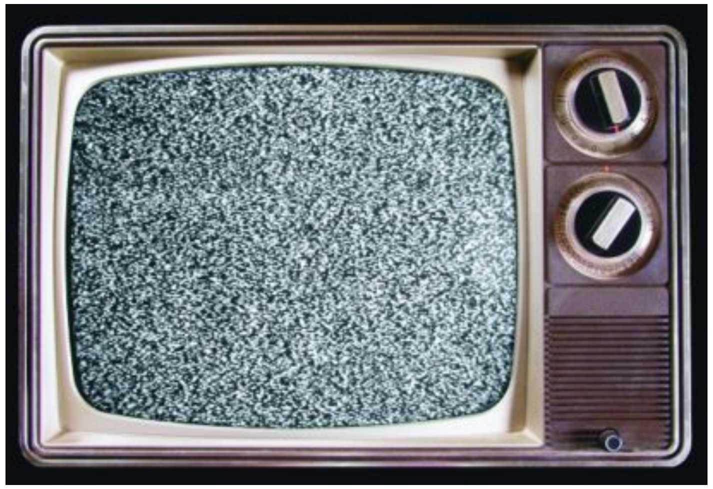
transcendent signals: merger of compact objects

(black holes, neutron stares, white dwarfs, …)




stationary signals: sum of unresolved transcendent sources

cosmological stochastic background



**In the following: focus on stationary signals**

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Introduction to gravitational wave physics

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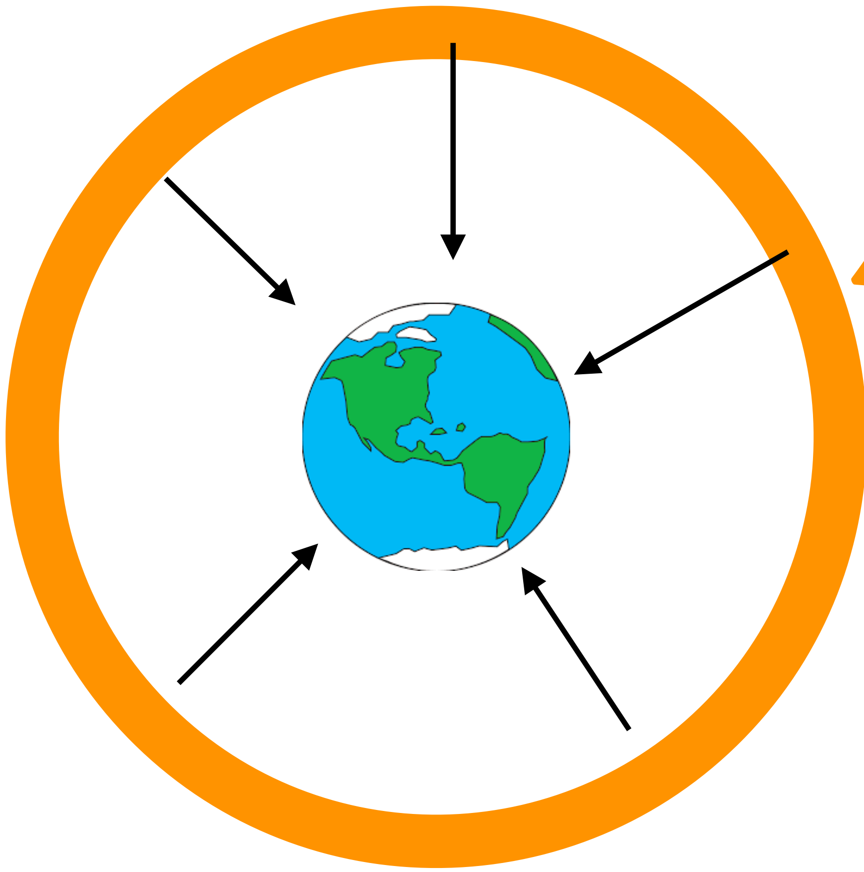
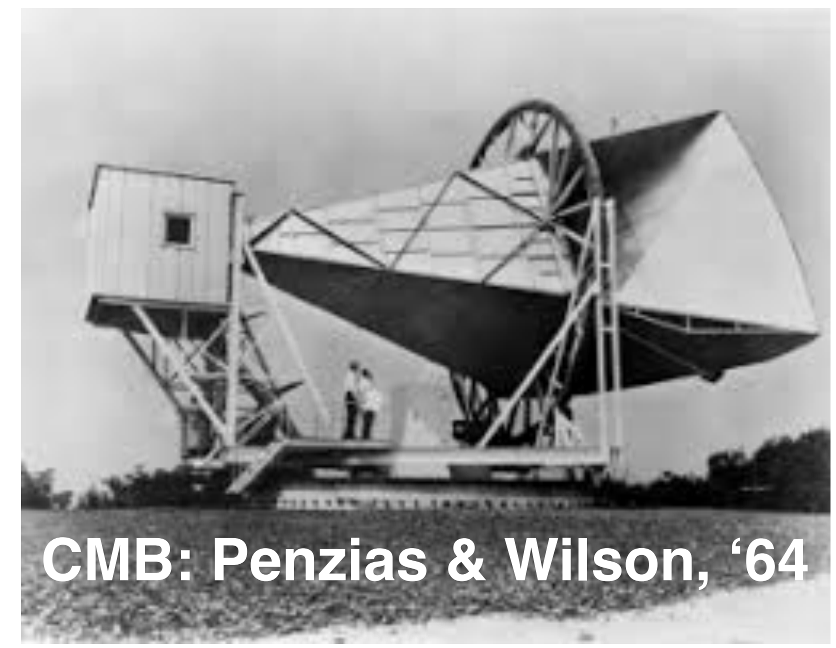
# The SGWB

Besides transient events (eg BH mergers) we also expect a stationary, isotropic **stochastic gravitational wave background** (noise):



cosmological event
or unresolved
astrophysical sources
(or instrument noise)



CMB: Penzias & Wilson, ‘64

probed by 2-point (cross-) correlation
of detector time stream

observational quantity in direct detection:

$$\Omega_{GW} = \frac{1}{\rho_c} \frac{\partial \rho_{\mathrm{GW}}(k,\tau)}{\partial \ln k}, \qquad \rho_{\mathrm{GW}}(\tau) = \frac{1}{32\pi G} \left\langle \dot{h}_{ij}\left(\boldsymbol{x},\tau\right) \dot{h}^{ij}\left(\boldsymbol{x},\tau\right) \right\rangle$$

# Decoding the SGWB

redshift of frequency in expanding Universe: $f_0 = f_* \frac{a(\tau_*)}{a(\tau_0)}\,,\qquad f_* = (\epsilon_* H_*^{-1})^{-1}$

~1 for cosmological sources

in a radiation dominated Universe,

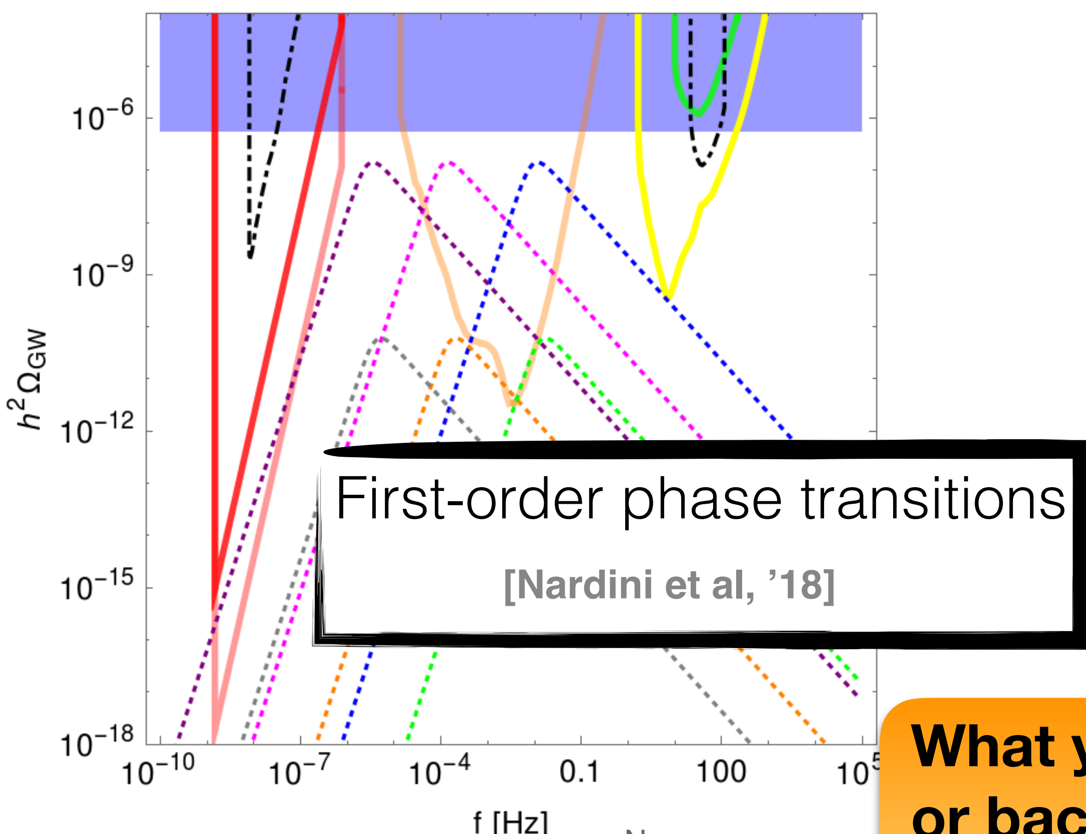
$$f_0 \simeq 10^{-8}\ \mathrm{Hz}\ \epsilon_*^{-1} \left(\frac{T_*}{\mathrm{GeV}}\right) \left(\frac{g_*}{100}\right)^{1/6}$$

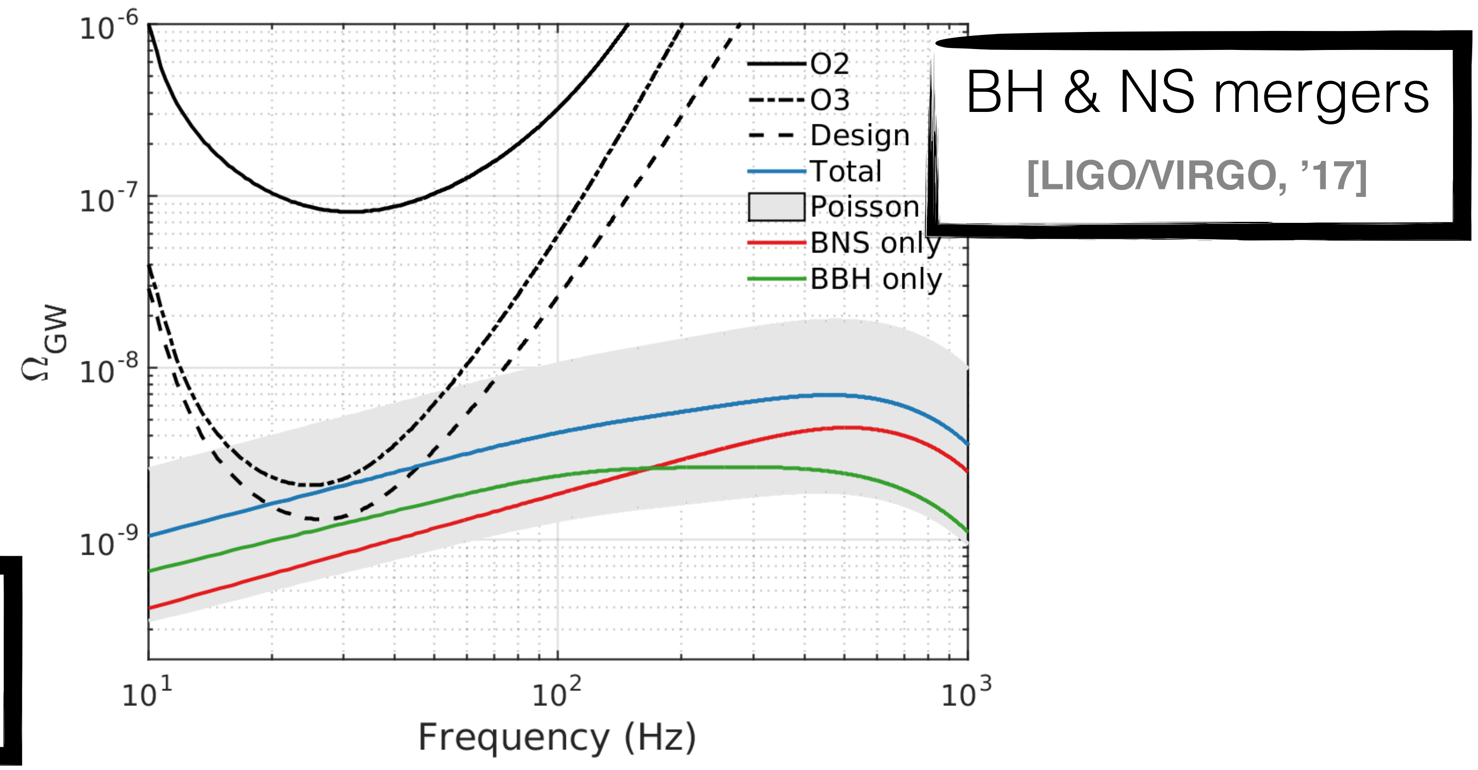
$$t_* \simeq 10^{-22}\ \mathrm{s}\ \epsilon_*^{-2} \left(\frac{\mathrm{Hz}}{f_0}\right)^2 \left(\frac{100}{g_*}\right)^{1/6}$$

| | $f_0$ [Hz] | $t_*$ [s] | $T_*$ [GeV] |
|---|---|---|---|
| PTA | $10^{-8}$ | $10^{-6}$ | $0.1$ |
| LISA | $10^{-2}$ | $10^{-18}$ | $10^5$ |
| ET/CE | $1$ | $10^{-22}$ | $10^7$ |
| LIGO | $10^2$ | $10^{-26}$ | $10^9$ |

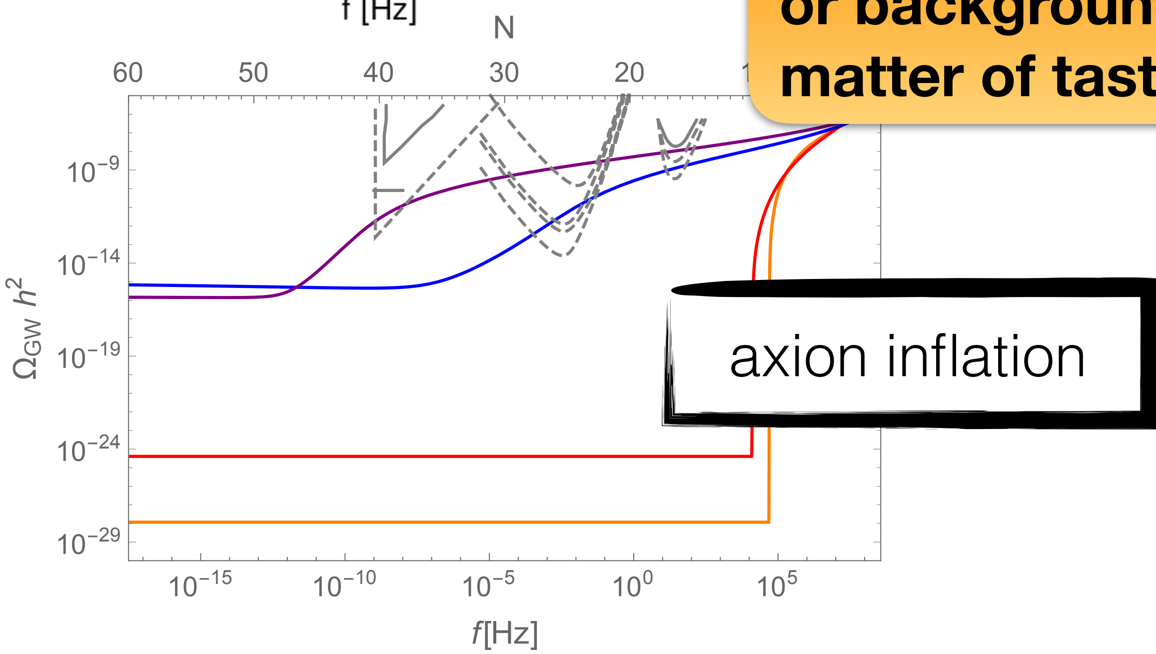
**probing early Universe physics at energy scales far beyond particle colliders**

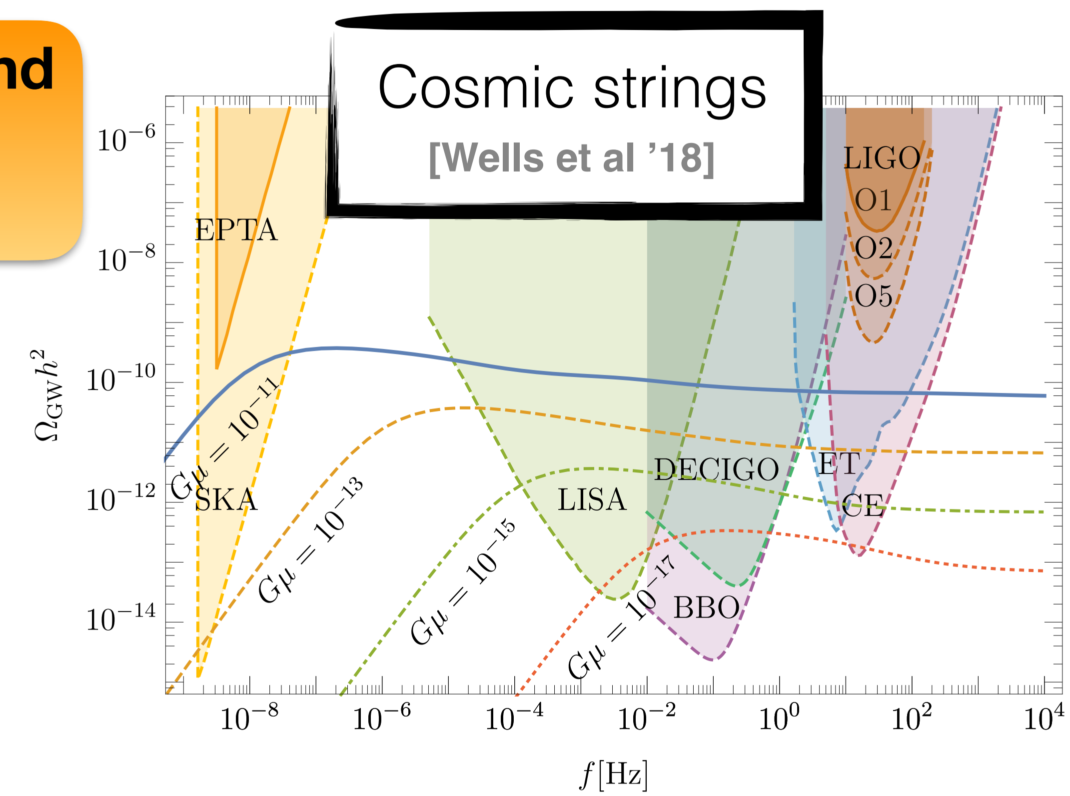
# Some possible sources




**What you call foreground or background is a matter of taste...**



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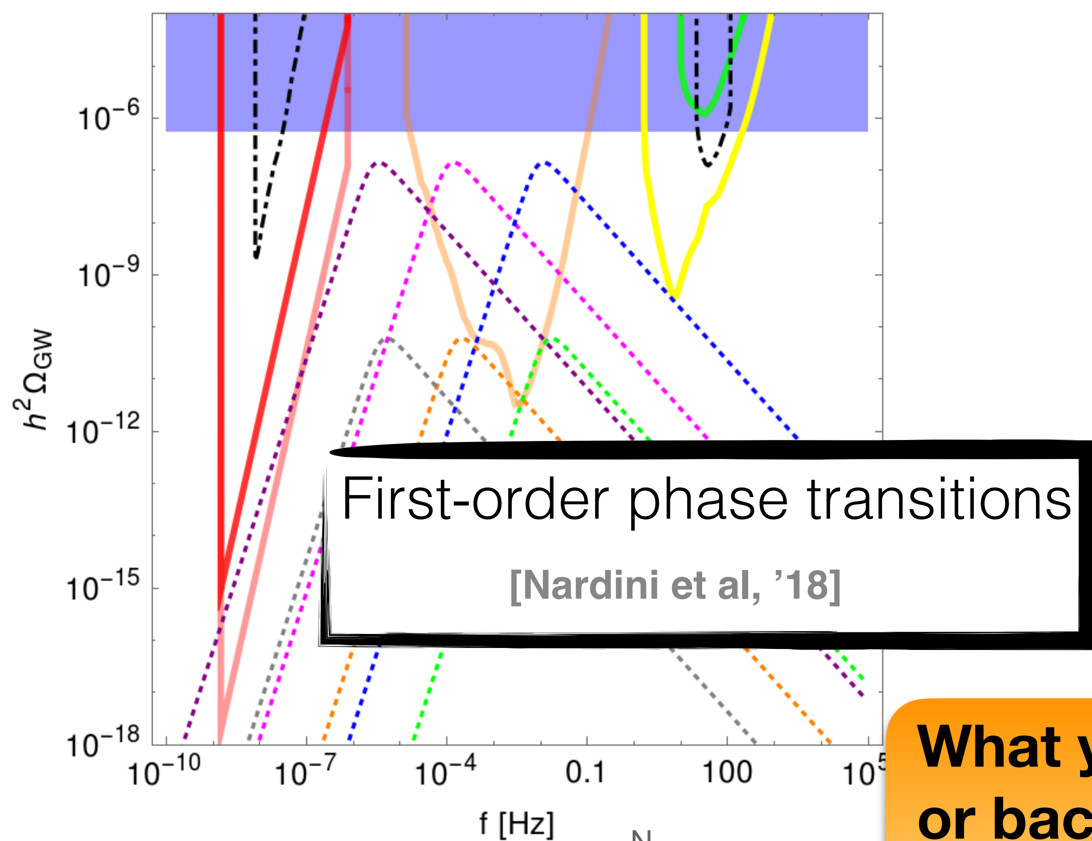


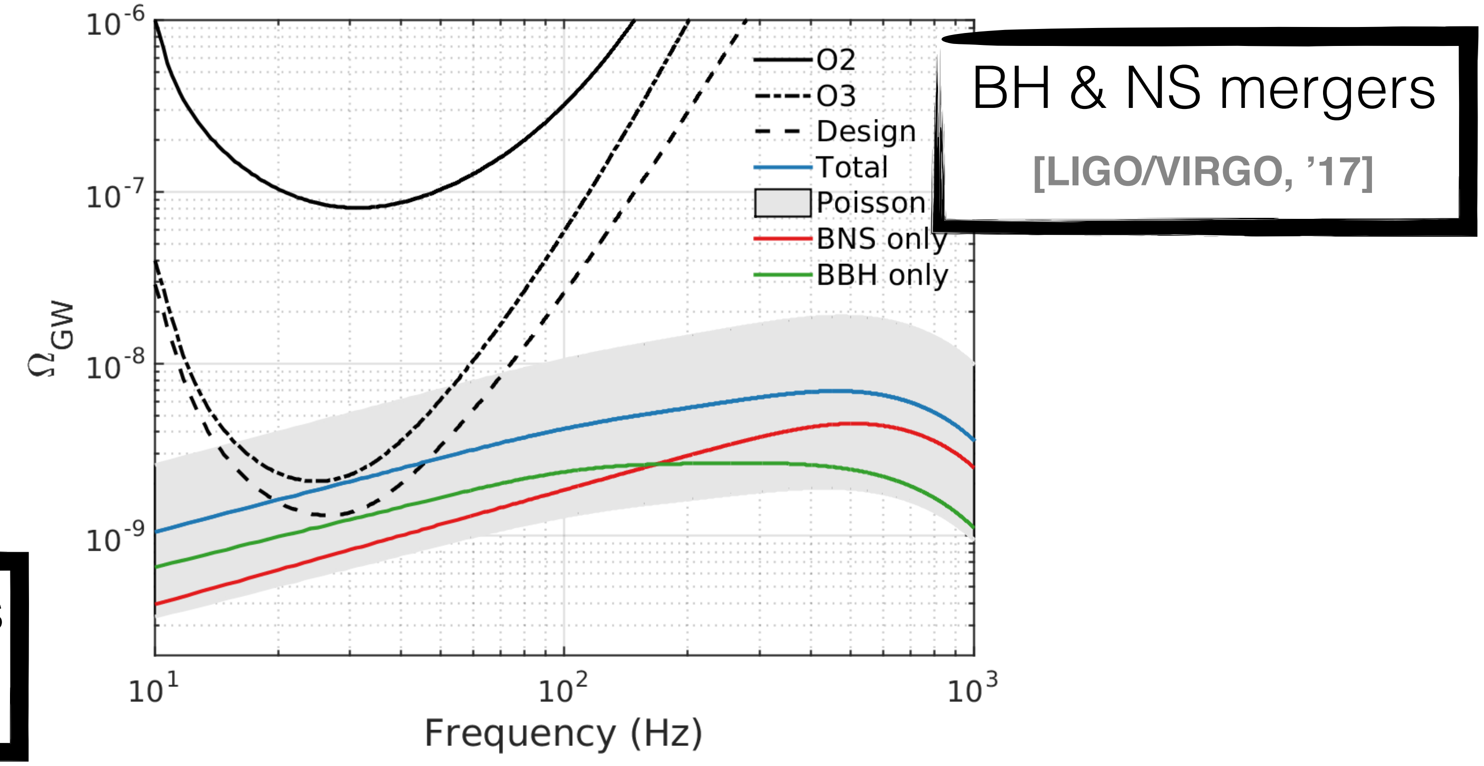


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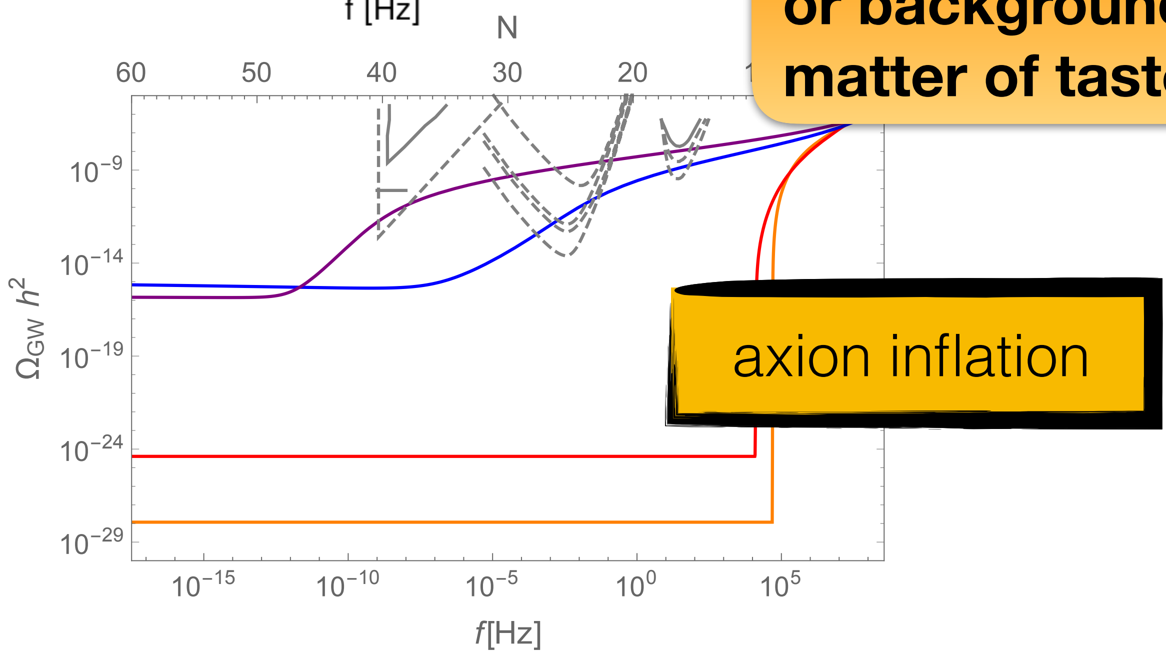


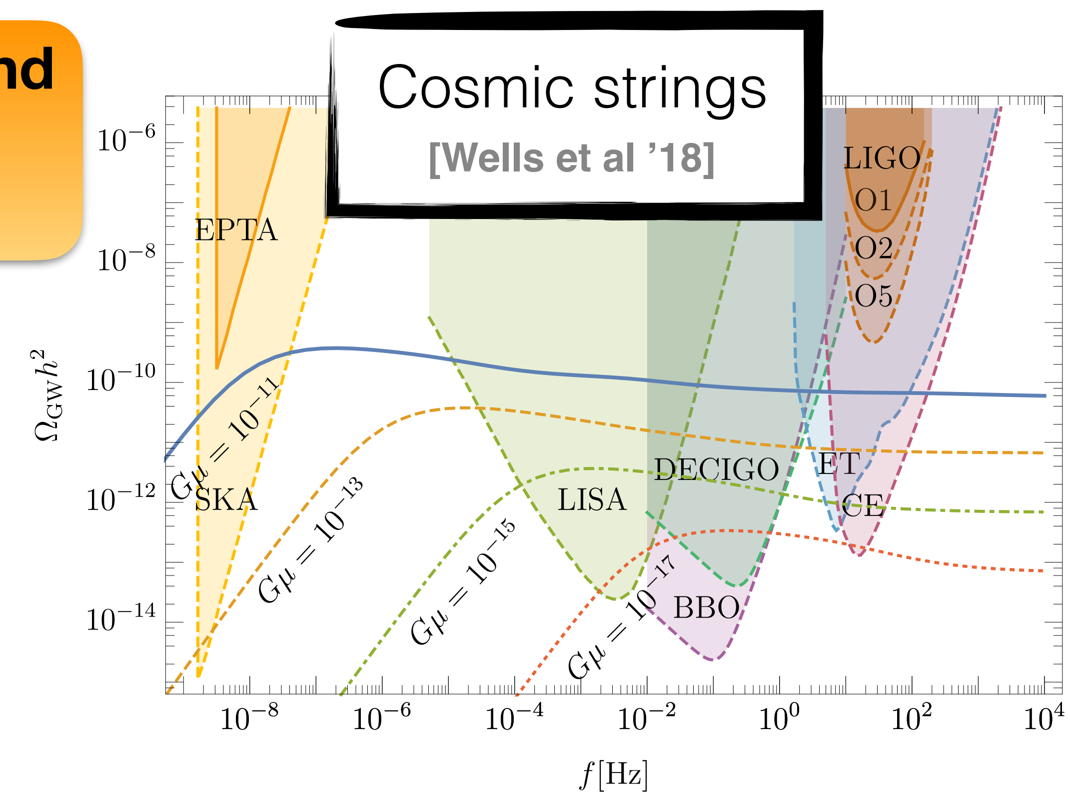

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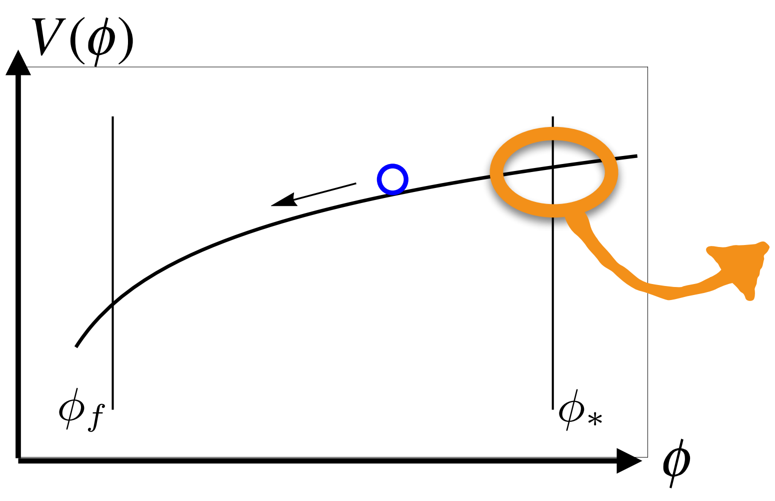
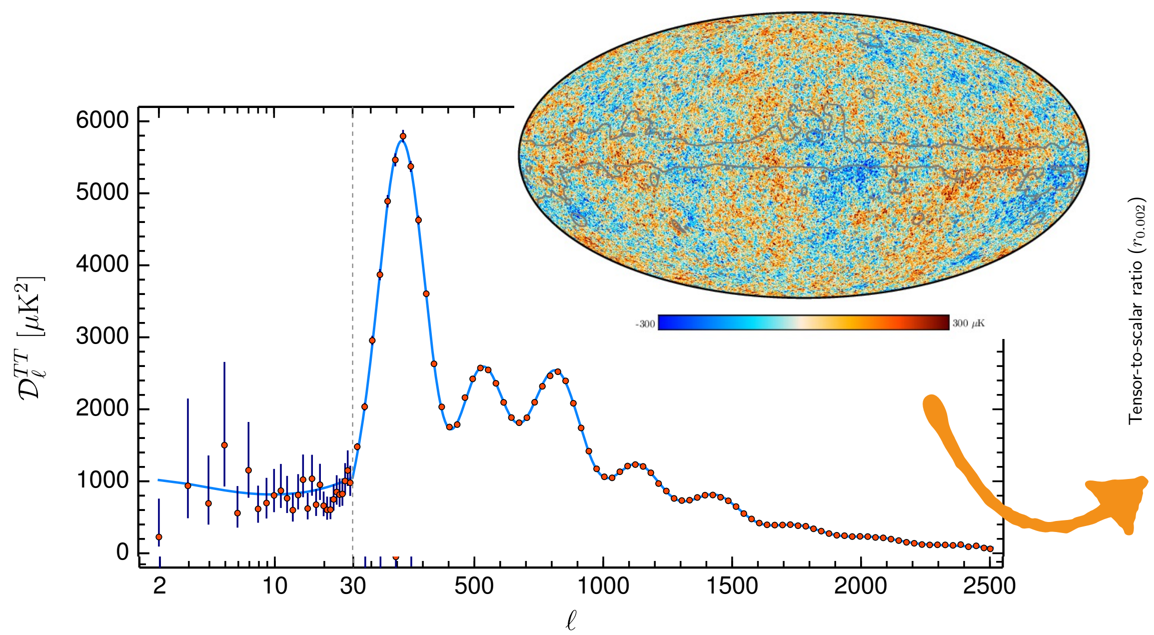
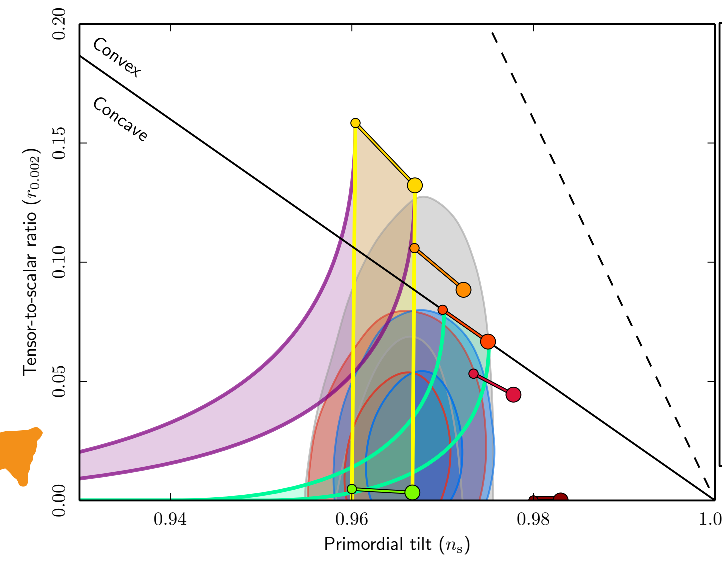
# cosmic inflation in a nutshell




Planck collaboration '18

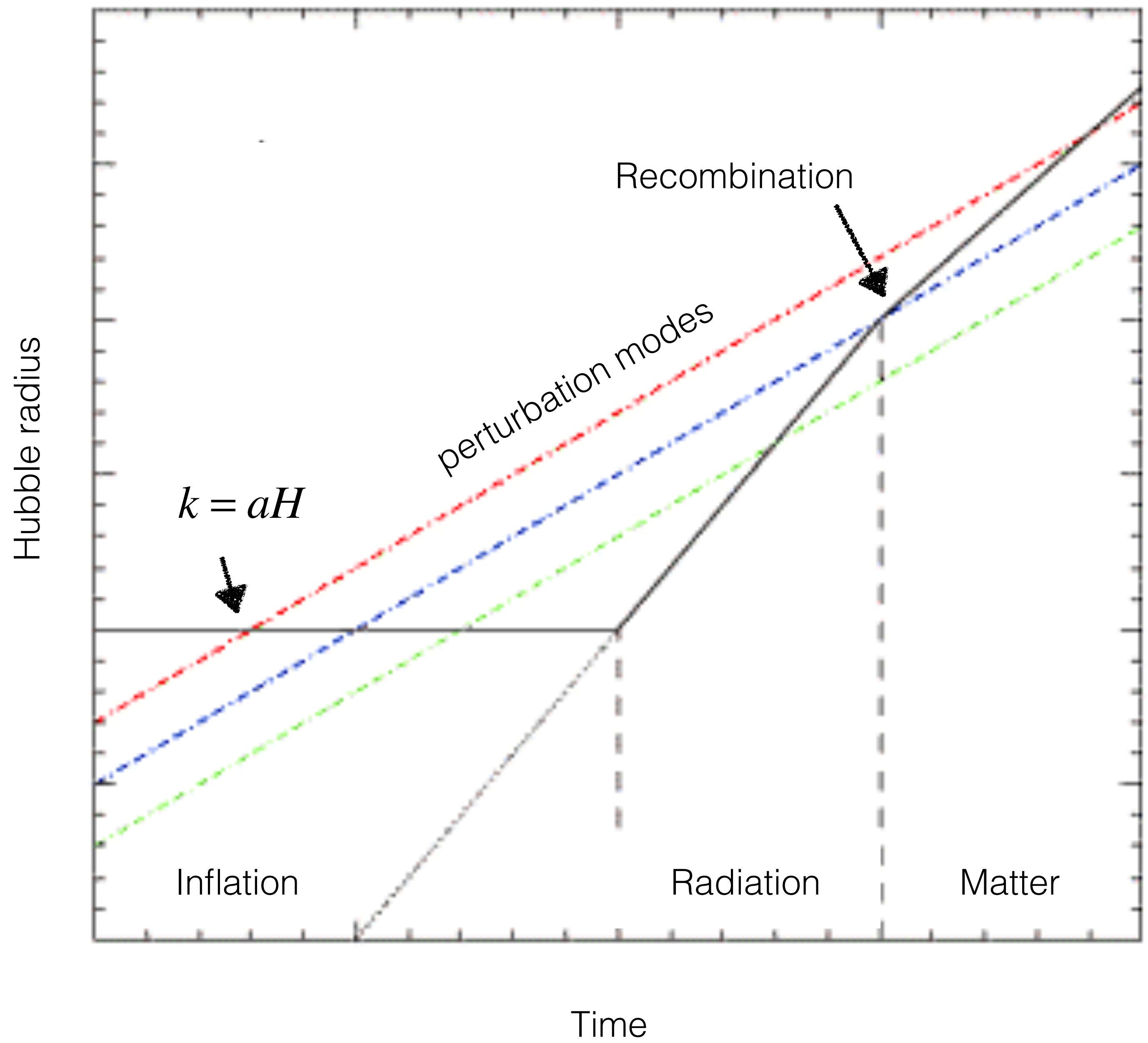
large vacuum energy ➔ exponential expansion ➔ homogeneity of CMB

quantum fluctuations ➔ become classical ➔ tiny anisotropies in the CMB

very successful paradigm, but very many possible realizations

we lack access to sub-CMB scales

# Scales and horizons

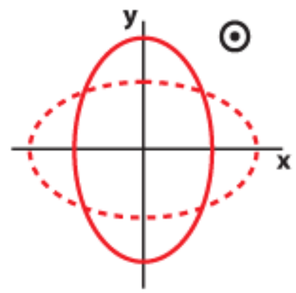


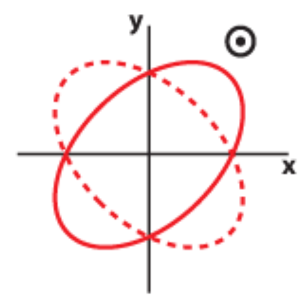

shorter wavelength = later stages of inflation

# Hunting for primordial GWs

$r = \Delta t^2 / \Delta s^2$

CMB

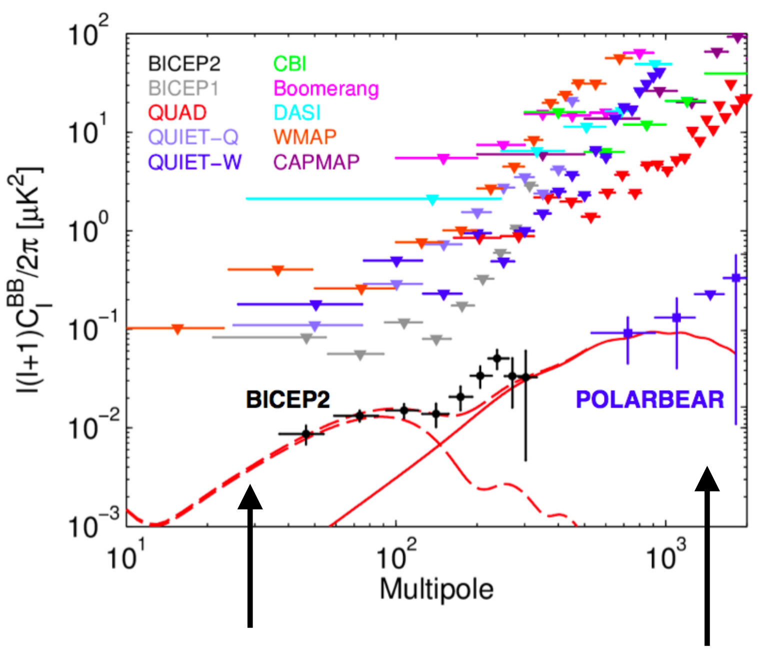



$$\Omega_{\rm GW}(k) = \frac{\Delta_t^2}{12} \frac{k^2}{a_0^2 H_0^2} T_k^2$$

direct

BICEP2 '14




hypothetical primordial contribution with r ~ 0.17

Lensing

sensitive to CMB scales

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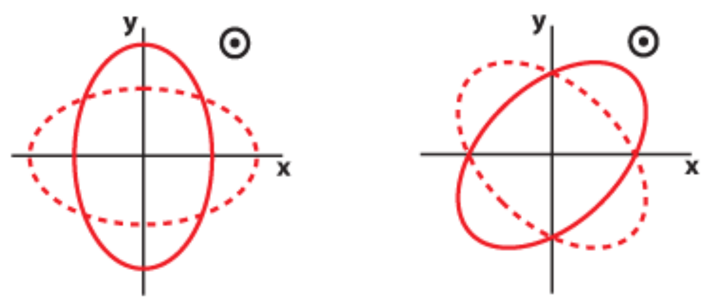


CMB

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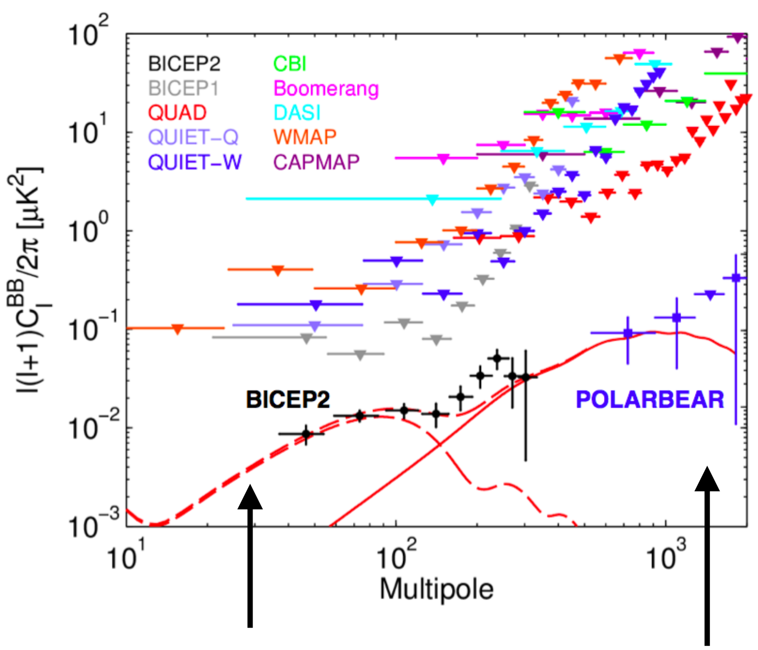


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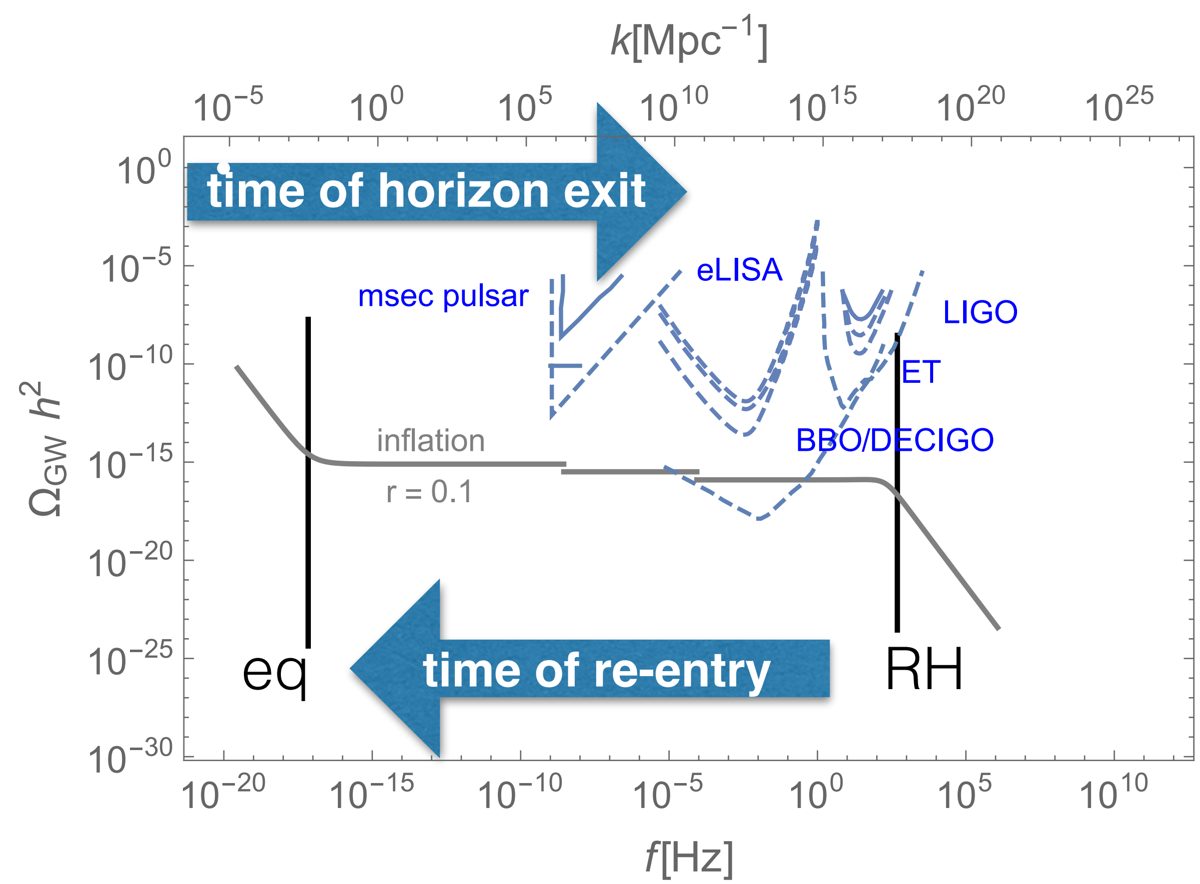


sensitive to CMB scales

with suitable detectors, probe 30 orders of magnitude

# Coupling Inflation to the SM

Slow-roll inflation → very flat scalar potential

Reheating after inflation → coupling to the SM

↓

**Inflaton as Pseudo Goldstone Boson with shift-symmetric couplings**

$$\phi F_{\mu\nu} \tilde{F}_{\mu\nu}$$

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

**Striking phenomenological signatures at sub-CMB scales !**

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**Striking phenomenological signatures at sub-CMB scales !**

# coupling to U(1) gauge fields

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

Turner, Widrow '88,
Garretson, Field, Caroll '92,
Anber, Sorbo '06./'10/'12,
Barnaby, Namba, Peloso '11,
Barnaby, Pajer, Peloso '12 ,
.....

↓

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

$$\xi = \frac{\alpha \dot{\phi}}{2 H f_a}$$

$$\pm = \text{helicity}$$

↓

**controlled by $\xi$ ↓ most relevant towards end of inflation**

**explosive production of large scale helical gauge fields towards end of inflation**

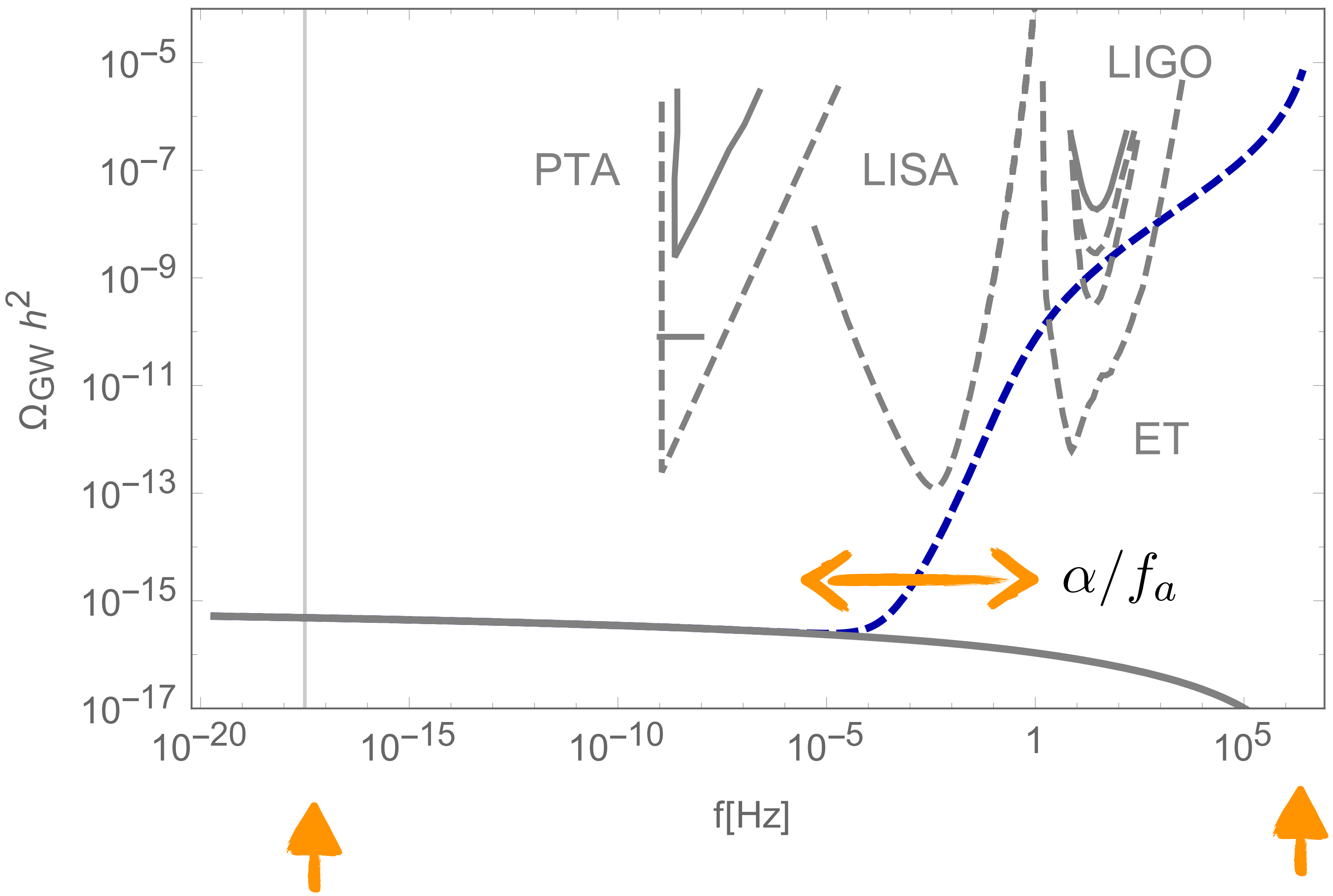
↓

**additional friction modifies dynamics of inflation** $\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = \frac{\alpha}{f_a} \langle \vec{E} \cdot \vec{B} \rangle$

**additional contribution to scalar and tensor power spectra**

# coupling to U(1) gauge fields

**gravitational wave spectrum**




**CMB**

**end of inflation**

inflaton scalar potential:

$$V = V_0 \left[1 - \cos\left(\frac{\phi}{f_\phi}\right)\right]$$

$$f_\phi \simeq 9.2\ M_P$$

see also [Binétruy, Domcke, Pieroni '16]

**strongly enhanced GW spectrum at small scales**

**maximally polarized, non-gaussian**

# dual fermion & gauge field production

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

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

chiral rotation

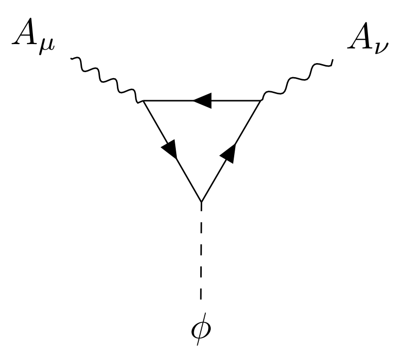
$$S = \int \mathrm{d}^4 x \left\{ \sqrt{-g}\left[\frac{g^{\mu\nu}}{2}\partial_\mu\phi\,\partial_\nu\phi - V(\phi)\right] - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \overline{\psi}\left(i\partial\!\!\!/ - gQA\!\!\!/\right)\psi - \frac{\phi}{2Q^2 f_a}\partial_\mu J_5^\mu\right\}$$

**Chiral anomalies in the SM:**

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

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

$$J_5^\mu = \bar{\psi}\gamma_\mu\gamma^5\psi$$



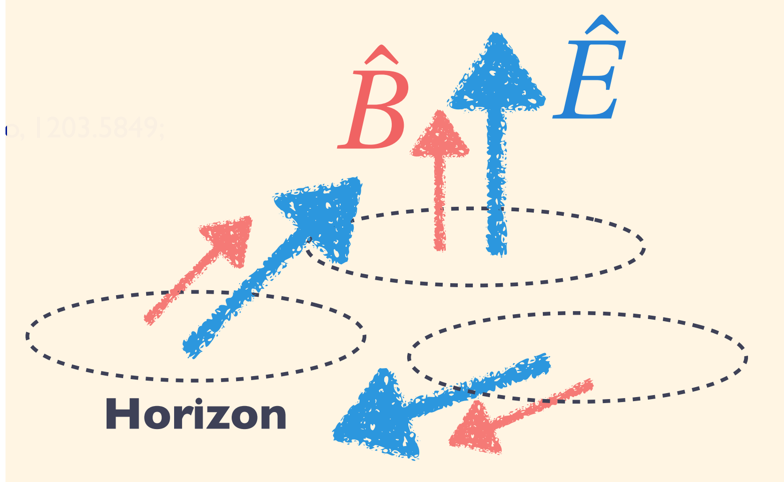

**dual production of helical gauge fields and chiral fermions**

# dual fermion & gauge field production

Domcke, Mukaida '18

**helical gauge field production**

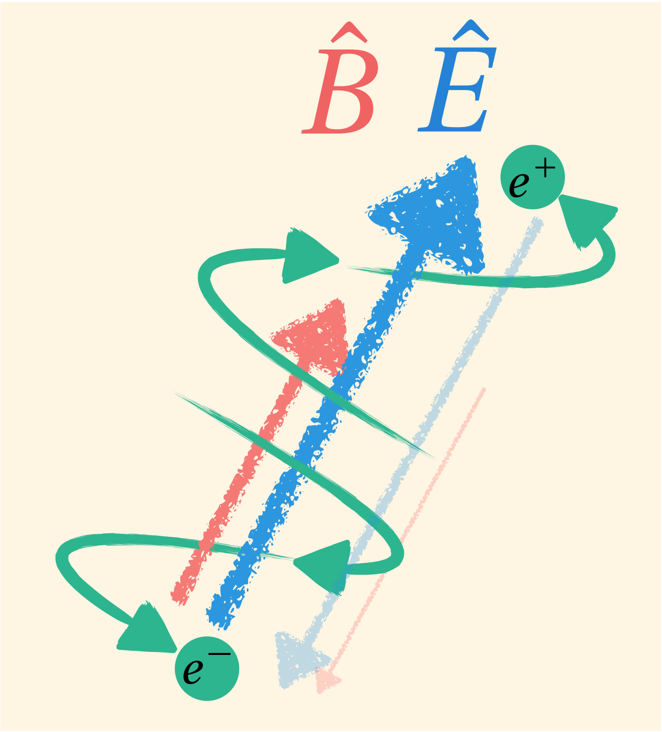
- one helicity of gauge field acquires tachyonic mass
- parallel E,B fields; constant & homogeneous on scales << $H^{-1}$




**(chiral) fermion production** Nielsen, Ninomiya '83

figures by K. Mukaida

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




**backreaction on gauge field production**

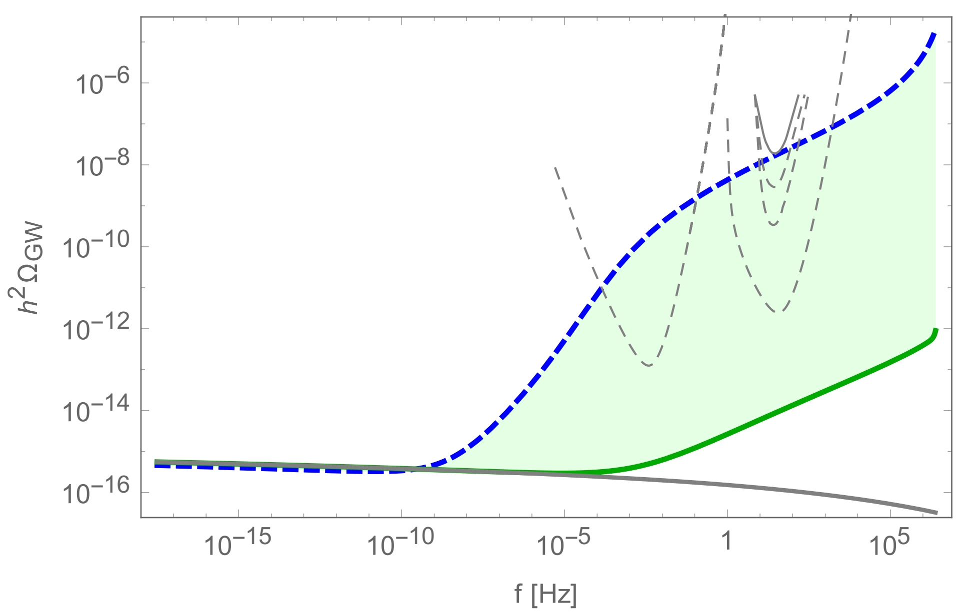
- fermions are accelerated in gauge field background
- induced current inhibits gauge field production

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

# phenomenological implications

- **GW spectrum**

Domcke, Mukaida '18
Domcke, Ema, Mukaida in preparation




no or very heavy fermions

~ lower bound for massless fermions

vacuum contribution

- **scalar power spectrum** — Domcke, Mukaida '18

- **production of SM fermions & gauge fields** → efficient reheating — Cuissa, Figueroa '18

- **production of long-range, classical gauge fields**
  → under certain conditions, these can survive until EW phase transition
  → baryogenesis from decaying magnetic fields @ EW phase transition

[Kamada, Long '16, Jimenez, Kamada, Schmitz, Xu '17, Domcke, v. Harling, Morgante, Mukaida '19 ]

**GWs as a probe of particle physics**

# Conclusion and Outlook

**The SGWB is our cosmic history book:**

- all `sufficiently violent' events are recorded, since the Big Bang
- different epochs correspond to different frequencies
- every record is a convolution of the actual event with the subsequent cosmological history
- It is very hard to decipher!

**Axion inflation**

- Axion as a PNGB with shift-symmetric couplings $\phi F_{\mu\nu} \tilde{F}_{\mu\nu}$ $(\partial_\mu \phi) \bar{\psi} \gamma^\mu \gamma^5 \psi$
- enhanced GW spectrum at sub-CMB scales with characteristic features
- connected to open questions in particle cosmology

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Thank you !

# Backup slides

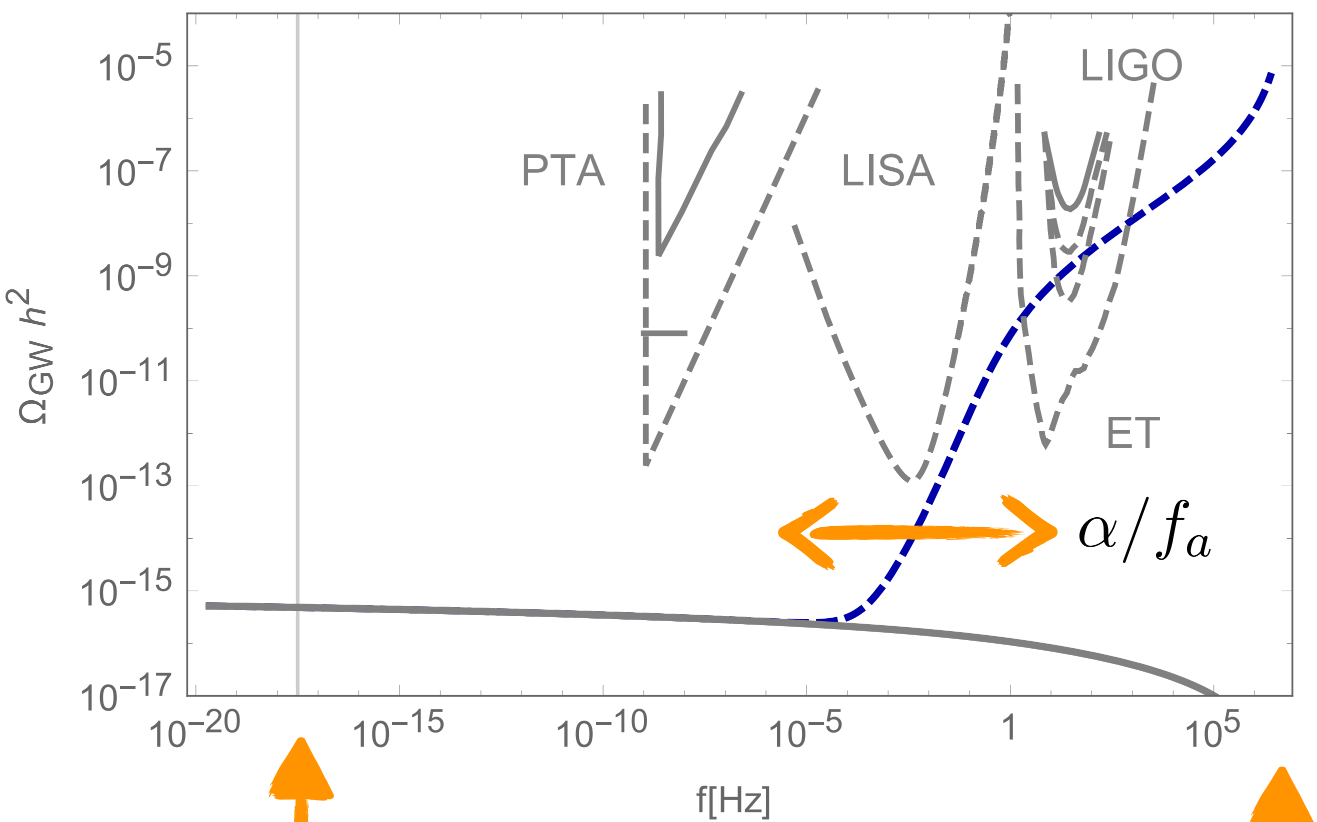
# coupling to U(1) gauge fields

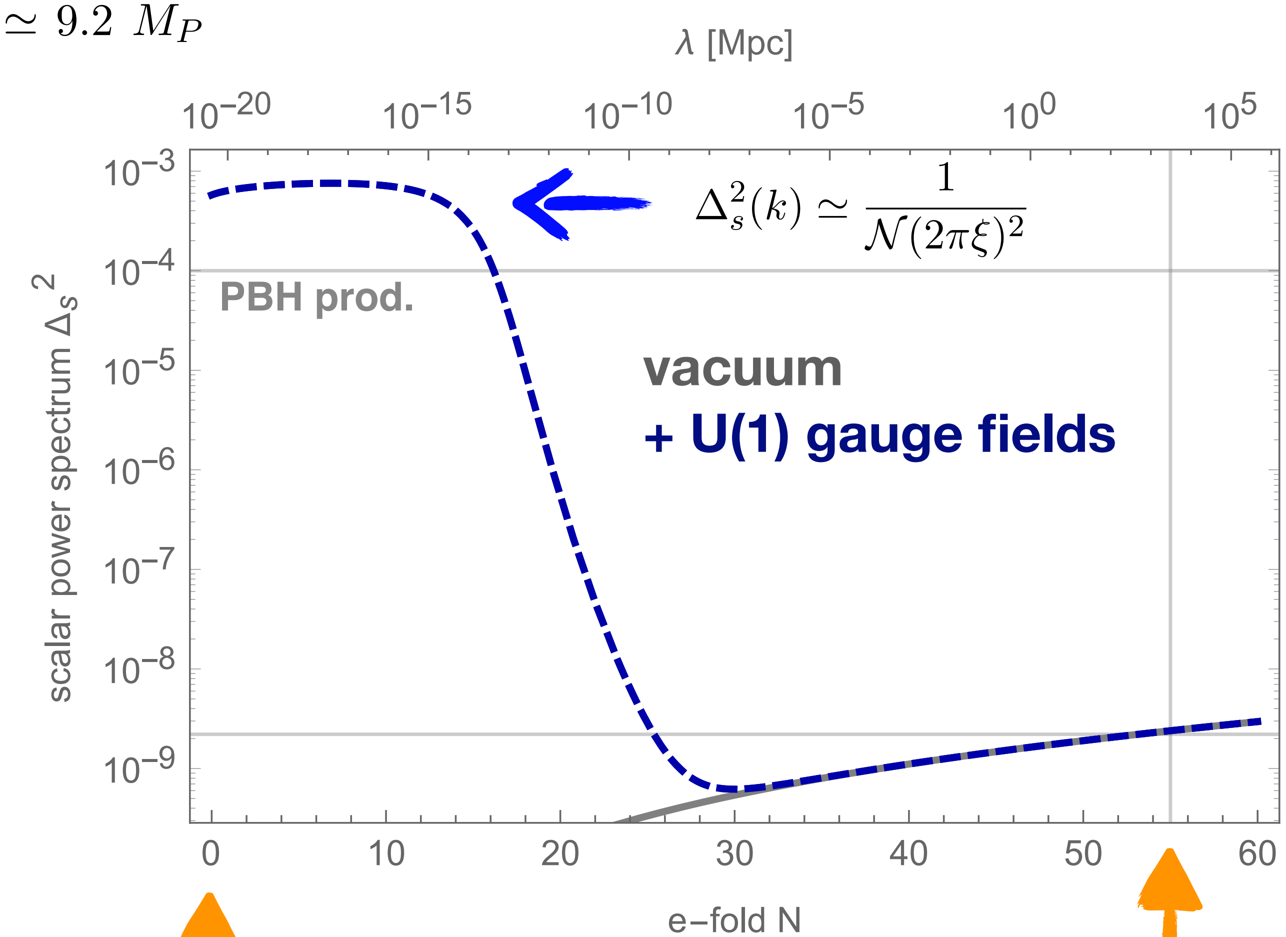
**tensor power spectrum**

$$V = V_0 \left[1 - \cos\left(\frac{\phi}{f_\phi}\right)\right]$$

$$f_\phi \simeq 9.2 \; M_P$$

**scalar power spectrum**




**CMB**

**end of inflation**

**CMB**

**strongly enhanced GW spectrum at small scales**

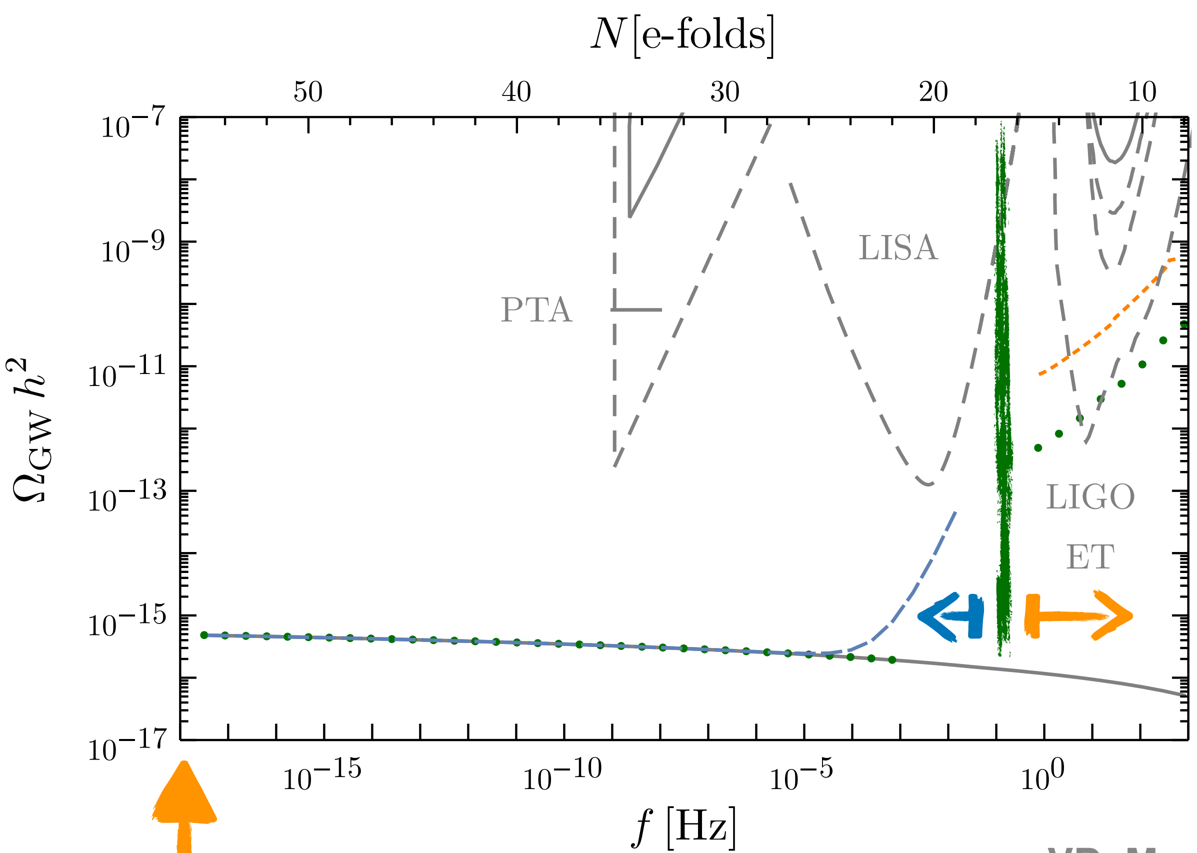
**maximally polarized, non-gaussian**

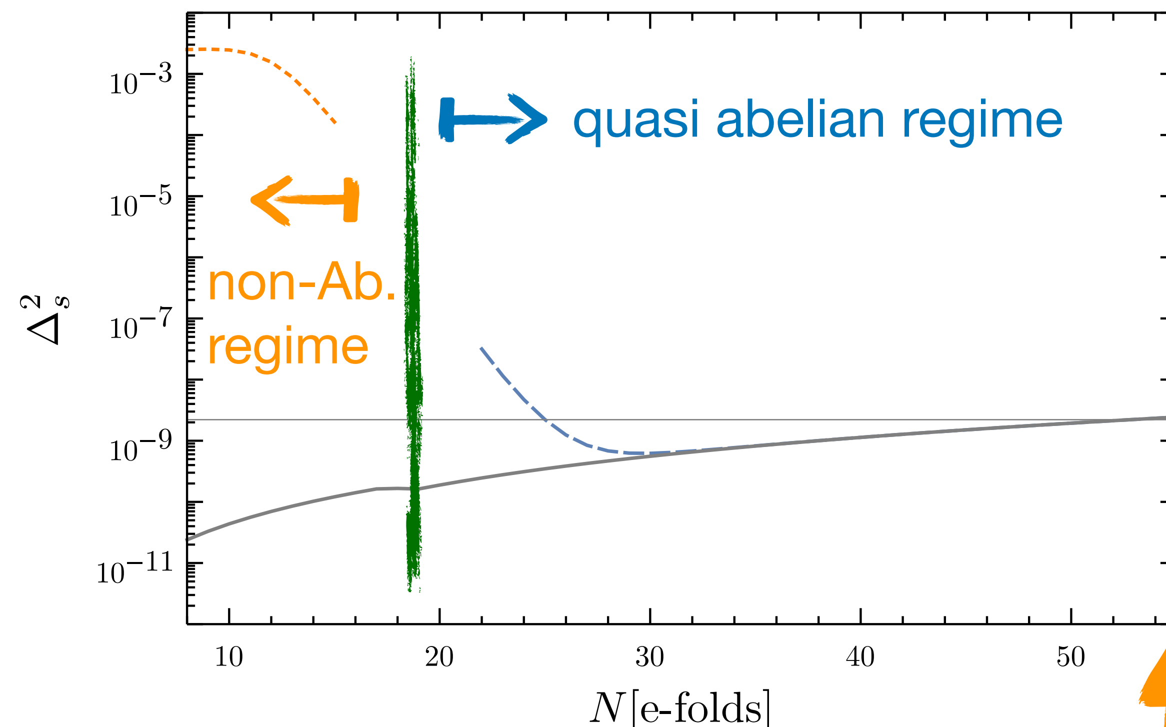
**strongly enhanced scalar power spectrum at small scales**

**plateau at smallest scales** $\Rightarrow \mathcal{N} \gtrsim 8$

# coupling to SU(2) gauge fields

**tensor power spectrum** $e = 5 \times 10^{-3}$ **scalar power spectrum**




VD, Mares, Muia, Pieroni ‘18

**CMB** **CMB**

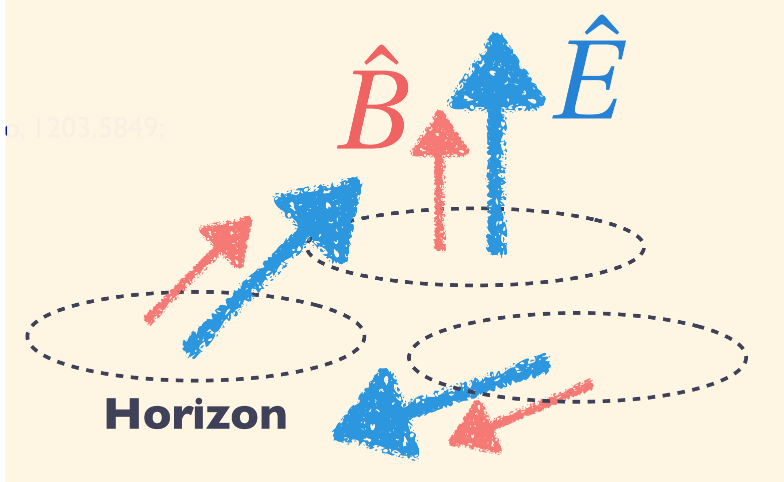
**strongly enhanced GW spectrum at small scales**

**maximally polarized**

**strongly enhanced scalar power spectrum at small scales**

**spectral shape different than for U(1) case**

# dual fermion & U(1) gauge field production




figures by K. Mukaida

## 1] helical gauge field production

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

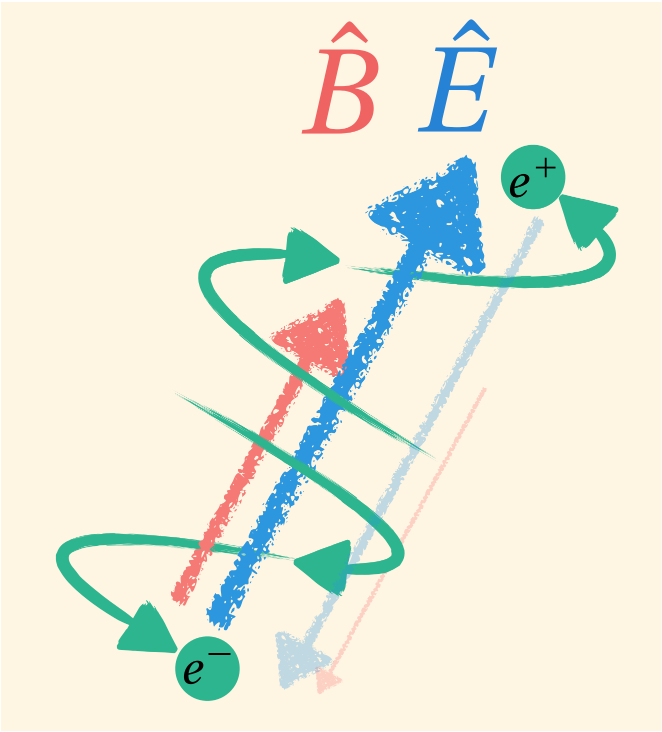
## 2] (chiral) fermion production

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

## 3] backreaction on gauge field production

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

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



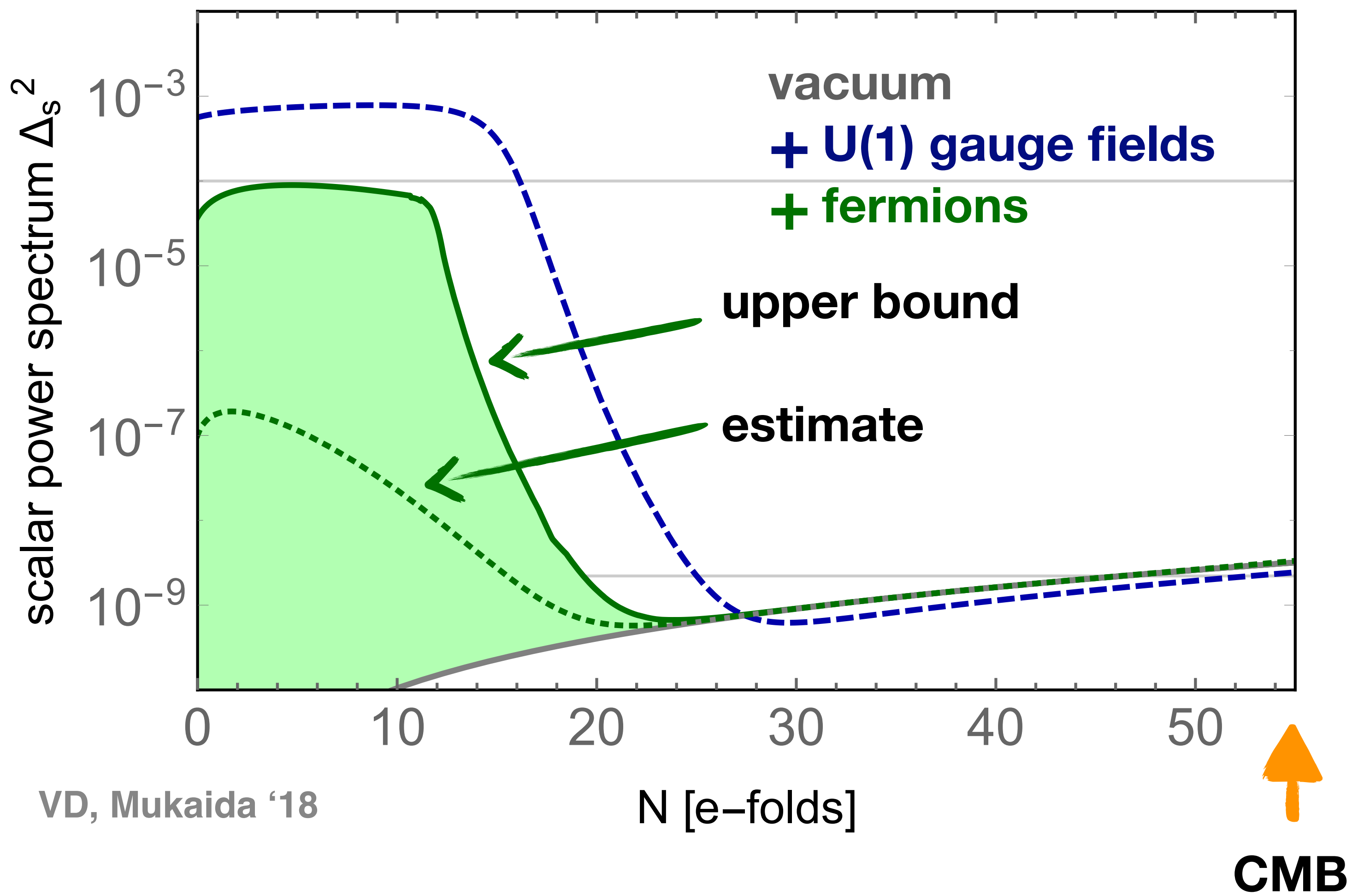
# dual fermion & U(1) gauge field production

**tensor power spectrum**

**???**

$g|Q| = 1/\sqrt{2}$

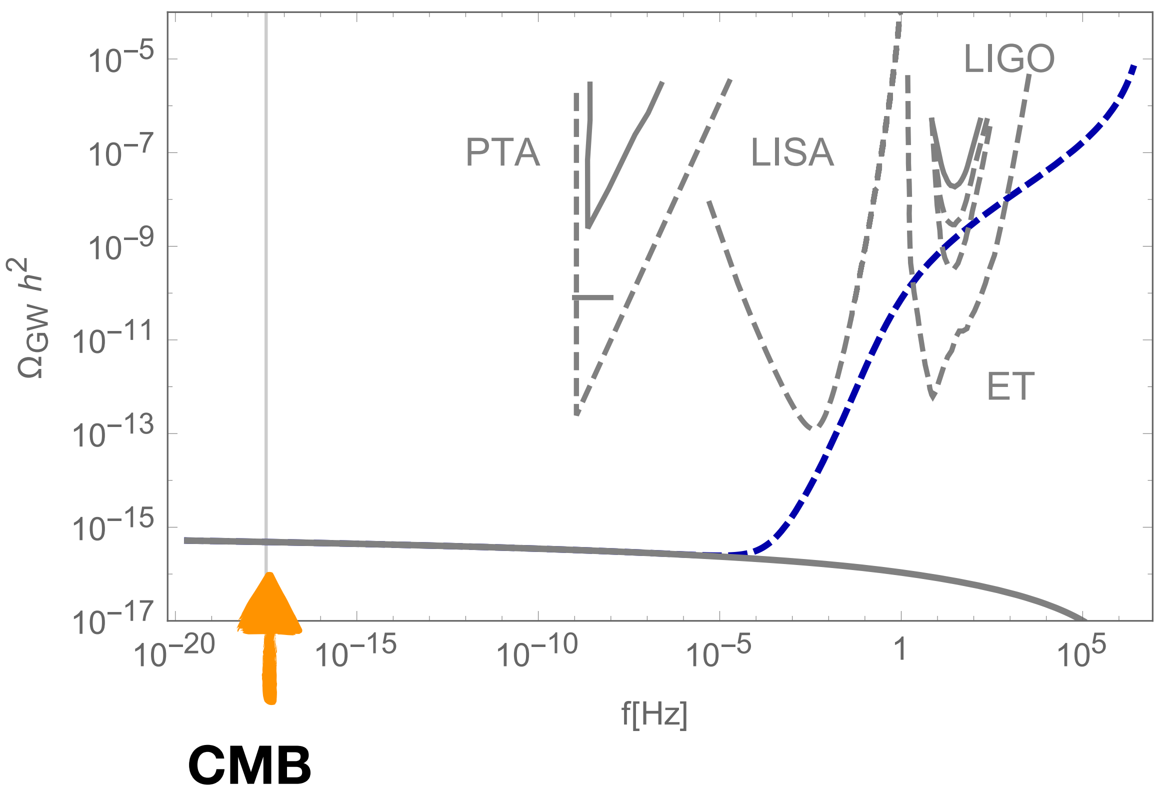
**scalar power spectrum**




**enhanced scalar power spectrum at small scales**

**backreaction from fermion current dampens gauge field production**

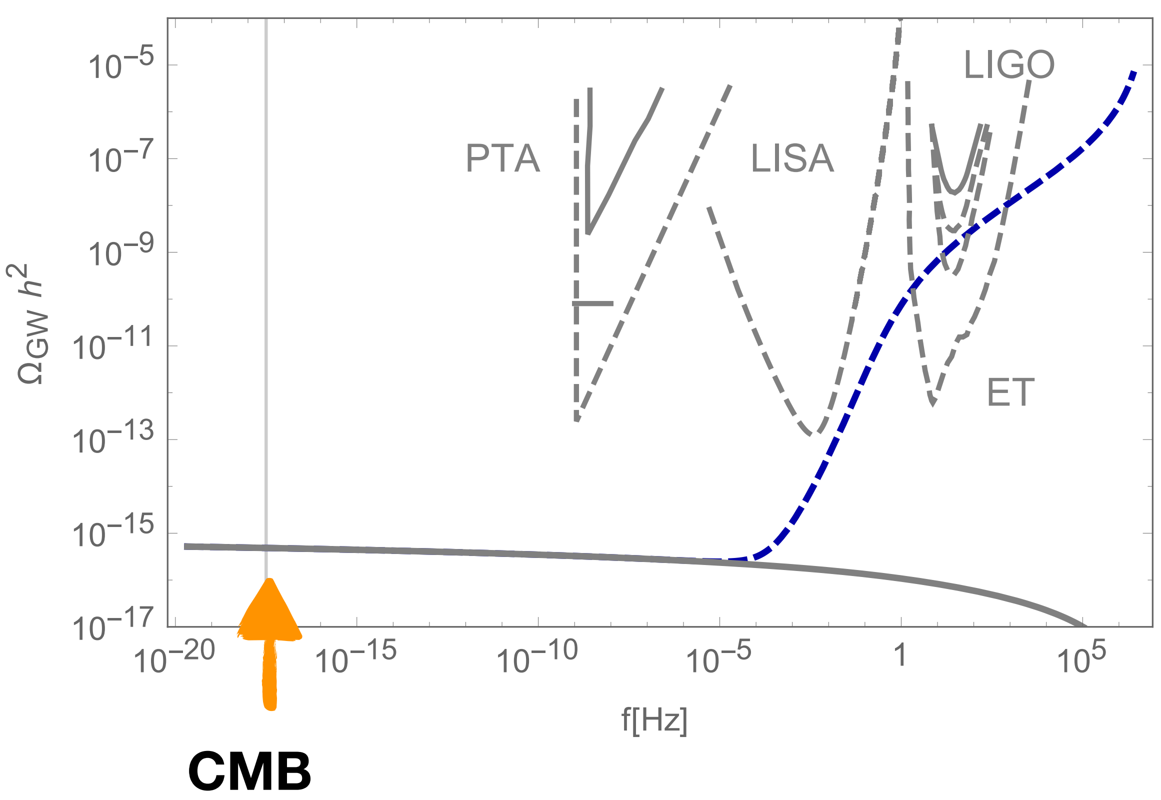
# probing the tensor power spectrum




- amplitude?
- spectral shape?
- non-gaussianities?
- polarization?

**Testing these particle physics model behind cosmic inflation requires measuring all these properties of the SGWB**

# probing the tensor power spectrum




- amplitude?
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- non-gaussianities?
- polarization?

**Figueroa, Ricciardone, VD, et al '18 [LISA Cosmo WG]**

**Testing these particle physics model behind cosmic inflation requires measuring all these properties of the SGWB**

# Tensor power spectrum

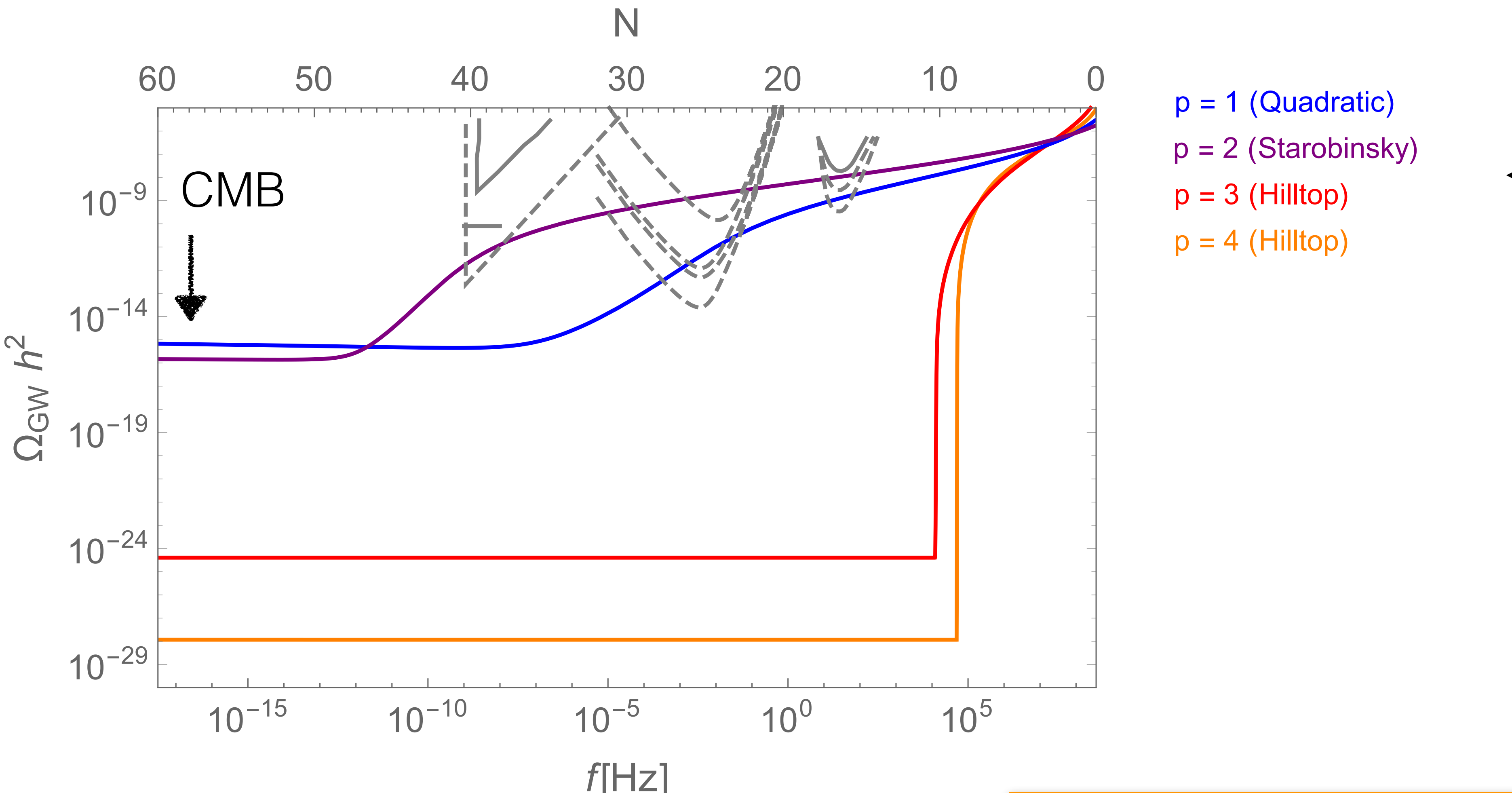
vacuum + sourced contribution:

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

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

strong enhancement on small scales

# Tensor power spectrum

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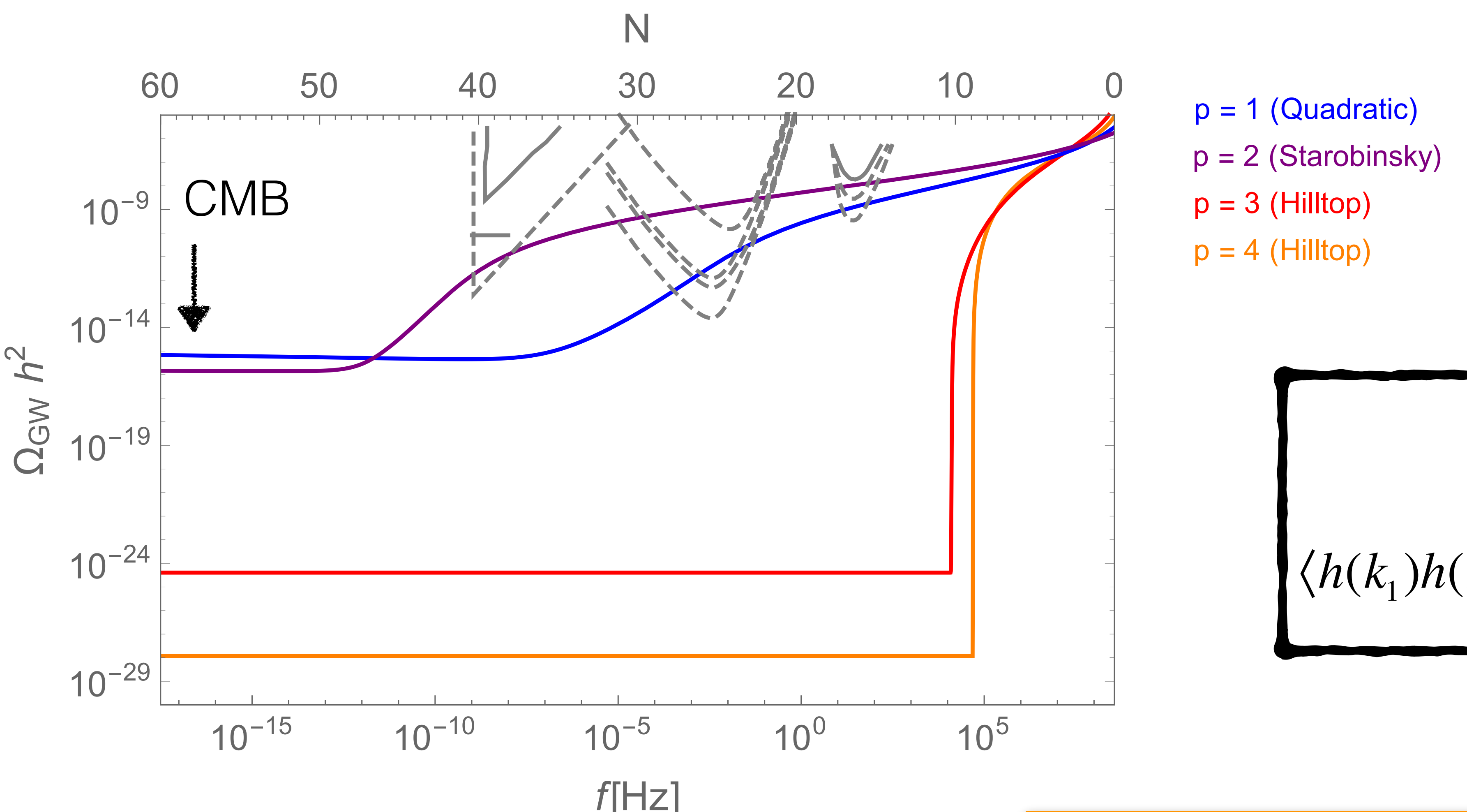



Binetruy, VD, Pieroni '16

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

strong enhancement on small scales

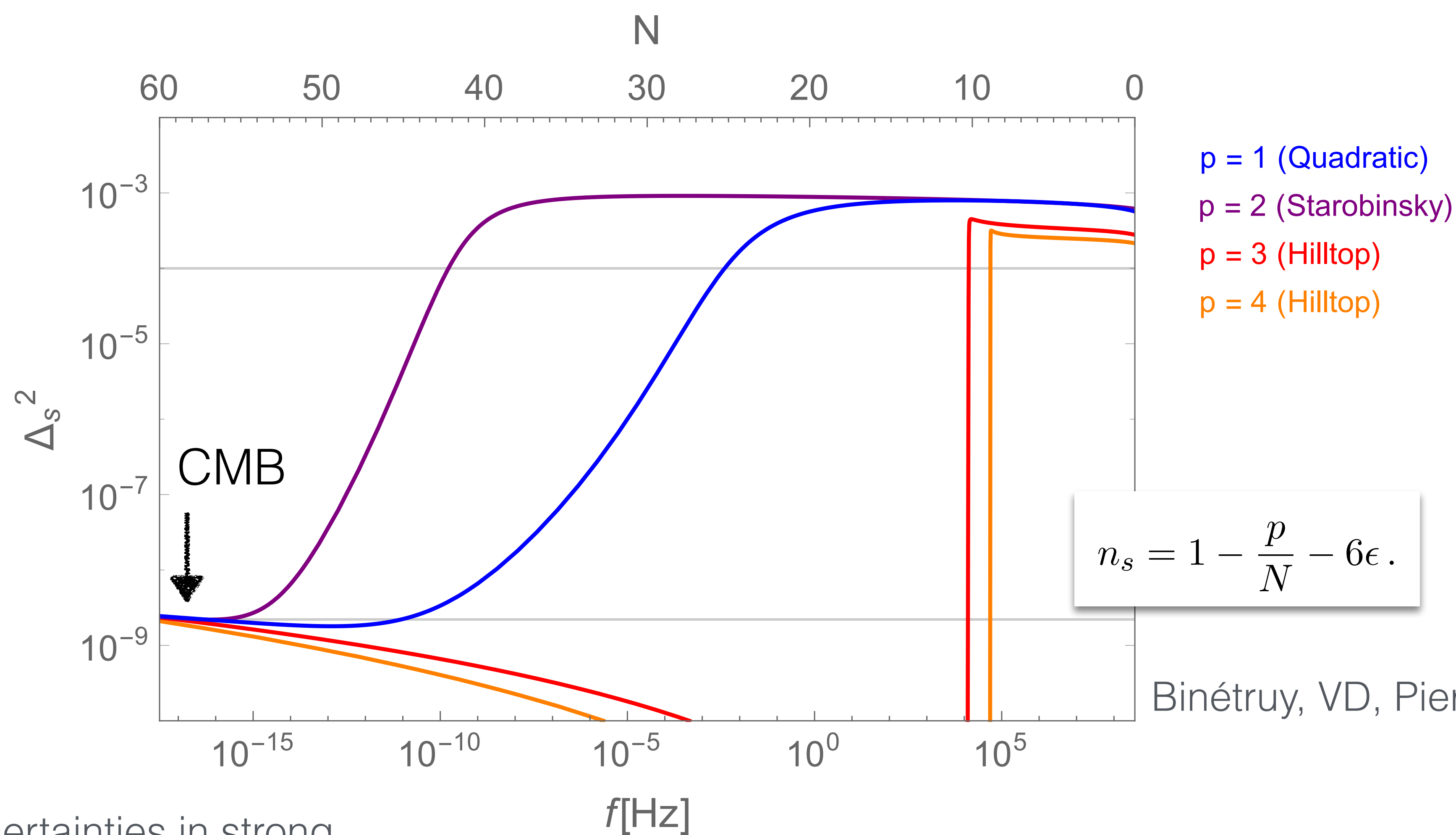
# Scalar power spectrum

vacuum + sourced contribution:

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

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

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




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

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

**chromo - natural inflation,**
**gauge - flation**

$$A(\tau, \vec{x}) = A^{(0)}(\tau) + \delta A(\tau, \vec{x}).$$

Maleknejad, Sheikh-Jabbari ’11,
Adshead, Wyman ’12
Dimastrogiovanni, Peloso ’13,
Adshead, Martinec, Wyman ’13
Dimastrogiovanni, Fasiello, Tolley ’13, …

**homogeneous, isotropic gauge field background**

**non-trivial attractor solution for** $\xi > 2$

$$A^{(0)}(\tau) = \frac{\xi}{g\,(-\tau)}\,\delta_i^a$$

**dynamically triggered by vacuum fluctuations**

**3 x 2 = 6 modes**

$A^{(0)} = 0$ **: 3 x U(1) -> 3 tachyonic modes**

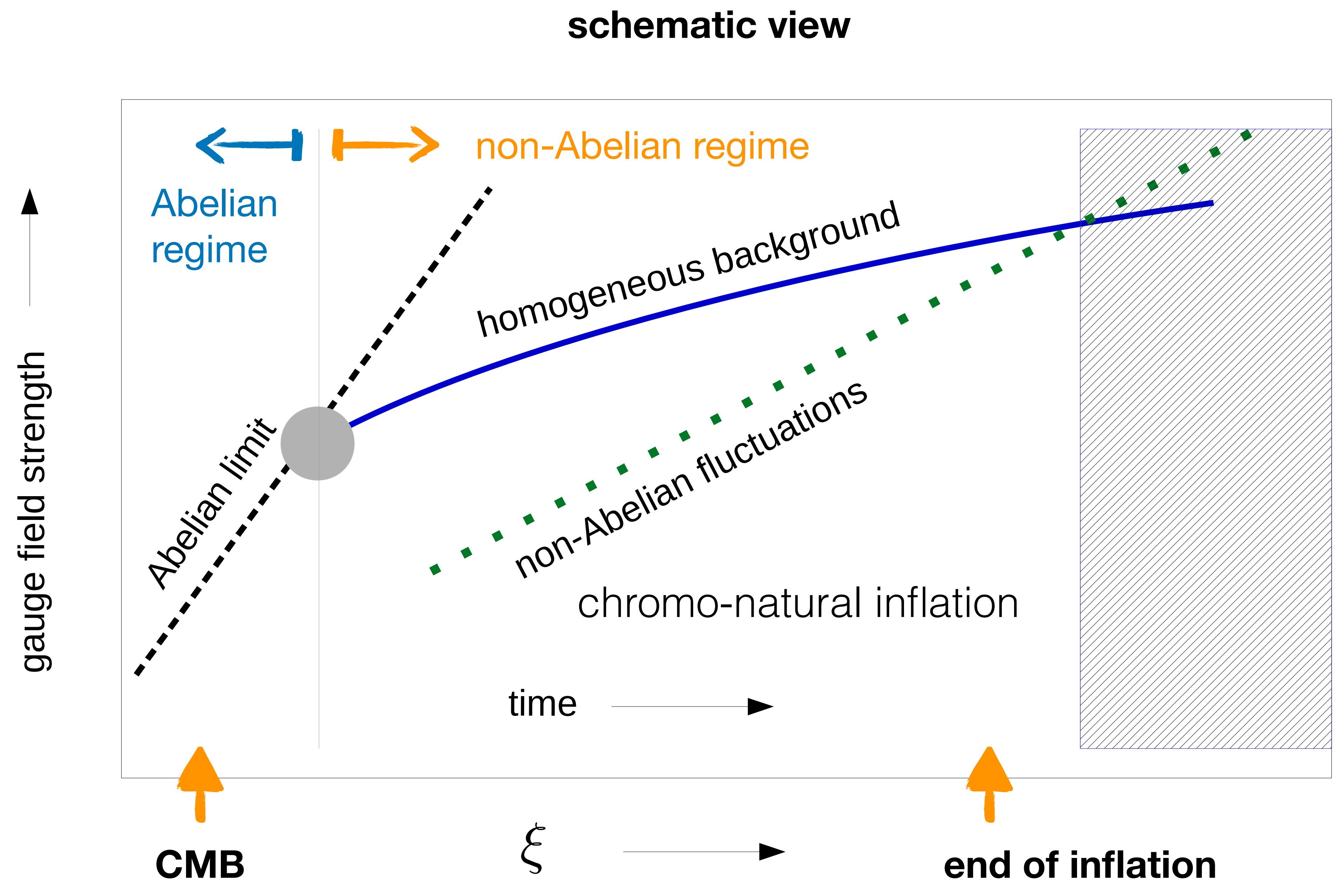
$A^{(0)} \neq 0$ **: 1 tachyonic mode, with helicity + 2**

**→ couples directly to spin 2 GW**

**self-interaction generates effective mass suppressing tachyonic instability, but non-zero background allows for new effects.**

# coupling to SU(2) gauge fields

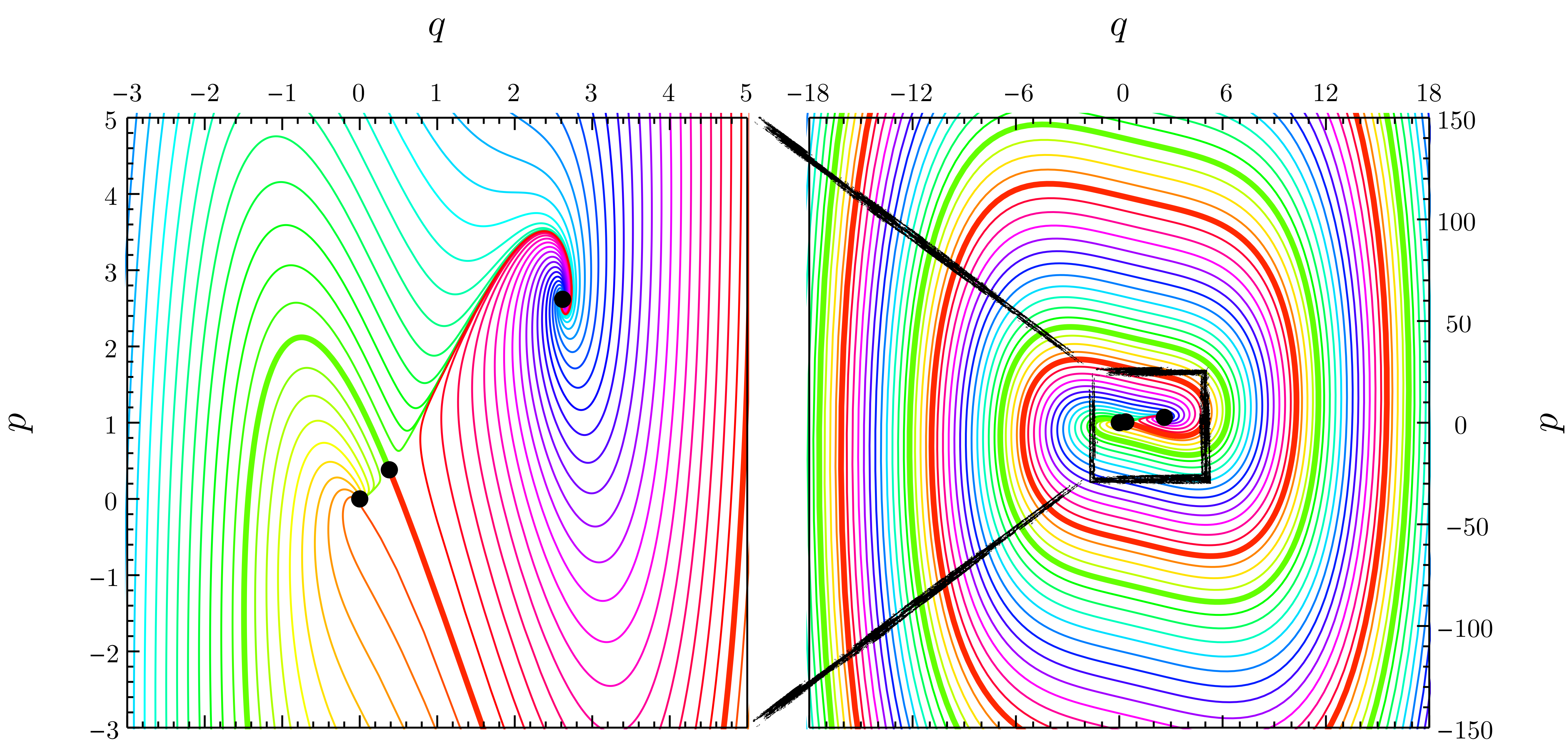
Emergence of a non-zero, isotropic & homogeneous gauge field background:




See also:
Maleknejad, Sheikh-Jabbari '11,
Adshead, Wyman '12
Dimastrogiovanni, Peloso '13,
Adshead, Martinec, Wyman '13
Dimastrogiovanni et al '13, …

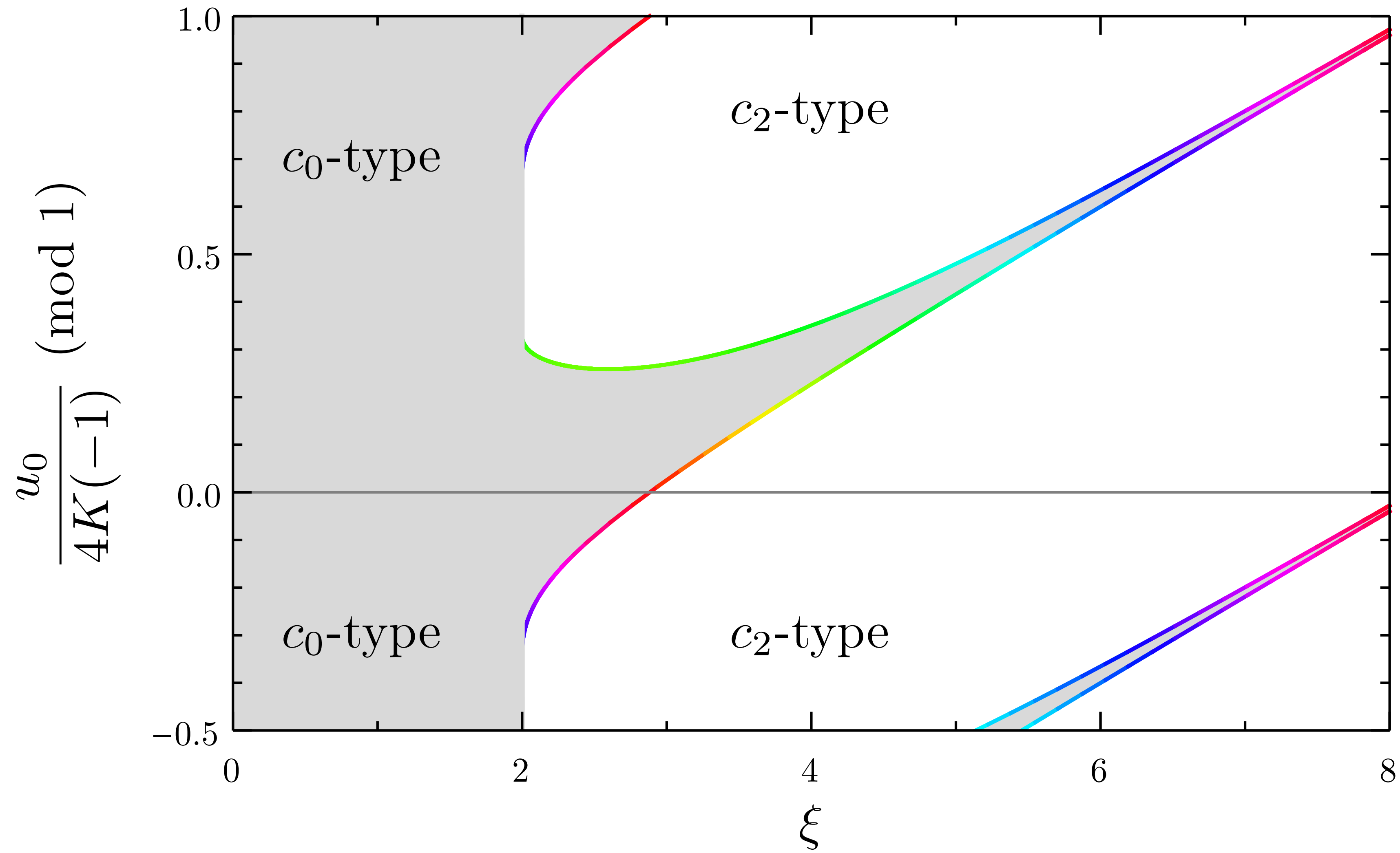
# SU(2) - background evolution

**evolution in phase space**



# SU(2) - background evolution

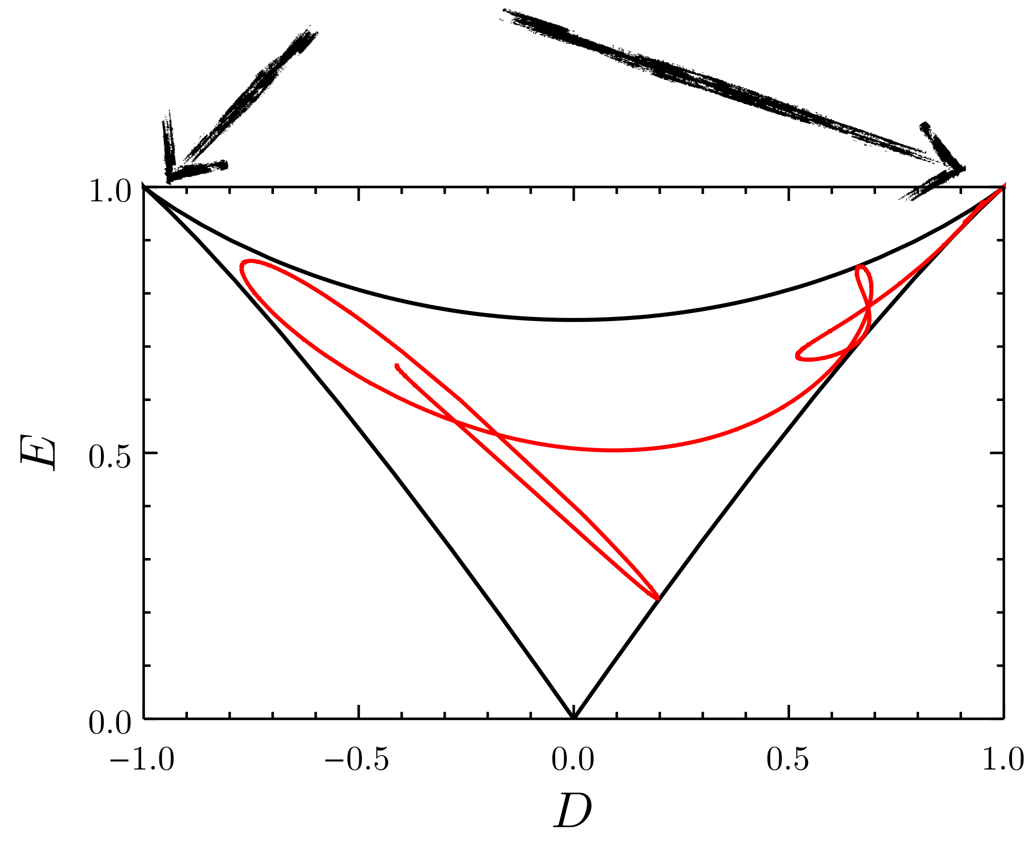
**non-trivial solution for** $\xi > 2$

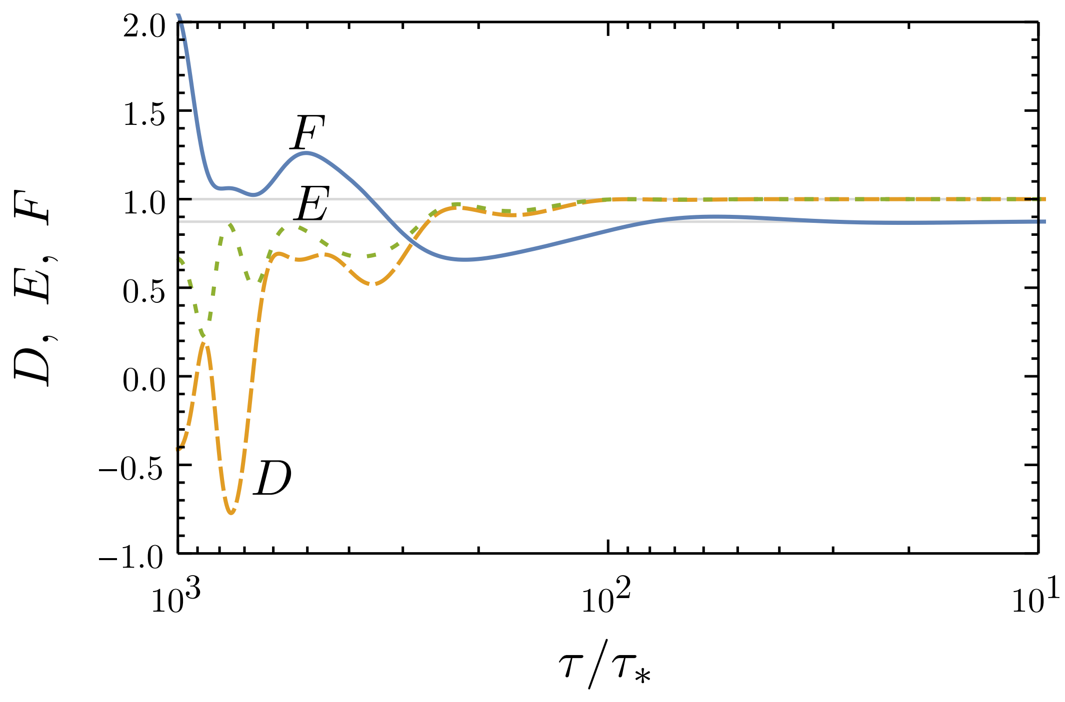


# SU(2) - background evolution

**decay of anisotropies**

**isotropy**



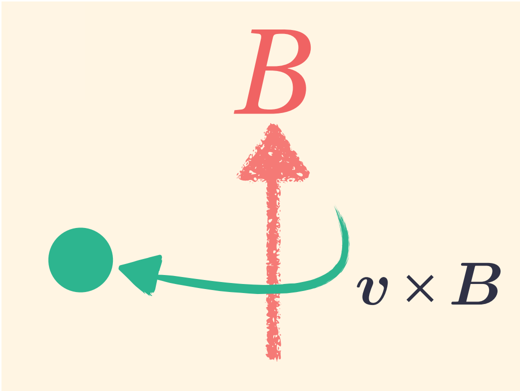



# fermion production

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

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

**auxiliary field:** $$\psi_{\mathrm{R/L}} \equiv (i\partial_\eta \mp i\boldsymbol{\nabla}\cdot\boldsymbol{\sigma} \mp gQ\boldsymbol{A}\cdot\boldsymbol{\sigma})\,\Phi_{\mathrm{R/L}}$$




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

**auxiliary eom:** $$0 = \left[-\frac{\partial^2}{\partial t^2} + \frac{\partial^2}{\partial x^2} - (gQBx - p_y)^2 - (gQEt + p_z)^2 + gQ\,(B \pm iE)\,\sigma_z\right]\Phi_{\mathrm{R/L}}$$

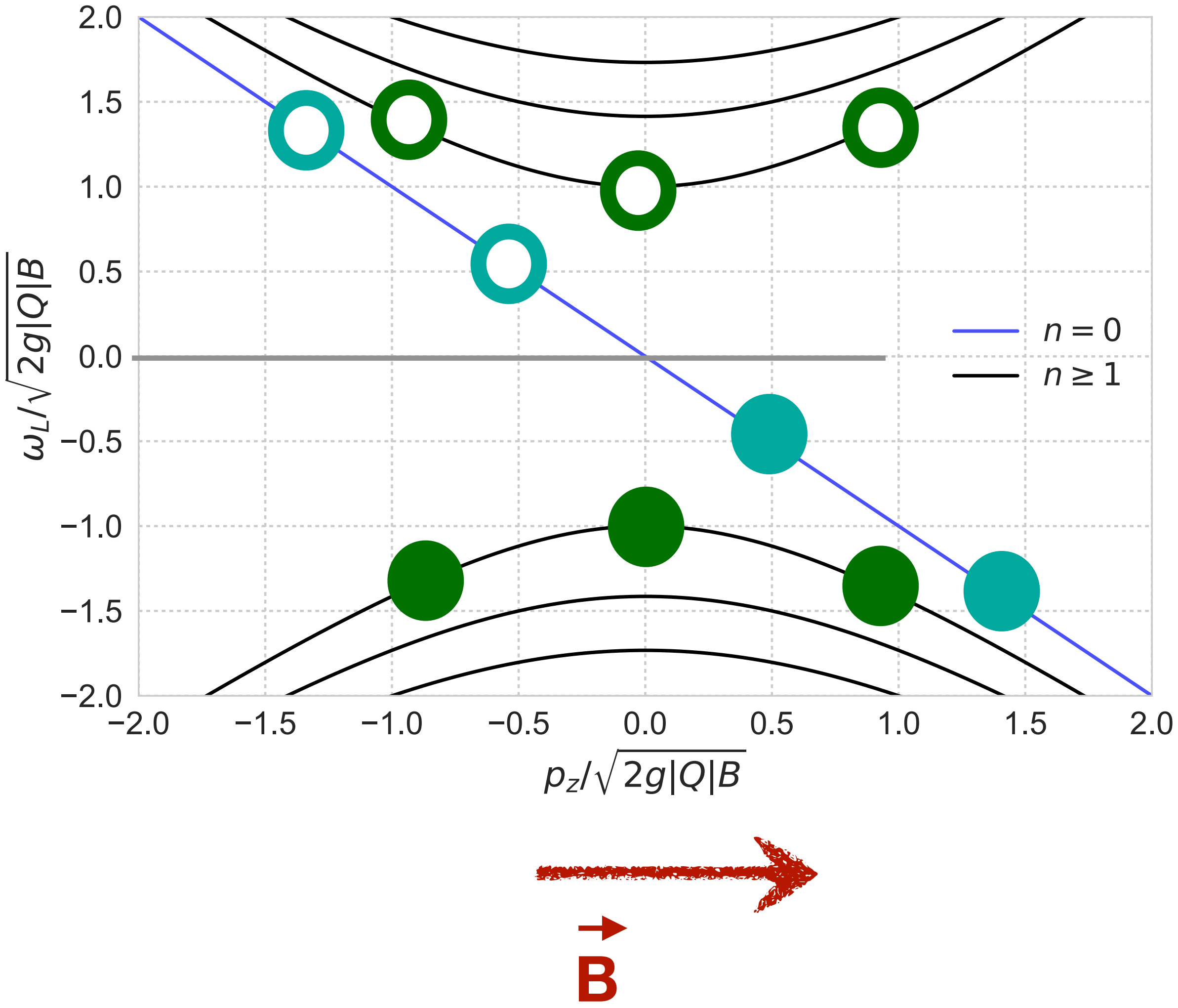
separable differential equation with **discrete energy levels** (Landau levels):

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

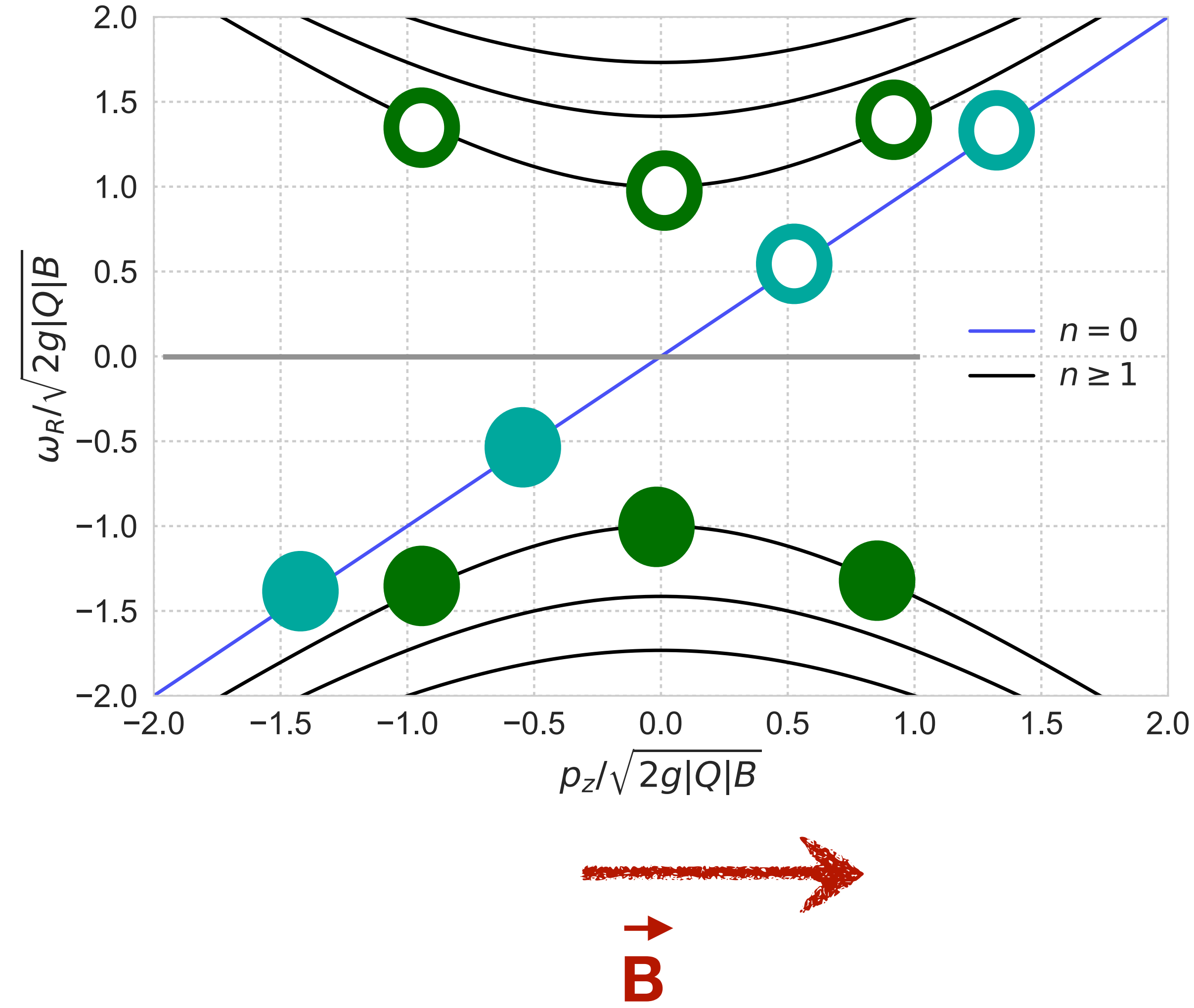
determine particle production induced by E-field

# fermion production (LLL)

**left-handed fermions**




**right-handed fermions**




**asymmetric fermion production**

# fermion production (LLL)

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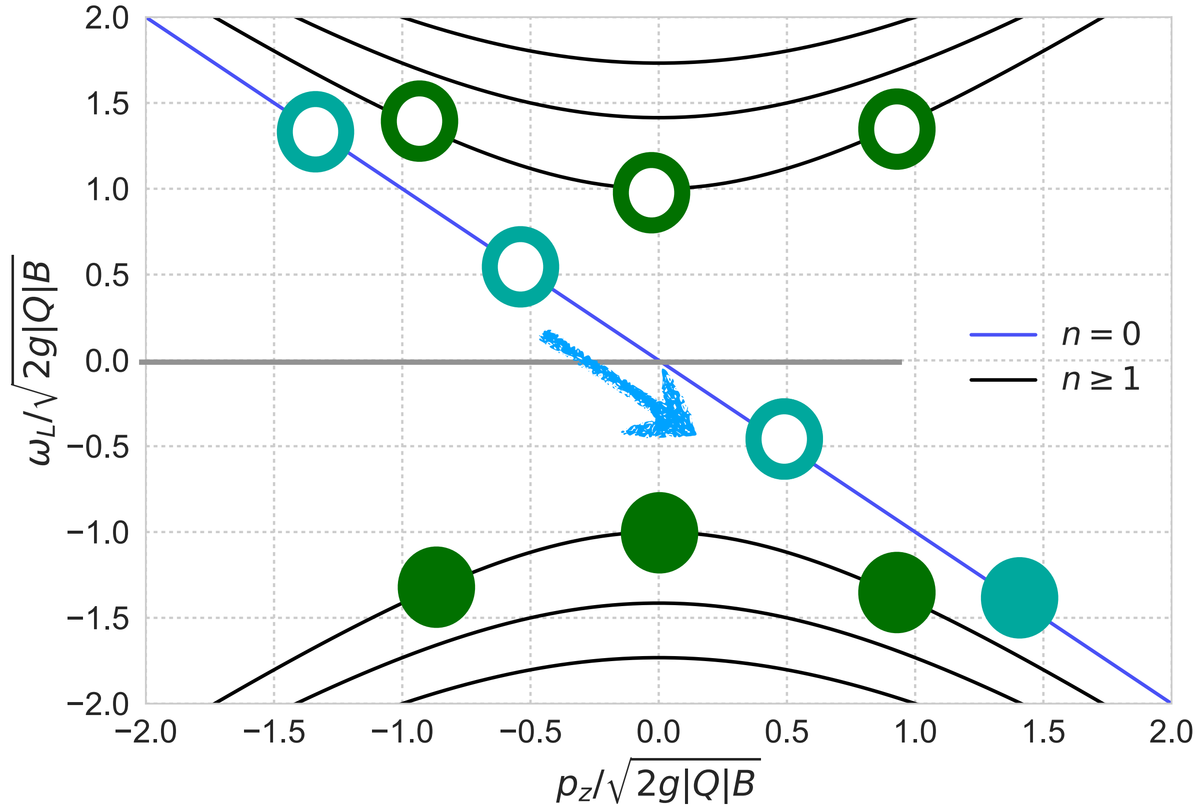


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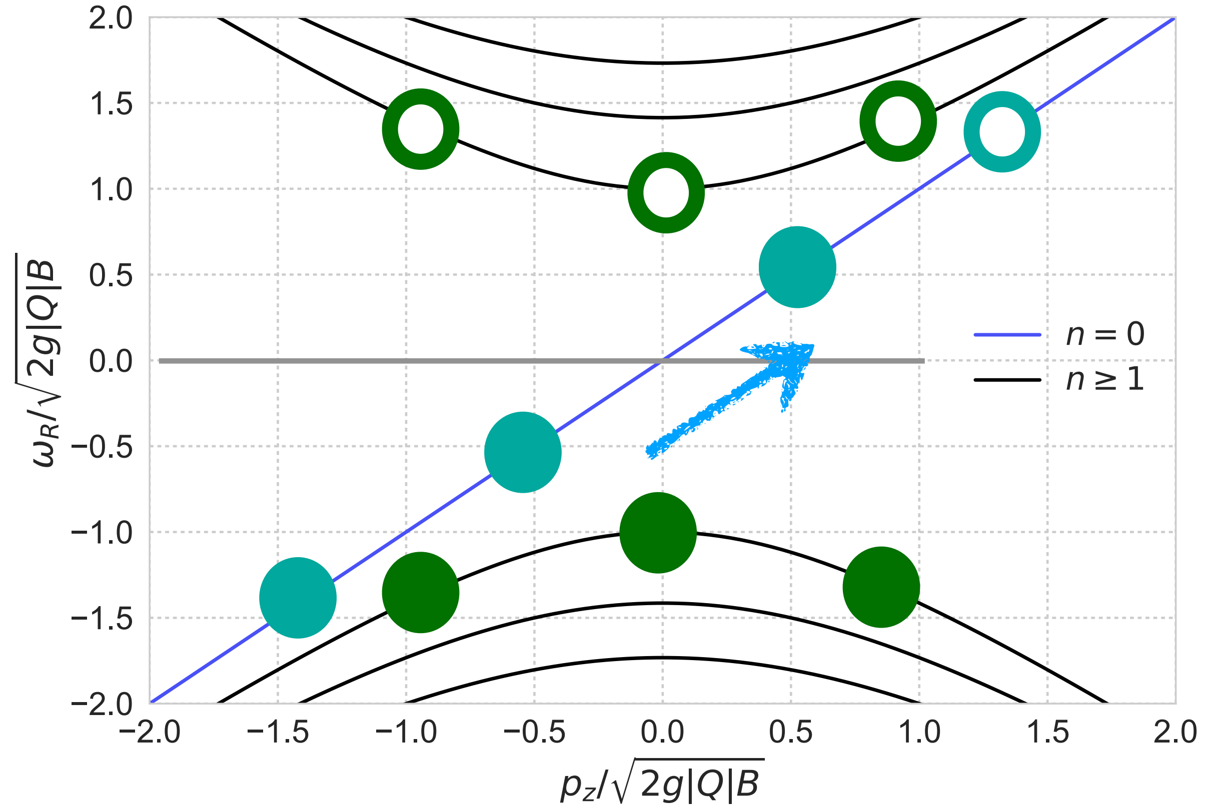


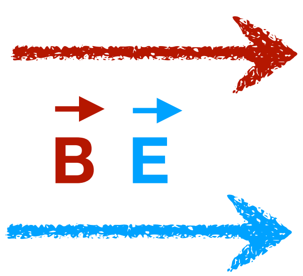


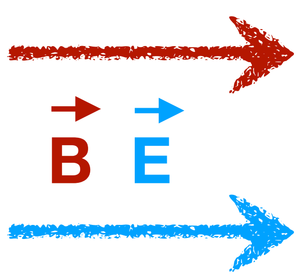


**asymmetric fermion production**

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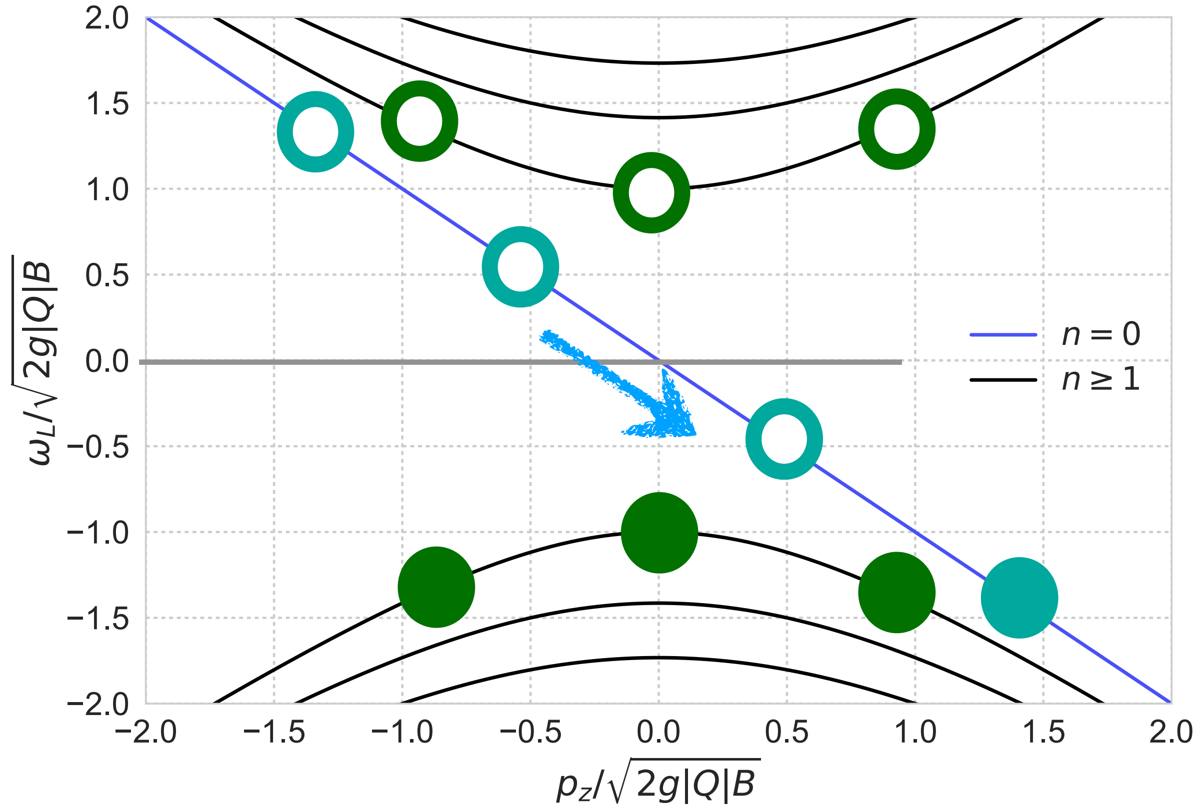


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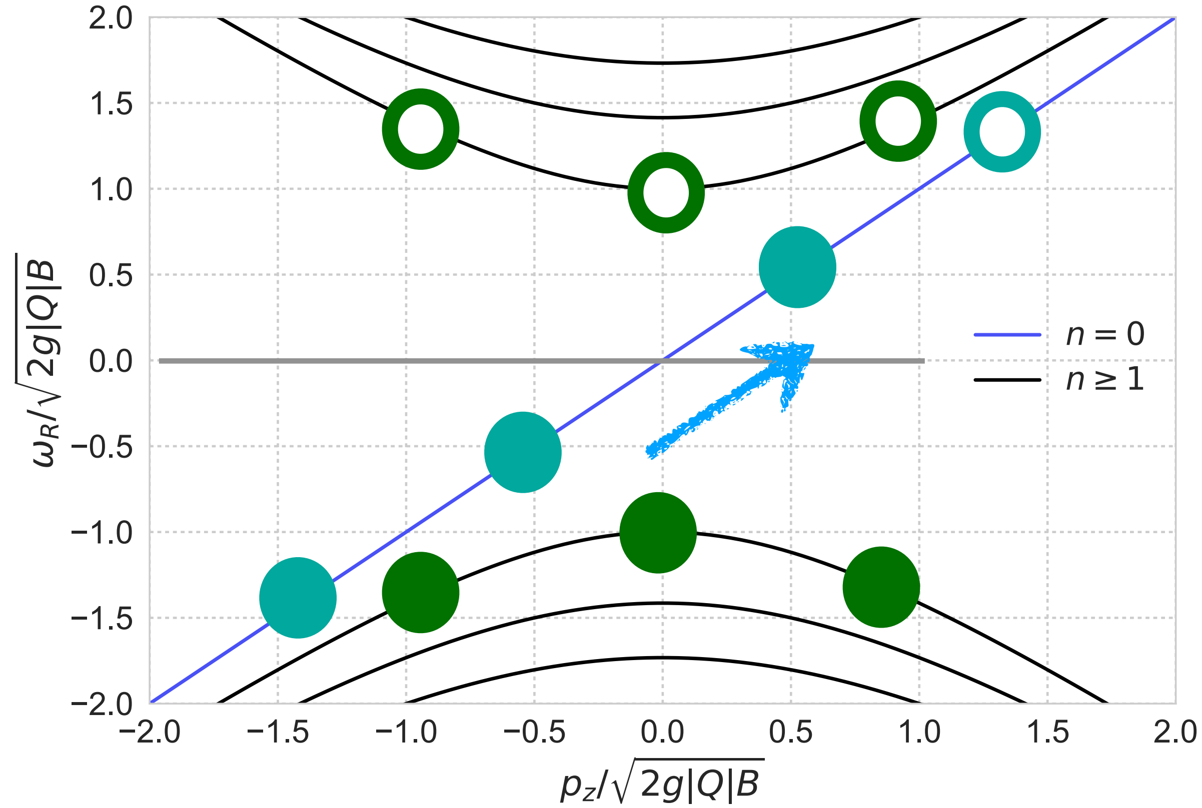
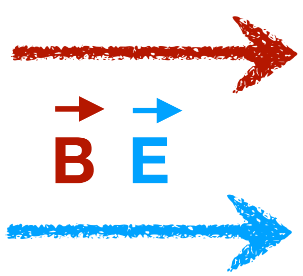
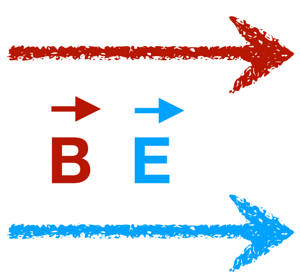



**asymmetric fermion production**

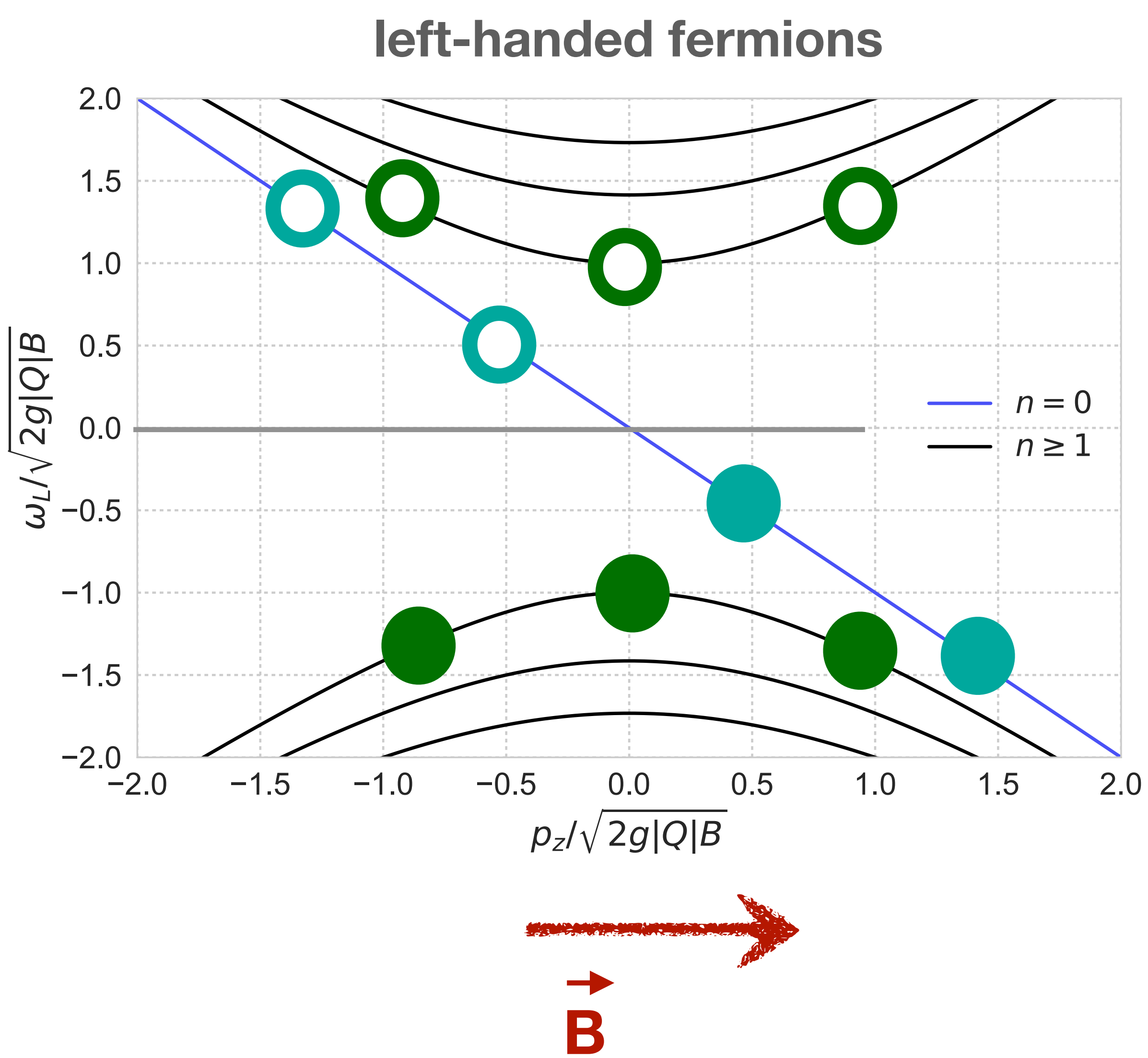
**anomaly equation !**

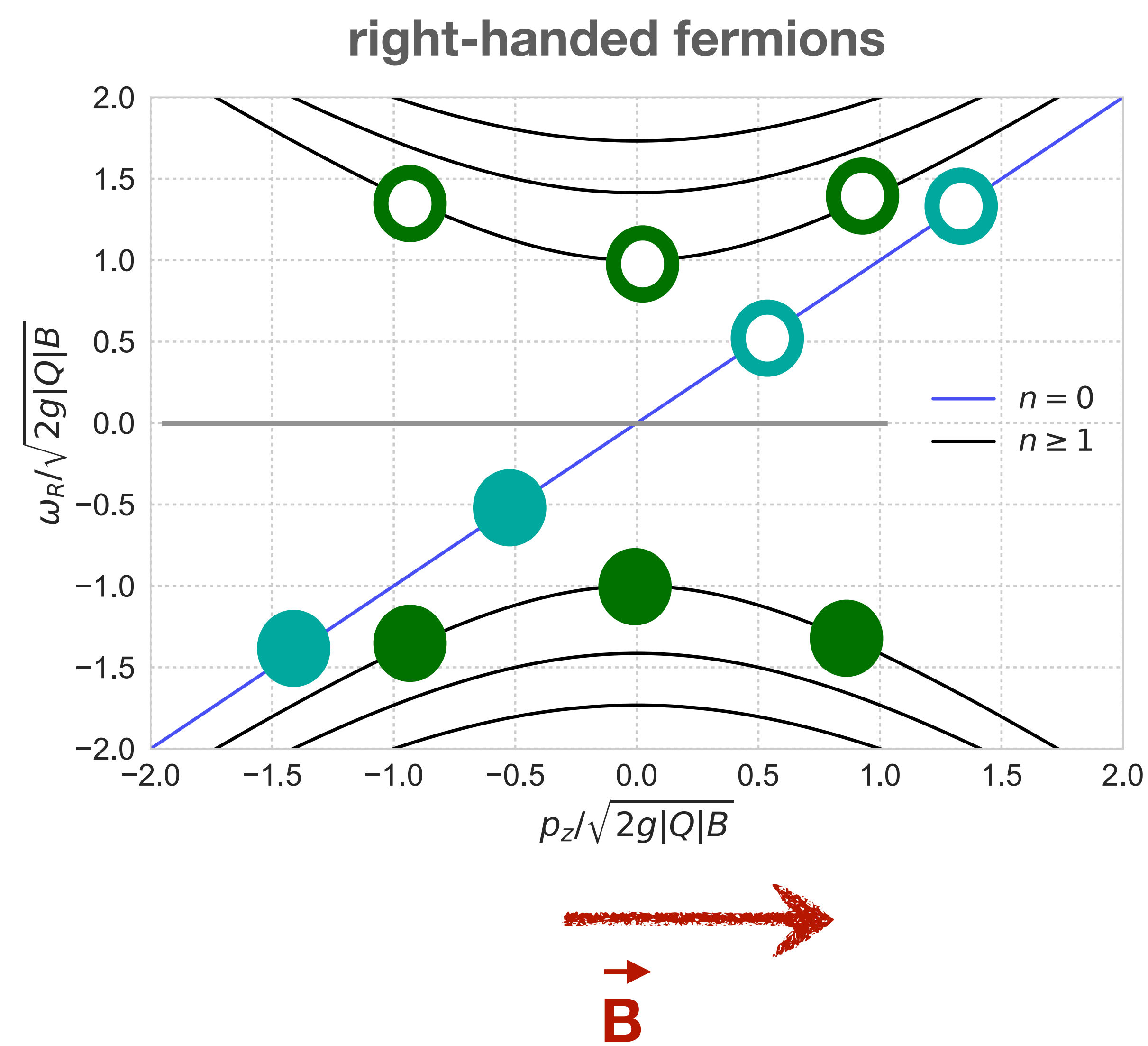
Nielsen, Ninomiya '83

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

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

# fermion production (HLL)

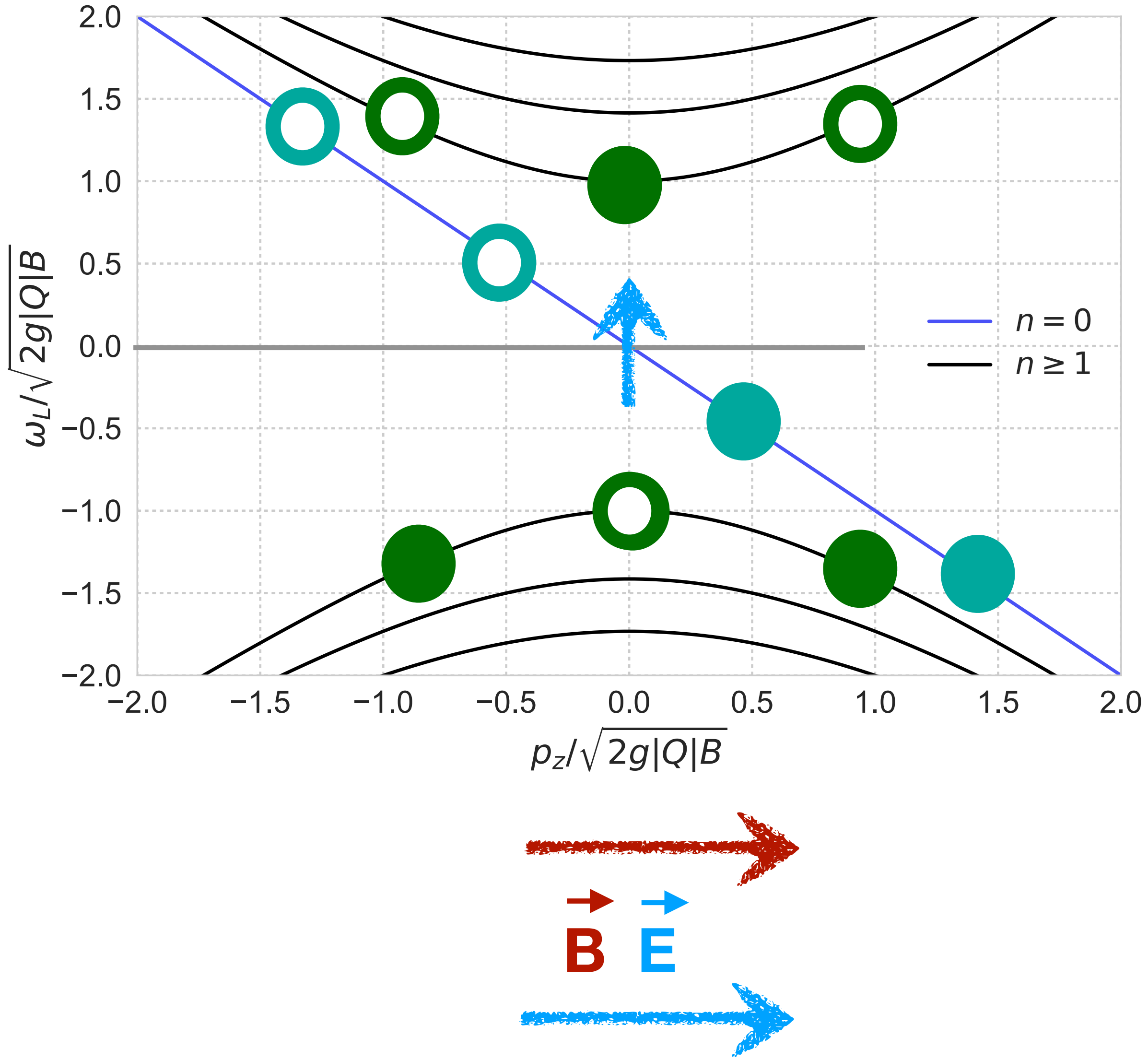


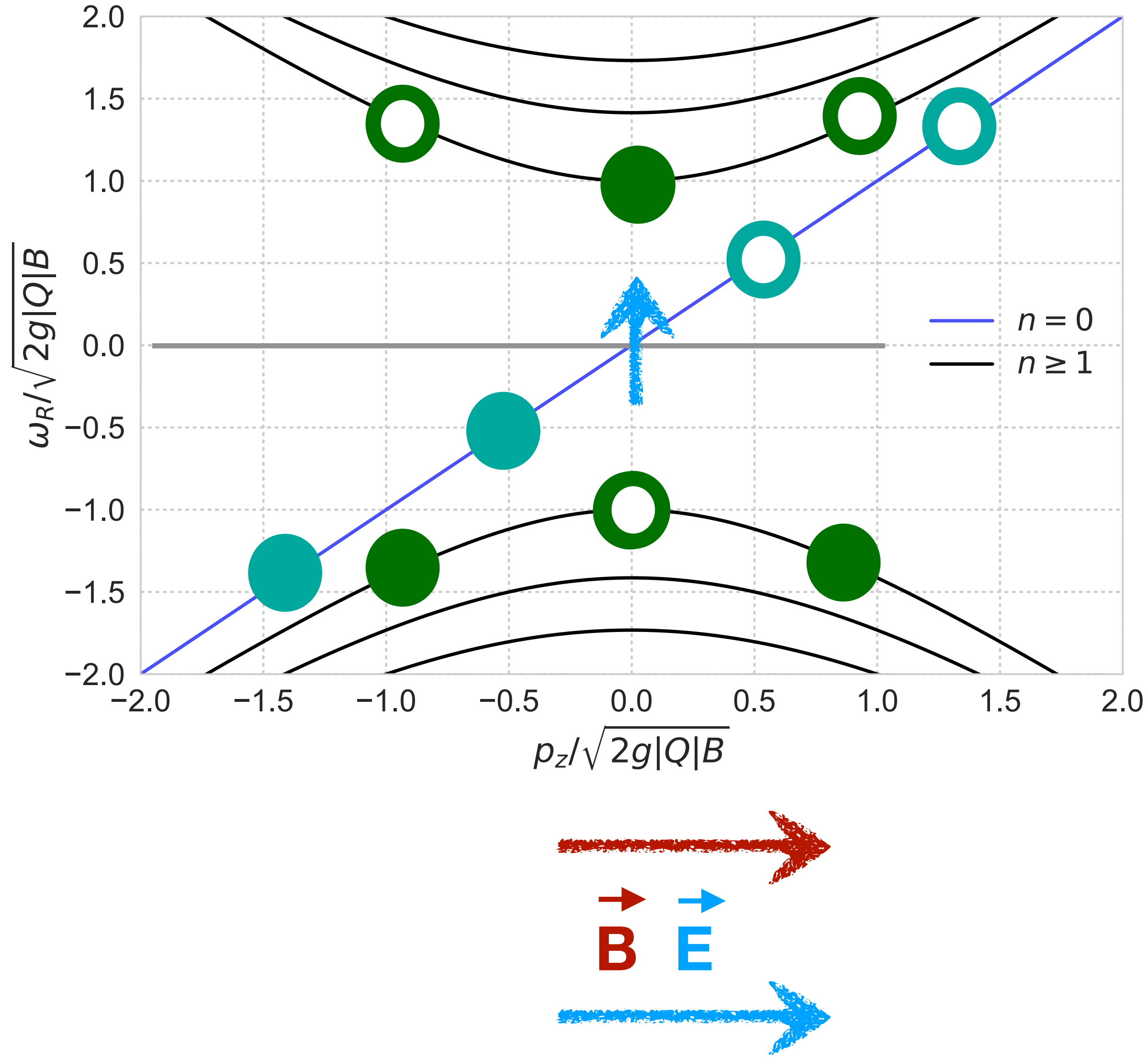

**symmetric fermion production**

# fermion production (HLL)

left-handed fermions



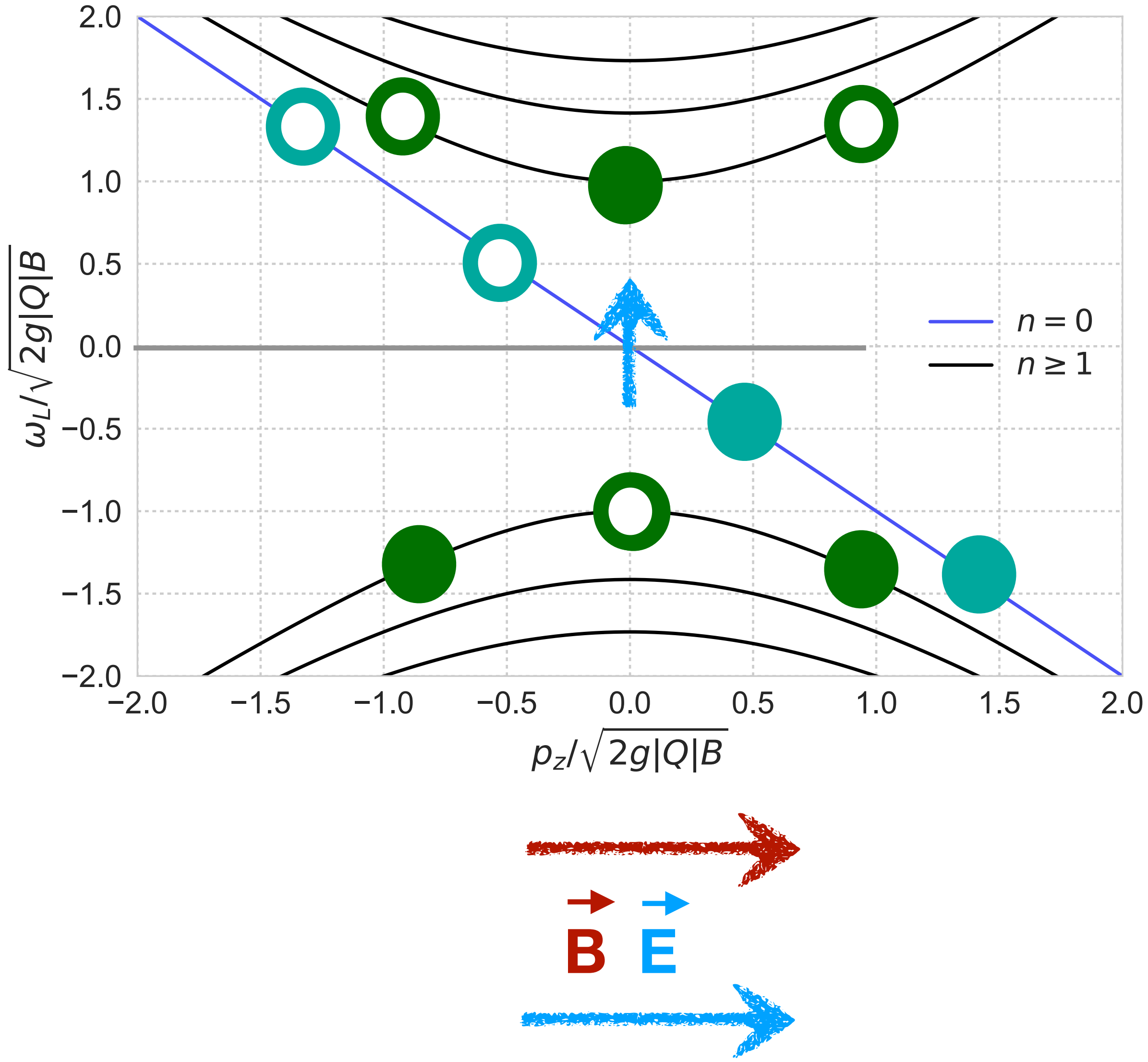

right-handed fermions



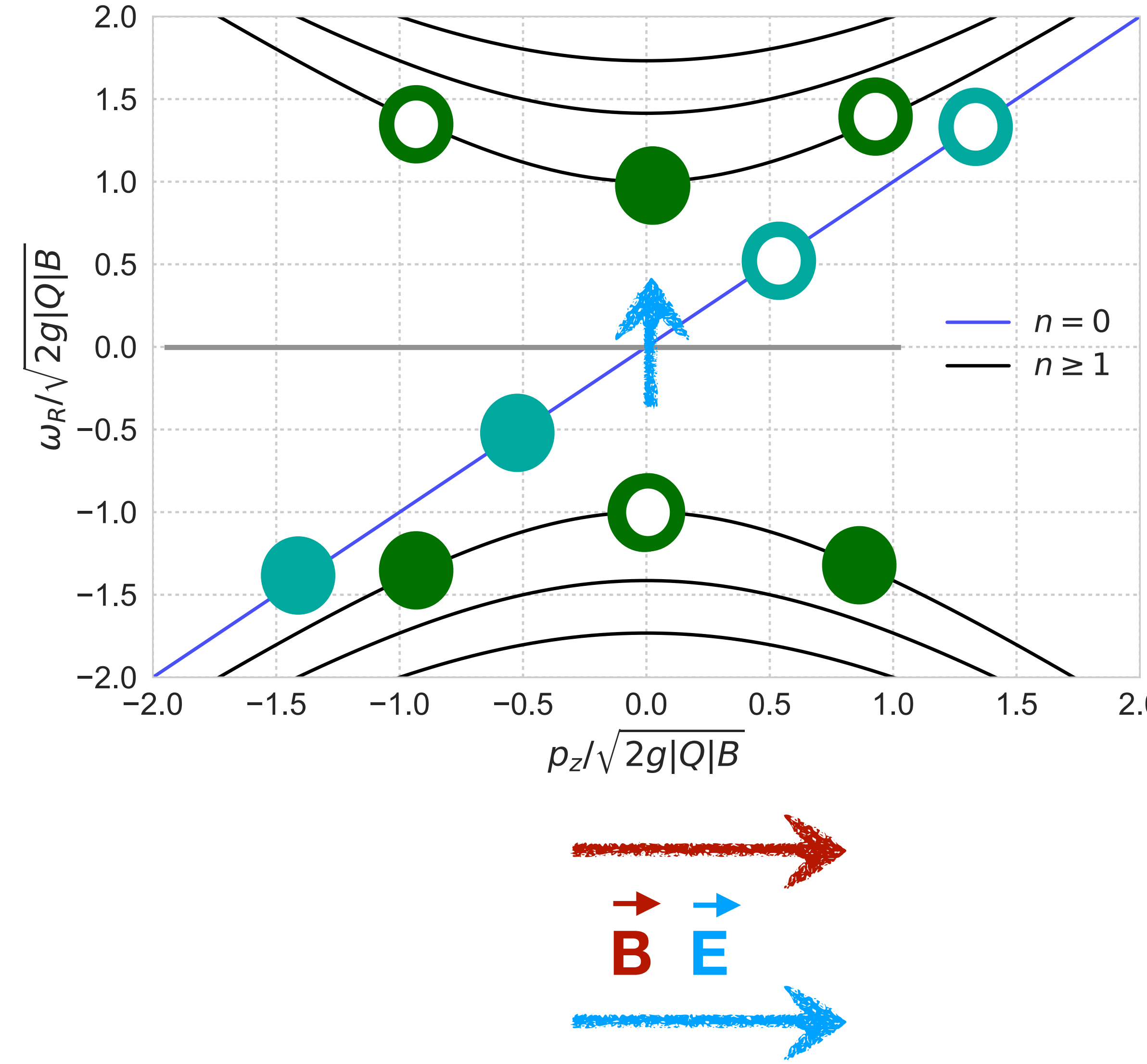

**symmetric fermion production**

# fermion production (HLL)

**left-handed fermions**




**right-handed fermions**

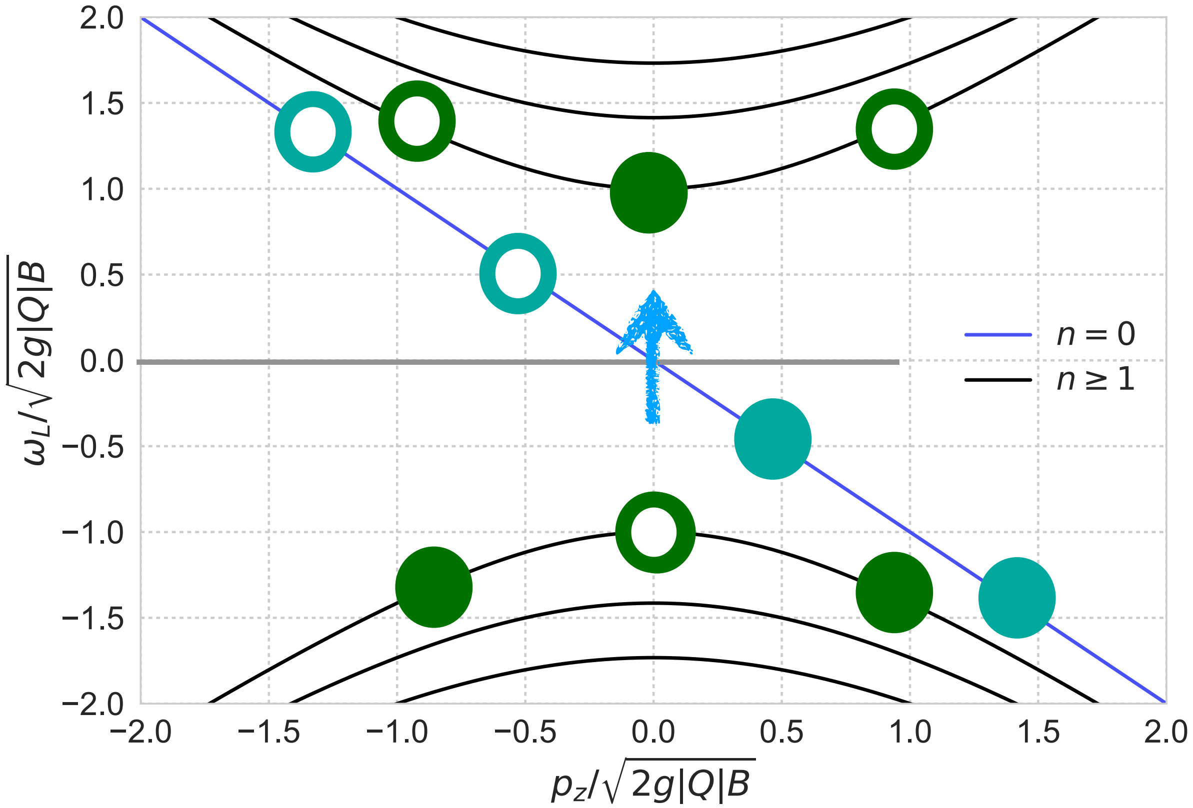



**symmetric fermion production**

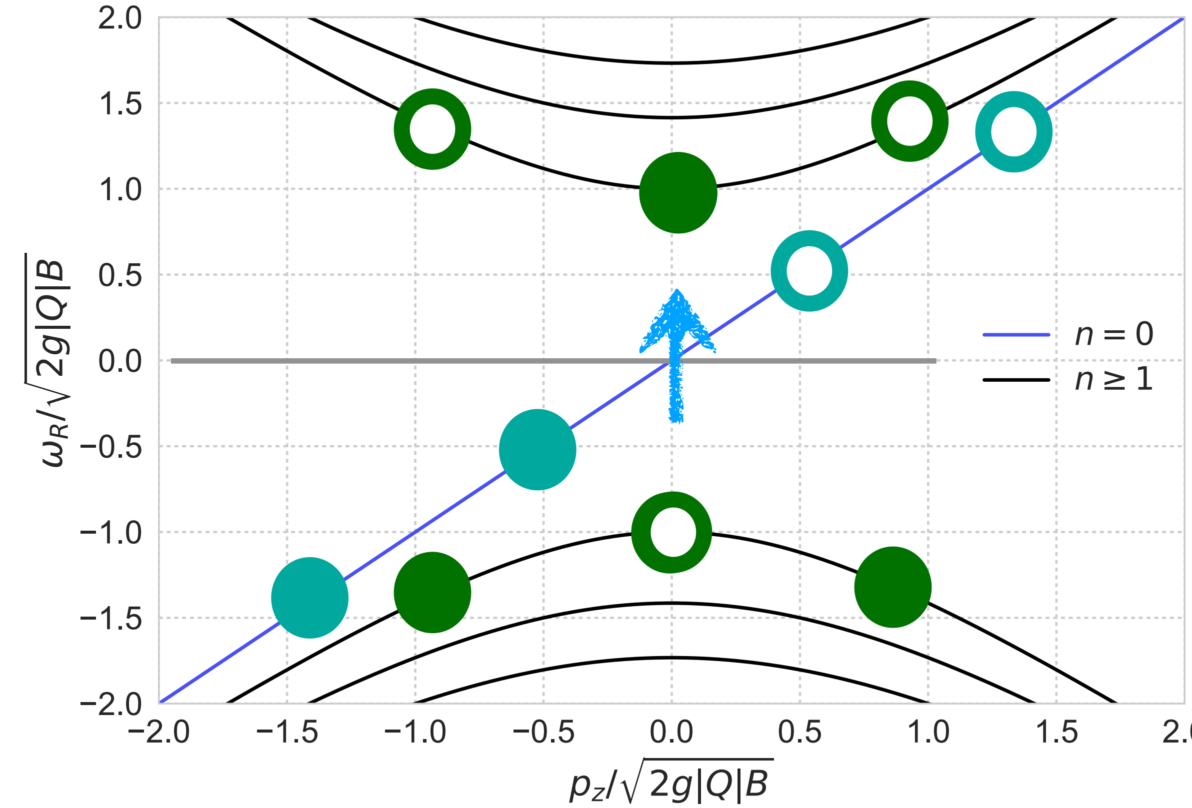
$$\dot{n}_\psi^{\mathrm{HLL}} = 4 \times \frac{g^2 Q^2}{8\pi^3}\left(E^2 - \pi E B + \frac{\pi^2}{3} B^2 + \cdots\right)$$

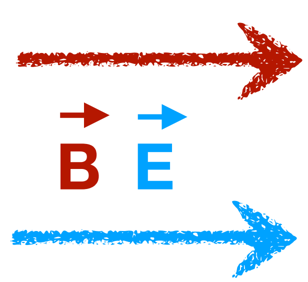
# fermion production (HLL)

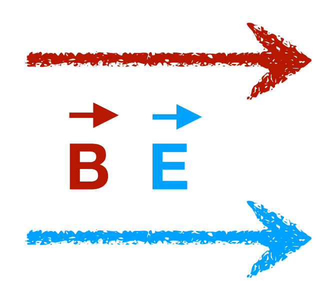
**left-handed fermions**




**right-handed fermions**




**symmetric fermion production**

**B = 0 : Schwinger production**

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

# fermion production - induced current

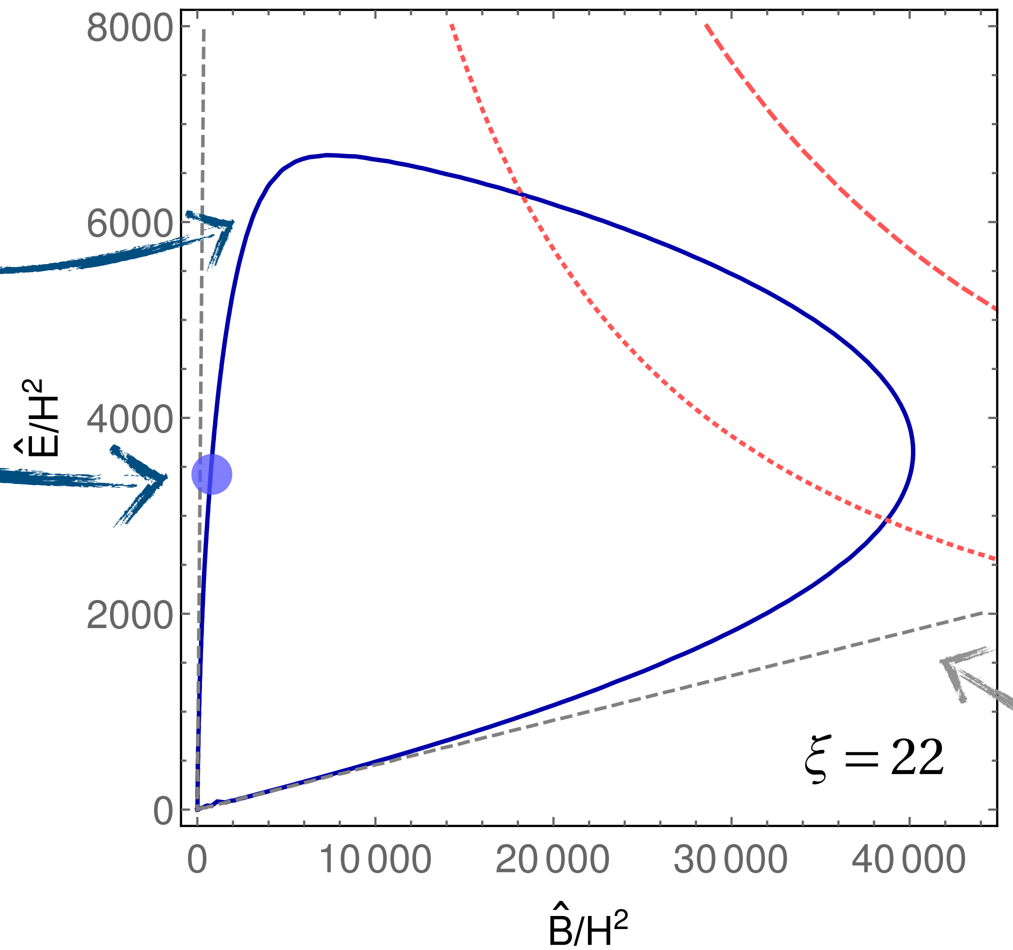
**backreaction** on gauge field production: $\Box A^\nu - \partial_\mu \left( \frac{\alpha \phi}{\pi f_a} \tilde{F}^{\mu\nu} \right) - gQ J_\psi^\nu = 0$

in **equilibrium:**

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

upper bound

estimate

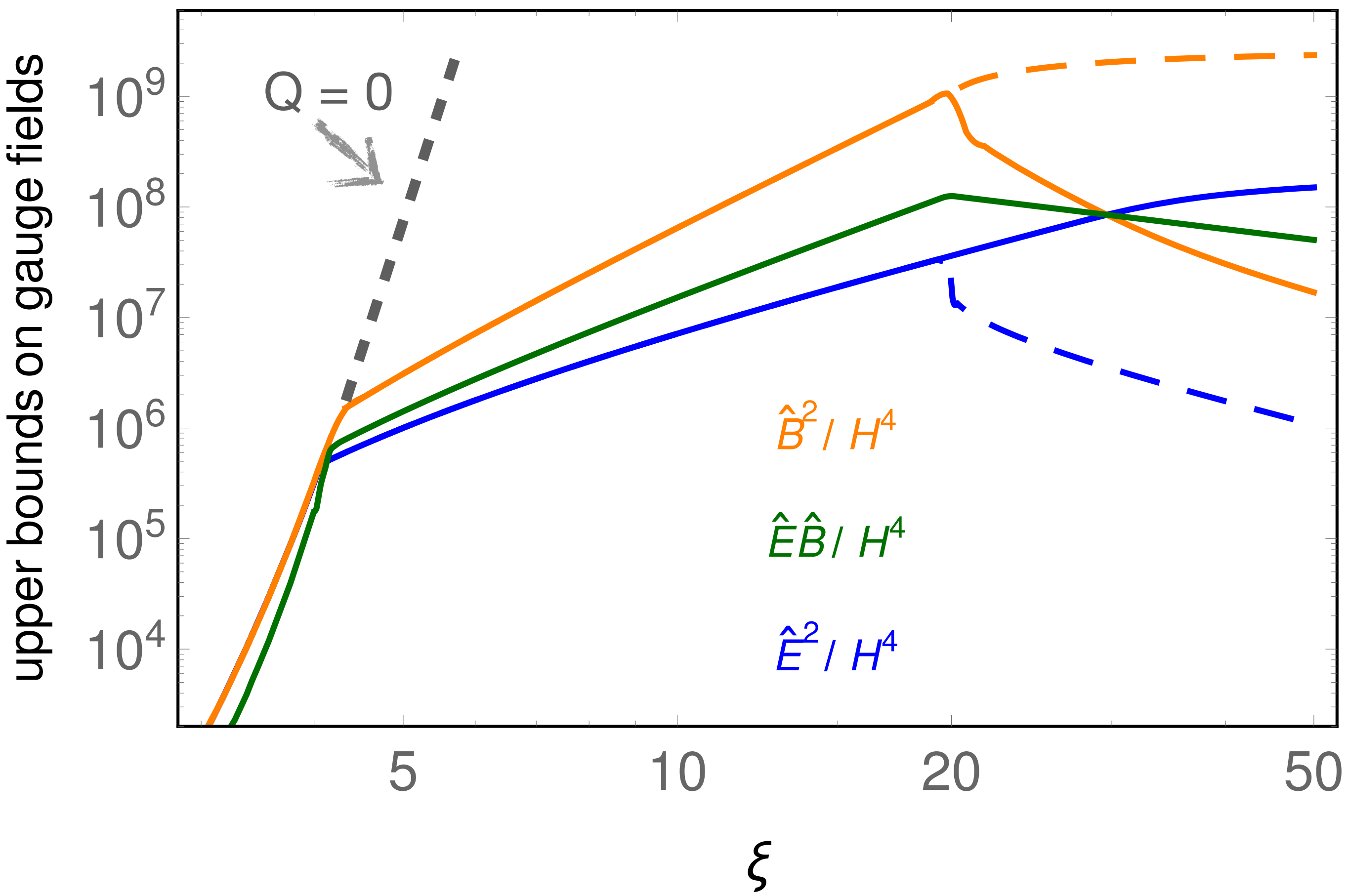



constraints from inflation with
r = 0.1
r = 0.05

Q = 0

**upper bounds on E- and B-fields**

# fermion production




**fermion production dampens gauge field production**

# PNGBs in the Early Universe

$$\phi F_{\mu\nu}\tilde{F}_{\mu\nu}$$

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

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

**explosive helical gauge boson production**

**additional friction modifies dynamics of inflation**

**additional contribution to scalar and tensor power spectrum**

↓

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

**inflation on steep potentials** Anber, Sorbo ’09

**`relaxation’ of the electro-weak scale** Hook, Marques-Tavares ’16

**polarized SGWB at LISA and LIGO** Cook, Sorbo ’11/’12, Barnaby, Pajer, Peloso ‘12

Dolgov, Freese ‘94

**chiral fermion production**

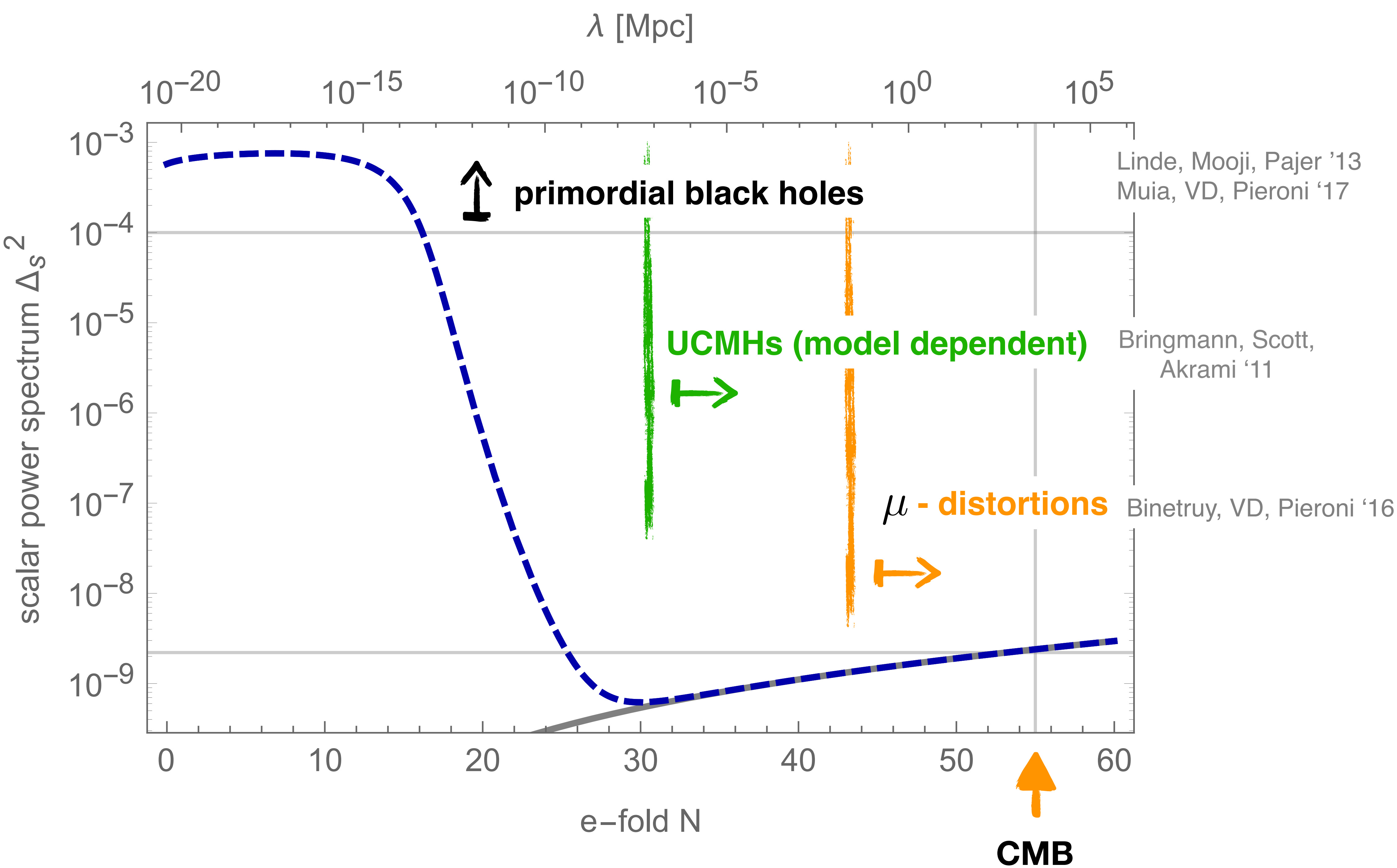
**spontaneous CPT violation**

↓

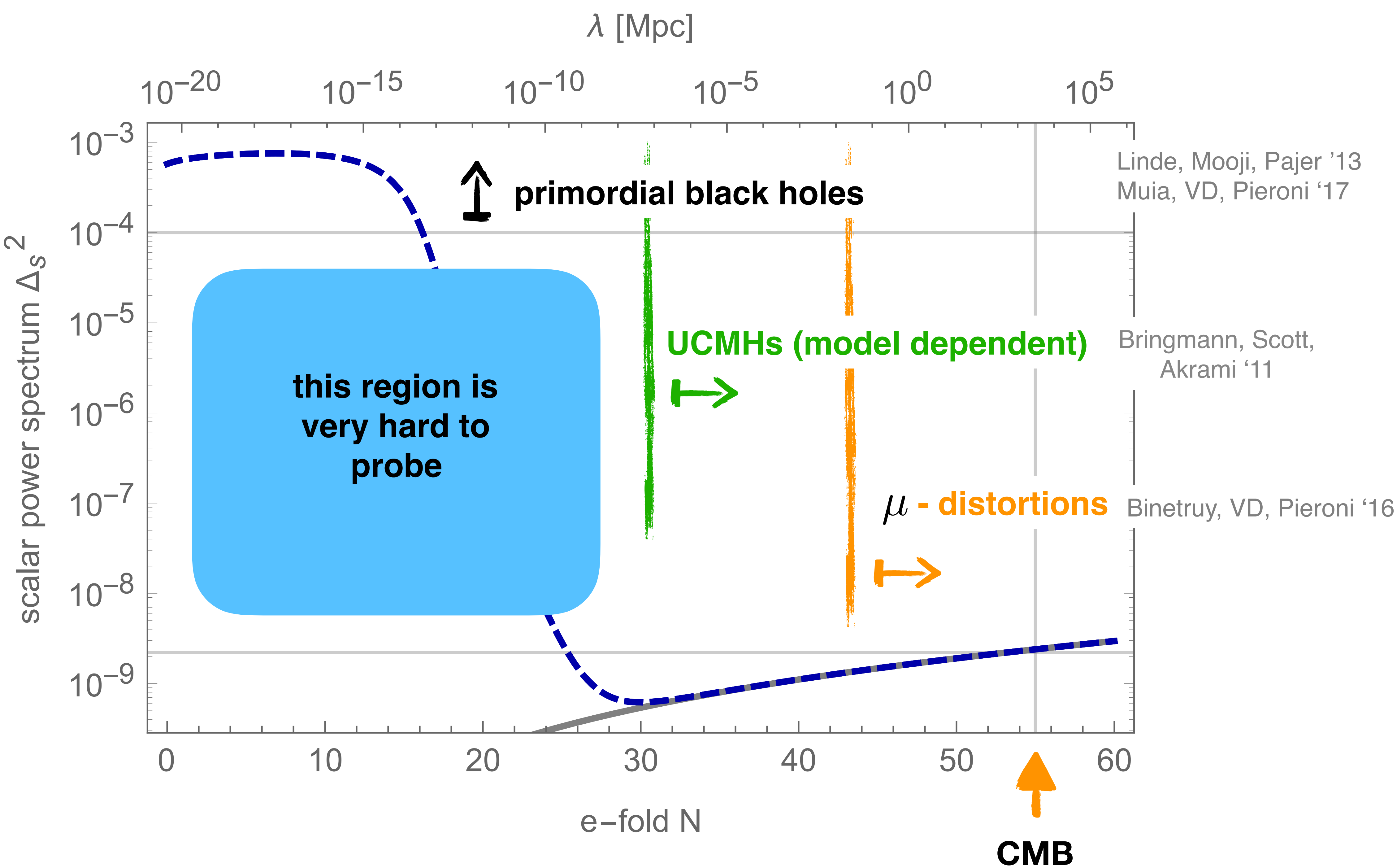
**add. contribution to scalar and tensor power spectrum** Anber, Sabancilar ’16, Adshead, Pearce, Peloso, Roberts, Sobrbo '18

**spontaneous baryogenesis** Kusenko, Schmitz, Yanagida ’14, Adshead, Sfakianakis ’15/‘16

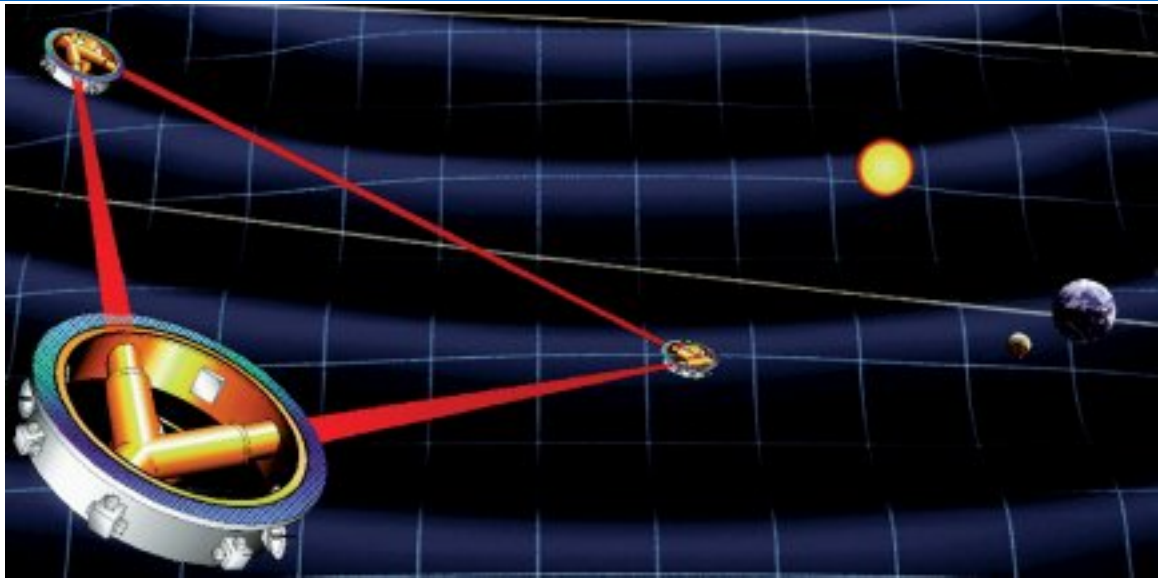
# probing the scalar power spectrum



# probing the scalar power spectrum



# probing the tensor power spectrum



signal from a single arm (return trip):

$$s_{12}(t,\vec{x}_1) - n_1(t,\vec{x}_1) = \Delta T_{12}(t-2L) + \Delta T_{21}(t-L)$$
$$= L\int d^3k\, e^{-2\pi i\vec{k}\cdot\vec{x}_1}\sum_\lambda \mathcal{I}\left(\vec{k},\hat{l}_{12}\right) h_\lambda\left(t-L,\vec{k}\right)$$

detector geometry

a stochastic gravitational wave background (SGWB):

see also [Romano, Cornish '17]

$$\left\langle h_\lambda\left(t,\vec{k}\right) h_{\lambda'}\left(t,\vec{k}'\right)\right\rangle = \frac{P_\lambda(k)}{4\pi k^3}\delta_{\lambda\lambda'}\,\delta^{(3)}\left(\vec{k}+\vec{k}'\right)$$

theory

combining the two:

noise

$$\langle s_{12}^2(t,\vec{x}_1)\rangle - \langle n_1^2(t,\vec{x}_1)\rangle = \frac{L^2}{4\pi}\int\frac{d^3k}{k^3}\sum_\lambda P_\lambda(k)\left|\mathcal{I}_\lambda(\vec{k},\hat{l}_{12}\right|^2$$

**stationary (correlated) "noise"**

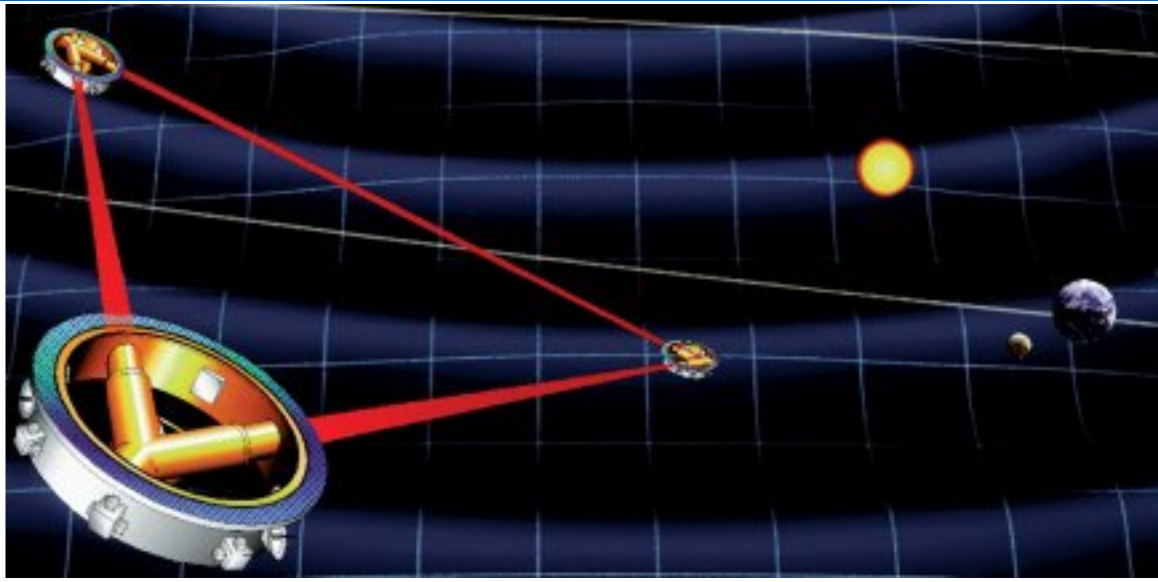
# probing the tensor power spectrum

signal from a single arm (return trip):

$$s_{12}(t,\,\vec{x}_1) - n_1(t,\,\vec{x}_1) = \Delta T_{12}(t-2L) + \Delta T_{21}(t-L)$$

$$= L\int d^3k\,\mathrm{e}^{-2\pi i\vec{k}\cdot\vec{x}_1}\sum_\lambda \mathcal{I}\left(\vec{k},\hat{l}_{12}\right) h_\lambda\left(t-L,\,\vec{k}\right)$$

detector geometry



a stochastic gravitational wave background (SGWB):

Figueroa, Ricciardone, VD, et al '18 [LISA Cosmo WG]

$$\left\langle h_{\lambda_1}\left(t,\,\vec{k}_1\right) h_{\lambda_2}\left(t,\,\vec{k}_2\right) h_{\lambda_3}\left(t,\,\vec{k}_3\right)\right\rangle = \delta^{(3)}\left(\vec{k}_1+\vec{k}_2+\vec{k}_3\right)\mathcal{B}_{\lambda_1,\lambda_2,\lambda_3}\left(\vec{k}_1,\vec{k}_2,\vec{k}_3\right)$$

theory

combining the two:

noise

$$\langle s_{12}^3(t,\,\vec{x}_1)\rangle - \langle n_1^3(t,\,\vec{x}_1)\rangle = L^3\int d^3k_1\int d^3k_2\int d^3k_3\,\delta^{(3)}\left(\vec{k}_1+\vec{k}_2+\vec{k}_3\right)\sum_{\lambda_1,\lambda_2,\lambda_3}\mathcal{B}_{\lambda_1,\lambda_2,\lambda_3}\left(\vec{k}_1,\vec{k}_2,\vec{k}_3\right)\prod_{i=1}^{3}\mathcal{I}_{\lambda_i}(\vec{k}_i,\,\hat{l}_{12})$$

**stationary (correlated) "noise"**

detector response

# probing the tensor power spectrum

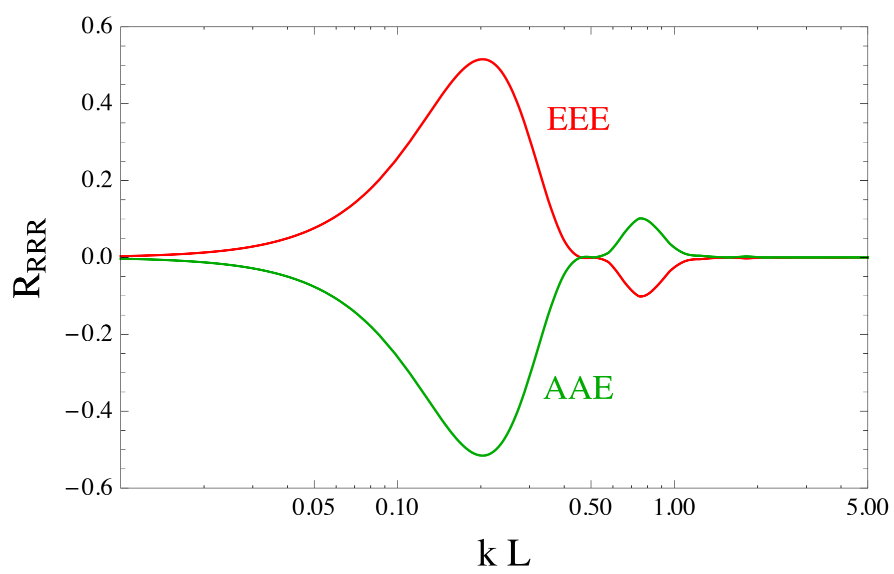
**LIGO/LISA will soon detect a SGWB  (from unresolved BH - BH mergers).**

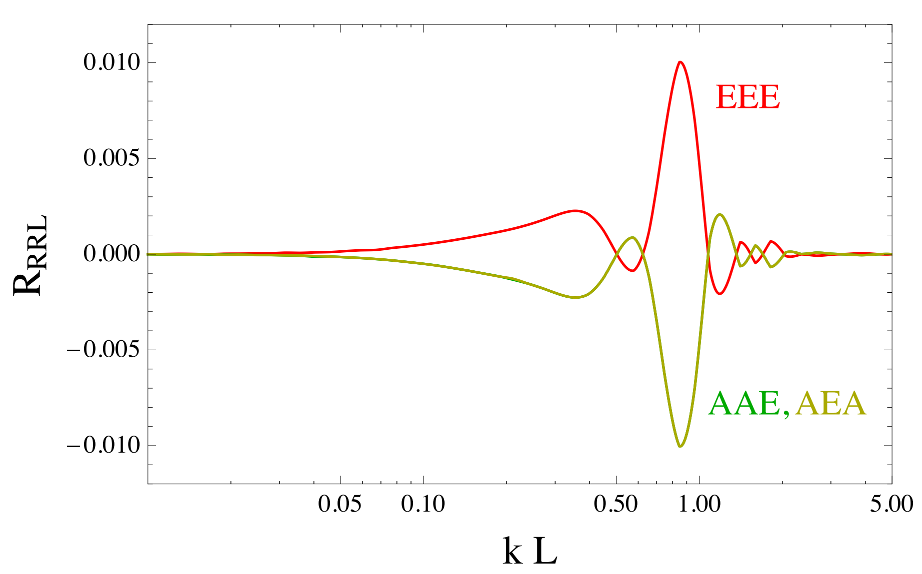
➜ **We need to measure its properties (spectral shape, polarization, non-gaussianity)**

**Consider LISA:**

2-pt instrument response cannot measure polarization  Smith, Caldwell '17

3-pt instrument response to different GW helicities:




Figueroa, Ricciardone, VD, et al '18 [LISA Cosmo WG]

**non-gaussianity and helicity information (in principle) accessible**