Kobayashi-Maskawa Institute
for the Origin of
Particles and the Universe

# To $B$ or not to $B$:

## Primordial magnetic fields from Weyl anomaly and Beyond

Takeshi Kobayashi

based on arXiv: 1808.08237 w/ A. Benevides, A. Dabholkar
arXiv: 1903.02561 w/ M. Sloth

C-E joint seminar, November 2019

# Are photons gravitationally produced in the early universe?

cf. inflaton, gravitons

# CLASICALLY, NO

$$\mathcal{L} = -\frac{1}{4}\sqrt{-g}\, F_{\mu\nu}F^{\mu\nu}$$

invariant under Weyl transformation: $g_{\mu\nu} \to \Omega^2 g_{\mu\nu}$

Photons do not feel gravity in an FRW universe.

# BUT QUANTUM MECHANICALLY ...

Weyl symmetry is anomalous.

$$\mathcal{L} = -\frac{1}{4}\sqrt{-g}\, F_{\mu\nu} F^{\mu\nu}$$

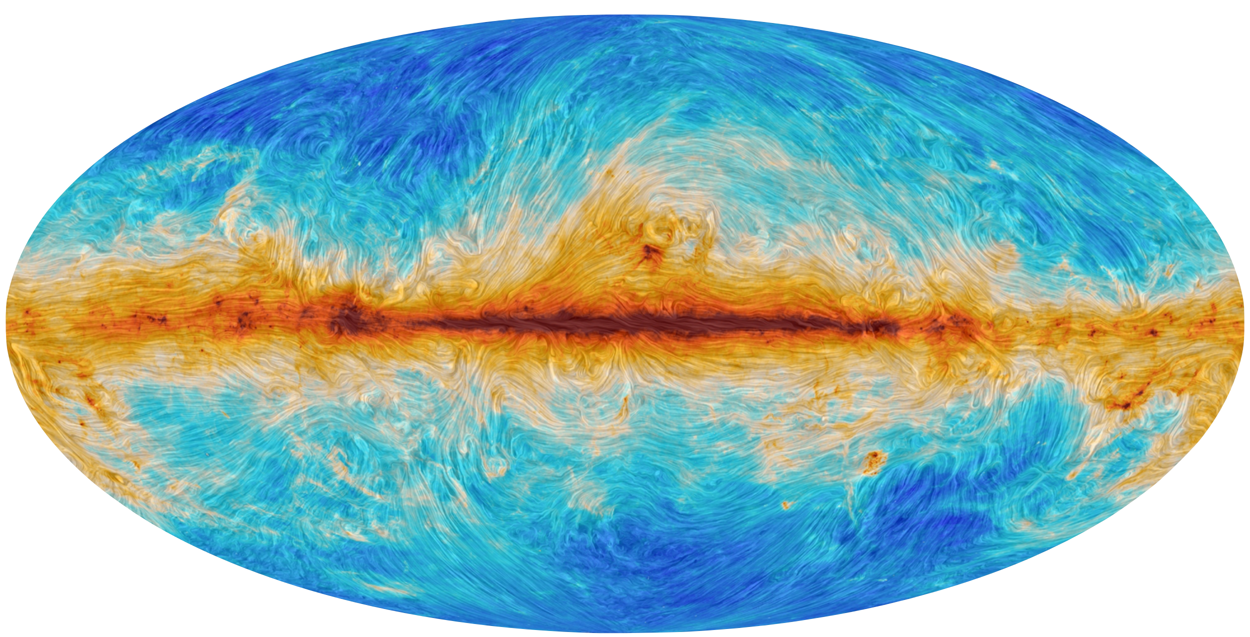
~~invariant~~ under Weyl transformation: $g_{\mu\nu} \to \Omega^2 g_{\mu\nu}$

Photons DO feel gravity in an FRW universe.

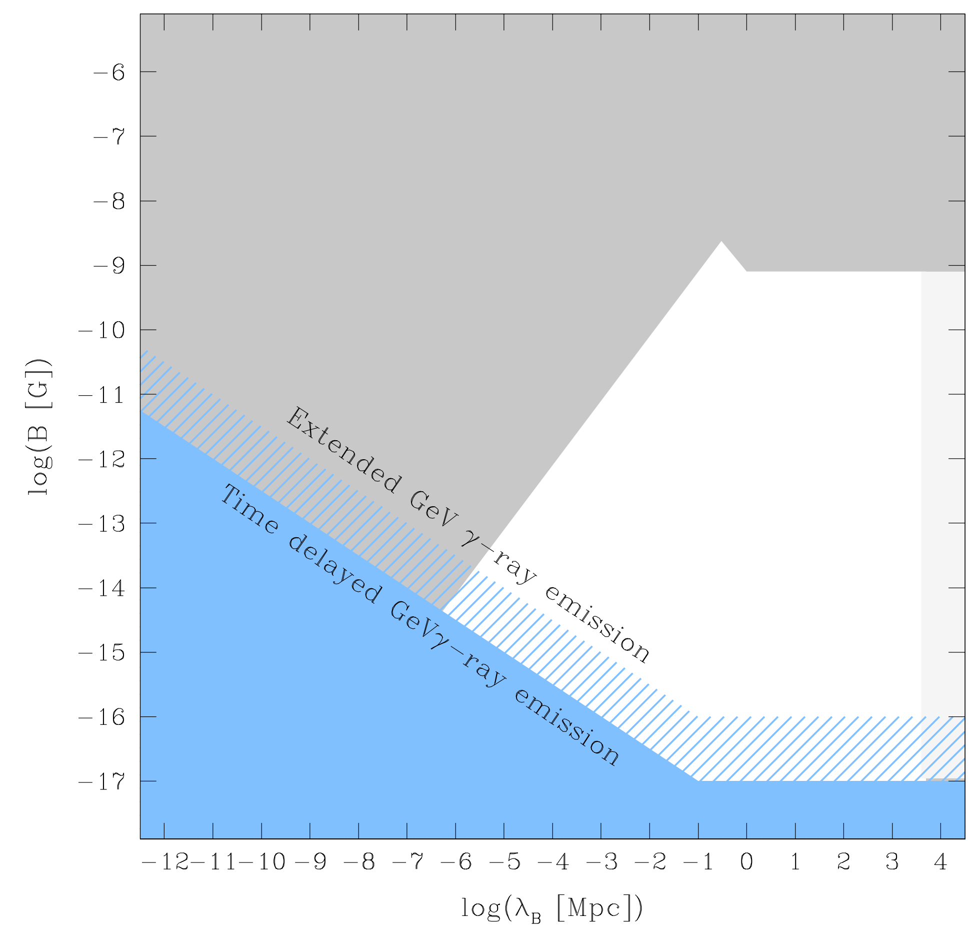
# IMPLICATIONS FOR OUR UNIVERSE

cosmological photon production

→ primordial magnetic fields



ESA and the Planck Collaboration




Durrer and Neronov, Astron.Astrophys.Rev. 21(2013)62

galactic $B$

seed field of $B \sim 10^{-20}\mathrm{G}$

(hints of) extragalactic $B$

$B \gtrsim 10^{-15}\mathrm{G}$ at $\gtrsim \mathrm{Mpc}$

# PRIMORDIAL $B$ FROM WEYL ANOMALY

- Intrinsic to the SM, so the produced $B$ (if any) serves as an irreducible contribution to the $B$ of our universe
- Many studies on this topic since Dolgov '93, but with little consensus on the $B$ strength

# PRIMORDIAL $B$ FROM WEYL ANOMALY

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- I will show that there is actually NO $B$ from Weyl anomaly

# PLAN OF THE TALK

- Primordial $B$ from Weyl Anomaly

    1. quantum effective action in curved space

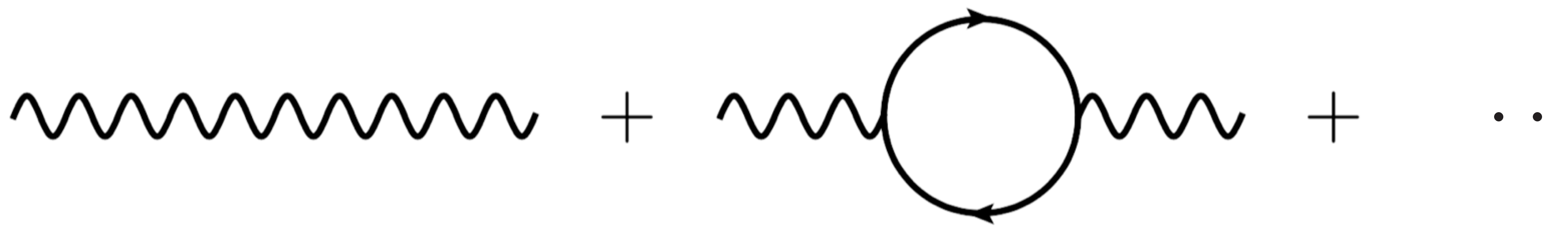
    2. quantum/classical nature of photons

- Primordial $B$ from beyond-SM

$B$ from Weyl Anomaly:

Quantum Effective Action

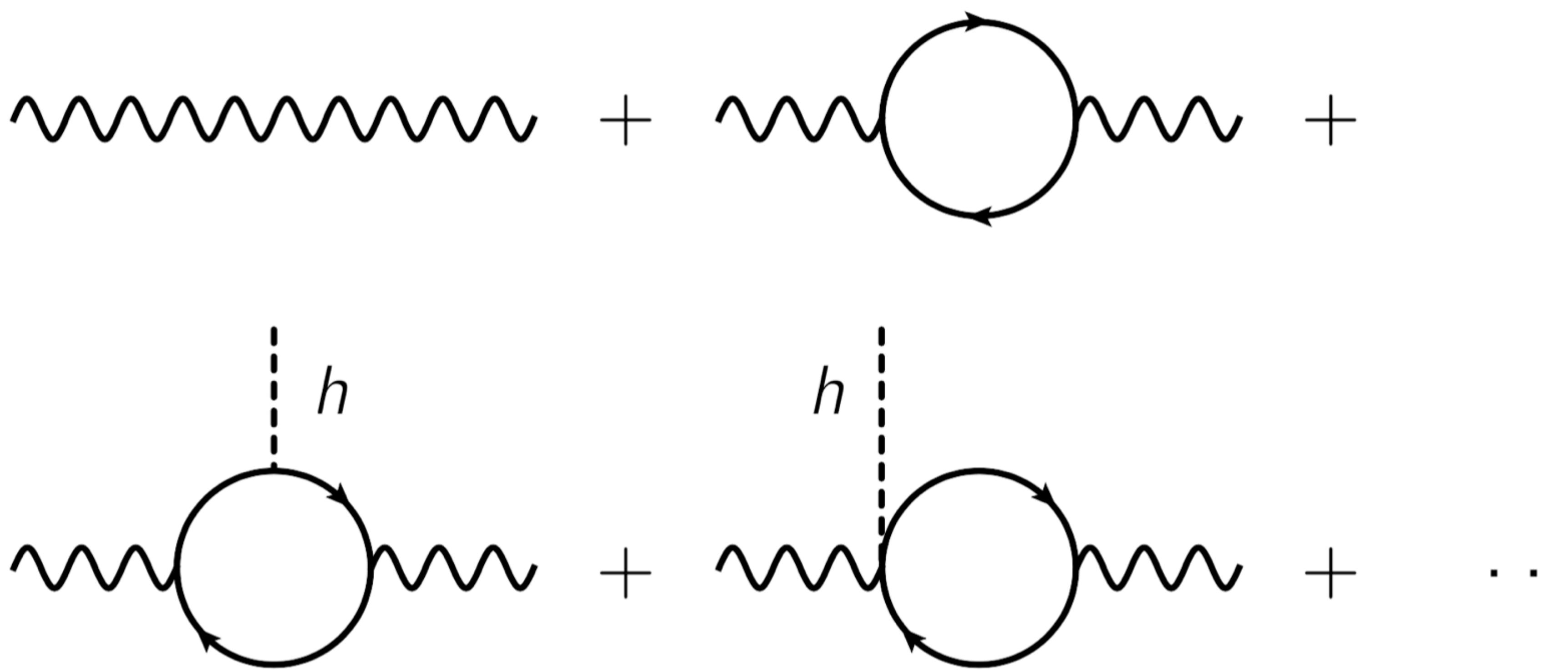
# QED EFFECTIVE ACTION IN FLAT SPACE



$$S = -\frac{1}{4e^2} \int d^4x \, F_{\mu\nu} \left[ 1 - \tilde{\beta} \log \left( \frac{-\partial^2}{M^2} \right) \right] F^{\mu\nu}$$

$$\tilde{\beta} = \frac{d \log e}{d \log M} > 0$$

# QED EFFECTIVE ACTION IN CURVED SPACE




Barvinsky, Vilkovisky '83 ~

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

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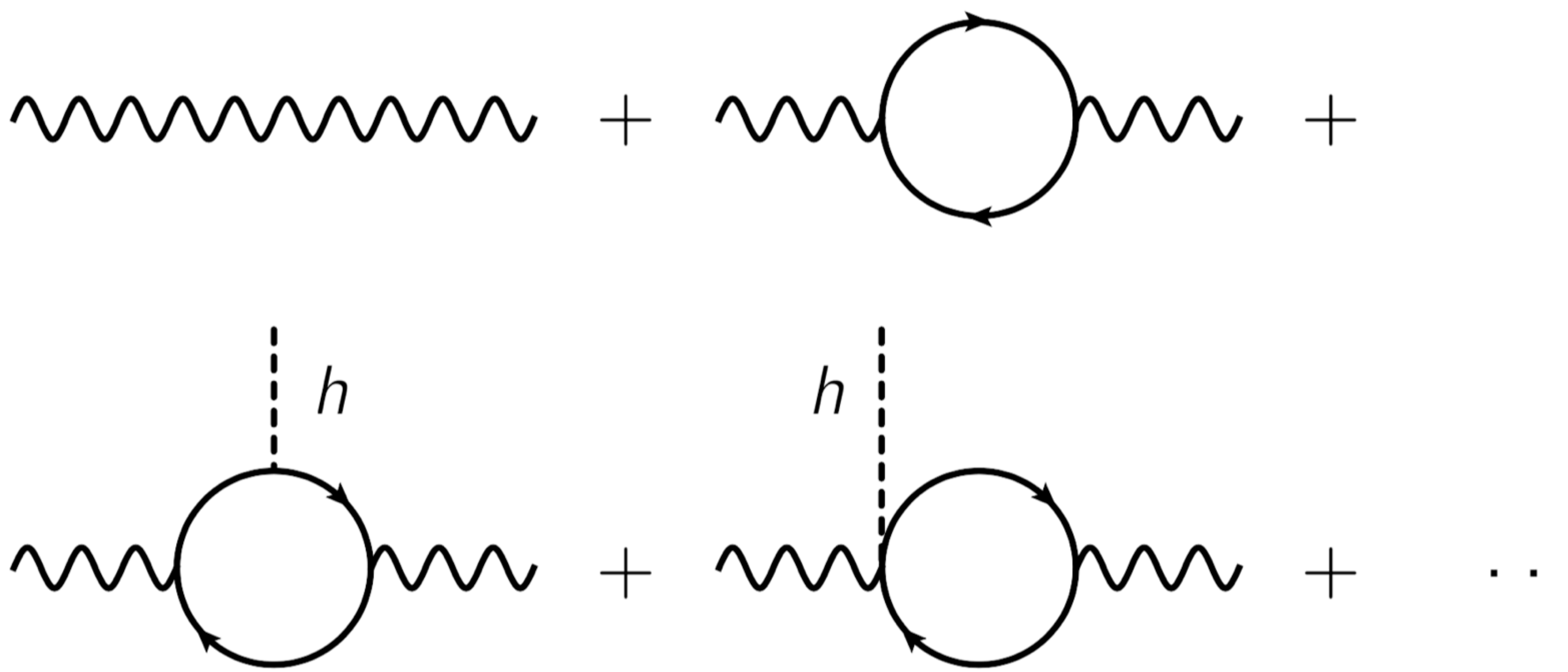


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Perturbative expansion valid if $R^2 \ll \nabla^2 R,$

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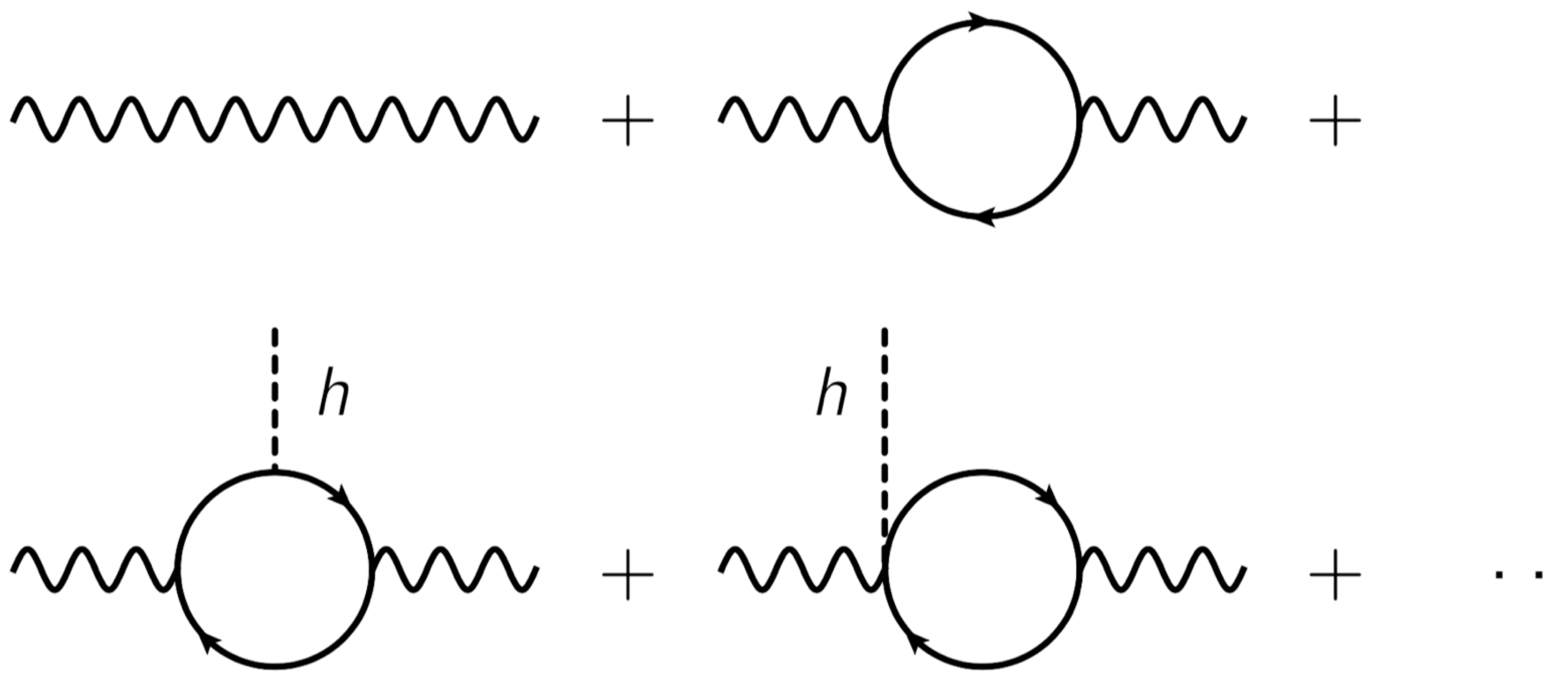



Barvinsky, Vilkovisky '83 ~

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

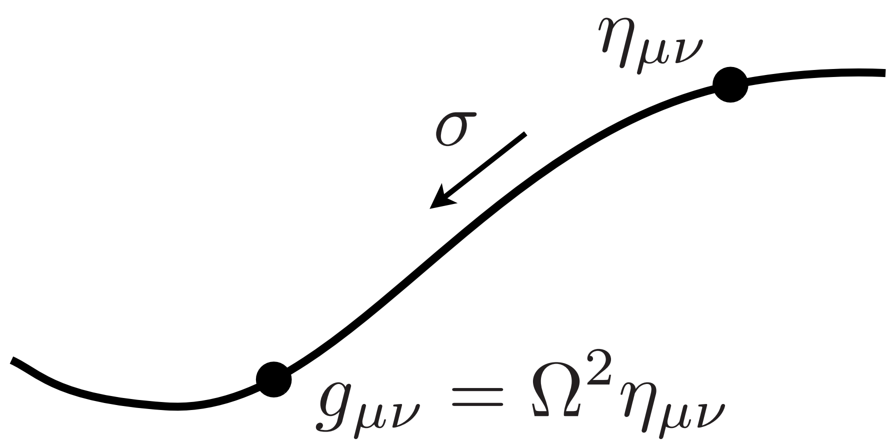
Perturbative expansion valid if $R^2 \ll \nabla^2 R$,

which is NOT the case in cosmology.

# BEYOND WEAK GRAVITY

Curvature expansion can be resummed to all orders for classically Weyl-invariant theories in Weyl-flat spacetimes.

Bautista, Benevides, Dabholkar '17




$$S[g, A] = S_{\text{flat}}[\eta, A] + \int_0^1 d\sigma \int d^4x \sqrt{-\Omega^{2\sigma}\eta}\, (\log \Omega)\, \mathcal{B}\left[\Omega^{2\sigma}\eta, A\right]$$

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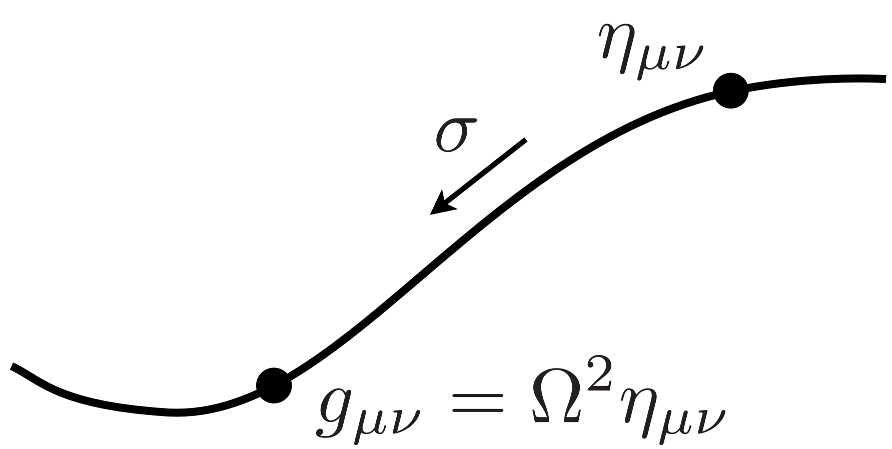


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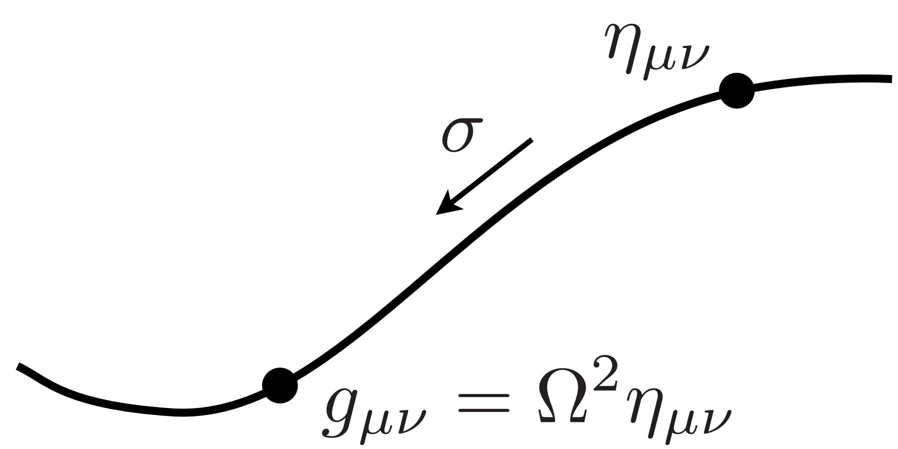


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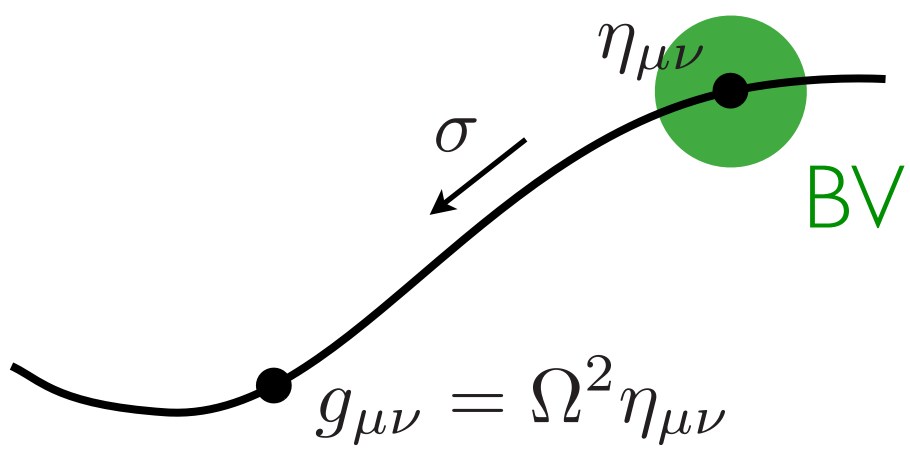


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# COMPARISON TO CURVATURE EXPANSION

$$S[g,A] = -\frac{1}{4e^2}\int d^4x\sqrt{|g|}\,\Bigg\{F_{\mu\nu}F^{\mu\nu} - \tilde{\beta}\,\Bigg[F^{\mu\nu}\log\left(\frac{-\nabla^2}{M^2}\right)F_{\mu\nu} + \frac{1}{3}\,F^2\frac{1}{\nabla^2}R$$

$$+ 4R^{\mu\nu}\frac{1}{\nabla^2}\left(\log\left(\frac{-\nabla^2}{M^2}\right)\left(F_{\mu\sigma}F_{\nu}{}^{\sigma} - \frac{1}{4}g_{\mu\nu}F^2\right) - F_{\mu\sigma}\log\left(\frac{-\nabla^2}{M^2}\right)F^{\sigma}_{\nu}\right.$$

$$\left. + \frac{1}{4}g_{\mu\nu}F^{\alpha\beta}\log\left(\frac{-\nabla^2}{M^2}\right)F_{\alpha\beta}\right) - \frac{1}{3}RF^{\mu\nu}\frac{1}{\nabla^2}F_{\mu\nu} + W^{\alpha}{}_{\beta\mu\nu}F_{\alpha}{}^{\beta}\frac{1}{\nabla^2}F^{\mu\nu}\Bigg]$$

$$+ 4\,\tilde{\beta}'\,F^{\mu\nu}F_{\alpha}{}^{\beta}\frac{1}{\nabla^2}W^{\alpha}{}_{\beta\mu\nu}\Bigg\} + \mathcal{O}(\mathcal{R}^4)$$

Barvinsky, Gusev, Vilkovisky, Zhytnikov '94
Donoghue, El-Menoufi '15

In Weyl-flat spacetimes,

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Barvinsky, Gusev, Vilkovisky, Zhytnikov '94
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Weyl invariant

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$$\log\Omega = -\frac{1}{6}\frac{1}{\nabla^2}R + \mathcal{O}(R^2)$$

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Barvinsky, Gusev, Vilkovisky, Zhytnikov '94
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Weyl invariant

$$\log\Omega = -\frac{1}{6}\frac{1}{\nabla^2}R + \mathcal{O}(R^2)$$

match in the weak field limit

In Weyl-flat spacetimes,

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# FRW BACKGROUND

$$ds^2 = a(\tau)^2 \left(-d\tau^2 + d\boldsymbol{x}^2\right)$$

$$S = -\frac{1}{4}\int d^4x\, d^4y\, \mathcal{I}^2(x,y)\, F_{\mu\nu}(x) F^{\mu\nu}(y)$$

$$\mathcal{I}^2(x,y) = \frac{1}{e^2}\int \frac{d^4k}{(2\pi)^4} e^{ik\cdot(x-y)} \left[1 - \tilde{\beta}\log\left(\frac{k^2}{a(\tau)^2 M^2}\right)\right]$$

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logarithmic running of coupling with physical momentum $k/a$

→ logarithmic dependence on $a$

## $B$ from Weyl Anomaly:

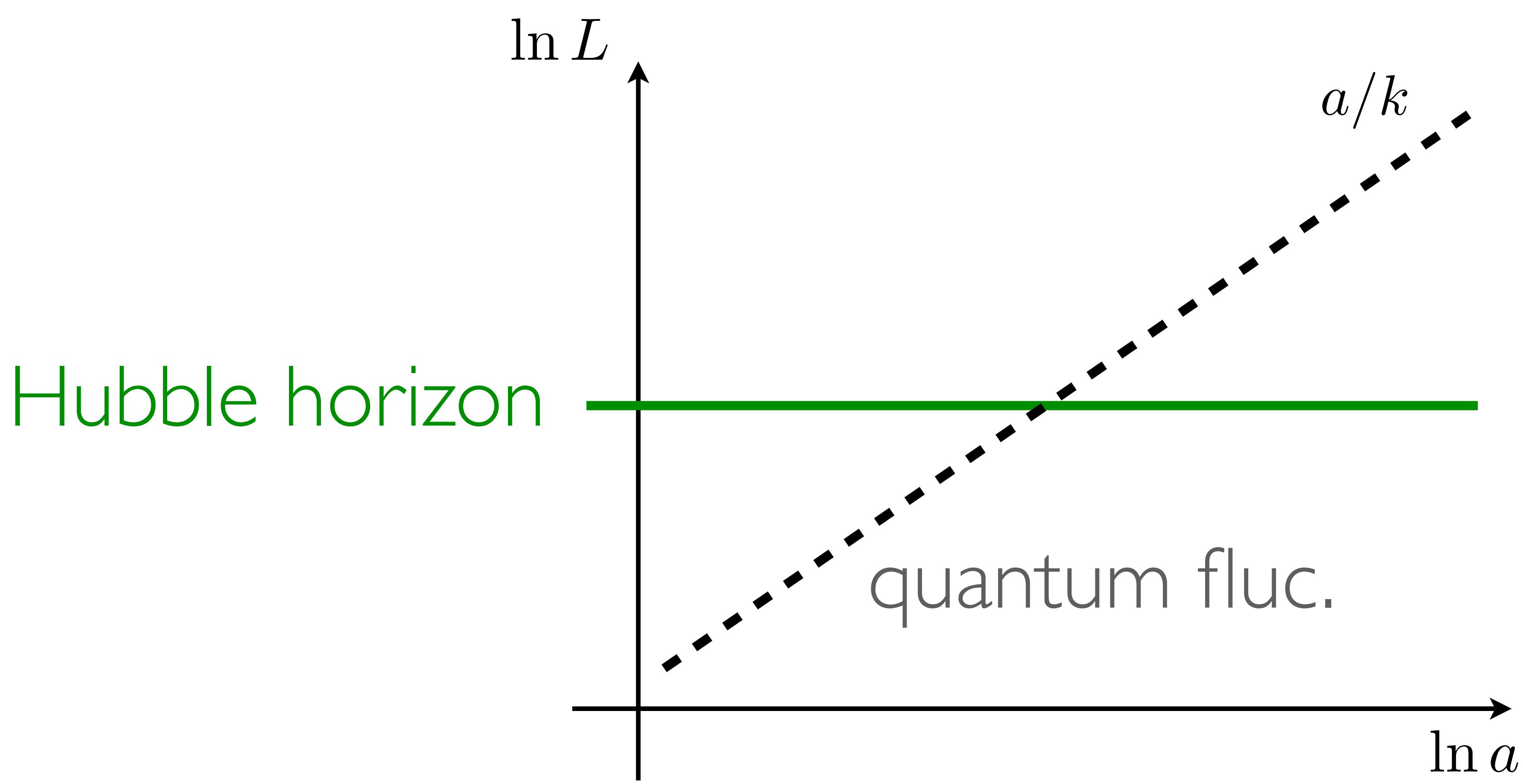
## Gauge Field Evolution

# REVIEW: MASSLESS SCALARS IN DS

$$S = -\frac{1}{2}\int d^4x\, a(\tau)^2\, \partial_\mu\phi\, \partial^\mu\phi$$

(indices raised with $\eta^{\mu\nu}$)

$$\phi_k'' + 2\frac{a'}{a}\phi_k' + k^2\phi_k = 0$$



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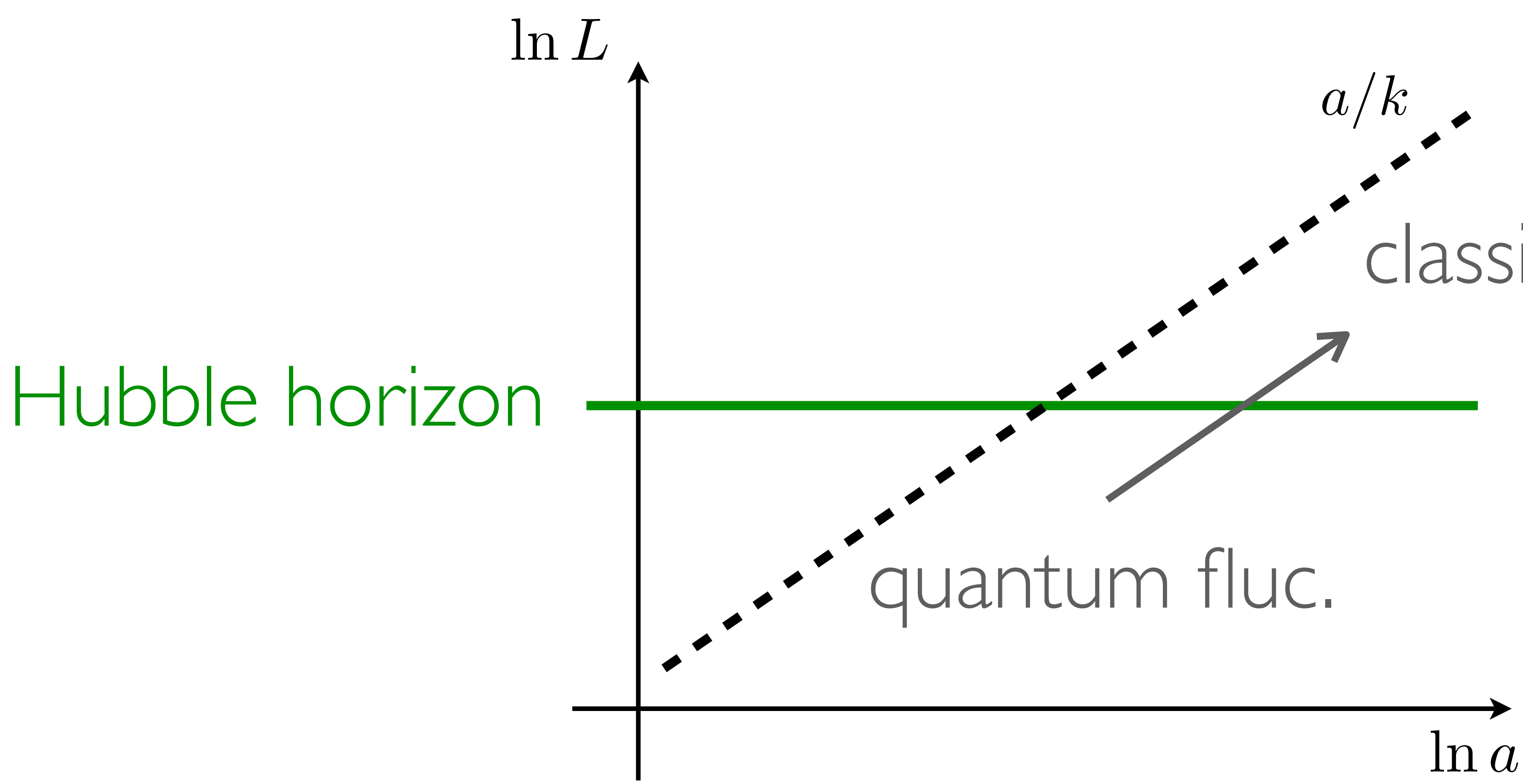

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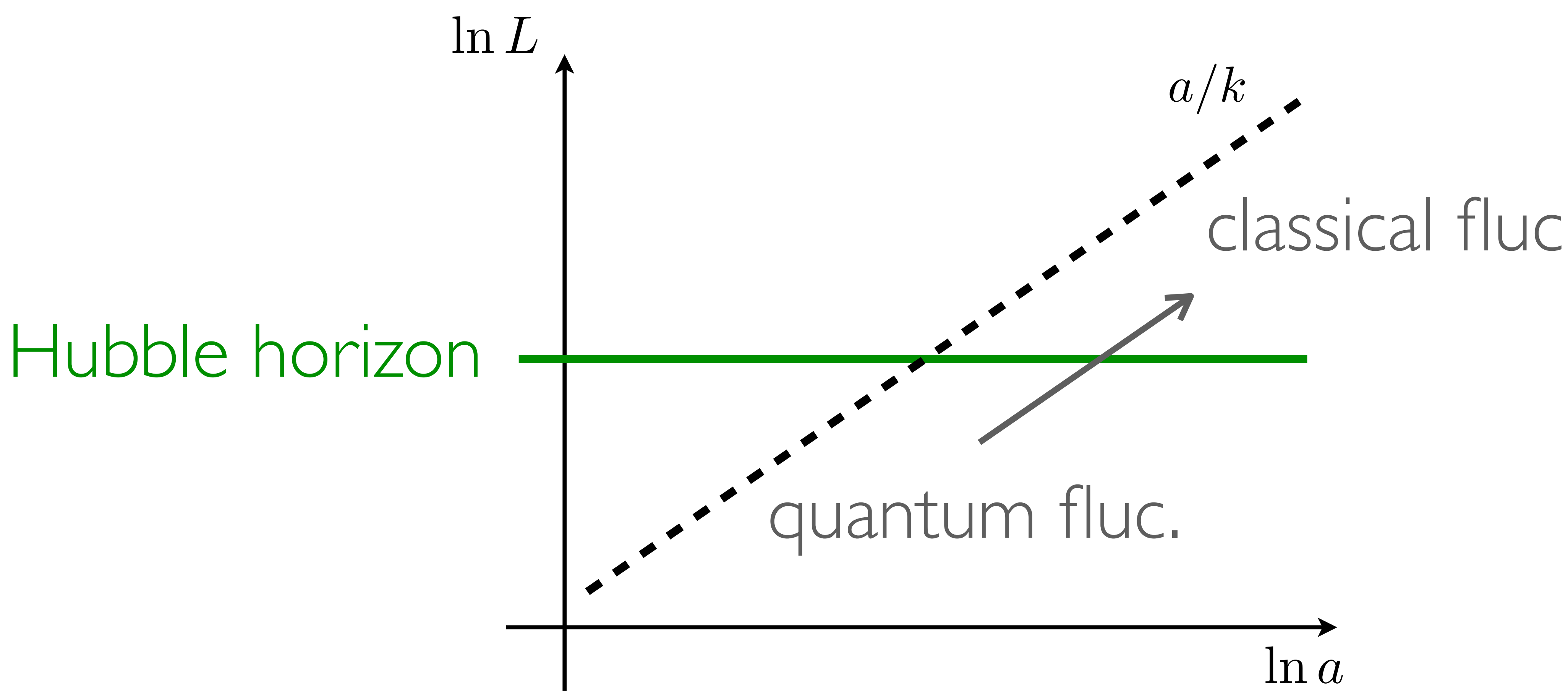
PHOTONS

$$S = -\frac{1}{4}\int d^4x\, I(\tau)^2\, F_{\mu\nu}F^{\mu\nu}$$

$$I(\tau)^2 = \frac{1}{e^2}\left[1 + 2\tilde{\beta}\log\left(\frac{a(\tau)}{a_\star}\right)\right]$$

$$v_k'' + 2\frac{I'}{I}v_k' + k^2 v_k = 0$$



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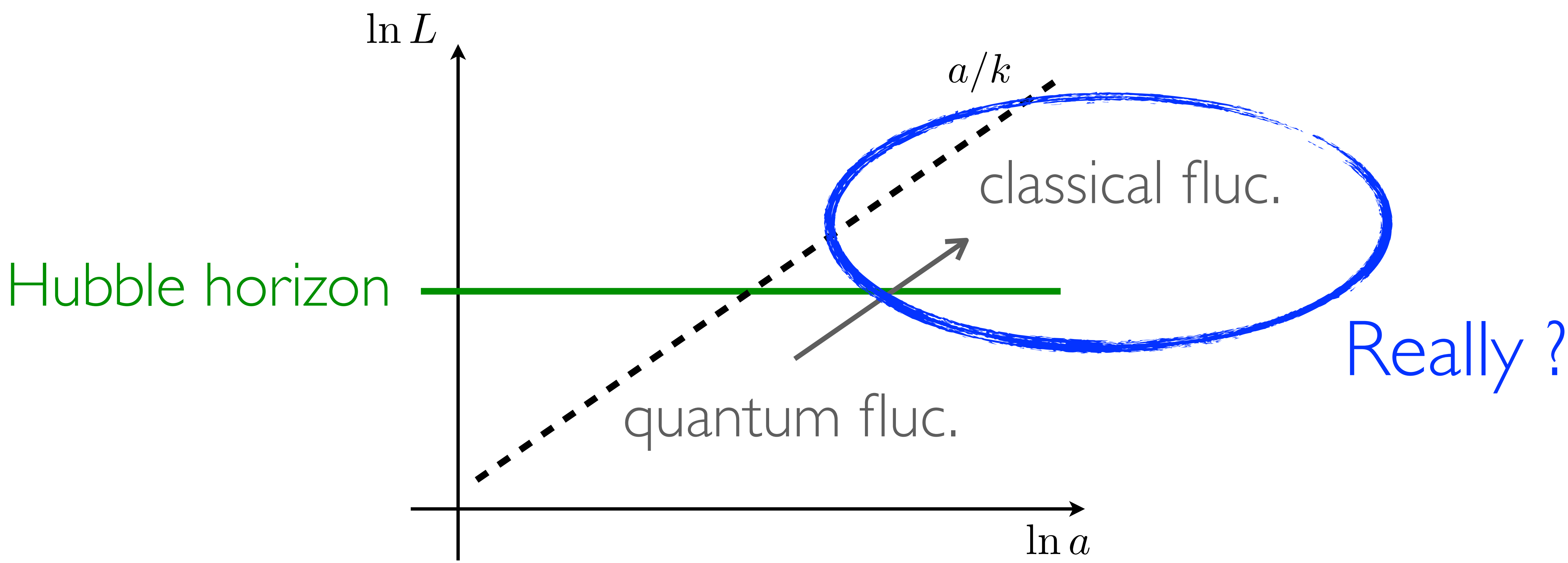


# MEASURES OF 'QUANTUMNESS'

Grishchuk, Sidorov '90
Maldacena '15 Green, TK '15

1. Bogoliubov coefficient

$|\beta_{\boldsymbol{k}}|^2$ : number of created photons per comoving phase volume

2. quantumness measure

$$\kappa_k \equiv \left| \frac{\langle 0|\phi_{\boldsymbol{k}}\,\phi_{-\boldsymbol{k}}(\tau)|0\rangle\,\langle 0|\pi_{\boldsymbol{k}}\,\pi_{-\boldsymbol{k}}|0\rangle}{[\phi_{\boldsymbol{k}},\pi_{-\boldsymbol{k}}]^2} \right|^{1/2} \quad \begin{cases} \sim 1 & \text{: quantum} \\ \gg 1 & \text{: classical} \end{cases}$$

$$\left( \kappa_k = \Delta Q \cdot \Delta P \geq \frac{1}{2} \qquad |\beta_k|^2 = \frac{(\Delta Q)^2 + (\Delta P)^2 - 1}{2} \right)$$

# CALCULATION

- Evolve the gauge field EoM starting from Bunch-Davies vacuum during inflation, until EW phase transition

- parameters :
  QED beta func ($\propto$ # of massless charged particles), $H_{\rm inf}$

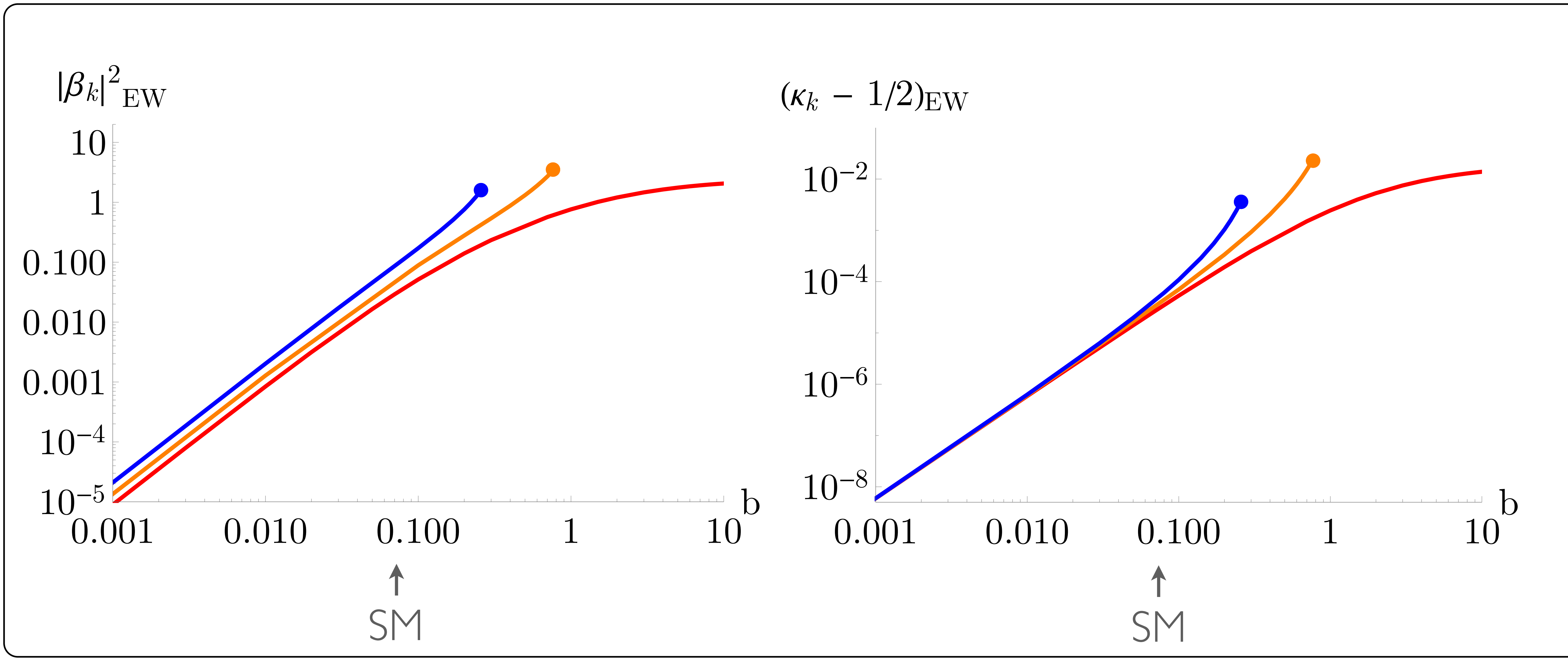
- Landau pole bound : $H_{\rm inf} < \Lambda_{\rm max}$

# RESULTS

- $H_{\rm inf} = 10^{14}$ GeV
- $H_{\rm inf} = 10^{6}$ GeV
- $H_{\rm inf} = 1$ GeV

$$\frac{k}{a_0} = (10\,\mathrm{Gpc})^{-1} \qquad b = \frac{\mathrm{Tr}\,(Q^2)}{6\pi^2}$$

endpoints of curves are set by Landau pole



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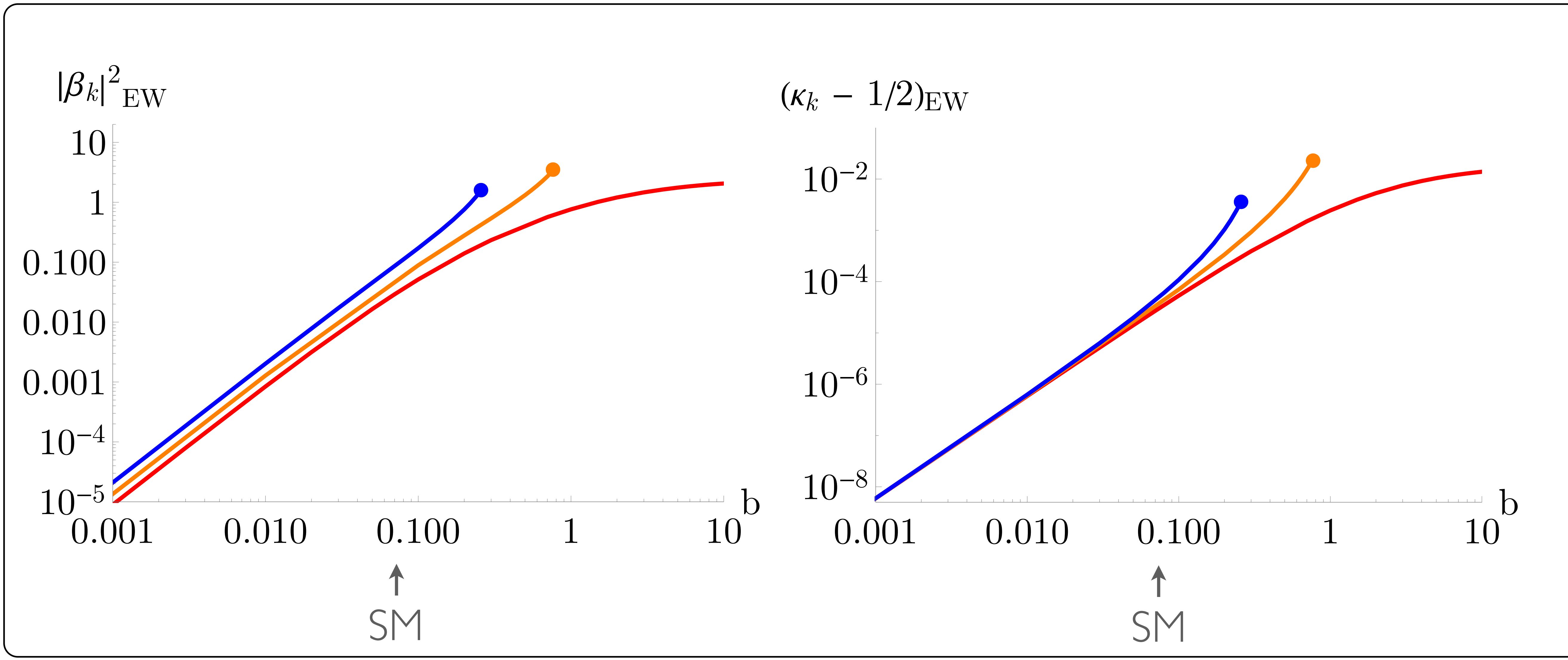


Logarithmic background dependence CANNOT convert vacuum fluc of gauge field into classical magnetic fields.

# THE MORAL

Zero-point fluctuations

$$B(k) \sim \left(\frac{k}{a}\right)^2$$

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Zero-point fluctuations

$$\cancel{B(k) \sim \left(\frac{k}{a}\right)^2}$$

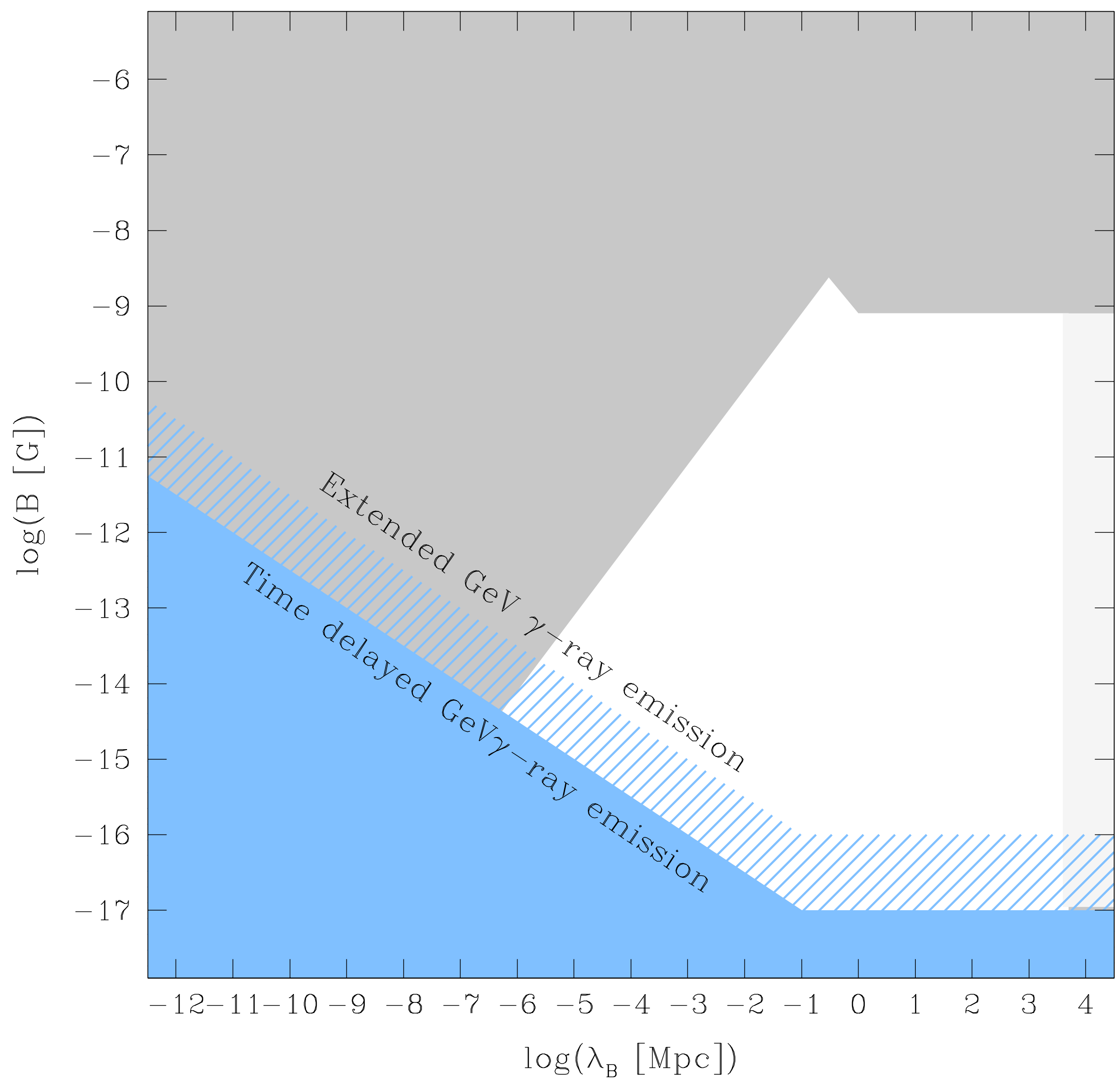
do not give coherent magnetic fields in the sky.

# SUMMARY OF WEYL ANOMALY $B$

# No $B$

- Weyl anomaly yields logarithmic dependence on scale factor
- Logarithmic dependence cannot produce classical magnetic fields, irrespective of # of massless charged particles in the theory

# THEN WHERE DID THE $B$ IN OUR UNIVERSE COME FROM?




Durrer and Neronov
Astron.Astrophys.Rev. 21(2013)62

Extragalactic $B$ is particularly mysterious… Beyond-SM?

(second order perturbation effects on Mpc scales, but tiny
Gopal, Sethi '04    Matarrese, Mollerach, Notari, Riotto '04    Ichiki, Takahashi, Sugiyama, Hanayama, Ohno '07)

# THE STANDARD LORE

- BSM physics can explicitly violate Weyl invariance to give rise to primordial magnetogenesis Turner, Widrow ’88 Ratra ’92

- But has various issues (strong couplings, cosmological backreaction, Schwinger effect, …)
  Gasperini, Giovannini, Veneziano ’95, Bamba, Yokoyama ’03, Demozzi, Mukhanov, Rubinstein, ’09, Barnaby, Namba, Peloso ’12, Fujita, Mukohyama ’12, Ferreira, Jain, Sloth ’13, Fujita, Yokoyama ’14, TK, Afshordi ’14, …

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All issues trace back to the post-magnetogenesis scaling:

$$B^2 \propto \frac{1}{a^4}$$

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- BSM physics can explicitly violate Weyl invariance to give rise to primordial magnetogenesis  Turner, Widrow '88  Ratra '92

- But has various issues (strong couplings, cosmological backreaction, Schwinger effect, …)
  Gasperini, Giovannini, Veneziano '95,  Bamba, Yokoyama '03,  Demozzi, Mukhanov, Rubinstein, '09,
  Barnaby, Namba, Peloso '12,  Fujita, Mukohyama '12,  Ferreira, Jain, Sloth '13,  Fujita, Yokoyama '14,  TK, Afshordi '14, …

All issues trace back to the post-magnetogenesis scaling:

$$\cancel{B^2 \propto \frac{1}{a^4}}$$

Not quite right!

# TRUE MAGNETIC SCALING

TK '14    TK, Sloth '19

$$\cancel{B^2 \propto \frac{1}{a^4}} \qquad (B^2 + E^2) \propto \frac{1}{a^4}$$

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$B$ and $E$ can exchange power (Faraday's law).

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$B$ and $E$ can exchange power (Faraday's law).

In the presence of stronger $E$, super-horizon $B$ scales as

$$B^2 \propto \frac{1}{a^6 H^2}$$

up until the time of reheating.

# TRUE MAGNETIC SCALING

TK '14 TK, Sloth '19

- Slower redshifting than previously assumed
- Corrects previous estimates of $B$ strength by up to 37 orders of magnitude
- New possibilities for primordial magnetogenesis

# SUMMARY

- No $B$ from Weyl anomaly
- Explicit Weyl symmetry breaking + correct $B$ scaling can explain femto-Gauss intergalactic fields
- Primordial $B$ may probe beyond-SM physics!