Standard Model in Weyl conformal geometry & inflation predictions

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Based on: arXiv: 2203.05381; 2104.15118 (EPJ C)

[related papers: arXiv: 1812.08613 (JHEP), 2007.14733, 2003.08516 (EPJC)]

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- Outline:

- Scale symmetry & Weyl geometry (WG)

- Weyl gravity: gauge theory of scale invariance, Einstein gravity as broken phase!

- SM in WG: min embedding, gauge theory of scale invariance including Einstein gravity.

- Implications: - origin of mass in non-metric geometry; Higgs from "geometry",
  - mass hierarchy solution, accelerated expansion, inflation: Starobinsky-Higgs.

• Beyond SM and GR - the origin of mass:

- SM + its gauge symmetry and Higgs mechanism confirmed experimentally (LHC); origin of EW scale.
- Gravity: origin of Planck mass M_P of mass? not clear. Is it geometric? must beyond Einstein gravity
- Mass hierarchy solution? seek an alternative to Susy/Sugra & Strings, using the gauge principle.

• Scale symmetry:

- SM with $m_{\rm Higgs}=0$ scale invariant; Early Universe or at short distances: EFTs are scale invariant.
- discrete (fractals, in Nature), global, local, gauged=Weyl gauge symmetry (WGS) =gauged dilatations (WGS $\Rightarrow$ quantum scale symmetry!)

• History:

- WGS: is a symmetry of Weyl geometry (WG)! first gauge theory (of scale invariance) 1918!
- WG $\Rightarrow$ Weyl $\tilde R^2$ gravity. Weyl thought it describes Gravity "+" Electromagnetism - soon disregarded!
- Einstein's critique: WG non-metric $\nabla_\mu g_{\alpha\beta}\neq 0$. btw: Einstein-Palatini quadratic gravity non-metric,too!
- we show: non-metricity not a problem but an advantage: the origin of mass!

• Global scale symmetry

$$x'_\mu = \rho\, x_\mu; \qquad \phi'(\rho\, x) = (1/\rho)\, \phi(x), \qquad \text{forbids} \quad \int d^4x\, m^2 \phi^2$$

- SM with Higgs ϕ of mass $m_\phi = 0$ is scale invariant [Bardeen 1995]
- no dim-ful couplings; scales generated from vev's, e.g. $M_P \sim \langle\sigma\rangle$. Broken by quantum corrections.
- Global symmetries broken by BH physics

[Kallosh, Linde, Susskind, hepth/9502069]

• Side remark: quantum scale symmetry (QSS):

- replace DR scale $\mu \to \sigma$ (dilaton) to keep scale invariance in $d{=}4-2\epsilon$; extra field! Different theory!
- QSS broken spontaneously; if $\langle\sigma\rangle \to \infty$ decouples, usual results (breaking by DR) recovered.
- at 1-loop [Englert et al 1976], Shaposhnikov 0809.3406; D.G. 1508.00595] and in SM [D.G., Z. Lalak, P. Olszewski, 1612.09120]]
- at 2-loops [D.G., Z. Lalak, P. Olszewski, 1608.05336]; 3-loops in SM [D.G. 1712.06024,Gretsch, Monin 1308.3863]
- protects a classical hierarchy $\phi \ll \sigma$; c-terms: ϕ^6/σ^2, ϕ^8/σ^4.... [D.G. 1508.00595, 1712.06024]
- Higgs-Gravity coupling: $\xi\, \phi^2 R \to$ tuning higgs selfcoupling $\beta_\lambda {\sim} \lambda(..){+}\xi\,(...)$.

• Local scale symmetry: L invariant under : $\hat g_{\mu\nu} = \Omega(x)^2\, g_{\mu\nu}$, $\hat\phi = \frac{\phi}{\Omega(x)}$, $\hat\psi = \frac{\psi}{\Omega(x)^{3/2}}$

- Include gravity (ϕ real):

$$L_0 = -\frac{1}{2}\sqrt{g}\left[\frac{1}{6}\phi^2 R + g^{\mu\nu}\,\partial_\mu\phi\,\partial_\nu\phi\right], \qquad \Leftrightarrow \qquad L_0 = -\frac{1}{2}\sqrt{\hat g}\,M_P^2\,\hat R \quad \text{generated spontaneously}$$

$$\Omega^2 = \frac{\phi^2}{\langle\phi\rangle^2}, \qquad M_P^2 \equiv \frac{1}{6}\langle\hat\phi\rangle^2, \quad \text{“gauge fixing”}$$

Einstein frame: $M_p \sim \langle\phi\rangle$ then ϕ decouples $\Rightarrow$ Conformal SM:

[t'Hooft 1104.4543; 1410.6675; Bars, Steinhardt, Turok 1307.1848, Englert et al 1976]

But:

a) - has a negative kinetic term for ϕ; not general, linear in R.

b) - Fake conformal symmetry! - vanishing current. [Jackiw, Pi 2015],

c) - ϕ: compensator, added “ad-hoc” to enforce symmetry; ϕ and $M_p \sim \langle\phi\rangle$: no geometric origin.

d) - L_0 has a symmetry that its underlying geometry (connection) does not! consistent? Γ: not invariant.

$\Rightarrow$ We want to avoid these issues: $\Rightarrow$ gauged scale invariance.

• Gauged scale symmetry: $\hat{\omega}_\mu(x) = \omega_\mu(x) - \frac{1}{\alpha}\partial_\mu \ln \Omega(x)^2, \quad \hat{g}_{\mu\nu}(x) = \Omega(x)^2\, g_{\mu\nu}(x), \quad \hat{\phi}(x) = \frac{\phi(x)}{\Omega(x)} \quad (*)$

• Weyl geometry: equiv classes $(g_{\mu\nu}, \omega_\mu)$

• Riemannian geometry $(g_{\mu\nu})$

$\tilde{\nabla}_\mu\, g_{\alpha\beta} = -\alpha\, \omega_\mu\, g_{\alpha\beta}\ , \quad \Rightarrow \quad \tilde{\nabla}'_\lambda g_{\mu\nu} = 0, \quad \tilde{\nabla}' = \tilde{\nabla}\big|_{\partial_\lambda \to \partial_\lambda + \text{charge}\times\alpha\times\omega_\lambda}$

$\nabla_\mu\, g_{\alpha\beta} = 0$

$\Rightarrow \tilde{\Gamma}^\rho_{\mu\nu} = \Gamma^\rho_{\mu\nu} + (\alpha/2)\left(\delta^\rho_\mu\, \omega_\nu + \delta^\rho_\nu\, \omega_\mu - g_{\mu\nu}\, \omega^\rho\right)$ inv of (*);

$\Gamma^\rho_{\mu\nu}$ = Levi-Civita; ∇_μ with Γ

$\Rightarrow \tilde{R} = R - 3\,\alpha \nabla_\mu \omega^\mu - 3/2\, \alpha^2 \omega^\mu \omega_\mu; \;\; \hat{\tilde{R}} = \frac{\tilde{R}}{\Omega^2}$ (!)

$\Rightarrow \tilde{D}_\mu \phi = (\partial_\mu - \alpha/2\, \omega_\mu)\, \phi \;\Rightarrow\; \hat{\tilde{D}}_\mu \hat{\phi} = \frac{1}{\Omega}\, \tilde{D}_\mu \phi;$

$\Rightarrow F_{\mu\nu} = \tilde{\nabla}_\mu\, \omega_\nu - \tilde{\nabla}_\nu\, \omega_\mu = \partial_\mu \omega_\nu - \partial_\nu \omega_\mu$ inv (*). Also $\alpha\, \omega_\mu \sim \tilde{\Gamma}_\mu - \Gamma_\mu$ deviation from Levi-Civita.

$\Rightarrow$ if $\omega_\mu \to 0$: $\tilde{\Gamma} \to \Gamma$, Weyl geometry $\to$ Riemannian; $\tilde{R} \to R$, Weyl tensor $\tilde{C}_{\mu\nu\rho\sigma} \to C_{\mu\nu\rho\sigma}$

$\Rightarrow$ All invariants of (*) [no matter]: $\sqrt{g}\, \tilde{R}^2, \;\; \sqrt{g}\, F^2_{\mu\nu}, \;\; \sqrt{g}\, \tilde{C}^2_{\mu\nu\alpha\beta};$ no higher dim ops (no scale!)

$\tilde{X}$ (X) notation in Weyl (Riemannian) geometry

• Weyl quadratic action $\Rightarrow$ Einstein gravity + massive ω_μ [D.G. arXiv:2203.05381, 2104.15118, 1812.08613]

$$\mathcal{L}_0 = \sqrt{g}\,\Big[\frac{1}{4!}\frac{1}{\xi^2}\,\tilde R^2 - \frac{1}{4}\,F_{\mu\nu}^{\,2}\Big] = \sqrt{g}\,\Big[\frac{1}{4!}\frac{1}{\xi^2}\,\big(-2\phi_0^2\,\tilde R - \phi_0^4\big) - \frac{1}{4}\,F_{\mu\nu}^{\,2}\Big], \qquad \text{eq. motion } \phi_0^2 = -\tilde R.$$

Riemannian notation: $\mathcal{L}_0 = \sqrt{g}\,\Big\{\frac{-1}{2\,\xi^2}\,\Big[\frac{1}{6}\,\phi_0^2\,R + (\partial_\mu\phi_0)^2\Big] - \frac{\phi_0^4}{4!\;\xi^2} + \frac{\alpha^2}{8\,\xi^2}\,\phi_0^2\,\Big[\omega_\mu - \frac{1}{\alpha}\partial_\mu \ln\phi_0^2\Big]^2 - \frac{1}{4}\,F_{\mu\nu}^2\Big\}.$

If $\langle\phi_0\rangle \neq 0$, "gauge fixing": $\Omega^2 = \phi_0^2/\langle\hat\phi_0\rangle^2 \;\Rightarrow\; \hat g_{\mu\nu} = \Omega^2 g_{\mu\nu},\; \langle\hat\phi_0\rangle^2 = 6\,\xi^2\,M_P^2,\; \hat\omega_\mu = \omega_\mu - \frac{1}{\alpha}\,\partial_\mu \ln\phi_0^2$

$$\mathcal{L}_0 = \sqrt{\hat g}\,\Big[-\frac{1}{2}M_p^2\hat R + \frac{3}{4}M_p^2\,\alpha^2\,\hat\omega_\mu\hat\omega^\mu - \frac{1}{4}\hat F_{\mu\nu}^2 - \Lambda\,M_p^2\Big], \qquad M_p^2 \equiv \frac{\langle\phi_0^2\rangle}{6\,\xi^2}, \quad \Lambda \equiv \frac{1}{4}\langle\phi\rangle^2.$$

$\Rightarrow$ Einstein-Proca action & M_p, Λ, m_ω by Stueckelberg mechanism. ω_μ massive $\rightarrow$ it decouples!

$\Rightarrow$ $\tilde\Gamma \rightarrow \Gamma$ then WG $\rightarrow$ Riemannian. Spontaneous breaking (# dof constant), non-trivial.

$\Rightarrow$ Einstein gravity=broken phase of Weyl action. Metricity restored below $m_\omega \sim M_p$! $\alpha \ll 1$? No ghost!

• Weyl quadratic gravity $\Rightarrow$ Einstein gravity + massive ω_μ

$\Rightarrow$ we have: $\nabla^\mu J_\mu = 0$; $J_\mu = \alpha/(2\xi^2)\ \phi_0 \left[\partial_\mu - (\alpha/2)\,\omega_\mu\right] \phi_0$; if ϕ_0 constant $\nabla_\mu \omega^\mu = 0$ gauge fixing.

$\Rightarrow$ if ω_μ not dynamical: $\omega_\mu \sim (1/\alpha)\,\partial_\mu(\ln\phi_0^2)$, $J_\mu = 0$ (metric case) $\Rightarrow$ local scale symmetry

- Eq. motion: $\Box\phi_0^2 = 0$; FRW: $\phi_0(t)^2 = c_1 \int^t d\tau/a(\tau)^3 + c_2 \rightarrow$ constant [G. Ross,C.T. Hill, P.Ferreira 1801.07676]

- ϕ_0 is part of $\tilde{R}^2$: then $M_p^2 \sim \langle\phi_0\rangle^2/\xi^2$, $\Lambda \sim \langle\phi_0\rangle^2$, $m_\omega^2 \sim \alpha^2 M_p$: have (non-metric) geometric origin.

$\Rightarrow$ Non-metric geometry as the origin of mass! [D.G. 2203.05381 [hep-th]]

- Other terms: Weyl tensor ($\tilde{C}_{\mu\nu\rho\sigma}$) does not change the result:

$$L_C = \frac{\sqrt{g}}{\eta}\,\tilde{C}_{\mu\nu\rho\sigma}\,\tilde{C}^{\mu\nu\rho\sigma} = \frac{\sqrt{g}}{\eta}\Big[C_{\mu\nu\rho\sigma}\,C^{\mu\nu\rho\sigma} + \frac{3}{2}\,\alpha^2\,F_{\mu\nu}^2\Big]$$

Weyl geometry Riemannian geometry

$\Rightarrow$ Weyl's theory: gauge theory of scale inv, an embedding of Einstein gravity. Renormalizable [Stelle 1979]

• SM Higgs in Weyl gravity/geometry:

$$\mathcal{L} = \sqrt{g}\,\Big\{ \frac{1}{4!\,\xi^2}\,\tilde R^2 - \frac{1}{4}\,F_{\mu\nu}^2 \;-\; \frac{1}{12}\,\xi_1\,h^2\,\tilde R \;+\; \frac{1}{2}\,(\tilde D_\mu h)^2 - \frac{\lambda}{4!}\,h^4\Big\}, \qquad \tilde R^2 \to -2\phi_0^2\,\tilde R - \phi_0^4$$

$$= \;\sqrt{g}\,\Big\{ - \frac{1}{12}\underbrace{\Big[\frac{1}{\xi^2}\phi_0^2 + \xi_1\,h^2\Big]}_{=\,6\,\rho^2}\tilde R - \frac{1}{4}\,F_{\mu\nu}^2 + \frac{1}{2}\,(\tilde D_\mu h)^2 - \frac{1}{4!}\,\Big[\lambda\,h^4 + \frac{1}{\xi^2}\phi_0^4\Big]\Big\}, \qquad \tilde D_\mu h = (\partial_\mu - \alpha/2\,\omega_\mu)h.$$

Riemannian notation:

$$\mathcal{L} = \sqrt{g}\,\Big\{-\frac{1}{2}\,\Big[\rho^2\,R + 6\,(\partial_\mu\rho)^2\Big] + \frac{3}{4}\,\rho^2\,\Big(\omega_\mu - \frac{1}{\alpha^2}\,\partial_\mu \ln\rho^2\Big)^2 - \frac{1}{4}\,F_{\mu\nu}^2 + \frac{1}{2}(\tilde D_\mu h)^2 - V(h,\rho)\Big\}.$$

Stueckelberg: radial direction $\ln\rho$ eaten by ω_μ. Next (*): $\quad \Omega = \frac{\rho^2}{\langle\hat\rho\rangle},\ \langle\hat\rho\rangle = M_P,\ \hat\omega_\mu = \omega_\mu - \frac{1}{\alpha^2}\partial_\mu \ln\rho^2$

$\Rightarrow$ Einstein-Proca: (ω_μ) : $\quad \mathcal{L} = \sqrt{\hat g}\,\Big\{ - \frac{1}{2}\,M_P^2\,\hat R + \frac{3}{4}\,\alpha^2\,M_p^2\;\hat\omega_\mu\hat\omega^\mu - \frac{1}{4}\,\hat F_{\mu\nu}^2 + \frac{1}{2}\,(\hat{\tilde D}_\mu\hat h)^2 - V\Big]\Big\},$

Unitarity gauge: $\hat{h} \to M_p\sqrt{6}\sinh\frac{\sigma}{M_p\sqrt{6}}, \qquad \hat{\omega}_\mu \to \hat{\omega}_\mu + \partial_\mu \ln\cosh^2\frac{\sigma}{M_p\sqrt{6}}$

$$\Rightarrow \quad \mathcal{L} = \sqrt{\hat{g}}\,\Big\{ -\frac{1}{2} M_p^2\,\hat{R} + \frac{3}{4}\alpha^2 M_p^2\,\hat{\omega}_\mu\hat{\omega}^\mu \cosh^2\frac{\sigma}{M_p\sqrt{6}} - \frac{1}{4}\hat{F}_{\mu\nu}^2 + \frac{1}{2}(\partial_\mu\sigma)^2 - V(\sigma)\Big\},$$

where
$$V(\sigma) = V_0\Big\{\xi^2\Big[1-\xi_1\sinh^2\frac{\sigma}{M_p\sqrt{6}}\Big]^2 + \lambda\sinh^4\frac{\sigma}{M_p\sqrt{6}}\Big\},$$

$\Rightarrow$ Higgs coupling to ω_μ: $\qquad \mathcal{L} \sim \sqrt{\hat{g}}\,(1/8)\,\alpha^2\,\sigma^2\,\hat{\omega}_\mu\hat{\omega}^\mu + ...$

- Higgs from Weyl vector fusion: $\omega_\mu\omega_\mu \to \sigma\sigma \Rightarrow$ Higgs has a (non-metric) geometric origin!.
- Matter (higgs) creation from geometry (ω_μ is "geometric"). Irreversible processes [I. Prigogine et al, 1986]

• Palatini quadratic gravity [D.G. arxiv:2003.08516; 2007.14733]

- Palatini approach to gravity due to Einstein (1925): $\tilde{\Gamma}$ unknown, fixed by eqs of motion (action).
- $\tilde{\Gamma}$ independent of $g_{\mu\nu} \Rightarrow$ invariant of (*); define $\omega_\mu = (1/2)(\tilde{\Gamma}_\mu - \Gamma_\mu)$. $\qquad \tilde{R} = R(\tilde{\Gamma}, g)$.
- same $V(\sigma)$ but $\xi_1 \to 4\,\xi_1$, $\lambda \to 16\lambda$, (different non-metricity) but many more operators.

• SM Fermions in Weyl gravity/geometry:

$$L_\psi = \frac{i}{2}\sqrt{g}\,\overline{\psi}\,\gamma^a\,e_a^\mu\,\underbrace{\Big[\partial_\mu + \frac{1}{2}\,s_\mu^{ab}\,\sigma_{ab}\Big]}_{\nabla_\mu}\psi + \text{h.c.}\qquad \text{spin connection (Riemann):}\quad s_\mu^{ab} = -e^{\lambda b}\,(\partial_\mu e_\lambda^a - \Gamma_{\mu\lambda}^\nu\,e_\nu^a).$$

- Weyl spin connection: $\tilde{s}_\mu^{ab} = s_\mu^{ab}\Big|_{\partial_\lambda\to\partial_\lambda+(\text{charge})\,\alpha\,\omega_\lambda}$, $\qquad s_\mu^{ab}\to\tilde{s}_\mu^{ab} = s_\mu^{ab} + (1/2)\,\alpha\,(e_\mu^a\,e^{\nu b} - e_\mu^b\,e^{\nu a})\;\omega_\nu.$

⇒ $\tilde{s}_\mu^{ab}$ is Weyl gauge invariant (like $\tilde{\Gamma}$). Lagrangian: replace $\partial_\lambda\psi\to\partial_\lambda + d_\psi\,\alpha\,\omega_\lambda$. Then ω_μ cancels out:

$$L_\psi = \frac{i}{2}\sqrt{g}\,\overline{\psi}\,\gamma^a\,e_a^\mu\Big[\partial_\mu + d_\psi\,\alpha\,\omega_\mu + \frac{1}{2}\,\tilde{s}_\mu^{ab}\,\sigma_{ab}\Big]\psi = \frac{i}{2}\sqrt{g}\,\overline{\psi}\,\gamma^a\,e_a^\mu\Big[\partial_\mu + \frac{1}{2}\,s_\mu^{ab}\,\sigma_{ab}\Big]\psi + \text{h.c.}$$

In SM: $$\mathcal{L}_\psi = \frac{i}{2}\sqrt{g}\,\overline{\psi}\,\gamma^a\,e_a^\mu\,\Big[\partial_\mu - i g\,\vec{T}\hat{\vec{A}}_\mu - i\,Y\,g'\hat{B}_\mu + \frac{1}{2}\,s_\mu^{ab}\,\sigma_{ab}\Big]\,\psi + \text{h.c.}$$

⇒ $\mathcal{L}_\psi$ as in SM in Riemannian geometry, no coupling to ω_μ! Yukawa interactions: invariant [Kugo 1977]

- Note: if U(1)$_Y\times$D(1) kinetic mixing: $\hat{B}_\mu = B'_\mu - \omega'_\mu\tan\tilde{\chi}$; coupling $\propto Y$. ω_μ anomaly free & massive!

• SM Gauge bosons:

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

with $F_{\mu\nu} = \tilde{\nabla}_\mu A_\nu - \tilde{\nabla}_\nu A_\mu ... = \partial_\mu A_\nu - \partial_\nu A_\mu ...$, symmetric $\tilde{\Gamma}$. $\mathcal{L}_b$ invariant under (*) for $\hat{A}_\mu = A_\mu$.
$\Rightarrow$ Action similar to (pseudo)Riemannian case. $\Rightarrow$ only SM Higgs sector changes!

$\Rightarrow$ SM in Weyl geometry: minimal embedding, no new dof's beyond SM & WG. Higgs coupling to ω_μ.

- $m_\omega \sim \alpha M_p$ can be light, few TeV for $\alpha \ll 1$. Current bound on non-metricity: few TeV! [Latorre, Y. Lobo]

- Higgs mass quantum corrections: $\delta m_\sigma^2 \propto m_\omega^2$. Light m_ω: solution to mass hierarchy!

- above m_ω symmetry restored; no scale, no counterterm; quantum scale invariance necessary!

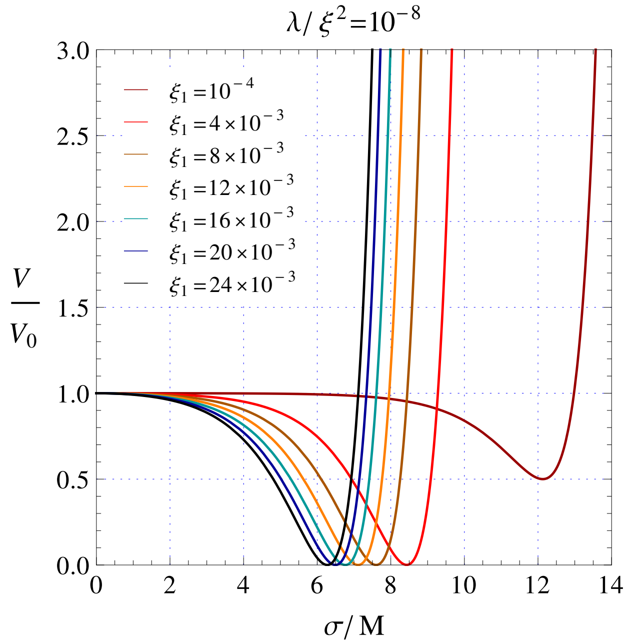
[D.G. 2203.05381, 2104.15118]

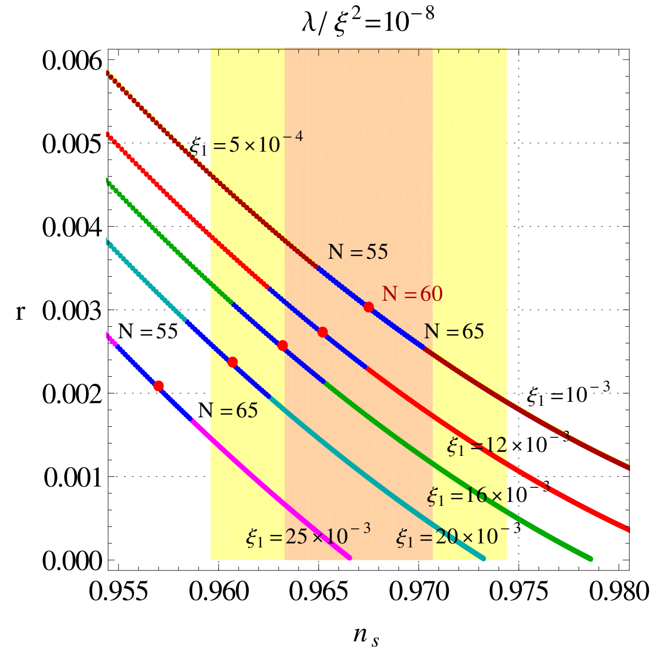
• Non-metricity (solid state physics): d=0 defects: metric anomalies/point defects: missing/extra atoms
- destroys crystalline structure, modify local notion of length, described by non-metric (Weyl) geometry.

[A. Roychowdhury, A. Gupta, 1601.06905]

• Weyl R^2-inflation

$$V = V_0 \left\{ \left[1 - \xi_1 \sinh^2 \frac{\sigma}{2\, M_p \sqrt{6}} \right]^2 + (\lambda/\xi^2)\ \sinh^4 \frac{\sigma}{2 M_p \sqrt{6}} \right\}$$





$$\lambda/\xi^2 \ll \xi_1^2 \ll 1 : \quad \epsilon = \frac{M_p^2}{2} \frac{V'^2}{V^2} = \frac{\xi_1^2}{3} \sinh^2 \frac{2\sigma}{M_p\sqrt{6}} + \mathcal{O}(\xi_1^3); \quad \eta = M_p^2 \frac{V''}{V} = -\frac{2\xi_1}{3} \cosh \frac{2\sigma}{M_p\sqrt{6}} + \mathcal{O}(\xi_1^2)$$

$$\Rightarrow \quad r = 3\,(1-n_s)^2 - (16/3)\,\xi_1^2 + \mathcal{O}(\xi_1^3)$$

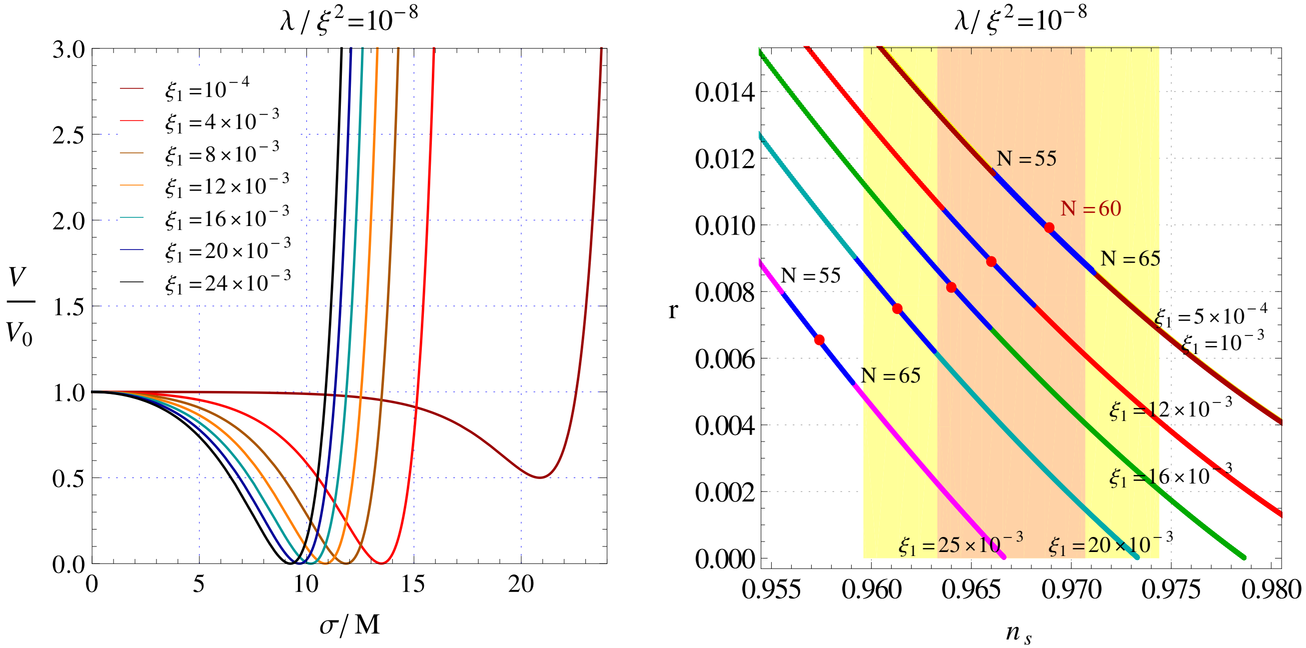
$0.002567 \leq r \leq 0.00303$ if $n_s = 0.9670 \pm 0.0037$; ($N = 60$) upper limit on r: Starobinsky: ($n_s \approx 0.968$)

- Starobinsky: $R^2 + M_p R$. Weyl: $\tilde{R}^2 + h^2 \tilde{R} \Rightarrow$ similarity of $r(n_s)$. Gauged version of Starobinsky model!

[D.G. arxiv:2007.14733, 1906.11572; G. Ross, C. Hill, P, Ferreira, J. Noller 1906.03415]

• Palatini R^2-Inflation ($\theta = 4$)

$$V = V_0 \left\{ \left[1 - \theta\, \xi_1 \sinh^2 \frac{\sigma}{2\, M_p \sqrt{6\,\theta}} \right]^2 + (\lambda/\xi^2)\ \theta^2 \sinh^4 \frac{\sigma}{2 M_p \sqrt{6\,\theta}} \right\}$$



$$\lambda/\xi^2 \ll \xi_1^2 \ll 1: \quad \epsilon = \frac{M_p^2}{2} \frac{V'^2}{V^2} = \frac{\xi_1^2}{3}\, \theta \sinh^2 \frac{2\sigma}{M_p\sqrt{6\theta}} + \mathcal{O}(\xi_1^3); \quad \eta = M_p^2\, \frac{V''}{V} = -\frac{2\xi_1}{3} \cosh \frac{2\sigma}{M_p\sqrt{6\theta}} + \mathcal{O}(\xi_1^2)$$

$$\Rightarrow \qquad r = 3\theta\, (1 - n_s)^2 + \mathcal{O}(\xi_1^2)$$

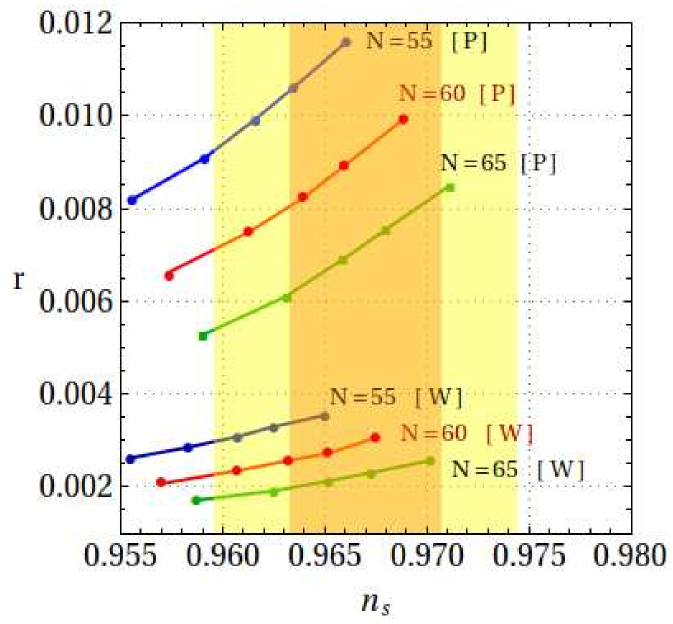
$0.00794 \leq r \leq 0.01002$ if $n_s = 0.9670 \pm 0.0037$; ($N = 60$)

[D.G. arxiv:2007.14733, 2003.08516]

• Weyl versus Palatini: R^2-inflation predictions [D.G. arXiv:2007.14733]

- tensor-to-scalar ratio r versus spectral index n_s
with orange (yellow) values of n_s at 68% (95%) CL.
- the difference (θ) due to different non-metricity of these theories.
- such values of r reachable by future CMB experiments
(0.0005 precision; LiteBIRD, CMB-S4).

$\Rightarrow$ One will be able test and discriminate Weyl vs Palatini model



• Conclusions:

- Weyl quadratic gravity action: viable gauge theory of scale invariance
- broken via Stueckelberg to Einstein-Proca action for ω_μ; ω_μ massive $>$ TeV
- Planck mass, m_ω, Λ: of (non-metric) geometric origin (no matter).

- SM in Weyl geometry: both geometry (connection) and action have this symmetry.
- Higgs coupling to ω: $\Delta L = \omega_\mu \omega^\mu h^2$: geometric origin of h: $\omega_\mu + \omega_\mu \rightarrow h + h$.
- Mass hierarchy solution: Weyl gauge symmetry protects m_h for light $m_\omega \sim$ TeV.

- Tests? a) Inflation: predictions close to those in Starobinsky, testable, $0.00257 \leq r \leq 0.00303$.
  b) Higgs physics related to non-metricity (m_ω).
  c) Gravitational waves? Dark matter?

$\Rightarrow$ SM in Weyl's quadratic gravity: viable gauge theory of scale invariance, includes Einstein gravity!

- A last word from Weyl:

“ The action [...] is [...] a linear combination of $\tilde{R}^2$ and $F_{\mu\nu}^2$. I believe that one can assert that this action principle implies everything that Einstein's theory has implied up to now, but in the more far-reaching questions of cosmology and the constitution of matter, it exhibits a clear superiority. Nevertheless, I do not believe that the laws of nature that are [..] applicable in reality are resolved by it. “

H. Weyl: Ann. Phys. (Leipzig) (4) 59 (1919), 101-133

- Parallel transport for vector u_μ:

$$\hat{\omega}_\mu(x) = \omega_\mu(x) - \frac{1}{\alpha}\partial_\mu \ln \Omega(x)^2, \quad \hat{g}_{\mu\nu}(x) = \Omega(x)^2\, g_{\mu\nu}(x), \quad \hat{\phi}(x) = \frac{\phi(x)}{\Omega(x)} \quad \hat{A}_\mu = A_\mu, \quad \hat{u}^\mu = \Omega^{z_u} u^\mu$$

Parallel transport along $\gamma(\tau)$:

$$\frac{D\, u^\mu}{d\tau} = 0, \quad \text{where} \quad D \equiv dx^\lambda\, D_\lambda, \quad D_\lambda\, u^\mu = \tilde{\nabla}_\lambda u^\mu \Big|_{\partial_\lambda \to \partial_\lambda + z_u\, \alpha\, \omega_\lambda}, \qquad \tilde{\nabla}_\lambda u^\mu = \partial_\lambda u^\mu + \tilde{\Gamma}^\mu_{\lambda\rho}\, u^\rho,$$

and $x = x(\tau)$. Then the differential variation: $d\, u^\mu = dx^\lambda\, \partial_\lambda u^\mu = -dx^\lambda \Big[z_u\, \alpha\, \omega_\lambda\, u^\mu + \tilde{\Gamma}^\mu_{\lambda\rho}\, u^\rho \Big],$

$$d\, \langle u, v \rangle = d\, \Big[u^\mu\, v^\nu\, g^{\mu\nu} \Big] = -\alpha\, dx^\lambda\, \omega_\lambda\, g_{\mu\nu} \Big[2 + (z_u + z_v) \Big]\, u^\mu\, v^\nu = -\alpha\, dx^\lambda\, \omega_\lambda \Big[2 + (z_u + z_v) \Big]\, \langle u, v \rangle$$

For the norm: $d \ln |u|^2 = dx^\lambda\, \omega_\lambda\, (-\alpha)\, (1 + z_u), \quad \Rightarrow \quad |u|^2 = |u_0|^2\, e^{-\alpha\,(1+z_u)\, \int_{\gamma(\tau)} \omega_\lambda dx^\lambda}.$

WG: $\Rightarrow$ symmetric phase: no mass $\Rightarrow$ no clock rate $\Rightarrow$ no second clock effect & no experiment possible.

WG: $\Rightarrow$ broken phase: mass generated; metric theory below m_ω $\Rightarrow$ second clock effect suppressed by m_ω.

Ratio $|u|/|v|$ independent of units of length if $z_u = z_v$. Integrable geometry $\omega_\lambda = \partial_\lambda(\ldots)$ then $|u| = |u_0|$.

• Weyl "photon" - photon mixing?: adding $U(1)_Y$ to $\mathcal{L}_0$; [source: SM fermions action]

$$\mathcal{L}_0 \to \mathcal{L}_1 = \sqrt{g}\left\{\frac{1}{4!\,\xi^2}\,\tilde{R}^2 - \frac{1}{4}\left[F_{\mu\nu}^2 + 2\sin\chi\,F_{\mu\nu}\,F_y^{\mu\nu} + F_{y\,\mu\nu}^2\right]\right\}.$$

Re-do calculation, diagonalize mixing by:

$$\hat{\omega}_\mu = \gamma\,\omega'_\mu \sec\chi, \qquad \hat{B}_\mu = B'_\mu - \omega'_\mu \tan\chi,$$

Then

$$\mathcal{L}_1 = \sqrt{\hat{g}}\,\left\{-\frac{1}{2}M_p^2\hat{R} + \frac{3}{4}M_p^2\,\alpha^2\,\gamma^2\sec\chi^2\,\omega'_\mu\omega'^\mu - \frac{1}{4}(F'^2_{\mu\nu} + F'^2_{y\,\mu\nu})\right\},$$

- the photon after EWSB:

$$A_\mu = B'_\mu \cos\theta_w + A^3_\mu \sin\theta_w = \left[\hat{B}_\mu + \hat{\omega}_\mu \sin\chi\right]\,\cos\theta_w + \sin\theta_w A^3_\mu.$$

- gauge kinetic mixing $\to$ photon includes a small 'piece' of ω_μ, suppressed by $\sin\chi$
- Weyl was not completely wrong in trying to relate ω_μ to the photon - they can mix;
- mixing not forbidden by Coleman-Mandula: symmetry direct product $U(1)_Y \times D(1)$; both broken spontaneously.

• Higgs sector in Weyl geometry: $\tilde{D}_\mu H = \big[\partial_\mu - i\mathcal{A}_\mu - (1/2)\,\alpha\,\omega_\mu\big]\,H,$

$$\mathcal{L}_H = \sqrt{g}\,\Big\{\frac{\tilde{R}^2}{4!\;\xi^2} - \frac{\xi_1}{6}\,|H|^2\tilde{R} + |\tilde{D}_\mu H\,|^2 - \lambda\,|H|^4 - \frac{1}{4}\Big[F_{\mu\nu}^2 + 2\sin\chi\,F_{\mu\nu}\,F_y^{\mu\nu} + F_{y\,\mu\nu}^2\Big]\Big\}.$$

where $\mathcal{A}_\mu = (g/2)\,\vec{\sigma}.\vec{A}_\mu + (g'/2)\,B_\mu$; $\vec{A}_\mu$ is the $SU(2)_L$ boson, B_μ is the $U(1)_Y$ boson.

- Potential:

$$\hat{V}(\sigma) \;=\; V_0\,\Big\{6\lambda\,\sinh^4\frac{\sigma}{M_p\sqrt{6}} + \xi^2\Big[1 - \xi_1\sinh^2\frac{\sigma}{M_p\sqrt{6}}\Big]^2\Big\}, \quad V_0 \equiv (3/4)M_p^4.$$

$$= \frac{1}{4}\Big[\lambda - \frac{1}{9}\xi_1\,\xi^2 + \frac{1}{6}\xi_1^2\,\xi^2\Big]\,\sigma^4 - \frac{1}{2}\,\xi_1\xi^2 M_p^2\,\sigma^2 + \frac{3}{2}\,\xi^2 M_p^4 + \mathcal{O}(\sigma^6/M_p^2).$$

if $\xi_1\xi^2 \ll 1$: $\langle\sigma\rangle^2 = (\xi_1\,\xi^2/\lambda)\,M_p^2, \quad m_\sigma^2 = 2\,\xi_1\,\xi^2\,M_p^2,$

- Hierarchy using $\xi\sqrt{\xi_1} \sim 3.5\times 10^{-17}$, $\lambda \sim 0.12$ (SM). Hierarchy controlled by ξ of $\tilde{R}^2$ term!

$$m_Z^2 = \frac{1}{4}\,(g^2 + g'^2)\,\langle\sigma\rangle^2\Big\{1 + \frac{\langle\sigma\rangle^2}{18M_p^2}\Big[1 - \frac{3\,g'^2}{\alpha^2}\sin^2\chi\Big] + \mathcal{O}(\langle\sigma\rangle^4/M_p^4)\Big\}.$$

$\Rightarrow$ Part of Z mass due to Weyl geometry (mixing with ω_μ), beyond Einstein gravity/Riemannian geometry

- Precision constraints (Z mass):

$$\varepsilon \equiv \frac{\Delta m_Z}{m_{Z^0}} = -\frac{g'^2 \langle\sigma\rangle^2}{12\, M_p^2} \frac{\sin^2\chi}{\alpha^2} + \mathcal{O}\Big(\frac{\langle\sigma\rangle^4}{M_p^4}\Big) = -\frac{1}{8}\Big(\frac{\langle\sigma\rangle}{m_\omega}\Big)^2 (g' \tan\chi)^2 + \mathcal{O}\Big(\frac{\langle\sigma\rangle^4}{m_w^4}\Big).$$

- $\langle\sigma\rangle = 246.22$ GeV; at 68% CL, $\varepsilon = 2.3\times 10^{-5}$, then: $\alpha \geq 2.17\times 10^{-15}\sin\chi.$

- in terms of the mass: $\frac{m_\omega}{\text{TeV}} \geq 6.35\times\tan\chi.$

- current bound on non-metricity scale $m_\omega \sim$ few TeV, then: $\tan\chi \leq 0.16$

$\Rightarrow$ the constraint from Z-mass is v. strong: e.g. effect of ω_μ to Δa_μ of muon magnetic moment:

$$\Delta a_\mu \sim \frac{1}{12\pi^2}\frac{m_\mu^2}{m_\omega^2}(g'\tan\chi)^2 = 2.56\times 10^{-13},$$

which is very small (cannot match the ongoing discrepancy).

• From Weyl to Palatini: [D.G. arxiv:2003.08516; 2007.14733]

- Palatini approach to gravity due to Einstein: $\tilde{\Gamma}$ unknown, fixed by eqs of motion.
- $\tilde{\Gamma}$ independent of $g_{\mu\nu} \Rightarrow$ invariant of (*); define $\omega_\mu = (1/2)(\tilde{\Gamma}_\mu - \Gamma_\mu)$.
- Minimal Palatini action with WGS as before, but with $\tilde{R} = R(\tilde{\Gamma}, g)$, $\tilde{\Gamma}$ Palatini.

$$L_2 = \sqrt{g}\,\Big\{ \frac{1}{4!\,\xi^2}\,\tilde{R}^2(\tilde{\Gamma}, g) - \frac{1}{4q^2}\,F_{\mu\nu}^2(\tilde{\Gamma}) \;-\; \frac{1}{12}\,\xi_1\,\phi^2\,\tilde{R}(\tilde{\Gamma}, g) \;+\; \frac{1}{2}(\tilde{D}_\mu\phi)^2 - \frac{\lambda}{4!}\phi^4 \Big\},$$

Solve for $\tilde{\Gamma}$ (difficult!) $\Rightarrow$ $\tilde{\nabla}_\lambda\, g_{\mu\nu} = (-2)(g_{\mu\nu}\,\omega_\lambda - g_{\mu\lambda}\,\omega_\nu - g_{\nu\lambda}\,w_\mu)$ non-metricity $\neq$ Weyl geometry.

$\Rightarrow$ Onshell $\tilde{\Gamma}$: Stueckelberg breaking, same steps as before, etc:

$$L_2 = \sqrt{g}\,\Big\{ -\frac{1}{2}\Big[\rho^2\,R + 6\,(\partial_\mu\rho)^2\Big] + \frac{3}{4}\,\theta\,\rho^2\,\big(\omega_\mu - \partial_\mu \ln\rho^2\big)^2 - \frac{1}{4\,q^2}\,F_{\mu\nu}^2 + \frac{1}{2}(\tilde{D}_\mu\phi)^2 - V(\phi,\rho)\Big\}.$$

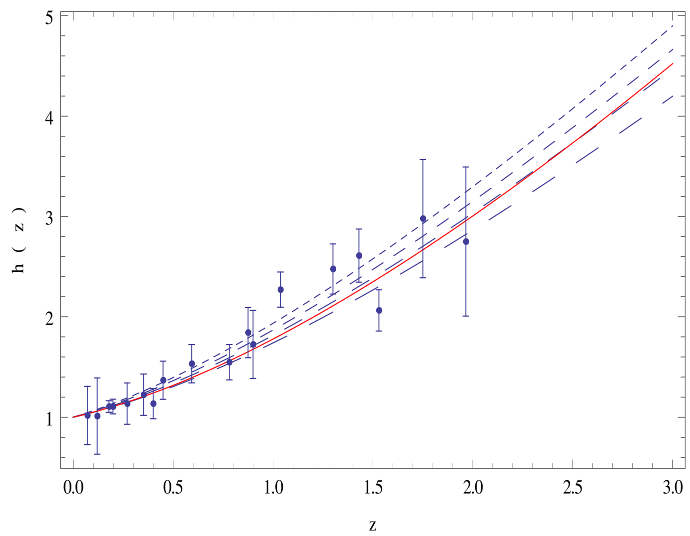
$\Rightarrow$ onshell, gauge fixing: again Einstein-Proca action, similar to Weyl theory but $\theta = 4$ (Weyl: $\theta = 1.$).

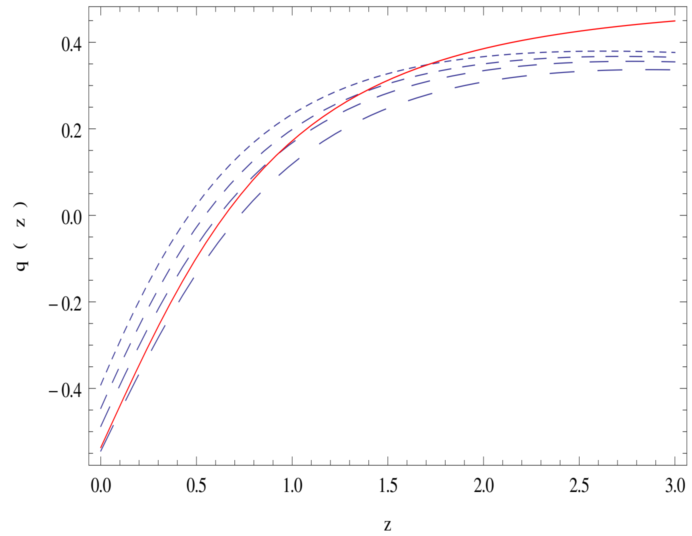
$\Rightarrow$ similar structure of V, θ different

$\Rightarrow$ In Palatini quadratic gravity: additional SI operators exist [Percacci 0910.5167 Bastero-Gill, Borunda, Janssen 0804.4440]

• Cosmological evolution: Weyl's theory versus ΛCDM [D.G., T. Harko, 2203.05381 [hep-th]]

Case: $\omega_\mu = (\omega_0, 0, 0, 0)$:





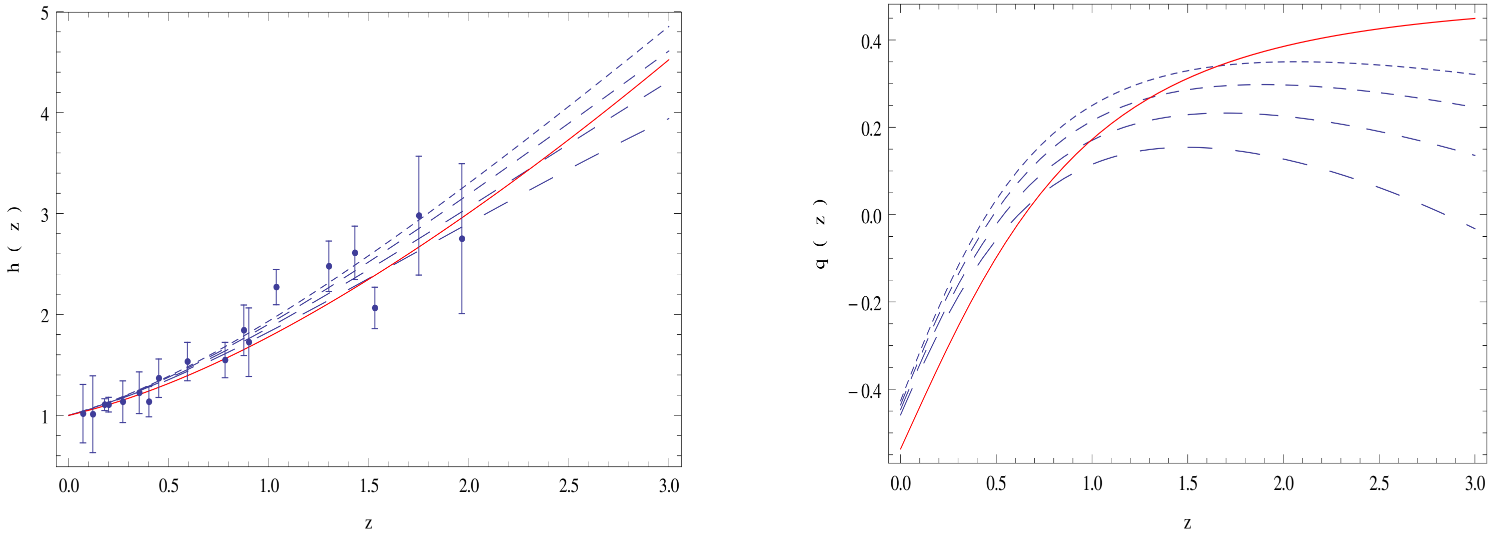
- left plot: Hubble function $h(z)$ for redshifts $z \leq 3$ in Weyl case (blue) and ΛCDM (in red)
- right plot: the deceleration $q(z)$ for redshifts $z \leq 3$ in Weyl case (blue) and ΛCDM (in red)

for suitable initial conditions.

$$H = H_0\, h, \qquad (H = \dot{a}/a); \qquad q(z) = (1+z)\frac{1}{h(z)}\,\frac{dh(z)}{dz} - 1.$$

• Cosmological evolution: Weyl's theory versus ΛCDM [D.G., T. Harko, 2203.05381 [hep-th]]

Case: $\omega_\mu = (\omega_0, 0, 0, \omega_3)$:



- left plot: Hubble function $h(z)$ for redshifts $z \leq 3$ in Weyl case (blue) and ΛCDM (in red)
- right plot: the deceleration $q(z)$ for redshifts $z \leq 3$ in Weyl case (blue) and ΛCDM (in red)

for suitable initial conditions. Results can be extended for more general ω_μ

$$\frac{\ddot{a}}{a} - 2\,\frac{\dot{\phi}_0^2}{\phi_0^2} - 3\,H\,\frac{\dot{\phi}_0}{\phi_0} - \frac{\phi_0^2}{12} = 0, \qquad \dot{\phi}_0(t) \sim \omega_0; \quad \phi_0^2(t) \to \Lambda/4 \ (t \to \infty).$$

- acceleration controlled by ω and ϕ_0 i.e. by Weyl geometry (both ω_μ and ϕ_0: geometric origin)
- in the early universe $\omega_\mu + \omega_\mu \to$ higgs + higgs: can alleviate any anisotropy due to ω_μ.