UNIVERSITAT DE BARCELONA

Institut de Ciències del Cosmos

Running Vacuum from QFT in curved spacetime: Phenomenological implications (σ_8 and H_0)

Joan Solà Peracaula

sola@fqa.ub.edu

Departament de Física Quàntica i Astrofísica (FQA) &
Institute of Cosmos Sciences (ICCUB), Universitat de Barcelona

Workshop on Standard Model and Beyond (Corfu August-September 2021)

Guidelines of the Talk

- Vacuum energy and the CC Problem
- Dynamical **DE** and Running Vacuum Models
- **Running Vacuum in QFT and beyond**
- **RVM** and ΛCDM troubles (H_0- and σ_8 tensions)
- Conclusions

Interpretation of Einstein's eqs.

$$\boxed{R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - \Lambda\, g_{\mu\nu} = 8\pi G_N\, T_{\mu\nu}}$$

1915 $\Downarrow$ 1917

Geometry $\Longleftrightarrow$ **Energy**

$$\nabla^{\mu} G_{\mu\nu} = 0, \text{ where } G_{\mu\nu} = R_{\mu\nu} - (1/2) g_{\mu\nu} R$$

$$\nabla_{\mu}\Lambda = \partial_{\mu}\Lambda = 0 \quad \Rightarrow \quad \Lambda = \text{const}\,. \quad !!$$

if $\nabla^{\mu}\left(G_N T_{\mu\nu}\right) = 0 \ldots$!!!

$$\rho_{\Lambda} = \frac{\Lambda}{8\,\pi\, G_N}$$

Cosmological Constant

Dark Energy

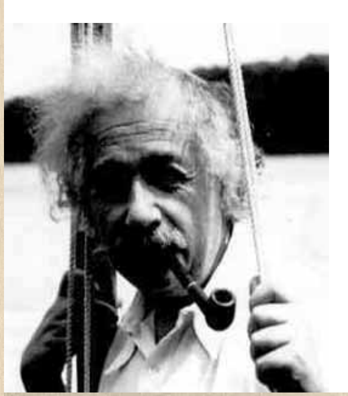
142 Sitzung der physikalisch-mathematischen Klasse vom 8. Februar 1917

$\Lambda\uparrow$

Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie.

Von A. Einstein.

Einstein: Zum kosmologischen Problem der allgemeinen Relativitätstheorie 235



$\Lambda\downarrow$

Zum kosmologischen Problem der allgemeinen Relativitätstheorie.

Von A. Einstein.

236 Gesamtsitzung vom 16. April 1931

14 yrs later !!

➢ The old CC problem as a fine tuning problem

The CC problem stems from realizing that the effective or physical vacuum energy is the sum of two terms:

$$\boxed{\rho_{\Lambda\mathrm{phys}} = \rho_{\Lambda\mathrm{vac}} + \rho_{\Lambda\mathrm{ind}}}$$

$$S_{EH} = \frac{1}{16\pi\, G_N}\int d^4x\sqrt{|g|}\,\left(R - 2\,\Lambda_{\mathrm{vac}}\right) = \int d^4x\sqrt{|g|}\left(\frac{1}{16\pi\, G_N}R - \rho_{\Lambda\mathrm{vac}}\right)$$

$$\boxed{\rho_{\Lambda\mathrm{vac}} = \frac{\Lambda}{8\pi\, G_N}}$$

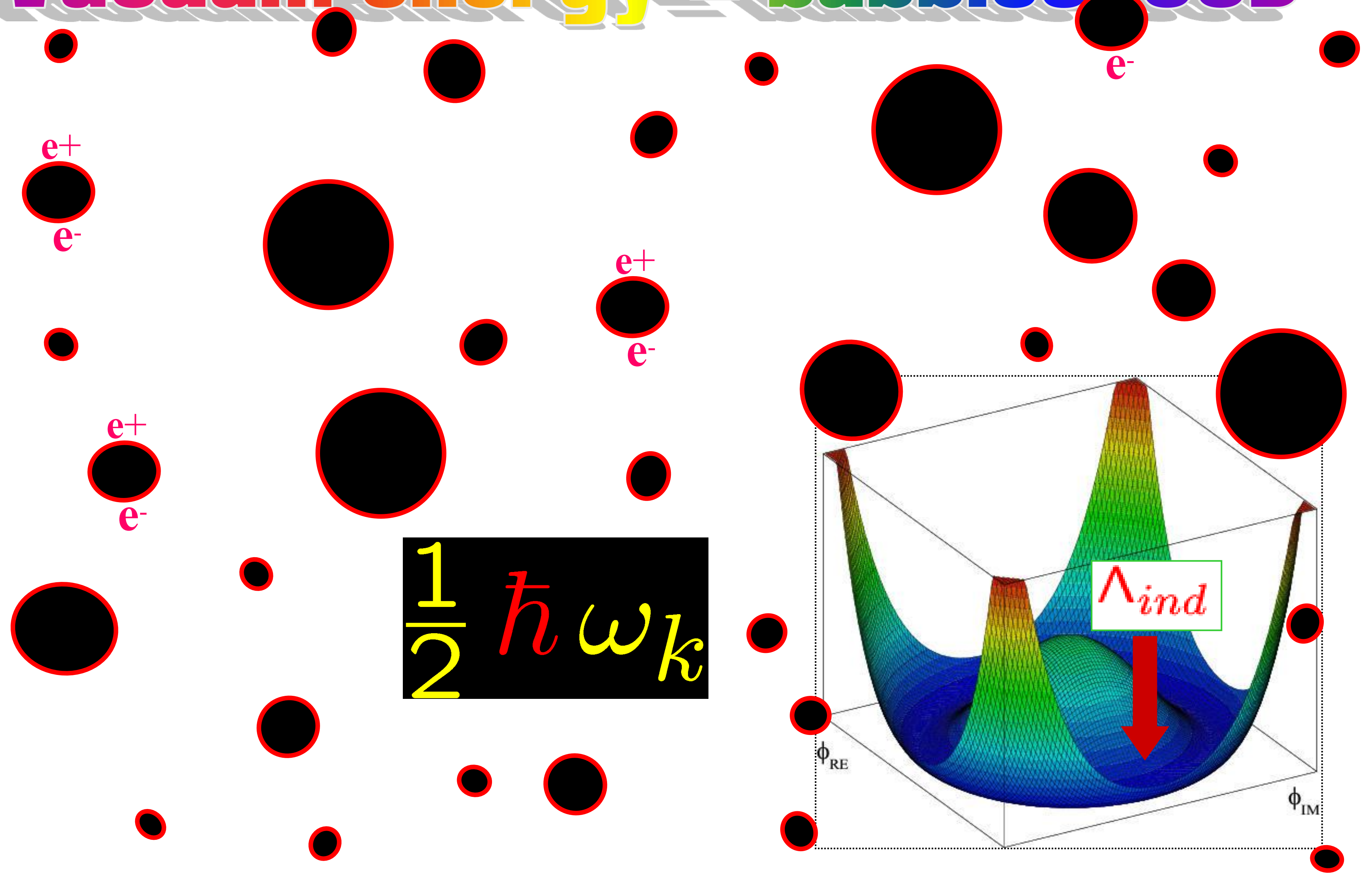
Vacuum bare term in Einstein eqs.

$$R_{ab} - \frac{1}{2}g_{ab}R = -8\pi\, G_N\left(\langle\tilde{T}^{\varphi}_{ab}\rangle + T_{ab}\right) = -8\pi\, G_N\, g_{ab}\left(\rho_{\Lambda\mathrm{vac}} + \rho_{\Lambda\mathrm{ind}} + T_{ab}\right)$$

Quantum effects $\Rightarrow$ $\rho_{\Lambda\mathrm{ind}} = \langle V(\varphi)\rangle + \mathrm{ZPE}$

...of quantum "bubles" !!
e+
e-
e+
e-
e+
e-
e+
e-
e+
e-
e+
e-
e+
e-
e+
e-
e+
e-
$\sum_k \frac{1}{2}\hbar\omega_k$
the quantum vacuum
is full!

Vacuum energy = bubbles+SSB



$$\frac{1}{2}\hbar\omega_k$$

Λ in the SM and beyond

Source	Effect (GeV^4)	Λ/Λ_{exp}
electron 0-point	10^{-16}	10^{31}
QCD chiral	10^{-4}	10^{43}
QCD gluon	10^{-2}	10^{45}
Electroweak SM	10^{+9}	10^{56}
typical GUT	10^{+64}	10^{111}
Quantum Gravity	10^{+76}	10^{123} !!

!!

$$\rho_\Lambda^0 = \Omega_\Lambda^0\,\rho_c^0 \simeq 6\,h^2 \times 10^{-47}\,\mathrm{GeV}^4 \simeq 3 \times 10^{-47}\,\mathrm{GeV}^4$$

$$\boxed{m_\Lambda \equiv \sqrt[4]{\rho_\Lambda^0} \simeq 2 - 3\ \mathrm{meV}}$$

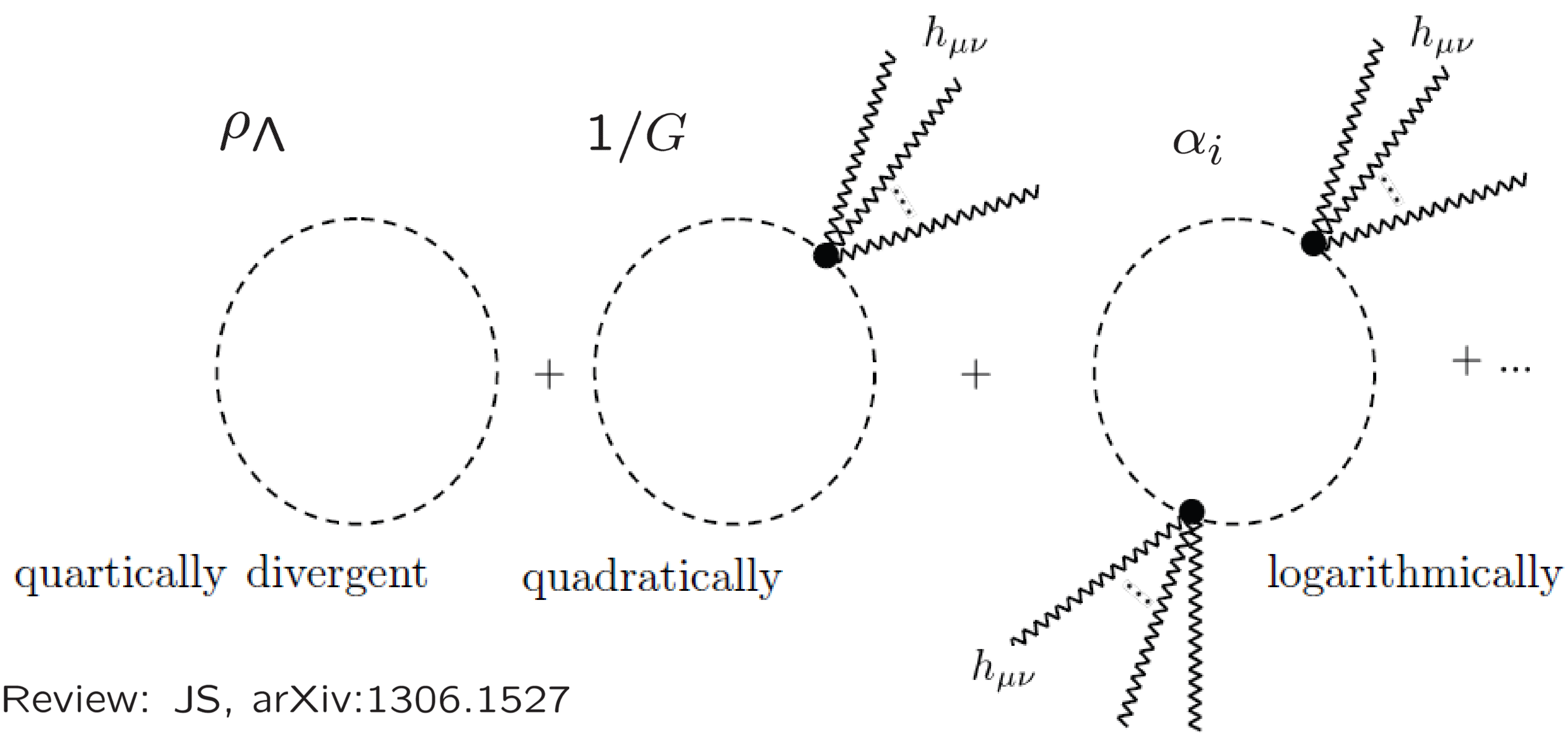
➢ Introducing an external gravitational field: QFT in curved spacetime!

In diagrammatic form, $\Rightarrow$ expansion $\sqrt{-g}$ around Minkowski space,

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

$$h = \eta^{\mu\nu} h_{\mu\nu}$$

$$\boxed{\sqrt{-g} = 1 + \frac{1}{2}h + \frac{1}{8}h^2 - \frac{1}{4}h_{\mu\nu}h^{\mu\nu} + \mathcal{O}\left(h^3\right)}$$



Review: JS, arXiv:1306.1527

RVM: inflation and cosmological expansion

Consider the class of time evolving vacuum models following a power series of the Hubble rate:

I. Shapiro and J. Solà (2000,2003,2009)

J. Solà and H. Stefancic (2005,2006)

J. Solà (2007) ...

$$\Lambda(H) = c_0 + c_1 H + c_2 H^2 + c_3 H^3 + c_4 H^4 + \ldots$$

JS, A. Gómez-Valent, J. de Cruz Pérez (2015-2019)
+ C. Moreno-Pulido (2019-2021)

Better fit than the ΛCDM and alleviates H_0 and σ_8-tensions

Reviews:

J. Solà (2011,2013,2014,,2016)

N. Mavromatos, J. Solà (2020)

(**"stringy-RVM" ...)**

Vacuum energy density: $\rho_\Lambda(H) = \Lambda(H)/(8\pi G)$

At low energy:

$$\Lambda(H) = c_0 + c_2 H^2 = \Lambda_0 + 3\,\nu\,(H^2 - H_0^2)$$

proposed (RG) equation for the vacuum energy density of the expanding Universe

$$\frac{d\rho_\Lambda(\mu)}{d\ln\mu^2} = \frac{1}{(4\pi)^2}\left[\sum_i B_i M_i^2\,\mu^2 + \sum_i C_i\,\mu^4 + \sum_i \frac{D_i}{M_i^2}\,\mu^6 \;+ \ldots\right]$$

$$\Downarrow \quad \mu^2 = aH^2 + b\dot{H}$$

(J. Solà, 2013,2014)

(J. Solà, A. Gómez-Valent, 2015)

$$\rho_\Lambda(H,\dot{H}) = \boxed{a_0} + a_1\,\dot{H} + \boxed{a_2\,H^2} + a_3\,\dot{H}^2 + \boxed{a_4\,H^4} + a_5\,\dot{H}\,H^2$$

$$\Downarrow \quad \mu^2 = H^2$$

$$\rho_\Lambda(H) = \frac{3}{8\pi G_N}\left(c_0 + \nu H^2 + \frac{H^4}{H_I^2}\right)$$

Distinctive from
Starobinsky's
inflation
!!

Can this be substantiated in QFT or string theory?

Adiabatic renormalization of the **VED** in QFT in a FLRW background: absence of quartic mass terms

C. Moreno-Pulido and JSP arXiv:2005.03164 (EPJ-C)

- The gravitational field equations read

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G_N T_{\mu\nu}^{matter},$$

where Λ is the Cosmological constant, with energy density $\rho_\Lambda \equiv \Lambda/(8\pi G_N)$. (this is not yet the physical VED)

Consider a toy-model (but non-trivial) calculation of the VED.

$$\Downarrow$$

- We will suppose that there is only one matter field contribution to the EMT in $T_{\mu\nu}^{matter}$ in the form of a real scalar field, ϕ.

(**nonminimal coupling** ξ)

$$S[\phi] = -\int d^4x \sqrt{-g} \left(\frac{1}{2} g_{\mu\nu} \partial_\nu \phi \partial_\mu \phi + \frac{1}{2}(m^2 + \xi R)\phi^2 \right)$$

(**no SSB contribution!**)

- The Energy-Momentum tensor (EMT) associated to the scalar field is

$$T_{\mu\nu}(\phi) = (1-2\xi)\,\partial_\mu\phi\partial_\nu\phi + \left(2\xi - \frac{1}{2}\right) g_{\mu\nu}\partial^\sigma\phi\partial_\sigma\phi$$
$$- 2\xi\nabla_\mu\nabla_\nu\phi + 2\xi g_{\mu\nu}\phi\Box\phi + \xi G_{\mu\nu}\phi^2 - \frac{1}{2}m^2 g_{\mu\nu}\phi^2.$$

- We can take into account the quantum fluctuations of the field ϕ by considering the expansion of the field around its background (or classical mean field) value ϕ,

$$\phi(\tau,\mathbf{x}) = \phi_b(\tau) + \delta\phi(\tau,\mathbf{x}),$$

$$\boxed{\langle T_{\mu\nu}^{vac}\rangle \equiv -\rho_\Lambda g_{\mu\nu} + \langle T_{\mu\nu}^{\delta\phi}\rangle.}$$

Total
vacuum contribution

(needs renormalization!!)

$$ds^2 = g_{\mu\nu}\,dx^\mu dx^\nu = a^2(\tau)\eta_{\mu\nu}\,dx^\mu dx^\nu \qquad \mathrm{sign}(g_{\mu\nu}) = (-,+,+,+)$$

Fluctuations split in Fourier modes:

$$\delta\phi(\tau,\mathbf{x}) = \frac{1}{(2\pi)^{3/2}a}\int d^3k\left[A_{\mathbf{k}}e^{i\mathbf{k}\mathbf{x}}h_k(\tau) + A_{\mathbf{k}}^{\dagger}e^{-i\mathbf{k}\mathbf{x}}h_k^*(\tau)\right]$$

$$(\Box - m^2 - \xi R)\delta\phi(\tau,x) = 0 \Rightarrow \boxed{h_k'' + \Omega_k^2 h_k = 0,}$$ (mode equation)

$$h_k' h_k^* - h_k h_k^{*\prime} = i$$

$$\Omega_k^2 \equiv k^2 + a^2m^2 + \boxed{a^2(\xi - 1/6)R}$$ (non-trivial!)

The solution is $$h_k(\tau) \sim \frac{e^{i\int^{\tau} W_k(\tau_1)d\tau_1}}{\sqrt{W_k(\tau)}},$$

$$W_k^2 = \Omega_k^2 - \frac{1}{2}\frac{W_k''}{W_k} + \frac{3}{4}\left(\frac{W_k'}{W_k}\right)^2$$

In order to solve this equation we should use the **WKB approximation** or **adiabatic regularization**. (slowly varying) Ω_k **!!**

$$W_k = \omega_k^{(0)} + \omega_k^{(2)} + \omega_k^{(4)} \ldots , \qquad \text{(\textbf{Adiabatic expansion})}^{(*)}$$

$$\left\{ \begin{aligned} \omega_k^{(2)} &= \frac{a^2\Delta^2}{2\omega_k} + \frac{a^2 R}{2\omega_k}(\xi - 1/6) - \frac{\omega_k''}{4\omega_k^2} + \frac{3\omega_k'^2}{8\omega_k^3} , \\ \omega_k^{(4)} &= -\frac{1}{2\omega_k}\left(\omega_k^{(2)}\right)^2 + \frac{\omega_k^{(2)}\omega_k''}{4\omega_k^3} - \frac{\omega_k^{(2)\prime\prime}}{4\omega_k^2} - \frac{3\omega_k^{(2)}\omega_k'^2}{4\omega_k^4} + \frac{3\omega_k'\omega_k^{(2)\prime}}{4\omega_k^3} . \end{aligned} \right.$$

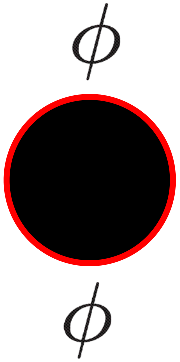
$$\left\{ \begin{aligned} &\omega_k^{(0)} \equiv \omega_k = \sqrt{k^2 + a^2 M^2}, \\ &\omega_k' = a^2\mathcal{H}\frac{M^2}{\omega_k}, \quad \omega_k'' = 2a^2\mathcal{H}^2\frac{M^2}{\omega_k} + a^2\mathcal{H}'\frac{M^2}{\omega_k} - a^4\mathcal{H}^2\frac{M^4}{\omega_k^3} . \end{aligned} \right.$$

The non-appearance of the odd adiabatic orders is justified by means of general covariance.

Explains why only even powers of H:

$$\boxed{\Lambda(H) = c_0 + \cancel{c_1 H} + c_2 H^2 + \cancel{c_3 H^3} + c_4 H^4 + \ldots}$$

(∗) Adiabatic methods: cf. Bunch, Parker, Fulling (70's), Birrell&Davies (80's) etc
Recent improv.: Ferreiro & Navarro-Salas etc (2019)



one-loop

$T_{00}^{\delta\phi}$ up to 4th adiabatic order:

$$\left\langle T_{00}^{\delta\phi}\right\rangle = \int dk k^2 \Big[|h_k'|^2 + \left(\omega_k^2 + a^2\Delta^2\right)|h_k|^2$$

$$\left(\xi-\frac{1}{6}\right)\left(-6\mathcal{H}^2|h_k|^2 + 6\mathcal{H}\left(h_k' h_k^* + h_k^{*\prime} h_k\right)\right)\Big]$$

unrenormalized

ZPE

UV-divergent !!

$$\begin{aligned}
\left\langle T_{00}^{\delta\phi}\right\rangle = \frac{1}{8\pi^2 a^2}\int dk k^2 \Bigg[& 2\omega_k + \frac{a^4M^4\mathcal{H}^2}{4\omega_k^5} - \frac{a^4M^4}{16\omega_k^7}\left(2\mathcal{H}''\mathcal{H} - \mathcal{H}'^2 + 8\mathcal{H}'\mathcal{H}^2 + 4\mathcal{H}^4\right) \\
& + \frac{7a^6M^6}{8\omega_k^9}\left(\mathcal{H}'\mathcal{H}^2 + 2\mathcal{H}^4\right) - \frac{105a^8M^8\mathcal{H}^4}{64\omega_k^{11}} \\
& + \left(\xi-\frac{1}{6}\right)\Bigg(-\frac{6\mathcal{H}^2}{\omega_k} - \frac{6a^2M^2\mathcal{H}^2}{\omega_k^3} + \frac{a^2M^2}{2\omega_k^5}\left(6\mathcal{H}''\mathcal{H} - 3\mathcal{H}'^2 + 12\mathcal{H}'\mathcal{H}^2\right) \\
& - \frac{a^4M^4}{8\omega_k^7}\left(120\mathcal{H}'\mathcal{H}^2 + 210\mathcal{H}^4\right) + \frac{105a^6M^6\mathcal{H}^4}{4\omega_k^9}\Bigg) \\
& + \left(\xi-\frac{1}{6}\right)^2\left(-\frac{1}{4\omega_k^3}\left(72\mathcal{H}''\mathcal{H} - 36\mathcal{H}'^2 - 108\mathcal{H}^4\right) + \frac{54a^2M^2}{\omega_k^5}\left(\mathcal{H}'\mathcal{H}^2 + \mathcal{H}^4\right)\right)\Bigg] \\
& + \frac{1}{8\pi^2a^2}\int dk k^2\Bigg[\frac{a^2\Delta^2}{\omega_k} - \frac{a^4\Delta^4}{4\omega_k^3} + \frac{a^4\mathcal{H}^2M^2\Delta^2}{2\omega_k^5} - \frac{5}{8}\frac{a^6\mathcal{H}^2M^4\Delta^2}{\omega_k^7} \\
& + \left(\xi-\frac{1}{6}\right)\left(-\frac{3a^2\Delta^2\mathcal{H}^2}{\omega_k^3} + \frac{9a^4M^2\Delta^2\mathcal{H}^2}{\omega_k^5}\right)\Bigg] + \ldots,
\end{aligned}$$

- We compute terms up to 4th order because the divergences are only present up to this adiabatic order.
- We define the renormalized ZPE in curved space-time at the scale M as follows:

$$\boxed{\langle T_{00}^{\delta\phi}\rangle_{Ren}(M) \equiv \langle T_{00}^{\delta\phi}\rangle(m) - \langle T_{00}^{\delta\phi}\rangle^{(0-4)}(M)}$$

$$\langle T_{00}^{\delta\phi}\rangle_{\rm Ren}(M) = \frac{a^2}{128\pi^2}\left(-M^4 + 4m^2M^2 - 3m^4 + 2m^4\ln\frac{m^2}{M^2}\right)$$
$$-\left(\xi-\frac{1}{6}\right)\frac{3\mathcal{H}^2}{16\pi^2}\left(m^2 - M^2 - m^2\ln\frac{m^2}{M^2}\right) + \left(\xi-\frac{1}{6}\right)^2\frac{9\left(2\mathcal{H}''\mathcal{H} - \mathcal{H}'^2 - 3\mathcal{H}^4\right)}{16\pi^2a^2}\ln\frac{m^2}{M^2} + \dots$$

$$\Downarrow$$

$$\boxed{\frac{1}{8\pi G_N(M)}G_{\mu\nu} + \rho_\Lambda(M)g_{\mu\nu} + a_1(M)H^{(1)}_{\mu\nu} = T^{\phi_b}_{\mu\nu} + \langle T^{\delta\phi}_{\mu\nu}\rangle_{\rm Ren}(M)}$$

Off-shell subtraction: $\Longrightarrow$ **Exploring different scales**

➤ Relating scales

$$\langle T_{\mu\nu}^{\delta\phi}\rangle_{\rm Ren}(M) - \langle T_{\mu\nu}^{\delta\phi}\rangle_{\rm Ren}(M_0) =$$

$$f_{G_N^{-1}}(m, M, M_0) G_{\mu\nu} + f_{\rho_\Lambda}(m, M, M_0) g_{\mu\nu} + f_{a_1}(m, M, M_0) H_{\mu\nu}^{(1)}$$

$$f_{G_N^{-1}}(m, M, M_0) = \left(\xi - \frac{1}{6}\right)\frac{1}{16\pi^2}\left[M^2 - M_0^2 - m^2 \ln\frac{M^2}{M_0^2}\right]$$

$$f_X(m, M, M_0) \equiv X(M) - X(M_0)$$

$$f_{\rho_\Lambda}(m, M, M_0) = \frac{1}{128\pi^2}\left(M^4 - M_0^4 - 4m^2(M^2 - M_0^2) + 2m^4 \ln\frac{M^2}{M_0^2}\right)$$

$$f_{a_1}(m, M, M_0) = \frac{-1}{32\pi^2}\left(\xi - \frac{1}{6}\right)^2 \ln\frac{M^2}{M_0^2}$$

Our definition of vacuum energy density was

$$\langle T_{\mu\nu}^{vac} \rangle \equiv -\rho_\Lambda g_{\mu\nu} + \langle T_{\mu\nu}^{\delta\phi} \rangle \qquad \rho_{vac}(M) = \rho_\Lambda(M) + \frac{\left\langle T_{00}^{\delta\phi} \right\rangle_{Ren}(M)}{a^2}$$

Relating two different scales one gets

$$\rho_{vac}(M) = \rho_{vac}(M_0) + \frac{3}{16\pi^2}\left(\xi - \frac{1}{6}\right) H^2 \left[M^2 - M_0^2 - m^2 \ln\frac{M^2}{M_0^2}\right]$$

$$\underbrace{- \frac{9}{16\pi^2}\left(\xi - \frac{1}{6}\right)^2 (\dot{H}^2 - 2H\ddot{H} - 6H^2\dot{H}) \ln\frac{M^2}{M_0^2}}_{\text{Adiabatic order 4:}}.$$

Absence of $\sim M^4$ contributions !!

$$\rho_\Lambda(H) = \frac{3}{8\pi G_N}\left(c_0 + \nu H^2 + \cancel{\frac{H^4}{H_I^2}}\right)$$

no $\sim H^4$ terms either !!

Early Universe

In the early universe, before and during inflation, it is assumed that only fields from the gravitational multiplet of the string exist, which implies that the relevant bosonic part of the effective action pertinent to the dynamics of the inflationary period is given by

$$S_B^{\rm eff} = \int d^4x\sqrt{-g}\Big[-\frac{1}{2\kappa^2}\,R + \frac{1}{2}\,\partial_\mu b\,\partial^\mu b + \sqrt{\frac{2}{3}}\,\frac{\alpha'}{96\,\kappa}\,b(x)\,R_{\mu\nu\rho\sigma}\,\widetilde{R}^{\mu\nu\rho\sigma} + \dots\Big]\,.$$

$$\alpha' = M_s^{-2} \qquad \kappa = \sqrt{8\pi G} = M_{\rm Pl}^{-1} \qquad M_{\rm Pl} \neq M_s \quad \text{in general}$$

It involves the usual Hilbert-Einstein term and the Kalb-Ramond axion field, $b(x)$, which is coupled to the **gravitational Chern-Simons topological density** through the string tension α'. Such topological term when averaged over the de Sitter spacetime produces an effective contribution to the vacuum energy density of the form $\sim H^4$.

During inflation $R_{\mu\nu\rho\sigma}\,\widetilde{R}^{\mu\nu\rho\sigma}$ triggers H^4 contributions to ρ_Λ

$\sim\ H^4$ terms are back !!

See talk by Nick Mavromatos tomorrow in CM3 !

Detailed review:

(N.E. Mavromatos and JSP)

"Stringy RVM"

arXiv:2012.07971 (EPJ-ST 2021)

- For instance let's fix $M_0 = M_X$, where $M_X \sim 10^{16} GeV$ is a GUT scale and is also associated to the inflationary scale.

- The second scale can be fixed at $M = H_0$, at today's value of Hubble parameter, which estimates the energy scale of the background gravitational field of our FLRW universe.

- Neglecting $\mathcal{O}(H_0^4)$ terms

for the current universe

$$\boxed{\rho_{vac}(H) \simeq \rho^0_{\rm vac} + \frac{3\nu_{\rm eff}}{8\pi}\left(H^2 - H_0^2\right) M_P^2 = \rho^0_{\rm vac} + \frac{3\nu_{\rm eff}}{8\pi G_N}\left(H^2 - H_0^2\right)}$$

RVM structure !!

J. Solà (2011,2013,2014,,2016)

from action: 0710.4151

(J.Phys.A **41** (2008) 164066)

$$\boxed{\nu_{\rm eff}(H) = \frac{1}{2\pi}\left(\frac{1}{6} - \xi\right)\frac{M_X^2}{M_P^2}\left(1 + \frac{m^2}{M_X^2}\ln\frac{H^2}{M_X^2}\right)}$$

naturally small parameter

Minimal unified model at high energy (early universe):

S. Basilakos, J.A.S Lima, and JS arXiv:1509.00163, arXiv:1307.6251
JS and A. Gómez-Valent arXiv:1501.03832
JS arXiv:1505.05863
JS and H. Yu arXiv:1910.01638

$$\boxed{\Lambda(t) = c_0 + 3\nu H^2 + 3\alpha \frac{H^4}{H_I^2}}$$

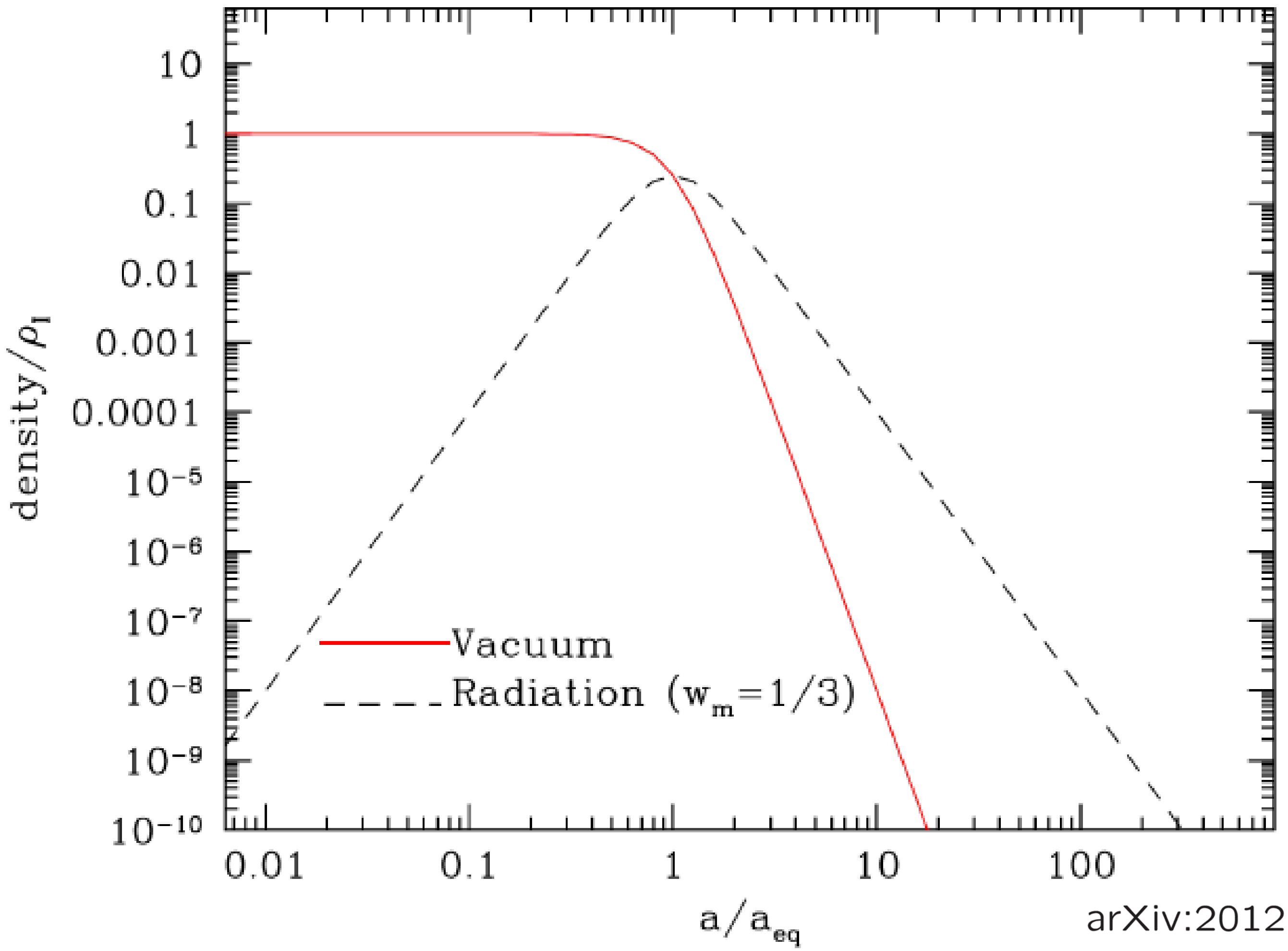
$$\Downarrow$$

$$\dot{H} + \frac{3}{2}(1+\omega_m)H^2\left[1 - \nu - \frac{c_0}{3H^2} - \alpha\frac{H^2}{H_I^2}\right] = 0$$

Inflationary solution: $H^2 = (1-\nu)H_I^2/\alpha$!!

$a(t) \propto e^{H_I t}.$

RVM inflation



arXiv:2012.07971 (EPJ ST)

Running vacuum energy at the expense of matter non-conservation

$$\boxed{\rho_\Lambda = C_1 + C_2\, H^2\,.}$$

$$\rho_\Lambda(H) = \frac{3}{8\pi G}\left(c_0 + \nu H^2\right)$$

$\Big\downarrow$ Bianchi identity

$$\dot\rho_\Lambda + \dot\rho_m + 3\,H(\rho_m + p_m) = 0$$

(matter non-conservation!!)

$$C_2 \propto \nu = \frac{M^2}{12\pi\, M_P^2}$$

$$\rho_m(z) = \rho_m^0\,(1+z)^{3(1-\nu)}$$

and “running“ vacuum energy: (**RVM**)

$$\rho_\Lambda(z) = \rho_\Lambda^0 + \frac{\nu\,\rho_m^0}{1-\nu}\left[(1+z)^{3(1-\nu)} - 1\right]$$

RVM: More on solving the H_0- and σ_8 tensions

(EPL 134 (2021) 19001)

General form at low energies:

$$\rho_{\rm vac}(H) = \frac{3}{8\pi G_N}\left(c_0 + \nu H^2 + \tilde{\nu}\dot{H}\right) + \mathcal{O}(H^4)$$

particular choice $\tilde{\nu} = \nu/2$

- Type I RVM: vacuum decay into cold dark matter

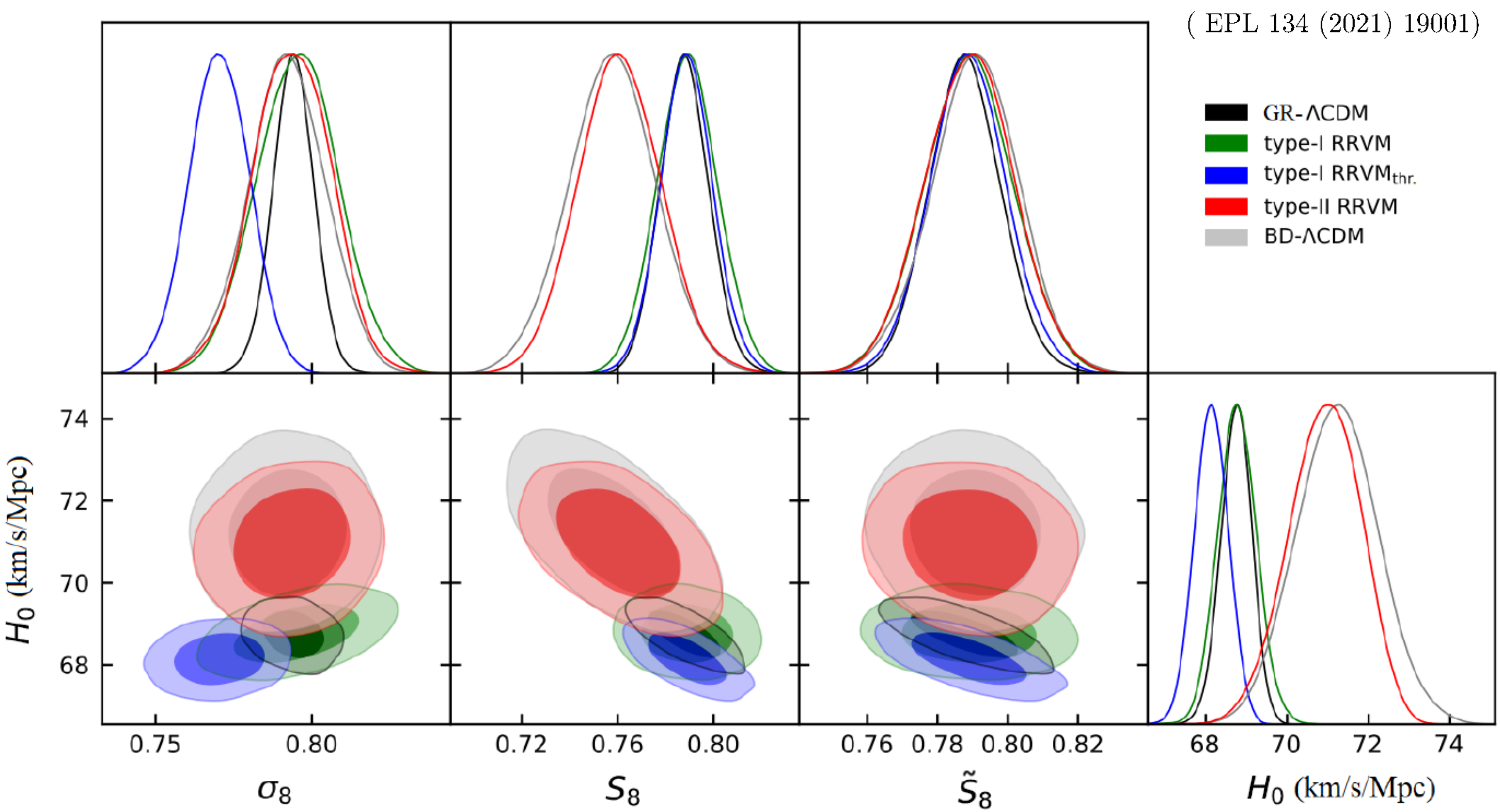
$$\dot{\rho}_{dm} + 3H\rho_{dm} = -\dot{\rho}_{\rm vac}$$

with threshold redshift $z_* \simeq 1$
(or without)

- Type II RVM: running vacum and G

$$\nu_{\rm eff} \equiv \nu/4 \qquad \varphi = G_N/G \xrightarrow{\text{Bianchi}} \frac{\dot{\varphi}}{\varphi} = \frac{\dot{\rho}_{\rm vac}}{\rho_t + \rho_{\rm vac}}$$

$$\boxed{\begin{aligned}&\rho_{\rm vac}(a) = C_0(1+4\nu_{\rm eff}) + \nu_{\rm eff}\,\rho_m^0\, a^{-3}\\ &\varphi(a) \propto a^{-\epsilon} \approx 1 - \epsilon \ln a\end{aligned}}$$



Type II RVM can alleviate **both tensions** at a time **!!**

Summarized conclusions

- **Dynamical DE**: natural proposal for an **expanding Universe**
- The **RVM** based on a **running Λ** term in interaction with matter or **G** is theoretically **well motivated**
- **Running vacuum models** seem to describe **better** the observations SNIa+BAO+$H(z)$+LSS+CMB **than the ΛCDM**
- Provide a **consistent solution** to the main **tensions**
- These ideas may signal a **connection** between the the **LSS** of the Universe and the **quantum phenomena** in the **microcosmos**