Non-dynamical torsion from fermions and CMBR phenomenology

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based on

P. Dona & A. Marciano, arXiv:1605.09337 (PRD 2016)

A. Addazi, P. Chen & A. Marciano, arXiv:1712.04848

works in progress…

Kavli-IPMU, 11th of March 2019

Separate Universe assumption

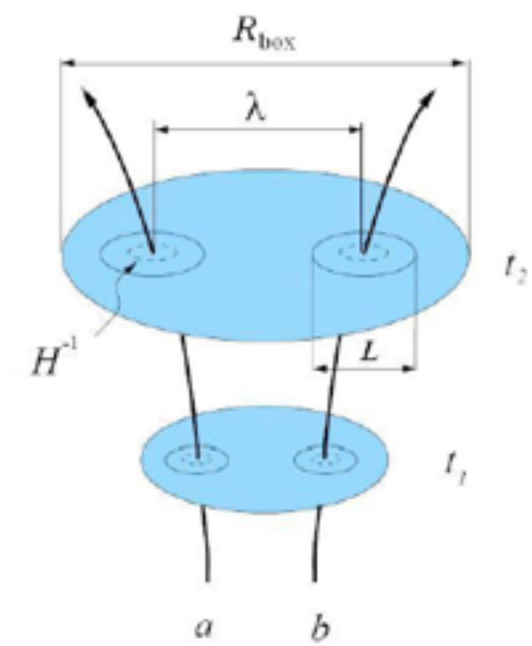
$$ds^2 = N^2 dt^2 - \gamma_{ij}(dx^i + N^i dt)(dx^j + N^j dt)$$

ADM decomposition

$$K_{ij} = -\nabla_{(j} n_{i)} = \frac{1}{2N}\left(-\partial_t \gamma_{ij} + {}^{(3)}\nabla_{(i} N_{j)} + {}^{(3)}\nabla_{(j} N_{i)}\right)$$

$$K_{ij} = -\frac{\theta}{3}\gamma_{ij} + A_{ij} \qquad \theta = \frac{3}{N}\left(\frac{\dot a(t)}{a(t)} + \dot\psi\right)$$

$$N(t_1, t_2; x_j) = \frac{1}{3}\int_{\gamma(\tau)} \theta d\tau, \qquad n_\mu = (N, 0)$$



Perturbations

$$\epsilon = k/(a\,H)$$

$$\gamma_{ij} = a(t, x_i)\,\tilde\gamma_{ij}, \quad \tilde\gamma_{ij} = (e^h)_{ij}, \quad a(t, x_i) = a(t)\,e^{\psi(t, x_i)}$$

Curvature perturbation variable

Lyth, Malik & Sasaki, JCAP 2015

$$\nabla_\mu T^{\mu\nu} = 0$$

→

$$\frac{d\rho(t,x_i)}{dt} + 3\tilde{H}(t,x_i)[\rho(t,x_i) + p(t,x_i)] = 0$$

$$\frac{d\rho(t)}{dt} + 3\frac{\dot{a}(t)}{a(t)}[\rho(t) + p(t)] = \dot{\psi}(t)$$

Uniform density slicing & adiabatic pressure

$$\psi(t_2,x^i) - \psi(t_1,x^i) = -\ln\left[\frac{a(t_2)}{a(t_1)}\right] - \frac{1}{3}\int_{\rho(t_1,x^i)}^{\rho(t_2,x^i)} \frac{d\rho}{\rho + p}$$

↓

$$-\zeta(x^i) = \psi(t,x^i) + \frac{\delta\rho}{3(\rho + p)}$$

Macroscopic quantum states of matter I

Dona & Marciano, arXiv:1605.09337 (PRD 2016)

I Classical background fields correspond to expectation values on macroscopic (condensed) states

$$\phi(x) := \langle \alpha | \hat{\phi} | \alpha \rangle$$

II Matter perturbations are evaluated as the the first order expansion of the expectation values on perturbed macroscopic states

$$\delta\phi(x) := \langle \alpha + \delta\alpha | \hat{\phi} | \alpha + \delta\alpha \rangle |_{O(\delta\alpha)}$$

Macroscopic quantum states of matter II

Dona & Marciano, arXiv:1605.09337 (PRD 2016)

III **Density matrix and infrared mode of the macroscopic state**

$$\rho_{1-\mathrm{p}}(x-x') \;=\; \int_{k,k'} e^{-\imath(kx-k'x')}\langle a^\dagger_k a_{k'}\rangle$$

$$\rho_{1-\mathrm{p}}(t-t';\vec{x}-\vec{x}') = \frac{N_0}{V} + \int_k e^{-\imath\vec{k}\cdot(\vec{x}-\vec{x}')}\,n(k)$$

II **Off-diagonal long ranged order (ODLRO) and vanishing of correlations at large space-time distances**

$$\lim_{||x-x'||\to\infty} \rho_{1-\mathrm{p}}(t-t';\vec{x}-\vec{x}') = \langle\phi(x)\phi^\dagger(x')\rangle_0 \equiv n_0$$

Bosonic statistics and coherent states

Dona & Marciano, arXiv:1605.09337 (PRD 2016)

$$\phi\left(x\right)=\int\frac{d^3k}{\left(2\pi\right)^3}\frac{1}{\sqrt{2E_k}}\left(a_k e^{-ikx}+a_k^\dagger e^{+ikx}\right)$$

Scalar field

Bosonic Hilbert space and infinite occupation numbers

$$\left|\alpha\right\rangle\equiv\prod_k\left|\alpha\left(k\right)\right\rangle=\prod_k e^{\alpha(k)a_k^\dagger-\alpha^*(k)a_k}\left|0\right\rangle=D\left(\alpha\right)\left|0\right\rangle$$

Displacement operator

$$D\left(\alpha\right)^\dagger\phi\left(x\right)D\left(\alpha\right)=\phi\left(x\right)+\phi_\alpha\left(x\right)$$

$$\left\langle\alpha\right|\mathcal{O}\left(\phi\left(x\right)\right)\left|\alpha\right\rangle=\left\langle 0\right|\mathcal{O}\left(\phi\left(x\right)+\phi_\alpha\left(x\right)\right)\left|0\right\rangle$$

Matter perturbations at linear order

Dona & Marciano, arXiv:1605.09337 (PRD 2016)

$$\delta G_{\mu\nu} = \frac{8\pi G}{c^4} \langle \alpha + \delta\alpha | \widehat{T_{\mu\nu}(\phi)} | \alpha + \delta\alpha \rangle \Big|_{\mathrm{O}(\delta\alpha)}$$

Expanding perturbations in the conservation equation

$$3(\zeta + \psi)\langle \alpha | \widehat{\rho} + \widehat{p} \,| \alpha \rangle = -\langle \alpha + \delta\alpha | \widehat{\rho} | \alpha + \delta\alpha \rangle \Big|_{\mathrm{O}(\delta\alpha)}$$

Example: Chaotic Inflation

$$\langle \alpha + \delta\alpha | \, \widehat{\rho} \, | \alpha + \delta\alpha \rangle = \lim_{x \to y} \frac{1}{2} m^2 \, \langle \alpha + \delta\alpha | \, \widehat{\phi}(x) \, \widehat{\phi}(y) \, | \alpha + \delta\alpha \rangle = \frac{1}{2} m^2 \, [\phi_{\alpha+\delta\alpha}(x)]^2$$

Power spectrum of scalar perturbations

Dona & Marciano, arXiv:1605.09337 (PRD 2016)

$$-\widehat{\Xi} = \widehat{\mathbb{1}}\,\psi(t, x^i) + \frac{\widehat{\rho}}{3\langle\alpha|\widehat{\rho} + \widehat{p}\,|\alpha\rangle}$$

Slow-roll condition

$$\langle\alpha|\ddot{\hat{\phi}} + 3H\dot{\hat{\phi}} + \widehat{V'(\phi)}|\alpha\rangle = 0 \quad \longrightarrow \quad 3H\phi_\alpha \simeq -V(\phi_\alpha)$$

Power spectrum

$$\mathcal{P}_\zeta = \lim_{x\to y} \langle\alpha + \delta\alpha|\,\widehat{\Xi}(x)\,\widehat{\Xi}(y)\,|\alpha + \delta\alpha\rangle\Big|_{O(\delta\alpha^2)}$$

Fermion fields and linear perturbations

Alexander, Brandenberger, Calcagni, Hui, Nicolis, Piazza, Prokopec, Sasaki, etc...

I Pressure perturbations (non adiabatic) and conservation of curvature perturbations

$$\dot{\zeta} = -\frac{H}{\rho + p}\delta p_{\rm na}$$

II A no-go argument:

$$\delta\phi \rightarrow \delta(\bar{\psi}\psi) = \delta\bar{\psi}\,\psi + \bar{\psi}\,\delta\psi$$

$$\psi(t) = \langle\alpha|\hat{\psi}|\alpha\rangle = \langle\alpha|R^\dagger(\varphi)\,R(\varphi)\hat{\psi}R^\dagger(\varphi)\,R(\varphi)|\alpha\rangle|_{\varphi=2\pi} = -\psi(t)$$

Fermion fields & macroscopic coherent states I

Dona & Marciano, arXiv:1605.09337 (PRD 2016)

Pauli exclusion principle and quasi particles

$$a_k^\dagger \quad \rightarrow \quad c_k^\dagger = a_{k\uparrow}^\dagger b_{-k\downarrow}^\dagger$$

BCS states as macroscopic coherent states

$$|\alpha\rangle \equiv e^{\int d^3k\, \alpha(k) c_k^\dagger - \alpha^*(k) c_k} |0\rangle = D(\alpha)|0\rangle$$

$$J_1 = \frac{1}{2}\left(a^\dagger b^\dagger + h.c.\right), \quad J_2 = -\frac{i}{2}\left(a^\dagger b^\dagger - h.c.\right), \quad J_3 = \frac{1}{2}\left(a^\dagger a + b^\dagger b - 1\right), \quad [J_i,\ J_j] = i\epsilon_{ij}{}^k J_k$$

BCS states are SU(2) coherent states

$$|\hat{n}\rangle = D(\hat{n})\,|j,-j\rangle = |\xi\rangle = \exp\left(\xi J^+ - \bar{\xi} J^-\right)|j,-j\rangle$$

Fermion fields & macroscopic coherent states II

Dona & Marciano, arXiv:1605.09337 (PRD 2016)

Linear perturbations and SU(2) rotations

$$\langle \hat{n} | \bar{\psi} \psi | \hat{n} \rangle = \int_k \vec{\zeta}_k \cdot \langle \hat{n} | \vec{J}_k | \hat{n} \rangle = \int_k \vec{\zeta}_k \cdot \hat{n}_k$$

$$|\hat{n} + \delta\hat{n}\rangle \equiv D(\delta\hat{n}) |\hat{n}\rangle = |R(\hat{z}, \delta\hat{n})\, \hat{n}\rangle$$

$$\langle \hat{n} + \delta\hat{n} | \vec{J} | \hat{n} + \delta\hat{n} \rangle \approx \hat{n} + \delta\hat{n} \times \hat{n} = \hat{n} - \hat{n} \times \langle \delta\hat{n} | \vec{J} | \delta\hat{n} \rangle$$

Bogolubov transformations & non-BD states

Dona & Marciano, arXiv:1605.09337 (PRD 2016)

Adjoint action of displacement operators

$$D(\alpha)^{\dagger} a_k D(\alpha) = a_k + \alpha(k)$$

$$D(\alpha)^{\dagger} a_k^{\dagger} D(\alpha) = a_k^{\dagger} + \alpha^{*}(k)$$

U(1) bosonic case

$$\tilde{a} = \cos(|\xi|)\, a + \frac{\xi}{|\xi|} \sin(|\xi|)\, b^{\dagger}$$

$$\tilde{b}^{\dagger} = \cos(|\xi|)\, a - \frac{\bar{\xi}}{|\xi|} \sin(|\xi|)\, b^{\dagger}$$

SU(2) fermionic case

The macroscopic state obtained is the Bogolubov transform of the vacuum

Gravity with non-dynamical torsion I

Rovelli & Perez, CQG 2005; Freidel & Minic, PRD 2005

$$\mathcal{S}_{\text{Holst}} = \frac{1}{2\kappa}\int_M d^4x\, |e|\, e^\mu_I e^\nu_J P^{IJ}{}_{KL} F_{\mu\nu}{}^{KL}(\omega)$$

$$P^{IJ}{}_{KL} = \delta^{[I}_K \delta^{J]}_L - \epsilon^{IJ}{}_{KL}/(2\gamma)$$

$$\mathcal{S}_{\text{Dirac}} = \int_M d^4x\, |e| \left\{ \frac{1}{2}\left[\overline{\psi}\gamma^I e^\mu_I \left(1 - \frac{\imath}{\alpha}\gamma_5\right)\imath\nabla_\mu\psi - m\overline{\psi}\psi\right] + \text{h.c.}\right\}$$

Theory with torsion!

[Alexander, Biswas, Cai, Magueijo, Prokopec, Kibble, Poplawski, Qiu…]

Gravity with non-dynamical torsion II

S. Alexander, Y. Cai & A. Marciano PLB 2015

Theory with torsion

$$e^{\mu}_{I}\, C_{\mu JK} = \frac{\kappa}{4}\,\frac{\gamma}{\gamma^2+1}\,\left(\beta\,\epsilon_{IJKL}\,J^L - 2\theta\,\eta_{I[J}\,J_{K]}\right)$$

$$J^L = \overline{\psi}\gamma^L\gamma_5\psi$$

$$\mathcal{S}_{GR} = \frac{1}{2\kappa}\int_M d^4x|e|e^{\mu}_{I}e^{\nu}_{J}R^{IJ}_{\mu\nu}$$

$$\mathcal{S}_{\rm Dirac} = \frac{1}{2}\int_M d^4x|e|\left(\,\overline{\psi}\gamma^I e^{\mu}_{I}\imath\widetilde{\nabla}_{\mu}\psi - m\overline{\psi}\psi\right) + \text{h.c.}$$

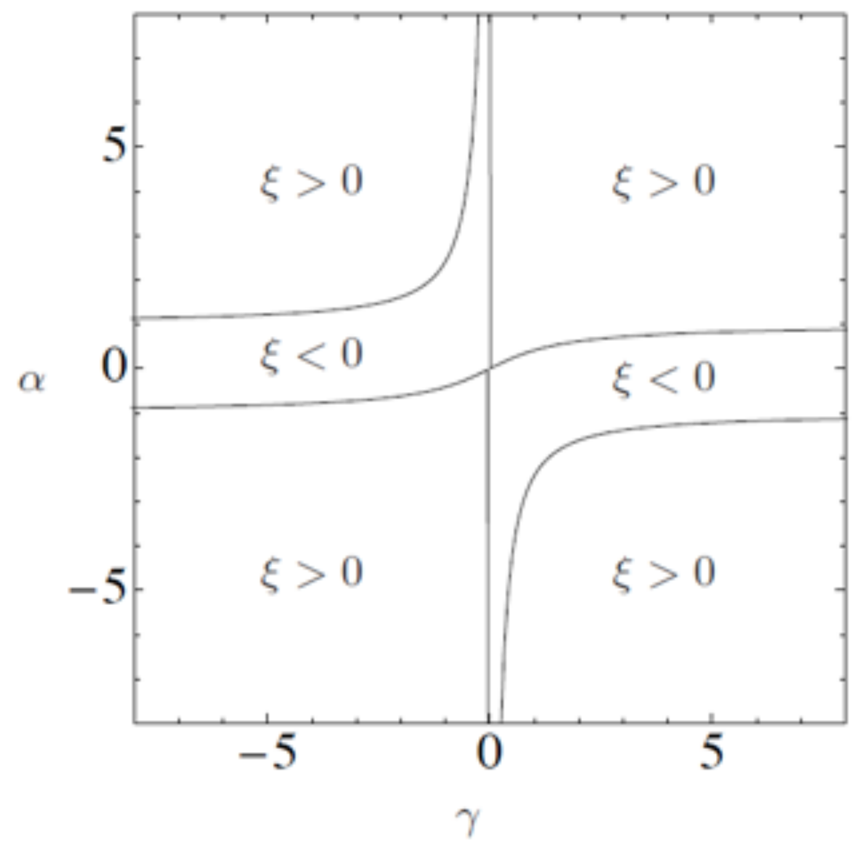
$$\mathcal{S}_{\rm Int} = -\xi\kappa\int_M d^4x|e|\,J^L\,J^M\,\eta_{LM}$$

Gravity with non-dynamical torsion III

S. Alexander, C. Bambi, A. Marciano & L. Modesto, [arXiv:1402.5880] PRD 90 (2014) 123510

A. Addazi, S. Alexander, Y. Cai & A. Marciano, arXiv: 1712.04848 (CPC 2018)

A. Addazi & A. Marciano, arXiv:1810.05513



$$\xi = \frac{3}{16}\frac{\gamma^2}{\gamma^2+1}\left(1+\frac{2}{\alpha\gamma}-\frac{1}{\alpha^2}\right)$$

NJL mechanism applied to SM fermions

A. Addazi, P. Chen & A. Marciano, arXiv:1712.04848

$$\int \sqrt{-g} d^4x \bar{\Psi}(\imath\gamma^\mu(x)\nabla_\mu - M)\Psi + \frac{\lambda}{2N_f}[(\bar{\Psi}\Psi)(\bar{\Psi}\Psi) + (\bar{\Psi}\imath\gamma_5\Psi)(\bar{\Psi}\imath\gamma_5\Psi)]$$

N_f number of fermions of the SM

$\downarrow$

$\lambda = \xi\kappa$

$$\int \sqrt{-g}\, d^4x\, [\bar{\Psi}\imath\gamma^\mu(x)\nabla_\mu\Psi - \frac{N_f}{2\lambda}(|\Pi|^2 + |\Sigma|^2) - \bar{\Psi}(\Sigma + \imath\gamma_5\Pi)\Psi]$$

Effective potential I

A. Addazi, P. Chen & A. Marciano, arXiv:1712.04848

Integrating out fermionic DOF

$$S_{\text{eff}} = \int d^4x\sqrt{-g}\{-\frac{1}{\lambda}(|\Pi|^2 + |\Sigma|^2) \\ -\imath \ln \mathrm{Det}\{\imath I \gamma^\mu(x)\nabla_\mu - (\Sigma + \imath\gamma_5\Pi)\}\}$$

with negligible corrections controlled by the number of fermions

$$S_{\text{eff}}[\Pi, \Sigma] + O(1/N_f)$$

$$\downarrow$$

$$V(\Pi, \Sigma) = \frac{1}{2\lambda}(|\Pi|^2 + |\Sigma|^2) + \imath \mathrm{Tr} \ln\langle x|\imath\gamma^\mu(x) I \nabla_\mu - (\Sigma + \imath\gamma_5\Pi)|z\rangle$$

Effective matrix potential

Effective potential II

A. Addazi, P. Chen & A. Marciano, arXiv:1712.04848

Π, Σ classical slowly varying fields

Introduce $A = \Sigma + \imath\gamma_5\Pi$ and estimate the trace within the proper time method

$$V = \frac{1}{2\lambda}(|\Pi|^2 + |\Sigma|^2) - \imath \mathrm{Tr} \ln S(x, x, A)$$

$$S(x, y; A) = \langle x|(\imath I\gamma^\mu \nabla_\mu - A)^{-1}|y\rangle$$

where the propagator is associate the classical matrix equation

$$(\imath I\gamma^\mu(x)\nabla_\mu - A)S(x, y; A) = I\frac{1}{\sqrt{-g(x)}}\delta^4(x - y)$$

Effective potential III

A. Addazi, P. Chen & A. Marciano, arXiv:1712.04848

The calculate the propagator, one performed the background expansion $A = \bar{A} + \delta A$

$$\ln \mathrm{Det}\,\{\imath I\gamma^{\mu}(x)\nabla_{\mu} - A\} = \mathrm{Tr}\ln\{\imath I\gamma^{\mu}\nabla_{\mu} - A\}$$

$$= \mathrm{Tr}\ln\{\imath I\gamma^{\mu}(x)\nabla_{\mu} - A\} - \int d^4 \mathrm{Tr}\{\delta A(x)\, S_F(x,x)\}$$

$$-\frac{1}{2}\int d^4x \int d^4y\, \delta A(x)\, S_F(x,y)\, \delta A(y)\, S_F(y,x) + \ldots$$

with fermion propagator

$$\sqrt{-g}(\imath I\gamma^{\mu}(x)\nabla_{\mu} - M)S_F(x,y) = \imath\delta^4(x-y)I$$

Effective potential IV

A. Addazi, P. Chen & A. Marciano, arXiv:1712.04848

In the large N one can calculate the bubble diagram x into x

$$S(x,x;A) = \int \frac{d^4q}{(2\pi)^4}\Big[(I\gamma^a q_a + A)\frac{1}{q^2-|A|^2} - \frac{1}{12}R(I\gamma^a q_a + A)\frac{1}{(q^2-|A|^2)^2} + \frac{2}{3}R_{\mu\nu}q^\mu q^\nu (I\gamma^a q_a + A)\frac{1}{(q^2-|A|^2)^3} - \frac{1}{8}\gamma^a[\gamma^c,\gamma^d]R_{cda\mu}q^\mu \frac{1}{(q^2-|A|^2)^2}\Big]$$

within the weakly varying curvature approximation $\dot{R} \simeq 0$

$$V(A) = \tilde{V}(A) - \frac{1}{(4\pi)^2}\frac{R}{6}\left[-|A|^2 \ln\left(1+\frac{\Lambda^2}{|A|^2}\right) + \frac{\Lambda^2|A|^2}{\Lambda^2+|A|^2}\right]$$

$$\tilde{V} = V_0 + \frac{1}{2\lambda}|A|^2 - \frac{1}{4\pi^2}\left[|A|^2\Lambda^2 + \Lambda^4 \ln\left(1+\frac{|A|^2}{\Lambda^2}\right) - |A|^4 \ln\left(1+\frac{\Lambda^2}{|A|^2}\right)\right]$$

Inflaton from SM fermions

A. Addazi, P. Chen & A. Marciano, arXiv:1712.04848

In FLRW, impose either a custodial global symmetry or a gauge flavor symmetry

↓

$$V(a) = V_0 + \frac{1}{2\lambda}|a|^2$$
$$-\frac{1}{4\pi^2}\left[|a|^2\Lambda^2 + \Lambda^4 \ln\left(1+\frac{|a|^2}{\Lambda^2}\right) - |a|^4 \ln\left(1+\frac{\Lambda^2}{|a|^2}\right)\right]$$
$$-\frac{1}{(4\pi)^2}(\dot{H}+2H^2)\left[-|a|^2 \ln\left(1+\frac{\Lambda^2}{|a|^2}\right) + \frac{\Lambda^2|a|^2}{\Lambda^2+|a|^2}\right],$$

$$\Lambda^2 = c(\xi\kappa)^{-1}$$

↓

$$\frac{\epsilon[a]}{M_{Pl}^2} = \frac{1}{2}\left(\frac{V'[a]}{V[a]}\right)^2, \quad \frac{\eta[a]}{M_{Pl}^2} = \frac{V''[a]}{V[a]}$$

Consistency with data on CMBR

A. Addazi, P. Chen & A. Marciano, arXiv:1712.04848

$$\Delta_R^2 \simeq \frac{V_0}{24\pi^2 M_{Pl}^4 \epsilon} \qquad \Delta^2_{R,\,\mathrm{exp}} = 2,215 \times 10^{-9}$$

$$\epsilon = 1/(2N/3+1)^{3/2} \qquad \eta = -1/(2N/3+1)$$

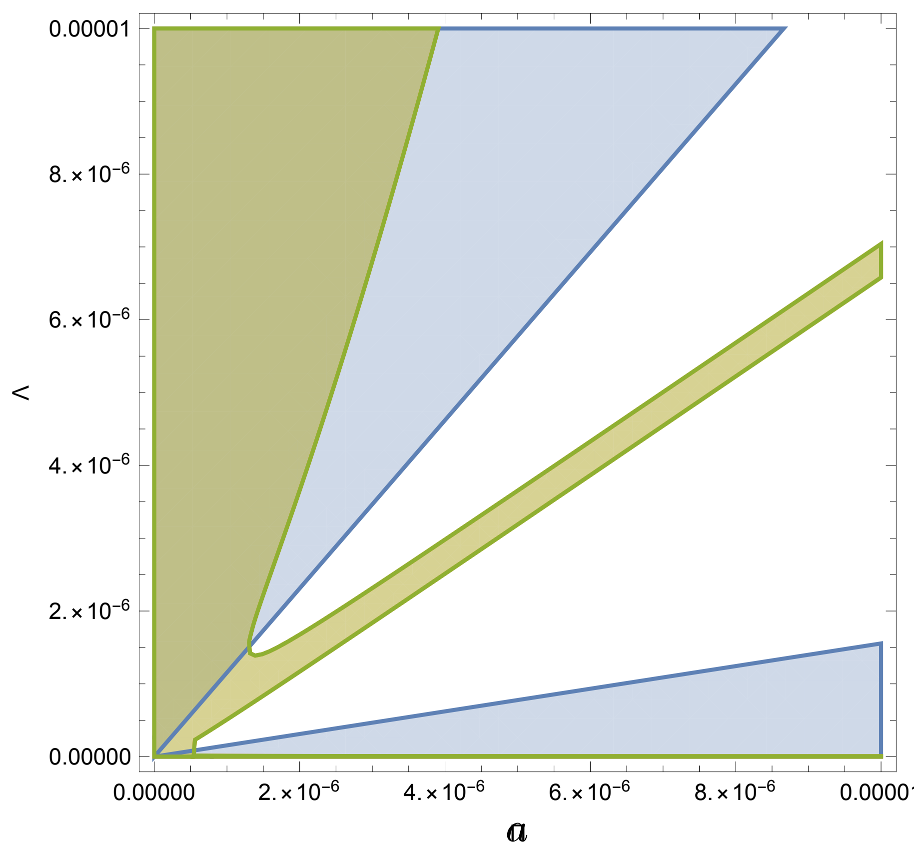
$$n_s - 1 = -2\,\epsilon - \eta \qquad n_{s,\mathrm{exp}} = 0.968 \pm 0.006$$

$$N = \frac{1}{M_{Pl}^2}\int_{\phi_{end}}^{\phi} d\phi \frac{V'}{V} \simeq 60 \qquad \Lambda \simeq 2 \times 10^{15} \div 10^{16}\,\mathrm{GeV}$$

$$\epsilon \simeq 0.003 \qquad |\eta| \simeq 0.02$$

Predictions on primordial tensor spectrum

A. Addazi, P. Chen & A. Marciano, arXiv:1712.04848



$$\lambda^{-1} = \frac{\Lambda^2}{2\pi^2}$$

$$\Lambda \simeq 2 \times 10^{15} \div 10^{16}\ \mathrm{GeV}$$

$$\mathcal{P}_T = \frac{2H_{inf}^2}{\pi^2 M_{Pl}^2} \simeq \frac{2V_0}{3\pi M_{Pl}^4} \sim 10^{-13} \div 10^{-11} \longrightarrow r = 10^{-4} \div 10^{-2}$$

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Critical branches

A. Addazi, P. Chen & A. Marciano, arXiv:1712.04848

There exist two critical branches for compatibility with data

I) $$\lambda^{-1} = \frac{\Lambda^2}{2\pi^2}$$

$$\Lambda \simeq 2 \times 10^{15} \div 10^{16}\ \mathrm{GeV} \qquad V_0 = \Lambda^4$$

II) $$\lambda^{-1} = \frac{\Lambda^2}{\pi^2}$$

$$|a| \ll \Lambda$$

Reheating mechanism and graceful exit

A. Addazi, P. Chen & A. Marciano, arXiv:1712.04848

For the second critical branch, perturbative reheating can be easily achieved

$|a| \ll \Lambda$

$$V(a) = V_0 + \frac{1}{2\lambda}|a|^2 - \frac{1}{4\pi^2}\left[|a|^2\Lambda^2 + \Lambda^4 \ln\left(1 + \frac{|a|^2}{\Lambda^2}\right) - |a|^4 \ln\left(1 + \frac{\Lambda^2}{|a|^2}\right)\right] - \frac{1}{(4\pi)^2}(\dot{H} + 2H^2)\left[-|a|^2 \ln\left(1 + \frac{\Lambda^2}{|a|^2}\right) + \frac{\Lambda^2|a|^2}{\Lambda^2 + |a|^2}\right],$$

$\Lambda^2 = c(\xi\kappa)^{-1}$

Quartic term

Quadratic term

The model converge to the form of the Coleman-Weinberg potential for $|a| \ll \Lambda$

Graceful exit mechanism from inflation, with a reliable re-heating mechanism

- A. Cerioni, F. Finelli, A. Tronconi and G. Venturi, Phys. Lett. B 2009
- G. Barenboim, E. J. Chun and H. M. Lee, Phys. Lett. B 2014

2PI effective action in Schwinger-Keldysh

A. Addazi, S. Lucat, A. Marciano & T. Prokopec, in preparation

$$-iF^{(h)}(k,x) \equiv \frac{1}{2}\int \mathrm{d}^D r e^{ik\cdot r} \sum_{h=\pm} \mathrm{Tr}\left(\hat{\rho}_H \left[\bar{\chi}_h(x-r/2), \chi_h(x+r/2)\right]\right)$$
$$= \sum_{h=\pm} g_{ah}(k,x)\rho^a \otimes \frac{1}{4}(\mathbb{1}+h\hat{k}\cdot\vec{\sigma}),$$

↓

$$\partial_\eta f_{0h}(\vec{k}) = 0,$$
$$\partial_\eta f_{1h}(\vec{k}) + 2h|\vec{k}|f_{2h}(\vec{k}) - 2am_I f_{3h}(\vec{k}) =$$
$$= \frac{6\pi G_N \xi^2}{a^2}\int \frac{\mathrm{d}\vec{p}}{(2\pi)^3}\left(\sum_{h_1} f_{3h_1}(\vec{p})f_{2h}(\vec{k}) - \frac{1}{4}\left(f_{3h}(\vec{p})f_{2h}(\vec{k}) + f_{3h}(\vec{k})f_{2h}(\vec{p})\right)\right)$$
$$\partial_\eta f_{2h}(\vec{k}) - 2h|\vec{k}|f_{1h}(\vec{k}) + 2am_R f_{3h}(\vec{k}) =$$
$$= -\frac{6\pi G_N \xi^2}{a^2}\int \frac{\mathrm{d}\vec{p}}{(2\pi)^3}\left(\sum_{h_1} f_{3h_1}(\vec{p})f_{1h}(\vec{k}) - \frac{1}{4}\left(f_{3h}(\vec{p})f_{1h}(\vec{k}) + f_{3h}(\vec{k})f_{1h}(\vec{p})\right)\right)$$
$$\partial_\eta f_{3h} - 2am_R f_{2h} + 2am_I f_{1h} = 0.$$

Gravitational perturbations I

A. Addazi, S. Alexander, R. Brandenberger, Y. Cai, L. Ji, A. Marciano & T. Qiu, in preparation

$$ds^2 = (1+2\Psi)dt^2 - a^2(1-2\Phi)\delta_{ij}dx^i dx^j$$

Perturbed Einstein equations

$$\delta G^{\mu}_{\nu} = 8\pi G \delta T^{\mu}_{\nu}$$

$$\nabla^2 \Phi - 3\mathcal{H}(\Phi' + \mathcal{H}\Psi) = 4\pi G a^2 \delta T^0_0,$$

$$(\Phi' + \mathcal{H}\Psi)_{,i} = 4\pi G a^2 \delta T^0_i,$$

$$\left[\Phi'' + \mathcal{H}(2\Phi' + \Psi') + (2\mathcal{H}' + \mathcal{H}^2)\Phi + \frac{1}{2}\nabla^2(\Psi - \Phi)\right]\delta_{ij} - 2(\Psi - \Phi)_{,ij} = -4\pi G a^2 \delta T^i_j$$

Gravitational perturbations II

A. Addazi, S. Alexander, R. Brandenberger, Y. Cai, L. Ji, A. Marciano & T. Qiu, in preparation

Perturbed energy-momentum tensor from fermion action $V = V(\bar{\psi}\psi)$

$$\delta T^0_0 = \langle V' \rangle_{O(\alpha)} \, \langle \bar{\psi}\psi \rangle |_{O(\delta\alpha)};$$

$$\delta T^0_i = \frac{3\imath}{8} \Phi_{,l} \langle \psi \gamma^0 \gamma^i \gamma^l \psi \rangle_{O(\alpha)}, \quad (l \neq i)$$

$$\delta T^i_j = \delta_{ij} V'' \langle \bar{\psi}\psi \rangle_{O(\alpha)} \, \langle \bar{\psi}\psi \rangle |_{O(\delta\alpha)} + \text{anisotropic terms}$$

ISW effect can be reconstructed

Anisotropic dof are present

Cross correlation functions

Conclusions

i) Fermionic matter cosmological perturbations

ii) Spinorial perturbations entail non-isotropic d.o.f. not present in the scalar field perturbations

iii) Spinorial contributions can be recast in terms of a multi-field approach in inflationary scenarios

iv) Inflation can be sourced by an infrared collective mode generated by condensation of SM fermions

v) Constraints are satisfied, but phenomenology is reacher

v) A falsifiable prediction for r can be provided

ありがとう

Thank you!

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Grazie!

谢谢

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