The Abdus Salam International Centre for Theoretical Physics
50th Anniversary 1964-2014

Workshop on Off-the-Beaten-Track Dark Matter and Astrophysical Probes of Fundamental Physics

Imperfect Dark Matter

Alexander Vikman

LMU Ludwig-Maximilians-Universität München

17.04.15

This talk is mostly based on

e-Print: arXiv: **1403.3961**,

JCAP 1406 (2014) 017

with *A. H. Chamseddine and V. Mukhanov*

and

e-Print: arXiv: **1412.7136**

with L. Mirzagholi

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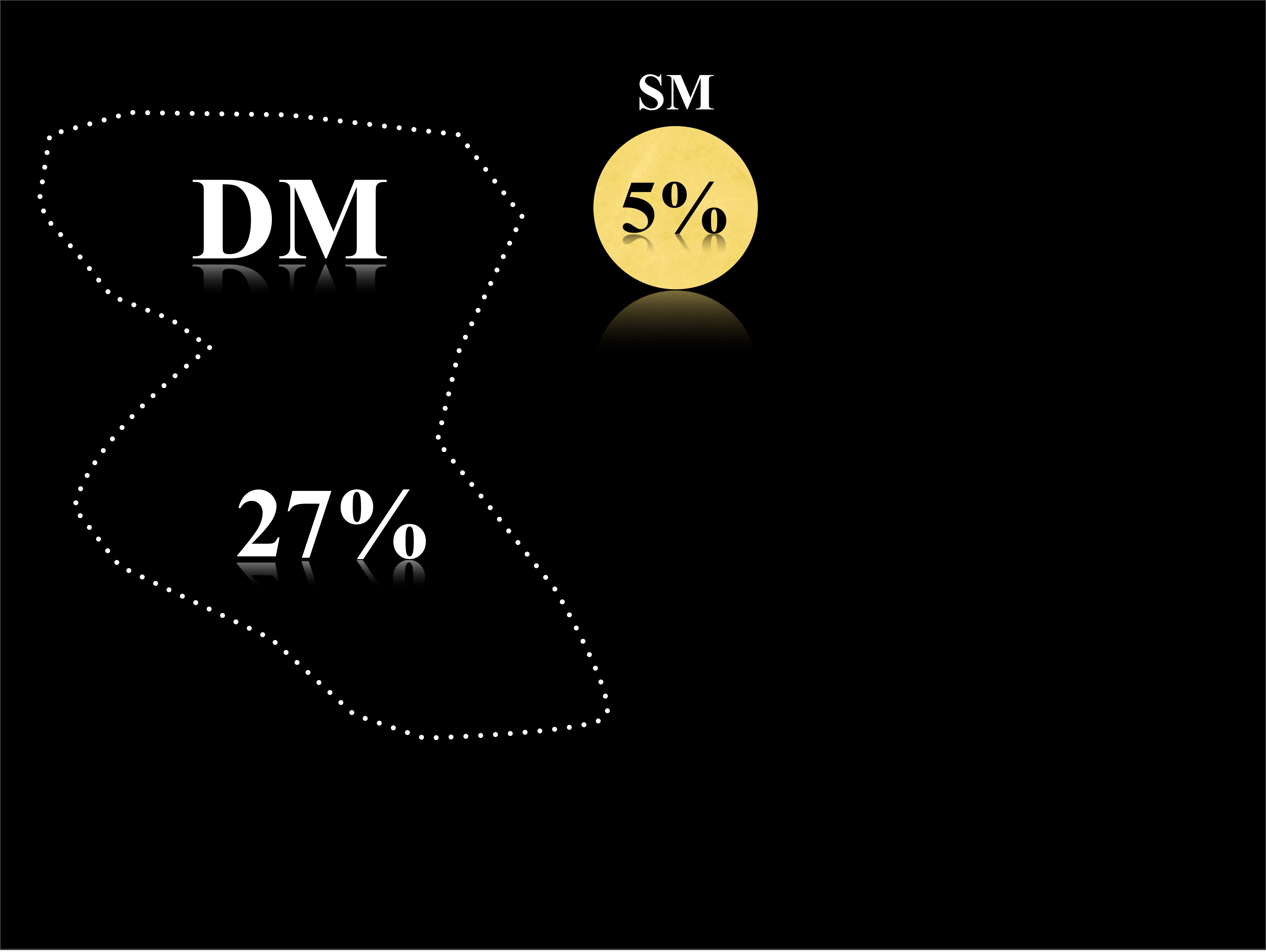
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Inflation

no vorticity on large scales

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Inflation

no vorticity
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$$u_\mu \propto \partial_\mu \varphi$$

normalized velocity $$u_\mu = \partial_\mu \varphi / m$$

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the dynamical part of dark sector moves along timelike geodesics $\Rightarrow$

$$m = m(\varphi)$$

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the dynamical part of dark sector moves along timelike geodesics

$$m = m\left(\varphi\right)$$

$$\varphi \to \phi \quad d\phi = d\varphi / m\left(\varphi\right) \quad u_\mu = \partial_\mu \phi$$

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the dynamical part of dark sector moves along timelike geodesics $\Rightarrow$ $m = m(\varphi)$

$$\varphi \to \phi \quad d\phi = d\varphi / m(\varphi) \quad u_\mu = \partial_\mu \phi$$

$$g^{\mu\nu} \partial_\mu \phi \, \partial_\nu \phi = 1$$

Constraint or the Hamilton-Jacobi equation

How to implement this constraint?

Mimetic Matter

Chamseddine, Mukhanov (2013)

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- One can encode the conformal / scalar part of the physical metric $g_{\mu\nu}$ in a scalar field ϕ :

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is *not* in the Horndeski (1974) construction of the most general scalar-tensor theory with *second order* equations of motion

But it is still a system with one degree of freedom + standard two polarizations for the graviton!

Dissformal Transformation

Nathalie Deruelle and Josephine Rua (2014)

One obtains the same dynamics
(***the same Einstein equations***),
if instead of varying the Einstein-Hilbert action
with respect to the metric $g_{\mu\nu}$

one plugs in a *dissformal transformation*

$$g_{\mu\nu} = F\left(\Psi, w\right)\ell_{\mu\nu} + H\left(\Psi, w\right)\partial_\mu\Psi\partial_\nu\Psi$$

with $w = \ell^{\mu\nu}\partial_\mu\Psi\partial_\nu\Psi$ and $w^2 F\frac{\partial}{\partial w}\left(H + \frac{F}{w}\right) \neq 0$

and varies with respect to $\ell_{\mu\nu},\ \Psi$

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Mimetic gravity is an exception! And it does provide new dynamics!

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Mimicking **any** cosmological evolution, But always with **zero sound speed**

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$$2\dot{H} + 3H^2 = V(t)$$

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- In particular $V(\phi) = \frac{1}{3}\frac{m^4\phi^2}{e^\phi + 1}$ gives the same cosmological inflation as $\frac{1}{2}m^2\phi^2$ potential in the standard case

Perturbations I

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Even with potential, the energy still moves along the timelike geodesics

$$c_{\mathrm{S}} = 0$$

Newtonian potential:

$$\Phi = C_1(\mathbf{x})\left(1 - \frac{H}{a}\int a dt\right) + \frac{H}{a} C_2(\mathbf{x})$$

*Here on **all scales** but in the usual cosmology it is an approximation for **superhorizon** scales*

Next term in the gradient expansion

Chamseddine, Mukhanov, Vikman (2014)

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$$\gamma\left(\Box\phi\right)^2$$

“unique” quadratic term

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"unique" quadratic term

$\nabla_\mu\nabla_\nu\phi\nabla^\mu\nabla^\nu\phi$ is not that useful:

$$\int \mathrm{d}^4x\,\sqrt{-g}\;\phi_{;\mu;\nu}\phi^{;\mu;\nu} = \int \mathrm{d}^4x\,\sqrt{-g}\left(\left(\Box\phi\right)^2 - R^{\mu\nu}\phi_{;\mu}\phi_{;\nu}\right)$$

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- There are only minor changes (rescaling) in the background evolution equations e.g.

$$2\dot{H} + 3H^2 = \frac{2}{2-3\gamma}V(t)$$

Perturbations II

Chamseddine, Mukhanov, Vikman (2014)

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$$\delta\ddot{\phi} + H\delta\dot{\phi} - \frac{c_s^2}{a^2}\Delta\delta\phi + \dot{H}\,\delta\phi = 0$$

with the sound speed

$$c_s^2 = \frac{\gamma}{2 - 3\gamma}$$

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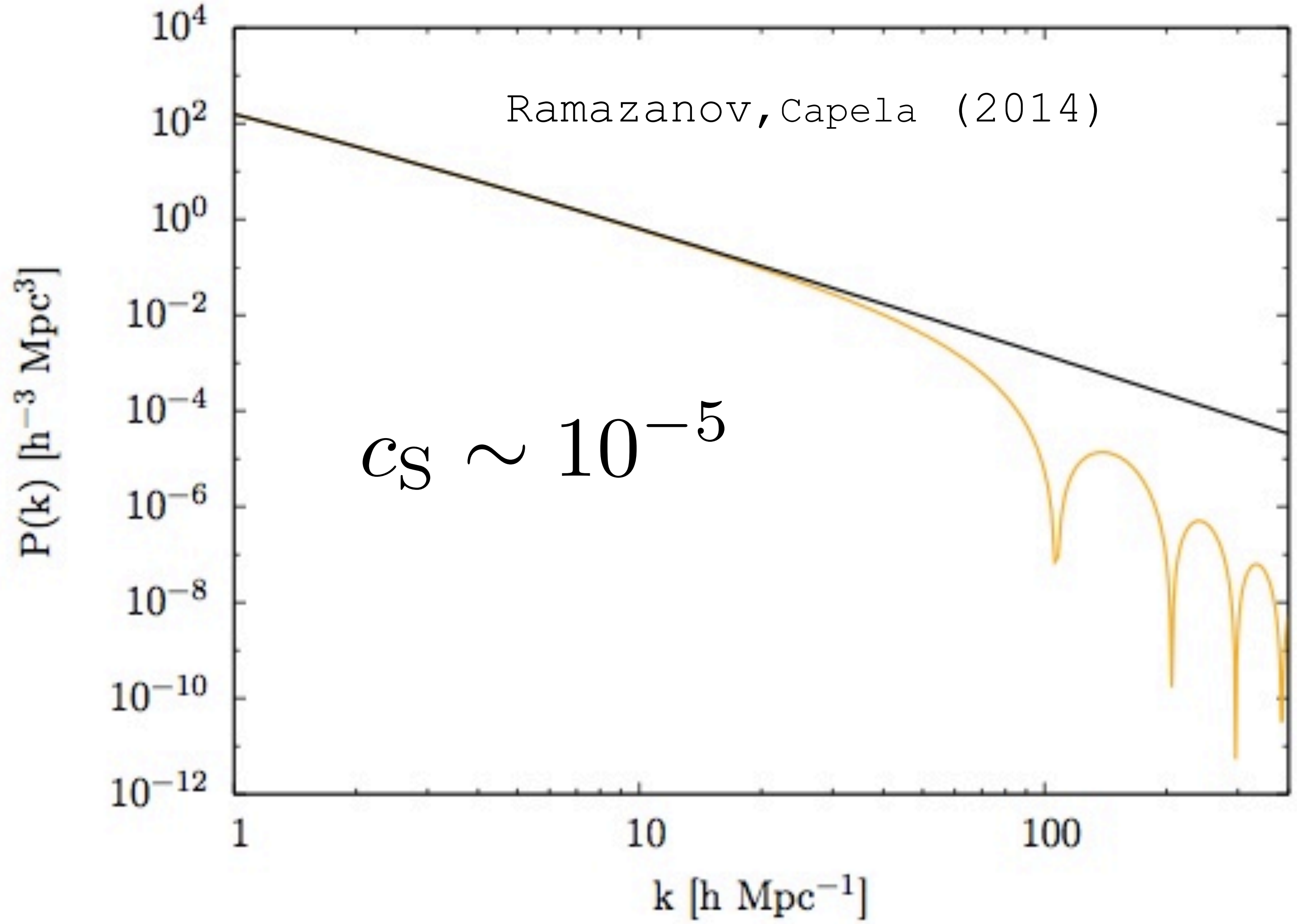

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energy flow $\quad q_\mu = -\gamma \perp_\mu^\lambda \nabla_\lambda \theta$

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pressure $\quad p = -\gamma \left(\dot{\theta} + \frac{1}{2}\theta^2 \right)$

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$$n \propto a^{-3}$$

Vorticity for a *single scalar dof* DM?

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in the frame moving with the charges (Eckart frame)

$$\Omega^\mu_{\mathrm{E}} = \frac{1}{2}\varepsilon^{\alpha\beta\gamma\mu} V_\gamma \perp^\lambda_\alpha V_{\beta;\lambda} \simeq \frac{\gamma}{4\lambda^2}\varepsilon^{\alpha\beta\gamma\mu}\vec{\nabla}_\alpha \lambda \, \vec{\nabla}_\beta \theta \, u_\gamma$$

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in the gradient expansion (without gravity)

$$T_{\mu\nu} \simeq (\varepsilon + p)\,U_{\mu}U_{\nu} - pg_{\mu\nu} + \mathcal{O}\left(\gamma^2\right)$$

$$p \simeq c^2_{\mathrm{S}}\varepsilon + \mathcal{O}\left(\gamma^2\right)$$

Raychaudhuri at work!

$$\dot{\theta} = -\frac{1}{3}\theta^2 - \sigma^2 - R_{\mu\nu}u^\mu u^\nu$$

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DM

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DM

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$$G_{\mathrm{eff}} = G_N\left(1 + 3c_{\mathrm{S}}^2\right)$$

Mimetic construction *and* inflation

↓

shift-symmetry breaking needed for DM

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$$\gamma(\phi) \quad : \quad \nabla_\mu J^\mu = \frac{1}{2}\gamma'(\varphi)\,\theta^2$$

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shift-symmetry breaking needed for DM

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easy to generate charge during radiation domination époque :

$$na^3 = \frac{9}{2}\int_{(t_{\mathrm{cr}}-\Delta t)}^{t} dt'\, a^3\dot{\gamma}H^2 \simeq \frac{3}{2}a^3\rho_{\mathrm{rad}}\left(t_{\mathrm{cr}}\right)\Delta\gamma$$

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$$\Delta\gamma = \frac{2}{3}\left(\frac{a_{\rm cr}}{a_{\rm eq}}\right) \simeq \frac{2}{3}\,\frac{z_{\rm eq}}{z_{\rm cr}} \qquad T_{\rm cr} \simeq \frac{T_{\rm eq}}{\Delta\gamma} \simeq \frac{\rm eV}{\Delta\gamma}$$

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$\delta G_{\rm N}$ bounds are mild:

Mimetic construction *and* inflation

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easy to generate charge during radiation domination époque :

$$na^3 = \frac{9}{2}\int_{(t_{\rm cr}-\Delta t)}^{t} dt'\, a^3\dot{\gamma}H^2 \simeq \frac{3}{2}a^3\rho_{\rm rad}\left(t_{\rm cr}\right)\Delta\gamma$$

$$\Delta\gamma = \frac{2}{3}\left(\frac{a_{\rm cr}}{a_{\rm eq}}\right) \simeq \frac{2}{3}\,\frac{z_{\rm eq}}{z_{\rm cr}} \qquad T_{\rm cr} \simeq \frac{T_{\rm eq}}{\Delta\gamma} \simeq \frac{\rm eV}{\Delta\gamma}$$

$\delta G_{\rm N}$ bounds are mild:

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Narimani, Scott, Afshordi (2014)

$$3\left(c_{\rm S}^2\big|_{\rm matter} - c_{\rm S}^2\big|_{\rm radiation}\right) \lesssim 0.066 \pm 0.039$$

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Thanks a lot for attention!