the D-material universe

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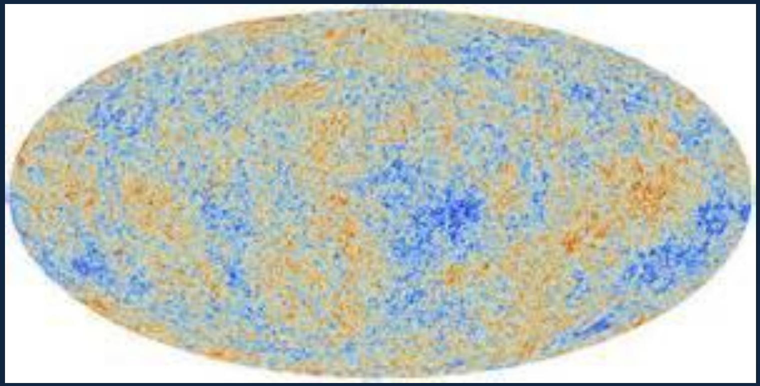
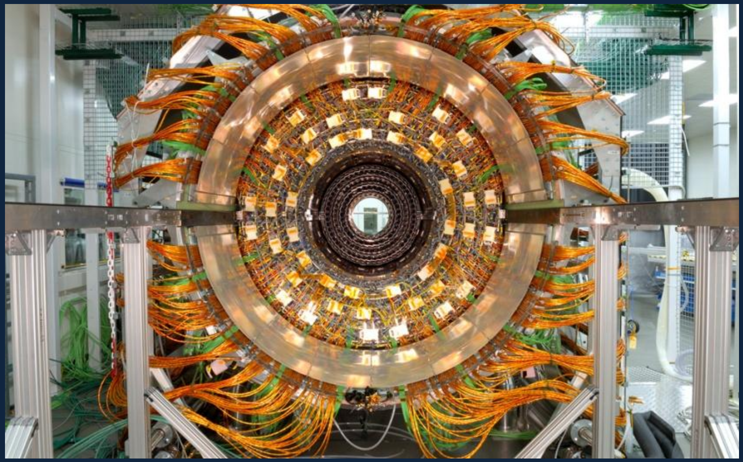
outline

- motivation
- the model: *D-material universe*
- matter perturbations, gravitational lensing phenomenology and dark energy contribution
- inflationary scenario
- possible signatures in the MoEDAL LHC experiment
- conclusions

motivation

early universe cosmological models can be tested with very accurate astrophysical data, while high energy experiments can test some of the theoretical pillars of these models





despite the golden era of cosmology, a number of questions:

- origin of DE / DM
- search for natural and well-motivated inflationary model

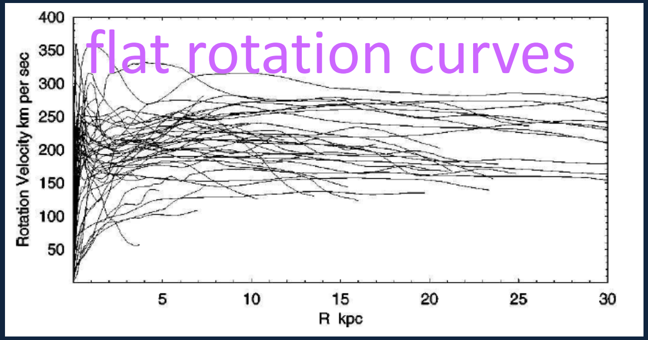
… are still awaiting for a definite answer

Λ CDM model: highly successful in fitting observations

- classical GR on a FLRW metric with $\Lambda > 0$
- CDM

one would expect a rotation linear velocity which first rises with galactocentric radius r and then drops asypmtotically as $r^{-1/2}$

but



however

- undetected status of DM 26%

(extensions of the SM – yet undiscovered)

- unknown DE component 69%

lack of direct experimental evidence for DM ⟶ MOND

flat rotation curves below an acceleration scale $a_0 \approx 1.2 \times 10^{-10}\mathrm{m/s^2}$

$$f\Big(\frac{|\vec{a}|}{a_0}\Big)\vec{a} = -\vec{\nabla}\Phi_{\mathrm{N}}$$

milgrom (1983)

$f(x) = 1$ usual newtonian dynamics

$f(x) \cong x$ deep MONDian regime

embedded in relativistic modified gravitational theories TeVeS

bekenstein (2004)

at least the simplest models are incompatible with lensing data in some galaxies, including bullet cluster (significant amount of DM is needed)

ferreras, sakellariadou, yusaf (2008) ; ferreras, mavromatos, sakellariadou, yusaf (2009, 2012)

MOND TeVeS

simple interpolating function

$$f(x) = \frac{x}{1+x}; \quad \mu(y) = \frac{\sqrt{\frac{y}{3}}}{1 - \frac{2\pi}{k}\sqrt{\frac{y}{3}}}$$

standard MONDian interpolating function

$$f(x) = \frac{x}{\sqrt{1+x^2}}$$

toy interpolating function

$$f(x) = \frac{2x}{1+2x+\sqrt{1+4x}}; \quad \mu(y) = \sqrt{\frac{y}{3}}$$

$$\boxed{f(x) = \frac{2x}{1+(2-\alpha)x+\sqrt{(1-x)^2+4x}}; \quad \mu(y) = \frac{\sqrt{\frac{y}{3}}}{1 - \frac{2\pi\alpha}{k}\sqrt{\frac{y}{3}}}; \quad 0 \leq \alpha}$$

the choice α=0 gives the lowest contribution from DM but it is ruled out by rotation curve data; other parametrisations show a greater contribution of DM lack of direct experimental evidence for DM $\longrightarrow$ MOND

flat rotation curves below an acceleration scale $a_0 \approx 1.2 \times 10^{-10} \mathrm{m/s}^2$

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ferreras, sakellariadou, yusaf (2008) ; ferreras, mavromatos, sakellariadou, yusaf (2009, 2012)

major drawback: there is no microscopic origin of TeVeS/MOND models, based on some underlying fundamental physics

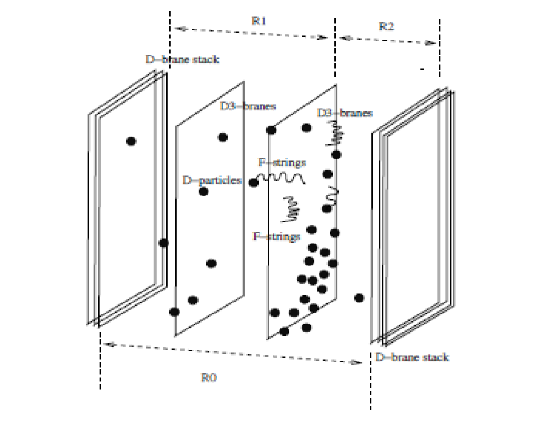
the model:

D-material universe

modified gravity models involving fundamental vector field (but different from TeVeS) may appear as the low-energy limit of certain brane theories

elghozi, mavromatos, sakellariadou, yusaf (2016)

D-material universe

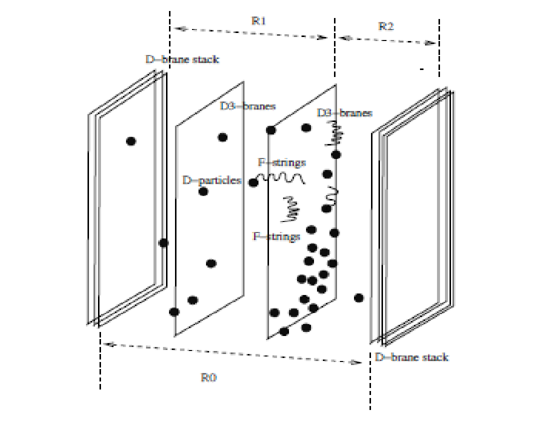


a compactified (3+1)dim brane propagates in a higher-dim bulk populated by point-like D0-brane (D-particles) defects

- as brane universe moves in the bulk, D particles cross it and look like *flashing on* and *off* foamy structures
- particle excitations (open strings) propagate in a medium of D-particles

brane-puncturing (massive) D-particles can be captured by (electrically neutral) matter open strings

D-material universe



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metric deformation of neighbouring spacetime due to recoil of D-particles

bi-metric theory: sigma model background metric related to einstein-frame metric, and a metric describing the distortion of space-time surrounding D-particles

mavromatos, sakellariadou (2007)

lorentz invariance locally broken, leading to emergence of vector-like excitations that can lead to an era of inflation and contribute to large scale structure (enhancing DM component) and galaxy formation

elghozi, mavromatos, sakellariadou, yusaf (2016) ; ferreras, mavromatos, sakellariadou, yusaf (2013)

interaction of stringy matter on a brane-world of 3 longitudinal large dimensions with a medium of recoiling D-particles :

$$S_{\rm eff\ 4D} = \int d^4x \left[-\frac{\sqrt{-g}}{4} e^{-2\phi} \mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} - \frac{T_3}{g_{s0}} e^{-\phi} \sqrt{-\det\left(g + 2\pi\alpha' F\right)} \left(1 - \alpha R(g)\right) - \sqrt{-g}\, \frac{e^{-2\phi}}{\kappa_0^2} \tilde{\Lambda} + \sqrt{-g}\, \frac{e^{-2\phi}}{\kappa_0^2} R(g) + \mathcal{O}\left((\partial\phi)^2\right) \right] + S_m \ ,$$

flux gauge field

brane tension

determinant of the gravitational field

string coupling

$g_{\rm s} = g_{\rm s0} e^{\phi}$

cosmological constant

dilaton field, assumed constant

4dim bulk induced gravitational constant $\frac{1}{\kappa_0^2} = \frac{V^{(6)}}{g_{\rm s0}^2} M_{\rm s}^2$

string scale

$M_{\rm s} = 1/\sqrt{\alpha'}$

interaction of stringy matter on a brane-world of 3 longitudinal large dimensions with a medium of recoiling D-particles :

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the vector field A_μ denotes the recoil velocity excitation during the string-matter/D-particle interactions and has field strength $F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu$

the vector field satisfies the constraint $A_\mu\, A_\nu\, g^{\mu\nu} = -\frac{1}{\alpha'}$ *which arises from* $u^\mu u_\mu = -1$

with the field strength (derivative wrt conformal time) $F_{0i} = -\frac{2}{\sqrt{\alpha'}}\, a'\, u_i$ where $M_s = 1/\sqrt{\alpha'}$

expand 4dim DBI action in derivatives (low-energy weak approximation)

$$g^{\mathrm{E}}_{\mu\nu} = e^{-2\phi} g_{\mu\nu}$$

$$S^E_{\rm eff\ 4D} = \int \mathrm{d}^4x \sqrt{-g} \left[-\frac{T_3\, e^{3\phi_0}}{g_{s0}} - \frac{\tilde{\Lambda}\, e^{2\phi_0}}{\kappa_0^2} - \frac{\widetilde{F}^2}{4} \left(1 - \alpha\, e^{-2\phi_0}\, R\right) + \left(\frac{\alpha\, T_3\, e^{\phi_0}}{g_{s0}} + \frac{1}{\kappa_0^2} \right) R + \lambda \left(\tilde{A}_\mu \tilde{A}^\mu + \frac{4\pi^2 \alpha' T_3\, e^{3\phi_0}}{g_{s0}} \right) \dots \right] + S_{\rm m}$$

$$\alpha = \alpha' \zeta(2) = \alpha' \pi^2/6$$

maxwell field strength for the field

$$\widetilde{A}_\mu \equiv \left(\frac{T_3 (2\pi\alpha')^2}{g_{s0}}\, e^{3\phi_0} \right)^{1/2} A_\mu$$

redefinition of the vector field

lagrange multiplier, implementing the constraint

$$\widetilde{A}_\mu\, \widetilde{A}_\nu\, g^{\mu\nu} = -\frac{4\pi^2 \alpha'\, T_3\, e^{3\phi_0}}{g_{s0}}$$

expand 4dim DBI action in derivatives (low-energy weak approximation)

$$S^E_{\mathrm{eff}\ 4\mathrm{D}} = \int \mathrm{d}^4x\sqrt{-g}\left[-\frac{T_3\, e^{3\phi_0}}{g_{s0}} - \frac{\tilde{\Lambda}\, e^{2\phi_0}}{\kappa_0^2} - \frac{\widetilde{F}^2}{4}\left(1-\alpha\, e^{-2\phi_0}\, R\right) + \left(\frac{\alpha\, T_3\, e^{\phi_0}}{g_{s0}} + \frac{1}{\kappa_0^2}\right) R + \lambda\left(\tilde{A}_\mu \tilde{A}^\mu + \frac{4\pi^2\alpha'\, T_3\, e^{3\phi_0}}{g_{s0}}\right)\ldots\right] + S_{\mathrm{m}}$$

graviton equation of motion

$$\left(R^\mu{}_\nu - \frac{\delta^\mu{}_\nu}{2} R\right)\left[\frac{\alpha\, T_3\, e^{\phi_0}}{g_{s0}} + \frac{1}{\kappa_0^2} + \frac{\alpha e^{-2\phi_0}\, \widetilde{F}^2}{4}\right] - \frac{1}{2}\left(1-\alpha e^{-2\phi_0} R\right) \widetilde{F}^{\mu\lambda}\, \widetilde{F}_{\nu\lambda}$$
$$+\frac{1}{8}\widetilde{F}^2\, \delta^\mu{}_\nu + \lambda\, \widetilde{A}^\mu\, \widetilde{A}_\nu - \lambda\, \frac{\delta^\mu{}_\nu}{2}\left(\widetilde{A}_\alpha \widetilde{A}^\alpha + \frac{1}{\alpha'}\mathcal{J}\right) + \frac{1}{2}\delta^\mu{}_\nu\, \Lambda_0 = \frac{1}{2}\, T^\mu{}_\nu$$

$$\mathcal{J} \equiv \frac{(2\pi\alpha')^2\, T_3\, e^{3\phi_0}}{g_{s0}}$$

matter stress tensor

$$T_{\mu\nu} = -2\frac{1}{\sqrt{-g}}\,\frac{\delta S_{\mathrm{m}}}{\delta g^{\mu\nu}}$$

expand 4dim DBI action in derivatives (low-energy weak approximation)

$$S^E_{\mathrm{eff}\ 4\mathrm{D}} = \int \mathrm{d}^4x \sqrt{-g}\left[-\frac{T_3\, e^{3\phi_0}}{g_{s0}} - \frac{\tilde{\Lambda}\, e^{2\phi_0}}{\kappa_0^2} - \frac{\widetilde{F}^2}{4}\left(1-\alpha\, e^{-2\phi_0}\, R\right) + \left(\frac{\alpha\, T_3\, e^{\phi_0}}{g_{s0}} + \frac{1}{\kappa_0^2}\right) R + \lambda\left(\tilde{A}_\mu \tilde{A}^\mu + \frac{4\pi^2\alpha'\, T_3\, e^{3\phi_0}}{g_{s0}}\right)\dots\right] + S_m$$

vector field equation of motion

background value of the lagrange multiplier field

$$\langle\lambda(x)\rangle = \frac{e^{-3\phi_0}\, g_{s0}}{8\pi^2\alpha'\, |T_3|}\widetilde{A}\mu\left[\widetilde{F}_{\nu\mu}\left(1-\alpha e^{-2\phi_0} R\right)\right]^{;\nu}$$

expand 4dim DBI action in derivatives (low-energy weak approximation)

$$S^E_{\rm eff\ 4D} = \int d^4x\sqrt{-g}\left[-\frac{T_3\, e^{3\phi_0}}{g_{s0}} - \frac{\tilde{\Lambda}\, e^{2\phi_0}}{\kappa_0^2} - \frac{\widetilde{F}^2}{4}\left(1 - \alpha\, e^{-2\phi_0}\, R\right) + \left(\frac{\alpha\, T_3\, e^{\phi_0}}{g_{s0}} + \frac{1}{\kappa_0^2}\right) R + \lambda\left(\tilde{A}_\mu \tilde{A}^\mu + \frac{4\pi^2\alpha' T_3\, e^{3\phi_0}}{g_{s0}}\right)\dots\right] + S_{\rm m}$$

dilaton equation of motion, in galactic scales:

the cosmological constant on the brane world with +tive tension is -tive

$$\Lambda_0 \simeq -\frac{1}{2}\frac{T_3}{g_{s0}}\, e^{3\phi_0} < 0$$

such anti-de-sitter type terms cancel against dilaton independent contributions to the brane vacuum energy → during the galactic era, only a small +tive cosmological constant survives

$$\Lambda^{\rm vac} \equiv \Lambda_0 + \frac{1}{8}\langle \mathcal{G}_{\mu\nu}\, \mathcal{G}^{\mu\nu}\rangle + \cdots > 0$$

gravitational lensing phenomenology

consider a static spherically symmetric background:

$$g_{\alpha\beta}\, \mathrm{d}x^\alpha \mathrm{d}x^\beta = -e^{\nu\left(\sqrt{x^2+y^2+z^2}\right)} \mathrm{d}t^2 + e^{\zeta\left(\sqrt{x^2+y^2+z^2}\right)}\, a^2(t)(\mathrm{d}x^2 + \mathrm{d}y^2 + \mathrm{d}z^2)$$

recoil fluctuations of D-particles due to interactions with open strings correspond to world-sheet deformations of gauge fields

$$A_i(\vec{x}, t) \simeq \frac{1}{\alpha'}\, g_{ij}(\vec{x}, t)\, u^j \left(t\, \frac{a(t_c)^2}{a(t)^2} - t_c \right) , \qquad t > t_c$$

collision time is of the same order of magnitude as the FLRW cosmic time of a galaxy of a given redshift z

$$t_c \sim \frac{2}{H_0\, [1 + (1+z)^2]}$$

time of observation $t = t_0$

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constraint $A_\mu\,A_\nu\,g^{\mu\nu} = -\frac{1}{\alpha'}$

$$t_c \sim \frac{2}{H_0\,[1+(1+z)^2]} \qquad a(t_c) = a_0\,\frac{1}{1+z}$$

"electric" type field strength components *associated with linear recoil momentum excitations*

$$F_{ti}(\vec{x},t) \sim \frac{1}{\alpha'}\,g_{ij}(\vec{x},t)\,u^j\left[\frac{1-3(1+z)^2}{(1+z)^2\,(1+(1+z)^2)}\right]$$

"magnetic" type field strength components (*corresponding to nonzero angular momentum of recoiling D-particles*)

F_{ij} are much smaller than F_{ti}

for late eras, consider populations of D-particles with fluctuating recoil velocities, which are assumed to be gaussian stochastic ⟹ macroscopically lorentz invariance is maintained

$$\langle\langle u^m u^n \rangle\rangle = \sigma_0^2(t)\,\delta^{mn}\ , \qquad \langle\langle u^m \rangle\rangle = 0\ , \qquad \sigma_0^2(t) = a(t)^{-3}\,|\beta|\ ,$$

statistical variance of the recoil velocity

the statistical fluctuations are proportional to the cosmic density of defects at a global scale

estimate of $|\beta|$ at late epochs

$$\boxed{|\beta| \sim \frac{1}{3}\,\frac{n_D^{(0)}}{n_\gamma^{(0)}}\,\widetilde{\xi}_0^2\,\frac{|\overline{p}_i^{\rm phys}|^2}{M_s^2}\,g_{s0}^2}$$

considering mainly scattering of D-particles with cosmic photons

an average energy of CMB photons as observed today

$$\sqrt{|p_i^{\rm phys\,CMB}|^2} \sim 7\times 10^{-4}\ {\rm eV}$$

spacetime local constant fudge factor $\widetilde{\xi}_0 < 1$ *characteristic of the microscopic theory*

$$10^4{\rm GeV} \le M_s \le 10^{18}{\rm GeV}$$

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aim: to find the magnitude of the quantity $|\beta|$ needed for the D-particle defects to play the role of dark matter candidates and providers of large scale structure for late eras, consider populations of D-particles with fluctuating recoil velocities, which are assumed to be gaussian stochastic $\Rightarrow$ macroscopically lorentz invariance is maintained

$$\langle\langle u^m u^n \rangle\rangle = \sigma_0^2(t)\, \delta^{mn} \ , \qquad \langle\langle u^m \rangle\rangle = 0 \ , \qquad \sigma_0^2(t) = a(t)^{-3}\, |\beta| \ ,$$

consider the graviton equation:

$$\mathcal{H}(z) = \left[\frac{1-3(1+z)^2}{(1+z)^2\,(1+(1+z)^2)}\right]$$

$$\left[\frac{1}{\kappa_0^2} + \mathcal{J}\,\frac{e^{-2\phi_0}}{24\,\alpha'}\,(1 - 6\pi^2 |\beta| \mathcal{H}(z)^2)\right] \left(R^t{}_t - \frac{1}{2}\,R\right) + \frac{3}{4\,\alpha'^2}\,\mathcal{J}\,|\beta|\,\mathcal{H}(z)^2 + \ldots \simeq \frac{1}{2}\,T^t{}_t$$

$\kappa_{\rm eff}^{-2}$ *effective inverse gravitational constant, which depends on statistical variance of the recoil velocity* $|\beta|$

gravitational lensing

$$g_{\alpha\beta}\,\mathrm{d}x^\alpha \mathrm{d}x^\beta = -e^{\nu\left(\sqrt{x^2+y^2+z^2}\right)}\mathrm{d}t^2 + e^{\zeta\left(\sqrt{x^2+y^2+z^2}\right)}\,a^2(t)(\mathrm{d}x^2+\mathrm{d}y^2+\mathrm{d}z^2)$$

deflection of light:

$$\boxed{\Delta\varphi = 2\int_{r_0}^{\infty}\frac{1}{r}\left(e^{\zeta(r)-\nu(r)}\frac{r_0^2}{b^2}-1\right)^{-1/2}\mathrm{d}r - \pi}$$

point of closest approach for the light ray

the observable impact parameter of the light ray

$$b^2 = e^{\zeta(r_0)-\nu(r_0)}\,r_0^2$$

the lensing system is defined by the thin lens equation:

$$\boxed{\hat{\beta} = \theta - \Delta\varphi \frac{D_{\mathrm{ds}}}{D_{\mathrm{s}}}}$$

unknown true angular position of the source galaxy

observable angular position of the source

angular distance to the source

angular distance from the source to the lens the lensing system is defined by the thin lens equation:

$$\hat{\beta} = \theta - \Delta\varphi \frac{D_{\mathrm{ds}}}{D_{\mathrm{s}}}$$

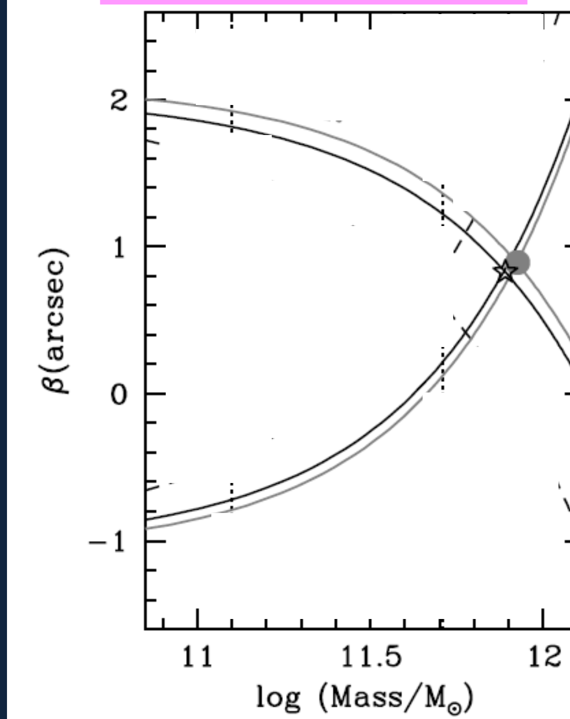
unknown true angular position of the source galaxy

deflection of light

$\Delta\varphi(\theta, M, b)$

there are two unknowns, so two images of the source are needed and the data from both are combined to find the actual position of the source and the mass of the lens *the lensing equation is represented by the pairs of curved lines that intersect at the true value of the lens position and lens mass*

$$\hat{\beta} = \theta - \Delta\varphi \frac{D_{\mathrm{ds}}}{D_{\mathrm{s}}}$$



the mass of the galaxy from lensing data is then compared to the mass of the luminous matter content of the galaxy, which depends on the mass distribution of stars at birth, i.e. the initial mass function (IMF)

- chabrier IMF
- salpeter IMF

the best fit values to $T_3\beta$ to get near zero DM for a galaxy

		Salpeter IMF		Chabrier IMF	
Lens	z_l	% DM in GR	$T_3\beta$ for no DM $(\times 10^{-121} M_{\rm Pl}^4)$	% DM in GR	$T_3\beta$ for no DM $(\times 10^{-121} M_{\rm Pl}^4)$
Q0142-100	0.49	0.4	1.4×10^{-2}	47.9	1.6
HS0812+123	0.39	37.8	1.3	67.6	2.4
LBQS1009-025	0.88	64.7	2.3	81.7	2.9
B1030+071	0.60	59.7	2.5	78.5	3.3
HE1104-181	0.73	63.2	2.3	81.9	3.0
B1152+200	0.44	25.1	1.3	61.0	3.1
SBS1520+530	0.71	41.1	1.7	67.5	2.7
B1600+434	0.42	61.4	2.4	78.9	3.1
HE2149-275	0.60	60.7	2.2	79.7	2.9
Q0957+561A	0.36	76.7	3.3	86.9	3.7
Q0957+561B	0.36	77.4	3.3	87.3	3.7

$M_s = 15\text{TeV}$

<u>remark</u>: *dark matter candidates come naturally with the string model we are working with*

$$\left[\frac{1}{\kappa_0^2} + \mathcal{J}\,\frac{e^{-2\phi_0}}{24\,\alpha'}\left(1 - 6\pi^2\,|\beta|\,\mathcal{H}(z)^2\right)\right]\left(R^t{}_t - \frac{1}{2}\,R\right) + \frac{3}{4\,\alpha'^2}\,\mathcal{J}\,|\beta|\,\mathcal{H}(z)^2 + \ldots \simeq \frac{1}{2}\,T^t{}_t$$

to model the lensing systems, we take the energy momentum tensor to describe an ideal presureless fluid

$$T^t{}_t = -\rho(r)\ , \qquad T^i{}_j = 0$$

demanding the recoil-vector-field contributions to the stress tensor to be at most of the same order of magnitude as the mass terms and considering typical values of the mass density for lenses to be $\rho(r) \sim 10^{-119}\,M_{\rm Pl}^4$

graviton eq.

$$|\beta| \le 10^{-120}\,(\mathcal{H})^{-2}\left(\frac{M_{\rm Pl}}{M_{\rm s}}\right)^2$$

e.g. $M_{\rm s} \simeq 10^4\ {\rm GeV}$ and $z \in (0,2)$ $\Rightarrow$ $|\beta| \le 10^{-92}$

consider small perturbations in the metric and the vector field

perturbed vector equation

$$\boxed{\ddot\zeta + b_1\dot\zeta + b_2\zeta = S[\Phi, C]} \longrightarrow \zeta \xrightarrow{\Phi} \frac{\delta\rho}{\rho}$$

$$S[\Phi, C] = \frac{\dot\Phi}{a} + \frac{\Phi}{a}\left(H + \frac{6\alpha e^{-2\phi_0}\left[2H^3 - \frac{\ddot a H}{a} - \frac{\dddot a}{a}\right]}{1 - 6\alpha e^{-2\phi_0}\left(H^2 + \frac{\ddot a}{a}\right)}\right) ,$$

$$b_1 = 3H + \frac{6\alpha e^{-2\phi_0}\left[2H^3 - \frac{\ddot a H}{a} - \frac{\dddot a}{a}\right]}{1 - 6\alpha e^{-2\phi_0}\left(H^2 + \frac{\ddot a}{a}\right)} ,$$

$$b_2 = \frac{\ddot a}{a} + H^2 + \frac{6\alpha e^{-2\phi_0} H\left[2H^3 - \frac{\ddot a H}{a} - \frac{\dddot a}{a}\right] - 2\langle\lambda(x)\rangle}{1 - 6\alpha e^{-2\phi_0}\left(H^2 + \frac{\ddot a}{a}\right)}$$

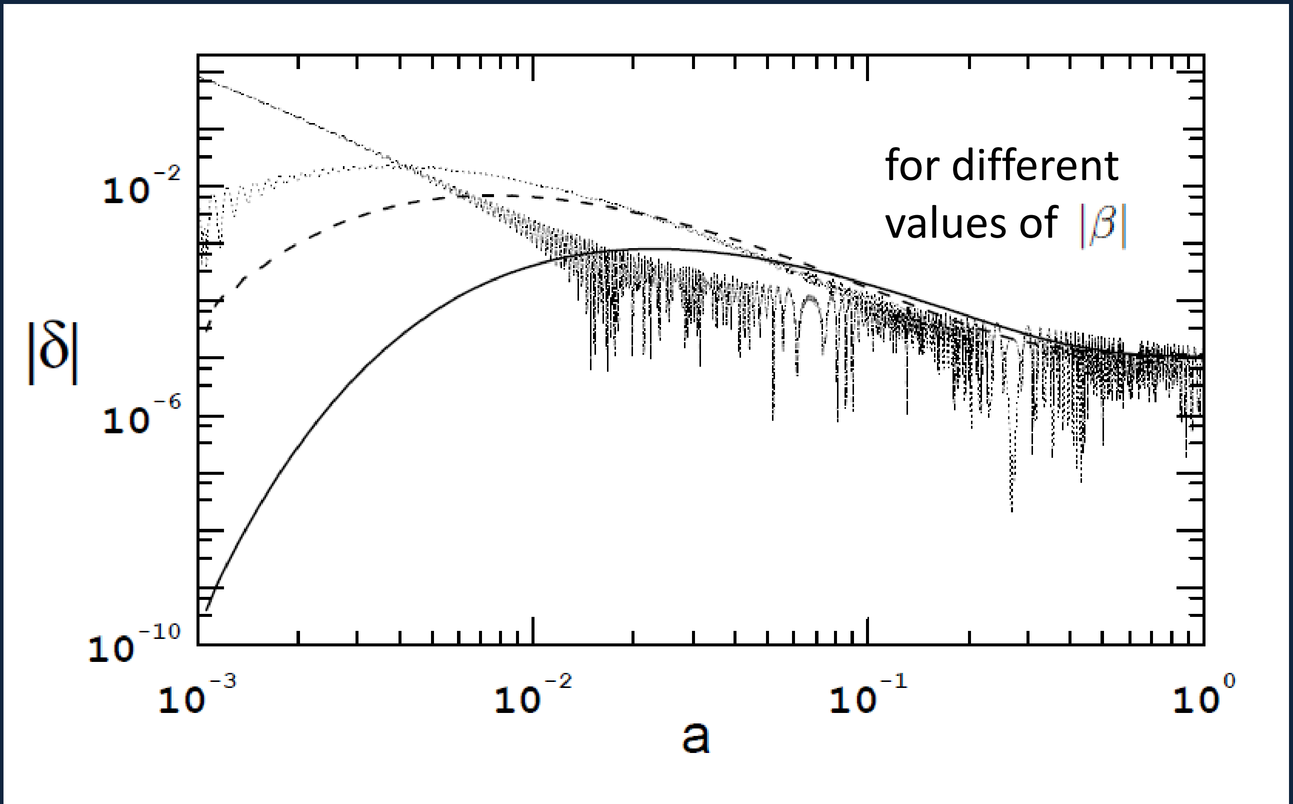
$$\langle\lambda\rangle\frac{2\pi\alpha'|T_3|e^{-\phi_0}}{g_{s0}} = 3\sigma_0^2 a^2\left[\frac{\ddot a}{a} + 2H^2 - 6\alpha e^{-2\phi_0}\left(\frac{H\dddot a}{a} + \frac{\ddot a^2}{a^2} + \frac{4H^2\ddot a}{a}\right)\right]$$

mavromatos, sakellariadou, yusaf (2013)

perturbed dilaton equation

$$0 = 2\Phi\left\{12\sigma_0^2 a^2\alpha\left[e^{-2\phi_0}\left(\frac{k^2H^2}{\cdots} + 6H^4 + \frac{6H^2\ddot a}{\cdots}\right) + 6e^{2\phi_0}\left(\frac{H\dddot a}{\cdots} + \frac{\ddot a^2}{\cdots} + \frac{3H^2\ddot a}{\cdots}\right)\right] + \frac{\alpha T_3 e^{\phi_0}}{\cdots}\left[\frac{k^2}{\cdots} + 6H^2 + \frac{6\ddot a}{a}\right]\right\}$$
$$+6\dot\Phi\left\{12\alpha\sigma_0^2 a^2\left[5H^3 e^{-2\phi_0} + \frac{4H\ddot a e^{\cdots}}{a}\right] + 5H\frac{\alpha T_3 e^{\cdots}}{g_{s0}}\right\} + 6\ddot\Phi\left\{\frac{\alpha T_3 e^{\cdots}}{g_{s0}} + 12\alpha\sigma_0^2\dot a^2 e^{-2\phi_0}\right\} .$$

it specifies the evolution of the metric perturbations entirely



the magnitude of the variance of the recoil velocity plays crucial role in allowing matter density perturbations to grow sufficiently to lead to structure formation

there is a minimum $|\beta|$, i.e. a minimum density of D-particles , that guarantees the existence of a growing mode

mavromatos, sakellariadou, yusaf (2013) for $M_{\mathrm{s}} \sim 10^4 \ \mathrm{GeV}$

$$\boxed{10^{-95} \le |\beta| \le 10^{-92} \qquad \Rightarrow \qquad 10^{-60}\,\widetilde{\xi}_0^{\,-2} \le \frac{n_D^{(0)}}{n_\gamma^{(0)}} \le 10^{-28}\,\widetilde{\xi}_0^{\,-2}\,, \qquad \widetilde{\xi}_0 < 1\,,}$$

an estimate of the required densities so that the D-matter recoil-velocity fluid can mimic dark matter in galaxies, in the sense that its contribution to the energy density is of the same order as the mass density of a galaxy

$$10^{-58} \ M_{\mathrm{Pl}}^4 \lesssim T_3 \lesssim 10^{-26} \ M_{\mathrm{Pl}}^4$$

combining with lensing results

dark energy contribution

neutrinos appear as dark matter candidates that could be "captured" by D-particles

after the capture by the D-particle defect, the emerging stringy matter excitation could have a different flavor than what it had initially

- D-particle populations in galaxies act as a "medium" inducing flavor oscillations
- significant contribution to vacuum energy density from oscillations $\nu_e \leftrightarrow \nu_\mu$

compute the average of the neutrino stress tensor w.r.t. flavor vacuum ${}_f\langle 0|T_{\mu\nu}|0\rangle_f$

$$\rho_{\rm vac} \sim \frac{2}{\pi}\sin^2\theta(\Delta m_{12}^2)^2$$

from atmospheric neutrino experiments

$$\Delta m_{12}^2 \sim 7\times 10^{-5}\ \mathrm{eV}^2$$

$$\sin^2\theta \sim .3$$

$$\boxed{\Omega_\Lambda^{\nu_{\rm mixing}} \sim 0.24}$$

extra time-dependent dark energy contribution

mavromatos, sakellariadou (2007)

inflation induced by D-particles

D-particles may induce inflation
through condensation of their recoil velocity field

M_s

large condensate fields
(dense populations in the EU,
but dilute today)

appropriate for low string mass
scales w.r.t. hubble inflationary scale

small condensates

appropriate for large string mass
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which is compatible with planck data?

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inflation for large recoil velocity condensate fields
(which can be induced by $\sigma(t) \gg 1$.)

$$M_s \ll H_I \sim \underbrace{10^{-5}\, M_{\rm Pl}}_{\textit{planck data}} \ll M_{\rm Pl}$$

hubble scale during inflation

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hubble scale during inflation

use finite temperature formalism, i.e. euclidean time, in order to account for the hawking-gibbons temperature (associated with observer-dependent horizon) of a de sitter space-time

➡ euclidean born-infeld action and at the end analytic continuation to minkowski space

$$S_{\rm eff\ 4D} \simeq \int {\rm d}^4 x \sqrt{g}\, \Big[-\frac{1}{4}\, \mathcal{G}_{\mu\nu}\, \mathcal{G}^{\mu\nu} - \frac{\sigma(t)}{\kappa_0^2\, \alpha} - \frac{\tilde{\Lambda}}{\kappa_0^2} + \frac{1}{\kappa_0^2}\Big(1 + \sigma(t)\Big) R(g) \Big]$$

dimensionless field

$$\sigma(t) \equiv \kappa_0^2\, \frac{\alpha\, T_3}{g_{s0}} \sqrt{\frac{\mathcal{C}^{\mathcal{E}}(t)}{2}} > 0$$

$$\sigma(t) \sim 8\sqrt{3}\, g_{s0} \left(\frac{H_{\rm I}}{M_{\rm s}}\right)^2 \gg 1$$

$$\mathcal{C}(t) \equiv (2\pi\alpha')^2 \, \langle\langle F_{\mu\nu}\, F^{\mu\nu} \rangle\rangle$$

successful starobinsky-type inflation can be induced by such large condensates

the born-infeld action reads:

$$S_{\text{eff 4D}} \simeq \int d^4x \sqrt{\tilde{g}} \left[\frac{1}{\kappa_0^2} R(\tilde{g}) + \frac{1}{2\,\kappa_0^2}\, \partial_\mu \varphi\, \partial^\mu \varphi - \frac{1}{4}\, \mathcal{G}_{\mu\nu} \mathcal{G}^{\mu\nu} - \frac{e^{-\sqrt{\frac{2}{3}}\,\varphi}}{\kappa_0^2\, \alpha} - \frac{\tilde{\Lambda}}{\kappa_0^2} \left(1 - \frac{1}{\alpha\, \tilde{\Lambda}} \right) e^{-2\sqrt{\frac{2}{3}}\,\varphi} \right]$$

redefinition of the metric

$$\tilde{g}_{\mu\nu} = (1 + \sigma) g_{\mu\nu}$$

$$\varphi = \sqrt{\frac{3}{2}} \ln\big(1 + \sigma(t)\big)$$

canonically normalised scalar field

assume that the flux field condensates into a constant one, which contributes to the vacuum energy as $\frac{1}{4} \langle\langle \mathcal{G}_{\mu\nu}\, \mathcal{G}^{\mu\nu} \rangle\rangle \equiv \mathcal{D}$

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redefinition of the metric $\tilde{g}_{\mu\nu} = (1+\sigma) g_{\mu\nu}$

$\varphi = \sqrt{\frac{3}{2}} \ln\Big(1 + \sigma(t)\Big)$ *canonically normalised scalar field*

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$$\Rightarrow \quad V^{\mathcal{E}} = -\kappa_0^2 \mathcal{D} - \frac{e^{-\sqrt{\frac{2}{3}}\varphi}}{\alpha} - \left(\tilde{\Lambda} - \frac{1}{\alpha}\right) e^{-2\sqrt{\frac{2}{3}}\varphi}$$

euclideanised effective potential for the canonically normalised scalar field

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euclideanised effective potential for the canonically normalised scalar field

performing analytic continuation back to minkowski:

$$V(\varphi) \simeq \kappa_0^2 \, \mathcal{D} + \tilde{\Lambda} \left(1 - \frac{1}{\alpha\,\tilde{\Lambda}} \right) e^{-2\sqrt{\frac{2}{3}}\tilde{\varphi}} + i\, \frac{1}{\alpha}\, e^{-\sqrt{\frac{2}{3}}\tilde{\varphi}}$$

real

the born-infeld action reads:

$$S_{\mathrm{eff}\ 4\mathrm{D}} \simeq \int d^4x\sqrt{\tilde{g}}\left[\frac{1}{\kappa_0^2}R(\tilde{g}) + \frac{1}{2\,\kappa_0^2}\partial_\mu\varphi\,\partial^\mu\varphi - \frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} - \frac{e^{-\sqrt{\frac{2}{3}}\varphi}}{\kappa_0^2\,\alpha} - \frac{\tilde{\Lambda}}{\kappa_0^2}\left(1 - \frac{1}{\alpha\,\tilde{\Lambda}}\right)e^{-2\sqrt{\frac{2}{3}}\varphi}\right]$$

the field rolls down, the condensate becomes small, the imaginary part disappears, and then one can expand the square-root of born-infeld action and recover the effective action valid at late eras

instability

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$$S_{\rm eff\ 4D} \simeq \int d^4x \sqrt{\tilde g}\left[\frac{1}{\kappa_0^2}R(\tilde g) + \frac{1}{2\,\kappa_0^2}\partial_\mu\varphi\,\partial^\mu\varphi - \frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} - \frac{e^{-\sqrt{\frac{2}{3}}\varphi}}{\kappa_0^2\,\alpha} - \frac{\tilde\Lambda}{\kappa_0^2}\left(1 - \frac{1}{\alpha\,\tilde\Lambda}\right)e^{-2\sqrt{\frac{2}{3}}\varphi}\right]$$

negative relative to $\tilde{\mathcal{D}}$

$${\rm Re}\,V(\tilde\varphi) = \tilde{\mathcal{D}} + \left(\tilde\Lambda - \frac{1}{\alpha}\right)e^{-2\sqrt{\frac{2}{3}}\tilde\varphi}\,, \quad \tilde{\mathcal{D}} \equiv \kappa_0^2\,\mathcal{D}$$

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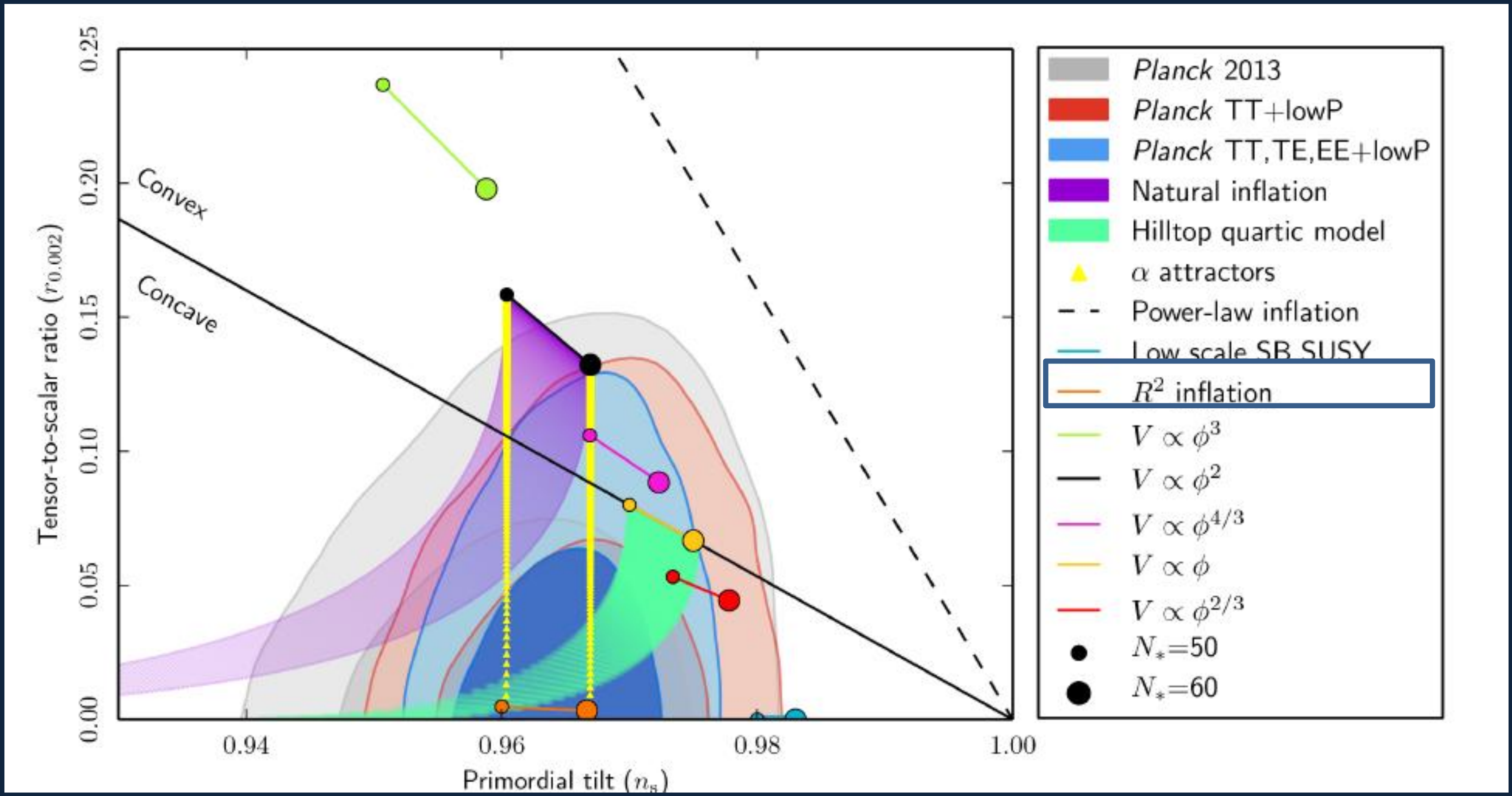


planck collaboration (2015)

starobinsky type, provided the flux field condensate is such that $\tilde{\mathcal{D}} > 0$ *and the minimum of the effective potential occurs for* $\tilde{\varphi} = 0$ *and corresponds to zero potential*

it is the gauge field flux condensate $\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu}$ that induces a de sitter phase (positive, almost constant, vacuum energy), and hence inflation, but it is the recoiling D-particles velocity vector field that induces a slowly rolling scalar degree of freedom that allows exit of inflation study of the slow-roll inflation

check agreement with

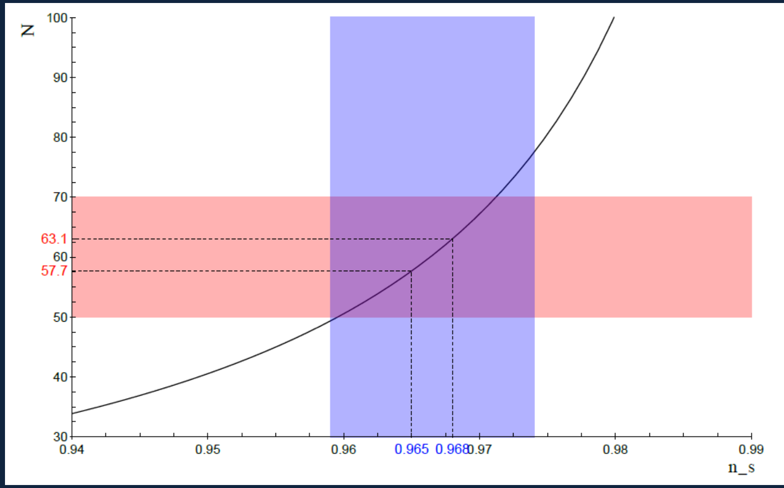
$$N \equiv -\int_{\varphi_i}^{\varphi_e} \frac{V}{V'}\,\mathrm{d}\varphi \simeq 60\;, \qquad \epsilon \equiv \frac{1}{2}M_{\mathrm{Pl}}^2\left(\frac{V'}{V}\right)^2 \ll 1\;, \qquad \eta \equiv M_{\mathrm{Pl}}^2\left(\frac{V''}{V}\right) \ll 1\;, \qquad \xi \equiv M_{\mathrm{Pl}}^4\left(\frac{V'''\,V'}{V^2}\right) \ll 1\;,$$

$$n_{\mathrm{s}} \equiv 1 - 6\epsilon + 2\eta \simeq 0.96\;, \qquad \left(\frac{\frac{1}{2\,\kappa_{\mathrm{eff}}^2}\,V}{\epsilon}\right)^{1/4} = 0.0275\,M_{\mathrm{Pl}}\;.$$

for

$$V(\tilde{\varphi}) = \tilde{\mathcal{D}} + \tilde{\Lambda}\left(1 - \frac{1}{\alpha\,\tilde{\Lambda}}\right) e^{-2\sqrt{\frac{2}{3}}\,\tilde{\varphi}}$$

fixing the spectral index fixes the number of e-folds (and vice versa)



for $n_{\mathrm{s}} = 0.965$ we get $N = 57.7$
leading to

$$\epsilon \simeq 5.6\cdot 10^{-5} \ll 1\;, \qquad \eta \simeq -1.7\cdot 10^{-2} \ll 1\;, \qquad \xi \simeq 3.0\cdot 10^{-4} \ll 1$$

and $\tilde{\mathcal{D}} \simeq 3.2\cdot 10^{-11}\,M_{\mathrm{Pl}}^2$

possible signatures in the MoEDAL LHC experiment

acharya,..., sakellariadou, ... (2014)

the MoEDAL (Monopole and Exotics Detector at the LHC) experiment at point 8 of the LHC ring is dedicated to the search for highly ionizing stable (or pseudo-stable) massive particles

D-particles may leave "scars" in the various types of passive detectors (such as TimePix) surrounding the collision point of the LHCb-experiment, near which MoEDAL is located

D-matter mass spectrum

$$m_{\mathrm{D}^*}^2 = m_{\mathrm{D}}^2 + nM_{\mathrm{s}}^2 \quad , \quad n \in Z^+$$

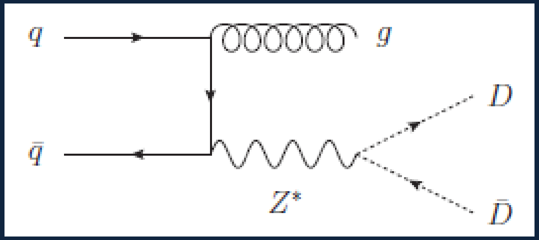
$m_{\mathrm{D}} \sim \frac{M_{\mathrm{s}}}{g_{\mathrm{s}}}$ lightest D-particle → TeV scale defects can exist in low scale string theory models

D-particles can be produced at LHC if $M_{\mathrm{s}} = \mathcal{O}(10\ \mathrm{TeV})$

example: TeV-size BH can be produced at colliders, which then undergo hawking radiation leading to the production of pairs of TeV D-$\overline{\mathrm{D}}$ pairs and SM particles

example: production of neutral D-$\overline{\mathrm{D}}$ pairs from decays of highly energetic off-shell Z^0- bosons

$$m_{\mathrm{D}} < 7\ \mathrm{TeV}$$



shiu, wang (2004)

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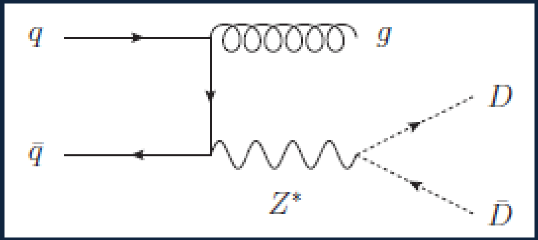


shiu, wang (2004)

the neutral D-$\overline{\mathrm{D}}$ pairs manifest themselves in a way similar to standard particle/antiparticle DM pairs at colliders

- D-matter pairs are weakly interacting → they will traverse the detector and exit undetected
- D-matter pairs are heavy, hence slow moving → they deposit all their energy inside detector
- D-particles distort space-time (as global monopoles) : deficit angle in neighbouring space-time

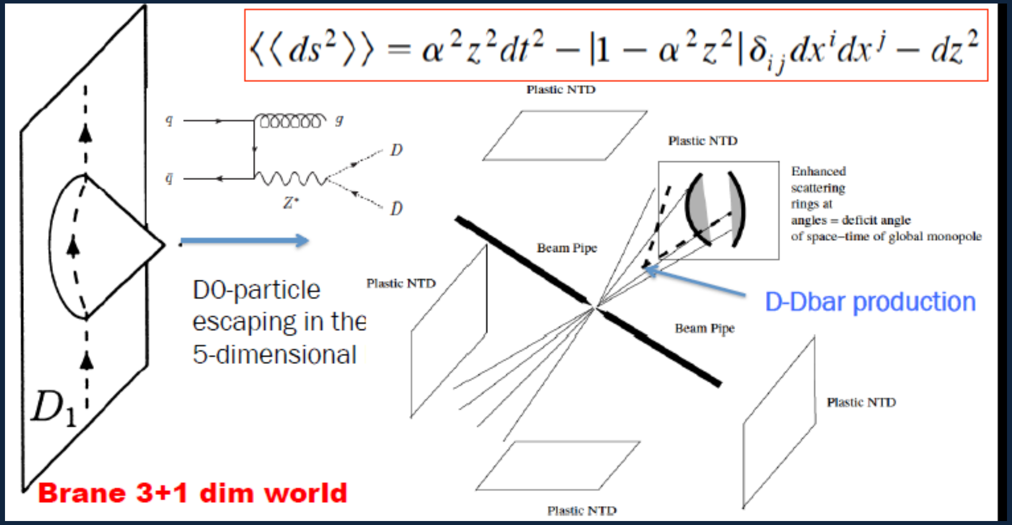
the colliding SM particles in the bean will find themselves in a space-time with a deficit angle

when the scattering angle equals the deficit one, the scattering amplitudes produce local maxima

mazur, papavassiliou (1991)

→ strange scattering patterns will appear around the trajectory of the defect, hence making its detection possible in the MoEDAL LHC experiment

similar induced effects on spacetime as from global monopoles: induced deficit angle due to recoil of D-particles → indirect detection due to scattering patterns of ordinary SM particles



5-dim spacetime with conical deficit, z: bulk extra dim

gravitational waves propagation

in progress

conclusions

D-material universe (a brane world punctured by populations of D-particles that propagates in a bulk space with varying densities of these defects)

- in the early universe: dense populations of D-particles
  for low string scales M_s w.r.t. hubble scale, and sufficiently large brane tensions w.r.t. M_s^4 the recoil velocity fluctuations lead to the formation of large condensate scalar fields that can drive inflation

  for large string scales M_s w.r.t. hubble scale, or smaller brane tensions of order of M_s^4 , the resulting condensates are small and cannot drive inflation

- in later times: the universe exits form a bulk region of dense D-particle populations, inflation ends and the universe starts RDE with power law expansion

  the recoil velocity fluctuations diminish with the inverse cubic power of the scale factor, and the condensates are weak

  the recoil-velocity-fluctuation fluid may “mimic” dark matter in agreement with lensing phenomenology

❑ D-particles may be detectable in the MoEDAL LHC experiment