If Dark Matter nonminimally couples to gravity. . .

Dmitry Gorbunov

Institute for Nuclear Research of RAS, Moscow

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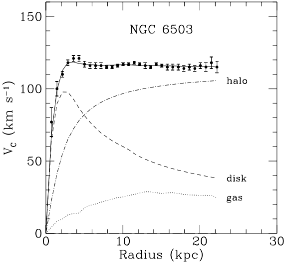
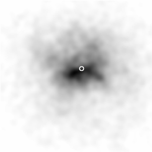
OAC
Kolymbari, Crete, Greece
(alas, via internet connection from Moscow)

Dark Matter in astrophysics

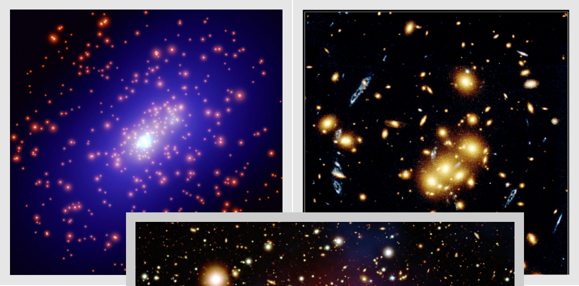
Rotational curves





X-rays from centers of galaxy clusters

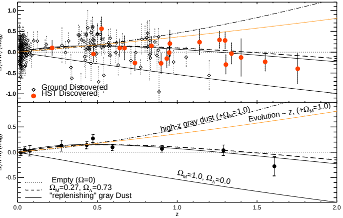
Gravitational lensing



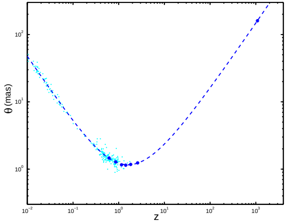
“Bullet” cluster

Dark matter in cosmology

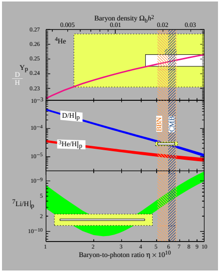
Standard candles

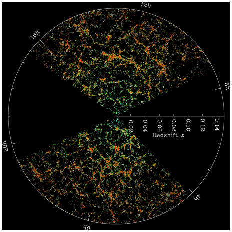


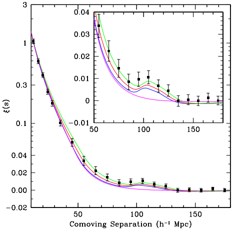
Angular distance

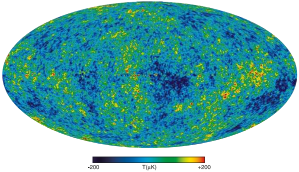


Nucleosynthesis









Large Scale Structures

Baryon acoustic oscillations

CMB anisotropy

Dark Matter properties from cosmology

(If) particles:

1. stable on cosmological time-scale
   requires new (almost) conserved quantum number
2. produced in the early Universe and being nonrelativistic
   well before RD/MD-transition ($T = 0.8\,\mathrm{eV}$)
3. (almost) collisionless $p = 0,\ v_{\mathrm{sound}} = 0$
4. (almost) electrically neutral CMB distortion
5. all matter inhomogeneities (perturbations) are adiabatic:

$$\delta\left(\frac{n_B}{n_{DM}}\right) = \delta\left(\frac{n_B}{n_\gamma}\right) = \delta\left(\frac{n_\nu}{n_\gamma}\right) = 0$$

Dark Matter properties from astrophysics

1. stable on cosmological time-scale
2. (almost) collisionless — to form ellipsoidal halos
3. (almost) electrically neutral — to be Dark
4. stability of globular stellar clusters — $M_X \lesssim 10^3 M_\odot \approx 10^{61}$ GeV
   otherwise too strong tidal forces
5. confinement in a galaxy: — quantum physics!

   de Broglie wavelength: $\lambda = 2\pi/(M_X v_X) < l_{\text{galaxy}}$, — for bosons

   in a galaxy $v_X \sim 0.5 \cdot 10^{-3}$ $\longrightarrow$ $M_X \gtrsim 3 \cdot 10^{-22}$ eV

   for fermions

   Pauli blocking: $M_X \gtrsim 750$ eV

$$f(\mathbf{p},\mathbf{x}) = \frac{\rho_X(\mathbf{x})}{M_X} \cdot \frac{1}{\left(\sqrt{2\pi} M_X v_X\right)^3} \cdot e^{-\frac{\mathbf{p}^2}{2M_X^2 v_X^2}} \Bigg|_{\mathbf{p}=0} \leq \frac{g_X}{(2\pi)^3}$$

Dark Matter Zoo

1. in the primordial plasma of SM particles:
   thermal production: freeze out(in), etc — WIMPs: neutralino, etc
   scatterings, oscillations: — gravitino
   sterile neutrino of 1-50 keV
2. at phase transitions:
   axion of $10^{-4} - 10^{-7}$ eV
   Q-balls
3. at inflation or preheating: — black holes
   any stable guy coupled to inflaton
   - perturbatively: — inflaton decays
     production by external (inflaton) field
   - non-perturbatively: — Bose-enhancement of
     coherent production by external field
4. while the Universe expands:
   gravity produces any particles at $H \sim M_X$

Gravity works admirably

Natural source of dark matter production: gravity

Gravity produces any free massive particle when metric changes in the expanding Universe

most efficiently when $H \sim M$

say, at radiation domination stage

$$\Omega_X \sim \left(\frac{M_X}{10^9\,\text{GeV}}\right)^{5/2}$$

S.Mamaev, V.Mostepanenko, A.Starobinsky (1976)

Modified gravity $(R \to R - R^2/6\mu^2)$

may be responsible for inflation and subsequent reheating

A.Starobinsky (1980)

that is (universal) production of all particles, including those of dark matter

$$\Omega_X \simeq 0.15 \times \left(\frac{M_X}{10^7\,\text{GeV}}\right)^3$$

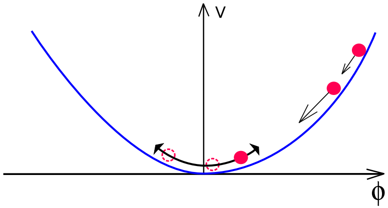
D.Gorbunov, A.Panin (2010)

Untestable

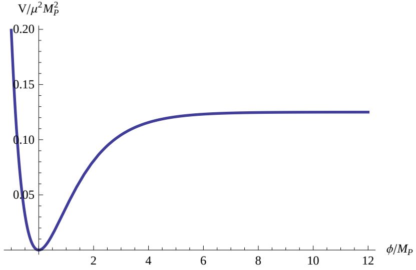
What changes with non-minimal coupling to gravity?

There are examples of a delightful performance…

$\lambda\phi^4 \longrightarrow$ Higgs inflation due to $R\phi^2$ term



$\Longrightarrow$



Scalar ϕ as a Dark Matter candidate

The simplest and safest extension is

$$\Delta\mathscr{L} \propto \phi^n R^m$$

$R^2_{\mu\nu}$, etc $\longrightarrow$ ghosts in the gravity sector

$g^{\mu\nu}\nabla_\mu\phi\nabla_\nu\phi$, etc $\longrightarrow$ higher order operators

The simplest operator

$$\Delta\mathscr{L} = M\,\phi\,R$$

has very dramatic consequences...

it violates Z_2-symmetry inducing DM decays F.Bezrukov,S.Demidov,D.G.(2020)

$$\mathscr{A} \propto \frac{M}{M_P^2} \quad\longrightarrow\quad \Gamma_{\phi\to\dots} \sim \frac{M^2}{M_P^4}\frac{m_\phi^3}{8\pi}$$

it still can be DM, provided

$$\tau_\phi \sim \left(\frac{10^3\,\text{GeV}}{m_\phi}\right)^3\left(\frac{10^{12}\,\text{GeV}}{M}\right)^2 \times \tau_U \gg \tau_U$$

so for $M = M_P$ it naively implies $m_\phi < 50\,\text{MeV}$

Decaying Dark Matter

$$\Delta\mathscr{L} = M\phi R$$

Have predictions for and limits from Cosmic Rays

where gravity is a mediator

To the leading order in model parameters

$\phi \nrightarrow GG$

$\phi \nrightarrow \psi\psi$ conformal invariance

$\phi \rightarrow hh, \quad W_L^+ W_L^-, \quad Z_L Z_L$

any scalars (e.g. squarks)

Indirect Searches give typically $\tau_\phi > 10^9 \times \tau_U$

Next-to-the-simplest operator for scalar DM χ

$$\Delta\mathscr{L} = \zeta\,\chi^2\,R$$

Z_2-symmetric

it cannot destroy DM,

moreover, it can amplify its production !!

$$S_\chi = \int d^4x\sqrt{-g}\left[\frac{g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi}{2} - \frac{m_\chi^2\chi^2}{2} + \frac{\zeta\chi^2 R}{2}\right].$$

time-dependent mass term $R \propto H^2\,,\ \dot{H}$

$$\omega_k = \sqrt{k^2 + a^2 m_\chi^2 + \frac{1}{6}(1-6\zeta)a^2 R}$$

tachyonic instability for $m_\chi^2 \lesssim \frac{1}{6}|1-6\zeta|\cdot|R|$

DM overproduction

Take conformal case, $\zeta = 1/6$

$$\omega_k = \sqrt{k^2 + a^2 m_\chi^2}$$

gravitational production in the adiabatic regime : $|\omega_k'/\omega_k^2| \ll 1$

Bogolyubov coefficient

$$\beta_k = \int_{\eta_{Pl}}^{+\infty} d\eta \cdot \frac{\omega_k'}{2\omega_k} \cdot \exp\left[-2i\int_{\eta_{Pl}}^{\eta} d\eta'\,\omega_k\right] \,,$$

we keep $m_\chi \gg H_{inf}$ to have pure adiabatic DM perturbations

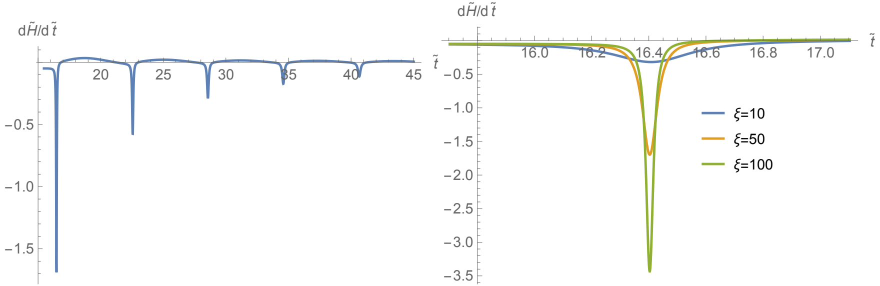
recall: perturbations of all the components are correlated

$$\delta\left(\frac{n_B}{n_{DM}}\right) = \delta\left(\frac{n_B}{n_\gamma}\right) = \delta\left(\frac{n_\nu}{n_\gamma}\right) = 0$$

$$\beta_k = \frac{1}{2}\int_{t_{Pl}}^{+\infty} dt \cdot \left[\frac{m_\chi^2 H(t)}{(\omega_k(t)/a(t))^2}\right] \cdot \exp\left[-2i\int_{t_{Pl}}^{t} dt'\,\frac{\omega_k(t')}{a(t')}\right]$$

Take $\lambda\phi^4$ inflation with $\xi R\phi^2$

E.Babichev,D.G.,S.Ramazanov, L.Reverberi (2020)



χ are produced at the spikes, where $|\dot{H}| \gg H^2$

$$|\beta_k| \simeq \frac{\sqrt{2\pi}\cdot m_\chi^2 \cdot H_{\rm infl}^{1/2}}{24\cdot(\omega_k(t_e)/a_e)^{5/2}}\cdot \exp\left[-\frac{4\cdot\omega_k(t_e)}{a_e\cdot\xi\cdot H_{\rm infl}}\right] \qquad \left(\frac{\omega_k(t_e)}{a_e} \gg \xi\, H_{\rm infl}\right)$$

$$\omega_k = \sqrt{k^2 + a^2 m_\chi^2}$$

DM is really heavy

$$dn_\chi = \frac{k^2 dk}{2\pi^2} \cdot \frac{1}{a^3(t)} |\beta_k|^2$$

so finally χ form DM if

and lighter χ are forbidden

$$\frac{8 m_\chi}{\xi H_{\text{infl}}} \approx 29 + 2\ln\xi + \frac{3}{2}\ln\frac{m_\chi}{\xi H_{\text{infl}}}$$

in particular,

$$\xi = 100 \quad \longrightarrow \quad m_\chi \approx 5 \cdot \xi H_{\text{infl}}$$

can be heavy up to... ?

to avoid strong coupling $\Lambda_s \simeq M_P/\sqrt{\xi} > H_{inf}$

$\xi \lesssim 100$, hence $m_\chi \lesssim 3 \times 10^{16}$ GeV...

Smooth gravity, homogeneous DM field χ

a stage with

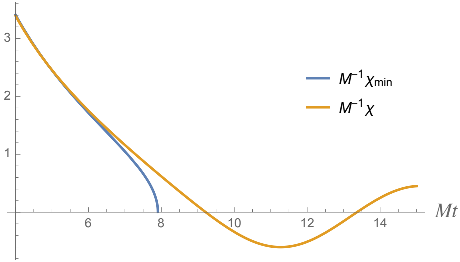
E.Babichev,D.G.,S.Ramazanov (2020)

$$p = w\rho\,, \quad R = -3\cdot(1-3w)\cdot H^2$$

DM with selfcoupling

$$\mathscr{L} = \frac{(\partial_\mu\chi)^2}{2} - \frac{M^2\chi^2}{2} - \frac{\lambda\chi^4}{4} - \frac{\zeta}{2}\cdot\chi^2\cdot R$$

χ is in the false vacuum at large H



at $-\zeta R(t_*) \simeq M^2$ it changes and χ starts to oscillate
gravitational misalignment

$$\rho_{DM}(t_*) = \frac{M^2\cdot\chi_*^2}{2} \simeq \frac{\left(M^5 H_*\right)^{2/3}}{4\lambda}$$

Summary

- Non-minimal coupling can make DM testable

$$\phi R \quad \Longrightarrow \quad \phi \to hh,\ W^+W^-,\ ZZ$$

- Strongly amplifies DM production

$$\phi^2 R$$

thus opening a room for superheavy DM
and naturally avoiding the isocurvature fluctuations, i.e.

$$m_\phi \gg H_{inf}$$

- Spinors, vectors? Higher order operators? ...