Scalar dark matter production by scalaron

Dmitry Gorbunov

(based on 1009.2448 with Alexander Panin, work in progress...)

Institute for Nuclear Research, Moscow

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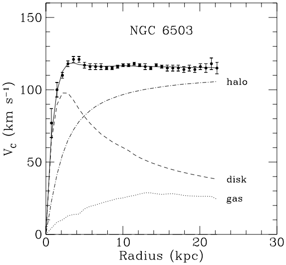
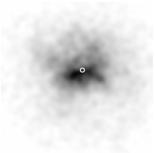
University of Warsaw, 27.08.2011

Dark Matter in Astrophysics

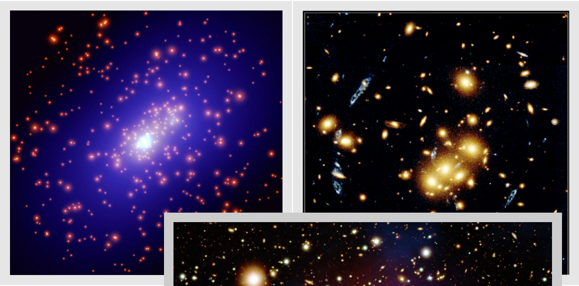
Rotation curves





X-rays from clusters

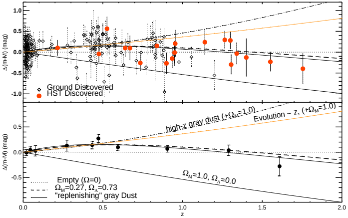
Gravitational lensing



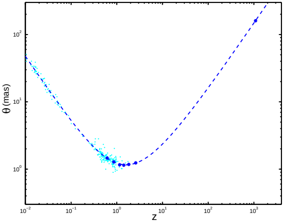
“Bullet” cluster

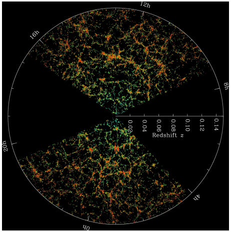
Dark Matter in Cosmology

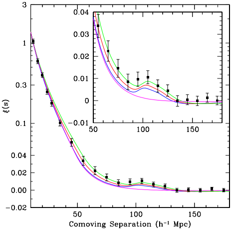
Standard candles

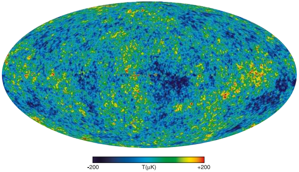


Angular distance







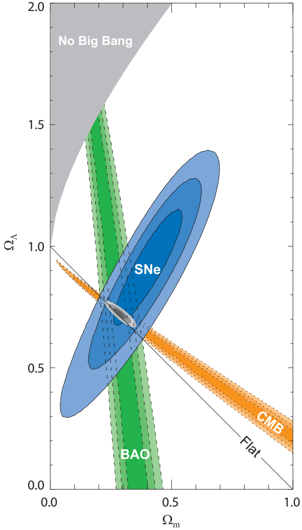


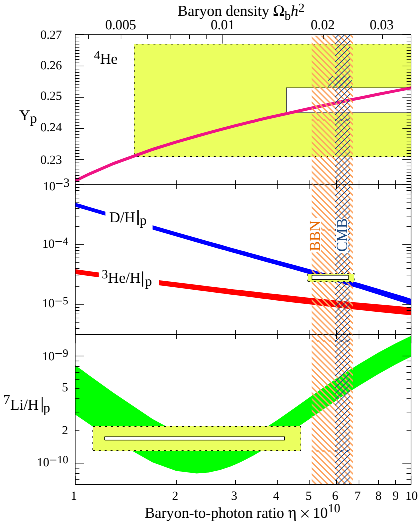
Structures

BAO

CMB fluctuations

Cosmological parameters: $\Omega_{DM} = 0.22$, $\Omega_B = 0.046$





arXiv:0804.4142

http://pdg.lbl.gov

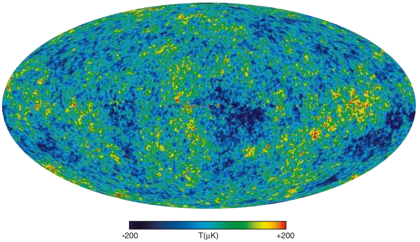
Standard Model: Success and Problems

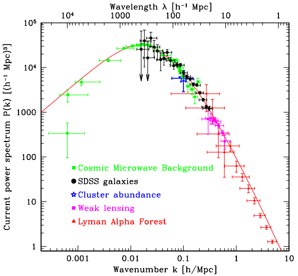
Gauge fields (interactions): γ, $W^{\pm}$, Z, g

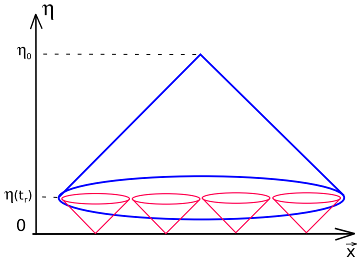
Three generations of matter: $L = \binom{\nu_L}{e_L}$, e_R; $Q = \binom{u_L}{d_L}$, d_R, u_R

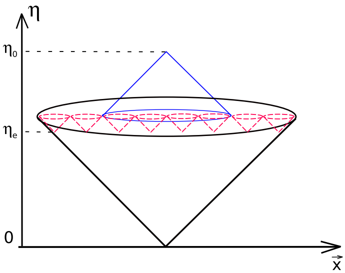
- Describes
  - all experiments dealing with electroweak and strong interactions
- Does not describe
  - Neutrino oscillations
  - Dark matter (Ω_{DM})
  - Baryon asymmetry (Ω_B)

Inflationary solution of Hot Big Bang problems









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  - Inflationary stage
  - Dark energy (Ω_Λ)
  - Strong CP: boundary terms, new topology, …
  - Gauge hierarchy: No new scales!
  - Quantum gravity

Try to explain all above

Gravity saves the day…?

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Inflation: R^2 term

$$S^{JF} = -\frac{M_P^2}{2}\int\sqrt{-g}\,d^4x\left(R - \frac{R^2}{6\mu^2}\right) + S^{JF}_{matter}\,,$$

Jordan Frame $\to$ Einstein Frame

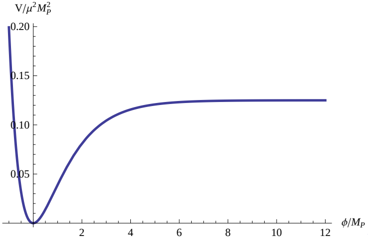
A.Starobinsky (1980)

$$g_{\mu\nu} \to \tilde{g}_{\mu\nu} = \chi\, g_{\mu\nu}\,, \qquad \chi = \exp\left(\sqrt{2/3}\,\phi/M_P\right)\,.$$

$$S^{EF} = \int\sqrt{-\tilde{g}}\,d^4x\left[-\frac{M_P^2}{2}\tilde{R} + \frac{1}{2}\tilde{g}^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - \frac{3\mu^2M_P^2}{4}\left(1 - \frac{1}{\chi(\phi)}\right)^2\right] + S^{EF}_{matter}\,,$$

generation of (almost) scale-invariant scalar perturbations from freezed in quantum fluctuations

$\delta\rho/\rho \sim 10^{-5}$ requires
$\mu = m_\phi \approx 1.3\times 10^{-5}\,M_P$



Post-inflationary Reheating: provided by gravity

$$S^{JF}_{matter} = S(g_{\mu\nu}, \varphi, A_\mu, \ldots) \to S^{EF}_{matter} = S(\tilde{g}_{\mu\nu}, \tilde{\varphi}, \tilde{A}_\mu, \ldots)$$

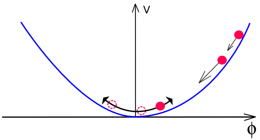
$$g_{\mu\nu} \to \tilde{g}_{\mu\nu} = \chi\, g_{\mu\nu}\,, \qquad \chi = \exp\left(\sqrt{2/3}\,\phi/M_P\right)\,.$$

for free (in the Jordan frame) scalar φ and fermion ψ fields:

$$S^{EF}_{\varphi} = \int \sqrt{-\tilde{g}}\, d^4x \left(\frac{1}{2}\,\tilde{g}^{\mu\nu}\partial_\mu\tilde{\varphi}\partial_\nu\tilde{\varphi} - \frac{1}{2\chi}\,m^2_\varphi\tilde{\varphi}^2 + \frac{\tilde{\varphi}^2}{12\,M_P^2}\,\tilde{g}^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + \frac{\tilde{\varphi}}{\sqrt{6}\,M_P}\,\tilde{g}_{\mu\nu}\partial_\mu\tilde{\varphi}\partial_\nu\phi\right)\,,$$

$$S^{EF}_{\psi} = \int \sqrt{-\tilde{g}}\, d^4x \left(i\bar{\tilde{\psi}}\tilde{\hat{\mathscr{D}}}\psi - \frac{m_\psi}{\sqrt{\chi}}\,\bar{\tilde{\psi}}\tilde{\psi}\right)\,.$$

$$\varphi \to \tilde{\varphi} = \chi^{-1/2}\,\varphi\,, \quad \psi \to \tilde{\psi} = \chi^{-3/4}\,\psi\,, \quad \hat{\mathscr{D}} \to \tilde{\hat{\mathscr{D}}} = \chi^{-1/2}\,\hat{\mathscr{D}}$$



New scale $m_\phi \sim \mu$ is screened:
$\delta\mathscr{L}^{JF} = \frac{M_P^2}{2\mu^2}R^2 \to \mathscr{L}^{EF}_{\phi} \propto 1/M_P$

Reheating: decay of scalarons

$\rho_\phi = \mu^2\phi^2/2 = \mu n_\phi \to \rho_{rad} \propto T^4$ $\qquad \mu \gg m_\varphi, m_\psi$

$$\Gamma_{\phi\to\varphi\varphi} = \frac{\mu^3}{192\pi M_P^2}\,,$$

$$\Gamma_{\phi\to\bar\psi\psi} = \frac{\mu\, m_\psi^2}{48\pi M_P^2}\,.$$

$$T_{reh} \approx 4.5\times 10^{-2}\times g_*^{-1/4}\cdot\left(\frac{N_{scalars}\,\mu^3}{M_P}\right)^{1/2}\,,$$

for the SM with 4 scalar degrees of freedom: A.Starobinsky (1980,1981)

$$T_{reh} \approx 3\times 10^9\ \mathrm{GeV}$$

Dark Matter

Most economic solution: stable scalars

The WIMP-like solution needs

1. special coupling to SM fields
2. special symmetry to prevent instability: decay into SM fields

In R^2-inflation the most economic solution is

production in the scalaron decay

both Inflation and Dark matter from the same source, GRAVITY

Scalar Dark Matter: production in scalaron decays

The same universal messenger: gravity

D.G., A.Panin 1009.2448

$\rho_\phi = \mu^2\phi^2/2 = \mu\, n_\phi \to \rho_{DM} = m_{DM}\, n_{DM}$

$$\Gamma_{\phi\to\varphi\varphi} = \frac{\mu^3}{192\pi M_P^2}\,,$$

$$m_\varphi \approx 7\ \mathrm{keV} \times \left(\frac{N_{scalars}}{4}\right)^{1/2}\left(\frac{g_*}{106.75}\right)^{1/4}\,,$$

Heavier stable particles ($m_\phi < \mu/2 \sim 10^{13}$ GeV) are excluded!

Scalars are hot!

$$p_\varphi \sim 10^{13}\,\mathrm{GeV} \quad @ \quad T_{reh} \approx 3\times 10^9\,\mathrm{GeV}$$

Scalars are still relativistic at eV-epoch!

Hence not DM

Scalar Dark Matter: other ways out

Two options within our paradigm of
AVOIDING NEW INTERACTIONS IN PARTICLE PHYSICS:

1. switch on nonminimal (conformal) coupling to GRAVITY: $\frac{\xi}{2} R\varphi^2$
2. consider a SUPERHEAVY dark matter candidate: $m_\varphi > \mu/2$

1: Light scalar with nonminimal coupling to gravity

$$S_\varphi^{JF} = \int \sqrt{-g}\, d^4x \left(\frac{1}{2} g^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi - \frac{1}{2} m_\varphi^2 \varphi^2 + \frac{\xi}{2} R \varphi^2 \right) ,$$

introducing no new scales, not interfering with inflation: $0 < \xi < 1$

$$g_{\mu\nu} \to \tilde{g}_{\mu\nu} = \chi\, g_{\mu\nu} , \qquad \chi = \exp\left(\sqrt{2/3}\, \phi / M_P \right) , \qquad \varphi \to \tilde{\varphi} = \chi^{-1/2} \varphi .$$

for free (in the Jordan frame) scalar field φ:

$$S_\varphi^{EF} = \int \sqrt{-\tilde{g}}\, d^4x \left[\frac{1}{2} \tilde{g}^{\mu\nu} \partial_\mu \tilde{\varphi} \partial_\nu \tilde{\varphi} + \frac{\xi}{2} \tilde{R} \tilde{\varphi}^2 - \frac{1}{2\chi} m_\varphi^2 \tilde{\varphi}^2 + \frac{1}{2} \left(\frac{1}{6} - \xi \right) \frac{\tilde{\varphi}^2}{M_P^2} \tilde{g}^{\mu\nu} \partial_\mu \phi \partial_\nu \phi + \sqrt{6} \left(\frac{1}{6} - \xi \right) \frac{\tilde{\varphi}}{M_P} \tilde{g}^{\mu\nu} \partial_\mu \tilde{\varphi} \partial_\nu \phi \right] .$$

$$\Gamma_{\phi \to \varphi\varphi} = \left(1 - 6\xi - 2 \frac{m_\varphi^2}{\mu^2} \right)^2 \frac{\mu^3}{192 \pi M_P^2} .$$

1: Warm or Cold scalar dark matter

$$\Gamma_{\phi\to\varphi\varphi} = \left(1 - 6\xi - 2\frac{m_\varphi^2}{\mu^2}\right)^2 \frac{\mu^3}{192\pi M_P^2}\,.$$

scalar 3-momentum @ production: $p_* = \sqrt{\mu^2/4 - m_\varphi^2}$, then redshifting $p = p_* \frac{a(t_*)}{a(t_{reh})}$

Spectrum of produced dark matter particles:

$$f(p) \propto \frac{1}{p^{3/2}}\,, \qquad \langle p\rangle(T_{reh}) = \frac{3}{5}p_* \gg T_{reh}$$

Ultrarelativistic @ reheating must be conformal "with 10%-accuracy"

To be Warm ($v_{DM} \sim 10^{-3}$ @ equilibrium, $T \sim 1$ eV) we need:

$$m_\phi \simeq 3\,\text{MeV}\,, \quad \text{then } \xi \approx 1/6 - 7.7\times10^{-3}\,, \text{ or } \xi \approx 1/6 + 7.7\times10^{-3}\,.$$

To be Cold ($v_{DM} \ll 10^{-3}$ @ equilibrium, $T \sim 1$ eV) we need:

$$1/6 - 7.7\times10^{-3} < \xi < 1/6 + 7.7\times10^{-3}\,, \quad m_\phi = m_\phi(\xi) > 3\,\text{MeV}$$

2: Superheavy dark matter candidate, $m_\varphi > \mu/2$

Particle production in the expanding Universe

$$ds^2 = a^2(\eta)\left(d\eta^2 - d\vec{x}^2\right)\,, \qquad \tilde{\varphi} = s/a(\eta)\,,$$

Main effect: production at the end of inflation $\qquad e^{-\phi/M_P}\, m_\varphi^2 \tilde{\varphi}^2$

$$\left\{\frac{\partial^2}{\partial\eta^2} - \frac{\partial^2}{\partial\vec{x}^2} + \frac{1}{\chi} a^2 m_\varphi^2 - \left(\frac{1}{6} - \xi\right)\left(6\frac{a''}{a} + \frac{\phi'^2}{M_P^2} + \frac{\sqrt{6}\,a^2}{M_P}\frac{\partial V(\phi)}{\partial\phi}\right)\right\} s(\eta,\vec{x}) = 0\,,$$

Calculation of Bogolubov's transformation coefficients: $\qquad$ vacuum initial conditions

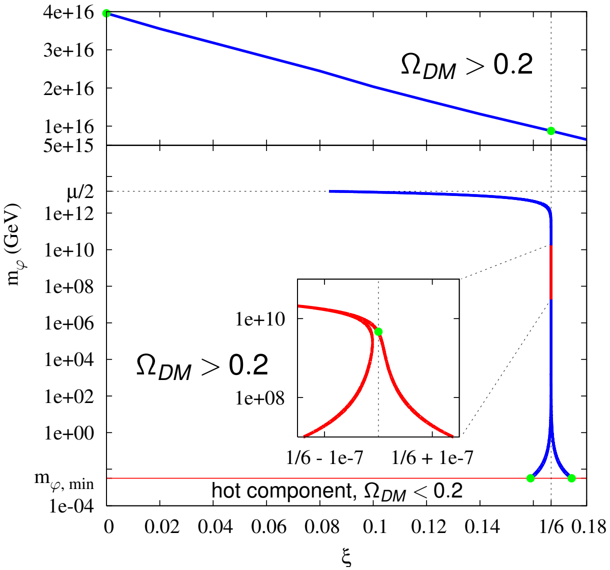
$$s(\eta,\vec{x}) = \frac{1}{(2\pi)^{3/2}}\int d^3p\left(\hat{a}_p s_p(\eta) e^{-i\vec{p}\vec{x}} + \hat{a}_p^\dagger s_p^*(\eta) e^{i\vec{p}\vec{x}}\right)\,, \qquad s_p \to 1/\sqrt{2\omega}\,,\;\; s_p' \to -i\omega s_p\,.$$

DM particle density in post-inflationary Universe $\qquad m_\varphi \sim 10^{16}$ GeV to explain DM

$$n_\varphi = \frac{1}{(2\pi a)^3}\int d^3p\,|\beta_p|^2\,, \qquad |\beta_p|^2 = \frac{|s_p'|^2 + \omega^2|s_p|^2}{2\omega} - \frac{1}{2}\,.$$

Summary on scalar Dark Matter:

D.G., Panin, 1109.xxxx



Minimal coupling to gravity, $\xi = 0$:
Superheavy DM:
$m_\phi = 4 \times 10^{16}$ GeV

Conformal coupling to gravity, $\xi = 1/6$:
Superheavy DM:
$m_\phi = 1 \times 10^{16}$ GeV
Heavy DM:
$m_\phi \sim 3 \times 10^{9}$ GeV
production @ $H \sim m_\phi$ neglected yet

Warm Dark Matter:

$m_\phi \sim 3\,\text{MeV}$

Back up slides

Summary

Simple inflationary model R^2
extended by three sterile fermions (neutrinos)
explains

- active neutrino masses and mixing angles
- DM as 10^7 GeV free fermions
- baryon asymmetry via leptogenesis due to heavy sterile neutrinos of 10^{12}-10^{13} GeV produced by scalaron decay (new scale)
- (or baryon asymmetry via leptogenesis due to light sterile neutrinos of 10^{-1}-10^{1} GeV produced by oscillations)

All above is due to universal coupling of scalaron to matter provided by gravity (and neutrino)

Predictions: n_s and r, m_h from Landau pole, one massless neutrino
active neutrino sector...? (and light sterile neutrinos)

BAU via leptogenesis: two options

Add sterile neutrinos to explain active neutrino oscillations

use oscillations to produce sterile neutrinos in primordial plasma (OK)
or
use the same universal messenger to produce sterile neutrinos: gravity (new scale)

$\rho_\phi = m_\phi^2 \phi^2/2 = m_\phi n_\phi \to \rho_N = m_N n_N$

$$\mathscr{L}^{JF} = i\bar{N}_I \gamma^\mu \partial_\mu N_I - y_{\alpha I} \bar{L}_\alpha N_I \tilde{\Phi} - \frac{M_I}{2} \bar{N}_I^c N_I + h.c.$$

$$\frac{n_{N_I}}{s}(T_{reh}) = 3 \times 10^{-6} \times \left(\frac{M_I}{5 \times 10^{12}\ \mathrm{GeV}} \right)^2 .$$

seesaw mechanism:

$$m_{\nu\,\alpha\beta} = -\sum_I y_{\alpha I} \frac{v^2}{2 M_I} y_{\beta I} ,$$

neutrino of $M_N > 10^{10}$ GeV decays before reheating:

$$\Gamma_{N_I} = \frac{M_I}{8\pi} \sum_\alpha |y_{\alpha I}|^2 \sim \frac{\sqrt{\Delta m^2_{atm}}}{4\pi} \frac{M_I^2}{v^2} .$$

Lepton asymmetry from seesaw neutrino decays

Only the lightest sterile neutrino contribution ($I = 1, 2$, $M_1 \ll M_2$) is enough

$$\delta_L = \frac{\Gamma(N_1 \to hl) - \Gamma(N_1 \to h\bar{l})}{\Gamma^{tot}_{N_1}} \lesssim \frac{3\,M_1\,\sqrt{\Delta m^2_{atm}}}{8\pi v^2}$$

an order of magnitude estimate for the asymmetry right before the reheating

$$\Delta_L = \frac{n_L}{s} = \delta_L \cdot \frac{n_{N_1}}{s} \lesssim 1.5 \times 10^{-9} \times \left(\frac{M_1}{5 \times 10^{12}\ \mathrm{GeV}}\right)^3 .$$

we got
$\Delta_{B,0} = \Delta_L/3 \sim 0.5 \times 10^{-9}$

we need
$\Delta_{B,0} \approx 0.88 \times 10^{-10}$

Cannot yield much larger...!