Dark matter in well-motivated extensions of the Standard physics: models, production mechanisms, strategy of (in)direct searches

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Idea of the talk:

Since we got no signals of Physics beyond the SM (so far. . .)

- And yet have phenomenological problems to deal with. . .
- There is a handful of very different models with (simple low energy phenomenology
  and) different dark matter candidates:
  differenet production mechanisms, different strategies of searches for
- When WIPS passed, there is no obvious favorite, hence keep your eyes open

Outline

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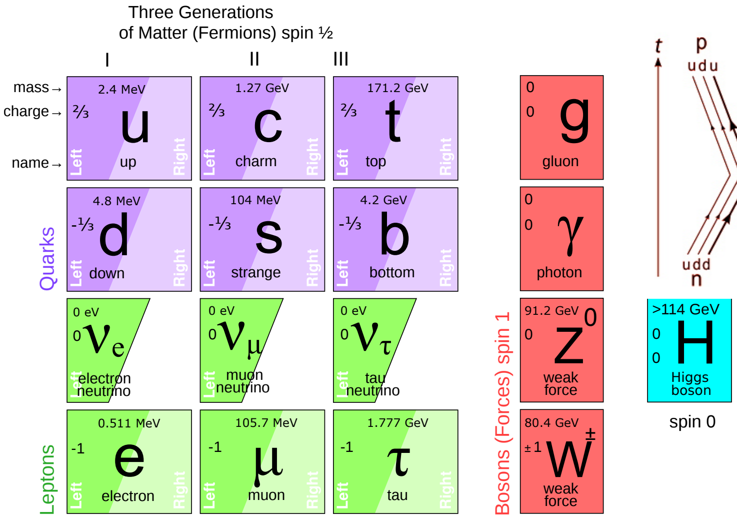
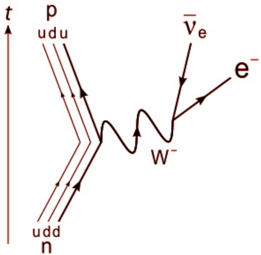
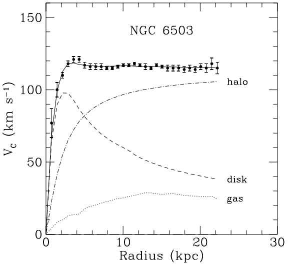
Neutrino oscillations: $\nu_\mu \leftrightarrow \nu_e$, $\nu_\mu \leftrightarrow \nu_\tau$, $\nu_e \leftrightarrow \nu_\tau$

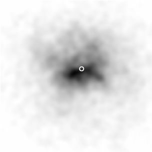




Universe content from astrophysics

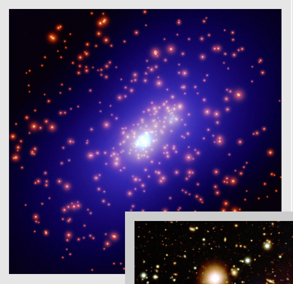
Rotational curves





X-rays from centers of galaxy clusters

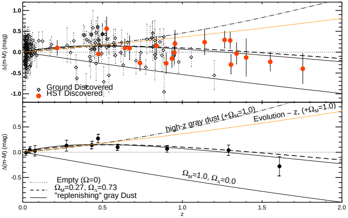
Gravitational lensing



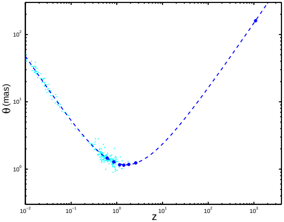
“Bullet” cluster

Universe content from cosmology

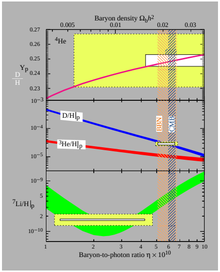
Standard candles

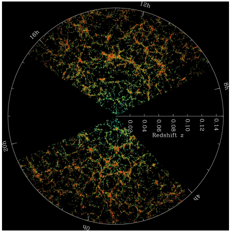


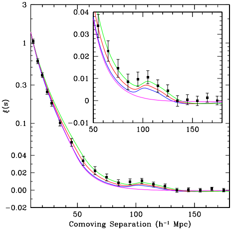
Angular distance

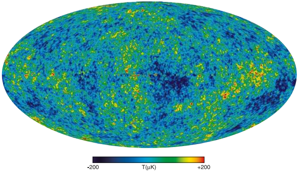


Nucleosynthesis



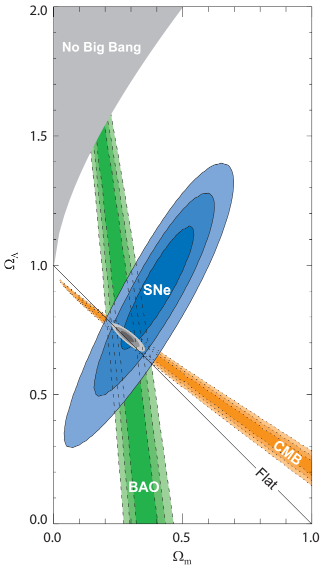






Large Scale Structures | Baryon acoustic oscillations | CMB anisotropy

Astrophysical and cosmological data are in agreement



$$\left(\frac{\dot{a}}{a}\right)^2 = H^2(t) = \frac{8\pi}{3} G \rho_{\text{density}}^{\text{energy}}$$

$$\rho_{\text{density}}^{\text{energy}} = \rho_{\text{radiation}} + \rho_{\text{matter}}^{\text{ordinary}} + \rho_{\text{matter}}^{\text{dark}} + \rho_\Lambda$$

$$\rho_{\text{radiation}} \propto 1/a^4(t) \propto T^4(t)\,, \quad \rho_{\text{matter}} \propto 1/a^3(t)$$

$$\rho_\Lambda = \text{const}$$

$$\frac{3H_0^2}{8\pi G} = \rho_{\text{density}}^{\text{energy}}(t_0) \equiv \rho_c \approx 0.53 \times 10^{-5}\,\frac{\text{GeV}\,c^2}{\text{cm}^3}$$

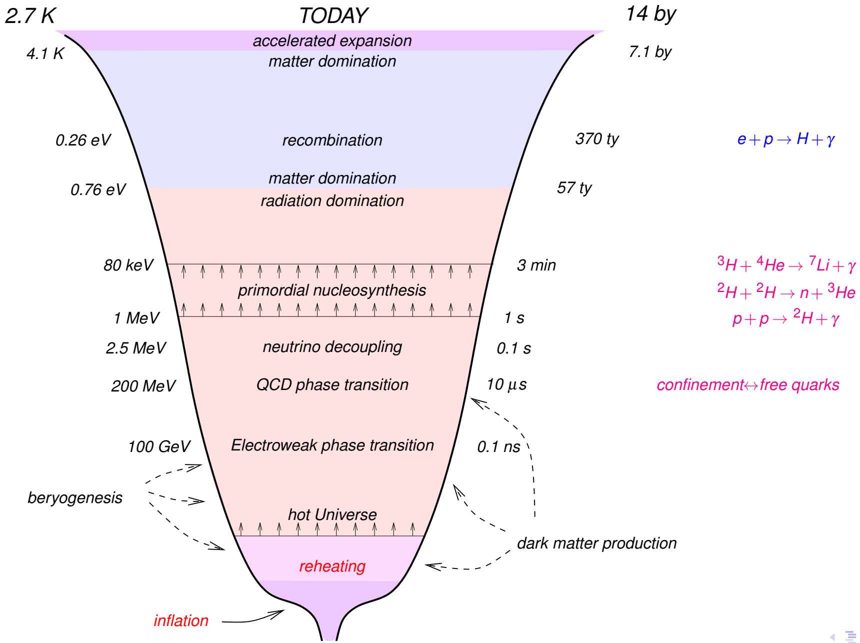
radiation: $\Omega_\gamma \equiv \frac{\rho_\gamma}{\rho_c} = 0.5 \times 10^{-4}$

Baryons (H, He): $\Omega_B \equiv \frac{\rho_B}{\rho_c} = 0.05$

Neutrino: $\Omega_\nu \equiv \frac{\sum \rho_{\nu_i}}{\rho_c} < 0.01$

Dark matter: $\Omega_{DM} \equiv \frac{\rho_{DM}}{\rho_c} = 0.25$

Dark energy: $\Omega_\Lambda \equiv \frac{\rho_\Lambda}{\rho_c} = 0.7$

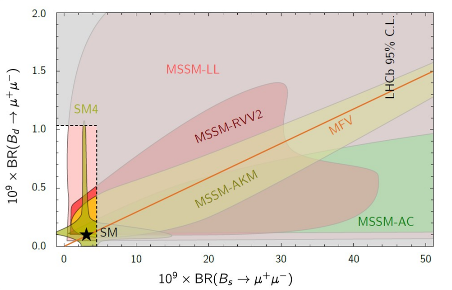

2.7 K
TODAY
14 by
accelerated expansion
4.1 K
matter domination
7.1 by
0.26 eV
recombination
370 ty
e + p → H + γ
matter domination
0.76 eV
radiation domination
57 ty
80 keV
3 min
³H + ⁴He → ⁷Li + γ
primordial nucleosynthesis
²H + ²H → n + ³He
1 MeV
1 s
p + p → ²H + γ
2.5 MeV
neutrino decoupling
0.1 s
200 MeV
QCD phase transition
10 μs
confinement↔free quarks
100 GeV
Electroweak phase transition
0.1 ns
beryogenesis
hot Universe
dark matter production
reheating
inflation

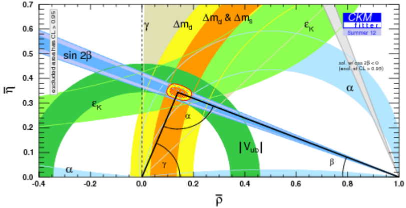
Physics beyond the SM . . . @ EW scale (LHC)?

- neutrino oscillations: masses are needed
  the only direct evidence, but the NP-scale is hidden: $m_\nu \sim M_D^2/M_N$
- baryon asymmetry of the Universe: baryogenesis
  requires NP, but the scale is hidden 100 GeV $< E < M_{Pl}$
- Hot Big Bang problems: inflation
  new scalars or interactions,
  but the scale is hidden 100 GeV $< E < M_{Pl}$
- strong CP-problem: axion
  requires NP @ $E > 10^{10}$ GeV. . . hierarchy problem?
-
- dark matter phenomena: Why $\Omega_B \sim \Omega_{DM}$? neutral stable particle
  a lack of gravity is observed: WIMPs @ EW? modified gravity?
- gauge hierarchy problem: NP @ EW-scale
  a) no new fields — no problem! b) already have to cancel Λ

Physics beyond the SM: no any signs in

- direct production of new particles: superpartners, KK-excitations, techno-resonances, etc
- rare processes: quantum correction from new (heavy) particles





Outline

Dark Matter Properties $p=0$

(If) particles:

1. stable on cosmological time-scale
2. nonrelativistic long before RD/MD-transition (either Cold or Warm, $v_{RD/MD} \lesssim 10^{-3}$)
3. (almost) collisionless
4. (almost) electrically neutral

If were in thermal equilibrium: $M_X \gtrsim 1$ keV

If not: for bosons

$\lambda = 2\pi/(M_X v_X)$, 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 Candidates

- WIMPs (neutralino, . . .)
- sterile neutrinos
- gravitino
- Heavy and not so heavy relics

Weakly Interacting Massive Particles

Assumptions:

1. no $X - \bar{X}$ asymmetry $\qquad n_X = n_{\bar{X}}$
2. @ $T < M_X$ in thermal equilibrium with plasma

$$n_X = n_{\bar{X}} = g_X \left(\frac{M_X T}{2\pi}\right)^{3/2} e^{-M_X/T}$$

$$X\bar{X} \longrightarrow \text{light particles}$$

freeze-out temperature T_f $\qquad M_{Pl}^* = M_{Pl}/1.66\sqrt{g_*}$

$$\frac{1}{n_X}\frac{1}{\langle \sigma_{ann} v \rangle} = H^{-1}(T_f) \longrightarrow T_f = \frac{M_X}{\ln\left(\frac{g_X M_X M_{Pl}^* \sigma_0}{(2\pi)^{3/2}}\right)}\,.$$

Bethe formulae: $\qquad$ s-wave: $\sigma_{ann} = \frac{\sigma_0}{v}$

Weakly Interacting Massive Particles

density after freeze-out: $n_X(T_f) = \frac{T_f^2}{M_{Pl}^* \sigma_0}$

present density: $n_X(T_0) = \left(\frac{a(T_f)}{a(T_0)}\right)^3 n_X(T_f) = \left(\frac{s_0}{s(T_f)}\right) n_X(T_f) \propto \frac{1}{T_f} \propto \frac{1}{M_X}$

$X + \bar{X}$ contribution to critical density:

$$\Omega_X = 2\frac{M_X n_X(T_0)}{\rho_c} = 7.6\frac{s_0 \ln\left(\frac{g_X M_{Pl}^* M_X \sigma_0}{(2\pi)^{3/2}}\right)}{\rho_c \sigma_0 M_{Pl}\sqrt{g_*(T_f)}}$$

$$= 0.1 \cdot \left(\frac{(10\text{ TeV})^{-2}}{\sigma_0}\right) \frac{0.3}{\sqrt{g_*(T_f)}} \ln\left(\frac{g_X M_{Pl}^* M_X \sigma_0}{(2\pi)^{3/2}}\right) \cdot \frac{1}{2h^2}$$

natural dark matter: $\sigma_0 \sim 0.01 \times \sigma_W$

naturaly “light” $\sigma_0 \lesssim \frac{4\pi}{M_X^2} \longrightarrow M_X \lesssim 100\text{ TeV}$

Supersymmetric extensions

- stability of gauge hierarchy (feature)
- gauge coupling unification (feature of MSSM)
- dark matter (natural)
- baryogenesis (untestable)
- ...

New problems

- some massive parameters (μ) or scales (M_{weak}) are still *adhoc*
- supersymmetric CP-problem: $M_{\tilde{Q}} > 20$ TeV
- large FCNC: ...or a special mechanism
- ...

Split SUSY: $M_{\tilde{Q}} \gg M_\lambda$

Whether it is possible in SUSY: Yes, moreover, even natural

- In many (simple) models where SUSY is broken spontaneously gauginos are light (massless), that was the problem
- the hierarchy $M_{\tilde{Q}} \gg M_\lambda$ is stable with respect to quantum corrections (RG-evolution)

$$\frac{dM_{\lambda_i}}{d\log Q^2} \propto \alpha_i M_{\lambda_i}$$

$$\frac{dM^2_{\tilde{Q}}}{d\log Q^2} \propto y^2 M^2_{\tilde{Q}} + \cdots + \alpha_i M^2_{\lambda_i}$$

$$\frac{dA_i}{d\log Q^2} \propto y^2 A_i + \cdots + \alpha_i M_{\lambda_i}$$

Split SUSY: $M_{\tilde{Q}} \gg M_\lambda$

@ 1 TeV: gauginos + higgsinos + SM-like Higgs boson

- dark matter (natural)
- gauge coupling unification (feature of Split MSSM)
- no FCNC (natural)
- stability of gauge hierarchy (LOST)
  - Though... in MSSM is (partially) lost as well: $(100\text{ GeV})^2 \ll (1\text{ TeV})^2$
  - String theory: $M_{\tilde{Q}} \gg M_\lambda$ is natural, as either
    small Λ and large M_{SUSY}
    or
    large Λ and small M_{SUSY}

Why NMSSM ?

- μ-problem :
  MSSM: $\hat{W} = \mu \hat{H}_u \hat{H}_d$ NMSSM: $\hat{W} = \hat{N} \hat{H}_u \hat{H}_d$
- testable mechanism of baryogenesis:
  MSSM: Affleck-Dine NMSSM : Electroweak

EWB does not work in SM:

- *CP*-violating processes are too weak
- crossover, so no departure from termal equilibrium

MSSM: new sources of *CP*-violation
NMSSM: the strongly first order phase transition as well

Electroweak baryogenesis is appealing:
both machanisms can be directly tested

Description of the model

Start with the most general NMSSM: D.G., S.Demidov (2007)

$$\mathscr{L}_{SUSY} = \hat{W}\Big|_{\theta^2} + h.c.\,, \qquad \hat{W} = \lambda \hat{N}\hat{H}_u\varepsilon\hat{H}_d + \frac{1}{3}k\hat{N}^3 + \mu\hat{H}_u\varepsilon\hat{H}_d + r\hat{N}$$

where $\hat{\Phi} = \Phi + \sqrt{2}\tilde{\Phi}\theta + F_\Phi\theta^2$. CP-source: $\mu = \Im(\mu)$

$$V_{soft} = \left(\lambda A_\lambda NH_u\varepsilon H_d + \frac{1}{3}kA_k N^3 + \mu BH_u\varepsilon H_d + A_r N + h.c.\right) + m_u^2 H_u^\dagger H_u + m_d^2 H_d^\dagger H_d + m_N^2|N|^2.$$

and the rest is like in MSSM

Splitting: $M_U^2 \sim M_D^2 \sim B\mu \sim M_{\text{Split}}^2 \ll M_W^2$

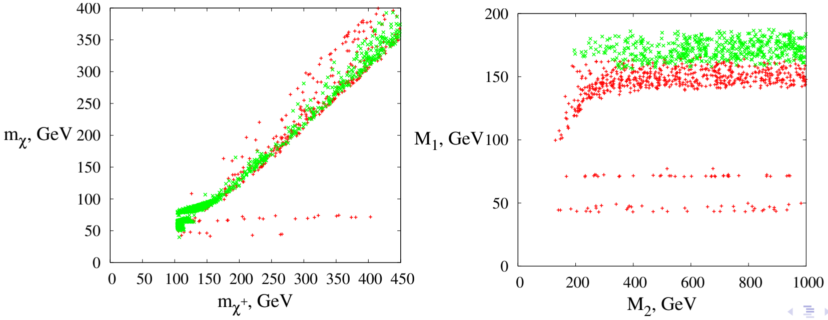
Dark Matter

$$\chi = N_{51}\tilde{B} + N_{52}\tilde{W} + N_{53}\tilde{H}_u + N_{54}\tilde{H}_d + N_{55}\tilde{N}$$

$$\frac{m_\chi}{T_F} = x_F = \log\left(\frac{m_\chi}{2\pi^3}\sqrt{\frac{45}{2g_* G_N x_F}}\langle\sigma v\rangle_{\text{Møl}}\right)$$

$$\langle\sigma v\rangle_{\text{Møl}} = \frac{1}{8m_\chi^4 T K_2^2(m_\chi/T)}\int_{4m_\chi^2}^{\infty} ds\sigma(s)(s-4m_\chi^2)\sqrt{s}K_1\left(\frac{\sqrt{s}}{T}\right)$$

$$\Omega_\chi h^2 = \frac{(1.07\times 10^9\,\text{GeV}^{-1})}{M_{Pl}}\left(\int_{x_F}^{\infty} dx \frac{\langle\sigma v\rangle_{\text{Møl}}(x)}{x^2} g_*^{1/2}\right)^{-1}.$$



Gravitino production: strong fine-tuning

$$\mathscr{L} = \frac{1}{F}\partial^\mu\psi\cdot J_\mu^{SUSY}\;, \quad \tilde{G}_\mu \to \tilde{G}_\mu + i\sqrt{4\pi}\frac{M_{Pl}}{F}\partial_\mu\psi$$

$$m_{3/2} = \sqrt{\frac{8\pi}{3}}\frac{F}{M_{Pl}}$$

$$1\text{ TeV} \lesssim \sqrt{F} \lesssim M_{Pl}\;, \quad 2\cdot 10^{-4}\text{ eV} \lesssim m_{3/2} \lesssim M_{Pl}\;.$$

LSP in low scale SUSY breaking models

$$2\cdot 10^{-4}\text{ eV} \lesssim m_{3/2} \lesssim 100\text{ GeV} \longrightarrow \sqrt{F} \lesssim 10^{10}\text{ GeV}$$

Thermal equilibrium is forbidden:

$$\Omega_{3/2} = \frac{m_{3/2}\cdot n_{3/2}}{\rho_c} = 0.2\frac{m_{3/2}}{200\text{ eV}}\left(\frac{g_{3/2}}{2}\right)\cdot\left(\frac{210}{g_*(T_f)}\right)\cdot\frac{1}{2h^2}$$

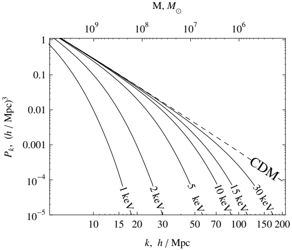
$$\tilde{X}_i \to \tilde{G} + X_i\;, \quad X_i + X_j \to X_k + \tilde{G}$$

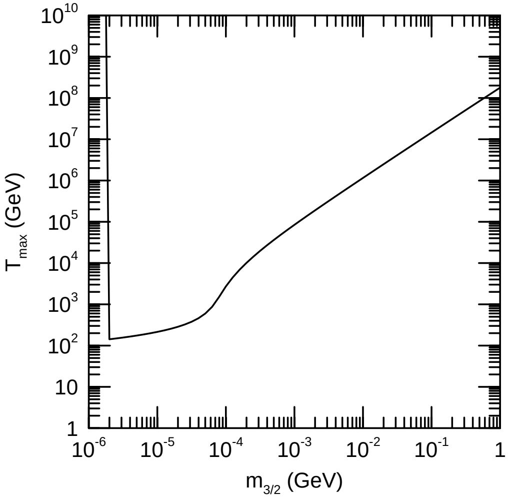
Gravitino non-thermal production

$$\frac{dn_{3/2}}{dt} + 3Hn_{3/2} = \sum_i \Gamma_{\tilde{X}_i} \cdot \gamma_i^{-1} \cdot n_{\tilde{X}_i} + \langle\sigma_{tot}\rangle \cdot n_\gamma^2 \,,$$

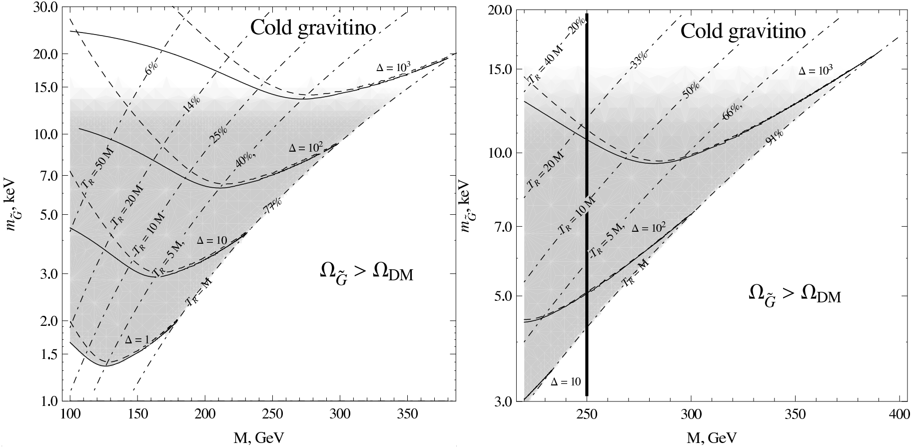
$$\Omega_{3/2} \sim \left(\frac{200}{m_{3/2}}\right) \cdot \left(\frac{T_{max}}{10}\right) \cdot \left(\frac{M_S}{1}\right)^2 \cdot \left(\frac{15}{\sqrt{g_*(T_{max})}}\right) \cdot \frac{1}{2h^2}$$

Cold or Warm ?





Gravitino: cold or warm



decay contribution is at dashed lines;
$\Delta = 3^{3/2} m_{\tilde{G}}^4 f/Q > 1$, where $Q = \rho/\sigma^3$ $Q = 5 \times 10^{-3} (M_{\odot}/pc^3)/(km/s)^3$

D.G., A.Khmelnitsky, V.Rubakov (2008)

Outline

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 $\rightarrow$ Einstein Frame

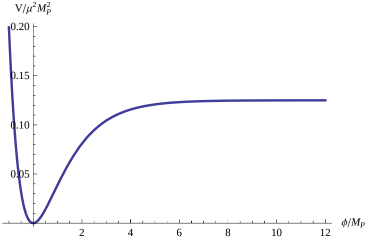
A.Starobinsky (1980)

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

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

generation of (almost) scale-invariant scalar perturbations from exponentially stretched 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

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

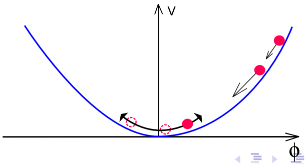
$$g_{\mu\nu} \to \tilde{g}_{\mu\nu} = \chi\, g_{\mu\nu}\,, \qquad \chi = \exp\left(\sqrt{2/3}\,\phi/M_P\right)\,.$$

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

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

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

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

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

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

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

D.G., A.Panin (2010)

Dark Matter production in scalaron decays

The same universal messenger: gravity

D.G., A.Panin (2010)

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

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not Dark Matter ☞ $m_\varphi \approx 7\ \text{keV} \times \left(\frac{N_{scalars}}{4}\right)^{1/2}\left(\frac{g_*}{106.75}\right)^{1/4}$,

Cold Dark Matter ☞ $m_\psi \approx 10^7\ \text{GeV} \times \left(\frac{N_{scalars}}{4}\right)^{1/6}\left(\frac{106.75}{g_*}\right)^{1/12}$.

Heavier stable particles are excluded!

Scalars are overheated: $p_\varphi \sim 10^{13}$ GeV at $T_{reh} \approx 3\times 10^9$ GeV

Still too fast for proper structure formation at 1 eV epoch. . . ☹

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Cold Dark Matter $\quad m_\psi \approx 10^7\ \text{GeV} \times \left(\frac{N_{scalars}}{4}\right)^{1/6}\left(\frac{106.75}{g_*}\right)^{1/12}$.

Heavier stable particles are excluded!

Scalars are overheated: $\quad p_\varphi \sim 10^{13}$ GeV at $T_{reh} \approx 3\times 10^9$ GeV

Still too fast for proper structure formation at 1 eV epoch...

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:

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

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

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 20%-accuracy”

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

$$m_\phi \simeq 0.7\,\text{MeV}\,, \quad \text{then } \xi \approx 1/6 - 0.019\,, \text{ or } \xi \approx 1/6 + 0.019\,.$$

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

$$1/6 - 0.019 < \xi < 1/6 + 0.019\,, \quad m_\phi = m_\phi(\xi) > 0.7\,\text{MeV}$$

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

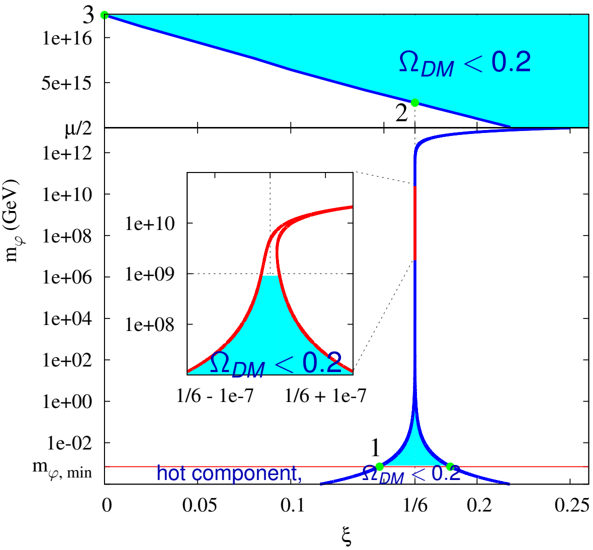
$$s(\eta,\vec{x}) = \frac{1}{(2\pi)^{3/2}}\int d^3p\left(\hat{a}_p s_p(\eta) e^{-i\vec{p}\vec{x}} + \hat{a}_p^\dagger s_p^*(\eta) e^{i\vec{p}\vec{x}}\right)\,, \qquad s_p \to 1/\sqrt{2\omega}\,,\;\; s_p' \to -i\omega s_p\,.$$

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, 1201.3539



Minimal coupling to gravity, $\xi = 0$:
Superheavy DM:
$m_\phi = 1.3 \times 10^{16}$ GeV

Conformal coupling to gravity, $\xi = 1/6$:
Superheavy DM:
$m_\phi = 2.8 \times 10^{15}$ GeV
Heavy DM: $m_\phi > 10^9$ GeV is forbidden
due to production @ $H \sim m_\phi$

Warm Dark Matter:

$m_\phi \gtrsim 0.7$ MeV

Outline

Higgs-driven inflation

F.Bezrukov, M.Shaposhnikov (2007)

$$S = \int d^4x \sqrt{-g}\left(-\frac{M_P^2}{2}R - \xi H^\dagger H R + \mathscr{L}_{SM}\right)$$

In a unitary gauge $H^T = \left(0, (h+v)/\sqrt{2}\right)$ (and neglecting $v = 246\,\text{GeV}$)

$$S = \int d^4x \sqrt{-g}\left(-\frac{M_P^2 + \xi h^2}{2}R + \frac{(\partial_\mu h)^2}{2} - \frac{\lambda h^4}{4}\right)$$

slow roll behavior due to modified kinetic term even for $\lambda \sim 1$

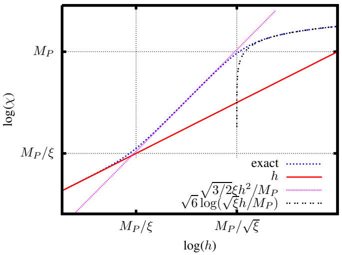
Go to the Einstein frame: $(M_P^2 + \xi h^2)\, R \to M_P^2\, \tilde{R}$

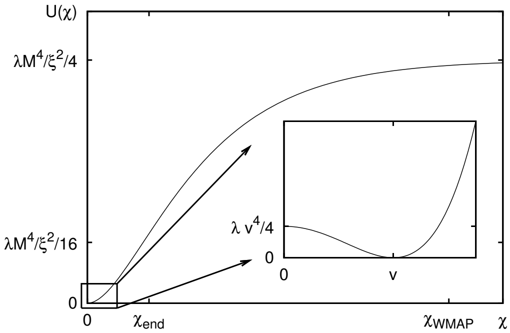
$$g_{\mu\nu} = \Omega^{-2}\tilde{g}_{\mu\nu}\,, \qquad \Omega^2 = 1 + \frac{\xi h^2}{M_P^2}$$

with canonically normalized χ:

$$\frac{d\chi}{dh} = \frac{M_P\sqrt{M_P^2 + (6\xi+1)\xi h^2}}{M_P^2 + \xi h^2}\,,\quad U(\chi) = \frac{\lambda M_P^4 h^4(\chi)}{4(M_P^2 + \xi h^2(\chi))^2}\,.$$

we have a flat potential at large fields: $U(\chi) \to \text{const}$ @ $h \gg M_P/\sqrt{\xi}$





Reheating by Higgs field

after inflation: $M_P/\xi < h < M_P/\sqrt{\xi}$

exponentially flat potential! @ $h \gg M_P/\sqrt{\xi}$:

$$U(\chi) = \frac{\lambda M_P^4}{4\xi^2}\left(1 - \exp\left(-\frac{\sqrt{2}\chi}{\sqrt{3}M_P}\right)\right)^2$$

effective dynamics : $h^2 \to \chi$

$$\mathscr{L} = \frac{1}{2}\partial_\mu\chi\partial^\mu\chi - \frac{\lambda}{6}\frac{M_P^2}{\xi^2}\chi^2$$

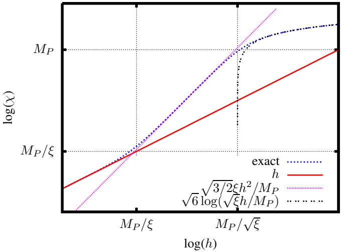
coincides with R^2-model!

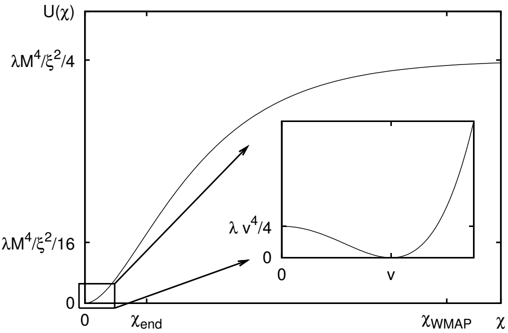
But NO NEW d.o.f. 0812.3622, 1111.4397

Advantage: NO NEW interactions to reheat the Universe

inflaton couples to all SM fields!

from WMAP-normalization: $\xi \approx 47000 \times \sqrt{\lambda}$





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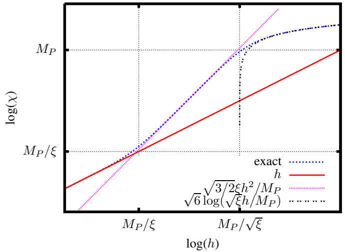
F.Bezrukov, D.G., M.Shaposhnikov, 0812.3622



$$m_W^2(\chi) = \frac{g^2}{2\sqrt{6}} \frac{M_P|\chi(t)|}{\xi}$$

$$m_t(\chi) = y_t \sqrt{\frac{M_P|\chi(t)|}{\sqrt{6}\,\xi}}\,\text{sign}\,\chi(t)$$

reheating via W^+W^-, ZZ production at zero crossings

then nonrelativistic gauge bosons scatter to light fermions

$$W^+W^- \to f\bar{f}$$

Reheating by Higgs field

after inflation: $M_P/\xi < h < M_P/\sqrt{\xi}$

effective dynamics : $h^2 \to \chi$

$$\mathscr{L} = \frac{1}{2}\partial_\mu\chi\partial^\mu\chi - \frac{\lambda}{6}\frac{M_P^2}{\xi^2}\chi^2$$

Hot stage starts almost from $T = M_P/\xi \sim 10^{14}$ GeV:

$$3.4 \times 10^{13}\text{GeV} < T_r < 9.2 \times 10^{13} \left(\frac{\lambda}{0.125}\right)^{1/4} \text{GeV}$$

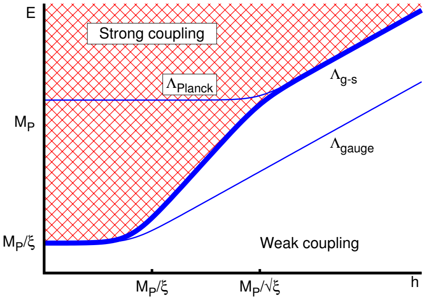
Advantage: NO NEW interactions to reheat the Universe

inflaton couples to all SM fields!

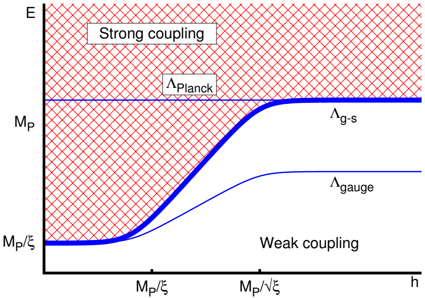
from WMAP-normalization: $\xi \approx 47000 \times \sqrt{\lambda}$

Strong coupling in Higgs-inflation

Jordan frame



Einstein frame



gravity-scalar sector:

$$\Lambda_{g-s}(h) \simeq \begin{cases} \frac{M_P}{\xi}, & \text{for } h \lesssim \frac{M_P}{\xi}, \\ \frac{\xi h^2}{M_P}, & \text{for } \frac{M_P}{\xi} \lesssim h \lesssim \frac{M_P}{\sqrt{\xi}}, \\ \sqrt{\xi}\, h, & \text{for } h \gtrsim \frac{M_P}{\sqrt{\xi}}. \end{cases}$$

gravitons: $\Lambda^2_{\text{Planck}} \simeq M_P^2 + \xi h^2$

gauge interactions:

$$\Lambda_{\text{gauge}}(h) \simeq \begin{cases} \frac{M_P}{\xi}, & \text{for } h \lesssim \frac{M_P}{\xi}, \\ h, & \text{for } \frac{M_P}{\xi} \lesssim h, \end{cases}$$

1008.5157

What can nonrenormalizable operators do?

F.Bezrukov, D.G., Shaposhnikov (2011)

$$\delta\mathscr{L}_{\rm NR} = -\frac{a_6}{\Lambda^2}(H^\dagger H)^3 + \cdots + \frac{\beta_L}{4\Lambda}F_{\alpha\beta}\bar{L}_\alpha \tilde{H} H^\dagger L^c_\beta + \frac{\beta_B}{\Lambda^2}O_{\text{baryon violating}} + \cdots + \text{h.c.} + \frac{\beta_N}{2\Lambda}H^\dagger H \bar{N}^c N + \frac{b_{L_\alpha}}{\Lambda}\bar{L}_\alpha (\not{D} N)^c \tilde{H} + \cdots ,$$

L_α are SM leptonic doublets, $\alpha = 1,2,3$, N stands for right handed sterile neutrinos potentially present in the model, $\tilde{H}_a = \varepsilon_{ab}H^*_b$, $a,b = 1,2$;

and

$$\Lambda = \Lambda(h) = \left\{\Lambda_{g-s}(h)\,,\ \Lambda_{\rm gauge}(h)\,,\ \Lambda_{\rm Planck}(h)\right\}$$

couplings can differ significantly in different regions of h:
today $h < M_P/\xi$, at preheating $M_P/\xi < h < M_P/\sqrt{\xi}$

Dark matter: an example of sterile fermion

$$\mathscr{L}_{\text{int}} = \beta_N \frac{H^\dagger H}{2\Lambda} \bar{N}^c N = \frac{\beta_N}{4} \frac{h^2}{\Lambda(h)} \bar{N}^c N \,.$$

can be produced at preheating or at the hot stage

DM fermion has to be light! (WDM?)

Indeed, today

$$\frac{b_{L\alpha}}{\Lambda} \bar{L}_\alpha (\not{D} N)^c \tilde{H}$$

$$f_\alpha \sim b_{L_\alpha} \frac{M_N}{\Lambda} \,.$$

So, N is unstable with the $\gamma\nu$ partial width of the order

$$\Gamma_{N\to\gamma\nu} \sim \frac{9\, b_{L_\alpha}^2 \alpha G_F^2}{512\pi^4} \frac{v^2 M_N^5}{\Lambda^2} \,.$$

EGRET gives $\tau_{\gamma\nu} \gtrsim 10^{27}$ s, hence

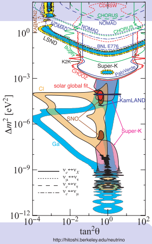
0709.2299

$$\text{for } \Lambda = M_P : \quad M_N \lesssim 200\,\text{MeV}\,, \qquad \text{for } \Lambda = M_P/\xi : \quad M_N \lesssim 4\,\text{MeV}$$

Outline

νMSM

- Use as little “new physics” as possible
- Require to get the correct neutrino oscillations
- Explain DM and baryon asymmetry of the Universe



Lagrangian

Most general renormalizable with 3 right-handed neutrinos N_I

$$\mathscr{L}_{\nu MSM} = \mathscr{L}_{MSM} + \overline{N}_I i \partial\!\!\!/ N_I - f_{I\alpha} H \overline{N}_I L_\alpha - \frac{M_I}{2} \overline{N}_I^c N_I + \text{h.c.}$$

Extra coupling constants:

3 Majorana masses M_i — T.Asaka, S.Blanchet, M.Shaposhnikov (2005)

15 new Yukawa couplings — T.Asaka, M.Shaposhnikov (2005)
(Dirac mass matrix $M^D = f_{I\alpha}\langle H\rangle$ has 3 Dirac masses, 6 mixing angles and 6 CP-violating phases)

ν Masses and Mixings: "seesaw" from $f_{I\alpha} H \overline{N}_I L_\alpha$

$M_I \gg M^D = f\, v$ says nothing about M_I ! dangerous: $\delta m_h^2 \propto M_I^2$

3 heavy neutrinos with masses M_I similar to quark masses

Light neutrino masses $M^\nu = -(M^D)^T \frac{1}{M_I} M^D \propto f^2 \frac{v^2}{M_I}$

$$U^T M^\nu U = \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix}$$

Mixings: flavor state $\nu_\alpha = U_{\alpha i} \nu_i + \theta_{\alpha I} N_I^c$

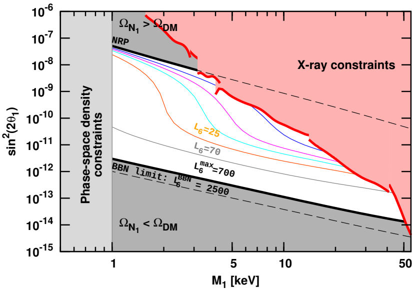
Active-sterile mixings $\theta_{\alpha I} = \frac{(M^D)^\dagger_{\alpha I}}{M_I} \propto f \frac{v}{M_I} \ll 1$

Lightest sterile neutrino N_1 as Dark Matter

Non-resonant production (active-sterile mixing) is ruled out

Resonant production (lepton asymmetry) requires $\Delta M_{2,3} \lesssim 10^{-16}$ GeV

arXiv:0804.4542, 0901.0011, 1006.4008



Outline

Inflation & Reheating: simple realization

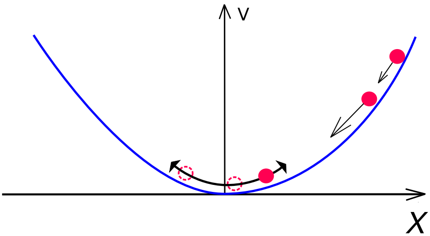
$$S_X = \int d^4x\sqrt{-g}\left[\frac{g^{\mu\nu}}{2}\partial_\mu X\partial_\nu X - V(X)\right]$$

$$ds^2 = dt^2 - a^2(t)d\mathbf{x}^2 = g_{\mu\nu}dx^\mu dx^\nu$$

$$\ddot{X} + 3H\dot{X} + V'(X) = 0$$

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3M_{Pl}^2}\left[\frac{1}{2}\dot{X}^2 + V(X)\right]$$

$X_e > M_{Pl}$



generation of scale-invariant scalar (and tensor) perturbations from exponentially stretched quantum fluctuations of X

Chaotic inflation, A.Linde (1983)

$\delta T/T \sim \delta\rho/\rho \sim 10^{-4}$ requires
$V = \beta X^4 : \beta \sim 10^{-13}$

reheating ? renormalizable?

larger α larger T_{reh}

the only choice: $\alpha H^\dagger H X^2$

quantum corrections $\propto \alpha^2 \lesssim \beta$

Inflation & Reheating: the model

$$\mathscr{L}_{XN} = \frac{1}{2}\partial_\mu X \partial^\mu X + \frac{1}{2} m_X^2 X^2 - \frac{\beta}{4} X^4 - \lambda \left(H^\dagger H - \frac{\alpha}{\lambda} X^2 \right)^2$$

The SM-like vacuum of the scalar potential

SM sector is scale-invariant

$$v = \sqrt{\frac{2\alpha}{\beta\lambda}} m_X = 246\,\text{GeV}\,, \quad m_h = \sqrt{2\lambda}\, v\,, \quad m_\chi = m_h \sqrt{\frac{\beta}{2\alpha}}$$

Higgs-inflaton ($h - \chi$) mixing angle

$$\theta = \sqrt{\frac{2\alpha}{\lambda}} = \frac{\sqrt{2\beta}\, v}{m_\chi} \sim 10^{-3} \times \left(\frac{100\text{ MeV}}{m_\chi} \right)$$

Amplitude of primordial perturbations: $\beta \approx 1.5 \times 10^{-13}$

F.Bezrukov, D.G. (2009)

Only one free parameter!

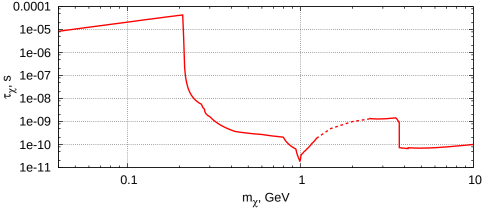
$50\text{ MeV} \lesssim m_\chi \lesssim 1.8\text{ GeV}$

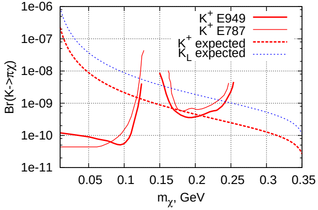
$T_{reh} > 100$ GeV, $m_h < 130$ GeV

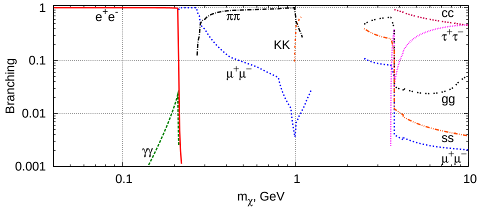
Landau pole above inflation scale

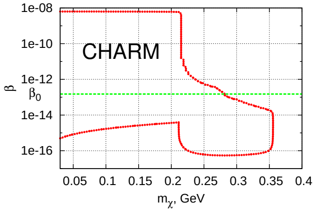
study of reheating:
A.Anisimov, Y.Bartocci, F. Bezrukov (2008)

Phenomenlogy: Higgs-inflaton mixing!









$m_\chi \lesssim$ 250 MeV is excluded !

from $K \to \pi\chi$ and $pN \to \ldots\chi(\chi \to \gamma\gamma,\, e^+e^-\, \mu^+\mu^-)$

Inflaton Phenomenlogy: direct searches

$$\mathrm{Br}\,(B \to \chi X_s) \simeq 0.3 \times \frac{|V_{ts} V_{tb}^*|^2}{|V_{cb}|^2} \left(\frac{m_t}{M_W}\right)^4 \left(1 - \frac{m_\chi^2}{m_b^2}\right)^2 \theta^2$$

$$\simeq 10^{-6} \times \cdot \left(1 - \frac{m_\chi^2}{m_b^2}\right)^2 \left(\frac{300\text{ MeV}}{m_\chi}\right)^2 ,$$

Recent sensitivity: Belle, LHCb

$\mathrm{Br}(B \to K^{(*)} l^+ l^-) \gtrsim 10^{-7}$ 250 MeV $\lesssim m_\chi \lesssim$ 1.8 GeV

Expectation for the Inflaton:

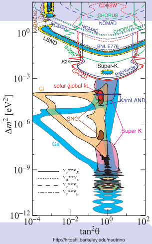
scalar channel $B \to K\chi$

displaced decay vertex $c\tau_\chi \sim 3 - 30$ cm

peaks at a given energy for $\mu^+\mu^-$, $\pi^+\pi^-$, K^+K^-

This INFLATIONARY model can be directly and fully explored thanks to B-physics!

Straightforward completion of νMSM



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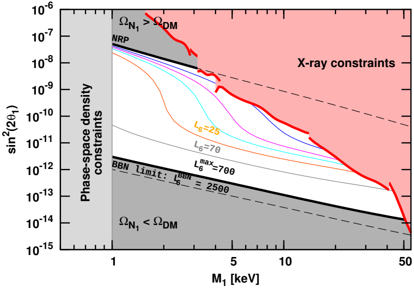


Dark Matter production
from inflaton decays in plasma at $T \sim m_\chi$

M.Shaposhnikov, I.Tkachev (2006)

$$M_{N_I} \bar{N}_I^c N_I \leftrightarrow f_I X \bar{N}_I N_I$$

Can be "naturally" Warm

F.Bezrukov, D.G. (2009)

$$M_1 \lesssim 15 \times \left(\frac{m_\chi}{300\ \text{MeV}}\right) \text{keV}$$

Outline

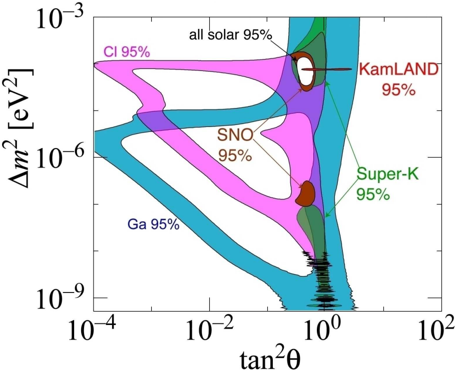
Conclusions on DM after LHC results

- Let's wait for a while…
- If we shall prove the SM @ 1 TeV…
  – Baryogenesis happened not @ EW-scale
  – DM-particles apparently are not WIMPs
  (axion $\to$ ADMX, sterile neutrinos $\to$ X-ray telescopes, mirror baryons $\to$ OPs$\to$nothing, etc)
  – May be, the minimal principle is at work (to be tested @ LHC):
  e.g., for DM: $V = m_X^2 X^2 + \beta X^2 H^\dagger H$

Backup slides

Neutrino oscillations: masses and mixing angles

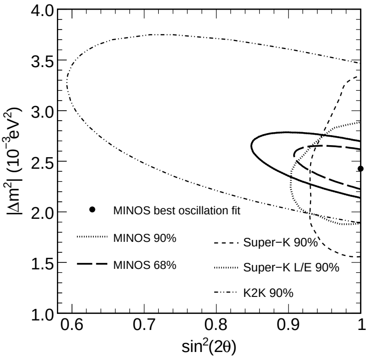
Solar 2×2 "subsector"



http://hitoshi.berkeley.edu/neutrino/

$m_1 > 0.008\,\text{eV}$

Atmospheric 2×2 "subsector"

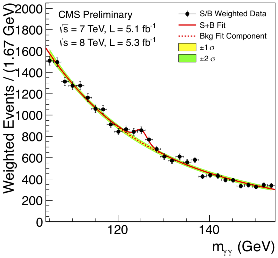


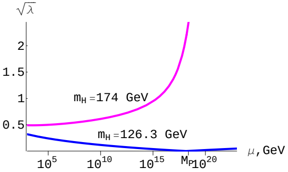
arXiv:0806.2237

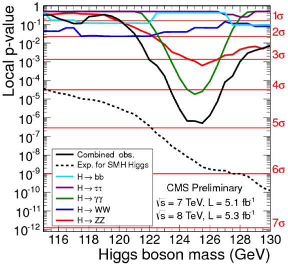
$m_2 > 0.05\,\text{eV}$

DAYA-BAY, RENO: $\sin^2 2\theta_{13} \approx 0.1$

LEPII, TeVatron & LHC: ... Higgs of 126 GeV?

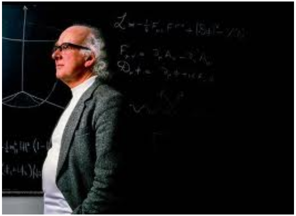






- LEPII: $m_h > 114$ GeV
- fit to EW data: $m_h \sim 90 < 114$ GeV
- TeVatron: not in $156 < m_h < 177$ GeV
- CMS: not in $127 < m_h < 600$ GeV
- ATLAS: not in 114-115, 131-237, 251-453 GeV

$$m_h = \sqrt{2\lambda}\,v$$



$$\lambda\left(H^\dagger H - \frac{v^2}{2}\right)^2$$

$$\to \frac{\lambda}{4} h^4 + \lambda v^2 h^2$$

$$\mathcal{L}_Y \propto Y_f h \bar{f} f/\sqrt{2}$$

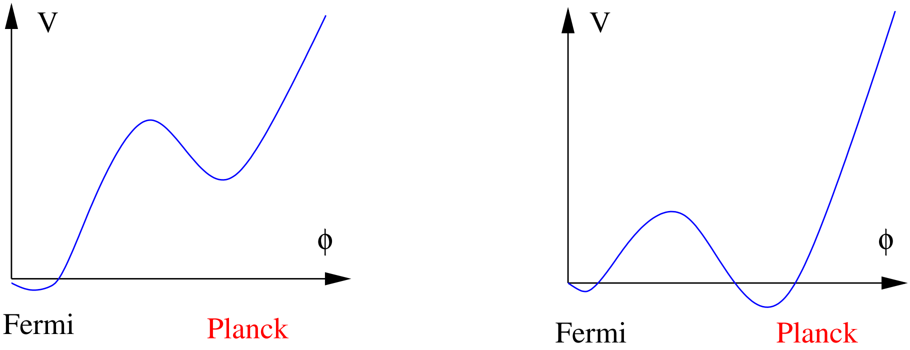
- renormgroup equation

$$\frac{d\lambda}{d\log\mu} \propto +\#\lambda^2 - \#Y_t^4$$

- 126 GeV: Looks as the SM Higgs. . . ?

QCD-background, QCD-corrections, . . .

Multiple point principle: D.Bennett, H.Nielsen (1993), C.Froggatt, H.Nielsen (1995)

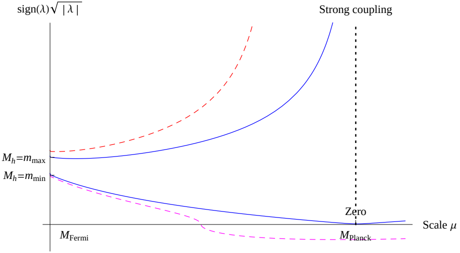


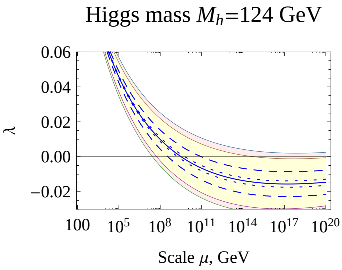
$$\Lambda \simeq 0 \Rightarrow V(\phi_{EW}) = V(\phi_{Planck}) = 0 \Rightarrow \lambda(\mu_{Planck}) = 0$$

Planck scale enters $\Rightarrow V'(\phi_{EW}) = V'(\phi_{Planck}) = 0 \Rightarrow \frac{d\lambda(\mu)}{d\log\mu}(\mu_{Planck}) = 0$

It gives $m_t \simeq 173$ GeV and $m_h \simeq 129$ GeV

Critical point: where EW-vacuum becomes unstable



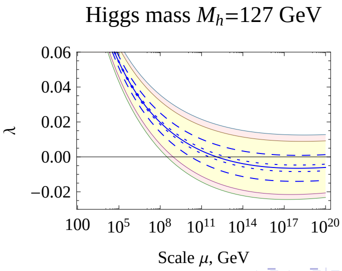


F.Bezrukov, M.Shaposhnikov (2009)
F.Bezrukov, D.G. (2011)
F.Bezrukov, M.Kalmykov, B.Kniehl, M.Shaposhnikov (2012)
G. Degrassi et al (2012)

$$m_h^{cr} > \left[129.0 + \frac{m_t - 172.9\,\mathrm{GeV}}{1.1\,\mathrm{GeV}} \times 2.2 - \frac{\alpha_s(M_Z) - 0.1181}{0.0007} \times 0.56\right] \mathrm{GeV}$$

present measurements at CMS and ATLAS:

$$m_h \simeq 125.8 \pm 0.9\ \mathrm{GeV}$$



Upper limit on the Higgs boson mass

F.Bezrukov, M.Shaposhnikov (2009)
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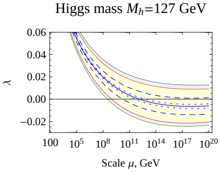
critical value refers to $\lambda(h \to M_P) \to 0$

May be important for pre-Big-Bang history...
say, at inflation naturally $h \sim H$

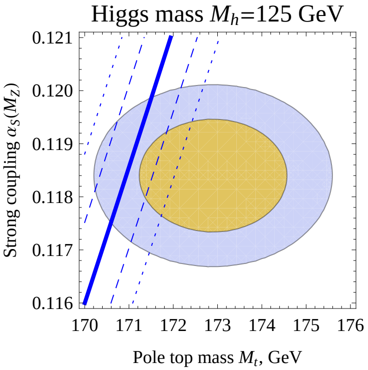
May be important for pre
Hot-Big-Bang History

$$\frac{d\lambda}{d\log\mu} = +\#\lambda^2 - Y_t^4 + \alpha_W + \ldots$$



Can end up in Wrong vacuum...

errors in M_W give uncertainties < 0.2 GeV



Experimental uncertainties: 2-3 GeV
Theoretical uncertainties: 1-2 GeV

Important for further improvement:

- 3-loop matching and QCD for t
- measurement of α_s, m_t and m_h at LHC(?)