Light inflaton
and 3.5 keV line from dark matter sterile neutrino

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based on 0912.0390, 1303.4395, 1403.4638 in collaboration with F. Bezrukov

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on High Energy Physics "QUARKS"

GTK "Suzdal", Suzdal, Russia

Outline

1. Inflation in brief
2. Higgs portal to X^4-inflation
3. Non-minimal coupling to gravity
4. Sterile neutrino dark matter from light inflaton
5. DM signal in X-rays
6. Summary

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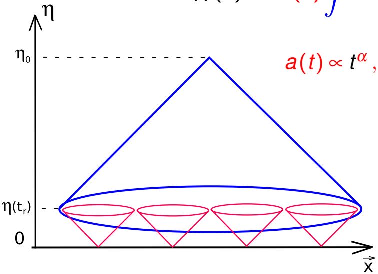
Horizon problem $l_H(t)$

a distance covered by photon emitted at $t = 0$

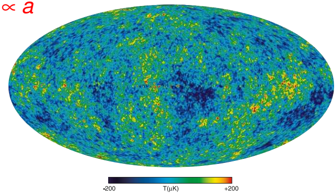
size of the causally connected part, that is the visible part of the Universe ("inside horison")

$$ds^2 = dt^2 - a^2(t)\,dx^2 = a^2(\eta)\,(d\eta^2 - dx^2) \qquad ds^2 = 0$$

$$l_H(t) = a(t)\int dx = a(t)\int d\eta = a(t)\int_0^t \frac{c\,dt'}{a(t')} \propto t$$



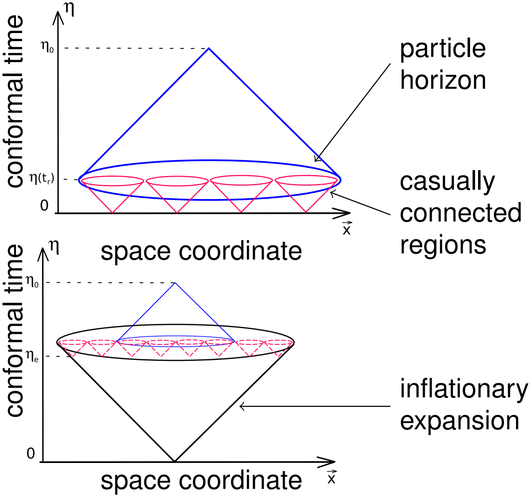
$a(t) \propto t^{\alpha}\,,\ 0 < \alpha < 1\,,\ L_{phys} \propto a$



$$l_{H_0}/l_{H,r}(t_0) \sim l_{H_0}/l_{H,r}(t_r)\,a(t_r)/a_0 \sim H_r/H_0\,a(t_r)/a_0 \sim \sqrt{1+z_r} \simeq 30$$

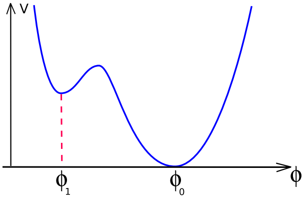
Inflationary solution of Hot Big Bang problems

- no initial singularity in dS space
- all scales grow exponentially, including the radius of the 3-sphere
  the Universe becomes exponentially flat
- any two particles are at exponentially large distances
  no heavy relics
  no traces of previous epochs!
- no particles in post-inflationary Universe
  to solve entropy problem we need post-inflationary reheating



Inflatinary stage: simplest models

"Old inflation" by Guth



does not work in fact!

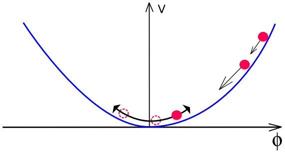
starts from a hot stage
and ends up in a false vacuum

reheating due to percollations

However: for sufficiently long inflationary stage requires $\Gamma < H^4_{infl}$

hence the bubbles never collide!

"Chaotic inflation"



needs superplanckian field values!

$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

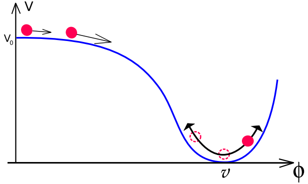
$$p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

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

$$\varepsilon = \frac{M_{Pl}^2}{16\pi}\left(\frac{V'}{V}\right)^2, \; \eta = \frac{M_{Pl}^2}{8\pi}\frac{V''}{V},$$

$$V(\phi) \propto \phi^n \;\Rightarrow \varepsilon, \eta \sim M_{Pl}^2/\phi^2 \ll 1$$

"New inflation"



Initial condition is very specific!

$$H^2 = \frac{8\pi}{3M_P^2}V(\phi), \quad a(t) \propto e^{Ht}$$

and we require

$$V(\phi) < M_{Pl}^4$$

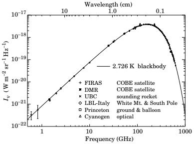
← slow-roll conditions

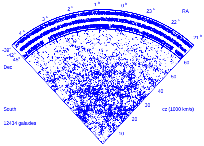
Key observable: matter perturbations

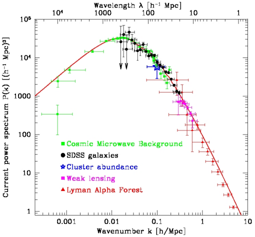
- CMB is isotropic, but "up to corrections, of course..."
  1. Earth movement with respect to CMB
     $$\frac{\Delta T_{\text{dipole}}}{T} \sim 10^{-3}$$
  2. More complex anisotropy: $\frac{\Delta T}{T} \sim 10^{-4}$
- There were matter inhomogenities $\Delta\rho/\rho \sim \Delta T/T$ at the stage of recombination $(e+p \to \gamma + H^*)$ $\Longrightarrow$

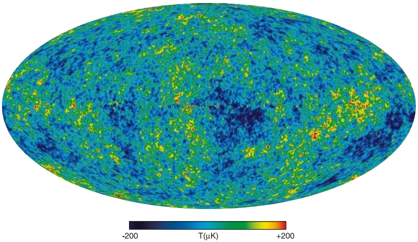
  Jeans instability in the system of gravitating particles at rest $\Longrightarrow$ $\Delta\rho/\rho \nearrow$ galaxies (CDM halos)
- There are neither sources no mechanisms to produce the initial inhomogeneities, if we the Universe is described by GR and SM

  we must modify the theory!









Unexpected bonus: generation of perturbations

- Quantum fluctuations of wavelength λ of a free massless field φ have an amplitude of $\delta\varphi_\lambda \simeq 1/\lambda$
- In the expanding Universe: $\lambda \propto a$

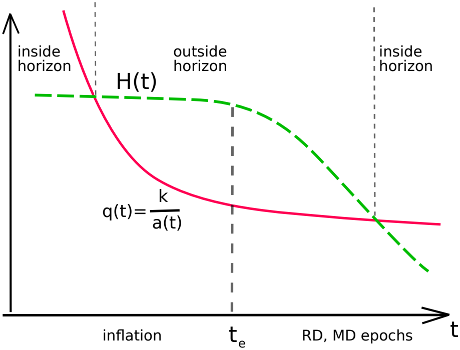
inflation: $l_H \sim 1/H = \text{const}$, so modes "exit horizon"
Ordinary stage: $l_H \sim 1/H \propto t$, $l_H/\lambda \nearrow$, modes "enter horizon"

Evolution at inflation

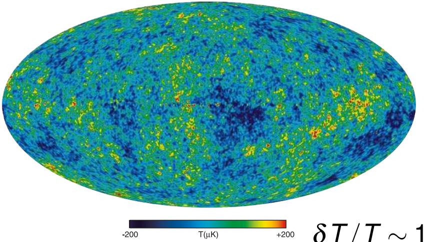
- inside horizon: $\lambda < l_H$
  $\lambda \propto a \Rightarrow$ $\delta\varphi_\lambda \propto 1/\lambda \propto 1/a$

- outside horison: $\lambda > l_H$
  $\lambda \propto a \Rightarrow$ $\delta\varphi_\lambda = \text{const} = H_{infl}$!!!

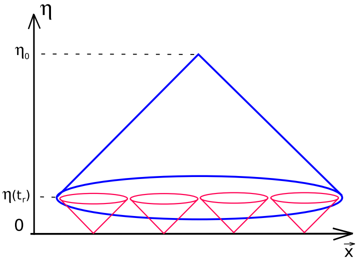
- got "classical" fluctuations:
  $\delta\varphi_\lambda = \delta\varphi_\lambda^{quantum} \times e^{N_e}$

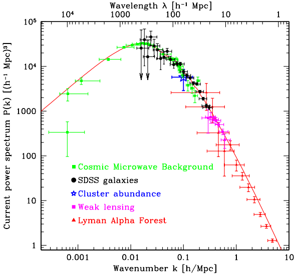


Inflationary solution of Hot Big Bang problems

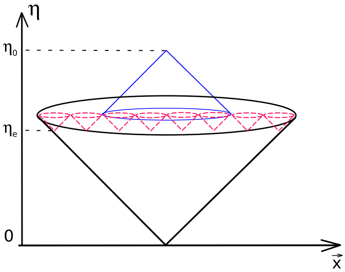


$\delta T/T \sim 10^{-5}$





$\delta\rho/\rho \sim 10^{-5}$



Transfer to matter perturbations: simple models

Local delay(advance)δt in evolution due to impact of $\delta\phi$ of all modes with $\lambda > H$:

$$\delta\phi = \dot\phi_c \, \delta t \,, \quad \delta\rho \sim \dot\rho \, \delta t$$

at the end of inflation $\dot\rho \sim -H\rho$, then

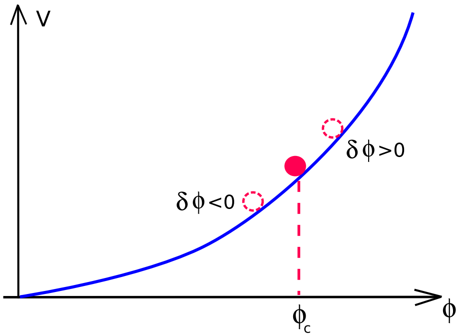
$$\frac{\delta\rho}{\rho} \sim \frac{H}{\dot\phi_c} \, \delta\phi$$

Power spectrum of scalar perturbations

$$\int_0^\infty \frac{dk}{k} \, \mathscr{P}_S(k) \equiv \langle \left(\frac{\delta\rho}{\rho}(x) \right)^2 \rangle$$

$$\mathscr{P}_S(k) = \left(\frac{H^2}{2\pi\,\dot\phi_c} \right)^2 \,,$$

calculated at $t = t_k \,:\, H = k/a \equiv H_k$



Analogously for the tensor perturbations: each of the two polarizations of the gravity waves solves the free scalar field equation!

$$\mathscr{P}_T(k) = \frac{16}{\pi} \, \frac{H_k^2}{M_{Pl}^2}$$

Inflaton parameters and spectral parameters

- Observation of CMB anisotropy gives $\delta T/T$

$$\frac{\delta T}{T} \sim \frac{\delta\rho}{\rho} \quad \Rightarrow \sqrt{\mathscr{P}_S} = 5\times 10^{-5}$$

- $\Delta_{\mathscr{R}} = 5\times 10^{-5} \Rightarrow$ fixes model parameters, e.g.:

$$V(\phi) = \frac{\beta}{4}\phi^4 \to \beta \sim 10^{-13}$$

Inflaton parameters and spectral parameters

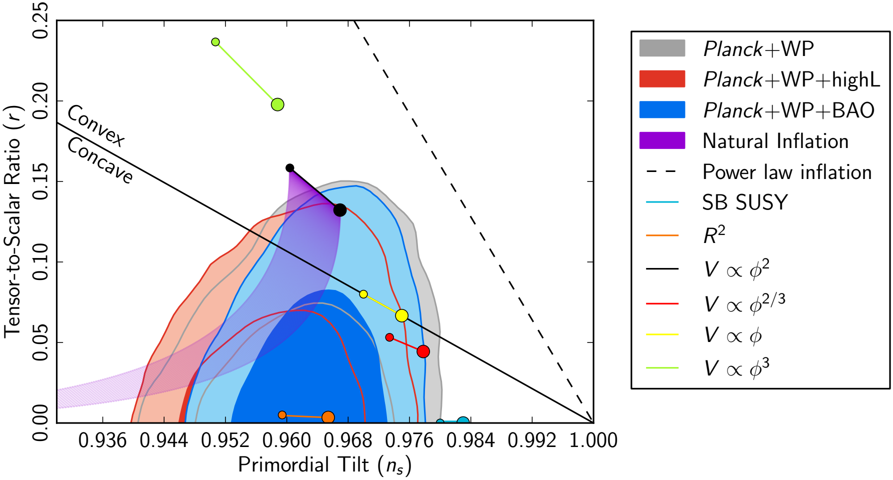
- To the leading order no k-dependence: both spectra are "flat" (scale-invariant)!
- In fact, spectra are a bit tilted, as H_{infl} slightly evolves

$$\mathcal{P}_S(k) = A_S \left(\frac{k}{k_*}\right)^{n_s - 1} , \qquad \mathcal{P}_T(k) = A_T \left(\frac{k}{k_*}\right)^{n_T} .$$

- Measure $\Delta_{\mathcal{R}}$ at present scales $q \simeq 0.002/\mathrm{Mpc}$, it fixes the number of e-foldings left N_e
- For tensor perturbations one introduces:

$$r \equiv \frac{\mathcal{P}_T}{\mathcal{P}_S} = \frac{1}{\pi} \frac{M_{Pl}^2 V'^2}{V} = 16\,\varepsilon \;\; \rightarrow \;\; \frac{16}{N_e} \;\text{ for }\; \beta\phi^4$$

Analysis (Planck) of cosmlogical data



1303.5062

$$N_e = 50 - 60$$

True Extension of the Standard Model should

- Reproduce the correct neutrino oscillations
- Contain the viable DM candidate
- Be capable of explaining the baryon asymmetry of the Universe
- Have the inflationary mechanism operating at early times

Guiding principle:

use as little “new physics” as possible

Why? No any hints observed so far!

Why inflation and scale invariance?

Inflation

- solves horizon problem
- solves curvature problem
- provides with matter perturbations
- ...

Phenomenological problems

Scale invariance

- gets rid of (classical) cosmological constant (need instead a quintessence? unimodular gravity?)
- eliminates quadratic divergences

$$\Delta T^{\mu}_{\mu} \propto \left(\# \Lambda^2 + \# m_h^2 \right) h^2$$

- no massive heavy particles

Theoretical problems

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Inflation & Reheating: simple realization

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

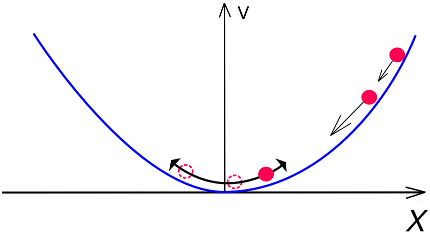
$X_e > M_{Pl}$

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

$\delta\rho/\rho \sim 10^{-5}$ requires
$V = \beta X^4 : \beta \sim 10^{-13}$

reheating ? renormalizable?

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



Chaotic inflation, A.Linde (1983)

larger α larger T_{reh}

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

No scale, no problem

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

M.Shaposhnikov, I.Tkachev (2006)

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

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: $\beta \approx 1.5 \cdot 10^{-13}$

F.Bezrukov, D.G. (2009)

Only one free parameter!

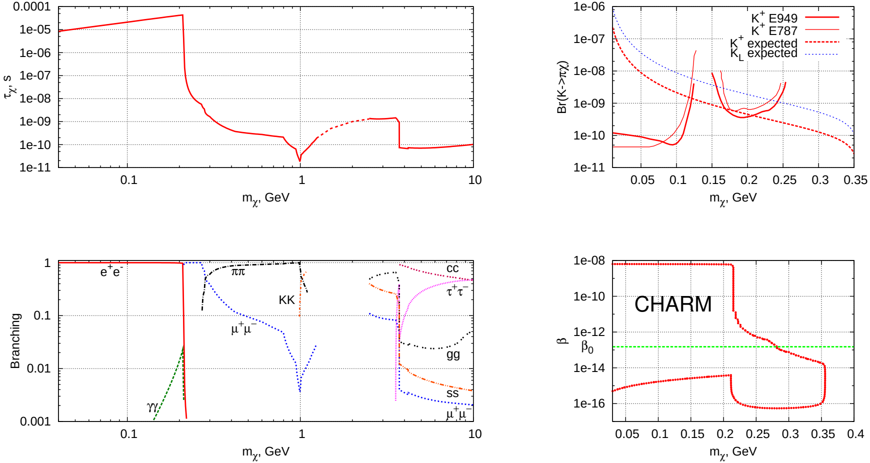
$30 \text{ MeV} \lesssim m_\chi \lesssim 1.8 \text{ GeV}$

$T_{reh} > 100$ GeV, $m_h < 190$ 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 already excluded ! from $K \to \pi\chi$ and $pN \to \ldots \chi(\chi \to \mu^+\mu^-)$

Inflaton Phenomenlogy: direct searches

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

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

Recent sensitivity: Belle

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

Expectation for the Inflaton:

scalar channel $B \to K\chi$

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

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!

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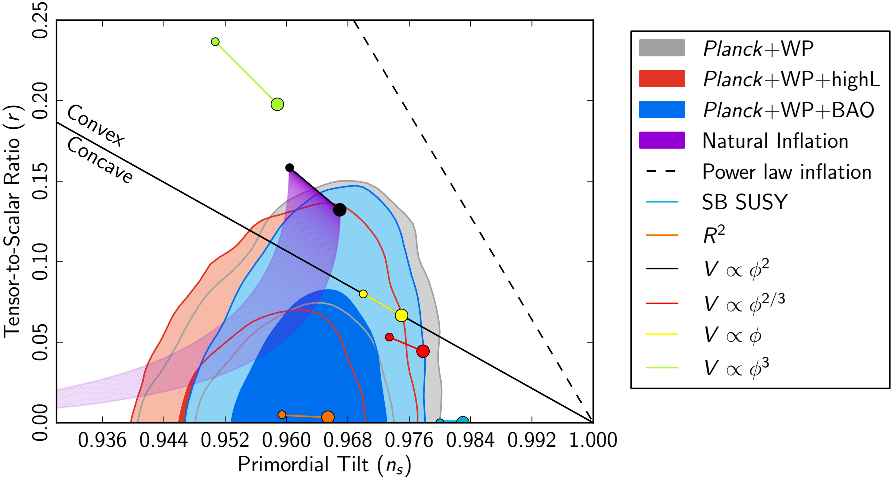

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Light inflaton: update in 1303.4395
Accepting LHC8, SPT, ACT, WMAP9 and Planck

$$-\frac{1}{2}\,\xi\,R\,X^2$$

Note, it is also scale-invariant...

Light inflaton nonminimally coupled to gravity

F.Bezrukov, D.G. (2013)

$$S_{XSM} = \int \sqrt{-g}\, d^4x \left(\mathscr{L}_{\rm SM} + \mathscr{L}_{XH} + \mathscr{L}_{\rm ext} + \mathscr{L}_{\rm grav}\right),$$

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

$$\mathscr{L}_{\rm grav} = -\frac{M_P^2 + \xi X^2}{2} R,$$

$$g_{\mu\nu} \to \tilde{g}_{\mu\nu} = \Omega^2 g_{\mu\nu}\,, \qquad \Omega^2 = 1 + \xi X^2/M_P^2,$$

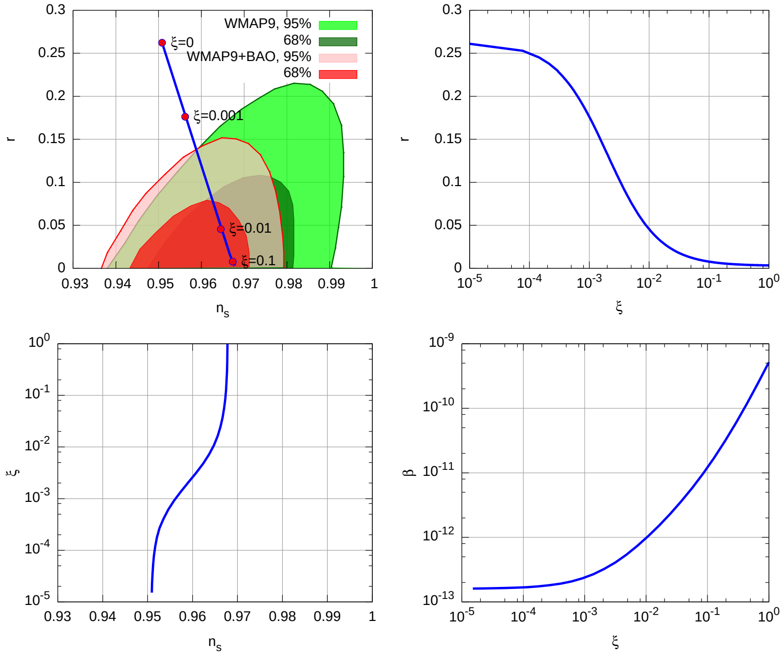
$$U(X) = \frac{\beta X^4}{4\Omega^4} \to \text{const} = \frac{\beta}{\xi^2} M_P^4 \quad \text{at} \quad X \to \infty.$$

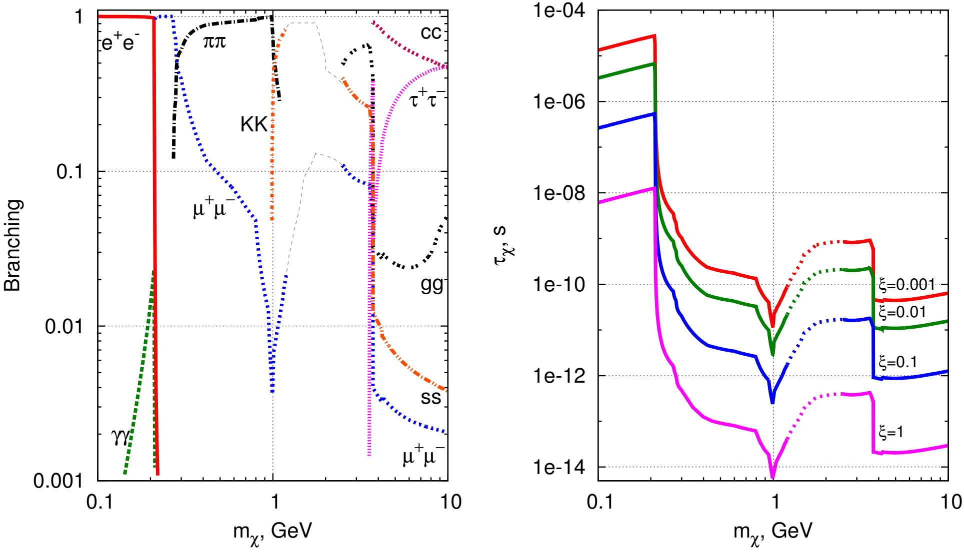
$$X \to \mathscr{X}: \quad \frac{d\mathscr{X}}{dX} = \sqrt{\frac{\Omega^2 + 6\xi^2 X^2/M_P^2}{\Omega^4}}$$

$$m_\chi = m_h \sqrt{\frac{\beta}{2\alpha}} = \sqrt{\frac{\beta}{\lambda \theta^2}}\,.$$

$$\theta^2 = \frac{2\beta v^2}{m_\chi^2} = \frac{2\alpha}{\lambda}\,.$$

Outcome: ONE MORE PARAMETER
for each value of mass m_χ have a range of mixing

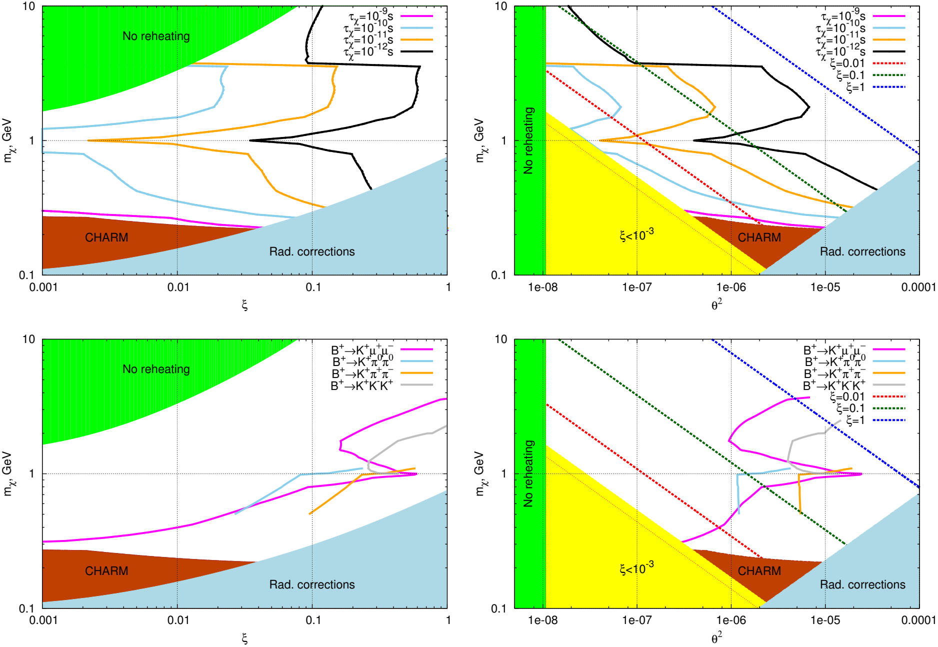

WMAP9, 95%
68%
WMAP9+BAO, 95%
68%
ξ=0
ξ=0.001
ξ=0.01
ξ=0.1
r
n_s
ξ
β
0.3
0.25
0.2
0.15
0.1
0.05
0
0.93
0.94
0.95
0.96
0.97
0.98
0.99
1
10^-5
10^-4
10^-3
10^-2
10^-1
10^0
10^-9
10^-10
10^-11
10^-12
10^-13



$$\mathrm{Br}(B \to \chi X_s) \simeq 10^{-6} \times \left(1 - \frac{m_\chi^2}{m_b^2}\right)^2 \left(\frac{\beta(\xi)}{1.5 \times 10^{-13}}\right) \left(\frac{300\ \mathrm{MeV}}{m_\chi}\right)^2$$

with $\xi > 10^{-2}$ inflaton decays earlier, at production point

and B-meson branching grows $\propto \beta$


No reheating
CHARM
Rad. corrections
$\tau_\chi=10^{-9}$s
$\tau_\chi=10^{-10}$s
$\tau_\chi=10^{-11}$s
$\tau_\chi=10^{-12}$s
$\xi=0.01$
$\xi=0.1$
$\xi=1$
$\xi<10^{-3}$
$B^+\to K^+\mu^+\mu^-$
$B^+\to K^+\pi^0\pi^0$
$B^+\to K^+\pi^+\pi^-$
$B^+\to K^+K^-K^+$
m_χ, GeV
ξ
θ^2
0.1
1
10
0.001
0.01
1e-08
1e-07
1e-06
1e-05
0.0001

The model of light inflaton

- simple
- renormalizable
  (up to gravity, of course)
- weakly coupled
- SM sector is scale-invariant
- directly testable !!!

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Guiding principle:

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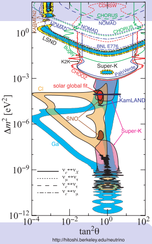
Why? No accidental hints observed so far!

Straightforward completion of 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

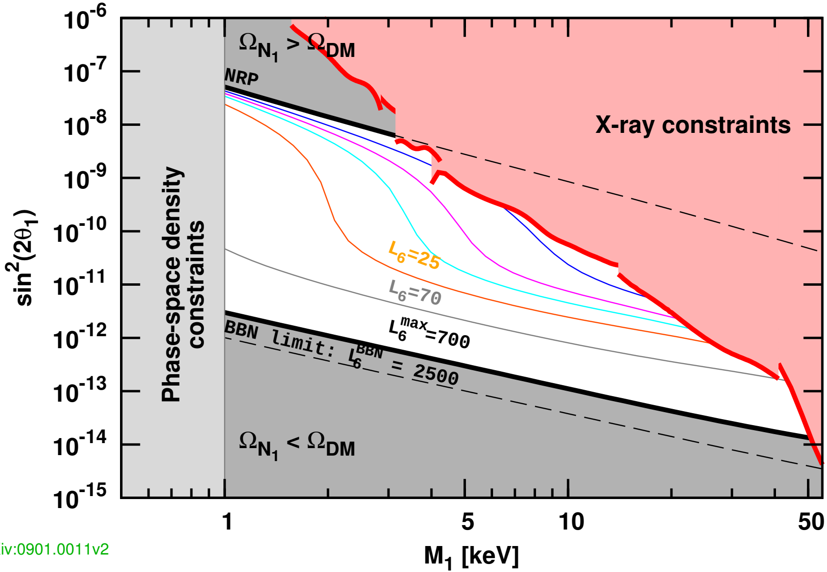
Light neutrino masses $M^\nu = -(M^D)^T \frac{1}{M_I} M^D \propto f^2 \frac{v^2}{M_I}$

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

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

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

DM is the lightest sterile neutrino N_1



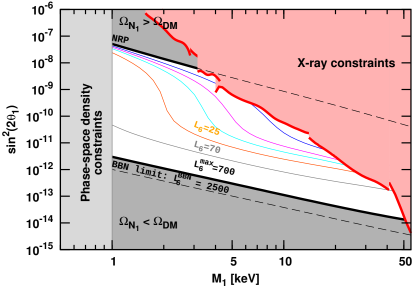
arXiv:0901.0011v2

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



Neutrino mass $M_I = f_I \langle X \rangle$
Dark Matter production $\Gamma \propto f_1^2 \to \Omega_{DM}$
from thermal inflaton decays at $T \sim m_\chi$

M.Shaposhnikov, I.Tkachev (2006)

$$M_{N_I} \bar{N}_I^c N_I \leftrightarrow f_I X \bar{N}_I^c N_I$$ scale-invariant term

Can be “naturally” Warm

F.Bezrukov, D.G. (2009)

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

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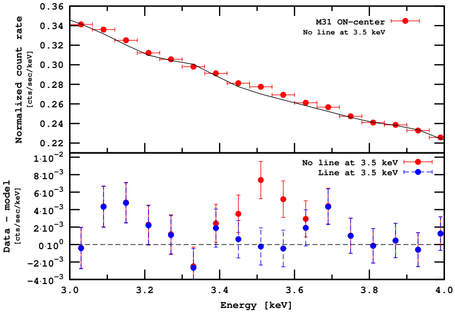
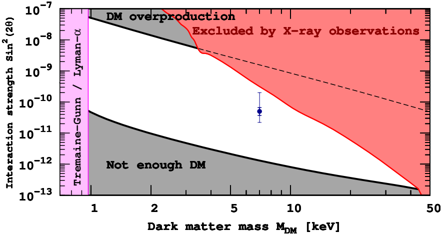
6. Summary

Dark Matter decay observed in X-ray?

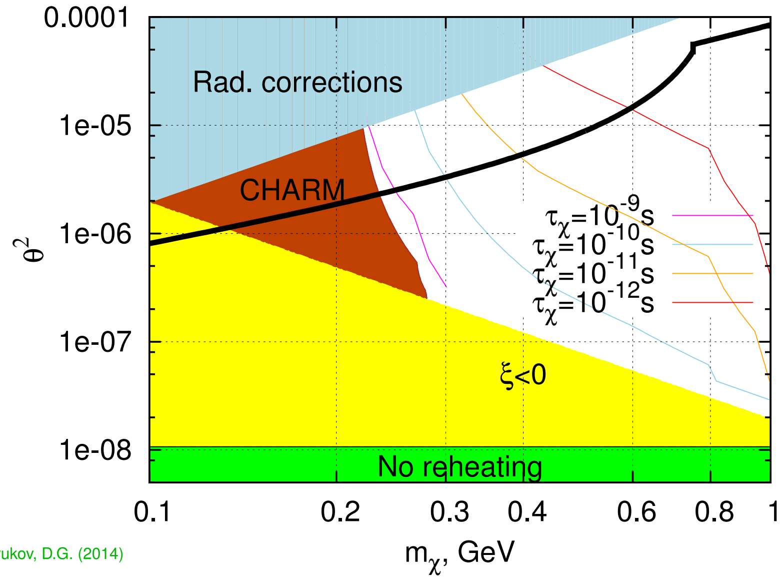




Stacking signals from many galaxies, especially Perseus cluster, then Andromeda

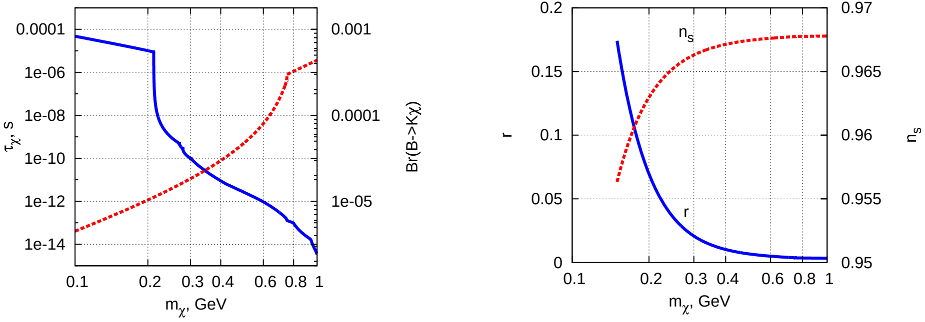
1402.2301, 1402.4119

$f_I X \bar{N}_I N_I \;\rightarrow\; M_1 = f_1 \langle X \rangle = 7\,\text{keV}$ and $\Omega_N = 0.25$



F.Bezrukov, D.G. (2014)

So, we are back to a unique prediction



F.Bezrukov, D.G. (2014)

$m_\chi > 220\,\text{MeV} \to r < 0.05$

BICEP2...

Outline

1. Inflation in brief
2. Higgs portal to X^4-inflation
3. Non-minimal coupling to gravity
4. Sterile neutrino dark matter from light inflaton
5. DM signal in X-rays
6. Summary

Summary

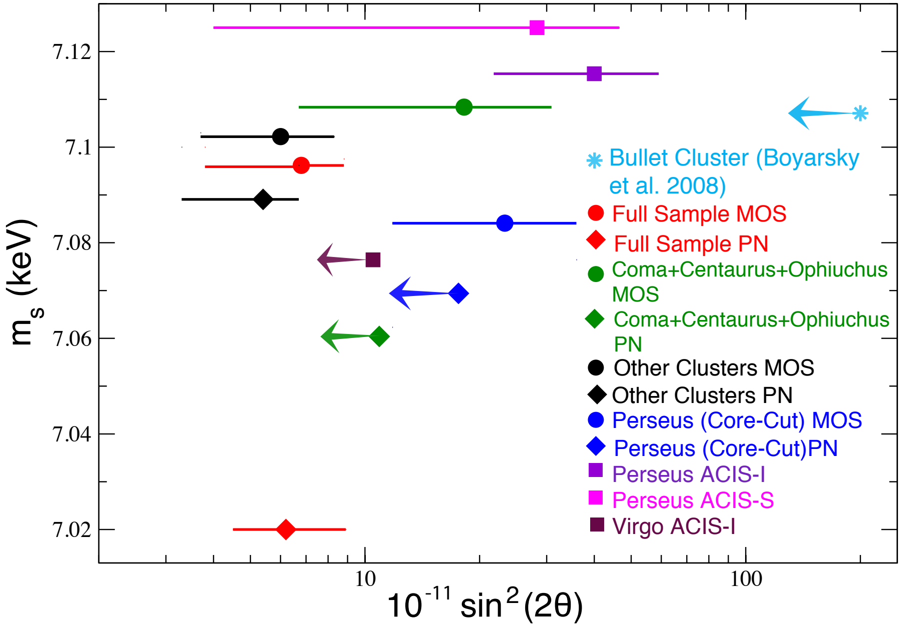
- Simple renormalizable model inflationary model $\xi R X^2 + \beta X^4$
  with viable reheating through the Higgs portal $\alpha X^2 H^\dagger H$
  (scale-invariant)
  can be explored by direct searches of $B \to X_s + \chi$ $\qquad$ $220\,\text{MeV} \lesssim m_\chi$

  F.Bezrukov, D.G. (2009) $\quad \text{Br}\,(B \to \chi X_s) \simeq 5 \times 10^{-6} \cdot \left(1 - \frac{m_\chi^2}{m_b^2}\right)^2 \left(\frac{\theta^2}{10^{-6}}\right)$

  $\chi \to \mu^+\mu^-\,, \pi^+\pi^-\,, K^+K^- \qquad c\tau_\chi \simeq 3 - 30\,\text{cm}$

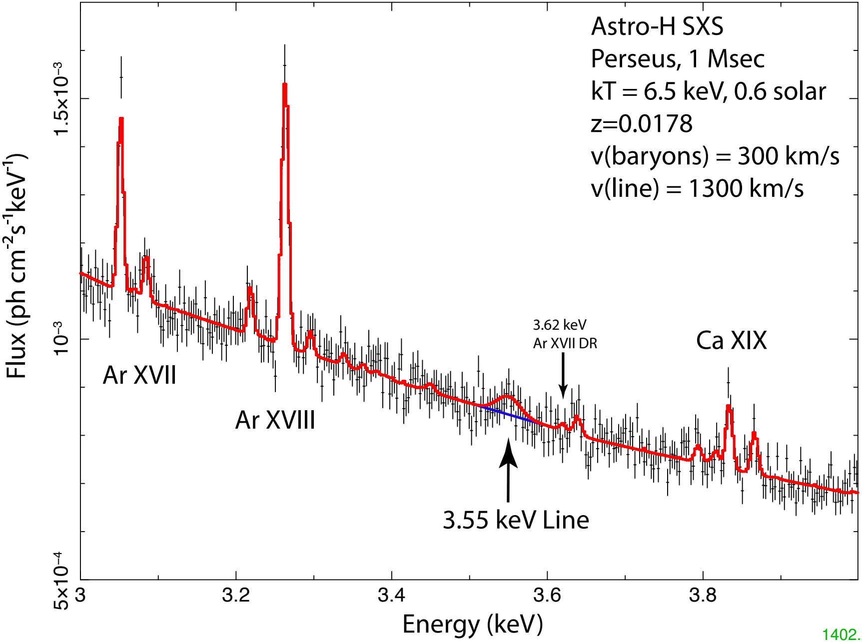
- combined with νMSM (completed with right handed neutrinos) provides
  - active neutrino masses and mixing angles
  - 1-50 keV neutrino as (warm) Dark Matter
    In particular, consistent with 3.5 keV line !
  - In the latter case tensor perturbations are below 0.05, so BICEP2 must be mostly due to dust

Backup slides



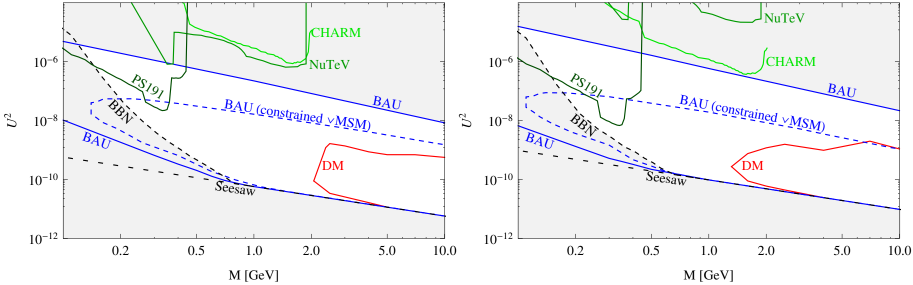
7.12
7.1
7.08
7.06
7.04
7.02
m_s (keV)
10
100
$10^{-11}\sin^2(2\theta)$
Bullet Cluster (Boyarsky et al. 2008)
Full Sample MOS
Full Sample PN
Coma+Centaurus+Ophiuchus MOS
Coma+Centaurus+Ophiuchus PN
Other Clusters MOS
Other Clusters PN
Perseus (Core-Cut) MOS
Perseus (Core-Cut)PN
Perseus ACIS-I
Perseus ACIS-S
Virgo ACIS-I

1402.2301


Astro-H SXS
Perseus, 1 Msec
kT = 6.5 keV, 0.6 solar
z=0.0178
v(baryons) = 300 km/s
v(line) = 1300 km/s
3.62 keV
Ar XVII DR
Ca XIX
Ar XVII
Ar XVIII
3.55 keV Line
Flux (ph cm-2s-1keV-1)
Energy (keV)
1.5×10−3
10−3
5×10−4
3
3.2
3.4
3.6
3.8

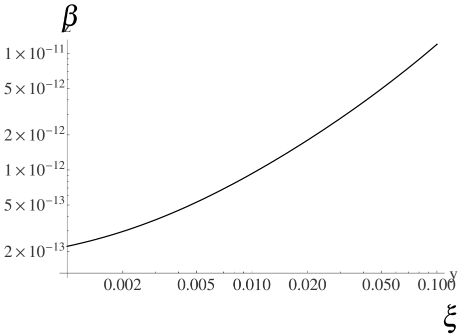
1402.2301

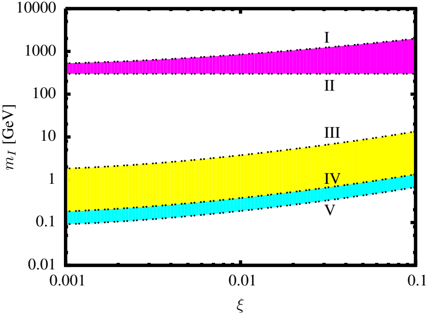
νMSM parameter space with resonant DM



L.Canetti, M.Drewes, M.Shaposhnikov 1204.3902

Inflaton mass as a function of ξ





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