Light inflaton in Bottom decays: a close look at the dawn of the Universe

Dmitry Gorbunov

Institute for Nuclear Research, Moscow, Russia

QFTHEP'2011

Sochi, Russia, 30.09.2011

Outline

1. Motivation: Phenomena Observed but Unexplained within the SM
2. Higgs portal to new physics
3. Higgs portal to X^4-inflation: light inflaton at LHCb

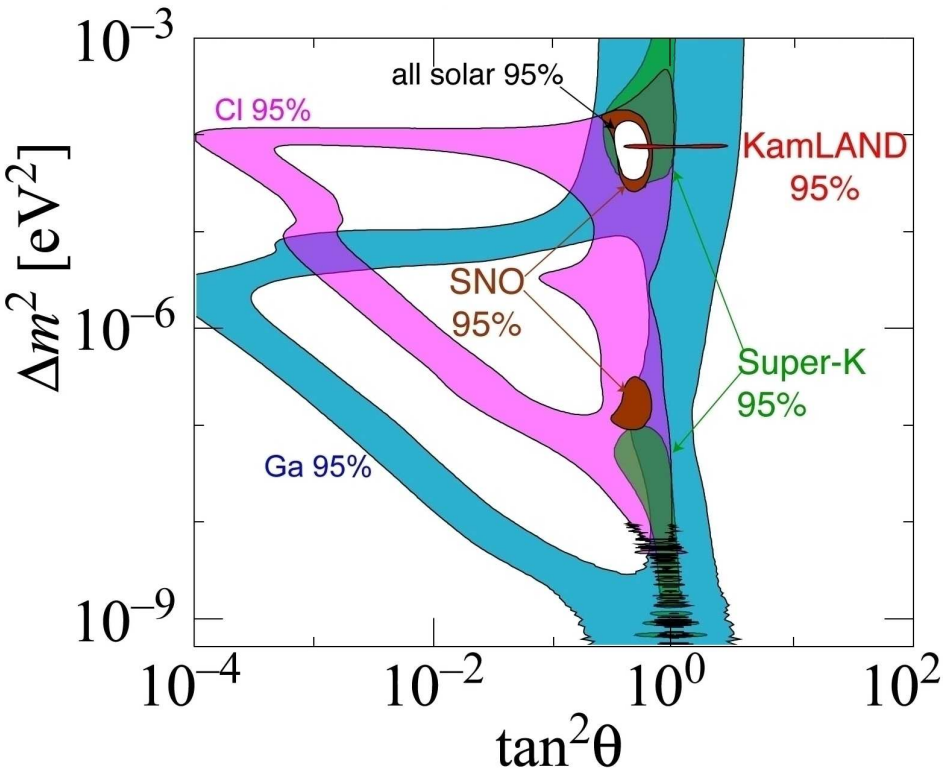
   F.Bezrukov, D.G., JHEP 1005 (2010) 010
4. Natural completion of νMSM: neutrino mass and mixing, dark matter, baryon asymmetry of the Universe... searches at LHCb?

   D.G., M.Shaposhnikov, JHEP 0710 (2007) 015
5. Summary of the results

Outline

Neutrino oscillations: masses and mixing angles

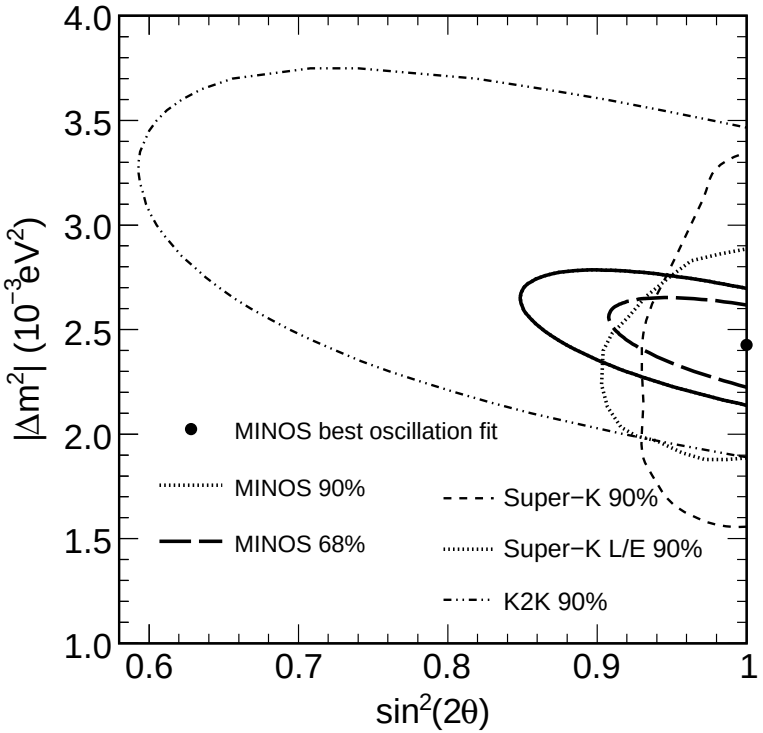
Solar 2×2 "subsector"



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

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

Atmospheric 2×2 "subsector"



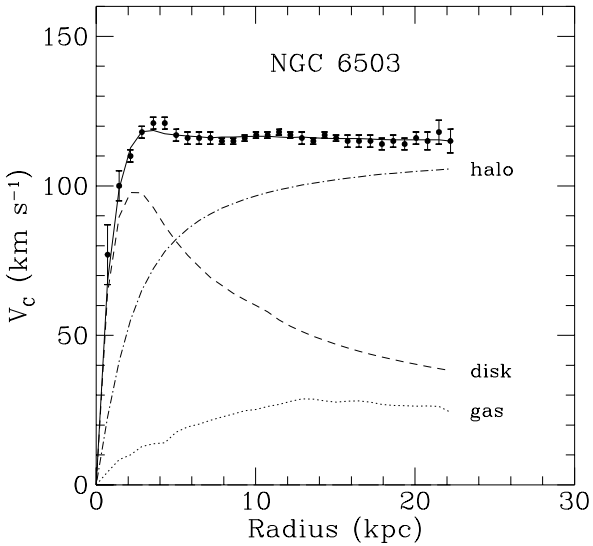
arXiv:0806.2237

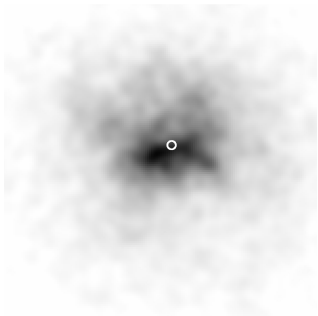
$m_2 > 0.05\,\text{eV}$

MINOS, T2K, SNO, ..., global fits: $\sin^2 2\theta_{13} \lesssim 0.3$

Baryons and Dark Matter in Astrophysics

Rotation curves





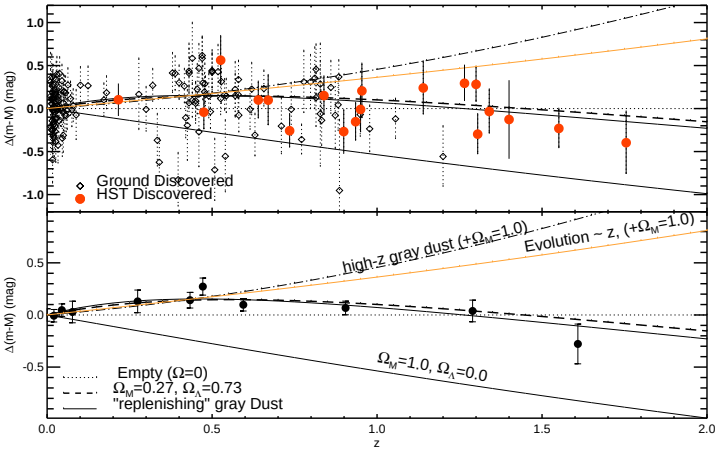
X-rays from clusters

Gravitational lensing

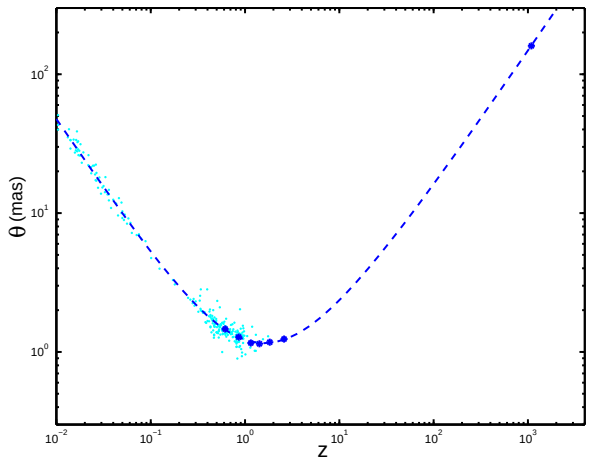
"Bullet" cluster

Baryons and Dark Matter in Cosmology

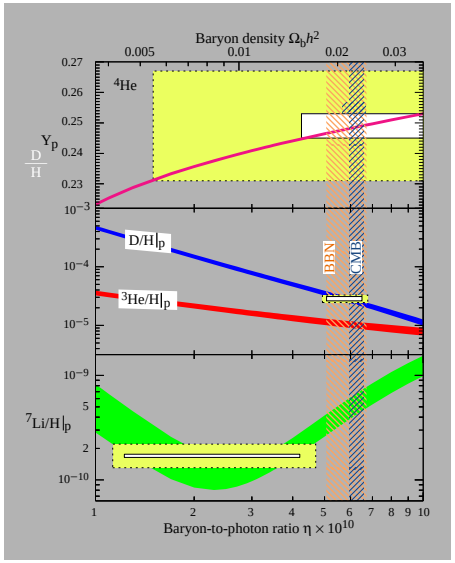
Standard candles

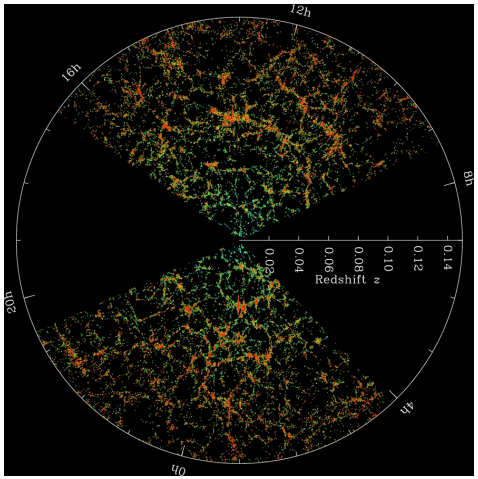


Angular distance

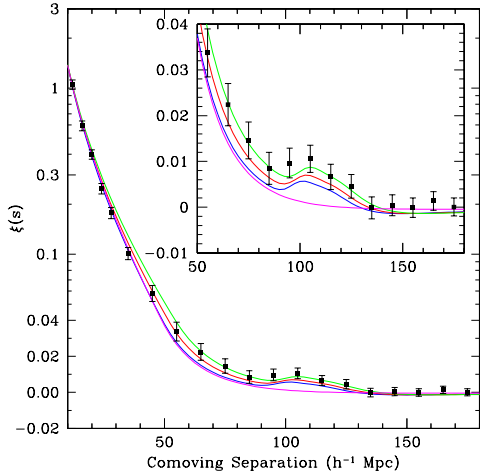


BBN

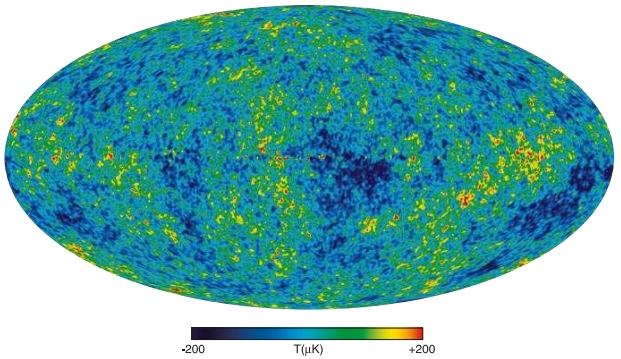




Structures

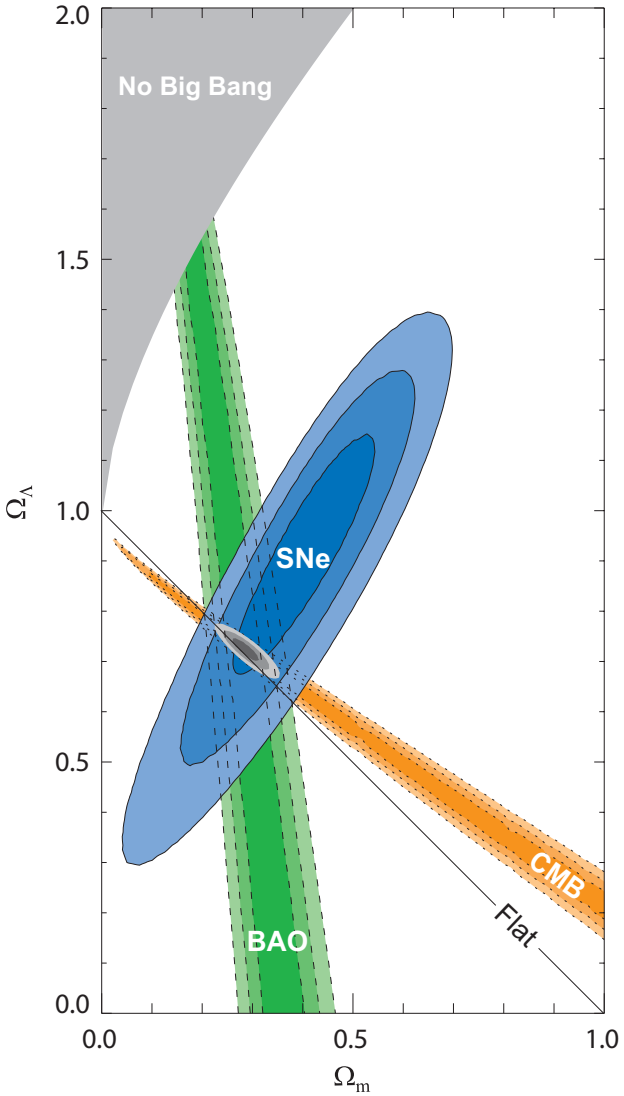


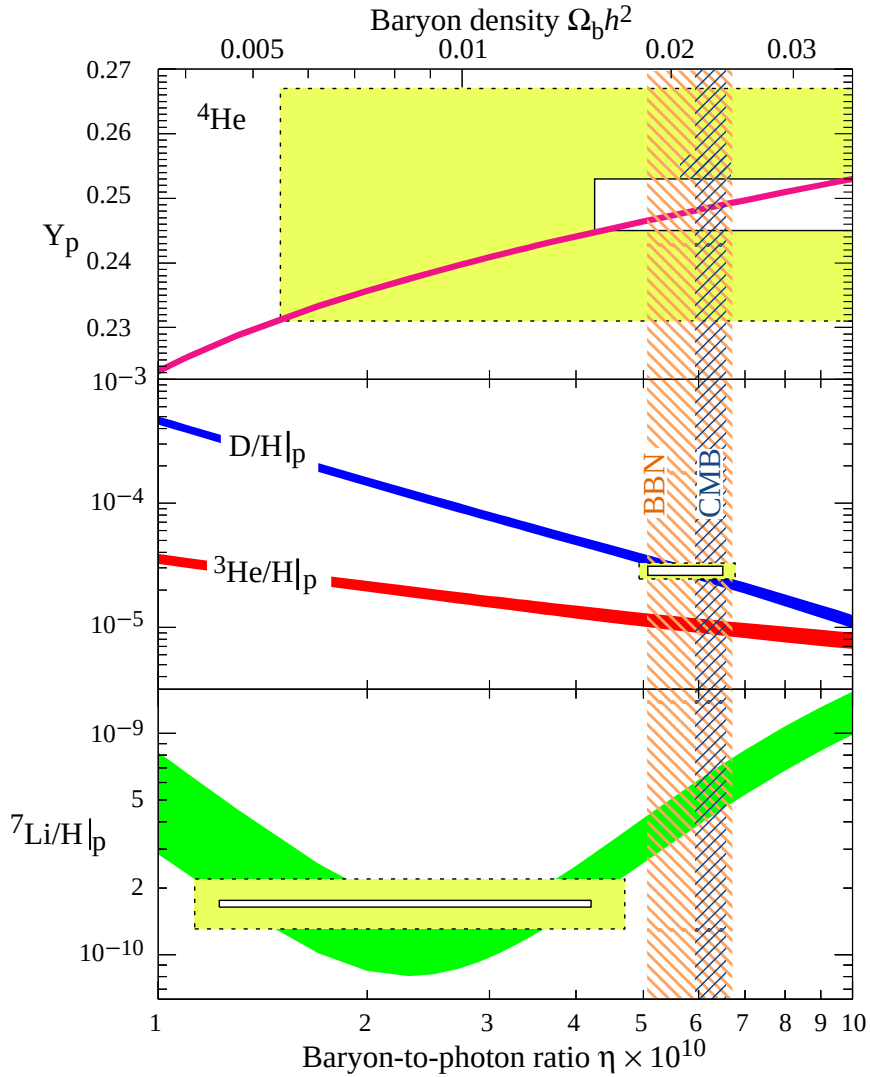
BAO



CMB fluctuations

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





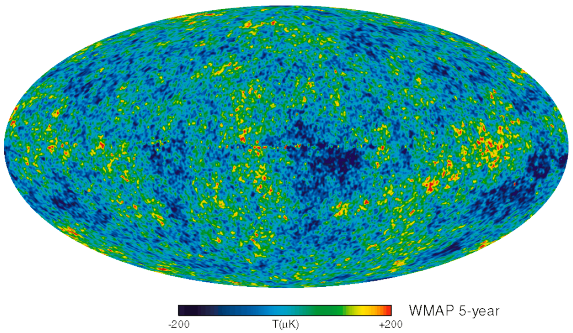
arXiv:0804.4142

http://pdg.lbl.gov

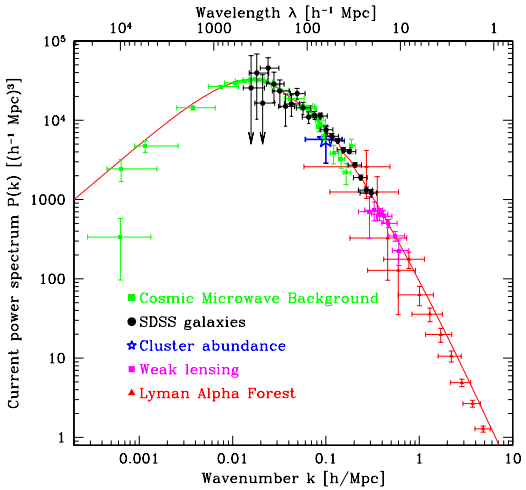
Inflationary solution of Hot Big Bang problems

Temperature fluctuations

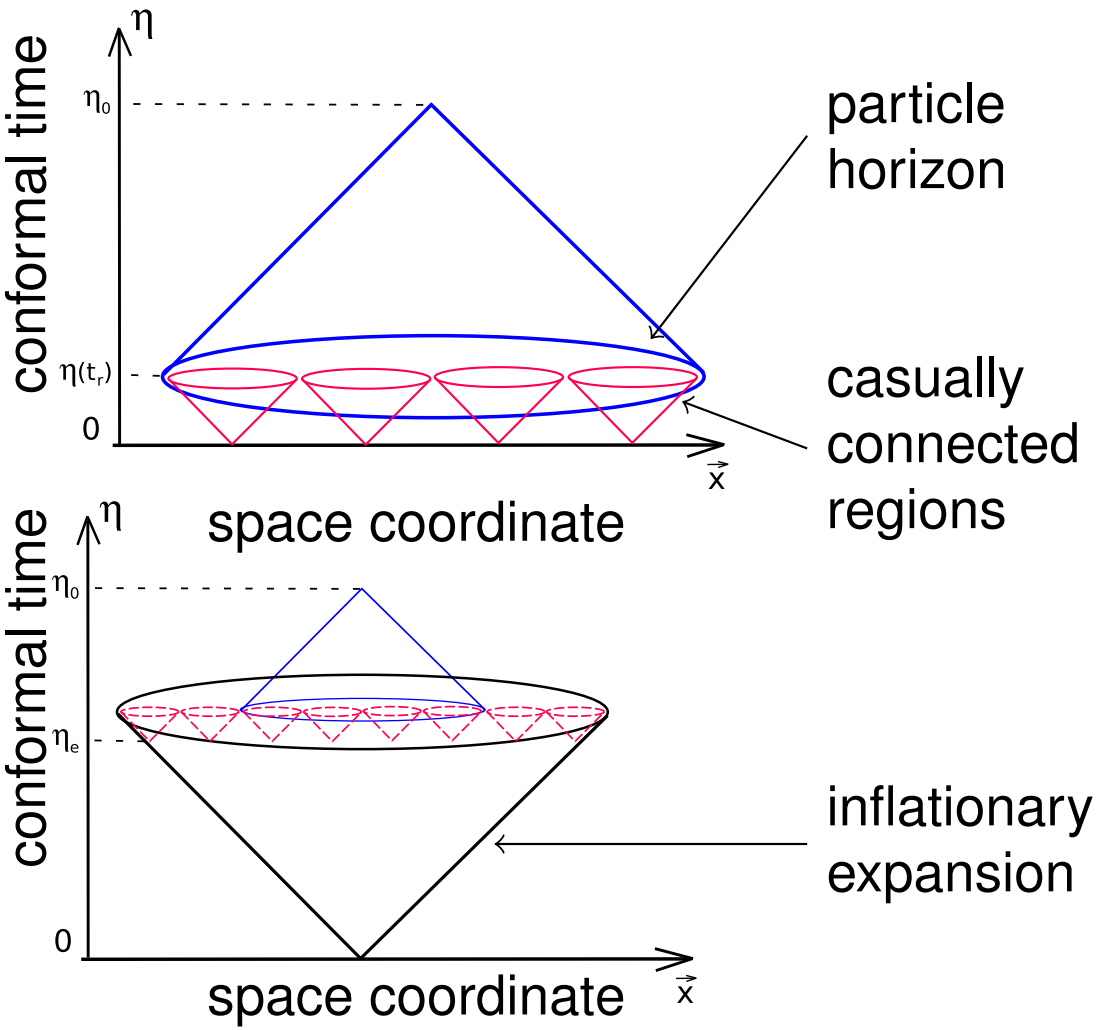
$\delta T/T \sim 10^{-5}$



Universe is uniform!



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



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 accidental hints observed so far!

Standard Model: Success and Problems

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

Three generations of matter: $L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$, e_R; $Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$, 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 stage
  - Dark energy (Ω_Λ)
  - Strong CP problem
  - Gauge hierarchy problem
  - Hierarchies in Yukawas, CKM, etc.
  - Quantum gravity

Complete extension of SM has to explain all above

probably at LHC scale

Standard Model: Success and Problems

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

Three generations of matter: $L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$, e_R; $Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$, 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 stage
  - Dark energy (Ω_Λ)
  - Strong CP: boundary terms, new topology, . . .
  - Gauge hierarchy: No new scales!
  - Quantum gravity

Try to explain all above

Planck-scale physics saves the day

Outline

New physics from the (still unknown) Higgs sector

- EW baryogenesis:
  not enough CP, not I order phase transition
  could be 2 Higgs doublets!
- Dark Matter candidate: stable due to Z_2-symmetry
  Natural CDM from primordial plasma
  Singlet scalar field: (e.g. Burgess, Pospelov, ter Veldhuis, 2001)

$$\mathscr{L} = \mathscr{L}_{SM} + \frac{1}{2}(\partial_\mu S)^2 - \frac{m_0^2}{2} S^2 - \lambda S^2 H^\dagger H + ...$$

- one of the SM portals to hidden sectors (SM-gauge singlets: no FCNC!)

$$\beta B^{\mu\nu}_{U(1)_Y} B^{\mu\nu}_{U(1)_{Y'}} \qquad \alpha H^\dagger H \cdot X^\dagger X$$

secluded $U(1)$
$Z - Z'$, $\gamma - \gamma'$

e.g. M.Pospelov
Phys Rev D80 (2009) 095002

renormalizable!
to be tested at
any energy scale!

fascinating example:
$h - \chi$ portal to inflaton!

F.Bezrukov, D.G.
JHEP 1005 (2010) 010

Outline

Inflation & Reheating: simple realization

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

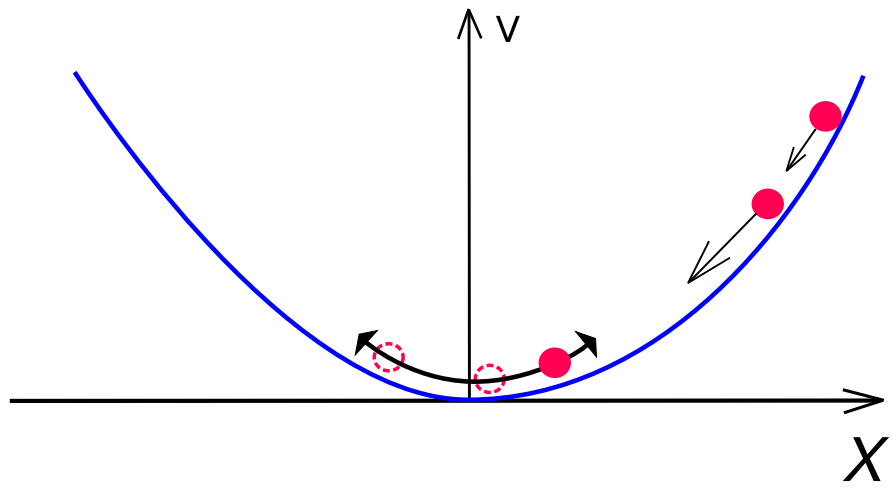
$X_e > M_{Pl}$

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

Gravity solves all problems — 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

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

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)

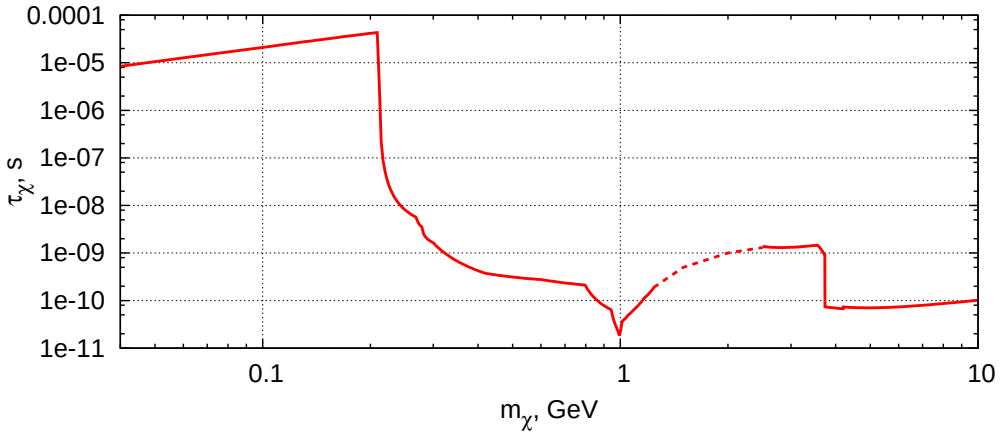
Only one free parameter!

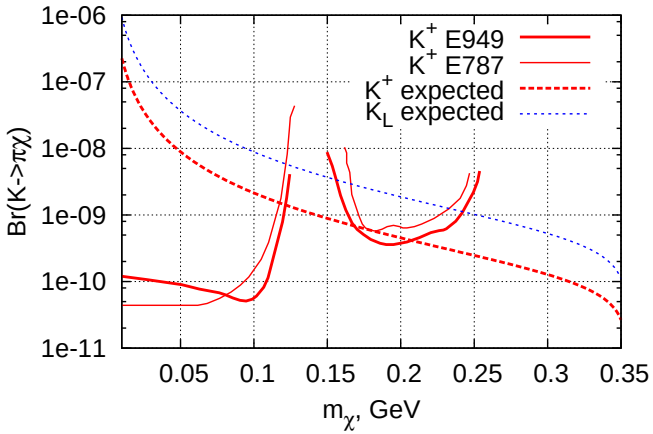
$30 \text{ MeV} \lesssim m_\chi \lesssim 1.8 \text{ GeV}$

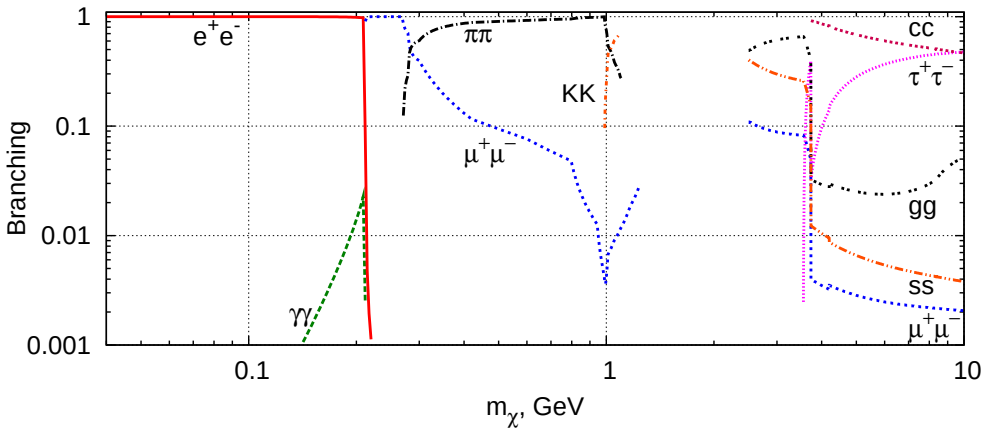
study of reheating:
A.Anisimov, Y.Bartocci, F. Bezrukov (2008)

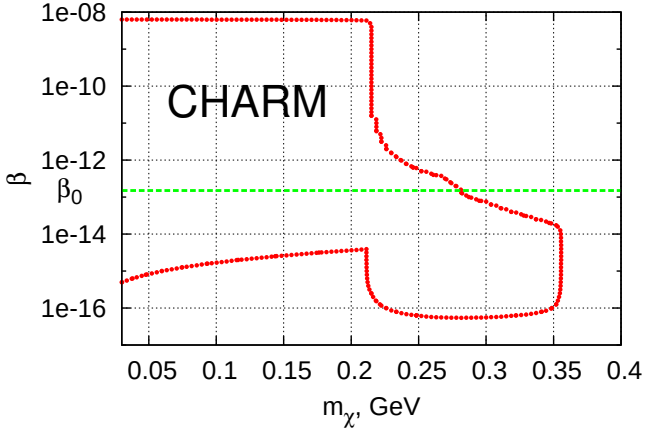
$T_{reh} > 100$ GeV, $m_h < 190$ GeV
Landau pole above inflation scale

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

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

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

Recent sensitivity:
$\mathrm{Br}(B \to K^{(*)} l^+ l^-) \gtrsim 10^{-7}$

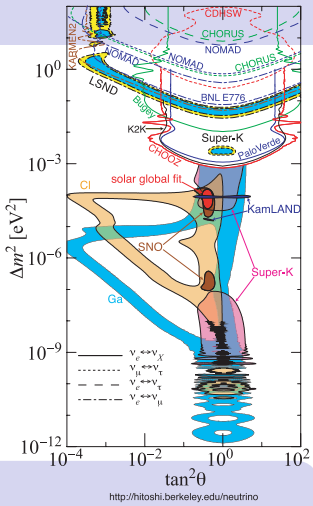
Belle
$250\ \mathrm{MeV} \lesssim m_\chi \lesssim 1.8\ \mathrm{GeV}$

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!

Outline

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 $f_{l\alpha} H \bar{N}_l L_\alpha$

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

3 heavy neutrinos with masses M_l similar to quark masses

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

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

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

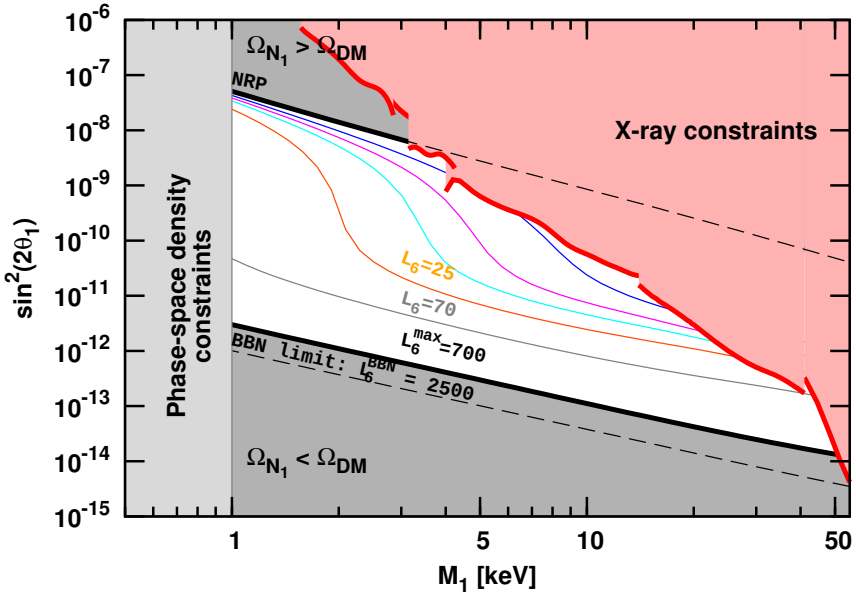
Active-sterile mixings $$\theta_{\alpha l} = \frac{(M^D)^\dagger_{\alpha l}}{M_l} \propto f \frac{v}{M_l} \ll 1$$

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



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

M.Shaposhnikov, I.Tkachev (2006)

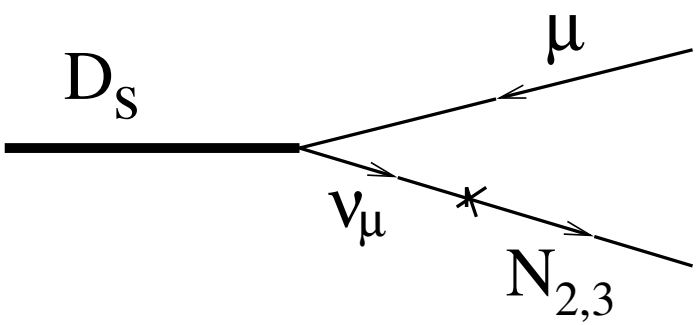
$$M_{N_I} \bar{N}_I^c N_I \leftrightarrow f_I X \bar{N}_I N_I$$

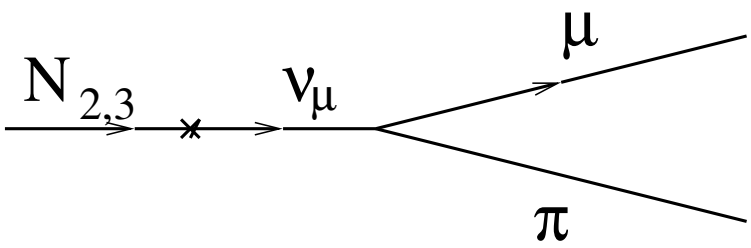
Can be "naturally" Warm

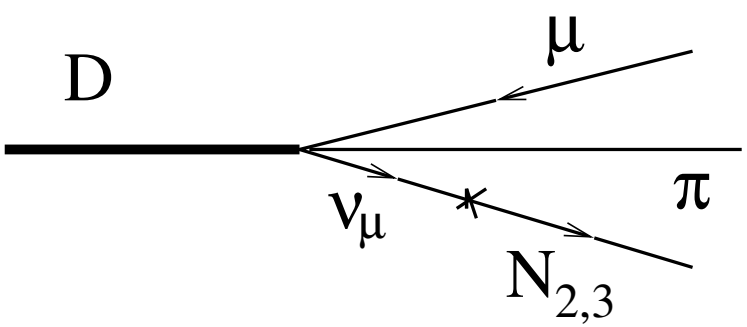
F.Bezrukov, D.G. (2009)

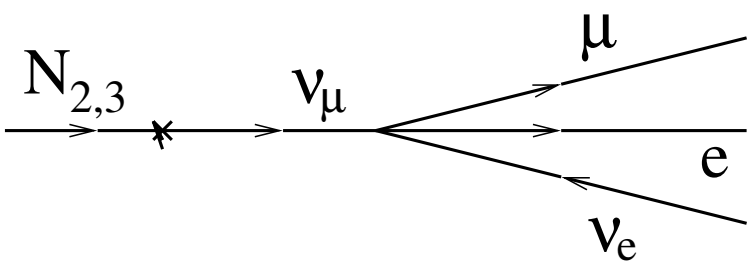
$$M_1 \lesssim 15 \times \left(\frac{m_\chi}{300 \text{ MeV}} \right) \text{ keV}$$

Production and Decays

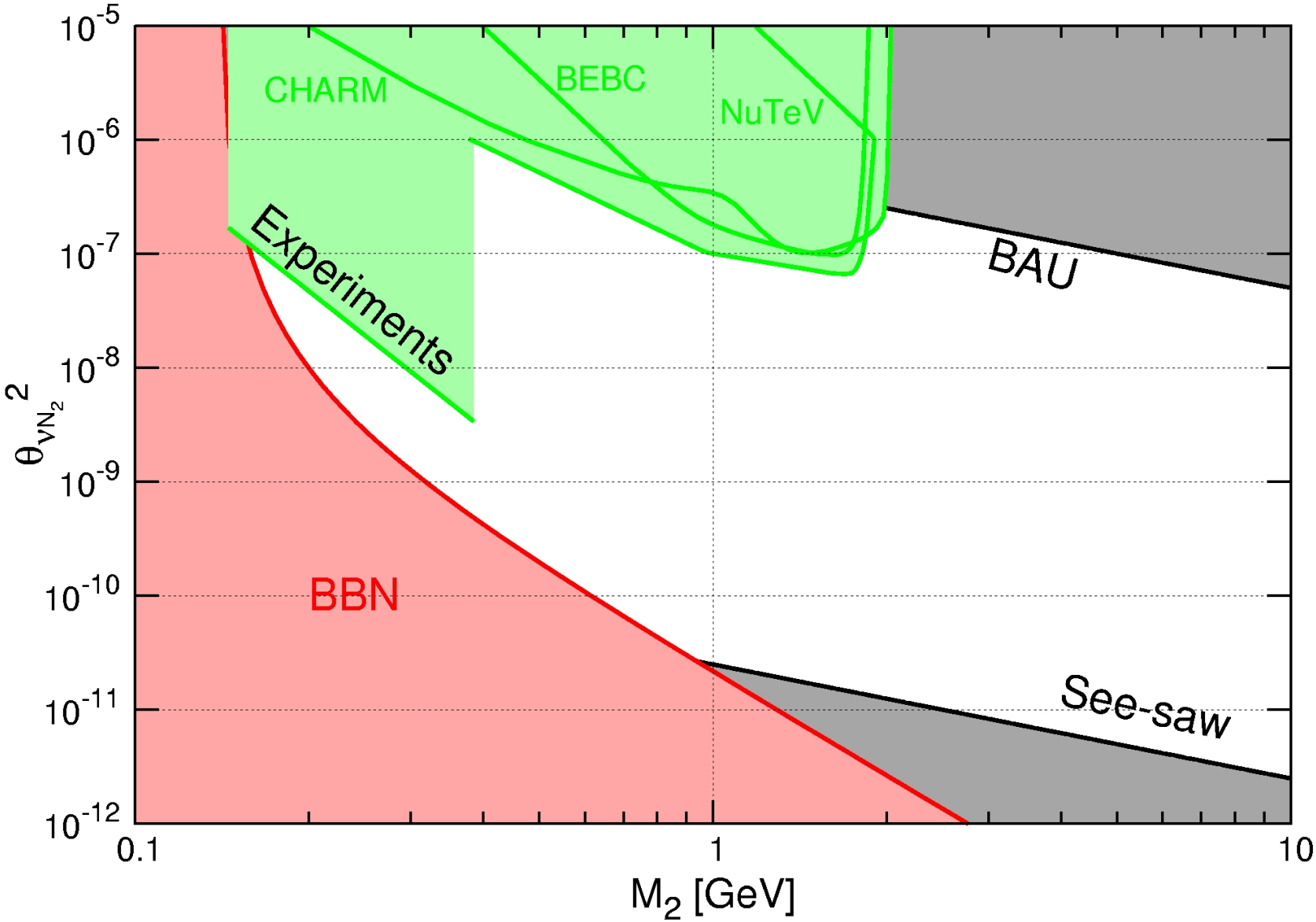




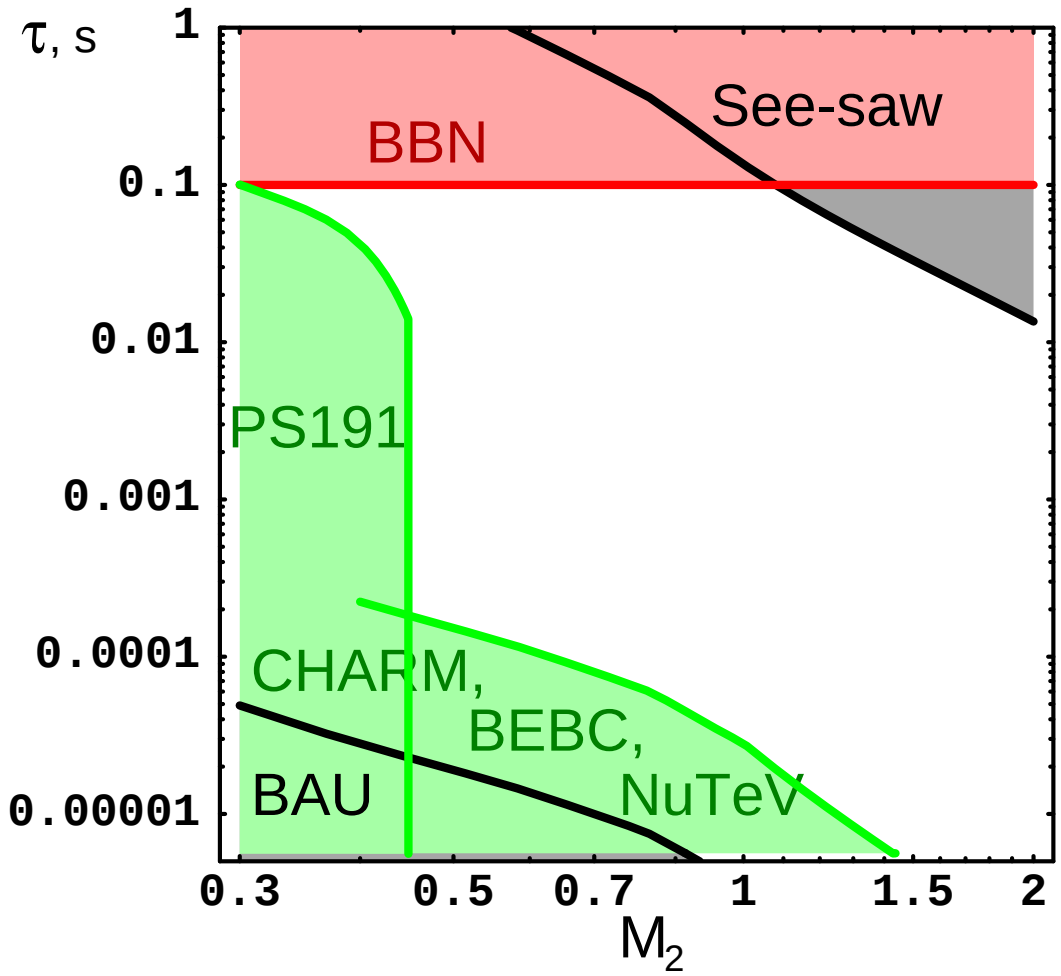




Searches for sterile seasaw neutrinos $N_{2,3}$



Searches for sterile seesaw neutrinos $N_{2,3}$



$$\mathrm{Br}(D \to lN) \lesssim 2 \cdot 10^{-8}$$

$$\mathrm{Br}(D_s \to lN) \lesssim 3 \cdot 10^{-7}$$

$$\mathrm{Br}(D \to KlN) \lesssim 2 \cdot 10^{-7}$$

$$\mathrm{Br}(D_s \to \eta lN) \lesssim 5 \cdot 10^{-8}$$

$$\mathrm{Br}(D \to K^* lN) \lesssim 7 \cdot 10^{-8}$$

$$\mathrm{Br}(B \to DlN) \lesssim 7 \cdot 10^{-8}$$

$$\mathrm{Br}(B \to D^* lN) \lesssim 4 \cdot 10^{-7}$$

$$\mathrm{Br}(B_s \to D_s^* lN) \lesssim 3 \cdot 10^{-7}$$

$c\tau_N \gtrsim 10^5$ cm

D.G., M.Shaposhnikov (2007)

Outline

Summary

- Simple inflationary model $\beta X^4 + \alpha X^2 H^\dagger H$ with viable reheating can be fully explored by direct searches of $B \to X_s + \chi$ $\quad 250\,\text{MeV} \lesssim m_\chi \lesssim 1.8\,\text{GeV}$

F.Bezrukov, D.G. JHEP 1005 (2010) 010 $\quad \text{Br}(B \to \chi X_s) \simeq 10^{-6} \cdot \left(1 - \frac{m_\chi^2}{m_b^2}\right)^2 \left(\frac{300\ \text{MeV}}{m_\chi}\right)^2$

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

- combined with νMSM (completed with right handed neutrinos) provides
  - active neutrino masses and mixing angles
  - 10-100 keV neutrino as (warm) Dark Matter
  - mechanism for baryon asymmetry generation
- Possible searches for "heavy" sterile neutrinos responsible for baryogenesis

D.G., M.Shaposhnikov, JHEP 0710 (2007) 015

  - sterile neutrino from K, D, B, τ decays with $\text{Br} \simeq 10^{-6} - 10^{-10}$
  - searches at: CNGS, T2K, Belle,..., LHCb $\quad c\tau_N \gtrsim 10^5\,\text{cm}$

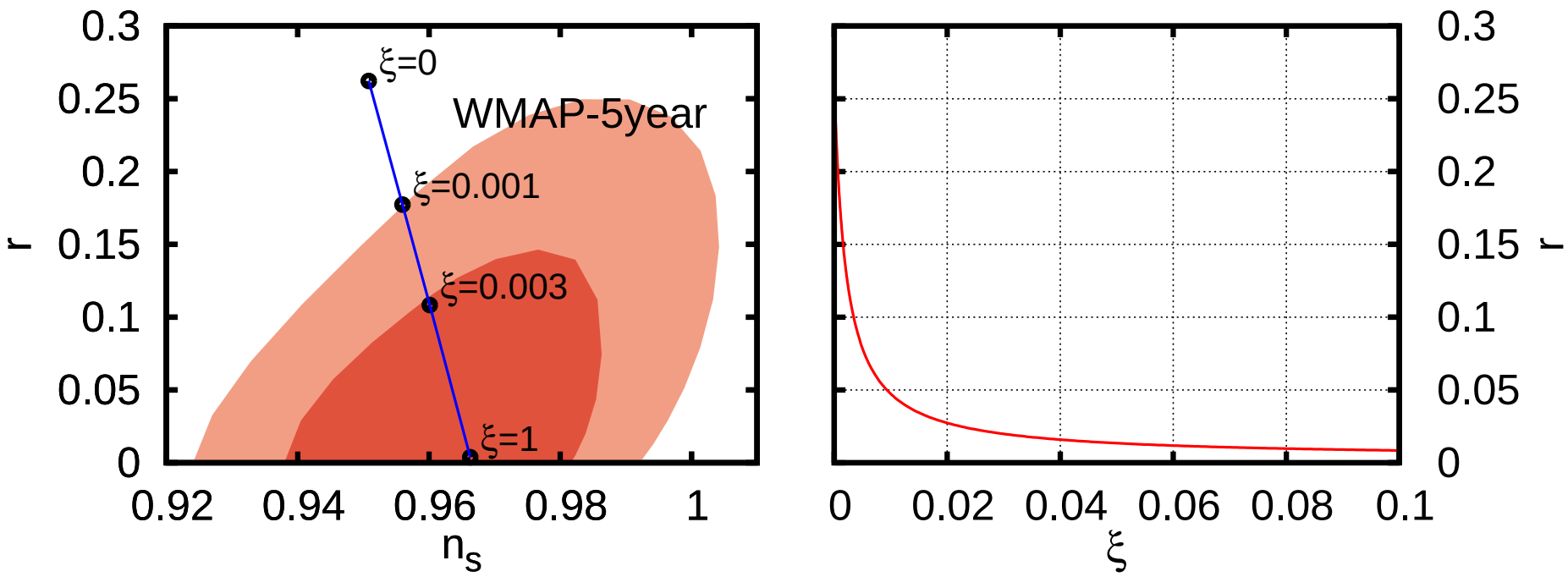
LHC: $\qquad$ Higgs mass from validity upto inflationary scale: $126\,\text{GeV} \lesssim m_h \lesssim 190\,\text{GeV}$

Backup slides

Cosmological test of λX^4-inflation ?

With non-minimal coupling to gravity

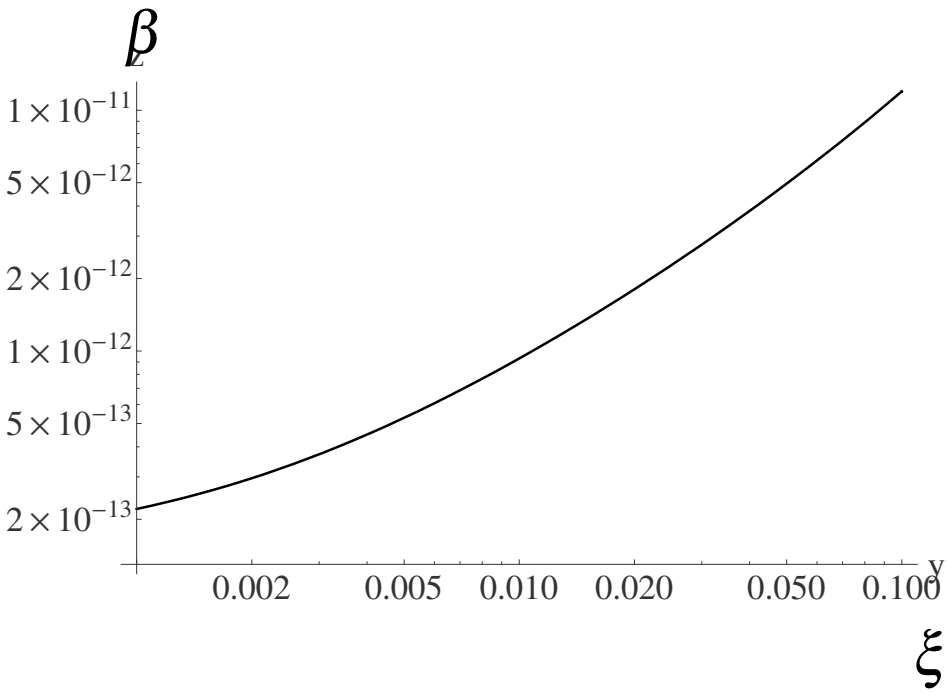
$$\xi R X^2$$

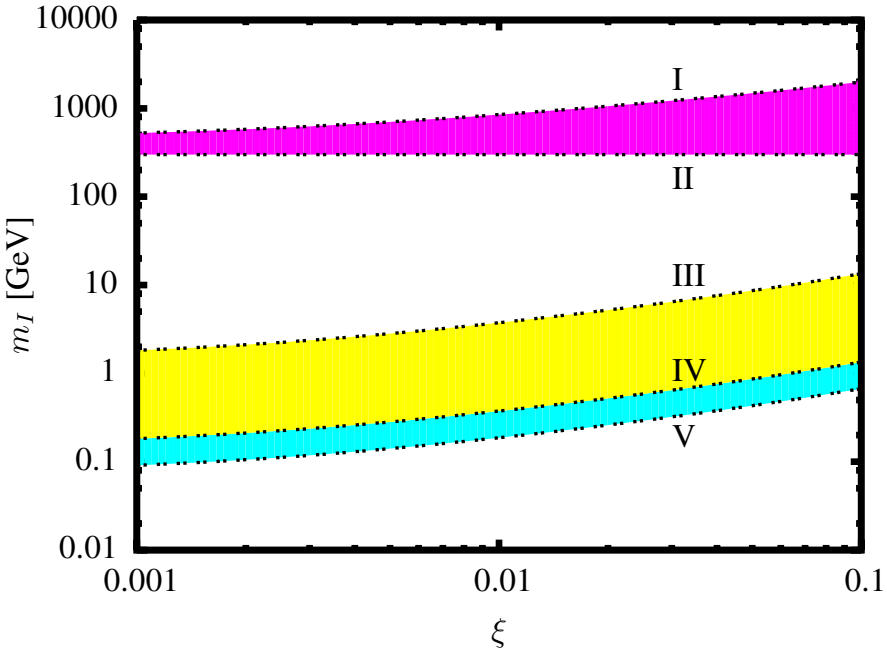


0810.3165

No arguments to forbid $\xi \lesssim 1$

Inflaton mass as a function of ξ





0809.1097