

# Minimal models of inflation – connecting cosmology and experiment

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# Outline

- 1 Our present knowledge of particle physics and the Universe
  - Standard Model
  - SM problems in laboratory and in cosmology
- 2 Minimal extension approach
  - Higgs mass bounds
- 3 Inflating with a light inflaton
  - Inflationary model
  - Bounds from cosmology – inflation and reheating
  - Experimental detection of the inflaton
- 4 Summary



# Standard Model – describes nearly everything that we know

Gauge theory  $SU(3) \times SU(2) \times U(1)$

Describes (together with Einstein gravity)  $\square\square\square\square$

- all laboratory experiments – electromagnetism, nuclear processes, etc.
- all processes in the evolution of the Universe after the Big Bang Nucleosynthesis ( $T < 1$  MeV,  $t > 1$  sec)

Three Generations of Matter (Fermions) spin $\frac{1}{2}$									
	I			II			III		
mass –	2.4 MeV	1.27 GeV	171.2 GeV						
charge –	$\frac{2}{3}$	$\frac{1}{3}$	$\frac{2}{3}$						
name –	u	c	t						
Left	up	charm	top						
Right	right	right	right						
Quarks	d	s	b						
Left	down	strange	bottom						
Right	right	right	right						
Leptons	$e^-$	$\mu^-$	$\tau^-$						
Left	electron	muon	tau						
Right	Right	Right	Right						
Bosons (Forces) spin 1	$g$	$\gamma$	$Z^0$	$W^\pm$					
Left	gluon	photon	weak force	weak force					
Right	Right	Right	Right	Right					
Bosons (Forces) spin 0	0	0	0	0					
Left									
Right									
Higgs boson	0	0	0	0					
Left									
Right									

# Standard Model has **experimental** problems

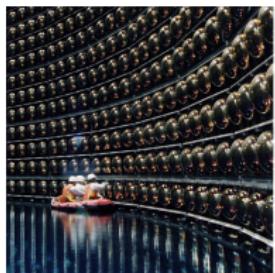
- Laboratory
  - Neutrino oscillations
- Cosmology
  - Baryon asymmetry of the Universe
  - Dark Matter
  - Inflation
    - Horizon problem (and flatness, entropy, ...)
    - Initial density perturbations
  - Dark Energy



# Neutrino oscillations



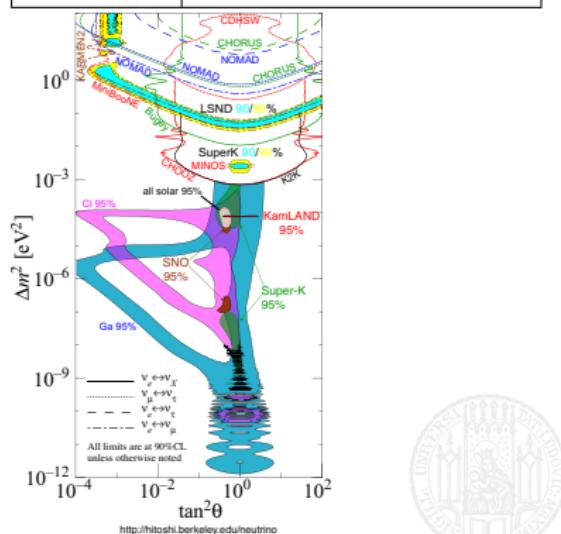
SAGE neutrino observatory  
(solar oscillations evidence)  
 $\nu_e \rightarrow \nu_\mu$ )



SuperKamiokande  
(atmospheric oscillations)  
 $\nu_\mu \rightarrow \nu_\tau$ )

Reactor neutrinos, accelerator neutrinos

Oscillation parameters	
$\Delta m_{21}^2$	$7.59 \pm 0.20 \times 10^{-5} \text{ eV}^2$
$\sin^2 2\theta_{12}$	$0.87 \pm 0.03$
$ \Delta m_{32}^2 $	$2.43 \pm 0.13 \times 10^{-3} \text{ eV}^2$
$\sin^2 2\theta_{23}$	$> 0.92$
$\sin^2 2\theta_{13}$	$< 0.15$



# Baryon asymmetry of the Universe

- Current universe contains baryons and no antibarions
- Current baryon density

$$\eta_B \equiv \frac{n_B}{n_\gamma} \simeq 6.1 \times 10^{-10}$$

- Does not fit into the SM (too weak CP violation, too smooth phase transition)

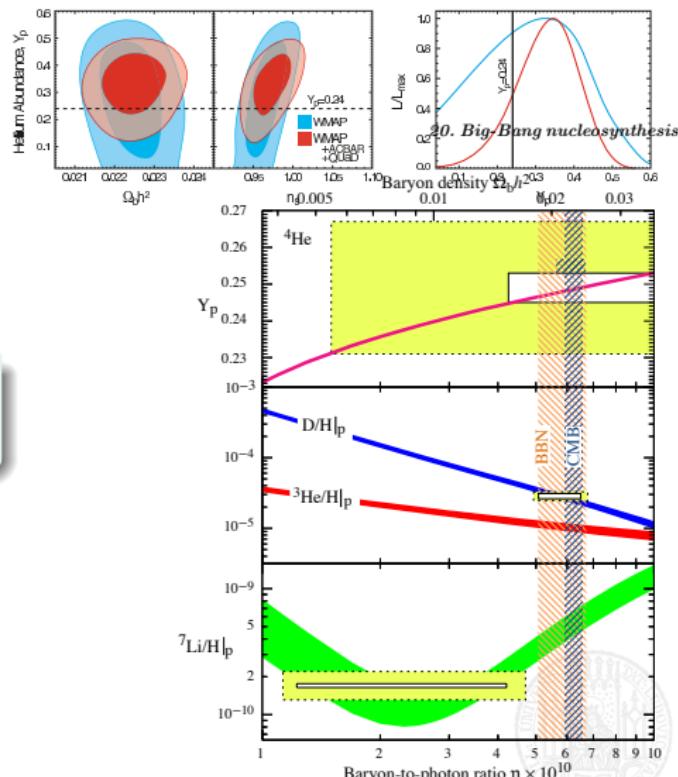
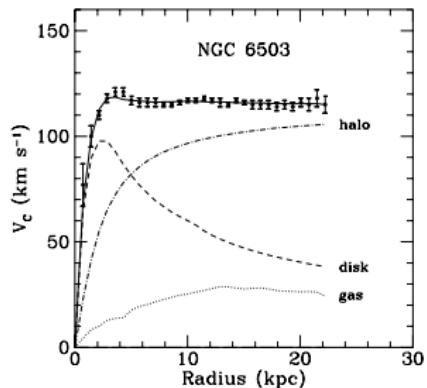
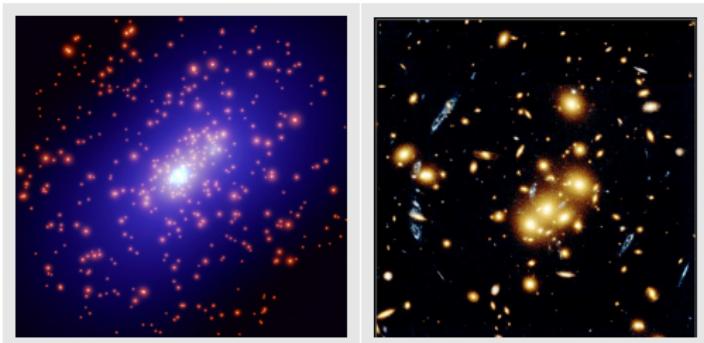


Figure 20.1: The abundances of  ${}^4\text{He}$ , D,  ${}^3\text{He}$ , and  ${}^7\text{Li}$  as predicted by the standard model of Big-Bang nucleosynthesis [11] – the bands show the 95% CL range. Boxes indicate the observed light element abundances (smaller boxes:  $\pm 2\sigma$  statistical

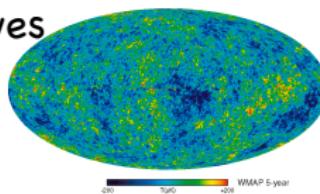
# Dark Matter



## Gravitational lensing

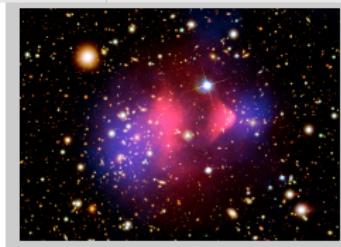


## Rotation curves



$$\Omega_{\text{DM}} \simeq 0.21$$

CMB fluctuations



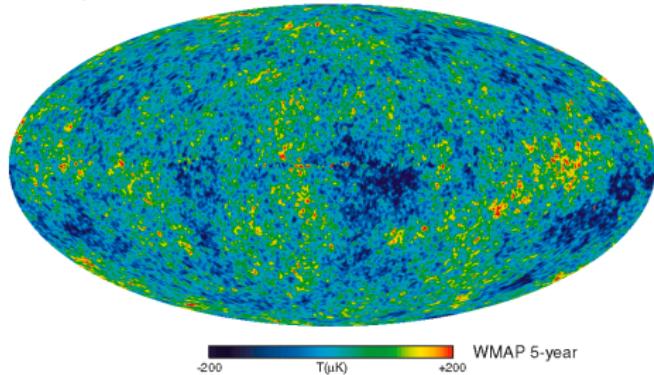
"Bullet" cluster



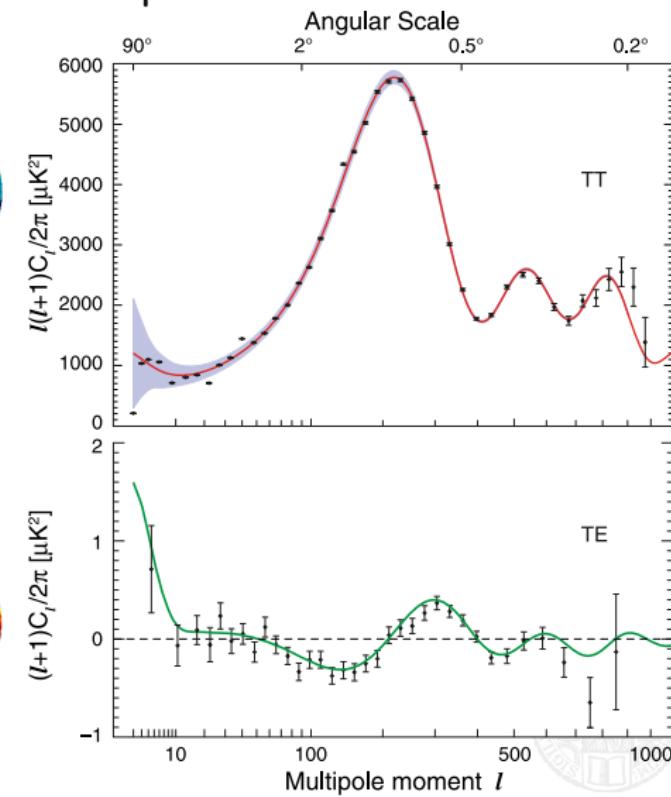
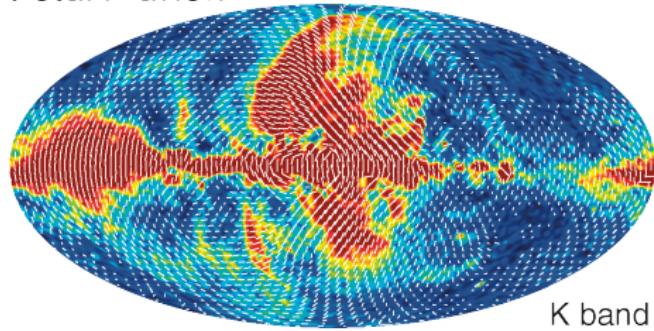
# CMB gives measured predictions from inflation

## CMB spectrum

Temperature fluctuations

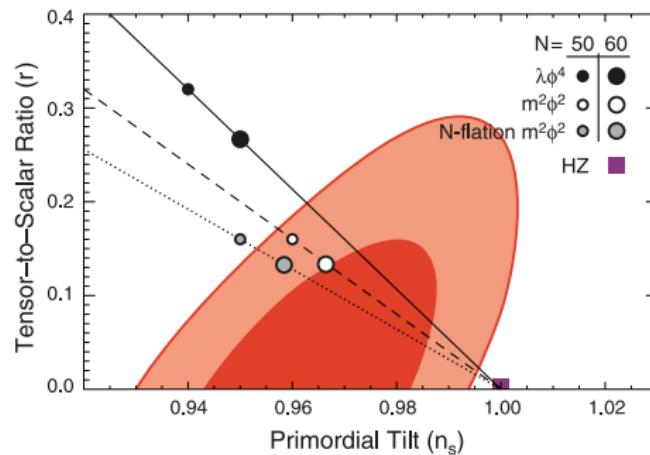


Polarization



# Inflationary parameters from CMB

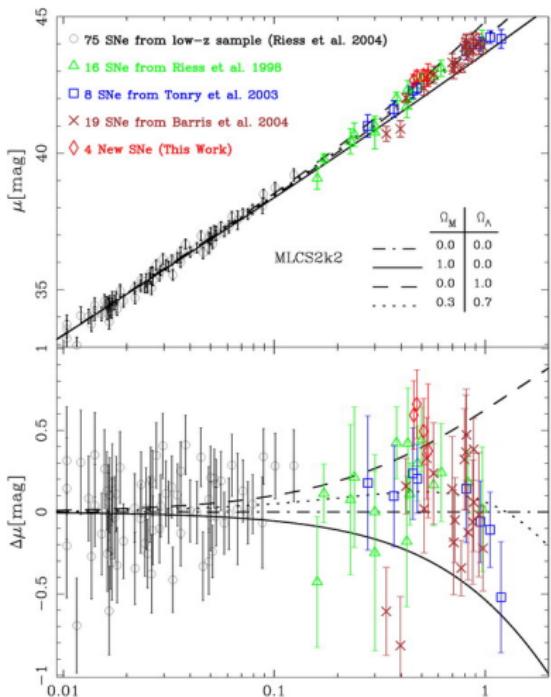
- Spectrum of primordial scalar density perturbations is just a bit not flat  $n_s - 1 \equiv \frac{d \log \mathcal{P}_{\mathcal{R}}}{d \log k}$
- Tensor perturbations are compatible with zero  $r \equiv \frac{\mathcal{P}_{\text{grav}}}{\mathcal{P}_{\mathcal{R}}}$



(WMAP07 results)



# Dark Energy



← Supernova type Ia redshifts

accelerated expansion of the  
Universe today

$$\Omega_\Lambda \simeq 0.74$$

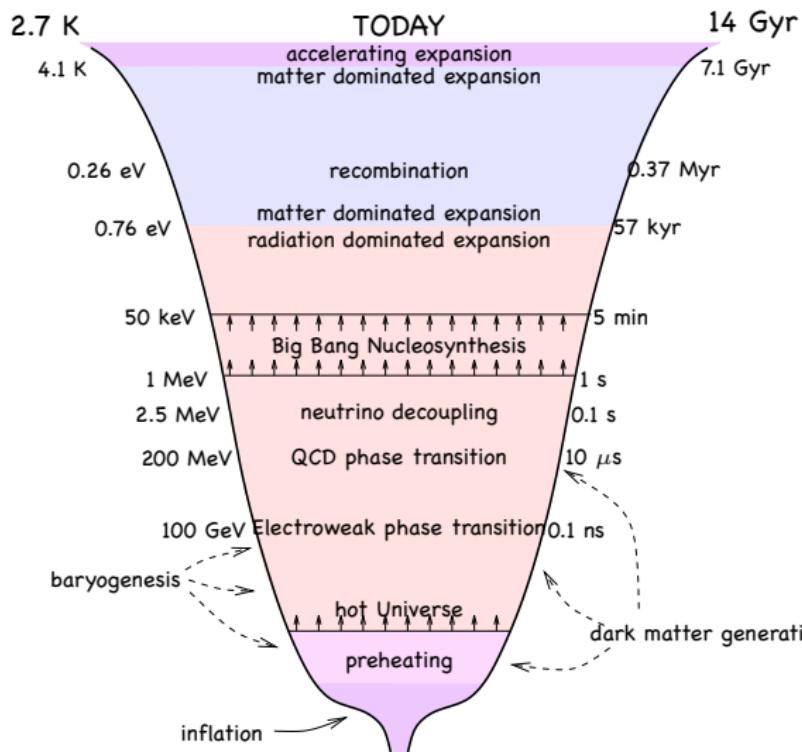
Different from inflation

- Much lower scale
- No need to stop it

Can be explained "just" by a  
**cosmological constant** (invented  
already by Einstein)



# Universe history



Standard Model works ok here



# Let us expand the model in a minimal way

I will follow a “Minimal” approach

Explain the **experimental** facts with

- minimal number of new particles
- no new physical scales

Different situation in usual approaches

Solve hierarchy problems first

- Supersymmetry, Extra dimensions ... } New physics at TeV energies – “masks” us from early Universe



# Several examples of minimal extensions leading to inflation

- Inflation with light inflaton

[Shaposhnikov, Tkachev'06]  
 [Anisimov, Bartocci, FB'09]  
 [FB, Gorbunov'10]

(Introduces new particle)

- Higgs boson inflation

[FB, Shaposhnikov'08]  
 [FB, Gorbunov, Shaposhnikov'09]  
 [FB, Magnin, Shapshnikov'09]

(Modifies Higgs-gravity interaction, new scales  $M_P/\xi$ ,  $M_P/\sqrt{\xi}$ )

- $R^2$  (scalaron) inflation

[Starobinsky'80]  
 [Gorbunov, Panin'10]

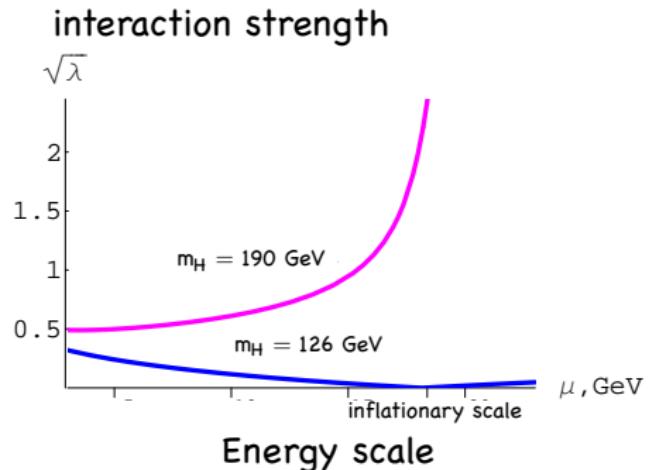
(Modification only in the gravity sector)



# Common prediction: Higgs mass window

The model should be valid up to inflationary scale:

Radiative corrections to the Higgs potential may spoil this



## Higgs mass bounds

$$126 \text{ GeV} \lesssim m_H \lesssim 190 \text{ GeV}$$



# The Light inflaton model

Let us try to do everything just within standard particle physics

Just add the inflaton!



# Light inflaton model adds one scalar particle to the SM

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \alpha H^\dagger H X^2 + \frac{\beta}{4} X^4$$

Standard Model      Interaction      Inflationary sector

(where  $\beta \simeq \beta_0 = 1.5 \times 10^{-13}$  – inflationary requirement)

$$m_\chi = m_h \sqrt{\frac{\beta}{2\alpha}}$$

– the inflaton mass is defined by  $\alpha$

The Higgs-inflaton scalar potential is

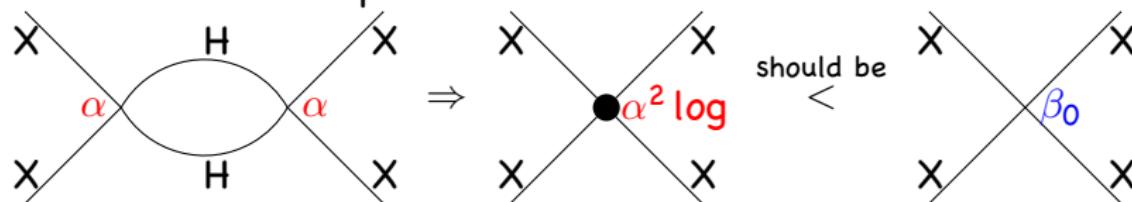
$$V(H, X) = \lambda \left( H^\dagger H - \frac{\alpha}{\lambda} X^2 \right)^2 + \frac{\beta}{4} X^4 - \frac{1}{2} \mu^2 X^2 + V_0$$

[Anisimov, Bartocci, FB'09, FB, Gorbunov'10]



# Radiative corrections require a small SM-inflaton coupling

Radiative corrections induce quartic coupling which should not spoil the flatness of the potential



This leads to an upper bound on the SM-inflaton interaction

$$\alpha \lesssim 10^{-7} \quad (\text{roughly: } \alpha < \sqrt{\beta})$$

Lower bound for the inflaton mass

$$m_\chi > 90 \text{ MeV}$$

# Radiative corrections require a small SM-inflaton coupling

Radiative corrections induce quartic coupling which should not spoil the flatness of the potential

$$\delta V = \frac{m^4(X)}{64\pi^2} \log \frac{m^2(X)}{\mu^2} \quad \text{should be} \quad < \quad V_{\text{inflaton}} = \frac{\beta}{4} X^4$$

$$m_h^2(X) = 4\alpha X^2 \quad (\text{Higgs boson})$$

This leads to an upper bound on the SM-inflaton interaction

$$\alpha \lesssim 10^{-7} \quad (\text{roughly: } \alpha < \sqrt{\beta})$$

## Lower bound for the inflaton mass

$$m_\chi > 90 \text{ MeV}$$

# Preheating requires large SM-inflaton coupling

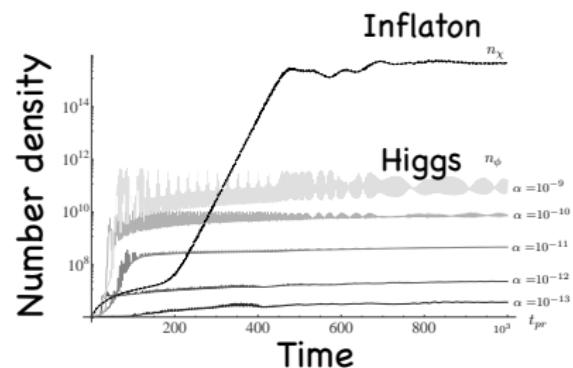
- After inflation: empty & cold
- Needed: hot,  $T_r > 150$  GeV (to get baryogenesis)

Equating H production rate ( $\propto \alpha^2$ )  
to Hubble expansion rate ( $\propto T^2$ )  
 $\Gamma_{XX \rightarrow HH} \sim \mathcal{H}$

## Lower bound on $\alpha$

$$\alpha \gtrsim 7 \times 10^{-10}$$

Parametric resonance?  
Not so easy to create the Higgs



The large Higgs self interaction  
destroys coherence and spoils  
parametric resonance.

[Anisimov, Bartocci, FB'09]

► Details

# Inflaton is in the experimentally explorable range

Inflaton mass window (from Cosmology)

$$90 \text{ MeV} < m_\chi < 1.8 \text{ GeV}$$

Lower bound: radiative corrections

Upper bound: sufficient reheating

Also possible:  $2m_H < m_\chi \lesssim 600 \text{ GeV}$



# Inflaton-SM Interactions

As the Higgs boson, but light and suppressed by  $\theta = \sqrt{2\beta}v/m_\chi$

- Created: in meson decays
- Decays: the heaviest particle pairs ( $e^+e^-$ ,  $\pi\pi$ ,  $\mu\mu$ ,  $K\bar{K}$ )
- Interacts with media: extremely weakly

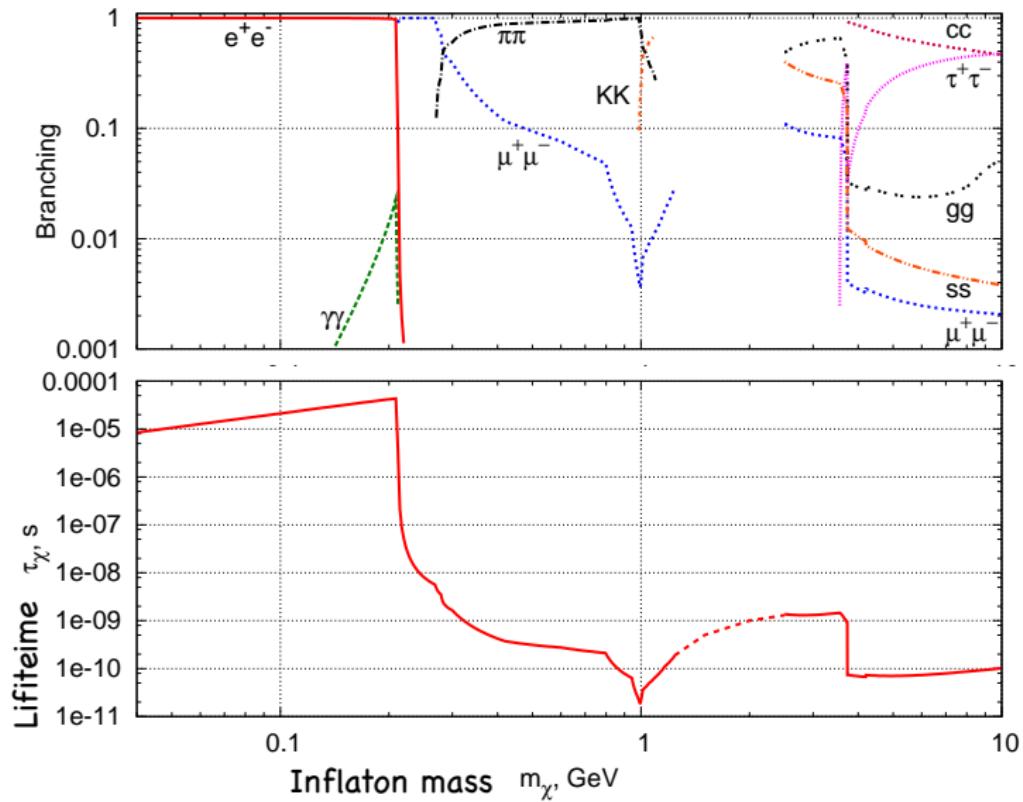
$$\mathcal{L}_{\chi\bar{f}f} = \theta \frac{m_f}{v} \chi \bar{f}f = \sqrt{2\beta} \frac{m_f}{m_\chi} \chi \bar{f}f$$

$$\begin{aligned} \mathcal{L}_{\chi\pi\pi} &= 2\kappa\sqrt{2\beta} \cdot \frac{\chi}{m_\chi} \cdot \left( \frac{1}{2}\partial_\mu\pi^0\partial^\mu\pi^0 + \partial_\mu\pi^+\partial^\mu\pi^- \right) \\ &\quad - (3\kappa+1)\sqrt{2\beta} \cdot \frac{\chi}{m_\chi} \cdot m_\pi^2 \cdot \left( \frac{1}{2}\pi^0\pi^0 + \pi^+\pi^- \right) \quad (\kappa = 2/9) \end{aligned}$$

$$\mathcal{L}_{\chi\gamma\gamma} \approx \frac{F_{\gamma\gamma}\alpha}{4\pi} \frac{\sqrt{2\beta}}{m_\chi} \chi F_{\mu\nu} F^{\mu\nu} \qquad \mathcal{L}_{\chi gg} \approx \frac{F_{gg}\alpha_s}{4\sqrt{8}\pi} \frac{\sqrt{2\beta}}{m_\chi} \chi G_{\mu\nu}^a G^{a\mu\nu}$$



# Inflaton is relatively long lived

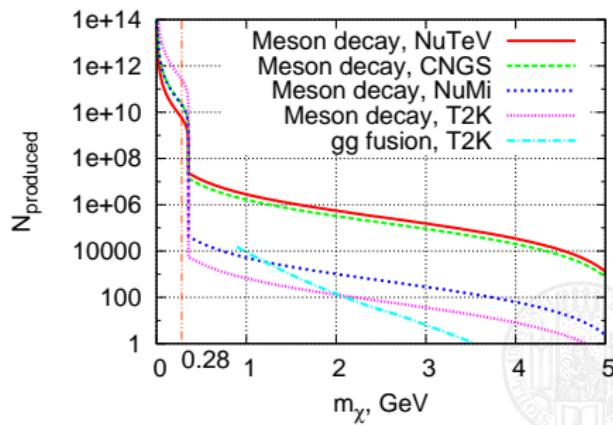


# Produced in meson decays and in beam dumps

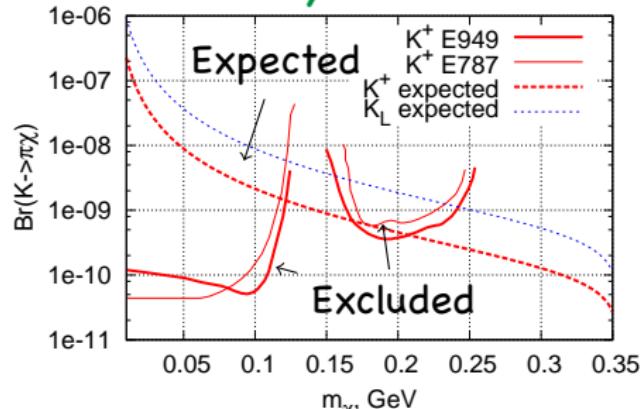
$$\left. \begin{array}{l} \text{Br}(K^+ \rightarrow \pi^+ \chi) \approx 2.3 \times 10^{-9} \\ \text{Br}(K_L \rightarrow \pi^0 \chi) \approx 1.0 \times 10^{-8} \\ \text{Br}(\eta \rightarrow \pi^0 \chi) \approx 1.8 \times 10^{-12} \\ \text{Br}(B \rightarrow X_s \chi) \approx 10^{-5} \end{array} \right\} \times \left( \frac{\beta}{\beta_0} \right) \cdot \left( \frac{100 \text{ MeV}}{m_\chi} \right)^2 \cdot k \left( \frac{m_\chi}{m_{\text{meson}}} \right)$$

In a p-beam dump (via meson decays), ideal luminosity

	$E, \text{ GeV}$	$N_{\text{POT}}, 10^{19}$
NuTeV	800	1
CNGS	400	4.5
NuMi	120	5
T2K	50	100

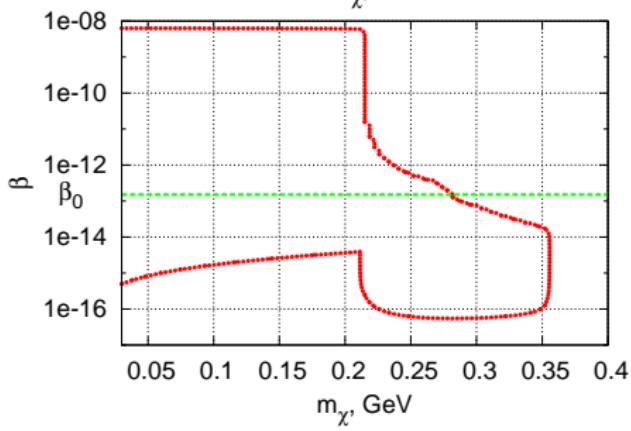


# Hadron decays constrain inflaton mass



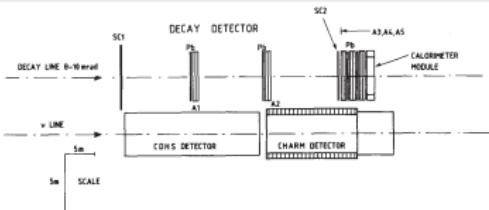
Bound from decay  
 $K^+ \rightarrow \pi^+ + \text{nothing}$

$$m_\chi > 120 \text{ MeV}$$



Bound from  $X$  decay into  $e^+ e^-$ ,  
 $\mu^+ \mu^-$

$$m_\chi > 270 \text{ MeV}$$



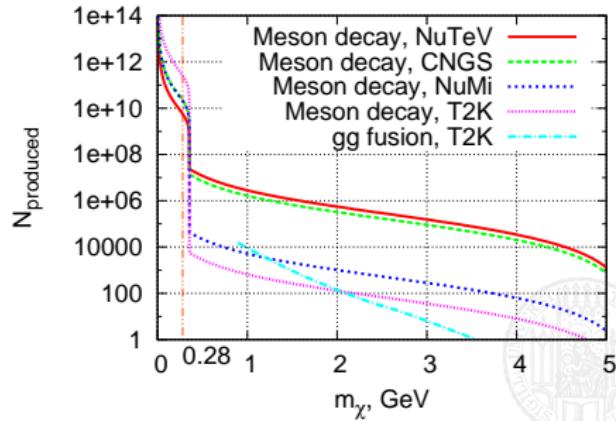
# B-meson decays – search for the inflaton!

$$\left. \begin{aligned} \text{Br}(K^+ \rightarrow \pi^+ \chi) &\approx 2.3 \times 10^{-9} \\ \text{Br}(K_L \rightarrow \pi^0 \chi) &\approx 1.0 \times 10^{-8} \\ \text{Br}(\eta \rightarrow \pi^0 \chi) &\approx 1.8 \times 10^{-12} \\ \text{Br}(B \rightarrow X_s \chi) &\approx 10^{-5} \end{aligned} \right\} \times \left( \frac{\beta}{\beta_0} \right) \cdot \left( \frac{100 \text{ MeV}}{m_\chi} \right)^2 \cdot k \left( \frac{m_\chi}{m_{\text{meson}}} \right)$$

LHCb: events with offset vertex

In a p-beam dump (via meson decays), ideal luminosity

	E, GeV	N <sub>POT</sub> , 10 <sup>19</sup>
NuTeV	800	1
CNGS	400	4.5
NuMi	120	5
T2K	50	100



# Dark matter – add $\nu$ MSM and stir

Light inflaton

+

Three Generations of Matter (Fermions) spin 1/2		
	I	II
mass →	2.4 MeV	1.27 GeV
charge →	2/3	2/3
name →	u up Left Right	c charm Left Right
Quarks	d down Left Right	s strange Left Right
Leptons	$\nu_e / N_1$ electron sterile neutrino neutrino Left Right	$\nu_\mu / N_2$ muon sterile neutrino neutrino Left Right
	e electron Left Right	$\mu$ muon Left Right
Bosons (Forces) spin 1	$\gamma$ photon Left Right	$\tau$ tau Left Right
	$Z$ weak force Left Right	$W$ weak force Left Right
	Higgs boson spin 0	Higgs boson spin 0

+  $f_I X \bar{N}^c N$

[Asaka, Blanchet, Shaposhnikov'05, Shaposhnikov, Tkachev'06]

- DM sterile neutrinos are produced in inflaton decays
- BAU via leptogenesis with two heavier sterile neutrinos

DM neutrino mass bound from production mechanism

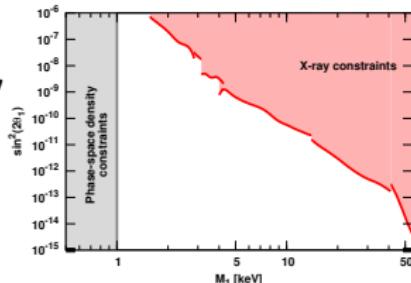
$$M_1 \lesssim 80 \text{ keV}$$



# Possible search for $\nu$ MSM neutrino in the lab and in the Universe

- DM sterile neutrino  $N_1$ ,  $M_1 \sim 1 - 80\text{keV}$ 
  - X-ray line from the DM radiative decay  
 $N_1 \rightarrow \nu \gamma$
  - Neutrinoless double beta decay  
 $m_{ee} < 50 \times 10^{-3} \text{ eV}$

[FB'05]  Details



- Lepton asymmetry generating  $N_{2,3}$ ,  $M_{2,3} \sim \text{GeV}$ 
  - Neutrino production hadron decays: kinematics
    - Missing energy in K decays
    - Peaks in momentum of charged leptons for two body decays
  - Neutrino decays into SM particles: "nothing" to leptons and hadrons
    - Beam target experiments with high intensity proton beam, detector (preferably not dense) after the shielding.

[D. Gorbunov, M.Shaposhnikov'07]



# Summary

Start from:

- Explain every **experimental fact**
- Expand the Standard Model in a **minimal way**

Arrive to:

- **Predictions** for low energy experiments!

Examples:

- Model with additional scalar inflaton
  - Light inflaton reachable in particle physics experiments
- ...!



# Non-minimal coupling to gravity solves the problem

Quite an old idea

Add  $h^2 R$  term (required by renormalization) to of the usual  $M_P R$  term in the gravitational action

- A.Zee'78, L.Smolin'79, B.Spokoiny'84
- D.Salopek J.Bond J.Bardeen'89

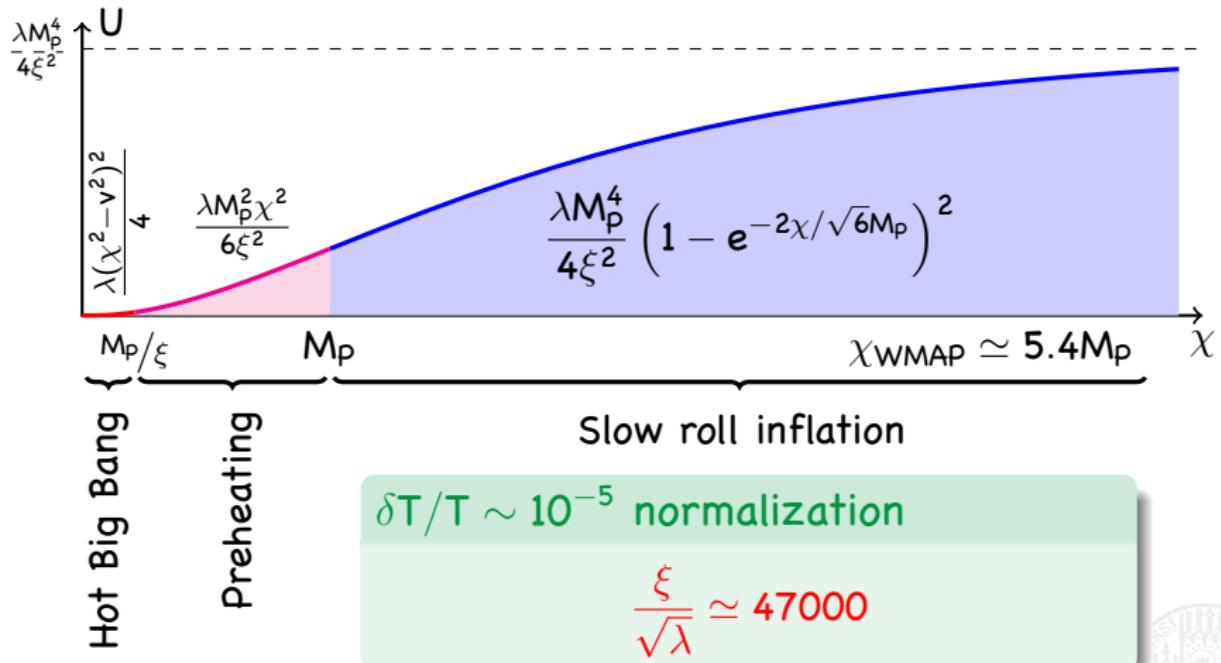
Scalar part of the (Jordan frame) action

$$S_J = \int d^4x \sqrt{-g} \left\{ -\frac{M_P^2}{2} R - \xi \frac{h^2}{2} R + g_{\mu\nu} \frac{\partial^\mu h \partial^\nu h}{2} - \frac{\lambda}{4} (h^2 - v^2)^2 \right\}$$

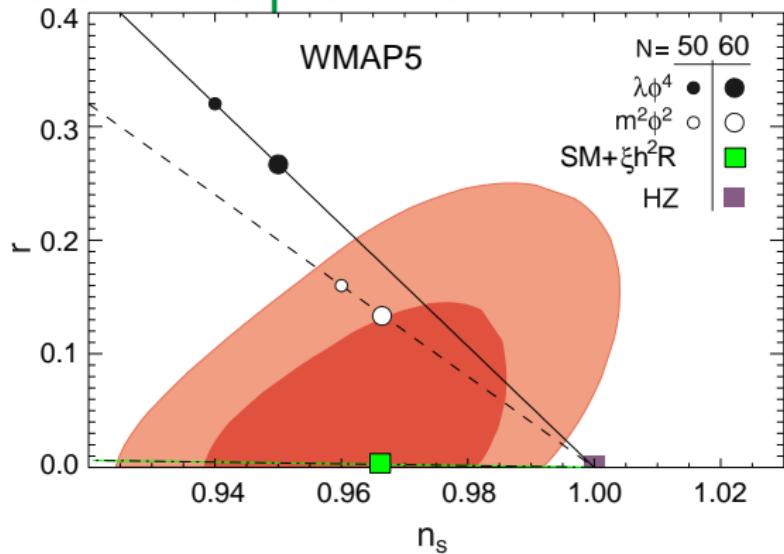
- $h$  is the Higgs field;  $M_P \equiv \frac{1}{\sqrt{8\pi G_N}} = 2.4 \times 10^{18} \text{ GeV}$
- SM higgs vev  $v \ll M_P/\sqrt{\xi}$  and can be neglected in the early Universe



# Potential – different stages of the Universe



# CMB parameters are predicted



spectral index  $n \simeq 1 - \frac{8(4N+9)}{(4N+3)^2} \simeq 0.97$

tensor/scalar ratio  $r \simeq \frac{192}{(4N+3)^2} \simeq 0.0033$

$$\delta T/T \sim 10^{-5} \implies \frac{\xi}{\sqrt{\lambda}} \simeq 47000$$



# Scalaron ( $\phi$ ) generation of fermionic CDM

$$S_{\varphi}^{\text{EF}} = \int \sqrt{-\tilde{g}} d^4x \left( \frac{1}{2} \tilde{g}^{\mu\nu} \partial_\mu \tilde{\varphi} \partial_\nu \tilde{\varphi} - \frac{1}{2} e^{-\frac{\phi}{\sqrt{3/2} M_P}} m_\varphi^2 \tilde{\varphi}^2 \right.$$

$$\left. - \frac{\tilde{\varphi}^2}{12 M_P^2} \tilde{g}^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - \frac{\tilde{\varphi}}{\sqrt{6} M_P} \tilde{g}_{\mu\nu} \partial_\mu \tilde{\varphi} \partial_\nu \phi \right),$$

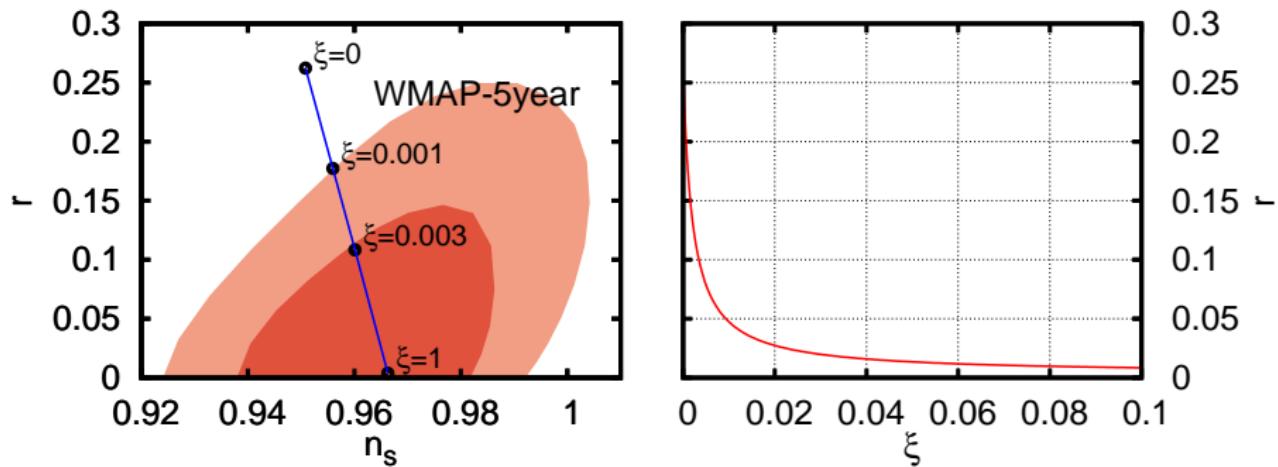
$$S_{\psi}^{\text{EF}} = \int \sqrt{-\tilde{g}} d^4x \left( i \bar{\psi} \hat{\mathcal{D}} \tilde{\psi} - m_\psi e^{-\frac{\phi}{\sqrt{6} M_P}} \bar{\tilde{\psi}} \tilde{\psi} \right).$$

$$\Gamma_{\phi \rightarrow \varphi \varphi} = \frac{\mu^3}{192\pi M_P^2}, \quad \Gamma_{\phi \rightarrow \bar{\psi}\psi} = \frac{\mu m_\psi^2}{48\pi M_P^2}.$$

$$m_\varphi \approx 6.9 \text{ keV} \times \left( \frac{N_s}{4} \right)^{1/2} \left( \frac{g_*}{106.75} \right)^{1/4} \left( \frac{\Omega_{\text{DM}}}{0.223} \right)$$

$$m_\psi \approx 1.2 \times 10^7 \text{ GeV} \times \left( \frac{N_s}{4} \right)^{1/6} \left( \frac{g_*}{106.75} \right)^{1/12} \left( \frac{\Omega_{\text{DM}}}{0.223} \right)^{1/3}$$

# WMAP-5 bounds



## Message

With non-minimal coupling it is very natural for  $\beta\phi^4$  inflation to be compatible with observations!



## Parametric enhancement

Let us suppose again that there is an inflaton  $X$  coupled to some particle  $\phi$ . Then, during inflaton oscillations, for the  $\phi$  modes with momentum  $k$  we have

$$\ddot{\phi}_k + 3H\dot{\phi}_k + \left( \frac{k^2}{a^2(t)} + g^2 X(t)^2 \right) \phi_k = 0$$

- Important –  $X(t)$  oscillates
- Let us neglect the Universe expansion, and say that  $X(t) = A \sin(\omega t)$ , then

## Mathieu equation

$$\frac{d^2 \phi_k}{d\eta^2} + (A_k - 2q \cos 2\eta) \phi_k = 0$$

where  $A_k = k^2/\omega^2 + 2q$ ,  $q = g^2 X_0^2/4\omega^2$ ,  $\eta = \omega t$ .



◀ Return

# Temperature estimate for the reheating

Equating mean free path  $n\sigma_{2I \rightarrow 2H}v \sim n \frac{\alpha^2}{\pi p_{avg}^2}$  with the Hubble rate

$H = \frac{T^2}{m_{Pl}} \sqrt{\frac{\pi^2 g_*}{90}}$  we get

$$T_R \approx \frac{\zeta(3)\alpha^2}{\pi^4} \sqrt{\frac{90}{g_*}} m_{Pl}$$

Requiring  $T_R > 150 \text{ GeV}$  we can obtain the lower bound on  $\alpha$

$$\alpha \geq 7.3 \times 10^{-8},$$

◀ Return



# Temperature estimate for the reheating II

However,  $p_{\text{avg}} \propto T$ , the cross-section is enhanced, so

$$\frac{\zeta(3)\alpha^2}{\pi^3} \frac{T^4}{p_{\text{avg}}^3} \sim \frac{T^2}{\sqrt{\frac{90}{8\pi^3 g^*} M_{\text{Pl}}}}$$

For this estimate the bound is weaker

$$\alpha \geq 7 \times 10^{-10}$$

## Upper bound for the inflaton mass

$$m_\chi \leq 1.5 \left( \frac{m_H}{150 \text{ GeV}} \right) \sqrt{\frac{\beta}{1.5 \times 10^{-13}}} \text{ GeV}$$



◀ Return

# Dark matter – add $\nu$ MSM and stir

A  $\nu$ MSM inspired model with inflation  $\chi$  [Shaposhnikov, Tkachev'06]

$$\mathcal{L} = (\mathcal{L}_{\text{SM}} + \bar{N}_I i \partial_\mu \gamma^\mu N_I - F_{\alpha I} \bar{L}_\alpha N_I \Phi - \frac{f_I}{2} \bar{N}_I^c N_I X + \text{h.c.}) + \frac{1}{2} (\partial_\mu X)^2 - V(\Phi, X)$$

$$\Omega_N = \frac{1.6 f(m_\chi)}{S} \cdot \frac{\beta}{1.5 \times 10^{-13}} \cdot \left( \frac{M_1}{10 \text{keV}} \right)^3 \cdot \left( \frac{100 \text{ MeV}}{m_\chi} \right)^3 ,$$

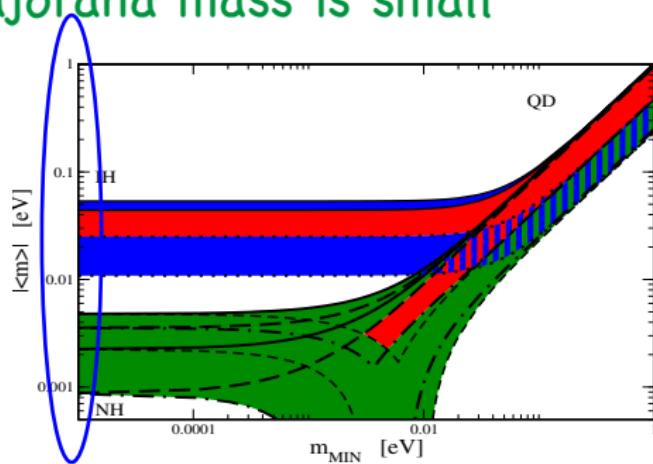
DM sterile neutrino mass should be

$$M_1 \sim 13 \cdot \left( \frac{m_\chi}{300 \text{ MeV}} \right) \left( \frac{S}{4} \right)^{1/3} \cdot \left( \frac{0.9}{f(m_\chi)} \right)^{1/3} \text{ keV} .$$



# $0\nu\beta\beta$ effective Majorana mass is small

$$m_{ee} = \left| \sum_i m_i V_{ei}^2 \right|$$



- contribution from  $N_1$  is negligible  $|M_1 \theta_{e1}^2| \leq 10^{-5}$  eV
- For heavier active neutrinos the contribution is always negative  
 $m_{ee} < \left| \sum_i m_i V_{ei}^2 \right|$       **smaller prediction**

$$m_{ee} < 50 \times 10^{-3} \text{ eV}$$

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