Light Inflaton – hunting for it from CMB through the Dark Matter and down to the colliders

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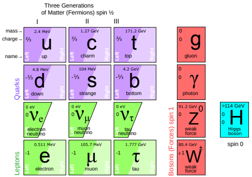
Outline

1. Minimally extending the Standard Model

2. Light Inflaton and cosmological constraints
   - The model and its parameters
   - Inflationary properties (tensor-to-scalar ratio)
   - Dark Matter generation

3. Search in the laboratory
   - Direct inflaton search
   - Is the Higgs compatible?

Standard Model – describes nearly everything



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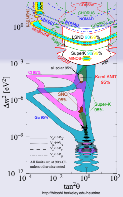
Einstein gravity

Describes

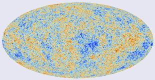
- all laboratory experiments – electromagnetism, nuclear processes, etc.
- all processes in the evolution of the Universe after the Big Bang Nucleosynthesis ($T < 1$ MeV, $t > 1$ sec)

Experimental problems:



- Laboratory
  - ? Neutrino oscillations
- Cosmology
  - ? Baryon asymmetry of the Universe
  - ? Dark Matter

  - ? Inflation



  - ? Dark Energy

Standard Model and nothing else above up to Planck scale?

No heavy particles/scales

- no physical high scale quadratic contributions to the Higgs boson vev
- hierarchy problem may be addressed by starting from a scale invariant theory
- Processes at the highest energy (inflation) may be directly related to the low energy properties

Should explain everything

- Inflation
- Dark Matter
- Neutrino oscillations
- Baryon asymmetry of the Universe

(Inflation, Dark Matter: this talk)

(Dark Matter, Neutrino oscillations, Baryon asymmetry of the Universe: νMSM)

Light Inflaton model essentials–one new scalar

$$\mathscr{L} = \mathscr{L}_{\text{SM,M=0}} + \alpha H^\dagger H \phi^2 +$$

Standard Model — Interaction

$$+ \frac{M_P^2}{2} R + \frac{(\partial\phi)^2}{2} + \frac{\xi\phi^2}{2} R - \frac{\beta}{4}\phi^4 + \frac{\mu^2}{2}\phi^2$$

Einstein gravity — Inflationary sector

$$+ i\bar{N}_I \partial\!\!\!/ N_I - F_{\alpha I}\bar{L}_\alpha N_I H - \frac{f_I}{2}\bar{N}_I^c N_I \phi$$

Sterile neutrinos — Dirac masses — Majorana masses

- Supports inflation for large ϕ
- Generates Higgs vev $\langle HH^\dagger \rangle = \frac{\alpha}{\lambda}\langle\phi\rangle$
- Produces DM sterile neutrino N_1 in decays $\phi \to NN$
- Gives mass to DM sterile neutrino $M_{N_1} = f\langle\phi\rangle$

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Sterile neutrinos — Dirac masses — Majorana masses

Parameter counting:

SM and νMSM

Higgs mass, N masses, $\langle H \rangle$

ξ fixed by CMB normalization

2 added *free* parameters

α and β, or:

inflaton mass $m_\chi = m_h\sqrt{\beta/2\alpha}$

Higgs-inflaton mixing $\theta^2 = 2\alpha/\lambda$

Light Inflaton model essentials–one new scalar

$$\mathscr{L} = \underbrace{\mathscr{L}_{\text{SM,M=0}}}_{\text{Standard Model}} + \underbrace{\alpha H^\dagger H \phi^2}_{\text{Interaction}} +$$

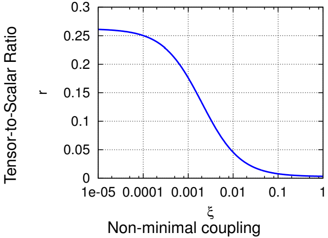
$$+ \underbrace{\frac{M_P^2}{2} R}_{\text{Einstein gravity}} + \underbrace{\frac{(\partial\phi)^2}{2} + \frac{\xi\phi^2}{2} R - \frac{\beta}{4}\phi^4 + \frac{\mu^2}{2}\phi^2}_{\text{Inflationary sector}}$$

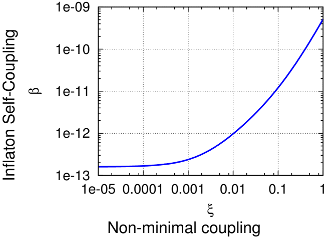
$$+ \underbrace{i\bar{N}_I \partial\!\!\!/ N_I}_{\text{Sterile neutrinos}} - \underbrace{F_{\alpha I} \bar{L}_\alpha N_I H}_{\text{Dirac masses}} - \underbrace{\frac{f_I}{2} \bar{N}_I^c N_I \phi}_{\text{Majorana masses}}$$

Scale symmetry breaking

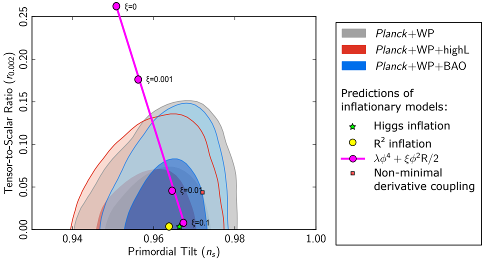
- Explicit μ^2 *only in the inflaton sector*

The tensor perturbations are suppressed, inflaton self-coupling β is increased by non-minimal coupling ξ



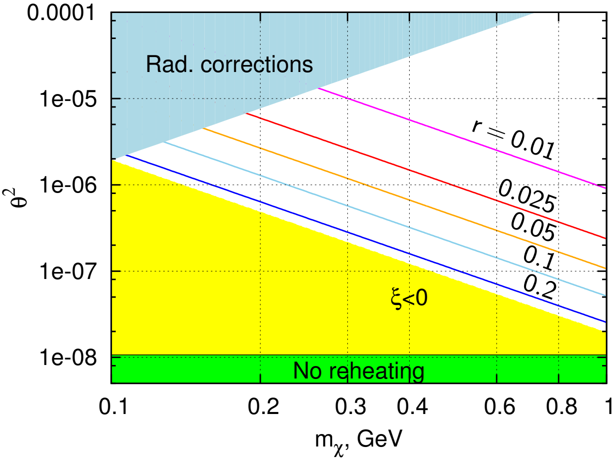


- Measurement of r is a measurement of ξ



[Tsujikawa, Gumjudpai'04, FB'08]

Parameters can be determined from cosmology



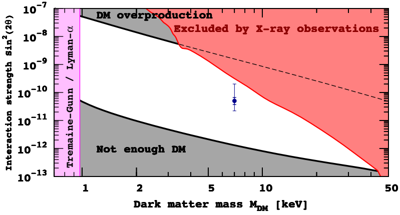
- Measuring tensor-to-scalar ratio *r* – one constraint
- Production of DM of a given mass (7 keV) – one constraint

Sterile-active mixing θ_1 is bound (discovered?!) in X-ray observations

- N_1 – keV scale sterile neutrino DM
- Can be seen in X-rays from decay $N \to \gamma\nu$ (Was seen? [Bulbul et.al.'14, Boyarsky et.al.'14])
- Produced in decays of the inflaton$\to NN$
- Amount of DM produced

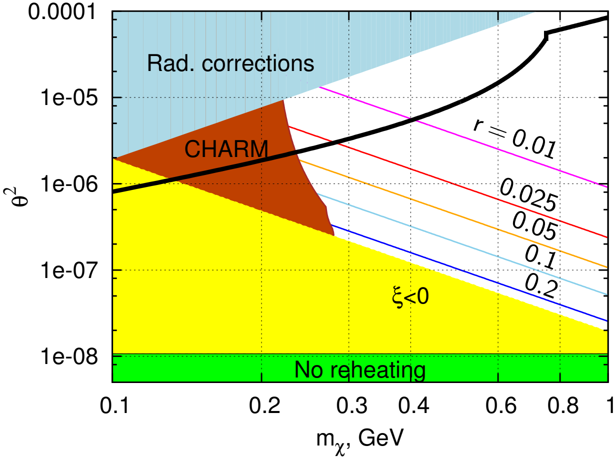
$$\Omega_{DM} \propto \frac{\Gamma_{\chi\to N_1 N_1} M_1}{m_\chi^2} \propto \frac{f_1^3 \theta^2}{m_\chi}$$

One more constraint for m_χ, θ^2



- 3.5 keV X-ray hint–mixing θ_1^2 (Dirak Yukawa F) too small mixing to produce DM via non-resonantly enhanced oscillations

Parameters can be determined from cosmology



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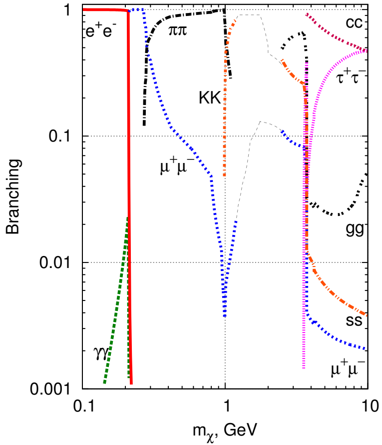
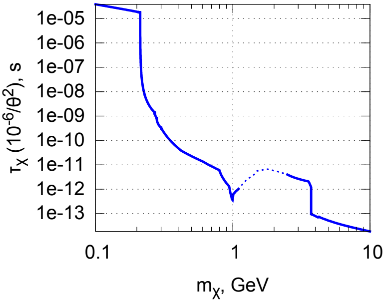
Inflaton decays and lifetime

Coupled to everything proportional particle mass

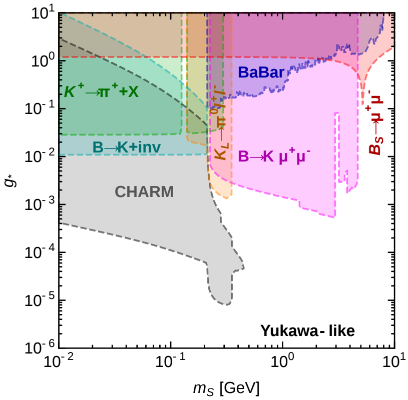




Created in meson decays:

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

Experimental searches are possible



Behaves as light "Higgs" boson, suppresed by $\theta = \sqrt{2\beta}v/m_\chi$

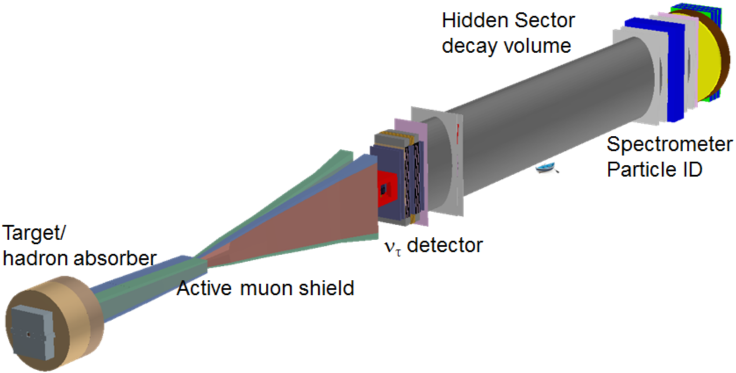
- Created in meson decays
- Decays: KK, $\pi\pi$, $\mu\mu$, ee, …
- Interacts with media: extremely weakly

Search (LHCb, Belle)

- Events with offset vertices in B decays
- Peaks in Daltiz plot of three body B decays

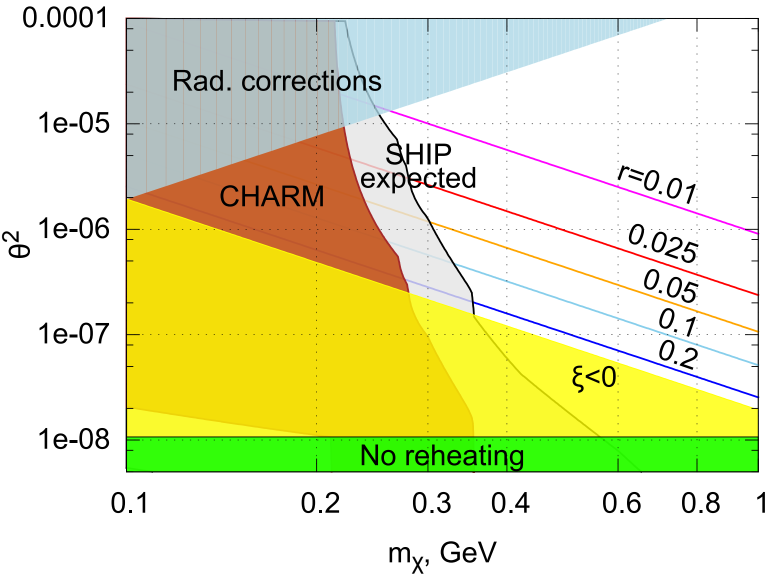
Search in beam target SHiP facility

proposed in CERN using SPS beam



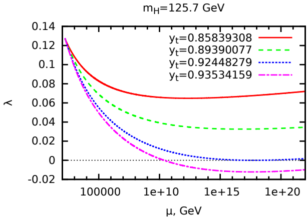
Search for decays of produced particle in empty volume
Existing bounds – CHARM (similar experiment at SPS)

Longer lifetimes are excluded by CHARM

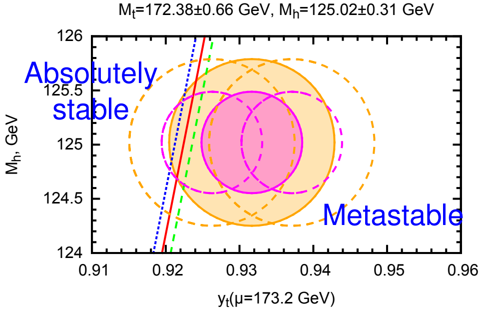


Another prediction: EW vacuum should be stable

- Inflation proceeds along $H^\dagger H = \frac{\alpha}{\lambda} X^2$
- The Higgs self-coupling λ: must be positive up to inflationary scales



Experimental values for y_t



- Measurement of top quark Yukawa is neded!
  - Lepton collider – TLEP, ILC?

[FB, Kalmykov, Kniehl„ Shaposhnikov'12,
Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice, Isidori„ Strumia'12]

Conclusions

- A minimal model without any new scales can
  - Fully describe the Universe
  - Can be constrained from *a combination* of cosmological and laboratory experiments
- Example: light non-minimally coupled inflaton
  - Searches in cosmology and astrophysics:
    - measurement of r (many experiments out there)
    - search for DM decays in X-rays (ASTRO-H)
  - Searches in the laboratory
    - Inflaton – search in rare decays of B (LHCb, SHIP)
    - Sterile neutrinos – no large neutrinoless double beta decay, search in rare decays, SHIP
    - Top quark Yukawa (and Higgs boson mass) – TLEP, ILC

Constraints and searches for heavier sterile $N_{2,3}$

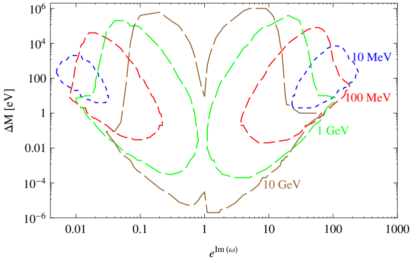
νMSM with inflaton decay into DM

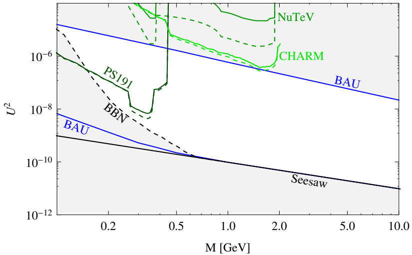
- Leptogenesys by $N_{2,3}$

  $$\Delta M/M \sim 10^{-3}$$

- Experimental searches
  - $N_{2,3}$ production in hadron decays:
    - Missing energy in K decays
    - Peaks in Dalitz plot
  - $N_{2,3}$ decays into SM
    - Beam target experiments – SHIP

[Gorbunov, Shaposhnikov'07]





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