The Higgs Portal to Cosmology

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Central idea:

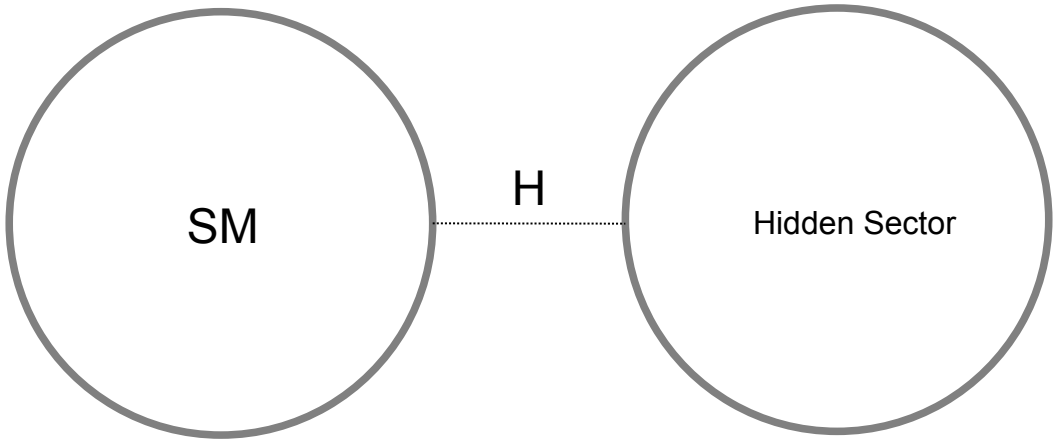
H^+H * (STUFF)

Keywords:

Higgs, inflation, vacuum stability, dark matter

(review: 2104.03342 [hep-ph])

The Higgs and the dark sector



Lowest order operators ("Higgs Portal") :

$\bar{H}H\,S^2$ + … (scalar)

$\bar{H}H\,V_\mu\,V^\mu$ + ... (vector)

$\bar{H}H\,\bar{\chi}\chi\,/\,\Lambda$ + ... (fermion)

"**Portal**" due to Patt, Wilczek'06 (earlier : Silveira, Zee'85 ; Shabinger, Wells'05 ; ...)

Silveira, Zee '85
Veltman, Yndurain '89
...

Special role of the Higgs :

$|H|^2$ = the only gauge and Lorentz-inv. dim-2 operator

$$L = a\,|H|^2\,S^2 + b\,|H|^2\,S$$

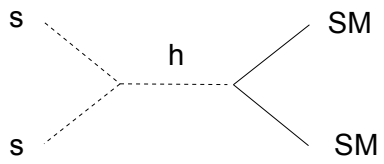
(*S = "hidden" scalar*)

b=0 (S has hidden charge):

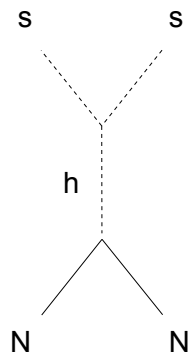
$$\boxed{L = a\,|H|^2\,S^2}$$

"S" is stable and couples weakly to SM ⇒ **DARK MATTER (?)**

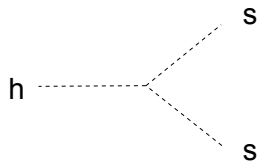
Dark matter:



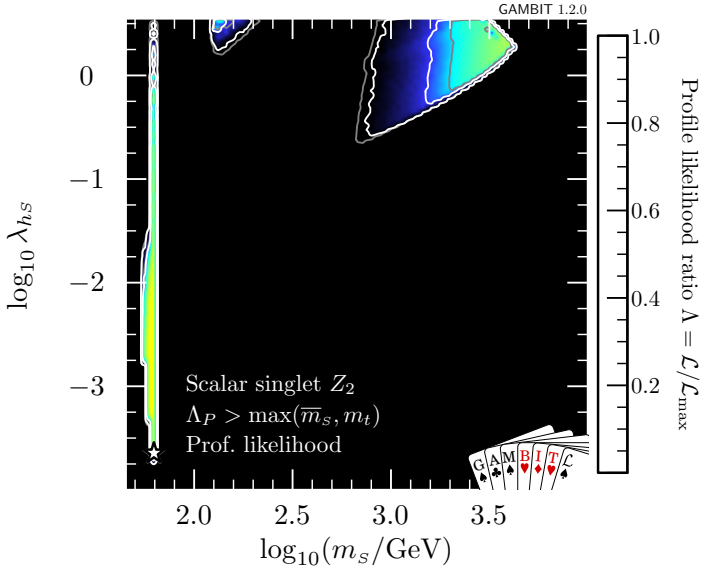
DM annihilation



DM direct detection



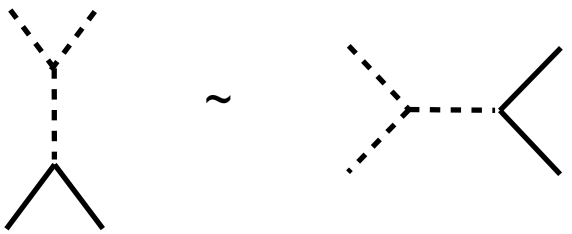
Higgs decay

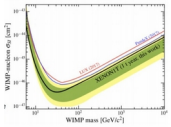


GAMBIT, 1806.11281 [hep-ph]

preference for multi-TeV DM masses

Driven by the relation





XENON1T

$\sigma < 10^{-46}\ cm^{-2}$

Model dependent. ***Does not apply if:***

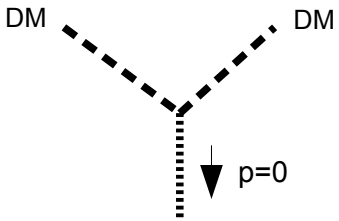
- *amplitude vanishes at q = 0*
- *∃ light unstable dark states*
- *broad resonant annihilation*

Example: **SM + a complex scalar *S*** (*pseudo-Goldstone DM*)

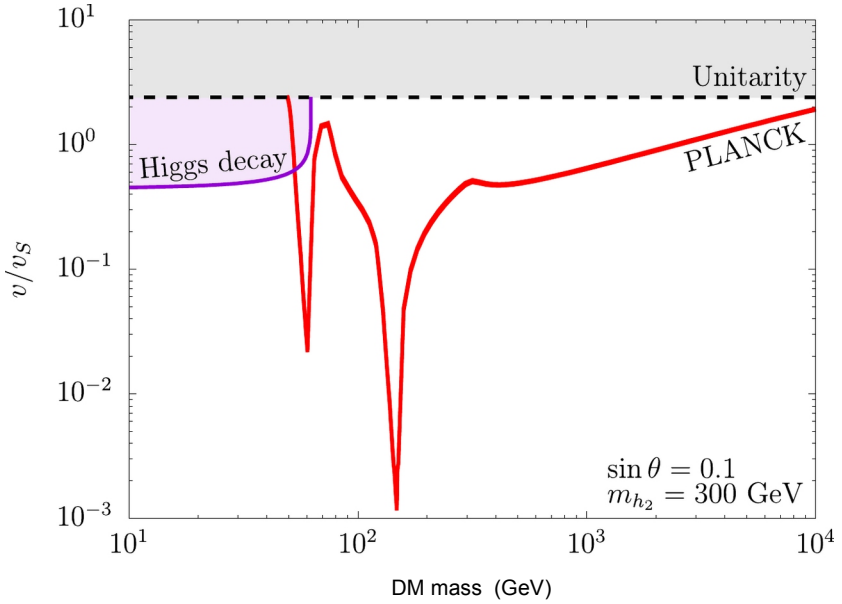
$$V = V_0 + V_{\rm soft}\ ,$$
$$V_0 = -\frac{\mu_H^2}{2}|H|^2 - \frac{\mu_S^2}{2}|S|^2 + \frac{\lambda_H}{2}|H|^4 + \lambda_{HS}|H|^2|S|^2 + \frac{\lambda_S}{2}|S|^4\ , \qquad V_{\rm soft} = -\frac{\mu_S'^2}{4}S^2 + \text{h.c.}$$

Im S = dark matter

Goldstone feature:



= 0



Direct detection = loop-suppressed

Annihilation = unsuppressed

excellent WIMP

(from 60 GeV to 10 TeV)

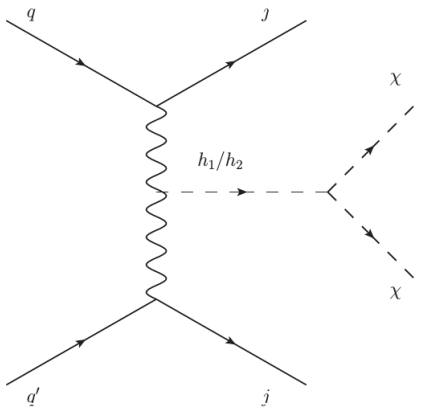
LHC:

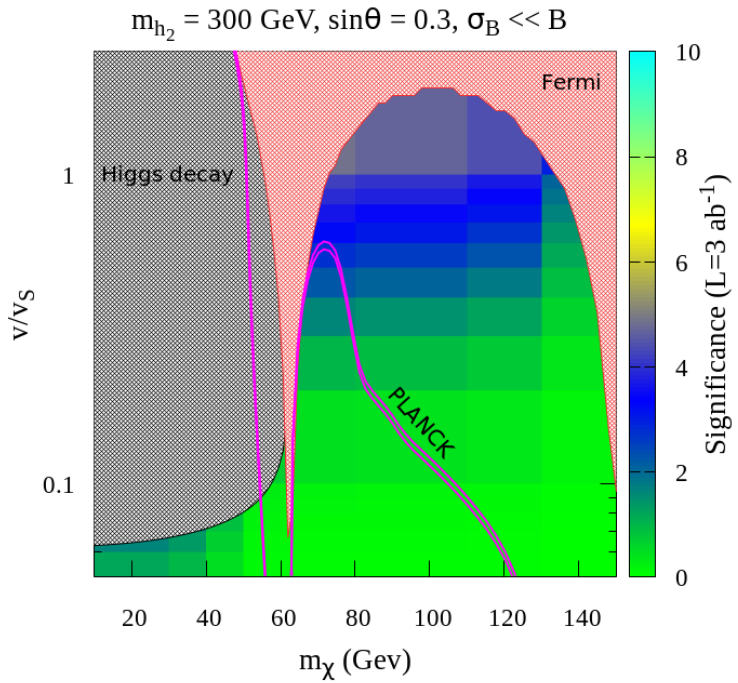
DM = missing E_T

Higgs portal: Higgs–mediated production (monojets, VBF, etc.)

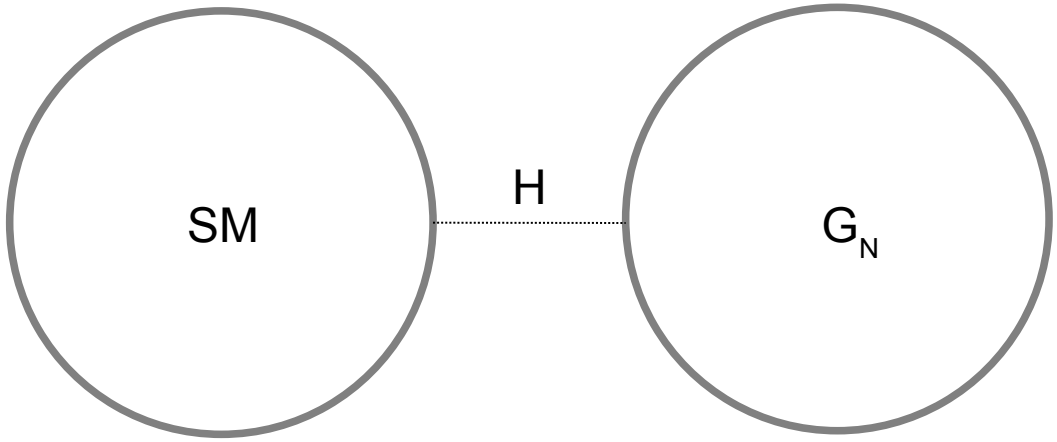
Problem: limited kinematic reach ($m_{DM} < m_{h_i}/2$)

Huitu, Koivunen, OL, Mondal '18





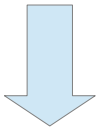
The Higgs and vector dark matter



$V \sim \bar{H}H\,\bar{S}S$ ⇨ H-S mixing ⇨ **h couples to G_N**

Gross,OL, Mambrini '15

Lie groups possess discrete symmetries



gauge fields as dark matter

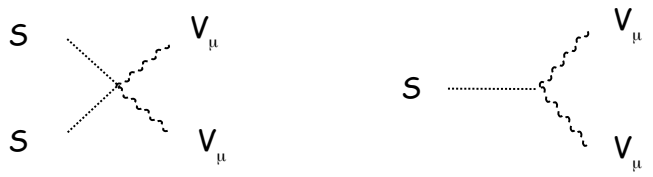
E.g. $U(1): A_\mu \rightarrow -A_\mu$

Lee, OL, Mambrini '11

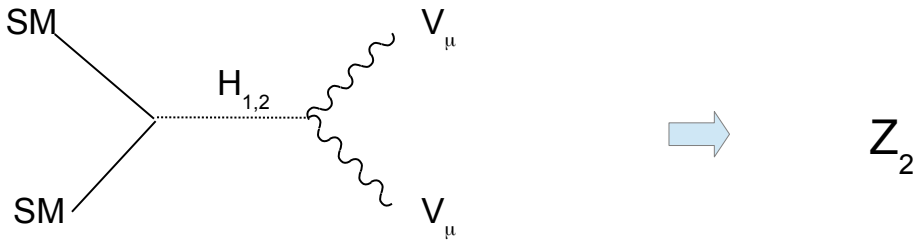
Higgs mechanism in the hidden sector :

$$L = -1/4\, F_{\mu\nu} F^{\mu\nu} + D_\mu S^* D^\mu S - V(S) + \lambda/4\, \bar{H}H\, S^*S$$

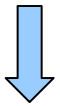
$$S \longrightarrow \text{VEV}$$



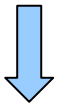
SM couplings:



gauge invariance (+ minimal field content)



Z_2

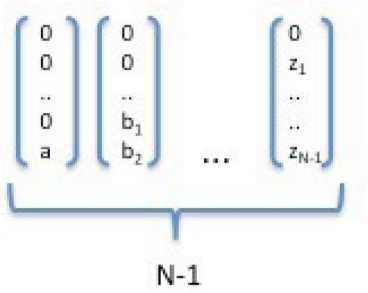


gauge fields are natural DM candidates

Gross, OL, Mambrini '15
Arcadi, Gross, OL, Pokorski, Toma '1

SU(N):

Break to nothing in minimal way ⇨ N-1 dark-Higgs N-plets



The scalar potential has an automatic global U(1) = overall phase multiplication

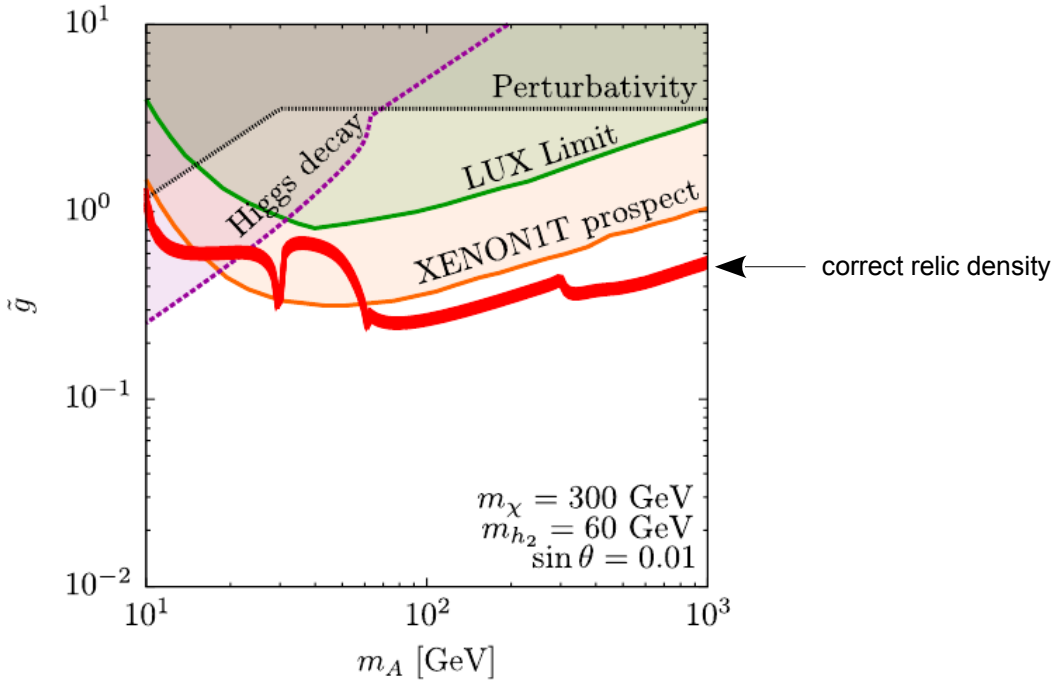
Unbroken U(1):

$$U = \underbrace{e^{-ix/N}\ \mathrm{diag}\,(e^{ix}, 1, \ldots 1)}_{SU(N)} \quad x \quad \underbrace{e^{ix/N}}_{U(1)}$$

Gauge fields non–invariant under this U(1) cannot decay

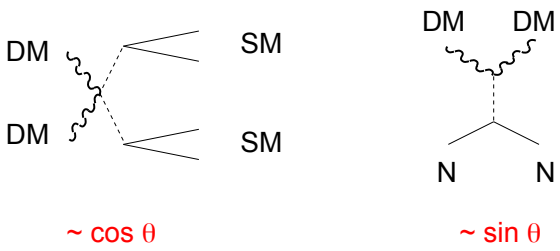
Arcadi, Gross, OL, Pokorski, Toma '16

SU(3) example:



"Secluded" dark matter:

(à la Pospelov et al. '07)



~ cos θ

~ sin θ

NB: non-WIMP options

– direct DM production by the inflaton (parametric resonance, decay, ...)
– freeze–in
– ...

initial state → thermalization → freeze-out

Common approach:

$$\begin{cases} f(p) = \dfrac{1}{e^{\frac{E-\mu}{T}} - 1} \\ \mu \to 0 \end{cases} \longrightarrow \quad f(p) = e^{-(E-\mu)/T}$$

Does not work in the relativistic regime T >>m !

Arcadi, OL, Pokorski, Toma '19

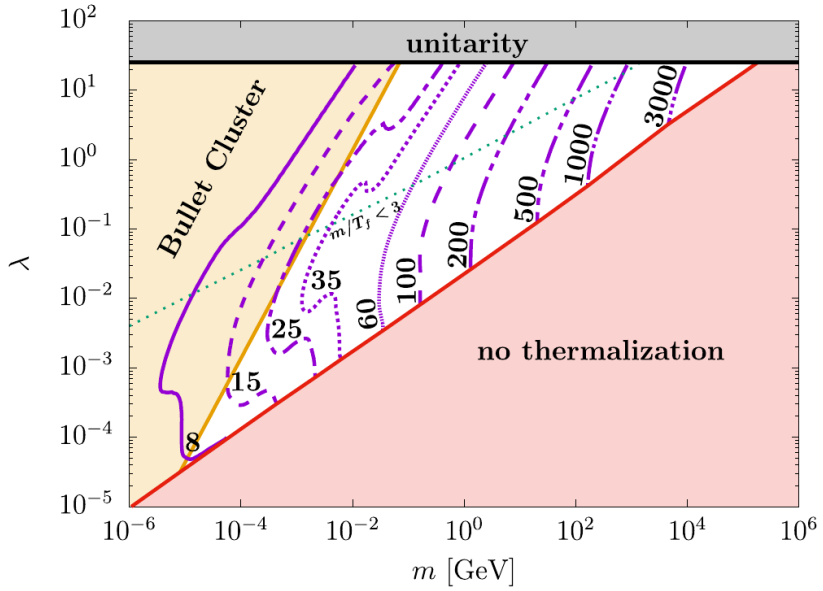
Simplest model:

$$V = \frac{m^2}{2} S^2 + \frac{\lambda}{4!} S^4$$

Relativistic analog of the Gelmini-Gondolo formula for the reaction rate:

$$\Gamma_{2\to 4} = \frac{4T}{\pi^4} \int_m^\infty dE\; E^3 \sqrt{E^2 - m^2} \int_0^\infty d\eta \frac{\sinh\eta}{e^{2(E\cosh\eta - \mu)/T} - 1} \ln \frac{\sinh \frac{E\cosh\eta + \sqrt{E^2-m^2}\sinh\eta - \mu}{2T}}{\sinh \frac{E\cosh\eta - \sqrt{E^2-m^2}\sinh\eta - \mu}{2T}} \sigma_{\rm CM}(E,\eta)$$

includes BE final state factors



---------- = *boundary of relativistic freeze-out*

8, 15, 25, ... = T_{SM} / T

The Higgs and inflation

Expect on general grounds (ϕ = inflaton):

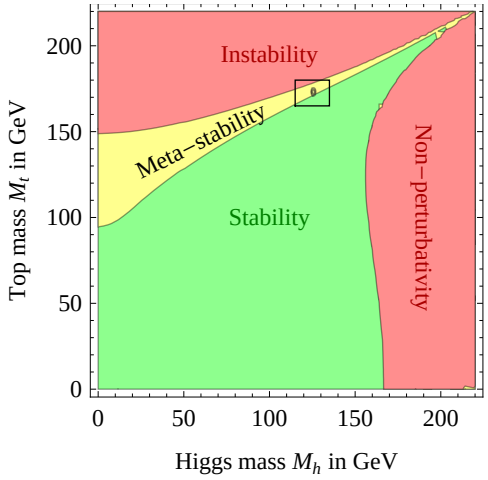
$$L = \lambda\, |H|^2\, \phi^2 + \mu\, |H|^2\, \phi$$

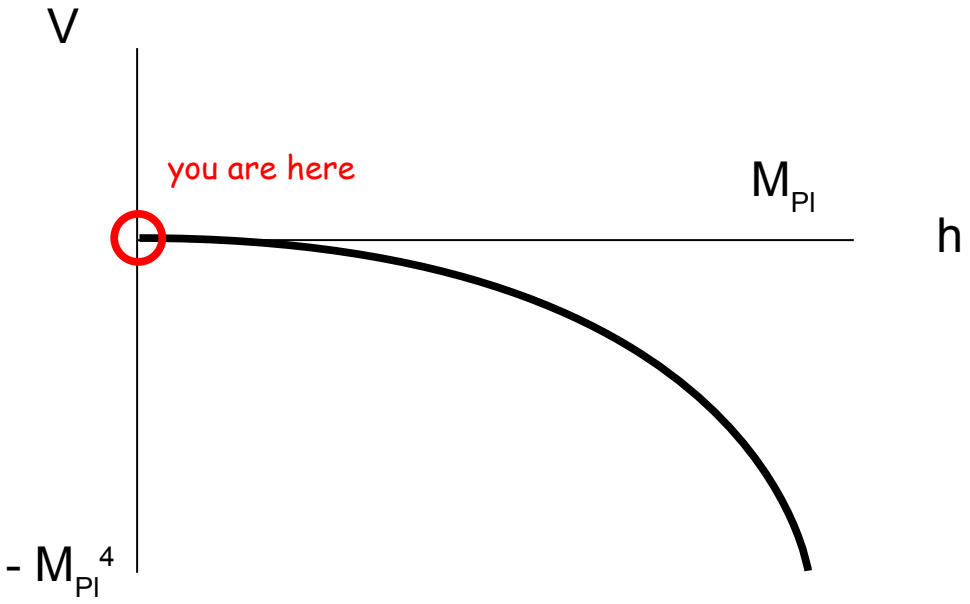
both interaction and mixing!

Early Universe + colliders

(Apparent) vacuum metastability:

Degrassi et al.'12





OL, Westphal ' 12

- how did the Universe end up at h ~ 0?

- why did it stay there during inflation ?

OL, Westphal ' 12

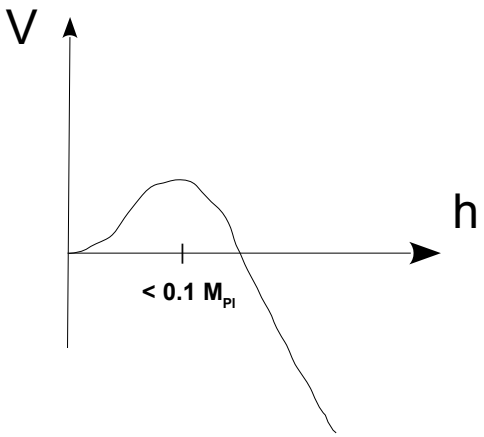
"Minimal" solution:

Higgs-inflaton coupling: $\Delta V = \frac{1}{2}\, \lambda_{h\phi}\, h^2 \phi^2$ with $\lambda_{h\phi} > 10^{-10}$

Espinosa, Giudice, Riotto '07
Herranen, Markkanen, Nurmi, Rajantie '14

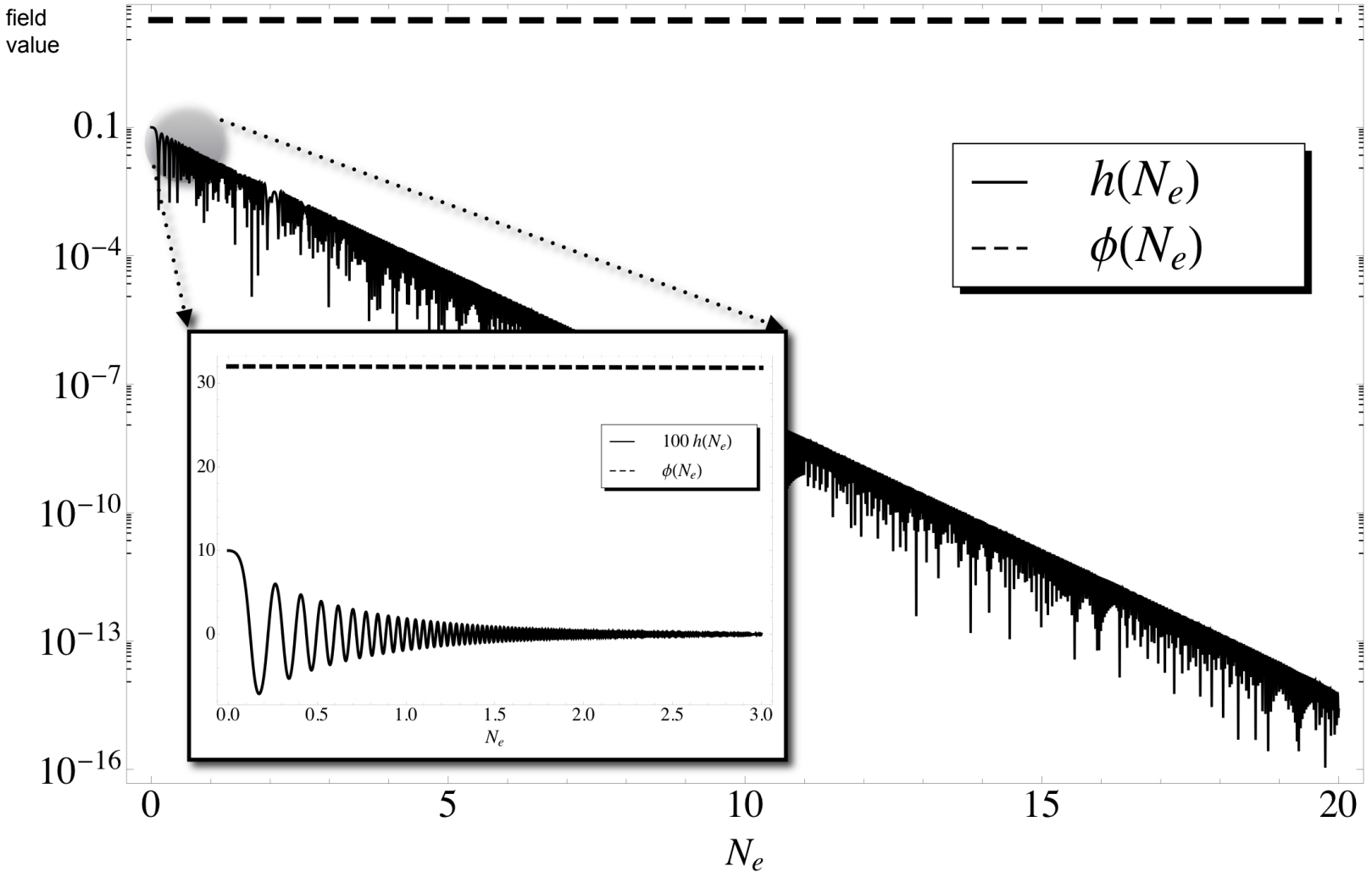
(or $\xi \mathbf{R} h^2$)

$\Delta V + V_{SM}$:



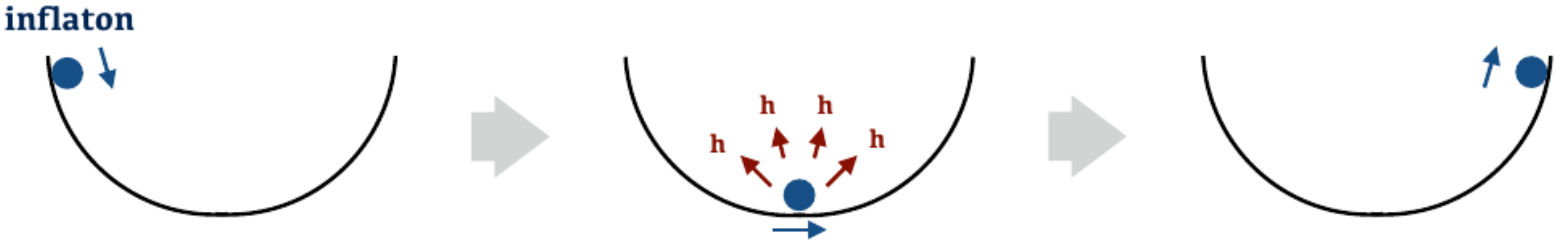
For all initial values of h up to 0.1 M_{pl} the h-potential is convex
(higher h-values → Planckian density)

Higgs/inflaton evolution (in M_{Pl}):



Karciauskas '14
Herranen, Markkanen,Nurmi,Rajantie '15
Ema, Mukaida, Nakayama '16
Enqvist, Karciauskas,OL, Rusak, Zatta '16

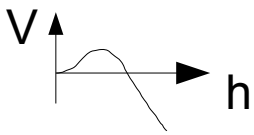
Destabilization issue:



Kofman, Linde , Starobinsky '98

$\Delta V = \frac{1}{2} \lambda_{h\phi} h^2 \phi^2$ ⇨ parametric resonance

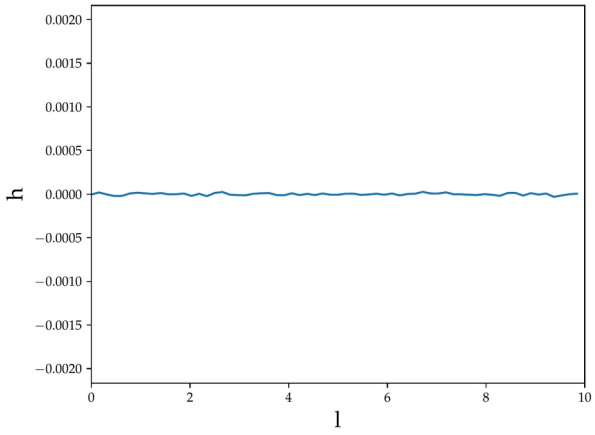
$\langle h^2 \rangle \propto$ Number of Higgs quanta



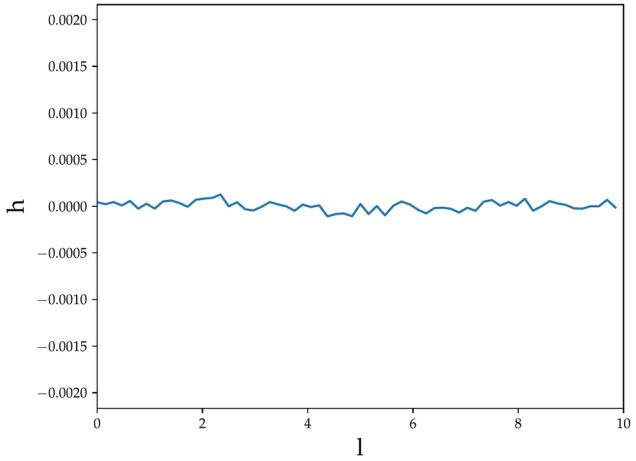
⇨ **destabilization for** $\lambda_{h\phi} > 10^{-8}$

Higgs field evolution (lattice results):

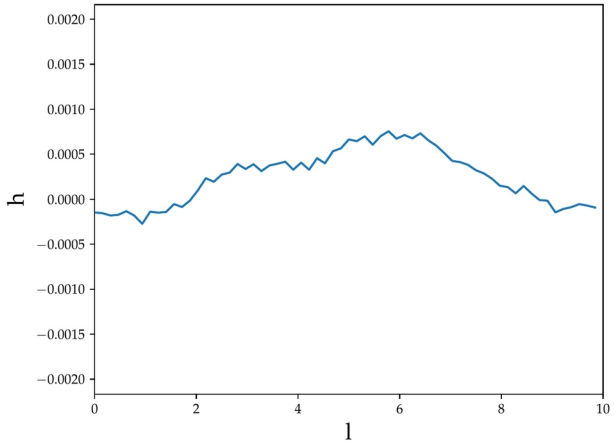
t=0



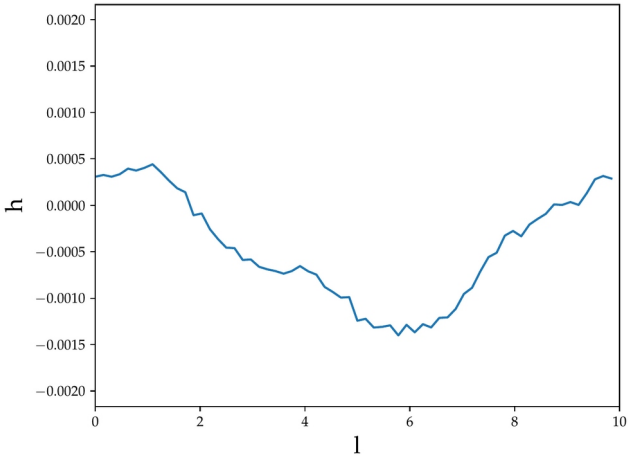
t=15



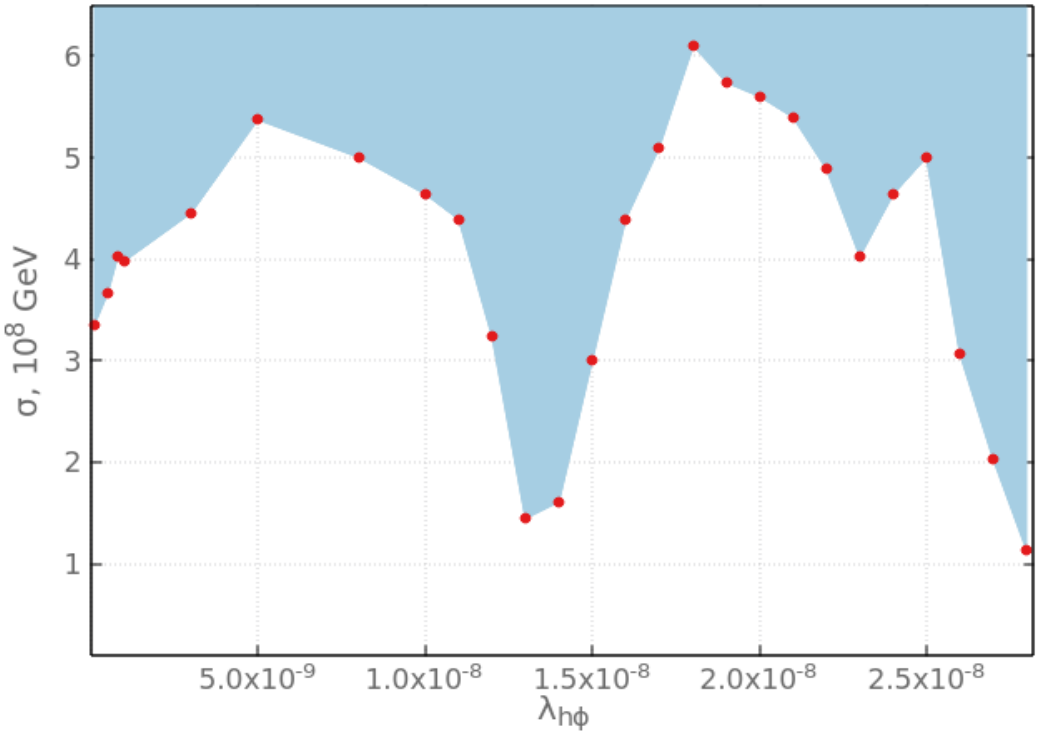
t=27



t=30



Bound on the trilinear coupling ϕhh :



Ema, Karciauskas, OL, Rusak,Zatta '17

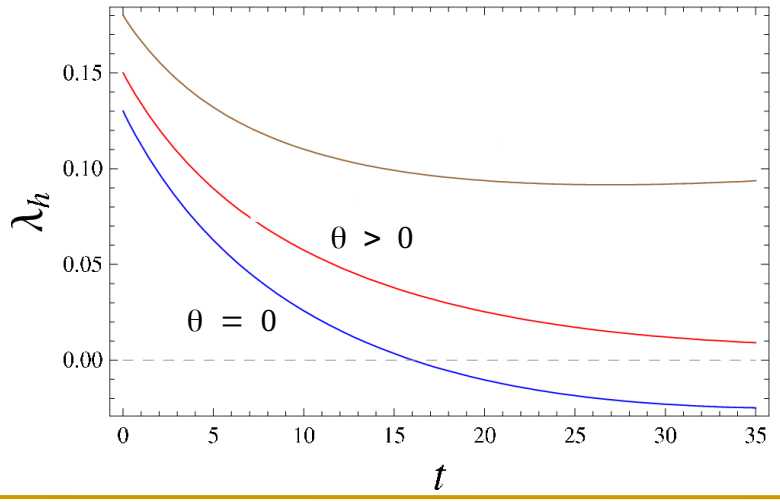
Stabilization via Higgs-inflaton mixing:

$$\Delta L \sim \phi\, H^\dagger H$$

Two mass eigenstates $h_{1,2}$ with mixing angle θ :

$$2\lambda_h v^2 \;=\; m_1^2 \cos^2\theta + m_2^2 \sin^2\theta$$

λ_h increases for $m_2 > m_1$!



- Tree level effect
- Affects boundary conditions
- Complete stability

$t = \ln(\mu/m_t)$

The Higgs+ inflaton lowest order terms :

$$S = \int d^4x\sqrt{-\hat{g}}\left[\frac{1}{2}\Omega^2\hat{R} - \frac{1}{2}\hat{g}^{\mu\nu}\partial_\mu\phi\,\partial_\nu\phi - \frac{1}{2}\hat{g}^{\mu\nu}\partial_\mu h\,\partial_\nu h - V(\phi,h)\right]$$

$$\Omega^2 = 1 + \xi_\phi\phi^2 + \xi_h h^2\,,$$

$$V(\phi,h) = \frac{\lambda_h}{4}h^4 - \frac{\mu_h^2}{2}h^2 + \frac{\lambda_{h\phi}}{2}h^2\phi^2 + \sigma h^2\phi + \frac{\lambda_\phi}{4}\phi^4 + \frac{b_3}{3}\phi^3 - \frac{\mu_\phi^2}{2}\phi^2 + b_1\phi\,,$$

Inflation is driven by ϕ with $\xi_\phi \gg 1$ (à la Bezrukov-Shaposhnikov) :

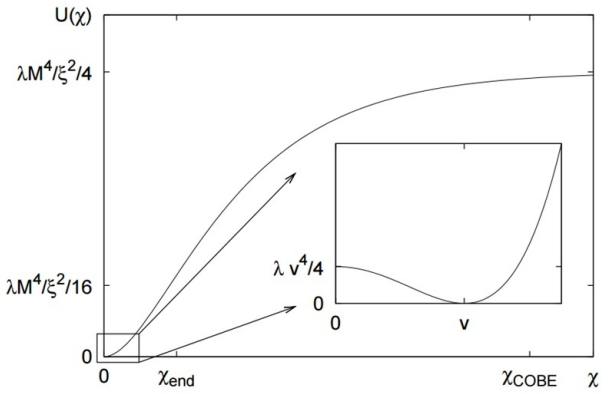


Fig. 1. Effective potential in the Einstein frame.

$$U(\chi) \simeq \frac{\lambda_\phi}{4\xi_\phi^2}\left(1 - e^{-\sqrt{\frac{2}{3}}\chi}\right)^2$$

$$\chi \simeq \sqrt{\tfrac{3}{2}}\ln\xi_\phi\phi^2$$

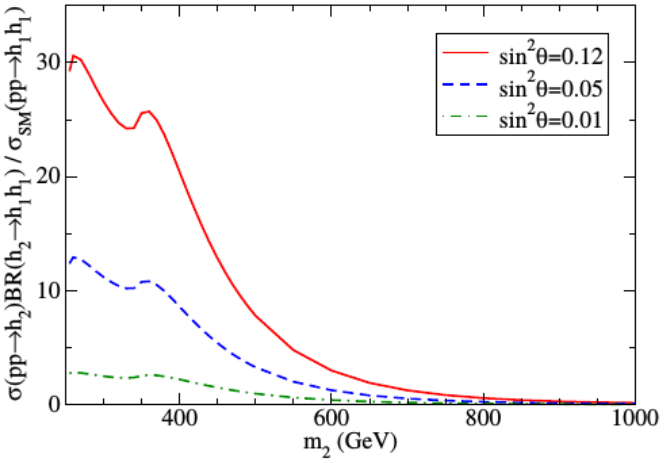
– dimensionless couplings → inflation

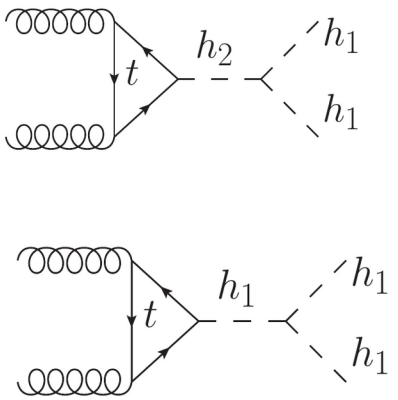
– dimensionful parameters << M_{Pl} → low energy physics

Inflaton search at LHC :

- universal Higgs coupling reduction
- heavy Higgs–like resonance
- resonant decay $h_2 \rightarrow h_1 h_1$

Lewis, Sullivan '17





Conclusion

- Higgs sector is special
- key to the hidden sector / DM / inflation
- to be tested at HL-LHC, DM detection, etc.