Higgs and Cosmology

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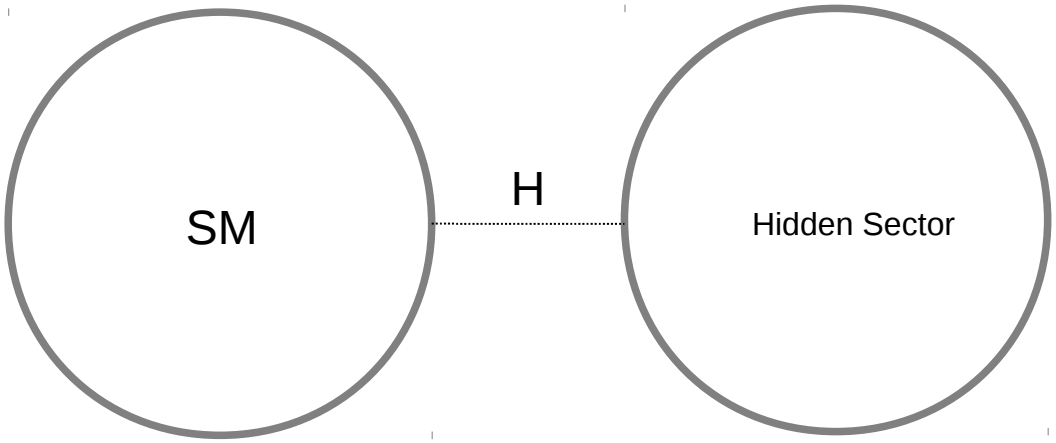
- the Higgs and the hidden sector
- the Higgs and dark matter
- the Higgs and inflation
- the Higgs and phase transitions/grav. waves

The Higgs and the dark sector



no spectacular LHC events

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

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

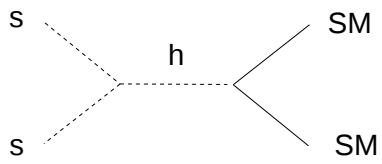
(*S = "hidden" scalar*)

b=0 (S has hidden charge):

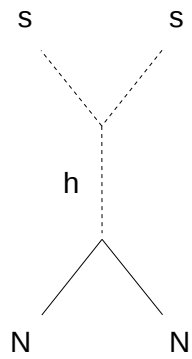
$$L = a\,|H|^2\,S^2$$

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

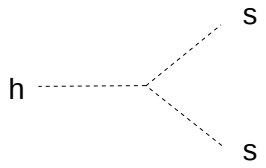
Dark matter:



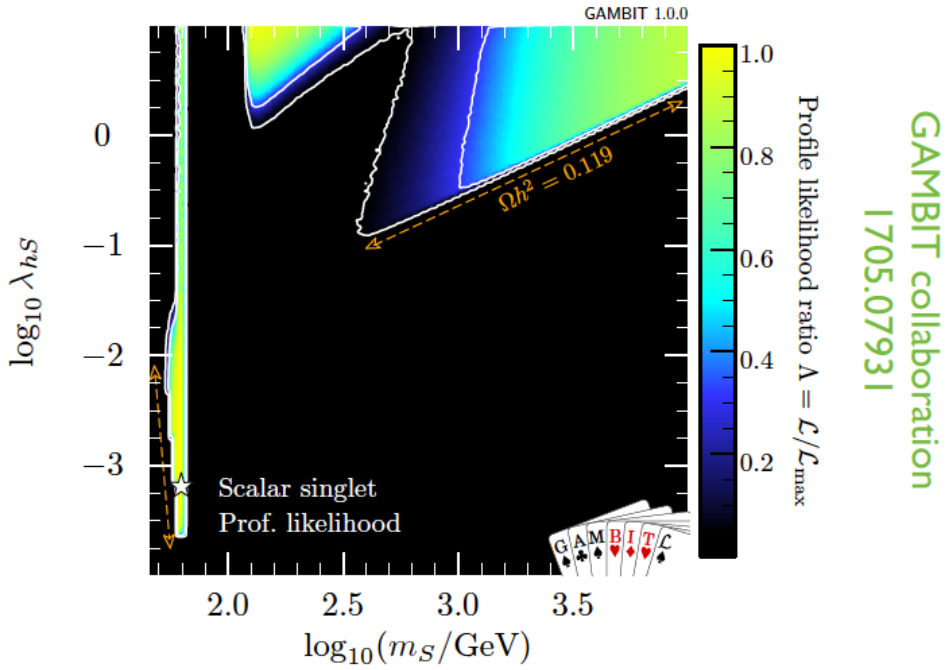
DM annihilation



DM direct detection



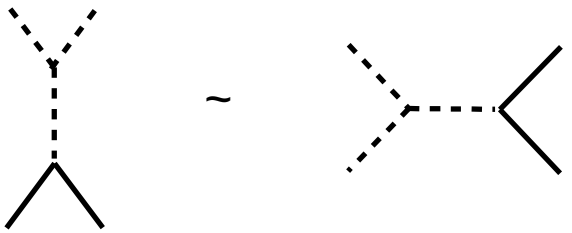
Higgs decay

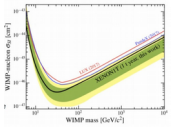


GAMBIT collaboration
1705.07931

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*

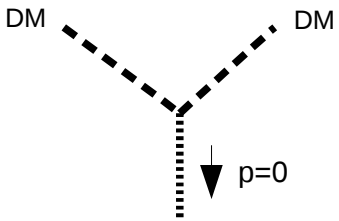
Gross, OL, Toma *PRL*'17

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

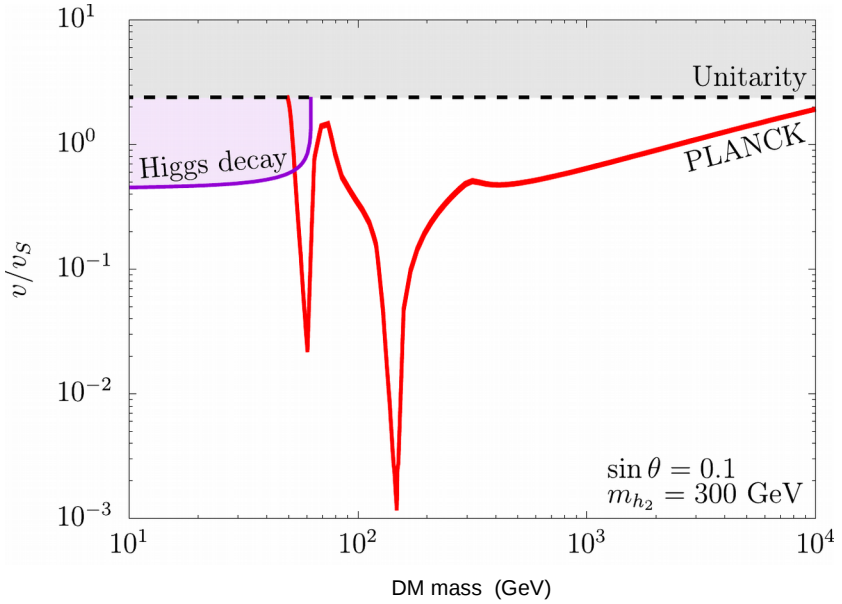
$$V = V_0 + V_{\rm soft}\ ,$$
$$V_0 = -\frac{\mu_H^2}{2}|H|^2 - \frac{\mu_S^2}{2}|S|^2 + \frac{\lambda_H}{2}|H|^4 + \lambda_{HS}|H|^2|S|^2 + \frac{\lambda_S}{2}|S|^4\ , \qquad V_{\rm soft} = -\frac{\mu_S'^2}{4}S^2 + \text{h.c.}$$

Im S = dark matter

Goldstone feature:



= 0



Direct detection = loop-suppressed

Annihilation = unsuppressed

excellent WIMP

(from 60 GeV to 10 TeV)

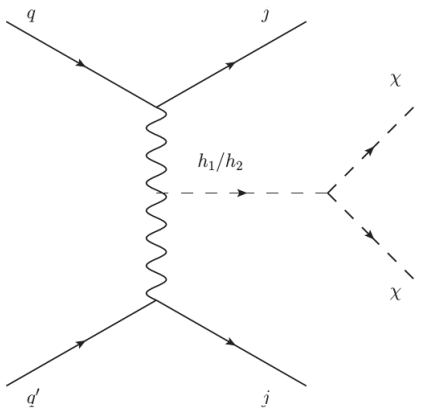
LHC:

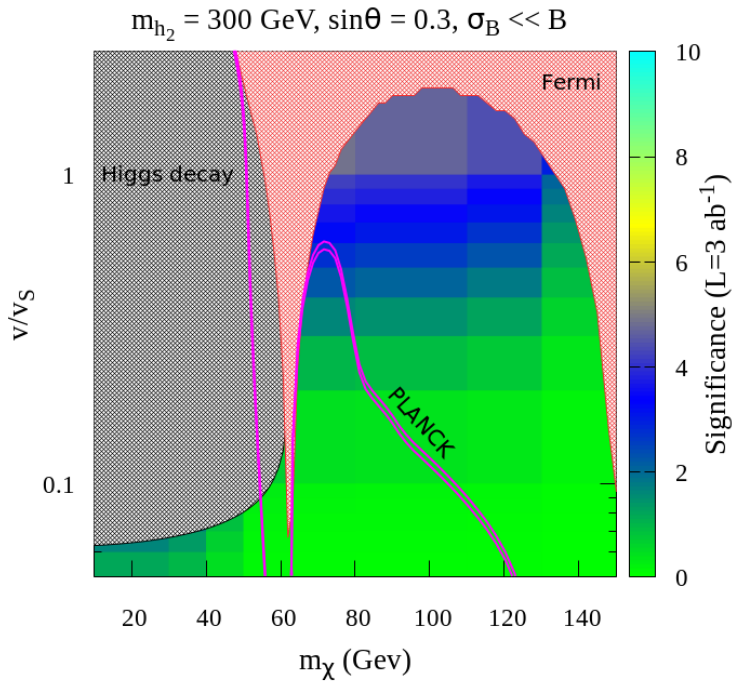
DM = missing E_T

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

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

Huitu, Koivunen, OL, Mondal '18



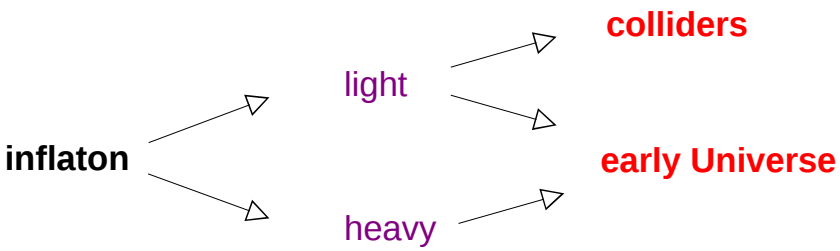


The Higgs and inflation

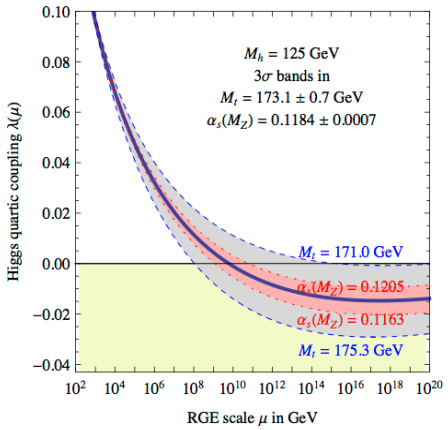
Expect on general grounds (ϕ = *inflaton*)*:*

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

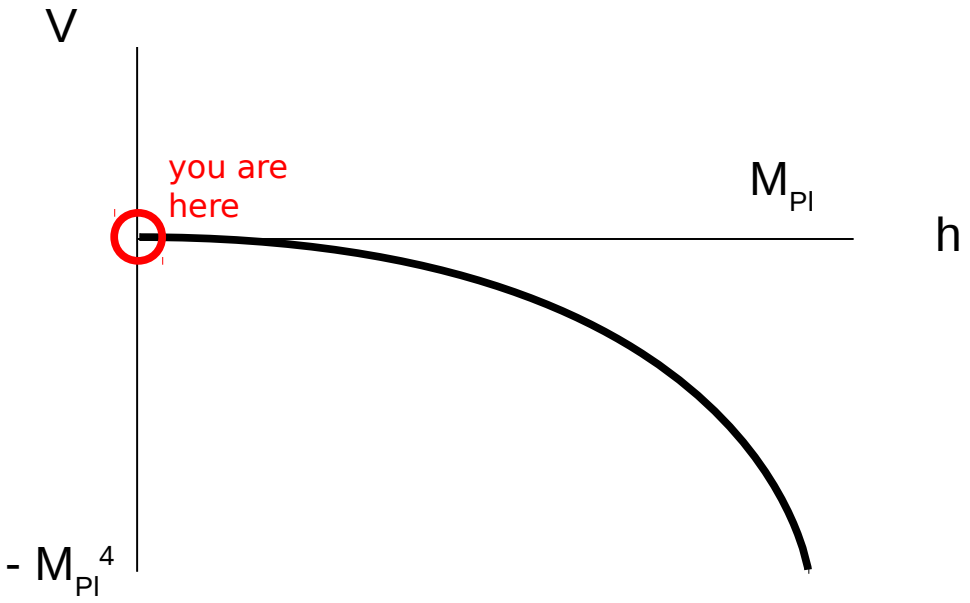
both interaction and mixing!



(Apparent) vacuum metastability:



Buttazzo et al.'13



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

- why did it stay there during inflation ?

OL, Westphal ' 12

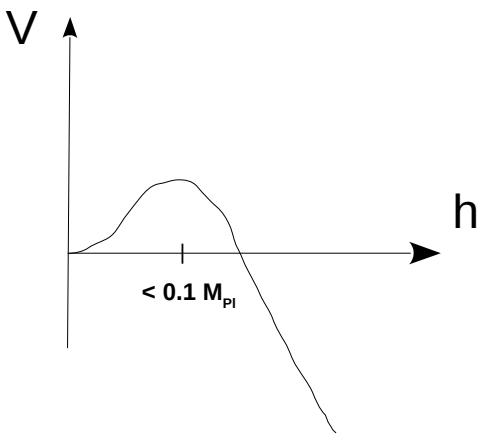
"Minimal" solution:

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 $\xi \mathcal{R} h^2$)

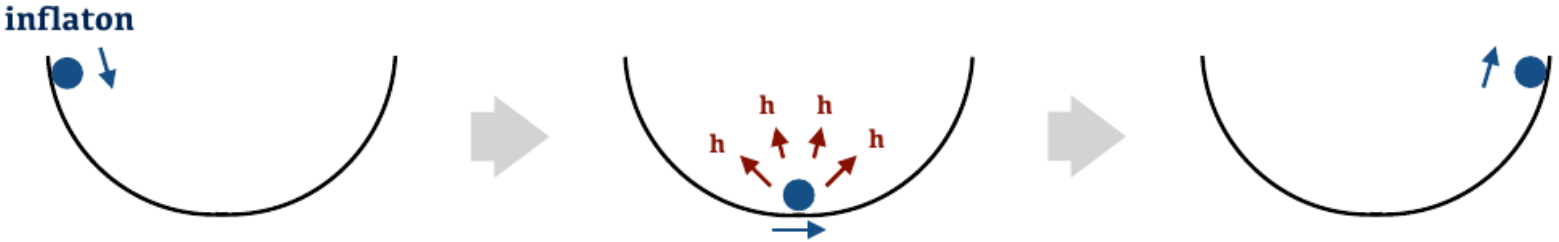
$\Delta V + V_{SM}$:



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

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

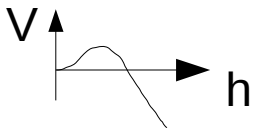
Destabilization issue:



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

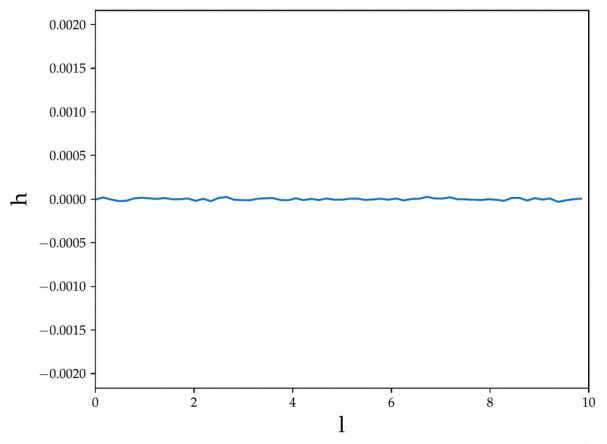


⇨ **destabilization for $\lambda_{h\phi} > 10^{-8}$**

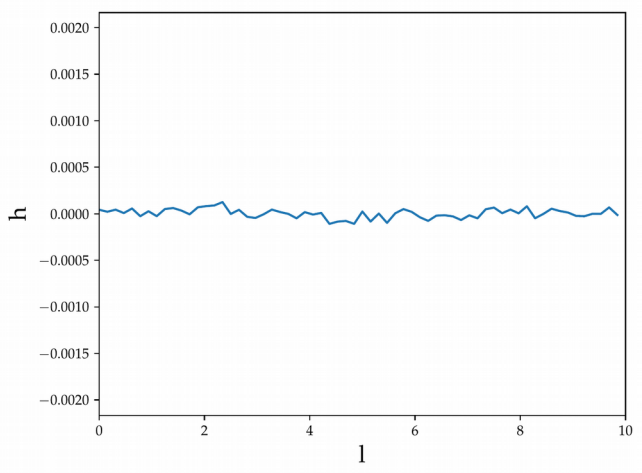
Lattice results:

Ema, Karciauskas, OL, Zatta '17

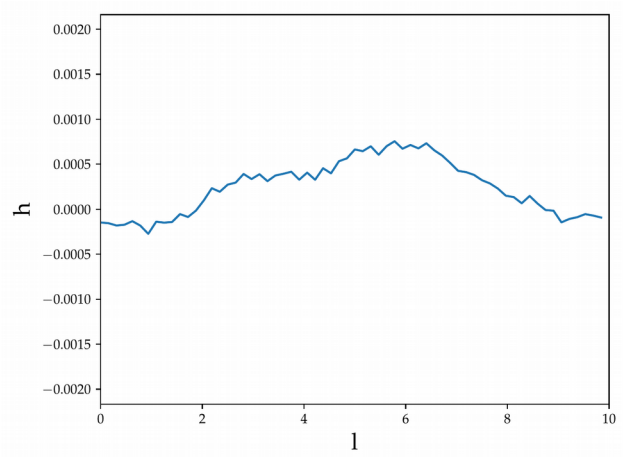
t=0



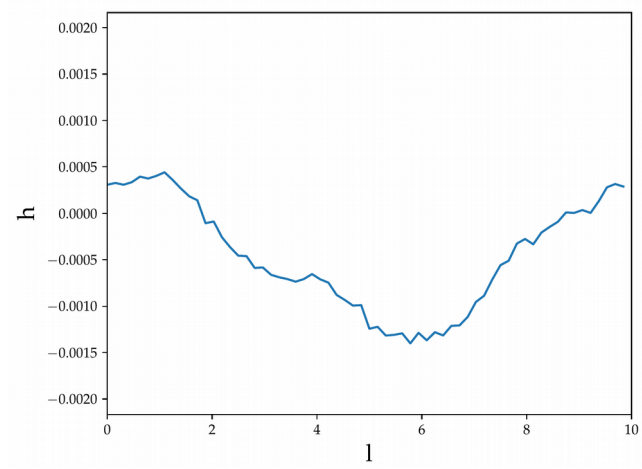
t=15



t=27



t=30



Ema, Karciauskas, OL, Zatta '17

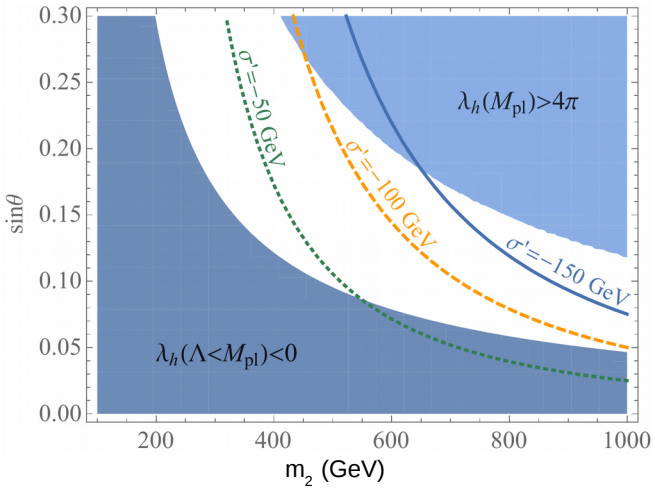
Higgs-inflaton mixing:

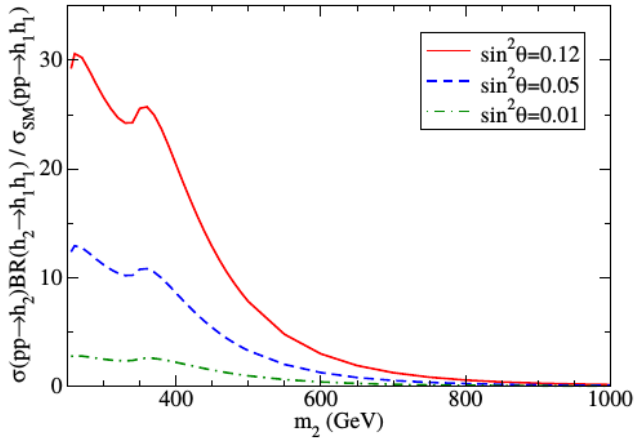
$$\Delta \mathcal{L} \sim \phi\, H^\dagger H$$

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 $m_2 > m_1$!





Lewis, Sullivan '17

Signatures:

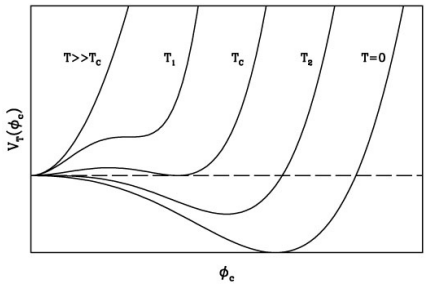
- **universal Higgs coupling reduction**
- **heavy Higgs–like resonance**
- **resonant decay $h_2 \to h_1 h_1$**

The Higgs and phase transitions

Profumo, Ramsey-Musolf,Shaughnessy '07
Espinosa, Konstandin, Riva ' 11

Add a singlet S → 1st order phase transition possible:

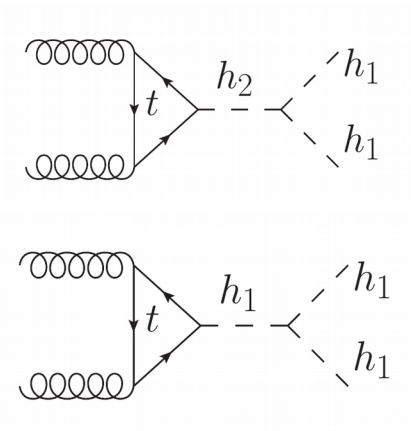
$$V_0(H,S) = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{1}{2}a_1 |H|^2 S + \frac{1}{2}a_2 |H|^2 S^2 + b_1 S + \frac{1}{2}b_2 S^2 + \frac{1}{3}b_3 S^3 + \frac{1}{4}b_4 S^4$$

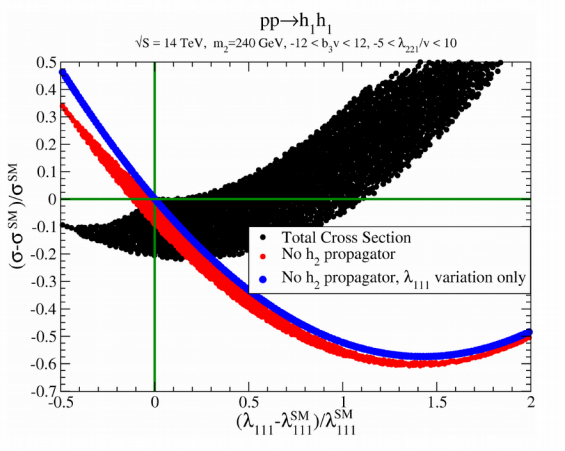


$$\frac{\phi_h(T_c)}{T_c} \gtrsim 1$$

LHC: modified di-Higgs rate

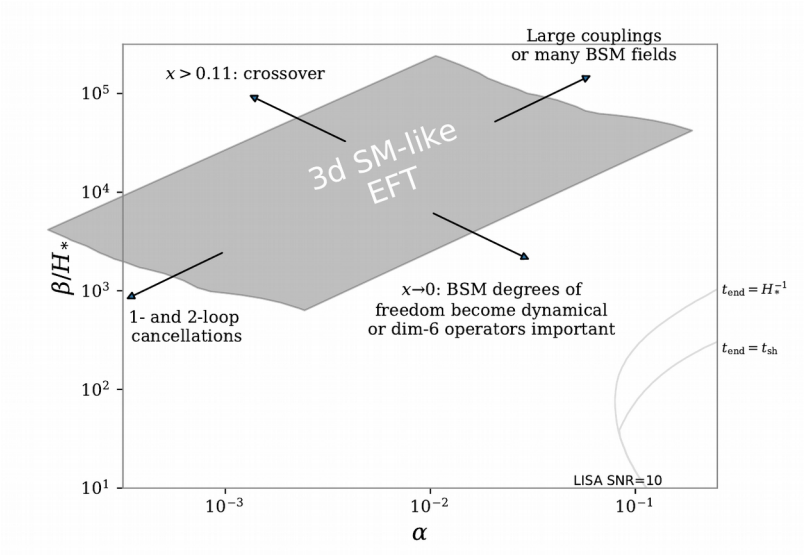
Chen, Kozaczuk, Lewis '17





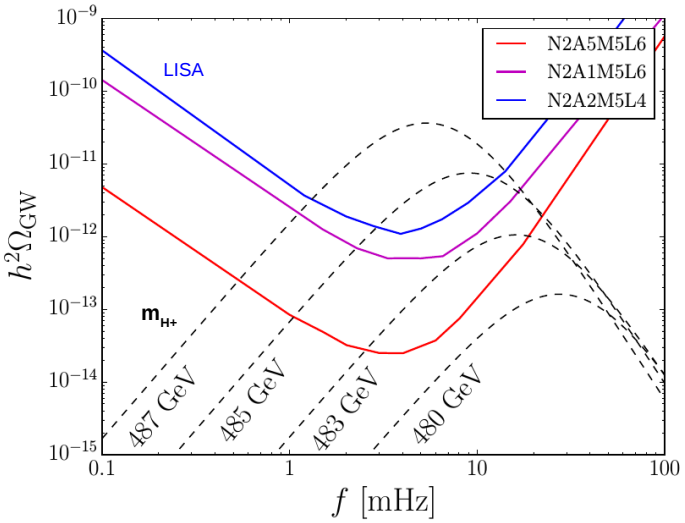
Gravitational wave detection (LISA):

Helsinki group 1903.11604



singlet extension

Dorsch, Huber, Konstandin,No '16



2HDM

Challenging!

Conclusion

- Higgs sector is special
- key to the hidden sector / DM / inflation
- LHC probeable (probable?)
- direct/indirect DM detection, grav. waves, etc.