

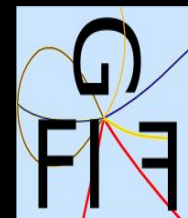


MOCa 2018: Materia Oscura en Colombia

31 de julio, 2018

Transición de fase electrodébil en modelos más allá del Modelo Estándar

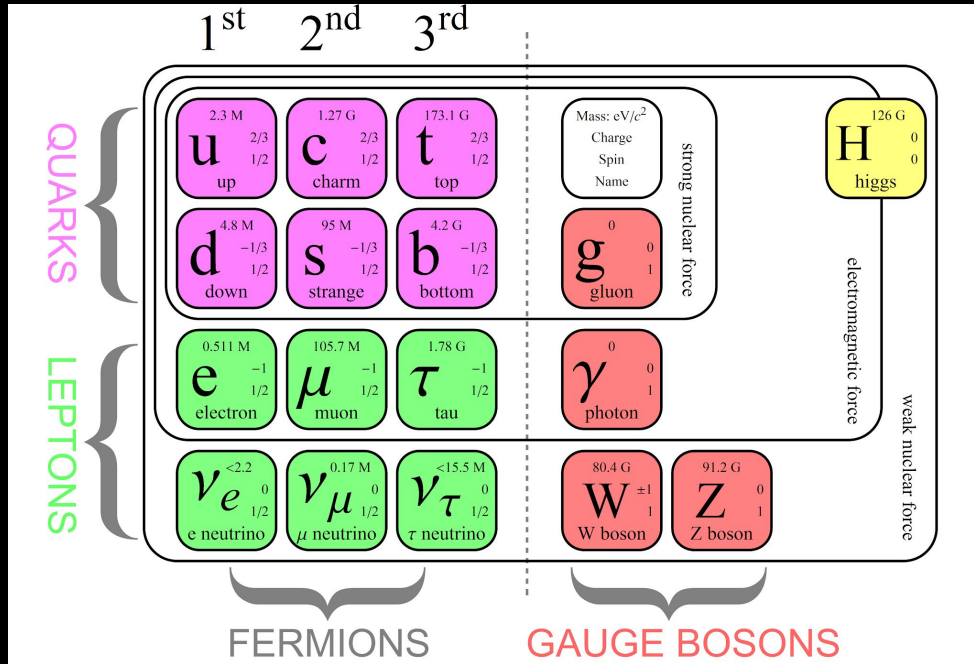
Alejandro Correa López
Universidad de Antioquia



Contenido

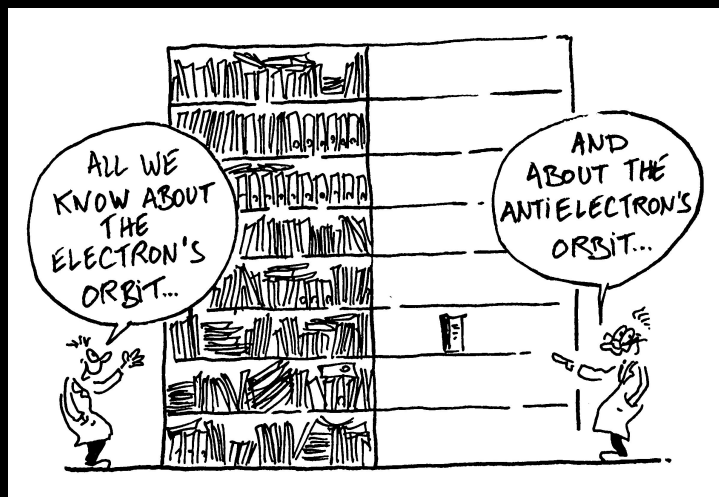
- Motivación
- El potencial efectivo
- Transición de fase electrodébil
- Modelos más allá
- Conclusiones

Motivación: modelo estándar (ME)



- Teoría efectiva a bajas energías
- Unifica 3 de las 4 fuerzas fundamentales
- Explica satisfactoriamente muchos de los fenómenos existentes
- Teoría de campo independiente de la temperatura

Motivación: asimetría bariónica



<http://home.cern>

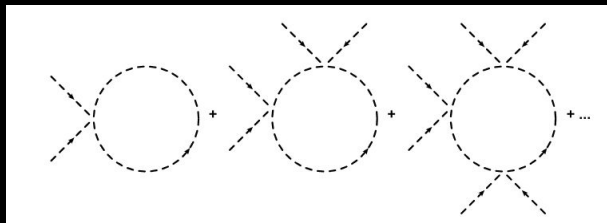
Razón barión-fotón:

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = \begin{cases} [5.8 - 6.6] \times 10^{-10}, & \text{from BBN} \\ (6.09 \pm 0.06) \times 10^{-10}, & \text{from CMB} \end{cases}$$

Cline, arXiv: 1807.08749

Potencial efectivo

- Coleman y Weinberg estudiaron las correcciones radiativas



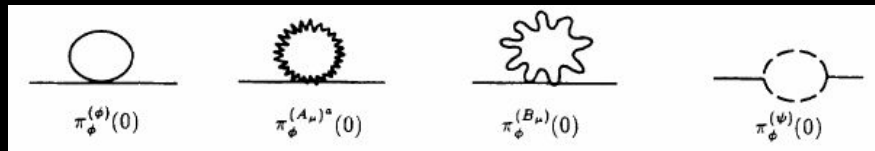
- Kirzhnits y Linde: la simetría electrodébil se restaura a altas temperaturas

$$m_{\langle\phi\rangle}^2 T^2$$

- Jackiw y Dolan mostraron que aparecen términos imaginarios

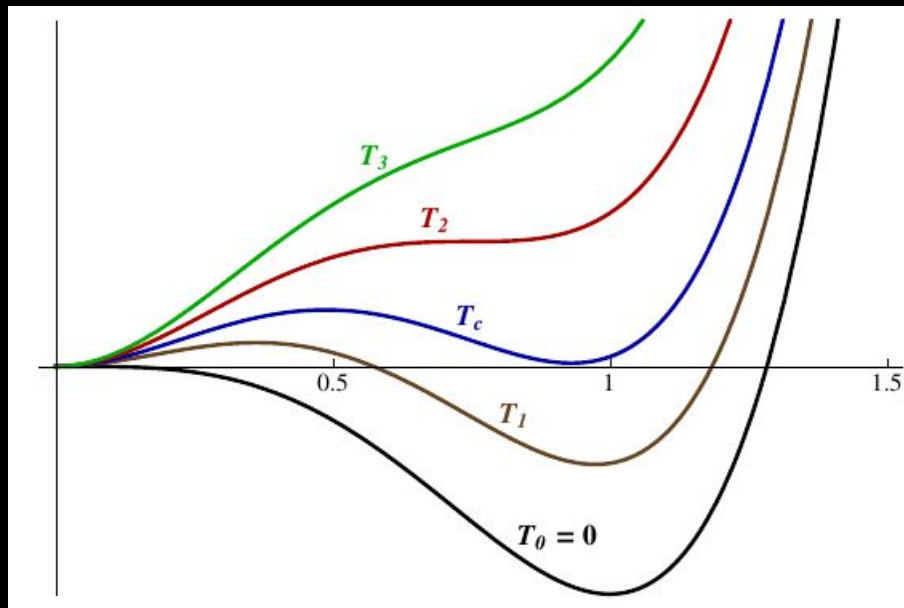
$$m_{\langle\phi\rangle}^3 T$$

- Carrington hizo el cálculo del potencial efectivo para el ME



Potencial efectivo

$$V_{eff} = V_{tree} + V_{CW} + V_T + V_{ring}$$



Potencial efectivo

$$V_{eff} = V_{tree} + V_{CW} + V_T + V_{ring}$$

$$V_{CW} \rightarrow \sum_i n_i \frac{m_i^4(\phi)}{64\pi^2} \left[\log \frac{m_i^2(\phi)}{Q^2} - c_i \right]$$

Potencial efectivo

$$V_{eff} = V_{tree} + V_{CW} + V_T + V_{ring}$$

$$V_T \longrightarrow \frac{T^4}{2\pi^2} \sum_i n_i J_{\pm} \left[\frac{m_i^2(\phi)}{T^2} \right]$$
$$J_{\pm}[y] = \int_0^{\infty} dx x^2 \log \left[1 \pm e^{-\sqrt{x^2+y^2}} \right]$$

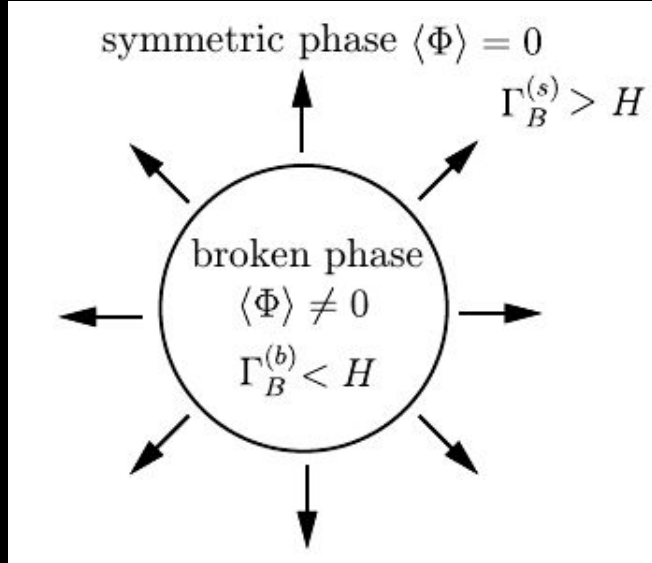
Potencial efectivo

$$V_{eff} = V_{tree} + V_{CW} + V_T + V_{ring}$$

$$V_{ring} \longrightarrow \sum_i \frac{T}{12\pi} \left(\frac{1-\varepsilon}{2} \right) n_i \left\{ m^{3/2}(\phi) - m^{3/2}(\phi, T) \right\}$$

$$m^2(\phi, T) = m^2(\phi) + cT^2$$

Transición de fase electrodébil: condiciones para bariogénesis electrodébil



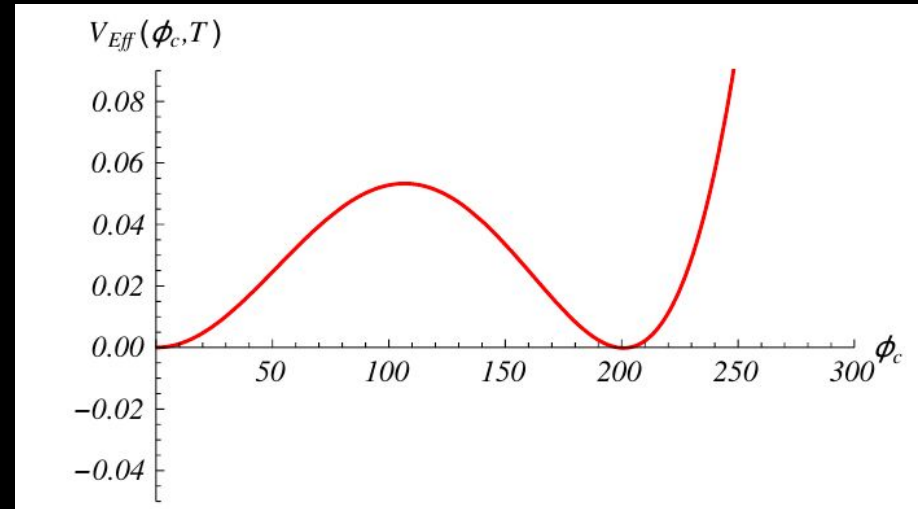
Condiciones de Sakharov:

- Violación de número bariónico
- Violación de C y CP
- Desviación del equilibrio térmico

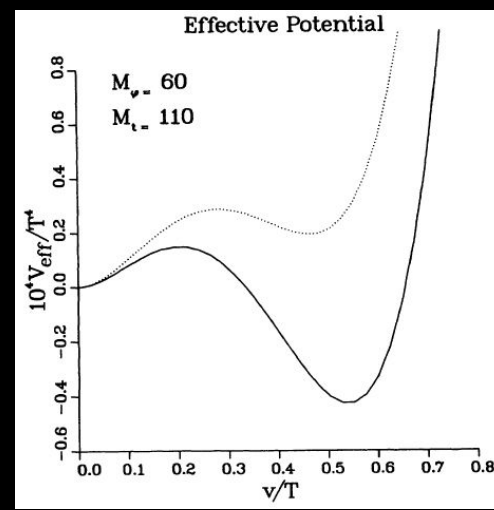
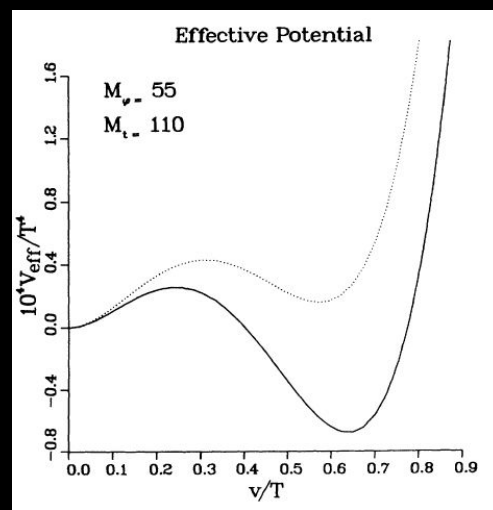
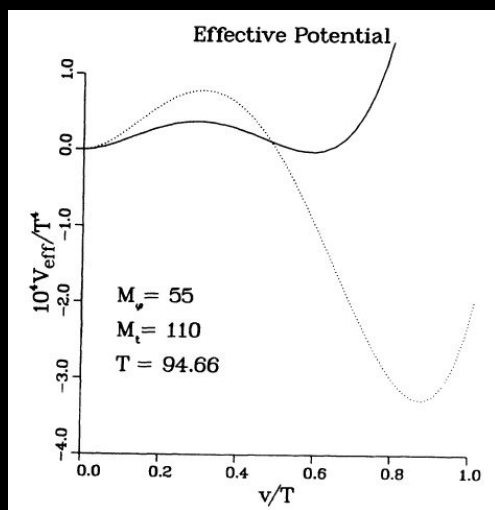
Transición de fase electrodébil: condiciones para bariogénesis electrodébil

La desviación del equilibrio
se da vía la transición de fase
electrodébil:

$$\frac{\langle \phi \rangle}{T_c} > 1$$



Transición de fase electrodébil: condiciones para bariogénesis electrodébil



Transición de fase electrodébil:
condiciones para bariogénesis electrodébil

Necesitamos entonces
extender el ME

ME + Nueva física

Transición de fase electrodébil:
condiciones para bariogénesis electrodébil

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$ME +$ Nueva física

Transición de fase electrodébil:
condiciones para bariogénesis electrodébil

Necesitamos entonces
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$ME +$ Nueva física

↓
Partículas y/o Simetrías

Modelos más allá del ME

- Singletes escalares reales

$$ME + \sum_i S_i$$

$$|H|^2 S_i^2$$

V_{tree} →

$$V_0 = m^2 H^\dagger H + \lambda (H^\dagger H)^2 + \zeta^2 H^\dagger H \sum_i S_i^2.$$

Para este modelo la interacción entre el ME y la nueva física se da vía

Modelos más allá del ME

- Singletes escalares reales

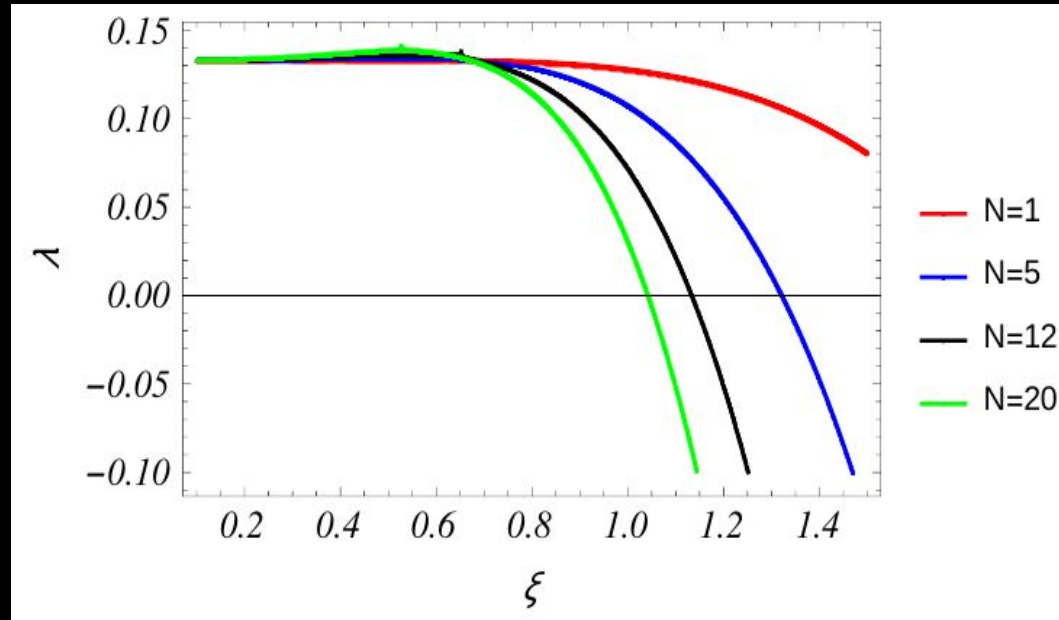
$$V_{eff}(T = 0)$$

$$V = \frac{m^2}{2} h^2 + \frac{\lambda}{4} h^4 + \sum_{\alpha} \frac{N_{\alpha} M_{\alpha}^4}{64\pi^2} \left[\ln \frac{M_{\alpha}^2}{Q^2} - C_{\alpha} \right],$$

Modelos más allá del ME

$$\begin{aligned}V''(0) &= 0, \\V''(v) &= 0, \\V(0) &= V(v)\end{aligned}$$

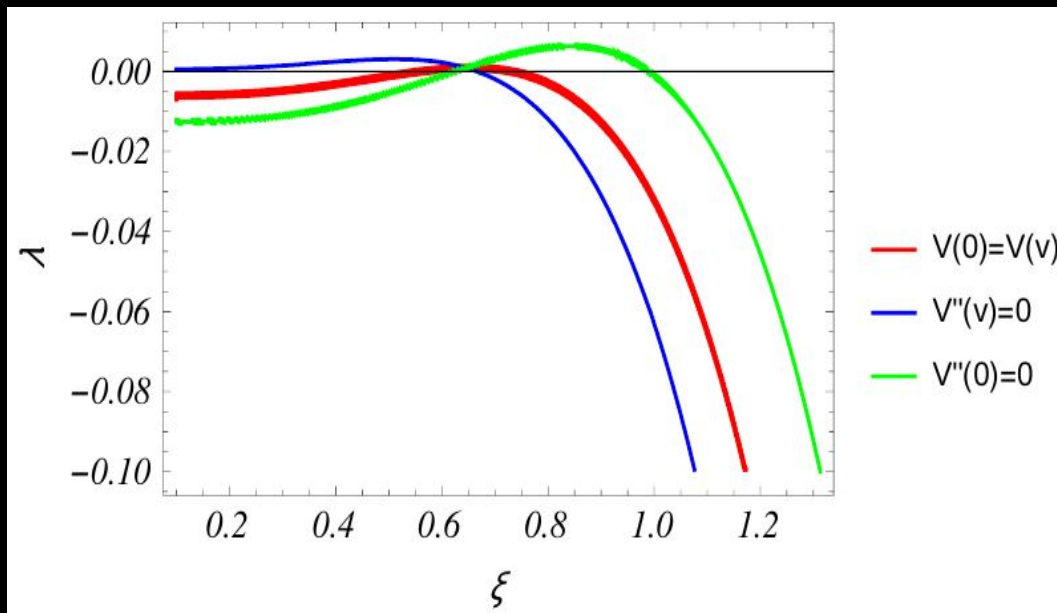
- Singletes escalares reales



Modelos más allá del ME

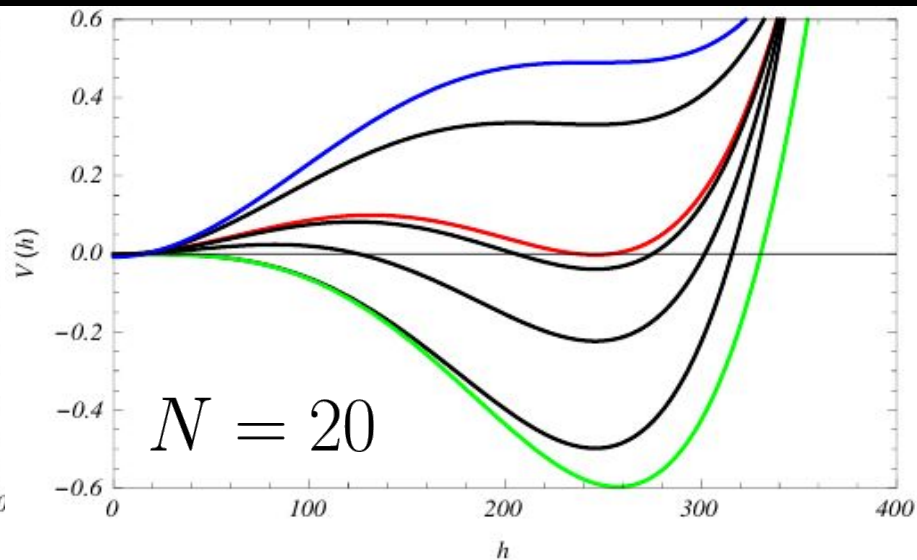
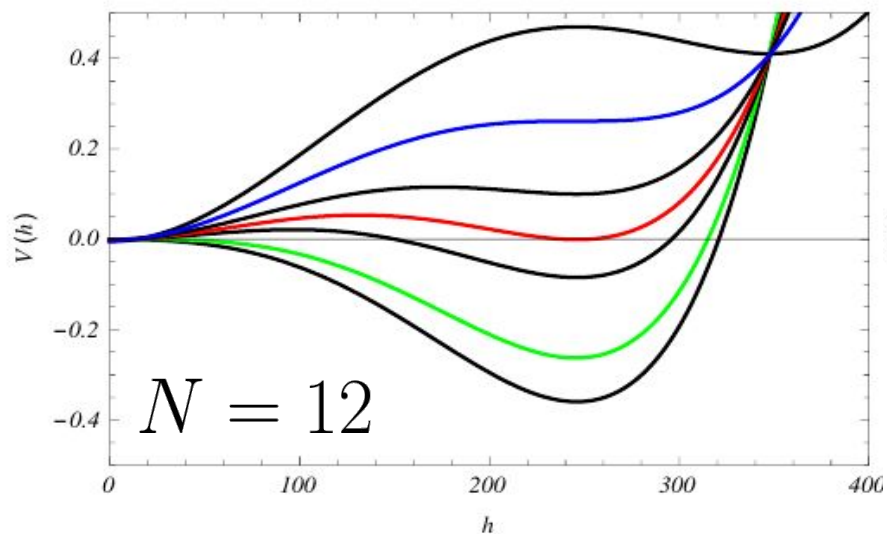
$$\begin{aligned}V''(0) &= 0, \\V''(v) &= 0, \\V(0) &= V(v)\end{aligned}$$

- Singletes escalares reales



Modelos más allá del ME

- Singletes escalares reales



Modelos más allá del ME

- **Singletes escalares reales**

$$\begin{aligned} V_{eff}(h, T) &= \frac{\mu^2}{2} h^2 + \frac{\lambda}{4} h^4 + \sum_i \frac{n_i m_i^4(h)}{64\pi^2} \left[\ln \frac{m_i^2(h)}{m_Q^2} - c_i \right] \\ &+ \frac{T^4}{2\pi^2} \sum_i n_i \int_0^\infty dx x^2 \ln \left[1 - \varepsilon_i e^{-\sqrt{x^2 + m_i^2(h)}/T} \right] \\ &+ \frac{T}{12\pi} \sum_i \frac{1 + \varepsilon_i}{2} n_i \left\{ m_i^3(h) - [m_i^2(h) + \Pi_i(T)]^{3/2} \right\} \end{aligned}$$

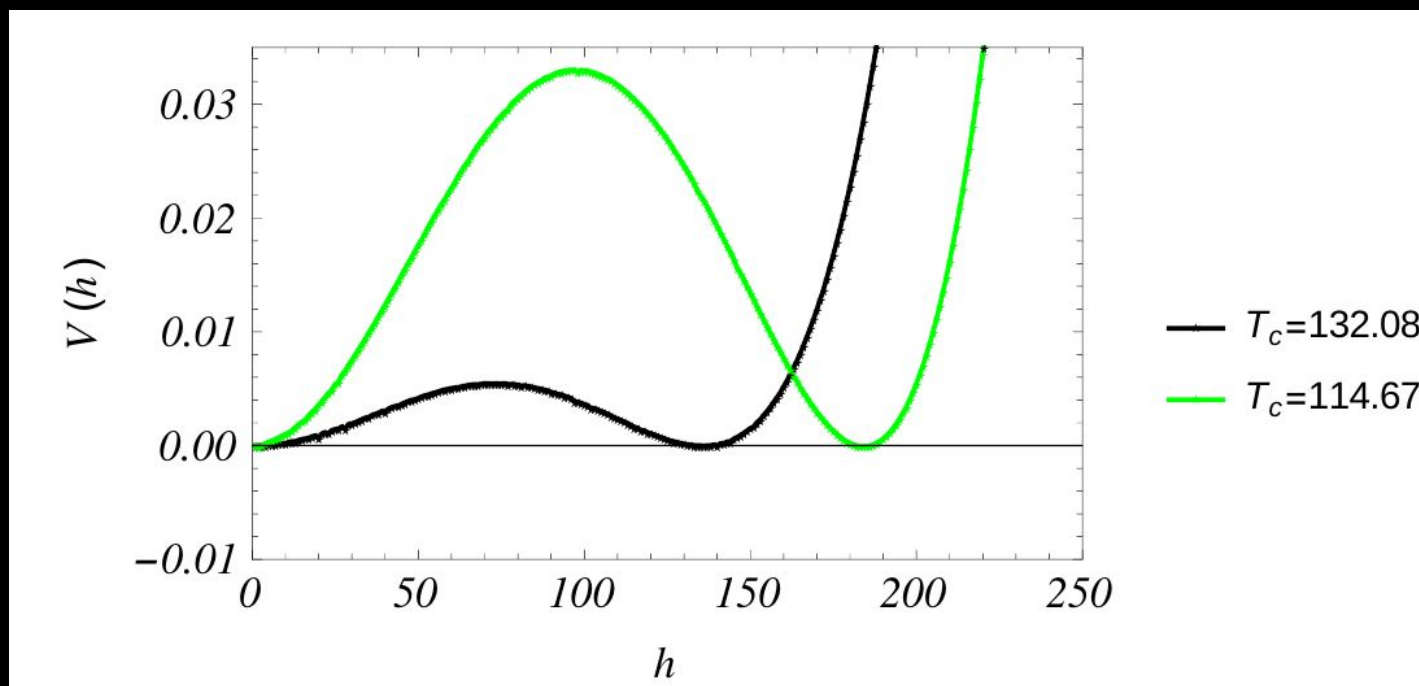
Modelos más allá del ME

- **Singletes escalares reales**

Masas térmicas:

$$\begin{aligned}\Pi_G = \Pi_H &= \left(\frac{1}{2}g^2 + \frac{1}{4}y_t^2 + \frac{\lambda}{2} + \frac{1}{12} \sum_i^N \xi_i^2 \right) T^2 \\ \Pi_S &= \frac{1}{3}\xi^2 T^2, \quad \Pi_{W_L} = \Pi_{Z_L} = \frac{11}{6}g^2 T^2.\end{aligned}$$

Modelos más allá del ME



Modelos más allá del ME

- **Doblete Inerte (IDM)**

Blinov, Profumo & Stefaniak, arXiv: 1504.05949

$$H = \begin{pmatrix} G^\pm \\ \frac{1}{\sqrt{2}}(h + v + iG^0) \end{pmatrix} \quad \Phi = \begin{pmatrix} H^\pm \\ \frac{1}{\sqrt{2}}(H^0 + iA^0) \end{pmatrix}$$

$$V = \mu_1^2 |H|^2 + \mu_2^2 |\Phi|^2 + \lambda_1 |H|^4 + \lambda_2 |\Phi|^4 + \lambda_3 |H|^2 |\Phi|^2 + \lambda_4 |H^\dagger \Phi|^2 + \frac{\lambda_5}{2} [(H^\dagger \Phi)^2 + \text{h.c.}] .$$

Modelos más allá del ME

- Doblete Inerte (IDM)

$$V_{eff}(v, \phi, T) = V_0 + V_1(v, \phi) + V_T(v, \phi, T),$$



$$V_0 = \frac{\mu_1^2}{2} v^2 + \frac{\mu_2^2}{2} \phi^2 + \frac{\lambda_1}{4} v^4 + \frac{\lambda_2}{4} \phi^4$$

Modelos más allá del ME

- Doblete Inerte (IDM)

$$V_{eff}(v, \phi, T) = V_0 + V_1(v, \phi) + V_T(v, \phi, T),$$



$$V(v, \phi) = \sum_i \frac{n_i m_i^4(v, \phi)}{64\pi^2} \left[\ln \frac{m_i^2(v, \phi)}{Q^2} - c_i \right]$$

Modelos más allá del ME

- Doblete Inerte (IDM)

$$V_{eff}(v, \phi, T) = V_0 + V_1(v, \phi) + V_T(v, \phi, T)$$



$$V_T(v, \phi, T) = \frac{T^4}{2\pi^2} \left\{ \sum_b n_b J_B \left[\frac{m_i^2(v, \phi)}{T^2} \right] + \sum_f n_f J_f \left[\frac{m_i^2(v, \phi)}{T^2} \right] \right\} \\ + \frac{T}{12\pi} \left(\frac{1 + \varepsilon}{2} \right) n \left\{ [m^2(v, \phi)]^3 - [m^2(v, \phi, T)]^3 \right\}$$

Modelos más allá del ME

- **Doblete Inerte (IDM)**

Blinov, Profumo & Stefaniak, arXiv: 1504.05949

Masas para las componentes neutras y cargadas

$$\begin{aligned} M_h^2 &= \begin{pmatrix} \mu_1^2 + 3\lambda_1 v^2 + \lambda_L \phi^2 & 2\lambda_L \phi v \\ 2\lambda_L \phi v & \mu_2^2 + 3\lambda_2 \phi^2 + \lambda_L v^2 \end{pmatrix} \\ M_A^2 &= \begin{pmatrix} \mu_1^2 + \lambda_1 v^2 + \lambda_S \phi^2 & \lambda_5 \phi v \\ \lambda_5 \phi v & \mu_2^2 + \lambda_2 \phi^2 + \lambda_S v^2 \end{pmatrix} \\ M_{\pm}^2 &= \begin{pmatrix} \mu_1^2 + \lambda_1 v^2 + \frac{1}{2}\lambda_3 \phi^2 & \frac{1}{2}(\lambda_5 + \lambda_4)\phi v \\ \frac{1}{2}(\lambda_5 + \lambda_4)\phi v & \mu_2^2 + \lambda_2 \phi^2 + \frac{1}{2}\lambda_3 v^2 \end{pmatrix}. \end{aligned}$$

Modelos más allá del ME

- **Doblete Inerte (IDM)**

Blinov, Profumo & Stefaniak, arXiv: 1504.05949

Masas térmicas para los dobletes:

$$\mu_i^2 \longrightarrow \mu_i^2 + c_i T^2$$

$$c_1 = \frac{1}{8}g^2 + \frac{1}{16}(g^2 + g'^2) + \frac{1}{2}\lambda_1 + \frac{1}{12}(\lambda_L + \lambda_S) + \frac{1}{12}\lambda_3 + \frac{1}{4}y_t^2$$

$$c_2 = \frac{1}{8}g^2 + \frac{1}{16}(g^2 + g'^2) + \frac{1}{2}\lambda_2 + \frac{1}{12}(\lambda_L + \lambda_S + \lambda_3)$$

Modelos más allá del ME

- **Doblete Inerte (IDM)**

Blinov, Profumo & Stefaniak, arXiv: 1504.05949

Masas térmicas para los bosones gauge:

$$\begin{pmatrix} \frac{1}{4}(v^2 + \phi^2)g^2 + 2g^2T^2 & -\frac{1}{4}(v^2 + \phi^2)gg' \\ -\frac{1}{4}(v^2 + \phi^2)gg' & \frac{1}{4}(v^2 + \phi^2)g'^2 + 2g'^2T^2 \end{pmatrix}$$

$$m_{W_l}^2 = m_{W_l}^2(v, \phi) + 2g^2T^2$$

Modelos más allá del ME

- **Doblete Inerte (IDM)**

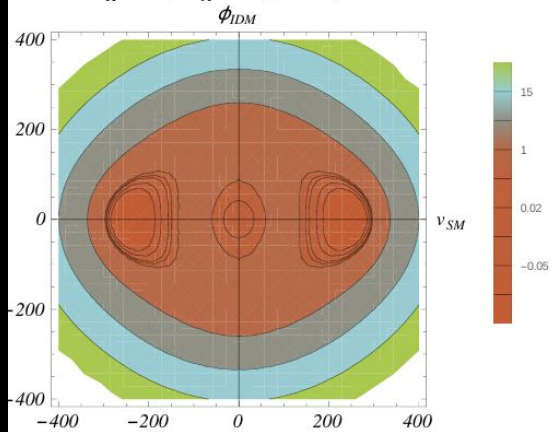
Blinov, Profumo & Stefaniak, arXiv: 1504.05949

Puntos del espacio de parámetros:

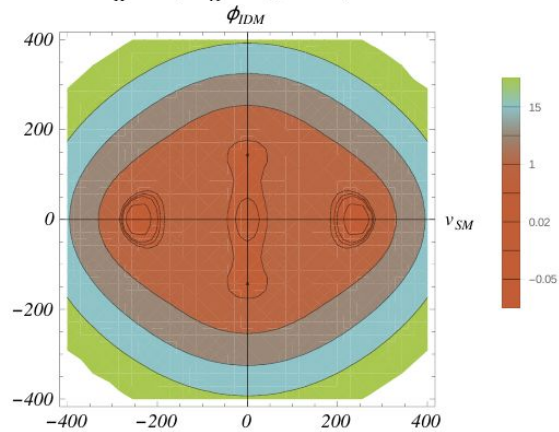
- P1 $m_{H^0} = 66 \text{ GeV}$
 - P2 $m_{H^0} = 200 \text{ GeV}$
 - P3 $m_{H^0} = 500 \text{ GeV}$
- $$m_{H^\pm} = m_{A^0} \geq 200 \text{ GeV}$$

P1

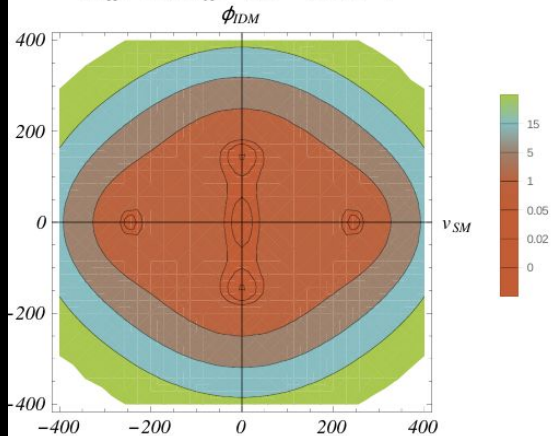
$$m_{H^0}=66, m_{A^0}=m_{H^\pm}=460, T=0$$



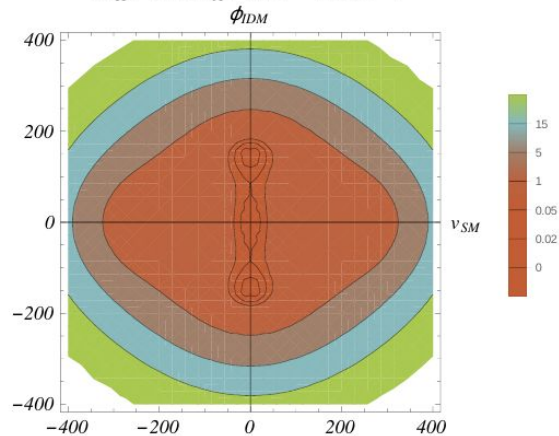
$$m_{H^0}=66, m_{A^0}=m_{H^\pm}=475, T=0$$



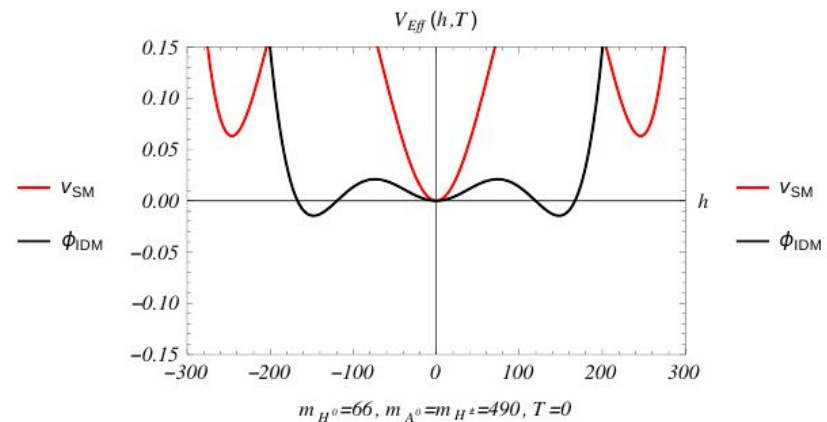
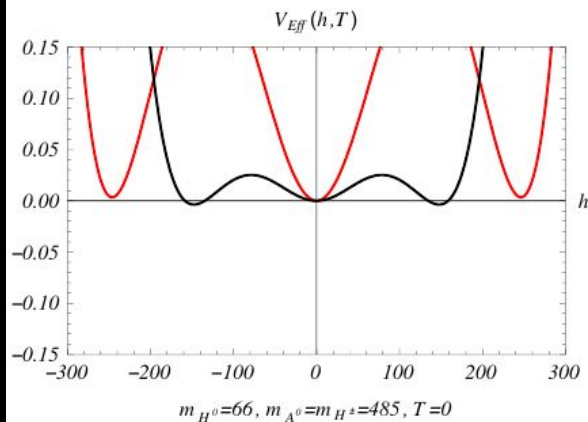
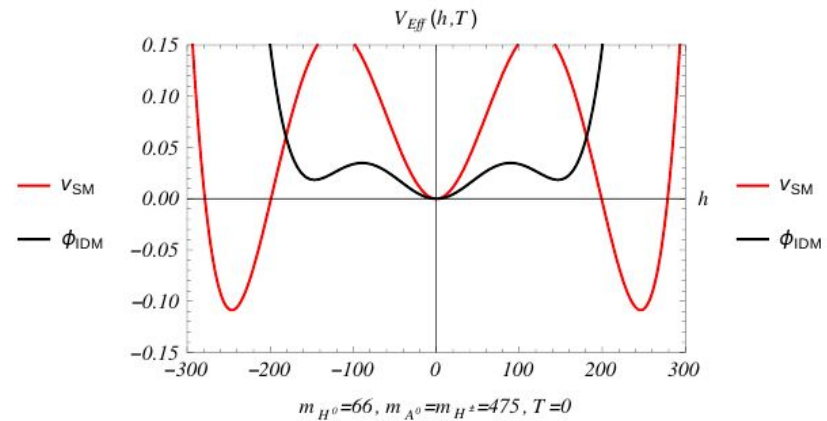
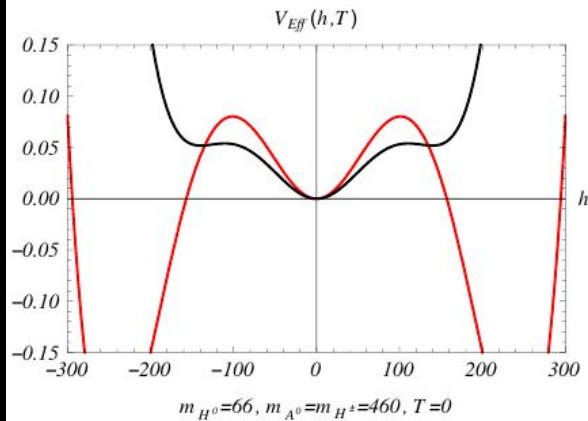
$$m_{H^0}=66, m_{A^0}=m_{H^\pm}=485, T=0$$



$$m_{H^0}=66, m_{A^0}=m_{H^\pm}=490, T=0$$



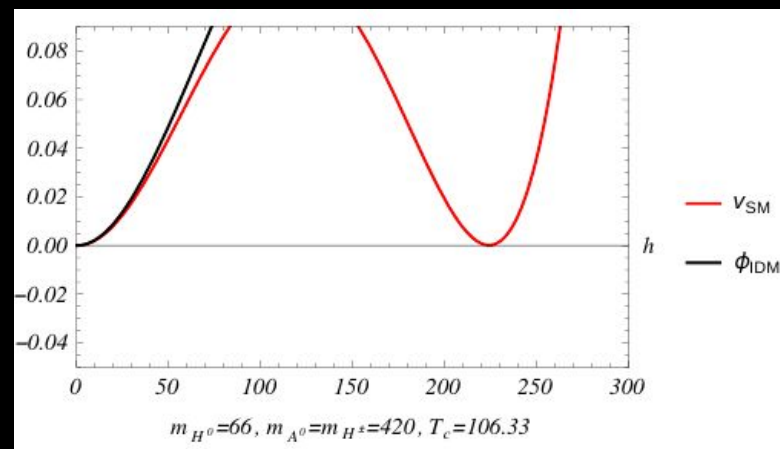
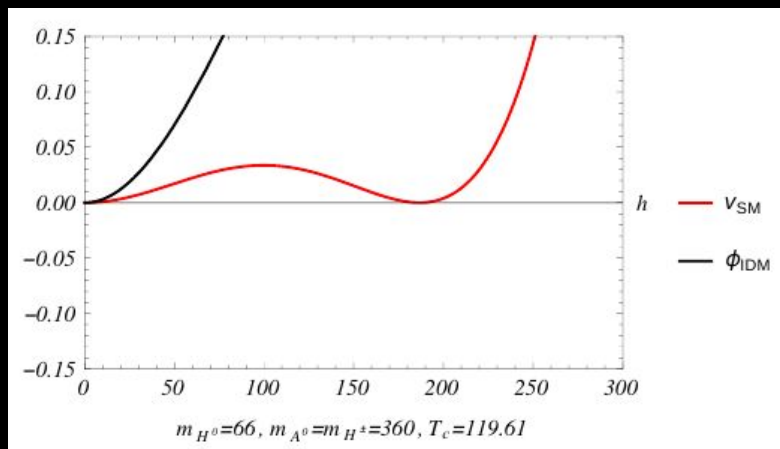
P1



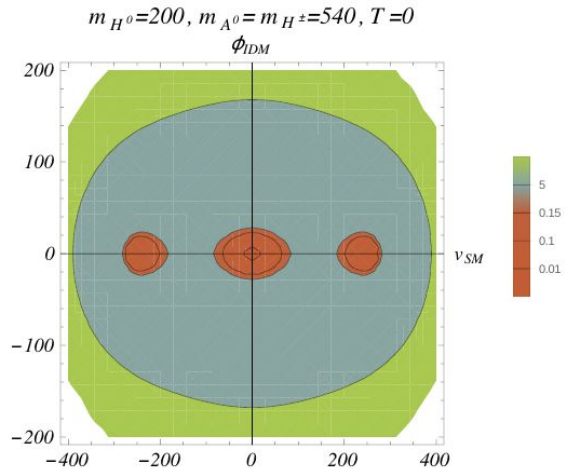
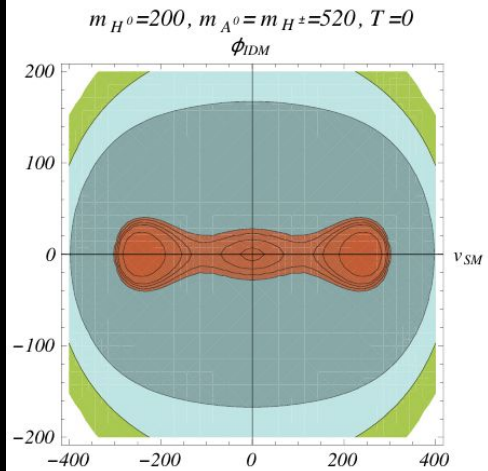
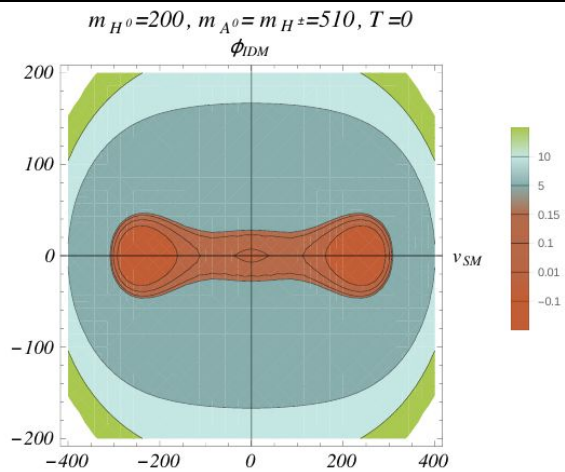
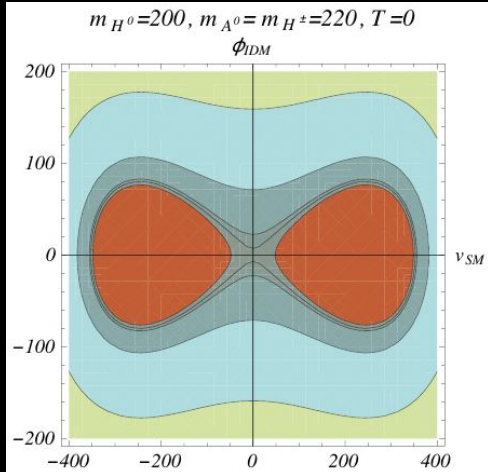
$$m_{H^0} = 66 \text{ GeV}$$

P1

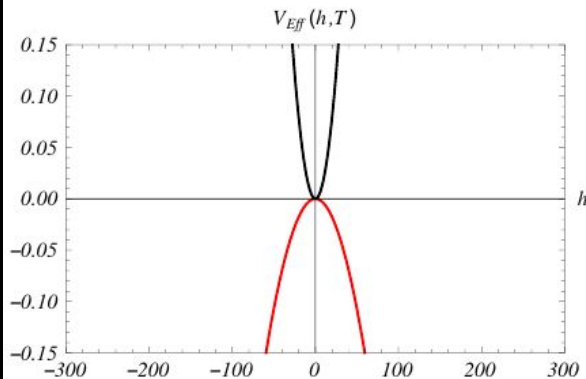
m_{H^\pm} (GeV)	T_c (GeV)	V_c (GeV)	R
360	119.61	186.05	1.55
380	115.98	201.18	1.73
400	111.71	213.04	1.91
420	106.33	224.71	2.11



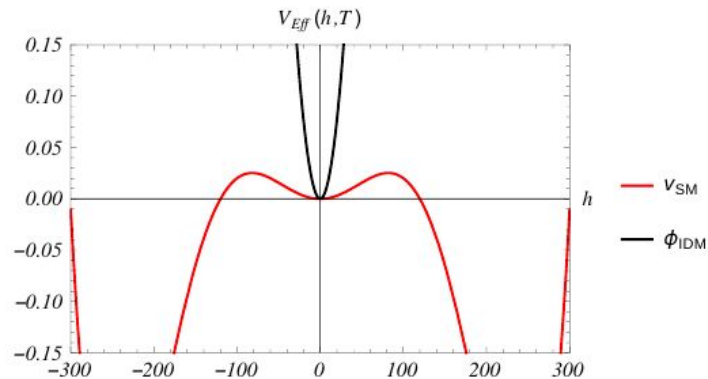
P2



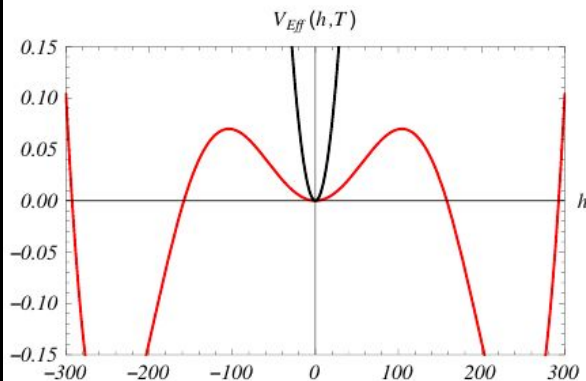
P2



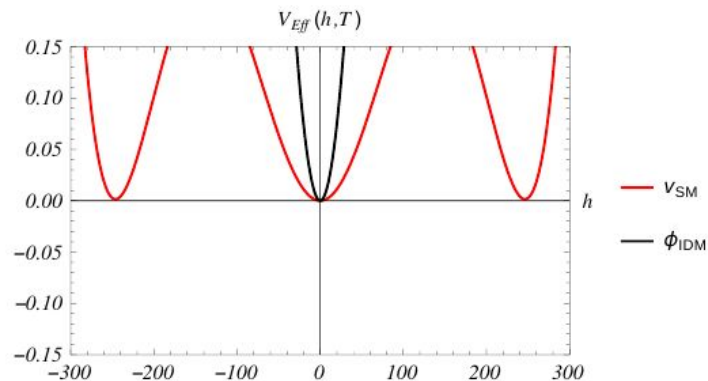
$m_{H^0}=200, m_{A^0}=m_{H^\pm}=220, T=0$



$m_{H^0}=200, m_{A^0}=m_{H^\pm}=510, T=0$

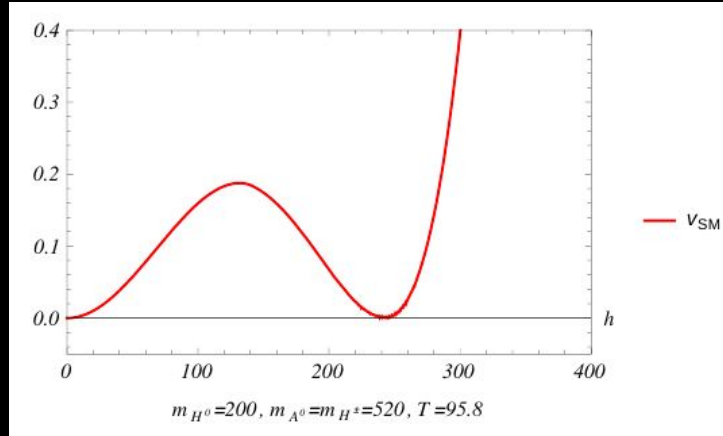
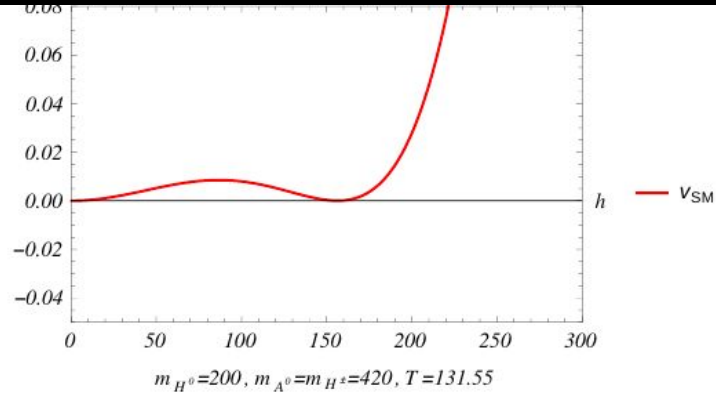
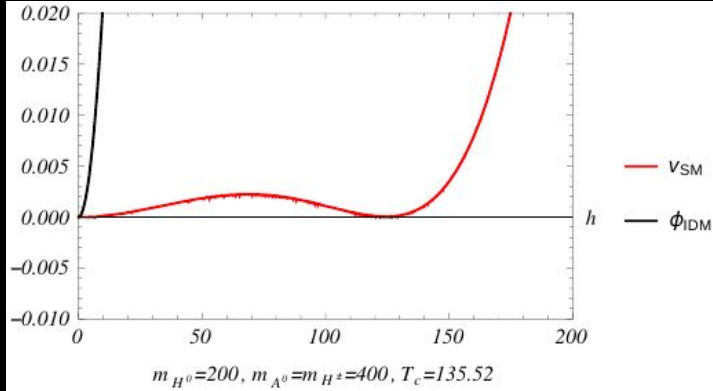


$m_{H^0}=200, m_{A^0}=m_{H^\pm}=520, T=0$

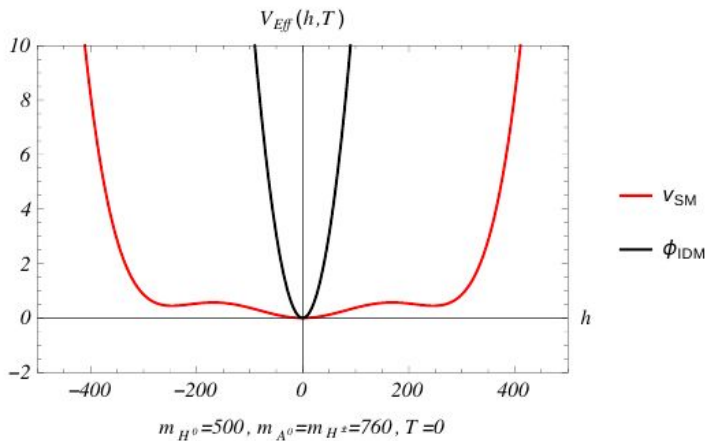
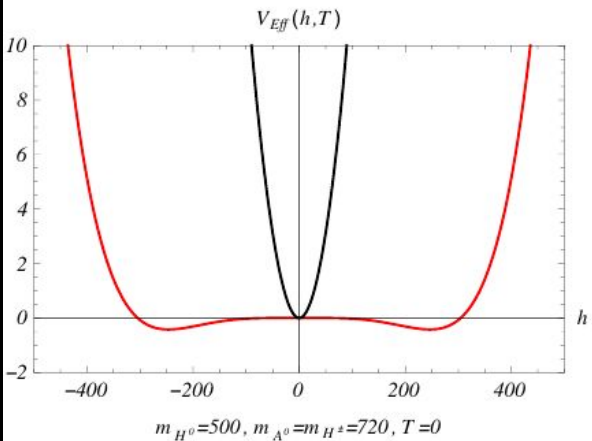
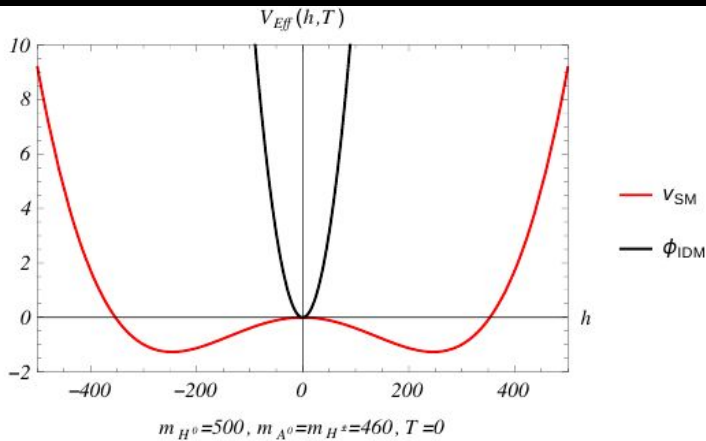
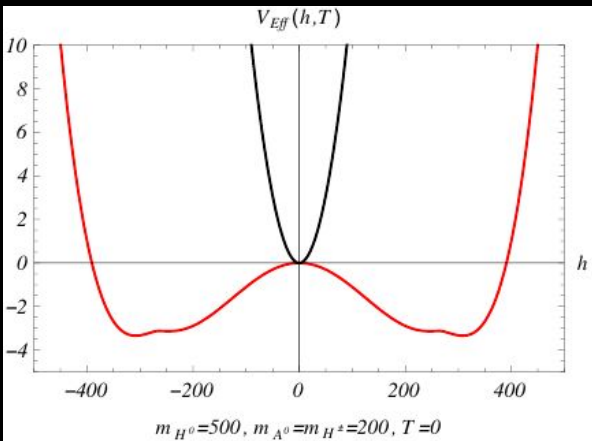


$m_{H^0}=200, m_{A^0}=m_{H^\pm}=540, T=0$

P2



P3



Modelos más allá del ME

- **Modelo escotogenico**

Merle & Platscher, arXiv: 1502.03098

$$IDM + 3N_R$$

A $T=0$, el comportamiento
de este modelo es similar al
IDM



Las masas dependientes
del campo son las
mismas

Modelos más allá del ME

- Modelo escotogenico

Merle & Platscher, arXiv: 1502.03098

$$IDM + 3N_R$$

Para T finita, la diferencia
radica en los neutrinos
derechos



$$\mathcal{L}_{\text{Yukawa}} \supset -h_{ij} \overline{N_R^i} \tilde{\eta}^\dagger \ell_L^j$$

$$h_\nu = 0.31, 1.0, 1.73$$

Modelos más allá del ME

- Modelo escotogenico

Merle & Platscher, arXiv: 1502.03098

$$IDM + 3N_R$$

Para T finita, la diferencia
radica en los neutrinos
derechos



$$c_1 \longrightarrow c_1, \quad c_2 \longrightarrow c'_2$$

$$c'_2 = c_2 + \frac{9}{12} h_\nu^2$$

P1

$$m_{H^0} = 66 \text{ GeV y } h_\nu = 0.31$$

m_H^\pm (GeV)	T_c (GeV)	V_c (GeV)	R
360	121.43	185.43	1.53
380	117.89	199.94	1.69
400	113.68	212.8	1.87
420	108.39	224.41	2.07

P1

$$m_{H^0} = 66 \text{ GeV y } h_\nu = 1.0$$

m_H^\pm (GeV)	T_c (GeV)	V_c (GeV)	R
360	143.20	171.74	1.19
380	141.29	191.31	1.35
400	139.28	207.28	1.49
420	136.80	221.32	1.61

P2

$$m_{H^0} = 200 \text{ y } h_\nu = 0.31$$

m_H^\pm (GeV)	T_c (GeV)	V_c (GeV)	R
360	-	-	-
380	-	-	-
400	137.24	122.5	0.89
420	133.37	156.73	1.17

P3

$$m_{H^0} = 500 \text{ y } h_\nu = 0.31, 1.0, 1.73$$

Para este punto en particular no se obtuvo resultado alguno

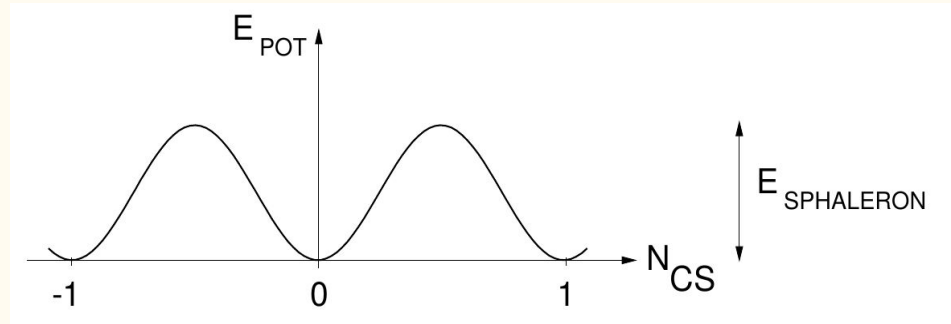
Conclusiones

- Necesitamos física más allá del ME
- Es necesario hacer uso teoría cuántica de campos a temperatura finita
- Es posible tener modelos que expliquen los tres problemas a la vez
- Las condiciones para bariogénesis electrodébil imponen cotas sobre las masas de las componentes neutras y cargadas del IDM y el modelo escotogenico

Suplementos

Sphaleron process

(Phys. Rev. D, 36:581595,
Jul 1987)



a “sphaleron” is a static, unstable, **finite-energy** solutions of the classical field equations for real time t .

Grand-Canonical Ensemble: the system can exchange energy and particles with a reservoir

Let's consider a dynamical system characterized by a Hamiltonian and conserved charges

$$\Phi \equiv \log \text{Tr} \exp \left\{ - \sum_A \alpha_A Q_A - \beta H \right\}$$

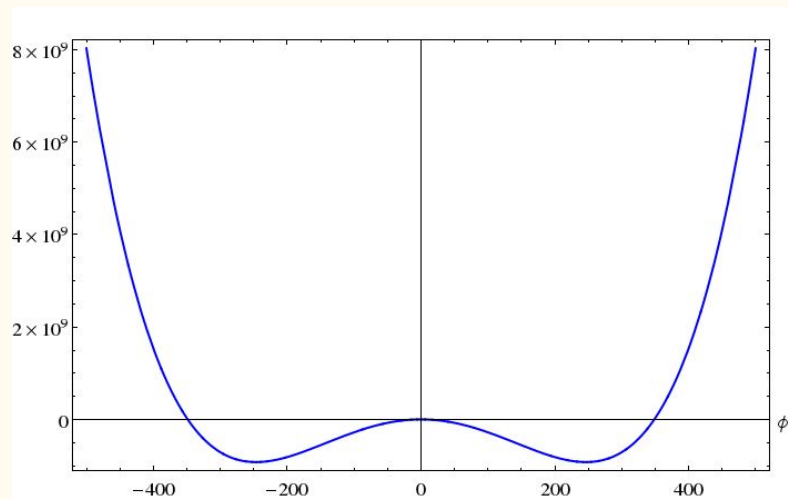
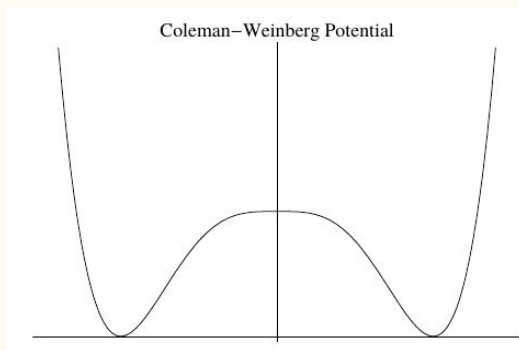
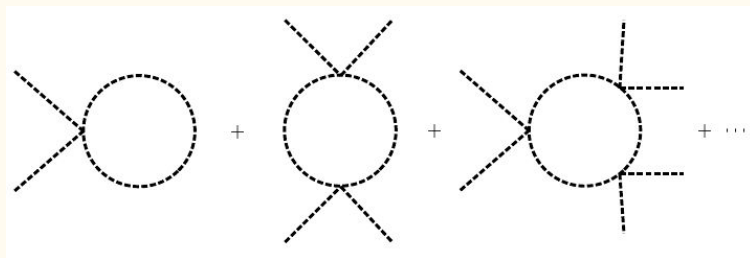
$$\rho = \exp(-\Phi) \exp \left\{ - \sum_A \alpha_A Q_A - \beta H \right\}$$

Generating Functionals: the way to represent the fields propagators.

$$\phi(x) = e^{itH} \phi(0, \vec{x}) e^{-itH}$$

$$G^{(C)}(x_1, \dots, x_n) \equiv \langle T_C \phi(x_1), \dots, \phi(x_n) \rangle$$

$$Z^\beta[j] = \sum_{n=0}^{\infty} \frac{i^n}{n!} \int_C d^4x_1 \dots d^4x_n j(x_1) \dots j(x_n) G^{(C)}(x_1, \dots, x_n)$$

V_{tree}  V_{c-w} 

Terminology:

an “instanton” is a localized, **finite-action** solution of the classical field equations for imaginary time τ ($\tau^2 \leq 0$);

a “topological soliton” is a static, stable, **finite-energy** solutions of the classical field equations for real time t ($t^2 \geq 0$);

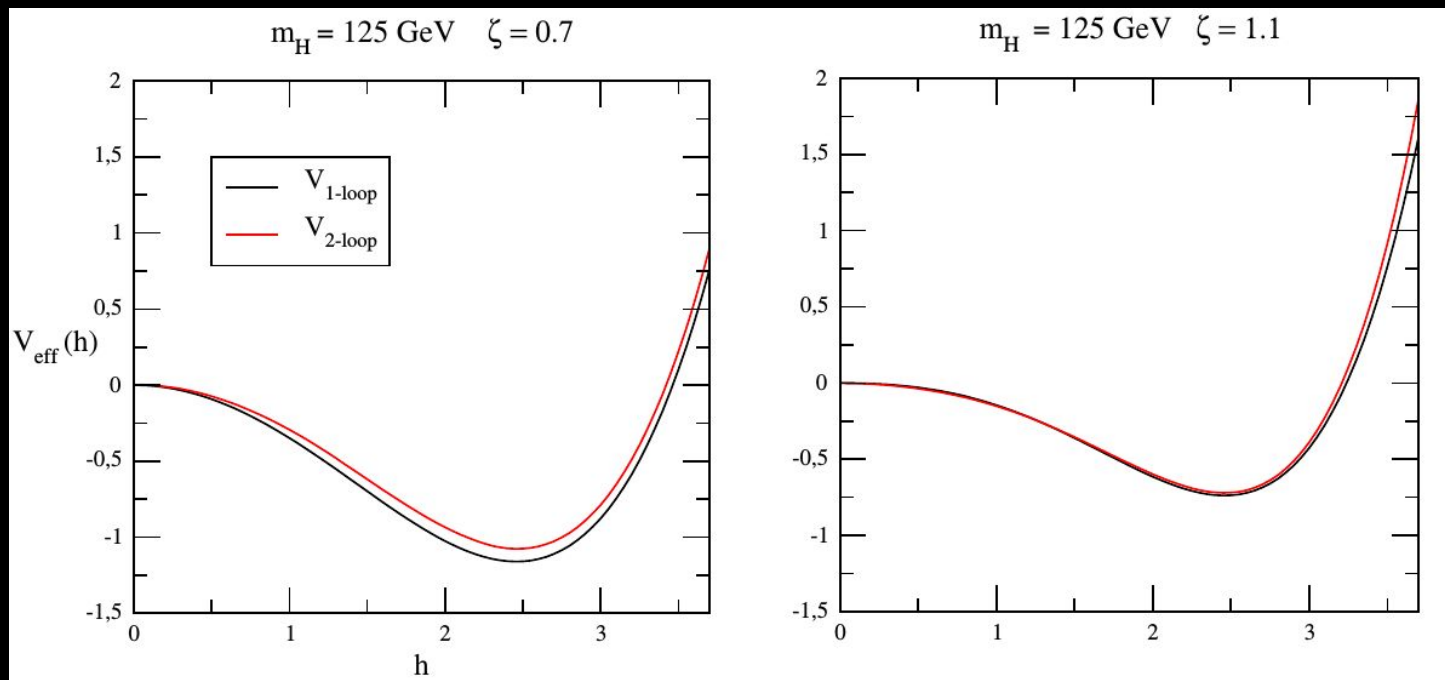
a “sphaleron” is a static, unstable, **finite-energy** solutions of the classical field equations for real time t .

$$\Gamma_B^{(b)}(T) \simeq (\text{prefactor})e^{-E_{\text{sph}}(T)/T} < H(T) \simeq 1.66\sqrt{g_*(T)}T^2/m_{\text{P}}$$

$$\frac{v(T)}{T} > \frac{g_2}{4\pi\mathcal{E}(T)} \left[42.97 + \log \text{ corrections} \right].$$

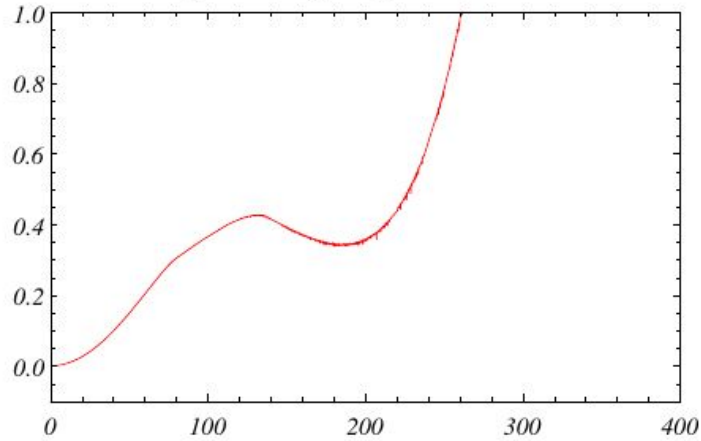
$$\frac{v(T)}{T} > 1.16$$

Modelos más allá del ME



P3

$m_{H^0}=500, m_{A^0}=m_{H^\pm}=760, T=150$



$m_{H^0}=500, m_{A^0}=m_{H^\pm}=760, T=200$

