Non-Thermal Dark Matter From the EW Phase Transition: Heavy WIMP's and *Baby-Zillas*

Jose Miguel No (Sussex U.)

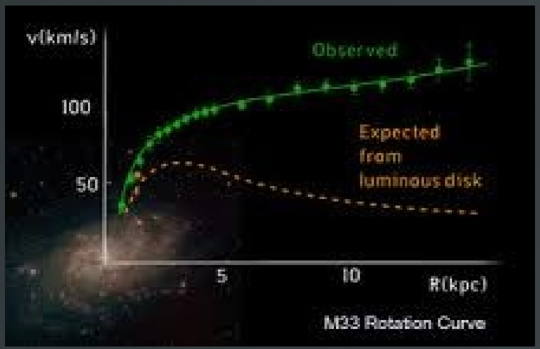
with Adam Falkowski

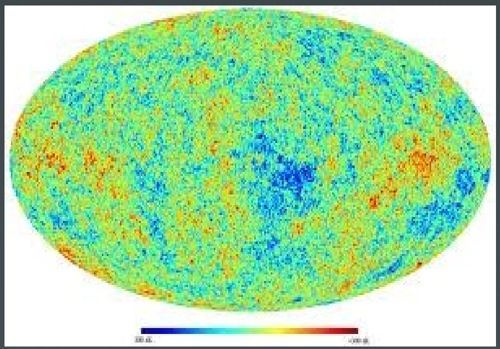
JHEP **1302** (2013) 034 (arXiv:1211.5615)

February 22nd 2013

Dark Matter in the Universe

Galaxy Rotation Curves, Gravitational Lensing (Bullet Cluster), CMB...





Particle Physics → DM Candidates:
- WIMP
- Non-WIMP: KeV Sterile Neutrino, Axion, Gravitino, Wimpzillas...

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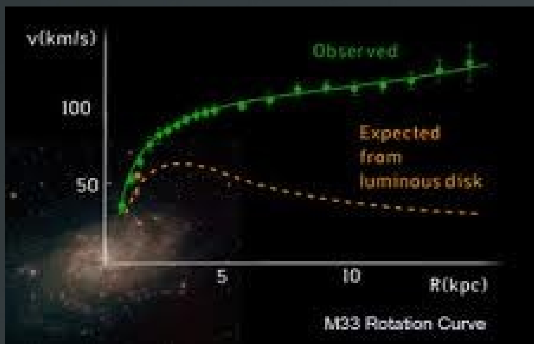
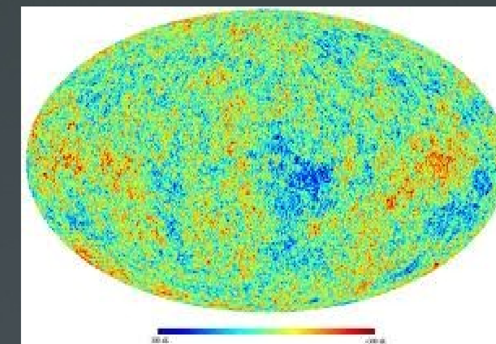
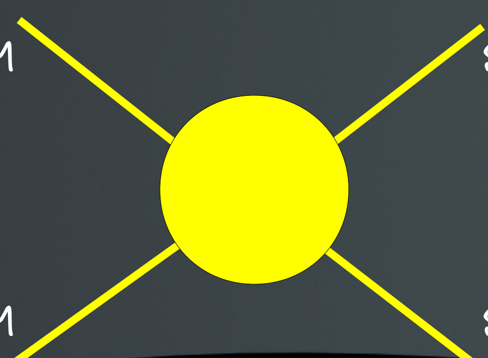




Particle Physics ➔ DM Candidates:
- WIMP
- Non-WIMP: KeV Sterile Neutrino, Axion, Gravitino, Wimpzillas...

"WIMP Paradigm"

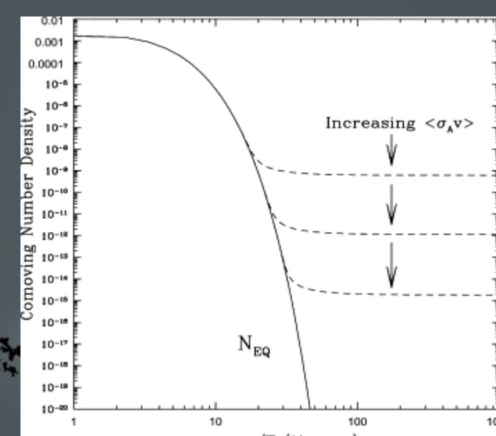
SUSY Neutralino, KK Dark Matter, Little Higgs (w. T-Parity), Singlet Scalar (Hidden Sector DM), Inert Doublet Model...



Dark Matter Annihilation

⟹

Thermal Freeze-out



Dark Matter in the Universe

Other Appealing Dark Matter Production Mechanisms...

Non-Thermal DM Production

⇨ Non-thermal DM Disconnected from EW Physics?

Axions, WIMPZILLAS, Moduly decay products...

DM Direct Detection? ***DM Indirect Detection?***

Dark Matter in the Universe

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DM Direct Detection? ***DM Indirect Detection?***

⇨ EW Phase Transition May Be Out-of-Equilibrium Process

+

⇨ Most DM canditates at the EW Scale Couple to Higgs

Non-Thermal DM Production at the EW Phase Transition

Outline

- → Dynamics of the Electroweak Phase Transition
  - ⇨ Bubble 1st Order Phase Transitions: Nucleation & Expansion
  - ⇨ Bubble Expansion Velocities: Runaway Bubbles
  - ⇨ Bubble Collisions
- → Particle Production in Bubble Collisions
- → Non-Thermal Dark Matter from the EW Phase Transition
  - ⇨ Multi-TeV WIMP's
  - ⇨ Baby-Zillas

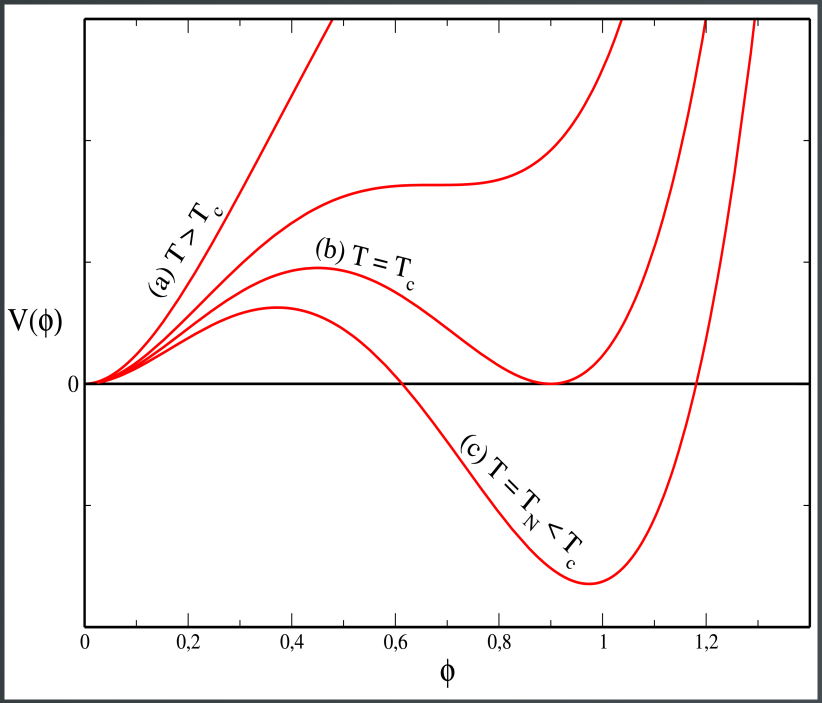
Electroweak Phase Transition

Universe Expands Adiabatically ⇨ **Equilibrium Thermal Field Theory** OK

Finite-T Effective Potential $V(\phi,T)$ for the Higgs

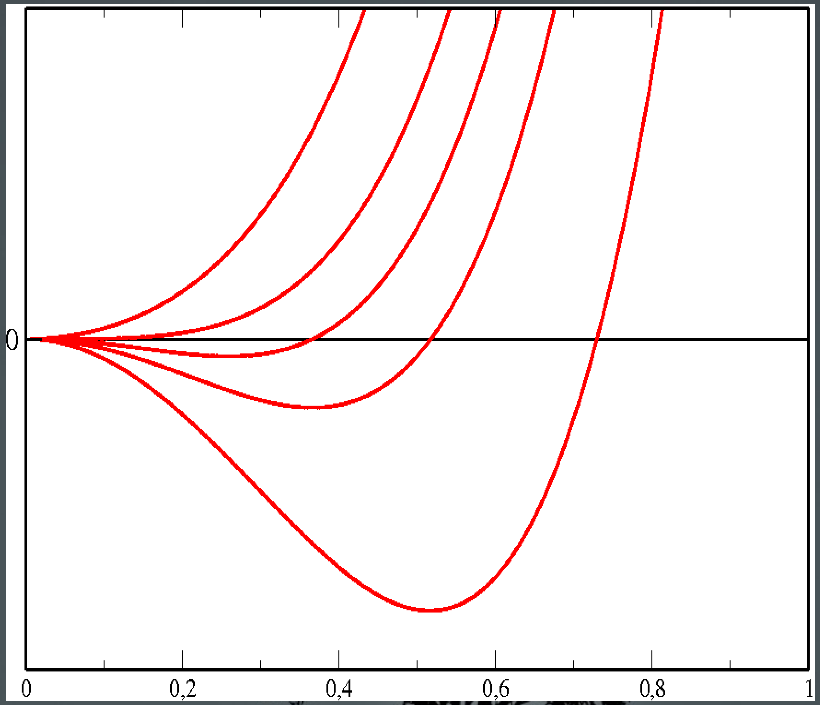
$$V(\phi,T) \approx (a\,T^2 - \mu^2)\,\phi^2 - b\,T\,\phi^3 + \lambda\,\phi^4$$

1st Order:	2nd Order:
$\langle\phi\rangle = 0 \to \langle\phi\rangle = \phi(T)$ Discontinuous	$\langle\phi\rangle = 0 \to \langle\phi\rangle = \phi(T)$ Continuous



Larger m_h →

← New Bosons



Electroweak Phase Transition

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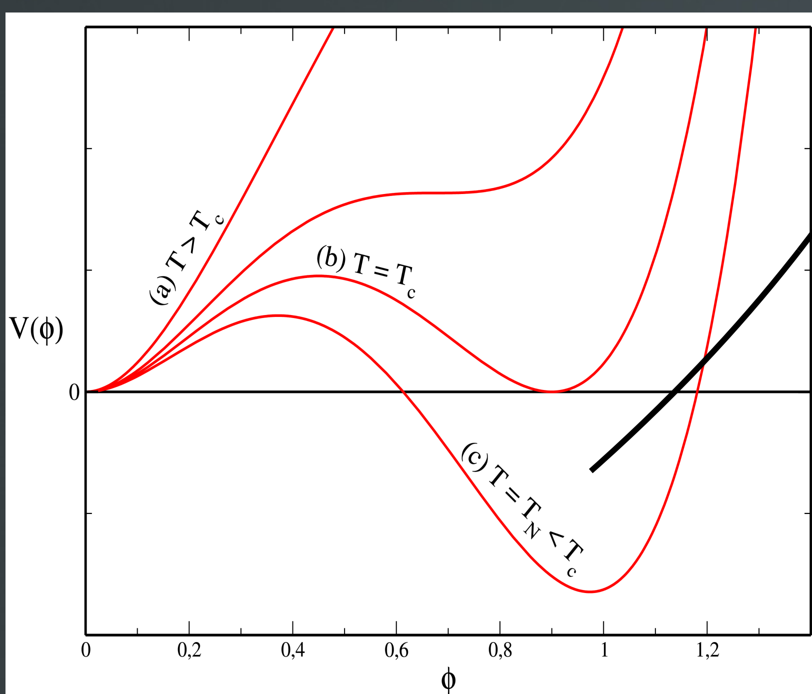
Finite-T Effective Potential $V(\phi,T)$ for the Higgs

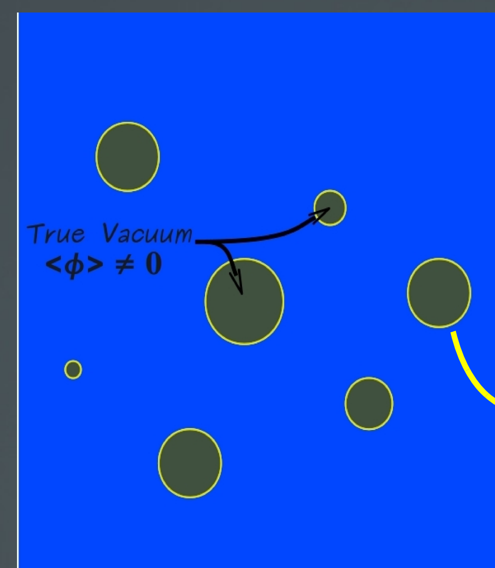
1[st] Order:

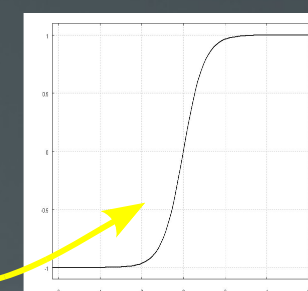
$\langle\phi\rangle = 0 \rightarrow \langle\phi\rangle = \phi(T)$ Discontinuous



Nucleation of True Vacuum Bubbles
(in False Vacuum Sea)

J. S. Langer, Ann. Phys. ***54*** *(1969) 258*
S. R. Coleman, Phys. Rev. D ***15*** *(1977) 2929*
A. D. Linde, Nucl. Phys. B ***216*** *(1983) 421*





Higgs Wall

How do Higgs Bubbles Expand?

Pressure ~ $\Delta\mathcal{F}$

$$\partial_\mu\partial^\mu\phi + \frac{\partial\mathcal{F}}{\partial\phi} - \mathcal{K}(\phi) = 0 \qquad \mathcal{K}(\phi) = -\sum_i \frac{dm_i^2}{d\phi}\int\frac{d^3p}{(2\pi)^3 2E_i}\delta f_i(p)$$

Friction

Particles Gain Mass When Crossing Wall

Particle Distributions $f_a(p)$ Away from Equilibrium Close to Wall

$$F_\eta(v_w) = \int_{-\infty}^{\infty} dz\, \frac{d\phi}{dz}\sum_i \frac{dm_i^2}{d\phi}\int\frac{d^3p}{(2\pi)^3 2E_i}\delta f_i(p) \simeq \eta\, v_w$$

Friction Reaches a Terminal Value! (F_{max})

*D. Bodeker and G. Moore, JCAP **0905** (2009) 009*

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→ If Pressure Exceeds F_{max} ⇨ Accelerated Bubble Expansion "Runaway Bubbles"

*D. Bodeker and G. Moore, JCAP **0905** (2009) 009*

→ Energy of the EW Phase Transition Stored on Higgs Bubble Walls

*J. R. Espinosa, T. Konstandin, J. M. N. and G. Servant, JCAP **1004** (2010) 028*

How do Higgs Bubbles Expand?

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Friction

Particles Gain Mass When Crossing Wall

Particle Distributions $f_a(p)$ ***Away from Equilibrium Close to Wall***

$$F_\eta(v_w) = \int_{-\infty}^{\infty} dz\,\frac{d\phi}{dz}\sum_i \frac{dm_i^2}{d\phi}\int\frac{d^3p}{(2\pi)^3 2E_i}\,\delta f_i(p) \simeq \eta\, v_w$$

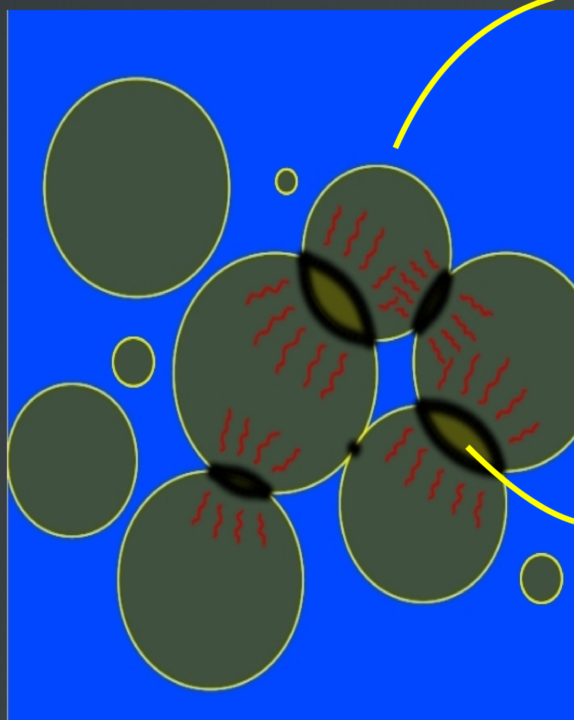
Runaway Bubbles are Possible in Extensions of the SM

D. Bodeker and G. Moore, JCAP ***0905*** *(2009) 009*

J. R. Espinosa, T. Konstandin, J. M. N. and G. Servant, JCAP ***1004*** *(2010) 028*

S. Huber and M. Sopena, arXiv: 1302:1044

The End of the Phase Transition: Bubble Collisions



Runaway Bubbles May Reach $\gamma_{max} \sim 10^{15}$

$$\gamma_w^{\text{max}} \sim \beta^{-1}\frac{M_{\text{pl}}}{v}$$

Bubble Collisions Release Energy in Walls

- ➔ Gravitational Wave Production
- ➔ Particle Production

Particle Production *from* Bubble Collisions

Higgs Wall ⇨ Classical Background

Particle Production (in a space-time dependent Classical Background)

Background $\phi(\mathbf{r},\mathbf{t})$ (Bubble wall Profile) + Quantum fields coupled to it

❶ Modelling the Background: a Bubble Collision

❷ Particle Production in Given Background

❶ Modelling the Background: a Bubble Collision

⇒ Large Bubbles at time of Collision → Planar Limit

$$\left(\partial_t^2 - \partial_z^2\right)\phi(z,t) = -\frac{\partial V(\phi)}{\partial \phi}$$

+ Initial condition (2 *planar bubble walls far away from each other and moving in opposite directions*)

S. Hawking, I. Moss and A. Steward, Phys. Rev. D ***26*** *(1982) 2681*

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Each Bubble Wall interpolates between two minima of potential:

Outside of Wall → $\left(\partial_t^2 - \partial_z^2\right)\phi(z,t) = 0$

$$\phi(z,t) = \frac{v}{2}\left[2 + \mathrm{Tanh}\left(\gamma_w \frac{z+t}{l_w}\right) - \mathrm{Tanh}\left(\gamma_w \frac{z-t}{l_w}\right)\right]$$

Approximate Solution Before the Collision ($t<0$)

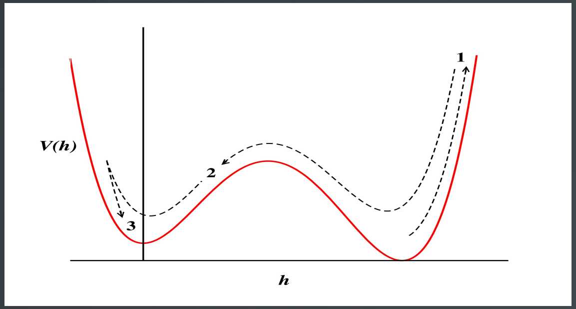
❶ Modelling the Background: a Bubble Collision

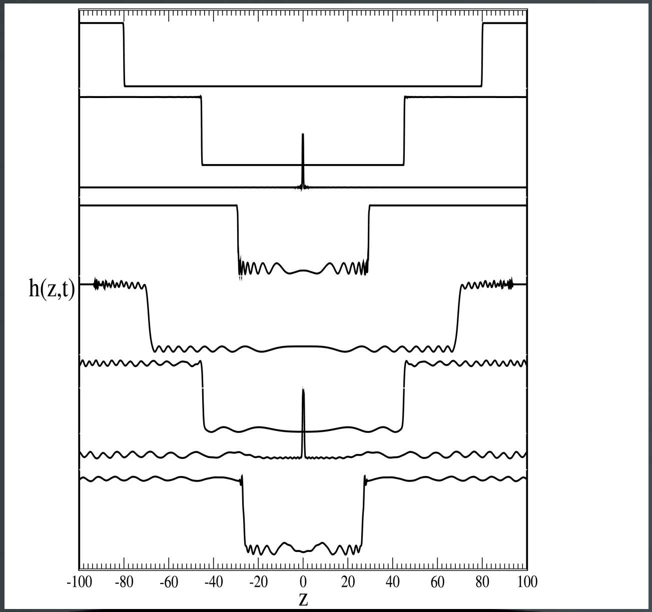
Elastic vs Inelastic Collisions:

*S. Hawking, I. Moss and A. Steward, Phys. Rev. D **26** (1982) 2681*
*T. Konstandin and G. Servant, JCAP **1107** (2011) 024*
*A. Falkowski and J. M. N. JHEP **1302** (2013) 034*

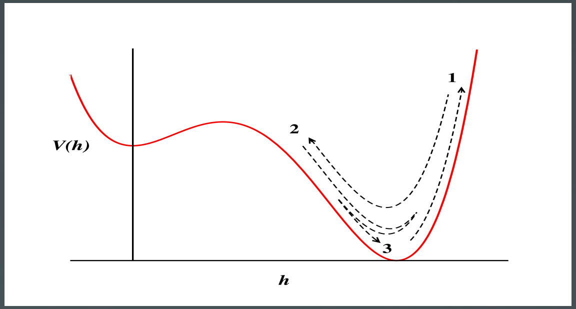
$$\left(\partial_t^2 - \partial_z^2\right) \phi(z,t) = -\frac{\partial V(\phi)}{\partial \phi}$$

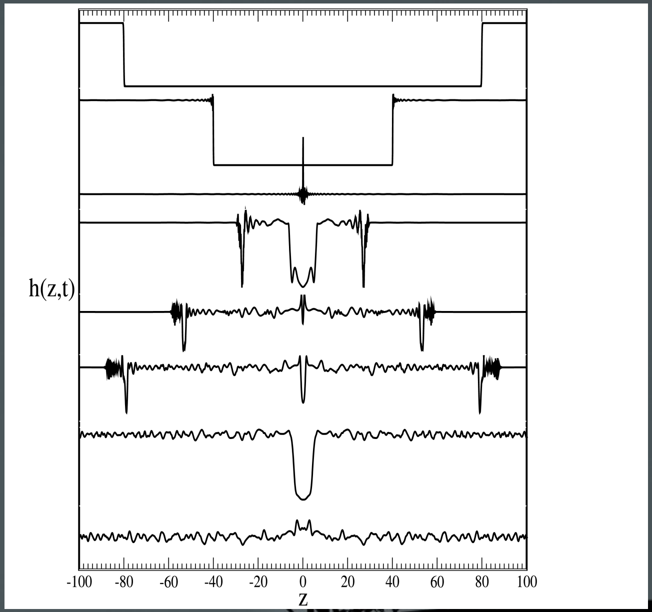
Elastic





Inelastic





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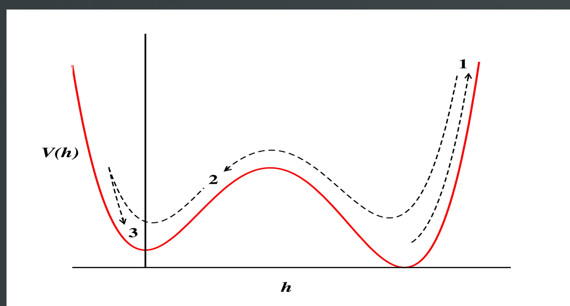

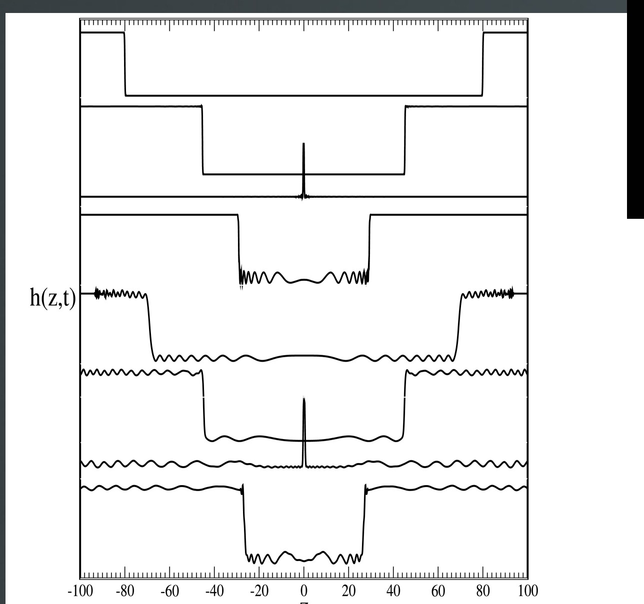

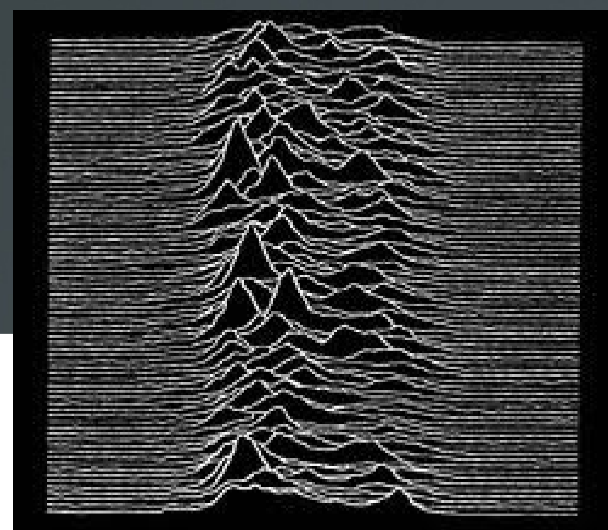

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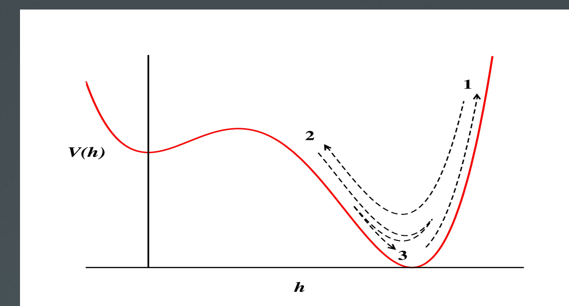

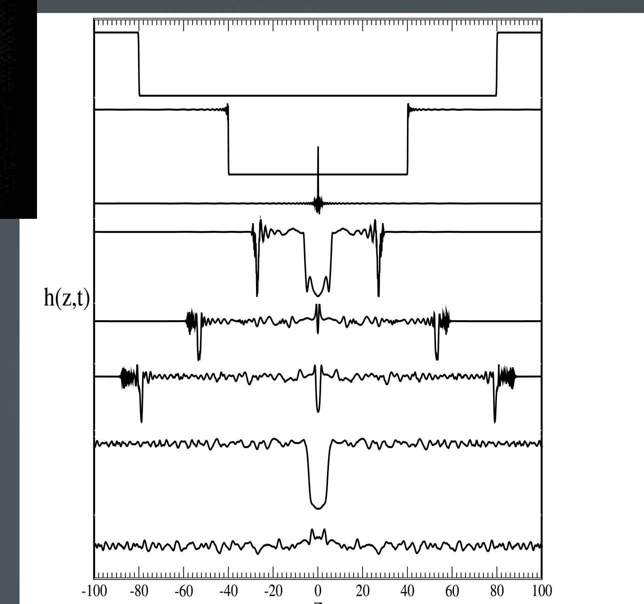

Although this type of figure had appeared earlier!

❶ Modelling the Background: a Bubble Collision

$$\left(\partial_t^2 - \partial_z^2\right)\phi(z,t) = -\frac{\partial V(\phi)}{\partial \phi}$$

Extreme Cases:

Perfectly Elastic Collision

S. Hawking, I. Moss and A. Steward, Phys. Rev. D ***26*** *(1982) 2681*

$$\phi(z,t) = \frac{v}{2}\left[2 + \mathrm{Tanh}\left(\gamma_w \frac{z-|t|}{l_w}\right) - \mathrm{Tanh}\left(\gamma_w \frac{z+|t|}{l_w}\right)\right]$$

$$\phi(z,t) = \begin{cases} 0 & \text{if } v_w\, t < z < -v_w\, t \qquad t<0, \\ 0 & \text{if } -v_w\, t < z < v_w\, t \qquad t>0, \\ v & \text{Otherwise,} \end{cases}$$

Totally Inelastic Collision

A. Falkowski and J. M. N. JHEP ***1302*** *(2013) 034*

$$V(\phi) \simeq \frac{m_h^2}{2}(\phi - v)^2 = \frac{m_h^2}{2}\delta\phi^2$$

$$\phi(z,t>0) = v\left[1 + \frac{l_w}{\gamma_w}\int_0^\infty dp_z \,\frac{p_z}{\sqrt{p_z^2+m_h^2}}\,\frac{\mathrm{Cos}\,(p_z\, z)}{\mathrm{Sinh}\left(\frac{\pi\, l_w\, p_z}{2\,\gamma_w}\right)}\,\mathrm{Sin}\left(\sqrt{p_z^2+m_h^2}\; t\right)\right]$$

❶ Modelling the Background: a Bubble Collision

Extreme Cases:

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Of course, particle production will affect $\boldsymbol{\phi}(\mathbf{r},\mathbf{t})$ → Backreaction

❷ Particle Production

Number of Produced Particles: $\mathcal{N} = 2\,\mathrm{Im}\left(\Gamma\left[\phi\right]\right)$

Effective action:

Generator of 1PI Green functions $\Gamma\left[\phi\right] = \frac{1}{2}\int d^4x_1\, d^4x_2\, \phi(x_1)\, \phi(x_2)\, \Gamma^{(2)}\left(x_1 - x_2\right) + \ldots$

$$\mathcal{N} = \int \frac{d^4p}{(2\pi)^4} \mathrm{Im}\left(\tilde{\Gamma}^{(2)}\left(p^2\right)\right) \int d^4x_1\, d^4x_2\, \phi(x_1)\, \phi(x_2)\, e^{ip(x_1 - x_2)}$$

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$$\mathcal{N} = \int \frac{d^4p}{(2\pi)^4} \mathrm{Im}\left(\tilde{\Gamma}^{(2)}\left(p^2\right)\right)\left|\tilde{h}(p)\right|^2$$

Planar Bubble Walls

$$\frac{\mathcal{N}}{A} = 2\int \frac{dp_z\, d\omega}{(2\,\pi)^2}\left|\tilde{h}(p_z,\omega)\right|^2 \mathrm{Im}\left(\tilde{\Gamma}^{(2)}\left(\omega^2 - p_z^2\right)\right)$$

*R. Watkins and L. M. Widrow, Nucl. Phys B**374** (1992) 446*

❷ Particle Production

$$\frac{\mathcal{N}}{A} = \frac{1}{2\pi^2}\int_0^\infty d\chi\, f(\chi)\,\mathrm{Im}\left(\tilde{\Gamma}^{(2)}(\chi)\right)$$

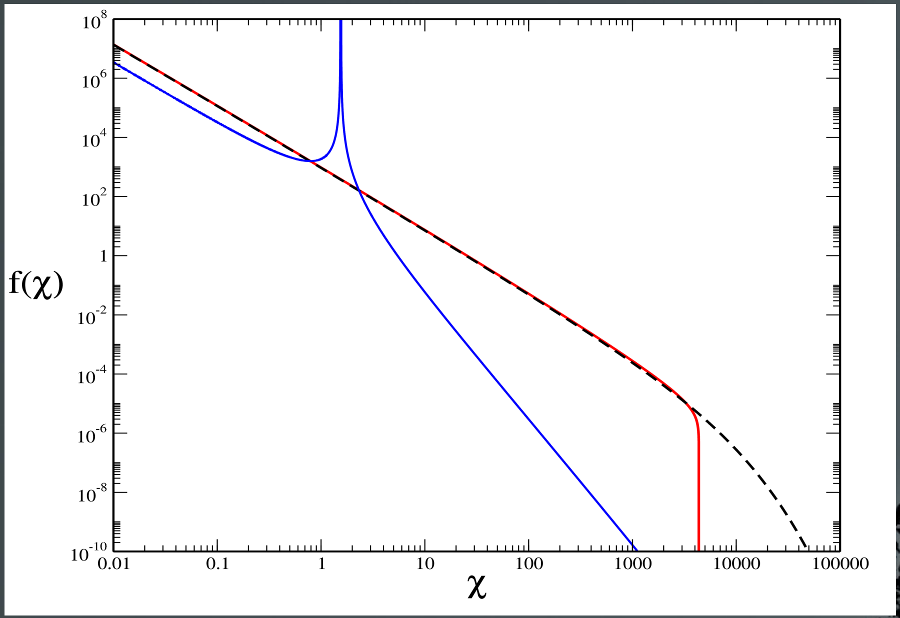
Particle Production Efficiency

Perfectly Elastic

$$f_{\mathrm{PE}}(\chi) = \frac{16\,v^2\,\mathrm{Log}\left[\frac{2\left(\frac{\gamma_w}{l_w}\right)^2-\chi+2\,\frac{\gamma_w}{l_w}\sqrt{\left(\frac{\gamma_w}{l_w}\right)^2-\chi}}{\chi}\right]}{\chi^2}\,\Theta\left[\left(\frac{\gamma_w}{l_w}\right)^2-\chi\right]$$

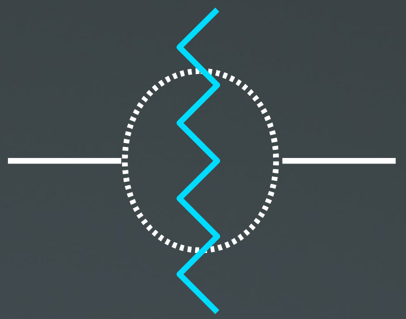
Totally Inelastic

$$f_{\mathrm{TI}}(\chi) = 4\,v^2\,m_h^4\,\frac{\mathrm{Log}\left[\frac{2\left(\frac{\gamma_w}{l_w}\right)^2+\chi+2\,\frac{\gamma_w}{l_w}\sqrt{\left(\frac{\gamma_w}{l_w}\right)^2+\chi}}{\chi}\right]}{\chi^2\left[\left(\chi-m_h^2\right)^2+m_h^6\,\frac{l_w^2}{\gamma_w^2}\right]}$$



❷ Particle Production

$$\frac{\mathcal{N}}{A} = \frac{1}{2\,\pi^2} \int_0^\infty d\chi\, f(\chi)\, \mathrm{Im}\left(\tilde{\Gamma}^{(2)}\left(\chi\right)\right)$$



$$\mathrm{Im}\left(\tilde{\Gamma}^{(2)}\left(\chi\right)\right) = \frac{1}{2} \sum_\alpha \int d\Pi_\alpha \left|\overline{\mathcal{M}}(h \to \alpha)\right|^2 \Theta\left[\chi - \chi_{\mathrm{min}}\right]$$

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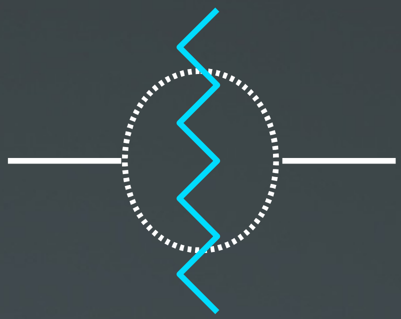

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⇒ Production of Scalars, Fermions, Vector Bosons.

$$\mathrm{Im}\left[\tilde{\Gamma}^{(2)}(\chi)\right]_S = \frac{\lambda_s^2 v^2}{8\pi}\sqrt{1-4\frac{m_s^2}{\chi}}\;\Theta\left(\chi - 4m_s^2\right)$$

$$\mathrm{Im}\left[\tilde{\Gamma}^{(2)}(\chi)\right]_f = \frac{m_f^2}{4\pi v^2}\,\chi\left(1-\frac{4m_f^2}{\chi}\right)^{\frac{3}{2}}\Theta\left(\chi - 4m_f^2\right)$$

$$\mathrm{Im}\left[\tilde{\Gamma}^{(2)}(\chi)\right]_V = \frac{\lambda_V^2 m_V^2}{8\pi}\left(3-\frac{\chi}{m_V^2}+\frac{\chi^2}{4m_V^4}\right)\sqrt{1-4\frac{m_V^2}{\chi}}\;\Theta\left(\chi - 4m_V^2\right)$$

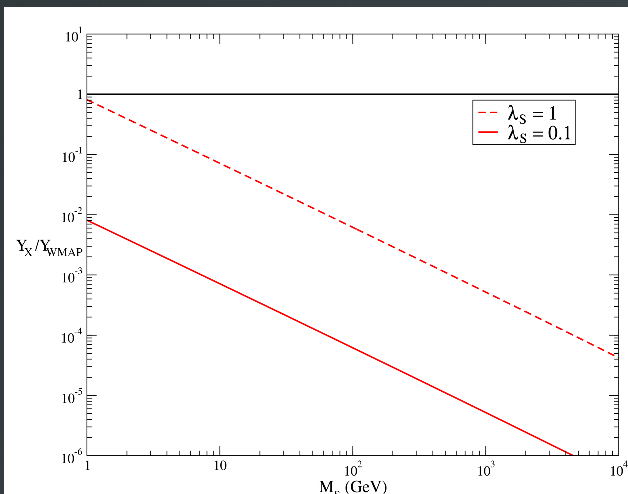
→ If effective coupling to the Higgs, production suppressed.

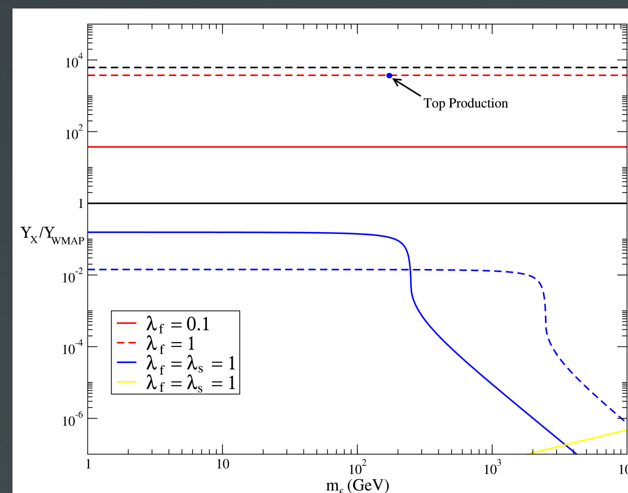
Bubble collisions excite very massive field modes $p^2 \gg \Lambda^2$ (eff. description breaks down)

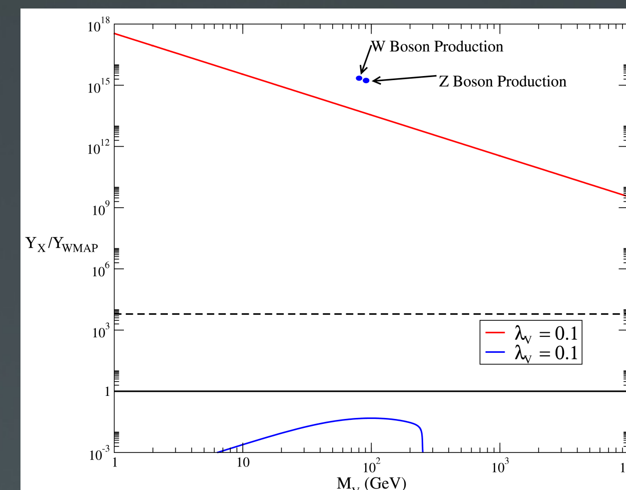
→ Possible Issues with Backreaction.

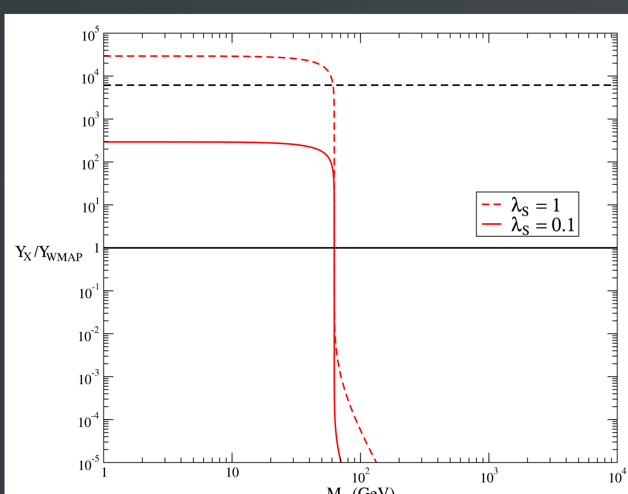
❷ Particle Production

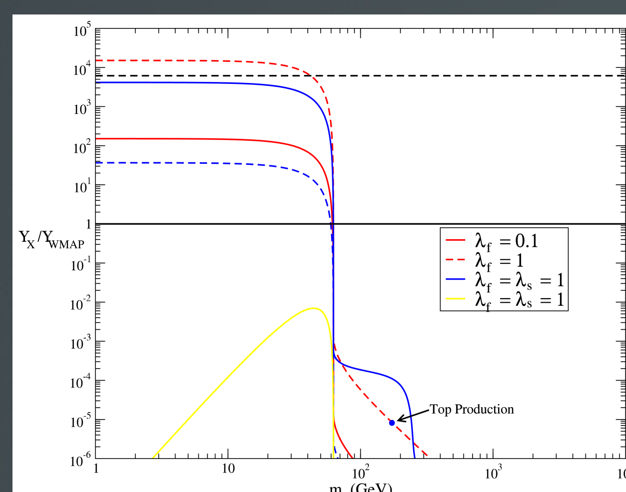
⇒ Production of Scalars, Fermions, Vector Bosons.

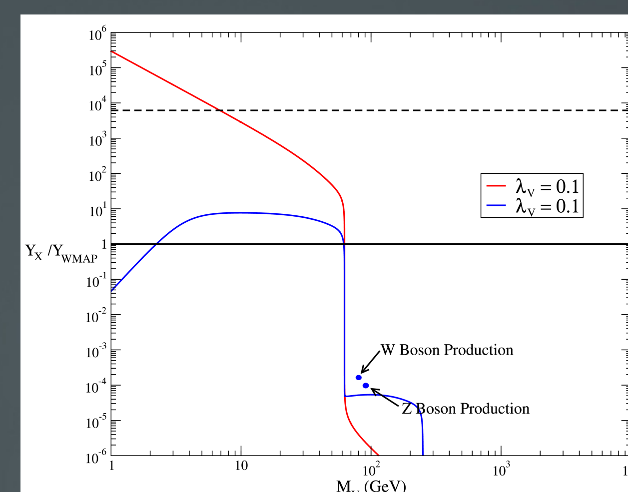






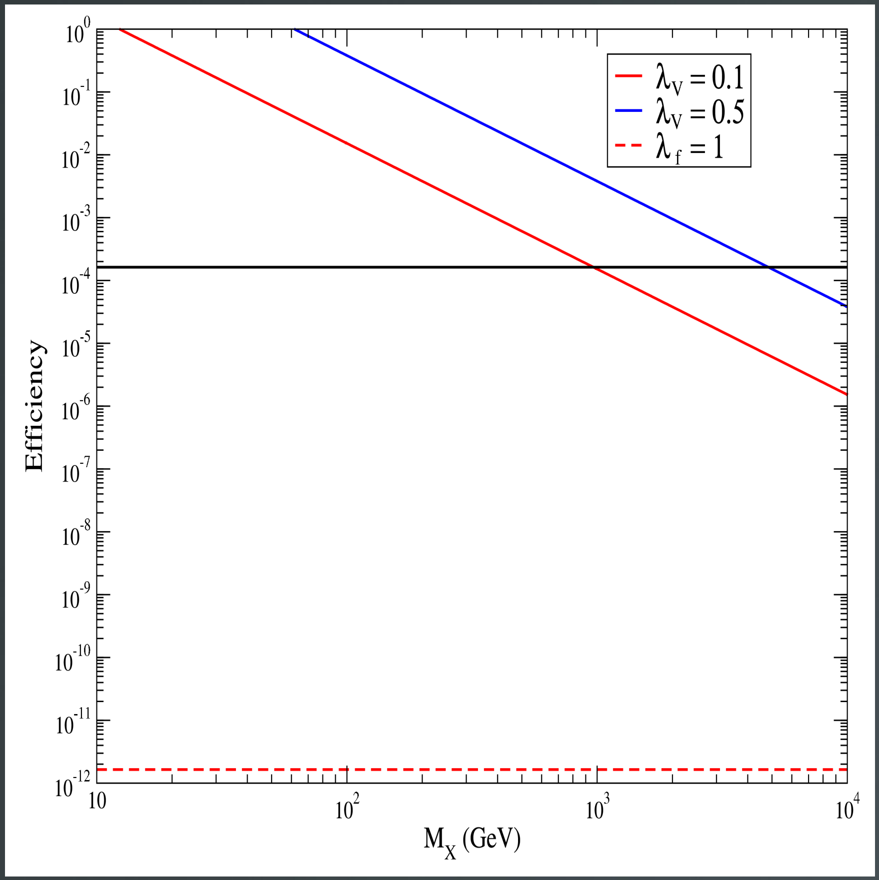


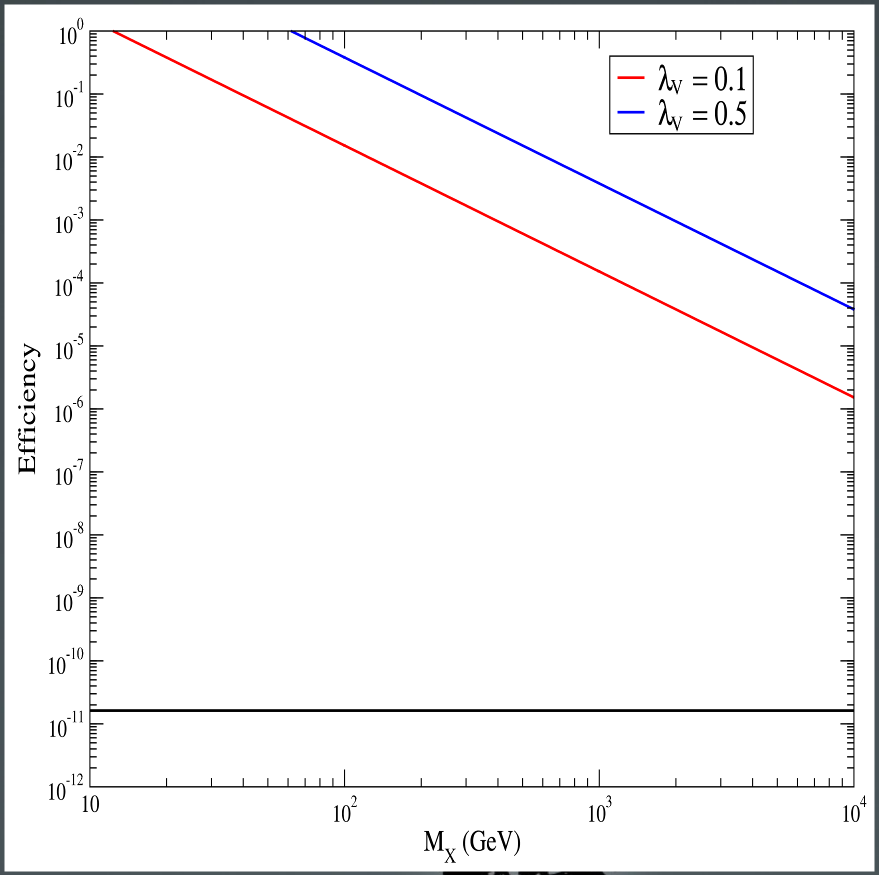




❷ Particle Production

⇒ Production of Scalars, Fermions, Vector Bosons.





Non-Thermal Dark Matter

→ Relatively Elastic Collisions

→ Dark Matter is a Heavy Vector Boson V_μ (with direct coupling to Higgs)

❶ $m_V \sim$ TeV ⇨ V_μ is a heavy WIMP

Possibilities: Kaluza-Klein DM, Little Higgs DM...

❷ $m_V \gg$ TeV ⇨ Baby-Zillas

Non-Thermal muti-TeV WIMPs

$$\mathcal{L}_V = \frac{1}{2} m_V^2 V_\mu V_\mu + \lambda_V v_T h V_\mu V_\mu$$

Non-thermal DM Production

Thermal Abundance

$$\left[\frac{\lambda_V}{M_V(\mathrm{TeV})}\right]_{\mathrm{WMAP}} \approx 0.3$$

Direct Detection

$$\sigma_{VN\to VN} \approx 4.2\cdot 10^{-44}\mathrm{cm}^2 \left[\frac{\lambda_V}{M_V(\mathrm{TeV})}\right]^2 < M_V \cdot 2.2\cdot 10^{-44}\mathrm{cm}^2$$

XENON bound

Non-Thermal muti-TeV WIMPs

$$\mathcal{L}_V = \frac{1}{2} m_V^2\, V_\mu V_\mu + \lambda_V v_T h V_\mu V_\mu$$

Non-thermal DM Production ($\gamma_w \sim 10^8$)

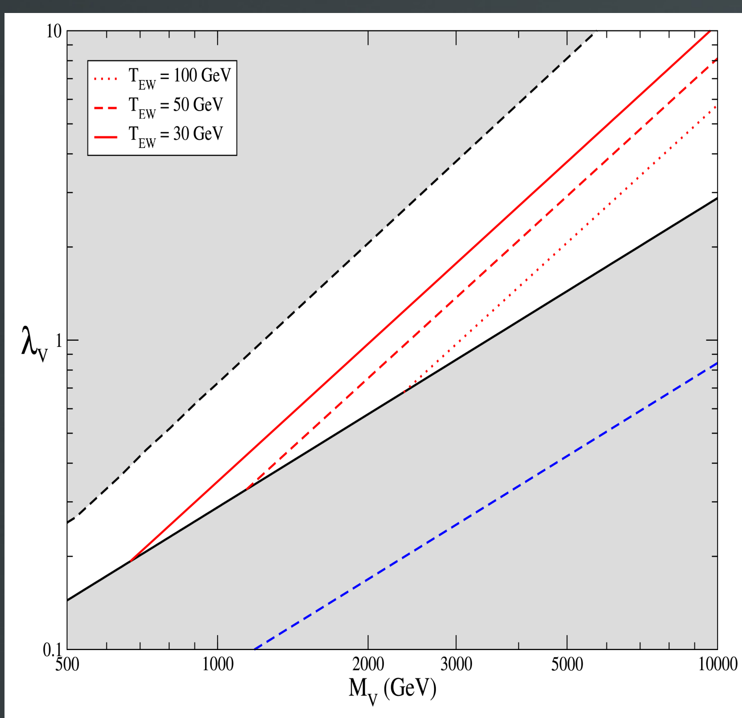
Thermal Abundance

$$\left[\frac{\lambda_V}{M_V(\mathrm{TeV})}\right]_{\mathrm{WMAP}} \approx 0.3$$

Direct Detection

$$\sigma_{VN\to VN} \approx 4.2\cdot 10^{-44}\mathrm{cm}^2 \left[\frac{\lambda_V}{M_V(\mathrm{TeV})}\right]^2 < M_V\cdot 2.2\cdot 10^{-44}\mathrm{cm}^2$$

XENON bound



$$\frac{dY}{dz} = -\alpha \frac{\langle \sigma\, v\rangle M_{\mathrm{Pl}} M_V}{z^2} Y(z)^2 \longrightarrow \frac{dy}{dz} = -\frac{1}{z^2} y^2(z) \longrightarrow \frac{1}{y(z)} - \frac{1}{y(z_{\mathrm{EW}})} = \frac{1}{z_{\mathrm{EW}}} - \frac{1}{z}$$

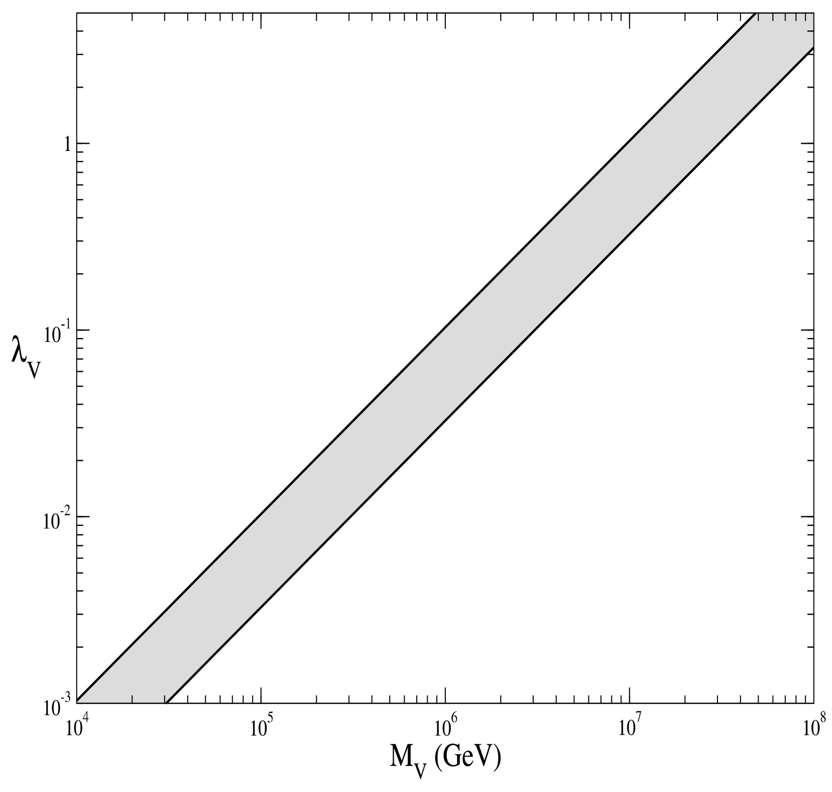
$$y(\infty) \simeq z_{\mathrm{EW}}$$

$$\langle \sigma\, v\rangle = \langle \sigma\, v\rangle_{\mathrm{WMAP}} \frac{T_{\mathrm{fo}}}{T_{\mathrm{EW}}}$$

Non-thermal "WIMP miracle"

Non-Thermal Baby-Zillas

→ If $\gamma_w \sim \gamma_{max} \sim 10^{15}$, possible to produce $m_V \gg$ TeV



$$M_{\mathrm{GUT}} \gg M_V \gg v$$

Baby-Zillas

$$T_{\mathrm{RH}} < M_V/10$$

Low Reheating T after Inflation Required

Conclusions

- → Efficient Particle Production in Strongly 1^{st} Order EW Phase Transitions

- → Possible Non-thermal Production of Vector DM
  - ⇨ Multi-TeV WIMP's **Kaluza-Klein DM, Little Higgs DM...**
  - ⇨ Baby-Zillas