# Gravitational wave signals of DM freeze-out

**Po-Yan Tseng (NTHU)**
**Danny Marfatia (U. of Hawaii)**

**Reference: JHEP02(2021)022 (arXiv:2006.07313)**

**Asia-Pacific Workshop on Particle Physics and Cosmology**
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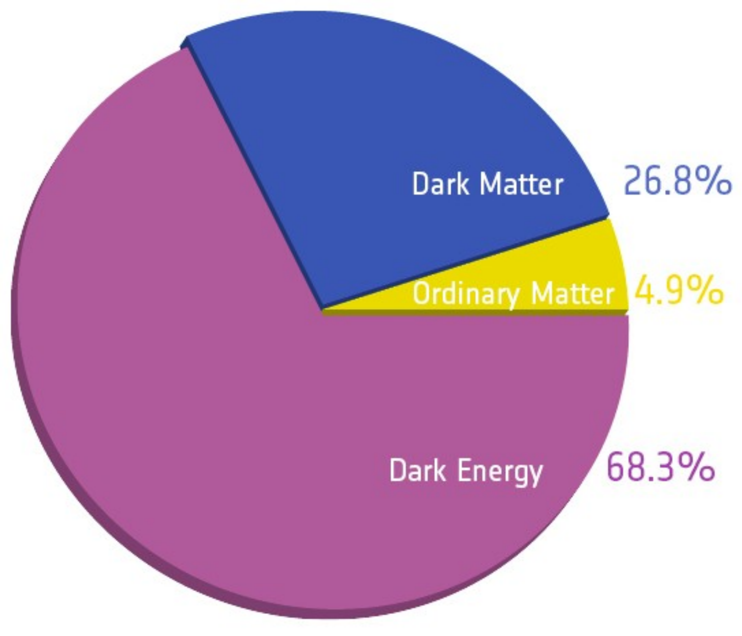
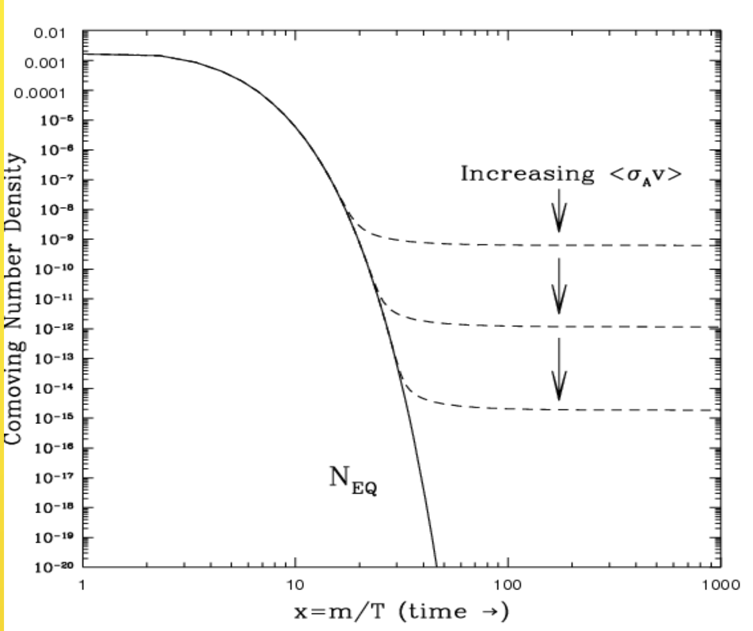
# Introduction

- DM production: **Thermal freeze-out** mechanism.
- Weakly interacting massive DM (WIMP), gives the correct relic density.




Planck collaboration




Dan Hooper: 0901.4090

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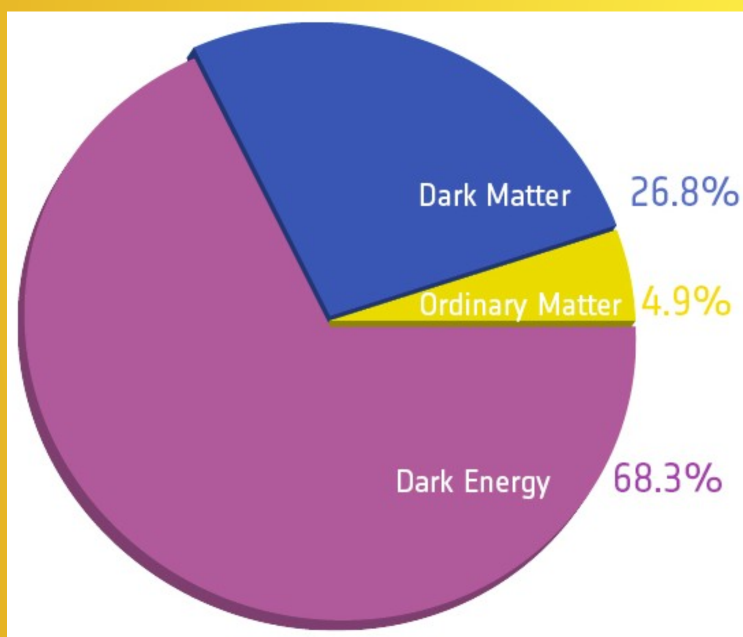


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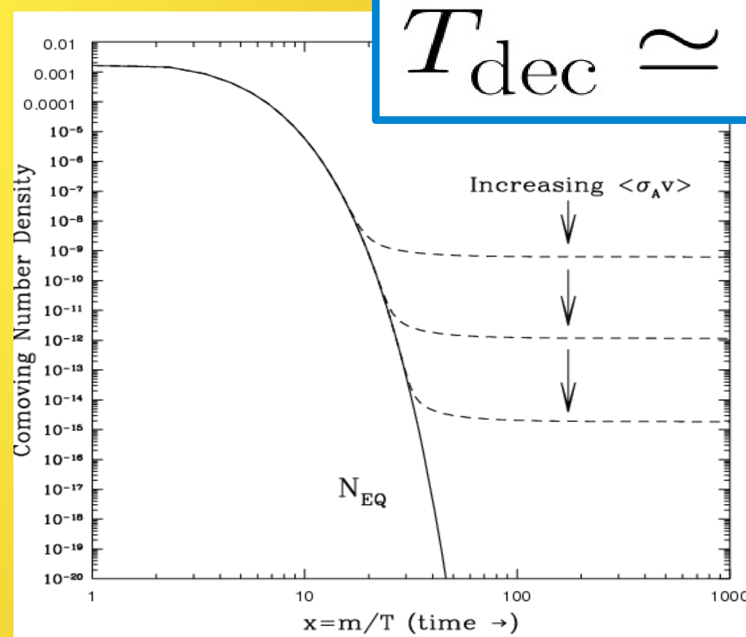
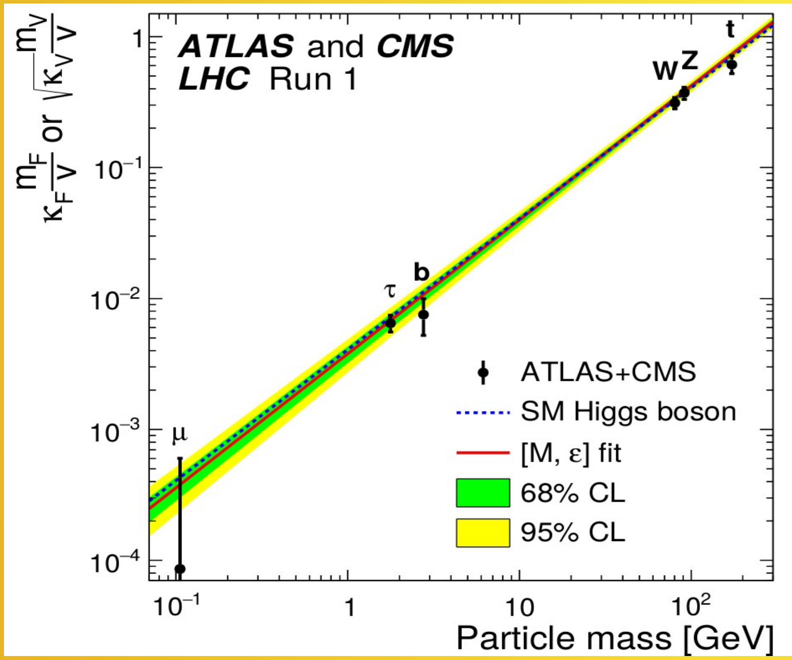


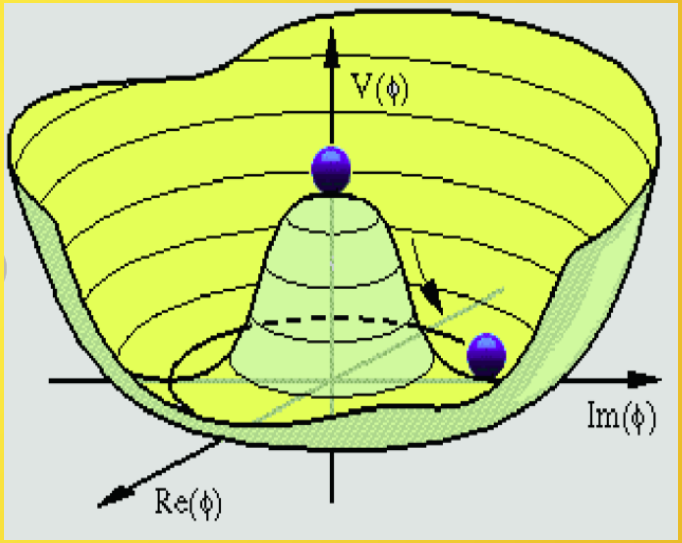

$$T_{\mathrm{dec}} \simeq \frac{m_\chi}{25}$$

Dan Hooper: 0901.4090

# Introduction

- 125 GeV Higgs gives the mass to the SM particles through **spontaneous symmetry breaking**.




Dezso Horvath: Higgs and BSM studies at the LHC

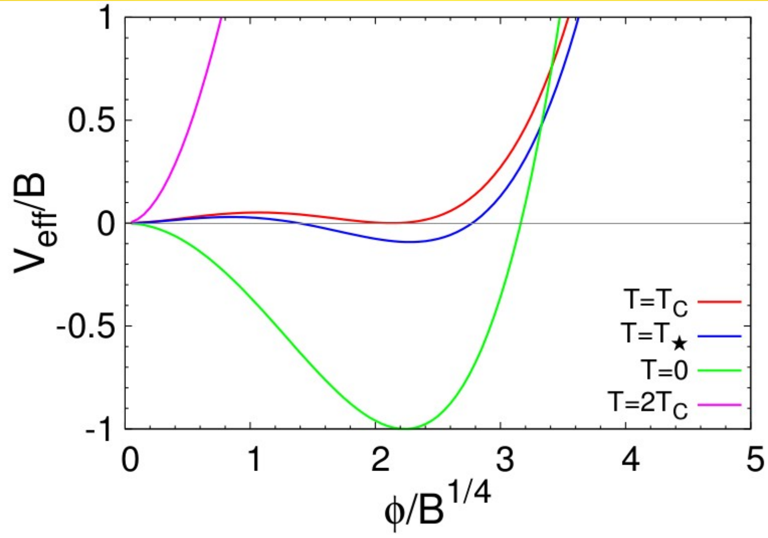
# Introduction

- The origin of DM mass may come from the **spontaneous symmetry breaking** inducing by another scalar.

$$\boxed{\mathcal{L} \supset \bar{\chi} i \partial\!\!\!/ \chi - g_\chi \phi \bar{\chi}\chi - V_{\rm eff}(\phi, T)}$$

$$\boxed{m_\chi \simeq g_\chi \langle \phi \rangle}$$

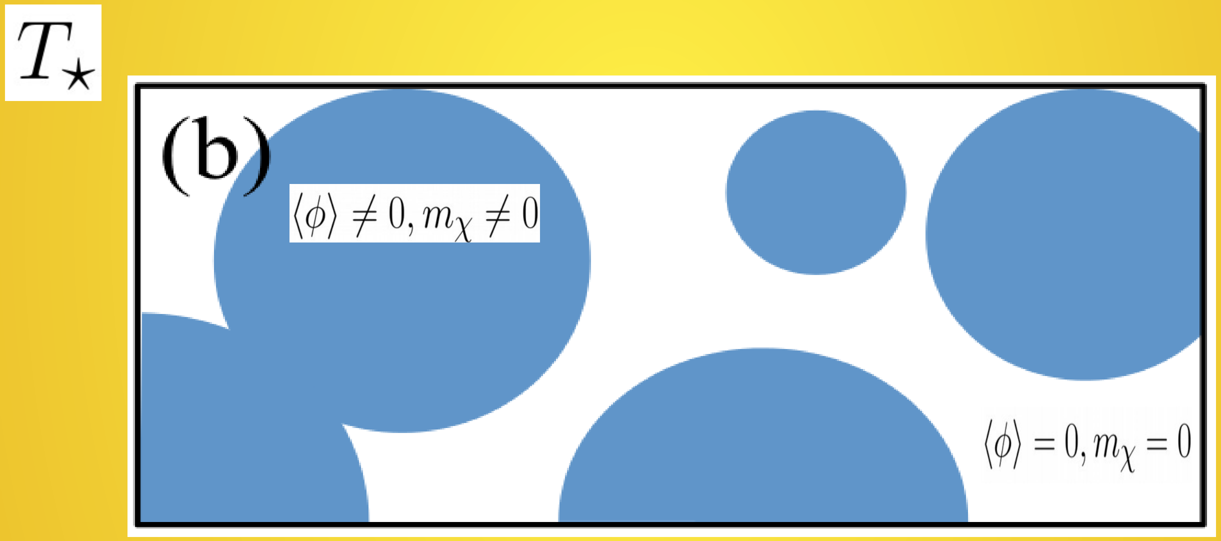
- We consider **1st order phase transition (FOPT)**.




D.Marfatia, P.Y.Tseng

# Introduction

- During **1st order phase transition (FOPT)**.




J.P.Hong, S.Jung, K.P.Xie: 2008.04430

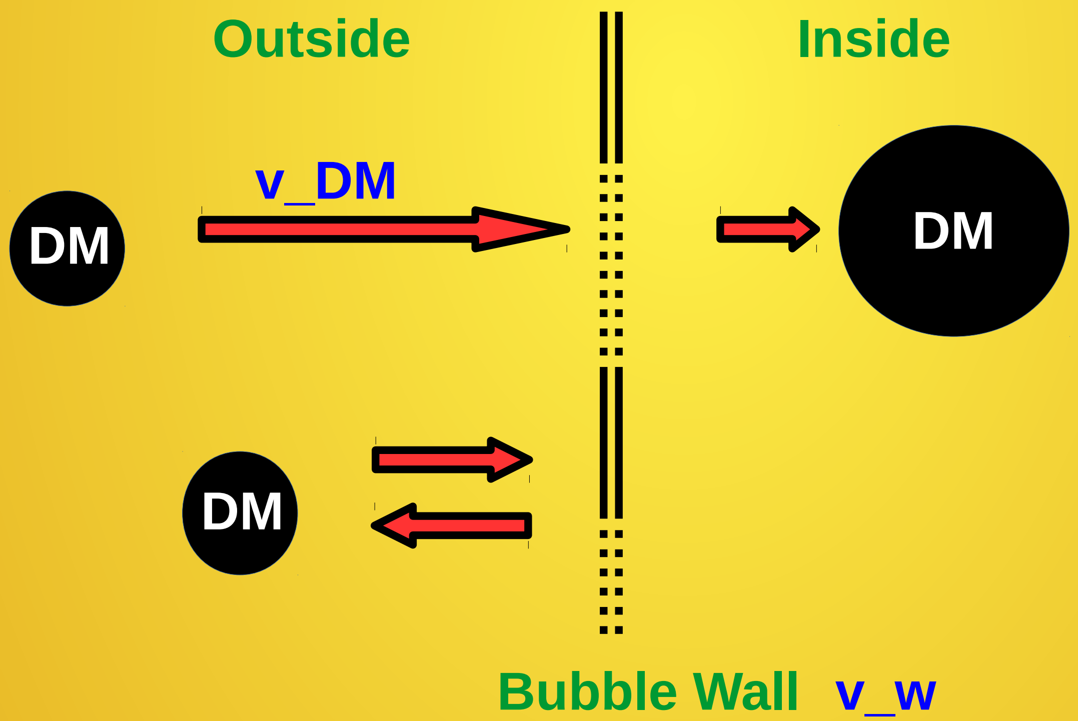
# Outline

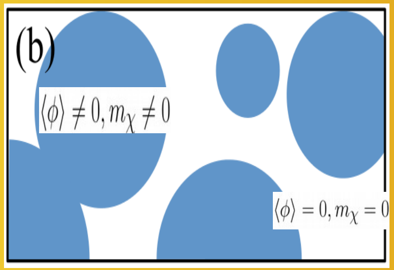
- Introduction
- Bubble filtering
- Gravitational wave production
- Models
- Summary

# Bubble filtering

# Bubble filtering

- During **FOPT**, massless (massive) DM particles locate outside (inside) the bubble, and momentum conservation much be satisfied at the **bubble wall**.



# Bubble filtering

- If a thermal DM flux is incident on the wall, the number density of DM that enter the bubble is:

$$\boxed{n_\chi^{\rm in} = n_{\bar\chi}^{\rm in} \simeq \frac{g_{\rm DM} T_\star^3}{\gamma_w v_w} \left( \frac{\gamma_w (1-v_w) m_\chi / T_\star + 1}{4\pi^2 \gamma_\omega^3 (1-v_w)^2} \right) e^{-\frac{\gamma_w (1-v_w) m_\chi}{T_\star}}}$$

D.Chway, T.H.Jung, C.S.Shin: 1912.04238

- **DMs are filtered** by the non-relativistic and relativistic bubble wall velocity:

$$\boxed{n_\chi^{\rm in} = \begin{cases} \sim e^{-m_\chi/T_\star} & \text{for } \; v_w \to 0 \\ \sim e^{-m_\chi/(2\gamma_w T_\star)} & \text{for } \; m_\chi/(\gamma_w T_\star) \to 0 \end{cases}}$$

# Bubble filtering

- If $T_\star < T_{\rm dec}$ , the DM inside the bubble is decoupled from the thermal bath and become DM relic abundance.

- DM relic abundance today can be calculated by dividing $n_\chi^{\rm in} + n_{\bar\chi}^{\rm in}$ by entropy $s = (2\pi^2/45) g_{\star S} T^3$ :

$$\boxed{\Omega_{\rm DM} h^2 \simeq 6.29 \times 10^8 \, \frac{m_\chi (n_\chi^{\rm in} + n_{\bar\chi}^{\rm in})}{\rm GeV} \frac{1}{g_{\star S} T_\star^3}}$$

$$\boxed{\Omega_{\rm DM} h^2 \simeq \begin{cases} 1.27 \times 10^8 \left(\frac{m_\chi}{\rm GeV}\right) \left(\frac{g_{\rm DM}}{g_{\star S}}\right) \left(\frac{m_\chi}{2\gamma_w T_\star} + 1\right) e^{-\frac{m_\chi}{2\gamma_w T_\star}} \,, & \text{for } v_w \to 1 \\ 3.19 \times 10^7 \left(\frac{m_\chi}{\rm GeV}\right) \left(\frac{g_{\rm DM}}{g_{\star S}}\right) \left(\frac{1}{v_w}\right) \left(\frac{m_\chi}{T_\star} + 1\right) e^{-\frac{m_\chi}{T_\star}} \,, & \text{for } v_w \to 0. \end{cases}}$$

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- For example: $m_\chi \simeq 1\ \mathrm{TeV},\ v_w \to 1$ requires

$$\boxed{\frac{m_\chi}{2\gamma_w T_\star} \simeq 27}$$

# Bubble filtering

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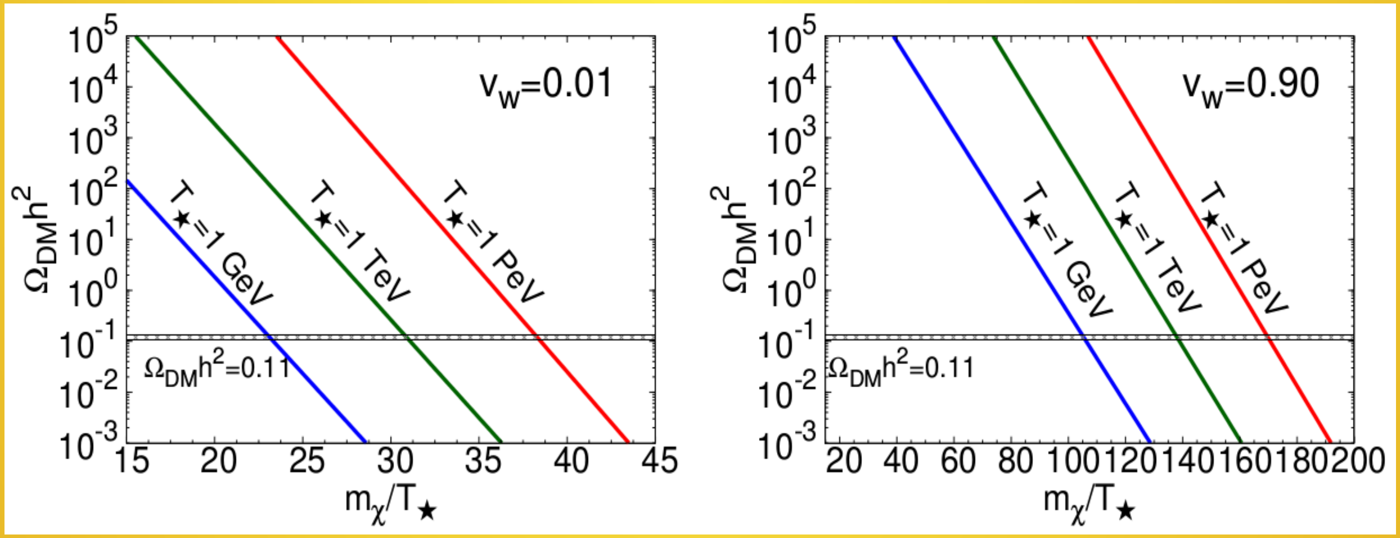

# Introduction

- **Sudden DM freeze-out** induced by a FOPT can easily accommodate DM mass above a **PeV,** which is beyond the current DM direct detection and LHC searches.

- We focus on the **Gravitational Wave (GW)** signals of **Sudden DM freeze-out** with a **FOPT**.

# Gravitational wave production

# Gravitational wave production

- A **FOPT** generates GWs from three processes: I). Bubble collisions, II). Sound wave in the plasma, III) Magnetohydrodynamic (MHD) turbulence.
- The relevant parameters are required to calculate the GW signals:

$$\begin{cases} T_\star\,, \\ \alpha \equiv \dfrac{\left(1 - T\frac{\partial}{\partial T}\right)\Delta V_{\rm eff}|_{T_\star}}{\rho(T_\star)}\,, \quad \rho \equiv \pi^2 g_\star T^4/30 \\ \dfrac{\beta}{H_\star} \simeq T_\star \dfrac{d(S_3/T)}{dT}\Big|_{T_\star} \\ v_w \end{cases}$$

# Gravitational wave production

- A **FOPT** generates GWs from: I). Bubble collisions

$$h^2\Omega_{\rm env}(f) \quad = \quad 1.67\times 10^{-5}\,\left(\frac{H_*}{\beta}\right)^2\left(\frac{\kappa\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{\frac{1}{3}}\left(\frac{0.11\,v_w^3}{0.42+v_w^2}\right)\,S_{\rm env}(f)$$

C.Caprini et. al: 1512.06239

$$S_{\rm env}(f) = \frac{3.8\,(f/f_{\rm env})^{2.8}}{1+2.8\,(f/f_{\rm env})^{3.8}}$$

- The peak frequency is determined by the time scale of **FOPT** $1/\beta$ :

$$\frac{f_*}{\beta} = \left(\frac{0.62}{1.8-0.1v_w+v_w^2}\right)$$

# Gravitational wave production

- A **FOPT** generates GWs from: I). Bubble collisions

$$h^2\Omega_{\rm env}(f) \;=\; 1.67\times 10^{-5}\left(\frac{H_*}{\beta}\right)^2\left(\frac{\kappa\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{\frac{1}{3}}\left(\frac{0.11\,v_w^3}{0.42+v_w^2}\right)S_{\rm env}(f)$$

C.Caprini et. al: 1512.06239

$$S_{\rm env}(f) = \frac{3.8\,(f/f_{\rm env})^{2.8}}{1+2.8\,(f/f_{\rm env})^{3.8}}$$

- The peak frequency is determined by the time scale of **FOPT.** Then red-shift to present epoch

$$f_{\rm env} = 16.5\times 10^{-3}\,{\rm mHz}\left(\frac{f_*}{\beta}\right)\left(\frac{\beta}{H_*}\right)\left(\frac{T_*}{100\,{\rm GeV}}\right)\left(\frac{g_*}{100}\right)^{\frac{1}{6}}$$

# Model

# Model: Scalar quartic Model

- The **finite-temperature** quartic effective scalar potential is:

$$\boxed{V_{\rm eff}(\eta, T) = \frac{\mu^2 + DT^2}{2}\eta^2 - \xi T\eta^3 + \frac{\lambda}{4}\eta^4}$$

F.C.Adams: hep-ph/9302321

- Including one-loop Coleman-Weinberg and finite-temperature contributions, potentials of this form are commonly found in *inert singlet, inert doublet, MSSM, and Majoron models*.

# Models: Scalar quartic Model

- The **finite-temperature** quartic effective scalar potential is:

$$\boxed{V_{\text{eff}}(\eta, T) = \frac{\mu^2 + DT^2}{2}\eta^2 - \xi T \eta^3 + \frac{\lambda}{4}\eta^4}$$

- Benchmark points:

**Table 1.** Benchmark points (with $\lambda = 0.1$) for the Scalar Quartic Model that give $\Omega_{\rm DM}h^2 = 0.11$.

| | **P1** | **P2** | **P3** | **P4** |
|---|---|---|---|---|
| $\xi$ | 0.943 | 0.863 | 0.796 | 0.901 |
| $D$ | 19.7 | 16.5 | 14.0 | 18.0 |
| $g_\chi$ | 2.97 | 3.22 | 3.48 | 3.31 |
| $\alpha$ | 0.089 | 0.082 | 0.076 | 0.121 |
| $\beta/H_\star$ | 1116 | 1062 | 1015 | 1085 |
| $v_\eta/T_\star$ | 25.71 | 23.41 | 21.49 | 24.51 |
| $v_w$ | 0.768 | 0.763 | 0.760 | 0.791 |
| $T_\star/\text{GeV}$ | 21.5 | 23.8 | 26.1 | 22.7 |
| $m_\chi/\text{GeV}$ | 1642 | 1799 | 1953 | 1838 |

D.Marfatia, P.Y. Tseng: 2006.07313

# Models: Scalar quartic Model

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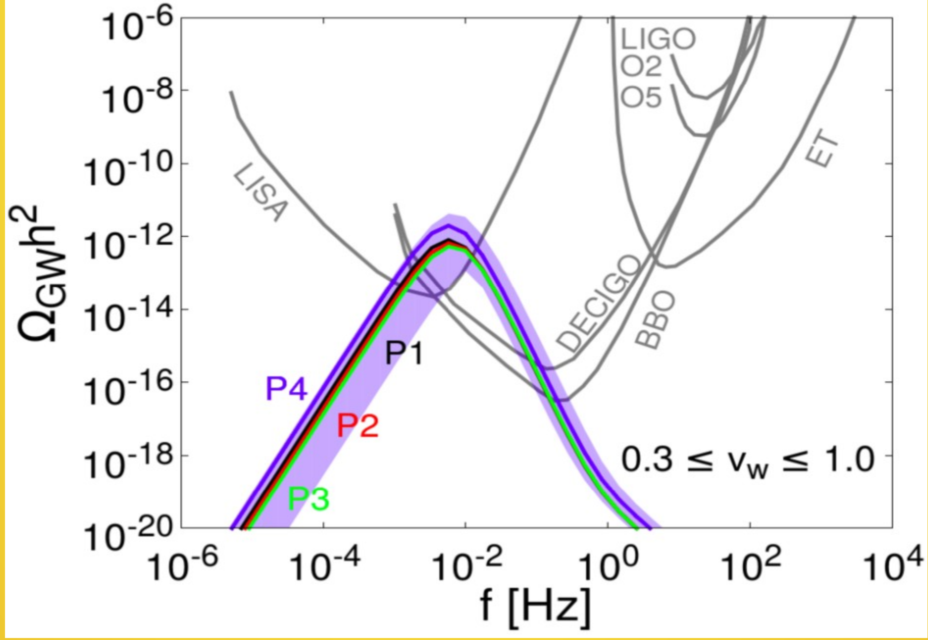
- GW signals:




D.Marfatia, P.Y. Tseng: 2006.07313

# Summary

- We studied the **sudden freeze-out DM** as an alternative to the continuous thermal freeze-out.
- A necessary ingredient is a **FOPT** generates DM mass.
- The DM relic abundance may be determined by bubble filtering.
- Because **FOPT** triggers sudden DM freeze-out, **GW** offers a signature.

Thank you!

# Back up

# Introduction

- Only massless **DM** particles carry kinetic energy larger than $m_\chi$ can penetrate the bubble walls and become massive.

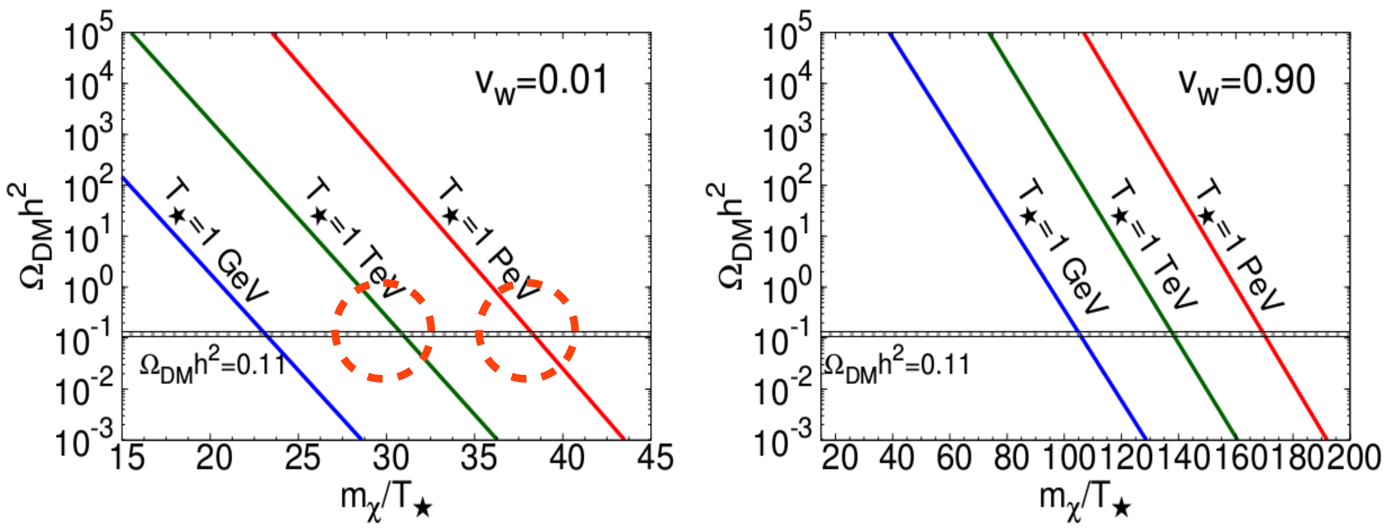
- DM inside the bubbles abruptly decouples from the thermal bath if $\boxed{T_\star < T_{\rm dec}}$ .

- The bubbles ***filter out*** certain amount of DM and determine the **DM relic abundance**.

# Introduction

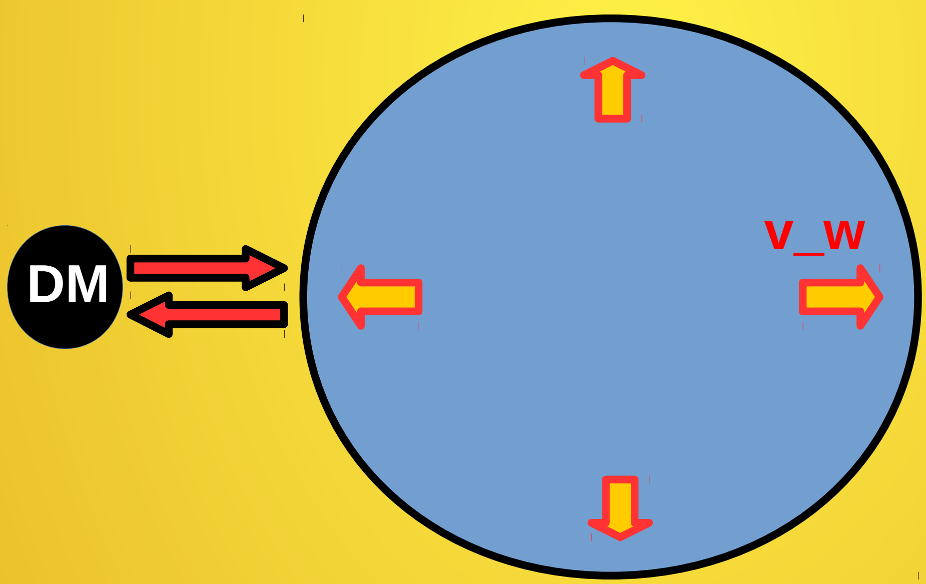
- The $m_\chi/T_\star$ needed to produce the DM relic abundance depends on the velocity of bubble wall $v_w$.

$$\boxed{T_\star = m_\chi/30 \text{ for } m_\chi = 1\text{ TeV}, v_w = 0.01}$$



# Bubble wall velocity

- Particles reflected by the bubble wall exert pressure on it, and slow down the bubble wall velocity.



# Bubble wall velocity

- In the ultrarelativistic limit, the **pressure** on bubble wall can be obtain from the light degree of freedom inside and outside the bubble:

$$P = \frac{d_n g_\star \pi^2}{90}(1+v_w)^3 \gamma_\omega^2 T_\star^4$$

$$d_n \equiv \frac{1}{g_\star}\left[\sum_{0.2M_i > \gamma_w T_\star} \left(g_i^b + \frac{7}{8} g_i^f\right)\right]$$

D.Chway et.al : 1912.04238
J.R.Espinosa et.al: 1004.4187
D.Bodeker et.al : 0903.4099

- The $v_w$ can be obtained by solving the eq. $P = \Delta V_{\rm eff}$ :

$$\alpha = \frac{d_n}{3}(1+v_w)^3 \gamma_\omega^2$$

$$\alpha \equiv \frac{\left(1 - T\frac{\partial}{\partial T}\right)\Delta V_{\rm eff}|_{T_\star}}{\rho(T_\star)}, \quad \rho \equiv \pi^2 g_\star T^4/30$$

# Bubble wall velocity

- For bubble wall velocity $v_w$ faster than the sound speed in plasma, but not ultrarelativistic, we use the approximation:

P.J.Steinhardt, Phys. Rev. D. 25, 2074 (1982)

$$\boxed{v_w = \frac{\frac{1}{\sqrt{3}} + \sqrt{\alpha^2 + \frac{2}{3}\alpha}}{1+\alpha}}$$

# Gravitational wave production

- A **FOPT** generates GWs from three processes: I). Bubble collisions, II). Sound wave in the plasma, III) Magnetohydrodynamic (MHD) turbulence.
- The Euclidean action:

$$\boxed{S_3(T) = 4\pi \int_0^\infty r^2 dr \left[ \frac{1}{2} \left( \frac{d\phi}{dr} \right)^2 + V_{\text{eff}}(\phi, T) \right]}$$

- Bubble nucleation rate per unit volume:

$$\boxed{\Gamma(T) = T^4 \left( \frac{S_3}{2\pi T} \right)^{3/2} e^{-\frac{S_3}{T}}}$$

# Gravitational wave production

- A **FOPT** generates GWs from three processes: I). Bubble collisions, II). Sound wave in the plasma, III) Magnetohydrodynamic (MHD) turbulence.
- The fraction of space in the false vacuum:

$$\boxed{F(t) = \exp\left[-\frac{4\pi}{3} v_w^3 \int_{t_c}^{t} dt'(t-t')^3 \Gamma(t')\right]}$$

- The percolation temperature $T_\star$ of **FOPT** is determined by :

$$\boxed{F(t_\star) = 1/e \simeq 0.37}$$

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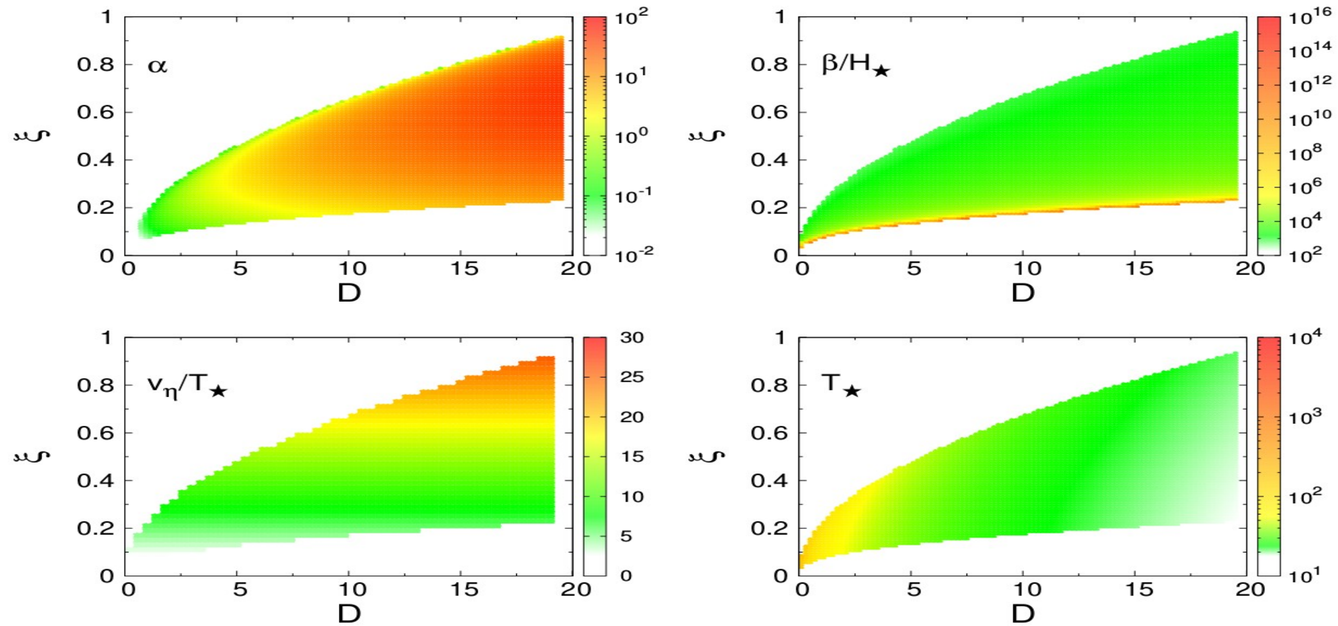


**Figure 2.** The parameters $\alpha$, $\beta/H$, $v_\eta/T_\star$, and $T_\star$ for the Scalar Quartic Model with $\lambda = 0.1$.

D.Marfatia, P.Y. Tseng: 2006.07313

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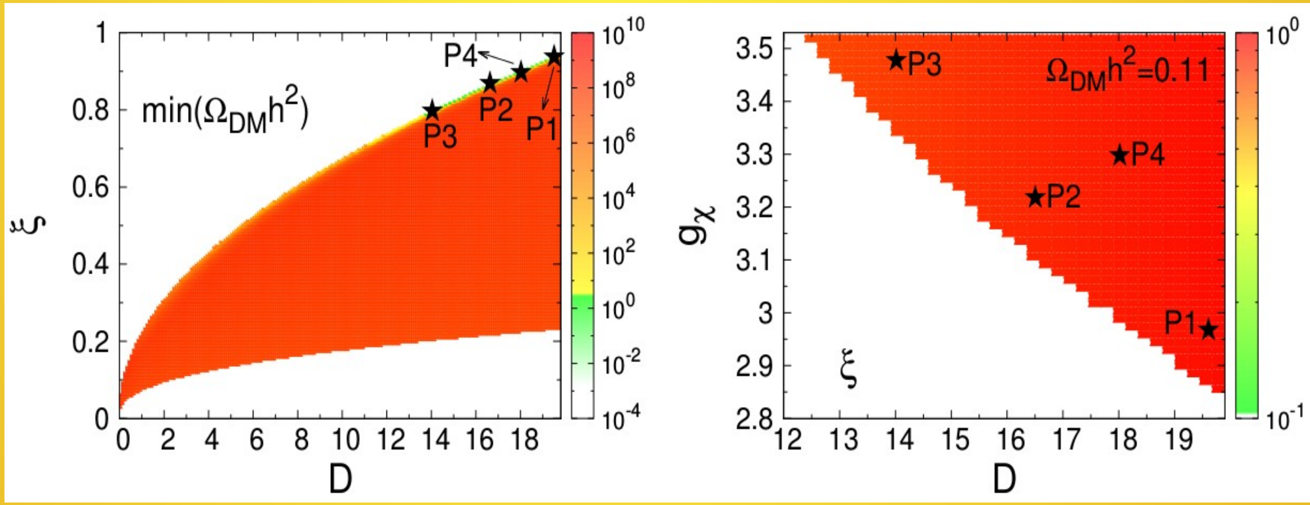
- Correct DM relic:




D.Marfatia, P.Y. Tseng: 2006.07313

# Models: SU(2)x model

- In this dimensionless model, the SM gauge group is extended by as SU(2)x