Production of heavy states via relativistic bubble expansion

2010.02590 and 2101.05721
with Aleksandr Azatov and Wen Yin

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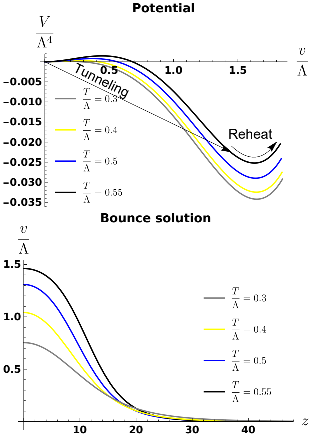
Nucleation and early expansion

- Nucleation at critical radius $R_c \sim \frac{1}{T_n}$



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- Approximate solution of eq. of motion

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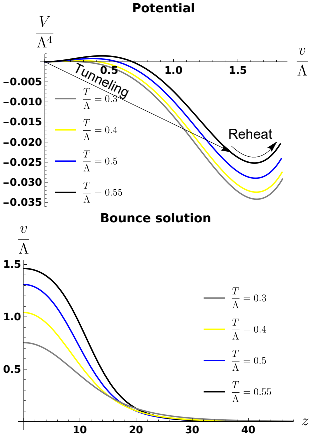

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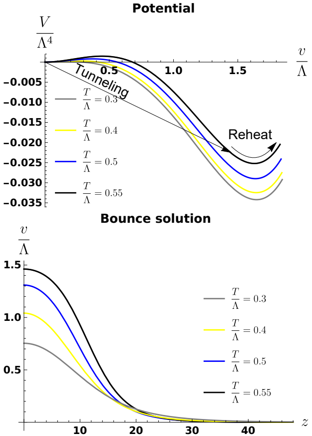

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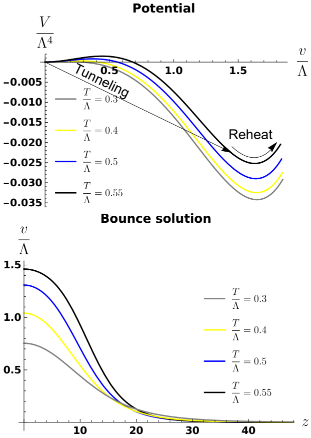
- Pressureless expansion

$$\gamma_{wp} \equiv \frac{1}{\sqrt{1 - v_w^2}} \quad \Rightarrow \gamma_{wp} \propto R$$



Velocity

- Terminal velocity regime: $\Delta V = \Delta\mathcal{P}(\gamma_{wp}^{MAX})$ $\Rightarrow$ GW signal from sound waves
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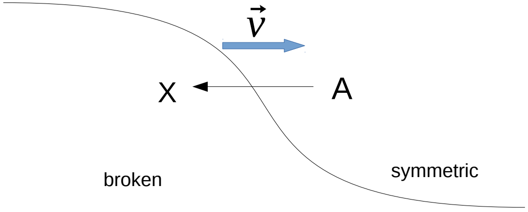

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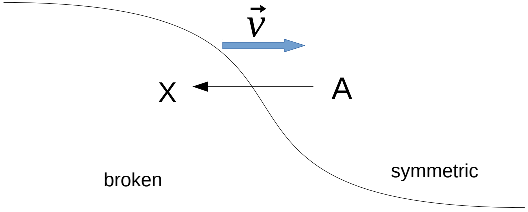

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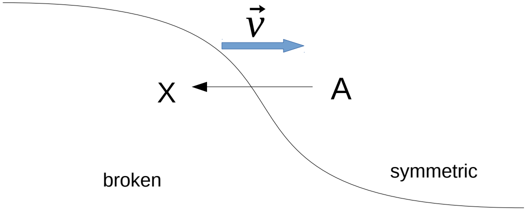
- Regime $\gamma \gg 1$ $\mathcal{C} \to 0$: Collisionless system of quasi-particles
- Pressure on the wall [2010.02590]

$$\mathcal{P} = \int \frac{p_z d^3 p}{p_0 (2\pi)^3} f_A(p) \times \sum_X \int dP_{A\to X}(p_A^Z - p_X^Z)$$



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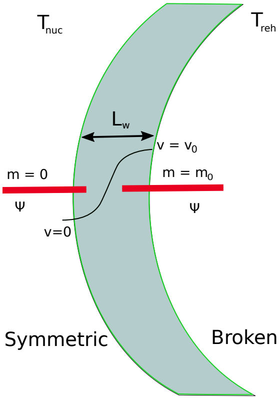

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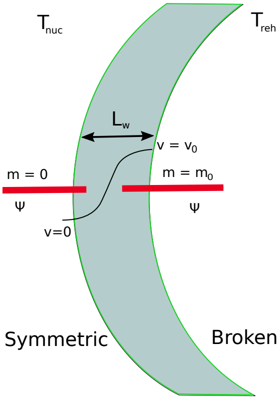
- LO relativistic pressure [0903.4099]

$$\int dP_{i\to i} \to 1, \qquad (p^Z_{i,out} - p^Z_{i,in}) \approx \frac{\Delta m_i^2}{2E}$$

$$\Rightarrow \boxed{\mathcal{P}_{1\to 1} \to \sum_i \frac{\Delta m_i^2 T^2}{24} c_i},$$

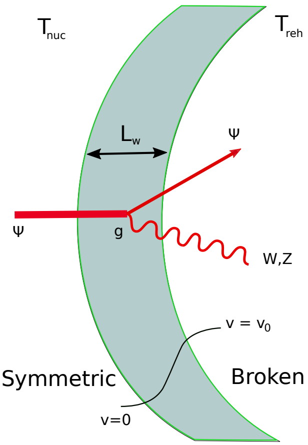
$$\Delta m_i^2 \equiv m^2_{bro,i} - m^2_{sym,i}$$



Pressure by splitting

- NLO relativistic pressure; gauge bosons V[1703.08215]

$$E_{\psi} \sim p_{z,\psi} \sim \gamma_{wp} T \gg T \quad \text{WKB applicable} \quad \frac{dp_z}{dz} \ll p_z^2$$



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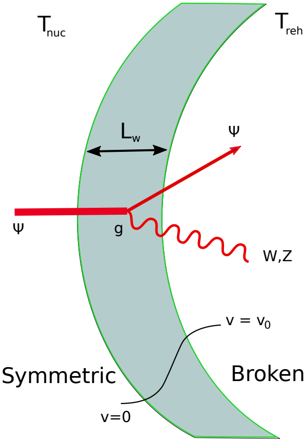

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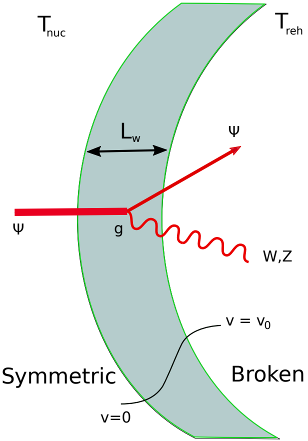

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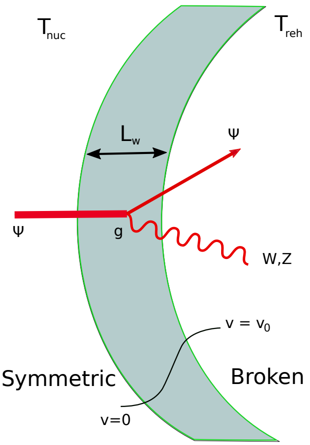
$$\Rightarrow \boxed{\mathcal{P}_{1\to 2} \sim \sum_i g_i \frac{g^3 v}{16\pi^2} \gamma_{wp} T^3}$$



Pressure by mixing with heavy states[2010.02590]

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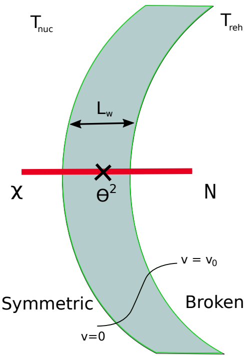

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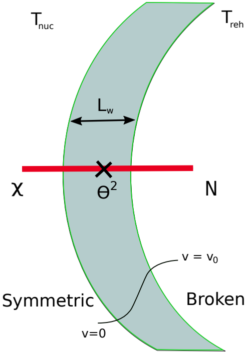

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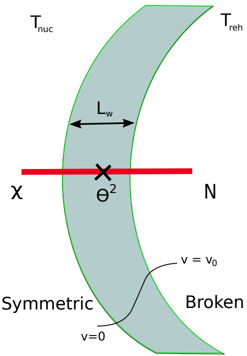

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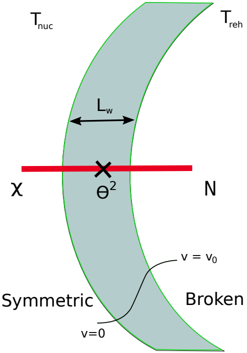

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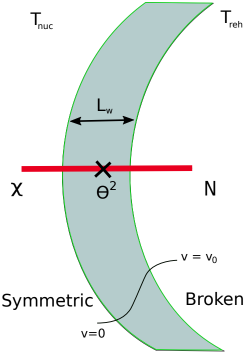

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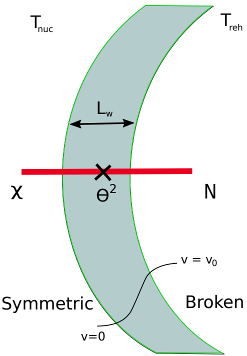

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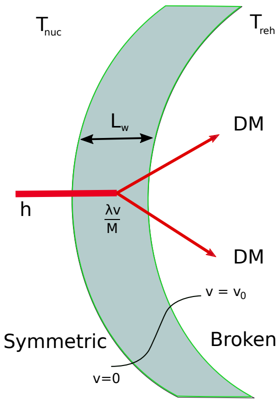
$$\Delta\mathcal{P}_{mixing} \approx \frac{Y^2 T^2 v^2}{48}\Theta(\gamma_{wp}T - M_N^2 L_w)$$

Pressure depends on M_N only in the Θ-function

Production mechanism[2101.05721]

- Portal Dark Matter: $\mathcal{L} \supset -\frac{\lambda}{2} h^2 \phi^2 - M_\phi^2 \phi^2 - V(h)$



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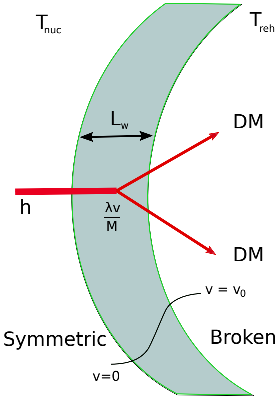

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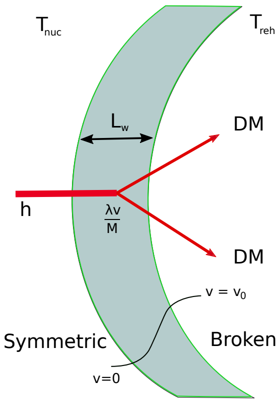

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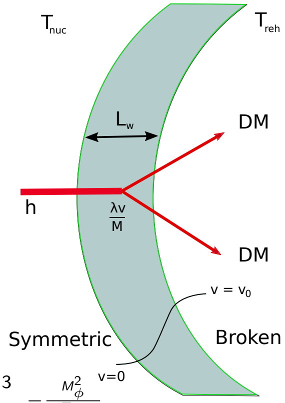
- Behind the wall, accumulation of relics ϕ

$$n_\phi^{\text{BE}} \approx \frac{T^3}{12\pi^4}\frac{\lambda^2 v^2}{M_\phi^2} e^{-\frac{M_\phi^2}{2vT\gamma_{wp}}} + \mathcal{O}(1/\gamma_w)$$

$$\Rightarrow \Omega_{\phi,\text{BE}}^{\text{today}} h^2 \approx 5.4\times10^5 \times \left(\frac{1}{g_{\star S}(T_{\text{reh}})}\right)\left(\frac{\lambda^2 v}{M_\phi}\right)\left(\frac{v}{\text{GeV}}\right)\left(\frac{T_{\text{nuc}}}{T_{\text{reh}}}\right)^3 e^{-\frac{M_\phi^2}{2vT\gamma_{wp}}}$$



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- Generalisation to $1 \to 2$: interesting for generation of DM
- Caveat: wall suppression for $\Delta p_z L_w > 1$

Back up

Back up slides

Can γ_{wp} be large enough to produce ϕ of M_ϕ?

Transition strong enough : $\boxed{\Delta V > \Delta \mathcal{P}_{LO}}$

Transition sector *without* Gauge Bosons

$$\Delta \mathcal{P} = \Delta \mathcal{P}_{LO}$$

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Runaway regime: acceleration until collision

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$$\gamma_{w,\mathrm{MAX}} \approx \mathrm{Min}\left[\frac{M_{\mathrm{pl}}T_{\mathrm{nuc}}}{v^2}, \frac{16\pi^2}{g_i g_{\mathrm{gauge}}^3}\left(\frac{v}{T_{\mathrm{nuc}}}\right)^3\right]$$

$$\Rightarrow \boxed{M_\phi^{\mathrm{MAX}} \sim \mathrm{Min}\left[T_{\mathrm{nuc}}\left(\frac{M_{\mathrm{pl}}}{v}\right)^{1/2}, 4\pi v\left(\frac{v}{T_{\mathrm{nuc}}}\right)\right]}$$

Putting ourselves in our universe: $\Omega^{\text{today}}_{\phi,\text{BE}} h^2 \approx 0.12$ and freeze-out

- If ϕ was in *thermal equilibrium*:

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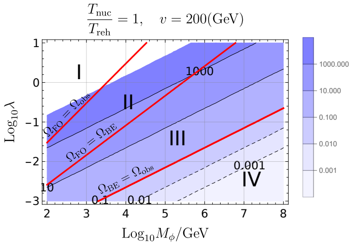

Large over-production of DM

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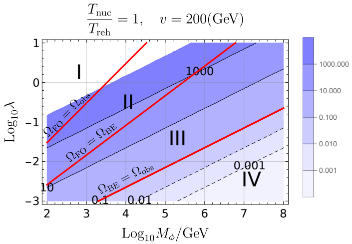

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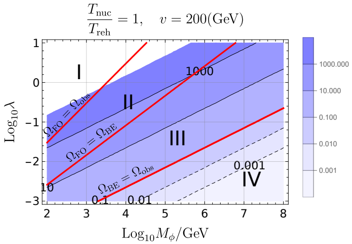

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- Annihilation of DM after production: $\Gamma_{\text{ann}} \sim \sigma_{\phi\phi} v_{\text{rel}} n_\phi > H \quad \Rightarrow$ **Annihilation**

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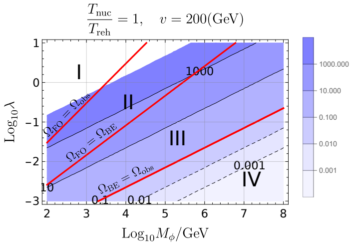

Large over-production of DM

Remedy to the over-production?

- Annihilation of DM after production: $\Gamma_{\text{ann}} \sim \sigma_{\phi\phi} v_{\text{rel}} n_\phi > H \quad \Rightarrow$ **Annihilation**
- Large supercooling: $\left(\frac{T_{\text{nuc}}}{T_{\text{reh}}}\right) \ll 1$

Putting ourselves in our universe: $\Omega^{\text{today}}_{\phi,\text{BE}} h^2 \approx 0.12$ and freeze-out

- If ϕ was in *thermal equilibrium*:

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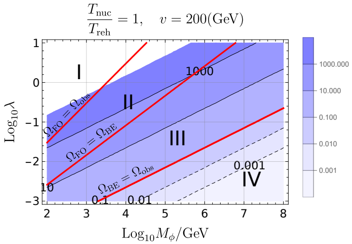

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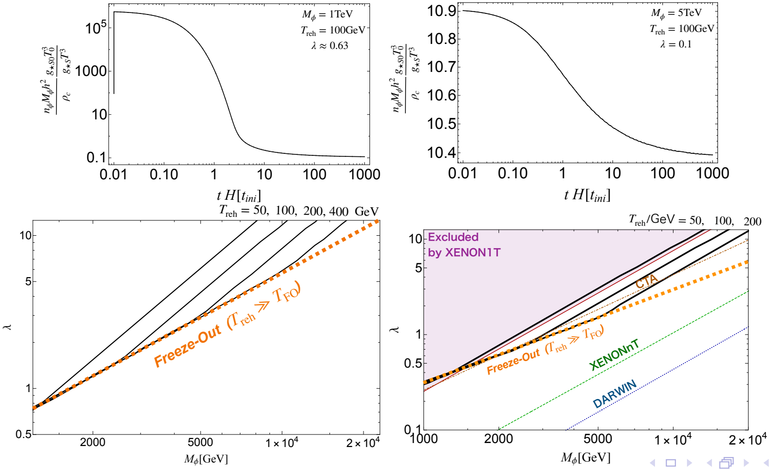
Annihilation after production

$$\Gamma_{\rm ann} \sim \sigma_{\phi\phi} v_{\rm rel} n_\phi > H \quad \Rightarrow \quad \frac{T_{\rm reh}}{16\pi M_\phi^2} \gtrsim \frac{T_{\rm reh}^2}{M_{\rm pl}} \quad \Rightarrow \quad \textbf{Annihilation}$$



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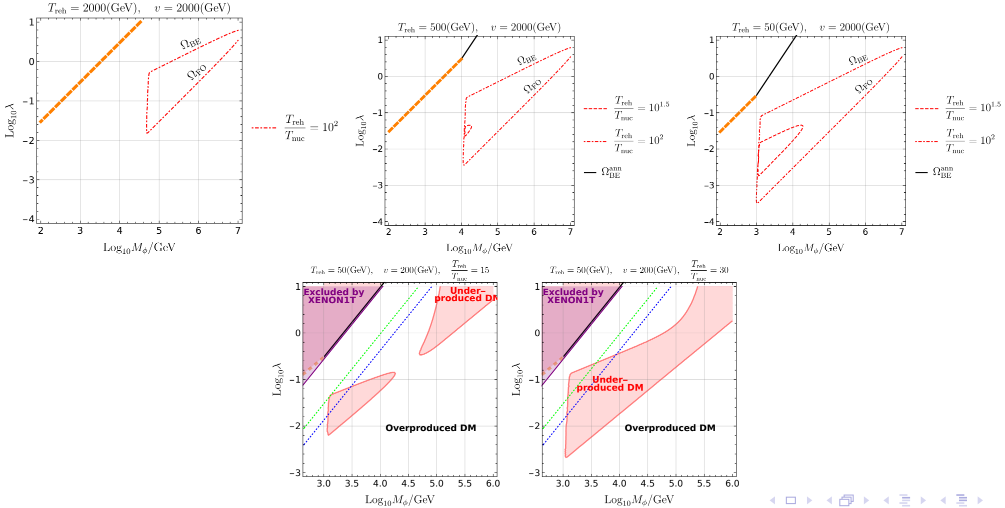

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- Maximal DM mass that can be produced in that way:

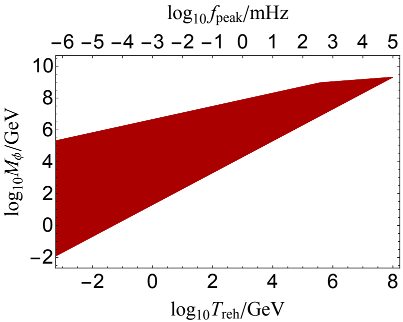
$$\lambda < 4\pi \quad \Rightarrow M_\phi < M_\phi^{\mathrm{MAX}} \approx 5 \times 10^6 \left(\frac{v}{\mathrm{GeV}}\right)^2 \mathrm{GeV}$$

observable GW from DM production mechanism

Strong GW signal

Strong GW signal obtained for: long supercooling, large bubbles, fast walls
⇒ **This is exactly the regime for optimal DM production**

$$10^{-6}\ \text{mHz} \lesssim f_{\text{peak}} \lesssim 100\ \text{Hz}$$



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