INVISIBLES

Interactions of plasma and bubbles during FOPTs

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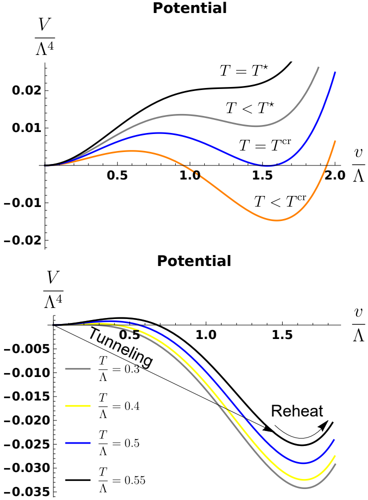
VUB, IIHE and COST Action

First order phase transition (FOPT) in the early universe

Universe high-T after inflation:cooling of primordial soup

- QFT = landscape of minima ⇒ PT



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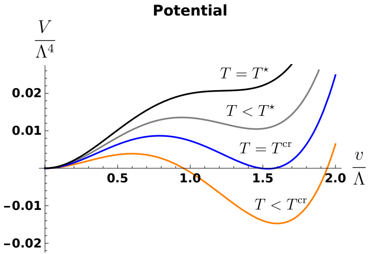

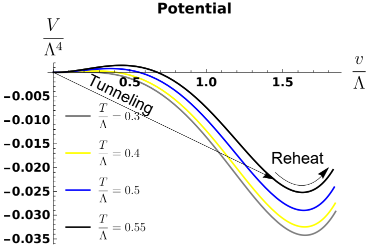

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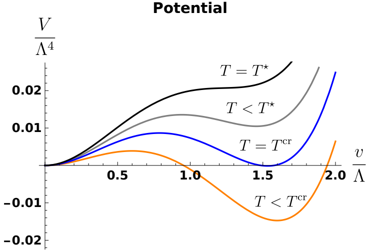

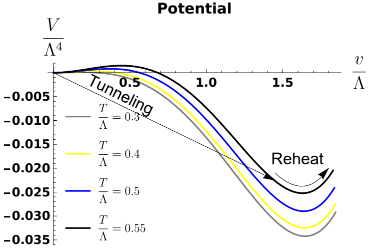

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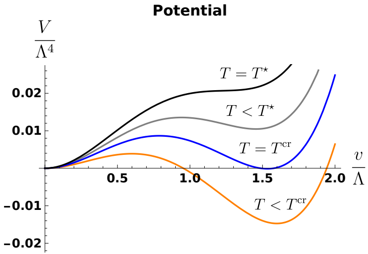

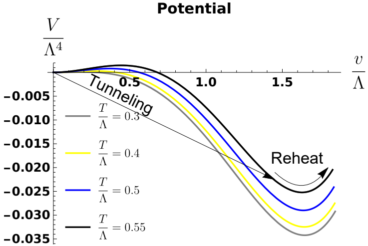

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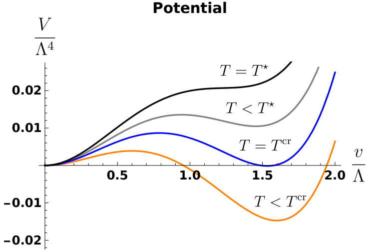
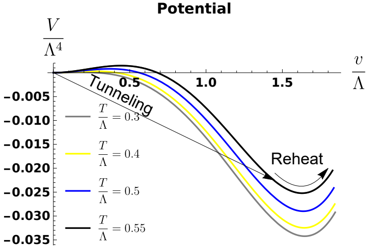
- Nucleation controlled by bounce solution

$$\Gamma \sim T^4 Exp\left[-\frac{S_3}{T}\right]$$



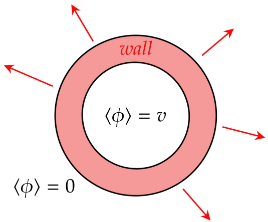


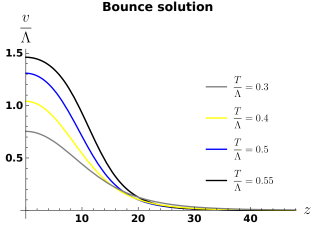
Nucleation and early expansion

- Energy released $\Delta V \Rightarrow$ Driving energy:

$$E_{\text{driving}} = -\frac{4}{3}\pi \Delta V R^3 \text{ VS } \Delta\mathcal{P}_{\text{tension}} = 4\pi\sigma R^2$$

Expansion when $R_{\text{initial}} > R_c \sim \sigma/\Delta V$





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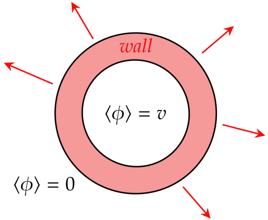

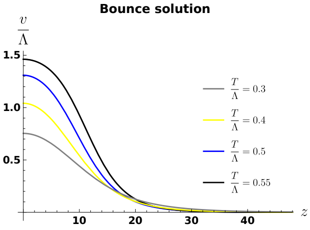

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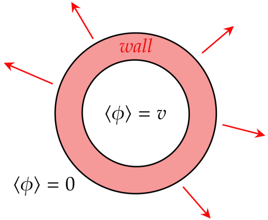
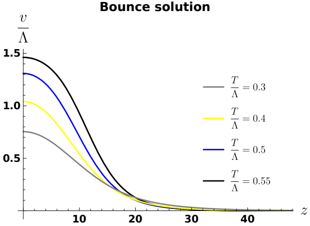
$$\alpha_N \equiv \frac{\Delta V}{\rho_r(T_{\text{nuc}})} \propto 1/T_{\text{nuc}}^4$$





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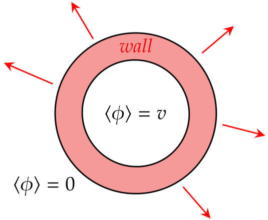
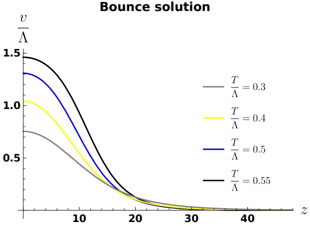
- Duration of the FOPT

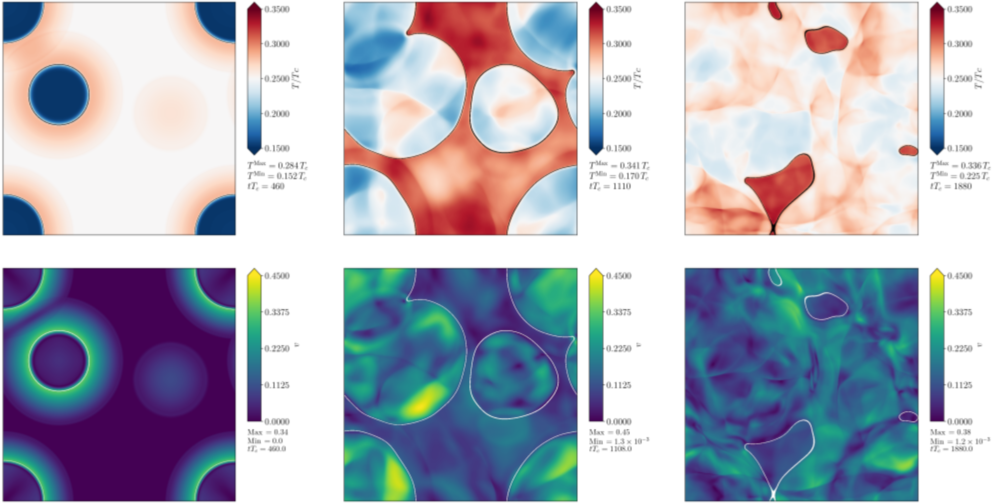
$$\beta \equiv \frac{t_{\text{exp}}}{t_{PT}} = \frac{1}{t_{PT} H} \propto R_{\text{collision}}^{-1}$$



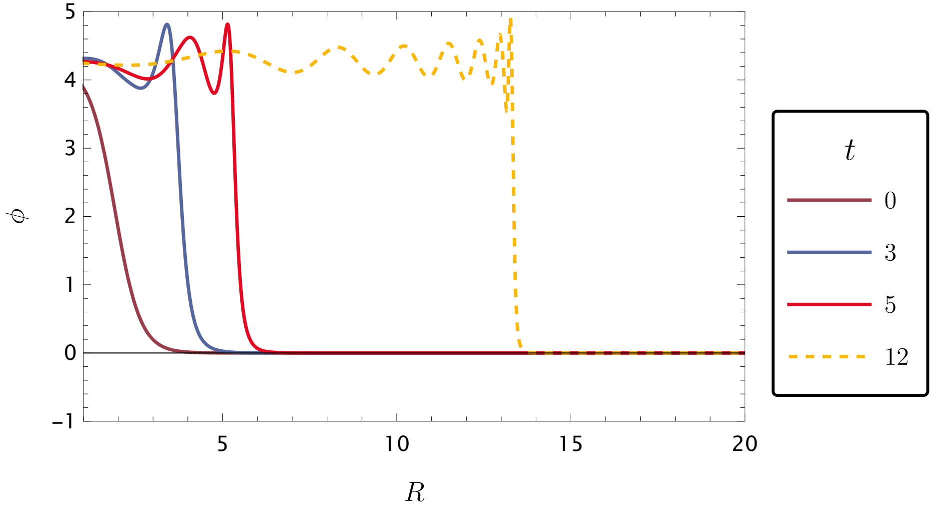


FOPT pictorially

Cutting, Hindmarsh and Weir:[1906.00480]: video in https://vimeo.com/showcase/5968055



The bubble wall in time



FOPT and Gravitational waves

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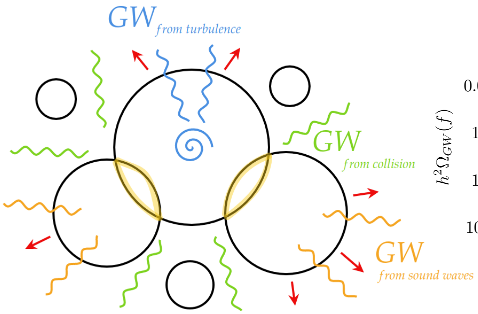
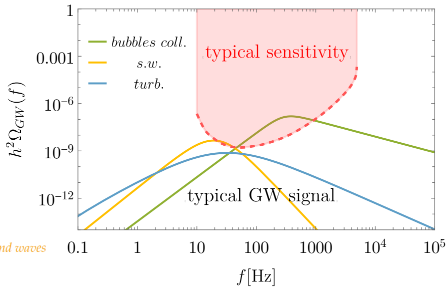
- bubble collision
- sound waves
- turbulence

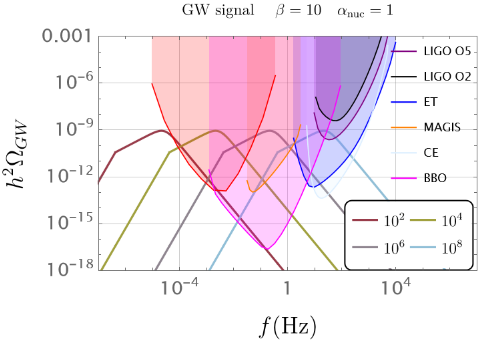


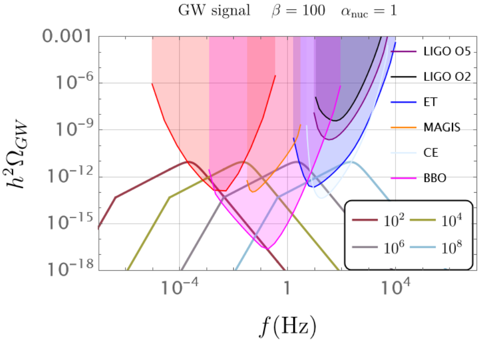


Primordial GWs could be observed soon: Frequency $\Rightarrow$ information about $T_{\rm reh}$: $f_{\rm peak} \propto T_{\rm reh}$

Observation prospects of GW

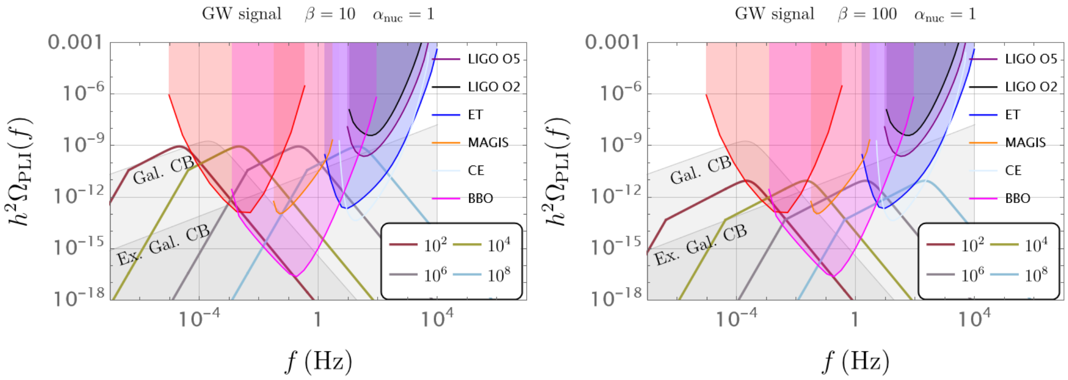
$$\left(T_{\rm reh}, \quad \beta, \quad \alpha_N, \quad v_w\right) \quad \Rightarrow \quad (\Omega^{GW}_{\rm peak}, \quad f^{GW}_{\rm peak})$$





Using Bulk flow model: Konstandin, Jinno, Takimoto, ...

But foregrounds ...



$$\Omega_{\rm GW} \propto v_w \left(\kappa_f \frac{\alpha_N}{1+\alpha_N}\right)^2 \frac{1}{\beta^2} \quad \Rightarrow$$

Need *strong*, *long* PT with *fast walls*

Where does the energy go ?

[1004.4187]: Espinosa,No,Konstandin, Servant,[2406.01596]:Barni,Blasi,MV

- Fluid motion $\Rightarrow$ GW !

$$\underbrace{\frac{\xi_w^3}{3}\epsilon}_{\text{vacuum}} + \underbrace{\frac{3}{4}\int \omega_N \xi^2 d\xi}_{\text{initial therm energy}} = \underbrace{\int \gamma^2 v^2 \omega \xi^2 d\xi}_{\text{fluid motion}} + \underbrace{\frac{3}{4}\int \omega \xi^2 d\xi}_{\text{final therm energy}}$$

- $$\frac{\rho_{\rm kin}}{\rho_i} \equiv \frac{\kappa_f \alpha_N}{1+\alpha_N} ,$$

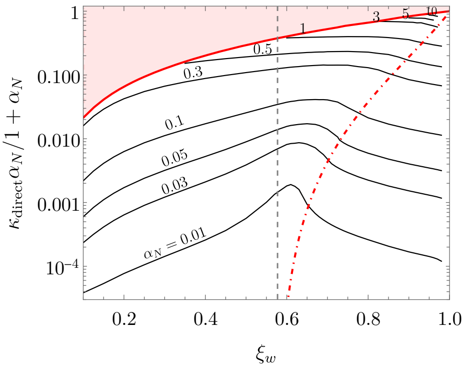


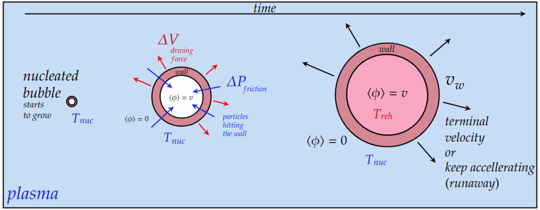
Figure: [2406.01596]:Barni,Blasi,MV

Good news: they *kinda* correlate

[2207.02230]: Azatov, Barni, Chakraborty,MV, Yin

v_w and α_N

- v_w: ΔV against $\Delta \mathcal{P}$



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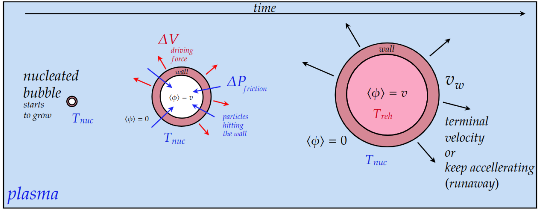

- $\Delta \mathcal{P} \propto T_{\rm nuc}^2, T_{\rm nuc}^3$

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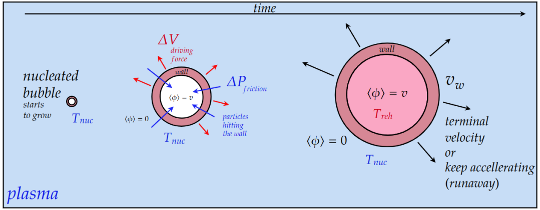

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- Two regimes: runaway and terminal velocity.

$$\text{Runaway}: \gamma_w \propto R/R_0 \quad \Rightarrow \gamma_w^{\rm collision} \propto M_{\rm pl}/\beta v$$

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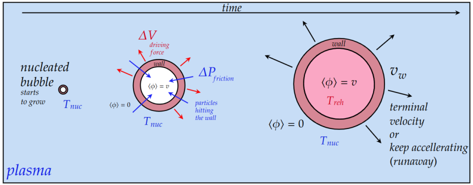

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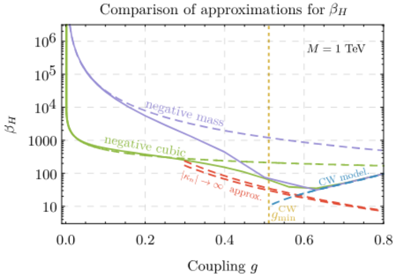
β and α_N

- In CW models: [2212.08085]:Levi, Opferkuch, Redigolo



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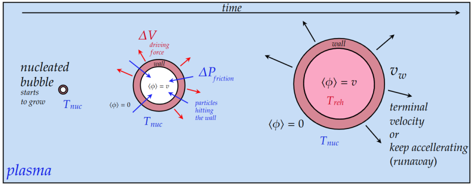

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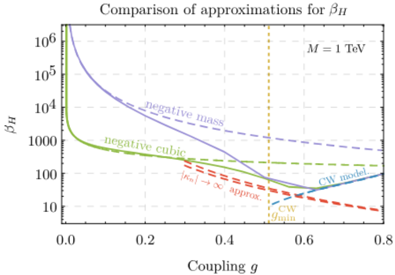

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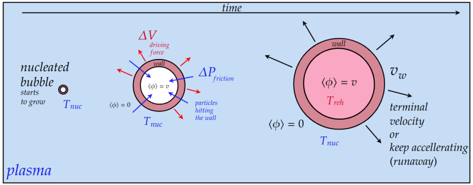

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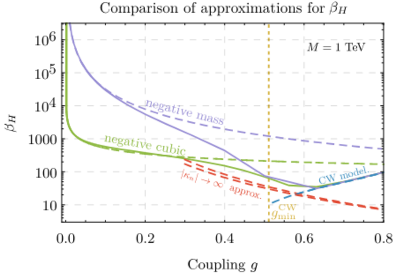

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For large GW signal $\Rightarrow$ cooling or supercooling

FOPT and Baryogenesis

1. Bubbles can create baryon anti-baryon asymmetry

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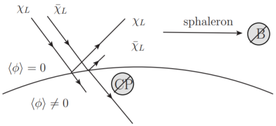
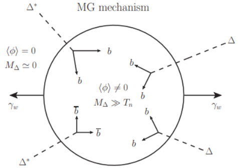
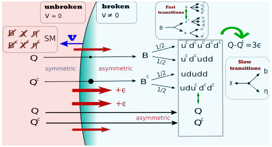


Figure: Credit:T.Konstandin [1302.6713]

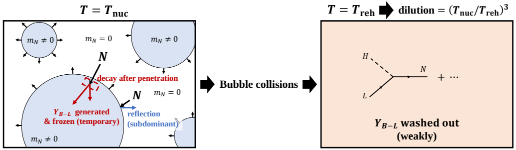


Traditional EWBG: $v_w \lesssim c_s$



Yin, Azatov, MV 21':
$$\gamma_w \equiv 1/\sqrt{1-v_w^2} \gtrsim M_B^2/vT_{\rm nuc}$$

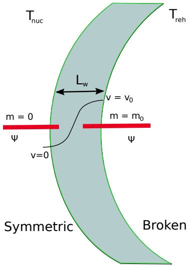
Baldes, Blasi, Mariotti, Sevrin, Turbang 21' $\gamma_w \gtrsim M_\Delta^2/vT_{\rm nuc}$



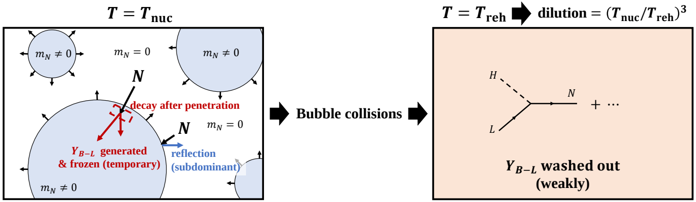
Eung,Dutka,Jung, Nagels, MV, 23': $\gamma_w \gtrsim M_{\rm RHN}/T_{\rm nuc}$

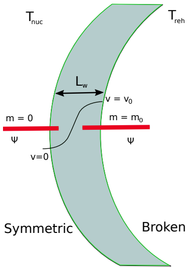
Bubble assisted leptogenesis

[2305.10759]: Eung, Dutka, Jung, Nagels, MV



- $$\mathcal{L}_{\text{int}} = \frac{1}{2}\sum_I y_I \Phi \bar{N}_I^c N_I + \sum_{\alpha,\, I} Y_{D,\alpha I} H \bar{L}_\alpha N_I + h.c. + V(\Phi)$$





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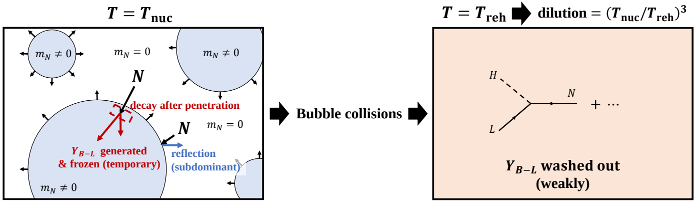

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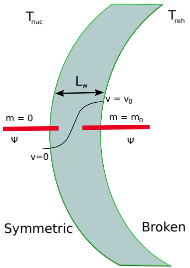

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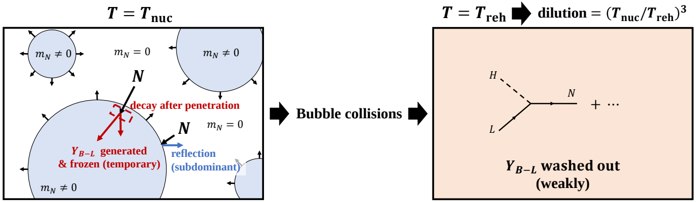

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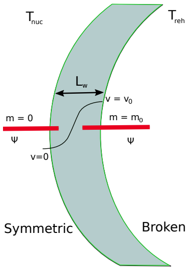

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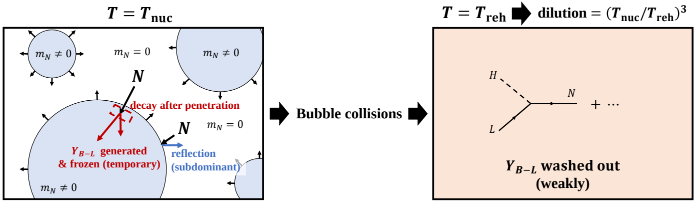
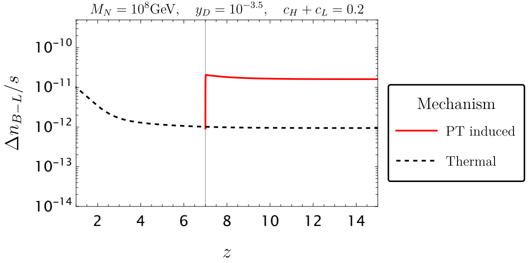
- Heavy neutrinos are strongly *out-of-equilibrium* is $M_N/T_{\text{nuc}} \gg 1$.

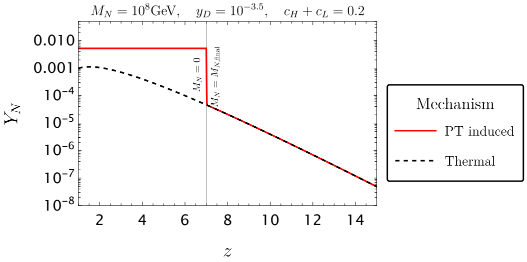


What are we hoping for ?

[2305.10759]: Eung,Dutka,Jung, Nagels, MV

- $$Y_{B-L}^{\text{thermal}} \propto \underbrace{\epsilon_{\text{CP}}}_{\text{CP}} \times \underbrace{\kappa_{\text{wash-out}}}_{\text{wash-out effects}} \times \underbrace{Y_N}_{\text{initial ab}}$$





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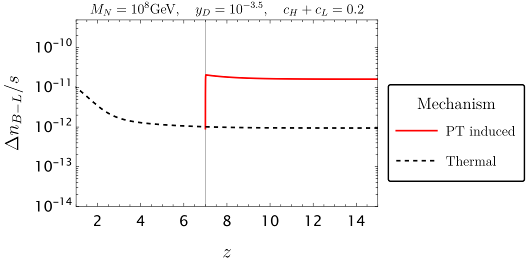

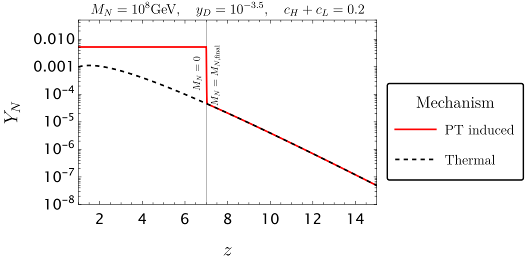

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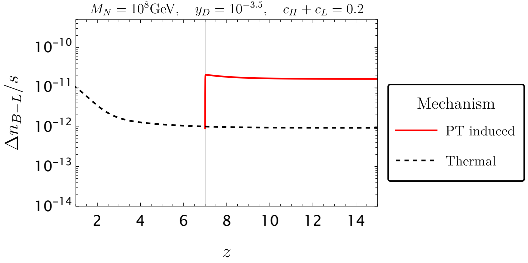
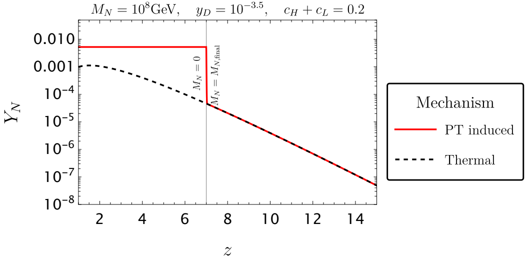
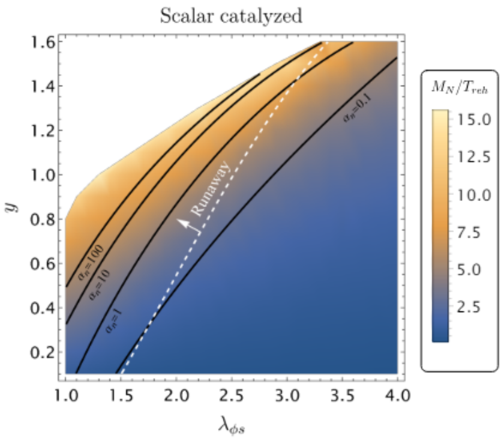
- bubble assisted leptogenesis has naturally $\kappa_{\text{wash-out}} \sim 1$.

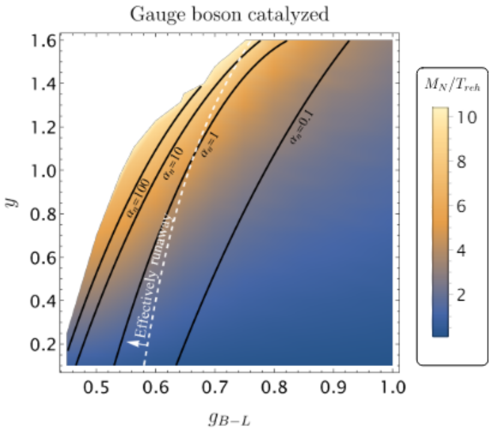




Phase transition sector

[2305.10759]: Eung,Dutka,Jung, Nagels, MV

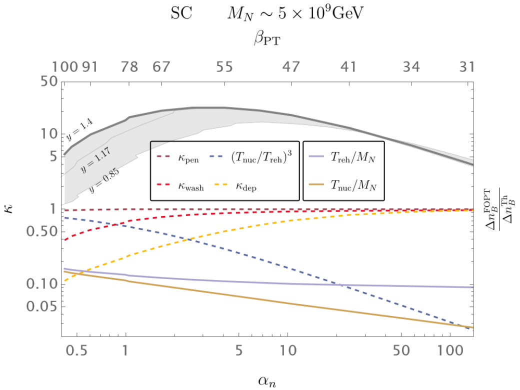




What is the final effect ?

[2305.10759]: Eung,Dutka,Jung, Nagels, MV

$$Y_B^{\rm FOPT} \sim Y_N^{\rm eq}\epsilon_{\rm CP}\,\kappa_{\rm sph} \times \underbrace{\kappa_{\rm pen}}_{\rm N-reflected} \times \underbrace{\kappa_{\rm dep}}_{NN\to\phi\phi,ff} \times \underbrace{\kappa_{\rm wash}}_{\text{residual wash-out}} \times \underbrace{\left(\frac{T_{\rm nuc}}{T_{\rm reh}}\right)^3}_{\text{entropy injection}}$$



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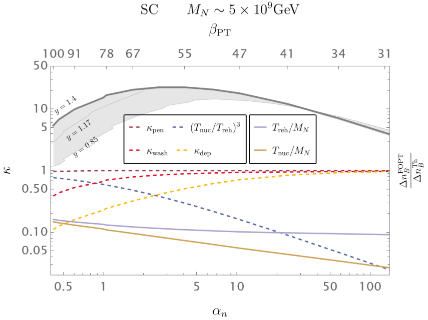
Competing effects

- $\kappa_{\rm pen} \sim 1$



Results: Peaks structure with maximal enhancement at

$$\boxed{\beta \sim \mathcal{O}(50), \alpha_N \sim \mathcal{O}(2-5)}$$

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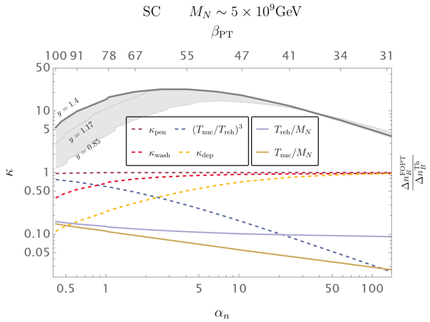

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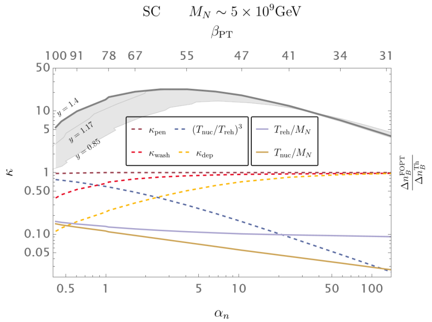

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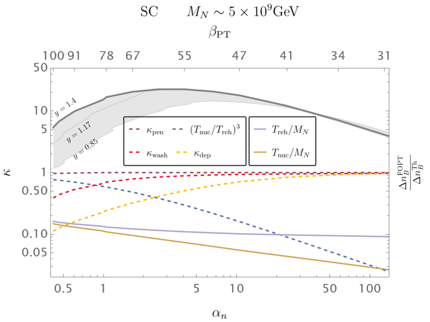
- Final injection of entropy: $\left(\frac{T_{\rm nuc}}{T_{\rm reh}}\right)^3$



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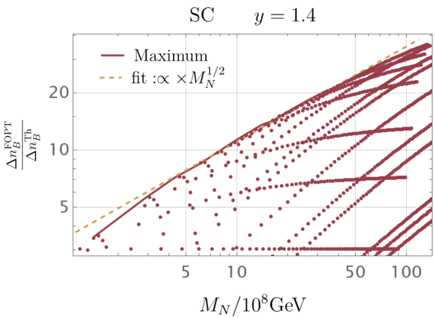
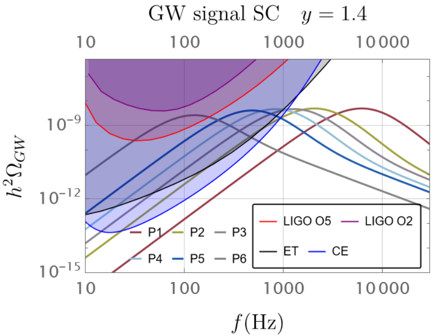
The peak properties

[2305.10759]: Eung,Dutka,Jung, Nagels, MV

Approximation of the enhancement: $\frac{n_B^{\text{FOPT,max}}}{n_B^{\text{thermal}}} \sim \left(\frac{M_N}{10^7\text{GeV}}\right)^{1/2}$

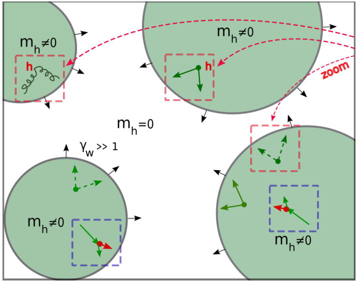




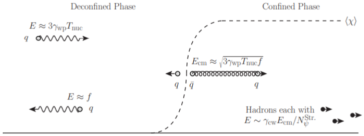
Confining PT: $M_{RHN}^{SC} \approx 4\pi v_\phi \gg M_{RHN}^{WC} = y v_\phi$: [2312.09282]: Dichtl, Nava, Pascoli, Sala

FOPT and DM

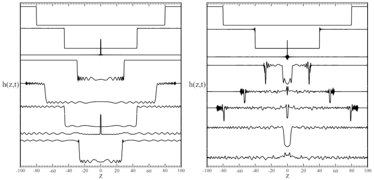
Supercool DM: Hambye, Strumia,Tesi 18'



Azatov, Yin, MV 21' ,
Baldes, Sala, Gouttenoire, 22'
Azatov, Yin, Nagels, MV 24'
$\gamma_w \gtrsim M_{\rm DM}^2/vT_{\rm nuc}$



Baldes,Gouttenoire, Sala, Servant, 22' : $\gamma_w \gg 1$

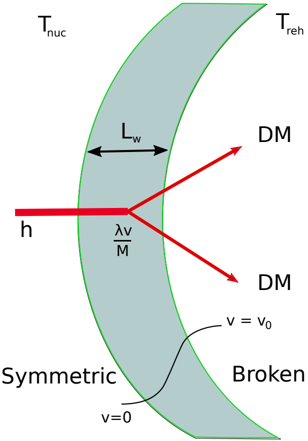


Falkowski, No, 12' Giudice, Pomarol, Lee, Shakya 24' :
Runaway walls: $\gamma_w \sim M_{\rm pl}/v \to 10^{15}$

Heavy DM from bubble wall

[2101.05721]: Azatov, Yin, MV

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



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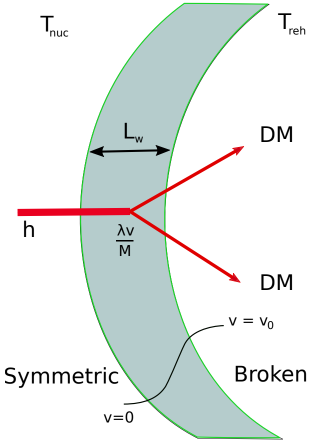

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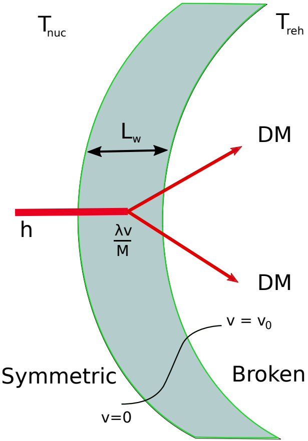
- In the *wall frame*: $E_h \sim p_{z,h} \sim \gamma_{wp} T \gg T$

$$P_{h\to\phi\phi} \sim \frac{\lambda^2 v^2}{M_\phi^2} \Theta(1 - \Delta p_z L_w)$$

$$p_{h,p} \approx \gamma_w T(1,0,0,1), \quad p_{h,w} \approx (0,0,0,1/L_w), \quad s > M_\phi^2$$

$$\Rightarrow \boxed{\gamma_w T v > M_\phi^2}$$



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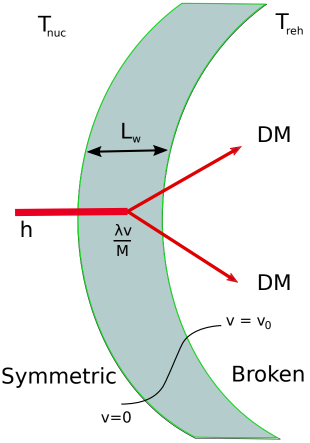
- Behind the wall, accumulation of relics

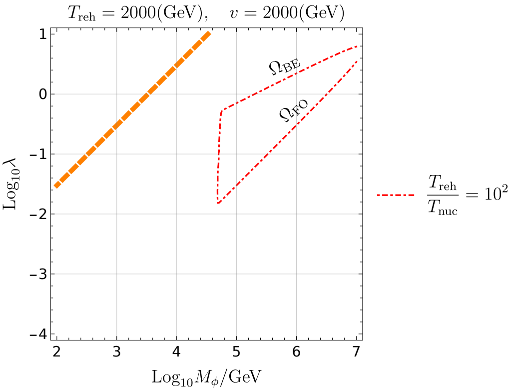
$$\Rightarrow \Omega_{\phi,\mathrm{BE}}^{\mathrm{today}} h^2 \approx 5.4\times 10^3 \left(\frac{\lambda^2 v^2}{M_\phi^2}\right)\left(\frac{M_\phi}{\mathrm{GeV}}\right)\left(\frac{T_{\mathrm{nuc}}}{T_{\mathrm{reh}}}\right)^3 e^{-\frac{M_\phi^2}{vT\gamma_{wp}}}$$



The DM is Heavy ...

[2101.05721]: Azatov, Yin, MV

h is a dark Higgs



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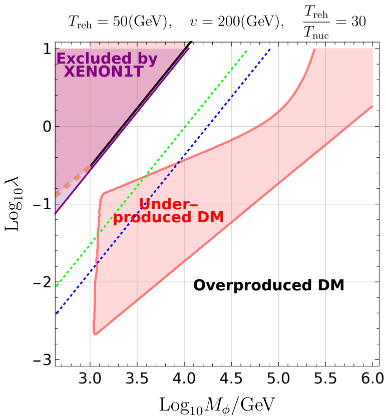


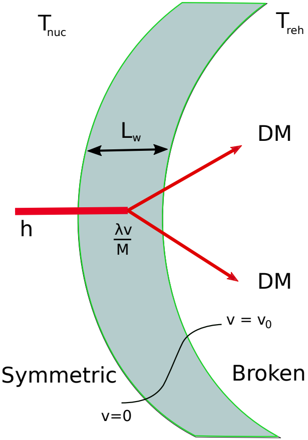
... and fast !

[2207.05096]: Baldes, Gouttenoire, Sala

- Warm Dark Matter

$$V_{\rm eq} \lesssim 4.2 \times 10^{-5} \qquad \text{From Lyman-}\alpha$$

$$\Rightarrow M_{\rm WDM} \sim \text{keV}$$



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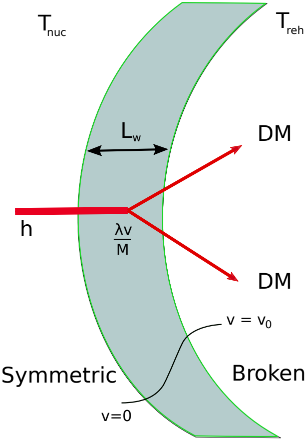

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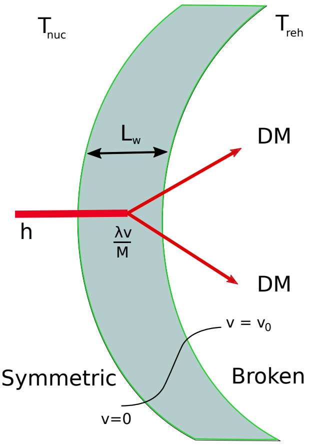

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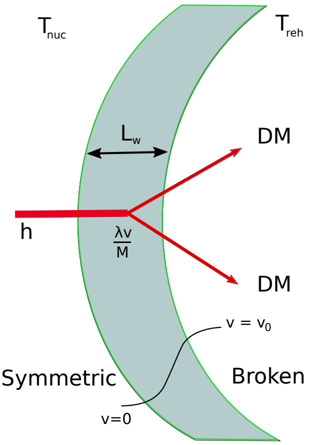
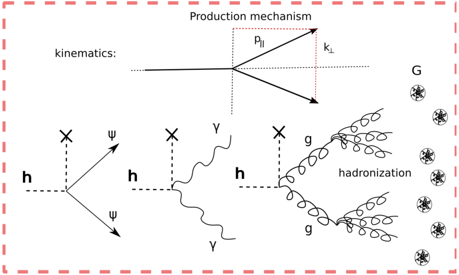
- Heavy WDM for

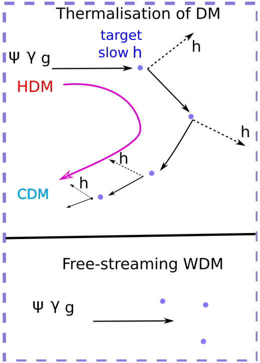
$$\boxed{V_{\rm eq} \sim 10^{-5}, \qquad v \sim 10^2\text{GeV}, \qquad M_\phi \sim 10^8\text{GeV}}$$



Secluded sectors ?

[2101.05721]: Azatov, Yin, MV, [2406.12554]:Azatov, Yin, Nagels, MV





$$\frac{\lambda}{2}h^2\phi^2, \qquad \frac{h^2\psi\bar{\psi}}{\Lambda}, \qquad \frac{h^2FF}{\Lambda^2}$$

$$P_{h\to\psi\bar{\psi}}(p_0) \approx |V|^2\Theta(1-\Delta p_z L_w)\Theta(\Lambda^2-2p_0 v)$$

$$h \to \phi\phi, \psi\bar{\psi}, \gamma\gamma,$$

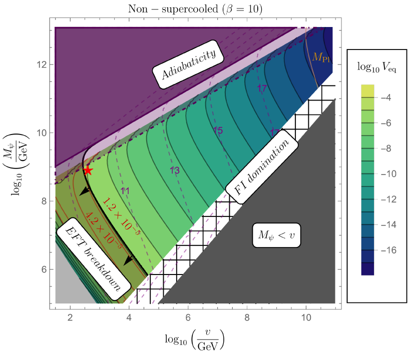
- Free-streaming regime
- Thermalised regime
- Transition between the regimes

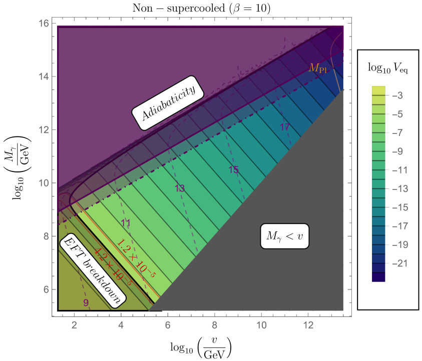
Secluded sectors ?

[2101.05721]: Azatov, Yin, MV, [2101.05721]:Azatov, Yin, Nagels, MV

$$\gamma_w(R) \approx \frac{2R}{3R_{\rm nuc}} \qquad \rightarrow \qquad \gamma_w^{\rm coll} \approx 0.06 \frac{M_{\rm pl} T_{\rm nuc}}{\beta v^2}$$

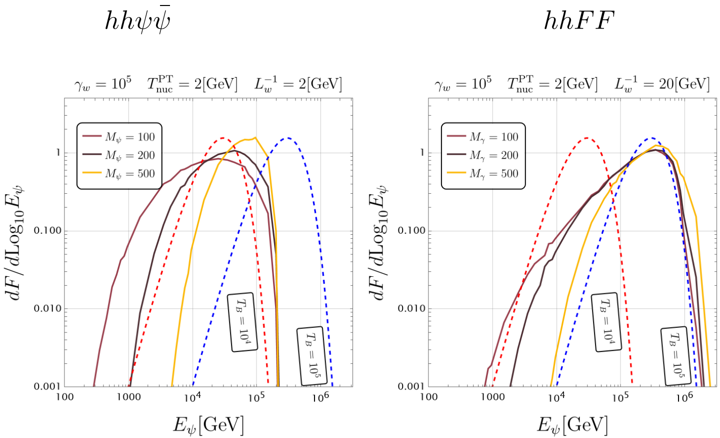
EFT bound : $s \approx \gamma_w T v < \Lambda^2$, adiabaticity : $s > M^2$





DM from bubble wall

[2101.05721]: Azatov, Yin, MV, [2406.12554]:Azatov, Yin, Nagels, MV



Conclusion

- Observable GW $\Rightarrow$ Need *strong*, *long* PT with *fast walls*

Thank you ;)

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Conclusion

- Observable GW $\Rightarrow$ Need *strong*, *long* PT with *fast walls*
- Relevant question is: what phenomena are impacted by such FOPTs ?
- bubble assisted leptogenesis (baryogenesis)
- Production of heavy and boosted DM
- But also: IGMF, primordial black holes, ...

Thank you ;)

Back-up

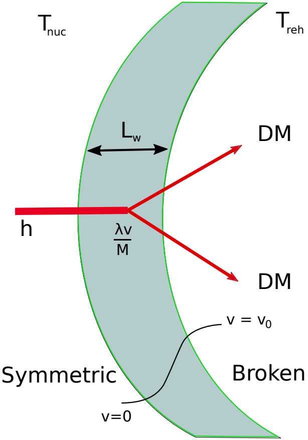
Back-up slides

What about the pressure on the wall ?

[2101.05721]: Azatov, Yin, MV

- Pressure on the wall in large γ_w regime

$$\mathcal{P}^{\gamma_w\to\infty} \approx \sum_{ij} \underbrace{\frac{p_z}{p_0} n_i}_{\propto \gamma_w T^3} \times \underbrace{P_{i\to j}}_{\text{probability } i \to j} \times \underbrace{\Delta p_{i\to j}}_{\text{exchange of momentum } i \to j}$$



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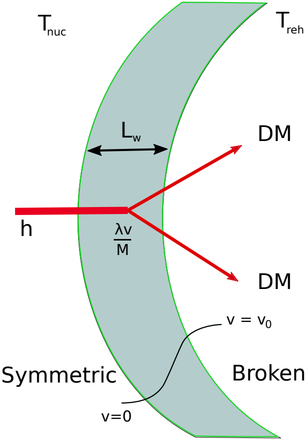

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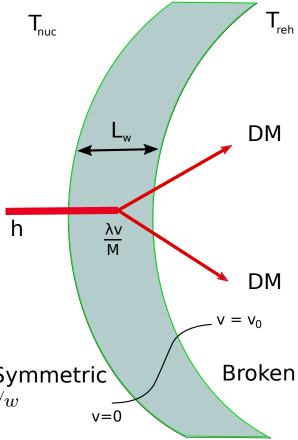
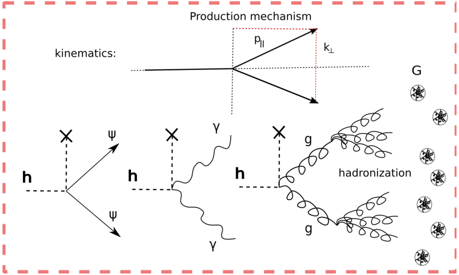
- Pressure from production

$$P_{1\to 2} \to \frac{v^2}{16\pi^2 M^2} \qquad \Delta p \approx \frac{M^2}{2\gamma_w T} \qquad \mathcal{P}_{1\to 2} \approx \frac{1}{16\pi^2} \frac{T^2 v^2}{24} \log \gamma_w$$



Pressure from Secluded sectors ?

[2101.05721]:Azatov, Yin, Nagels, MV



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$$P_{h\to\psi\psi} \approx \frac{v^2}{8\pi^2\Lambda^2} \qquad P_{h\to\gamma\gamma} \approx \frac{v^4\gamma_w}{8\pi^2\Lambda^4}$$

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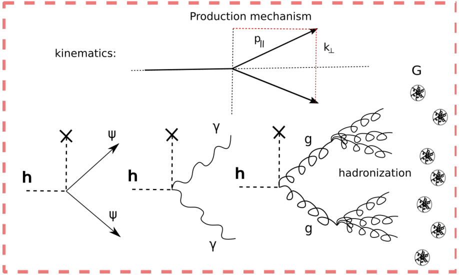

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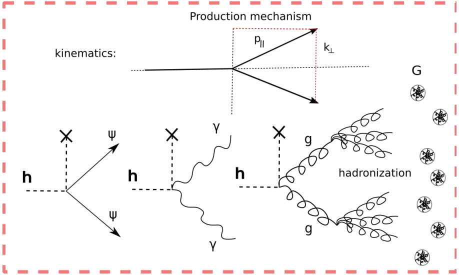

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$$s \approx \gamma_w T v \to \Lambda^2 :$$

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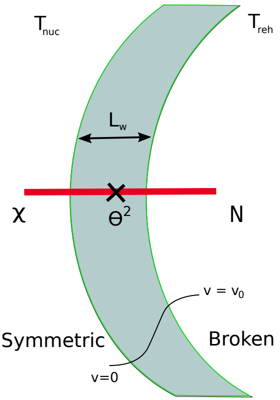
Production of heavy states via mixing[2010.02590]:Idea

Scale of the transition and particles involved

CLAIM: *transition is dictated by fields* $M \lesssim T_{\rm nuc} \sim v_\phi$ *because* $n_{\rm heavy} \propto e^{-M/T_{\rm nuc}}$



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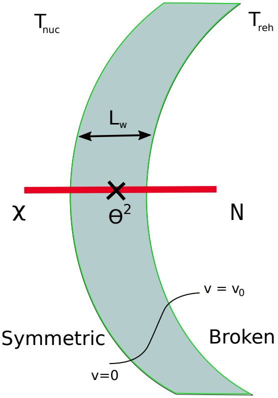

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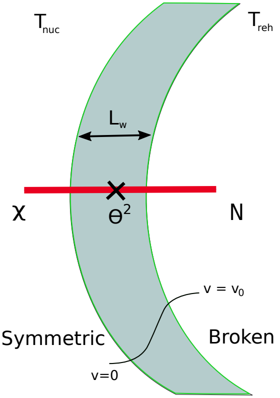

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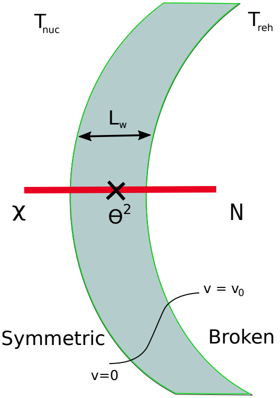

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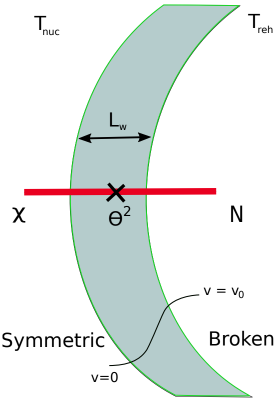

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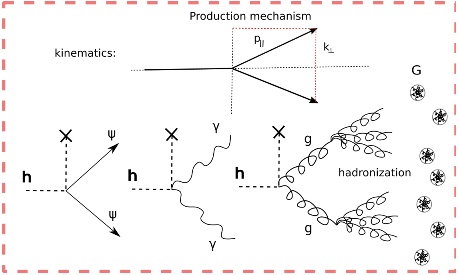
- With wall: $p^z = p^z_N - p^z_\chi$ not conserved: if $E > M$, $\chi \to N$ allowed

$$\int d^3x_\perp e^{ip_\perp \cdot x_\perp} \int \langle\phi\rangle(z) e^{izp_z} dz \propto (2\pi)^3 \delta^3(p_\perp) \frac{\sin \Delta p_z L_w}{\Delta p_z L_w}$$

Boosted glueballs DM

[2101.05721]:Azatov, Yin, Nagels, MV



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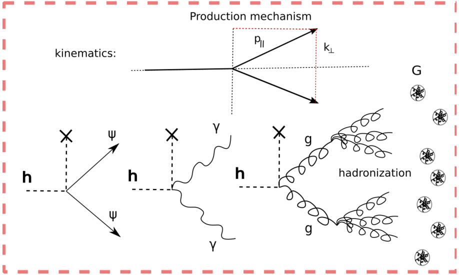

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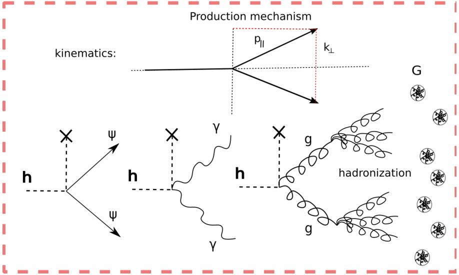

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- $\Lambda_{\rm conf} \gtrsim 0.3\text{GeV}$ Bullet cluster bound

Glueball DM parameter space

[2101.05721]:Azatov, Yin, Nagels, MV

$\Lambda_{\rm conf} = 0.25\text{GeV}, \quad T_{\rm nuc}/v = 1, \quad N = 3, \quad \beta = 10$