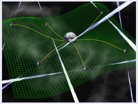
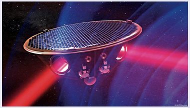
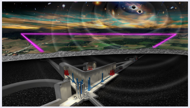
Bubbletrons and Dark Matter

Iason Baldes
Work done with Dichtl, Gouttenoire, Sala, 2306.15555, 2403.05615

CosmoChart
Horizon 2020, grant agreement No 101002846

Astroparticle Symposium, Pascal Institute
27 November 2024

Future landscape of GW observatories in 10-15 years.


Significant interest for astrophysics and fundamental physics/cosmology.

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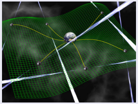 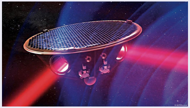 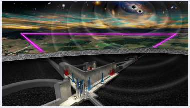 

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Making use of the Experimental GW programme.

$\rightarrow$ Motivates study of strong phase transitions with relativistic walls, and alternative scenarios for baryon, DM, PBH production...

Early Universe First Order Phase Transition

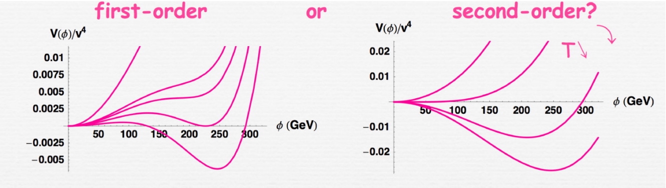

Image credit: G. Servant

Barrier in the potential leads to phase transition via bubble nucleation

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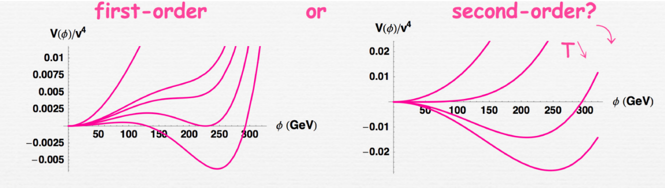

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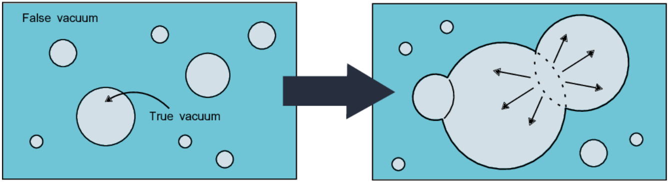
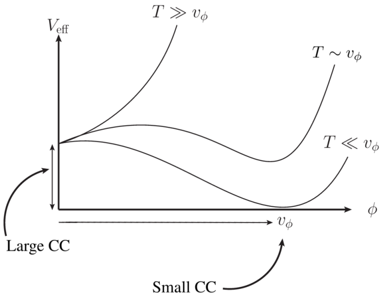


Image credit: D. Weir

Bubble dynamics create out-of-equilibrium conditions and GWs.

Supercooled Phase Transition - Timeline



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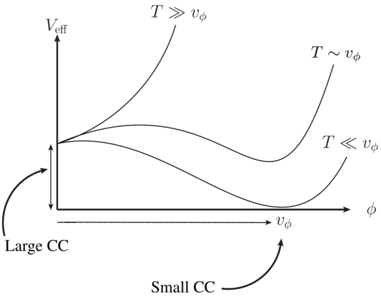

- Begin in radiation domination

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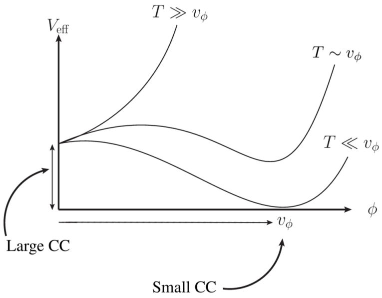

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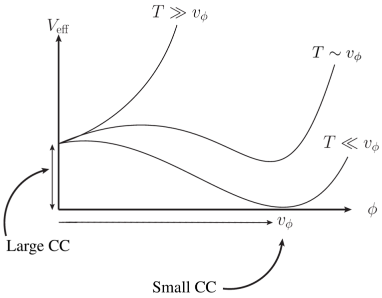

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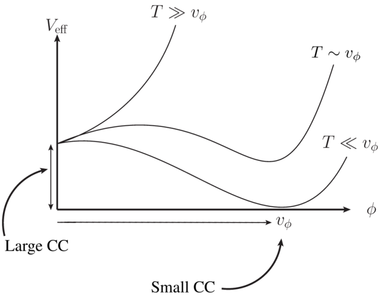

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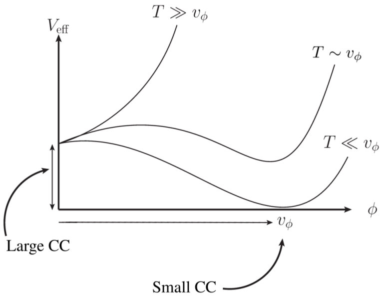

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- A scalar field becomes stuck behind a barrier
- We will be interested in supercooled phase transitions, where the universe becomes vacuum dominated (or close to it).
- Temperature evolution avoids graceful exit problem
- Bubbles accelerate and collide, reheating universe: $\rho_{\text{vac}} \to$ Bubble walls $\to$ Oscillations $\to$ Radiation.

Ballistic limit - $f_i = f_i^{eq}$

One quantity of importance: Lorentz factor of the bubble wall
Processes of importance for us here in calculating frictional P_{max}:

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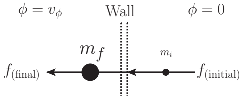

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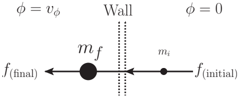

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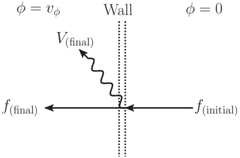

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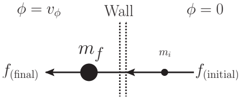

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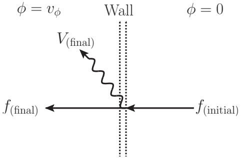
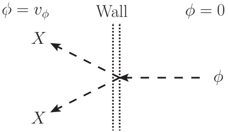


3. Pair production $\rightarrow$ typically subdominant for $P_{\max}$.



Wall velocity - Ballistic Limit

Driving pressure:

$$\mathcal{P}_{\text{Driving}} = V(\phi_{\text{symmetric}}) - V(\phi_{\text{broken}}) = c_{\text{vac}} v_\phi^4$$

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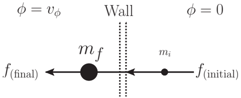

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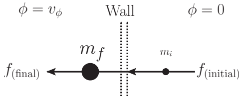

The maximum LO friction pressure in the ballistic regime is:
- Bödeker and Moore 0903.4099

$$\mathcal{P}_{\text{LO}} \simeq \sum_a \Delta(m_a^2) \int \frac{d^3 p f_a^{\text{eq}}}{(2\pi)^3 2E_a} \equiv g_a \frac{v_\phi^2 T_n^2}{24}$$

Wall velocity - Ballistic Limit

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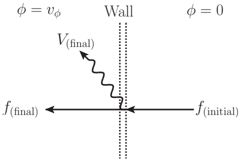

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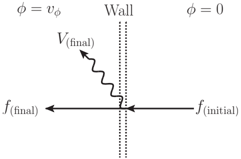

NLO friction pressure in case of gauged PTs:

- Bödeker and Moore 1703.08215, Gouttenoire, Jinno, Sala 2112.07686

$$\mathcal{P}_{\rm NLO} \approx \mathcal{O}(1) \times \alpha_X \gamma_{\rm wall} M_V T_n^3 \log\left(\frac{v_\phi}{T_n}\right)$$

Ultra-relativistic wall

For $\Delta V > \mathcal{P}_{\rm LO} + \mathcal{P}_{\rm NLO}$ effectively runaway

$$\gamma_{\rm wall} \simeq \frac{1}{3}\frac{R_{\rm coll}}{R_{\rm nuc}} \approx \left(\frac{H}{\beta}\right)\frac{T_n M_{\rm pl}}{v_\phi^2} \gg 1$$

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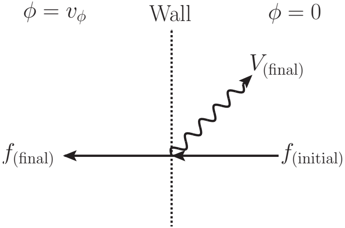
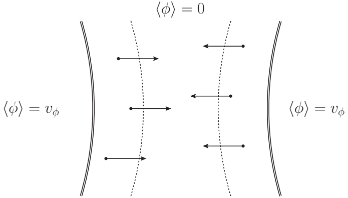
Shell properties and free streaming conditions - IB, Dichtl, Gouttenoire, Sala, 2403.05615

Application: DM from shell collisions - IB, Dichtl, Gouttenoire, Sala, 2306.15555

Shell-crossing production of DM "Bubbletron"

Picture: Radiated Reflected Shell $\rightarrow$ Shell Collision $\rightarrow$ DM production





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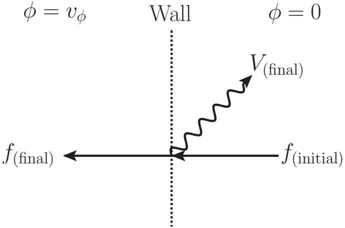

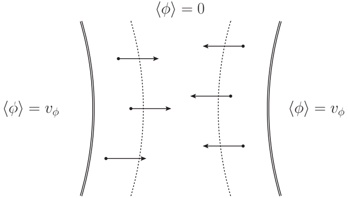

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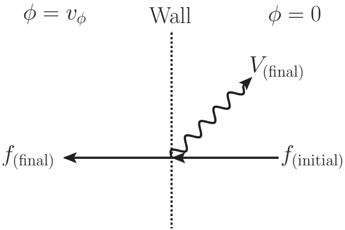

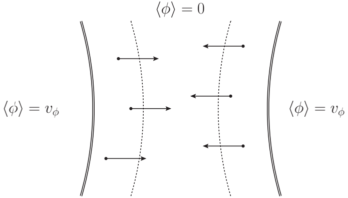

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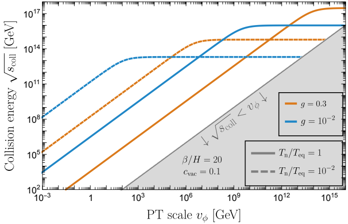
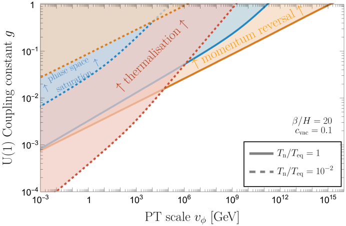
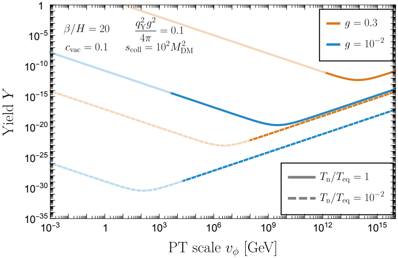
Shell freestreaming parameter space





DM "Bubbletron" Yield

Assume heavier Y fermion with charge q_Y acts as DM.



Found the DM Yield using:

$$Y_Y \equiv \frac{n_Y}{s_{\rm RH}} = \frac{R_{\rm coll}}{3s_{\rm RH}} n_b^2 P_{b\to V} P_{b\to V} \sigma_{VV\to Y\bar{Y}}$$

$$\sigma_{VV\to Y\bar{Y}} = \frac{q_Y^4 g^4}{4\pi s} f_{Y\bar{Y}} \xrightarrow[s\gg M_Y^2]{} \frac{q_Y^4 g^4}{4\pi s}\left(\log\frac{s}{M_Y^2} - 1\right)$$

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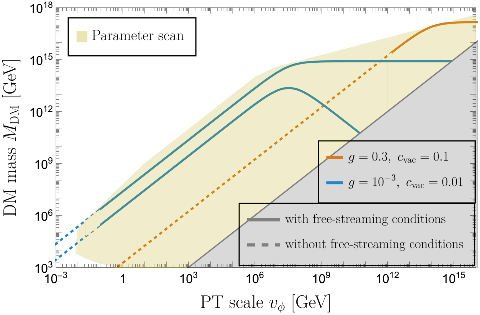


$\beta/H = 20$ and $T_n/T_{\rm eq} = 1$ for the benchmarks.

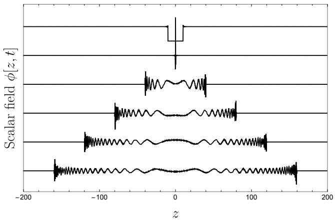
Parameter scan over:

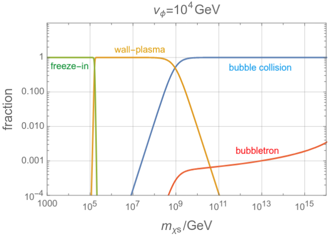
$1 \geq T_n/T_{\rm eq} \geq 10^{-4}, \quad 1 \geq g \geq 10^{-5}, \quad 10^4 \geq \beta/H \geq 10,$
$1 \geq c_{\rm vac} \geq 10^{-3}, \quad 10^{-4} < g^2 q_Y^2/4\pi < 0.1$
with the perturbativity condition $P_{b\to V} < 1$

Production at Bubble Collision Instead?

Recent re-evaluation of heavy particle production from wall collisions.

- Mansour, Shakya 2308.13070, Shakya 2308.16224





- From IB et al. 2403.05615 - Giudice, Hyun Min Lee, Pomarol, Shakya 2403.03252

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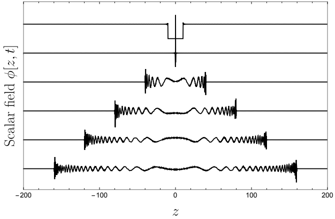

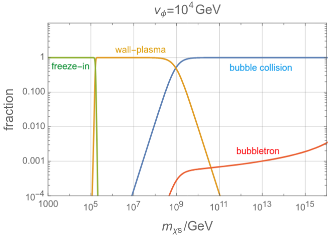

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Where is the vacuum energy transferred:

- Runaway: Bubble Wall
- Non-Runaway (i.e. due to V production): Particle Shells

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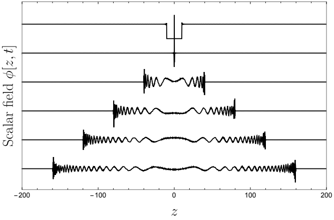

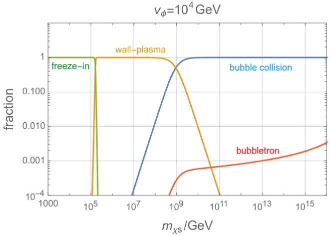

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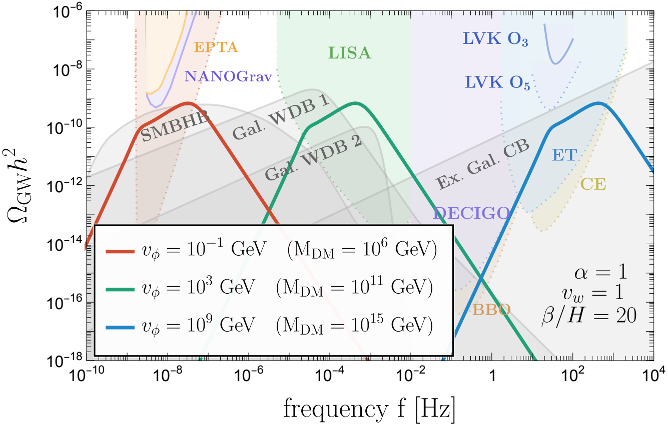
Bubbletron production dominant in second case.

Bubbletron DM Expected GW signals



Current state-of-the art estimates.

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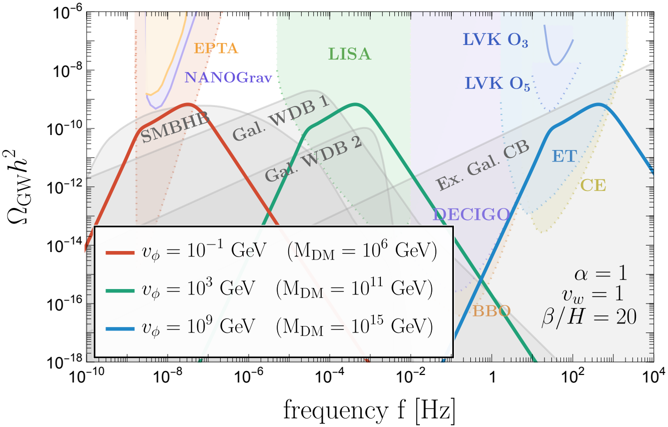
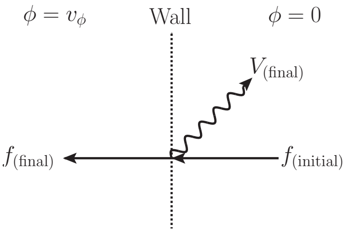
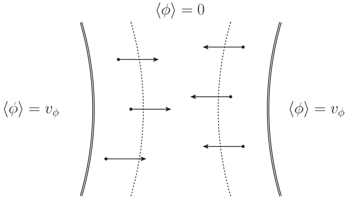


Current state-of-the art estimates.

Open question: effect of shell free-streaming length.

Conclusions





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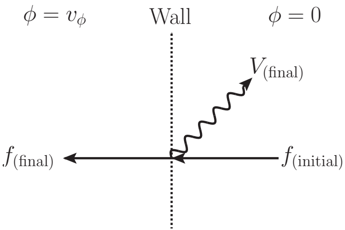

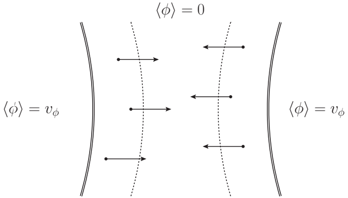

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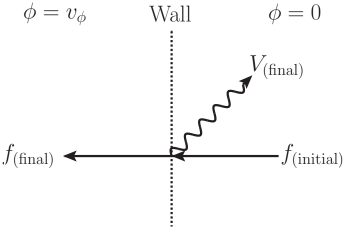
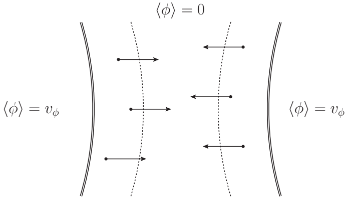
Conclusions

- Motivated in part by GW signal: interest in supercooled PTs.
- Possible production of DM/PBHs/Baryon asymmetry.
- Need to carefully consider particle production/shell evolution.
- Both to understand DM/Baryon production, determine $T_{\mu\nu}$ and GWs.





$$E \approx \gamma_{\text{wall}} M_V = \gamma_{\text{wall}} g v_\phi$$

Conclusions

- Motivated in part by GW signal: interest in supercooled PTs.
- Possible production of DM/PBHs/Baryon asymmetry.
- Need to carefully consider particle production/shell evolution.
- Both to understand DM/Baryon production, determine $T_{\mu\nu}$ and GWs.

Thanks

Further slides

Ultra-relativistic particle shells - more generally

Channel		Multiplicity $\mathcal{N}$ per incoming particle	Momentum of shell particles (p_c or p_X)	$\bar{L}_b = (L_b^2 - \frac{1}{p_X^2})^{\frac{1}{2}}$ (L_b = effective shell thickness)
Leading-order interaction (LO): $a \to a$ Particles acquiring a mass [43, 50]		1	$\Delta m^2/T_n$	$\frac{R_c}{2(\Delta m/T_n)^2}$
Gauge interaction $\alpha_D \ll 4\pi$: Bremsstrahlung radiation $a \to bc$ [44–47] and App. A.1	transmitted	$2\frac{\alpha_D}{\pi} L_m L_E$	$\gamma_w m_{c,h}$	$\frac{R_c}{2\gamma_w^2}$
	reflected	$\frac{\alpha_D}{\pi} L_m^2$		
Gauge interaction $\alpha_D \simeq 4\pi$: Hadronization [23]	string fragmentation	$\frac{\alpha_D}{\pi} L_E$	$\gamma_w v_\phi$	$\frac{R_c}{2\gamma_w^2}$
	ejected quarks			
Scalar interaction $\lambda\phi^4/4!$: Scalar Bremsstrahlung $a \to bc$ App. A.3	transmitted	$\lambda^2 v_\phi^2/192\pi^2 m_{c,h}^2$	$\gamma_w m_{c,h}^2/E_a$	$\frac{R_c}{2\gamma_w^2}$
	reflected	$\lambda^2 v_\phi^2/32\pi^2 E_a^2$	$\gamma_w m_{c,h}$	
Heavier particle production $\lambda\phi^2 X^2/4$ (Azatov-Vanvlasselaer mechanism $\phi \to XX$) $M_X \gg v_\phi$ [45]		$\lambda^2 v_\phi^2/192\pi^2 M_X^2 \times \Theta\left(\gamma_w - M_X^2/T_n v_\phi\right)$	M_X^2/T_n	$\frac{R_c}{2(M_X/T_n)^2}$

Shell properties and free streaming conditions - IB, Dichtl, Gouttenoire, Sala, 2403.05615

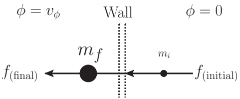
Particle production from shell collisions - IB, Dichtl, Gouttenoire, Sala, 2306.15555

Shell free streaming

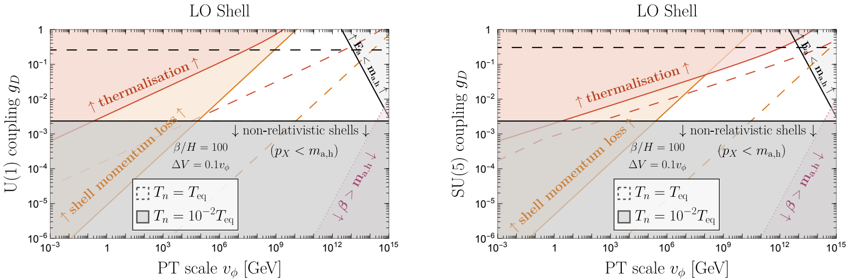
Processes to prevent shell free streaming:

- Phase space saturation/perturbativity, i.e. finite-density corrections $\rightarrow$ affect calculation of shell production.
- Momentum changes of the shell due to $2 \rightarrow 2$ interactions with the bath.
- Thermalization, i.e. $3 \rightarrow 2$ interactions within the shells and between the shell and the bath.
- Shell interactions with the collided bubble walls (important for free streaming up until shell-shell collision).

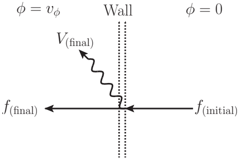
Shell Free Streaming Conditions



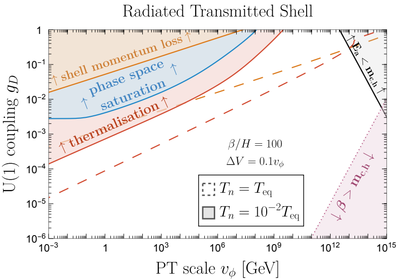
Leading Order Shell (Mass Gain)

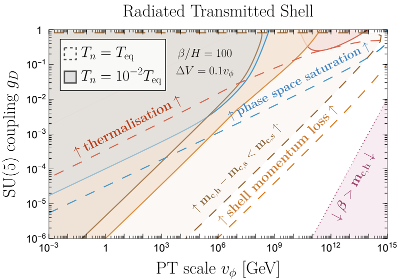


Shell Free Streaming Conditions

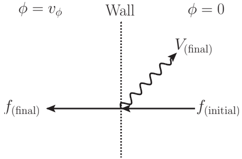


Radiated Transmitted Shell

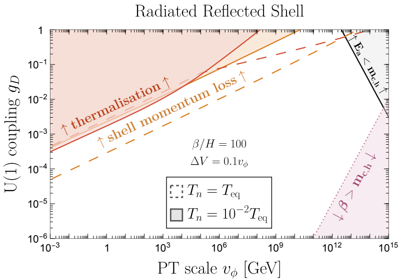


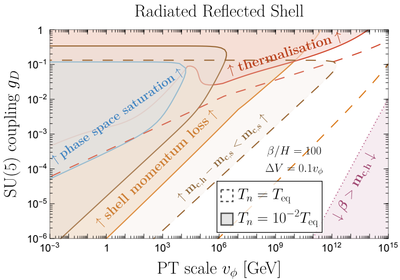


Shell Free Streaming Conditions



Radiated Reflected Shell





Bubble collisions

End of the phase transition

- The phase transition completes through bubble nucleation/percolation.
- The bubble collisions lead to a gravitational wave signal.

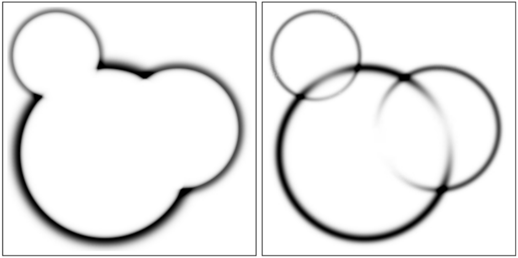
$$\Omega_{\mathrm{GW}}(\nu) \equiv \frac{d\Omega_{\mathrm{GW}}}{d\log\nu}$$

The spectra depend on the macroscopic properties

1. Latent heat $\alpha \approx \rho_{\mathrm{vac}}/\rho_{\mathrm{rad}}$.
2. Inverse timescale of the transition $\beta = -\frac{dS}{dt}$. (Sets bubble size).
3. The Hubble scale (determines redshifting).
4. The wall velocity v_w. For us $v_w \simeq 1$.

We can calculate these quantities from microphysics and then match onto results from simulations/semi-analytic studies.

Bubble collisions



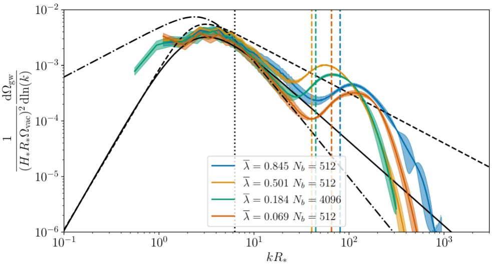
Left: envelope approximation. Right: bulk flow model.
Image from Konstandin 1712.06869

The GW spectrum

For such supercooled PTs: seems to be captured by the *bulk flow* model.

See: Ryusuke Jinno, Masahiro Takimoto 1707.03111,
Thomas Konstandin 1712.06869

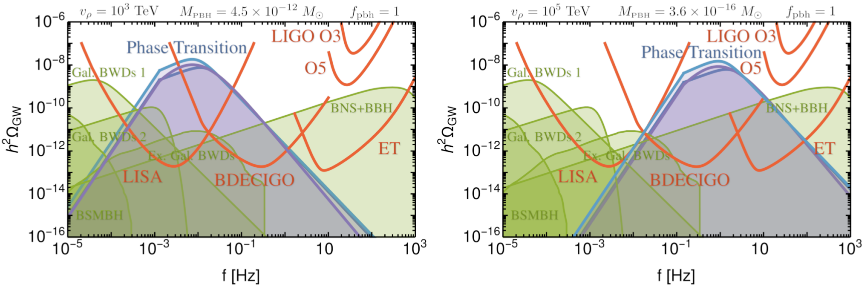
Comparison of bulk flow to simulations.



Cutting et al. 2005.13537 (also see Lewicki, Vaskonen 2007.04967)

- Amplitude scales as $(R_* H_*)^2 \approx (H_*/\beta)^2$.
- The peak frequency is set by the redshifted mean bubble size.
- Below the peak: region of $\Omega_{\rm GW}(\nu) \propto \nu^{0.9}$.
  $\rightarrow$ Eventually $\Omega_{\rm GW}(\nu) \propto \nu^3$ for superhorizon modes.
- Above the peak: $\Omega_{\rm GW}(\nu) \propto \nu^{-2.1}$.
- Second peak: suppressed by $\sim n_b/H_*^3 (m_\phi/M_{\rm Pl})^2$.

Details - GWs



Three estimates are used:

- (3+1)D Lattice simulation of scalar field - Cutting et al. 2005.13537
- Hybrid simulation including gauge field - Lewicki/Vaskonen 2012.07826
- Semi-analytic bulk flow model - Konstandin 1712.06869

These all return similar estimates. Detectable above astro foregrounds.

Uncertainties in the GW spectrum

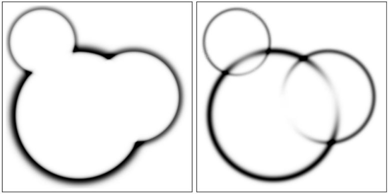


Illustration of envelope vs bulk flow - Konstandin 1712.06869

- The high frequency tail is completely different in the envelope ($\propto 1/f$) compared to the bulk flow model ($\propto 1/f^2$).
- The latter more closely matches 3D lattice simulations for strong supercooling.
- The full simulations have limited resolution/frequency range.

Common systematic: Ignores expansion during PT itself

Effect calculated in the envelope approximation assuming radiation domination

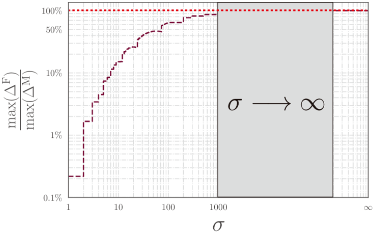


Figure 5. The step plot of the fraction of the maximum value of Δ^F to the maximum value of Δ^M versus σ. When $\sigma \lesssim \mathcal{O}(10)$, the corresponding GW spectrum is significantly influenced by the expansion of the universe. Even when $\sigma \sim 100$, the GW spectrum is still be depressed by 50%

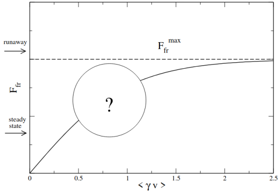
From Zhong et al, JHEP 02 (2022) 077 arXiv:2107.01845.

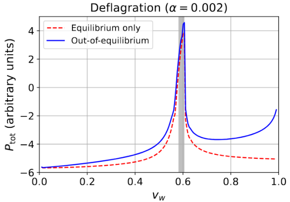
Friction Force and Hydrodynamic obstruction

Equation of Motion for ϕ:

$$\Box\phi + \frac{\partial V(\phi)}{\partial \phi} + \sum_i \frac{dm_i^2}{d\phi} \int \frac{d^3p}{(2\pi)^3 2E_i} f_i(p,z) = 0$$

Self-consistent determination of $\phi(z)$ and $f_i(p,z)$ typically difficult.





- Espinosa et al. 1004.4187 - Laurent and Cline 2204.13120

Clarifications about $f_{\rm eq}$ term: - Wen-Yuan Ai, Garbrecht, Tamarit 2109.13710

Hydrodynamic obstruction at large α? - Wen-Yuan Ai et al. 2401.05911, Beyond steady state - Lewicki et al. 2402.15408

Here we will assume a ballistic limit/runaway wall is reached.

(i.e. hydrodynamic obstruction overcome and MFP larger than wall thickness) .

Example: Electroweak baryogenesis - basic picture

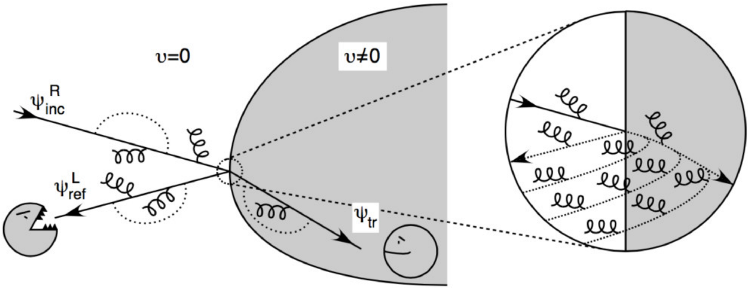
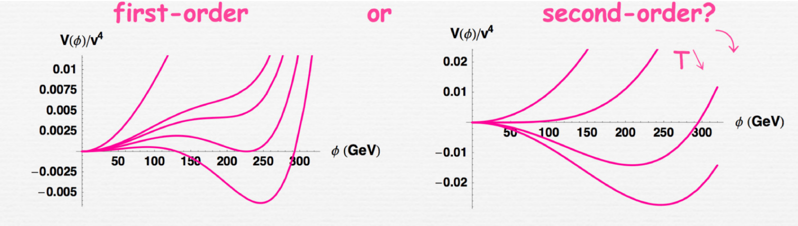


Image from - Gavela, Hernandez, Orloff, Pène, Quimbay [hep-ph/9406289]

- CP violating collisions with the bubble walls lead to a chiral asymmetry.
- Sphalerons convert this to a Baryon Asymmetry.
- This is swept into the expanding bubble where sphalerons are suppressed.

Electroweak baryogenesis - Requirements



Electroweak baryogenesis requires:

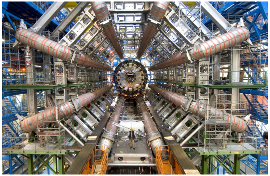
- A strong first order phase transition ($\phi_n/T_n \gtrsim 1$)
- Sufficient CP violation

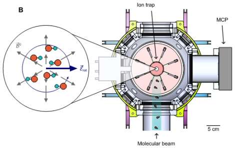
However in the SM:

- The H boson mass is too large
- Quark masses are too small

Requires new EW-scale physics.

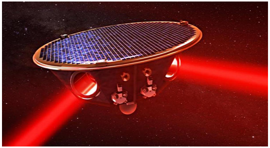
Experimental signatures

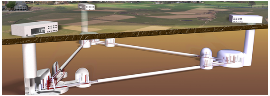


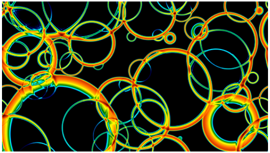


BSM Experimental signatures for EWBG

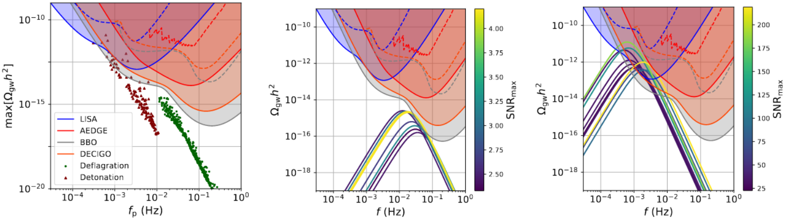
1. Collider signals associated with $V(H)$ modificiation.
2. Electric Dipole Moments associated with low scale CP violation.
3. Gravitational waves from the strong FOPT.







From a simulation by Weir et al.

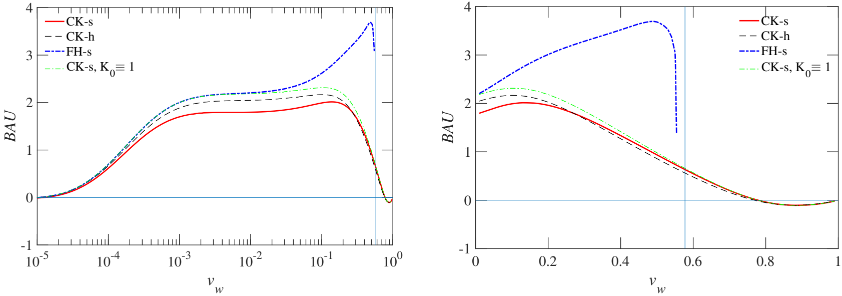


Singlet model - Cline et al. 2102.12490

Only the strongest transitions are detectable by LISA.

But: problem if $v_{\text{wall}} \simeq 1$ (strongest transitions).

- Less of the plasma is pushed by the wall at high v_{wall}.
- This suppresses the BAU.
- EWBG typically occurs in a radiation dominated background.



From: Cline, Kainulainen 2001.00568

Also see: Dorsch, Huber, Konstandin 2106.06547