

Particle Production from Bubble Wall Collisions

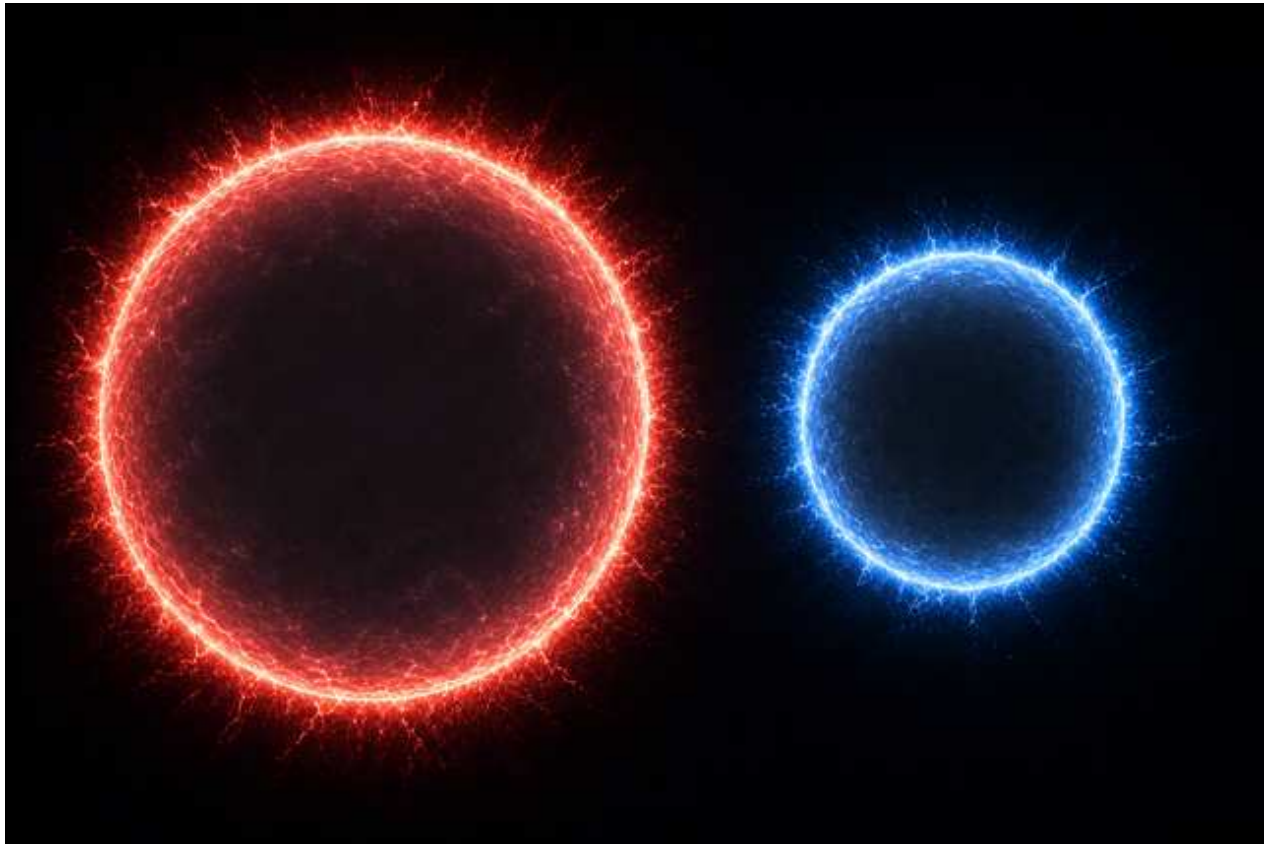
Alessandro Strumia, talk at Cargese SW18 +2026

From arXiv:2607.15279 with Ghoshal, Pal

Runaway walls can reach Planckian energies

Data able of probing new physics above the weak scale will come from cosmology. A possibility: some scalar s with mass m_s underwent a first order phase transition. Bubbles nucleate and expand, accelerated by ΔV, decelerated by friction $\sim T_{\rm nuc}^4$. In super-cooled transitions $\Delta V \gg T_{\rm nuc}^4$ bubbles go runaway, collect most of the energy of the universe reaching huge Lorentz factors γ when bubbles finally collide

$$\gamma_{\rm runaway} m_s \lesssim \bar{M}_{\rm Pl}.$$



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Various authors computed particle production and its testable phenomenology:

- First computation, Watkins, Widrow, [NPB 1992].
- EW baryogenesis, Konstandin, Servant [1104.4793], Katz, Riotto [1608.00583].
- Dark matter: Falkowski, No [1211.5615], Giudice, Lee, Pomarol, Shakya [2403.03252].
- Leptogenesis: Cataldi, Shakya [2407.16747], Ghoshal, Pal [2601.02458].
- Cogenesis: Cataldi, Müürsepp, Vanvlasselaer [2506.12123].
- Higgs: Shakya [2512.13815].
- Gravitational waves: Inomata, Kamionkowski, Kasai, Shakya [2412.17912].
- Precision: Mansour, Shakya [2308.13070], Shakya [2308.16224], ...

We show that standard results contain qualitative mistakes, and redo.

The standard 'off-shell' formalism

A scalar s jumps by Δs and ΔV. Consider its field configuration $s_2(x,t)$ with *two* bubble walls colliding with Lorentz factor $\gamma \gg 1$. The collision sends the quanta off shell with density given by the Fourier transform $s_2(p)$. Quanta s_p^* with $p^2 \gg m_s^2$ next decay into particles. The probability of particle production is

$$\wp = 2\mathrm{Im}\,\Gamma[s_2] \approx \int \frac{d^4p}{(2\pi)^4}|s_2(p)|^2 \mathrm{Im}\,\Pi(p^2)$$

having approximated the action Γ as quadratic, in terms of the propagator $\Pi(p^2)$. The optical theorem relates $\mathrm{Im}\,\Pi$ to the decay rate into final states f

$$\mathrm{Im}\,\Pi(p^2) = \frac{1}{2}\sum_f \int d\Phi |\mathscr{A}(s_p^* \to f)|^2.$$

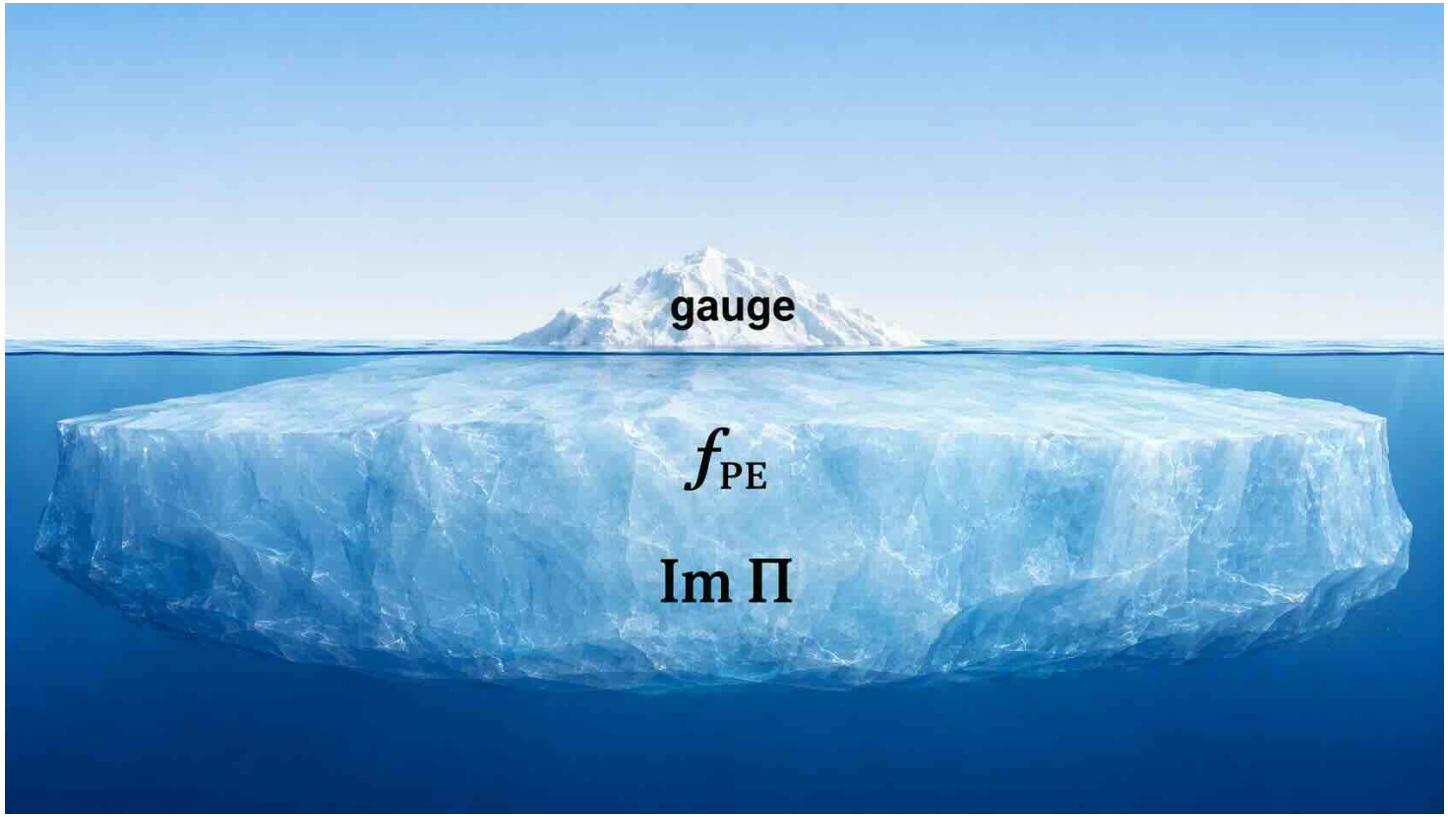
The collision is approximated as Perfectly Elastic or Inelastic getting the density

$$f_{\rm PE}(p) \sim |s_2(p)|^2 \sim \frac{\Delta s^2}{p^4} \qquad \text{up to} \qquad p \lesssim \gamma m_s.$$

A first order phase transition at low energy m_s probes high energy γm_s.

Both ingredients are problematic

Giudice et al. noticed that the rate $s_p^* \to VV$ for vector production is gauge dependent, even badly $\operatorname{Im}\Pi \sim -p^4$! Fixed it with Goldstone equivalence jugaad.



It's the tip of iceberg, bigger problems below: both factors in the convolution

$$\frac{\text{Number of produced particles}}{\text{Wall area}} = \frac{N}{A} \sim \int d^4p\, f_{\rm PE}(p)\, \operatorname{Im}\Pi(p)$$

are wrong. We propose how to do correctly.

The problem in the off-shell propagator

Consider a free scalar with $\Pi_0(p^2) = p^2 - m_s^2$, re-parameterise $s \to s + gs^2$, seems interacting, on-shell amplitudes recognise and vanish, the one loop propagator is

$$\Pi(p^2) = \Pi_0(p^2) - 2g^2\Pi_0(p^2)[6A + \Pi_0(p^2)B(p)] + \cdots$$

where the complex Passarino-Veltman function B contributes off-shell.

Off-shell propagators are not physical, they depend on field reparametrizations.

The effective action $\Gamma[s]$ is physical when computed over a solution to $\delta\Gamma/\delta s = 0$. The quadratic approximation is ok when the field has negligible self-interactions.

For bubbles one should compute the full Γ. But it's difficult, as a vacuum decay bubble is so intense that their collision is classically non-perturbative in λ:

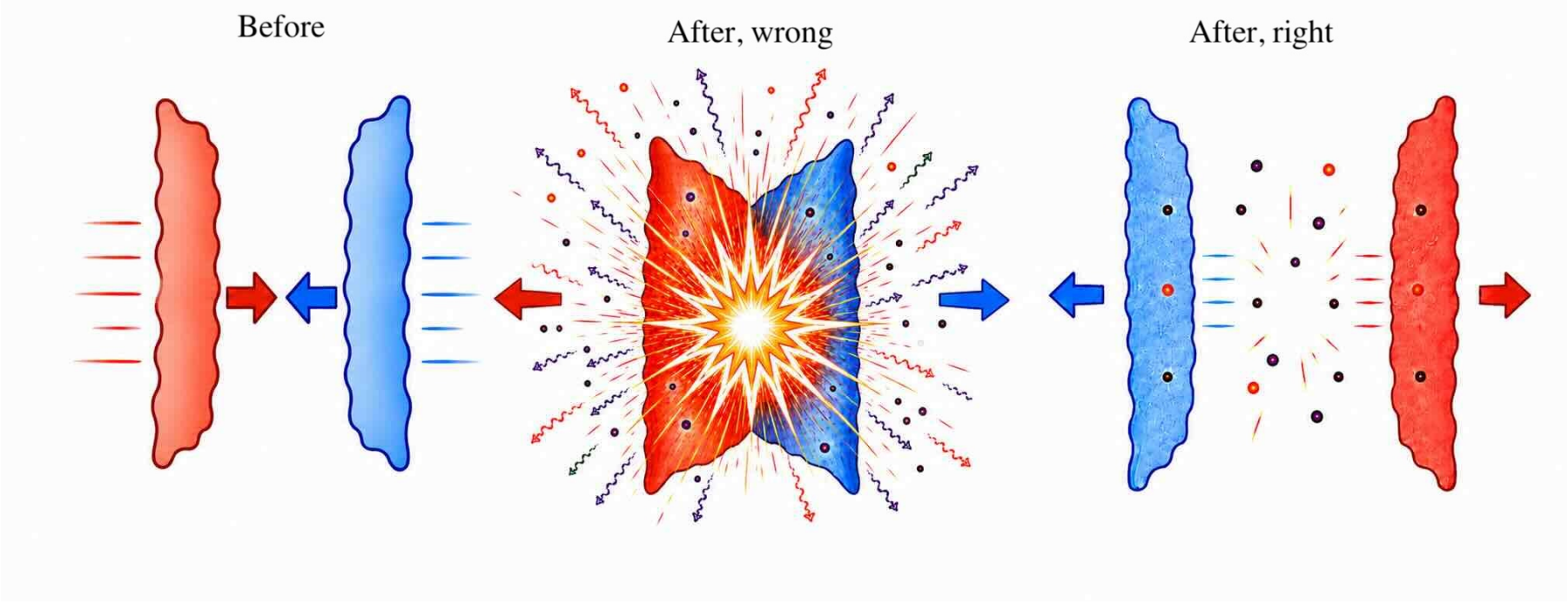
$$\partial^2 s = -V' \sim \lambda s^3 \qquad \Rightarrow \qquad \delta s/s \sim \lambda s^2/p^2 \sim 1.$$

Seems a $\mathcal{O}(1)$ issue with no simple solution. It's intuitively obvious that ultra-relativistic walls collide making a huge messy smash. Elastic, inelastic, who cares?

Right?

The problem in the off-shell density $f(p)$

Two ultra-relativistic walls collide making something simple: almost nothing.



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Two ultra-relativistic walls collide making something simple: almost nothing.

Why? Because relativistic walls are Lorentz contracted $\ell = \ell_0/\gamma$.
The collision is so fast that the potential force $V'(s)$ has no time to act:

$$s_2(x,t) = s_L(x - vt) + s_R(x + vt) \qquad \text{up to} \qquad \delta s/s \sim 1/\gamma^2.$$

V' later slowly drives rollback and re-collisions, but giving soft particles only.
The Fourier transform of s_2 is nearly on-shell, up to soft virtuality.

Confirmed by analytic solutions in toy models. Known in GW production papers.

How was this missed? It's counter-intuitive. A perfectly elastic collision looks like no collision, if the identity of the two waves is confused. E.g. classical ansatz $s_2(x,t)$ with $t \to |t|$ discontinuity gives an artificially hard Fourier $s_2(p) \sim 1/p^2$. An and Jang [2607.16398] confirm getting a power suppression $s_2(p) \sim 1/p^4$.

This suggests a 'new' approach to correctly approximate hard particle production.

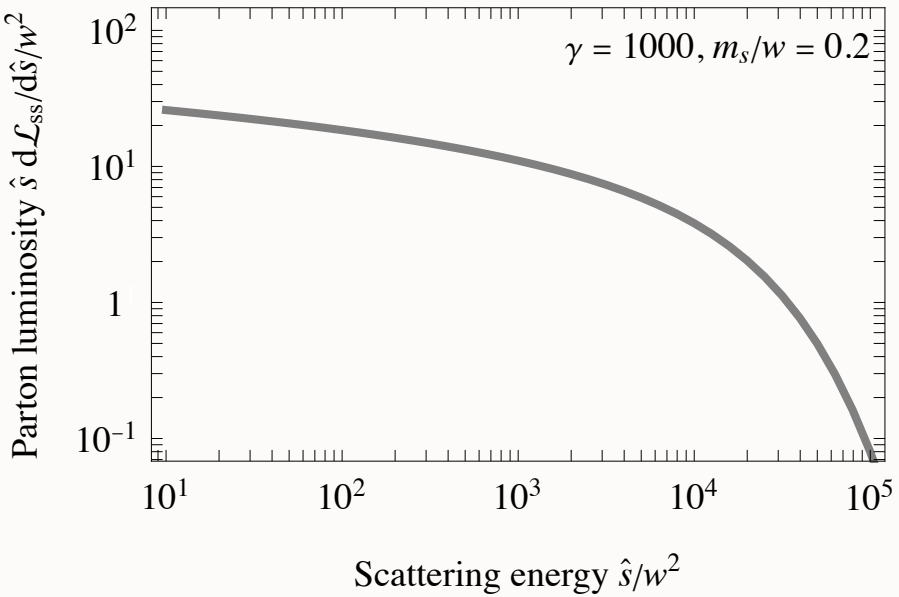
A new on-shell approximation

New idea: the ultra-relativistic walls are so much Lorentz-contracted that, during the collision, the different parts of each wall don't have time to self-interact.

So, one can approximate each wall as nearly-free constituent partons, the s quanta.
The density $F(p)$ of nearly-on-shell partons in *one* ultra-relativistic wall $s_1(x,t)$ is obtained by squaring its Fourier transform.
The hard event rate is obtaining convoluting with 'partonic cross sections':

$$\frac{N_f}{A} = \int d\hat{s} \frac{d\mathcal{L}_{ss}}{d\hat{s}} \hat{\sigma}_{ss\to f}(\hat{s}), \qquad \frac{d\mathcal{L}_{ss}}{d\hat{s}} = \int dp_L dp_R \, F_L(p_L) F_R(p_R) \delta(\hat{s} - 4p_L p_R).$$

A typical $s_1(x') = w \tanh(m_s x'/2)$ wall in the rest frame $x' = \gamma(x \pm vt)$ gives



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$$\hat{s}\frac{d\mathcal{L}_{ss}}{d\hat{s}} \simeq \frac{32 w^4}{\pi^2} \begin{cases} \ln \dfrac{\gamma e m_s}{\pi\sqrt{\hat{s}}} & \sqrt{\hat{s}} \ll \gamma m_s \\ \dfrac{\pi^4 \hat{s}^{7/4}}{2(m_s\gamma)^{7/2}} e^{-2\pi\sqrt{\hat{s}}/m_s\gamma} & \sqrt{\hat{s}} \gg \gamma m_s \end{cases}$$

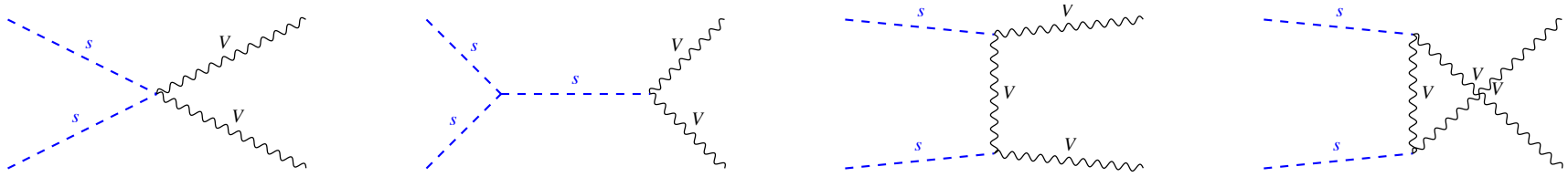
It contains a soft log tail, possibly corrected by saturation effects.

Up to these corrections, the new on-shell approach should approximate hard events $\hat{s} \gg m_s^2$ produced by ultra-relativistic wall-wall collisions.

SM particles can accumulate around the walls. They collide too as extra partons.

Cross sections

We compute $\hat{\sigma}$ for production of scalars, fermions, vectors, even gravitons:



The total $\hat{\sigma}$ is gauge-invariant, while s-channel exchange diagram alone is not.

Result: in quantum mechanics high energy means small length, so small $\hat{\sigma}$

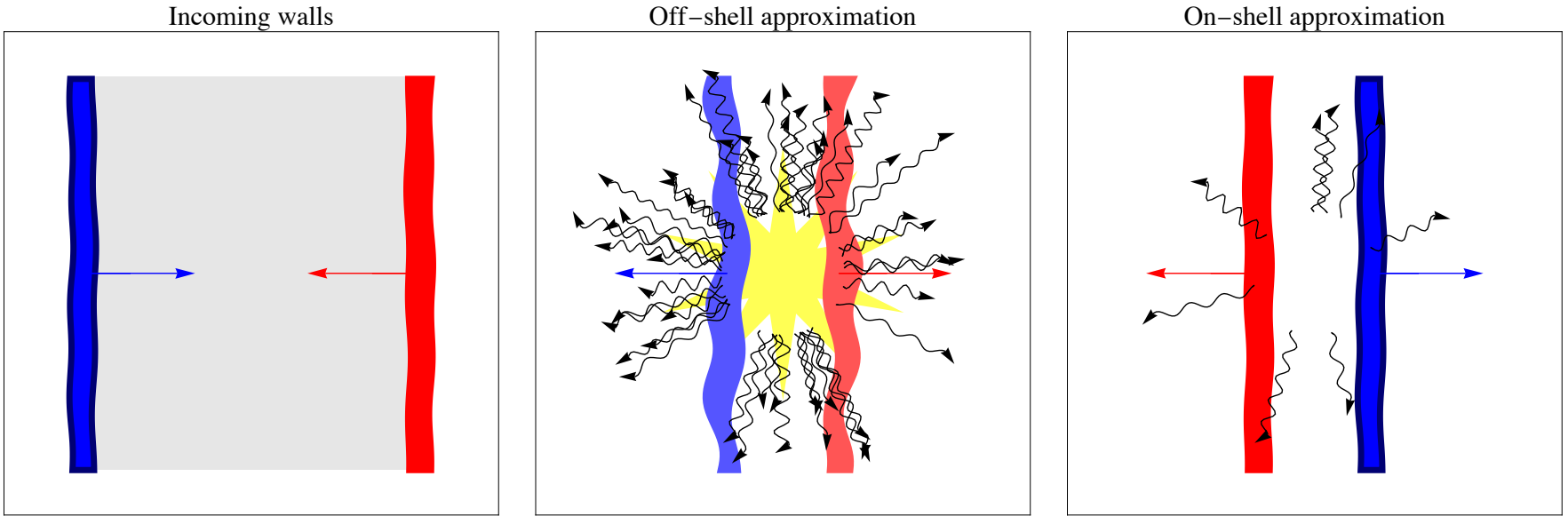
$$\hat{\sigma}(ss \to f\bar{f}) \sim y^4/\hat{s} + \cdots \propto 1/\gamma^2.$$

The off-shell approach over-estimated hard rates by $\hat{s}/m_s^2$.

Detail: $\hat{\sigma}(ss \to VV)$ gets constant at high energy, due to Coulomb long-range.

We reinvented the wheel to reinvent the wall

Weizsäcker-Williams did the same as 'equivalent' photons. Feynman for hadrons.



Surprisingly, even collider physicists did something else, similar to approximating pp as perfectly (in)elastic collisions of proton balls, claiming that all quarks and gluons inside go off-shell, getting a rate that violates quantum and relativity.
If that were true, high energy colliders would not need high luminosity.

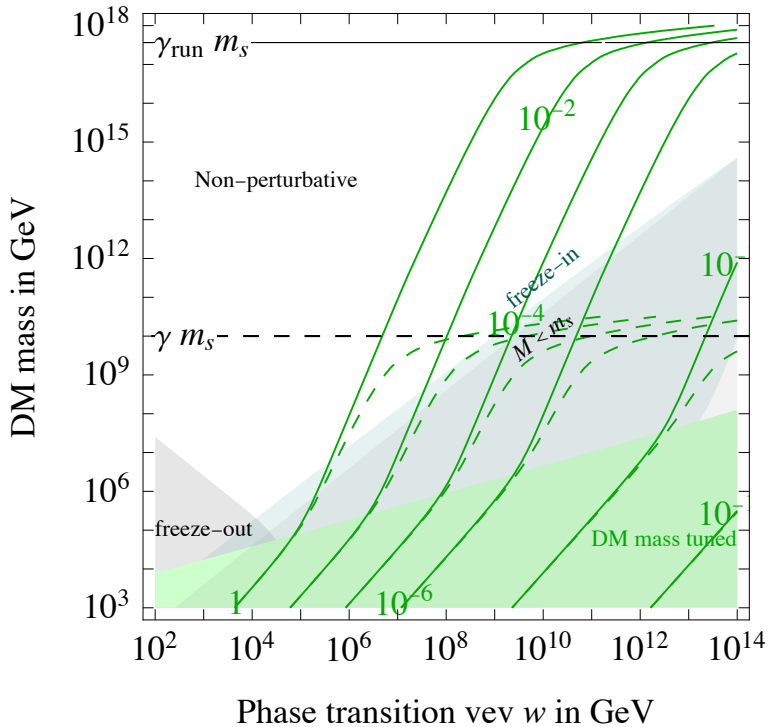
Dark matter

Can bubble collisions generate $\gg 100\,\mathrm{TeV}$ DM with the correct Ω_{DM}?

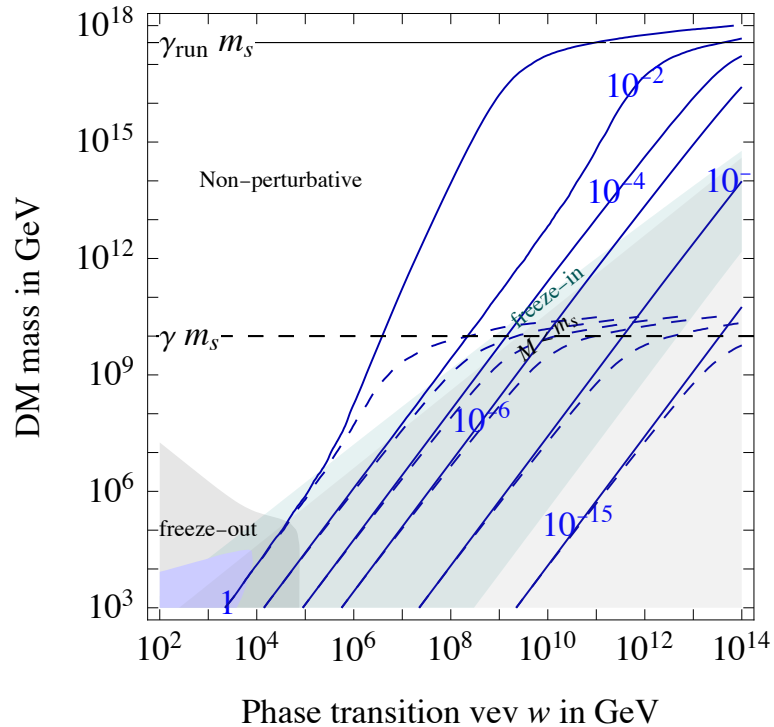
$$\Omega_{\mathrm{DM}}h^2 = 0.1\,\frac{\beta}{H}\,\frac{M_{\mathrm{DM}}w}{(100\,\mathrm{TeV})^2}\left[\frac{\alpha}{(1+\alpha)c_V}\right]^{1/4}\frac{1}{w^2}\,\frac{N}{A}.$$

Assume phase transition parameters $\alpha = \Delta V/\rho_{\mathrm{rad}} = 1$, inverse velocity $\beta/H = 10$. The on-shell $N/Aw^2 \sim y^4 w^2/M_{\mathrm{DM}}^2$ needs these values of couplings:

Scalar DM coupling $\lambda_{s\phi}$



Fermion DM coupling y



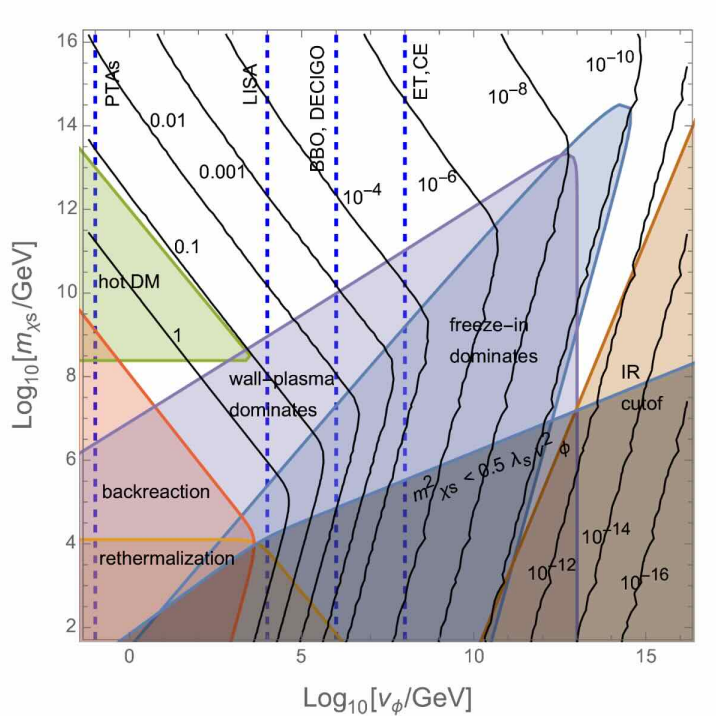
$M_{\mathrm{DM}} \gg w \sim$ TeV needs non-perturbative. Some regions survive to freeze-in/out.

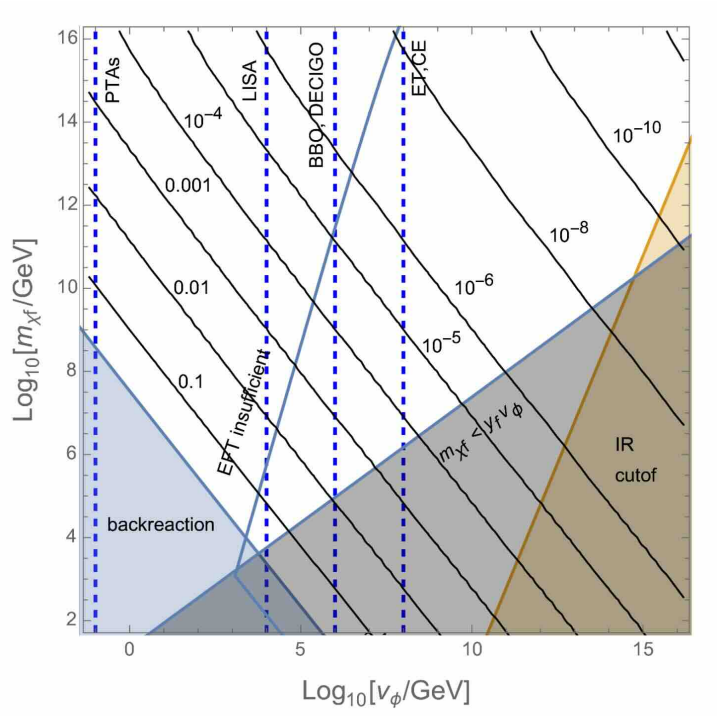
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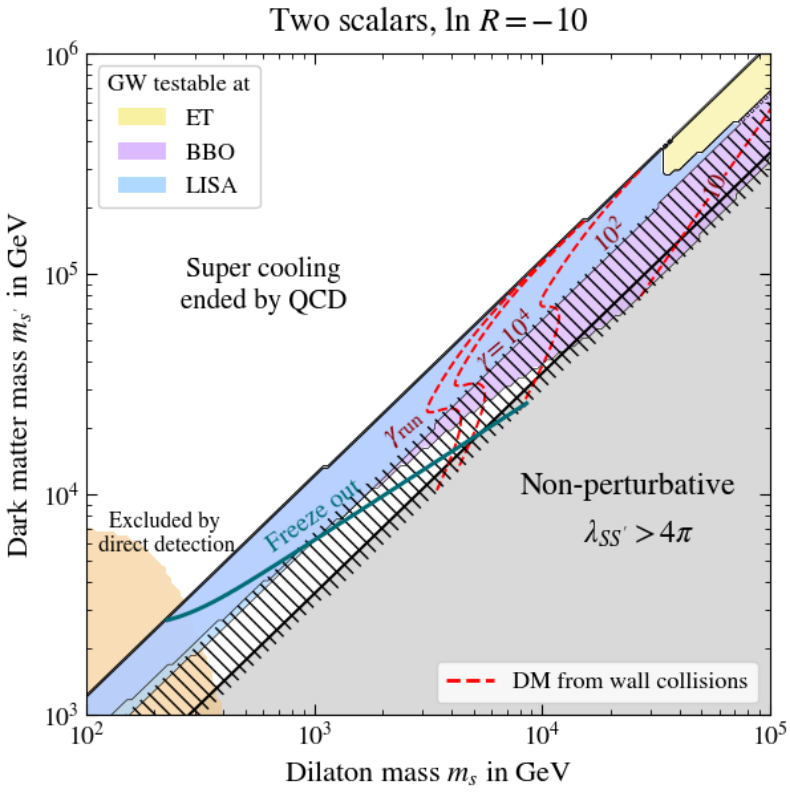
Assume phase transition parameters $\alpha = \Delta V/\rho_{\mathrm{rad}} = 1$, inverse velocity $\beta/H = 10$. The old off-shell $N/Aw^2 \sim y^2$ was significantly different allowing $M \gg w$:

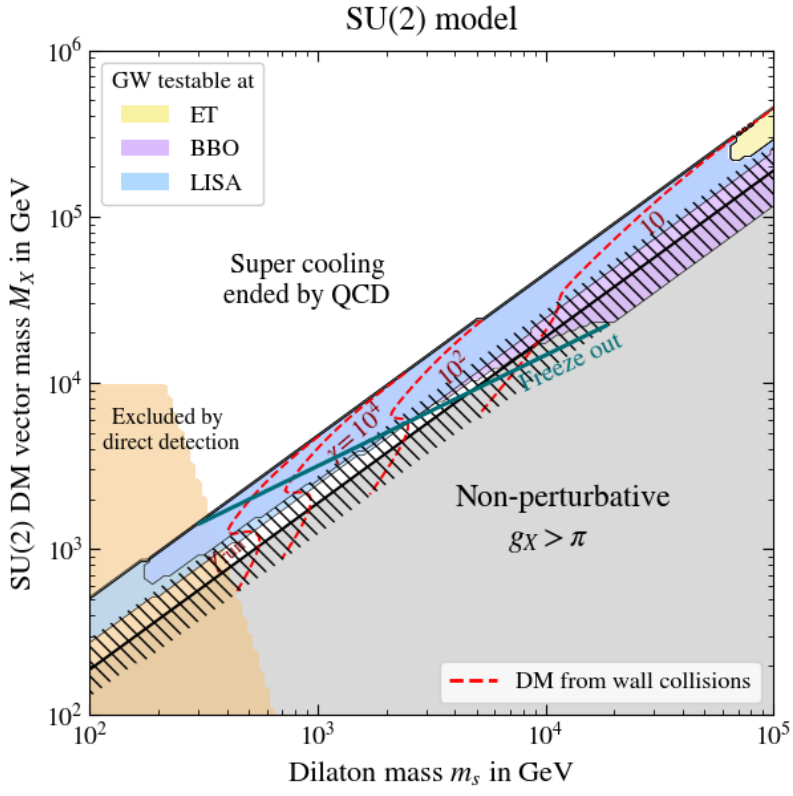




A dark matter model

Minimal models of dynamical EW symmetry breaking triggered by DM.
In these models bubble collisions could provide $\Omega_{\rm DM}$ but freeze-in/out do more.



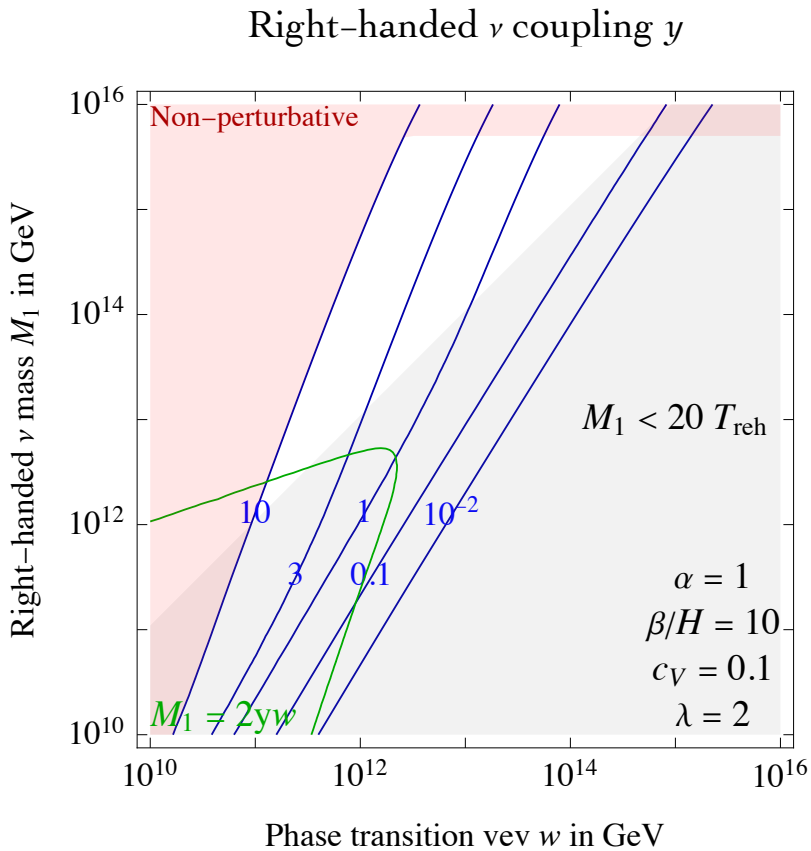


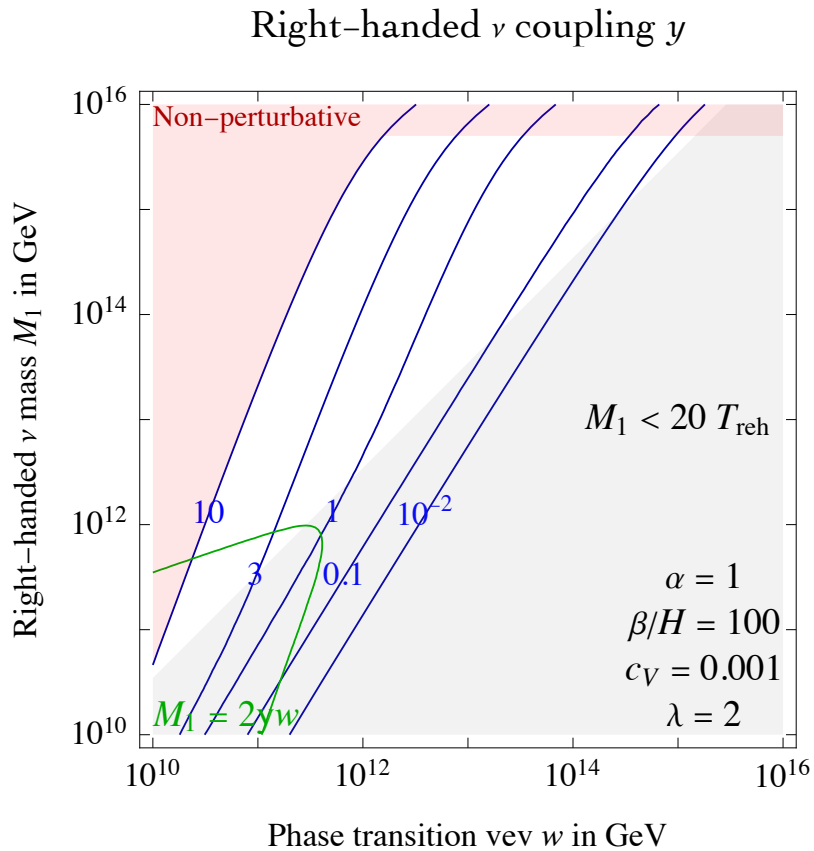
Leptogenesis

Super-cooling washes out baryons, need to regenerate after the phase transition. Assume that right-handed neutrinos couple to the walls scalar as $y\, sN^2/2$:

$$\frac{n_B}{n_B|_{\rm exp}} \approx \frac{{\rm Im}\,\tilde{m}}{0.05\,{\rm eV}}\,\frac{\beta}{H}\,\frac{wM_1}{(2.6\ 10^{12}\,{\rm GeV})^2}\left[\frac{\alpha}{(1+\alpha)c_V}\right]^{1/4}\frac{1}{w^2}\,\frac{N}{A}.$$

Despite the reduced N/A bubble collision can re-do successful leptogenesis but only for $w \gtrsim 10^{10}$ GeV: inflation with $T_{\rm RH} \ll M_1 \gtrsim 10^{10}$ GeV is no longer allowed.





Gravitational waves

Bubble collisions give 'usual' Gravitational Waves signals peaked around

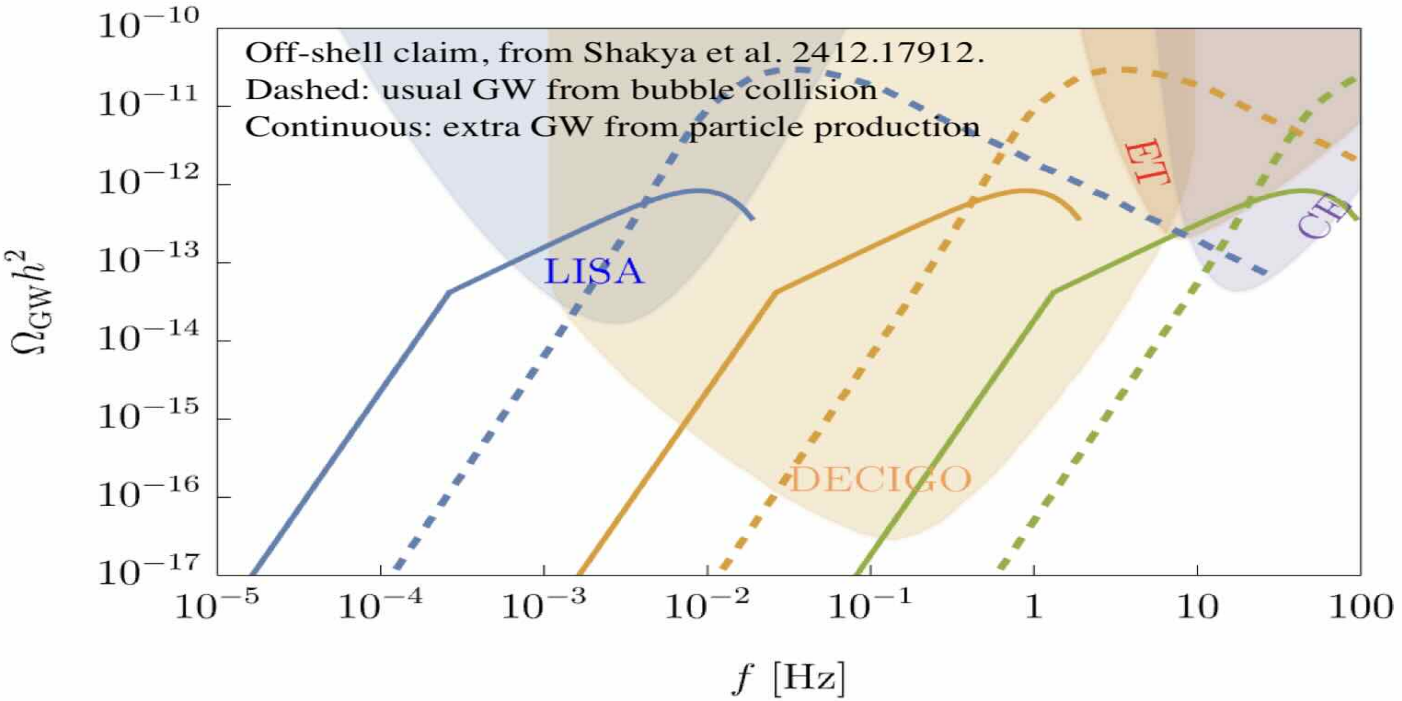
$$f \sim \text{Hz} \frac{\beta}{H} \frac{T_{\text{reh}}}{10^7\,\text{GeV}}.$$

E.g. $w \sim 10^{10}\,\text{GeV}$ would be good for the Einstein Telescope.

The motion of scattered particles sources extra GW with a peculiar spectrum. Their intensity depends on the total energy scattered in bubble collisions

$$\frac{E}{A} = \langle E \rangle \frac{N}{A}.$$

The off-shell approach gave $\langle E \rangle \sim \gamma m_s$, $\sim 100\%$ energy scattered if $\lambda, y, g \sim 1$. This would allow to learn something about particle physics from cosmology:



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This would allow to learn something about particle physics from cosmology:

The on-shell approach gives $\hat{\sigma} \propto 1/\hat{s}$, so $\langle E \rangle \sim m_s$ is soft, like at LHC.
$\Omega_{\text{GW}}^{\text{extra}}$ is $1/\gamma^2$ suppressed compared to the off-shell claim.
Suppressed even for $ss \to VV$, where $\hat{\sigma}(\hat{s})$ is constant, but only at small $\hat{t}, \hat{u}$.
Suppressed even for $\gamma \sim$ few, as reducing γ needs friction so low total energy.

The 'usual' gravitational waves from bubble collisions remain unaffected.

Gravitons

Bubble collisions can reach nearly Planckian energy, directly scattering gravitons.

The dominant effect is single-graviton production, model-dependent $\hat{\sigma} \sim g^2/\bar{M}_{\rm Pl}^2$.

Today these gravitons have energy density

$$\Omega_g \approx 1.8\ 10^{-6}\,\frac{\beta}{H}\left(\frac{g\langle E_g\rangle}{M_{\rm Pl}}\right)^2\left[\frac{\alpha}{(1+\alpha)c_V}\right]^{1/2} \lesssim 2.5\ 10^{-6}\ \text{[CMB,BBN]}$$

and 'high' frequency

$$\langle f_0\rangle = \frac{\langle E_g\rangle}{2\pi}\,\frac{T_0}{T_{\rm reh}}\left(\frac{g_{s0}}{g_s}\right)^{1/3} \sim 10^{10}\,{\rm Hz}\,\frac{\gamma m_s}{T_{\rm reh}}$$

where direct detection experiments are difficult. Only extra radiation tests it?

Conclusions

Bubble collisions after 1st order phase transitions can reach $\lesssim$Planckian energies.

But the standard formalism is wrong, because

1) relies on off-shell quanta: gauge and parameterisation-field dependent.

Fixing 1) seems impossible, until one realises that there is a second problem:

2) Ultra-relativistic wall collisions do almost nothing. Not a big splash. Fantastic production rates of heavy particles simply do not exist.

The solution was well known to collider physicists

Ultra-relativistic walls behave like quasi-real partons at $\hat{s} \gg m_s^2$.
It's simple, it's gauge invariant, it's independent of field redefinitions.

We computed wall parton densities and partonic cross sections, and applied to:

- Dark matter? Still possible in a different parameter space.
- Leptogenesis? Possible but no longer nicely.
- Gravitational waves from particles? Negligible.
- Gravitons? Computed.